Title: Strain Induces Helical Flat Band & Interface Superconductivity in Topological Crystalline Insulators

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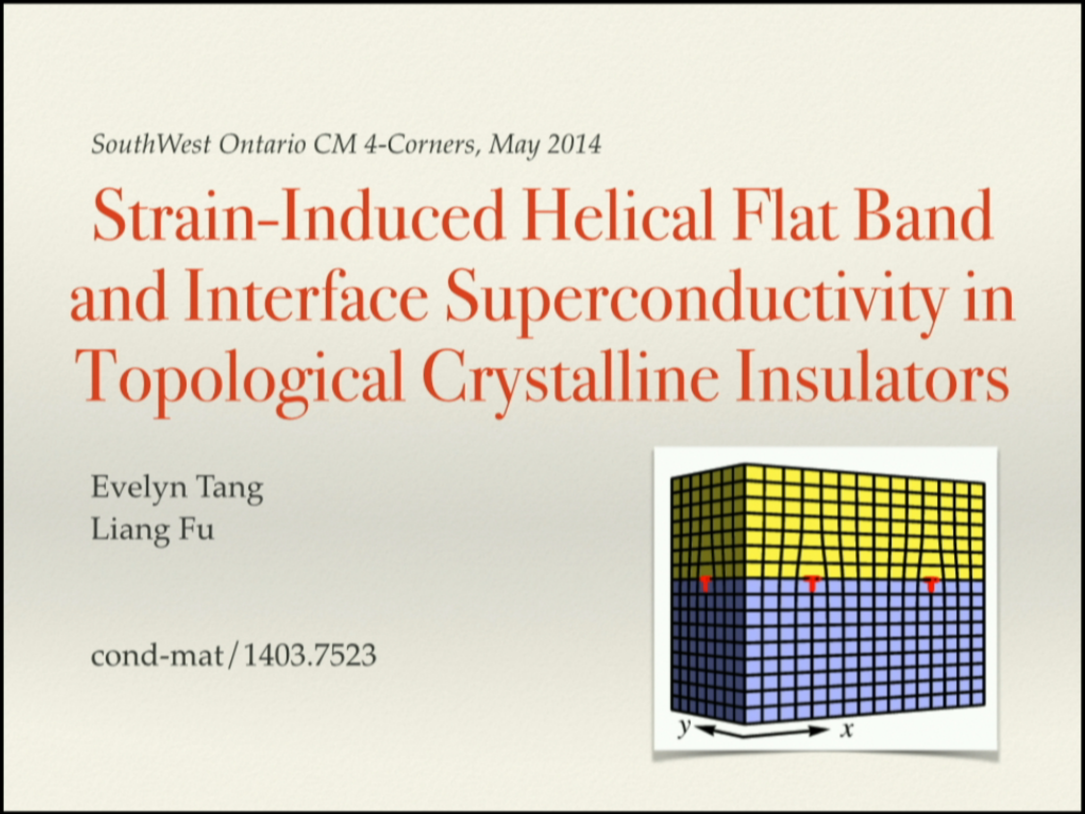
Abstract: <span>Topological crystalline insulators in IV-VI compounds host novel topological surface states, that at low energy, consist of multi-valley massless Dirac fermions. We show that strain generically acts as an effective gauge field on these Dirac fermion surface states and creates pseudo-Landau orbitals without breaking time-reversal symmetry. We predict this is naturally realized in IV-VI semiconductor heterostructures due to the spontaneous formation of a misfit dislocation array at the interface, where the zero-energy Landau orbitals form a nearly flat band. We propose that the high density of states of this topological flat band gives rise to the experimentally observed interface superconductivity in IV-VI semiconductor multilayers at temperatures that are unusually high for semiconductors, and explains its non-BCS dependence on dislocation array period.</span><span></span>



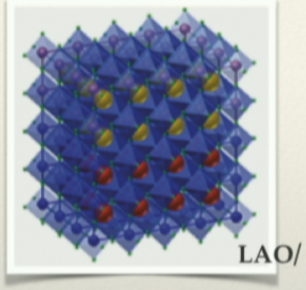
*SouthWest Ontario CM 4-Corners, May 2014*

