Title: Defects: A new window into topological quantum matter

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Abstract: Topologically ordered states, such as the fractional quantum Hall (FQH) states, are quantum states of matter with various exotic properties, including quasiparticles with fractional quantum numbers and fractional statistics, and robust topology-dependent ground state degeneracies. In this talk, I will describe a new aspect of topological states: their extrinsic defects. These include extrinsically imposed point-like or line-like defects that couple to the topological properties of the state in non-trivial ways. The extrinsic point defects localize topologically protected "parafermion" zero modes, which generalize the notion of Majorana fermion zero modes, and provide a new direction for realizing non-Abelian quantum statistics and topological quantum computation. The line defects allow direct quantum mechanical coupling between electrons and fractionalized anyons, leading to new ways to probe fractionalization. After describing the conceptual framework, I will focus on a specific set of experimental proposals, using conventional bilayer FQH states, to detect parafermion zero modes and to directly observe the long-predicted topological ground state degeneracy of FQH states. In the end I will comment on other ways in which extrinsic defects provide a new window into fractionalization.

SIMONS FOUNDATION

Microsoft

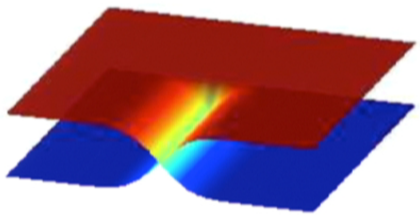
Defects: A New Window into Topological Quantum Matter

Maissam Barkeshli

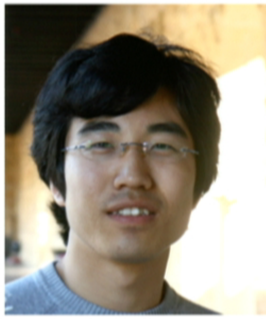
Microsoft Station Q

Perimeter Institute

October 2014



Collaborators



Xiao-Liang Qi
(Stanford)

Chao-Ming Jian
(Stanford)

Yuval Oreg
(Weizmann)

Steven Kivelson
(Stanford)

Erez Berg
(Weizmann)

What are the possible states of matter?

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Intrinsic Interest

New Technologies

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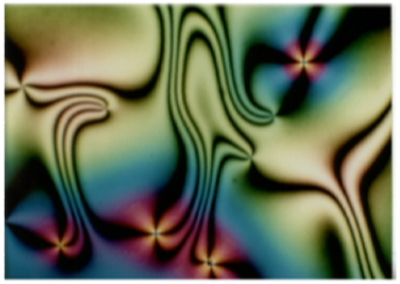
Intrinsic Interest

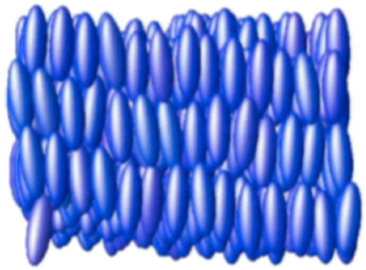
New Technologies

Insight into the origin of space, matter, fundamental forces

Some interesting (and useful) states of matter

Liquid Crystals and displays





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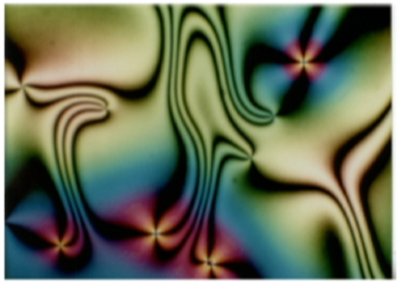
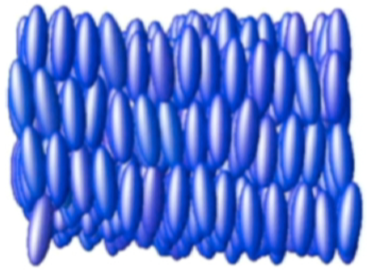
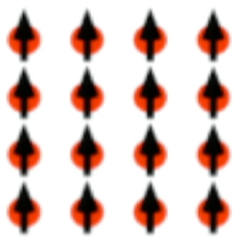
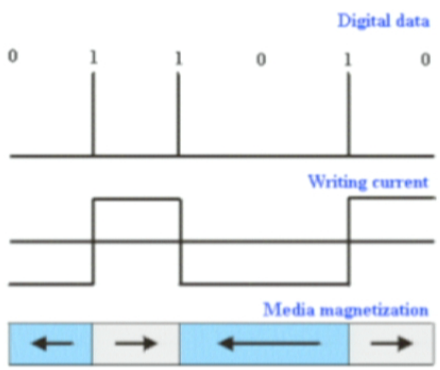
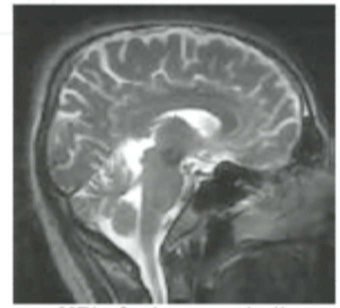




Magnets and Hard Drives

Some interesting (and useful) states of matter

Superconductors



MRI of a human skull.

Some interesting (and useful) states of matter

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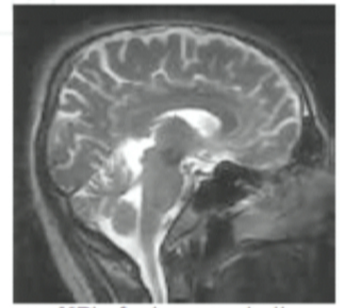
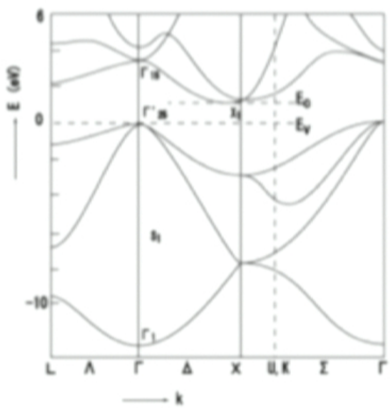
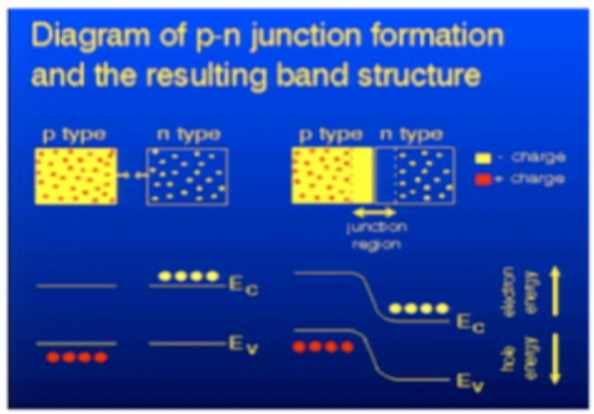
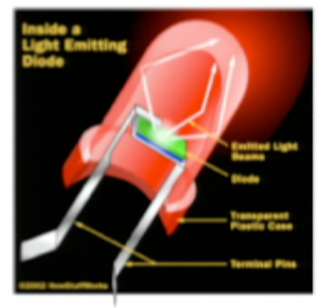


MRI of a human skull.

Crystals and Semiconductors (Transistors and LED)







Insight into high-energy physics

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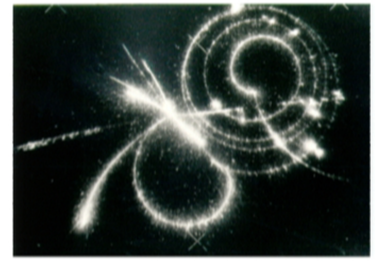

- Spontaneous symmetry breaking, Goldstone modes (e.g. pions)

Insight into high-energy physics

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  "Gauge symmetry-breaking," Anderson-Higgs Mechanism

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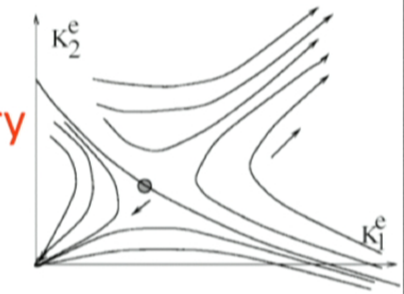
- Renormalization-Group Theory
  Quantum field theory = low energy effective theory



Insight into high-energy physics

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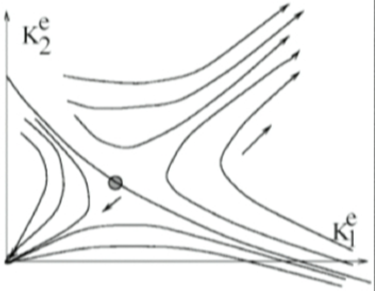


Or, more speculatively:

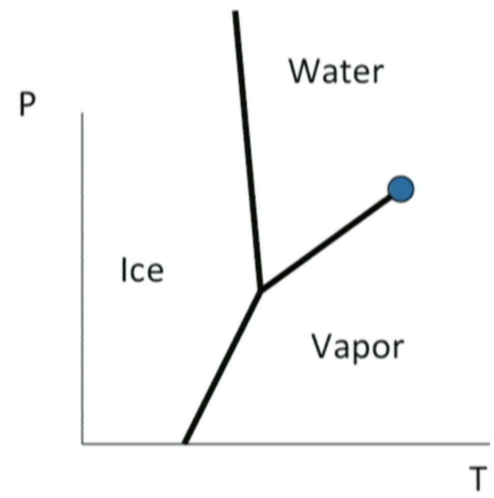
- Origin of fermions and gauge symmetry, emergent symmetries, origin of spatial dimensionality, etc.

Abstract definition of "states of matter"

Two concepts:

1. Phase Transitions

Singularity in free energy



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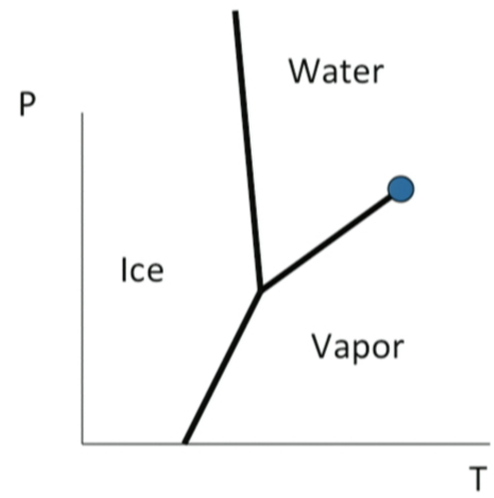


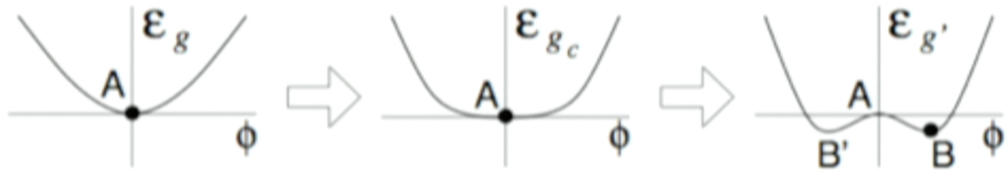
2. Universality

Long-wavelength, low energy behavior is *universal*

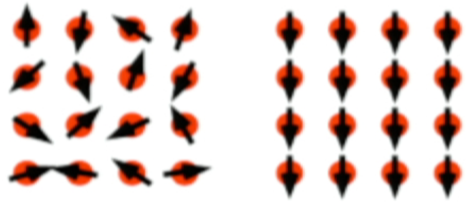
Independent of microscopic details

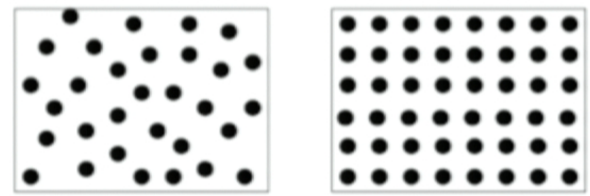
Try to characterize possible universal behaviors

Phases = symmetry-breakings (pattern formation)



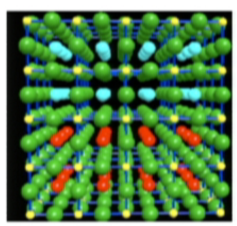
Spontaneous symmetry-breaking



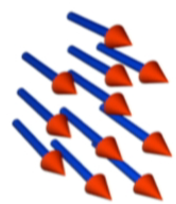


Ginzburg-Landau Theory

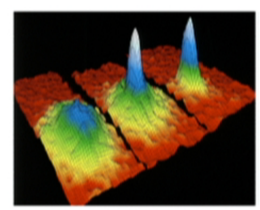
$$F[\phi] = \int |\nabla\phi|^2 + \alpha|\phi|^2 + \beta|\phi|^4 + \ldots.$$



