Neutral fermions in kagome spin liquids and spin liquid crystals

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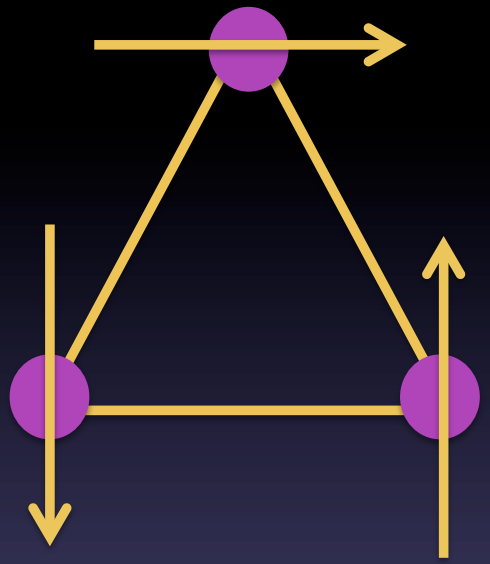
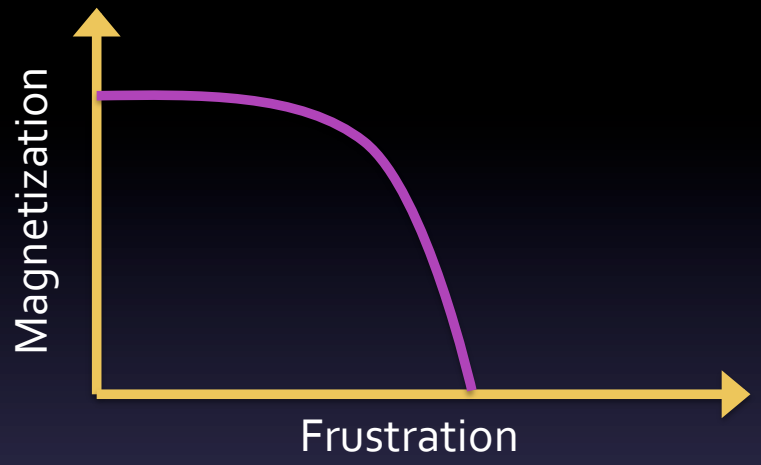
FUNDAMENTAL PROBLEMS IN FRUSTRATED MAGNETISM



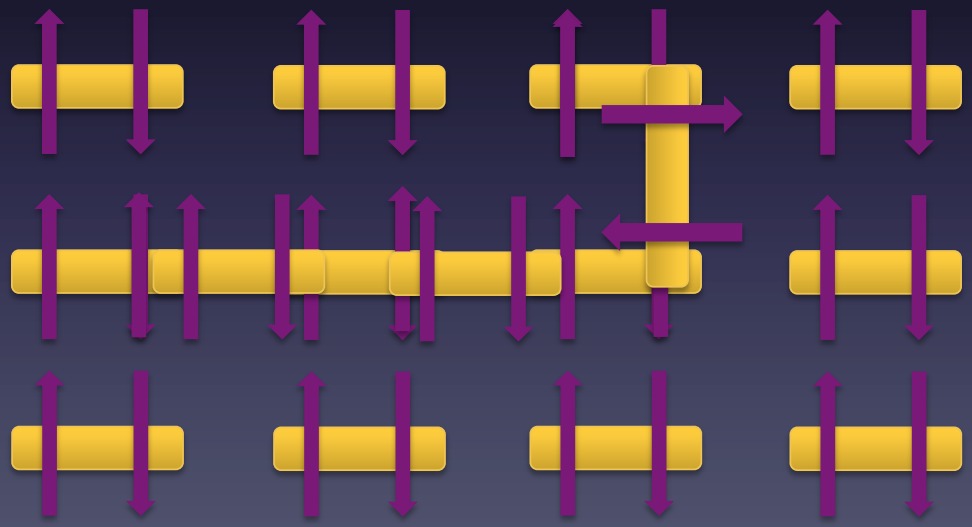


- CAN FRUSTRATION PRODUCE A SPIN LIQUID PHASE?
- IF SO, WOULD IT BE USEFUL?

Cartoon view of spin liquids

Original idea from Anderson, 1973

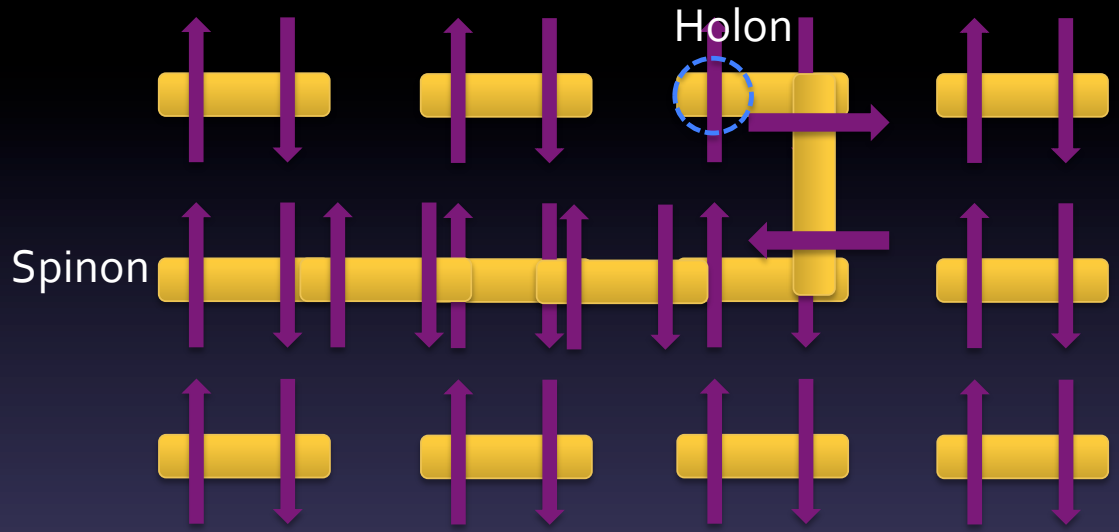
- Ground state: a superposition of singlet states
- Has spin ½ excitations called spinons



- Has singlet excitations called photons or visions

Useful for superconductivity?

Anderson, 1987



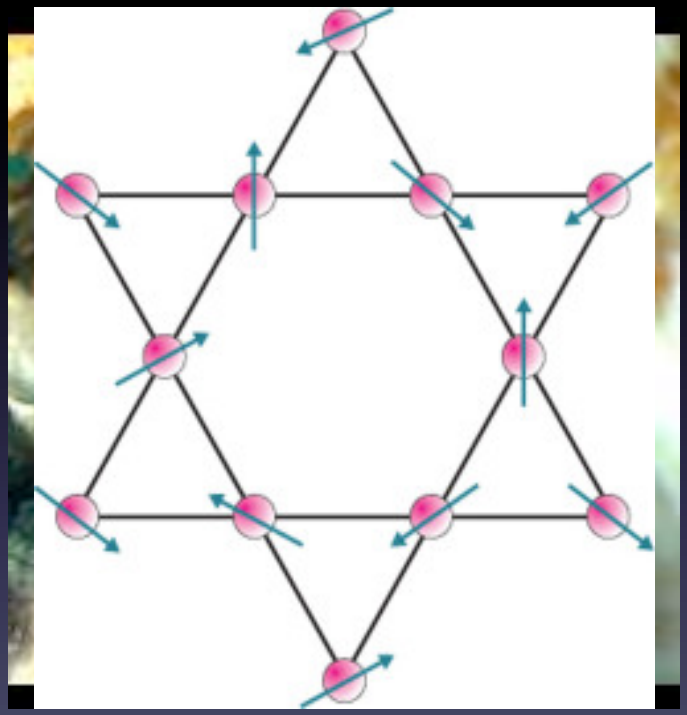
- Mobile singlets become Cooper pairs!
- Slave boson picture: $c_{i\sigma} = b_i f^\dagger_{i\sigma}$
  coherence obtained when bosonic holons condense

