Quantum Magnetism and Spin Liquids

Lucile Savary

Santa Fe, April 30th, 2019

Four talks this morning

- **Steve Nagler** - *Possible Kitaev spin liquid physics and topological transitions in $RuCl_3$*
- **Rajiv Singh** - *Entropy plateaus in Spin-S Kitaev Models*
- **Hide Takagi** - *Spin-orbital entangled quantum liquid on the honeycomb lattice*
- **Gang Chen** - *Topological thermal Hall effect from induced internal gauge flux in a U(1) spin liquid*

The context

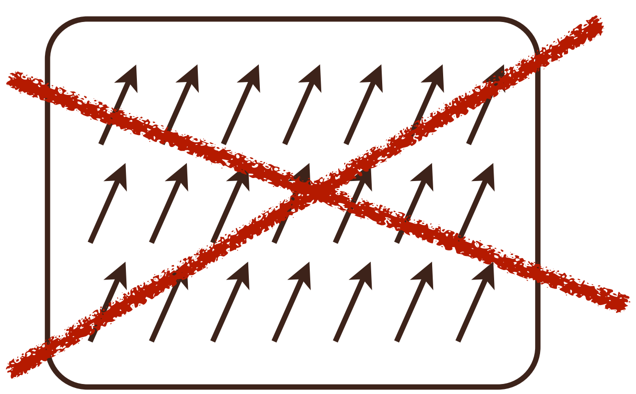
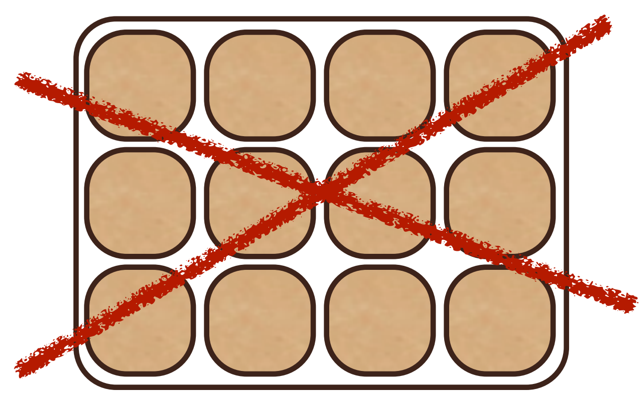
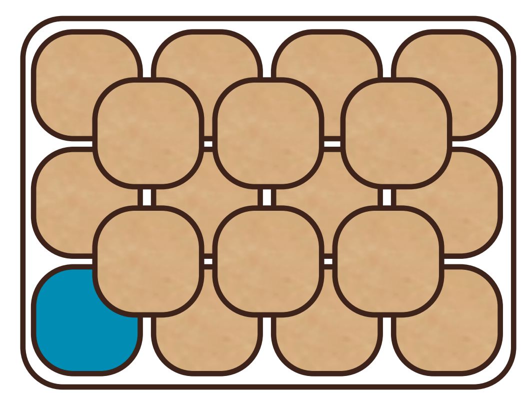
- quantum spin liquids
  - challenges of their experimental and theoretical understanding
  - thermal Hall effect: an important probe ⟶ Gang
- Kitaev honeycomb model
  - candidates: $RuCl_3$ ⟶ Steve
  - beyond the "pure" model and materials

Rajiv

Hide

What are QSLs, and why are they interesting?

- *insulating* states of quantum magnets (*no* free electrons)
- **Essentially the most quantum state of magnets**
  - They are quantum superpositions of very many product states, which cannot be adiabatically deformed to a product state

note: interactions (the Hamiltonian) are local $H \sim \sum_x \mathcal{H}(x)$

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  - They are quantum superpositions of very many product states, which cannot be adiabatically deformed to a product state
  - lead to emergent gauge fields, fractional particles

$$\left.\begin{array}{llll} \bullet\ \text{electrons} & & & q=-e,\ s=1/2 \\ \bullet\ \text{spin flips} & \underset{s^z=-1/2}{|\downarrow\rangle} \longrightarrow \underset{s^z=1/2}{|\uparrow\rangle} & & q=0,\ s=1 \end{array}\right\} \text{“integer particles”}$$

<u>fractional particles:</u> e.g. q=0 s=1/2

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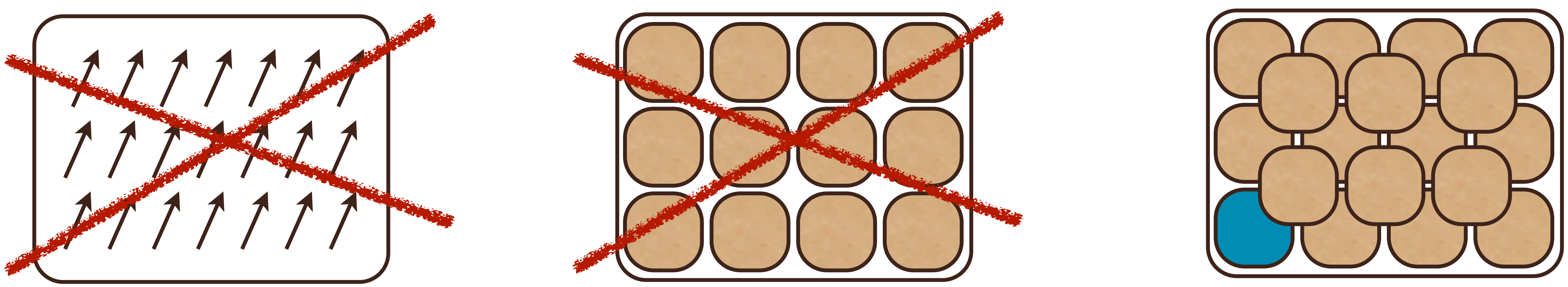


