Center for Theoretical Physics
(CNRS / Ecole Polytechnique)

Activity Report
2013-2018

List of Acronyms

CNRS is the French acronym for "Centre National de la Recherche Scientifique"

"l'X" is the nickname of the Ecole Polytechnique

CRCN CNRS ≡ Researcher at CNRS *

DR2 CNRS ≡ 2nd grade Senior Researcher at CNRS

DR1 CNRS ≡ 1st grade Senior Researcher at CNRS

ESR CNRS ≡ Emeritus Senior Researcher at CNRS

AP X ≡ Assistant Professor at Ecole Polytechnique

PR X ≡ Full Professor at Ecole Polytechnique

AE X ≡ Assistant Engineer at Ecole Polytechnique

AE CNRS ≡ Assistant Engineer at CNRS

RE X ≡ Research Engineer at Ecole Polytechnique

RE CNRS ≡ Research Engineer at CNRS

HPC ≡ High-Performance Computing

*The CRCN position ("Chargé de Recherche de Classe Normale") is the merging of the former CR2 and CR1 positions, that is, 2nd grade Researcher and 1st grade Reseacher, respectively.

CONTENTS

Contents (detailed)

OVERVIEW OF THE CPHT AND ITS EVOLUTION OVER THE 2013-2018 PERIOD

We describe the CPHT and its evolution over the past 5 years, in successively finer steps.

Bird's eye view

The CPHT (acronym for Centre de Physique Théorique) is a Mixed Research Unit (UMR is the French acronym) between the CNRS and the Ecole Polytechnique. It was created in 1958 by Louis Michel.

Snapshot view as of June 30 2018. The CPHT has 80 members.† This number is composed as follows. The permanent research staff consists of 36 people:

- 23 CNRS Researchers;
- 2 Research Engineers at Ecole Polytechnique;
- 5 Teachers-Researchers (4 at Ecole Polytechnique and 1 Professor at Collège de France‡));
- 6 Emeritus Senior Researchers at CNRS.

There are 19 PhD theses in progress and 18 Postdoctoral Fellows.
The administrative staff consists of 4 people and the IT staff consists of 2 people.

Structure of the CPHT as of June 30 2018. The lab is structured in six groups. We indicate the number of *permanent* researchers for each group in parentheses, *without counting Emeritus Senior Researchers at CNRS*. This structure is the same as that of the previous 5-year period.

Research Groups		
Condensed Matter (7)	Laser Plasma Interaction (2.6)	Magnetized Plasmas (5.4)
Mathematical Physics (4)	Particle Physics (5)	String Theory (6)

*N*ote: there is a researcher working for two groups, which explains the non-integer values.

A few figures. The following figures are relevant indicators of the vitality of the CPHT:

- about 530 publications in international refereed journals for the 2013-2018 period;
- about 1400 "missions" for the 2013-2018 period. By "missions" we mean invitations of researchers at the CPHT, or researchers from the CPHT going to other labs or to conferences in France and abroad;
- 3 ongoing ERC grants (one "Starting", one "Consolidator", and one "Synergy") / 9 ANR projects (8 of them managed by the CPHT), with 5 ongoing ones / 3 EUROfusion projects / 1 Simons Foundation grant;
- 21 defended PhD theses during the 2013-2018 period, and 19 PhD theses in progress.

† One should also aggregate the visitors and undergraduate interns to have the effective size of the lab.

‡ A formalization of our partnership is in progress since part of the Condensed Matter group also works at the Physics Institute of Collège de France.

Research highlights

The CPHT is known for its expertise and research achievements in a variety of areas. In this section we present very briefly the 6 groups, together with their research highlights.

Condensed Matter group. The Condensed Matter group of CPHT spans a large spectrum of topics, ranging from materials questions addressed within the framework of first principles electronic structure calculations to new phenomena appearing in coupled light-matter systems.

During the reporting period, the group has made substantial progress on the theoretical understanding of the mysterious "pseudogap state", a state characterized by a depletion of low-energy excitations in some regions of the Brillouin zone, that is experimentally observed in high-temperature superconducting copper oxide materials. W. Wu, M. Ferrero and A. Georges (Phys Rev B 96, 041105R (2017)) have shown that the pseudogap state can be reached using improvements of the diagrammatic Monte- Carlo technique, identifying short-range antiferromagnetic fluctuations as the physical mechanism for the pseudogap in the 2D Hubbard model. Distinctive features of the pseudogap appearing in numerical simulations have been related to a novel kind of topological order.

A similar phenomenology as in these cuprate systems was recently also found in iridium oxides. In collaboration with colleagues performing angle-resolved photoemission spectroscopy (L. Perfetti, LSI – Ecole Polytechnique, and V. Brouet, LPS Orsay), the team around S. Biermann has elaborated a first principles description of spectroscopic properties of pure and electron-doped Sr2IrO4, shedding light on the putative pseudogap also in this family of materials (Martins et al., Phys. Rev. Mat. Rapid 2, 032001(R) (2018)).

At a more general level, the development of truly first principles techniques for correlated materials has been a core activity of the CPHT scientists over the period of reporting: within the ERC project of S. Biermann, a combined screened exchange dynamical mean field theory has been developed, tested and applied, avoiding the ad hoc character of standard density functional dynamical mean field theory schemes. L. Pourovskii and collaborators have proposed a new approach to the ab initio evaluation of the crystal field splittings in rare earth 4f shells based on a quasi-atomic approximation for the many-electron effects. Their scheme suppresses the unphysical "self-interaction" contribution to the crystal field parameters, which arises due to an incorrect treatment of localized states within the standard density-functional-theory framework. The method was successfully applied to prospective rare-earth-based hard-magnetic intermetallics (PhD thesis of P. Delange – co-supervised by L. Pourovskii and S. Biermann), in the framework of the bilateral French-German ANR-DFG project "RE-MAP", in collaboration with the Max-Planck-Institut für Eisenforschung, Düsseldorf, and the TU Darmstadt, Germany.
Structural properties have been in the focus of work by A. Subedi on LiVO2 (A. Subedi, Phys. Rev. B 95 , 214119 (2017)). He identified two unstable phonon branches in this compound and was able to stabilize a structure – exhibiting vanadium trimers due to V 3d covalency – that is lower in energy than the high-temperature structure. Such a phase was described using a phenomenological model by J. Goodenough, and A. Subedi's work provides a microscopic basis for it as well as a prediction for its crystal structure. Finally, within the context of the ERC "Frontiers in Quantum Materials Control", A. Georges and collaborators have constructed a microscopic theory of nonlinear phononics phenomena.

The PhD thesis of C. Crosnier de Bellaistre (supervised by L. Sanchez-Palencia) studied the effect of an electric field on a system displaying Anderson localization. In the one-dimensional case, a universal scaling theory of Landauer conductance and localization in one dimensional wires subjected to a finite drift force could be derived (Crosnier de Bellaistre et al., PRB (R) 2017, PRA 2018). The team of L. Sanchez-Palencia further studied the out-of-equilibrium dynamics of correlated matter, demonstrating and characterizing a universal twofold spreading in spin systems with long-range exchange interactions (Cevolani et al., Phys. Rev. B 98, 024302 (2018)). On the methodological side, L. Sanchez-Palencia and collaborators developed a time-dependent variational approach for continuous systems using a Jastrow-Feenberg ansatz (Carleo et al., PRX 2017).

The dynamics of correlated quantum matter has also been in the focus of K. Le Hur and collaborators. They have elaborated a stochastic Schrödinger equation approach to address the real-time dynamics of interacting effective quantum spin systems, realized, *e.g.*, in cold atom systems, mesoscopic systems or quantum materials (for a review, see K. Le Hur, et al., Comptes Rendus Académie des Sciences 2018, arXiv:1702.05135). The method was also generalized to describe topological properties of a spin-1/2 coupled to a bath on the Bloch sphere (Henriet et al. Phys. Rev. B 95, 054307 (2017)) and the dynamics of the dissipative quantum Rabi model (L. Henriet, Z. Ristivojevic, P. P. Orth, K. Le Hur, Phys. Rev. A 90, 023820 (2014)) making a link with quantum optics.

Finally, K. Le Hur and collaborators have studied the phase diagram of the interacting bosonic Haldane model and identified a new chiral superfluid phase as a result of gauge fields (I. Vasic, A. Petrescu, K. Le Hur, W. Hofstetter, Phys. Rev. B 91, 094502 (2015)). The Mott phase shows topological excitations at high energy. Very recently, the analysis has been extended to provide the phase diagram for the bosonic-Kane-Mele model for the first time. The most intriguing finding is a new chiral spin state in the Mott phase of the bosonic system (K. Plekhanov, et al., Phys. Rev. Lett. 120, 157201 (2018)).

Laser Plasma Interaction group. The laser-plasma interaction group is mostly concerned with the modeling of the propagation of the laser light through hot plasmas, partially ionized gases, or liquids. The most prominent processes studied are: (i) the absorption of the laser light and the wave-wave coupling instabilities in the context of inertial confinement fusion (ICF) with laser, (ii) laser-driven particle acceleration, (iii) the generation of secondary radiation sources and their applications.

In addition to the important long term programmatic work on these subjects, elaborated within this report (see Chapter 2), several highlights in our research over the past 5 years can be mentioned:

(i) In the context of laser fusion, the uncontrolled energy exchanged between the incident laser beams that cross each other in the plasma inside the cavity containing the D-T fusion capsule remains an unsolved problem of high priority. This process (commonly called "CBET" for Cross Beam Energy Transfer) has been modeled in the limit where the speckle structure, inherent to realistic laser beams, is ignored. With the models and the numerical tools developed in our group, we have shown for the first time that the speckle structure has a strong influence on the angular aperture of beams after energy exchange. The knowledge of the regimes of such enhanced angular spread is of fundamental importance for the laser fusion target design. In the same context, we have determined in collaboration with an experimental group the onset of collective laser-plasma instabilities that can appear in multiple-beam configurations.

(ii) Laser-driven particle acceleration schemes are in constant evolution. To achieve high ion (mostly proton) energies with laser-plasma acceleration, the common scheme consists of a sub-picosecond laser pulse that impinges normally or obliquely the vacuum-plasma interface of a solid-density target. A part of the accelerated electrons penetrate into the target and exit at the rear surface with high energy, being consequently followed by energetic ions. The laser energy absorption on the vacuum-plasma interface plays a major role for the acceleration efficiency of this scheme; it can be strongly improved by an imprinted surface structure on the interface.

Due to the variety of possible imprints and their dynamics, the optimization of this process is currently a 'hot topic'.

P. Mora did a pioneering work to model the influence of the rear plasma expansion on the ion acceleration. Besides the extension of this model itself, we continued on this subject and carried out particle-in-cell (PIC) simulations with our PIC code and obtained new important results concerning the surface gratings and/or surface wave excitation: we derived clear criteria on the robustness of excited surface wave and their role in the particle acceleration.

(iii) The control of laser energy deposition in transparent solids is of major importance for micro-machining applications (ultra-fast cutting, drilling, structuring of glasses, micro-fluidics). By means of theoretical and numerical studies we have shown that intense high-order Bessel beams allow for a tubular deposition of laser energy within a glass target, providing an additional degree of control for the aspect-ratio of the focal region. Optimization of the conditions for versatile micro-machining or structuring of glasses can be realized by properly shaping the Bessel beams. On the basis of these works, a patent for ultra-fast micro-machining of transparent media by filamentation with Bessel beams carrying angular momentum has been submitted.

Magnetized Plasmas group. Historically, the scientific activity and the international recognition of the team are at the interface between the theoretical modelling of nonlinear phenomena in magnetized plasmas, the development of numerical methods and codes for their simulation and the use of these tools within strong collaborations with experimentalists for interpretation and prediction in experiments. We are involved as a key component in national and international programs.

In tokamak physics, an important effort was dedicated in the last years to the inclusion of collisions in the kinetic module of our 3D hybrid fluid/kinetic code XTOR-K. Collisions are necessary in the kinetic part of the code to relax fast ion distributions after a crash, to simulate neoclassical radial transport of heavy ion markers, and to obtain self-consistent slowing down particle distributions, for example fusion alphas or fast ions generated by external heating devices. The methods used in XTOR-K are based on the Landau-Fokker Planck approximation of the Boltzmann collision operator. One uses domain cloning and relies on Langevin kicks of effective Maxwellian distributions. Another uses domain decomposition and binary collisions and is based on the direct sampling of the Landau-Fokker-Planck equation. The advantage of the latter method is that it is very robust, contains all the nonlinearities of the problem, and is energy/momentum conserving. Moreover it turned out to be more efficient in terms of HPC. The model in the two-fluid version of the code was adapted to address several important issues, such as the control of internal plasma instabilities by external heating devices (RF antennas and current deposition with gyrotrons), the migration of heavy impurities inside the plasma in the presence of macroscopic instabilities. We introduced also equilibrium boundary conditions given by a set of poloidal magnetic field coils and a plasma shell with finite resistivity. The latter issue is important because it allows the generalization of equilibrium magnetic field topologies to the one characteristic of large tokamaks, with a singular poloidal magnetic flux surface (WEST, ASDEX Upgrade, JET, ITER). This opens the investigation field to new families of macroscopic tokamak instabilities.

The work in astrophysical plasmas mainly covered the characterization and the identification of mechanisms at the origin of large scale eruptive phenomena in the solar corona and of the heating of the solar atmosphere. An important piece of work consisted in the exploitation of results provided by space missions and in the participation of national and international space weather programs (CNES, DGA, ESA, NASA). By studying the genesis of real eruptions which occurred in 2006 and 2014, using our models and magnetic and coronal measures from different satellites, we discovered that these two classes of eruptions are associated with the formation/presence of a magnetic structure (twisted magnetic ropes) whose evolution towards an ejective or a confined instability depends, as predicted by one theoretical model, on the presence of another discovered structure: a magnetic cage. These studies led to two front page articles in Nature. In our work on the heating of the solar atmosphere, our simulations revealed that the heating is the result of a combination of two different mechanisms: the generation of the magnetic field by surface dynamo effect under the photosphere produces a magnetic and velocity field with a high enough energy to heat the chromosphere with multiple, continuous micro-eruptions and a few more important, sporadic eruptive phenomena reaching the lower corona, but not frequent enough for its heating. The interaction of this chromospheric dynamics with the field at large scale generates waves which transport the energy into the core of the corona.

Our activities in Hall thruster physics results from previous theoretical and numerical works showing the existence of electronic cyclotronic instabilities and their consequence on the electronic transport in the operation of a Hall thruster. We have compared our numerical simulations with experimental results with the SNECMA PPS1350 thruster in the ICARE laboratory within the framework of a CNES contract. The PIC2D simulations in (z,θ) corresponding to the case without secondary electron emission, show an increase of the current and of its standard deviation as a function of the voltage, as in the experimental results. They also show an increase in the electronic fluctuations due to the electron cyclotron instability, slightly inside the exit plane, in connection with an increase of the accelerator field.

Mathematical Physics group. Over the past five years, random tensors underwent a tremendous transformation. The group in CPHT has been at the forefront of the research in this field. From 2013 to 2016, the activity of the CPHT group centered on non perturbtive results for models with quartic interactions and the study of the double scaling limit. A fundamental result, the classification of edge colored graphs by the degree, has been obtained by R. Gurau in collaboration with G. Schaeffer at LIX (Ecole Polytechnique).

Building on the results obtained by the group in CPHT, Witten introduced in 2016 a tensor quantum mechanical model and showed that it is equivalent in the large N limit to the Sachdev-Ye-Kitaev model. Contrary to the Sachdev-Ye-Kitaev model, Witten's model does not require disorder. The study of tensor quantum mechanics and tensor field theory started in earnest, with work by Klebanov and collaborators, Volovich and collaborators, Tseytlin and collaborators, Minwalla and collaborators, Vasiliev, etc. The group in CPHT continued to actively contribute to this line of research. An important result obtained recently by R. Gurau, in collaboration with D. Benedetti, S. Carrozza and M. Kolanowski, is the proof that (as conjectured by Klebanov and Tarnopolsky) a model for a symmetric traceless tensor in rank three has a $1/N$ expansion dominated by melonic graphs.

Perturbative renormalizability of the different sectors of the standard model in the Polchinski framework has been studied over several decades. On the way to a complete solution the difficulties increase exponentially when going from massive scalar fields to massless nonabelian gauge fields, this even more so when the mathematical proofs is supposed to apply to physical parametrizations of the theory. The step to massless nonabelian gauge theories has been achieved in 2017 in joint work by Efremov, Guida and Kopper. It has also been shown that the perturbative operator product expansion still converges for massless fields.

In mathematical ecology, our main achievement is the fine, and mathematically rigorous, description of the quasi-stationary behaviour of a class of birth- and-death processes describing a population which is made of d sub-populations of different types which interact with one another, and goes almost surely to extinction. These processes are parametrized by a scaling parameter K. For any fixed finite time span, it is well-known that such processes, when renormalized by K, are close, *in the limit* $K \to +\infty$, to the solutions of a certain differential equation whose vector field is determined by the birth and death rates. Let us stress that we were interested in what happens for finite K, which reveals in particular different time scales not previously described. To precisely describe this behavior, we have proven the existence of a quasi-stationary distribution. In fact, we have established a bound for the total variation distance between the process conditioned to non- extinction before time t and the quasi-stationary distribution. This bound is exponentially small in t, for $t \gg \log K$. As a by-product, we have proved an estimate for the mean time to extinction in the quasi-stationary distribution. We have also quantified how close is the law of the process (not conditioned to non-extinction) either to the Dirac measure at the origin or to the quasi-stationary distribution, for times much larger than $\log K$ and much smaller than the mean time to extinction, which is exponentially large as a function of K.

The Editors of Journal of Physics A: Mathematical and Theoretical have selected a paper by Ph. Mounaix, in collaboration with G. Schehr, entitled 'First gap statistics of long random walks with bounded jumps' for inclusion in its 'Highlights of 2017' collection. This distinction actually crowns a series of four papers published between 2013 and 2017 about the large n statistics of the gap and time interval between the two highest positions of an n-step random walk/Lévy flight. The originality of this work, in collaboration with S. Majumdar and G. Schehr, is the transposition to random walk theory of results from half-space transport problems – the Hopf-Ivanov formula – which, together with appropriate Tauberian theorems for generating functions, turns out to be a very powerful tool for studying order statistics of long random walks. Thereby, the authors have been able to prove the existence of a limiting joint distribution of the gap and time interval a thorough analytical study of which, for both discrete and continuous time random walks, has revealed a rich variety of behaviors depending on the tail of the jump distribution.

Particle Physics group. The particle physics group published outstanding results within three very active domains in the field of quantum chromodynamics (QCD).

The understanding of the 3-dimensional structure of the proton in terms of partons (namely quarks and gluons) is one of the main goals of hadronic physics. This structure is encoded in a set of so-called "Parton Distribution Functions" which can be extracted from the data, and the properties of which can be predicted in QCD. We discovered new ways to extract some elusive Generalized Parton Distributions (namely those related to the transverse spin structure of the nucleon), in particular through reactions initiated by a neutrino beam. We collaborated with JLab experimentalists to uncover the QCD structure of electroproduction of mesons in a new kinematical region, where Generalized Parton Distributions are to be replaced by Transition Distribution Amplitudes (matrix elements of three quark-operators). We also studied in more detail the physics content of Generalized Parton Distributions, with a focus on the QCD energy-momentum tensor which allows us to address the fundamental question of the origin of mass and spin of hadrons and determine the pressure forces inside these systems. Moreover, we established the connections between the Transverse-Momentum-Dependent gluon distributions introduced in three different approximations of QCD for high energies, namely the leading-twist truncation, the Color Glass Condensate effective theory and the Catani- Ciafaloni-Hautmann formalism.

With respect to the so-called dense regime of QCD (defined by large parton occupation numbers and large field strength), which is reached, *e.g.*, in very high-energy scattering of hadrons and nuclei, we discovered connections between the nature of the event-by-event fluctuations of the parton numbers on the one hand, and more general problems relevant in the broader context of branching random walks on the other hand. We arrived at new mathematical conjectures on random variables which characterize the realizations of such processes, and we examined the different consequences of these results for observables measured in high-energy hadronic collisions. The most prominent result we have obtained in this field is an analytical expression for the asymptotics of the distribution of a variable used to label diffractive events in deep-inelastic scattering, the "rapidity gap" variable.

Last but not least, in order to understand the fundamental property of confinement in QCD, we contributed to the development of a novel pertubative approach to tackle some of the infrared properties of QCD. In particular, we have shown that the Curci-Ferrari model (a massive extension of the standard, but incomplete Faddeev-Popov gauge-fixing) allows one to capture many of the features of the confinement/deconfinement transition, from a simple perturbative expansion.

String Theory group. The activity of the string-theory team over the last five years includes mathematical approaches to strings and supergravities, cosmology and phenomenology, quantum gravity and black holes, and gauge/gravity holographic correspondence.

New families of remarkable supersymmetric models have been constructed by reconsidering non-linear realizations of supersymmetry. These models have promising cosmological applications, which have been only partly explored at present (Antoniadis, Dall'Agata, Dudas, Farakos, Ferrara, Sagnotti).

Understanding the origin of the cosmological constant has been part of our agenda. It is small but non-zero, and this requires again supersymmetry to be broken at a low and stable scale. This has been achieved within the class of no-scale models (Angelantonj, Brandenberger, Coudarchet, Fleming, Kounnas, Partouche, Patil, Toumbas).

Sequential supersymmetry breaking has also been studied in $N = 2$ supergravity coupled to a single vector and a single hypermultiplet. This breaking pattern is normally possible if the quaternion-Kähler space of the hypermultiplet admits one pair of commuting isometries. For this class of manifolds, explicit metrics exist and a generic electromagnetic (dyonic) gauging of the isometries has been analysed, leading to partial-breaking vacua both in Minkowski and anti-de Sitter spacetime (Antoniadis, Derendinger, Petropoulos, Siampos).

Non-perturbative effects in string and field theory play a significant role. Their determination in the relevant observables requires combining methods from string theory and supergravity. One of the most important recent achievements was the development of an effective-field-theory derivation of the four- graviton amplitudes up to fourteen derivatives (Bossard, Kleinschmidt). This amplitude exhibits an exact cancellation of the supergravity divergences from the infinite tower of massive BPS (Bogomolny-Prasad-Sommerfeld) states up to three-loop order.

String theory is a potential ultraviolet completion of gravitation, where phenomena such as black-hole evaporation can be addressed. The determination of the black-hole microstates responsible for the black-hole entropy has led to the concept of fuzzballs. Studying their dynamics and investigating their distinguishability from the usual black hole at the horizon scale has been successfully investigated in the group (Chen, Marolf, Michel, Polchinski, Puhm).

Last but not least one should quote our contribution to the long-standing extension of AdS/CFT[§], *i.e.*, the asymptotically flat / conformal field theory correspondence. In its fluid/gravity version, the latter exhibits a Carrollian fluid, which has a specific dynamics, different from that of the relativistic fluid present in the usual AdS holography (Ciambelli, Marteau, Petkou, Petropoulos, Siampos).

[§]AdS/CFT means Anti-de Sitter/Conformal Field Theory Correspondence

PERMANENT STAFF AND ORGANIZATION AT A GLANCE (AS AT 30 JUNE 2018)

DIRECTOR
Jean-René CHAZOTTES ¶

ADMINISTRATIVE STAFF	IT STAFF
Florence AUGER (manager)	Jean-Luc BELLON (manager)
Fadila DEBBOU	Danh PHAM KIM
Malika LANG	David DELAVENNAT ‖
Jeannine THOMAS**	Sylvain FERRAND ‖

RESEARCH GROUPS		
CONDENSED MATTER	**LASER PLASMA INTERACTION**	**MAGNETIZED PLASMAS**
Silke BIERMANN (coord.)	Stefan HÜLLER (coord.)	Hinrich LÜTJENS (coord.)
Michel FERRERO	Arnaud COUAIRON	Tahar AMARI
Antoine GEORGES	Anne HÉRON (60%)	Aurélien CANOU
Karyn LE HUR	Patrick MORA††	Anne HÉRON (40%)
Leonid POYUROVSKII	Denis PESME††	Jean-François LUCIANI
Laurent SANCHEZ-PALENCIA	Jean-Claude ADAM (60%)††	Timothée NICOLAS
Alaska SUBEDI		Jean-Claude ADAM (40%)††
MATHEMATICAL PHYSICS	**PARTICLE PHYSICS**	**STRING THEORY**
Christoph KOPPER (coord.)	Stéphane MUNIER (coord.)	Marios PETROPOULOS (coord.)
Jean-René CHAZOTTES	Cédric LORCÉ	Guillaume BOSSARD
Razvan GURAU	Cyrille MARQUET	Emilian DUDAS
Philippe MOUNAIX	Urko REINOSA	Blaise GOUTÉRAUX
Pierre COLLET††	Claude ROIESNEL	Hervé PARTOUCHE
Jacques MAGNEN††	Bernard PIRE††	Andrea PUHM

¶Bernard Pire served as a director of the CPHT from July 2012 till December 2016. Jean-René Chazottes was appointed in January 2017.

‖David Delavennat is a member of the CMLS and Sylvain Ferrand a member of the CMAP. They appear because they are part of the joint IT staff, called PHYMATH, between the CPHT, the CMLS and the CMAP. More details are provided in a dedicated chapter.

**She is working part-time for health reasons.

††Emeritus Senior Researcher at CNRS.

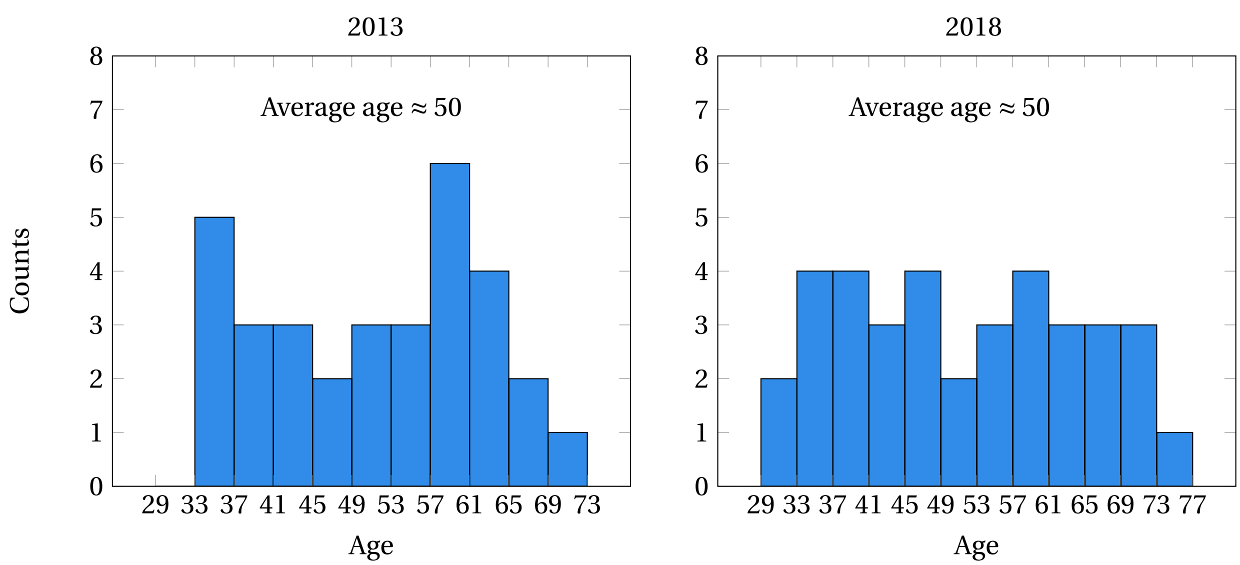
EVOLUTION OF THE STAFFING

We can hire permanent researchers through the CNRS and the Ecole Polytechnique. Most researchers are affiliated to the section 02 of the National Committee (CoNRS). Section 04 is our secondary section, and one researcher is affiliated to section 05 and another one to section 17. We start with a table showing the global evolution of the *permanent staffing* between 2013 and 2018.

GLOBAL EVOLUTION OF THE PERMANENT STAFFING		
LABORATORY WORKFORCE	Number as at 2013/12/31	Number as at 2018/06/30
Permanent professors	3	5
Permanent researchers from Institutions	25 (= 24 CNRS + 1 X)	25 (= 23 CNRS + 2 X)
Emeritus Senior Researcher at CNRS	3	6
Other permanent staff (without research duties)	5.5	5.5
Total	36.5	41.5

Comments: There are 4 permanent professors at Ecole Polytechnique and one at Collège de France. On the line "Permanent researchers from Institutions": we mean that, in 2013, there were 24 CNRS Researchers and 1 Research Engineer at Ecole Polytechnique, whereas in 2018, there are 23 CNRS Researchers and 2 Research Engineers at the Ecole Polytechnique.

We go on by showing the changes in the age structure of the permanent researchers between 2013 and 2018:



One can observe a different age distribution between the two periods, but the average age is the same.

We now show the arrivals of new permanent researchers and professors[‡‡] during the 2013-2018 period, in parallel with the people who left CPHT and the researchers who became Emeritus at CNRS during the same period.

Researchers and professors hired, or arrived, between January 2013 and June 2018:

- A. CANOU (Research Engineer X, hired in 2016)
- B. GOUTÉRAUX (Assistant Prof. X, hired in 2017)
- C. LORCÉ (Assistant Prof. X, hired in 2015)
- C. MARQUET (CRCN CNRS, hired in 2013)
- T. NICOLAS (CRCN CNRS, hired in 2017)
- A. PUHM (CRCN CNRS, hired in 2016)
- L. SANCHEZ-PALENCIA (DR2 CNRS, arrived in 2017)
- A. SUBEDI (CRCN CNRS, hired in 2017)

Researchers who retired or left the CPHT during the 2013-2018 period:

- A. RAMANI (DR CNRS, moved to Univ. of Paris-Sud in 2015)
- A. KATZ (DR CNRS, retired in 2018)
- F. DELYON (CRCN CNRS, moved to LPTMC, Sorbonne Univ., in 2015)

The following people became Emeritus at CNRS during the 2013-2018 period:

- B. PIRE
- P. MORA
- D. PESME

Note: S. Backes was hired in 2018 as an Assistant Professor at the Ecole Polytechnique. He will be in the Condensed Matter group. He starts officially in September 2018, that is why we do not put him in the above list.

For each group, difference between the recruitements of new permanent researchers and professors and the number of people who left CPHT between 2008 and 2018:

Group \ Year	2008-2013	2013-2018	Balance
Condensed Matter	+3 -1	+2	+4
Laser Plasma Interaction	-1	0	-1
Magnetized Plasmas	0	+2	+2
Mathematical Physics	+1 -2	-2	-3
Particle Physics	-1	+2	+1
String Theory	+1 -1	+2	+2

Legend:

- a "+n" for n new permanent researchers (CNRS) or professors (Ecole Polytechnique);
- a "-n" for n departures of permanent researchers (retirement or change of lab);
- a "0" otherwise.

Nota Bene: we do not indicate the researchers who became Emeritus at CNRS since they are still researchers.

Additional details. Between 2000 and 2018, there were two new researchers hired in the Mathematical Physics group (one in 2001, the other in 2012), and 4 retirements. In the Magnetized Plasmas group, the recruitments of A. Canou (2016) and T. Nicolas (2017) were the first ones since 1999. In the Laser Plasma Interaction group, the last recruitment was in 2001.

[‡‡] A literal translation of "enseignant-chercheur" would be "teacher-researcher" but we prefer to use the term "professor".

PhD students. During the 2008-2013, there were 13 defended PhD theses. During the 2013-2018, there were 21 defended PhD theses. Moreover, 19 PhD theses are in progress. This increase is largely due to the research grants (ANR, ERC, etc).

Evolution of the budget

The two institutions funding directly the CPHT are the CNRS and the Ecole Polytechnique.

Consolidated summary of the financial ressources (in €)					
	2013 allocations	2014 allocations	2015 allocations	2016 allocations	2017 allocations
Funds directly allocated by the Institutions	140 984	202 784	187 904	177 000	140 000
Own resources	1 166 706	1 063 527	1 138 173	985 101	1 037 845
Total amount of funding	1 307 691	1 266 311	1 326 077	1 162 101	1 177 845
Wage bill	3 472 168	3 537 823	3 632 409	3 380 221	3 444 700
Other funds indirectly allocated	0	0	0	0	81 051
Consolidated budget	4 779 859	4 804 134	4 958 486	4 542 322	4 703 596

Some comments are in order:

- The fluctuations observed in the values of the funds coming directly from the Institutions is essentially due to the fact that there were some specific demands for certain years, typically for computing resources and IT infractructure.
- The own resources essentially have come from 3 ERC grants, 8 ANR projects (4 are ongoing), 3 EUROfusion projects, and 1 Simons Foundation grant.
- One observes that the funds coming directly from the Institutions represents on average approximately 16% of the total funding of the CPHT.
- Let us specify that the wage bill does not only include the salaries of the permanent members of the lab. It also counts the fix-term contracts for visiting professorships that the lab has obtained from the CNRS (total of 19 months) and the Ecole Polytechnique (total of 47 months).

A glance at "local", national, and international collaborations

The CPHT has many collaborations across the world, virtually in every country in which there are activities in the field of theoretical physics. There is little point in trying to give an exhaustive list here.

The CPHT has of course many collaborations with French laboratories, and other institutions, like the CEA.[§§]
Here we want to emphasize the labs of the Ecole Polytechnique with which we have collaborations: CMAP, LIX, LMS, LPP, LOA, LOB, LSI, LULI, PMC. Notice that we have collaborations with almost all the physics laboratories of the Ecole Polytechnique.

ABOUT THE FUNCTIONING OF THE LAB

We are very fortunate to have efficient and competent administrative and IT staffs. In today's research world, these are keys to the running of a lab like the CPHT.

As mentioned above, F. Debbou, assisted by J. Thomas, manages about 300 "missions" per year. Among other things, F. Auger manages various and numerous research contracts (ERC, ANR, CEA, CNES, DGA, EUROfusion, Simons Foundation, etc). M. Lang manages visitor badges, office space, the website, the electronic directory called "XAJAM", and the library.

The IT staff have become increasingly more important, notably due to the explosion of HPC. A chapter is dedicated to its activities (Chapter 7). Since 1990, the CPHT and CMLS have been putting together their computing means by sharing equipment and mutualizing personnel. More recently, the CMAP has joined this IT staff. It is the perimeter defined by these three research labs that we have called "PHYMATH". The personnel is still attached to its own research lab and its tutelage. It is currently distributed as follows: at the CPHT, one Assistant Engineer (CNRS) and one Research Engineer (CNRS), at the CMLS one Research Engineer (CMLS), at the CMAP one Research Engineer (Ecole Polytechnique) and one apprentice (Ecole Polytechnique). Let us mention that, although the CNRS promotes the pooling of ressources, our initiatives are poorly recognized.

According to the rules of the CNRS, the CPHT has a Laboratory Council whose members are the following:

Ex-officio member:

- J.-R. Chazottes

Appointed members:

- F. Auger
- S. Biermann
- S. Hüller
- H. Lütjens
- S. Munier
- M. Petropoulos

Elected members:

- G. Bossard
- A. Couairon
- C. Lorcé
- C. Kopper
- M. Lang
- A. Soret (PhD students representative)
- U. Reinosa
- L. Sanchez-Palencia

The council meets 3 or 4 times a year, with a full agenda.

[§§]The French Alternative Energies and Atomic Energy Commission

About teaching activities

A characteristic feature of the CPHT is that it is made of 84% of CNRS Researchers who do not have teaching duties. Therefore, it is not obvious at all to have interactions between its researchers and the students of the Ecole Polytechnique. Given that among the latter are potential PhD students of the highest quality, this is a shame. Therefore, in recent years, the CPHT has made an effort to strengthen its presence in the engineering curriculum of the Ecole Polytechnique. That effort bore fruit because, as af 2018, there are 5 full-time professors (without counting S. Backes who was hired in 2018), and 8 part-time professors[¶¶]. These professors are with the Physics Department, except one who is with the Applied Mathematics Department. There are also PhD students and postdoctoral fellows who teach.

The involvement of the CPHT in the Physics Department of the Ecole Polytechnique is witnessed by the fact that Christoph Kopper (Mathematical Physics Group) is its chair since 2015 (and was its vice-chair from 2006 to 2014). Silke Biermann (Condensed Matter Group) was elected vice-chair this year, and she is likely to succeed him in 2019.

More details about all teaching activities of the members of the CPHT can be found in one of the Annexes.

About gender balance

For the 2008-2013 period, there were 3 women out of 31 permanent researchers (*i.e.*, ≈ 9.7%), and 7 women out of 38 permanent members (administrative staff: 4 women out of 4; IT staff: 0 women out of 2).

For the period 2013-2018, the situation has very slightly improved: There are 4 women out of 36 permanent researchers (*i.e.*, ≈ 11%), and 8 women out of 42 permanent members (administrative staff: 4 women out of 4; IT staff: 0 women out of 2).

Only one woman was hired out of the 6 new recruits (3 CRCN CNRS, 2 Assistant Prof. X, 1 Research Engineer X).

On the positive side, let us mention that the proportion of women among PhD students and post-doctoral fellows increased, although we do not have the precise figures for the previous period (2008-2013). For instance, there are 3 women among the 19 students (*i.e.*, ≈ 16%) who are currently doing their PhD thesis at the CPHT.

[¶¶] the exact title in french is “professeurs chargés de cours à temps partiel”

Scientific Results, Research Activities, and Computing Ressources

This part is devoted to the detailed presentation of each of the six groups. There is also a chapter dedicated to the PhysMath IT staff and mesocenter. As a matter of fact, this staff can be considered as the seventh group of the lab.

Here is the table of contents:

The presentation of each research group is structured as follows:

- The achievements of the group;
- PhD supervisions;
- Contracts and grants;
- Administrative duties;
- Publications (articles, proceedings, books, etc).

Let us emphasize that we list *selected* administrative duties (on top of juries, refereeing, edition, conference organization, etc). For the comprehensive list of administrative duties and services to the scientific community, we refer to one of the Annexes. We only intend to give an idea of the involvement of many members of the CPHT.