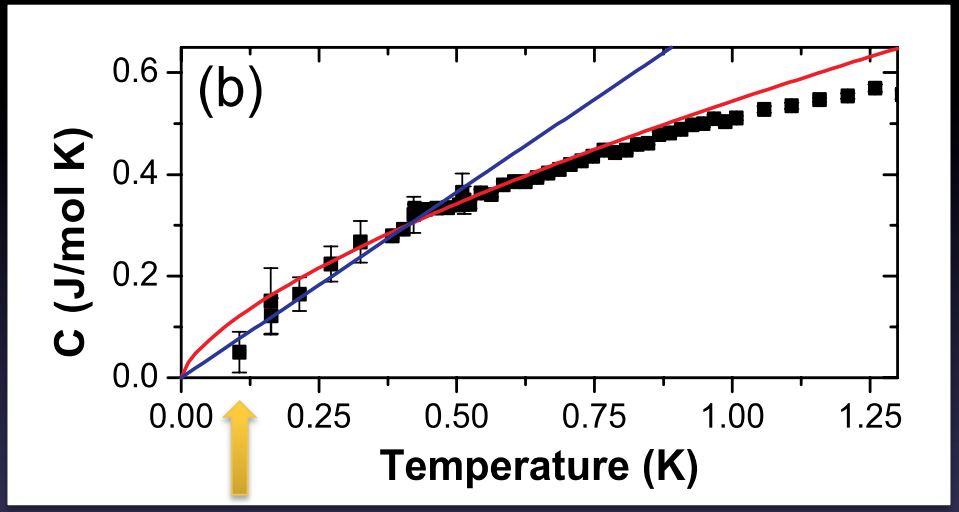
Baskaran, Zou, Anderson, 1987

SO, DO SPIN LIQUIDS EXIST ON FRUSTRATED LATTICES?

Evidence from experiment: Herbertsmithite

Helton et. al. PRL 2007





100 mK!

But $J\vec{S}_i \cdot \vec{S}_j$ has $J \approx 200K$!

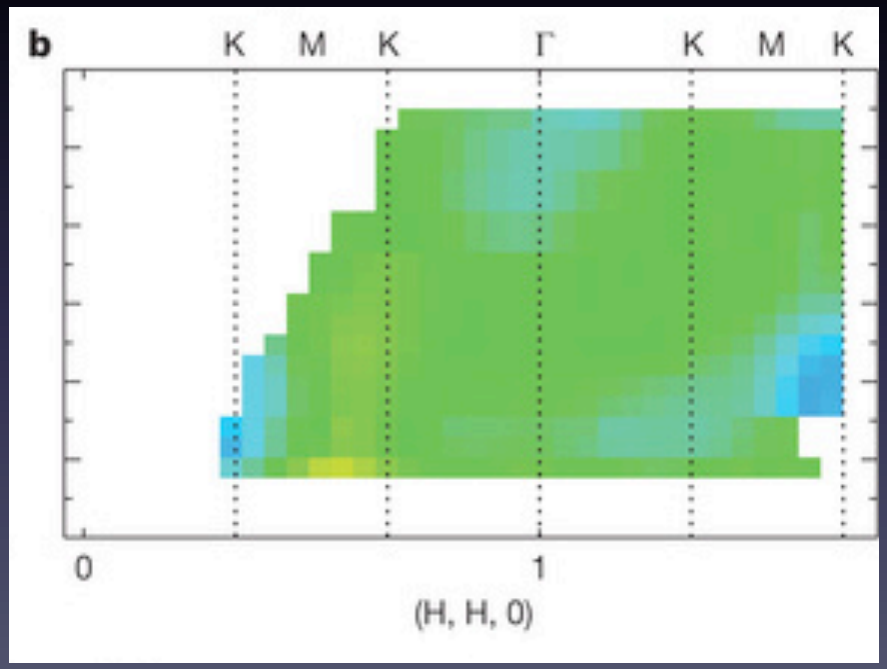
What is this new phase of matter?

http://scepticalprophet.wordpress.com/tag/herbertsmithite/

Certainly not magnetic order!

A recent neutron scattering study found

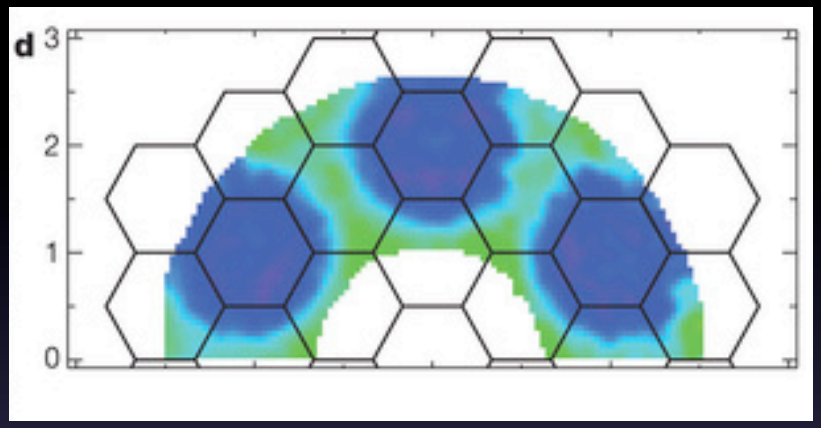
Han et. al. Nature 2012



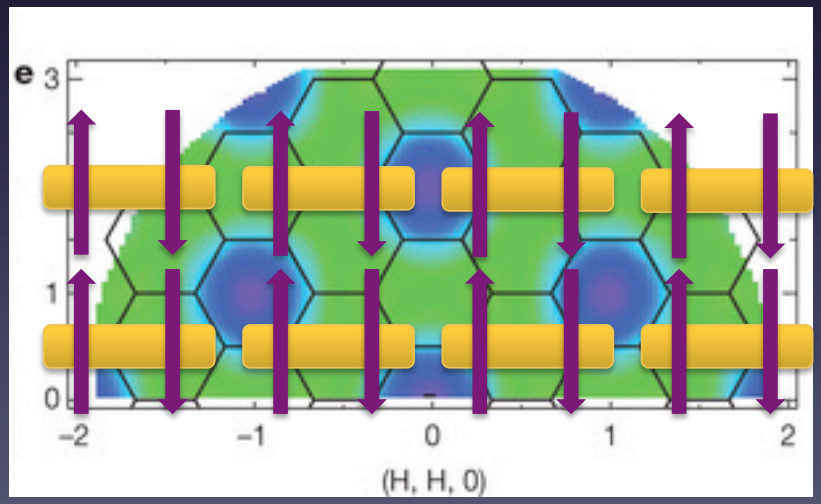
No sign of spin waves!

