Condensed matter physics and quantum simulators

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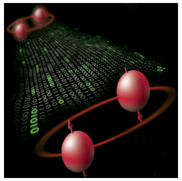
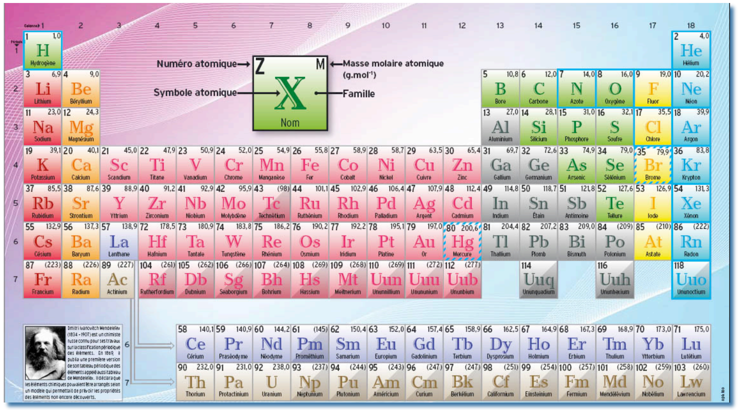
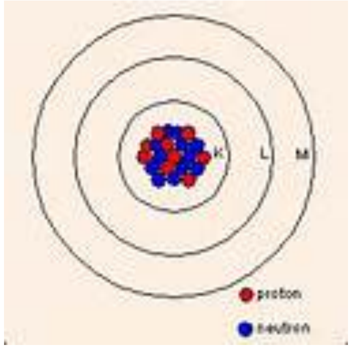
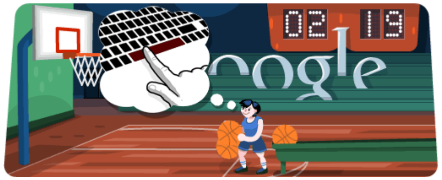






Google simulator



Colloquium type talk (some technical details at some points)

« Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws » Feynman 1982

Thanks to DFG Germany & Labex PALM Paris-Saclay
Collaborators cited in the talk

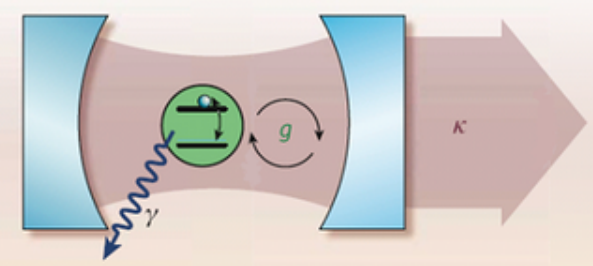
Cavity & Circuit QED:

Prix Nobel S. Haroche

Coupling atoms to the EM field

- atoms can couple to the EM field via dipole moment
- coupling strength can be enhanced by confining field to a cavity

cavity QED LKB ENS & collège de France



$2g$ = vacuum Rabi frequency
γ = atomic relaxation rate
κ = photon escape rate

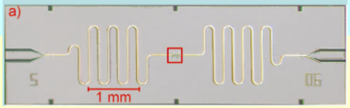
Also Rabi, Dicke models

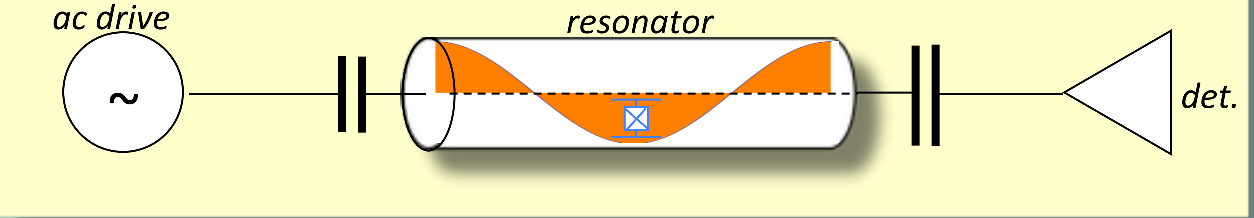
Jaynes-Cummings Hamiltonian

$$H = \frac{1}{2}\omega_a\sigma_z + \omega_r a^\dagger a + g\left(\sigma_- a^\dagger + \sigma_+ a\right) + \left(H_{\text{drive}} + H_{\text{baths}}\right)$$

A. Blais et al. 2004

- same concept works for superconducting qubits!





Experiments in
SPEC CEA Saclay (**C. Urbina**)
ENS Paris, Grenoble
LPS Orsay

Santa Barbara, Yale,
Zurich, Princeton, Berkeley,
Gothenburg…

J.M. Raimond, M. Brune, S. Haroche, Rev. Mod. Phys. **73**, 565 (2001); R. J. Schoelkopf, S.M. Girvin, Nature **451**, 664 (2008)

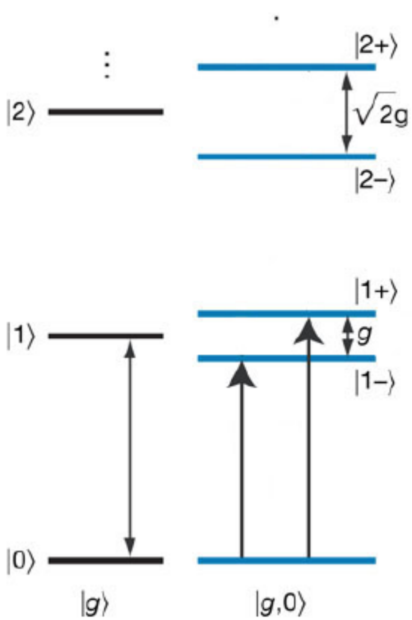
Driven light-matter Systems (AC driving Periodic in time): Floquet

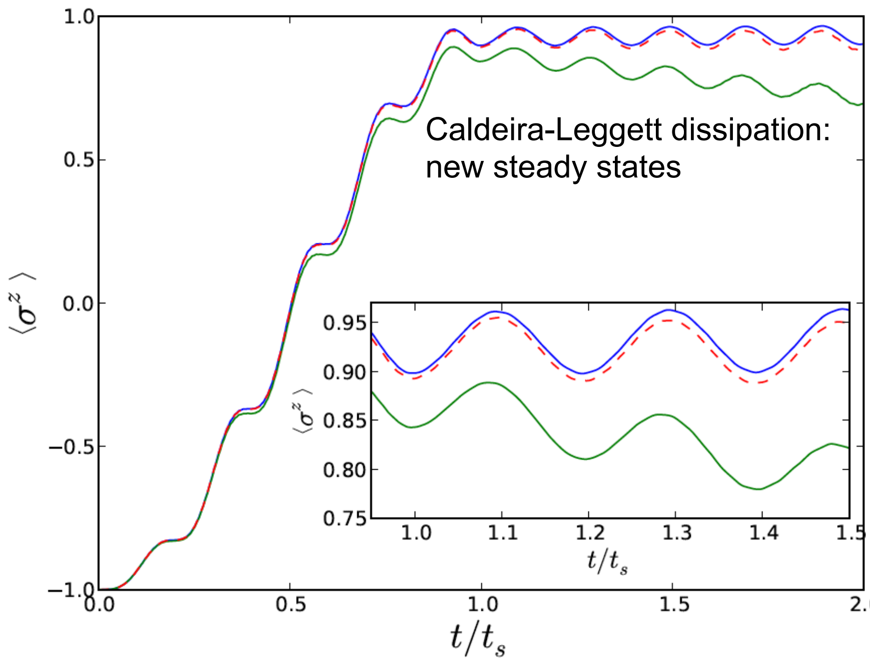
Π rotation to achieve 1 polariton

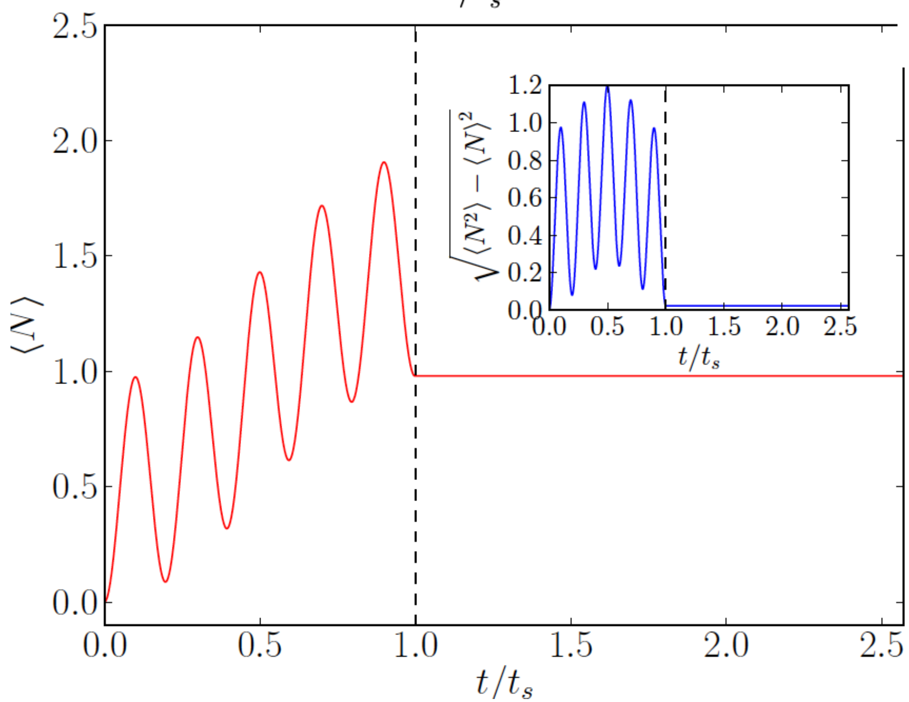
$$N = a^\dagger a + \frac{1}{2}(\sigma^z + 1)$$

Small g limit:

Jaynes-Cummings ladder

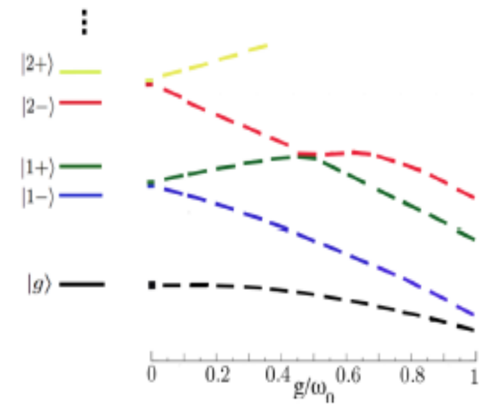






L. Henriet
Z. Ristivojevic
P. P. Orth, KLH, 2014
(arXiv:1401.4558)
Stochastic approach

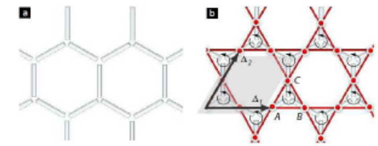
Progress in Rabi model
Braak, Moroz, Batchelor
integrability

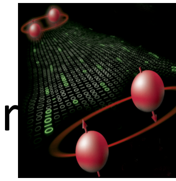


Π rotation also useful to measure Berry phase **(see later, topology)**

Related Experiments
Zuerich, 2007 (Ramsey)
Boulder, 2014
Santa Barbara 2014
Saclay

Quantum engineering





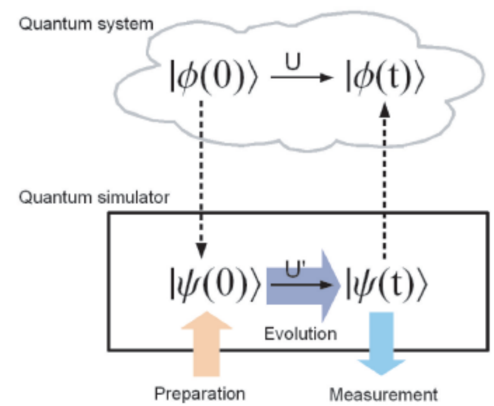
<u>What are the goals:</u>

Complement efforts in **quantum materials** and address solvable, toy models for new emergent behaviors and novel applications (quantum information and macroscopic quantum entanglement)

Deep relation with quantum engineering (ultra-cold atoms, circuits, nano)
Back and Forth between Simulation and Numerical Efforts (quantum computer)

<u>New Frontiers</u>

- Examples of emergent phases and quantum phase transitions
- Simulating artificial gauge fields and topological phases, « protection »
- New way of sensing (dynamics, transport, light-matter systems)
- Quantum info: entanglement measures, efforts in methods & numerics
- quantum walks, cellular automata, quantum math & machines
- *Connection with high-energy physics and other frontiers chemistry …*



Recent Reviews: Georgescu, Ashhab, Nori, Review Modern Physics 2015
Several reviews: Nature Physics Insight quantum simulation 2012

K. Le Hur, L. Henriet, A. Petrescu, K. Plekhanov, G. Roux, M. Schiro Académie of Sciences 2016 (arXiv 2015)

Hubbard model &Magnetism

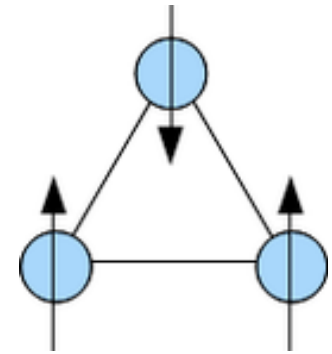
$$\mathbf{S}_i = c^{\dagger}_{i\alpha}\sigma^{\beta}_{\alpha}c_{i\beta}$$
$$J \sim 4t^2/U$$

Hubbard model, Heisenberg and Mott Localization

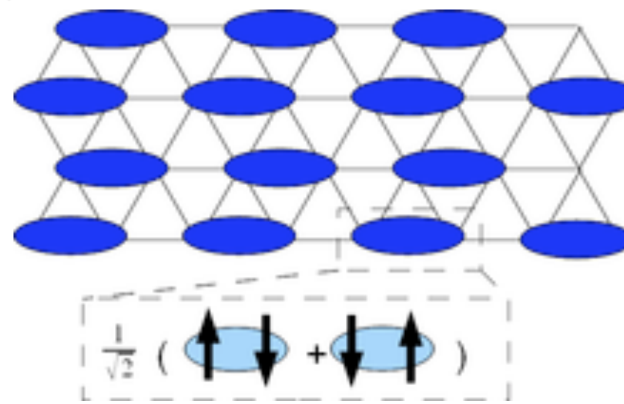
Sir Nevil Mott: 1 electron per site and it costs
A large energy U to put 2 electrons on the same site

Néel state : up down up down …. (Goldstone modes)

$$H = -t \sum_{\langle i,j\rangle,\sigma} (c^{\dagger}_{i,\sigma}c_{j,\sigma} + c^{\dagger}_{j,\sigma}c_{i,\sigma}) + U\sum_{i=1}^{N} n_{i\uparrow}n_{i\downarrow},$$



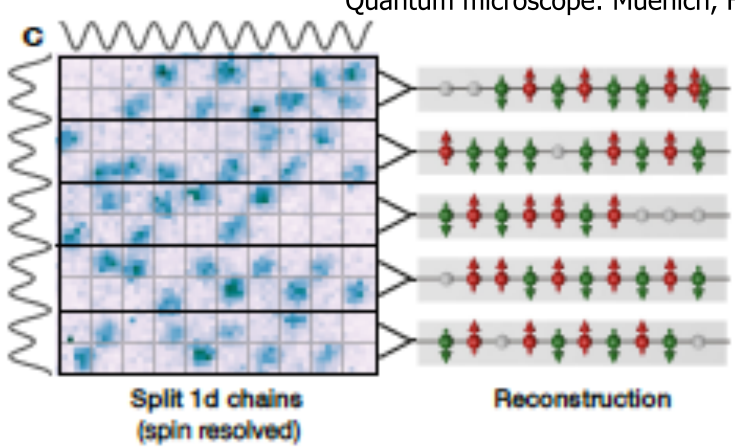
RVB state of Ph. Anderson



One dimension: spinon excitations, Luttinger liquid
SU(N) expansions (hyperfine states in cold atoms); Ph. Lecheminant

Exactly Solvable models (Bethe Ansatz, CFT..)
Numerics: DMRG efforts, Exact diagonalization, DMFT, PEPS…

Quantum microscope: Muenich, Harvard

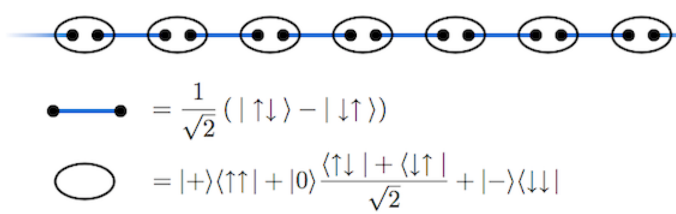


T. Giamarchi

Gogolin, Nersesyan, Tsvelik

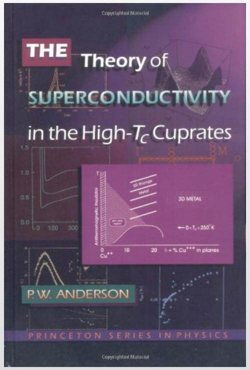
Korepin Essler Maillet Andrei, Saleur…

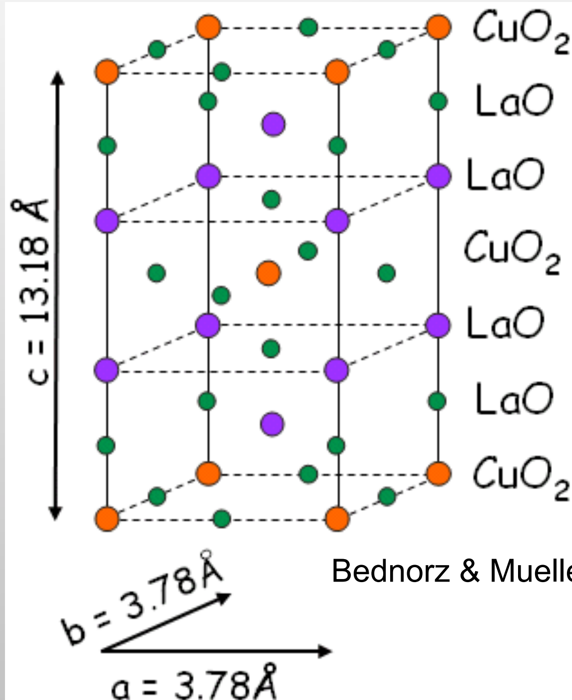
Exact construction spin 1 chain (SPT)
Affleck-Kennedy-Lieb-Tasaki 1987



Haldane phase; « edge ½-semions »

