ISSP Spintronics and Mesoscopics 2015

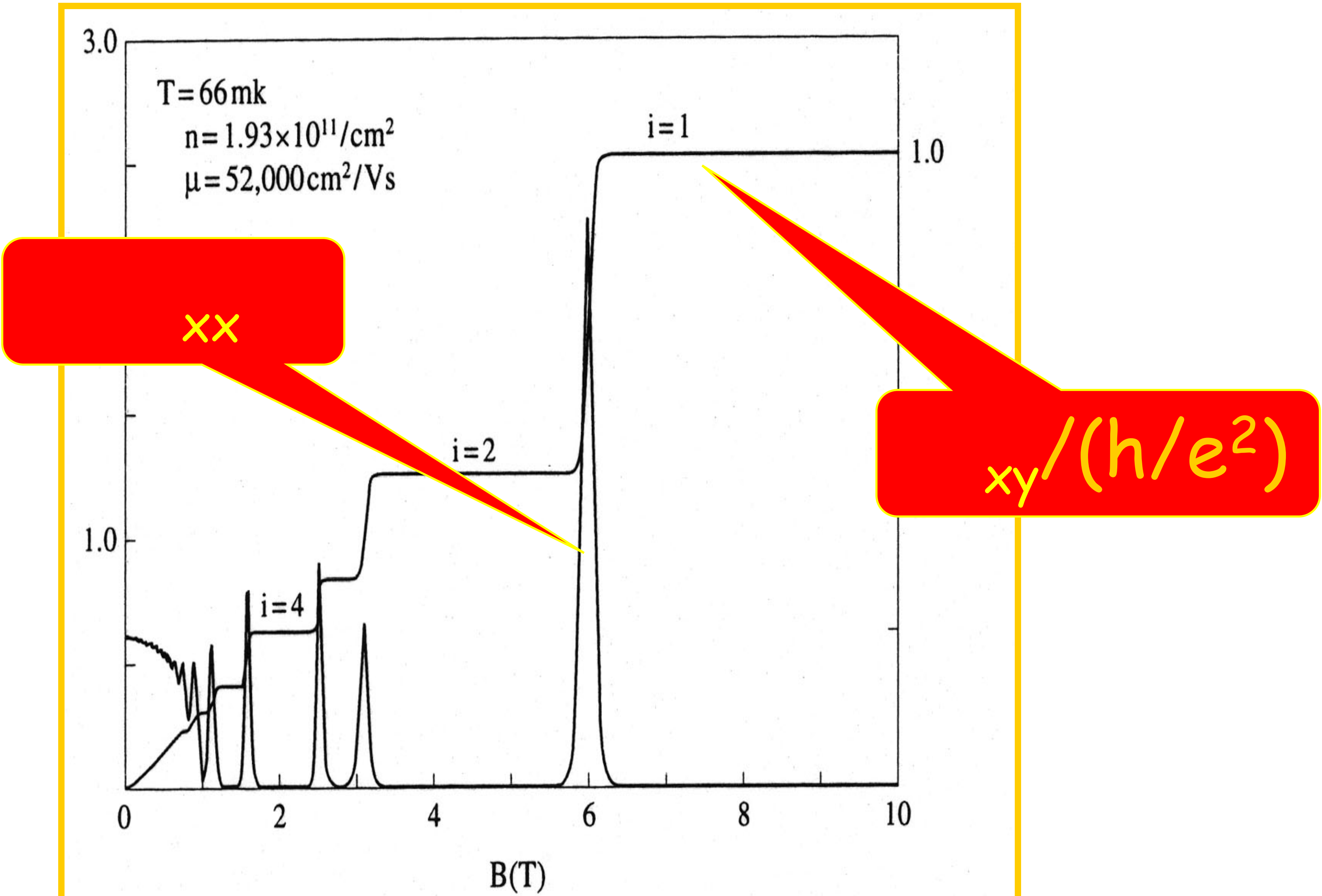
Anomalous Charge and Spin Hall Effects

Allan MacDonald - University of Texas at Austin
Anna Pertsova, Carlo Canali - LNU Kalmar Sweden
Massoud Masir - University of Texas at Austin

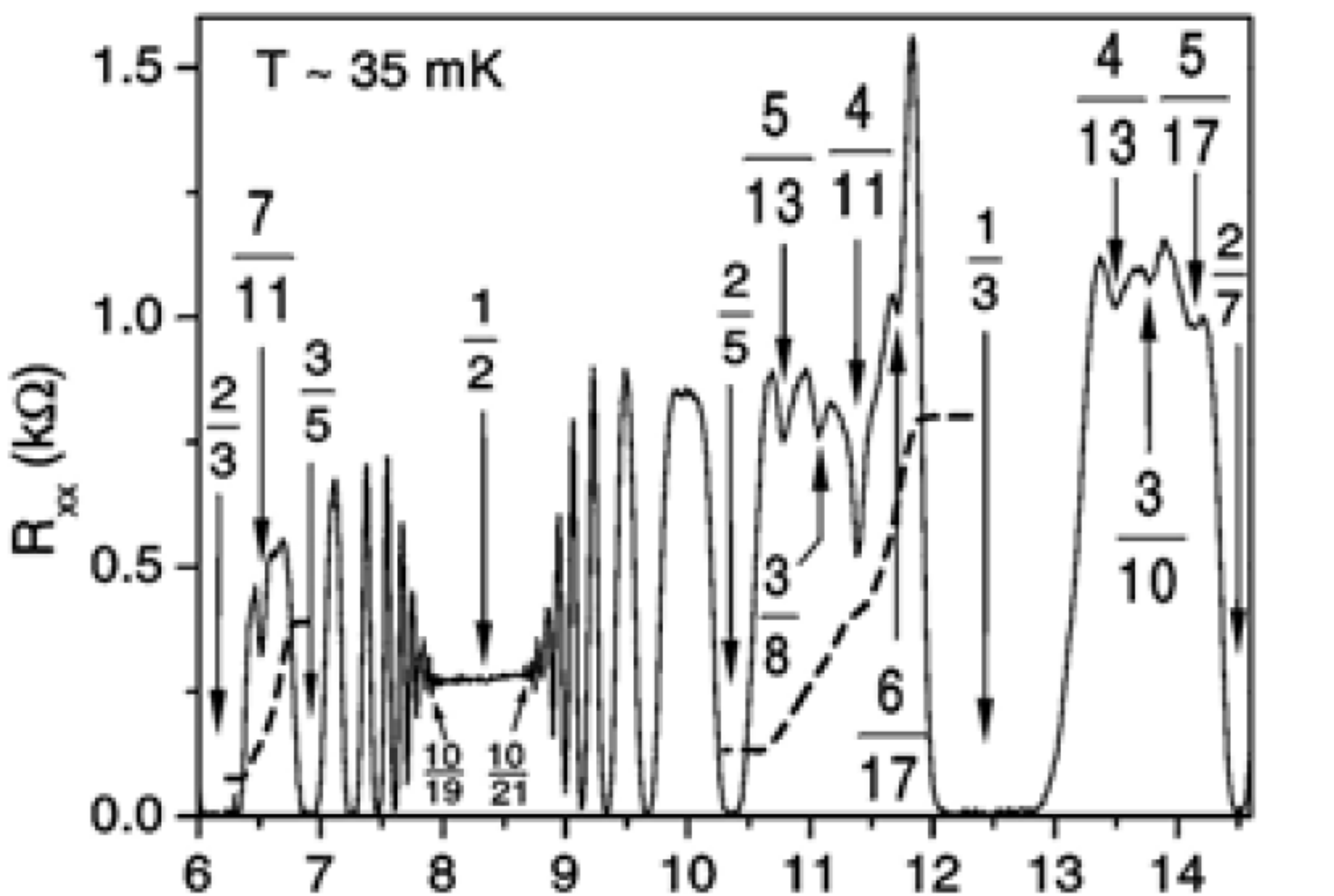
Quantum Hall Effect
(Insulators)

