Title: Spin liquids on kagome lattice and symmetry protected topological phase

Date: Apr 19, 2016 03:30 PM

URL: http://pirsa.org/16040106

Abstract: <p>In my talk I will introduce the spin liquid phases that occur in kagome antiferromagnets, and discuss their physical origin that are closely related with the newly discovered symmetry protected topological phase (SPT). I will first present our numerical (DMRG) study on the kagome XXZ spin model that exhibits two distinct spin liquid phases, namely the chiral spin liquid and the kagome spin liquid (the groundstate of the nearest neighbor kagome Heisenberg model). Both phases extend from the extreme easy-axis limit, through</p>

<p>SU(2) symmetric point, to the pure easy-plane limit. The two phases are separated by a continuous phase transition. Motivated by these numerical results, I will then focus on the easy-axis kagome spin system, and reformulate it as a lattice gauge model. Such formulation enables us to achieve a controlled theoretical description for the spin liquid phases. We then show that the chiral spin liquid is indeed a gauged U(1) SPT phase. On the other hand, we also propose that the kagome spin liquid is a critical spin liquid phase, which can be considered as a gauged deconfined critical point between a SPT and a superfluid phase.</p>

Spin liquids on kagome lattice and Symmetry protected topological phase

Yin-Chen He
MPI-PKS, Dresden, Germany

(Apr 2016, Perimeter Institute)

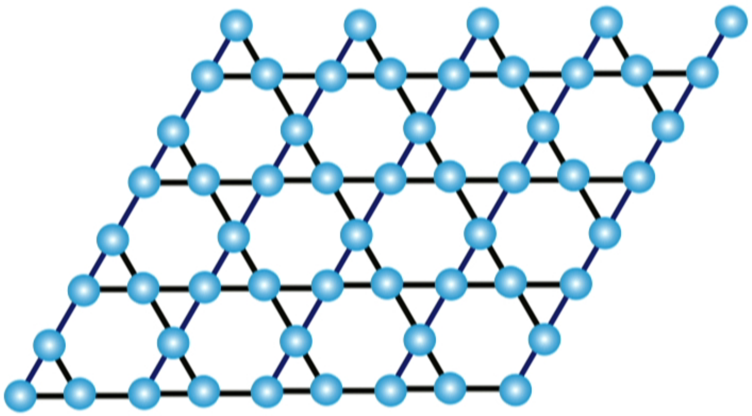
MAX-PLANCK-GESELLSCHAFT

mpipks

DFG SFB 1143

YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015).
YCH, Bhattacharjee, Pollmann, and Moessner, PRL 115, 267209 (2015).
YCH, Bhattacharjee, Moessner, and Pollmann, PRL 115, 116803 (2015).
YCH and Chen, PRL 114, 037201 (2015).
YCH, Sheng and Chen, PRL 112, 137202 (2014).

Spin liquids on kagome lattice



Kagome Heisenberg model

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

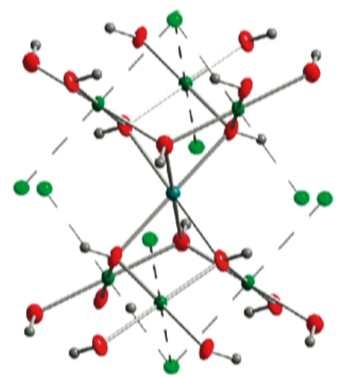
What is the ground state?

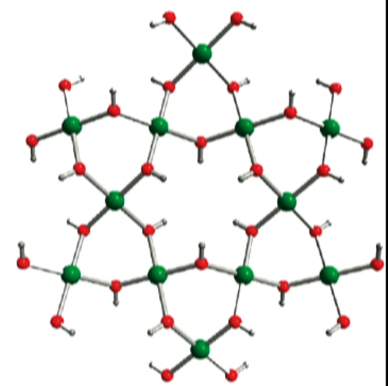
Yan, Huse, and White

Spin liquid! But which one?

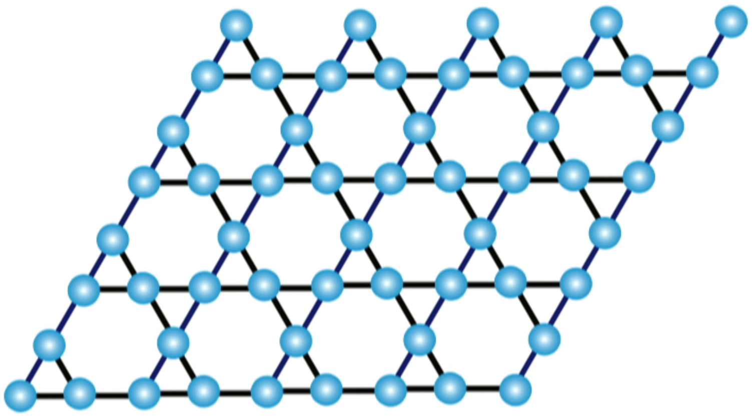
Herbersmithite $ZnCu_3(OH)_6CL_2$

YS Lee group





Spin liquids on kagome lattice



Kagome Heisenberg model

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

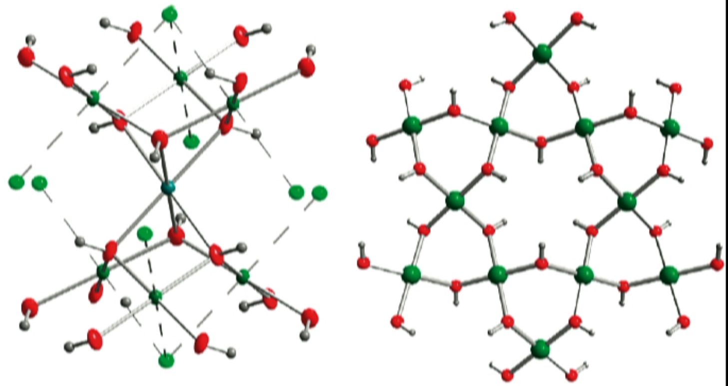
What is the ground state?

Yan, Huse, and White

Spin liquid! But which one?

