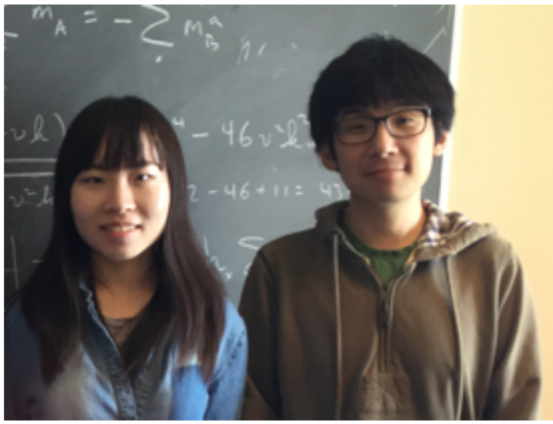
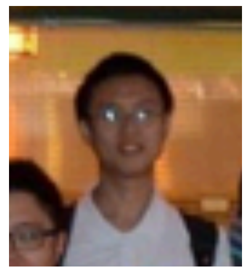

Quantum Spin
Liquids
Leon Balents, KITP
ISCOM2017, Miyagi

Collaborators (whose work I'll mention)



Xue-Yang Song
Yi-Zhuang You

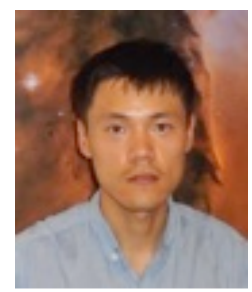


Chunxiao Liu

Lucile Savary

Gábor Halász

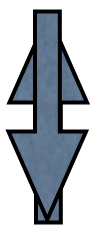
Jason Iaconis



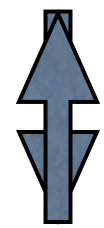
Xiao Chen

Quantum non-locality

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

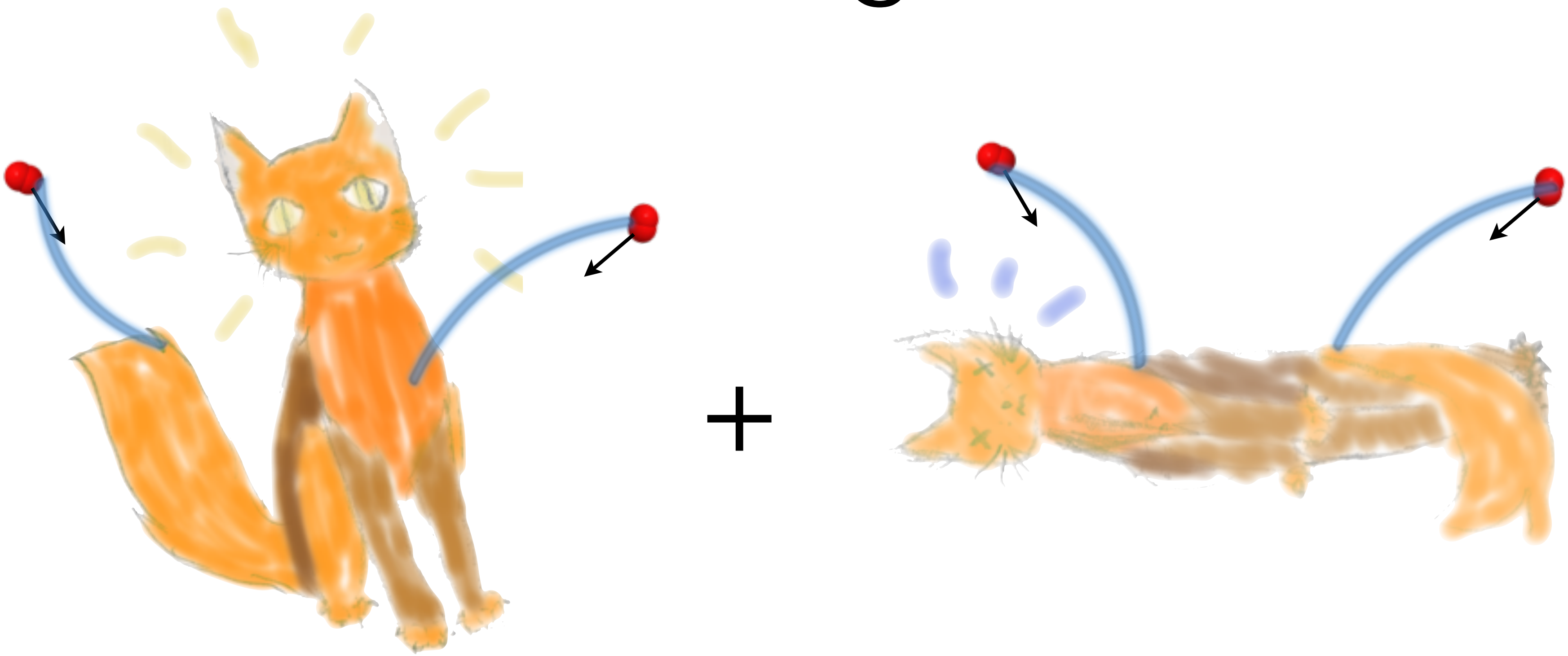


??where is the information??



A. Einstein B. Podolsky N. Rosen

Schrödinger’s Cat

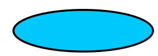


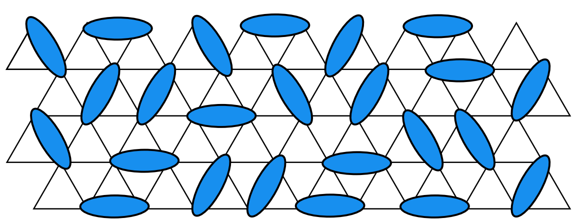
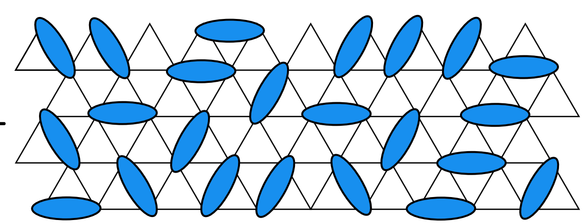
UNSTABLE to decoherence - uncontrolled entanglement with the environment

Strange Stuff

Phil Anderson, 1973

a "quantum liquid" of spins

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

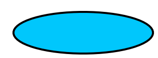
Ψ =  $+$  $+\ldots$

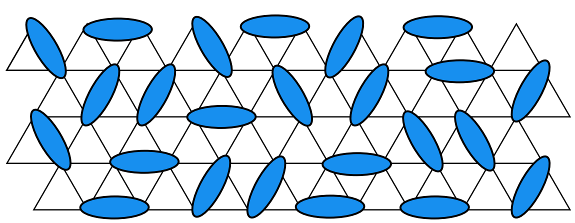
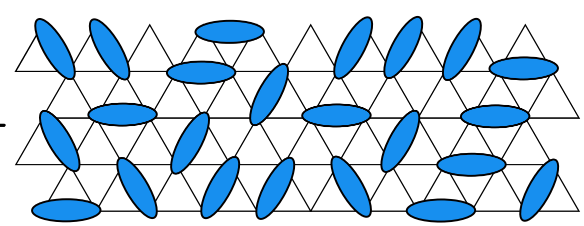
Resonating **V**alence **B**ond state

Strange Stuff

Phil Anderson, 1973

a "quantum liquid" of spins

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

Ψ =  +  + ...

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

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

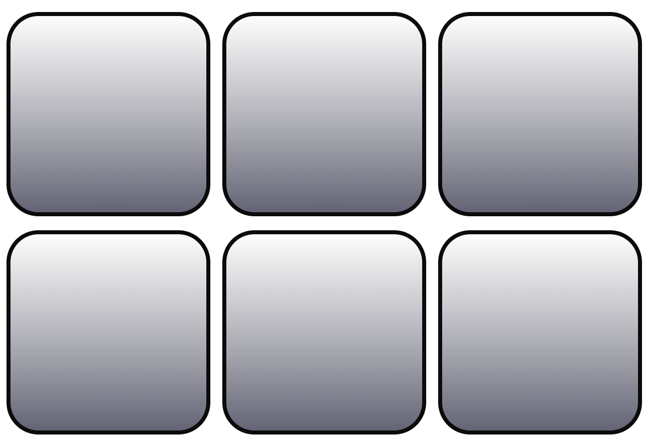
Hamiltonian is local

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

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

Ground state is "essentially" a product state

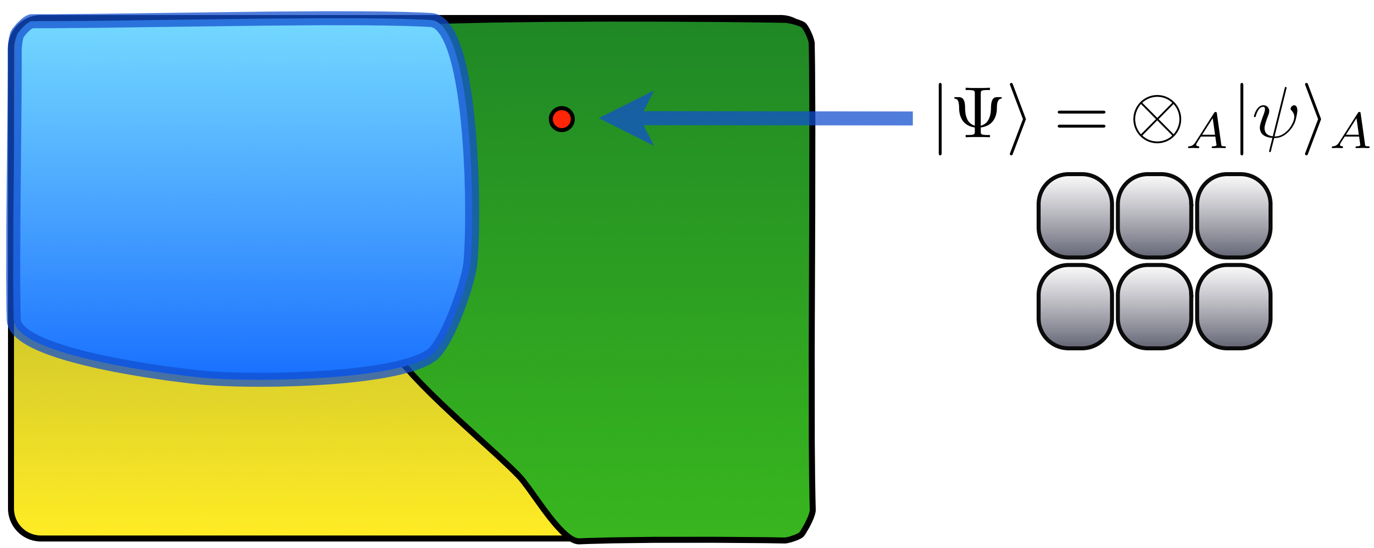
$$|\Psi\rangle = \otimes_A |\psi\rangle_A$$



no entanglement between blocks

"Essentially" a product state?

- Adiabatic continuity

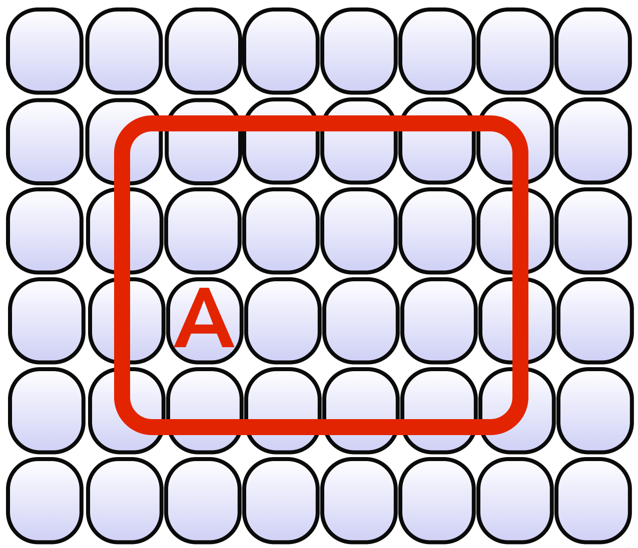


phase space

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

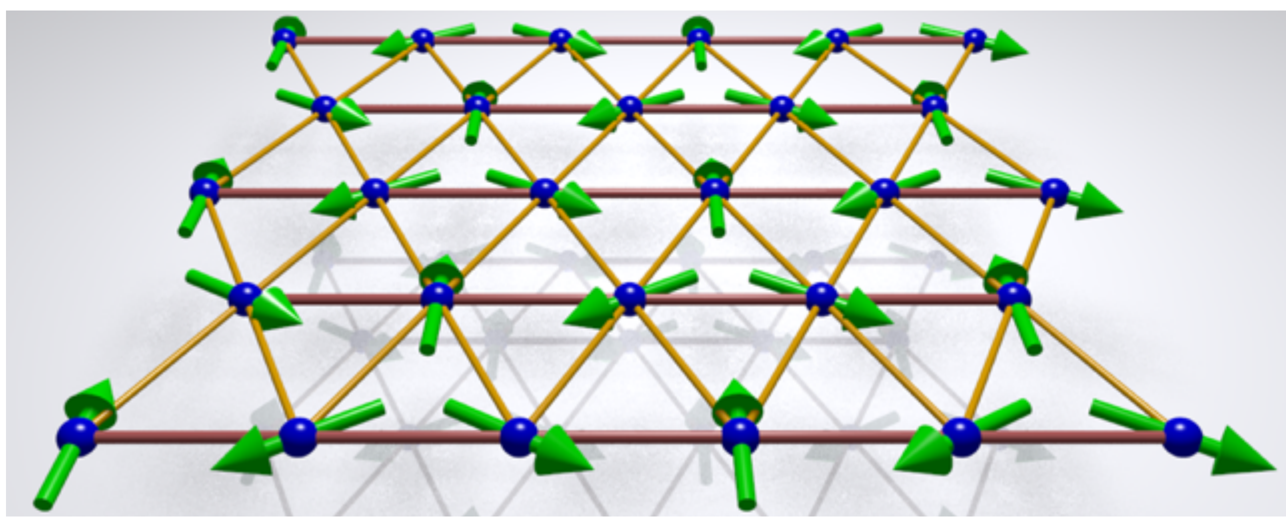
$$H = \sum_{(ij)} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