Evidence for valence bonds

Han et. al. Nature 2012



Energy Integrated S(q,w)



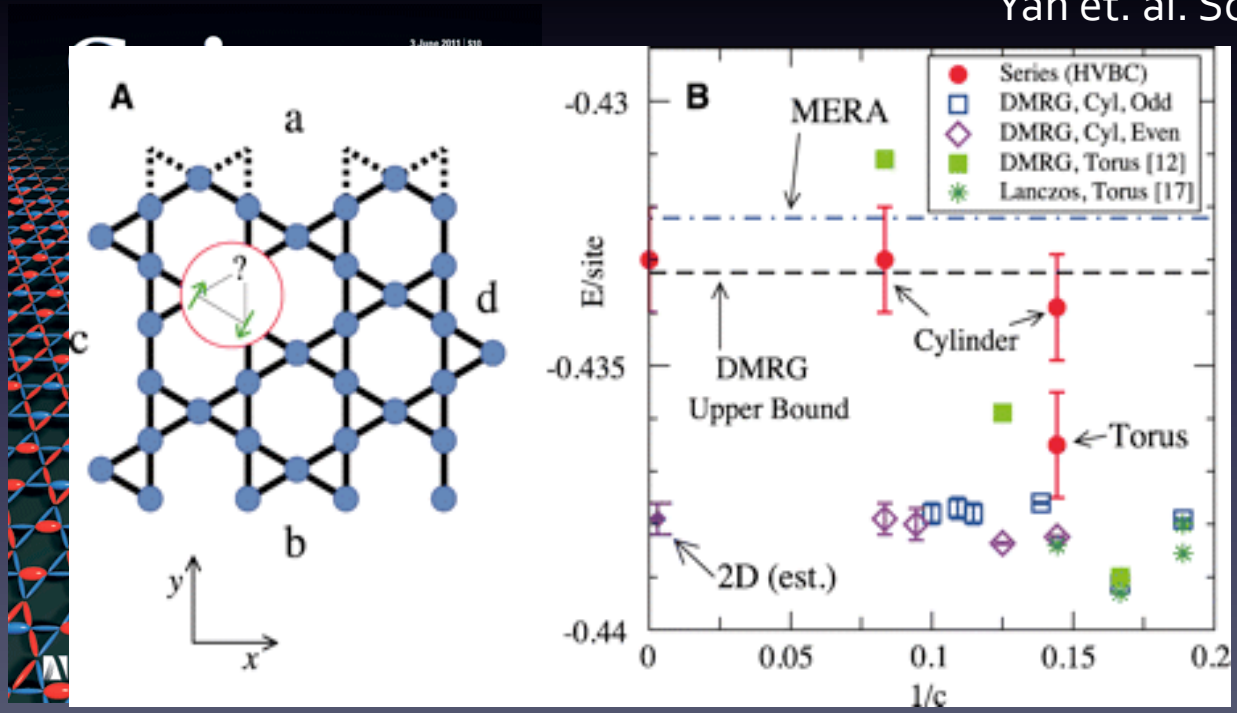
Prediction from an average over many valence bond crystal states

However, it is hard to see how the spinons behave!

Evidence from numerics

A spin liquid was recently found in DMRG calculations!

Yan et. al. Science 2011

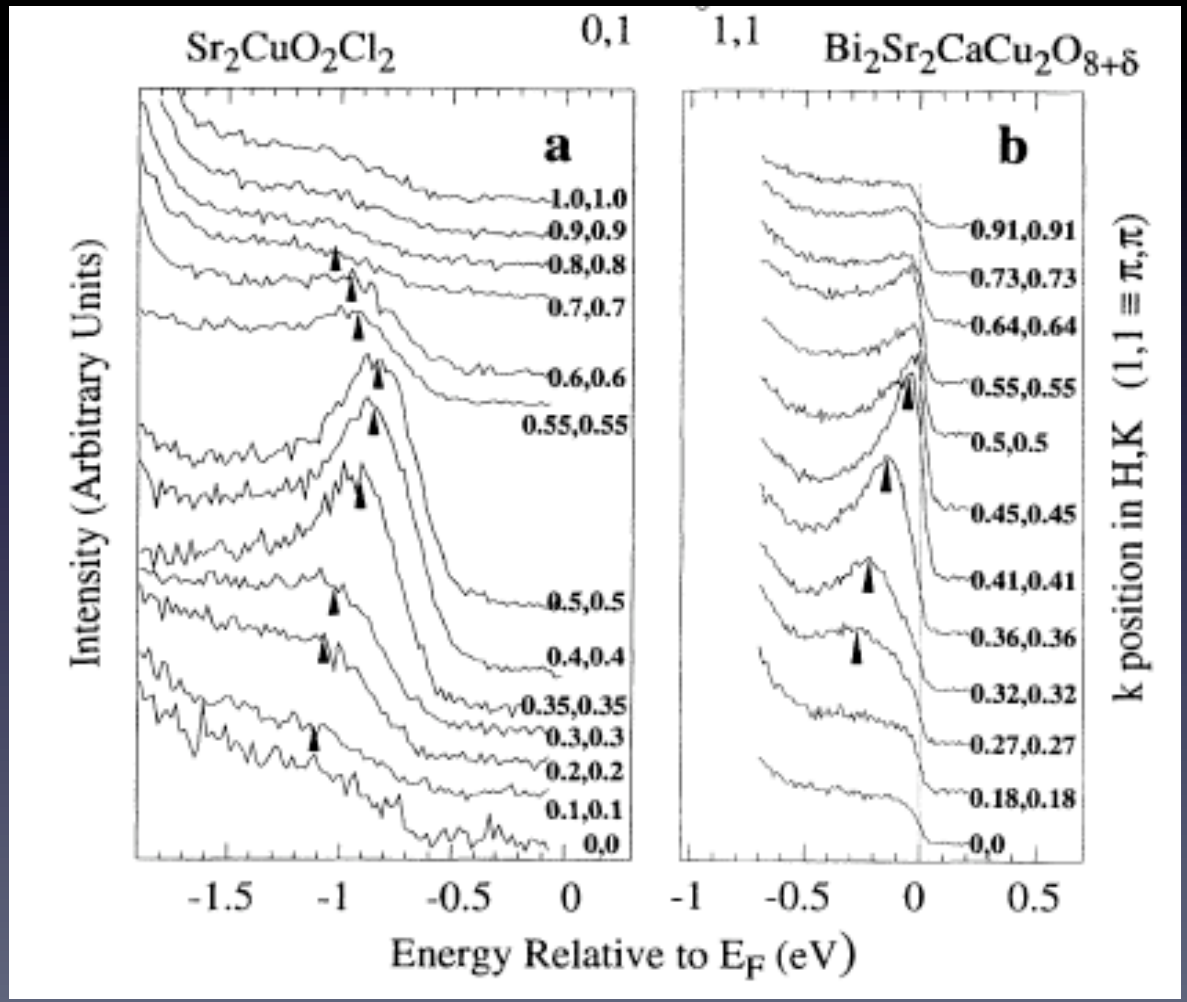


Future directions for the field

- Do spinon's exist? Are they fermions?
- How can we find more spin liquid phases?
- Are there other exotic magnetic phases?
- Which spin liquid is it?
- Do they produce superconductivity?
- Are there broader implications for this research in other areas of physics?

Do spinons exist?

ARPES on undoped cuprates: spinons and holons?