# Strain-Induced Helical Flat Band and Interface Superconductivity in Topological Crystalline Insulators

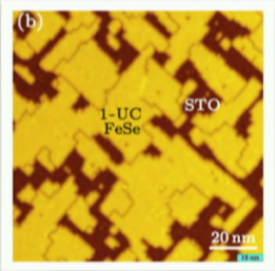
Evelyn Tang
Liang Fu

cond-mat/1403.7523

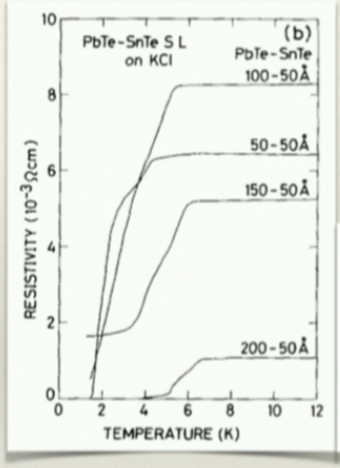
# Interface superconductivity



**LAO/ STO**

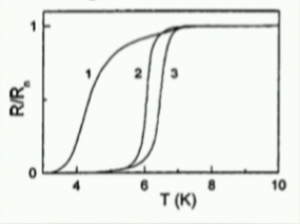


**1-UC FeSe/ STO**

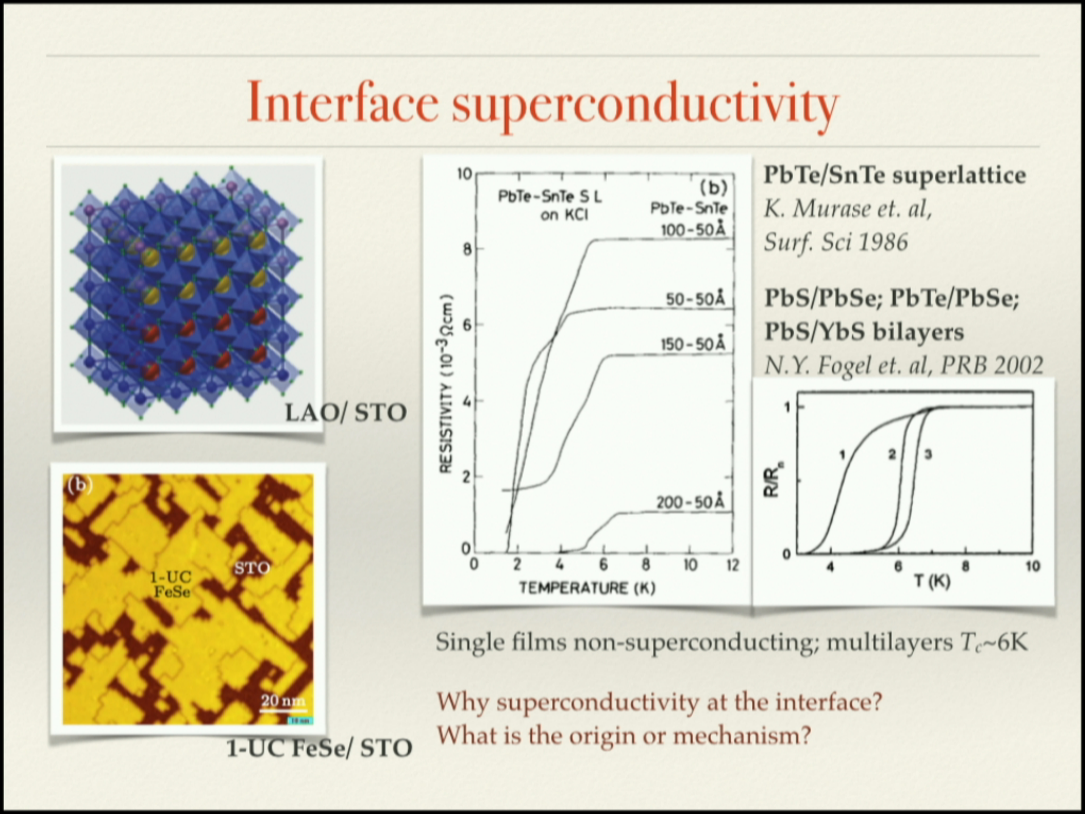


**PbTe/SnTe superlattice**
*K. Murase et. al,*
*Surf. Sci 1986*

**PbS/PbSe; PbTe/PbSe; PbS/YbS bilayers**
*N.Y. Fogel et. al, PRB 2002*



Single films non-superconducting; multilayers $T_c$~6K



# Interface superconductivity

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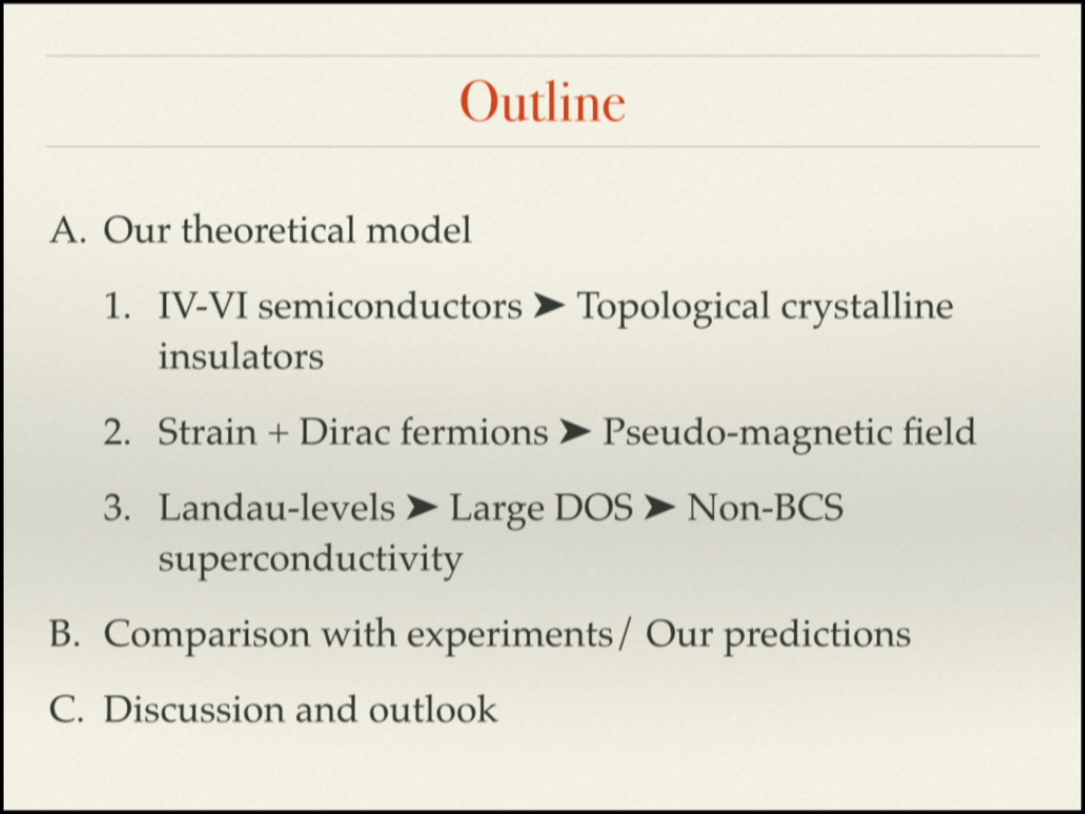
Why superconductivity at the interface?
What is the origin or mechanism?



