Leon Balents
CIFAR school, Toronto, April 2016

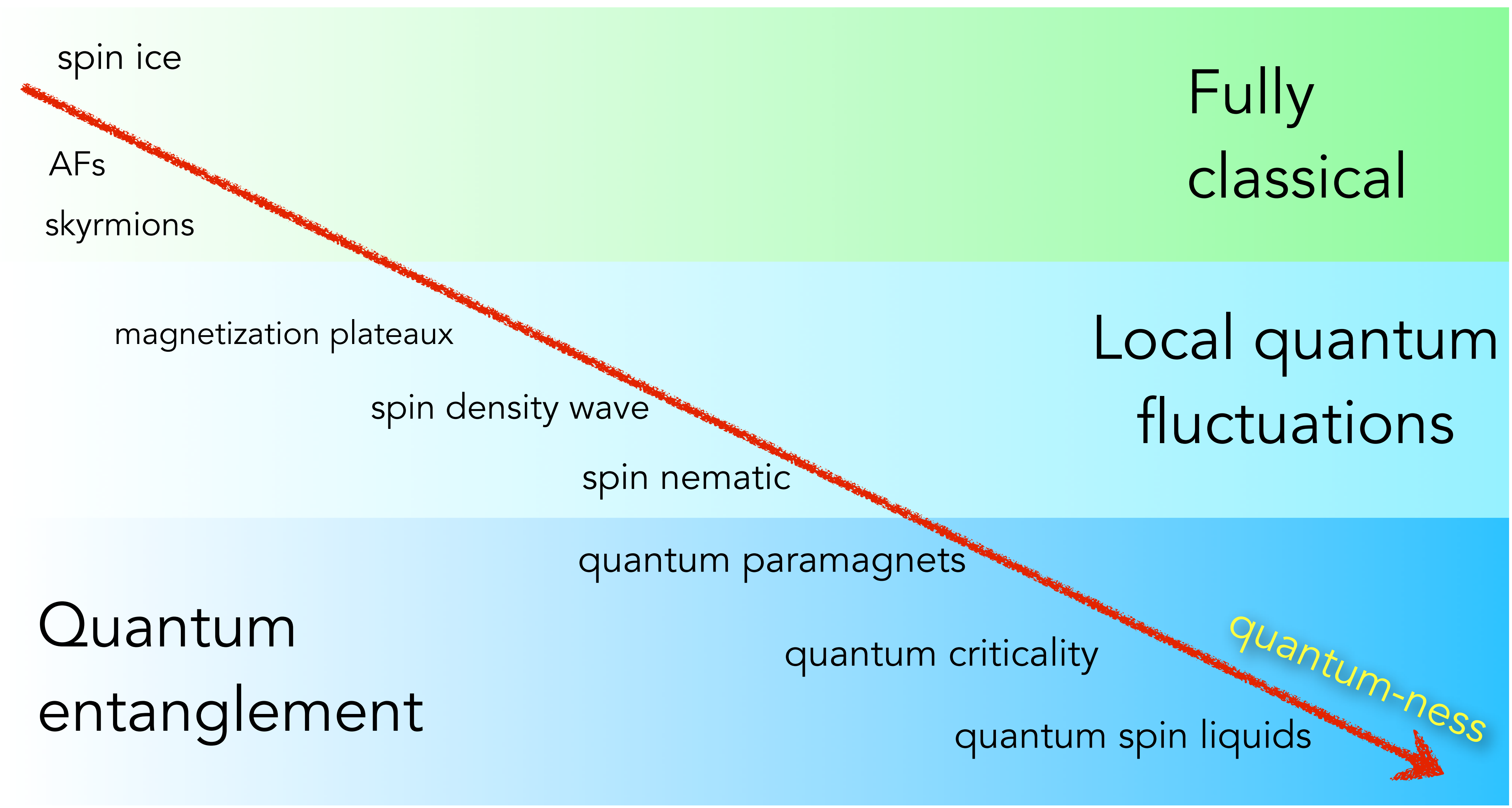
Quantum Spin Liquids

Plan

- The bird's eye view: QSLs as *ultra-quantum matter*
  - What is different from ordinary stuff?
- Review experimental status and recent developments

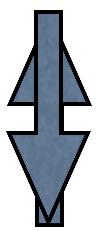
References here: https://spinsandelectrons.com/pedagogy/

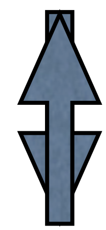
Quantum Magnetism



Quantum non-locality

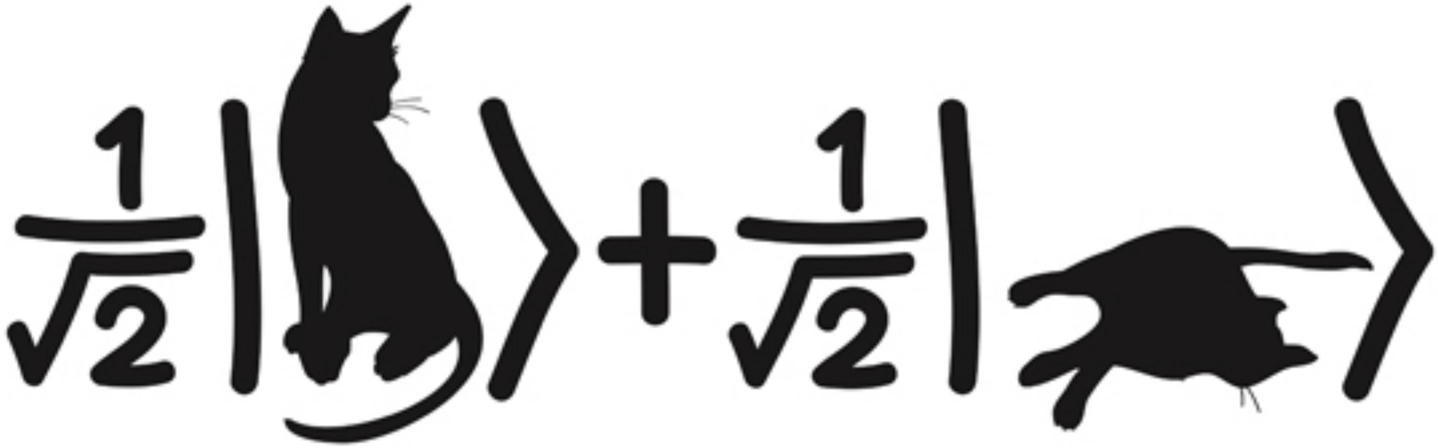
EPR $$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$





A. Einstein B. Podolsky N. Rosen

Schrödinger Cat



Cat states - superposition of a small number of macroscopically distinct components - are exponentially unstable: any local measurement collapses the superposition. They also require an exponentially long time to assemble with local unitary operators

How quantum can dense matter *stably* be?

Quantum spin liquids are ground states that retain long-distance entanglement and are robust to perturbations

"Ultra-quantum matter": stable *phases* of matter that retain some degree of quantum non-locality

Ordinary (local) Matter

We can consistently assign local properties (elastic moduli, etc.) and obtain all large-scale properties

- Measurements far away do not affect one another
- From local measurements we can deduce the global state

Ordinary (local) Matter

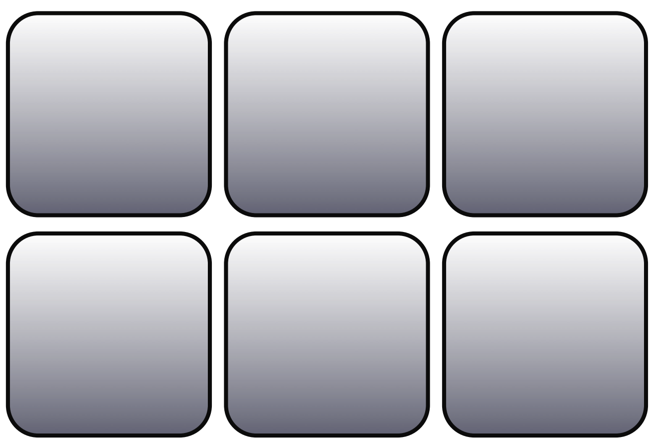
Hamiltonian is local

$$H = \sum_{\mathbf{x}} \mathcal{H}(x)$$

$\mathcal{H}(x)$ has local support near x

Ground state is "essentially" a product state

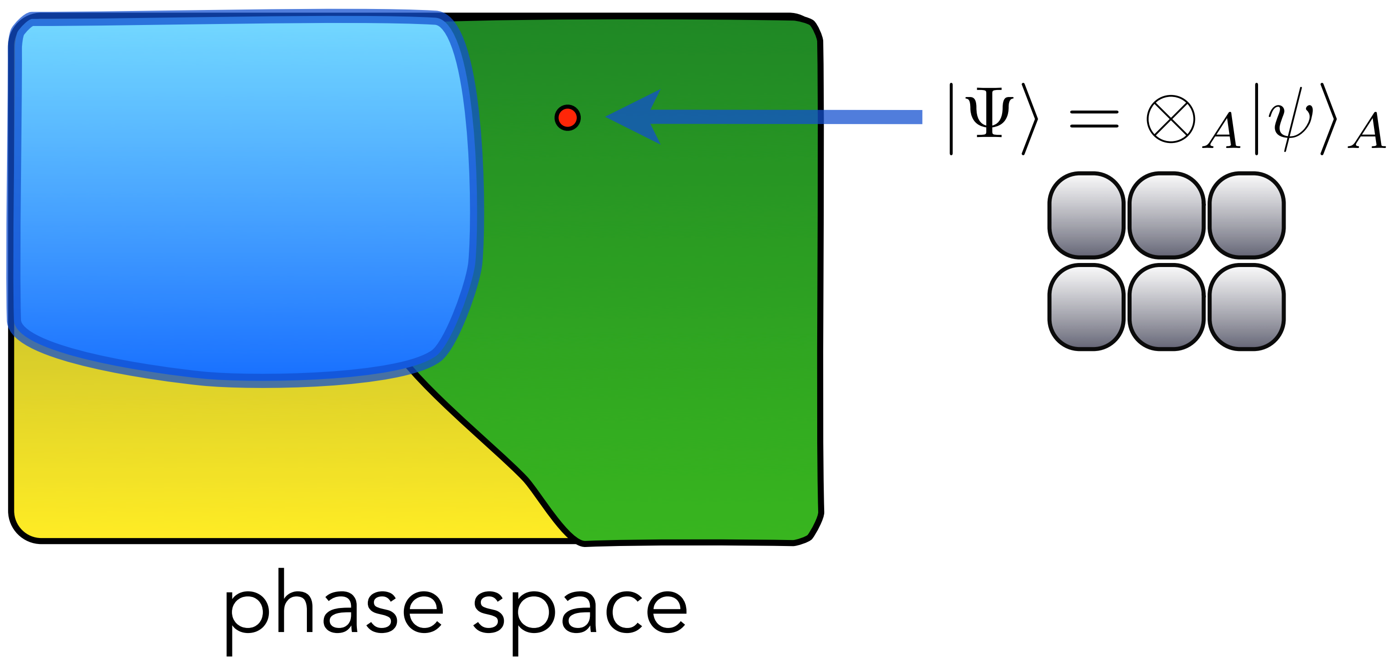
$$|\Psi\rangle = \otimes_A |\psi\rangle_A$$



no entanglement between blocks

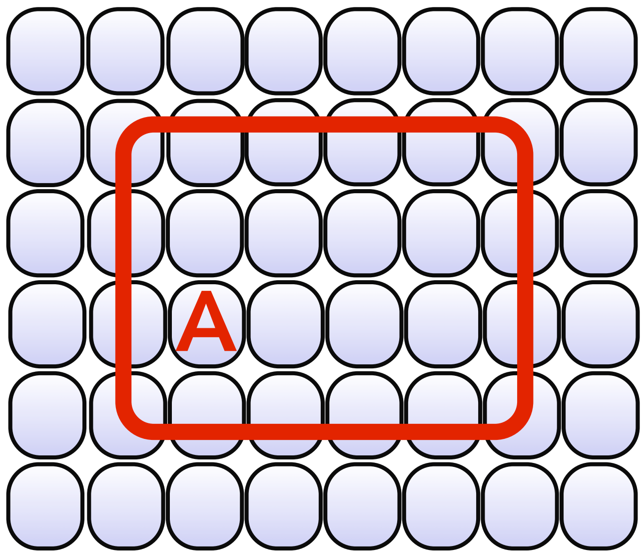
“Essentially” a product state?

- Adiabatic continuity



"Essentially" a product state?

- Entanglement scaling



$$\rho_A = \mathrm{Tr}_{\bar{A}} |\Psi\rangle\langle\Psi|$$

$$S(A) = -\mathrm{Tr}_A \left(\rho_A \ln \rho_A\right)$$

$S(A) \sim \sigma L^{d-1}$ area law

satisfied with exponentially small corrections

Best example: ordered magnet

Hamiltonian

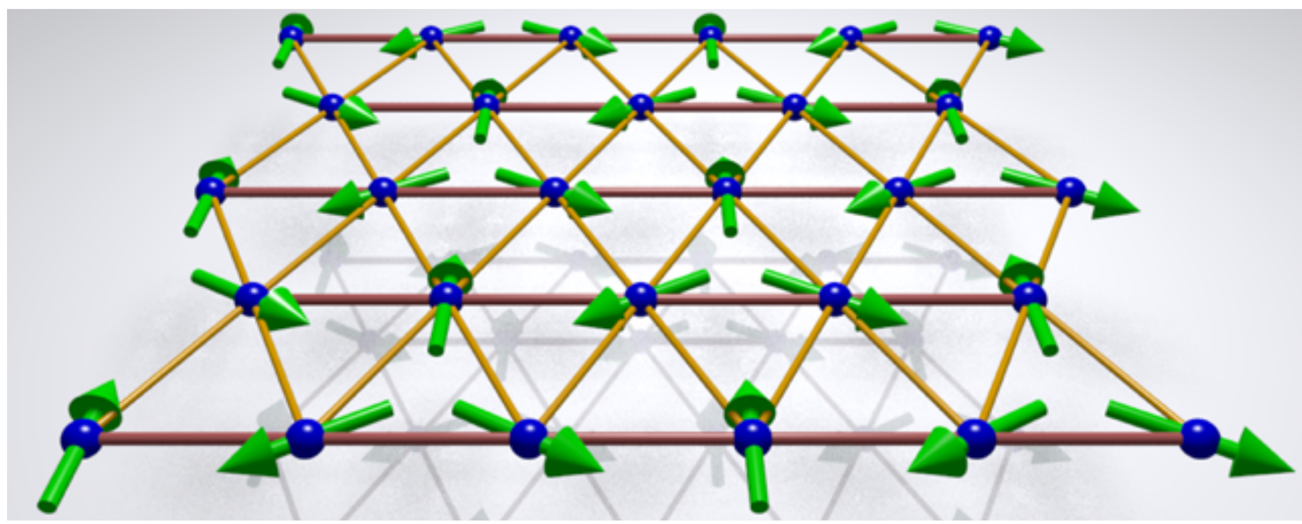
$$H = \sum_{(ij)} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

