Title: Low-energy electrodynamics of topological insulator thin films

Date: May 02, 2016 03:30 PM

URL: http://pirsa.org/16050013

Abstract: <p>Topological insulators (TIs) are a recently discovered state of matter characterized by an â€œinvertedâ€• band structure driven by strong spin-orbit coupling. One of their most touted properties is the existence of robust "topologically protected" surface states. I will discuss what topological protection means for transport experiments and how it can be probed using the technique of time-domain THz spectroscopy applied to thin films of Bi2Se3. By measuring the low frequency optical response, we can follow their transport lifetimes as we drive these materials via chemical substitution through a quantum phase transition into a topologically trivial regime[1]. I will then discuss our work following the evolution of the response as a function of magnetic field from the semi-classical transport regime[2] to the quantum regime[3]. In the semi-classical regime, an anomalous increase of the transport scattering rate was observed at high field, which contribute from electron-phonon interaction[2]. In the highest quality samples[3,4], we observe a continuous crossover from a low field regime where the response is given by semi-classical transport and observed in the form of cyclotron resonance to a higher field quantum regime[3]. In the later case, we find evidence for Faraday and Kerr rotation angles quantized in units of the fine structure constant[3]. This quantized rotation angle can be seen as evidence for a novel magneto-electric of the TIâ€™s surface e.g. the much heralded axion electrodynamics of topological insulators. Among other aspects this give a purely solid-state measure of fine structure constant[3].</p>

<p> </p>

<p>1. Wu, et al, Nat. Phys. 9, 410 (2013).</p>

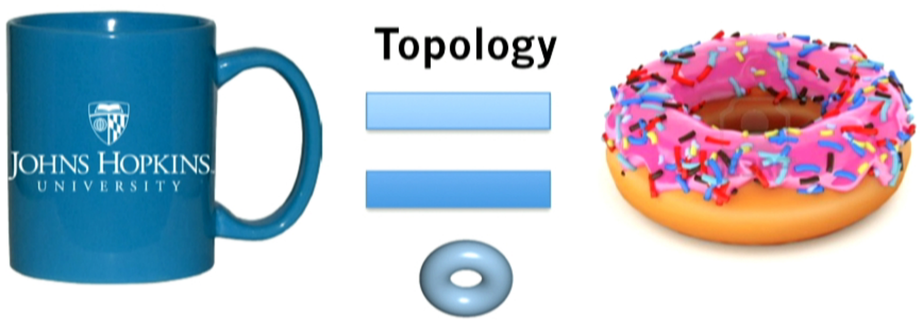
<p>2. Wu, et al, Phy. Rev. Lett. 115, 217602 (2015).</p>

<p>3. Wu, et al, arXiv. 1603.04317 (2016)</p>

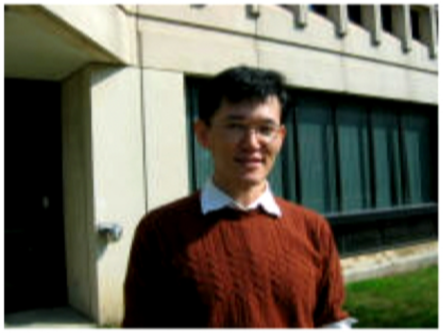
<p>4. Nikesh, et al, Nano. Lett. 15, 8245 (2015)</p>

Low-energy electrodynamics of 3D topological insulator thin films

Liang Wu
Department of Physics
University of California, Berkeley



Acknowledgement



Prof. Peter Armitage (JHU)

Prof. Seongshik Oh (Rutgers)

Porf. Howard Katz (JHU)
Robert Ireland (JHU)

Matthew Brahlek (Rutgers→PSU)
Maryam Salehi (Rutgers)
Nikesh Koirala (Rutgers)

Theory: Wang-Kong Tse (LANL→UA)

Gordon and Betty MOORE FOUNDATION

Overview of results

1st part

- Why THz spectroscopy? --- Low energy, long wavelengh limit
- Low-energy signatures of Surface states (SSs) in topological insulator (TI) Bi_2Se_3
- 'Kill' SSs by TI-conventional insulator transition in $(Bi_{1-x}In_x)_2Se_3$

2nd part

- Cyclotron resonances (CRs) from SSs, Landau Level transitions
- CR broadening → electron phonon coupling

3rd part

- Axion electrodynamics of SSs
- Quantized Faraday/Kerr rotation → Topological magneto-electric effect

THz (~meV) is the right energy to study these Physics!

Topological Insulators

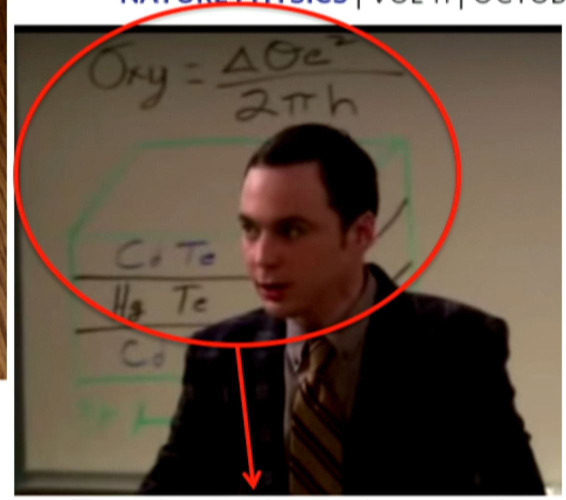
Exotic states of matter…
not characterized by broken symmetry

Insulating bulk

An 'unrealistic 'demo made by me …

Helical **metallic surface**

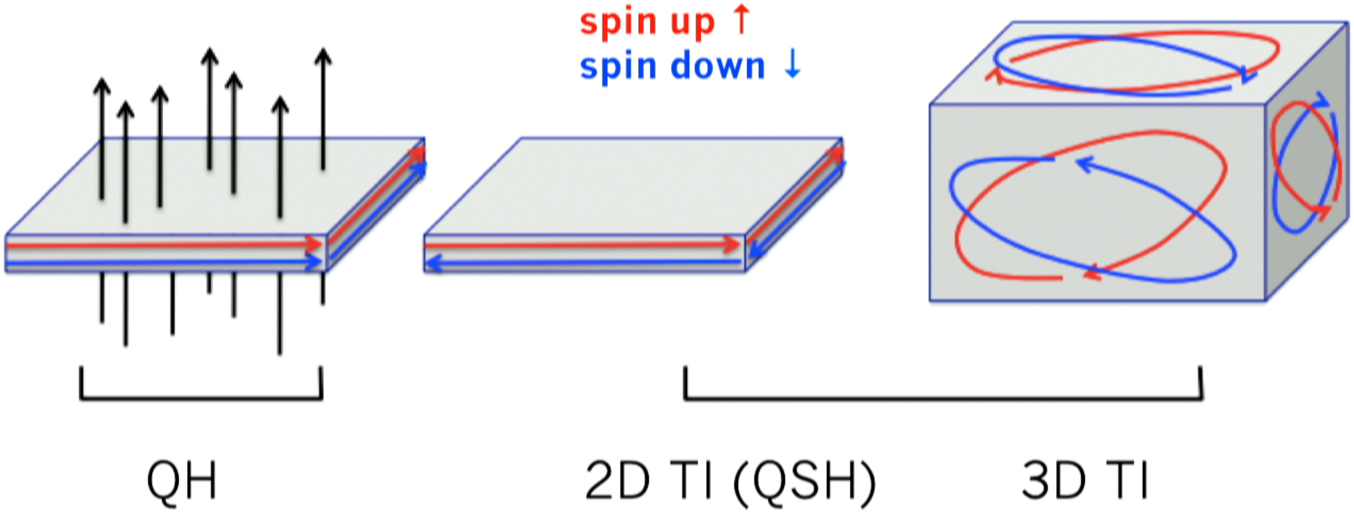
NATURE PHYSICS | VOL 11 | OCTOBER 2015



Topological insulators showed up in *'Big Bang Theory'* TV series!

QHE in 3D without magnetic field?

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



broken time-reversal symmetry

Quantized resistance

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

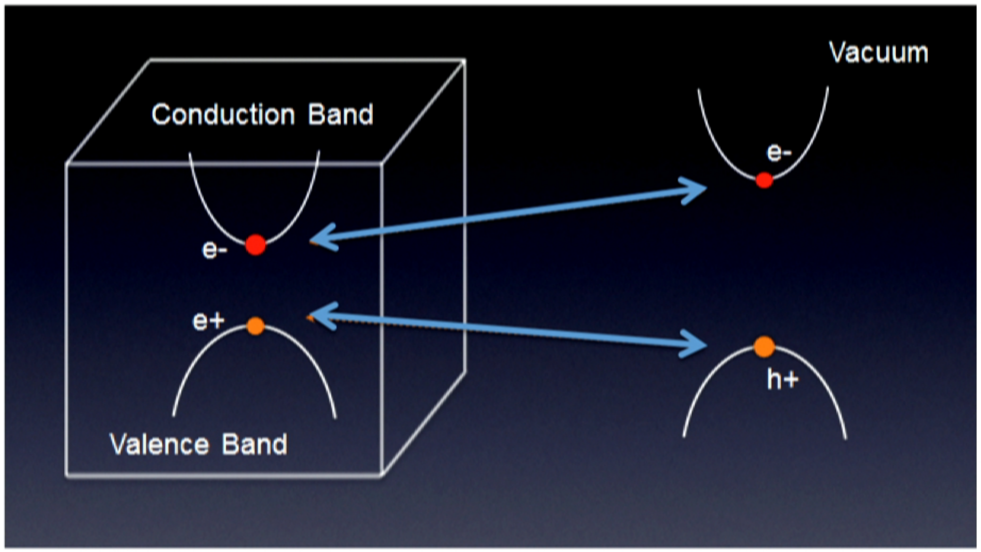
time-reversal symmetric

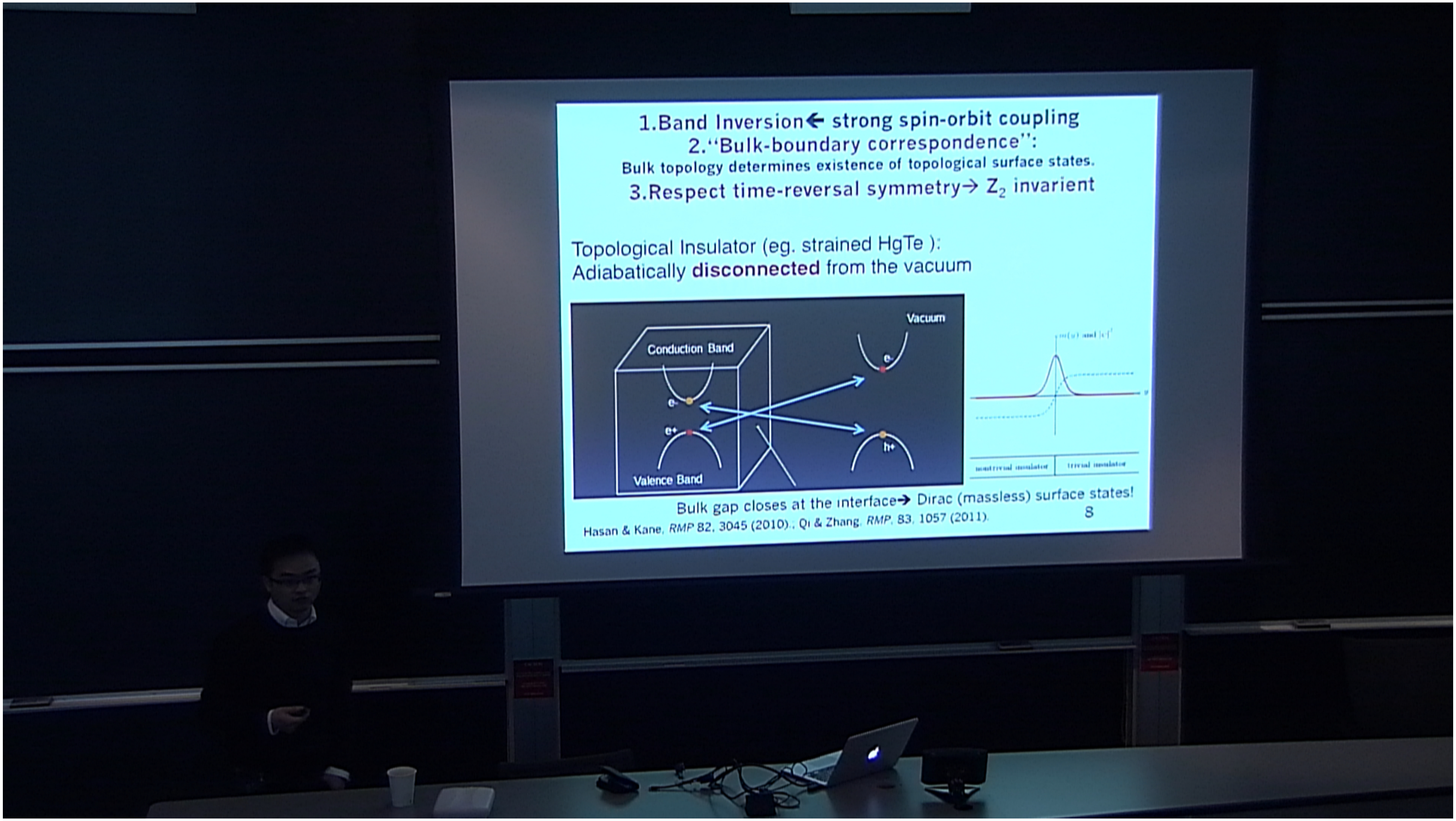
$$H_{SOC} = \frac{\hbar}{4m^2c^2}(\nabla V \times \vec{p})\vec{\sigma}$$

Spin-orbit coupling can look like a momentum dependent magnetic field

How to classify TIs?

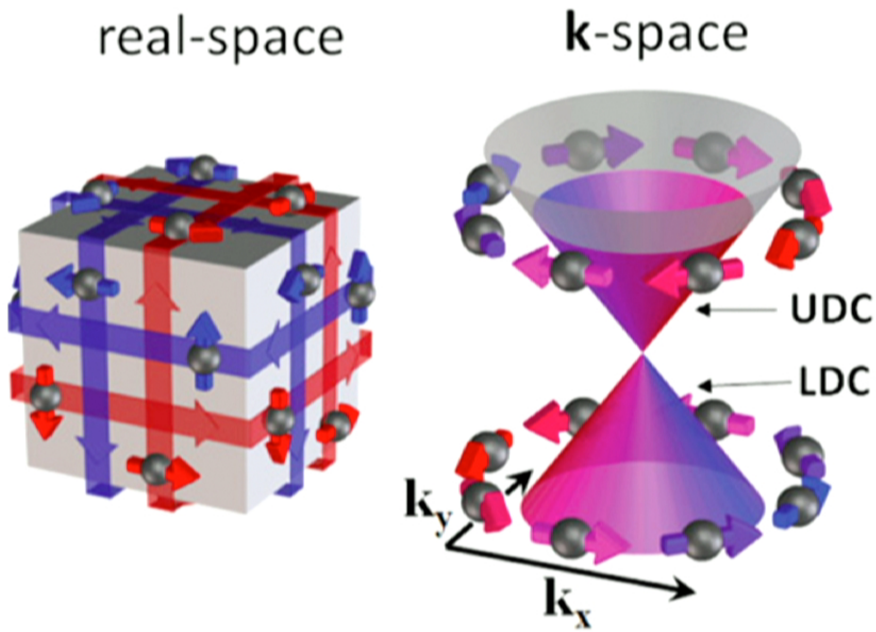
Conventional Insulator (eg. GaAs) :
Adiabatically connected to the vacuum




1.Band Inversion← strong spin-orbit coupling
2."Bulk-boundary correspondence":
Bulk topology determines existence of topological surface states.
3.Respect time-reversal symmetry→ Z2 invarient
Topological Insulator (eg. strained HgTe):
Adiabatically disconnected from the vacuum
Vacuum
Conduction Band
e-
e+
h+
Valence Band
Bulk gap closes at the interface→ Dirac (massless) surface states!
Hasan & Kane, RMP 82, 3045 (2010)., Qi & Zhang, RMP, 83, 1057 (2011).
8

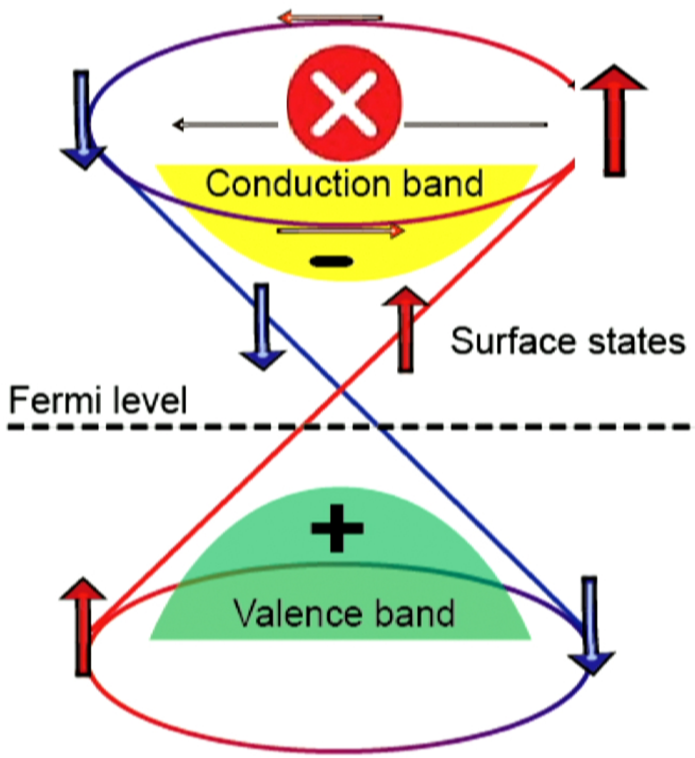
Proposed *“Flipper Bridge”* between Hong Kong (left-hand traffic) & Mainland China (right-hand traffic)

Dirac surface states



Fermion doubling theorem (Nielssen & Ninomiya 1983): Dirac points much come in pairs in a time-reversal invariant system**.** 3D TIs **"invades"** this theorem by putting one Dirac point on the opposite side.

