Title: Spin-1/2 Heisenberg Antiferromagnet on the Kagome Lattice: a Z2 Spin Liquid with Fermionic Spinons

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Abstract: Motivated by recent numerical and experimental studies of the spin-1/2 Heisenberg antiferromagnet on kagome, we formulate a many-body model for fermionic spinons, which are just uncoupled spins. The spinons interact with an emergent U(1) gauge field and experience strong short-range attraction in the S=0 channel. The ground state of the model is generically a Z(2) liquid. We calculate the edge of the two-spinon continuum and compare the theory to the slave-fermion approach to the Heisenberg model.


Spin ½ antiferromagnet on kagome:
a Z_2 liquid with fermionic spinons
Zhihao Hao
University of Waterloo
Hao and Tchernyshyov, arXiv:1301.3261

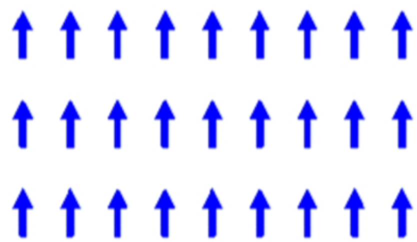
Outline

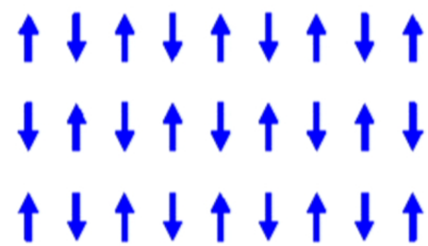
- Background.
- Prelude: a field trip with two spinons.
- The many-body model: a Z_2 liquid with fermionic spinons.
- Some properties of the Z_2 liquid.
- Future directions.

Motivation I

- Magnetic phases.

Classical paramagnetic phase → "Spin gas"



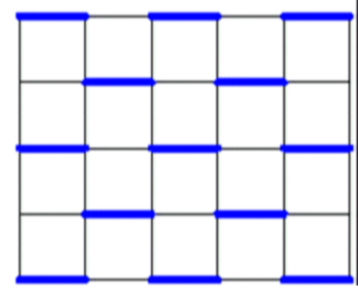


Ferromagnet → "Spin solid" ← Anti-ferromagnet

What else is out there?

Quantum spin liquid (?)

- No semiclassical ordered moment: $\langle \vec{S}_i \rangle = 0.$
- A coherent quantum state with no broken symmetry, thus a "liquid".
- Resonate valence bond state (RVB)[1]: superposition of states with maximum number of singlets.



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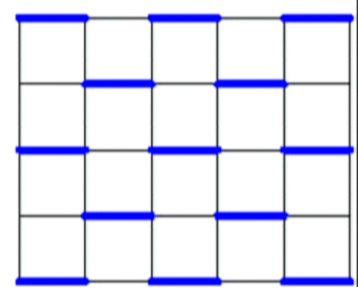

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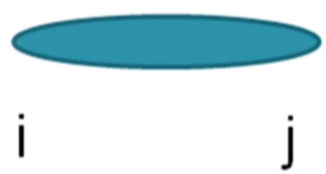
"Melting" the "spin solid"

- $H = J\sum_{<ij>} \vec{S}_i \cdot \vec{S}_j$

The classical ground state: E= −0.25 *J* per bond for *S*= ½.

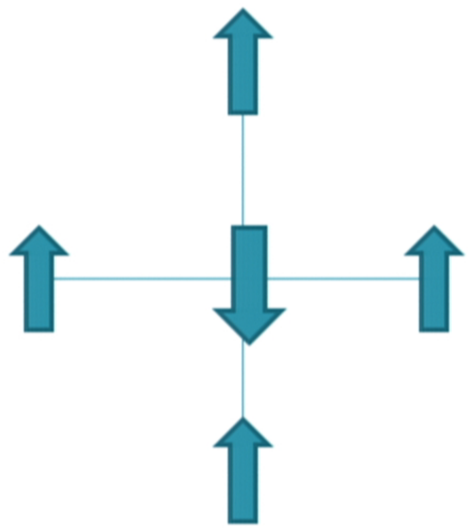


The quantum ground state for *S*=1/2, a singlet . Also known as a valence bond or a dimer. E= −0.75*J*.