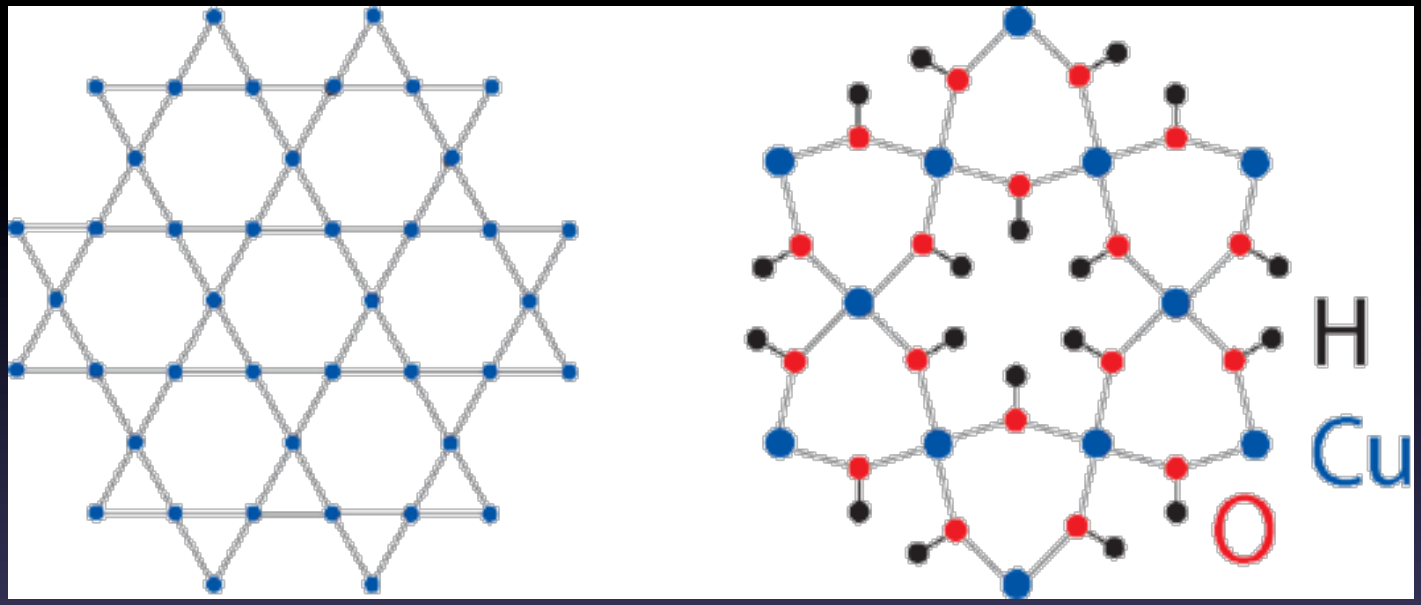


Laughlin, PRL,1997: electron decays into a spinon and a holon

$$c_{i\sigma} = b_i f^\dagger_{i\sigma}$$

Wells et. al., 1995

ARPES on Herbertsmithite?



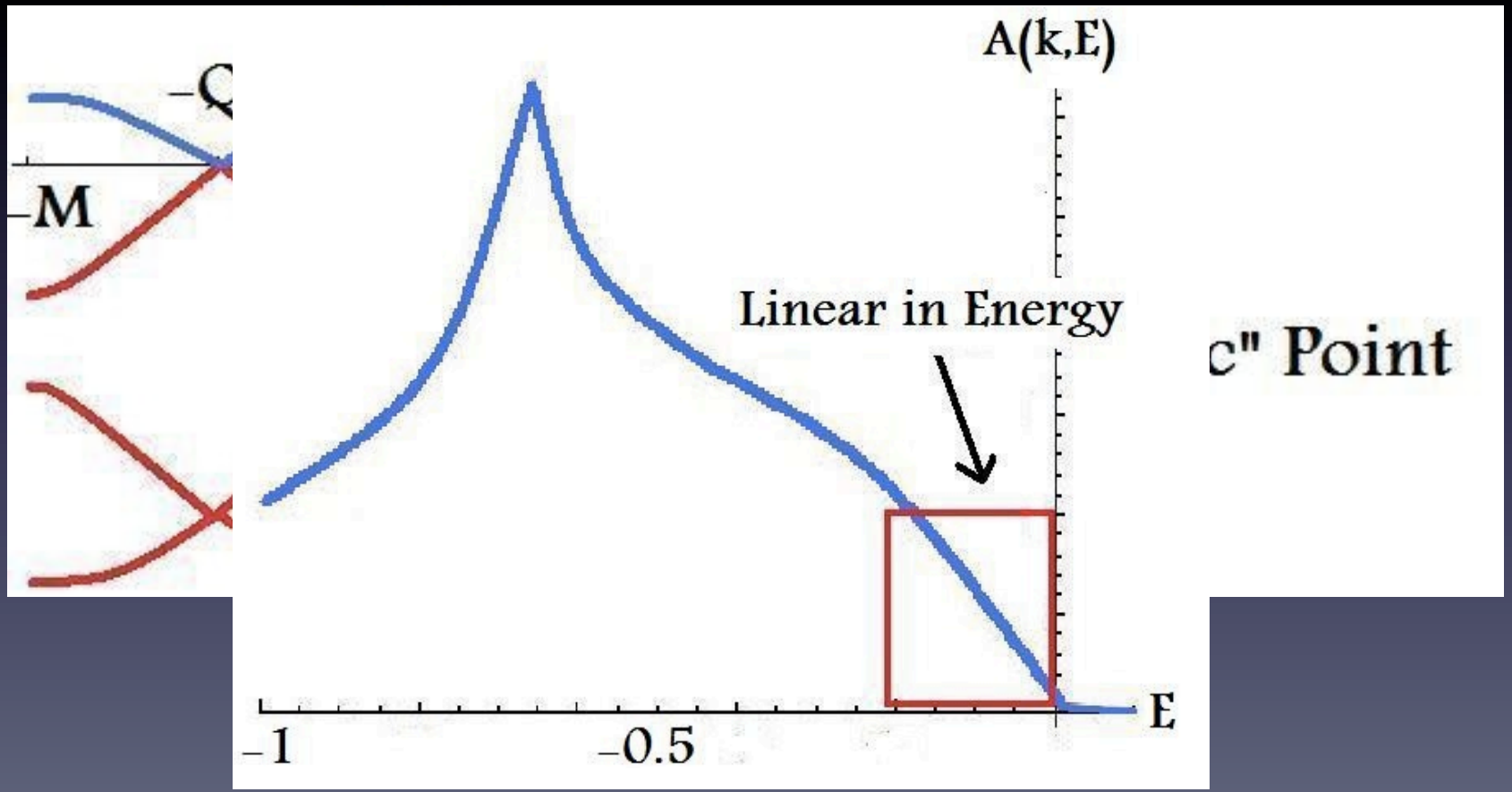
Leading theory of spinons in herbertsmithite proposes they are Dirac fermions interacting with a maxwell-like photon

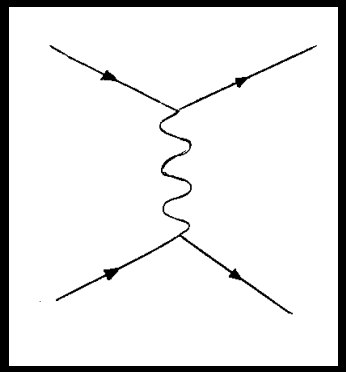
Ran et. al. PRL. 2007

Predictions of Free Dirac spinons

Pujari and Lawler, PRB, 2013

Spin-Orbit perturbation of the Dirac node in k-space:





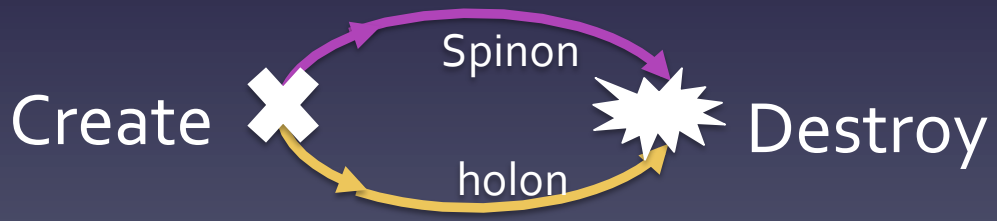
Interacting Dirac Spinons

Pujari and Lawler, PRB, 2013

Free fixed point

Interacting fixed point $\eta>0$

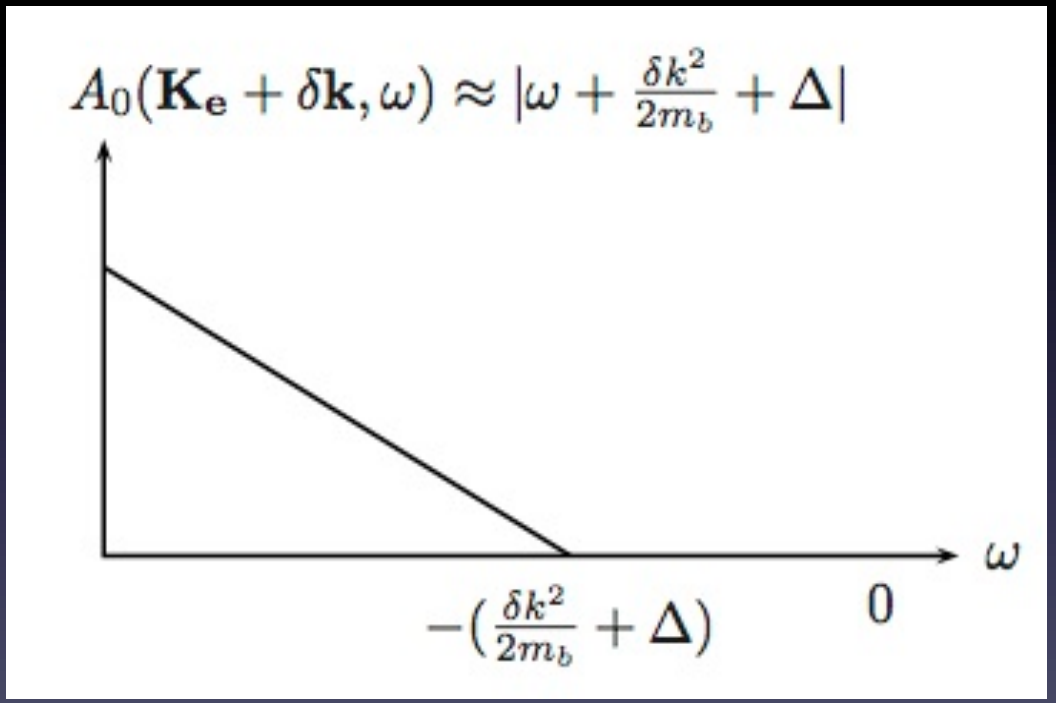
However



Electron correlations unrenormalized!

Contact interaction

Tang, Fisher, Lee, PRB 2013



Justified by crude contact interaction model with no understanding of gauge invariance.

Future directions for the field

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- How can we find more spin liquids?
- Are there other types of magnetic phases?
- Which spin liquid is it?
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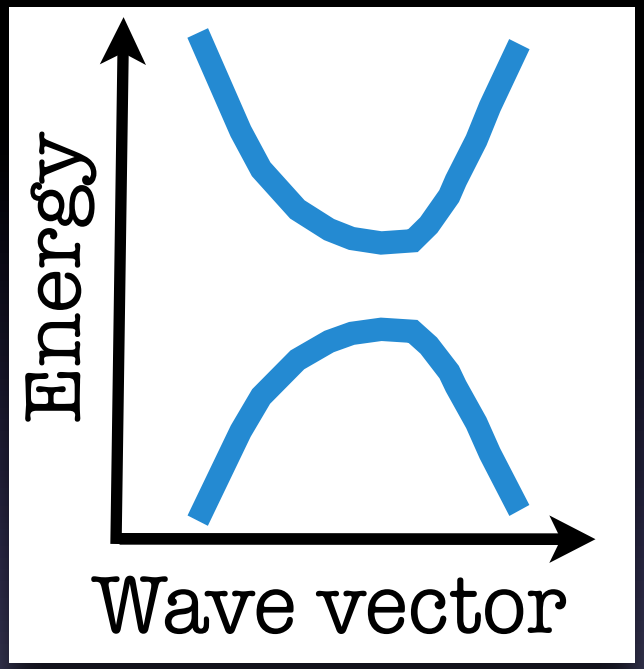
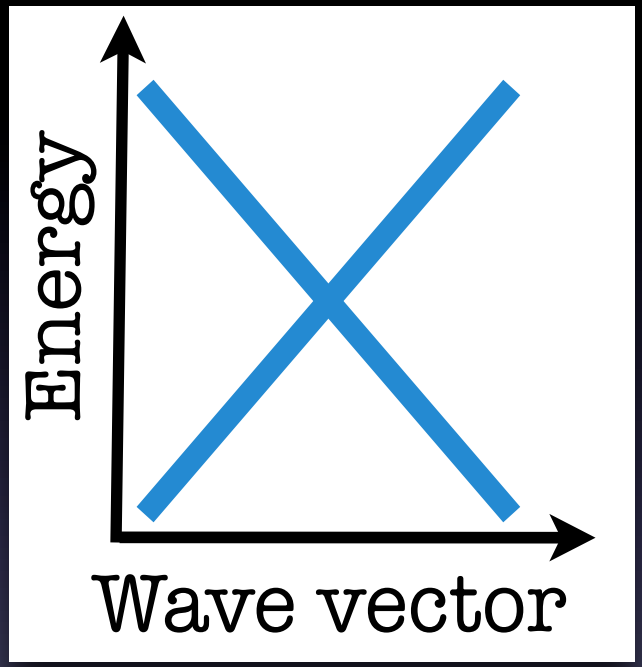
Instability of Dirac spinons

Lu, Ran, Lee, PRB 2012



"Cooper" Pairing



Spin liquid in DMRG

U(1) Dirac State

DMRG ➡ Dirac state unstable at low temperatures

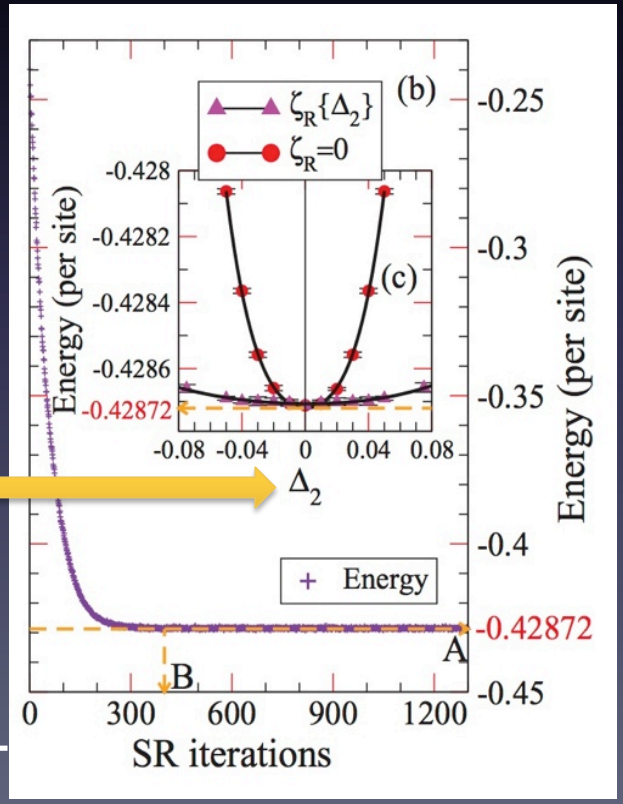
But how?