exchange is short-range: local

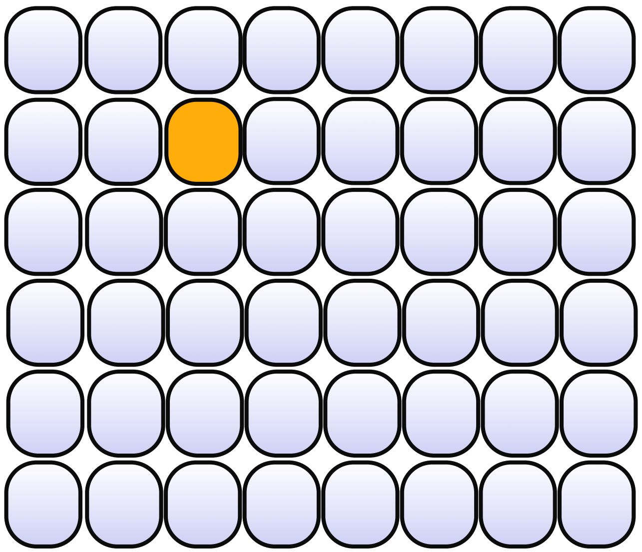
ordered state

$$|\Psi\rangle \approx \bigotimes_i |\boldsymbol{S}_i \cdot \hat{n}_i = +S\rangle$$

block is a single spin



Quasiparticles

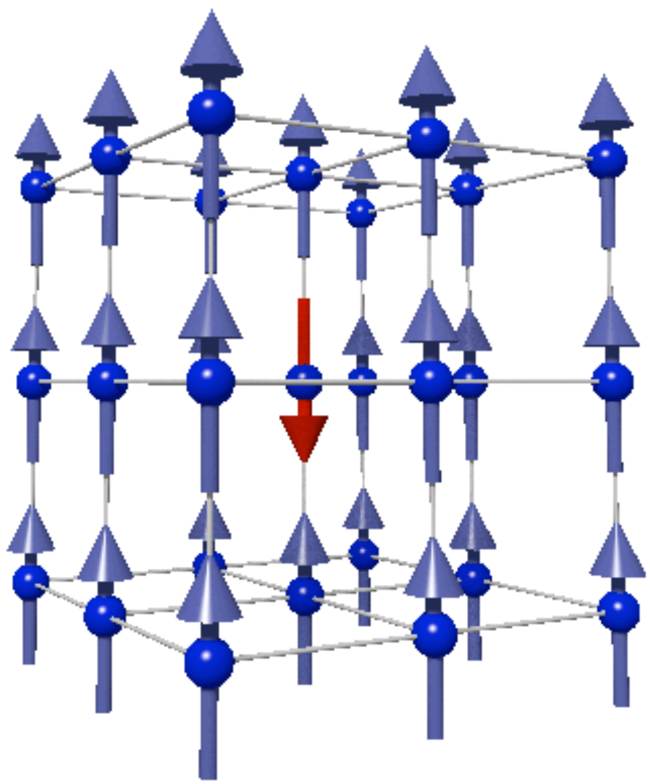


excited states ~ excited levels of one block

- local excitation can be created with operators in one block
- localized excitation has discrete spectrum with non-zero gap, and plane wave forms sharp band

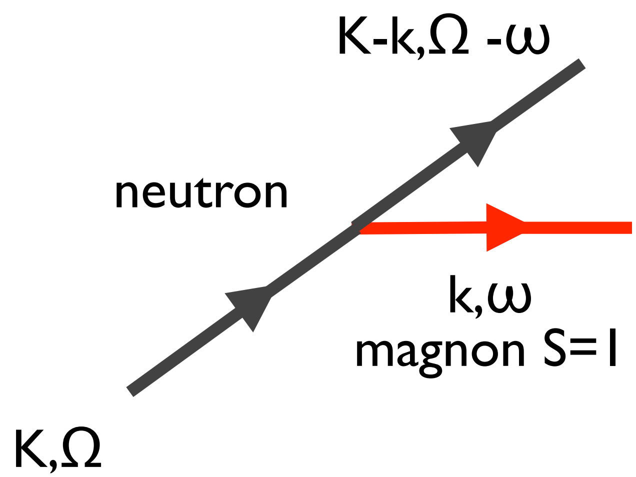
- quantum numbers consistent with finite system: no emergent or fractional quantum numbers

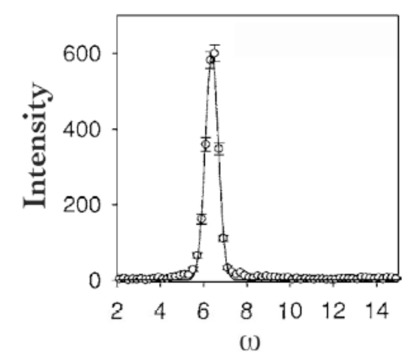
Spin wave



$$\omega(k) \approx \Delta - 2t\cos k_x a - \cdots$$

$$|f\rangle = S_k^+|i\rangle$$





Line shape in Rb_2MnF_4

How quantum can dense matter *stably* be?

Quantum spin liquids are ground states that retain long-distance entanglement and are robust to perturbations

©Bruce Gaulin

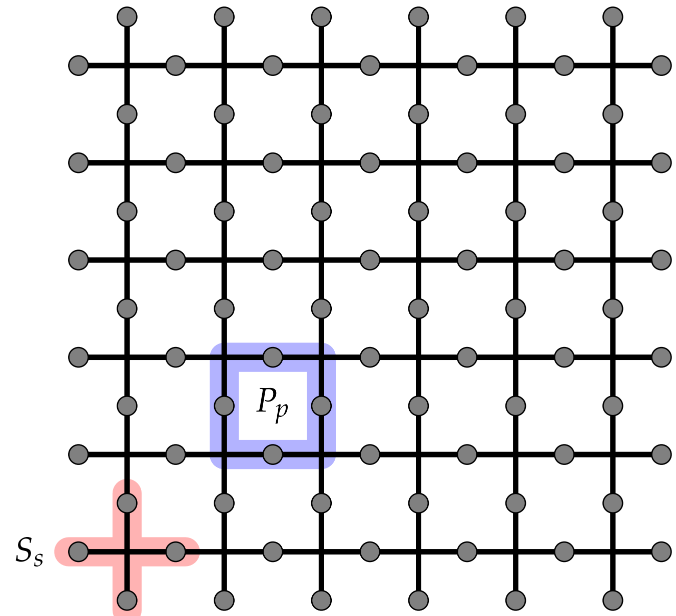
"Ultra-quantum matter": stable *phases* of matter that retain some degree of quantum non-locality

Example: toric code

A. Kitaev

$$H_{\rm tc} = -K\sum_p P_p - K'\sum_s S_s,$$

$$P_p = \prod_{i\in p} \sigma_i^z \qquad S_s = \prod_{i\in S} \sigma_i^x$$



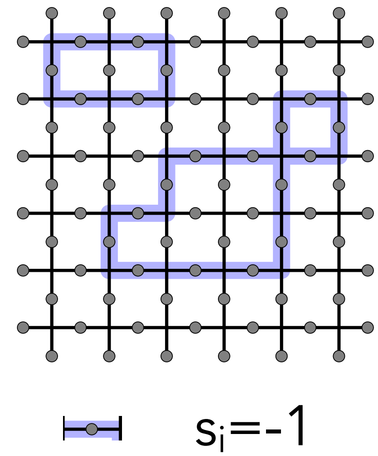
Everything commutes!

→ In ground state simply $P_p = S_s = +1$

But what is the state?

Ground state

Product basis $|\{s_i\}\rangle = \bigotimes_i |\sigma_i^x = s_i\rangle$



Solve S_s=+1:

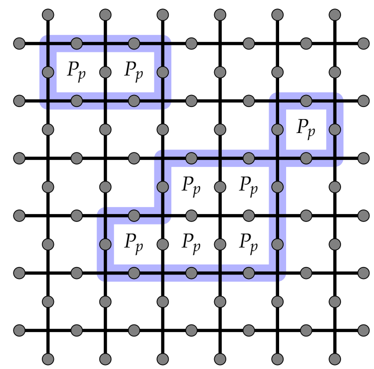
$$|\psi_0\rangle = \bigotimes_i |\sigma_i^x = +1\rangle$$

Now project to P_p=+1: $Q_p = \frac{1+P_p}{2} = \frac{1}{2}\sum_{q_p=0,1} P_p^{q_p},$

$$|0\rangle = \prod_p Q_p |\psi_0\rangle = 2^{-N} \sum_{q_1 \cdots q_N = 0,1} \prod_p P_p^{q_p} |\psi_0\rangle$$

Ground state

$$|0\rangle = 2^{-N} \sum_{q_1 \cdots q_N = 0,1} \prod_p P_p^{q_p} |\psi_0\rangle \quad = \sum_{\text{loops}}$$



massive superposition state

(similar form in Z variables)

All spins are uncertain

$$\langle 0|\sigma_i^x|0\rangle = \langle 0|S_s\sigma_i^x S_s|0\rangle = -\langle 0|\sigma_i^x|0\rangle = 0$$

$$\langle 0|\sigma_i^z|0\rangle = \langle 0|P_s\sigma_i^z P_p|0\rangle = -\langle 0|\sigma_i^z|0\rangle = 0$$

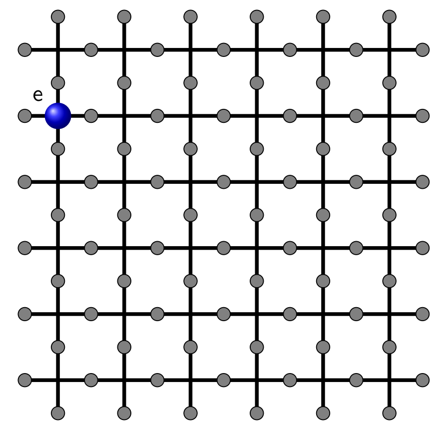
And yet there is some structure…

Excitations

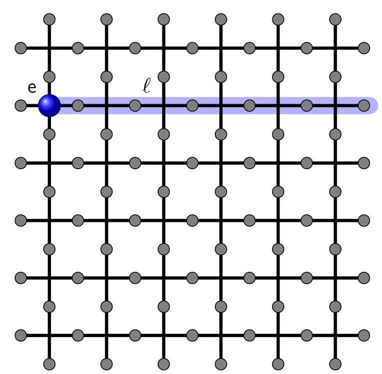
$$H_{\rm tc} = -K \sum_p P_p - K' \sum_s S_s,$$

Consider state with just one S_s=-1

$$|\mathsf{e}_s\rangle =$$



$$|\mathsf{e}_s\rangle = \prod_{i \in \ell} \sigma_i^z |0\rangle$$

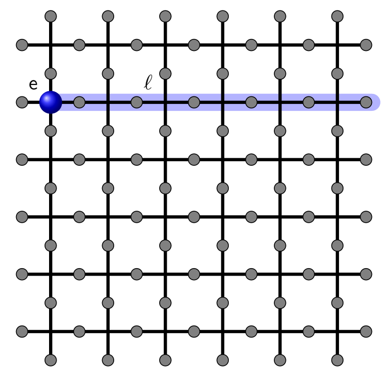


non-local excitation!

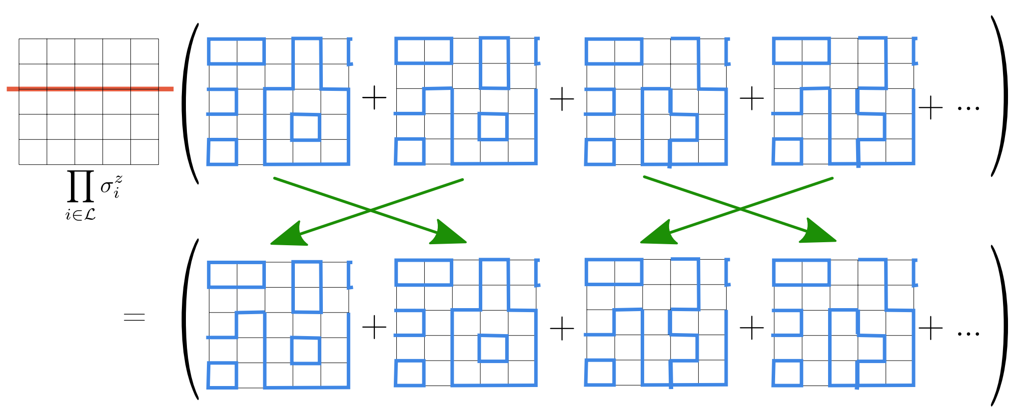
local operators, like finite product of Z operators, create **e** particles in pairs

Non-local excitations and entanglement

$$|\mathsf{e}_s\rangle = \prod_{i\in\ell} \sigma_i^z |0\rangle$$



<u>Why does this have finite energy?</u> $\langle \mathsf{e}_s | H | \mathsf{e}_s \rangle \not\propto L_\ell$??

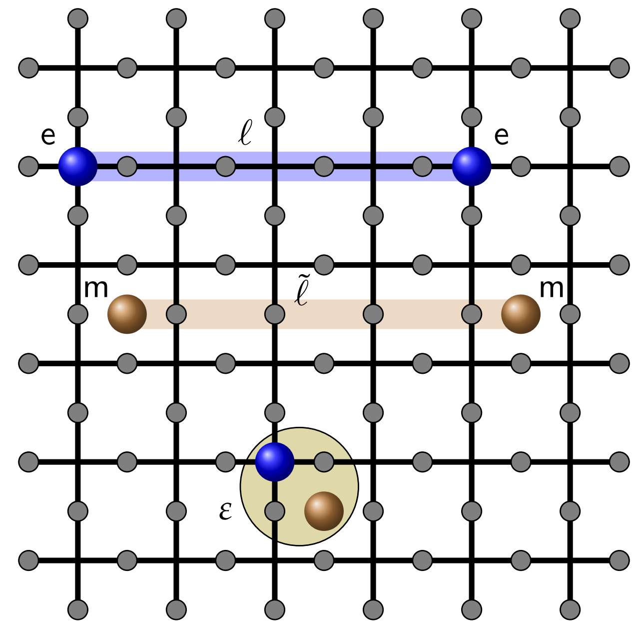


away from the ends, the string just reshuffles elements of the superposition

Excitations

There is also an **m** excitation

$$P_p = -1$$



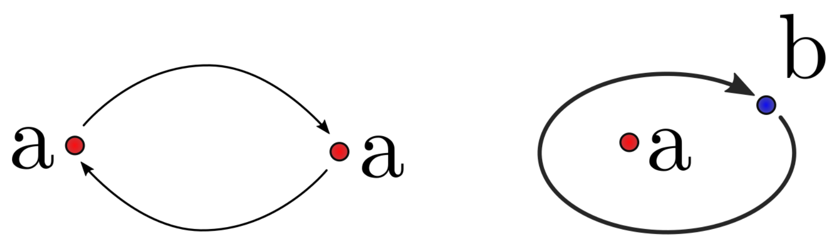
And we can consider two of these together

$$\varepsilon = \mathsf{e} \times \mathsf{m}$$

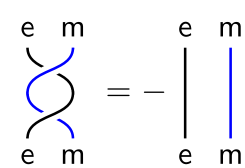
e,**m**,**ε** are the *emergent non-local quasiparticles* of the toric code

Non-locality

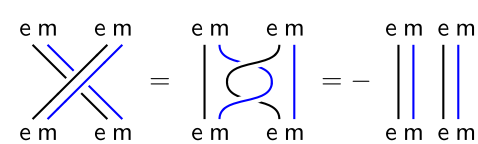
For the toric code, and in general for *topological phases* (i.e. gapped QSLs), the non-locality of excitations manifests as *statistics*



the excitations are *anyons*, i.e. the state acquires a unitary rotation (e.g. phase) when one excitation is taken around another



e and **m** see each other as “pi flux”



ε is a fermion

Stability

One can show that the toric code phase is *absolutely stable* to arbitrary (small) local perturbations, even those which break all symmetries.

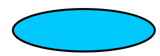
This is because the “order” of the toric code is purely a type of entanglement, not any symmetry breaking. Only by bringing the gap of a quasiparticle to zero can one “unwind” the entangled ground state.