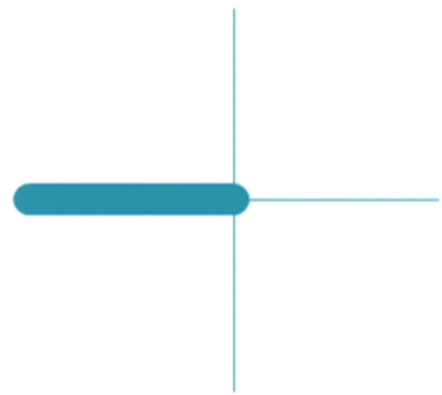
$$\frac{1}{\sqrt{2}}\left(\left|i,\uparrow;j,\downarrow\right\rangle-\left|i,\downarrow;j,\uparrow\right\rangle\right)$$

"Melting" the "spin solid"

- Semiclassical long-range order can lower the energy of all nearest neighbors.



$E = -0.5\,J$ per site



$E = -0.375\,J$ per site

"Melting" the "spin solid"

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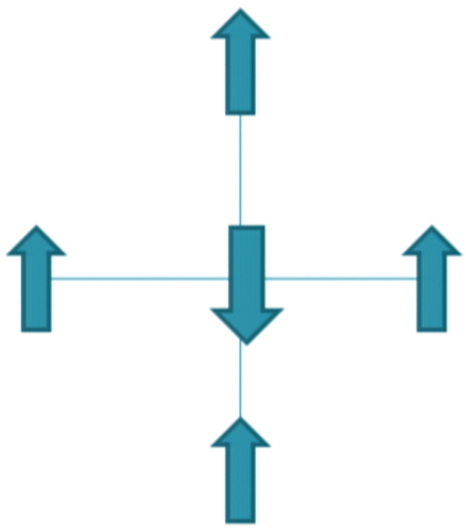
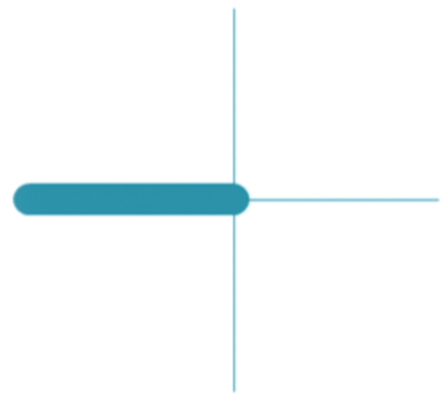
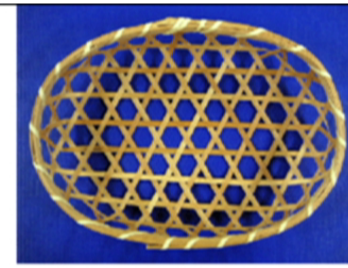




