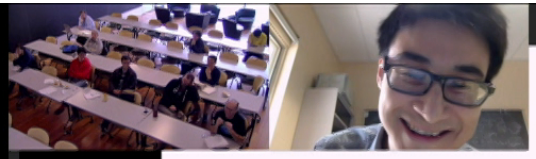
Title: Harnessing Topological Quantum Matter

Date: Mar 10, 2017 04:00 PM

URL: http://pirsa.org/17020099

Abstract: Topological quantum computing requires phases of matter which host fractionalized excitations that are neither bosons nor fermions. I will present a new route toward realizing such fractionalized phases of matter by literally building on existing topological phases. I will first discuss how existing topological phases, when interfaced with other systems, can exhibit a â€œtopological proximity effectâ€• in which nontrivial topology of a different nature is induced in the neighboring system. Then, I will show how this enables a new entanglement based technique (the â€œtopological bootstrapâ€•) for upgrading topological phases from the integer into the fractional quantum Hall variety. Finally, I will highlight the rich phenomenology of systems with interacting Majorana modes. Such systems can exhibit physics ranging from black hole scrambling to supersymmetry and from alternative surface code architectures to topological phases in three dimensions with completely immobile excitations. I will discuss my plans for understanding both general properties and specific models of such fascinating systems.



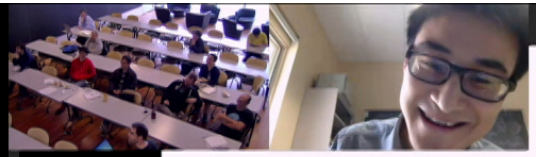
Harnessing Topological Quantum Matter

Tim Hsieh

KITP, UCSB

Perimeter Institute Seminar

3/10/17



The Maple Bacon Donut

Outline

I. Topological Materials

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)

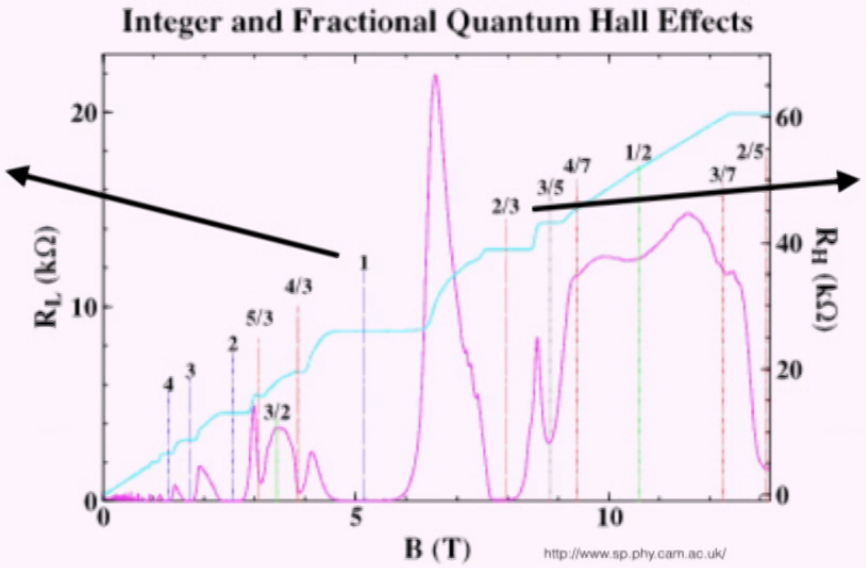
III. Topological Bootstrap

arXiv:1610.04614 (2016)

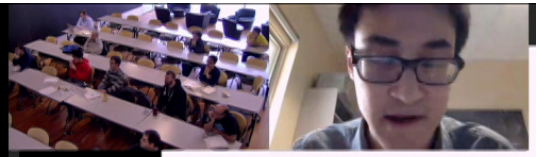
w/ Yuan-Ming Lu (Ohio State U.)
Andreas Ludwig (UCSB)

A Tale of Two Topologies

Integer Quantum Hall Variety



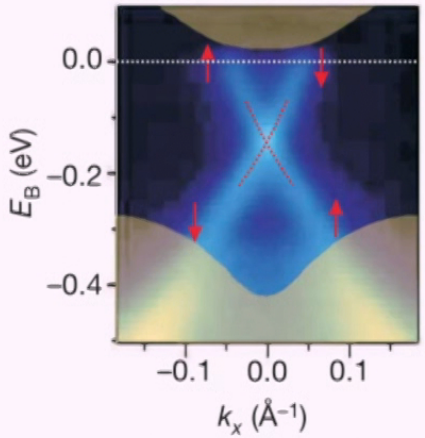
Fractional Quantum Hall Variety



Topological Materials

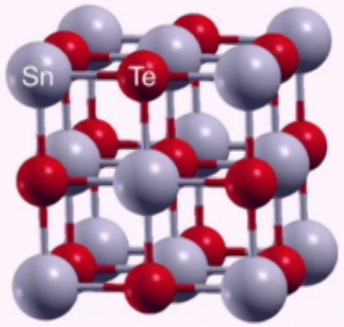
Bi_2Se_3

time reversal symmetry protects gapless surface states



D. Hsieh et.al. Nature 2009

Topological Materials

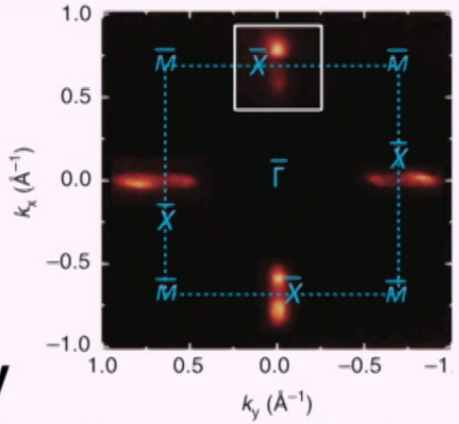


SnTe:
Topological Crystalline Insulator (TCI)