Crystal



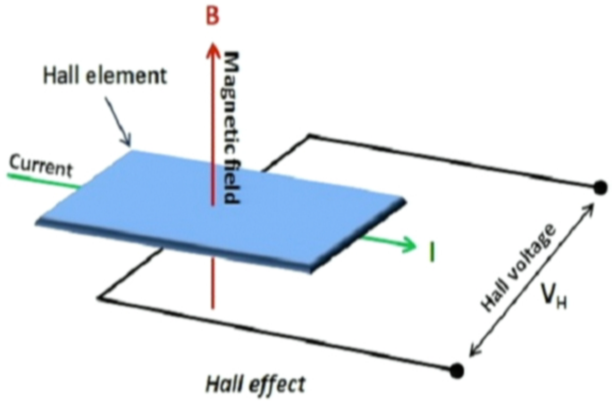
Magnet



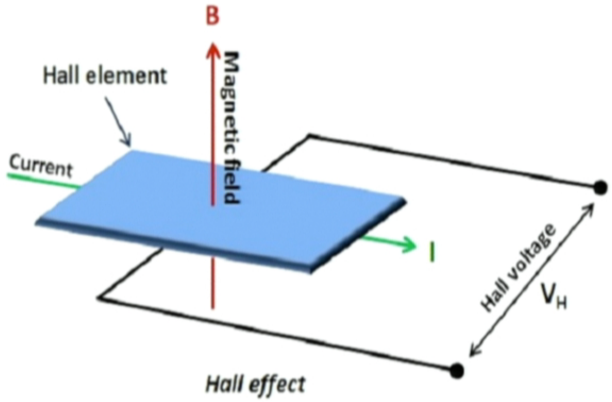
Superfluid

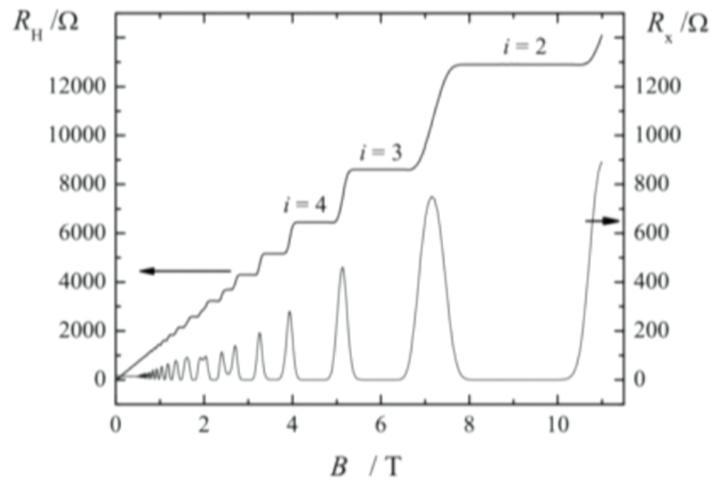
Quantum Hall States: A new chapter

Quantum Hall States: A new chapter



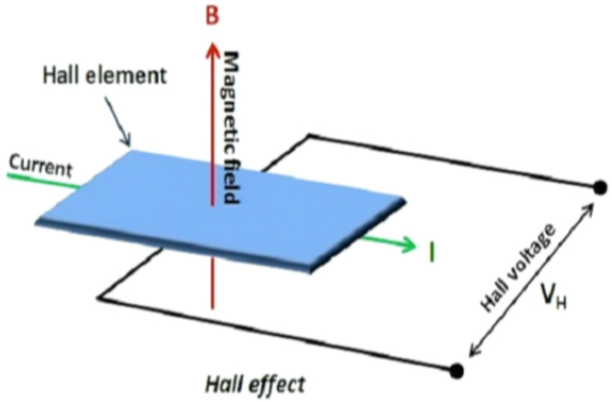
Quantum Hall States: A new chapter

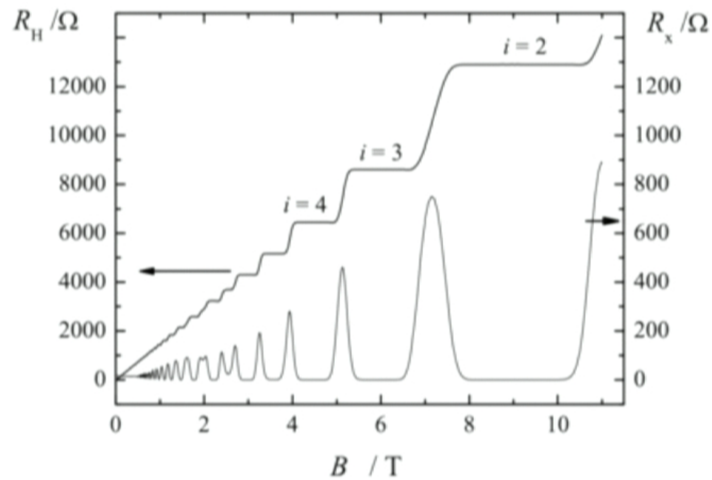




$$\rho_{xy} = \frac{1}{n}\frac{h}{e^2} \qquad \rho_{xx} = 0$$

Quantum Hall States: A new chapter





$$\rho_{xy} = \frac{1}{n}\frac{h}{e^2} \qquad \rho_{xx} = 0$$

Different quantum Hall states: same symmetry, different physical properties. **Failure of symmetry-breaking theory**

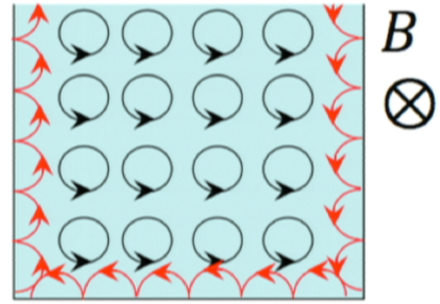
Nobel Prize

1985: Klitzing

1998: Tsui, Störmer, Laughlin

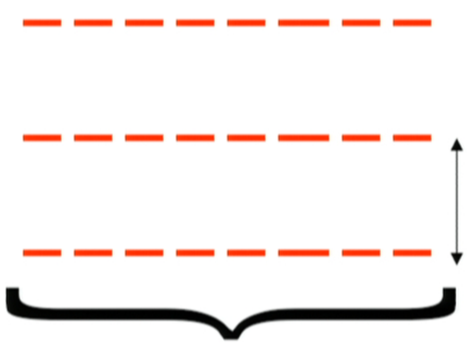
Quantum Hall Basics

- 2D electrons, perpendicular B-field
- Single-Particle Spectrum: **Landau Levels**



$$H = \frac{1}{2m}(p - A)^2 \qquad E_n = (n + 1/2)\hbar\omega_c \qquad \omega_c = \frac{eB}{mc}$$

Filling Fraction: $\nu = \frac{N_e}{N_\Phi}$



$n = 1$

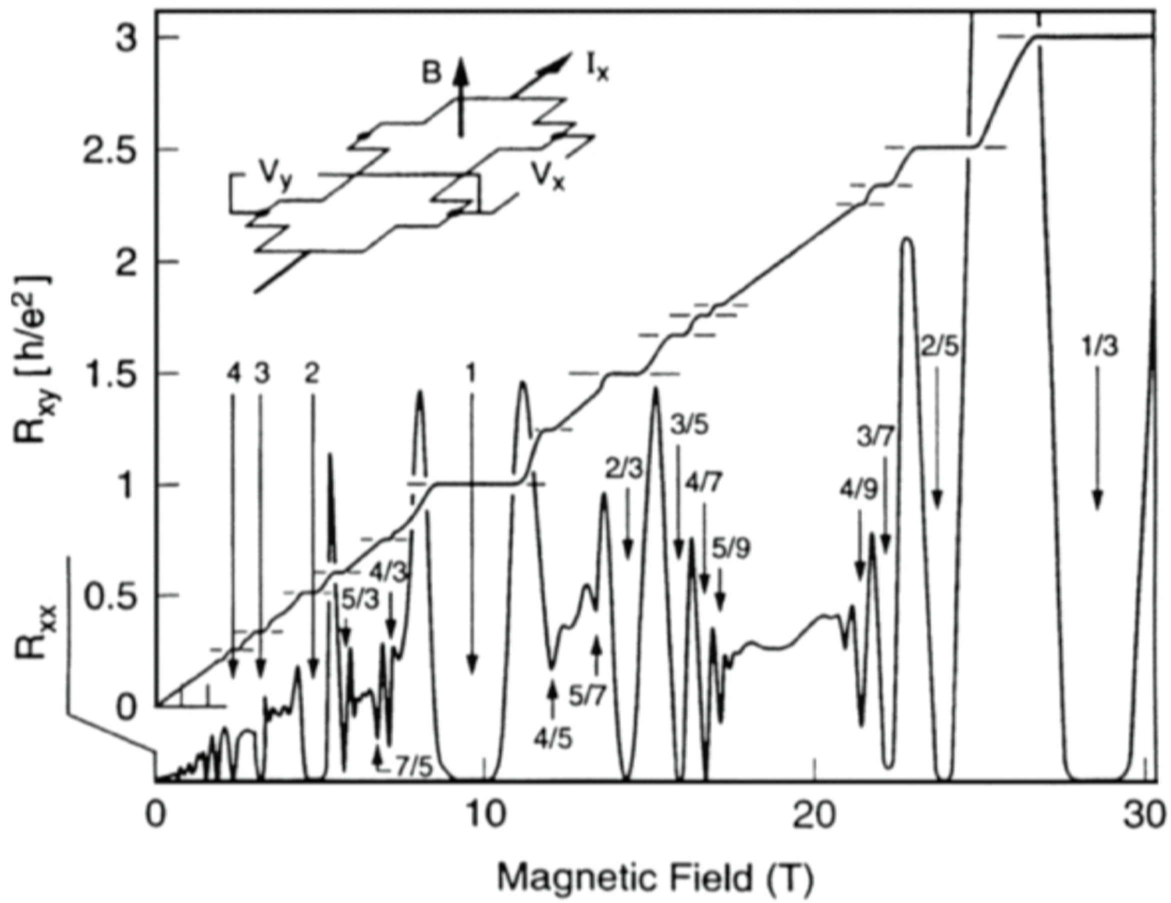
$n = 0$

$\Delta E = \hbar\omega_c \sim B$

$N_\Phi = \Phi / \Phi_0$ States

Incompressible states at integer filling

Fractional Quantum Hall Effect



What is going on at fractional fillings?

Laughlin wave function:

(Laughlin 1983)

$$\Phi_{1/3}(\{z_i\}) = \prod_{i<j}(z_i - z_j)^3 e^{-\sum_i |z_i|^2/l_B^2}$$

$$\nu = 1/3$$

$$z_i = x_i + iy_i$$

Good overlap with exact ground state

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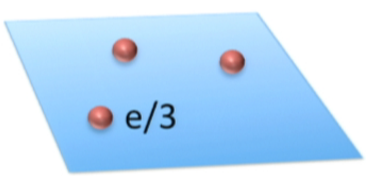
Good overlap with exact ground state

Quasihole wave function:

$$\Phi_{1/3}(\eta;\{z_i\}) = \prod_i (z_i - \eta)\prod_{i<j}(z_i - z_j)^3 e^{-\sum_i |z_i|^2/l_B^2}$$



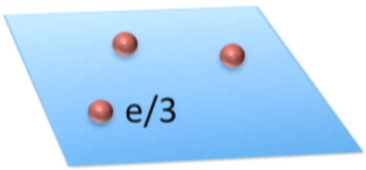
Quasiparticle excitations carry fractional charge

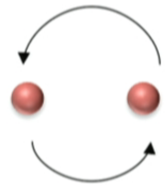
→ Topologically non-trivial!

Fractional Quantum Hall States

- Fractional statistics

Halperin, 1984;
Arovas, Schrieffer, Wilczek, 1984





$$|\Psi\rangle \rightarrow e^{i\pi/3}|\Psi\rangle$$

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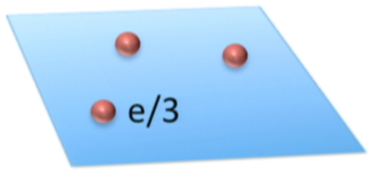
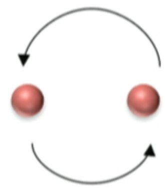
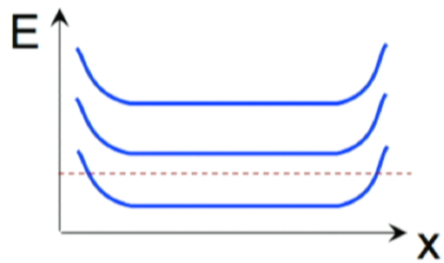
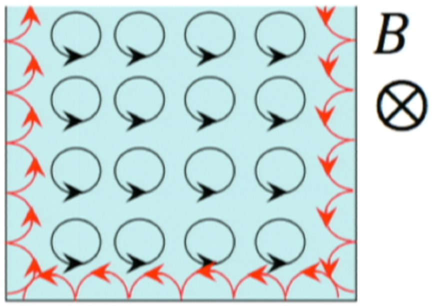




$$|\Psi\rangle \to e^{i\pi/3}|\Psi\rangle$$

- Protected chiral gapless edge states



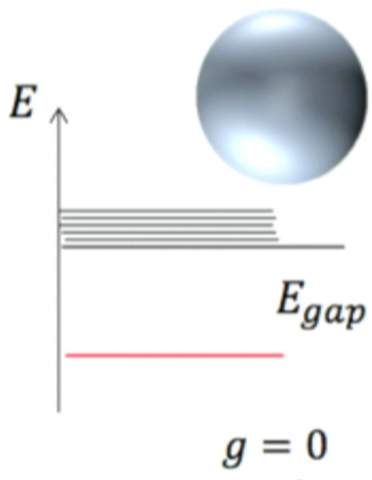


Halperin, 1982
Wen, 1990

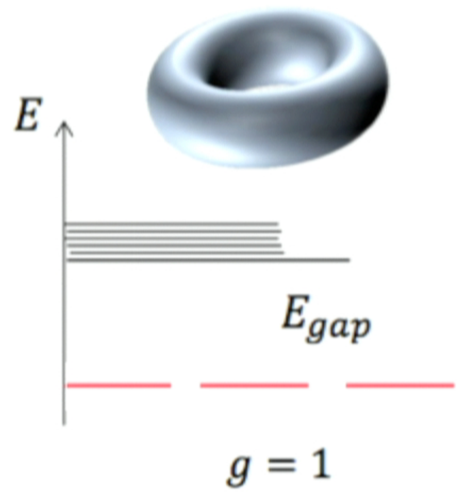
Fractional Quantum Hall States

- Topology-dependent ground state degeneracies

Wen 1989



1 state



3 states

3^g states
(1/3 Laughlin)