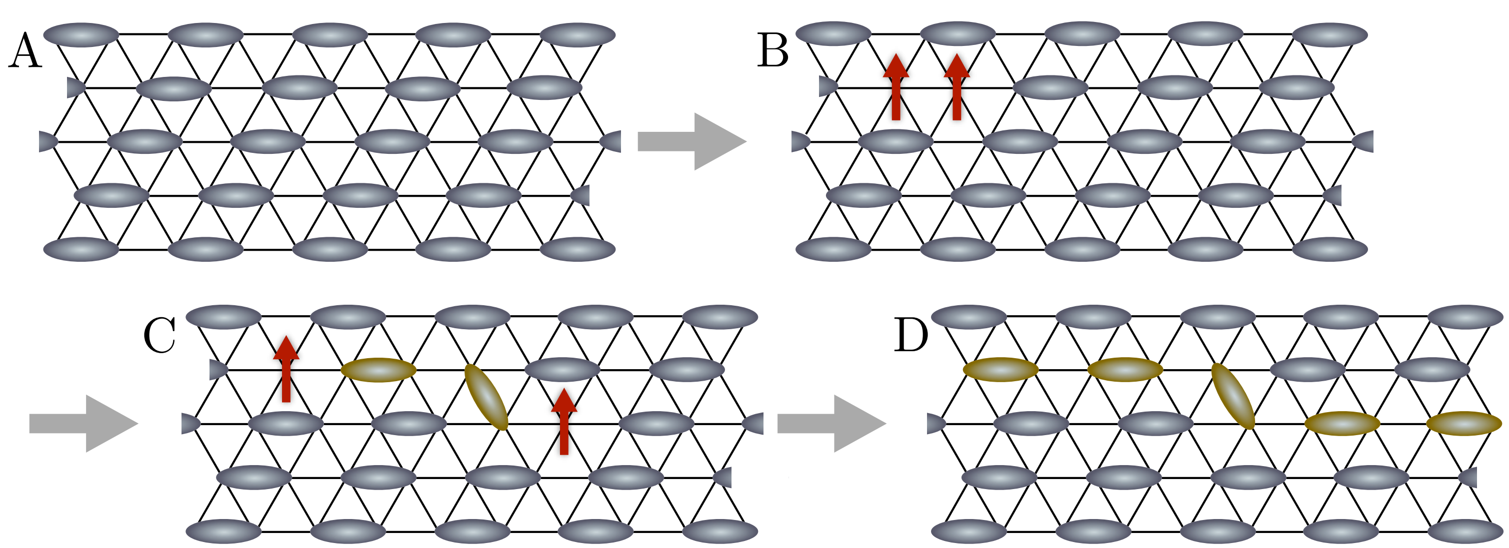
what kind of state is this?

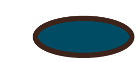
note: interactions (the Hamiltonian) are <u>local</u> $H \sim \sum_x \mathcal{H}(x)$

Example

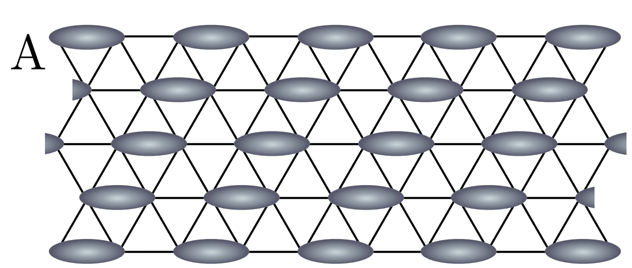
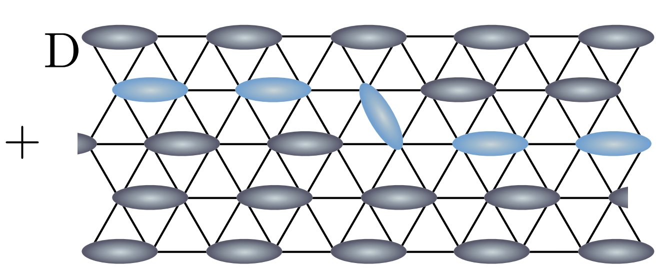
- Anderson's idea (1973): "Resonating valence bonds"

valence bond solid





$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$|\psi_{\rm QSL}\rangle =$  $+$  $+\cdots$

RVB

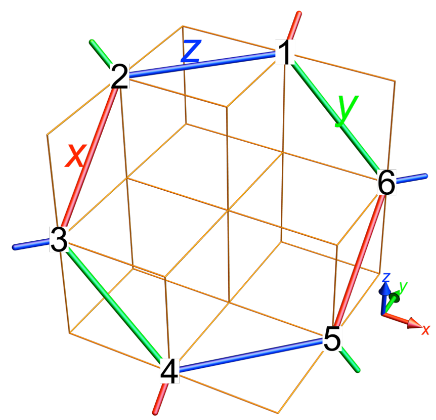
entangled state

quasiparticles are "deconfined"

Important points

- Very stable states: perturbations keep you in the phase -- might need phase transition
- Obtained from *local* interactions
- Characteristic features typically stem from nonlocal properties => hard to understand theoretically, and hard to probe experimentally!
- There is no one single sharp indicator of a QSL
- Experimentally, no definitive proof yet, but...