1

CONDENSED MATTER

PERMANENT STAFF	Silke BIERMANN (PR X, Group Leader) Michel FERRERO (CRCN CNRS) Antoine GEORGES (Prof. at Collège de France) [*] Karyn LE HUR (DR1 CNRS) Leonid POUROVSKII (RE X) Laurent SANCHEZ-PALENCIA (DR2 CNRS) [†] Alaska SUBEDI (CRCN CNRS) [‡]
NON-PERMANENT STAFF as at June 2018	8 PhD students and 10 postdoctoral fellows

Note: Steffen BACKES, who was a postdoctoral fellow in this group, was hired as an Assistant Professor at the Ecole Polytechnique in 2018. He starts officially in September 2018.

1.1 Introduction

The research activities of the condensed matter group are devoted to the theory of correlated quantum systems, covering the whole spectrum from crystalline materials, mesoscopic or nanoscopic systems to ultracold atom gases and systems coupling matter and radiation. We aim at

1. Identifying and describing emergent collective behaviour arising from the interactions in fermionic or bosonic systems;

2. Characterizing novel quantum phases of matter (including their topological properties) and the associated quantum phase transitions;

3. Understanding structural, spectral, magnetic and transport properties of correlated systems.

An important aspect of our work is the development of theoretical approaches to tackle such systems. We make use of a wide panel of techniques, including analytical approaches (*e.g.* mean field theory, Bethe ansatz, Yang-Yang theory, bosonization, renormalization group analysis, slave-rotor techniques...) and large-scale numerical simulations for many-body systems (*e.g.* dynamical mean field theory (DMFT), exact diagonalization, quantum Monte Carlo, density matrix renormalization group (DMRG) and matrix-product states,...) and within an ab initio framework (density functional theory (DFT) and density functional perturbation theory, ab initio many-body perturbation theory ("GW approximation"), constrained random phase approximation techniques...).

In the following, we give a non-exhaustive description of some of our main lines of research and a few highlights of our results.

[*] also Director of the Center for Computational Quantum Physics, Flatiron Institute, Simons Foundation, New York

[†] L. Sanchez-Palencia joined the CPHT in 1/2017. His previous affiliation was the Institut d'Optique, Palaiseau.

[‡] A. Subedi was hired as CRCN CNRS in 2017. From 9/2012 to 8/2014 and from 2/2016 to 8/2017, he was a postdoctoral fellow at CPHT. For this reason, we have included his publications over the reporting period except for those in between 9/2014-1/2016 in this report.

1.2 Models of correlated fermions – methods and algorithms

Understanding the behaviour of strongly-correlated fermionic systems is an outstanding challenge. Unlike weakly interacting systems, they cannot be described by a theory (like band theory) where electrons are thought of as single entities evolving in an effective environment. Instead, in order to describe the properties of strongly-correlated systems, the interaction between all fermions has to be explicitly considered.

Our research team is actively developing new models and methods to address this many-body problem. For example, the Hubbard model is often taken as a starting point to develop and test new theoretical approaches. Very much like the Ising model in classical statistical physics, the Hubbard model is an important milestone in quantum many-body physics. Very promising methods that are currently being developed in the condensed-matter group are (1) extensions of DMFT and (2) techniques based on diagrammatic Monte Carlo algorithms. In the latter, a perturbation theory for physical observables is constructed. For example, the Coulomb interaction between electrons can be treated as a perturbation. The resulting perturbation series can be seen as a sum of (Feynman) diagrams. Their number grows factorially with the perturbation order, so they cannot be computed explicitly. Instead, a Monte Carlo algorithm stochastically samples the most relevant diagrams to obtain a controlled estimate of the physical observables, see *e.g.* Phys. Rev. B 97, 085117 (2018). A lot of work is in progress to better understand the mathematical structure of these perturbation series and to develop new algorithms.

Let us emphasize that our research group not only elaborates new algorithms but also implements them as numerical codes. Often this implementation can become very time consuming, especially for students entering the field. In order to reduce the time spent in the actual implementation of a code, we have been working since 2011 on a numerical library called TRIQS (Toolbox for Research on Interacting Quantum Systems). This library, developed at the CPHT mainly by M. Ferrero, in collaboration with O. Parcollet at CEA/Saclay, provides tools, both at the C++ and Python programming language level, that make it much easier to code and explore new algorithms. It is an open-source project (see Comp. Phys. Comm. 4, 23 (2015) and TRIQS (website)), which is actively used by a growing international user community. It is regularly presented in summer schools, *e.g.* 2017 Simons Summer School, 2018 International Summer School on Computational Quantum Materials.

Highlight: physical origin of the pseudogap in the 2D Hubbard model.
Above some critical temperature (T_c), the "normal" state of high-temperature superconductors is nothing like a normal metal: it displays a depletion of available excited states in the "antinodal" region of the Brillouin zone. Understanding this "pseudo-gap" state is one of the greatest challenges in condensed-matter physics. In the past two years, Wu, Ferrero, Georges and collaborators have obtained some breakthrough results towards this goal. In Wu et al. Phys Rev B 96, 041105R (2017), we have shown that the pseudogap state can be reached using improvements of the diagrammatic Monte-Carlo technique, and performed a fluctuation analysis that unambiguously demonstrates that the physical mechanism responsible for the pseudogap in the 2D Hubbard model are short-range magnetic correlations. In Wu et al. Physical Review X 8, 021048 (2018) and Scheurer et al, PNAS 115, E3665 (2018), we have been able to relate, for the first time, distinctive features of the pseudogap appearing in numerical calculations based on cluster extensions of DMFT to low-energy field theoretical analysis using an SU(2) gauge theory framework, which points at the existence of topological order in the pseudogap state. We have also been able to reveal the relationship between the pseudogap and Fermi surface topology, shedding light on the recent experimental findings in the groups of A.Sacuto

(Paris) and L.Taillefer (Sherbrooke). [§]

Pseudogap physics has also been studied by K. Le Hur and collaborators, in the context of new topological superconducting phases in honeycomb materials, described by a t-J model. Using quantum field theory, renormalization group arguments, and quantum Monte Carlo they have identified a d+id superconducting phase which is related to recent developments in bilayer twisted graphene materials and iridate materials (Wu, Scherer, Honerkamp, Le Hur. Phys. Rev. B 87, 094521 (2013); A. Black-Schaffer et al. Phys. Rev. B 90, 054521 (2014)].

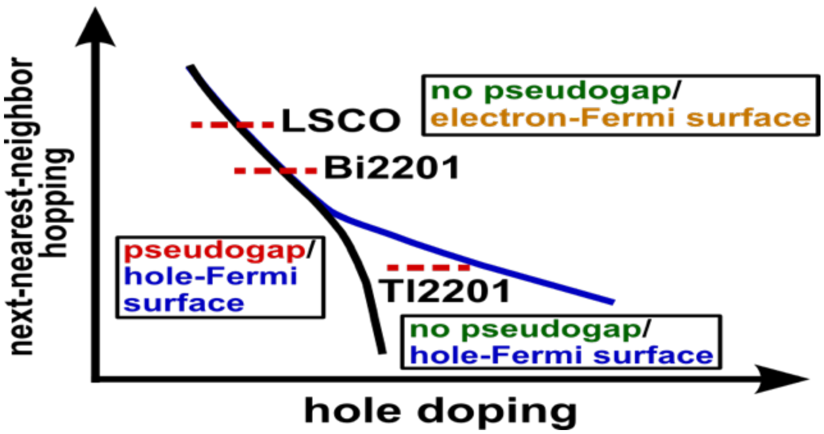


Figure 1.1: Interplay between Fermi surface topology and the pseudogap state: the black line signals the opening of the pseudogap while the blue line signals a change of topology of the Fermi surface. Importantly, a pseudogap never forms when the interacting Fermi surface is electron-like. Dashed red lines indicate where several standard cuprate compounds are located in this phase diagram.

1.3 Ab initio electronic structure calculations for correlated electron materials

Electronic structure work at CPHT focuses on an ab initio (i.e. without adjustable parameters) description of the properties of crystalline materials with strong electronic Coulomb correlations. It extends both to challenging applications in materials physics and to the further development of suitable methods to tackle them. The latter involves advances towards a truly parameter-free description of the electronic Coulomb interactions, in the framework of the ERC project "Predictive electronic structure calculations for materials with strong electronic correlations: Long-range Coulomb interactions and many-body screening" (S. Biermann), as well as the elaboration of new tools to make different properties accessible to calculations (see *e.g.* L. V. Pourovskii, et al., Phys. Rev. B 87, 115130 (2013) for a new trick for the calculation of electronic entropy and free energy or L.V. Pourovskii, Phys. Rev. B 94, 115117 (2016), for an ab initio approach to intersite magnetic interactions in insulating materials). The combined "screened exchange dynamical mean field theory" scheme elaborated by S. Biermann and collaborators – reviewed in Delange et al., J. Phys. Soc. Jpn. 87, 4, 041003 (2018) – allows for first principles calculations of spectral properties of materials of similar accuracy as the combined many-body perturbation theory + DMFT (so-called "GW+DMFT") method, but at much cheaper computational cost.

[§] K. Le Hur and A. Georges are members of the Canadian CIFAR Program on Quantum Materials, headed by L. Taillefer and L. Balents.

Examples of materials applications range from questions inspired by "real" problems in materials science to puzzles of interest in fundamental science. Illustrative examples are provided by the work by L. Pourovskii who has demonstrated a significant impact of many-body effects on the relative phase stability, magnetism, and thermal conductivity of pure iron at the extreme conditions of the inner core of Earth as well as in the moderate pressure range. His calculations have also predicted a pressure-induced orbital transition for several heavy-fermion superconductors of the CeM2X2 family (M=Cu,Au, X=Si,Ge), thus identifying possible fluctuations responsible for the Cooper pairing in those compounds.

The hiring of A. Subedi, who joined the lab permanently in 2017 (after being a postdoctoral member of it 2012-2014 and 2016-2017), adds expertise on first principles calculations of phonon dispersions and electron-phonon couplings to the portfolio of the CPHT electronic structure team. A major focus of his work is on materials that exhibit phase transitions whose low-temperature structure is not fully known. Calculating phonon dispersions not only allows to identify structural instabilities; a specialty developed recently is to also investigate ways for controlling and enhancing the physical properties of materials, via large-amplitude excitations of infrared-active phonons to nonlinear regimes by intense terahertz frequency laser pulses. Within the ERC project "Frontiers in Quantum Materials Control (QMAC)" (Synergy grant held by A. Georges, in collaboration with A. Cavalleri, D. Jaksch and J.M. Triscone), A. Subedi, A. Georges and collaborators have constructed a microscopic theory to describe such nonlinear phononics phenomena using symmetry considerations, first-principles calculations of the energy surface and classical equations of motion (A. Subedi, A. Cavalleri, and A. Georges, Phys. Rev. B 89 , 220301(R) (2014)). A. Subedi has recently applied this theory to propose ultrafast switching of ferroelectrics and a transient paraelectric to ferroelectric transition using mid-infrared pulses (A. Subedi, Phys. Rev. B 95 , 134113 (2017)).

Highlight: Spectral properties of Sr_2IrO_4 from first principles. ¶

The spin-orbit compound Sr_2IrO_4 is (nearly) isostructural to the celebrated high-temperature superconducting copper oxides of the La_2CuO_4 family, and intriguing similarities in the low-energy electronic structure, which is dominated by a single half-filled orbital, have provoked strong interest in the community. Using first principles calculations within a novel "oriented cluster"-dynamical mean field theory scheme, we have elucidated the role of non-local Coulomb correlations for the spectral properties of the compound, in good agreement with experimental angle-resolved photoemission spectra, see Figure 1.2. In the electron-doped case we find an exotic metallic state, whose properties we relate to the findings of recent angle-resolved photoemission spectra. In particular, our calculations offer a surprisingly simple picture for the antinodal pseudogap found in experiments as a direct consequence of strong inter-site Ir-Ir fluctuations (Martins et al., Phys. Rev. Matt. 2, 032001 (Rapid) (2018); see also Moutenet et al. Phys Rev B 97, 155109 (2018) for a Monte Carlo study of the pseudogap in iridates). In the light of these findings, despite the numerous similarities of the electronic structure of the iridates with the one of the cuprates, the absence of superconductivity in the iridates remains an open puzzle.

Iridate materials have also been studied by K. Le Hur and collaborators who made progress on the doped Kitaev spin model, identifying a novel Fulde- Ferrell-Larkin-Ovchnikov superconducting phase (T. Liu, et al., Phys. Rev. B 94, 180506 (2016)). Spin chain and spin ladder analogs of the Kitaev model have been studied in K. Le Hur, et al., Phys. Rev. B 96, 205109 (2017).

¶This work is supported by the ANR project "Nouveaux états électroniques corrélés émergeant d'un couplage spin-orbite fort : le cas des iridates", coordinated by V. Brouet (LPS Orsay), of which the team of S. Biermann is an associated partner.

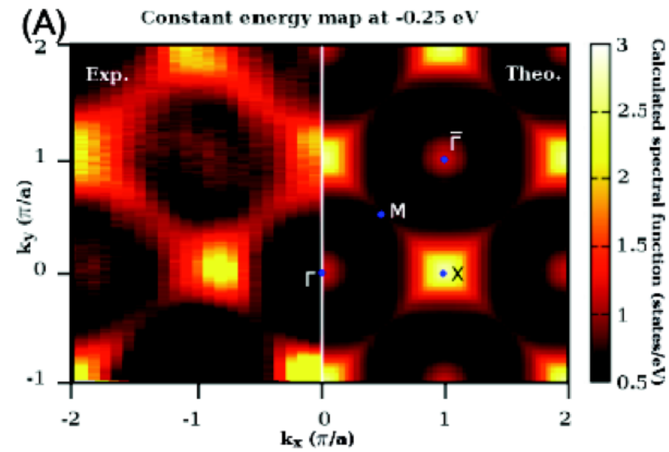


Figure 1.2: Constant energy map of the spectral function of Sr2IrO4. Experimental angle-resolved photoemission spectrum (left) and calculated spectral function (right) at 0.25 eV binding energy. Blue points indicate high-symmetry points in the Brillouin zone. In the calculations, spectra in the first and second Brillouin zones are identical, in the experimental spectra matrix elements describing the light-matter-coupling cause differences. (From: Martins et al., Phys. Rev. Mat. 2, 032001 (Rapid) (2018)).

Highlight: Ab initio determination of crystal-field parameters in rare-earth permanent magnet materials.
Finding new materials for high-performance permanent magnets is currently a hot topic in applied materials science. Such compounds are required to have a high Curie temperature, a large magnetization as well as a strong uniaxial magnetic anisotropy that determines their magnetic hardness. Currently known hard magnetic compounds, like $SmCo_5$ or $Nd_2Fe_{14}B$, contain a significant amount of expensive rare-earth (RE) elements, the $4f$ local moments of which provide the main contribution to the magnetic anisotropy. A quantitative theory of the $4f$ single-ion anisotropy is thus required to find new materials exhibiting a strong uniaxial anisotropy, but with lower RE concentration. This anisotropy is determined by the crystal-field (CF) splitting of the localized $4f$ states, which is however notoriously difficult to predict theoretically due to its overall small magnitude (of the order of few tens of meV) and its sensitivity to the treatment of the $4f$ states. L. Pourovskii and co-workers have recently proposed a new approach to the ab initio evaluation of the CF splitting on RE $4f$ shells based on a quasi-atomic approximation for the many-electron effects (Delange et al. Phys. Rev. B 96, 155132 (2017)). Their scheme suppresses the unphysical "self-interaction" contribution to the CF parameters, which arises due to an incorrect treatment of localized states within the standard DFT framework. Our method successfully reproduces the experimental CF splitting in the well-known hard magnet $SmCo_5$. It was subsequently applied to prospective hard-magnetic intermetallics of the RFe12X family (where R is a rare-earth element, X is a an interstitial and typically a 2p element like N). A strong sensitivity of the single-ion anisotropy to the nature of interstitial X was identified and explained by a quantitative analysis of the mixing between R $4f$ states and X 2p(2s) states. These theoretical calculations have also predicted the hypothetical $SmFe_{12}Li$ compound to feature exceptionally good hard-magnetic properties. A major part of this work was carried out in the framework of the PhD thesis of P. Delange (co-supervised by L. Pourovskii and S. Biermann). This line of research at CPHT is supported by the bilateral French-German ANR-DFG project "RE-MAP", in collaboration

with the Max-Planck-Institut für Eisenforschung, Düsseldorf, and the TU Darmstadt, Germany.

Highlight: Mott-to-Goodenough insulator-insulator transition in $LiVO_2$.
$LiVO_2$ has been studied in relation to spin-liquid physics and battery applications. In 1957, it was found that this material undergoes a structural insulator-to-insulator transition around 490 K [1]. However, its low-temperature electronic, magnetic and structural properties have still not been fully clarified. Using calculations that combine DFT with DMFT, we found that the high-temperature phase is a Mott insulator, consistent with experimental observations (A. Subedi, Phys. Rev. B 95 , 214119 (2017)). We calculated the phonon dispersions of the high-temperature structure and found that it exhibits two unstable phonon branches. Using the eigenvectors of the unstable phonon modes, we were able to stabilize a structure that is lower in energy than the high-temperature structure. This structure exhibits formation of vanadium trimers due to V 3d covalency. This low-temperature phase is a band insulator and does not show any magnetic instabilities. Such a phase was described using a phenomenological model by J. Goodenough, and our work provides a microscopic basis for it as well as a prediction for its crystal structure.

1.4 Ultracold atom gases and quantum simulators

The field of ultracold atoms is by now a well-established intersection between condensed matter physics and quantum optics: The ability to manipulate ultracold atomic gases enables studies of "artificial materials". The study of the quantum many-body problem arising in these setups is an active field of research, with strong synergies with solid state physics. For instance, an optical lattice mimics the periodic ionic potential and the atomic gas the electrons, hence realizing a quantum simulator for electronic transport. At CPHT, this field is represented by A. Georges and K. Le Hur, and has recently been reinforced by the arrival of L. Sanchez-Palencia with his team who joined the lab in January 2017. ‖

During the period covered by this report, we have developed three research lines in this area. On the one hand, we have pursued our activities on quantum disordered systems. On the other hand, we have initiated two new projects, namely one-dimensional quantum gases and out-of-equilibrium dynamics of correlated matter. Our most important results in the period are as follows:

Disordered systems - Analytical theory of the renormalization of the mobility edge for Anderson localization in three dimensions [Piraud et al., NJP 2013; PRA 2014] ; Universal scaling theory of Landauer conductance and localization in one dimensional wires subjected to a finite drift force [Crosnier de Bellaistre et al., PRB (R) 2017, PRA 2018]; Phase diagram and Berezinskii-Kosterlitz-Thouless phase transition in disordered two- dimensional Bose gases [Carleo et al., PRL 2013]; Anderson localization of many-body excitations in disordered and quasi-periodic systems [Lellouch et al., PRA (R) 2014, PRA 2015].

One-dimensional quantum gases - First unbiased determination of the Mott-U and Mott-d transitions in arbitrary weak periodic potentials using large-scale quantum Monte Carlo calculations: Characterization of the critical lines and validation of a quantum simulator based on ultracold atoms

‖Since his present activity is the direct continuation of long-term work initiated in his previous affiliation (Institut d'Optique), the following review contains his contribution in the full period 2013-2018. Formally, only the work since January 2017 should be counted in the CPHT production (and only publications since 2017 are included in the publication list).

[Boéris et al., PRA (R) 2014] (collaboration with the experimental group of G. Modugno and M. Inguscio, Florence, Italy).

Out-of-equilibrium dynamics of correlated matter - Accurate determination of Lieb-Robinson velocity for correlation spreading in one- and two-dimensional Bose Hubbard models using time-dependent variational Monte Carlo simulations [Carleo et al., PRA (R) 2014]. Demonstration and characterization of universal twofold spreading in spin systems with long-range exchange terms [Cevolani et al., PRA (R) 2015, NJP 2016].

Our work is complemented by methodological developments of many-body numerical methods, for instance, the team around L. Sanchez-Palencia developed a time-dependent variational approach for continuous systems using a Jastrow-Feenberg ansatz [Carleo et al., PRX 2017].

1.5 Driven hybrid systems and quantum electrodynamics

The fields of condensed matter and quantum optics become even more strongly connected, when including radiation modes in a cavity and coupling those coherently to electronic degrees of freedom, provided *e.g.* by a mesoscopic quantum dot. In collaboration with M. Schiro (IPhT, Saclay), K. Le Hur has studied such an hybrid system, in a Anderson-Holstein model (M. Schiro and K. Le Hur, Phys. Rev. B 89, 195127 (2014)).

Highlight: A new stochastic Schrödinger equation approach.
K. Le Hur and collaborators have elaborated a stochastic Schrödinger equation approach to address the real-time dynamics of interacting effective quantum spin systems, which can be realized *e.g.* in cold atom systems, mesoscopic system or quantum materials. The method consists in a decoupling of the long-range interactions in time and writing the effective dynamics in time as a local Schrödinger equation. A review (K. Le Hur, et al., Comptes Rendus Académie des Sciences 2018, arXiv:1702.05135) was published in a special issue on Quantum Simulation. The first version of the method was elaborated with P. Orth and A. Imambekov (Phys. Rev. B 87, 014305 (2013)). We have also generalized the method to describe topological properties of a spin-1/2 coupled to a bath on the Bloch sphere (Henriet et al. Phys. Rev. B 95, 054307 (2017)) and the dynamics of the dissipative quantum Rabi model (L. Henriet, Z. Ristivojevic, P. P. Orth, K. Le Hur, Phys. Rev. A 90, 023820 (2014)) making a link with quantum optics.

1.6 Topological Quantum Matter: Interplay with Mott physics and Quantum Information

The field of topological phases has attracted attention recently, boosted by the Nobel prize in physics in 2016 of Haldane, Kosterlitz and Thouless. This field of research is at the interface between quantum materials, cold atoms and photon systems and, concerning the methods, borrows from mathematical physics and high-energy physics. On applications in photon systems and ultra-cold atoms, we have written a review (K. Le Hur et al. Comptes Rendus Académie des Sciences, 17 (2016) 808-835). [**]

[**]This line of research at CPHT is supported by the German DFG, via a “Forschergruppe” on Topological Phases and Artificial Gauge Fields of which K. Le Hur is a member.

Highlight: Phase diagrams of the bosonic Haldane and Kane-Mele models.
Based on her previous work on the fermionic Hubbard-Kane-Mele model (see *e.g.* T. Liu, B. Douçot, K. Le Hur, Phys. Rev. B 88, 245119 (2013)), K. Le Hur has studied, with her collaborators in Frankfurt, Walter Hofstetter and Ivana Vasic, and with A. Petrescu at CPHT, the first phase diagram of the interacting bosonic Haldane model and identified a new chiral superfluid phase as a result of gauge fields (I. Vasic, A. Petrescu, K. Le Hur, W. Hofstetter, Phys. Rev. B 91, 094502 (2015)). The Mott phase shows topological excitations at high energy. Very recently, the analysis has been extended to provide the first phase diagram for the bosonic-Kane-Mele model. The most intriguing finding is a new chiral spin state in the Mott phase of the bosonic system (K. Plekhanov, et al., Phys. Rev. Lett. 120, 157201 (2018)). The model is in relation with new materials (K. Ross et al. Boulder, arxiv1712.06208).

Novel phases have been identified in ladder systems, related to Mott-Meissner phases and a new Quantum Hall phase analogue at $\nu = 1/2$ using analytical arguments and DMRG (A. Petrescu, M. Piraud, G. Roux, McCulloch, K. Le Hur., Phys. Rev. B 96, 014524 (2017)). K. Le Hur and collaborators have introduced the concept of "bi-partite fluctuations" (Song et al. Phys. Rev. B 85, 035409 (2012)), and here we used this tool to define the quantum Hall phase. A review on applications of bipartite fluctuations for quantum Hall states was then written making links with entanglement entropies and the entanglement spectrum (A. Petrescu et al. J. Stat. Mech. (2014) P10005). This tool was generalized to topological superconducting and insulating systems in L. Herviou et al. Phys. Rev. B 96, 121113 (2017).

1.7 PhD supervisions

- Louis Villa, "Generalized hydrodynamic approach for strongly-correlated Bose and Fermi systems". PhD started in September 2018. Supervisor L. Sanchez-Palencia.
- Alice Moutenet, "Nouveaux algorithmes diagrammatiques pour le problème à N corps, application aux systèmes d'électrons fortement corrélés". PhD started in 2017. Supervisors A. Georges and M. Ferrero.
- Marcello Turtulici, "Materials simulations for correlated electron systems with defects". PhD started in 2017. Supervisor: Silke Biermann.
- Fan Yang, "Interacting Topological Phases and Kitaev Spin Models", started September 2017. Supervisor: Karyn Le Hur.
- Hepeng Yao, "Quantum phase transitions in low-dimensional Bose gases". PhD started in September 2017. Supervisor L. Sanchez-Palencia.
- Julien Despres, "Out-of-equilibrium dynamics in strongly-correlated quantum matter". PhD started in September 2016. Supervisor L. Sanchez-Palencia.
- Ariane Soret, "Casimir Physics and Mesoscopic Effects", started October 2016; co-supervisors: Karyn Le Hur (CPHT) and Eric Akkermans (Universion Technion, Israel).
- Jakob Steinbauer, "Multiorbital physics in strongly correlated materials". PhD started in 2016. Supervisor: Silke Biermann.
- Kirill Plekhanov, "Floquet theory and artificial gauge fields, topological phases". PhD defense on September 7th 2018. Co-supervisors Karyn Le Hur (CPHT) and Guillaume Roux (LPTMS Orsay).

- Cécile Crosnier de Bellaistre, "Conductance and expansion of a quantum wave in a one-dimensional guide : Effect of a force". PhD defense in November 2017. Supervisor L. Sanchez-Palencia.

- Pascal Delange, "Many-electron effects in transition metal and rare earth compounds: Electronic structure, magnetic properties and point defects from first principles". PhD defense in September 2017. Co-supervisors Silke Biermann and Leonid Pourovskii.

- Loic Herviou, "Phases Topologiques et Fermions de Majorana". PhD on September 8th 2017. Co-supervisors Karyn Le Hur (CPHT) and Christophe Mora (LPA ENS Paris).

- Sophie Chauvin, "Cobaltates in the high-doping regime : Insights from first-principles calculations and extended dynamical mean-field theory". PhD defense in December 2016. Co-supervisors Silke Biermann and Lucia Reining (LSI, Ecole Polytechnique).

- Loic Henriet, "Non-Equilibrium Dynamics of Many-Body quantum systems". PhD in September 8th 2016. Supervisor Karyn Le Hur (CPHT).

- Thomas Ayral, "Nonlocal Coulomb interactions and electronic correlations : novel many-body approaches", PhD in September 2015. Co-supervisors Silke Biermann and Olivier Parcollet (IPhT Saclay).

- Tudor Alexandru Petrescu, "Topological Phases with ultracold atoms and photons". PhD obtained from Yale University and from Ecole Polytechnique. PhD defense August 2015. Supervisor : Karyn Le Hur (Yale and CPHT Ecole Polytechnique).

- Tianhan Liu, "Strongly Correlated Topological Phases". PhD in September 2015. Co-supervisors Karyn Le Hur (CPHT) and Benoit Doucot (LPTHE UPMC).

- Ambroise van Roekeghem, "Electronic Coulomb interactions in transition metal pnictides". PhD defense in October 2014. Joint PhD (cotutelle) between Ecole Polytechnique and Chinese Academy of Sciences, Peking. Cosupervisors Silke Biermann and Hong Ding (IOP, Chinese Academy of Sciences). Thesis Prize of RTRA Triangle de la Physique (2015). Thesis Prize of Ecole Polytechnique (2015).

- Prasenjit Dutt, "Strongly Correlated quantum transport out of equilibrium", PhD in September 2013 at Yale University. Co-supervisors Karyn Le Hur (Yale and CPHT Ecole Polytechnique) and Ramamurti Shankar (Yale University).

1.8 Contracts and grants

- ERC Consolidator Grant: "Predictive electronic structure calculations for materials with strong electronic correlations: long-range Coulomb interactions and many-body screening", 2014-2019, PI S. Biermann.

- Simons Foundation Grant (Many Electron Collaboration), 02/2014-02/2019, A. Georges (group leader), PI M. Ferrero.

- ERC Synergy grant: "Frontiers in Quantum Materials Control", 2013-2019, Antoine Georges (cPI) jointly with Jean-Marc Triscone (UNIGE), Andrea Cavalleri (MPI Hambourg and Oxford) and Dieter Jaksch (Oxford).

- ANR-DFG Grant "Rare earth-based permanent magnet materials", 2017-2019, Project Leader : T. Hickel (Max-Planck-Institute for Iron and Steel Research, Düsseldorf, Germany), Project Partners : CPHT (S. Biermann, L. Pourovskii), TU Darmstadt Germany (O. Gutfleisch).
- DFG-Research Unit 2414, 2016-2019, "Artificial Gauge Fields and Interacting Topological Phases in Ultra-Cold Atoms", K. PI Le Hur. (Will fund the PhD thesis of Fan Yang until 2020.)
- ANR on the electronic structure of iridates ("SOCRATE"), 2016-2019, together with the experimental groups of V. Brouet (LPS Orsay), Y. Gallais (Paris VII), and the theoreticians of LPS Orsay (M. Civelli, M. Rozenberg).
- Projet FET-Proactive QUIC (QUantum Insulators and Conductors), 03/2015-02/2019 (PI G. Modugno, LENS, Florence; Responsible for the French node L. Sanchez-Palencia).
- Grant from LabEx PALM, Univ. Paris-Saclay, "Quantum.Climate", 2017-2018, 1 year post-doctoral fellowship completed with a 1 year post-doctoral position from Ecole Polytechnique for Tal Goren. In addition, funding of the internships of Andrea Pizzi (Master student M2 of Paris-Saclay and Ecole Polytechnique Turin; now PhD in Cambridge) and Peng Cheng (Master student from Ecole Polytechnique). PI Karyn Le Hur.
- Grant from LabEx PALM, Univ. Paris-Saclay, "Quantum Dynamics in Many-Body Quantum Systems", Post-doctoral Funding for Zoran Ristivojevic, 2013-2014, PI Karyn Le Hur.
- Grant from LabEx PALM, Univ. Paris-Saclay, "Electronic structure of f-electron materials", Post-doctoral Funding for Priyanka Seth, 2013-2014, PI S. Biermann.
- ANR "Iron pnictides", 2010-2014, together with the experimental groups of F. Albenque (CEA Saclay), H. Alloul, V. Brouet (Orsay, Université Paris-Sud, Orsay).
- Grant within the French-Argentinian ECOS program, for project "LDA+DMFT approach to realistic strongly correlated electron systems in the Wien2k scheme: methods and materials", 2013-2017, S. Biermann, L. Pourovskii and the Argentinian group of P. Roura-Bas, V. Vildosola, and P. Cornaglia (Buenos Aires/Bariloche, Argentina).
- Chinese-French collaboration grant "Cai Yuanpei", 2012-2014, S. Biermann, together with H. Jiang (Peking University).

1.9 Administrative duties (on top of juries, edition, conference organization, etc)

This is a non-exhaustive list. For a complete one, please refer to one of the Annexes.

- Silke Biermann:
  - 2013: Created exchange program between the Freie Universität Berlin and Ecole Polytechnique: double master program in physics, supported by the Deutsch-Franzoesische Hochschule (Université Franco-Allemande). Responsible contact person for the program at Ecole Polytechnique since 2013.
  - 2016- : Tutor ("Vertrauensdozentin") for the German National Scholarship Foundation ("Studienstiftung des deutschen Volkes"), since 7/2016. Responsible for coordination of tutoring groups ("Federfuehrende Vertrauensdozentin") in the wider Paris area.

- 2017- : Initiated cooperation program between the German National Scholarship Foundation and Ecole Polytechnique (integrated Master and PhD program offered as part of scientific program of the Foundation), since 1/2017.
- 2015-2018 : Member of the coordination committee of the French "Groupement de Recherche" (GDR "REST") on Theoretical Spectroscopy.
- 2014-2018: Member of the Scientific Council of the Institute of Physics of the French Centre National de la Recherche Scientifique (CNRS-INP).
- 2010-2014: Elected member of the office of the Solid State Physics Division of the French Physical Society ("Société Française de Physique").
- 2007-2017 : Member of the steering committee of the "Chaire Sciences des matériaux et surfaces actives", an industrial grant financed by the French materials company Saint Gobain, with the aim to promote research and teaching in the field of condensed matter physics and materials science at Ecole Polytechnique and Ecole Supérieure de Physique et Chimie Industrielles. Scientific representative for Ecole Polytechnique, together with T. Gacoin (PMC Ecole Polytechnique), during the negotiation phase (2006/07) and over the whole duration of the grant. Initial contract (2007-2012) and prolongation 2013-2017.
- 2007-2015: Member of the steering committee of the Theory Division of the network "Réseau Thématique de Recherche Avancée Triangle de la Physique" Orsay-Saclay-Palaiseau.
- 2016- : Member of the steering committee of the Quantum Materials Section of the network "Laboratoire d'Excellence" PALM Orsay-Saclay-Palaiseau.
- 2008- : Member of the Scientific Advisory Committee of the European "Psi-k Network for Electronic Structure Calculations".
- 2017- : Trustee of the Charity of the Psi-k Network.
- 2009-2014: Member of the hiring committee of the language department of Ecole Polytechnique.
- 2013- : Contact person of CPHT and Research Team Leader within the European Theoretical Synchrotron Facility (ETSF). The Centre de Physique Théorique is an associate node of this network dedicated to electronic structure calculations for spectroscopy (www.etsf.eu).
- 2015: Member of the HCERES committee of INAC Grenoble.
- Search committee Professorship Mathematical Physics, CPHT Ecole Polytechnique, January-Sept. 2018.

• Karyn Le Hur

- 2012-2016: Member of the Bureau of section 02 of the National Committee (CoNRS).
- 2012-2018: Member of the Editorial Board of Physical Review B.
- Spring 2013: Participation in the selection committee of 2nd class Senior Researchers (CNRS) in Section 03 of the National Committee.
- January 2013: Participation in AERES committee, visit of LPTMC UPMC UMR 7600.
- February 2018: President of the HCERES committee for the LPTMC (Sorbonne Univ.).

• Laurent Sanchez-Palencia:

- 2017 - : Member of council of the Doctoral School Waves and Matter (EDOM) at University Paris-Saclay.
- 2014-2017: Member of the steering committee of the Institute of Advanced Physics Blaise Pascal at University of Paris-Saclay.
- 2014-2018: Member of the steering committee of the Department of Physics of Waves and Matter at University of Paris-Saclay.
- 2013-2016: Member of the scientific committee of the massive computing center of University of Paris-Sud.
- 2012-2016: Co-head of the Atom Optics group (with C. Westbrook) at Laboratoire Charles Fabry.
- 2011-2015: Member of the steering committee of the RTRA "Triangle de la Physique".
- 2012 - : Co-head of the research theme "Matter and light waves, coherence and disorder" (with G. Labeyrie) of the GdR "Cold Atoms".
- 2010-2016: Member of the council of group and team leaders at Laboratoire Charles Fabry.

1.10 Publications

1.10.1 Papers in refereed journals (sorted by year)

2013

1. Ayral T, Biermann S, Werner P. Screening and nonlocal correlations in the extended Hubbard model from self-consistent combined GW and dynamical mean field theory. Physical Review B. 2013;87(12):125149.

2. Berthod C, Mravlje J, Deng X-Y, Zitko R, van der Marel D, Georges A. Non-Drude universal scaling laws for the optical response of local Fermi liquids. Physical Review B. 2013;87(11):115109.

3. Brouet V, Lin PH, Texier Y, Bobroff J, Taleb-Ibrahimi A, Le Fevre P, et al. Large Temperature Dependence of the Number of Carriers in Co-Doped BaFe2As2. Physical Review Letters. 2013; 110(16):167002.

4. Cao G, Subedi A, Calder S, Yan JQ, Yi JY, Gai Z, et al. Magnetism and electronic structure of La2ZnIrO6 and La2MgIrO6: Candidate J(eff)=1/2 Mott insulators. Physical Review B. 2013;87(15): 155136.

5. Chung C-H, Le Hur K, Finkelstein G, Vojta M, Woelfle P. Non-equilibrium quantum transport through a dissipative resonant level. Physical Review B. 2013;87:245310.

6. Deng X-Y, Mravlje J, Zitko R, Ferrero M, Kotliar G, Georges A. How Bad Metals Turn Good: Spectroscopic Signatures of Resilient Quasiparticles. Physical Review Letters. 2013;110(8):086401.

7. Dutt P, Le Hur K. Strongly-Correlated Thermoelectric Transport beyond Linear Response. Phys. Rev. B. 2013;88: 235133.

8. Dutt P, Schmidt TL, Mora C, Le Hur K. Strongly correlated dynamics in multichannel quantum RC circuits. Physical Review B. 2013;87(15):155134.

9. Filippone M, Le Hur K, Mora C, Vojta M, Woelfle P. Admittance of the SU(2) and SU(4) Anderson quantum RC circuits. Physical Review B. 2013;88:045302.

10. Glazyrin K, Pourovskii LV, Dubrovinsky L, Narygina O, McCammon C, Hewener B, et al. Importance of Correlation Effects in hcp Iron Revealed by a Pressure-Induced Electronic Topological Transition. Physical Review Letters. 2013;110(11):117206.

11. Grenier C, Kollath C, Georges A. Quantum oscillations in ultracold Fermi gases: Realizations with rotating gases or artificial gauge fields. Physical Review A. 2013;87(3):033603.

12. Hansmann P, Ayral T, Vaugier L, Werner P, Biermann S. Long-Range Coulomb Interactions in Surface Systems: A First-Principles Description within Self-Consistently Combined GW and Dynamical Mean-Field Theory. Physical Review Letters. 2013;110(16):166401.

13. Hansmann P, Vaugier L, Jiang H, Biermann S. What about U on surfaces? Extended Hubbard models for adatom systems from first principles. Journal of Physics-Condensed Matter. 2013;25(9): 094005.

14. Liu T, Douçot B, Le Hur K. Anisotropic quantum spin Hall effect, spin-orbital textures, and the Mott transition. Physical Review B. 2013;88(24):245119.