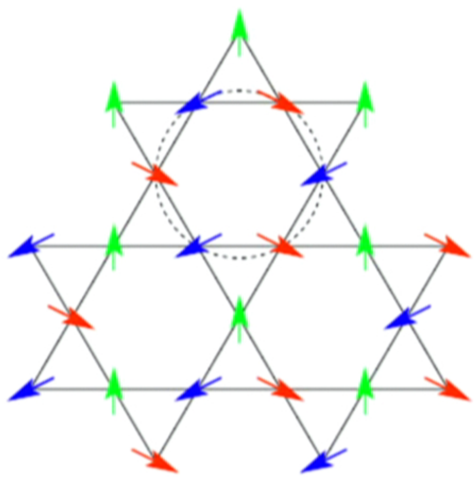
E=−0.5 J per site

E=− 0.375 J per site

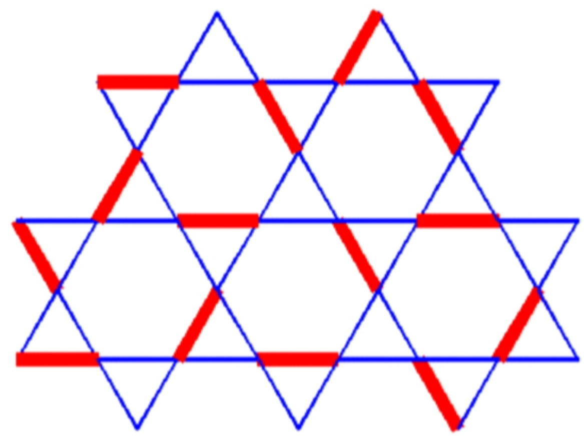
Kagome lattice



- For $S = \frac{1}{2}$, energy per site E= $-0.25J$ for classical order $> -0.375J$ for a dimer state.



E=−0.25 J per site



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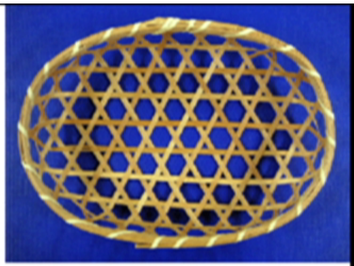
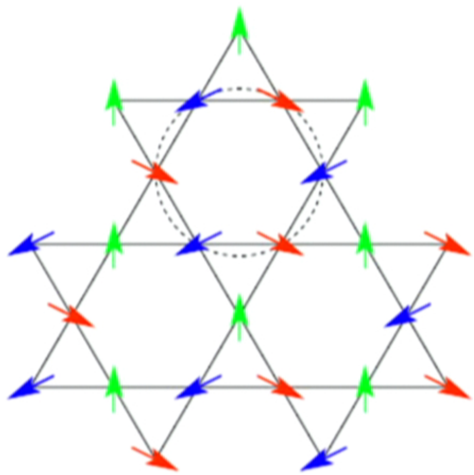


- For $S = ½$, energy per site E= $-0.25J$ for classical order $> -0.375J$ for a dimer state.



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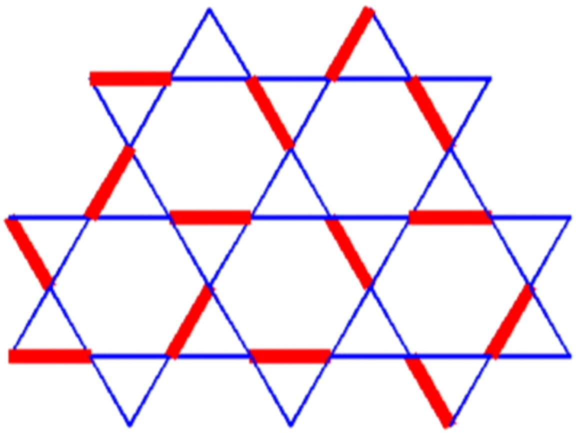
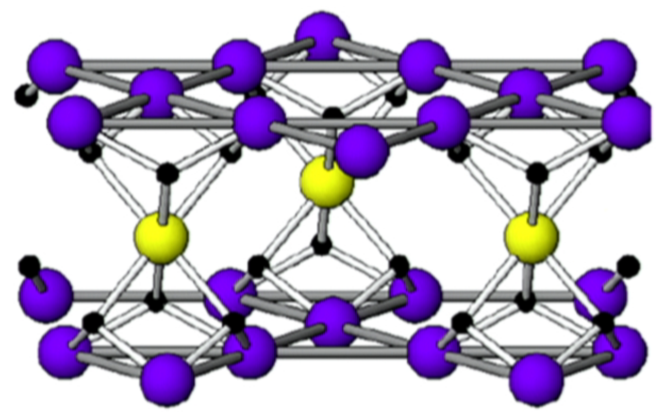


