Topological States, protected quantum Transport and Light-Matter Control

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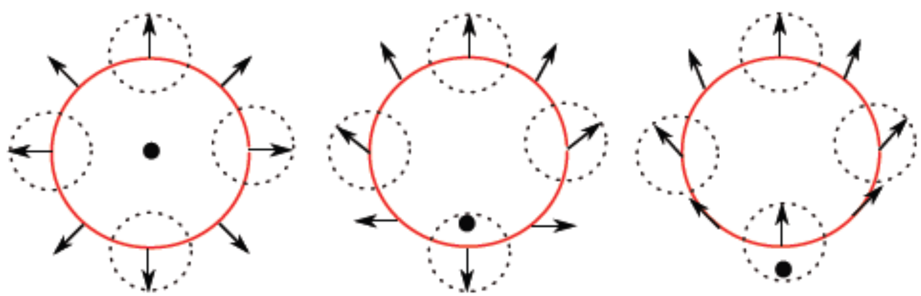
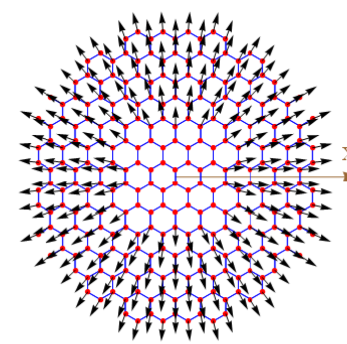
ESPOO LT28 Conference Finland, August 6th 2017, 45 Minutes (**15 general intro+30**)



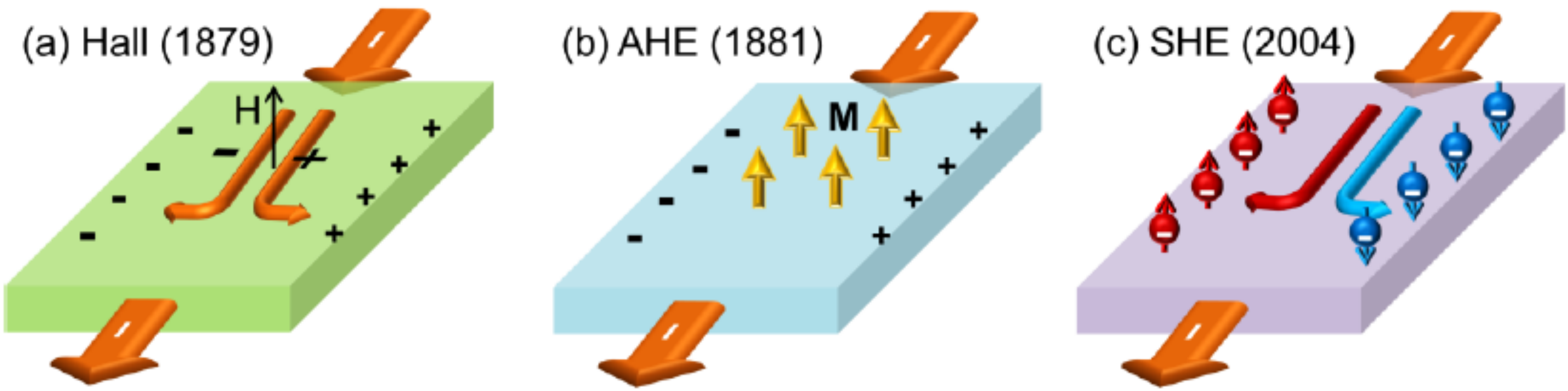


arXiv:0806.0379

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

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

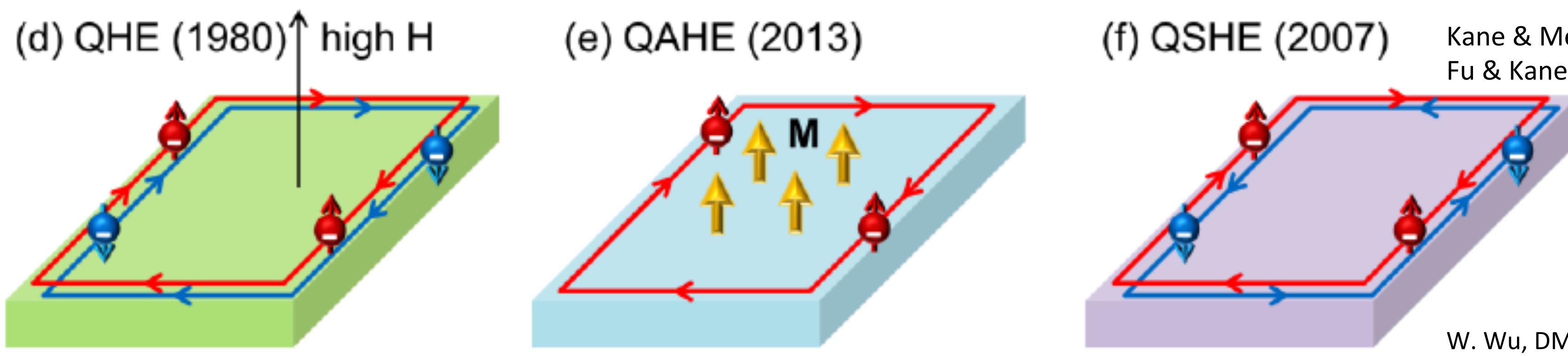
Topological states of matter:



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…)

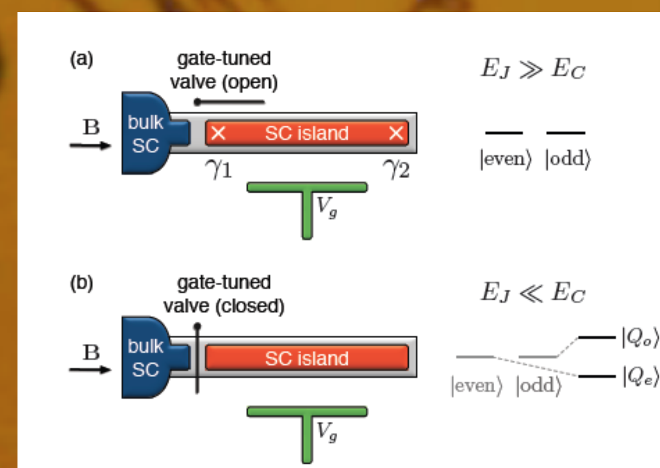
Particle and its own antiparticle

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…)

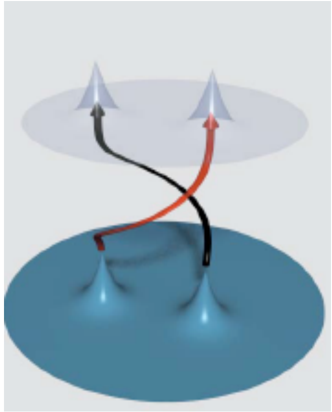


T. Kontos, A. Cottet (ENS)

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 $\quad \gamma_1 \to \gamma_2$
$\gamma_2 \to -\gamma_1$

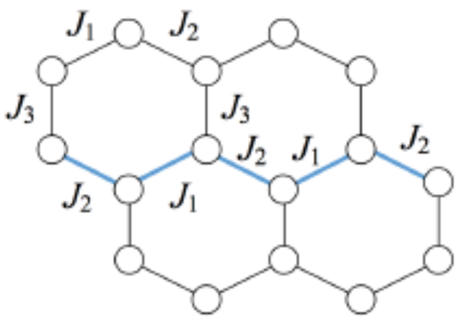
$$(\hat{\gamma}_2 + i\hat{\gamma}_1)\,|\Psi_0\rangle = i\,(\hat{\gamma}_1 - i\hat{\gamma}_2)\,|\Psi_0\rangle = i\hat{c}|\Psi_0\rangle$$

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

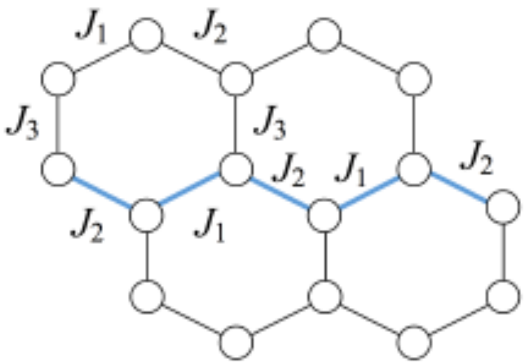


Recent efforts M. Hermanns, S. Trebst
J. Vidal, S. Dusuel,...
Works with T. Liu, B. Douçot; F. Yang, A. Soret

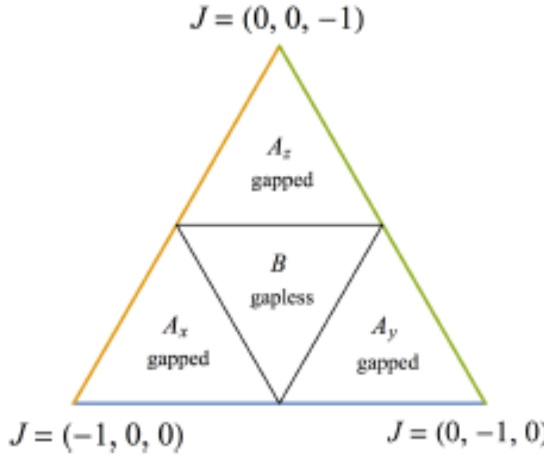
Spin Liquids & Superconductivity

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

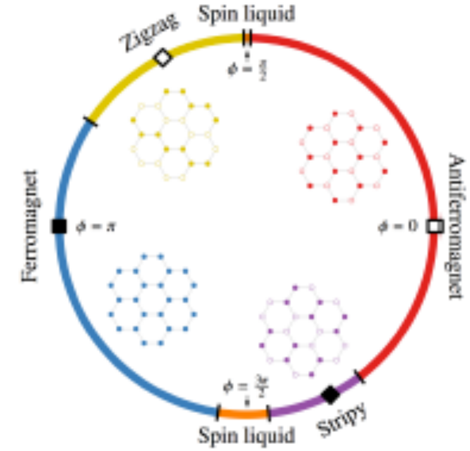
Simulation in cold atoms:
Duan, Demler, Lukin 2003
Kitaev paper 2005 published later



A. Kitaev
1997 toric code
2005 arXiv

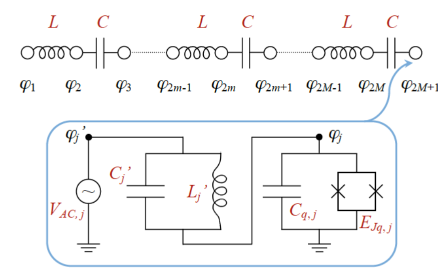


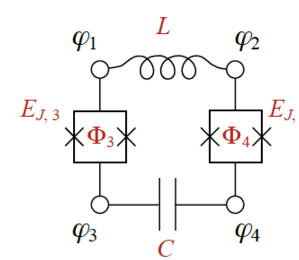
J. Rau & H. Y. Kee, review
S. Trebst, review
Iridate materials, αRuCl3
Mixing angle (Heisenberg & Kitaev)



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





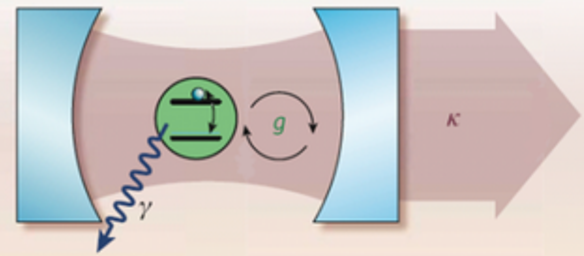
Engineering minimal spin liquid models,
connection to p-wave BCS theory, topology from Mott, doped Mott insulators
Ladders and Boxes in cQED & Josephson junctions; work with Fan Yang & Ariane Soret, see ArXiv 2017

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

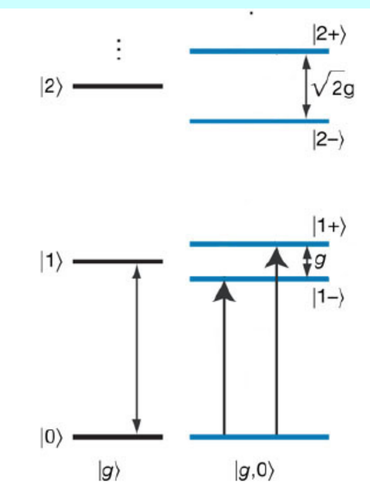
cavity QED, ENS Paris and Collège De France



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

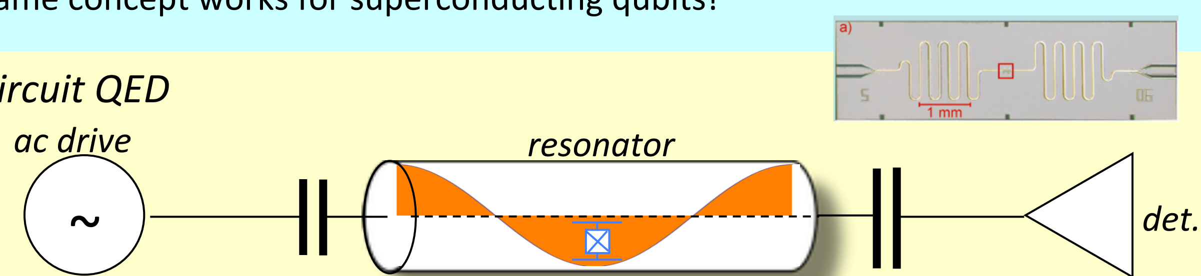
Jaynes-Cummings Hamiltonian

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



- same concept works for superconducting qubits!

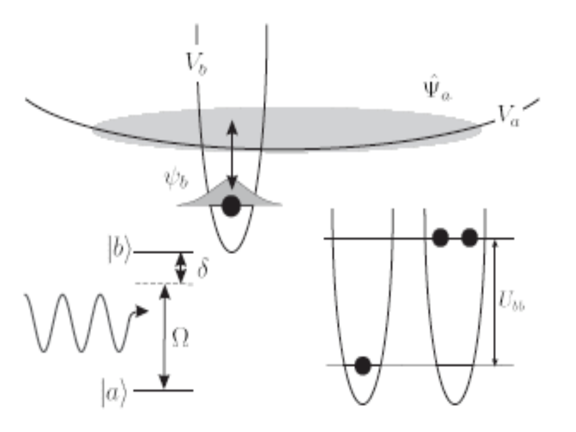
circuit QED



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); H. Pothier…

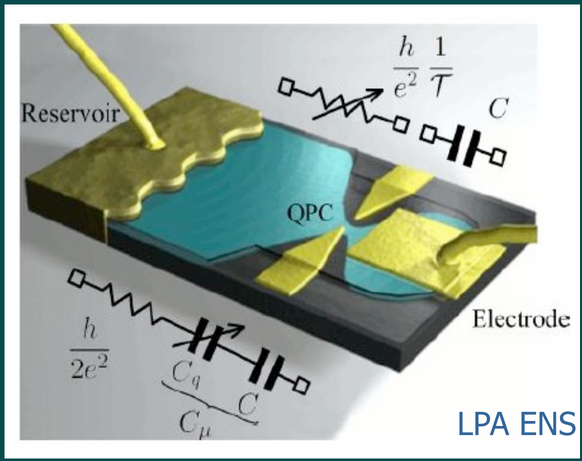
COLD-ATOMIC Quantum IMPURITIES

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)



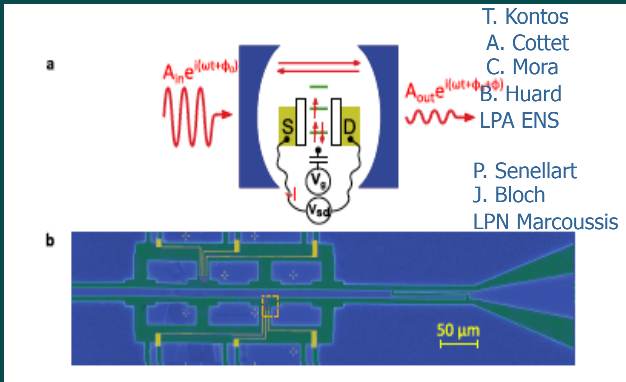
RC circuits

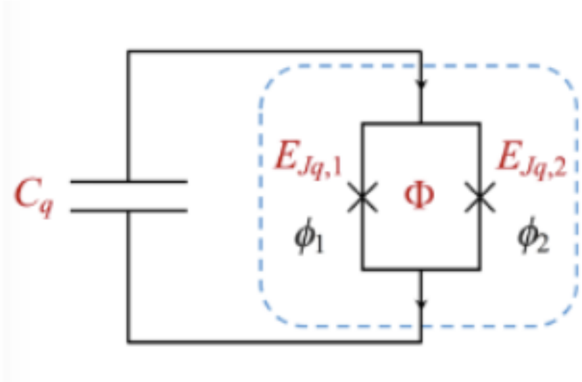
M. Buettiker, H. Thomas, and A. Pretre, Phys. Lett. A 180, 364 - 369,(1993)
J. Gabelli et al., Science **313**, 499 (2006); G. Feve et al. 2007 (LPA ENS)
J. Gabelli et al. Rep. Progress 2012
C. Mora and K. Le Hur, Nature Phys. 6, 697 (2010)
Y. Hamamoto, et al. Phys. Rev. B **81**, (2010) 153305
Y. Etzioni,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