High Temperature Superconductors:
1 BAND HUBBARD MODEL IN 2D STILL challenging





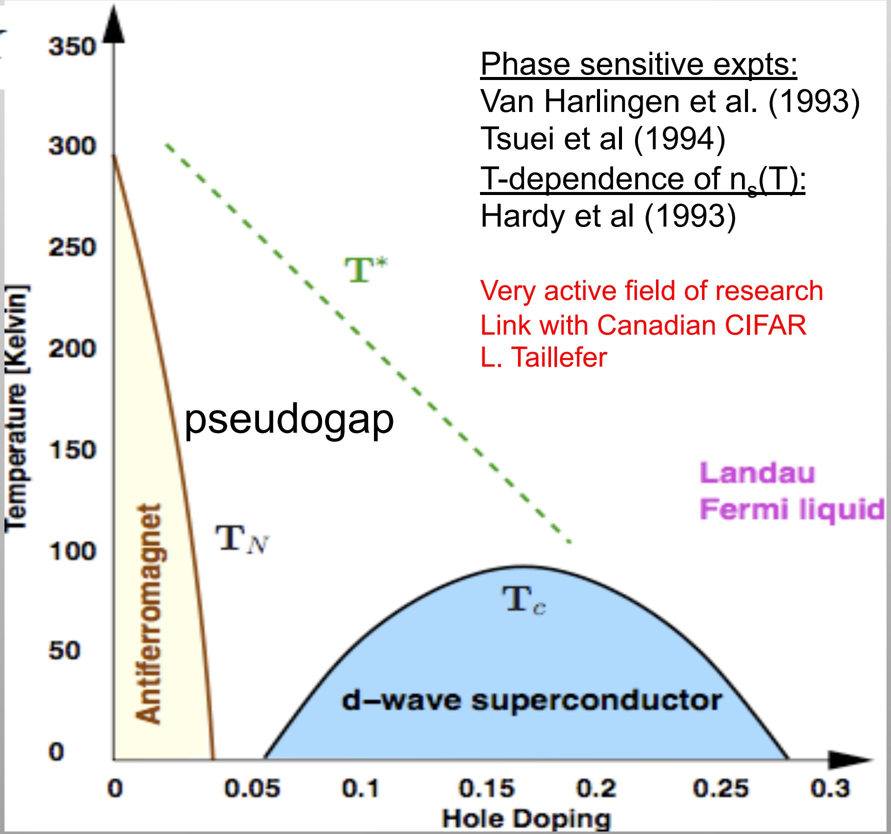
Bednorz & Mueller

Progress in DMFT (A. Georges, G. Kotliar, W. Krauth, M. Rozenberg, O. Parcollet, M. Ferrero, E. Gull, A. Millis, A. M. Tremblay, D. Senechal)

Recent QMC analysis and stochastic approaches
E. Berg, M. Metlitski, S. Sachdev, Science 2012
Efetov, Meier, Pepin, Nature Physics 2013; M. Ferrero

$J_{copper} \sim 1500K$

Scalapino, Chubukov…



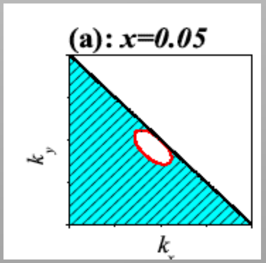
Phase sensitive expts:
Van Harlingen et al. (1993)
Tsuei et al (1994)
T-dependence of $n_s(T)$:
Hardy et al (1993)

Very active field of research
Link with Canadian CIFAR
L. Taillefer

- Coupled CuO_2 layers

Efforts to compute electron Green function Based on Yang, Rice, Zhang

K. Le Hur & Maurice Rice
Review 2009, 98 pages
solvable "engineery" in cold atoms



Efforts in QED3, and AdS-CFT

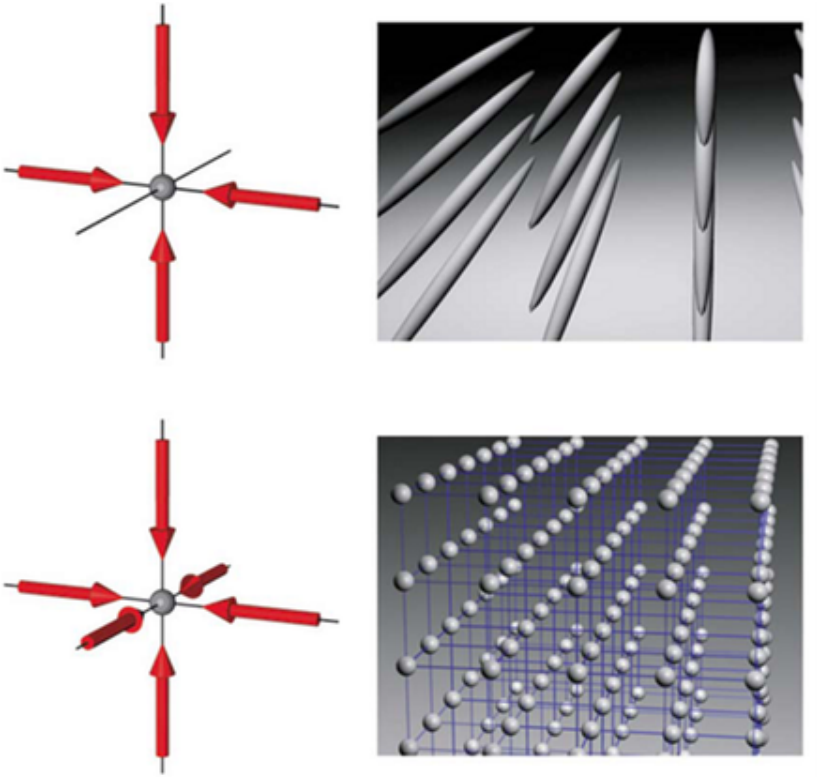
- Normal phase is not a Fermi liquid at low doping: SIMULATORS COULD HELP

Ultracold atomic gases

I. Bloch, J. Dalibard, W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008)

Z. Hadzibabic, M. Albert (more on the quantum box)

D. Jaksch et al., Phys. Rev. Lett. **81**, 3108 (1998)
M. Greiner et al., Nature **415**, 39 (2002)

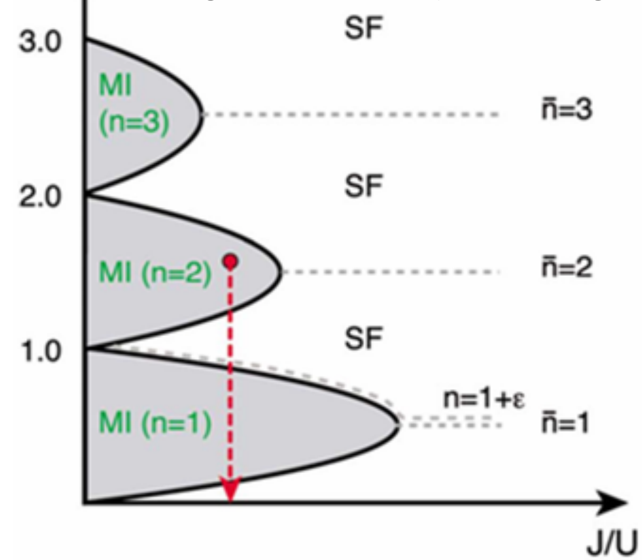


e.g., realization of the Bose-Hubbard model:

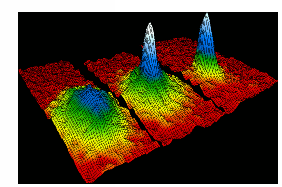
$$H = \sum_j [-\mu a_j^\dagger a_j + \frac{1}{2} U n_j(n_j - 1)] - J \sum_{\langle i,j \rangle} (a_j^\dagger a_i + \text{h.c.})$$

M.P.A. Fisher et al., PRB 40, 546 (1989)
Continuous quantum phase transition (second order) in 2D
Progress in methods (QMC, strong-coupling, …)

μ/U

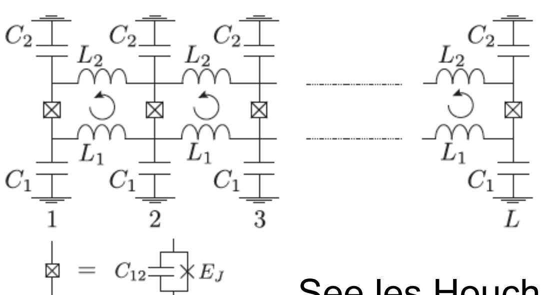


Nobel price 2001



Bose-Einstein condensate

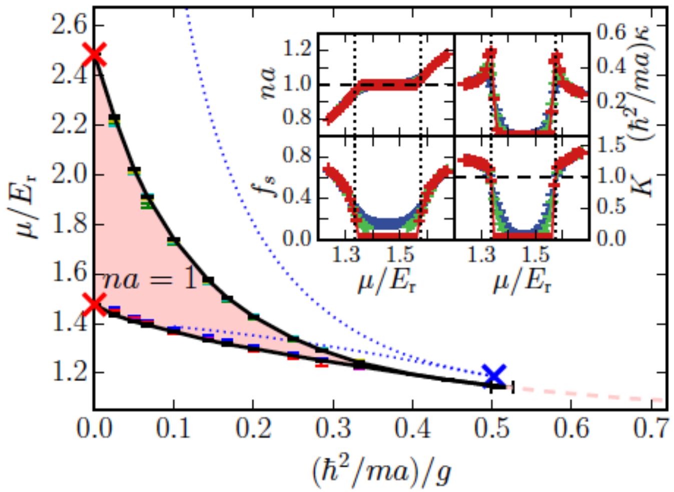
Also Josephson junction arrays



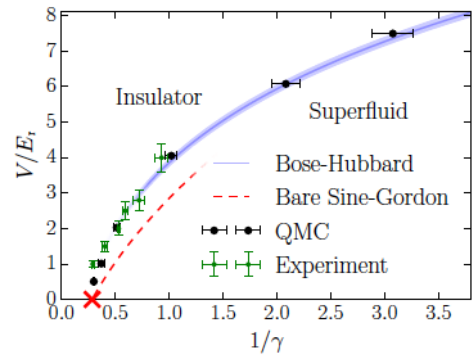
See les Houches lectures: D. Esteve & D. Vion; M. Devoret; J. Martinis & Kevin Osborne 2004

Progress simulations….

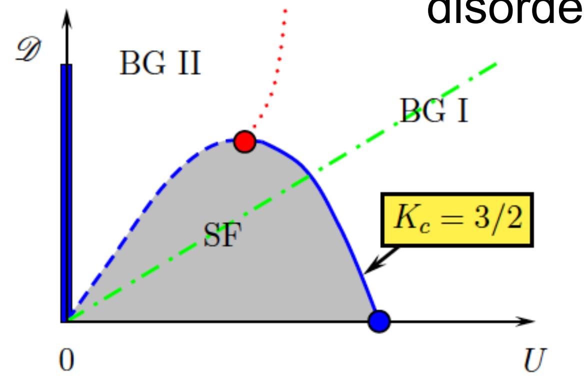
disorder ; Alain Aspect,
Vincent Josse, **Philippe Bouyer**
Juliette Billy…
Anderson localization



1D: interactions are included
in fluid Luttinger description
K is the Luttinger parameter
Haldane 1981 (K=1 Tonks limit)



disorder

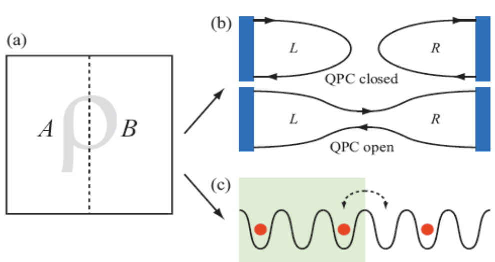


H.-J. Schulz & T. Giamarchi 1988
Z. Ristivojevic, A. Petkovic, (Toulouse)
T. Giamarchi, P. Le Doussal (ENS) 2012

2016
Experiment Modugno, Florence. Theory & numerics T. Giamarchi (Geneva), L. Sanchez Palencia (Institut Optique, LCFIO)

New probes: bi-partite entanglement
Entropies, entanglement spectrum
Linked with conformal field theory

Many-Body Localization: Monday sessi



See later
PhD H. Francis Song, Yale 2011

Kosterlitz-Thouless transition
2D analogue Villetaneuse (talk by L. Longchambon)

Kc=2 (Lieb-Liniger)

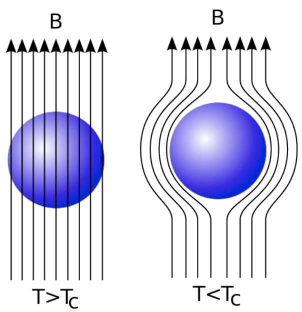
Year	Reference	Technique	Observable	Estimate
1991	Krauth [5]	(approximate) Bethe Ansatz		$1/(2\sqrt{3}) \simeq 0.2887$
1992	Batrouni *et al.* [6]	QMC	Superfluid stiffness	0.2100(100)
1994	Elesin *et al.* [7]	Exact Diagonalization	Gap	0.2750(50)
1996	Kashurnikov *et al.* [8]	QMC	Gap	0.3000(50)
1999	Elstner *et al.* [9]	Strong coupling	Gap	0.2600(100)
2000	Kühner *et al.* [10]	DMRG	Correlation function	0.2970(100)
2008	Zakrzewski *et al.* [11]	Time Evolving Block Decimation	Correlation function	0.2975(5)
2008	Laüchli *et al.* [12]	DMRG	von Neuman entropy	0.2980(50)
2008	Roux *et al.* [13]	DMRG	Gap	0.3030(90)
2011	Ejima *et al.* [14]	DMRG	Correlation function	0.3050(10)
2011	Danshita *et al.* [15]	Time Evolving Block Decimation	Excitation spectrum	0.3190(10)
2011	This work	DMRG	Bipartite Fluctuations	0.2989(2)

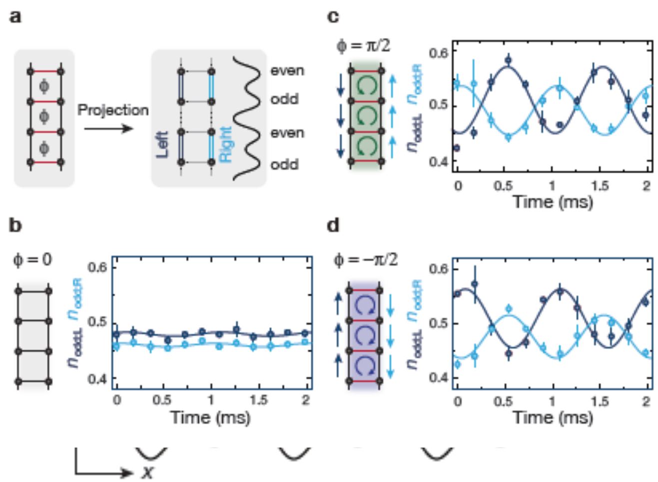
S. Rachel, **N. Laflorencie** (Toulouse), H. F. Song, and K. Le Hur 108, 116401 (2012)

Observation of the Meissner effect with ultracold atoms in bosonic ladders

M. Atala[1,2], M. Aidelsburger[1,2], M. Lohse[1,2], J. T. Barreiro[1,2], B. Paredes[3] & I. Bloch[1,2]

Nature Physics 2014

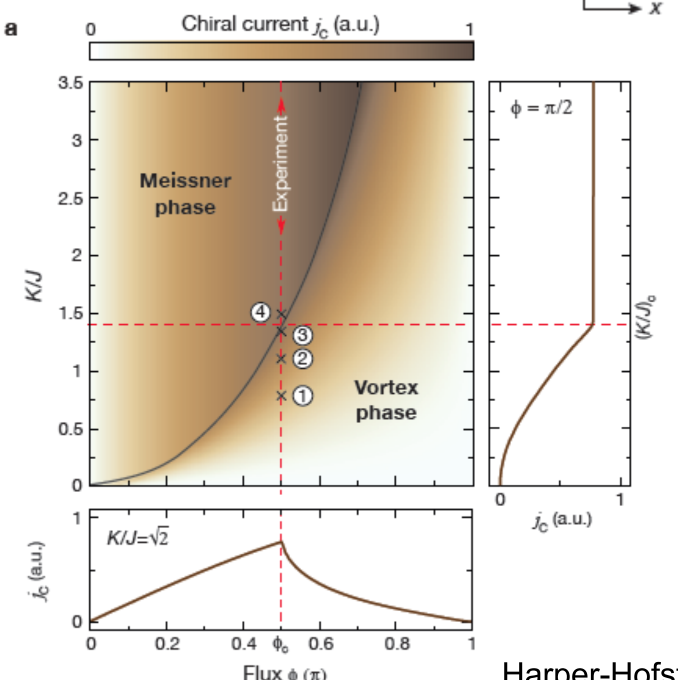


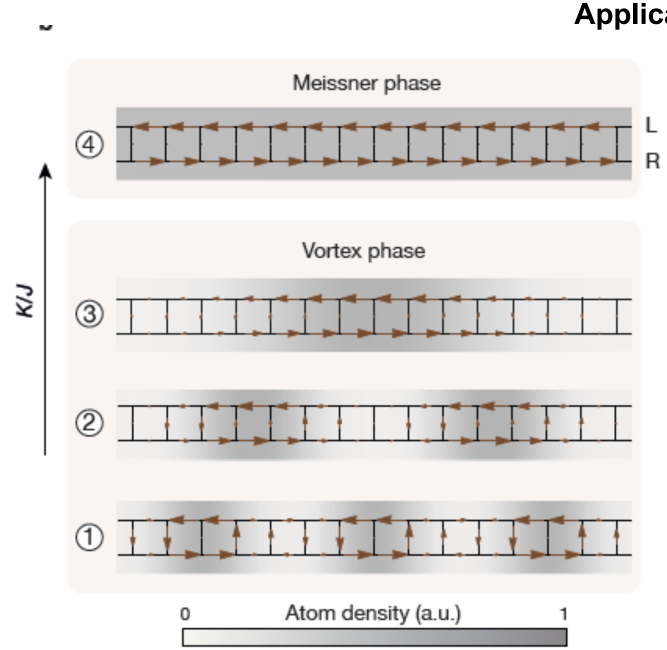


Theory by
E. Orignac & T. Giamarchi 2001

Meissner currents can survive in Mott insulating phases
A. Petrescu & KLH, PRL 2013

M. Piraud, F. Heidrich-Meisner, I. McCulloch, S. Gershner, T. Vekua, U. Schollwock, 2015
Application DMRG





Harper-Hofstadter model

consequence of Josephson effect

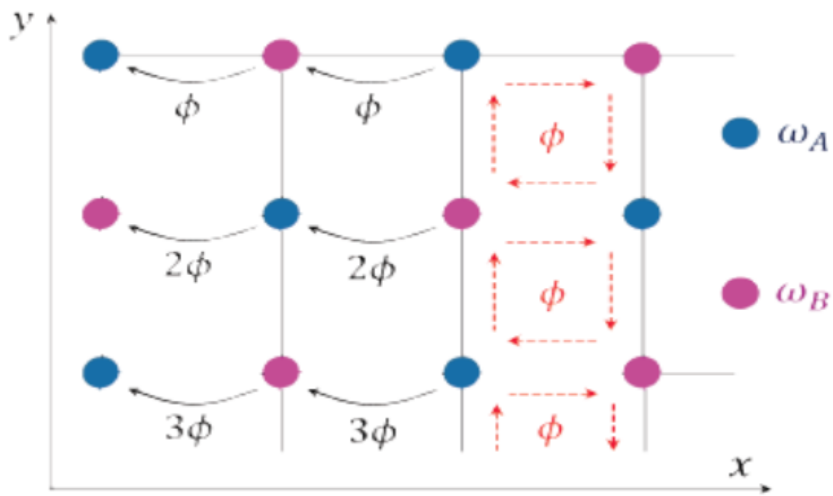
Phase coherence

Mesoscopic Effect

(C. Urbina)

Magnetic field for neutral particles

Cours Jean Dalibard collège de France



$$H = \omega_A \sum_i a_i^\dagger a_i + \omega_B \sum_i b_i^\dagger b_i + \sum_{\langle i;j\rangle} V \cos(\Omega t + \phi_{ij})(a_i^\dagger b_j + h.c).$$