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

Mirror reflection symmetry
protects gapless surface states

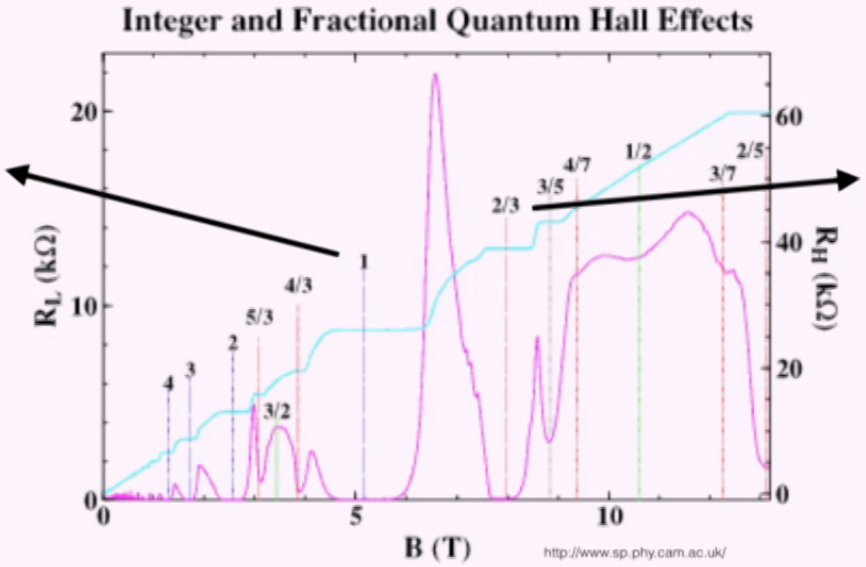
No need for time reversal symmetry



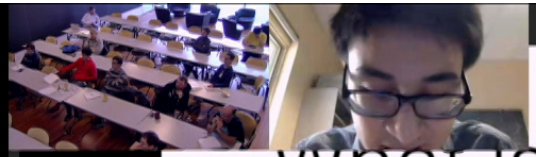
$Pb_{1-x}Sn_xTe$ ARPES (S. Xu et.al. Nature Materials, 2012)

A Tale of Two Topologies

Integer Quantum Hall Variety

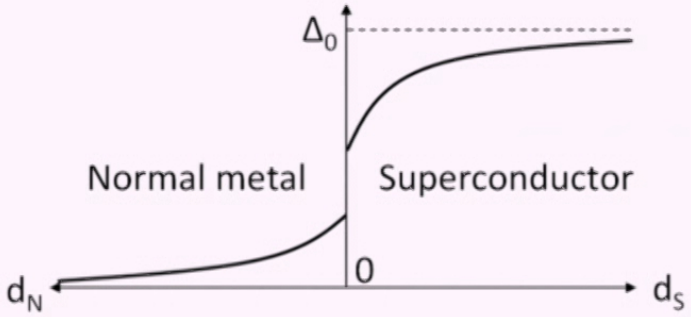


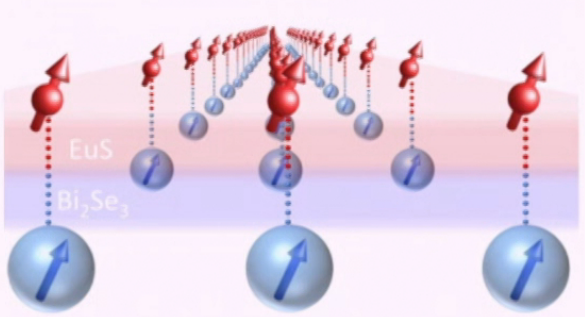
Fractional Quantum Hall Variety



What is the effect of topological phases on proximate systems?

Existing proximity effects all have local order:



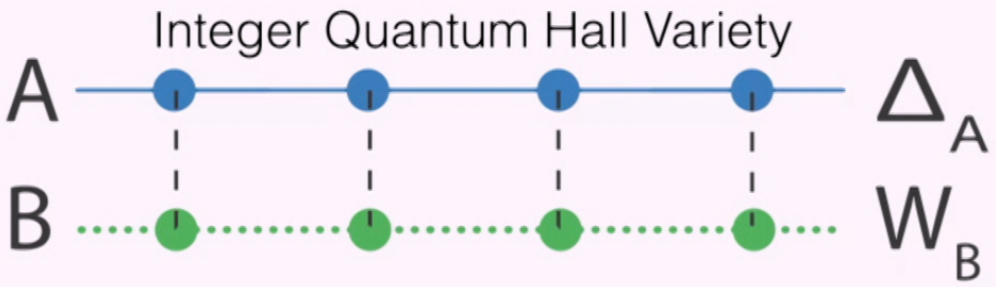


Katmis, et.al. Nature 2016

Is there a topological proximity effect?

