Title: Exotic emergent phenomena from many-body entanglement

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Abstract: <p>Many-body entanglement can lead to exotic phases of matter beyond conventional symmetry breaking paradigm. Those exotic phases may contain fractionalized quasiparticles and emergent gauge fields. In this talk, I will focus on a wide class of long-range entangled phasesâ€”quantum spin liquid. In quantum spin liquids, the spins are entangled in some intricate fashion giving rise to interesting physics such as emergent topological field theory and QED3 theory. I will show in detail how such exotic physics can emerge in simple spin systems.</p>

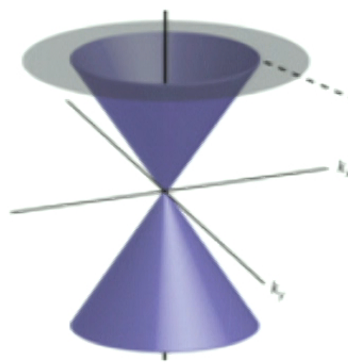
Exotic emergent phenomena from many-body entanglement

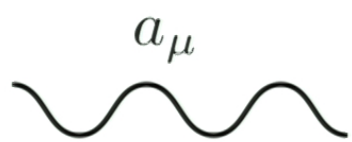
Yin-Chen He
(何寅琛)
Harvard University

GORDON AND BETTY MOORE FOUNDATION

PHYSICS HARVARD

Perimeter Institute, May 1, 2017





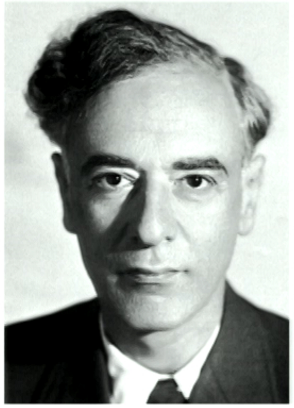
Part I: Introduction

- Phase of matter and phase transition
- Many-body entanglement
- Numerical simulation: using entanglement

Phases of matter

Universal feature

Spontaneous symmetry breaking

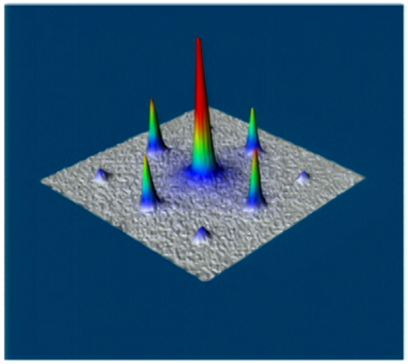


Landau's paradigm

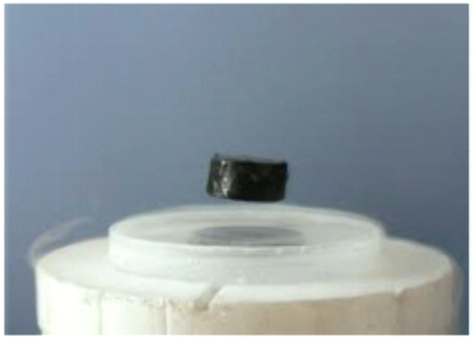
Phases "are classified by symmetry breaking"

Captured by an order parameter

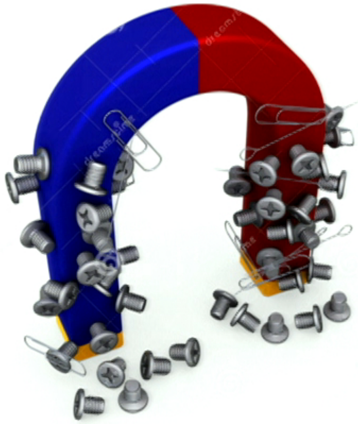
superfluid



superconductor

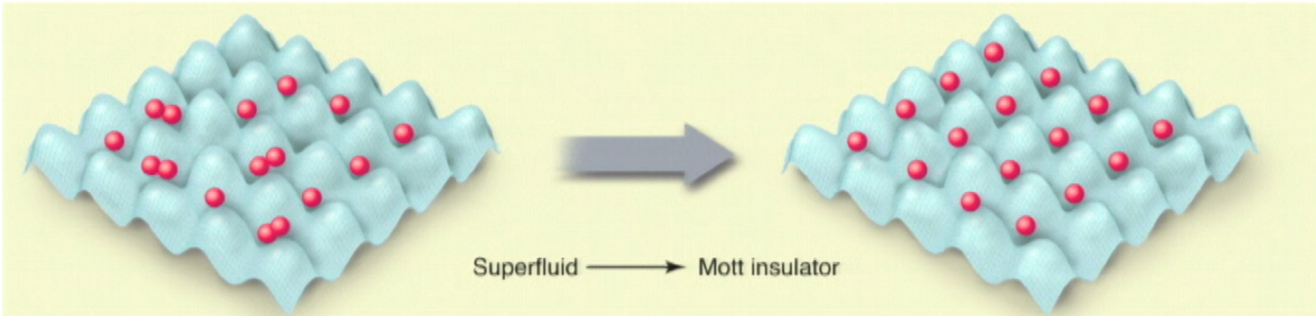


Ferromagnet



Phase transition

Superfluid | Mott insulator



$\langle \phi \rangle \neq 0$ | Wilson-Fisher | $\langle \phi \rangle = 0$

Spontaneous symmetry breaking

$$\mathcal{L} = |\partial_\mu \phi|^2 + m|\phi|^2 + \lambda|\phi|^4$$

Quantum entanglement

Product states: $|0\rangle \otimes |0\rangle, |1\rangle \otimes |1\rangle$

EPR pair: $\frac{1}{\sqrt{2}}(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle)$

Quantum entanglement

Product states: $|0\rangle \otimes |0\rangle, |1\rangle \otimes |1\rangle$

EPR pair: $\frac{1}{\sqrt{2}}(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle)$

$$\frac{1}{2}(|0\rangle \otimes |0\rangle + |1\rangle \otimes |1\rangle + |0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$$

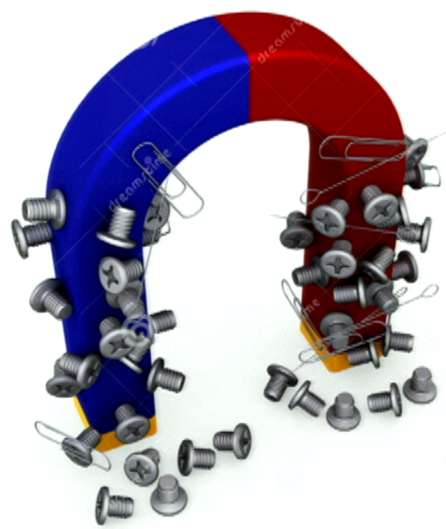
$$\downarrow$$

Product state $\frac{|0\rangle + |1\rangle}{2} \otimes \frac{|0\rangle + |1\rangle}{2}$

Symmetry breaking phase

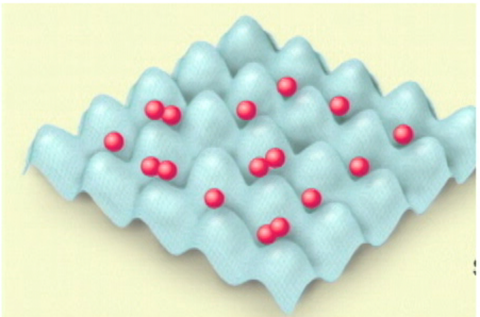
Entanglement pattern is "trivial"

Ferromagnet



$$|\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle$$

Superfluid

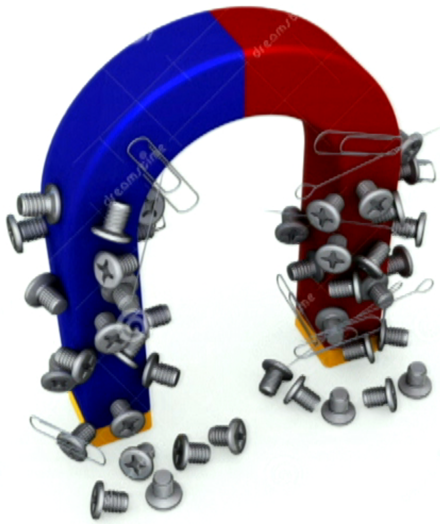


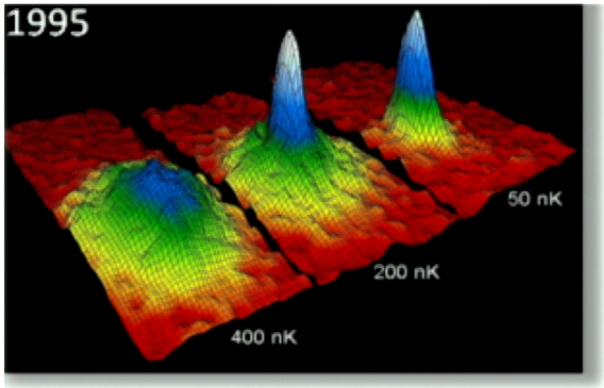
Symmetry breaking phase

Entangement pattern is "trivial"

Ferromagnet

Superfluid





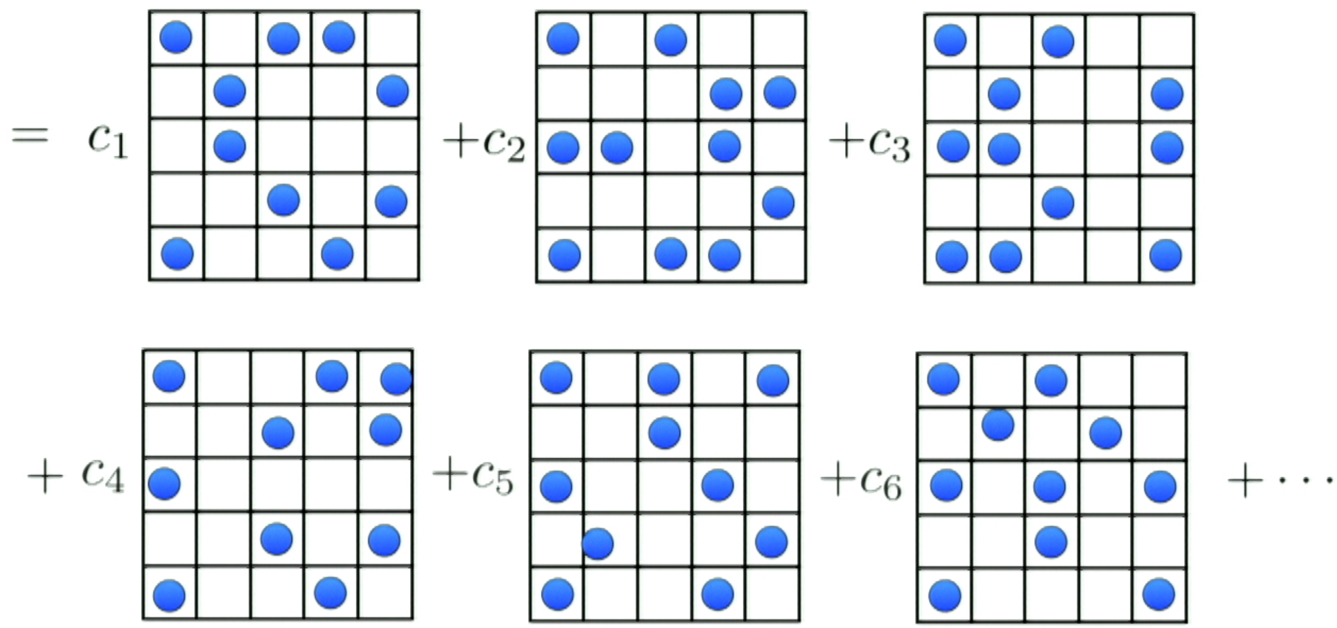
$$|\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle \otimes |\uparrow\rangle$$