15. Mora C, Le Hur K. Probing dynamics of Majorana fermions in quantum impurity systems. Phys. Rev. B 2013;88:241302.

16. Orth PP, Cocks D, Rachel S, Buchhold, Le Hur K, Hofstetter W. Correlated Topological Phases and Exotic Magnetism with Ultracold Fermions. Journal of Physics B-Atomic Molecular and Optical Physics. 2013;46:134004.

17. Orth PP, Imambekov A, Le Hur K. Nonperturbative stochastic method for driven spin-boson model. Physical Review B. 2013;87(1):014305.

18. Petrescu A, Le Hur K. Bosonic Mott Insulator with Meissner Currents. Physical Review Letters. 2013;111(15): 150601.

19. Pourovskii LV, Miyake T, Simak S, Ruban AV, Dubrovinsky L, Abrikosov IA. Electronic properties and magnetism of iron at the Earth's inner core conditions. Physical Review B. 2013;87(11):115130.

20. Ristivojevic Z, Matveev KA. Relaxation of weakly interacting electrons in one dimension. Physical Review B. 2013;87(16):165108.

21. Rodney M, Song HF, Lee SS, Le Hur K, Sorensen ES. Scaling of entanglement entropy across Lifshitz transitions. Physical Review B. 2013;87(11):115132.

22. Subedi A. Electron-phonon superconductivity and charge density wave instability in the layered titanium-based pnictide BaTi2Sb2O. Physical Review B. 2013;87(5):054506.

23. Tomczak JM, Pourovskii L, Vaugier L, Georges A, Biermann S. Rare-earth vs. heavy metal pigments and their colors from first principles. PNAS. 2013;110(3):904-7.

24. Wu W, Scherer MM, Honerkamp C, Le Hur K. Correlated Dirac particles and superconductivity on the honeycomb lattice. Physical Review B. 2013;87(9):094521.

25. Xu N, Richard P, van Roekeghem A, Zhang P, Miao H, Zhang WL, et al. Electronic Band Structure of BaCo2As2: A Fully Doped Ferropnictide Analog with Reduced Electronic Correlations. Physical Review X. 2013;3(1):011006.

26. Xu N, Richard P, Wang XP, Shi X, van Roekeghem A, Qian T, et al. Angle-resolved photoemission observation of isotropic superconducting gaps in isovalent Ru-substituted Ba(Fe0.75Ru0.25)(2)As-2. Physical Review B. 2013;87(9):094513.

<u>2014</u>

26. Akerlund O, de Forcrand P, Georges A, Werner P. Extended mean field study of complex phi(4)-theory at finite density and temperature. Physical Review D. 2014;90(6):065008.

27. Biermann S. Dynamical screening effects in correlated electron materials-a progress report on combined many-body perturbation and dynamical mean field theory: "GW plus DMFT". Journal of Physics - Condensed Matter. 2014;26(17):173202.

28. Black-Schaffer AM, Wu W, Le Hur K. Chiral d-wave superconductivity on the honeycomb lattice close to the Mott state. Physical Review B. 2014;90(5):054521.

29. Catalano S, Gibert M, Bisogni V, Peil OE, He F, Sutarto R, et al. Electronic transitions in strained SmNiO3 thin films. APL Materials. 2014;2(11):116110.

30. de la Torre A, Hunter EC, Subedi A, Walker SM, Tamai A, Kim TK, et al. Coherent Quasiparticles with a Small Fermi Surface in Lightly Doped Sr3Ir2O7. Physical Review Letters. 2014;113(25):256402.

31. Grenier C, Georges A, Kollath C. Peltier Cooling of Fermionic Quantum Gases. Physical Review Letters. 2014;113(20):200601.

32. Hansmann P, Parragh N, Toschi A, Sangiovanni G, Held K. Importance of d-p Coulomb interaction for high T-C cuprates and other oxides. New Journal of Physics. 2014;16:033009.

33. Haverkort MW, Sangiovanni G, Hansmann P, Toschi A, Lu Y, Macke S. Bands, resonances, edge singularities and excitons in core level spectroscopy investigated within the dynamical mean-field theory. EPL. 2014;108(5):57004.

34. Henriet L, Ristivojevic Z, Orth PP, Le Hur K. Quantum dynamics of the driven and dissipative Rabi model. Physical Review A. 2014;90(2):023820.

35. Huang L, Ayral T, Biermann S, Werner P. Extended dynamical mean-field study of the Hubbard model with long-range interactions. Physical Review B. 2014;90(19):195114.

36. Jagannathan A, Duneau M. The eight-fold way for optical quasicrystals. European Physical Journal B. 2014;87(7):149.

37. Luo Y, Pourovskii L, Rowley SE, Li Y, Feng C, Georges A, et al. Heavy-fermion quantum criticality and destruction of the Kondo effect in a nickel oxypnictide. Nature Materials. 2014;13(8):777-81.

38. Ma JZ, van Roekeghem A, Richard P, Liu ZH, Miao H, Zeng LK, Xu N, Shi M Cao C, He JB, Chen GF, Sun YL, Cao GH, Wang SC, Biermann S, Qian T, Ding H. Correlation-Induced Self-Doping in the Iron-Pnictide Superconductor Ba2Ti2Fe2As4O. Physical Review Letters. 2014;113(26):266407.

39. Mankowsky R, Subedi A, Forst M, Mariager SO, Chollet M, Lemke HT, et al. Nonlinear lattice dynamics as a basis for enhanced superconductivity in YBa2Cu3O6.5. Nature. 2014;516(7529): 71-U150.

40. Peil OE, Ferrero M, Georges A. Orbital polarization in strained LaNiO3: Structural distortions and correlation effects. Physical Review B. 2014;90(4):045128.

41. Petrescu A, Song HF, Rachel S, Ristivojevic Z, Flindt F, Laflorencie N, Klich I. , Regnault N., Le Hur K. Fluctuations and Entanglement spectrum in quantum Hall states. Journal of Statistical Mechanics: Theory and Experiment Invited Article for. 2014;Special Issue of JSTAT on “Quantum Entanglement in Condensed Matter Physics”:P10005.

42. Pourovskii LV, Hansmann P, Ferrero M, Georges A. Theoretical Prediction and Spectroscopic Fingerprints of an Orbital Transition in CeCu2Si2. Physical Review Letters. 2014;112(10):106407.

43. Pourovskii LV, Mravlje J, Ferrero M, Parcollet O, Abrikosov IA. Impact of electronic correlations on the equation of state and transport in epsilon-Fe. Physical Review B. 2014;90(15):155120.

44. Ren Z, Pourovskii LV, Giriat G, Lapertot G, Georges A, Jaccard D. Giant Overlap between the Magnetic and Superconducting Phases of CeAu2Si2 under Pressure. Physical Review X. 2014;4(3): 031055.

45. Rezaei N, Hansmann P, Bahramy MS, Arita R. Mechanism of charge transfer/disproportionation in LnCu(3)Fe(4)O(12) (Ln = lanthanides). Physical Review B. 2014;89(12):125125.

46. Ristivojevic Z. Excitation Spectrum of the Lieb-Liniger Model. Physical Review Letters. 2014; 113(1):015301.

47. Ristivojevic Z, Matveev KA. Decay of Bogoliubov quasiparticles in a nonideal one-dimensional Bose gas. Physical Review B. 2014;89(18):180507.

48. Ristivojevic Z, Petkovic A, Le Doussal P, Giamarchi T. Superfluid/Bose-glass transition in one dimension. Physical Review B. 2014;90(12):125144.

49. Sakuma R, Martins C, Miyake K, Aryasetiawan F. Ab initio study of the downfolded self-energy for correlated systems: Momentum dependence and effects of dynamical screening. Physical Review B. 2014;89(23): 235119.

50. Schiró M, Le Hur K. Tunable Hybrid Quantum Electrodynamics from Non-Linear Electron Transport. Physical Review B. 2014;89:195127.

51. Shi Y, Huang Y, Wang XP, Shi X, Van Roekeghem A, Zhang WL, et al. Observation of Strong-Coupling Pairing with Weakened Fermi-Surface Nesting at Optimal Hole Doping in Ca0.33Na0.67Fe2As2. Chinese Physics Letters. 2014;31(6):067403.

52. Souliou SM, Subedi A, Song YT, Lin CT, Syassen K, Keimer B, et al. Pressure-induced phase transition and superconductivity in YBa2Cu4O8. Physical Review B. 2014;90(14):140501.

53. Stricker D, Mravlje J, Berthod C, Fittipaldi R, Vecchione A, Georges A, et al. Optical Response of Sr2RuO4 Reveals Universal Fermi-Liquid Scaling and Quasiparticles Beyond Landau Theory. Physical Review Letters. 2014;113(8):087404.

54. Subedi A. Unconventional sign-changing superconductivity near quantum criticality in YFe2Ge2. Physical Review B. 2014;89(2):024504.

55. Subedi A, Cavalleri A, Georges A. Theory of nonlinear phononics for coherent light control of solids. Physical Review B. 2014;89(22):220301.

56. Tokuno A, Georges A. Ground states of a Bose-Hubbard ladder in an artificial magnetic field: field-theoretical approach. New Journal of Physics. 2014;16:073005.

57. Tomczak JM, Casula M, Miyake T, Biermann S. Asymmetry in band widening and quasiparticle lifetimes in SrVO3: Competition between screened exchange and local correlations from combined GW and dynamical mean-field theory GW plus DMFT. Physical Review B. 2014;90(16): 165138.

58. van Roekeghem A, Ayral T, Tomczak JM, Casula M, Xu N, Ding H, et al. Dynamical Correlations and Screened Exchange on the Experimental Bench: Spectral Properties of the Cobalt Pnictide BaCo2As2. Physical Review Letters. 2014;113(26):266403.

59. van Roekeghem A, Biermann S. Screened exchange dynamical mean-field theory and its relation to density functional theory: SrVO3 and SrTiO3. EPL. 2014;108(5):57003.

60. Wadati H, Mravlje J, Yoshimatsu K, Kumigashira H, Oshima M, Sugiyama T, et al. Photoemission and DMFT study of electronic correlations in SrMoO3: Effects of Hund's rule coupling and possible plasmonic sideband. Physical Review B. 2014;90(20):205131.

2015

61. Ayral T, Parcollet O. Mott physics and spin fluctuations: A unified framework. Physical Review B. 2015;92(11): 115109.

62. Black-Schaffer AM, Le Hur K. Topological Superconductivity in Two Dimensions with Mixed Chirality. Physical Review B. 2015;92:140503(R).

63. Dang HT, Mravlje J, Georges A, Millis AJ. Band Structure and Terahertz Optical Conductivity of Transition Metal Oxides: Theory and Application to CaRuO3. Physical Review Letters. 2015; 115(10):107003.

64. Dang HT, Mravlje J, Georges A, Millis AJ. Electronic correlations, magnetism, and Hund's rule coupling in the ruthenium perovskites SrRuO3 and CaRuO3. Physical Review B. 2015;91(19): 195149.

65. Deng YJ, Kozik E, Prokof'ev NV, Svistunov BV. Emergent BCS regime of the two-dimensional fermionic Hubbard model: Ground-state phase diagram. Epl. 2015;110(5):57001.

66. Dubrovinsky L, Dubrovinskaia N, Bykova E, Bykov M, Prakapenka V, Prescher C, et al. The most incompressible metal osmium at static pressures above 750 gigapascals. Nature. 2015;525(7568): 226-9.

67. Henriet L, Jordan AN, Le Hur K. Electrical Current from Quantum Vacuum Fluctuations in Nanoengines. Physical Review B. 2015;92:125306

68. Kozik E, Ferrero M, Georges A. Nonexistence of the Luttinger-Ward Functional and Misleading Convergence of Skeleton Diagrammatic Series for Hubbard-Like Models. Physical Review Letters. 2015;114(15): 156402.

69. Krivenko IS, Biermann S. Slave rotor approach to dynamically screened Coulomb interactions in solids. Physical Review B. 2015;91(15):155149.

70. Le Hur K. Condensed-matter physics: Quantum dots and the Kondo effect. Nature 2015;526:203-4, News and Views.

71. LeBlanc JPF, Antipov AE, Becca F, Bulik IW, Chan GKL, Chung CM, et al. Solutions of the Two-Dimensional Hubbard Model: Benchmarks and Results from a Wide Range of Numerical Algorithms. Physical Review X. 2015;5(4):041041.

72. Parcollet O, Ferrero M, Ayral T, Hafermann H, Krivenko I, Messio L, et al. TRIQS: A toolbox for research on interacting quantum systems. Computer Physics Communications. 2015;196:398-415.

73. Perepelitsky E, Shastry BS. Diagrammatic lambda series for extremely correlated Fermi liquids. Annals of Physics. 2015;357:1-39.

74. Petrescu A, Le Hur K. Chiral Mott Insulators, Meissner Effect, and Laughlin States in Quantum Ladders. Physical Review B. 2015;91:054520

75. Razzoli E, Matt CE, Kobayashi M, Wang XP, Strocov VN, van Roekeghem A, Biermann, S. Plumb NC, Radovic M, Schmitt T, Capan C, Fisk Z, Richard P, Ding H, Aebi P, Mesot J, Shi M. Tuning electronic correlations in transition metal pnictides: Chemistry beyond the valence count. Physical Review B. 2015;91(21):214502.

76. Ruppen J, Teyssier J, Peil OE, Catalano S, Gibert M, Mravlje J, et al. Optical spectroscopy and the nature of the insulating state of rare-earth nickelates. Physical Review B. 2015;5(4):041041.

77. Sakai S, Civelli M, Nomura Y, Imada M. Hidden fermionic excitation in the superconductivity of the strongly attractive Hubbard model. Physical Review B. 2015;92(18):180503.

78. Shinaoka H, Nomura Y, Biermann S, Troyer M, Werner P. Negative sign problem in continuous-time quantum Monte Carlo: Optimal choice of single-particle basis for impurity problems. Physical Review B. 2015;92(19):195126.

79. Steiner K, Nomura Y, Werner P. Double-expansion impurity solver for multiorbital models with dynamically screened U and J. Physical Review B. 2015;92(11):115123.

80. Subedi A, Peil OE, Georges A. Low-energy description of the metal-insulator transition in the rare-earth nickelates. Physical Review B. 2015;91(7):075128.

81. Uchino S, Tokuno A. Population-imbalance instability in a Bose-Hubbard ladder in the presence of a magnetic flux. Physical Review A. 2015;92(1):013625.

82. Vasic I, Petrescu A, Le Hur K, Hofstetter W. Chiral Bosonic Phases on the Haldane Honeycomb Lattice. Physical Review B. 2015;91:094502 (Editors Suggestion).

83. Vekilova OY, Pourovskii LV, Abrikosov IA, Simak SI. Electronic correlations in Fe at Earth's inner core conditions: Effects of alloying with Ni. Physical Review B. 2015;91(24):245116.

84. Vildosola V, Pourovskii LV, Manuel LO, Roura-Bas P. Reliability of the one-crossing approximation in describing the Mott transition. Journal of Physics - Condensed Matter. 2015;27(48): 485602.

85. Wu SF, Richard P, van Roekeghem A, Nie SM, Miao H, Xu N, et al. Direct spectroscopic evidence for completely filled Cu 3d shell in BaCu2As2 and alpha-BaCu2Sb2. Physical Review B. 2015;91(23):235109.

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87. Zhang X, Wu W, Li G, Wen L, Sun Q, Ji A-C. Phase diagram of interacting Fermi gas in spin-orbit coupled square lattices. New Journal of Physics. 2015;17:073036.

2016

88. Aichhorn M, Pourovskii L, Seth P, Vildosola V, Zingl M, Peil OE, et al. TRIQS/DFTTools: A TRIQS application for ab initio calculations of correlated materials. Computer Physics Communications. 2016;204:200-8.

89. Alkurtass B, Bayat A, Affleck I, Bose S, Johannesson H, Sodano P, Le Hur K. Entanglement structure of the two-channel Kondo model. Physical Review B. 2016;93(8):081106.

90. Biermann S, van Roekeghem A. Electronic polarons, cumulants and doubly dynamical mean field theory: Theoretical spectroscopy for correlated and less correlated materials. Journal of Electron Spectroscopy and Related Phenomena. 2016;208:17-23.

91. Delange P, Ayral T, Simak SI, Ferrero M, Parcollet O, Biermann S, et al. Large effects of subtle electronic correlations on the energetics of vacancies in alpha-Fe. Physical Review B. 2016;94(10): 100102.

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93. Grenier C, Kollath C, Georges A. Thermoelectric transport and Peltier cooling of cold atomic gases. Comptes Rendus Physique. 2016;17(10):1161-74.

94. Hansmann P, Ayral T, Tejeda A, Biermann S. Uncertainty principle for experimental measurements: Fast versus slow probes. Scientific reports. 2016;6:19728.

95. Henriet L, Le Hur K. Quantum sweeps, synchronization, and Kibble-Zurek physics in dissipative quantum spin systems. Physical Review B. 2016;93(6):064411.

96. Herviou L, Le Hur K, Mora C. Many-terminal Majorana island: From topological to multichannel Kondo model. Physical Review B. 2016;94(23):235102.

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2

Laser Plasma Interaction

Permanent staff	Jean-Claude Adam (ESR CNRS since 2009) Arnaud Couairon (DR1 CNRS) Anne Héron (CRCN CNRS)* Stefan Hüller (DR2 CNRS, Group Leader) Patrick Mora (ESR CNRS since 2018) Denis Pesme (ESR CNRS since 2016)
Non-permanent staff as at June 2018	2 PhD students and 1 postdoctoral fellow

2.1 Introduction

The group has three main research axes, all centered around the propagation and the interaction of laser pulses with plasmas and, more generally, with ionized nonlinear media. These axes are:

- Modelling of the interaction of complex laser beams with plasma waves in the context of inertial confinement fusion (*i.e.*, laser fusion);
- Interaction of intense and ultra-intense short laser pulses in plasmas and their applications;
- Nonlinear light matter interaction at moderate laser intensities.

2.2 Modelling of laser-plasma interaction in the context of laser fusion

The activities of the group in the context of laser fusion are currently concentrated on the modelling of fundamental processes of laser-plasma coupling. Such processes take place in under-dense plasmas where the plasma waves and the plasma flow influence the propagation of the laser light that should be absorbed in order to achieve a symmetric implosion of the fusion capsule containing a D-T mixture. It is well-known that wave-wave coupling phenomena provoke so-called parametric instabilities, like stimulated scattering and light filamentation, all deleterious for a good laser-plasma coupling. The understanding and the appropriate modelling of these instabilities is in the centre of our current efforts; the challenge is to be able to describe the laser propagation in the presence of these processes under the realistic conditions corresponding to the present day configurations of laser fusion experiments. The difficulty lies not only in the nonlinear nature of the processes, requiring solving systems of coupled nonlinear partial differential equations, but also in the various temporal and spatial scales involved. As we have complementary competence in the theoretical-analytical modelling of parametric instabilities and in the numerical simulations at various scales, our main effort in the past five years was focused on the proper description of the laser-plasma interaction in the case of several realistic laser beams giving rise to multiple couplings between the laser lights and plasma waves. In this context, we have investigated the laser light flux transfer between two or more

*60% of her time in this group

laser beams that cross in the plasma surrounding the fusion capsule. This process, commonly named "CBET" for "crossed beam energy transfer" attracts currently a strong attention due of its importance for the control of the laser light energy deposition. Its control plays a key role for the design studies both for the direct- and indirect laser fusion schemes. The CBET process is a resonant process when two beams are coupled via an ion sound wave, either when the beams frequencies are equal in the presence of a sonic flow, or when the beams frequencies differ by the plasma ion sound wave. The CBET process has been studied in the past by modelling large crossing laser beams, but without taking into account the realistic speckle substructure of these beams. Although these studies were conceptually very important, significant differences have been observed in the recent experimental campaigns between the predictions based on these models and the experimental results.

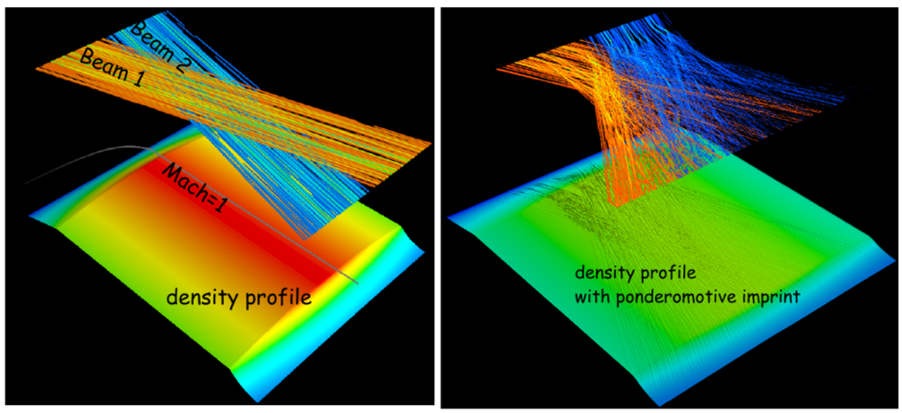

Figure 2.1: Transfer of energy between two laser beams (of equal laser flux) with speckles structure that overlap in an expanding plasma with inhomogeneous flow, including the region with sonic flow (Mach=1) where transfer is resonant. Left: scheme of crossing beams, early time before interaction. Right: late time (100ps) when transfer is established, and where ponderomotive profile modifications cause, besides energy transfer, spatio-temporal incoherence and significant increase in the angular aperture of both beams.

Energy transfer between crossed laser beams with speckle structure. In the continuation of on our theoretical work on the so-called "smoothed" laser beams [Hüller 2015, Afeyan 2013], we have carried out numerical studies on the propagation of laser beams with speckle structure, such as used nowadays in energetic lasers for fusion, in order to understand the role of the speckle structure in CBET. In collaboration with the CELIA/Bordeaux group we have investigated the feasibility to model complex laser beams with speckle structure with ray-based methods. Such paraxial complex geometrics optics (PCGO) methods allow to compute the laser light propagation so efficiently that they can be integrated in hydrodynamics codes for "long-duration" simulations, i.e. on the nanosecond scale. In order to get a validity test of these methods, we have used our two-dimensional wave coupling code Harmony; this code is coupled to the plasma hydrodynamics and it solves – in contrast to the PCGO model – time dependent paraxial equations on the acoustic (pico-second) time scale. In the limit of moderate laser intensities, the comparison consolidated the applicability of the PCGO model [Colaïtis 2016]. Being aware of the limits of the ray-tracing type PCGO approach to describe processes that need a transient description in time, we then went beyond this first study and investigated crossed laser beams interaction in order to understand self-focusing when the laser speckles come into play.

The results were surprising [Raj 2017; Hüller 2018] since they show a strong departure from theory and modelling without taking into account speckle structure, which is in particular pertinent for the indirect-drive scheme for laser fusion. We observe that the onset of self-focusing in laser speckles was generally underestimated in previous studies because the influence of plasma flow, although know to lower the threshold for the instability, was often ignored.

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Collective laser plasma instabilities. The indirect-drive scheme for inertial confinement fusion uses a large number of laser beams arranged in a symmetric angular distribution. We have studied, in collaboration with an experimental group from CEA and LULI, the collective nature of laser plasma instabilities which can develop due to the coupling of all the incident laser waves located in a cone with a daughter wave growing along the cone symmetry axis. With adequate diagnostics on the scattered light, indirect-drive experiments have been able to demonstrate the occurrence of collective stimulated Brillouin side-scattering (SBSS) resulting from the coupling of the laser beams to a common ion acoustic waves; these results have been predicted and verified by theory. [Neuville 2016 a]. In the continuation of these experimental and theoretical collaborations, we have investigated the effect on SBSS of a laser temporal incoherence added to its spatial smoothing produced by random phase plates; in the case of a large number of incident laser beams, it has been experimentally observed that a weak temporal smoothing has a dramatic effect on the SBSS reflectivity, reducing it to a very low level, of the order of a few %, by contrast with the no temporal smoothing case, where it can reach up to 50%. By applying statistical methods to describe laser-plasma interaction in this context we have been able to theoretically predict this very significant reduction of the SBSS reflectivity [Depierreux 2018]. Similarly, in the context of shorter time scales, the collective coupling in the stimulated Raman scattering (SRS) process can produce light scattering in (unexpected) directions out of the planes of incidence of the beams. These findings may be relevant for laser fusion experiments where anomalously large levels of SRS have been measured [Depierreux 2016]. In a similar context, we have collaborated with experimental groups from CEA and LULI to investigate the energy transfer between laser pulses of two (or more) RPP beams characterized by speckle structures in the spatial domain of laser-plasma coupling. The ability to vary the intensity and duration of the shortest of the laser pulses made it possible to examine the transient nature of the energy transfer from one beam (ns duration) mainly into intense speckles, namely in the case of 1ps duration for the shortest pulse, or into the entire short pulse beam for a duration of ~ 10ps. [Neuville 2016 b] These studies are of fundamental interest in the context of laser fusion and for the amplification of short laser pulses by stimulated scattering processes as well. A potential issue is the modification of the polarization in the crossing beams produced by energy transfer within the laser speckles [Neuville 2017].

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2.3 Interaction of intense short laser pulses in plasmas and their applications

Enhancement and control of laser wakefields via a backward Raman amplifier. The ability to create large amplitude plasma waves traveling near the speed of light using a laser pulse has led to several scientific breakthroughs such as laser wakefield acceleration (LWFA). In general the performance of LWFA can be limited by laser diffraction, depletion, and particle dephasing in the LWFA. In a recent study in the frame of our collaborations with the U. of Alberta, Lawrence Livermore (LLNL) and CEA we have used a particle-in-cell model (U Alberta) and a wave-wave coupling model (CPHT) to study the feasibility a scheme in which backward Raman amplification (BRA) of a short seed pulse is used to maintain the driving laser pulse and hence to enhance and control the wakefield generation. While the overall goal for BRA up to now has been to maximize laser pulse amplification, still with a mixed success, we consider its use as a control mechanism during plasma wake generation. Our work is the first application of BRA to amplify and sustain a short seed laser pulse while simultaneously enhancing wakefield generation in a plasma.

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Numerical modelling of multi-GeV laser wakefield electron acceleration inside a dielectric capillary tube. We have performed the numerical modelling of laser wakefield electron acceleration inside a gas filled dielectric capillary tube. We have demonstrated the guiding of a short pulse laser inside a dielectric capillary tube over a long distance (1m) and the acceleration of an externally injected electron bunch to ultra-relativistic energies (~5-10 GeV) in the quasi-linear regime of laser wakefield acceleration. We performed two dimensional axisymmetric simulations with the code WAKE-EP (Extended Performances), which allows computationally efficient simulations of such long scale plasma. The code is an upgrade of the quasi-static particle code, WAKE [P. Mora and T. M. Antonsen, Jr., Phys. Plasmas 4, 217 (1997)], to simulate the acceleration of an externally injected electron bunch (including beam loading effect) and propagation of the laser beam inside a dielectric capillary. The influence of the transverse electric field of the plasma wake on the radial loss of the accelerated electrons to the dielectric wall has been investigated. The stable acceleration of electrons to multi-GeV energy with a non-resonant laser pulse with a large spot-size has been demonstrated.

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Self-channeling of intense laser pulses in underdense plasma and stability analysis. The propagation of intense laser pulses in large scale underdense plasmas is an important subject for applications in the domains of laser fusion, laser particle acceleration and radiation sources. It was known since the seventies that relativistic self-focusing (RSF) takes place whenever the laser power P exceeds a well-defined critical power, denoted here as P_{cr}. On the other hand, it was important to predict the non linear behaviour of laser plasma interaction in realistic 3D plasmas. By means of 3D PIC codes and analytic modelling, we investigated in the frame of our collaboration with the University of Alberta the propagation of intense laser pulses in an underdense plasma for various laser powers P above P_{cr} and for various plasma densities. We found that the laser pulse propagation takes place under the form of a single fully evacuated stationary channel for a plasma density n_0 in the range $0.001 < n_0/n_{cr} < 0.1$, and for laser powers above the critical power P_{ch} for channelling $P_{ch} \approx 1.1P_{cr}$. We did not observe stable channelling for plasma densities larger than $0.1n_{cr}$. We observed the formation of an evacuated ring enclosed by an electron filament for laser powers exceeding $33P_{cr}$, as predicted analytically. However we found that these ring structures are unstable with regards to azimuthal perturbations.

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Physics of the interaction of intense laser pulses with cold collisional plasmas using large scale kinetic simulations. For the coupling of ultra-intense laser pulses with dense plasmas, the comprehension of the transport of relativistic electrons inside the plasma is of great importance. Reduced "hybrid" models, not requiring the resolution of the fast time scale in Maxwell's equations, are often based on the applicability of Ohm's law. We have therefore examined the electron transport when intense laser pulses with fluxes ranging from $10^{18}\,\mathrm{W.cm^{-2}}$ up to $10^{20}\,\mathrm{W.cm^{-2}}$ interact with over-dense cold collisional plasmas with the help of 2D collisional particle-in-cell simulations with our code EMI2D. The size of the simulations chosen allowed us to study in detail the transport due to energetic particles over a duration of 400fs without perturbations due to the influence of boundary effects. Our simulations confirm the existence of a threshold in intensity close to the relativistic threshold above which the beam of energetic particles diverges when it penetrates the cold plasma. Concerning the applicability of Ohm's law, our study shows that half of the heating is anomalous, *i.e.*, not obeying to the standard Joule effect. This confirms what has been seen in work of Sherlock et al. suggesting that a possible source of heating is the damping of the wake field inside the dense plasma created by a beam of energetic particles via the $j \times B$ mechanism. These simulations, run on the HPC resources of CINES/IDRIS under the allocations 2012/2014-056044 made by GENCI, clearly demonstrate the difficulty to rely on reduced, *i.e.*, not fully kinetic, models for the interaction of a ultra-high intensity laser with cold plasma at solid density.

Reference:

- Héron A and Adam JC, Phys. Plasmas 22, 072306 (2015).

Ion cooling in collisionless plasma expansion. We have revisited the ion cooling in collisionless plasma expansion. We have shown that, in the case of an initial Maxwellian ion distribution, the ion cooling is much slower than predicted by an adiabatic law linking the ion temperature to the ion density. The origin of this behaviour is a strong distortion of the ion distribution function resulting in a large ion heat flow (not predicted by a simple water-bag model). Also noticeable is the increase of the electron heat flux in the unperturbed plasma compared to the zero ion temperature case.

Reference:

- Mora P, Phys Rev E 91, 013107 (2015).

High intensity surface plasma waves, theory and PIC simulations. In collaboration with Michèle Raynaud (LSI, Ecole Polytechnique), we have investigated the laser excitation of surface plasma waves (SPW) on grating preformed over-dense plasma in the relativistic regime ranging from 10^{19} up to $10^{21}\,\mathrm{W.cm^{-2}}$. We have compared collisional 2D PIC simulations with fluid description and have shown that the fluid description is useful to optimize the conditions of interaction with gratings. We have evidenced the role of the relativistic detuning that shifts the SPW vector towards a higher value. Nevertheless the SPW seems to be robust up to $10^{21}\,\mathrm{W.cm^{-2}}$. We have also pointed out that although the use of short pulse durations is needed to preserve the grating shape during the interaction in order to excite the SPW, the short pulse limits the SPW amplitude. Finally, using a focused pulse in the experiments induces a spectral width larger than that of the SPW. Consequently, the energy of the SPW is reduced. The PIC simulations were performed using the HPC BlueGene/Q IDRIS resources from the GENCI Grant number 2015–2017/056851.

Reference:

- Raynaud M, Héron A and Adam JC, Plasma Phys. Control. Fusion 60, 014021 (2018).

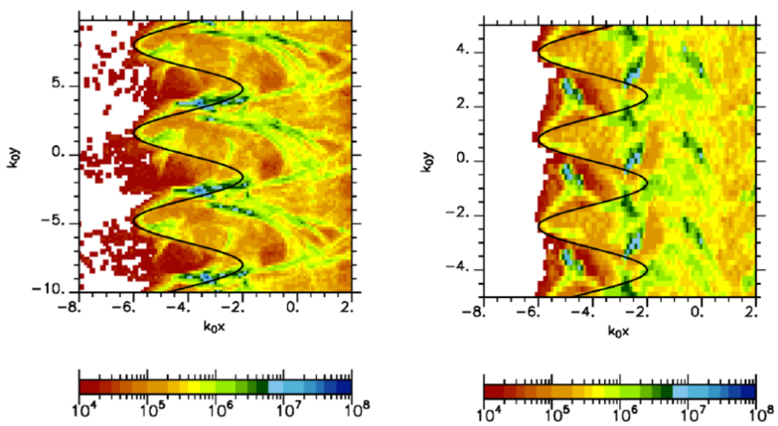

Figure 2.2: Contour plot of electron energy density due to interaction of a ultra-short (18fs) intense laser pulse with a solid-density plasma, computed with the EMI2d-3V particle-in-cell code. Shown is the zoom of the vacuum-plasma interface at the central part of the laser focal spot. The plasma density on surface is modulated with an imprinted perturbation. The surface plasma wavelength, along y, is varied by a factor ~ 1/2 between the left and the right image, resulting in two obviously different regimes of laser absorption.

Absorption of ultra-short and ultra-intense pulses by target at solid density, application to ion acceleration. The first goal of this work was to study the ion acceleration due to the interaction of a laser with characteristics and typical parameters available at the Apollon laser (CILEX-CNRS situated on the site of CEA Saclay, operational from end of 2018) with a thin target. We performed simulations with a 1ps laser pulse to obtain a quasi-asymptotic regime of ion acceleration. Our simulations were designed such that effects of boundary conditions of the simulation box are avoided. The absorption of the laser pulse on a plane (unstructured) target surface is only of 10%. To augment the laser absorption, we added to the front target surface a grating structure or an exponential density gradient. We varied the wavelength of the grating and the length of the density gradient. No correlation between the absorption of the laser pulse and the cut-off in the ion energy spectra could be deduced. The wavelength of the grating which corresponds to the excitation of a surface plasma wave yields neither the best absorption of the laser pulse nor the most efficient acceleration of the ions. The ion acceleration on the rear face seems to obey to a simple theoretical model depending on the temperature of hot electrons. This temperature has however no evident relationship with the absorption of the laser pulse. This work was granted access to the HPC resources of IDRIS under the allocation 2016/2017-056044 made by GENCI.

Reference:

- Héron A, Adam JC and Mora P, IFSA2017, Saint Malo, France.

Currently, we study with 3D simulations the interaction of laser pulses with the characteristics of the Apollon laser with structured targets. For gratings, we have obtained a similar absorption between the 2D simulations and the 3D simulations, but the ion beam on the rear face is not isotropic. The study with a target of 3d structure is in progress. For do this study, we obtained a GENCI allocation of 25000000 hours for the year 2018/2019 on the machine Blue/gene of IDRIS.

2.4 Nonlinear light matter interaction at moderate laser intensities

We developed new models and numerical tools for understanding fundamental processes associated with laser-matter interaction at moderate intensities, and femtosecond filamentation physics. In particular, we focused on the generation of secondary radiation such as broadband super-continuum spectra and THz radiation. In parallel, we worked on applications of filamentation such as laser guided discharges, micro-machining of glasses with femtosecond laser pulses undergoing filamentation, atmospheric applications such as filament-based detection of pollutants, and the generation of underwater acoustic signals by femtosecond laser .

Filaments with Bessel beams in glasses - Micromachining applications. In the framework of an ANR project (with F. Courvoisier, Femto-ST Besançon), we worked on the control of laser energy deposition in glasses for micro- and nano-machining applications. The main goal of these works was to control laser energy deposition in the bulk of a transparent solid so as to obtain a high aspect ratio plasma channel and drill the material, potentially in a single shot, which is desirable in applications such as ultrafast ablation and prototyping of glass, microfluidics. We investigated the nonlinear propagation of Bessel beams for their ability to focus along a line rather than a localized region. We extended these works to the case of high-order Bessel beams, the main lobe of which focus along a tubular focal region, allowing for a simultaneous control of the diameter, length and density of the micro-plasma channel generated in a glass. On the basis of these works, a patent for ultrafast micro-machining of transparent media by filamentation with Bessel beams carrying angular momentum was deposited.

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- Jukna V, Milián C, Xie C, Itina T, Dudley J, Courvoisier F, et al. Filamentation with nonlinear Bessel vortices. Optics Express 22, 25410-25 (2014).
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- Xie C, Giust R, Jukna V, Furfaro L, Jacquot M, Lacourt PA, et al. Light trajectory in Bessel-Gauss vortex beams. Journal of the Optical Society of America A 32, 1313-6 (2015).
- Xie C, Jukna V, Milián C, Giust R, Ouadghiri-Idrissi I, Itina T, et al. Tubular filamentation for laser material processing. Scientific Reports. 5, 8914 (2015).
- Courvoisier F, Stoian R, Couairon A, Ultrafast laser micro- and nano-processing with nondiffracting and curved beams, Optics and Laser Technology 80, 125-37 (2016).

Filamentation from a satellite for global measurements of pollutants in the atmosphere. In collaboration with the European Space Agency, we worked on modelling and numerical simulations of filamentation in the atmosphere from a laser source onboard a satellite. This was motivated by femtosecond LIDAR applications. The principle is illustrated in Fig. 2.3: A femtosecond laser source generates a filament and its associated white light super-continuum in the atmosphere. The backscattered signal is collected by the satellite allowing a multispectral and global analysis of the atmosphere. Compared to a standard terrestrial LIDAR technique, this system takes advantage of scanning an extended spectral domain in single shot. It also allows global measurement of the atmosphere with a

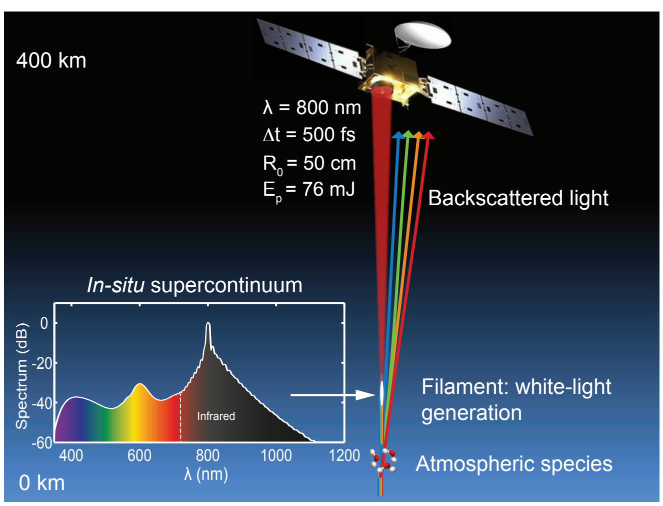

Figure 2.3: Principe for the femtosecond LIDAR onboard a satellite.

single (orbiting) laser source. We have determined the laser parameters for generating the filament and the continuum of white light at a given altitude, in order to develop future space missions for global measurements of the atmosphere.