[Observed in numerics, not in experiments]

Fractional Quantum Hall States

Incompressible (gapped) quantum liquids

No Local Order Parameter

Characterized by Fractional statistics, edge states, topological degeneracies, etc

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Effective description:

- Topological Quantum Field Theory — Witten, Atiyah, ...
- Emergent gauge theory (Chern-Simons) — Zhang-Hansson-Kivelson
- Mathematics: Unitary Braided Tensor Category Theory

Non-Abelian Quasiparticles

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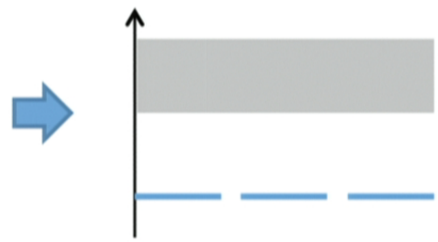
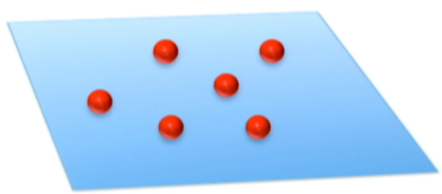
Can have topological degeneracy in presence of QPs (Non-Abelian)





Quantum Dimension

$$\# \text{ states } \propto d^N$$

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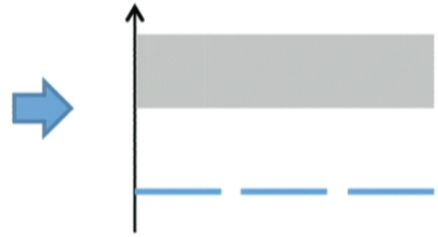
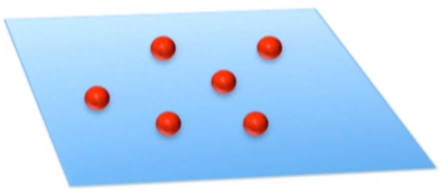
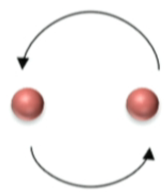




Quantum Dimension

$$\# \text{ states } \propto d^N$$

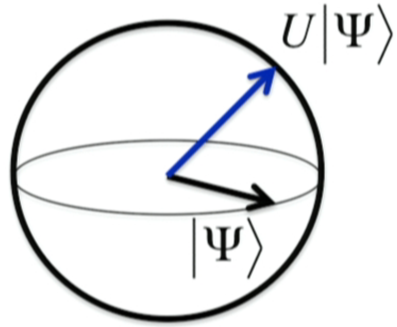
Braiding: Abelian vs. Non-Abelian Anyons

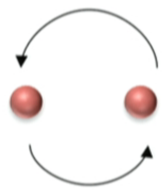


$$|\Psi_n\rangle \rightarrow U_{nm} |\Psi_m\rangle$$

Application: Topological Quantum Computation

Non-Abelian excitations → robust quantum computation





$$|\Psi_n\rangle \rightarrow U_{nm}|\Psi_m\rangle$$

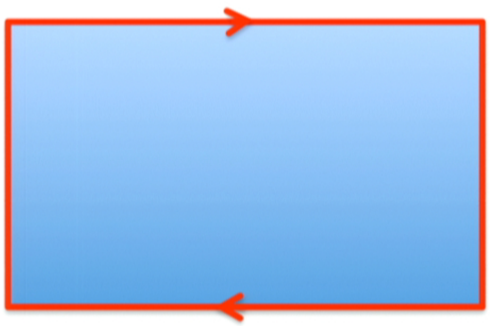
Nayak et al RMP 2008

- Information stored non-locally in topological subspace
- Only accessed via non-local (e.g. braiding) operations
- Intrinsically decoherence-free

Chiral edge theory (Wen 1990)

$$\mathcal{L}_{edge} = -\frac{3}{4\pi}\partial_x\phi\partial_t\phi - v(\partial_x\phi)^2$$

$$[\phi(x), \phi(y)] = i\frac{\pi}{3}sgn(x-y) \qquad \phi \sim \phi + 2\pi$$

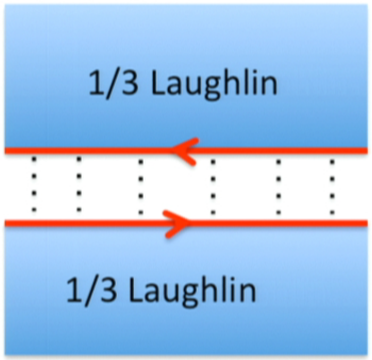


Charge density $\rho = \frac{1}{2\pi}\partial_x\phi$

Charge a/3 qp $V_a = e^{ia\phi}$

Electron operator $\Psi_e = e^{i3\phi}$

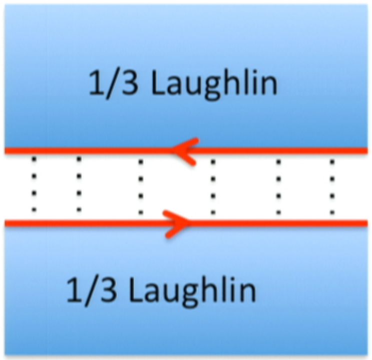
Electron tunneling across two 1/3 Laughlin states



$$\mathcal{L}_{edge} = -\frac{3}{4\pi}\partial_x\phi_1\partial_t\phi_1 + \frac{3}{4\pi}\partial_x\phi_2\partial_t\phi_2 - V_{IJ}\partial_x\phi_I\partial_x\phi_J$$

Electron tunneling $\quad \delta\mathcal{L} = -t\cos(3(\phi_1 - \phi_2))$

Electron tunneling across two 1/3 Laughlin states



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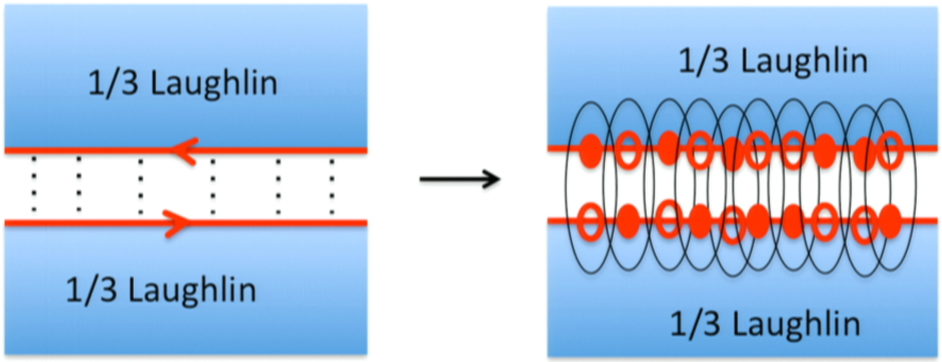

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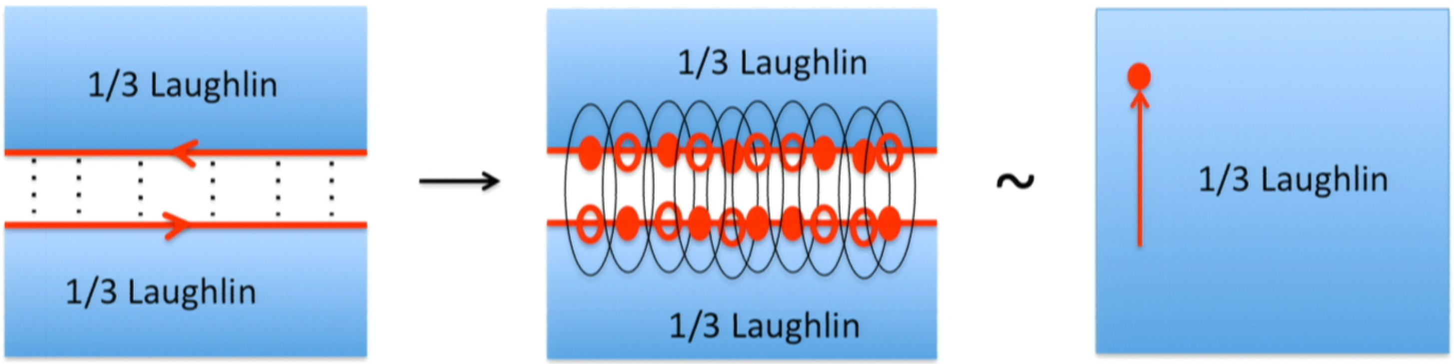
Electron tunneling $\delta\mathcal{L} = -t\cos(3(\phi_1 - \phi_2))$

Large t → Gaps modes $\langle e^{i(\phi_1-\phi_2)}\rangle = e^{2\pi i n/3}$

Electron tunneling across two 1/3 Laughlin states



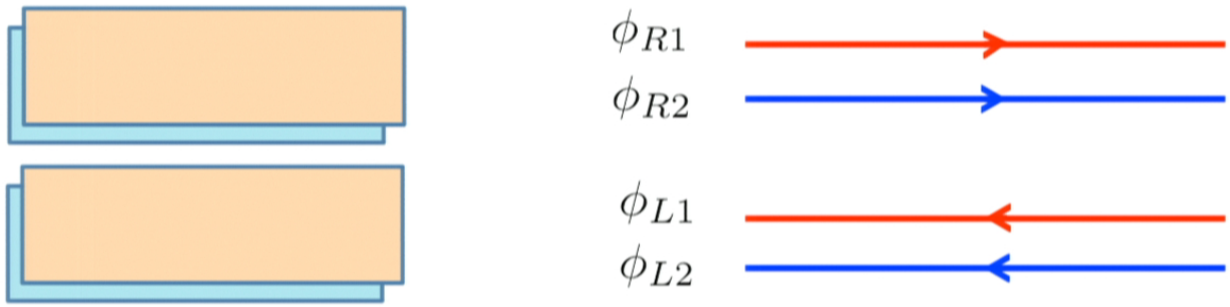
$$\mathcal{L}_{edge} = -\frac{3}{4\pi}\partial_x\phi_1\partial_t\phi_1 + \frac{3}{4\pi}\partial_x\phi_2\partial_t\phi_2 - V_{IJ}\partial_x\phi_I\partial_x\phi_J$$

Electron tunneling $\delta\mathcal{L} = -t\cos(3(\phi_1 - \phi_2))$

Large t → Gaps modes $\langle e^{i(\phi_1-\phi_2)}\rangle = e^{2\pi i n/3}$

Double layer (1/3 + 1/3)

Barkeshli, Qi PRX 2012



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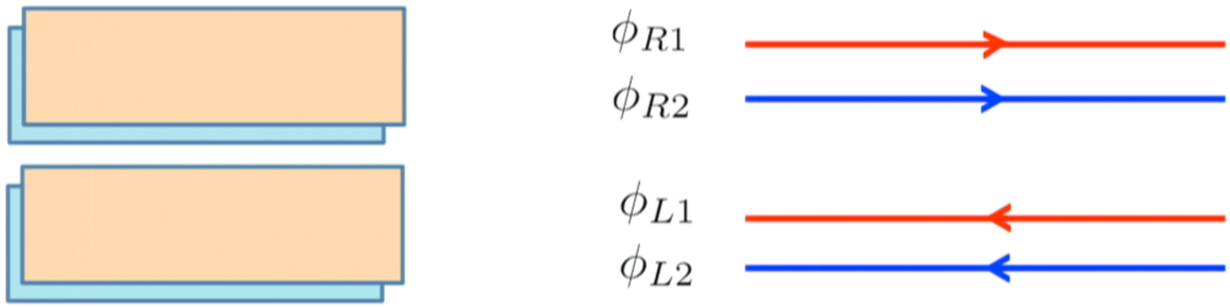
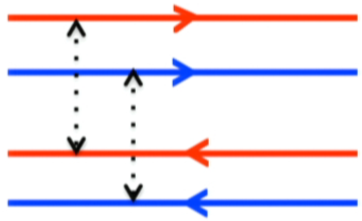
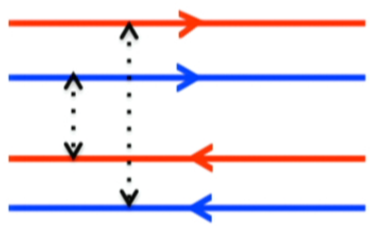
Barkeshli, Qi PRX 2012





$$\cos(3(\phi_{R1}-\phi_{L1})) + \cos(3(\phi_{R2}-\phi_{L2})) \longrightarrow \langle e^{i(\phi_{R1}-\phi_{L1})}\rangle \neq 0 \quad \langle e^{i(\phi_{R2}-\phi_{L2})}\rangle \neq 0$$