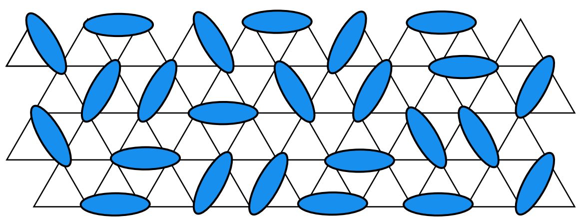
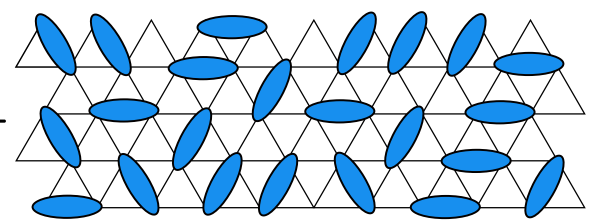
rigorous proofs by Hastings, Bravyi

RVB states

Historically the first proposal of a QSL by Anderson in 1973

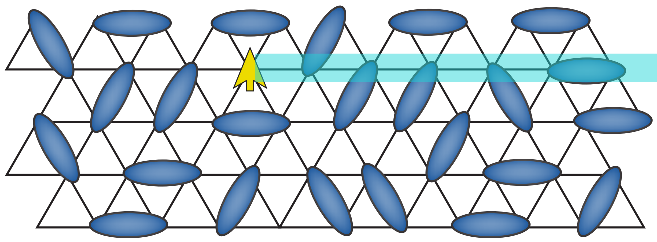
$$H = J \sum_{\langle ij \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

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

$|\Psi\rangle =$  $+$  $+ \cdots$

superposition of singlets is quite similar to sum of loops in toric code, and indeed when made precise such a nearest-neighbor RVB state is typically *in the same phase as the toric code*

Spinon

$|\Psi\rangle =$  $+\cdots$

create a spinon by rearranging valence bonds to expose a single free spin

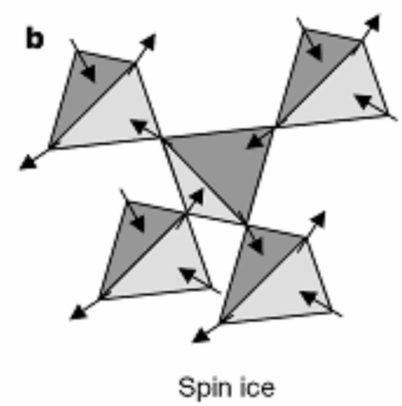
New feature: SU(2) spin symmetry

- spinon excitation has S=1/2, a *fractional quantum number* (spin flips are S=1)
- this "enriches" the topological label **e,m,ε**

many efforts to understand Symmetry Enriched Topological order

Quantum spin ice

Minimal XXZ model on *pyrochlore* lattice



$$H = \sum_{\langle ij \rangle} J_{zz} S_i^z S_j^z - J_{\pm}(S_i^+ S_j^- + \text{h.c.})$$

$$\frac{J_{zz}}{2} \sum_t \left(\sum_{i \in t} S_i^z \right)^2$$

$J_{\pm} \ll J_{zz}$ is the spin ice limit

$\sum_{i \in t} S_i^z = 0$ in the classical ground state: "2in-2out"

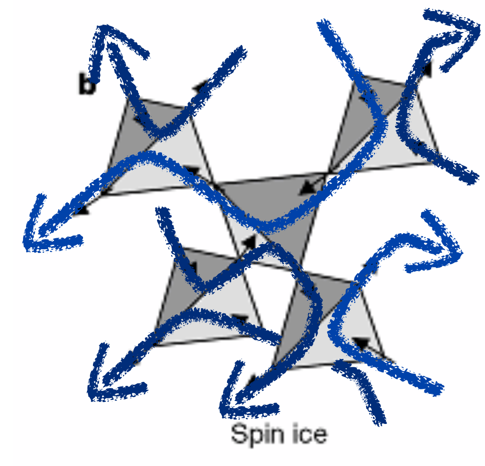
With a lot more work one can show that $J_{\pm}$ selects a massive superposition of these states

M. Hermele, MPA Fisher, L.B., 2004;
A. Banerjee *et al*, 2008

Quantum spin ice

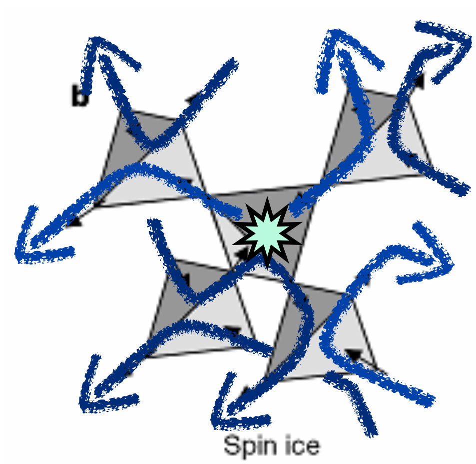
like the toric code, the QSL state can be viewed as a sum of loops - follow the arrows!

$$\sum_{\text{loops}}$$



There are also non-local excitations

$$\sum_{i \in t} S_i^z = \pm 1$$

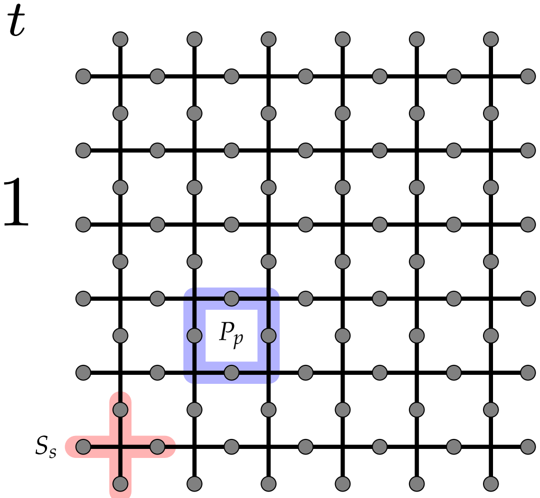


"spinons"
"monopoles"

Gauge theory

These QSL states are all conveniently described mathematically by *gauge theory*

- Local constraints: $S_s = +1$ $\sum_{i \in t} S_i^z = 0$
- Generate local unitaries



$$U = U^\dagger = \prod_s S_s^{(1-q_s)/2} \quad q_s = \pm 1$$

$$\sigma^z_{ss'} \to U^\dagger \sigma^z_{ss'} U = q_s q_{s'} \sigma^z_{ss'}$$

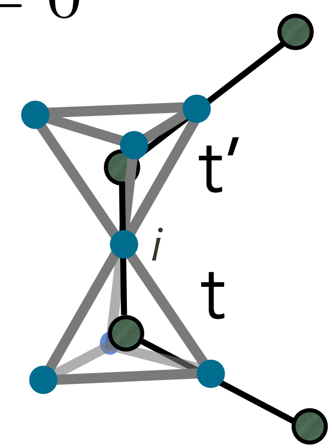
$\sigma^z_{ss'}$ are Z_2 gauge fields

toric code = "Z_2 QSL"

Gauge theory

These QSL states are all conveniently described mathematically by *gauge theory*

- Local constraints: $S_s = +1 \quad \sum_{i \in t} S_i^z = 0$
- Generate local unitaries



$$U = \prod_t e^{i\chi_t S_t^z} \qquad \chi_t \in U(1)$$

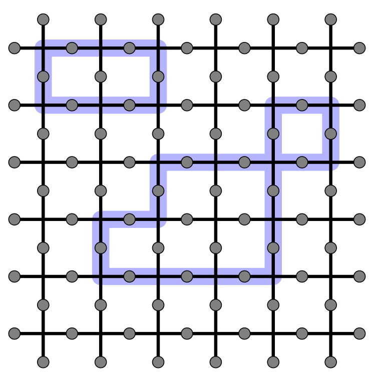
$$S_{tt'}^{\pm} \to U^\dagger S_{tt'}^{\pm} U = e^{i(\chi_t - \chi_{t'})} S_{tt'}^{\pm}$$

$S_{tt'}^{\pm} \sim e^{\pm i A_{tt'}}$ is a U(1) gauge connection

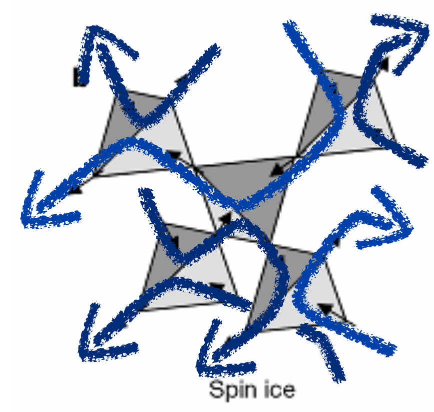
QSI hosts a U(1) QSL

Gauge theory

- Loops ~ field lines describing "vacuum fluctuations"



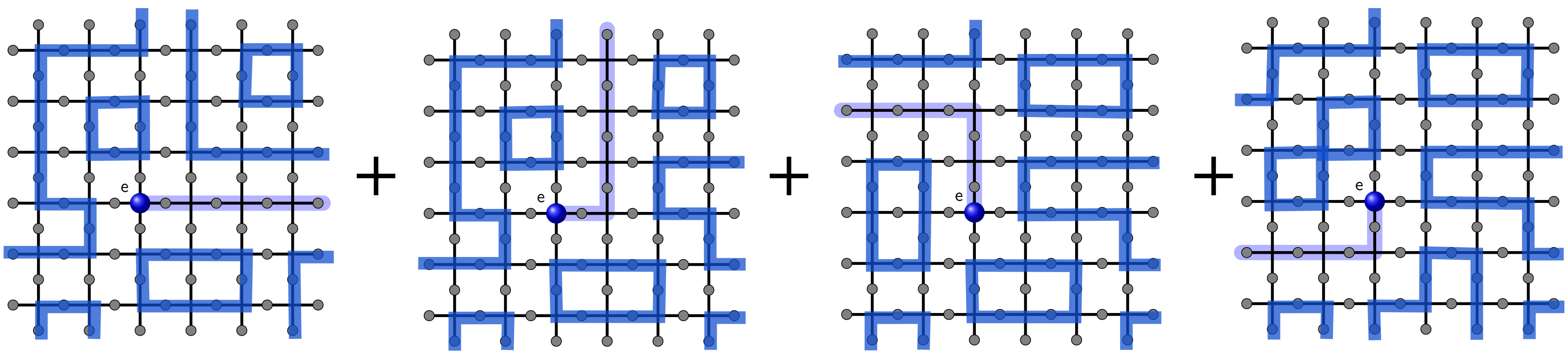
toric code: Z_2



QSI: U(1)

Deconfinement

$|\mathrm{e}_s\rangle =$



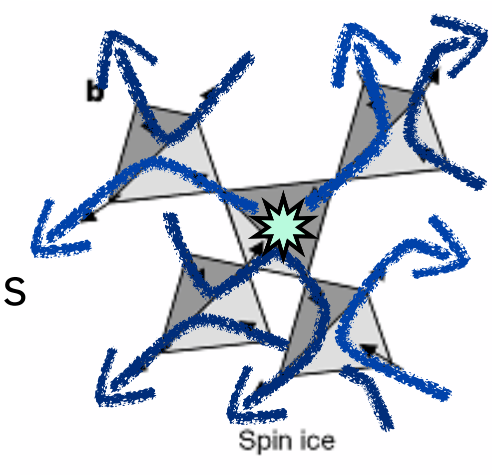
The superposition of different string configurations "smears out" the flux emanating from **e**, so that it cannot be detected by any *local* measurement away from the quasiparticle

- consequently the string tension is zero = deconfinement
- the complete local undetectability of the flux is characteristic of a *topological* QSL

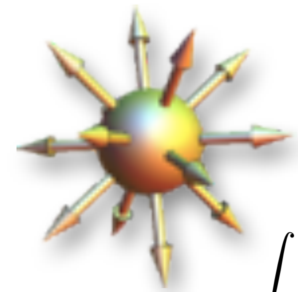
Deconfinement

U(1) QSL

$$|\text{spinon}\rangle = \sum_{\text{flux lines}}$$



$\sim$



$$\int_{S\ni *} \boldsymbol{B}\cdot d\boldsymbol{A} = q$$

Here the flux is a number, not a parity, and can be added. The superposition of many field lines smears the flux into a "uniform" dispersed magnetic/electric field

$$\boldsymbol{B} \sim \frac{\hat{r}}{r^2}$$

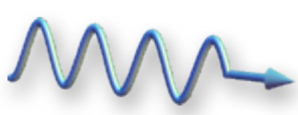
This leads to the usual 1/r Coulomb interaction between charges. It decays with distance so charges are "deconfined", but the flux is locally detectable

Photon

Since there is a detectable average field, there is energy density associated with the field lines

Consequently, there are "pure gauge" excitations. These are not non-local particles but emergent collective excitations. They are exactly analogous to the photons of electromagnetism.

$$\omega \sim ck$$

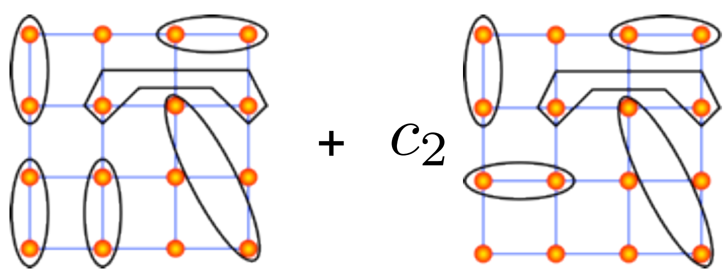


U(1) QSL is a gapless, not topological example of ultra-quantum matter

Variational method

- Up to now I described results out of soluble or otherwise tractable models
- Variational wavefunctions are an attractive way to approach models when no other handle is available

RVB: $\Psi = c_1$ [diagram] $+ c_2$ [diagram] $+ \ldots$

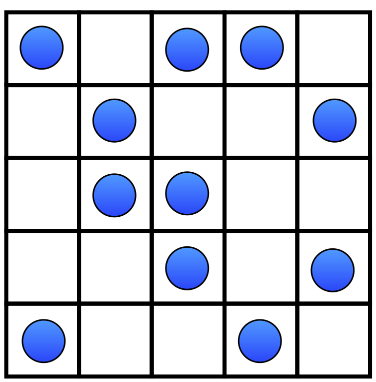
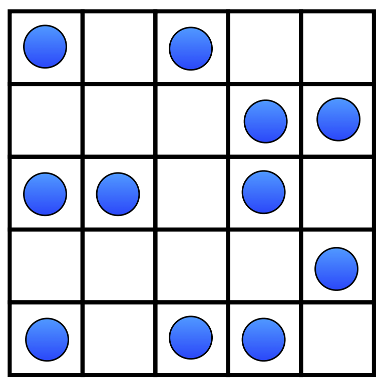
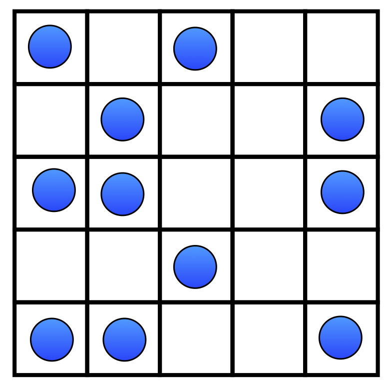


but how to keep track of so many coefficients??

