Quantized Magnetoelectric Response of a Topological Insulator

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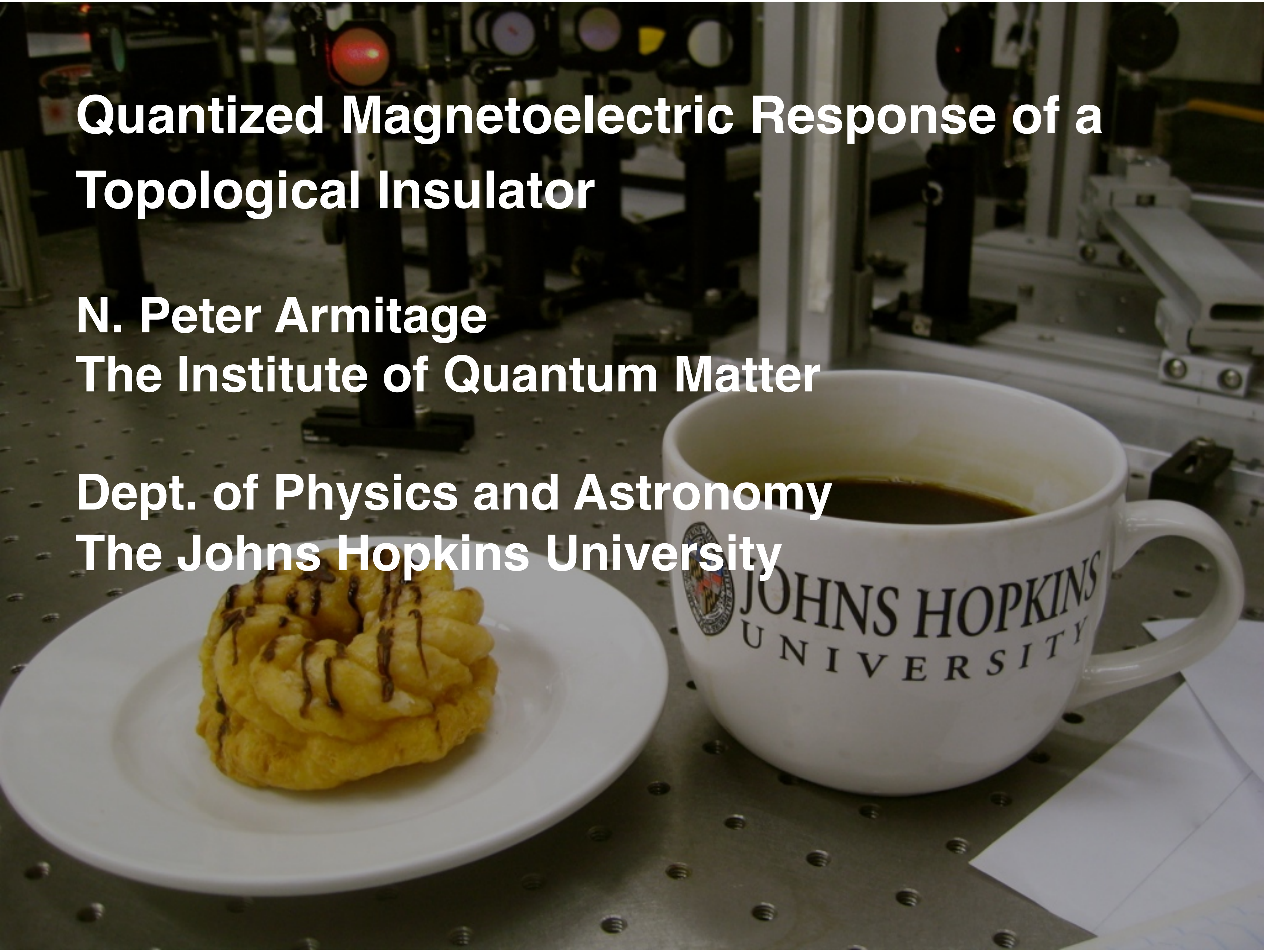
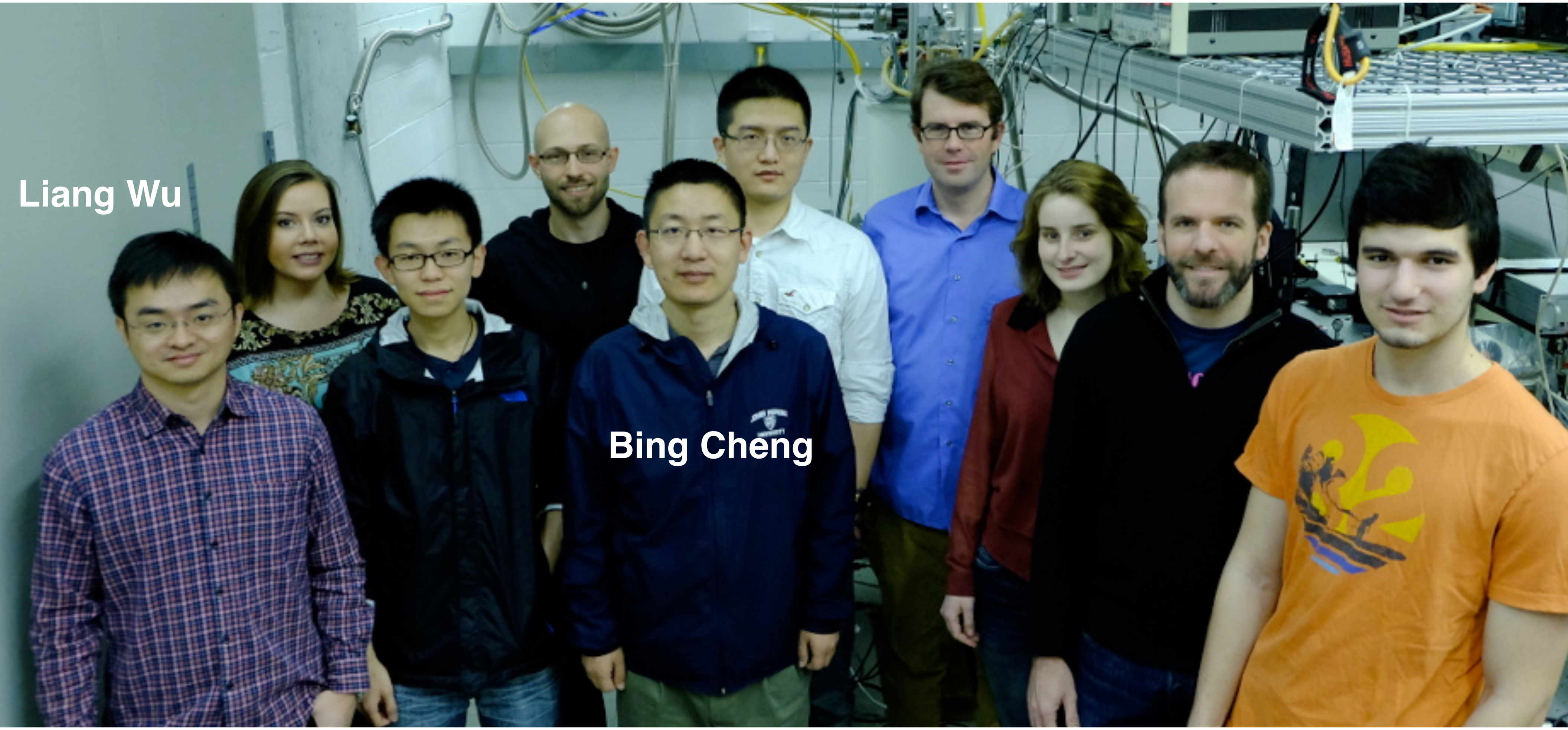
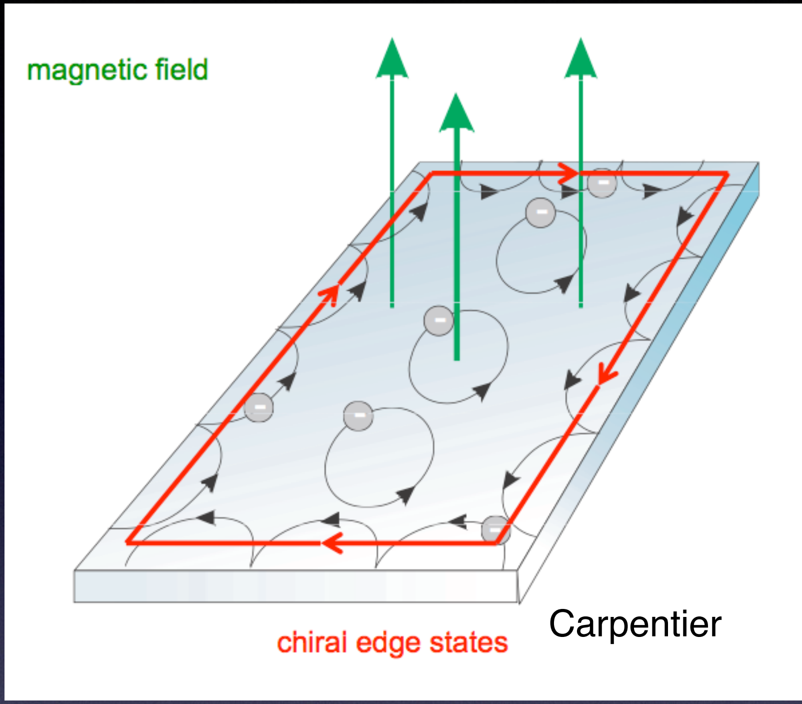




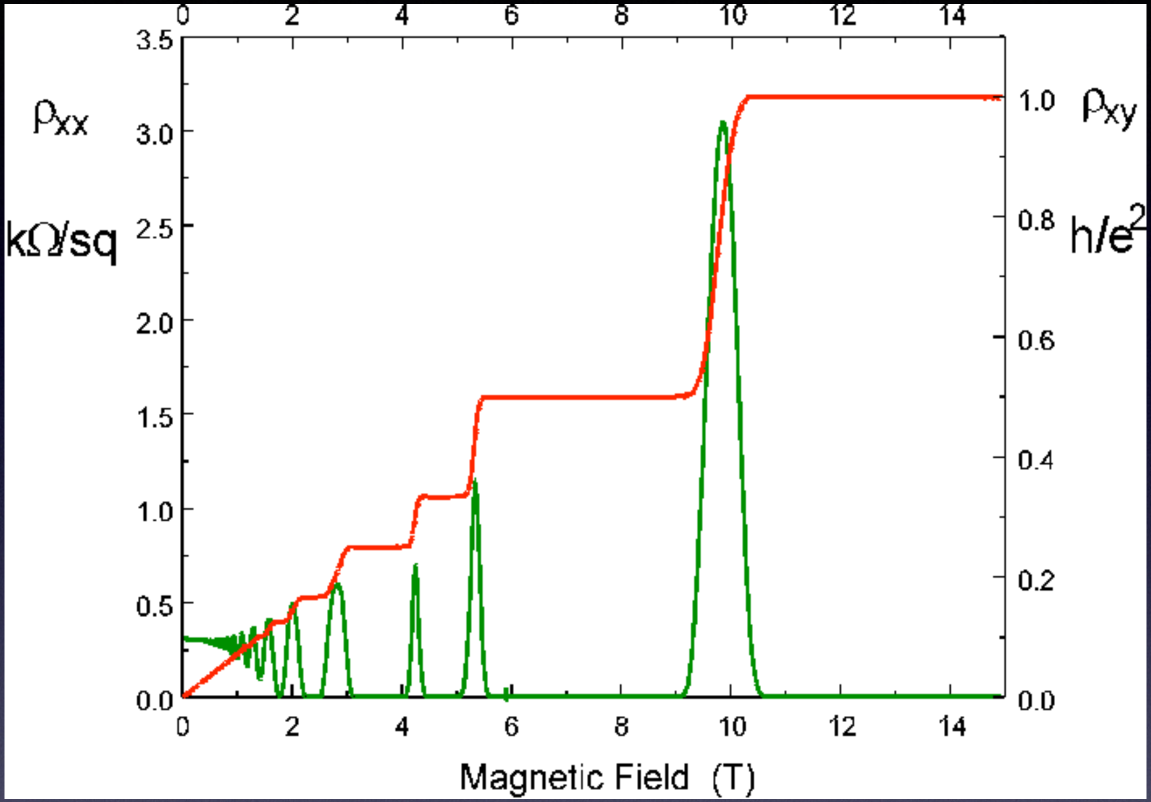
Seongshik Oh (Rutgers)

Matt Brahlek (Rutgers)
Namrata Bansal (Rutgers)
Nikesh Koirala (Rutgers)
Maryam Salehi (Rutgers)

The Quantum Hall effect showed states can be different, despite same symmetry



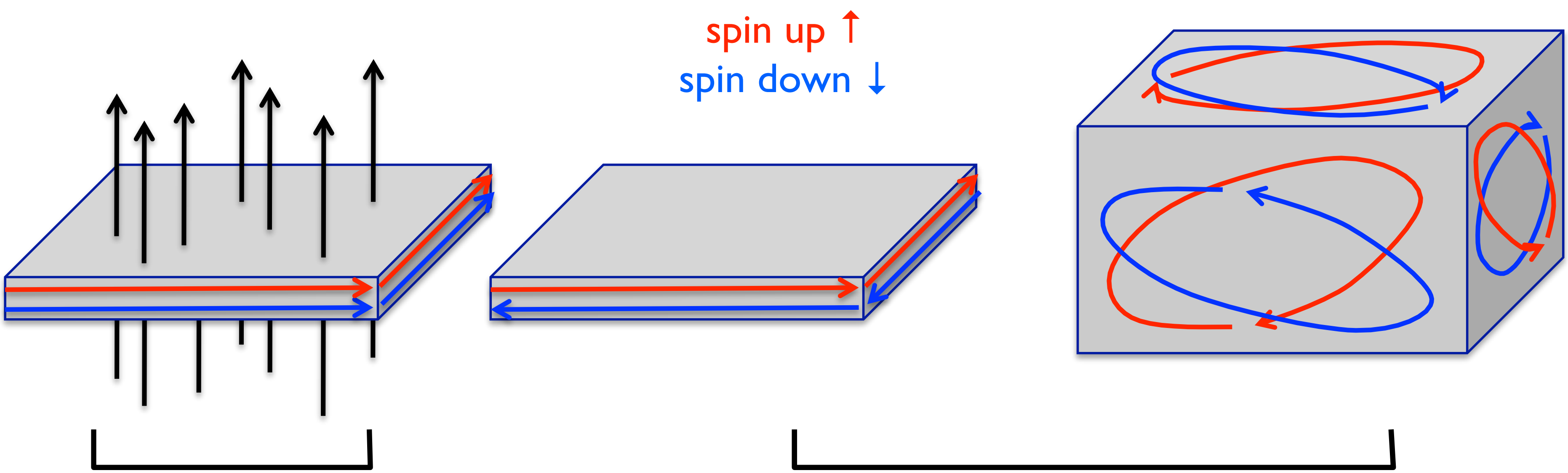
2D Cyclotron Motion



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

- Different plateaus are different states with the **same** symmetry,
- Quantization exact to $1/10^9$ → Cannot be same state
- Wavefunctions have different topology - net curvature of wavefunction in BZ.
- 1st discovered topological insulator

