
Quantum Spin Liquids
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PSSCMP 2020

Influenced by

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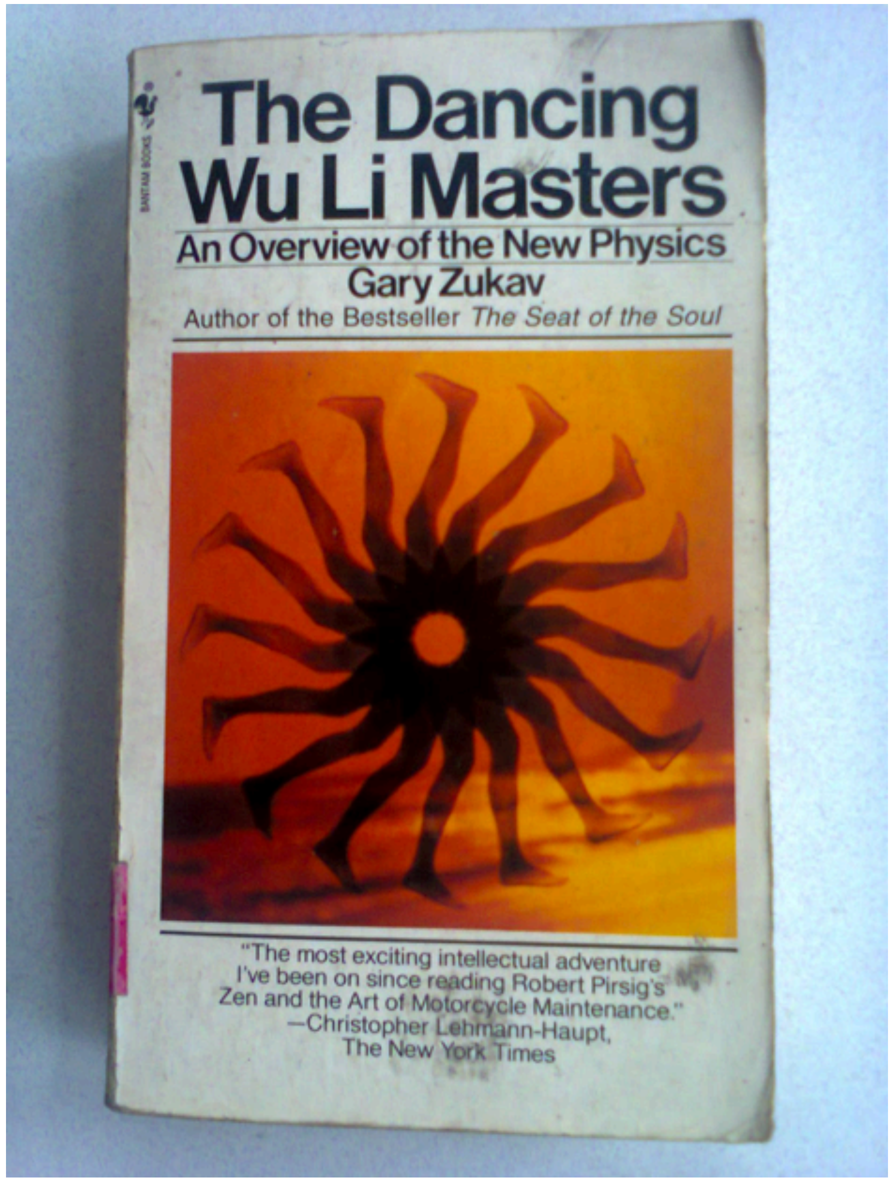
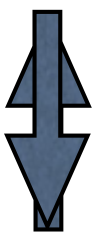
Quantum Spin Liquid

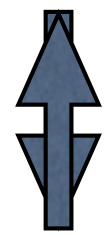


Quantum non-locality

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



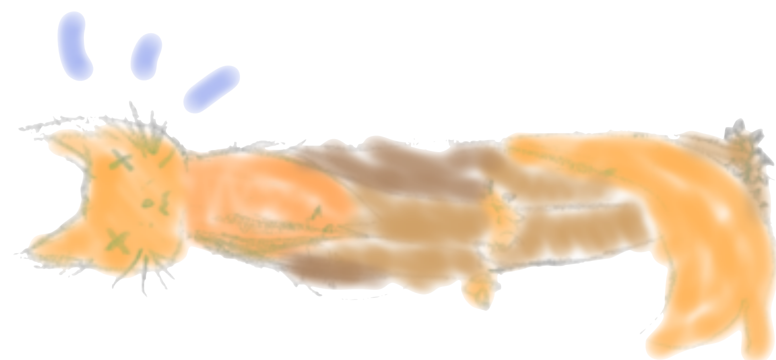
??where is the information??



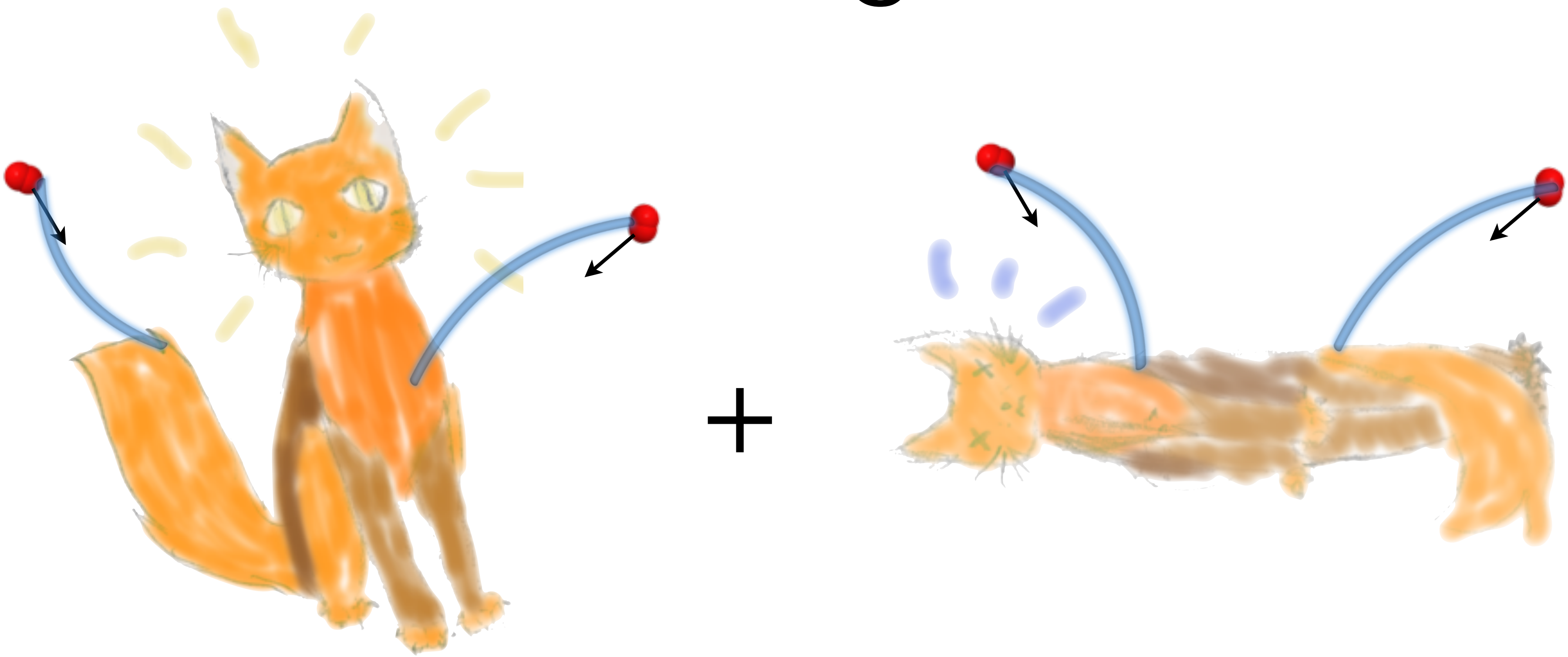
A. Einstein B. Podolsky N. Rosen

Schrödinger's Cat

+



Schrödinger’s Cat

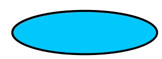


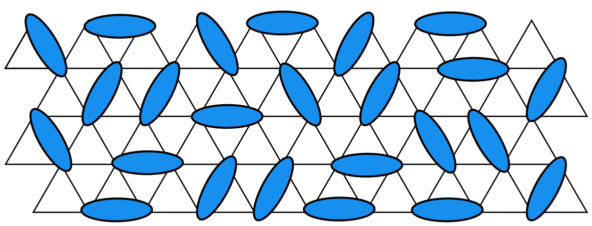
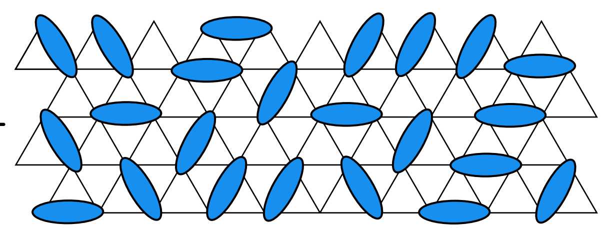
UNSTABLE to decoherence - uncontrolled entanglement with the environment

Strange Stuff

Phil Anderson, 1973

a "quantum liquid" of spins

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

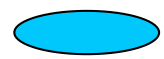
Ψ =  +  + ...

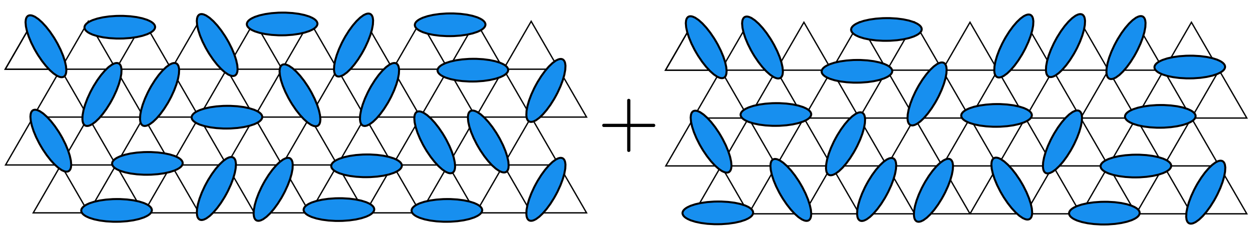
Resonating **V**alence **B**ond state

Strange Stuff

Phil Anderson, 1973

a "quantum liquid" of spins

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

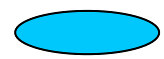
$\Psi \quad = $  $+ \ldots$

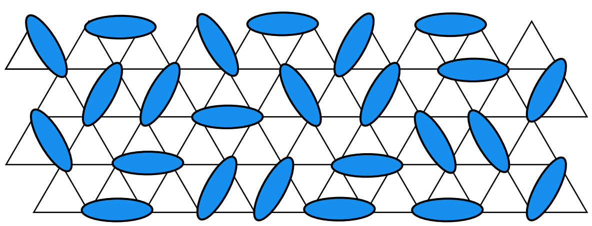
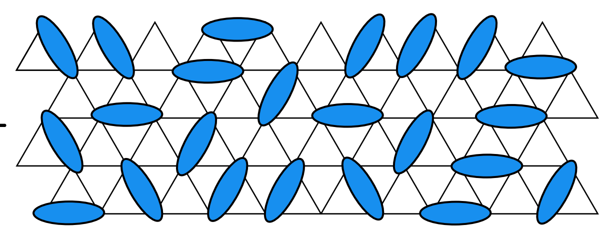
Resonating **V**alence **B**ond state

Strange Stuff

Phil Anderson, 1973

a "quantum liquid" of spins

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

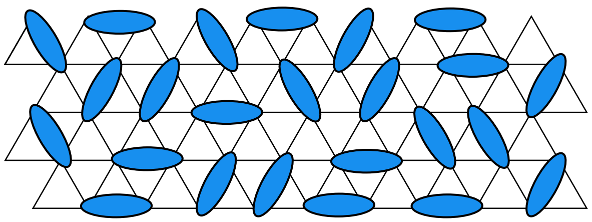
$\Psi =$  $+$  $+ \ldots$

Two features:
1. Spin-zero pairs
2. Massive superposition

When do we expect RVB?

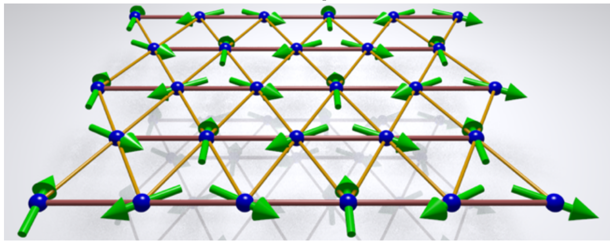
- Compare singlet energy to ordered energy:

Singlets



versus

The competition



caveats:

Neglects superposition

Neglects zero point fluctuations

When do we expect RVB?

- Compare singlet energy to ordered energy:

$$\vec{S}_i \cdot \vec{S}_j = \frac{1}{2}\left(\vec{S}^2_{\text{tot}} - \vec{S}^2_i - \vec{S}^2_j\right)$$

$$\left\langle \vec{S}_i \cdot \vec{S}_j \right\rangle_{\text{AF}} = -S^2 x \qquad \left\langle \vec{S}_i \cdot \vec{S}_j \right\rangle_{\text{singlet}} = -S(S+1)$$

When do we expect RVB?

- Compare singlet energy to ordered energy:

$$\vec{S}_i \cdot \vec{S}_j = \frac{1}{2}\left(\vec{S}^2_{\rm tot} - \vec{S}^2_i - \vec{S}^2_j\right)$$

$$\left\langle \vec{S}_i \cdot \vec{S}_j \right\rangle_{\rm AF} = -S^2 x \qquad \left\langle \vec{S}_i \cdot \vec{S}_j \right\rangle_{\rm singlet} = -S(S+1)$$

$$E_{AF}/\text{bond} = -S^2 x$$

angular factor

$$E_{singlet}/\text{bond} = -S(S+1) f_{\rm singletbonds} = -\frac{1}{z} S(S+1)$$

Coordination number

- Favorable for small S, small z, small x (frustration)

To understand what is strange about spin liquids, we should understand

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

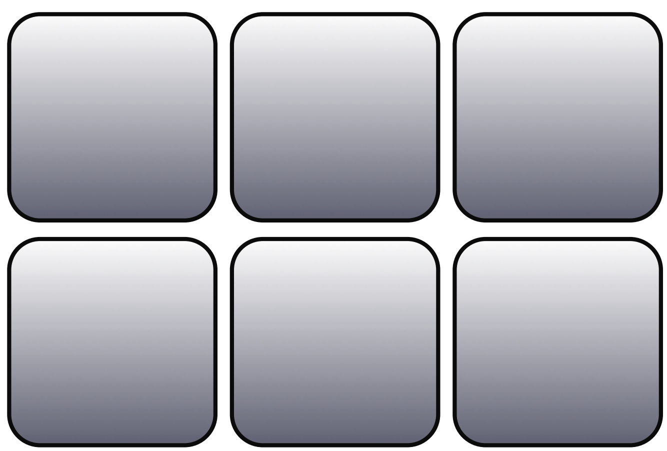
Ordinary (local) Matter

Hamiltonian is local

$$H = \sum_{\mathbf{x}} \mathcal{H}(x) \qquad \mathcal{H}(x) \text{ has local support near x}$$

Ground state is "essentially" a product state

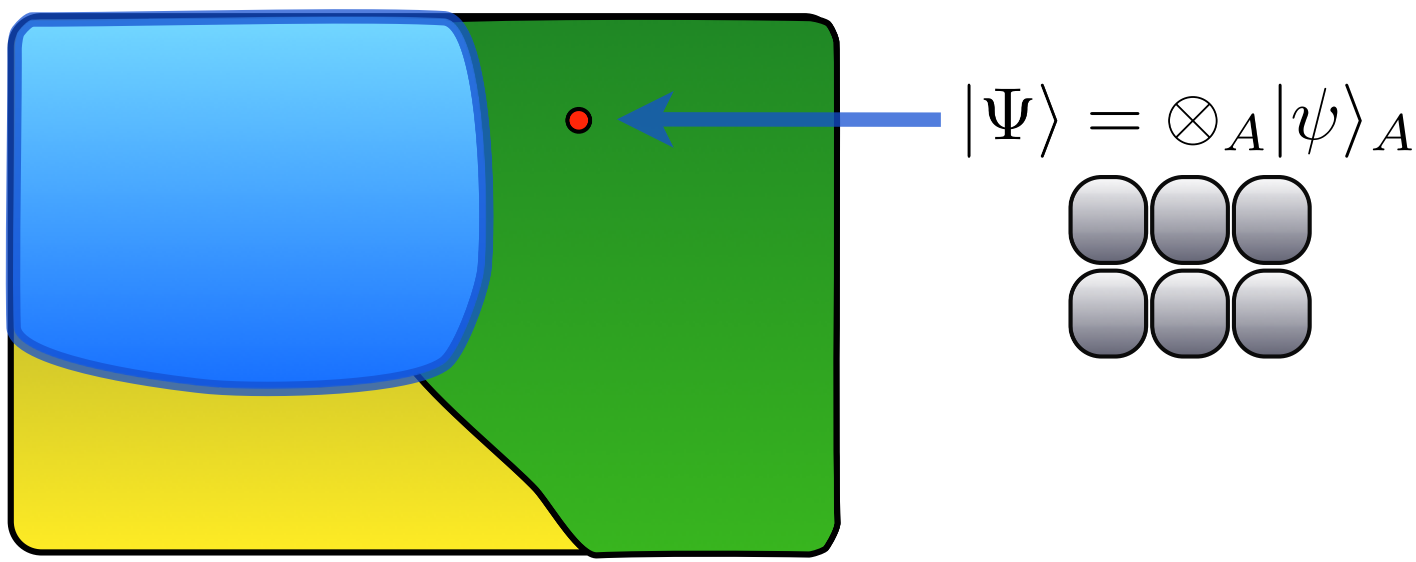
$$|\Psi\rangle = \otimes_A |\psi\rangle_A$$



no entanglement between blocks

"Essentially" a product state?

- Adiabatic continuity

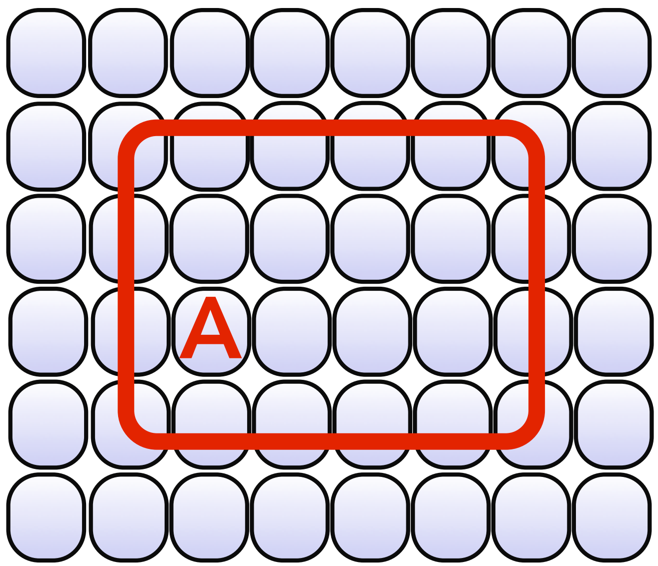


phase space

n.b. This is not true for gapless fermi systems

“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

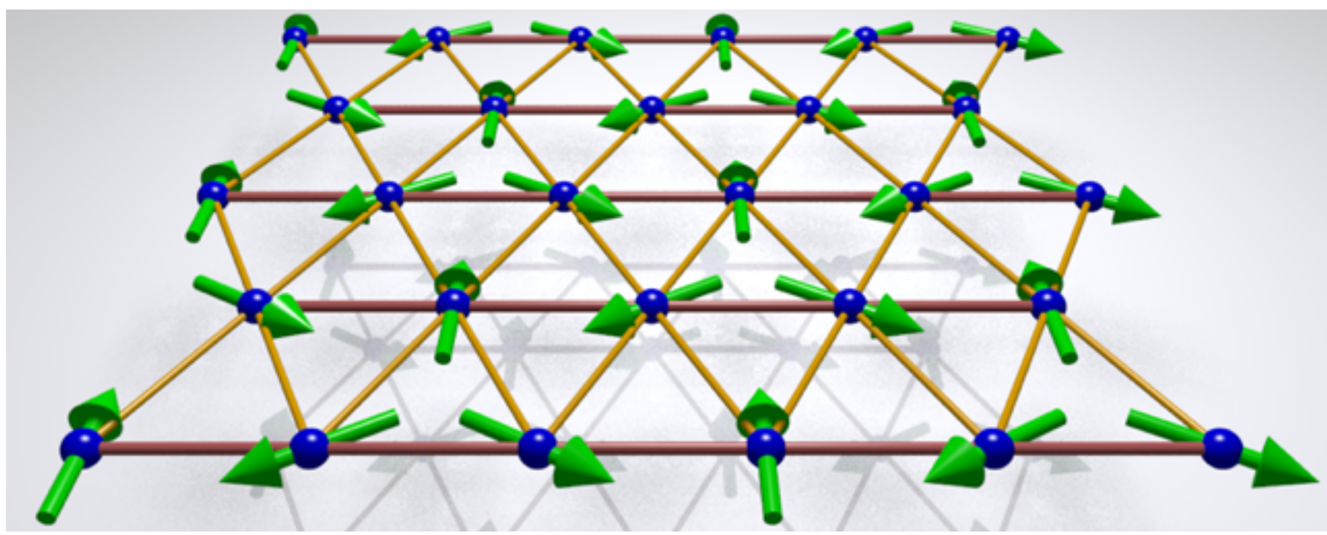
$$H = \sum_{(ij)} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

exchange is short-range: local

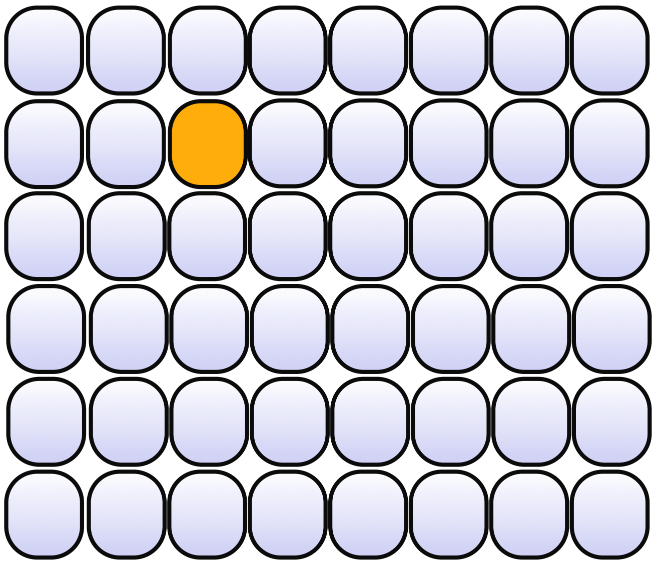
ordered state

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

block is a single spin



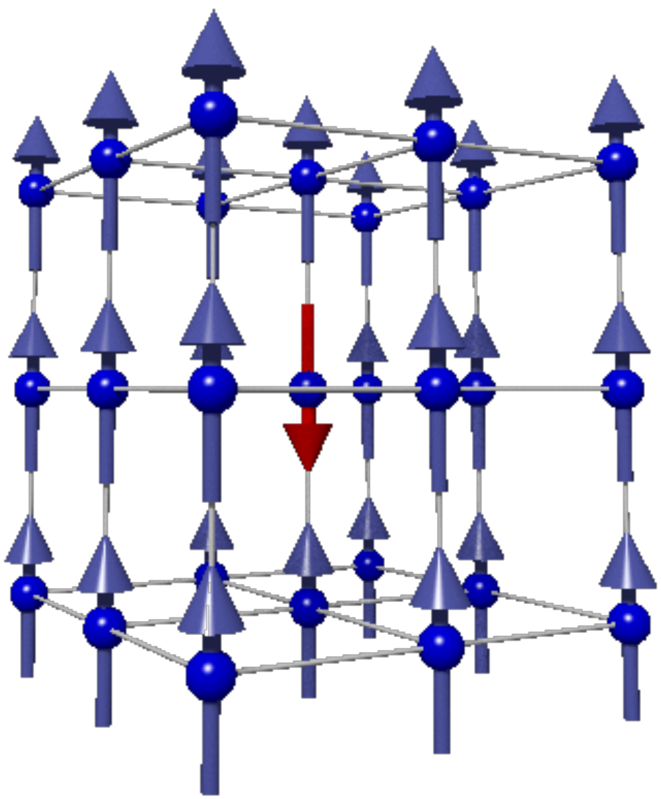
Quasiparticles



excited states ~ excited levels of one block

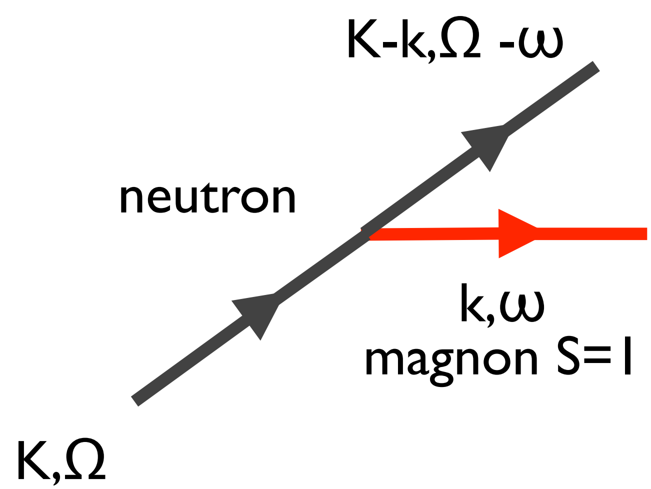
- local excitation can be created with operators in one block
- localized excitation has discrete spectrum with non-zero gap, and plane wave forms sharp band
- quantum numbers consistent with finite system: no emergent or fractional quantum numbers