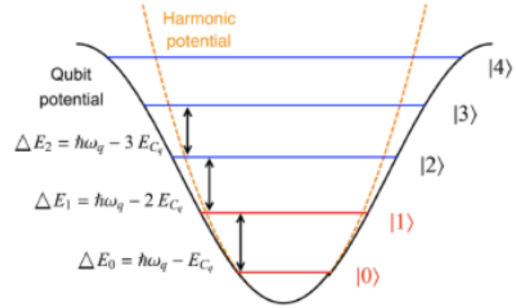


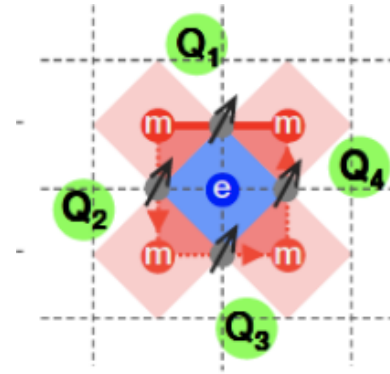
Hybrid Photon-Nano Systems, Impurities with Photons

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 …
Experiments in China, Deng et al. arXiv:1509.06141 (G.-P. Guo)







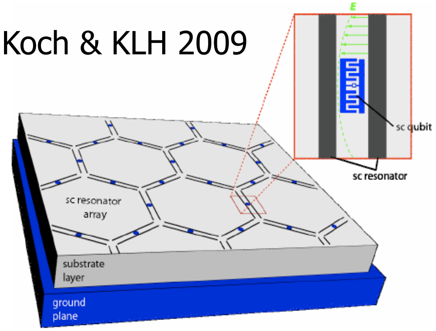


Light-Matter engineering:

$$H_{\exp}/\hbar = \omega_r a^\dagger a + \sum_{j=1}^{4} \omega_j \sigma_j^\dagger \sigma_j + g \sum_{j=1}^{4} (\sigma_j^\dagger a + \sigma_j a^\dagger),$$

Zhong et al. arXiv: 1608.04890 (PRL)

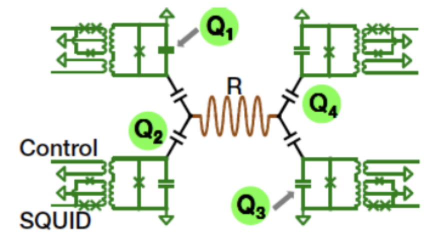
Koch & KLH 2009



$$C_{\text{loop}} = X_4' X_3' X_2' X_1'$$

$$C_{\text{loop}} |\psi_g\rangle = |\psi_g\rangle$$

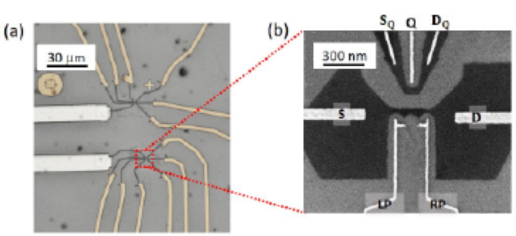
$$Z' C_{\text{loop}} Z' |\psi_g\rangle = -|\psi_g\rangle.$$

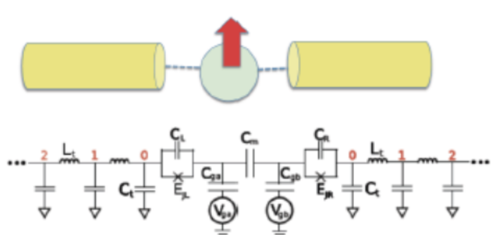


A. Houck, H. Tureci, J. Koch
Nature Physics insight

H. N. Dai et al. arXiv:1602.05709
Simulation of ring processes
Rb cold atoms

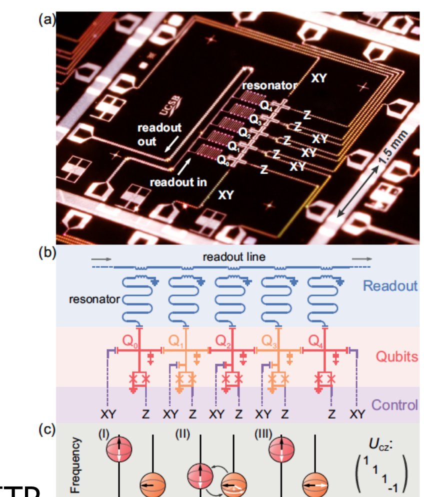
Mesoscopic Kondo graphene
cQED, group of G.-P. Guo





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

Peropadre et al. 2013,
Scattering center



J. Martinis
Group google, KITP

Goals of the presentation

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

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

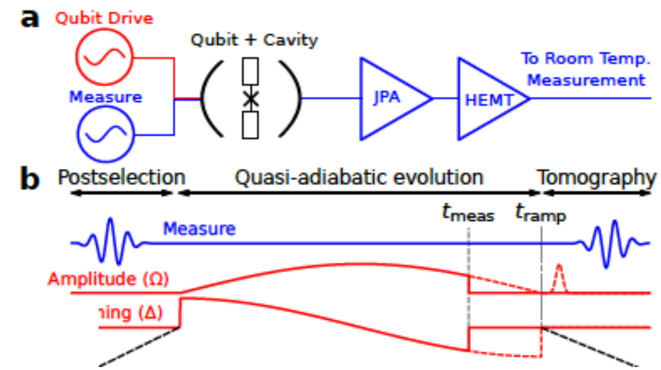
Drive and Floquet protocols, interactions, Majorana particles

Quantum information probes

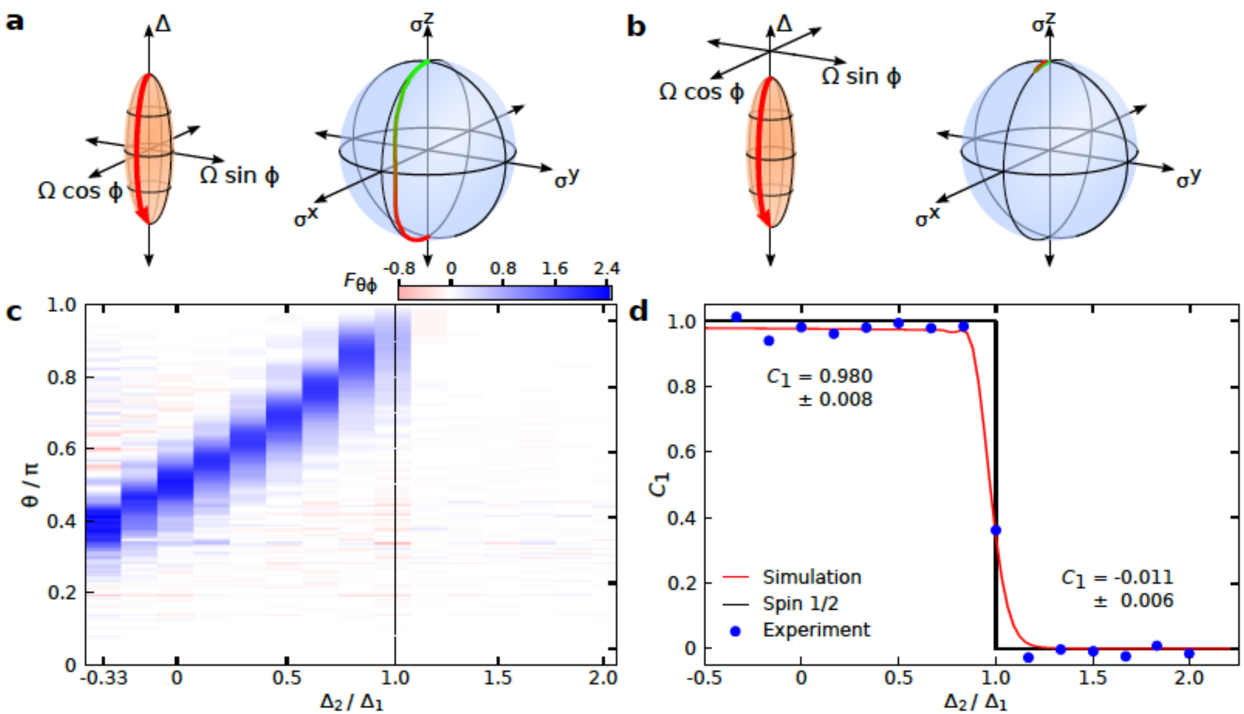
Let's Start from a measurement

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

Similar devices at Chalmers, Goteborg P. Delsing & G. Johansson



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



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

Ramp protocole

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

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

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

Tramp 1micro.s

What does this mean?

Theory by Polkovnikov
Gritsev and Kolodrubetz

Topology on a Sphere

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

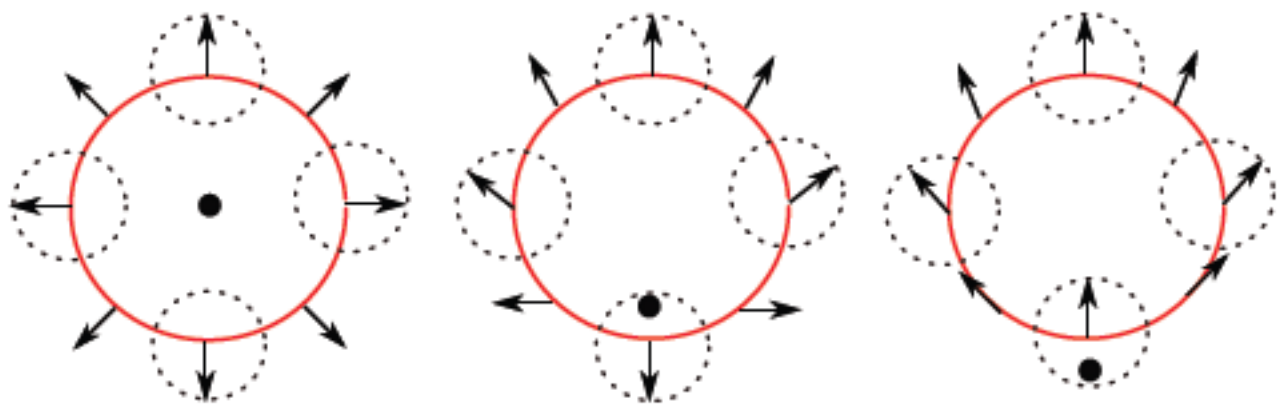
Topology of a spin-1/2 particle

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

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

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)

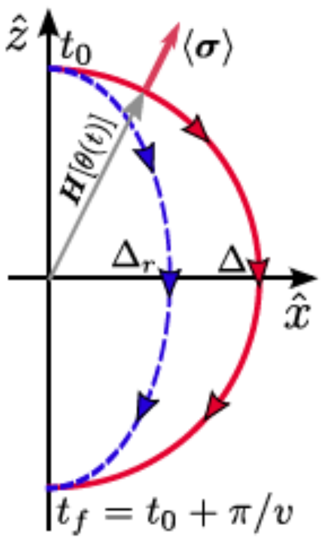
Berry curvature and Chern number

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

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**

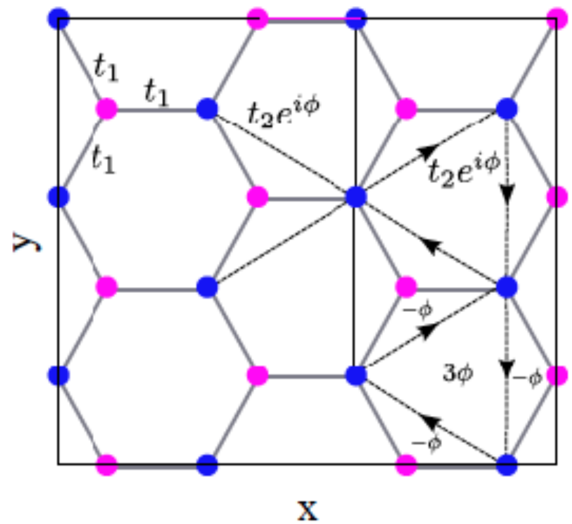
Berry Phase can be simulated by a time-dependent spin-boson model (see later)

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

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

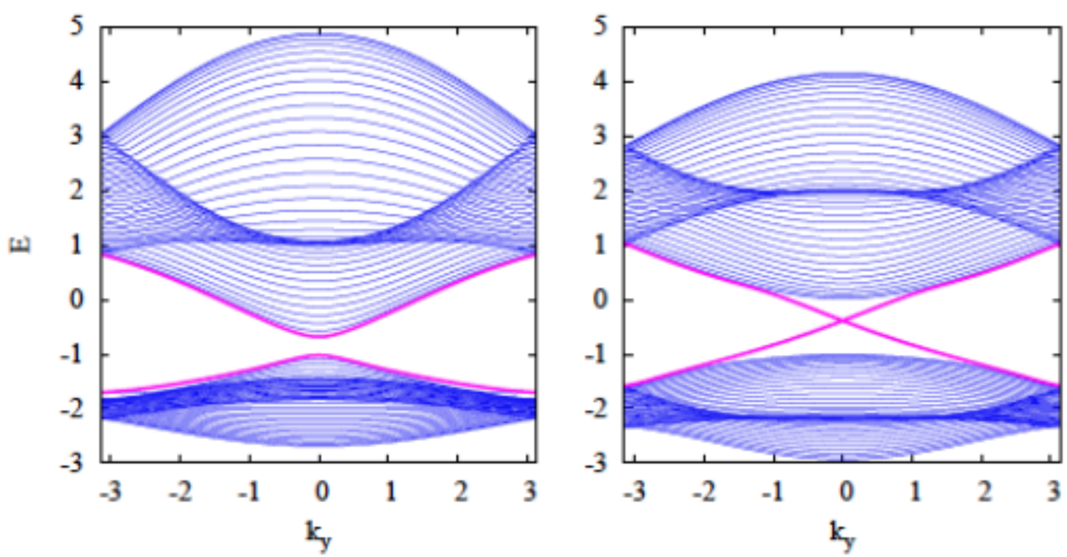
F. D. M. Haldane, Phys. Rev. Lett. **61**, 2015 (1988)

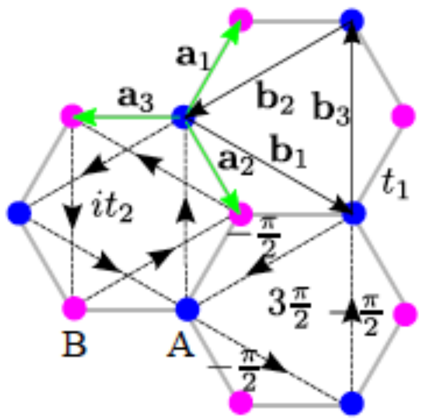
No net flux

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 $M < 3\sqrt{3} t_2 \sin\phi$





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

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

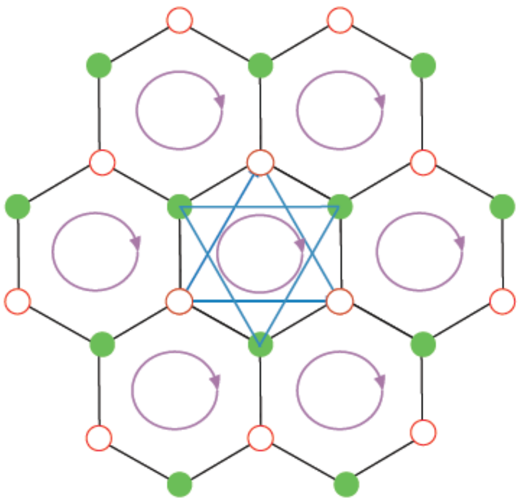
Jotzu et al. arXiv:1406.7874

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



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

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

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

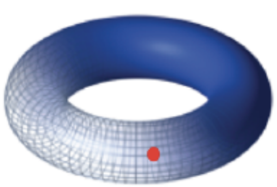
$$F_{xy}^{\alpha} = [\nabla_{\boldsymbol{k}} \wedge \mathcal{A}^{\alpha}(\boldsymbol{k})]_z = \partial_{k_x} A_y^{\alpha} - \partial_{k_y} A_x^{\alpha}.$$