Close to resonance

Analogy Two-level systems coupled to light

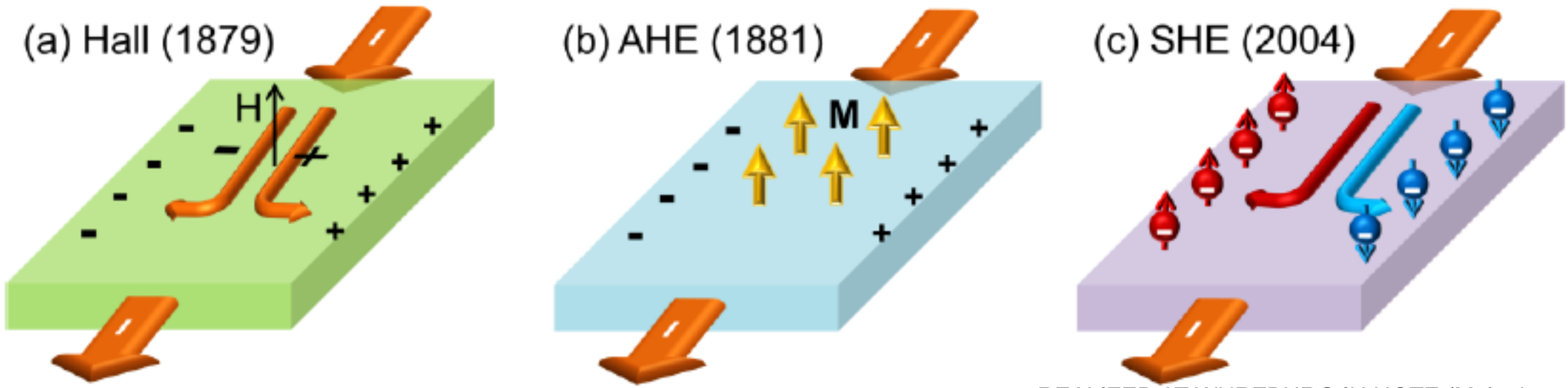
$$c_{i(j)} = e^{[i\omega_{A(B)} t c_{i(j)}^\dagger c_{i(j)}]} a_i(b_j)$$

$$H_{eff} = \sum_{\langle i;j\rangle} \frac{V}{2}(e^{-i\phi_{ij}} c_i^\dagger c_j + e^{i\phi_{ij}} c_j^\dagger c_i).$$

$$\int_i^j \mathbf{A}_{eff} \cdot d\mathbf{l} = \phi_{ij}$$

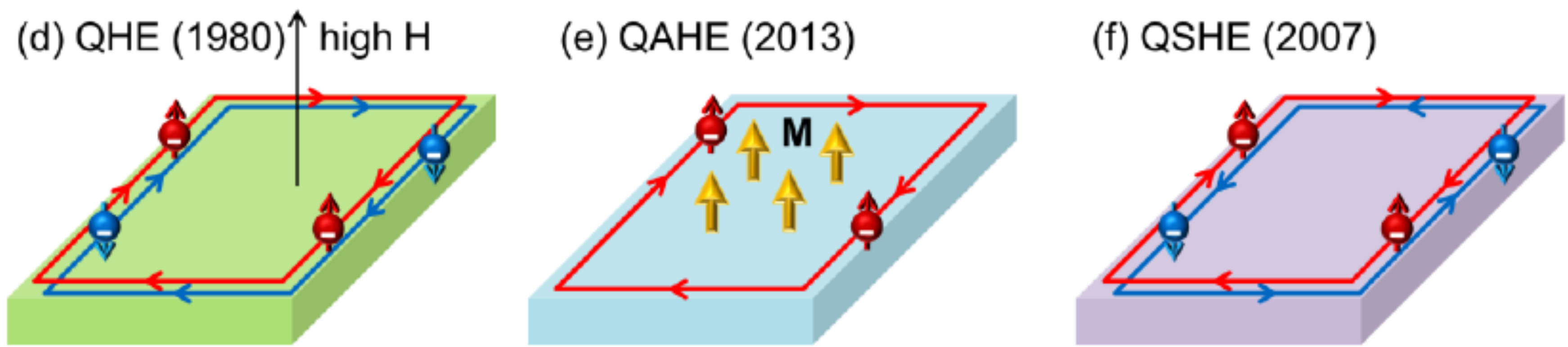
Lattice gauges theories

Topological states of matter: TRANSPORT AT THE EDGES



Von Klitzing, Dorda, Pepper;
fractional charges (Grenoble, CEA Saclay, Weizmann)

REALIZED AT WURZBURG IN HGTE (Molenkamp)
3D MERCURY ANALOGUES, PRINCETON (Hassan)



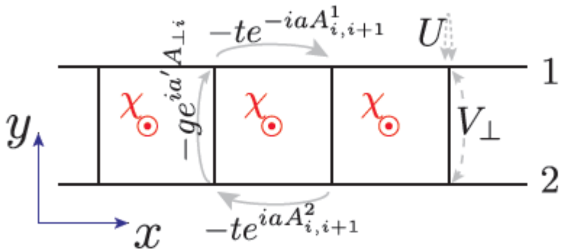
C. Z. Chang and M. Li, Topical Review, arXiv:1510.01754
From material science, to cold atoms and photons

Application spintronics: D. Pesin & A. H. Macdonald, Nature Materials 2012

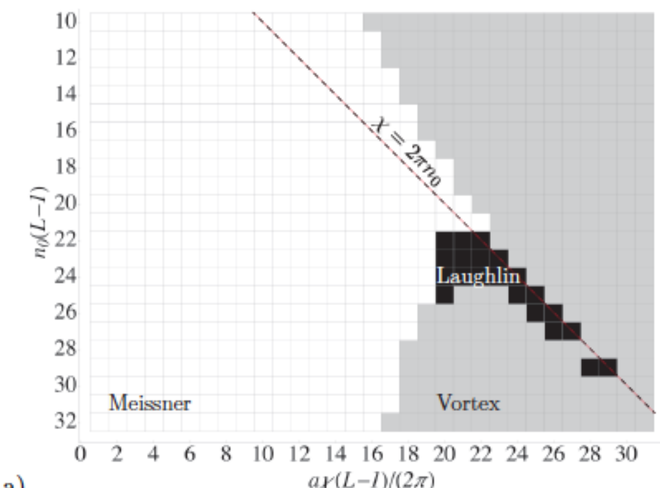
Quantum Hall physics: A meso Sim

C. L. Kane, Lubensky, Mukhopadyay; Teo & Kane, classification of quantum Hall phases in ladders
Observation for fermions cold atoms Florence, M. Mancini et al. Science 2015

A. Petrescu & KLH, 2013, 2015 (analytics)
A. Petrescu, M. Piraud, I. McCulloch, G. Roux, KLH



DMRG



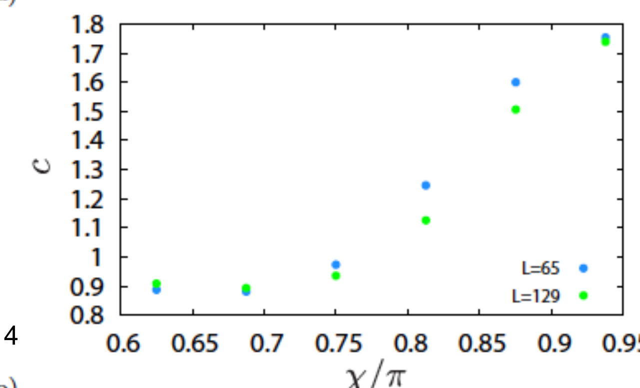
a)

Laughlin phase: chiral edge modes with fractional charges
Bipartite fluctuations confirm Laughlin phase theoretically and numerically

Measurement in quantum wires of fractional charges

H. Steinberg, G. Barak, A. Yacoby, L. N. Pfeiffer, K. W. West
B. Halperin and K. Le Hur, 2008

K.V. Pham, M. Gabay, P. Lederer, 2000
I. Safi & H. Schulz, 1995
Application topological insulators edge modes: Ion Garate & KLH, 2012

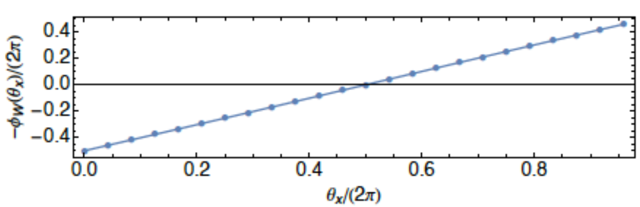


b)

$$\sigma_{xy} = \frac{1}{d}\frac{1}{2\pi}\int_0^{2\pi} d\theta_x \frac{\partial}{\partial\theta_x}\phi_W(\theta_x) = \frac{1}{d}\frac{1}{2\pi}\left[\phi_W(\theta_{x,N_x}) - \phi_W(\theta_{x,0})\right].$$

Torus geometry:
Thouless Laughlin pump

See also F. Grusdt – M. Honing 2014
L. Taddia et al 2016

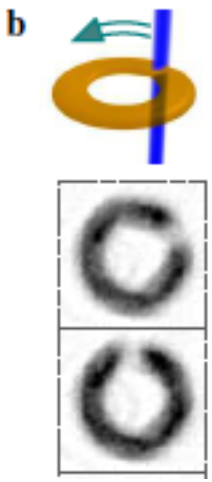


Ground state	Meissner	Vortex	Laughlin
c	1	2	1
N_V	1		>1

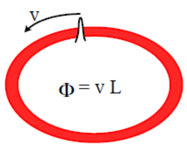
Artificial Gauge Fields & Protection

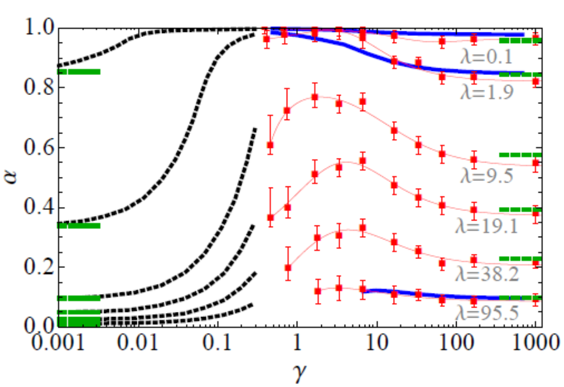
A. L. Fetter RMP 2009; J. Dalibard, F. Gerbier, G. Juzeliunas, P. Ohberg RMP 2011;
I. Bloch et al. Nature (2012); Juzeliunas & Spielman NJP (2012);...

Atomtronics



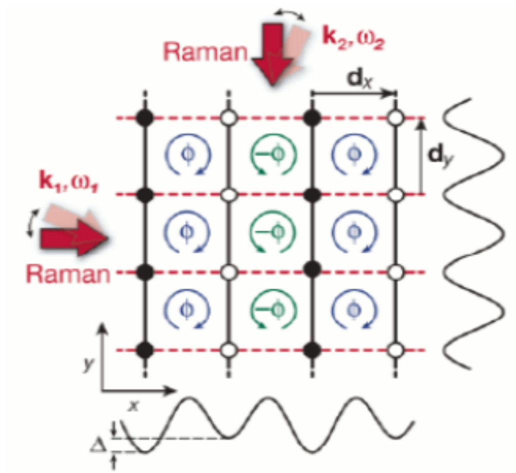
NIST Maryland
William D. Philipps
Gretchen K. Campbell
Nature 2014





Frank Hekking & Anna Minguzzi
(LPMMC Grenoble)
Expérience Villataneuse

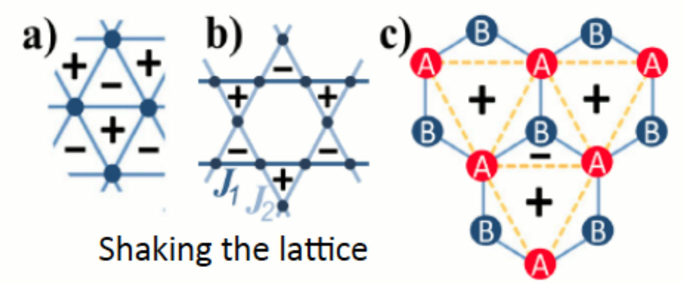
M. Aidelsburger et al. Muenich



Jaksch & Zoller 2003
Laser-assisted tunneling in optical superlattice PRL 107, 255301 (2011)

Floquet engineering: perturbations periodic in time to engineer topological phases

Hamburg (J. Simonet, C. Weitenberg, K. Sengstock),
MIT (W. Ketterle)

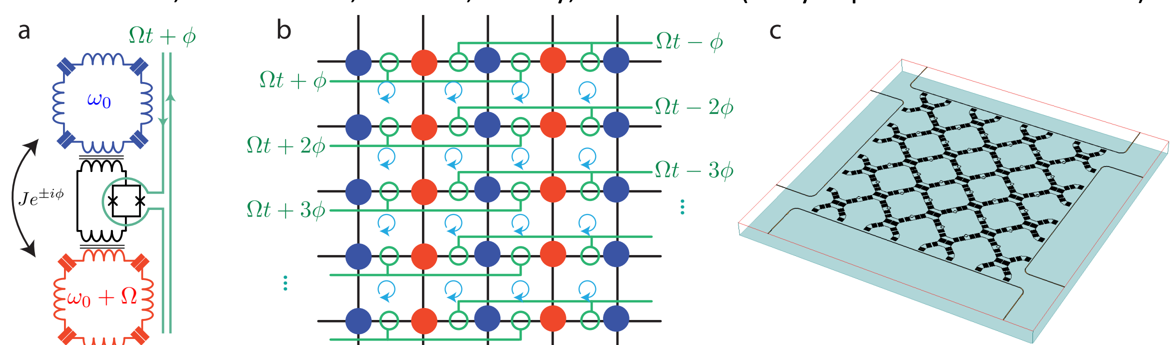


Shaking the lattice

...

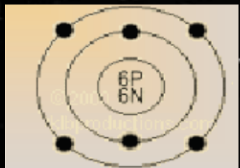
Floquet Topological Insulators:
Reviews: J. Cayssol, B. Dora, F. Simon, R. Moessner, arXiv:1211.5623
N. Goldman, J. Dalibard, PRX 2014
P. Delplace, D. Carpentier (Lyon)

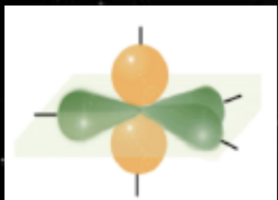
K. Fang et al. Nature Photonics 2012
On-going J. Gabelli, J. Esteve, M. Aprili LPS Orsay; progress Santa Barbara, P. Roushan et al 2016
Grenoble: O. Buisson, W. Guichard, N. Roch, L. Levy, V. Bouchiat (early experiment B. Pannetier)



complex and adaptive matter

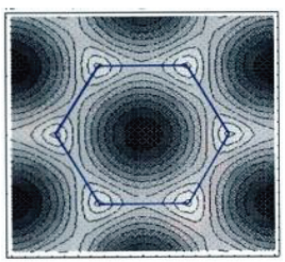
Also benzene



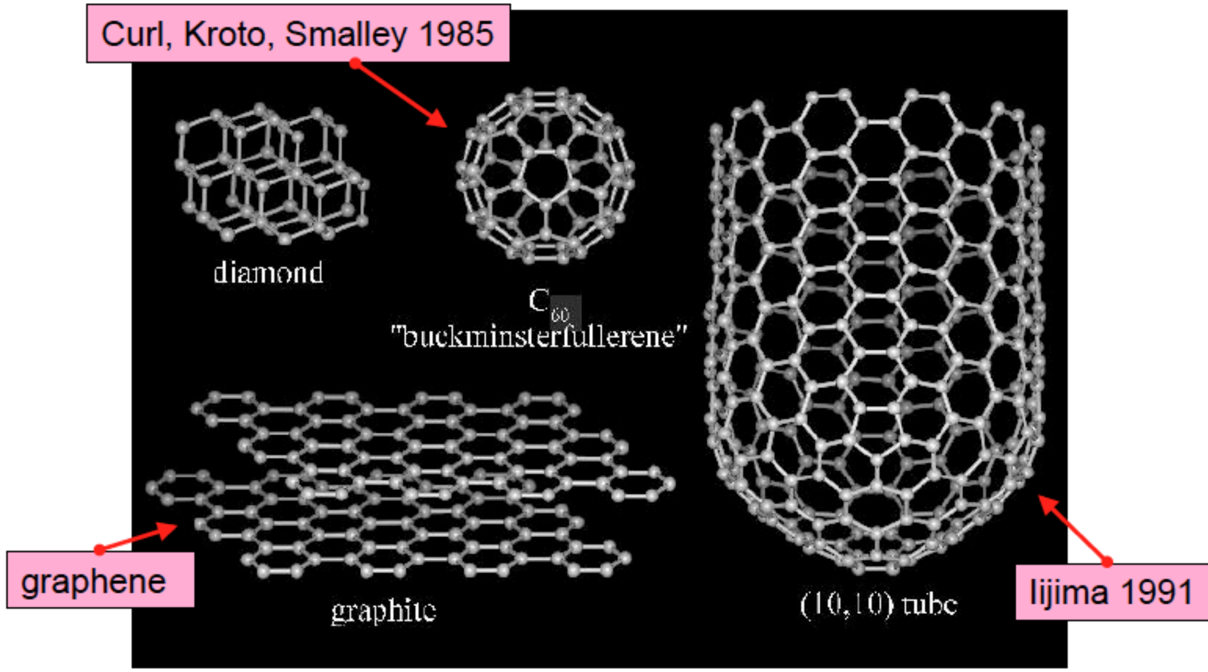


t~2.8eV

$a_{C\text{-}C}$~1.42Å



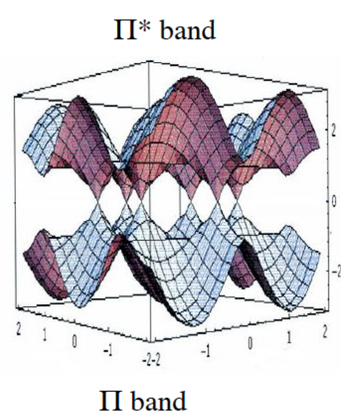
Wallace, 1947

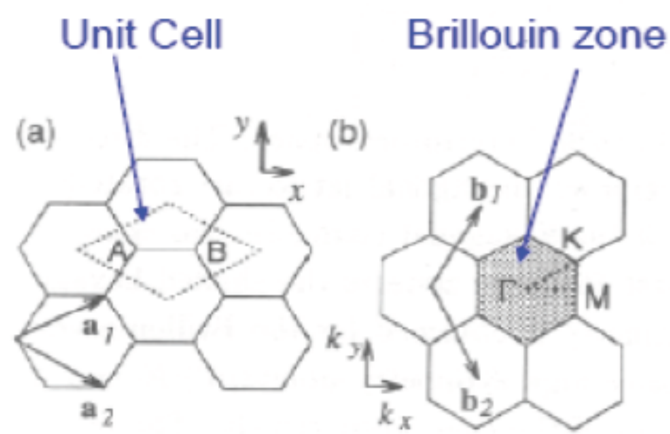


A. K. Geim & K. S. Novoselov, Nature Materials **6**, 183 (2007)

P. L. McEuen, Physics World **13**, 31 (2000) Philip Kim group

v_F ~3ta/2 ~ 10^6m/s = c/300





Analogy with spin-1/2:
2 sub-lattices A and B

Hamiltonian can be written
as 2 by 2 matrix, continuum limit
Dirac (2D Pauli matrix algebra)

$$-iv_F\boldsymbol{\sigma}\cdot\nabla\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