Intrinsic
Charge and Spin Hall Effects
and SOITs

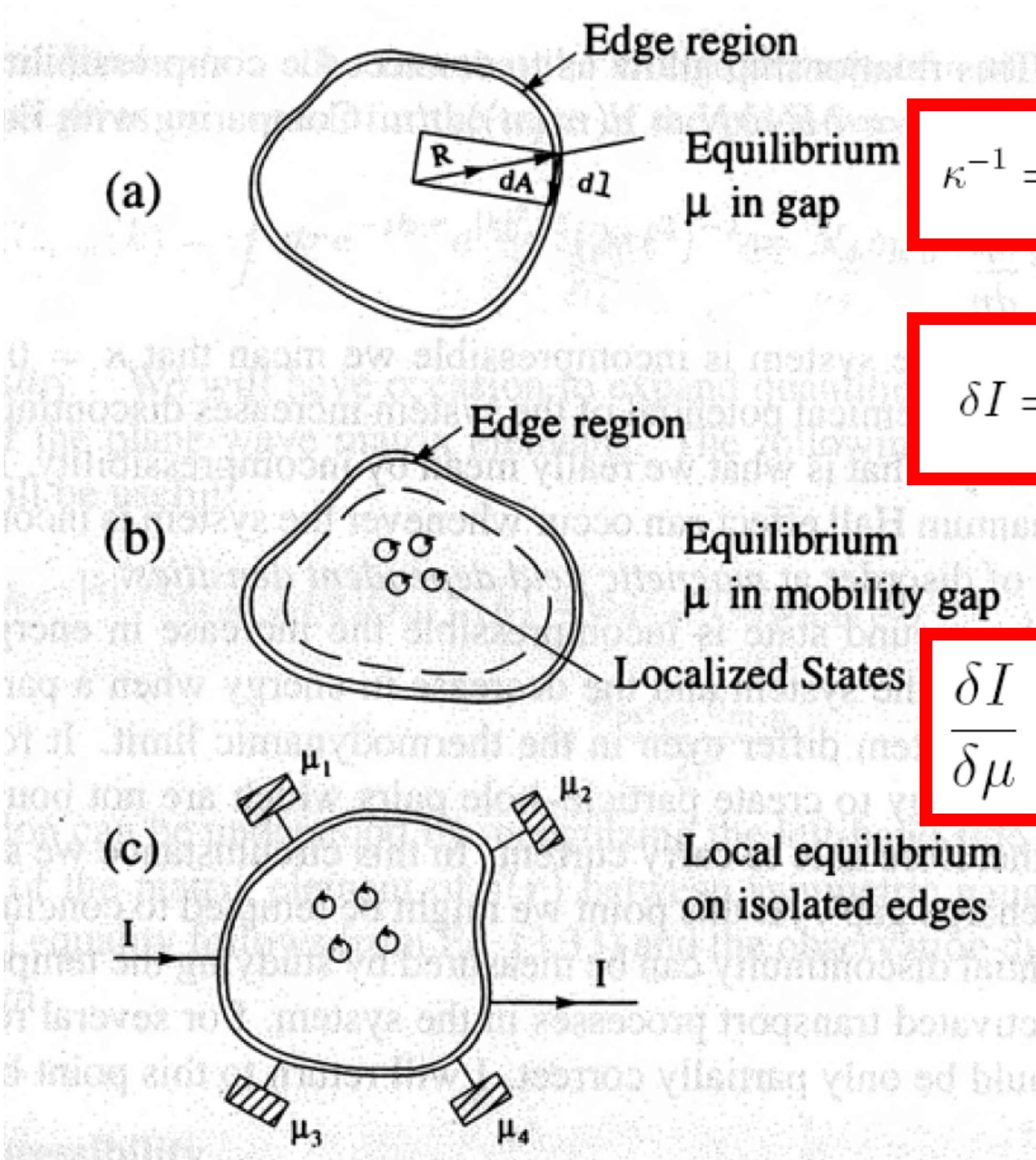
Integer Quantum Hall Effect



Fractional Quantum Hall Effect



Incompressible States & Streda Formula



$$\kappa^{-1} = n^2 \frac{d\mu}{dn}$$

Compressibility

$$\delta I = \frac{c}{A} \delta M$$

Edge Current

$$\frac{\delta I}{\delta \mu} = c \frac{\partial n}{\partial B}\Big|_{\mu}$$

Conductance and LL degeneracy

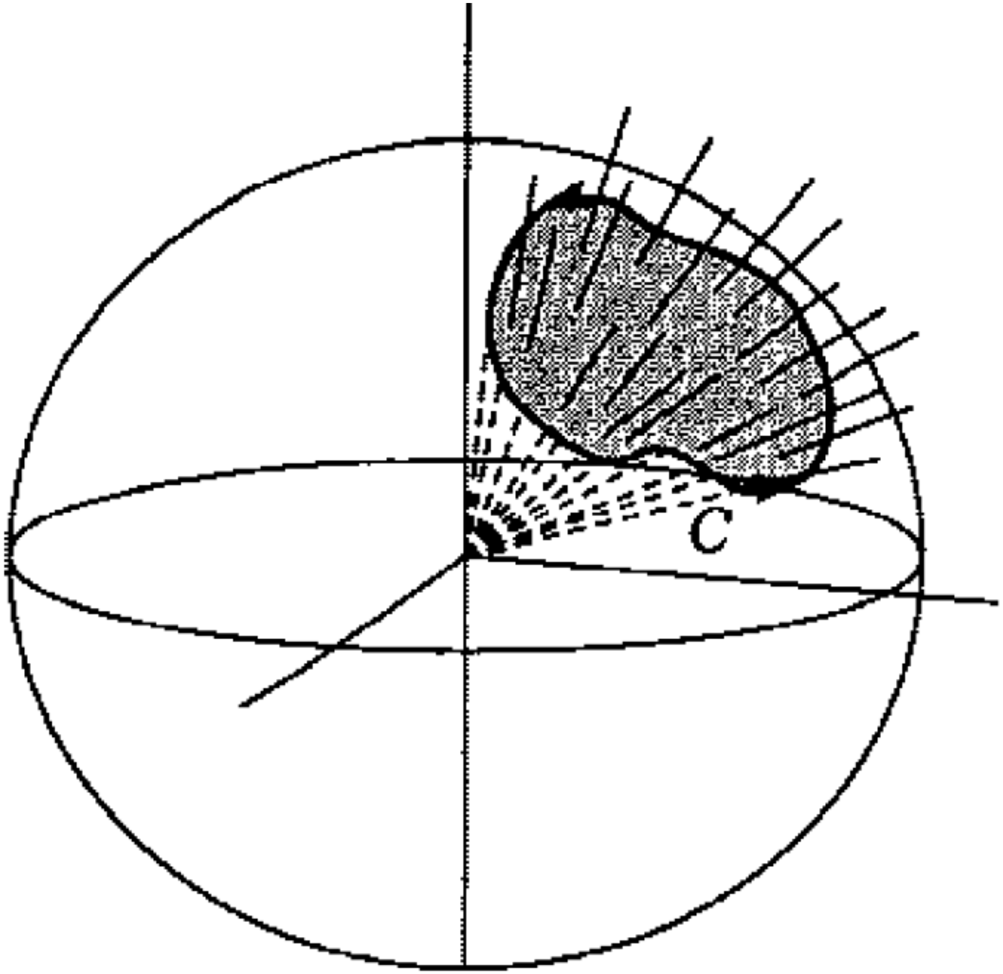
Quantized Hall Conductance in a Two-Dimensional Periodic Potential

D. J. Thouless, M. Kohmoto,[a] M. P. Nightingale, and M. den Nijs
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 30 April 1982)

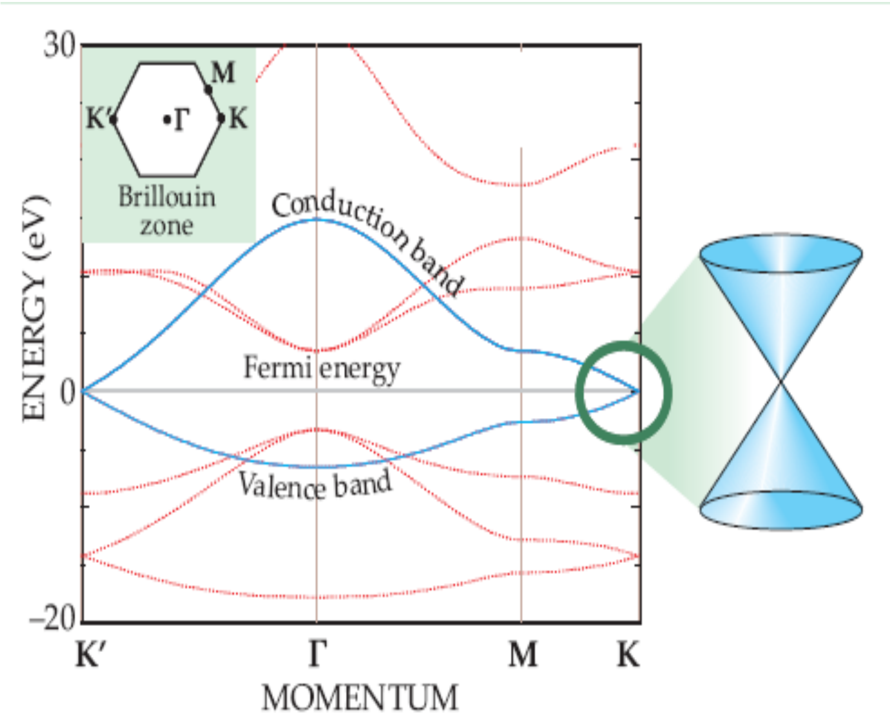
$$\sigma_H = \frac{ie^2}{2\pi h} \sum \int d^2k \int d^2r \left(\frac{\partial u^*}{\partial k_1} \frac{\partial u}{\partial k_2} - \frac{\partial u^*}{\partial k_2} \frac{\partial u}{\partial k_1} \right)$$

Berry
Curvature
Chern Index

Joe Zwanziger
Berkeley
Ph.D. Thesis 1990



Dirac Points and Berry Curvature



$$\tau_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\tau_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$H = -vk \cdot \tau$$

Intersublattice Hopping

PseudospinChirality !

Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly"

F. D. M. Haldane

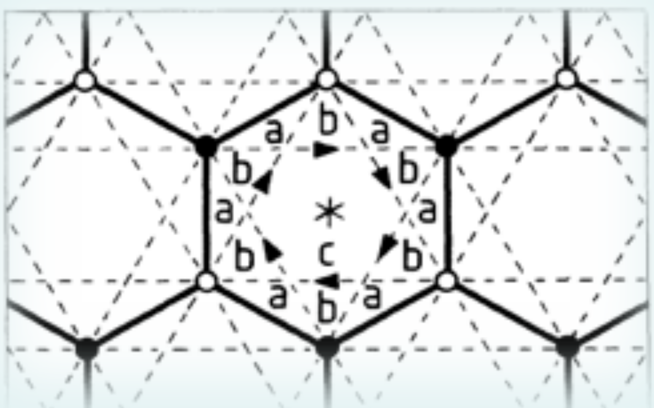
Department of Physics, University of California, San Diego, La Jolla, California 92093

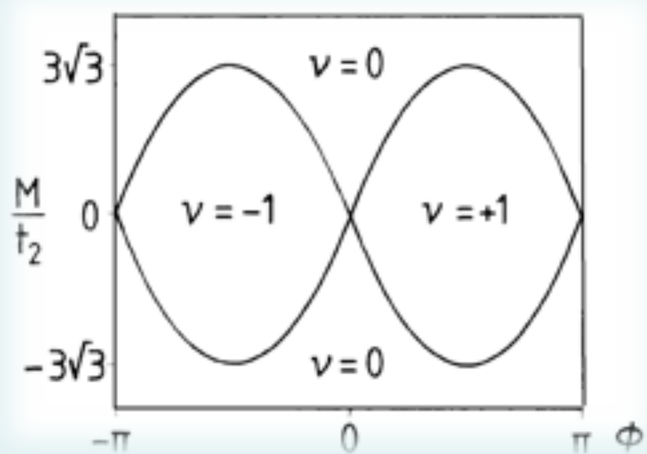
(Received 16 September 1987)

$$H(\mathbf{k}) = 2t_2\cos\phi\left(\sum_i \cos(\mathbf{k}\cdot\mathbf{b}_i)\right)\mathbf{I} + t_1\left(\sum_i [\cos(\mathbf{k}\cdot\mathbf{a}_i)\sigma^1 + \sin(\mathbf{k}\cdot\mathbf{a}_i)\sigma^2]\right) + \left[M - 2t_2\sin\phi\left(\sum_i \sin(\mathbf{k}\cdot\mathbf{b}_i)\right)\right]\sigma^3$$