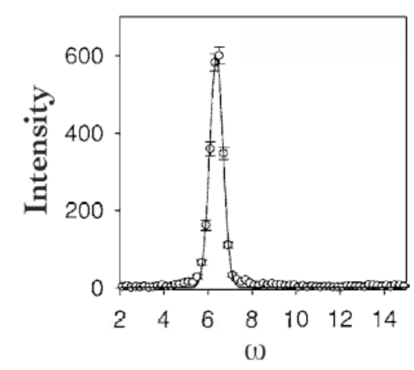
Spin wave



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

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

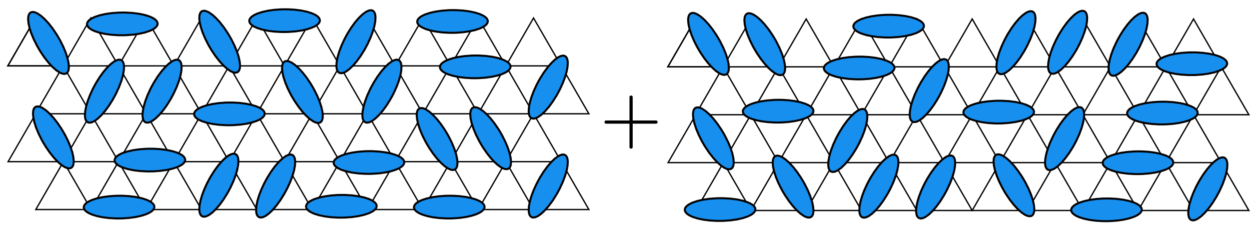


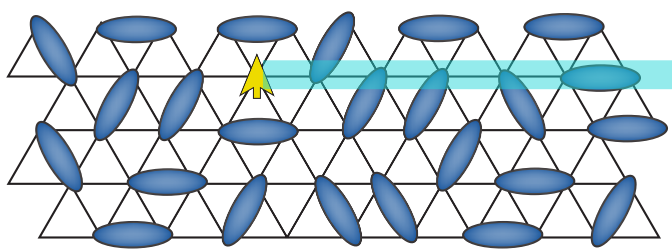


Line shape in Rb_2MnF_4

Quantum spin liquid

Entanglement -> non-local excitation

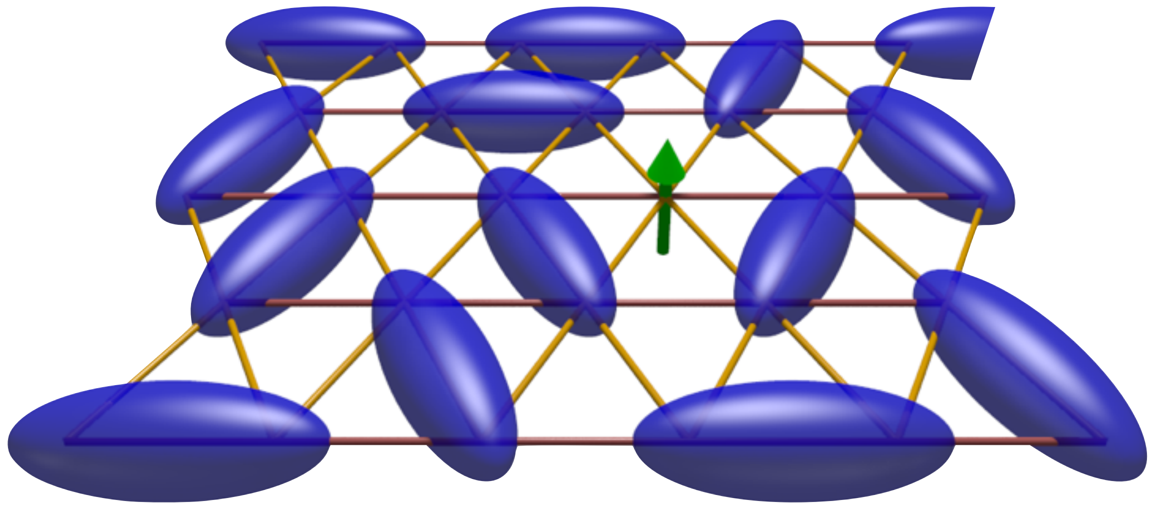
$\Psi =$  $+ \ldots$

$\Psi =$  $+ \cdots$

“spinon”

“quasiparticle” above a non-zero gap

Fractional quantum number

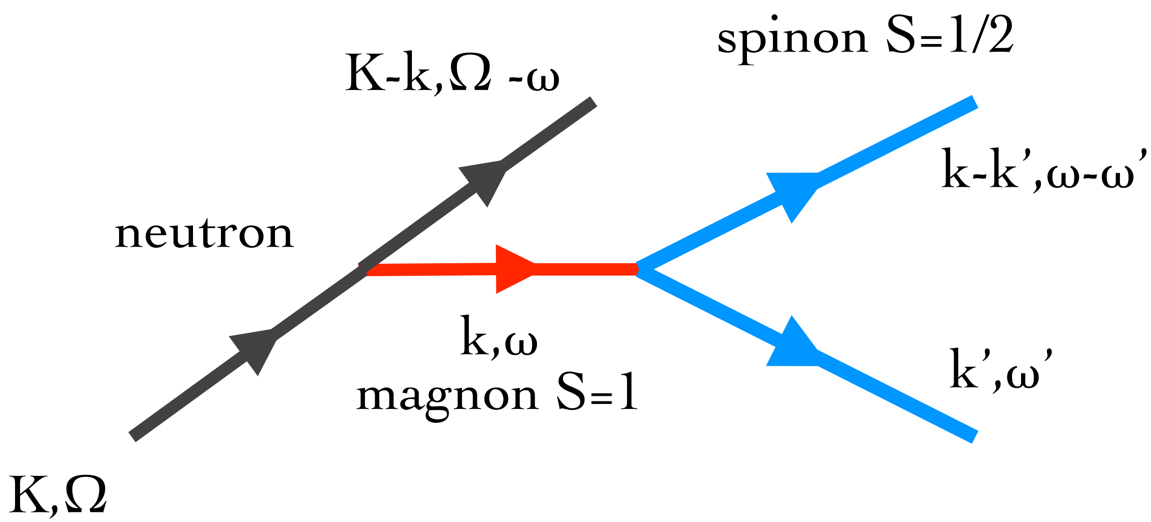


excitation with $\Delta S = 1/2$
not possible for any finite
cluster of spins

always created in pairs by any
local operator

No spin waves

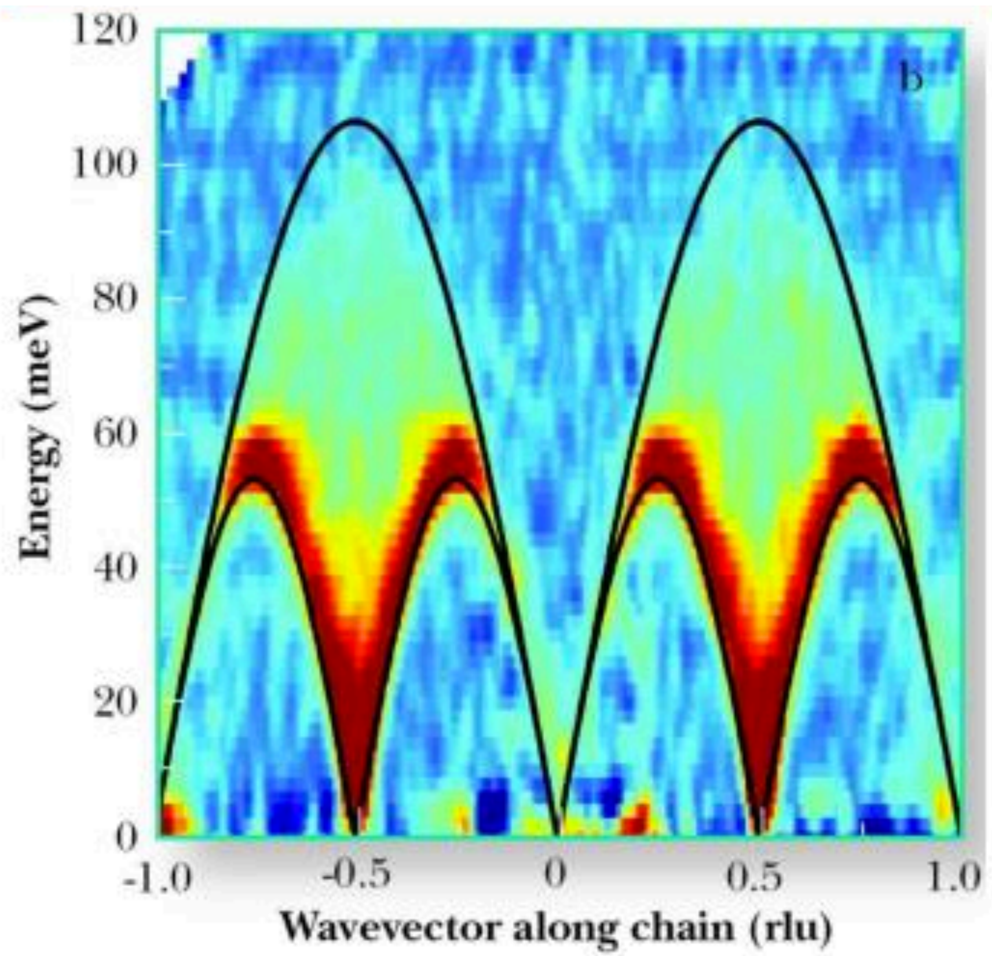
- In a quantum spin liquid, the elementary spin excitations are *fractional, S=1/2 spinons*



broad peak with $\omega=\varepsilon(k')+\varepsilon(k-k')$

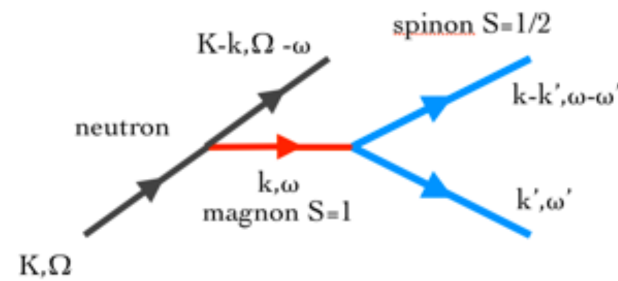
- Sharp peaks should be reduced or absent in the spin structure factor

c.f. One dimension

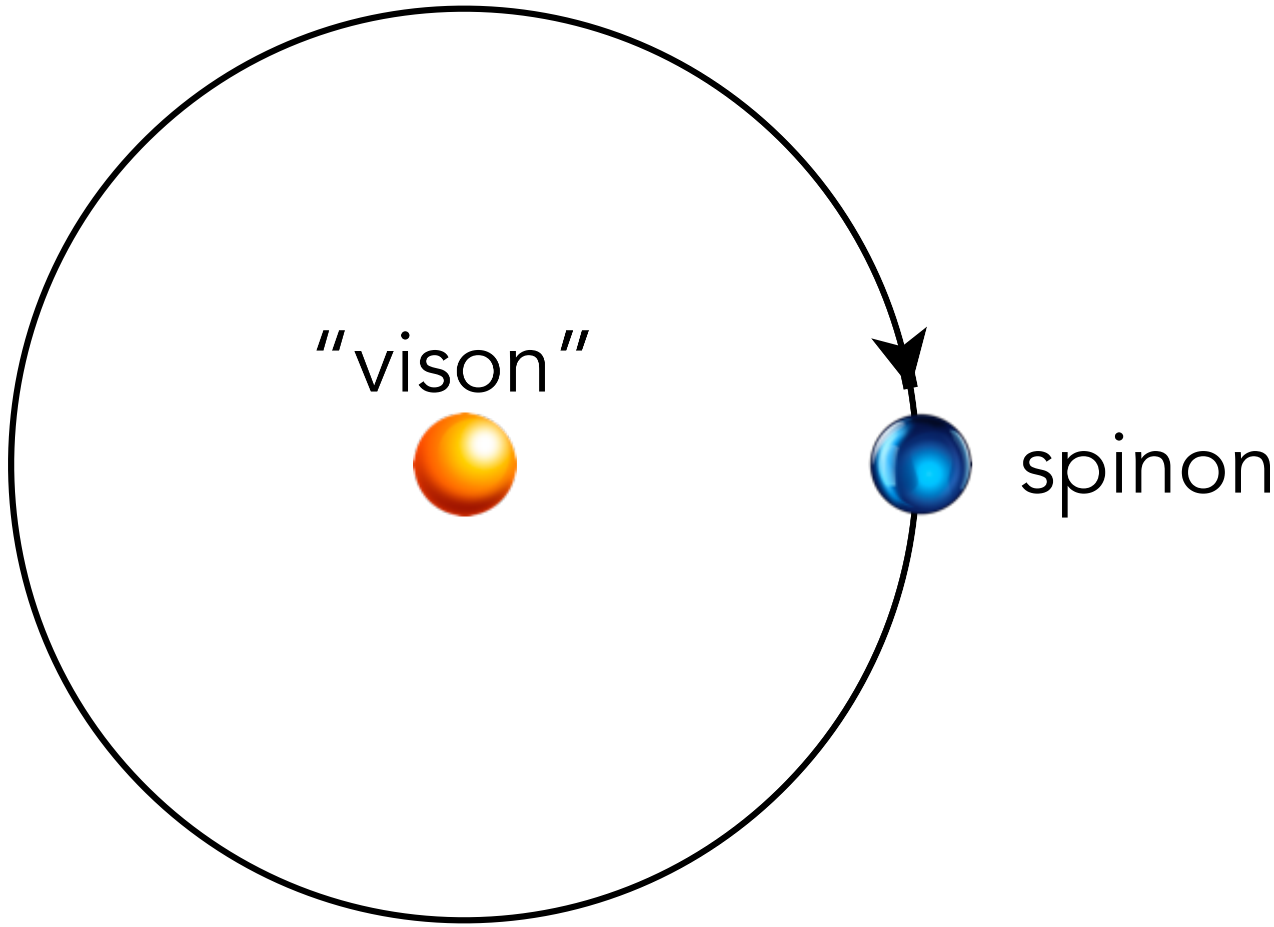


A. Tennant *et al*, 2001

$KCuF_3$



Anyons



$$\Psi \rightarrow -\Psi$$

"mutual semions"

X.-G. Wen

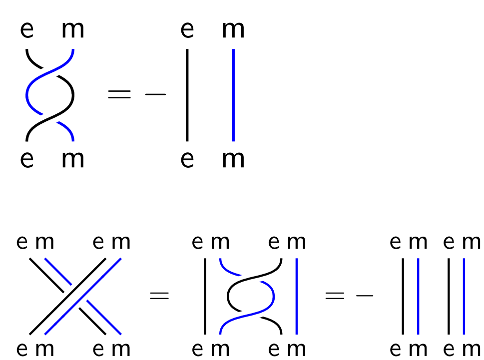
Topological phases

A. Kitaev

The American Physical Society
OLIVER E. BUCKLEY
SOLID STATE PHYSICS PRIZE

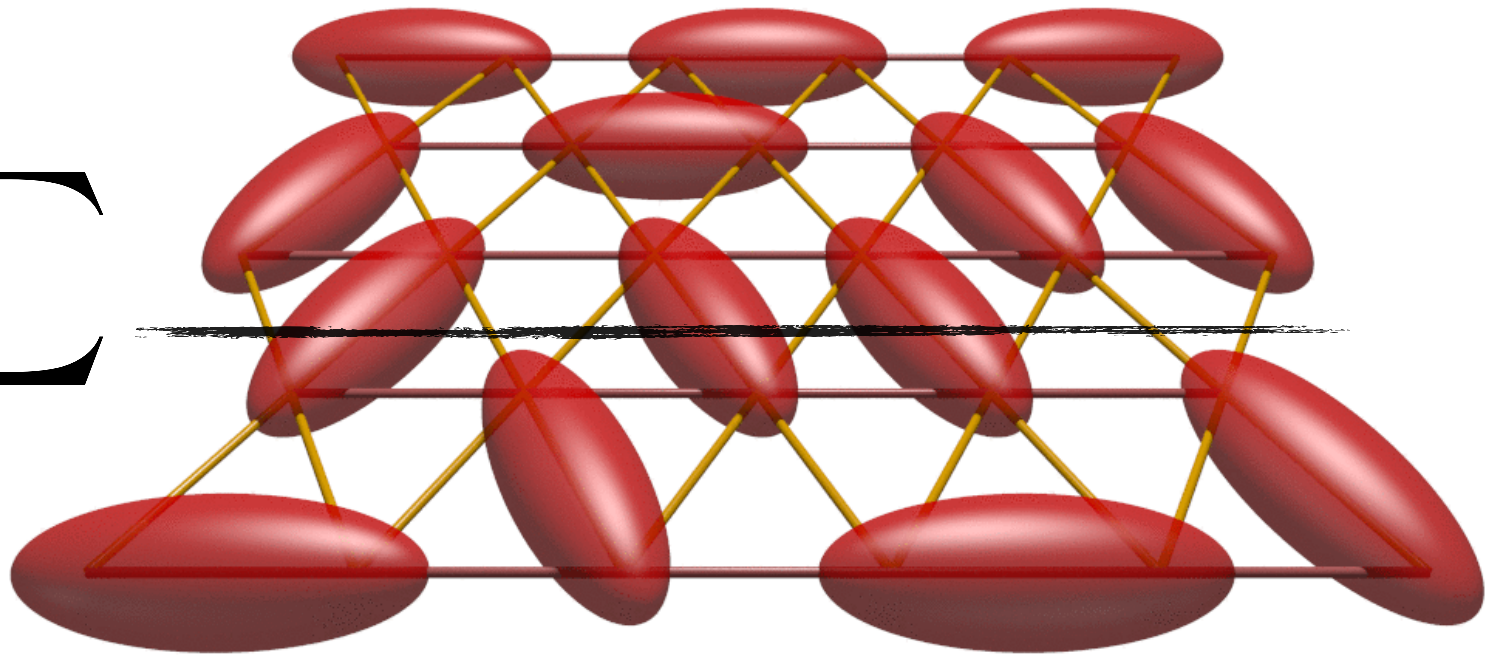
Anderson's RVB state is thus an example of a "topological phase" - the best understood sort of QSL

Understood and classified by anyons and their braiding rules in 2d



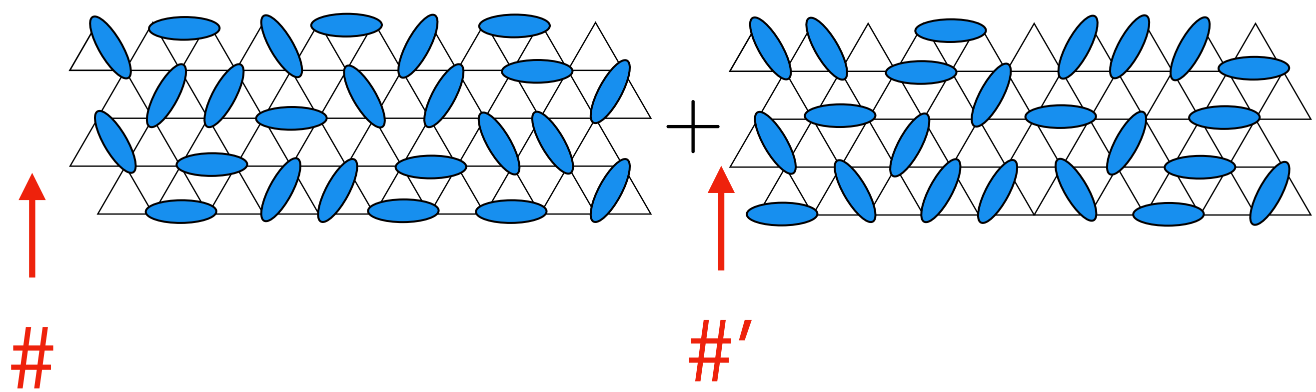
Stability

$$\Psi = \sum$$



Robustness arises from topology: a QSL is a stable *phase* of matter (at T=0)

Many kinds of QSLs

$\Psi =$ 

$+ \ldots$

For ~500 spins, there are more amplitudes than there are atoms in the visible universe!

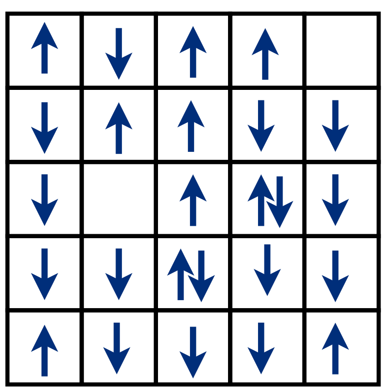
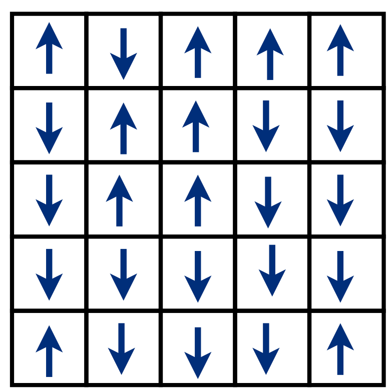
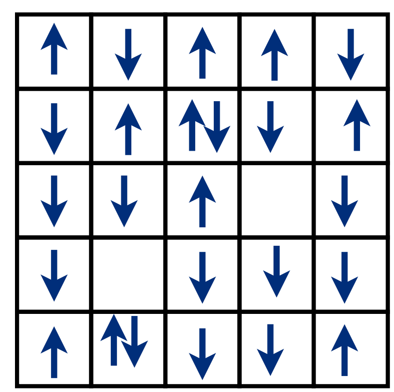
Different choices of amplitudes can realize different QSL phases of matter.

Gutzwiller Construction

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

$$|\Psi_0\rangle = \prod_{k \in FS} c^\dagger_{k\uparrow} c^\dagger_{k\downarrow} |0\rangle$$

"partons"
"spinons"

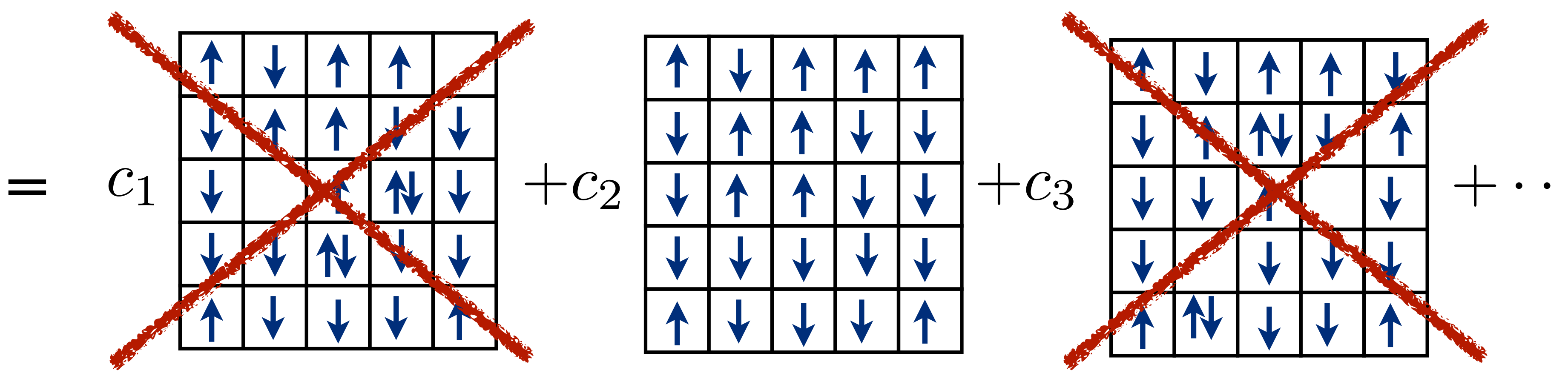
$= \; c_1$  $+c_2$  $+c_3$  $+\cdots$

Gutzwiller Construction

- Project out any components with empty or doubly occupied sites

$$|\Psi\rangle = \hat{P}_G|\Psi_0\rangle$$

"partons"
"spinons"

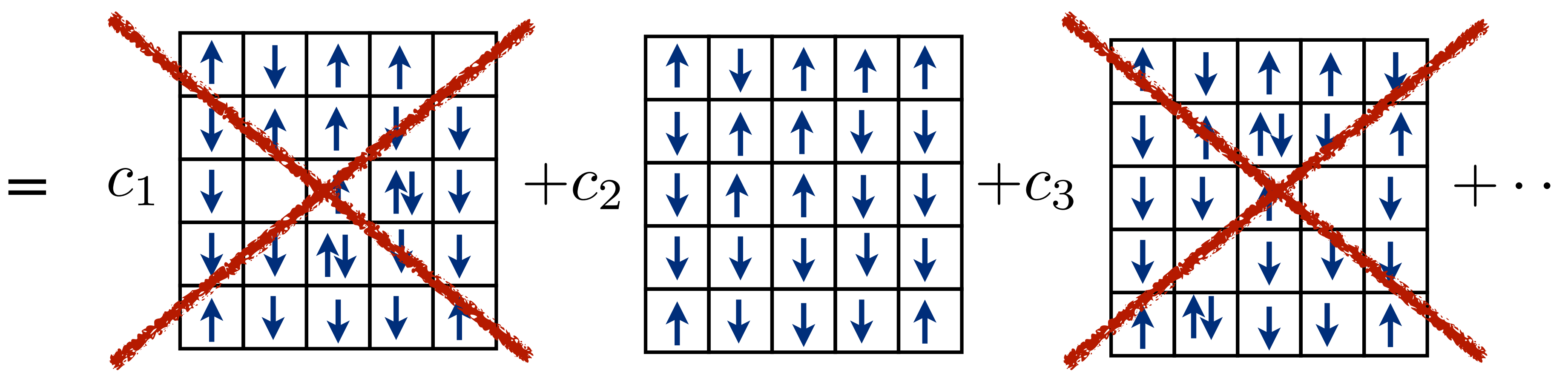


Gutzwiller Construction

- Can build many QSL states by choosing different free fermion states

$$|\Psi\rangle = \hat{P}_G|\Psi_0\rangle$$

"partons"
"spinons"