Herbersmithite $ZnCu_3(OH)_6CL_2$

YS Lee group

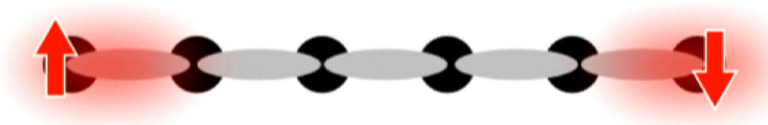


Symmetry protected topological phase

interacting system

Chen, Gu, Liu, Wen

1D bosonic SPT: Haldane's spin-1 chain

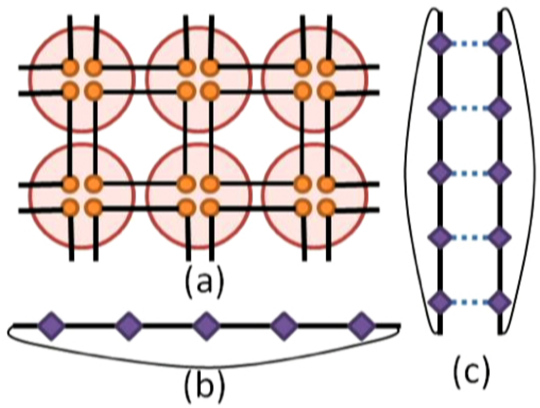


projective symmetry group

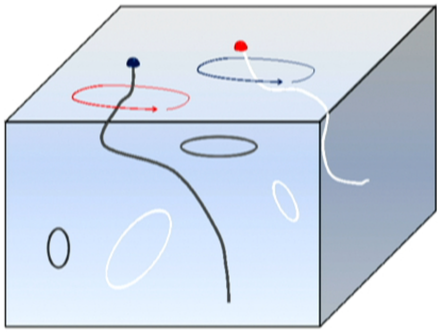
Pollmann, Turner, Berg, Oshikawa

beyond 1D: cohomology group

Chen, Gu, Liu, Wen



Chen, Liu, Wen

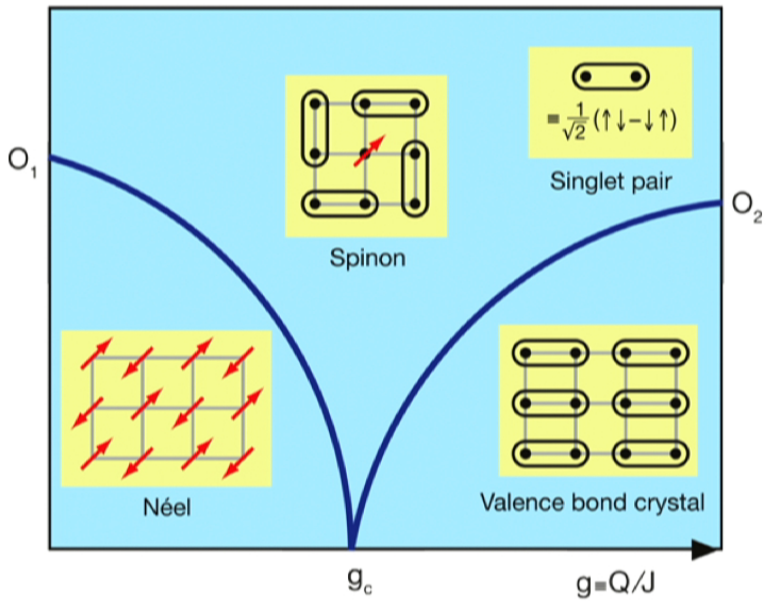


Vishwanath, Senthil

Deconfined criticality

Senthil, Vishwanath, Balents, Sachdev, Fisher

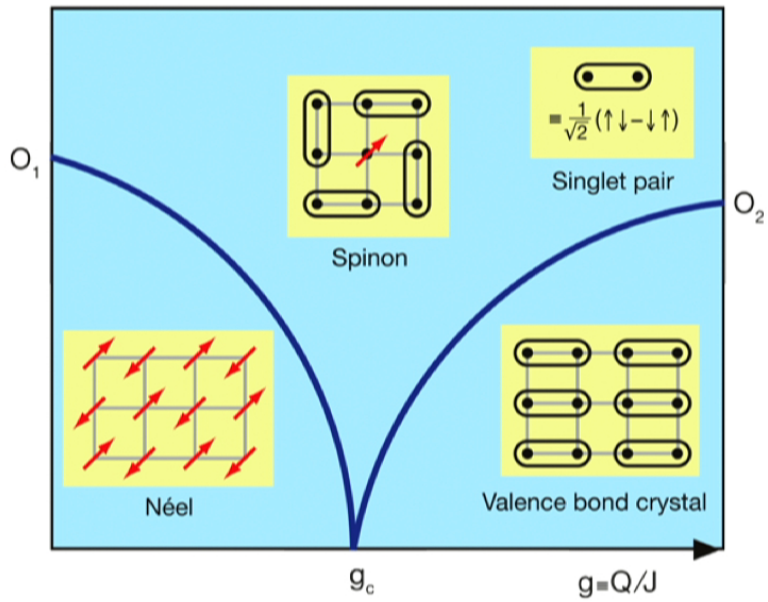
Neel to VBS

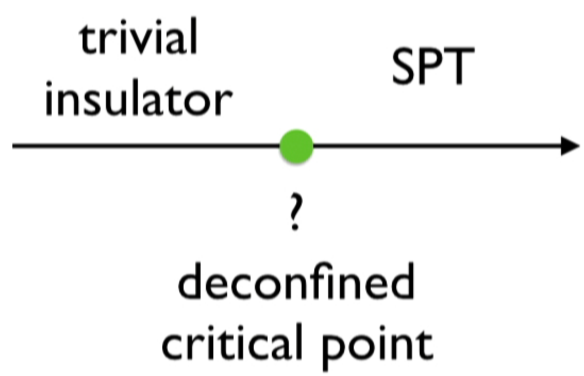


Deconfined criticality

Senthil, Vishwanath, Balents, Sachdev, Fisher

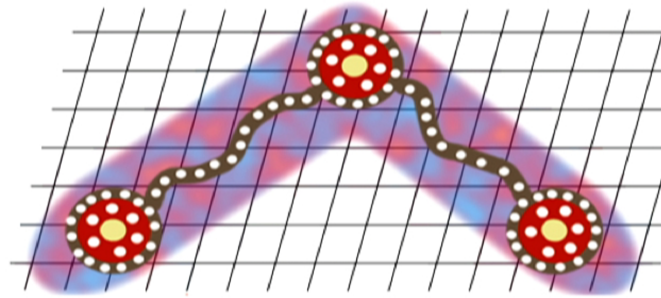
Neel to VBS





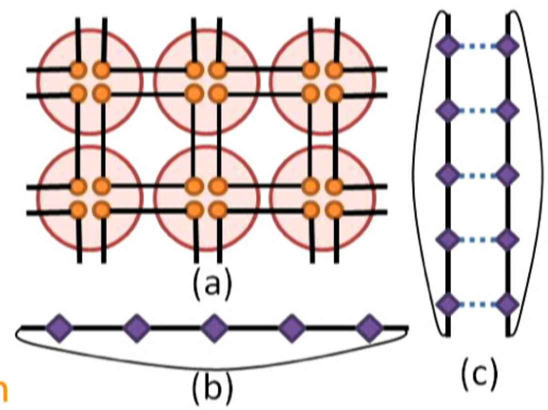
Outline

Pompidou Metz



1. spin liquids on kagome lattice → 2. lattice gauge theory

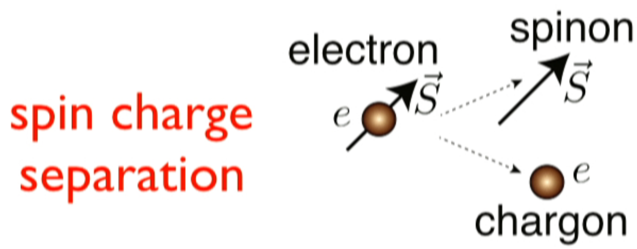
3. symmetry protected
topological phase (SPT)
and its deconfined criticality



Chen, Gu, Liu, Wen

Spin liquid: more than absence of order

- Fractionalization in 2D/3D

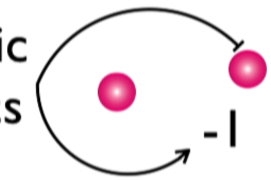


- Emergent gauge field: U(1), Z2……
- Fractional quasiparticles (anyon)
- Parent state of a superconductor
- …

Examples of spin liquid

- Chiral spin liquid, gapped   Kalmeyer & Laughlin 1987 PRL

spinon ● 1/2 spin   Semionic statistics

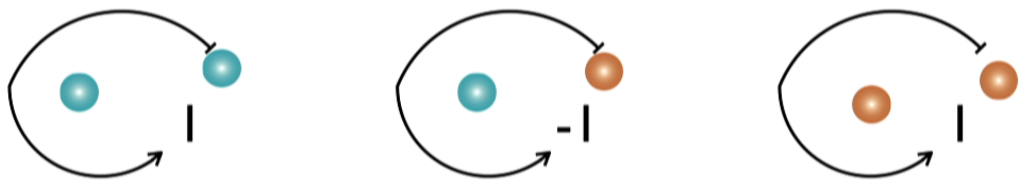


- Z2 spin liquid, gapped

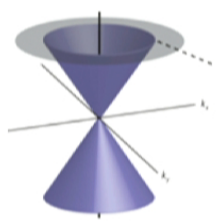
Read & Sachdev PRL 1991; Moessner & Sondhi PRL 2001…

spinon ●

vison ●



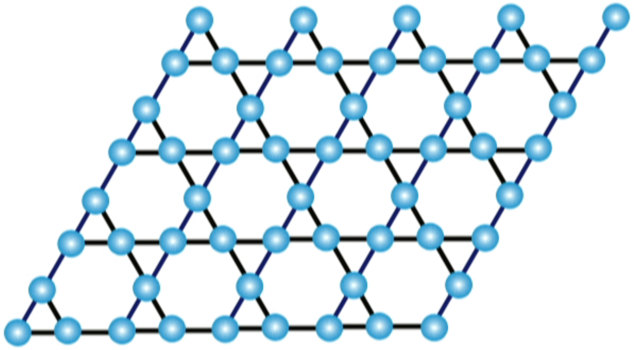
- Dirac spin liquid, gapless



$$\mathcal{L} = \sum_{i=1}^{4} \bar{\psi}_i i\gamma_\mu(\partial_\mu + iA_\mu)\psi + \frac{1}{2e^2}F_{\mu\nu}F_{\mu\nu}$$

Hastings PRB 2000; Ran, Hermele, Lee & Wen PRL 2007

Kagome Heisenberg model



$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

What is the ground state?

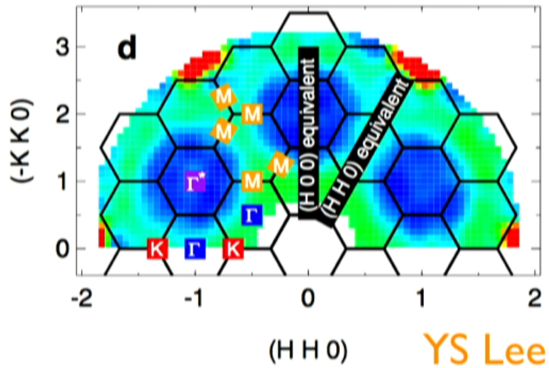
every possible candidate
has been proposed?!

"kagome spin liquid"

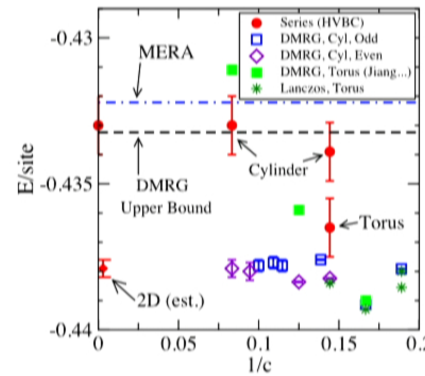
Partial list…

Read & Sachdev (1991)
Marston & Zeng (1991)
Chalker, Holdsworth, Shender (1992)
Yang, Warman & Girvin (1993)
Hastings (2000)
Wang & Vishwanath (2006)
Ran, Hermele, Lee & Wen (2007)
Singh & Huse (2007)
Evenbly & Vidal (2010)
Yan, Huse & White (2011)
Lauchli, Sudan, Sorensen (2011)
Iqbal, Becca & Poilblanc (2011)
Depenbrock, McCulloch & Schollwock (2012)
Jiang, Wang & Balents (2012)
Xie, et. al., Xiang (2014)
YCH, Sheng, & Chen (2014)
….

Current status



YS Lee group



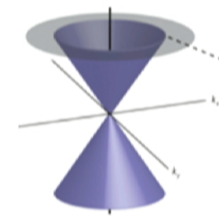
S.White group

Experiments	Numerics
no order	no order
spinon detected	spinon detected
gapless (or gapped?)	gapped (or gapless?)

Spin liquid, but which one?

"kagome spin liquid"

How to solve?



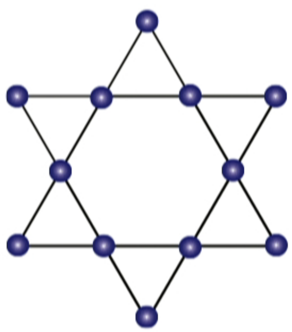
gauge field

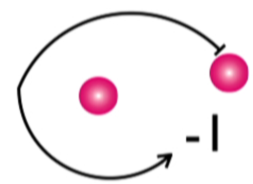
spinon

$: J \sum \vec{S}_i \cdot \vec{S}_j$

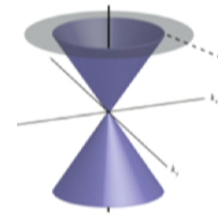
$\bar{\psi} i \gamma_\mu (\partial_\mu + i \mathcal{A}_\mu) \psi$

Spin model → Deconfined spin liquid

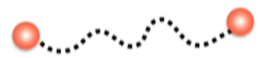




How to solve?