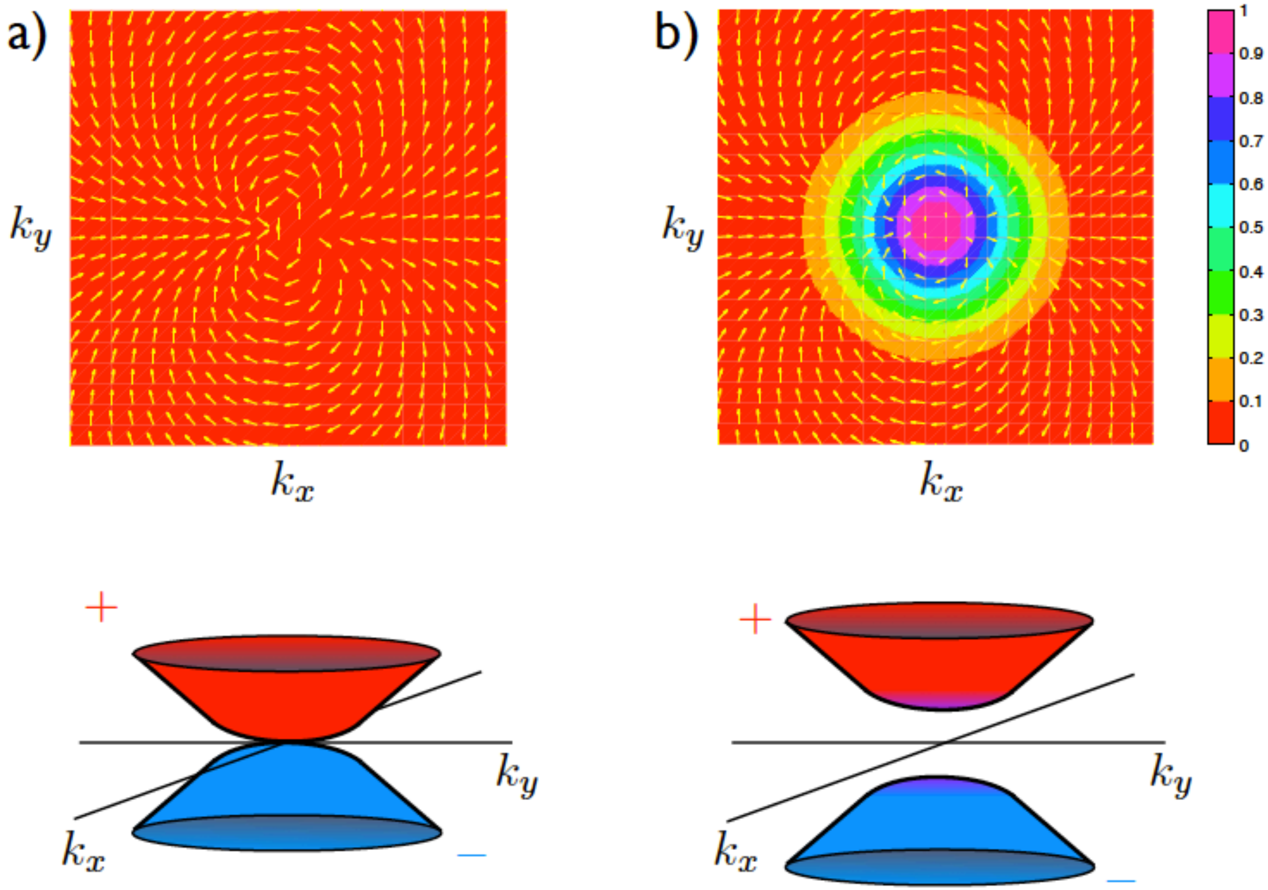
Chern Index Phase Diagram

Pseudospin-Orbit Coupling



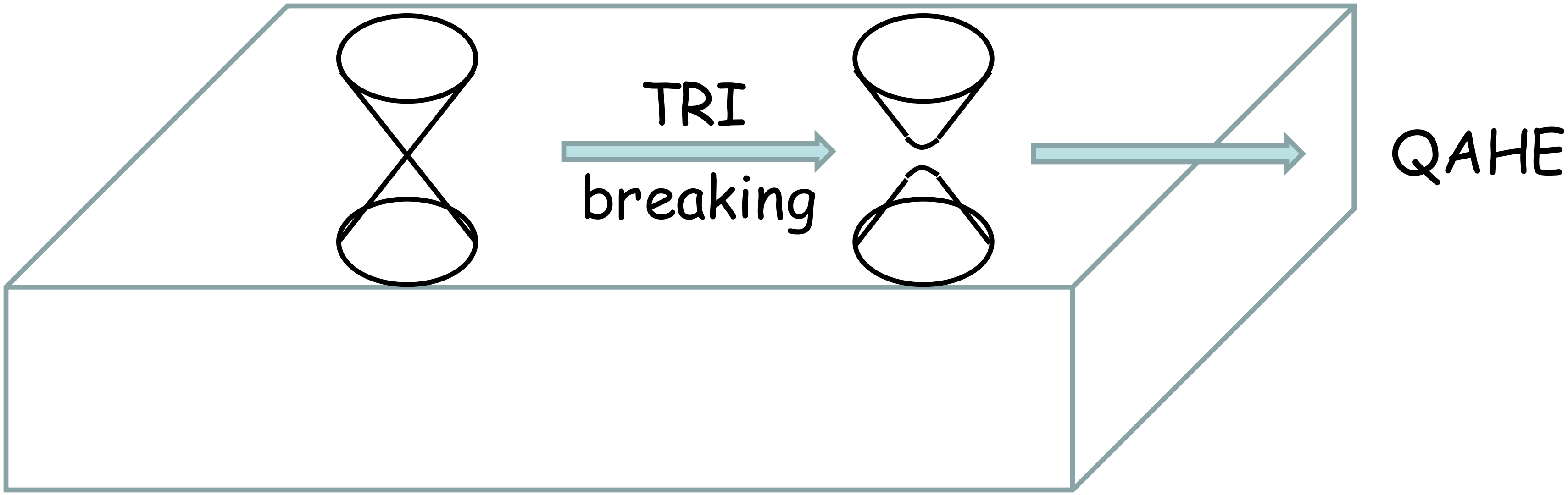


Bilayer Graphene Ps Ferromagnet



Quantum Hall Effect
of
TI Thin Film Surface States

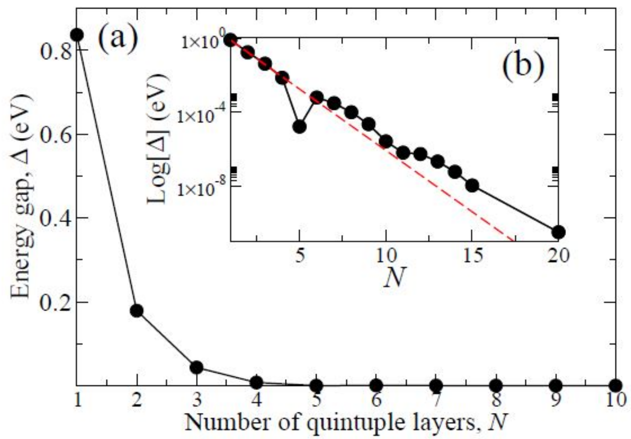
"To gain something one must lose everything"



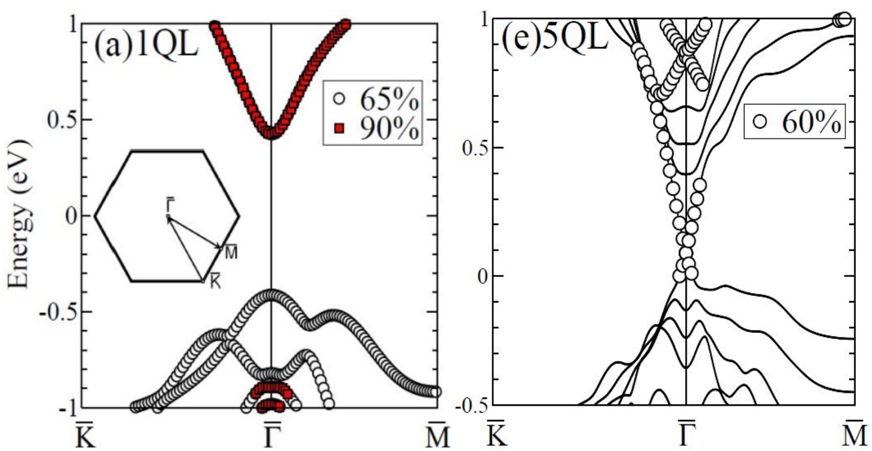
Qi, Wu, Zhang PRB (2008)

Microscopic Model B=0

*sp*³ TB model with parameters fit to DFT
[Kobayashi, PRB **84**, 205424 (2011)]