$$(b^{\dagger}_{K=0})^N|0>$$

Many entangled electrons

$$\Psi = \prod_{k<k_F} f_k^\dagger |0\rangle$$

Fermi liquid

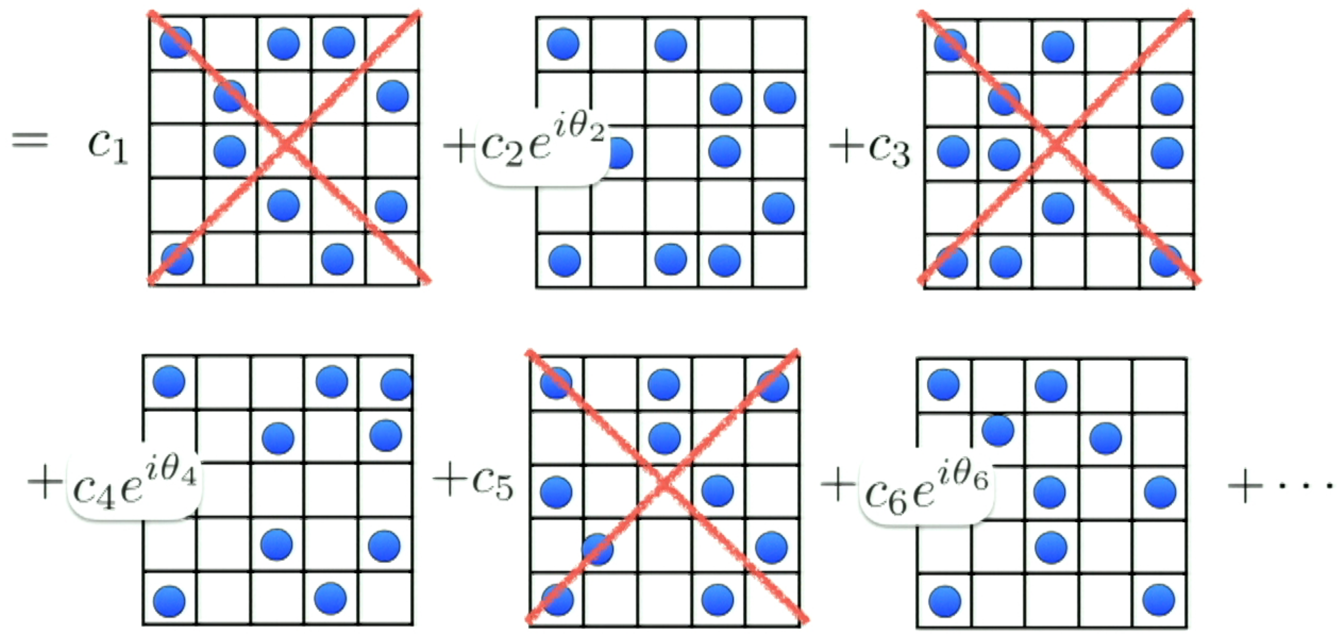


Many entangled electrons

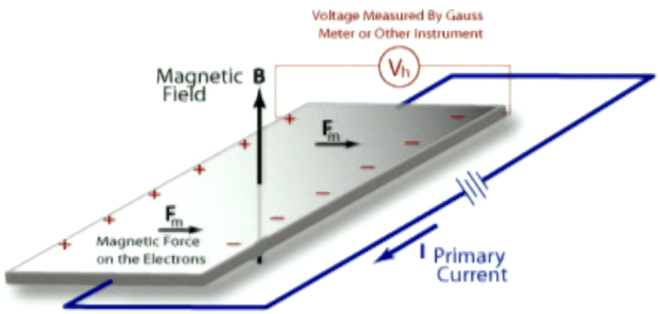
$$\Psi = \left[\prod (z_i - z_j)^3\right] e^{-\frac{\sum |z_k|^2}{4 l_B^2}}$$

Laughlin wave-function

$$z_k = x_k + i y_k$$



Fractional quantum Hall state

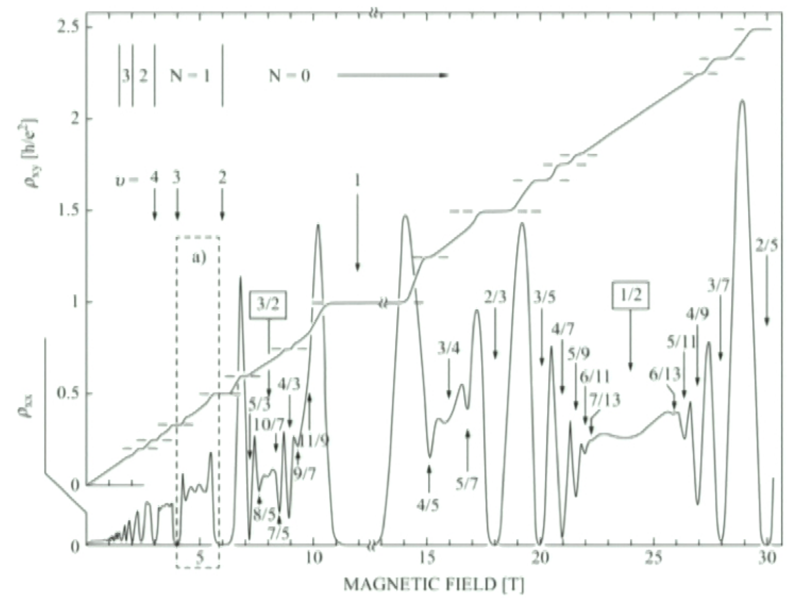


Classical

$$R_{xy} = 1/\sigma_{xy} \sim B$$

Stormer, Tsui, Laughlin

Quantum $\sigma_{xy} = \nu \frac{e^2}{h}$

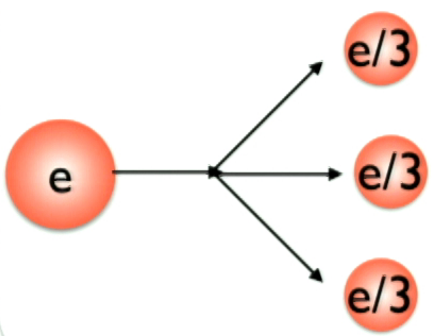


Fractional quantum Hall state

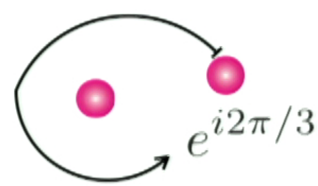
$$\Psi = \left[\prod (z_i - z_j)^3\right] e^{-\frac{\sum |z_k|^2}{4l_B^2}} \qquad z_k = x_k + i y_k$$

Emergent topological field theory: $\frac{3}{4\pi} ada$

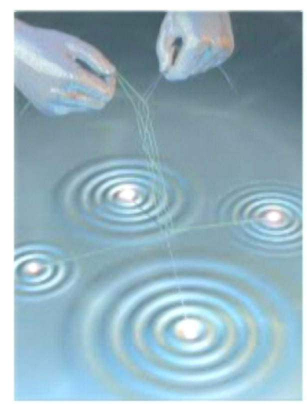
Fractionalization



Fractional statistics

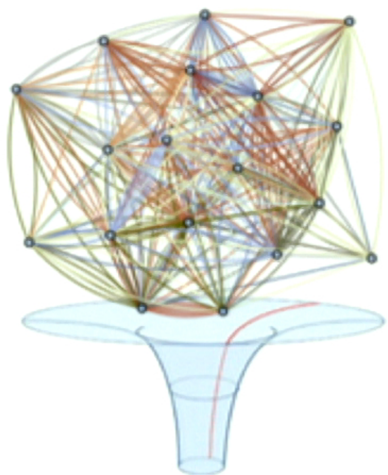


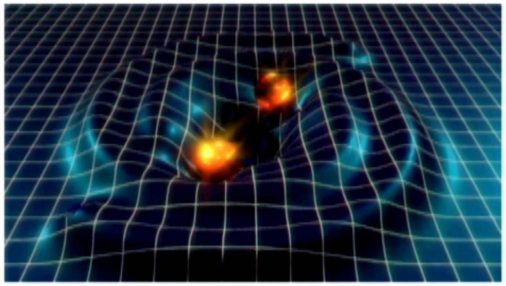
Topological quantum computation



Exotic emergent phenomena from many-body entanglement

Many entangled fermions





Sachdev-Ye-Kitaev model

Quantum gravity?

Complexity from Entanglement

The Hilbert space dimension of N qubits: 2^N

Typical condensed matter system: $N \sim 10^{23}$

Example: memory cost

N~32

laptop

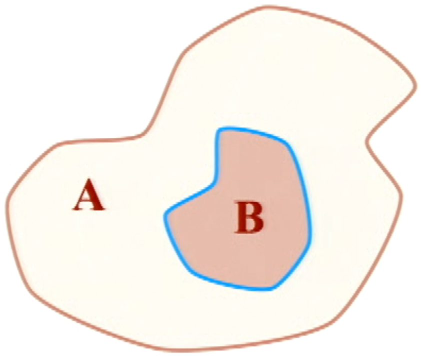
N~48

supercomputer

N~266

observable universe

Entanglement area law



$$\rho^B \equiv \mathrm{Tr}_A(|\Psi^{AB}\rangle\langle\Psi^{AB}|)$$

Entanglement entropy

$$S(B) \equiv -\mathrm{Tr}(\rho^B \ln \rho^B)$$

Generic volume law: $S(B) \sim L^D$

Groundstate of a local, gapped Hamiltonian in D spatial dimension

Area law

$$S(B) \sim |\partial B| \sim L^{D-1}$$

A gapless system may have $S(B) \sim L^{D-1} \log L$

Matrix product state

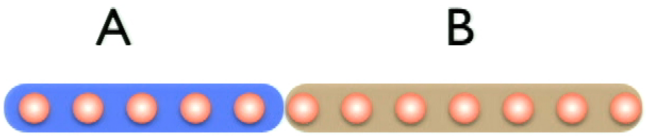
$$|\Psi\rangle = \sum_{\{s_i\}} c_{s_1,\cdots,s_N} |s_1,\cdots,s_N\rangle$$

$c_{s_1,\cdots,s_N}$: d^N complex numbers

Matrix product state

$$|\Psi\rangle = \sum_{\{s_i\}} c_{s_1,\cdots,s_N} |s_1, \cdots, s_N\rangle$$

$c_{s_1,\cdots,s_N}$: d^N complex numbers



$$S_B(l_B) = \text{const}$$

Matrix product state

$$|\Psi\rangle = \sum_{\{s_i\}} c_{s_1,\cdots,s_N} |s_1,\cdots,s_N\rangle$$

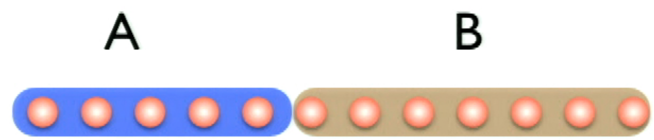
$c_{s_1,\cdots,s_N}$: d^N complex numbers

$$c_{s_1,\cdots,s_N} = \prod_i A^{s_i}_{v_i,v_{i+1}}$$

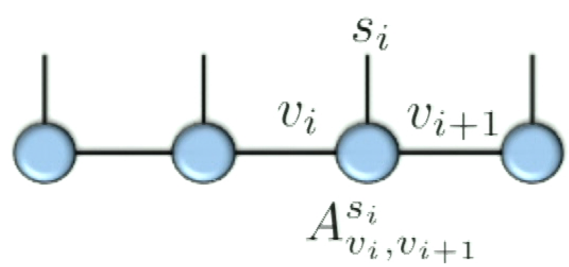
Matrix product states

DMRG (density matrix renormalization group)

