Condensed Matter, Quantum Fluids and Quantum Simulation

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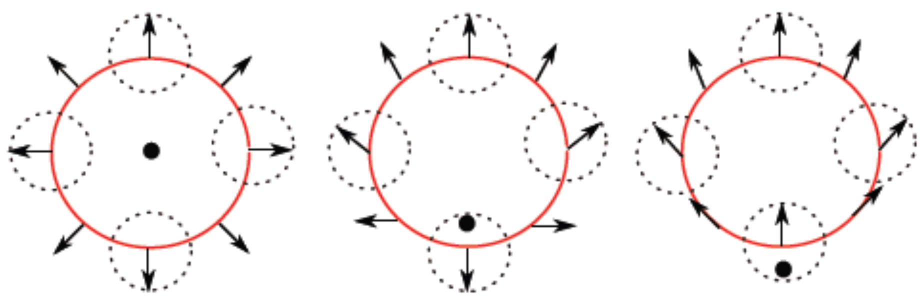
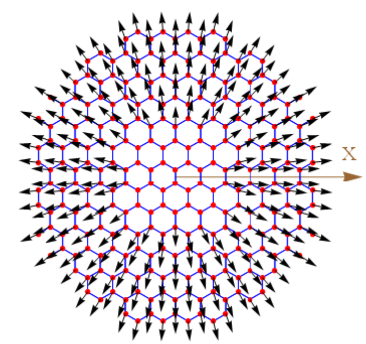
LT28 Gothenburg Sweden, 30 minutes



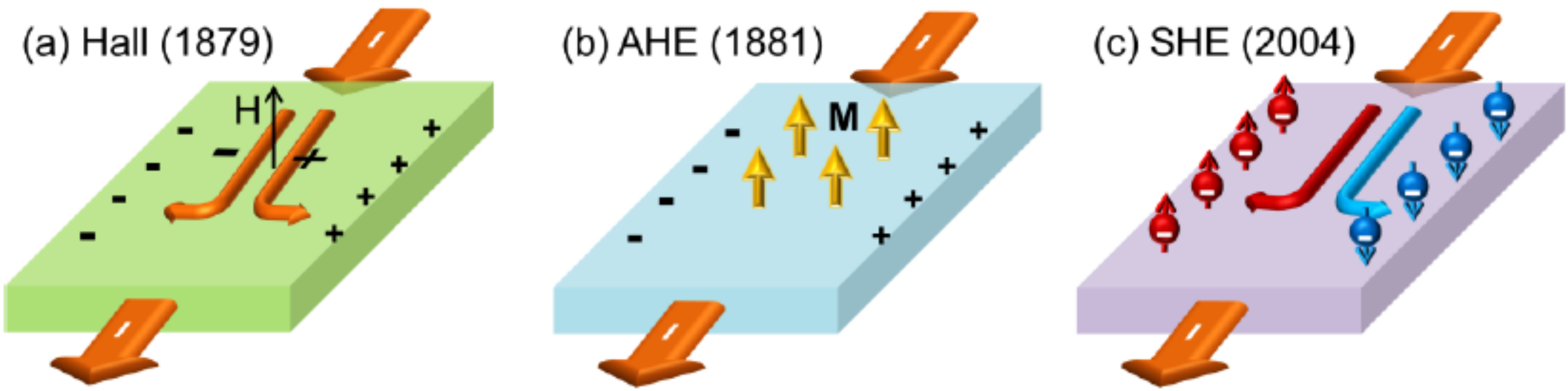


arXiv:0806.0379

Thanks to NSF, DOE, Labex Palm Paris-Saclay and German DFG for support

Link to the Nobel Prize in physics « **topology** » 2016, work by D. Haldane, D. Thouless, **M. Kosterlitz**

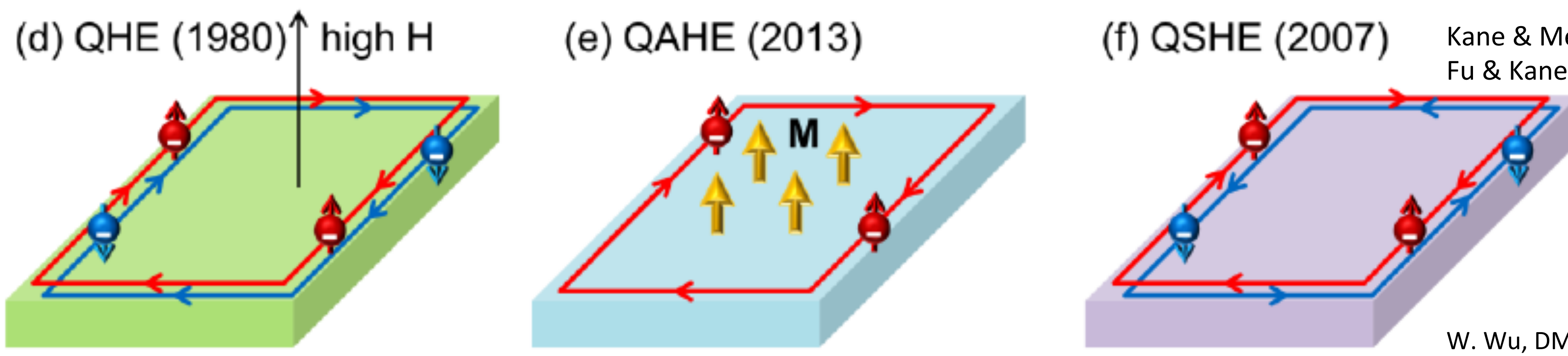
Topological states of matter:



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

Haldane 1988

REALIZED AT WURZBURG IN HGTE (Molenkamp, theory Stanford)
3D MERCURY ANALOGUES, PRINCETON (Hasan)



Kane & Mele
Fu & Kane

W. Wu, DMFT
China & Yale 2011
College de France
CPHT, PRB 2012

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

Stable towards interactions: exemples S. Rachel & KLH Kane-Mele-Hubbard model 2010 QSH; D. Pesin & L. Balents, 3D (2010)
C. Varney, K. Sun, M. Rigol, V. Galitski (Maryland) 2010 QAH

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…)

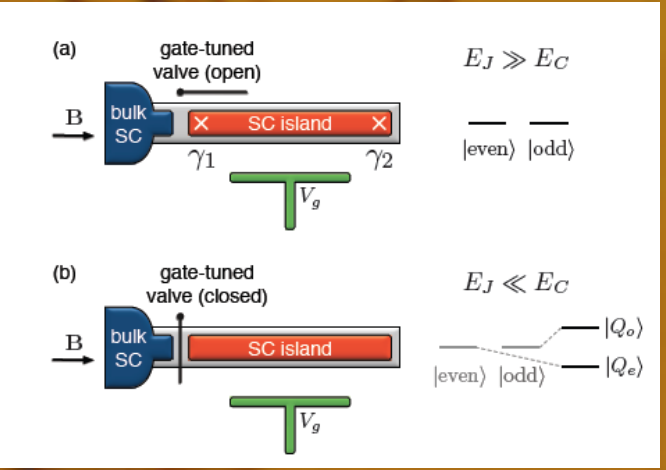
Particle and its own antiparticle

γ

- Alexei Kitaev
- Nick Read
- Leonid Levitov
- Hans Mooij
- Liang Fu
- Charles Kane
- Carlo Beenakker
- Matthew Fisher
- Bert Halperin
- Daniel Loss
- Pascal Simon…

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

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

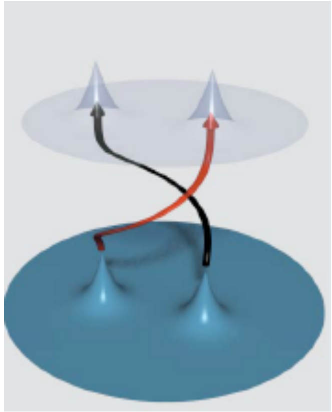


T. Kontos, A. Cottet (ENS)

D. Aaasen et al. arXiv 2015
Charles Marcus, F. Nichel 2016
Also Ali Yazdani, Princeton

Deduction in transport of (2-channel) Kondo model with Majoranas:
H. T. Mebrathu et al. Nature physics 2013 (Duke, G. Finkelstein)
L. Herviou, KLH, C. Mora 2016; K. Michaeli, E. Sela and L. Fu, 2016 (multi-channel)

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 $\quad \gamma_1 \to \gamma_2$

$\gamma_2 \to -\gamma_1$

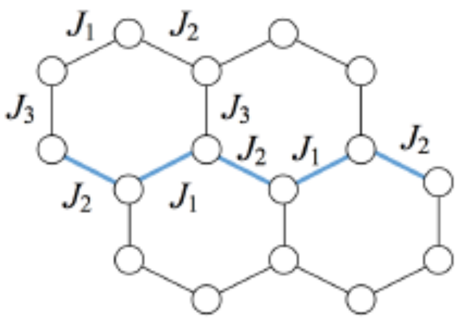
$$(\hat{\gamma}_2 + i\hat{\gamma}_1)\,|\Psi_0\rangle = i\,(\hat{\gamma}_1 - i\hat{\gamma}_2)\,|\Psi_0\rangle = i\hat{c}|\Psi_0\rangle$$

Different final state! – Non-Abelian statistics.

Application qubits : quantum computing

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

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

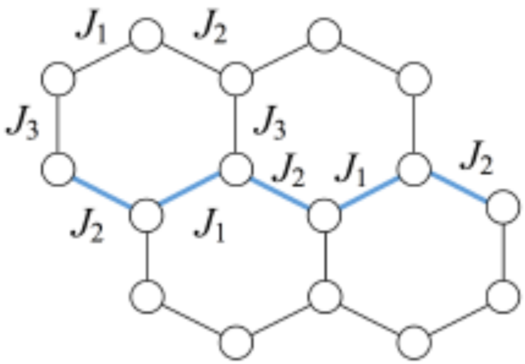
Spin Liquids & Superconductivity

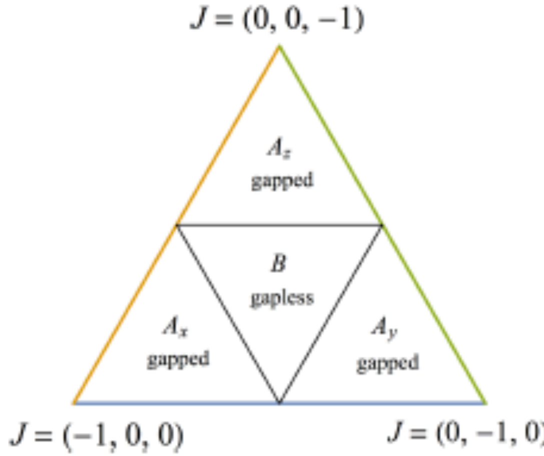
KLH & T. M. Rice, review 2009 (Heisenberg systems)

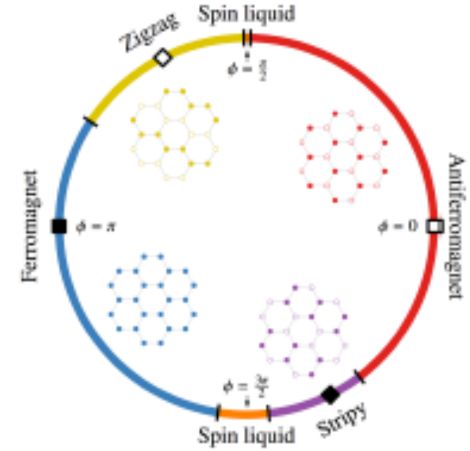
Simulation in cold atoms:
Duan, Demler, Lukin 2003
Kitaev paper 2005 published later

A. Kitaev
1997 toric code
2005 arXiv

J. Rau & H. Y. Kee, review
S. Trebst, review
Iridate materials, αRuCl3
Mixing angle (Heisenberg & Kitaev)

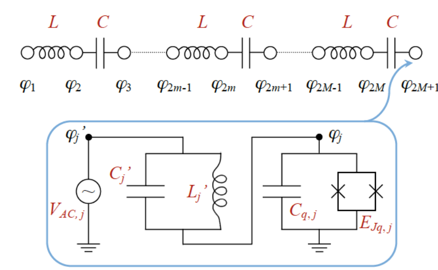


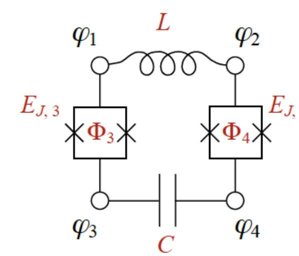




Kitaev model on honeycomb lattice: exactly solvable Majorana representation (2006)
3 gapped Anderson Resonating Valence Bond States with short range correlations
B gapless phase