States exist where role of B field is played by spin-orbit coupling



QH

2D TI

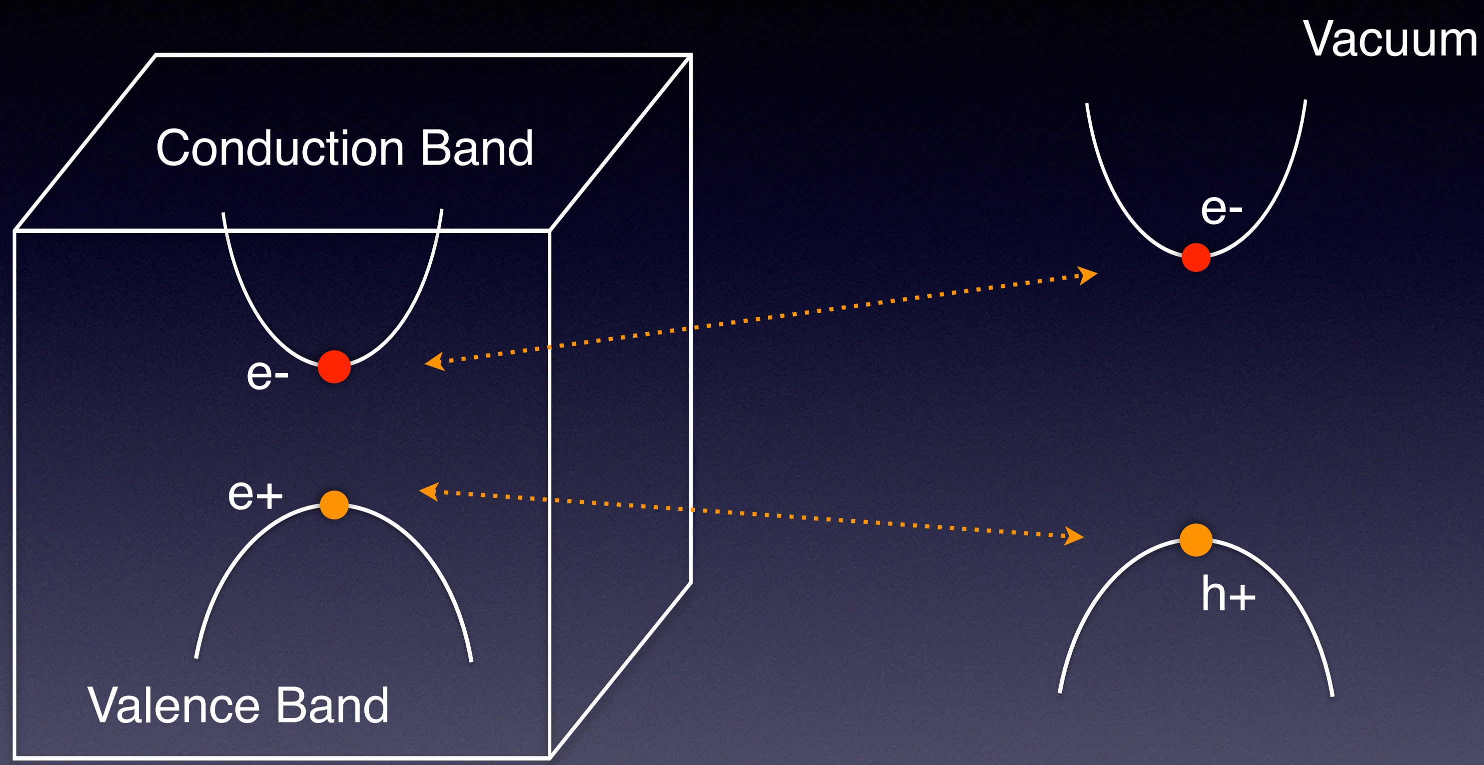
3D TI

broken time-reversal symmetry

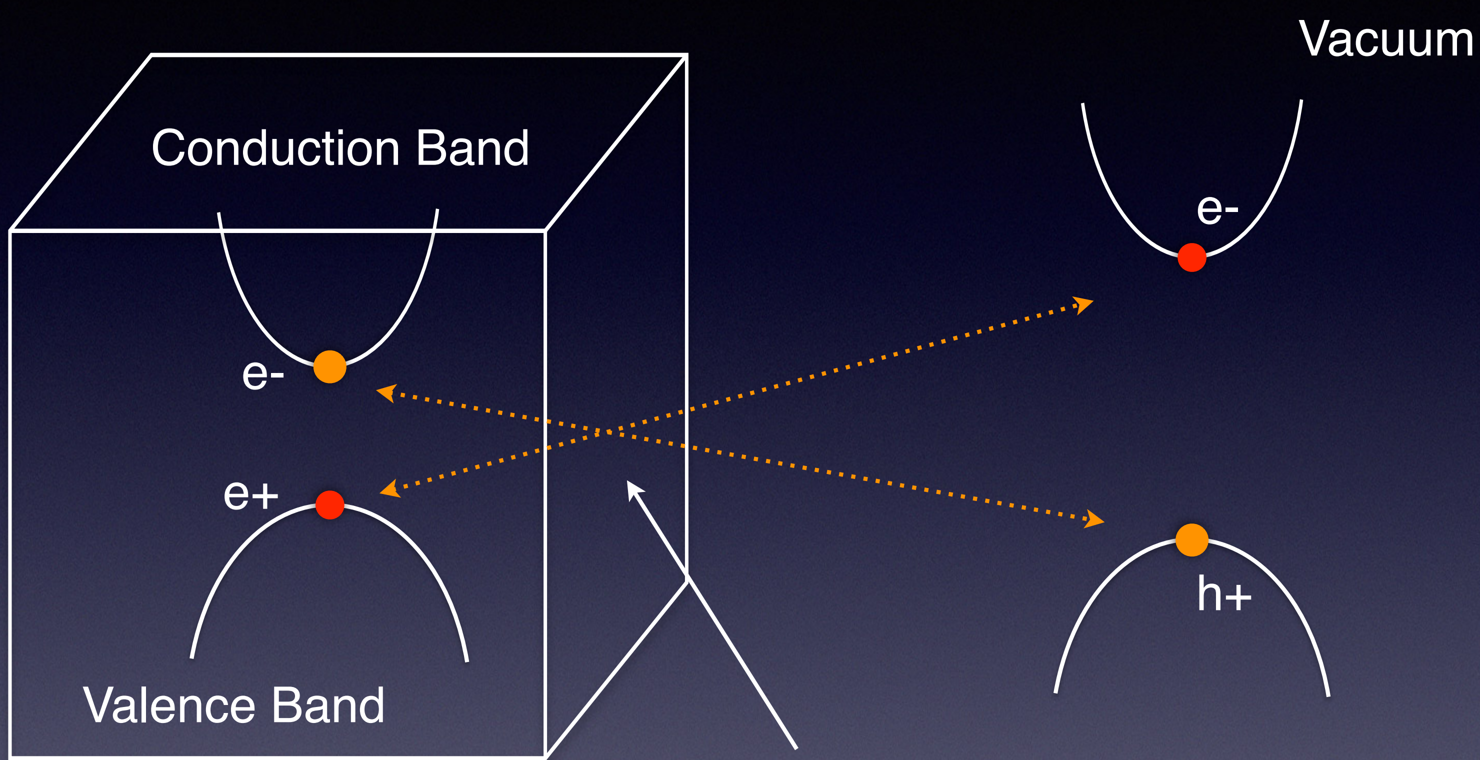
time-reversal symmetric

$$H_{\mathrm{SOC}} = \frac{\hbar}{4m^2c^2}(\nabla V \times \vec{p})\vec{\sigma}$$

Conventional Insulator: Adiabatically connected to the vacuum



Topological Insulator: Adiabatically disconnected from the vacuum



Theory --> Haldane, Kane, Mele, Fu, Zhang, Bernevig, Hughes, Roy, Moore, Balents, Vanderbilt many others; Experiment --> Molenkamp, Buhmann, Hasan, many others

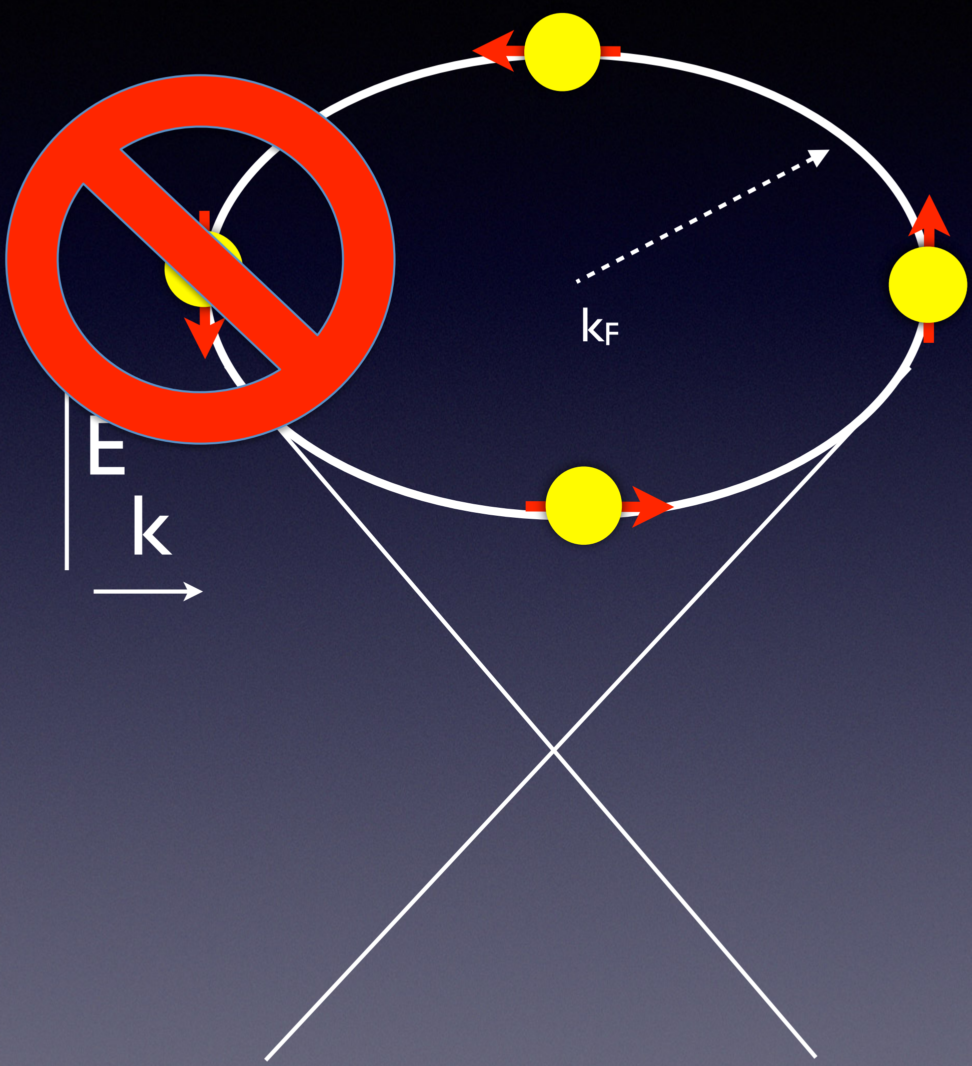
Gap closes between two different vacua; Topologically protected surface metals

Driven by spin-orbit coupling --> heavy atom compounds

$$H_{SOC} = \frac{\hbar}{4m^2c^2}(\nabla V \times \vec{p})\vec{\sigma}$$

Proposed “Flipper Bridge” between Hong Kong (left-hand traffic) and mainland China (right-hand traffic). Design by nl architects (www.nlarchitects.nl). Concept by Phillip Hoffman, Aarhus University

Surface state Dirac dispersion: Topological protection



Small angle scattering does not usually affect transport lifetime. Backscattering dominates

$$1/\tau_{trans} = (1/\tau_{qp})\frac{1}{2\pi}\int d\theta\Big(\frac{1-\cos\theta}{2}\Big)$$

$$1/\tau^{TSS}_{trans} = (1/\tau_{qp})\frac{1}{2\pi}\int d\theta\Big(\frac{1-\cos\theta}{2}\Big)\Big(\frac{1+\cos\theta}{2}\Big)$$

In TI SS 180° backscattering suppressed → "spin"-momentum locking

Differences of order unity in classical transport regime → small but significant

Bigger differences expected for high disorders where quantum interference is significant

Quantized Magnetoelectric effect in TI

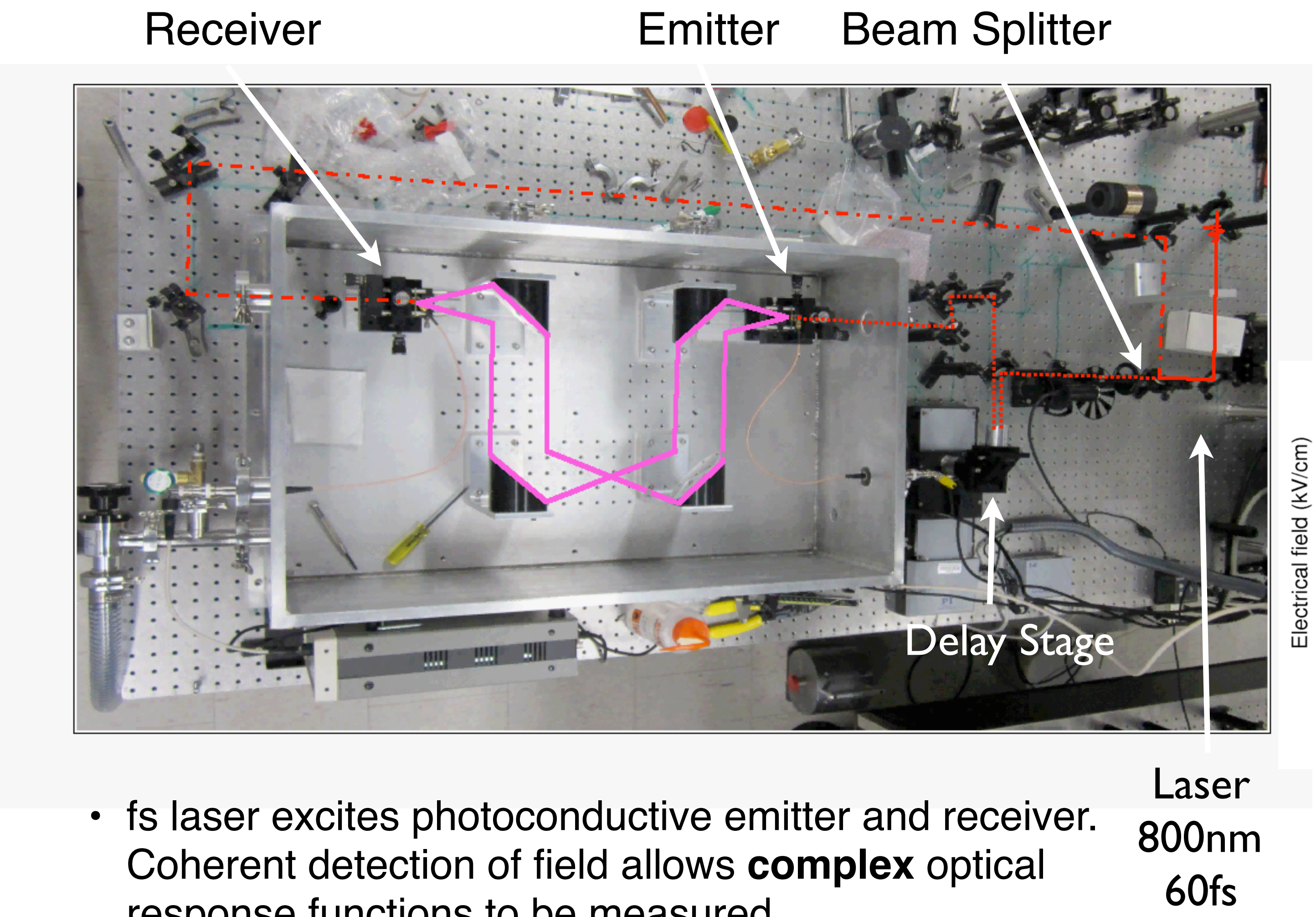
Thickness independent (surface state) transport in Bi_2Se_3 topological insulator film