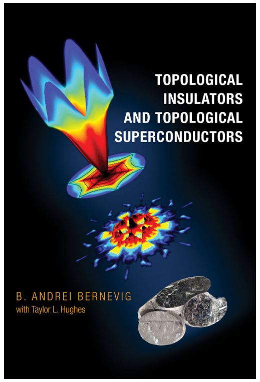
Spin-1/2 fermions: simulating spin-orbit coupling

Kane & Mele, PRL 95, 226801 (2005); Fu-Kane

see also: **Bernevig, Hughes, and Zhang, Science 314, 1757 (2006) + Molenkamp-experiments in three dimensions, experiments by M. Z. Hasan et al. (Bismuth materials)**

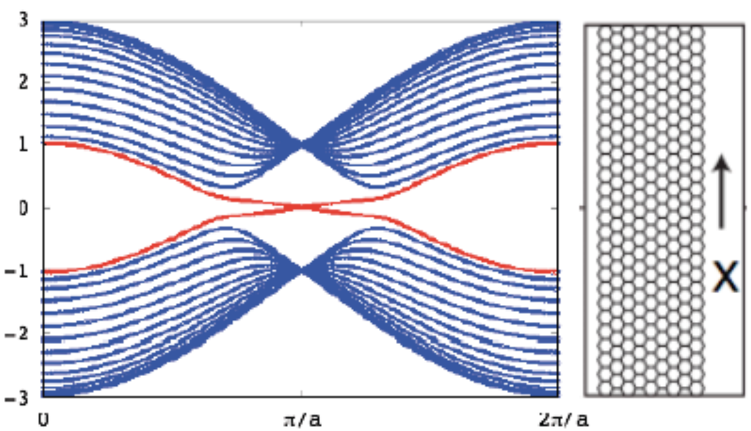
Also realizations in photon systems for example: M. Hafezi, S. Mittal, J. Fan, A. Migdall, J. Taylor (2013)
Mikael C. Rechtsman, Julia M. Zeuner, Yonatan Plotnik, Yaakov Lumer, Stefan Nolte, Mordechai Segev, Alexander Szameit (2013)

$$\mathcal{H} = -t \sum_{<ij>\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + i\lambda \sum_{\ll ij \gg} \sum_{\sigma\sigma'} \nu_{ij} \sigma^{z}_{\sigma\sigma'} c^{\dagger}_{i\sigma} c_{j\sigma'} \quad \nu_{ij} = \pm 1$$



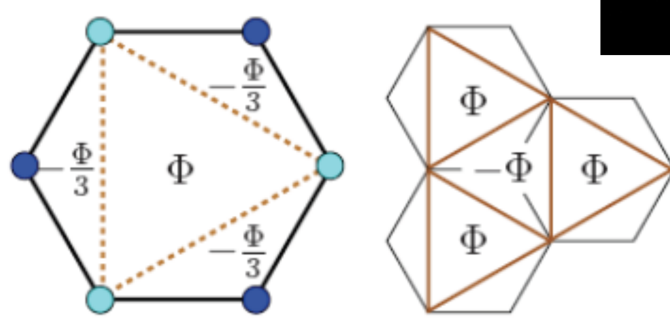
strip geometry:

QSH



edge states: Kramers's pair

$$\mathcal{H} \propto \Psi^{\dagger}_{k} \sigma^{z} \tau^{z} \Psi_{k}$$



Joel Moore, perspective Nature 2010

Half-filling

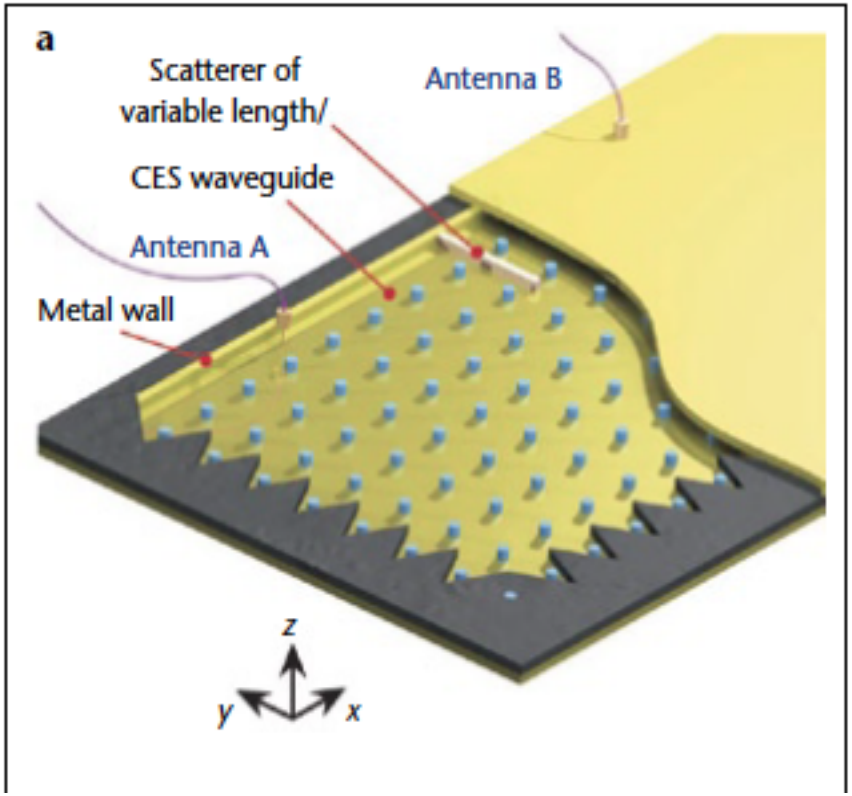
D. Carpentier, P. Delplace, K. Gavitski, M. Fruchart, N. Regnault
Gilles Montambaux, Jean-Noel Fuchs, Mark Goerbig, F. Piechon

Stable towards (moderate) interactions
S. Rachel and K. Le Hur, 2010
Interactions: see later

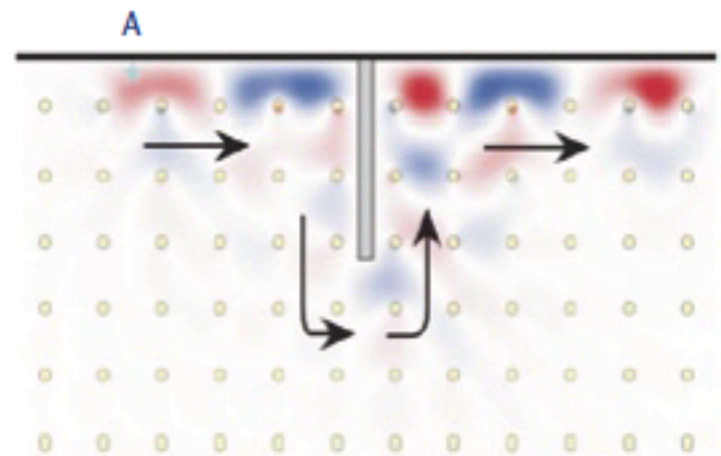
Also 3D analogues: Bismuth … Weyl fermions
QCD and flavor models

One-Way Road in a Photonic Crystal

Chiral edge states channel light waves in one direction, like electrons in the quantum Hall effect



Analogy STM: measure LDOS



(a) A model of the photonic crystal. The distance between the ferrite rods is 4 cm.

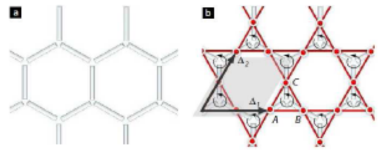
Realizations of AQHE in Photonic crystals: following Haldane & Raghu, PRL 2008 (Dirac points and Faraday effect opens a gap breaking time-reversal symmetry)

Experiment: M. Soljacic et al. Nature **461**, 772 (2009) – see review

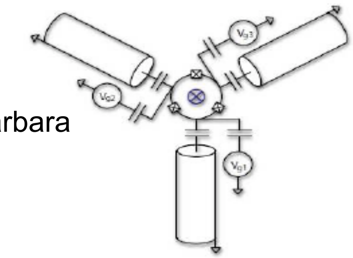
This group has also measured Weyl particles with light

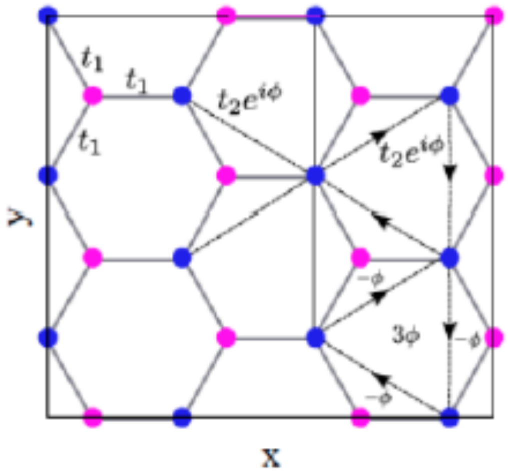
Quantum Anomalous Hall Effect

F. D. M. Haldane 1988
« single copy of Kane-mele »

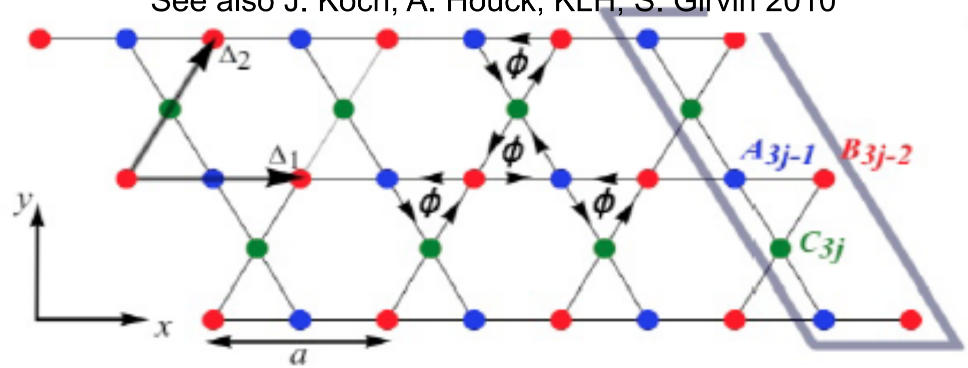


Circulator: idea by S. Girvin
Realized at Yale, Boulder, Santa Barbara
P. Roushan et al. 2016

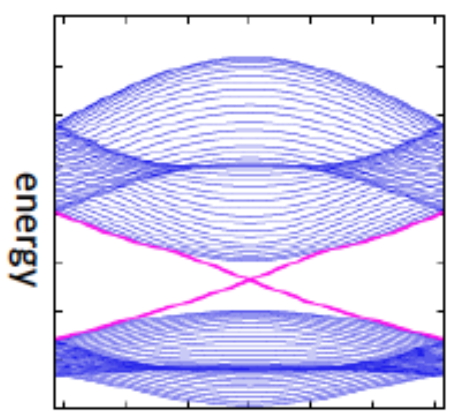


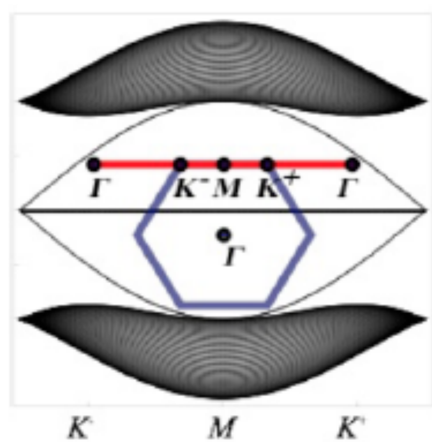


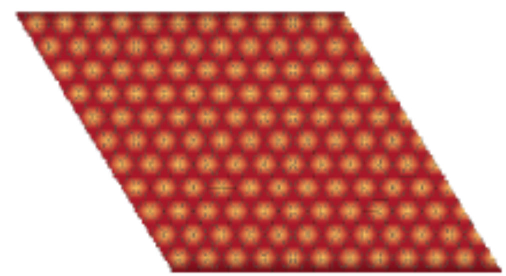
Kagome version:
A. Petrescu, A. A. Houck and KLH, 2012
See also J. Koch, A. Houck, KLH, S. Girvin 2010



Flat bands observed in polaritons (**A. Amo Friday talk**, J. Bloch)







Localization in
Hexagon rings

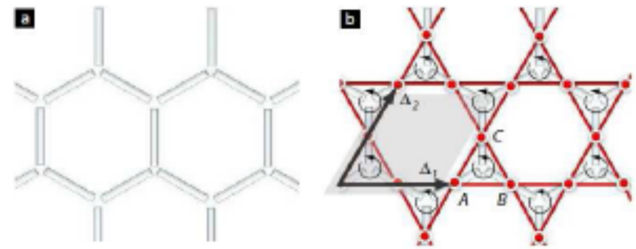
Graphene
+gap

Figure from KLH, Henriet, Petrescu, Roux, Schiro Académie of Sciences 2016

Kagome lattice: why interesting…

Flat band (search for ferromagnetism)

A. Mielke; H. Tasaki; E. Lieb



Exotic Topological Phases: fractional quantum Hall state

E. Tang, J.-W. Mei, X.-G. Wen, PRL 2011

N. Regnault and A. Bernevig, PRB 2012,…

Spin liquid search, classical degeneracies Fabrice Bert, Philippe Mendels Orsay

Experimentally relevant: 2D Materials (Orsay; Princeton;…)

Cold atoms: Berkeley; see D. Stamper-Kurn group, 2011

L. Balents, Nature 464, 199 (2010)

S. Yang, D. Huse and S. White, Science (2011)

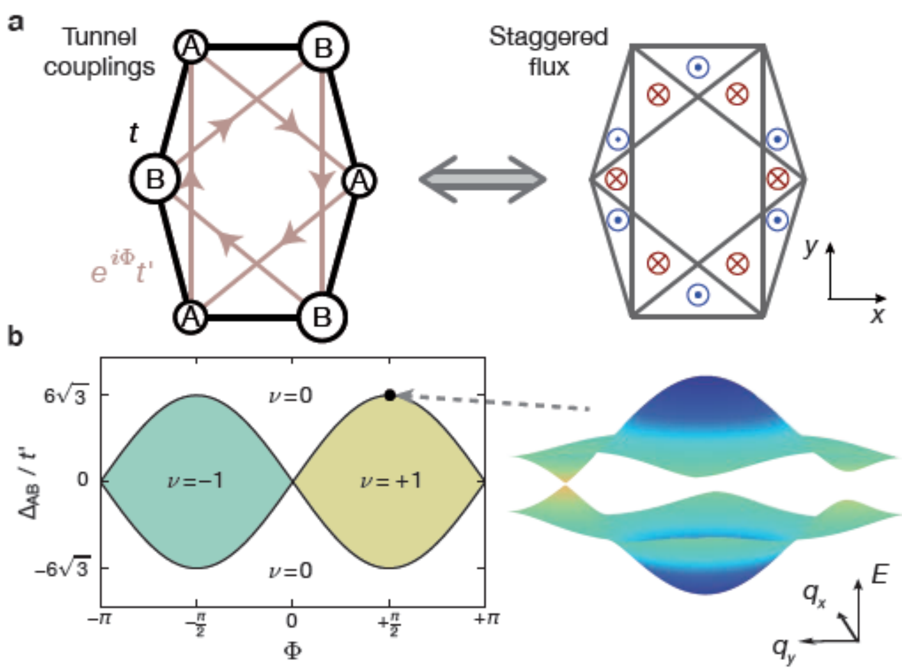
Work by Claire Lhuillier and co-authors,…

Philippe Lecheminant, G. Misguish, L. Messio, B. Bernu, Ph. Sindzingre

Simulation of Haldane model

Group of T. Esslinger, 2014
arXiv:1406.7874

- Ultra-cold atoms – (ETH) Jotzu et al. ; L. Tarruel (now Barcelona)
- Ultra-cold atoms: importance of Floquet-type point of view



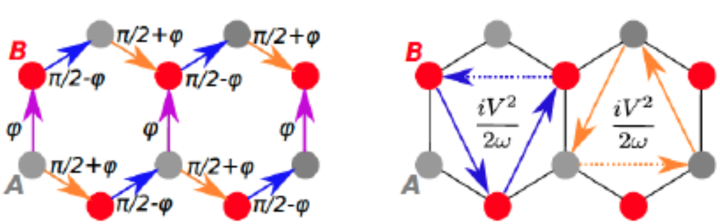
$$\hat{U}(T,t_0) = \zeta \exp\left(-i\int_{t_0}^{T+t_0} \hat{H}(t)dt\right) = \exp(-iT\hat{H}_{\mathrm{eff}})$$

<u>Modulation of optical lattice</u>

$$\mathbf{r}_{\mathrm{lat}} = -A\Big(\cos(\omega t)\mathbf{e}_x + \cos(\omega t-\varphi)\mathbf{e}_y\Big),$$

$$\boldsymbol{F}(t) = -m\ddot{\boldsymbol{r}}_{\mathrm{lat}}(t)$$

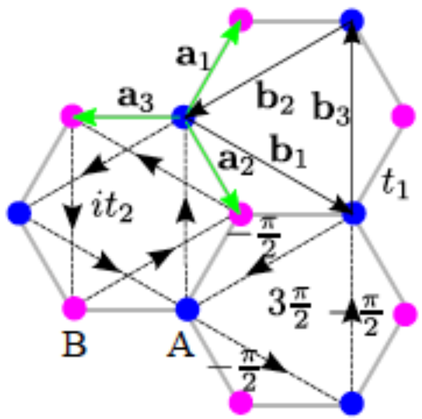
$$\hat{H}_{\mathrm{lat}}(t) = \sum_{\langle ij\rangle} t_{ij}\hat{c}_i^\dagger \hat{c}_j + \sum_i \left(\boldsymbol{F}(t)\cdot\boldsymbol{r}_i\right)\hat{c}_i^\dagger \hat{c}_i$$



Other protocole: K. Plekhanov, G. Roux, KLH
Recent paper arXiv 2016 (submitted)
Topology robust to deformation (anisotropy)

T : Hamiltonian periodic in time

Pauli matrices



$$\mathcal{H}_{\mathrm{H}}(\mathbf{k}) = -\mathbf{d}\,(\mathbf{k}) \cdot \hat{\sigma},$$

We have introduced the field $\psi(\mathbf{k}) = (b_A(\mathbf{k}), b_B(\mathbf{k}))^T$ of Fourier transforms of the annihilation operators for bosons on sublattices A and B. We wrote $\mathcal{H}_{\mathrm{H}}$ in the basis of Pauli matrices $\hat{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ in terms of

$$\mathbf{d}(\mathbf{k}) = \left(t_1 \sum_i \cos \mathbf{k}\,\mathbf{a_i}, t_1 \sum_i \sin \mathbf{k}\,\mathbf{a_i}, -2t_2 \sum_i \sin \mathbf{k}\,\mathbf{b_i} \right).$$

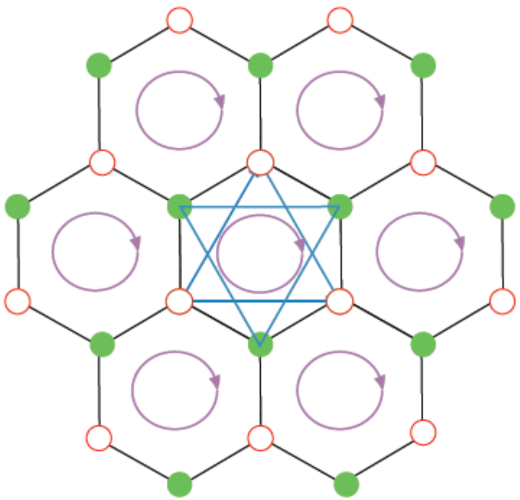
Realized in cold atoms:
Group of T. Esslinger, 2014
arXiv:1406.7874

The non-trivial topology of the Bloch bands translates to a nonzero winding number of the map $\hat{\mathbf{d}} = \mathbf{d}/|\mathbf{d}|$ from the torus (the first Brillouin zone) to the unit sphere.

$$\mathcal{C}_- = \frac{1}{4\pi} \int_{\mathrm{BZ}} d\mathbf{k}\, \hat{\mathbf{d}} \cdot \left(\partial_1 \hat{\mathbf{d}} \times \partial_2 \hat{\mathbf{d}} \right)$$

This is the Chern number of the lower Bloch band, and takes the value $\mathcal{C}_- = 1$. The formula for the upper band is obtained by replacing $\hat{\mathbf{d}}$ by $-\hat{\mathbf{d}}$, and leads to $\mathcal{C}_+ = -1$.