exchange is short-range: local

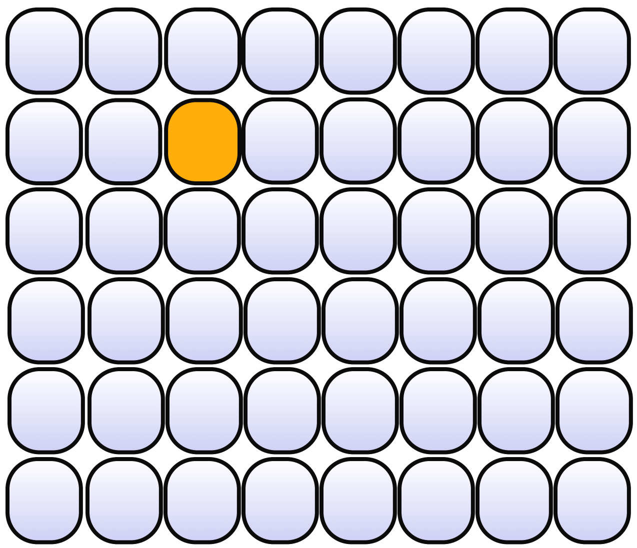
ordered state

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

block is a single spin



Quasiparticles

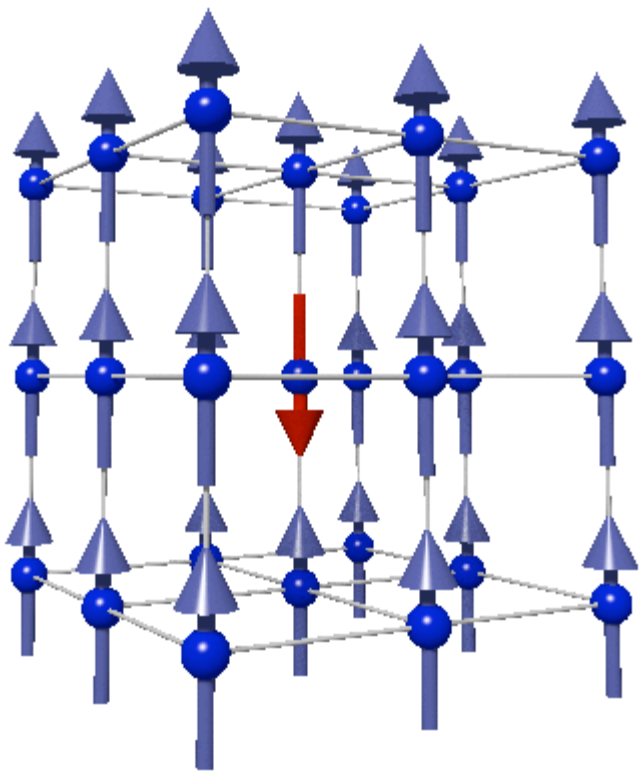


excited states ~ excited levels of one block

- 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

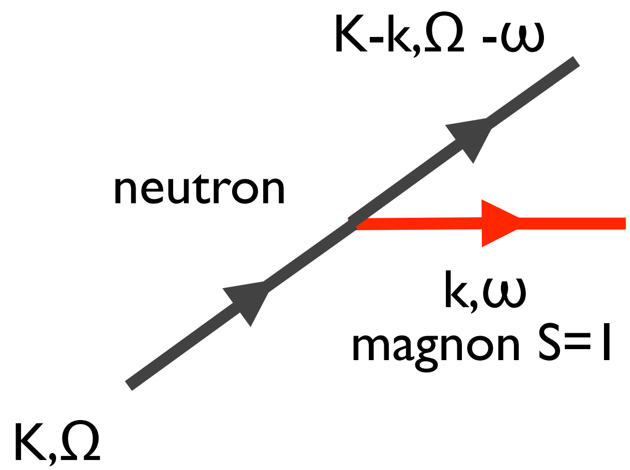
- quantum numbers consistent with finite system: no emergent or fractional quantum numbers

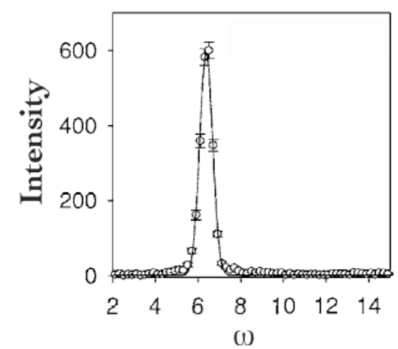
Spin wave



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

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



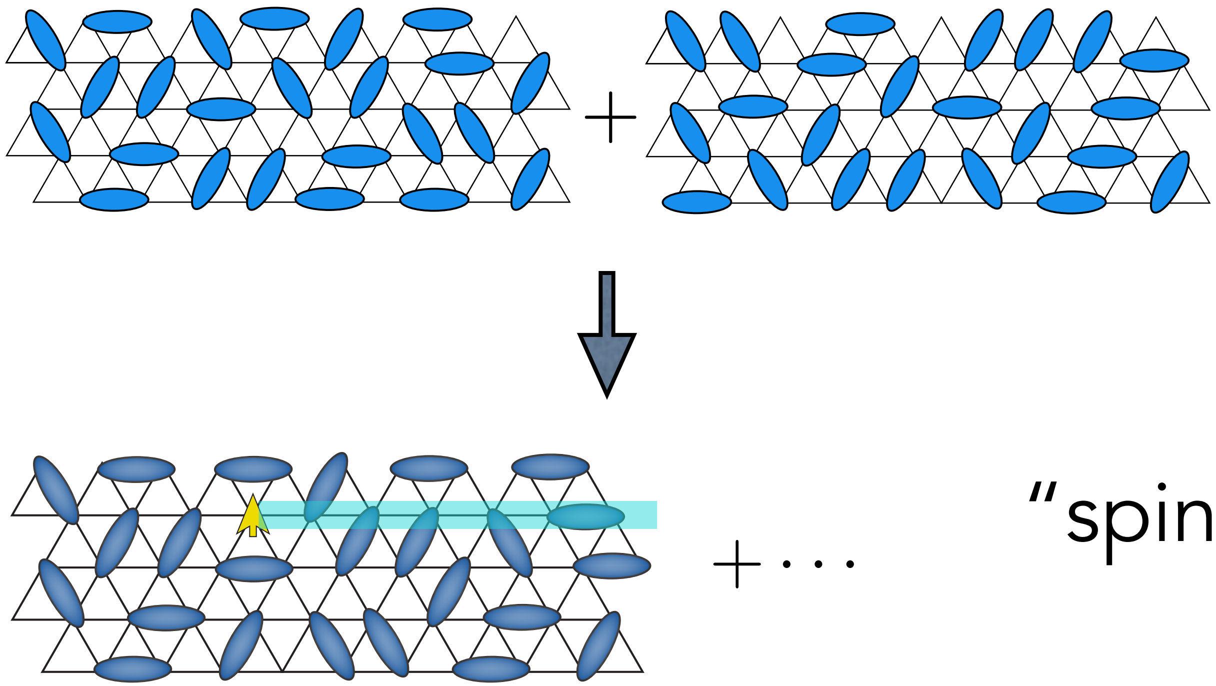


Line shape in Rb_2MnF_4

Quantum spin liquid

Entanglement -> non-local excitation

Ψ =



$+\ldots$

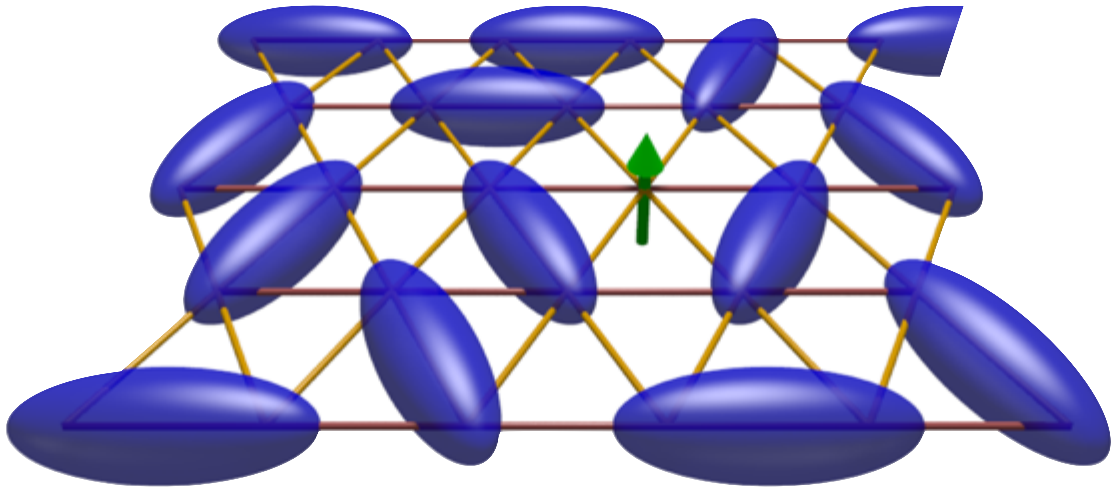
Ψ =

$+\cdots$

"spinon"