E=$-\,0.375\,J$ per site

Herbertsmithite

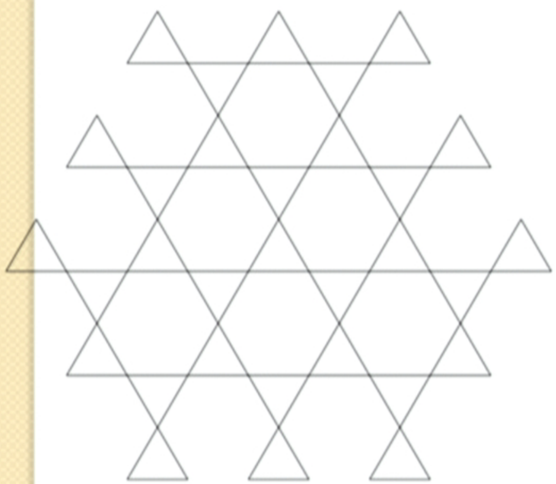


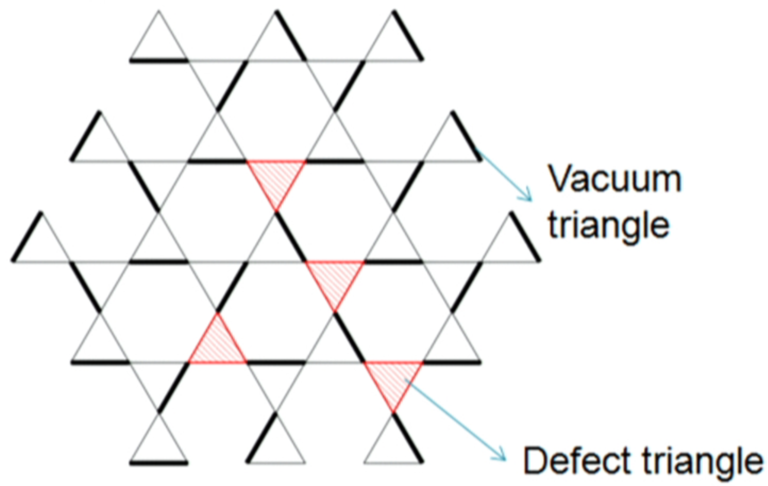
Mendels and Zorko, (2010).

Herbertsmithite, $ZnCu_3(OH)_6Cl_2$, is the best realization of S=1/2 antiferromagnet on kagome so far.

Our approach: variational approach

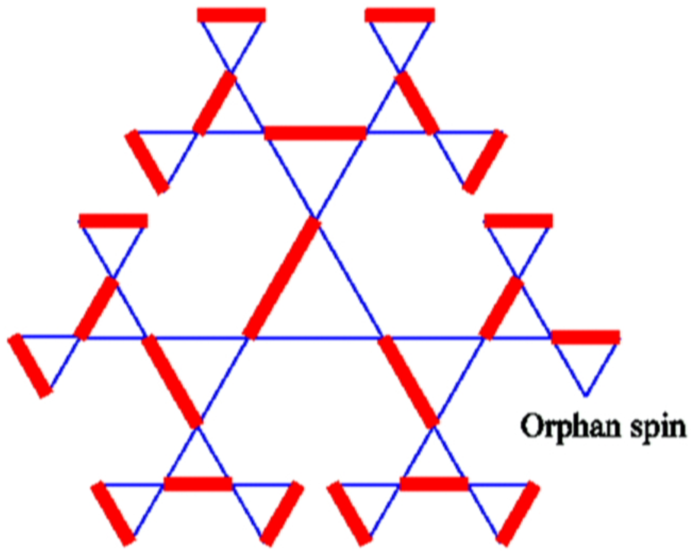
- $H = J\sum_{\Delta}\left[\sum_{\langle ij\rangle\in\Delta}\vec{S}_i\cdot\vec{S}_j + \frac{3}{4}\right] = \frac{J}{2}\sum_{\Delta}\left[S_{\Delta}^2 - 3/4\right]$
- Energy of a triangle is *0* if two out of three spins into a singlet so that $S_{\Delta}=1/2$.





The Husimi cactus[1]

- A tree of corner sharing triangles.
- Any dimer covering is a ground state.