State	$8 \times 8 \times 3$ lattice	$12 \times 12 \times 3$ lattice
U(1)-Dirac spin liquid	−0.42866(2)	−0.42863(2)
VBS state ($\lvert\chi_1/\chi_2\rvert = 1.05$)	−0.42848(2)	−0.42844(2)
VBS state ($\lvert\chi_1/\chi_2\rvert = 0.95$)	−0.42846(2)	−0.42846(2)
Chiral spin liquid ($\theta = 0.05$)	−0.42857(2)	−0.42853(2)

Spin liquid	$8 \times 8 \times 3$ lattice	$12 \times 12 \times 3$ lattice
SL-$[\frac{\pi}{2}, 0]$	−0.4010(1)	−0.4010(1)
SL-$[\pm\frac{\pi}{2}, 0]$	−0.3907(1)	−0.3910(1)
SL-$[\frac{\pi}{2}, \pi]$	−0.3814(1)	−0.3822(1)
SL-$[0, 0]$	−0.4115(1)	−0.4121(1)
SL-$[0, \pi]$	−0.42866(2)	−0.42863(2)

Ran et. al., PRL 2007

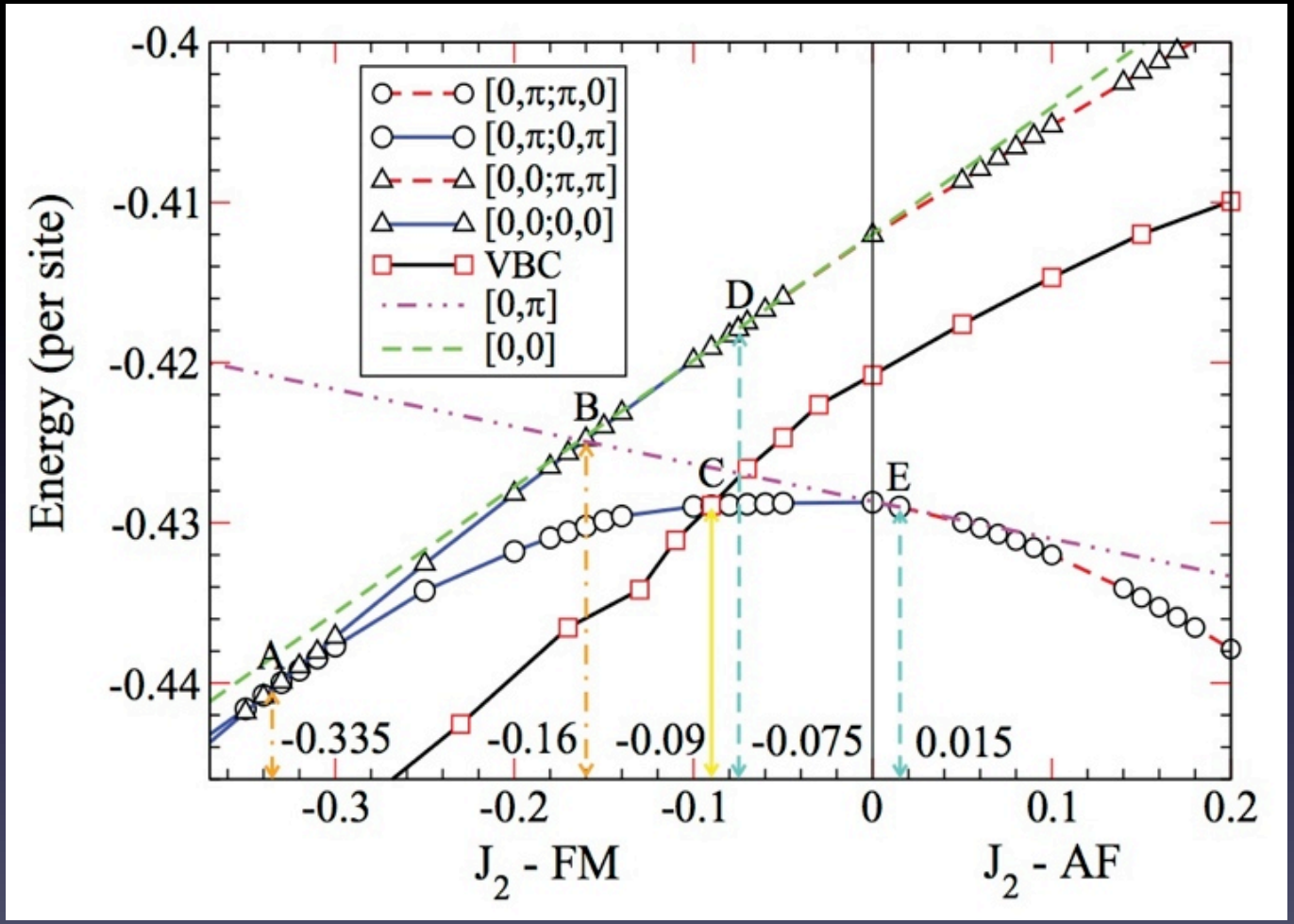
BCS pairing gap



Yqbal, Becca, Poiblanc, PRB, July 2011

But how?

Yqbal, Becca, Poiblanc, PRB, March 2011



Dirac spin liquid wins again at J2 = 0

Look at all modified BCS wave functions!

Clark et. al.,
under review at PRL

Lu, Ran, Lee PRB 2010

No.	η_{12}	Λ_s	u_α	u_β	u_γ	$\tilde{u}_\gamma$	Label	Gapped?
1	$+1$	τ^2,τ^3	τ^2,τ^3	τ^2,τ^3	τ^2,τ^3	τ^2,τ^3	$Z_2[0,0]A$	Yes
2	-1	τ^2,τ^3	τ^2,τ^3	τ^2,τ^3	τ^2,τ^3	0	$\mathbb{Z}_2[0,\pi]\beta$	**Yes**
3	$+1$	0	τ^2,τ^3	0	0	0	$Z_2[\pi,\pi]A$	No
4	-1	0	τ^2,τ^3	0	0	τ^2,τ^3	$Z_2[\pi,0]A$	No
5	$+1$	τ^3	τ^2,τ^3	τ^3	τ^3	τ^3	$Z_2[0,0]B$	Yes
6	-1	τ^3	τ^2,τ^3	τ^3	τ^3	τ^2	$Z_2[0,\pi]\alpha$	No
7	$+1$	0	0	τ^2,τ^3	0	0	–	–
8	-1	0	0	τ^2,τ^3	0	0	–	–
9	$+1$	0	0	0	τ^2,τ^3	0	–	–
10	-1	0	0	0	τ^2,τ^3	0	–	–
11	$+1$	0	0	τ^2	τ^2	0	–	–
12	-1	0	0	τ^2	τ^2	0	–	–
13	$+1$	τ^3	τ^3	τ^2,τ^3	τ^3	τ^3	$Z_2[0,0]D$	Yes
14	-1	τ^3	τ^3	τ^2,τ^3	τ^3	0	$Z_2[0,\pi]\gamma$	No
15	$+1$	τ^3	τ^3	τ^3	τ^2,τ^3	τ^3	$Z_2[0,0]C$	Yes
16	-1	τ^3	τ^3	τ^3	τ^2,τ^3	0	$Z_2[0,\pi]\delta$	No
17	$+1$	0	τ^2	τ^3	0	0	$Z_2[\pi,\pi]B$	No
18	-1	0	τ^2	τ^3	0	τ^3	$Z_2[\pi,0]B$	No
19	$+1$	0	τ^2	0	τ^2	0	$Z_2[\pi,\pi]C$	No
20	-1	0	τ^2	0	τ^2	τ^3	$Z_2[\pi,0]C$	No