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- I. Dicaire, V. Jukna, C. Praz, C. Milián, L. Summerer, A. Couairon, Spaceborne laser filamentation for atmospheric remote sensing. Laser Photonics Reviews. 10, 481 (2016).

- M.N. Quinn, V. Jukna, T. Ebisuzaki, I. Dicaire, R. Soulard, L. Summerer, et al. Space-based application of the CAN laser to LIDAR and orbital debris remediation. European Physical Journal, Special Topics 224, 2645 (2015).

Generation of acoustic waves in water by femtosecond laser. In the framework of a DGA-Ecole Polytechnique contract and in collaboration with A. Houard's team at LOA (Ecole Polytechnique), we worked on theory and numerical simulation of the generation of acoustic sources in water by focusing a femtosecond laser beam. The interest of using a femtosecond laser is to be able to generate remote acoustic signals thanks to the long-distance propagation properties of filaments, without immersion of the acoustic source.

We have investigated the propagation dynamics of a femtosecond laser pulse in water by means of numerical simulations and comparisons with dedicated measurements. Laser energy deposition in water was carefully investigated. To investigate heating and formation of a cavitation bubble, we developed a hydrodynamic code solving compressible Euler equations with heat conduction. The acoustic signal was propagated over centimetric distances to model an experiment aiming at characterizing the acoustic source. The radiation pattern was found to correspond to a highly directive acoustic source.

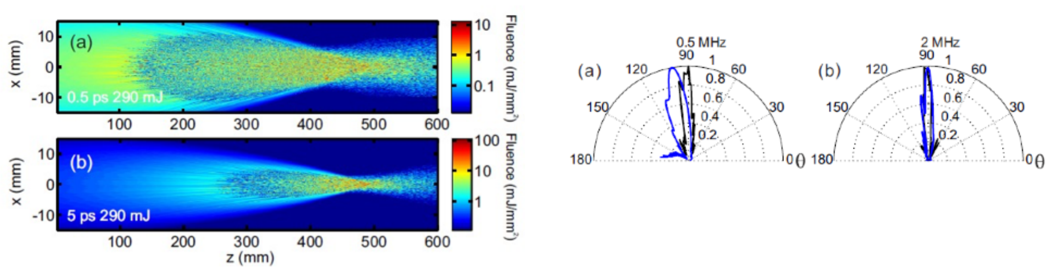

Figure 2.4: Left : Simulation results for the propagation in water of a 290 mJ laser pulse of duration (a) 0.5 ps and (b) 5 ps.. Right: Radiation pattern of the acoustic signal (measurements: blue curves; numerical simulations in black curves) for frequencies (a) 0.5 MHz and (b) 2 MHz. [Jukna et al. 2016].

Our compressible hydrodynamic code has also been exploited for investigations of femtosecond laser guided electric discharges in air. In particular, using Airy beams as a laser pulse guide made it possible to obtain a plasma filament and laser energy deposition of parabolic form, and a parabolic discharge after expansion of the hot column of air.

In collaboration with K. Plamann and M.C. Schanne-Klein (LOB), our simulation code was also used in the context of laser cornea surgery, to investigate the propagation of the shock wave generated after laser energy deposition, towards the endothelium.

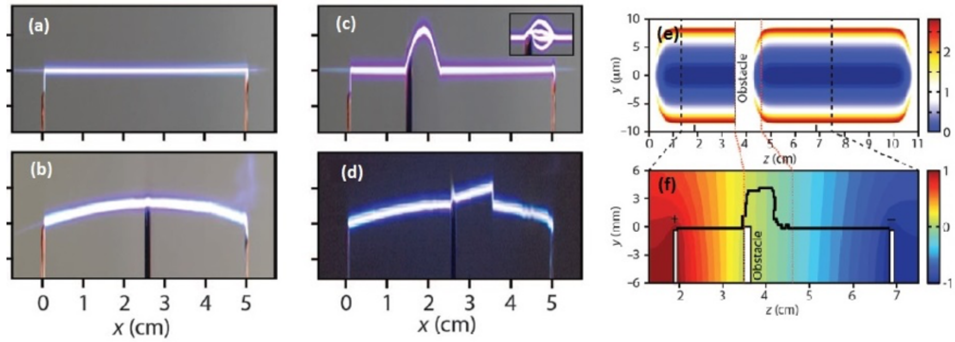

Figure 2.5: Laser guided discharges: (a) A Bessel beam generates a straight plasma channel between the electrodes. (b) An Airy beam generates a parabolic plasma channel; the discharge avoids the obstacle. (c) The Bessel beam or (d) the Airy beam hit the obstacle but self-heal behind it, allowing the discharge to pass over the obstacle (e) Numerical simulation of the expansion of the hot column of air (in case (c)) and (f) simulation of the path of electrons. [Clerici 2015].

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- Jukna V, Jarnac A, Milián C, Brelet Y, Carbonnel Y, Andre YB, et al. Underwater acoustic wave generation by filamentation of terawatt ultrashort laser pulses. Physical Review E 93, 063106 (2016).

- Clerici M, Hu Y, Lassonde P, Milián C, Couairon A, Christodoulides DN, et al. Laser-assisted guiding of electric discharges around objects. Science Advances 1:e1400111 (2015).

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Generation of THz radiation. With the team of R. Morandatti (INRS, Varennes), we have shown that the generation of terahertz radiation using the so called two-color (fundamental and second harmonic) laser-plasma interaction scheme is 30 times more efficient when using a mid-infrared laser (1800 nm) compared to a near infrared wavelength (800 nm). THz electric fields as high as high (4.4 MV/cm) were predicted by our model, and measured. With the teams of G. Ravindra Kumar (Tata Institute, Mumbai) and S. Tzortzakis (Texas A &M University Quatar), we have demonstrated an unconventional way of generating high-energy, ultra-broadband terahertz pulses by ultrafast laser filamentation in liquids, obtaining a remarkably high conversion efficiency larger than 10^{-3}, Our simulations have shown that the efficient generation of terahertz radiation in liquids is due to a local in-phase generation of a srong second harmonic component as part of the nonlinear spectral broadening of the fundamental laser pulse, followed by a standard two-color laser-plasma interaction scheme.

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- Dey I, Jana K, Fedorov VY, Koulouklidis AD, Mondal A, Shaikh M, Sarkar D, Lad AD, Tzortzakis S, Couairon A, Ravindra Kumar G, Highly efficient broadband terahertz generation from ultrashort laser filamentation in liquids, Nat. Commun. 8, 1184 (2017).

2.5 PhD supervisions

- Guillaume Tran, "Etude et la modélisation de la diffusion Raman stimulée en configuration multidimensionnelle pour la FCI", PhD defense on November 9, 2015. Supervisor Stefan Hüller, co-supervisor Pascal Loiseau (CEA-DIF Arpajon).

- Grégoire Varillon, "Analyse de stabilité linéaire d'écoulements d'ablation en fusion par confinement inertiel", PhD started in 01/2017. Supervisor A. Couairon, co-supervisor J.-M. Clarisse (CEA-DIF, Arpajon).

- Mufei Luo, "The role of laser bandwidth and random phase effects on the coupling of stimulated scatter in inhomogeneous plasmas", PhD starts in October 2018. Co-supervisors S. Hüller, Min Chen (Shanghai Joao Tong Univ.).

2.6 Contracts and grants

- ANR Project Blanc ANR-12-BS04-0006 'ILPHYGERIE' ("Interaction laser plasma en configuration multiplasmas/multifaisceaux"), 11/2012-10/2016 (PI S. Depierreux, CEA-DIF Arpajon, leader at CPHT S. Hüller).

- ANR project ANR-11-BS04-0010 blanc 'NANOFLAM' ("Contrôle de la FiLAMentation et de la génération de plasma avec les impulsions non-diffractantes femtoseconde en régime nonlinéaire. Applications à la NANO-structuration laser à ultra haut rapport de forme"), 09/2011-5/2015 (PI F. Courvoisier, FemtoST Besançon, leader at CPHT A. Couairon).

- Euratom project EURATOM IFE KiT, 2007-2013 (PI S. Jacquemot (LULI/CEA), leader at CPHT S. Hüller).

- EuroFusion project WP14-ER-01/CEA-12 'ToIFE' (Towards demonstration of Inertial Fusion for Energy), 01-12/2014 (PI S. Jacquemot, LULI/CEA, leader at CPHT S. Hüller).

- EuroFusion project AWP15-ENR-01/CEA-02 'TOIFE' (Towards demonstration of Inertial Fusion for Energy), 01/2015-12/2018 (PI S. Jacquemot (LULI/CEA), leader at CPHT S. Hüller). Consult for details and reports there.

2.7 Administrative duties (on top of juries, edition, conference organization, etc)

Anne Héron: member of the committee for computer equipment at the Department of Informatics (DSI) of Ecole Polytechnique.

Arnaud Couairon:

- member of the "Conseil National des Universités", section 30 (physics of diluted matter), since 2015;
- member of the programme comittee Lidyl-CELIA-LOA laser facilities;
- member of the bureau "theory-simulation" of the Department PHOM (Physics of Wave and Matter), U. Paris Saclay;

- member of scientific council of Department PSI2 (Physical Sciences and Interfaces), U. Paris Saclay.

Stefan Hüller:

- head of the programme committee for acces to LULI laser facilities, since 2012;
- director of the CNRS unit "GDR2017", Groupement de Recherche "LEPICE-HDE" on High-Energy-Density Physics in Laser plasmas, since 2018;
- member of the Scientific Advisory Committee of the Laser MégaJoule – Petal ("LMJ-Petal") facility, since 2012;
- member of the committee for professor position at U. of Bordeaux, 2017;
- member of the bureau "extreme light" of the Department PHOM (Physics of wave and matter), Univ. Paris Saclay;
- member of the organisation committe of the Forum Laser et Plasmas (from 2018), principal organizer June 2018.

Patrick Mora:

- director of Institut Laser et Plasmas (ILP), till April 2018;
- head of the Scientific Advisory Committee of the Laser MégaJoule – Petal ("LMJ-Petal") facility, 2012-2016;
- member of the HCERES committee at Institut Jean Lamour (Nancy), Dec. 5-7, 2016;
- member of the organisation committee of the 33rd European Conference on Laser Interaction with Matter (ECLIM), Paris, Sept. 2014;
- member of the organisation committee of the Conference on Inertial Fusion Sciences and Applications (IFSA);
- vice-president of the 8th IFSA (Nagoya, Japan 2013) and 9th IFSA (Seatte, USA, 2015);
- member of the organisation committee of the Forum Laser et Plasmas (till 2018);
- member of the selection committee of scientific director of the ELI-NP at Bucharest, Romania;
- member of the selection committee for research directors at CEA-DAM.

2.8 Publications

2.8.1 Papers in refereed journals (sorted by year)

2013

1. Andreev NE, Baranov VE, Cros B, Maynard G, Mora P, Veysman ME. Laser wakefield compression and acceleration of externally injected electron bunches in guiding structures. Journal of Plasma Physics. 2013;79(2):143-52.

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3. Bigongiari A, Raynaud M, Riconda C, Héron A. Improved Ion Acceleration via Laser Surface Plasma Waves Excitation. Physics of Plasmas. 2013;20:05701.

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5. Clerici M, Peccianti M, Schmidt BE, Caspani L, Shalaby M, Giguère M, Lotti A, Couairon A, Légaré F, Ozaki T, Faccio D, Morandotti R, Wavelength Scaling of Terahertz Generation by Gas Ionization, PRL 110, 253901 (2013).

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7. Durand M, Jarnac A, Houard A, Liu Y, Grabielle S, Forget N, et al. Self-Guided Propagation of Ultrashort Laser Pulses in the Anomalous Dispersion Region of Transparent Solids: A New Regime of Filamentation. Physical Review Letters. 2013;110(11):115003.

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11. Hüller S, Porzio A, Robiche J. Order statistics of high-intensity speckles in stimulated Brillouin scattering and plasma-induced laser beam smoothing. New Journal of Physics. 2013;15:025003.

12. Hemmer M, Baudisch M,Thai A, Couairon A, Biegert J. Self-compression to sub-3-cycle duration of mid-infrared optical pulses in dielectrics. Optics Express 21 (2013) 28095.

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14. Panagiotopoulos P, Papazoglou DG, Couairon A, Tzortzakis S, Sharply autofocused ring-Airy beams transforming into non-linear intense light bullets, Nat. Commun. 4:2622 (2013).

15. Paradkar BS, Cros B, Mora P, Maynard G. Numerical modeling of multi-GeV laser wakefield electron acceleration inside a dielectric capillary tube. Phys. Plasmas 20, 083120 (2013).

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2.8.3 Other publications

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3

MAGNETIZED PLASMAS

PERMANENT STAFF	Tahar AMARI (DR1 CNRS) Aurélien CANOU (RE X) Anne HÉRON (CRCN CNRS)* Jean-François LUCIANI (DR2 CNRS) Hinrich LÜTJENS (DR2 CNRS, Group Leader) Timothée NICOLAS (CRCN CNRS)
NON-PERMANENT STAFF as at June 2018	1 PhD students and 1 postdoctoral fellow

3.1 Presentation of the team

Introduction. The research activity of the "Magnetized Plasmas" group is centered on theory and the simulation of laboratory and natural magnetized plasmas. In particular, we are interested in the nonlinear dynamics of tokamak plasmas, astrophysical plasmas and Hall thrusters. Historically, the scientific activity and the international recognition of the team are at the interface between the theoretical modelling of these phenomena, the development of numerical methods and codes for their simulation and the use of these tools within strong collaborations with experimentalists for interpretation and prediction in experiments. The latter issue is of most importance because these interactions with experimentalists (for our fusion activities: WEST, TCV, ASDEX-Upgrade, JET, ITER, for our astrophysical activities: Programme National Soleil Terre, CNES, NASA and for our thruster activities: CNES, CNRS, SNECMA) impacts the physical models used for the plasma description and the development of new numerical methods and tools.

Staff and resources. T. Nicolas was appointed as CRCN in 2017, after more than a decade of unsuccessful attempts to hire a young scientist at CNRS in our group. A. Canou was hired as a Research Engineer at Ecole Polytechnique in 2016. J-F. Luciani and A. Héron will retire during the next 5 years contract. This reduction of the permanent staff represents a risk for the future activity of the team.

The team hired 2 post-docs during the last contract, Robin Huart (DGA and INSU contracts from 2011 to 2017) and François Orain (ANR AMICI, 2018-2019). It also obtained the funding for 2 PhDs, Pierre Chopin (Ecole Polytechnique, then EDOM, 2014-2017) and Alain Marx (Monge, then EDOM, 2014-2017). Lütjens is/was also PhD advisor of 2 PhD's funded by CEA, (JH Ahn 2014-2017 and G Brochard 2016-in progress).

During the period 2013-2018, the group benefited from financial resources through several external contracts:

- Tokamak plasmas: A contract with the French Federation in Magnetic Confined Plasmas (FR-FCM), renewed every year between 2013 and 2018 (PI Lütjens). The ANR project AMICI which involves CPHT and IRFM from CEA Cadarache between 10.2014 and 09.2019 (PI Maget, CEA.

*40% of her time for this group

Lütjens for CPHT). In 2014, the Eurofusion "Enabling Research" (ER) project WP14-ER-01/CEA-06 in collaboration with IRFM/CEA Cadarache and SPC/EPFL Lausanne (PI Lütjens). For 2017 and 2018, the Eurofusion ER project WPENR-AWP17-ENR-CEA-06 for 2 years with the same collaborators but the Italians (PI Lütjens). A third Eurofusion ER project has been submitted for the period 2019-2020.

- Astrophysical plasmas: Two contracts with DGA, Ecole Polytechnique (PI Amari). And two contracts with CNES (PI Amari). These contracts were renewed every year between 2013 and 2018. They allowed to finance in part the post-doc of Robin Huart. Moreover, two research collaboration contracts with the ESA and the NASA.
- Hall thrusters : A CNES contract in 2015 and 2016, in collaboration with ICARE, CNRS, Orléans.

In 2016, the team bought with its own financial resources a computer cluster called XMHD which is installed in the mesocenter PHYMATH at Ecole Polytechnique. It consists of 32 processors (384 cores) and serves for the developments of parallel codes and small parallel simulations. For large parallel simulations, projects are submitted every year at the national supercomputer center GENCI to obtain computer resources on these facilities. For example, in 2017-18, call A3, we obtained a credit of about 10 million CPU hours for our simulations.

3.2 Tokamak plasmas

H. Lütjens, J-F. Luciani, , T. Nicolas (PhD at first, now CRCN CNRS), A. Marx,
J-H. Ahn, G. Brochard (Docs), F. Orain (Postdoc).
Main collaborators: P. Maget, X. Garbet, R. Dumont (CEA-Cadarache), J. Graves,
O. Février, A. Kleiner (SPC, EPFL, Lausanne).

3.2.1 Team strategy

Instabilities and transport phenomena are among the main processes causing the deconfinement of a tokamak plasma. The difficulties in the study of these phenomena with realistic plasma parameters are due to the large variety of spatial and temporal scales in play. Moreover, plasma pressure effects are intrinsically linked with the curvature of the magnetic field line, which forces a treatment in 3D toroidal geometry. The research activity of "magnetized plasmas" team is the theoretical and the numerical study of the dynamics of macroscopic instabilities in these plasmas with extended MagnetoHydroDynamic (MHD) physical models including two-fluid and/or kinetic effects. Experimental observations show indeed that MHD is unable to explain the mechanisms at play even qualitatively, thus forcing to model refinements.

For this purpose, the team has been developing a suite of initial value codes since 1987, called XTOR. The physical model in these codes has first evolved from 3D resistive MHD towards two-fluid MHD (with only one density and one pressure equation). The stabilized two-fluid MHD version of the code, XTOR-2F, [H.Lütjens et al, JCP 229 (2010) 8130] served as central tool for 7 PhD's (Leblond, CPHT 2011, Meshcheriakov, IRFM 2012, Nicolas, IRFM 2013, Ahn and Février, IRFM 2016, Marx, CPHT 2017 and Brochard, IRFM in progress) and more marginally in another one (Brunetti, EPFL 2015). It is also used intensively within our collaborations with IRFM, CEA Cadarache and SPC, EPFL Lausanne. The latest version of the code, XTOR-K, includes a hybrid fluid-kinetic model: it couples self-consistently the time advance of a complete set of two-fluid equations in full tokamak geometry, with a Particle-In-Cell (PIC) exact full-f 6D Lorentz-force ion orbit integrator, thus taking into account all kinetic ion

Finite Larmor Radius (FLR) effects. To our knowledge XTOR-K is so far the only European hybrid code where the kinetic part is 6D (i.e. is not based on gyrokinetics), and able to treat kinetic thermal ions and/or energetic particles.

3.2.2 Team activities

Hybrid two-fluid/kinetic simulations in tokamaks.

Implementation of collisions in the XTOR-K code
This work is supported financially by the Eurofusion project AWP-ENR CEA-06. Ref. 24

Since 2016, we have worked on the introduction of collisions into XTOR-K. Collisions are necessary in the kinetic part of the XTOR-K code to relax fast ion distributions after a crash, to simulate neoclassical radial transport of heavy ion markers, and to obtain self-consistent slowing down alpha particles distributions.

Several methods are used in plasma physics to simulate collisions. They are all based on the Landau-Fokker Planck approximation of the Boltzmann collision operator. Initially, we decided that the chosen method should be compatible with the domain cloning parallelization of the code. In domain cloning parallelism, neighbor markers in general live on different MPI tasks, which excludes using in particular binary collisions. Other methods such as the two-weight scheme [Brunner et al PoP 1999] are very complex to implement, so we developed a novel method based on Langevin kicks off effective Maxwellian distributions [Nicolas et al. PPCF 2017]. This method solves the well-known background reaction problem for self-collisions, is not especially numerically expensive, and adapts to the parallel environment of XTOR-K. It compares very well with theory for relaxation of the distributions in velocity space.

However, it turned out to be difficult to tune because the method fails when the PIC sampling is too small. Eventually, we decided to drop the method, and realized that the code parallelization could be easily changed from domain cloning to domain decomposition. We have carried out this modification in early 2018, which allowed to implement binary collisions. Binary collisions is a method of direct sampling of the Landau-Fokker-Planck equation, which contains all its nonlinearities, and therefore is very robust, and energy/momentum conserving. In addition, it is very fast and easy to implement. It only requires that particles be sorted by cell. This sorting is fast and has an additional numerical advantage: when particles are sorted by cell, the number of so-called "cache misses", an overhead due to the processor grabbing noncontiguous data in the cache, is greatly reduced. The communication combined overhead of particle transfers (MPI communication) across the processors at each fluid time step, of sorting and of collisions, is largely compensated by the speed gain due to the reduction of cache misses. In the end, the code is 1.5 to 2 times faster in the kinetic phase than when domain cloning was used. We are now testing the collision algorithm before using it in full-fledged simulations.

Implementation of an external neutral beam heating source
Post-doc François Orain
This work is supported financially by the ANR project AMICI.

In current and future tokamaks, plasma heating is partly provided by neutral beam injection (NBI). Ionization of the injected neutrals results in the presence of fast ions in the plasma. The transport of these fast ions and their interaction with MHD modes are key issues regarding plasma stability, and thus the plasma confinement. As a first step, in order to reproduce the experimental facts and in fine predict the behavior of future experiments, a realistic NBI source has been implemented in XTOR-K. A number of neutral particles are randomly generated on the source grid and follow the experimental beam path. Along this path, the ionization cross-section is calculated, depending on the beam energy and the plasma density and temperature. When each neutral overcomes a related ionization threshold, an ion is injected in the simulation. This ionization model is currently compared with the Venus-Levis code from SPC, EPFL, Lausanne, using typical parameters from TCV tokamak discharges. In a second step, the dynamics of the generated fast ions will be studied for experimental configurations of TCV and Asdex Upgrade tokamaks.

Linear stability of alpha fishbone instabilities in burning tokamak plasmas
PhD Guillaume Brochard
This work is supported financially by the FR-FCM. The PhD is financed by CEA ("sujet phare").[†]

The validation of a complex numerical code like XTOR-K is a difficult and tedious process. In the 90's, a theoretical model was developed to study the stability of kinetic $m = 1/n = 1$ modes due to a resonant coupling between a hot fusion alpha population and MHD, the so-called alpha-fishbone instabilities [F. Porcelli et al., Phys. of Plasmas 1, (1994) 470]. We developed the model further to take into account the effects of trapped *and* passing fast ions, and implemented it into a new linear code which solves non perturbatively the dispersion relation of the $m = 1/n = 1$ internal mode in the presence of a kinetic ion population in the entire phase space. First comparisons between the linear model and XTOR-K results show a good agreement for low energy ions when passing ions are taken into account. Theory and full numerical simulations depart from each other for high energy fusion alphas, but still show qualitative agreement. This is mainly due to the shape of the trapped particle orbits, which depart significantly from the assumptions made in the linear model. This work will be pursued by the determination of realistic conditions where fishbone may grow using the linear model, and the study of their nonlinear dynamics with the XTOR-K code.

Tearing instability dynamics
PhD Dmytro Meshcheriakov
Refs : 3, 5, 10, 20, 21, 28, 31

Resistive MHD and neoclassical tearing instabilities lead to a significant plasma de-confinement. They are the subject of intense studies both theoretical and experimentally to avoid them or to control their dynamics, in particular with external heating devices. However, comparisons with the experiment show that the observations and numerical simulations differ quantitatively within the framework of resistive MHD and neoclassical theory. A generalization of the model is required for a quantitative understanding of the dynamics of these instabilities.

In his PhD work, D. Meshcheriakov studied the linear and nonlinear stability properties of tearing modes including two-fluid and toroidal curvature effects. In particular, it was shown that the combination of strong curvature and diamagnetic effects reduces significantly the saturation size of the tearing island.

Neoclassical transport theory leads to corrections in the resistive MHD model due to a combination of collisional effects (plasma resistivity and viscosity), trapped and passing particles trajectories in the tokamak magnetic field and drift velocities due to magnetic field norm gradient and field line curvature. At equilibrium, this leads to the so-called bootstrap current, proportional at lowest order

[†] "sujet phare" can be translated as "flagship theme"

to plasma resistivity and pressure gradient. This current is destabilizing for tearing instabilities and therefore significantly modifies their dynamics (stability thresholds and saturation levels).

The neoclassical model in the XTOR-2F code was generalized by the inclusion of neoclassical stress tensors in the CGL form [J.D. Callen, Phys. Plasmas 17 (2010) 056113]. These effects play an important role in the dynamics of tearing modes in high pressure tokamak plasmas, such as the ones of today large tokamaks and the future ITER. These upgrades of the physical model allowed several studies on tearing modes during the last 5 years, either generic or applied to real plasma discharges of the Tore-Supra, Asdex-Upgrade, and JET tokamaks. The objective of these works is a precise understanding of the dynamics of these instabilities in physical conditions characteristic of large tokamaks, both for the interpretation of measures in existing and predictions in today and future experimental devices. For an easier interpretation of experimental measures, diagnostics mimicking the real ones were added into XTOR-2F.

Controlling the dynamics of internal instabilities with external heating devices
Refs: 18, 22, 29, 30

We are interested in two families of internal instabilities observed in tokamaks, tearing modes and internal kinks. The internal kink is linked with the so-called sawtooth oscillations, a periodic crash of the central temperature of the plasma and observed in all tokamaks. In a burning reactor, these modes serve for the evacuation of cold fusion products from the plasma core (= impurities). Both of these instabilities require a control during a burning plasma discharge. This is done in experiments using external heating devices (electron cyclotron current drive -ECCD- with gyrotrons, or RF antennas).

During his PhD, O. Février has implemented a current source term modeling the ECCD. The influence of parameters such as ECCD current intensity, source width and position with respect to the island was evaluated. Our numerical results show a good agreement with a reduced model (a modified Rutherford equation) regarding the variations of control efficiency with source width and position. This work revealed that the precise source intensity and location in the vicinity of the tearing island is a crucial issue for the stabilization of the mode. Several strategies were presented using XTOR-2F simulations to control the tearing dynamics and eventually their suppression with ECCD.

The control of the sawtooth oscillations and thus of the $m = 1/n = 1$ internal kink dynamics is an important issue in tokamaks. These modes play an important role in the plasma confinement and impurity transport in the central region of a tokamak discharge. Moreover, they can trigger secondary instabilities such as neoclassical tearing modes, which need a finite magnetic seed for their destabilization. The source in XTOR-2F was generalized to include an electron cyclotron range heating (ECRH) power deposition term. XTOR-2F simulation show that ECCD inside or outside the resonant $q = 1$ surface of the internal kink lead to an increase or a decrease of the sawtooth period, respectively, as observed in the experiments. The impact of ECCD and ECRH on the sawtooth shape was also investigated, which is an important issue to prevent the triggering of secondary instabilities.

Migration of heavy impurities in the presence of plasma core instabilities
PhD's Timothée Nicolas and Jae-Heon Ahn
Refs: 11, 16

The transport of impurities during a sawtooth crash was simulated with the XTOR-2F code. This is an important concern in the perspective of a burning plasma because the cold helium ash must be evacuated from the plasma core and the migration of heavy impurities (Carbon, Tungsten) towards the plasma center must be reduced as much as possible.

In a first work (PhD T. Nicolas), impurities were modeled as passive scalars, evolving in the compressible MHD flow inferred from the main MHD plasma in the presence of an $m = 1/n = 1$ internal kink instability. Our simulations have shown that a peaked impurity density profile, the non-linear kink flow of the sawtooth crash redistributes the profile efficiently and most of the particles in the peak inside the $q = m/n = 1$ surface are expelled. For an initially hollow impurity density profile, the crash leads to a significant penetration into the plasma core, up to the magnetic axis.

In a second work (PhD Ahn), the impurity model was refined. Indeed, the impurities are highly collisional (because of the high charge number) whereas the main ion species (D or T) remain in a low collisional regime. In that situation, neoclassical transport theory predicts that the main ion temperature gradient drives an outward impurity flux in the absence of an instability, and is therefore responsible for a favorable thermal screening effect. However, this screening effect disappears in the presence of a sawtooth crash, and the impurity dynamics previously discovered in Nicolas PhD with a simpler transport model is recovered.

The introduction of collisions into the kinetic module of XTOR-K opens new prospects in the study of the interplay between heavy impurity neoclassical transport and MHD or two-fluid instabilities.

Implementation of free boundary conditions
PhD Alain Marx
This work is supported financially by the FR-FCM. The PhD was financed by a Monge grant.
Ref: 26

A part of the PhD work of A Marx consisted in the introduction of free boundary conditions into the XTOR-2F code. The initial XTOR was restricted to magnetic equilibria supposing an infinitely conducting shell at the plasma surface, thus limiting the equilibrium magnetic topology to a set of toroidal nested magnetic flux tubes. The new free boundary version of the code allows for a resistive plasma shell, and the equilibrium boundary conditions are given by a set of poloidal magnetic field coils. In terms of equilibrium magnetic field topologies, the code can handle a singular surface inside the plasma shell, which is standard in today large experimental devices with a divertor (WEST, ASDEX-Upgrade, JET, ITER). Linear ideal and resistive MHD stability tests comparing the results of the code with asymptotical theoretical models revealed good agreement. First nonlinear simulations of tearing instabilities with zero plasma pressure were performed. We plan to transfer the free-boundary setup into the hybrid XTOR-K code in the coming year.

3.2.3 Ongoing work and perspectives

Since the arrival of T. Nicolas in the group as CRCN in January 2018, we have worked on improvements in the model and the numerical method of the XTOR-K code. These include the switch in the kinetic module from a domain cloning method towards a domain decomposition one with the introduction of binary collisions. Also, the free-boundary conditions will be transferred from the two-fluid code into XTOR-K (and improved). At the same time, the entire code will be optimized in terms of hybrid MPI/OpenMP parallelization by a global amelioration of the cache memory management.

These issues will have a large impact on our future scientific activity. On the one hand, free-boundary conditions will expand our domain of investigation from the study of plasma core instabilities toward new families of tokamak instabilities (external kinks, Edge Localized Modes, plasma disruptions,...) and their control in plasma geometries characteristic of large tokamaks (divertor plasmas). On the other hand, numerical optimizations will pave the way for long time fluid-kinetic studies such as tearing dynamics or multiple sawtooth oscillations including kinetic effects.

As in the past, as soon as our numerical tools are stabilized, our policy is their dissemination within our collaborations in the framework of research contracts and collaborations, and their use for the interpretation and eventually the prediction of experimental data of today and future large tokamaks.

3.3 Astrophysical plasmas

T. Amari, J.F. Luciani, A. Canou (Postdoc at first, now IR[a] Ecole Polytechnique),
P. Chopin (PhD), R. Huart (Postdoc).
Main collaborators: J.J. Aly (CEA-Saclay), F. Alauzet (INRIA) , Z. Mikic, J. Linker.

[a]Research Engineer

3.3.1 Team strategy

Our work mainly covered the characterization and the identification of mechanisms at the origin of large scale eruptive phenomena in the solar corona and of the heating of the solar atmosphere. Important contributions were achieved for both subjects. Both parts are dominated by the crucial role of the magnetic field in the solar atmosphere, but also in the layers under the solar surface.

As a consequence, associated numerical codes were developed within the framework of Magnetohydrodynamics. As an added value, with our expertise in these fields, we provide theoretical and numerical tools and results to our community and we participate in the exploitation of today and future missions. We participate as a key component to national and international space weather programs (ESA, NASA), which play a growing societal role. These activities are also supported by contracts with national institutions such as DGA and CNES.

3.3.2 Team activites

Eruptive phenomena
Refs: 8, 27

Concerning major eruptive phenomena, different theoretical models existed for both coronal mass ejections and confined eruptions (without ejection), but there was no clear identification of the key model in action. By studying the genesis of real eruptions which occurred in 2006 and 2014, using our models and magnetic (HINODE and later SDO) and coronal (HINODE, SDO) measures, we discovered that these two classes of eruptions are associated with the formation/presence of a magnetic structure (twisted magnetic ropes) whose evolution towards an ejective or a confined instability depends, as predicted by one theoretical model, on the presence of another discovered structure: a magnetic cage. Our works in this field appeared twice as front page articles in Nature.

Our present and near future activity in this field consists in the construction of a reference base of such eruptions. We are also interested in large scale transport of eruptive phenomena in the solar wind and the interplanetary environment. These works include fundamental theoretical and numerical as well as predictive aspects.

Heating of the solar atmosphere
Ref: 13

Concerning the solar atmosphere and its heating, the case of a “quiet” Sun was considered, away from active regions. Several possible theoretical mechanisms existed for this problem (amongst them in particular waves and eruptions). In the frame of simulations involving several regions of the solar atmosphere, we have demonstrated that it is a combination of two different mechanisms which can act in different regimes or levels. First, the generation of the magnetic field by surface dynamo effect (under the photosphere) produces a magnetic and velocity field with a high enough energy to heat the chromosphere with multiple, continuous micro-eruptions and a few more important, sporadic eruptive phenomena reaching the lower corona, but not frequent enough for its heating. However, it is the interaction of this chromospheric dynamics with the field at large scale which generates waves which transport the energy into the core of the corona.

The identification of generic mechanisms of energy transport in the highest layers of the Sun and at larger scales represent a major challenge in our present and future activities in terms of theory and numerics.

Models
Refs: 32, 35

We have developed several numerical models for the resolution of the different preceding problematics and the production of scientific results.

On the solar hand, we develop several numerical codes to model environments at the scale of an active region to the ones including the entire Sun (XTRAPOL, METEOSOL, XTRAPOLS, MESHMHD). With these models, processes at the origin of the triggering of solar eruptions, the characterization of the pre-eruptive environment and the dynamics of eruptions can be addressed. They also allow the study of the heating of the corona at the origin of solar wind. This last issue requires the addition of another model describing the evolution in a layer under the Sun surface.

On the earth hand, the understanding of physical processes and their application to Space Weather with the global, Solar wind / Magnetosphere / Ionosphere model of the earth environment MESHMHD is developed in our group. The MESHMHD code has the specificity to be able to handle multi- geometric solutions.

Some of these models are regularly used internationally for comparisons of models developed by other groups. The extension of these numerical models for applications in our different research fields will be essential in future. Transverse collaborations are important, as e.g. with applied mathematicians.

Space weather

All existing Space Weather programs rely heavily on the modelization of the Sun for more operational methods.

The developed models are in the center of the activities aiming to study the spatial environment of solar spatial missions (such as Solar Probe, Solar Orbiter) and the connection of their measures with the Sun, as well as the prediction of solar eruptions and the interaction with the magnetosphere. The creation of data bases of solar eruptions serves also as a reference for the exploitation of instruments on Solar Orbiter such as STIX.

Contractual studies were carried out on the national level for DGA and CNES. These activities are also integrated on the world (NASA) and European level, in particular in the frame of the program “ESA Space Situational Awareness (SSA)”, one of its component being the development of a “Virtual Space Weather Modelling Center. ESA has selected a few European groups, each expert in one of the components of this Solar, Heliosphere, Magnetosphere program. T. Amari is also member of the Science Advisory Team of ESA. Our group has been chosen to be the solar node of this chain to provide models constituted by the model basis SOLARMODELS supported by CNES. Several phases of the project have been achieved and the work is in progress to achieve an operational European modelization service.

3.4 Hall thruster

A. Héron, J-C. Adam.
Main collaborators: C. Honoré (LPP, Ecole Polytechnique), S. Tsikita (ICARE, CNRS, Orléans).
Anomalous transport in Hall thruster
Refs.: 4, 12, 26, 34, 52, 61

Our previous work has shown theoretically and numerically the existence of electronic cyclotronic instabilities and their consequence on the electronic transport in the operation of a Hall thruster (SPT100 ML). The coherent Thomson scattering experiments carried out by the LPP at Ecole Polytechnique confirmed the existence of the electron cyclotron instabilities in a thruster in operation. We have also demonstrated with our simulations the influence of radial heating due to the electron cyclotron instability on the secondary electron emission rate of the walls.

Our activity was limited to the collaboration with the laboratory ICARE (CNRS, Orleans) within the framework of the contract CNES on the impact of the materials of the walls on the operation of the thruster. Experiments have been performed on the SNECMA PPS1350 thruster (laboratory model) with two contrasting wall materials: standard BnSiO2 and a zero-emission engineered material (carbon velvet). The "current-voltage" characteristics show that the average value and the standard deviation increase for a voltage larger than 200 Volts in the case (velvet carbon) where there is no secondary electron emission. The PIC2D simulations in (z,θ) corresponding to the case without secondary electron emission, show an increase of the current and of its standard deviation as a function of the voltage, as in the experimental results. They also show an increase in the electronic fluctuations due to the electron cyclotron instability, slightly inside the exit plane, in connection with an increase of the accelerator field. Probe measurements were performed to obtain the value of the accelerator field. They proved to be technically difficult and this campaign gave only qualitative indications which are in agreement with the results of the simulations. All experiments have shown that the conductivity due to the secondary emission has a stabilizing role in the operation of the PPS1350 thruster.

3.5 PhD supervisions

- Dmytro Meshscheriakov, "Evolution non linéaire des modes MHD dans les Plasmas de Fusion". PhD defense in October 2012. Co-supervisor H. Lütjens, P. Maget (CEA Cadarache) and P. Beyer (AMU).
- Jae-Heon Ahn, "Effects of MHD instabilities on impurity dynamics". PhD defense in November 2016. Co-supervisor H. Lütjens and X. Garbet (CEA Cadarache).
- Pierre Chopin, "Relations Soleil-Terre : origine et dynamique des perturbations solaires". PhD defense in September 2017. Supervisor T. Amari.
- Alain Marx, "Deux étapes majeures pour le développement du code XTOR : parallélisation poussée et géométrie à frontière libre". PhD defense in November 2017. Supervisor H. Lütjens.
- Guillaume Brochard, "Interactions entre ions énergétiques et instabilités dans un plasma de tokamak". PhD started in fall 2016, in progress. Co-supervisor H. Lütjens and R. Dumont (CEA Cadarache).