General Setup I

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

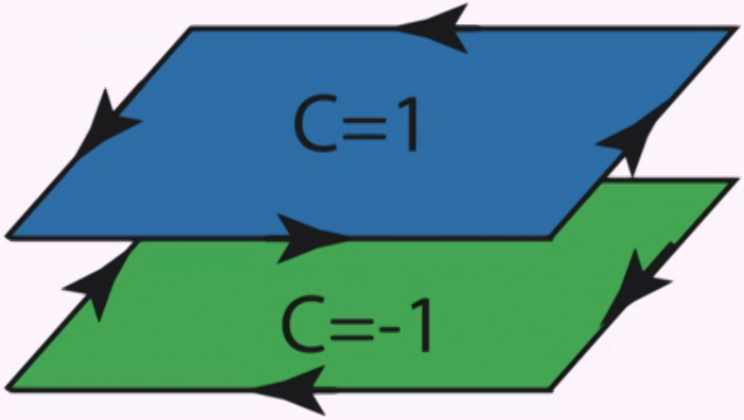


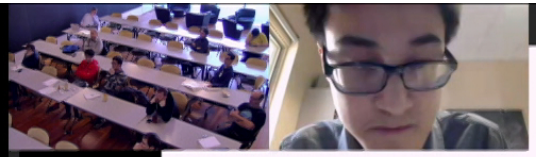
$$W_B << g_{AB} << \Delta_A$$

Integer Quantum Hall Variety

Chern insulator: Integer Chern number

Dictates number of chiral gapless edge modes





Integer Quantum Hall Variety

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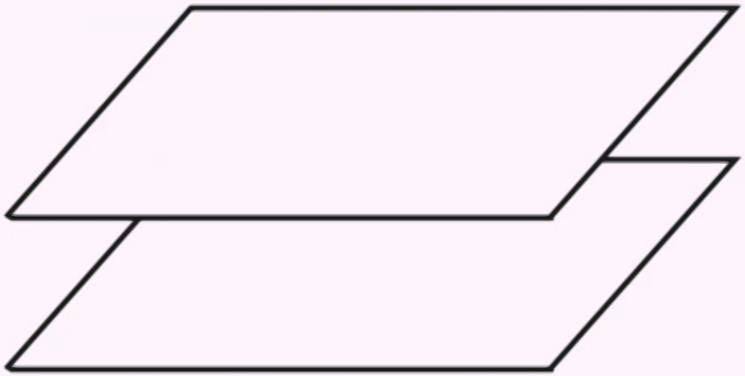
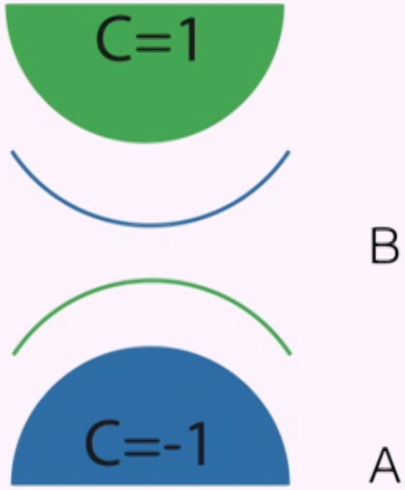
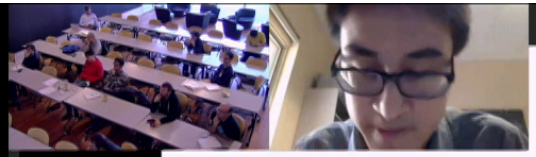


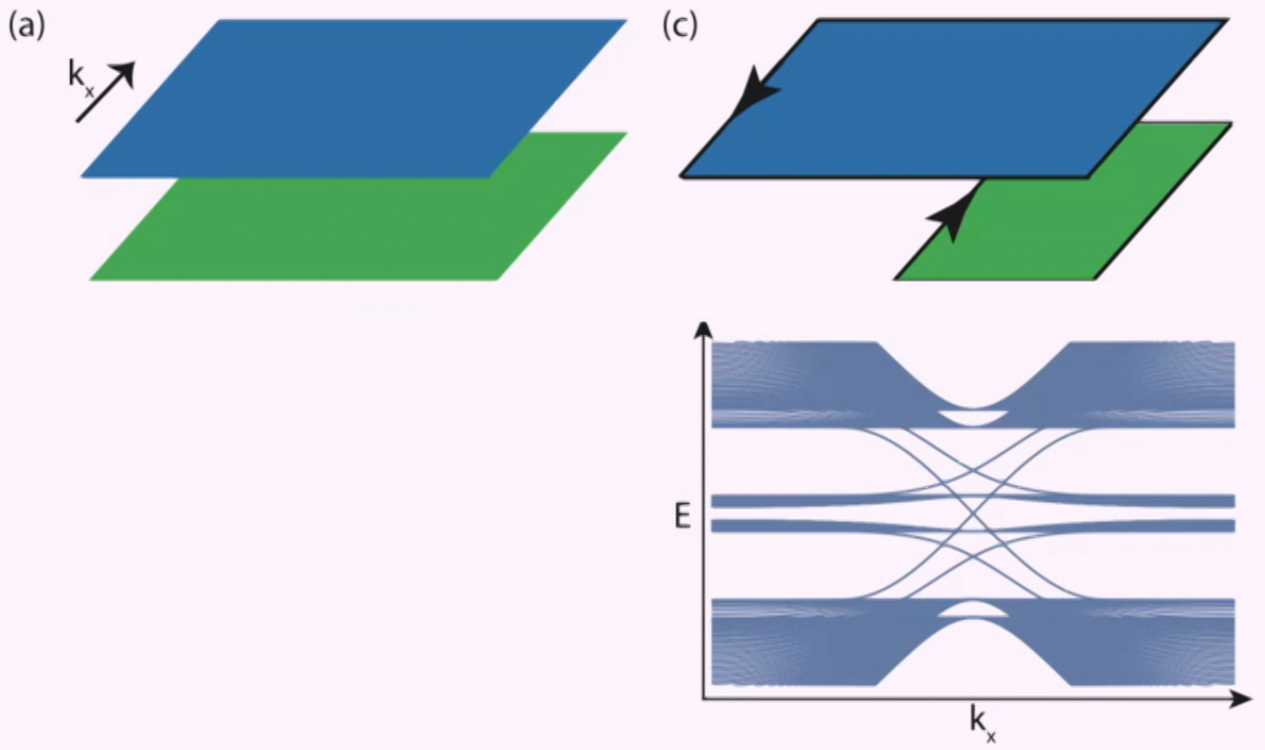
Chern Insulator, Proximitized



$$h_B^{\text{eff}}(k) = -\frac{4g^2}{\Delta(k)}|\psi_k^{\text{ex}}\rangle\langle\psi_k^{\text{ex}}|$$



Phenomenology



Generalizes to **All** Free Fermion Topological Phases

$$\begin{pmatrix} \mathtt{E1} & 0 & \mathtt{g} & 0 \\ 0 & \mathtt{E2} & 0 & \mathtt{g} \\ \mathtt{g} & 0 & 0 & 0 \\ 0 & \mathtt{g} & 0 & 0 \end{pmatrix}$$

