Title: Topology in Real and Momentum Space: Vortex Majorana Modes and Weyl Semimetals

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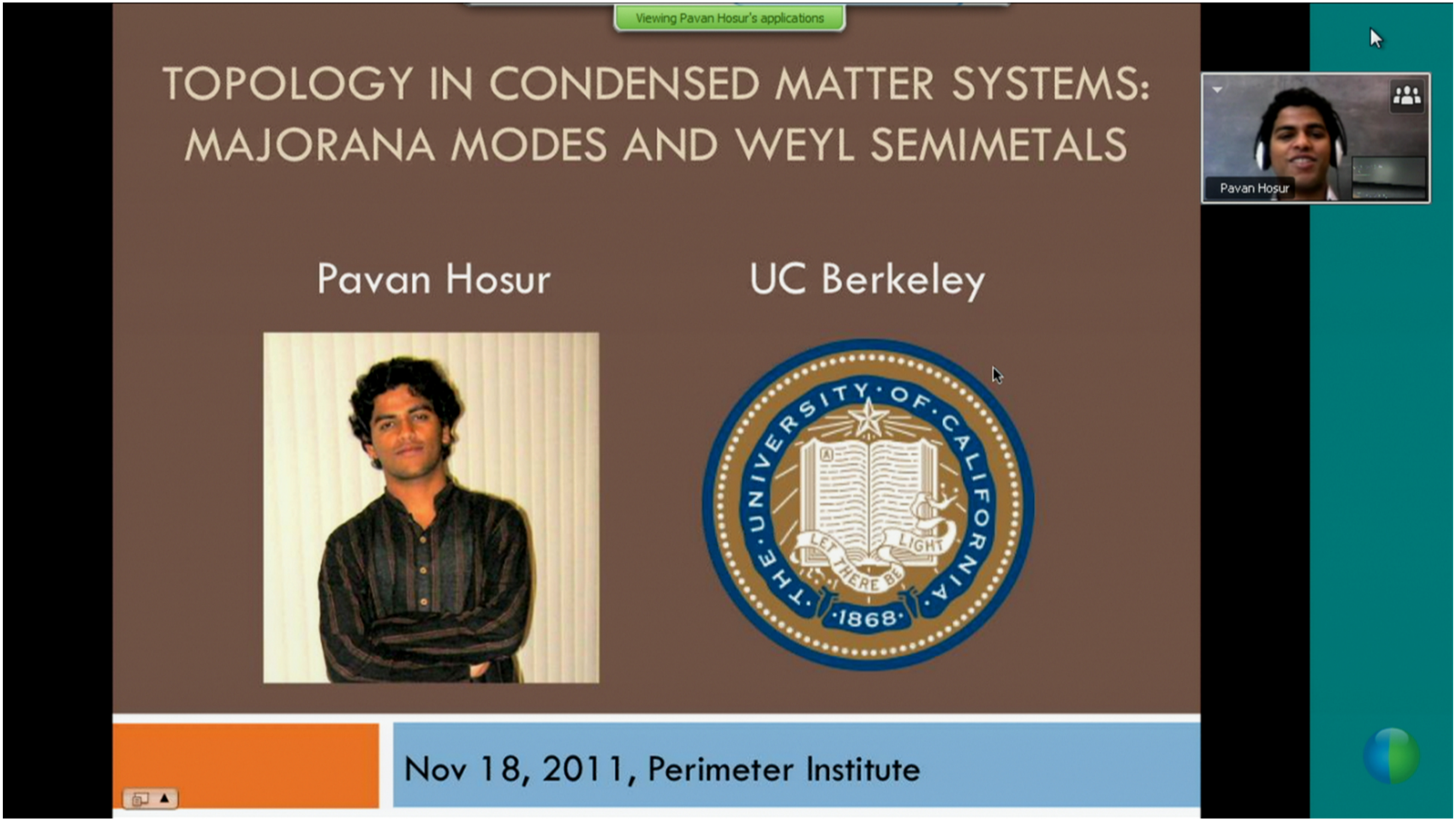
Abstract: Topology has many different manifestations in condensed matter physics. Real space examples include topological defects such as vortices, while momentum space ones include topological band structures and singularities in the electronic dispersion. In this talk, I will focus on two examples. The first is that of a vortex in a topological insulator that is doped into the superconducting state. This system, we find, has Majorana zero modes and thus, is a particularly simple way of obtaining these states. We derive general existence criteria for vortex Majorana modes and find that existing systems like Cu-doped Bi2Se3 fulfill them. In the process, we discover a rare example of a topological phase transition within a topological defect (the vortex) at the point when the criteria are violated.

The second example is that of Weyl semimetals, which are three-dimensional analogs of graphene. Interestingly, the Dirac nodes here are topological objects in momentum space and are associated with peculiar Fermi-arc surface states. We discuss charge transport in these materials in the presence of interactions or disorder, and find encouraging agreement with existing experimental data.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TOPOLOGY IN CONDENSED MATTER SYSTEMS: MAJORANA MODES AND WEYL SEMIMETALS
Pavan Hosur
UC Berkeley
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·1868·
Nov 18, 2011, Perimeter Institute
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Acknowledgements

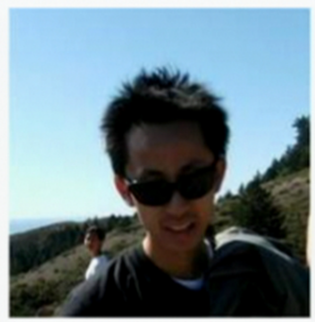
Advisor:

Ashvin Vishwanath
UC Berkeley

Collaborators:

Pouyan Ghaemi
UC Berkeley → UIUC

Roger Mong
UC Berkeley



Sid Parameswaran
UC Berkeley

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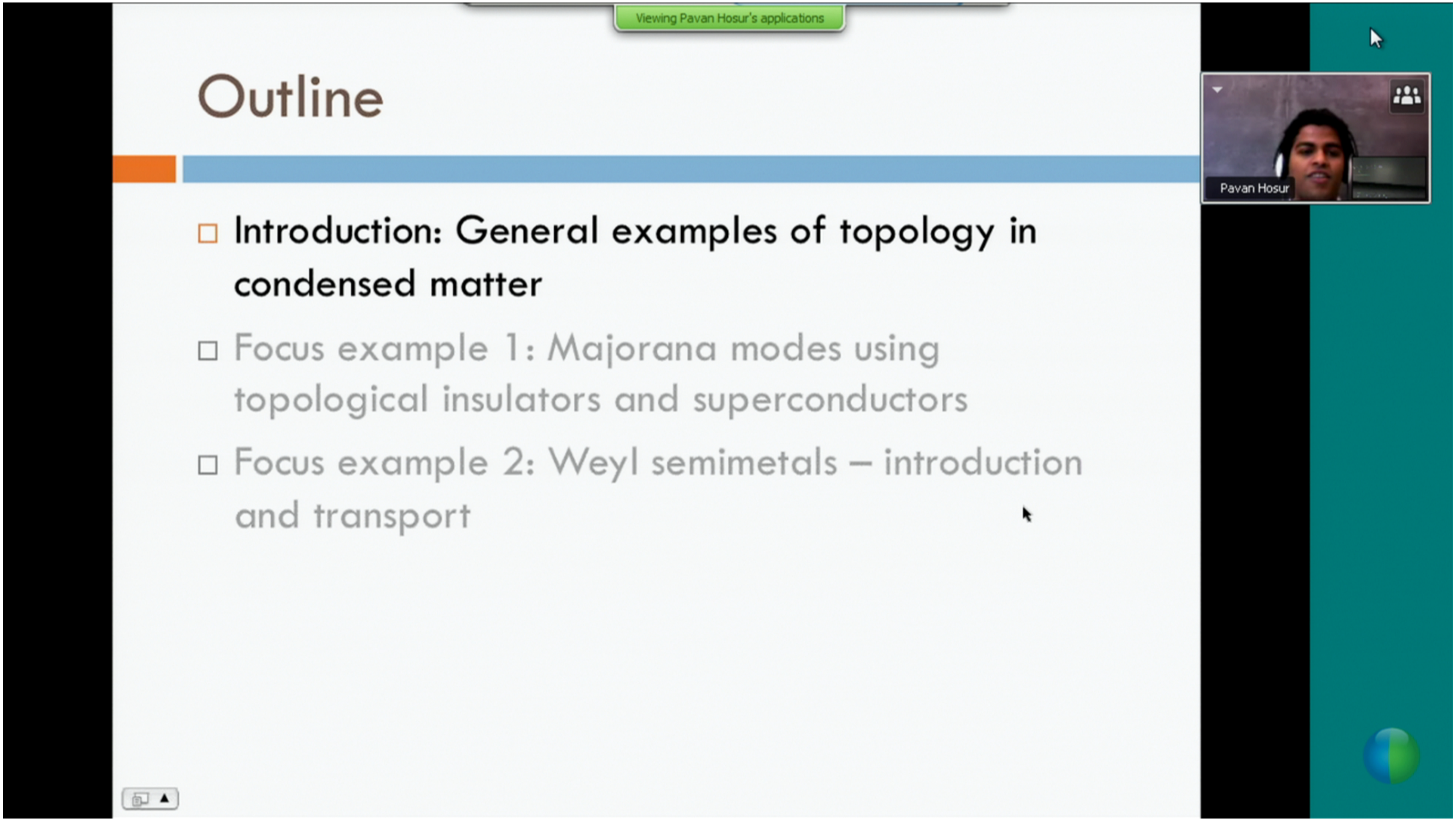
Outline

- Introduction: General examples of topology in condensed matter
- Focus example 1: Majorana modes using topological insulators and superconductors
- Focus example 2: Weyl semimetals – introduction and transport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Topology in real space

Topological defects

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Topology in real space

Topological defects

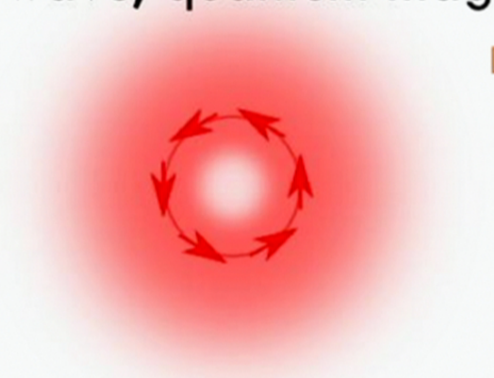
- Domain walls – charge density wave, quantum magnets

Topology in real space

Topological defects

- Domain walls – charge density wave, quantum magnets

- Vortices – type-II superconductors, superfluids



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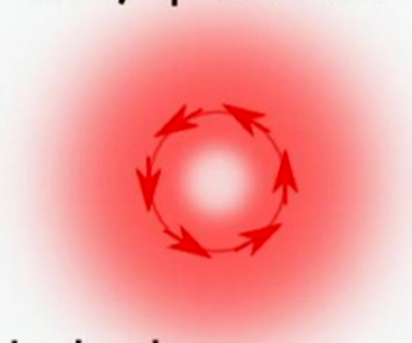
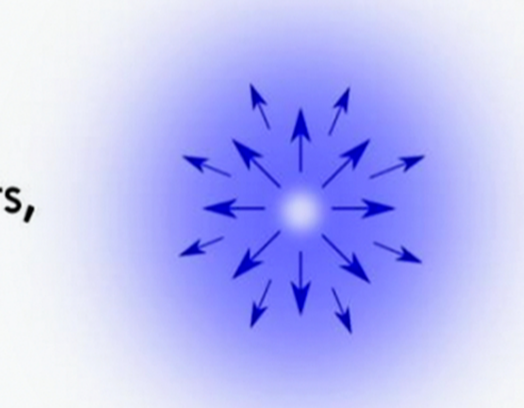
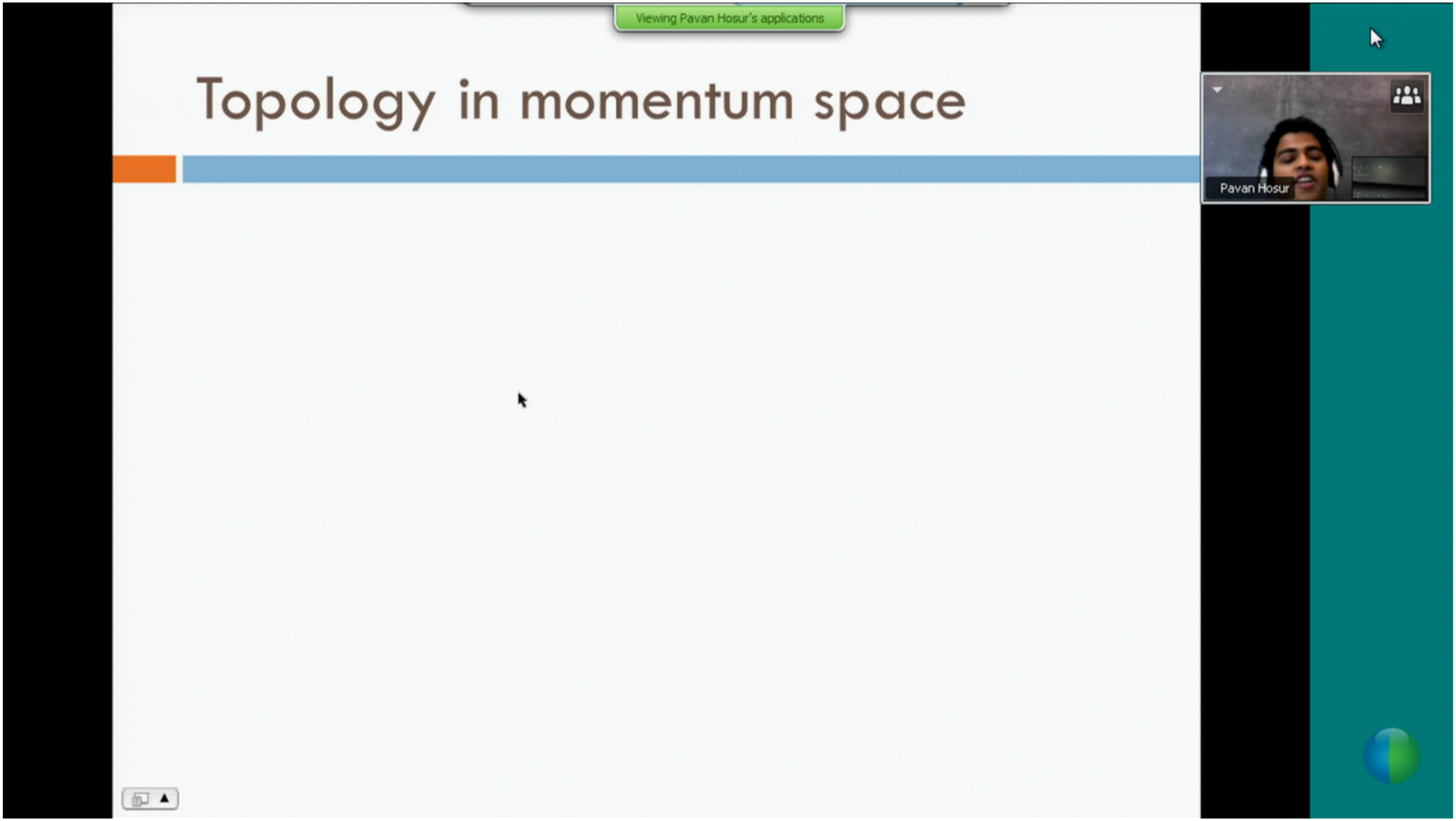


- Hedgehogs – quantum magnets, valence bond solids

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Topology in momentum space
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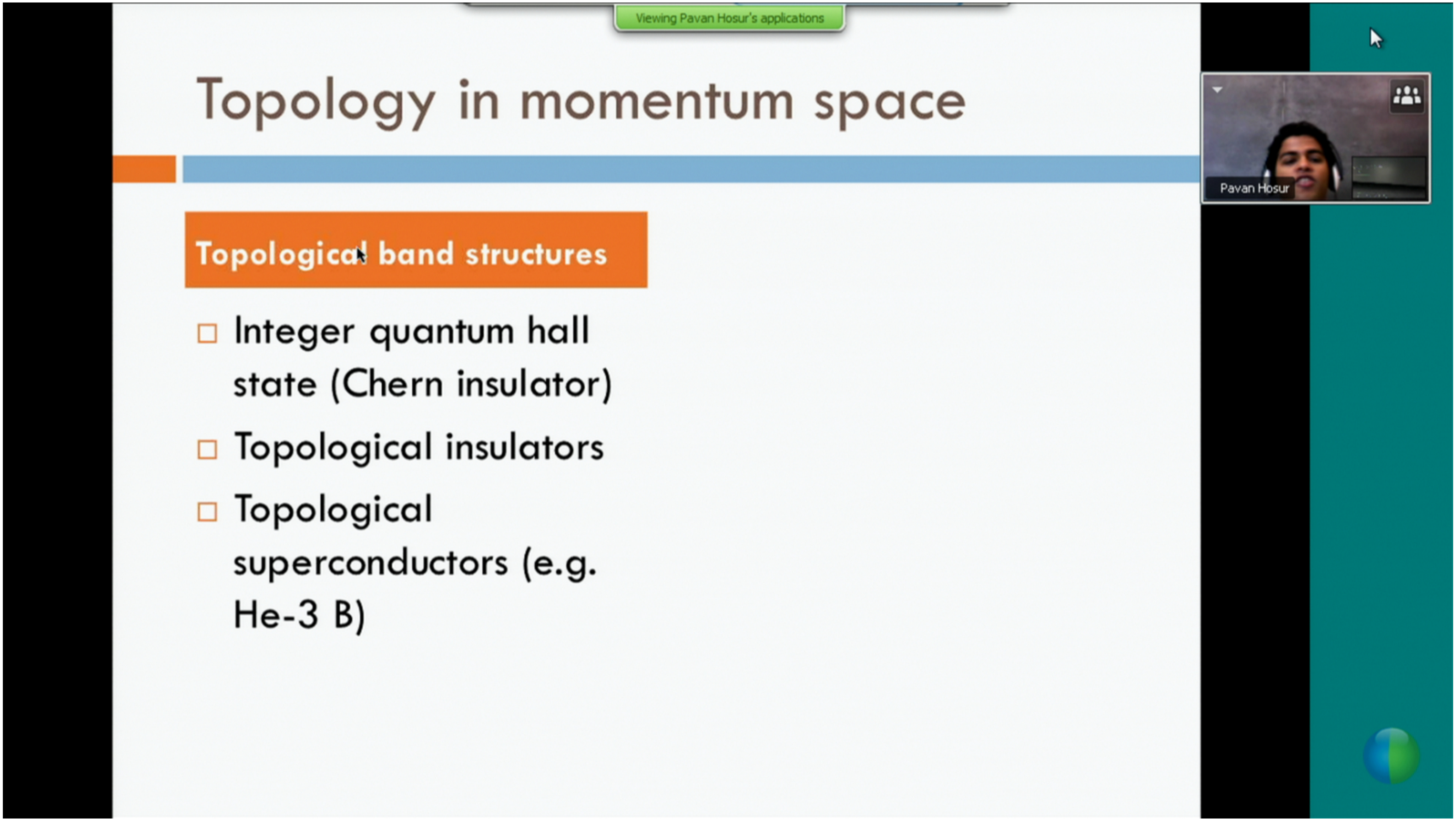
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Topology in momentum space
Topological band structures
Integer quantum hall state (Chern insulator)
Topological insulators
Topological superconductors (e.g. He-3 B)
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Topology in momentum space

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Singularities in dispersion

- Fermi surface
- Line nodes (e.g. graphite)
- Point nodes (e.g. Graphene, **Weyl semimetals**)

Combining real and momentum space topologies

- Fermionic Hopf skyrmion in topological insulator-superconductor system[Ran, PH, Vishwanath '11]
- Vortex in $p+ip$ superconductor[Read-Green'00]
- Vortex in superconductor on topological insulator surface[Fu-Kane'08]

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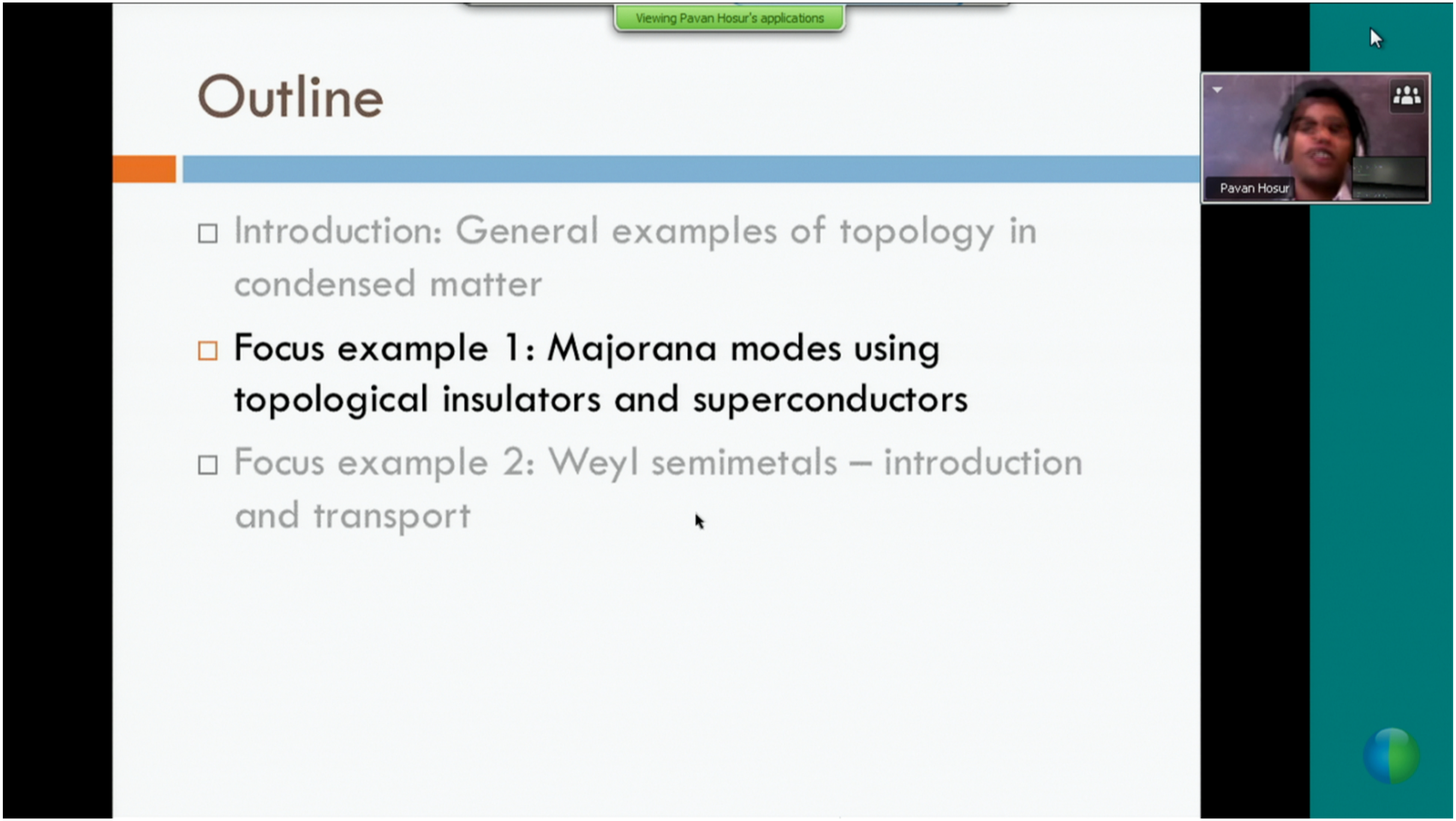
Carry Majorana zero modes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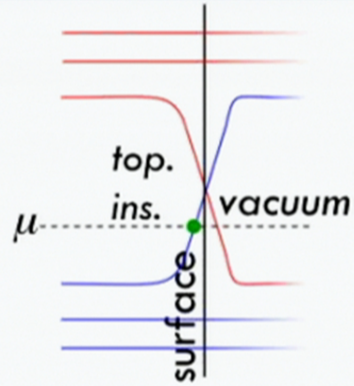
Crash-course on topological insulators: surface states

