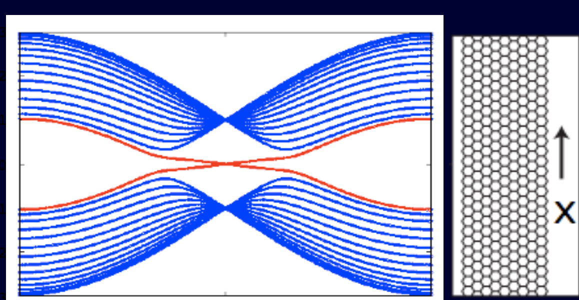
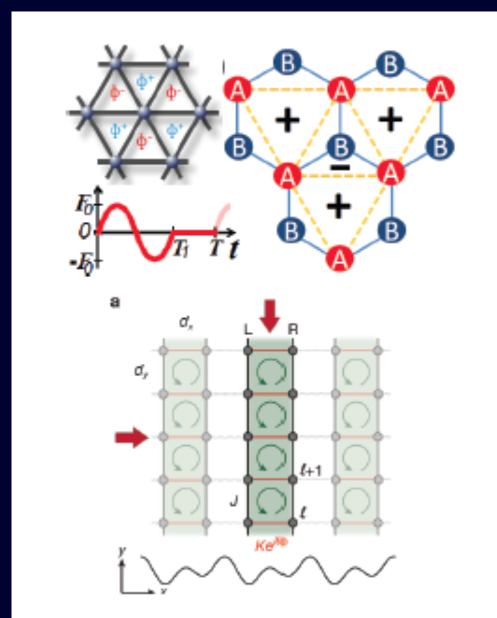
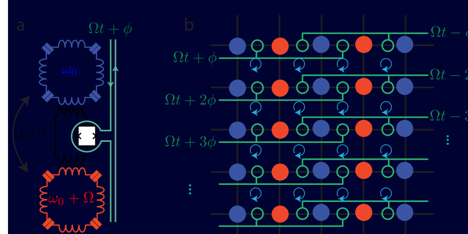
July 2017: conference on Spin-Orbit Materials, Luxembourg
organizers: Thomas Schmidt, Bjorn Trauzettel, Patrik Recher

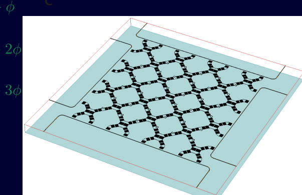
Spin-Orbit Coupling in the Mott State : Quantum Spin Liquids, Superconductivity & Majorana Boxes

Karyn Le Hur
CPHT Ecole Polytechnique, France & CNRS









Funding DFG & Labex Palm

Topological Phases, Interaction Effects & Gauge Fields

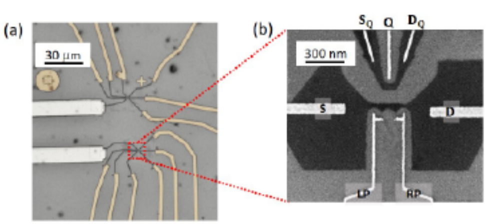
From Materials, to Ultra-Cold Atoms and Photon Simulators

Start from Graphene: **Majorana fermions in SC Graphene**

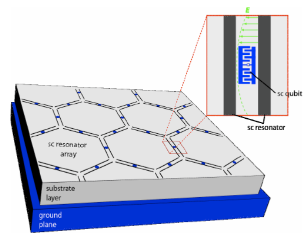
D. Bergman and KLH, PRB 2009
following P. Ghaemi & F. Wilczek
[di Bernardo et al 2017 (p-wave like?); progress in realization]

- Spin-orbit coupling in graphene lattices
  Kane-Mele Model, Interaction Effects (fermions, bosons)
  Topological Mott Insulators, quantum spin liquids in 2D?
  ladder system: QHE of bosons U=infinity

- Z2 quantum Majorana liquids
  Kitaev chain, Ladders
  Majorana Boxes, cQED
  SSH model of hole pair

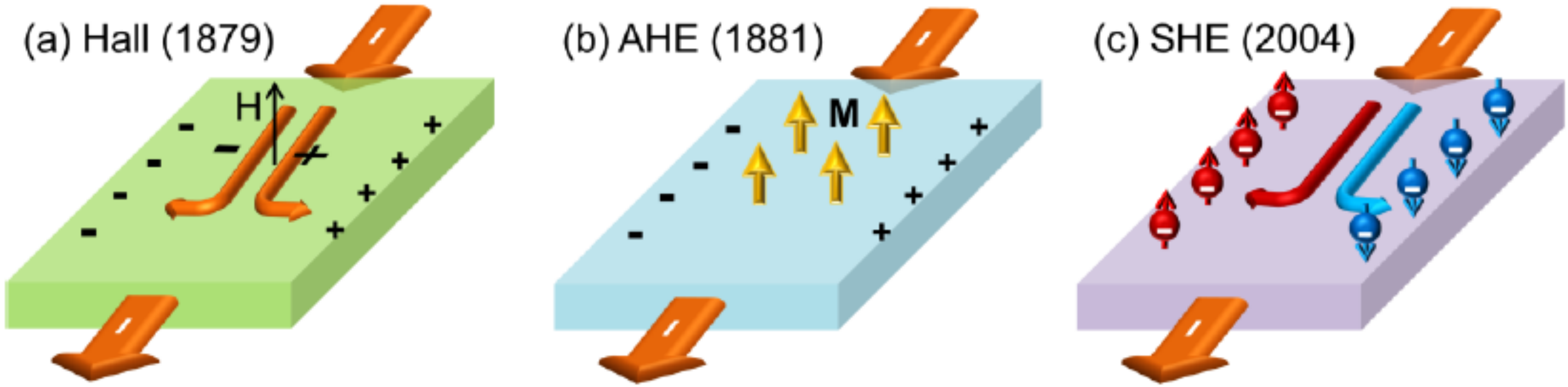


Mesoscopic graphene
cQED, group of G.-P. Guo



J. Koch & KLH, 2009
Artificial graphene

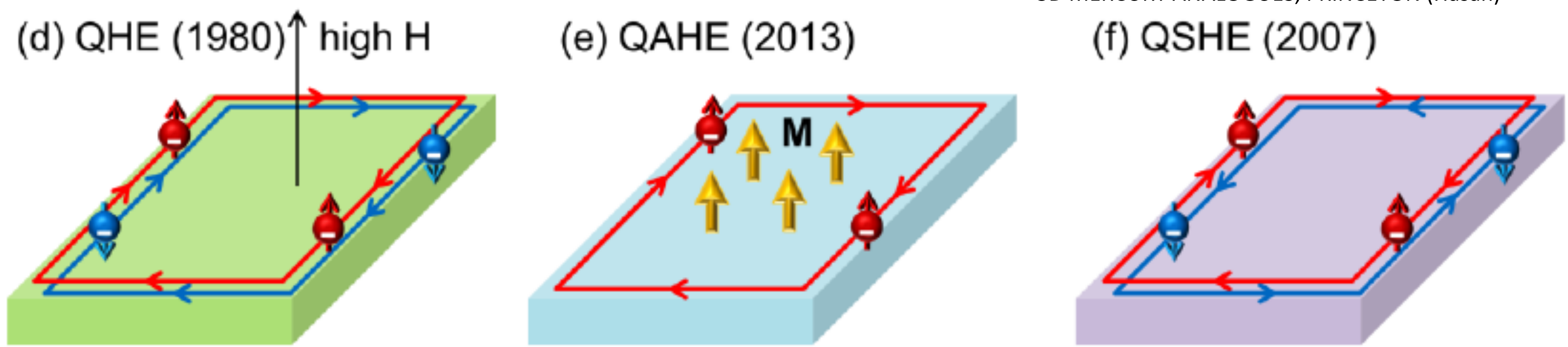
Topological states of matter
simple zoology from flat land



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

Haldane (1988)

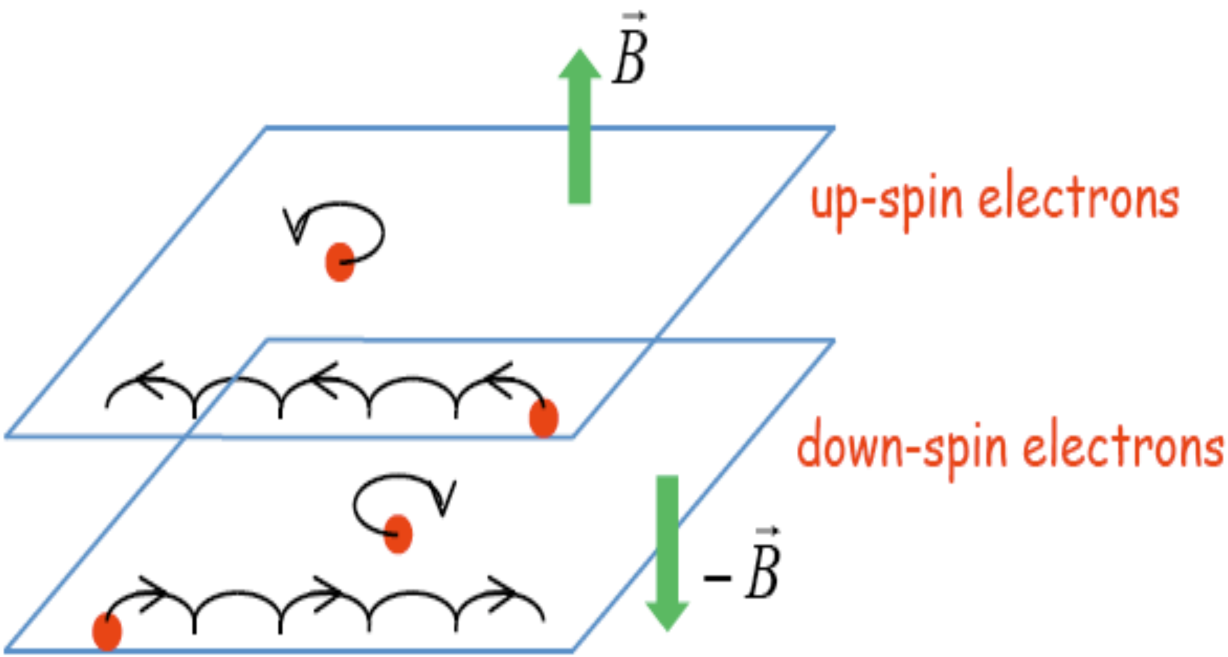
REALIZED AT WURZBURG IN HGTE (Molenkamp)
3D MERCURY ANALOGUES, PRINCETON (Hasan)



C. Z. Chang and M. Li, Topical Review, arXiv:1510.01754
From material science (spintronics), 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

- Time-reversal invariant band insulator
- Strong spin-orbit interaction $\lambda\vec{L}\cdot\vec{\sigma}$
- Gapless helical edge mode (Kramers pair)



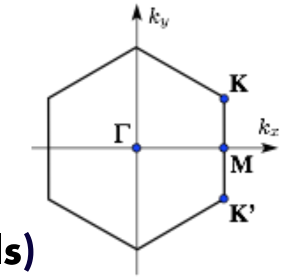
No spin rotation symmetry

Microscopic Description: Simple Standard Model, Kane-Mele

Time reversal invariant of <u>**Haldane model**</u> **(1988): Kane-Mele model**

Kane & Mele, PRL 95, 226801 (2005)

