Title: Entangling with Topological Quantum Matter

Date: Apr 24, 2017 02:00 PM

URL: http://pirsa.org/17040078

Abstract: <p>Topological phases of matter serve as one of the most striking examples of the richness and novelty of quantum systems with many degrees of freedom. In contrast to conventional matter, they are characterized by both non-local properties and non-classical notions such as entanglement. I will discuss two broad categories of topological phases, distinguished by whether or not they possess fractionalized â€œanyonâ€• excitations that are neither bosons nor fermions. I will demonstrate that entanglement not only provides an understanding of such phases but also enables the transmutation between these two categories of topological phases. </p>

Entangling with Topological Quantum Matter

Tim Hsieh

KITP, UCSB

Perimeter Institute

4/24/17

+

The Maple Bacon Donut

Overview

Topological phases: what, where, why

Deconfinement and supersymmetry

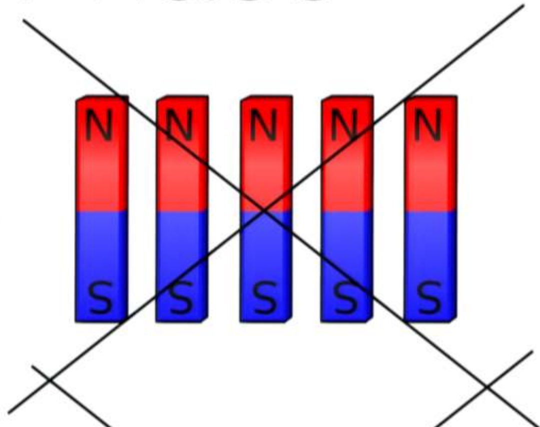
Topological quantum computing

How to realize? Use entanglement.

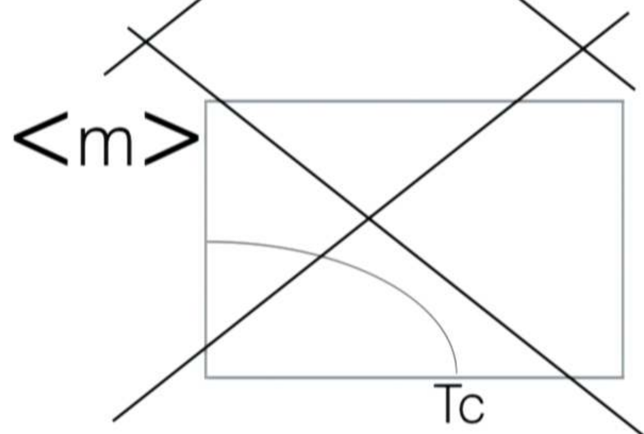
Application to fracton topological phases

Topological Phase

Unlike symmetry-breaking phases



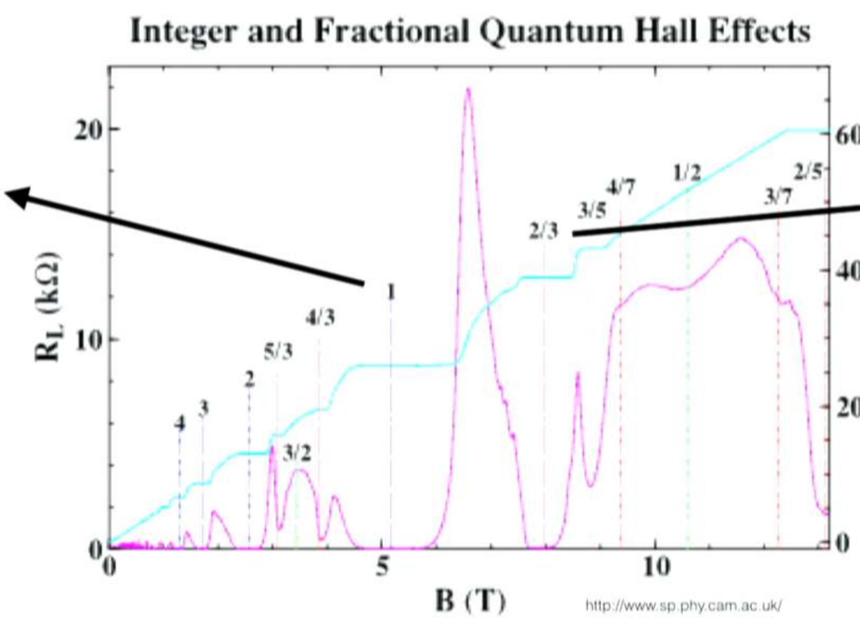
No local order parameter



How to characterize? Global properties, boundaries, entanglement

A Tale of Two Topologies

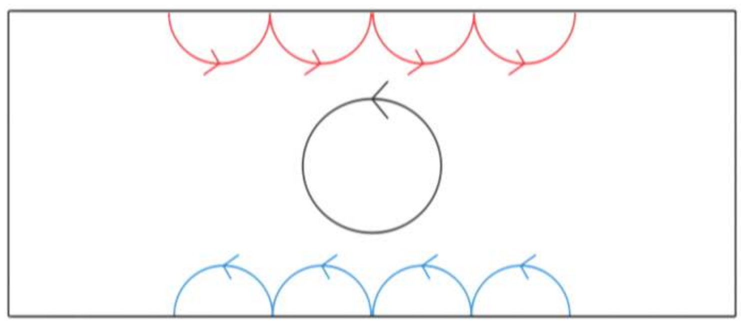
Integer Quantum Hall Variety



Fractional Quantum Hall Variety

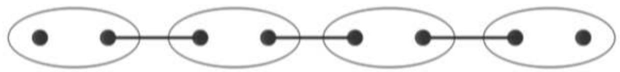
Integer Quantum Hall

(2+1)d electron gas in magnetic field



Electron in bulk is split at boundaries

Integer Quantum Hall Variety



Spin 1

Spin 1/2 Spin 1/2

Haldane phase / AKLT state

Symmetry Protected Topological Phases

Electron

Majorana Majorana

Gu and Wen (2009)
Pollmann et.al. (2010)
Chen et.al. (2013)

$$c = \gamma_1 + i\gamma_2$$

Kitaev wire

These exist!

Observation of S=1/2 degrees of freedom in an S=1 linear-chain Heisenberg antiferromagnet

M. Hagiwara, K. Katsumata, Ian Affleck, B. I. Halperin, and J. P. Renard
Phys. Rev. Lett. **65**, 3181 – Published 17 December 1990

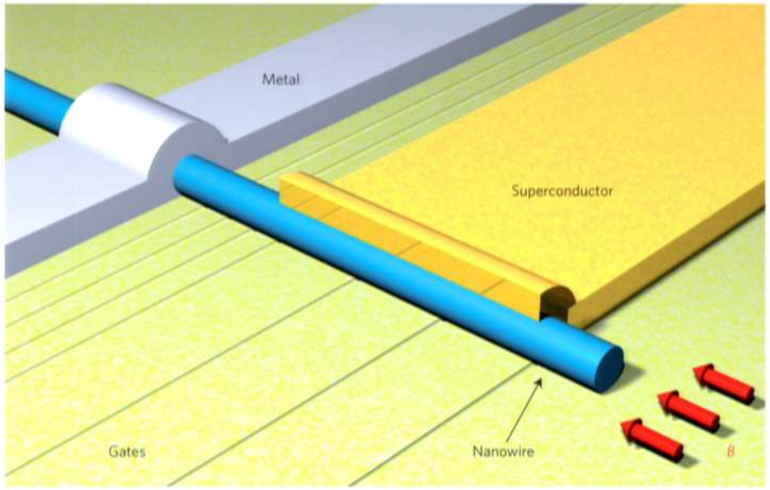
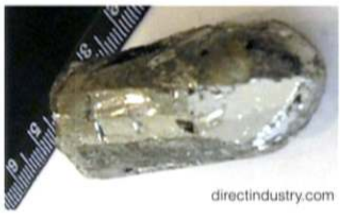