"quasiparticle" above a non-zero gap

Fractional quantum number

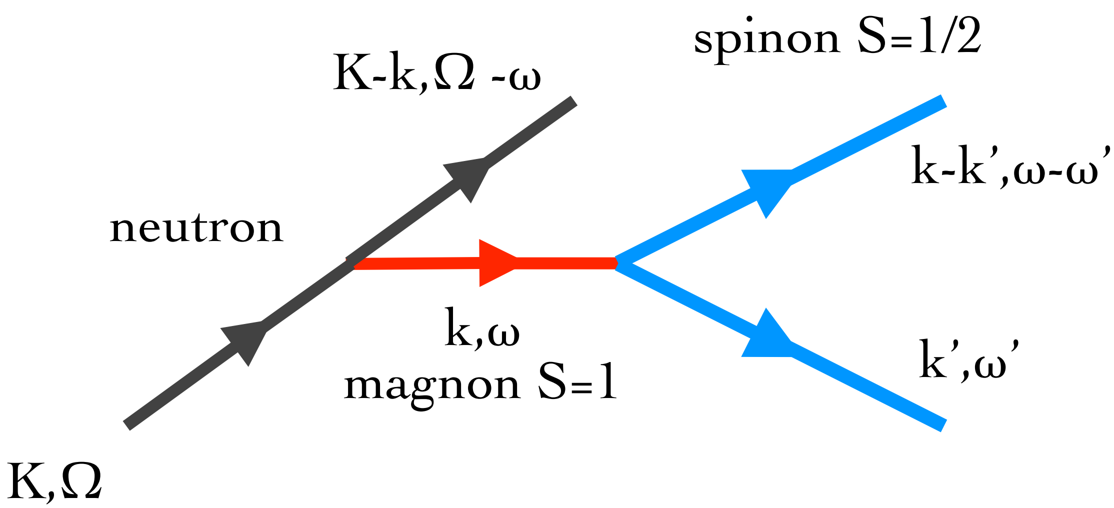


excitation with $\Delta S = 1/2$
not possible for any finite
cluster of spins

always created in pairs by any
local operator

No spin waves

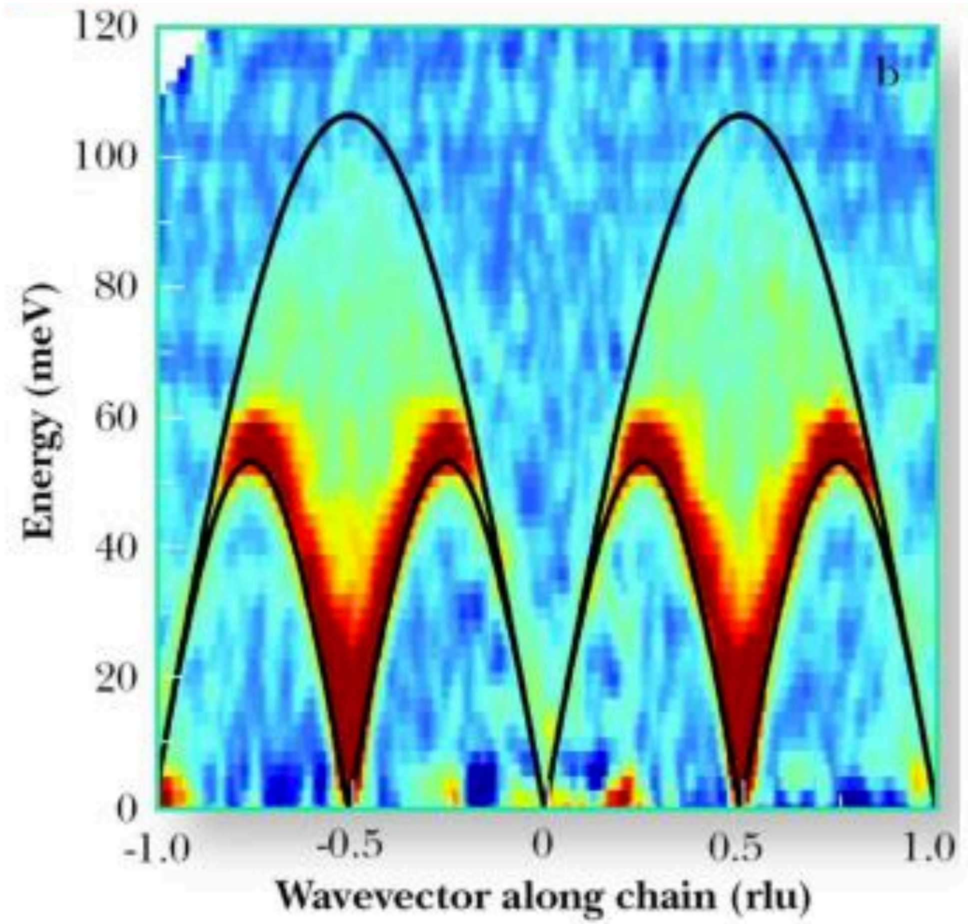
- Magnon is not elementary: decays into two spinons



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

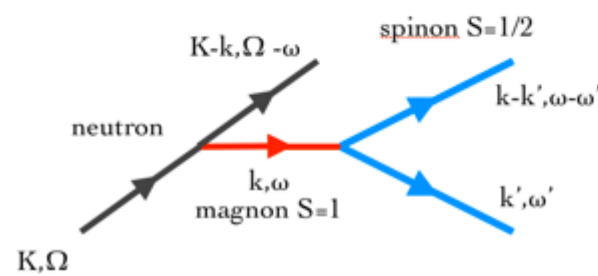
- Sharp peaks should be reduced or absent in the spin structure factor

c.f. One dimension

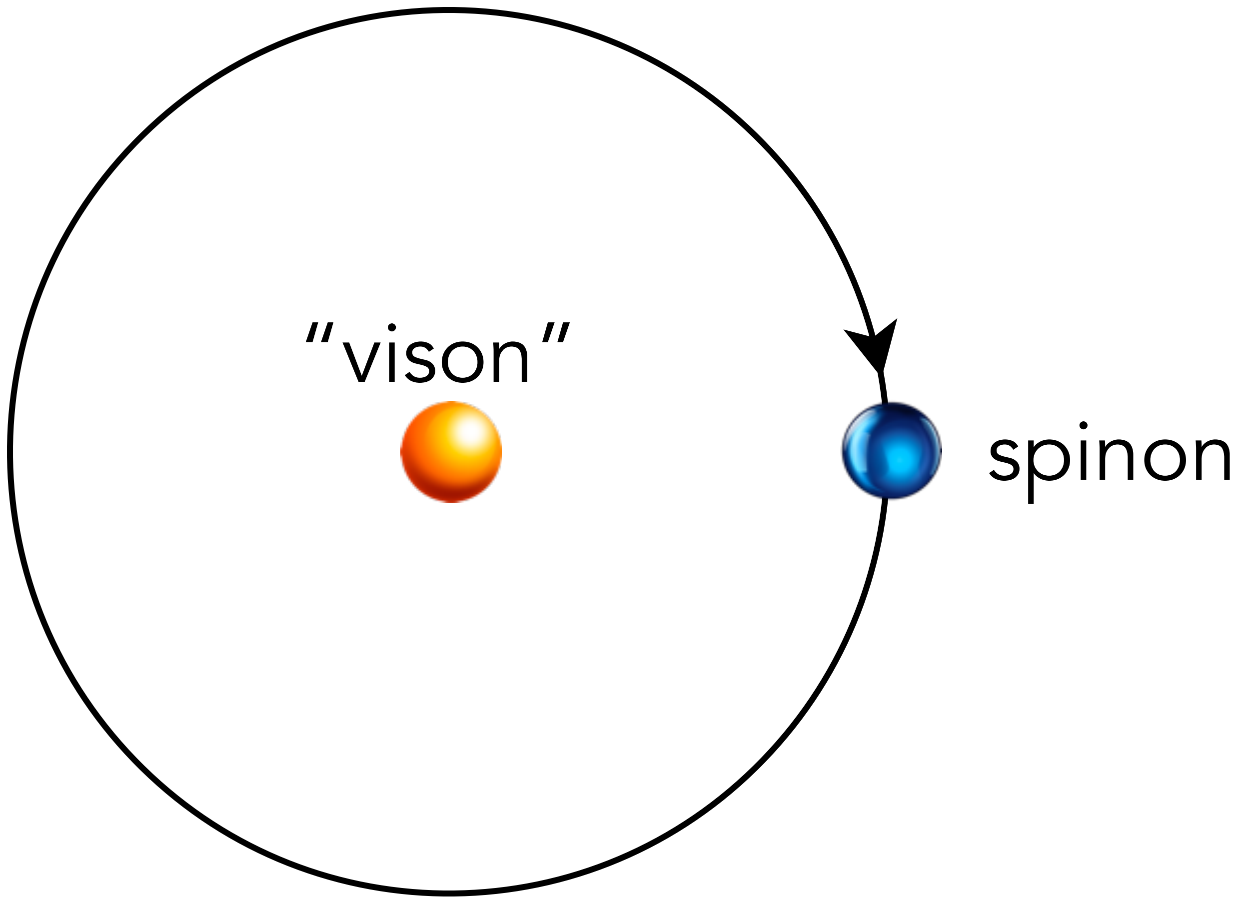


A. Tennant *et al*, 2001

$KCuF_3$



Anyons



$$\Psi \to -\Psi$$

"mutual semions"

X.-G. Wen

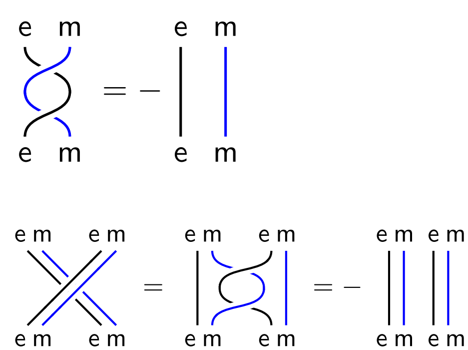
Topological phases

A. Kitaev

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

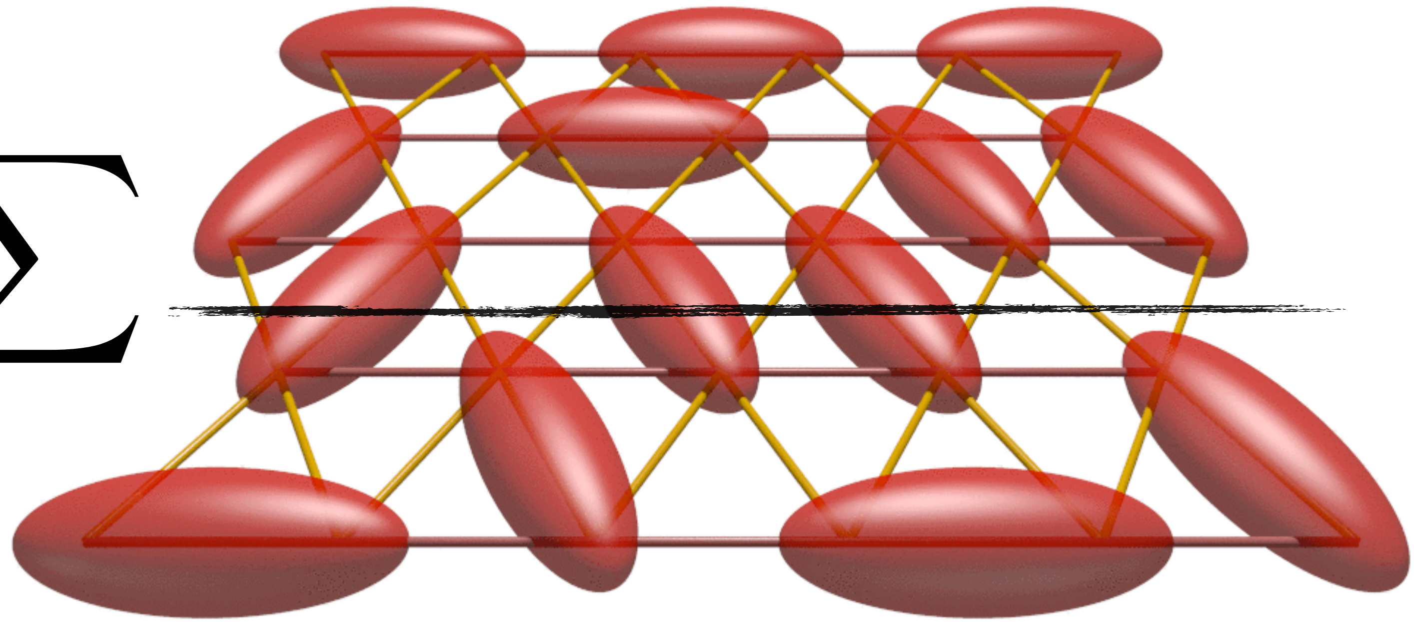
Anderson's RVB state is thus an example of a "topological phase" - the best understood sort of QSL

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



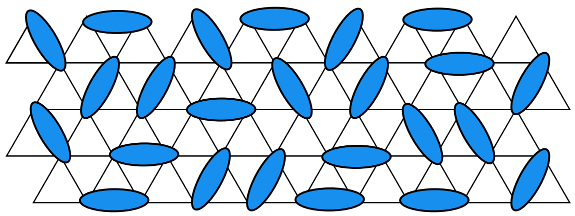
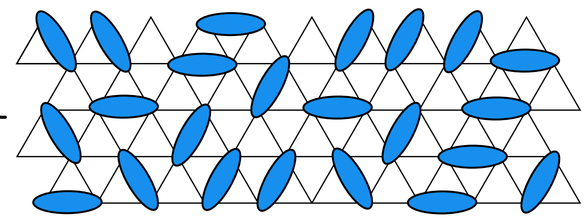
Stability

$$\Psi = \sum$$



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

Quantum spin liquid

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

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

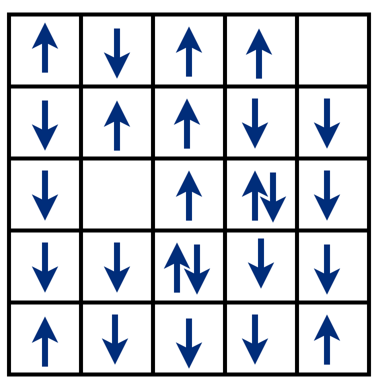
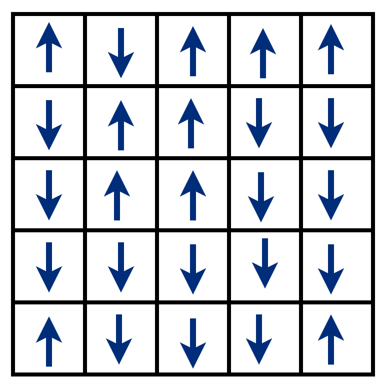
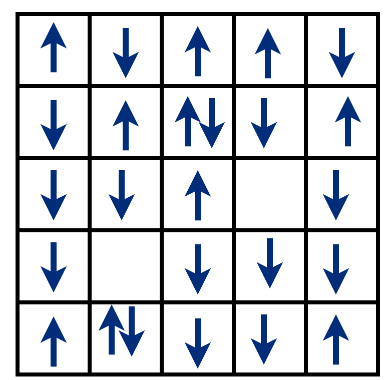
Different choices of amplitudes can realize different QSL phases of matter.