Free Fermions

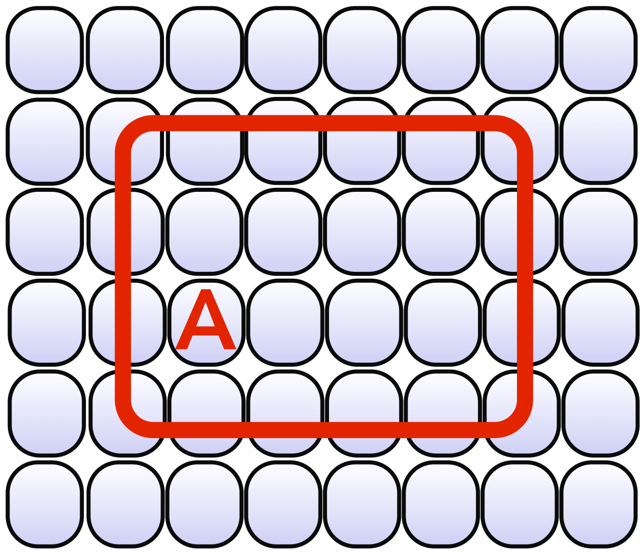
- One useful construction uses a Fermi gas: a product in momentum space rather than real space

$$\Psi = \prod_{k<k_F} c_k^\dagger |0\rangle$$

$= \; c_1$  $+c_2$  $+c_3$  $+\cdots$

Entanglement Entropy

- Free fermions $S \sim \sigma L^{d-1} \log L$



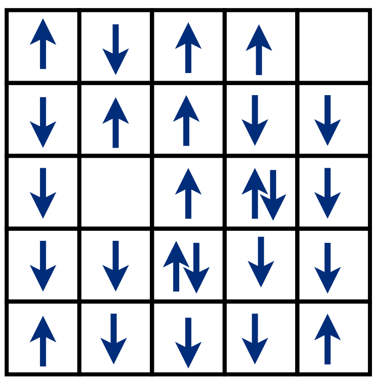
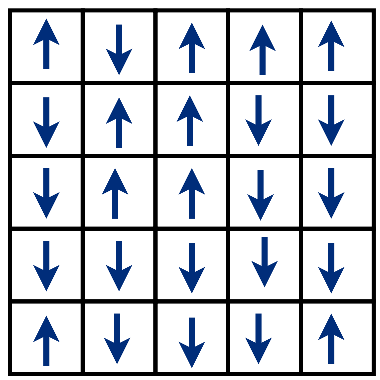
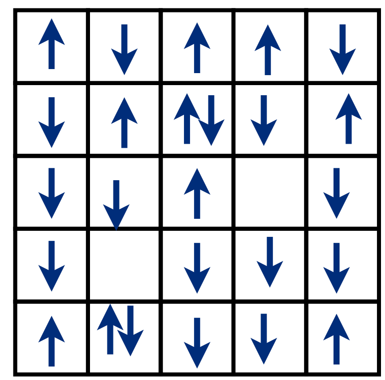
D. Gioev+I. Klich, 2006
M.M. Wolf, 2006

- Very large entanglement is generic. A metal is in this sense "ultraquantum"

however, it has local quasiparticles

Gutzwiller Construction

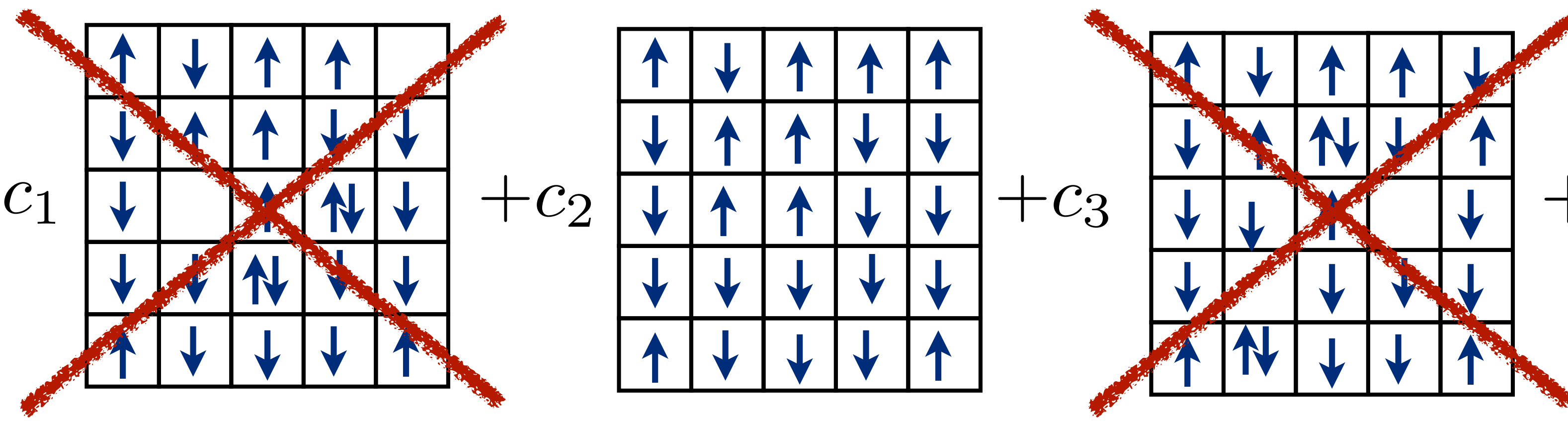
- Construct QSL state from free fermi gas with spin, with 1 fermion per site (S=0)

$\Psi_0 = c_1$  $+c_2$  $+c_3$  $+\cdots$

Gutzwiller Construction

- Construct QSL state from free fermi gas with spin, with 1 fermion per site (S=0)

$\Psi = c_1 \,[\ldots]\, + c_2 \,[\ldots]\, + c_3 \,[\ldots]\, + \cdots$



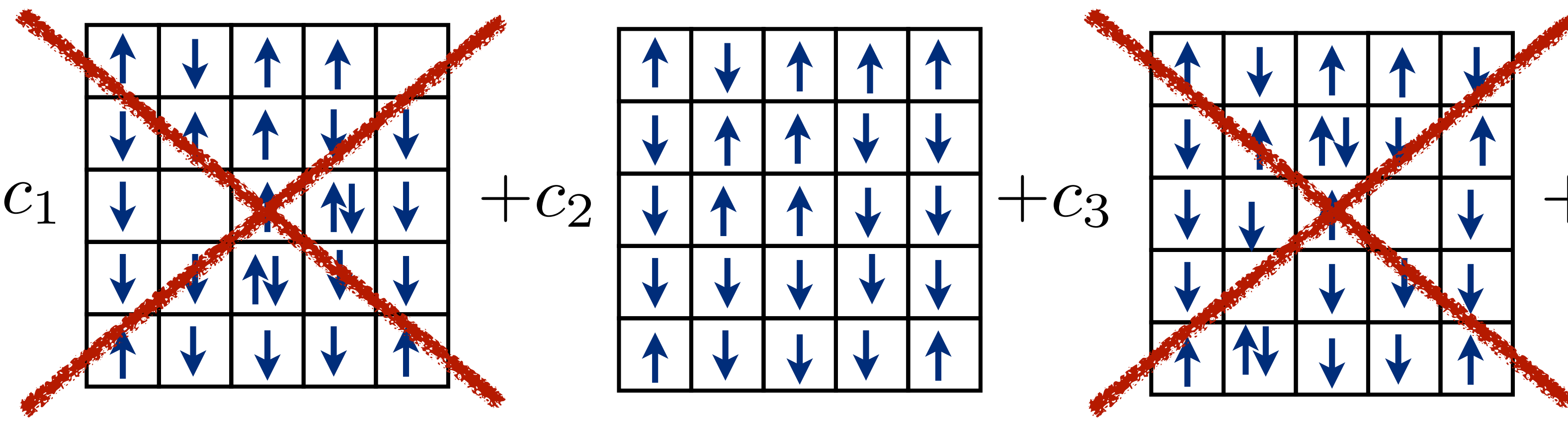
- Projection removes empty and doubly occupied sites $\Psi = P_G \Psi_0$

"like" a gauge constraint $n_i = 1$

Gutzwiller Construction

- Construct QSL state from free fermi gas with spin, with 1 fermion per site (S=0)

$$\Psi = c_1 \quad + c_2 \quad + c_3 \quad + \cdots$$



- Such wavefunctions can be efficiently simulated using Monte Carlo methods

Partons

- Gutzwiller-type variational wavefunction uses a reference Hamiltonian

$$H_{ref} = \sum_{ij} \left[t_{ij} c^\dagger_{i\alpha} c_{j\alpha} + \text{h.c.} + \Delta_{ij} c^\dagger_{i\uparrow} c^\dagger_{j\downarrow} + \text{h.c.} \right]$$

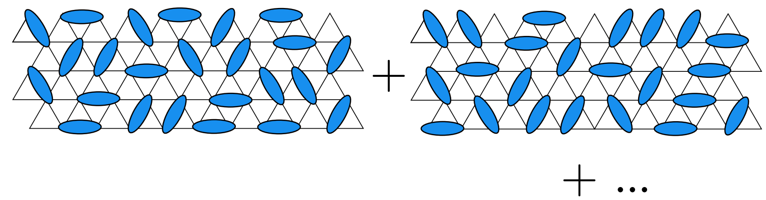
- Project

$$|\Psi_{var}\rangle = \prod_i \hat{P}_{n_i=1} |\Psi_{ref}\rangle$$

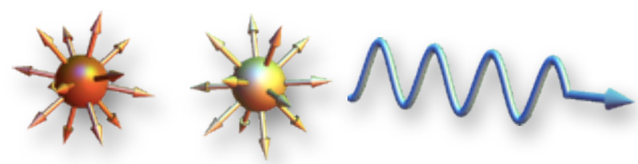
- The fermions are “partons” $\vec{S}_i = c^\dagger_{i\alpha} \frac{\vec{\sigma}_{\alpha\beta}}{2} c_{i\beta}$
- Standard (MIT) belief: each such projected wavefunction represents a true QSL phase, in which the partons become the non-local quasiparticles - “spinons” - and they are coupled to an effective gauge field

Classes of QSLs

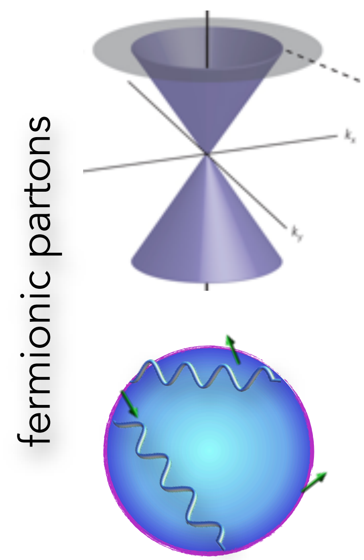
- Topological QSLs
  - full gap
- U(1) QSL
  - gapless emergent "photon"
- Algebraic QSLs
  - Relativistic CFT (power-laws)
- Spinon Fermi surface QSL



TQFT



compact U(1) gauge theory



QED_3

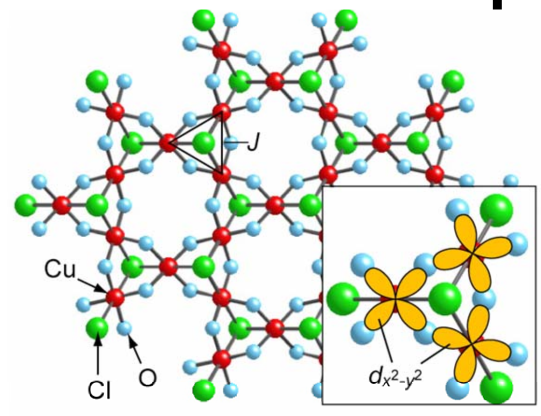
QED_3 w/ $\mu>0$

Summary so far

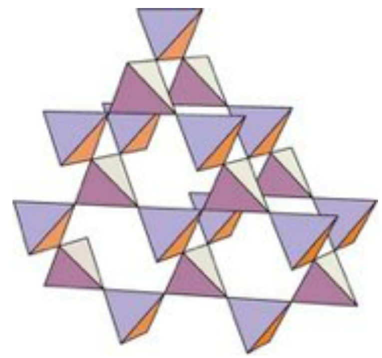
- QSLs are examples of "ultra-quantum matter" whose ground states are massive superpositions and exhibit long-range entanglement
- Characteristically they support *non-local* excitations, which might be anyons or other exotic particles
- The natural theoretical description of many QSLs is gauge theory
- Many QSLs are absolutely stable to all small perturbations, irrespective of symmetry. "Highly gapless" QSLs are less stable.

Spin liquid candidates

Top experimental platforms



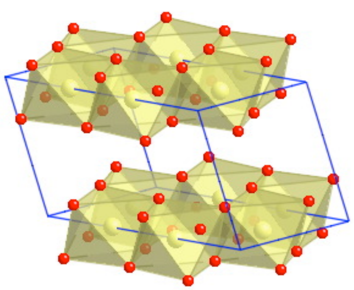
Herbertsmithite



$Yb_2Ti_2O_7$

...

Quantum spin ice



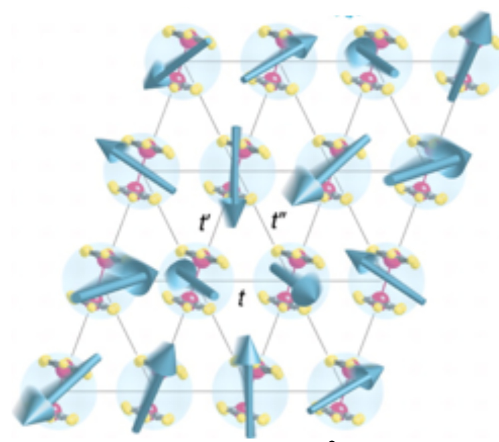
Na_2IrO_3,

(α,β,γ)-

Li_2IrO_3

α-$RuCl_3$

Kitaev materials



organics

A rough guide to experiments on QSLs

Does it order?

- NMR line splitting
- muSR oscillation
- thermodynamic transition via specific heat, susceptibility
- Bragg peak in neutron/ x-ray

Is there a gap?

- Specific heat
- NMR $1/T_1$
- Dynamic susceptibility
- T-dependence of χ

Exotica

- Local measurements
- thermal Hall
- ARPES (on insulator!)
- Proximity effects

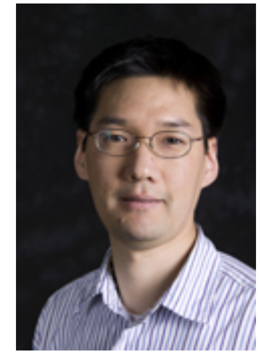
Delocalized excitations?

- thermal conductivity
- INS

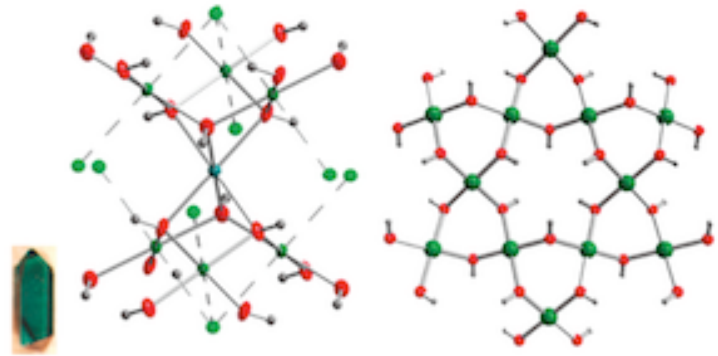
Structure of excitations?