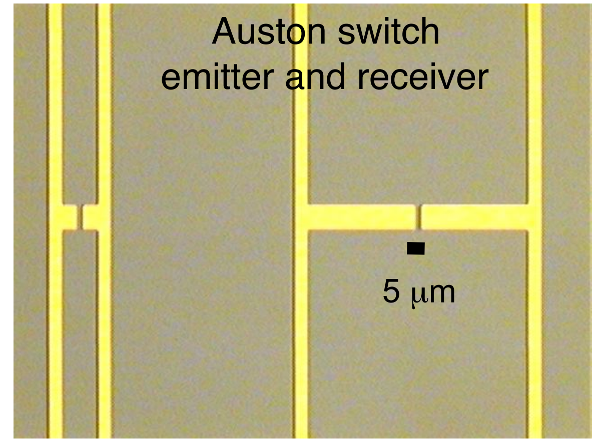
Distinct top and bottom surface states that we can see through TI/nTI phase transition in In-doped Bi_2Se_3 investigated with THz
→ Band gap closure and change in topological class
Lifetime collapse in surface state transport

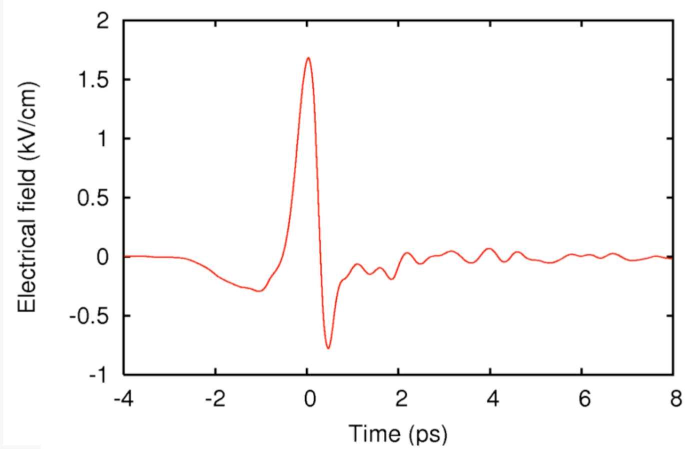
Quantized Faraday and Kerr rotation. Axion electrodynamics

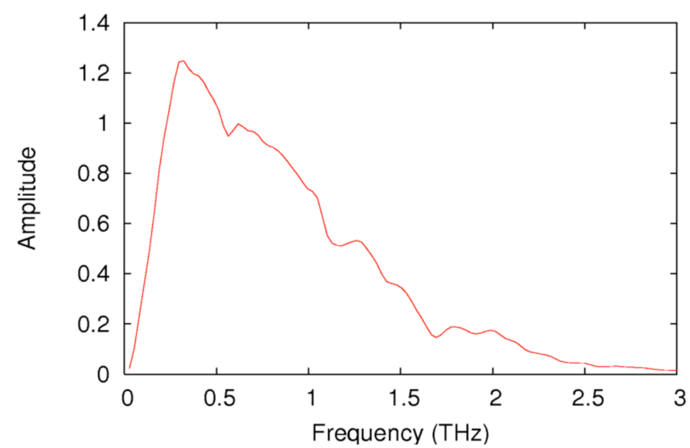
Valdes Aguilar et al., PRL 2012
Wu et al. Nature Physics 2014
Wu et al. PRL 2015
Wu et al. Science 2016
Cheng et al. PRB 2016

Time Domain THz Spectroscopy







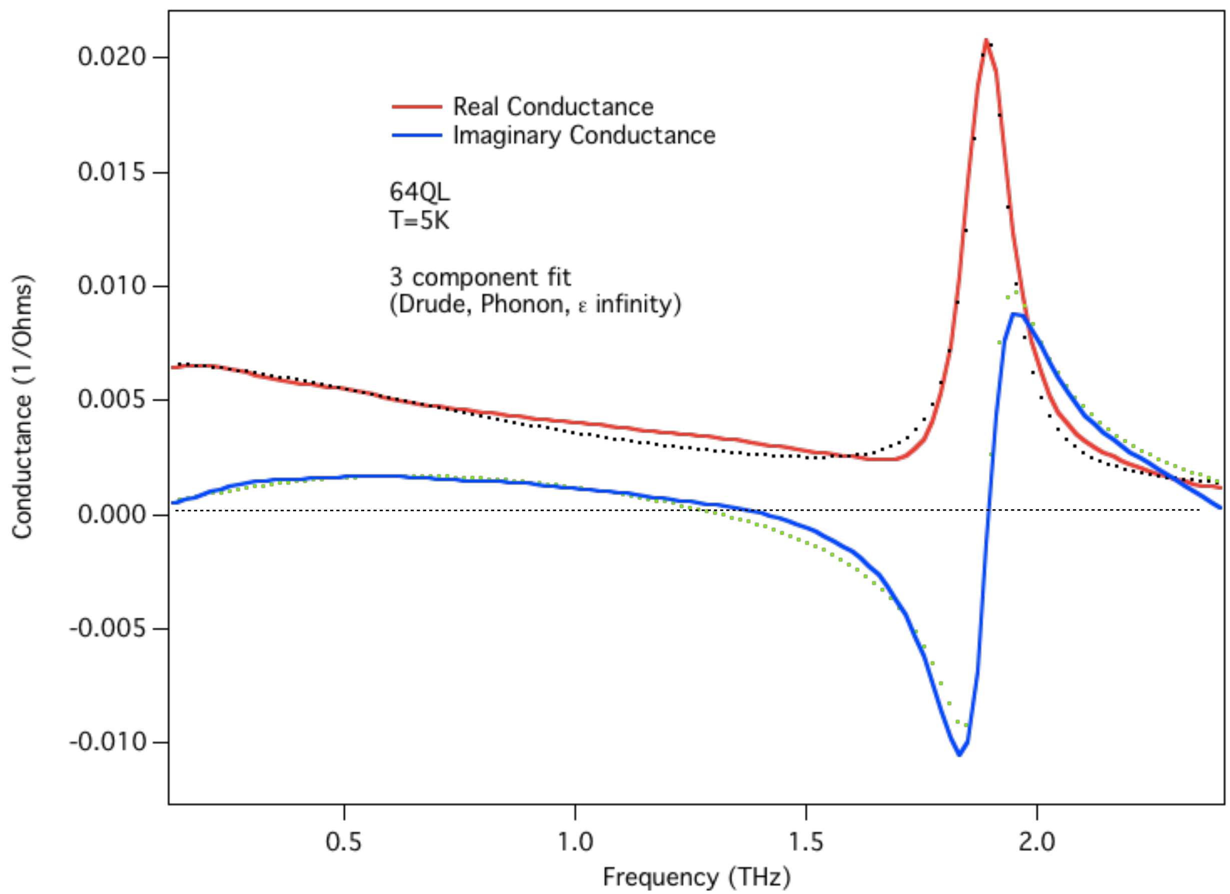


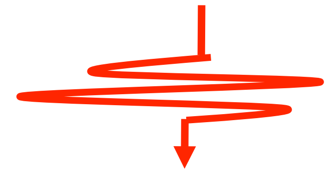
- fs laser excites photoconductive emitter and receiver. Coherent detection of field allows **complex** optical response functions to be measured

$$T(\omega) = \frac{4n}{n+1}\frac{e^{i\Phi_s}}{n+1+\sigma(\omega)dZ_0}$$

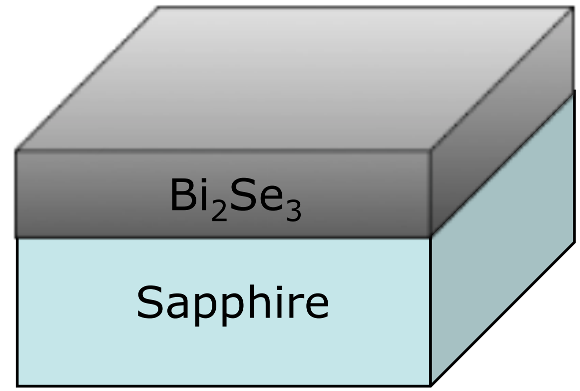
- 100 GHz - 3 THz (0.8 meV - 12 meV), @ 1.4K - 300K.

THz Conductance Measurements: Data and Fits





time-domain THz spectroscopy



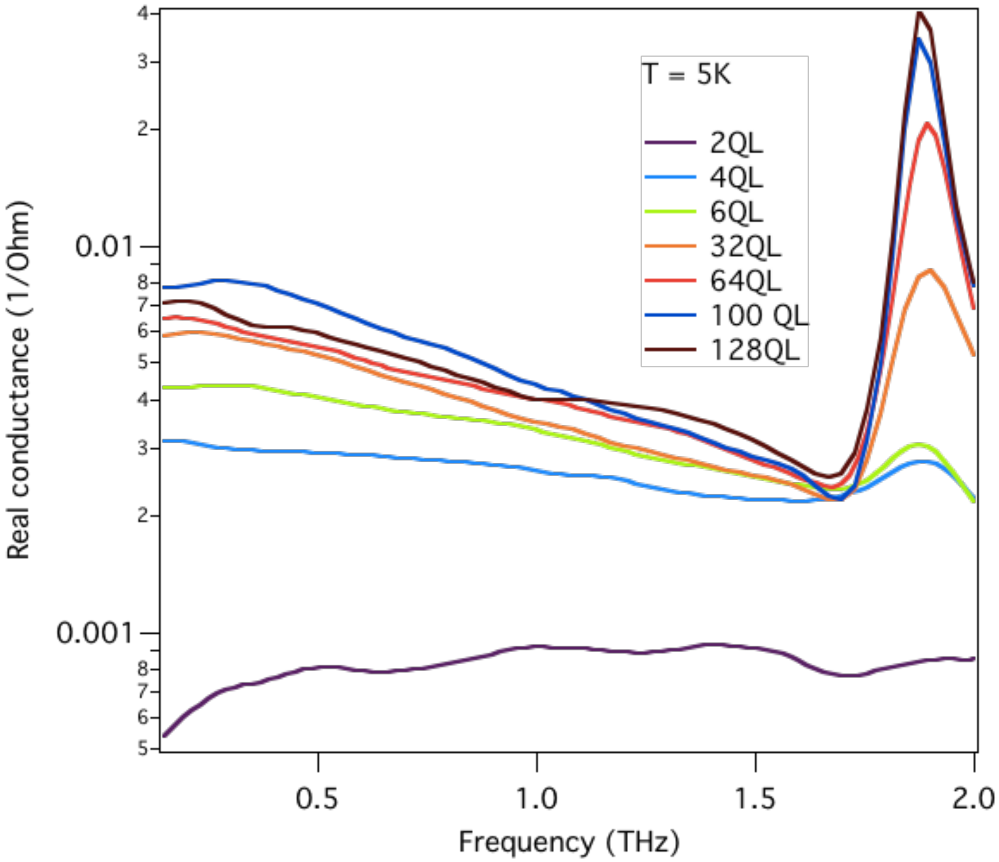
MBE grown films

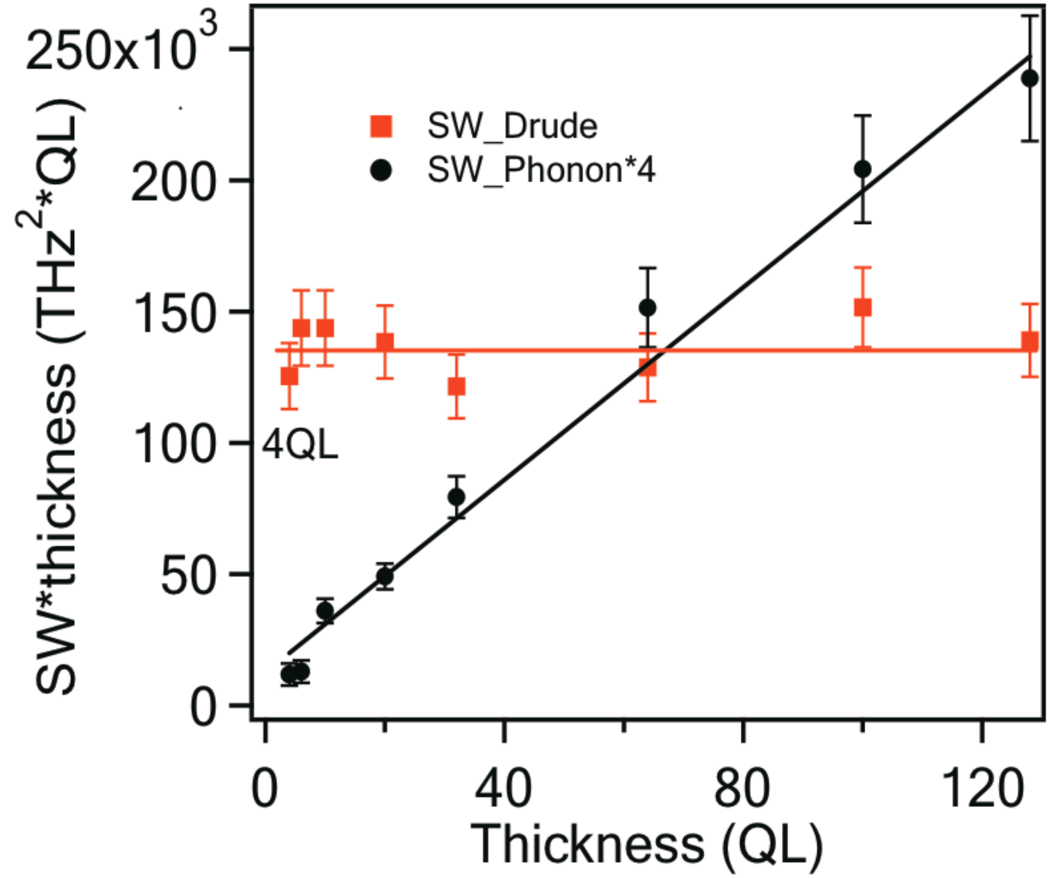
Surface conduction dominates for less than 150 unit cells (QL)