Topological protection in transport



Transport is sensitive to backscattering.
Suppression of back scattering due to spin-momentum locking

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

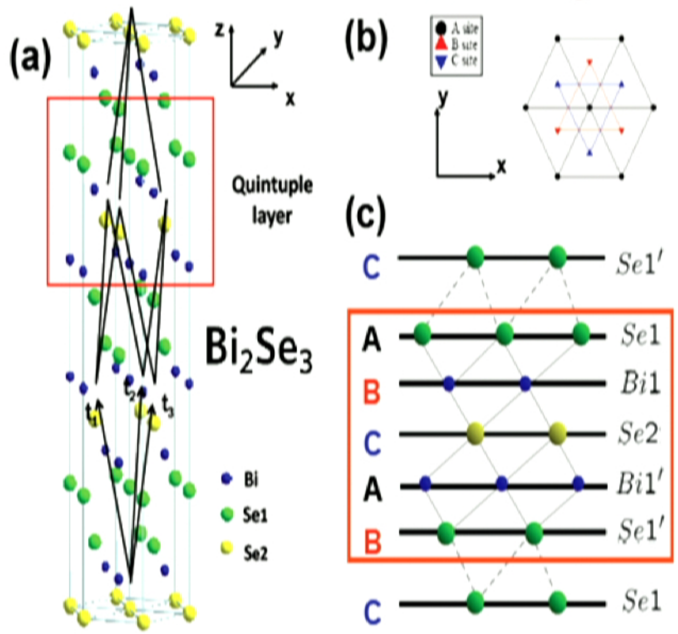
$$1/\tau^{TSS}_{trans} = \frac{1}{8}(1/\tau_{qp})$$

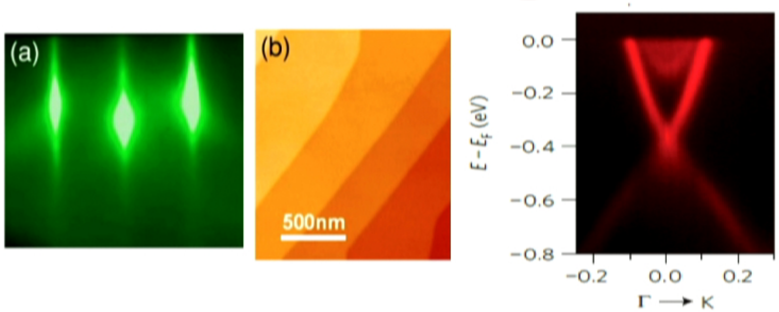
$$1/\tau_{trans} = (1/\tau_{qp})\frac{1}{2\pi}\int d\theta\left(\frac{1-\cos\theta}{2}\right)$$

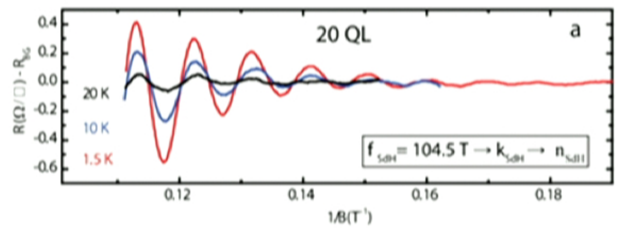
$$1/\tau_{trans} = \frac{1}{2}(1/\tau_{qp})$$

Enhancement of scattering rate by factor of unity when topological protection is lost.

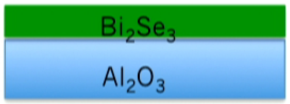
MBE Bi_2Se_3 films from Rutgers





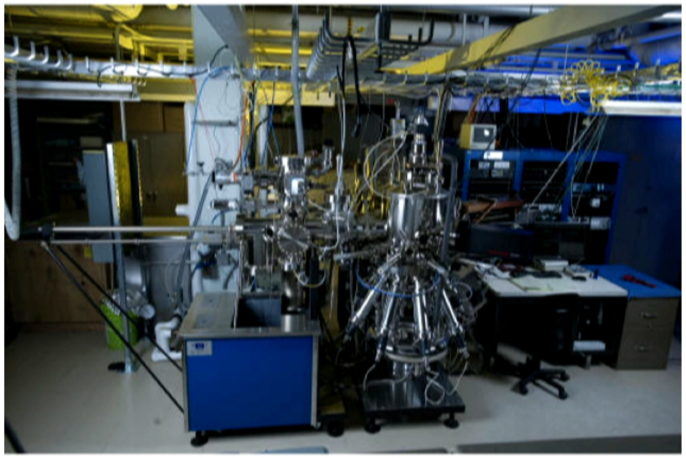


1QL~1nm

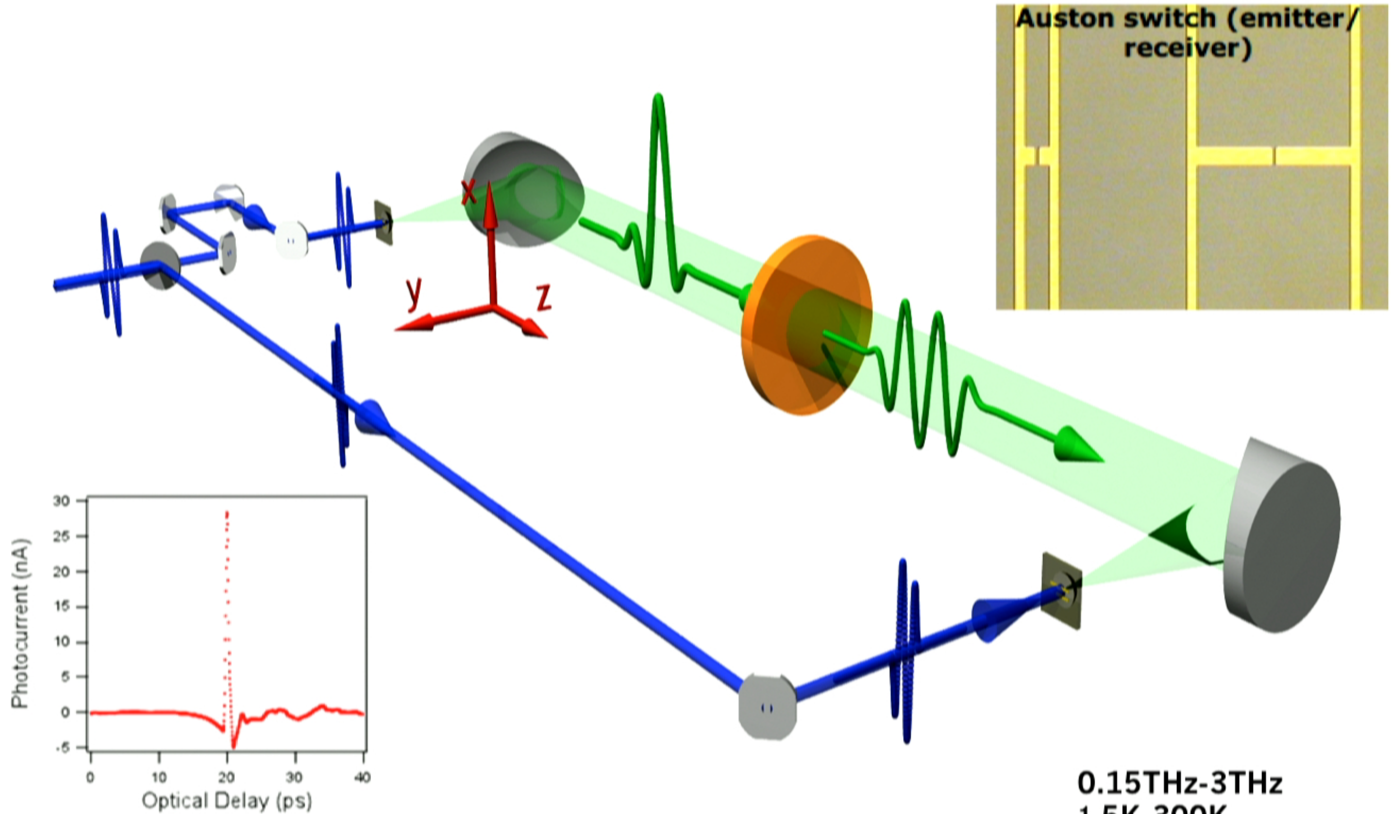


Two step growth on sapphire substrate.

Bansal *et al. PRL*, 109, 116804, (2012)
Brahlek *et al. PRL*, 113, 026801 (2014)



Time-domain THz spectroscopy (TDTS)

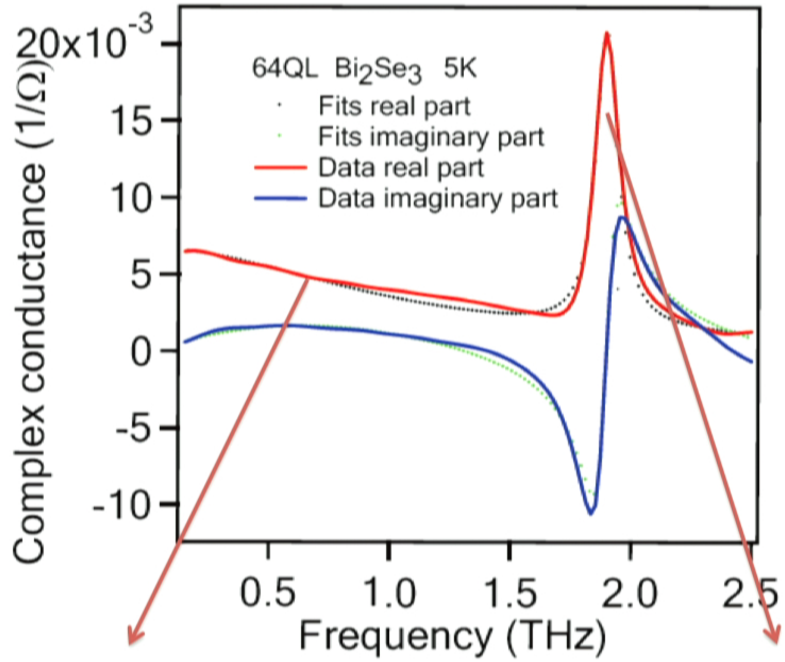


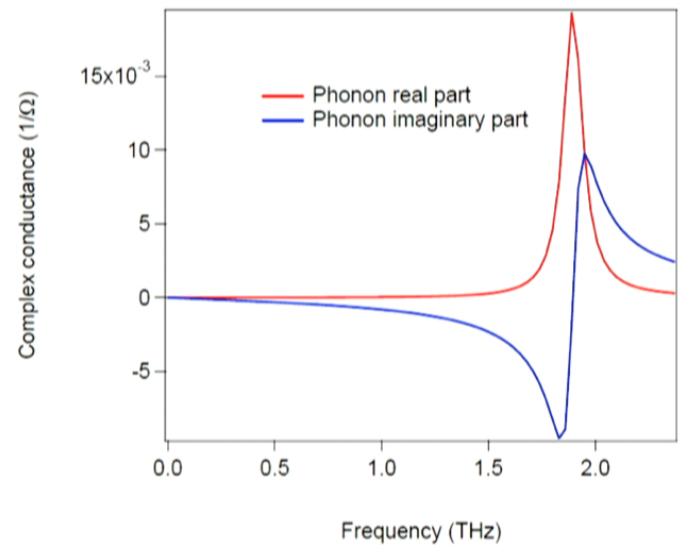
0.15THz-3THz
1.5K-300K

$$\tilde{T}(\omega) = \frac{1+n}{1+n+Z_0\tilde{\sigma}(\omega)d}e^{i\Phi_s}$$

1THz~ 4meV~50K

Complex conductance in TI Bi_2Se_3





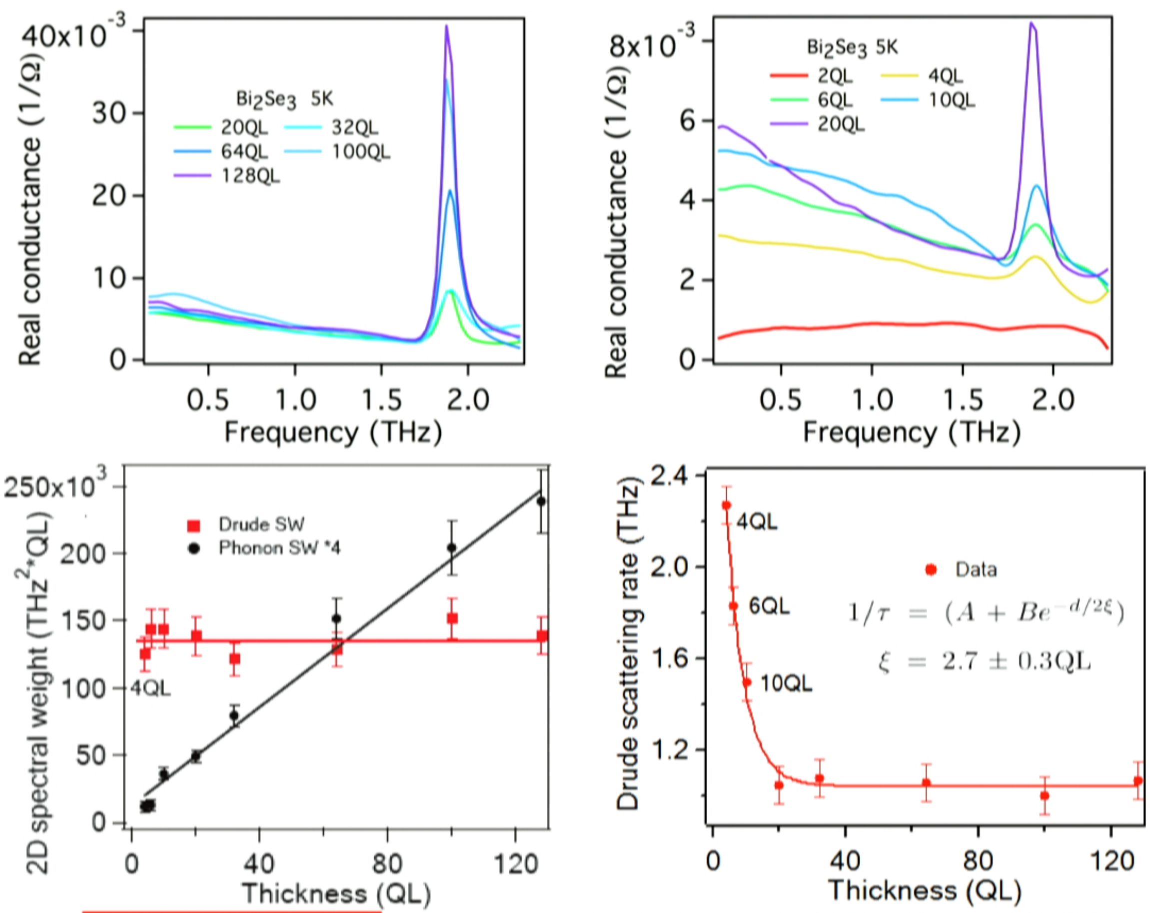
Drude responce – motion of electrons   Phonon

$$\sigma_{xx}(\omega) = \frac{\omega_{pD}^2/4\pi}{i\omega - \Gamma_D} - \frac{i\omega\omega_{pDL}^2/4\pi}{\omega_{DL}^2 - \omega^2 - i\omega\Gamma_{DL}} - \frac{i(\epsilon_\infty - 1)\omega}{4\pi}$$

Sum rule

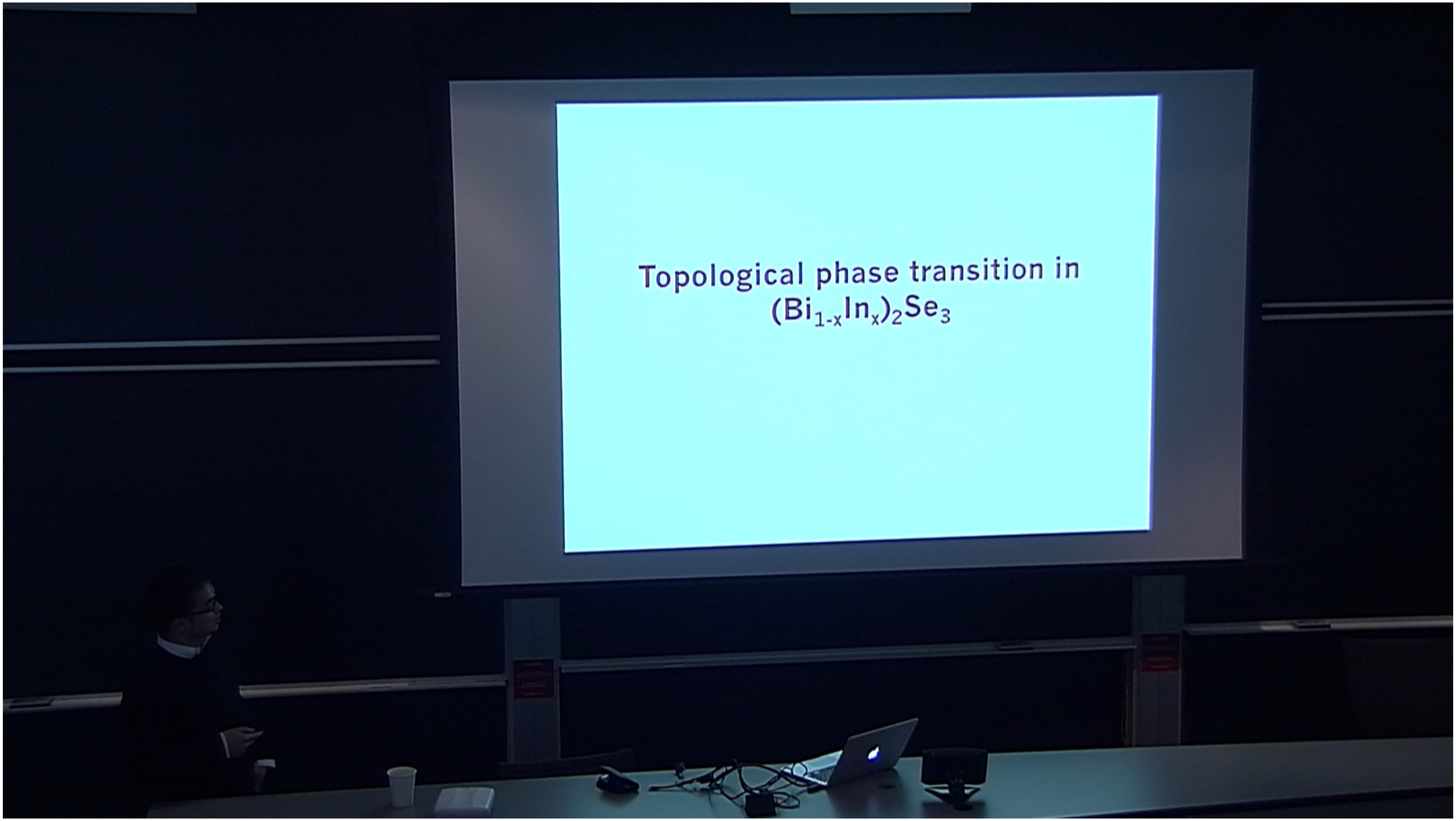
$$\frac{2}{\pi\epsilon_0}\int G_1 d\omega = \omega_p^2 d = \frac{n_{2D}e^2}{m^*\epsilon_0}$$