- E(k) from INS,RIXS
- optics, Raman

Herbertsmithite



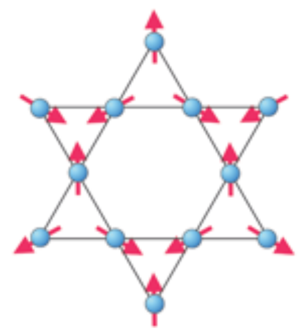
$ZnCu_3(OH)_6Cl_2$



kagomé layers of Cu
S=1/2 spins, separated
by non-magnetic Zn

Hamiltonian

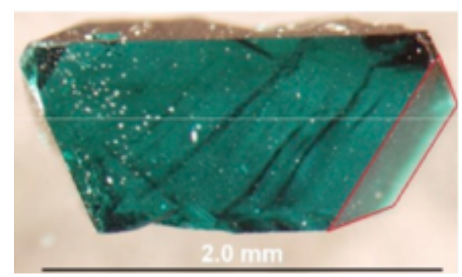
$$H = J \sum_{\langle ij \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \ldots$$



J ~ 200K

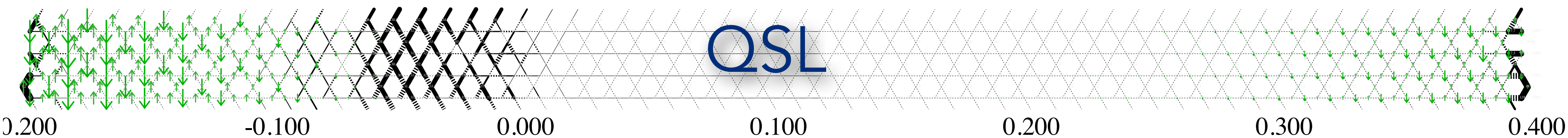
Long efforts by Nocera, Young Lee
groups produced crystals

beautiful material, but complicated by Cu/Zn site defects

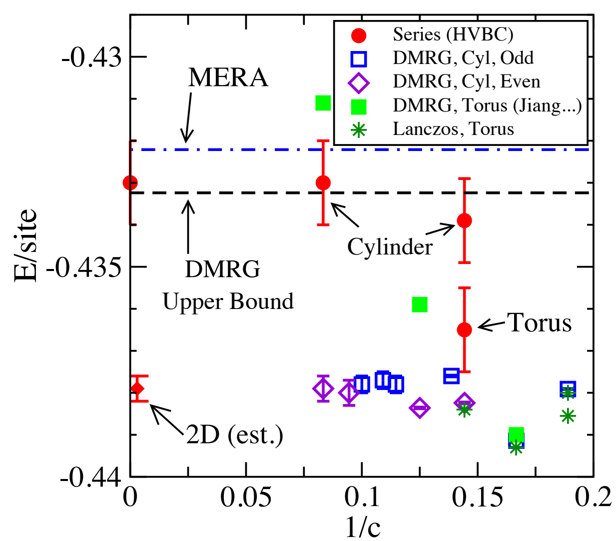


S=1/2 kagomé AF

- Long history - but definitive evidence for QSL by DMRG



© Steve White



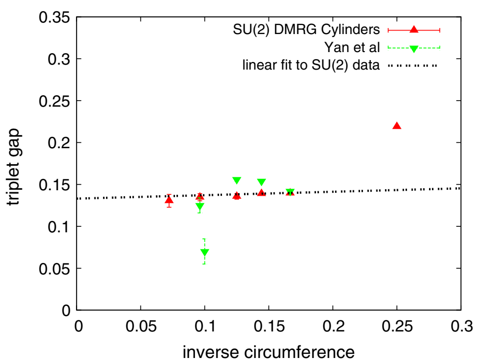
S. Yan *et al*, 2010

many other studies support existence of some QSL phase

S=1/2 kagomé AF

- What kind of QSL?

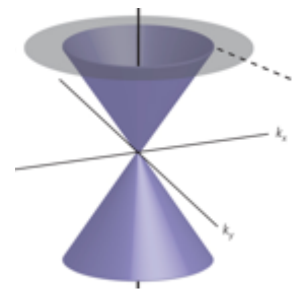
DMRG



S. Depenbrock *et al*, 2012

gapped, presumably Z_2 topological QSL

partons



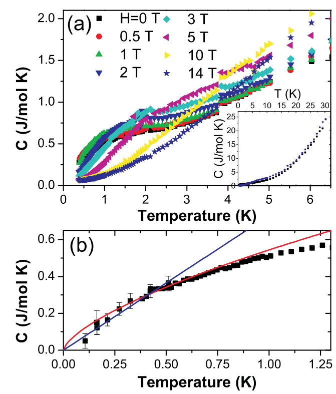
Y. Ran *et al*, 2007
F. Becca...

gapless U(1) Dirac QSL

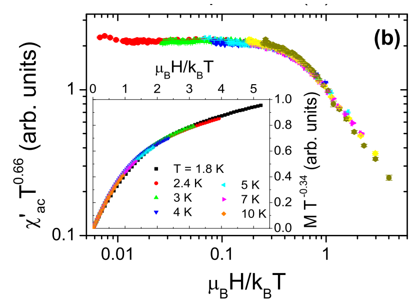
+ various other proposals with weaker quantitative support

Herbertsmithite

Lots of early evidence for gaplessness



Helton *et al*, 2007

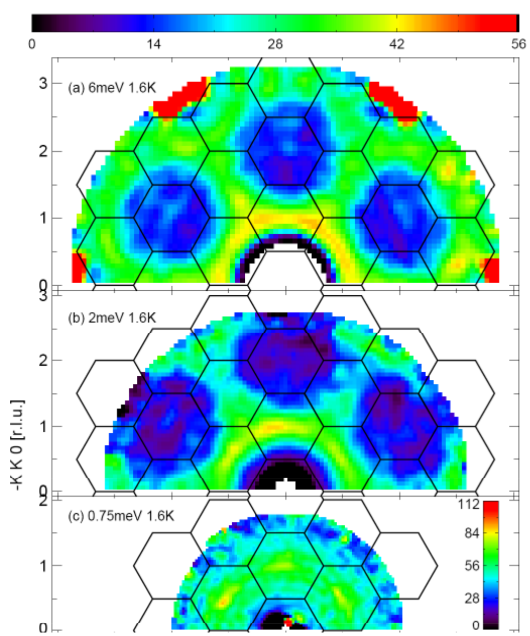


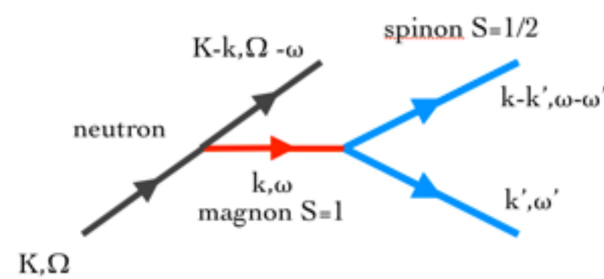
Helton *et al*, 2010

Single crystal INS

smooth continuum scattering

T-H Han *et al*, 2012





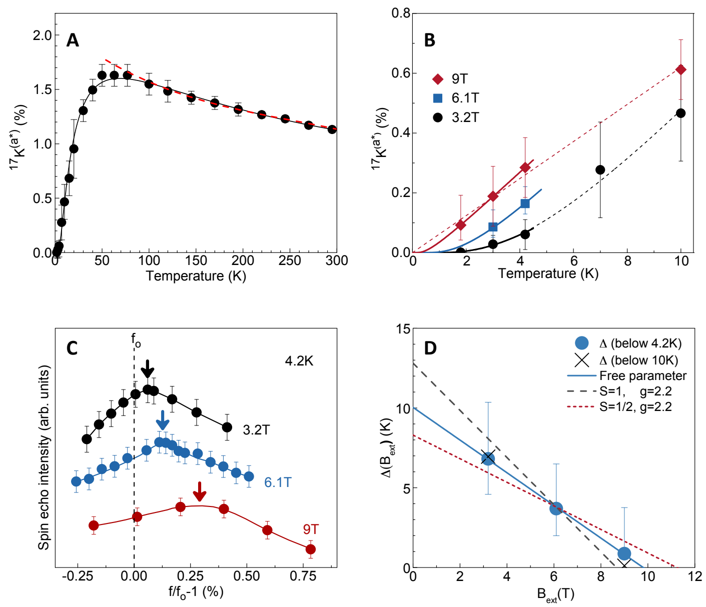
continuum scattering expected
...but probably with more structure?

Herbertsmithite

Single crystal NMR

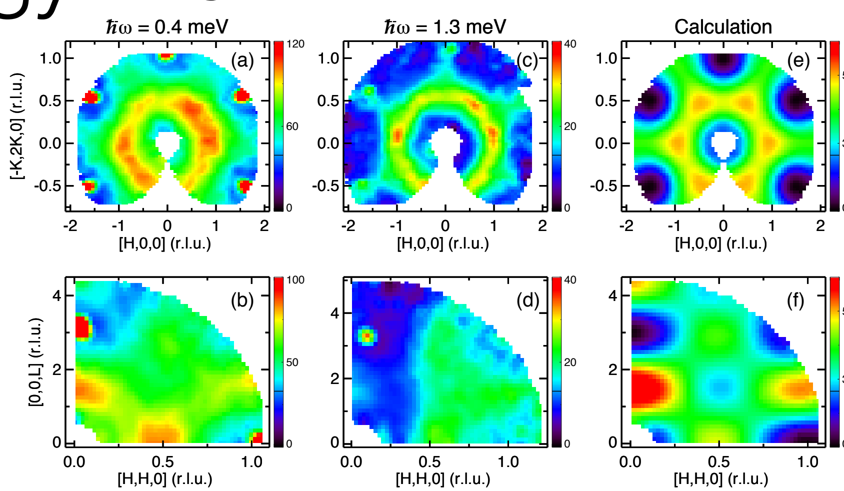
M. Fu *et al*, 2015

c.f. T. Imai lecture



estimate gap ~ 10K

Low energy INS



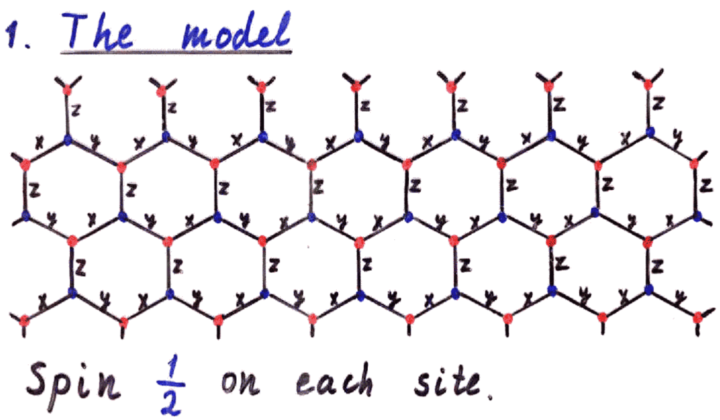
T-H Han *et al*, 2015

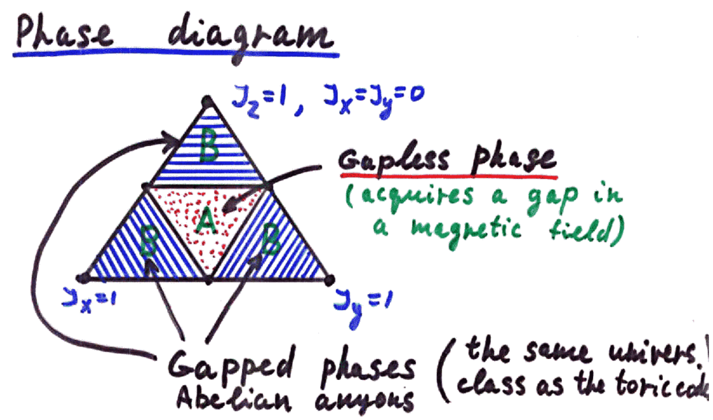
claim to separate impurity signal below 0.7meV

Kitaev model

Kitaev's honeycomb model $H = \sum_{i,\mu} K_\mu \sigma_i^\mu \sigma_{i+\mu}^\mu$

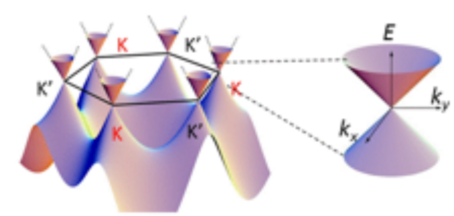
KITP, 2003



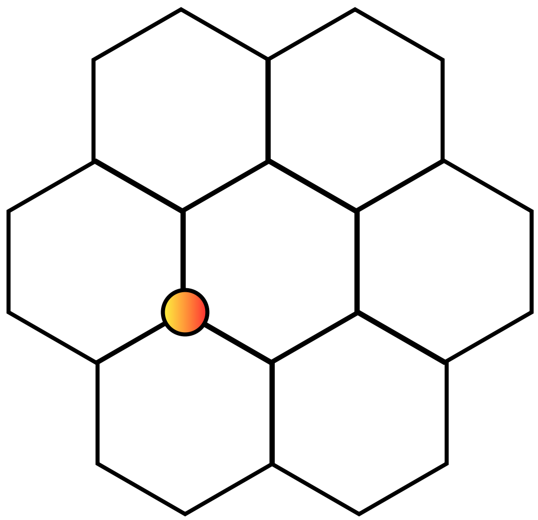


exact parton construction $\sigma_i^\mu = i c_i c_i^\mu \quad c_i c_i^x c_i^y c_i^z = 1$

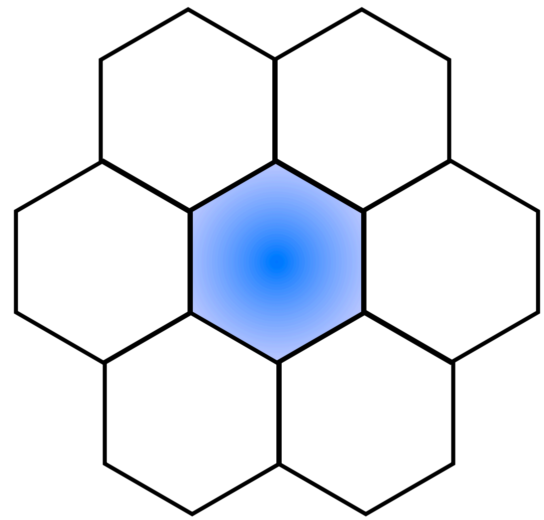
physical Majoranas $H_{\mathrm{m}} = K \sum_{\langle ij \rangle} i c_i c_j$



Non-local excitations



Majorana ε



Flux e, m

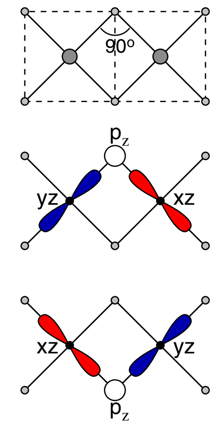
In Kitaev's model:

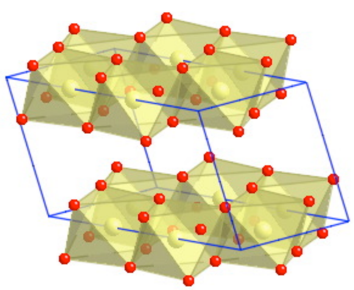
- Majorana's dispersion ~ K and gapless
- Fluxes are localized and gapped