Conductance is a complex quantity
$E\sigma = J$

$$T(\omega) = \frac{4n}{n+1}\frac{e^{i\Phi_s}}{n+1+\sigma(\omega)dZ_0}$$

Thickness independent transport @ Low Energy





Important quantities are areas and widths of peaks -- We fit them

$$8 \int_0^W \sigma_1(\omega) d\omega = \frac{4\pi n e^2}{m_b}$$

Conductivity Sum Rule

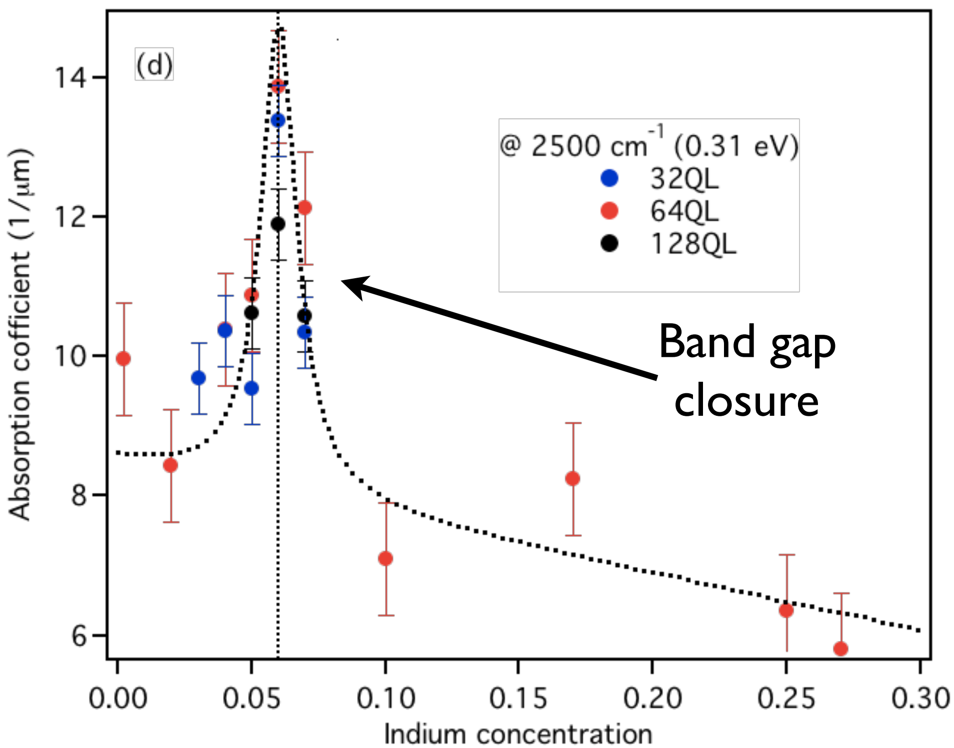
Scattering rate of Drude piece dependent on thickness, but “area” is preserved.

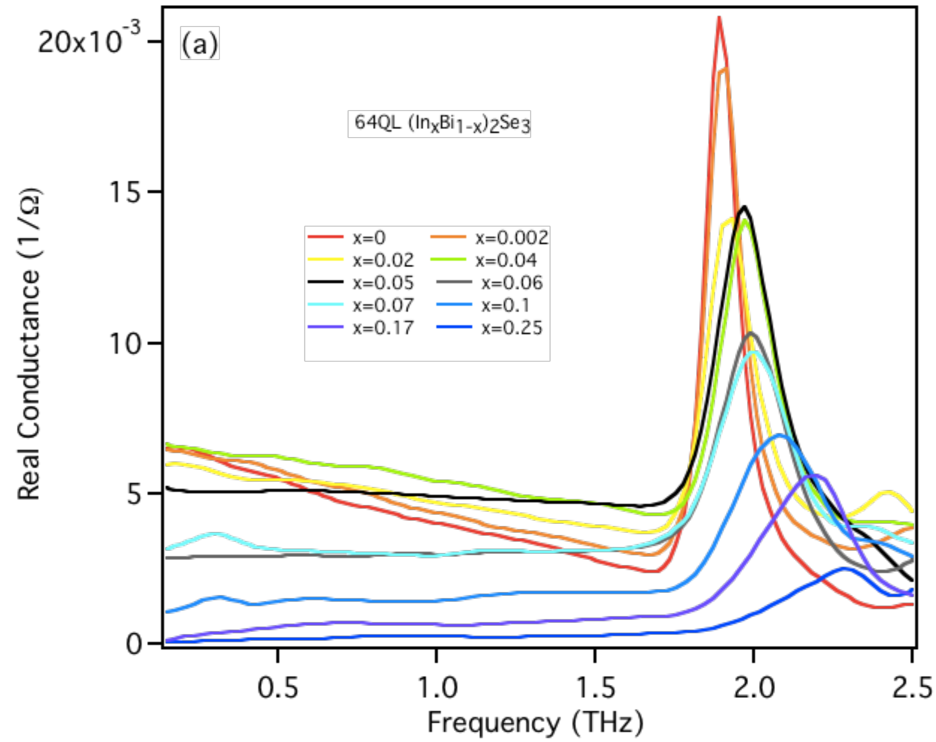
Area of phonon component depends linearly on thickness

Topological Transition in $Bi_{2-2x}In_{2x}Se_3$

Topological Transition in $Bi_{2-2x}In_{2x}Se_3$

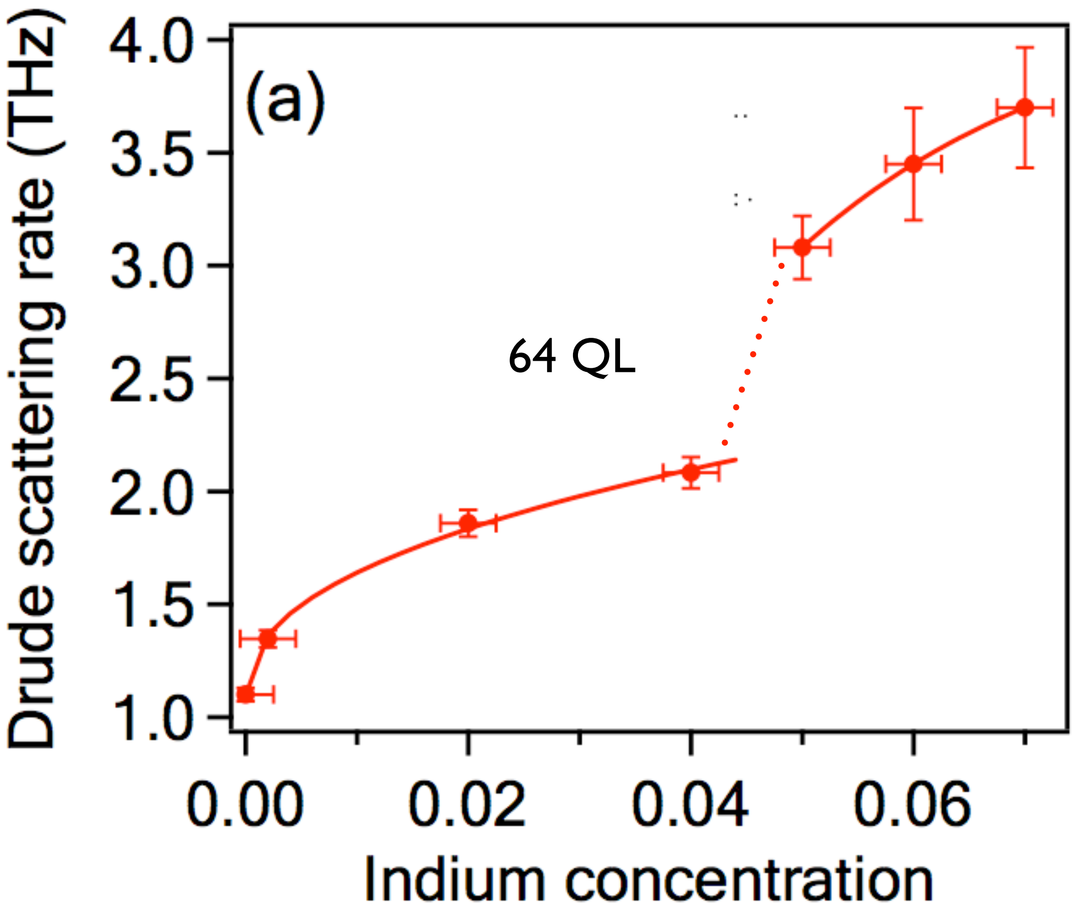
The only way to change topological class is to close band gap.
In_2Se_3 is a band insulator with same structure

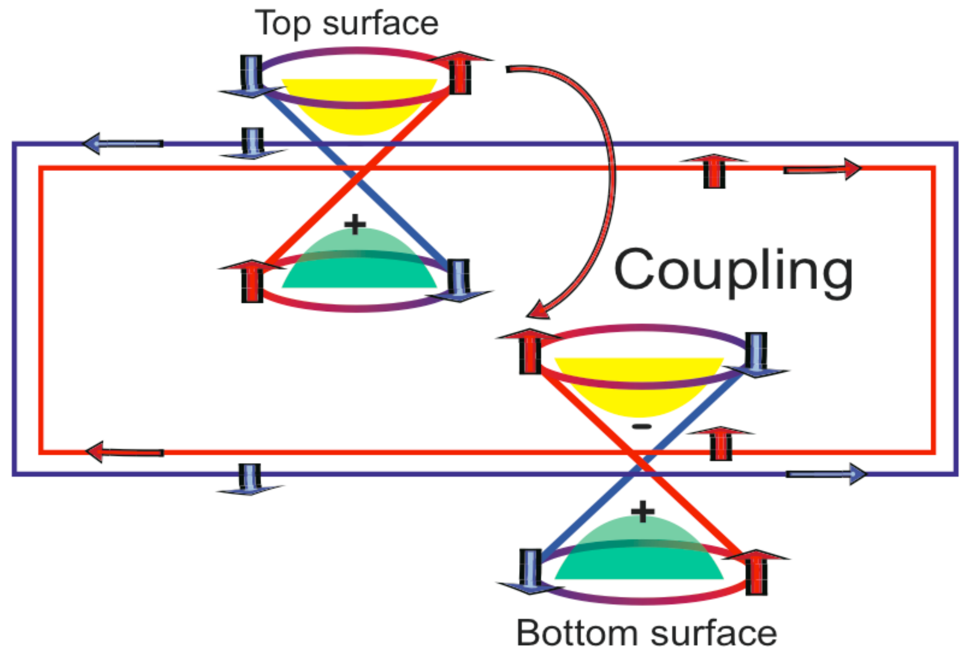




6% doping band gap closure and topological transition

Topological Transition in $Bi_{2-2x}In_{2x}Se_3$





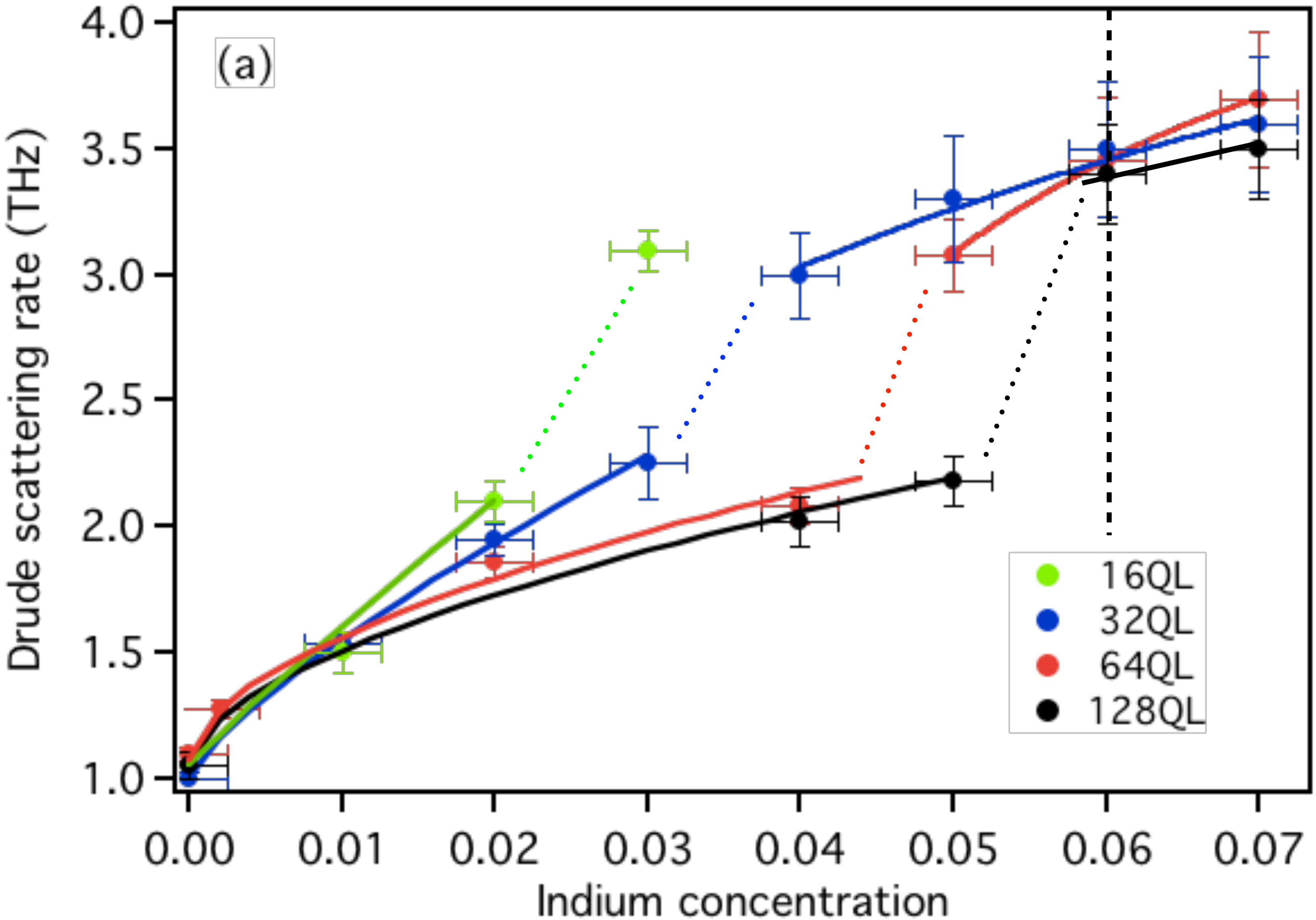
$\xi \sim v_F/\Delta \sim 2 \text{ nm} * 0.3 \text{ eV}/\Delta(x)$