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"

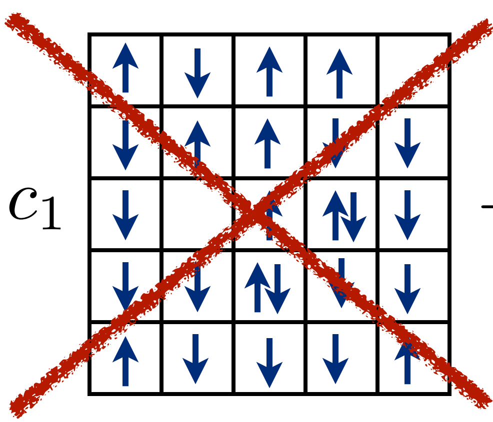
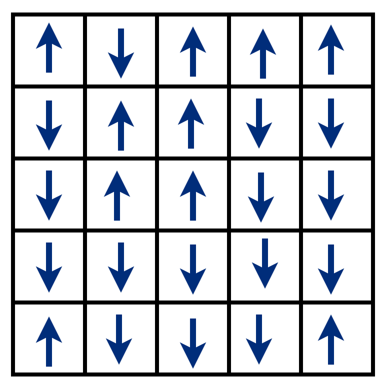
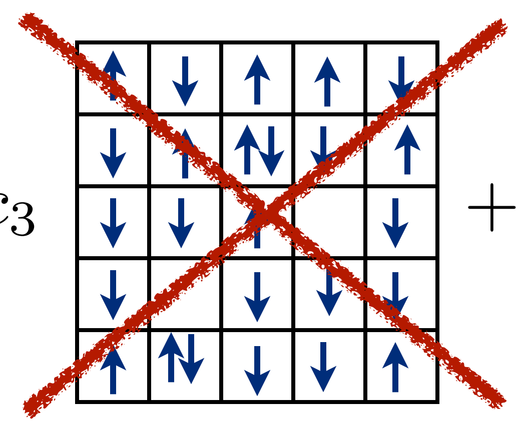
$= \quad c_1$  $+c_2$  $+c_3$  $+\cdots$

Gutzwiller Construction

- Project out any components with empty or doubly occupied sites

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

"partons"
"spinons"

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

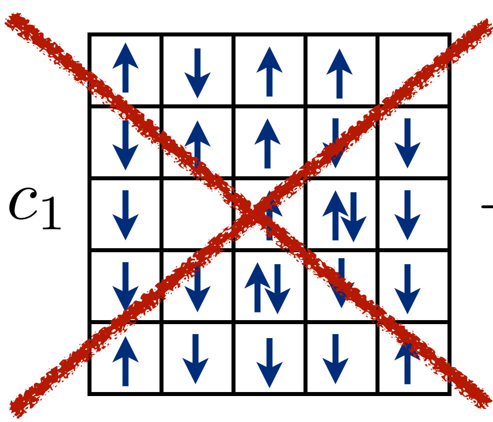
Gutzwiller Construction

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

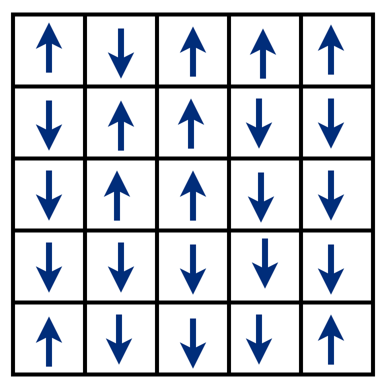
$$|\Psi\rangle = \hat{P}_G|\Psi_0\rangle$$

"partons"
"spinons"

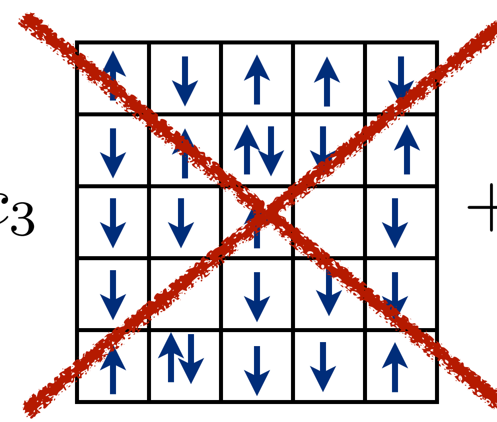
$= \; c_1$



$+c_2$



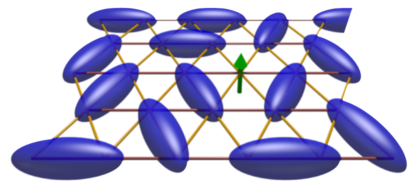
$+c_3$



$+\cdots$

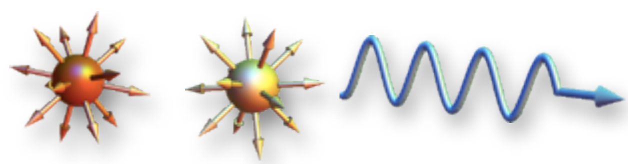
Classes of QSLs

- Topological QSLs



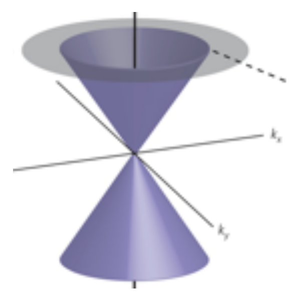
projected superconductor

- U(1) QSL



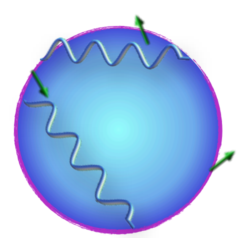
projected 3d band insulator

- Dirac QSLs



projected graphene

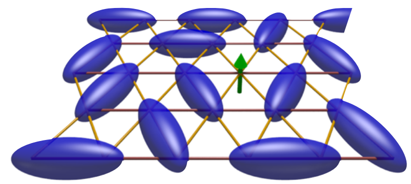
- Spinon Fermi surface



projected metal

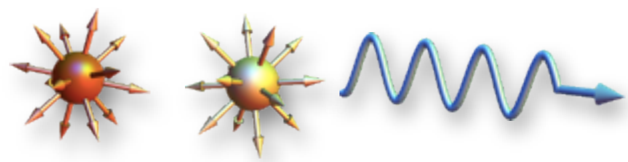
Classes of QSLs

- Topological QSLs



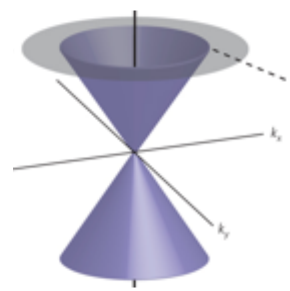
anyonic spinons

- U(1) QSL



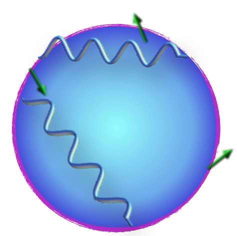
electric+magnetic monopoles, photon

- Dirac QSLs



strongly interacting Dirac fermions

- Spinon Fermi surface

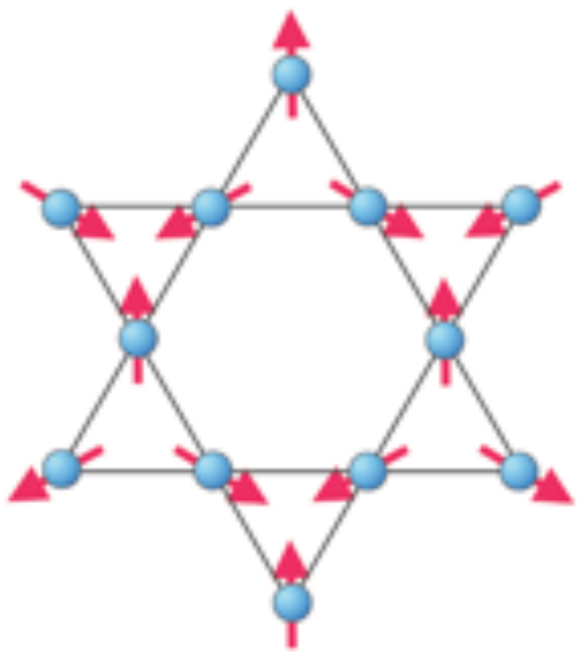


non-Fermi liquid “spin metal”

Strange stuff

where do we find it?

Kagomé antiferromagnet



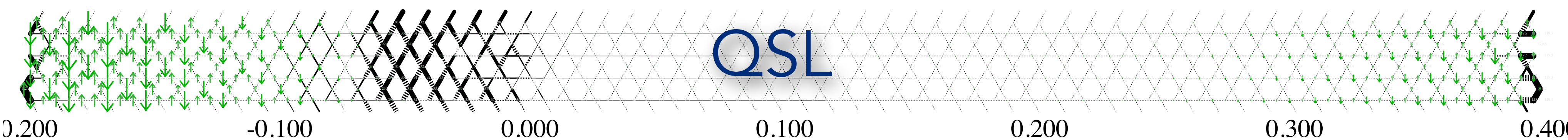
$$H = J \sum_{\langle ij \rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \ldots$$

Very large classical degeneracy → likely to be a QSL

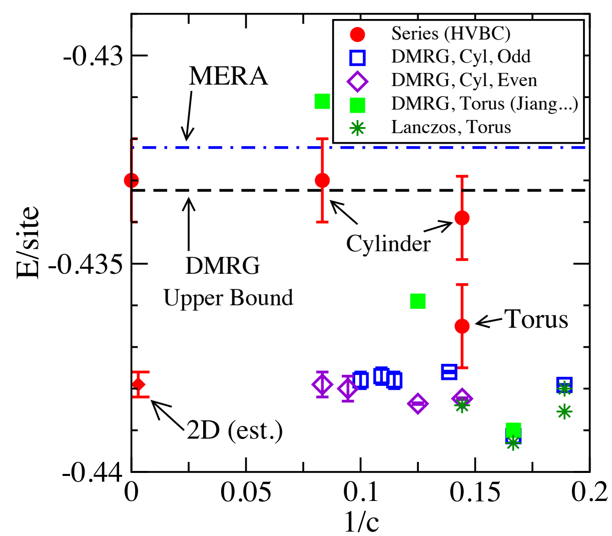
V. Elser, 1989 + many many others

S=1/2 kagomé AF

- Rather definitive evidence for QSL by DMRG



© Steve White

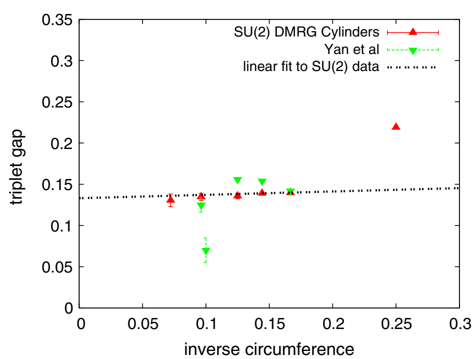


S. Yan *et al*, 2010

many other studies support existence of some QSL phase

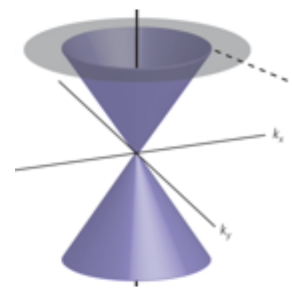
Theory

- What kind of QSL?