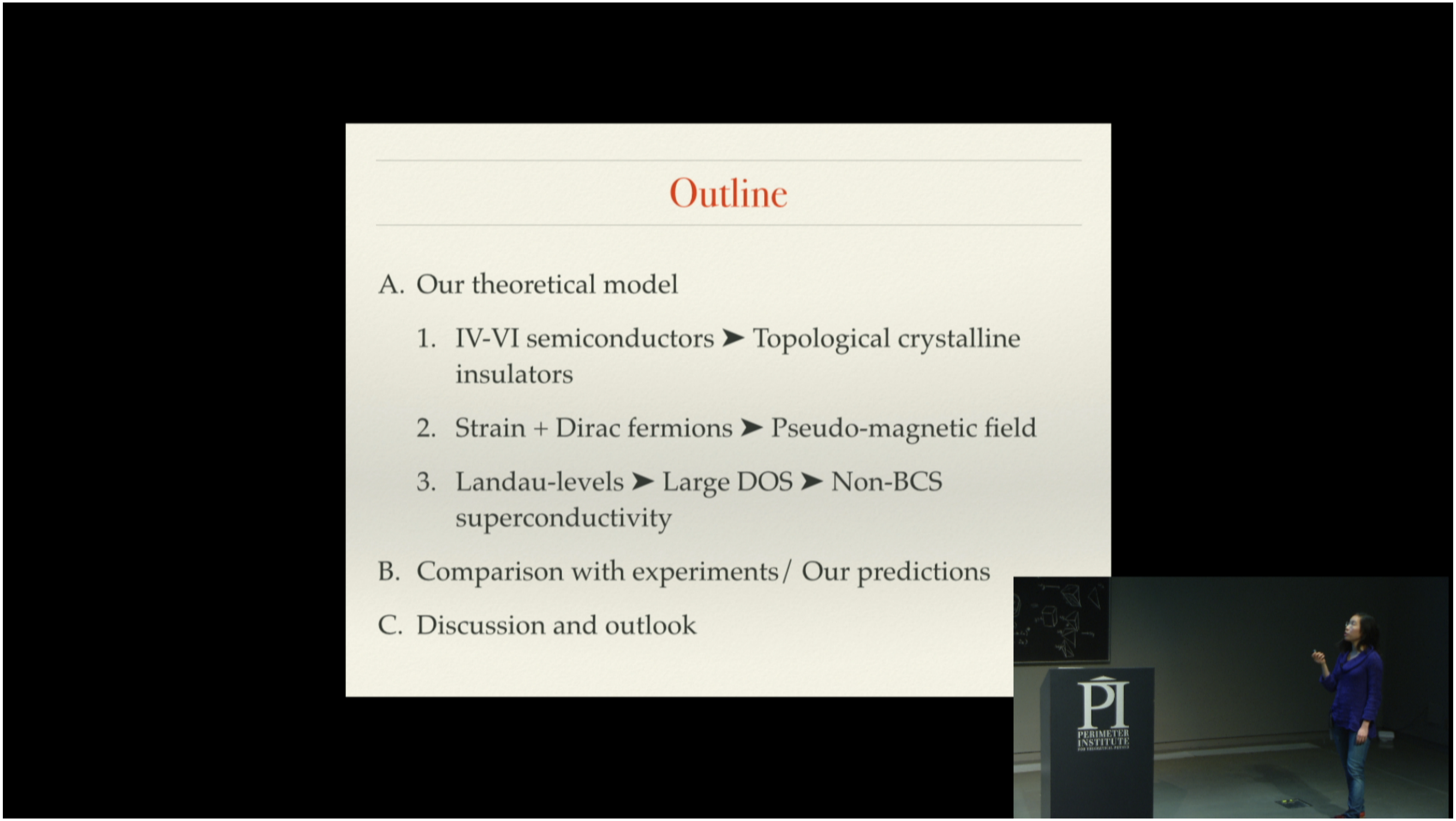
# Outline

A. Our theoretical model

   1. IV-VI semiconductors ➤ Topological crystalline insulators
   2. Strain + Dirac fermions ➤ Pseudo-magnetic field
   3. Landau-levels ➤ Large DOS ➤ Non-BCS superconductivity

B. Comparison with experiments / Our predictions

C. Discussion and outlook



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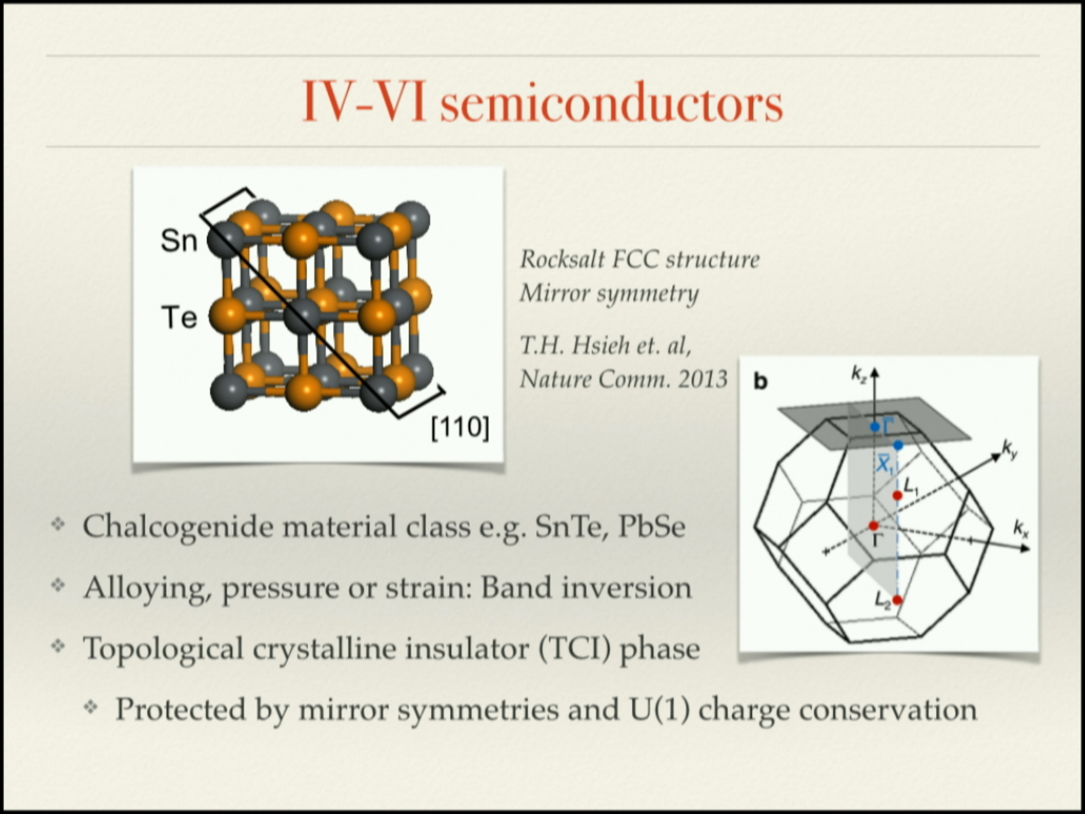
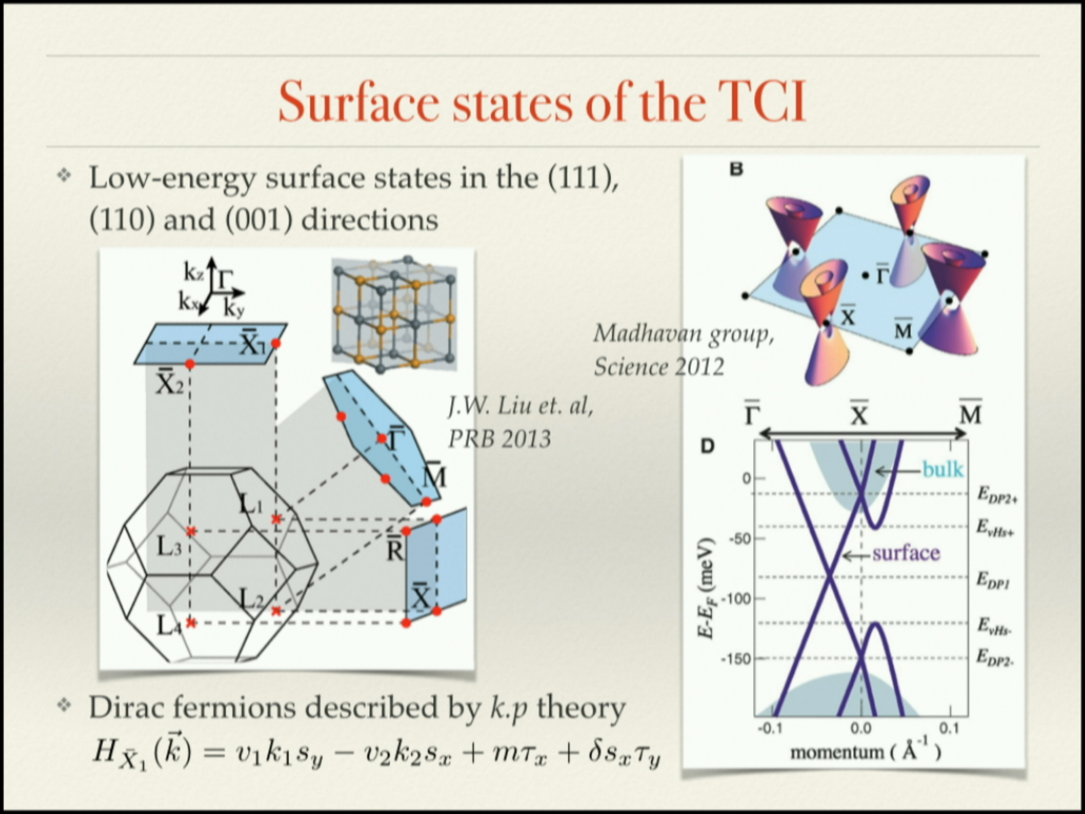