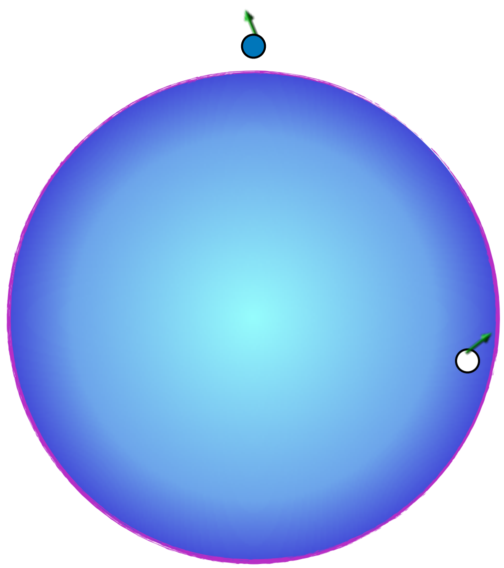


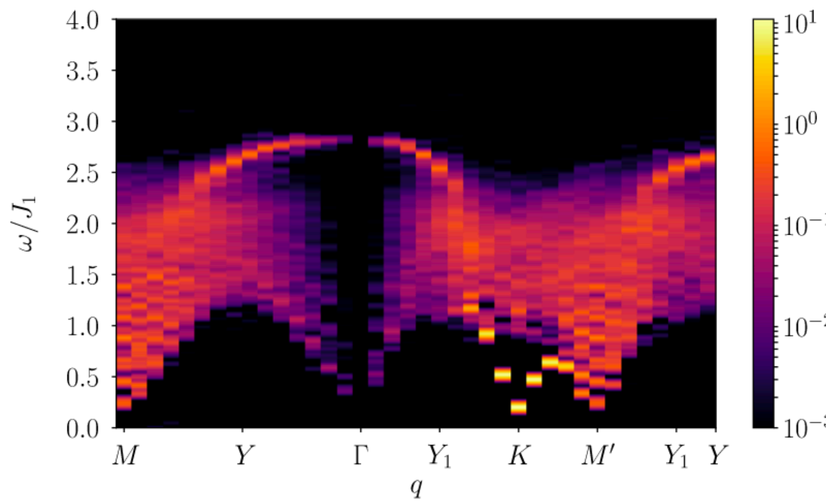
Gutzwiller Construction

- Partons/spinons as quasiparticles

$$|\Psi'\rangle = \hat{P}_G \left(c^\dagger_{k\alpha} c_{q\beta} |\Psi_0\rangle \right)$$

Two spinons but independent (before projection)

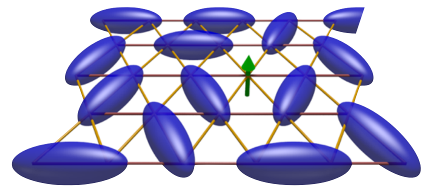




Applied to triangular lattice to compute S(q,w), F. Ferrari + F. Becca, 2019

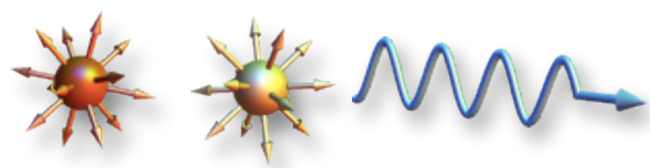
Classes of QSLs

- Topological QSLs



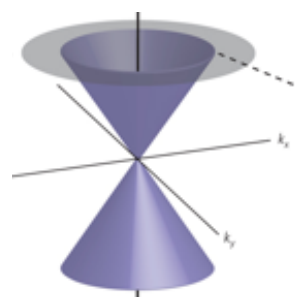
projected superconductor

- U(1) QSL



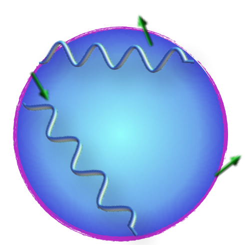
projected 3d band insulator

- Dirac QSLs



projected graphene

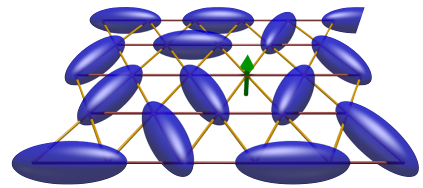
- Spinon Fermi surface



projected metal

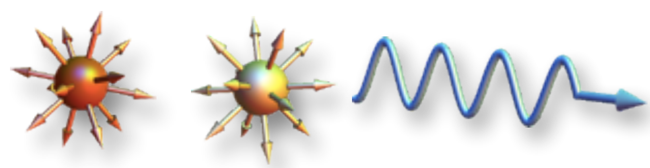
Classes of QSLs

- Topological QSLs



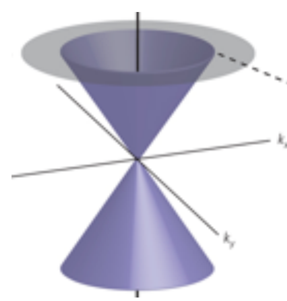
anyonic spinons

- U(1) QSL



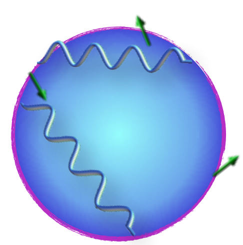
electric+magnetic monopoles, photon

- Dirac QSLs



strongly interacting Dirac fermions

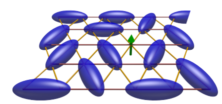
- Spinon Fermi surface



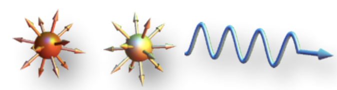
non-Fermi liquid “spin metal”

Classes of QSLs

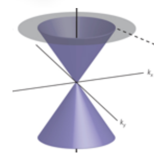
- Topological QSLs



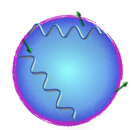
- U(1) QSL



- Dirac QSLs

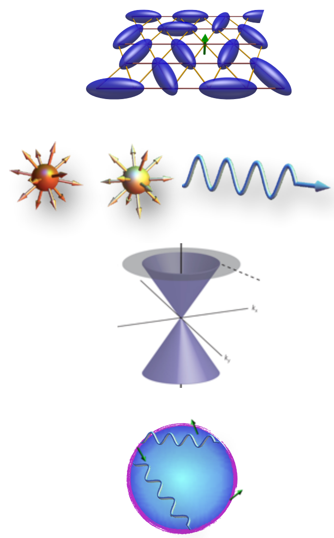


- Spinon Fermi surface



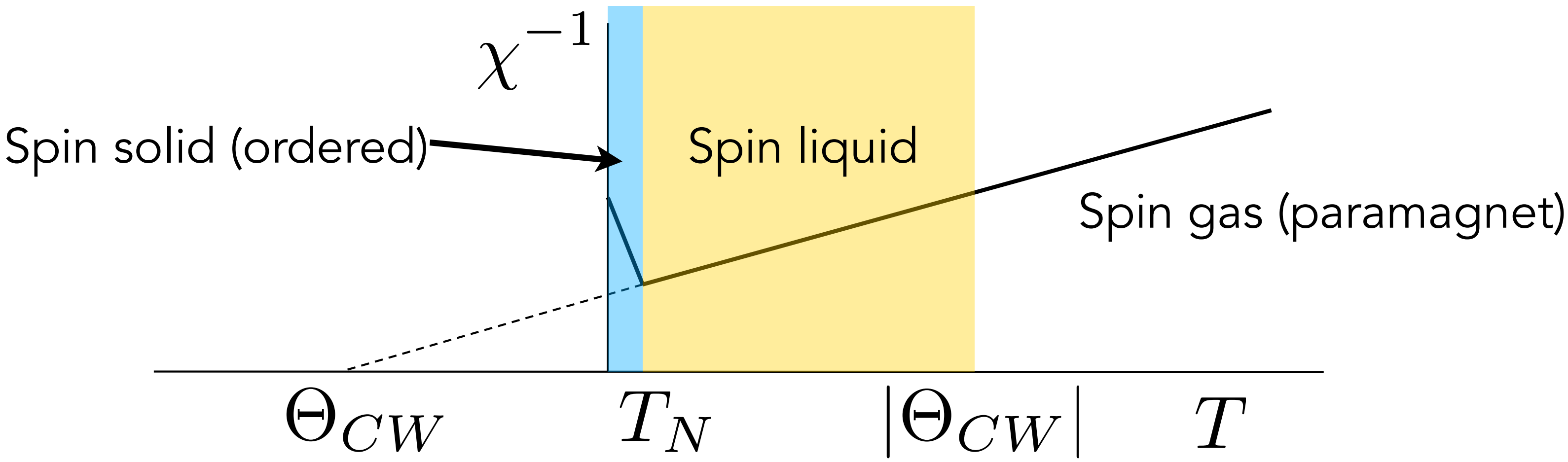
These spin liquids are all different phases of matter, and are rather different from one another. Like the corresponding unprojected states, their phenomenology can be quite distinct. Too naive to look for a single identifying feature for all QSLs.

Strange stuff



where do we find it?

Ramirez Plot



- Local moments: Curie-Weiss law at high T

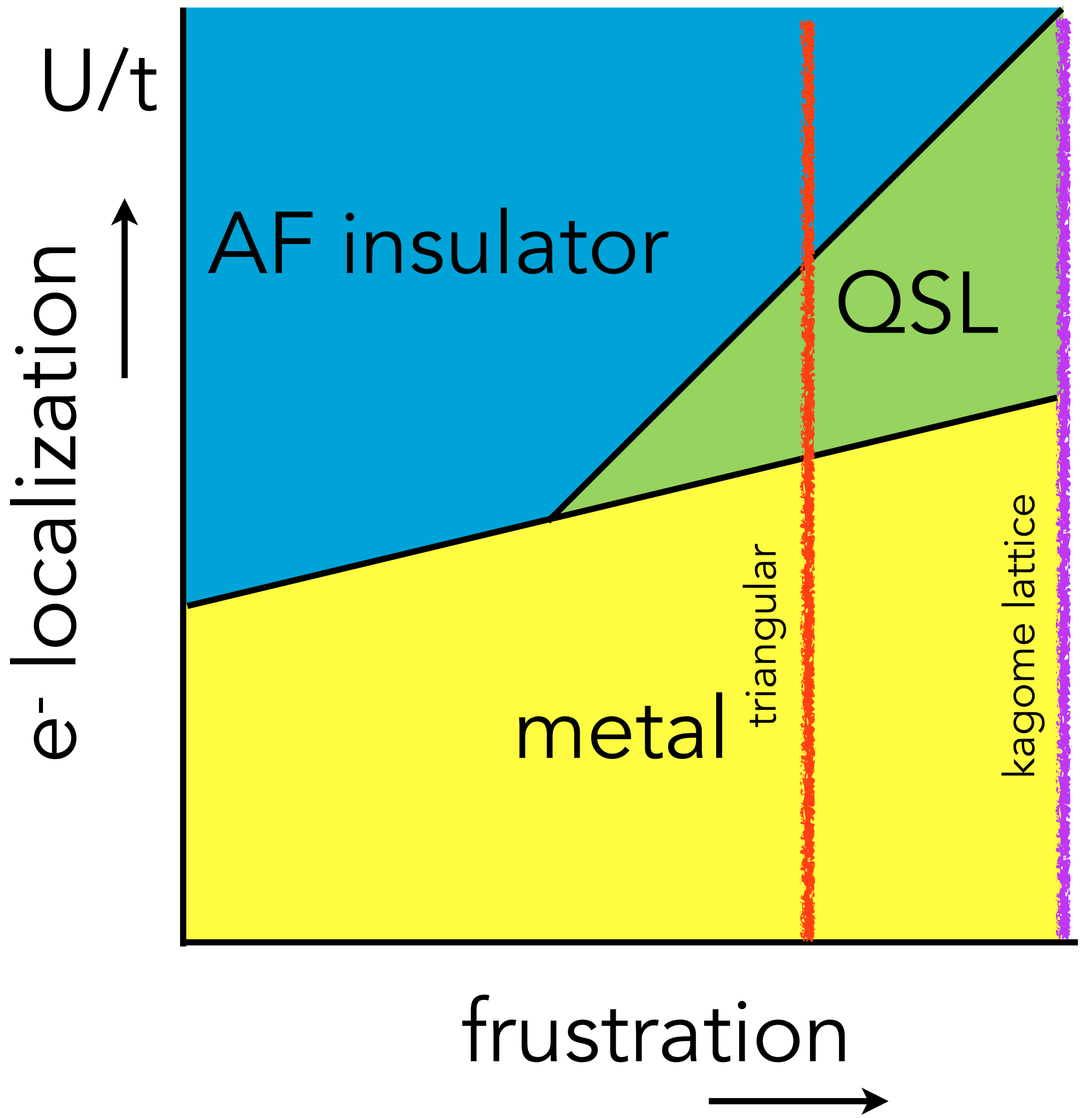
$$\chi \sim \frac{A}{T - \Theta_{CW}}$$

- Frustration parameter: $f = |\Theta_{CW}|/T_N$
- Larger f >> 1 is better. $f = \infty$ for true QSL

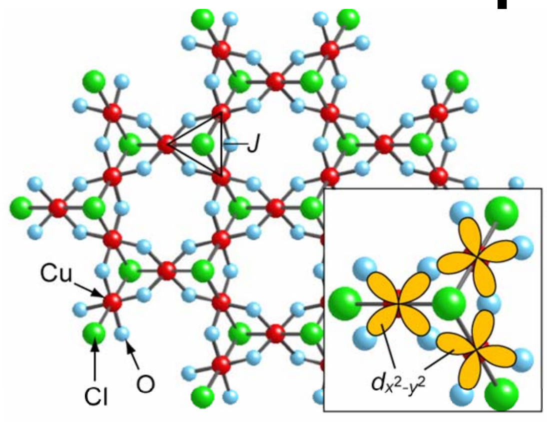
Materials criteria

- S=1/2 spins
- Geometrical or exchange frustration
- Significant charge fluctuations
- Exotic interactions (c.f. Spin-orbit coupling)

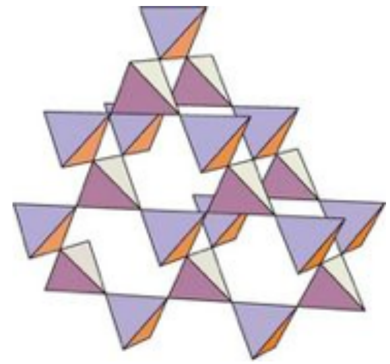
Where to look?



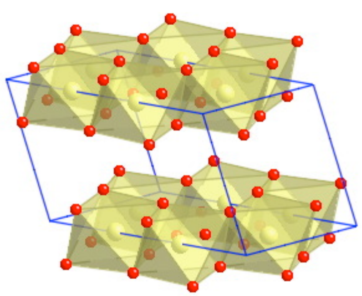
Top experimental platforms



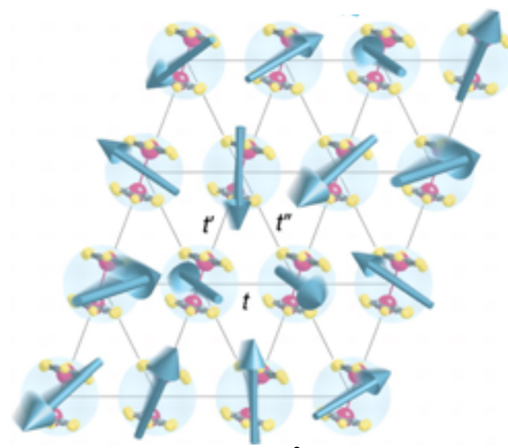
kagomé



Quantum spin ice



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

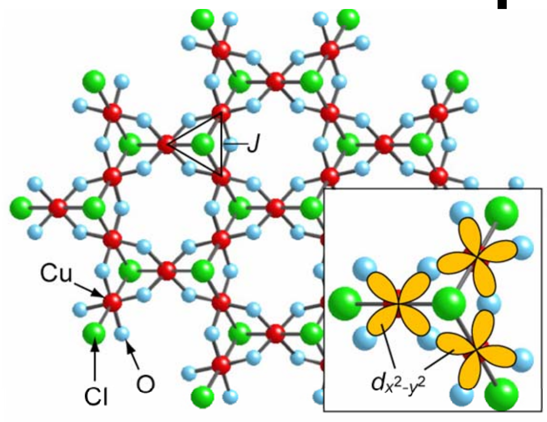
Delocalized excitations?

- thermal conductivity
- INS

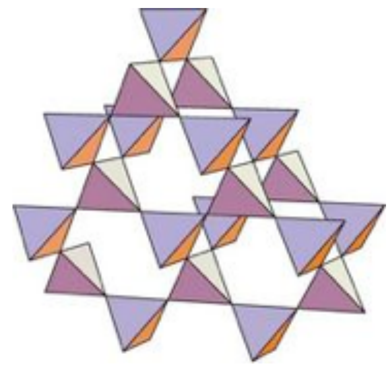
Structure of excitations?

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

Top experimental platforms



kagomé



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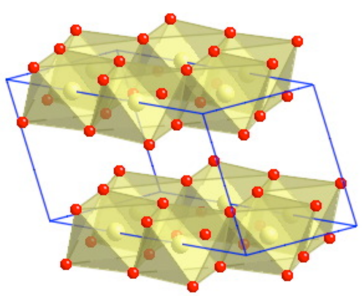
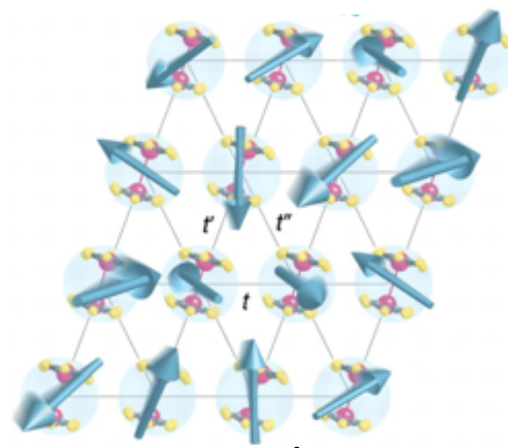
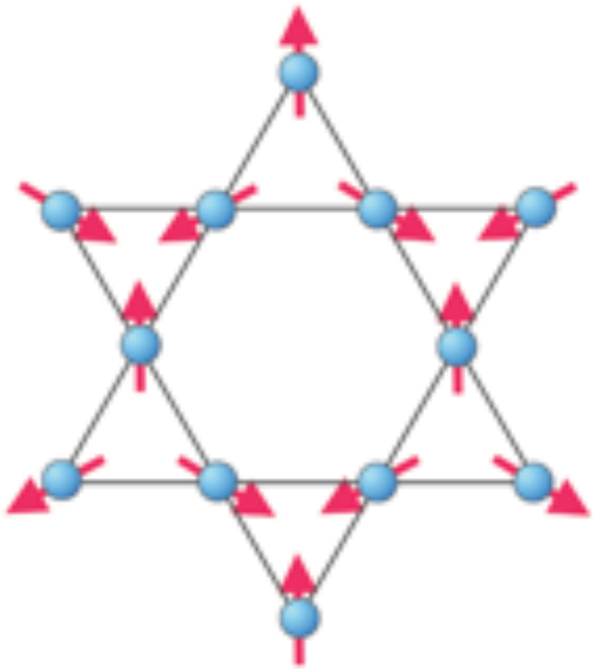


Kitaev materials



organics

Kagomé antiferromagnet



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

Very large classical degeneracy
Small z=4, x=1/2

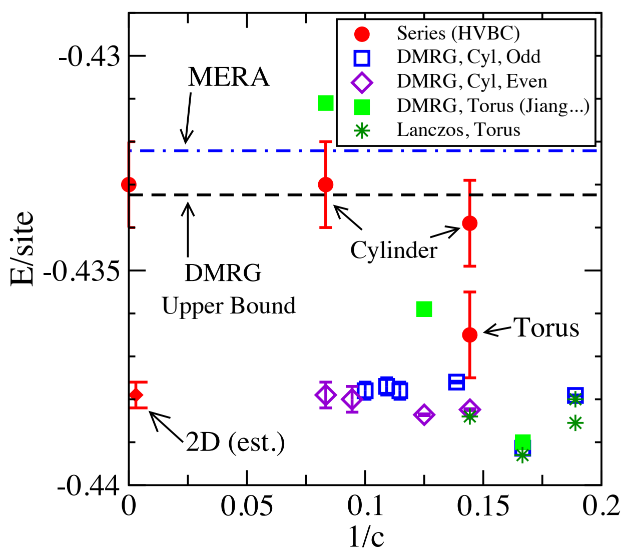
likely to be a QSL

V. Elser, 1989 + many many others

S=1/2 kagomé AF

- Rather definitive evidence for QSL by DMRG

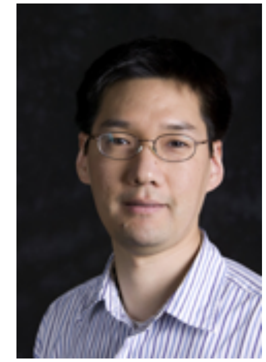
© Steve White



S. Yan *et al*, 2010

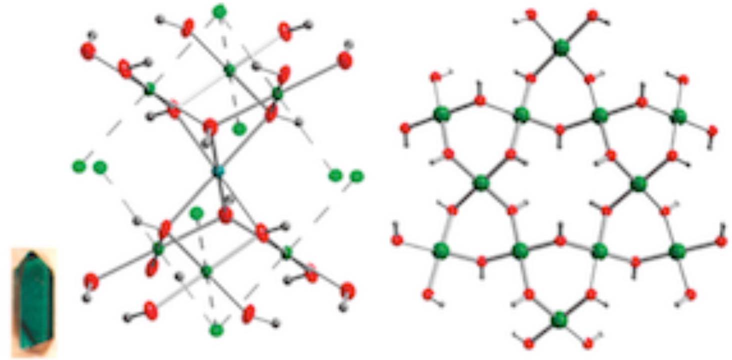
many other studies support existence of some QSL phase

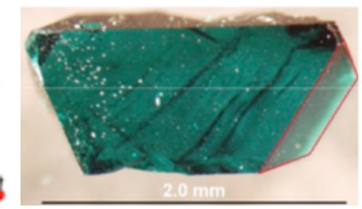
Herbertsmithite



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

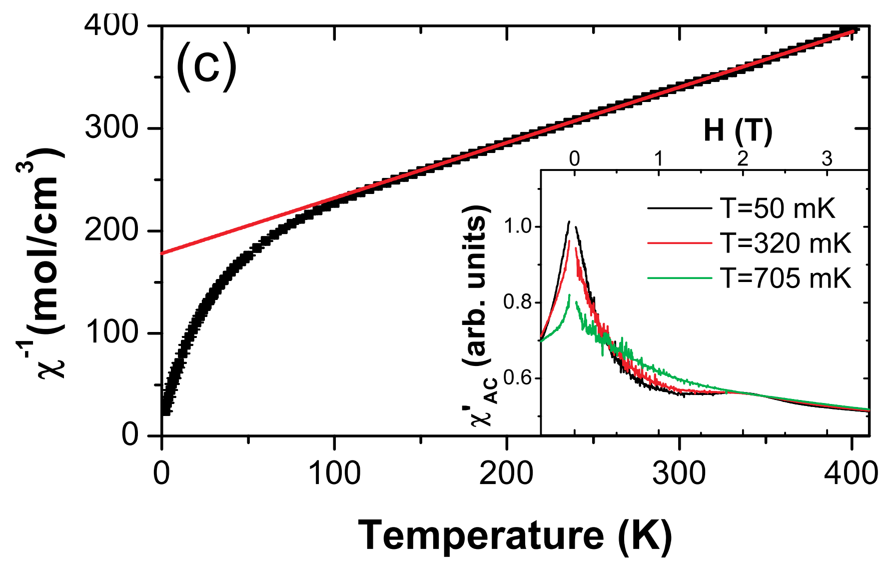
$ZnCu_3(OH)_6Cl_2$





Heisenberg-like with J ~ 200K

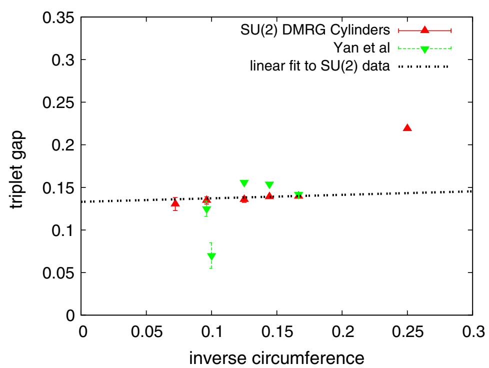
no order down to 50mK



Helton *et al*, 2007

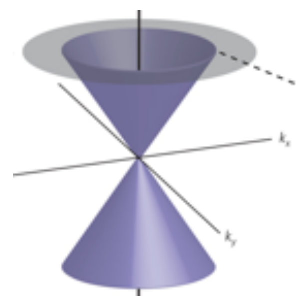
Theory

- What kind of QSL?