Berry curvature & 2-level systems



$$\Phi^{+}(\boldsymbol{k}) = \begin{pmatrix} u_1^{+}(\boldsymbol{k}) \\ u_2^{+}(\boldsymbol{k}) \end{pmatrix} = \begin{pmatrix} \cos\frac{\theta_{\boldsymbol{k}}}{2} e^{i\phi_{\boldsymbol{k}}} \\ \sin\frac{\theta_{\boldsymbol{k}}}{2} \end{pmatrix},$$

$$\Phi^{-}(\boldsymbol{k}) = \begin{pmatrix} u_1^{-}(\boldsymbol{k}) \\ u_2^{-}(\boldsymbol{k}) \end{pmatrix} = \begin{pmatrix} \sin\frac{\theta_{\boldsymbol{k}}}{2} e^{-i\phi_{\boldsymbol{k}}} \\ -\cos\frac{\theta_{\boldsymbol{k}}}{2} \end{pmatrix},$$

$$\mathcal{A}^{\alpha}(\boldsymbol{k}) = i \sum_{a=1}^{2} (u_a^{\alpha})^{*} \nabla_{\boldsymbol{k}} u_a^{\alpha},$$

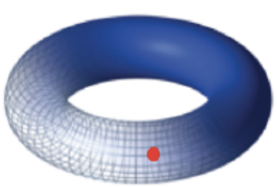
$$F_{xy}^{\alpha} = [\nabla_{\boldsymbol{k}} \wedge \mathcal{A}^{\alpha}(\boldsymbol{k})]_z = \partial_{k_x} A_y^{\alpha} - \partial_{k_y} A_x^{\alpha}.$$

$$C^{\alpha} = \frac{1}{2\pi} \int_{\mathrm{BZ}} dk\, F_{xy}^{\alpha}(\boldsymbol{k}),$$

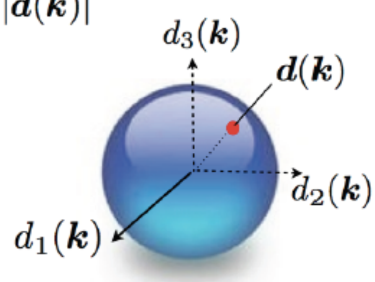
$$C^{-} = \frac{1}{4\pi} \int_{\mathrm{BZ}} dk \sin\theta_{\boldsymbol{k}} \left(\frac{\partial\theta_{\boldsymbol{k}}}{\partial k_x} \frac{\partial\phi_{\boldsymbol{k}}}{\partial k_y} - \frac{\partial\phi_{\boldsymbol{k}}}{\partial k_x} \frac{\partial\theta_{\boldsymbol{k}}}{\partial k_y} \right)$$

Brillouin zone

$\boldsymbol{k}$ → $\hat{\boldsymbol{d}}(\boldsymbol{k}) = \boldsymbol{d}(\boldsymbol{k})/|\boldsymbol{d}(\boldsymbol{k})|$



Bloch sphere



$$\hat{\boldsymbol{d}}(\boldsymbol{k}) = \frac{\boldsymbol{d}(\boldsymbol{k})}{|\boldsymbol{d}(\boldsymbol{k})|} = \begin{pmatrix} \cos\phi_{\boldsymbol{k}} \sin\theta_{\boldsymbol{k}} \\ \sin\phi_{\boldsymbol{k}} \sin\theta_{\boldsymbol{k}} \\ \cos\theta_{\boldsymbol{k}} \end{pmatrix},$$

Review by J. Cayssol académie des sciences 2013, arXiv:1310.0792

I. Carusotto & C. Ciuti
RMP 2013

Systems of interacting photons: Theory surveys

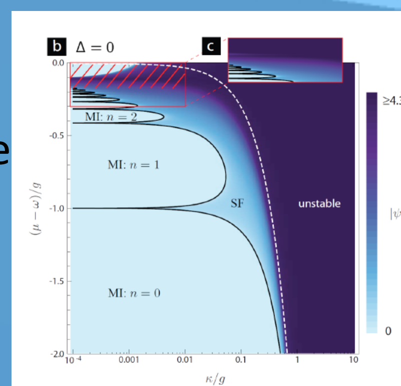
▶ M. Hartmann et al., Laser & Photonics Review 2, 527 (2008), new survey
A. Tomadin & R. Fazio, J. Opt. Soc. Am B 27, A130 (2010)
KLH, L. Henriet, A. Petrescu, K. Plekhanov, G. Roux, M. Schiro
académie des sciences 2016

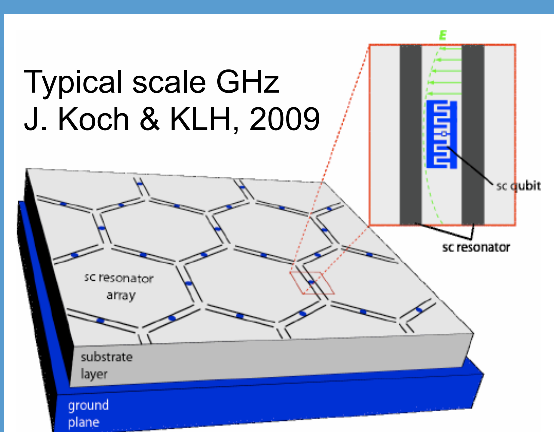
R. Fazio, G. Blatter,
S. Bose, Y. Yamamoto, P. Littlewood,
M. Plenio, J. Keeling, J. Taylor,...

A. Houck; H. Tureci; J. Koch
Nature Physics insight 2012

Greentree et al., Nat. Phys. **2**, 856 (2006)
Angelakis et al., PRA **76**, 031805 (2007)

* photonic band gap cavities
* arrays of silicon micro-cavitie
• fibre based cavities

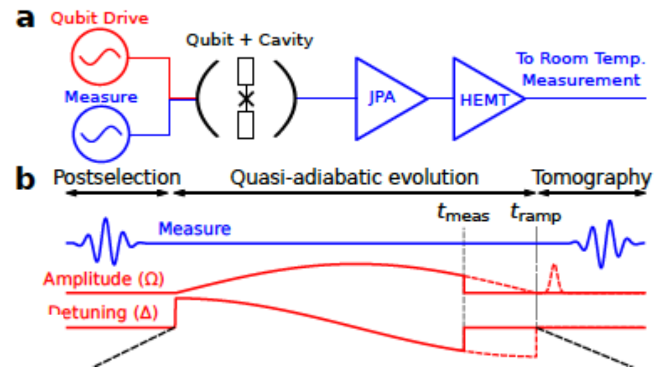




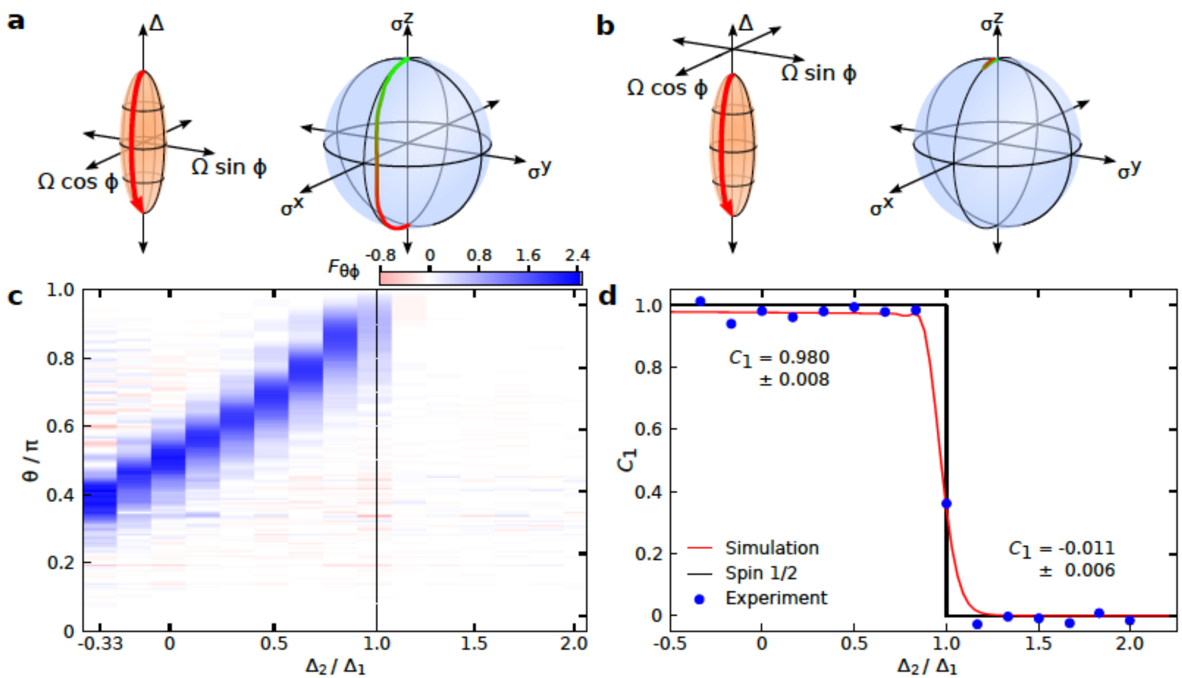
+ tunability
+ access to single lattice site
- must be treated as open system
+ interesting: transitions between
different steady states

spin-1/2 analogue: gate in curved space

Konrad Lehnert group (Colorado)
D. Schroer et al. PRL 2014
P. Roushan et al. Nature (John Martinis, Santa Barbara) 2014



$$H/\hbar = \frac{1}{2}\left[\Delta\, \sigma_z + \Omega\, \sigma_x \cos\phi + \Omega\, \sigma_y \sin\phi\right] \;,$$



$$\Delta = \Delta_1 \cos\theta + \Delta_2 \;,\;\; \Omega = \Omega_1 \sin\theta$$

ARP protocole

$$\theta(t) = \pi t / t_{\text{ramp}}$$

$$F_{\theta\phi} = \frac{\langle \partial_\phi H \rangle}{v_\theta} = \frac{\Omega_1 \sin\theta}{2 v_\theta} \langle \sigma^y \rangle,$$

$$C_1 = \int_0^\pi F_{\theta\phi} d\theta \,.$$

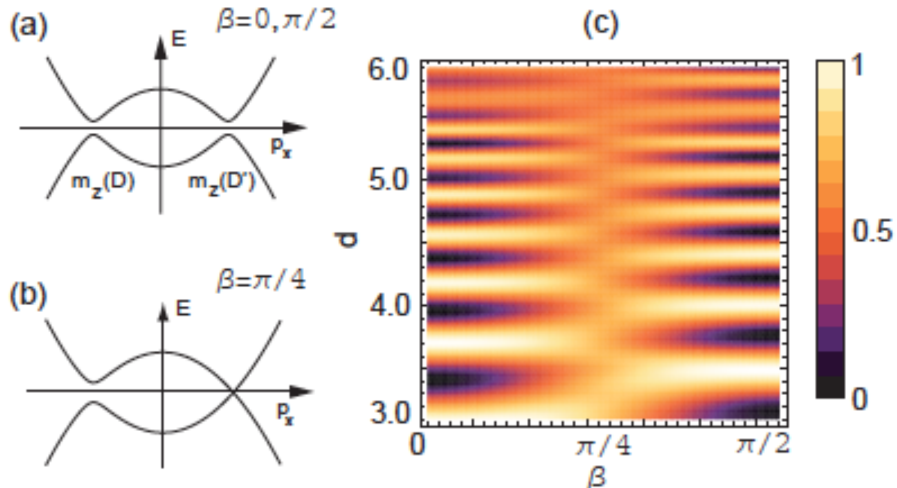
Tramp 1micro.s
Theory by Polkovnikov

Stochastic approach for non-equilibrium systems + dissipation effects (PhD thesis Loic Henriet (2016))
Dissipative quantum phase transition in curved space (in progress); L. Henriet, A. Sclocchi, P. Orth, KLH
See also P. P. Orth, A. Imambekov, KLH 2013 and L. Henriet, Z. Ristivojevic, P. P. Orth, KLH PRA 2014

Dynamical Sensing & bath

Graphene;
Stuckelberg

Lim Lih King
J.-N. Fuchs (LPTMC)
LPS Orsay
G. Montambaux
Mark Goerbig,
Frédéric Piechon



applications
Cold atoms:

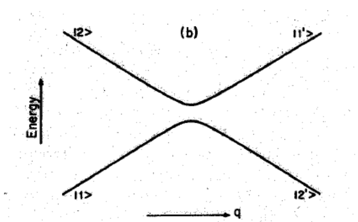
Muenich
Tracy Li et al.
Science 2016

Interferometer
Lucia Duca et al.
Science 2014

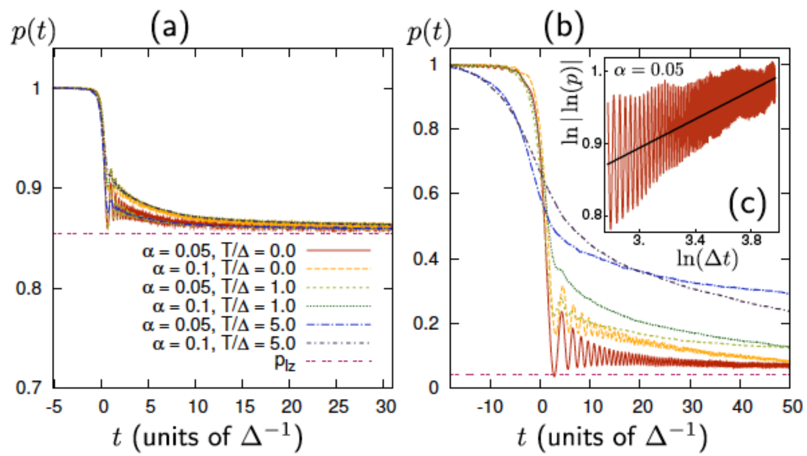
Cambridge
Z. Hadzibabic

Heidelberg
M. Oberthaler

Landau-Zener-Majorana (1932)



dissipation



Importance of
Fast and slow

Dissipation included following
A. J. Leggett et al. 1987
Bath of harmonic oscillators

FIG. 2. (Color online) (a) $p(t)$ for a fast sweep with $v/\Delta^2 = 10$, $\omega_c/\Delta = 200$, $\alpha = \{0.05, 0.1\}$ and $T/\Delta = \{0, 1, 5\}$ (here, $\hbar = k_B = 1$). We choose $m_{\max} = 4000$, $N = 4 \cdot 10^6$. (b) Slow sweep with $v/\Delta^2 = 0.5$. Other parameters as in (a). (c) Fit of universal decay of $p[\epsilon(t)]$ using Eq. (12) with $\alpha = 0.05$ and single fit parameter $C = 0.59$.

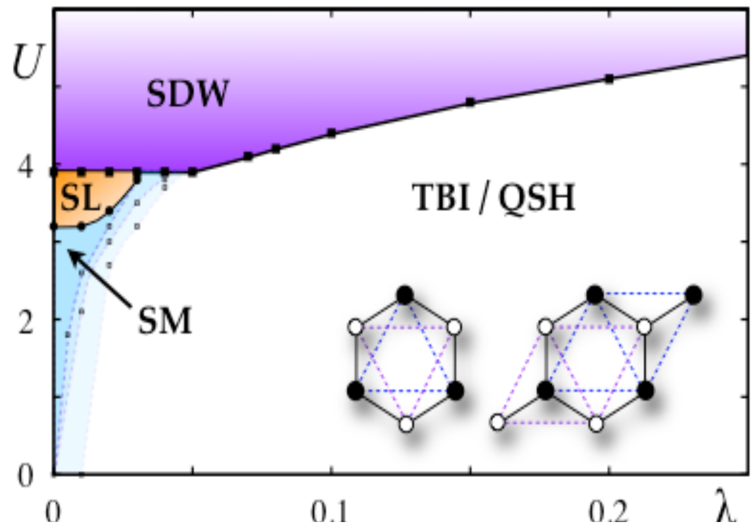
Peter Orth, Adilet Imambekov and Karyn Le Hur, 2010; see also previous works by Adilet in Russia and Harvard with Eugene Demler
Loic Henriet & KLH, PRB 2016 applications spin chains with dissipation, synchronization, quantum phase transition & Kibble Zurek
R. Whitney, M. Clusel, T. Ziman 2011 (Grenoble); see also Camille Aron

Mott frontiers in "Kane-Mele-Hubbard"

Wei Wu,
Stephan Rachel,
Wu-Ming Liu
and KLH, PRB 2012

CDMFT

A. Georges, G. Kotliar
O. Parcollet, …

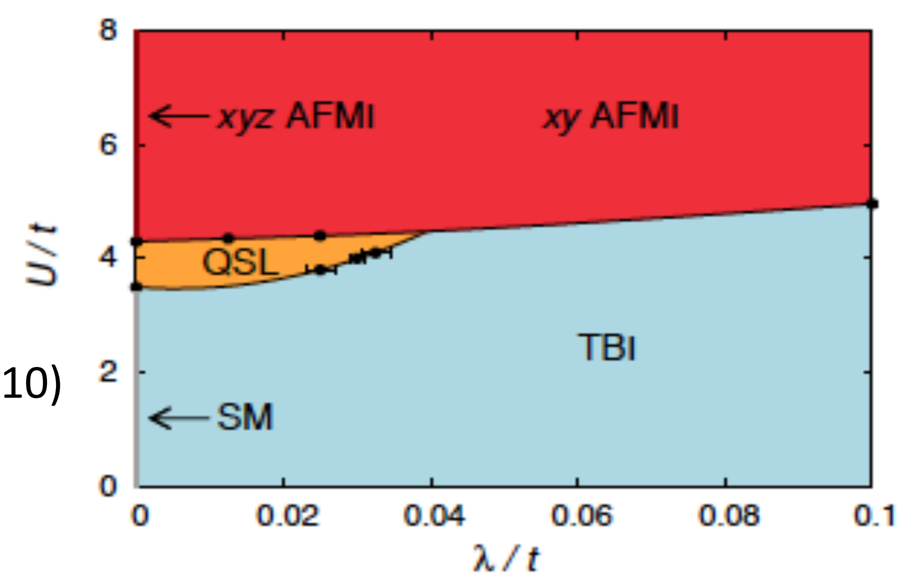


Analytics:
Young, Lee, Kallin 2008
S. Rachel & KLH, 2010
Griset & C. Xu, 2011
D.-H. Lee, 2011 …