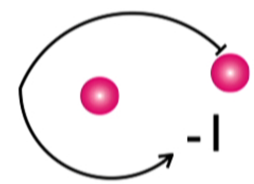
gauge field



spinon

$J\sum \vec{S}_i \cdot \vec{S}_j$ | $t\sum e^{i\mathcal{A}_{ij}} c_i^\dagger c_j$ | $\bar{\psi} i\gamma_\mu(\partial_\mu + i\mathcal{A}_\mu)\psi$

Spin model — **Exact?** → Effective lattice gauge model → Deconfined spin liquid



~~uncontrolled mean field~~

~~slave particle~~

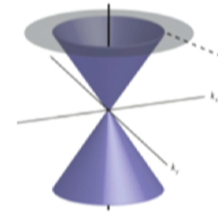
~~$\vec{S}_i = c^\dagger_{i,s}\vec{\sigma}_{s,s'}c_{i,s'}$~~

~~$\langle c_i^\dagger c_j \rangle \neq 0$~~

How to solve?

gauge field

spinon



$J \sum \vec{S}_i \cdot \vec{S}_j$

$t \sum e^{i\mathcal{A}_{ij}} c_i^\dagger c_j$

$\bar{\psi} i \gamma_\mu (\partial_\mu + i\mathcal{A}_\mu)\psi$

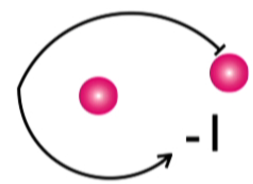
Spin model — **Exact?** → Effective lattice gauge model → Deconfined spin liquid

~~uncontrolled mean field~~

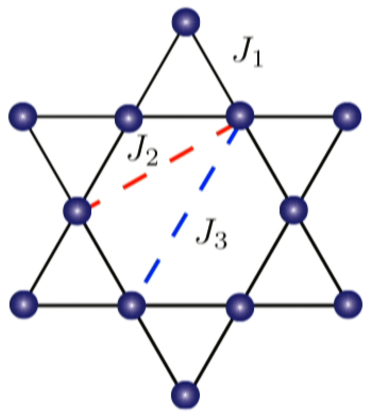
~~slave particle~~

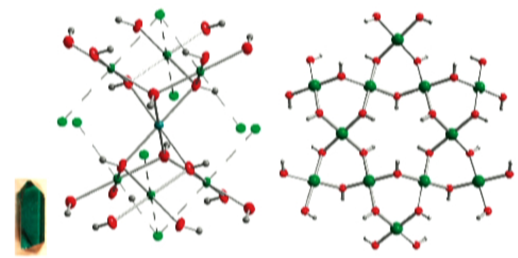
~~$\vec{S}_i = c_{i,s}^\dagger \vec{\sigma}_{s,s'} c_{i,s'}$~~

~~$\langle c_i^\dagger c_j \rangle \neq 0$~~



Make it more general





$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

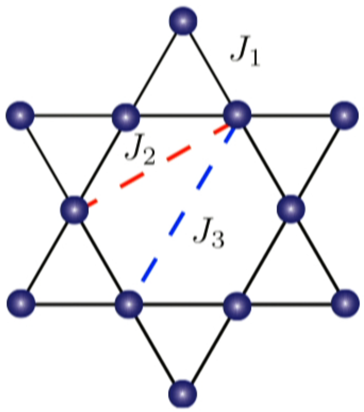
XXZ anisotropy
second neighbor
third neighbor
DM interaction
interlayer coupling
impurity
....

Extended kagome model

YCH & Chen, PRL 2015

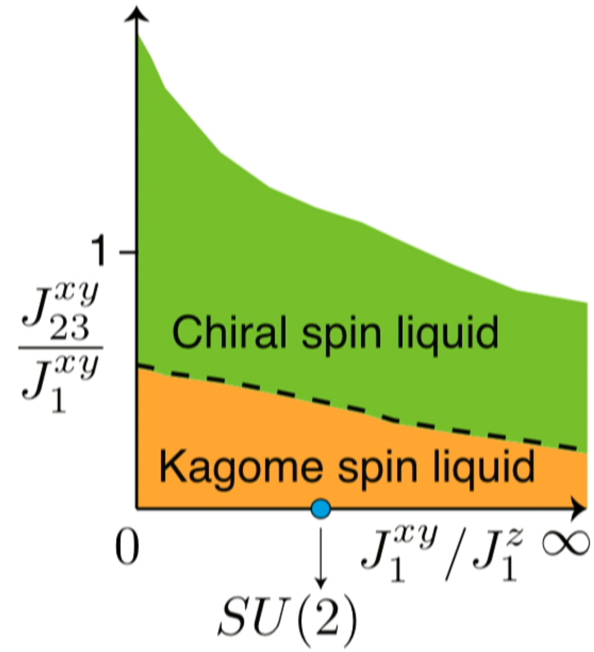
$$H_{XXZ} = J_1^z \sum_{\langle pq \rangle} S_p^z S_q^z + \frac{J_1^{xy}}{2} \sum_{\langle pq \rangle} (S_p^+ S_q^- + h.c.)$$ 1st XXZ

$$+ \frac{J_{23}^{xy}}{2} \left(\sum_{\langle\langle pq \rangle\rangle} + \sum_{\langle\langle\langle pq \rangle\rangle\rangle} \right) (S_p^+ S_q^- + h.c.)$$ 2nd, 3rd XY



DMRG results

independent of XXZ anisotropy



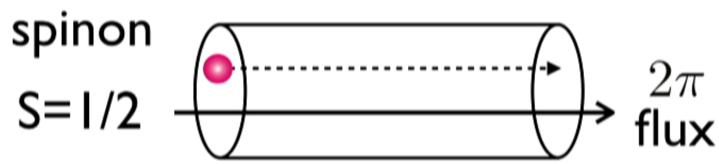
also see ED calculation:

Lauchli & Moessner, arXiv (2015)

Numerics for the chiral spin liquid

Hall conductance

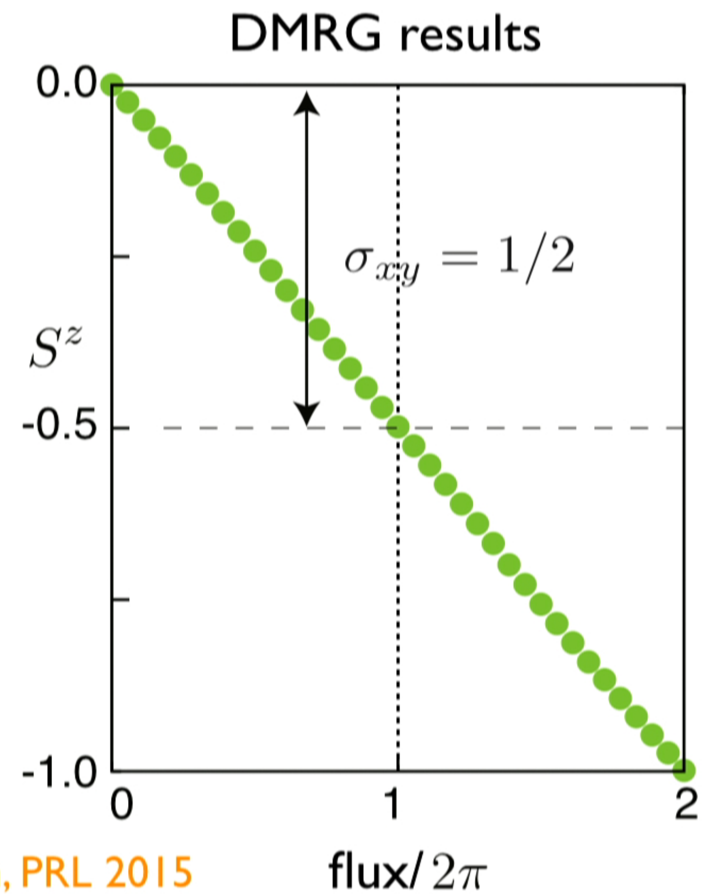
Flux insertion Laughlin, PRB 1981



2π flux pumps one spinon

DMRG: YCH, Sheng, Chen PRB 2014

YCH, Sheng & Chen, PRL 2014;
Gong, Zhu & Sheng, Sci. Rep 2014;
Bauer, et al. Nat. Comm. 2014; YCH & Chen, PRL 2015

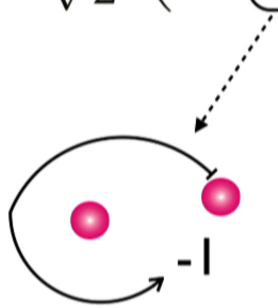


Fractional statistics from DMRG

Wen, Int. J. Mod. Phys. B, 1990
Zhang, Grover, Turner, Oshikawa & Vishwanath, PRB 2012
Cincio & Vidal, PRL 2013

Modular Matrix $V_{ij} = \langle \psi_i | R_{2\pi/3} | \psi_j \rangle \sim \mathcal{U}\mathcal{S}$

$$\mathcal{S} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & \boxed{-1} \end{pmatrix} \qquad \mathcal{U} = e^{-i(2\pi/24)} \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$



YCH, Sheng & Chen, PRL 2014; Gong, Zhu & Sheng, Sci. Rep 2014; Bauer, et al. Nat. Comm. 2014; YCH & Chen, PRL 2015

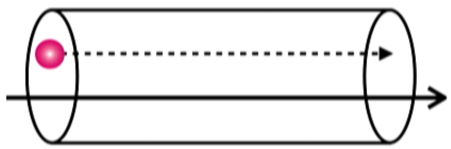
Numerics for the chiral spin liquid

Hall conductance

Flux insertion Laughlin, PRB 1981

spinon

S=1/2

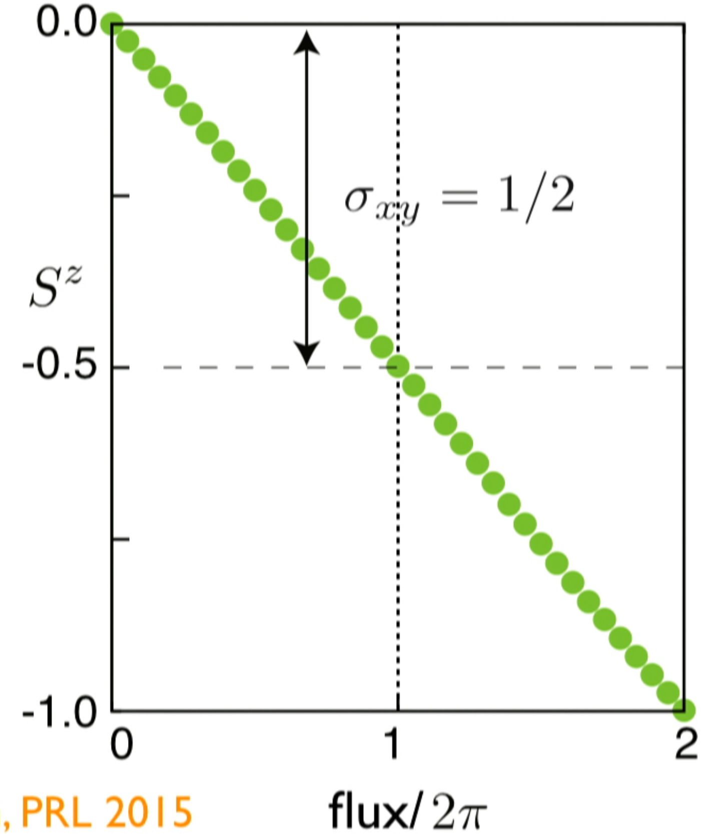


2π flux pumps one spinon

DMRG: YCH, Sheng, Chen PRB 2014

YCH, Sheng & Chen, PRL 2014;
Gong, Zhu & Sheng, Sci. Rep 2014;
Bauer, et al. Nat. Comm. 2014; YCH & Chen, PRL 2015