1. Chandra and Doucot (1994). Elser and Zeng (1993).

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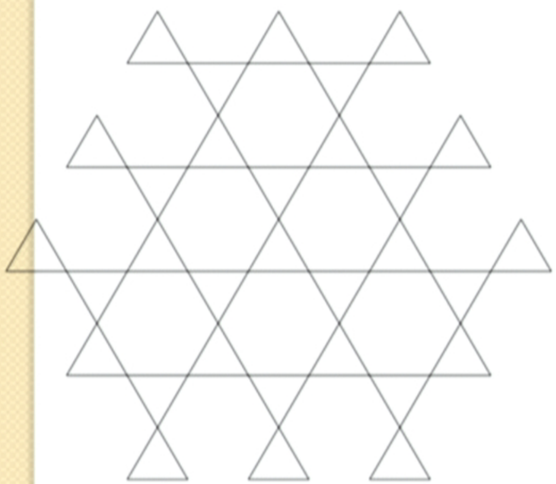
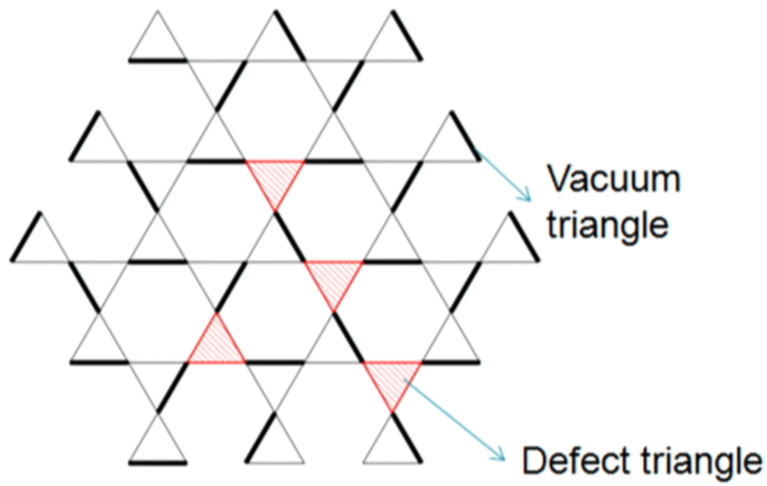


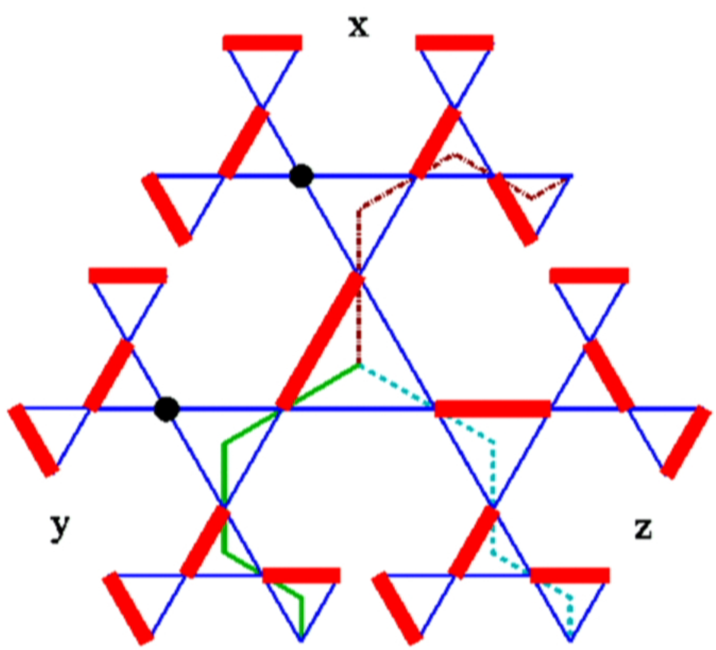


Variational basis

- Dimer covering states.
- Spinon states: states with each defect triangle broken into two spinons.

Two spinons

- Two spinons can move on three one dimensional trails *x*, *y* and *z* of length R.