Generalization Non-Abelian flavor model
Collaboration with Frankfurt
Group of W. Hofstetter, D. Cocks et al
PRL 2012, review 2013

QMC

Z.Y. Meng et al.
Nature **464**, 847 (2010)



M. Hohenadler et al.
arXiv:1111.3949

Phys. Rev. Lett. **106**,
100403 (2011)

Reviews: Hohenadler & Assaad, 2013
Maciejko-Fiete, 2015

Absence of spin liquid for Hubbard (QSL and SL Needs frustration – see later):
S. Sorella et al. Scientific Reports 2012; S. R. Hassan & D. Senechal PRL 2013

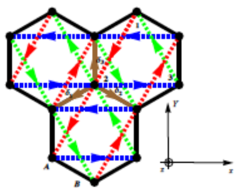
Connection to reality (importance of ab-initio): iridates

- Na_2IrO_3: anisotropic spin-orbit coupling

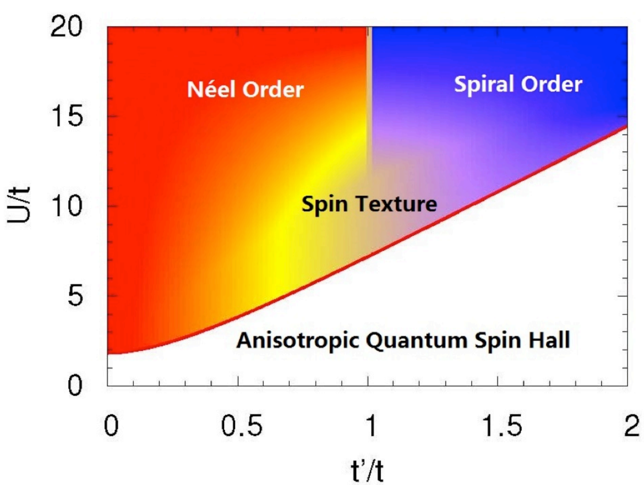
(thin films: arXiv:1303:5245, M. Jenderka et al)

Shitade et al. PRL **102** 256402 (2009); G. Jackeli & G. Khaliullin, PRL 102, 017205 (2009)

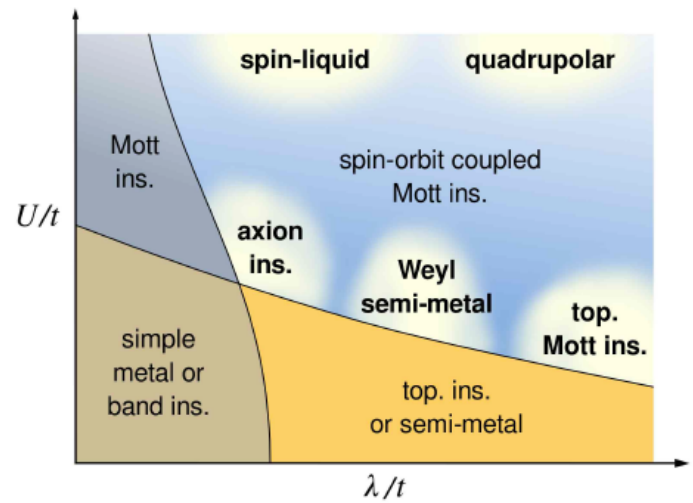
07



gauge U(1) and Z2 theories: splitting an electron in charge & spin
S. Florens & A. Georges; applications of Polyakov ideas for gauge theories



α Lithium Iridates and Spiral order R. Coldea



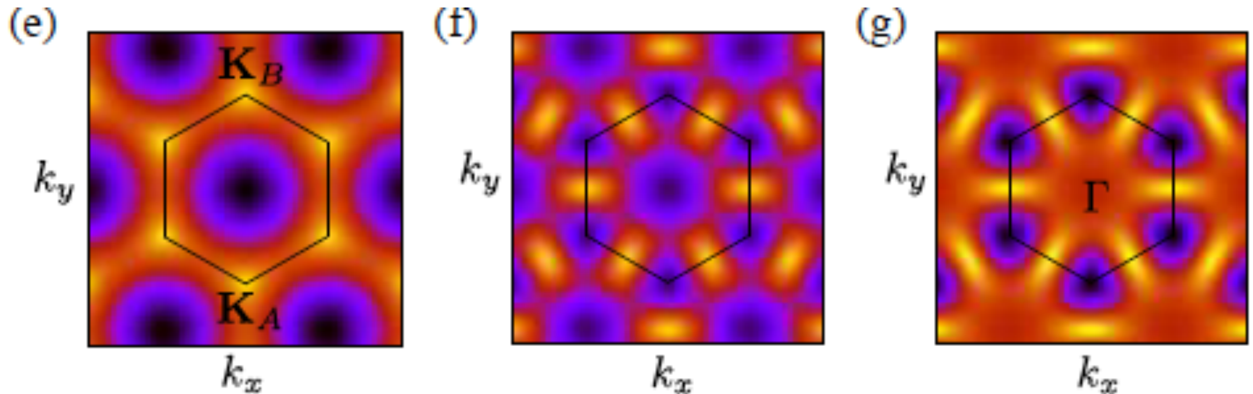
Tianhan Liu, Benoit Doucot, Karyn Le Hur, PRB 2013
A. Ruegg and G. Fiete, PRL 2012
J. Reuther, R. Thomale & S. Rachel, PRB 2012
M. Kargarian, A. Langari, G. Fiete PRB 2012

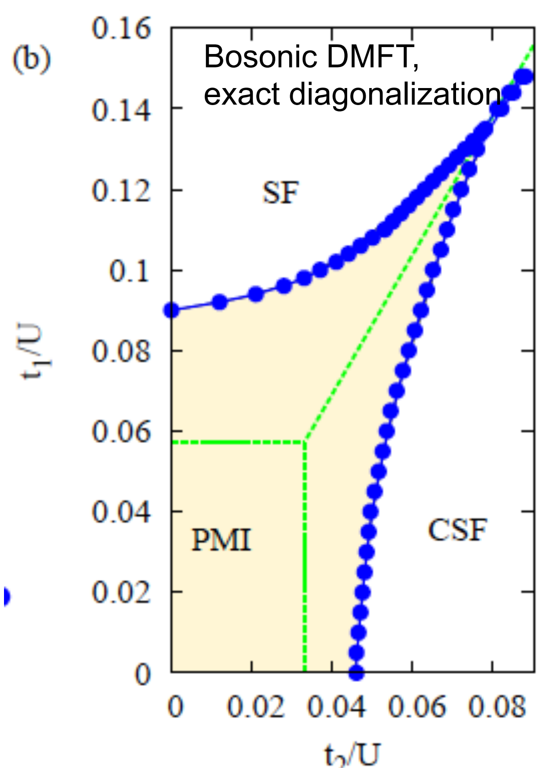
D. Pesin & L. Balents, Nature Phys. 2010
Krempa, Choy, Y.-B. Kim & L. Balents

Spin “Ice physics” at large interactions
Lucile Savary, Ludovic Jaubert, Peter Holdsworth..

Exotic bosonic phases: Haldane model

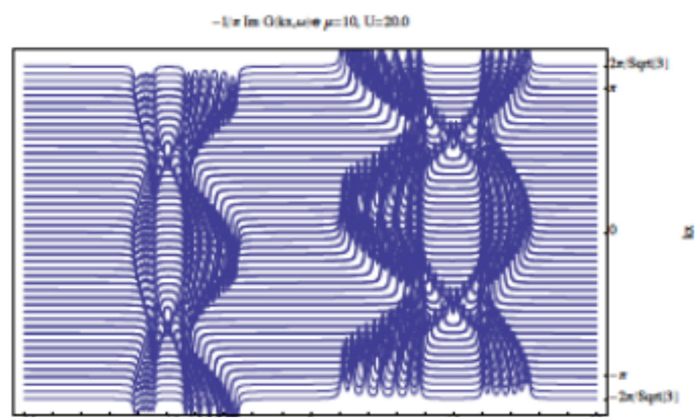
I. Vidanovic Vasic, A. Petrescu, K. Le Hur, W. Hofstetter, arXiv:1408.1411 (PRB)
K. Plekhanov, G. Roux, KLH recent paper arXiv August 2016 (submitted)





Bosonic DMFT,
exact diagonalization

Strong coupling cluster expansion in Mott



FFLO analogue in Heisenberg-Kitaev doped models
Tianhan Liu, Cécile Repellin,
Benoît Douçot, Nicolas Regnault
Karyn Le Hur, submitted to PRL

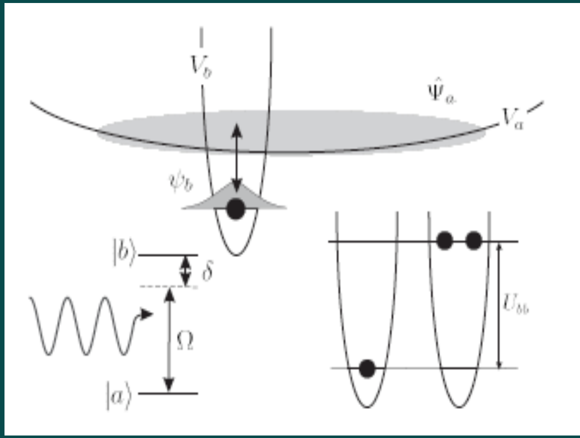
Kitaev-Heisenberg models

Non-trivial chiral
Edge excitations
In Mott phase

Similar models on <u>square</u> lattice:
L. K. Lim, C. M. Smith and A. Hemmerich,
Phys. Rev. Lett. 100, 130402 (2008) and PRA 2010

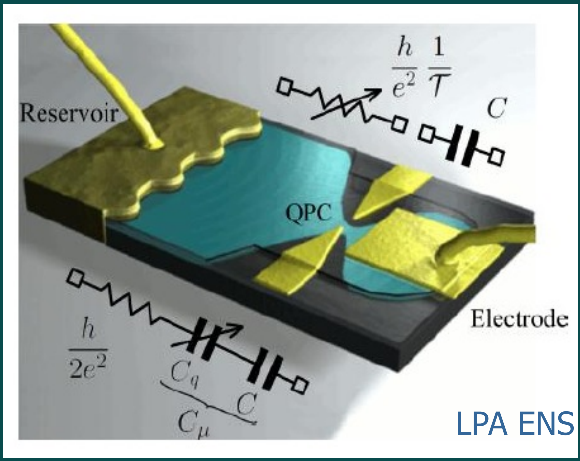
COLD-ATOMIC Quantum IMPURITIES

A. Recati et al. PRL **94**, 040404 (2005)
Peter Orth, Ivan Stanic, Karyn Le Hur, PRA (2008)
Single Atom: Ph. Grangier et al. Science **309**, 454 (2005)
A. Fuhrmanek, Y. R. P. Sortais, P. Grangier, A. Browaeys
Phys. Rev. A 82, 023623 (2010).
D. Porras, F. Marquardt, J. von Delft, J. I. Cirac (2007),...
M. Knap et al. Phys. Rev. X 2, 041020 (2012)
M. Knap, D. A. Abanin, E. Demler, PRL 111, 265302 (2013)
J. Bauer, C. Salomon, E. Demler PRL 111, 215304 (2013)



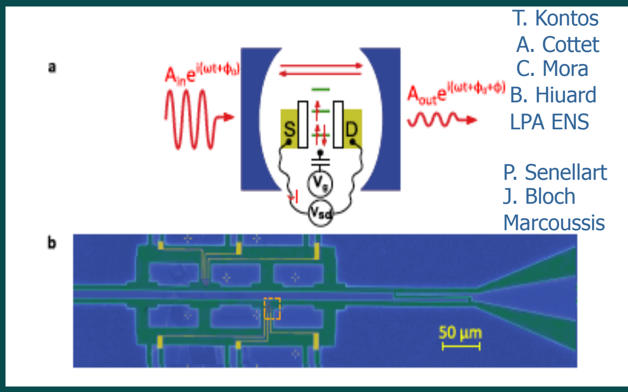
RC circuits

M. Buettiker, H. Thomas, and A. Pretre, Phys. Lett. A 180, 364 - 369,(1993)
J. Gabelli et al., Science **313**, 499 (2006); G. Feve et al. 2007 (LPA ENS)
J. Gabelli et al. Rep. Progress 2012
C. Mora and K. Le Hur, Nature Phys. 6, 697 (2010)
Y. Hamamoto, et al. Phys. Rev. B **81**, (2010) 153305
Y. Etzioni, B. Horovitz, P. Le Doussal, PRL **106**, 166803 (2011)
M. Filippone, KLH, C. Mora; P. Dutt, T. Schmidt, C. Mora, KLH, 2013,…

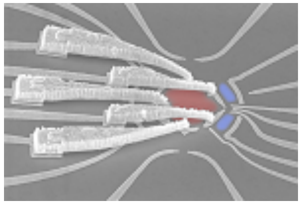


Hybrid Photon-Nano Systems, Impurities with Photons

K. Le Hur, Phys. Rev. B 85, 140506(R) (2012)
A. Leclair, F. Lesage, S. Lukyanov and H. Saleur (1997)
M. Goldstein, M. H. Devoret, M. Houzet and L. I. Glazman, 2012
Grenoble: S. Florens, H. Baranger, N. Roch and collaborators
M. Hofheinz et al. arXiv:1102.0131
M. Delbecq et al. PRL 107, 256804 (2011)
M. Schiro & KLH, arXiv 1310.8070, PRB 2014 …

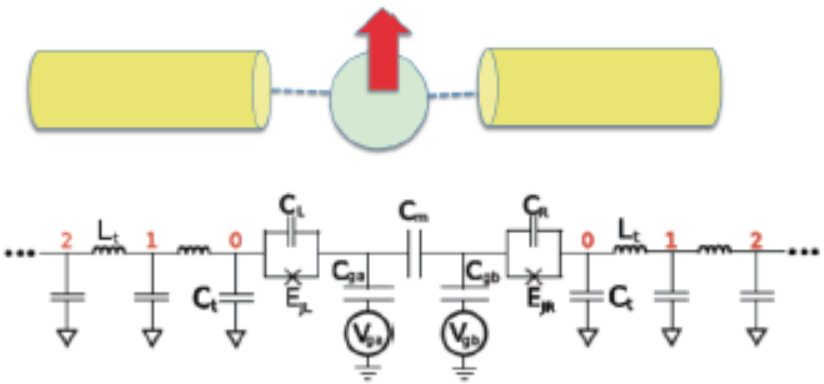


One way motion of light with Kondo « correlations »

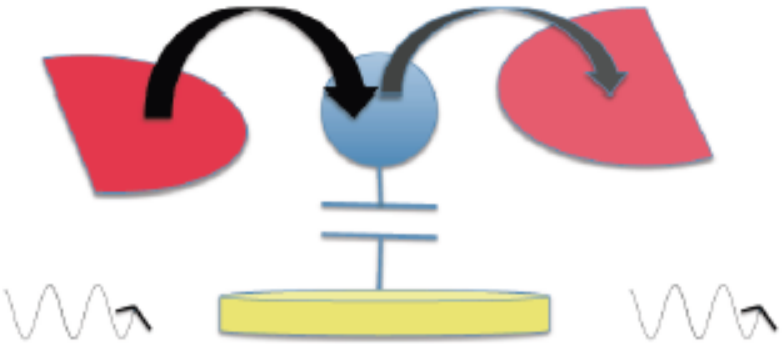


D. Goldhaber-Gordon

Kondo physics and Heavy fermions
Book by Alex Cyril Hewson, Cambridge University Press
Ph. Nozières 1974, Nobel Prize Kenneth Wilson



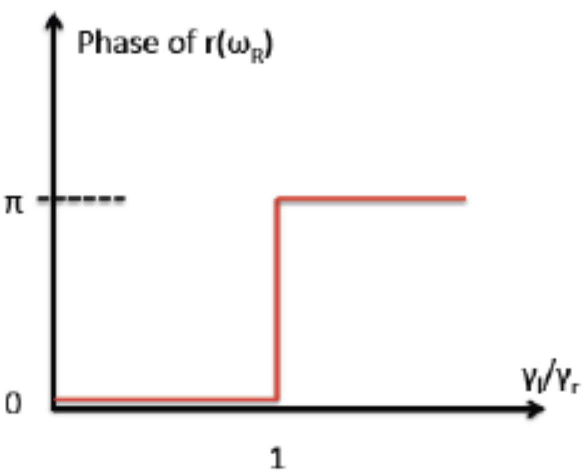
K. Le Hur 2012
M. Goldstein, M. Devoret, M. Houzet, L. Glazman
2013

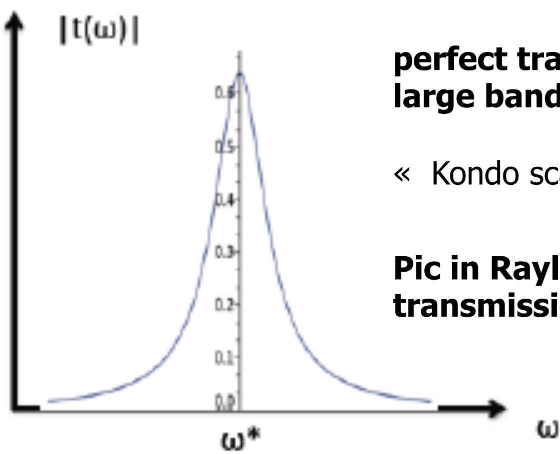


M. Schiro & KLH, 2014

analogy Friedel sum rule for electrons in DC transport
L. Kouwenhoven & L. Glazman, physics world 2001

« cut » waveguide





perfect transmission
large band-width

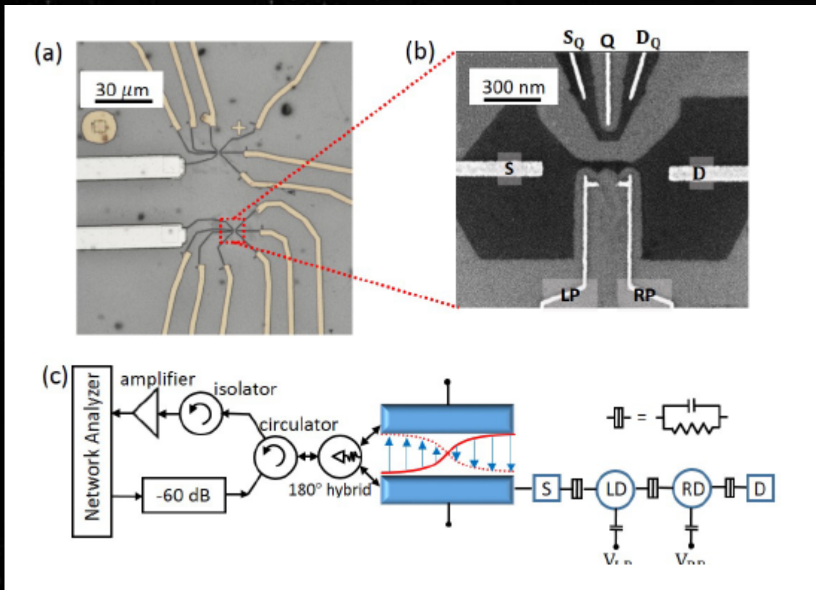
« Kondo scale »

