# Transport experiments on topological insulators

J. Checkelsky, Dongxia Qu, NPO, *Dept of Physics, Princeton Univ.*
Y. S. Hor, R. J. Cava, *Dept of Chemistry, Princeton Univ.*

1. **Introduction to Topological Insulators and ARPES expt.**
2. **Magneto-fingerprint in Ca-doped Bi2Se3**
2. **Tuning chemical potential in Bi2Se3 by gate voltage**
3. **First measurement of mobility in non-metallic bulk Bi2Te3**

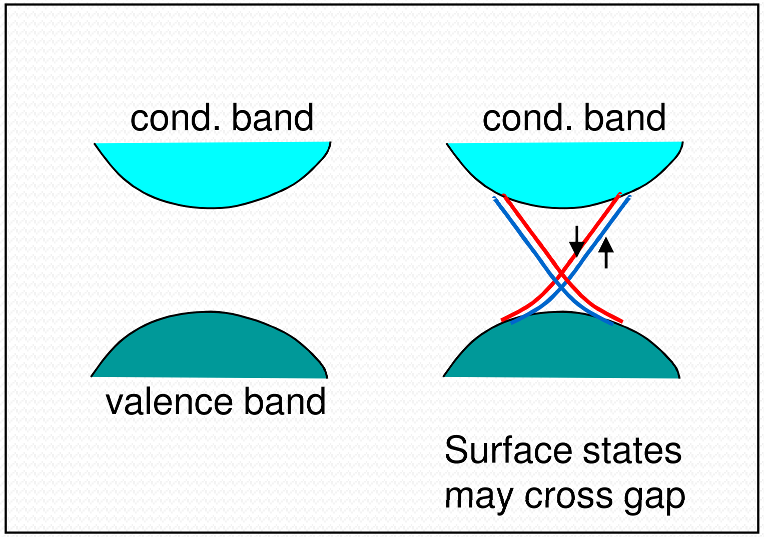
Supported by NSF DMR 0819860

Seminar, Technion, May 3, 2010

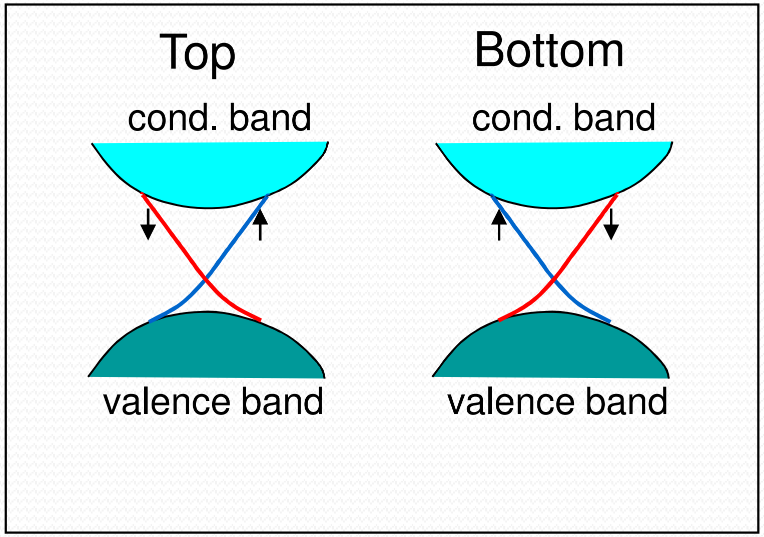
# A new class of insulators

Fu, Kane ’06
Zhang et al. ’06
Moore Balents ‘06
Xi, Hughes, Zhang ‘09

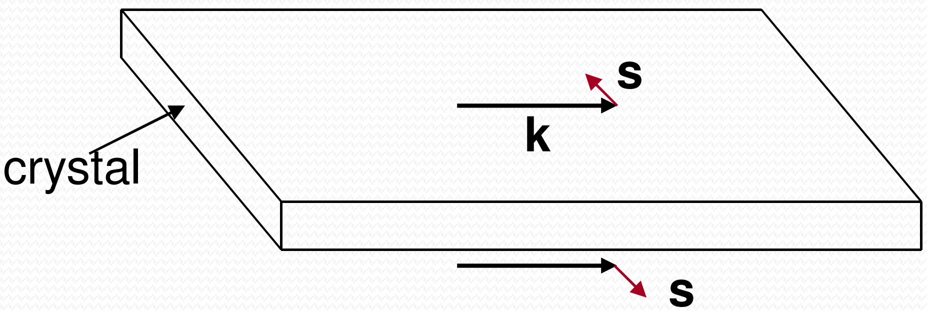
Conventional insulator



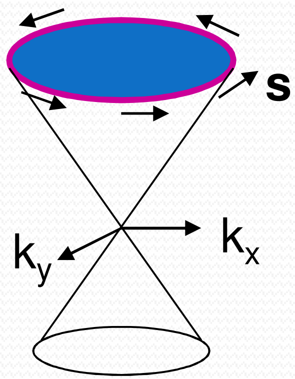

Topological insulator




Surface states are *helical* (spin locked to **k**)
Large spin-orbit interactn




Surface state has
Dirac dispersion



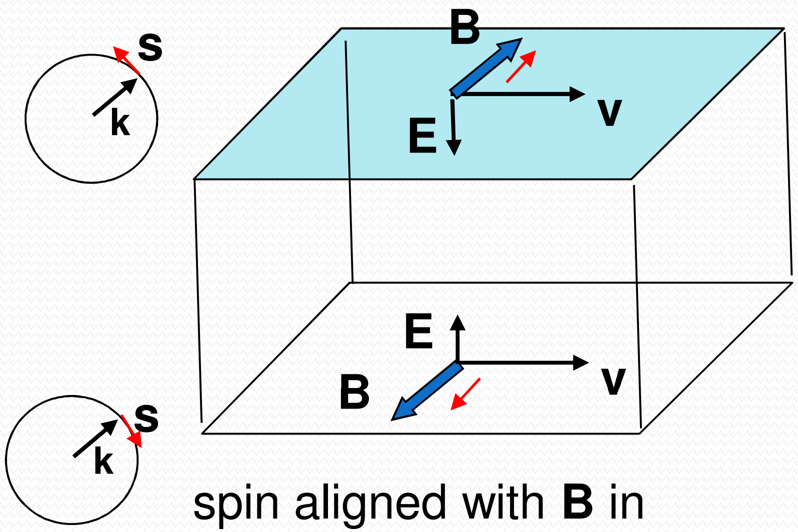
# Helicity and large spin-orbit coupling

- Spin-orbit interaction and surface
  **E** field → effectv **B** = **v** × **E** in rest frame