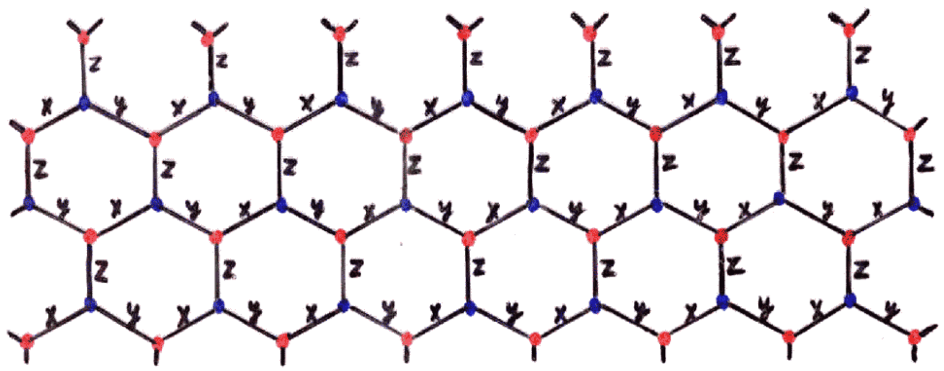
Kitaev spin liquids



$$H = \sum_{i,\mu} K_\mu \sigma_i^\mu \sigma_{i+\mu}^\mu$$

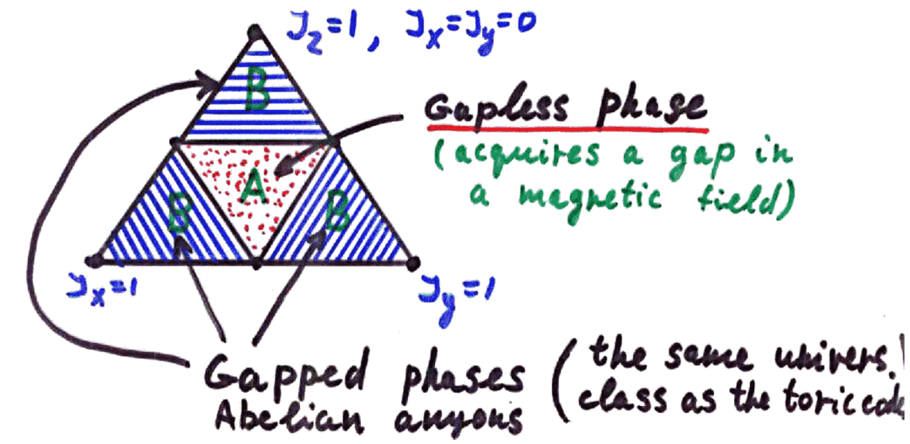
KITP, 2003

1. The model



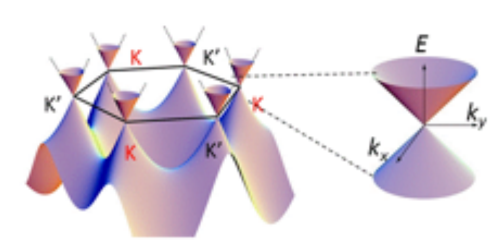
Spin $\frac{1}{2}$ on each site.

Phase diagram in zero field

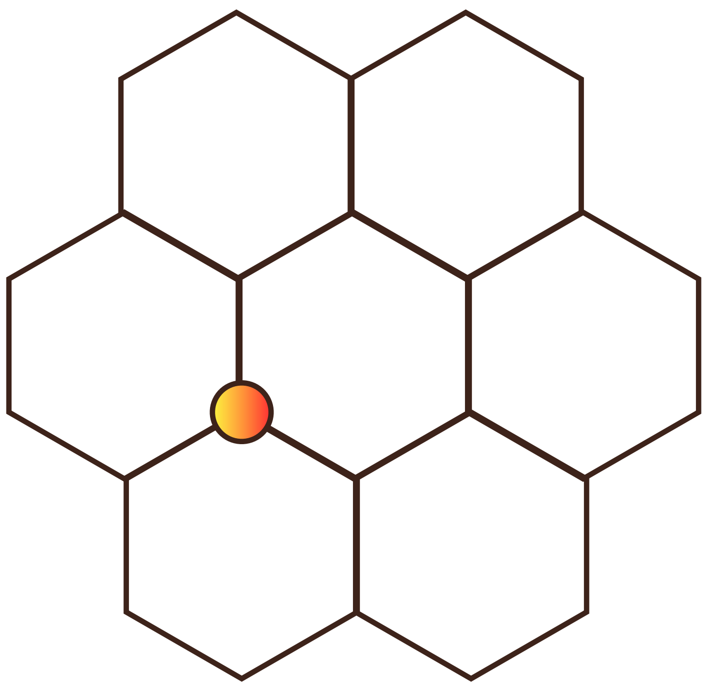


exact parton construction $\quad \sigma_i^\mu = i c_i c_i^\mu \qquad c_i c_i^x c_i^y c_i^z = 1$