S. Depenbrock *et al*, 2012

gapped,
topological QSL



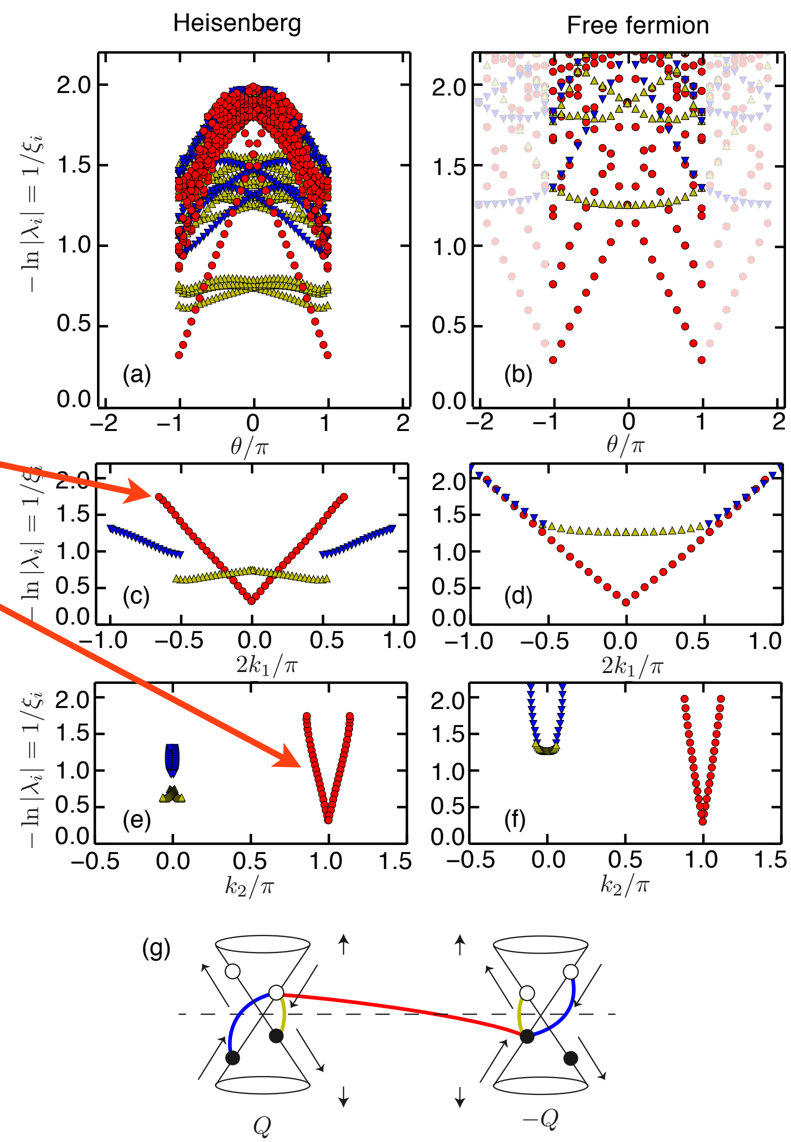
Y. Ran *et al*, 2007
F. Becca...

gapless
Dirac QSL

+ various other proposals with weaker quantitative support

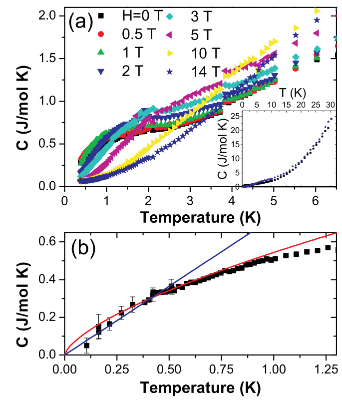
DMRG (2016)

Y.-C. He *et al*:
evidence for
Dirac QSL

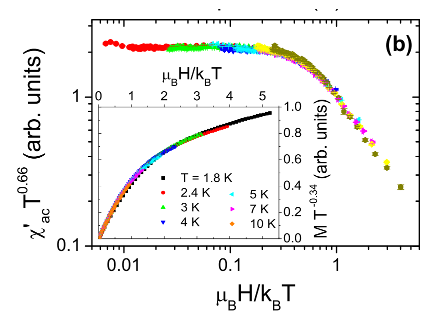


Herbertsmithite

Lots of early evidence for gaplessness



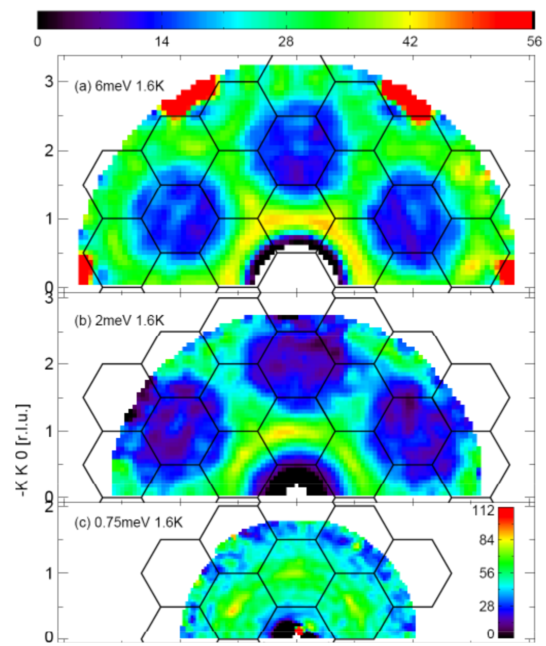
Helton *et al*, 2007



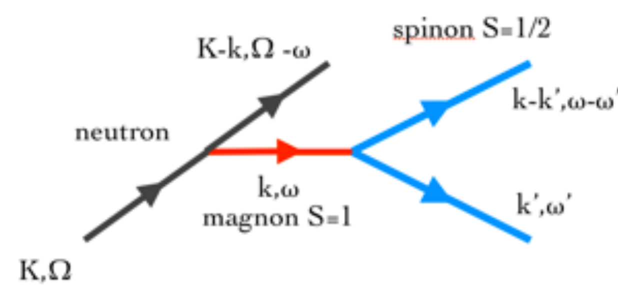
Helton *et al*, 2010

Single crystal INS

smooth continuum scattering



T-H Han *et al*, 2012



continuum scattering expected

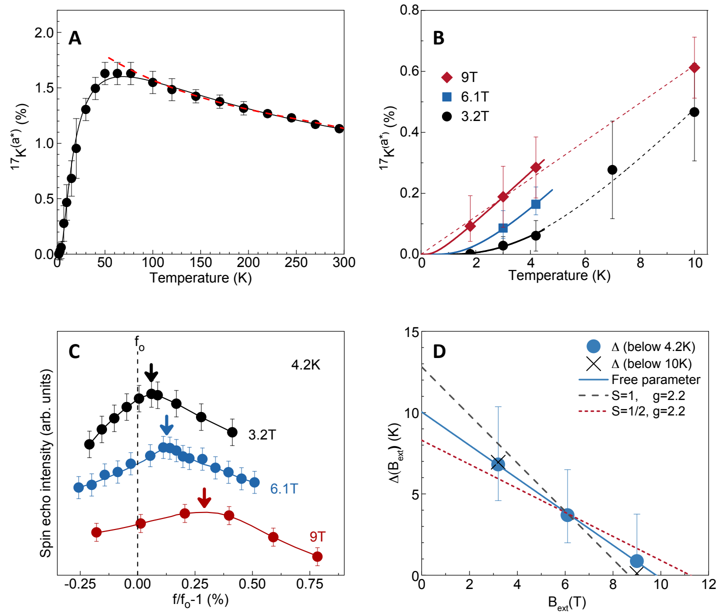
...but probably with more structure?

Herbertsmithite

Single crystal NMR

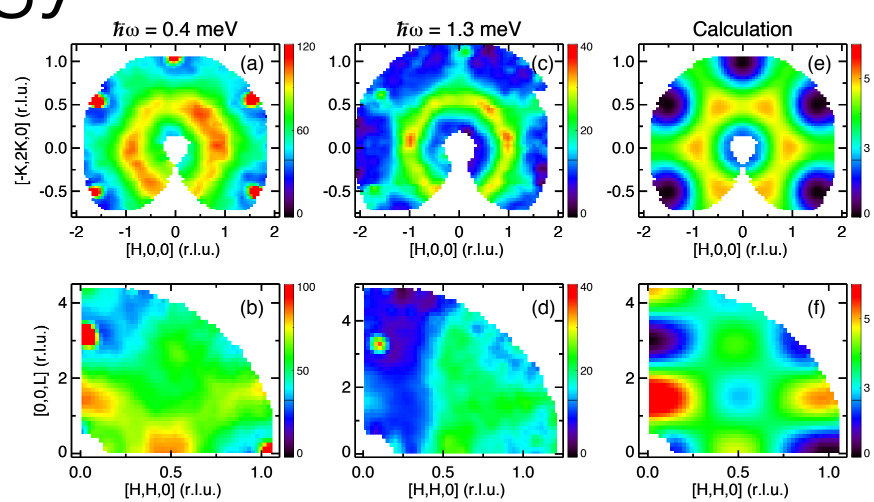
M. Fu *et al*, 2015

McMaster



estimate gap ~ 10K

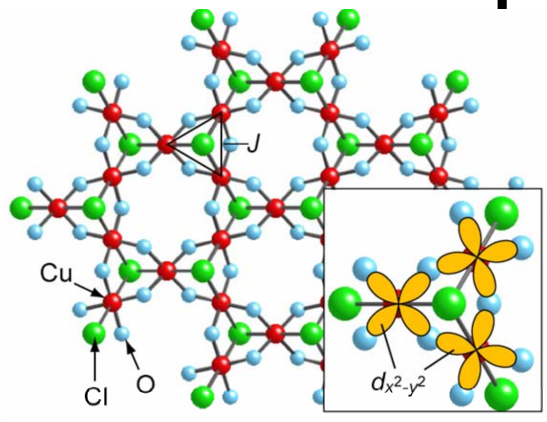
Low energy INS



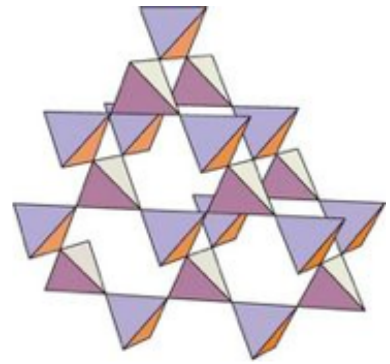
T-H Han *et al*, 2015

claim to separate impurity signal below 0.7meV

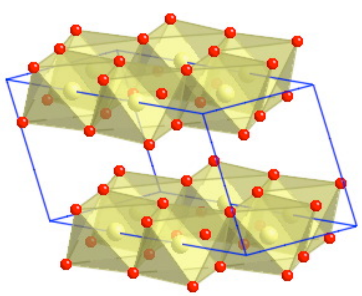
Top experimental platforms



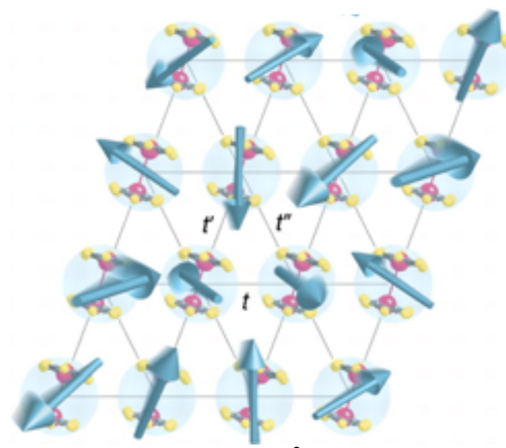
kagomé



Quantum spin ice



<u>Kitaev materials</u>



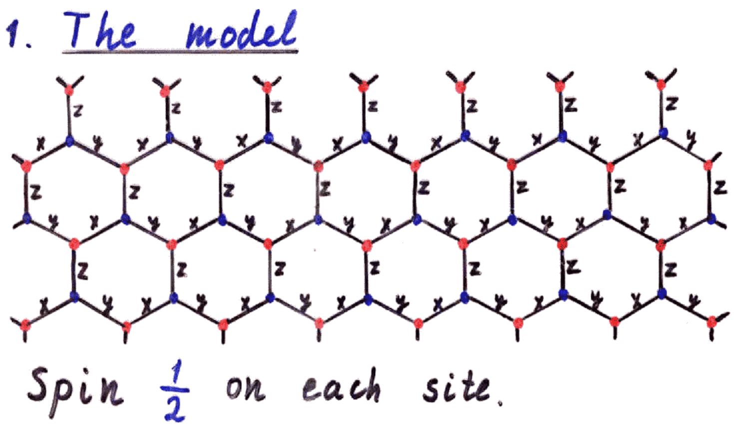
organics

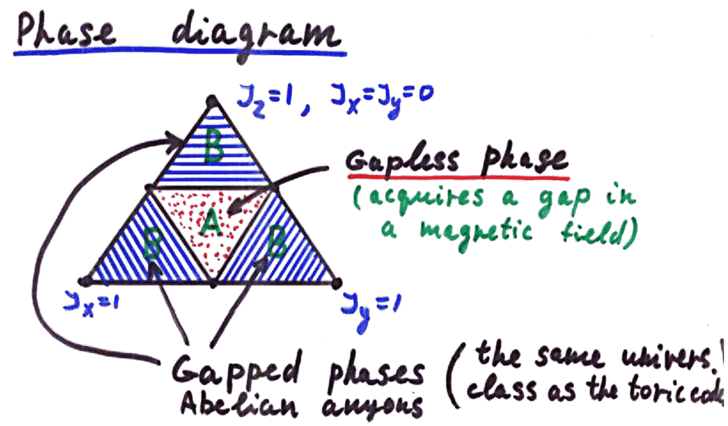
Kitaev model

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

c.f. Kitaev, Annals of Physics, 2006

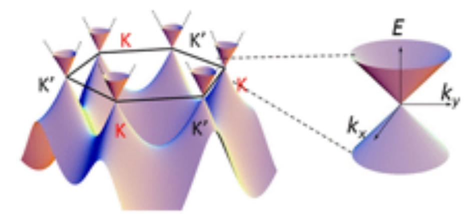
KITP, 2003





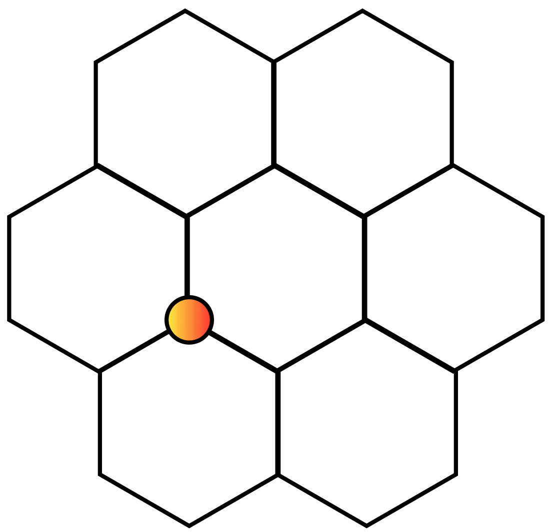
exact parton construction $\sigma_i^\mu = i c_i c_i^\mu \quad c_i c_i^x c_i^y c_i^z = 1$

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

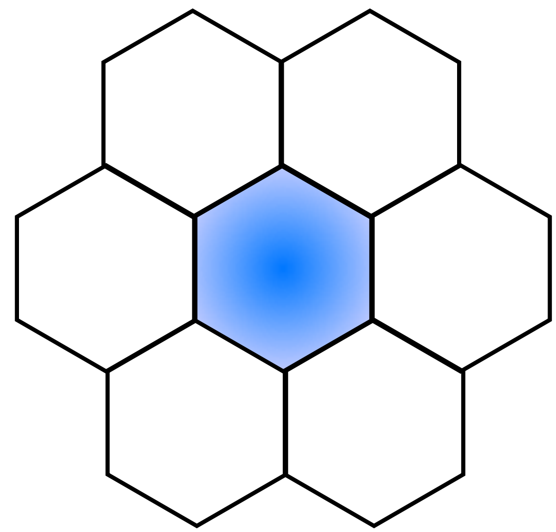


No S=0 singlets, but highly entangled.

Non-local excitations



Majorana ε



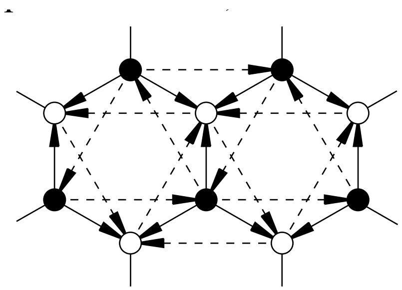
Flux e, m

In Kitaev's model:

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

Non-Abelian Phase

- In an applied magnetic field, the Majoranas acquire a gap

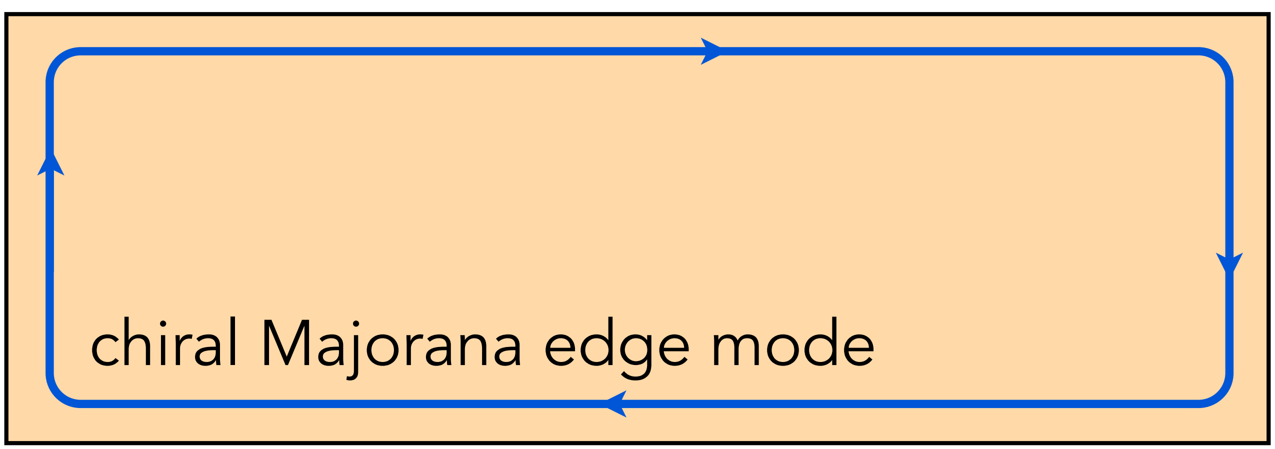


$$H_{\text{eff}} = \frac{\mathrm{i}}{4} \sum_{j,k} A_{jk} c_j c_k,$$

$$A = 2J\,(\longleftarrow) + 2\kappa\,(\leftarrow - - -),$$

$$\kappa \sim \frac{h_x h_y h_z}{J^2}.$$

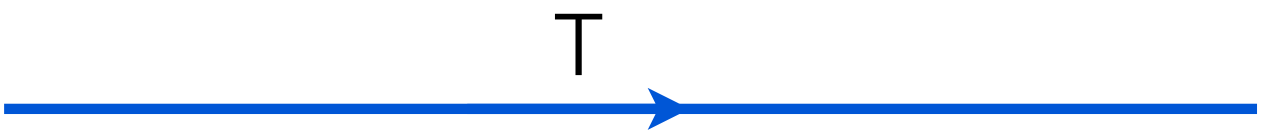
field induces a fermion mass, very similar to the Haldane model (except Majorana)



$$H_e = -\frac{iv}{4} \int dx\, \eta \partial_x \eta$$

Quantum Hall Effect?

- No charge. Have to study heat transport!



$$I = \int_0^\infty \frac{dq}{2\pi} v^2 q f(vq) = \frac{c\pi k_B^2}{12\hbar} T^2$$

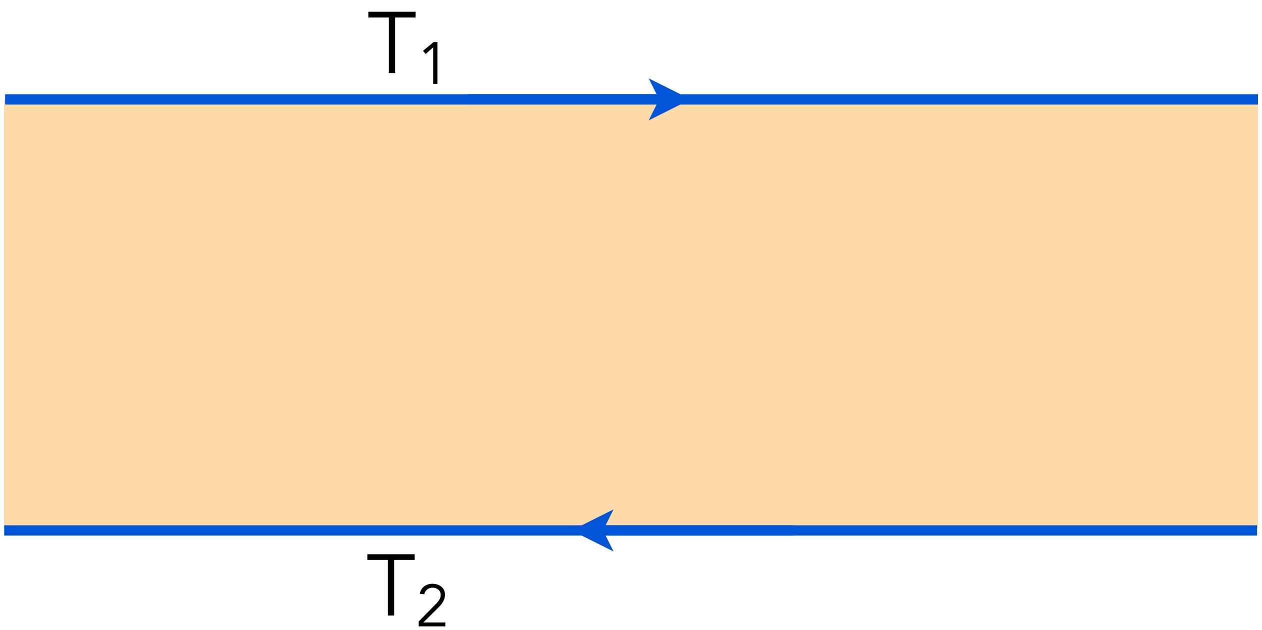
central charge c=1/2

<u>c.f. c=1 for both IQHE *and* FQHE abelian states</u>

implies the existence of bulk non-abelian excitations (the fluxes, bound to MZMs)

Quantum Hall Effect?

- No charge. Have to study heat transport!

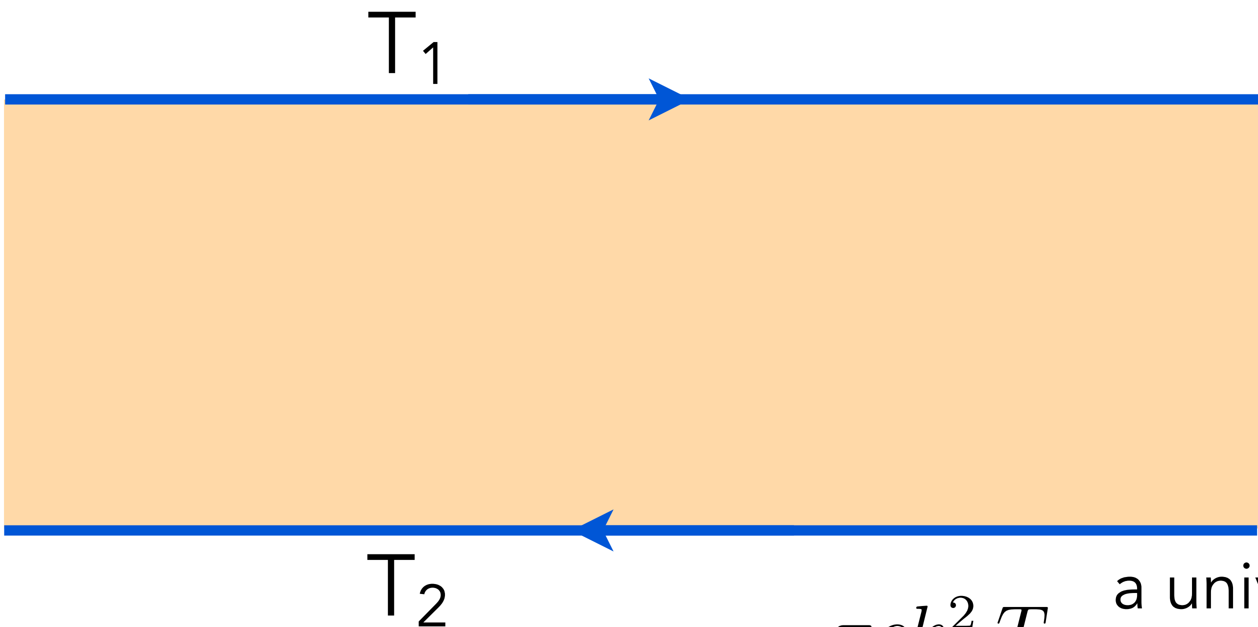


$$I = \frac{c\pi k_B^2}{12\hbar}\left(T_1^2 - T_2^2\right)$$

$$\approx \frac{c\pi k_B^2 T}{6\hbar}\left(T_1 - T_2\right)$$

Quantum Hall Effect?