- spin locked to **B**

- Rashba-like Hamiltonian

$$H = v_F\, \hat{\mathbf{n}} \times \mathbf{k} \cdot \mathbf{s}$$



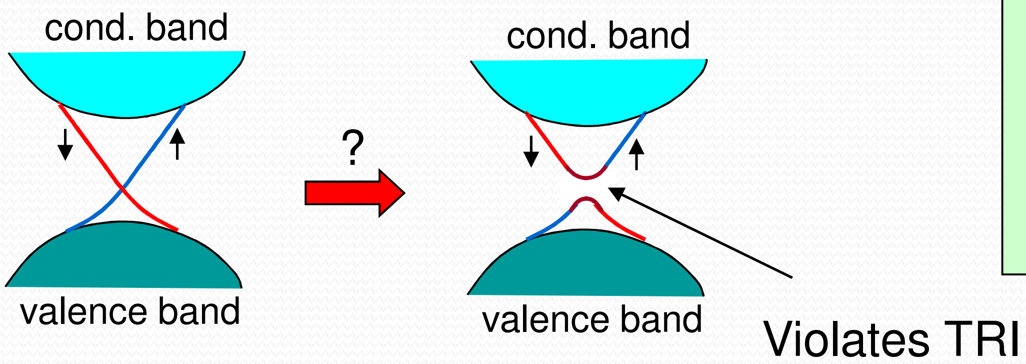

spin aligned with **B** in
rest frame of moving electron

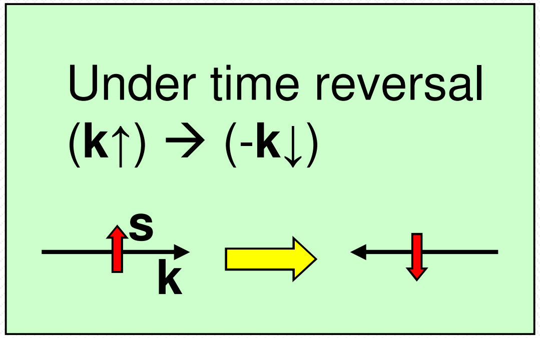
Helical, massless Dirac states with opposite chirality on opp. surfaces of crystal

Like *LH* and *RH* neutrinos in different universes

# Protection of helical states

## 1. Time-reversal invariance prevents gap formation at crossing

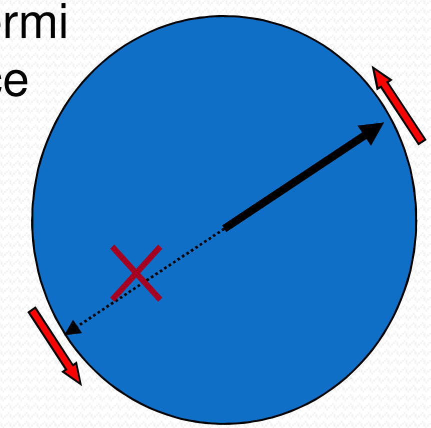



Kane, Mele, PRL '05

## 2. Suppression of $2k_F$ scattering

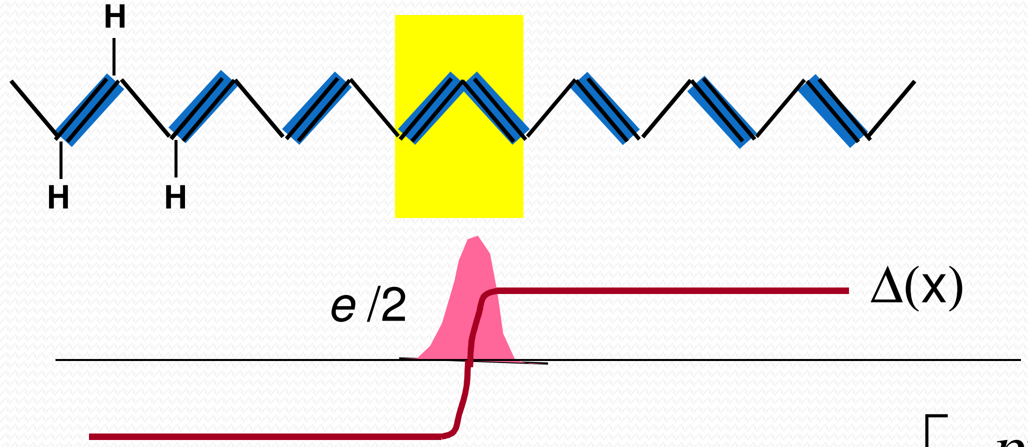
2D Fermi surface



Spinor product kills matrix element
Large surface conductance?

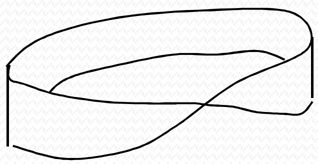
# A twist of the mass (gap)

## Doped polyacetylene (Su, Schrieffer, Heeger '79)




**Domain wall (soliton) traps ½ charge**

$$H = \begin{bmatrix} pv & \Delta(x) \\ \Delta^*(x) & -pv \end{bmatrix}$$



Mobius strip

1. **Gap-twist produces domain wall**
2. **Domain wall traps fractional charge**
3. **Topological (immune to disorder)**
   **Mobius strip like**

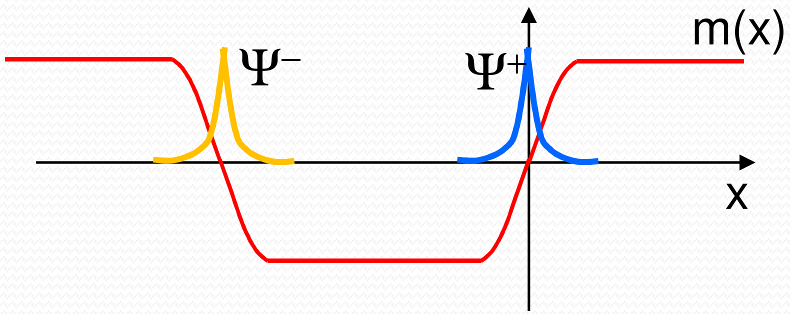
# Dirac fermions as domain wall excitation

## QFT with background mass-twist field

Jackiw Rebbi, PRD '76
Goldstone Wilczek, PRL '81
Callan Harvey, Nuc Phys B '85
Fradkin, Nuc Phys B '87
D. Kaplan, Phys Lett B '92

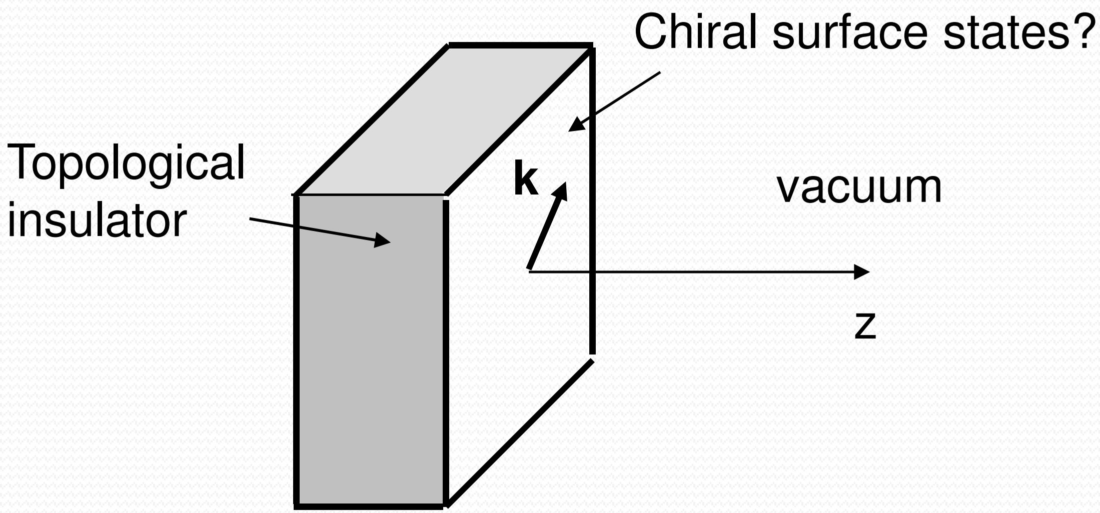
Dirac modes on domain walls of mass field