$$H = \begin{pmatrix} H_A^d & g \\ g & 0 \end{pmatrix}$$

$$H_A^d = U H_A U^{-1}$$

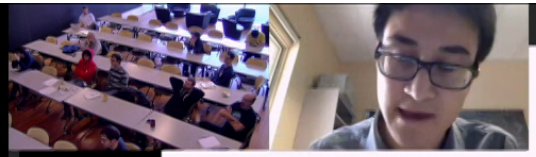
E_n^0: eigenvalues of H_A

Generalizes to **All** Free Fermion Topological Phases

$$H = \bigoplus_n \begin{pmatrix} E_n^0 & g \\ g & 0 \end{pmatrix}$$

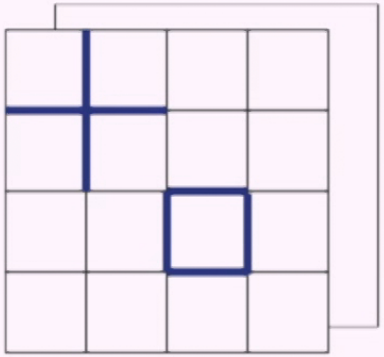
Gap increases monotonically

No phase transition from weak to strong coupling



Fractionalized Phases

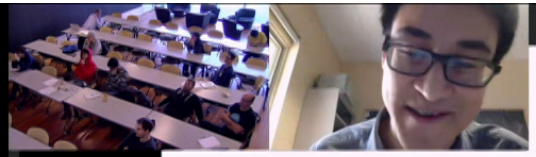
Kitaev's Toric Code



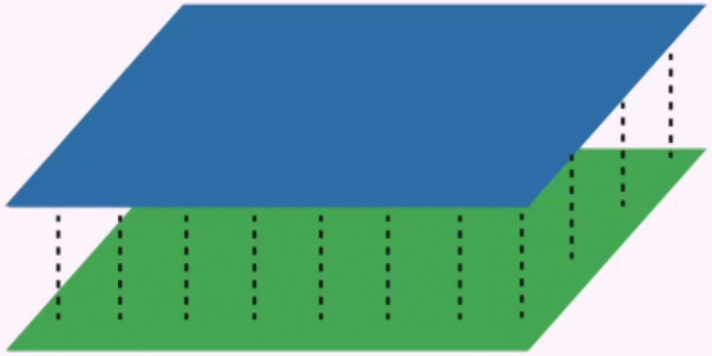
$$H_A = -\sum_s \prod_{l \in s} \sigma_l^z - \sum_p \prod_{l \in p} \sigma_l^x,$$

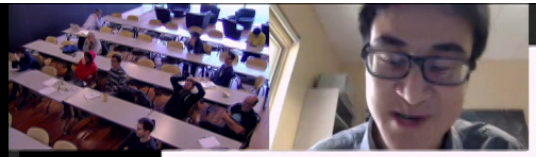
$$H_{AB} = g \sum_i (\sigma_i^z \tilde{\sigma}_i^z + \sigma_i^x \tilde{\sigma}_i^x)$$

Toric code duplicates itself!



Part III: Topological Bootstrap





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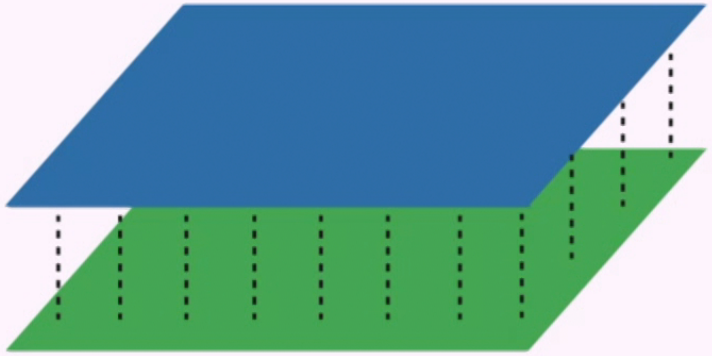
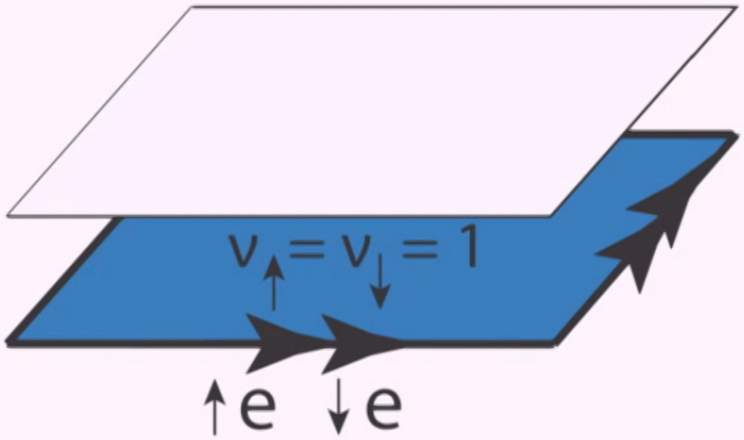


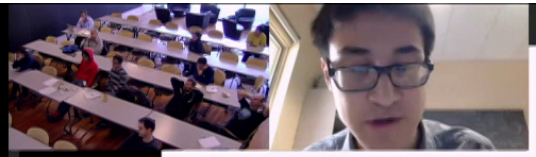
General Setup II



B: Free spin-1/2s

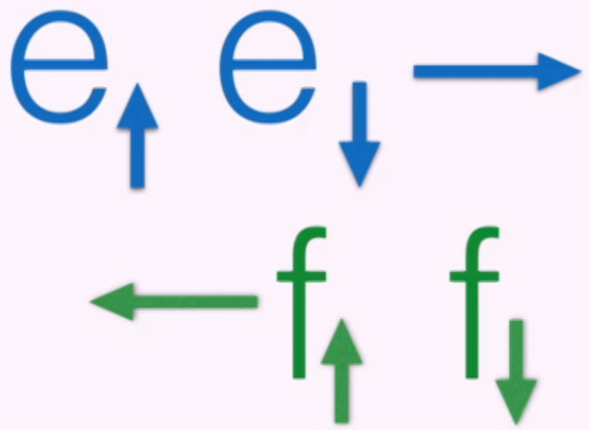
A: Free fermions with spin in Chern band

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



Not the Usual Kondo Lattice

- Gapped electron system —> singlet formation evaded for small coupling ($g \ll \Delta_A$)
- Intuition from topological proximity effect: spins want to screen out Chern insulator



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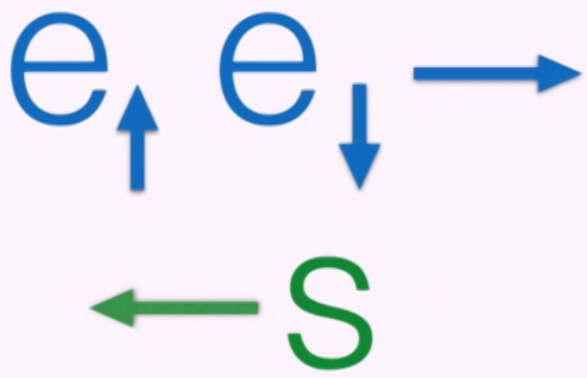
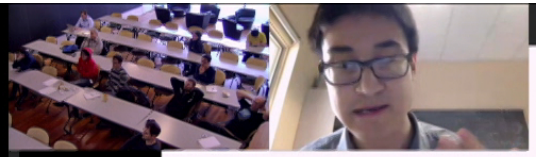