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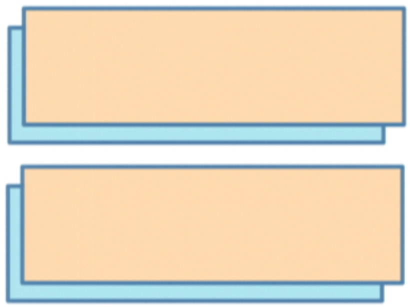
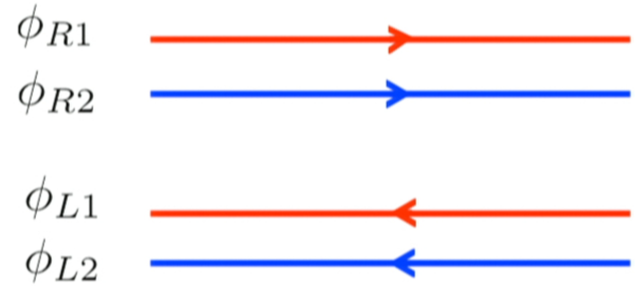
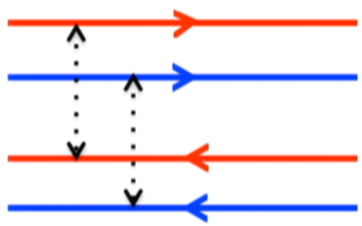
Double layer (1/3 + 1/3)

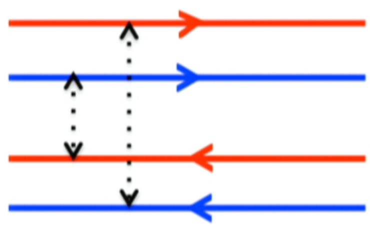
Barkeshli, Qi PRX 2012







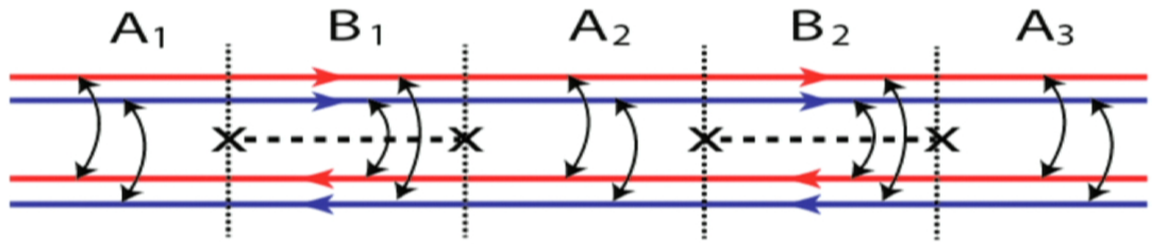
$$\cos(3(\phi_{R1} - \phi_{L1})) + \cos(3(\phi_{R2} - \phi_{L2})) \longrightarrow \langle e^{i(\phi_{R1} - \phi_{L1})} \rangle \neq 0, \quad \langle e^{i(\phi_{R2} - \phi_{L2})} \rangle \neq 0$$

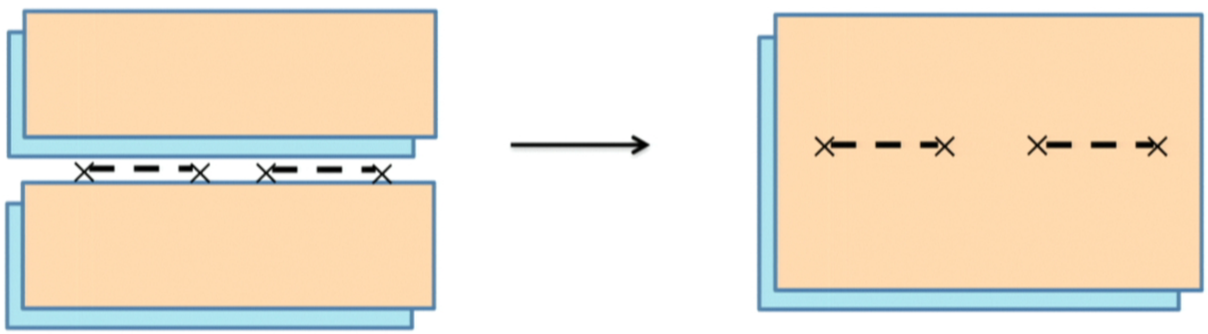


$$\cos(3(\phi_{R1} - \phi_{L2})) + \cos(3(\phi_{R2} - \phi_{L1})) \longrightarrow \langle e^{i(\phi_{R1} - \phi_{L2})} \rangle \neq 0, \quad \langle e^{i(\phi_{R2} - \phi_{L1})} \rangle \neq 0$$

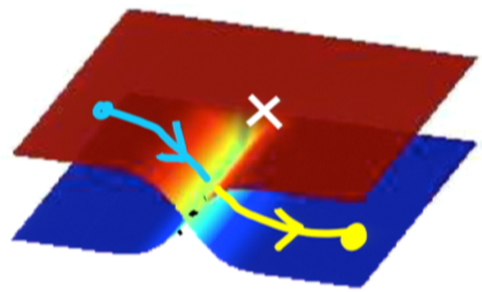
Topologically Distinct Edge Phases!

Domain Walls Between Different Edge Phases



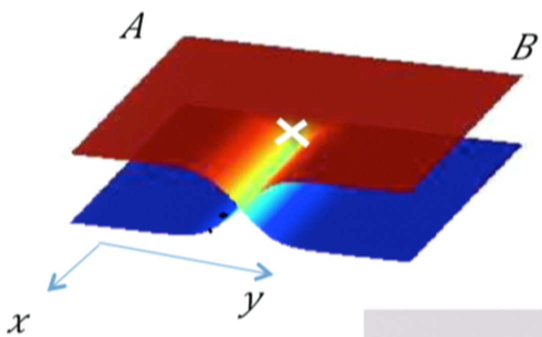


“Twisted” tunneling induces branch cut between layers

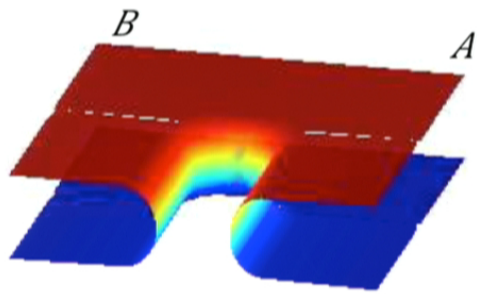


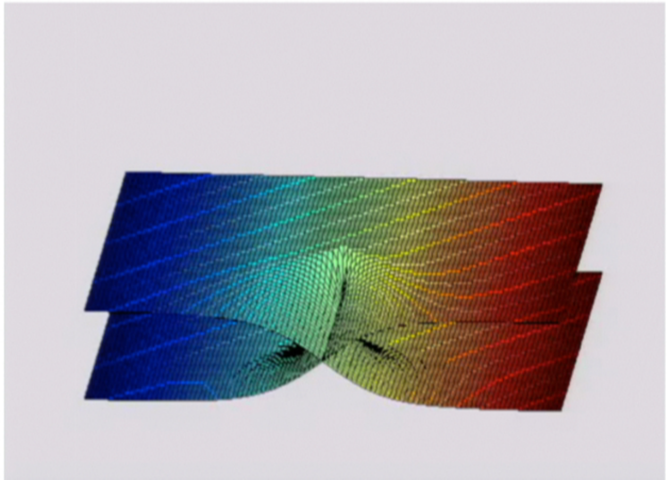
Branch cut effectively changes topology

- In bilayers, pair of defects (branch points) creates "worm hole"



flip the
top layer
⟺



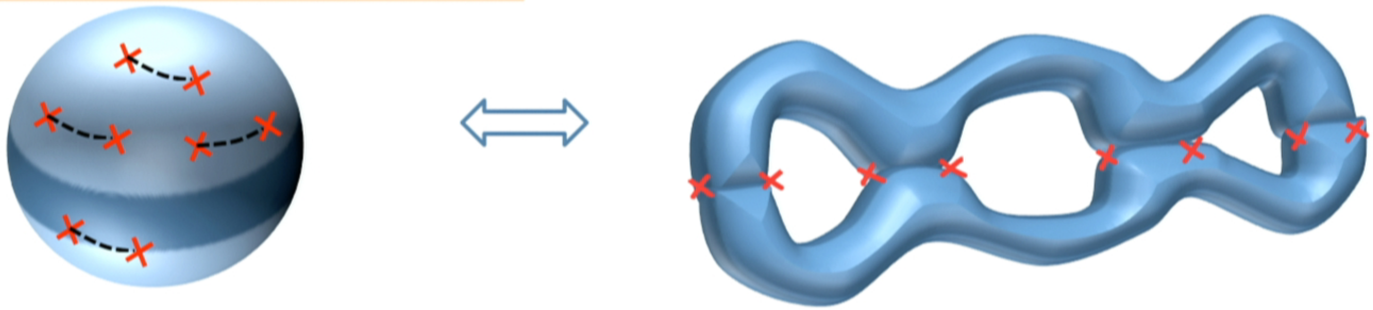


Barkeshli, Wen (2010)
Barkeshli, Qi (2012)

- Every pair of defects add genus 1 to the manifold

$2n$ defects on a sphere

genus $g=n-1$ surface



Defects called genons---genus generators

Barkeshli, Wen (2010)
Barkeshli, Qi (2012)

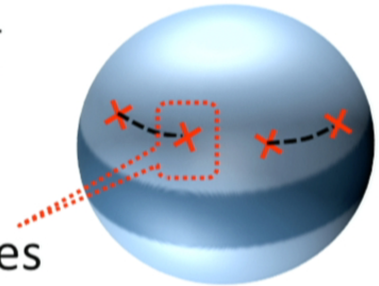
Quantum dimension of genons

- $\nu = 1/m$ Laughlin FQH state in each layer →

  ground state degeneracy m^g,

  each pair of defects add ***m*** degrees of freedom

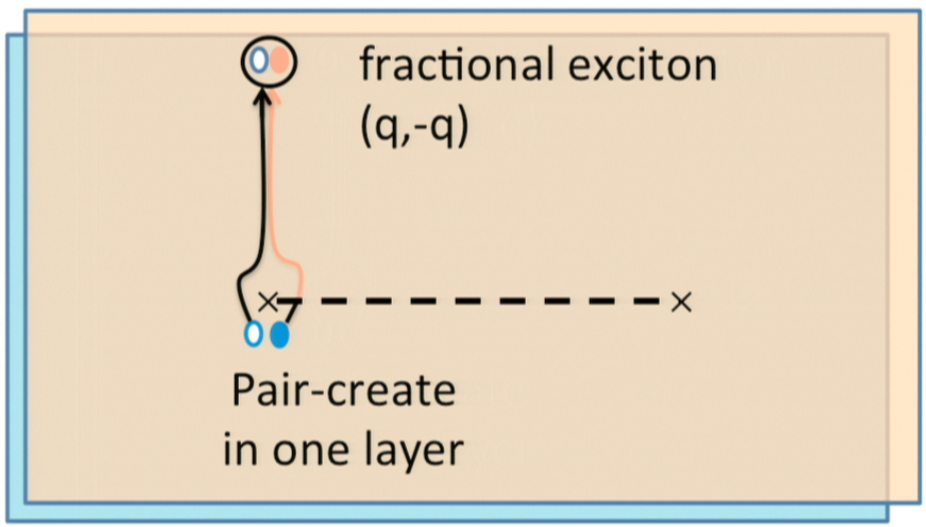
→ Each defect has quantum dimension $\sqrt{m}$



$\sqrt{m}$ states

Localized “parafermion” zero modes

- Twist defects/genons lead to localized zero energy states for some quasiparticles
- Genons in bilayers can absorb/emit fractional excitons :



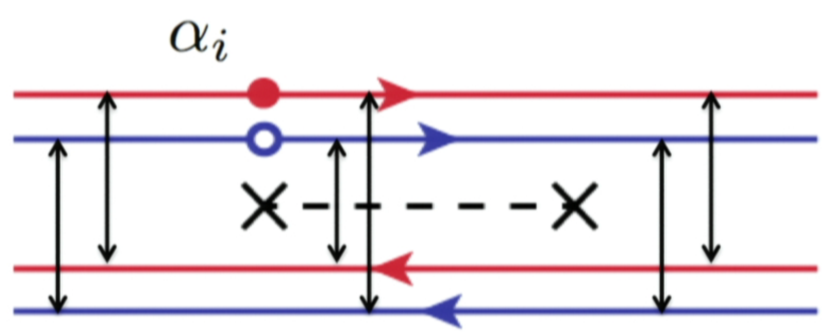
Parafermion zero mode operators

- Zero mode = quasiparticle exciton operators at domain walls:

$$\alpha_i = e^{i(\phi_{R1}-\phi_{R2})(x_i)}$$

$$\alpha_j \alpha_k = \alpha_k \alpha_j e^{2\pi i sgn(j-k)/3}$$

Exponentially localized to defect.



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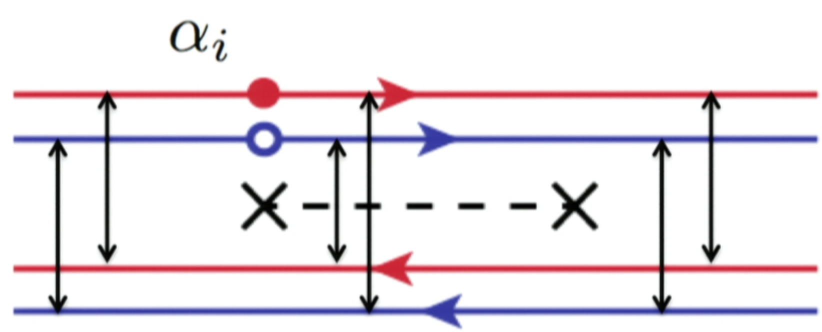
Z_3 "parafermion" algebra

Beyond Majorana zero modes [Read-Green 2000 Kitaev 2001]

Exponentially localized to defect.