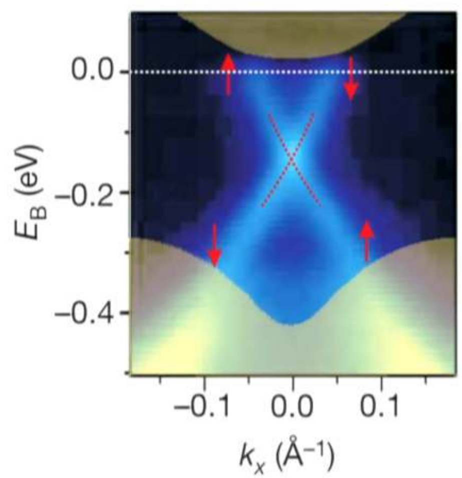
Figure from Franz (2013)

Topological Materials



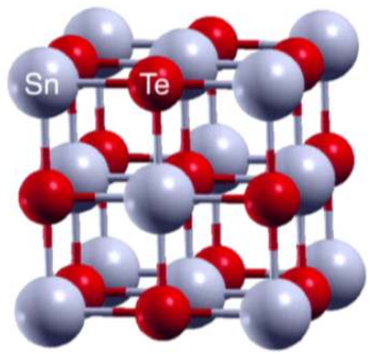
Bi_2Se_3

time reversal symmetry protects
gapless surface states



D. Hsieh et.al. Nature 2009

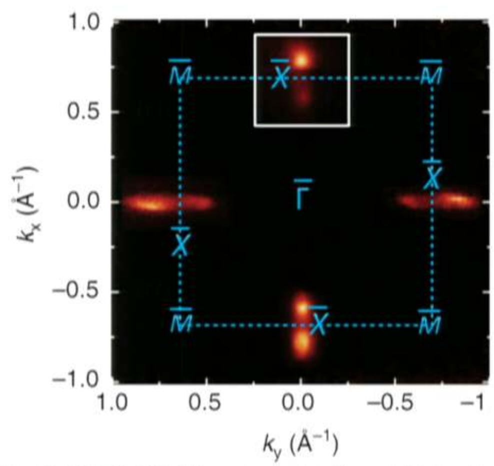
Topological Materials



TH, et.al. Nature Communications 3:982 (2012)

SnTe:
Topological Crystalline Insulator (TCI)

Mirror reflection symmetry
protects gapless surface states

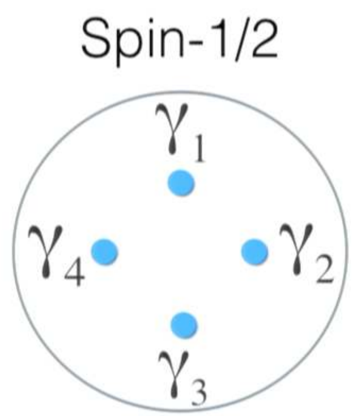


$Pb_{1-x}Sn_xTe$ ARPES (S. Xu et.al. Nature Materials, 2012)

Fractional Quantum Hall Variety

Exhibit fractionalized bulk excitations

Spin-1/2 decomposed into Majorana partons



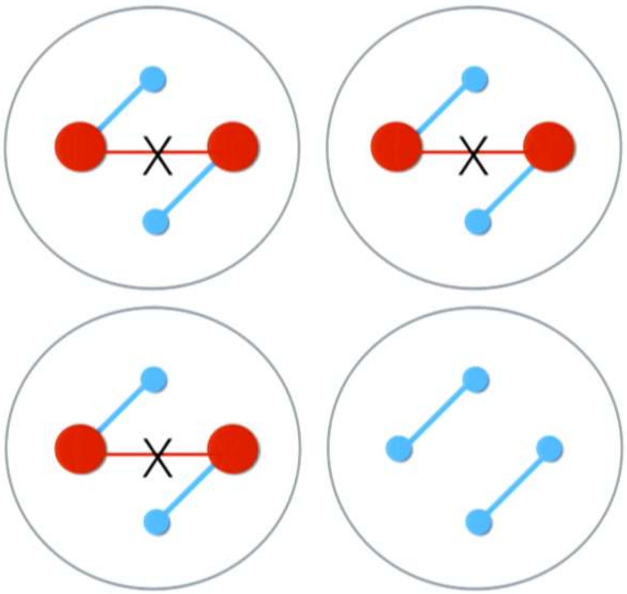
$$\{\gamma_i, \gamma_j\} = 0$$

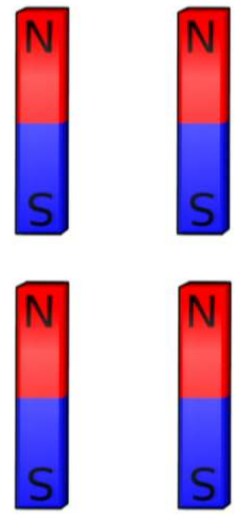
$$\gamma^2 = 1$$

$$\gamma_1\gamma_2\gamma_3\gamma_4 = 1$$

Kitaev (2003)
Wen (2003)