Observation of superconductivity in graphene (p-wave)
(proximity effect with PCCO): di Bernardo et al 2017
Related to D. Bergman & KLH, 0806.0379.pdf





Engineering minimal spin liquid models,
connection to p-wave BCS theory, topology from Mott, doped Mott insulators
Ladders and Boxes in cQED & Josephson junctions; work with Fan Yang & Ariane Soret, see ArXiv 2017

Summary of the presentation

Topology of a spin-1/2 particle on a sphere: number C

Connect with Lattice Haldane model (1988)
Role of statistics and interactions (fermions versus bosons)

Kosterlitz-Thouless phase transition (70's)
Make several connections with topology

New frontiers:

Quantum phase transitions

Drive and Floquet protocols, interactions, Majorana particles

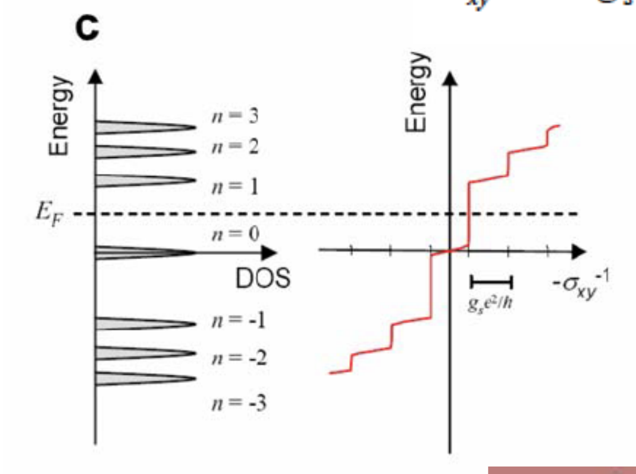
Quantum information probes

Berry Phase measurement in Transport & Monopole

Berry phase in graphene

Y. Zhang et al.
0509355

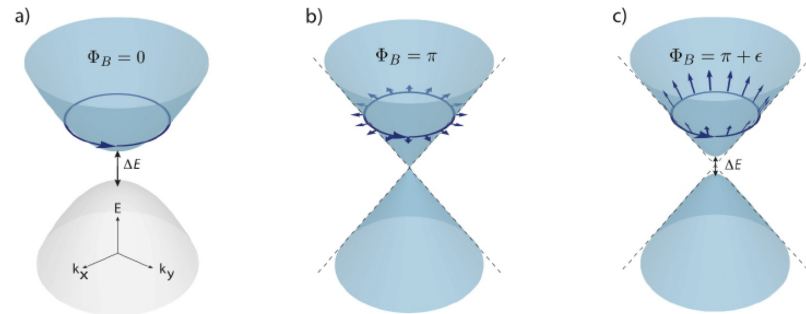
$$R_{xy}^{-1} = \pm g_s \left(n + \frac{1}{2}\right)\frac{e^2}{h}$$



Cuprate and Berry phase

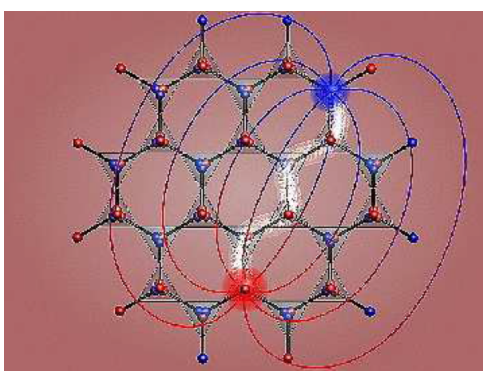
$$\Delta\sigma_{xx} \propto \cos\left[2\pi\left(\frac{B_f}{B} - \delta + \beta\right)\right]$$

δ=1/2

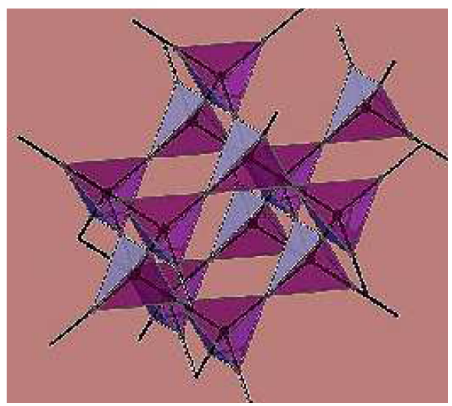


N. Doiron-Leyraud et al. 1407.1388

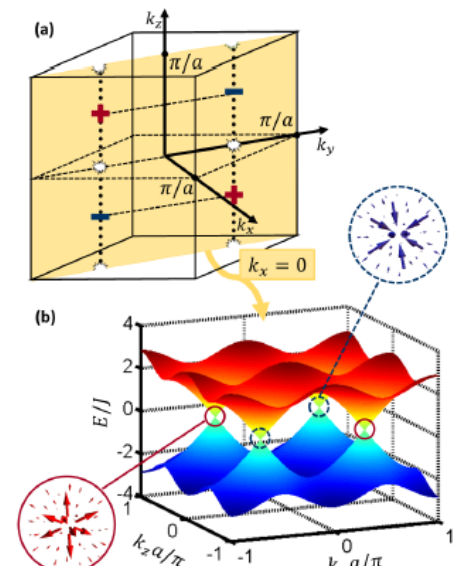
Monopole in spin ices



Castelnovo, Moessner, Sondhi 2007



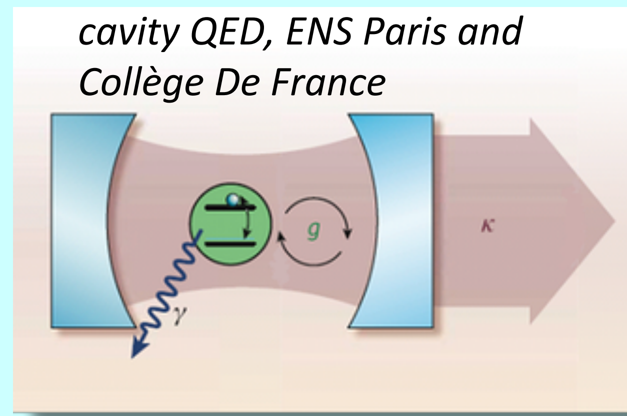
Prediction Weyl fermions in optical lattices
T. Dubcek et al. 1412.7615
Observation in photonic crystals Ling Lu et al. 2015



Cavity & Circuit QED: 1 mode of light …

Coupling atoms to the EM field

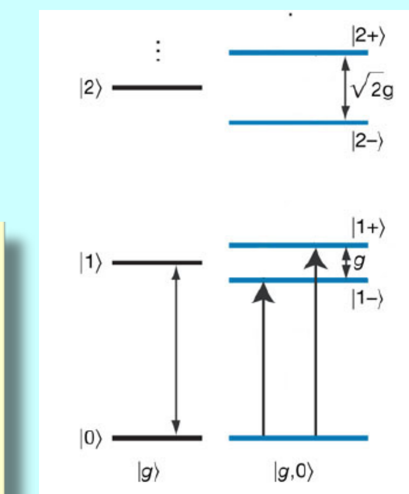
- atoms can couple to the EM field via dipole moment
- coupling strength can be enhanced by confining field to a cavity



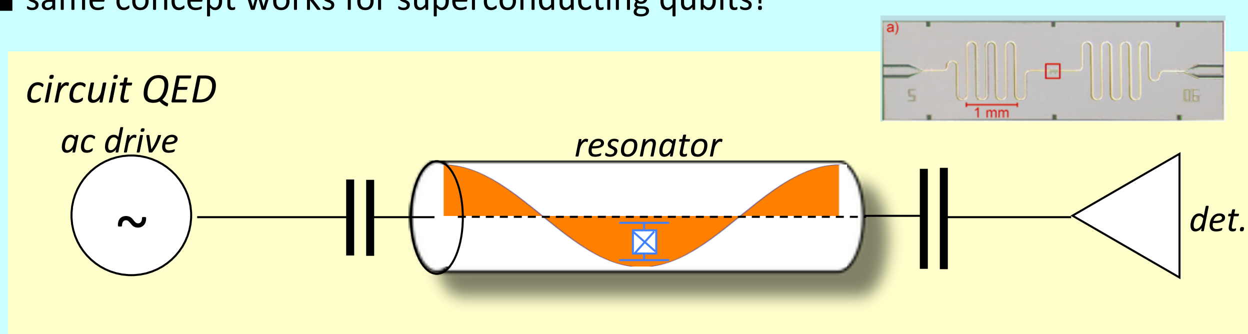
$2g$ = vacuum Rabi frequency
γ = atomic relaxation rate
κ = photon escape rate

Jaynes-Cummings Hamiltonian

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



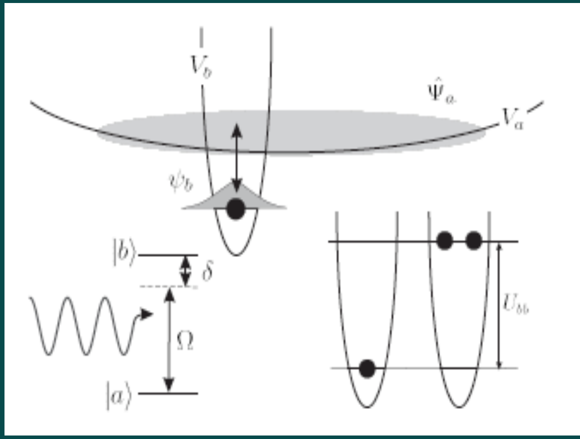
- same concept works for superconducting qubits!



J. M. Raimond, M. Brune, S. Haroche, Rev. Mod. Phys. **73**, 565 (2001)
R. J. Schoelkopf, S. M. Girvin, Nature **451**, 664 (2008) and A. Blais et al.; D. Vion et al. (SPEC Saclay) 2002; J. Martinis

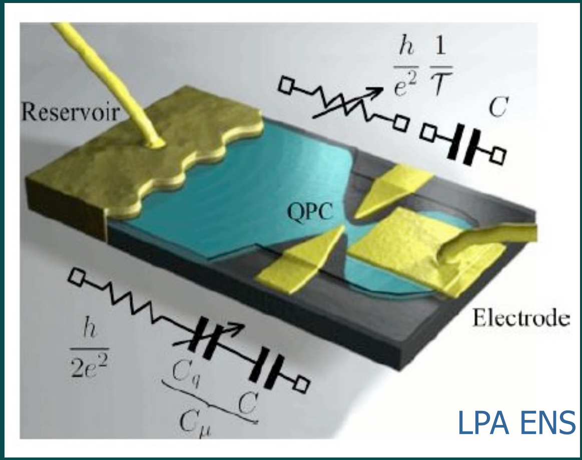
COLD-ATOMIC Quantum IMPURITIES

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)



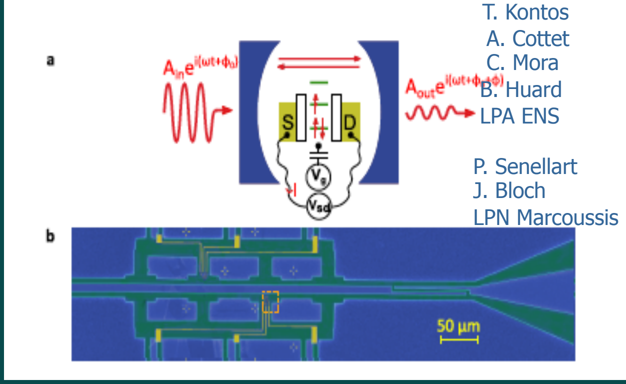
RC circuits

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

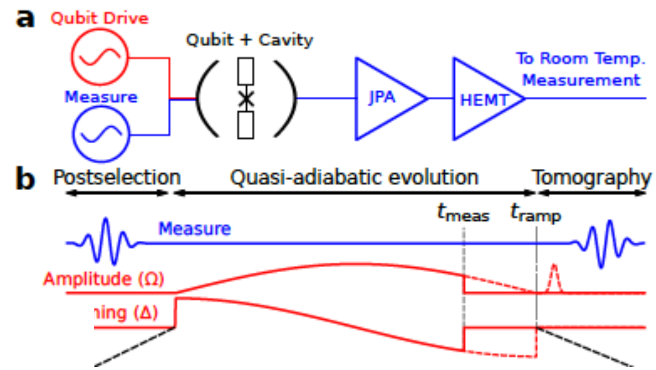
K. Le Hur, Phys. Rev. B 85, 140506(R) (2012)
A. Leclair, F. Lesage, S. Lukyanov and H. Saleur (1997)
M. Goldstein, M. H. Devoret, M. Houzet and L. I. Glazman, 2012
Grenoble: S. Florens, H. Baranger, N. Roch and collaborators
M. Hofheinz et al. arXiv:1102.0131
M. Delbecq et al. PRL 107, 256804 (2011)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