3.6 Contracts and grants

- ANR Project ("défi de tous les savoirs") AMICI (Advanced Modelling of Island Control for ITER), 10/2014-09/2018 (PI P. Maget, IRFM, responsable CPHT Lütjens).
- EUROfusion (Enabling Research grant): "Nonlinear 3D simulations of plasma core instabilities beyond MHD in tokamak plasmas", in 2014. The members of the project are CPHT, IRFM/CEA Cadarache, CNR/ENEA Milan, Italy and CRPP/EPFL, Lausanne, Switzerland. (PI Lütjens).
- EUROfusion (Enabling Research grant): "Implementation of a Fokker-Planck collision module into the 3D bi-fluid kinetic code XTOR-K using a Langevin formulation", in 2017 and 2018. The members of the project are CPHT, IRFM/CEA Cadarache, and CRPP/EPFL, Lausanne, Switzerland. (PI Lütjens).
- Project with the French Federation in Magnetic Confined Plasmas (FR-FCM) which was renewed every year between 2013 and 2018 (PI Lütjens).
- Ecole Polytechnique DGA contract: Un modèle global pour l'interaction vent solaire magnetosphère 2013-2018 (PI Amari).
- Ecole Polytechnique DGA contract: Pression des Eruptions Solaires, 2013-2018 (PI Amari).
- CNES contract : Caractérisation de l'environnement magnétique solaire pour la prévision des éruptions, 2013-2018 (PI Amari).
- CNES contract : Physique solaire pour la prévision des éruptions, 2013-2018 (PI Amari).
- CNES contract : Interaction plasma-surfaces dans les propulseurs de Hall, 2015-2016 (PI S. Mazouffre, ICARE, CNRS).
- ESA research collaboration contract: Models for the Virtual Space Weather Modelling center.
- NASA research collaboration contract: The Evolution of the Solar Corona and its Influence on the Structure of the Solar Wind.

3.7 Administrative duties (on top of juries, edition, conference organization, etc)

- Scientific secretary of Section 04 of the Comité National de la Recherche Scientifique (CoNRS) (H. Lütjens).
- CT5 de GENCI since 2013 (H. Lütjens).
- Comité du Pôle 2 de PHOM (Physique des ondes et de la matière) Université Paris-Saclay, 2015-2015 (H. Lütjens).

3.8 Numerical research codes and model bases

- XTRAPOL : Code de reconstruction de l'environnement solaire, àa l'échelle des regions actives, en géométrie Cartesienne (Amari, Boulmezaoud, Ay) : 2006.
  Amari T, Aly JJ: 2010 Observational implications on well posed reconstruction methods and the optimization-Grad-Rubin Method. Astronomy and Astrophysics 522 : A52 (2010).

- XTRAPOLS : Code de reconstruction de l'environnement solaire global (soleil entier) en géométrie sphérique : Amari T, Aly JJ, Canou A, Mikic Z.
  Reconstruction of the solar coronal magnetic field in spherical geometry. Astronomy and Astrophysics 2013;553:A43.

- METEOSOL : Code pour la simulation numérique de l'évolution l'environnement solaire, à l'échelle des régions actives, en géométrie cartésienne : Amari T, Luciani J-F, Joly P: 1999
  A Preconditioned Semi-Implicit Method for Magnetohydrodynamics Equations. S.I.A.M Journal on Scientific Computing, Vol 21, 3, p. 970-986.

- MESHMHD : Code d'environnement Solaire, Magnétosphère, MHD statique et dynamique multi-échelle, région active et soleil entier: Amari T, Delyon F, Alauzet F, Frey P, Huart R, Canou A and Olivier G (2011).
  On some algorithm for modeling the solar coronal magnetic field as MHD equilibrium on unstructured mesh. Numerical modeling of space plasma flows (Astronum 2011). ASP Conference Series, Vol. 459. Edited by NV Pogorelov, JA Font, E Audit, and GP Zank. San Francisco: Astronomical Society of the Pacific, p.189 (2012).

- XTOR-2F: Lütjens H, Luciani J-F. "XTOR-2F: a fully implicit Newton-Krylov solver applied to nonlinear 3D extended MHD in tokamaks", J. Comp. Physics 229 (2010) p.8130, and
  Marx A, Lütjens H, "Hybrid parallelization of the XTOR-2F code for the simulation of two-fluid MHD instabilities in tokamaks", Computer Phys. Communications 212 (2017) p.90.

- XTOR-K: Hybrid fluid/kinetic nonlinear code coupling self-consistently the time advance of a complete set of two-fluid equations in full tokamak geometry, now including an equilibrium separatrix and a vacuum zone, with a Particle-In-Cell (PIC) exact full-f 6D Lorentz-force ion orbit integrator, thus taking into account all kinetic ion finite Larmor (FLR) effects.

- PIC2D implicite: Adam JC, Héron A and Laval G. Study of stationary plasma thrusters using two dimensional fully kinetic simulations, Physics of Plasmas 11 (2004)

- PIC2D (r,θ) : Héron A, Adam JC. Anomalous conductivity in Hall thrusters: Effects of the non-linear coupling of the electron-cyclotron drift instability with secondary electron emission of the walls, Physics of Plasmas 20 (2013)

- SOLARMODELS: Evolving model base for the community, supported by CNES.

3.9 Publications

3.9.1 Papers in refereed journals (sorted by year)

<u>2013</u>

1. Amari T, Aly JJ, Canou A, Mikic Z. Reconstruction of the solar coronal magnetic field in spherical geometry. Astronomy and Astrophysics. 2013;553:A43.

2. Bécoulet A, et al. Science and technology research and development in support to ITER and the Broader Approach at CEA . Nuclear Fusion. 2013;53:10423.

3. Cooper WA, Chapman IT, Schmitz O, Turnbull AD, Tobias BJ, Lazarus EA, et al. Bifurcated helical core states in tokamaks. Nuclear Fusion 2013;53:073021.

4. Héron A, Adam JC. Anomalous conductivity in Hall thrusters: Effects of the non-linear coupling of the electron-cyclotron drift instability with secondary electron emission of the walls. Physics of Plasmas. 2013;20:082313.

5. Mellet N, Maget P, Lütjens H, Meshcheriakov D, Tore-Supra Team. Neoclassical viscous stress tensor for nonlinear simulations with XTOR-2F. Nuclear Fusion. 2013;53:043022.

6. Maget P, Mellet N, Lütjens H, Meshcheriakov D, Garbet X. Curvature effect on tearing modes in presence of neoclassical friction. Phys. Plasmas 2013; 20:112504.

7. Nicolas T, Sabot R, Garbet X, Lütjens H, Luciani JF, Sirinelli A, et al.. Particle flow during sawtooth reconnection: Numerical Simulations of experimental observations. Plasma and Fusion Research 2013; 8:2402131.

2014

8. Amari T, Canou A, Aly JJ. Characterizing and predicting the magnetic environment leading to solar eruptions. Nature. 2014;514:465-469. (Cover Paper)

9. Meshcheriakov D, Maget P, Lütjens H, Beyer P, Garbet X. Nonlinear dynamics of the tearing mode with two-fluid and curvature effects in tokamaks. Physics of Plasmas. 2014;21(1):012516.

10. Maget P, Lütjens H, Luciani JF, Garbet X, Fevrier O, Segui JL. Bi-fluid and neoclassical effect on a Double-Tearing mode in Tore Supra. Physics of Plasmas. 2014;21(6):062504.

11. Nicolas T, Lütjens H, Luciani JF, Garbet X, Sabot R. Impurity behavior during sawtooth activity in tokamak plasmas. Physics of Plasmas. 2014;21(1):012507.

12. Tsikata S, Cavalier J, Héron A, Honoré C, Lemoine N, Grésillon D, et al. An axially propagating two-stream instability in the Hall thruster plasma. Physics of Plasmas. 2014;21:072116.

2015

13. Amari T, Luciani JF, Aly JJ. Small-scale dynamo magnetism as the driver for heating the solar atmosphere. Nature. 2015;522:188-91.

14. 14. Brunetti D, Graves JP, Halpern FD, Luciani JF, Lütjens H, Cooper WA. Extended MHD simulations of infernal mode dynamics and coupling to tearing modes. Plasma Physics and Controlled Fusion. 2015;57(5): 054002.

15. 15. DeRosa ML, Wheatland MS, Leka KD, Barnes G, Amari T, Canou A, et al. The Influence of Spatial Resolution on Nonlinear Force-Free Modeling. Astrophysical Journal. 2015;811(2):107.

2016

16. Ahn JH, Garbet X, Lütjens H, Guirlet R. Dynamics of heavy impurities in non-linear MHD simulations of sawtoothing tokamak plasmas Plasma Physics and Controlled Fusion. 2016;58(12): 125009.

17. Ahn JH, Garbet X, Lütjens H, Marx A, Nicolas T, Sabot R, et al. Non-linear dynamics of compound sawteeth in tokamaks. Physics of Plasmas. 2016;23(5):052509.

18. Février O, Maget P, Lütjens H, Luciani JF, Decker J, Giruzzi G, et al. First principles fluid modelling of magnetic island stabilization by electron cyclotron current drive (ECCD). Plasma Physics and Controlled Fusion. 2016;58(4):045015.

19. Kleiner A, Graves JP, Brunetti D, Cooper WA, Halpern FD, Luciani JF, Lütjens H. Neoclassical tearing mode seeding by coupling with infernal modes in low-shear tokamaks. Nuclear Fusion. 2016;56(9):092007 (11pp).

20. Maget P, Fevrier O, Lütjens H, Luciani JF, Garbet X. Bifurcation of magnetic island saturation controlled by plasma viscosity. Plasma Physics and Controlled Fusion. 2016;58(5):055003.

21. Maget P, Fevrier O, Garbet X, Lütjens H, Luciani JF, Marx A. Extended magneto-hydro-dynamic model for neoclassical tearing mode computations. Nuclear Fusion. 2016;56(8):086004.

2017

22. Février O, Maget P, Lütjens H, Beyer P. Comparison of magnetic island stabilization strategies from magneto-hydrodynamic simulations. Plasma Physics and Controlled Fusion. 2017;59(4): 044002.

23. Marx A, Lütjens H. Hybrid parallelization of the XTOR-2F code for the simulation of two-fluid MHD instabilities in tokamaks. Computer Physics Communications. 2017;212:90.

24. Marx A, Lütjens H. Free Boundary simulations with the XTOR-2F code. Plasma Physics and Controlled Fusion. 2017;59(6):064009.

25. Nicolas T, Luciani JF, Lütjens H, Garbet X, Graves J. A novel approach to ion-ion Langevin self-collisions in particle-in-cell modules applied to hybrid MHD codes. Plasma Physics and Controlled Fusion. 2017;59(5): 054005.

26. S, Heron A, Honoré C. Hall thruster microturbulence under conditions of modified electron wall emission. Physics of Plasmas. 2017;24(5):053519.

2018

27. Amari T, Canou A, Aly J-J, Delyon F, Alauzet F. Magnetic cage and rope as the key for solar eruptions. Nature 2018;554:211-5. (Cover Paper)

28. Lazzaro E, et al. Physics conditions for robust control of tearing modes in a rotating plasma. Plasma Physics and Controlled Fusion. 2018;60(1):014044.

29. Maget P, Widmer, Février O, Garbet X, Lütjens H. Stabilization of a magnetic island by localized heating in a tokamak with stiff temperature profile. Physics of Plasmas. 2018;25(2):022514.

3.9.2 Submitted papers

30. Février O, Nicolas T, Maget P, Ahn JH, Garbet X, Lütjens H. Non?linear MHD simulations of sawteeth and their control. Nuclear Fusion, in press.

31. Maget P, Widmer F, Février O, Lütjens H, Garbet X. Numerical experiments of island stabilization by RF heating with stiff temperature profile. Plasma Physics and Controlled Fusion, in press.

32. Yeates AR, Amari T, Contopoulos I, Feng X, Mackay DH, Mikic Z, Wiegelman et al. Global Non-Potential Magnetic Models of the Solar Corona During the March 2015 Eclipse Space Science Reviews. In press (2018).

3.9.3 General public publications

33. Amari T, Delyon F, Alauzet F, Frey P, Huart R , Canou A and Olivier G. (Invité Amari). “La modélisation des plasmas spatiaux : relations Soleil Terre” Flash n^{o} 16, La revue scientifique de l’Ecole polytechnique, Juillet 2014.

34. Héron A, Adam JC, Mazouffre S, Tsikata S, Les propulseurs à plasma, Flash n^{o} 16, La revue scientifique de l’Ecole polytechnique, Juillet 2014.

3.9.4 Conference proceedings papers

Invited

35. Amari T, Delyon F, Alauzet F, Frey P, Huart R , Canou A and Olivier G. Magnetohydrodynamics modeling at local and global Scale for Solar-Terrestrial physics. Astronum Conference “Numerical Modelling of Space Plasma Flows”. Juin 2013. Biarritz . France. (Invited Amari)

36. Lütjens H, Luciani J-F. Effect of kinetic ions on internal kink modes with XTOR-K. 16th European Fusion Theory Conference, 05-08.10.2015 Lisbon, Portugal. (Invited Lütjens)

37. Amari T, Canou A , Aly JJ. Magnetic Environment for Solar Eruptions. International Symposium on Recent Observations and Simulations of the Sun?Earth System III. Varna Bulgaria. 11-16 Septembre 2016. (Invited Amari)

38. Garbet X, Ahn J-H, Breton S, Donnel P, Esteve D, Guilet R, Lütjens H, et al. Synergetic Effects of Collisions, Turbulence and Sawtooth Crashes on Impurity Transport. Proc of 26th IAEA Fusion Energy Conference (October 17-22, 2016), Kyoto, Japan, TH/3-1. (Invited Garbet)

39. Amari T, Canou A, Aly JJ, Alauzet F. Solar Eruptions and their magnetic origin. Frontiers in Theoretical and Applied Physics. American University of Sharja. UAE. 22-25 February 2017. (Invited Amari)

40. Amari T, Canou A, Aly JJ, Alauzet F. Solar Eruptions and their environment. Parker Solar Probe and Solar Orbiter Science Working Group Meeting. JH APL. Laurel, Maryland, USA. 3-6 October 2017. (Invited Amari)

Orals

41. Canou A, Amari T, Title A, Schrijver K, and the HMI Team. Progress on Reconstructing the Solar Coronal Magnetic Field above Active Regions at different scales. Mars 2013 LWS Solar Dynamics Observatory Science Workshop (SDO-7): "Exploring the Network of SDO Science", Cambridge, MD (Oral Canou).

42. Nicolas T, Sabot R, Garbet X, Lütjens H, Luciani J-F, Guirlet R, et al. Role of the sawtooth crash in the electron and impurity transport in the Tore-Supra and JET tokamaks. 40th EPS Conference on Plasma Physics, Espoo, Finland, 1-5.7.2013, O2108 (Oral Nicolas)

43. Amari T , Aly JJ, Chopin P, Canou A, Mikic Z. Large scale reconstruction of the solar coronal magnetic field Journal of Physics: Conference Series 544 (2014). (Oral Amari)

44. Ahn JH, Garbet X, Lütjens H, Luciani JF, Guirlet R. A transport model for heavy impurity transport in MHD simulations 7th IAEA Technical Meeting, Theory of Plasma Instabilities, Frascati, Italy, 4-6.3.2015 (Oral Ahn).

45. Février O, Maget P, Lütjens H, Luciani JF, Decker J, Giruzzi G, et al. Modeling of magnetic island modications by ECCD using XTOR-2. 7th IAEA Technical Meeting, Theory of Plasma Instabilities, Frascati, Italy, 4-6.3.2015 (Oral Février).

46. Février O, Maget P, Lütjens H, Luciani JF, Decker J, Giruzzi G, et al. First principle bifluid modeling of magnetic island stabilization by ECCD. 25th Meeting of the ITPA MHD Topical Group 2015 (Oral Février).

47. Dumont R, Lütjens H. Kinetic effects on tokamak macroscopic modes with the XTOR-K code, 14th ITPA Topical Group on Energetic Particles Meeting, ITER Headquarters, Cadarache, France, 25-27.03.2015. (Oral Lütjens).

48. Tsikata S, Honoré C, Héron A, Pétin A, Mazouffre S. Plasma-wall interaction and Hall thruster microturbulence. Joint Conference of 30th ISTS, 34th IEPC and 6th NSAT, 4-10 Juin 2015, Huygo-Kobe, Japon (Oral Tsikata).

49. Kleiner A, Graves JP, Cooper WA, Lütjens H, Nicolas T. Ideal saturated 3D kink structures in quiescent H-mode plasmas 17th European Fusion Theory Conference, 9-12.10.2017, Athens 2017 (Greece), P1.14 (Oral Kleiner).

4

MATHEMATICAL PHYSICS

PERMANENT STAFF	Jean-René CHAZOTTES (DR2 CNRS) Pierre COLLET (ESR CNRS since 2013) Razvan GURAU (CRCN CNRS) Christoph KOPPER (PR X, Group Leader) Jacques MAGNEN (ESR CNRS since 2012) Philippe MOUNAIX (CRCN CNRS)
NON-PERMANENT STAFF as at June 2018	2 PhD students and 1 postdoctoral fellow

4.1 Introduction

In a nutshell, one can define the field of mathematical physics as the application of mathematics to problems in physics and the development of mathematical methods suitable for such applications and for the formulation of physical theories. The activities of the mathematical physics group perfectly match this definition, with a broad spectrum of research topics, including mathematical ecology:

- Field Theory (e.g., tensor field theory, renormalization group flow equations);
- Mathematical Statistical Physics (e.g., concentration inequalities for lattice systems);
- Dynamical Systems (e.g., statistics of return times, integrability of discrete dynamical systems);
- Mathematical Ecology (e.g., approximation of quasi-stationary distributions in birth-and-death processes);
- Stochastic Processes (e.g., asymptotics of the heat kernel in multi-cone domains, conditional random Gaussian fields);
- Applied Mechanics (e.g., method for separating and rebuilding dispersive waves in Split-Hopkinson pressure bars, and industrial applications).

This diversity of research topics is remarkable in view of the size of the group. Its members have long-standing international colloborations (CMM, Chile; ETH Zurich; TU Delft; Univ. Leipzig; UASLP, Mexico; etc). They also collaborate with some researchers in other labs of the Ecole Polytechnique, namely, the Center for Applied Mathematics (CMAP), the Computer Science Laboratory (LIX), and the Solid Mechanics Laboratory (LMS). Some of them have also strong collaborations with some members of the LPT and LPTMS (Univ. of Paris-Sud).

4.2 Field Theory

4.2.1 Random Tensors and Tensor Field Theory

R. Gurau.
Main collaborators: D. Benedetti (Univ. of Paris-Sud), S. Carrozza (postdoctoral fellow at the Perimeter Institute for Theoretical Physics), G. Schaeffer (LIX, Ecole Polytechnique), V. Rivasseau (Univ. of Paris-Sud).

Refs.: 8, 18, 27, 28, 29, 35, 36, 38, 42, 43, 44, 52, 56, 57, 65, 66, 69, 70, 72.

Over the past five years, random tensors underwent a tremendous transformation. The contributions from the CPHT has been at the forefront of the research in this field. From 2013 to 2016, we centered on non-perturbative results for models with quartic interactions and the study of the double scaling limit. A fundamental result, the classification of edge colored graphs by the degree, has been obtained in collaboration with Gilles Schaeffer from LIX.

Building on the results obtained at the CPHT, Witten introduced in 2016 a tensor quantum mechanical model and showed that it is equivalent in the large N limit to a Sachdev-Ye-Kitaev model. Contrary to the Sachdev-Ye-Kitaev model, Witten's model does not require disorder. The study of tensor quantum mechanics and tensor field theory started in earnest, with work by Klebanov and collaborators, Volovich and collaborators, Tseytlin and collaborators, Minwalla and collaborators, Vasiliev, etc. The group in the CPHT continued to actively contribute to this line of research. An important result obtained recently by R. Gurau, in collaboration with D. Benedetti, S. Carrozza and M. Kolanowski, is the proof that (as conjectured by Klebanov and Tarnopolsky) a model for a symmetric traceless tensor in rank three has a $1/N$ expansion dominated by melonic graphs.

4.2.2 Renormalization Group Flow Equations

Ch. Kopper.
Main collaborators: R. Guida (CEA Saclay), S. Hollands (Univ. Leipzig).

Refs.: 45, 58, 64.

Our work is part of a program intended to base renormalization theory entirely and with mathematical rigour on the flow equations of the renormalization group. This programme had already been pushed quite far, the most important lacking issue being the treatment of massless non-abelian Yang-Mills theory. For this theory two intricate problems have to be solved simultaneously: on the hand one has to show that gauge symmetry, necessarily broken at an intermediate stage by the renormalization group flow, can be restored in the final theory for a suitable choice of renormalization conditions; on the other hand, one has to control the infrared singularities generated by the presence of massless fields. These singularities impose severe restrictions on the renormalization points to be chosen. In fact, certain relevant terms have to be renormalized at non-exceptional external momenta which requires a detailed analysis of the tensor structure of those relevant terms. Extensions of ideas based BRS-nilpotency are an important ingredient in the proof insofar as they permit to show that certain renormalization conditions are automatically fulfilled without introducing new (unphysical) constants in the theory. This part of the programme has been achieved recently in joint work Alexander Efremov and Riccardo Guida. With hindsight to a complete renormalizability proof of the standard model of particle physics, an all orders proof on the absence of (chiral) anomalies in this model is still lacking. Partial results in this respect have been obtained in collaboration with Benjamin Lévêque and R. Guida.

Together with Stefan Hollands and Jan Holland we have been working on the operator product expansion in four-dimensional quantum field theory. A previous, largely unexpected result, saying that this expansion is convergent in the Euclidean regime within the perturbative framework, has been extended to massless theories which are of great importance in the standard model, but pose considerable technical problems on the infrared side.

4.2.3 The KPZ Equation

J. Magnen.
Main collaborator: J. Unterberger (IECN, Nancy).

Ref.: 73.

J. Magnen and J. Unterberger (IECN, Nancy) studied the Kadar-Parisi-Zhang equation in $d \geq 3$ dimensions in the perturbative regime. They proved a large-scale diffusive limit for the solution, in particular a time-integrated heat-kernel behavior for the covariance in a parabolic scaling. The proof is based on a rigorous implementation of K. Wilson's renormalization group scheme. A double cluster/momentum- decoupling expansion allows for perturbative estimates of the bare resolvent of the Cole-Hopf linear PDE in the small-field region where the noise is not too large, following the broad lines of Iagolnitzer-Magnen. Standard large deviation estimates make it possible to extend the above estimates to the large-field region. Finally, they showed, by resumming all the by-products of the expansion, that the solution may be written in the large-scale limit (after a suitable Galilei transformation) as a small perturbation of the solution of the underlying linear Edwards-Wilkinson model with renormalized coefficients.

4.3 Mathematical ecology

J.-R. Chazottes, Pierre Collet.
Main collaborators : V. Bansaye, S. Méléard (CMAP, Ecole Polytechnique), S. Billiard (Evo-Eco-Paleo laboratory, Univ. of Lille).
This collaboration fits into the Chair "Modélisation Mathématique et Biodiversité" (Ecole Polytechnique, Muséum national d'Histoire naturelle, Fondation de l'Ecole Polytechnique, VEOLIA Environnement).

Refs.: 5, 6, 7, 50, 51, 71, 75.

Approximation of quasi-stationary distributions for birth-and-death processes. Our main achievement is the fine description of the quasi-stationary behaviour of a class of birth-and-death processes describing a population made of d sub-populations of different types which interact with one another. The state space is $\mathbb{Z}_+^d$ (unbounded). We assume that the population goes almost surely to extinction, so that the unique stationary distribution is the Dirac measure at the origin. These processes are parametrized by a scaling parameter K which can be thought as the order of magnitude of the total size of the population at time 0. For any fixed finite time span, it is well-known that such processes, when renormalized by K, are close, in the limit $K \to +\infty$, to the solutions of a certain differential equation in $\mathbb{R}_+^d$ whose vector field is determined by the birth and death rates. We consider the case where there is a unique attractive fixed point (off the boundary of the positive orthant) for the vector field (while the origin is repulsive). What is expected is that, for K large, the process will stay in the vicinity of the fixed point for a very long time before being absorbed at the origin. To precisely describe this behavior, we prove the existence of a quasi-stationary distribution (qsd, for short). In fact, we establish a bound for the total variation distance between the process conditioned to non- extinction before time t and the qsd. This bound is exponentially small in t, for $t \gg \log K$. As a by-product, we obtain an estimate for the mean time to extinction in the qsd. We also quantify how close is the law of the process (not conditioned to non- extinction) either to the Dirac measure at the origin or to the qsd, for times much larger than $\log K$ and much smaller than the mean time to extinction, which is exponentially large as a function of K. Let us stress that we are interested in what happens for finite K. We obtain results much beyond what large deviation techniques could provide. The one species case uses WKB approximations for precise asymptotics. The existence in the case of several species was proved using an abstract result of Champagnat and Villemonais together with quantitative Lyapunov function techniques. We are finishing a paper in which we exploit the properties of these quasi-stationary distributions and prove some more in order to estimate the resilience (stability) through Einstein-like relations and temporal correlations.

A microscopic stochastic model for functional responses. Functional responses are widely used to describe interactions and resources exchange between individuals in ecology. The form given to functional responses dramatically affects the dynamics and stability of populations and communities. Despite their importance, functional responses are generally considered with a phenomenological approach, without clear mechanistic justifications from individual traits and behaviours. Together with S. Billiard (biologist, University of Lille) and Vincent Bansaye (CMAP, Ecole Polytechnique), J.-R. Chazottes developed a bottom-up stochastic framework grounded in the renewal theory showing how functional responses emerge from the level of the individuals through the decomposition of interactions into different activities. Our framework has many applications for conceptual, theoretical and empirical purposes.

Evolutionary ecology. P. Collet, in joint work with S. Billiard (University of Lille), R. Ferrière (ENS Paris), S. Méléard (CMAP) and V.C. Tran (University of Lille), studied genes transfer between interacting population of two species using individual based models. In particular the questions of invasion, fixation and coexistence were analysed.

4.4 Dynamical systems and mathematical statistical physics

J.-R. Chazottes and P. Collet.
Main collaborator: F. Redig (TU Delft).

Refs.: 2, 3, 20, 21, 37, 62, 63, 77, 78, 81.

Lattice systems. We derived some consequences of concentration inequalities for Gibbs measures on the d- dimensional cubic lattice (speed of convergence of empirical measures, fluctuations for the occurrence of patterns, almost-sure central limit theorems, etc.). We also studied the evolution of concentration bounds under several types of stochastic dynamics.

J.-R. Chazottes and F. Redig (TU Delft) introduced the multiplicative Ising model and proved basic properties of its thermodynamic formalism such as existence of pressure and entropies. We generalized to one-dimensional "layer-unique" Gibbs measures for which the same results can be obtained. For more general models associated to a d-dimensional multiplicative invariant potential, we proved a large deviation theorem in the uniqueness regime for averages of multiplicative shifts of general local functions. This thermodynamic formalism is motivated by the statistical properties of multiple ergodic averages.

Non-uniformly hyperbolic dynamical systems. J.-R. Chazottes and P. Collet studied the number of visits to balls $B_r(x)$, up to time $t/\mu(B_r(x))$, for a class of non-uniformly hyperbolic dynamical systems, where μ is the SRB measure. Outside a set of "bad" centers x, we proved that this number is approximately Poissonian with a controlled error term. In particular, when $r \to 0$, they got convergence to the Poisson law for a set of centers of μ-measure one. Their theorem applies for instance to the Hénon attractor and, more generally, to systems modelled by a Young tower whose return-time function has an exponential tail and with one-dimensional unstable manifolds. Along the way, they proved an abstract Poisson approximation result of independent interest. This is the first paper proving Poisson statistics for balls in dimension higher than one.

A. Ramani (affiliated with CPHT until 2015).
Main collaborators: B. Grammaticos (IMNC, Orsay), R. Willox (Tokyo Univ.).

Refs.: 10, 11, 14, 15, 16, 24, 25, 26, 32, 33, 34, 39, 40, 41, 48, 49, 54, 55, 61.

Integrability of discrete dynamical systems. A. Ramani has been working on integrable dynamical systems, in particular discrete ones, i.e., ordinary or partial difference equations, the first also being called discrete Painlevé equations and the second equations on lattices. His main collaborator is B. Grammaticos. The concepts of symmetric and asymmetric mapping have been introduced by Quispel, Roberts and Thompson to describe a large class of discrete integrable equations of second order. Symmetric mappings can be presented in form of a single equation, asymmetric ones can be written as a system of two equations of first order with independent variables. This terminology is used also for discrete Painlevé equations. Typically for the asymmetric systems the right-hand sides of the two equations are nearly identical, the only difference being the precise values of some coefficients. Nevertheless, it was found that this hypothesis of "weak asymmetry" was too restrictive. There exist many systems, neglected so far, where the right-hand side terms of the two equations are essentially different. This case was analysed in two publications, where there were obtained several tenths of new Painlevé equations, which so far had not been thought of.

Two papers were dedicated to the study of discrete Painlevé equations with periodic coefficients. Using the geometric interpretation of the discrete Painlevé equations with the aid of Weyl groups, it is clear that in each group there must exist an equation whose coefficients have the maximal periodicity allowed by the geometry of the group. All equations of maximal periodicity have now been identified.

A first promising line of research concerns the discrete Painlevé equations associated with the Weyl group E8. As was shown by Sakai, in his work on the classification of discrete Painlevé equations, the most complex (and the richest) equations of this type are those described by E8. They have hardly been studied so far because of technical difficulties. These difficulties have now been circumvented on introducing a new representation of these equations, which has been termed "trihomographic". It permits to analyse the singularities (and thus to isolate the integrable cases) in an easy way. In this way, several new equations could be proposed, difference equations, multiplicative et even elliptic ones.

A second line of research, even more important, proposes to revisit the criterion of discrete integrability which had been proposed by Ramani et al. under the name of "confinement of singularities". Initially this was a heuristic approach based on the observation that the singularities of integrable systems by spectral methods have the property of confinement, this means that each singularity which appears spontaneously, disappears after a few iterations of the discrete system.

With the help of recent progress from the study of discrete systems with methods from algebraic geometry it was decided to come back on the question of confinement with the help of these new methods. In a first paper, we have explained the situation of retarded confinement: when one does not profit from the first occasion to confine the system obtained by a retarded confinement, then it is non-integrable.

4.5 Stochastic processes: diffusions, order statistics of random walks and conditional random Gaussian fields

Diffusions. P. Collet, V. Bansaye (CMAP), S. Méléard (CMAP), and S. Martínez (CMM, Chile) and J. San Martin (CMM, Chile) defined and studied one dimensional diffusions starting from infinity. They obtained various results on entrance times, fluctuations of trajectories, etc.

Asymptotics of the heat kernel with Dirichlet boundary conditions in multi-cone domains were studied by P. Collet with M. Duarte (U. A. Bello, Chile), S. Martínez), Arturo Prat-Waldron (Max Planck, Bonn), and J. San Martin. The time exponents for the transition probability and the probability of survival were derived, as well as a renormalized Yaglom limit.

Ph. Mounaix .
Main collaborators: S. Majumdar (LPTMS, Orsay), G. Schehr (LPTMS, Orsay).

Refs.: 13, 31, 60, 67, 68, 74, 76.

Order statistics of long random walks and Lévy flights. We have investigated the large n statistics of the gap and time interval between the two highest positions of an n-step random walk/ Lévy flight. Basing our analysis on the Hopf-Ivanov formula and appropriate Tauberian theorems for generating functions, we have proved the existence of a limiting joint distribution of the gap and time interval. We have performed a thorough analytical study of this distribution for both discrete and continuous time random walks, revealing a rich variety of behaviors depending on the tail of the jump distribution. If the tail decreases faster than exponential, we have found an unexpected concentration of the probability onto configurations with adjacent two highest positions, in the large gap limit. We have found a similar concentration for bounded jumps when the gap approaches its maximum possible value. We have investigated the persistence for long random walks/Lévy flights as a function of the starting position. Our goal was to reconcile the standard Brownian scaling regime and the Sparre Andersen result saying that the persistence goes to a non-zero value as the starting position goes to zero. We have proved that the paradox between Brownian and Sparre Andersen results is lifted by the existence of a boundary layer near the origin in which the Brownian regime is replaced with a new "quantum" regime where the discrete-time nature of the walk significantly alters the standard scaling behavior. We have studied the large n behavior of the expected maximum of an n-step random walk/Lévy flight in the presence of a drift. Generalizing the Hopf-Ivanov formula to this case, we have derived a new, convenient, factorized form of the Pollaczek-Spitzer formula for the distribution of the maximum. From this result, we have determined the full asymptotic expansion of the expected maximum comprising all the terms surviving the large n limit, explicitly. In all cases, we have found that this asymptotic expansion does not depend on the jump distribution (with same Lévy index, jump length scale, and drift) except the smallest, constant, term which does depend on the jump distribution. We have derived the scaling form interpolating smoothly between the cases with and without drift.

4.6 Applied mechanics

P. Collet continue his collaboration with G. Gary (LMS) on the analysis of signals from Hopkinson pressure bars used for the determination of the dynamic properties of materials under shocks. The deconvolution and noise correction technique of M.-N. Bussac (CPHT), P. Collet and G. Gary (LMS, Ecole Polytechnique) was recently applied together with G. Gary (LMS) and D. Mohr (Institute for mechanical systems ETH Zurich) to the design of a new sensor having a much larger bandwidth for fast hydraulic machines. A sensor was installed in the Volkswagen research center (Wolksburg) for the dynamical test of materials under fast dynamic loading.

4.7 PhD supervisions

- Etienne Adam "Persistance et vitesse d'extinction pour des modèles de populations stochastiques multitypes en temps discret". PhD defense in July 2016. Joint supervision J.-R. Chazottes and Vincent Bansaye (CMAP).

- Thibault Delepouve, "Quartic Tensor Models". PhD defense in May 2017. Supervisor R. Gurau.

- Alexandre Efremov. "Analyse des équations différentielles du groupe de renormalisation". PhD defense in September 2017. Supervisor C. Kopper.

- L. Mahé. "Approximations déterministes de modèles aléatoires individus-centrés. PhD started in fall 2015, in progress. Supervisor J.-R. Chazottes.

- J. Moles. "Inégalités de concentration pour des chaînes stochastiques de mémoire infinie". PhD started in fall 2016, in progress. Joint supervision J.-R. Chazottes and E. Ugalde (UASLP, Mexico).

- M. Shinoda, visiting PhD student from Keio Univ., Japan. PhD started in spring 2016. Collab. with J.-R. Chazottes.

4.8 Contracts and grants

- ANR project (Défi des autres savoirs): "Approximations and Behavior of stochastic Individual-based Models" (ABIM), 2017-2012 (PI V. Bansaye, CMAP, Ecole Polytechnique, coord. at CPHT J-R. Chazottes).

- PICS project 7299 France-The Netherlands (2016-2018), partner: TU/Delft, The Netherlands (French PI J-R Chazottes).

4.9 Administrative duties (on top of juries, edition, conference organization, etc)

- J.-R. Chazottes is ex-officio member of the board of the Physics Department of the Ecole Polytechnique since January 2017.
  He was also elected member of the board of the Applied Mathematics Department of the Ecole Polytechnique untill December 2016.
  He is also member of the Office and the Executive Board of the SMF (French Mathematical Society) since June 2017.

- From 2009 to 2015, P. Collet was member of the steering committee of the Chair "Modélisation Mathématique et Biodiversité" (Ecole Polytechnique, Muséum national d'Histoire aturelle, Fondation de l'Ecole Polytechnique, VEOLIA Environnement).
- C. Kopper is the chair of the Physics Department of the Ecole Polytechnique since September 2015.

4.10 Publications

4.10.1 Papers in refereed journals (sorted by year)

2013

1. Chakrabarti A, Chakraborti A, Hidalgo EG. New classes of spin chains from $S\hat{O}_{(q)}(N)$, $S\hat{p}_{(q)}(N)$ Temperley-Lieb algebras: Data transmission and (q, N) parametrized entanglement entropies. Journal of Mathematical Physics. 2013;54(1):013517.
2. Chazottes JR, Collet P. Poisson approximation for the number of visits to balls in non-uniformly hyperbolic dynamical systems. Ergodic Theory & Dynamical Systems. 2013;33(1):49-80.
3. Collet P, De Coninck J, Drouiche K, Dunlop F. From substrate disorder to contact angle hysteresis, and back. Colloid and Polymer Science. 2013;291(2):291-8.
4. Collet P, Gary G, Lundberg B. Noise-corrected estimation of complex modulus in accord with causality and thermodynamics: application to an impact test. Journal of Applied Mechanics - Transactions of the ASME. 2013;80(1):011018.
5. Collet P, Martínez S, Méléard S, San Martin J. Stochastic models for a chemostat and long-time behavior. Advances in Applied Probability. 2013;45(3):822-36.
6. Collet P, Martínez S, Méléard S, San Martin J. Quasi-stationary distributions for structured birth and death processes with mutations. Probability Theory and Related Fields. 2013;151(1-2):191-231.
7. Collet P, Méléard S, Metz JAJ. A rigorous model study of the adaptative dynamics of Mendelian diploids. Journal of Mathematical Biology. 2013;67:569-607.
8. Dartois S, Gurau R, Rivasseau V. Double Scaling in Tensor Models with a Quartic Interaction. Journal of High Energy Physics. 2013;13(09):088.
9. Disertori M, Magnen J, Rivasseau V. Parametric Cutoffs for Interacting Fermi Liquids. Annales Henri Poincaré. 2013;14(4):925-45.
10. Grammaticos B, Ramani A, Viallet CM. From Yang-Baxter maps to integrable recurrences. Journal of Nonlinear Mathematical Physics. 2013;20(2):260-70.
11. Grammaticos B, Ramani A, Willox R. A sine-Gordon cellular automaton and its exotic solitons. Journal of Physics A -Mathematical and Theoretical. 2013;46(14):145204.
12. Lebowitz JL, Mounaix P, Wang W-M. Approach to Equilibrium for the Stochastic NLS. Communications in Mathemathical Physics. 2013;321(1):69-84.