$$H = \begin{bmatrix} m(x) & p \\ p & -m(x) \end{bmatrix}$$



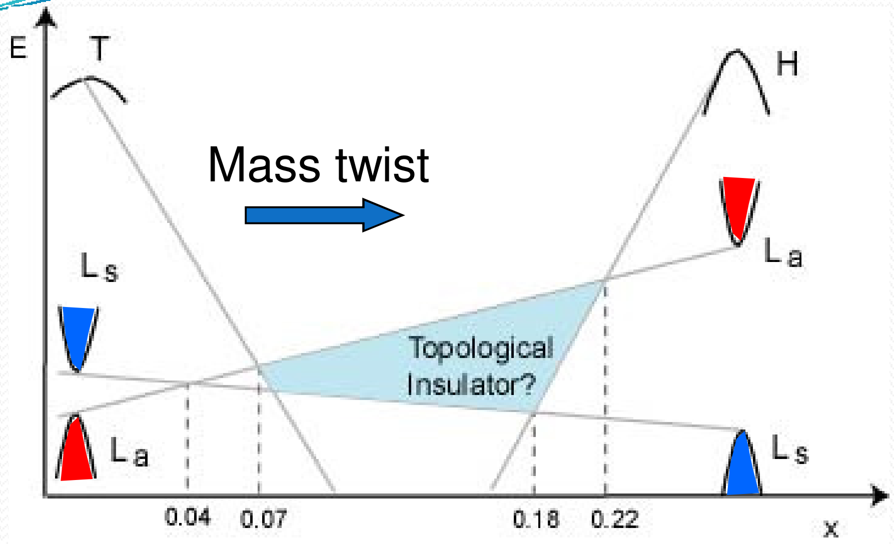

**Chiral zero-energy mode**
**Domain-wall fermion**

Callan-Harvey: Domain walls *exchange* chiral current to solve anomaly problm



# Fu Kane prediction of topological insulator

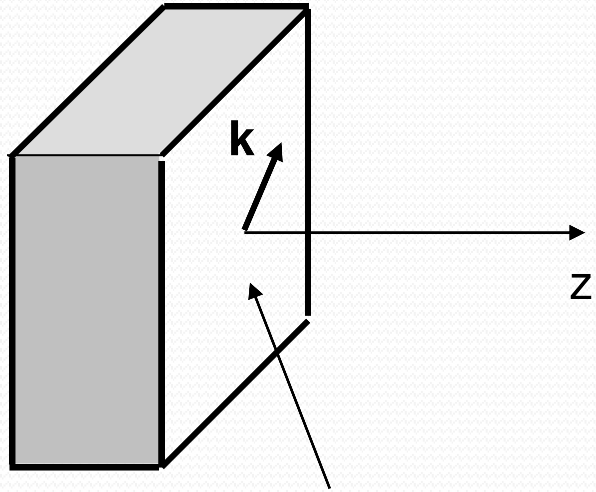
Fu, Kane, PRB ‘06



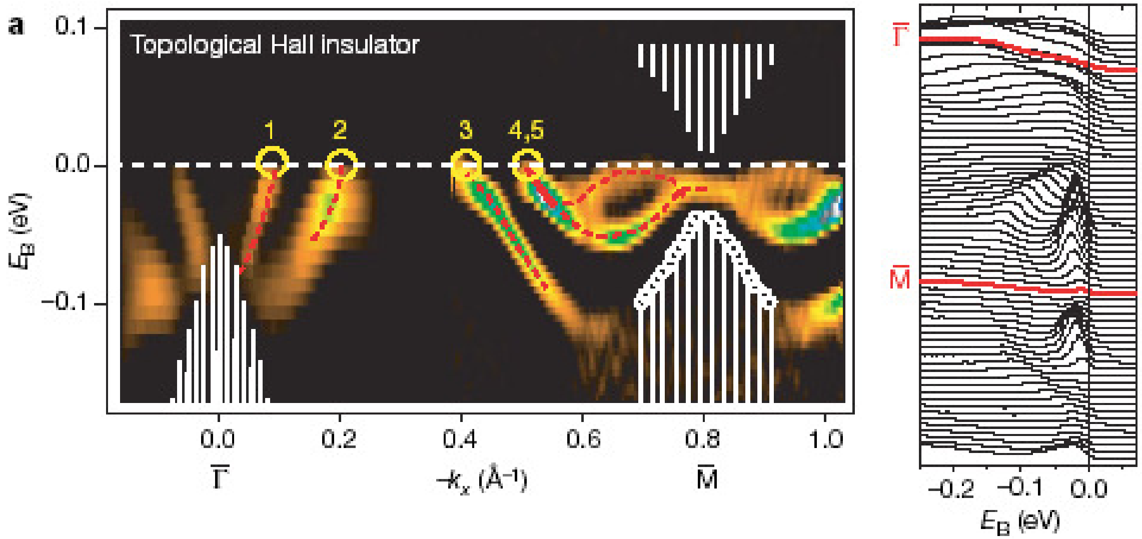

Bi

$Bi_{1-x}Sb_x$

Sb



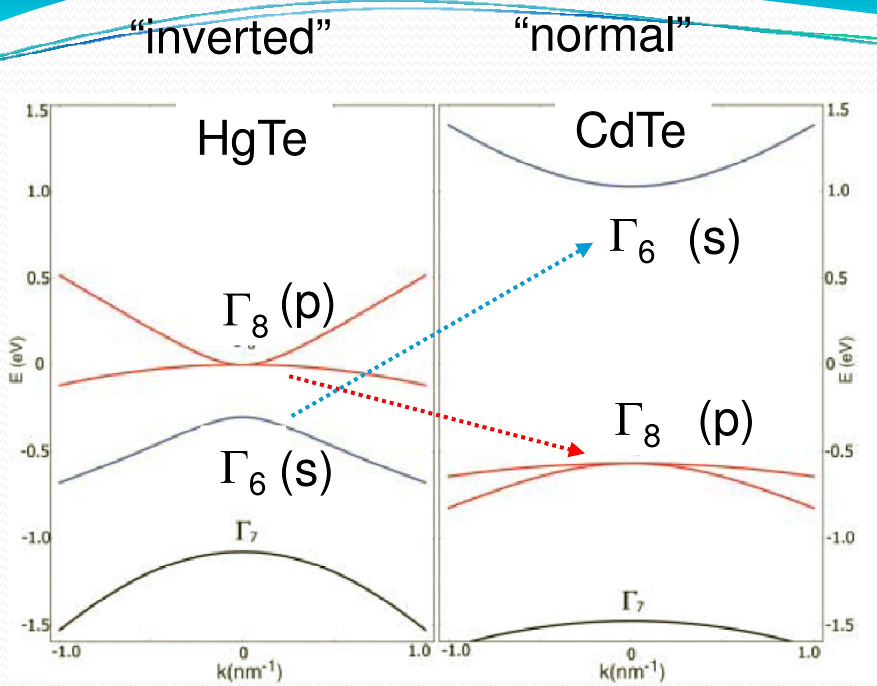

Mass twist traps surface
Weyl fermions




ARPES confirmation
Hsieh, Hasan, Cava et al.
Nature ‘08

Confirm 5 surf states in BiSb

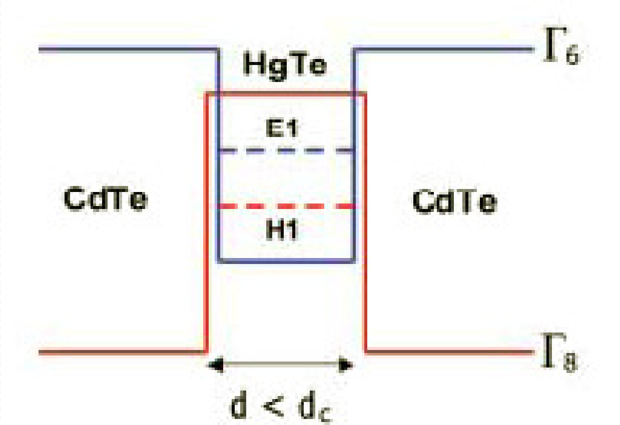
# Quantum Spin Hall effect in HgTe/CdTe quantum well