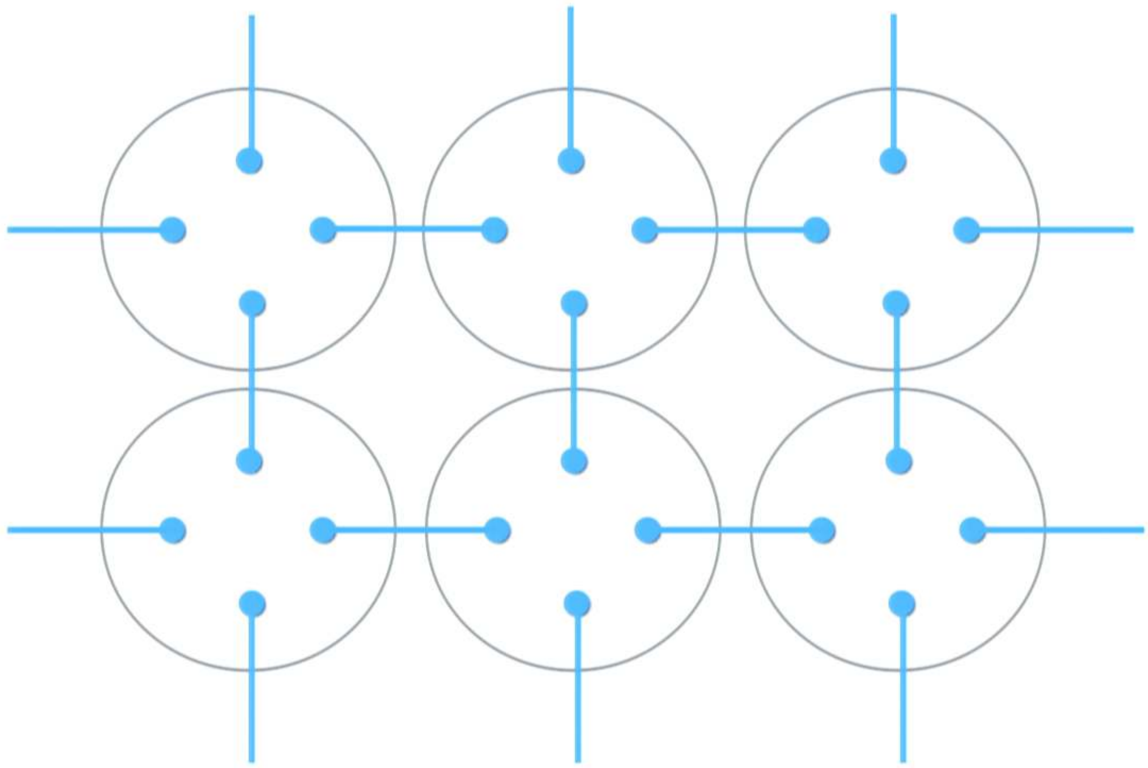
Trivial, Confined



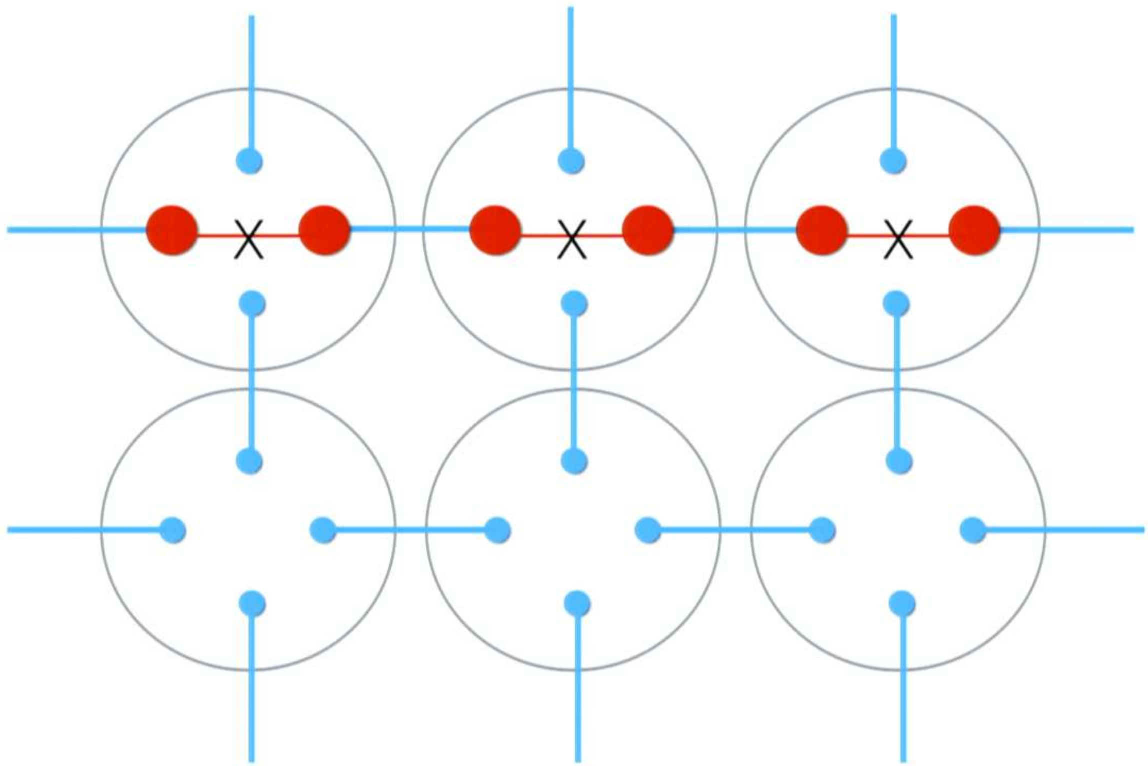


means $i\gamma_1\gamma_2 = 1$

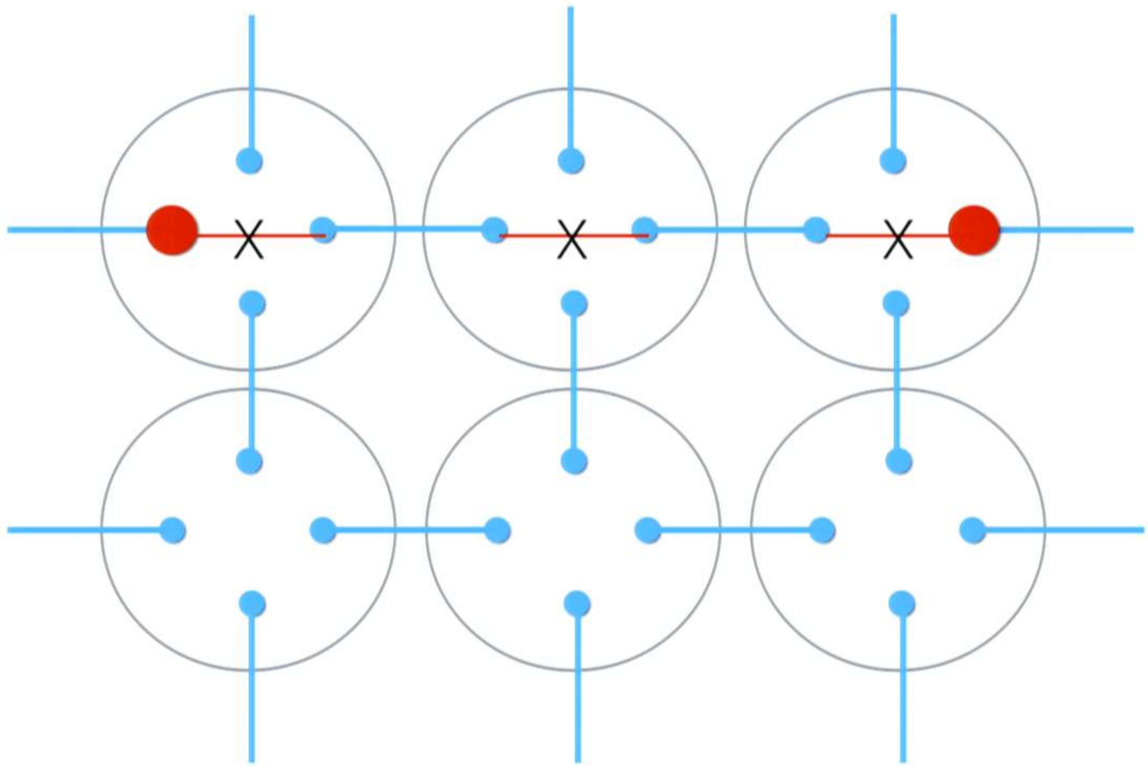
Deconfined Model



Deconfined Model



Deconfined Model

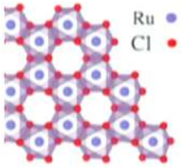


Fractional Quantum Hall Variety

Materials???

?

Herbertsmithite

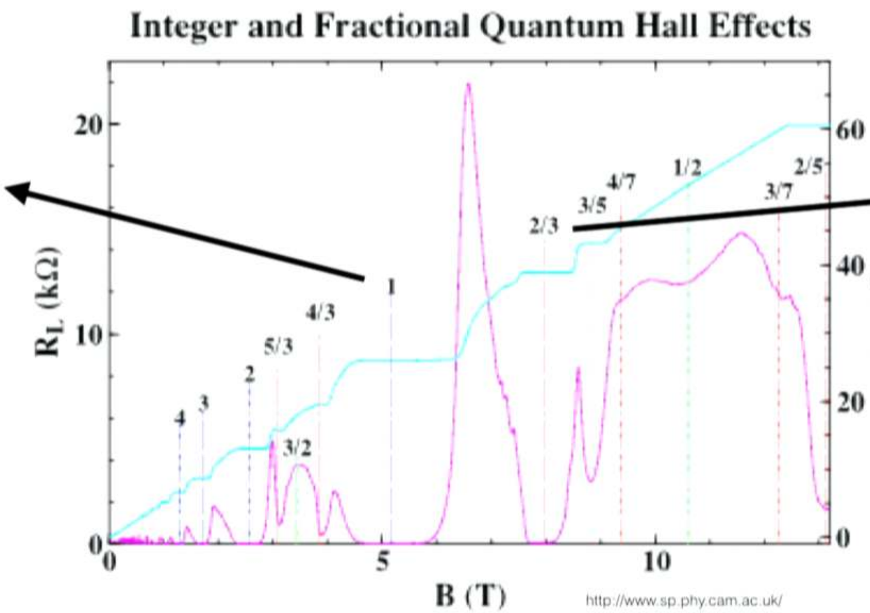


$RuCl_3$

?