DMRG results

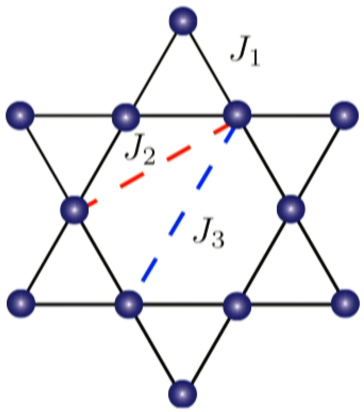


Extended kagome model

YCH & Chen, PRL 2015

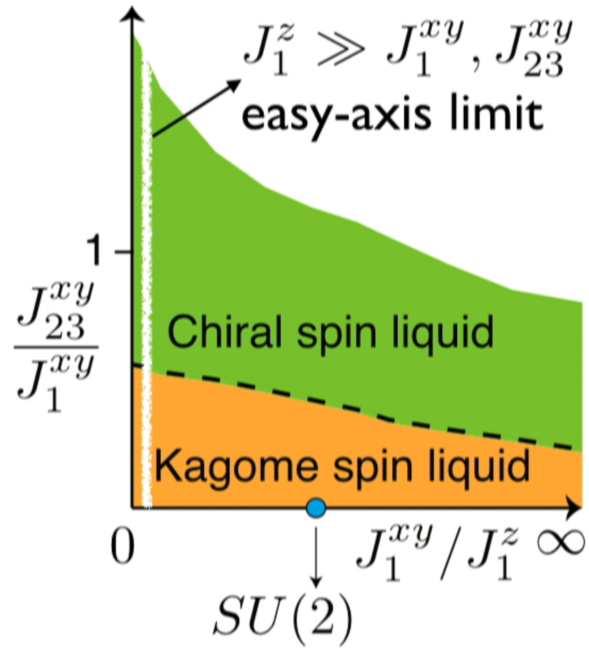
$$H_{XXZ} = J_1^z \sum_{\langle pq \rangle} S_p^z S_q^z + \frac{J_1^{xy}}{2} \sum_{\langle pq \rangle} (S_p^+ S_q^- + h.c.) \quad \text{1st XXZ}$$

$$+ \frac{J_{23}^{xy}}{2} \left(\sum_{\langle\langle pq \rangle\rangle} + \sum_{\langle\langle\langle pq \rangle\rangle\rangle} \right) (S_p^+ S_q^- + h.c.) \quad \text{2nd, 3rd XY}$$



DMRG results

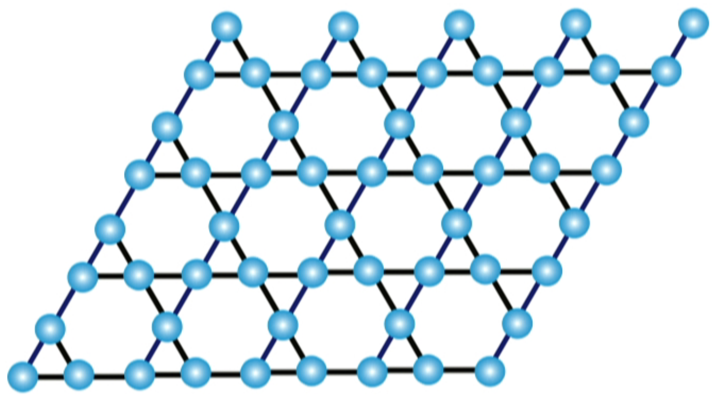
independent of XXZ anisotropy



also see ED calculation:

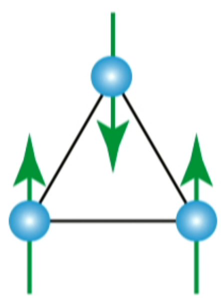
Lauchli & Moessner, arXiv (2015)

Easy axis kagome

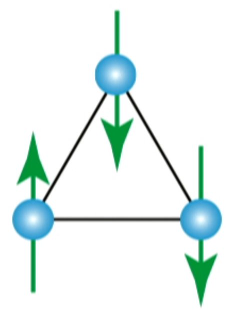


$$H = J_1^z \sum_{\mathrm{1st}} S_i^z S_j^z + \lambda H_1$$

$$J_z \gg \lambda > 0$$



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



$$\sum S_i^z = -\frac{1}{2}$$

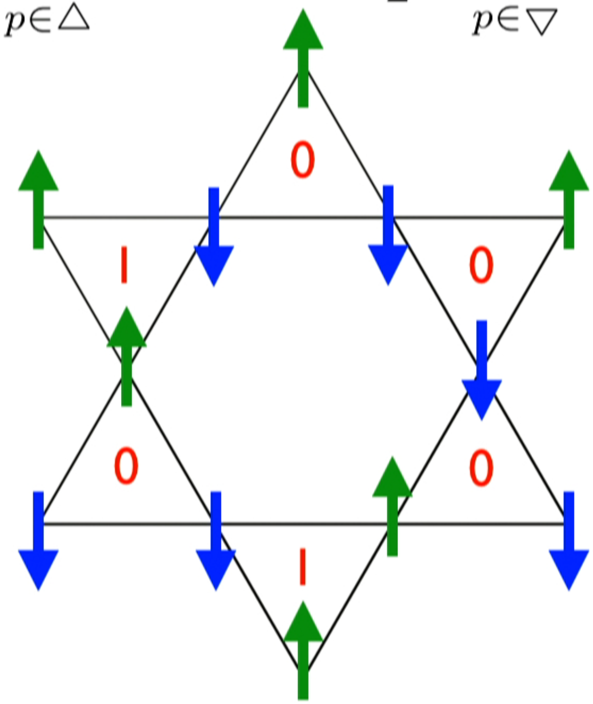
extensive classical degeneracy

H_1 lifts the classical degeneracy

Exact lattice gauge mapping

$$\sum_{p\in\triangle} S_p^z = a^\dagger a - \frac{1}{2} \quad \sum_{p\in\nabla} S_p^z = b^\dagger b - \frac{1}{2}$$

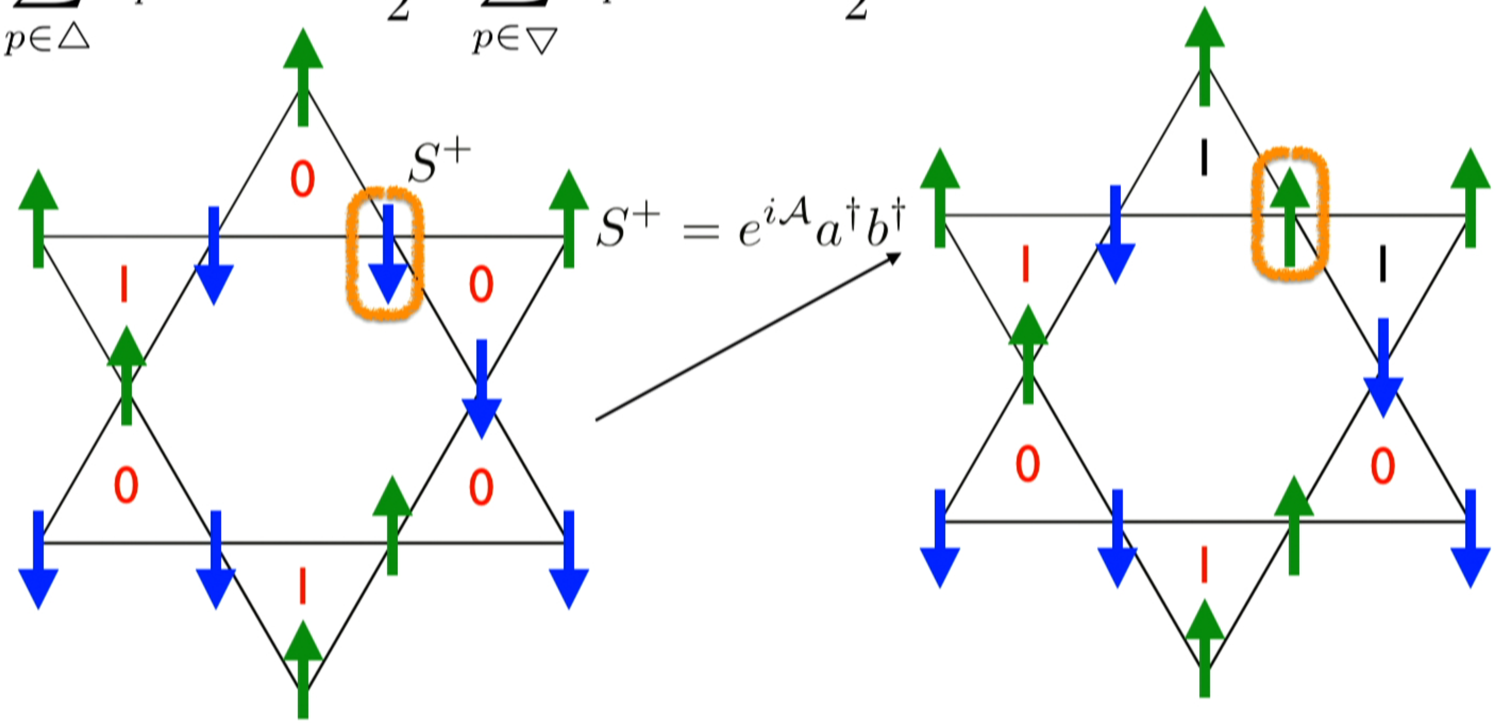
Nikolic & Senthil 2005 PRB



Exact lattice gauge mapping

$$\sum_{p\in\triangle} S_p^z = a^\dagger a - \frac{1}{2} \qquad \sum_{p\in\nabla} S_p^z = b^\dagger b - \frac{1}{2}$$