Surface state dominating transport

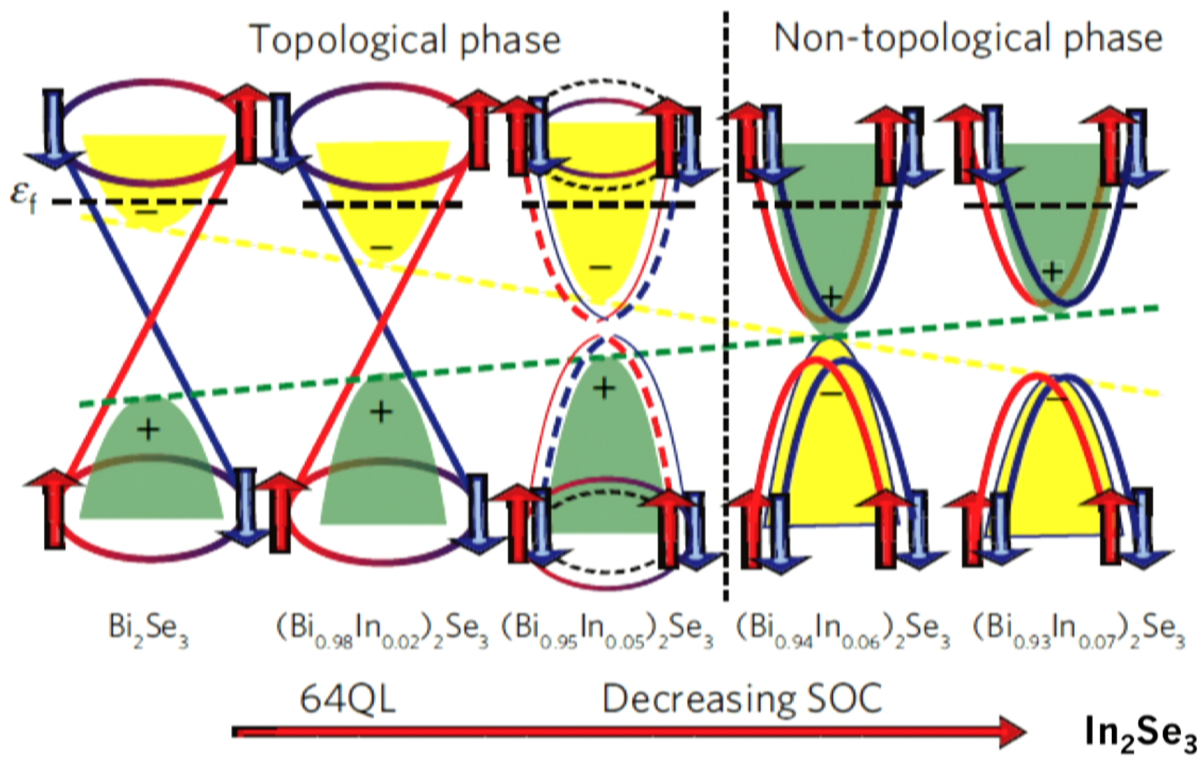


$$\frac{2}{\pi\epsilon_0}\int G_1 d\omega = \omega_p^2 d = \frac{n_{2D}e^2}{m^*\epsilon_0}$$

Valdes Aguilar, *et al.* PRL, **108**, 087403 (2012)
Wu, *et al.* Nat. Phys. **9** 410 (2013).

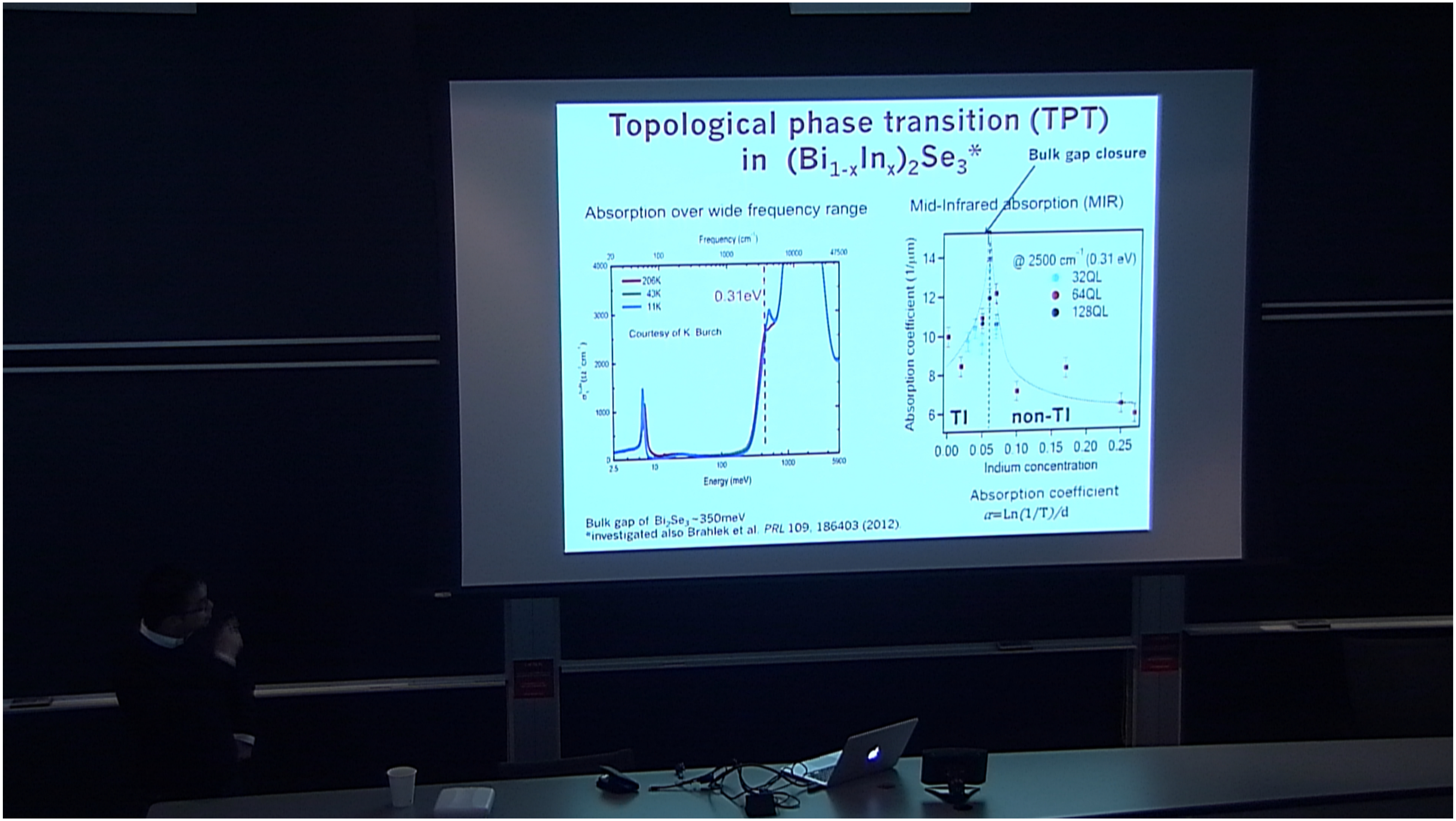

Topological phase transition in
$(Bi_{1-x}In_x)_2Se_3$

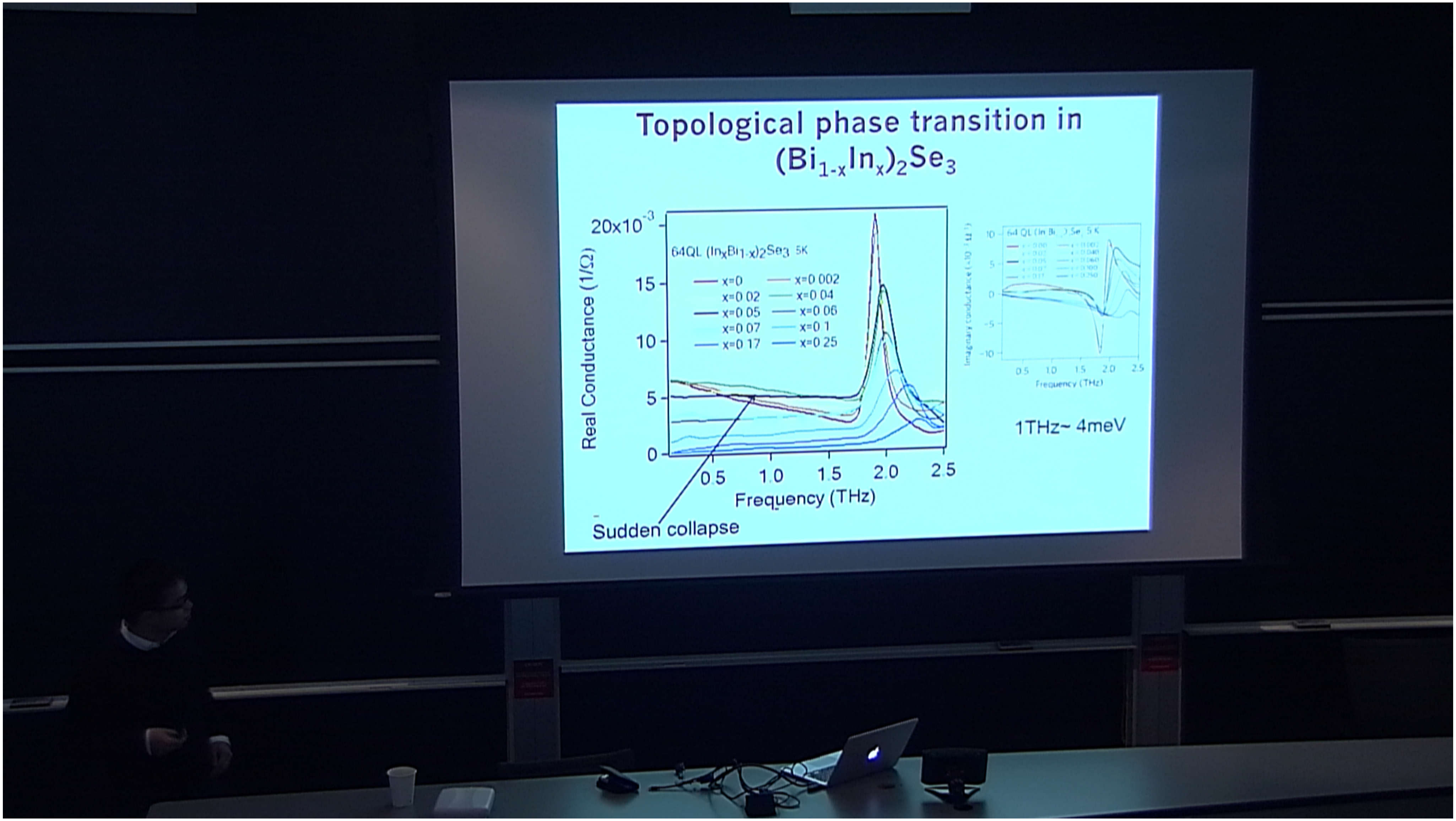
How to 'kill' surface states? Gap closing, Band Inversion



In_2Se_3
same structure.

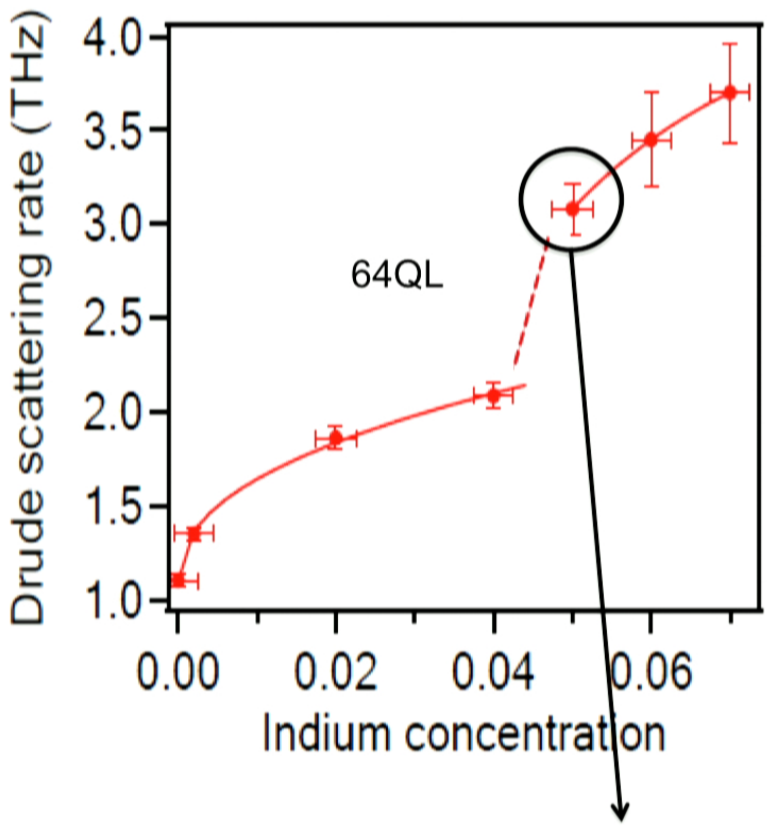
Wu, *et al.* ***Nat. Phys.***, 9, 410 (2013)


Topological phase transition (TPT)
in (Bi1-xInx)2Se3*
Bulk gap closure
Absorption over wide frequency range
Mid-Infrared absorption (MIR)
0.31eV
206K
43K
11K
Courtesy of K. Burch
Frequency (cm-1)
Energy (meV)
Absorption coefficient (1/μm)
@ 2500 cm-1 (0.31 eV)
32QL
64QL
128QL
TI
non-TI
Indium concentration
Absorption coefficient
α=Ln(1/T)/d
Bulk gap of Bi2Se3~350meV
*investigated also Brahlek et al. PRL 109, 186403 (2012)

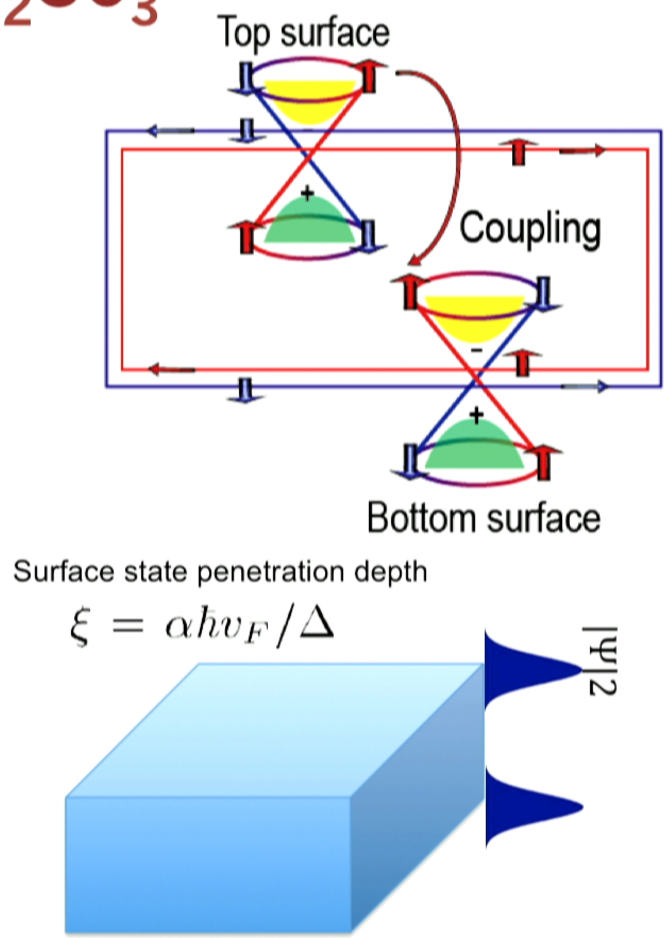


Topological phase transition in $(Bi_{1-x}In_x)_2Se_3$
64QL $(In_xBi_{1-x})_2Se_3$ 5K
x=0
x=0.002
x=0.02
x=0.04
x=0.05
x=0.06
x=0.07
x=0.1
x=0.17
x=0.25
Real Conductance (1/Ω)
20x10^-3
15
10
5
0
0.5
1.0
1.5
2.0
2.5
Frequency (THz)
Sudden collapse
1THz~ 4meV

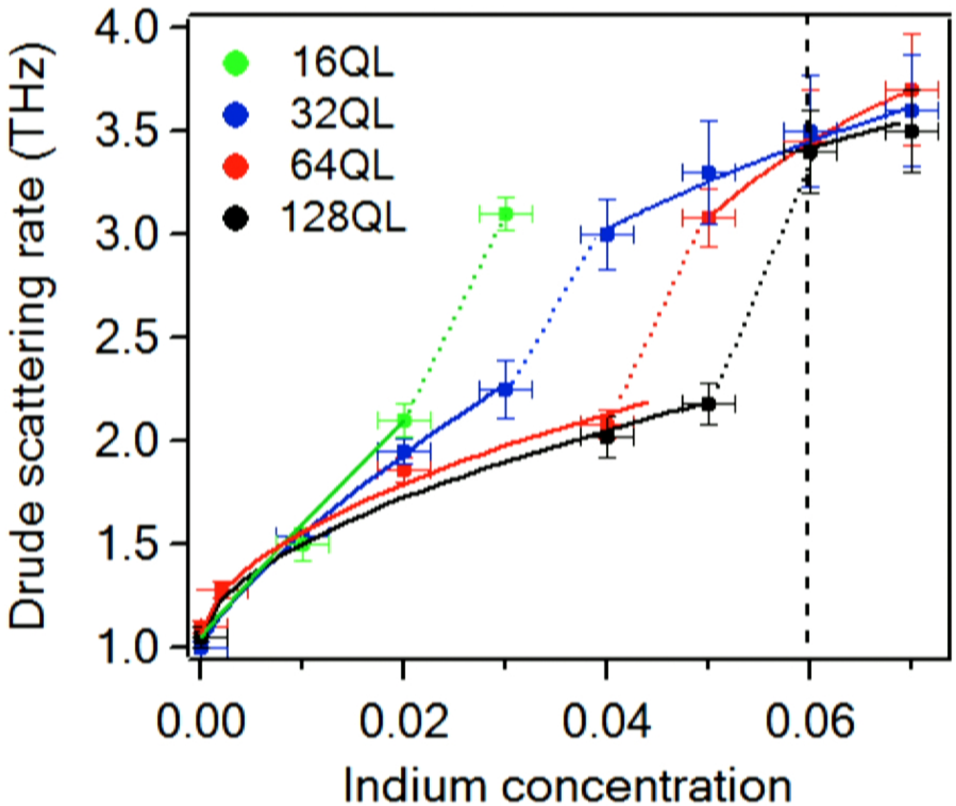
Topological phase transition in $(Bi_{1-x}In_x)_2Se_3$



SSs hybridization → 'Jump'



Novel finite size effect in $(Bi_{1-x}In_x)_2Se_3$

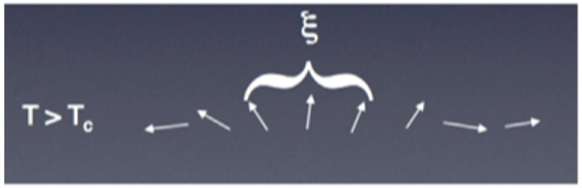


Surface states can hybridize before bulk gap closing in a finite-size system!