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

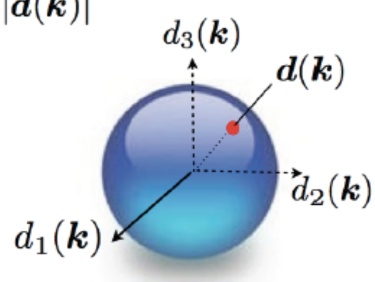
$$C^{-} = \frac{1}{4\pi}\int_{\mathrm{BZ}} dk\, \sin\theta_{\boldsymbol{k}} \left(\frac{\partial\theta_{\boldsymbol{k}}}{\partial k_x}\frac{\partial\phi_{\boldsymbol{k}}}{\partial k_y} - \frac{\partial\phi_{\boldsymbol{k}}}{\partial k_x}\frac{\partial\theta_{\boldsymbol{k}}}{\partial k_y} \right)$$

Brillouin zone

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



Bloch sphere



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

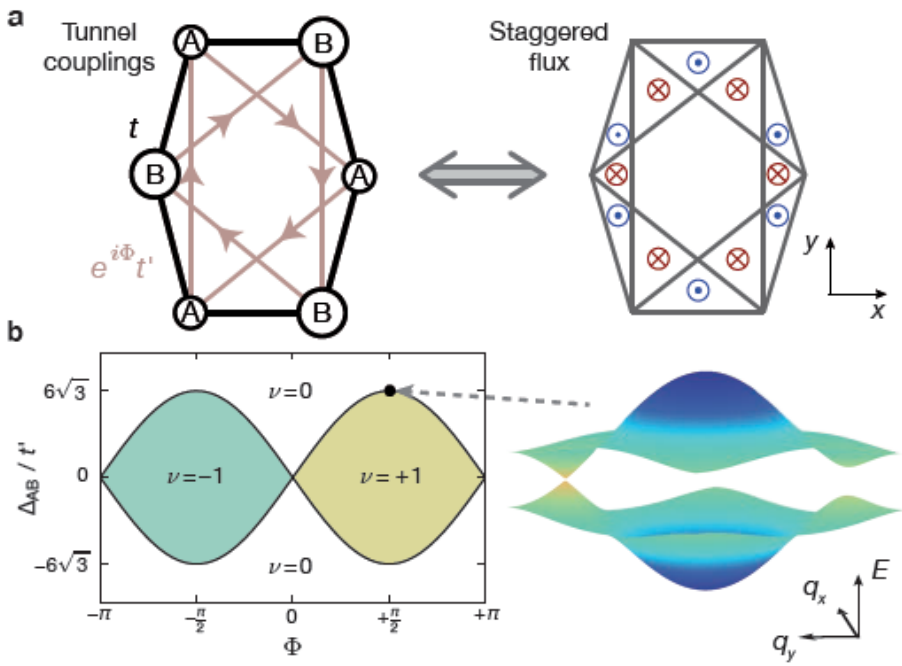
Review by J. Cayssol académie des sciences 2013, arXiv:1310.0792

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

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

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



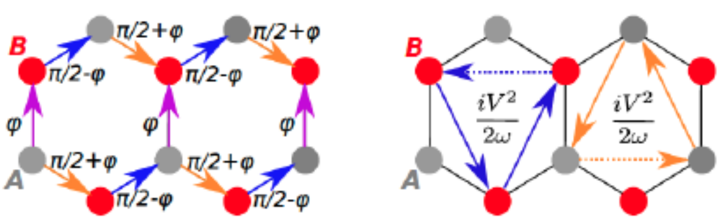
$$\hat{U}(T,t_0) = \zeta \exp\left(-i\int_{t_0}^{T+t_0} \hat{H}(t)dt\right) = \exp(-iT\hat{H}_{\text{eff}})$$

Modulation of optical lattice

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

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

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

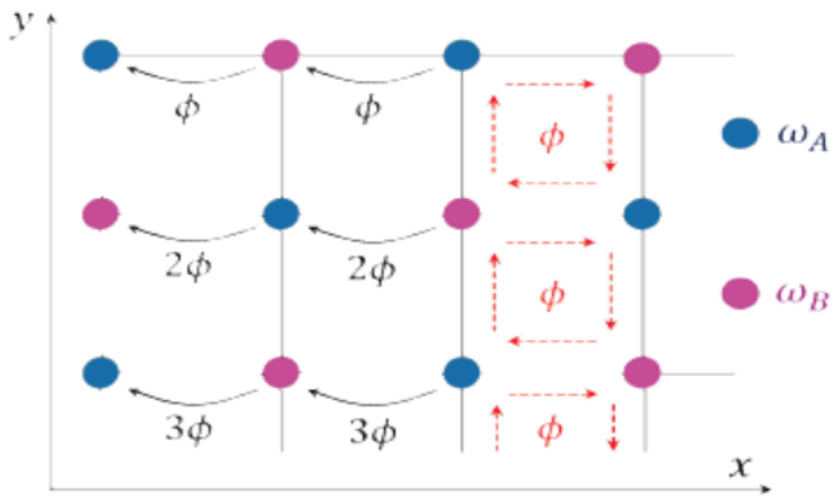


Other protocole:
K. Plekhanov, G. Roux, KLH
Recent paper PRB 2017, arXiv 2016
Topology robust to deformation (anisotropy)

K. Plekhanov, Phd 2018

Magnetic field for neutral particles

Cours Jean Dalibard collège de France



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

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

Cold Atoms:

Jaksch & Zoller 2003

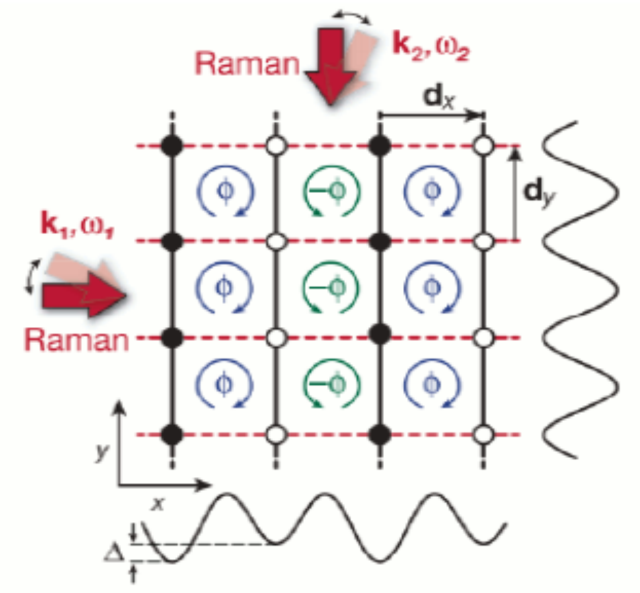
A. L. Fetter RMP 2009; J. Dalibard, F. Gerbier, G. Juzeliunas, P. Ohberg RMP 2011;
I. Bloch et al. Nature (2012); Juzeliunas & Spielman NJP (2012);...
D. Cocks, P. Orth, S. Rachel, M. Buchhold, KLH, W. Hofstetter PRL 2012

- Ways to implement magnetic fields & gauge fields

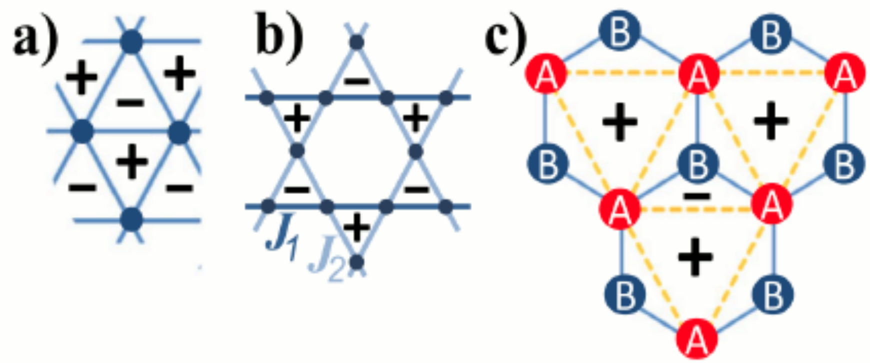
N. Goldman et al. Phys. Rev. Lett. 103, 035301 (2009)

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)

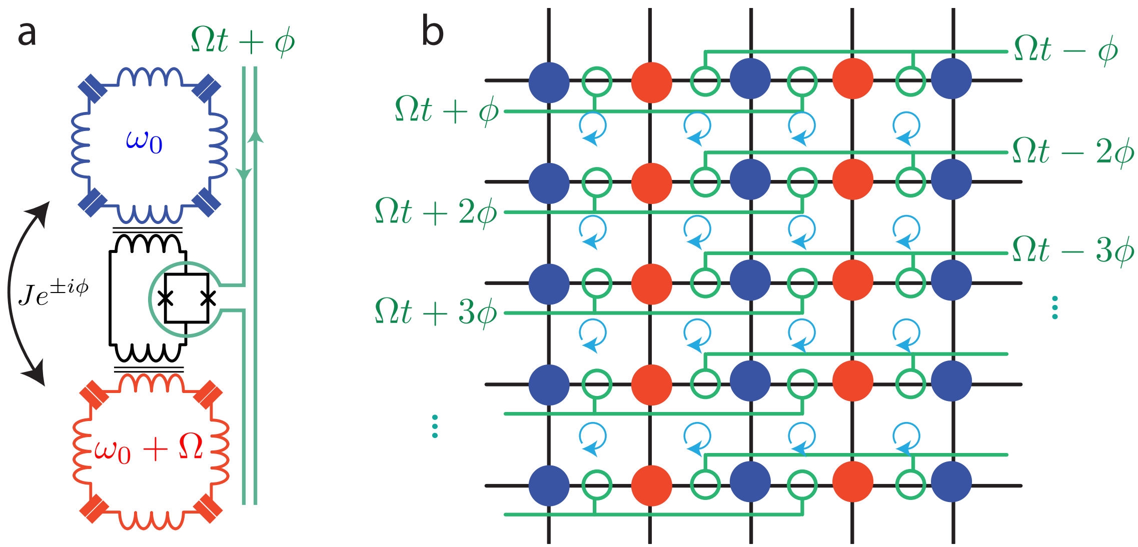


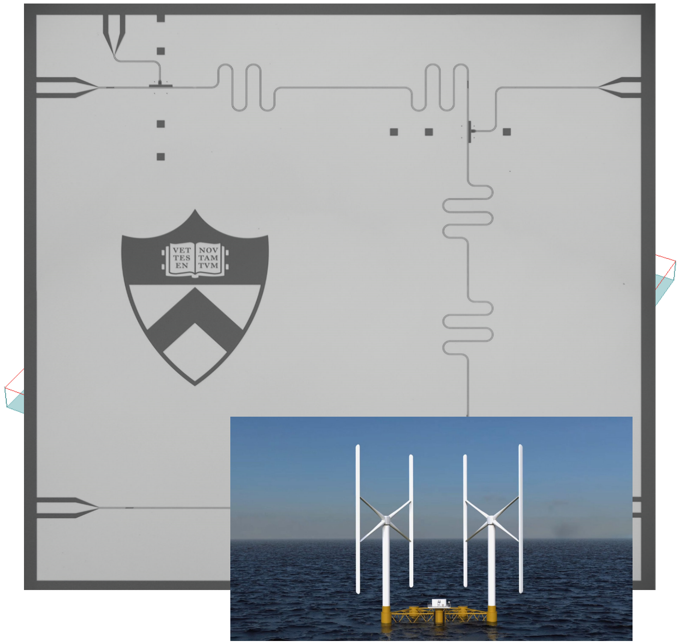
Floquet Topological Insulators:
Review J. Cayssol, B. Dora, F. Simon, R. Moessner, arXiv:1211.5623

Other Way to Produce Gauge Fields

Uniform Magnetic Field

Mini lattice in Nb: A. Houck lab

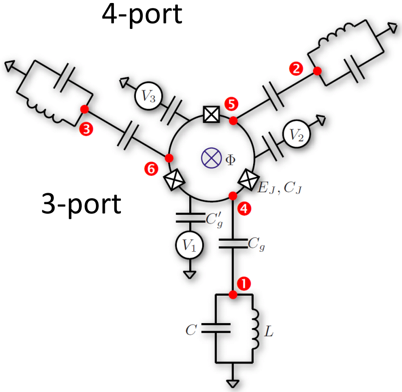




K. Fang, Z. Yu and S. Fan Nature Photonics 6, 782 (2012)

Seems feasible to realize in cQED arrays

(J. Gabelli, J. Esteve, F. Appas); Orsay



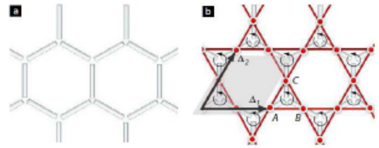
Nano Circulator implementation (other ferrite devices, see later):

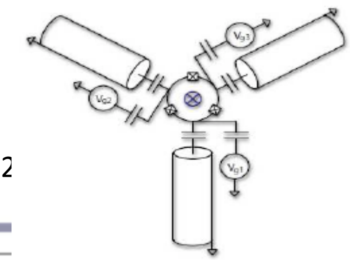
J. Koch, A. Houck, KLH and S. Girvin 2010; A. Kamal, J. Clarke, M. Devoret Nat. Phys. 2011

Realization: P. Roushan, C. Neill et al. Nature Physics 2017 (Santa Barbara)

Quantum Anomalous Hall Effect

F. D. M. Haldane 1988

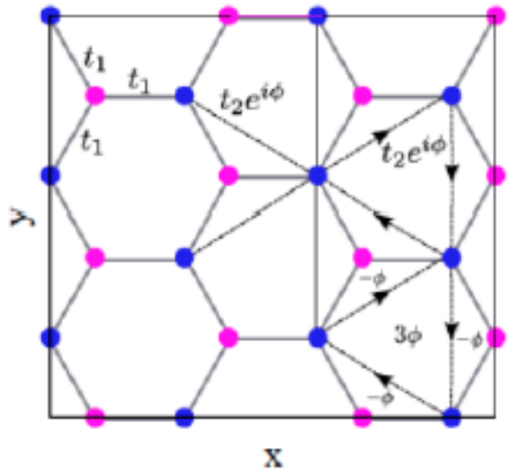


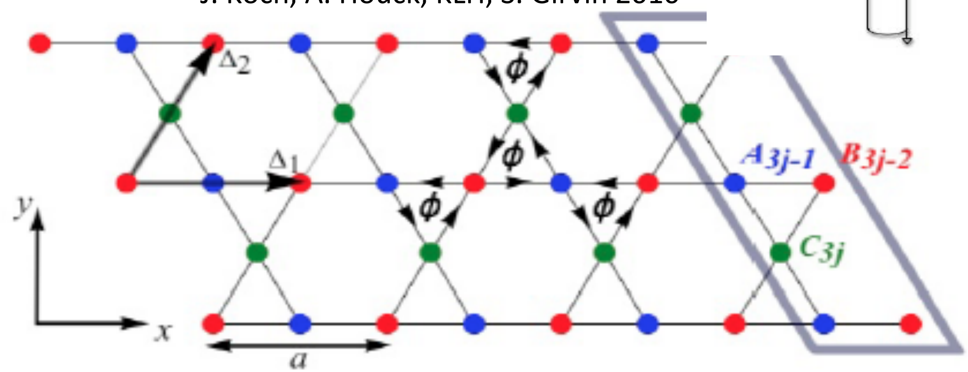


Kagome version:

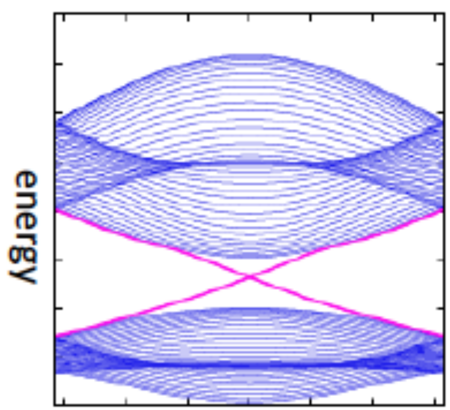
A. Petrescu, A. A. Houck and KLH, 2012

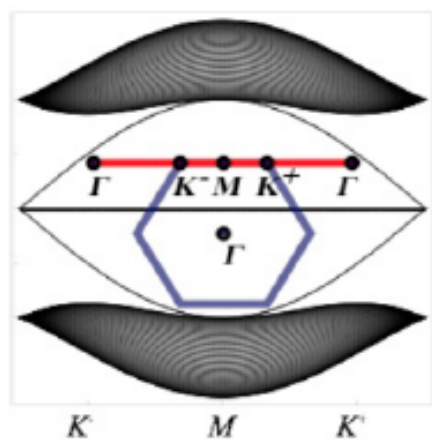
J. Koch, A. Houck, KLH, S. Girvin 2010

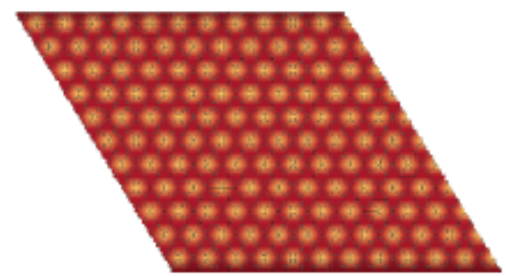




Flat bands observed in polaritons (A. Amo , J. Bloch)







Localization in Hexagon rings

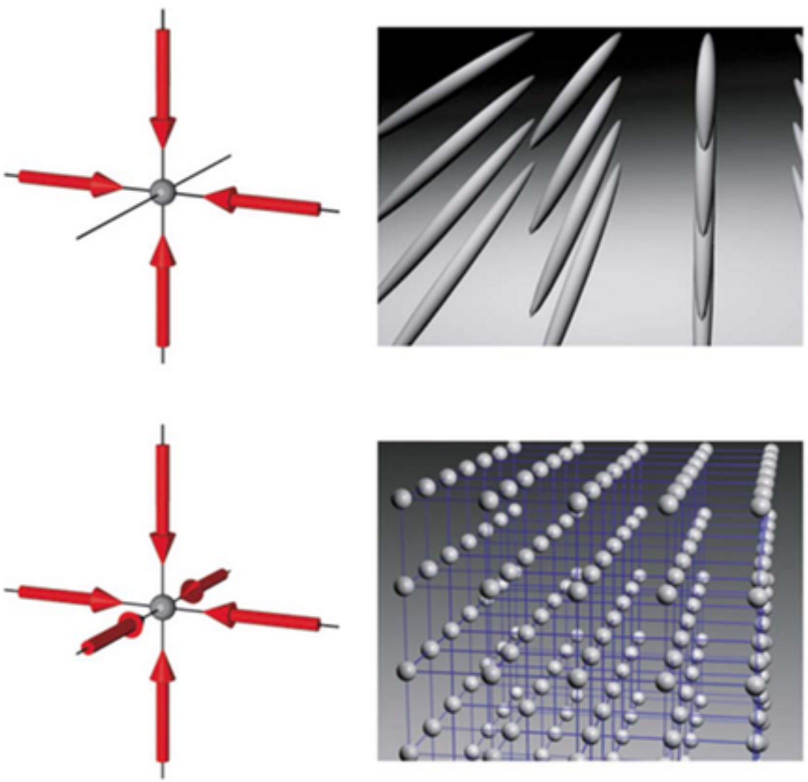
Graphene +gap

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)

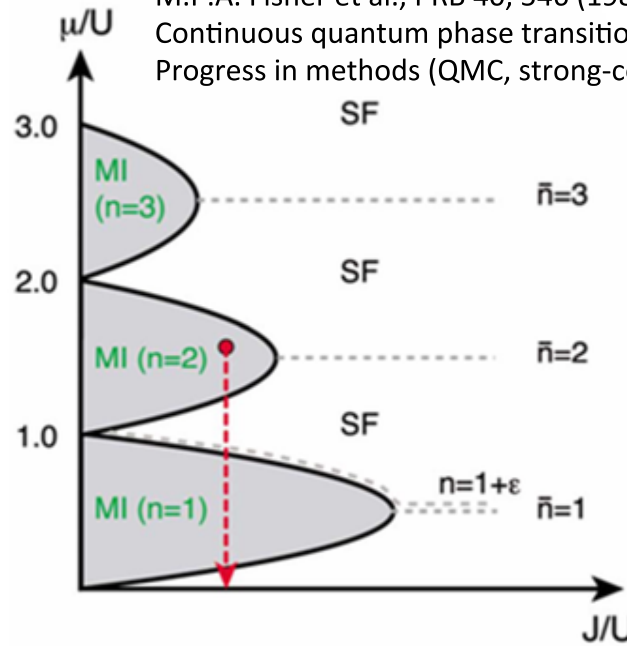
D. Jaksch et al., Phys. Rev. Lett. **81**, 3108 (1998)
M. Greiner et al., Nature **415**, 39 (2002)



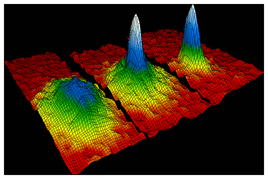
e.g., realization of the Bose-Hubbard model:

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

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



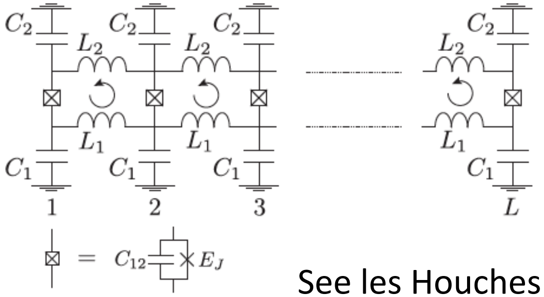
Nobel price 2001



Bose-Einstein condensate

Also Josephson junction arrays

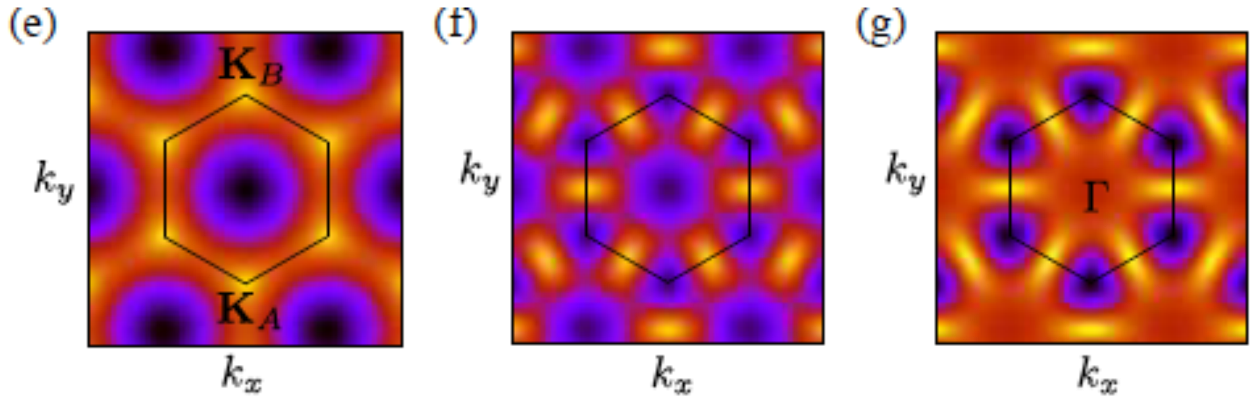
Progress
Neel,
Grenoble

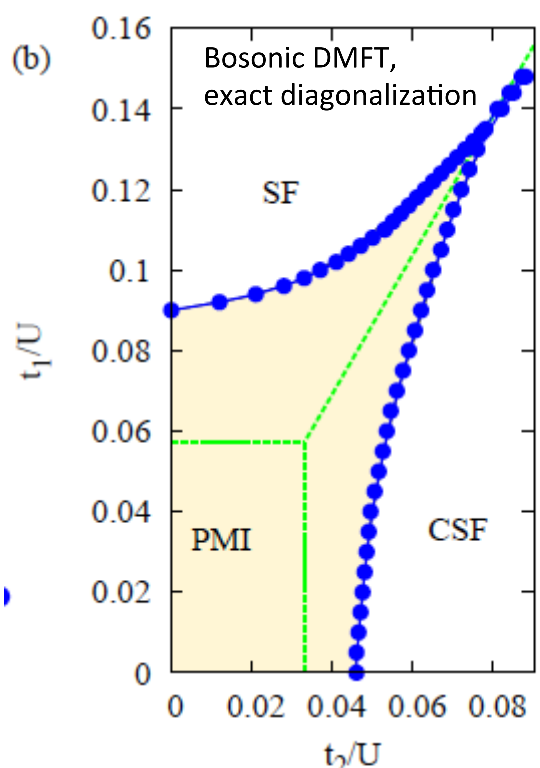


See les Houches lectures: D. Esteve & D. Vion; M. Devoret; J. Martinis & Kevin Osborne 2004

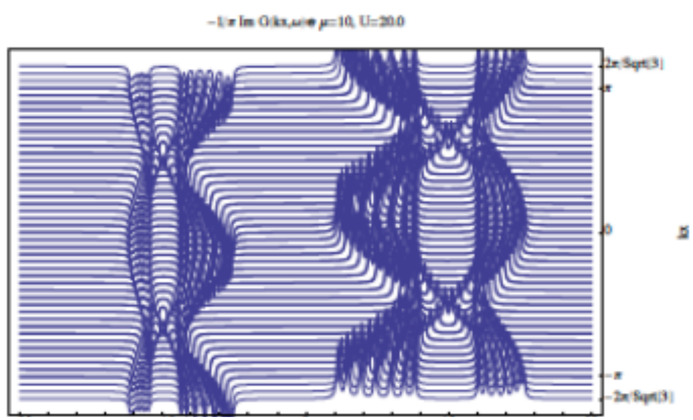
Exotic bosonic phases: Haldane model

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

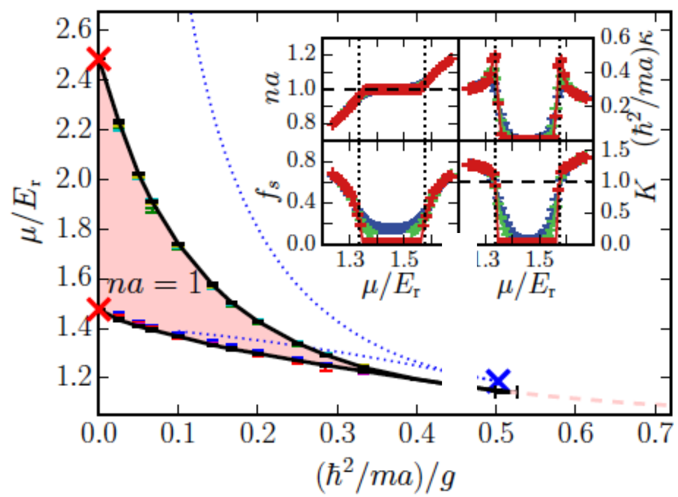
Similar models on <u>square</u> lattice:
L. K. Lim, C. M. Smith and A. Hemmerich,
Phys. Rev. Lett. 100, 130402 (2008) and PRA 2010

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

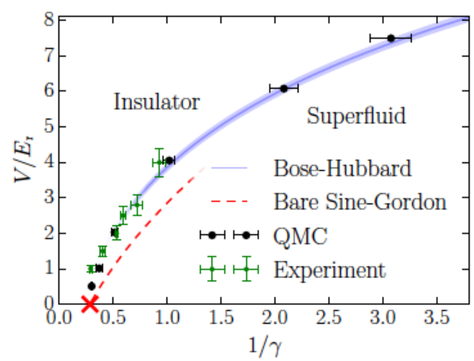
Mott 1D….

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

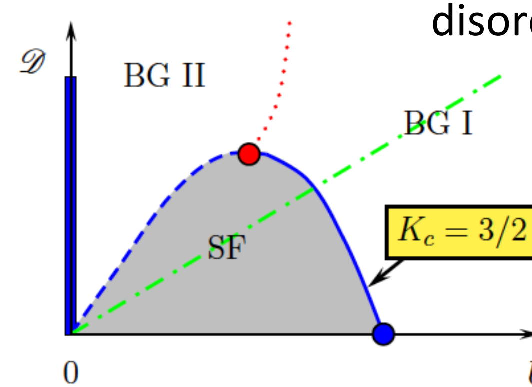
Kosterlitz-Thouless transition



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



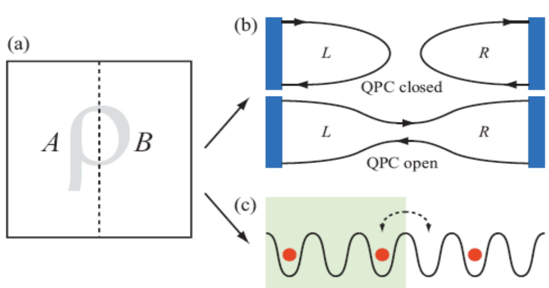
disorder



H. J. 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)



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)

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

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

Bloch sphere: dissipation

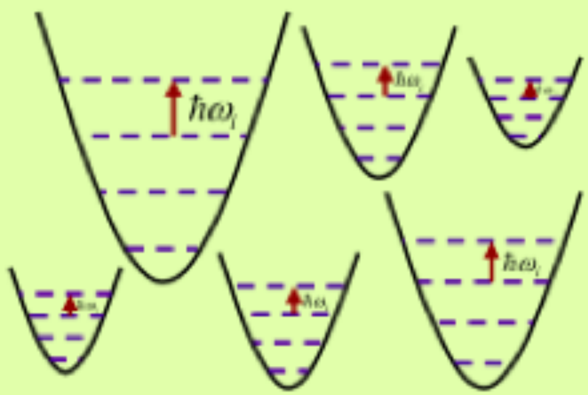
Review submitted at Comptes Rendus Academie des Sciences, arXiv: 1702.05135

Kosterlitz-Thouless transition and topology

- Model the environment by quantum harmonic oscillators

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

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



Bosonic bath

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

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

Ohmic dissipation

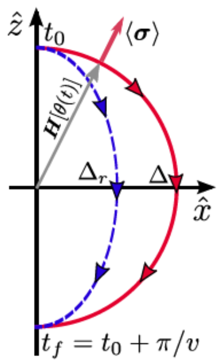
$$J(\omega) = \alpha \pi \hbar\omega/2$$

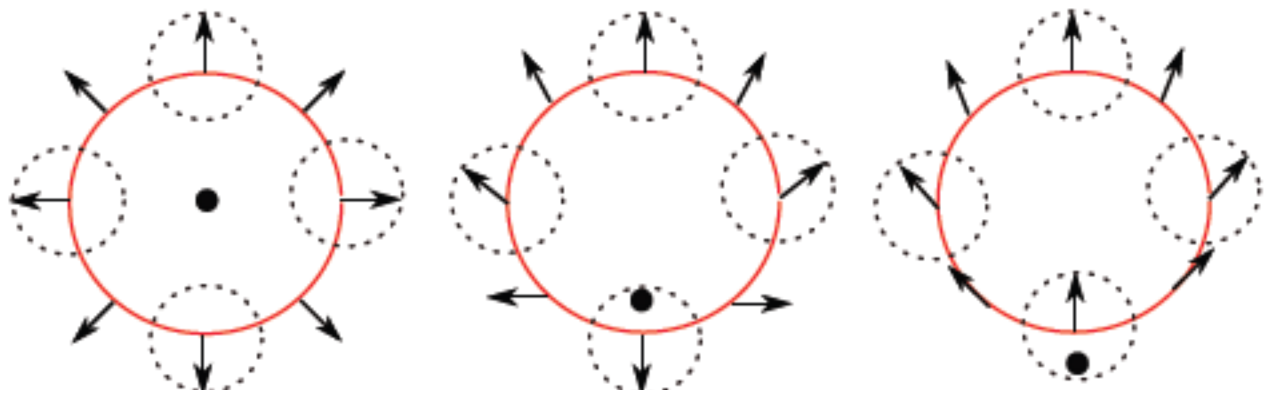
Dissipation strength

Influence of a Caldeira-Leggett bath

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

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





Bi-partite measurement

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

$$\mathcal{H}_{diss} = \sigma^z \sum_k \frac{\lambda_k}{2}(b_k + b_k^\dagger) + \sum_k \omega_k \left(b_k^\dagger b_k + \frac{1}{2}\right).$$