- Bulk insulators; surface states in bulk gap protected by time-reversal symmetry



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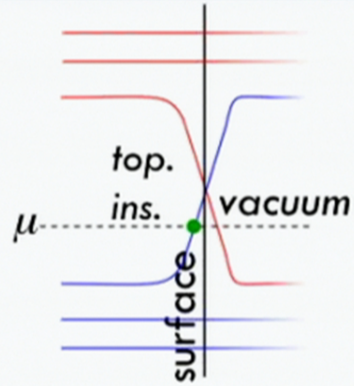
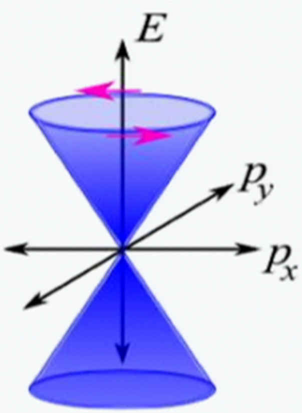
- Surface states "relativistic" at low energies





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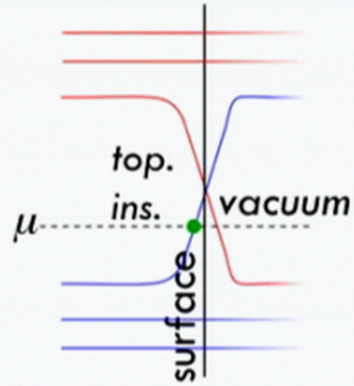
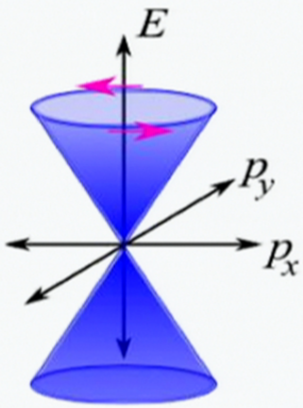
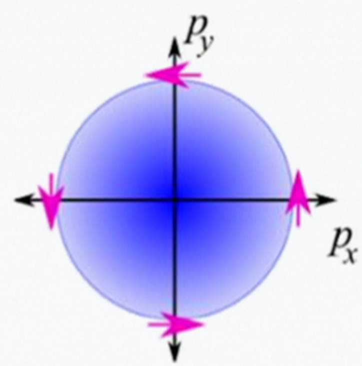




- π−Berry phase around the Fermi surface



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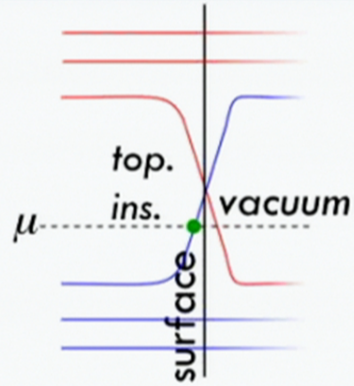

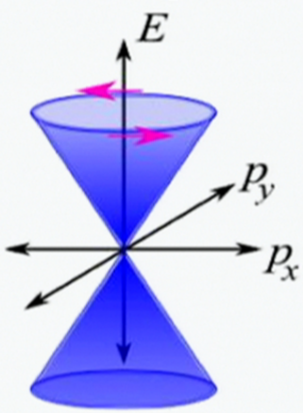

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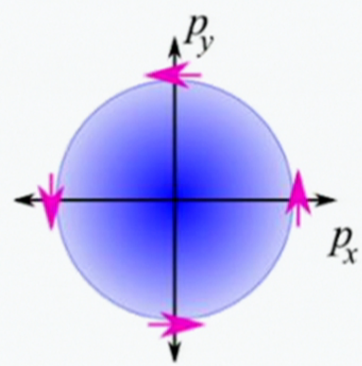

Crash-course on topological insulators: Z_2 invariant ν_0

$$\nu_0 \begin{cases} = -1 \Rightarrow \text{topological insulator} \\ = 1 \Rightarrow \text{trivial insulator} \end{cases}$$

Surface: $\nu_0 = (-1)^{\text{number of Dirac nodes}}$

Inversion symmetric bulk:

$$\nu_0 = \prod_{\mathbf{k} \in TRIM} P_{occ}(\mathbf{k})$$

$TRIM$ = time-reversal invariant momenta

P = parity eigenvalue

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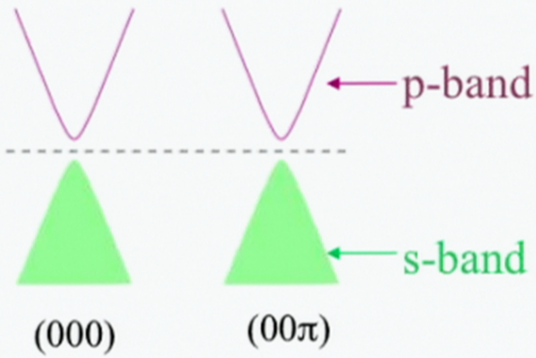
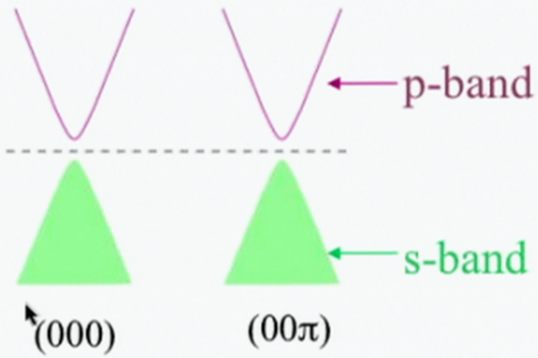


$$\nu_0 = P(000)P(00\pi) = (1)(1) = 1$$

...trivial insulator

(Assuming no band inversions at other TRIMs)

Crash-course on topological insulators: ν_0 with inversion symmetry



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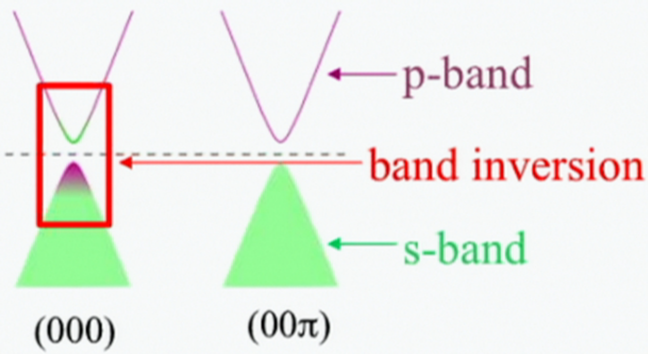

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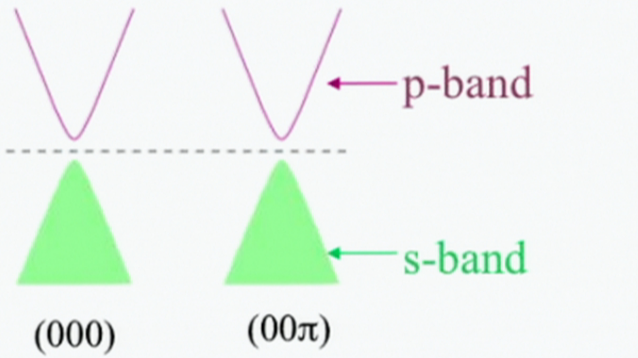

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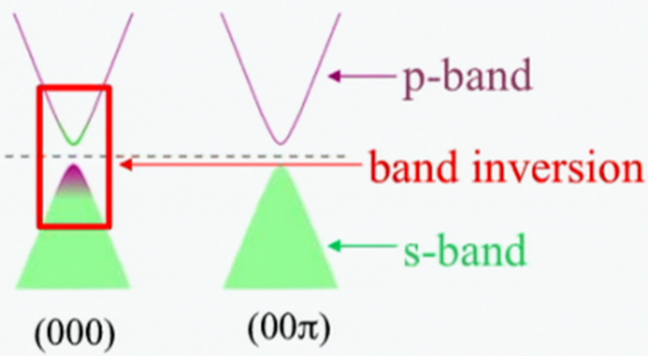

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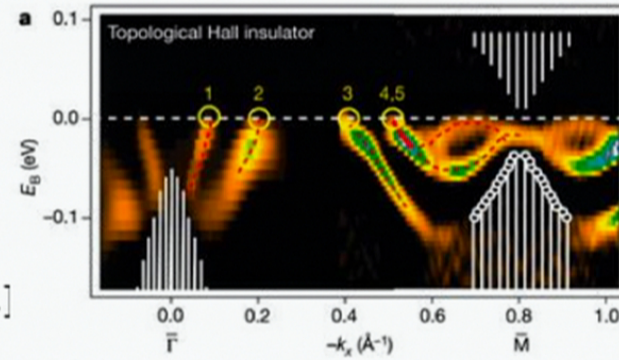
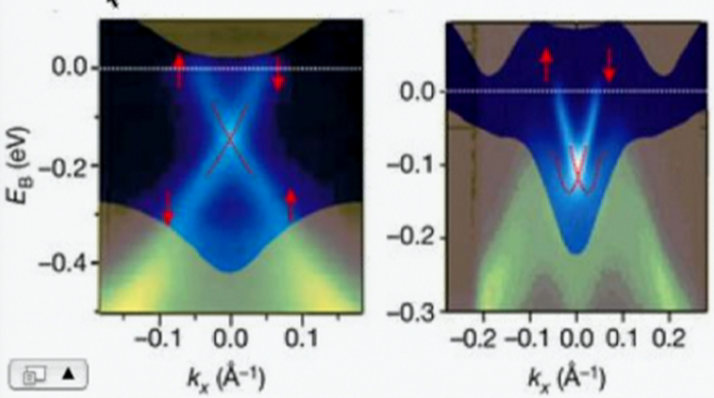
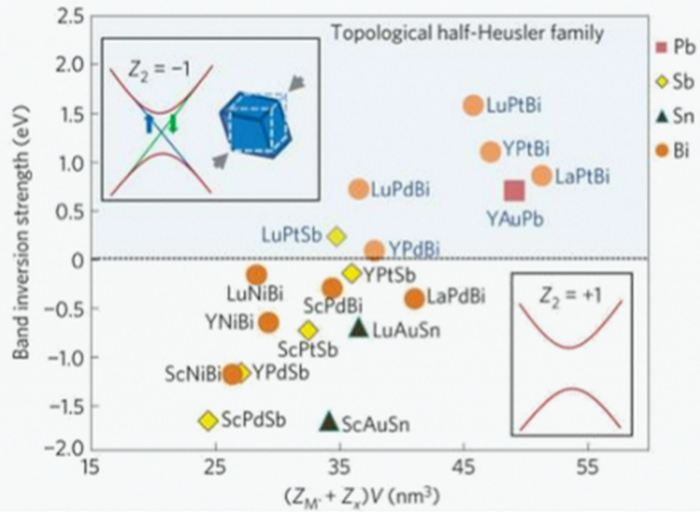
Crash-course on topological insulators: real materials

- Bi-Sb alloy[Fu'07, Hsieh'09]
- Bi_2X_3, X=Se,Te[Chen'09, Hsieh'09…]
- Tl-chalcogenides[Yan'10,…]
- Half-heusler compounds[Xiao'10,…]

…and many more







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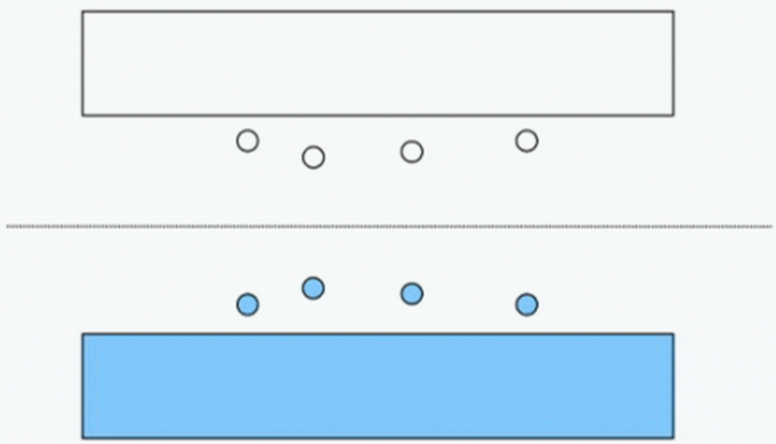
Majorana fermions in superconductors

- Majorana fermion: particle that is its own anti-particle
- Bogoliubov-de Gennes Hamiltonian has inherent $E \to -E$ symmetry



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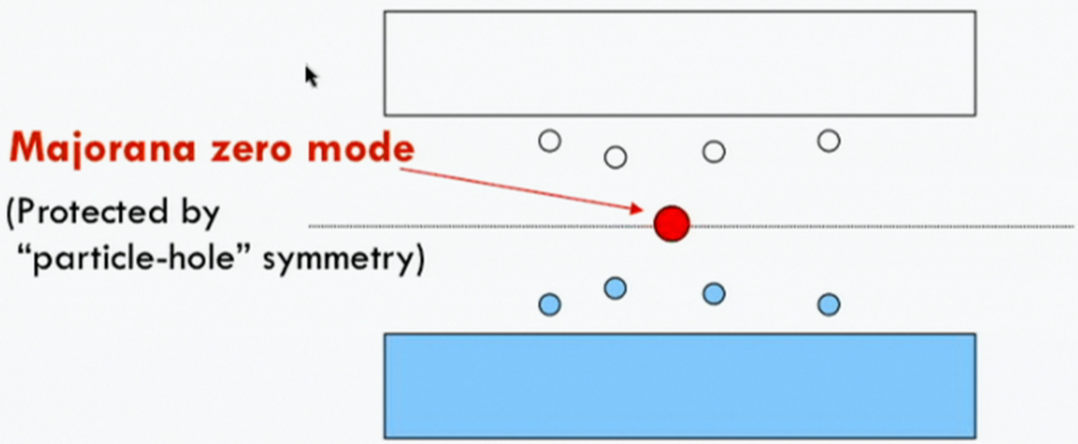

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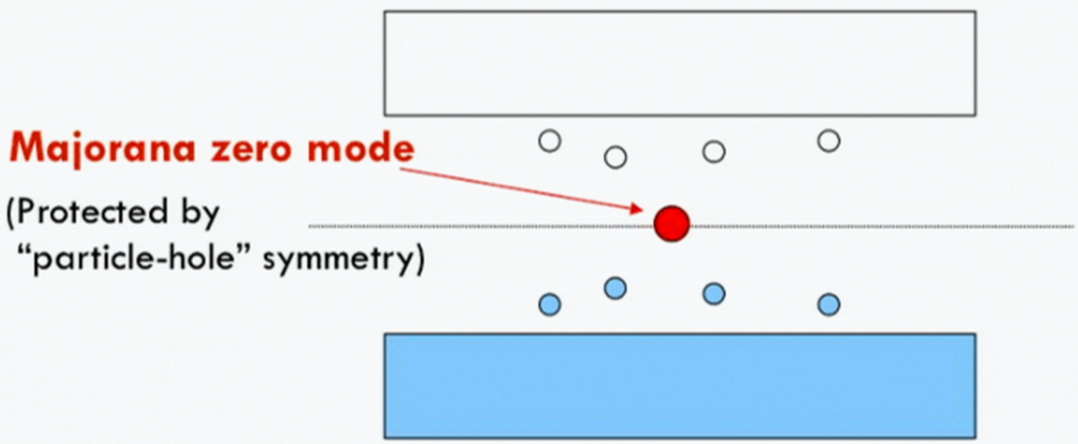

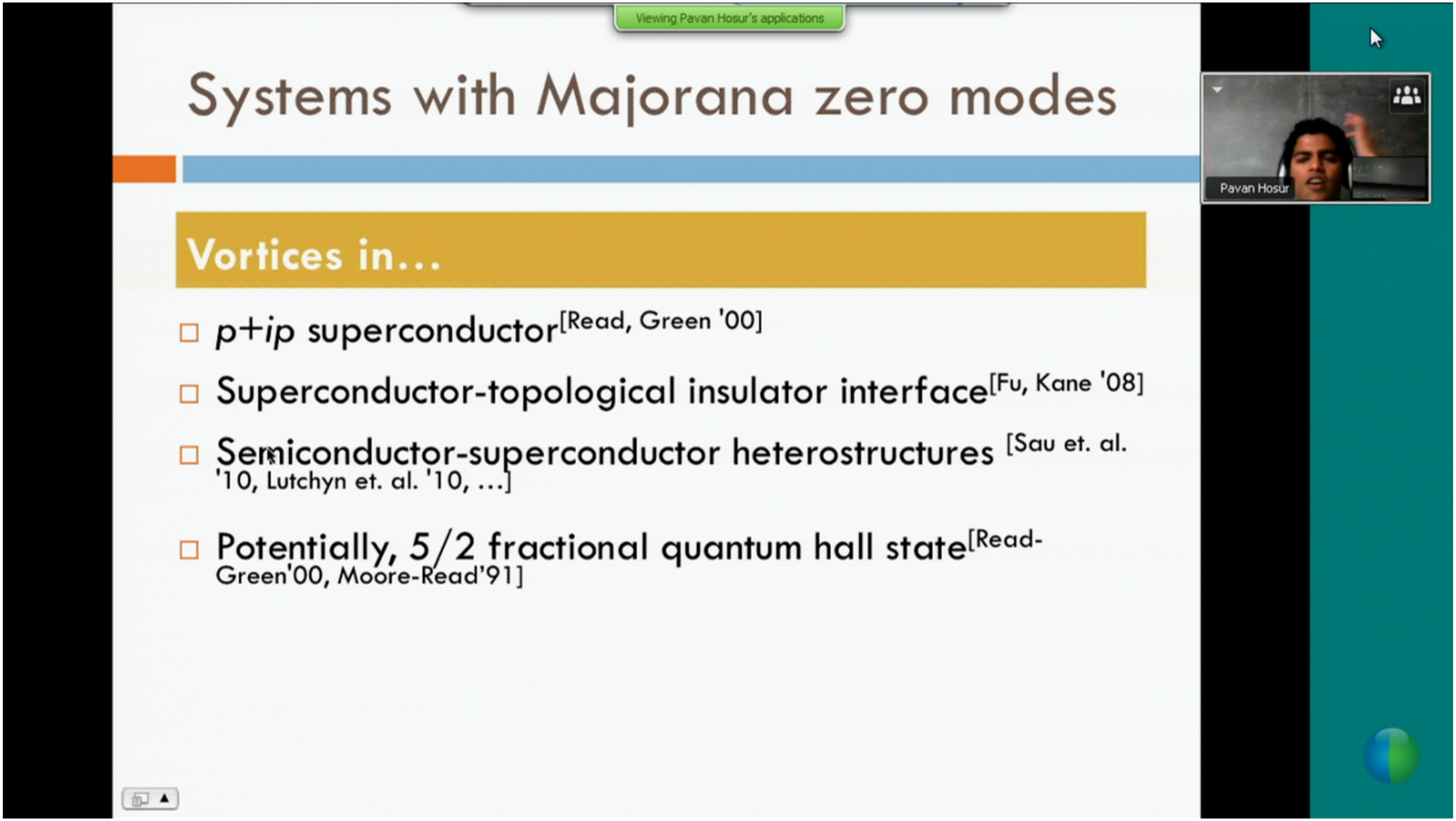
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Systems with Majorana zero modes
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Vortices in…
p+ip superconductor[Read, Green '00]
Superconductor-topological insulator interface[Fu, Kane '08]
Semiconductor-superconductor heterostructures [Sau et. al. '10, Lutchyn et. al. '10, …]
Potentially, 5/2 fractional quantum hall state[Read-Green'00, Moore-Read'91]

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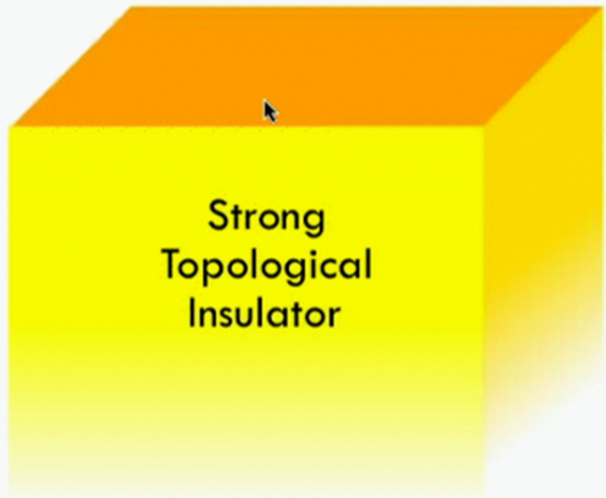
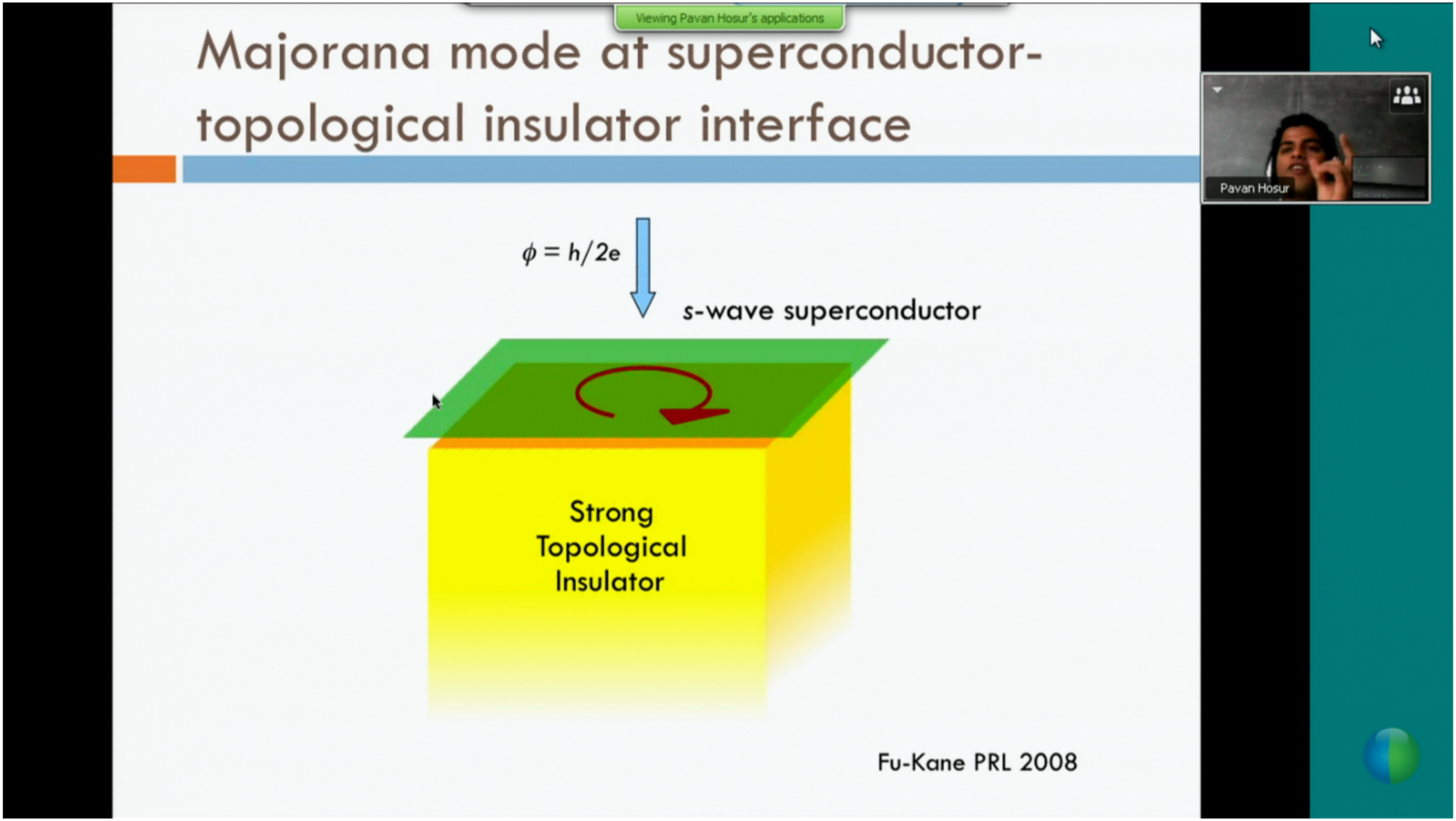
Majorana mode at superconductor-topological insulator interface