S. Depenbrock *et al*, 2012

gapped, topological QSL

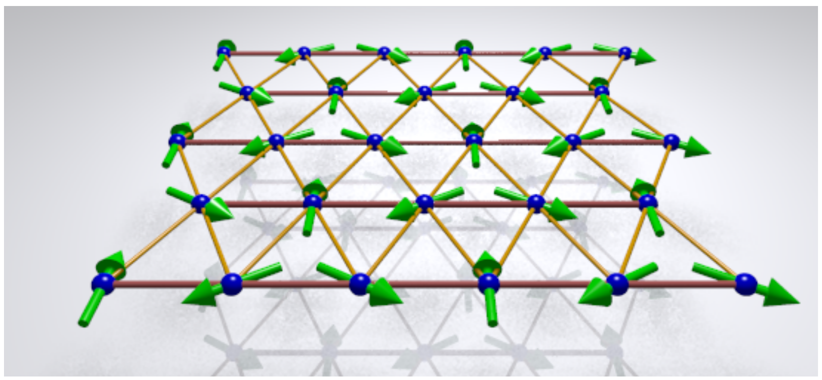


Y. Ran *et al*, 2007
F. Becca...
Y.C.He *et al*, 2016

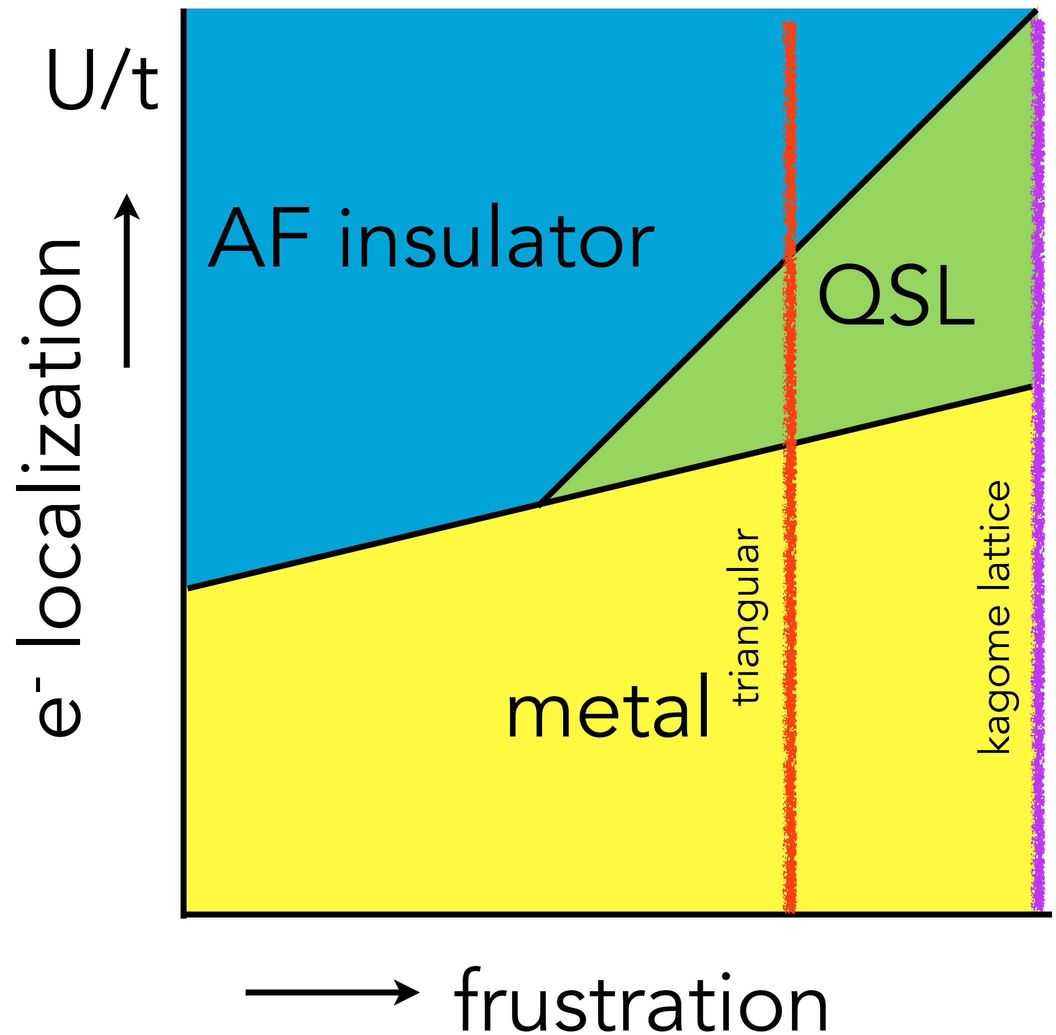
gapless Dirac QSL

+ various other proposals with weaker quantitative support

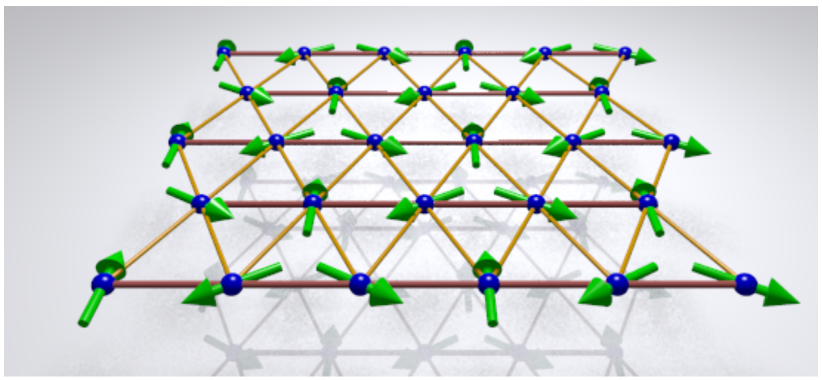
Triangular lattice w/ ring exchange

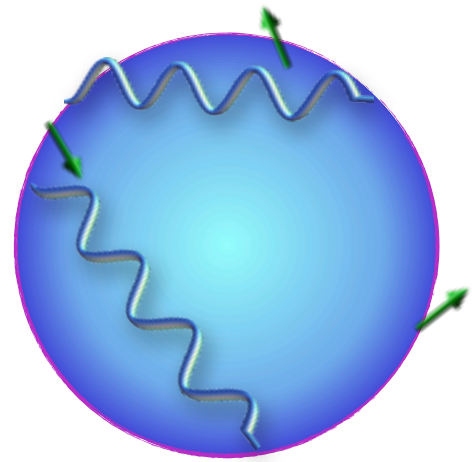


- Motrunich (2005): ring exchange stabilizes a spin liquid



Triangular lattice w/ ring exchange





- Motrunich (2005): ring exchange stabilizes a spin liquid
- Motrunich, Lee/Lee: spin liquid state favored by ring exchange is the "spinon Fermi sea" state

SOC triangular

Heavy elements:

highly localized electrons, strong spin-orbit coupling

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

Y. Li *et al*, 2015

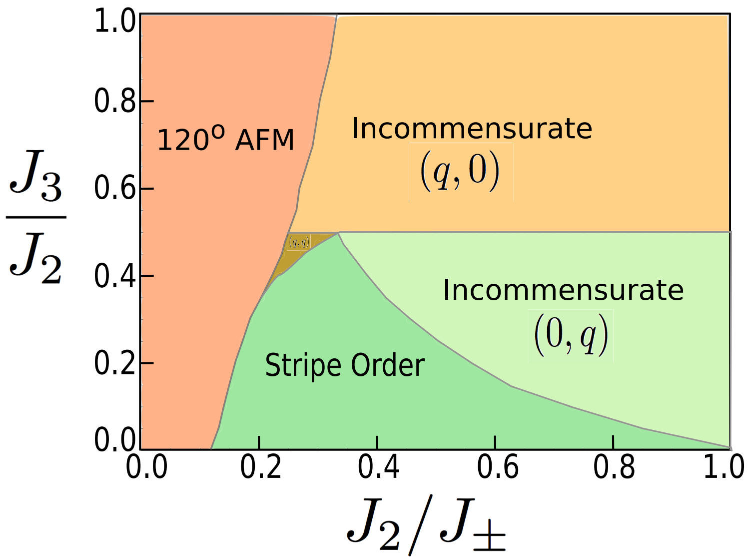
XXZ

bond-dependent couplings

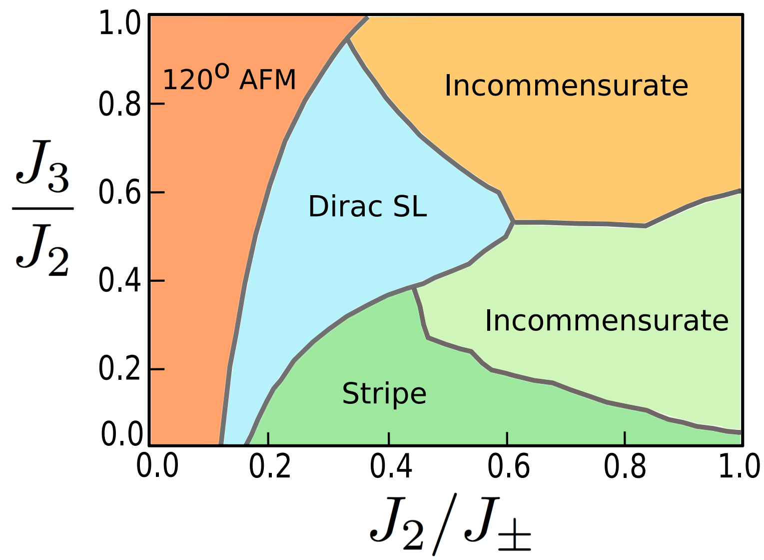
SOC triangular

QSLs versus magnetic order

classical

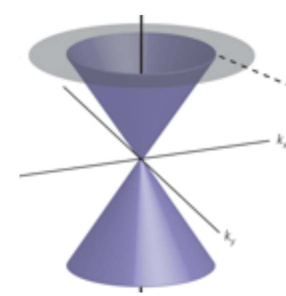


quantum



Some window exists for Dirac QSL

J. Iaconis, C. Liu, G. Halász, LB, 2017

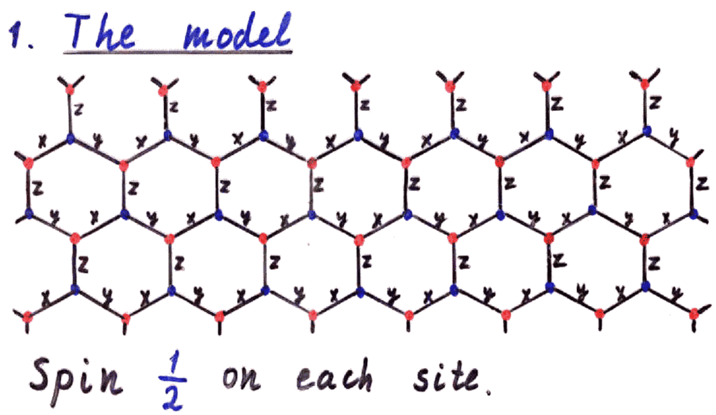


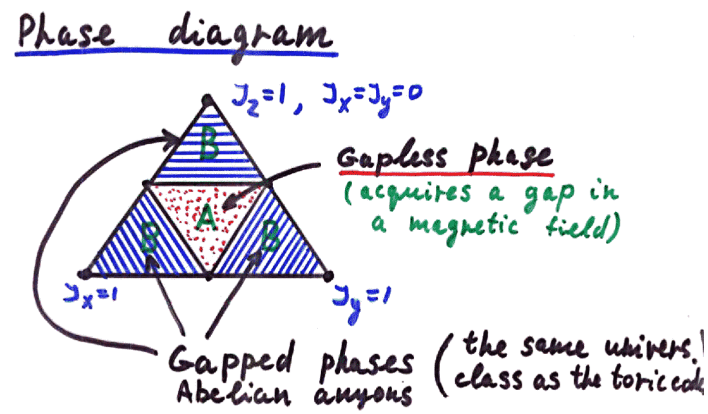
Kitaev model

Kitaev's honeycomb model

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

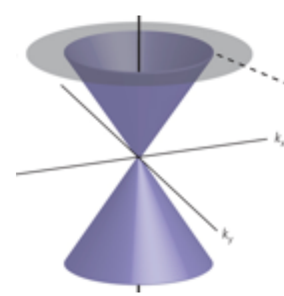
KITP, 2003





exact parton construction

- spinon is a gapless Majorana fermion



How to probe QSLs?

Two main characteristics:

- Massive entanglement
  - Almost no experiments known to probe this.
- Fractional/non-local excitations
  - Probed by most low energy response measurements. Challenge is to distinguish the fractional/non-local nature.

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

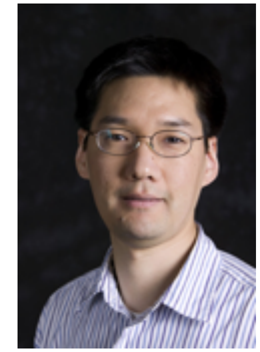
Delocalized excitations?

- thermal conductivity
- INS

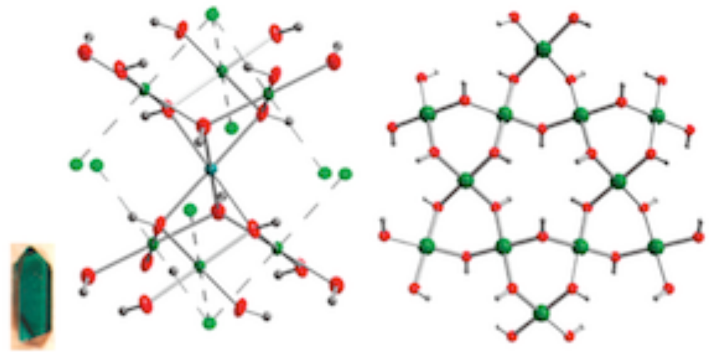
Structure of excitations?