# IV-VI semiconductors

*Rocksalt FCC structure*
*Mirror symmetry*

*T.H. Hsieh et. al,*
*Nature Comm. 2013*

- Chalcogenide material class e.g. SnTe, PbSe
- Alloying, pressure or strain: Band inversion
- Topological crystalline insulator (TCI) phase
  - Protected by mirror symmetries and U(1) charge conservation



# Surface states of the TCI

- Low-energy surface states in the (111), (110) and (001) directions

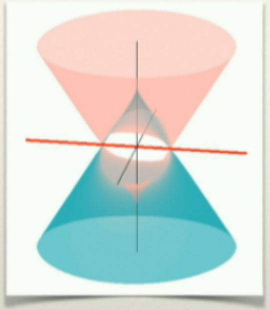
*J.W. Liu et. al, PRB 2013*

*Madhavan group, Science 2012*

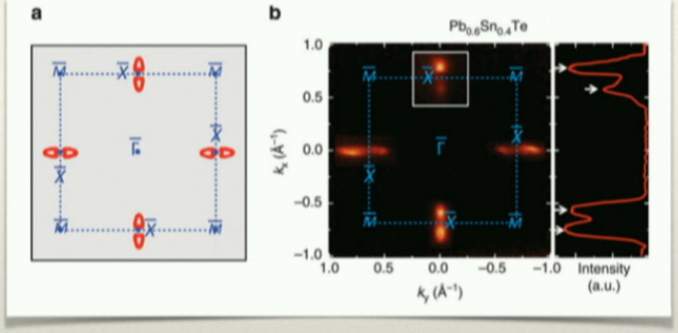
- Dirac fermions described by *k.p* theory

$$H_{\bar{X}_1}(\vec{k}) = v_1 k_1 s_y - v_2 k_2 s_x + m\tau_x + \delta s_x \tau_y$$

# (001) surface: Dirac points along mirror axes

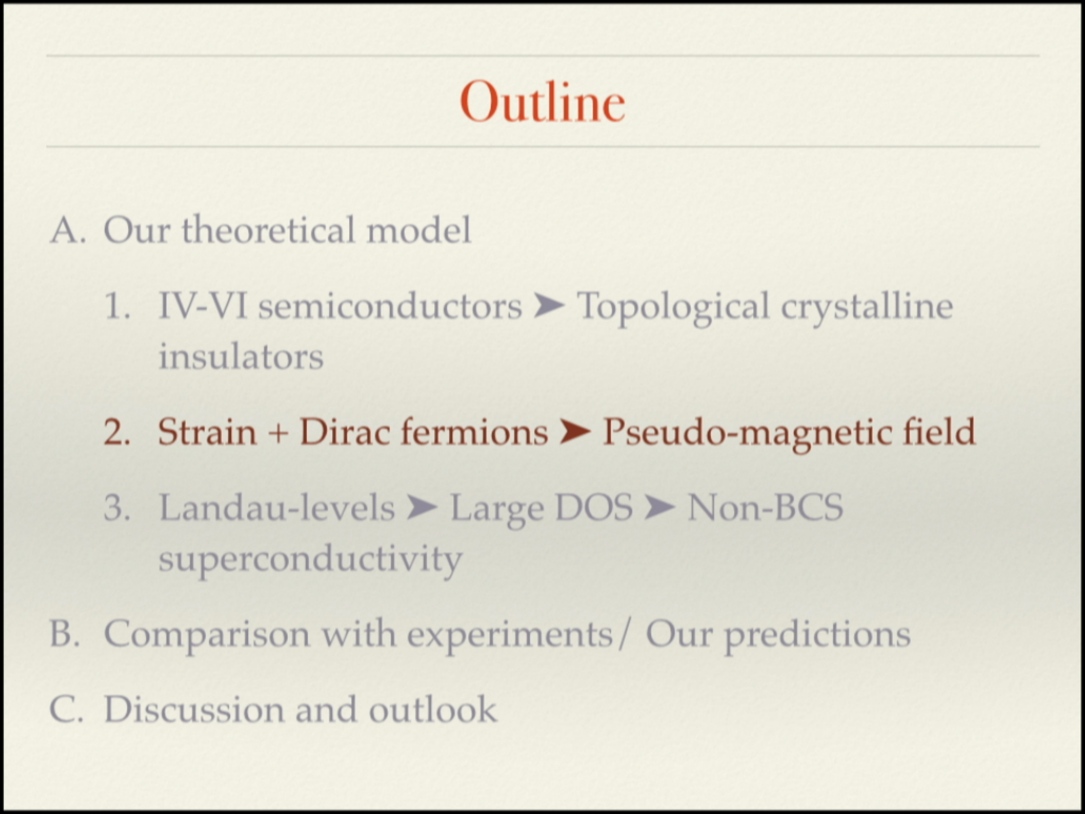


*Two Dirac nodes along mirror axis*



ARPES: *Hasan group, Nature Comm. 2012*

- Mirror symmetry forbids hybridization along ΓX direction
- Pair of time-reversed partners: couple oppositely to strain-induced pseudo gauge-field
- Unlike Dirac points in a regular TI which cannot couple to strain