Nikolic & Senthil 2005 PRB



similar system: quantum dimer model, pyrochlore lattice

Fradkin & Kivelson, 1990

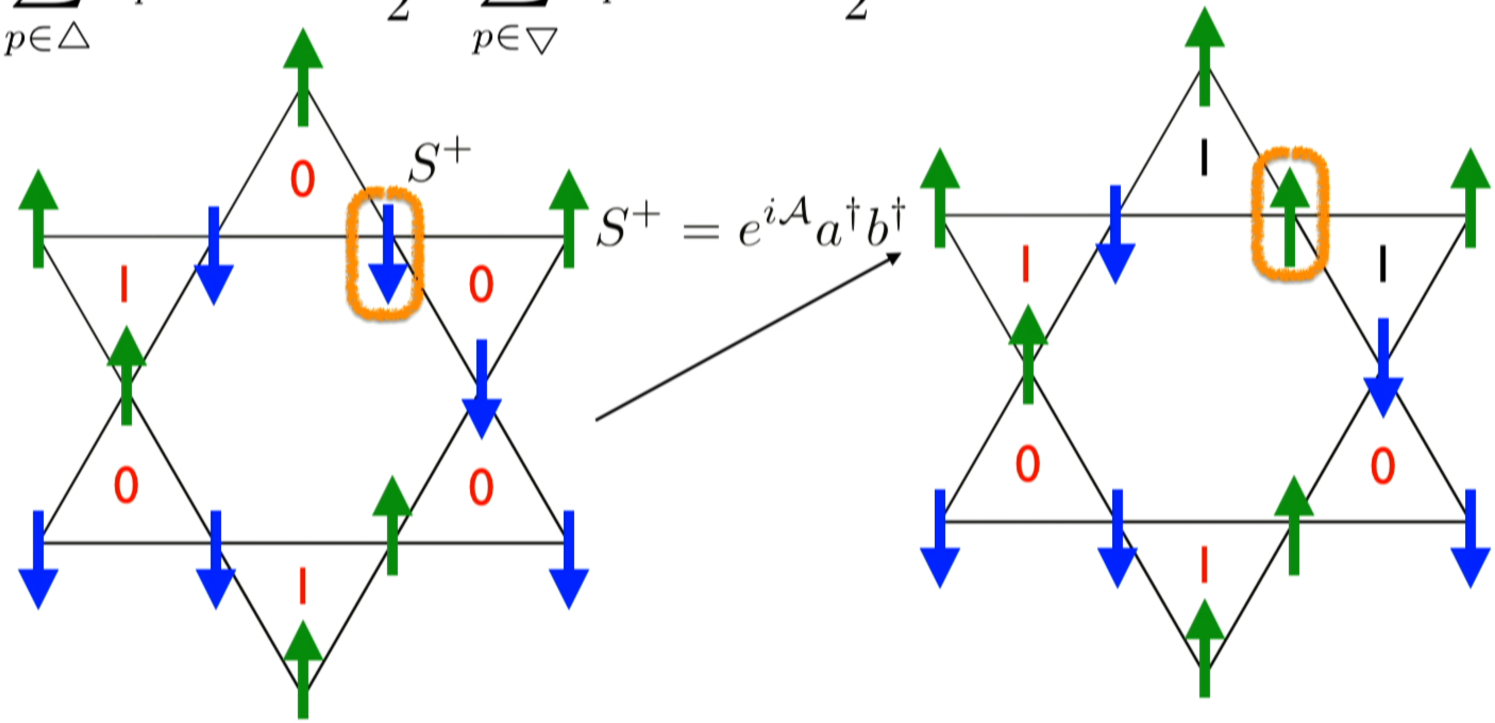
Hermele, Fisher & Balents 2004

Castelnovo, Moessner & Sondhi 2008

Exact lattice gauge mapping

$$\sum_{p\in\triangle} S_p^z = a^\dagger a - \frac{1}{2} \qquad \sum_{p\in\nabla} S_p^z = b^\dagger b - \frac{1}{2}$$

Nikolic & Senthil 2005 PRB



similar system: quantum dimer model, pyrochlore lattice

Fradkin & Kivelson, 1990

Hermele, Fisher & Balents 2004

Castelnovo, Moessner & Sondhi 2008

Lattice gauge mapping: XXZ kagome

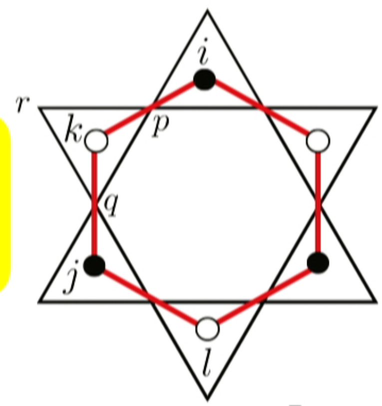
$$H = J_1^z \sum_{\langle pq \rangle} S_p^z S_q^z + \frac{J_1^{xy}}{2} \sum_{\langle pq \rangle} (S_p^+ S_q^- + h.c.)$$

$$+ \frac{J_{23}^{xy}}{2} \sum_{\langle\langle pq \rangle\rangle} (S_p^+ S_q^- + h.c.) + \frac{J_{23}^{xy}}{2} \sum_{\langle\langle\langle pq \rangle\rangle\rangle} (S_p^+ S_q^- + h.c.)$$

Exact!

$$S_p^+ = e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger$$

lattice gauge mapping



$$H^{\mathrm{LGT}} = J_1^{xy} \Big[\sum_{\langle\langle ij \rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl \rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c. \Big]$$

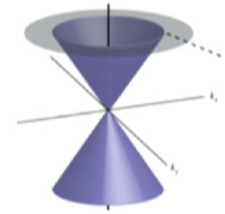
$$+ J_{23}^{xy} \sum_{\langle ik \rangle, \langle jl \rangle \in \hexagon} \Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c. \Big]$$

$$+ \kappa \sum E_{ik}^2 + 1/\kappa \sum \cos\left(\sum \mathcal{A}_{ik}\right) \qquad \kappa \sim \kappa_{\mathrm{SL}}$$

Solving the kagome spin liquid phase

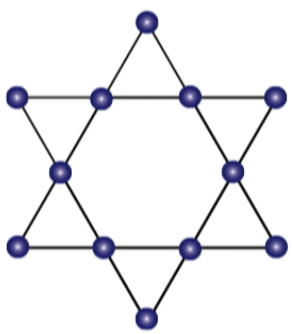
gauge field

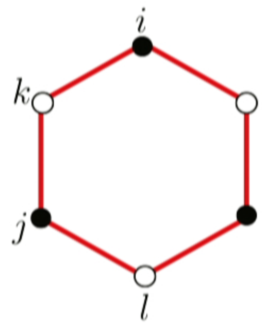
spinon

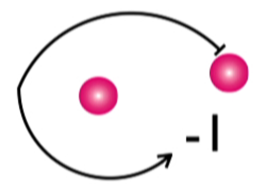


$J \sum \vec{S}_i \cdot \vec{S}_j$ $\quad$ $t \sum e^{i\mathcal{A}_{ij}} c_i^\dagger c_j$ $\quad$ $\bar{\psi} i \gamma_\mu (\partial_\mu + i\mathcal{A}_\mu) \psi$

Spin model — **Exact!** → Effective lattice gauge model — **?** → Deconfined spin liquid







No "free" spin liquid

U(1) compact gauge field + Dynamical bosonic spinons

confinement in 2+1D

Polyakov

Phases in a lattice gauge model

Phases in a lattice gauge model

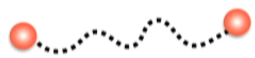
gauge field + matter

interacting bosonic matter

gauge field

gauging

spinon



Higgs phase

Superfluid

Z2 spin liquid

Fradkin & Shenker

Charge-2 superfluid

Phases in a lattice gauge model

gauge field + matter

interacting bosonic matter

gauge field

gauging

spinon

Higgs phase

Superfluid

Z2 spin liquid

Fradkin & Shenker

Charge-2 superfluid

Chiral spin liquid

Levin & Gu

U(1) symmetry protected topological phase

Symmetry protected topological phase!

Classified by cohomology group $H^{d+1}[G, U(1)]$

Chen, Gu, Liu & Wen, PRB 2012

SPT protected by U(1) charge conservation

⇕

Bosonic integer quantum Hall

Senthil & Levin, PRL 2013
Lu & Vishwanath, PRB 2012

Symmetry protected topological phase!