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[Read-Green 2000
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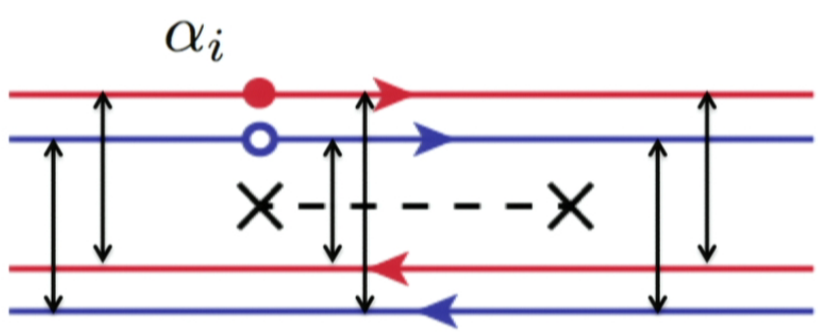
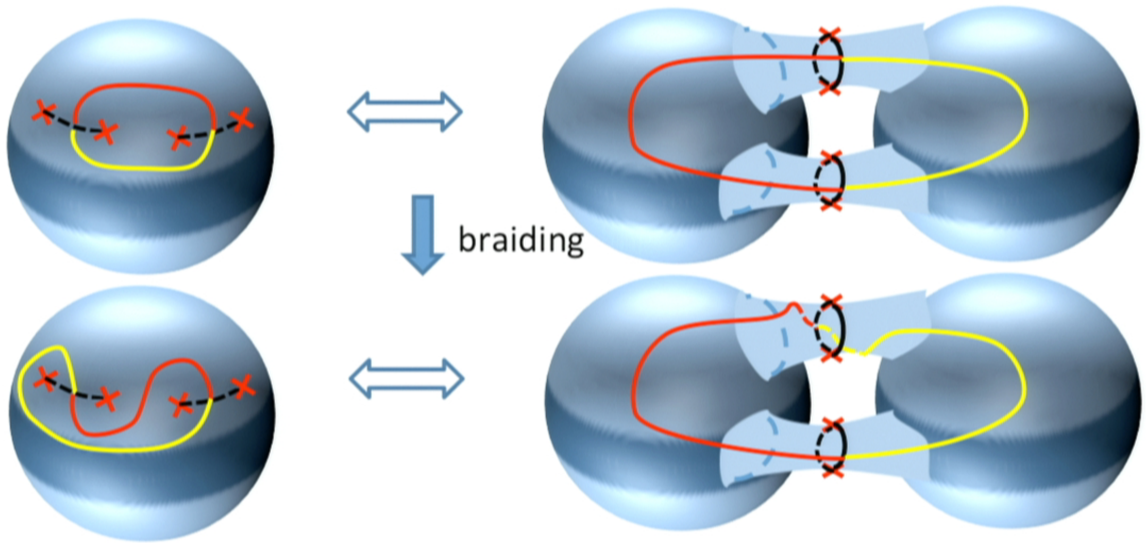


Projective braiding statistics of genons

- Braiding two genons = “Dehn twist” on the high genus surface

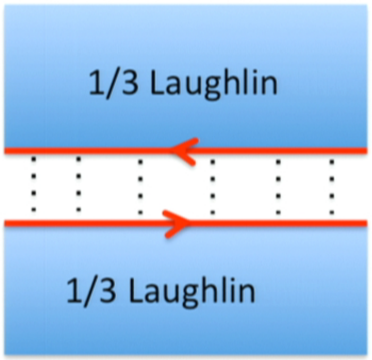
Overall phase not topological → **Projective non-Abelian statistics**



Universal topological quantum computation
from non-universal states

Barkeshli, Jian, Qi (2013)

Cooper pair tunneling in 1/3 Laughlin state



$$\delta\mathcal{L} = -\frac{t}{2}(\Psi^{\dagger}_{eR}\Psi^{\dagger}_{eL} + H.c.) = -t\cos(3(\phi_R + \phi_L))$$

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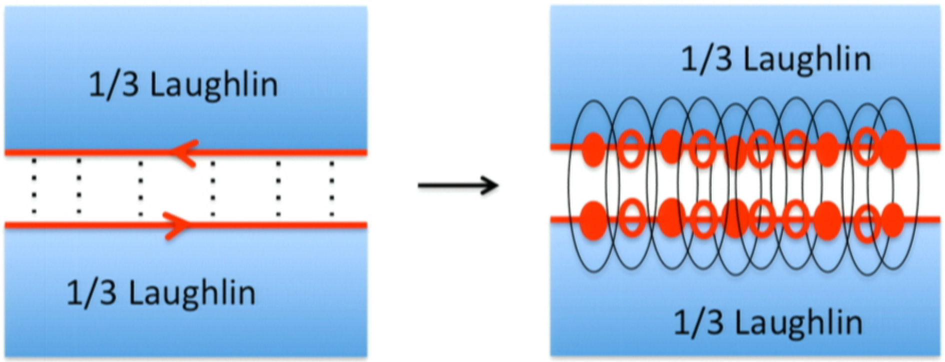

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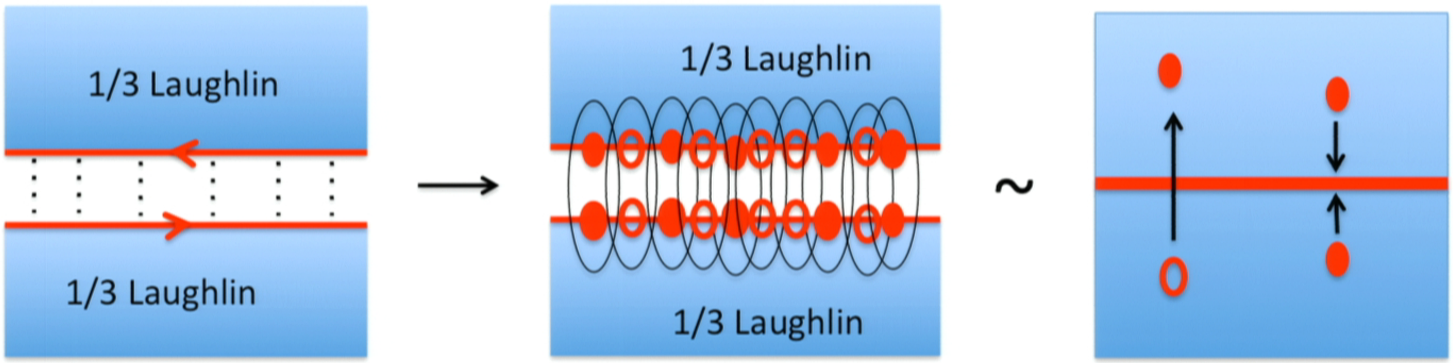

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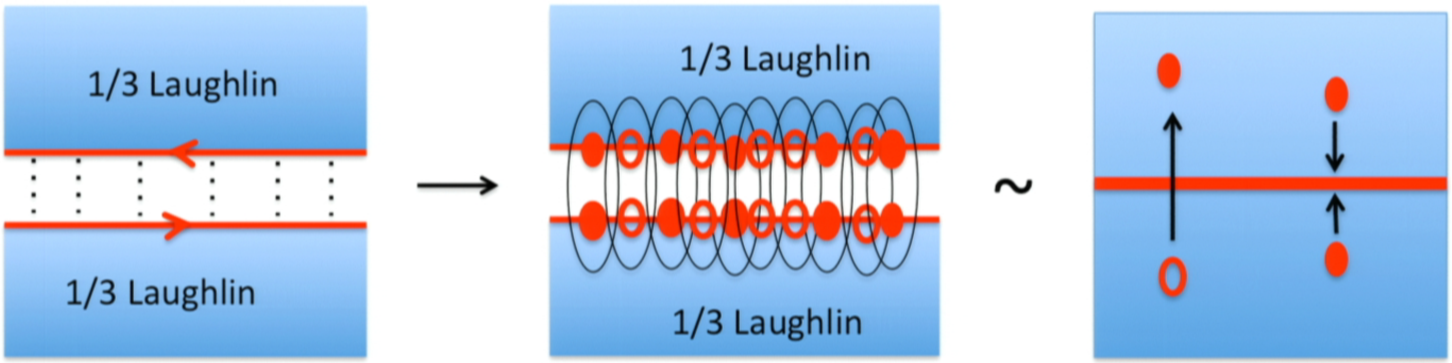

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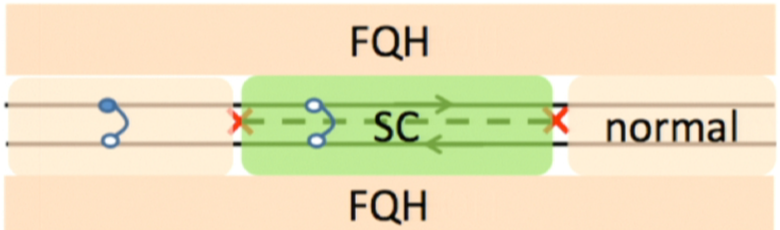
Topologically distinct way to gap out modes (cf. normal tunneling)

Normal – Superconducting Domain Walls



Lindner, Berg, Refael, Stern 2012; Clarke, Alicea, Shtengel 2012; Cheng 2012; Vaezi 2012

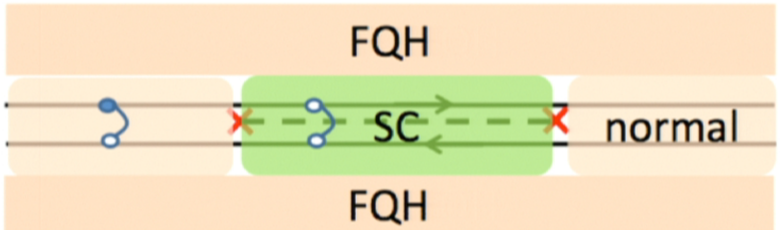
IQSH: Fu-Kane 2008

Quantum Dimension of domain walls:

$\sqrt{2}\sqrt{m}$ m odd

$\sqrt{m/2}$ m even

Normal – Superconducting Domain Walls



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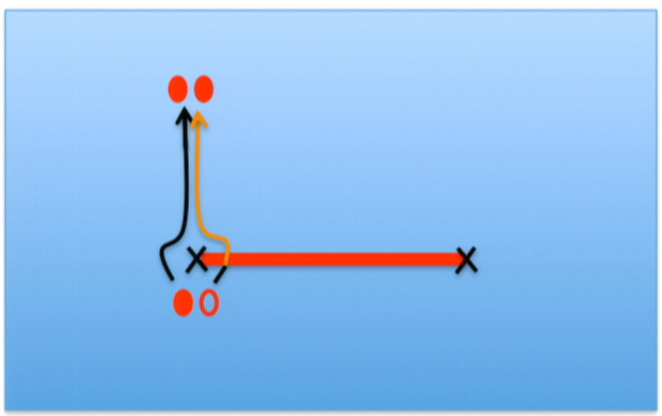

Parafermion zero modes

Line Defects

More abstractly, these were gapped line defects:

General classification of gapped line defects:

For certain lattice models: Kitaev-Kong (2012); Beig-Shor-Whalen (2011)

For general Abelian states: Barkeshli, Jian, Qi (2013); Levin (2013)

[see also Kapustin-Saulina (2011), Fuchs et al (2013)]

Line Defects

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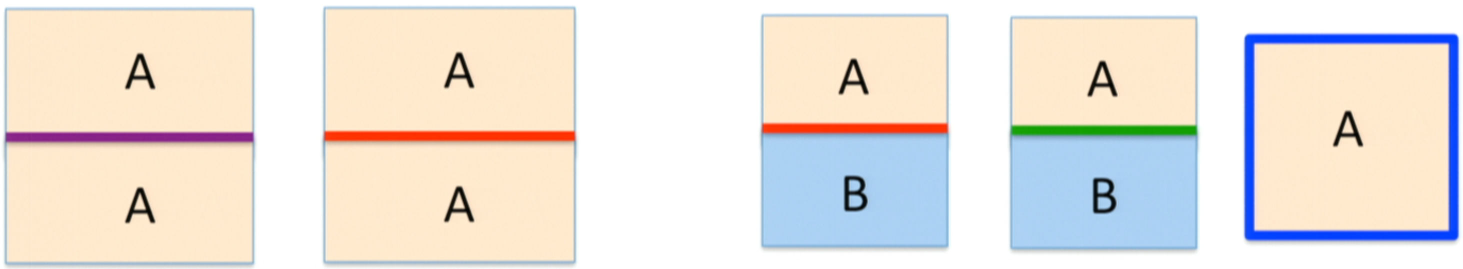

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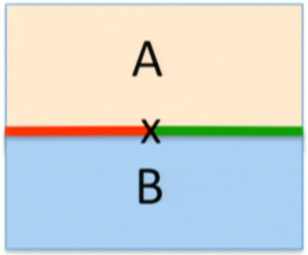
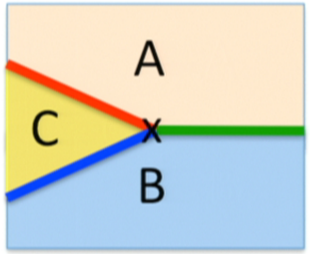
Point-like Defects