Penetration depth of surfaces is governed by band gap

Enhanced scattering “near” the TI/nTI transition

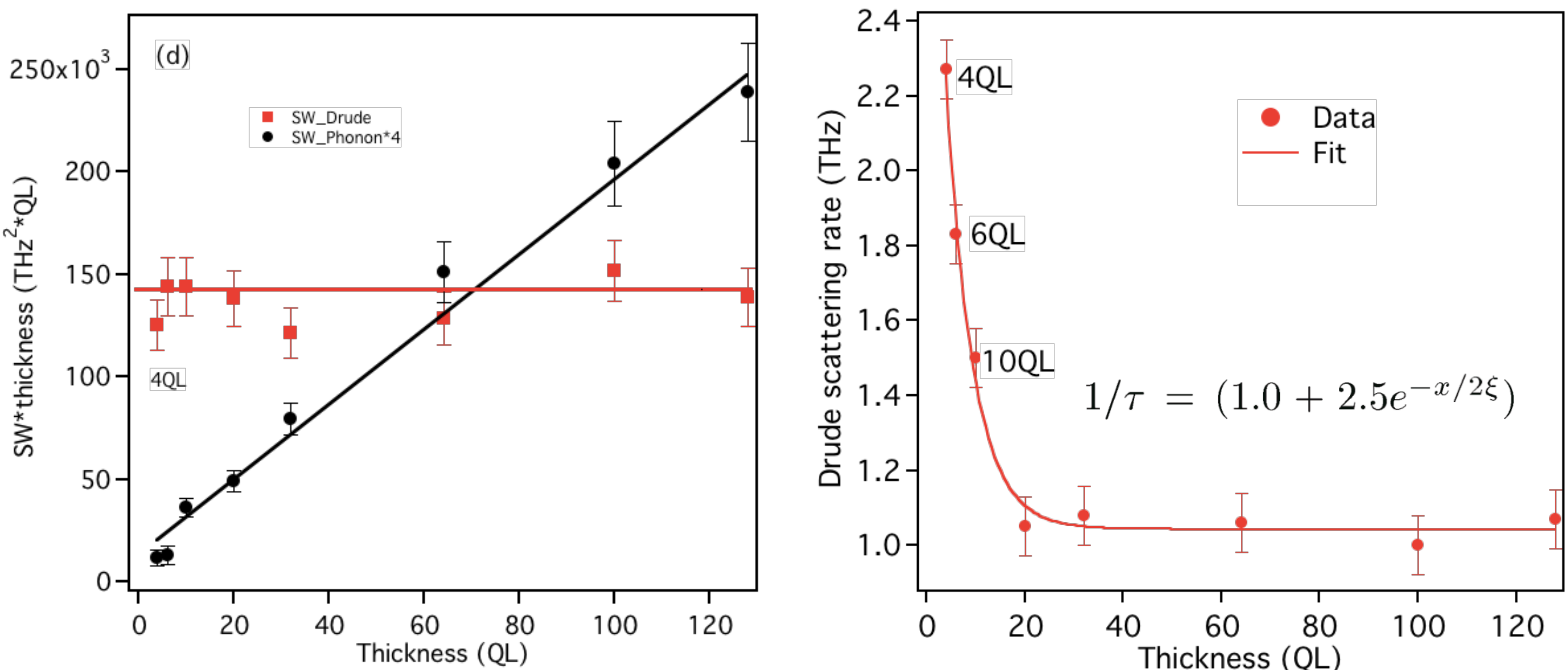
But wait! ... there is a mismatch between x~0.05 where jump in $1/\tau$ is seen and x~0.06 where band gap closes

Scattering rates through the TI/non-TI “phase transition”



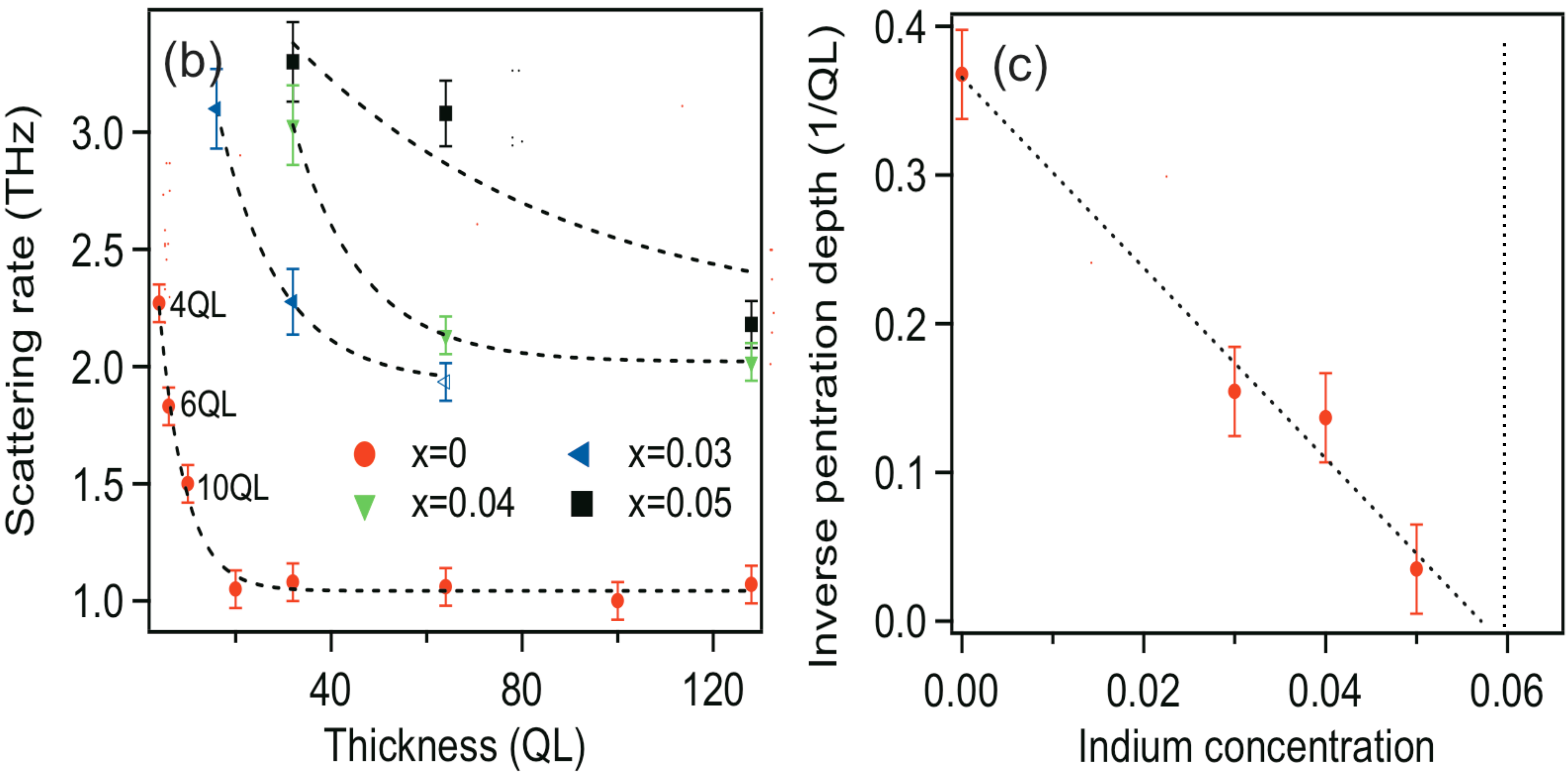
The low energy excitations near the transition ARE the boundary states!

Surface State Hybridization in Transport



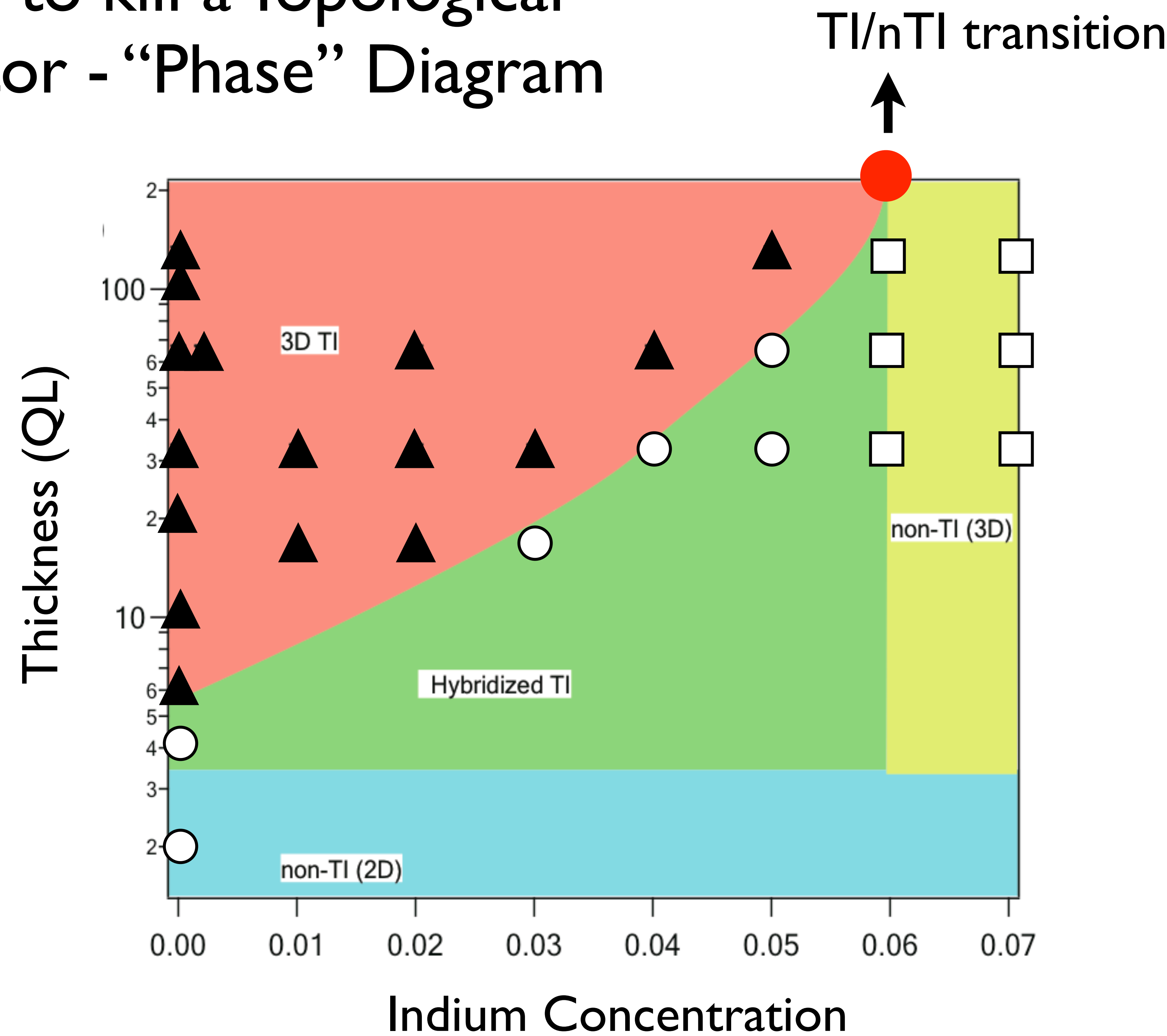
simple ansatz gives penetration of surface state
ξ ~ 2.7 QL is close to that extracted with ARPES

Finite size scaling analysis



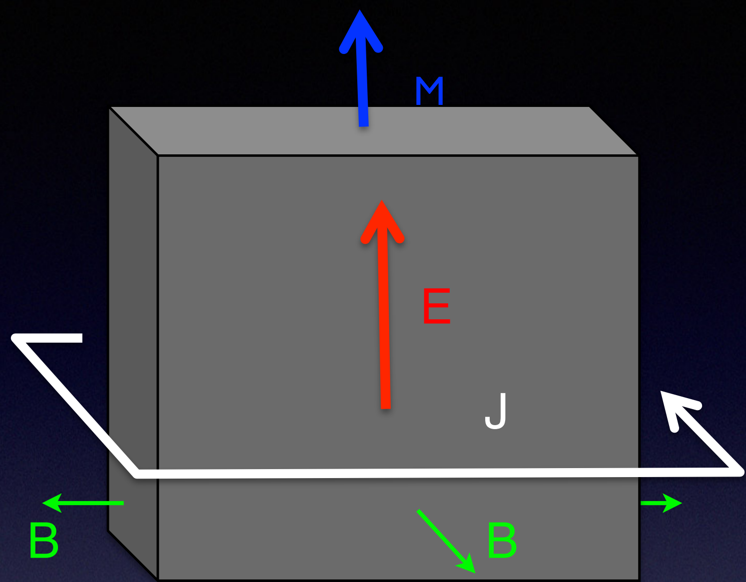
Finite size analysis gives dependence of critical length

How to kill a Topological Insulator - "Phase" Diagram



The topological magnetoelectric effect

Magnetoelectric response of a topological insulator



TI with magnetically gapped surface and QH effect.
Preserve inversion "deep inside"

$$K_x = G_{xy} E_y = \frac{e^2}{h}(n + \tfrac{1}{2}) E_y$$

$$\mathbf{K} = \mathbf{M} \times \hat{n} \rightarrow M_y = \frac{e^2}{h}(n + \tfrac{1}{2}) E_y$$

Surface current is equivalent to bulk magnetization;
Bulk magnetoelectric polarizability

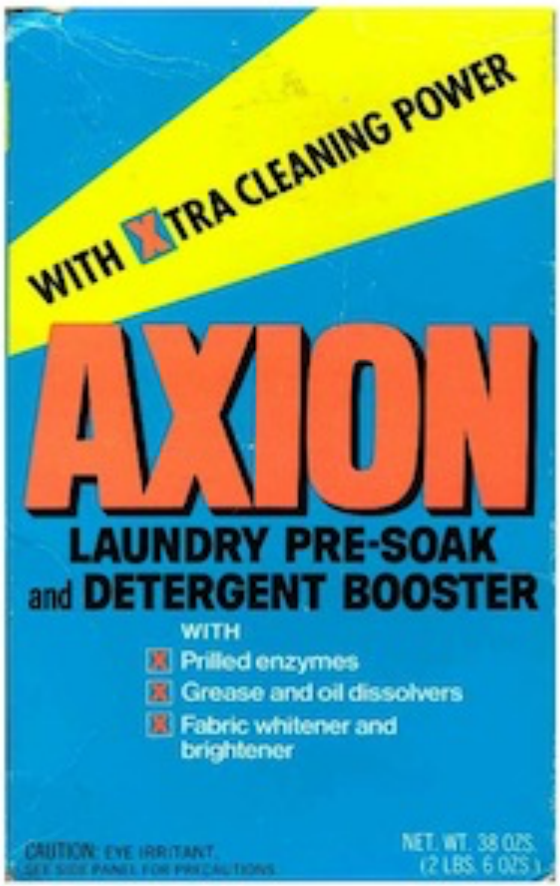
the 1/2 is set by the bulk topological properties

Can be described by axion modification to EM Lagrangian

$$\Delta \mathcal{L}_{EM} = \frac{\theta e^2}{2\pi h} \mathbf{E} \cdot \mathbf{B} = \frac{\theta e^2}{16\pi h} \epsilon^{\alpha\beta\gamma\delta} F_{\alpha\beta} F_{\gamma\delta}.$$

Exotic mangetoelectric effects (quantized axion EM response, induced monopoles)
Qi, et al. '08; Essin, et al.'09; Tse et al. '10,'11; Maciejko '10

"Axion Electrodynamics"



Axions had been postulated in 1977 in an attempt to explain the absence of charge- parity (CP) violation in the strong interaction between quarks. Wilczek called them the axion because they "**cleaned up**" a problem with CP violation.

`"I called this particle the axion, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving axial currents."` -F. Wilczek

In 1987 Wilczek pointed out that existence of axions modifies Maxwell equations.