13. Majumdar SN, Mounaix P, Schehr G. Exact Statistics of the Gap and Time Interval between the First Two Maxima of Random Walks and Lévy Flights. Physical Review Letters. 2013;111(7):070601.

14. Mimura N, Satsuma J, Ramani A, Grammaticos B. Linearisable ultradiscrete systems with sign variables and the confinement of singularities. Journal of Mathematical Physics. 2013;54(2): 023504.

15. Ramani A, Grammaticos B. A new family of discrete Painlevé equations and associated linearisable systems. Journal of Nonlinear Mathematical Physics. 2013;20(Supplement 1/SI):153-64.

16. Ramani A, Grammaticos B, Tamizhmani KM, Tamizhmani T. Higher linearizable mappings and their explicit integration. Journal of Physics A -Mathematical and Theoretical. 2013;46(6):065201.

2014

17. Baguet L, Delyon F, Bernu B, Holzmann M. Properties of Hartree-Fock solutions of the three-dimensional electron gas. Physical Review B. 2014;90(16):165131.

18. Baratin A, Freidel L, Gurau R. Weighting bubbles in group field theory. Physical Review D. 2014;90(2):024069.

19. Bonzom V, Gurau R, Ryan JP, Tanasa A. The double scaling limit of random tensor models. Journal of High Energy Physics. 2014(9):051.

20. Chazottes JR, Gambaudo JM, Gautero F. Tilings of the plane and Thurston semi-norm. Geometriae Dedicata. 2014;173(1):129-42.

21. Chazottes JR, Redig F. Thermodynamic formalism and large deviations for multiplication-invariant potentials on lattice spin systems. Electronic journal of probability. 2014;19:1-19.

22. Collet P, Eckmann JP, Younan M. Trees of Nuclei and Bounds on the Number of Triangulations of the 3-Ball. Communications in Mathematical Physics. 2014;325(1):259-89.

23. Collet P, Leonardi F. Loss of Memory of Hidden Markov Models and Lyapunov Exponents. Annals of Applied Probability. 2014;24(1):422-46.

24. Grammaticos B, Ramani A. Discrete Painlevé equations: an integrability paradigm. Physica Scripta. 2014;89(3):038002.

25. Grammaticos B, Ramani A, Scimiterna C, Satsuma J. On the integrability of a new lattice equation. Journal of Physics A - Mathematical and Theoretical. 2014;47(40):405201.

26. Grammaticos B, Ramani A, Tamizhmani KM, Tamizhmani T, Satsuma J. Strongly asymmetric discrete Painlevé equations: The additive case. Journal of Mathematical Physics. 2014;55(5): 053503.

27. Gurau R. The $1/N$ Expansion of Tensor Models Beyond Perturbation Theory. Communications in Mathemathical Physics. 2014;330(3):973-1019.

28. Gurau R, Ryan JP. Melons are branched polymers. Annales Henri Poincaré. 2014;15(11):2085-131.

29. Gurau R., Universality for Random Tensors. Annales de L'Institut Henri Poincaré-Probabilités et Statistiques.2014;4: 1474-1525

30. Jagannathan A, Duneau M. The eight-fold way for optical quasicrystals. European Physical Journal B. 2014;87(7):149.

31. Majumdar SN, Mounaix P, Schehr G. On the gap and time interval between the first two maxima of long random walks. Journal of Statistical Mechanics -Theory and Experiment. 2014:P09013.

32. Ramani A, Grammaticos B. Discrete Painlevé equations with maximal periodicities. Journal of Physics A - Mathematical and Theoretical. 2014;47(38):385201.

33. Ramani A, Grammaticos B. On two discrete Painlevé equations with high periodicities. Journal of Physics A - Mathematical and Theoretical. 2014;47(19):19001.

34. Willox R, Ramani A, Grammaticos B. Solutions of the lattice sine-Gordon equation and the solitons of its cellular automaton. Journal of Physics a-Mathematical and Theoretical. 2014;47(12): 125202.

2015

35. Benedetti D, Gurau R. Symmetry breaking in tensor models. Physical Review D. 2015;92(10):104041.

36. Bonzom V, Delepouve T, Rivasseau V. Enhancing non-melonic triangulations: A tensor model mixing melonic and planar maps. Nuclear Physics B. 2015;895:161-91.

37. Collet P, Dunlop F, Huillet T. Wetting Transitions for a Random Line in Long-Range Potential. Journal of Statistical Physics. 2015;160(6):1545-622.

38. Delepouve T, Gurau R. Phase Transition in Tensor Models. Journal of High Energy Physics. 2015(03):089.

39. Grammaticos B, Ramani A. On a novel representation of discrete Painlevé equations. Journal of Mathematical Physics. 2015;56(8):083507.

40. Grammaticos B, Ramani A. Elliptic and multiplicative discrete Painlevé equations from the affine Weyl group E-8. Journal of Physics a-Mathematical and Theoretical. 2015;48(16):16FT02.

41. Grammaticos B, Ramani A, Willox R, Mase T, Satsuma J. Singularity confinement and full-deautonomisation: A discrete integrability criterion. Physics D - Nonlinear Phenomena. 2015;313:11-25.

42. Gurau R, Krajewski T. Analyticity results for the cumulants in a random matrix model. Annales de l'Institut Henri Poincaré. 2015;2(2):169-228.

43. Gurau R, Rivasseau V. The Multiscale Loop Vertex Expansion. Annales Henri Poincaré. 2015;16(8): 1869-97.

44. Gurau R, Tanasa A, Youmans DR. The double scaling limit of the multi-orientable tensor model. Epl. 2015;111(2):1869-97.

45. Holland J, Hollands S. Recursive construction of operator product expansion coefficients. Communications in Mathematical Physics. 2015;336(3):1555-606.

46. Lundberg B, Collet P. Optimal wave shape with respect to efficiency in percussive drilling with detachable drill bit. International Journal of Impact Engineering. 2015;86:179-87.

47. Mounaix P. Quasi-Deterministic Properties of Random Gaussian Fields Constrained by a Large Quadratic Form. Journal of Statistical Physics. 2015;160(3):561-82.

48. Ramani A, Grammaticos B. Discrete Painlevé equations associated with the affine Weyl group E-8. Journal of Physics A-Mathematical and Theoretical. 2015;48(35):355204.

49. Ramani A, Grammaticos B, Willox R, Mase T, Kanki M. The redemption of singularity confinement. Journal of Physics A-Mathematical and Theoretical. 2015;48(11):11FT02.

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50. Billiard S, Collet P, Ferrière R, Méléard S, Tran VC. The effect of competition and horizontal trait inheritance on invasion, fixation, and polymorphism. Journal of Theoretical Biology. 2016;411:48-58.

51. Chazottes J-R, Collet P, Méléard S. Sharp asymptotics for the quasi-stationary distribution of birth-and-death processes. Probability and related fields. 2016;164(1-2):285-332.

52. Delepouve T, Gurau R, Rivasseau V. Universality and Borel summability of arbitrary quartic tensor models. Annales de L'Institut Henri Poincaré-Probabilités et Statistiques. 2016;52(2):821-48.

53. Delepouve T, Rivasseau V. Constructive Tensor Field Theory: the T-3(4) Model. Communications in Mathematical Physics. 2016;345(2):477-506.

54. Grammaticos B, Ramani A. Parameterless discrete Painleve equations and their Miura relations. Journal of Nonlinear Mathematical Physics. 2016;23(1):141-9.

55. Grammaticos B, Ramani A, Tamizhmani KM, Tamizhmani T, Satsuma J. Strongly asymmetric discrete Painleve equations: The multiplicative case. Journal of Mathematical Physics. 2016;57(4): 043506.

56. Gurau R. Invitation to Random Tensors. Symmetry, Integrability and Geometry: Methods and Applications (SIGMA). 2016;12:094.

57. Gurau R, Schaeffer G. Regular colored graphs of positive degree. Annales de L'Institut Henri Poincaré-Probabilités et Statistiques. 2016;3(3):257-320.

58. Holland J, Hollands S, Kopper C. The operator product expansion converges in massless phi(4)(4)-Theory. Communications in Mathemathical Physics. 2016;342(2):385-440.

59. Mace N, Jagannathan A, Duneau M. Quantum Simulation of a 2D Quasicrystal with Cold Atoms. Crystals. 2016;6(10):124.

60. Mounaix P, Schehr G, Majumdar SN. On the gap and time interval between the first two maxima of long continuous time random walks. Journal of Statistical Mechanics-Theory and Experiment. 2016:013303.

61. Ramani A, Grammaticos B. A Class of Integrable Non-QRT Mappings and Their Deautonomisation. Letters in Mathematical Physics. 2016;106(3):433-44.

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62. Chazottes JR, Collet P, Redig F. On Concentration Inequalities and Their Applications for Gibbs Measures in Lattice Systems. Journal of Statistical Physics. 2017;169(3):504-46.

63. Collet P, Martínez S. Measure evolution of cellular automata and of finitely anticipative transformations. Ergodic Theory & Dynamical Systems. 2017;37(1):129-45.

64. Efremov AN, Guida R, Kopper C. Renormalization of SU(2) Yang-Mills theory with flow equations. Journal of Mathematical Physics. 2017;58(9):093503.

65. Gurau R. The complete $1/N$ expansion of a SYK like tensor model. Nuclear Physics B. 2017;916:386-401.

66. Gurau R. Quenched equals annealed at leading order in the colored SYK model. EPL. 2017;119(3): 30003.

67. Majumdar SN, Mounaix P, Schehr G. Survival probability of random walks and Lévy flights on a semi-infinite line. Journal of Physics a-Mathematical and Theoretical. 2017;50(46):465002.

68. Mounaix P, Schehr G. First gap statistics of long random walks with bounded jumps. Journal of Physics A - Mathematical and theoretical. 2017;50(18):185001. (Paper selected for the "Highlights of 2017".)

2018

69. Benedetti D, Carrozza S, Gurau R, Sfondrini A. Tensorial Gross-Neveu models. Journal of High Energy Physics. 2018(1):003.

70. Benedetti D, Gurau R. 2PI effective action for the SYK model and tensor field theories. Journal of High Energy Physics. 2018(5):156.

71. Chazottes JR, Bansaye V, Billiard S. Rejuvenating functional responses with the renewal theory. Accepted at Journal of the Royal Society Interface (2018).

72. Gurau R. The $1/N$ Expansion of Tensor Models with Two Symmetric Tensors. Communications in Mathematical Physics. 2018;360(3):985-1007.

73. Magnen J, Unterberger J. The Scaling Limit of the KPZ Equation in Space Dimension 3 and Higher. Journal of Statistical Physics. 2018;171(4): 543-98.

74. Mounaix P, Majumdar SN, Schehr G. Asymptotics for the expected maximum of random walks and Lévy flights with a constant drift. J. Stat. Mech. 083201 (2018).

4.10.2 Papers submitted for publication

75. Chazottes JR, Collet P, Méléard S. On time scales and quasi-stationary distributions for multitype birth-and-death processes (51 pages). arXiv:1702.05369

76. Mounaix P. Almost sure uniform convergence of a random Gaussian field conditioned on a large linear form to a non random profile. arXiv:1712.02344

4.10.3 Conference proceedings papers

77. Chazottes JR. Fluctuations of observables in dynamical systems: from limit theorems to concentration inequalities. 42 pages. Nonlinear dynamics new directions, 11-14 May 2010, CIMAT, Guanajuato, Mexique / Editors González-Aguilar, Ugalde.

78. Collet P. On the complexity of some geometrical objects. 18 pages. Nonlinear dynamics new directions, 11-14 May 2010, CIMAT, Guanajuato, Mexique / Editors González-Aguilar, Ugalde.

4.10.4 Ebooks and books

79. Chazottes JR, Monticelli M. Differential Equations: An invitation through embedded visual interactive digital experiments. * Preface by C. Villani. CRNS Editions, 2018.
Web site. (format iOS, OSX Mavericks).

80. Collet P, Martínez S, San Martin J. Quasi-stationary distributions: Markov chains, diffusions and dynamical Systems. Springer, 2013.- 280 p. - (Probability and Its Applications).

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*This ebook is the first one of its kind. It contains 68 embedded interactive digital experiments.

5

PARTICLE PHYSICS

PERMANENT STAFF	Cédric LORCÉ (AP X) Cyrille MARQUET (CRCN CNRS) Stéphane MUNIER (CRCN CNRS, Group Leader) Bernard PIRE (ESR CNRS since 2017) Urko REINOSA (CRCN CNRS) Claude ROIESNEL (CRCN CNRS)
NON-PERMANENT STAFF as at June 2018	2 PhD students and 3 postdoctoral fellows

5.1 Introduction

Quantum chromodynamics (QCD) is the established theory of the strong interaction, one of the fundamental forces of Nature. It encompasses some of the most striking, and to a large extent still mysterious properties of nature: confinement, according to which, the elementary constituents sensitive to the strong interaction (the quarks and the gluons), are never observed individually but only as bound states (the hadrons), and spontaneous breaking of chiral symmetry. At high temperature and/or densities it predicts a deconfined phase of matter, the quark-gluon plasma, which could have dominated the early stages of the Universe, and which can be produced artificially in heavy-ion collisions.

QCD is formulated as a consistent quantum field theory, and possesses a considerable predictive power: One can in principle derive the hierarchy of the masses of the hadrons, and at the same time the hadronic and nuclear decay rates and scattering cross sections; One can also pin down the properties of the transition between its confined and deconfined phases. However, QCD being a non-Abelian gauge theory, computing physical quantities in its framework poses formidable technical challenges, which call for the development of new, perturbative and nonperturbative, analytical and numerical, calculation methods. Furthermore, the behavior of an asymptotically-free theory being notably counter-intuitive, arriving at a clear physical understanding of the observed phenomena is always an achievement.

For these reasons, although QCD was set up as early as in the seventies, many fundamental questions are still awaiting satisfactory answers. How are the constituents of the nucleons, the quarks and the gluons, distributed spatially? How does the spin of the nucleons emerge as a combination of the spins and orbital angular momenta of their constituents? What is the detailed structure of the QCD phase diagram beyond the main division between a confined and a deconfined phase? How should one think of the nonperturbative regimes of the theory, at strong coupling, or at weak coupling but large field strength? How does this very classification of phenomena into perturbative or non-perturbative ones depend on the details of the necessary gauge-fixing procedure? These are some of the questions addressed by the particle physics group at CPHT. Studying QCD at a fundamental level in close connection with the latest experimental data collected at running (or proposed) accelerators or colliders is indeed the main focus of the group. We investigate theoretically several complementary aspects of QCD, from the very structure of the nucleons to the properties of dense hadronic and nuclear matter in collisions involving hadrons and nuclei at very high energies.

5.2 Towards a 3-D tomography of the nucleons

In the last decade, there has been a huge interest in a new set of physical quantities, the Generalized Parton Distributions (GPDs), which offer a three-dimensional (or tomographic) view of the internal structure of the hadrons and, eventually, of the nuclei. Moreover, the GPDs also give access to the gravitational form factors which characterize the distribution of mass and pressure forces inside the nucleon.

5.2.1 New ways to constrain experimentally the GPDs

Accessing generalized parton distributions (GPD) in hard exclusive reactions with neutrino beams [B. Pire with L. Szymanowski and J. Wagner (NCBJ, Varsovie)]
We demonstrated that the transversity chiral-odd GPDs contribute to the transverse cross section for exclusive neutrino production of a charmed meson on an unpolarized target in the collinear QCD approach, where GPDs factorize from perturbatively calculable coefficient functions. We calculated [Phys. Rev. D 95, 094001 (2017)] the leading-order QCD amplitude, including both heavy quark mass terms in the coefficient functions and meson mass term contributions in the heavy meson distribution amplitudes. We showed how to access these elusive GPDs through the azimuthal dependence of the differential cross section.

Study of exclusive photoproduction of large invariant mass ($\gamma\rho$ and $\gamma\gamma$) pairs [B. Pire with A. Pedrak, L. Szymanowski, J. Wagner (NCBJ, Varsovie) and S. Wallon (LPT Orsay)]
To diversify and multiply the phenomenological ways to access GPDs, we propose to study photo- or electroproduction of large invariant mass pairs of bosons (mesons or photons). In particular the $\gamma\rho$ case allows one to access the chiral-odd transversity quark GPDs. Rate estimates show that these studies are feasible in near future JLab experiments [JHEP 1702 (2017) 054].

Twist-3 GPDs in deeply-virtual Compton scattering [C. Lorcé with F. Aslan, M. Burkardt (NMSU), A. Metz (Temple U.) and B. Pasquini (Pavia U.)]
We critically reviewed the possibility of extracting some of the twist-3 GPDs, focusing in particular on the one directly related to the quark contribution to orbital angular momentum [Phys. Rev. D 98, 014038 (2018)]. We observed that even beyond the Wandzura-Wilczek approximation, only specific combinations of GPDs can be extracted from experimental data.

5.2.2 Further physical information from the GPDs; Relation to the energy-momentum tensor of the nucleon

Hadron mass structure [C. Lorcé with A. Trawinski and H. Moutarde (CEA, Saclay)]
We revisited the various mass sum rules proposed in QCD and showed that pressure contributions are significant and should be included in the description [Eur. Phys. J. C 78, 120 (2018)]. We are currently extending this work thanks to a P2IO project by revisiting the spatial distribution of energy and pressure forces inside the nucleon. This is very timely as new experimental results related to these concepts have recently been reported in a Nature paper [Nature 557, 396 (2018)].

Orbital angular momentum inside nucleons [C. Lorcé with K.F. Liu (U. Kentucky), L. Mantovani and B. Pasquini (Pavia U.)]

It has recently been realized that the orbital angular momentum (OAM) of quarks and gluons represents a key contribution in the resolution of the nucleon spin puzzle. We reviewed [Eur. Phys. J. A 52, 160 (2016)] the various definitions and how OAM can be accessed in experiments, in particular through GPDs. We investigated in detail the spatial distribution of OAM and solved the apparent discrepancies among the various definitions [Phys. Lett. B 776, 38 (2018)].

In the near future, we plan to pursue in this direction and generalize the results to the deuteron target, which is drawing more and more attention at the Jefferson Laboratory in relation with the nucleon radius puzzle, nuclear modifications, and new higher spin effects.

5.2.3 Other non-perturbative hadronic correlation functions

Nucleon to meson Transition Distribution Amplitudes (TDAs) [B. Pire with K. Semenov-Tian-Shansky (St Petersbourg) and L. Szymanowski (NCBJ, Varsovie), in collaboration with JLab experimentalists]
The proposed factorization of backward exclusive reactions such as $\gamma^*(Q^2)N \to N\pi$ and $\gamma^*(Q^2)N \to N\omega$ has been tested in JLab experiments for moderate energy (and hence quite low values of Q^2) and agrees remarkably with our theoretical predictions [Phys. Rev. D 91, 094006 (2015)], showing the possibility of early scaling for these reactions [Phys.Lett. B780 (2018) 340]. This opens the way to a new tomography of nucleons through the extraction of matrix elements of three quark operators between the nucleon and various mesonic states. We participated to the writing up of letters of intent for the study of these processes at JLab 12.

Generalized Transverse-Momentum Dependent Distributions (GTMDs) [C. Lorcé with M.G. Echevarria (Barcelona U.), A. Idilbi (Wayne State U.),K. Kanzawa, A. Metz (Temple U.), B. Pasquini (Pavia U.) and M. Schlegel (Tübingen U.)]
GPDs and Transverse-Momentum Distributions (TMDs) provide complementary three-dimensional pictures of the hadron structure. They can be seen as two limiting cases of more general correlation functions known as Generalized TMDs (GTMDs). We have shown that these functions are directly related to the phase-space distribution of quarks and gluons, and are the natural object from which OAM and spin-orbit correlations can be defined. Recently, we studied in detail the multipole structure [Phys. Rev. D 93, 034040 (2016)] and identified all the possible angular correlations accessible through measurements of GPDs and TMDs. We also addressed the question of evolution of GTMDs with Q^2 [Phys. Lett. B 759, 336 (2016)] and observed that it is essentially the same as that of the TMDs in the appropriate regime.

So far, the energy-momentum tensor in QCD (and hence OAM and mechanical forces) has only been related to GPDs and the spatial distributions of quarks and gluons. In the near future, we plan to relate this tensor to PDFs and TMDs, and hence the momentum distribution of partons. This project has the exciting potential to change radically our picture and understanding of the hadron structure.

5.3 High-energy QCD

It was realized long ago that, due to the soft singularity of the splitting function of non-Abelian gauge bosons, hadronic wave functions would contain a large number of gluons carrying a small momentum fraction x of the total momentum. This expectation was confirmed by deep-inelastic scattering experiments: In scattering processes at very high energies (or "in the small-x regime"), the color fields get strong, or, in the corresponding partonic language, the number density of the gluons (and of the quarks) get large. At the same time it also became clear that such fast growth of the gluon density in hadrons towards small values of x could not continue indefinitely or, otherwise, the unitarity of the theory would be violated. Rather, it was found that at sufficiently small-x, a novel non-linear dynamics of the strong color fields emerges, taming the non-Abelian avalanche of soft gluons towards the small-x domain, hereby restoring unitarity. This new phenomenon is commonly referred to as saturation of the gluon density.

In the saturation regime, hadrons and nuclei can essentially be thought of as sets of dense gluons, sometimes called "Color Glass Condensates" (CGC). The gluon density, as well as the scattering cross sections, obey nonlinear equations. The CGC effective theory, which approximates well QCD in the dense regime, provides a tool to obtain those equations, and to properly formulate and calculate observables.

Because of the large number of quanta, a (semi-)classical limit can be used as a starting point, in which parton evolution bears a lot of similarities with statistical processes, which can be used in order to cross-fertilize particle and statistical physics. Work in this direction has represented a significant part of our activity. Another important realization of the group over the last years is to have firmly established the connections between the CGC, and the so-called "Transverse Momentum Dependent (TMD) factorization" framework. We have also studied TMDs numerically taking advantage of this new understanding. Finally, the wealth of data on hadronic and nuclear cross section being presently recorded has fostered our interest for searching for new observables sensitive to the dense regime of QCD.

Interface with statistical physics: Parton evolution as a branching random walk [S. Munier with A.H. Mueller (Columbia U.)]
At very high energy/rapidity, the evolution of the gluon densities with the energy at which they are probed can be thought of as a branching-diffusion process. We had already shown that some properties of the scattering cross sections (such as geometric scaling in deep-inelastic scattering) follow quite straightforwardly from universal statistical features of branching random walks. Therefore, it is fruitful to investigate the latter from a general viewpoint, and to try and draw more consequences from this analogy.

Phenomenological picture of fluctuations in branching random walks:

Consider a particle on a line, whose time evolution is a Brownian motion and which may furthermore branch (say at a constant rate) into two particles, which subsequently evolve with the same rule independently of each other. One may ask what the distribution of the position of, say, the rightmost particle of the set at a given time is, and try to characterize phenomenologically its event-by-event fluctuations.

This distribution turns out to solve the Fisher-Kolmogorov-Petrovsky-Piscounov equation. Some properties of the solutions to the latter equation have been established, for asymptotically large times. One knows that the integrated distribution tends to a so-called "traveling wave", the position of which grows linearly with the time t at leading order. The first correction is of the form $\log(t)$, and the next one goes like the inverse square-root of t. The calculations from which these results are drawn start from the master equation, and do not refer to the underlying stochastic process: Hence the interpretation of the different terms, and especially of the correction which vanishes at large times, is not obvious.

We have proposed a physical picture of fluctuations in branching random walks which, in particular, leads to a new understanding of the correction terms in the time-dependence of the position. We have shown that fluctuations are important in the beginning of the evolution, when the total number of particles in the system is of order one, and in the vicinity of the extremal particles where the occupation numbers are low at all times. The latter type of fluctuations, the so-called tip fluctuations, do actually generate corrections going like the inverse square-root of t. We could model the tip fluctuations in a simple and intuitive way, and derive new results on the statistics of the position of the tip particles in this kind of processes. This work is published in a statistical physics journal [Phys.Rev. E90 (2014) no.4, 042143], and was presented at the mathematical conference “Stochastic processes and applications” in an invited session. Taking over the results for branching random walks to QCD, we have found that the statistical fluctuations have a measurable effect on total cross sections at very high energies [Phys.Lett. B737 (2014) 303-310].

New observable consequences: diffraction and genealogies:

Very recently [Phys.Rev.Lett. 121 (2018) 082001, Phys.Rev. D98 (2018) 034021], we have observed that another property of branching random walks is intimately related to an observable in particle physics. Indeed, we have pointed out an analogy between diffractive electron-nucleus scattering events, and realizations of some one-dimensional branching random walks selected according to the height of the genealogical tree of the particles near their boundaries. This correspondence is particularly transparent in an event-by-event picture of diffraction emphasizing the statistical properties of gluon evolution. New quantitative predictions straightforwardly follow from this very picture: We have been able to determine the distribution of the total invariant mass produced diffractively, which is an interesting observable that can potentially be measured at a future electron-ion collider.

Transverse momentum dependent (TMD) factorization [Cyrille Marquet, Claude Roiesnel, Elena Petreska (post-doc) and Pieter Taels (visiting PhD student); main collaborators: Piotr Kotko, Krzysztof Kutak, Sebastian Sapeta, Andreas Van Hameren (Krakow)]

Analytic results:

In hadronic collisions that feature a large transfer of momentum, the standard perturbative QCD framework of collinear factorization can be used to calculate scattering cross sections. This is typically the case at the Large Hadron Collider, but it is not so for hadronic processes that involve smaller momentum transfers. In particular, for a large number of observables at high energies, it is useful and sometimes necessary to resort to the more advanced framework known as transverse momentum dependent (TMD) factorization. This allows to consistently deal with the transverse momentum of the partons making up the colliding hadrons.

The physics encompassed in TMDs is very broad. For instance, one can compute in a systematic way the transverse spin asymmetries measured in high-energy collisions with polarized beams. In the case of the gluon TMD, one can actually study spin physics without polarized beams, through the distribution of linearly polarized gluons. To develop and exploit TMD factorization is crucial in order to make full use of current and future collider experiments.

The transverse momentum of gluons also plays a crucial role in small-x physics, and a success of the group is the establishment of fundamental connections between the TMD and the CGC approaches. This was done using the production of di-jets in hadron-hadron collisions as a case study. When the two jets are produced in the same hemisphere, and very forward, the CGC framework is applicable. When the two jets are produced back-to-back in the plane transverse to the collision axis, TMD factorisation is applicable. In the overlapping domain of validity, when both previous situations concur, di-jet production can be calculated in both approaches, and we found that they give identical expressions [JHEP 1610 (2016) 065].

Approaching the problem from the TMD side, it was shown that the various TMD gluon distributions involved in the formulation of the cross-section (gauge invariance implies the existence of several distributions, with different operator definitions) can all be expressed in terms of Wilson line correlators, when the small-x limit is considered (jets produced forward). Approaching the problem from the CGC side, it was shown that those exact same correlators arise when the back-to-back limit is considered.

We have also analyzed in the CGC framework the linear limit, which corresponds to di-jets away from the back-to-back regime [JHEP 1509 (2015) 106]. In that case, TMD factorization does not apply. Instead, the Catani-Ciafaloni-Hautmann formalism called “high-energy factorization” is recovered. We have also proposed an interpolating formulation which encompasses both limiting cases, and which is much simpler to handle that the full CGC expressions [JHEP 1509 (2015) 106]. Using it, the azimuthal angle distribution of forward dijets could be predicted over the full range [JHEP 1612 (2016) 034].

Numerical calculations on the lattice:

All the TMD gluon distributions can be evaluated in the small-x regime, from numerical solutions of the CGC evolution equations. The numerical resolution methods for the nonlinear QCD evolution equation (called JIMWLK) are very close to the ones used in ab-initio calculations of the properties of QCD on the 4-dimensional lattice. Indeed, Weigert has reformulated the JIMWLK evolution in rapidity at fixed coupling as a Langevin equation for a diffusion process in SU(3) variables on a two-dimensional lattice. The matrix degrees of freedom represent the partonic Wilson lines along a lightcone direction and the lattice discretizes the two-dimensional transverse plane.

None of the (about half a dozen) existing JIMWLK codes are open. Taking advantage of the lattice QCD expertise in the group, we have thus developed a code which reproduces the known results using an optimized algorithm that updates the configurations upon evolution in rapidity. We have used this code in references [JHEP 1610 (2016) 065, Phys.Rev. D97 (2018), 014004] for the calculation of the rapidity evolution of some TMD gluon densities.

These distributions are those which appear in the differential cross section for the forward production of either a pair of jets [JHEP 1610 (2016) 065], or a massive quark-antiquark pair [Phys.Rev. D97 (2018), 014004] in proton-nucleus collisions, when the total transverse momentum of the quark pair is close to zero. Indeed, in this kinematical limit, an explicit factorization of the differential cross section exists if one describes the interaction within the CGC formalism. The gluon TMDs parametrize the interaction with the target and can be expressed in terms of Wilson line correlators which depend on the considered production process.

In particular, we have shown that at fixed small x and at large transverse momentum, larger than the saturation scale $Q_s(x)$, the gluon TMDs exhibit a universal behavior, independent on the production process, in the “geometric” scale invariance window on the lattice. This means that the gluon TMDs become functions of $k_t/Q_s(x)$ in this window and that they decay according to a power law that depends on x. On the other hand, sizeable differences between the various gluon TMDs were predicted in the non-linear regime, at small gluon transverse momentum. This manifestation of the saturation regime should be accessible at the LHC, using the di-jets process, or other “simpler” ones which we have also addressed.

More observables in proton-nucleus scattering at the LHC [S. Munier; C. Lorcé; E. Petreska; main collaborators: T. Liou and A.H. Mueller (Columbia U.); S. Peigné (SUBATECH Nantes)]
The data on proton-nucleus collisions at the LHC opens new windows on high-density QCD. For example, we have shown that the fluctuations of the multiplicity of the hadrons produced in such experiments may be related to the stochasticity of the gluon density in the proton at the time of its interaction with the nucleus [Phys.Rev. D95 (2017), 014001]. Hence such measurements could give access to the event-by-event fluctuations of the gluon density, a quantity which has not been much studied so far but for which there is a lot of interest in the community. Work is in progress to constrain theoretically the tails of the multiplicity distribution, in order to pave the way for phenomenological studies.

Still in the context of proton-nucleus scattering, we have also computed the medium-induced, coherent gluon radiation spectrum associated with the hard forward scattering of an energetic parton off a nucleus, in the CGC formalism [Phys.Rev. D95 (2017), 014001, PoS DIS2017 (2018) 069]. This study may serve as a first step in order to implement consistently induced coherent energy loss and gluon saturation of hadron nuclear suppression in proton-nucleus collisions.

5.4 Lattice QCD (C. Roiesnel)

It is notably very difficult to simulate numerically QCD on the lattice with physical masses for the light quarks. The reason for that is the impossibility to reproduce the locality and chiral invariance properties of the Dirac operator with a non-zero lattice spacing in the continuum limit. The universally-adopted scheme has been to keep a local formulation of the Dirac operator on the lattice, and to break chiral invariance explicitly. Presently, there exist several such formulations with a viable ecosystem, in spite of the serious drawbacks of each of them.

We have approached the problem from a new perspective. In the continuum, the definitions of the Dirac operator and of the gauge covariant derivation operator are very intimately related. In Ref. [Phys.Rev. D87 (2013) 074505], we have revisited the naive, local, discretization of the covariant derivative, and identified the unitary operators which enable a natural definition of an antihermitian nonlocal gauge covariant derivative. The associated Dirac operator is antihermitian, chiral invariant, with the same number of fermionic degrees of freedom as in the continuum, and nonlocal, in agreement with the Nielsen-Ninomya theorem. The new covariant derivative on the lattice coincides in the free case with the so-called "SLAC derivative", but differs with the latter for the presence of additional gauge interaction terms which depend on the boundary conditions on a finite-size lattice.

The SLAC lattice formulation of nonlocal fermions coupled to a gauge field was questioned already about 30 years ago. The present consensus is that it is not possible to recover the continuum weak-coupling perturbation theory in this formulation. We have shown very precisely in which sense our nonlocal covariant Dirac operator exhibits the correct continuum classical limit. The nonlocal boundary terms are crucial to arrive at this result. It remains to be checked that their presence enables a consistent continuum limit at the quantum level.

5.5 Interface between perturbative and non-perturbative QCD (U. Reinosa)

It is generally accepted that the low energy regime of QCD is not amenable to perturbative calculations. Indeed, as a mirror property to asympotic freedom, the perturbative QCD running coupling grows as the typical energy scale of the problem is decreased, and even diverges at an infrared Landau pole known as Λ_{QCD}. Therefore, it is usually assumed that perturbative approaches can in no way contribute to the theoretical understanding of prominent QCD phenomena such as confinement or chiral symmetry breaking, whose relevant energy scales are of the order of $\Lambda_{\rm QCD}$.

This prejudice is based, however, on the application of perturbation theory beyond its regime of validity, and this, for two reasons. One obvious reason is that, whenever the coupling grows above some large enough value, any conclusion that emerges from the perturbative running coupling should be considered with care. A less obvious reason is that perturbation theory in a non-abelian gauge theory such as QCD is always necessarily linked to the gauge-fixing procedure, and, in most gauges, this procedure suffers from ambiguities, the most famous one being the so-called Gribov ambiguity. In practice, this means that the starting gauge-fixed action that is used to define the perturbative expansion, the Faddeev-Popov (FP) action, is, at best, valid at large energies, and should, a priori, be modified at low energies. It is therefore legitimate to ask how such a modification could affect our prejudice concerning the validity and usefulness of perturbative methods in the low energy regime of QCD.

There are various ways one can try to address this question. A well known approach is the Gribov-Zwanziger set-up that solves the Gribov ambiguity partially and leads to a modified gauge-fixed action in the form of a local and renormalizable field theory. A more phenomenolocical approach is based on using lattice simulations (and ideally also experimental measurements) to constrain the form of the action beyond the FP construction. In particular, gauge-fixed lattice simulations in the Landau gauge have concluded that the gluon correlator should saturate to a finite, non-zero value at small momenta. This has recently triggered some activity, to which our group has contributed to a large extent, around the so-called Curci-Ferrari (CF) model that adds a gluon mass operator to the Landau-gauge FP action.

The CF model possesses a number of very interesting properties that make it relevant to the present discussion. In particular, as compared to the FP framework, part of the renormalization group trajectories of the CF model are infrared safe in the sense that they do not display any Landau pole. Instead, after an initial growth with decreasing energy, the running coupling saturates and starts decreasing as the energy is further decreased. Provided the maximal value reached by the coupling is not large enough, this smooth change of monotony of the running coupling opens the interesting possibility of extending perturbative methods down to the deep infrared. This idea has been tested by comparing Landau-gauge correlation functions computed on the lattice to the one-loop correlation functions of the CF model. Surprisingly, the lattice correlators are reproduced by the CF correlators to a very good level of accuracy, comparable to the one obtained with the most sophisticated non-perturbative approaches in the field.

These results have encouraged us into pursuing the study of the perturbative predictions of the CF model and of their relevance to QCD phenomena. In particular, from 2013 to 2018, we have investigated how the most intriguing properties of QCD such as confinement and chiral symmetry breaking could find a perturbative description within the CF model.

Deconfinement transition in SU(N) theories from perturbation theory [U. Reinosa; main collaborators: J. Serreau (APC, Paris 7), M. Tissier (LPTMC, Paris 6), N. Wschebor (Universidad de la RepIJblica, Montevideo, Uruguay)]

We have used the CF model to investigate the QCD confinement-deconfinement transition in the quenched limit, where one concentrates on the dynamics of the gluon fields, the quarks being treated only as static sources. In that case, the confining properties of the medium can be probed using the Polyakov loop whose logarithm measures the energy cost for having an isolated quark or anti-quark source. We have computed the one-loop thermodynamical potential for the Polyakov loop within the

CF model and we have concluded that there are indeed two phases, in agreement with lattice simulationsÊ[PLB742, 61-68 (2015)] : a low temperature, confining phase where the Polyakov loop vanishes, signaling an infinite free-energy cost for having an isolated colored matter source in the medium, an a high-temperature, deconfined phase where the Polyakov loop acquires a non-zero value. We have also obtained predictions for the transition temperatures in good agreement with the lattice simulations. Finally, in order to test the convergence properties of the perturbative expansion within the CF model, we have computed higher order corrections to the Polyakov loop potential [PRD91, 045035 (2015) & PRD93, 105002 (2016)].

Perturbative study of the QCD phase diagram for heavy quarks at non-zero chemical potential [U. Reinosa; main collaborators: J. Maelger (PhD student at CPHT and APC), J. Serreau (APC, Paris 7), M. Tissier (LPTMC, Paris 6)]
We have extended the previous calculations in the presence of dynamical quarks, first in the limit of heavy-quarks [PRD92, 025021 (2015)]. In this regime, we have analysed the so-called Columbia plot which displays the nature of the confinement-deconfinement transition as a function of the up, down and strange quark masses. In agreement with the results of lattice simulations, we could identify a critical line separating a regime where the transition is first order from a regime where the transition becomes a crossover. The agreement with the lattice simulations is not only qualitative. In fact we could measure the ratios of the quark masses to the temperature along the boundary line and obtained very good agreement with the same measurement done on the lattice. As before, we have evaluated higher order corrections to this one loop analysis [PRD97, 074027, (2018)] and concluded that our perturbative expansion shows signs of good convergence properties. More recently, we have unveiled some universal properties of the Columbia plot in the heavy quark regime [arXiv:1805.10015], useful beyond the particular CF model that we are using.

Small parameters in infrared quantum chromodynamics [U. Reinosa; main collaborators: J. Serreau (APC, Paris 7), M. Tissier (LPTMC, Paris 6), M. Peláez and N. Wschebor (Universidad de la República, Montevideo, Uruguay)]
We have also initiated the study of QCD with physical quark masses. In this case, an important test for our approach based on the CF model is whether it is able to reproduce the physics of spontanous chiral symmetry breaking, the relevant symmetry in this regime. A difficulty we have faced in this case is that, even though the Yang-Mills sector of the model can still be considered perturbative, this is not so for the quark-gluon interaction which is roughly two to four times larger than the gluon self-interaction. However combining the perturbative nature of the Yang-Mills sector of the CF model together with an expansion in the number of colors, we could devise a systematic and controlled double expansion that allows to capture zero-temperature chiral symmetry breaking at leading order in the expansion [PRD96, 114011 (2017)].