Thickness-dependent gap

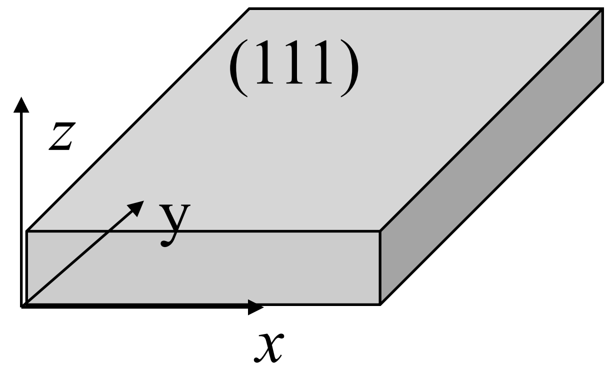


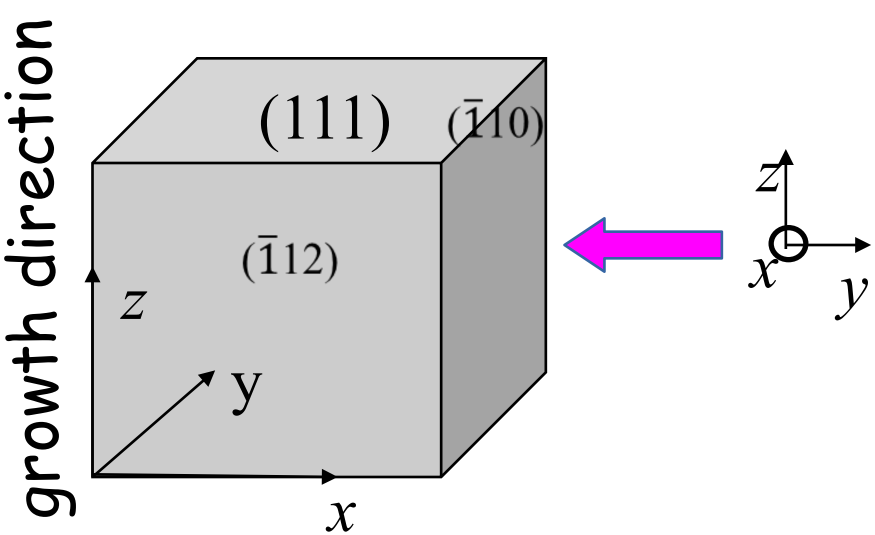
Surface bandstructures

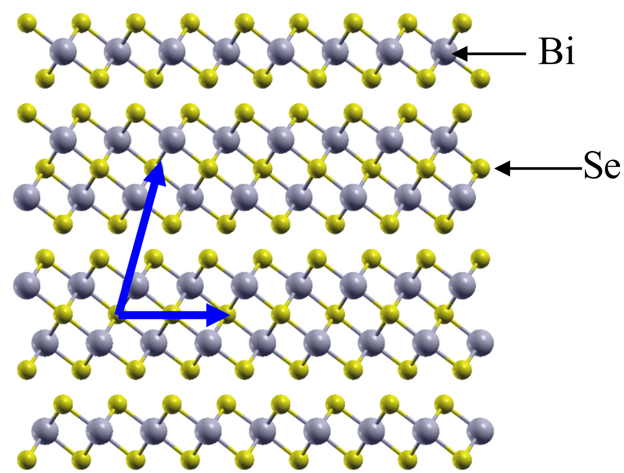
Pertsova & Canali
LNU - Kalmar
NJP 16, 063022 (2014)

Side Wall States

- Consider a bar, finite in ***x*** and ***z*** but infinite in ***y*** direction: two crystal facets are present, for instance (111) (*top and bottom surfaces along QL growth)* and $(\bar{1}10)$ (*side walls)*
- (111) surface is well known
- What the side wall states look like if the surfaces were infinite? → look at Dirac cone on $(\bar{1}10)$ surface



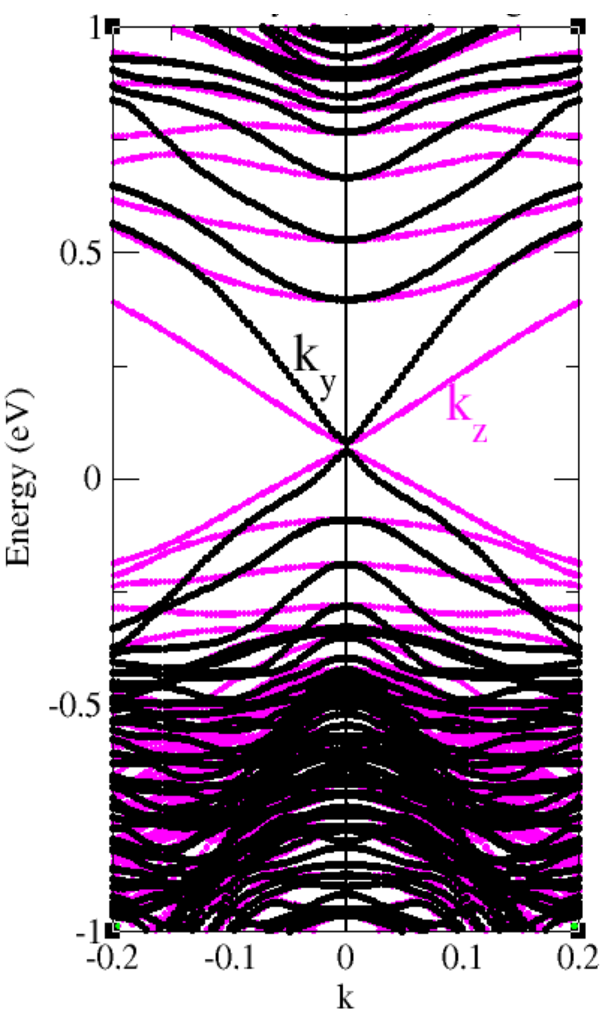


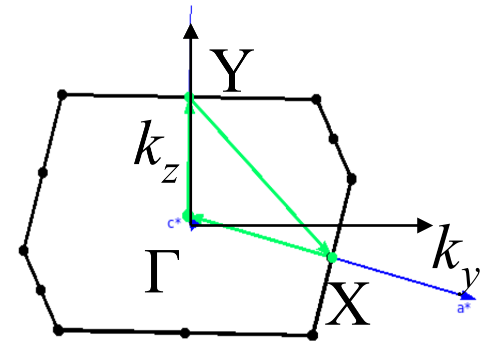


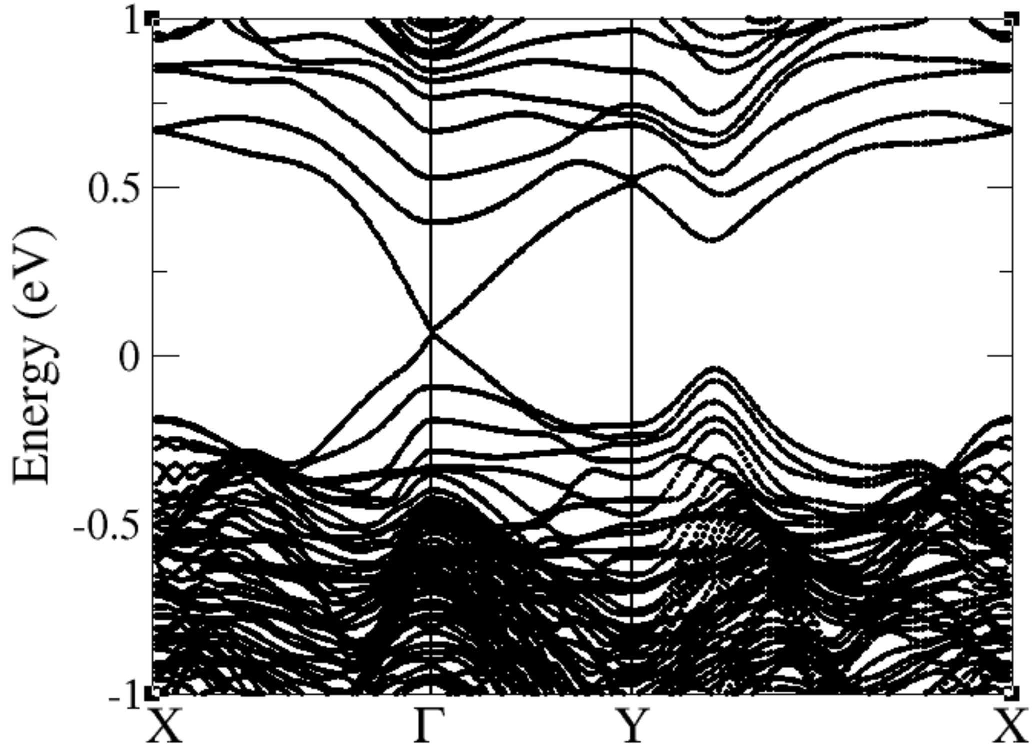
Top view of $(\bar{1}10)$ surface

Anistoropic Dirac Cones

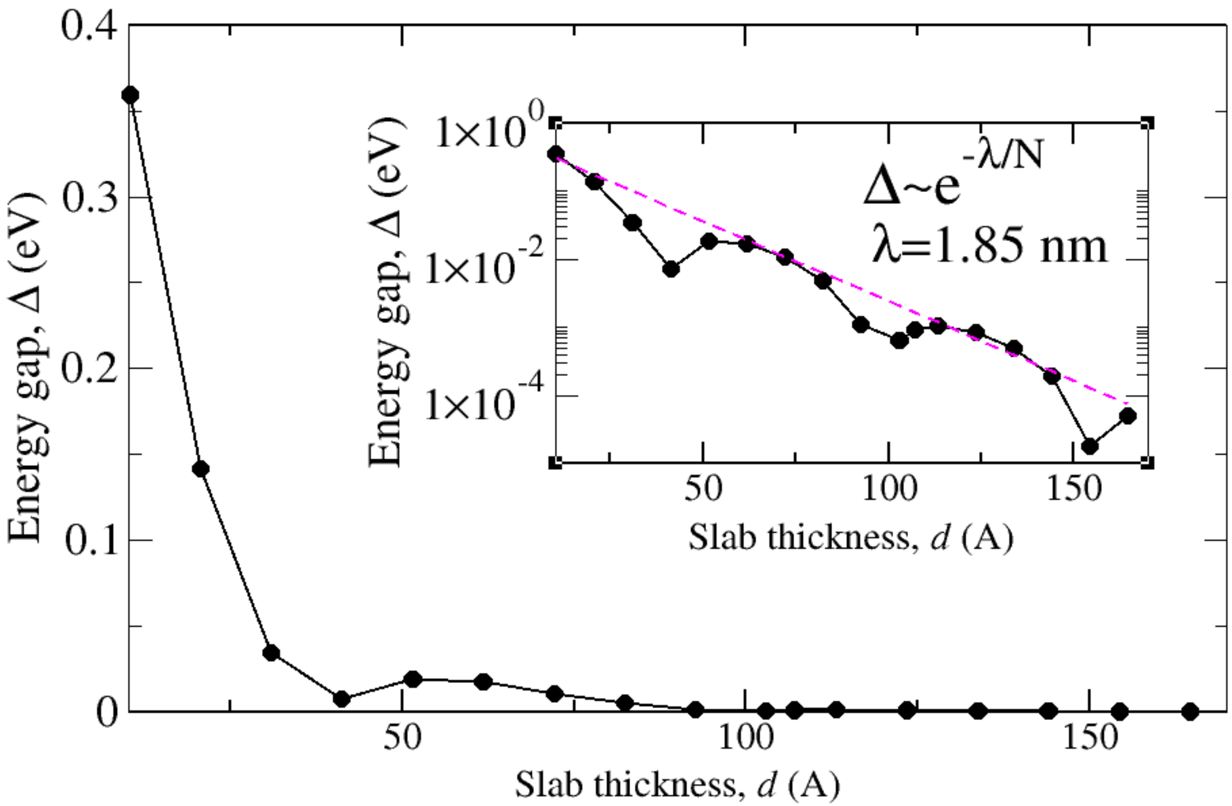
Energy bands for 5nm-thick $(\bar{1}10)$ slab Bi_2Se_3