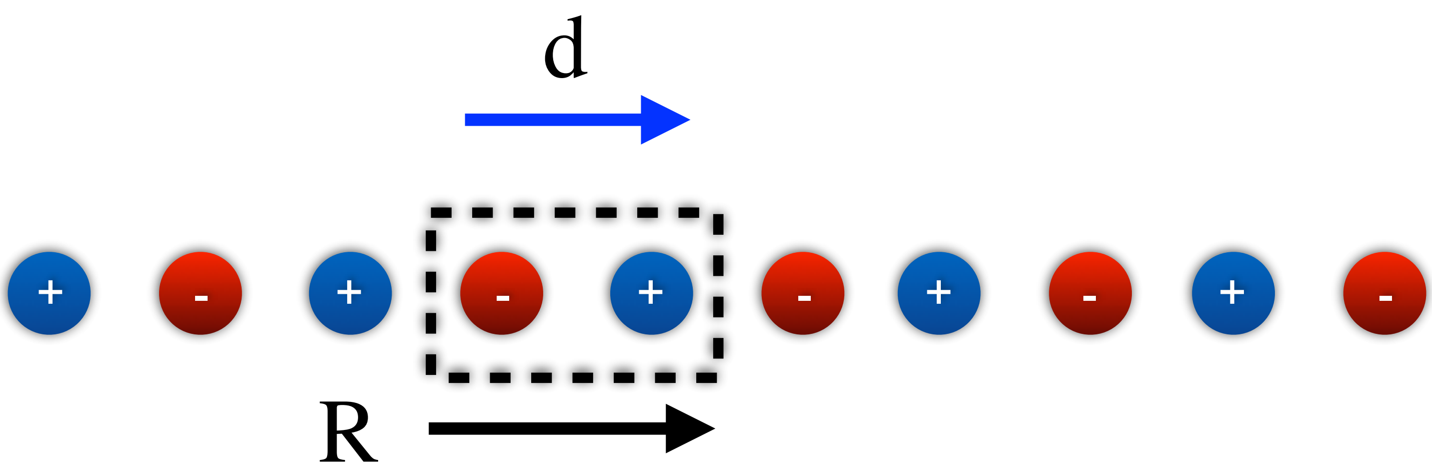
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} - 2c\alpha\nabla(\frac{\theta}{2\pi}) \cdot \mathbf{B}.$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t} + \frac{2\alpha}{c}[\mathbf{B}\frac{\partial}{\partial t}(\frac{\theta}{2\pi}) + \nabla(\frac{\theta}{2\pi}) \times \mathbf{E}]$$

$\theta = 2\pi$ (N + 1/2) can only be defined as a bulk quantity modulo 2π (like ferroelectric polarization **P**)

3D magnetoelectric effect will manifest as quantized Faraday and Kerr rotations
Scale set by fine structure constant $\alpha = e^2/2h\varepsilon_0 c \sim 0.418^o$

Problem with textbook definition of polarization

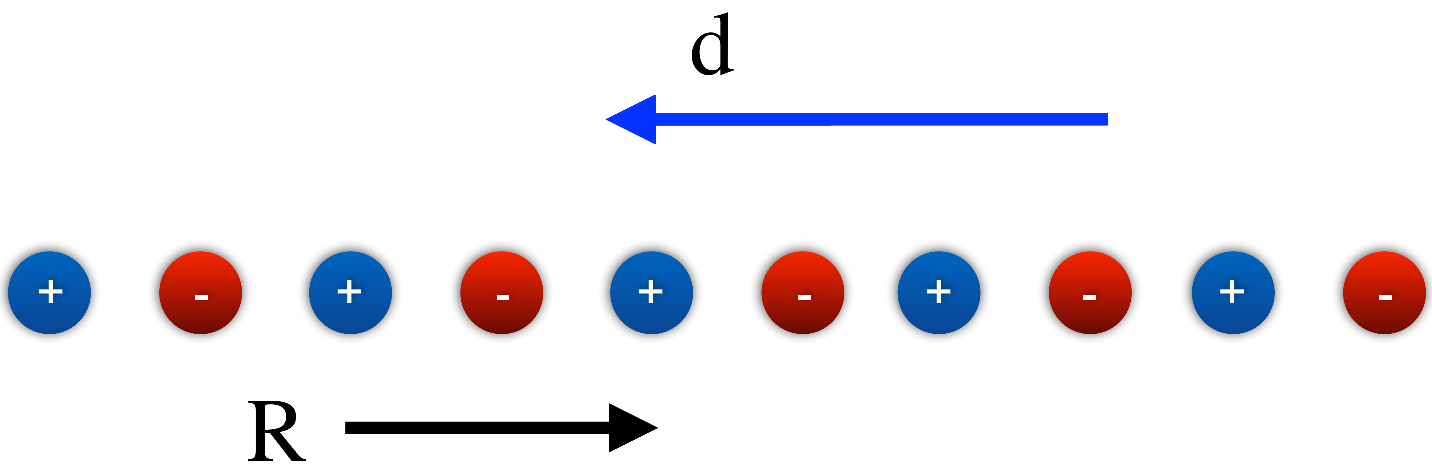


As a bulk quantity only changes in polarization are well defined → Modern theory of polarization

$$\mathbf{d} = V \cdot (\mathbf{P} + \frac{e}{\Omega}\mathbf{R})$$

Macroscopic dipole has ambiguity that originates either from definition of local dipole or surface charge → In fact these are same thing.

Ambiguity in local measures of polarization



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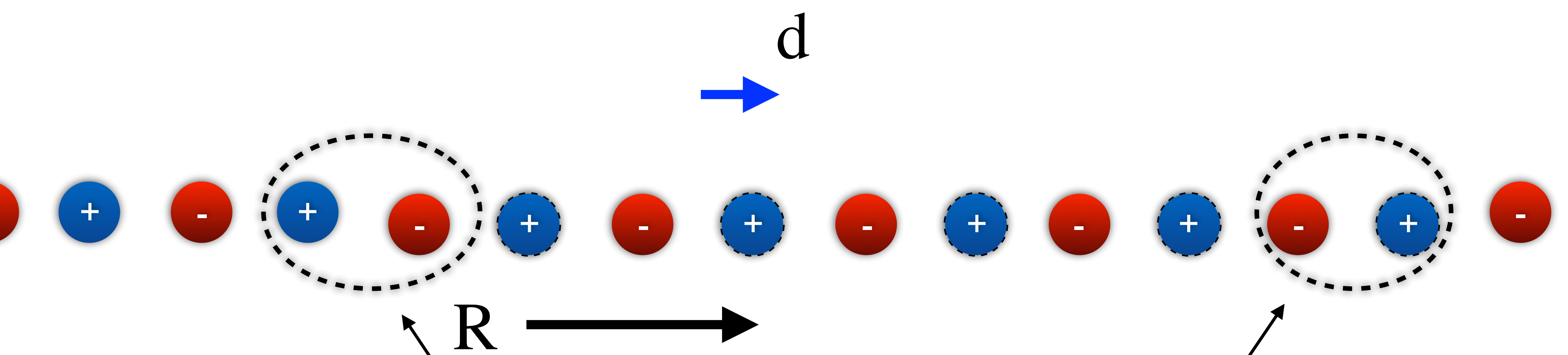


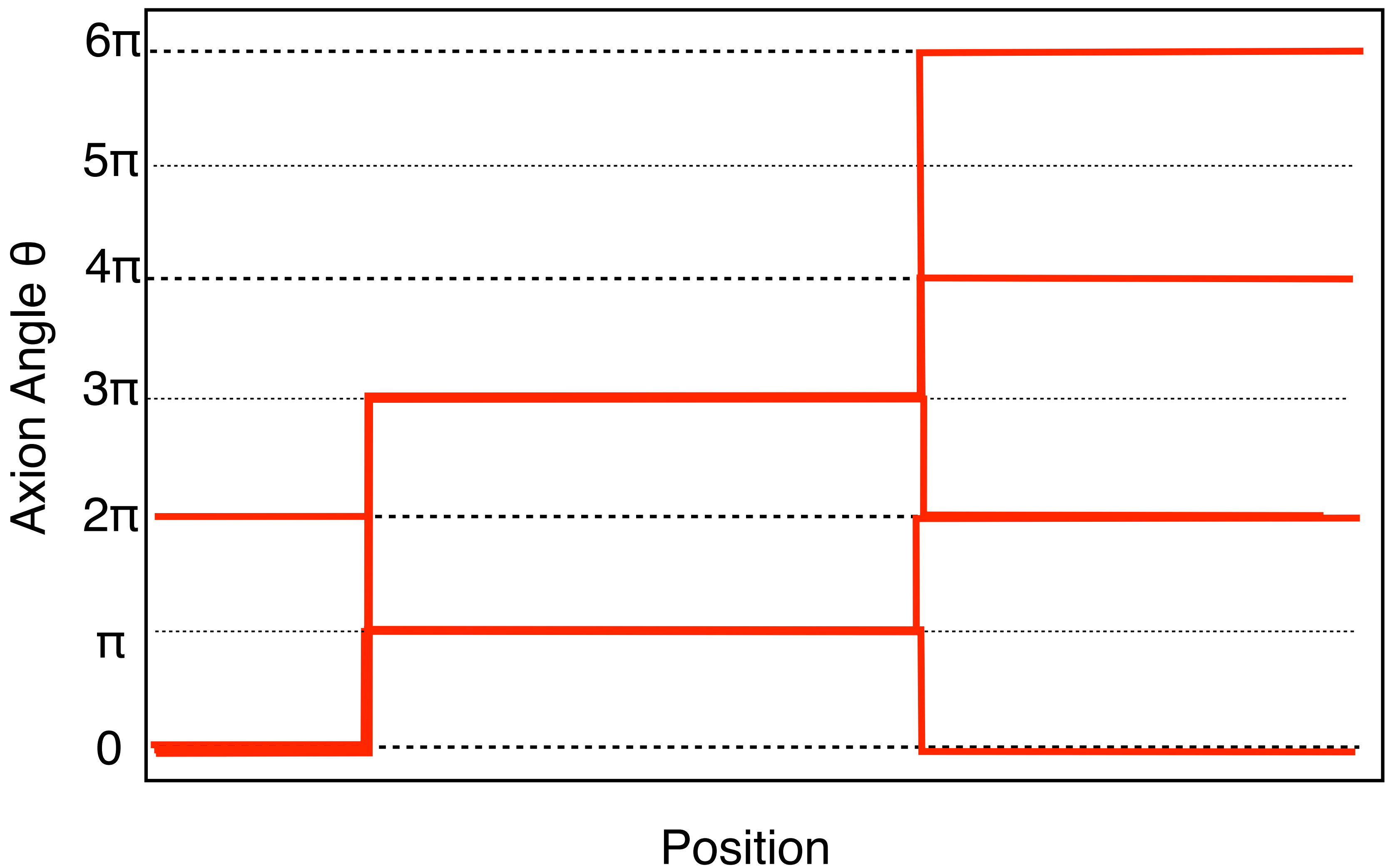
With this definition even inversion symmetric structures can have polarization (changes) defined, but the polarization must be quantized.

But in this scheme we can define two inversion symmetric structures, which have half quantized polarization difference → analogy to a TI.

$\frac{1}{2}$ e charge trapped at interfaces

But arising from bulk property.

Only changes in θ are physically accessible



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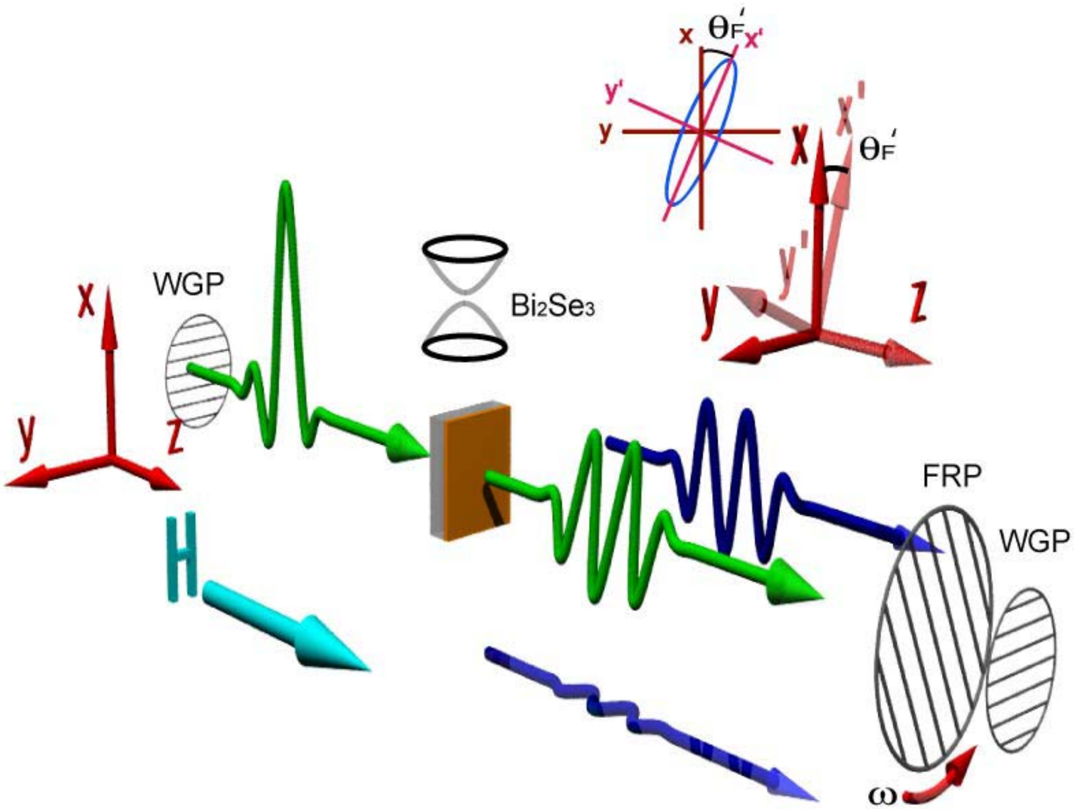
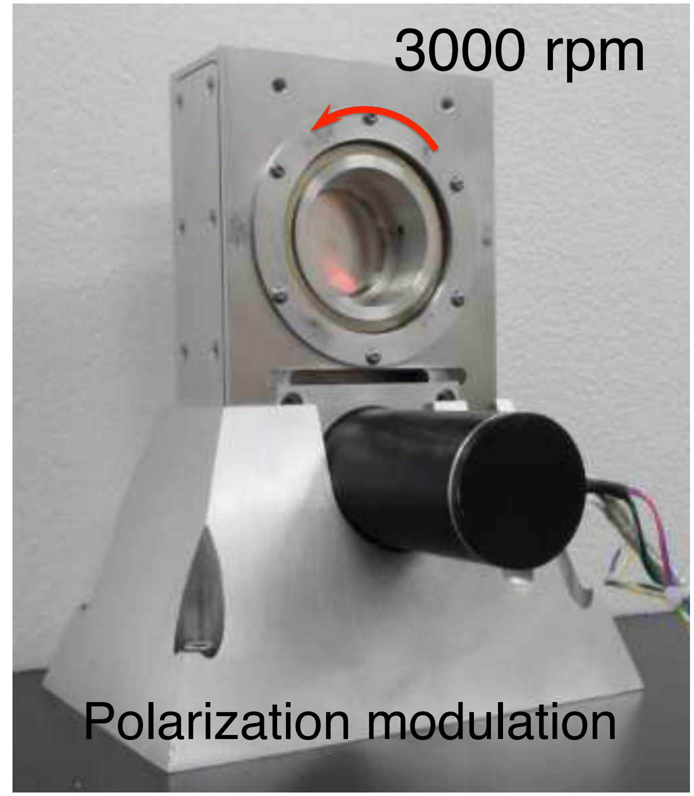
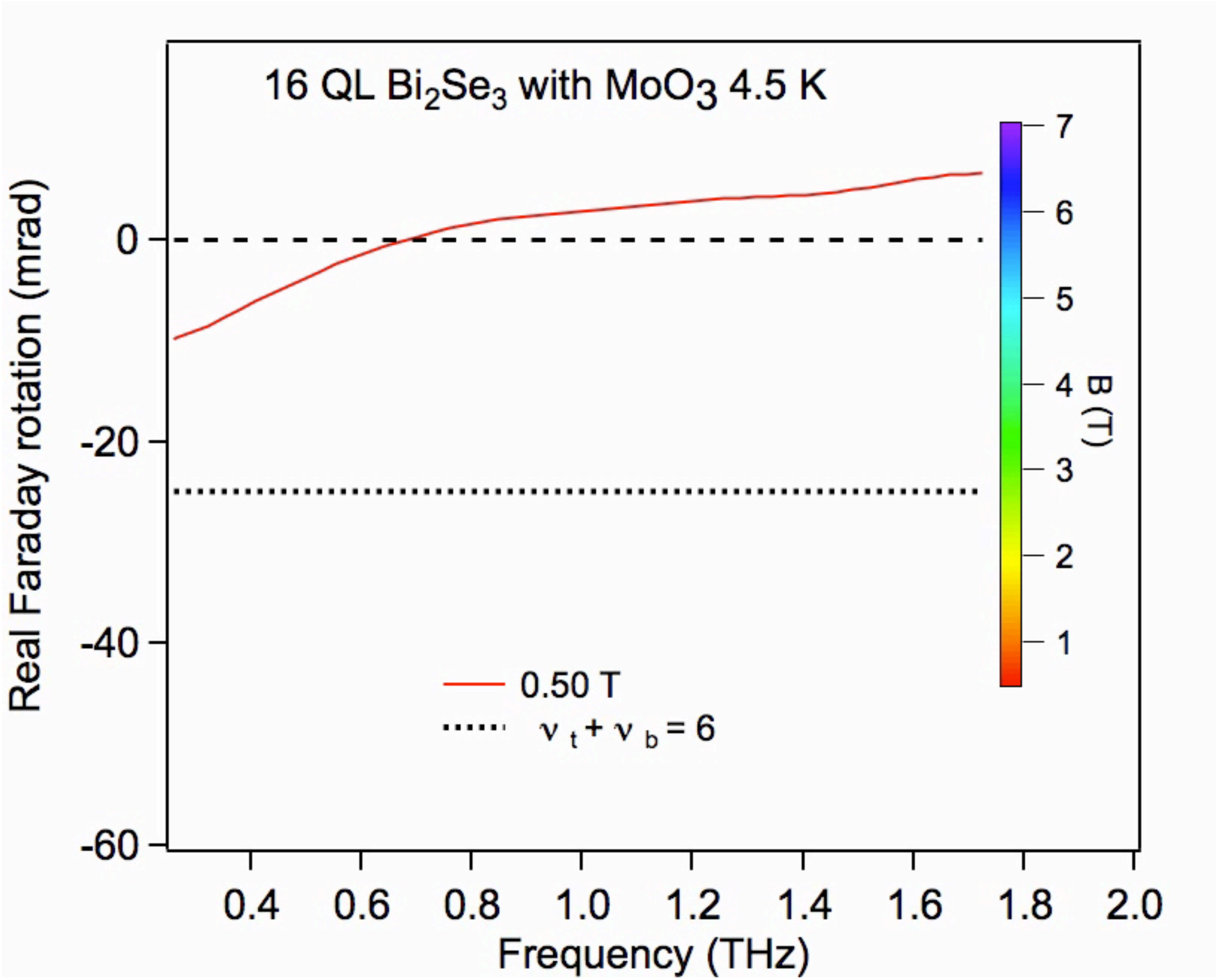
THz Faraday (polarization) rotation