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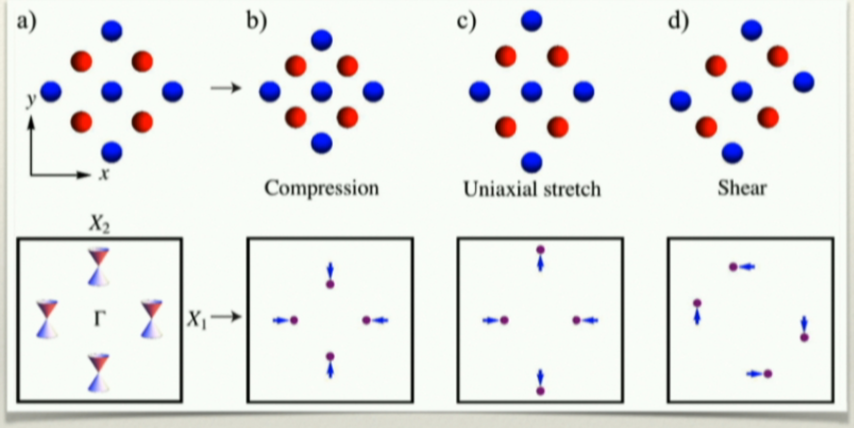
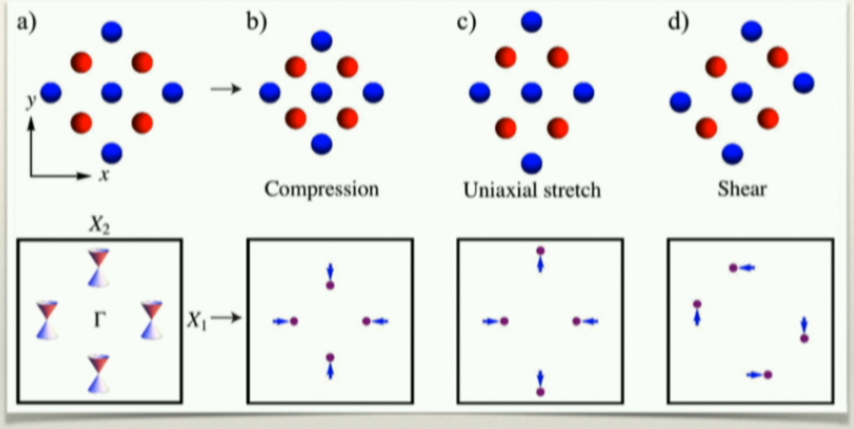
# Strain: pseudo gauge-field for Dirac fermions



- For the Dirac fermion at valley $\mathbf{K}_j$, the strain-induced vector potential $\mathbf{A}_j \equiv \mathbf{K}_j' - \mathbf{K}_j$ is to lowest order

$$\mathbf{A}_j = (A_j^x, A_j^y); \qquad \begin{aligned} \mathbf{A}_1 &= (\alpha_1 u_{xx} + \alpha_2 u_{yy},\ \alpha_3 u_{xy}), \\ \mathbf{A}_2 &= (\alpha_3 u_{xy},\ \alpha_1 u_{yy} + \alpha_2 u_{xx}). \end{aligned}$$

# Strain: pseudo gauge-field for Dirac fermions



- For the Dirac fermion at valley $\mathbf{K}_j$, the strain-induced vector potential $\mathbf{A}_j \equiv \mathbf{K}'_j - \mathbf{K}_j$ is to lowest order

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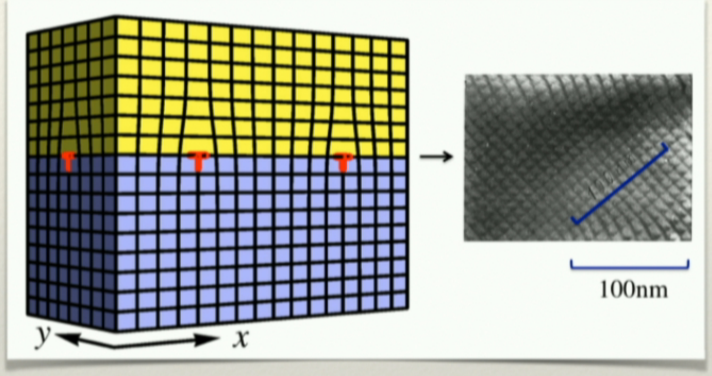
# Strain profile in a TCI bilayer

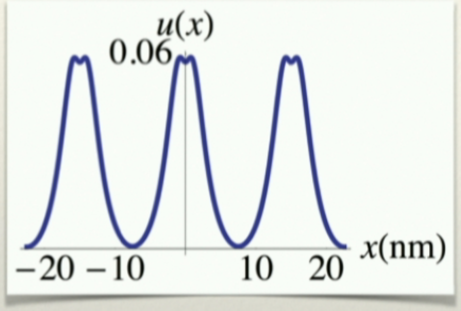


*TEM image of the square misfit dislocation grid, which forms at the interface of PbTe/PbSe (lattice spacing is 0.64nm)*

*N.Y. Fogel et. al, PRB 2002*

- Lattice mismatch between two materials of 3-10%
- Spontaneous formation of misfit edge dislocations
- Regular two-dimensional dislocation array along the mirror axes