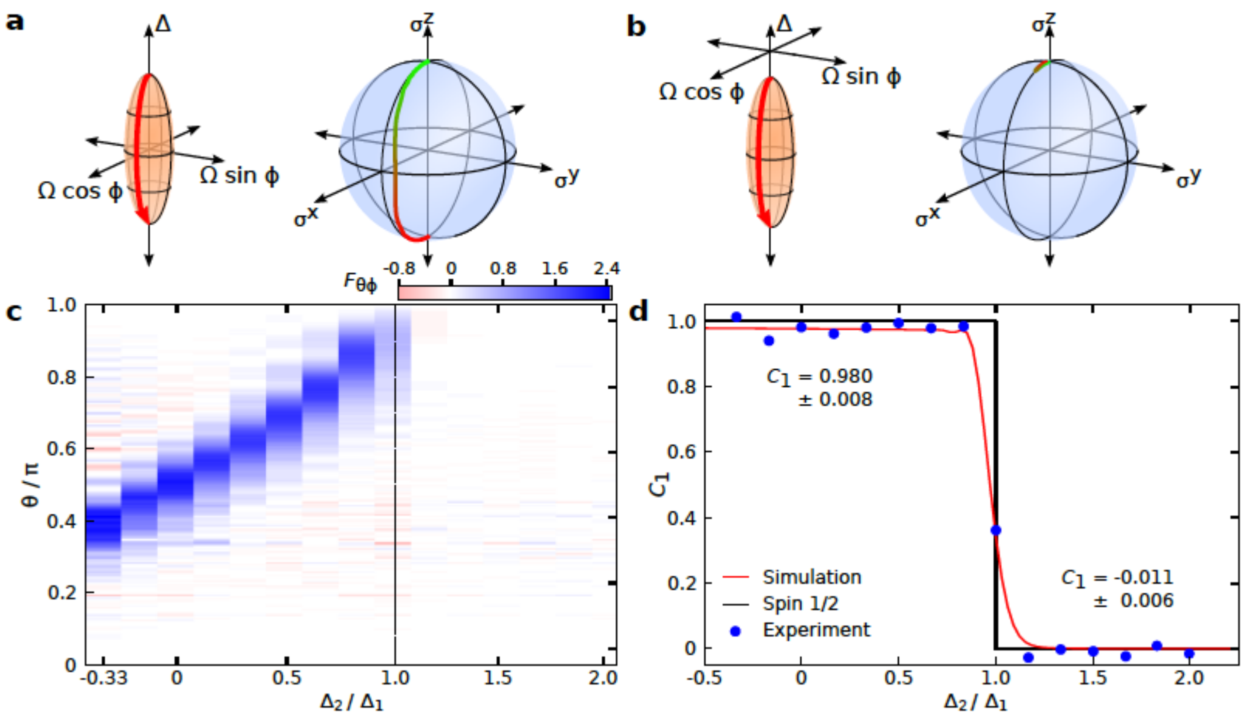
Let's Start from a measurement

Similar devices at Chalmers
P. Delsing

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



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



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

Ramp protocole

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

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

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

Tramp 1micro.s

What does this mean?

Theory by Polkovnikov
Gritsev and Kolodrubetz

Topology on a Sphere

L. Henriet, A. Sclocchi, P. Orth, KLH 2017

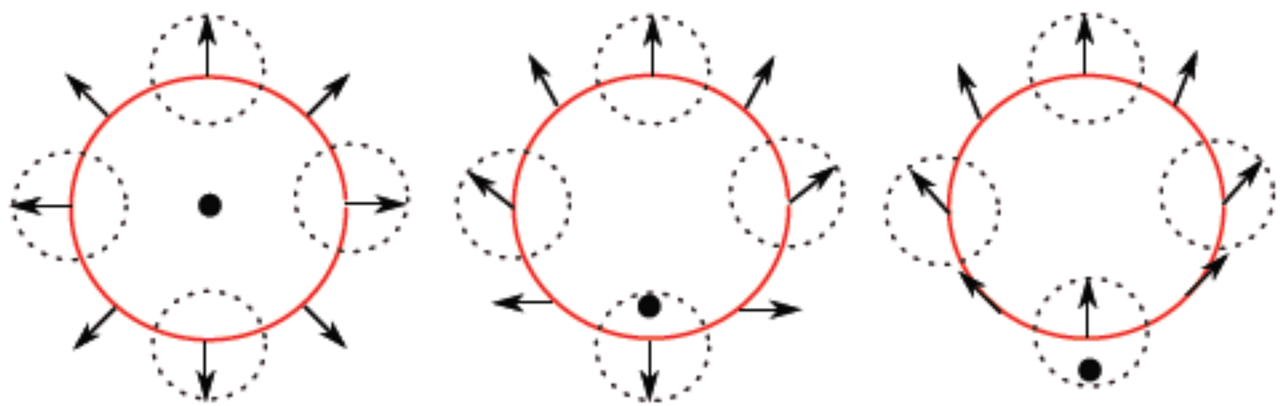
Topology of a spin-1/2 particle

$$\mathcal{H}_{TLS} = -\frac{1}{2}\vec{d}.\vec{\sigma},$$

$$\vec{d} = (H \sin\theta \cos\phi, H \sin\theta \sin\phi, H_0 + H \cos\theta)^T.$$

Quantum mechanics: ground state simple to find

Radial
Magnetic
Field
Response



L. Henriet, PhD CPHT 2017 now Barcelona
P. Orth, PhD Yale 2011 now prof. Iowa, Ames Lab

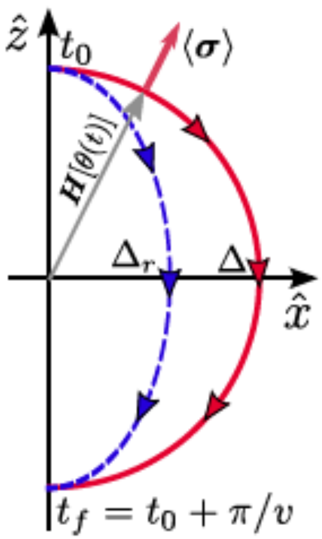
« topological » phase transition at $H=H_0$

Poincare-Hopf argument (Appendix A)

Berry curvature and Chern number

$$\mathcal{F}_{\phi\theta} = \partial_\phi \mathcal{A}_\theta - \partial_\theta \mathcal{A}_\phi,$$

Particular path to reproduce C



$$\mathcal{A}_\phi = \langle g | i\partial_\phi | g \rangle,$$
$$\mathcal{A}_\theta = \langle g | i\partial_\theta | g \rangle.$$

Not gauge invariant

$$C = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \mathcal{F}_{\phi\theta}.$$

½ sin ϑ

C=1 or C=0 (gauge invariant)

$$C = \frac{\langle \sigma^z(\theta = 0)\rangle - \langle \sigma^z(\theta = \pi)\rangle}{2}.$$

Influence of environment: spin-boson model and **Kosterlitz-Thouless phase transition**

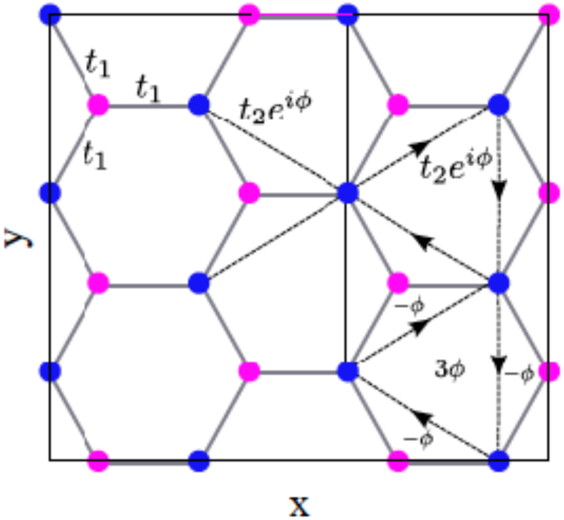
Berry Phase can be simulated by a time-dependent spin-boson model (see later)

This Chern number is in relation with lattice tight-binding models, **Haldane model (Thouless-Kohmoto-Nightingale-den Nijs number linked with Hall conductivity)**

Haldane model: lattice model QAHE

Picture from
Ph. Kim lab

GRAPHENE, Wallace
A. Geim, K. Novoselov



Haldane model

$$\mathcal{H}_0 = \sum_i (-1)^i M c_i^\dagger c_i - \sum_{<i,j>} t_1 c_i^\dagger c_j - \sum_{\ll i,j \gg} t_2 e^{i\phi_{ij}} c_i^\dagger c_j$$

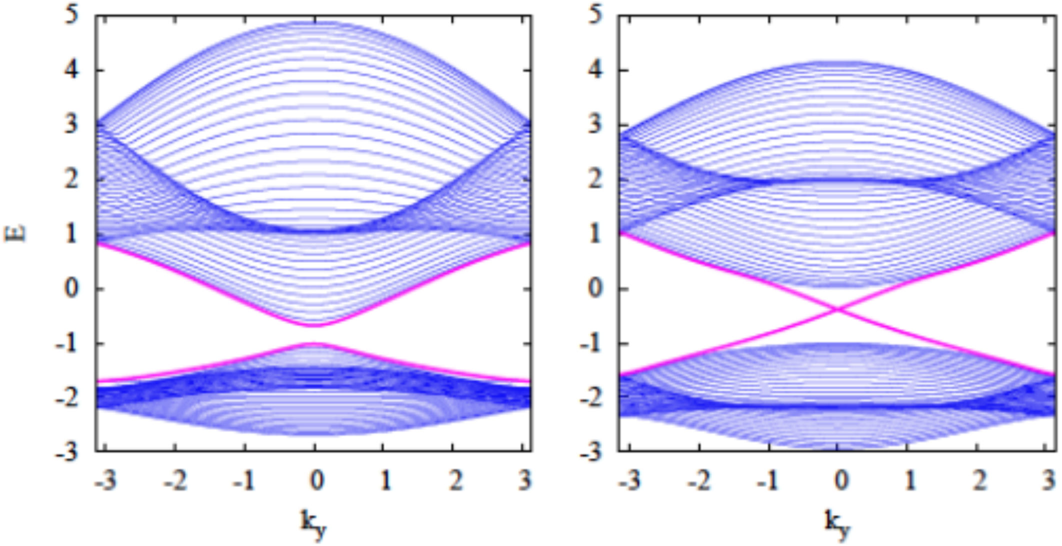
F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988)

No net flux

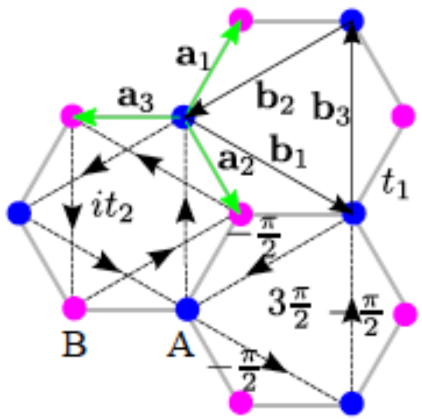
M = Semenoff mass (high-energy)

Spectrum of the non-interacting model

- t_1 only $\Rightarrow$ Dirac cones
- M or t_2 can open the gap
- Non–trivial topological properties if $M < 3\sqrt{3} t_2 \sin\phi$



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

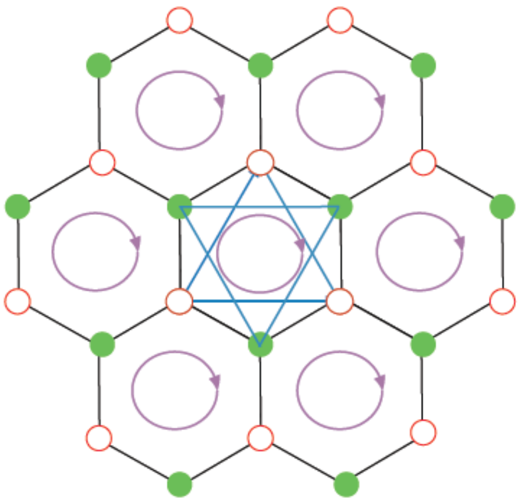
Jotzu et al. arXiv:1406.7874

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



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

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

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

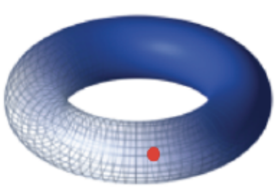
$$F_{xy}^\alpha = [\nabla_{\boldsymbol{k}} \wedge \mathcal{A}^\alpha(\boldsymbol{k})]_z = \partial_{k_x} A_y^\alpha - \partial_{k_y} A_x^\alpha.$$