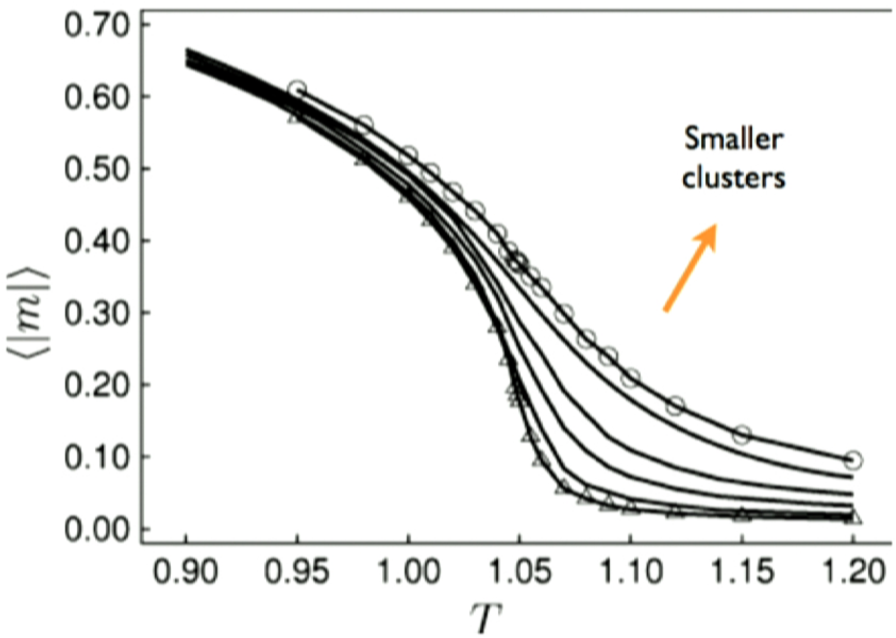
Conventional finite size effect near (continuous) phase transition

Discontinuity happens at phase transition point because of divergence of ξ . Finite size cuts off the divergence.

$$\xi = \xi_0 (1 - T/T_c)^{\nu}$$

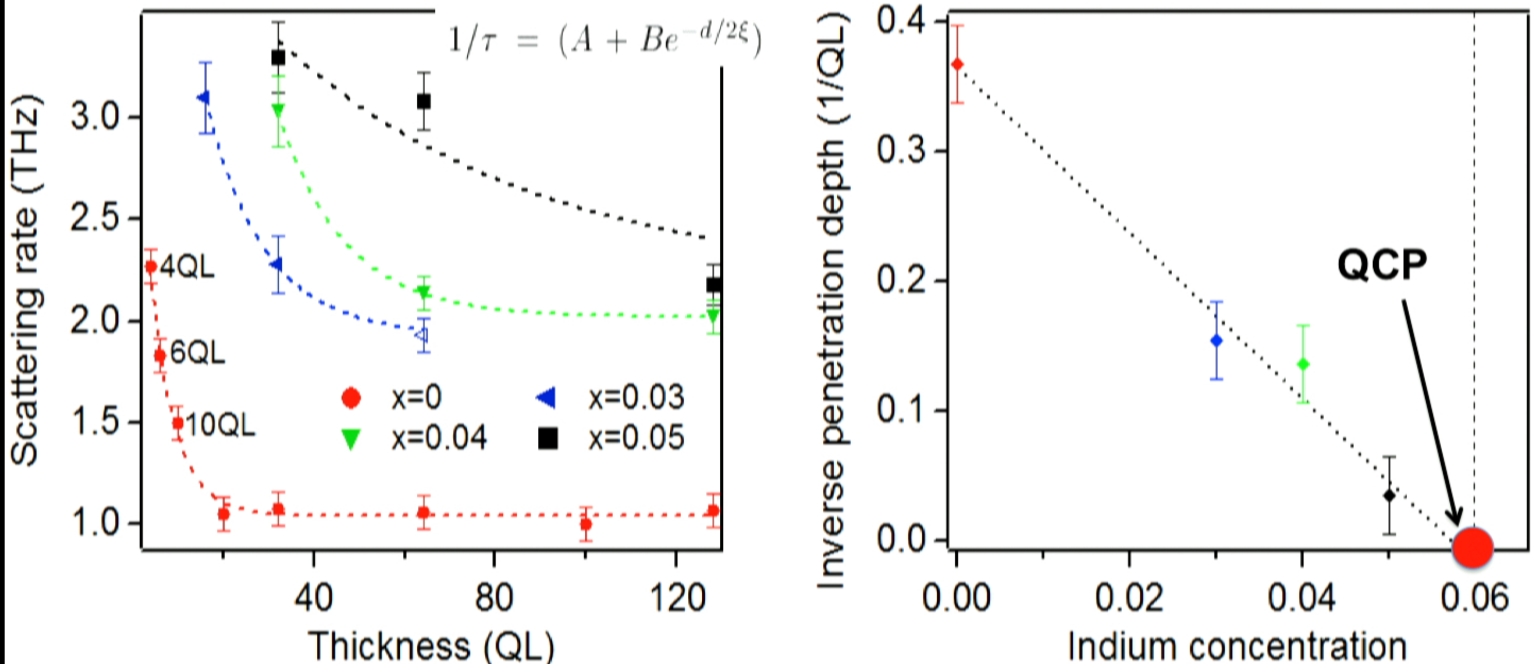


Magnetization of ferromagnetic nanoclusters



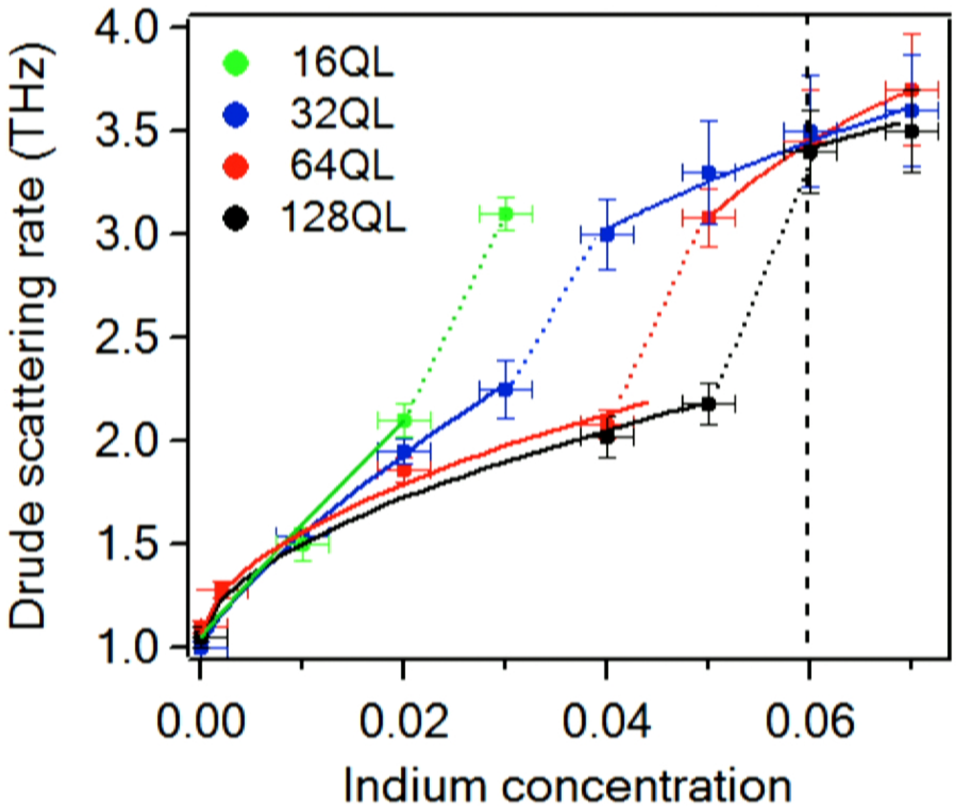
23

Finite size scaling on $(Bi_{1-x}In_x)_2Se_3$



Evanescent length appears as the correlation length in the phase transition.
No order parameter.
Similar to percolation picture between different plateau transitions in QHE.

Novel finite size effect in $(Bi_{1-x}In_x)_2Se_3$



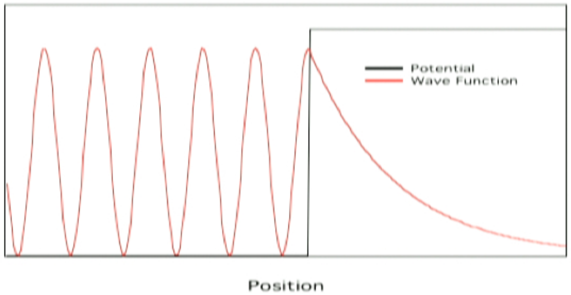
Surface states can hybridize before bulk gap closing in a finite-size system!

Energy independent evanescent decay length!

$\Psi = \exp(-z/\xi)$ $\xi = i/kz$

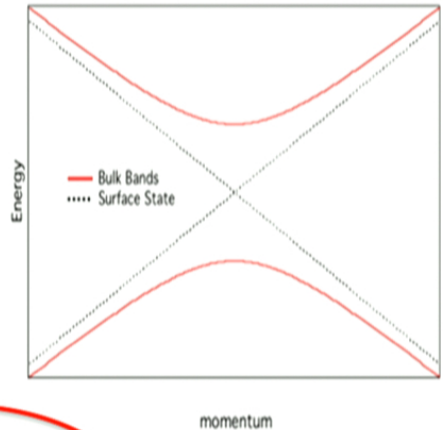
$$k_z = \sqrt{2m(E-V)}/\hbar$$

Binding energy decreases at finite $k_{||}$!



a toy model of the linearized Dirac Hamiltonian

$$H(k_z, k_{||}) = \begin{bmatrix} \Delta & \hbar(v_z k_z - i v_F k_{||}) \\ \hbar(v_z k_z + i v_F k_{||}) & -\Delta \end{bmatrix}.$$



$$k_z = \sqrt{E^2 - \Delta^2 - (\hbar v_F k_{||})^2}/\hbar v_z.$$

$$k_z = i\Delta/\hbar v_z$$
$$\xi = \alpha\hbar v_F/\Delta$$

for all energies at high symmetry momentum points

massless Dirac dispersion $E = \hbar v_F k_{||}$

Thanks discussion from Fan Zhang, E.J. Mele, Liang Fu, Gil Rafael!

Particular properties for Dirac Surface states

25

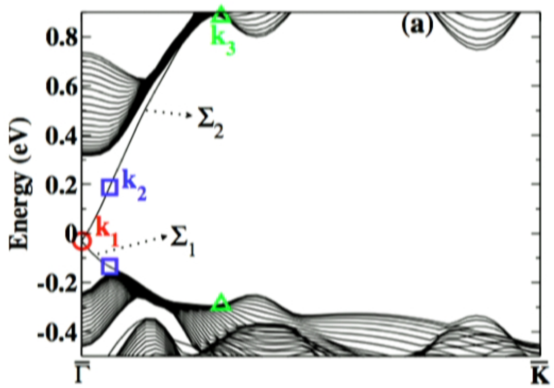
Energy independence of evanescent length

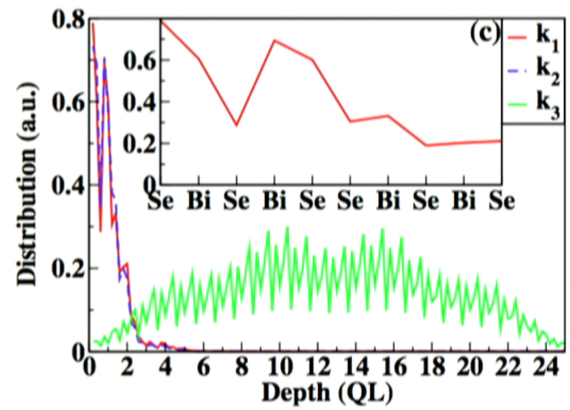
New Journal of Physics
The open-access journal for physics

First-principles studies of the three-dimensional strong topological insulators Bi_2Te_3, Bi_2Se_3 and Sb_2Te_3

Wei Zhang, Rui Yu, Hai-Jun Zhang, Xi Dai and Zhong Fang
Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
E-mail: zfang@iphy.ac.cn

Supported by first principles calculation

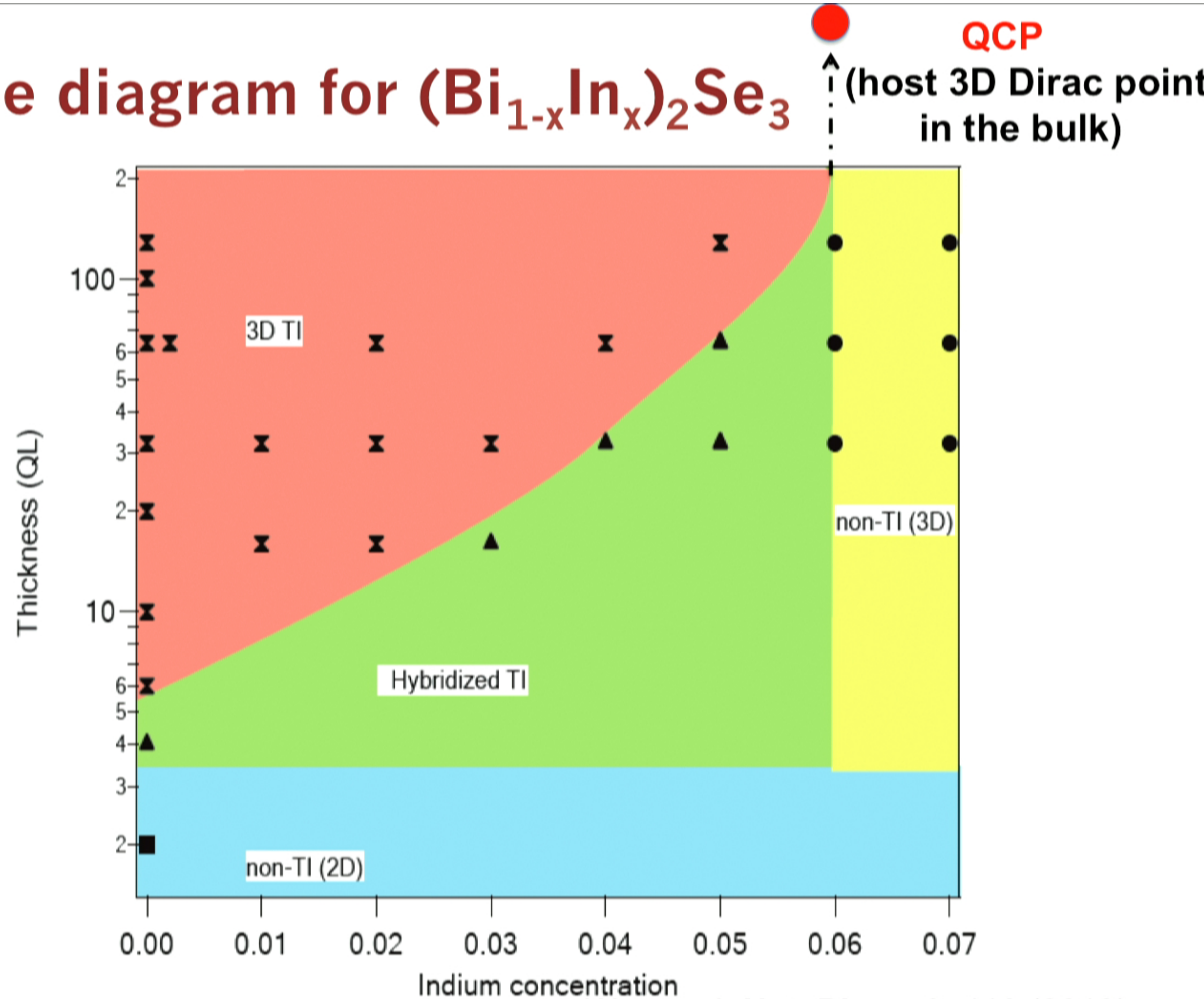




"By moving away from the Dirac point, the penetration depth increases, and finally for k3 point, where the surface state almost merges with the bulk states, the eigenwavefunction becomes an extended state."