A Tale of Two Topologies

Integer Quantum Hall Variety



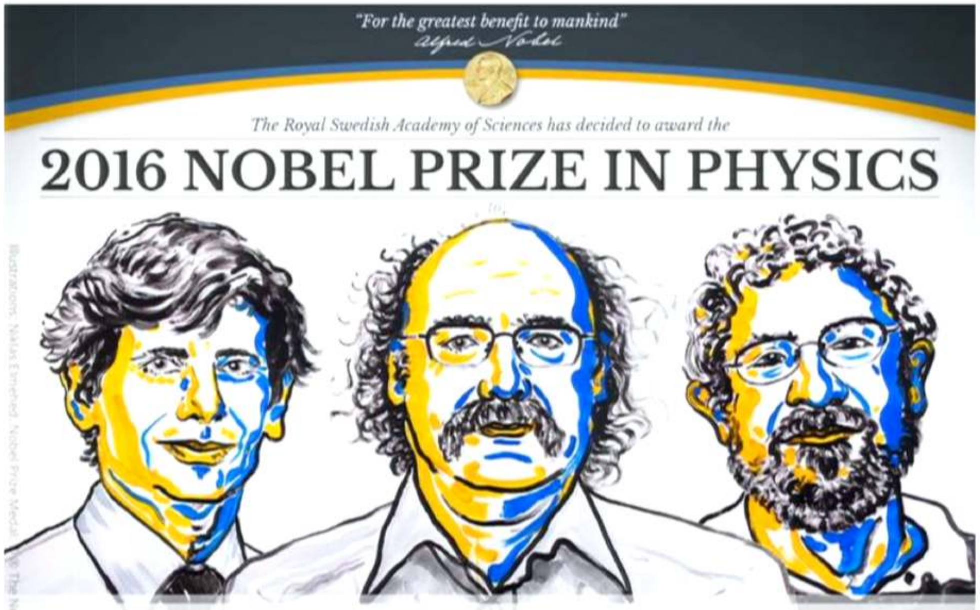
Fractional Quantum Hall Variety

Presidential Motivation

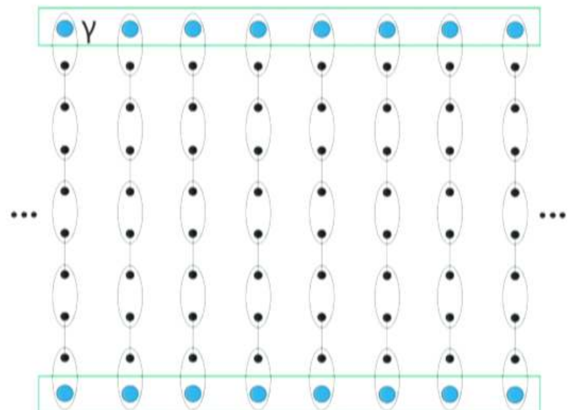
"Ask not what your country can do for you, ask what you can do for your country." (JFK)

Ask not what you can do for topological phases, **ask what topological phases can do for you**

What Topological Phases Can Do For You



Supersymmetry



translation symmetry => supersymmetry

$$\hat{Q} = \sqrt{\frac{H}{2}}\hat{T}(\hat{1} + \hat{P}) \quad \{\hat{Q}, \hat{Q}^\dagger\} = 2H \quad \hat{Q}^2 = (\hat{Q}^\dagger)^2 = 0$$

TH, Halasz, Grover (2016)

Topological Quantum Computing

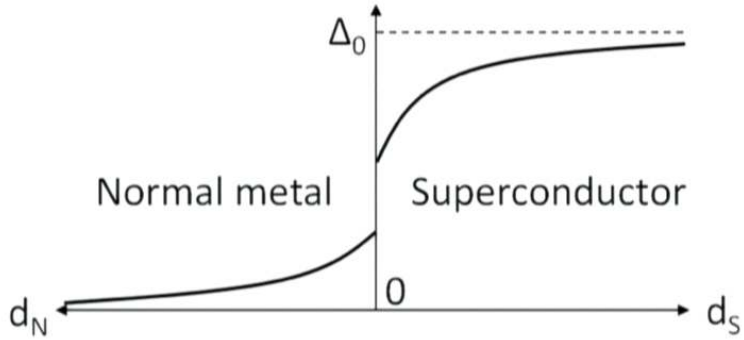
"Anyon" excitations of fractionalized phases encode information non-locally

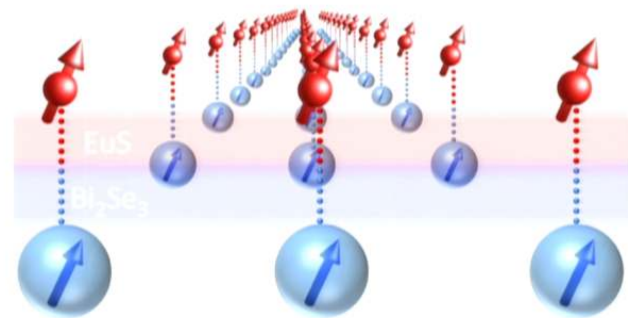
Braiding anyons realize logical gates

Topological Quantum Computing

What is the effect of topological phases on proximate systems?

Existing proximity effects all involve local order:





Katmis, et.al. Nature 2016

Is there a topological proximity effect?