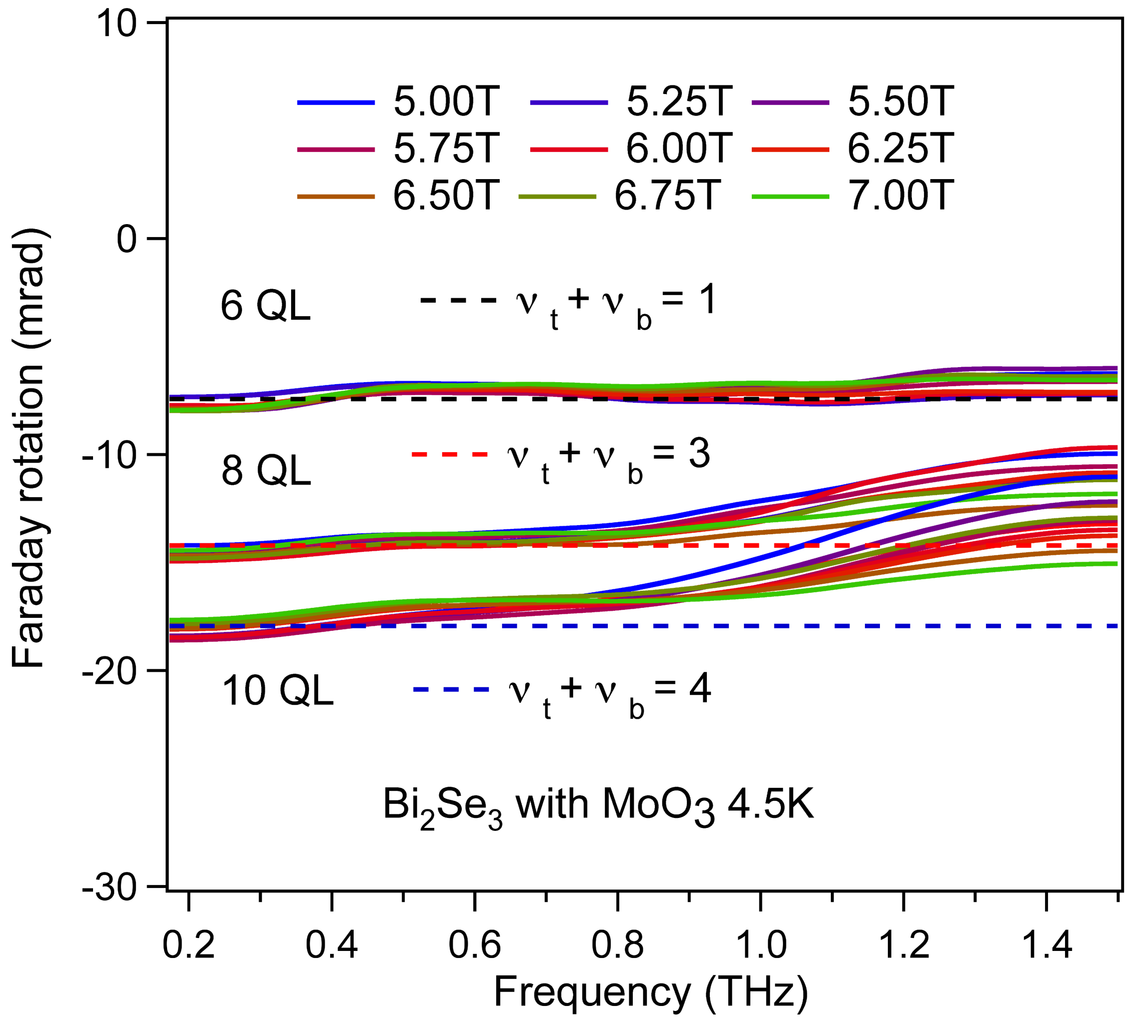
In- and out-of-phase components lockin @ 2ω are proportional to E_x and E_y

- Allows phase sensitive detection of E_x and E_y; Very accurate 0.01 degree sensitivity
- Frequency **and** field dependence gives lots of information
- Mobility, mass, and density of *multiple* channels can be resolved *separately* by cyclotron resonance



$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2}),$$ ← Quantization condition

A quantum regime of quantized Faraday rotation



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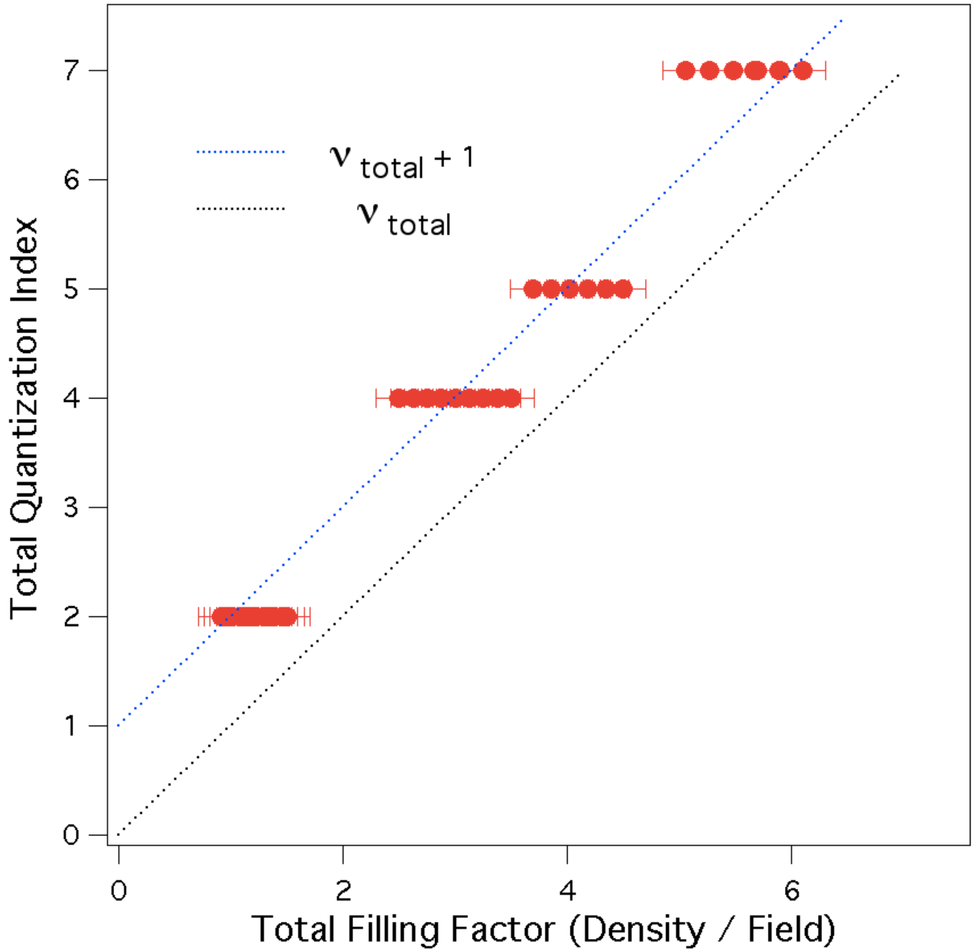


With spectral weight and cyclotron mass, we measure filling factors directly (ν=n/B)

Quantization index

$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2}),$$

Quantization index shows offset. With two surfaces each surface has minimum $\sigma_{xy}=e^2/2h$.

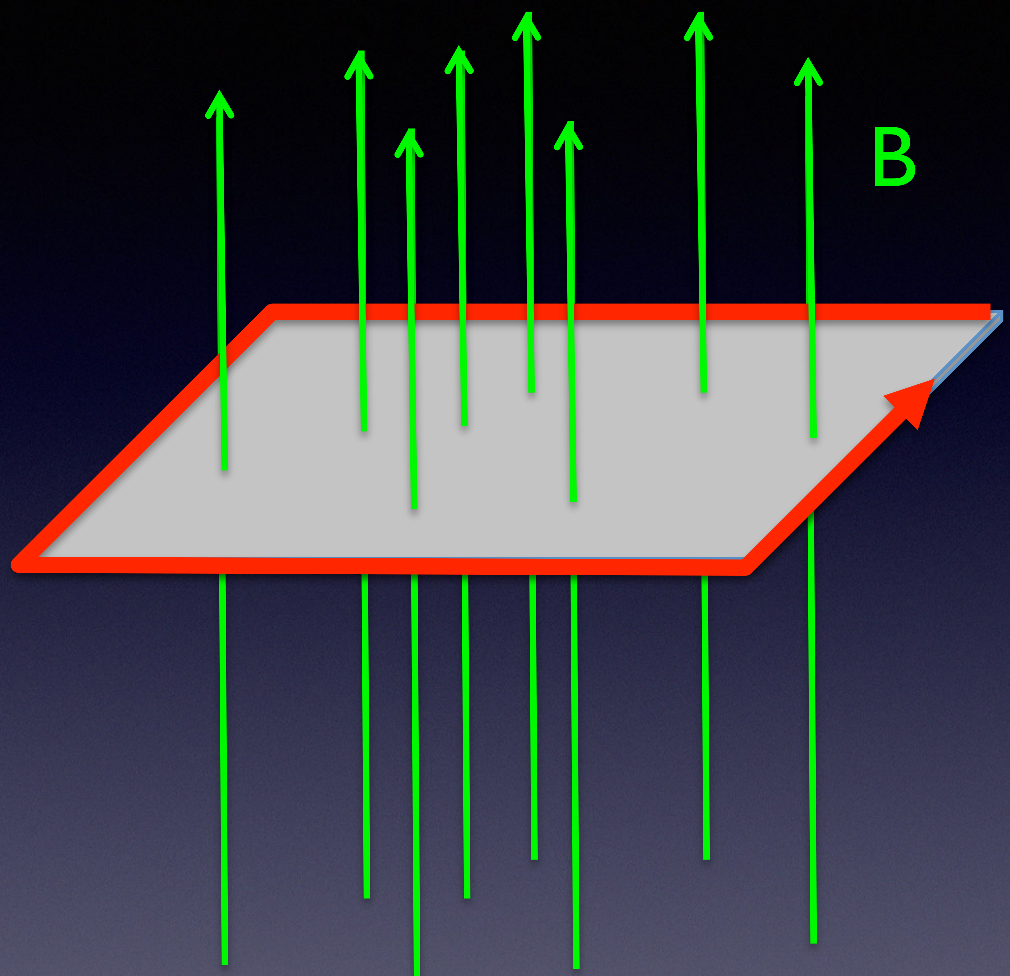
Consistent with topological magnetoelectric effect

Must be a bulk effect as gapped 2D material must have $\sigma_{xy}=ne^2/h$

Is this just the normal integer quantum Hall effect?

NO!