# Spatially-varying strain field



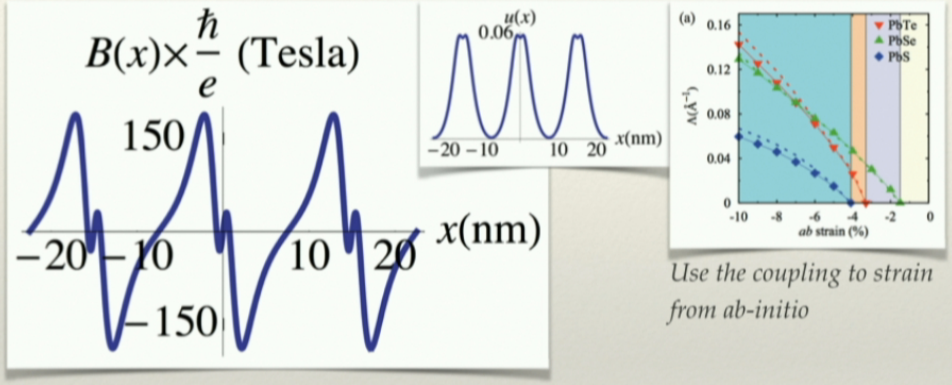
*Plotted using representative parameters: array period 15nm, Poisson ratio for PbTe of 0.26, lattice constant 0.64nm*

$$u_{xx}(x) = \sum_N u^0_{xx}(x - N\lambda),$$

$$u^0_{xx}(x) = \frac{bz}{2\pi(1-\nu)} \frac{(3x^2+z^2)}{(x^2+z^2)^2}.$$

- Total strain field is sum of contributions from each dislocation
- Field for single dislocation given by classical strain theory
- Similar behavior along other mirror axis obtained by rotation

# Periodically-alternating B-field



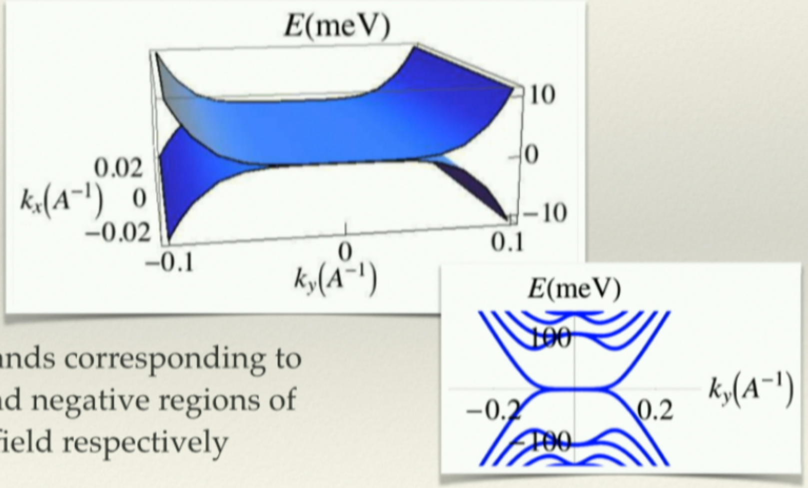
*Use the coupling to strain from ab-initio*

- At one pair of Dirac points, $B_2(x) = \nabla \times \mathbf{A}_2^T(x)$
- Spatially-varying strain necessary for a pseudo-magnetic field
- Maximum magnetic field is ~180 Tesla

# Flat bands at low momenta

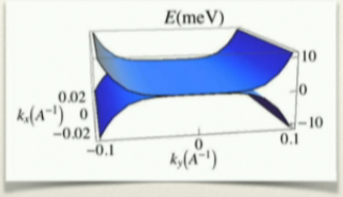
- Approximate periodic field with first Fourier component

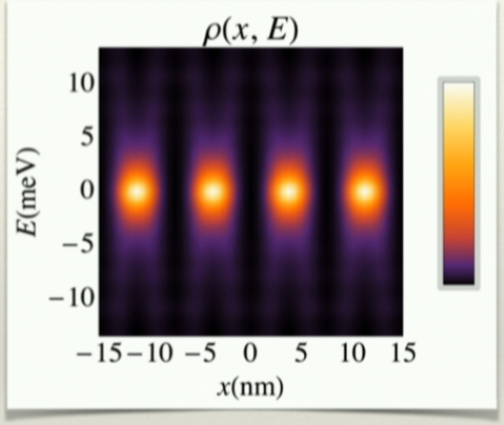
$$H = -iv_x \partial_x s_y - v_y (k_y - A_y(x)) s_x, \quad A_y(x) = A_0 \cos(2\pi x/\lambda)$$



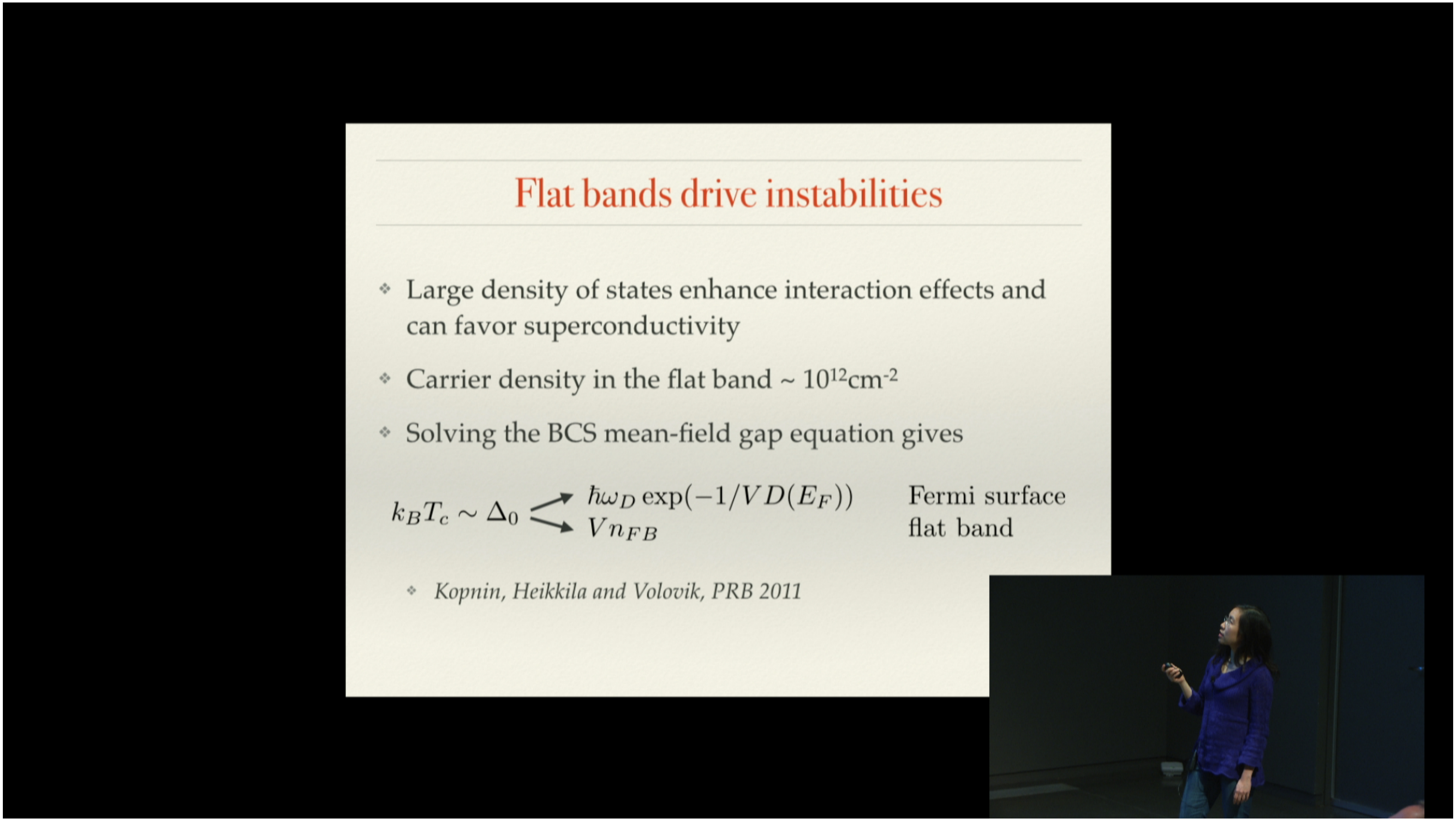
- Two flat bands corresponding to positive and negative regions of pseudo B-field respectively