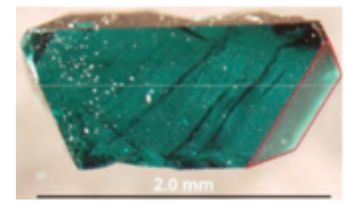
- E(k) from INS,RIXS
- optics, Raman

Scattering



$ZnCu_3(OH)_6Cl_2$

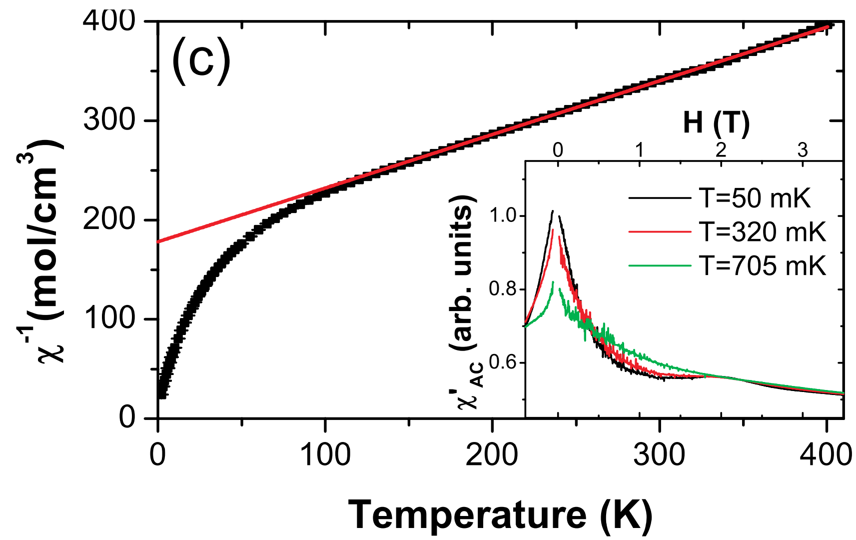




Herbertsmithite

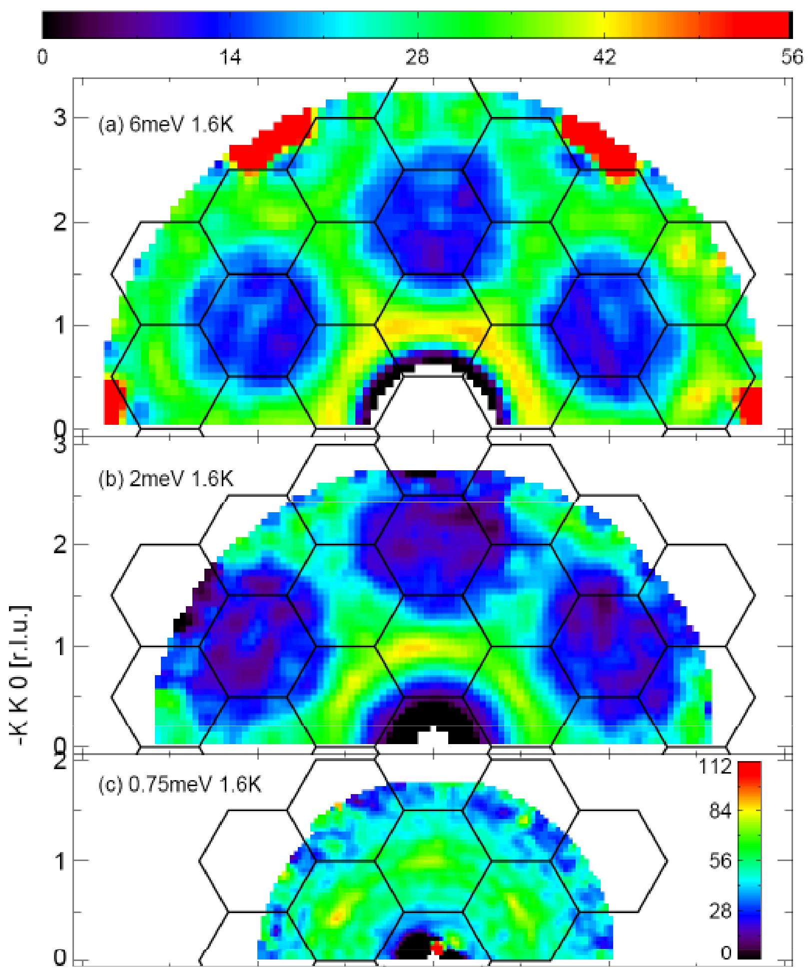
Heisenberg-like
with J ~ 200K

no order down to
50mK

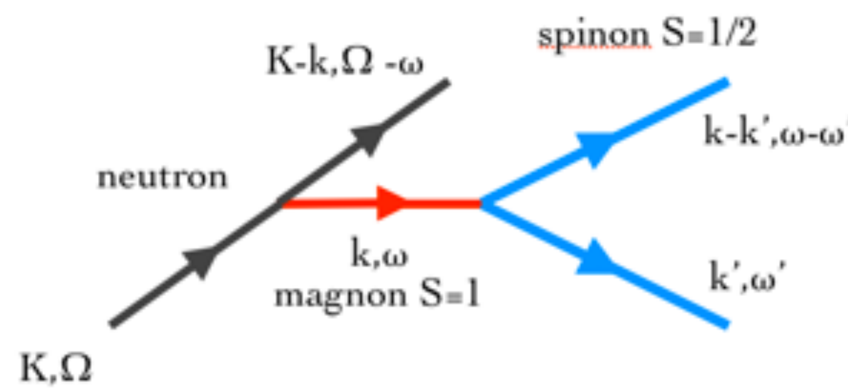


Helton *et al*, 2007

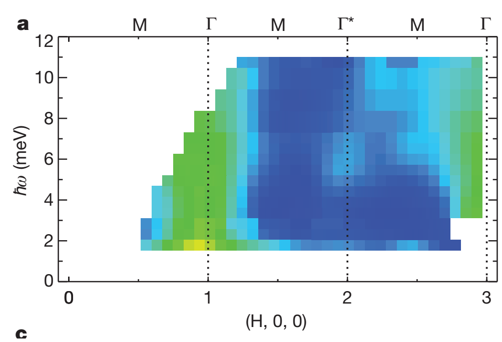
Scattering



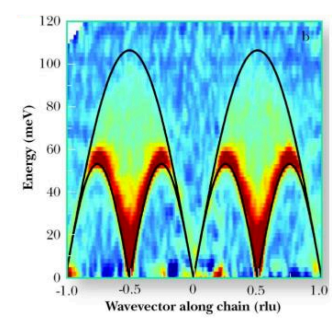
T-H Han *et al*, 2012

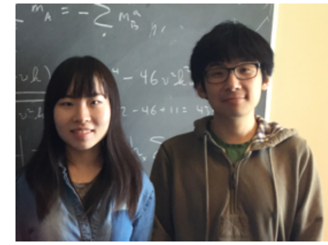


continuum scattering
expected
...but probably with more
structure?



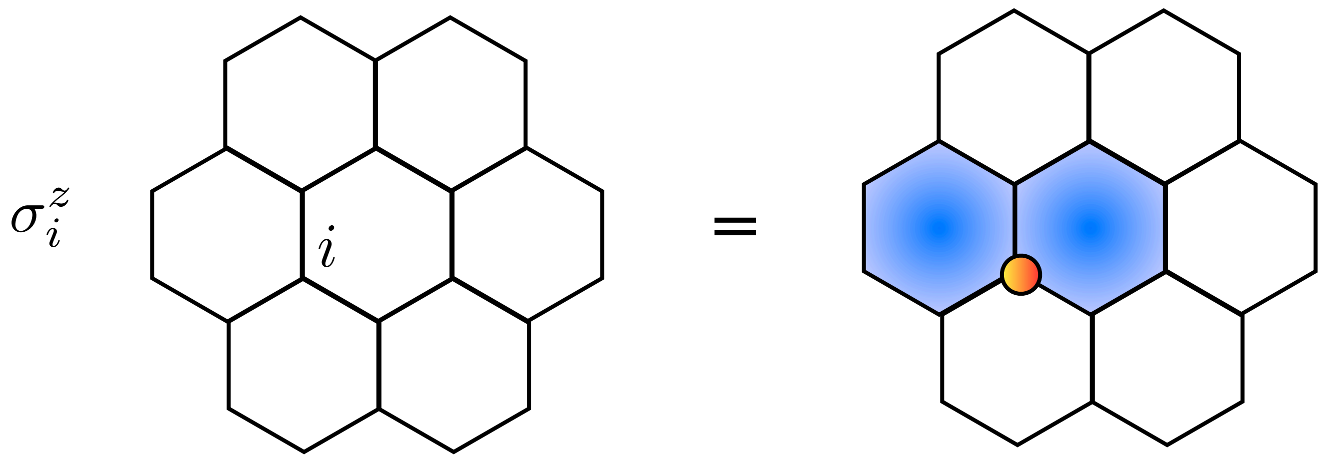
vs





Kitaev QSL

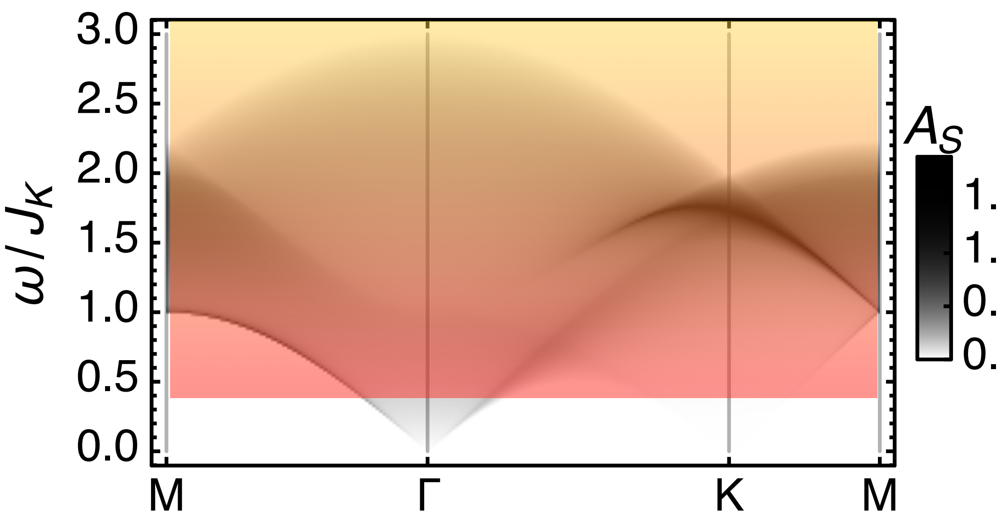
Spin flip produces a free Majorana fermion and two immobile fluxes