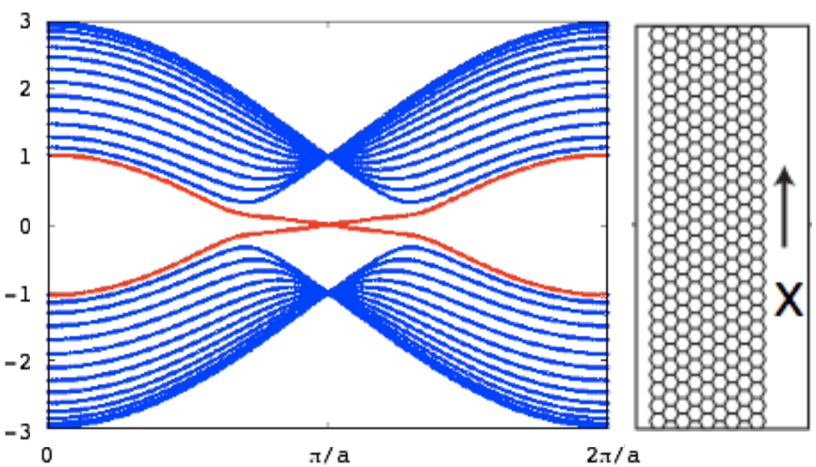
see also: **Bernevig, Hughes, and Zhang, Science 314, 1757 (2006)**
+ Molenkamp-experiments (Mercure)
in three dimensions, experiments by M. Z. Hasan et al. (Bismuth materials)



Wallace
Fu-Kane, invariant

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

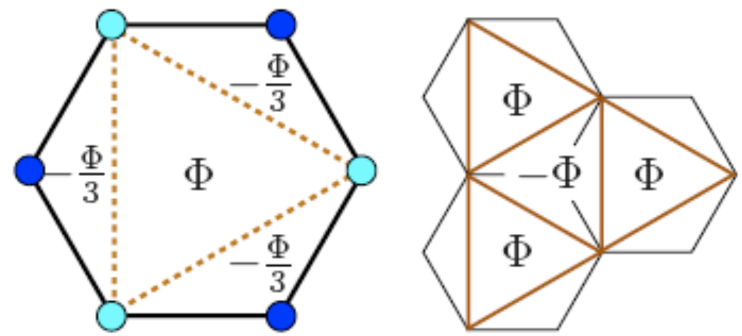
strip geometry:



edge states: Kramers's pair

Transition semi-metal to Mott graphene

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



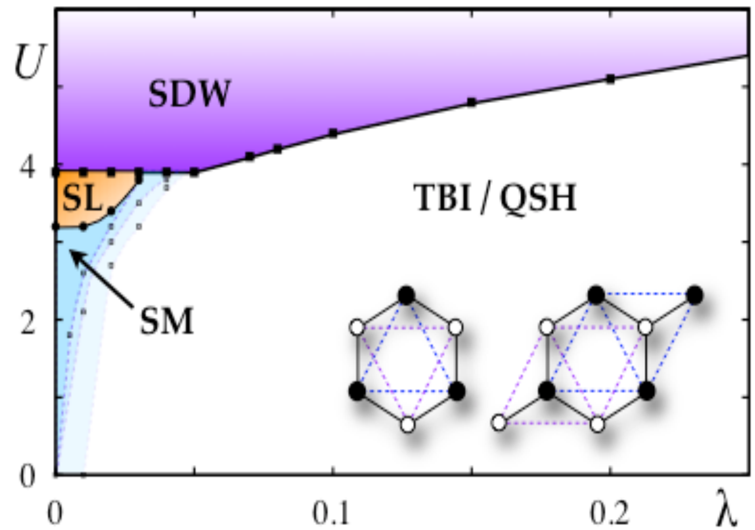
Transition from topological band insulator to Mott Insulator? Relevant to iridates…

“Kane-Mele-Hubbard”: XY Neel

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

CDMFT

Real-space version
QMC continous-time
Impurity solver

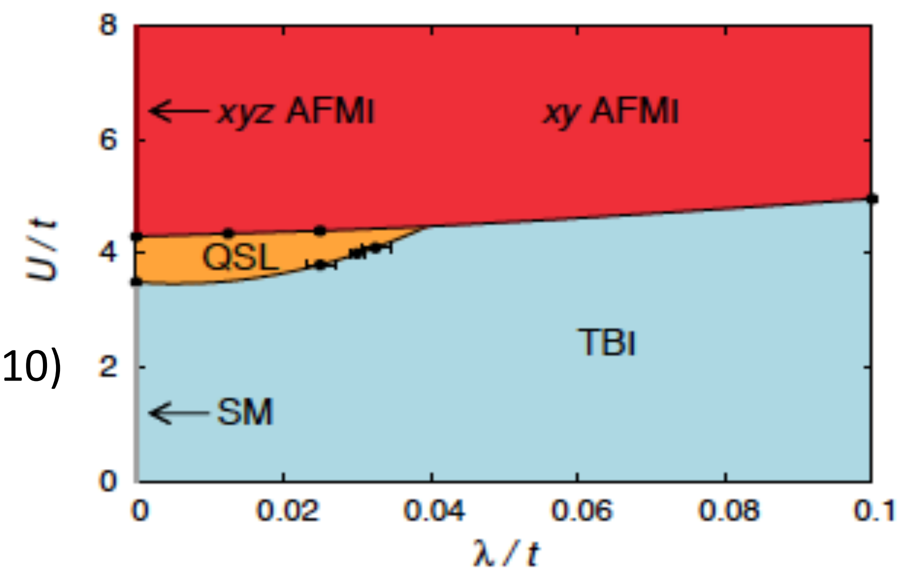


S. Rachel & KLH, PRB 2010

3D XY (charge model, Josephson model)
S. Rachel & KLH, 2010
Griset & C. Xu, 2011
D.-H. Lee, 2011

QMC

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



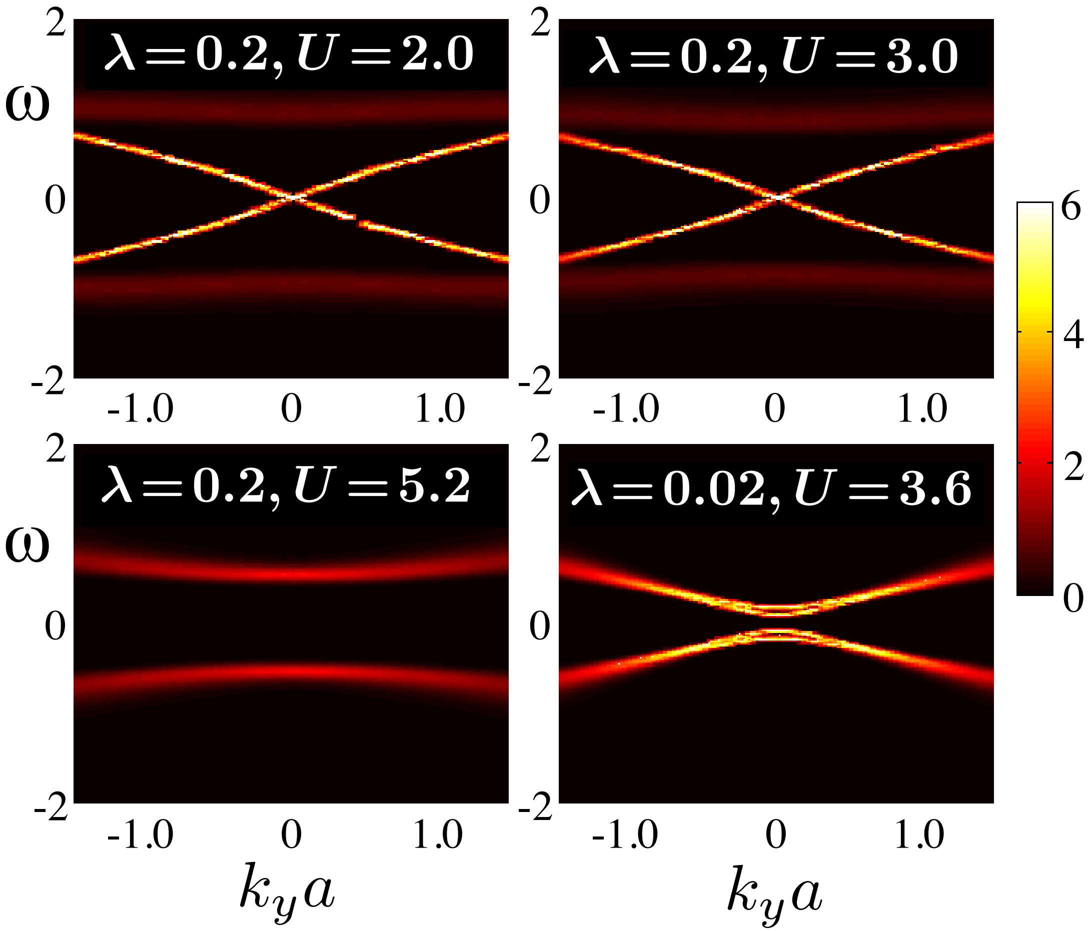
M. Hohenadler et al.
arXiv:1111.3949

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

Absence of spin liquid:
S. Sorella et al. Scientific Reports 2012; S. R. Hassan & D. Senechal PRL 2013 (large N limit, I. Herbut)

No single-particle gap closing at TBI-Mott transition

SDW, breaks time-reversal symmetry: edge states vanish
in agreement with Luttinger theory + Sine Gordon argument



CDMFT

Real-space version
QMC continous-time
Impurity solver

Some Reviews (not full list):
G. Kotliar et al, RMP 2006
T. Maier et al, RMP 2005
A.-M. Tremblay, B.-S. Kyung,
D. Senechal, 2006

DMFT:
A. Georges, G. Kotliar,
W. Krauth & M. Rozenberg et al.;
Metzner & Vollhardt

Wei Wu, Stephan Rachel, Wu-Ming Liu and KLH, PRB **85**, 205102 (2012)
See also Yamaji & Imada, 2011; Yu, Xie & Li 2011; Zheng, Zhang & C. Wu, 2011

Connection to reality?