$$\hat{\mathcal{P}} \prod_{ij} \left(1 + \phi_{ij} f^\dagger_{i\uparrow} f^\dagger_{j\downarrow}\right) |0\rangle$$

Initial values

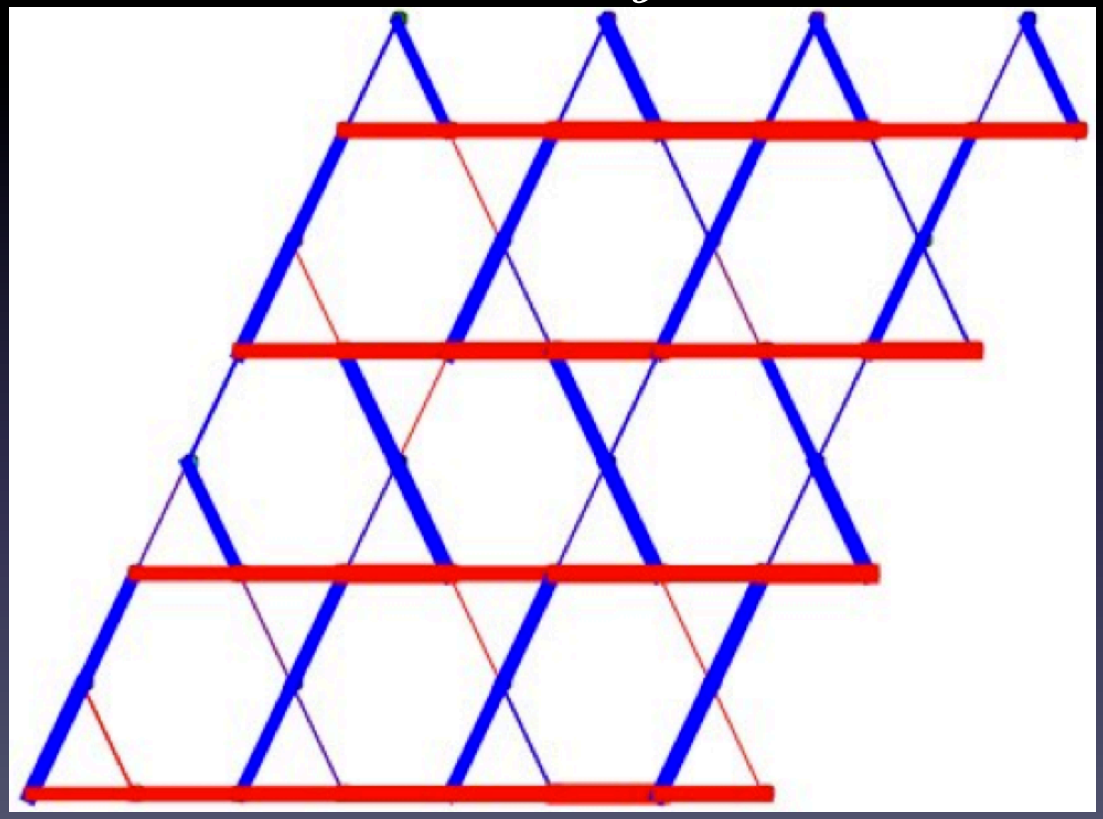
Minimize N^2 Variational Parameters

Largest known catelog of kagome spin liquids

New Ground State?

Smectic spin liquid!

$$\langle \Psi | \vec{S}_i \cdot \vec{S}_j | \Psi \rangle$$



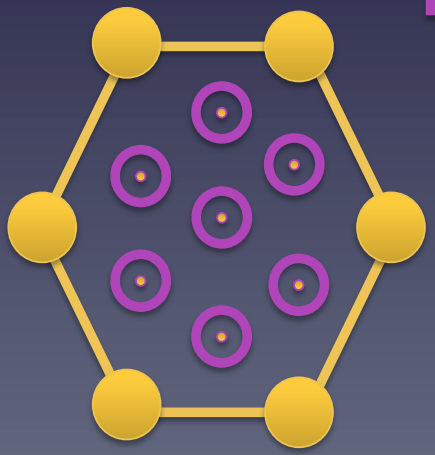
Also, we find evidence for Cooper pairing of the spinons