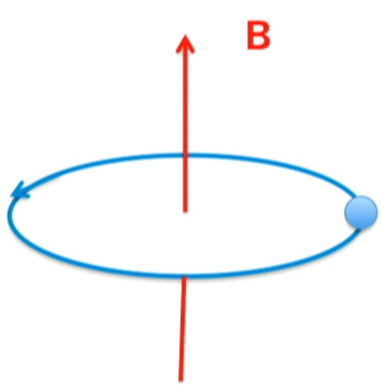
See also Fan Zhang, C. L. Kane, and E. J. Mele, PRB 2012

Phase diagram for $(Bi_{1-x}In_x)_2Se_3$

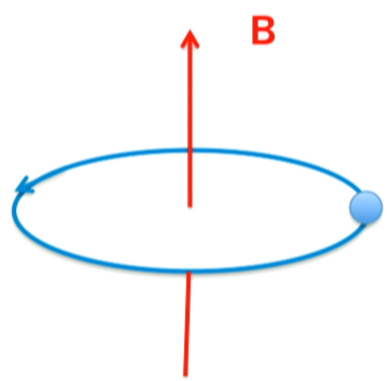


Wu, *et al*. ***Nat. Phys.***, 9, 410 (2013)

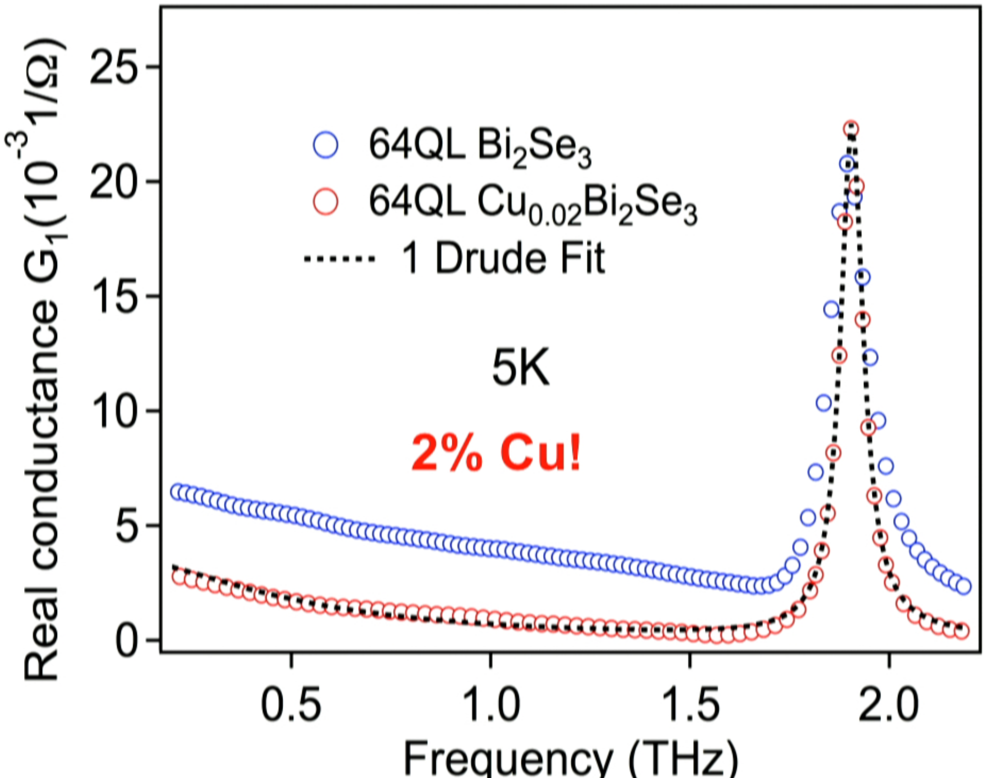
Cyclotron resonances & Electron-phonon interaction in bulk-insulating $Cu_{0.02}Bi_2Se_3$

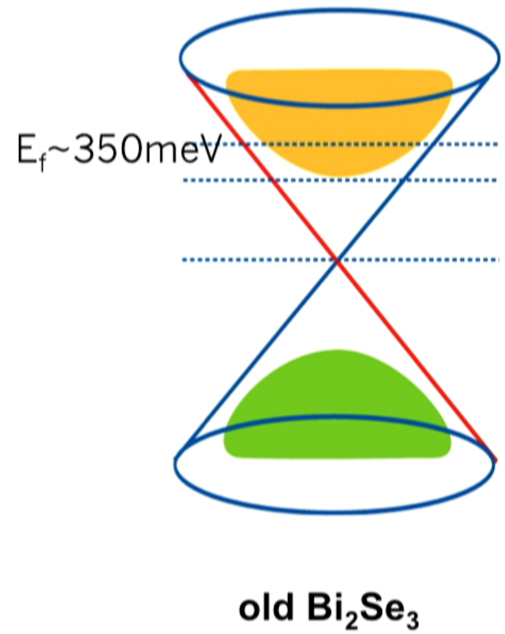


Cyclotron resonances & Electron-phonon interaction in bulk-insulating $Cu_{0.02}Bi_2Se_3$



Lowering chemical potential...



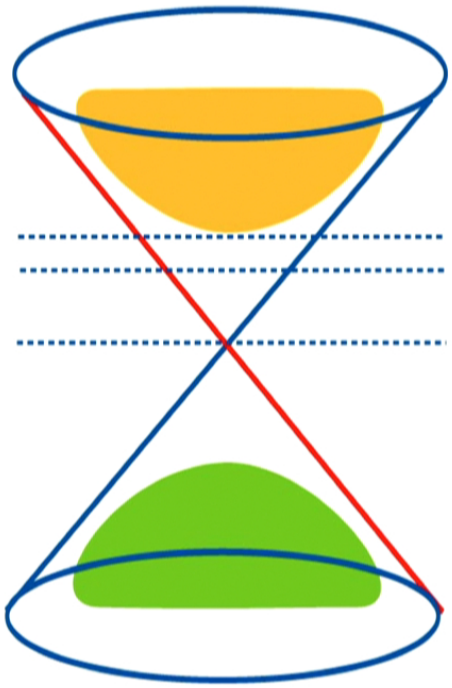


Lower spectral weight → Lower carrier density.

$$\frac{2}{\pi\epsilon_0}\int G_1 d\omega = \omega_p^2 d = \frac{n_{2D}e^2}{m^*\epsilon_0}$$

Wu, *et al.* ***PRL*** 115, 217602 (2015)

Sum rule for Dirac fermion



$$\frac{2}{\pi\epsilon_0}\int G_{D1}d\omega = \omega_{pD}^2 d = \frac{n_{2D}e^2}{m^*\epsilon_0}$$

$$n_{2D} = k_F^2/4\pi$$
$$E = Ak_F + Bk_F^2$$
$$v_F = \partial E_F/\hbar\partial k_F$$
$$m^* = \hbar k_F/v_F$$

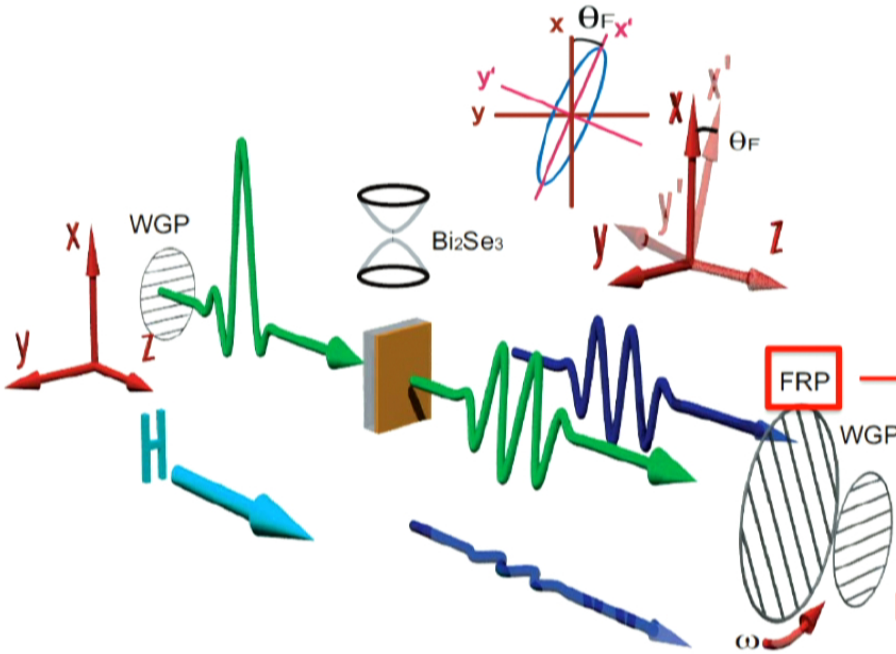
$$\omega_{pD}^2 d = \frac{k_F(A+2Bk_F)e^2}{2\pi\hbar^2\epsilon_0}$$

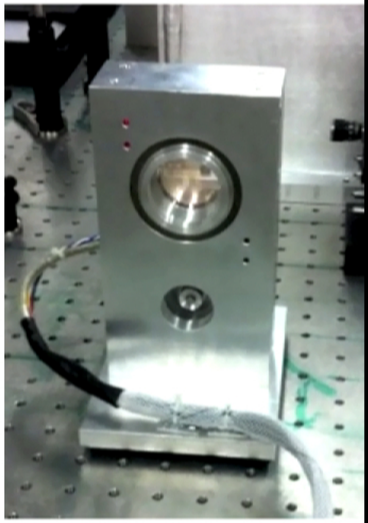
$Cu_{0.02}Bi_2Se_3$

Wu, *et al.* ***PRL*** 115, 217602 (2015)

$$\mu \sim 4000\ \mathrm{cm^2/V\cdot s}$$
$$n_{2D} \sim 5\times 10^{12}/\mathrm{cm}^2$$

Cyclotron resonance (CR) experiments





Fast rotating polarizer
10,000 rpm

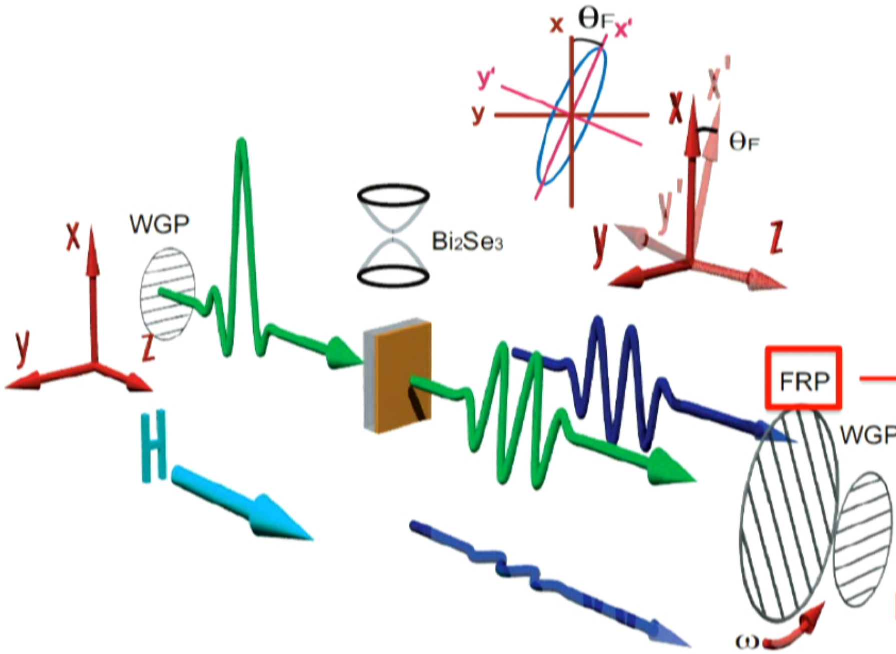
Measured G_{xx}, G_{xy}, $\theta_F = \theta'_F + \theta''_F$ in a single scan!

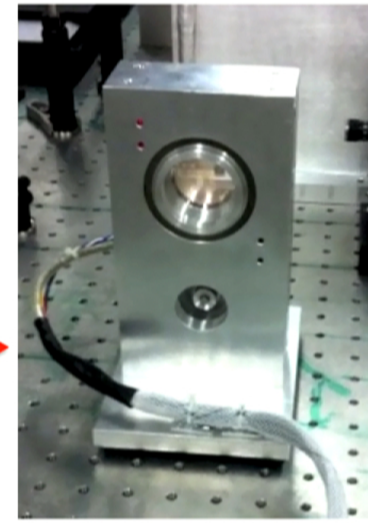
Polarization modulation technique
0.5 mrad resolution

$$\theta_F = \mathrm{atan}[E_{xy}(\omega)/E_{xx}(\omega)]$$

Morris, *et al.* **OE**, 20, 12303 (2012).
Valdés Aguilar,…Wu, *et al.* ***PRL***, 108, 087403 (2012)

Cyclotron resonance (CR) experiments





Fast rotating polarizer 10,000 rpm

Measured G_{xx}, G_{xy}, $\theta_F = \theta'_F + \theta''_F$ in a single scan!

Polarization modulation technique
0.5 mrad resolution

$$\theta_F = \mathrm{atan}[E_{xy}(\omega)/E_{xx}(\omega)]$$

Morris, *et al.* **OE**, 20, 12303 (2012).
Valdés Aguilar,…Wu, *et al.* ***PRL***, 108, 087403 (2012)

Jones matrix formalism

$$\begin{bmatrix} E_y^f \\ E_x^f \end{bmatrix} = \begin{bmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{bmatrix} \begin{bmatrix} E_y^i \\ E_x^i \end{bmatrix}$$

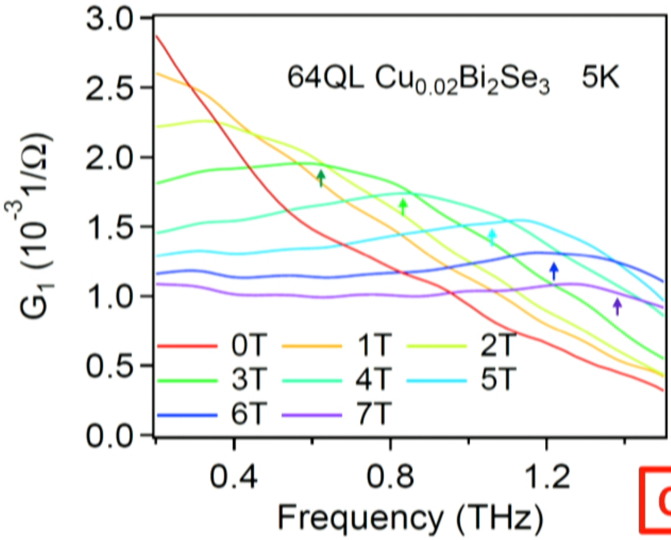
Bi_2Se_3 C_3 rotation

$T_{xx} = T_{yy}$ and $T_{xy} = -T_{yx}$

$$\begin{bmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{bmatrix} = \begin{bmatrix} T_{xx} + iT_{xy} & 0 \\ 0 & T_{xx} - iT_{xy} \end{bmatrix} = \begin{bmatrix} t_+ & 0 \\ 0 & t_- \end{bmatrix}$$

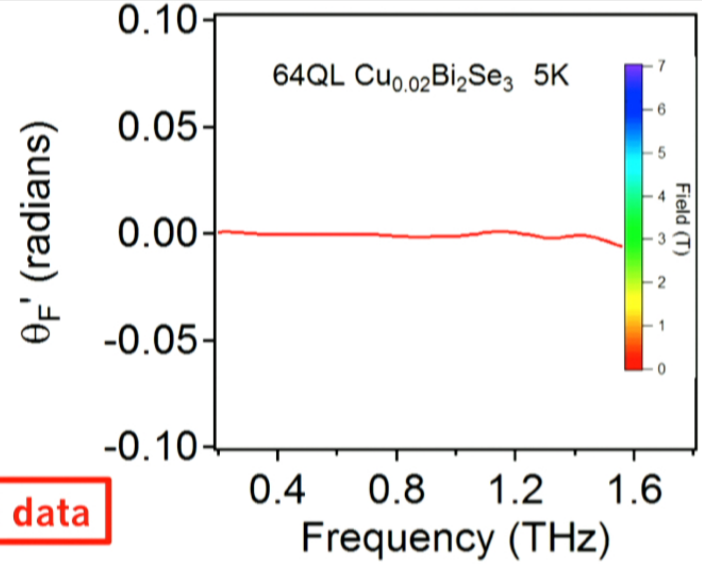
$$\tan(\theta_F) = -i\frac{t_+ - t_-}{t_+ + t_-} \qquad \theta_F = \text{atan}[E_y(\omega)/E_x(\omega)]$$

Armitage ***PRB*** (2014).

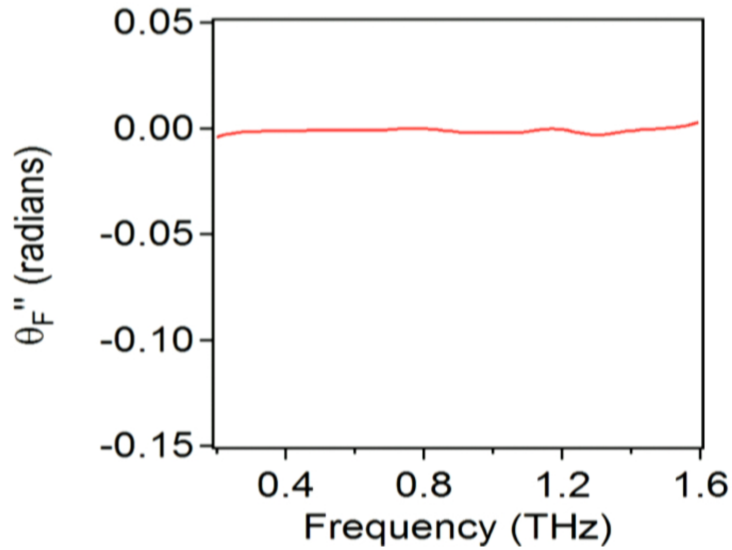


64QL $Cu_{0.02}Bi_2Se_3$ 5K
G_1 (10^{-3} 1/Ω)
0T 1T 2T 3T 4T 5T 6T 7T
Frequency (THz)