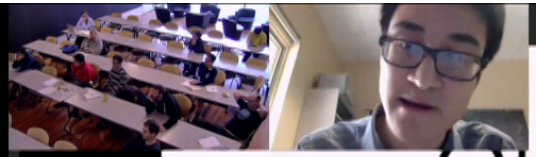
Not the Usual Kondo Lattice

- Gapped electron system —> singlet formation evaded for small coupling $(g \ll \Delta_A)$
- 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”

shaken and stirred

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

An Exact Limit

AFM Kondo coupling = local projectors onto singlets

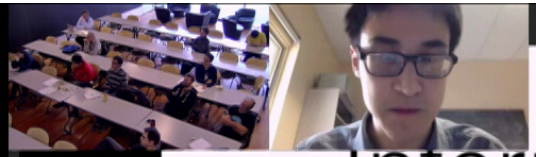
$|\psi_{AB}\rangle$ =

Replace Kondo coupling with global projector:

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

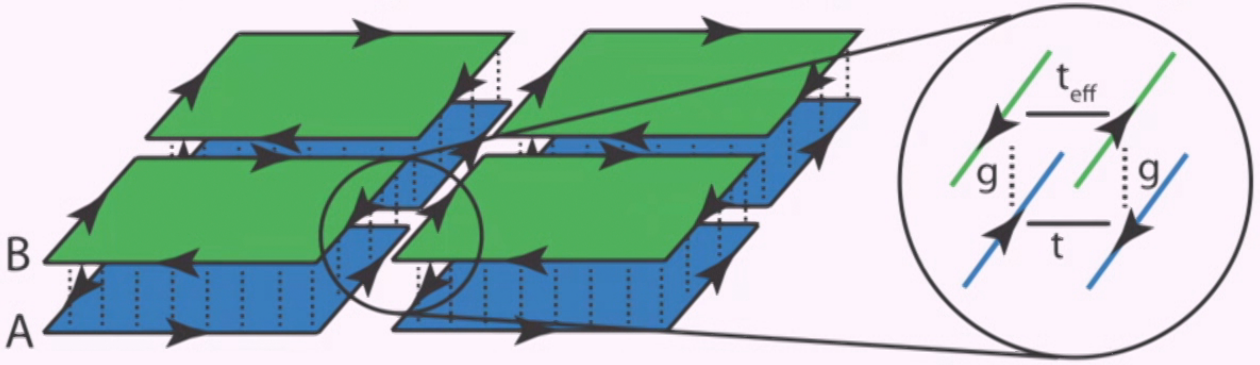
$$H^B_{eff} = -g|\overline{\psi^s_0}\rangle\langle\overline{\psi^s_0}|$$

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



Interpolate from Global to Local Kondo

Partition A,B into regions r of size $l > \xi$ (correlation length of A)

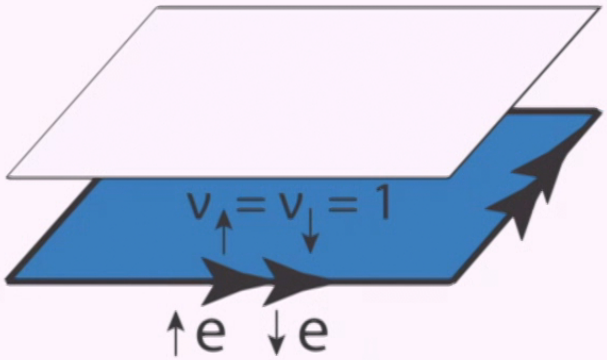


Quasi-local projector $P_r = -g|\psi_{AB,r}\rangle\langle\psi_{AB,r}|$

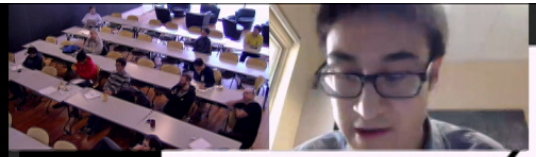
To interpolate all the way, require ξ to be minimal (—> 0)

Expect CSL to be induced for range of Kondo coupling g

Phenomenology



Z_2 Spin Liquid from Superconductor



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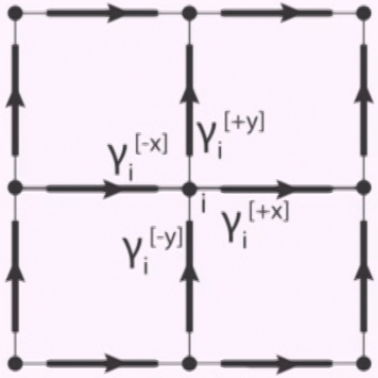
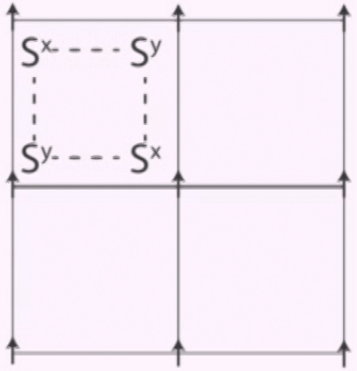


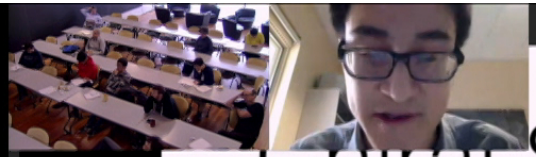
$$H_{AB} = g \sum_{i,\alpha,\beta} \vec{S}_i \cdot \left(c^{\dagger}_{i,\alpha} \vec{\sigma}_{\alpha\beta} c_{i,\beta} \right)$$



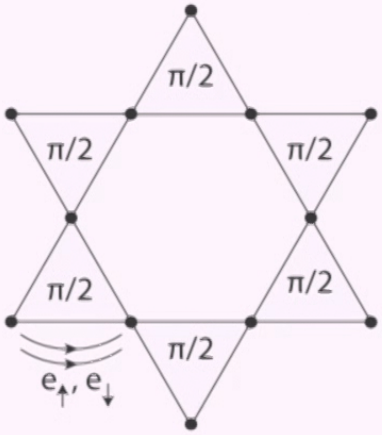
$$H_A = \sum_i \sum_{\mu=+x,+y} i\gamma_i^{[+\mu]}\gamma_{i+\mu}^{[-\mu]}$$

$$H_B^{eff} \propto g^4 \sum_i S_i^y S_{i+x}^x S_{i+x+y}^y S_{i+y}^x$$

Wen plaquette model (toric code)