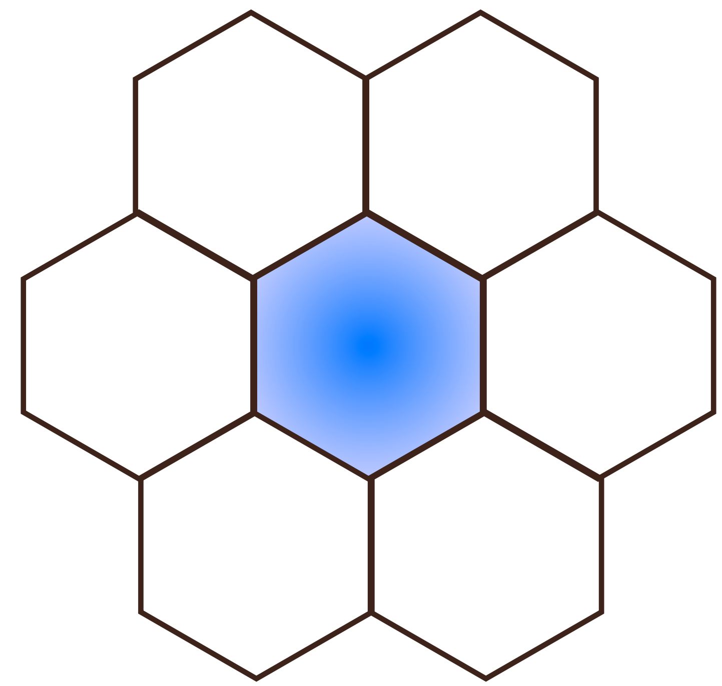
physical Majoranas $\quad H_{\mathrm{m}} = K \sum_{\langle ij \rangle} i c_i c_j$



Non-local excitations



Majorana ε



Flux e, m

In Kitaev's model:

- Majorana's dispersion ~ K and Dirac-like
- Fluxes are localized and gapped

Kitaev spin liquids

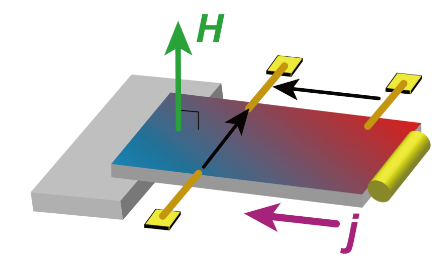
- 3 types:
  - gapless (minimal model) → Steve in zero field Hide?
  - gapped (minimal model with one larger interaction constant)
  - chiral (in TR breaking Hamiltonian) → Steve in magnetic field

"Ising anyon phase"

gapped non-abelian bulk

Majorana edge state

half-quantized thermal Hall conductivity



$$\kappa_H = \frac{\pi c T}{6}$$

Kitaev Ann. Phys.

Jackeli & Khaliullin PRL

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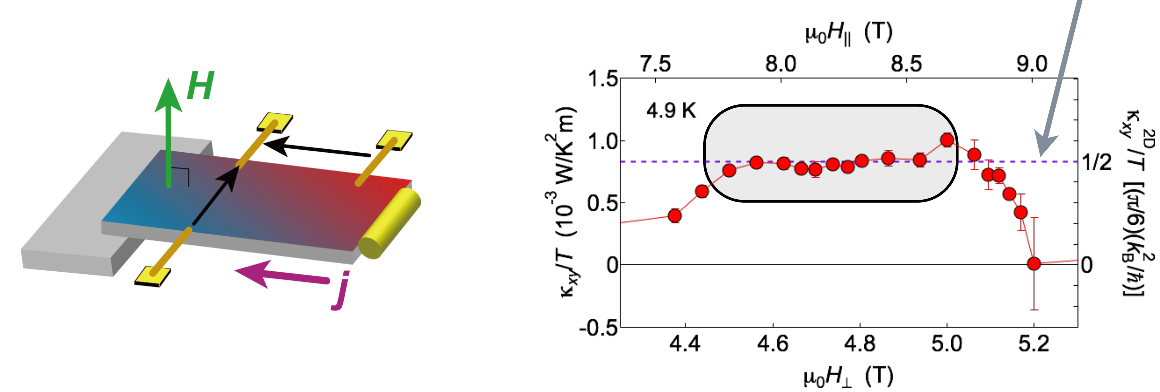
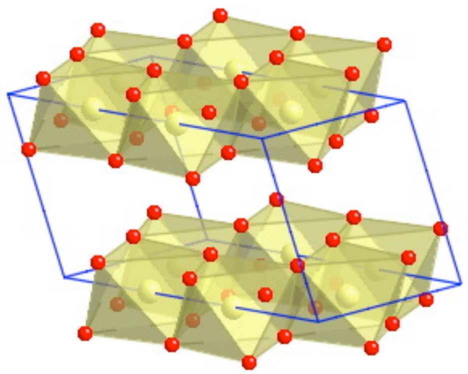