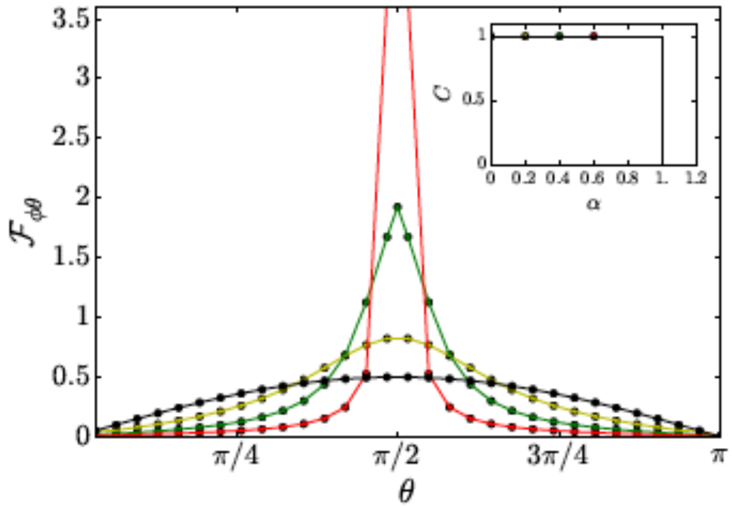
$J(\omega) = \sum_i |\lambda_i|^2 m_i \, \delta(\omega-\omega_i) = J(\omega) \propto \alpha\omega$

Loic Henriet, A. Sclocchi, Peter P. Orth, KLH 2017

Kosterlitz-Thouless transition

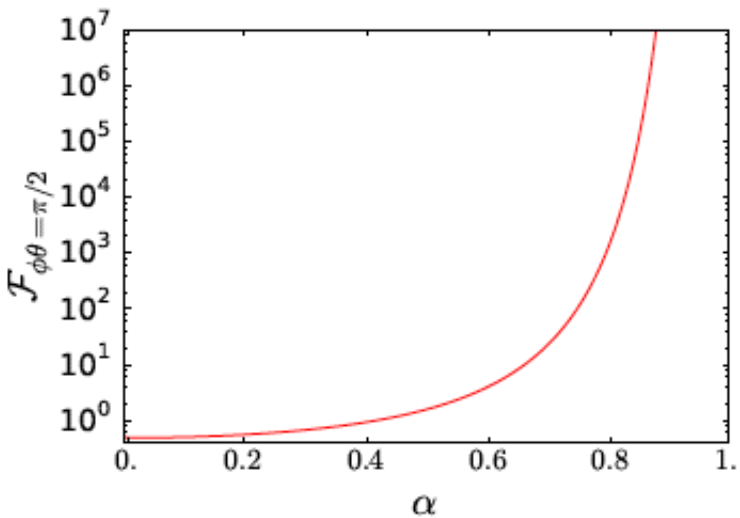
$$|g\rangle = \frac{1}{\sqrt{p^2+q^2}}\left[pe^{-i\phi}|\uparrow_z\rangle \otimes |\chi_\uparrow\rangle + q|\downarrow_z\rangle \otimes |\chi_\downarrow\rangle\right],$$

Variational method
1 polaron expansion (Silbey Harris)



$$\mathcal{F}_{\phi\theta} = -\partial_\theta\langle\sigma^z\rangle/2.$$

Bethe Ansatz calculation (based on
Cedraschi & Buttiker Annals of Physics paper)



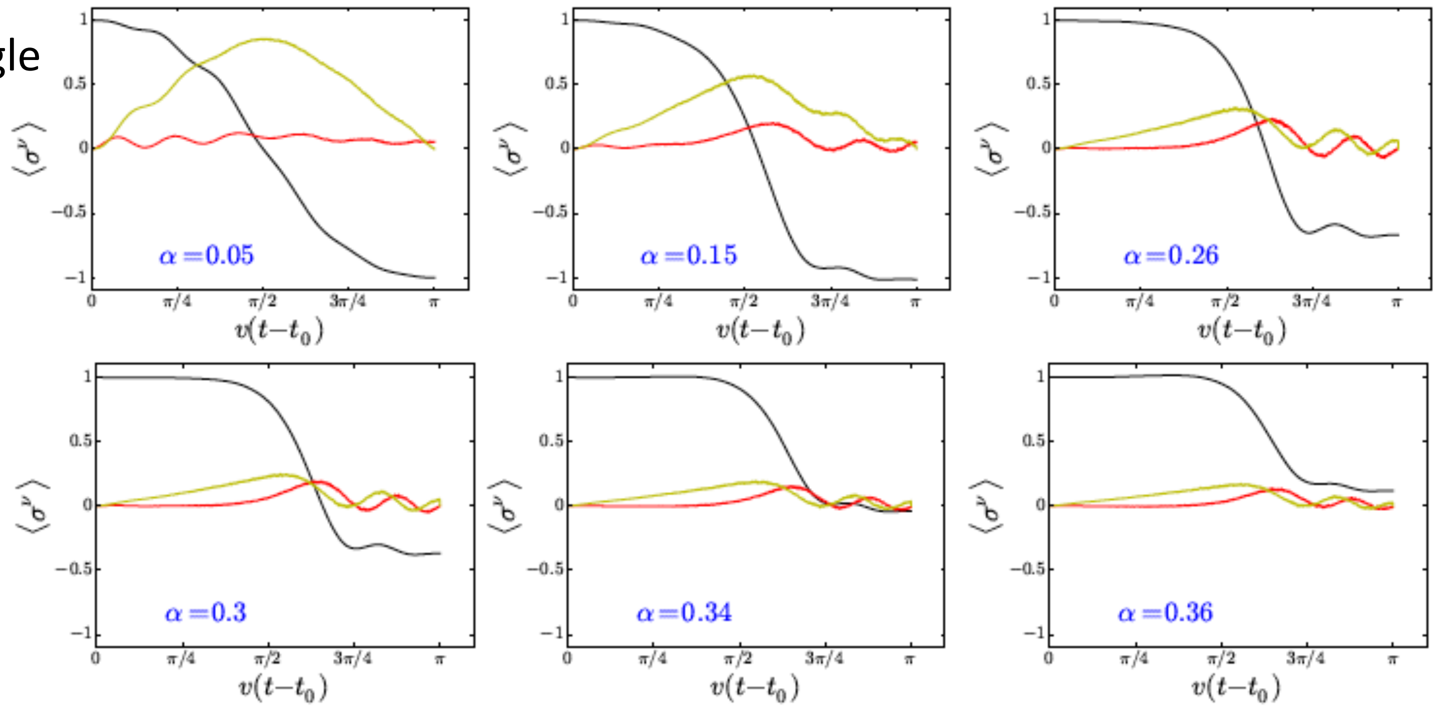
$$\mathcal{F}_{\phi\theta=\pi/2} = F(\alpha)\left(\frac{\omega_c}{H}\right)^{\frac{\alpha}{1-\alpha}},$$

In Agreement with Kosterlitz-Thouless transition at α=1
Antiferromagnetic-Ferromagnetic transition of Kondo model

Driven effects: stochastic approach

Polar angle = vt

(1 pulse)



Faraday Response: Climbing Up-hill

[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).

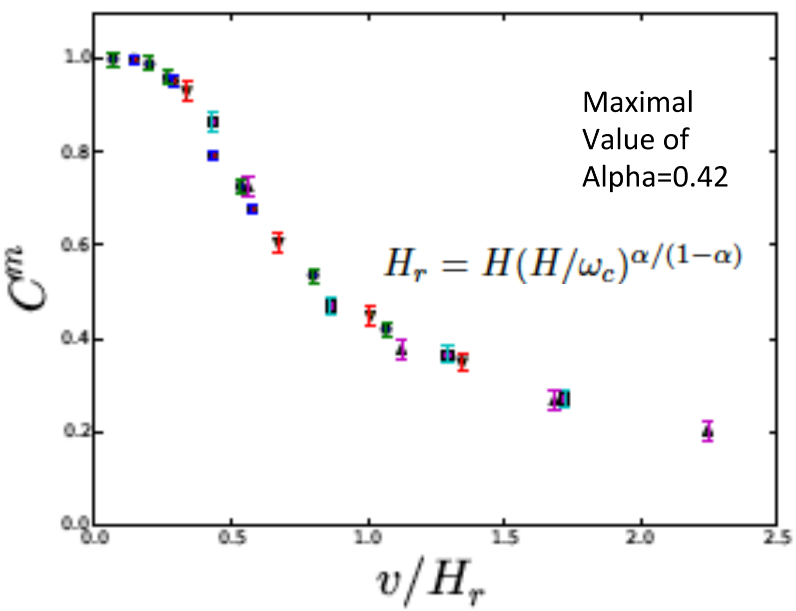
[35] P. P. Orth, A. O. Imambekov, and K. Le Hur, Phys. Rev. A **82**, 032118 (2010).
[36] P. P. Orth, A. O. Imambekov, and K. Le Hur, Phys. Rev. B **87**, 014305 (2013).
[37] L. Henriet, Z. Ristivojevic, P. P. Orth, and K. Le Hur, Phys. Rev. A **90**, 023820 (2014).
[38] L. Henriet and K. Le Hur, Phys. 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).

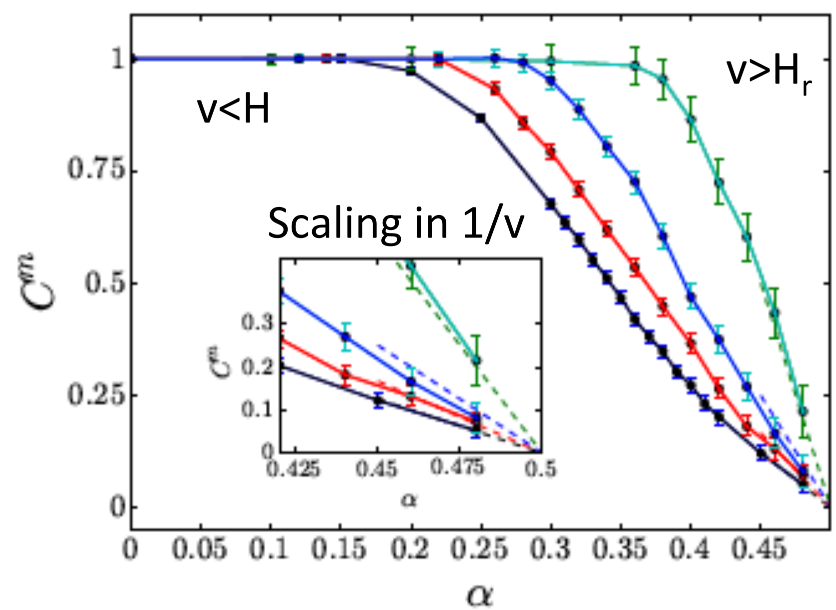
Adiabatic versus non Adiabatic limit

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

$v \ll H_r,$

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, 1969)

Effective model

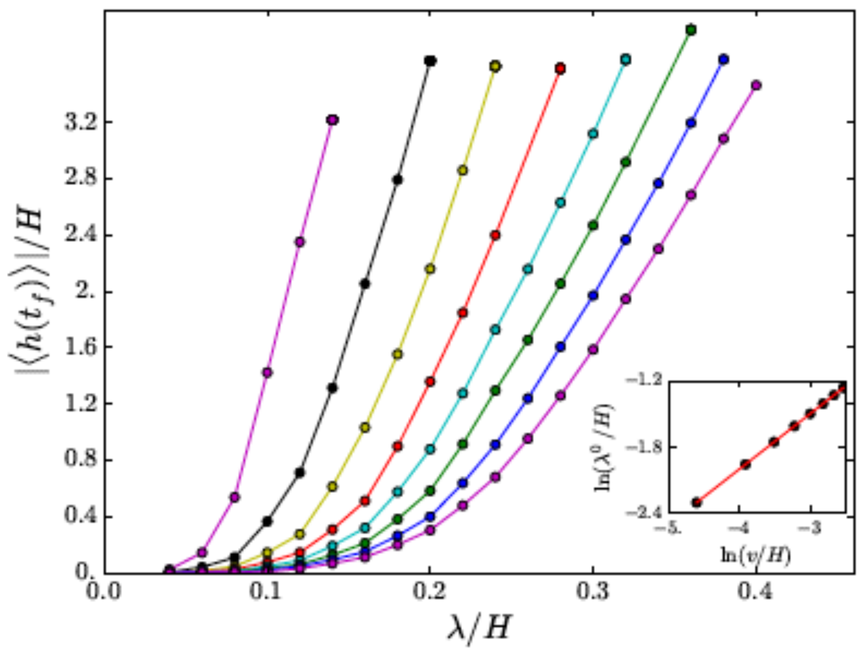
Induced field compensates the applied magnetic field: « photo-emission »
Loic Henriet, A. Sclocchi, Peter P. Orth, KLH 2017

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

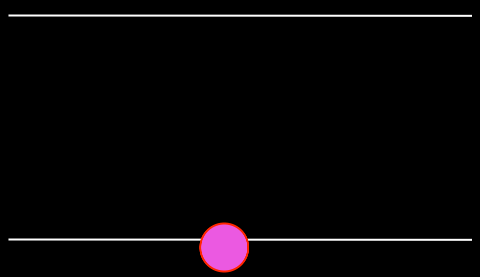


Ramsey Interferometry with environment, QPC: T. Goren, KLH, E. Akkermans, submitted

Entanglement, Uncertainty & Mixed State for spin

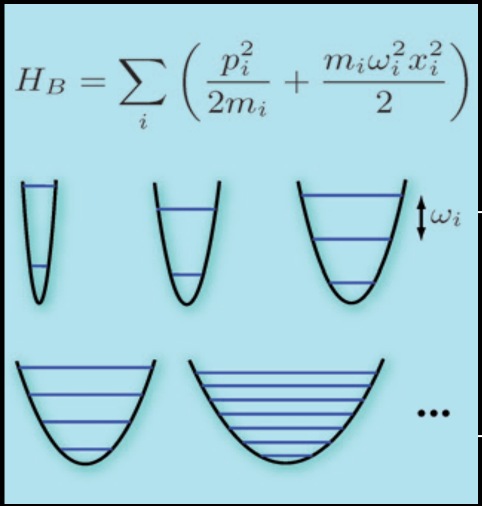
For a large sub-system, uniformity of Teff:
entanglement spectrum, Li and Haldane; Bernevig; Regnault···

E=0

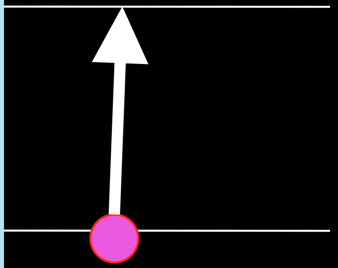


p_-

p_+



$E \sim \alpha \ln(\omega_c/\Delta)$



$\alpha = 0$

$\alpha \neq 0$

$p_+(\alpha) = \exp -E_+/k_B T_{eff}$

$p_-(\alpha) = \exp -E_-/k_B T_{eff}$

Spin is in a <u>pure</u> state

$$p_\pm = \left(1 \pm (\langle S_x\rangle^2 + \langle S_z\rangle^2)^{1/2}\right)/2$$

$$S = E = -p_+ \log_2 p_+ - p_- \log_2 p_-$$

Bridge to quantum thermo
N. Williams, A. Jordan and K. Le Hur 2011
(also work by A. Jordan & M. Buttiker
on entanglement energetics)