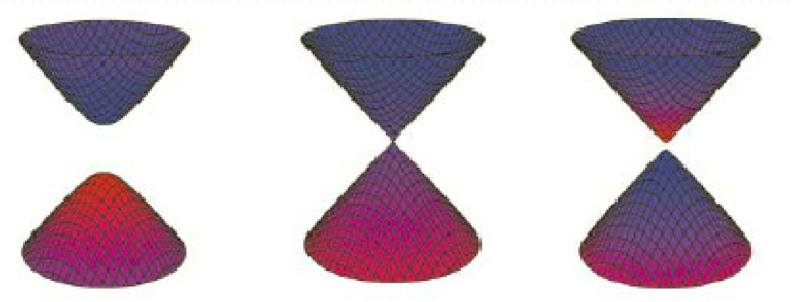



Bernevig, Hughes, Zhang, Science '06

Konig, Molenkamp et al. Science '07

Gap twist in HgTe/CdTe QW



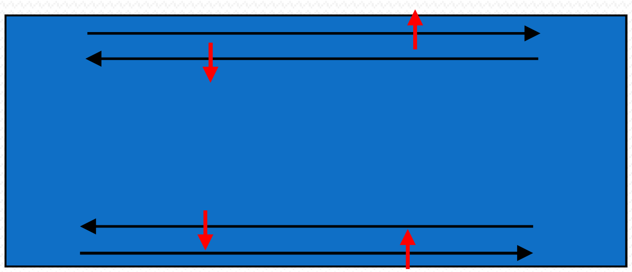



CdTe like

HgTe like

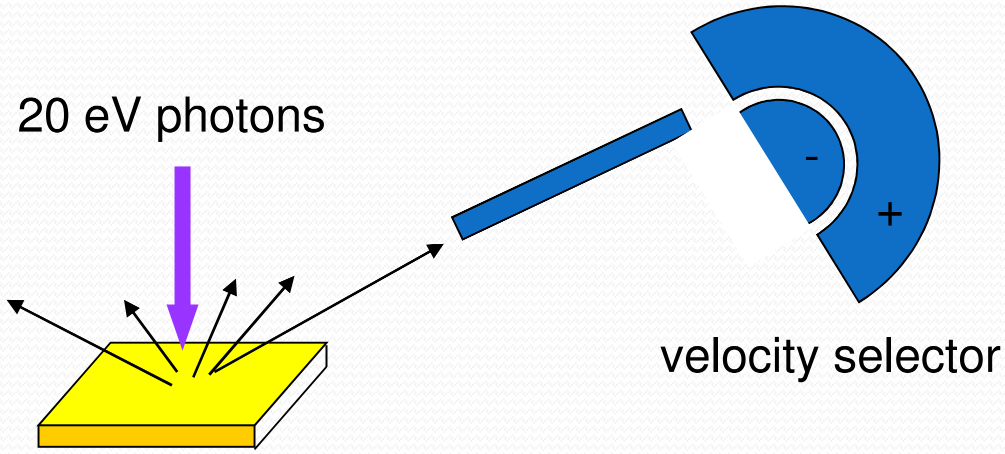
well width $d$

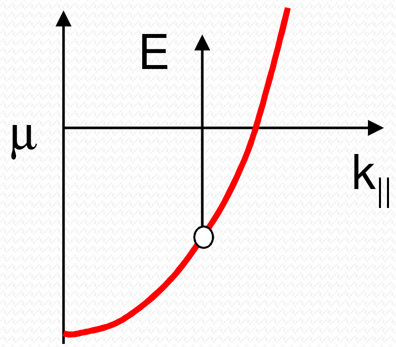
helical edge states

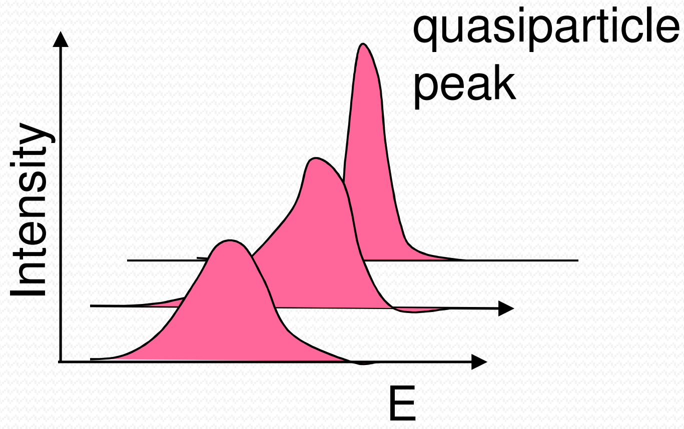


Quantum spin Hall effect