Kasahara *et al.* 2018

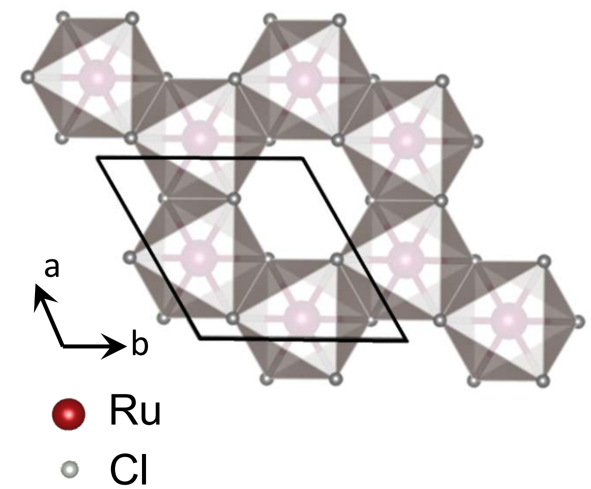
Kitaev Ann. Phys.　　Jackeli & Khaliullin PRL

but $\kappa_{xx} \gg \kappa_H$, see Ye et al., Winkler-Aviv et al.

Which materials?

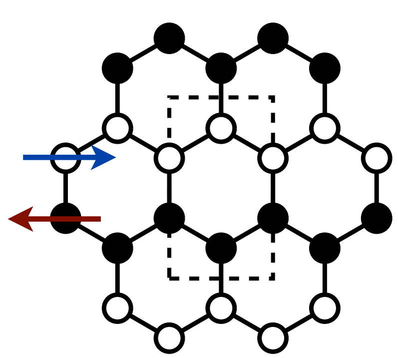


α-Na_2IrO_3,
(α,β,γ)-Li_2IrO_3

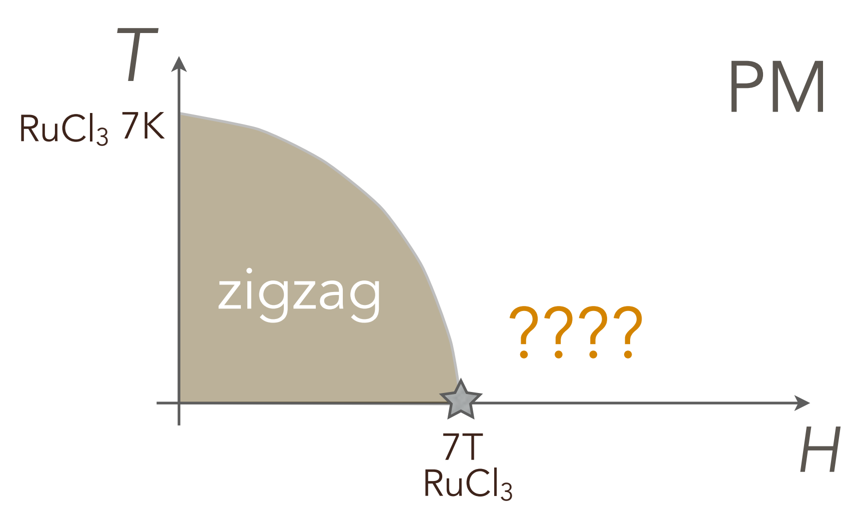


α-$RuCl_3$

all order in *zero* field so far (they contain extra interactions -- Heisenberg, out-of-plane, etc.)



“zigzag”