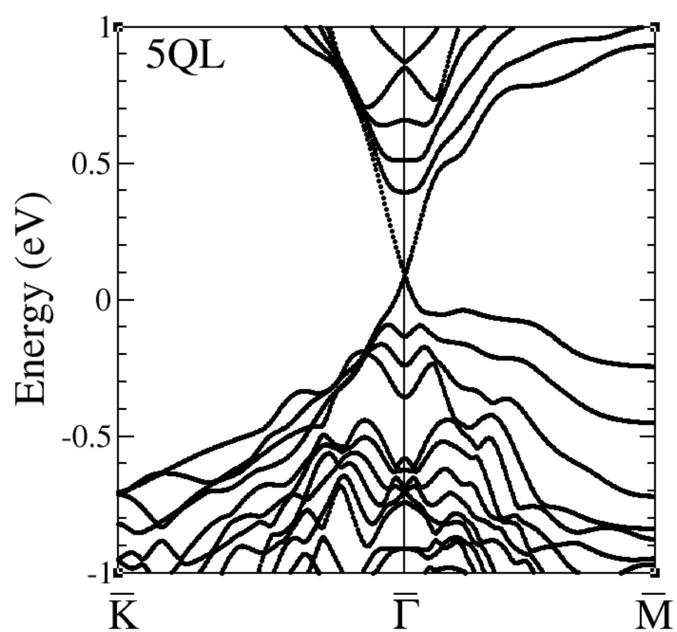
Side Wall Localization



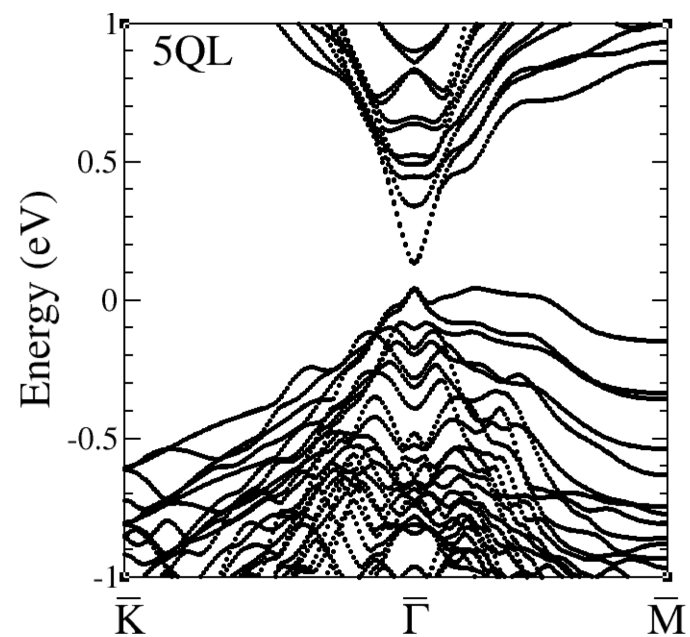
Penetration depth of the surface states ~1.85 nm [~0.7 nm for for (111) surface]