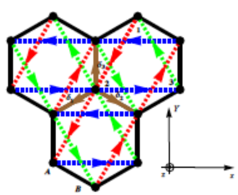
- Na_2IrO_3: anisotropic spin-orbit coupling (thin films: arXiv:1303:5245, M. Jenderka et al)

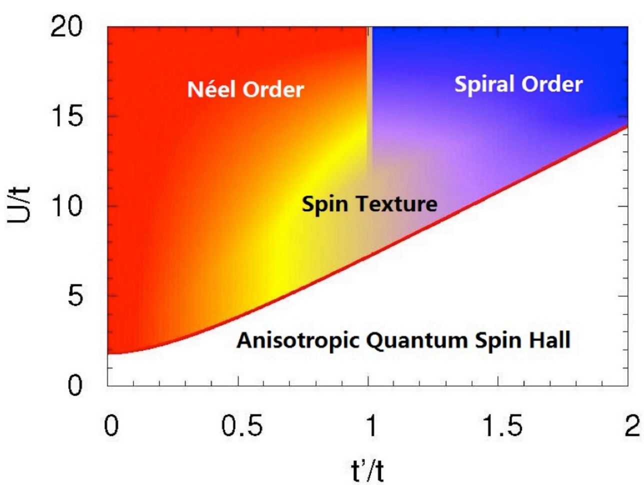
Shitade et al. PRL **102** 256402 (2009); G. Jackeli & G. Khaliullin, PRL 102, 017205 (2009)

H.-C. Jiang, Z.-C. Gu, X.-L. Qi and S. Trebst, Phys. Rev. B 83, 245104 (2011);

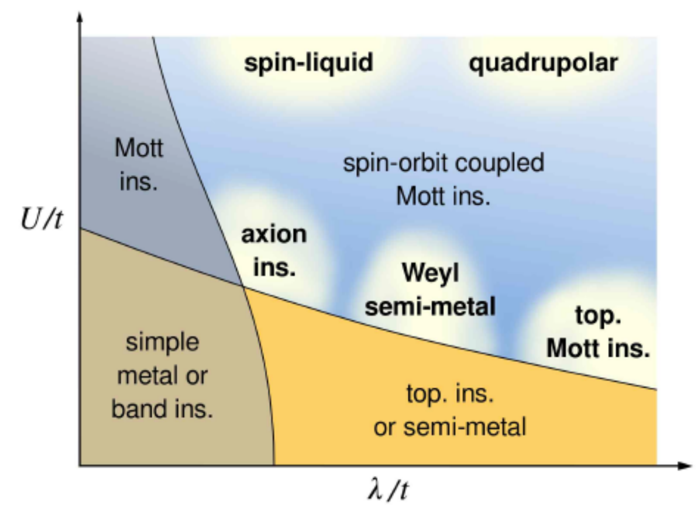
S. Bhattacharjee, Sung-Sik Lee and Yong-Baek Kim, New J. Phys. 14, 073015 (2012)

Y. Singh et al. 2012; Z. Nussinov & J. van den Brink, arXiv:1303.5922 …





α Lithium Iridates and Spiral order R. Coldea



Tianhan Liu, Benoit Doucot, Karyn Le Hur, PRB 2013

A. Ruegg and G. Fiete, PRL 2012

J. Reuther, R. Thomale & S. Rachel, PRB 2012

M. Kargarian, A. Langari, G. Fiete PRB 2012

D. Pesin & L. Balents, Nature Phys. 2010

Krempa, Choy, Y.-B. Kim & L. Balents

New attempt in 2D: Bosonic KMH model

K. Plekhanov, I. Vasic, A. Petrescu, R. Nirwan, G. Roux, W. Hofstetter & KLH, arXiv:1707.07037

$$S^z_{\mathbf{r}_i} = (n_{\uparrow,\mathbf{r}_i} - n_{\downarrow,\mathbf{r}_i})/2$$

$$S^x_{\mathbf{r}_i} + iS^y_{\mathbf{r}_i} = b^\dagger_{\uparrow,\mathbf{r}_i} b_{\downarrow,\mathbf{r}_i},\; S^-_{\mathbf{r}_i} = S^x_{\mathbf{r}_i} - iS^y_{\mathbf{r}_i} = b^\dagger_{\downarrow,\mathbf{r}_i} b_{\uparrow,\mathbf{r}_i}$$

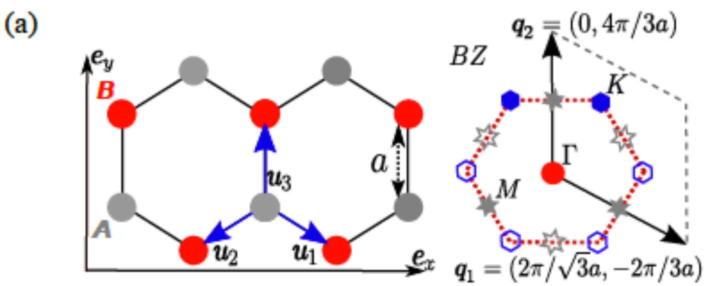
$$H = -\sum_{\langle ij\rangle}\left[J_1\left(S^+_{\mathbf{r}_i}S^-_{\mathbf{r}_j} + \text{h.c.}\right) - K_1 S^z_{\mathbf{r}_i}S^z_{\mathbf{r}_j}\right] + \sum_{\langle\langle ik\rangle\rangle}\left[J_2\left(S^+_{\mathbf{r}_i}S^-_{\mathbf{r}_k} + \text{h.c.}\right) + K_2 S^z_{\mathbf{r}_i}S^z_{\mathbf{r}_k}\right],$$

MOTT space

chiral spin state (CSS); Chern-Simons, topological?
Sedrakyan, Glazman, Kamenev

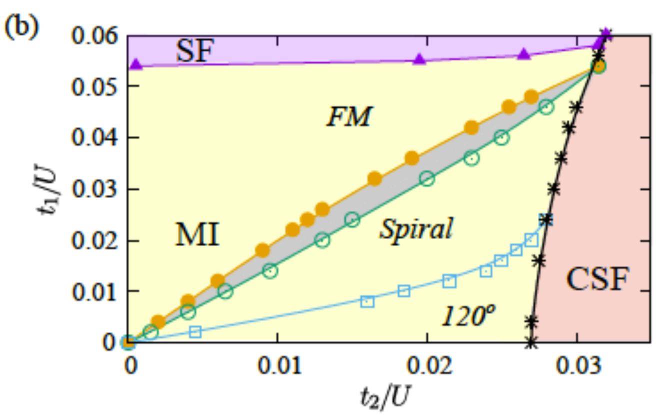
$$\chi = \langle \mathbf{S}_{\mathbf{r}_i} \cdot (\mathbf{S}_{\mathbf{r}_i+\mathbf{u}_1} \times \mathbf{S}_{\mathbf{r}_i+\mathbf{u}_2})\rangle$$

J1,J2>0



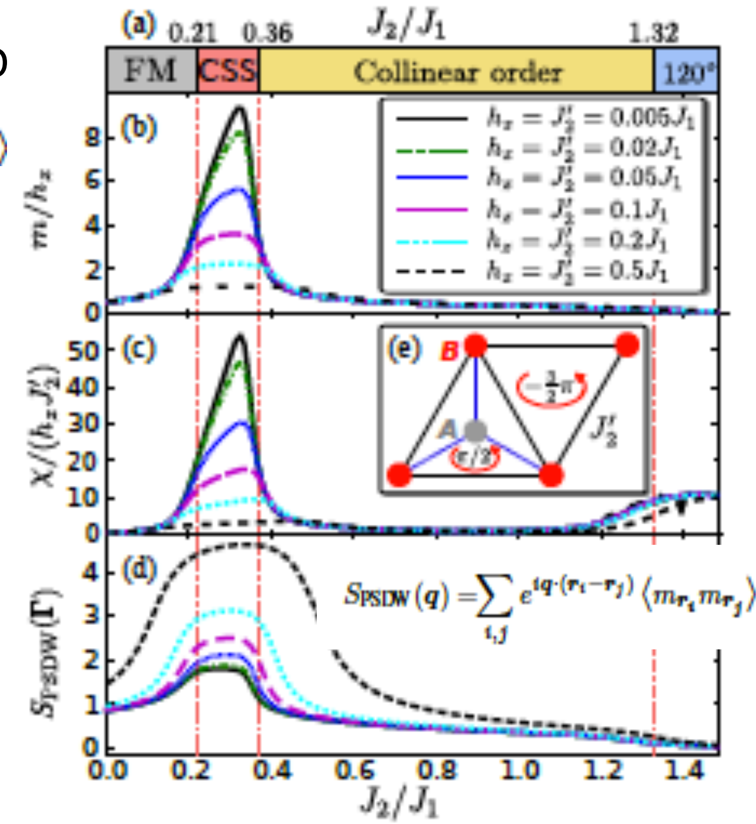
ED

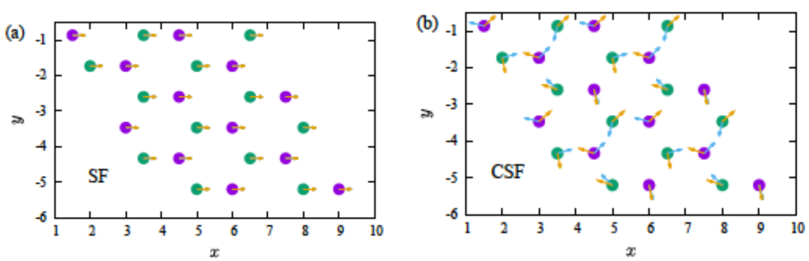
$$m = \langle m_{\mathbf{r}_i}\rangle = \langle S^z_{\mathbf{r}_i} - S^z_{\mathbf{r}_i+\mathbf{u}_3}\rangle$$



BDMFT

CSS; no order in XY plane (see next slide)





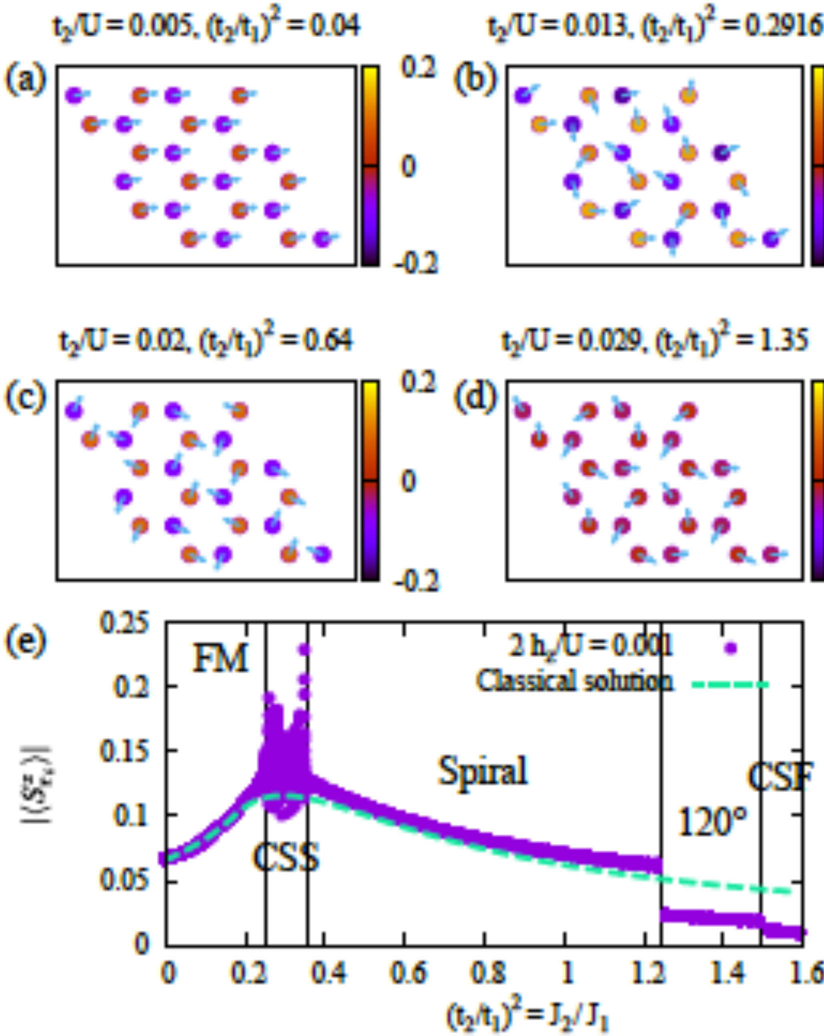
Discuss nature of Phase transitions

Magnetism & Berry analysis

$$C = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{2\pi} B(\theta_1,\theta_2)d\theta_1 d\theta_2 \ .$$