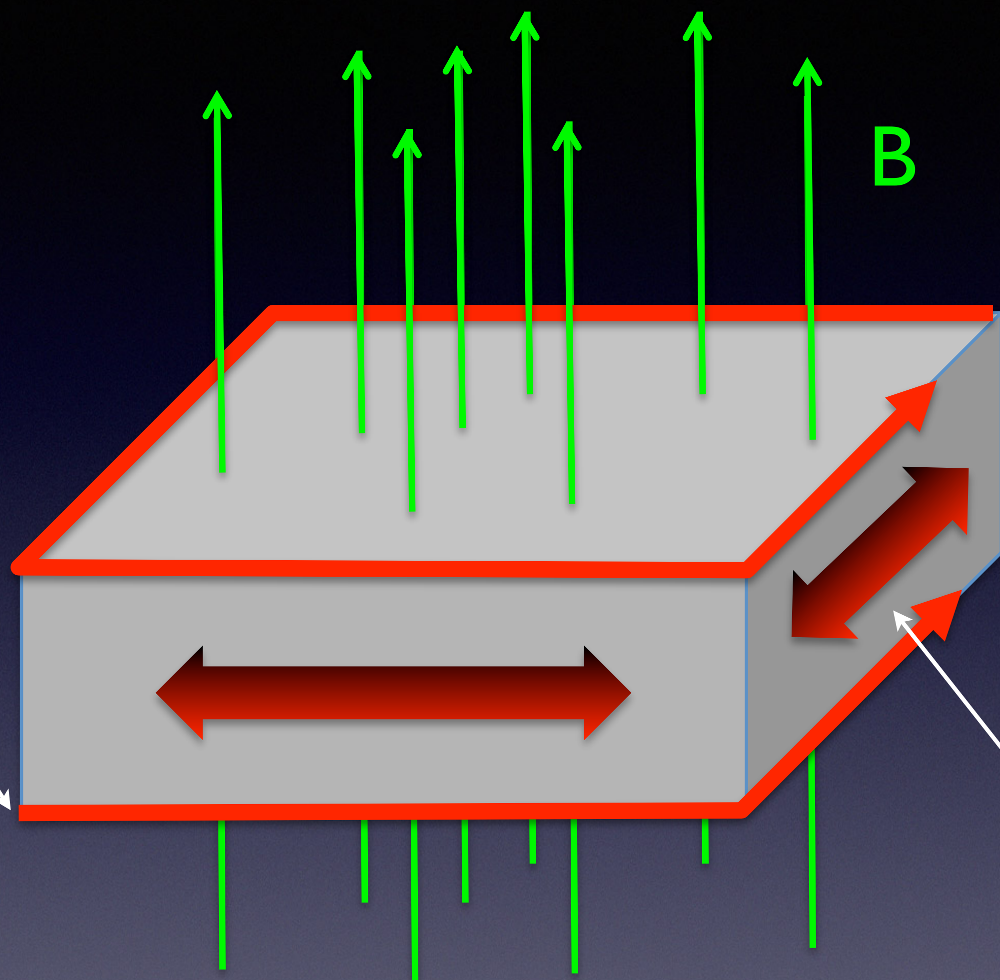
Topological insulator in magnetic field



$$J_x = \sigma_{xy} E_y = \frac{e^2}{h}(n + \tfrac{1}{2}) E_y$$

n depends on filling factor (Field, chemical potential), but the 1/2 is a property derived from bulk

Topological insulator in magnetic field

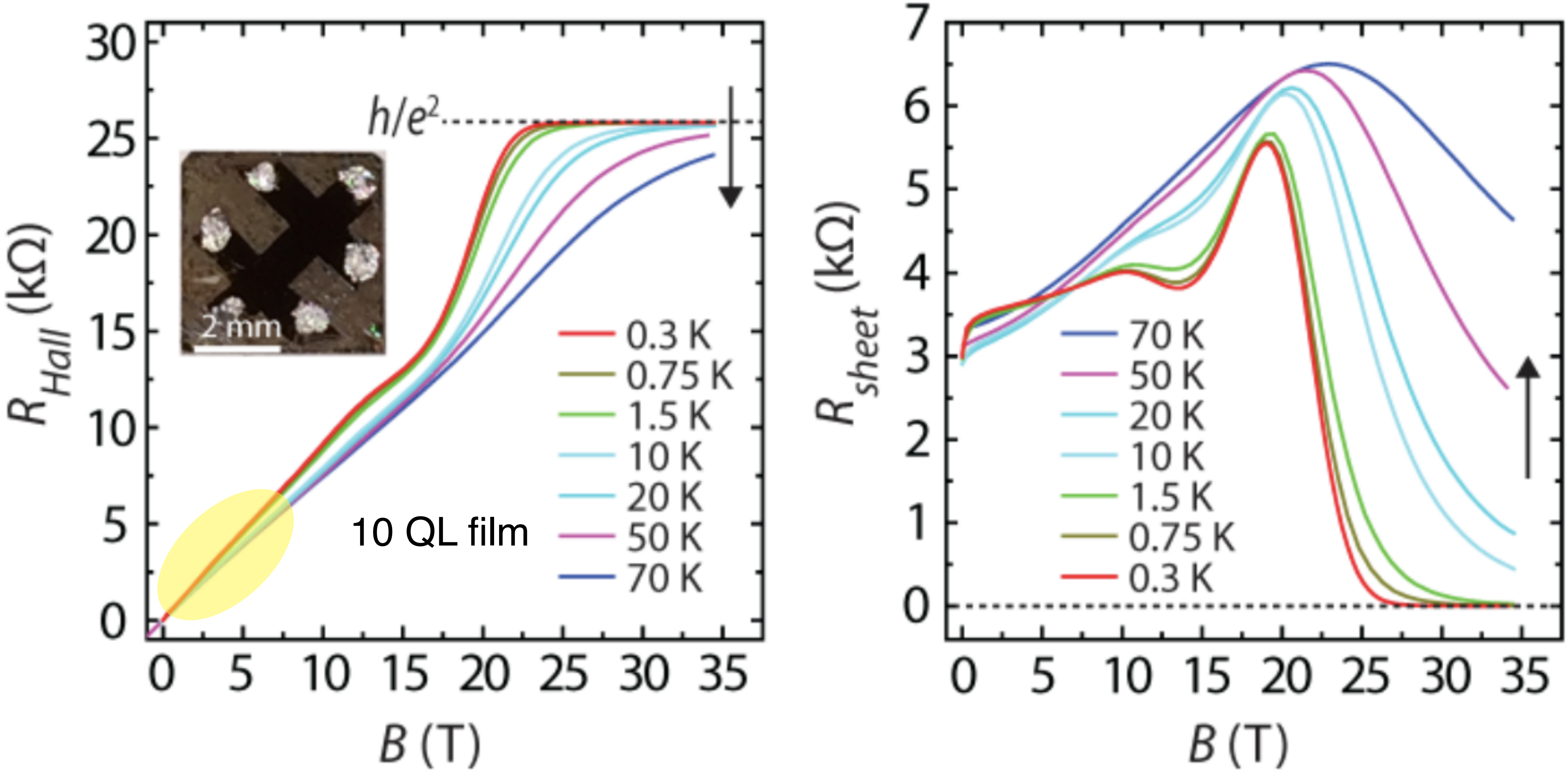


Edges states each may contribute 1/2 QH effect

Non chiral Dirac metal side surfaces; will short out Hall voltage, except at high field where they may localize

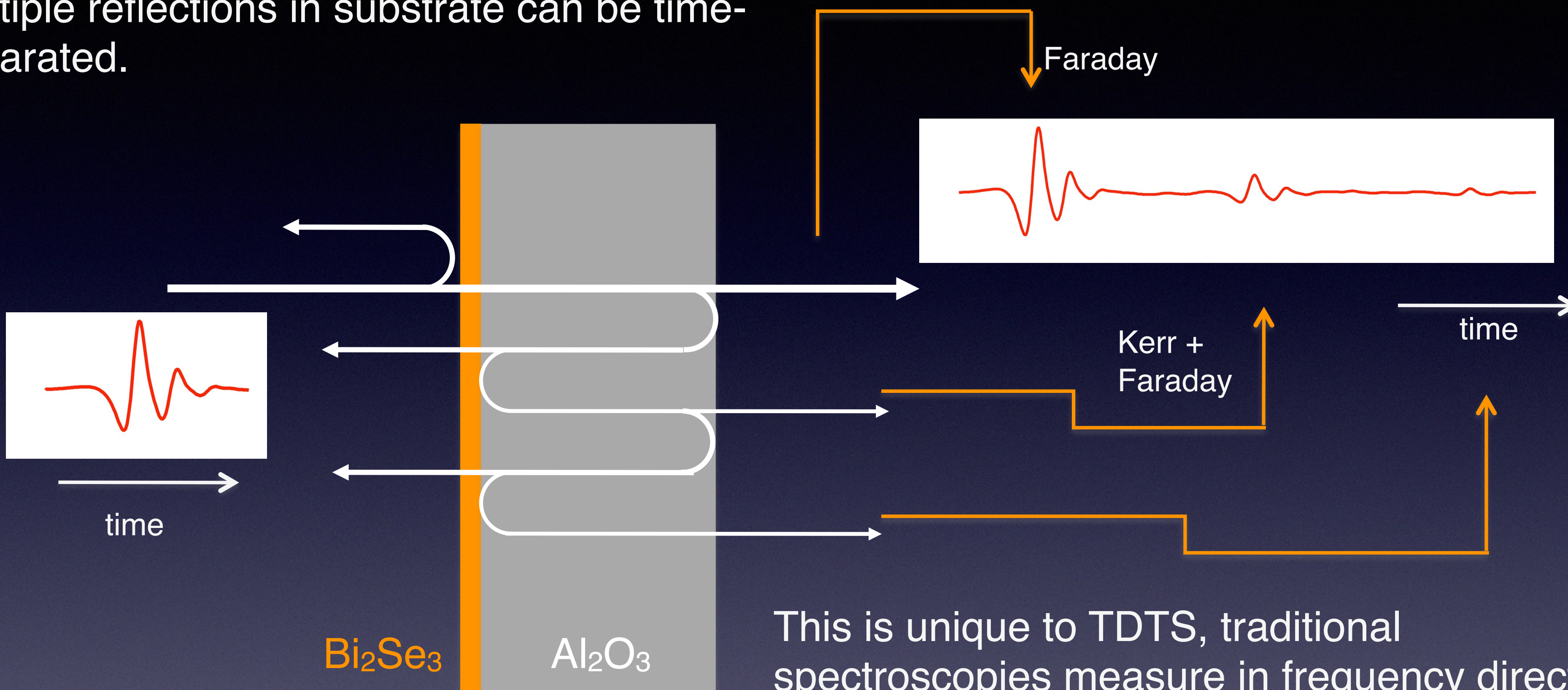
$$J_x = \sigma_{xy} E_y = \frac{e^2}{h}(n + \tfrac{1}{2}) E_y$$

DC Quantum Hall effect only at high fields



Kerr and Faraday Measurements

In TDTS, E field is measured in time.
Multiple reflections in substrate can be time-separated.



This is unique to TDTS, traditional spectroscopies measure in frequency directly.

Faraday rotation

$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2}),$$

Kerr rotation

$$\tan(\phi_K) = \frac{4n\alpha}{n^2-1}(N_t + \frac{1}{2} + N_b + \frac{1}{2}).$$

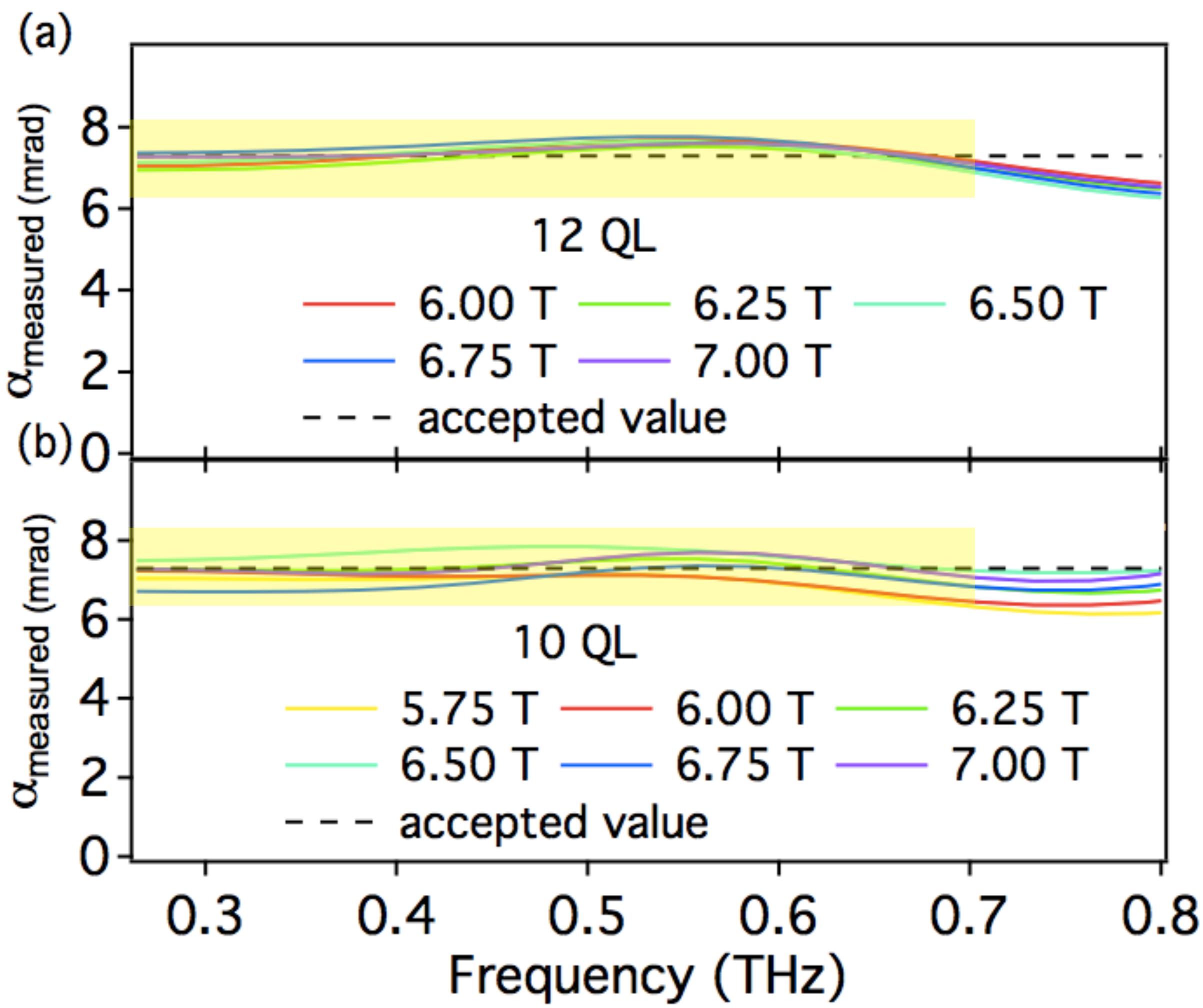
Axion regime: well-defined surface Hall effect

α is fine structure constant. *N is LL index.*
n is substrate index of refraction.

arcTan(α) ~ 0.418°

A solid state measure of α

$$\alpha_{measured} = \frac{1}{N_t + N_b + 1/2 + 1/2} \frac{\tan(\phi_F)^2 - \tan(\phi_F)\tan(\phi_K)}{\tan(\phi_K) - 2\tan(\phi_F)}$$



(average over 3 samples and 0.25 – 0.7 THz)

accepted: $\alpha^{-1} \sim 137.04$

measured: $\alpha^{-1} \sim 137.9$

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Thickness independent (surface state) transport in Bi_2Se_3 topological insulator film

Two surface states that we can see through Topological Non-topological phase transition in In-doped Bi_2Se_3 investigated with THz

→ Band gap closure and change in topological class
Lifetime collapse in surface state transport

Quantized magnetoelectric effects. Axion electrodynamics

Valdes Aguilar et al., PRL 2012
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Wu et al. Science 2016