White



$$S_B(l_B) = \text{const}$$



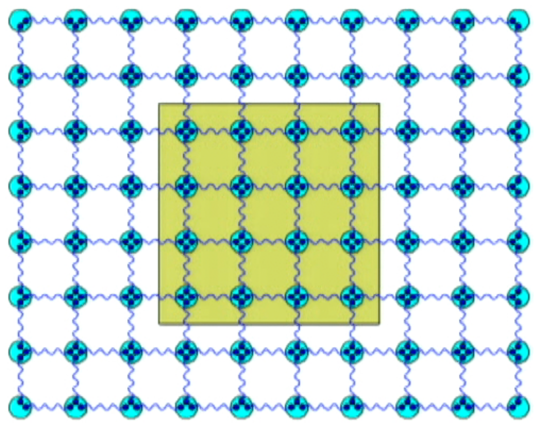
$Nd\chi^2$ complex numbers

Physical index: $s_i = 1,\cdots,d$

Virtual index: $v_i = 1,\cdots,\chi$

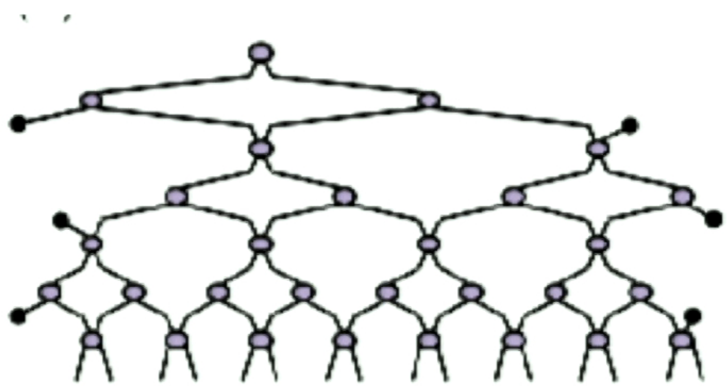
Tensor network state

PEPS



Verstraete, Cirac

MERA



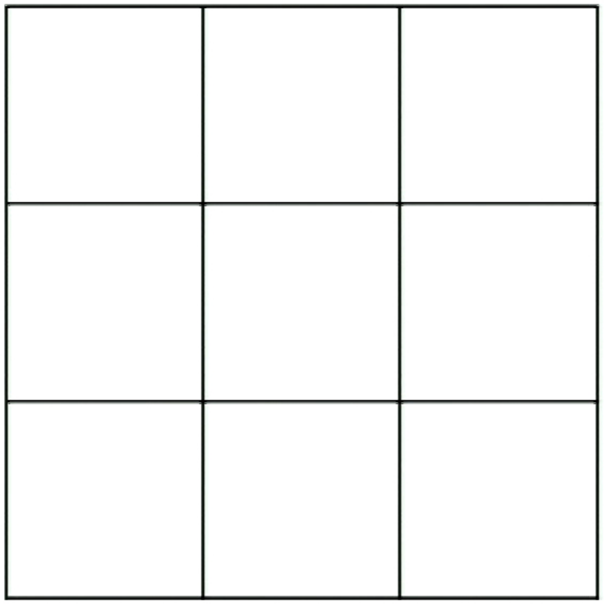
Vidal

Part II: Spin liquid on kagome lattice

1. Introduction of spin liquid
2. Numerics: Dirac spin liquid and chiral spin liquid
3. Theory: emergent gauge field and Dirac fermions