- No charge. Have to study heat transport!



$$I_x = \kappa_H \Delta T_y$$

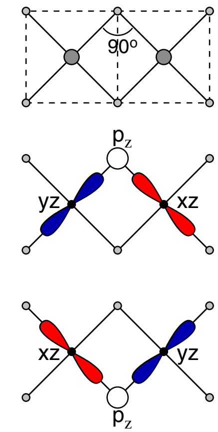
$$\kappa_H = \frac{\pi c k_B^2 T}{6\hbar}$$

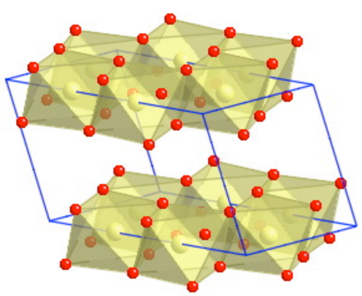
a universal prediction for chiral "Ising anyon" phase: *agnostic to microscopic spin interactions*

Kitaev Materials

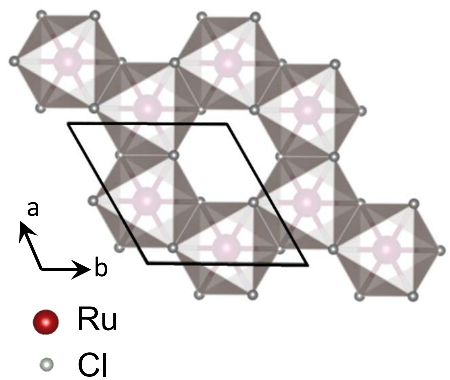
Jackeli, Khaliullin
2009

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

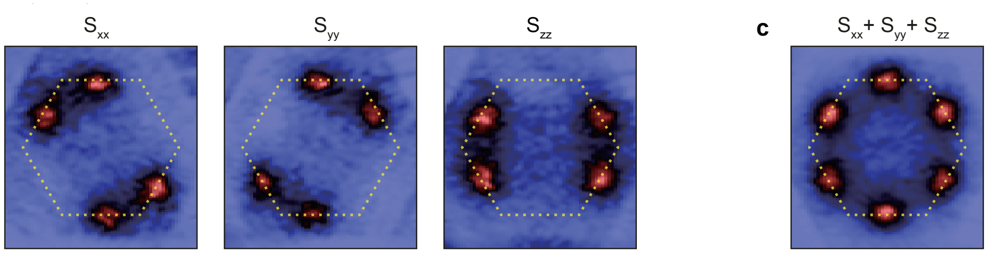


α-$RuCl_3$

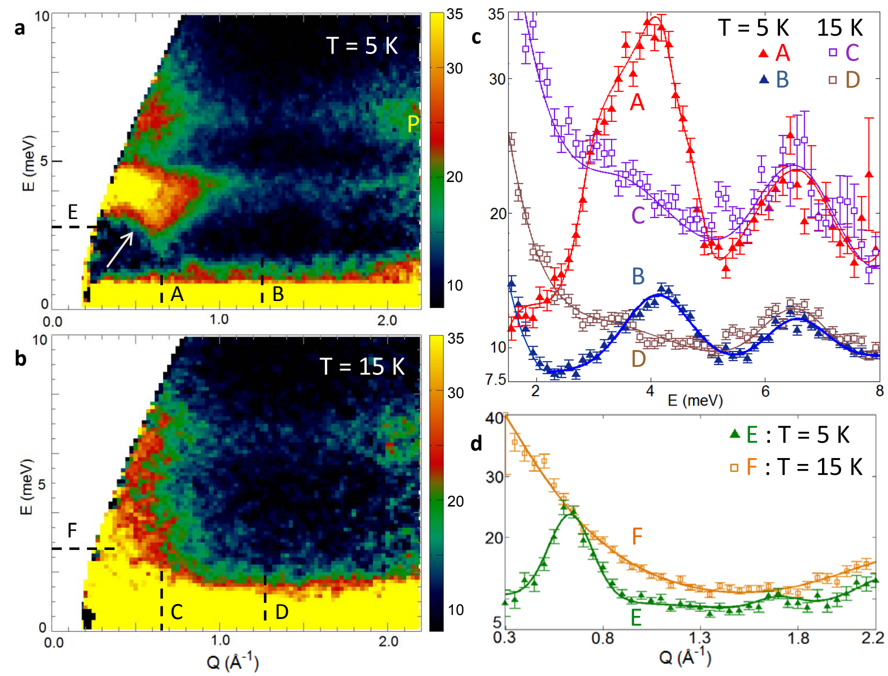
Y.-J. Kim...

Honeycomb and hyper-honeycomb structures

Kitaev Materials



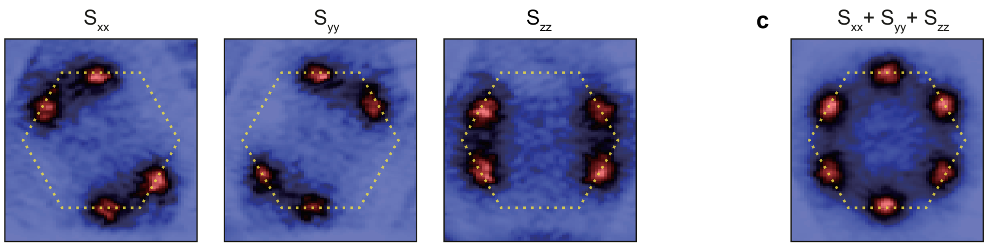
direct evidence for direction-dependent anisotropic exchange from diffuse magnetic x-ray scattering in Na_2IrO_3 (BJ Kim group)



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



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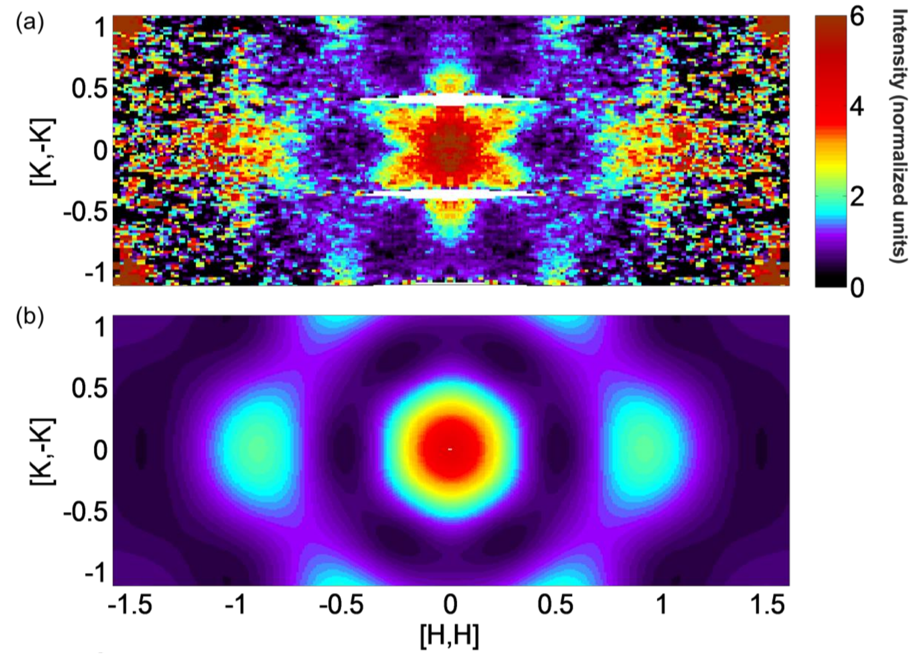


single-crystal datain α-$RuCl_3$ compared to Kitaev's soluble model (A. Banerjee *et al)*

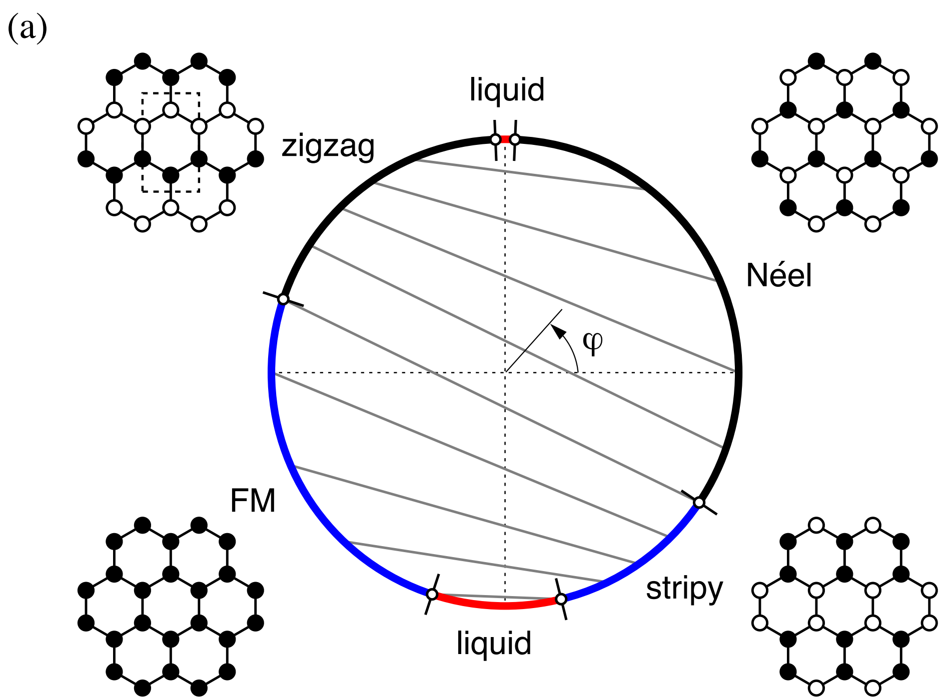
there is pretty strong evidence of substantial Kitaev exchange in quite a few materials

Magnetism

- But…they all order so far

due to additional interactions, e.g. Heisenberg

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



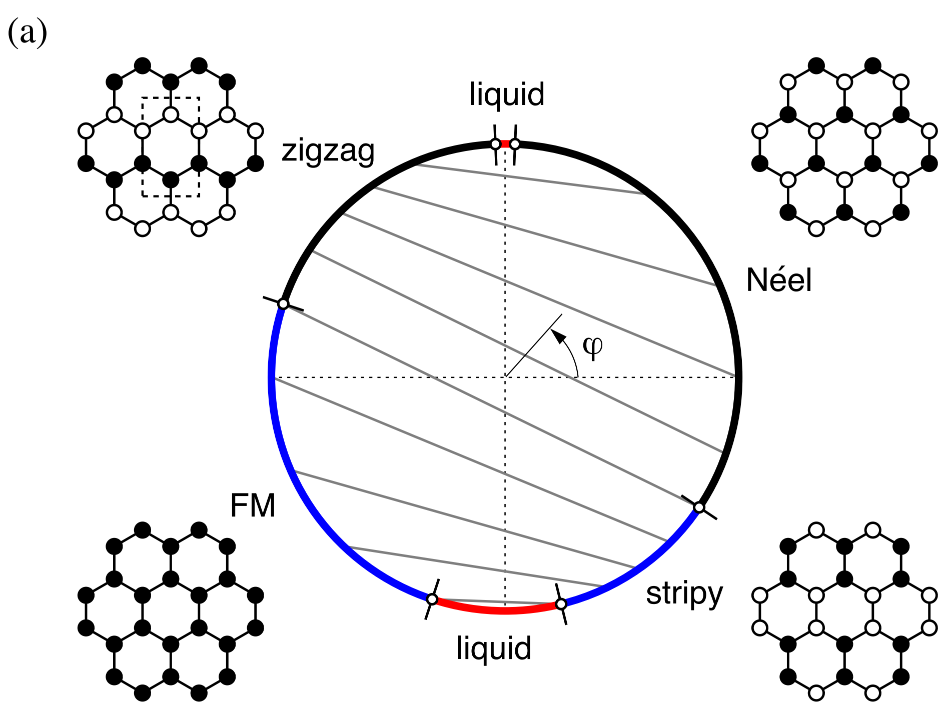
zigzag ordered state has been observed in Na_2IrO_3 and α-$RuCl_3$; incommensurate order in Li_2IrO_3

Magnetism

- But…they all order so far

due to additional interactions,
e.g. Heisenberg

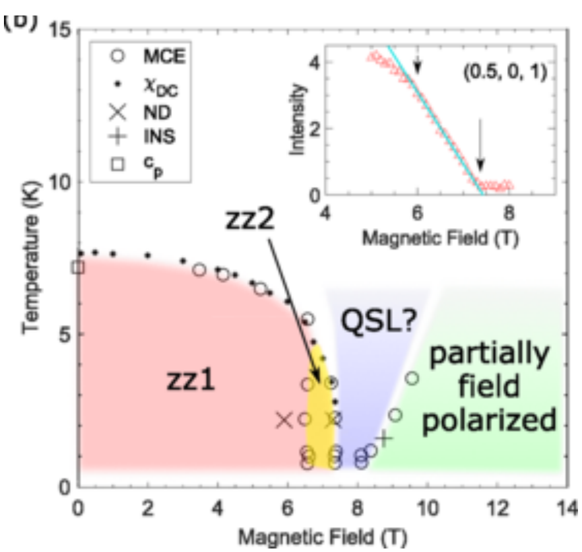
$$H = \sum_{i,\alpha} K S_i^\alpha S_{i+\alpha}^\alpha + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



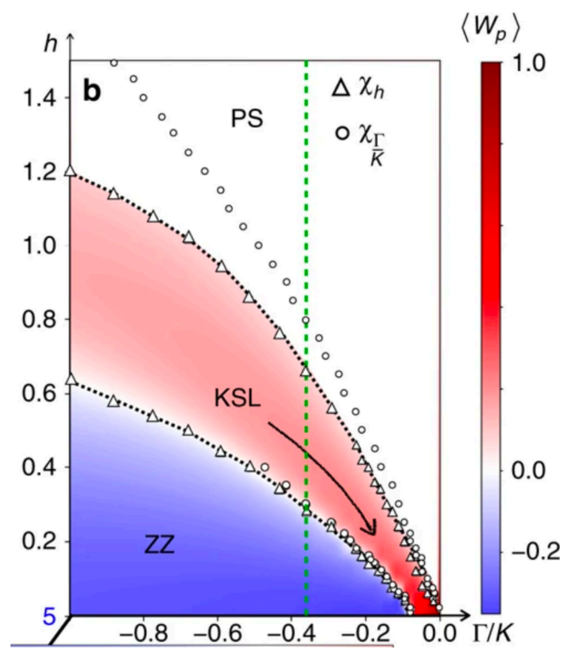
so far no QSL!

α-$RuCl_3$

Huge effort to understand field-induced paramagnetic state



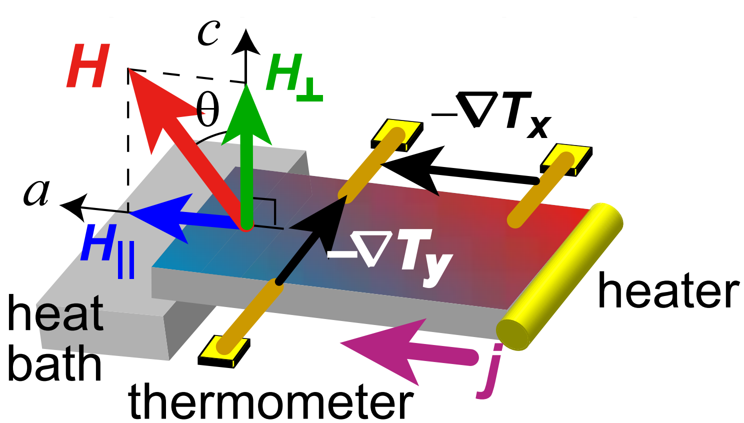
C. Balz *et al*, 2019

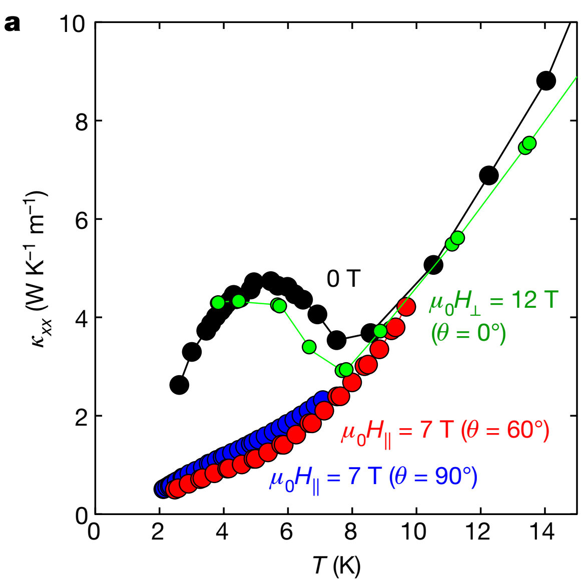


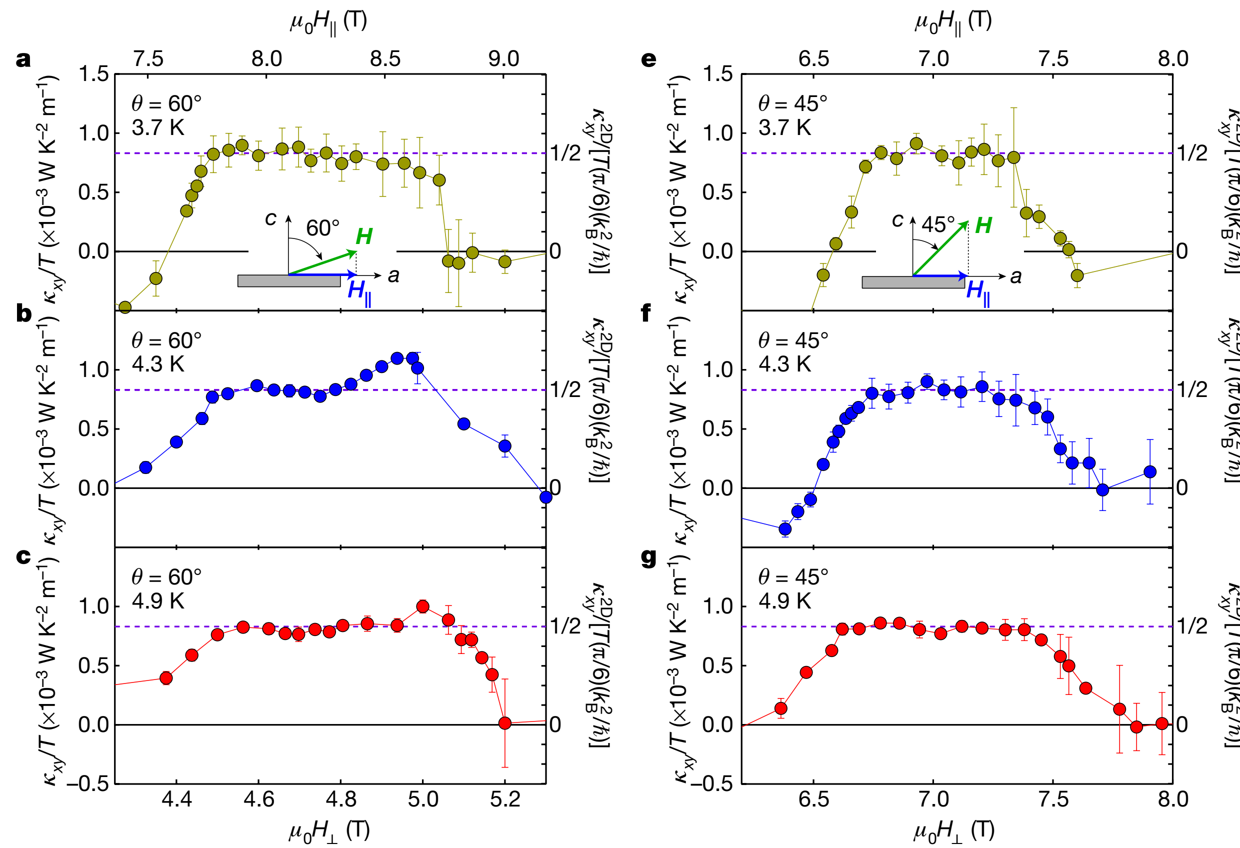
J. Gordon *et al*, 2019

Thermal Hall Effect?

Y. Kasahara *et al*, Nature 2018

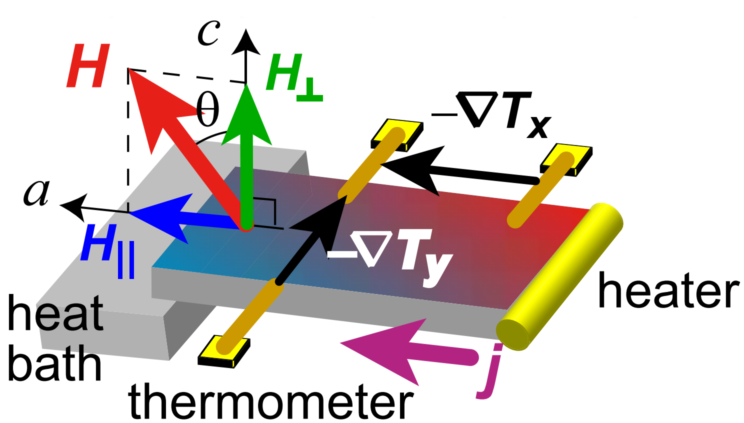


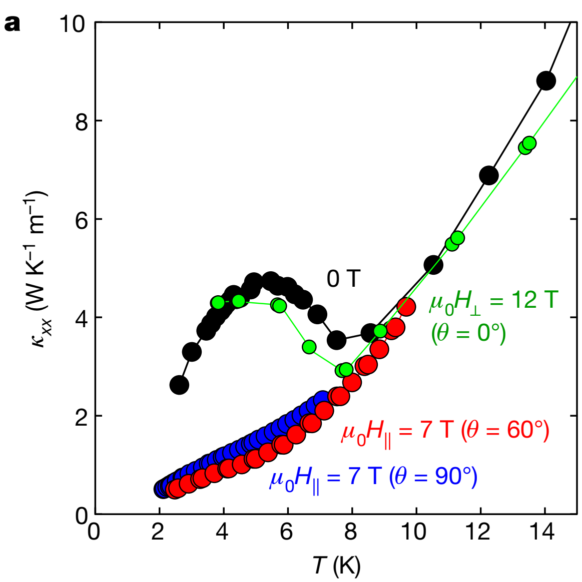


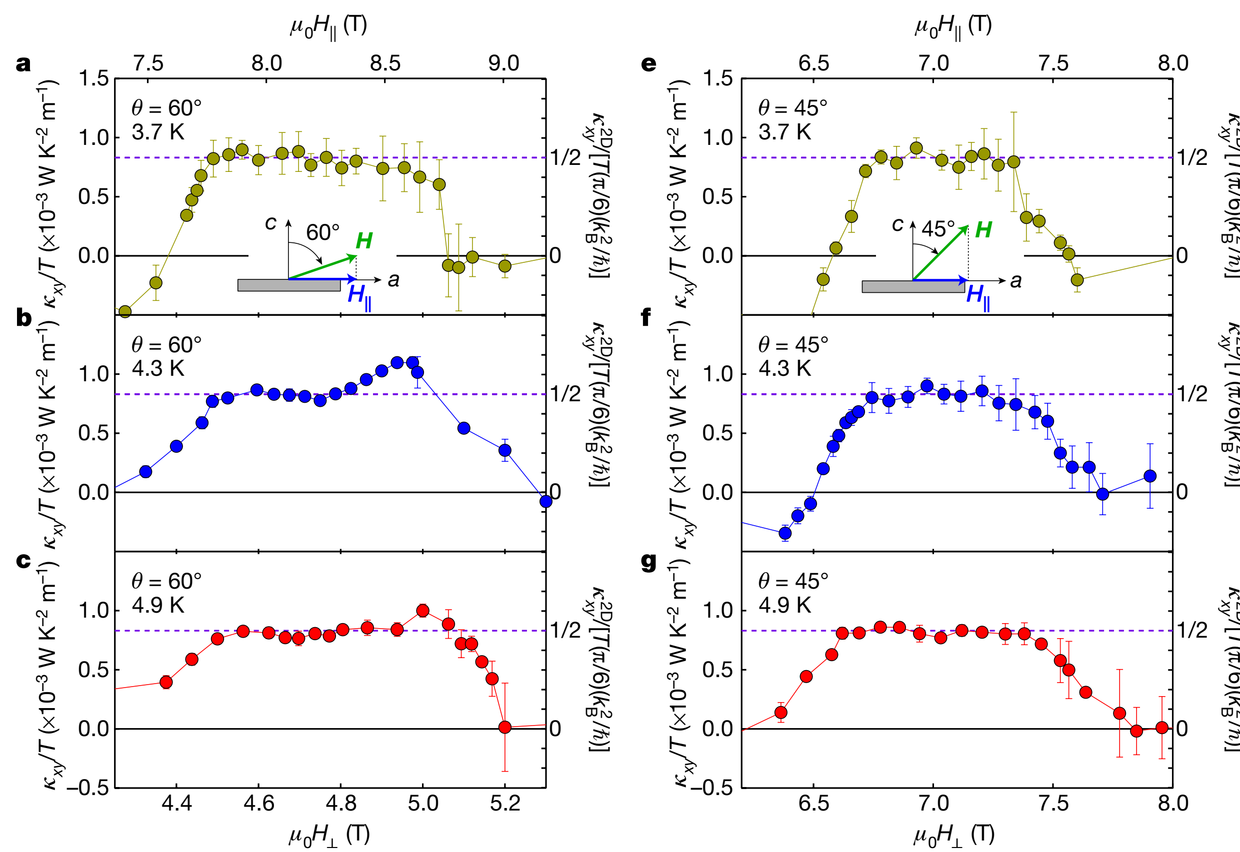


Thermal Hall Effect?