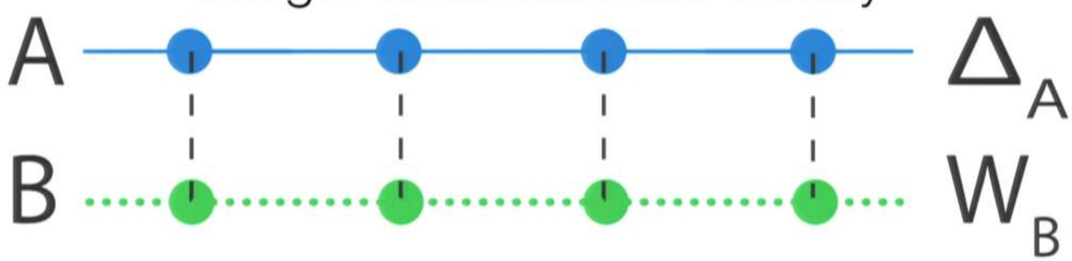
Topological Proximity Effect

e.g. $c_A^\dagger c_B + c_B^\dagger c_A$

$$H = H_A + \cancel{H_B} + H_{AB}$$

$|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B$

Integer Quantum Hall Variety

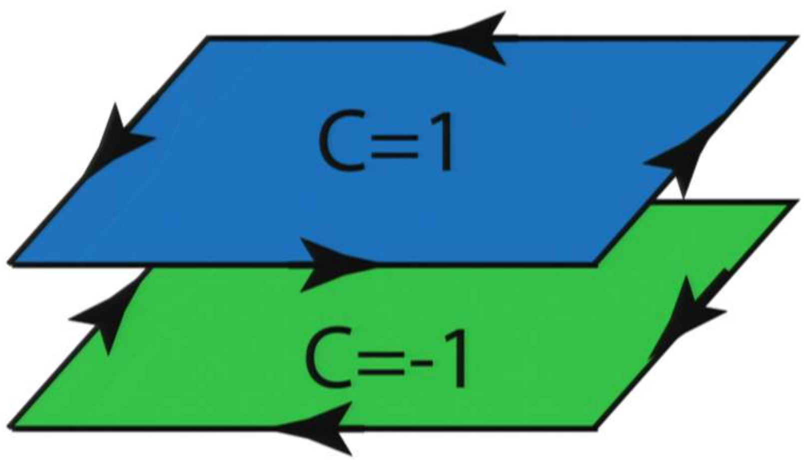


$$W_B << g_{AB} << \Delta_A$$

Integer Quantum Hall Variety

Chern insulator: Integer Chern number

Dictates number of chiral gapless edge modes



Integer Quantum Hall Variety

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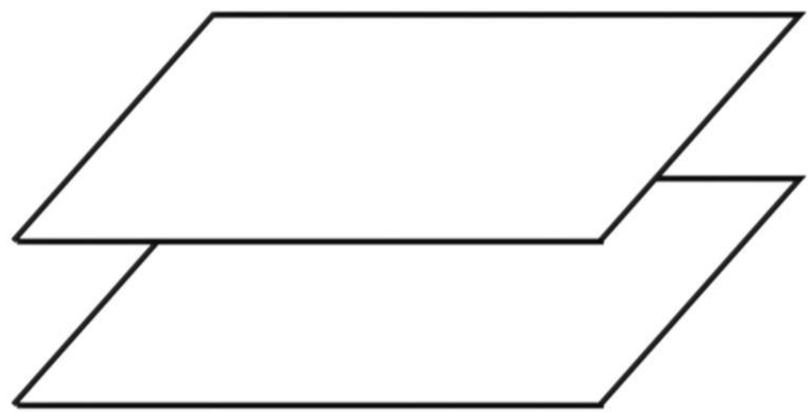
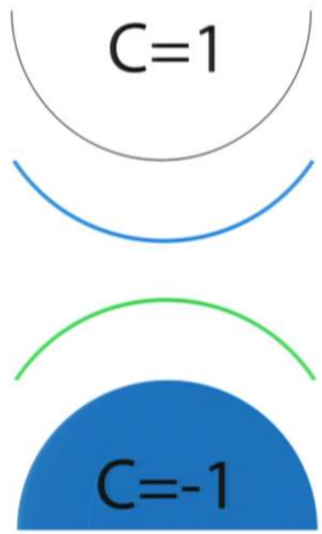


Chern Insulator, Proximitized

Energy (band) structure:

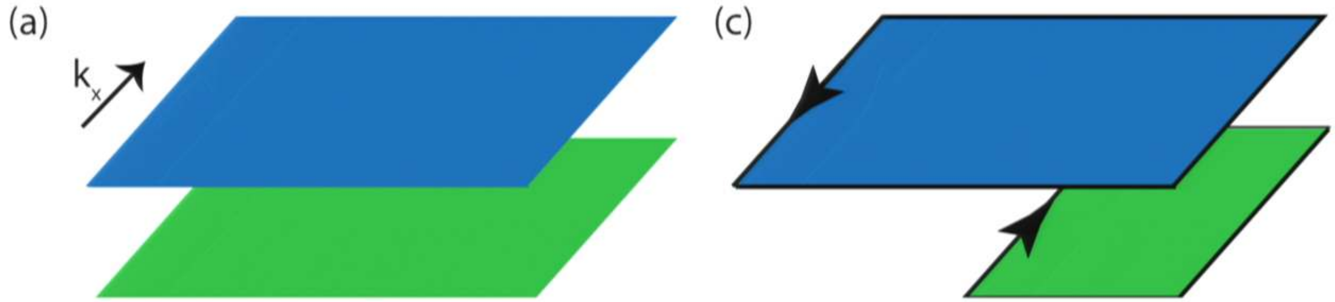


$(g \ll \Delta_A)$

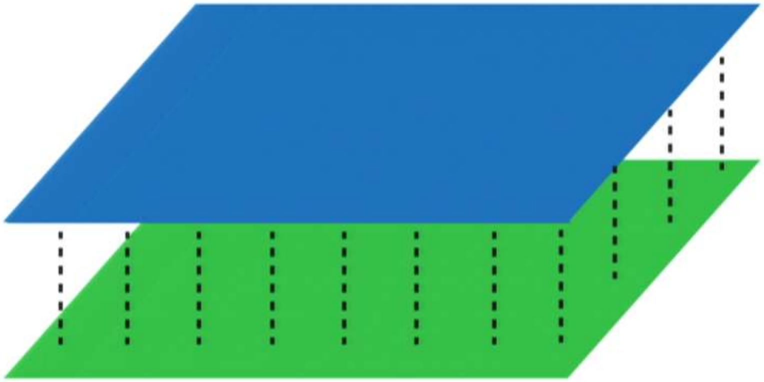
System B inherits the opposite Chern number

TH et.al. (2016)

Phenomenology

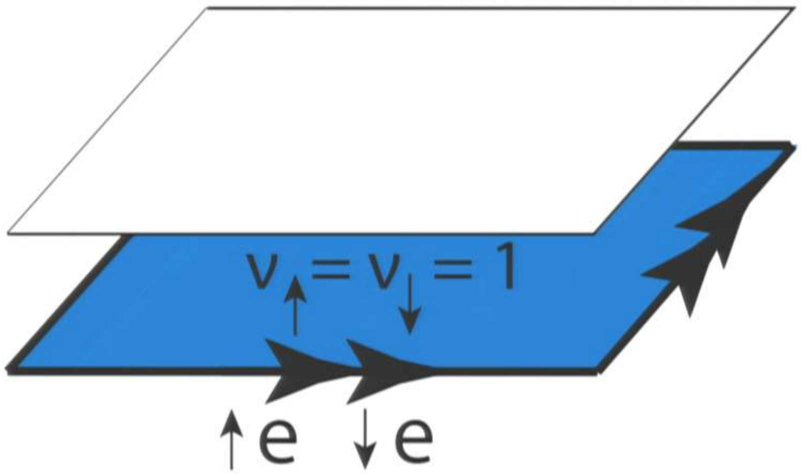


Cloning a Topological Phase



“Shrek- the Renegade Sheep
that Avoided Shearing
By Hiding in a Cave for Six Years”

Topological Bootstrap



B: Free spin-1/2s

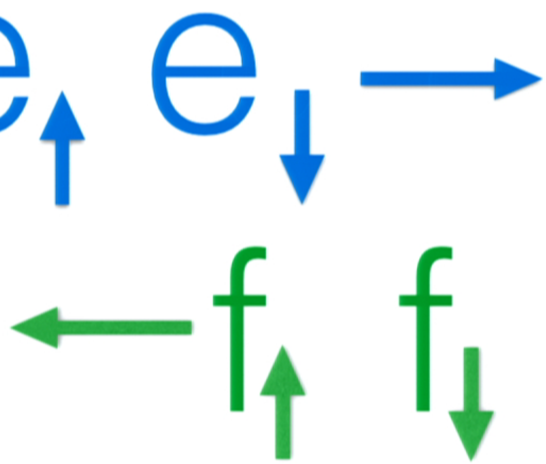
A: Free fermions with spin in Chern band

$$H = H_0 + H_K =$$
$$= H_{\nu=1}(c_\uparrow) + H_{\nu=1}(c_\downarrow) + g\sum_i (c_i^\dagger \vec{\sigma} c_i) \cdot \vec{S}_i$$

TH, Y-M. Lu, A. Ludwig (2016)

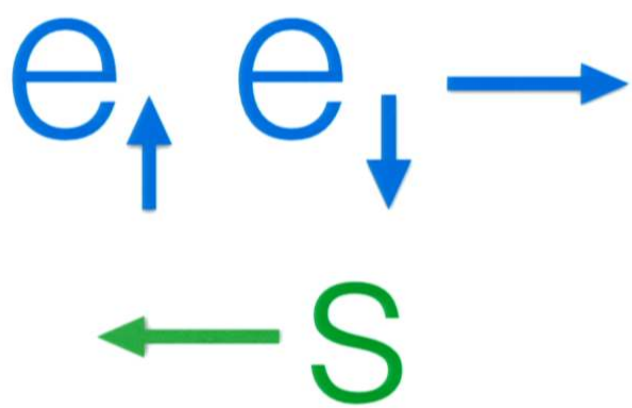
Topological Bootstrap

- Intuition from topological proximity effect: spins want to screen out Chern insulator