Top Surface 2DEG with PMA

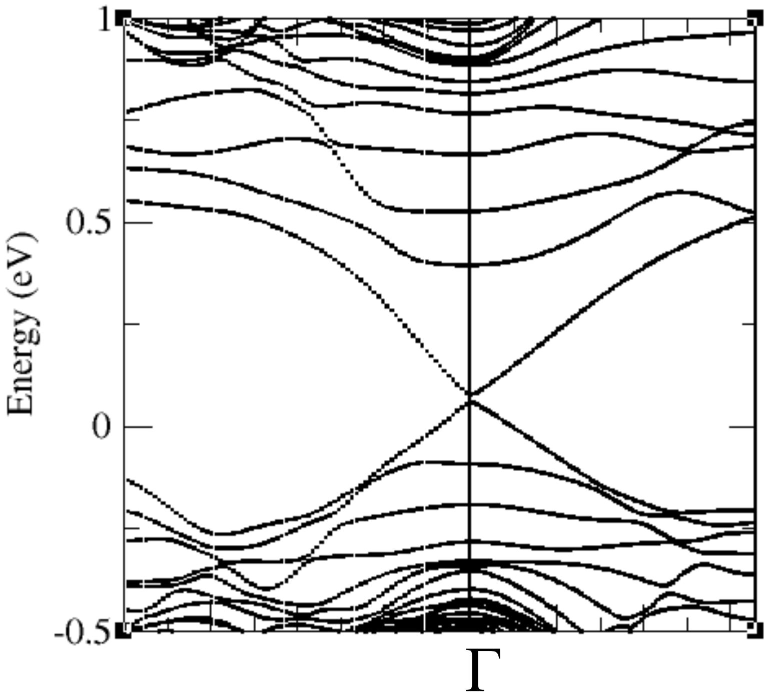
(111) surface, no exchange field

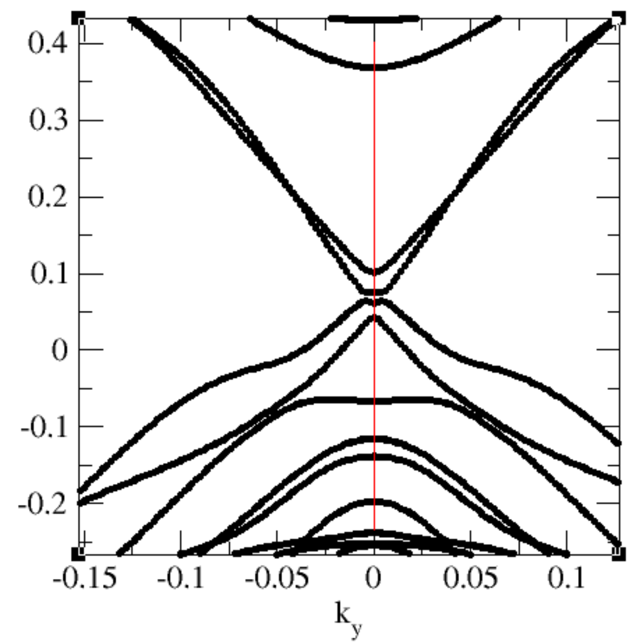


(111) surface, exchange field 0.1eV along *z* axis



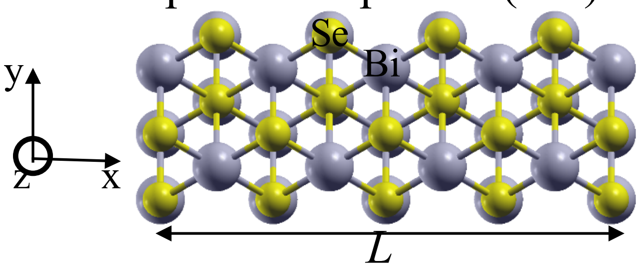
Side Wall 2DEG with PMA



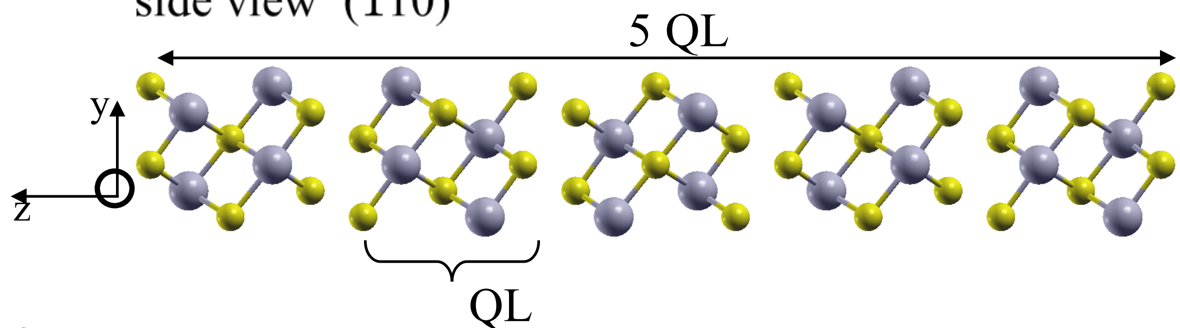


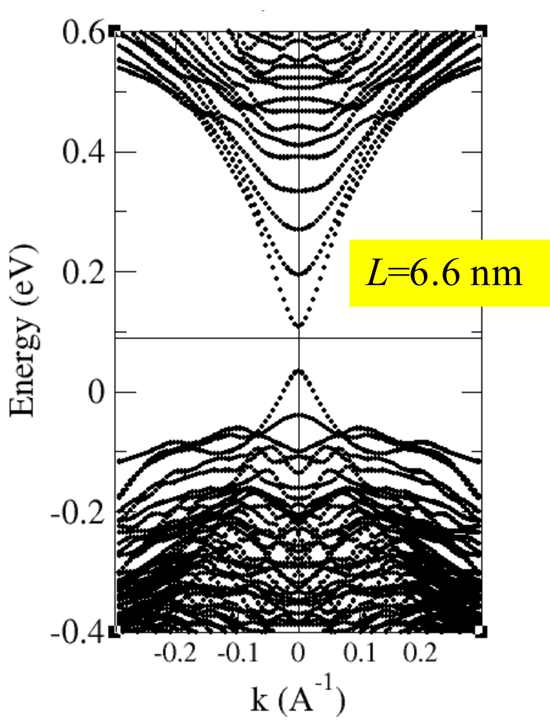
Ribbon at B=0

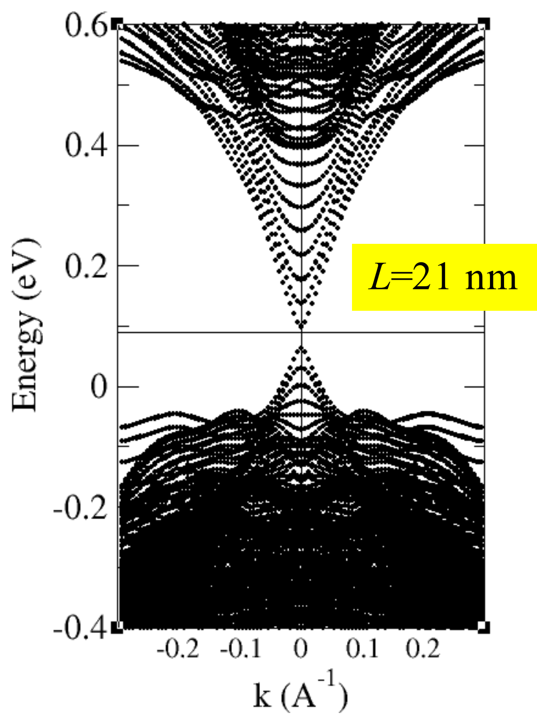
supercell: top view (111)



side view $(\bar{1}10)$

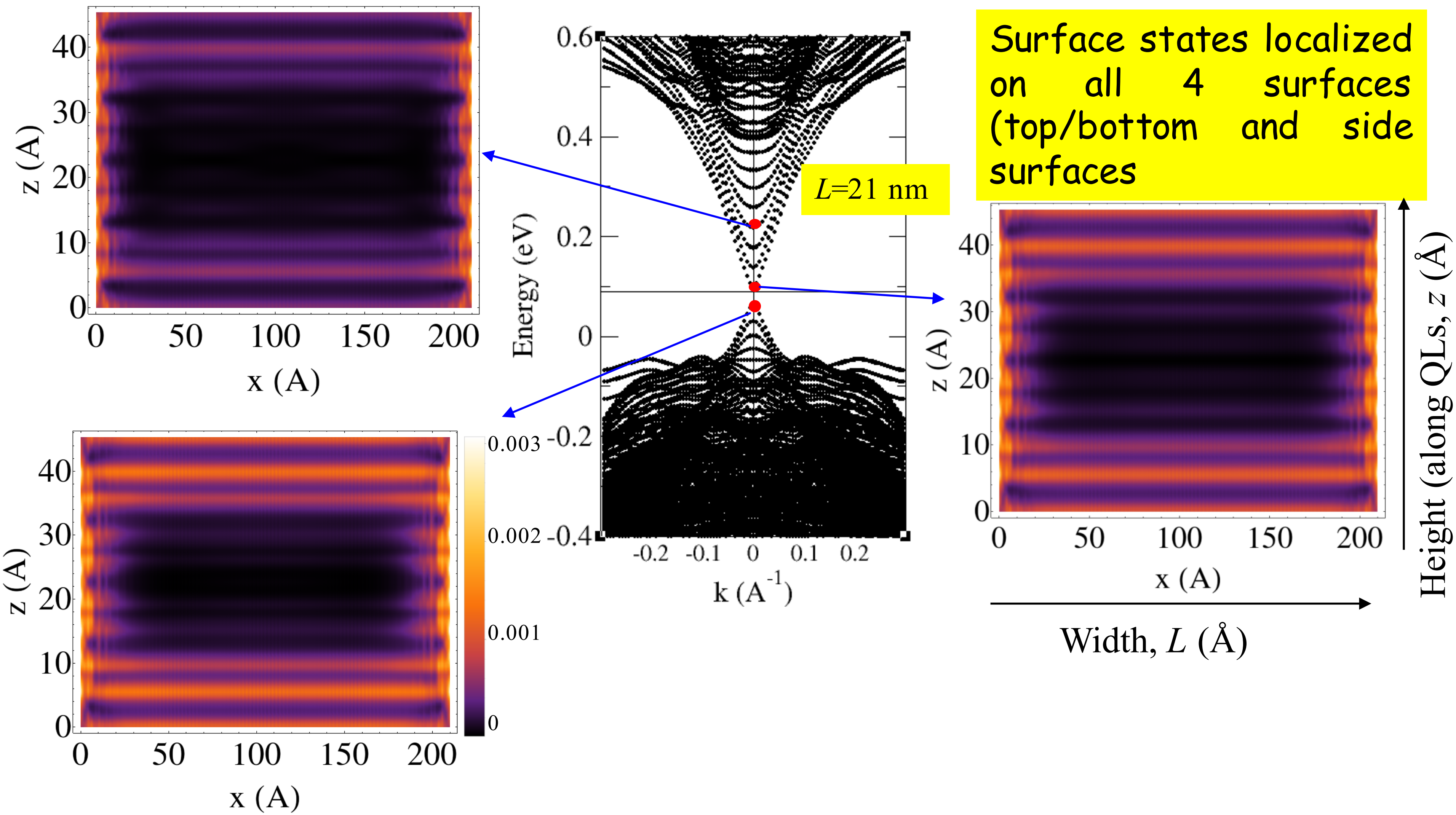






- Surface-state subbands due to confinement along *x*
- In the limit of large *L*, continuum Dirac cone is formed
- For a fixed number of QLs, the energy gap at Γ decreases with *L*