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

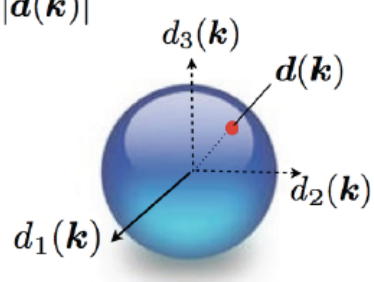
$$C^- = \frac{1}{4\pi}\int_{\mathrm{BZ}} dk\, \sin\theta_{\boldsymbol{k}} \left(\frac{\partial\theta_{\boldsymbol{k}}}{\partial k_x}\frac{\partial\phi_{\boldsymbol{k}}}{\partial k_y} - \frac{\partial\phi_{\boldsymbol{k}}}{\partial k_x}\frac{\partial\theta_{\boldsymbol{k}}}{\partial k_y} \right)$$

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

Cold Atoms:

Jaksch & Zoller 2003

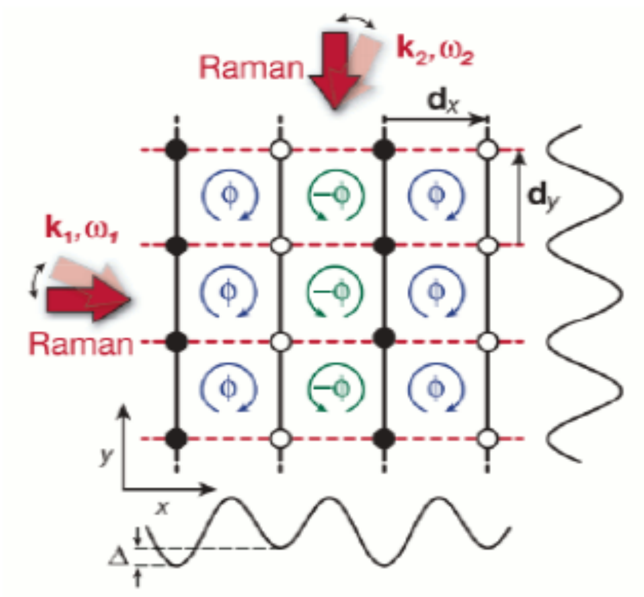
A. L. Fetter RMP 2009; J. Dalibard, F. Gerbier, G. Juzeliunas, P. Ohberg RMP 2011;
I. Bloch et al. Nature (2012); Juzeliunas & Spielman NJP (2012);...
D. Cocks, P. Orth, S. Rachel, M. Buchhold, KLH, W. Hofstetter PRL 2012

- Ways to implement magnetic fields & gauge fields

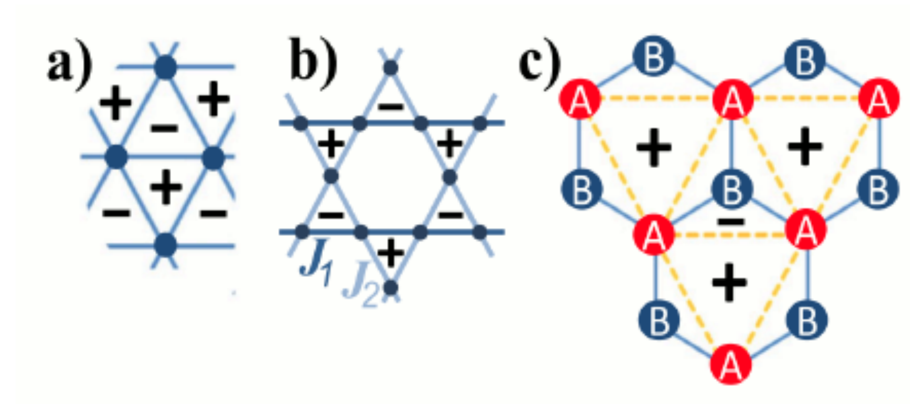
N. Goldman et al. Phys. Rev. Lett. 103, 035301 (2009)

M. Aidelsburger et al. arXiv:1110.5314 (Muenich's group, PRL)

J. Struck et al. arXiv:1203.0049 (Hamburg's group)



Laser-assisted tunneling in optical superlattice PRL 107, 255301 (2011)



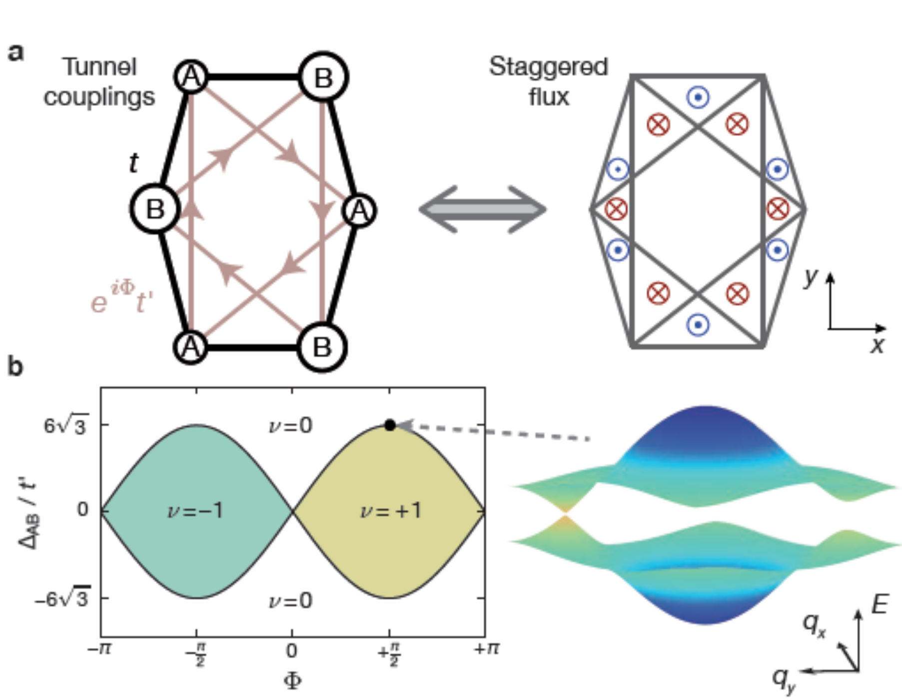
Floquet Topological Insulators:
Recent review J. Cayssol, B. Dora, F. Simon, R. Moessner, arXiv:1211.5623

Simulation of Haldane model

First realization with light, ferrite road square lattices, MIT
Review: Lu, Soljacic, Johannopoulos, Nature photonics 2014
Ferrite developments at Chicago: Anderson, Ma, Owens, Schuster, Simon (FQHE simulation)
Magnetically doped HgTe: review Liu, Zhang and Qi, arXiv:1508.07106; Cr-Bi systems: Chang et al. Science 2013

Group of T. Esslinger, 2014
Jotzu et al. arXiv:1406.7874

Ultra-cold atoms: importance of Floquet-type point of view



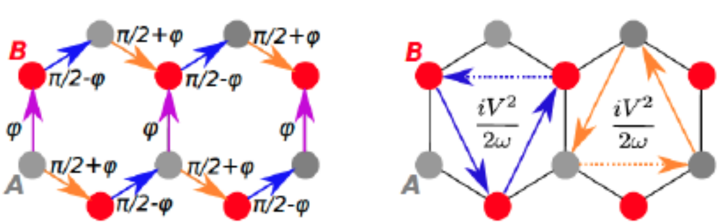
$$\hat{U}(T,t_0) = \zeta \exp\left(-i\int_{t_0}^{T+t_0} \hat{H}(t)dt\right) = \exp(-iT\hat{H}_{\text{eff}})$$

Modulation of optical lattice

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

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

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



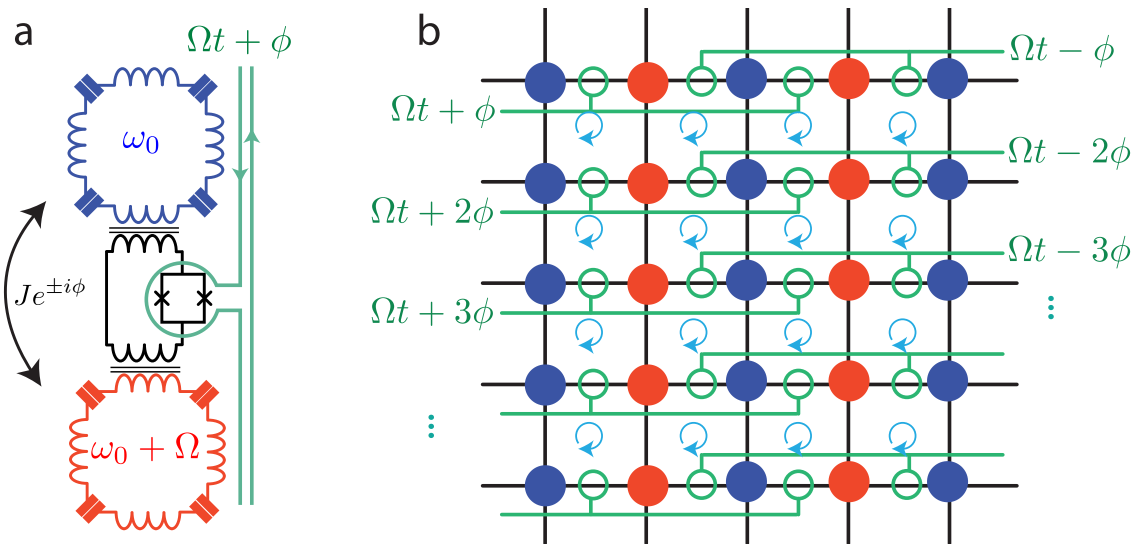
Other protocole:
K. Plekhanov, G. Roux, KLH
Recent paper PRB 2017, arXiv 2016
Topology robust to deformation (anisotropy)

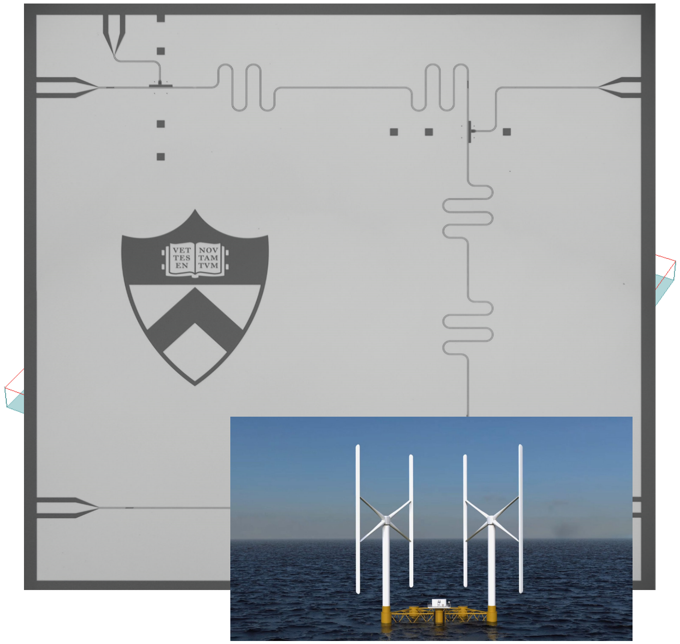
K. Plekhanov, Phd 2018

Other Way to Produce Gauge Fields

Uniform Magnetic Field

Mini lattice in Nb: A. Houck lab

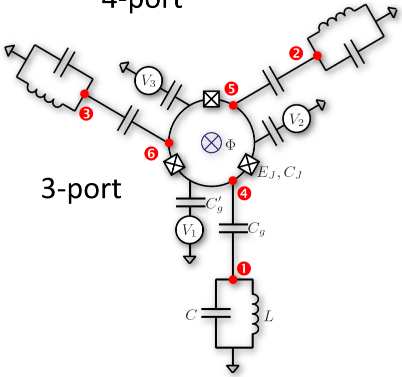




K. Fang, Z. Yu and S. Fan Nature Photonics 6, 782 (2012)

Seems feasible to realize in cQED arrays
(J. Gabelli, J. Esteve, F. Appas); Orsay