Y. Kasahara *et al*, Nature 2018

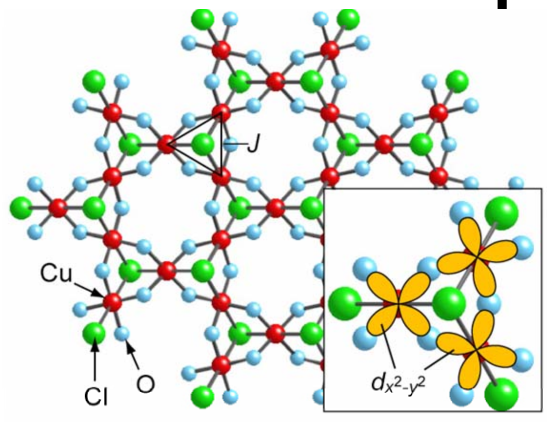




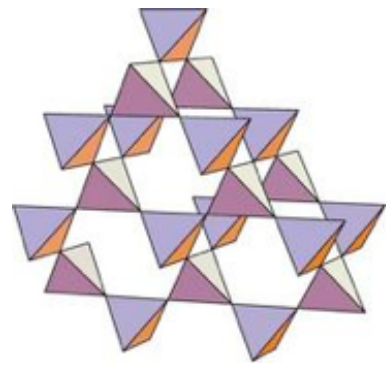


** Not reproduced. c.f. Ong talk?

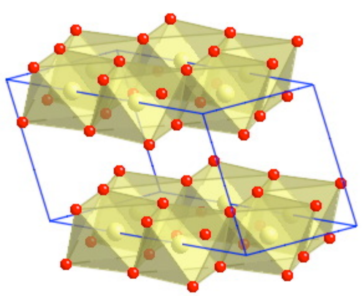
Top experimental platforms



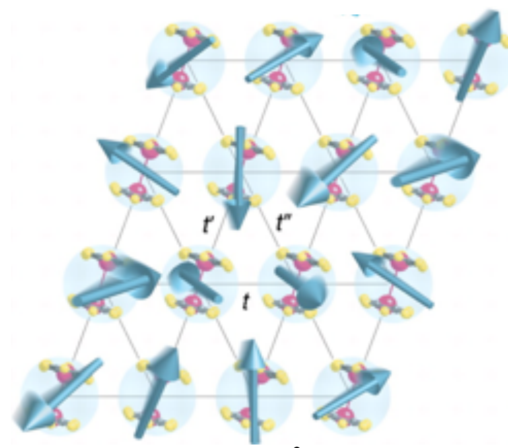
kagomé



Quantum spin ice



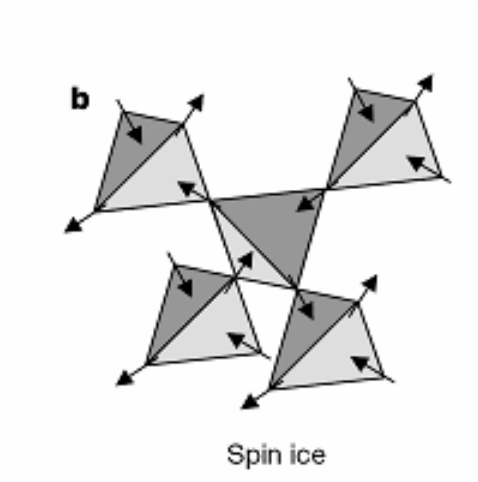
Kitaev materials



organics

Spin ice

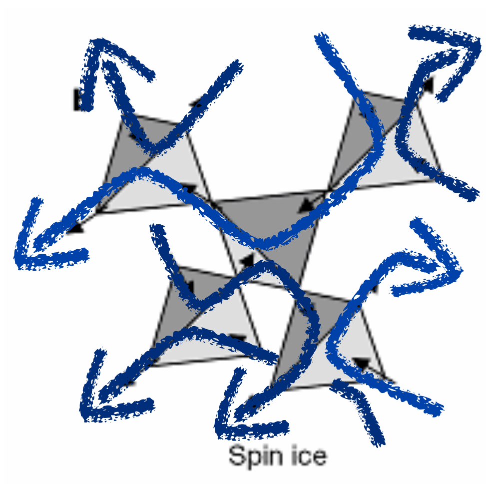
- Spins in $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$ have dominant NN Ising coupling J_{zz} enforcing classical 2in-2out "ice rules" for T<1K



thermal fluctuations through many degenerate states

Spin ice

- Spins in $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$ have dominant NN Ising coupling J_{zz} enforcing classical 2in-2out “ice rules” for T<1K



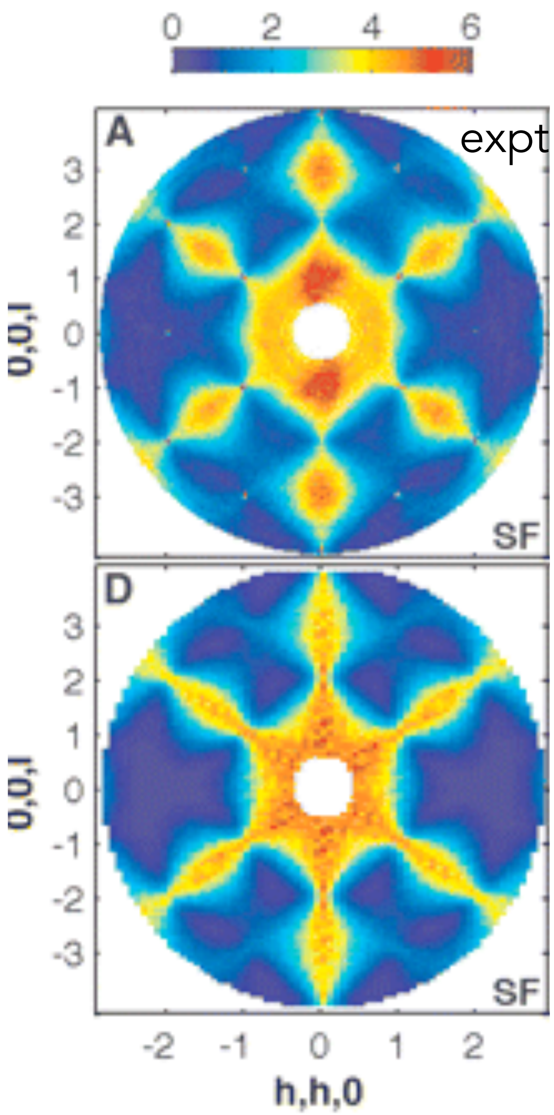
$$\vec{S} \sim \vec{b}$$

$$\vec{\nabla} \cdot \vec{b} = 0$$

artificial magnetostatics: spins map to field lines

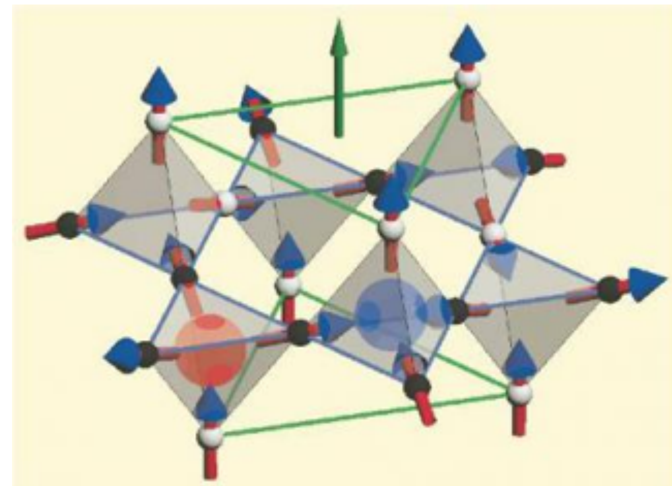
Classical spin liquid

T. Fennell *et al*, 2009

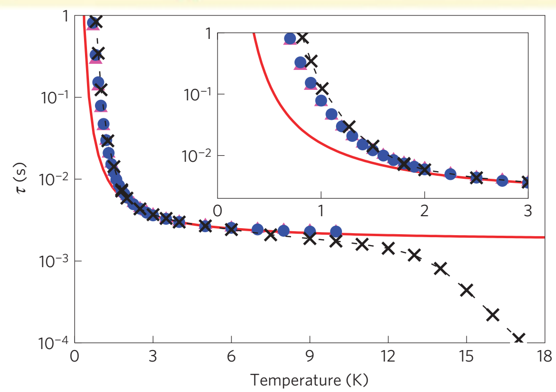


pinch
points

$$\vec{\nabla} \cdot \vec{b} = 0$$



Castelnovo
et al, 2008



Jaubert and
Holdsworth

magnetic monopoles
behave like diffusing
ions in a polyelectrolyte

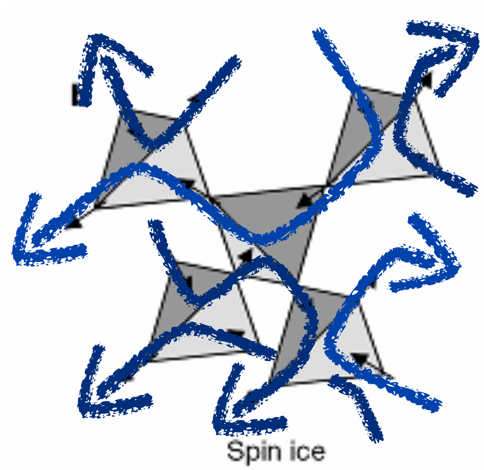
M. Hermele, MPA Fisher, L.B., 2004;
A. Banerjee *et al*, 2008

Quantum spin ice

$$H = H_{CSI} + J_{\pm} \sum_{\langle ij \rangle} \left(S_i^+ S_j^- + \text{h.c.} \right)$$

quantum dynamics creates superposition state

$$|\Psi\rangle = \sum_{\text{loops}}$$

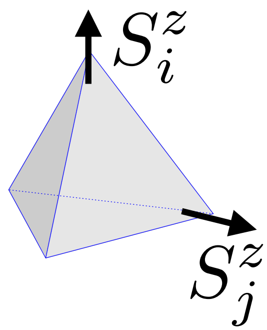


QSL which "simulates" quantum electrodynamics - vacuum fluctuations

M. Hermele, MPA Fisher, L.B., 2004

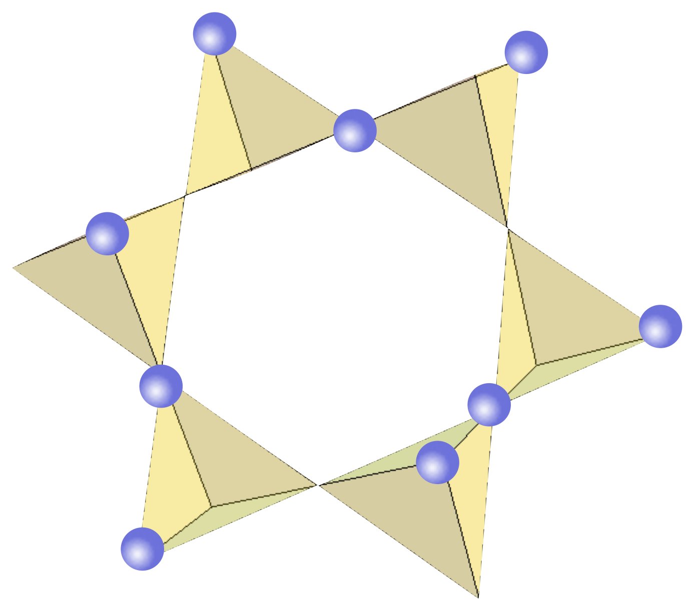
Mapping to E+M

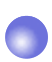
1. Degenerate perturbation theory



$$H_0 = \frac{J_{zz}}{2} \sum_t \left(\sum_{i \in t} S_i^z \right)^2$$

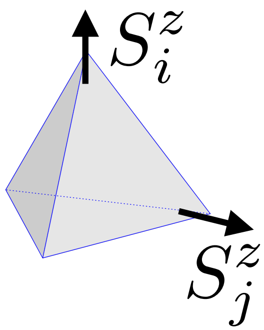
$$H_1 = J_\pm \sum_{\langle ij \rangle} \left(S_i^+ S_j^- + \mathrm{h.c.} \right)$$



 $S_i^z = +\frac{1}{2}$

Mapping to E+M

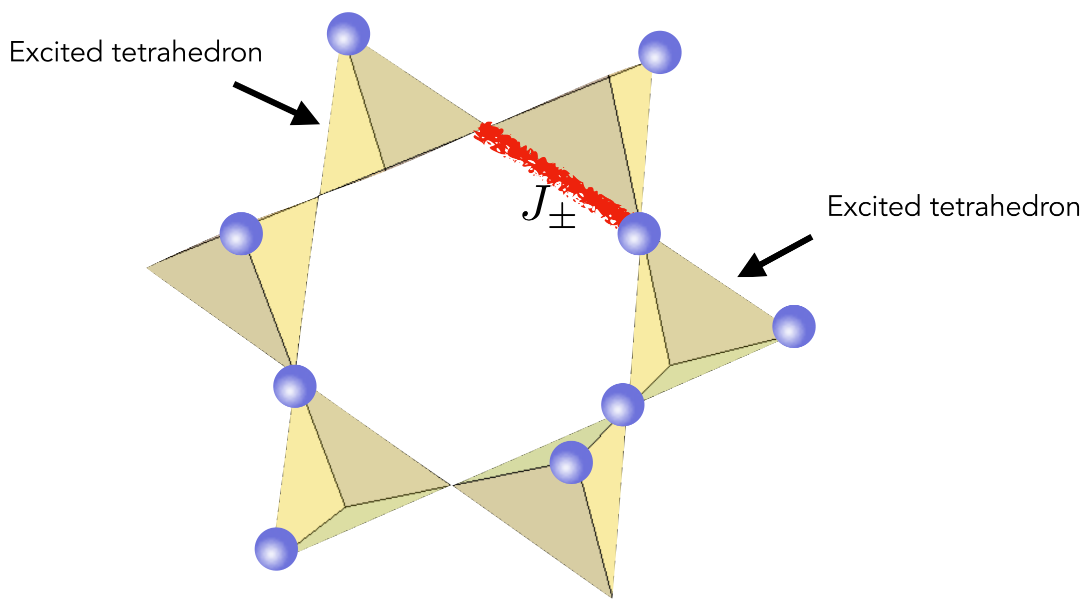
1. Degenerate perturbation theory



$$H_0 = \frac{J_{zz}}{2} \sum_t \left(\sum_{i \in t} S_i^z \right)^2$$

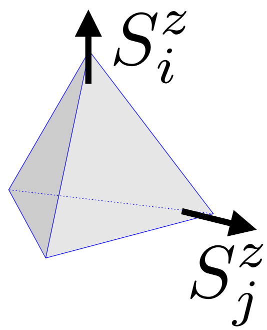
$$H_1 = J_{\pm} \sum_{\langle ij \rangle} \left(S_i^+ S_j^- + \mathrm{h.c.} \right)$$

1. Act once with H_1



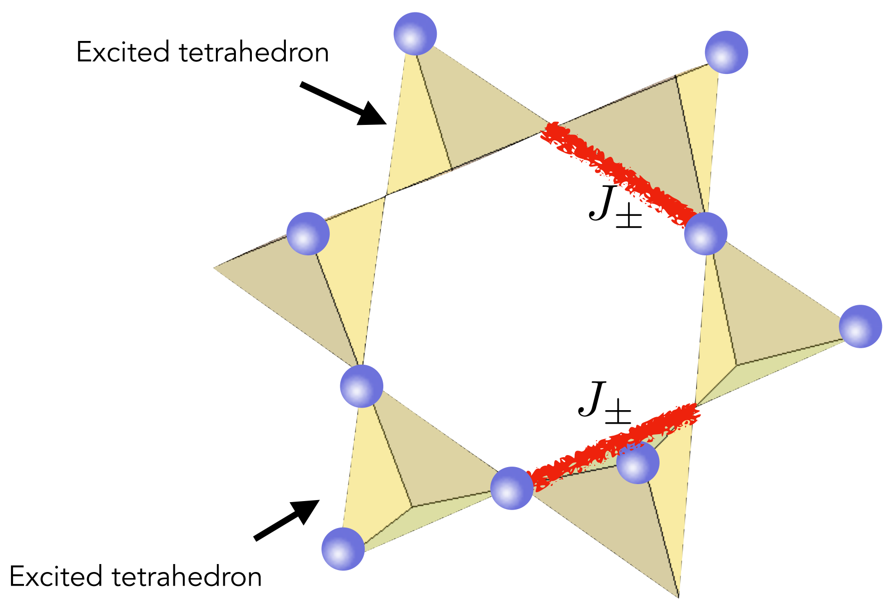
Mapping to E+M

1. Degenerate perturbation theory



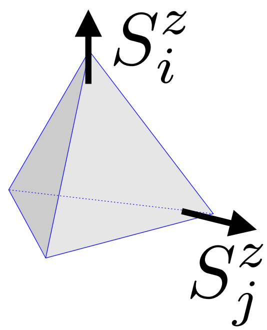
$$H_0 = \frac{J_{zz}}{2} \sum_t \left(\sum_{i \in t} S_i^z \right)^2 \qquad H_1 = J_\pm \sum_{\langle ij \rangle} \left(S_i^+ S_j^- + \mathrm{h.c.} \right)$$

1. Act once with H_1
2. Act twice with H_1



Mapping to E+M

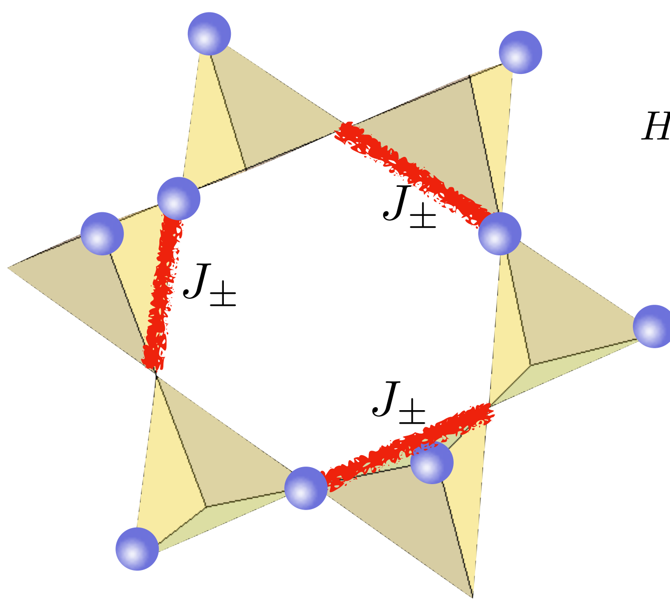
1. Degenerate perturbation theory



$$H_0 = \frac{J_{zz}}{2} \sum_t \left(\sum_{i \in t} S_i^z \right)^2$$

$$H_1 = J_\pm \sum_{\langle ij \rangle} \left(S_i^+ S_j^- + \text{h.c.} \right)$$

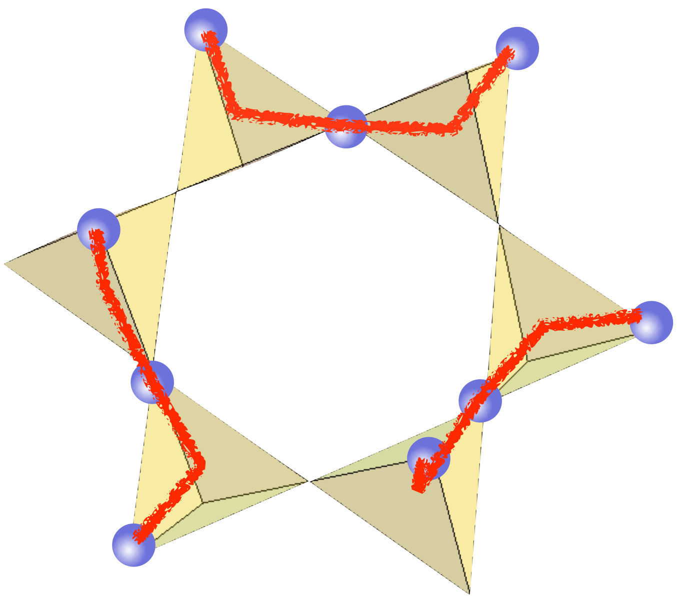
1. Act once with H_1
2. Act twice with H_1
3. Act thrice with H_1



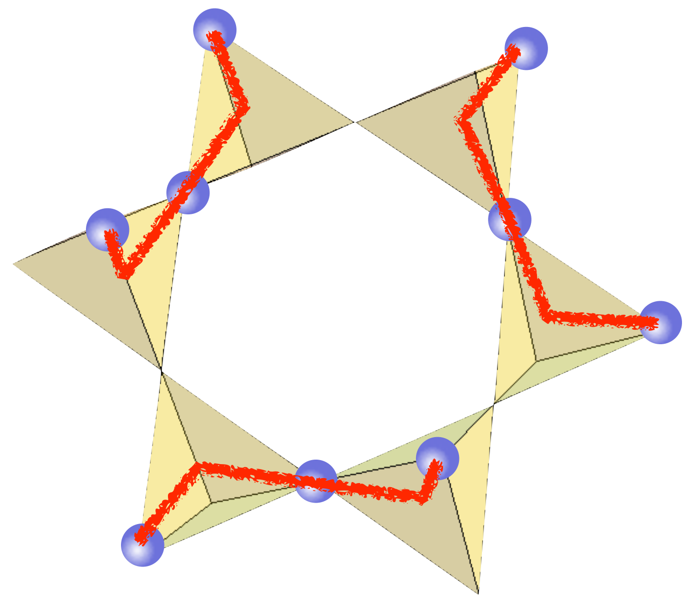
$$H_{\text{eff}} \sim \frac{J_\pm^3}{J_{zz}^2} \sum_h \left(S_1^+ S_2^- S_3^+ S_4^- S_5^+ S_6^- + \text{h.c.} \right)$$

"ring exchange"

Ring exchange



$$K \sim \frac{J_{\pm}^3}{J_{zz}^2}$$

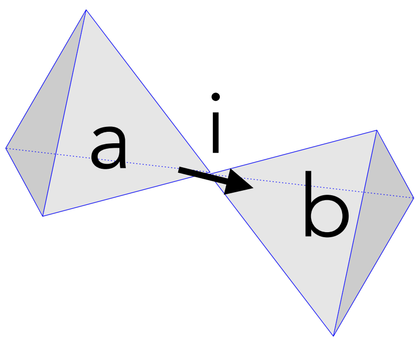


$$H_{\text{eff}} \sim \frac{J_{\pm}^3}{J_{zz}^2} \sum_h \left(S_1^+ S_2^- S_3^+ S_4^- S_5^+ S_6^- + \text{h.c.} \right)$$

Tunneling reconnects field lines

Mapping to E+M

2. Introduce gauge fields



$$S_i^z = E_{ab}$$

$$S_i^{\pm} = e^{\pm i A_{ab}}$$

$$H_{\rm eff} = U \sum_{\langle ab \rangle} \left(E_{ab}^2 - \frac{1}{4} \right) - K \sum_h \cos(\nabla \times A)$$

"odd" lattice compact U(1) gauge theory

(means E is half integer)

(means A_{ab} is a 2π periodic phase)

Mapping to E+M

3. Deconfined phase

$$H_{\rm eff} = U\sum_{\langle ab\rangle}\left(E_{ab}^2 - \frac{1}{4}\right) - K\sum_h \cos(\nabla\times A)$$

$$\approx U\sum_{\langle ab\rangle}\left(E_{ab}^2 - \frac{1}{4}\right) + \frac{K}{2}\sum_h \underbrace{(\nabla\times A)^2}_{B^2}$$

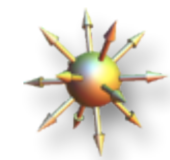
Based on extensive study of lattice gauge theory, numerics, this is a qualitatively good approximation (gauge fields are the "right" choice of variables)

The rest is textbook E+M

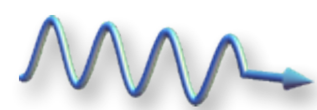
Excitations

- fully coherent propagating monopoles = "spinons" (charges in gauge theory)

- dual monopoles (dual charges)



- artificial photon: a gapless protected collective excitation which is *not* a Goldstone mode



Artificial photon

- gapless, linear, *non-Goldstone* mode

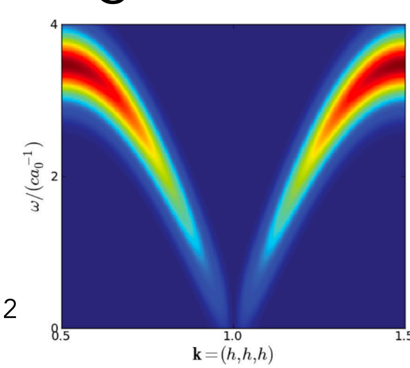
Mapping to EM: $S_i^z \sim \boldsymbol{E} \cdot \hat{n}_i$

Quantization of SHO: $E_\mu \sim \frac{1}{\sqrt{V}} \sum_{k,\sigma} i\sqrt{k} \left(a_{k\sigma} e^{ik\cdot r} - a^\dagger_{k\sigma} e^{-ik\cdot r} \right) \epsilon_{\mu\sigma}(k)$

$$\Rightarrow \quad \langle S^z_k S^z_{-k} \rangle \sim |k| \delta(\omega - v|k|)$$

K.Ross *et al*, 2011

- Linearly dispersion mode at Bragg point but vanishing weight at low energy
- Completely robust to anisotropy, magnetic field, etc: does not arise from breaking any physical symmetry