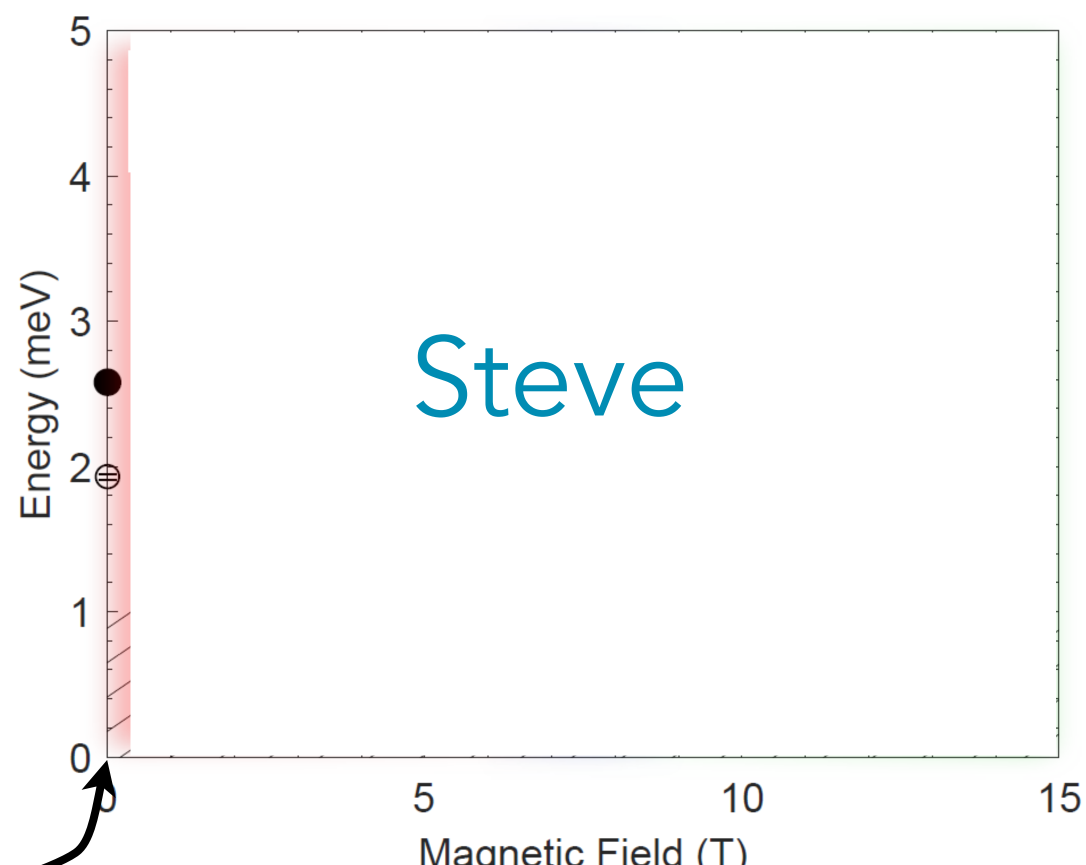


but…

Kitaev physics - $RuCl_3$

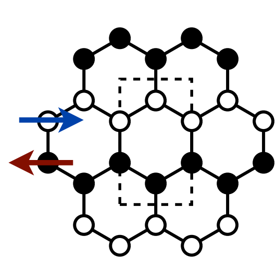
- Steve - one of the first leaders for $RuCl_3$ - new results
  - inelastic neutron scattering in field

Γ point gap



Nagler et al.

“zigzag” (ordered) phase (gapped)