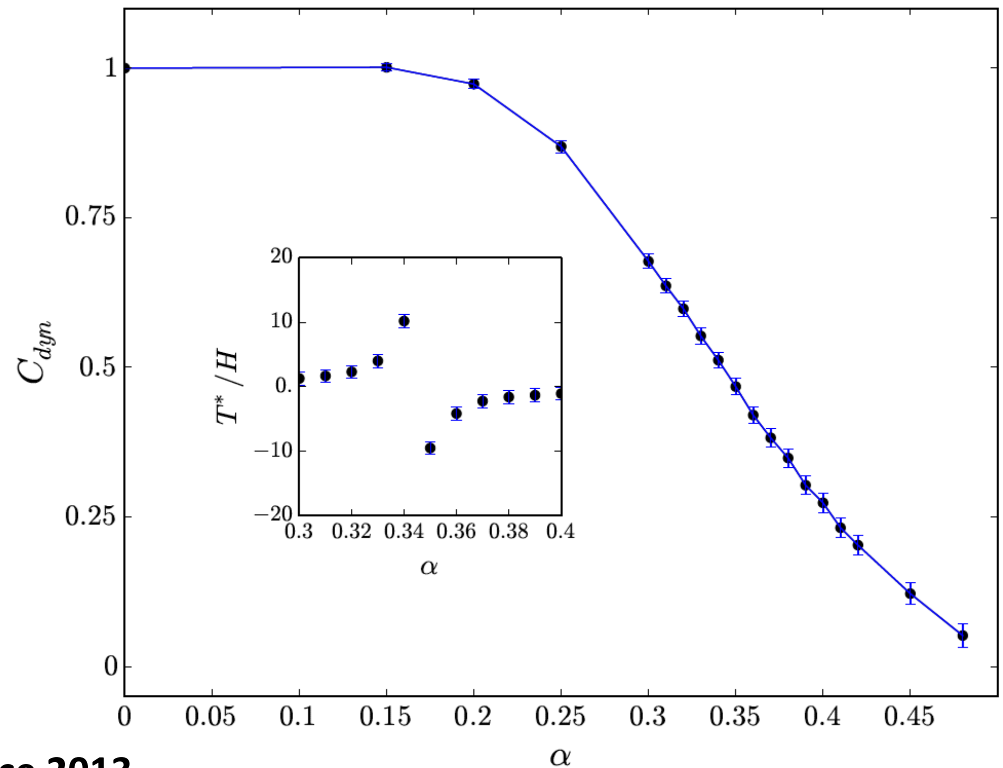
E observed in qubits (Santa Barbara)

Pseudo thermodynamics: quantum climate

Loic Henriet, A. Sclocchi, Peter P. Orth, KLH 2017

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

Quantum climate
Funded by Labex PALM



Inversion of population
Observed in cold atoms
Simon Braun et al Science 2013

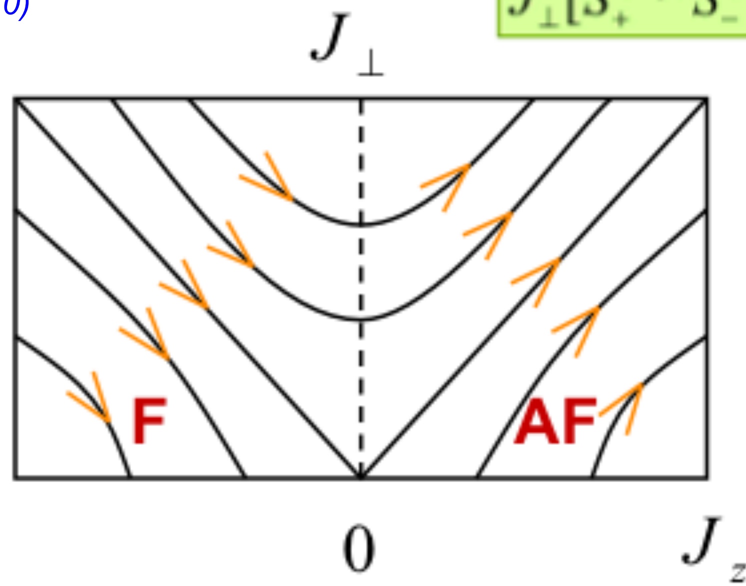
Could be measured in cQED coupled to a transmission line (α is the resistance)
Progress in ultra-strong coupling to simulate the Kondo effect with light
Waterloo Canada & Spain, Forn-Diaz et al Nature Physics **13,** 39 (2017)

Analogy to another quantum impurity Kondo problem

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

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

Perturbative calculations

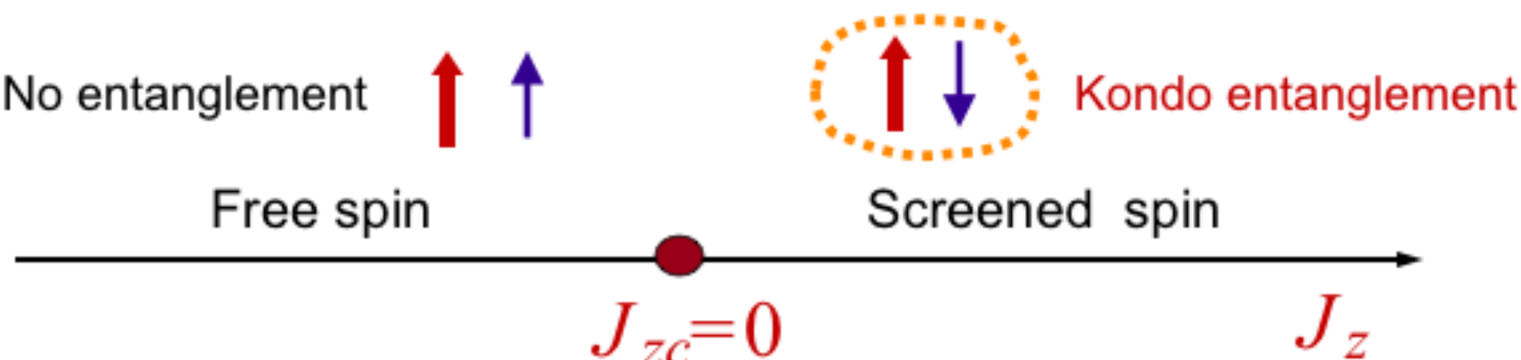


$$S^e(x=0) = \sum_{\substack{k,k' \\ \alpha,\beta}} c_{k\alpha}^\dagger \frac{\sigma_{\alpha\beta}}{2} c_{k'\beta}$$

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
Kondo lattices: S. Doniach…

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 = $|\Psi| \exp(i\varphi)$

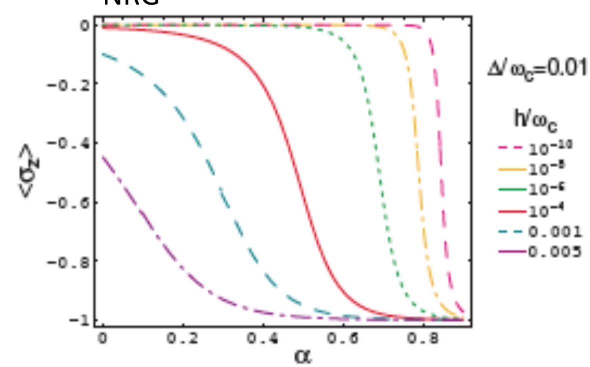
$S_x + iS_y = \exp(i\varphi)$

KT transition: High Temperature disordered phase (free vortices)

Low-Temperature quasi-long range order

Bethe Ansatz
NRG

KLH
Annals of Physics 2008



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

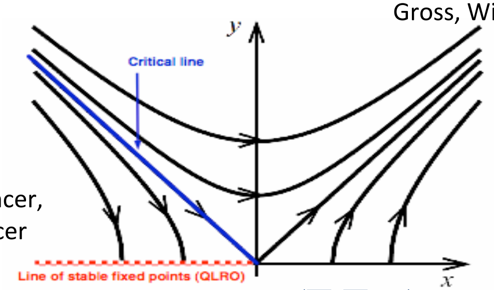
(vortex fugacity)

« QCD »
Asymptotic
Freedom 1973
Gross, Wilczek, Politzer

Kosterlitz-
Thouless papers

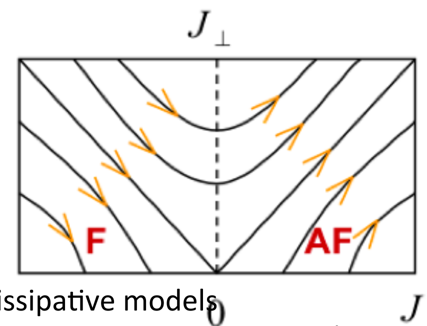
D. Nelson
D. Fisher,

McBryan & Spencer,
Frohlich & Spencer



$(T-T_{KT})$

Kondo
Singlet,
Low-energy



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

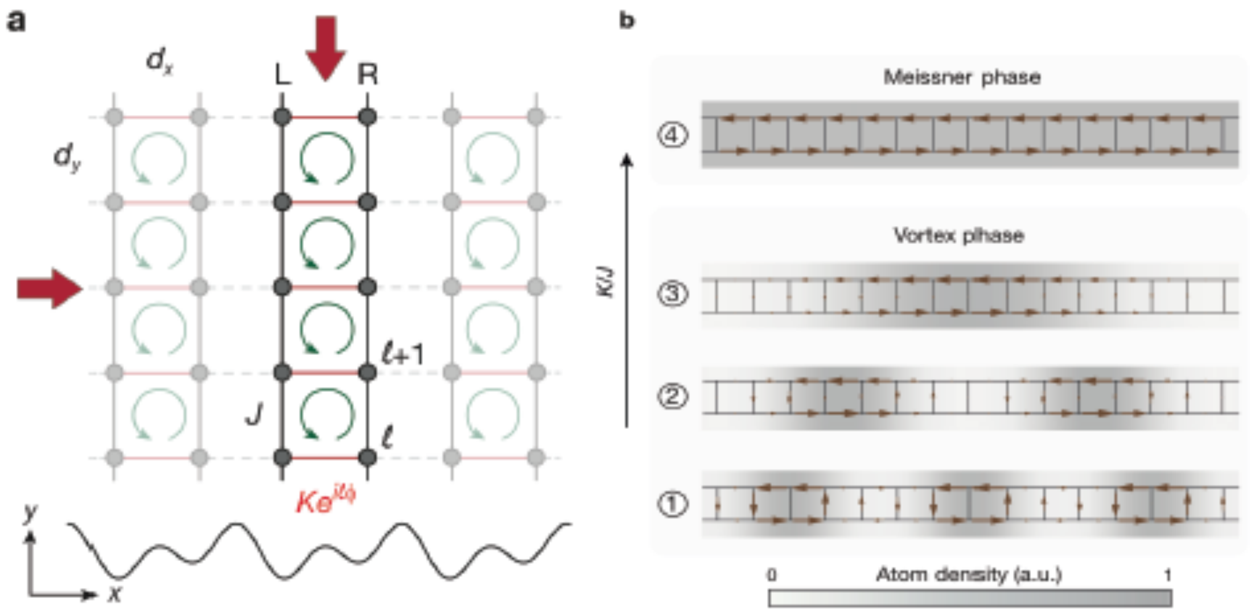
Ising models in 1D & Caldeira-Leggett dissipative models
(D. Thouless 1969 & Anderson, Yuval, Hammann; Freeman Dyson)

Meissner effect and IQHE in 1D ladder

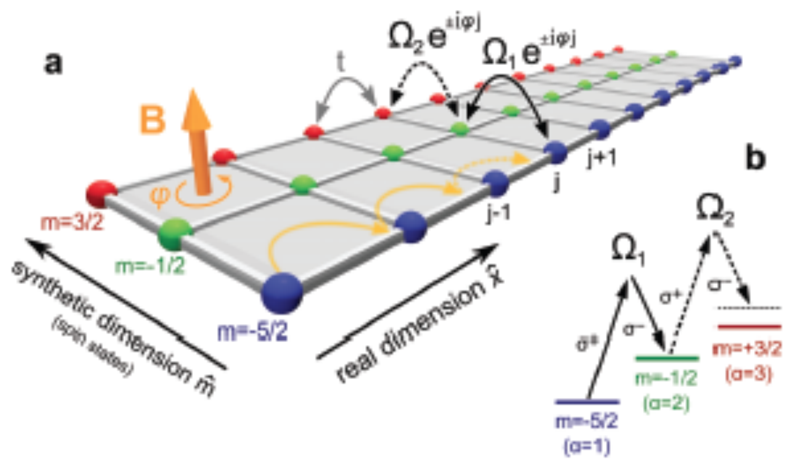
BOSONS: currents screen the flux superfluids

Giamarchi
Orignac, 2001

analogy to Superconductors
Fritz & London
London & London, 1930s
Josephson phase locking



FERMIONS: IQHE: chiral edge modes



Theory by
P. Zoller et al.
and R. Fazio et al.

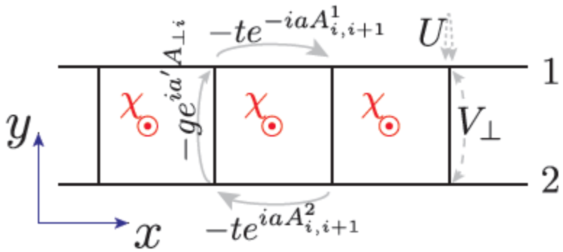
^{87}Rb Meissner/vortex transition [Atala et al. 2014],

^{173}Yb fermion IQHE[Mancini et al. 2015]. See also [Stuhl et al. 2015]

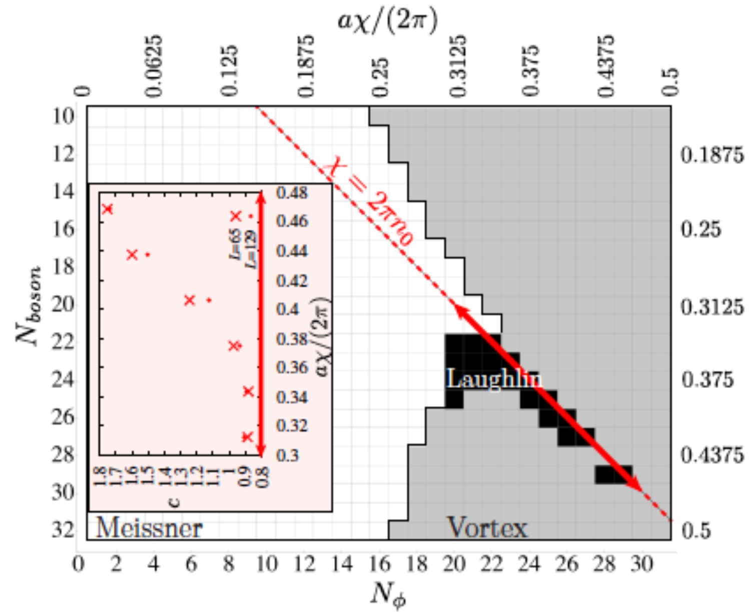
FQHE bosons: 2-leg ladder?

C. L. Kane, Lubensky, Mukhopadyay; Teo & Kane, classification of quantum Hall phases in ladders

A. Petrescu & KLH, PRB 2015 (analytics : V needed for infinite systems)
A. Petrescu, M. Piraud, I. McCulloch, G. Roux, KLH, **PRB 2017**
M. Calvanese Strinati, Eyal Cornfeld, Davide Rossini, Simone Barbarino, Marcello Dalmonte, Rosario Fazio, Eran Sela, Leonardo Mazza PRX 2017



DMRG Small densities



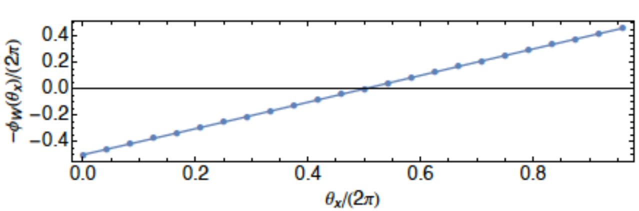
Laughlin phase: chiral edge modes with fractional charges

Bipartite fluctuations confirm Laughlin phase theoretically and numerically

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

Torus geometry: gap the edges
Thouless Laughlin pump

See also F. Grusdt – M. Honing 2014



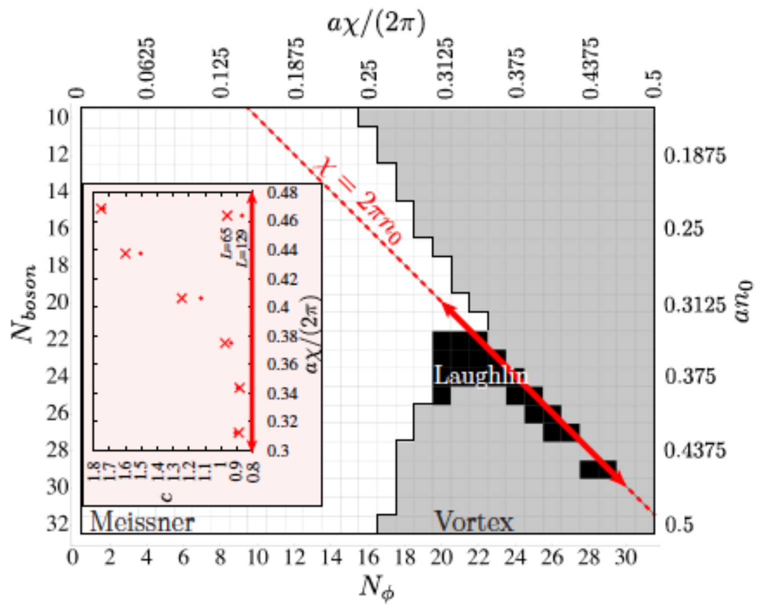
Experiment in Muenich, Bloch's group
Zak phase (work D. Abanin, E. Demler)
measures the polarization « 1/2 »