Plot from O. Benton *et al*, 2012

<u>Not yet observed -</u>

challenge is narrow bandwidth due to small exchange in candidate materials

Quantum spin ice

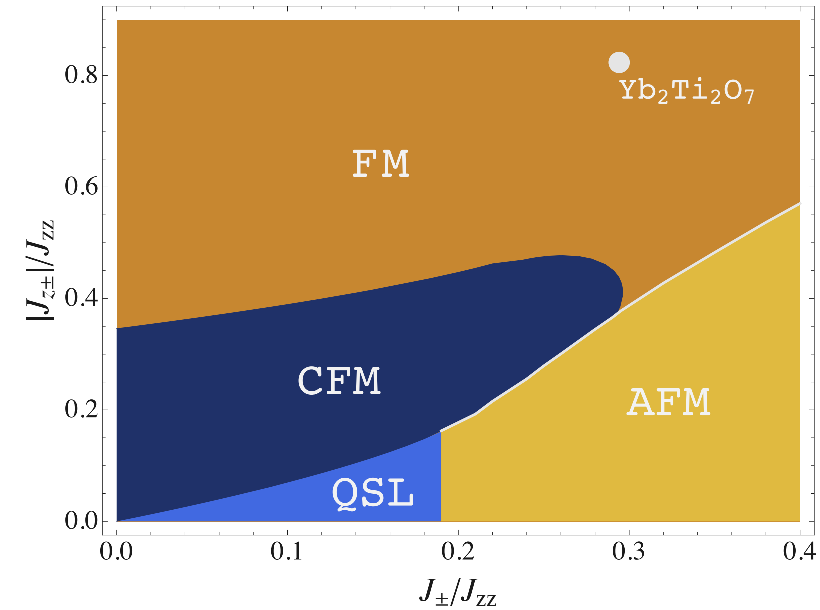
Realistic theory for quantum rare earth pyrochlores

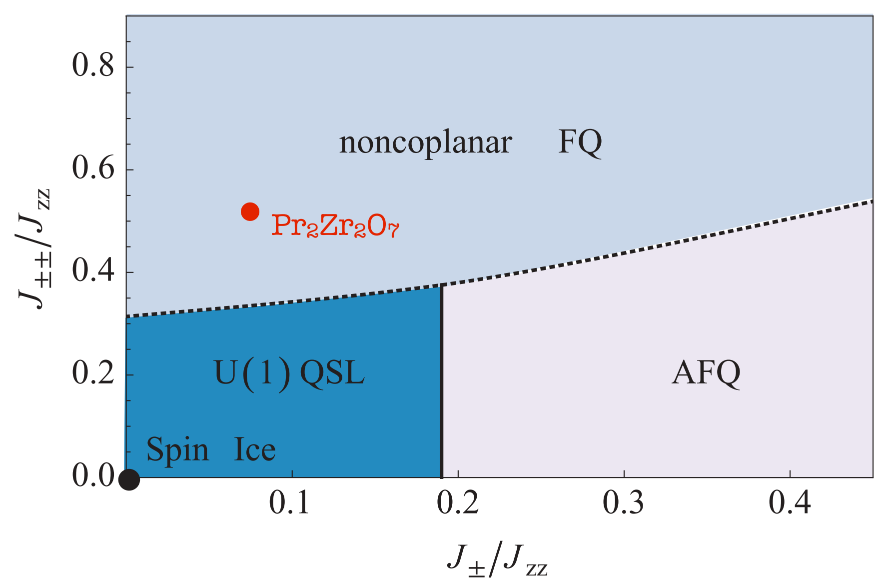
L. Savary + LB, 2012

S.B. Lee, S. Onoda + LB, 2012

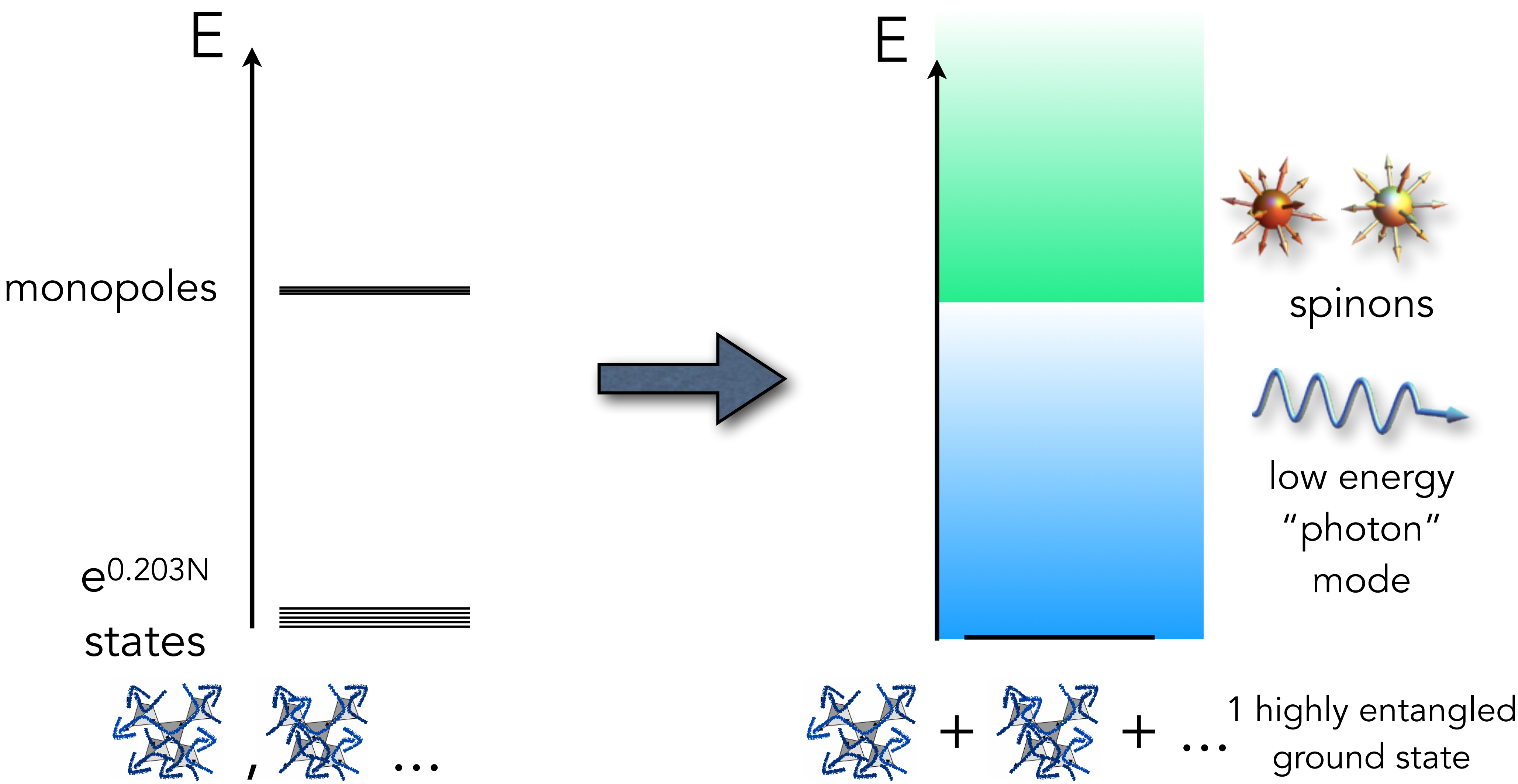
+ Many subsequent numerical and analytical works

Possible application to $Yb_2Ti_2O_7$, $Pr_2Zr_2O_7$, others...

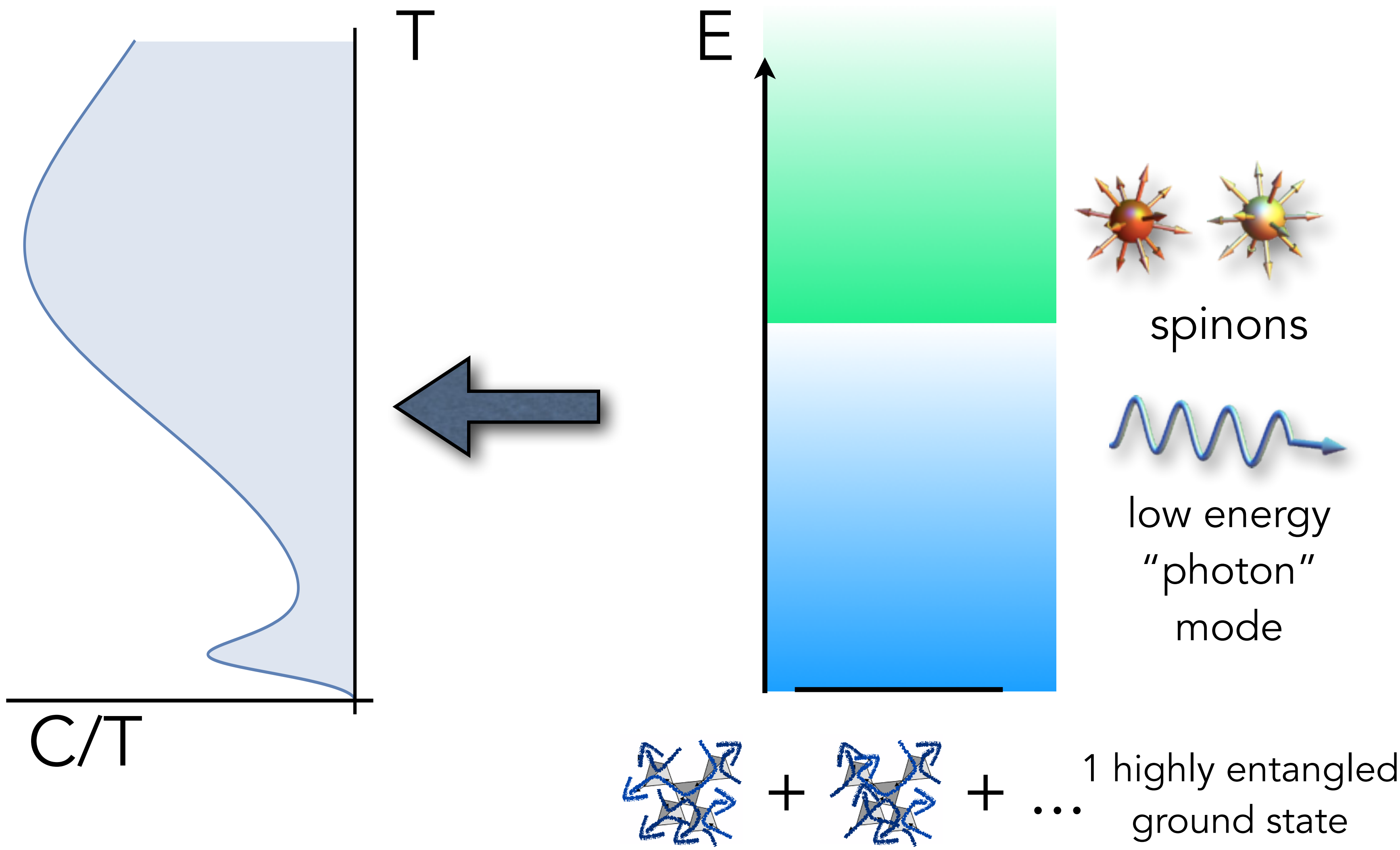




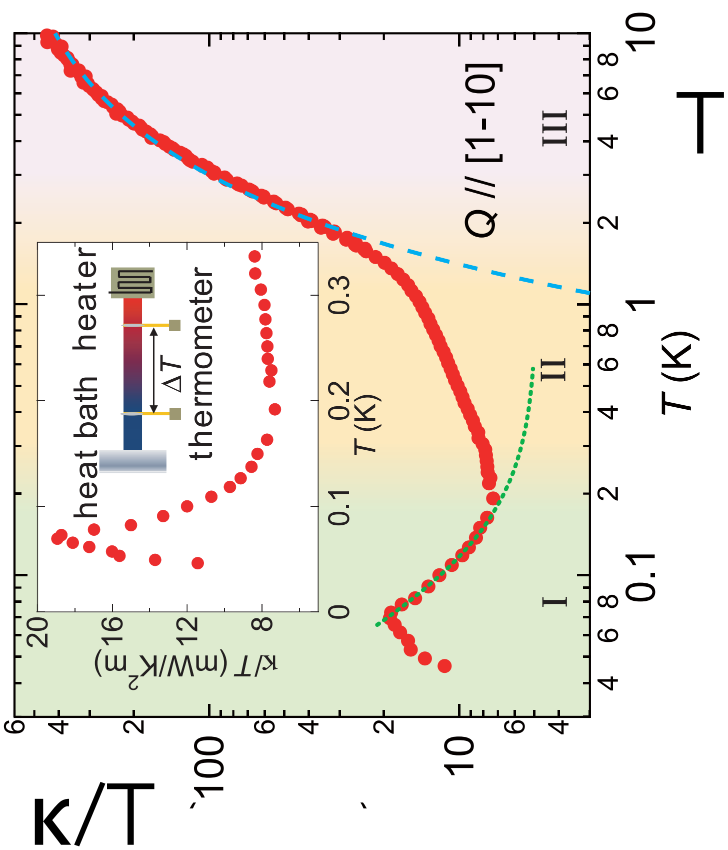
Quantum versus classical



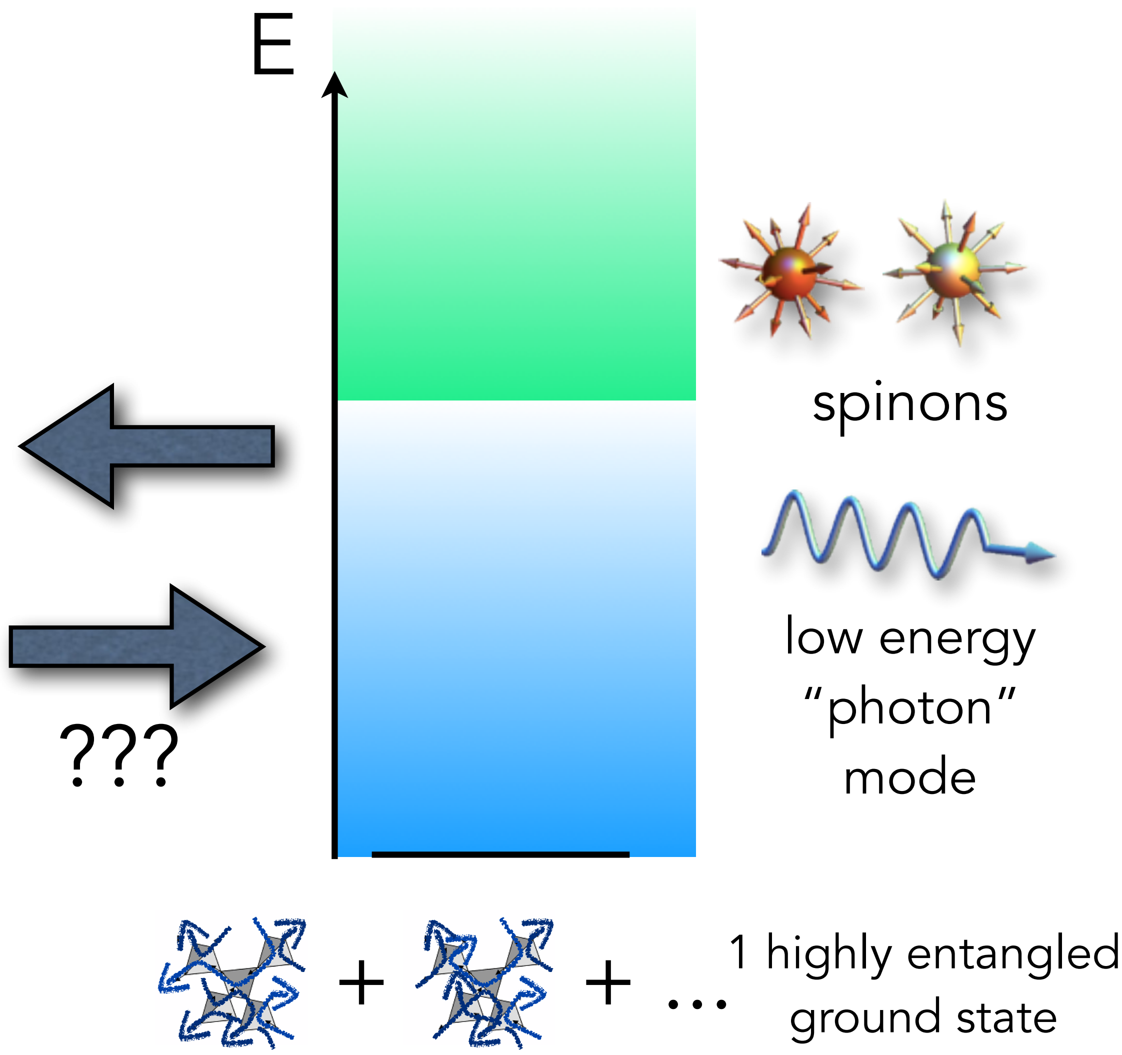
Quantum spin ice



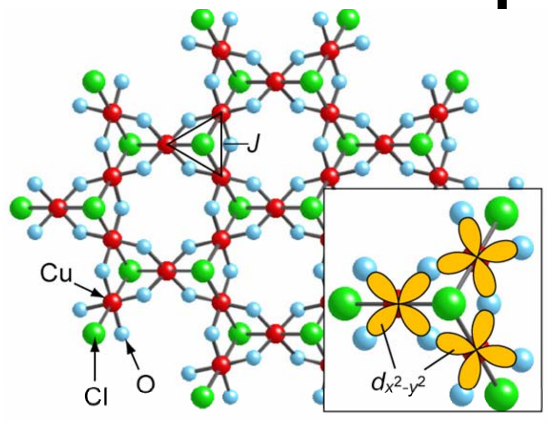
Quantum spin ice



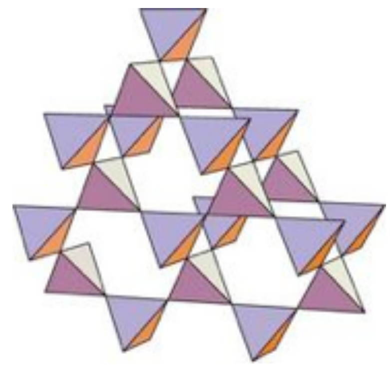
Y. Tokiwa *et al*, 2018



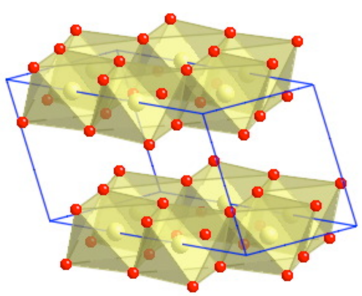
Top experimental platforms



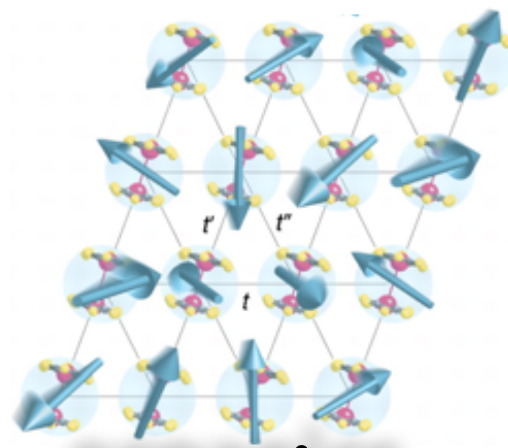
kagomé



Quantum spin ice

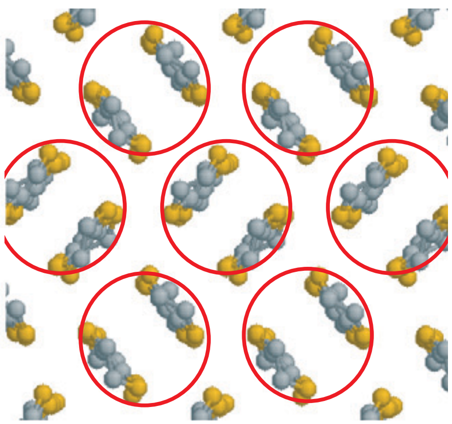


Kitaev materials

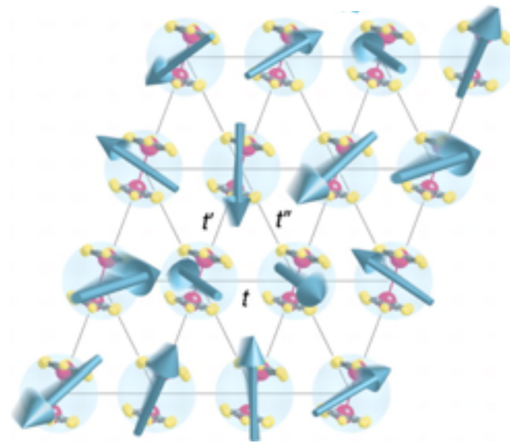


organics

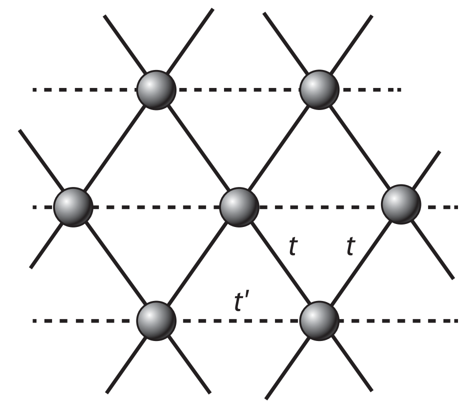
Organics



κ-$(ET)_2X$

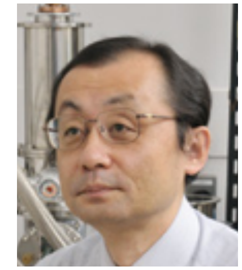


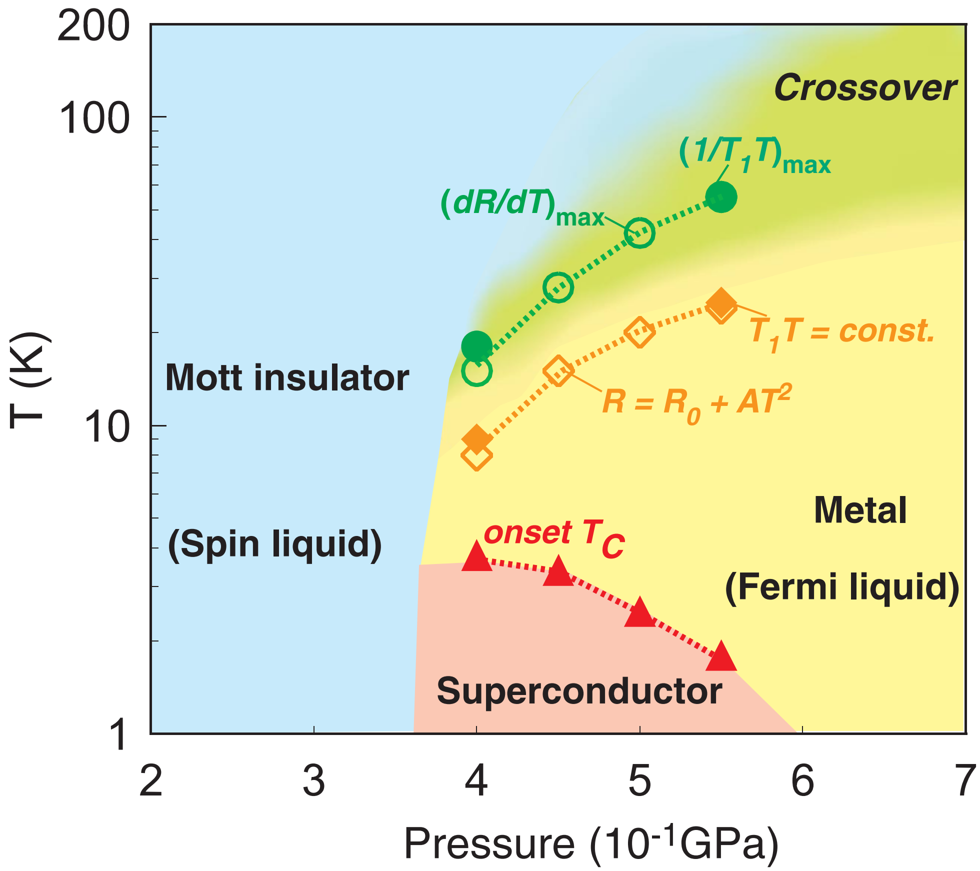
β′-$Pd(dmit)_2$

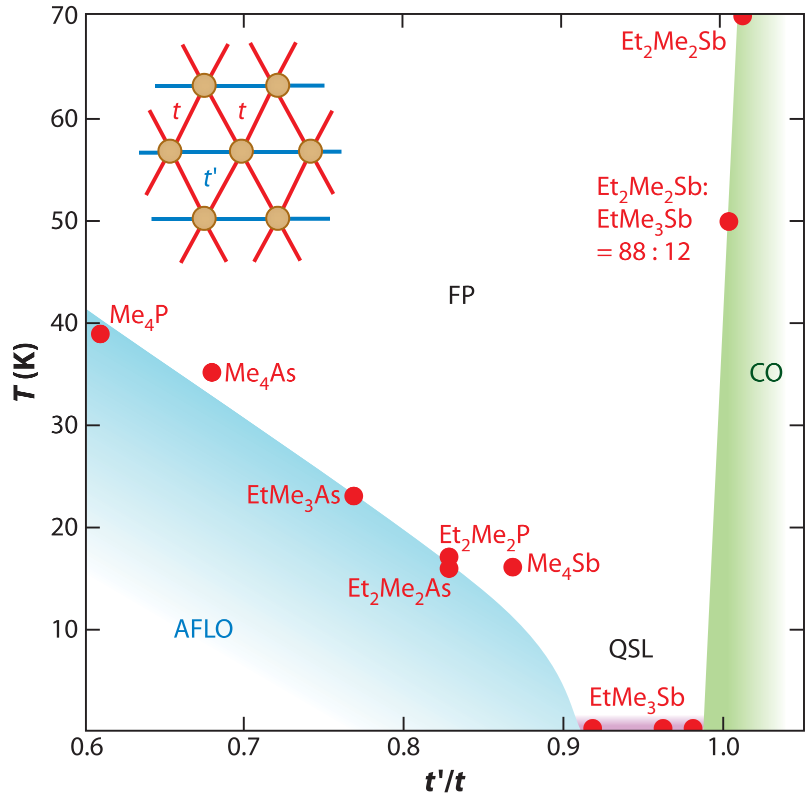


- Molecular materials which behave as effective triangular lattice S=1/2 antiferromagnets with J ~ 250K
    - significant charge fluctuations