5.6 PhD supervisions

- Jan Maelger, “Phase transitions in Quantum Chromodynamics”, PhD started beginning of October 2016, CPHT supervisor: Urko Reinosa; Co-supervisor at APC (Paris 7): Julien Serreau.

- Pablo Guerrero Rodriguez, “Early-time dynamics of Heavy Ion Collisions in Quantum Chromodynamics”, PhD started in October 2015, CPHT Supervisor: C. Marquet; Co-supervisor in Granada: J.L. Albacete.

5.7 Contracts and grants

- ANR Project DenseQCD@LHC ("Étude du régime de haute densité partonique de QCD dans les collisions hadroniques au LHC"), 01/10/2016-30/09/2021 (PI: E. Iancu, IPhT; responsable CPHT: S. Munier; participants CPHT: C. Lorcé, C. Marquet).
- ANR Project (Tremplin ERC 2018 call) FEMTO-ISH ("Femtoscopie avec l'opérateur tenseur énergie-impulsion et structure interne des hadrons"), 27/04/2018-26/04/2020 (PI: C. Lorcé).
- ANR Project PARTONS ("Partonic Tomography of Nucleon Software"), 01/10/2012-30/09/2016 (PI: H. Moutarde, IRFU; responsable CPHT: B. Pire).

5.8 Administrative duties (on top of juries, edition, conference organization, etc)

- Head of the CPHT (B. Pire, until 2016).
- Academic board of the "High Energy Physics master", Ecole polytechnique and ETH Zürich, (S. Munier, since 2015).
- Working group of the Department P2I, University of Paris-Saclay (S. Munier, 2014-2016).
- Board of the Doctoral School PHENIICS, University of Paris-Saclay (S. Munier, 2014-2015; then C. Marquet until now).
- Trustee Committee of the LabEx P2IO (B. Pire, until 2014).
- Scientific Evaluation Committee of the LabEx P2IO (U. Reinosa).
- "Bureau des Théoriciens de Physique des Particules"* (S. Munier, 2011-2016; then C. Marquet until now).
- Thematic Committee of GENCI (CT5) (B. Pire).

5.9 General prospects

Our research field is currently boosted by the huge amount of new data collected at accelerators and colliders on many different observables, in all energy ranges. It is clear that the Large Hadron Collider, initially designed as a discovery machine, is going to perform more measurements of great interest for the QCD community. There is also a growing interest worldwide for an Electron-Ion Collider, and our group actively contributes to preparing its physics program. Finally the GSI facility in Darmstatd should provide access to new processes (e.g. proton-antiproton annihilation at PANDA) and to new regions of the QCD phase diagram, in particular at low temperatures and finite densities.

Thanks to the diversity in the expertise of the group members, we are in a perfect position to take full advantage of the present and future abundant experimental activity. In the recent years, the group has attracted more visitors, students and postdocs than ever, and is ready to significantly expand in the forthcoming years.

*which can be translated as "Board of the theoretical particle physicists"

5.10 Publications

5.10.1 Papers in refereed journals (sorted by year)

2013

- Albacete JL, Dumitru A, Marquet C. The initial state of heavy-ion collisions. International Journal of Modern Physics A. 2013;28(11):1340010.
- Goritschnig AT, Pire B, Schweiger W. Double handbag description of proton-antiproton annihilation into a heavy meson pair. Physical Review D. 2013;87:014017.
- Hatta Y, Marquet C, Royon C, Soyez G, Ueda T, Werder D. A QCD description of the ATLAS jet veto measurement. Physical Review D. 2013;87(5):054016.
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6

STRING THEORY

PERMANENT STAFF	Guillaume BOSSARD (CRCN CNRS) Emilian DUDAS (DR1 CNRS) Blaise GOUTÉRAUX (AP X) Hervé PARTOUCHE (CRCN CNRS) Marios PETROPOULOS (DR2 CNRS, Group Leader) Andrea PUHM (CRCN CNRS)
NON-PERMANENT STAFF as at June 2018	4 PhD students and 2 postdoctoral fellows

6.1 Introduction

String theory embraces a wide and diverse area of modern physics ranging from the study of black-hole microstates to the understanding of quantum phase transitions in strongly coupled systems. Although particle physics and cosmology are still in the arena, they do not play any longer the prominent role they used to. The profound perspective of grand unification and quantization of gravity has given way to various applications sitting far beyond the original motivations of string theory. Despite this evolution, the original spirit is still a source of inspiration, in particular when discussing phenomenological applications.

The activity of the CPHT string group is emblematic of this trend. Over the last years, we have investigated mathematical aspects of strings and supergravity theories, string-inspired models for the big-bang or cosmological evolution, inflation and dark matter, patterns for supersymmetry breaking, black-hole microstates, holographic fluids, etc. Permanent members, PhD students, post-doctoral fellows and visitors [*] have participated in many ways, sometimes opening new directions. Dozens of papers have been published in first-rank journals, many scientific talks were delivered in conferences, while some of us are also involved in outreach events. We are taking advantage of various funding programs (ITN, ERC, Marie-Curie, ANR, PICS, PEPS, CEFIPRA, GIS P2I, LABEX P2IO,...) and contribute to the synergy of our field among the surrounding institutions. [†]

Our recent hiring settlements testify to our wish of keeping a leading position in the field. With Andrea Puhm (CR CNRS, 2016-17) and Blaise Goutéraux (MC Ecole Polytechnique, 2017-18) we mean to cover a wide spectrum of interests from quantum gravity and black holes to the most advanced condensed-matter activities, pursuing in this way the tradition of our group.

[*] For the period 2013-2018, the group has hosted 9 full-time students, 11 post-docs, 17 undergraduate interns, 2 visiting PhD students and many foreign visitors and collaborators.

[†] Common seminar (Rencontres Théoriciennes), common journal club, organisation of international conferences in Paris and abroad.

6.2 Formal aspects of string and supergravity theories (Bossard, Dudas, Partouche, Petropoulos)

Strings and supergravities require specific formalism and tools, worth investigating in their own right, irrespective of potential particle or cosmological applications. Relevant questions in this framework concern symmetries, higher-dimensional theories, properties of compactifications, low-energy effective actions, non-linear sigma models, etc.

When studying symmetries, and in particular supersymmetries, the option exists of realizing them linearly or non-linearly. In the former approach, the implementation is simpler but requires more fields; eliminating those fields leads to the latter. An important achievement was reached by reconsidering non-linear supersymmetry in theories coupled to gravity (Antoniadis, Dall'Agata, Dudas, Farakos, Ferrara, Sagnotti). Despite the enormous amount of work already performed in this direction, it has led to unexpected new families of supergravity models, with clear microscopic interpretation of the constraints (those which allow eliminating the extra fields), and well-understood effective actions. These models turn out to have promising cosmological applications.

Non-linear symmetry realization appears also in sigma models, like those describing the kinetic terms in the action of hypermultiplet scalars in $N = 2$ supersymmetric theories. The scalar manifolds are in this case quaternionic or hyper-Kähler depending on whether gravity is present or not. The Heisenberg-group symmetry (non-compact three-generator group in the Bianchi family) plays a distinguished role in these scalar manifolds, with many open questions potentially relevant for phenomenological applications. We have successfully investigated this area, regarding the symmetry properties, the decoupling of gravity, and the possibility of sequential (partial) supersymmetry breaking (Antoniadis, Derendinger, Petropoulos, Siampos).

Symmetries are also at the heart of compactifications. String theories or supergravities, are always defined in more than 4 dimensions and less than 12. Hence, going down to four requires making several extra dimensions compact. A great deal of activity has been devoted in designing compactifications with good phenomenological properties: toroidal, Calabi-Yau, flux compactifications, etc. Certain six-dimensional gauge theories with internal fluxes (magnetic fields) have been investigated in the group (Buchm§ller, Dierigl, Dudas, Schweitzer), from an innovative perspective. The notable novelty was to obtain the low-energy effective action for massless and massive modes. Not only this provides a richer four-dimensional theory, but also it allows tracing back symmetries present in 6 dimensions, and invisible in four, due to the mixing of the infinite tower of massive states the compactification produces. Although formal, this kind of results has potential applications in the study of inflation.

String theory also includes non-perturbative effects due to extended, brane-like objects that can be studied in detail in solutions preserving a large set of supersymmetries, using constraint from U-duality. It is very important to understand these effects, because they cannot be neglected in regimes relevant to quantum gravity, in which the string length is small while the gravitational coupling is finite. Computing observables non-perturbatively requires combining methods from string theory and supergravity. For toroidal compactifications in particular, the low-energy effective action can often be determined using constraints from U-duality (Green, Gutperle, Vanhove, Russo, Pioline). We have derived the explicit constraints from supersymmetry on the low-energy effective action couplings (Bossard, Howe, Stelle, Verschinin). One of the most important recent achievements was the development of an effective-field-theory derivation of the four-graviton amplitudes up to fourteen derivatives (Bossard, Kleinschmidt). This amplitude exhibits an exact cancelation of the supergravity divergences from the infinite tower of massive BPS (Bogomolny-Prasad-Sommerfeld) states up to three-loop order. We have also analyzed in detail theories with sixteen supercharges. The asymptotic expansion of these non-perturbative couplings encapsulates relevant information about the non-perturbative states of the theory. We have used this to derive the index counting BPS dyonic black holes in $N = 4$ supersymmetric theories (Bossard, Cosnier-Horeau, Pioline). More general compactifications require to master duality symmetries in a genuinely unified framework. This has led to introduce exceptional geometry and exceptional field theories (Waldram, Hohm, Samtleben). Their generalization to Kac-Moody groups has been investigated in our team (Bossard, Cederwall, Kleinschmidt, Palmkvist, Pope, Samtleben, Sezgin).

In closing the present section, it is fair to quote some results on plain conformal field theory (Gepner, Partouche): the construction of a twisted theory as a coset with respect to the field conjugation. This procedure is universal, as every conformal field theory is symmetric under conjugation, and is timely due to the importance arbitrary-dimension conformal theories have recently acquired.

6.3 Cosmology and particle phenomenology (Dudas, Partouche)

The most challenging questions of particle physics stem out of cosmological observations. Is inflation really necessary and what are the microscopic fields responsible for it? What is dark matter made of? What is the quantum origin of dark energy, *i.e.*, of the cosmological constant?

String theory and string-inspired models provide a good groundwork for addressing these questions. Being an ultraviolet completion of general relativity, they also enable, at least theoretically, to study physics beyond the Planck scale and reconsider e.g. the primordial singularity. Hence, alternative views have emerged over the years, and even though they have often been rather speculative, they have the virtue of bringing new ideas in the crucible.

To set up the stage on the cosmological constant, let us remind that from a microscopic viewpoint it is identified with the quantum vacuum energy density. In supersymmetric theories, often advocated in approaches beyond the standard particle model, the latter vanishes. Observationally, however, the cosmological constant is small but non-zero, and this requires supersymmetry to be broken. To account for this, the natural starting point is usually a class of supergravity theories describing the spontaneous breaking of local supersymmetry compatible with flat space and known as no-scale models. In these models, the supersymmetry breaking scale is arbitrary, and allows tuning at wish the vacuum energy density. The main difficulty encountered in this type of approach is the stability of this scale under quantum corrections. Understanding the stabilization conditions, searching for the relevant models and unravelling their physics have been a major axis of long-term research in the team (Angelantonj, Brandenberger, Coudarchet, Fleming, Kounnas, Partouche, Patil, Toumbas).

Whenever the above no-scale supergravity models are promoted to string models, the quantum corrections are accessible. One then realizes that in most cases, quantum corrections push the cosmological constant to unrealistic, very high values. However, under specific assumptions (regarding light states in the spectrum and defining the subclass of quantum no-scale models) the situation is qualitatively different: the cosmological constant can be stabilised around its experimental value. A thorough analysis of these phenomena has been performed, accompanied by the description of the inherited dynamics for the universe. It was shown in particular that in some cases one ends up in a flat expanding universe, whereas in others the expansion comes to a halt and the universe eventually collapses into a Big Crunch. The role of the temperature with possible phase transitions, the fluctuation spectrum and the bouncing phenomena have also been investigated, in comparison with their counterparts in the standard inflation proposal. It is interesting to observe that some of the models at hand could provide alternative paths to understand the history of the universe.

As mentioned earlier, supersymmetry must be broken, and this breaking was usually advocated to occur at rather low-energies for maintaining all benefits of supersymmetry. The absence of any experimental sign in favour of the latter, forces us to figure out what will happen if it is broken at larger scales. In this case, all super-partners of standard model particles are very heavy, but there is room for matching the known physics if the mediator of supersymmetry, the gravitino, is lighter. This class of models and the possibility of using the gravitino as a dark-matter candidate have been part of the agenda in several collaborations (Benakli, Chen, Dudas, Mambrini, Gherghetta, Kaneta, Olive). Other dark-matter candidates are pseudo-scalars known as axions. The latter acquire their (small) masses through anomalies of continuous global symmetries, and were originally used as a mean to solve the strong CP problem of the standard model. The coupling to gravity often breaks continuous global symmetries and eliminates these light scalars. Searching for an efficient gauge protection of axionic symmetries is a relevant task, which has been conducted successfully by Bonnefoy, Dudas and Pokorski.

Supersymmetry breaking is both necessary and not easy. An important drawback of the spontaneous loss of this symmetry in theories defined in higher dimensions is the emergence of large threshold corrections to gauge couplings, which invalidate perturbative expansions. This must be avoided and a wide range of safe models was systematically explored by Faraggi, Kounnas, Partouche.

6.4 Quantum gravity and black holes (Bossard, Puhm)

In 1975, Stephen Hawking showed that when taking quantum effects into account a black hole is unstable: it radiates energy to infinity and evaporates. Moreover, this radiation is similar to the one emitted by a black body at the Hawking temperature TH. This remarkable discovery had far-reaching implications. Before HawkingÕs result, the laws of black hole mechanics, derived in classical general relativity, had suggested an analogy between black-hole mechanics and thermodynamics. In this analogy, the same quantity TH could be formally identified with a temperature. The Hawking effect strikingly showed that TH really is the temperature of the black hole, and suggested that the laws of black hole mechanics may indeed be thermodynamics laws. In this pattern a black hole acquires an entropy, proportional to the area of its horizon.

The supposed black-hole evaporation phenomenon is nowadays qualified as information-loss paradox, reflecting the non-unitary transformation of a pure state into a mixed (thermal) state. As usual, paradoxes are merely the contemplation of our ignorance, which here seemingly sits in our poor understanding of quantum gravity. Since string theory is a potential ultraviolet-complete theory of gravitation, it provides a good framework for recasting these issues, and trying to elucidate the microscopic properties of the black holes. Constructing the black hole microstates responsible for the black-hole entropy is a starting point, which has led e.g. to the concept of fuzzball. Studying the dynamics of these objects at the horizon, investigating their distinguishability from the usual black hole at the horizon scale, and wondering whether their low-energy (supergravity) description is accurate has been part of our agenda (Chen, Marolf, Michel, Polchinski, Puhm).

Studying these problems in full generality is not an easy task, and the first steps are taken, based on toy models of gravity systems in string theory (small black holes). These show nevertheless in a robust fashion that typical microstates are not described by smooth geometries as long thought. Smooth-geometry microstates do exist, but they turn out to be unstable, and this instability acts as a thermalization process driving atypical microstates towards typical ones, which are very hard to distinguish from the black hole in supergravity. One can recast nevertheless the question of distinguishability in the framework of holographic correspondence (AdS/CFT), and this is under investigation.

The above questions are ambitious and difficult. Fortunately, the issue of distinguishability can be undertaken from a statistical perspective: the average relative entropy provides a measure of the average distinguishability, and this is amenable to calculations. Using methods from conformal field theory and quantum information theory, it has been possible to compute this quantity (including corrections in an expansion in the central charge of the conformal field theory) for the aforementioned class of small black holes in string theory. Building on these results we showed that the microstates of these black holes are indeed on average distinguishable from the thermal state of the black hole.

To get a quantitative understanding of the fuzzball proposal, one still needs a global picture of the microstates that can be semi-classically approximated by supergravity solutions. There are only few very atypical solutions that are known to correspond to black holes with a non-vanishing temperature. We have defined a solvable system of equations that allows to systematically investigate such configurations (Bossard, Katmadas). Using it we have derived the most general class of non-extremal fuzzball solutions associated with a five-dimensional black hole (Bena, Bossard, Katmadas, Turton). As a step towards the definition of more typical microstate geometries, we have been able to push one angular momentum below the extremality bound.

6.5 General aspects of holography (Petropoulos, Puhm)

In its original formulation, holographic correspondence is a duality relationship between two fundamental theories with infinite degrees of freedom: type IIB string theory on $AdS5 \times S5$ on the one hand, and $N = 4$ super Yang-Mills on the four-dimensional flat conformal boundary of AdS5, on the other. The latter is a conformal field theory, and the whole scheme comes under the name AdS/CFT. Although still conjectural, this correspondence has led to many developments and extensions, and has been an important component of our activity. At the first place, we should quote some achievements rooted in the microscopic approach, *i.e.*, based on string theory or supergravity (Petropoulos, Sfetsos, Siampos). These works aim at constructing pairs of dual theories, by scanning remarkable solutions of 11-dimensional supergravity. Based on our expertize about four-dimensional self-dual gravitational instantons, (Bourliot, Estes, Petropoulos, Pozzoli, Siampos, Spindel) and on their relationship to integrable equations like Darboux, Halphen or Toda, we found a systematic procedure to uplift these instantons to 11 dimensions. The solutions reached in this way (in supergravity, *i.e.*, on the AdS side of the correspondence) are based on quasi-modular forms and enjoy notable symmetry properties. This specific structure makes their holographic duals (CFT side) accessible. Studying their conformal duals is part of our short-term projects.

Then comes the core of our activity, which is more macroscopic, and based on long-term projects started around 2012. Here, we do not embarrass with supersymmetry, but consider instead ordinary gravity (Einstein or Einstein-Maxwell) on the AdS side, and expectation values on some quantum state on the CFT side. The central question in this frame is how to reconstruct the AdS bulk space-time from the boundary data consisting of the boundary metric and the boundary expectation value of the energy-momentum tensor. The later is often assumed being in the hydrodynamic regime, leading to the known fluid/gravity correspondence, as a full branch of AdS/CFT on it own right. This activity (Caldarelli, Ciambelli, Gath, Jeong, Leigh, Marteau, Mukhopadhyay, Petkou, Petropoulos, Siampos, Tripathy) has been a real laboratory for investigating many aspects of gravity and conformal field theory: Fefferman-Graham expansion versus derivative expansion, local versus global asymptotic properties, role of the vorticity, resummability properties of the series expansion leading to the bulk geometry, Geroch symmetries in anti-de Sitter spaces. This study has recently culminated with the understanding of a long-debated extension of AdS/CFT: the asymptotically flat / conformal field theory correspondence. In this case the Fefferman-Graham expansion breaks down, but the derivative expansion is well behaved. Using the latter enables to reconstruct the bulk theory from the boundary, which is a Carrollian space-time reached at null infinity. This is consistent with the flat asymptotic symmetries, which form the BMS algebra (Bondi, Sachs, van der Burg, Metzner). Hence, the boundary degrees of freedom hosted by this surface are a Carrollian fluid, which as a specific dynamics, different from that of the relativistic fluid present in the usual AdS holography.

All this has been performed in four-dimensional bulks and for fluid/gravity correspondence. The extension to other dimensions and to Einstein-Maxwell is under process (with Barnich, Campoleoni, Humbert), while the deep microscopic setting will require more time. Asymptotic symmetries mentioned above have become quite popular. For a long time, they have been known to play a central role in describing the conserved charges of gauge theories, as e.g. gravity. Recently new connections emerged between asymptotic symmetries, soft theorems and the memory effect. In some specific situations (like flat four-dimensional space-time), this has led to new attempts to describe graviton scattering amplitudes in terms of two-dimensional objects defined on the spatial section at null infinity. Although ultimately these objects should be understood in terms of the holographic dual Carrollian degrees of freedom, they provide a temporary handle over some aspects of the microscopic flat-space holography, awaiting for a more systematic treatment. Extensions from Einstein to Einstein-Maxwell are under investigation (Donnay, Puhm, Strominger).

6.6 Holographic applications (Goutéraux)

An important feature of the holographic correspondence is the inversion of the perturbative regime across the duality. Strong coupling is traded for weak coupling, and this has motivated the quest of macroscopic non-supersymmetric extensions, like AdS/QCD, supposed to help understanding the strong-coupling regime of quantum chromodynamics, or AdS/CMT, designed for condensed-matter set-ups. Although holography has not allowed solving these systems, it has undoubtedly contributed shedding light, by recasting the underlying problems in a perhaps more tractable language.

Examples of systems relevant for the present discussion are bad metals, graphene near the charge neutrality point or high-Tc superconductors. As interactions are strong, weak-coupling concepts may not necessarily be relevant or even the right language to describe these phases. For instance, conventional metals like iron or copper are well described by Landau's Fermi liquid theory, which posits the existence of long-lived quasiparticles. These can be loosely thought of as electrons adiabatically dressed with interactions. Since they are the longest-lived excitations in the system, they govern its late time dynamics, which can be analysed in the framework of Boltzmann kinetic theory. At strong coupling, these quasiparticles lose their coherence and become short-lived. Their lifetime appears to be governed by the so-called Planckian timescale, which is believed to be the fastest scale in nature allowed by quantum mechanics. New concepts are needed to go beyond the quasiparticle picture.

Gauge/gravity holographic duality, memory matrices and hydrodynamics are examples of such non-quasiparticle approaches. This explains why one expects to gain insight on the above physical systems by trying to explore their holographic properties. First steps have been taken (Amoretti, Arean, Goutéraux, Musso) in studying phases with spontaneously broken symmetry (charge and spin density waves, nematicity, superconductivity) abound in the phase diagram of high-T_c superconductors. Transport has been successfully studied in these phases using the methods mentioned above. Much remains however to be done, including studying spin density waves, nematic phases, the effects of magnetic fields, etc. This is part of our projects.

6.7 PhD supervisions

- Valentin Verschinin, “BPS corrections in maximal supergravity”. PhD defense in September 2015, co-supervised by G. Bossard and M. Petropoulos.

- Charles Cosnier-Horeau, “BPS states and BPS amplitudes in string theory”. PhD started in September 2015, defense September 2018, co-supervised by G. Bossard and B. Pioline (LPTHE Jussieu).

- Luca Ciambelli, “Flat holography from fluid gravity”. PhD started in September 2016, defense September 2019, supervised by M. Petropoulos.

- Charles Marteau, “Charged Carrollian fluids and holography”. PhD started in September 2017, defense September 2020, supervised by M. Petropoulos.

- Quentin Bonnefoy, “Physics beyond the standard model and cosmology”. PhD started in September 2016, defense September 2019, supervised by E. Dudas.

- Lucien Heurtier, “Particle physics and cosmology beyond the standard model: inflation, dark matter and flavour”. PhD defense in July 2015, supervised by Emilian Dudas.

6.8 Contracts and grants

- ERC Starting grant (2017-2022): “Hydrodynamics, , holography and strongly-coupled quantum matter”, B. Goutéraux (PI).

- ANR project (Défi de tous les savoirs): “Black Hole Microstate and de Sitter Landscape in String Theory” (Black-dS-String), 5/2017-5/2021 (PI I. Bena IPhT Saclay, coord. at CPHT G. Bossard).

- Royal Society International Exchanges Award, 2017-2019 (Emilian Dudas).

- CEFIPRA project: French-Indian programme “Glipses of New Physics”, 2016-2019 - Indian partner Saha Institute Calcutta and Bangalore (French PI Emilian Dudas).

- PICS project 6482 France-USA: 2014-2016, partners: Univ. of Minneapolis, Arizona, Stanford and Northeastearn (French PI Emilian Dudas).

- PICS project France-USA: 2018-2020, partners: Univ. of Minnesota (French PI Emilian Dudas).

- PICS project 52879 France-Cyprus: 2011-2013, partners: University of Cyprus, Nicosia (French PI Hervé Partouche).

- Marie-Curie individual project of Oscar Varela FP7-PEOPLE-2012-IO CPHT - Harvard: Holographic applications of supergravity (2013-2015) (French PI M. Petropoulos, US partner A. Strominger).

- Germaine de Staël project: French – Swiss collaborative programme Applications des théories de la gravitation et de la supersymétrie (2015-2016), (French PI M. Petropoulos, Swiss partner, J.-P. Derendinger, Bern Univ.).

6.9 Administrative duties (on top of juries, edition, conference organization, etc)

- G. Bossard is an elected member of the Physics Department of Ecole Polytechnique.
- E. Dudas:
  - Member committees STFC (Science and Technology Facility Council), Phenomenological Review, United Kingdom, 2015 and report Institute of Particle Physics Phenomenology (IPPP) Durham, 2016.
  - Member gouvernement committee CNATDCU ("Conseil National d'Attestation des titres, diplomes et certificats universitaires"), Romania, 2011-2015.
- M. Petropoulos:
  - Committees FNRS/FWO (Belgium).
  - Vice chair of the Division Fields and Particles of the SFP (French Society of Physics).

6.10 Publications

6.10.1 Papers in refereed journals (sorted by year)

2013

1. Anastasopoulos P, Goodsell M, Richter R. Three- and four-point correlators of excited bosonic twist fields. Journal of High Energy Physics. 2013;10:182.
2. Bernard L, Faraggi AE, Glasser I, Rizos J, Sonmez H. String derived exophobic $SU(6) \times SU(2)$ GUTs. Nuclear Physics B. 2013;868(1):1-15.
3. Bossard G, Howe P, Stelle KS. Invariants and divergences in half-maximal supergravity theories. Journal of High Energy Physics. 2013;13(07):117.
4. Bossard G, Howe PS, Stelle KS. Anomalies and divergences in $N = 4$ supergravity. Physics Letters B. 2013;719(4-5):424-9.
5. Bossard G, Katmadas S. Duality covariant multi-centre black hole systems. Journal of High Energy Physics. 2013;13(08):007.
6. Bossard G, Katmadas S. Non-BPS walls of marginal stability. Journal of High Energy Physics. 2013; 10:179.
7. Burgess CP, Horbatsch MW, Patil SP. Inflating in a trough: single-field effective theory from multiple-field curved valleys. Journal of High Energy Physics. 2013(1):133.
8. Caldarelli M, Camps J, Goutéraux B, Skenderis K. AdS/Ricci-Flat correspondence and the Gregory-Laflamme instability. Physical Review D. 2013;87(6):061502.
9. Carlevaro L, Israel D. Gauge threshold corrections for $N = 2$ heterotic local models with flux, and mock modular forms. Journal of High Energy Physics. 2013;3:049.

10. Condeescu C, Dudas E. Kasner solutions, climbing scalars and big-bang singularity. Journal of Cosmology and Astroparticle Physics. 2013(8):013.

11. Dudas E, Heurtier L, Mambrini Y, Zaldivar B. Extra U(1), effective operators, anomalies and dark matter. Journal of High Energy Physics. 2013;1311:083.

12. Dudas E, Linde A, Mambrini Y, Mustafayev A, Olive K. Strong Moduli Stabilization and phenomenology. European Physical Journal C. 2013;73:2268.

13. Dudas E, Mambrini Y, Mustafayev A, Olive KA. Erratum to: Relating the CMSSM and SUGRA models with GUT-scale and super-GUT-scale supersymmetry breaking. European Physical Journal C. 2013;73(5):2430.

14. Dudas E, Petersson C, Tziveloglou P. Low scale supersymmetry breaking and its LHC signatures. Nuclear Physics B. 2013;870(2):353-83.

15. Dumont B, Fichet S, von Gersdorff G. A Bayesian view of the Higgs sector with higher dimensional operators. Journal of High Energy Physics. 2013;7:065.

16. Hristov K, Katmadas S, Pozzoli V. Ungauging black holes and hidden supercharges. Journal of High Energy Physics. 2013(1):110.

17. Kuperstein S, Mukhopadhyay A. Spacetime emergence via holographic RG flow from incompressible Navier-Stokes at the horizon. Journal of High Energy Physics. 2013;11:086.

18. Maharana A, Palti E. Models of particle physics from type II string theory and F-theory: a review. International Journal of Modern Physics A. 2013;28(5-6):1330005.

19. Mayrhofer C, Palti E, Weigand T. Hypercharge flux in IIB and F-theory: anomalies and gauge coupling unification. Journal of High Energy Physics. 2013;9:082.

20. Palti E. A note on hypercharge flux, anomalies, and $U(1)$s in F-theory GUTs. Physical Review D. 2013;87(8):085036.

21. Petropoulos PM, Sfetsos K, Siampos K. Gravity duals of $N = 2$ superconformal field theories with no electrostatic description. Journal of High Energy Physics. 2013;11:118.

2014

22. Anderson LB, Constantin A, Gray J, Lukas A, Palti E. A Comprehensive Scan for Heterotic $SU(5)$ GUT models. Journal of High Energy Physics. 2014;1:047.

23. Antoniadis I, Dudas E, Ferrara S, Sagnotti A. The Volkov-Akulov-Starobinsky supergravity. Physics Letters B. 2014;733:32-5.

24. Antoniadis I, Florakis I, Hohenegger S, Narain KS, Zein Assi A. Non-perturbative Nekrasov partition function from string theory. Nuclear Physics B. 2014;880:87-108.

25. Borchmann J, Mayrhofer C, Palti E, Weigand T. SU(5) tops with multiple U(1)s in F-theory. Nuclear Physics B. 2014;882:1-69.

26. Bossard G, Katmadas S. A bubbling bolt. Journal of High Energy Physics. 2014(7):118.

27. Bossard G, Verschinin V. Minimal unitary representations from supersymmetry. Journal of High Energy Physics. 2014;10:008.

28. Brandenberger RH, Kounnas C, Partouche H, Patil SP, Toumbas N. Cosmological perturbations across an S-brane. Journal of Cosmology and Astroparticle Physics. 2014(3):015.

29. Buchmuller W, Dudas E, Heurtier L, Wieck C. Large-Field Inflation and Supersymmetry Breaking. Journal of High Energy Physics. 2014(9):053.

30. Dudas E. Three-form multiplet and Inflation. Journal of High Energy Physics. 2014;12(014).

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32. Dudas E, Heurtier L, Mambrini Y. Generating X-ray lines from annihilating dark matter. Physical Review D. 2014;90(3):035002.

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34. Gaddam N, Gnecchi A, Vandoren S, Varela O. Rholography, black holes and Scherk-Schwarz. 2014.

35. Leigh RG, Petkou AC, Petropoulos PM, Tripathy PK. The Geroch group in Einstein spaces. Classical and Quantum Gravity. 2014;31(22):225006.

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37. Petropoulos PM, Sfetsos K, Siampos K. Gravity duals of N=2 SCFTs and asymptotic emergence of the electrostatic description. Journal of High Energy Physics. 2014;9:057.

2015

38. Bossard G, Ivanov E, Smilga A. Ultraviolet behavior of 6D supersymmetric Yang-Mills theories and harmonic superspace. Journal of High Energy Physics. 2015(12):085.

39. Bossard G, Katmadas S. Floating JMaRT. Journal of High Energy Physics. 2015(4):067.

40. Bossard G, Kleinschmidt A. Supergravity divergences, supersymmetry and automorphic forms. Journal of High Energy Physics. 2015(8):102.

41. Bossard G, Verschinin V. epsilon del(4) R-4 type invariants and their gradient expansion. Journal of High Energy Physics. 2015(3):089.

42. Bossard G, Verschinin V. The two del R-6(4) type invariants and their higher order generalisation. Journal of High Energy Physics. 2015(7):154.

43. Buchmuller W, Dudas E, Heurtier L, Westphal A, Wieck C, Winkler M. Challenges for Large-Field Inflation and Moduli Stabilization. Journal of High Energy Physics. 2015(04):058.

44. Di Dato A, Gath J, Pedersen AV. Probing the hydrodynamic limit of (super)gravity. Journal of High Energy Physics. 2015;4:171.

45. Dudas E, Ferrara S, Kehagias A, Sagnotti A. Properties of nilpotent supergravity. Journal of High Energy Physics. 2015;9:217.

46. Dudas E, Ghilencea DM. Effective operators in SUSY, superfield constraints and searches for a UV completion. Journal of High Energy Physics. 2015(6):124.

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56. Iancu E, Mukhopadhyay A. A semi-holographic model for heavy-ion collisions. Journal of High Energy Physics. 2015;6:003.

57. Plefka J, Schuster T, Verschinin V. From six to four and more: massless and massive maximal super Yang-Mills amplitudes in 6d and 4d and their hidden symmetries. Journal of High Energy Physics. 2015(1):098.

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63. Chakrabortty J, Ghosh P, Mondal S, Srivastava T. Reconciling (g-2)(mu) and charged lepton flavor violating processes through a doubly charged scalar. Physical Review D. 2016;93(11):115004.

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65. Dall'Agata G, Ferrara S, Zwirner F. Minimal scalar-less matter-coupled supergravity. Physics Letters B. 2016;752:263-6.

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7

THE PHYMATH IT STAFF AND MESOCENTER

PHYMATH IT STAFF
Jean-Luc BELLON (CPHT, Research Engineer CNRS, manager)
Danh PHAM KIM (CPHT, Assistant Engineer CNRS)
David DELAVENNAT (CMLS*, Research Engineer CNRS)
Sylvain FERRAND (CMAP†, Research Engineer Ecole Polytechnique)

The IT staff of the CPHT has an exceptional versatility. On the one hand, J.-L. Bellon and D. Pham Kim provide support for the "basic" users and for the admistrative staff (software and computer installation, IT infrastructure, etc). On the other hand, they are able to deploy and manage HPC clusters. As mentioned at the beginning of this report, they are part of larger staff called "PHYMATH" which gathers (in the same office) the IT staffs of three labs of Ecole Polytechnique. In particular, this has led to the creation of the "PHYMATH mesocenter".

The PHYMATH mesocenter has been created in 2016, it is hosted in the datacenter of Ecole Polytechnique. It is referenced on the CNRS Computation Group (Link). The goal of a mesocenter is to cover a specific perimeter, to maintain an inventory of computing resources and to gather common tools that are useful to scientific research. Historically, since 1990, the CPHT and CMLS have been putting together their computing means by sharing equipment and mutualizing personnel. More recently, the CMAP has joined this IT staff. It is the perimeter defined by these three research labs that we have called "PHYMATH". The personnel is still attached to its own research lab and its tutelage. It is currently distributed as follows: at the CPHT, one Assistant Engineer (CNRS) and one Research Engineer (CNRS), at the CMLS one Research Engineer (CMLS), at the CMAP one Research Engineer (Ecole Polytechnique) and one apprentice (Ecole Polytechnique).

7.1 The common resources

The common resources of PhyMath are divided into two categories: basic services for research, such as the network infrastructure with its central services, *e.g.*, authentication, storage, and support services for research, such as the HPC computing clusters. It is worth noting that some basic services, historically hosted by the research labs, have been readily transferred at the institution level (DSI Ecole Polytechnique). This is true for the email (ZIMBRA), the web (DRUPAL) and the primary directory (LDAP). The target is to free the IT staff from some infrastructure tasks so that they can focus on the support for scientific research.

Common infrastructure. The computing equipment is distributed over three computing rooms: two small rooms that can rescue each other (classified ZRR‡) and in the datacenter of Ecole Polytechnique for heavier resources such as HPC.

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‡ZRR means Restricted Access Zone

The three rooms are connected by a private broadband ethernet network, entirely managed by PhyMath: double optical fiber link at 40 GB/s. The VLANs of every research lab are propagated over this common network. It is also over this network that the VLAN common to the research labs of Ecole Polytechnique is propagated.

Common services:

- `labos.polytechnique.fr`: The PhyMath staff has been at the origin of the request and of the implementation of a common network for all the research labs of Ecole Polytechnique: this network is visible through its own DNS by publishing over the *labos.polytechnique.fr* zone.
- `www.labos.polytechnique.fr`: A web service portal for the research labs.
- `wiki.labos.polytechnique.fr`: A documentation wiki for the IT staff (ASR).
- `ldap.labos.polytechnique.fr`: A secondary LDAP server for the identification and authentication of the users: one LDAP branch per research lab.
- `listes.labos.polytechnique.fr`: A mailing list tool (SYMPA).
- `booked.labos.polytechnique.fr`: A resource booking server: meeting rooms, visio-conference equipment, laptops.
- `gitlab.labos.polytechnique.fr`: A local git repository and continuous integration manager.
- `bareos.labos.polytechnique.fr`: A backup service (LT07 tape storage for a total of 45×15TB).

Figure 7.1: The Hopper cluster

Common computing HPC server:

- `Hopper`: At first restricted to the PhyMath perimeter, this computing cluster has been opened to another physics research lab (LPP) and to two chemistry research labs (LPMC, LCM).

Name	Nr of cores	Storage TB
Hopper	700	40

This cluster is managed by a steering committee and follows an operating mode similar to that of national computing centers: the steering committee establishes the rules of good use, the computing request load is absorbed and distributed using the SLURM scheduler. Quality of service (QOS) rules have been enforced in order to avoid overflows and ensure a better distribution of the resources among all users.

- `Accounting`: Exploiting the accounting provided by SLURM allows to follow the evolution of the load and its distribution for every research lab.