Kitaev Materials

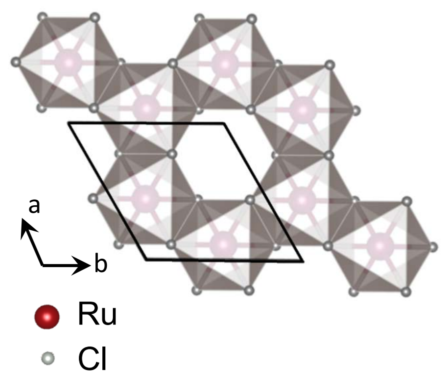
Jackeli, Khaliullin

Showed that Kitaev interaction can be large in edge-sharing octahedra with large spin-orbit-coupling





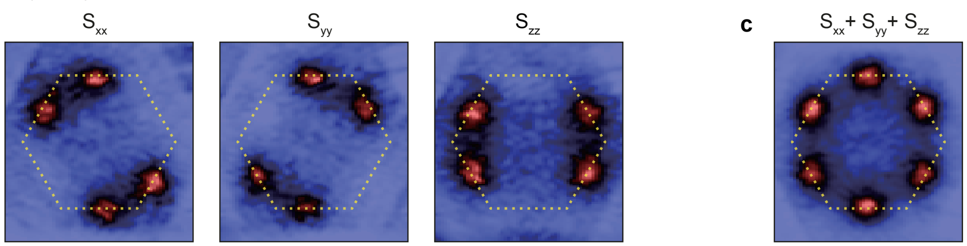
Na_2IrO_3, (α,β,γ)-Li_2IrO_3



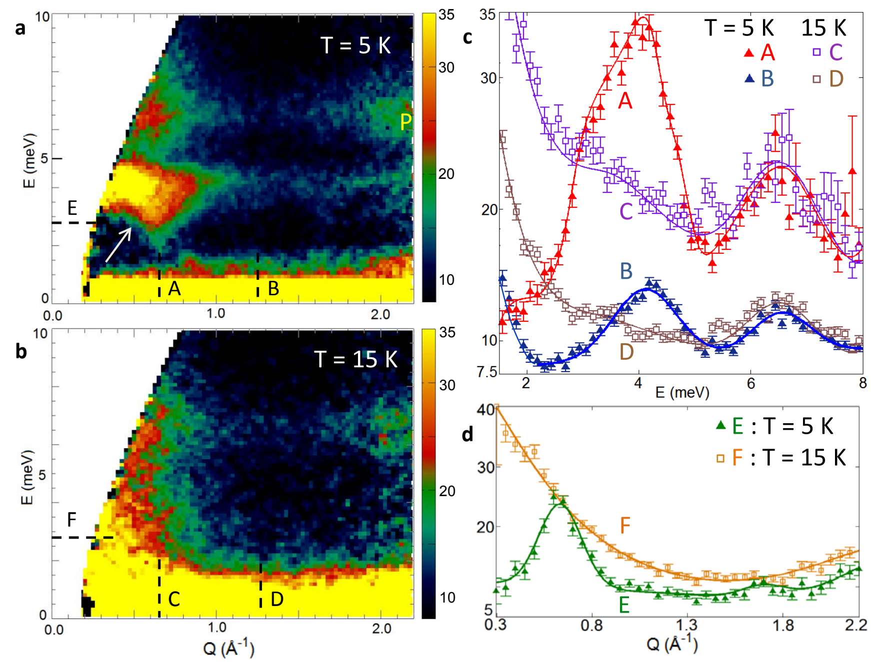
α-$RuCl_3$

Honeycomb and hyper-honeycomb structures

Kitaev Materials



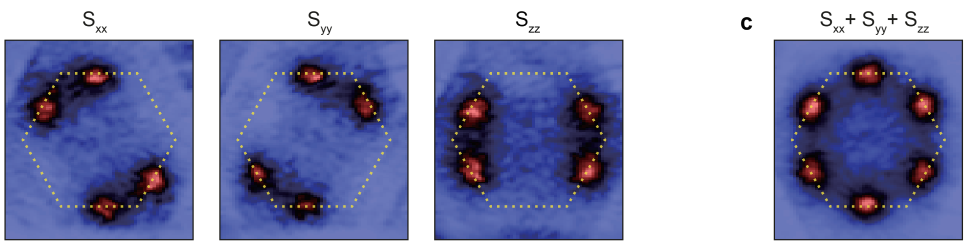
direct evidence for direction-dependent anisotropic exchange from diffuse magnetic x-ray scattering in Na_2IrO_3 (BJ Kim group)



Observation of gapped continuum mode persisting above T_N in α-$RuCl_3$ consistent with Majoranas (A. Banerjee *et al*)

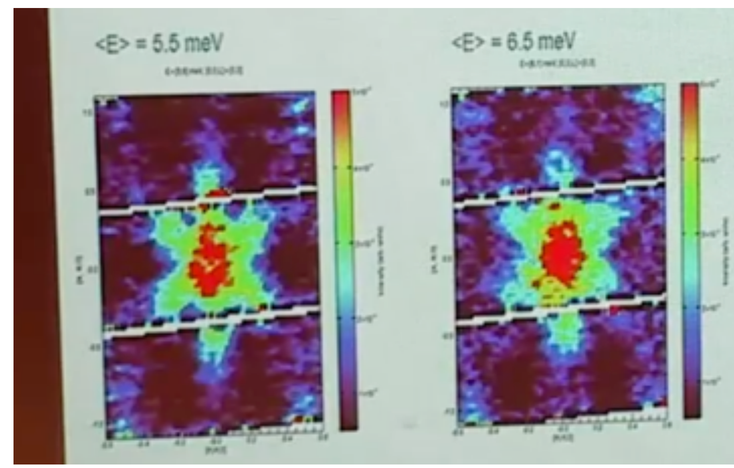
there is pretty strong evidence of substantial Kitaev exchange in quite a few materials

Kitaev Materials



direct evidence for direction-dependent anisotropic exchange from diffuse magnetic x-ray scattering in Na_2IrO_3 (BJ Kim group)

there is pretty strong evidence of substantial Kitaev exchange in quite a few materials



Unpublished single-crystal data (A. Banerjee *et al)* in α-$RuCl_3$ has expected momentum structure for Kitaev QSL

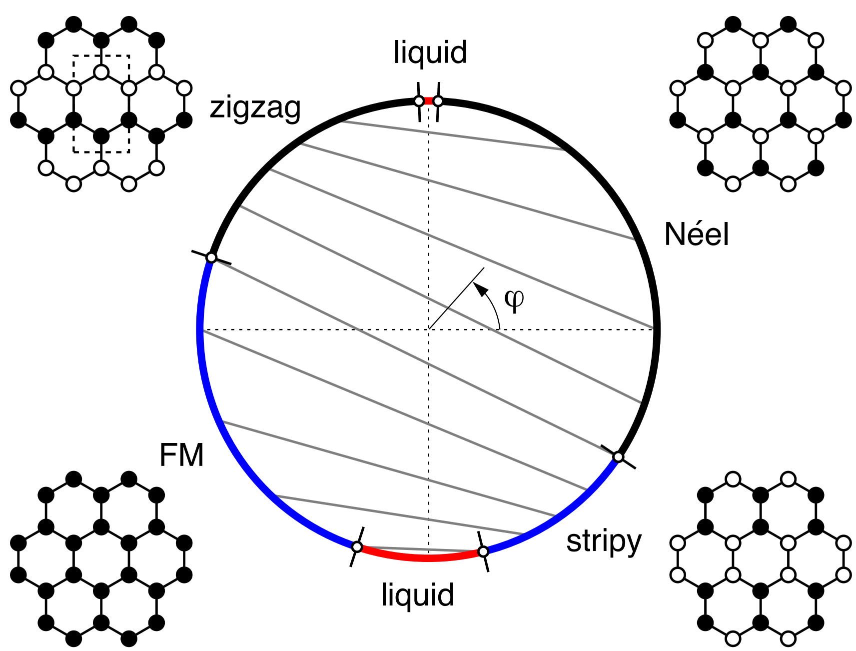
Magnetism

- But…they all order so far

due to additional interactions,
e.g. Heisenberg

$$H = \sum_{i,\alpha} K S_i^\alpha S_{i+\alpha}^\alpha + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

(a)



zigzag ordered state has been observed in Na_2IrO_3 and incommensurate order in Li_2IrO_3

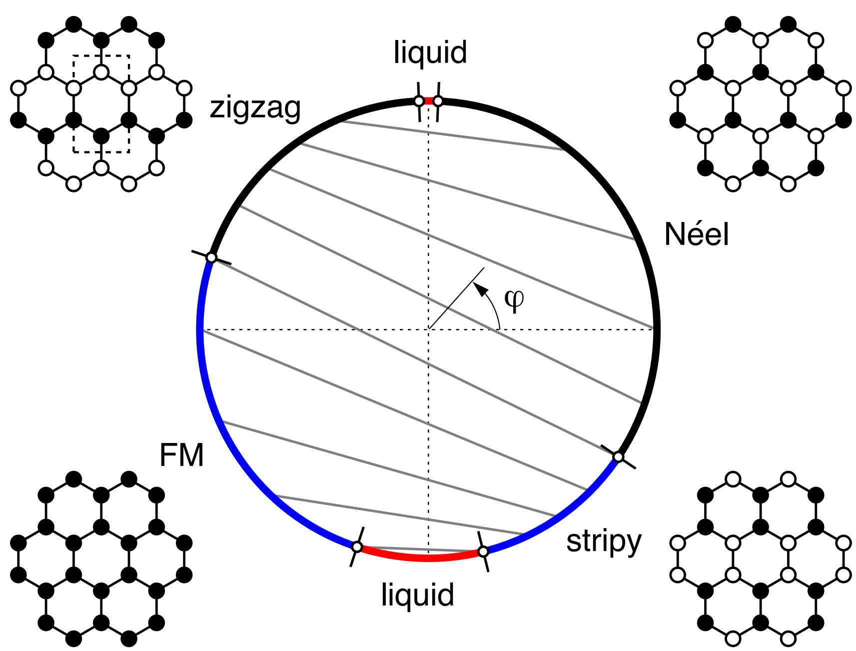
Magnetism

- But…they all order so far

due to additional interactions,
e.g. Heisenberg

$$H = \sum_{i,\alpha} K S_i^\alpha S_{i+\alpha}^\alpha + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

(a)

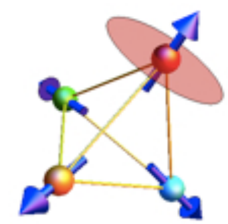


so far no QSL!

Real quantum spin ice

- Symmetry constrains form of generic Hamiltonian for Kramer's doublets

S. Curnoe, 2008

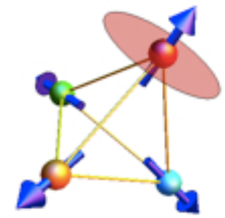


$$
\begin{aligned}
H = \; & J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z \\
& -J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) \\
& + J_{z\pm} \sum_{\langle i,j \rangle} \left[S_i^z \left(\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^- \right) + i \leftrightarrow j \right] \\
& + J_{\pm\pm} \sum_{\langle i,j \rangle} \left(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^- \right)
\end{aligned}
$$

} these terms give the earlier model

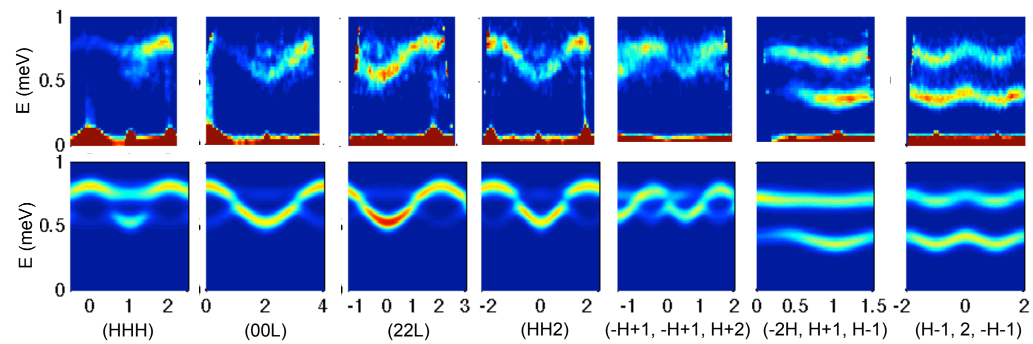
Hamiltonian

- Symmetry constrains form of generic Hamiltonian for Kramer's doublets



L. Savary *et al*, 2012

$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z$$
$$-J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right)$$
$$+J_{z\pm} \sum_{\langle i,j \rangle} \left[S_i^z \left(\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^- \right) + i \leftrightarrow j \right]$$
$$+J_{\pm\pm} \sum_{\langle i,j \rangle} \left(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^- \right)$$



$Er_2Ti_2O_7$

XY-like

J_{zz} = -2.5 ± 1.8 × 10^{-2} meV

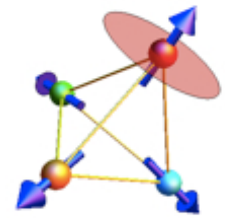
$J_{z\pm}$ = -0.88 ± 1.5 × 10^{-2} meV

$J_{\pm}$ = 6.5 ± 0.75 × 10^{-2} meV

$J_{\pm\pm}$ = 4.2 ± 0.5 × 10^{-2} meV

Hamiltonian

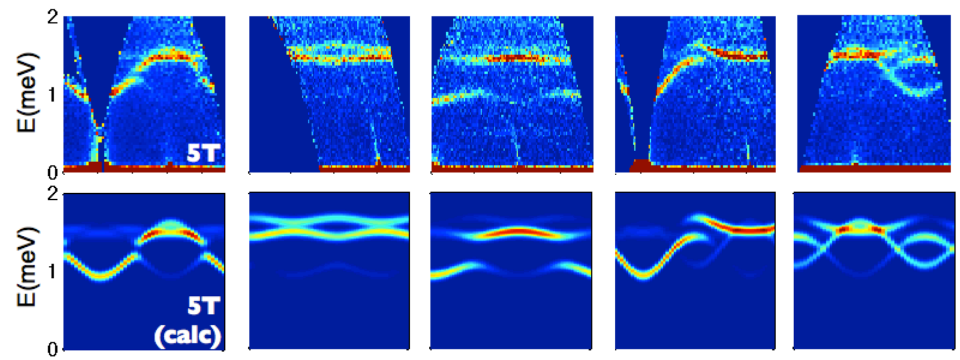
- Symmetry constrains form of generic Hamiltonian for Kramer's doublets



local z axes

K. Ross *et al*, 2011

$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z$$
$$- J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right)$$
$$+ J_{z\pm} \sum_{\langle i,j \rangle} \left[S_i^z \left(\zeta_{ij} S_j^+ + \zeta_{ij}^* S_j^- \right) + i \leftrightarrow j \right]$$
$$+ J_{\pm\pm} \sum_{\langle i,j \rangle} \left(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^- \right)$$