Proliferation of Monopoles

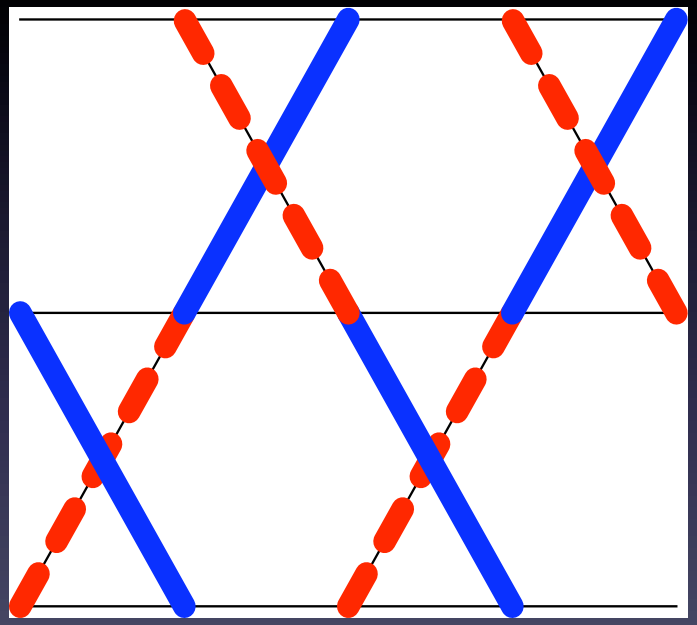
π Flux

Same Energy

3π Flux



Monopole operator found in 3D CFT
Hermele, et. al. PRB 2008

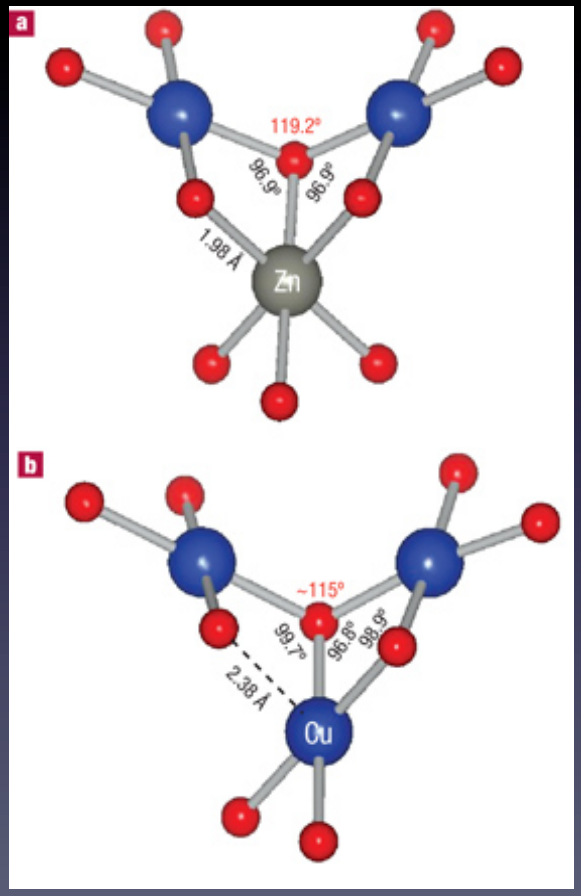


Monopole wave function

Clark, et. al., under review at PRL

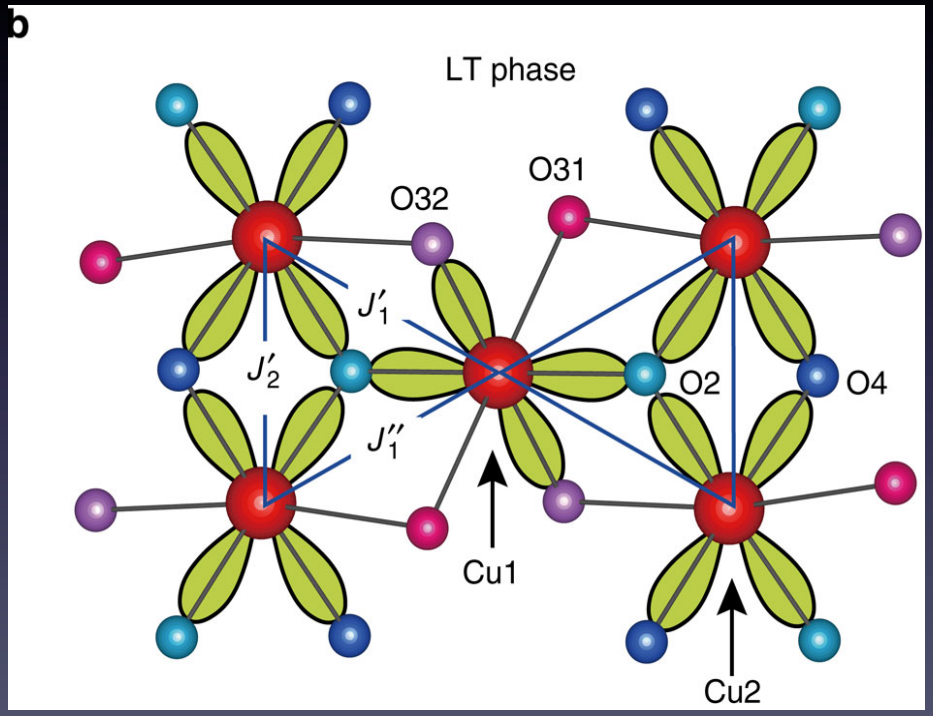
Distorted Kagome Systems

Zn free Herbertsmithite (clinoatacamite)



S.-H. Lee, Nat. Mat. 2007

Single Crystals of Volborthite



Yoshida et. al. Nat. Comm. 2012

Future directions for the field

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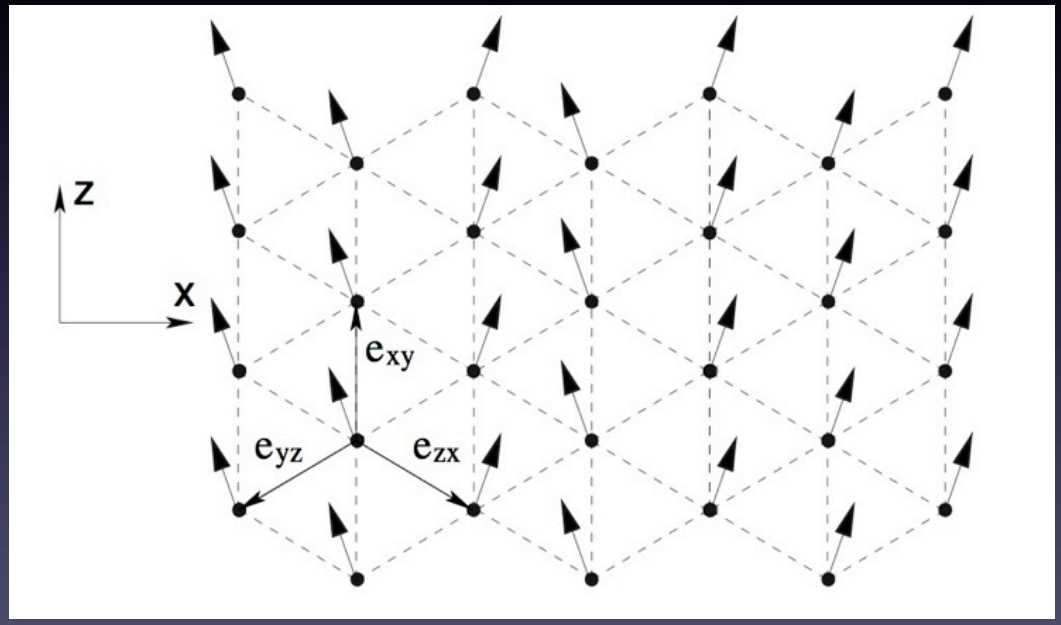
Orbital Frustration in $LiNiO_2$

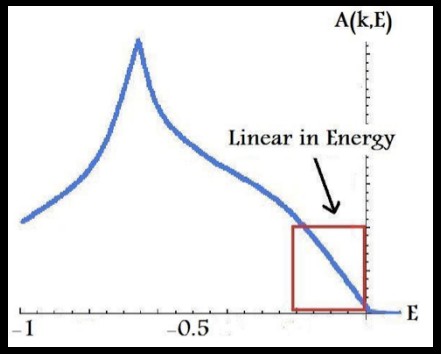
- Well known Li-ion Battery material (Ohzuku et. al. J. Electrochem. Soc., 1993)

Pseudospin eg Orbitals don't order

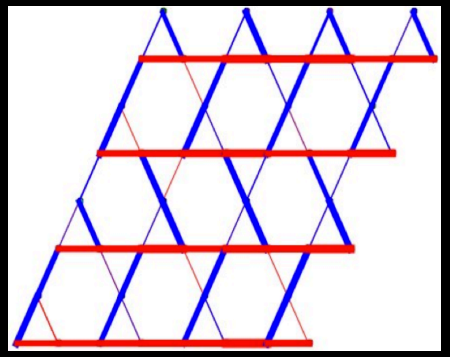


Mostovoy and Khomskii, J. of Phys. A, 2003

So does frustration help?



Conclusions



- Substantial evidence for spin liquid phases but exotic properties still undetected
- Proposed a signature for fermionic spinons in ARPES
- Proposed the existence of spin liquid crystals that also have fermionic spinons