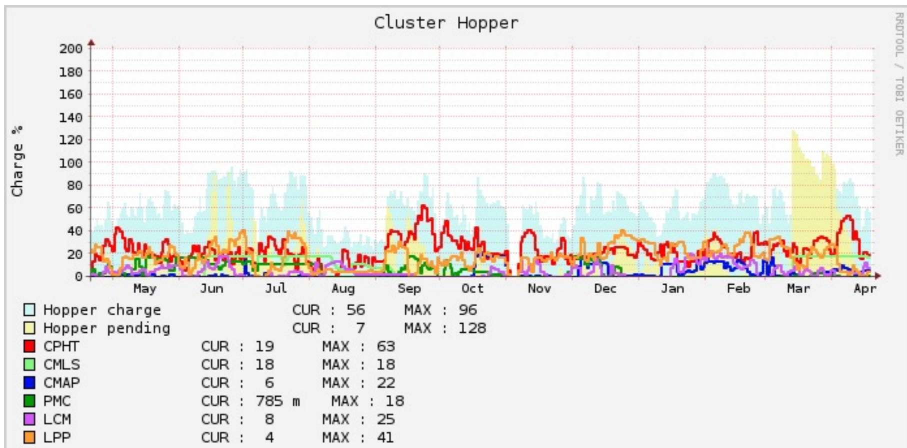

Figure 7.2: Hopper annual load

7.2 Resources owned by the CPHT

File storage. Several storage spaces are available for the users and are organized according to their volume and access type:

`HOME` Daily work space, secured and double backup

`NEXTCLOUD` A private CLOUD-type storage, accessible from anywhere but hosted locally at CPHT

`work` Several large capacity spaces that are not backed up

`WORK (CAPS)` Several larger capacity spaces that are not backed up

`scratch` Fast access temporary spaces

`ZRR` Space reserved to the members of the CPHT ZRR.

The management of the data life cycle together with a ranking are crucial in consideration of the evolution of the data volume. Every research lab has seen its storage capacities explode with the ensuing reliability, security and performance risks: the larger the volumes, the less reliable and backed up they become. Moreover, any heavy operation on the data becomes hard or impossible given the access and transfer delays: copying a data volume of some dozens of TB will take several days clearly showing the limits of today's technology. We are closely investigating and testing distributed file system alternatives. We are at the origin of and participate in the project of a centralized storage over all the research labs of Ecole Polytechnique (DSI).

Computing clusters of the CPHT. The 8 workstations casimir[1-8] are available either through direct access to execute interactive jobs (Matlab, Mathematica, Maple, etc.) or through a scheduler (SLURM).

HPC computation at the CPHT. The following projects have lead to the acquisition of an HPC cluster:

- CORRELMAT ERC Consolidator Grant;
- QMAC ERC Synergy Grant;
- Simons Foundation Grant;
- Misc. contracts.

A total of five clusters are available at the CPHT, with over 5000 cores in addition to the 6000 cores of the PHYMATH mesocenter.

The access to these five clusters is private and limited to the members of given research groups at CPHT and the same is true for their management which is completely taken care of by the two IT scientists of the research lab.

Table 7.1: CPHT clusters

Name	Nr of cores	Storage TB
Montblanc	1984	60
Hedin	1200	32
Tianlong	928	32
Xmhd	384	37
Calculator	500	1

Structure of the clusters: seen from the IT staff

`Scheduler` SLURM

`Broadband network` InfiniBand QDR (40GB/s)

`File system` NFS over InfiniBand (currently being tested: GlusterFS, BeeGFS, RozoFS)

Just as for the Hopper cluster, the other clusters have an architecture close to that of big national computing centers (CINES, IDRIS, TGCC) in order to facilitate the adaptation and compilation of codes. The equipment has been bought via the national ESR Matinfo4 market and installation has been delegated to ClusterVision (HPC installer in the Netherlands) and the management/deployment software is either Bright (with a license per node) or Trinity (open-source).
Currently, we are envisaging to configure future clusters ourselves with our own deployment tool.

This is what we have done for the Calculator cluster which is a test platform build from old servers and cores. The tool is a fusion of several elements used in professional tools and completed by other open-source tools.
Cluster architecture of the Calculator cluster and deployment steps of the nodes:

- master node: allows to manage one or several virtual clusters
  - calculatorcreate: create a new virtual cluster
  - calculatornodes: dynamically assign nodes to a virtual cluster
  - calculatordelete: delete a virtual cluster
- nodes: commands applied to the nodes
  - nodeslist: list the nodes in use
  - nodesinfo: list the node assignments
  - nodespdsh: issue a command on the nodes in parallel
- Deployment of a node: in less than 3 minutes
  - PXE DHCP: start booting process through the network
  - LLDP: network protocol to identify the node without knowing its machine address (MAC ADDR)
  - QCOW2: format of a skeleton virtual machine image that serves as a node model
  - qemu-img: command to transfer and write an image on the node
  - kexec: command to setup the image kernel without final reboot

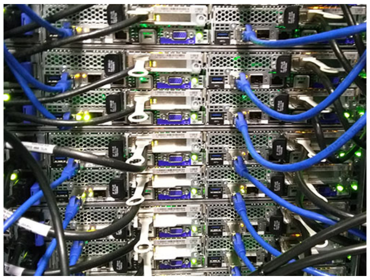

Figure 7.3: IB QDR network 40 GB/s

Operating mode: seen from the users. Just as for national computing centers: in order to perform a calculation, every user prepares and moves his codes and data on the cluster. At the end of the computation, he transfers back his results on the central storage systems of the research unit. The SLURM scheduler that we use is the same as the one used on big computing centers: the users can then get familiarized with the queuing system on our local clusters.

Table 7.2: DARI projects in 2017

Applicant	Allocated hours	Cluster
A. Héron	34 000 000	IDRIS Turing
H. Lütjens	5 000 000	TGCC Curie
H. Lütjens	5 000 000	CINES Occigen
S. Hüller	1 600 000	IDRIS Turing
T. Amari	130 000	IDRIS Ada
T. Amari	400 000	CINES Occigen
S. Biermann	661 000	TGCC Curie

Numerical libraries The list of numerical libraries is always evolving, following the new versions of the relevant software. The libraries are available as modules (using the commands *module* or *lmod*): using the available modules on the national computing centers and at CPHT allows to link the environment to the computing job rather than the user. Thus, a job that has its own environment becomes independent from its user and therefore easier to share. For a given job, the version evolutions are also easier to deal with and one can keep track of intermediate states and versions.
The maintained libraries are build from historical physics codes that have been tested and often developed in FORTRAN (BLAS, LAPACK) but they must also evolve and propose more recent tools such as Python and last-generation solvers (GNU GCC, Clang, Intel Parallel Studio, etc.).

Different groups at CPHT use big national computing centers through DARI project calls. In some cases, the requested computing time goes well below the local capacity of our clusters. In this case, local clusters are used first before the calculations are then sent to the big national centers. They are also used to process the final results. Local clusters are complementary to the national resources and in no way competing with each other. To illustrate this point, the largest DARI project of the CPHT is asking for 34 million hours and is by itself of the order of the capacity of the Hopper cluster if it were given to just one user for a full year.

7.3 Protection of the scientific and technical heritage

7.3.1 The CPHT ZRR

Several projects of the CPHT have been classified in the ZRR zone. On this occasion, a logical ZRR has been tentatively setup in the beginning of 2016 and validated in the early 2018: the project is to secure data space localized in two computer rooms at CPHT. The physical access and the tractability are ensured by a badged access, while the logical access is strictly filtered and limited to secured SSH/SCP protocols.

7.3.2 Entrance gateway of the CPHT

The entire data and tools of the CPHT are also subject to security risks via the multiple external connections that are necessary for a collaborative work and via the permanent access that are granted to external resources or users.

The configuration requires a secured entrance gateway limited to the SSH protocol. With the centralization of services provided by Ecole Polytechnique (mail, web, and other teaching services) we are starting to converge to a unique identifier name.surname and widely spread to directories and mails. Conscious about the increasing risk of phishing, we have introduced tools as well as a double authentication method: the user must provide both a personal password and a one-time password at every connection which is limited in time (TOTP: TimeOneTimePasswd). Several solutions have been explored and we retained a single password software solution that one can use with little constraints with his smartphone or an application in his web browser. We also reinforced the security in using the SSH protocol by inciting users to use SSH key pairs instead of a password and in suggesting, for the keys, the options provided by an OpenSSH certificate, such as login reservations and a preemption time of the certificate.

Currently, the following services are proposed with a double factor: SSH (+ OpenSSH certificate), ZRR, NextCloud, Gitlab, ZIMBRA.

7.4 Projects and perspectives

7.4.1 Cluster management

We are carrying on the synthesis of our knowledge in deploying and managing HPC clusters: we have a complete set of already tested software that will be available for the next production setup of a cluster. This solution allows us to avoid a paid software often linked to a remote assistance contract that is not always efficient for our always-evolving research clusters. We have also validated a virtual cluster architecture that offers greater flexibility in proposing users with versatile software resources both at the development and production stage.

7.4.2 Numerical HPC services

Thank to virtual clusters and a module-based management, we have been able to keep up with the rapid demand for new tools or their modification. Similarly, having a control of both the hardware and software allows to ensure that enough production computing hours are available to make local clusters a viable complement to national computing resources. Also, aside from the production, our architecture offers a development platform for researchers that work on new numerical algorithms. Our virtualized infrastructure configured with modules allows to think about new executable packages: for example using Singularity and Docker containers that allow to generate and compile a job on one's workstation, integrate it in a container and finally execute it on a cluster, thus eliminating any dependence between the job and the cluster. With these technologies, our numerical library is getting richer every day and the code development work is sustained.

7.4.3 Future mesocenter of the Ecole Polytechnique

Since early 2017, the direction for teaching and research (DER) of Ecole Polytechnique has started a mesocenter project at the campus level. The PhyMath mesocenter is at the very center of this project and serves as a reference for the new team that is being built.

SWOT ANALYSIS AND SCIENTIFIC PROJECT FOR THE NEXT FIVE YEARS

8

Swot Analysis

8.1 Strengths

When compared with the other laboratories of theoretical physics across the world, it is clear that the CPHT is a unique place by the diversity of its research areas. The scientific policy of the CPHT is to maintain this tradition.

The recognition of excellence of the research of the CPHT is witnessed by three ongoing ERC grants, just to mention the most visible indicator. Let us point out that two researchers have been selected for Step 2 of the 2018 ERC call projects for Consolidator grants (C. Lorcé, Particle Physics group, and R. Gurau, Mathematical Physics group).

At first sight, the scientific activities of the CPHT look scattered but there is actually an underlying unity since there are common mathematical tools and cross-fertilization of ideas. Let us mention a few examples. For instance, the ERC project of Blaise Goutéraux, entitled “Hydrodynamics, holography and strongly-coupled quantum matter”, puts forward new and unexpected synergies between string theory and condensed matter. Another example is an analogy discovered in the Particle Physics group between diffractive electron-nucleus scattering events and realizations of some one-dimensional branching random walks selected according to the height of the genealogical tree of the particles near their boundaries. Let us mention a last example found in one of the works in the Mathematical Physics group about mathematical ecology. The fine description of the so-called quasi-stationary distribution is obtained using the WKB method which has a priori nothing to do with this problem.

While the principal research axes in CPHT are oriented on conceptional theoretical work, the modeling of physical phenomena in relation to experiments is strongly developed. Several groups at CPHT have continuous and fruitful collaboration with experimental teams, and institutions involved in applied sciences, both on a regular basis and in the frame of research projects (*e.g.*, ANR projects). The impact of this collaborative work is highly visible in our publication record.

Last but not least, we have an outstanding IT staff which has enabled the CPHT to develop its own HPC clusters, in parallel of large-scale national computing centers. This “meso-scale” structure has inspired Ecole Polytechnique to develop its computing mesocenter (see below).

8.2 Weaknesses

As shown in the opening part of this report (see page 12), the situation is critical for the Laser Plasma Interaction group as there were 0 new permanent researchers between 2008 and 2018 that joined the group, and one retirement. The last recruitment of a permanent researcher was in 2001! To make things worse, one of its members will retire in the course of 2019, leaving this group with only 2 CNRS researchers who are not Emeritus Researchers. This critical situation was already pointed out in the previous report. Let us emphasize that there were excellent candidates hired by the CNRS during the period mentioned above who could have been assigned to the CPHT very naturally.

The evolution of the Mathematical Physics group over the past 18 years has been negative in terms of recruitment since there were only two new recruitments (J.-R. Chazottes in 2001 and R. Gurau in 2012) whereas during the same period, 4 members of this group have retired or moved. On the positive side, let us mention that there is an ongoing recruitment thanks to a special position, with generous startup funds, opened by the Ecole Polytechnique.

8.3 Opportunities

As shown in the opening part, we could hire several young professors thanks to the Ecole Polytechnique, as well as one Research engineer. We hope that this process will go on. There is no shortage for outstanding candidates! The Ecole Polytechnique also provided us with a generous amount of fix-term contracts for visiting professorships (47 months over the 2013-2018 period).*

An exciting project at Ecole Polytechnique is the creation of a computing mesocenter whose core is the PhyMath IT staff and its mesocenter (see Chapter 7). This mesocenter will be beneficial for the participating labs by allowing economy of scales and, more importantly, by creating a real community around HPC.

The creation of "NewUni"†, which will gather the Ecole Polytechnique, ENSTA ParisTech, ENSAE ParisTech, Télécom ParisTech et Télécom SudParis, and maybe HEC Paris, has been decided by the President of the French Republic at the end of 2017. It is difficult to predict the real benefits of this decision for laboratories like the CPHT. An important part of this new university is the creation of a Doctoral School which should be a real improvement over the current system which is too complicated and uncontrollable.

Maybe one can also hope that, as part of the NewUni project, there will be a substantial renovation plan for the "historical" part of the campus, in particular the one where most of the labs are located, which is now surrounded by many new buildings.

8.4 Threats

A major threat is the upcoming retirement of Jean-Luc Bellon, the manager of the IT staff, and more broadly, of the PhyMath IT staff. The CNRS is aware of this situation but we are concerned because we are looking for a person willing to have a financially unattractive career with respect to the required technical and management skills.

The CPHT is currently in expansion but there is a real lack of physical space. Moreover, many buildings of Ecole Polytechnique, including the one housing the CPHT, are not maintained as they should be. We are of course aware that this is a widespread situation in many French universities. The problem is the large discrepancy between the state of the buildings housing the laboratories and the scope of the NewUni project, which is to create a university with the highest international standards. On top of this situation, administrative inflexibility of Ecole Polytechnique does not help competitiveness and attractivity for hirings at an international stage

The restructuring of the research landscape following the "divorce" of Polytechnique from the University of Paris-Saclay bears the danger of excluding Ecole Polytechnique from a number of well-running research collaborations. Several groups of CPHT (condensed matter, plasmas) have been and are still members of the LabEx Physique, Atomes, Lumiére, Matière (PALM), and the interactions, *e.g.*, of the condensed matter team with the experimentalists of LPS (Univ. Paris-Sud) or the theoreticians at IPhT (CEA Saclay) are quite vital.

As shown in the opening part of this report (see page 11, the number of retirements of CNRS researchers exceeds the number of young CNRS researchers who have joined the CPHT. This is mainly

*19 months were allocated by the CNRS during that period.

†This is of course a temporary name.

due to the shortage of budgeted posts at CNRS. In parallel, it is difficult to be promoted to Senior Research Fellow. For instance, there is no Senior Researcher in the Particle Physics group while S. Munier should have been promoted some years ago given his scientific achievements.

Another important threat is the insufficient number of PhD fellowships with respect to the number of outstanding students who want to do their PhD at CPHT. This is a very frustrating situation. One should add that most of our PhD students easily find a job in academia or in industry.

Let us end by an innocent-looking problem which is the cost of master internships. For that we have spent 10200 € in 2016[‡], 14300 € in 2017 and 18750 € in 2018. Looking at the summary of the financial ressources on page 13, one sees that, for instance, it represents 10% of the funds directly allocated by the Institutions (*i.e.*, "CNRS + Ecole Polytechnique") for the year 2017! Another point of view is to realize that each permanent researcher at CPHT has about 2000 € per year coming from the Institutions to travel and invite colleagues. For instance, we spent in 2018 the equivalent of the allocation of 9 permanent researchers! It is clear that without sharing our own ressources among the groups, we cannot afford to have the master interns we want, which is obviously a serious issue in the perspective of detecting our future PhD students. Compensating students for their internships is a progress but no support measures were made.

[‡]the year when financial rewards for internships became mandatory by a national law

9

SCIENTIFIC PROJECT: MAIN LINES

We end this report by sketching out, group by group, the main research projects. This chapter is neither an exhaustive list of projects nor a detailed research program.

9.1 Condensed Matter

Correlated quantum systems, from crystalline materials to ultracold atom gases, continue to play the role of an overarching theme of the condensed matter group. The interactions between the constituants of these systems give rise to emergent collective behavior which is at the heart of exotic quantum phases of matter, phase transitions, and – quite often – unconventional structural, spectral, magnetic or transport properties of materials. The theoretical description of these phenomena remains one of the big challenges in the field. Our work covers the whole spectrum of such systems, from crystalline materials, mesoscopic or nanoscopic systems to ultracold atom gases and systems coupling matter and radiation, as well as the development of suitable theoretical and numerical methods, including their implementation. Below we highlight a selection of more specific lines of research that are on our agenda for the coming years.

Development of new computational methods for the Quantum Many Body problem. We plan in particular to push forward the diagrammatic Monte Carlo method, both at equilibrium and out of equilibrium. These methods will be implemented into the TRIQS library (`https://triqs.github.io`), which will moreover be developed along several directions (especially concerning new applications and extensions of DMFT). This project is partially funded by the Simons Foundation Many Electron collaboration (PI: M.Ferrero), and is part of a collaboration with the Center for Computational Quantum Physics, Flatiron Institute, Simons Foundation (New York). The ongoing PhD thesis of Alice Moutenet is part of this activity.

Refined first principles approaches to correlated materials: further development and spectroscopic applications. Over the last few years, this topic has been boosted by the ERC project "Predictive electronic structure calculations for materials with strong electronic correlations", but will extend beyond the end of the ERC funding period. Moreover, thanks to the developed refined electronic structure tools beyond standard DFT+DMFT, we are now in a position to address the low-energy electronic excitations of a variety of correlated materials with unprecedented precision. This allows for decisive advances, since in our target materials (transition metal pnictides/oxides,...) minor differences in the low-energy excitations lead quite generically to qualitative differences in their properties. The CPHT team is enjoying fruitful interactions with experimental spectroscopy groups (on campus (LSI), on the plateau (Synchrotron Soleil, LPS-Orsay), and all over the world (China, Japan, Switzerland, Germany, USA,...)) on a variety of challenging spectroscopy problems.

Complex magnetic and multipolar ordering phenomena. We are currently developing several lines of research related to materials displaying magnetic and multipolar ordering phenomena. This involves trying to understand the physical properties of intriguing new materials as they are synthesized, identifying relevant order parameters and interactions, establishing a microscopic modelisation from first principles and developing the theoretical tools for addressing thermodynamic properties. Specifically, we will focus on the following topics:

1. Understand newly synthesized transition metal compounds such as the iridate H3LiIr2O6, the

spin-dimer compound K2NiMoO8, or the organometallic Ni3O6N6C60H54 that exhibit complex magnetic ground states and/or exotic low-energy excitations.

2. Develop an ab initio approach to complex magnetic and multipolar order in localized transition-metal and f-electron systems. The linear-response method of L. Pourovskii and a generalization thereof will be employed to compute inter-site exchange interactions between complex local degrees of freedom like, for example, quadrupole or octupole moments. The properties of the ordered phases will be subsequently evaluated from calculated ab initio effective Hamiltonians.

3. Develop a theoretical description of the electronic structure, thermodynamic and transport properties of transition metals and their alloys within an ab initio DMFT framework. The focus will be on a more realistic treatment of these systems (especially, iron-based ones) compared to the previous works by including lattice vibrations and alloying effects. This subject will also present synergies with the ongoing PhD thesis of M. Turtulici which focuses on the first principles description of oxide materials with vacancies.

4. Study the interplay of exchange field, RKKY magnetic interactions and Kondo effect in Ce and Yb compounds, employing a sophisticated DMFT treatment of on-site f-electron correlations in conjunction with a more simple perturbative approach to inter-site many-electron effects.

Electronic structure of functional materials. We will continue to push the frontier of materials physics by using first principles calculations to understand, design and control materials. Examples include the search for new layered oxides with high Na concentration that can be used in sodium-ion batteries using both rational design principles and evolutionary algorithms. Pursuing a research line initiated within the ERC project QMAC, A. Subedi will look for ways to employ nonlinear phononics in new avenues such as light generation and amplification or even enhancing the performance of electrocatalysts. Finally, within the French-German ANR-DFG project RE-MAP, we will continue our research program on potential new permanent magnet materials.

Ultracold atom gases and quantum simulators. In the next years, we plan to further develop our activities along the three lines of research in this area highlighted in the report. In all cases, we will focus on strongly-correlated quantum regimes, using a combination of analytical and numerical approaches. For instance, as regards disordered systems, we will search for new signatures of emblematic correlated phases such as the Bose- glass phase, in new situations. The study of one-dimensional systems will be extended to time-dependent situations. In particular, we plan to develop generalized hydrodynamic approaches, which exploit the integrability of equilibrium phases. Finally, out-of- equilibrium dynamics will now focus more specifically on the study of ergodicity and its breaking in integrable or non-integrable systems. In addition, strong efforts will be devoted to combine the approaches and knowledge developed in all these aspects in the last years. For instance, the study of out-of-equilibrium dynamics of disordered systems and one-dimensional gases will be pursued actively.

Hybrid systems and topological quantum matter. Topological phases bring up new important questions in relation with quantum materials and quantum fluids on one hand (photons, cQED systems[*] and ultra-cold atoms) and mathematical concepts and methods from high-energy physics on the other hand. We will pursue our activity with specific questions related to strongly-correlated topological phases and design of new materials, in relation with solvable models and algorithm efforts, to

[*]This line of research is at the heart of the newly accepted ANR project "Simulating the Bose Hubbard Model in Superconducting Circuits" (K. Le Hur, in collaboration with experimentalists from LPS-Orsay and Institut Neél, Grenoble)

include interaction effects especially in the strong-coupling limit, in the Mott phase. These efforts will allow us to build a unified approach for topological insulating and superconducting phases of matter. We also intend to pursue our efforts on “new probes” to tackle these phases, related to light-matter systems, entanglement and quantum information tools. Finally, quantum electrodynamics appears as an important unifying keyword, since gauge fields emerge (rigorously) in the description of interacting models such as in the Kitaev spin model, and also from a quantum engineering perspective in circuit QED systems. From a methodological point of view, linked to these circuit QED systems and light-matter systems, we will continue to develop methods, to tackle time-dependent phenomena, fluctuations and interactions.

Synergies between string theory and condensed matter: Is holography good for bad metals? Following the recent hiring of B. Goutéraux in the string theory group, the condensed matter team is looking forward to fruitful interactions exploring synergies between field theory concepts developed in the former and electronic phenomena studied by the latter. We plan to organize an interdisciplinary working group on holography and related concepts on the one hand, and the physics of bad metals on the other hand.

9.2 Laser Plasma Interaction

Classical regimes of laser-plasma interaction

(i) The improvement of the modeling of the laser-plasma instabilities remains a major goal in the mid-term research plans of our group. Our first goal is to enlarge the capacities to efficiently describe plasma wave processes on the electron motion timescale, including particle trapping effects. Such a modeling will eventually be incorporated in larger scale simulations tools, relevant to experimental studies. Of great importance is the ability to control the evolution and the level of the plasma waves excited by laser plasma instabilities. This control is relevant for instabilities concerning laser fusion as well as for the applications such as short laser pulse amplification. In our future studies the various options of laser pulse shaping, laser bandwidth, as well as the laser beam spatial phase front shaping will be carefully studied.

(ii) Laser-plasma acceleration with thin solid density targets is still very timely and competitive. We will pursue our current project concerning the imprinted surface structures in order to find an optimized regime for ion acceleration, and/or for the emission of coherent radiation sources off the front surface. Our group has excellent simulation capacities to maintain this activity.

New regimes of laser-plasma interaction In the next coming years, new high intensity laser sources will become operational, both in our direct neighbourhood and at several other sites in Europe, namely: Apollon (CNRS, site close to the Polytechnique campus), and Extreme Light Infrastructure facilities in Tcheque Republic, Hungary, and Romania.

These facilities will significantly change the "parameter space" accessible in laser matter interaction, in concentrating laser flux in presently available short and ultra-short pulses in focal volumes smaller than the present ones.

Strongly focused light at these 10-PetaWatt facilities will hence allow achieving electromagnetic fields that will go well beyond the regime of classical relativistic electron motion in laser fields. Although such soon available laser fields will still be by orders of magnitude below the Schwinger limit, the probability that QED processes occur increases very significantly: indeed, several mechanisms originating from laser-matter interaction can catalyze processes such as electron-positron pair production (for instance through intermediate interactions via high-energy (gamma) photon rays or particle beams). Thus, the discovery of QED processes in matter, via laser-plasma interaction, is highly challenging.

In this domain of research, it is of primary interest to identify "catalyzing" mechanisms for QED processes detectable on the new facilities. It is also of fundamental importance to revisit the approaches and model equations to describe laser-plasma interaction in these new regimes. An important favourable factor at CPHT is the existence of expertise in both laser-plasma interaction and in QED.

Laser-matter interaction at moderate intensity

With the new availability of ultrashort pulse laser sources in the mid-infrared (MIR, wavelength λ= 2-4 μm) we enter a new frontier in ultrafast science, where many applications in strong field physics benefit greatly from an increase of the quiver energy of the electron in the longer wavelength laser field. Many open questions were raised regarding the roles of various nonlinear processes that drive the long-range propagation of MIR pulses in air. In the next years, we will tackle the problem of accurately describing the linear and nonlinear optical properties of common gases in the atmosphere in order to achieve predictive modeling of the long-range propagation of MIR laser pulses. The critical power for self-focusing, which constitutes the threshold for the regime of ultrashort laser pulse propagation, is shifted to higher values by a factor of λ^2. Presently available MIR sources at 4 μm are reaching the power threshold, advocating for revisiting the entire field of ultrafast nonlinear optics with these new sources. We will conduct our investigations on laser-matter interaction and filamentation of ultrashort laser pulses in air at mid-infrared wavelengths with the aim of generating new sources of secondary radiations on both sides of the electromagnetic spectrum with respect to wavelength of the driving laser pulse.

We will also carry on with our investigations on the generation of terahertz and far-infrared radiation from filamentation in air. The interest for this work lies in the possibility for numerous applications that require a stand-off generation and/or detection of THz radiation (spectroscopy in hazardous places, security applications, etc). In this context, the recently created International Research Network (GDRI NanoTeraMIR - France-Russie) is participated by our group.

9.3 Magnetized Plasmas

The research activity of the Magnetized Plasmas group will be pursued in tokamak- and astro- physics at the interface between the theoretical modelling of these phenomena, the development of numerical methods and codes for their simulation and the use of these tools within strong collaborations with experimentalists for interpretation and prediction in experiments. As in the past, our policy is the dissemination of our numerical models and stabilized numerical tools in the framework of research contracts and collaborations, and their use for the interpretation and eventually the prediction of experimental data. Unfortunately, our Hall thruster activity will probably end because of the retirement of Anne Héron.

Since the arrival of T. Nicolas in the group as CRCN in January 2018, we have worked on improvements in the model and the numerical method of the XTOR-K code. These include the switch in the kinetic module from a domain cloning method towards a domain decomposition one with the introduction of binary collisions. The free-boundary conditions, and part of the model in the two-fluid version of the code, such as the external heating modules mimicking heating with RF antennas and current deposition will also be transferred from the two-fluid code into XTOR-K. At the same time, the entire code will be optimized in terms of hybrid MPI/OpenMP.

These issues will have a large impact on our future scientific activity. On the one hand, free-boundary conditions will expand our domain of investigation from the study of plasma core instabilities toward new families of tokamak instabilities (external kinks, Edge Localized Modes, plasma disruptions, etc) and their control in plasma geometries characteristic of large tokamaks. On the other hand, the introduction of collisions will allow long time hybrid fluid-kinetic studies such as tearing dynamics or multiple sawtooth oscillations including kinetic effects. The introduction of collisions into the kinetic module of XTOR-K also opens new prospects in the study of the interplay between heavy impurity neoclassical transport and MHD or two-fluid instabilities. In current and future tokamaks, plasma heating is partly provided by neutral beam injection (NBI). Ionization of the injected neutrals results in the presence of fast ions in the plasma. The transport of these fast ions and their interaction with MHD modes are key issues regarding plasma stability, and thus the plasma confinement. In order to reproduce the experimental observations and predict the behavior of future experiments, we work on the implementation of a realistic NBI source.

Validating a numerical code like XTOR-K against theoretical models is a difficult problem but an absolute necessity. For this reason, we work at moment on a new linear theoretical model for internal $m = 1/n = 1$ instabilities (so-called fishbone instabilities), which generalizes previous ones by taking into account trapped and passing fast ions. The objective is the comparison of this model with XTOR-K calculations in the initial linear growing phase of these internal instabilities in the presence of, *e.g.*, a fusion alpha population. After this validation, the code will be used to study the saturation mechanisms of these instabilities. This subject is important in the perspective of a fusion device like ITER because fishbones could cause a deconfinement of alphas, which serve as the main heating source in a burning plasma.

In astrophysics, our present and near future activity consists in the construction of a reference base of solar eruptions. We are also interested in the large scale transport of eruptive phenomena in the solar wind and the interplanetary environment. These works include fundamental theoretical and numerical as well as predictive aspects. The identification of generic mechanisms of energy transport in the highest layers of the Sun and at larger scales remains also a major challenge in our future activities in terms of theory and numerical methods. We have developed several numerical models to study these topics. They will be used in new codes which will allow us in fine to study the entire environment of the sun (including a layer under the sun surface) and of the earth. Amongst the objectives, we would like to investigate, *e.g.*, the processes at the origin of the triggering of solar eruptions or the processes and their application to Space Weather with the global, Solar wind / Magnetosphere / Ionosphere model of the earth environment.

Our group is part of the “Virtual Space Weather Modelling Center” of the program “ESA Space Situational Awareness (SSA)”. We have been selected by ESA to be the solar node of this Solar, Heliosphere, Magnetosphere program and we will provide our models to the model basis SOLARMODELS supported by CNES. Several phases of the project have been achieved and work is in progress to achieve an operational European modelization service.

9.4 Mathematical Physics

Research in tensor field theory at CPHT will continue in earnest. We are now in the position to conjecture that tensor field theory will most likely be solved order by order in $1/N$. Achieving this is possible in the next five years. To this end, the group in CPHT will continue its research into the renormalization of large N field theories and into the derivation of effective descriptions for these theories.

While there are a number of perturbative renormalization computations (for instance for some models beta functions have been computed up to two loops), it is of foremost importance to develop non perturbative renormalization schemes for tensor field theories. These will require to combine functional renormalization flow equations with the melonic $1/N$ expansion of tensor field theory. Both R. Gurau and C. Kopper at CPHT have an extensive expertise in renormalization, and the it is expected that the mathematical physics group here will play a significant role in this line of research.

Effective descriptions for tensor field theories (in the two particle irreducible formalism) have recently been derived by R. Gurau and D. Benedetti in dimensions 1 and 0. In order to understand the effective behavior of tensor field theories, similar results will be needed in higher dimensions. Of course in higher dimensions one will need to deal with divergences, hence both the $1/N$ expansion and the renormalization will need to be revisited in this new effective theory language. This reformulation of the tensor field theory should allow one direct access to the phenomenology of these model.

Finally a number of applications of tensor field theory to condensed matter (more precisely by providing new models of quantum critical points) and the AdS/CFT correspondence will be explored by the mathematical physics group at CPHT over the next several years.

Cluster expansion methods which originated in statistical mechanics permit to construct (massive) quantum field theories as long as there are no serious ultraviolet problems, *i.e.*, in dimensions lower than four. The flow equations of the renormalization group, of nonperturbative nature in the beginning, allow for simple perturbative constructions which do not differ very much in four or lower dimensions. Obstacles of combinatoric nature, present even in the one-dimensional case, prevent us however from going beyond perturbation theory. The goal is to master both aspects (nonperturbative and ultraviolet) simultaneously, noting that each of them can be analyzed transparently if the other is not present.

J.-R. Chazottes and Pierre Collet will continue their program on quasi-stationary distributions of population models which are destined to die out. Much remains to be done, for instance the case of an attractive limit cycle for the deterministic approximation has not been studied. Such a situation occurs in the Rosenzweig-McArthur model. Another very natural case is that of multistability. This line of research deals with the so-called demographic stochasticity where the mean time to extinction is exponentially large with the scaling parameter K (see Chapter 4, Section 4.3). A wide open line of reseach is to mathematically describe what happens in the presence of the so-called environmental stochasticity. Recall that this is a collaboration with the CMAP (Ecole Polytechnique) through the Chair "Modélisation Mathématique et Biodiversité"[†].

Ph. Mounaix and his collaborators are planning to apply the formalism and analytical tools we have recently developed to extract the asymptotics for the expected maximum of random walks with a drift to other interesting problems. These include, for instance, the mean perimeter of the convex hull of a 2D random walk process and the expected flux in the Schmoluchovski capture problem.
As for conditional random fields, Ph. Mounaix is planning to study the concentration of the realizations of a Gaussian random laser field through an optically active medium in the limit of a large amplification of the scattered light, taking diffraction into account. He will use the method, proposed by Falkovich et al., to determine the non Gaussian tails of the probability distribution of solutions to stochastic PDEs.

9.5 Particle Physics

In the coming years, we plan to continue our investigation of the different regimes of quantum chromodynamics (QCD), to develop theoretical methods as well as phenomenological models in close

[†]Ecole Polytechnique, Muséum national d'Histoire naturelle, Fondation de l'Ecole Polytechnique, VEOLIA Environnement

connection with the expected experimental data from LHC, JLab, Panda@GSI, and with the preparatory physics studies for the future Electron-Ion Collider (EIC) project.

In the medium-energy range, we will further study the QCD energy-momentum tensor, mainly by adding the information about the parton momentum to the picture and by identifying key experiments to constrain it. To realize this project, an application to an ERC Consolidator Grant has been submitted and is currently under review. Another aspect we plan to develop in the coming years is the impact of twist-3 contributions to physical observables and their relations to the QCD dynamics. The study of observables related to the 3-dimensional tomography of hadrons will be continued, in particular by taking into account the specificities of the deuteron case.

As for the higher-energy and density regime, we plan to develop more the phenomenology of the TMD factorization obtained in that regime from the Color Glass Condensate approach. In view of phenomenology, we plan to supplement the resummation of the small-x logarithms with both running-coupling corrections and a resummation of Sudakov logarithms. On the more theoretical side, the formalism will be extended to more complicated final-states, and to next-to-leading order for the simplest processes. In addition, we will pursue another line of research recently started, which concerns the early-time dynamics in heavy-ion collisions: An important theoretical result on the correlation of the energy-momentum tensor describing the matter produced in such collisions has just been obtained, which opens the door for several new developements. We will also help to prepare more precise experimental investigations of the onset of the high-density regime, which will be possible at a future Electron-Ion collider, currently under very active study: The latter will enable detailed measurements of diffraction in deep-inelastic scattering off nuclei, an observable which is particularly sensitive to that regime. To this aim, we shall deduce definite phenomenological predictions from the theoretical results we have just obtained on the distribution of rapidity gaps in such processes. In parallel, we will continue our fruitful work on related mathematical problems, such as the statistics of genealogical trees in general evolution models.

Finally, part of our future activity will be focused on studying the predictions of the Curci-Ferrari model concerning some of the non-perturbative QCD distribution functions. We will continue investigating the properties of the perturbative expansion within that model. In particular, we are now planning to evaluate the two-loop corrections to the two- and three-point correlation functions. We will also continue to investigate the predictions of the model concerning the phase structure of QCD, notably the spontaneous chiral symmetry breaking and how it is restored at high temperature or high chemical potential.

9.6 String Theory

Keeping diversity is a priority of the group, and string theory makes this possible. The research we have conducted during the past five years will be a source of inspiration for the future. Many fundamental problems, as often mentioned earlier, require further investigation and part of our activity will be focused on them. This is surely the case for the more mathematical side, because the problems addressed there are rooted to the deep structure of the theory or the formalism. Formal aspects of gravity and supergravity will be with us for a long time, together with black-hole physics.

On the phenomenology/cosmology side, the searches for dark-matter candidates, dark energy, or alternatives to inflation are also important questions, which will persist until a satisfactory answer is found, theoretically or observationally. String theory with spontaneously broken supersymmetry provides a framework for addressing various issues in cosmology and gauge theories, and in particular for studying properties of phase transitions occurring along the evolution of the universe. String theory with no supersymmetry might be the ultimate goal in this area, and although inaccessible in the framework of closed strings, promising open-string models do exist, which deserve a deeper analysis.

It should be kept in mind, however, that the methods we have been using for several decades in trying to overcome the various obstacles met in this field might not be the appropriate ones. The stringent absence of any experimental sign in favour of supersymmetry should sooner or later trigger our attention towards radically novel angles. We should accept to abandon our favourite supersymmetric model with supersymmetry-breaking scale sitting just around the corner. Similarly we might need to reconsider our interpretation of Hawking radiation, and our expectations of quantum gravity, as emanating from string for many years.

In the chapter of applications of string theory, the flat fluid/gravity correspondence has paved the way to the flat microscopic correspondence, which must now be thoroughly understood. This requires developing a novel kind of quantum field theories based on Carrollian symmetry, which is ultra-relativistic, *i.e.*, dual to Galilean symmetry. This is a wide and timely project involving many field-theoretical and gravitational aspects resumed around the holographic correspondence.

Five years ago, the following was claimed in our group report: “Dans le sujet des applications holographiques, un rapprochement avec la matière condensée pourrait être envisagé”. Blaise Goutéraux has joined the group in 2017. His projects are oriented towards the systematic investigation of universal thermoelectric-transport properties in strongly coupled phases, where quantum effects are dominant. Examples of such systems are high-T_c superconductors, graphene or quark-gluon plasma. Non-perturbative methods are thus required, calling, *e.g.*, for non-quasiparticle pictures, which can be extended towards different problems relevant for other phases of matter or materials than those mentioned above. Large-N techniques and gauge/gravity correspondence, particularly in the hydrodynamic regime, will be the main tools, hence making contact with other activities in the team as well as in the condensed-matter group.

We are glad our forecast has been realized, bringing new breath to the group and more synergy to the CPHT. In the same spirit, we would like to take advantage of new hirings oriented towards statistical mechanics or dynamical systems, and bridge our interests with those of the mathematical-physics group. These may include bootstrap methods or out-of-equilibrium physics.