# Angle-resolved photoemission spectroscopy (ARPES)

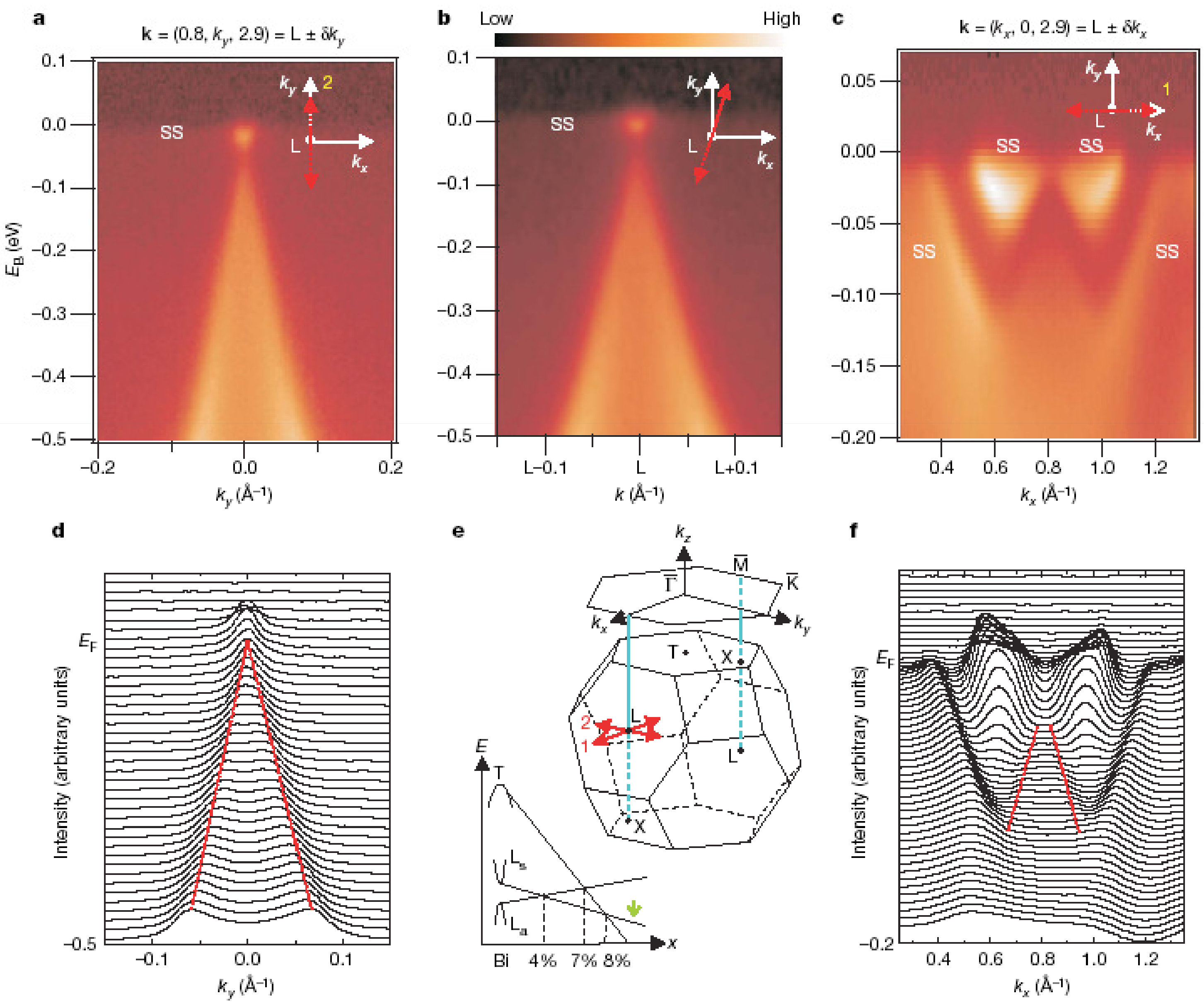


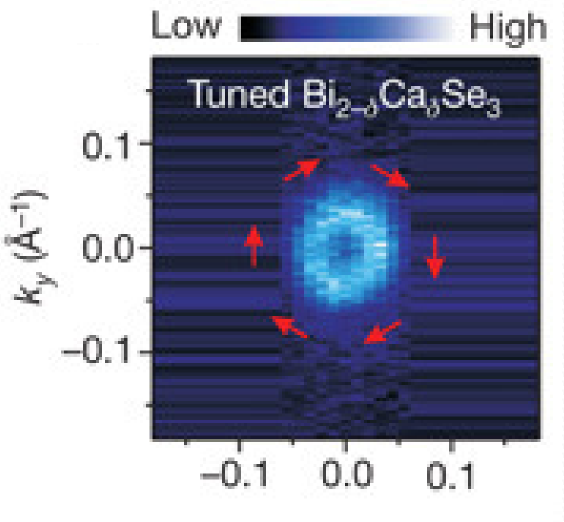



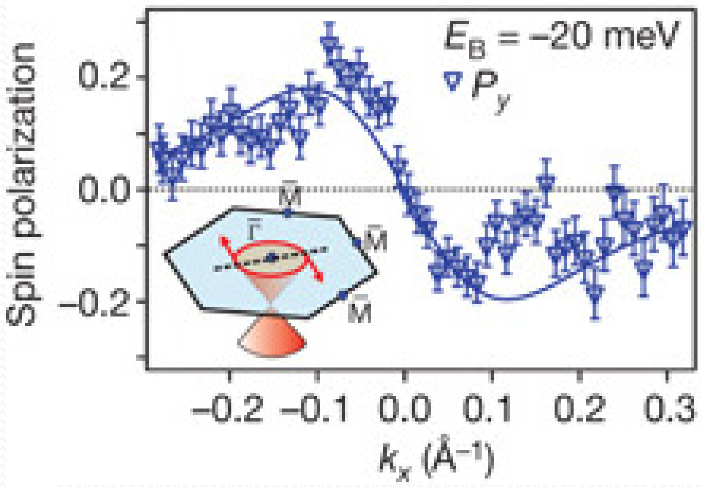
# ARPES of surface states in $Bi_{1-x} Sb_x$

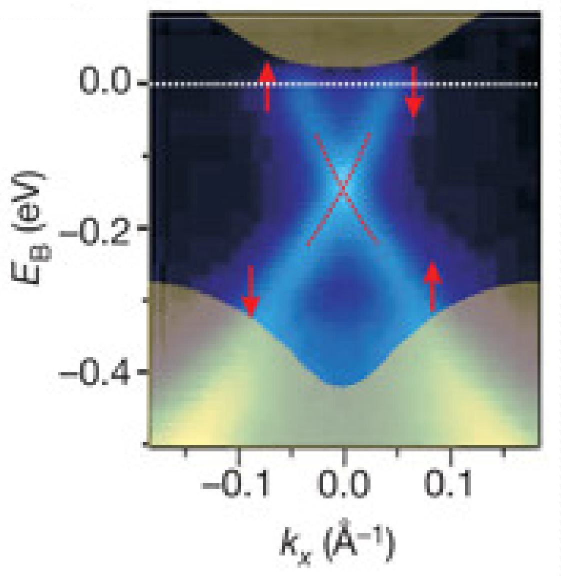
Hsieh, Hasan, Cava *et al*. Nature 2008



# Photoemission evidence for Topological Insulators




Why spin polarized?

→Rashba term on surface

What prevents a gap?