- Domain walls/junctions between distinct line defects





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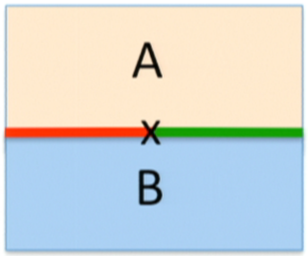
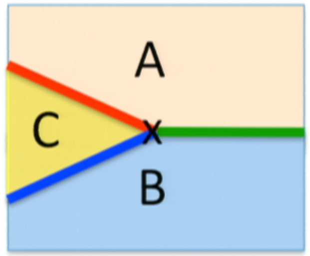


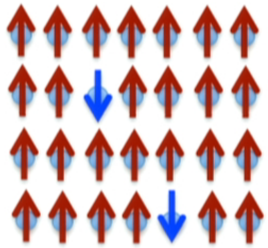


Not finite energy quasiparticle excitations

(Not thermally activated at low T)

Extrinsically imposed deformations of Hamiltonian

For symmetry-broken order:



Finite energy excitations

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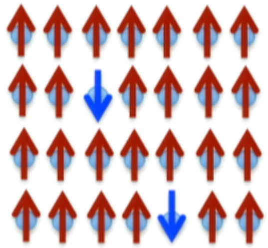

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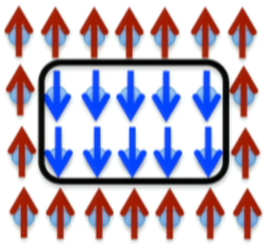

Line defects (linear energy cost)

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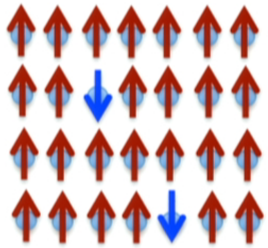

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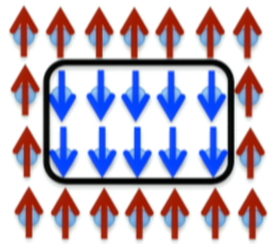
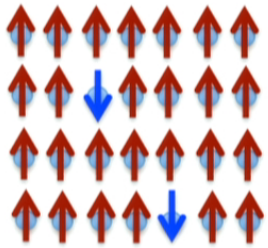


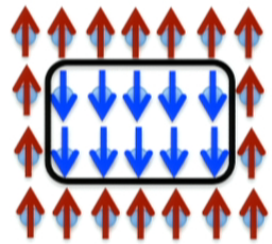
Line defects (linear energy cost)

Point-like defects (log confined)

For symmetry-broken order:



Finite energy
excitations



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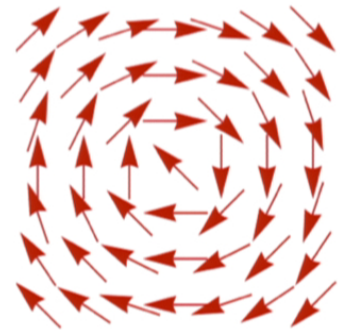

Point-like defects
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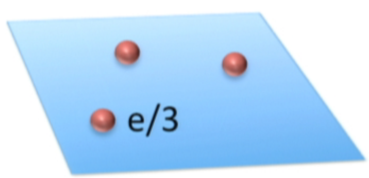
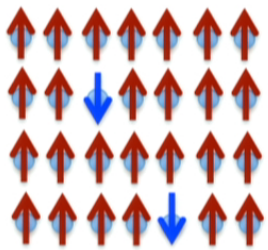
For topological order:



Fractional anyons
= finite energy
excitations

For symmetry-broken order:



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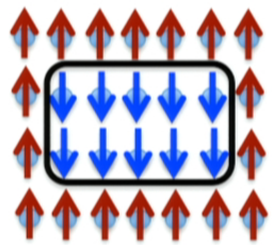

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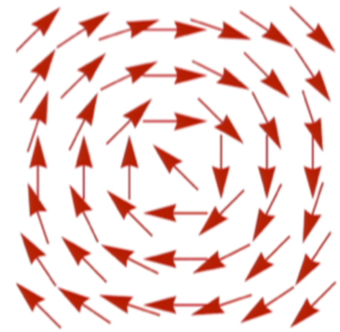

Point-like defects
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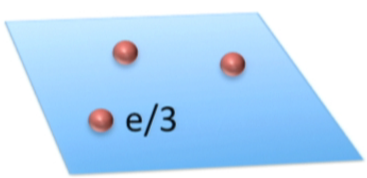

Fractional anyons
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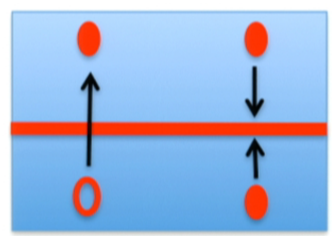

Line defects
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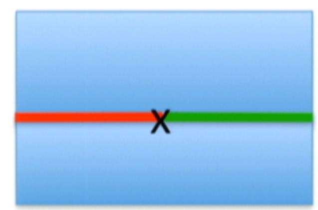

Point-like defects
(confined)

Experimental Proposal

MB, XLQ (2013)

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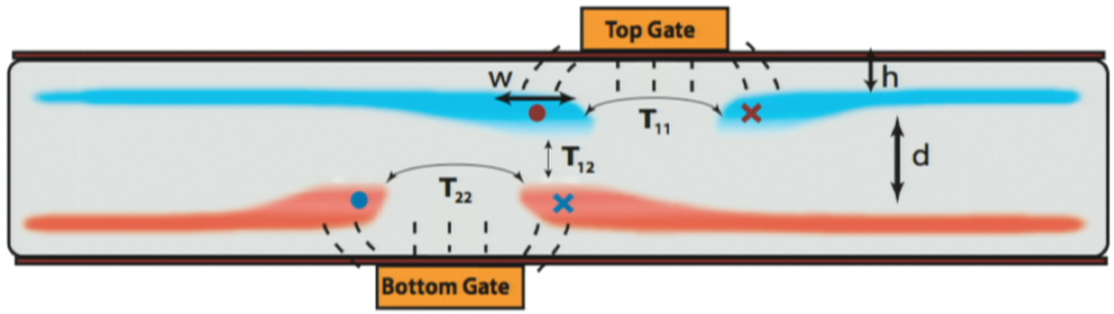
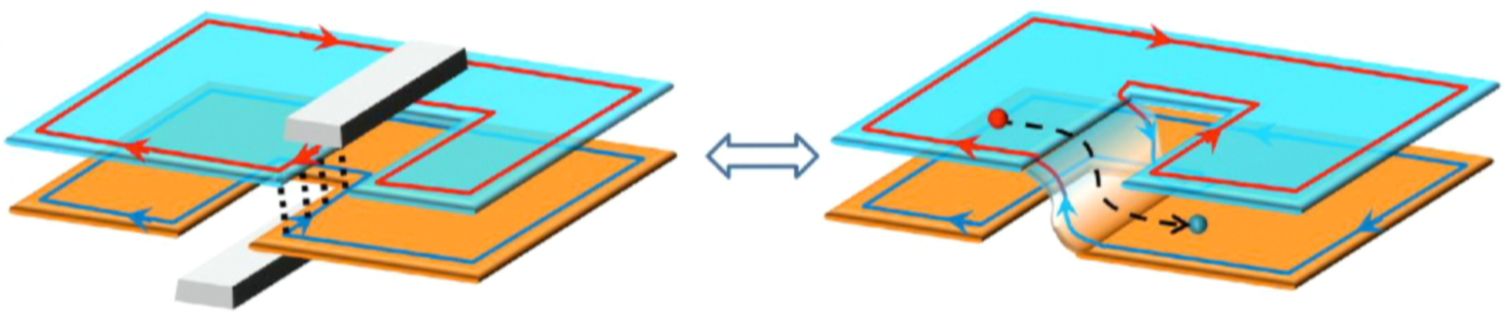
Bilayer FQH system (two layers of 1/3 Laughlin FQH state):



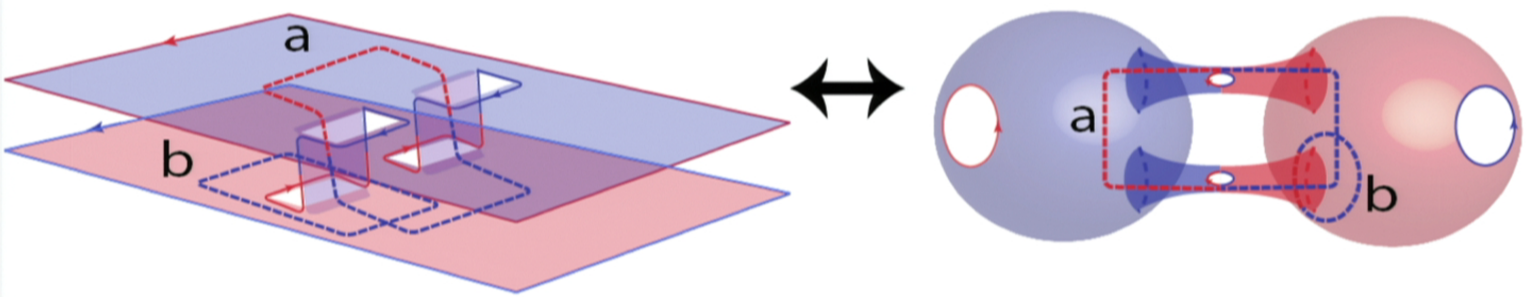
Need $T_{12} >> T_{11}$, T_{22}



- Adding a staircase (one pair of gates) adds genus by 1.
  ➔ One staircase = 2 genons

- Uncoupled edges do not destroy topological protection.
  Parafermion zero modes still exponentially localized!

Barkeshli, Qi 2013



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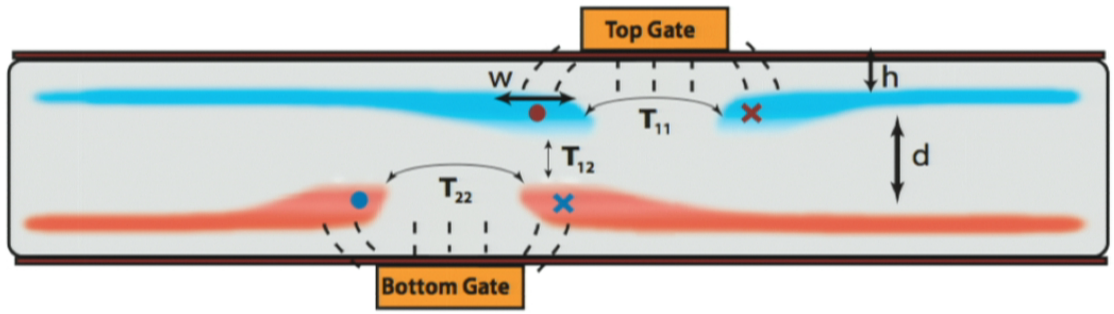

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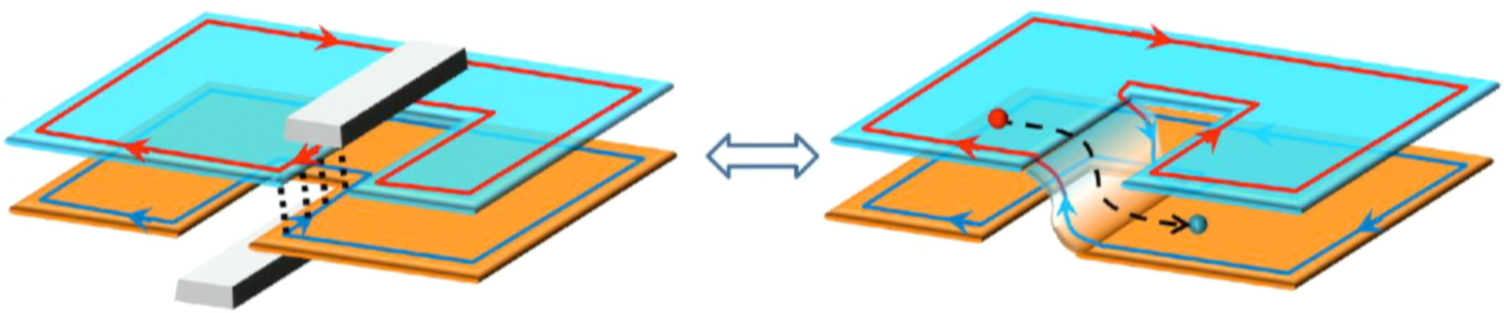
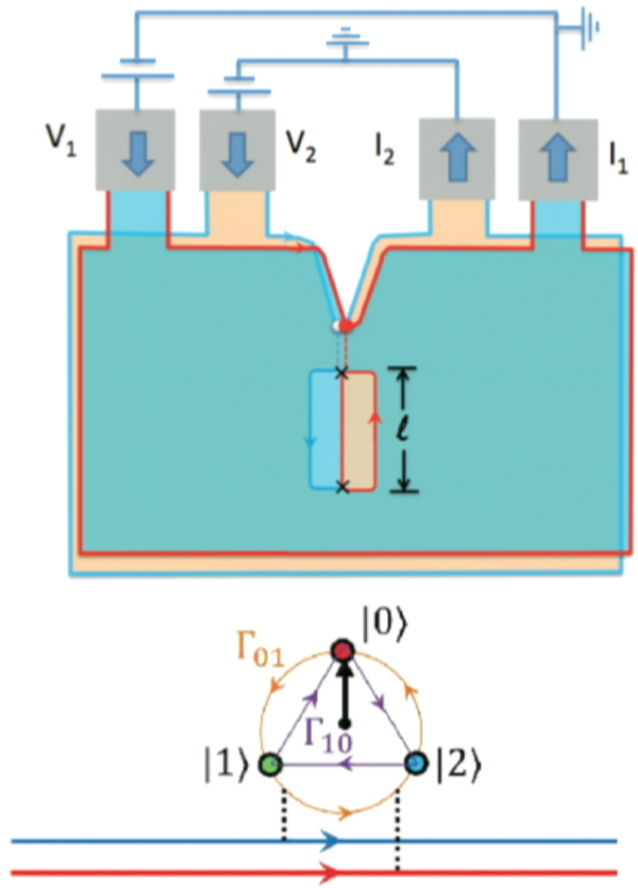