$Yb_2Ti_2O_7$

QSI

J_{zz} = 0.17±0.04 meV

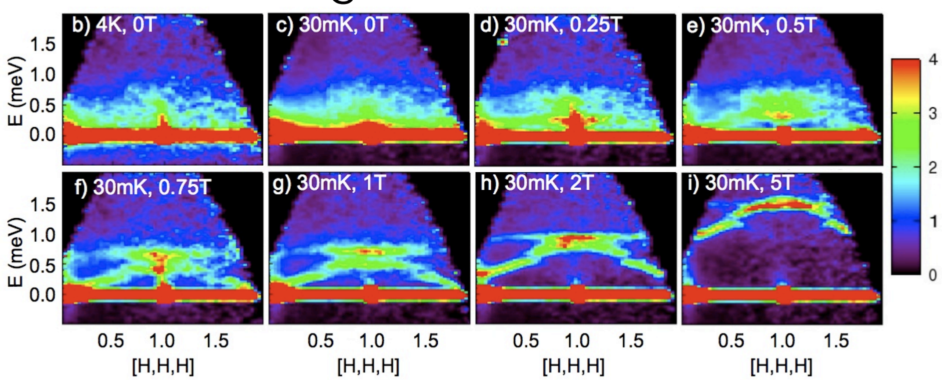
$J_{z\pm}$ = 0.14±0.01 meV

$J_{\pm}$ = 0.05±0.01 meV

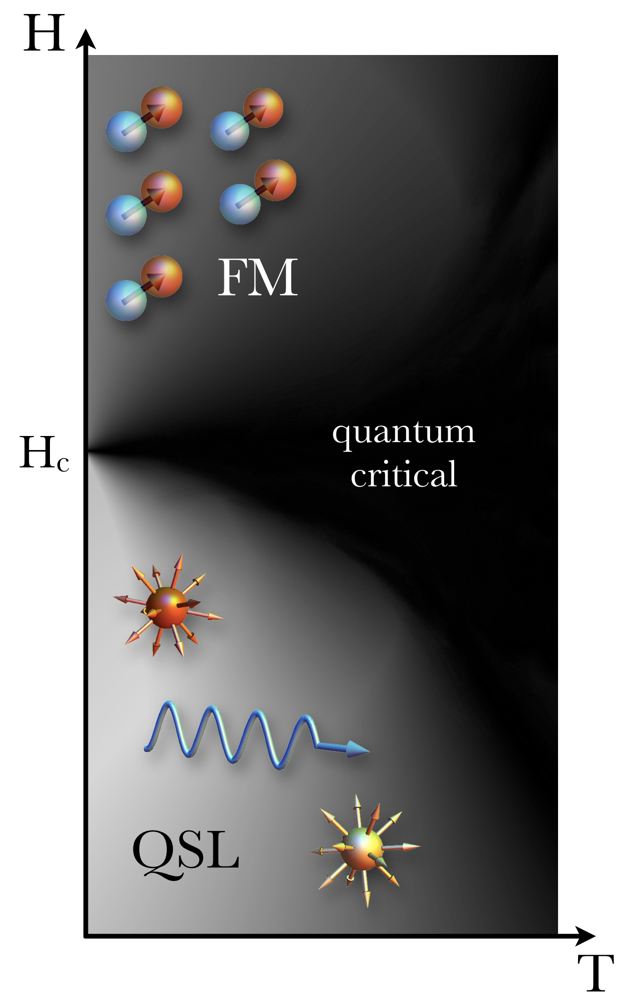
$J_{\pm\pm}$ = 0.05±0.01 meV

$Yb_2Ti_2O_7$?

missing magnon?

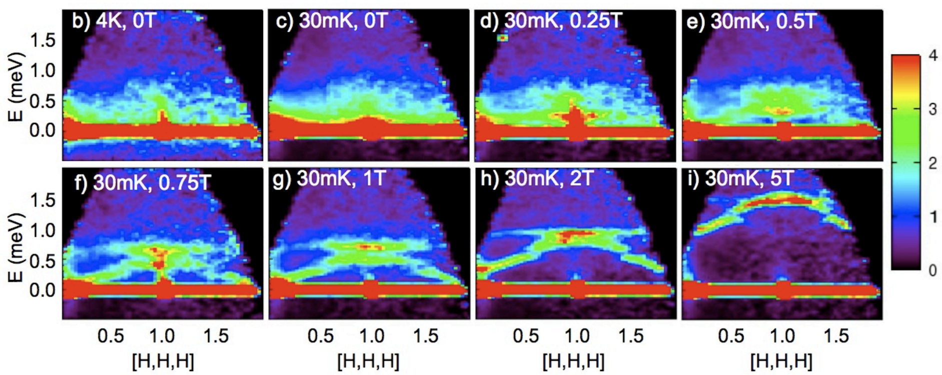


K.A. Ross *et al* (2009)



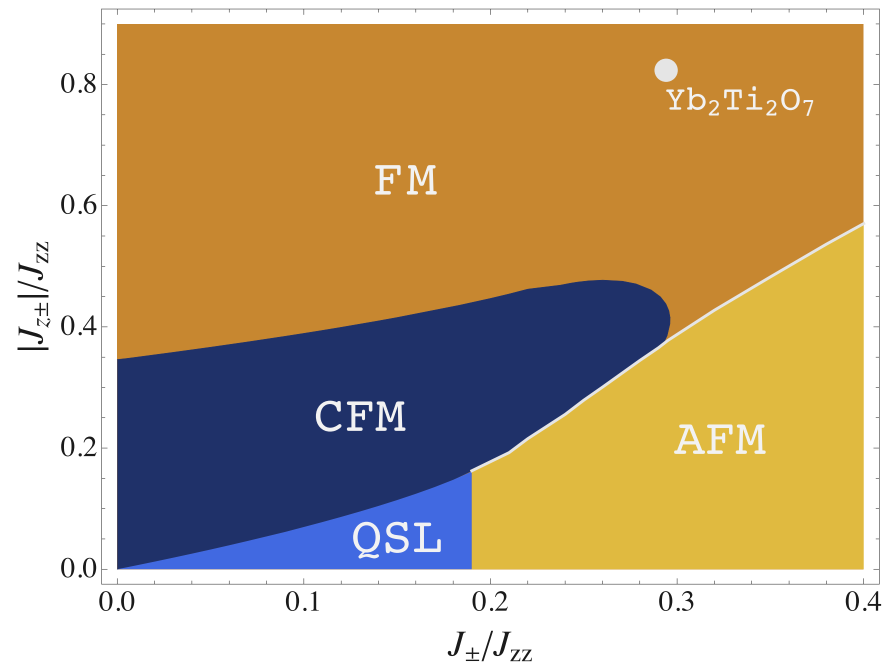
$Yb_2Ti_2O_7$?

missing magnon?



K.A. Ross *et al* (2009)

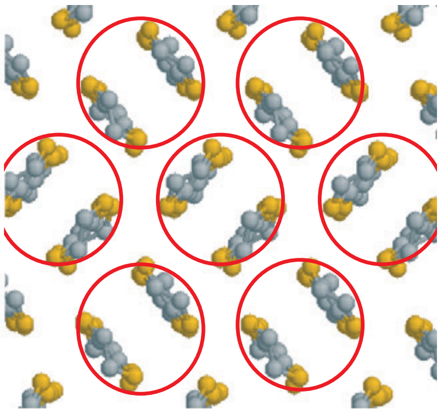
L. Savary + LB, 2012



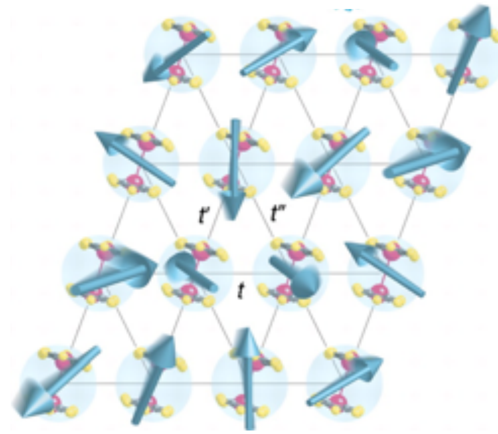
I tend to think recent evidence points away from the U(1) QSL and toward an unconventional FM. But this is still an unfinished story.

$J_{\pm\pm}$ might help?
disorder effects?
other materials?

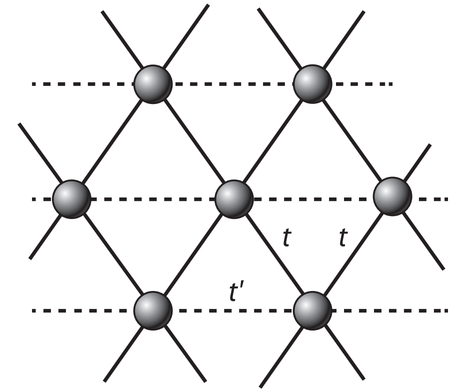
Organics



κ-$(ET)_2X$

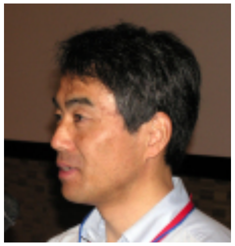


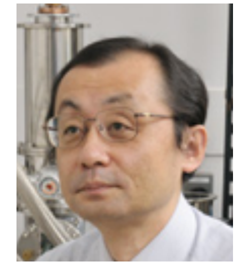
β'-$Pd(dmit)_2$

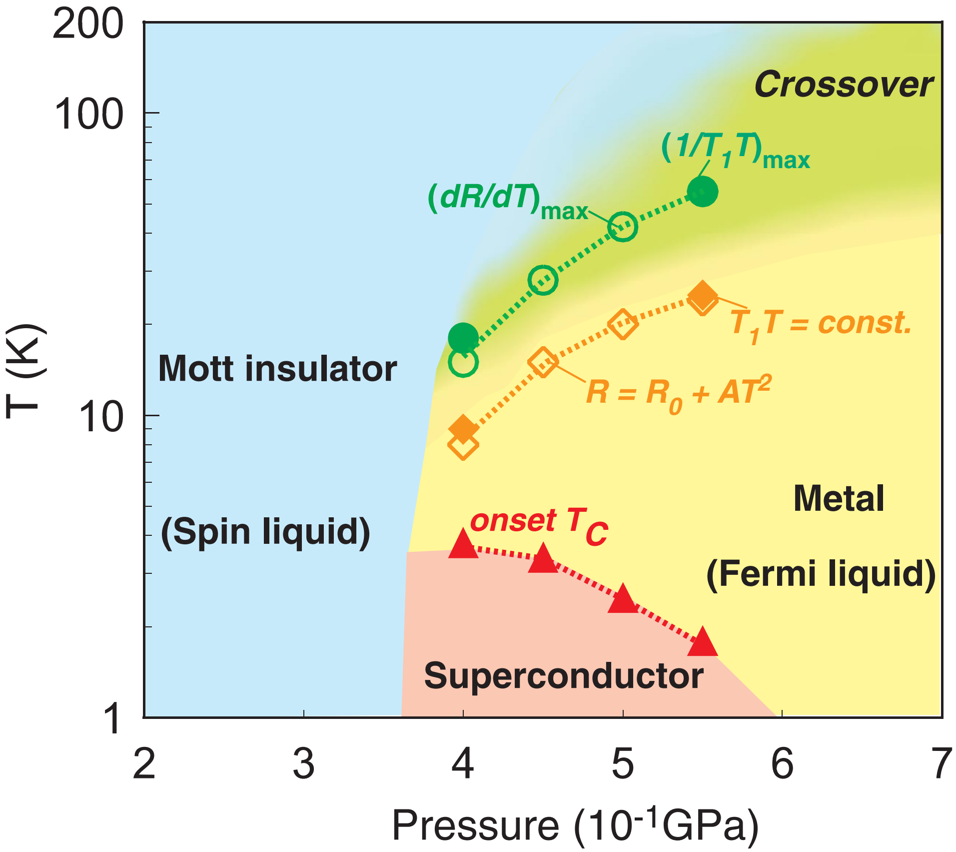


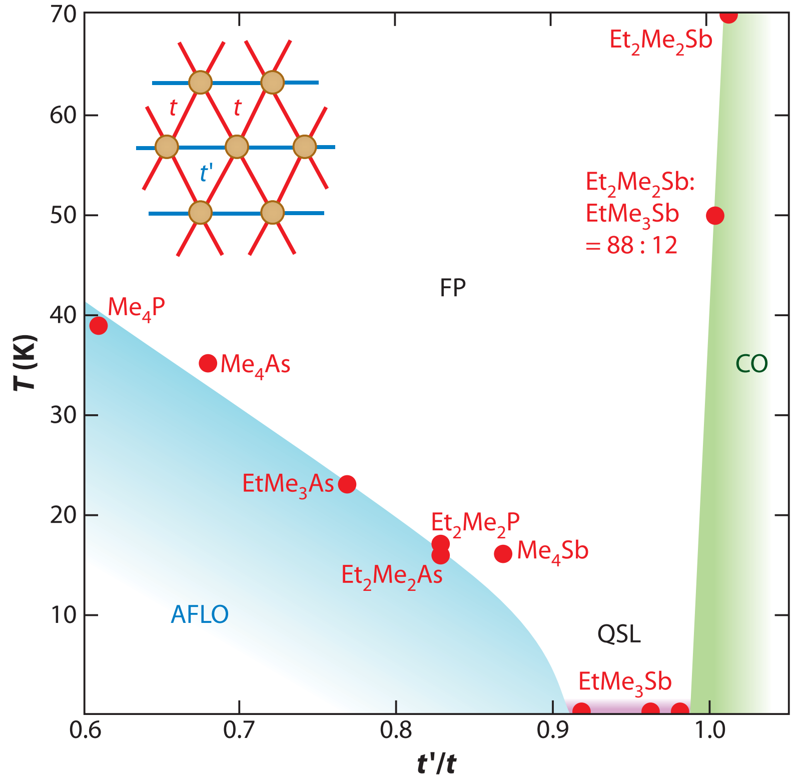
- Molecular materials which behave as effective triangular lattice S=1/2 antiferromagnets with J ~ 250K
  - significant charge fluctuations