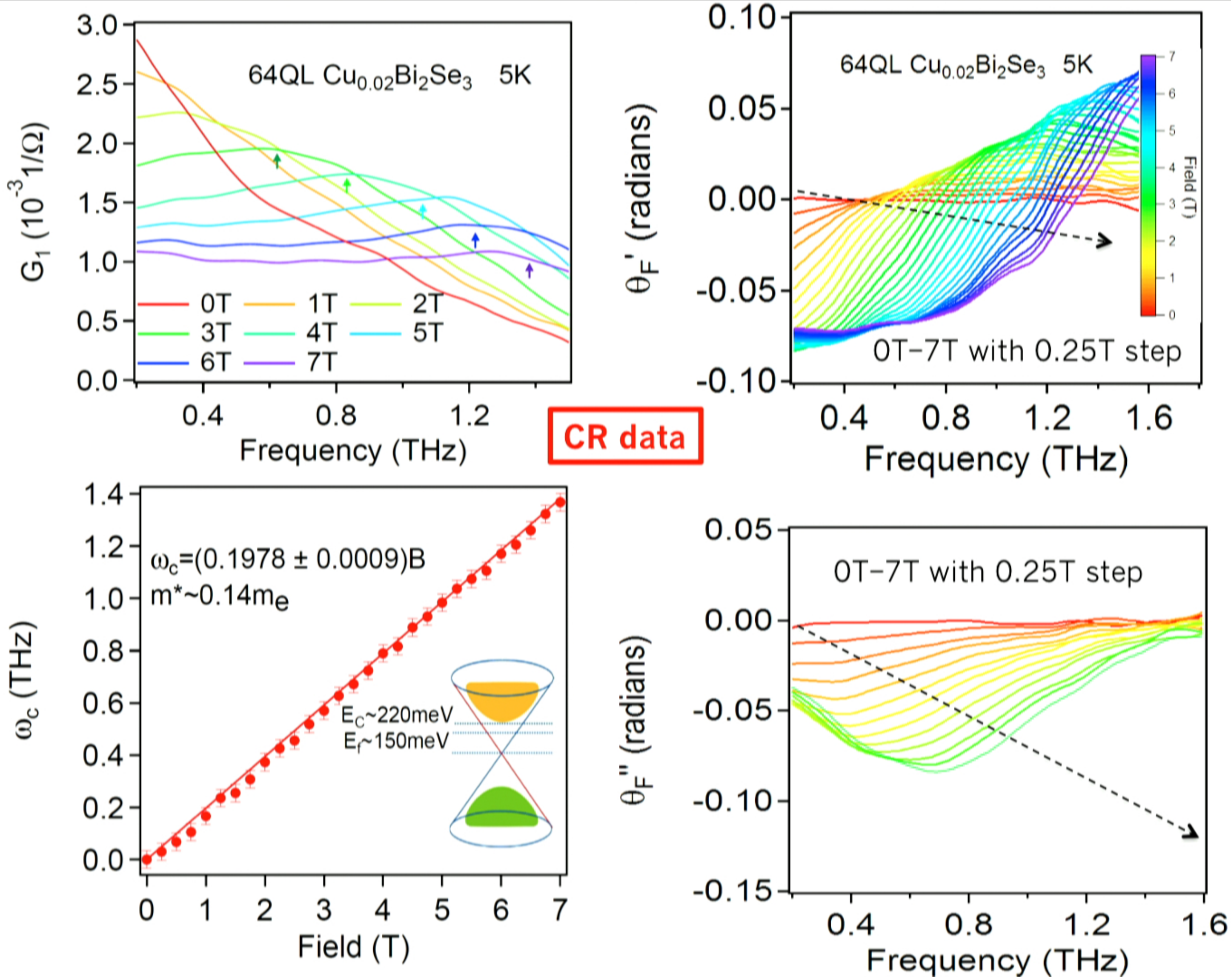
CR data



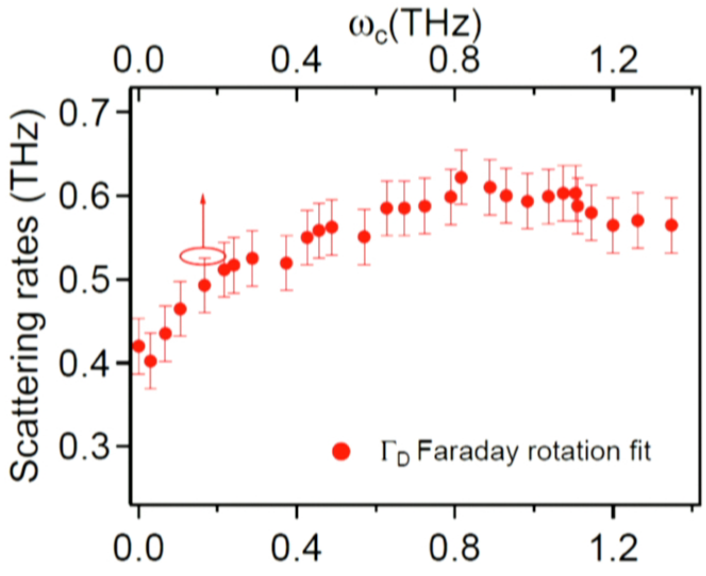
64QL $Cu_{0.02}Bi_2Se_3$ 5K
θ_F' (radians)
Field (T)
Frequency (THz)



θ_F'' (radians)
Frequency (THz)


64QL Cu0.02Bi2Se3 5K
G1 (10^-3 1/Ω)
Frequency (THz)
0T 1T 2T
3T 4T 5T
6T 7T
θF' (radians)
Field (T)
0T-7T with 0.25T step
CR data
ωc=(0.1978 ± 0.0009)B
m*~0.14me
EC~220meV
Ef~150meV
ωc (THz)
Field (T)
θF'' (radians)
0T-7T with 0.25T step

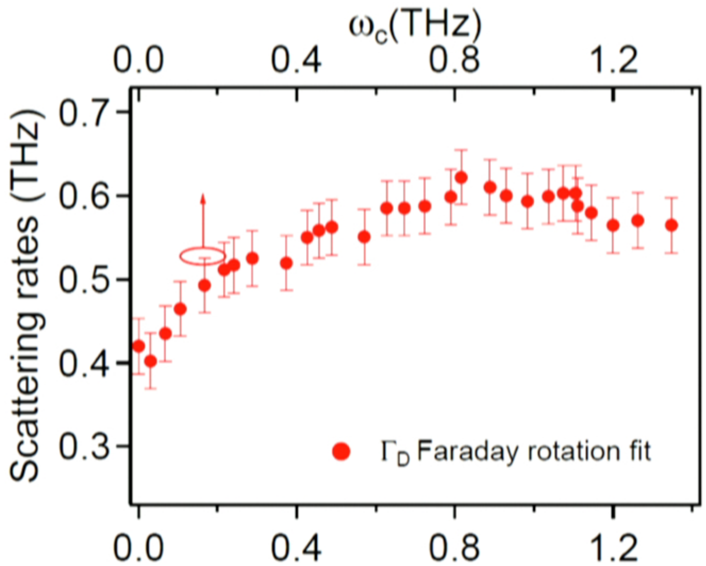
CR broadening ← electron-phonon interaction

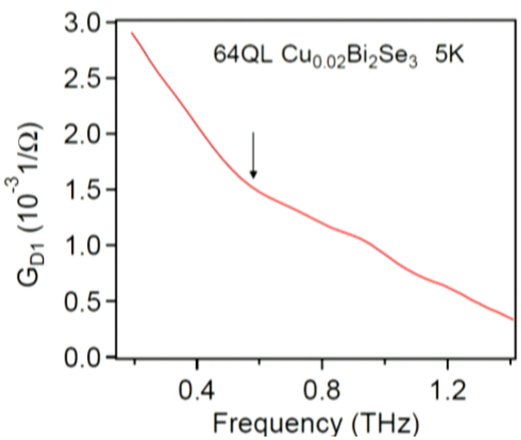


Zeeman & orbital effect cannot explain field dependence.

Wu, *et al*. ***PRL*** 115, 217602 (2015)

CR broadening ← electron-phonon interaction





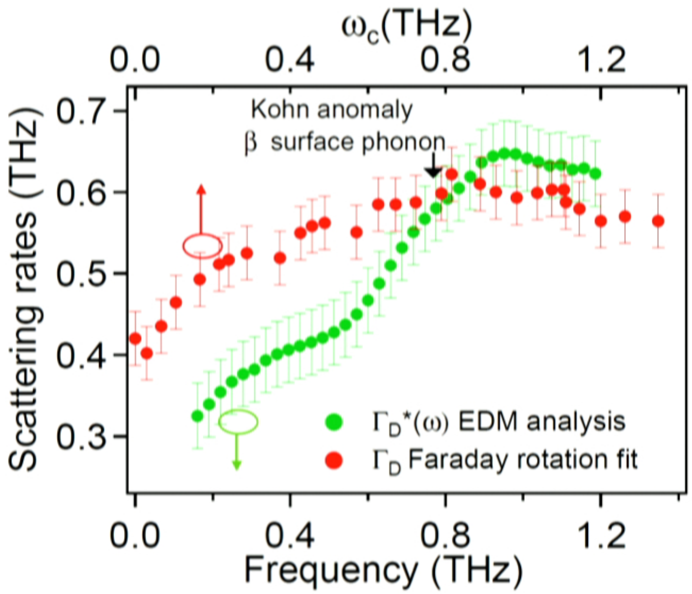
Extended Drude model

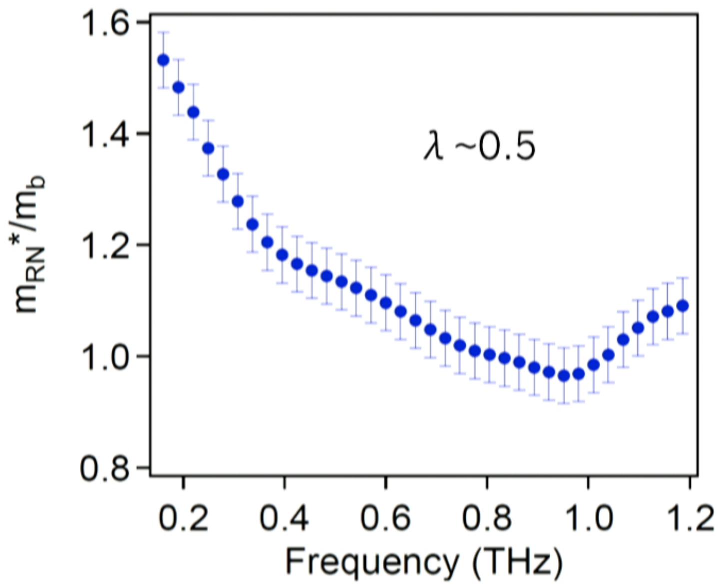
$$\Gamma_D(\omega) = \frac{1}{2\pi\tau(\omega)} = \frac{\omega_{pD}^2 d}{2}\mathrm{Re}\left(\frac{1}{G_D}\right)$$

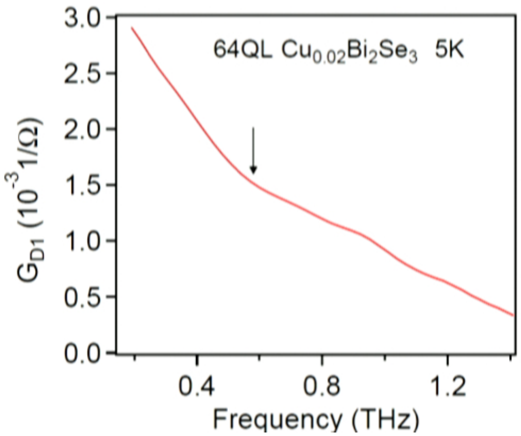
$$\frac{m^*_{RN}(\omega)}{m_b} = -\frac{\omega_{pD}^2 d}{2\omega}\mathrm{Im}\left(\frac{1}{G_D}\right) = 1 + \lambda(\omega)$$

$$\Gamma_D(\omega)^* = \Gamma_D(\omega)/(1+\lambda(\omega))$$

CR broadening ← electron-phonon interaction







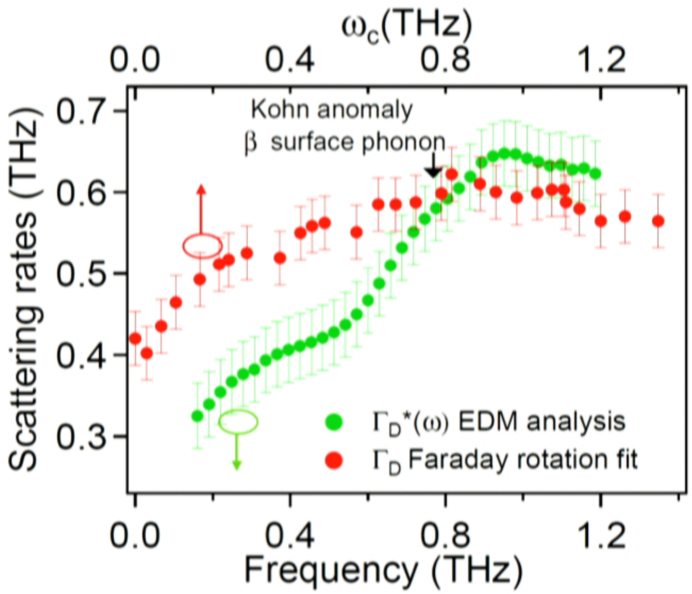
Extended Drude model

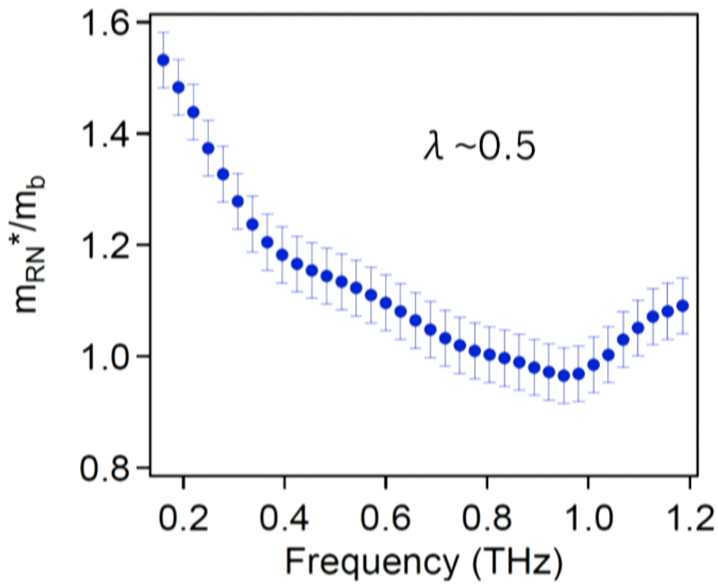
$$\Gamma_D(\omega) = \frac{1}{2\pi\tau(\omega)} = \frac{\omega_{pD}^2 d}{2}\mathrm{Re}\left(\frac{1}{G_D}\right)$$

$$\frac{m_{RN}^*(\omega)}{m_b} = -\frac{\omega_{pD}^2 d}{2\omega}\mathrm{Im}\left(\frac{1}{G_D}\right) = 1 + \lambda(\omega)$$

$$\Gamma_D(\omega)^* = \Gamma_D(\omega)/(1+\lambda(\omega))$$

CR broadening ← electron-phonon interaction





Extended Drude model

$$\Gamma_D(\omega) = \frac{1}{2\pi\tau(\omega)} = \frac{\omega_{pD}^2 d}{2}\mathrm{Re}(\frac{1}{G_D})$$

$$\frac{m_{RN}^*(\omega)}{m_b} = -\frac{\omega_{pD}^2 d}{2\omega}\mathrm{Im}(\frac{1}{G_D}) = 1 + \lambda(\omega)$$

$$\Gamma_D(\omega)^* = \Gamma_D(\omega)/(1 + \lambda(\omega))$$

Quantized Faraday (Kerr) rotation & Axion electrodynamics of TSSs

Axion electrodynamics of TSSs

$$\triangle L_{axion} = \theta(\frac{e^2}{2\pi hc}\mathbf{E}\cdot\mathbf{B})$$

$$\nabla\cdot\mathbf{E} = \rho - e^2/2\pi hc(\nabla\theta\cdot\mathbf{B}),$$

Wilczek ***PRL (***1987)

$$\nabla\times\mathbf{B} - \frac{\partial\mathbf{E}}{\partial t} = \mathbf{j} + e^2/2\pi hc\left(\nabla\theta\times\mathbf{E} + \frac{1}{c}\left(\partial_t\theta\right)\mathbf{B}\right)$$

Axion electrodynamics of TSSs

$$\triangle L_{axion} = \theta(\frac{e^2}{2\pi hc}\mathbf{E}\cdot\mathbf{B})$$

$$\nabla\cdot\mathbf{E} = \rho - e^2/2\pi hc(\nabla\theta\cdot\mathbf{B}),$$

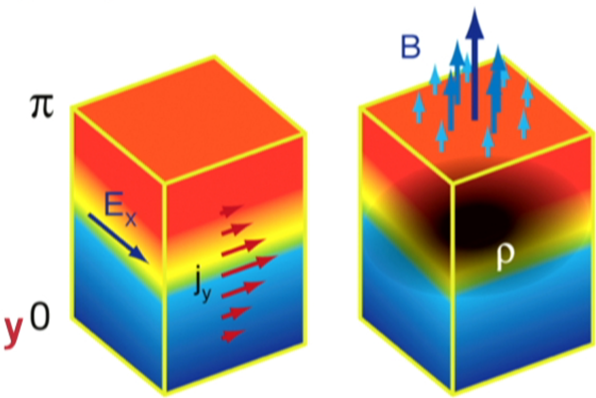
Wilczek ***PRL (***1987)

$$\nabla\times\mathbf{B} - \frac{\partial\mathbf{E}}{\partial t} = \mathbf{j} + e^2/2\pi hc\left(\nabla\theta\times\mathbf{E} + \frac{1}{c}\left(\partial_t\theta\right)\mathbf{B}\right)$$

Provided that time reversal symmetry is respected, all 3D insulators can be characterized by a quantized value of the axion field in the bulk.

$$\theta = 2\pi(n+1/2)$$ **TI**

$$\theta = 2\pi n$$ **Non-TI**



Qi, Hughes, Zhang ***PRB (***2008)

The extra charge and current density only appear at TI/non-TI boundary
→ Half-integer QHE
→ & topological magneto-electric effect (TME).

36

Axion electrodynamics of TSSs

$$\triangle L_{axion} = \theta(\frac{e^2}{2\pi hc}\mathbf{E}\cdot\mathbf{B})$$

$$\nabla\cdot\mathbf{E} = \rho - e^2/2\pi hc(\nabla\theta\cdot\mathbf{B}),$$

Wilczek ***PRL (***1987)

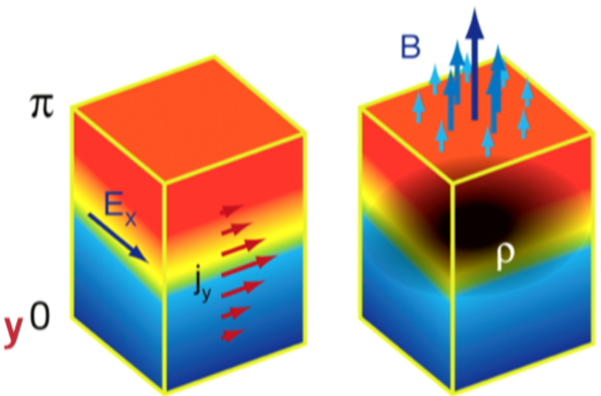
$$\nabla\times\mathbf{B} - \frac{\partial\mathbf{E}}{\partial t} = \mathbf{j} + e^2/2\pi hc\left(\nabla\theta\times\mathbf{E} + \frac{1}{c}(\partial_t\theta)\,\mathbf{B}\right)$$

Provided that time reversal symmetry is respected, all 3D insulators can be characterized by a quantized value of the axion field in the bulk.