Detecting Topology-Dependent Degeneracy

MB, Y. Oreg, X-L Qi, 2014



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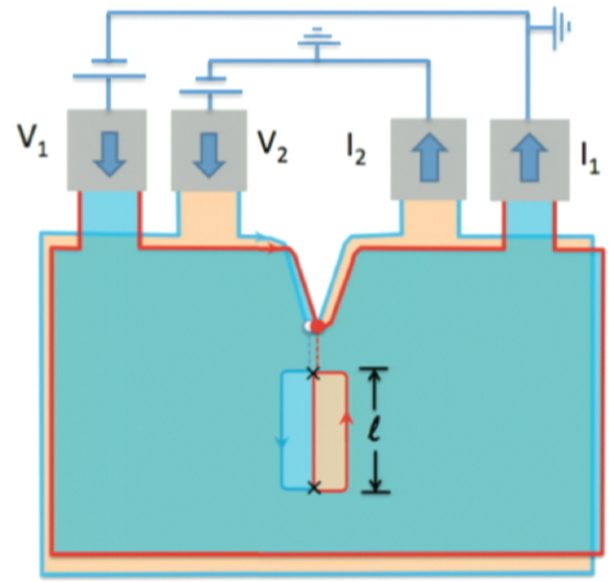
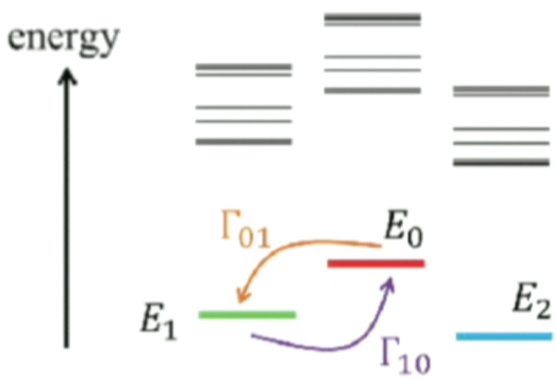
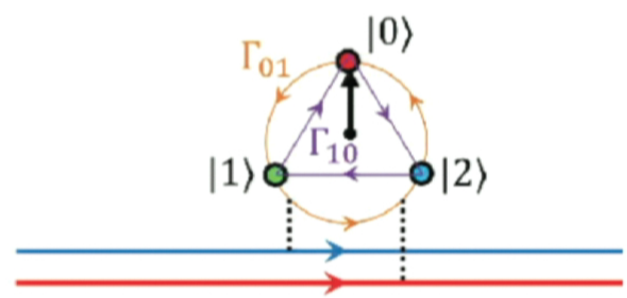
MB, Y. Oreg, X-L Qi, 2014

- Finite-size gives exponential splitting between topological states

$$\propto e^{-\ell/\xi_{loc}}$$







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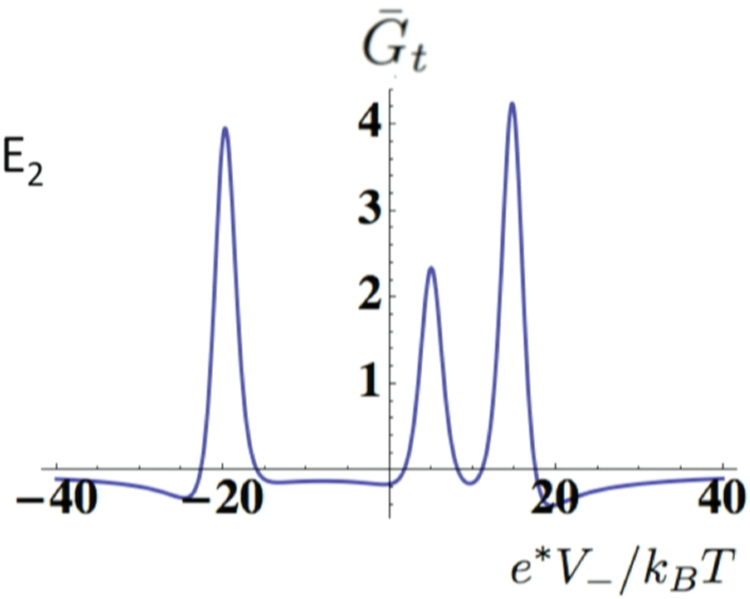
- Tunneling conductance calculated through master equation approach

MB, Y. Oreg, X-L Qi, 2014

$$\frac{dp_n}{dt} = \sum_{l=1}^{m-1} [\Gamma_{n+l,n} p_{n+l} - \Gamma_{n,n+l} p_n] = 0$$

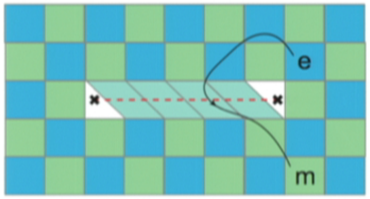
- **3 peaks** exist in general at energies $E_1 - E_0$, $E_2 - E_1$, $E_0 - E_2$

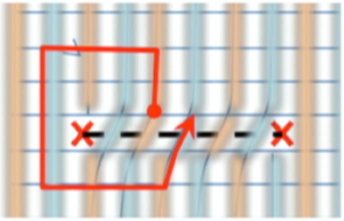
Topological Spectroscopy



Other realizations of genons/twist defects:

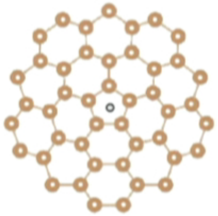
- Lattice dislocations in Fractional Chern Insulators (in C > 1 bands) or exactly solvable (Kitaev/Levin-Wen) models Barkeshli & Qi, (2012)





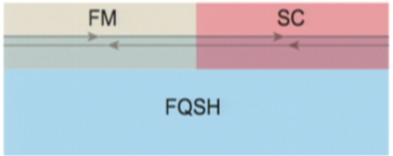
Kitaev-Kong (2012), Bombin (2010) You-Wen (2012)

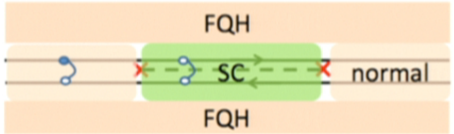
- Lattice dislocations/disclinations in graphene FQH states



Barkeshli, Lee, Qi, to appear

- Normal/SC domain walls in FQH / FQSH states





Clarke et al, Lindner et al, Cheng (2012)

Defects:
A new chapter in the theory of topological order

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- Point-like defects are non-Abelian, even in Abelian state.

  Exotic "parafermion" zero modes

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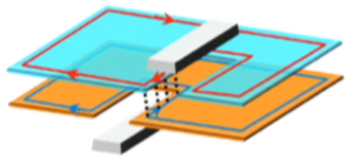
- Experimental proposal

    Spectroscopy of topology-dependent ground state degeneracies



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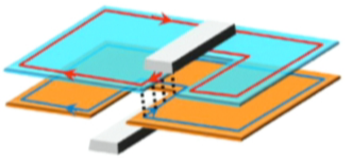
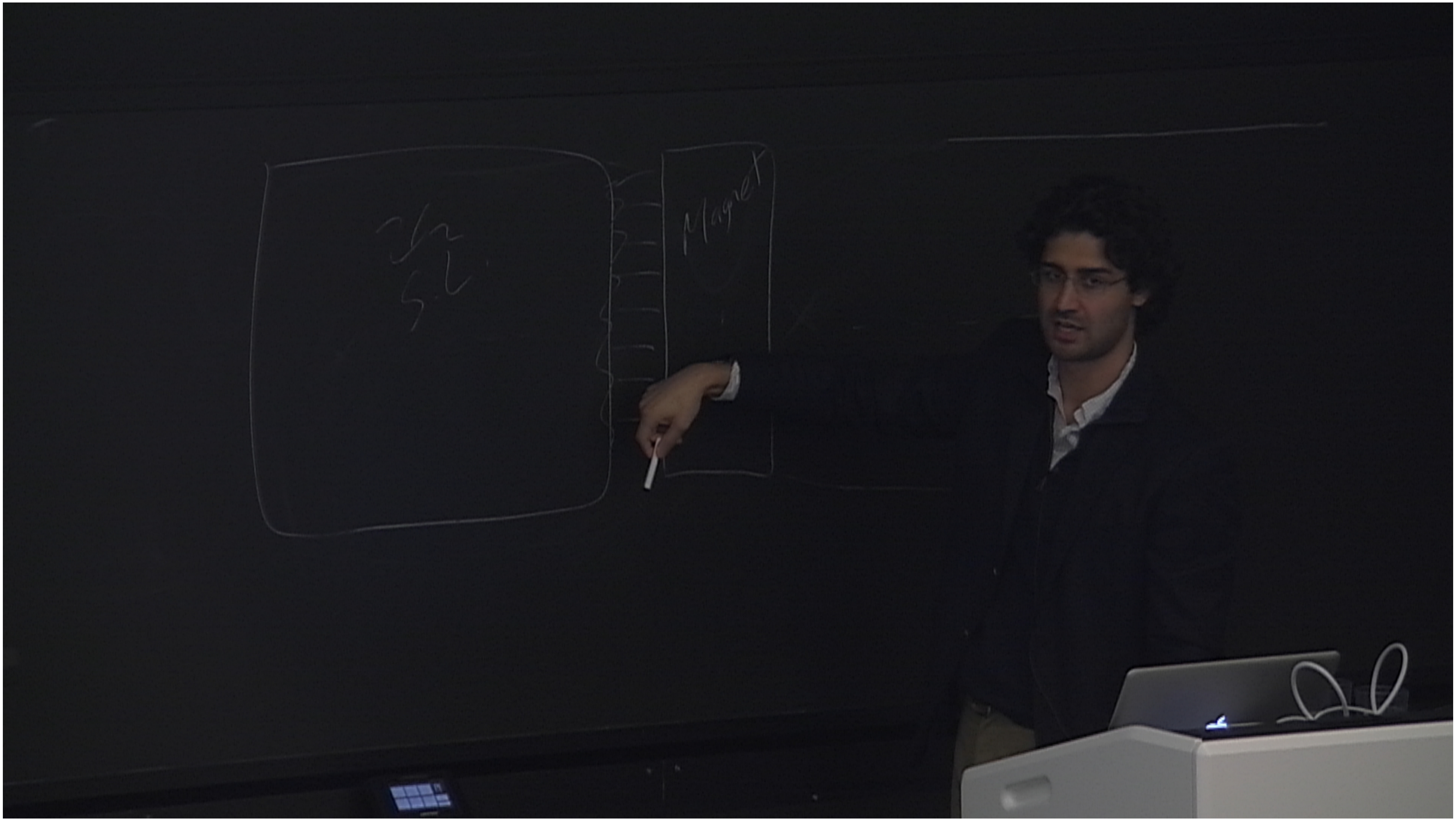


- Direct coupling between electrons and fractionalized anyons → "smoking-gun" signatures of quantum spin liquids