→ Time Reversal Symmetry

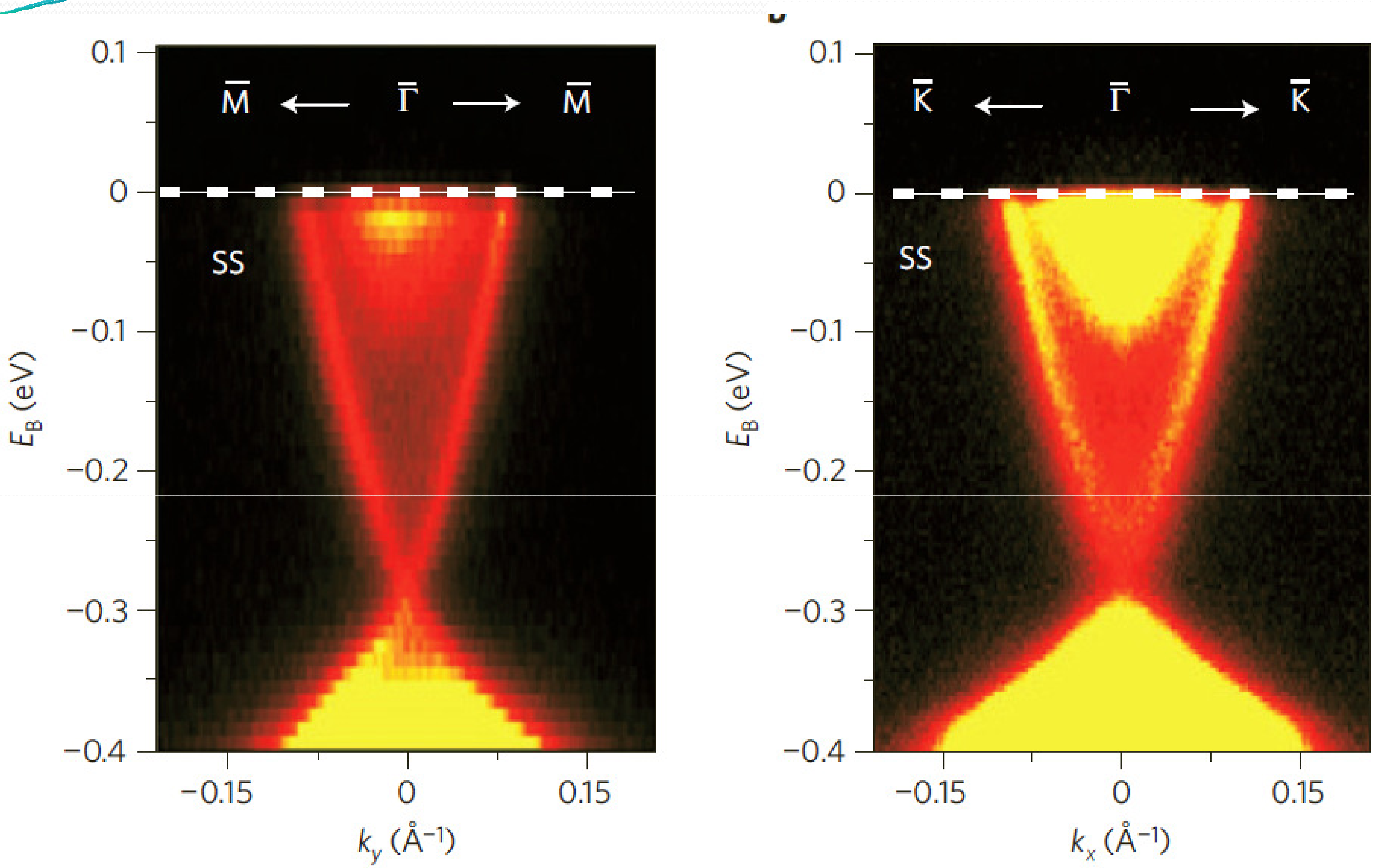
What is expected from transport?

- No 2 $k_F$ scattering
- SdH
- Surface QHE (like graphene except ¼)
- Weak anti-localization

Hsieh, Hasan *et al.*, Nature '09

# ARPES results on $Bi_2Se_3$ (Hasan group)

**Xia, Hasan et al. Nature Phys '09**




Large gap ~ 300meV

As grown, Fermi level in conduction band

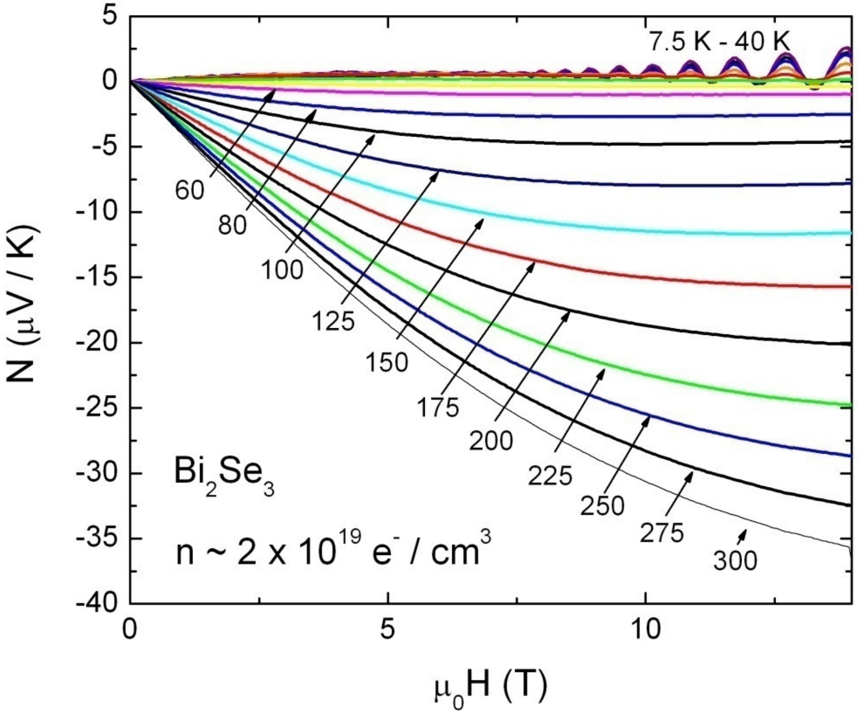
Se defect chemistry difficult to control for small DOS

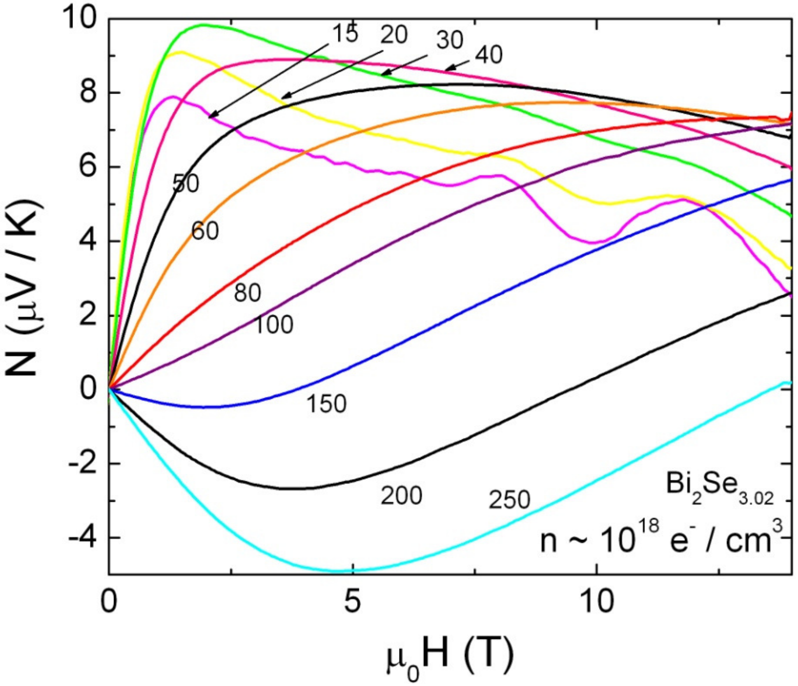
# Quantum oscillations of Nernst in *metallic* $Bi_2Se_3$

## Problem confronting transport investigation

As-grown xtals are always excellent conductors,
$\mu$ lies in conduction band (Se vacancies).