(n+1/2) electrons each flux quantum

$$\theta = 2\pi(n+1/2)$$ **TI**

$$\theta = 2\pi n$$ **Non-TI**

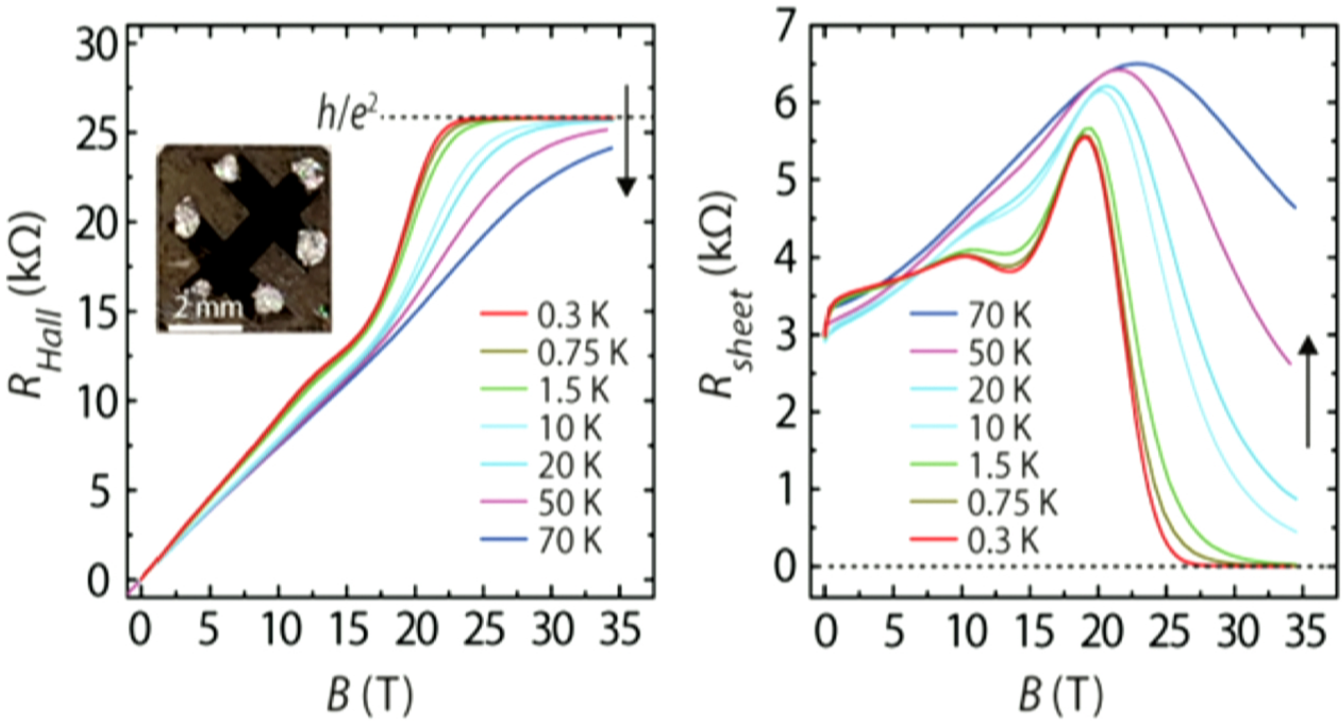


Qi, Hughes, Zhang ***PRB (***2008)

The extra charge and current density only appear at TI/non-TI boundary
→ Half-integer QHE
→ & topological magneto-electric effect (TME).

Dissipationless Half-integer QHE

For each SS, $\sigma_H = e^2/h(\nu + 1/2)$ **8QL Bi_2Se_3/MoO_3**

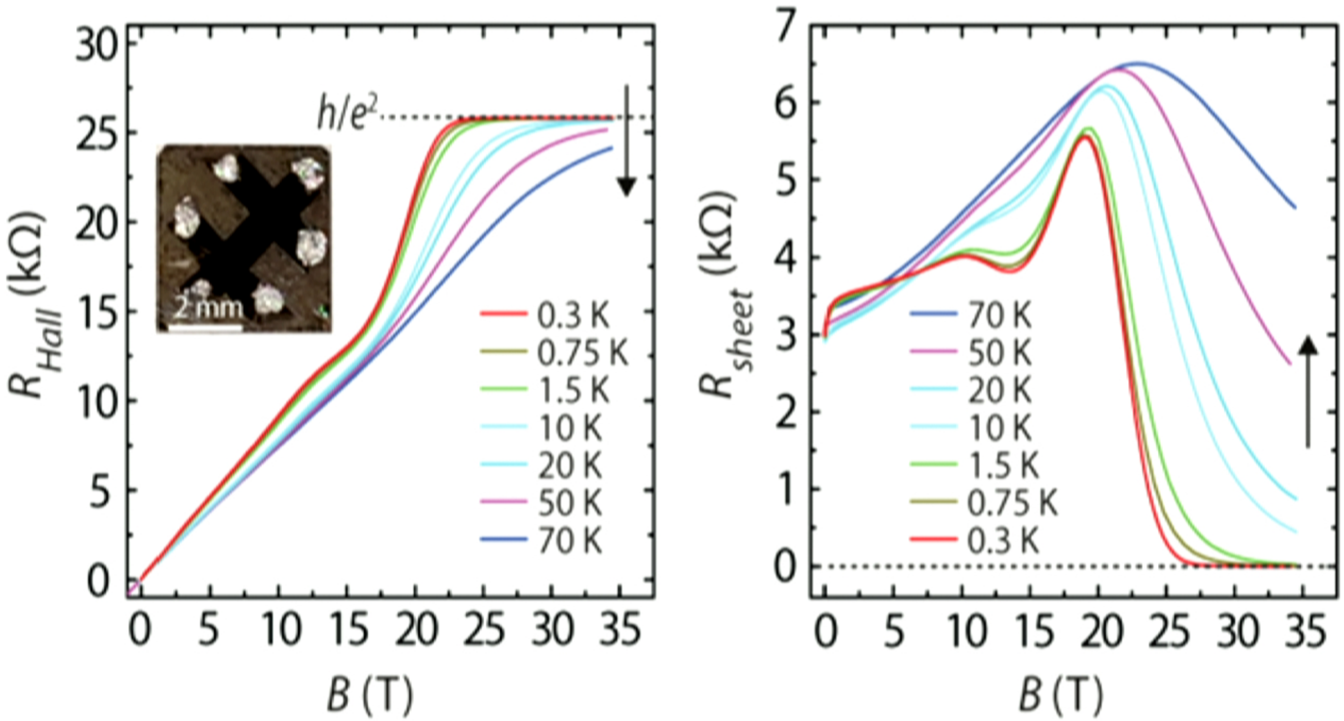


(1+ 0.00004) e^2/h!

Nikesh…**Wu**, *et al.* ***Nano. Lett.*** 15, 8245 (2015)

Dissipationless Half-integer QHE

For each SS, $\sigma_H = e^2/h(\nu + 1/2)$ **8QL Bi_2Se_3/MoO_3**



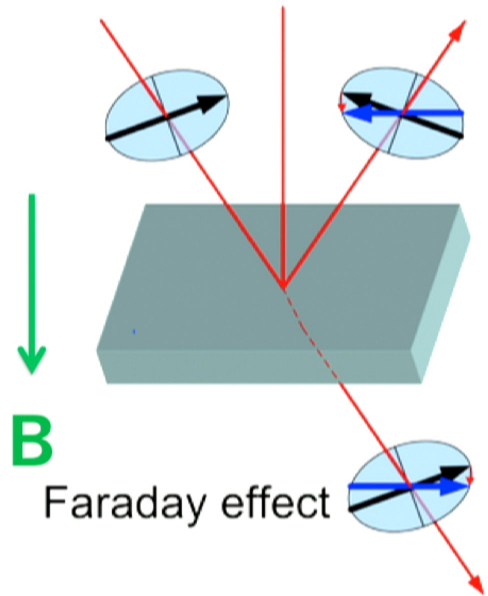
(1+ 0.00004) e^2/h!

Nikesh…**Wu**, *et al.* ***Nano. Lett.*** 15, 8245 (2015)

37

Quantized Faraday and Kerr rotation

--- topological magneto-electric effect (TME)



QHE regime $\sigma_{xy} = \frac{e^2}{h}(\nu + 1/2)$

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

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

$$\tan(\varphi_F) = i\frac{t_+ - t_-}{t_+ + t_-}$$

$$\tan(\varphi_K) = i\frac{r_+ - r_-}{r_+ + r_-}$$

α is fine structure constant.
n is substrate index of refraction

N_T ,N_B : LL index for top/bottom SSs

Qi *et al.* **PRB** (08); Essin *et al.* **PRL** (09);
Tse *et al.* **PRL** (10), Maciejko, *et al.* **PRL** (10)

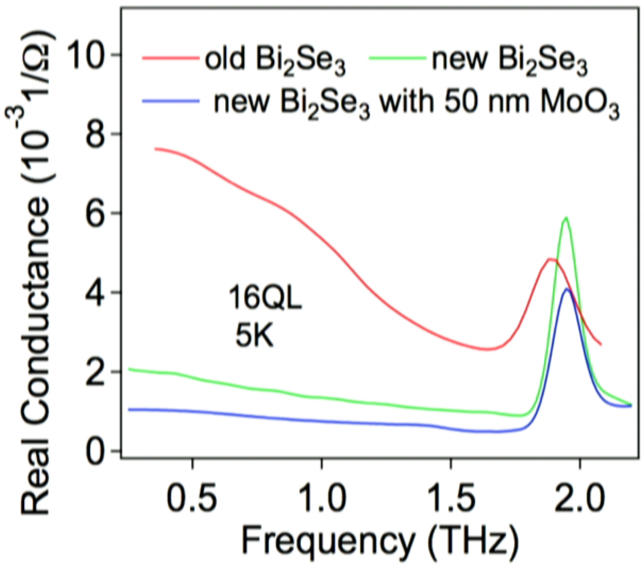
A few challenges to realize TME…

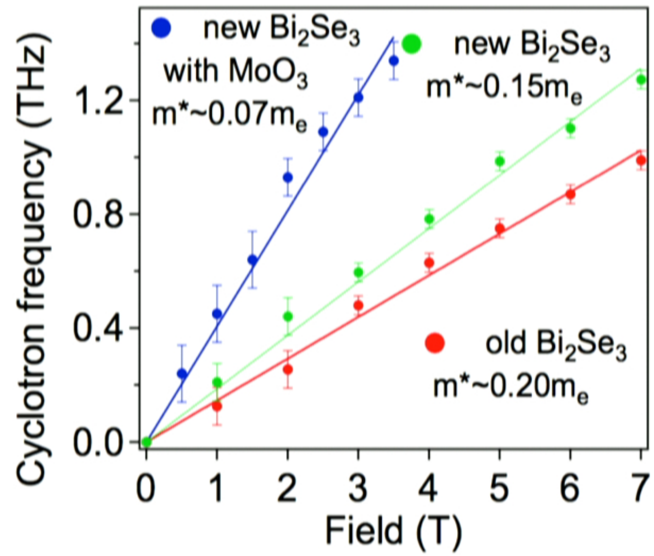
Qi *et al.* **PRB** (08); Essin *et al.* **PRL** (09);
Tse *et al.* **PRL** (10), Maciejko, *et al.* **PRL** (10)

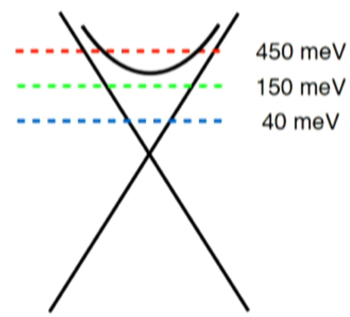
- **Bulk-insulating, very low carrier density**
- **Metallic gate has its own Faraday and Kerr effect → Gating doesn't work.**
- **Low frequency (THz), long wavelength → needs uniform samples with a few millimeters across**
- **Small rotation (mrad)→ needs high-precision THz polarimetry**

After three years, we solved all of the above problems!

Approaching the Dirac point







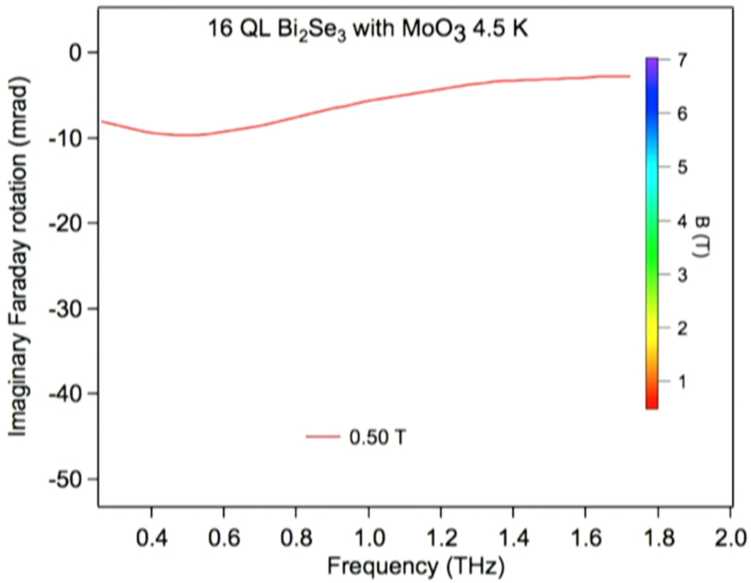
Sum rule

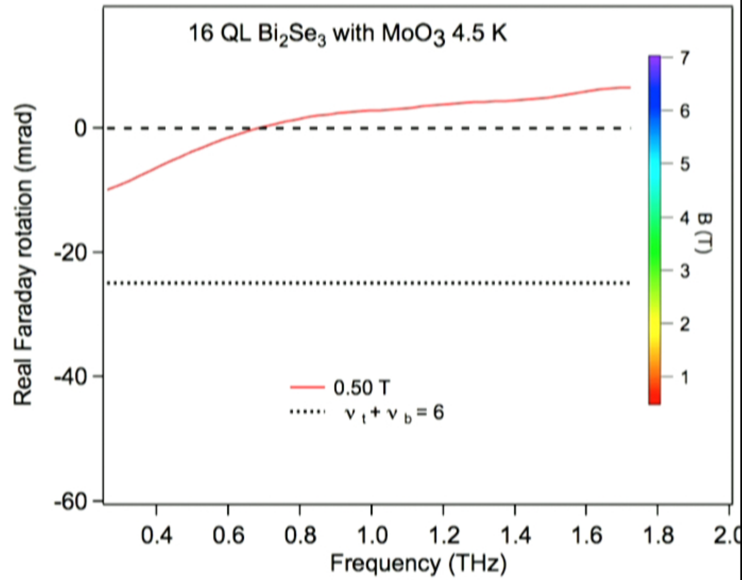
$$\frac{2}{\pi\epsilon_0}\int G_1 d\omega = \omega_p^2 d = \frac{n_{2D}e^2}{m^*\epsilon_0}$$

Spectral weight

Wu, *et al.* arXiv.1603.04317 (2016)

Crossover from cyclotron resonance to quantum regime



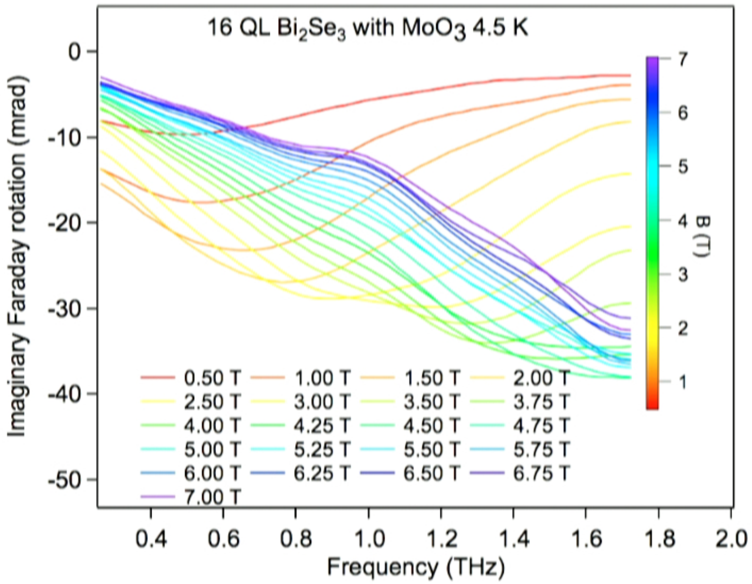


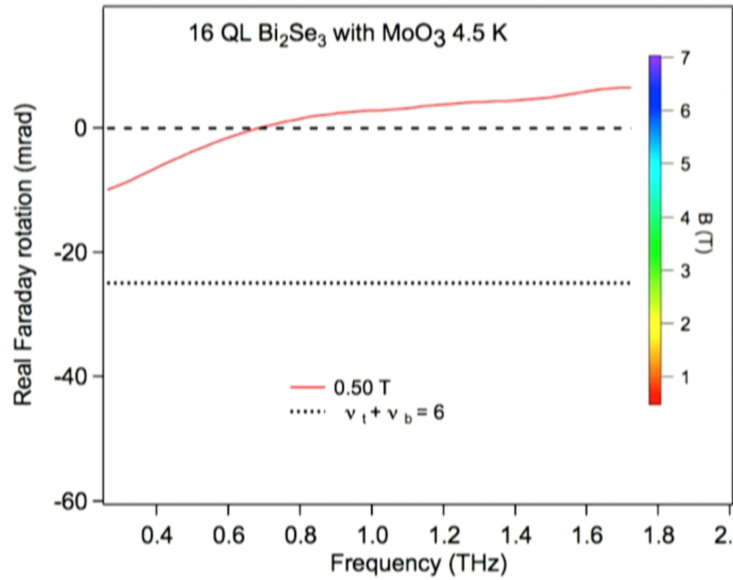
$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2})$$

Wu, *et al.* arXiv.1603.04317 (2016)