4-port

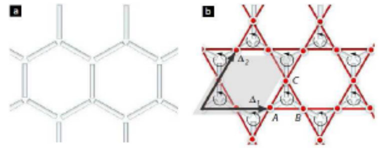


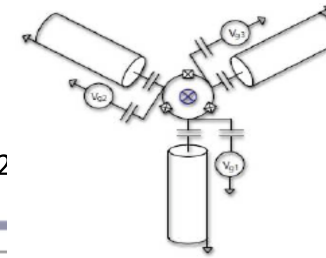
3-port

Nano Circulator implementation (other ferrite devices, see later):
J. Koch, A. Houck, KLH and S. Girvin 2010; A. Kamal, J. Clarke, M. Devoret Nat. Phys. 2011
Realization: P. Roushan, C. Neill et al. Nature Physics 2017 (Santa Barbara)

Quantum Anomalous Hall Effect

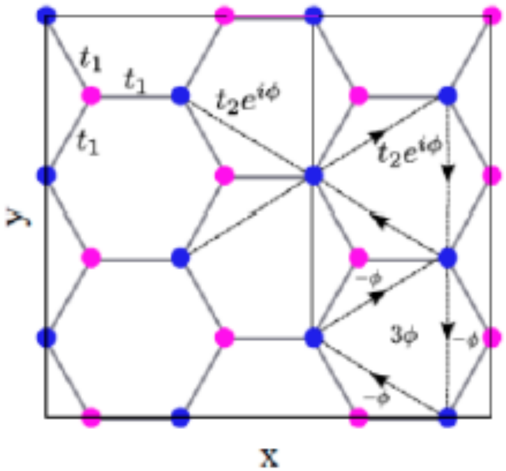
F. D. M. Haldane 1988

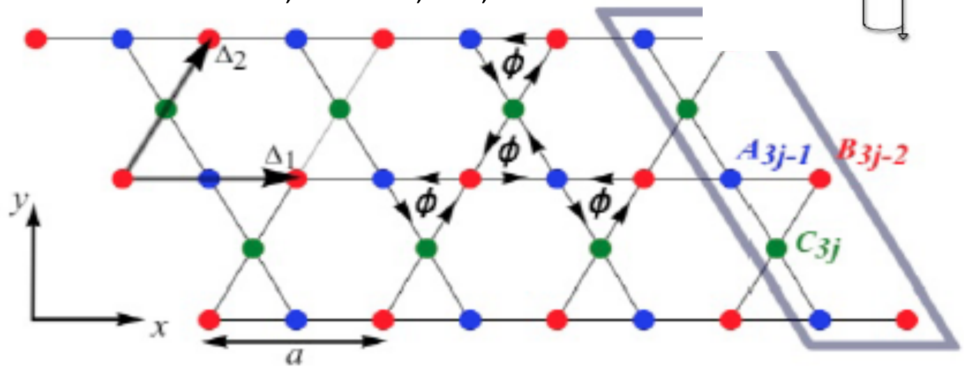




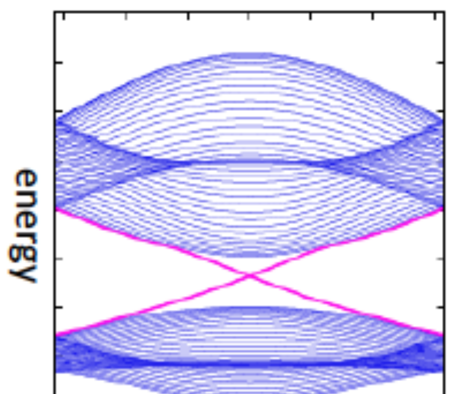
Kagome version:

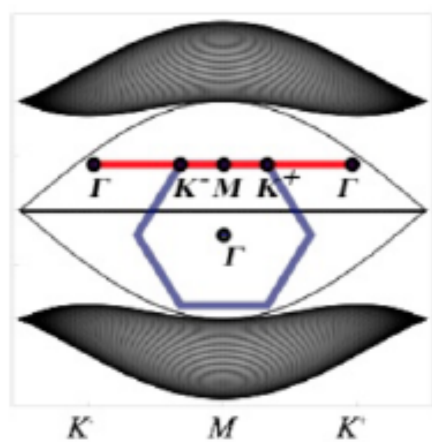
A. Petrescu, A. A. Houck and KLH, 2012
J. Koch, A. Houck, KLH, S. Girvin 2010

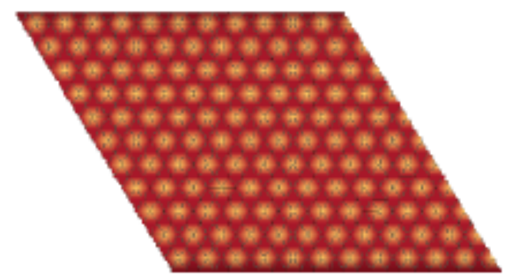




Flat bands observed in polaritons (A. Amo , J. Bloch)







Localization in
Hexagon rings

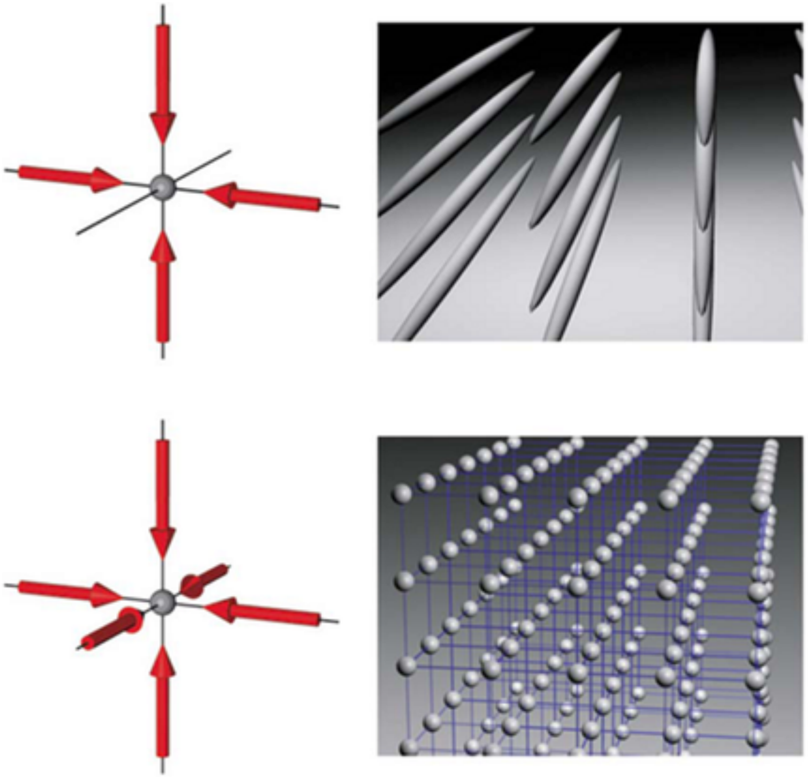
Graphene
+gap

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

Statistics matter

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

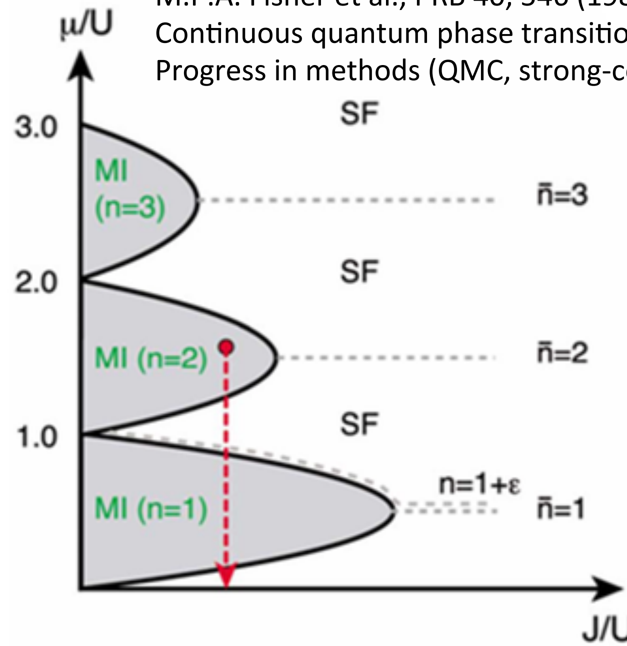
D. Jaksch et al., Phys. Rev. Lett. **81**, 3108 (1998)
M. Greiner et al., Nature **415**, 39 (2002)



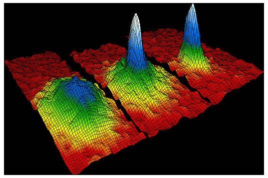
e.g., realization of the Bose-Hubbard model:

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

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



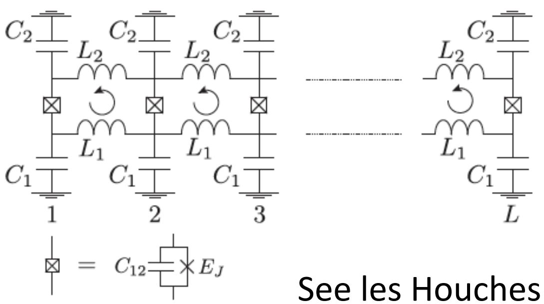
Nobel price 2001



Bose-Einstein condensate

Also Josephson junction arrays

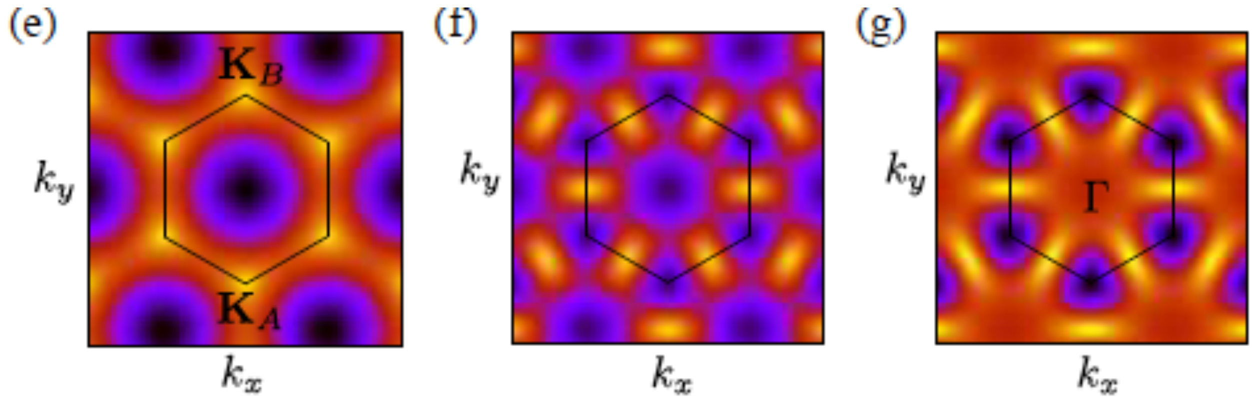
Progress
Neel,
Grenoble

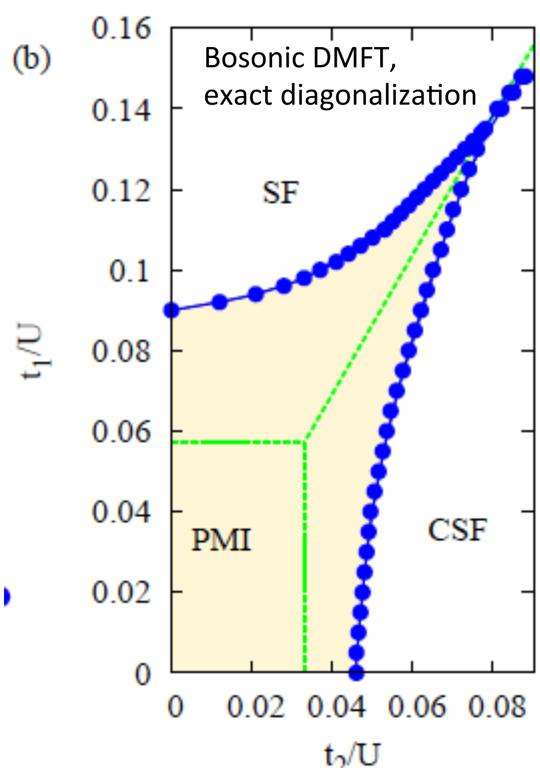


See les Houches lectures: D. Esteve & D. Vion; M. Devoret; J. Martinis & Kevin Osborne 2004