# Transition regions: snake states





- Large DOS at $E=0$ from flat bands
- Dispersive states at transition regions: chiral snake states
  - $\sigma_{xy} = \text{sgn}(\mu B)\frac{1}{2}\frac{e^2}{h}$
- Another time-reversed copy from opposite valley
  - Jointly give helical snake states

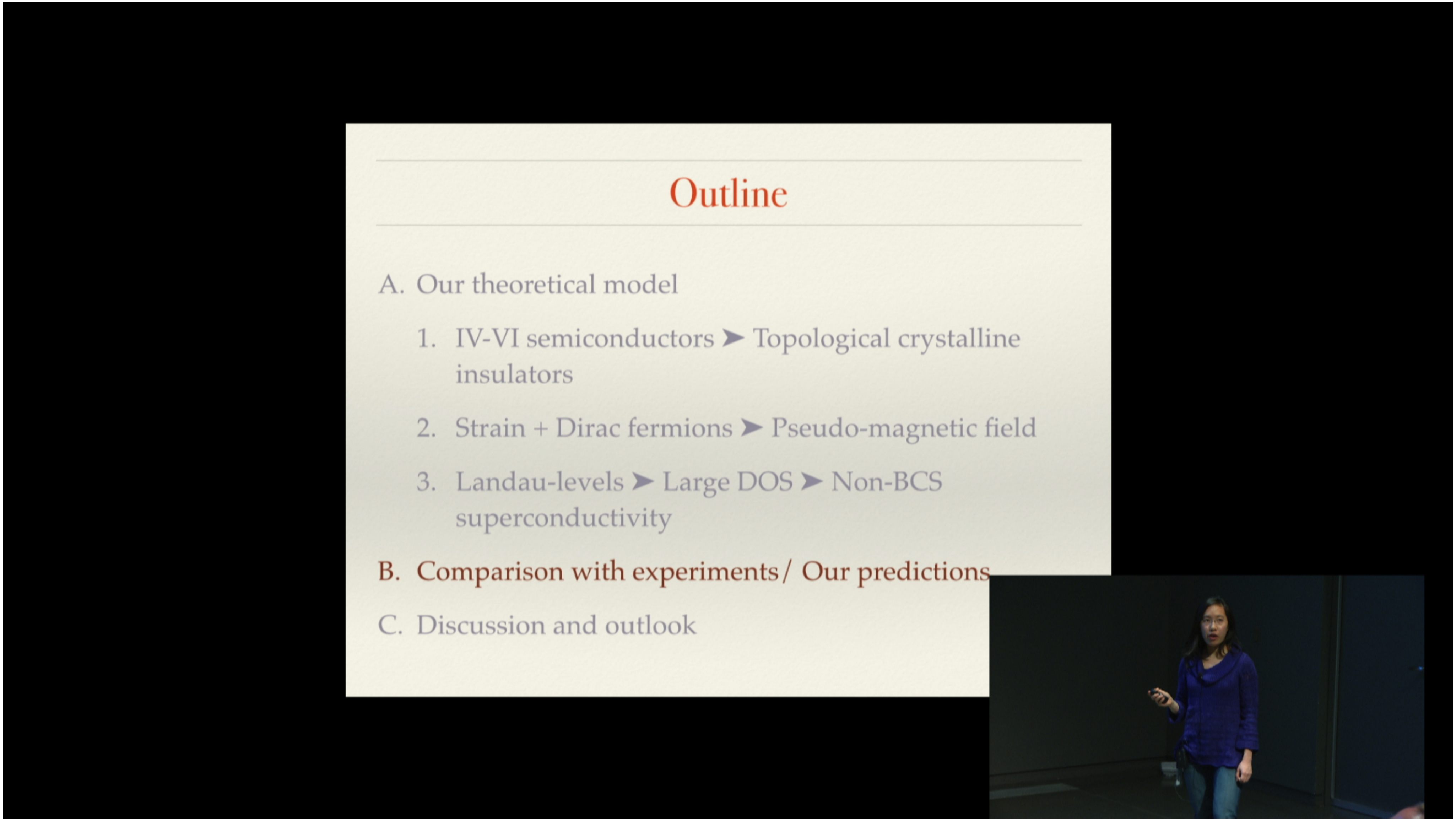


# Flat bands drive instabilities

- Large density of states enhance interaction effects and can favor superconductivity
- Carrier density in the flat band ~ $10^{12}\text{cm}^{-2}$
- Solving the BCS mean-field gap equation gives

$$k_B T_c \sim \Delta_0 \begin{array}{ll} \nearrow \hbar\omega_D \exp(-1/VD(E_F)) & \text{Fermi surface} \\ \searrow V n_{FB} & \text{flat band} \end{array}$$

- *Kopnin, Heikkila and Volovik, PRB 2011*



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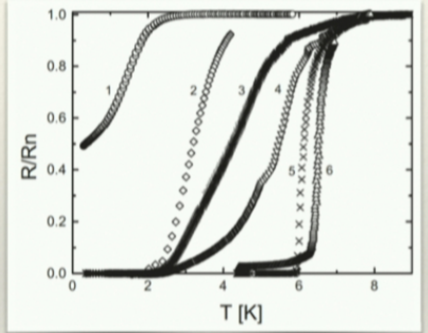
# Experimental features