42

Crossover from cyclotron resonance to quantum regime



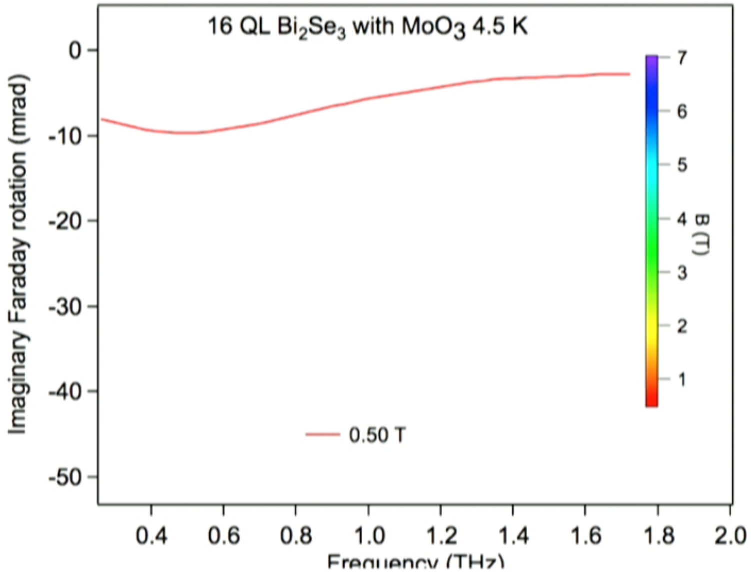


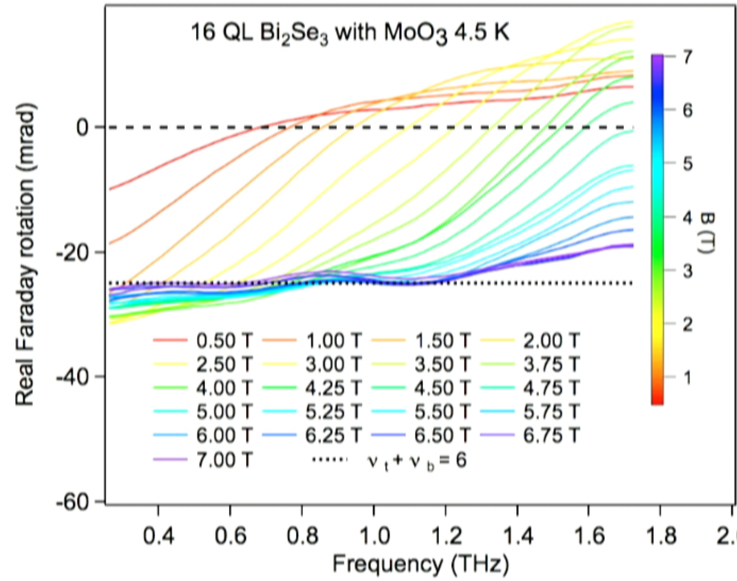
$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2})$$

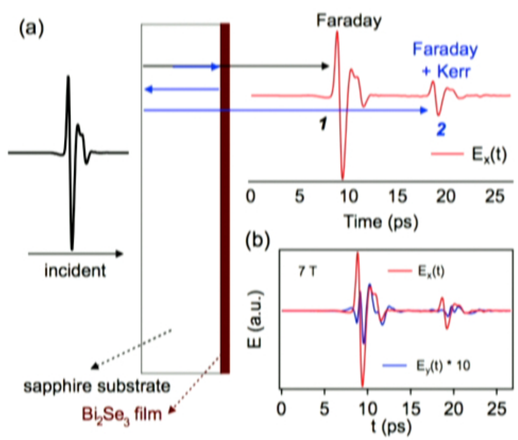
Wu, *et al*. arXiv.1603.04317 (2016)

42

Crossover from cyclotron resonance to quantum regime



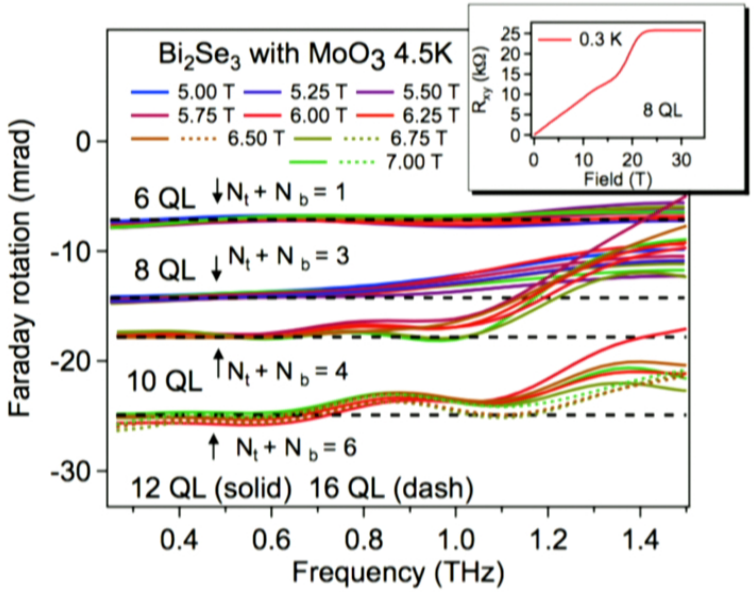


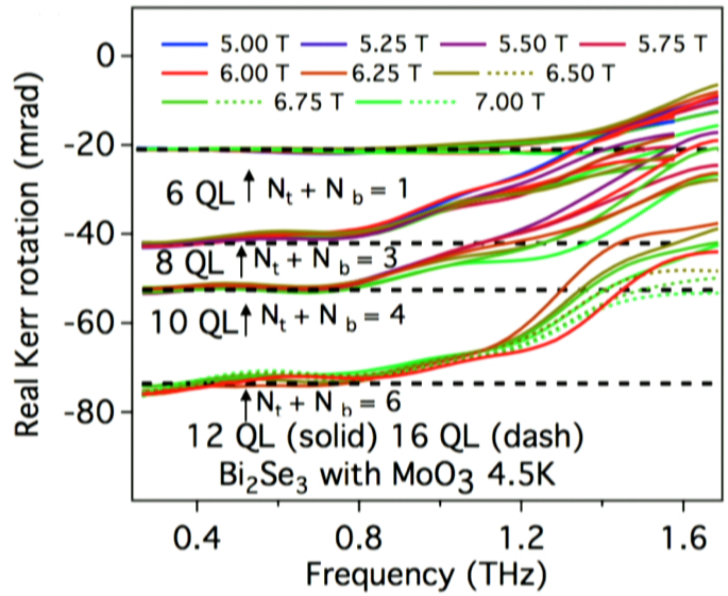


$$\tan(\phi_F) = \frac{2\alpha}{1+n}(N_t + \frac{1}{2} + N_b + \frac{1}{2})$$

Wu, *et al*. arXiv.1603.04317 (2016)

Quantized Faraday and Kerr rotation





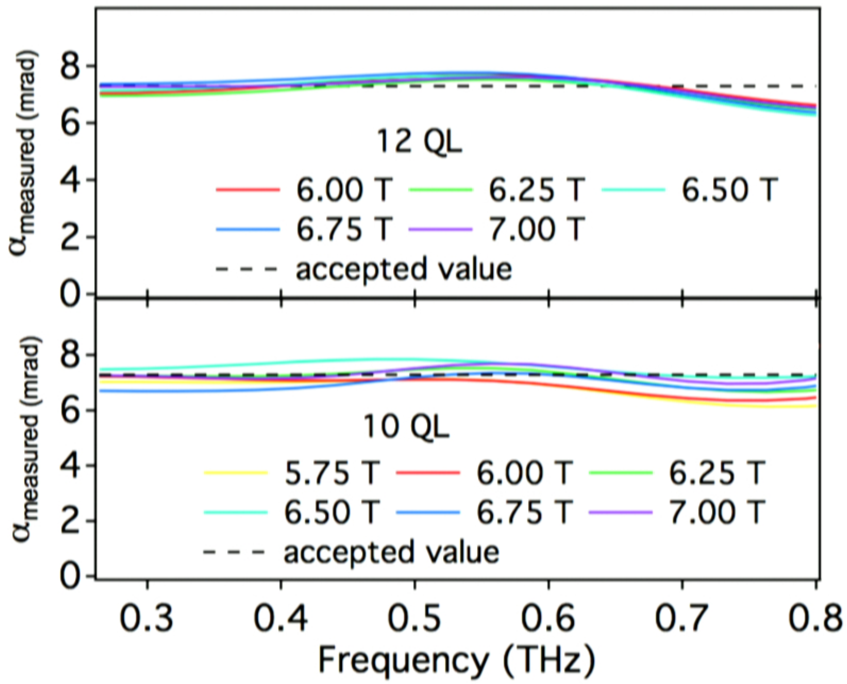
Wu, *et al.* arXiv.1603.04317 (2016)

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

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

A solid-state measure of the fine structure constant

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



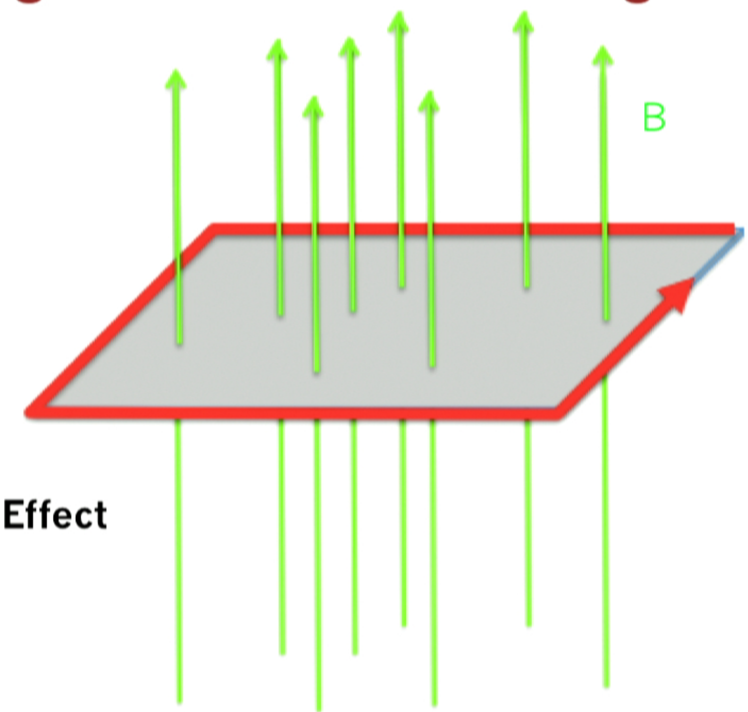
Average over three samples and all the fields (<0.8 THz)

measured: α^{-1} ~ 137.9

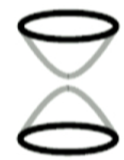
accepted: α^{-1} ~ 137.04

Wu, *et al.* arXiv.1603.04317 (2016)

Topological Insulators in magnetic field



Gapped SSs



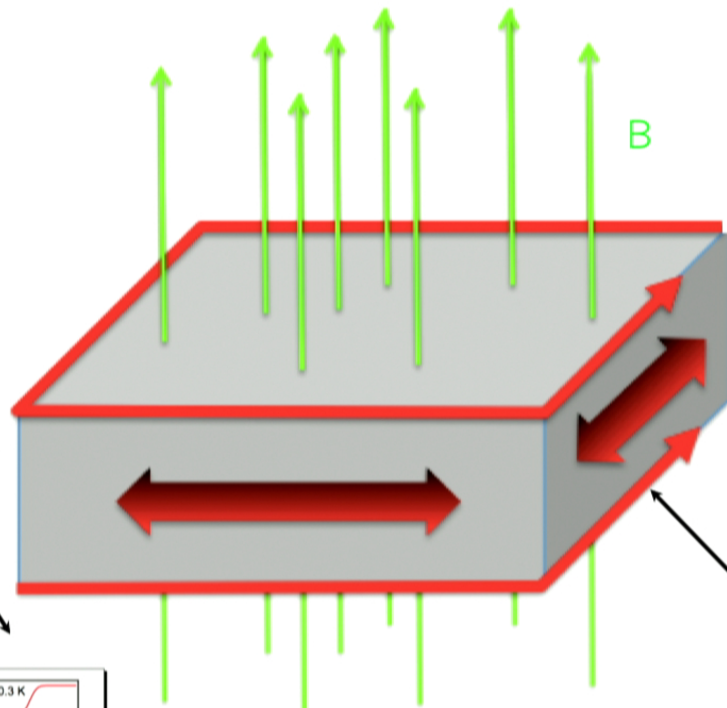
Half-quantized Hall Effect
'¼' of graphene

$$\sigma_{xy} = \frac{e^2}{h}(\nu + 1/2)$$

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

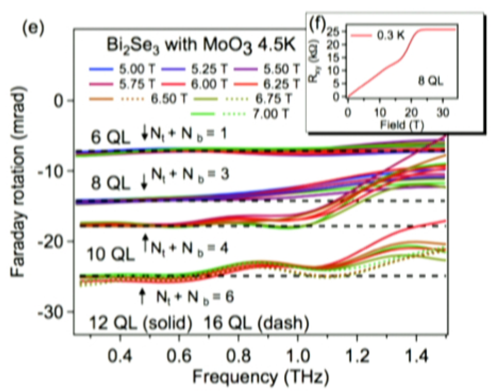
Topological Insulators in magnetic field

Edges states each may contribute 1/2 QH effect



$$\sigma_{xy} = \frac{e^2}{h}(\nu + 1/2)$$

Non gapped Dirac Metal Side surfaces, will short out Hall voltage

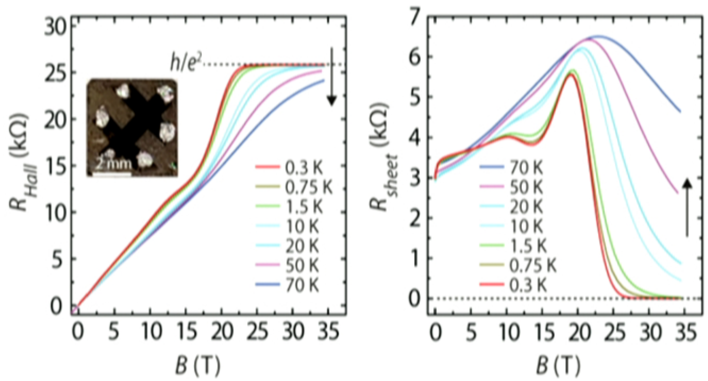


Can we directly measure the ½?

PHYSICAL REVIEW B **92**, 245118 (2015)

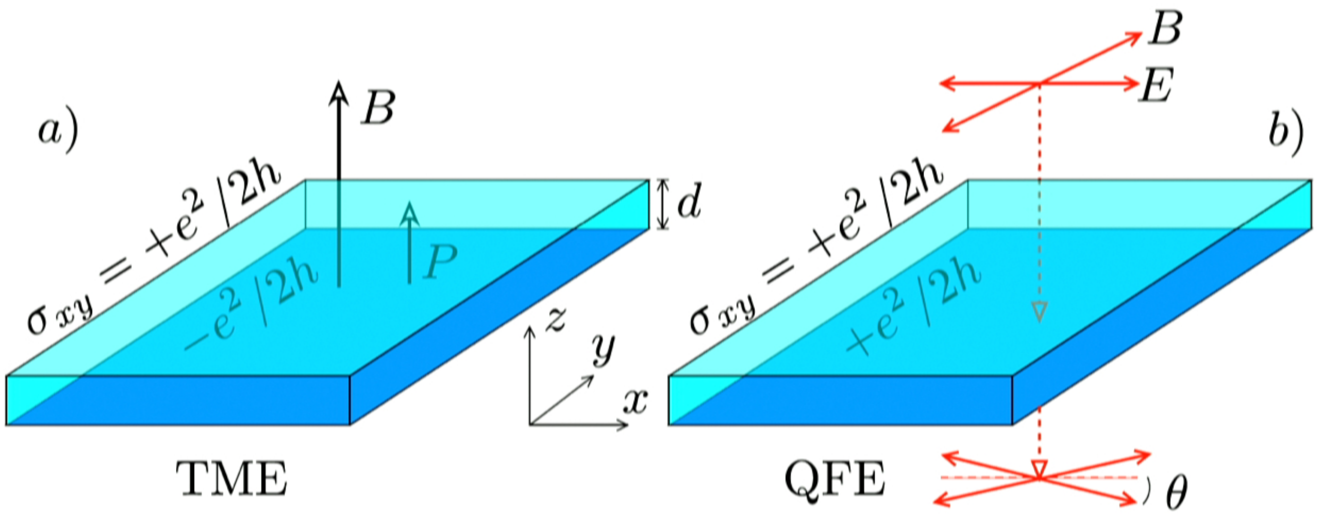
Interaction correction to the magnetoelectric polarizability of $\mathbb{Z}_2$ topological insulators

Karin Everschor-Sitte, Matthias Sitte, and Allan H. MacDonald
Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA
(Received 17 August 2015; published 10 December 2015)



We show below that the surface Hall effect is no longer exactly half quantized when interactions between surface-state quasiparticles and quantum fluctuations of the bulk magnetization, described as magnons, are included. The total Hall effect obtained by summing over the top and bottom surfaces of a thin film remains quantized, however, in agreement with experiment.

TME vs QFE



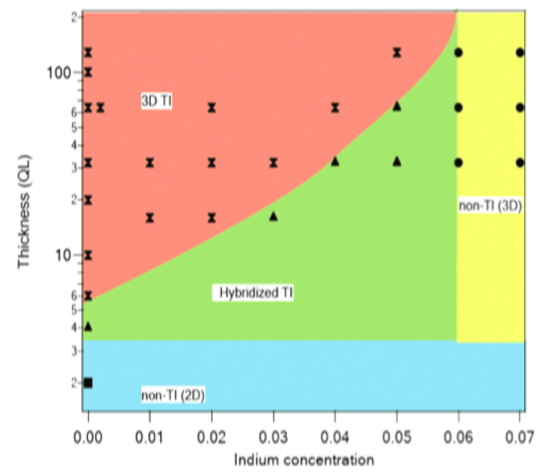
$$\chi_{\mathrm{ME}} = 4\pi\, \partial P/\partial B = (\nu_{\mathrm{T}} - \nu_{\mathrm{B}})\alpha, \qquad \theta_{\mathrm{F}} \simeq (\nu_{\mathrm{T}} + \nu_{\mathrm{B}})\alpha$$

Future works: Measure only one surface state
interaction driving nonuniversal corrections

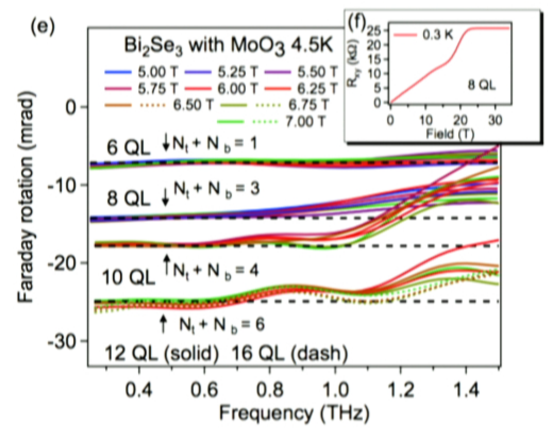
Summary

- Topological phase transition in $(Bi_{1-x}In_x)_2Se_3$.
- Novel finite size effect:
  SSs hybridization can happen before gap closing.
- Cyclotron resonance (CR) from SSs
- CR broadening ← electron-phonon interaction.
- Quantized Faraday and Kerr rotation → Topological magneto-electric effect
- A solid–state measure of the fine structure constant for the first time as a topological invariant

Thanks !



Wu, *et al*. ***Nat. Phys.***, 9, 410 (2013)



Wu, *et al*. ***PRL*** 115, 217602 (2015)
Wu, *et al*. ***arxiv:*** **1603.04317** (2016)