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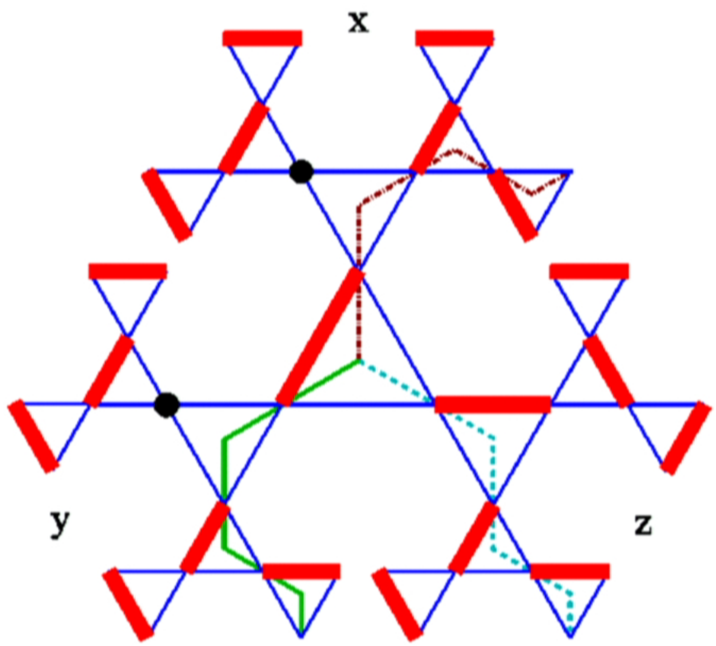
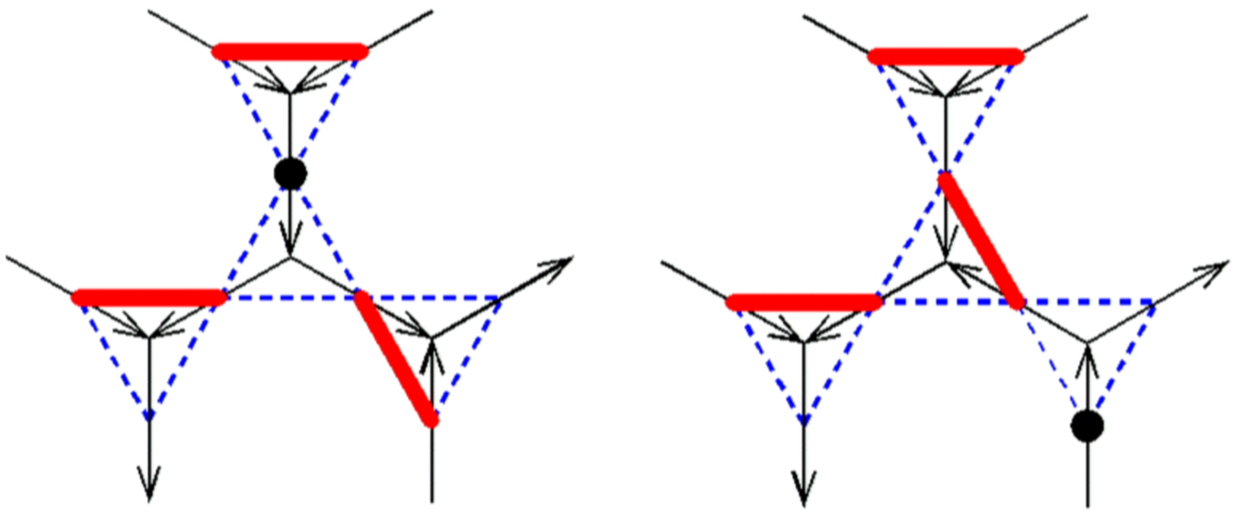


Summary

- Spinons are fermions.
- Spinons tend to delocalize to gain kinetic energy.
- A pair of spinons attract each other if they form a singlet.
- The motion of spinons is strongly *constrained* by singlets.

Spinon motion

- To capture the spinon motion, we introduce the arrow representation.