Organics







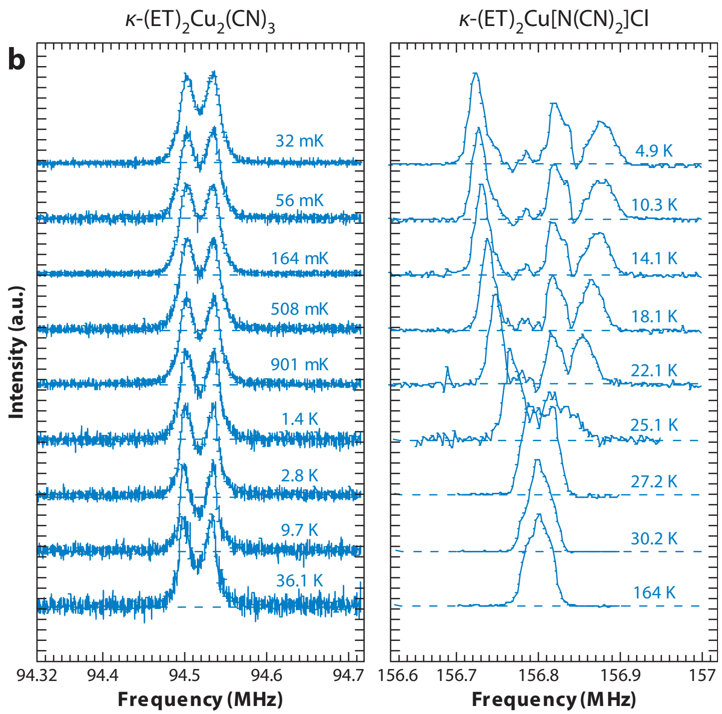
κ-$(ET)_2Cu_2(CN)_3$

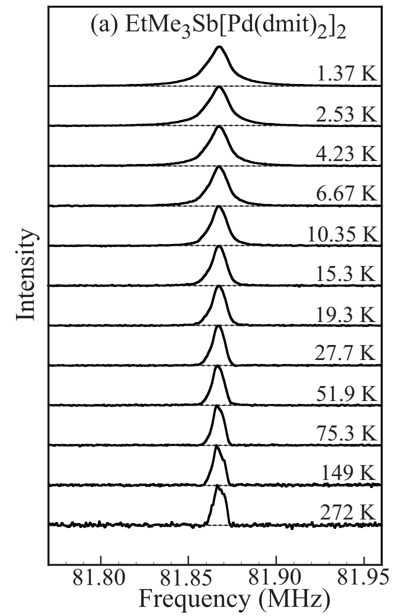
β′-$Pd(dmit)_2$

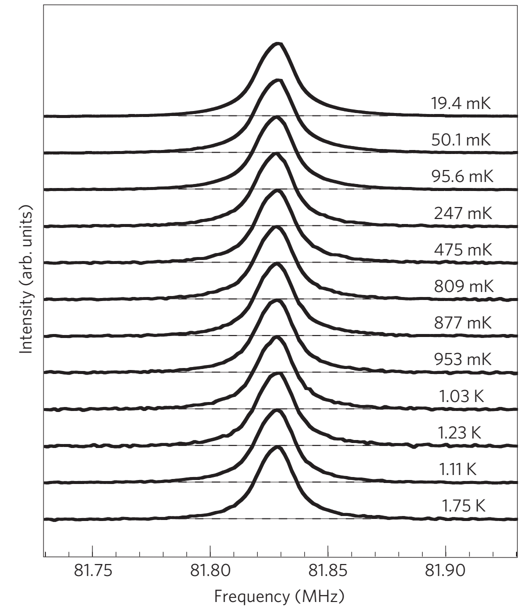
K. Kanoda group (2003-)

R. Kato group (2008-)

NMR lineshapes







κ-$(ET)_2Cu_2(CN)_3$

β′-$Pd(dmit)_2$

Y. Shimizu *et al*, 2003 ^{1}H NMR

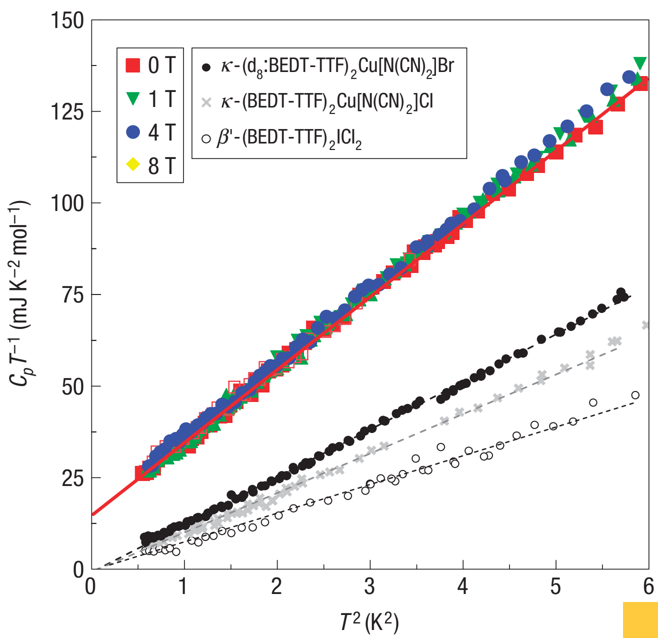
T. Itou *et al*, 2008,2010

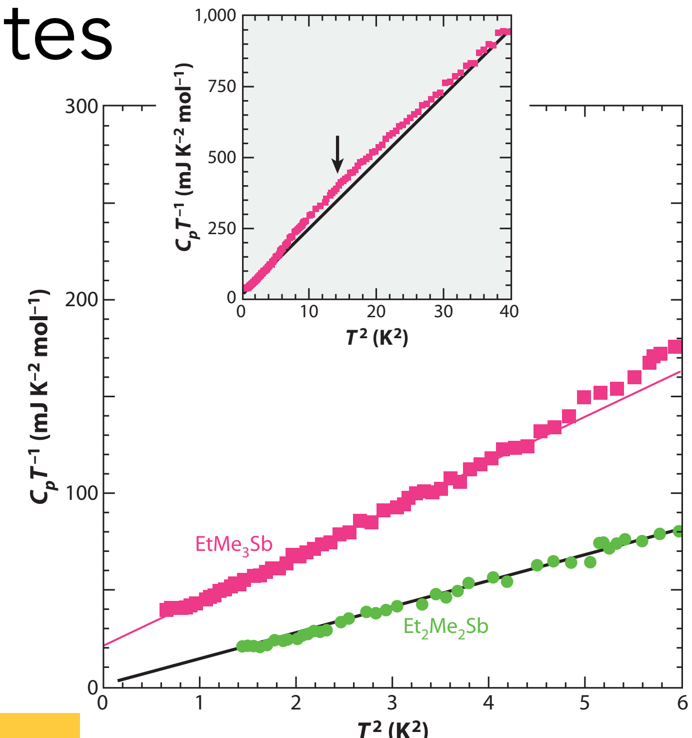
^{13}Cs NMR

Evidence for lack of static moments: f > 1000!

Specific Heat

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





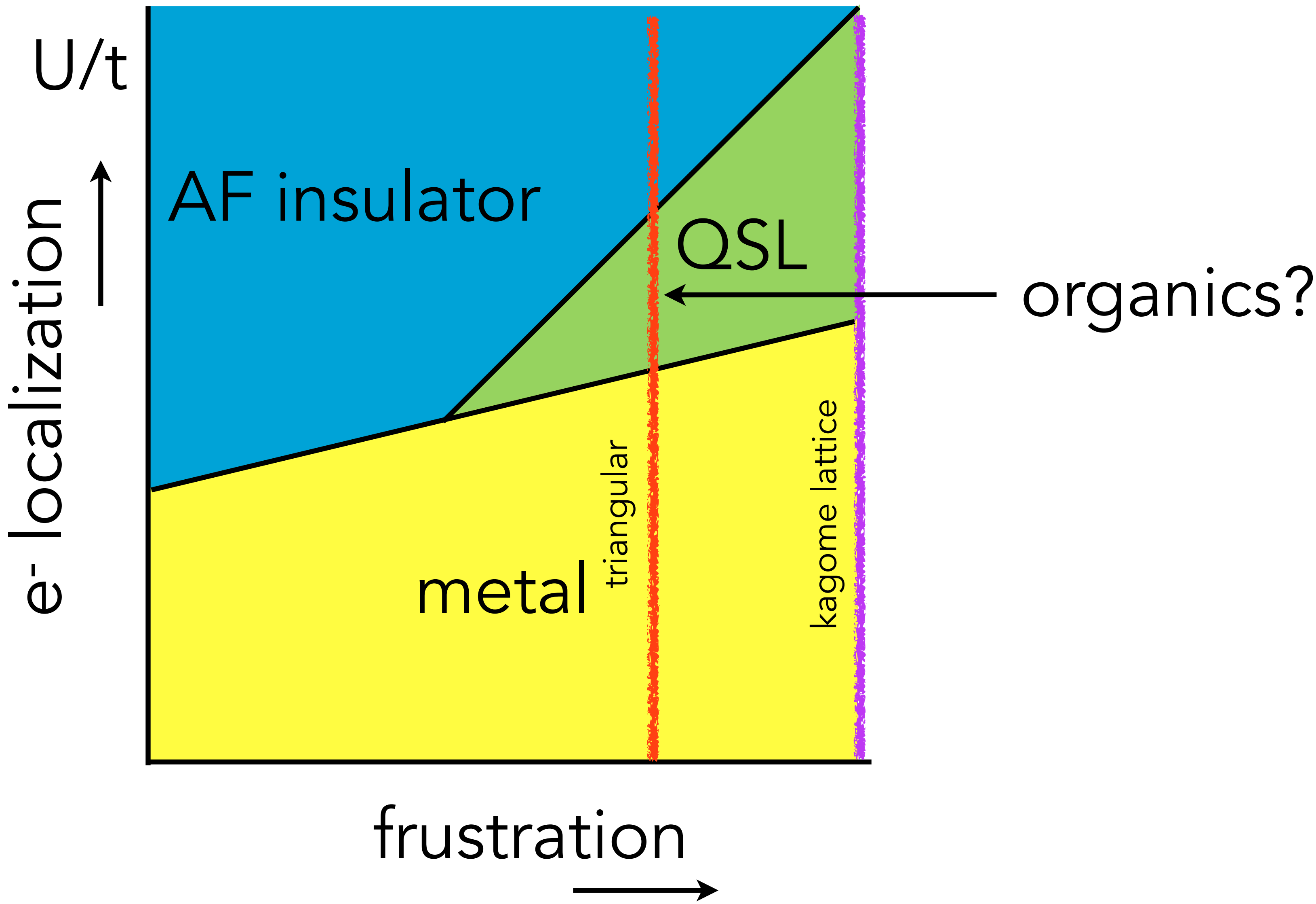
γ_{Cu} ~ 0.7 !!

κ-$(ET)_2Cu_2(CN)_3$

β′-$Pd(dmit)_2$

S. Yamashita *et al*, 2008

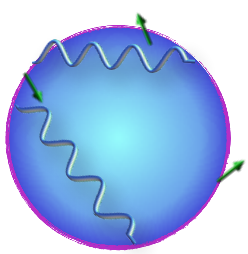
Charge fluctuations



Organics - Theory

- RVB/QSL state:
    - Motrunich, Lee+Lee: (2005) "uniform RVB"
    - It is described by a **"Fermi sea" of spinons** coupled to a U(1) gauge field

$$|\Psi\rangle = \prod_i \hat{n}_i(2-\hat{n}_i) \prod_{k<k_F} c^\dagger_{k\uparrow} c^\dagger_{k\downarrow}|0\rangle$$



- The most gapless/highly entangled QSL state
- Like a "metal" of neutral fermions w/ a U(1) gauge field
- Prototype "non-Fermi liquid" state of great theoretical interest

Spinon Fermi surface

Calculations based on effective field theory "uniform RVB"

- Fermions w/ U(1) gauge field

Zeeman term

$$S_\psi = \int d^3x\, \psi^\dagger \Big(\partial_\tau - \mu - \frac{1}{2m}(\boldsymbol{\nabla}_{\mathbf{r}} - i\mathbf{A})^2 - \omega_B \sigma^3\Big)\psi,$$

Kinetic energy   Emergent gauge field

$$S_A = \int \frac{d^3q}{(2\pi)^3}\,\frac{1}{2}\left(\gamma|\omega_n|/q + \chi q^2\right)|A(q)|^2,$$

Landau damping

$$S_u = \int d^3x\, u\, \psi^\dagger_\uparrow \psi_\uparrow \psi^\dagger_\downarrow \psi_\downarrow.$$

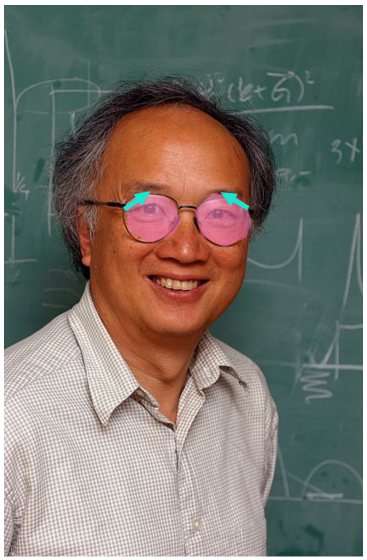
Short-range repulsion (from a_0)

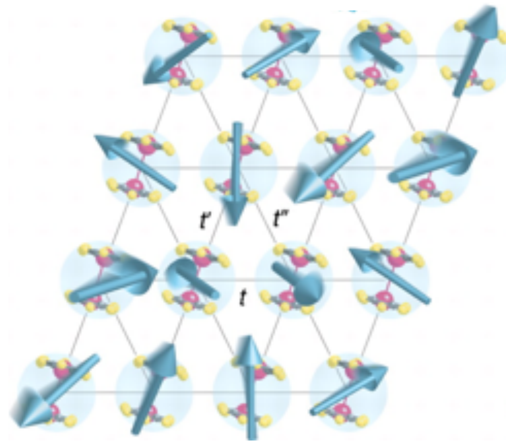
Ioffe,Larkin 1989   Nagaosa 1999

Kim, Furusaki, Lee, Wen 1994

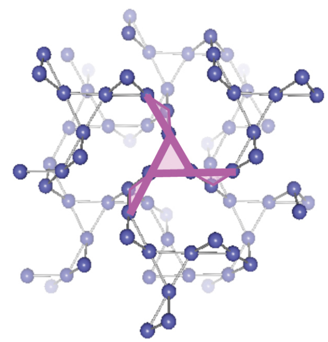
Sachdev, Metlitski, Senthil, McGreevy…

Spinon Fermi surface

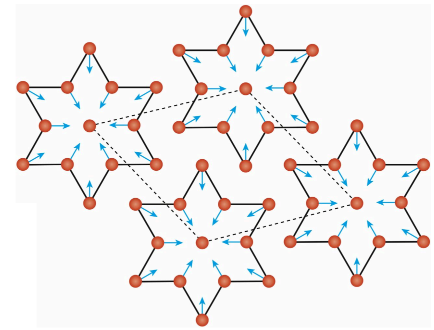




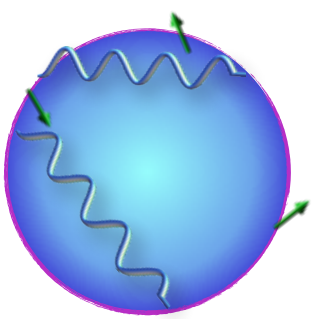
k-ET

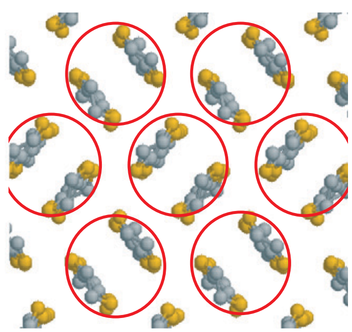


$Na_4Ir_3O_8$

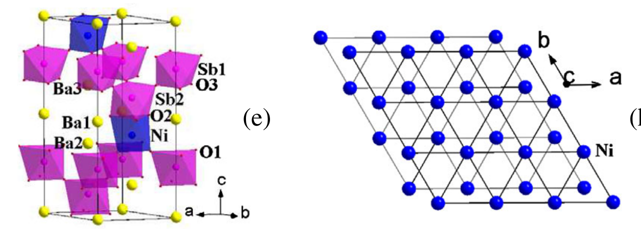


1T-TaS_2





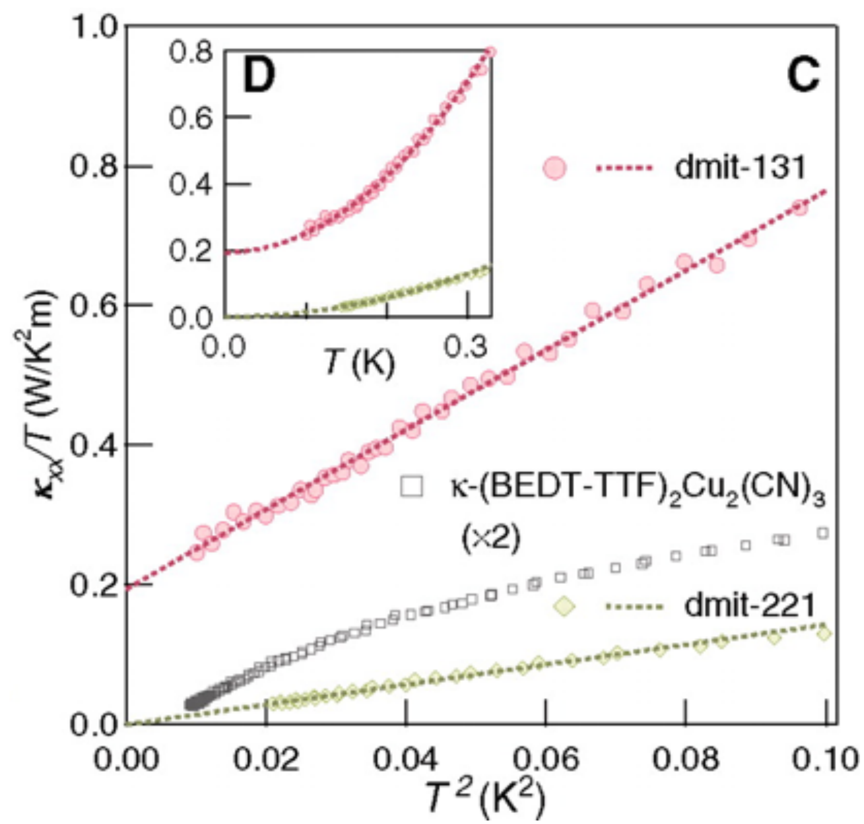
dmit



$Ba_3NiSb_2O_9$

Thermal conductivity

- Huge linear thermal conductivity indicates the gapless excitations are propagating
- Consistent with spinon Fermi surface?
- Estimate for a *metal* would correspond to a mean free path *l* ~ 1 μm ≈1000 a !



M. Yamashita *et al*, 2010

9 years later…

PHYSICAL REVIEW X **9**, 041051 (2019)

Thermal Conductivity of the Quantum Spin Liquid Candidate $EtMe_3Sb[Pd(dmit)_2]_2$: No Evidence of Mobile Gapless Excitations

P. Bourgeois-Hope,[1] F. Laliberté,[1] E. Lefrançois,[1] G. Grissonnanche,[1] S. René de Cotret,[1] R. Gordon,[1] S. Kitou,[2] H. Sawa,[2] H. Cui,[3] R. Kato,[3] L. Taillefer,[1,4,*] and N. Doiron-Leyraud[1,†]

PHYSICAL REVIEW LETTERS **123**, 247204 (2019)

Editors' Suggestion

Absence of Magnetic Thermal Conductivity in the Quantum Spin Liquid Candidate $EtMe_3Sb[Pd(dmit)_2]_2$

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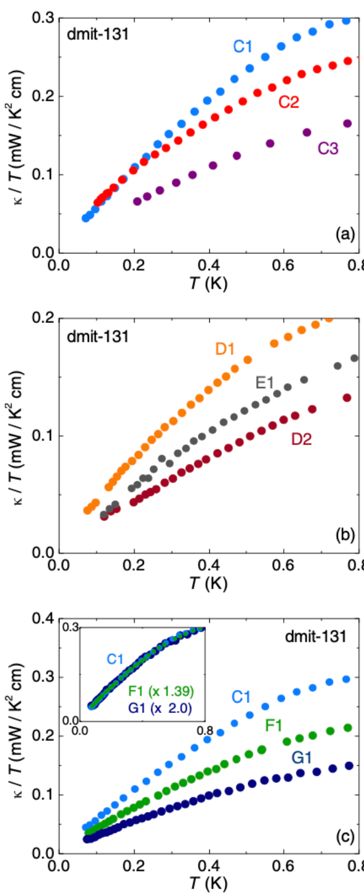
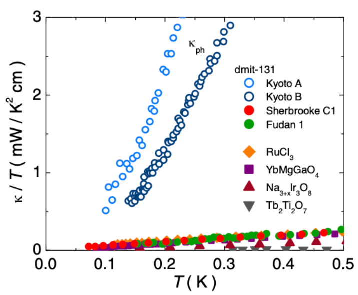
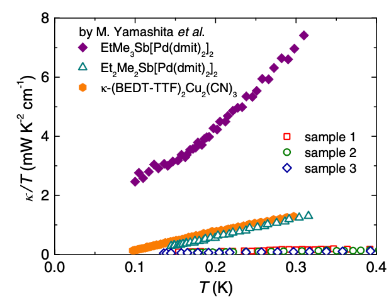
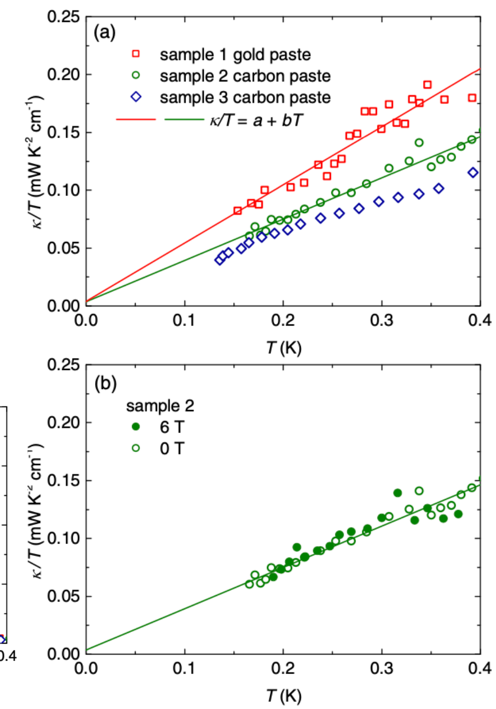


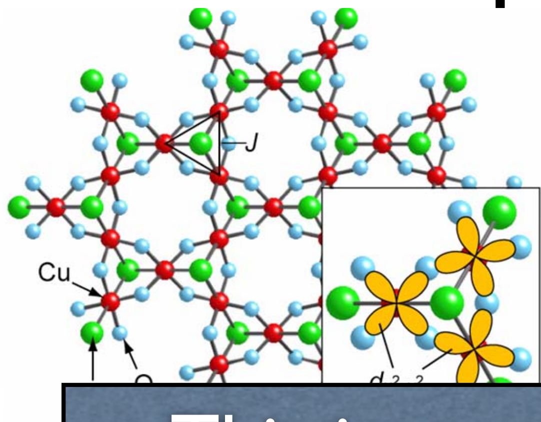


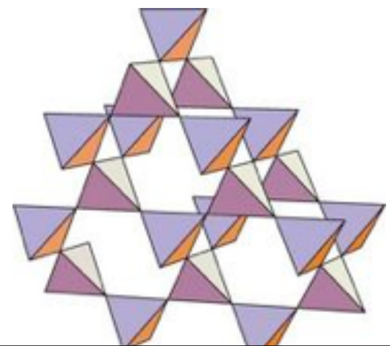




Controversy!

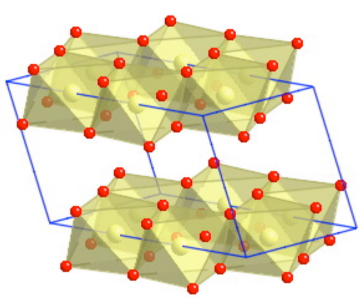
Top experimental platforms



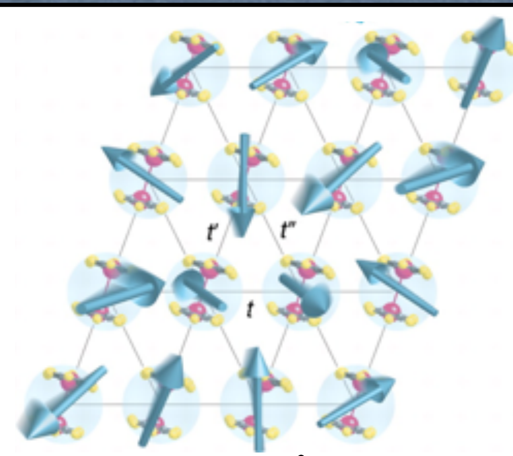


This just scratches the surface: many more materials being studied

ice



Kitaev materials



organics

Frontiers

New phases

- Fractons
- Quenched disorder

Fundamental problems

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

Reality

- New Materials! Maybe QSLs in VdW crystals?
- Definitive experimental signatures
  - Thermal Hall? Non-linear spectroscopy?
- Computational methods: less bias, reliability of variational methods, beyond ground states

Thanks for your attention

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

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Simons Collaboration on Ultra-Quantum Matter