Real space BDMFT & classical analysis

can be related to Z2 pump for bosons



1st order

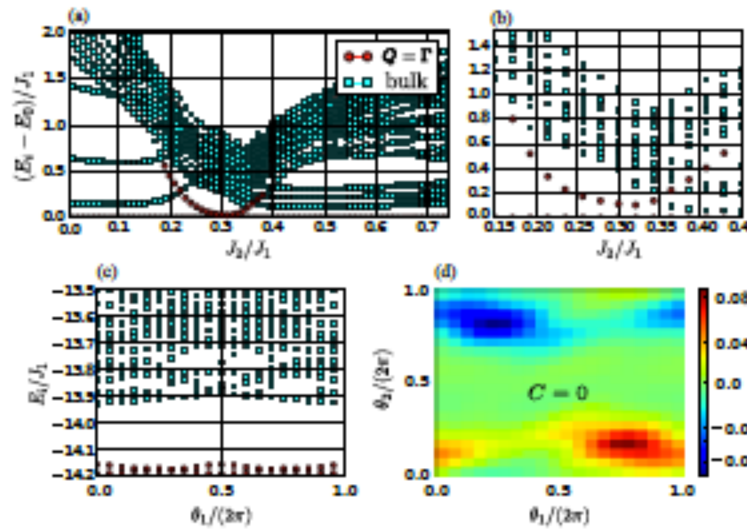
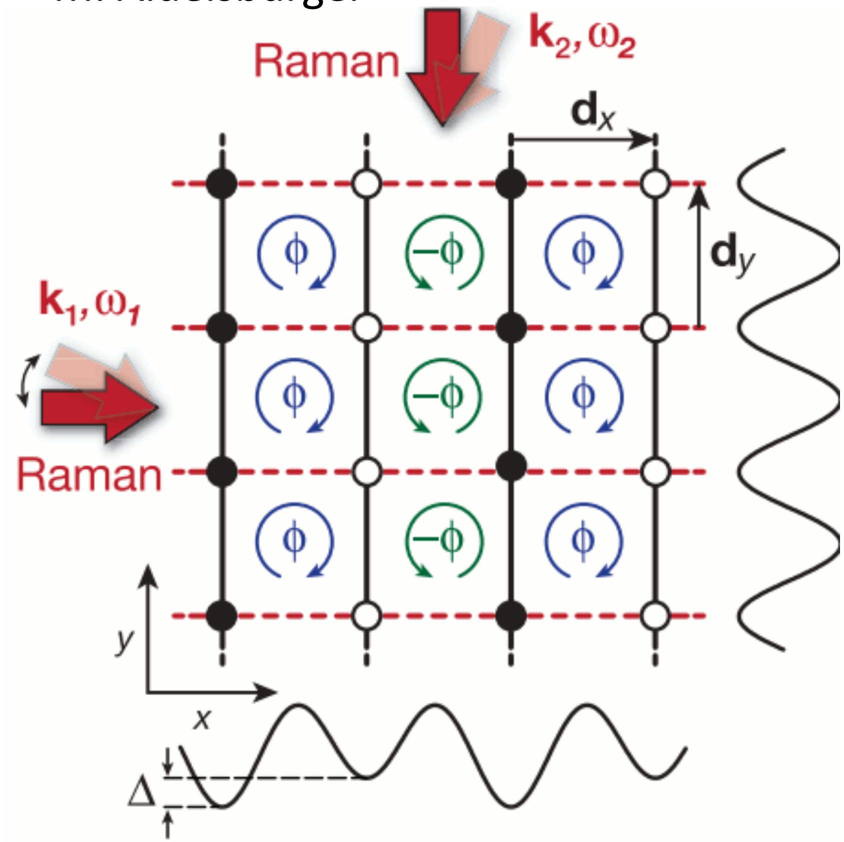


FIG. 4. ED calculations of the low energy spectra as a function of J_2/J_1 **(a)** on a lattice of 4×3 unit cells for various $S^z_{\rm Tot}$; **(b)** on a lattice of 4×4 unit cells in the $S^z_{\rm Tot} = 0$ sector only. **(c)** Low energy spectrum as a function of the twist angle θ_1 for $J_2/J_1 = 0.3$ and $\theta_2 = 0$ on a lattice of 4×3 unit cells. **(d)** Typical shape of the Berry curvature calculated using the non-abelian formalism resulting in a vanishing Chern number shown for $J_2/J_1 = 0.3$, $h_z/J_1 = J_2'/J_1 = 0.02$ on a lattice of 4×3 unit cells.

Cold Atoms & Gauge Fields

Goal: strongly correlated atoms in strong artificial magnetic fields.
Maximal flux per plaquette of order π

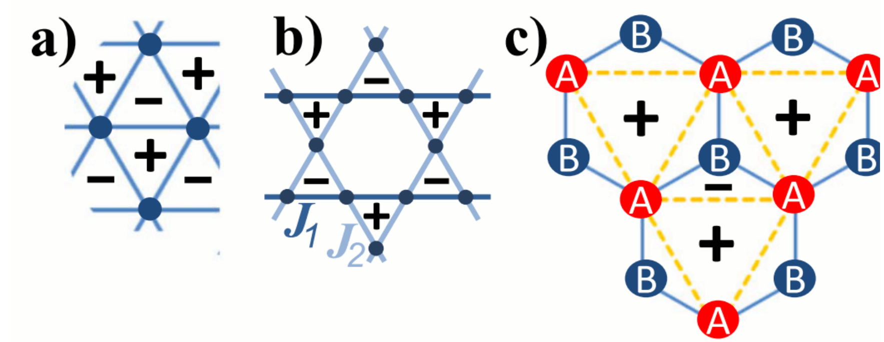
M. Aidelsburger



Laser-assisted tunneling in optical superlattice. PRL 107, 255301 (2011) (Immanuel Bloch's lab at Muenich)

Non-Abelian Models with interactions

P. P. Orth, D. Cocks et al J. Phys. B: At. Mol. Opt. Phys. 46 (2013) 134004 (review);
M. Scheurer, S. Rachel, P. Orth Sci. Reports 2015



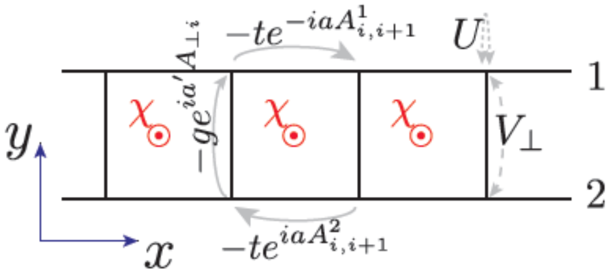
$$\hat{H}(t) = -\sum_{\langle ij \rangle} J_{ij} \hat{a}_i^\dagger \hat{a}_j + \sum_i v_i(t) \hat{n}_i + \hat{H}_{\text{on-site}}.$$

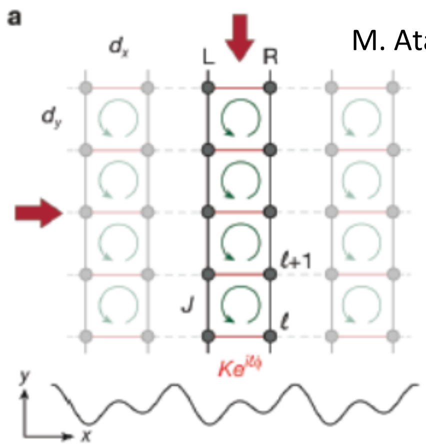
K. Sengstock's lab at Hamburg
Realization of Haldane model at Zurich, Jotzu et al. (Esslinger lab)

A lot of efforts at NIST, Paris, MIT,…
I. Spielman, W. Philipps (NIST)
J. Dalibard, F. Gerbier (Paris)…

Ladder simulation: bosons

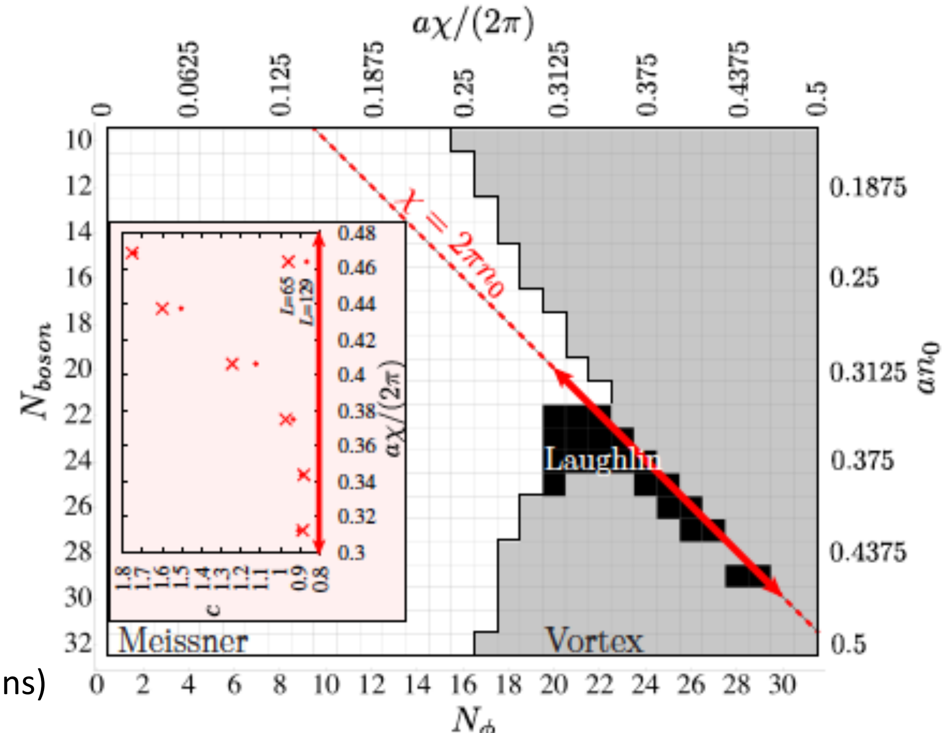
A. Petrescu, M. Piraud, G. Roux, I. McCulloch, KLH 2016 to appear PRB
M. Calvanese Strinati et al. PRX 2017; classification Teo-Kane