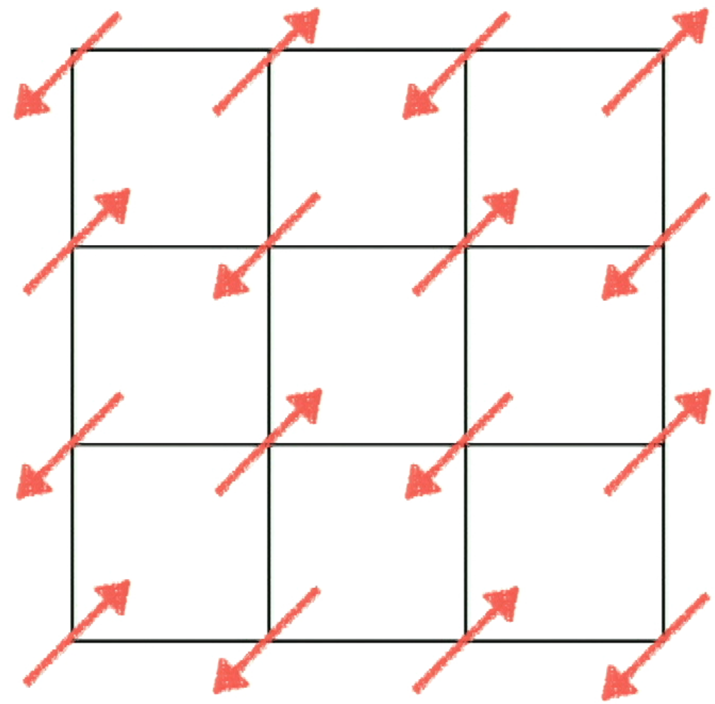
Spins on a lattice

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



Spins on a lattice

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

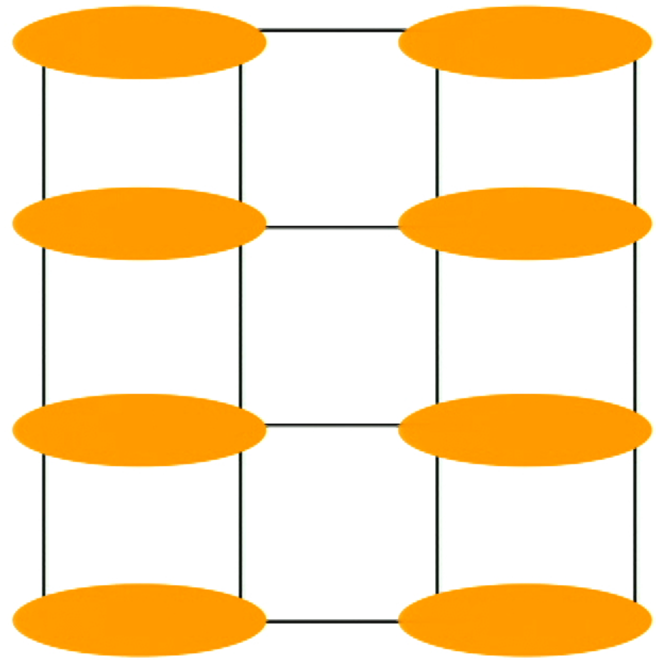


Magnetic order

Spins on a lattice

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

$$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$

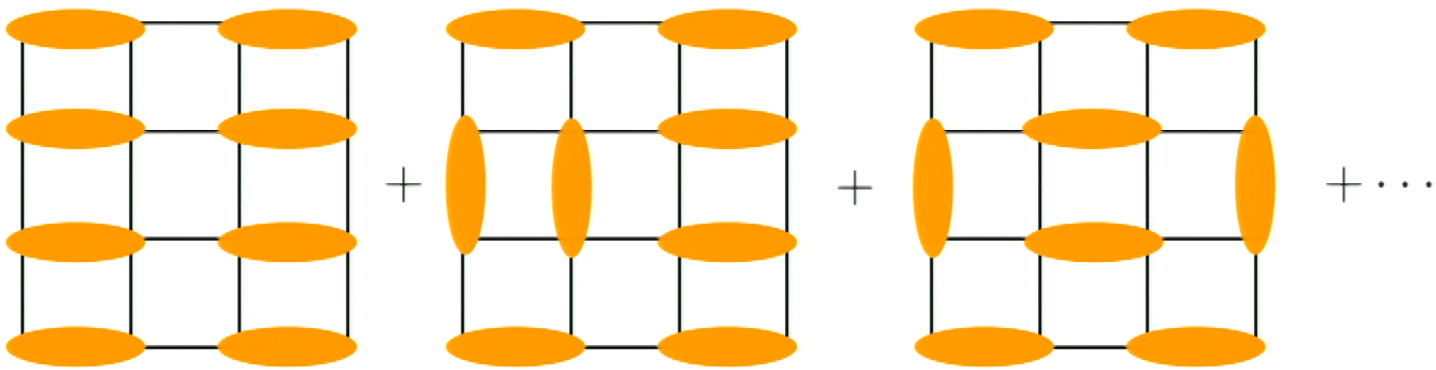


Valence bond solid

Spins on a lattice

Resonating valence bond state—A spin liquid

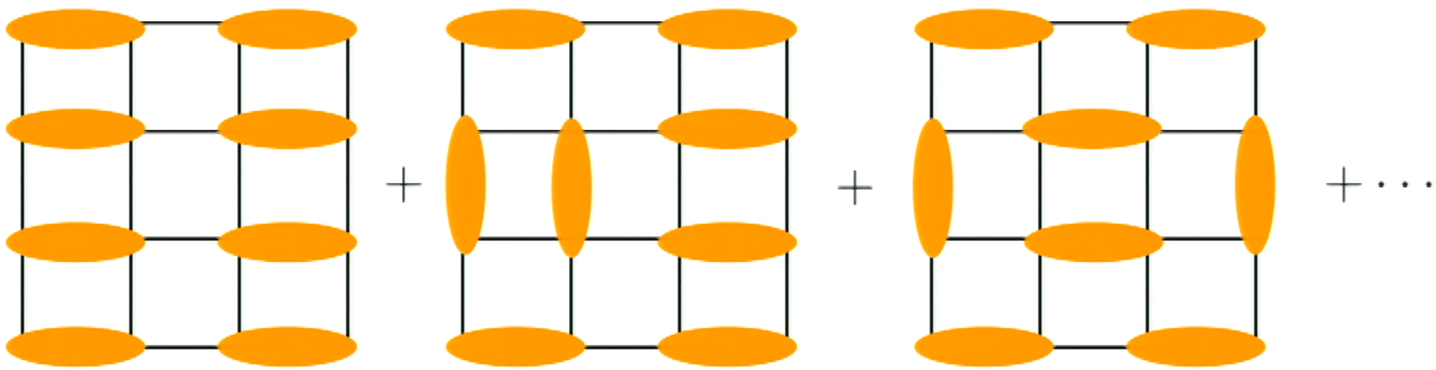
Anderson



Spins on a lattice

Resonating valence bond state—A spin liquid

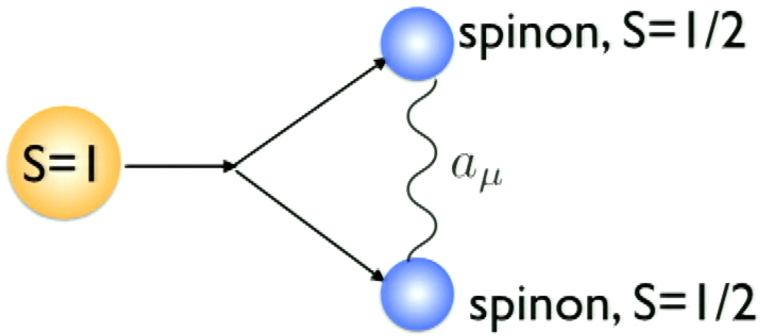
Anderson



1. What is its property?

2. Where to find such state?

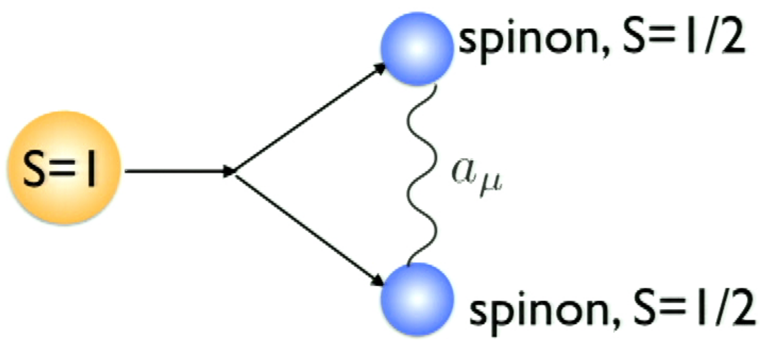
Quantum spin liquid



Fractionalization

Emergent gauge field

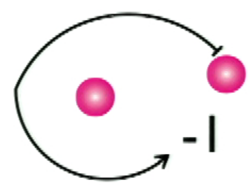
Quantum spin liquid



Fractionalization

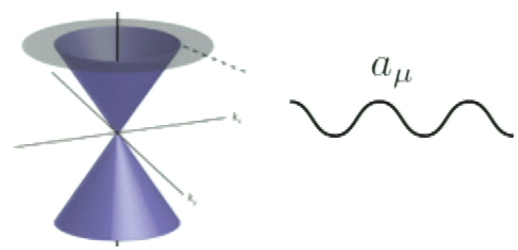
Emergent gauge field

Topological field theory

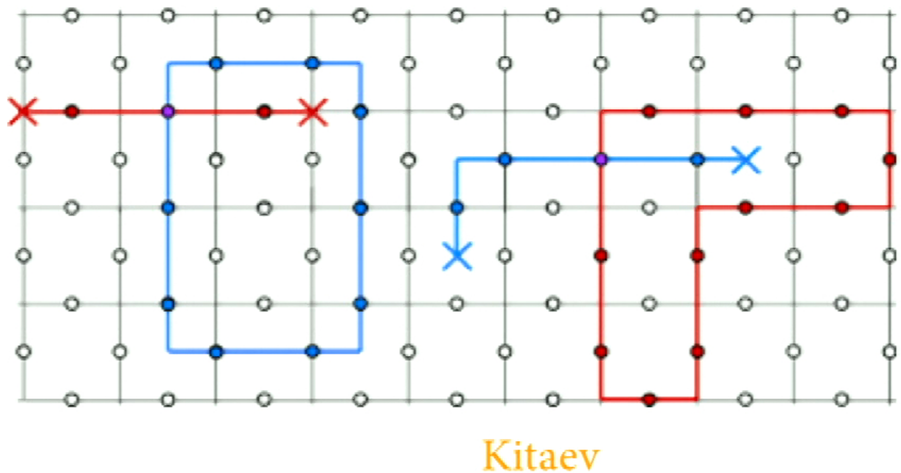


Z2 gauge theory

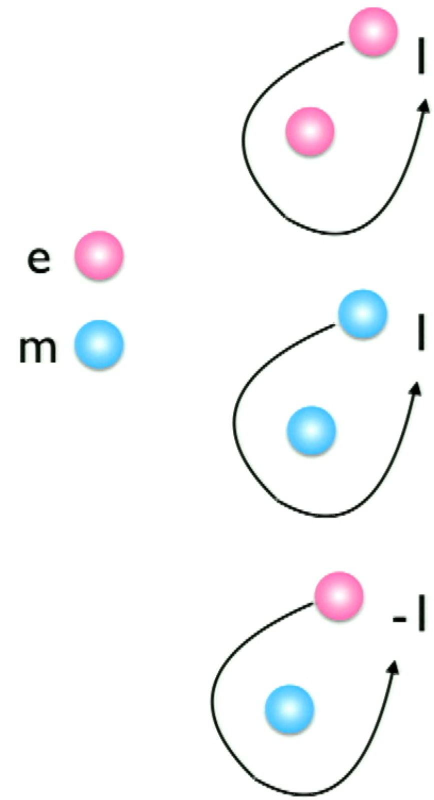
QED3 theory



Example: Toric code

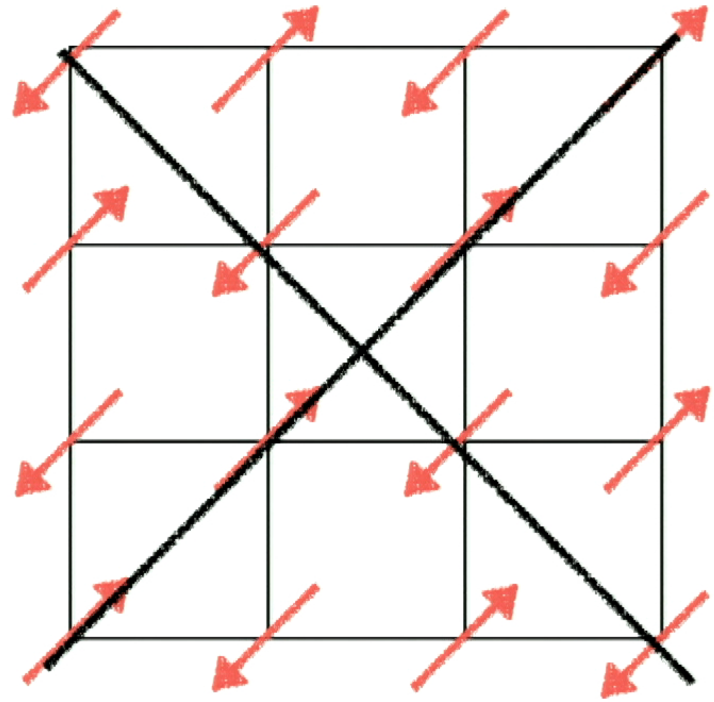


$$H = -\sum_v \prod_{l \in v} \sigma_l^z - \sum_p \prod_{l \in p} \sigma_l^x$$



Finding a spin liquid

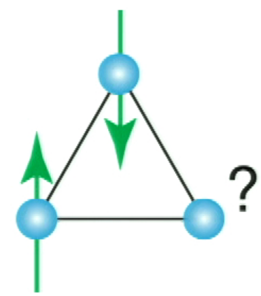
$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$



Finding a spin liquid

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

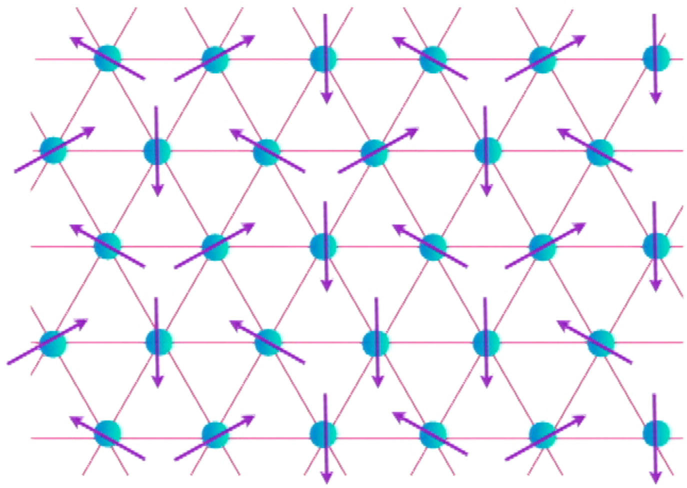
Frustration



Finding a spin liquid

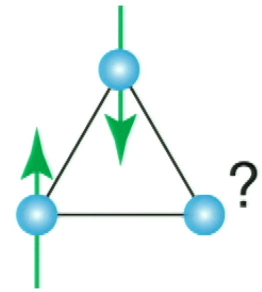
$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

Triangular lattice



Magnetic ordered

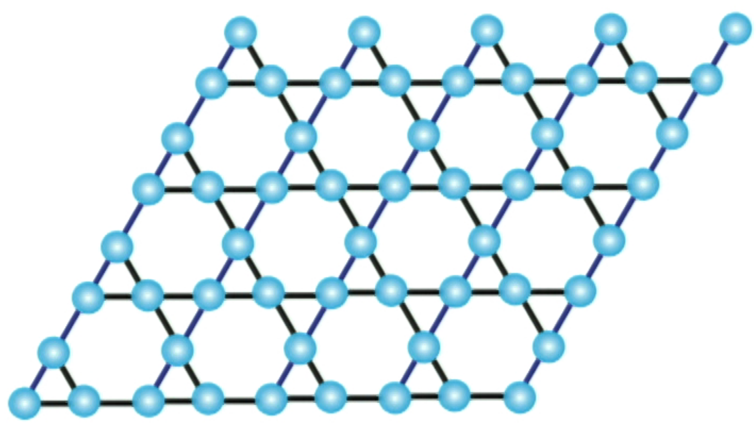
Frustration



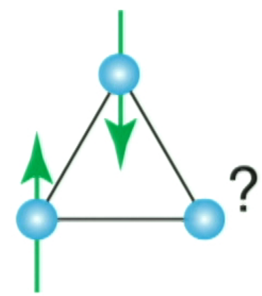
Finding a spin liquid

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

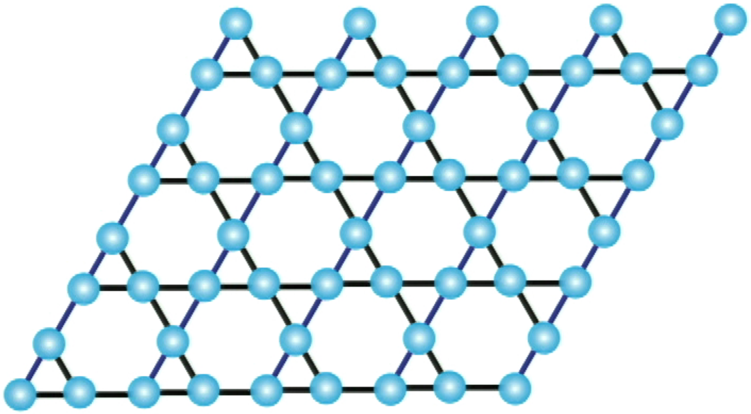
Kagome lattice



Frustration



Spin liquids on kagome lattice

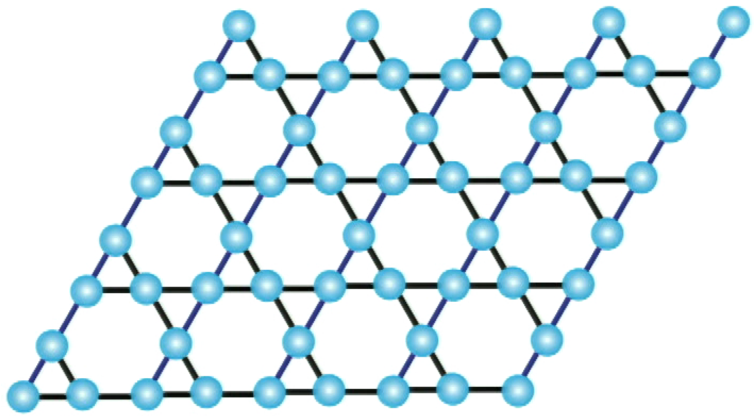


Kagome Heisenberg model

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

What is the ground state?

Spin liquids on kagome lattice



Kagome Heisenberg model

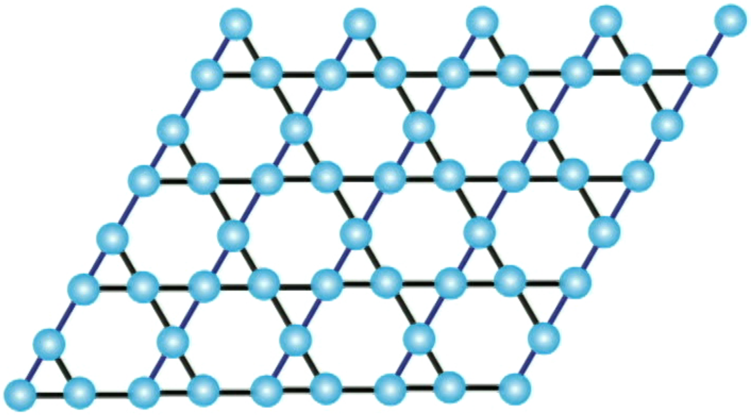
$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j, \quad J > 0$$

What is the ground state?

Every possible candidate has been proposed?!

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); Jiang, Sheng, Weng (2008); 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)….

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?

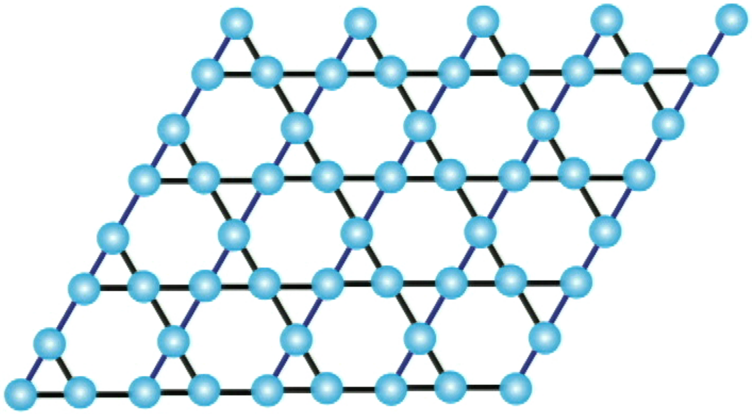
Yan, Huse, and White (2011)

Kagome spin liquid

Spin liquid! But which one?

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); Jiang, Sheng, Weng (2008); 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)….

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?

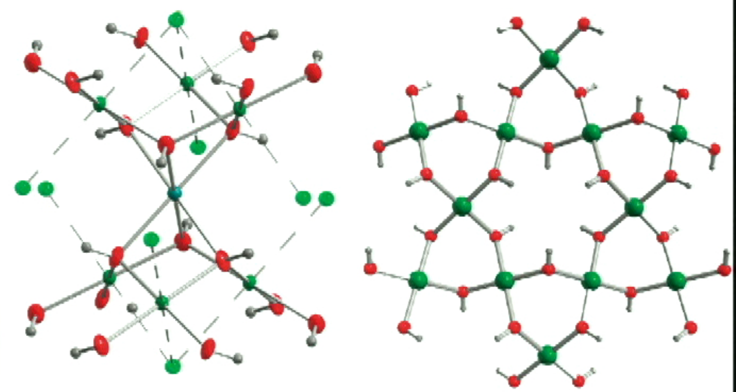
Yan, Huse, and White (2011)

Kagome spin liquid

Spin liquid! But which one?