Construction of the model

$$H = t\sum_{\langle ij\rangle}\left(a^{+}_{i\sigma,A}S^{+}_{ij}a_{j\sigma,B} + h.c\right) - U\sum_{i} a^{+}_{i\uparrow}a_{i\uparrow}a^{+}_{i\downarrow}a_{i\downarrow}$$

- Bare parameters: $t \approx \frac{J}{2}, \ U \approx \frac{3J}{4}.$
- One spinon per unit cell.
- Arrows are represented by pseudo spin ½.
- S_z=±1/2 if the arrow points from sublattice A to sublattice B.

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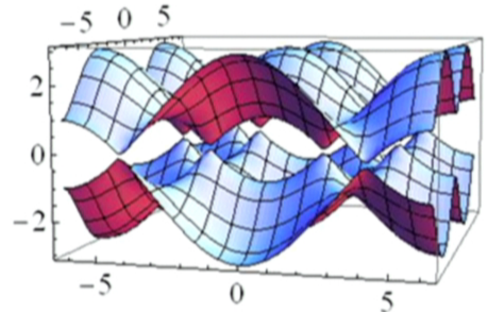
- One spinon per unit cell.
- Arrows are represented by pseudo spin ½.
- $S_z=\pm 1/2$ if the arrow points from sublattice A to sublattice B.

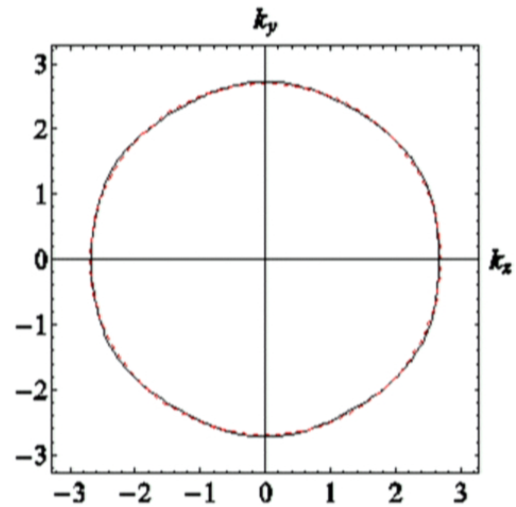
Emergent compact U(1) symmetry

- $$L = S\sum_{\langle ij\rangle}(\cos\theta_{ij}-1)\dot{\phi}_{ij} + i\sum_{i,\sigma} a^{+}_{i\sigma}\dot{a}_{i\sigma}$$
$$+\sum_{i} A_{i0}\left[n_i - S - \tau_i \sum_{j\in\langle i\rangle} S^{z}_{ij}\right] - H$$

U=0 limit: zero-flux phase

- Gauge meanfield theory[1].
- Two bands. The lower band is half-filled. U(1) spin liquid with spinon Fermi surface.





1. Savary and Balents (2012).

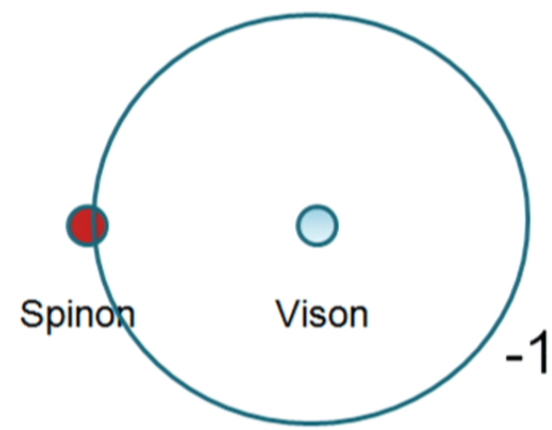
$U \approx t$: strong attraction

- Charge-2 Higgs phase: Z_2 spin liquid[1].
- Large spin gap for zero-flux state.
- Small spin gap for π flux state: vanishing density of state close to Dirac points.

1. Fradkin and Shenker (1979). Bhanot and Freedman (1981).

Z_2 liquid: anyon statistics

- Fermionic spinons with π flux per plaquette:
- Bosonic visons (Abrikosov vortices) with π flux per plaquette.
- Mutual semionic statistics between spinon and vison.



Lower edge of the two spinon continuum

- We calculated the lower edge of the two spinon continuum for the π flux state.