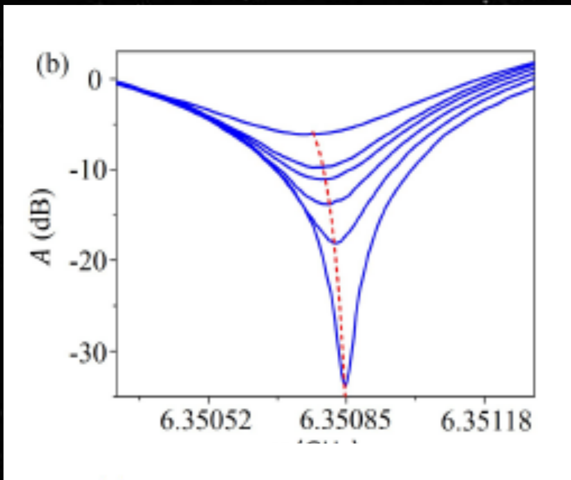
Pic in Rayleigh
transmission

Experiment N. Roch Grenoble
Also Garching, Waterloo …

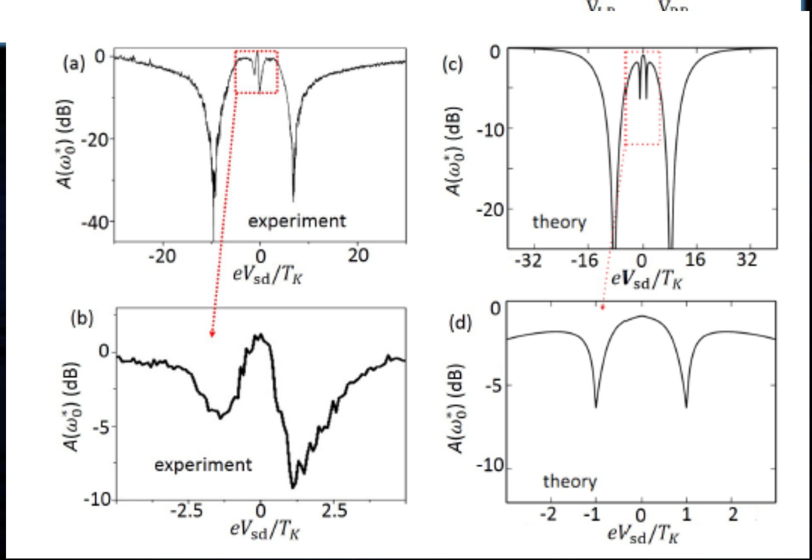
KLH, L. Henriet, A. Petrescu, K. Plekhanov, G. Roux, M. Schiro Académie of Sciences 2016 and Arxiv 2015

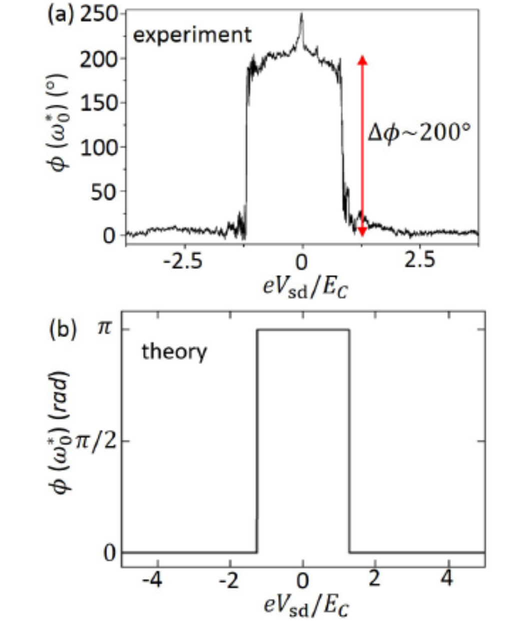
Explore Hybrid Kondo System in graphene





submitted





Phase of
Π observed

T=30mK

2 cooling
procedures

T_K is a new energy scale: the Kondo energy scale (amplitude & DC transport favor SU(4) Kondo physics)

Guang-Wei Deng†,[1,2] Loïc Henriet†,[3] Da Wei,[1,2] Shu-Xiao Li,[1,2] Hai-Ou Li,[1,2] Gang Cao,[1,2] Ming Xiao,[1,2] Guang-Can Guo,[1,2] Marco Schiró,[4] Karyn Le Hur,[3] and Guo-Ping Guo[1,2,*]

XXI, Detect the Majorana in topological SCs: L. Kouwenhoven Delft, 2012

See F. Wilczek, Majorana returns, Nat. Physics 2009

They appear accidently in spin chains: via Jordan-Wigner transformation (1928)
Generalization of Dirac algebra for harmonic oscillators 1925 (group theory)
high energy physics (neutrino)

Particle and its own antiparticle

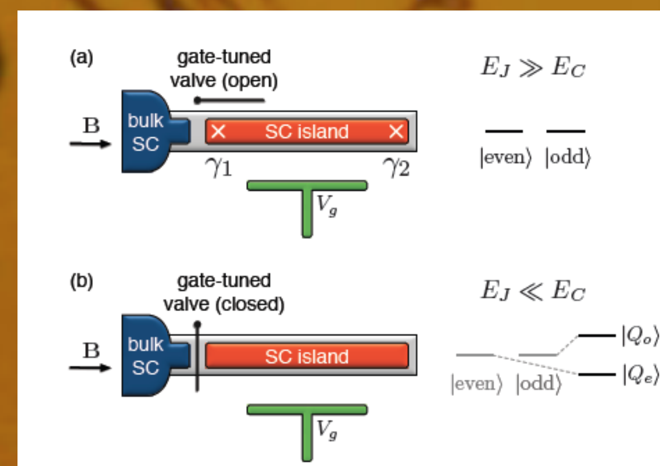
γ

<u>Proposals:</u>

Alexei Kitaev
Nick Read
Leonid Levitov
Hans Mooij
Liang Fu
Charles Kane
Carlo Beenakker
Matthew Fisher
Bert Halperin
Pascal Simon (talk yesterday)

Challenge taking into account that the Man who discovered the Majorana disappeared 1938

Progress in nano-engineering to reveal the Majoranas (see Bieri Cooper, Egger, Altand, C. Mora, E. Eriksson, J. Meyer…)

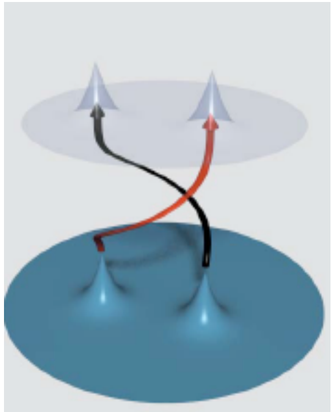


D. Aaasen et al. arXiv 2015
Charles Marcus group 2016

Also Ali Yazdani, Princeton

Note: recent work on 2 coupled topological SC chains
Loic Herviou, Christophe Mora, KLH 2016

The Majorana fermion states must be occupied in pairs, since the entire physical system can only occupy real fermion states.
So only combinations of Majorana fermions can be occupied



This occupied state is inherently delocalized – it has weight in two spatially separated vortex cores.

N. Read & D. Green
N. Read & G. Moore
D. Ivanov, Volovik

$$\hat{c}^{\dagger}|\Psi_0\rangle = (\hat{\gamma}_1 + i\hat{\gamma}_2)\,|\Psi_0\rangle$$

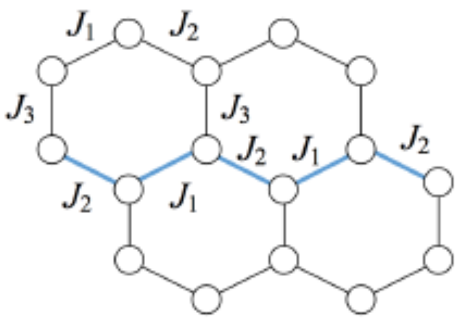
Exchange of 1 and 2 $\quad \gamma_1 \to \gamma_2$

$$\gamma_2 \to -\gamma_1$$

$$(\hat{\gamma}_2 + i\hat{\gamma}_1)\,|\Psi_0\rangle = i\,(\hat{\gamma}_1 - i\hat{\gamma}_2)\,|\Psi_0\rangle = i\hat{c}|\Psi_0\rangle$$

Different final state! – Non-Abelian statistics.

Kitaev model 2006
Magnetic analogues, solvable
Spin liquids and BCS superconductors



Recent efforts M. Hermanns, S. Trebst
J. Vidal, S. Dusuel,…
Works with T. Liu, B. Douçot, F. Yang, A. Soret

Application qubits : quantum computing

Sankar Das Sarma, Michael Freedman, Chetan Nayak arXiv:1501.02813

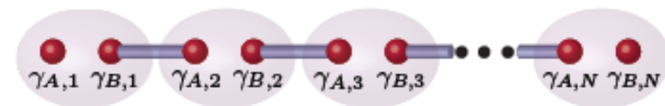
Recent « simulation »: quantum InAs wires (Delft 2012, for example)

Review: J. Alicea et al. 2010

$$H = -\mu \sum_{x=1}^{N} c_x^\dagger c_x - \sum_{x=1}^{N-1} \left(t c_x^\dagger c_{x+1} + |\Delta| e^{i\phi} c_x c_{x+1} + h.c. \right)$$

Kitaev chain 2001

(a)



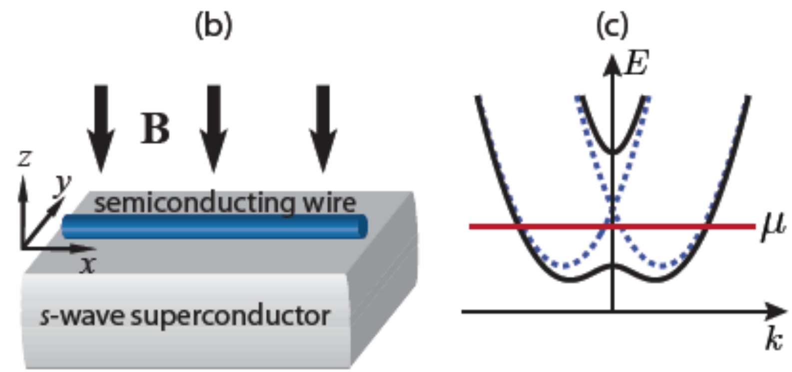
Difficulty to find p-wave SCs in nature?

Equivalent quantum Ising spin chain

Implementation cold atoms (harvard) & trapped ions (maryland), Circuits Santa Barbara, Zurich, …

Book Subir Sachdev, quantum phase transitions

Take advantage of spin-orbit coupling



$$c_x = \frac{1}{2} e^{-i\frac{\phi}{2}} (\gamma_{B,x} + i\gamma_{A,x}),$$

$$H = -it \sum_{x=1}^{N-1} \gamma_{B,x}\gamma_{A,x+1}.$$

$$\mathcal{H} = \int dx \Big[\psi_x^\dagger \Big(-\frac{\hbar^2 \partial_x^2}{2m} - \mu - i\hbar u \hat{\mathbf{e}} \cdot \boldsymbol{\sigma} \partial_x - \frac{g\mu_B B_z}{2} \sigma^z \Big) \psi_x + (|\Delta| e^{i\varphi} \psi_{\downarrow x} \psi_{\uparrow x} + h.c.) \Big].$$

<u>Theory Proposals (2010):</u>

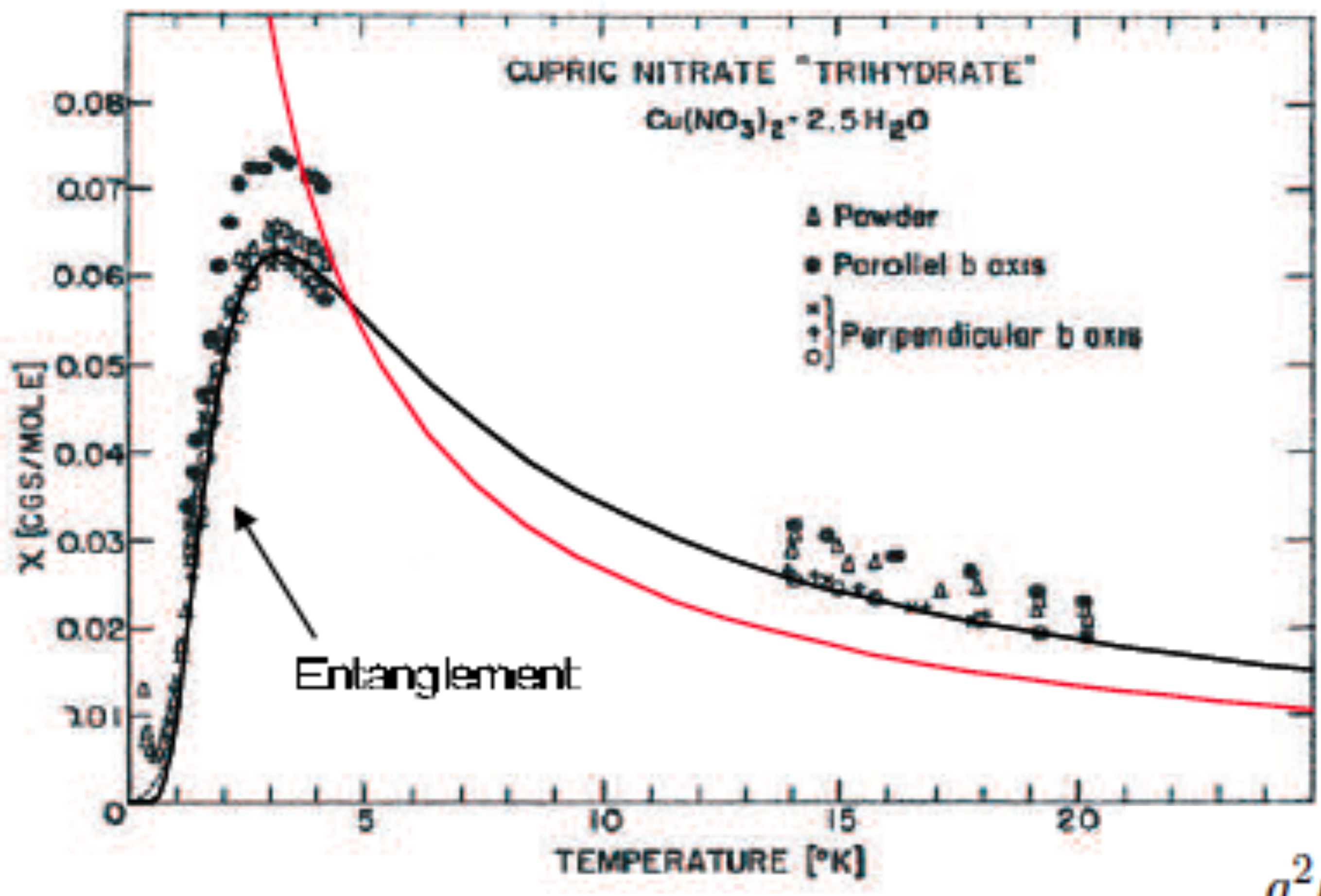
G. Refael, Y. Oreg, F. von Oppen

R. Lutchin, J. Sau and S. das Sarma

Dresselhaus or Rashba

Quantum Entanglement in Bulk Properties of Solids:

Quantum spin chain different from Ising classical chain? How?



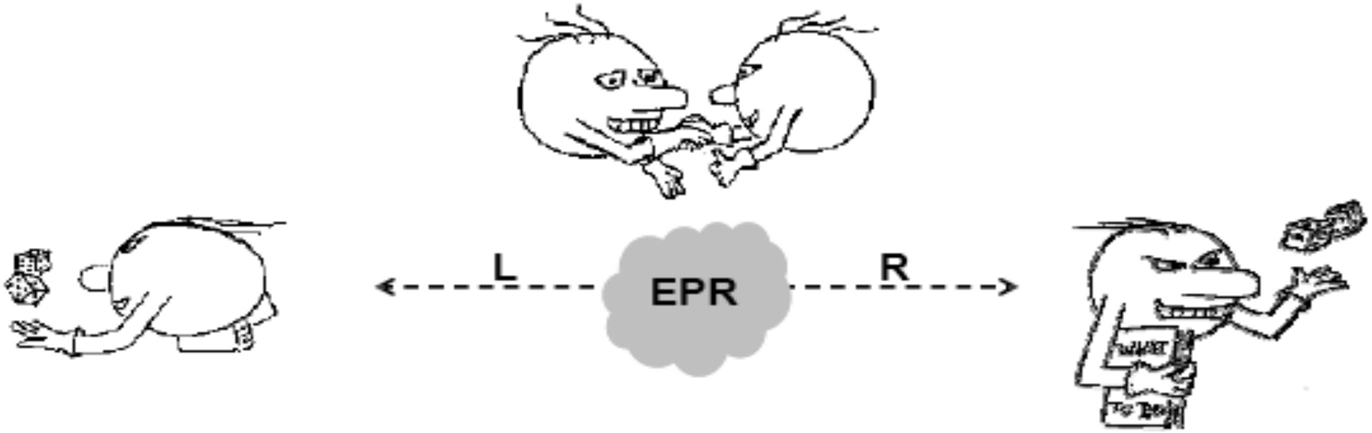
$$\chi \geq \frac{g^2 \mu_B^2 N}{kT} \frac{1}{6}$$

Brukner,
Vedral,
Zeilinger, 2004

implies separable state (?

Also relevant for generalized Gibbs ensemble (quenchs)

What is Entanglement?
Spooky action at Distance (Einstein)



Simple example: 2 Qbits forming a singlet pair

$$|\Psi_S\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow_A\rangle|\downarrow_B\rangle - |\downarrow_A\rangle|\uparrow_B\rangle\right)$$

Wave function is NOT factorizable into individual wave functions…
Quantum states of 2 (or more) particles are linked together

Detection (for photons) lies on violation of Bell's inequalities
(see for example experiment by A. Aspect, P. Grangier, G. Roger 1981)
also J. Dalibard

Entanglement Entropy (quantum limit)

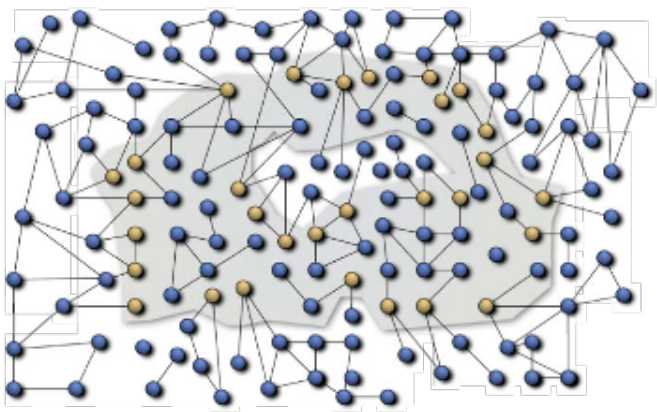
Review: J. Eisert, M. Cramer, M. Plenio RMP 2010

quantum mechanics:
entropy > 0 without an objective lack of information

non-degenerate
pure ground state

$$\rho_0 = |\psi\rangle\langle\psi|$$

$$\Rightarrow S(\rho_0) = 0$$



shaded region A
remainder B

$$\rho_A = \mathrm{tr}_B(\rho)$$

$$\Rightarrow S(\rho_A) \neq 0$$

Entanglement
Entropy

von Neumann entropy

$$S(\rho) = -\mathrm{tr}\left(\rho \log_2 \rho\right)$$

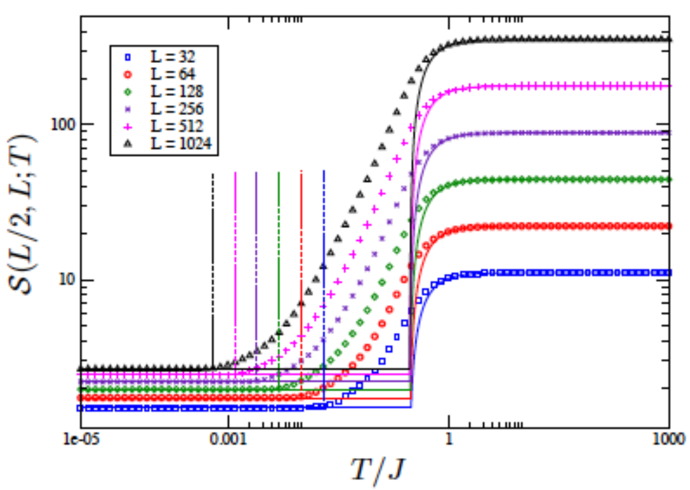
L. Amico et al. Rev Mod Phys (2008)

A. Sorensen, Lu-Ming Duan, I. Cirac, P. Zoller, many-body entanglement in BEC Nature 2001

Is this Entropy Important?