Herbersmithite $ZnCu_3(OH)_6CL_2$

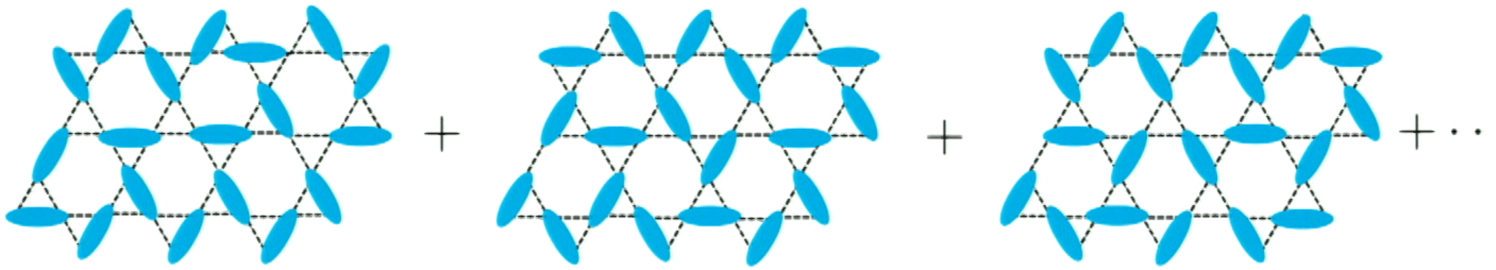
YS Lee group



Kagome spin liquid candidate

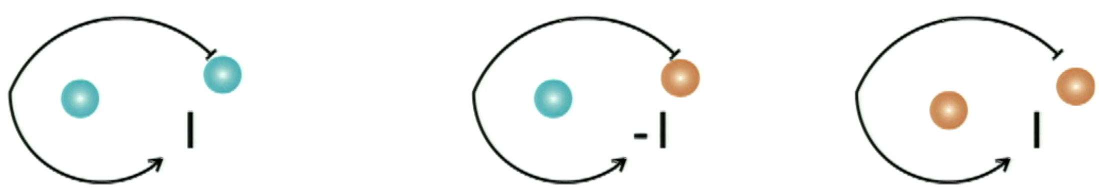
Short-range RVB, Z2 spin liquid, gapped

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

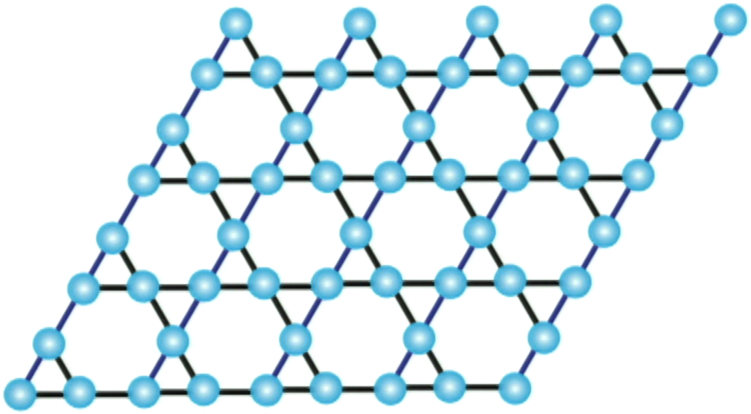


Toric code topological order

fractional quasiparticle   spinon   vison



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?

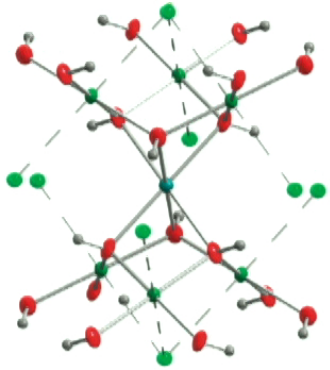
Yan, Huse, and White (2011)

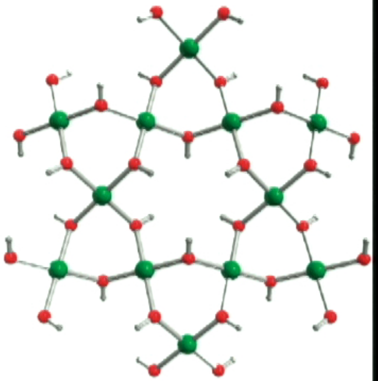
Kagome spin liquid

Spin liquid! But which one?

Herbersmithite $ZnCu_3(OH)_6CL_2$

YS Lee group

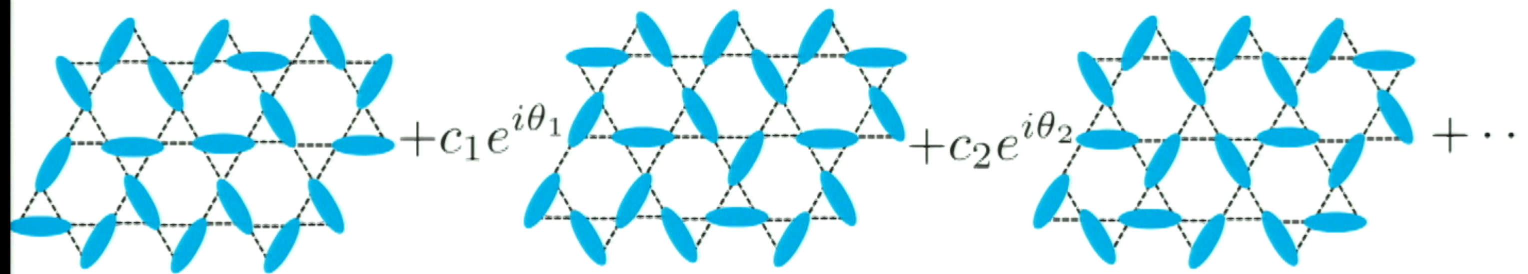




Kagome spin liquid candidate

Short-range RVB, chiral spin liquid, gapped

Kalmeyer & Laughlin, PRL 1987

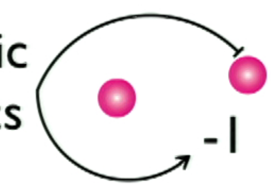


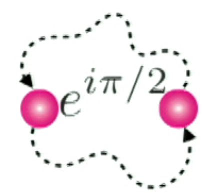
1/2 Laughlin state, breaks time-reversal symmetry

Chern-Simons $\frac{2}{4\pi} a da$

spinon  1/2 spin

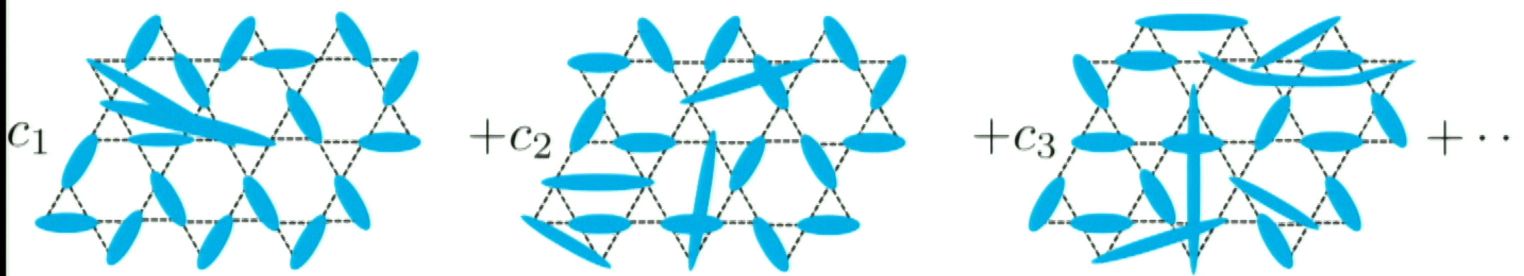
Semionic statistics





Kagome spin liquid candidate

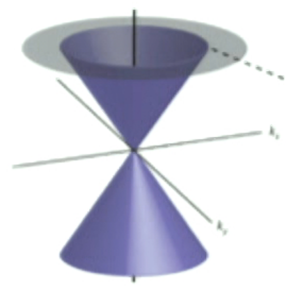
Long-range RVB, gapless spin liquid



Dirac spin liquid

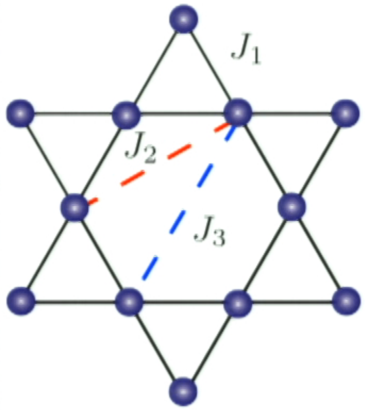
$$\mathcal{L} = \sum \bar{\psi}_i [i\gamma^\mu (\partial_\mu - i a_\mu)] \psi_i$$

Emergence of Dirac fermions in a bosonic system!!



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

Spin liquids on kagome lattice

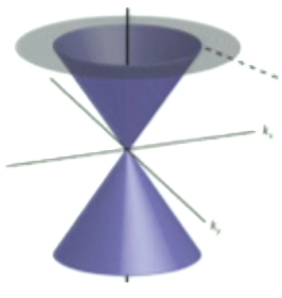


$$H = J_1 \sum_{1\text{st}} \vec{S}_i \cdot \vec{S}_j + J_2 \sum_{2\text{nd}} \vec{S}_i \cdot \vec{S}_j + J_3 \sum_{3\text{rd}} \vec{S}_i \cdot \vec{S}_j$$

$$J_2 = J_3 = J'$$

0.0 — ~0.3 — 0.8 J'/J_1

Dirac Spin Liquid | Chiral Spin Liquid

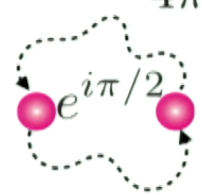


a_μ

CFT

$$\mathcal{L} = \sum \bar{\psi}_i [i\gamma^\mu (\partial_\mu - i a_\mu)] \psi_i$$

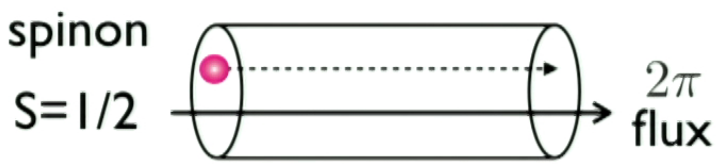
Chern-Simons $\frac{2}{4\pi} ada$



Numerics for the chiral spin liquid

Hall conductance

Flux insertion Laughlin, PRB 1981

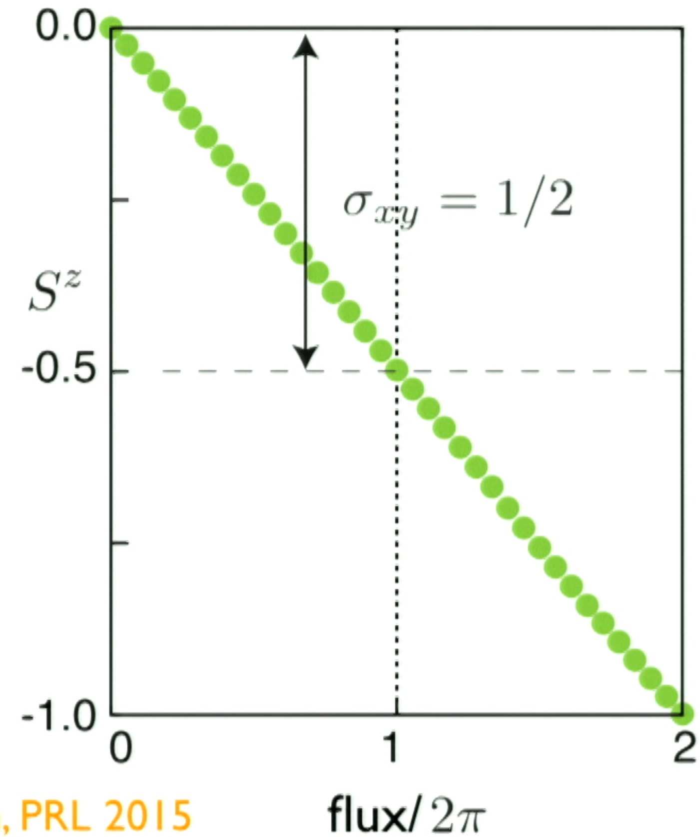


2π flux pumps one spinon

Chern-Simons $\frac{2}{4\pi} ada$

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

DMRG results

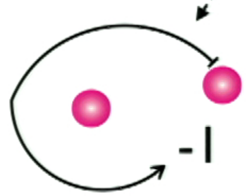


Fractional statistics from DMRG

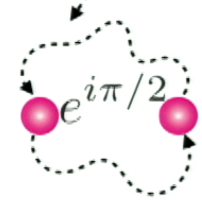
Wen, Int. J. Mod. Phys. B, 1990
Zhang, Grover, Turner, Oshikawa & Vishwanath, PRB 2012
Cincio & Vidal, PRL 2013