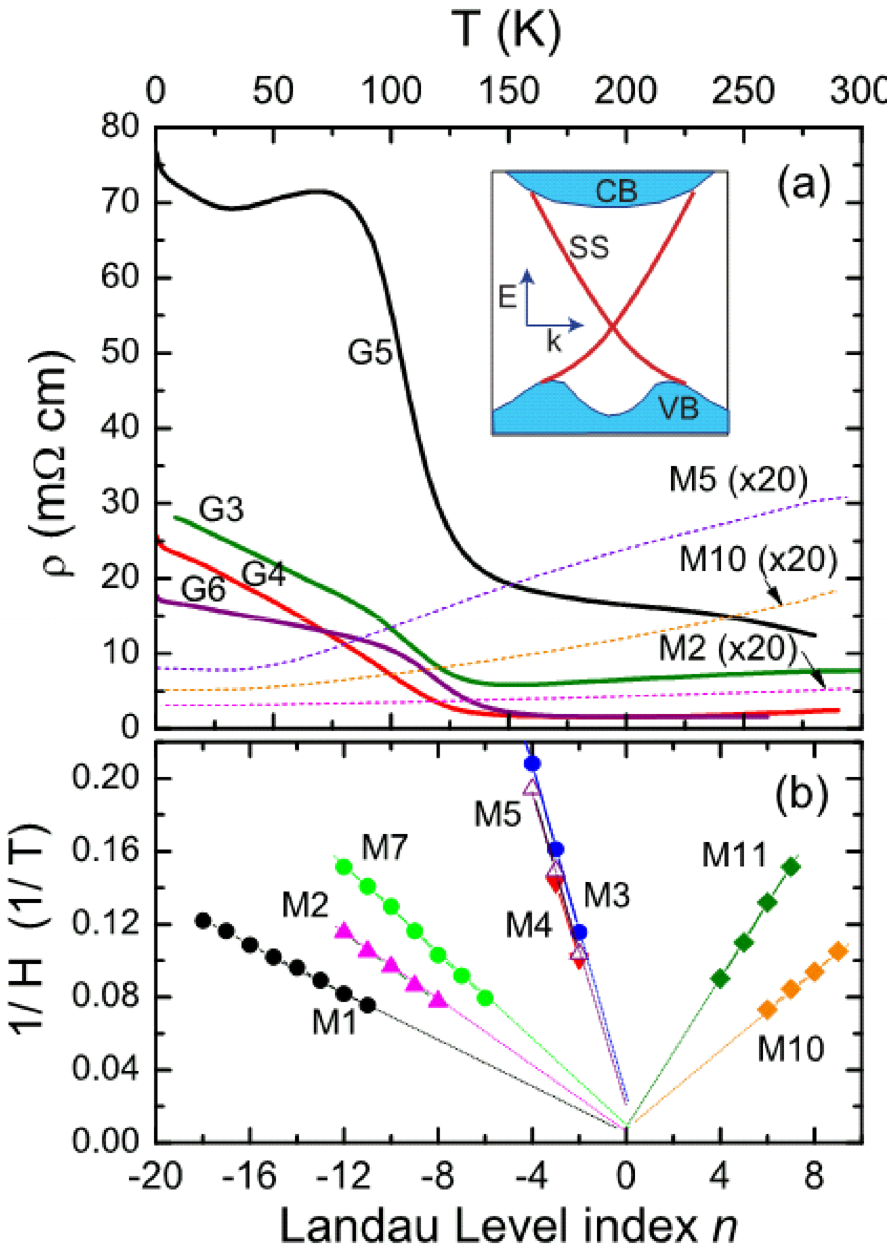
$\rho$ (1 K) ~ 0.1-0.5 m$\Omega$cm, n ~ 1 x $10^{18}$ cm$^{-3}$
$m^*$ ~ 0.2, $k_F$ ~ 0.1 Å$^{-1}$