Fu-Kane PRL 2008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Strong Topological Insulator
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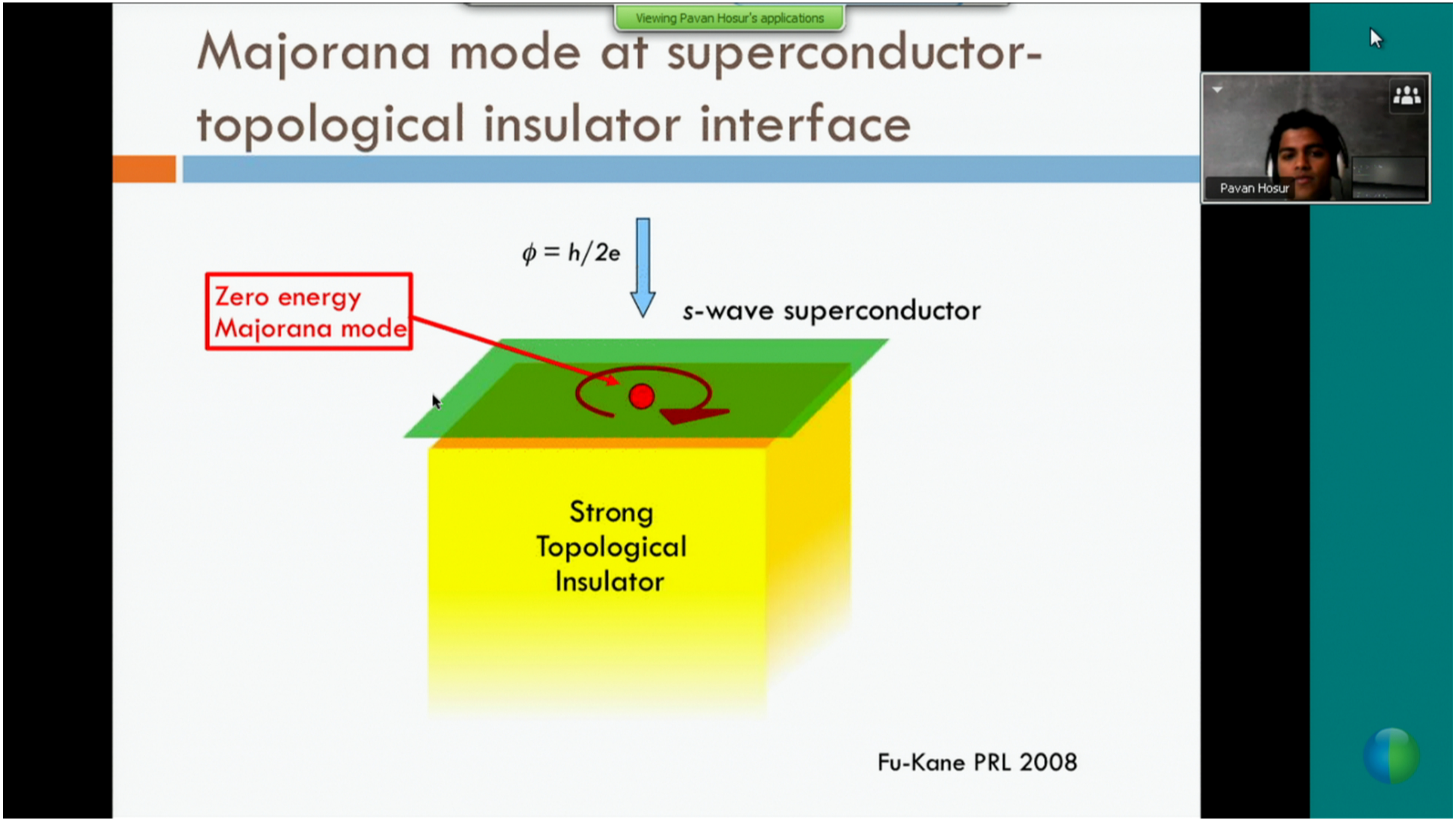
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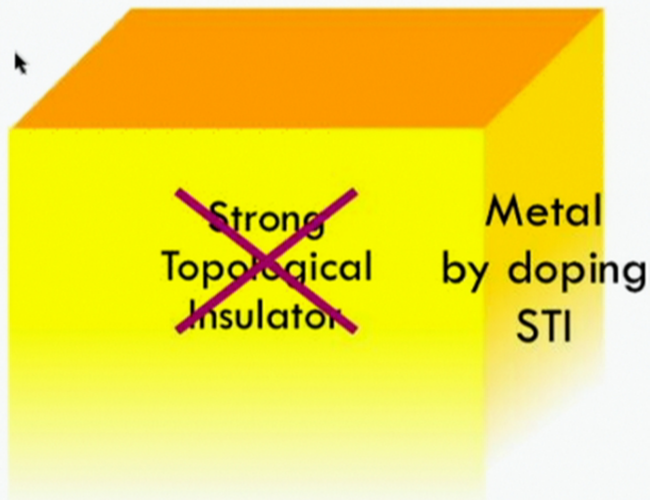
Majorana mode in superconducting-doped topological insulator?



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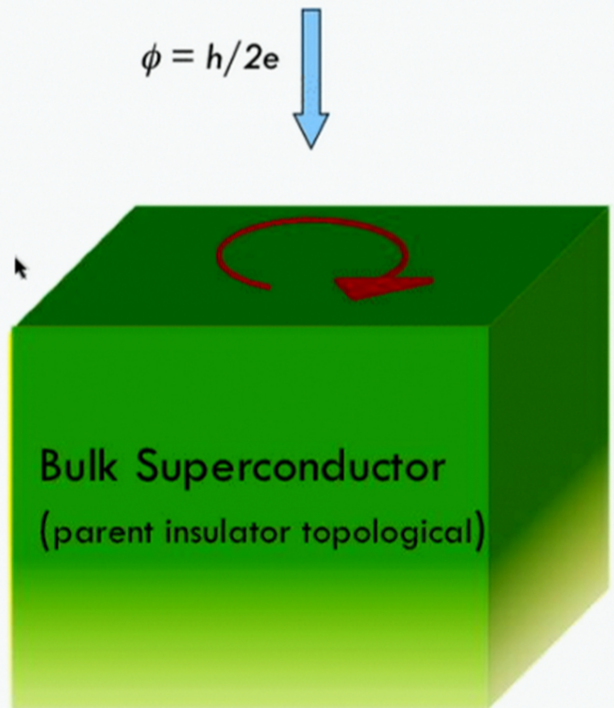

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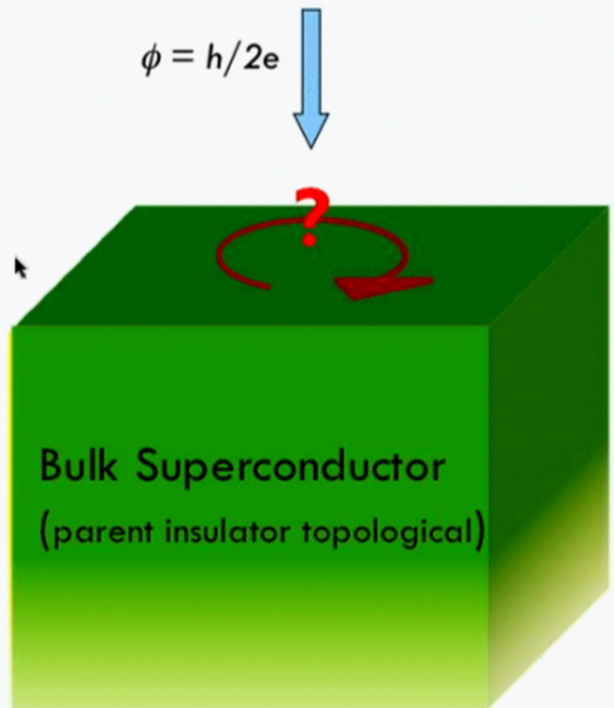

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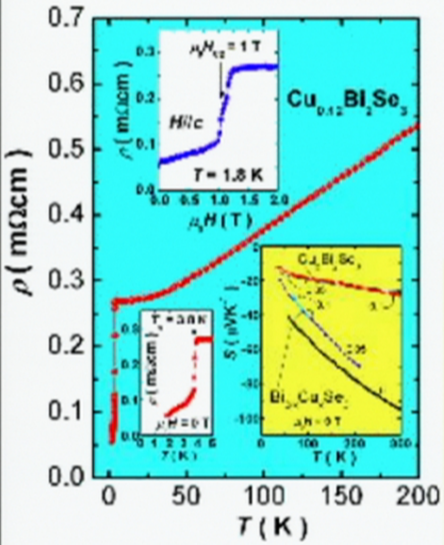

Superconductivity in Bi_2Se_3
Hor et. al. PRL 2010

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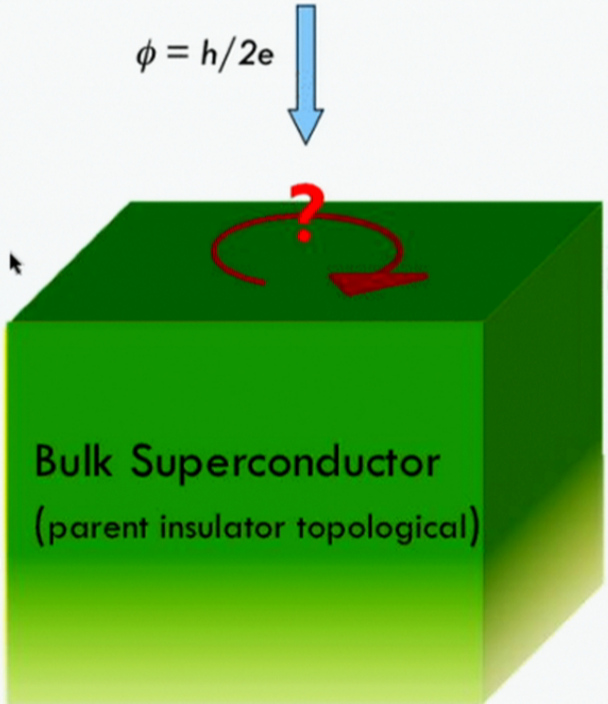

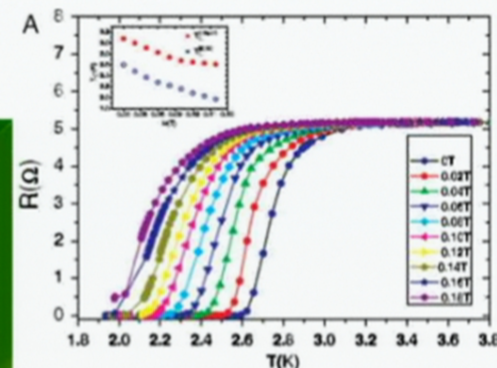

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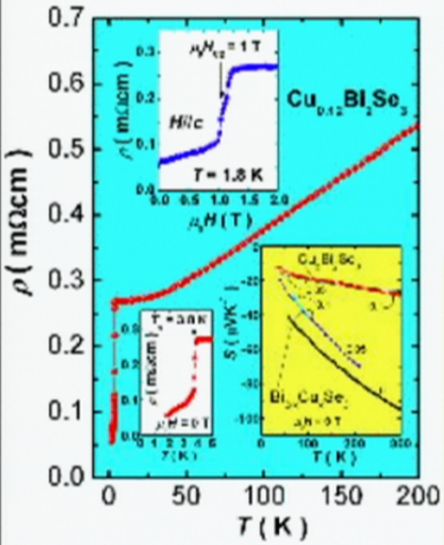

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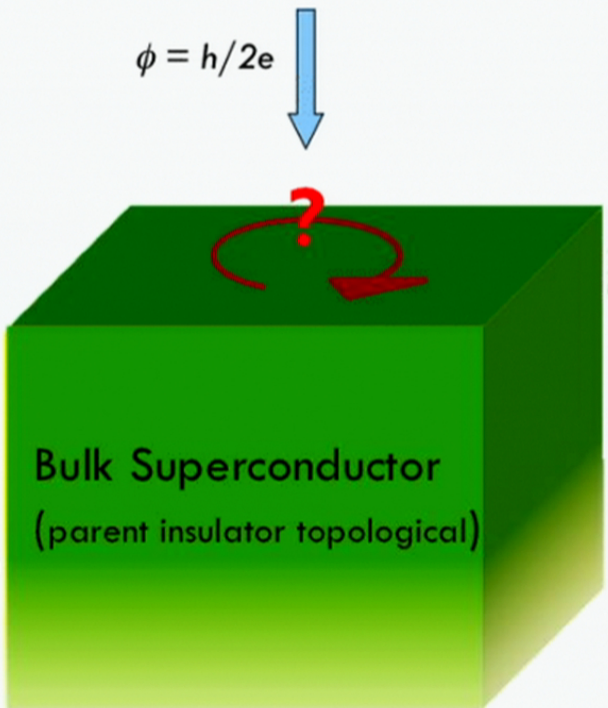

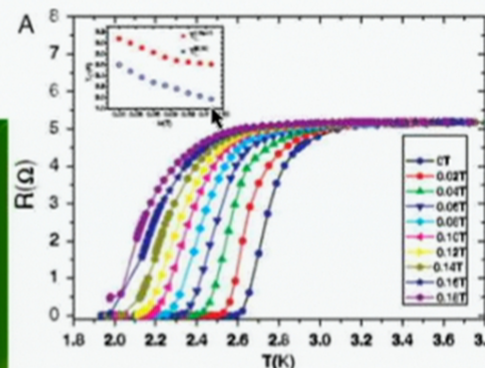

Superconductivity in Bi_2Te_3
Zhang et al. PNAS '11

Yes! But only if…

PH, Ghaemi, Mong, Vishwanath, PRL'11

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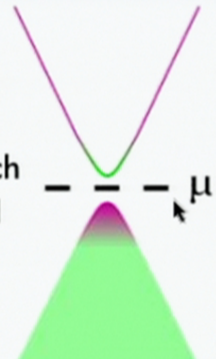
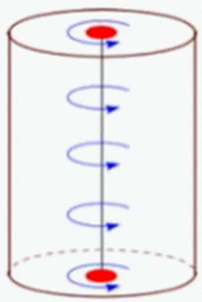
Evolution as μ is raised…

Fermi level in normal phase, which has a band inversion

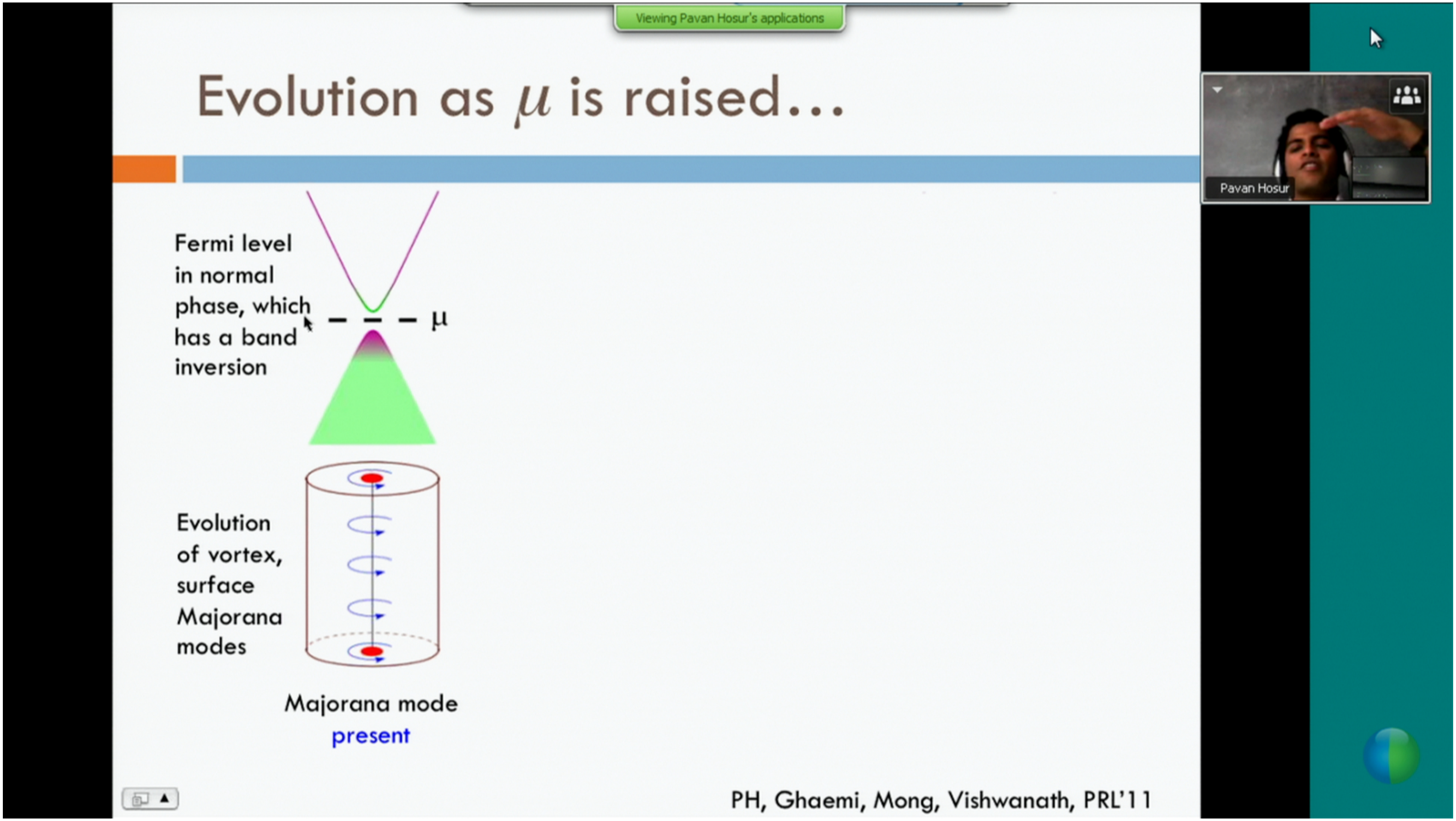


Evolution of vortex, surface Majorana modes



Majorana mode present

PH, Ghaemi, Mong, Vishwanath, PRL'11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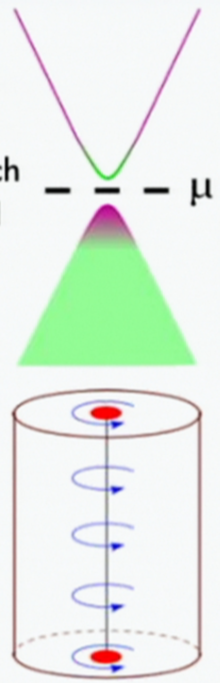
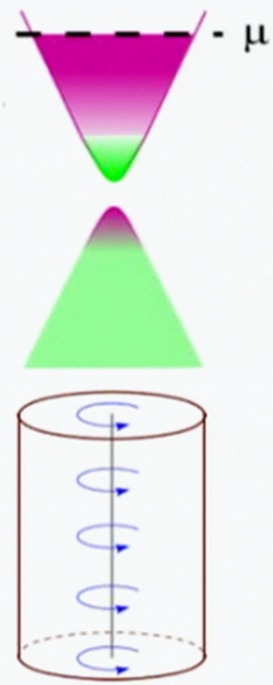
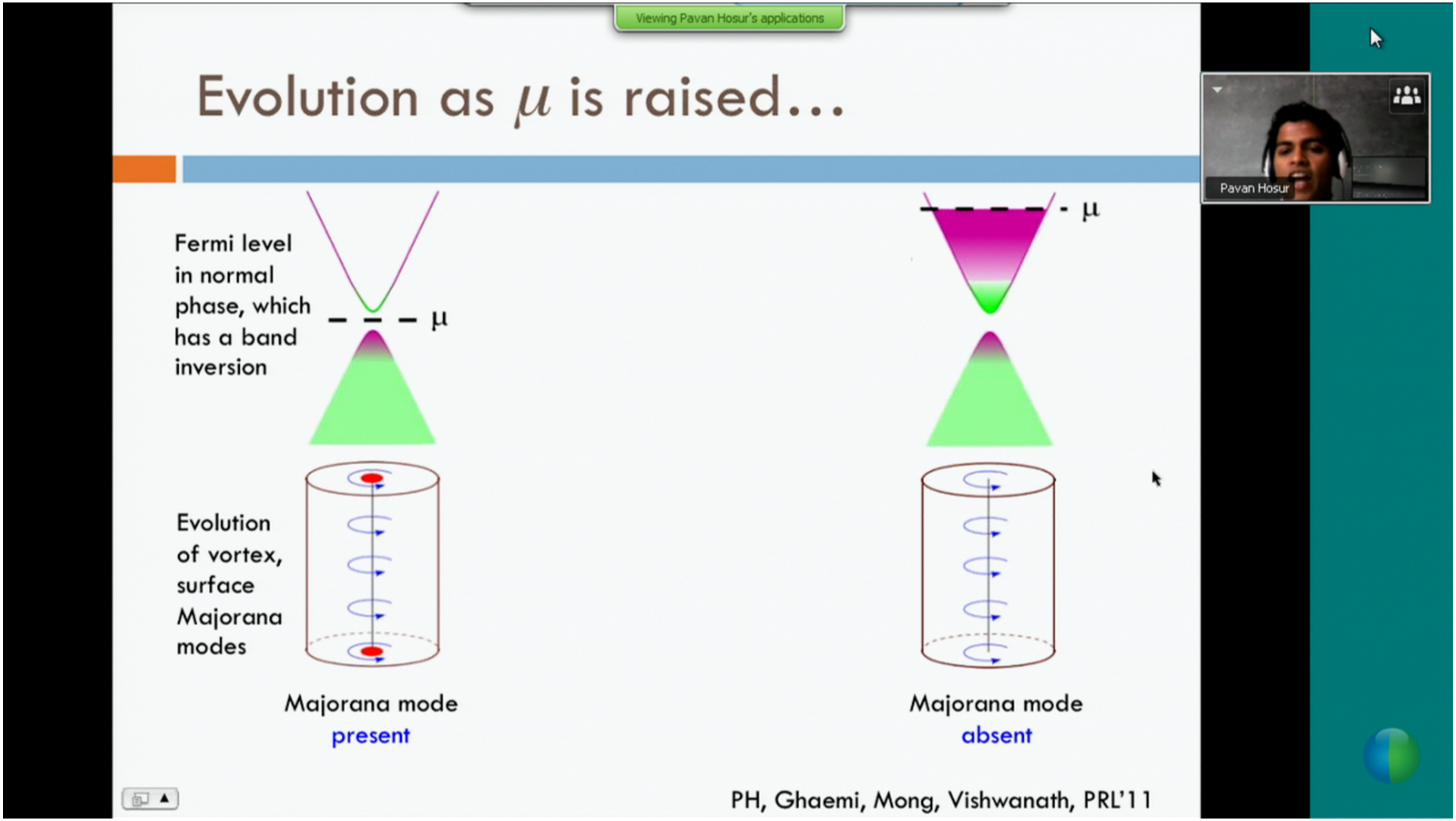