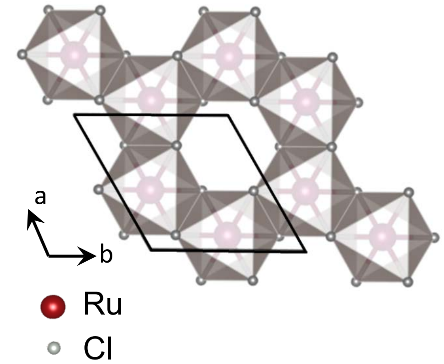
J. Knolle *et al*, 2014

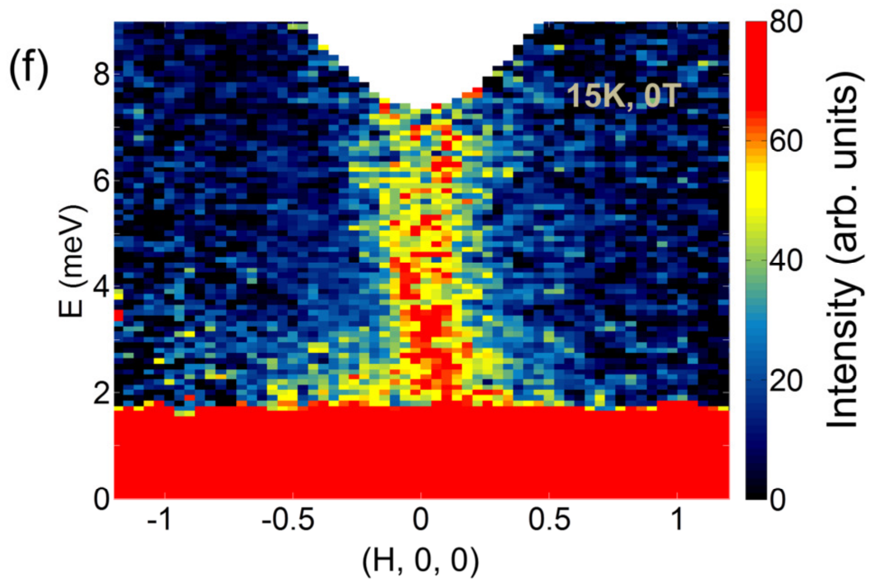
Xueyang Song, Yi-Zhuang You + LB, 2016

dynamical spin correlations in the Kitaev QSL

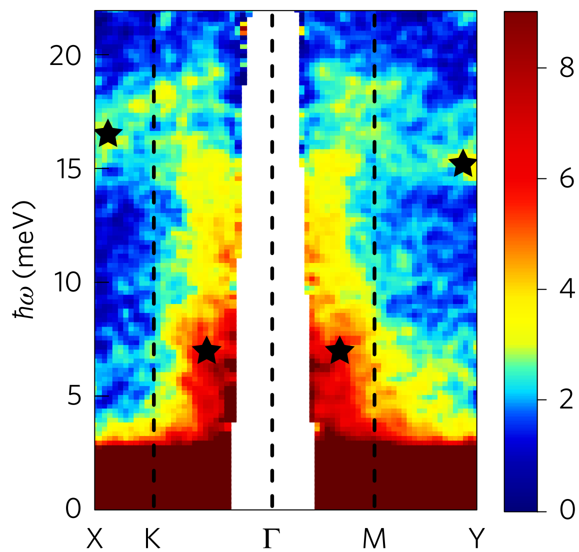


alpha-$RuCl_3$





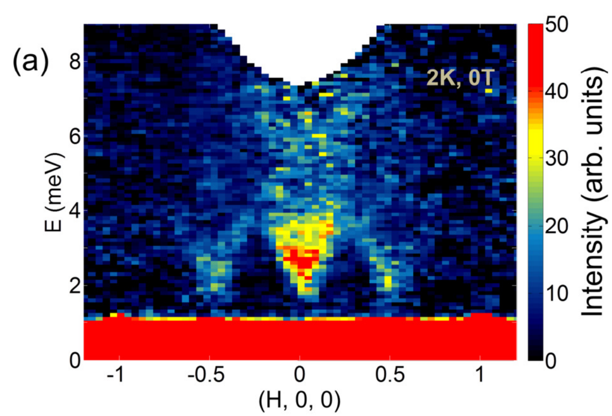
A. Banerjee *et al*, 2017



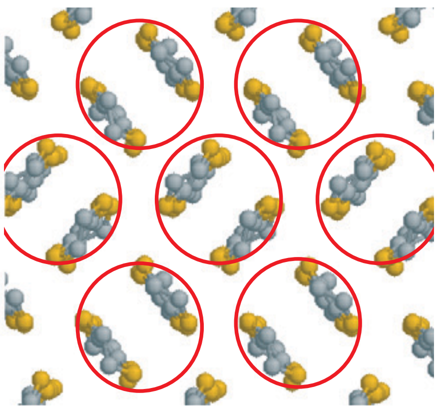
S.-H. Do *et al*, 2017

"column" of scattering suggested to be related to Majorana spinons

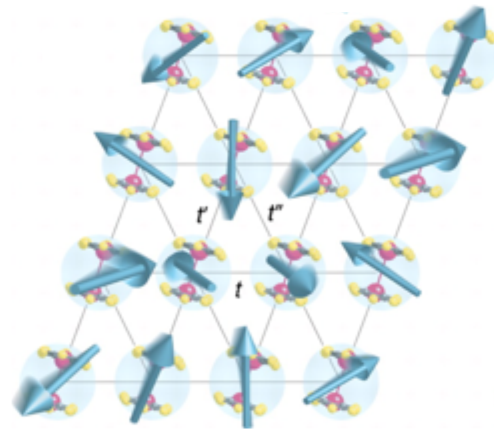
c.f.



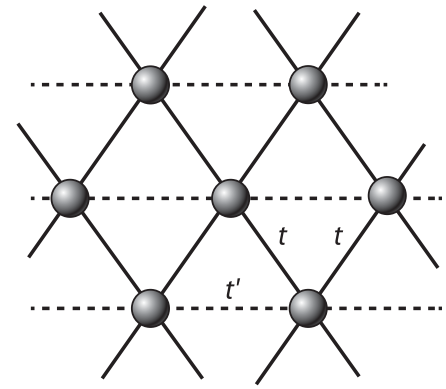
Low energy signatures: triangular organics



κ-$(ET)_2X$

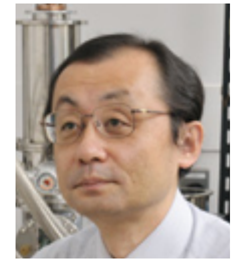


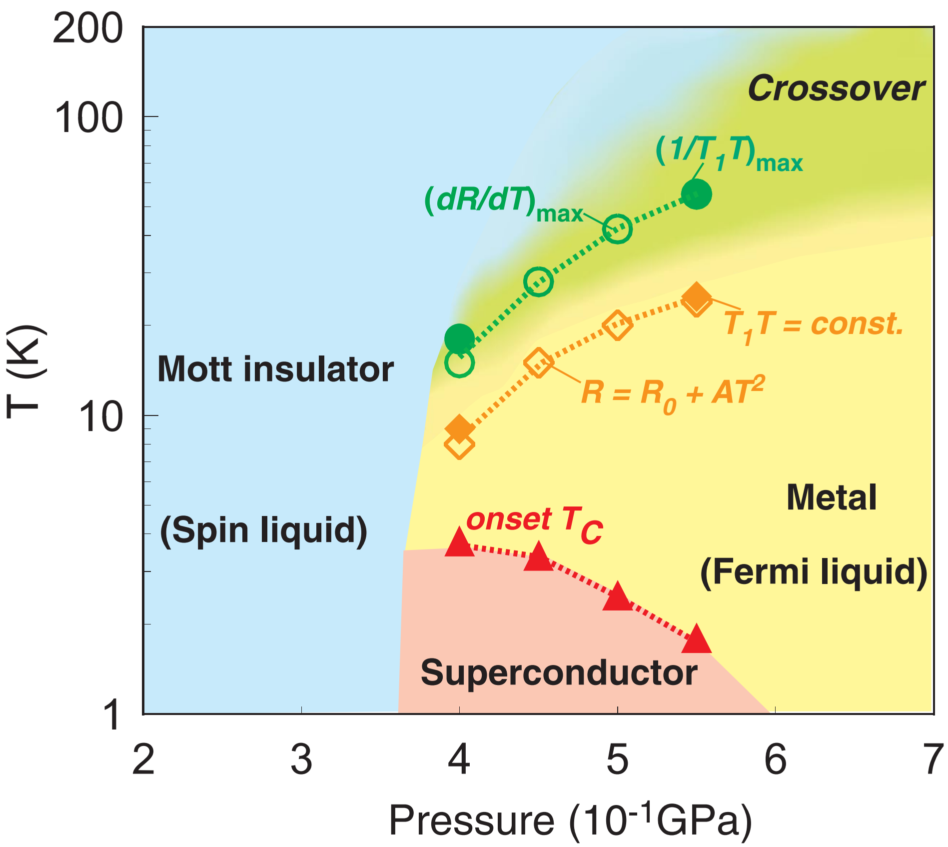
β'-$Pd(dmit)_2$

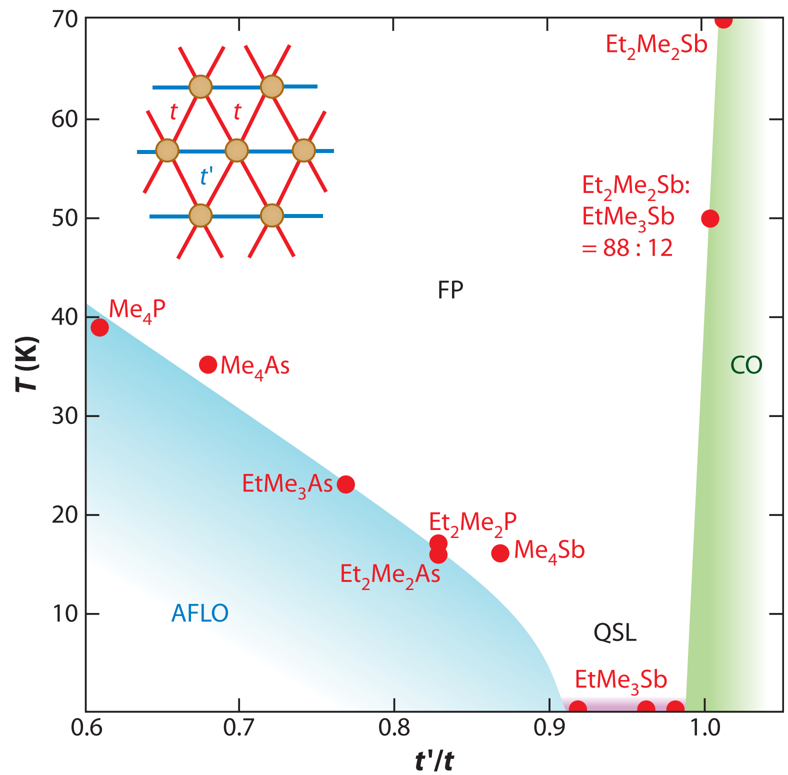


- Molecular materials which behave as effective triangular lattice S=1/2 antiferromagnets with J ~ 250K
  - significant charge fluctuations

triangular organics







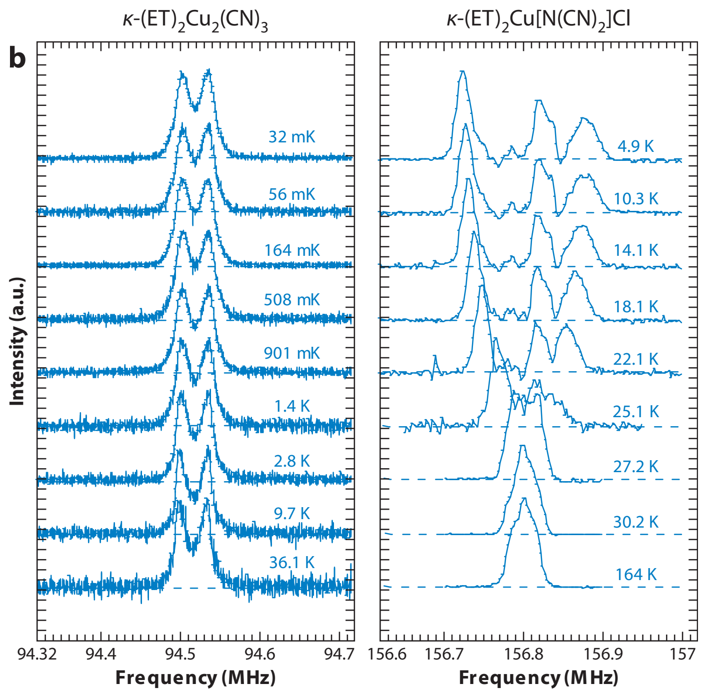
κ-$(ET)_2Cu_2(CN)_3$

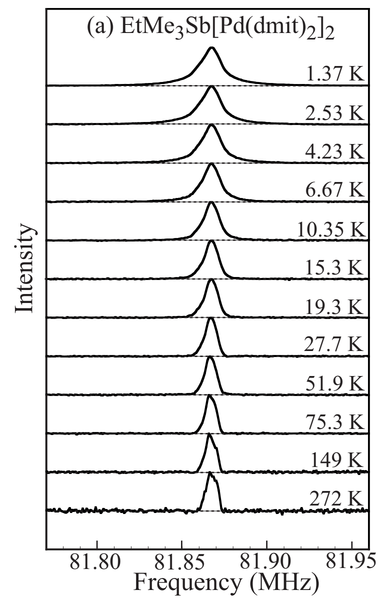
β′-$Pd(dmit)_2$

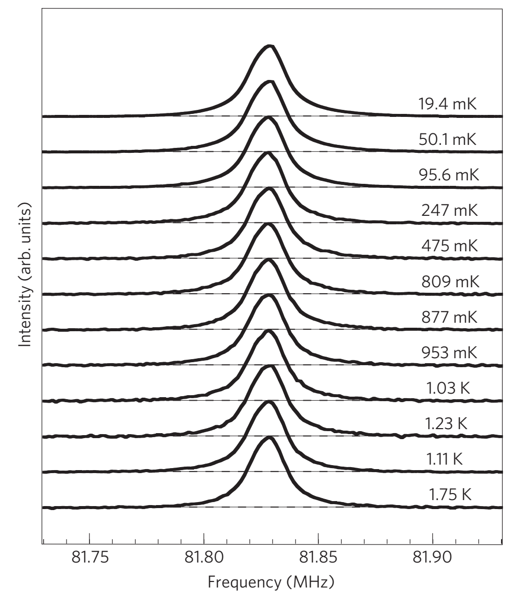
K. Kanoda group (2003-)

R. Kato group (2008-)

NMR lineshapes







κ-$(ET)_2Cu_2(CN)_3$

β′-$Pd(dmit)_2$

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

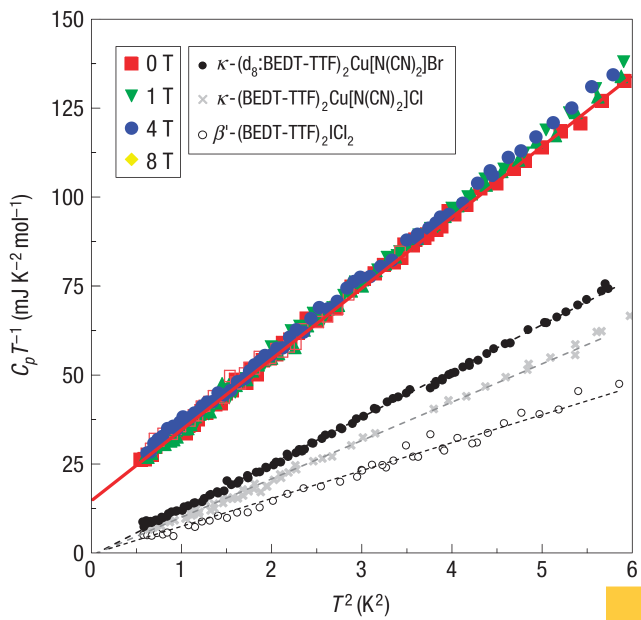
T. Itou *et al*, 2008,2010

^{13}Cs NMR

Evidence for lack of static moments: f > 1000!