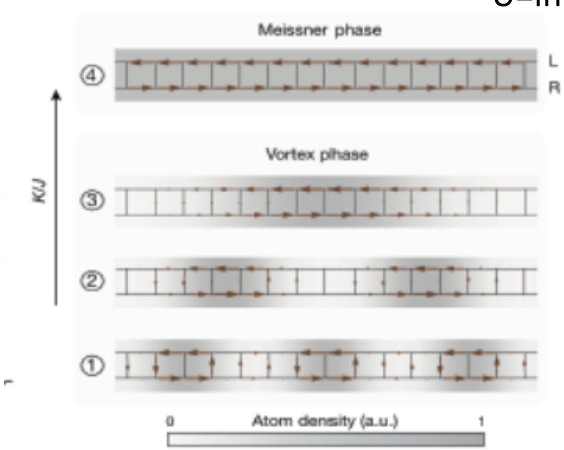


M. Atala et al 2014

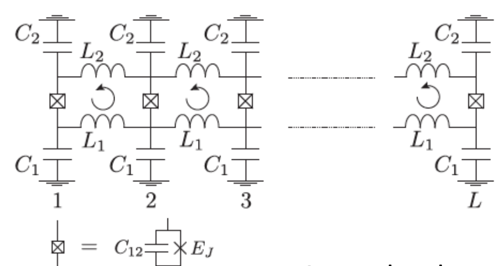
Munich



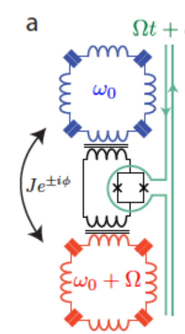
U=infinity, V=0 (spins)



Neel group: Josephson circuits



J. Gabelli
J. Esteve
Orsay



QHE, Thouless pump gives C=1/2 (Grusdt-Honing)
charges at the edges 2/5 (talk by M. Sassetti;
bipartite fluctuations Talk by Loic Herviou)

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…)

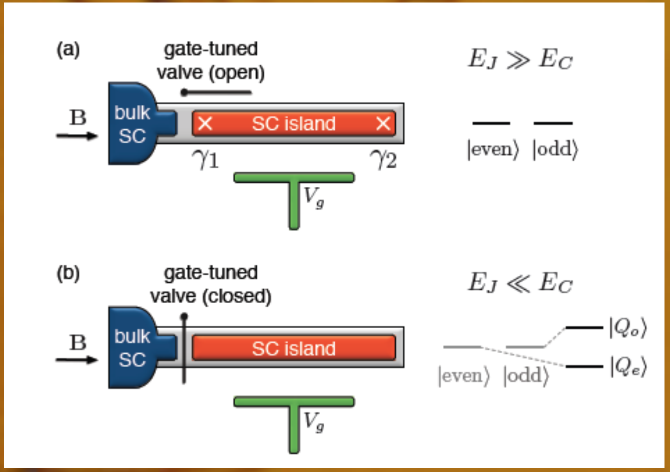
Particle and its own antiparticle

γ

Proposals:

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

Progress in nano-engineering to reveal the Majoranas
(talks by F. Nichele, P. Grunberg)



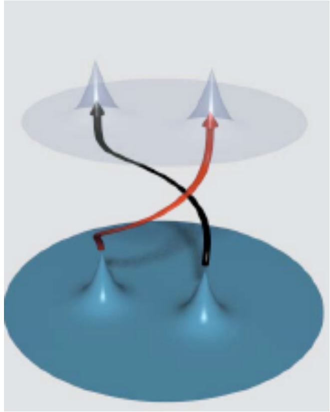
T. Kontos, A. Cottet (ENS)

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

Note: recent work on 2 coupled topological SC chains & Kondo box (B. Beri)
Loic Herviou, Christophe Mora, KLH, 2016

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

So only combinations of Majorana fermions can be occupied



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

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

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

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

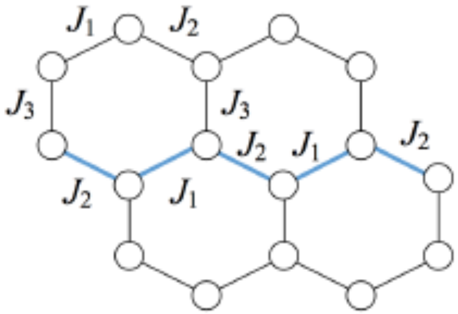
$\gamma_2 \rightarrow -\gamma_1$

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

Different final state! – Non-Abelian statistics.

Application qubits : quantum computing

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



Recent efforts M. Hermanns, S. Trebst
J. Vidal, S. Dusuel,...
T. Liu, B. Douçot, C. Repellin, N. Regnault, KLH

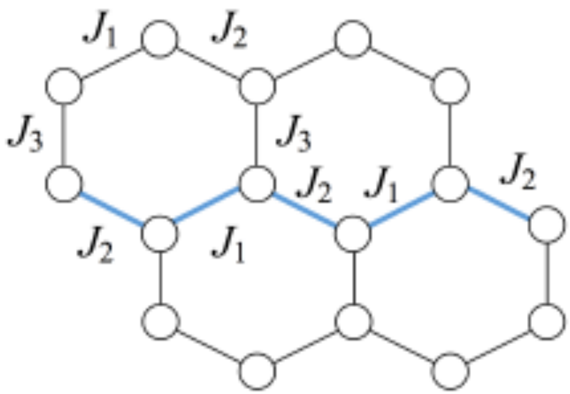
Sankar Das Sarma, Michael Freedman, Chetan Nayak arXiv:1501.02813

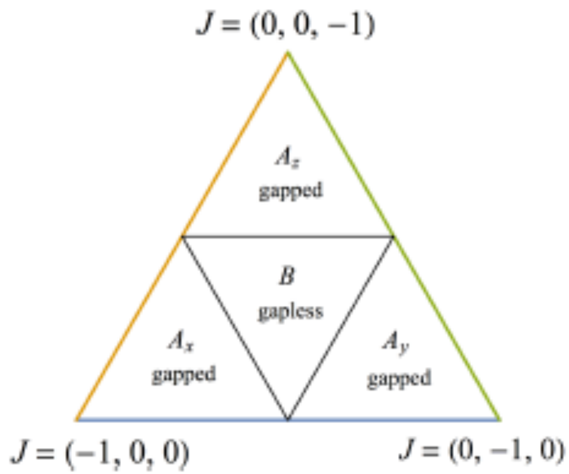
Talks Frank Pollmann & Simon Trebst

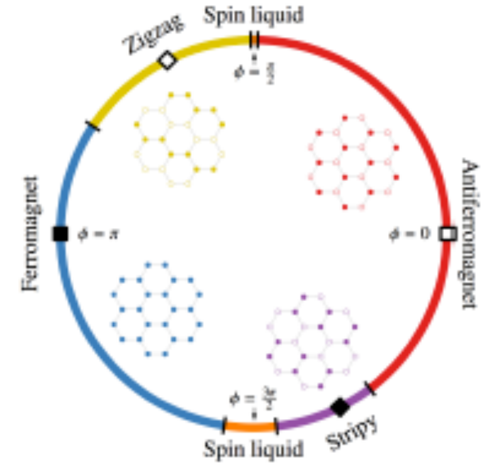
Anisotropic Spin-Orbit Z2 Models

Simulation in cold atoms:
Duan, Demler, Lukin

J. Rau & H. Y. Kee, review
Iridate materials,
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

Possible application to quantum materials, iridates and RuCl3 (J. Banerjee et al. Nature)

Question: Engineering minimal Z2 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

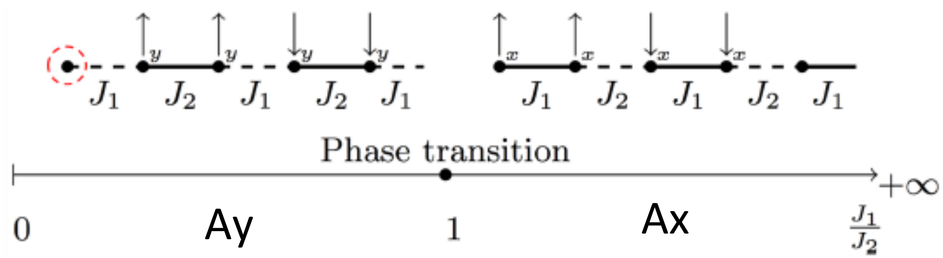
Related works by F. Hassler (talk), B. Terhal; B. Beri; Egger-Altland-Flensberg; L. Fu; …

RVB picture

work with Fan Yang & Ariane Soret, see ArXiv 2017

$$H = \sum_k (J_1 + J_2)\cos(kl)(a_k^\dagger a_k - a_k a_k^\dagger) + i(J_1 - J_2)\sin(kl)(a_{-k}^\dagger a_k^\dagger + a_{-k} a_k)$$

Phase transition:
Power law decay
(can be probed from
Bipartite fluctuations
Talk by Loic Herviou)



Feng et al. 2007

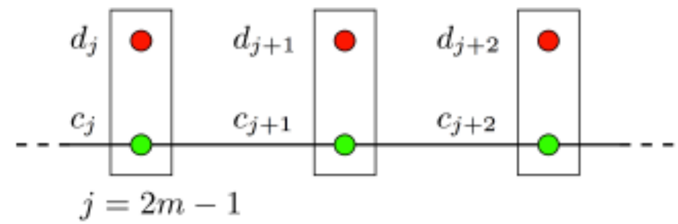
- Pairing term: odd parity $\rightarrow$ p-wave superconductors (topological)
  e.g. He^3, Sr_2RuO_4, 1D quantum wire etc. Anderson-Morel; Anderson-Brinkmann; Balian-Werthamer; Leggett (He3)
- $\epsilon(k) = \pm\sqrt{J_1^2 + J_2^2 + 2J_1J_2\cos(2kl)}$: invariant under $J_i \rightarrow -J_i$, $i = 1, 2$.

J1→0; edge modes are spin-1/2
Winding number can be computed (1 or 0)
Perturbation theory in spin space couples edges to order $(J1/J2)^{\text{number sites}}$ only
Non-local topological string order parameter similar to spin-1 chain (Feng et al. 2007)

Majorana representation

Spin liquid states in gapped phases

- Pre-formed pairs are similar to spin-1 BCS pairs in He^3. RVB states with exponentially decreasing correlation functions.