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

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



Chern-Simons $\frac{2}{4\pi} a da$



YCH, Sheng & Chen, PRL 2014; Gong, Zhu & Sheng, Sci. Rep 2014;
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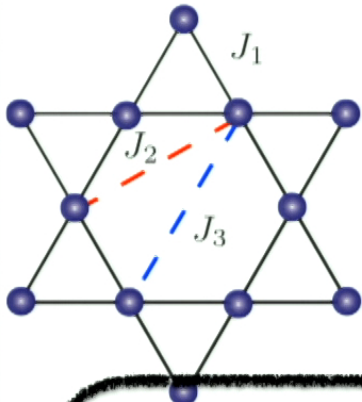
Spin liquids on kagome lattice



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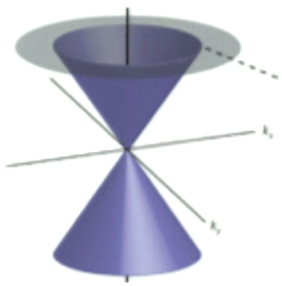
Dirac Spin Liquid



a_μ

CFT

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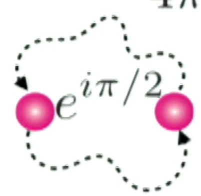
Chiral Spin Liquid

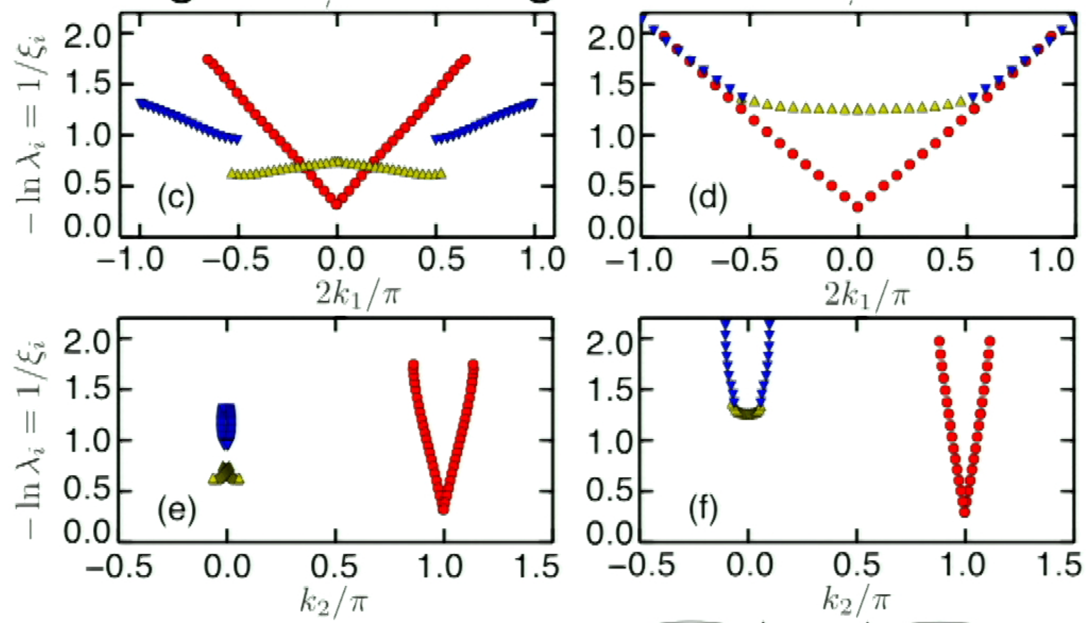
Chern-Simons $\frac{2}{4\pi} a da$



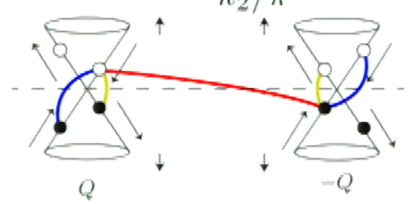
Spectrum of triplet excitation

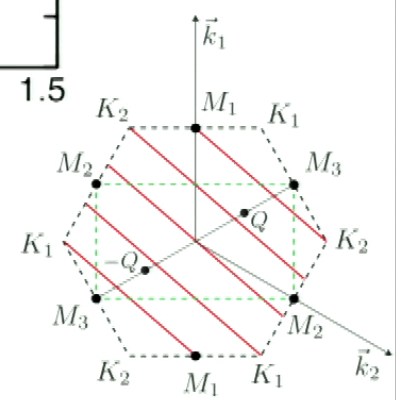
YCH, Zaletel, Oshikawa, Pollmann arXiv:1611.06238 (2016)

Kagome Heisenberg | Free fermion (parton pi-flux)



DMRG data





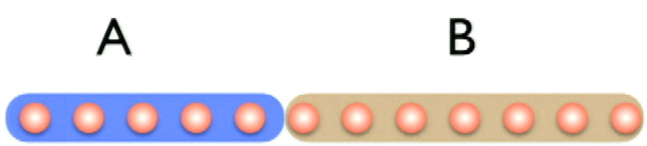
$$S^+(p-q) = f_\uparrow^\dagger(p) f_\downarrow(q)$$

Zauner, et. al., Verstraete, arXiv:1408.5140

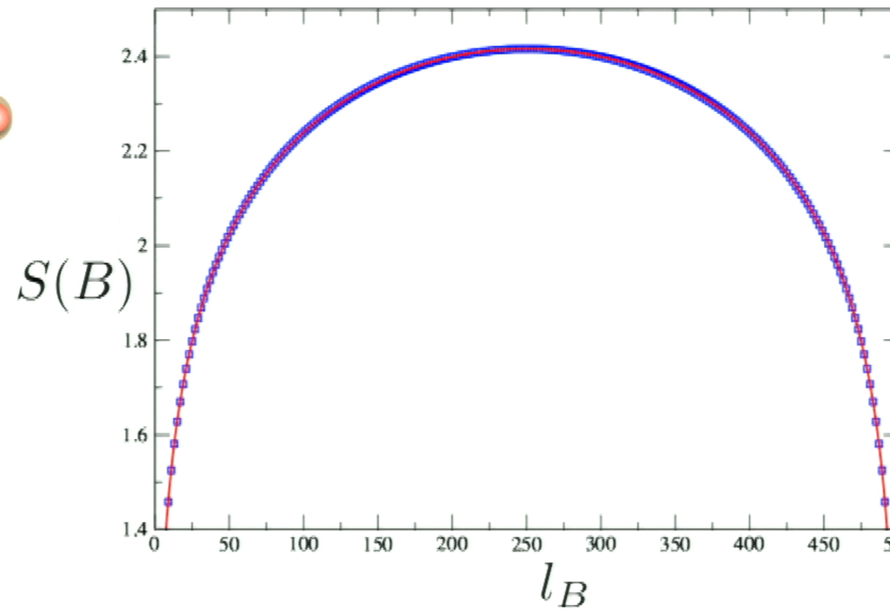
Entanglement entropy as a probe

1+1D CFT $$S(B) = \frac{c}{3}\log\left(\frac{L}{\pi}\sin\left[\frac{\pi l_B}{L}\right]\right) + \text{const}$$

Vidal, Latorre, Rico, Kitaev, 2003; Calabrese & Cardy 2004

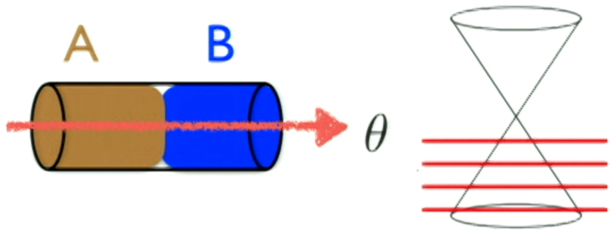


$$\rho^B \equiv \mathrm{Tr}_A(|\Psi^{AB}\rangle\langle\Psi^{AB}|)$$
$$S(B) \equiv -\mathrm{Tr}(\rho^B \ln \rho^B)$$



Entanglement entropy as a probe

2+1D CFT



Free Dirac fermions:

$$S = -\frac{1}{3}\log(2\sin(\theta/2)) + AL_c + \cdots$$

Metlitski, et. al. (2009)
Chen, et. al (2016)

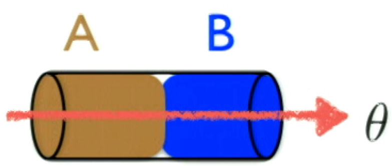
Other probe: e.g. Melko

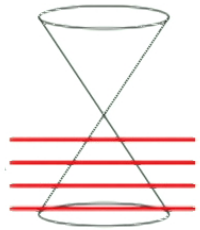
Entanglement entropy as a probe

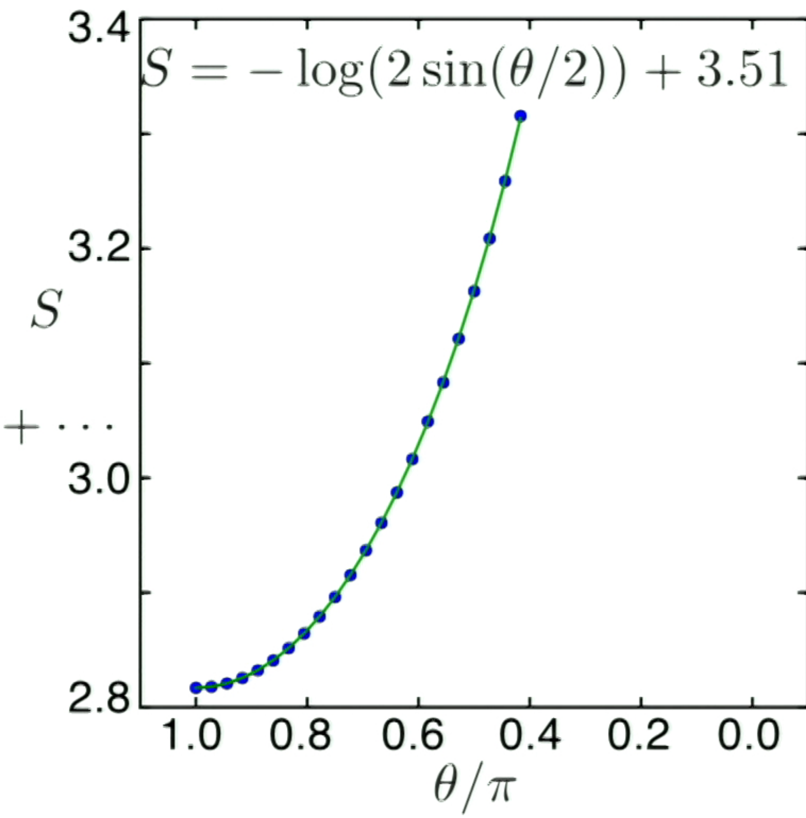
YCH, et. al. (in prepare)

2+1D CFT

Kagome spin liquid: QED3







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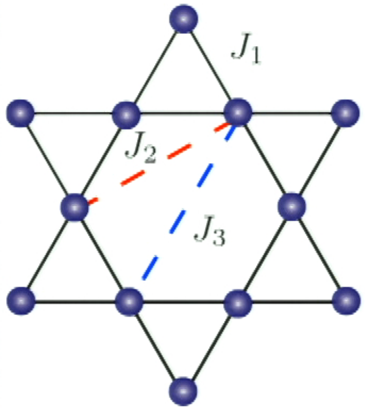
Spin liquids on kagome lattice



$$H = J_1 \sum_{\text{1st}} \vec{S}_i \cdot \vec{S}_j + J_2 \sum_{\text{2nd}} \vec{S}_i \cdot \vec{S}_j + J_3 \sum_{\text{3rd}} \vec{S}_i \cdot \vec{S}_j$$

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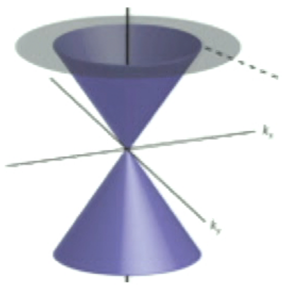
Dirac Spin Liquid

Chiral Spin Liquid



a_μ

CFT

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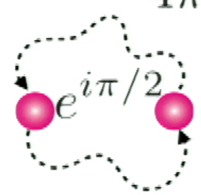
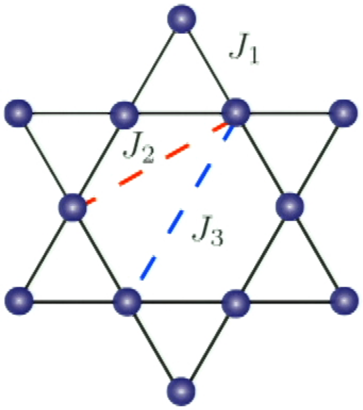
Chern-Simons $\frac{2}{4\pi} ada$