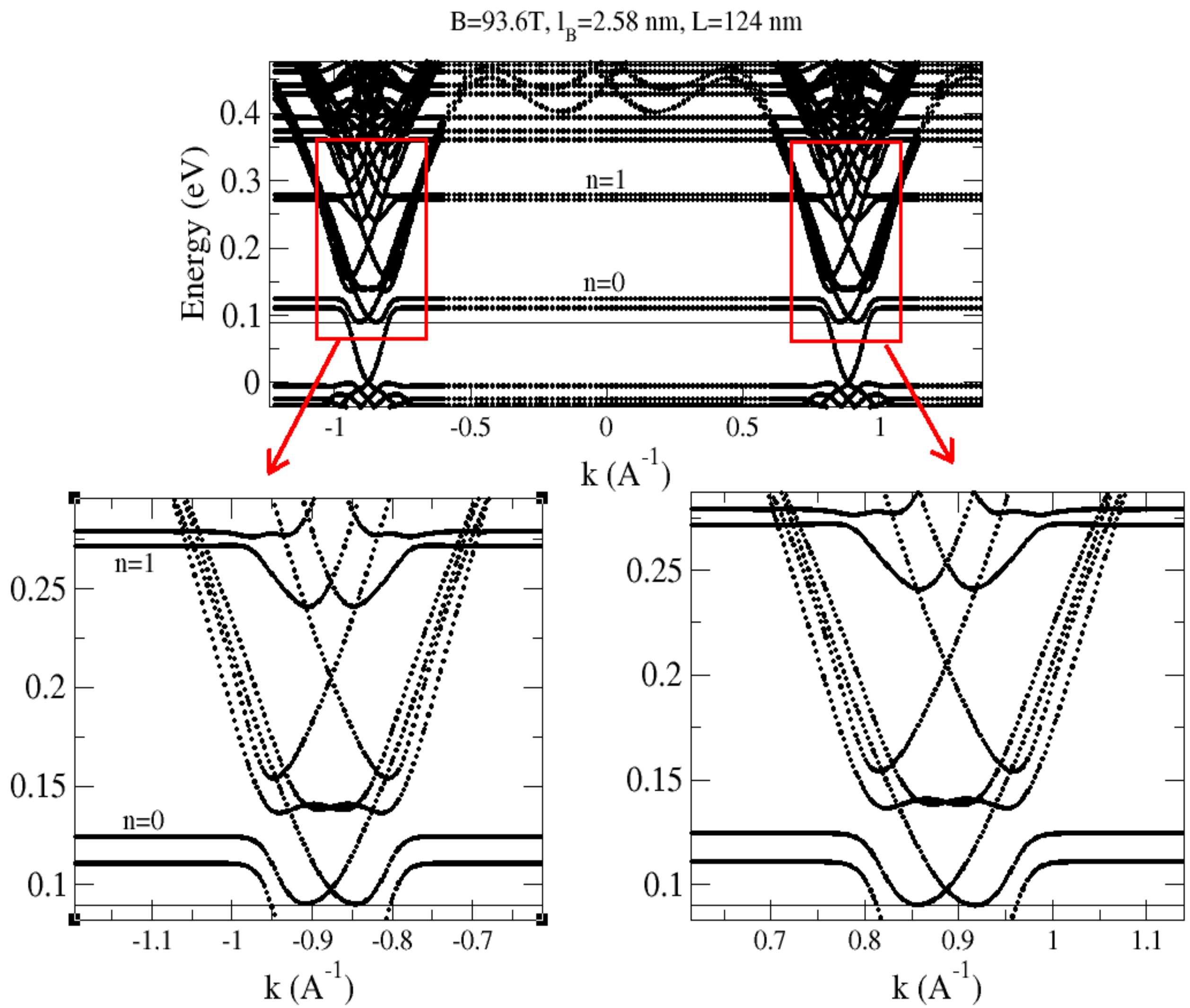
Ribbon at B=0



Surface states localized on all 4 surfaces (top/bottom and side surfaces

Ribbon with Broken TR

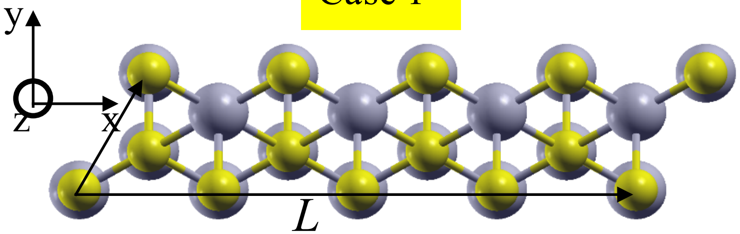
Counter-Propagating Edge Channels



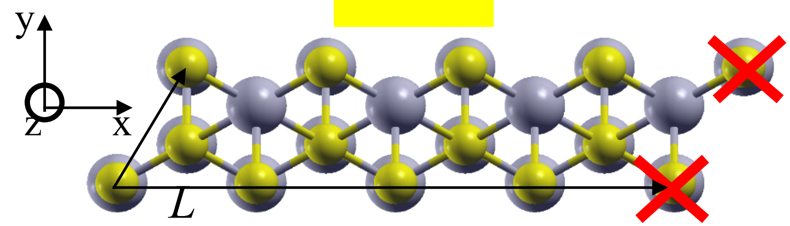
Disorder on the Side Wall

Non-symmetric side surfaces: top view of the supercell

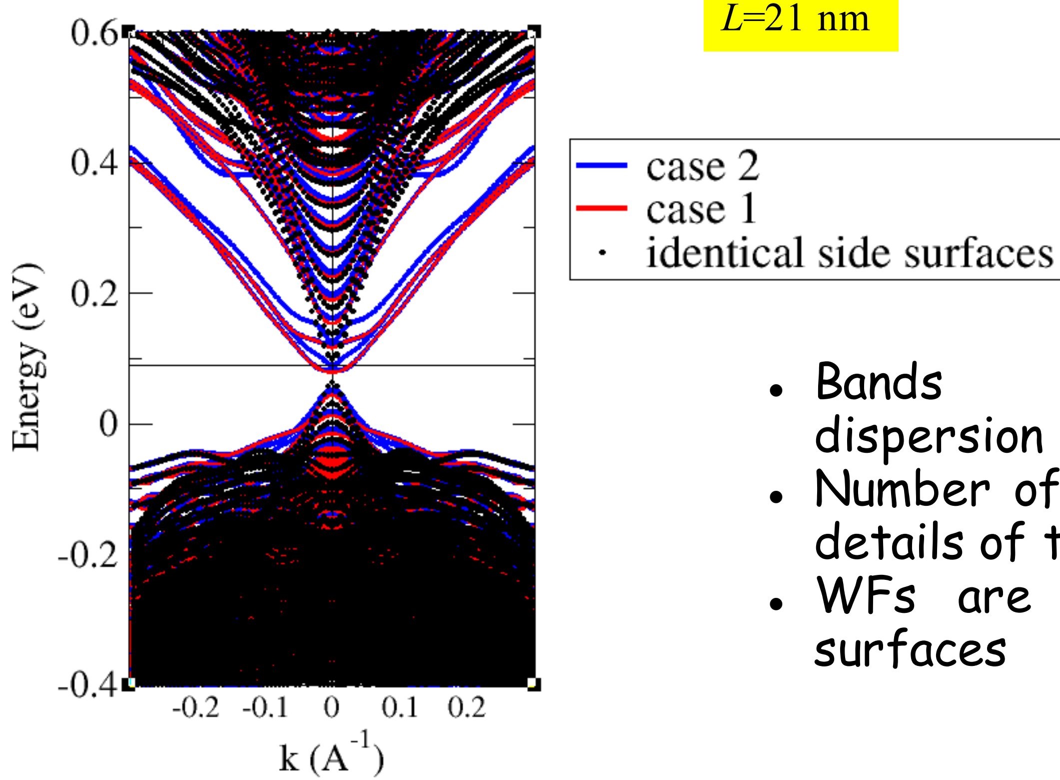
Case 1



Case 2



L=21 nm



- Bands with non-linear dispersion
- Number of bands depends on details of the termination
- WFs are localized on side surfaces

Quantum Anomalous Hall Effect Materials by Design

- Quasi-2D Systems
(TI surface states, graphene, …)

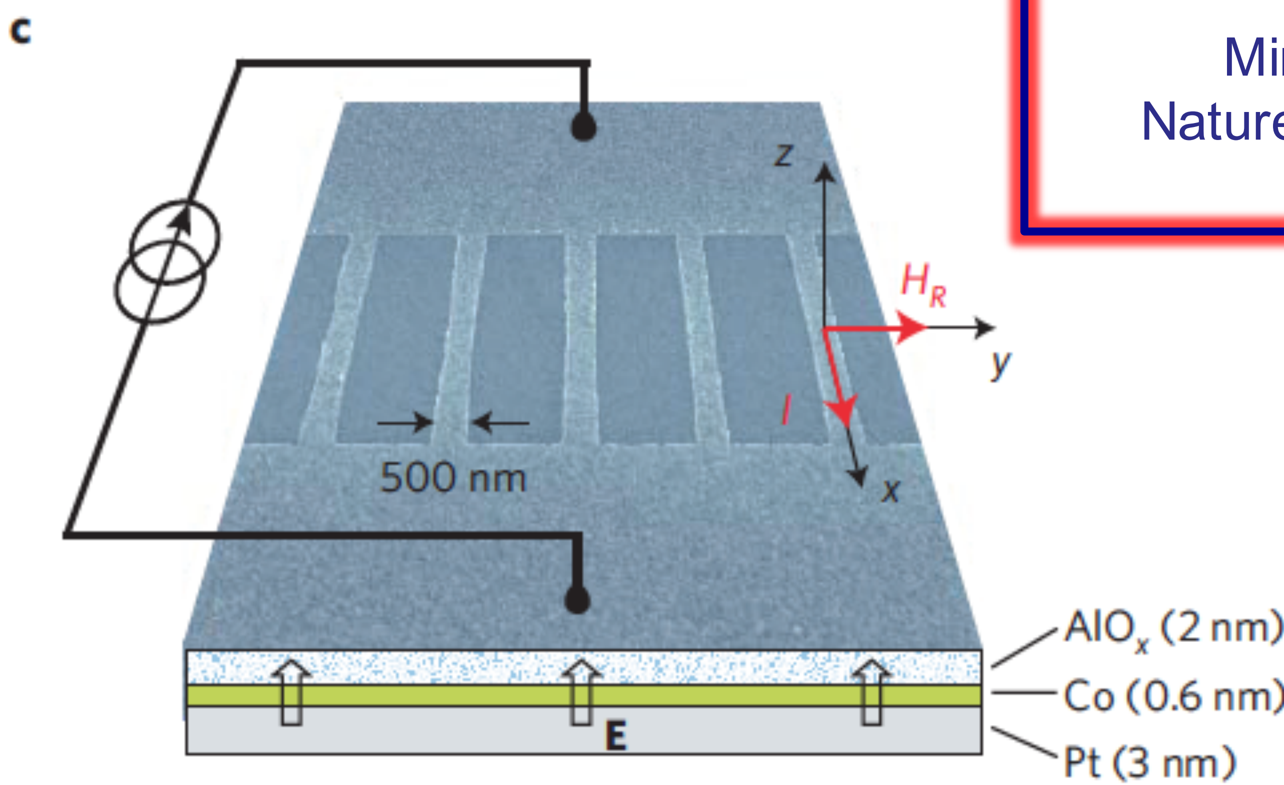
- Strong SO – Fermi Level
Near Time-Reversal Invariant Point

- Ternary Chalcogenides ?

Quantum Hall Effect
(Insulators)

Intrinsic
Charge and Spin Hall Effects
and SOITs

Heavy Metal/ Ferromagnet Bilayers (Structural Inversion Assymetry)



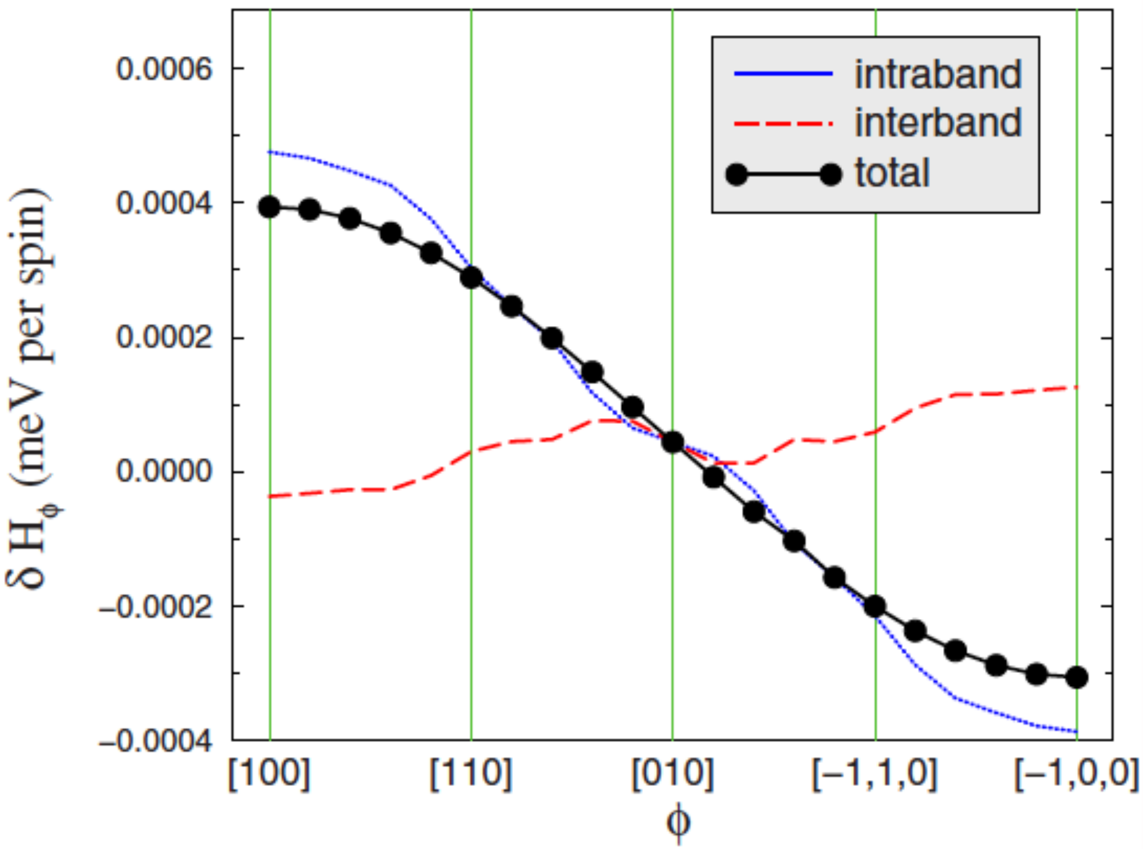
Miron *et al.*
Nature 476 (2011)