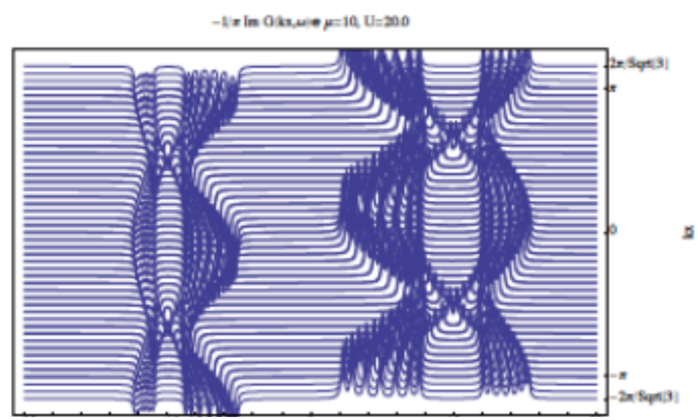
Exotic bosonic phases: Haldane model

I. Vidanovic Vasic, A. Petrescu, K. Le Hur, W. Hofstetter, arXiv:1408.1411 (PRB)
K. Plekhanov, G. Roux, KLH recent paper PRB 2017





Strong coupling cluster expansion in Mott



FFLO analogue in Heisenberg-Kitaev doped models
Tianhan Liu, Cécile Repellin, Benoît Douçot, Nicolas Regnault Karyn Le Hur, 2016

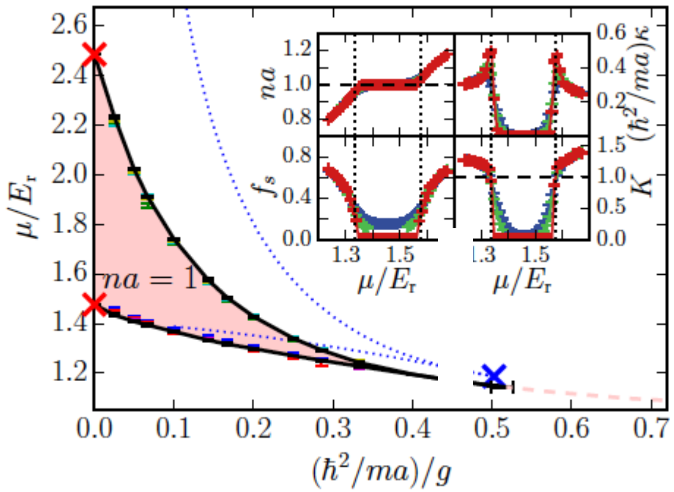
Similar models on <u>square</u> lattice:
L. K. Lim, C. M. Smith and A. Hemmerich, Phys. Rev. Lett. 100, 130402 (2008) and PRA 2010

New exploration in Mott: 2 flavors K. Plekhanov, I. Vasic, A. Petrescu, N. Rajbir, G. Roux, W. Hofstetter, KLH, 2017 (chiral spin state)

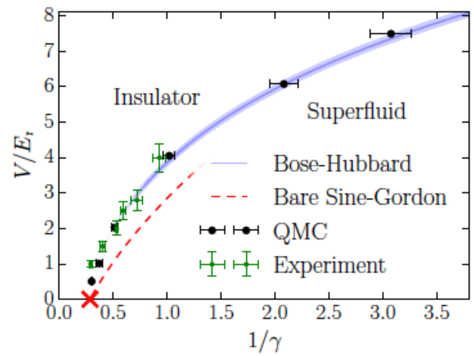
Mott 1D....

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

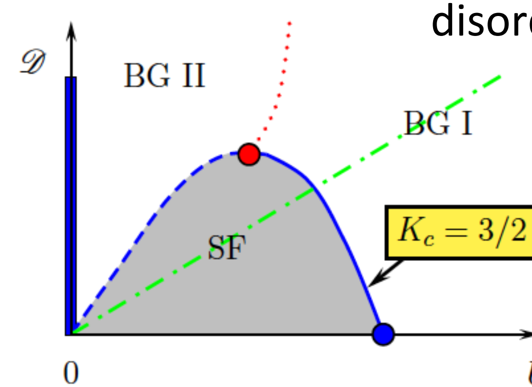
Kosterlitz-Thouless transition



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



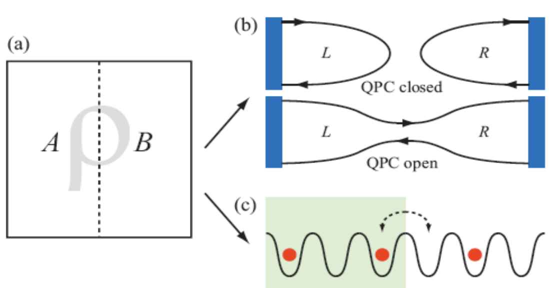
disorder



H. Ɉ. Schulz & T. Giamarchi 1988
Z. Ristivojevic, A. Petkovic, (Toulouse)
T. Giamarchi, P. Le Doussal (ENS) 2012
E. Altman, Y. Kafri, A. Polkovnikov, G. Refael

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

New probes: bi-partite entanglement
Entropies, bi-partite fluctuations
Linked with conformal field theory
(John Cardy, P. Calabrese)



PhD H. Francis Song, Yale 2011
PhD Loic Herviou CPHT 2017 (Z2 models)

Review: H. F. Song, S. Rachel, C. Flindt, N. Laflorencie, I. Klich, KLH 2012

Critical coupling strength

Kc=2

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)

Bloch sphere: dissipation

Review submitted at Comptes Rendus Academie des Sciences, arXiv: 1702.05135

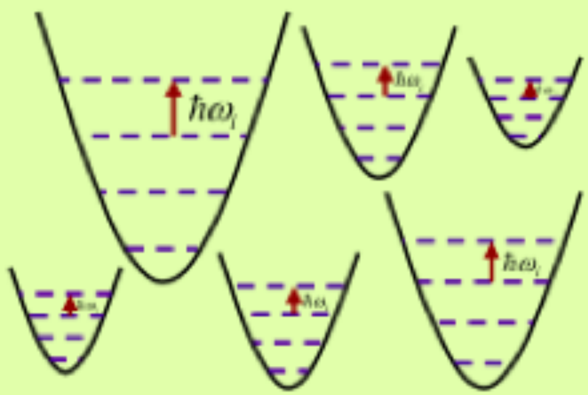
Kosterlitz-Thouless transition and topology

- Model the environment by quantum harmonic oscillators

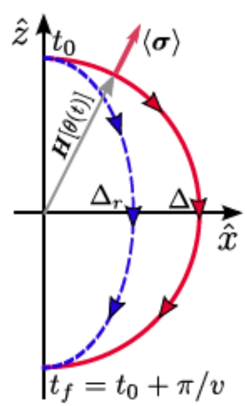
$$H_{CL} = hS_z + \Delta(S_+ + S_-) + S_z \sum_i \lambda_i x_i + H_B$$

A. Leggett et al. Rev. Mod. Phys. **59**, 1 (1987)
U. Weiss book, quantum dissipative systems, 1999

$$H_B = \sum_i \left(\frac{p_i^2}{2m_i} + \frac{m_i \omega_i^2 x_i^2}{2} \right)$$



Bosonic bath



$$\frac{1}{2}\left\langle \sum_i \lambda_i x_i(t) \cdot \sum_i \lambda_i x_i(0) \right\rangle_\omega = \hbar J(\omega) \coth(\omega / 2k_B T)$$

Ohmic dissipation

$$J(\omega) = \alpha \pi \hbar \omega / 2$$

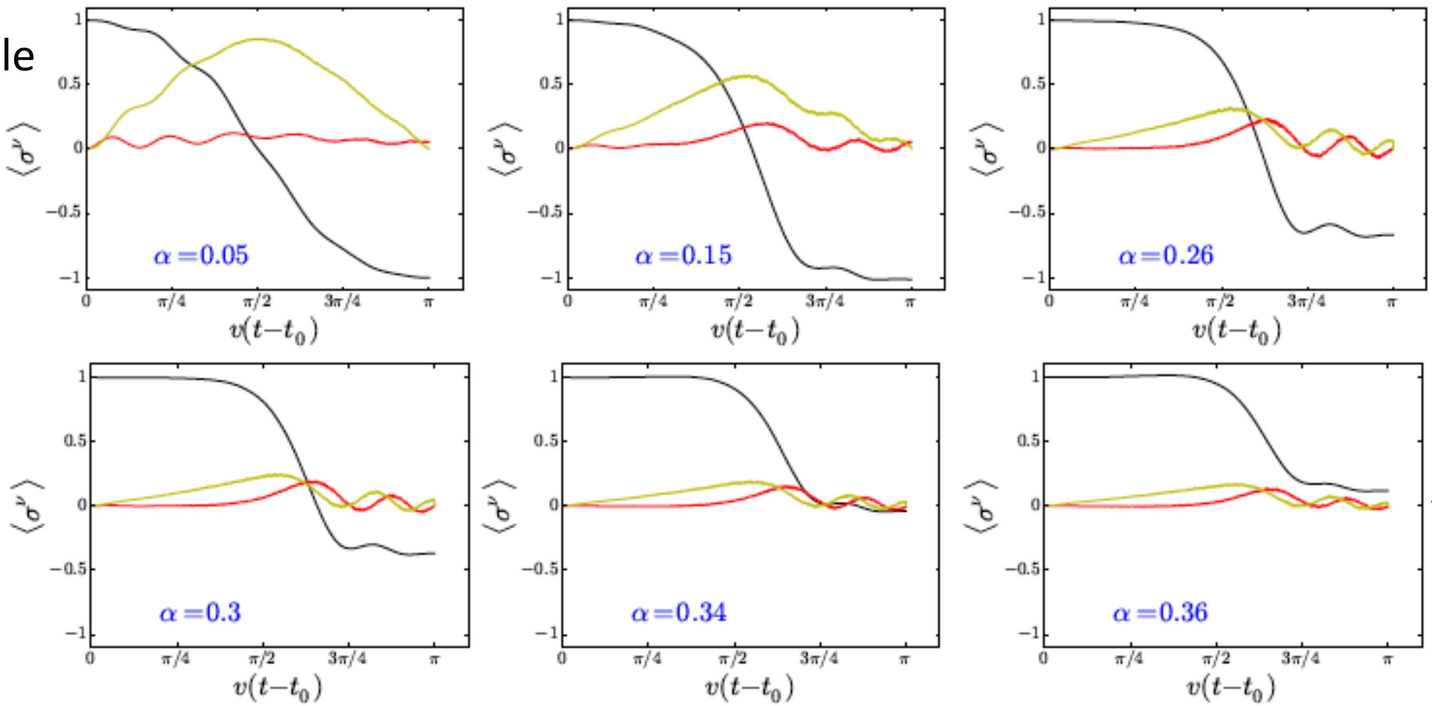
Dissipation strength

Bloch sphere driving: stochastic approach

L. Henriet, A. Sclocchi, P. Orth, KLH 2017

Polar angle = vt

(1 pulse)



Faraday Response:

The bath produces an effective field

[12] A. J. Leggett, S. Chakravarty, A. T. Dorsey, M. P. A. Fisher, A. Garg, and W. Zwerger, Rev. Mod. Phys **59**, 1 (1987).
[13] P. W. Anderson, G. Yuval, and D. R. Hamann, Phys. Rev. B **1**, 4464 (1970).