- Mapping to Majoranas:

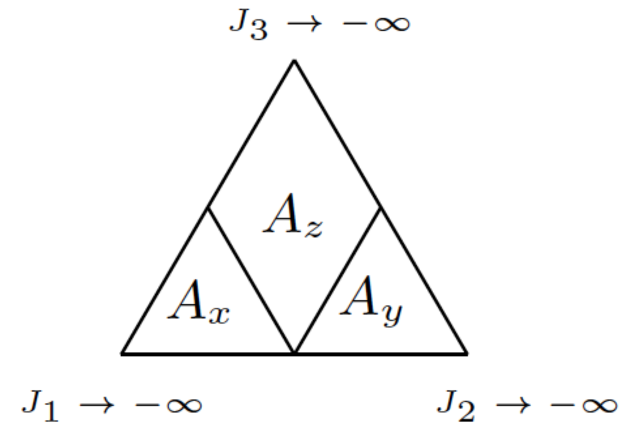
$$\begin{cases} c_j = i(a_j^\dagger - a_j), & d_j = a_j^\dagger + a_j, & j = 2m-1; \\ c_j = a_j^\dagger + a_j, & d_j = i(a_j^\dagger - a_j), & j = 2m. \end{cases}$$

$$H = -i \sum_{j=2m-1} (J_1 c_j c_{j+1} - J_2 c_{j+1} c_{j+2}).$$

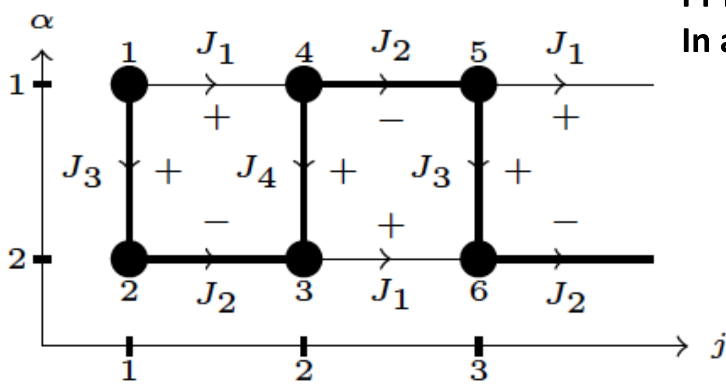
The free d-Majorana fermions in the bulk traduce the 2-fold degeneracy of a bond
The c1 Majorana fermion in the Ay phase weakly couples to the bulk
The spin-1/2 edge mode thus turns into a d1 Majorana fermion in the *infinite* time limit for larger J1 (The d Majorana fermions are not protected against local fields in 1 chain)
See also DeGottardi et al. 2011 and Pedrocchi et al. 2012

Ladder:

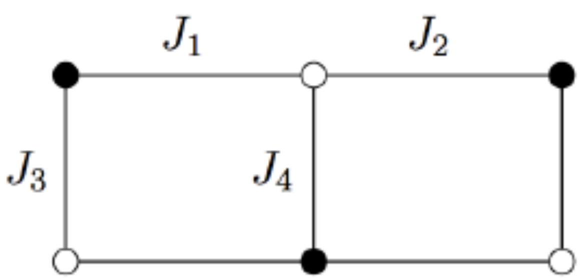
Feng et al. 2007
DeGottardi et al. 2011
Pedrocchi et al. 2012 (inhomogeneous ladder)
H. H. Lai and O. Motrunich, PRB 2011



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



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



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

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

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

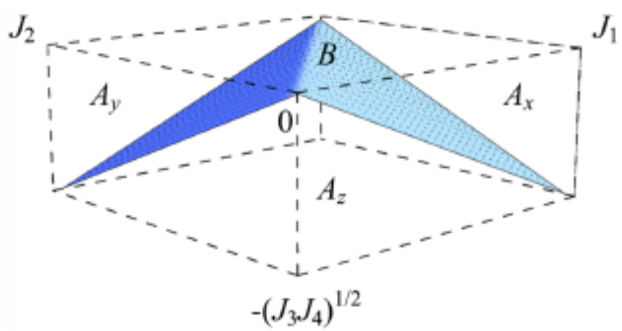
0 flux
for J4=0

KLH, A. Soret and F. Yang, 2017

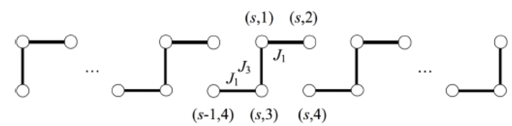
honeycomb or ribbon ladder: J4=0

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

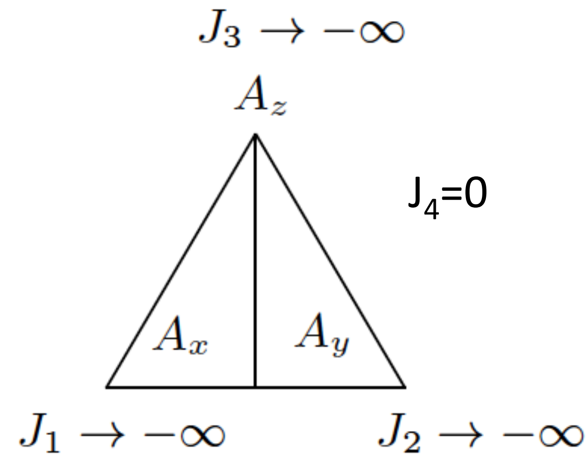
Generalized ladder: arXiv:1703.07322



Cluster solvable 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

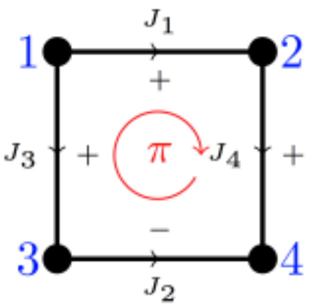
$$H = H_{\text{chain},1} + H_{\text{chain},2} + H_I ,$$

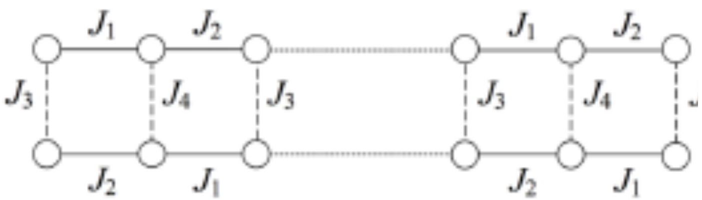
$$H_I = \sum_{j=2m-1} J_3 \sigma^z_{j,1} \sigma^z_{j,2} + J_4 \sigma^z_{j+1,1} \sigma^z_{j+1,2} \quad \text{(four-body)}$$

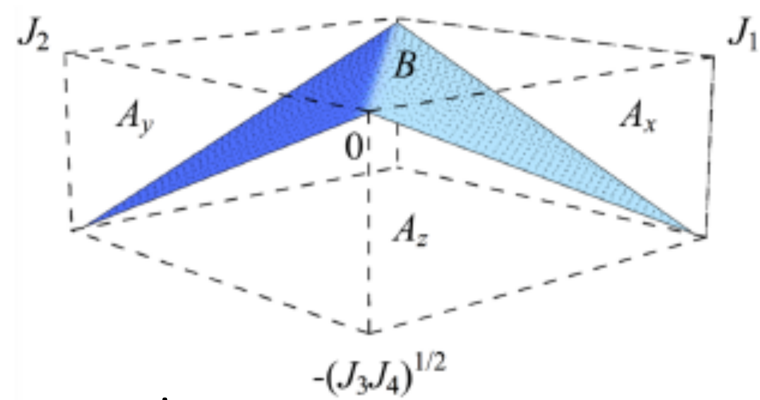
$$= -i \sum_{j=2m-1} \left(J_3 c_{j,1} c_{j,2} + J_4 c_{j+1,1} c_{j+1,2} \right) \quad \text{(Lieb's theorem, 1994)}$$

Line : pre-formed pairs resonating along chains (rung tensor product states; bosonization c=1)

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)

$D_{1,3} = (-i)d_1 d_3$ and $D_{2,4} = (-i)d_2 d_4$ 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 $d_1 d_2 d_3 d_4$

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

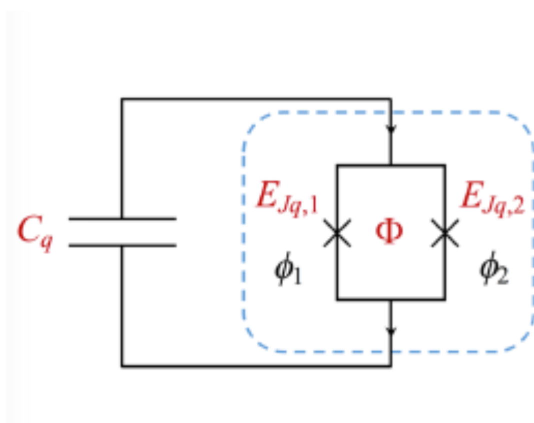
Effective spin representation

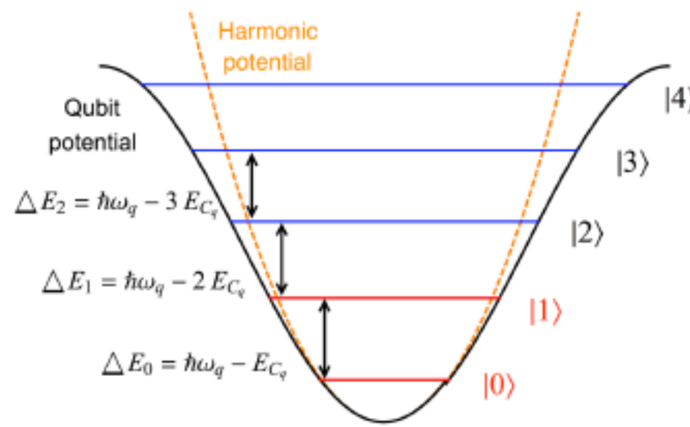
Quantization of transmon qubit

- Harmonic oscillators with anharmonicity from Josephson junctions $(t \gg 1)$:

$$H_q = \frac{\hat{Q}^2}{2C_q} - E_{J_q}\cos\hat{\varphi} = -E_{J_q} + \hbar\omega_q\left(b^\dagger b + \frac{1}{2}\right) - \frac{E_{C_q}}{12}\left(b^\dagger + b\right)^4$$

$$[\hat{\varphi}, \phi_0 \hat{Q}] = i\hbar, \qquad \hat{\varphi} = \frac{1}{t}\left(b^\dagger + b\right), \qquad \hat{Q} = \frac{-et}{i}\left(b^\dagger - b\right), \quad t = \left(\frac{E_{J_q}}{2E_{C_q}}\right)^{1/4}$$

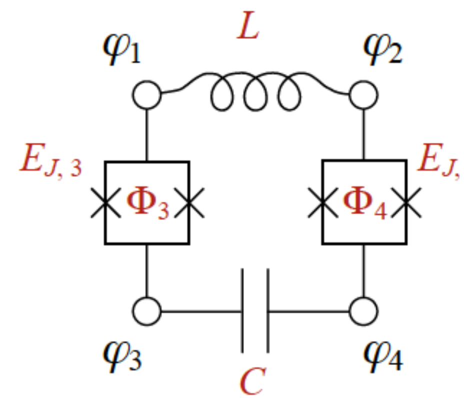




Yale, Santa Barbara (implementation of a small toric code),…

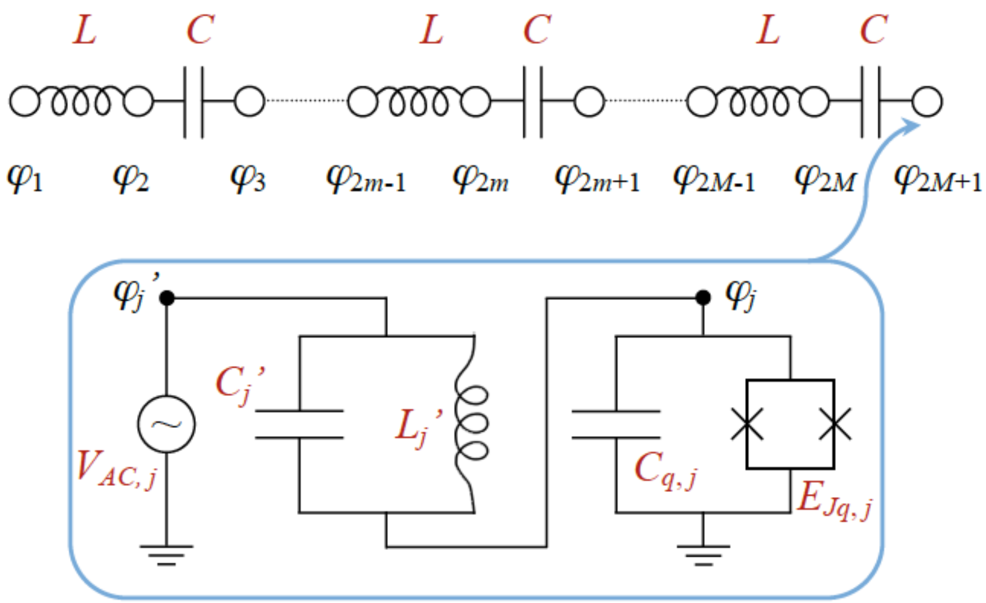
Simulation of New Devices with SC devices and Transmons