Majorana mode **present**



Majorana mode **absent**

PH, Ghaemi, Mong, Vishwanath, PRL'11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μ
μ
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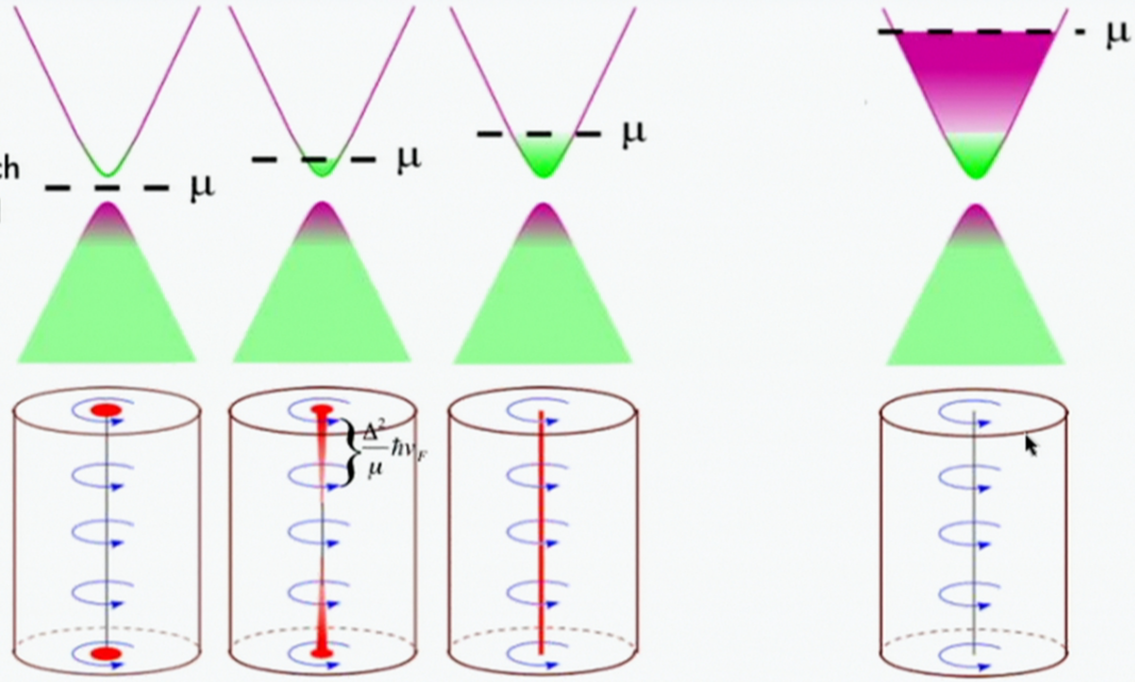
Evolution of vortex, surface Majorana modes



Majorana mode **present**

Majorana mode **absent**

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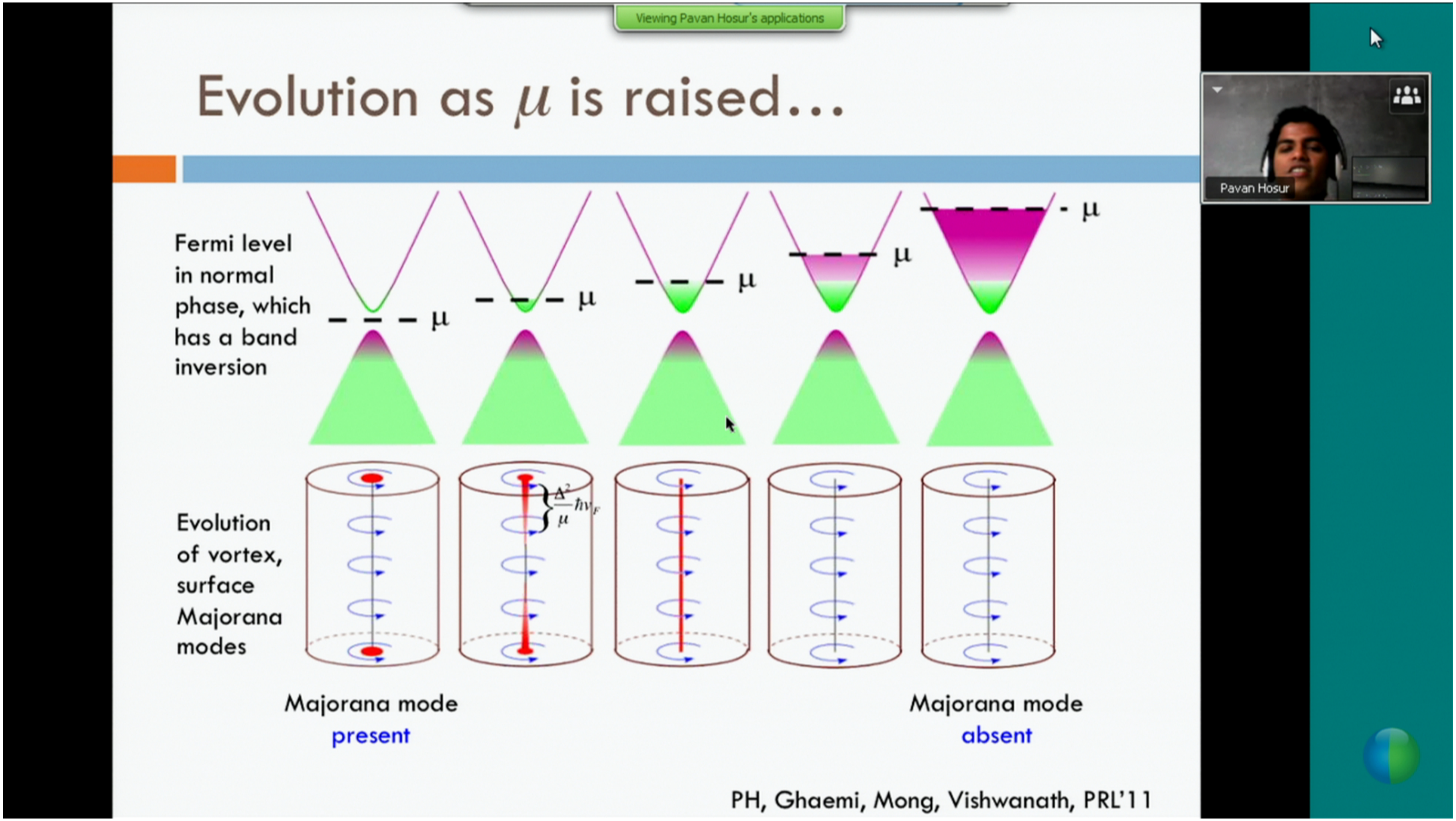
Viewing Pavan Hosur's applications
Evolution as μ is raised…
Fermi level in normal phase, which has a band inversion
μ
μ
μ
μ
μ
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$\frac{\Delta^2}{\mu}\hbar v_F$
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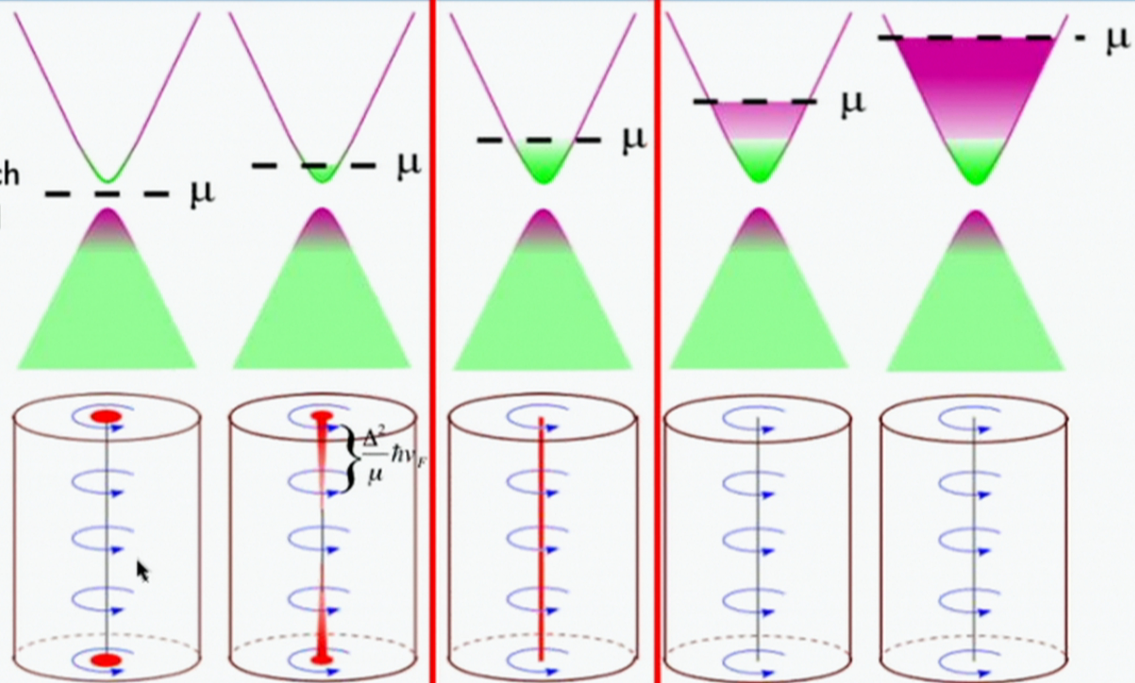
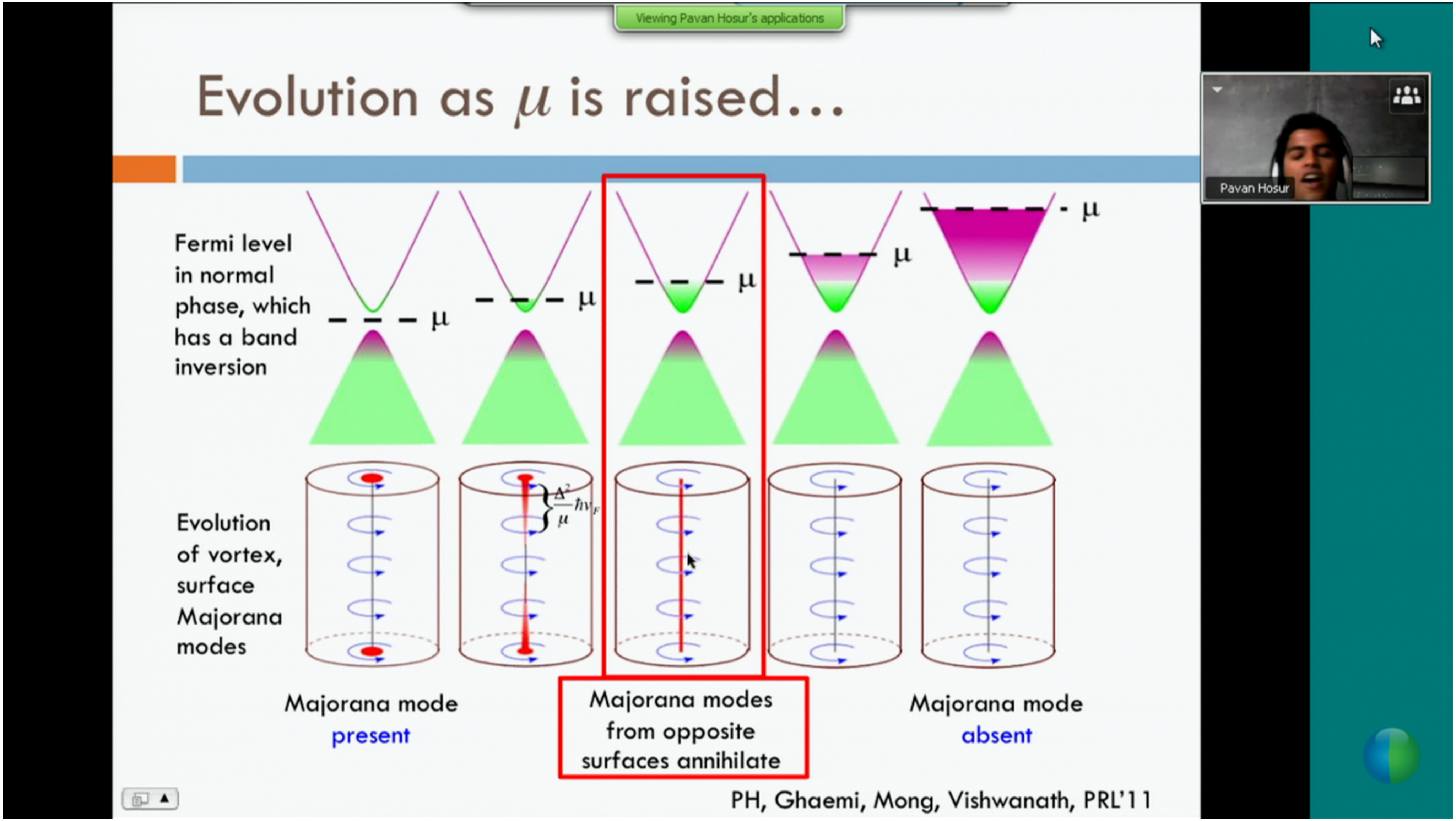


Majorana mode **present**

Majorana modes from opposite surfaces annihilate

Majorana mode **absent**

PH, Ghaemi, Mong, Vishwanath, PRL'11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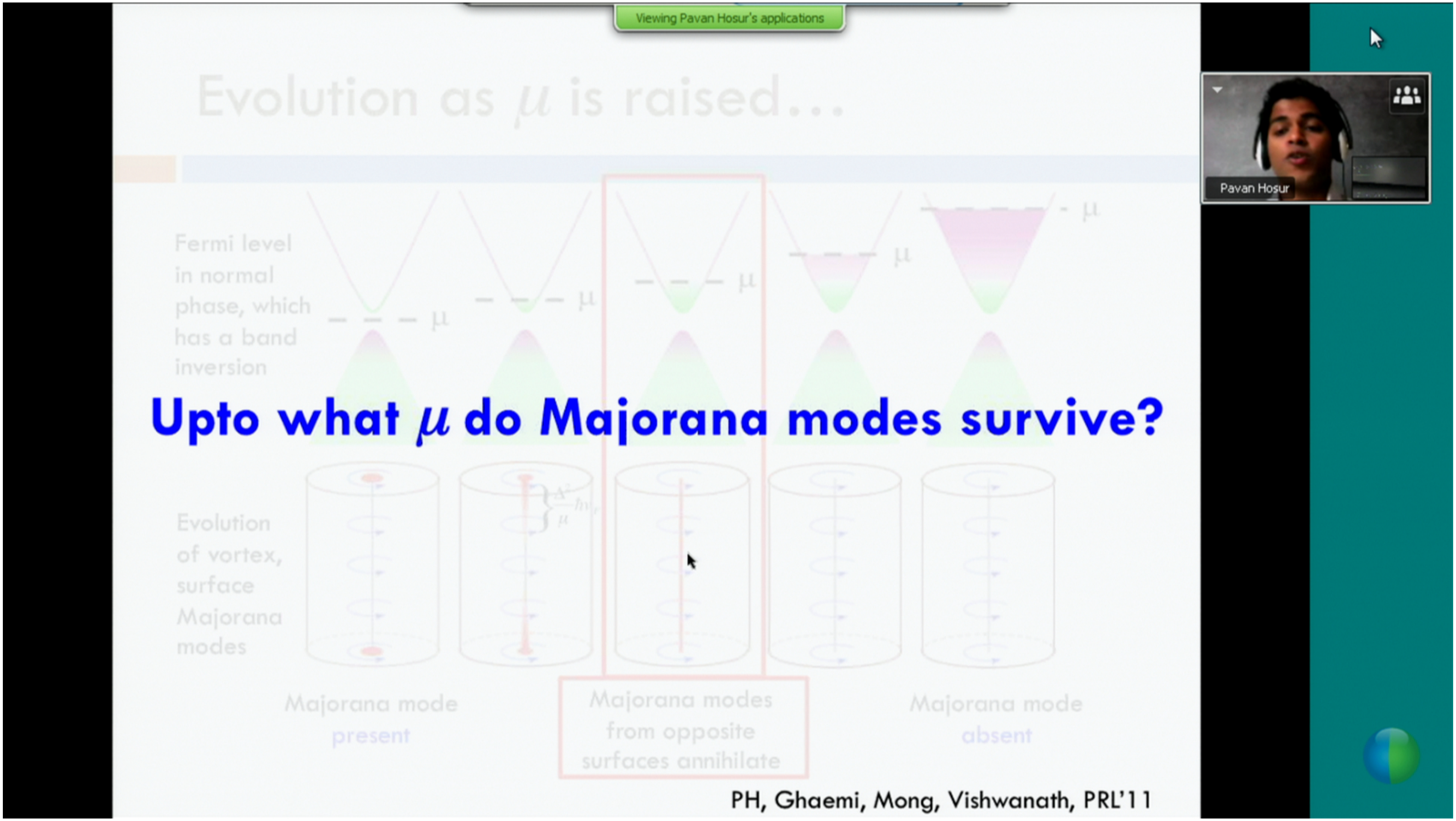

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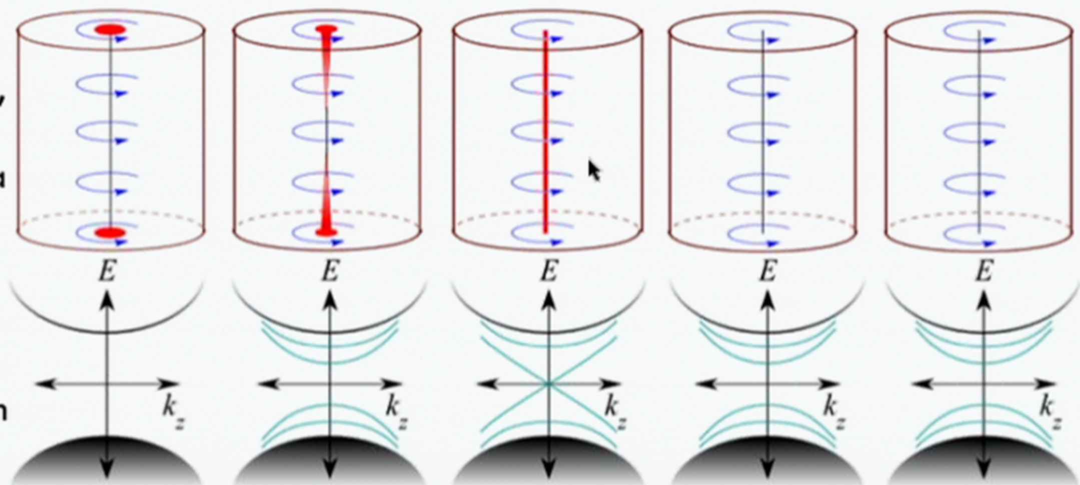
Another perspective: Topological phase transition inside a topological defect

- Vortex = 1D system in class D (BdG with no time-reversal or spin-rotation symmetry)
- Z_2 invariant signals presence/absence of end Majorana modes[Kitaev'01]

Evolution of vortex, surface Majorana modes

Evolution of vortex dispersion



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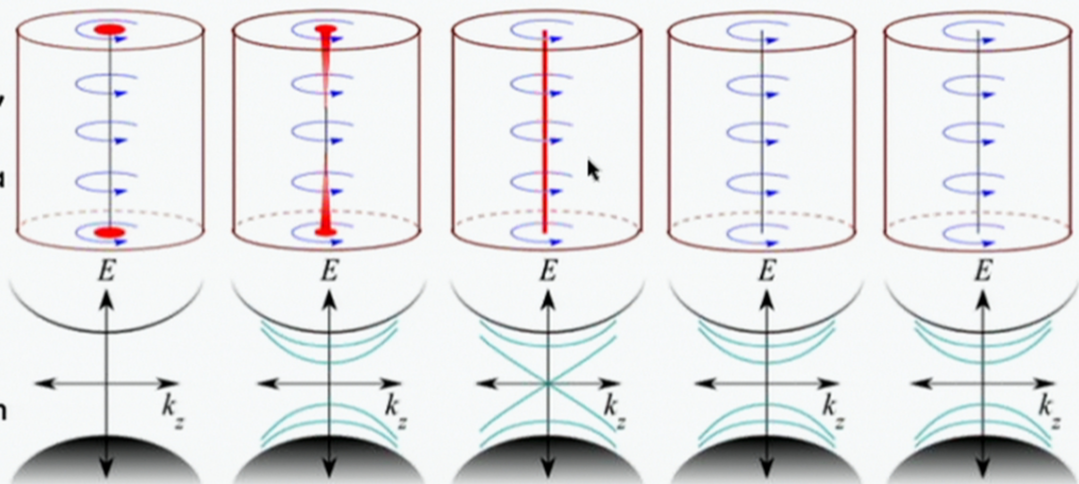

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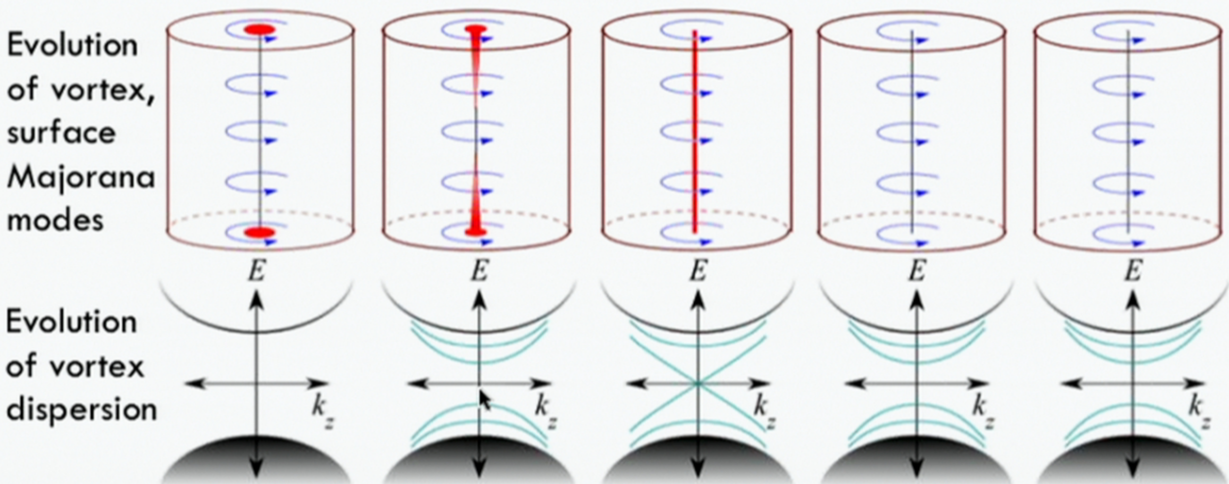