Barkeshli, Berg, Kivelson, Science (2014), to appear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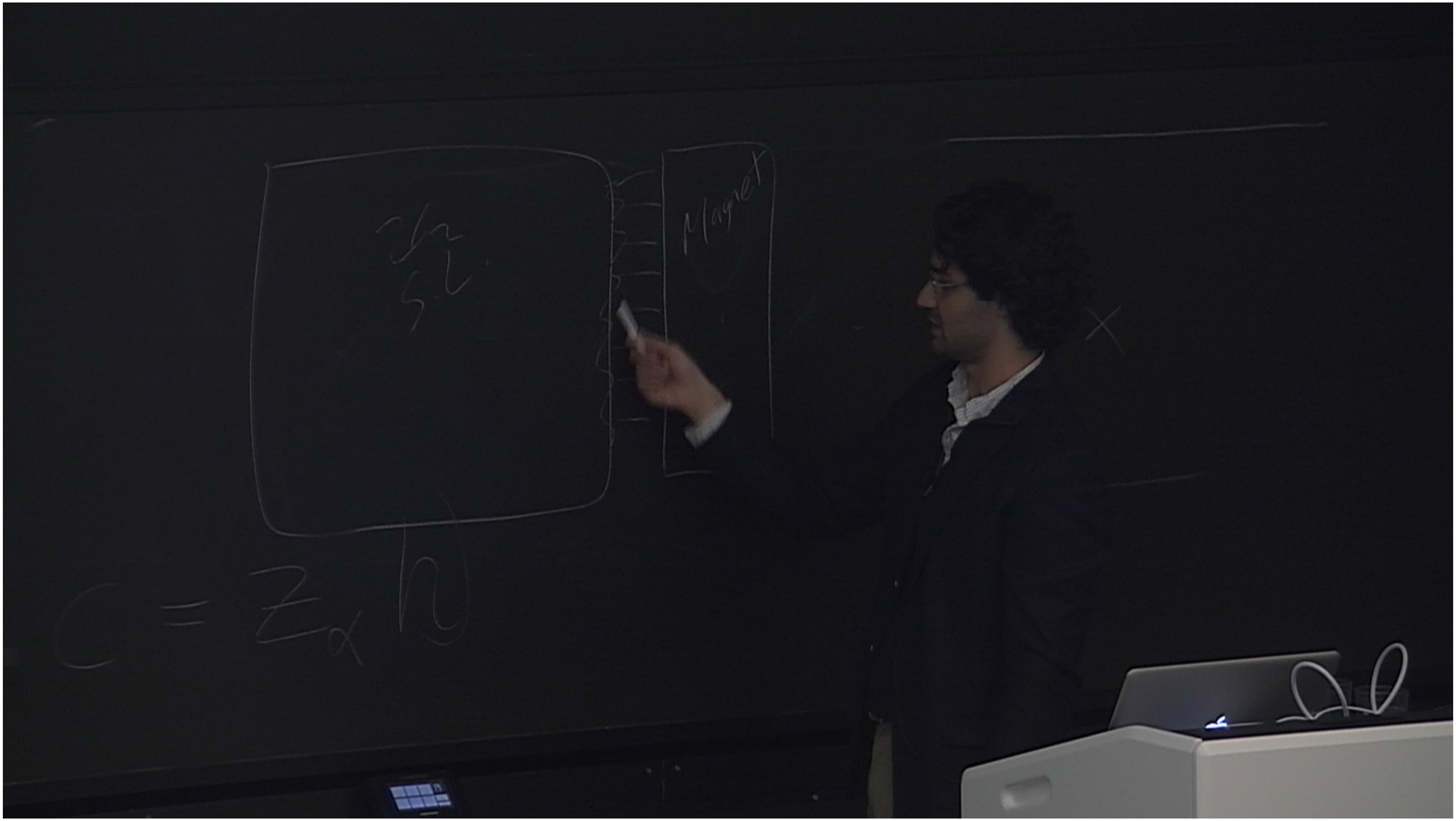
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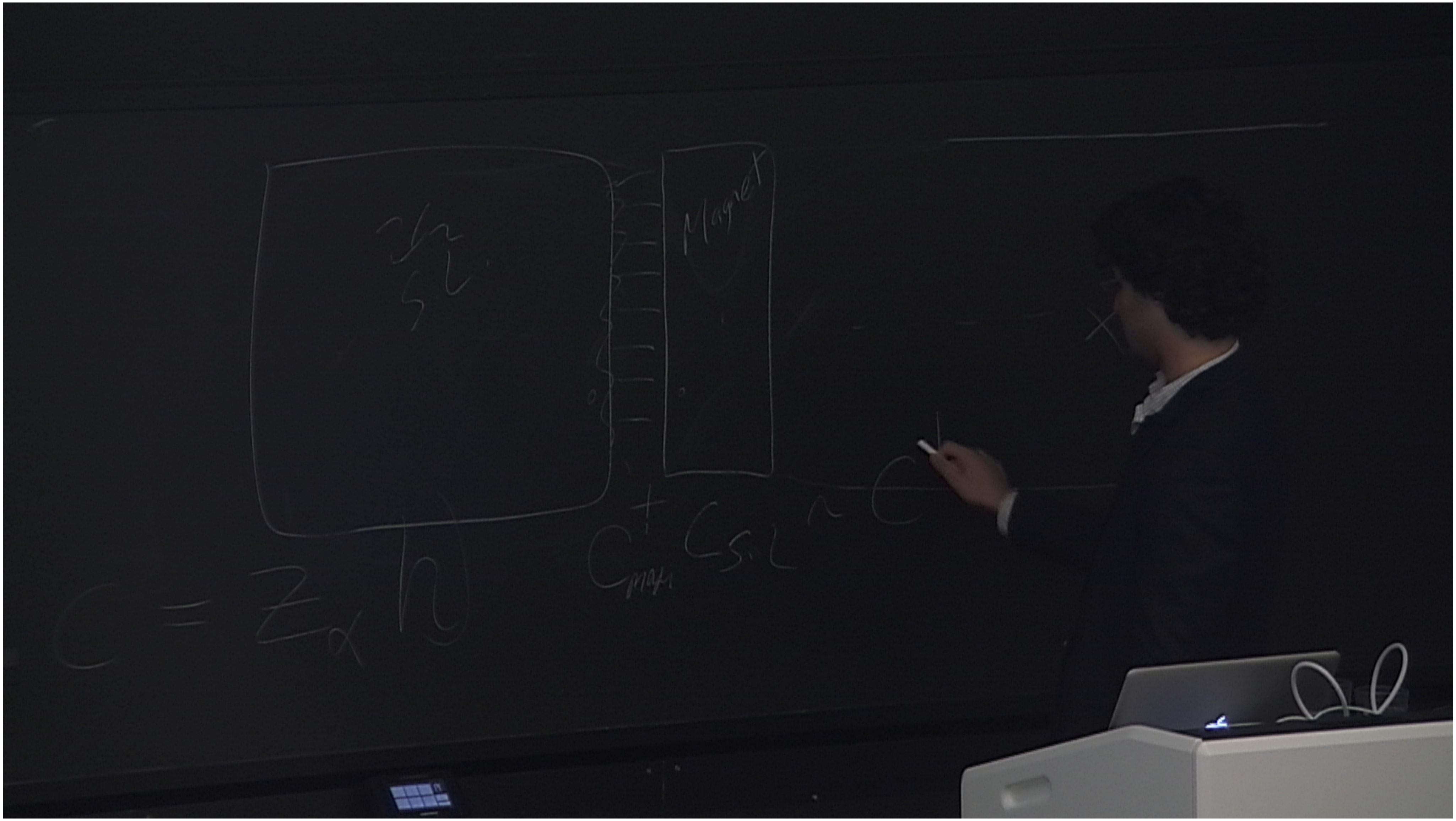
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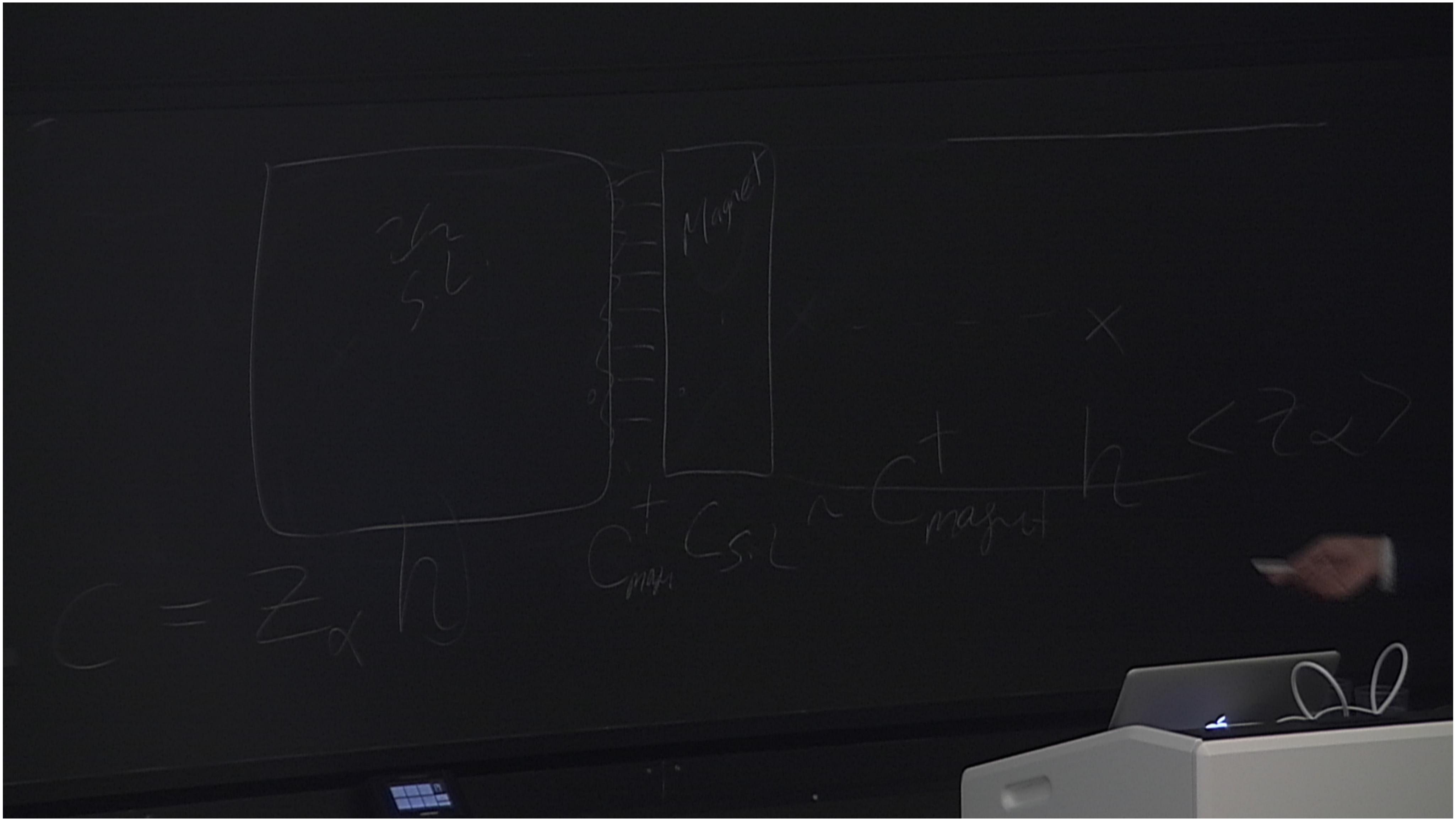
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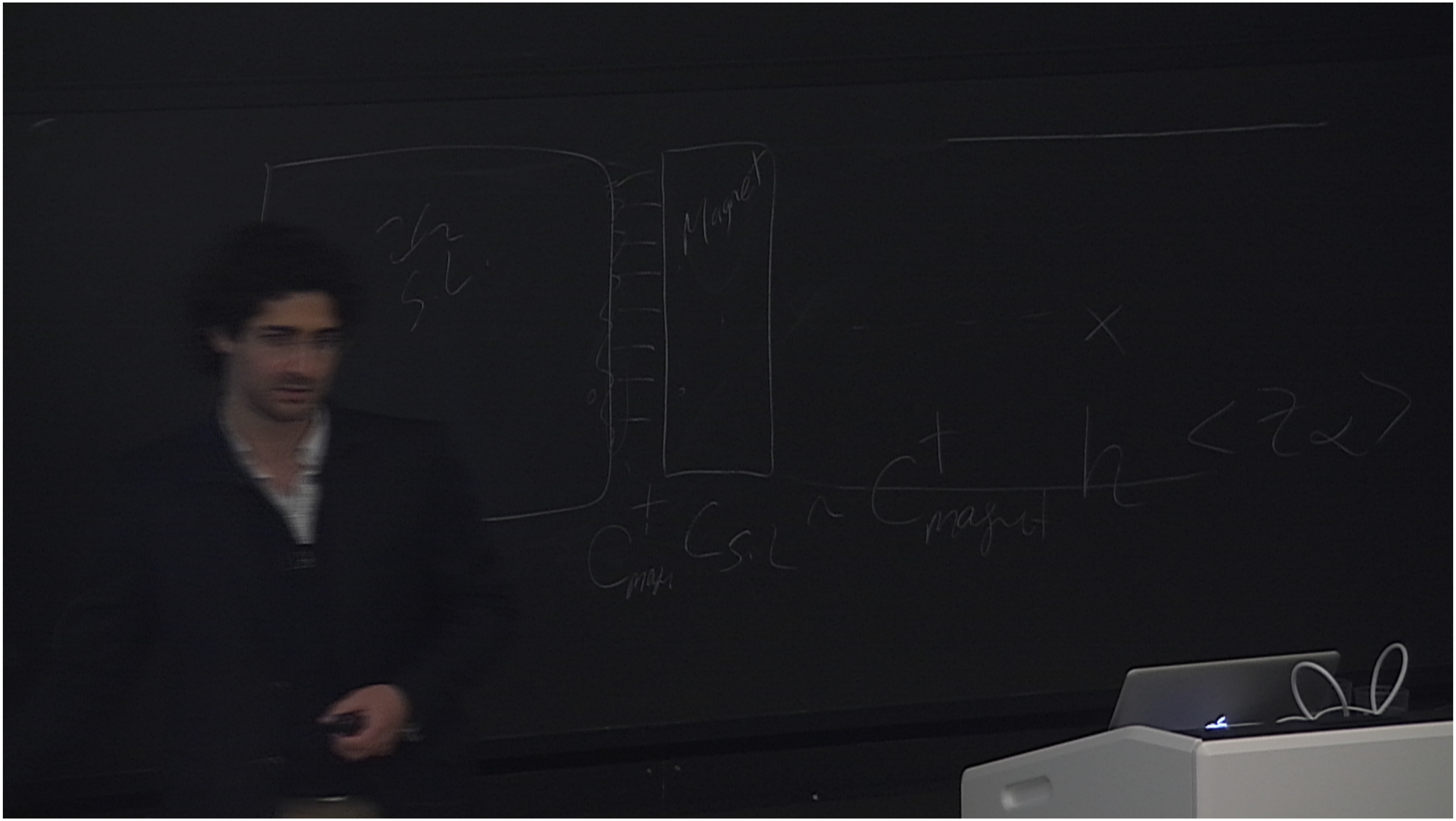
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