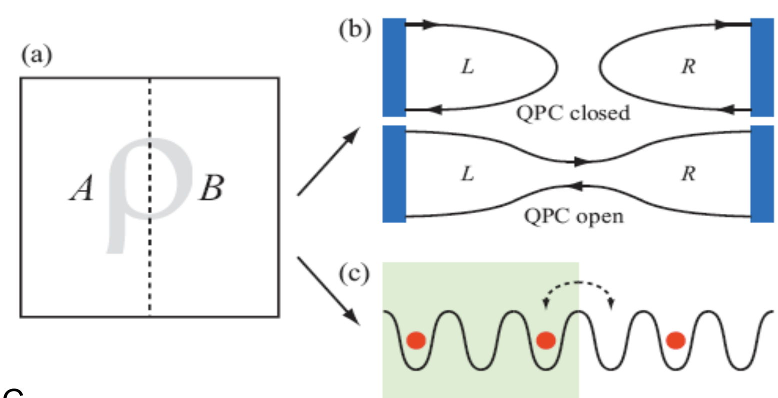
Perhaps: Beckenstein-Hawking black hole entropy scales as the area and not volume (zero temperature); entanglement origin ? non-gravitational view of black holes (Bombelli, K. Koul, Lee, Sorkin PRD 1986)… But, other possible interpretations (holographic principle AdS-CFT, Maldacena 1997, see Wikipedia).

Our (simple) Understanding: Take electrons (quasiparticles), fields (photons). Mixing entropy at zero temperatures



XX chain

Fit with CFT



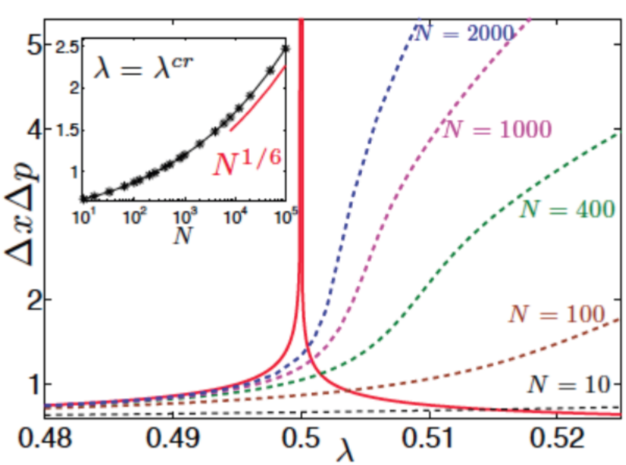
N. Laflorencie, QMC
S. Rachel, F. Song, DMRG

Note that quantifying entanglement in many-body systems is not unique: Here, we have chosen cases where naturally we can divide the system into two pieces; still this gives new ways to think about "fluctuations"

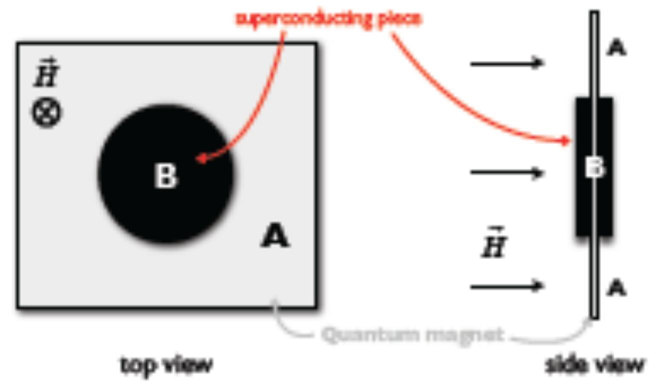
Interacting cases: see paper by J. Cardy (PRL 2011); P. Calabrese etc…

Dicke Model
Super-radiance

$$S \sim \log_2\{\Delta x \Delta p\} \quad \text{if} \quad \Delta x \Delta p \gg 1$$



Pierre Nataf, Mehmet Dogan and Karyn Le Hur, arXiv: 1204.3065 (PRA)



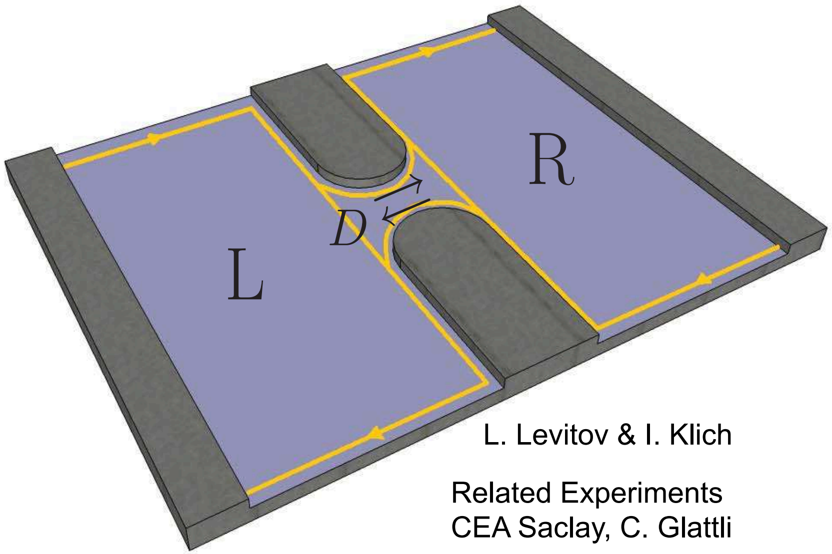
Application Néel phase in 2D (analogy to
Black hole calculation, harmonic oscillators 1986)
H. Francis Song et al. PRB 2011

Also, experimental progress in cold atom systems to measure bi-partite fluctuations

- Measure of local spin susceptibility, T. Esslinger ETH Zuerich 2012
- Parity number correlation functions (Harvard, Muenich)
- Correlation functions in SC qubit systems (John Martinis Group/Google/Santa Barbara)

- Measure of Renyi entropies (purity) in a cold atom experiment, M. Greiner Harvard

Role of Nanotechnology & Math, Machines



L. Levitov & I. Klich

Related Experiments
CEA Saclay, C. Glattli

H. Francis Song, Stephan Rachel, Christian Flindt, Israel Klich, Nicolas Laflorencie, Karyn Le Hur (review)
Phys. Rev. B **85**, 035409 (2012)

Application to Renyi entropies and quantum Hall systems
A. Petrescu, H. F. Song, S. Rachel, Z. Ristivojevic, C. Flindt, N. Laflorencie, I. Klich, N. Regnault, K. Le Hur (review)
J. Stat. Mech. (2014) P10005

For integer QHE, one can measure the entanglement spectrum (Li and Haldane; Sterdyniak, Thomale, Regnault, Bernevig…)

See also G. Misguich, J.-M. Stephan, J. Dubail, V. Pasquier…

Entanglement entropy of free fermions

$$\mathcal{S} = \lim_{K\to\infty} \sum_{n=1}^{K+1} \alpha_n(K) C_n,$$

where

$$\alpha_n(K) = \begin{cases} 2\sum_{k=n-1}^{K} \frac{S_1(k,n-1)}{k!k} & \text{for } n \text{ even,} \\ 0 & \text{for } n \text{ odd.} \end{cases}$$

Here $S_1(n,m)$ are **unsigned Stirling numbers of the first kind**. Practically, K is the number of available cumulants and should be taken to be even.

Interface, Optics & Nano
Ramsey protocoles
Tal Goren, KLH, Eric Akkermans

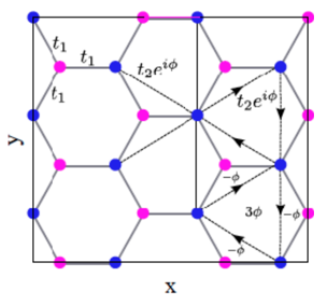
Nanomachines
and thermotransport
Extension to quantum limit

Markus Buttiker, Andrew Jordan,
Rafael Sanchez, Bjorn Sothman
Rosa Lopez, D. Sanchez…

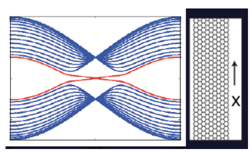
Quantum Simulators :

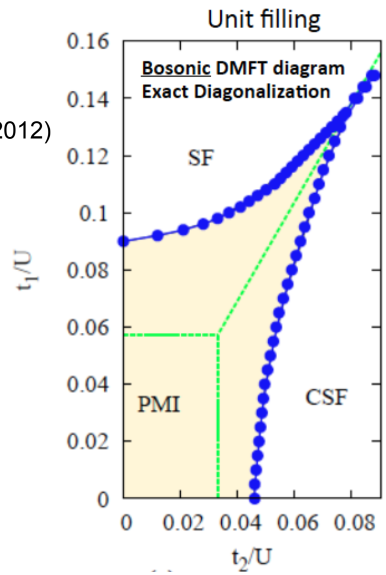
Quantum Hall phases, topological insulators, spin liquids (Kagome, Kitaev model, spin-1 chain) symmetry protected phases, bosons and superconductors, Majoranas, …

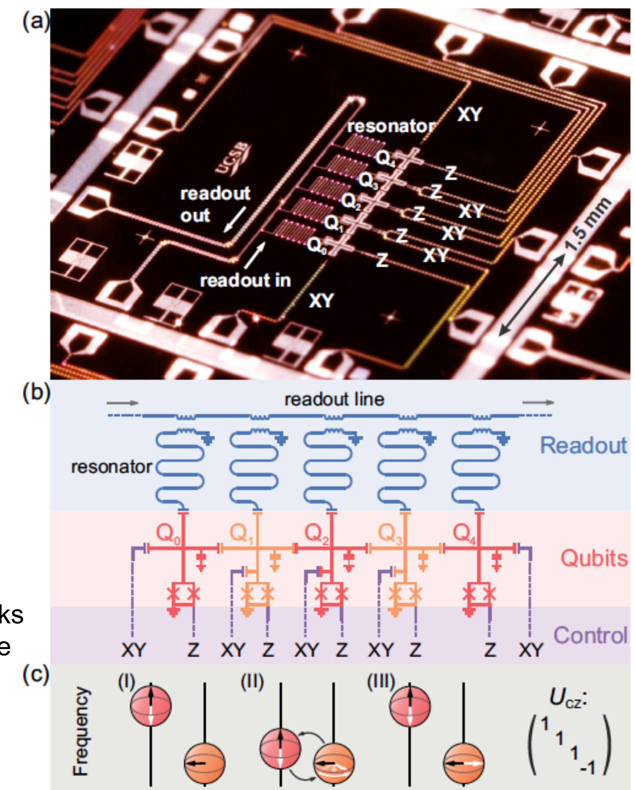
J. Martinis group



Collaboration CPHT & Frankfurt
With Walter Hofstetter
Guillaume Roux, LPTMS
CDMFT fermions (W. Wu et al 2012)





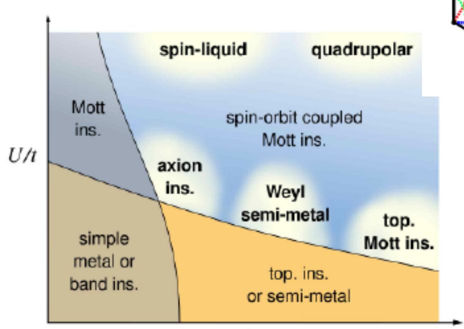


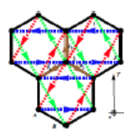
Chern insulators on graphene
realized experimentally in ultra-cold atoms
Photons and quantum materials
Many theorists involved (ENS Lyon, Bordeaux, ENS Paris, CPHT, LPS Orsay, UPMC, Cergy Pontoise, Toulouse,…)

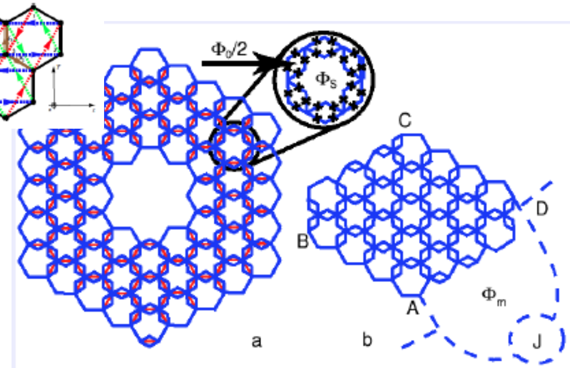
Protected qubits & Majoranas
Pannetier, Buisson superconducting networks
Theory Benoît Douçot, Julien Vidal, Lev Ioffe
Implementing the Kitaev toric code;
Majorana analogues (Barbara Terhal)

Developments in engineering gates
Efforts in quantum graphs, walks in curve space
P. Arrighi, F. Debbasch, M.-E. Brachet

Simulating Quantum Materials (iridates) with Spin-orbit coupling (link with high energy and gauge theories: Chern-Simons models, gravitation),
L. Balents; Jackeli - Khaliulin







Some Developments of numerical efforts,
DMRG, ED, DMFT, QMC, stochastic approaches,…
D. Poilblanc (Toulouse) PEPS methods
Entanglement spectrum of Li and Haldane,
Numerically N. Regnault (ENS)

Conclusion

Interface condensed matter, engineering, simulation, computation

Matrix Product States, DMRG & PEPS methods
F. Verstraete, I. Cirac, N. Schuch, D. Poilblanc complementing DMFT, QMC and stochastic, …
Real material calculations: ab-initio …

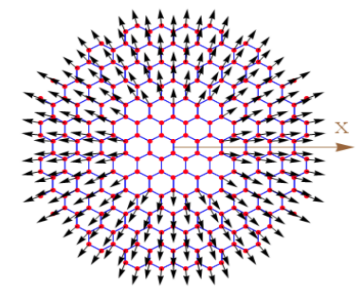
topological matter,
topological qubits
with Majoranas
Nano-engineering

New methods for open and dissipative systems
Stochastic approaches, Matrix Product States, Monte Carlo Keldysh…

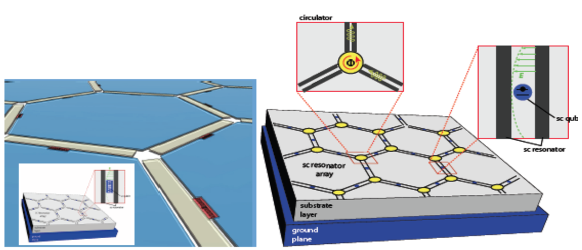
Lattice gauge theories and artificial gauge fields:
emergent « fields » from interacting models
Simulating U(1) and Z2 gauge theories on a lattice, QCD

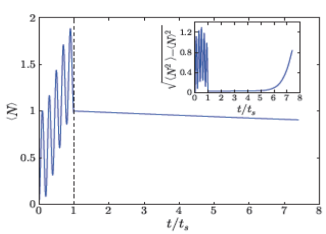
Quasi-crystals : P. Kalugin, J. Bloch, E. Akkermans, A. Jagannathan **(morning)**, P. Vignolo, J.-N. Fuchs

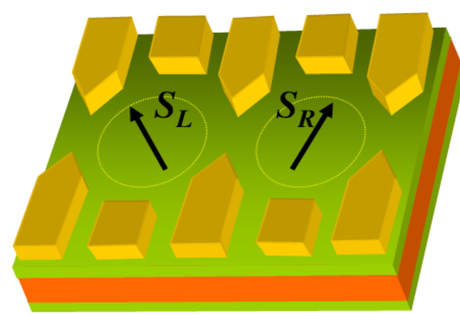
One dimensional systems & quantum impurities offer analytical solutions:
Bethe Ansatz, bosonization, CFT etc… test for simulators and numerical methods
New frontiers (dynamics, artificial gauge fields, Majoranas, fractionalization…)



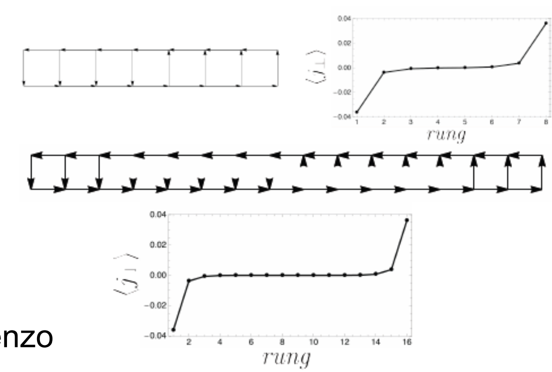
Bergman & Le Hur, PRB 2009







D. Loss
D. Divincenzo



Collaboration with UC London, UBC Vancouver, Natal, Gotenburg, McMaster
Entanglement entropy of 2 channel Kondo model, B. Alkurtass et al. PRB 2016
Nozieres & Blandin 1980, recent experiment F. Pierre (Marcoussis) Nature 2015

Students and Post-docs involved in talk (summer 2016): thanks

Sherbrooke & Yale
2002 - 2011

More Informations at:

https://www.cpht.polytechnique.fr/cpht/lehur/Karyn.LeHur.html

Picture Jean-Francois Dars, Anne Papillault, CNRS

PhD players :

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Kirill Plekhanov (LPTMS G. Roux, CPHT), Tal Goren (Technion U., E. Akkermans, X post-doc)

Francis H. Song (now New-York University post-doc, Yale 2012)
Tianhan Liu (UPMC and X, 2015 co-direction B. Douçot, now Cambridge post-doc)
Alexandru Petrescu (Yale and Ecole Polytechnique 2015, now Princeton post-doc)
Peter P. Orth (Yale 2010, now Minneapolis soon at Ames lab Faculty position)
Prasenjit Dutt (Yale PhD 2013, now Mathematical Finance at Stamford UBS)
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Ion Garate (Yale, now professor Sherbrooke)
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Marie Piraud (Muenich), Marco Schiro (Princeton, Columbia now CNRS IPHT),
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Ecole Polytechnique 2015