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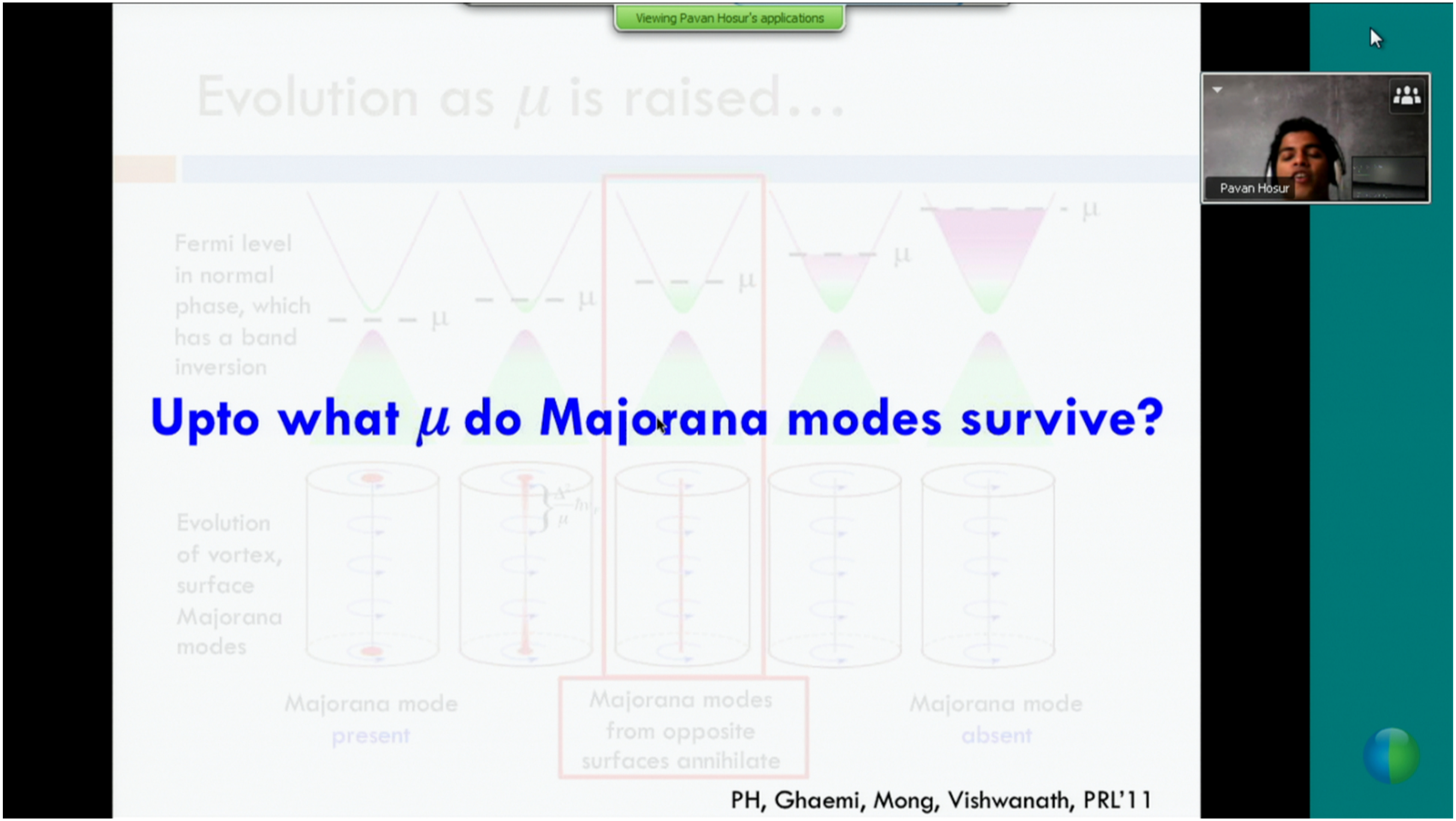
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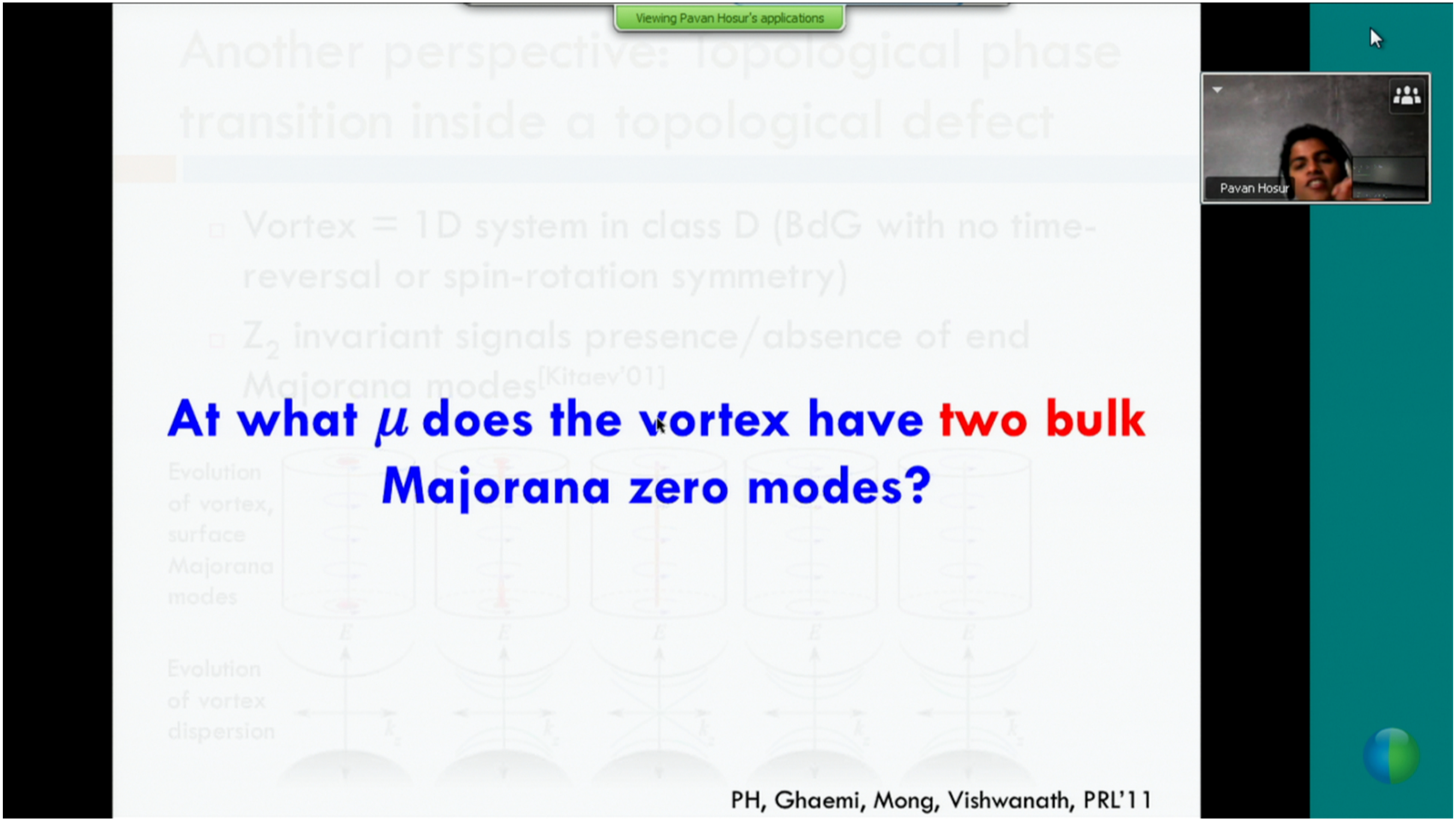
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Viewing Pavan Hosur's applications

Towards main result: Analogy with $p+ip$ superconductor at fixed k_z

PH, Ghaemi, Mong, Vishwanath, PRL'11 Read-Green, PRB 2000

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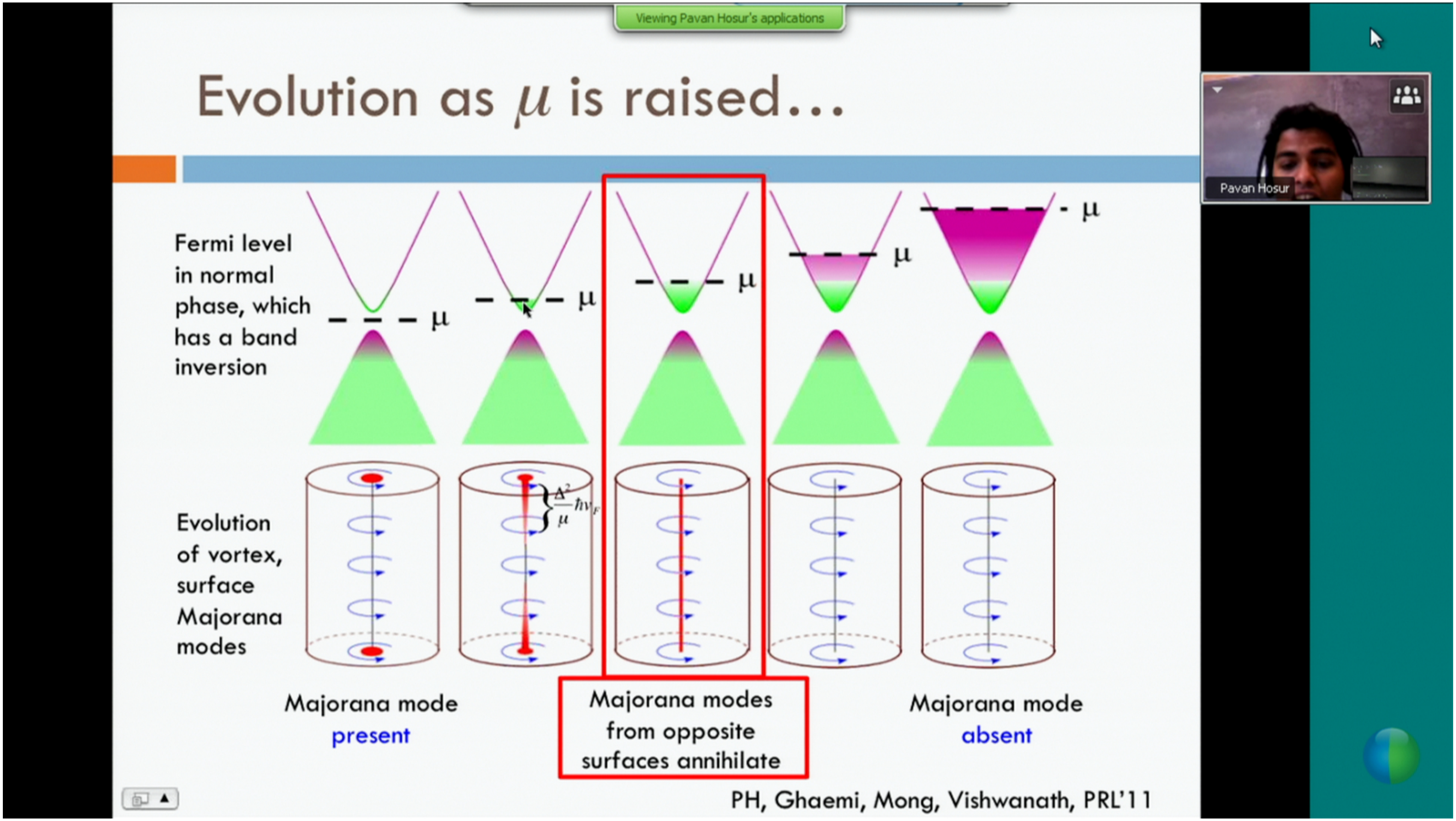
Superconducting doped topological insulator

$$H_{BdG} = \begin{bmatrix} H_{\mathbf{k}} - \mu & \Delta(\mathbf{r}) \\ \Delta^*(\mathbf{r}) & \mu - H_{\mathbf{k}} \end{bmatrix}$$

PH, Ghaemi, Mong, Vishwanath, PRL'11 Read-Green, PRB 2000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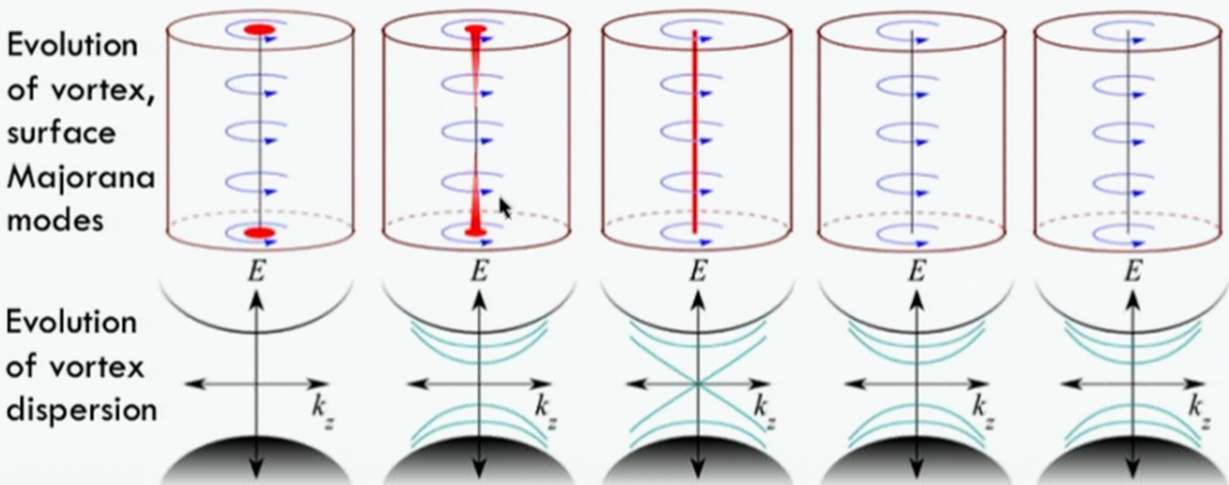

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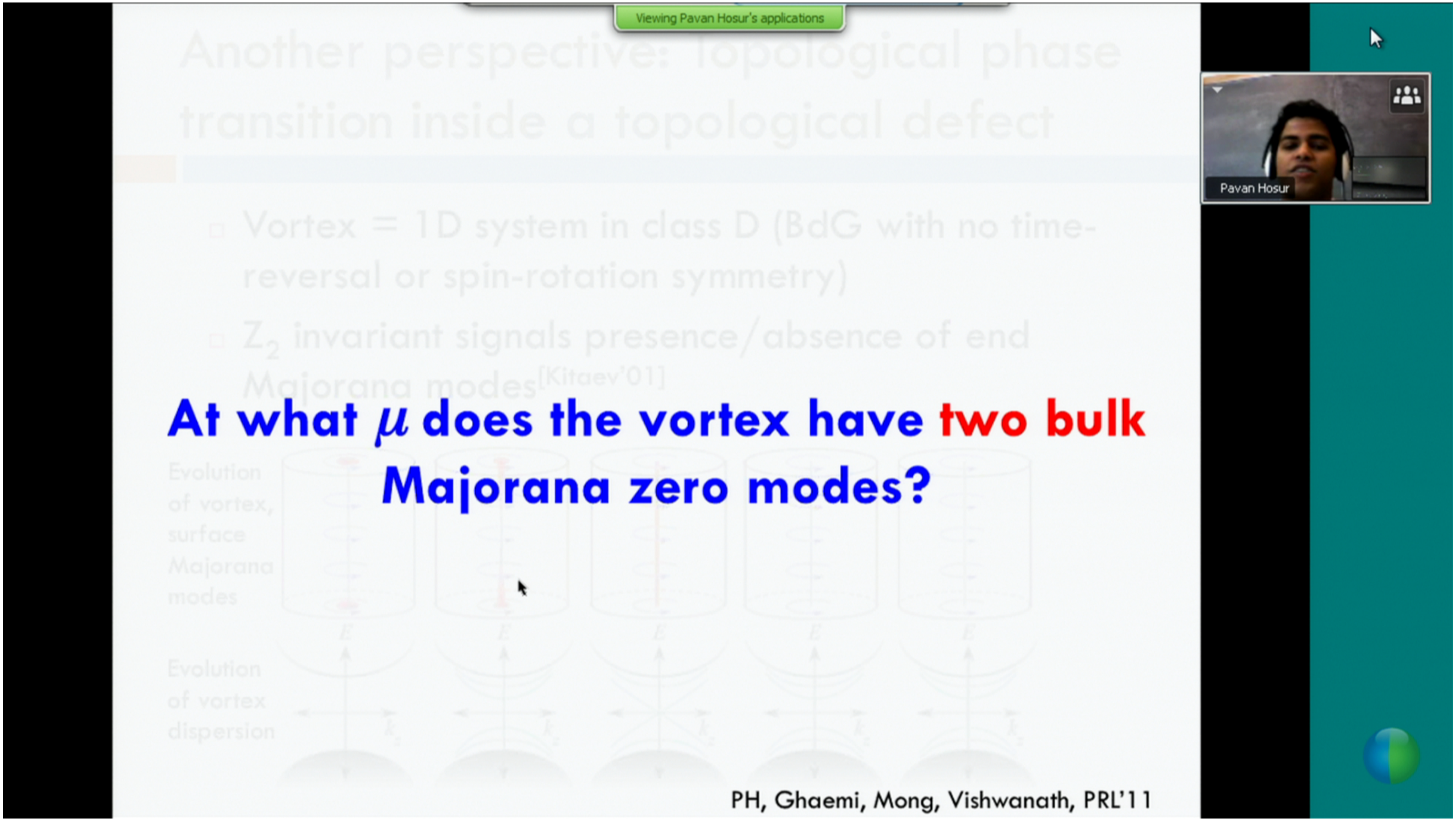
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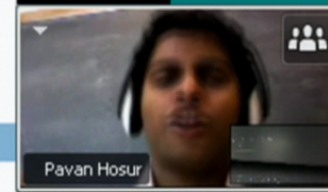
Towards main result: Analogy with $p+ip$ superconductor at fixed k_z



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Viewing Pavan Hosur's applications

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$$\equiv \Delta_0(i\partial_{k_x} - \partial_{k_y})$$

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***p+ip* superconductor**

$$H_{p_x+ip_y} = \begin{bmatrix} \varepsilon(\mathbf{r}) & \Delta(i\partial_x - \partial_y) \\ \Delta(i\partial_x + \partial_y) & -\varepsilon(\mathbf{r}) \end{bmatrix}$$

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Superconducting doped topological insulator	$p+ip$ superconductor

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$$\mathbf{k} \leftrightarrow \mathbf{r}$$

Fermi surface has $\langle H_{\mathbf{k}}\text{-}\mu\rangle = 0$. Expect a Majorana zero mode at π-Berry phase

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Pavan Hosur

Main result: $SU(2)$ Berry phase and μ_c

Time-reversal + inversion ⇒

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Main result: $SU(2)$ Berry phase and μ_c

Time-reversal + inversion ⇒

- Bands doubly degenerate (Kramer's degeneracy)

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Viewing Pavan Hosur's applications

Main result: *SU(2)* Berry phase and μ_c

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$$\mathbf{A}_{ij}(\mathbf{k}) = i\left\langle u_i(\mathbf{k}) \mid \nabla_k u_j(\mathbf{k})\right\rangle;\ i,j \in \{1,2\}$$

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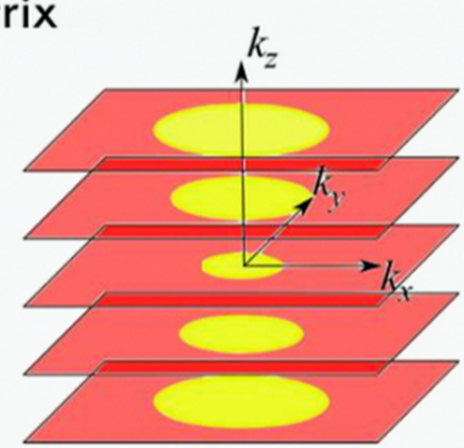

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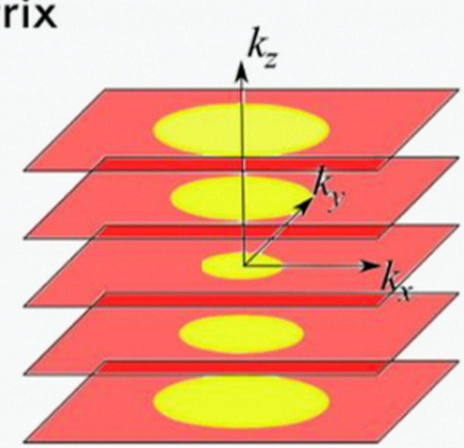
- At each k_z, Berry phase factor around Fermi surface

$$U_B(k_z) = P\left[\exp\left(i\oint \hat{\mathbf{A}}(\mathbf{k})\cdot\hat{\mathbf{z}}\right)\right] \in SU(2)$$

P = path-ordering;

$U(1)$-part vanishes due to time-reversal+inversion;



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Viewing Pavan Hosur's applications

Main result: *SU(2)* Berry phase and μ_c

$$\text{eigenvalues}\left(U_B(k_z)\right) = \left\{ e^{i\phi(k_z)},\ e^{-i\phi(k_z)} \right\}$$

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Viewing Pavan Hosur's applications

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$$\boxed{\varepsilon_{BdG}(k_z) = \varepsilon_0[(2n+1)\pi - \phi(k_z)]} \qquad \varepsilon_0 \sim \Delta^2/\mu$$

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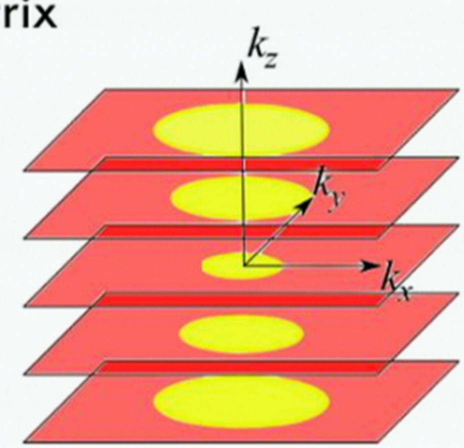

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has zero mode if $\phi(k_z) = \pi$

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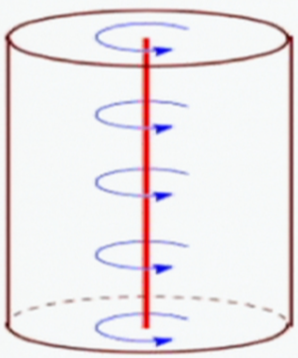

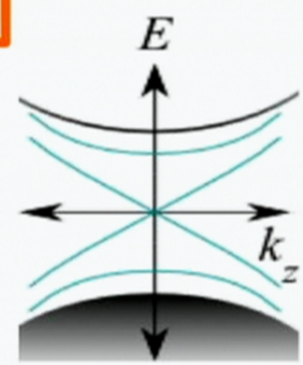

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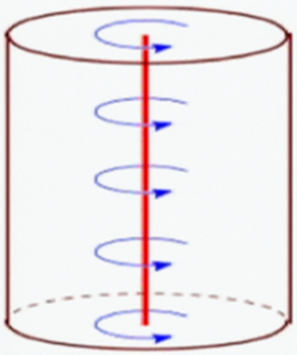
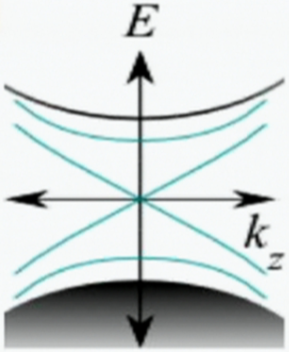


$\phi(k_z) = \phi(-k_z)$

$\Rightarrow$ 0, 4, 8…. zero modes at $k_z \neq 0$

$\Rightarrow$ sufficient to focus on $k_z = 0, \pi$



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Candidate Materials

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Candidate Materials

Among doped topological insulators:

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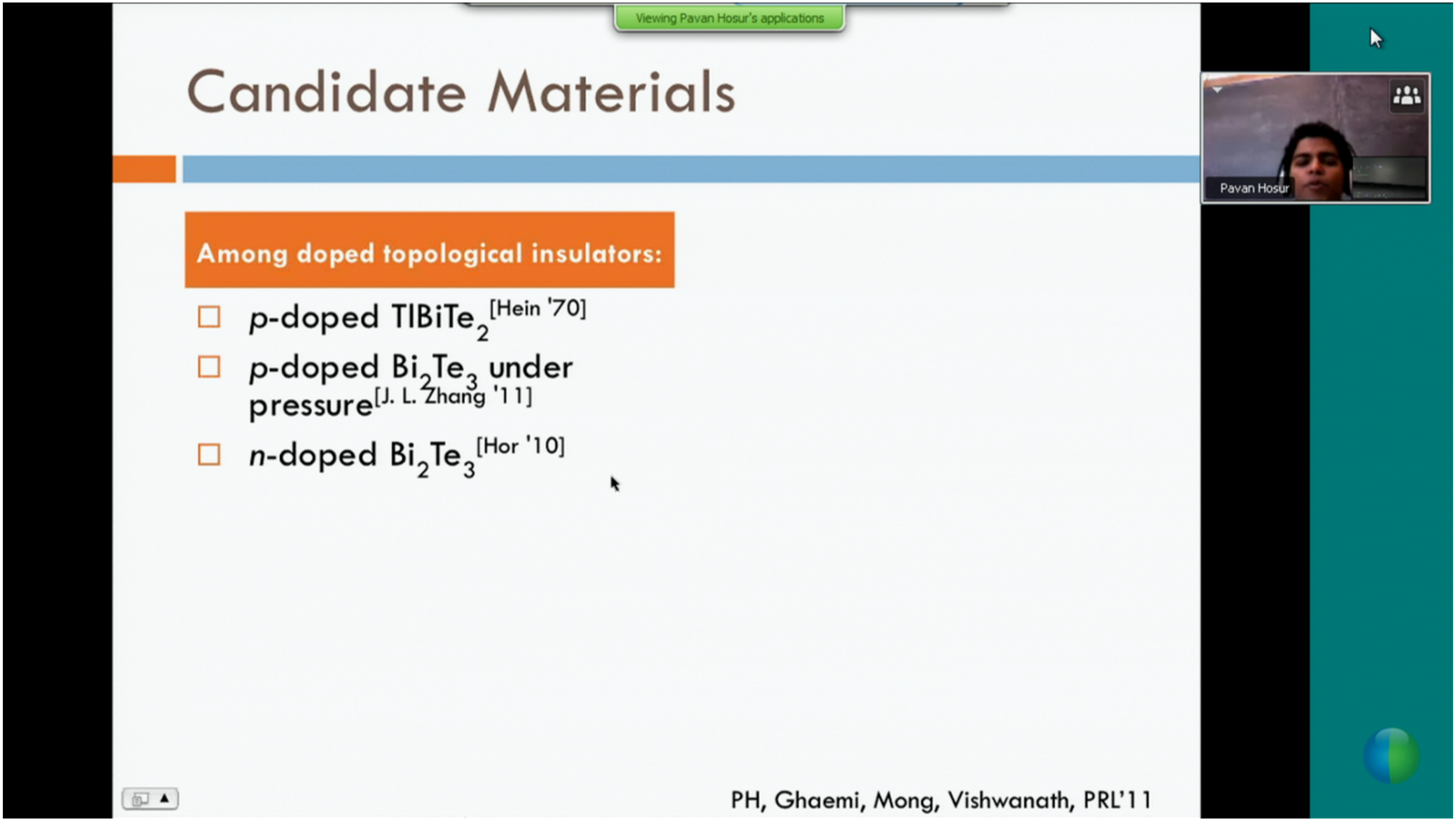
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Candidate Materials
Among doped topological insulators:
p-doped TlBiTe2 [Hein '70]
p-doped Bi2Te3 under pressure [J. L. Zhang '11]
n-doped Bi2Te3 [Hor '10]
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Candidate Materials

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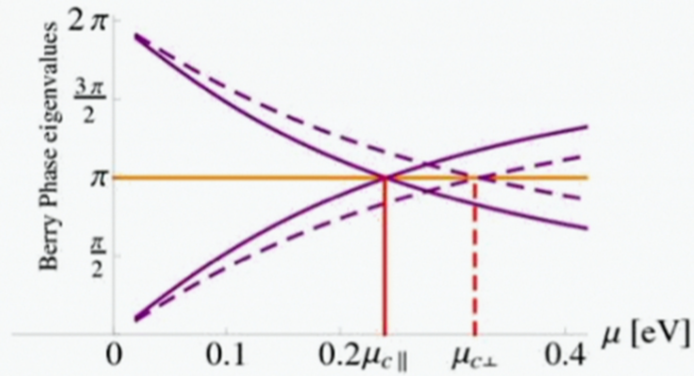
- $Cu\text{-}Bi_2Se_3$ [Hor '10, Wray'10] near phase transition for c-axis vortex, but has Majorana modes for *ab*-axis vortex



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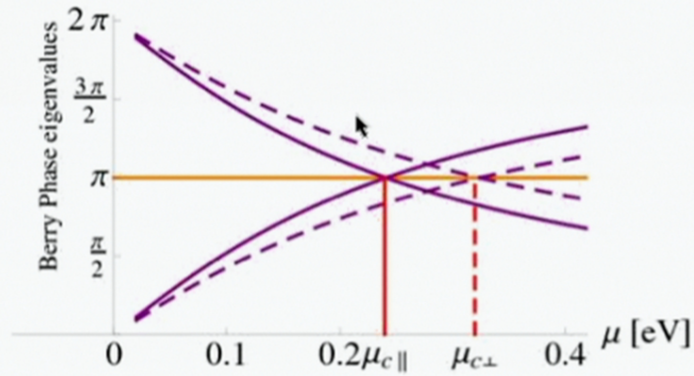

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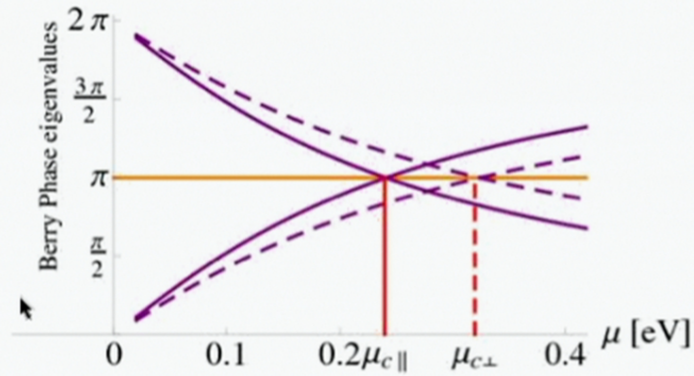

Among ordinary insulators

- Either PbTe or SnTe and GeTe (PbTe has four band inversions relative to SnTe and GeTe)

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Majorana modes summary

Viewing Pavan Hosur's applications

Majorana modes summary

- Surface Majorana zero modes present in vortex of superconducting doped topological insulator below critical doping determined by Berry phase of normal state Fermi surface

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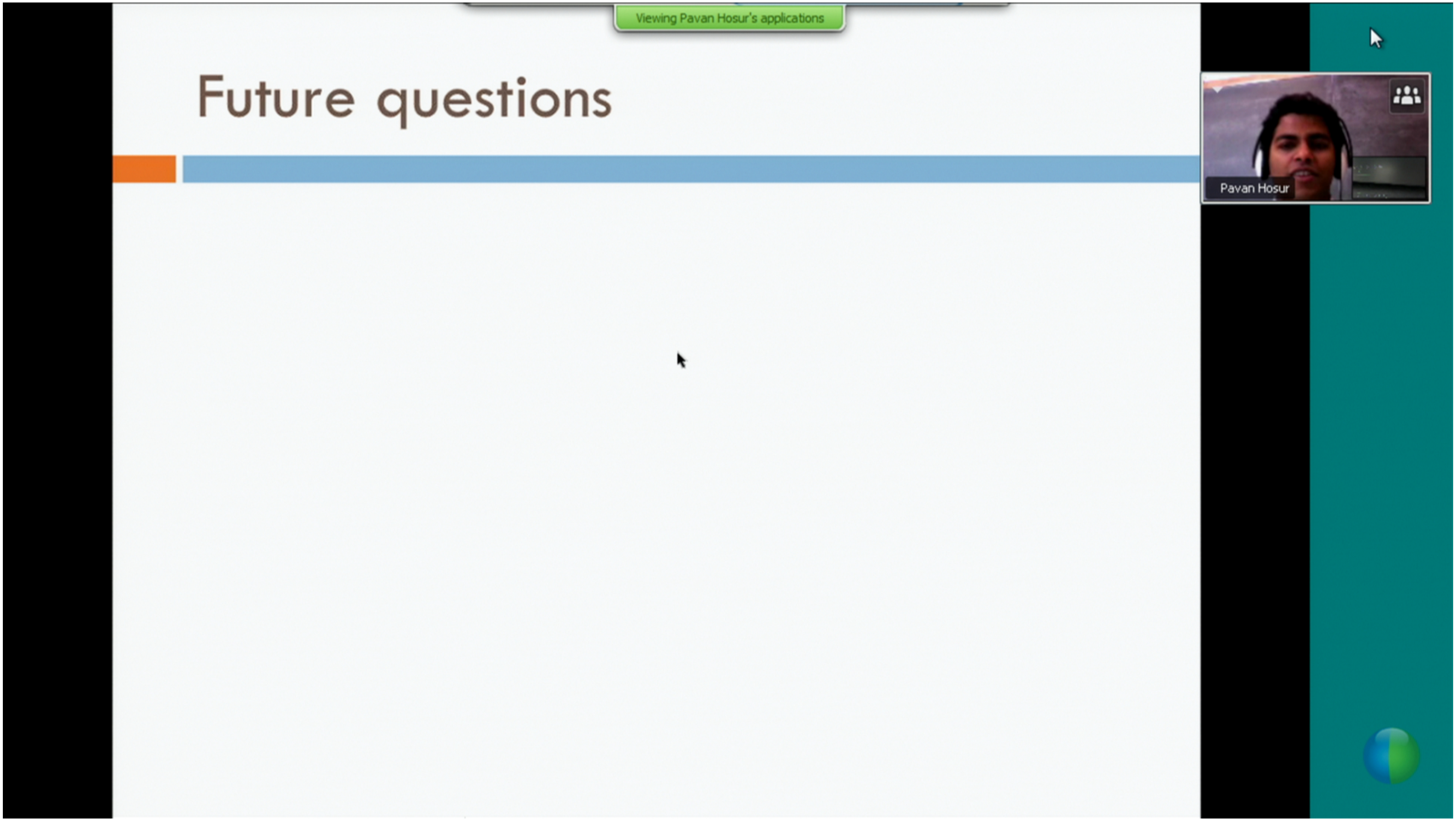
Majorana modes summary

- Surface Majorana zero modes present in vortex of superconducting doped topological insulator below critical doping determined by Berry phase of normal state Fermi surface
- Several existing superconductors expected to carry vortex Majorana modes, possibly even non-topological insulator-based ones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Future questions
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- What if parent insulator breaks inversion?

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- What about other geometries such as domain walls?

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Future questions

- What if parent insulator breaks inversion?
- What about other geometries such as domain walls?
- What if pairing is *p*-wave, as several papers (Fu-Berg'10, Das *et. al.*'11) suggest?

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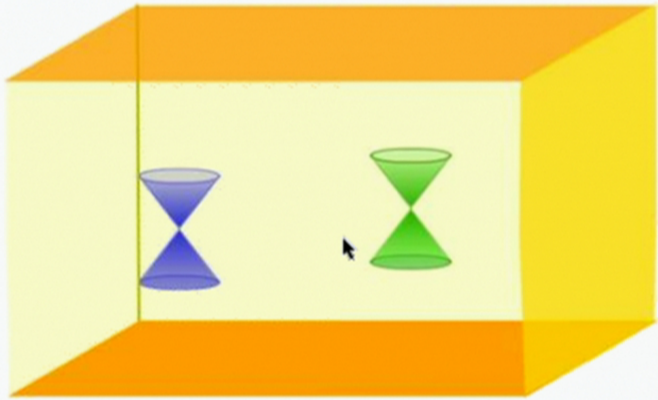
Outline

- Introduction: General examples of topology in condensed matter
- Focus example 1: Majorana modes using topological insulators and superconductors
- **Focus example 2: Weyl semimetals – introduction and transport**

Weyl semimetals

3D materials with linear band-touchings



Weyl semimetals

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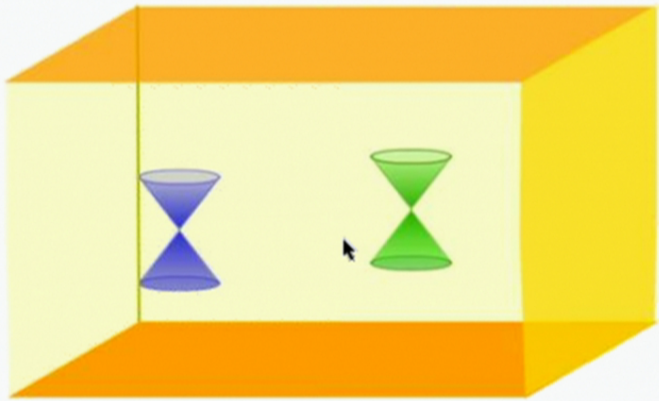

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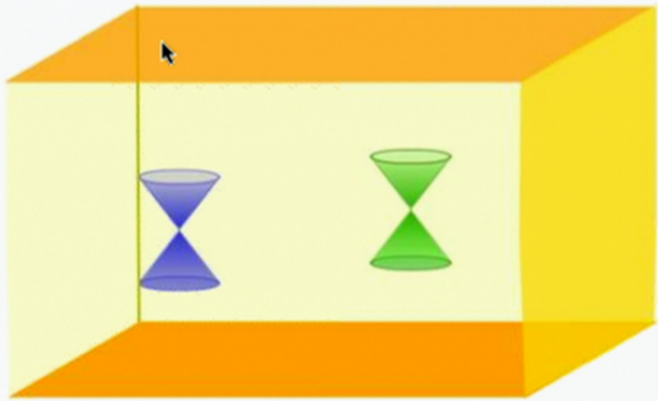

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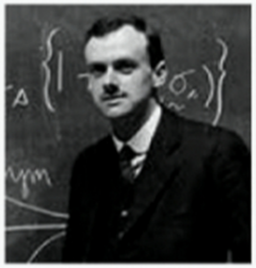

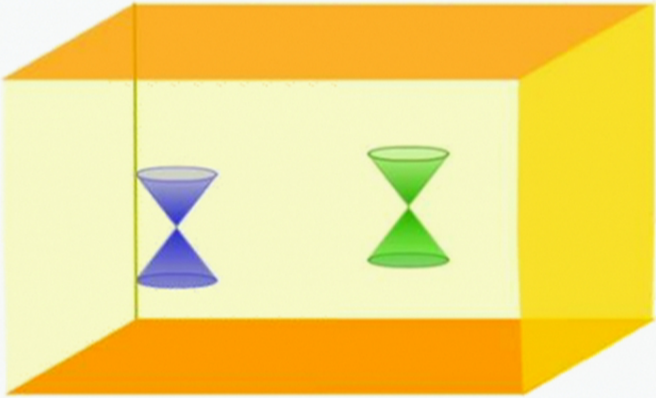

Dirac equation

$$H = \hat{\alpha}_x p_x + \hat{\alpha}_y p_y + \hat{\alpha}_z p_z + \hat{\beta} m$$

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \\ \psi_4 \end{pmatrix}$$

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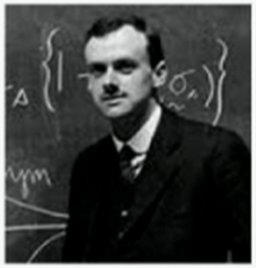

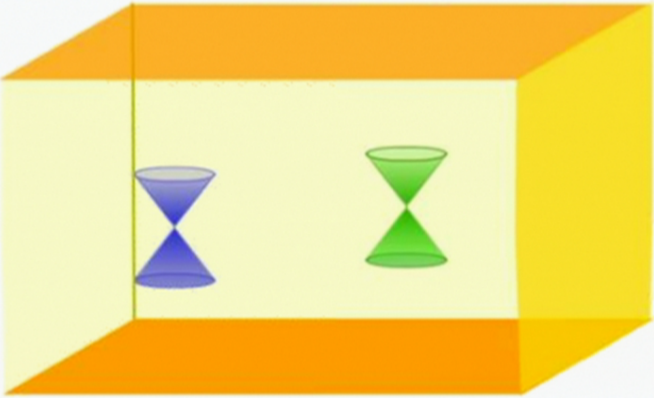

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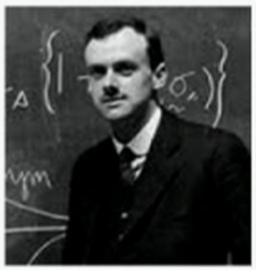

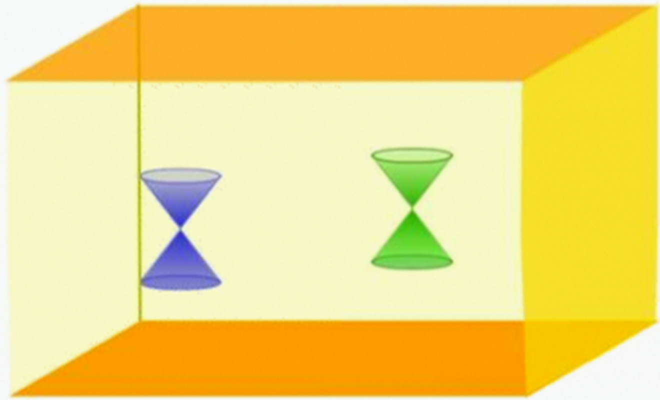

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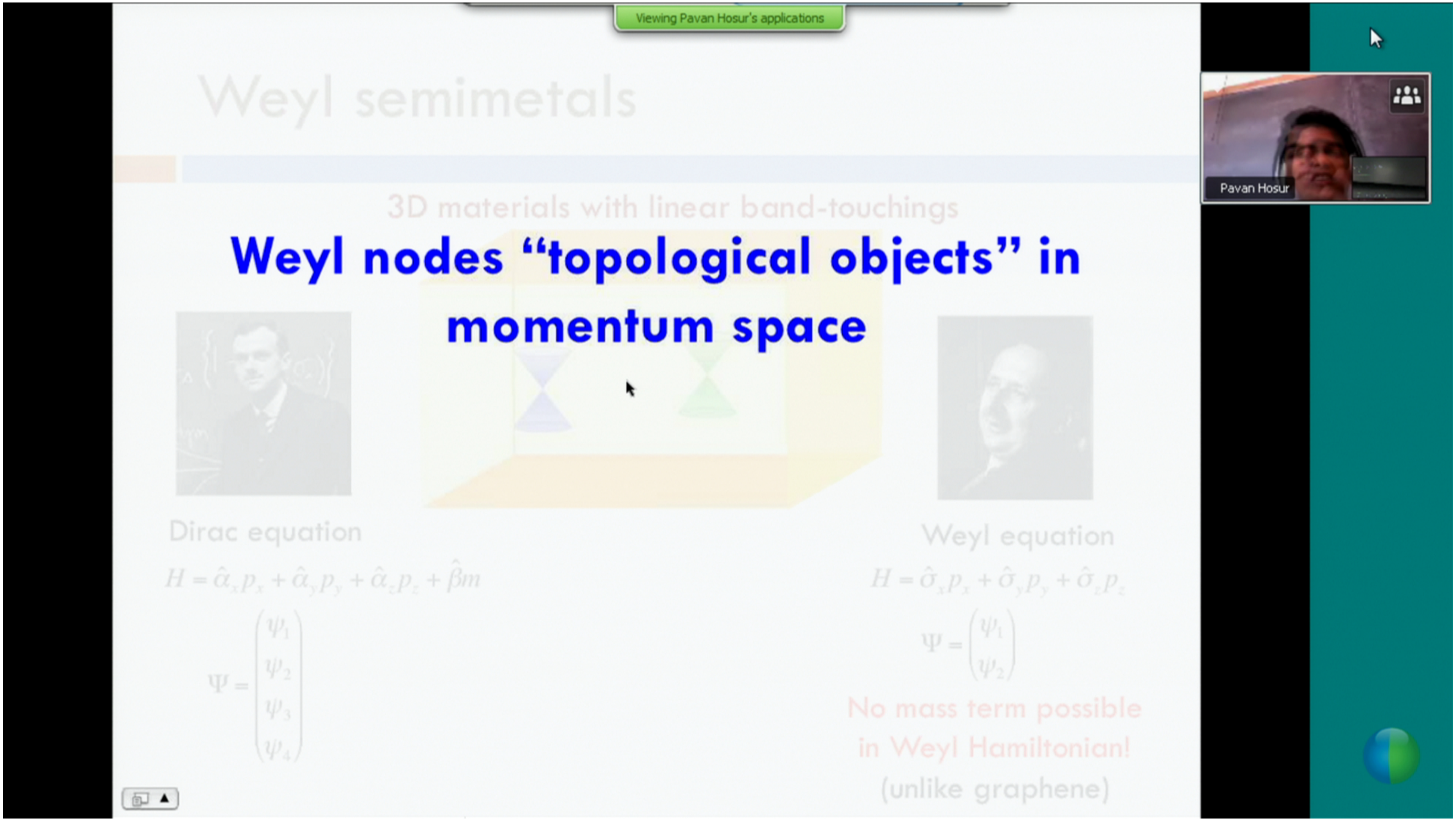
(unlike graphene)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Weyl semimetals
3D materials with linear band-touchings
Weyl nodes "topological objects" in momentum space
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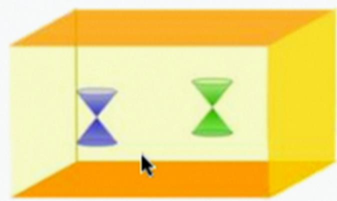
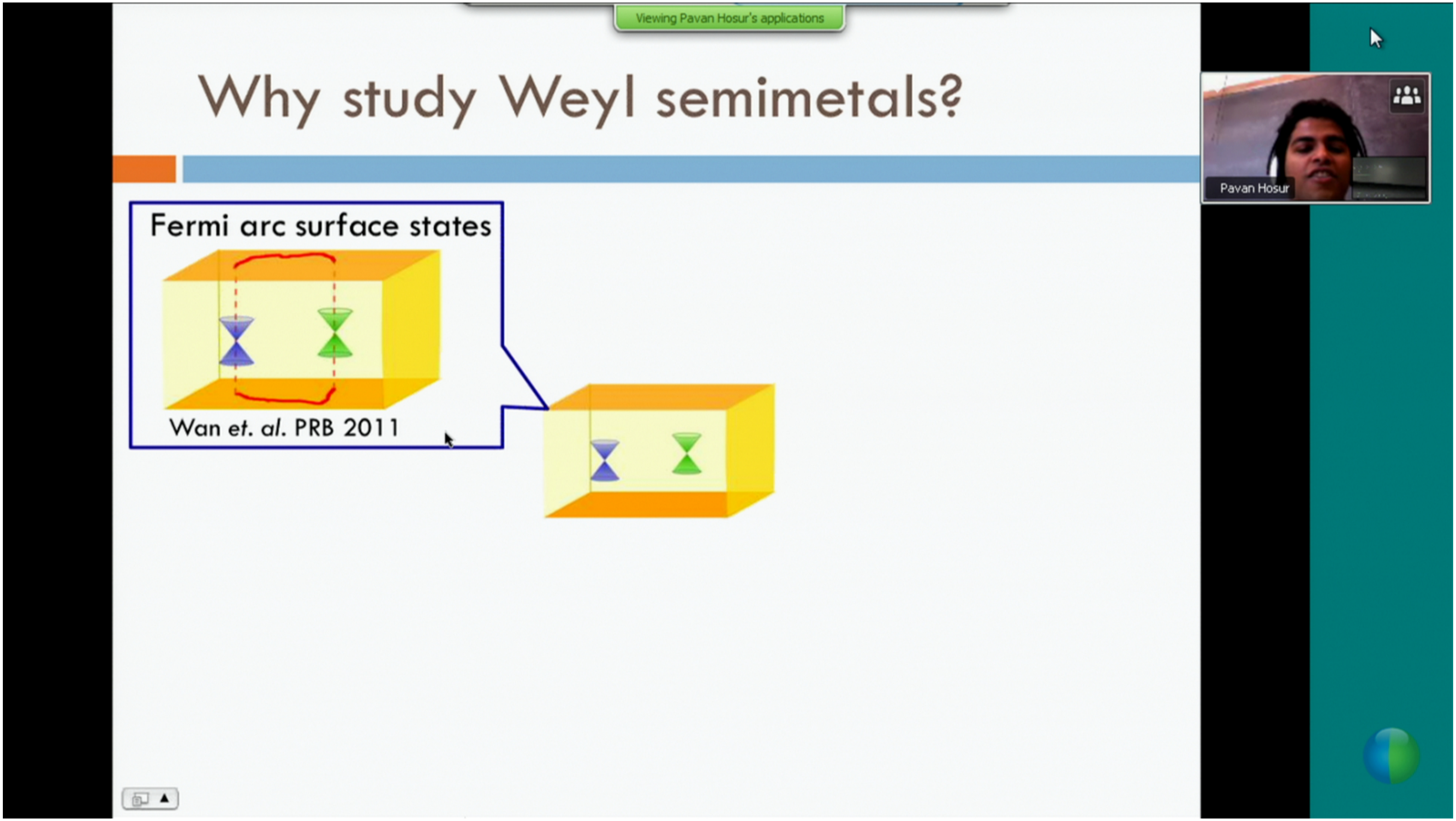
Why study Weyl semimetals?