- Superconductivity measured in several IV-VI multilayers, $T_c$ is 2.5-6.4K

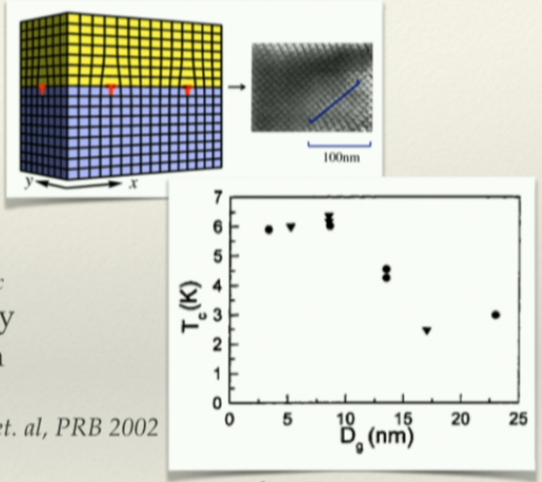


*Six PbTe/PbS bilayers*
*(different thicknesses)*
*N.Y. Fogel et. al, PRB 2006*

- Superconductivity is two-dimensional
- In narrow-gap semiconductors ($E_g < 0.3$eV)

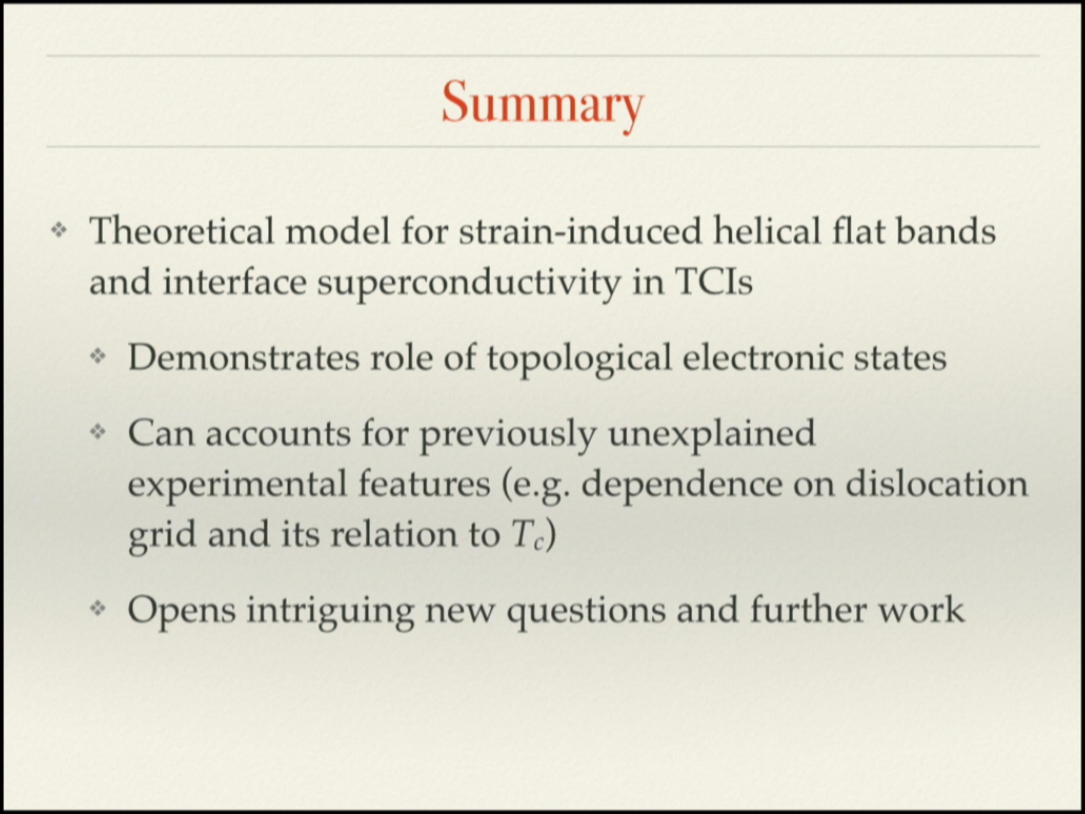
# Dependence on dislocation array

- Samples without a regular dislocation array show only partial superconducting transitions
- In superconducting samples, $T_c$ increases from 3K to 6K as array period $D_g$ decreases from 23nm to 10nm



N.Y. Fogel et. al, PRB 2002

- Consistent with $T_c$ depending parametrically on the flat band degeneracy — non-BCS dependence

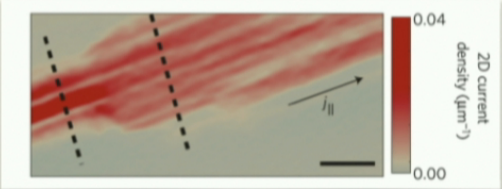


# Summary

- Theoretical model for strain-induced helical flat bands and interface superconductivity in TCIs
    - Demonstrates role of topological electronic states
    - Can accounts for previously unexplained experimental features (e.g. dependence on dislocation grid and its relation to $T_c$)
    - Opens intriguing new questions and further work

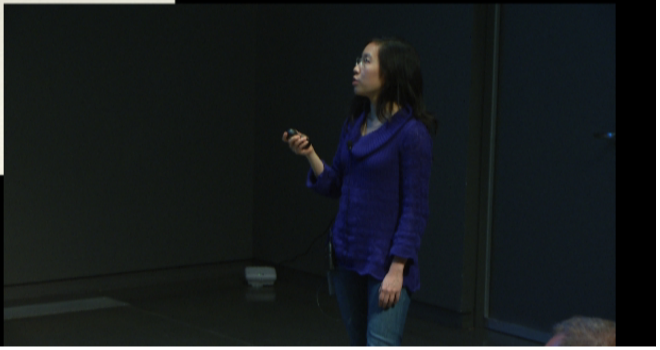
# Further work

- Related questions
  - Role of interactions? (Jörn)
  - Analytical description? (Vlad)



*Moler group, Nature Mat. 2013*

- Connection to interface superconductivity in other systems?
  - Conductance channels in STO related to structural distortions
  - Strain effects seem important
- Usefulness of flat bands
  - New states with repulsive interactions? E.g. FQHE
  - Possible route towards higher $T_c$ by strain engineering



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**Thank you!**