Spin liquids on kagome lattice



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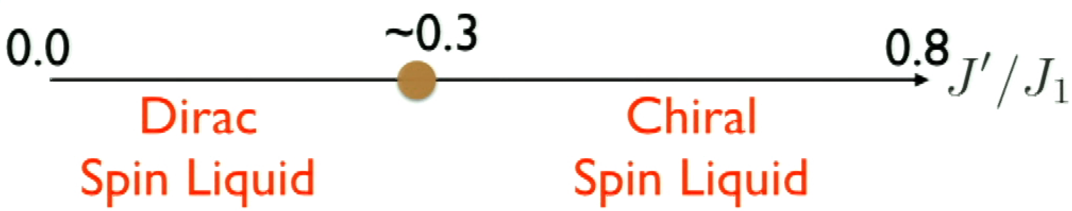


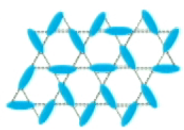
$\langle \phi \rangle = 0$ $\langle \phi \rangle \neq 0$

Gross-Neveu-QED3

$$\mathcal{L} = \sum \bar{\psi}_i [i\gamma^\mu(\partial_\mu - i a_\mu)]\psi_i + \phi \left(\sum \bar{\psi}_i \psi_i \right) + \lambda |\phi|^2 + u|\phi|^4 + \cdots$$

Exotic emergent phenomena from many-body entanglement

Many entangled
bosonic spins

$\sum c_i \big|$  $\big\rangle$

→

Topological field theory

e.g.Chern-Simons $\frac{k}{4\pi} ada$

Electrodynamics

QED3: Dirac fermions

Various CFTs

……

Exotic emergent phenomena from many-body entanglement

Topological field theory

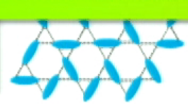
e.g.Chern-Simons $\frac{k}{4\pi} ada$

Many entangled

boso

Theoretical understanding?

cs

$\sum c_i |$  $\rangle$

QED3: Dirac fermions

Various CFTs

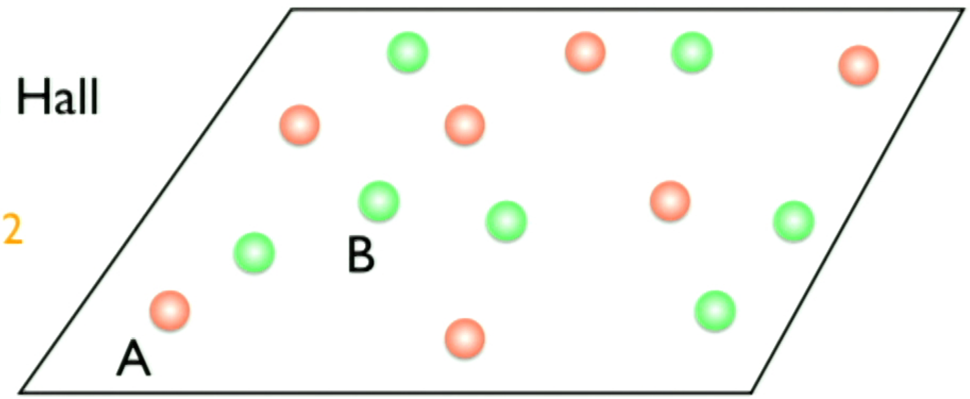
……

Emergent Dirac fermions

A set up: two species of bosons

Bosonic integer quantum Hall

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



Relation with spin liquid: YCH, Fuji, and Bhattacharjee, arXiv:1512.05381

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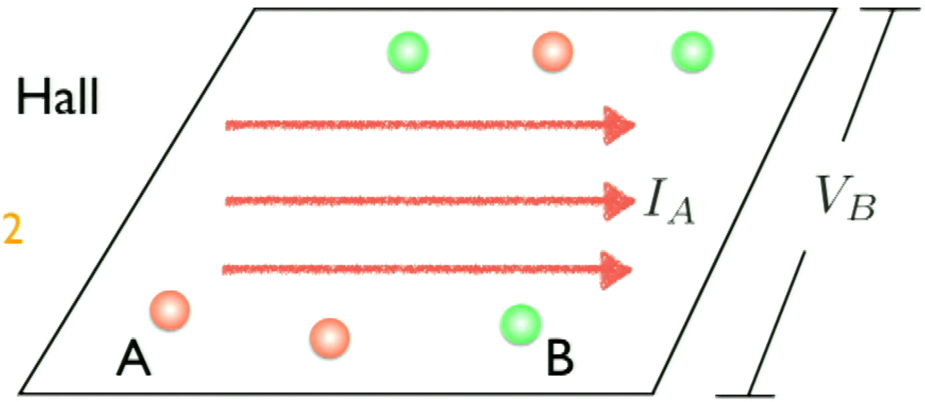


$$\frac{2}{4\pi} A^a dA^b$$

A^a, A^b Probe field of A, B

Relation with spin liquid: YCH, Fuji, and Bhattacharjee, arXiv:1512.05381

Emergent Dirac fermions

A^a, A^b Probe field of A, B

$$\frac{2}{4\pi} A^a dA^b \qquad\qquad \frac{0}{4\pi} A^a dA^b$$

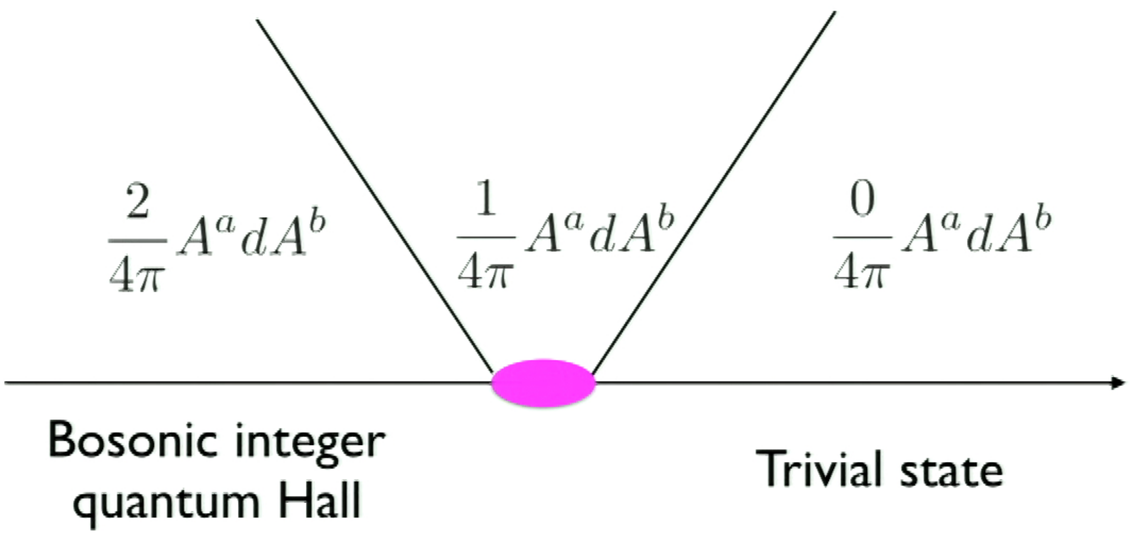
Bosonic integer quantum Hall

Trivial state

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

Emergent Dirac fermions

A^a, A^b Probe field of A, B



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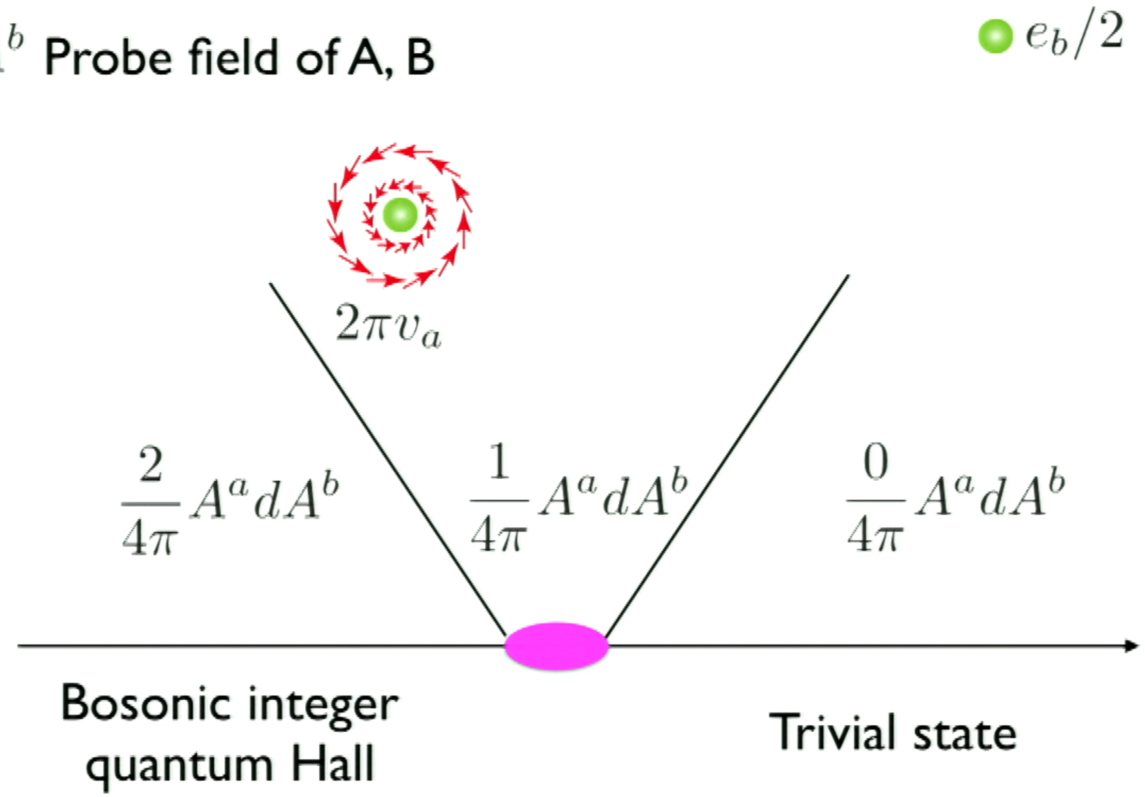

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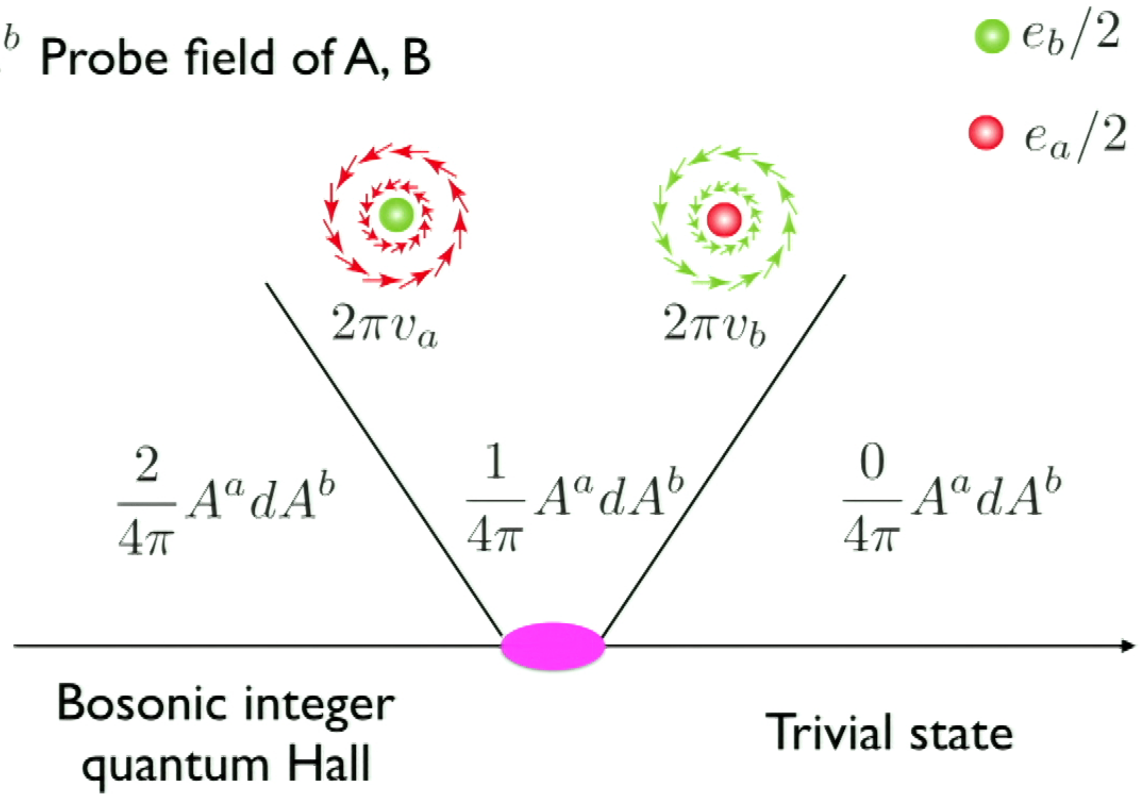