Chiral Spin Liquid from Chern Insulator



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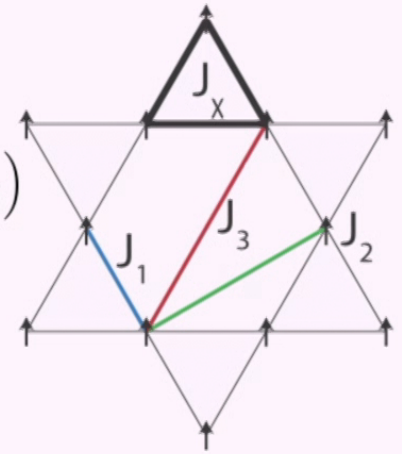


$|\nu_\uparrow = 1\rangle \otimes |\nu_\downarrow = 1\rangle$

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

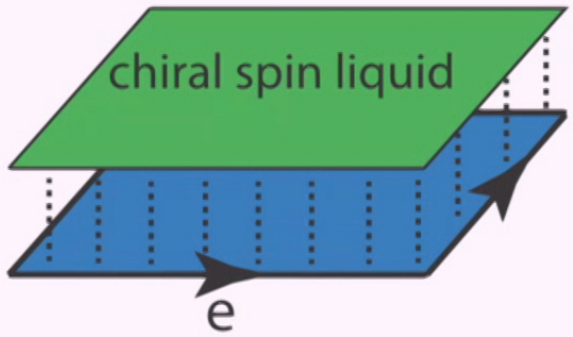
S-S. Gong, W. Zhu, and D. Sheng, Sci.Reports 4, 6317 (2014)

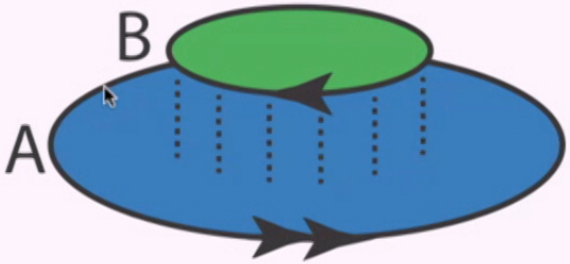
B. Bauer et.al. Nat. Comm. 5, 5137 (2014)