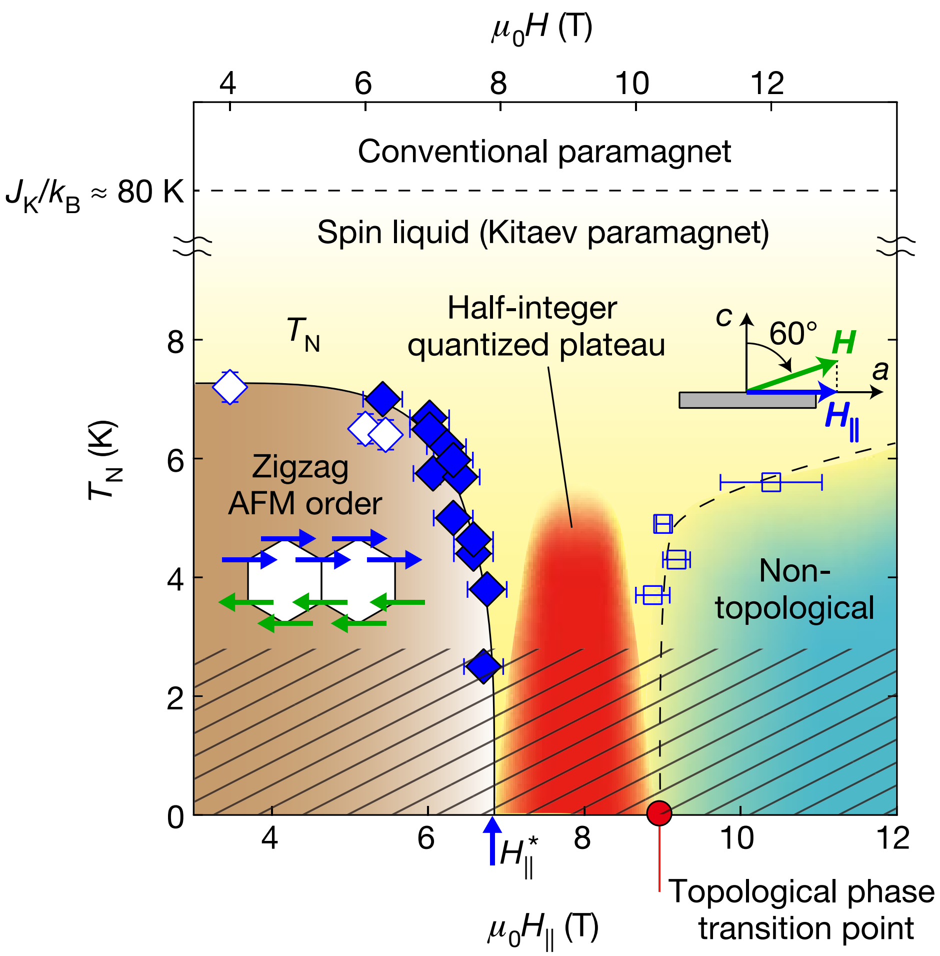


$RuCl_3$ in field - phase transitions

- magnetocaloric effect
  shows several transitions

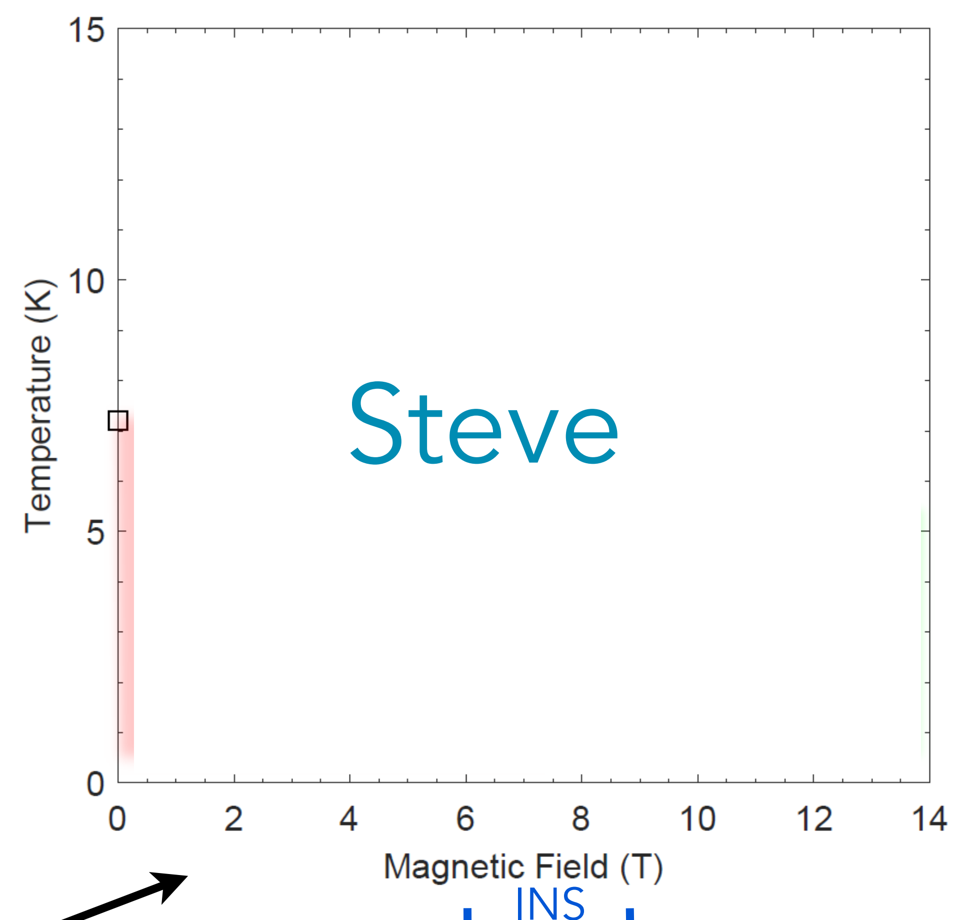
variation in magnetic field strength changes the magnetic contribution to the entropy

at fixed entropy measure temperature changes



Kasahara et al. 2018

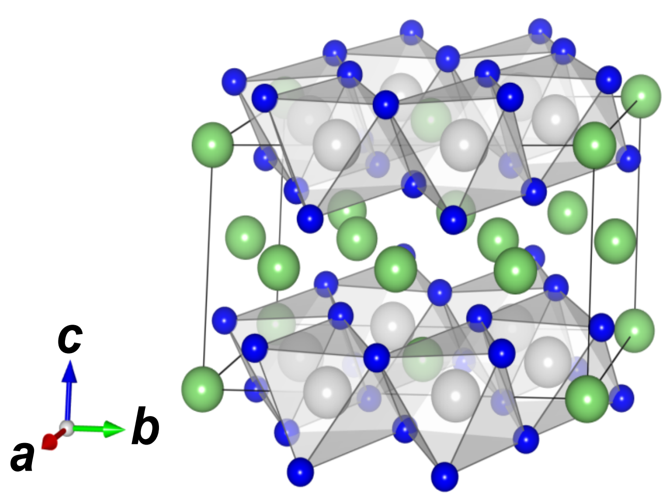
phase transitions?



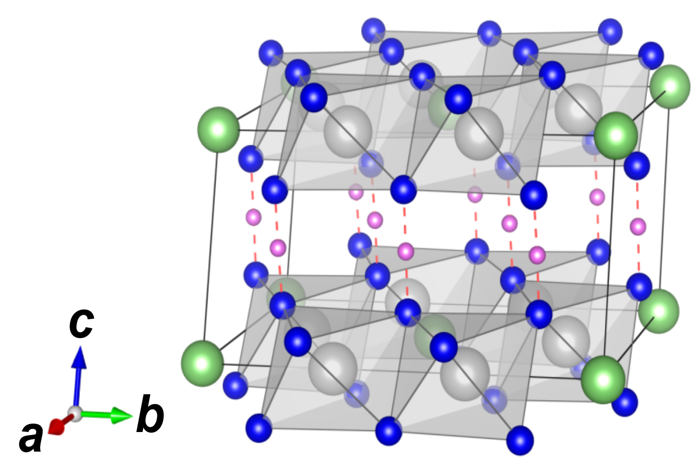
Nagler et al.