Classified by cohomology group $H^{d+1}[G, U(1)]$

Chen, Gu, Liu & Wen, PRB 2012

SPT protected by U(1) charge conservation

⇕

Bosonic integer quantum Hall

Senthil & Levin, PRL 2013
Lu & Vishwanath, PRB 2012

gauging ↓ $\frac{2}{4\pi}\varepsilon_{\mu\nu\lambda}A_\mu\partial_\nu A_\lambda$

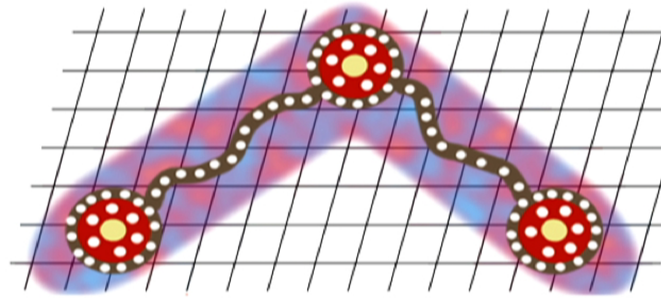
chiral spin liquid

YCH, Bhattacharjee, Pollmann, and Moessner, PRL 2015

See also:
Barkeshli, arxiv 2013

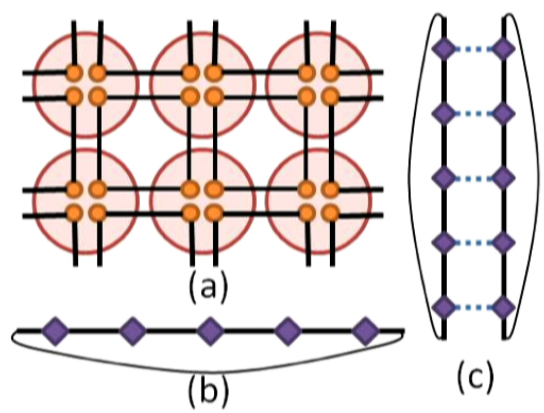
Outline

Pompidou Metz



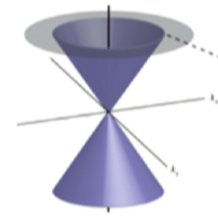
1. spin liquids on kagome lattice → 2. lattice gauge theory

3. symmetry protected topological phase (SPT)

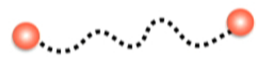


Chen, Gu, Liu, Wen

Solving the kagome spin liquid phase



gauge field



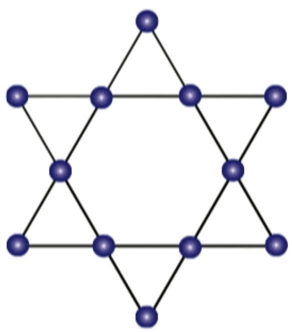
spinon

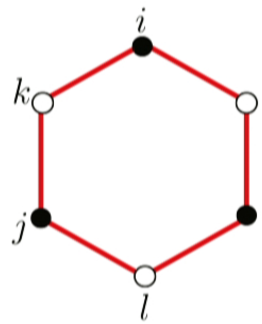
$J\sum \vec{S}_i \cdot \vec{S}_j$

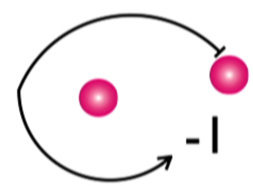
$t\sum e^{i\mathcal{A}_{ij}} c_i^\dagger c_j$

$\bar{\psi} i\gamma_\mu(\partial_\mu + i\mathcal{A}_\mu)\psi$

Spin model — **Exact!** → Effective lattice gauge model —— **?** → Deconfined spin liquid



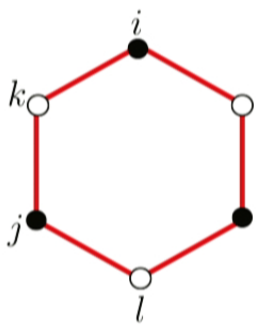


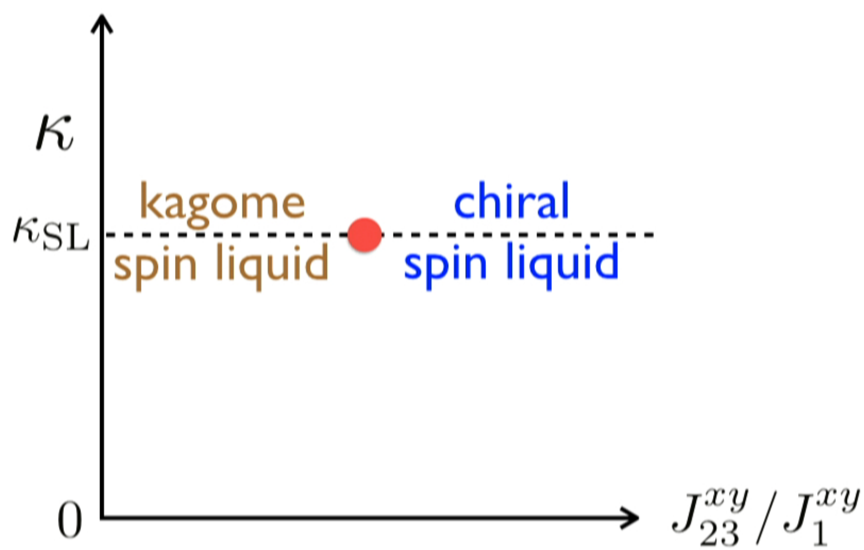


Lattice gauge model

YCH, Bhattacharjee, Pollmann, and Moessner, PRL 2015

$$H^{\rm LGT} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c.\Big]$$
$$+J_{23}^{xy}\sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon}\Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c.\Big]$$
$$+\kappa\sum E_{ik}^2 + 1/\kappa\sum\cos(\sum\mathcal{A}_{ik})$$

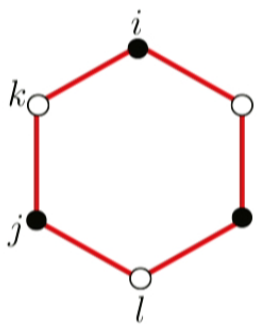


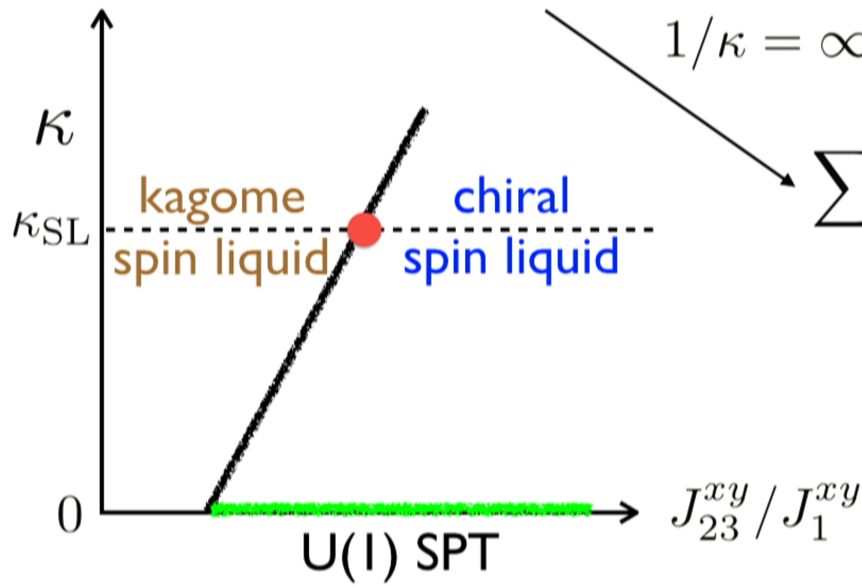


Lattice gauge model

YCH, Bhattacharjee, Pollmann, and Moessner, PRL 2015

$$H^{\mathrm{LGT}} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c.\Big]$$
$$+J_{23}^{xy}\sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon}\Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c.\Big]$$
$$+\kappa\sum E_{ik}^2 + 1/\kappa\sum\cos\Big(\sum\mathcal{A}_{ik}\Big)$$





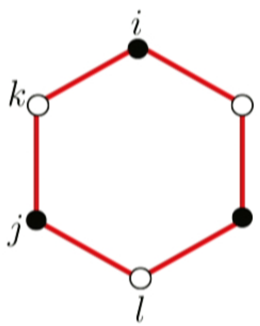
$\kappa = 0$ or
$1/\kappa = \infty$

$$\sum A^0 = \pi$$

Lattice gauge model

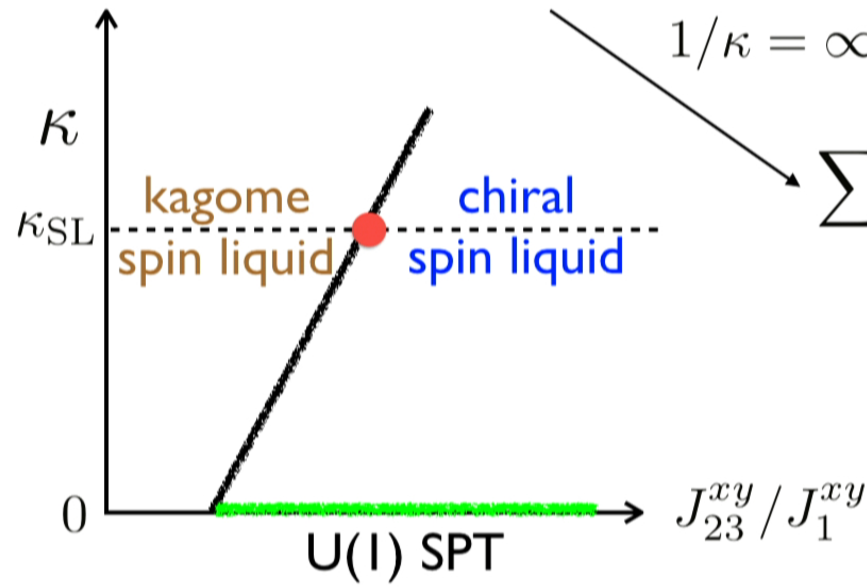
YCH, Bhattacharjee, Pollmann, and Moessner, PRL 2015

$$H^{\mathrm{LGT}} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c.\Big]$$
$$+J_{23}^{xy}\sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon}\Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c.\Big]$$
$$+\kappa \sum E_{ik}^2 + 1/\kappa \sum \cos(\sum \mathcal{A}_{ik})$$