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

Bi-partite fluctuations: probe of Laughlin phase

A. Petrescu, M. Piraud, I. McCulloch, G. Roux, KLH, to appear

$$\mathcal{F}^{\pm}(\ell) \equiv \langle [N^{\pm}(\ell)]^2 \rangle_{\text{conn}}.$$

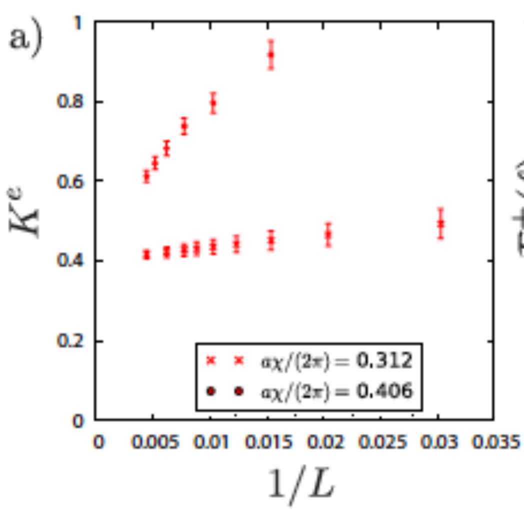


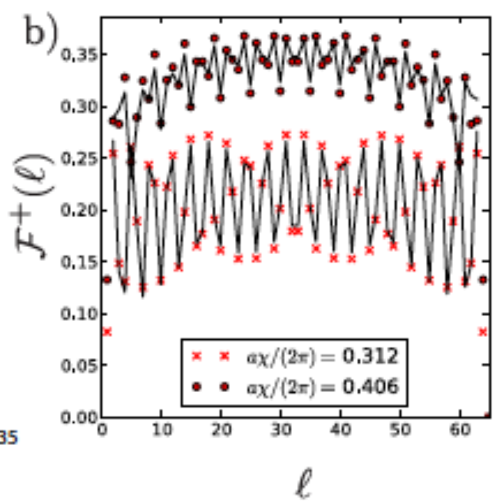
$$\mathcal{F}^{+}_{Laughlin}(\ell) = \frac{K^e}{2\pi^2} \log\left[d(\ell|L)\right] + c + d b_E(\ell).$$

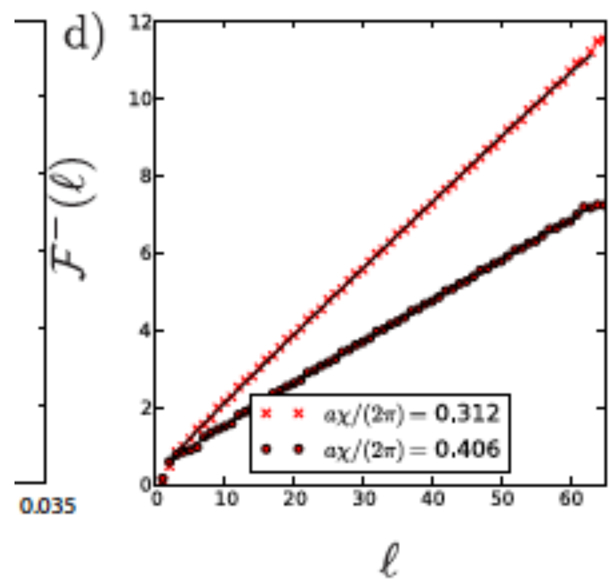
Filling factor ½ with « definitions »
Small backscattering between edges Ke=2/5
(quasi-SPT; class A analogue T. Neupert et al. 2014)

$$\mathcal{F}^{-}_{Laughlin}(\ell) = \frac{1}{2\pi^2 K^e} \log\left[d(\ell|L)\right] + b\ell + c + d b_E(\ell),$$

b probes the « gap » in bulk







Loic Herviou, C. Mora & KLH, PRB 2016 (Majorana Kitaev SC ladders)
L. Herviou, C. Mora, KLH 2017 and L. Herviou, KLH, C. Mora, in preparation

$$H = -\sum_i \left(J \sigma_i^y \sigma_{i+1}^y + \Delta \sigma_i^x \right)$$

Quantum phase transition at $J = \Delta$
Model exactly solvable through Jordan-Wigner
Model with no total charge conservation
Relation to Kitaev model   CRITICAL model

CFT allows to compute bi-partite fluctuations

$$\iint \langle \sigma^x(a)\, \sigma^x(b) \rangle_c \, da\, db$$

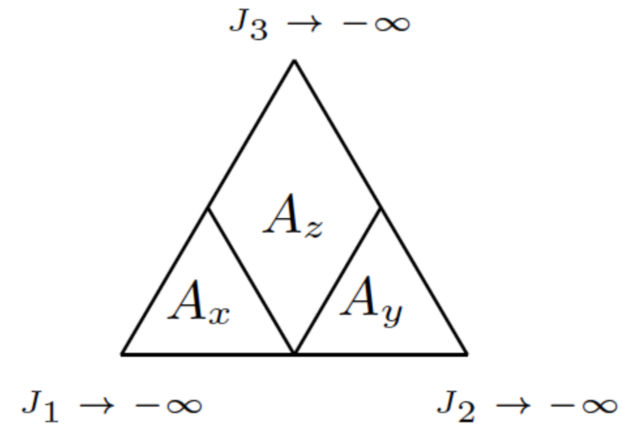
DMRG Check

General formula $\alpha x + \beta \ln \frac{x}{a} + \dots$

$\beta < 0$ here ($c = \frac{1}{2}$ theory)

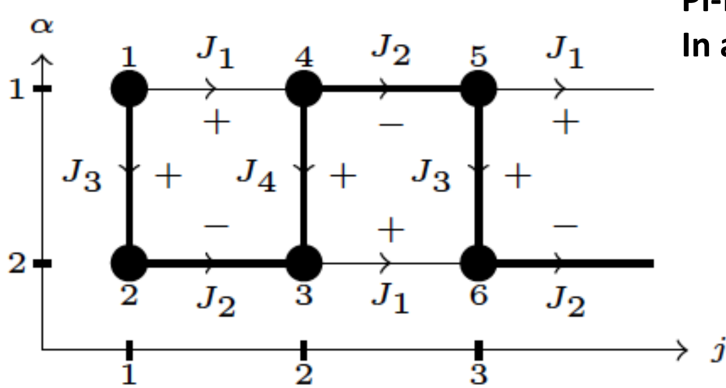
Kitaev magnetic ladders: work with Ariane Soret and Fan Yang see arXiv 2017

Kitaev magnetic Ladder:



Feng et al. 2007
DeGottardi et al. 2011
Pedrocchi et al. 2012 (inhomogeneous ladder)
H. H. Lai and O. Motrunich, PRB 2011

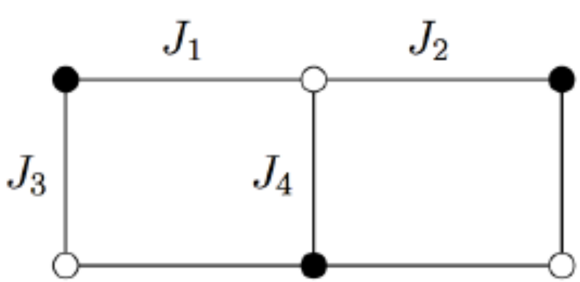
Lieb' theorem
Pi-flux here
In agreement with Kitaev view



$$H = -i \sum_{j=2m-1} [J_1 c_{j,1} c_{j+1,1} - J_2 c_{j+1,1} c_{j+2,1} + J_1 c_{j+1,2} c_{j+2,2} - J_2 c_{j,2} c_{j+1,2} + J_3 D_{j,1} c_{j,1} c_{j,2} + J_4 D_{j+1,1} c_{j+1,1} c_{j+1,2}],$$

$$\tilde{\sigma}_i^{\alpha} = i b_i^{\alpha} c_i.$$

$$D_{j,\alpha} = (-i) a_{j,\alpha} a_{j,\alpha+1}$$



Square ladder, Feng et al 2007
Az phase all Majoranas paired
Ax and Ay phase, edge modes

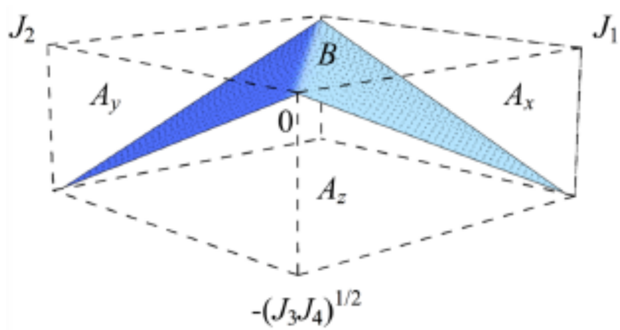
0 flux
for J4=0

KLH, A. Soret and F. Yang, 2017

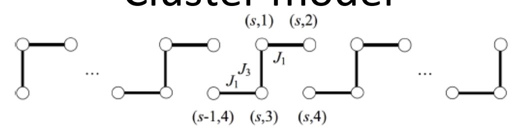
honeycomb or ribbon ladder: J4=0

Generality of the phase diagram?
Honeycomb ladder, etc… gapless phase
Z2 protection of ground state
Loop operators

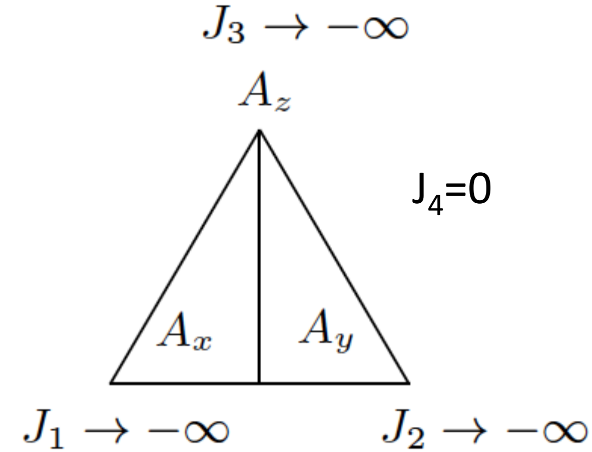
Generalized ladder: arXiv:1703.07322



Cluster model



Adiabatic evolution from
X to Z polarization



J_4=0

No flux frustration in the ground state (pi flux; 0 flux J4=0)

honeycomb ribbon

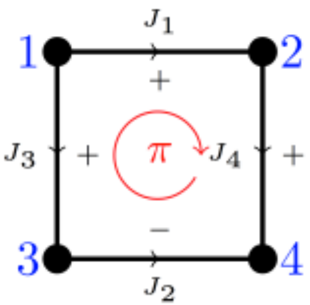
$$H = H_{\text{chain},1} + H_{\text{chain},2} + H_I,$$

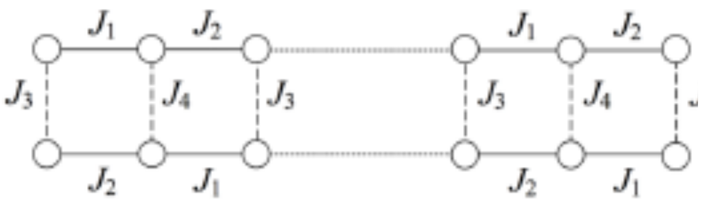
$$H_I = \sum_{j=2m-1} J_3 \sigma^z_{j,1}\sigma^z_{j,2} + J_4 \sigma^z_{j+1,1}\sigma^z_{j+1,2} \quad \text{(four-body)}$$

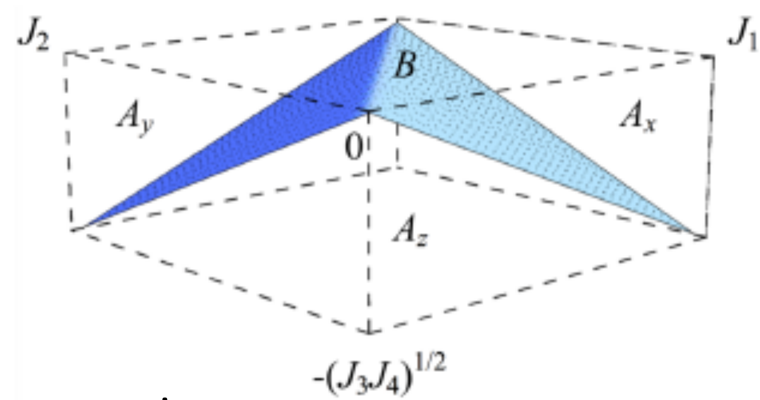
$$= -i \sum_{j=2m-1} (J_3 c_{j,1}c_{j,2} + J_4 c_{j+1,1}c_{j+1,2}) \quad \text{(Lieb's theorem, 1994)}$$

Line : pre-formed pairs resonating along chains (rung tensor product states; bosonization c=1)
Superconductivity and topological transition by doping with holes

Loop qubit: « Majorana box »







<u>Az phase of the phase diagram:</u> Pi flux ground state protection
the c-Majoranas and d Majoranas are massive (local noisy fields, robustness)

$D_{1,3} = (-i)d_1d_3$ and $D_{2,4} = (-i)d_2d_4$ are fixed to the same value $+1$ or -1 in the ground state.

one can introduce a four-spin operator $\sigma_1^z\sigma_2^z\sigma_3^z\sigma_4^z$

The qubit operator can be re-written as $d_1d_2d_3d_4$

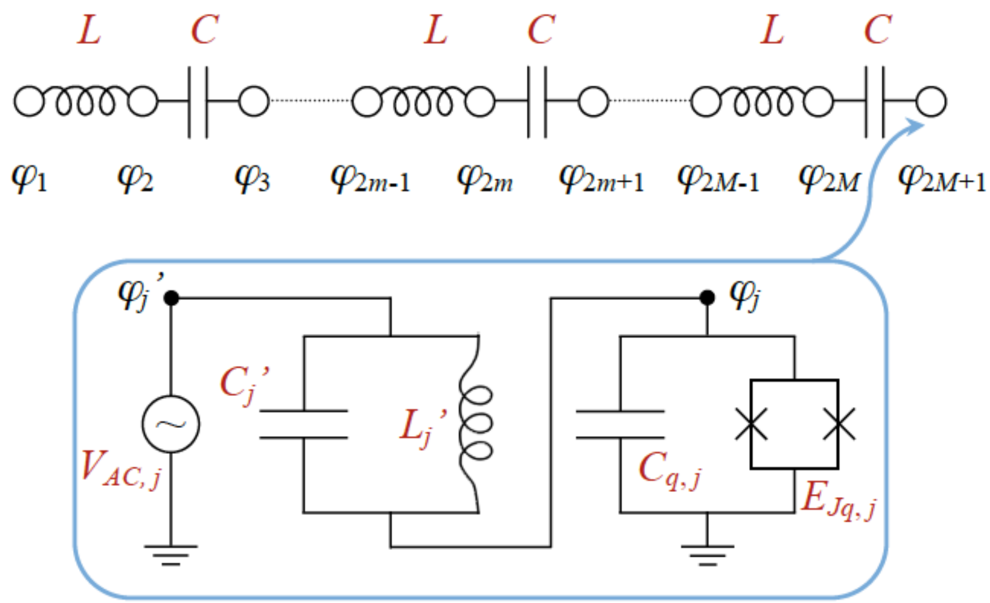
Protocol to braid d1 and d2: operate and measure in spin space (x,y, z Bell correlation functions for the spins 1 and 2)

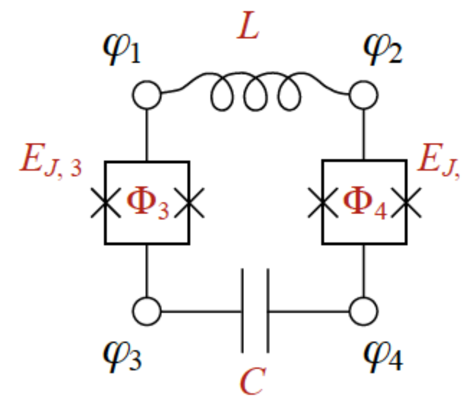
- Braiding: $\delta J_2\sigma_j^y\sigma_{j+1}^y = i\delta J_2 d_j d_{j+1}$, $\delta J_2 \rightarrow -\delta J_2 \Rightarrow d_j \leftrightarrow d_{j+1}$.