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



Coupling 4 Majoranas

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



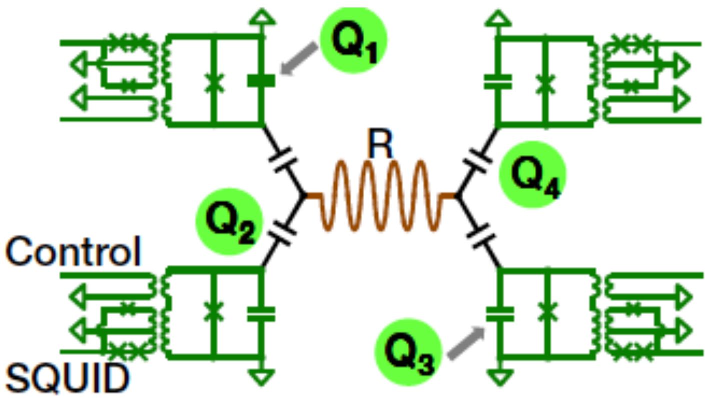
A 4-site toric code has been initiated
Y. P. Zhong et al
PRL 117, 110501 (2016)

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**)

Networks in circuit QED and atoms: progress

Zhong et al. arXiv: 1608.04890 (PRL)



Non-Abelian statistics

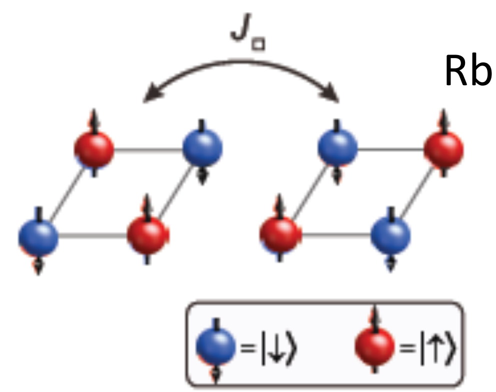
$$H_{\mathrm{exp}}/\hbar = \omega_r a^\dagger a + \sum_{j=1}^{4} \omega_j \sigma_j^\dagger \sigma_j + g \sum_{j=1}^{4} (\sigma_j^\dagger a + \sigma_j a^\dagger),$$

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

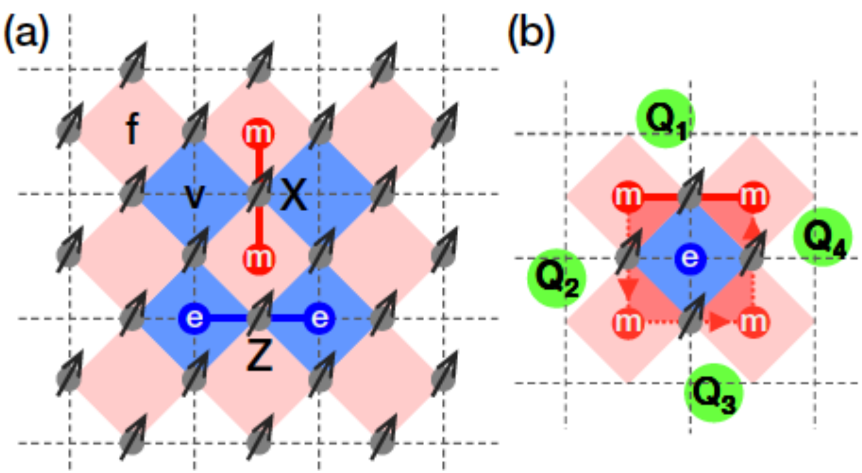
$$C_{\mathrm{loop}} |\psi_g\rangle = |\psi_g\rangle$$

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

H. N. Dai et al. arXiv:1602.05709
Simulation of ring processus

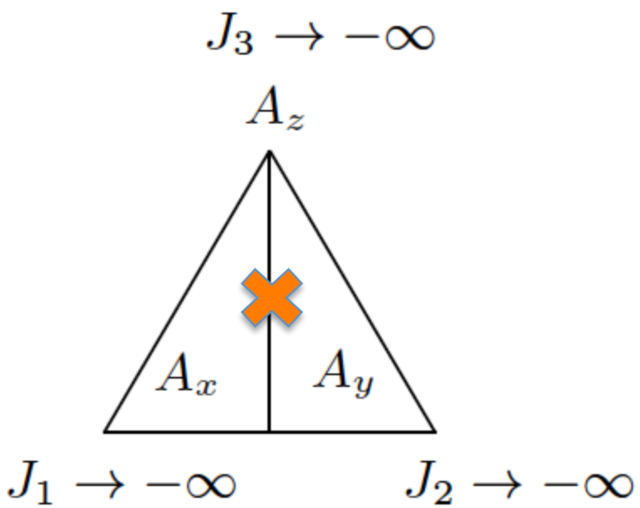


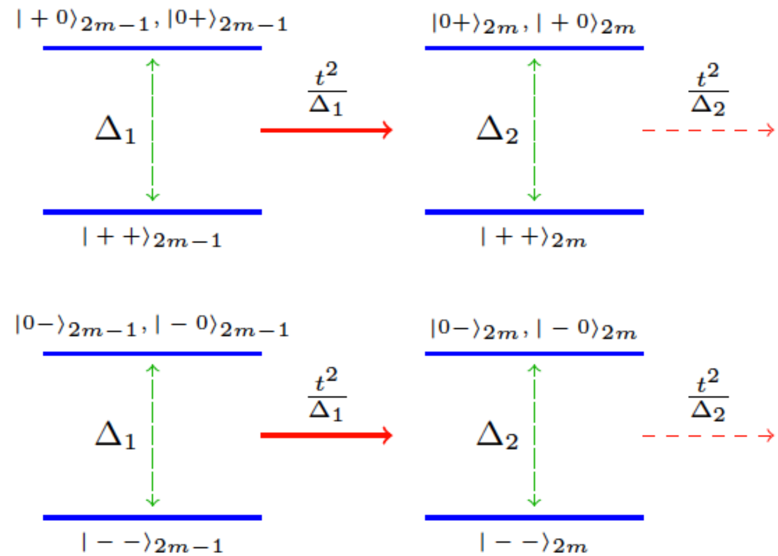
$$\hat{H}_{\mathrm{T}} = -J_{\square} \sigma_1^x \sigma_2^x \sigma_3^x \sigma_4^x - \frac{J_+}{4} \sum_{\langle j,k \rangle} \sigma_j^z \sigma_k^z,$$



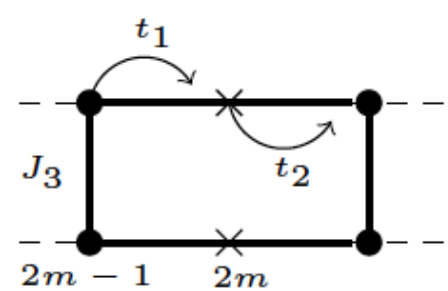
Other proposals to realize ring processus
H. P. Buchler et al. (PRL 2005)

Topology of hole pair



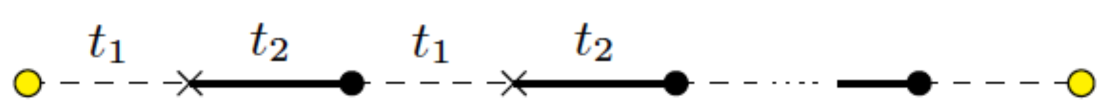


Analogy to SSH model for hole pair:
- Insulating phase : hole pair at boundary
- Superconducting transition at intermediate Coupling (p-wave SC); non topological SC can also be found from Az phase



2D work with T. Liu, C. Reppelin, B. Doucot, N. Regnault; see also B. Rosenow, G. Khaliullin, C. Honerkamp,…

Doping at the edges

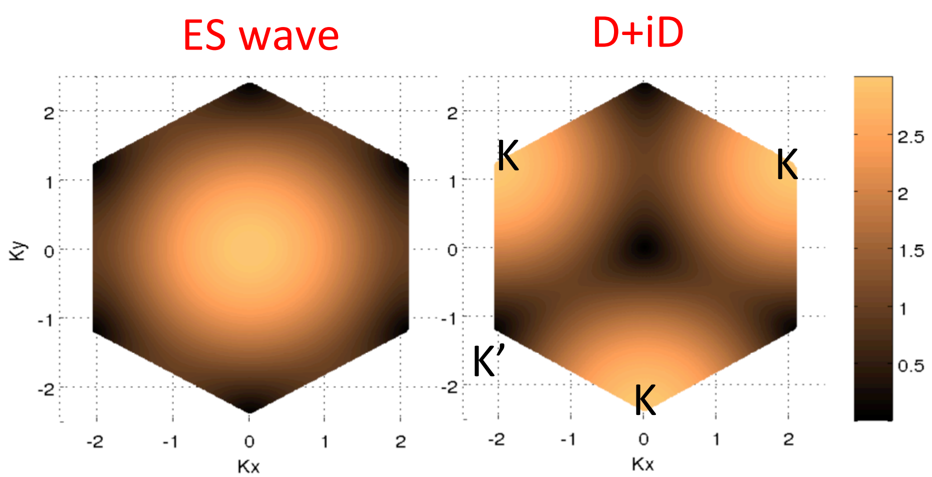


Still Chirality from Hubbard...