$\kappa = 0$ or $1/\kappa = \infty$

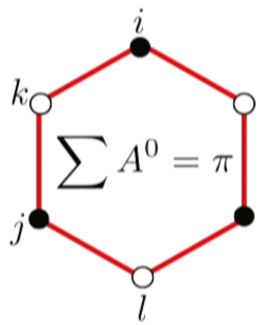
$\sum A^0 = \pi$



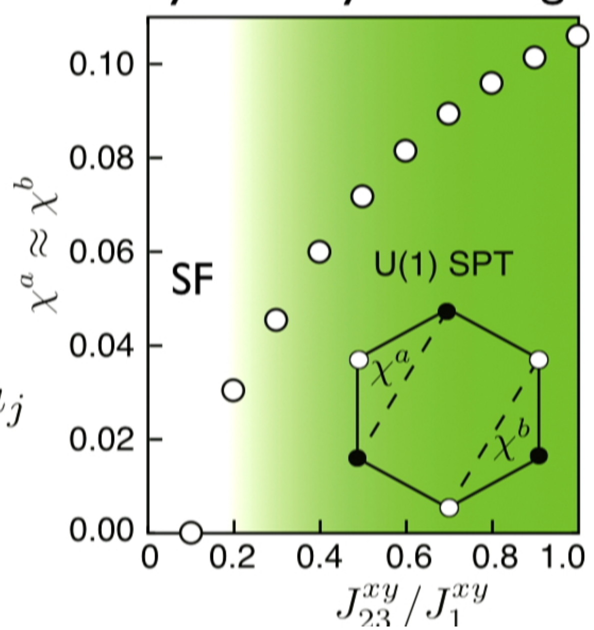
U(1) SPT phase

$$\widetilde{H} = J_1^{xy}\left[\sum_{\langle\langle ij\rangle\rangle} e^{iA^0_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{iA^0_{lk}} b_k^\dagger b_l + h.c.\right] + J_{23}^{xy}\sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon}\left[(e^{iA^0_{ik}} a_i^\dagger b_k^\dagger)(e^{iA^0_{lj}} b_l a_j) + h.c.\right]$$

spontaneous time-reversal symmetry breaking



$$\chi^a = i e^{i\pi n_k^b} a_i^\dagger a_j$$

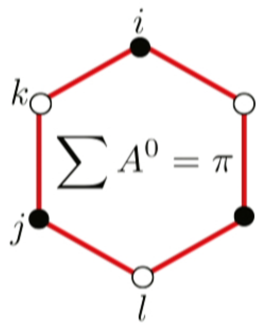


U(1) SPT phase

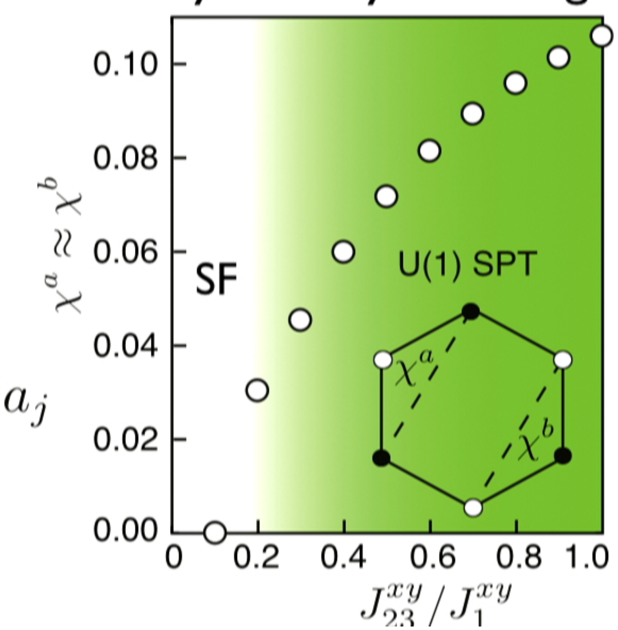
$$\widetilde{H} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{iA^0_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{iA^0_{lk}} b_k^\dagger b_l + h.c.\Big]$$

$$+J_{23}^{xy} \sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon} \Big[(e^{iA^0_{ik}} a_i^\dagger b_k^\dagger)(e^{iA^0_{lj}} b_l a_j) + h.c.\Big]$$

spontaneous time-reversal symmetry breaking



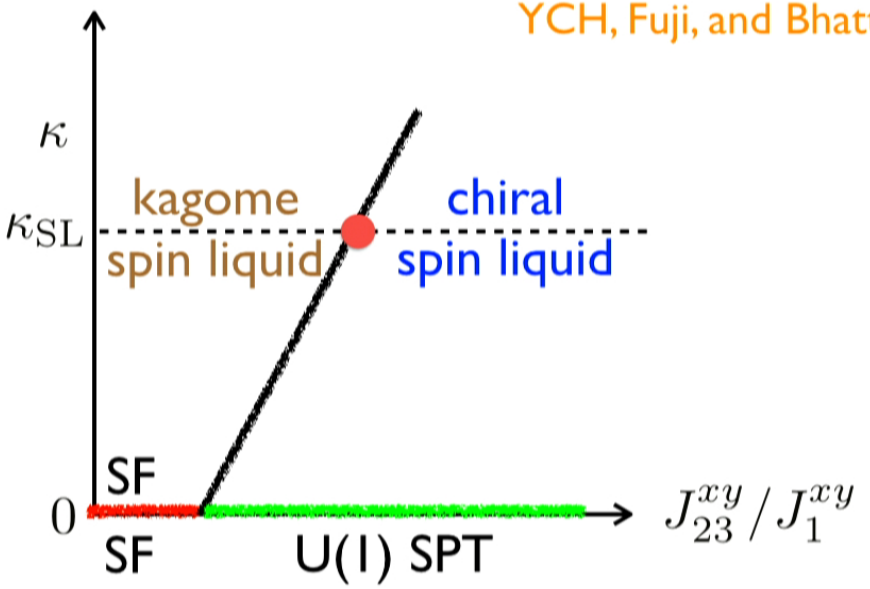
$$\chi^a = ie^{i\pi n_k^b} a_i^\dagger a_j$$



Whole phase diagram

$$H^{\mathrm{LGT}} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c.\Big]$$
$$+J_{23}^{xy} \sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon} \Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c.\Big]$$
$$+\kappa \sum E_{ik}^2 + 1/\kappa \sum \cos(\sum \mathcal{A}_{ik})$$

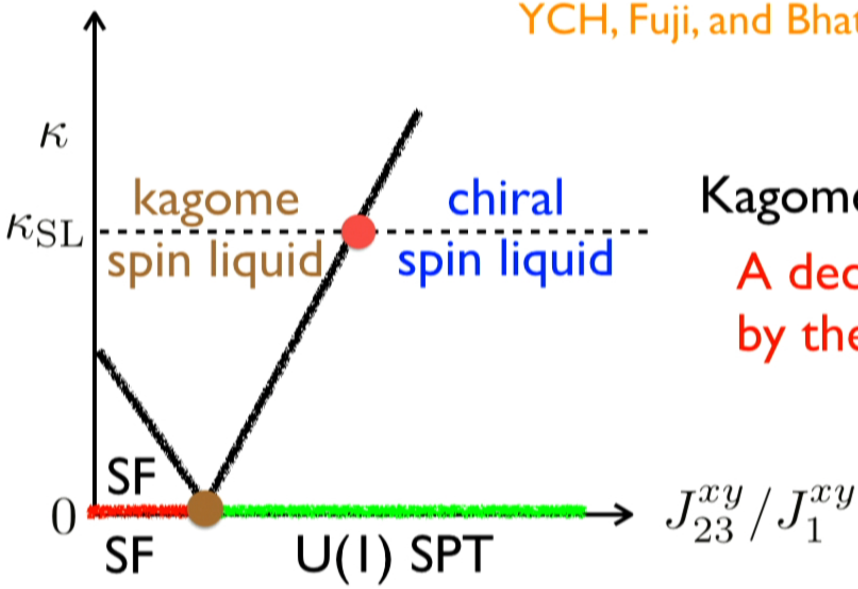
YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015).



Whole phase diagram

$$H^{\rm LGT} = J_1^{xy}\Big[\sum_{\langle\langle ij\rangle\rangle} e^{i\mathcal{A}_{ij}} a_i^\dagger a_j + \sum_{\langle\langle kl\rangle\rangle} e^{i\mathcal{A}_{lk}} b_k^\dagger b_l + h.c.\Big]$$
$$+J_{23}^{xy}\sum_{\langle ik\rangle,\langle jl\rangle\in\hexagon}\Big[(e^{i\mathcal{A}_{ik}} a_i^\dagger b_k^\dagger)(e^{i\mathcal{A}_{lj}} b_l a_j) + h.c.\Big]$$
$$+\kappa\sum E_{ik}^2 + 1/\kappa\sum\cos(\sum\mathcal{A}_{ik})$$

YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015).



Kagome spin liquid:

A deconfined phase driven by the U(1) gauge fluctuation!

"gauged" deconfined critical point

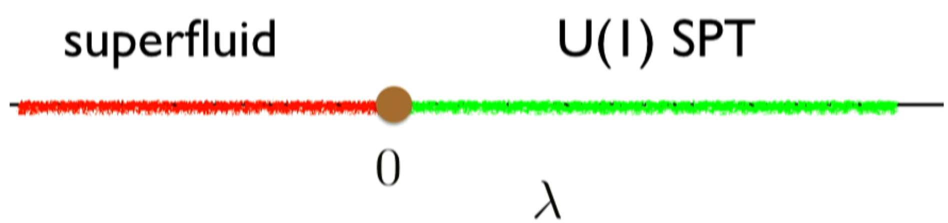
Field theory for zero gauge fluctuation

$$\mathcal{L} = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - itA^c_\mu)]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^f_\rho$$

$$+ \sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - itA^c_\mu)]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^g_\rho$$

$$+ \sum_{t=\pm} \phi(\bar{f}_t f_t + \bar{g}_t g_t) - 2\lambda\phi^2 + u\phi^4 + \cdots$$

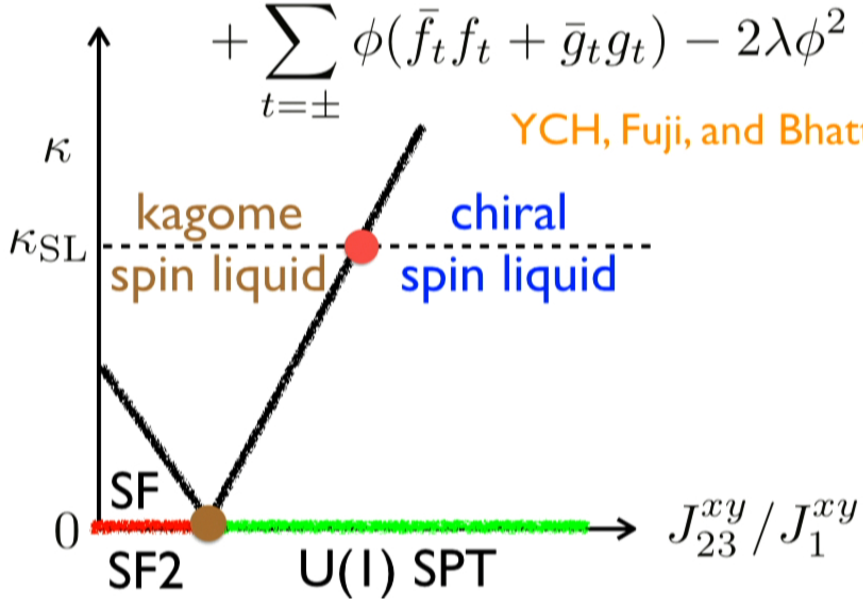
U(1) charge A^c U(1) pseudospin A^s



Field theory for finite gauge fluctuation

$$\mathcal{L} = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - itA^c_\mu)]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^f_\rho$$
$$+ \sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - itA^c_\mu)]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^g_\rho$$
$$+ \sum_{t=\pm} \phi(\bar{f}_t f_t + \bar{g}_t g_t) - 2\lambda\phi^2 + u\phi^4 + \cdots$$

YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015)



$$A^c \longrightarrow \frac{A^{S^z}}{2}$$

$$A^s \longrightarrow \mathcal{A}$$

Fate of DCP under gauge fluctuation

$$\mathcal{L} = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - itA^c_\mu)]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^f_\rho$$

$$+\sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - itA^c_\mu)]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}A^s_\mu\partial_\nu a^g_\rho$$

Nf=2 QED3

$$A^c \longrightarrow \frac{A^{S^z}}{2} \qquad A^s \longrightarrow \mathcal{A}$$

Nf=4 QED3!!!!

$$\mathcal{L}_D = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - it\frac{A^{S^z}_\mu}{2})]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^f_\rho$$

$$+\sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - it\frac{A^{S^z}_\mu}{2})]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^g_\rho$$

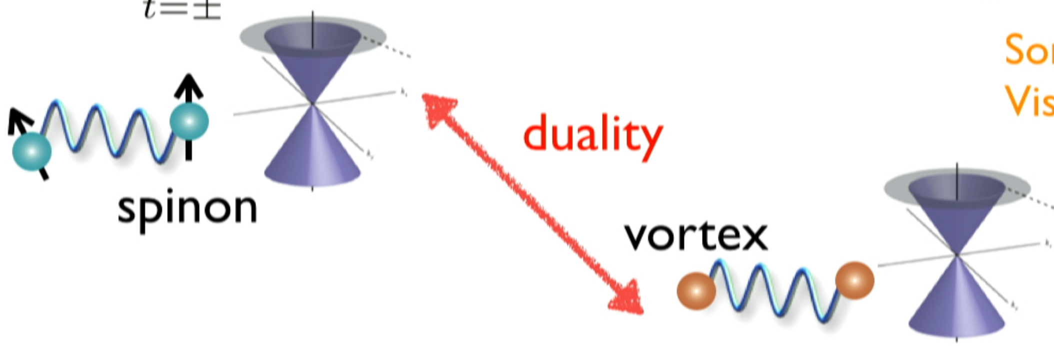
Integrate out dynamical gauge field $\mathcal{A}$ $\qquad a^f = a^g = a$

Dirac spin liquid, and more!

$$\mathcal{L}_D = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - it\frac{A^{S^z}_\mu}{2})]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^f_\rho$$

$$+ \sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - it\frac{A^{S^z}_\mu}{2})]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^g_\rho$$

Son, Metlitski, Senthil
Vishwanath, Wang,…



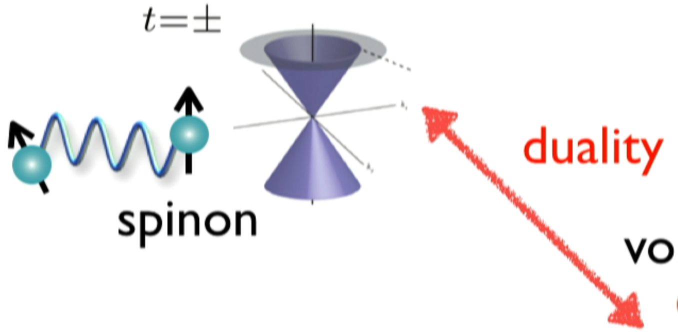
$$\mathcal{L}_D = \sum_{t=\pm} \bar{\tilde{f}}_t\left[i\gamma^\mu(\partial_\mu - i\tilde{a}^f_\mu - it\mathcal{A}_\mu)\right]\tilde{f}_t - \frac{1}{4\pi}\varepsilon_{\mu\nu\rho}A^{S^z}_\mu\partial_\nu\tilde{a}^f_\rho$$

$$+ \sum_{t=\pm} \bar{\tilde{g}}_t\left[i\gamma^\mu(\partial_\mu - i\tilde{a}^g_\mu - it\mathcal{A}_\mu)\right]\tilde{g}_t + \frac{1}{4\pi}\varepsilon_{\mu\nu\rho}A^{S^z}_\mu\partial_\nu\tilde{a}^g_\rho$$

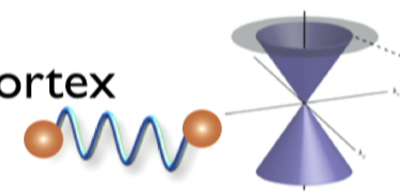
Dirac spin liquid, and more!

$$\mathcal{L}_D = \sum_{t=\pm} \bar{f}_t[i\gamma^\mu(\partial_\mu - ia^f_\mu - it\frac{A^{S^z}_\mu}{2})]f_t - \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^f_\rho$$

$$+ \sum_{t=\pm} \bar{g}_t[i\gamma^\mu(\partial_\mu - ia^g_\mu - it\frac{A^{S^z}_\mu}{2})]g_t + \frac{1}{2\pi}\varepsilon_{\mu\nu\rho}\mathcal{A}_\mu\partial_\nu a^g_\rho$$



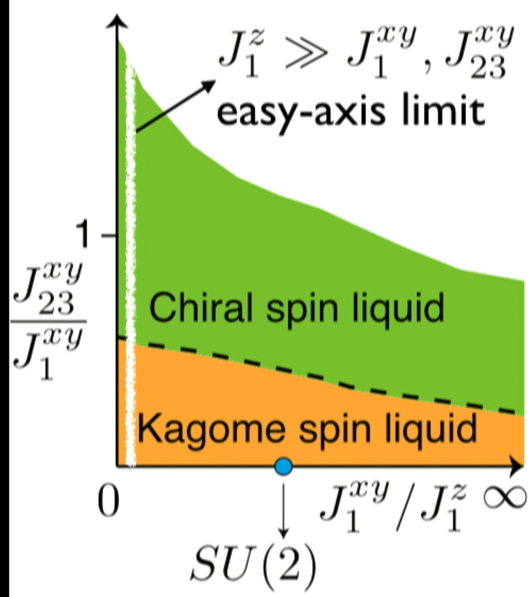
Son, Metlitski, Senthil
Vishwanath, Wang,…

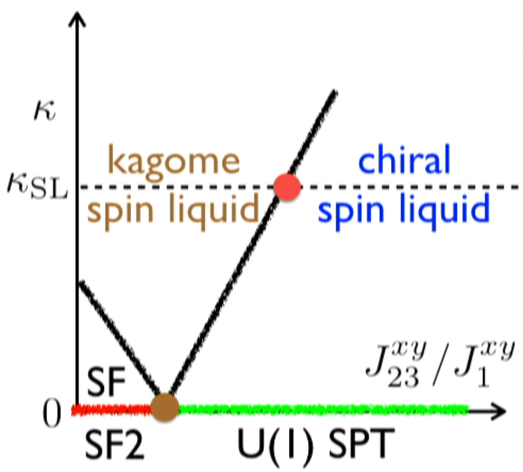


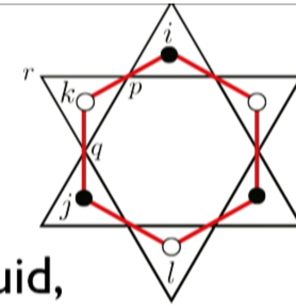
$$\mathcal{L}_D = \sum_{t=\pm} \bar{\tilde{f}}_t \left[i\gamma^\mu(\partial_\mu - i\tilde{a}^f_\mu - it\mathcal{A}_\mu)\right] \tilde{f}_t - \frac{1}{4\pi}\varepsilon_{\mu\nu\rho}A^{S^z}_\mu \partial_\nu \tilde{a}^f_\rho$$

$$+ \sum_{t=\pm} \bar{\tilde{g}}_t \left[i\gamma^\mu(\partial_\mu - i\tilde{a}^g_\mu - it\mathcal{A}_\mu)\right] \tilde{g}_t + \frac{1}{4\pi}\varepsilon_{\mu\nu\rho}A^{S^z}_\mu \partial_\nu \tilde{a}^g_\rho$$

Summary



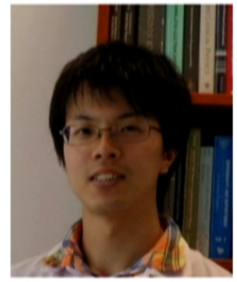




1. Besides the kagome spin liquid, we discover a chiral spin liquid.
2. Spin liquids on kagome lattice are independent of the XXZ anisotropy.
3. A controlled theoretical analysis for the chiral spin liquid.
4. Kagome spin liquid is a deconfined phase driven by gauge fluctuation (gauged DCP)?
5. Make a concrete connection between topological order, critical spin liquid, SPT phase, deconfined criticality.

Thanks for your attention!

Subhro Bhattacharjee
MPI-PKS, Dresden;
ICTS, Bangalore



Yohei Fuji
MPI-PKS, Dresden

Yan Chen
Fudan, Shanghai

Frank Pollmann
MPI-PKS, Dresden

Roderich Moessner
MPI-PKS, Dresden

also thanks D. N. Sheng (CSUN)

DFG SFB 1143

YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015).
YCH, Bhattacharjee, Pollmann, and Moessner, PRL 115, 267209 (2015).
YCH, Bhattacharjee, Moessner, and Pollmann, PRL 115, 116803 (2015).
YCH and Chen, PRL 114, 037201 (2015).
YCH, Sheng and Chen, PRL 112, 137202 (2014).

Numerical results on the spin gap