Simulation of New Devices with SC devices and Transmons

Anderson RVB states and Majoranas, p-wave SC
KLH, Ariane Soret, Fan Yang (25 pages) : arXiv:1703.07322
« loop » devices in link with Sachdev-Ye-Kitaev models, ring exchange models
Precise Device engineering in progress, Fan Yang master project M2 below

Su-Schrieffer-Heeger and Rice-Mele model with LC chains
T. Goren, K. Plekhanov, F. Appas, G. Roux, KLH − **in progress**
Probe of topology, Bloch bands, and transport with photons





Coupling
4 Majoranas

A 4-site toric code
has been initiated
Y. P. Zhong et al
PRL 117, 110501 (2016)

Exemple Realization of a Kitaev spin chain (emergent Majorana chain): NMR device on each port

Loic Herviou, C. Mora and KLH (collaboration with P. Roushan, C. Neill − google Santa Barbara
on generalized quenches and bi-partite fluctuations **in XY and Ising quantum spin chains**)

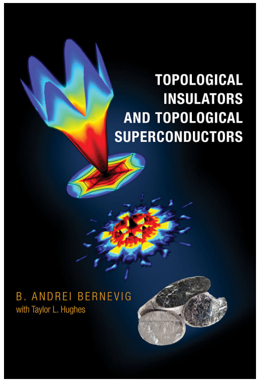
Spin-1/2 fermions: simulating spin-orbit coupling

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)**

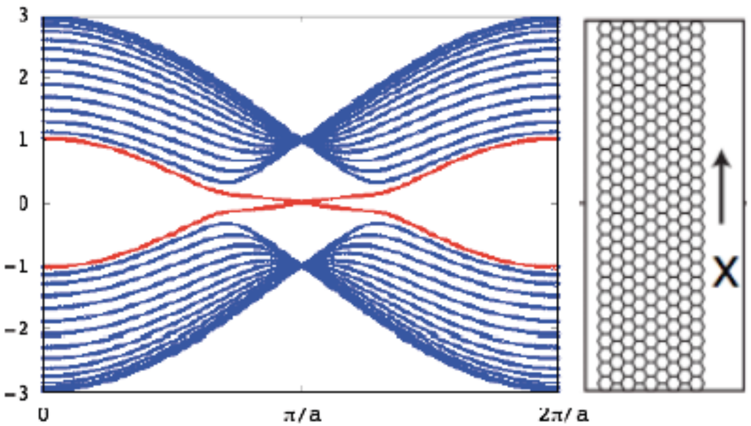
Also realizations in photon systems for example: M. Hafezi, S. Mittal, J. Fan, A. Migdall, J. Taylor (2013) Mikael C. Rechtsman, Julia M. Zeuner, Yonatan Plotnik, Yaakov Lumer, Stefan Nolte, Mordechai Segev, Alexander Szameit (2013)

$$\mathcal{H} = -t \sum_{<ij>\sigma} c^\dagger_{i\sigma} c_{j\sigma} + i\lambda \sum_{\ll ij \gg} \sum_{\sigma\sigma'} \nu_{ij} \sigma^z_{\sigma\sigma'} c^\dagger_{i\sigma} c_{j\sigma'} \qquad \nu_{ij} = \pm 1$$



QSH

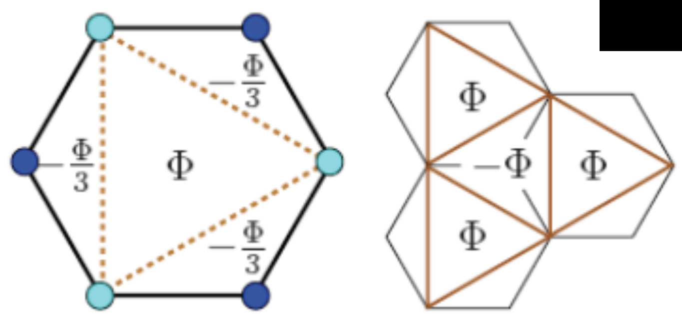
strip geometry:



edge states: Kramers's pair

Half-filling

$$\mathcal{H} \propto \Psi^\dagger_k \sigma^z \tau^z \Psi_k$$



Joel Moore, perspective Nature 2010

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

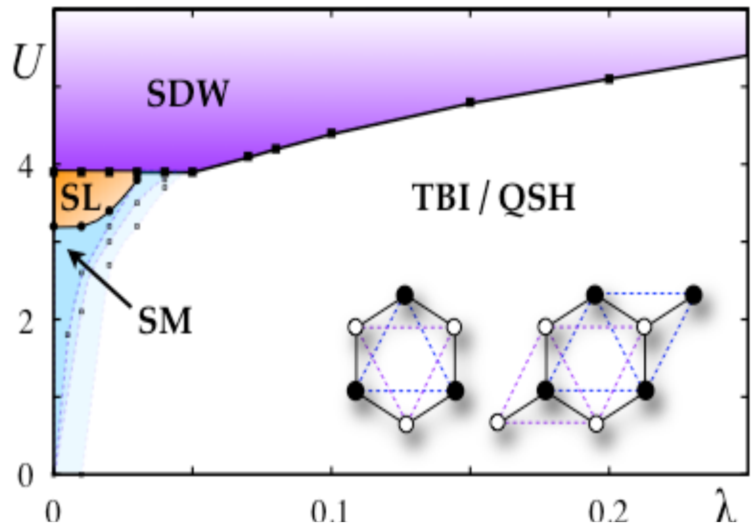
Also 3D analogues: Bismuth … Weyl fermions
QCD and flavor models

Mott frontiers in "Kane-Mele-Hubbard"

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

CDMFT

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

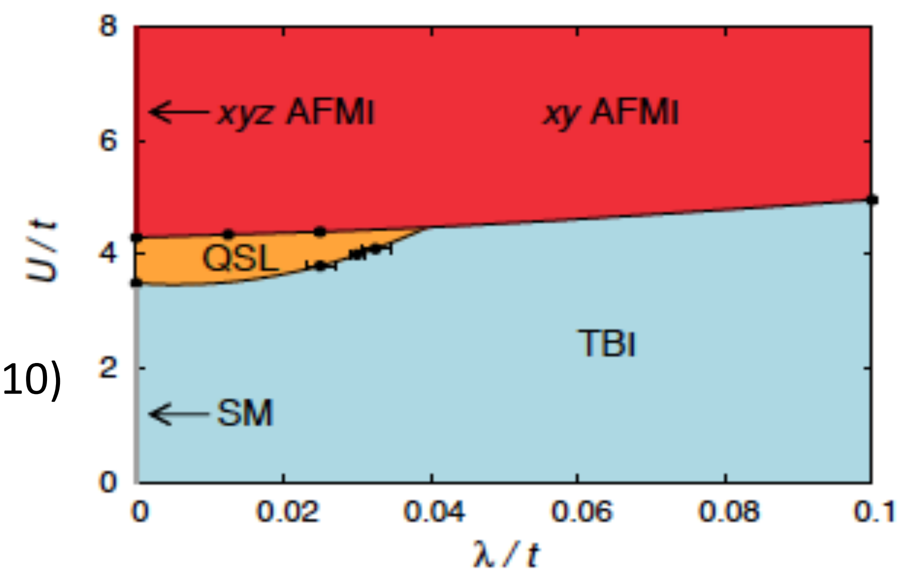


Analytics:
Young, Lee, Kallin 2008
S. Rachel & KLH, 2010
Griset & C. Xu, 2011
D.-H. Lee, 2011 …

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)

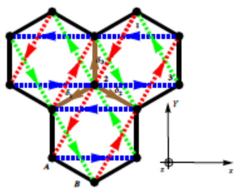
Reviews: Hohenadler & Assaad, 2013
Maciejko-Fiete, 2015

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

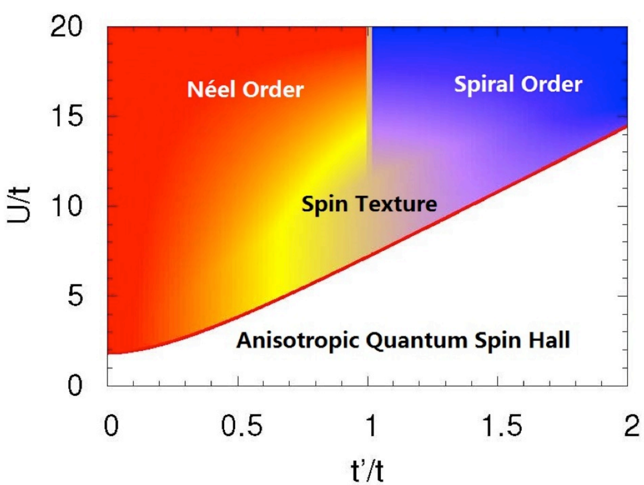
- Na_2IrO_3: anisotropic spin-orbit coupling

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



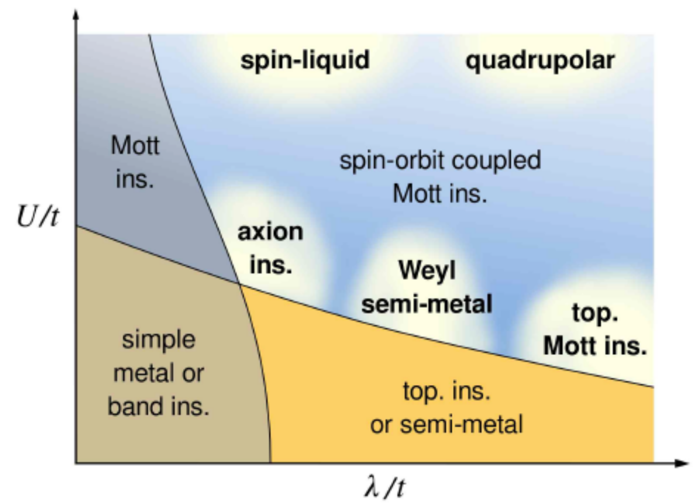
Shitade et al. PRL **102** 256402 (2009); G. Jackeli & G. Khaliullin, PRL 102, 017205 (2009)

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

New phase with bosons
K. Plekhanov et al.
arXiv:



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

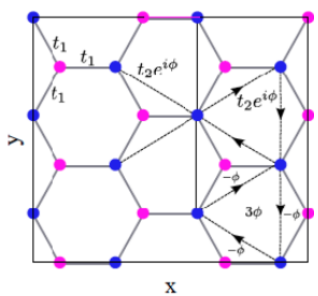
Tianhan Liu, Benoit Doucot, Karyn Le Hur, PRB 2013
A. Ruegg and G. Fiete, PRL 2012
J. Reuther, R. Thomale & S. Rachel, PRB 2012
M. Kargarian, A. Langari, G. Fiete PRB 2012

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

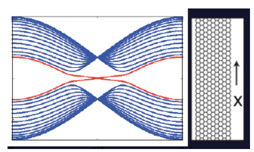
Quantum Simulators :

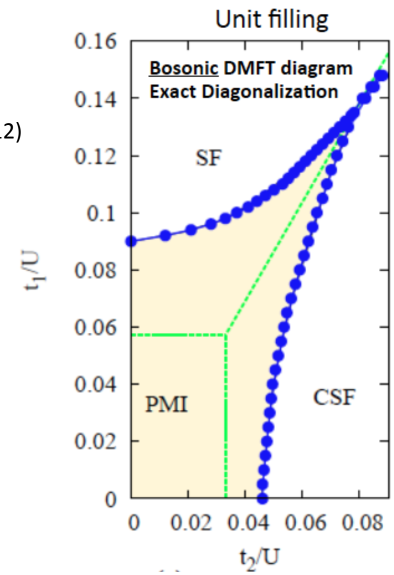
Quantum Hall phases, topological insulators, spin liquids (Kagome, Kitaev model, spin-1 chain) symmetry protected phases, bosons and superconductors, Majoranas, …

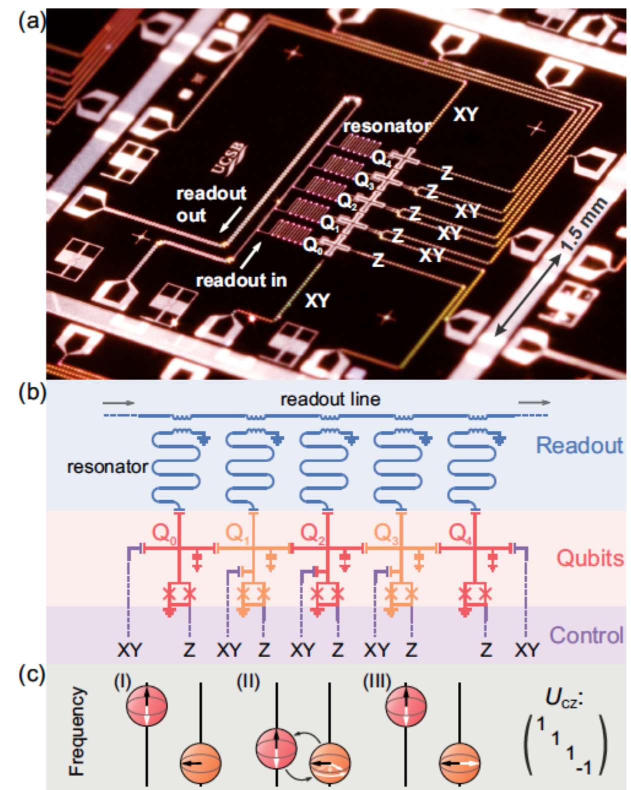
J. Martinis group



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





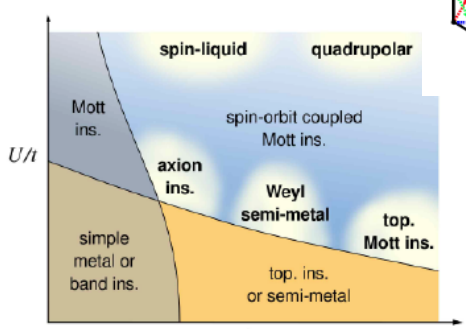


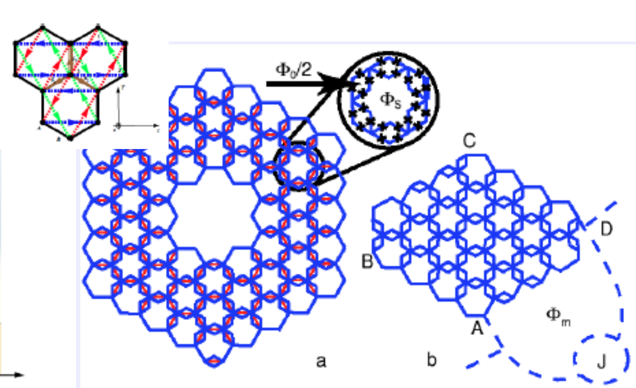
Chern insulators on graphene
realized experimentally in ultra-cold atoms
Photons and quantum materials
Many theorists involved (ENS Lyon, Bordeaux, ENS Paris, CPHT, LPS Orsay, UPMC, Cergy Pontoise, Toulouse,…)

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 :

Loic Henriet (CPHT PhD 2016 Barcelona), Loic Herviou (CPHT & ENS, C. Mora PhD 2017; post-doc Stockholm), Kirill Plekhanov (LPTMS G. Roux, CPHT), Ariane Soret (CPHT and Technion E. Akkermans), Fan Yang (CPHT)

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)
Wei Wu (Yale 2010 and China, now collège De France Paris post-doc)
Prasenjit Dutt (Yale PhD 2013, Mathematical Finance at Stamford UBS); M. Filippone (ENS C. Mora, Geneva)
Emilie Dupont (Sherbrooke 2006, teacher); Michel Pioro-Ladriere (Sherbrooke professor),
Georg Seelig (Geneva 2002 M. Buttiker, Caltech biophysics and prof. U. Washington at Seattle)
Urs Ledermann (ETH Zurich 2001 T. M. Rice; at ABB)

Post-doctoral (senior) associates :

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.)
Zoran Ristivojevic (CPHT, now Toulouse CNRS), Marco Schiro (Princeton, Columbia now CNRS IPHT),
Marie Piraud (Muenich), Ivana Vasic Frankfurt with W. Hofstetter (Frankfurt), now Belgrade Faculty),
Tal Goren (CPHT Ecole Polytechnique), Cecile Reppelin (PhD LPA ENS N. Regnault, Dresden),…

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