Beyond the "early" materials

- Hide: "hydrogen-intercalated lithium iridate": α-$H_3LiIr_2O_6$"



α-Li_2IrO_3



$H_3LiIr_2O_6$

"out-of-plane compressed"

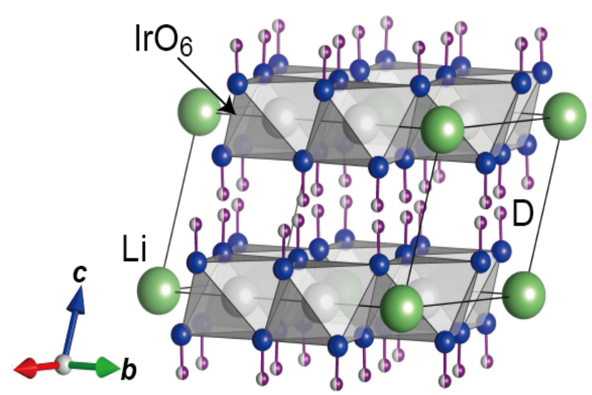
can this help to remove the zero-field ordering?

Many probes

Hide

- insulator from resistivity
- no phase transition from C or χ
- no magnetic order from NMR
- spin dynamics
- isotope effect

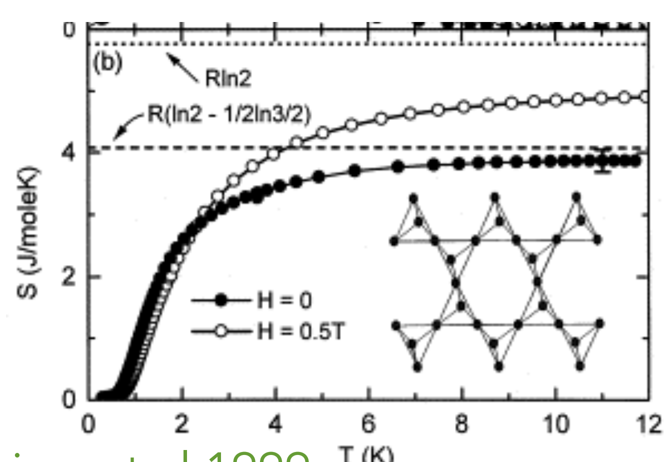
consistent with QSL ground state, but, if so, which one?



Entropy plateaus in spin-s Kitaev models

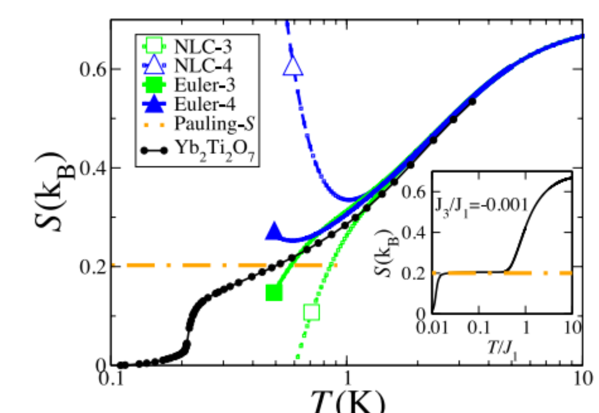
- Classical models with large degeneracies show entropy plateaus at a function of T

e.g. classical spin ice



Ramirez et al 1999

expect plateau-like features with perturbations



Applegate et al 2012

classical Kitaev has large degeneracy $\longrightarrow$ entropy plateaus in model with Heisenberg as well? quantum model?

Rajiv

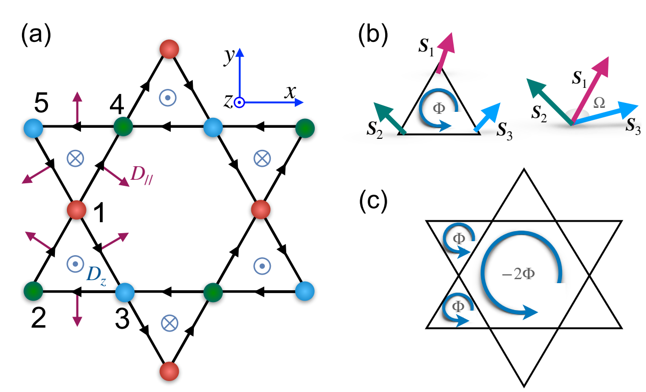
Thermal Hall effect

- when quantized: smoking gun of fermionic edge modes   cf. Kitaev in field
- otherwise: probes the nature of the state

can come from non-zero chirality

$$H = \sum_{i,j} J_{ij} \boldsymbol{S_i} \cdot \boldsymbol{S_j} + \sum_{i,j} \boldsymbol{D}_{ij} \cdot \boldsymbol{S_i} \times \boldsymbol{S_j} - \sum_i B S_i^z$$

$$\langle \boldsymbol{S}_i \times \boldsymbol{S}_j \cdot \boldsymbol{S}_k \rangle \sim \langle \boldsymbol{S}_i \times \boldsymbol{S}_j \rangle \cdot \langle \boldsymbol{S}_k \rangle \neq 0$$



Gang

Please enjoy the session!