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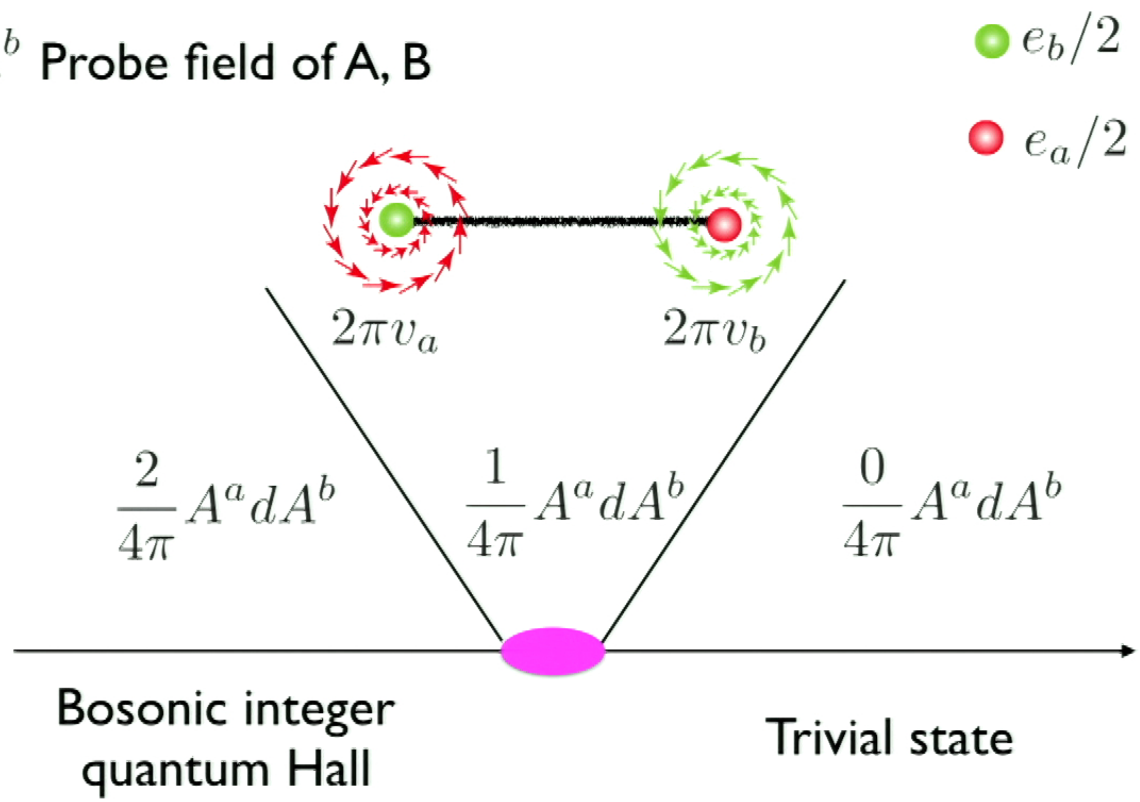
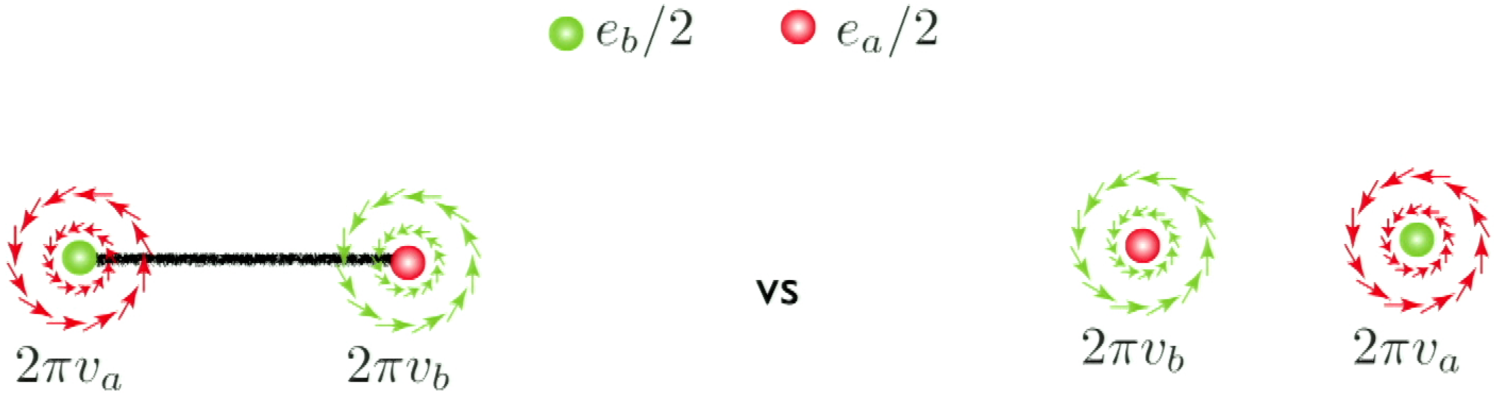


YCH, Fuji, and Bhattacharjee, arXiv:1512.05381 (2015).

Dualities



$$\sum_{\alpha=1,2} \bar{\psi}_\alpha [i\gamma^\mu(\partial_\mu - i a_\mu)]\psi_\alpha$$

QED3

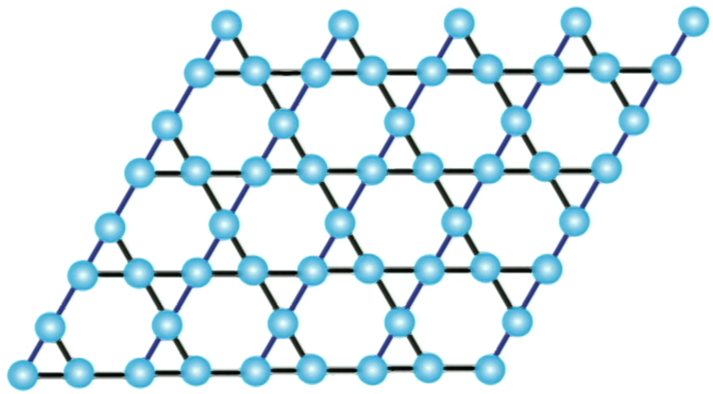
$$\sum_{\alpha=1,2} |(\partial_\mu - i b_\mu) z_\alpha|^2$$

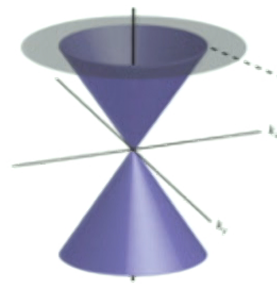
CP^1

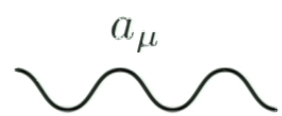
Senthil & Fisher, 2006; Wang, Senthil, 2015, Metlitski & Vishwanath, 2015; Xu & You, 2015; Karch & Tong 2016; Seiberg, Senthil, Wang, & Witten, 2016

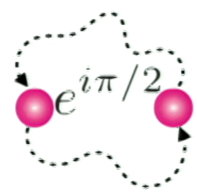
Summary

1. Exotic phenomena can emerge from many-body entanglement.
2. Spin liquids are prominent examples of the long-range entangled states.
3. We discuss the spin liquid phases on the kagome lattice.









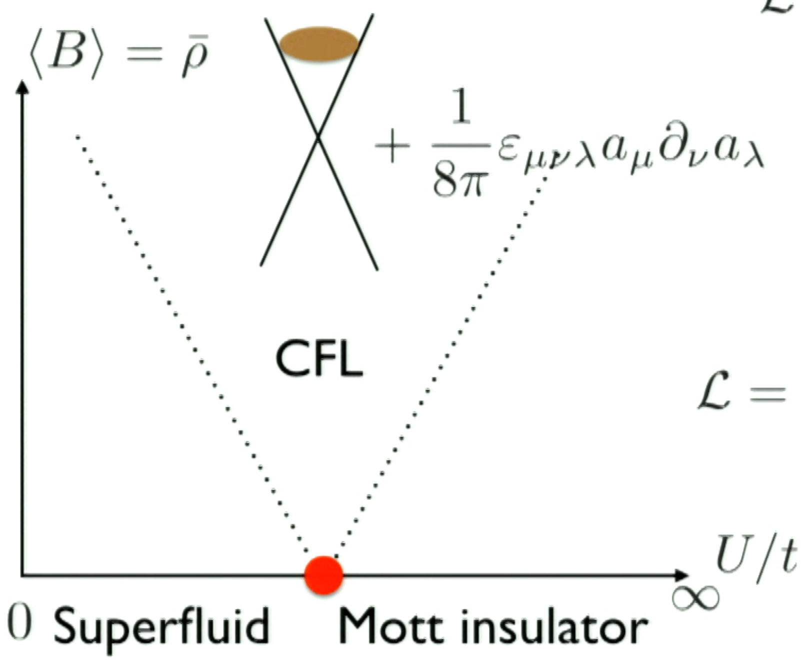
Composite fermi liquid from Wilson-Fisher critical point

YCH, Vishwanath, Wang (in prepare)

$$\mathcal{L} = |\partial_\mu \phi|^2 + m|\phi|^2 + \lambda|\phi|^4$$

Dual

$$\mathcal{L} = \bar{\psi}(\partial - ia_\mu)\psi + \frac{1}{8\pi}\varepsilon_{\mu\nu\lambda} a_\mu \partial_\nu a_\lambda$$



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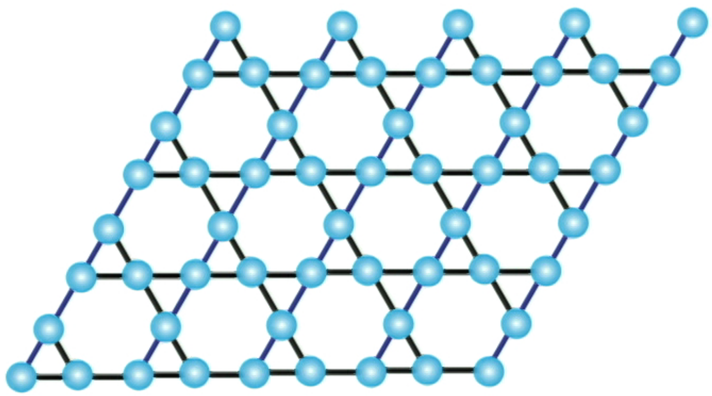
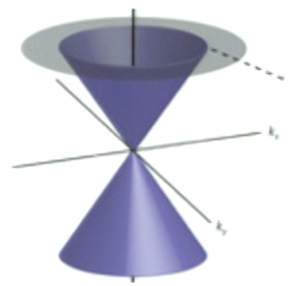
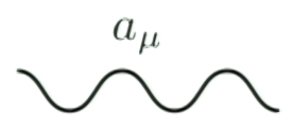
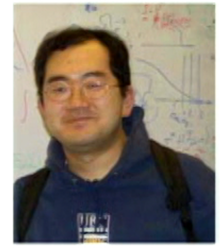
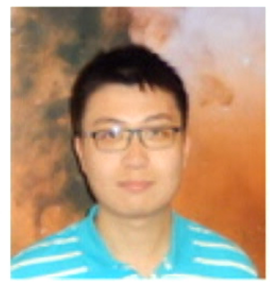
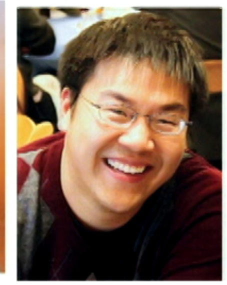
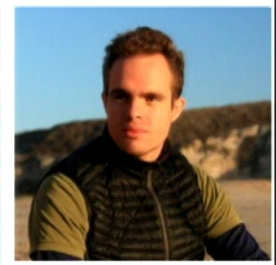






Thanks for your time!

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Summary

1. Exotic phenomena can emerge from many-body entanglement.
2. Spin liquids are prominent examples of the long-range entangled states.
3. We discuss the spin liquid phases on the kagome lattice.