Organics









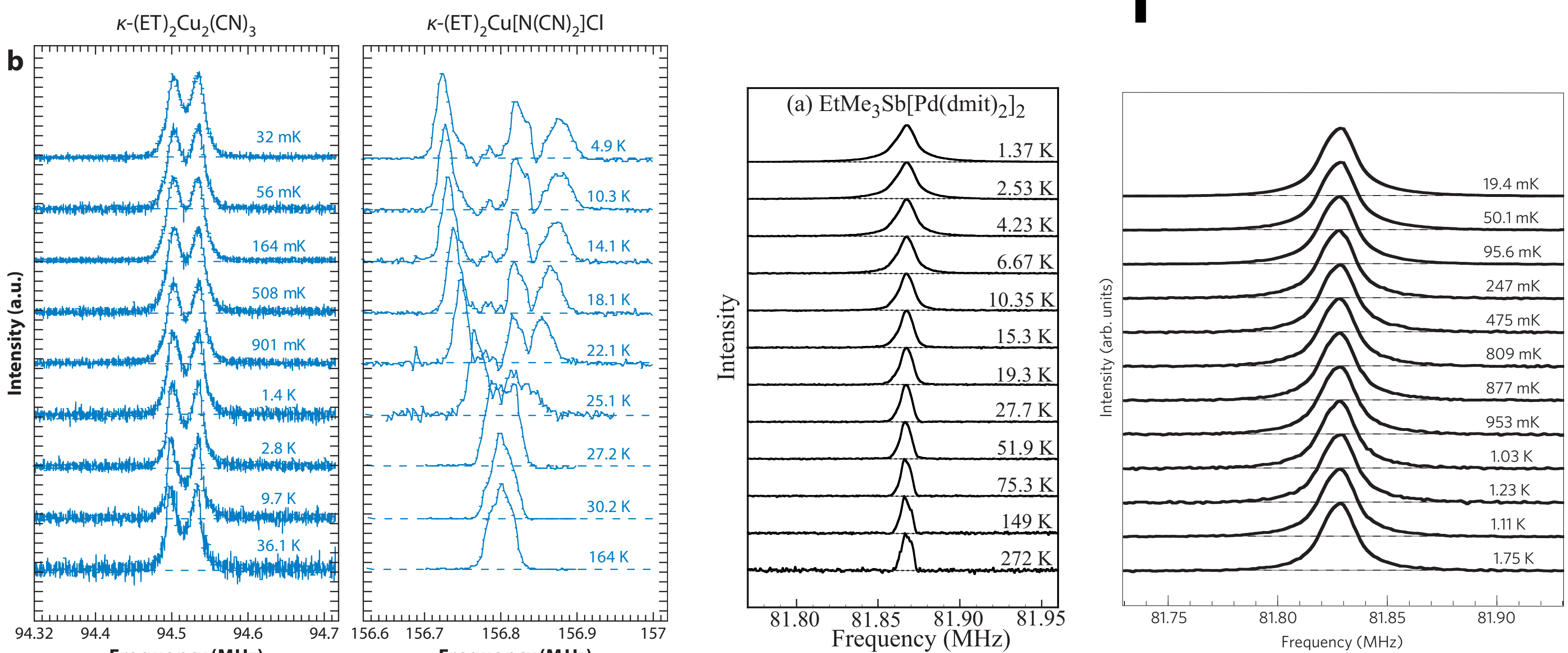
κ-$(ET)_2Cu_2(CN)_3$

β′-$Pd(dmit)_2$

K. Kanoda group (2003-)

R. Kato group (2008-)

NMR lineshapes



κ-$(ET)_2Cu_2(CN)_3$

β′-$Pd(dmit)_2$

Y. Shimizu *et al*, 2003

^{1}H NMR

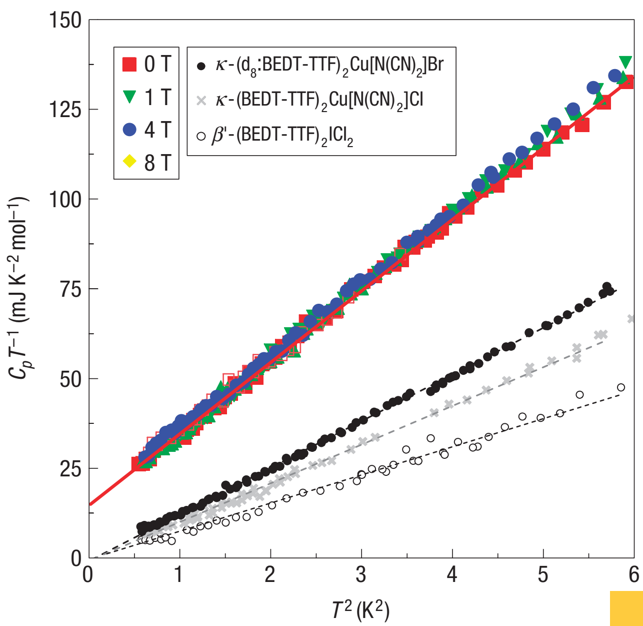
T. Itou *et al*, 2008,2010

^{13}Cs NMR

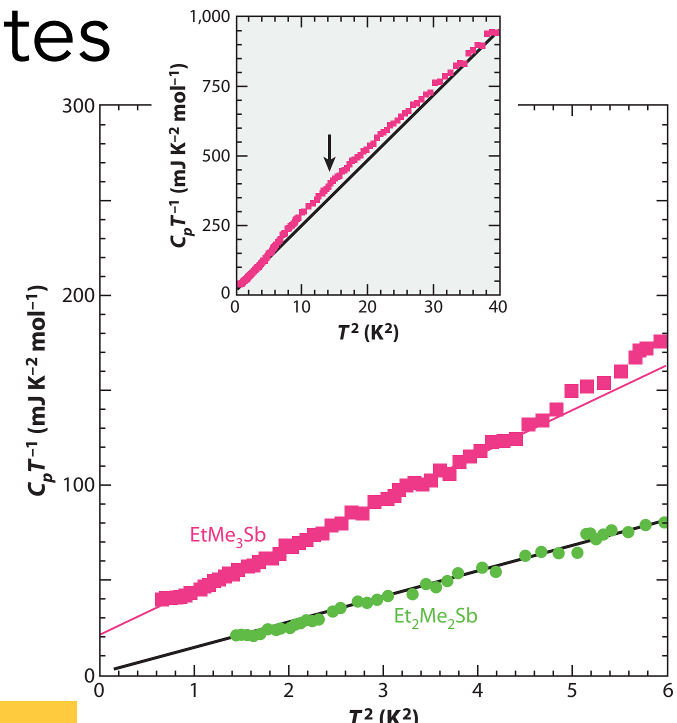
Evidence for lack of static moments: f > 1000!

Specific Heat

- C ~ γT indicates gapless behavior with large density of states



γ_{Cu} ~ 0.7 !!



κ-$(ET)_2Cu_2(CN)_3$

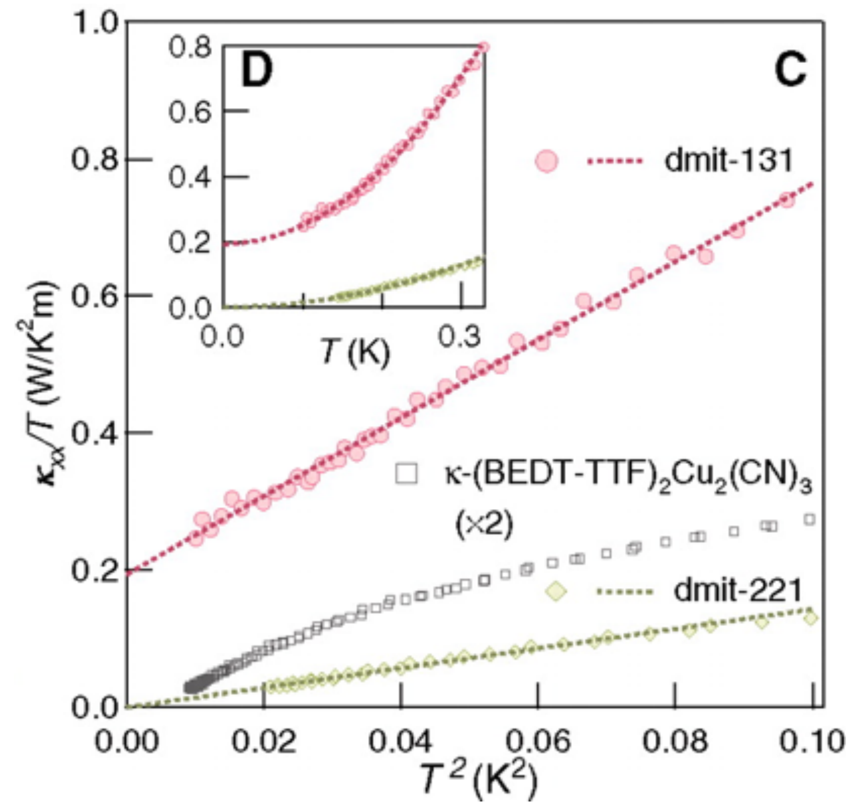
β′-$Pd(dmit)_2$

S. Yamashita *et al*, 2008

Thermal conductivity

- Huge linear thermal conductivity indicates the gapless excitations are propagating, at least in dmit

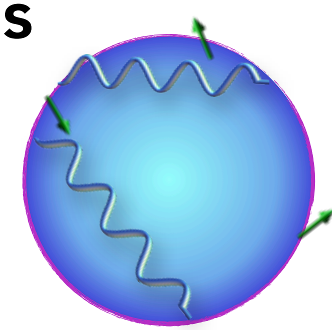
- Estimate for a *metal* would correspond to a mean free path l ~ 1 μm ≈1000 a !



M. Yamashita *et al*, 2010

Organics - Theory

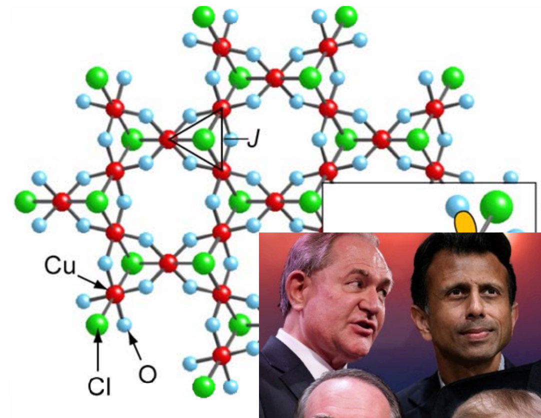
- RVB/QSL state:
  - Motrunich, Lee+Lee: (2005) “uniform RVB”
  - this is a kind of RVB state with very many (maybe a maximal number of?) long-range VBs
  - It is described by a **“Fermi sea” of spinons** coupled to a U(1) gauge field
- Good variational energy for triangular lattice Hubbard model



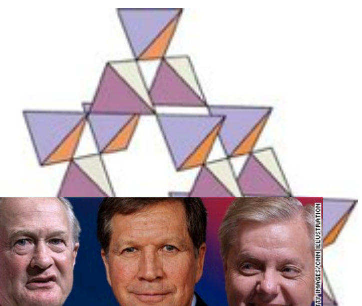
Organics: issues

- Why these very small set of materials?
- Spatial homogeneity?
- Indications of phase transitions. Gaps opening? Charge ordering?
- Quantitative inconsistencies with expected scaling behavior from theory (c.f. $C \sim T^{2/3}$ etc.)
- Large isotope effects. Role of molecular rotations?
- Almost all experimental checks of QSL are limited to $T<5K$, and many are not directly tied to spins, while $J \sim 200\text{-}300K$. Hampered by nature of materials.

New candidates are desirable



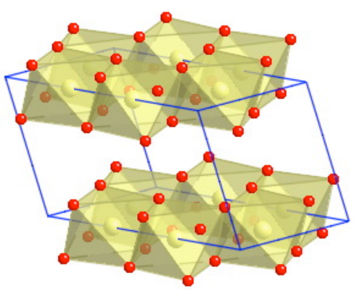
Herbert



$Yb_2Ti_2O_7$

...

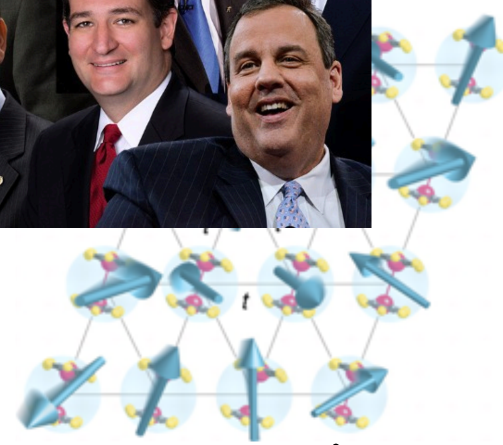
spin ice



Li_2IrO_3

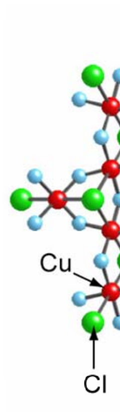
α-$RuCl_3$

Kitaev materials



organics

New candidates are desirable

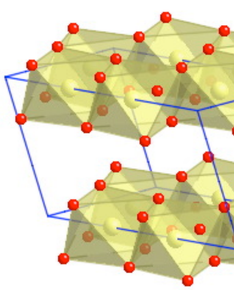


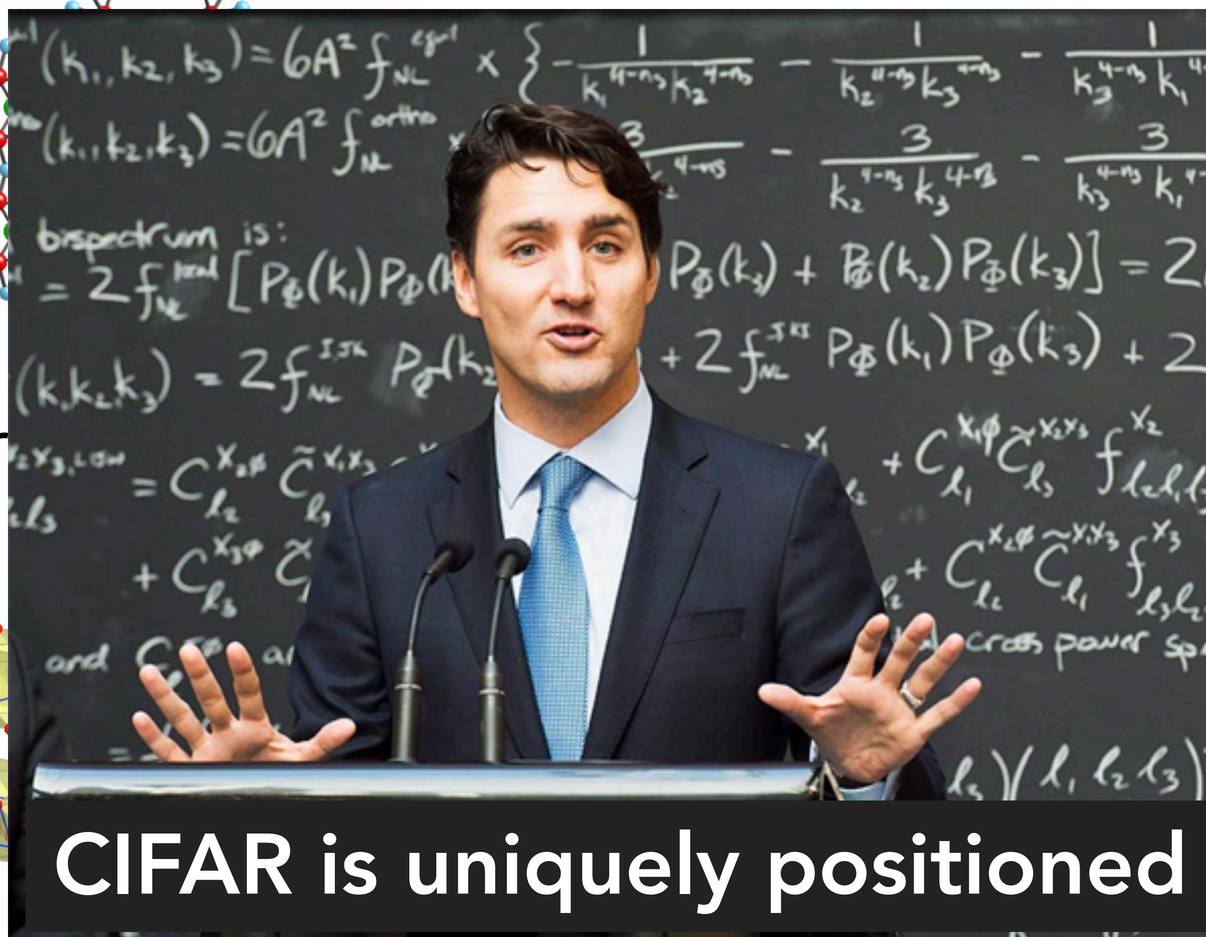
Her

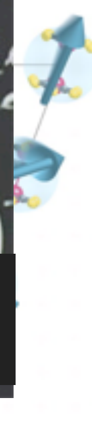
$Yb_2Ti_2O_7$

...

pin ice







Kitaev materials

organics

Theory: Frontiers

New phases

- Fractal spin liquids (Haah++) in 3d
- SPT phases
- Quenched disorder

Fundamental problems

- QSLs with strongly coupled matter-gauge theory
- QCPs to/from QSL phases
- Out of equilibrium
- Doping

Reality

- Devise experimental protocols to reveal quantum non-locality of QSLs
- Computational methods: less bias, reliability of variational methods, beyond ground states

Thanks for your attention

References here: https://spinsandelectrons.com/pedagogy/

NSF
Office of Basic Energy Sciences · Serving the Present, Shaping the Future
GORDON AND BETTY MOORE FOUNDATION
CIFAR CANADIAN INSTITUTE FOR ADVANCED RESEARCH | ICRA INSTITUT CANADIEN DE RECHERCHES AVANCÉES