Conceptual Picture of LL Equation Torques

$$\vec{\tau} = \hbar\dot{\vec{s}} = i[\mathcal{H}, \vec{s}] = \vec{s} \times \vec{H}_{eff}$$

$$\vec{T} = \sum_{\alpha} f_{FD}(\epsilon_\alpha)\left[\langle\psi_\alpha|\,\vec{s} \times \vec{\Delta}\,|\psi_\alpha\rangle + \frac{\hbar}{2m^2c^2}\langle\psi_\alpha|\vec{\nabla}V \times \vec{p} \times \vec{s}|\psi_\alpha\rangle\right]$$

SOIT in bulk (Ga,Mn)As



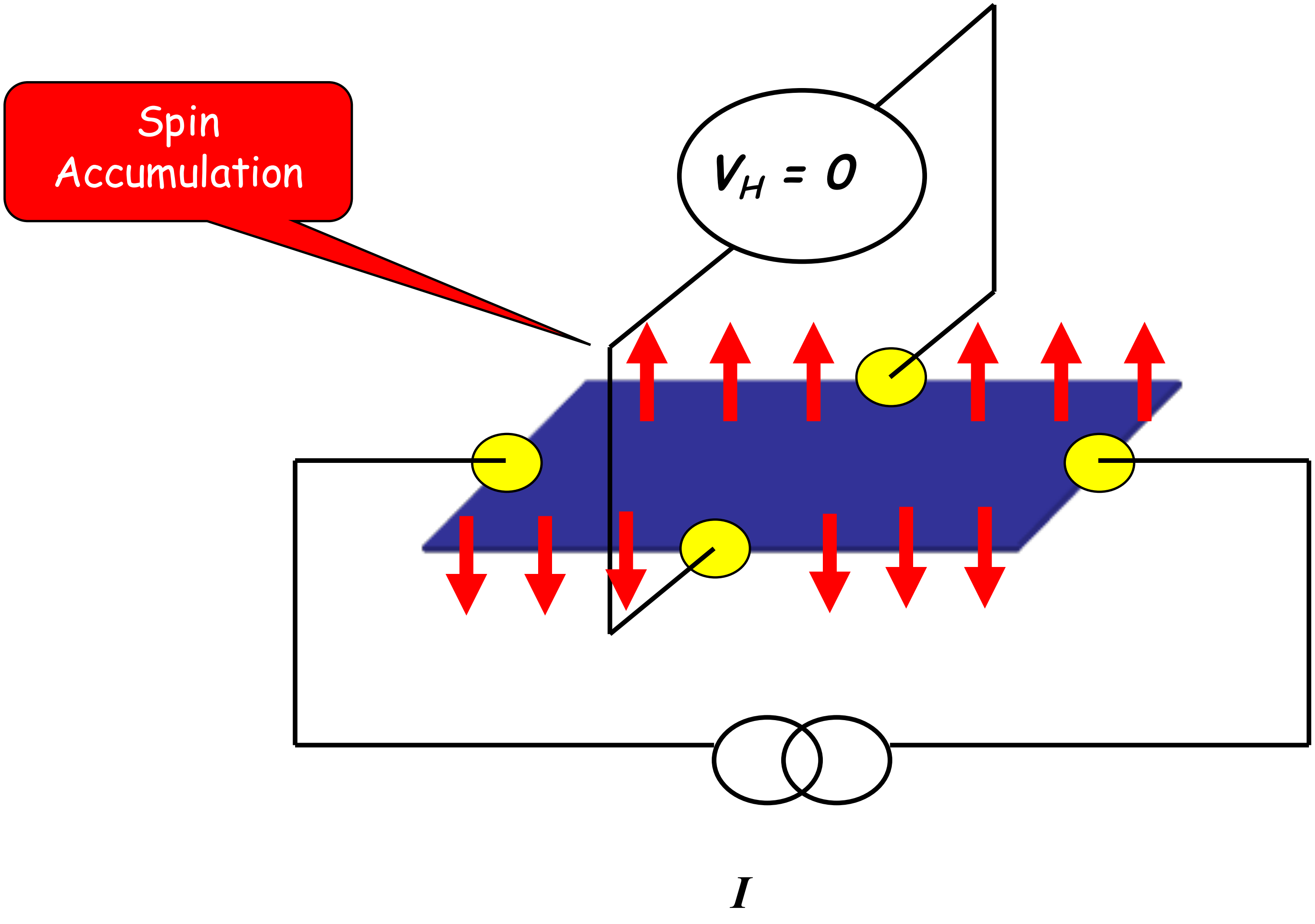
Manchon & Zhang
PRB 79 (2009)

Garate & AHM
PRB 80 (2009)

Chernyshev *et al.*
Nat. Phys. 5 (2009)

Sinova *et al.*
arXiv:1306.1893

Spin Hall Effect

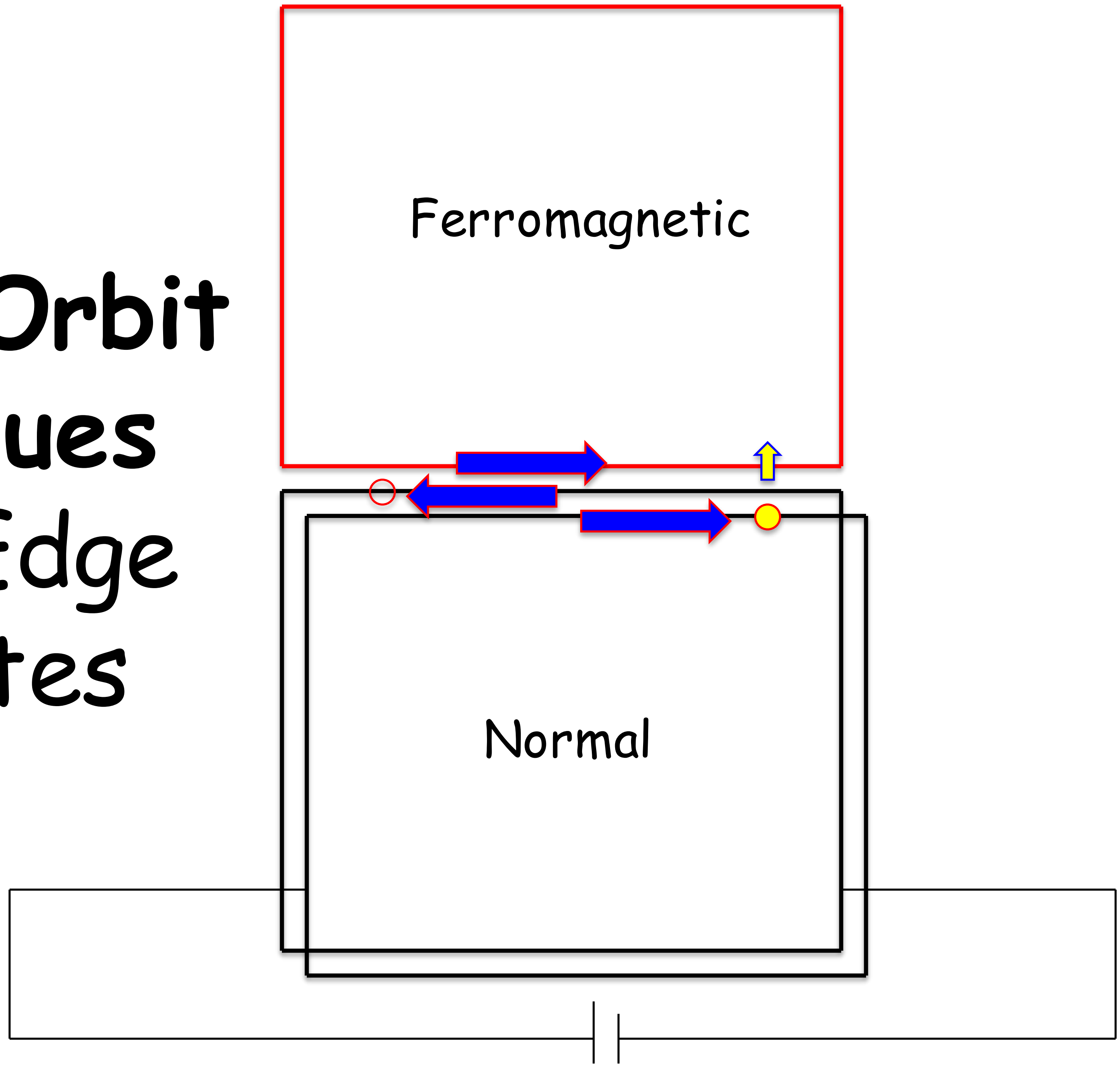


Anomalous Hall Effect

Linear Response Theory

$$\sigma_H(z) = \frac{e^2\hbar}{L^2}\sum_{\alpha,\beta}\frac{f_\alpha - f_\beta}{(E_\alpha - E_\beta)(z + E_\alpha - E_\beta)}\ \mathrm{Im}\left[\langle\alpha|v_x|\beta\rangle\langle\beta|v_y|\alpha\rangle\right]$$

Spin-Orbit Torques and Edge States



Quantum Hall Effect (Insulators)

Intrinsic Charge and Spin Hall Effects and SOITs