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Fermi arc surface states
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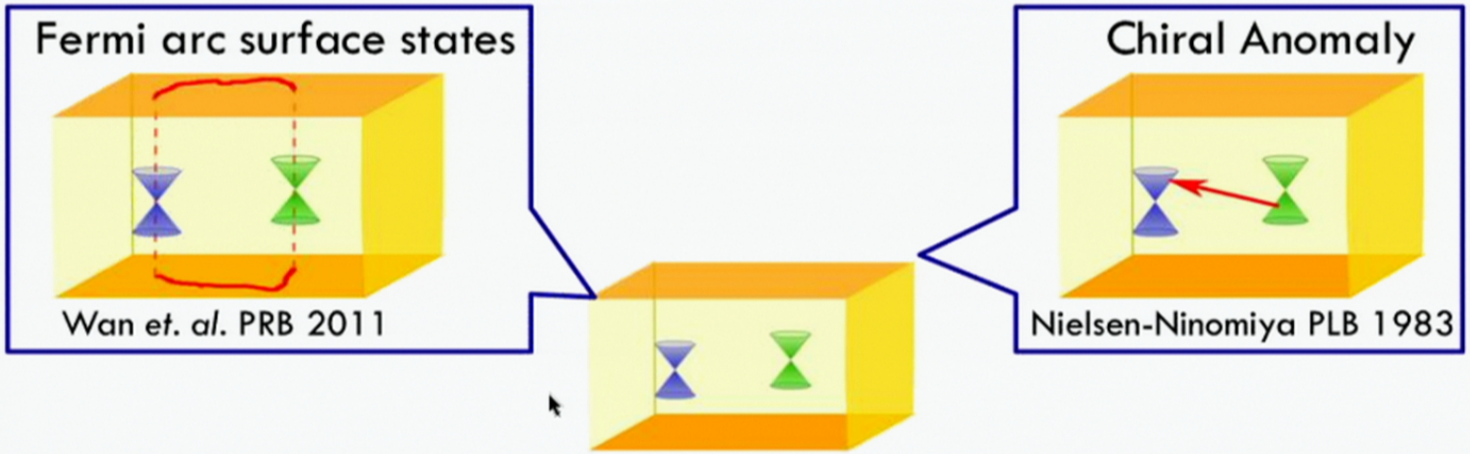

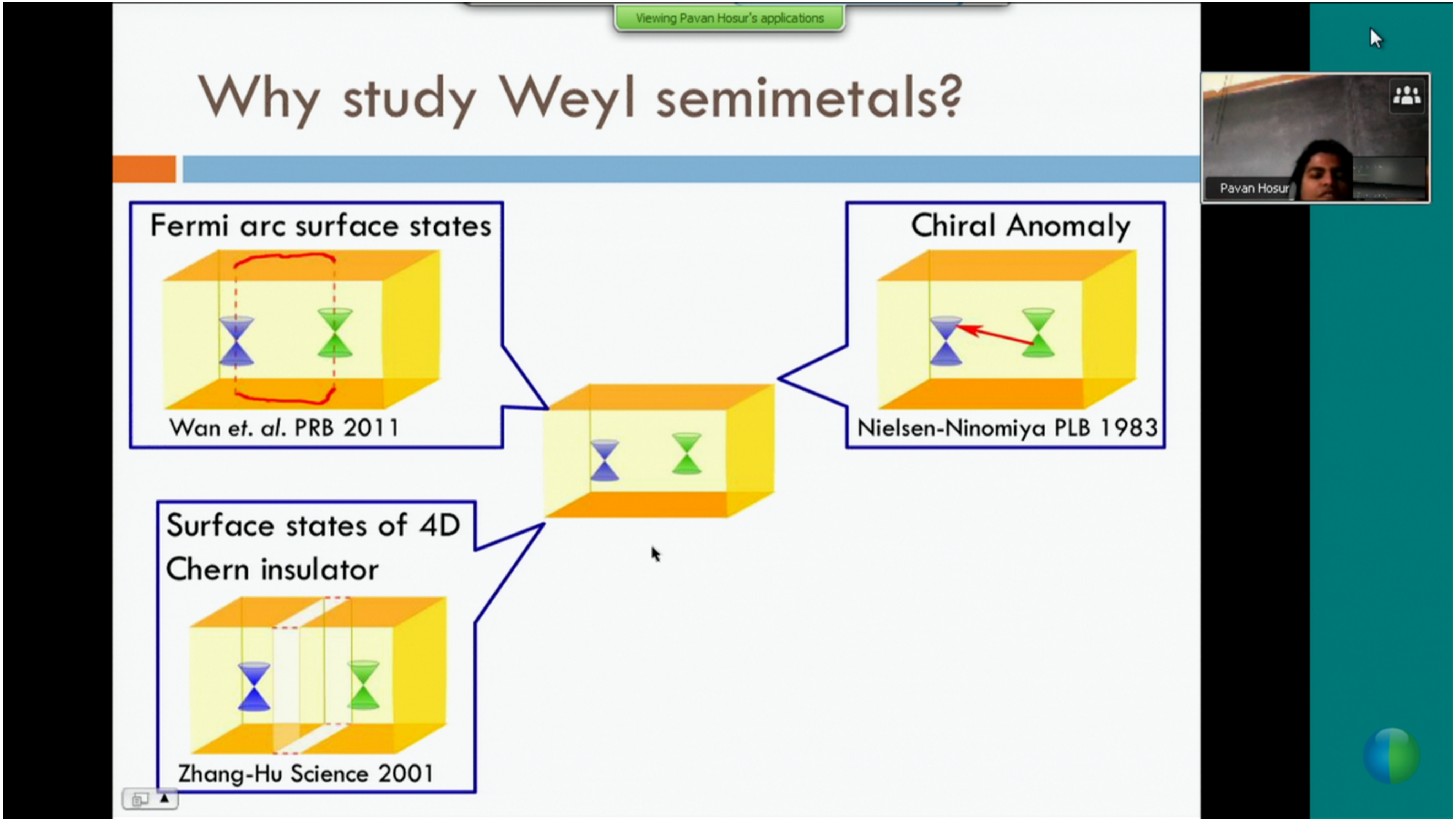
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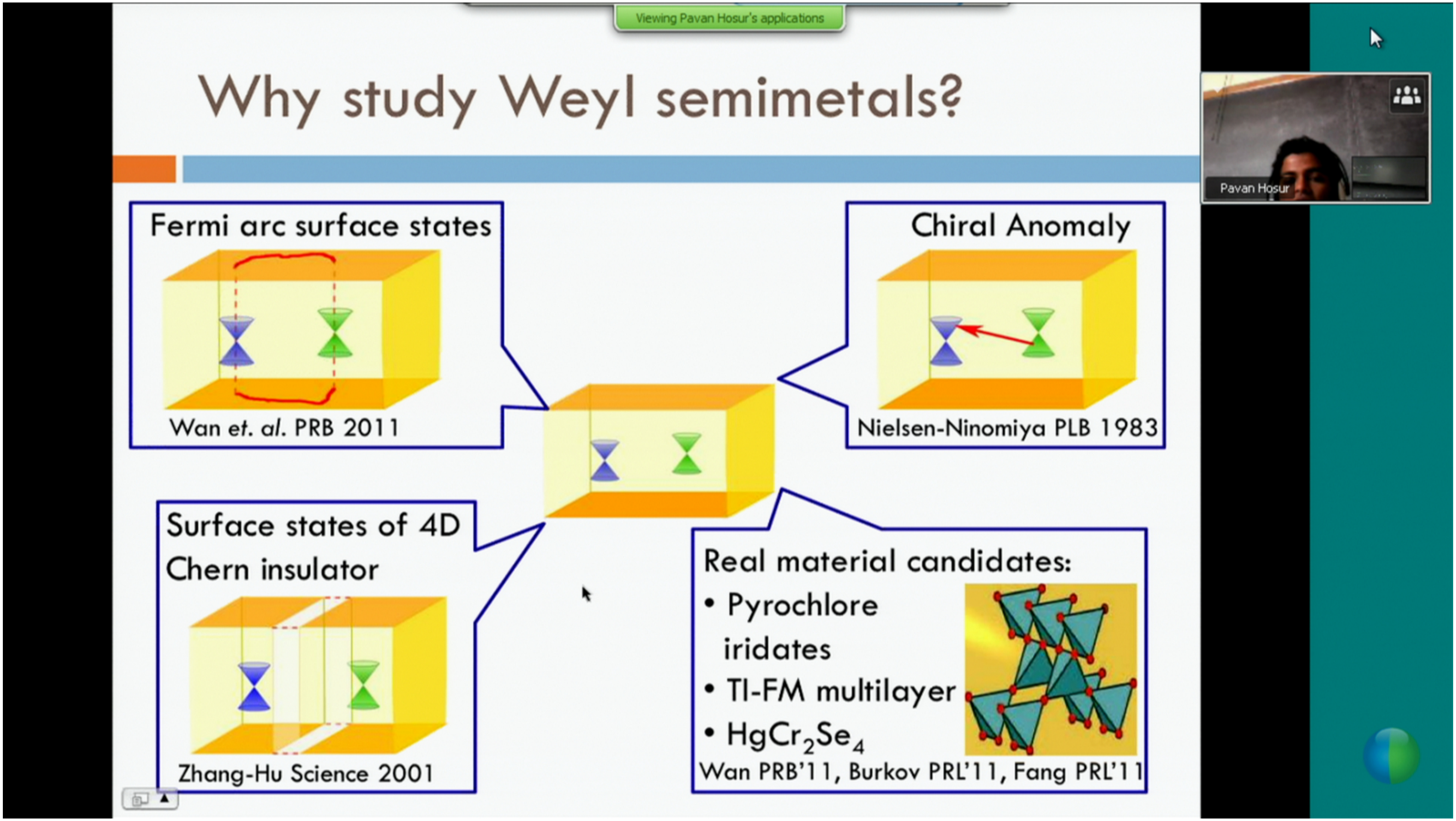
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Real material candidates:
• Pyrochlore iridates
• TI-FM multilayer
• HgCr2Se4
Wan PRB'11, Burkov PRL'11, Fang PRL'11
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Transport in Weyl semimetals

$$\sigma = \frac{e^2}{h}[L]^{-1}$$

PH, Parameswaran, Vishwanath, arXiv:1109.6330

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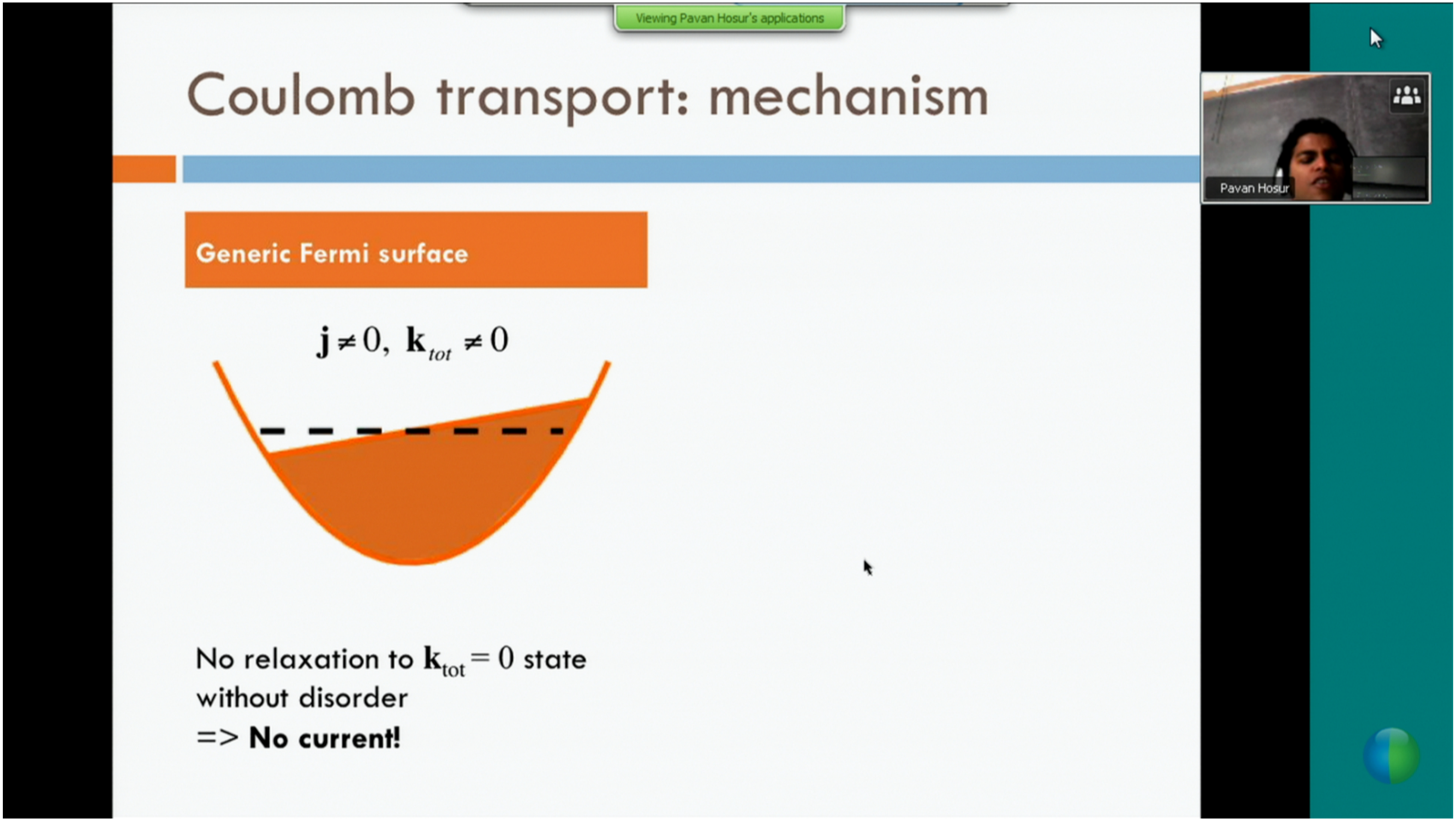
Coulomb transport: mechanism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$\mathbf{j} \neq 0, \ \mathbf{k}_{tot} \neq 0$
No relaxation to $\mathbf{k}_{\text{tot}} = 0$ state
without disorder
=> **No current!**
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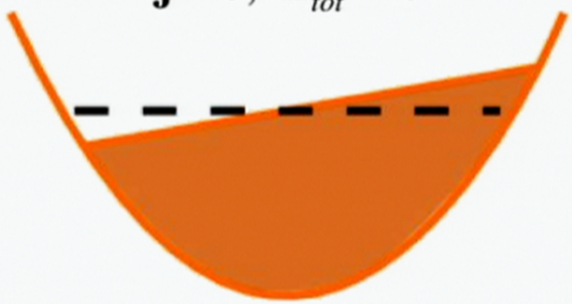

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Interactions, even though they conserve momentum, sufficient to relax current

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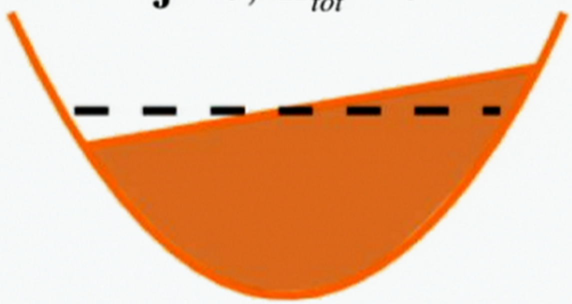

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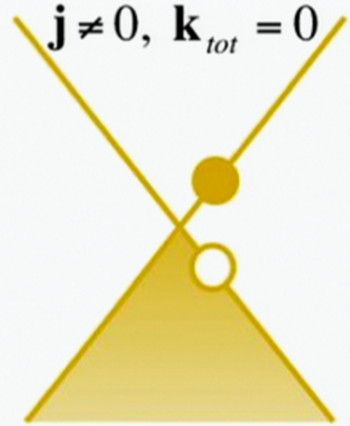

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Coulomb transport: calculation

Quantum Boltzmann analysis

- $\mathbf{j}(t) = ev_F \sum_{\lambda=\pm} \int_{\mathbf{k}} \lambda \hat{\mathbf{k}} f(\mathbf{k},t) = \sigma \mathbf{E}(t)$
- QBE: $(\partial_t + e\mathbf{E}\cdot\nabla_{\mathbf{k}}) f(\mathbf{k},t) = w\left[f(\mathbf{k},t)\right]$ w = scattering rate; use Fermi's golden rule

Fritz *et. al.*, PRB 2008

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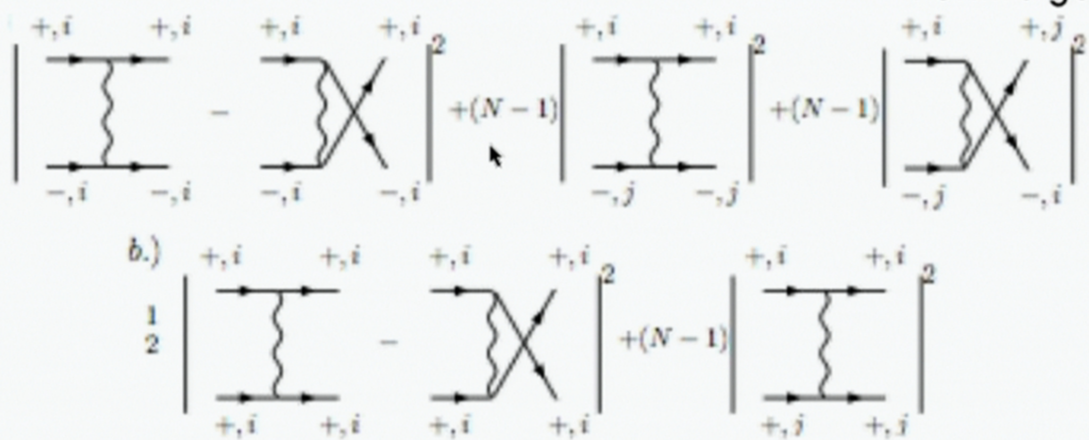

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Quantum Boltzmann analysis contd.

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PH, Parameswaran, Vishwanath, arXiv:1109.6330

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Coulomb transport: results

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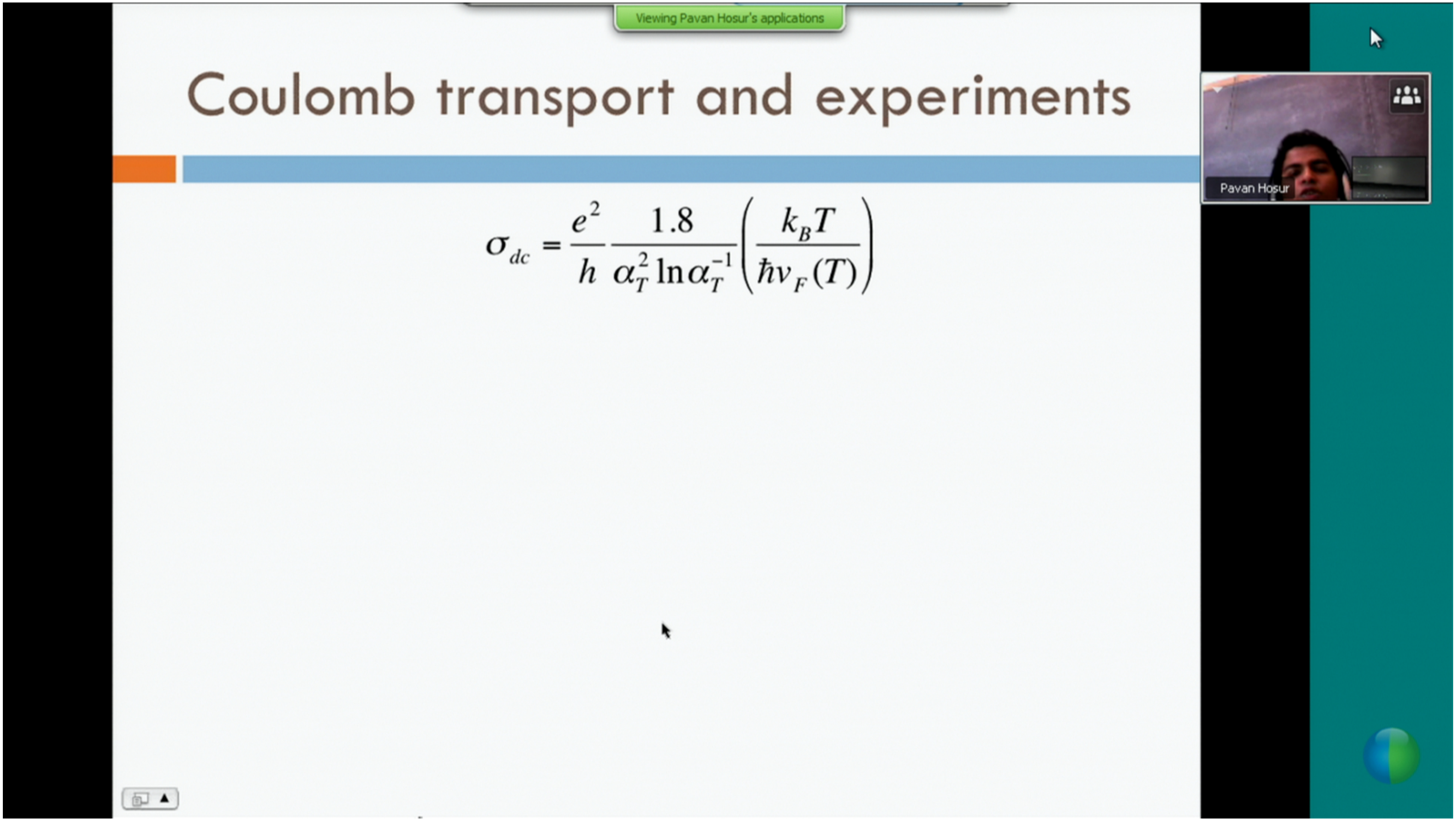
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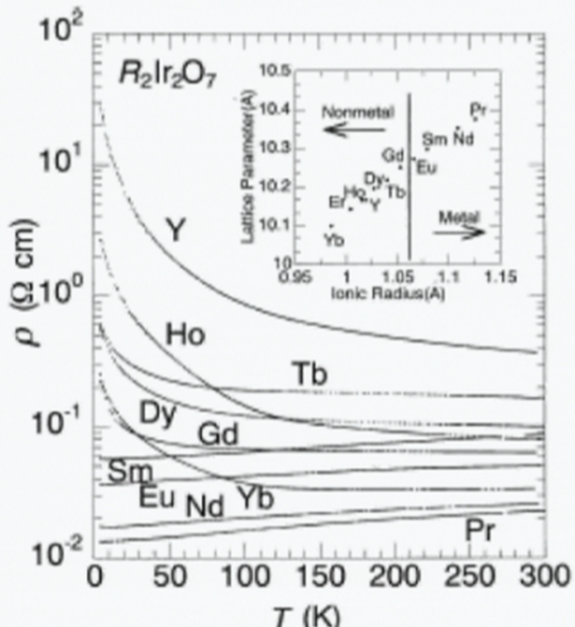

Yanagishima-Maeno JPSJ 2001

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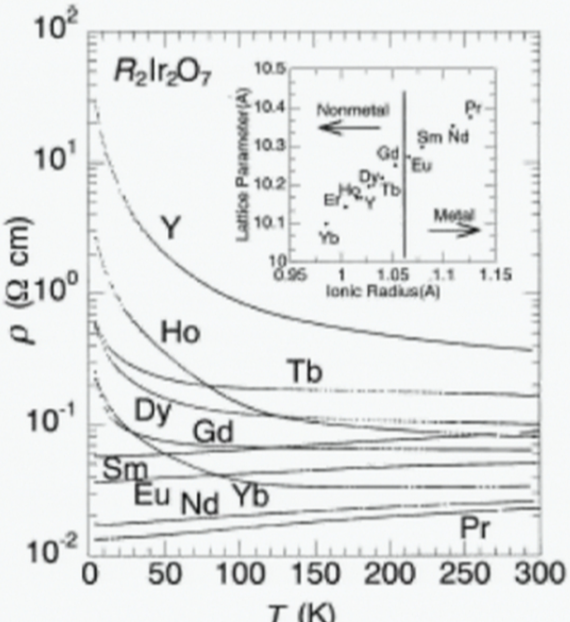