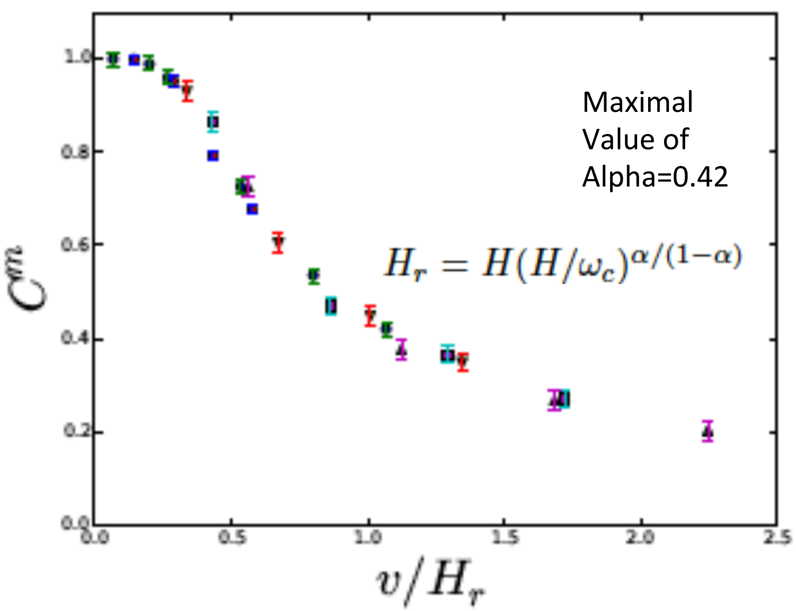
[35] P. P. Orth, A. O. Imambekov, and K. Le Hur, Phys. Rev. A **82**, 032118 (2010).
[36] P. P. Orth, A. O. Imambekov, and K. Le Hur, Phys. Rev. B **87**, 014305 (2013).
[37] L. Henriet, Z. Ristivojevic, P. P. Orth, and K. Le Hur, Phys. Rev. A **90**, 023820 (2014).
[38] L. Henriet and K. Le Hur, Phys. Rev. B **93**, 064411 (2016).
[39] J. Cao, L. W. Ungar, and G. A. Voth, The Journal of Chemical Physics **104**, 4189 (1996).
[40] J. T. Stockburger and C. H. Mac, J. Chem. Phys. **110**, 4983 (1999).
[41] J. T. Stockburger and H. Grabert, Phys. Rev. Lett. **88**, 170407 (2002).
[42] G. B. Lesovik, A. O. Lebedev, and A. O. Imambekov, JETP Lett. **75**, 474 (2002).

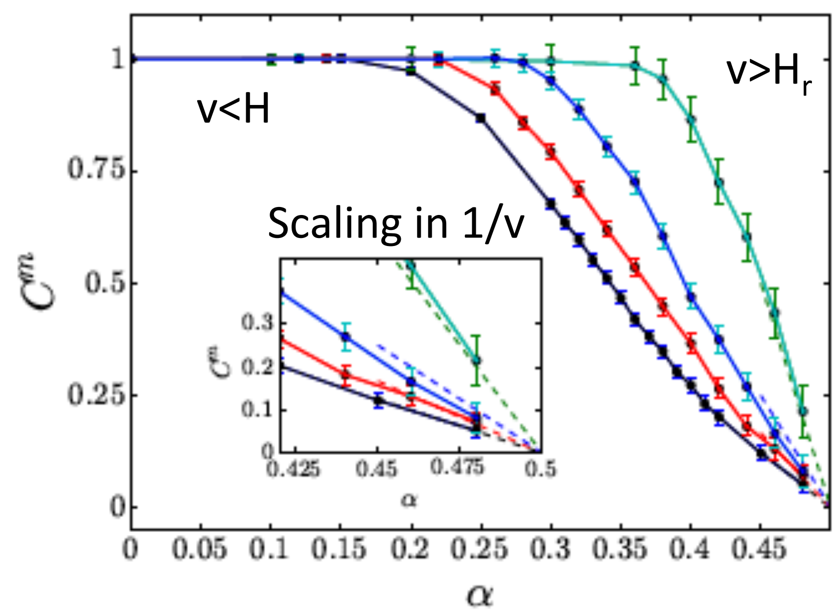
Adiabatic versus non Adiabatic limit

$$C = \underbrace{\frac{\langle \sigma^z(t_0)\rangle - \langle \sigma^z(t_f = t_0 + \pi/v)\rangle}{2}}_{C^m} + o(v).$$

$v \ll H_r,$

Effective Boltzmann-Gibbs description for the spin:
N. Williams, K. Le Hur, A. Jordan
J. Phys. A: Math. Theor. 44 (2011) 385003





A dynamical phase transition was observed at Hamburg in cold atoms (C. Weitenberg et al.)

α =1/2 solvable limit; perturbative scaling (G. Toulouse)

Effective model

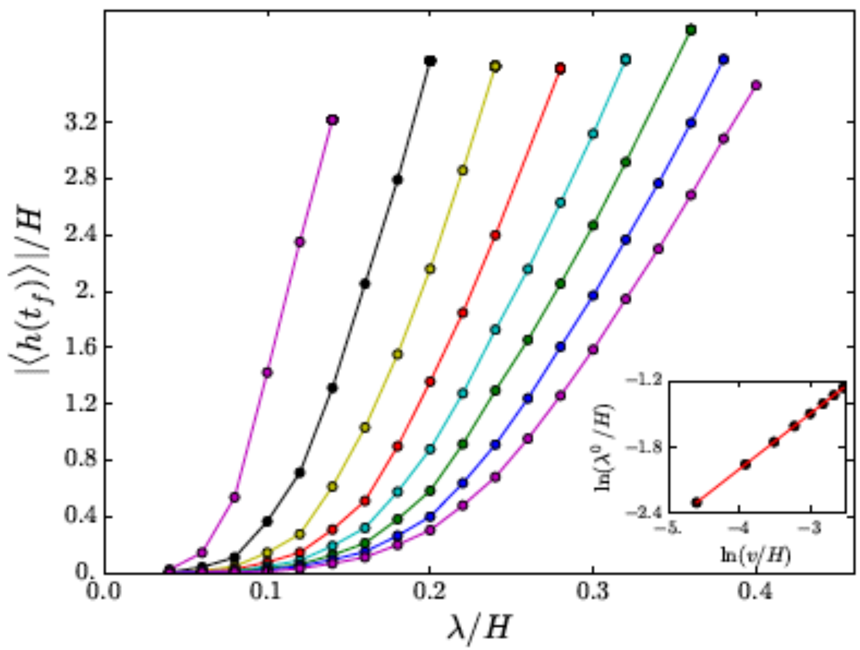
Induced field compensates the applied magnetic field: « photo-emission »

h induced

$$H_{toy} = \frac{H}{2}\cos vt\sigma^z + \frac{H}{2}\sin vt\sigma^x + \frac{\lambda}{2}\sigma^z(b+b^\dagger) + vb^\dagger b.$$

$\lambda \,\breve{=}\, \sqrt{2\alpha v H}$

Rotating the Spin produces Artificial light



Ramsey Interferometry with environment, QPC: T. Goren, KLH, E. Akkermans, submitted

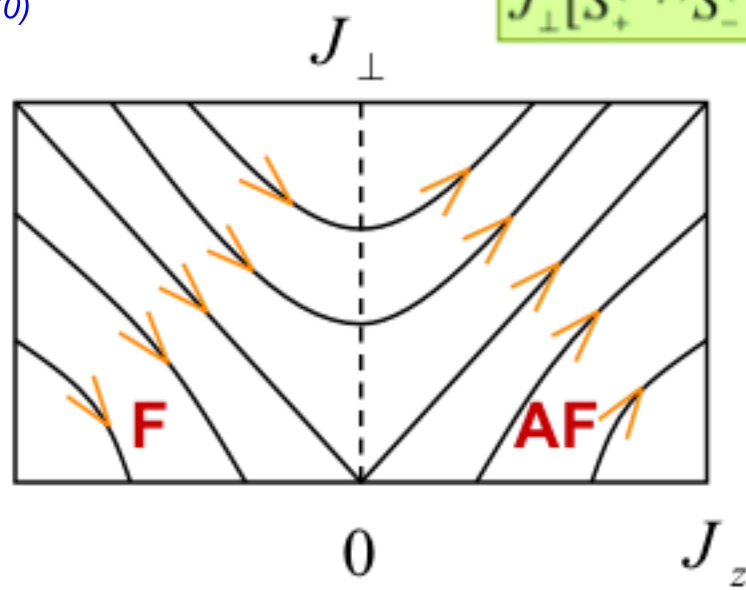
Analogy to another quantum impurity Kondo problem

Blume, V.J. Emery & A. Luther (1970)
Guinea, Hakim, Muramatsu (1985)

$$J_\perp[S_+^{(imp)}S_-^{(e)} + h.c.] + J_z S_z^{(imp)} S_z^{(e)}$$

$$S^e(x=0) = \sum_{\substack{k,k' \\ \alpha,\beta}} c_{k\alpha}^\dagger \frac{\sigma_{\alpha\beta}}{2} c_{k'\beta}$$

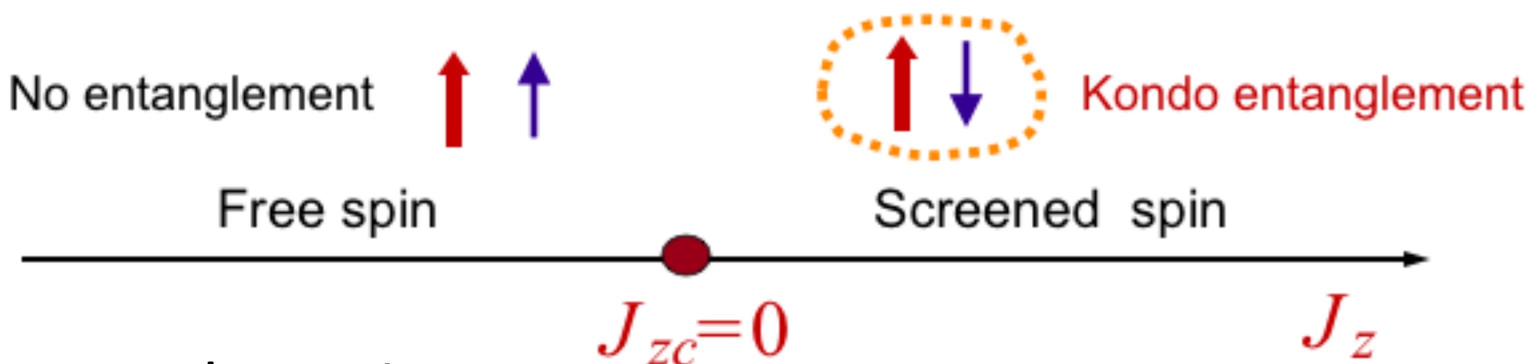
Perturbative calculations



Bethe Ansatz:
See N. Andrei; A. Tsvelik; P. Wiegmann
CFT: Affleck-Ludwig

See also K. Wilson, NRG (Nobel prize)
Ph. Nozières, **Fermi liquid**, 1974
Coqblin-Schrieffer, Newns-Read
Kondo lattices: S. Doniach, Coleman…

Small $J_\perp$



Jzc = 0 corresponds to α = 1

Berezinskii-Kosterlitz-Thouless:

2D XY models: Superconductors, ^{4}He, Cold atomic bosons

$$H = -J \sum_{<i;j>} \cos(\varphi_i - \varphi_j)$$

SC order parameter = $|\Psi| \exp(i\varphi)$

$$S_x + iS_y = \exp(i\varphi)$$

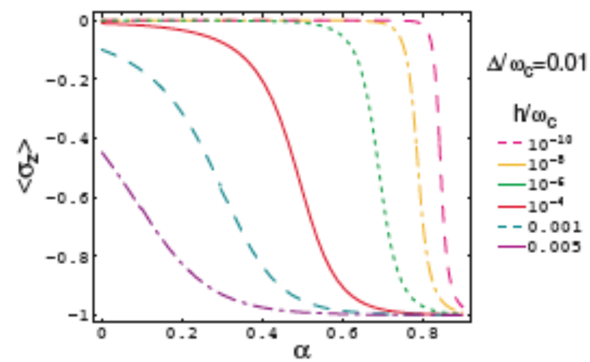
KT transition: High Temperature disordered phase (free vortices)

Low-Temperature quasi-long range order

Universal Jump of Superfluid density at T_{KT}
(Helium 4, Reppy et al 1974, 78
and cold atoms Hadzibabic, Cambridge)

Bethe Ansatz
NRG

KLH
Annals of Physics 2008



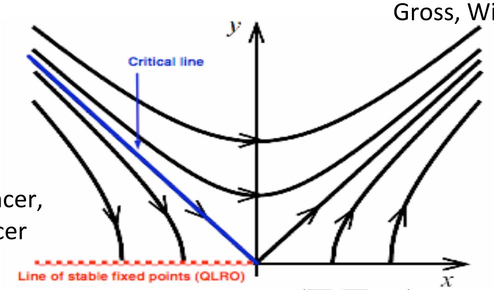
(vortex fugacity)