Topological Bootstrap

- Intuition from topological proximity effect: spins want to screen out Chern insulator



spins form analogue of Chern insulator

$$\vec{S} = \frac{1}{2} f^\dagger \vec{\sigma} f$$

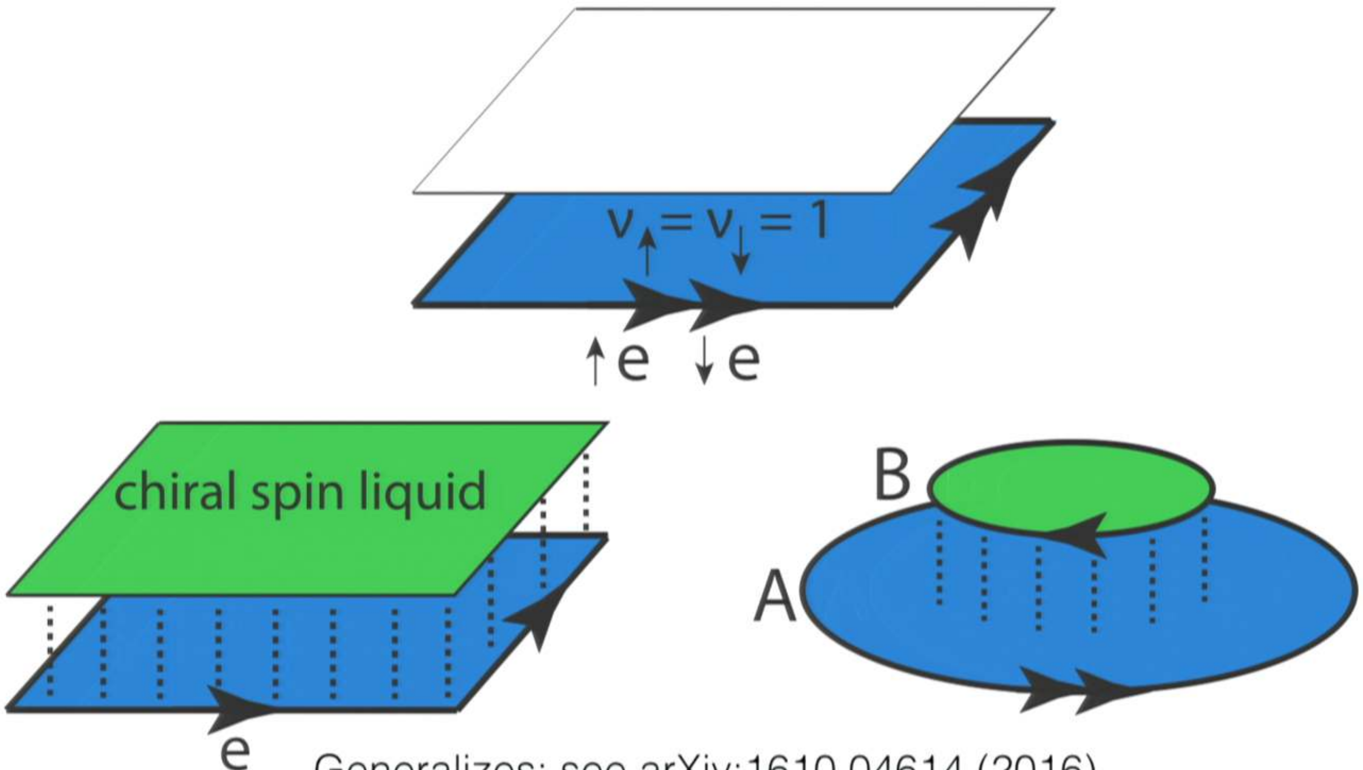
slave fermions inherit inverse Chern #

Chiral Spin Liquid

- No local magnetic order
- Breaks time-reversal symmetry; chiral edge states
- Fractionalized phase
- Excitations are "semions"

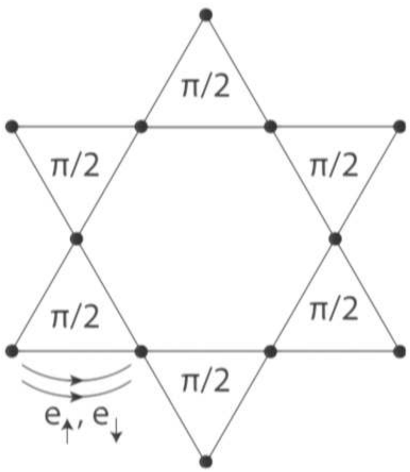
V. Kalmeyer and R. Laughlin, PRL 59, 2095 (1987)
X. Wen, F. Wilczek, and A. Zee, PRB 39, 11413 (1989)

Phenomenology

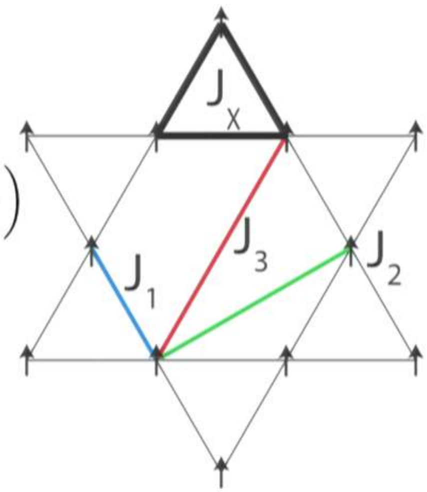


Generalizes; see arXiv:1610.04614 (2016)

Chiral Spin Liquid from Chern Insulator



$$H_{AB} = g \sum_{i,\alpha,\beta} \vec{S}_i \cdot \left(c^\dagger_{i,\alpha} \vec{\sigma}_{\alpha\beta} c_{i,\beta} \right)$$



$$|\nu_\uparrow = 1\rangle \otimes |\nu_\downarrow = 1\rangle$$

$$H^B_{eff} = \sum_{ij} J_{ij} S_i \cdot S_j + \sum_{ijk} J_{ijk} S_i \cdot (S_j \times S_k) + ...$$

$$J_1 = 1, J_2 = 0.51, J_3 = 0.56$$

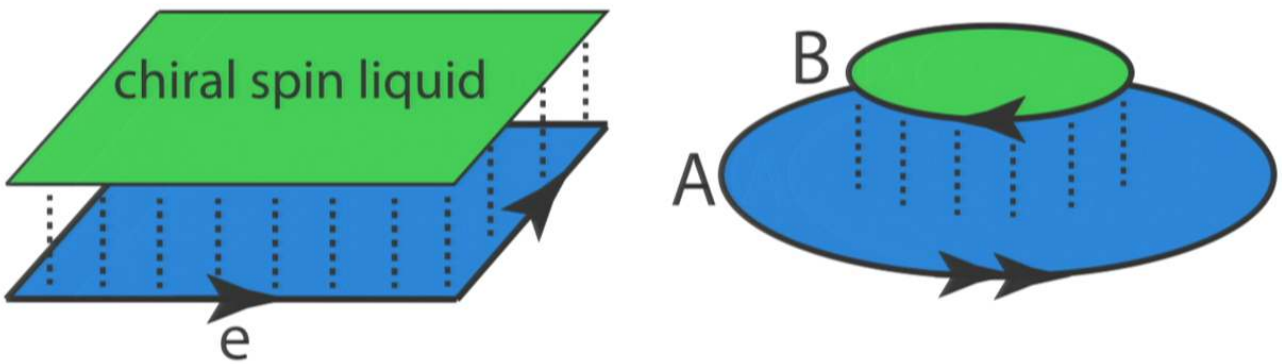
S-S. Gong, W. Zhu, and D. Sheng, Sci.Reports 4, 6317 (2014)