Possibility of gapped spin liquid

Let's start from Néel half-filled phase and dope the system

Difficulty to solve
this model exactly
Start from Mean-Field
Atomic picture



Doping leads to
Interesting pairing

$$\Delta_{\mathbf{k}}^{d+id} = \cos(\tfrac{\pi}{3})\Delta_{x^2-y^2} + i\sin(\tfrac{\pi}{3})\Delta_{xy}.$$

<u>d+id SC state</u>

A. Black-Schaffer & S. Doniach

C. Honerkamp

R. Nandkishore, L. Levitov, A. Chubukov
¼ filling ...

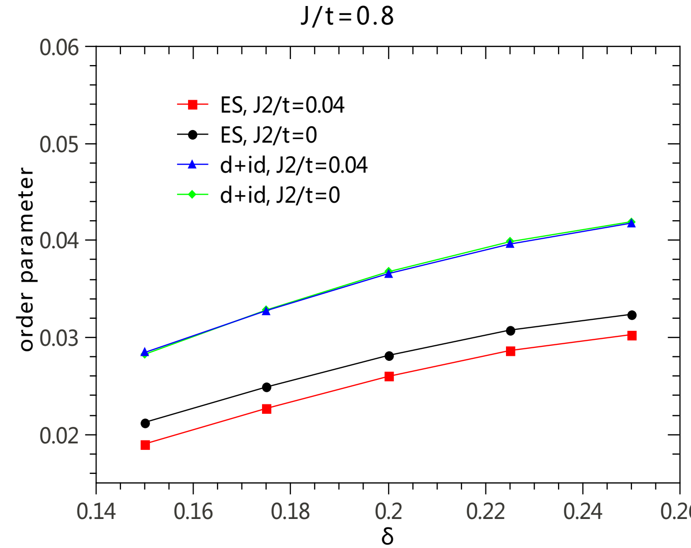
1) Wei Wu, Michael M. Scherer, Carsten Honerkamp & KLH, PRB 2013 (RMFT, fRG: t-J1-J2)
2) A. Black-Schaffer, W. Wu and KLH, PRB 2014 (**symmetries,** RMFT t-J, QMC on Hubbard)
3) A. Black-Schaffer & KLH, arXiv:1503.02509 (topological phase transition due to SDW)

d+id Pairing: RMFT & QMC

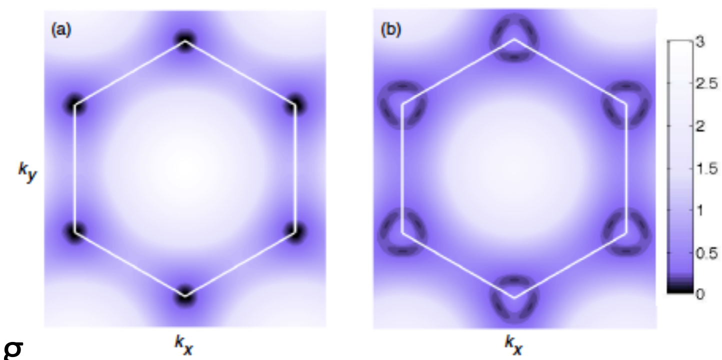
Renormalized mean-field theory

F. C. Zhang, C. Gros, T. M. Rice, and H. Shiba, Supercond. Sci. Tech. **1**, 36 (1988).
P. W. Anderson, P. A. Lee, M. Randeria, T. M. Rice, N. Trivedi, and F. C. Zhang, J. Phys.: Condens. Matter **16**, R755 (2004).
B. Edegger, V. N. Muthukumar, and C. Gros, Adv. Phys. **56**, 927 (2007).
M. Ogata and H. Fukuyama, Rep. Prog. Phys. **71**, 036501 (2008).
K. Le Hur and T. M. Rice, Ann. Phys. **324**, 1452 (2009).

1)



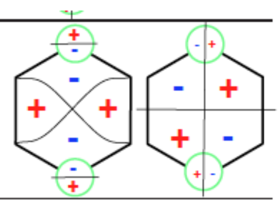
2)



BdG spectrum

½ filling

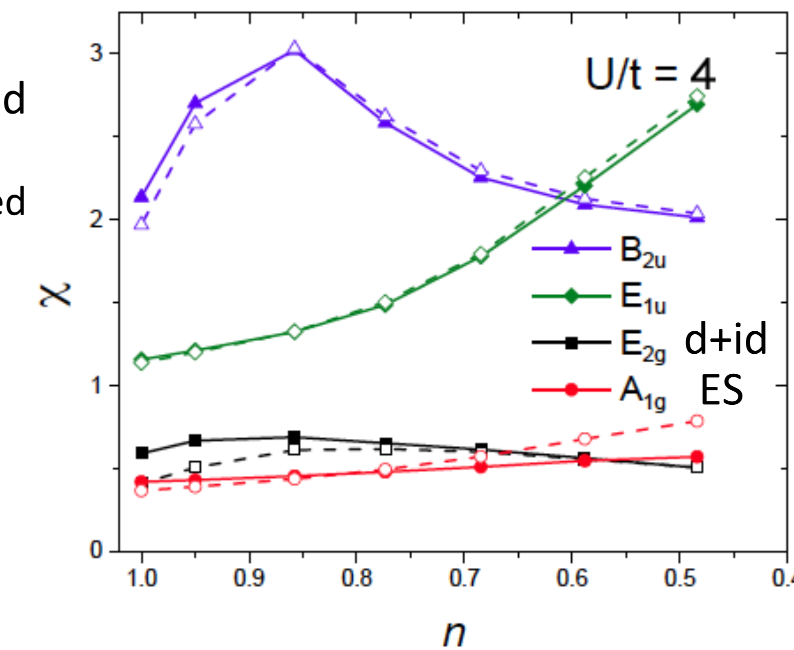
Doped
Fully
gapped

E_{2g}	$(k_x^2 - k_y^2, 2k_xk_y)$	

Intraband pairing wins

QMC

2)

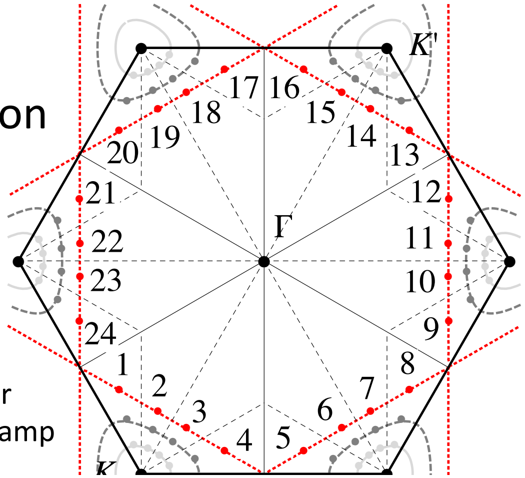


See also results from L. Balents, X. G. Wen :
Z. G. Gu et al. Phys. Rev. B **88**, 155112 (2013)
Grassmann Tensor Network Approach, DMRG

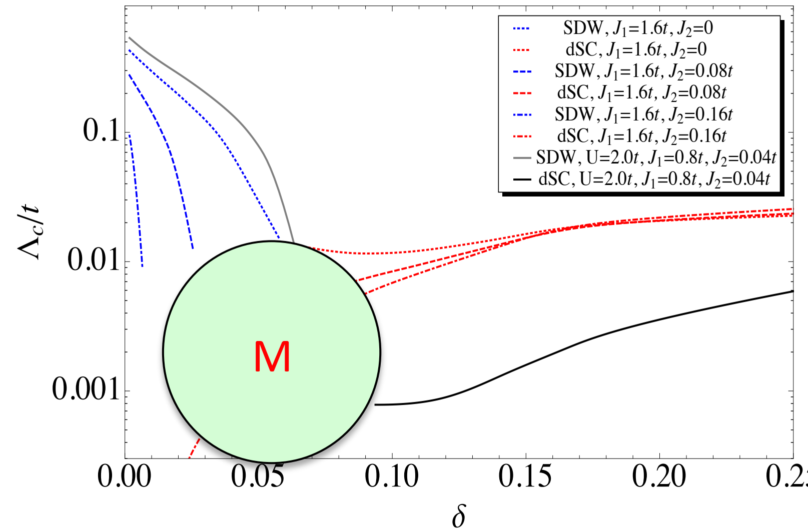
SDW and SC: Two chiral Superconductors

fRG solution

1)



M. Scherer
C. Honerkamp



Class A

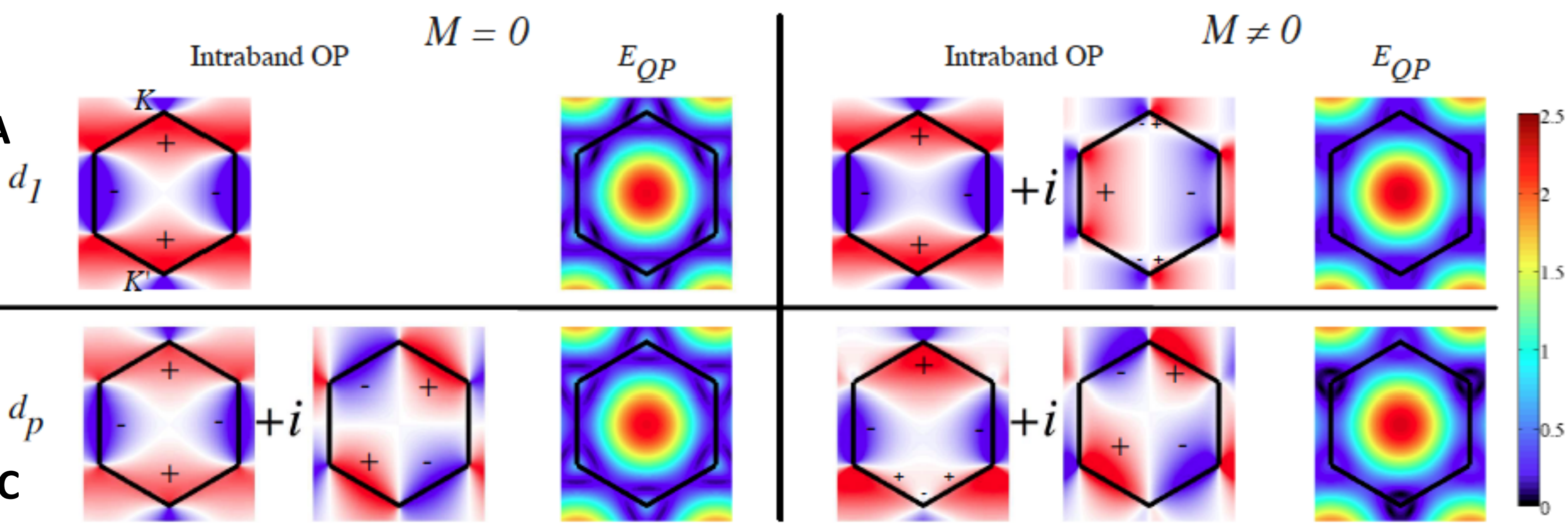
d+id

d-id

3)

d+id

Class C



Universality class C=2 (2 co-propagating edge modes)

Counter-propagating helical edge modes (**class A**): analogy to Kane-Mele model

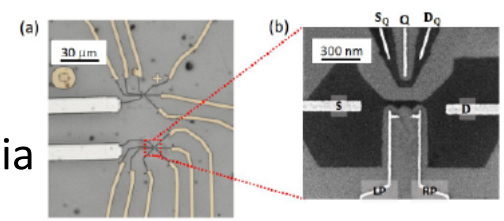
Topological Phases, Interaction Effects & Gauge Fields

From Materials, to Ultra-Cold Atoms and Photon Simulators

- Spin-orbit coupling in graphene lattices
  Kane-Mele Model, Interaction Effects (fermions and Mott, XY Neel)
  bosons yield a new CSS (chiral spin state) phase

  ladder system: FQHE of bosons U=infinity

- Z2 quantum Majorana liquids
  Kitaev chain, Ladders (linking RVB states with BCS theory exactly)
  Majorana Box, cQED
  SSH model of hole pair



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

Progress on stochastic dynamics and simulation in dissipative media
KLH, L. Henriet, L. Herviou, K. Plekhanov, A. Petrescu, T. Goren
M. Schiro, C. Mora and P. P. Orth, arXiv:1702.05135