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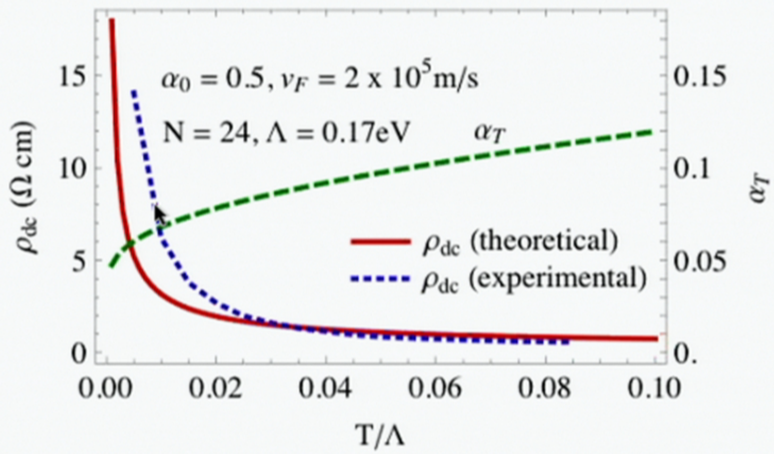

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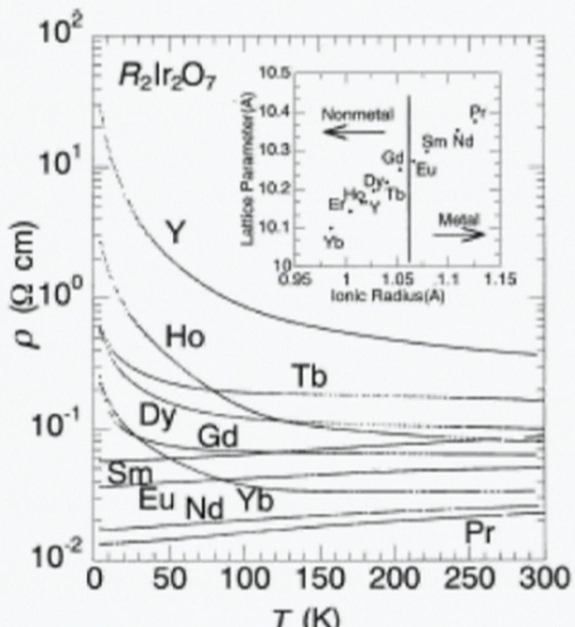

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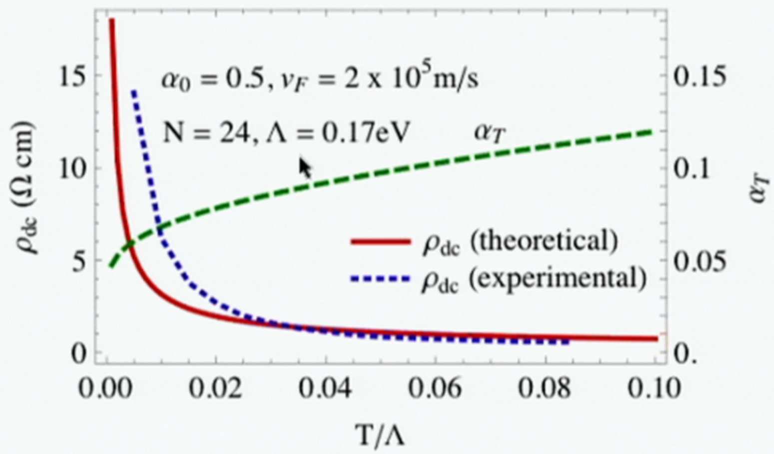

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Fit to theory – Coulomb interactions-driven resistivity

Transport with disorder

PH, Parameswaran, Vishwanath, arXiv:1109.6330

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Transport with disorder

- Born-approximation for self-energy

PH, Parameswaran, Vishwanath, arXiv:1109.6330

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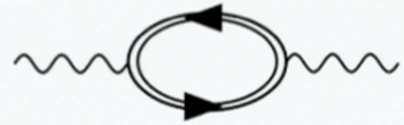

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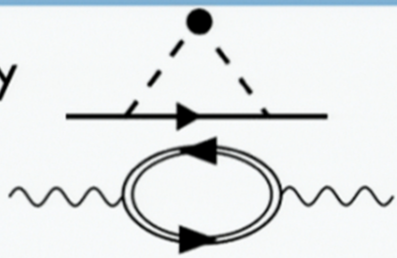

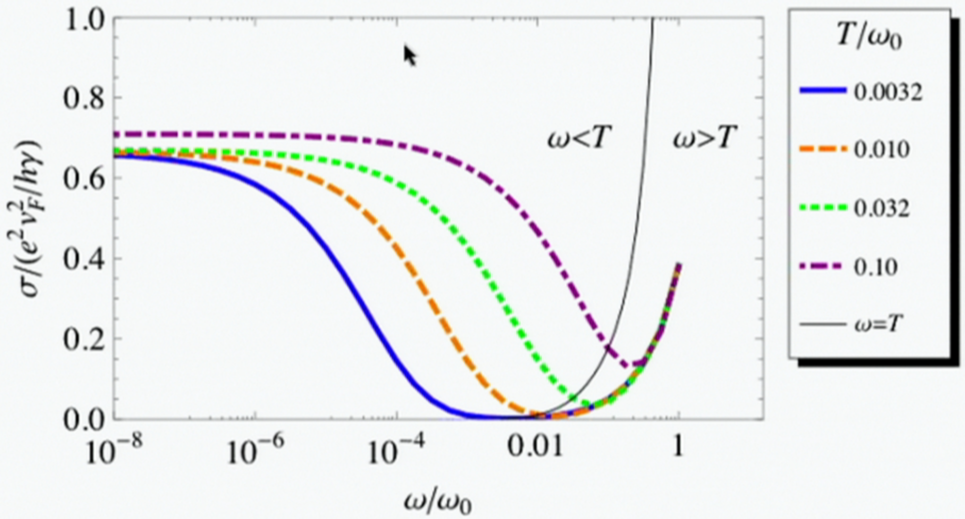

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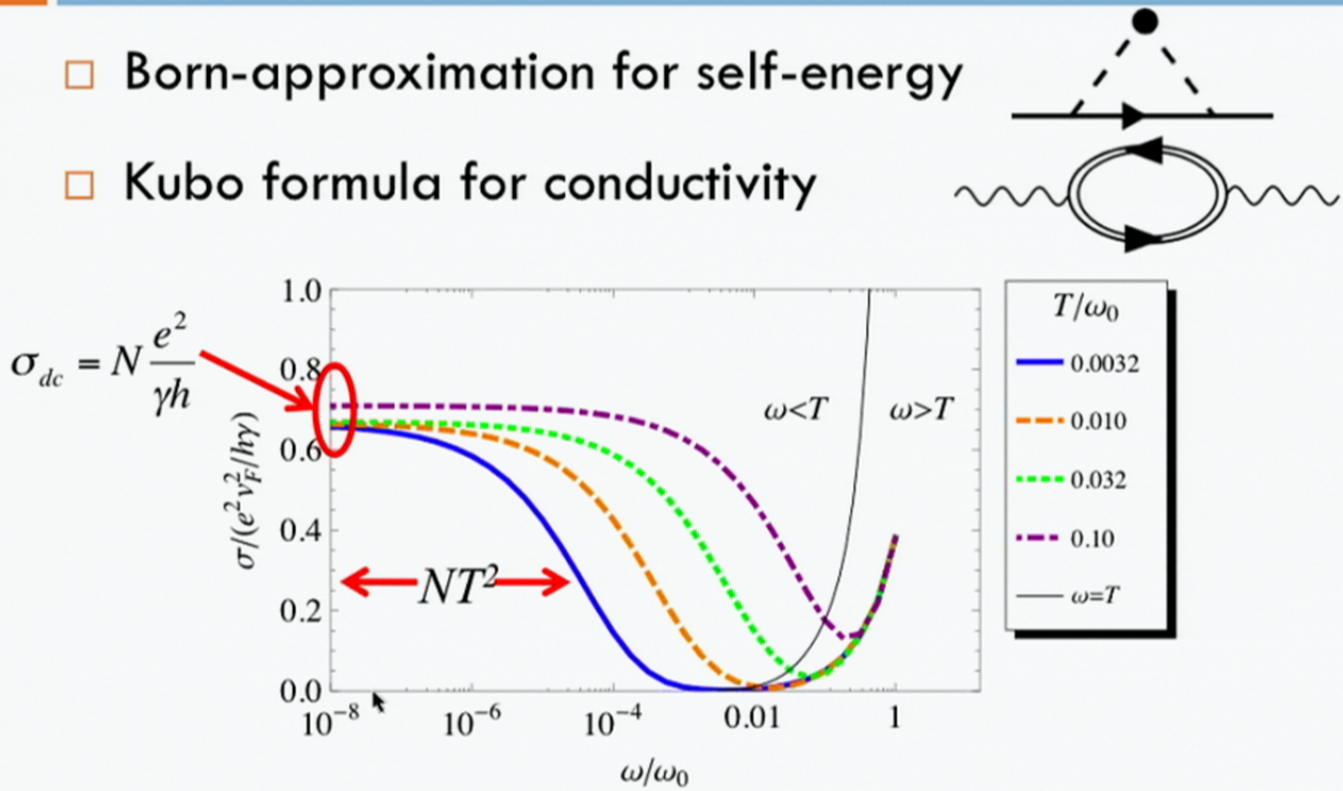

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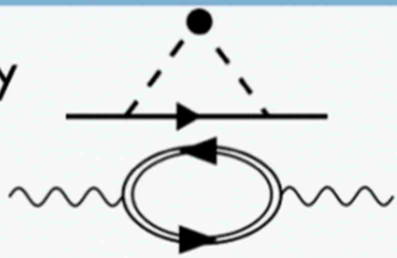
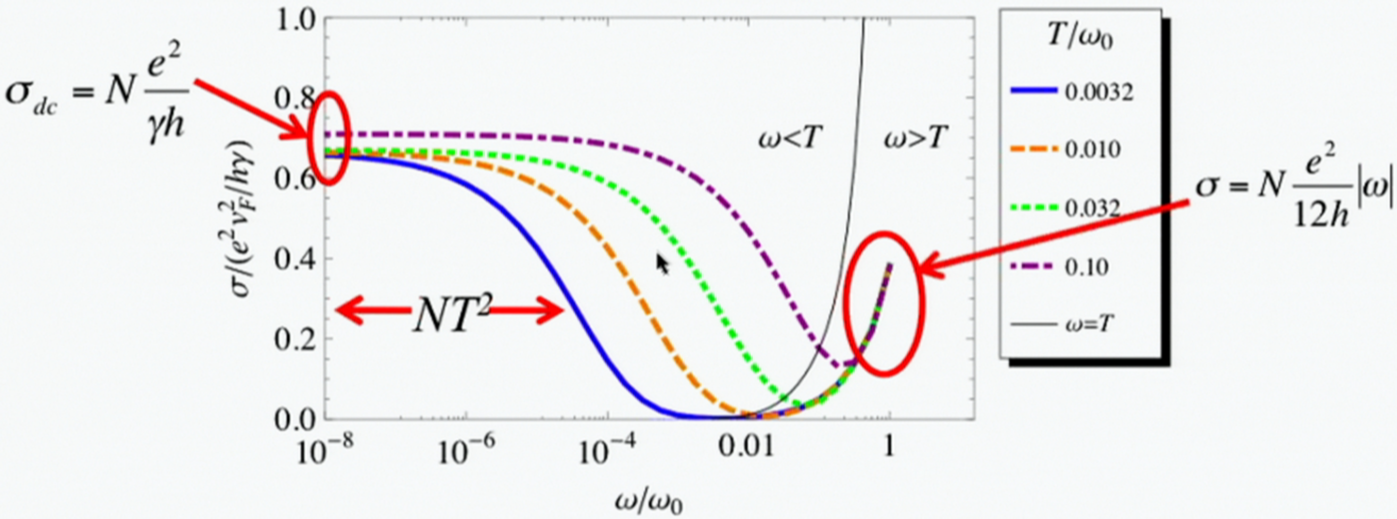
- Born-approximation for self-energy
- Kubo formula for conductivity





PH, Parameswaran, Vishwanath, arXiv:1109.6330

Weyl semimetals transport summary

PH, Parameswaran, Vishwanath, arXiv:1109.6330

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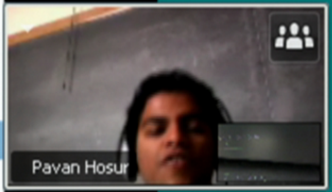
Weyl semimetals transport summary

With interactions

- Quantum Boltzmann equation solved within leading-log approx.
- $\sigma_{dc} \sim T$ resembles experimental data

PH, Parameswaran, Vishwanath, arXiv:1109.6330



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Weyl semimetals transport summary

With interactions

- Quantum Boltzmann equation solved within leading-log approx.
- $\sigma_{dc} \sim T$ resembles experimental data

With disorder (strength γ)

- Different behavior for $\omega << T$ and $\omega >> T$
- $\omega << T$: γ^{-1} Drude peak of width $\sim T^2$
- $\omega >> T$: $\sigma \sim |\omega|$

PH, Parameswaran, Vishwanath, arXiv:1109.6330

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Future research

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Future research

- Quantum oscillations due to Fermi arcs (in progress)

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- Signatures of chiral anomaly

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Future research

- Quantum oscillations due to Fermi arcs (in progress)
- Signatures of chiral anomaly
- Weyl semimetals and superconductivity
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…and more

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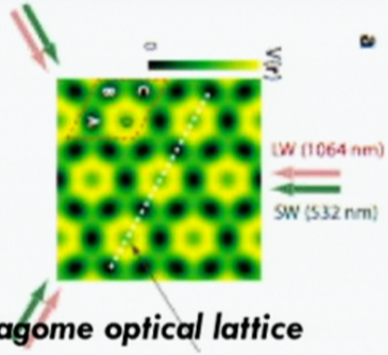
Other projects

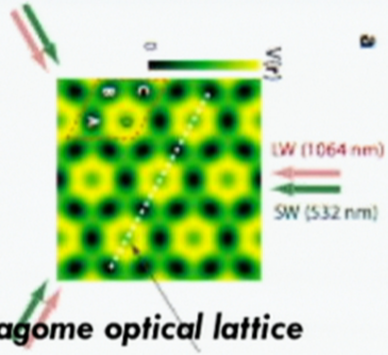


Bosons in Kagome optical lattice

Jo, Guzman Thomas, **PH**, Vishwanath, Stamper-Kurn

arXiv: 1109.1591

Other projects



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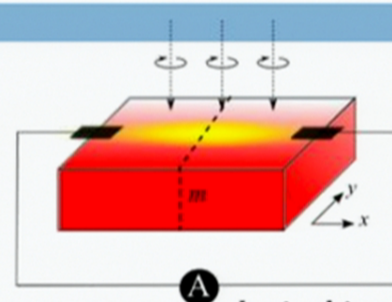
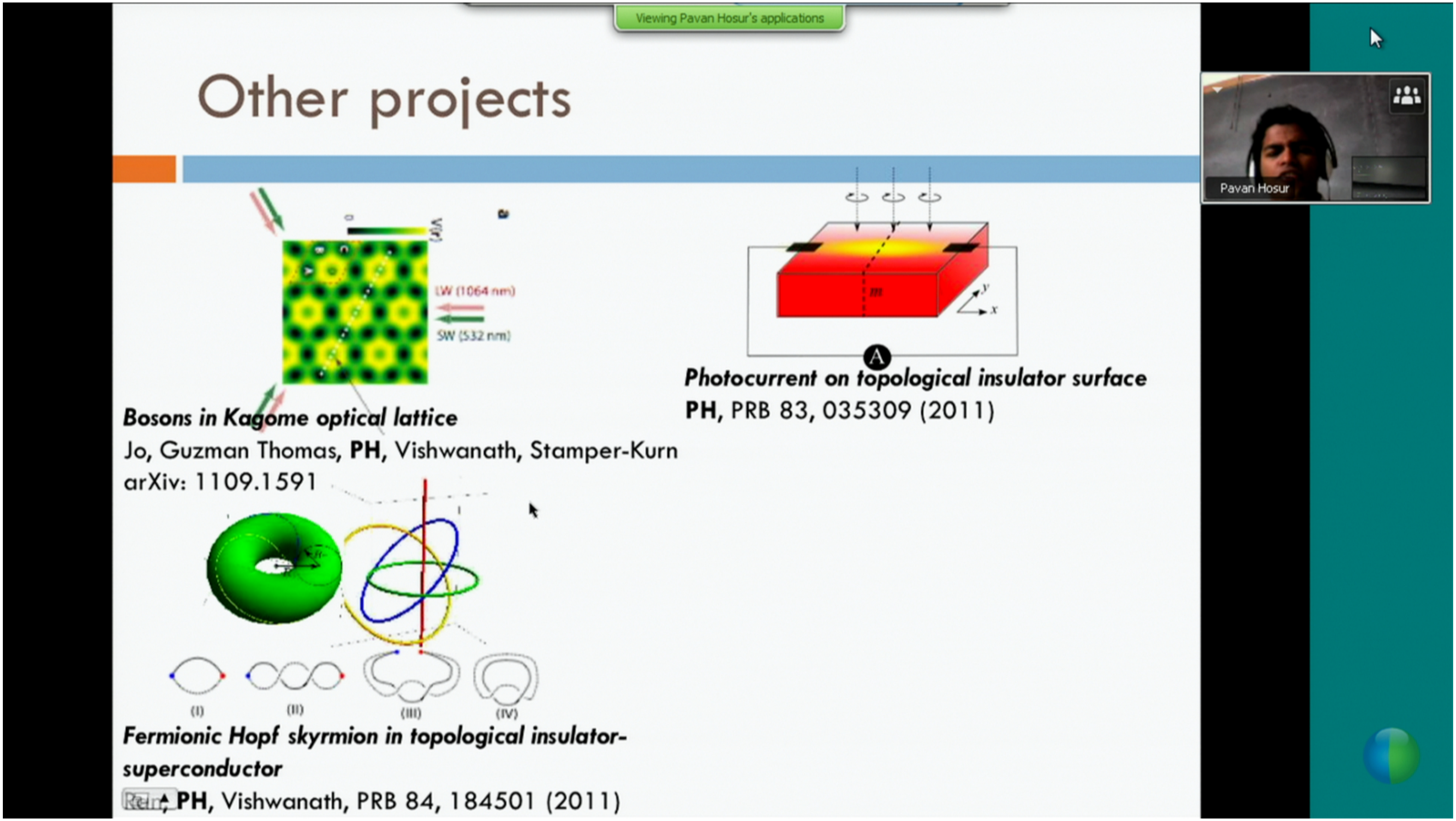


Photocurrent on topological insulator surface

PH, PRB 83, 035309 (2011)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Other projects
LW (1064 nm)
SW (532 nm)
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Jo, Guzman Thomas, PH, Vishwanath, Stamper-Kurn
arXiv: 1109.1591
(I)
(II)
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(IV)
Fermionic Hopf skyrmion in topological insulator-superconductor
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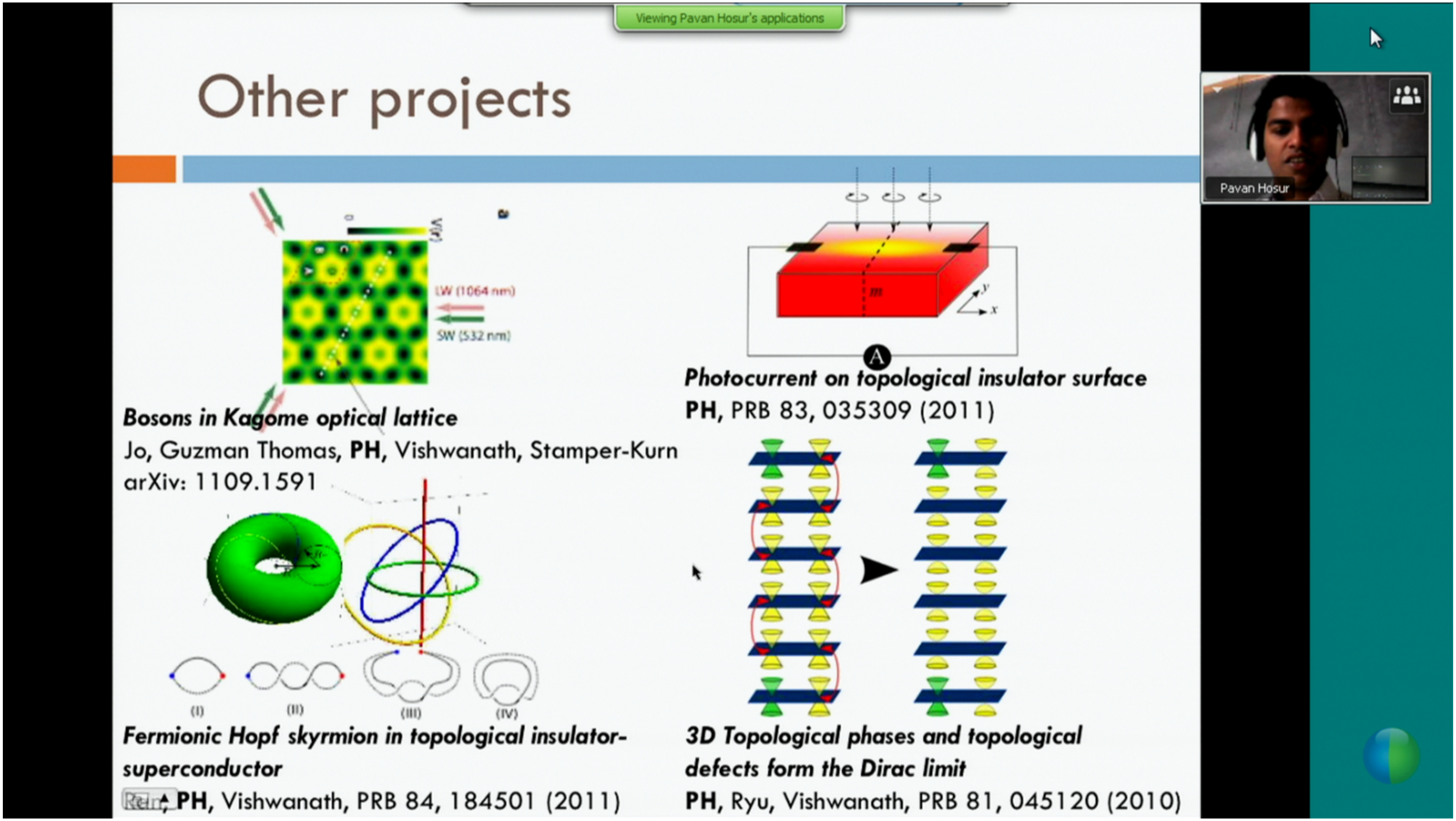
Pavan Hosur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3D Topological phases and topological defects form the Dirac limit
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Thank you

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1. *Majorana modes at the ends of superconductor vortices in doped topological insulators*
   PH, Ghaemi, Mong, Vishwanath, PRL 107, 097001 (2011)
   Viewpoint by Taylor Hughes: *Majorana fermions inch closer to reality,* Physics 4, 67 (2011)
2. *Transport in Weyl semimetals*
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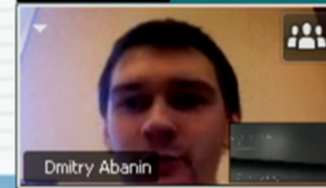

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