B. Bauer et.al. Nat. Comm. 5, 5137 (2014)

✔ Chiral Spin Liquid

Topological Bootstrap

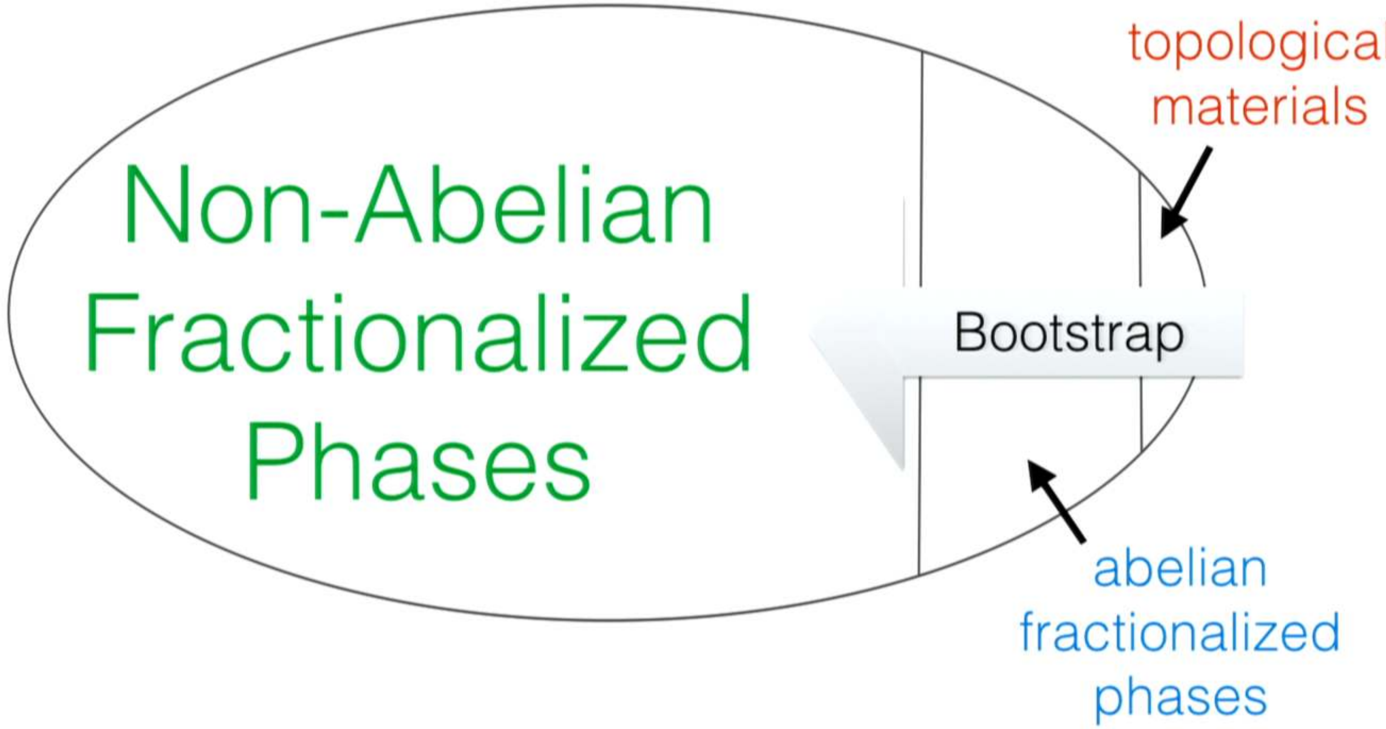
More is different and less: Fractionalization via coupling



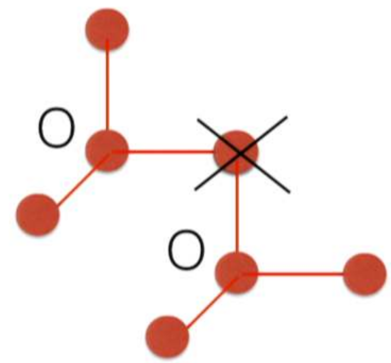
Leveraging an “entangling Hamiltonian” to go from integer to fractional quantum Hall variety

Potential realization in synthetic quantum matter

Many Topological Phases



Fracton Phases



(3+1)d topological phases
where excitations cannot move without creating more excitations

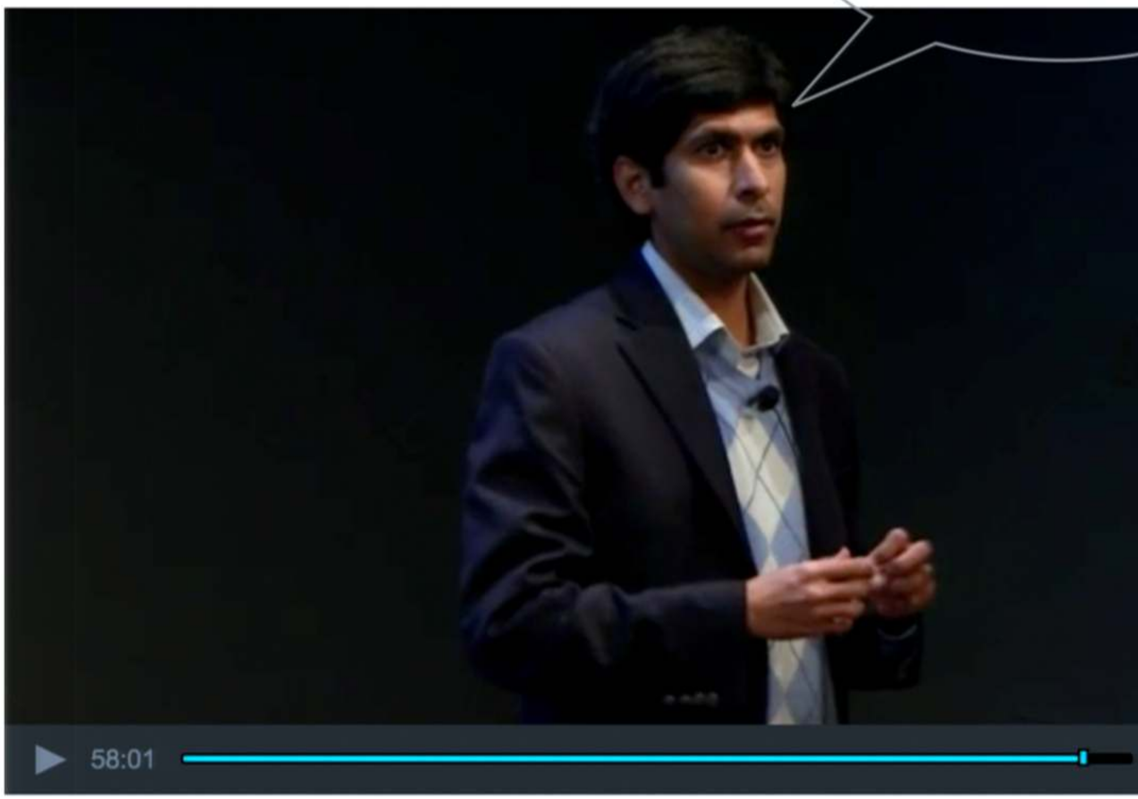
quantum memory more robust at finite temperature

Haah, Chamon, Bravyi, Leemhuis, Terhal, Yoshida, Vijay, Fu, etc.

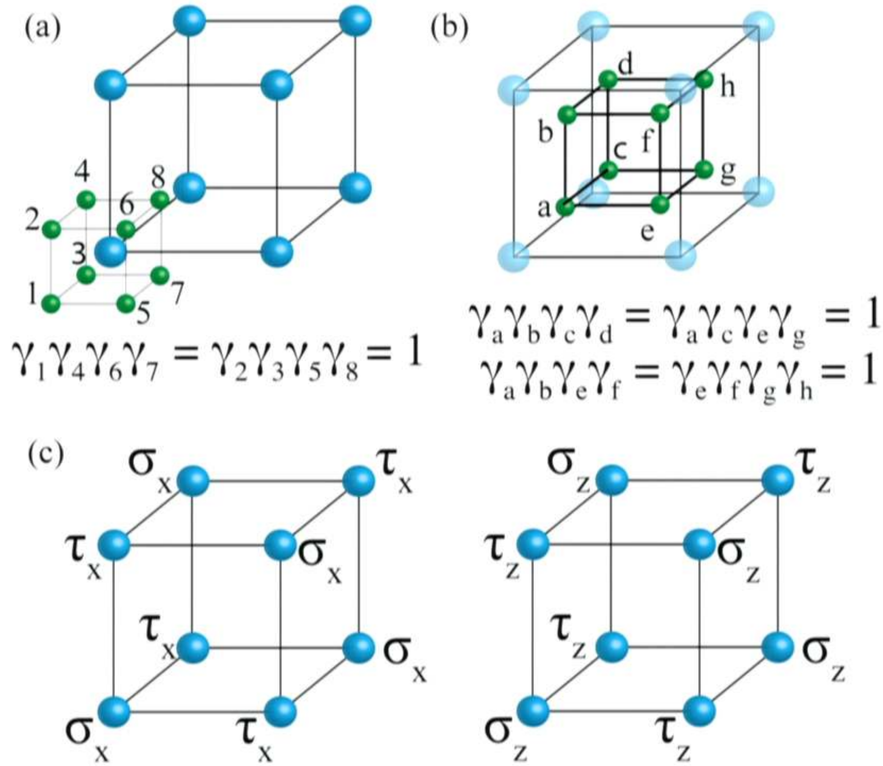
Fractons
from
Partons?