Chiral Spin Liquid

Topological Bootstrap

More is different and less: Fractionalization via Kondo coupling

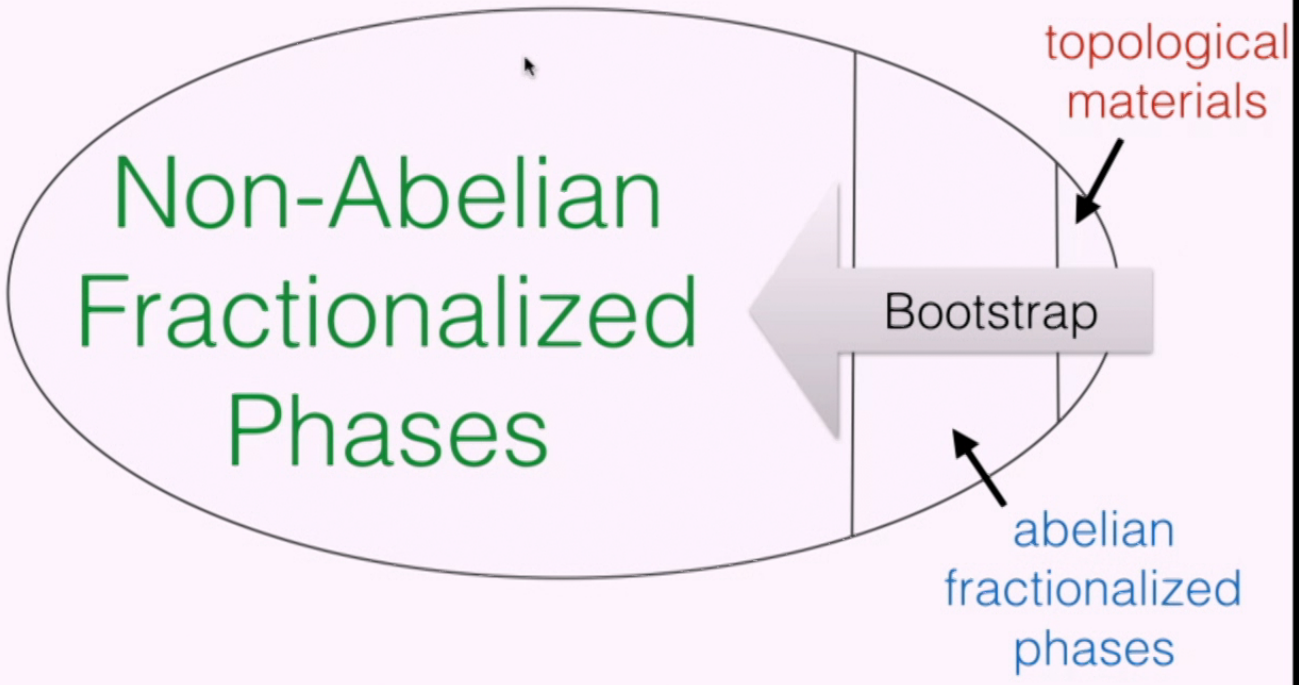


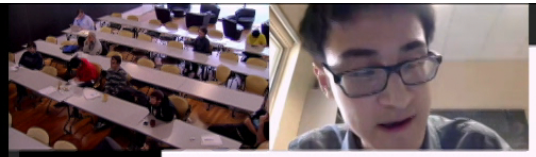


Potential realization in synthetic quantum matter

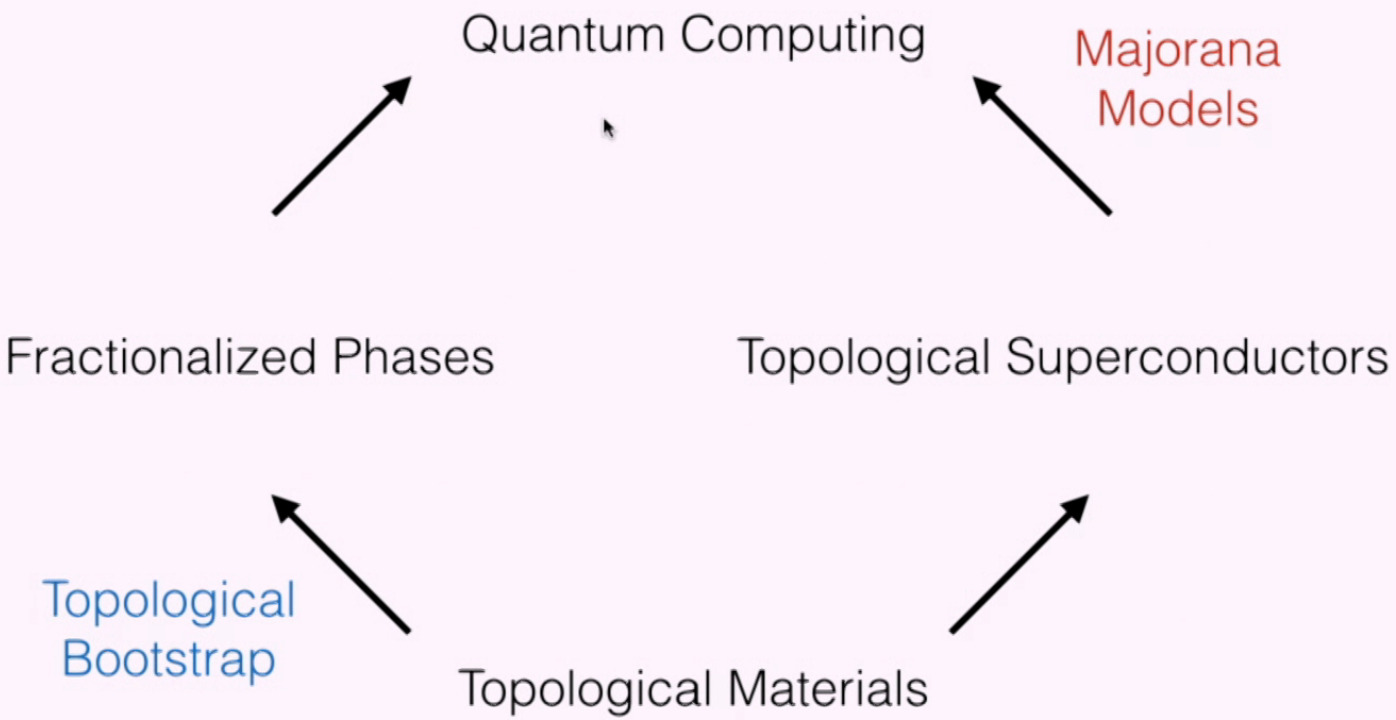
Apply techniques to Kondo lattices in heavy fermion systems, e.g. SmB_6

Pushing the Topological Frontier via Bootstrap



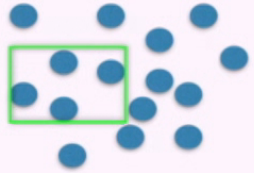


The Bigger Picture



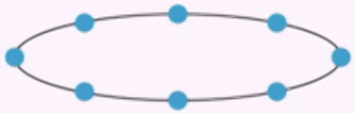
Majorana Models

0d: quantum chaos, black holes



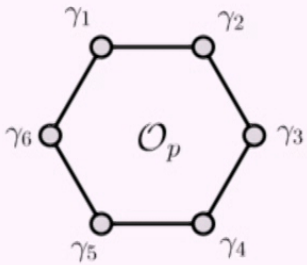
Sachdev,Ye (1993), Kitaev (2015)

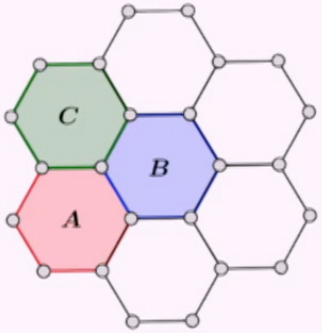
1d: supersymmetry



TH, Halasz, Grover (2016)

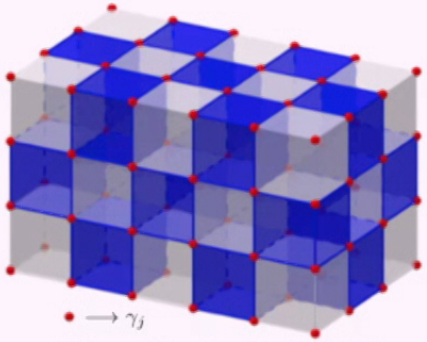
2d: Majorana surface codes



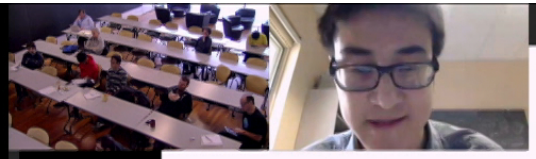


Vijay, **TH**, Fu (2015)

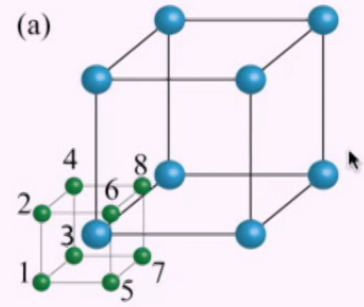
3d: Fracton topological order



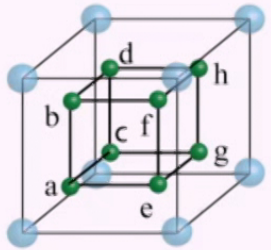
Vijay, Haah, Fu (2016)