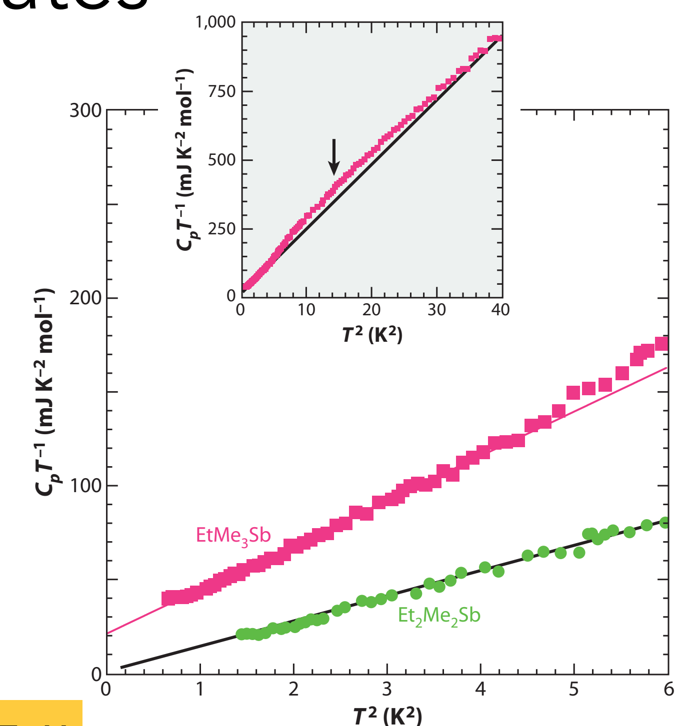
Specific Heat

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



κ-$(ET)_2Cu_2(CN)_3$

γ_{Cu} ~ 0.7 !!

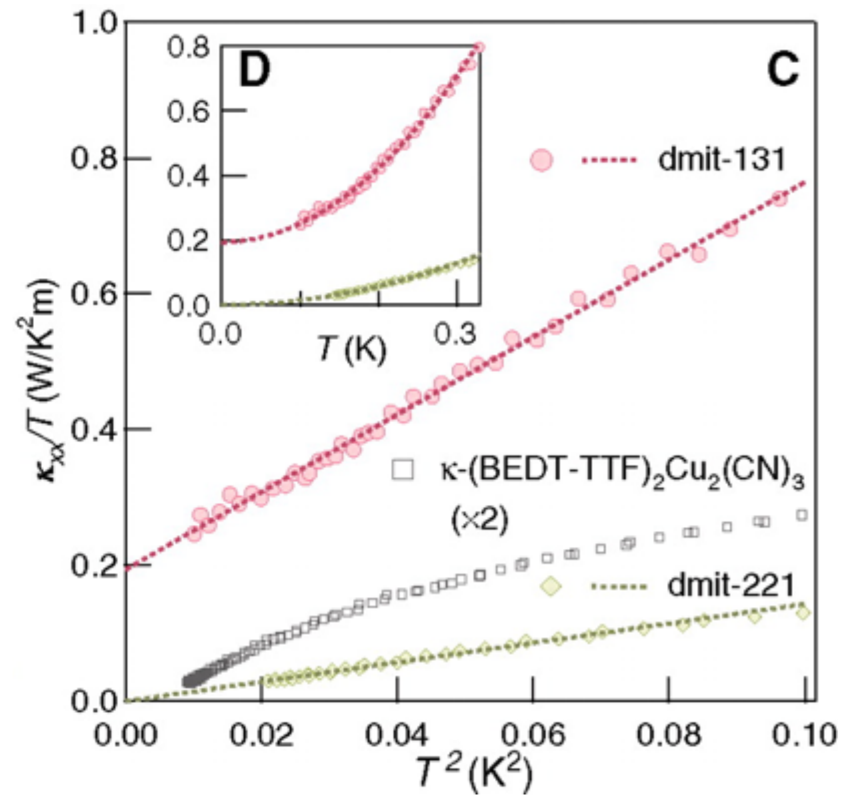


β′-$Pd(dmit)_2$

S. Yamashita *et al*, 2008

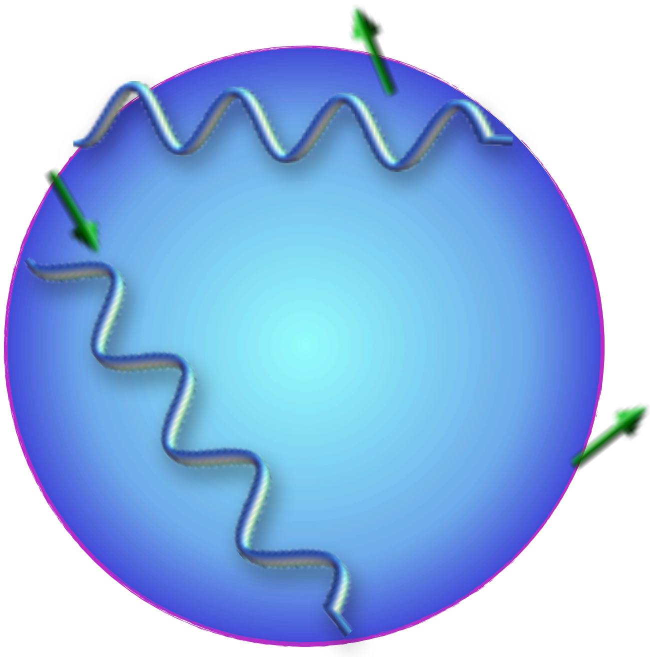
Thermal conductivity

- 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 !

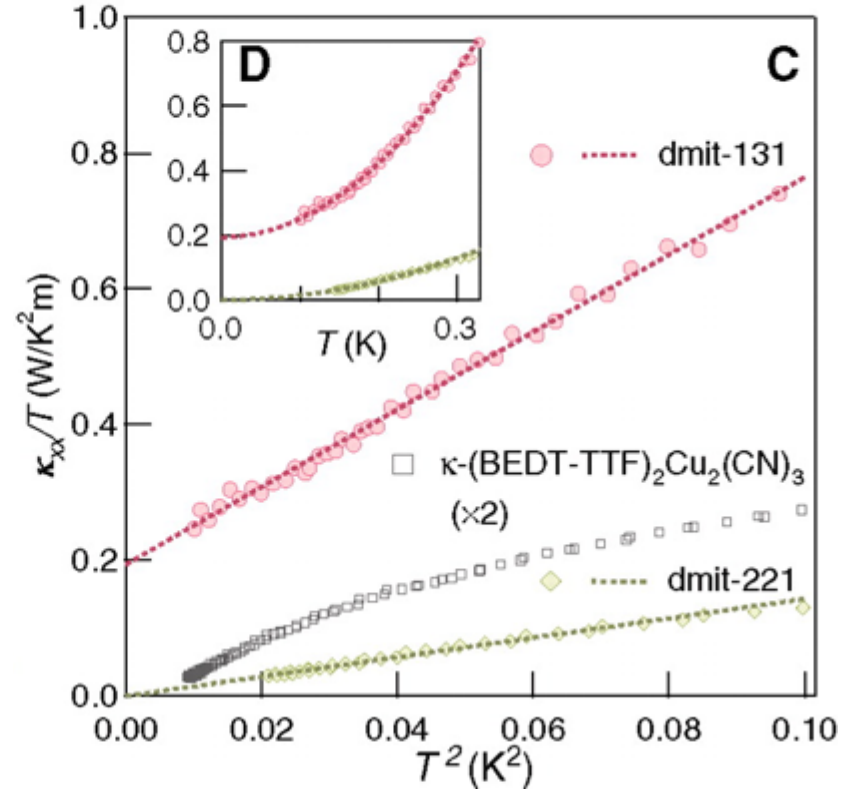


M. Yamashita *et al*, 2010

Thermal conductivity



?

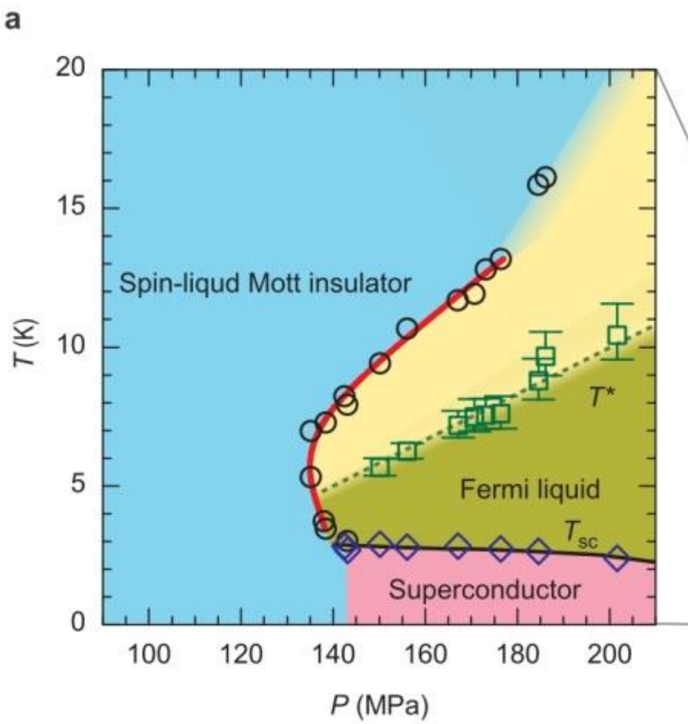


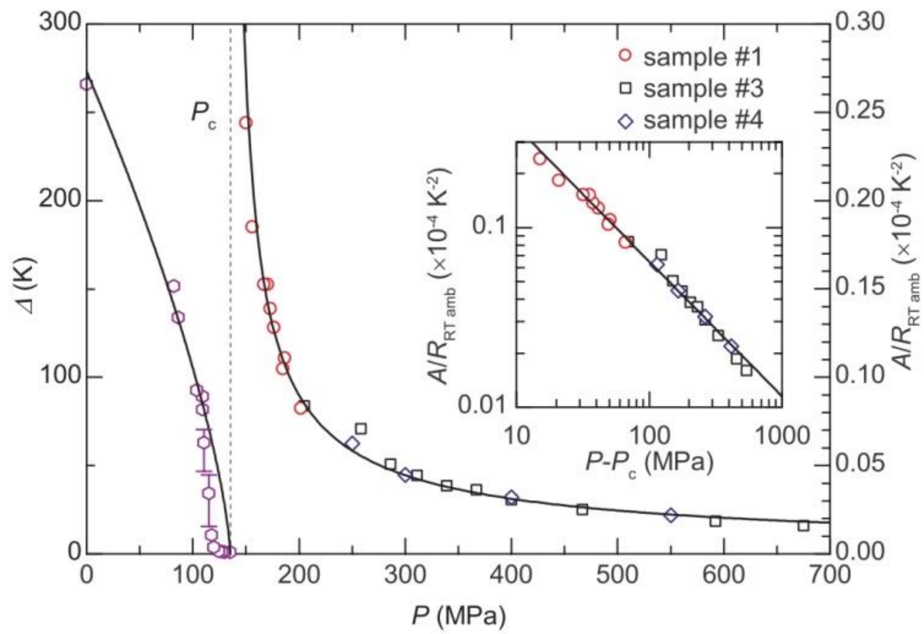
M. Yamashita *et al*, 2010

Spinon Fermi surface

- How could we firm this up?
  - Spinons should be *confined* to 2d. Can we see evidence of this?
    - e.g. $\kappa_c << \kappa_{ab}$ (c.f. Y. Werman *et al*, 2017)
  - See signs of $\mathbf{k_F}$?
    - quantum oscillations, RKKY
  - Possible quantization effects in small systems
  - Observe *conversion* of spinons to electrons in adjacent metal (c.f. T. Senthil, 2008)

Spinons → Electrons?

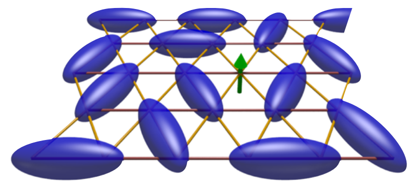




T. Furukawa *et al*, 2017

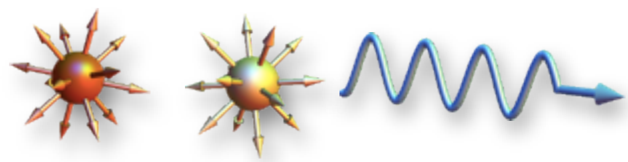
Other QSLs in organics?

- Topological QSLs



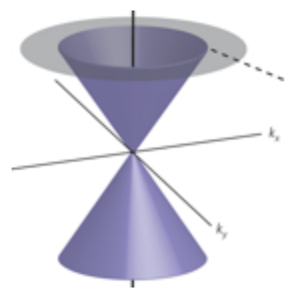
anyonic spinons

- U(1) QSL



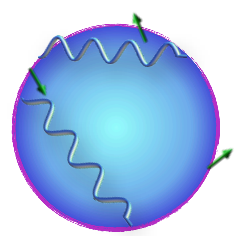
electric+magnetic monopoles, photon

- Dirac QSLs



strongly interacting Dirac fermions

- Spinon Fermi surface



non-Fermi liquid “spin metal”

Thanks for your attention

References here:

- https://spinsandelectrons.com/
- https://spinsandelectrons.com/pedagogy/