Pirsa: 15030117 - Highly Entangled Quantum Matter

Speaker(s): Tarun Grover

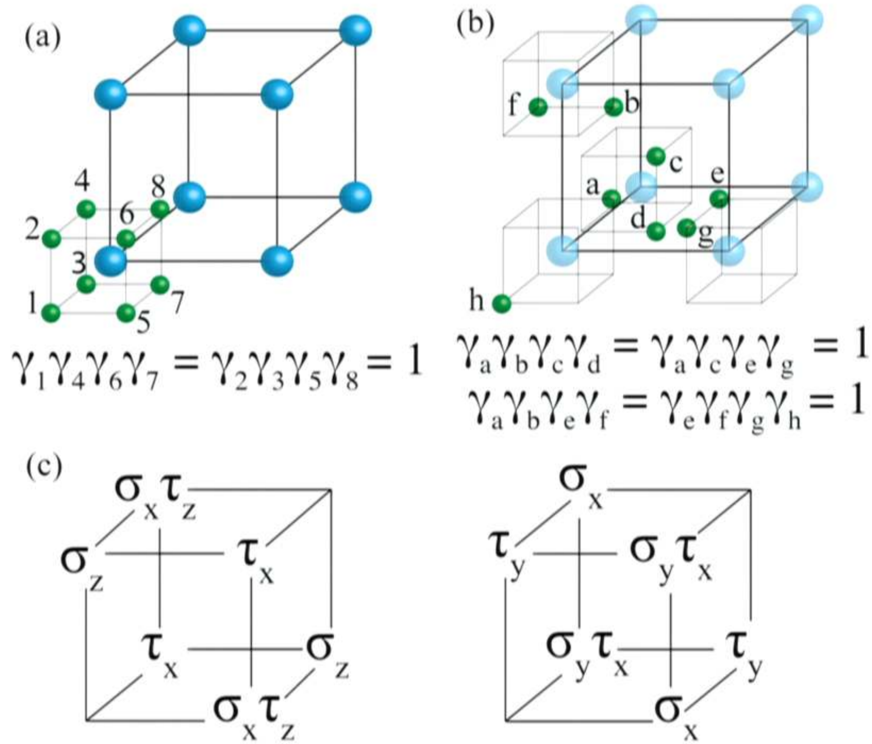


Fractons from Partons



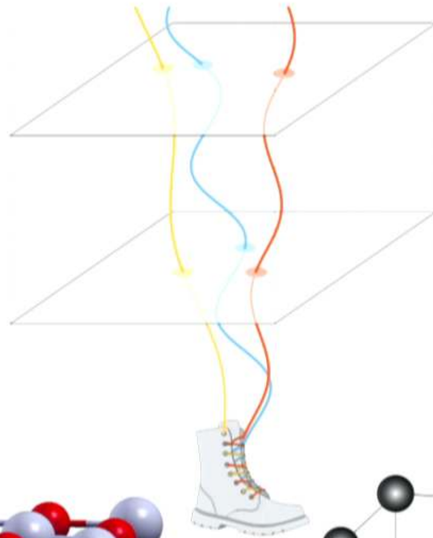
TH and G. Halasz,
arXiv:1703.02973

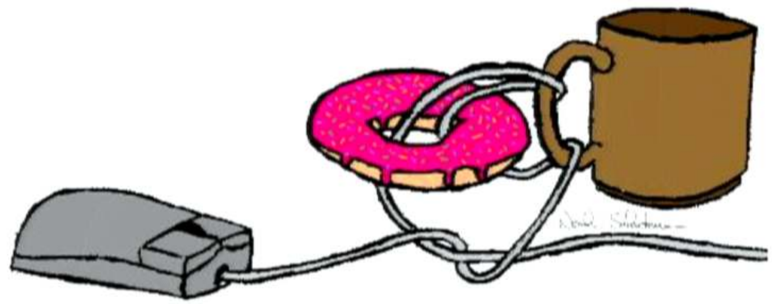
Fractons from Partons

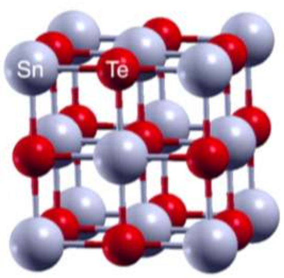


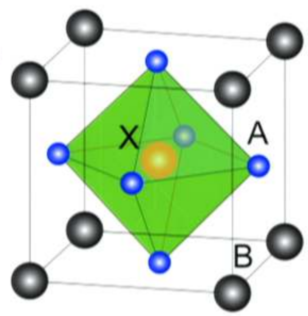
TH and G. Halasz,
arXiv:1703.02973

Topological Phases, Entangled









Thanks!

I. Topological Phases

Nature Communications 3:982 (2012)
Nature Materials 13:178 (2014)

w/ Liang Fu (MIT)
Junwei Liu (MIT)
Arun Bansil (Northeastern)
Wenhui Duan (Tsinghua)
Jagadeesh Moodera (MIT)
Peng Wei (UCR)

II. Topological Proximity Effect

PRL 116, 086802 (2016)
PRB Rapid 94, 161112 (R) (2016)

w/ Hiro Ishizuka (U. Tokyo)
Leon Balents (KITP)
Taylor Hughes (UIUC)

III. Topological Bootstrap

arXiv:1610.04614 (2016)

w/ Yuan-Ming Lu (Ohio State U.)
Andreas Ludwig (UCSB)

IV. Fractons from Partons

arXiv:1703.02973 (2017)

w/ Gabor Halasz (KITP)

CIQM CENTER for INTEGRATED QUANTUM MATERIALS

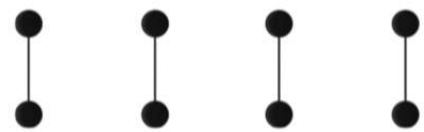
GORDON AND BETTY MOORE FOUNDATION

NSF

An Exact Limit

AFM Kondo coupling = local projectors onto singlets

$$|\psi_{AB}\rangle \quad =$$



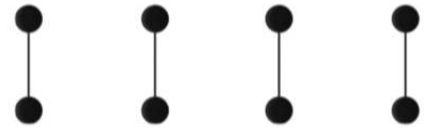
Replace Kondo coupling with global projector:

$$H = H_{\nu=1}(c_{\uparrow}) + H_{\nu=1}(c_{\downarrow}) - g|\psi_{AB}\rangle\langle\psi_{AB}|$$

An Exact Limit

AFM Kondo coupling = local projectors onto singlets

$|\psi_{AB}\rangle$ =



Replace Kondo coupling with global projector:

$$H = H_{\nu=1}(c_\uparrow) + H_{\nu=1}(c_\downarrow) - g|\psi_{AB}\rangle\langle\psi_{AB}|$$

$$H^B_{eff} = -g|\overline{\psi^s_0}\rangle\langle\overline{\psi^s_0}|$$

$|\overline{\psi^s_0}\rangle$ = Time-reversed Gutzwiller projection of Chern bands

= chiral spin liquid with opposite chirality