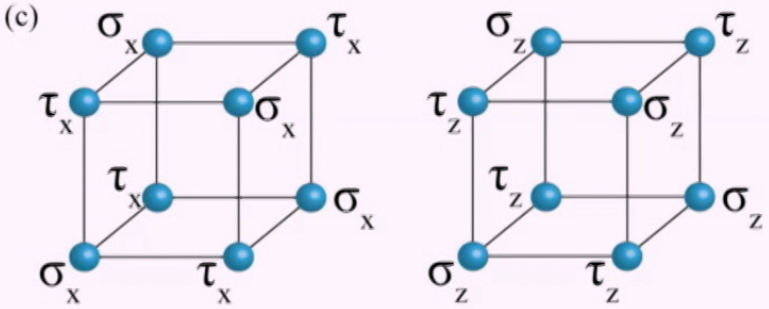
Fractons from Partons



$$\gamma_1\gamma_4\gamma_6\gamma_7 = \gamma_2\gamma_3\gamma_5\gamma_8 = 1$$

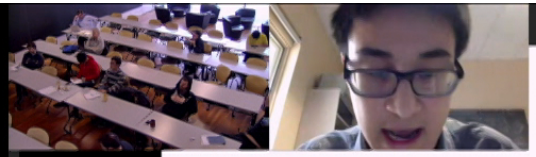


$$\gamma_a\gamma_b\gamma_c\gamma_d = \gamma_a\gamma_c\gamma_e\gamma_g = 1$$
$$\gamma_a\gamma_b\gamma_e\gamma_f = \gamma_e\gamma_f\gamma_g\gamma_h = 1$$

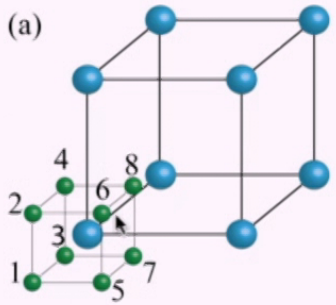


TH and G. Halasz, arXiv:1703.02973

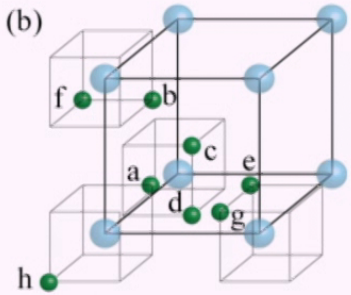
New Type-I fracton w/ string and membrane logical operators



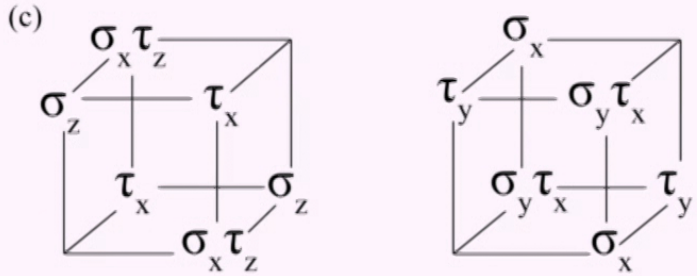
Fractons from Partons



$$\gamma_1\gamma_4\gamma_6\gamma_7 = \gamma_2\gamma_3\gamma_5\gamma_8 = 1$$



$$\gamma_a\gamma_b\gamma_c\gamma_d = \gamma_a\gamma_c\gamma_e\gamma_g = 1$$
$$\gamma_a\gamma_b\gamma_e\gamma_f = \gamma_e\gamma_f\gamma_g\gamma_h = 1$$



TH and G. Halasz,
arXiv:1703.02973

New Type-II non-CSS fracton w/ fractal logical operators

The Bigger Picture

Quantum Computing

Majorana Models

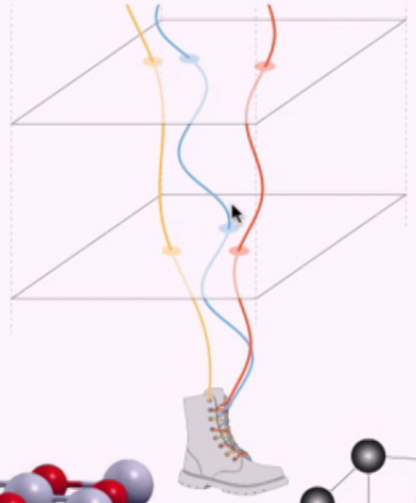
Fractionalized Phases

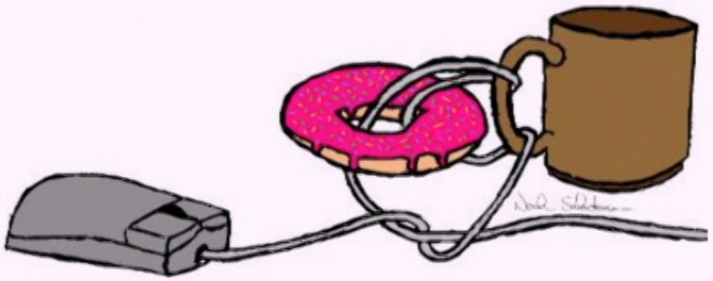
Topological Superconductors

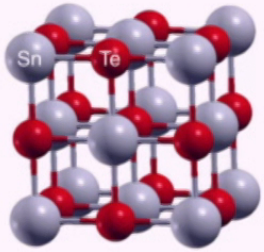
Topological Bootstrap

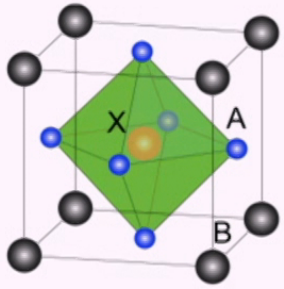
Topological Materials

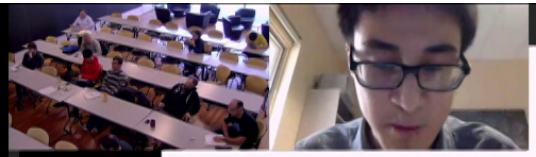
Transforming Topology











Collaborations

Theory: L. Fu (MIT), L. Balents (KITP), A. Ludwig (UCSB),
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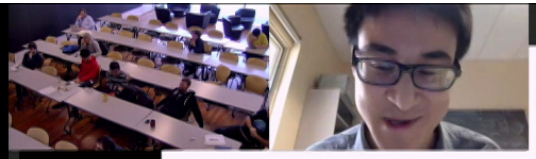
Project supervision: W. Ho (Geneva -> Harvard),
T. Iadecola (BU -> JQI Maryland)



Thanks!

SnTe TCIs	Nature Communications 3:982 (2012)
SnTe Thin Film TCIs	Nature Materials 13:178 (2014)
Bulk Topological Proximity Effect	PRL 116, 086802 (2016)
Entangled Cloning	PRB 94, 161112 (R) (2016)
Topological Bootstrap	arXiv:1610.04614 (2016)
Majorana Surface Code	PRX 5, 041038 (2015)
Majorana Supersymmetry	PRL 117, 166802 (2016)
Fractons from Partons	arXiv:1703.02973 (2017)

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