« QCD »
Asymptotic
Freedom 1973
Gross, Wilczek, Politzer

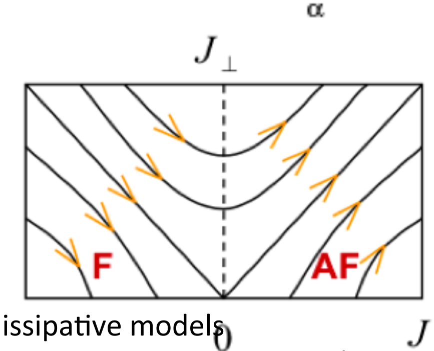
Kosterlitz-Thouless papers

D. Nelson
D. Fisher,

McBryan & Spencer,
Frohlich & Spencer



$(T-T_{KT})$

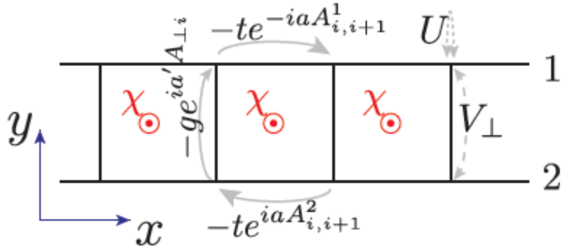


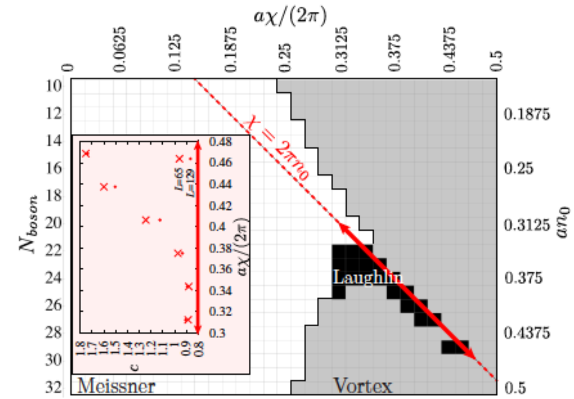
Kondo
Singlet,
Low-energy

P. W. Anderson 1969
related RG **of Kondo model**

Ising models in 1D & Caldeira-Leggett dissipative models
(D. Thouless 1969 & Anderson, Yuval, Hammann; Freeman Dyson)

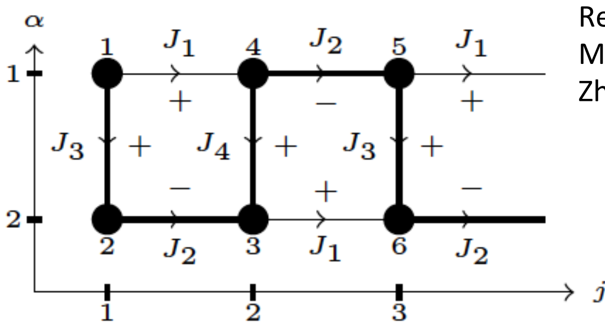
Interplay between Emergent and External Gauge Fields: « view »



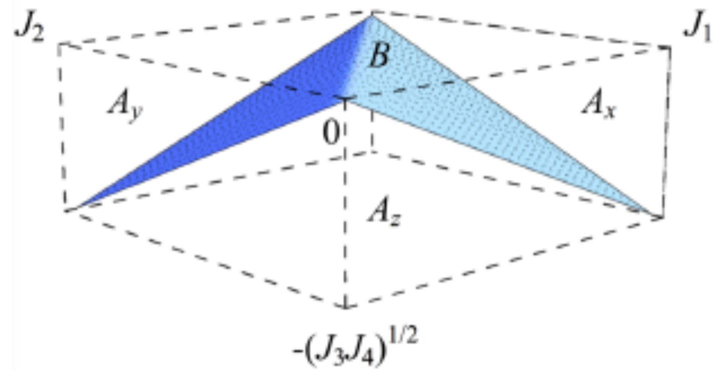


A. Petrescu et al.
arXiv: 1612.05134
(just published in PRB)

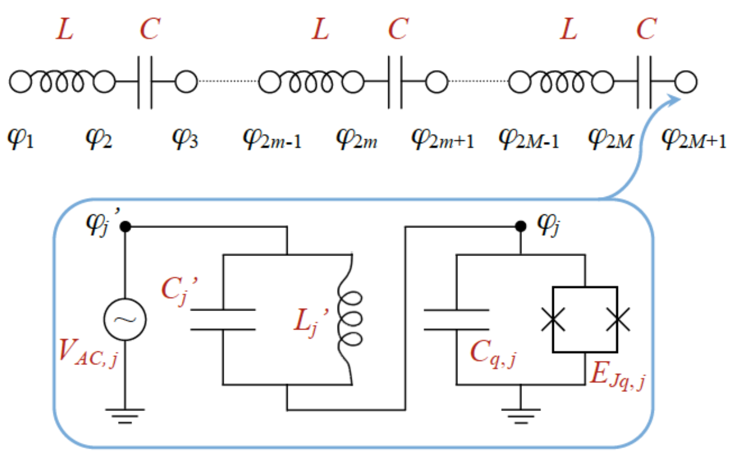
Kitaev spin ladders

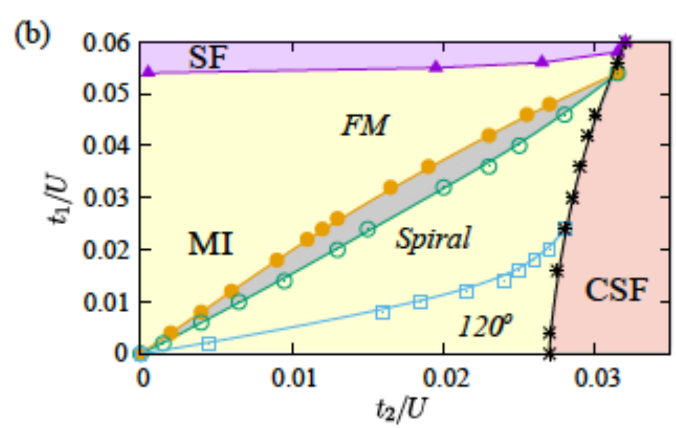


Realization of
Mini-toric code
Zhong et al. 2016



arXiv:1703.07322





Bosonic-Kane-Mele
Hubbard model

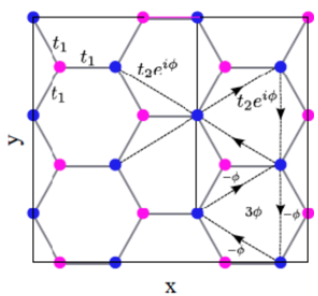
New chiral spin state

K. Plekhanov et al.
arXiv:1707.07037

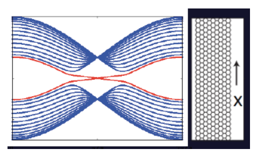
Quantum Simulators :

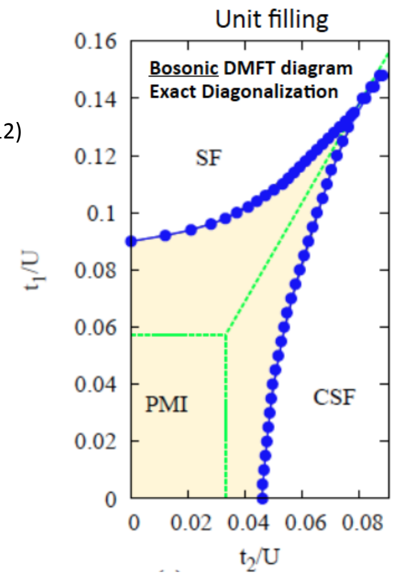
Quantum Hall phases, topological insulators, spin liquids (Kagome, Kitaev model, spin-1 chain) symmetry protected phases, bosons and superconductors, Majoranas, …

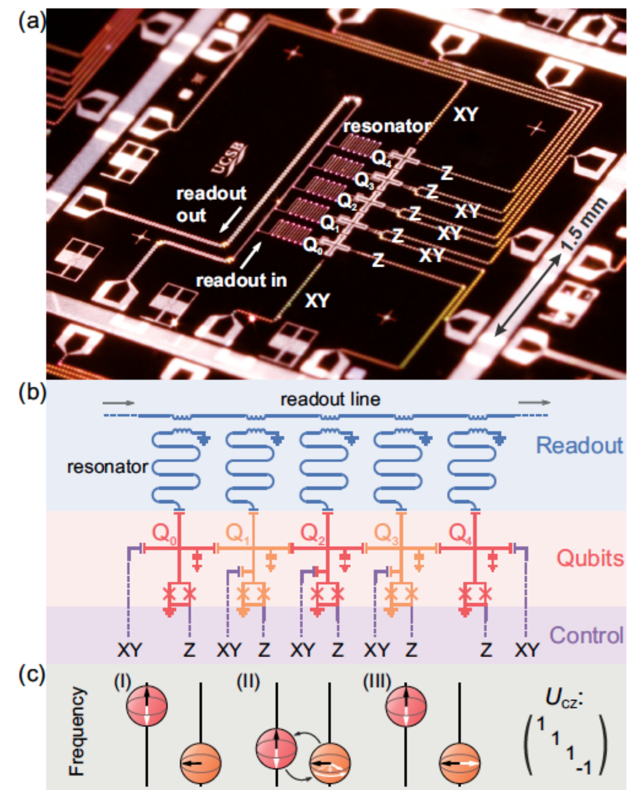
J. Martinis group



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





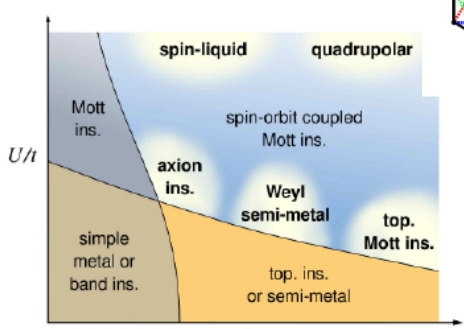


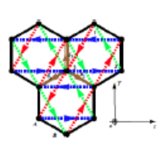
Chern insulators on graphene
realized experimentally in ultra-cold atoms
Photons and quantum materials
Many theorists involved (ENS Lyon, Bordeaux, ENS Paris, CPHT, LPS Orsay, UPMC, Cergy Pontoise, Toulouse,…)

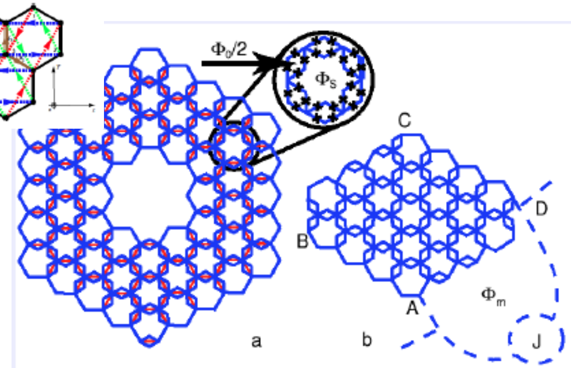
Simulating Quantum Materials (iridates) with Spin-orbit coupling (link with high energy and gauge theories: Chern-Simons models, gravitation),
L. Balents; Jackeli - Khaliulin

Protected qubits & Majoranas
Guichard, 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







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); A. Sterdyniak

Students and Post-docs involved in talk : thanks

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

Sherbrooke & Yale
2002 - 2011

Picture Jean-Francois Dars, Anne Papillault, CNRS

PhD players :

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Francis H. Song (New-York University, position at Google London 2017; Yale PhD 2012)
Tianhan Liu (UPMC and X, 2015 co-direction B. Douçot, now Cambridge & Oxford post-doc)
Alexandru Petrescu (Yale and Ecole Polytechnique PhD 2015, now Princeton post-doc)
Peter P. Orth (Yale 2010, Ames lab Faculty position)
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Prasenjit Dutt (Yale PhD 2013, Mathematical Finance at Stamford UBS); M. Filippone (ENS C. Mora, Geneva)
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Urs Ledermann (ETH Zurich 2001 T. M. Rice; at ABB)

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John Hopkinson (Sherbooke; now at UBC lecturer); Meirong Li (Sherbrooke; now Canadian Bank Director)
Doron Bergman (UCSB & Yale University; Big Data center, California), Stephan Rachel (Yale, prof. Melbourne),
Jens Koch (Yale, now Northwestern professor, Thomas Schmidt (Yale, prof. U. Luxembourg),
Ion Garate (Yale, now professor Sherbrooke), Christian Flindt (Aalto, prof.)
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Ecole Polytechnique