# Resistivity vs. Temperature : In and out of the gap

Checkelsky *et al.*, PRL '09

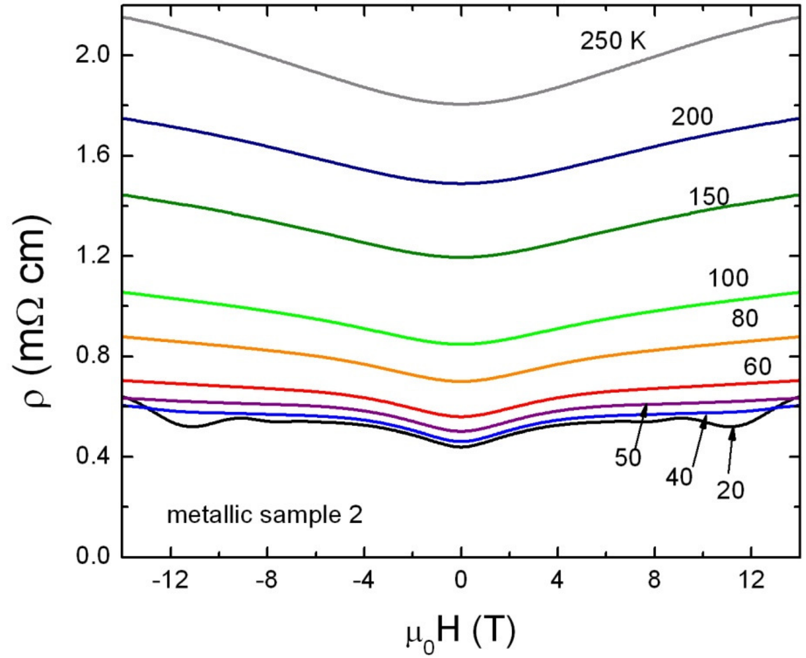


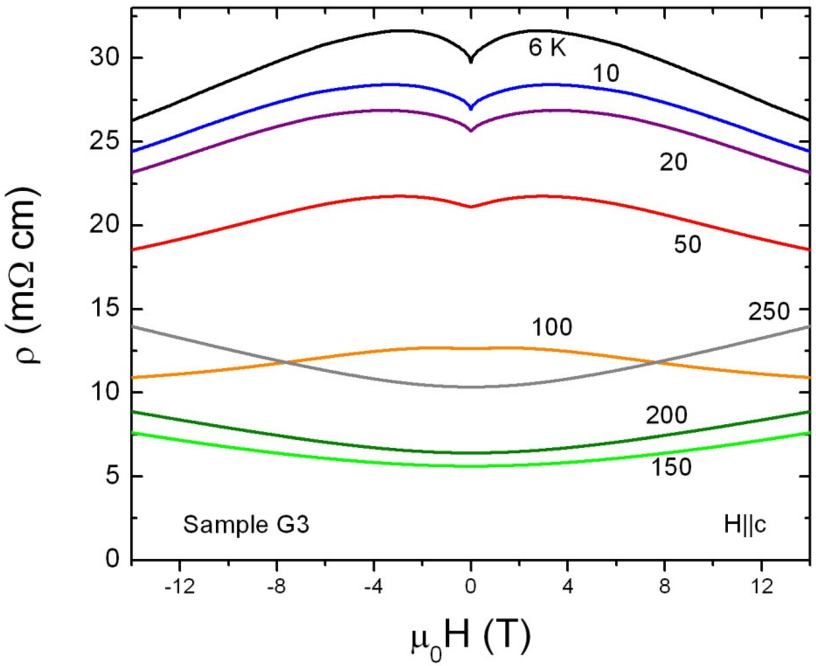

Onset of non-metallic behavior ~ 130 K

SdH oscillations seen in both n-type and p-type samples

Non-metallic samples show no discernable SdH

# Metallic vs. Non-Metallic Samples: R(H)

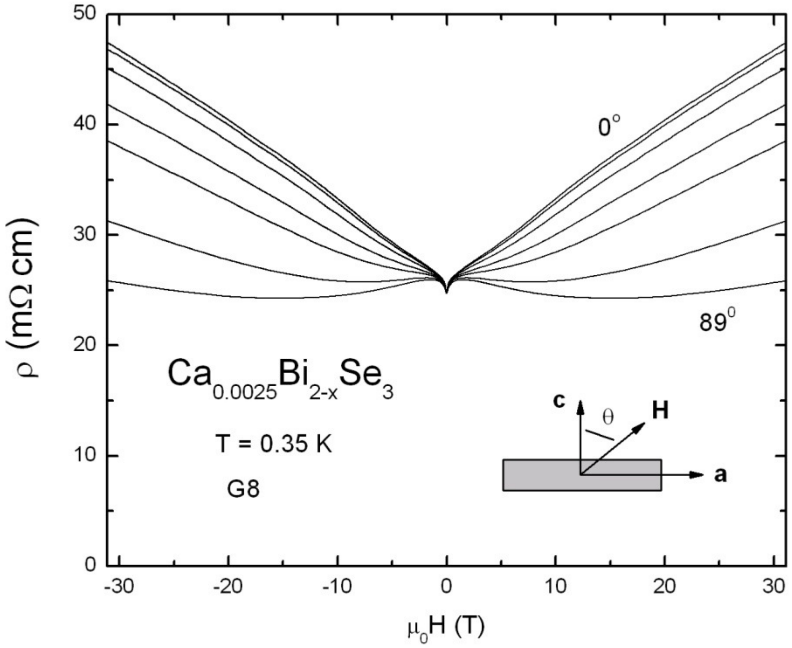


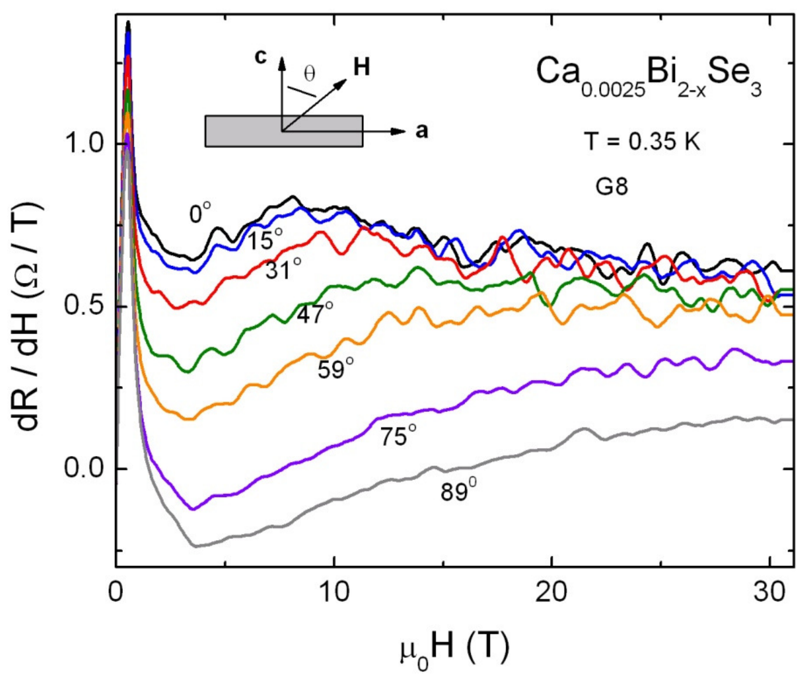




Metallic samples display positive MR and detectable SdH oscillations

R(H) profile changes below T onset of non-metallic behavior
Low H feature develops below 50 K

# Non-Metallic Samples in High Field



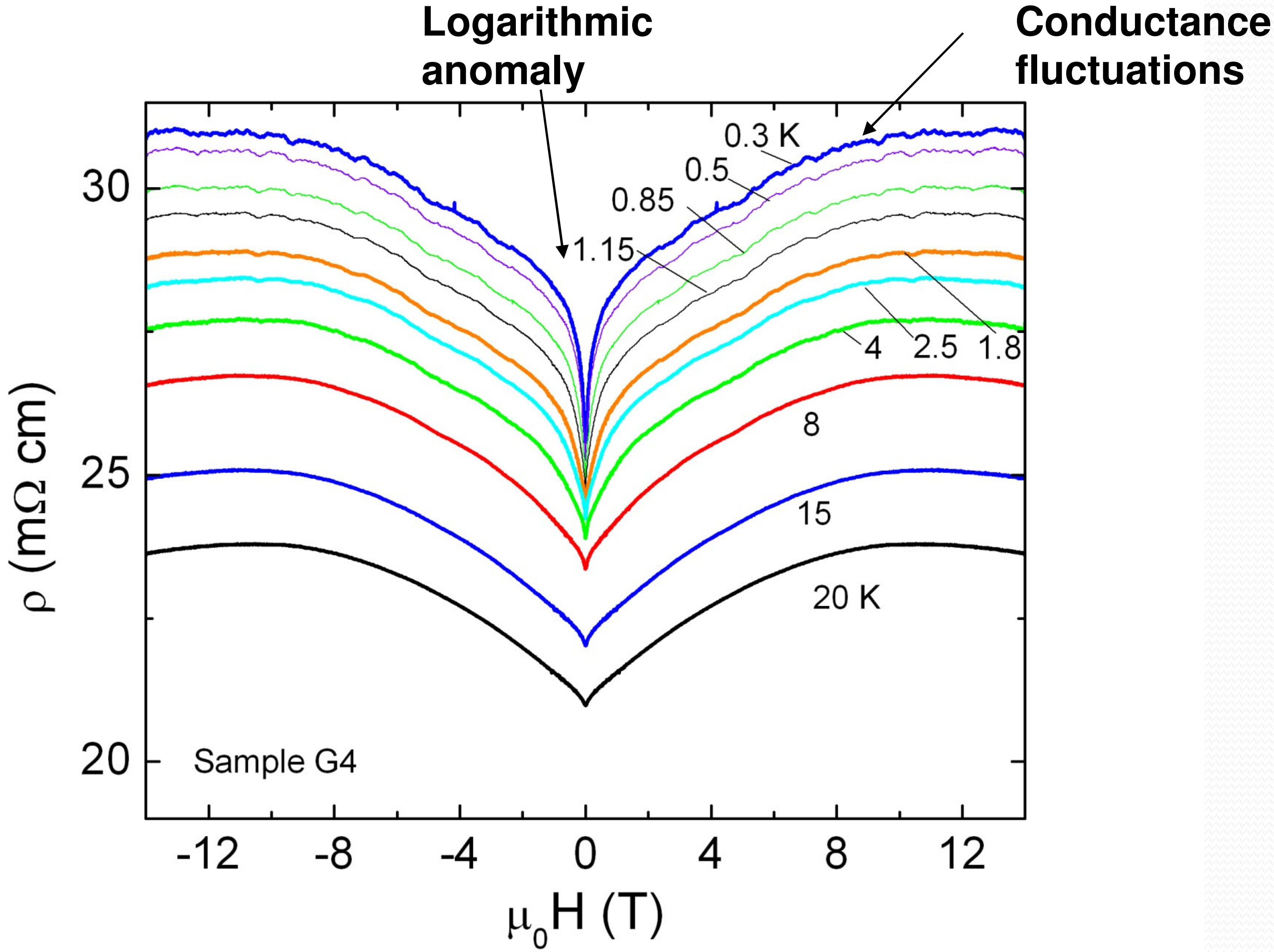

Fluctuation does not change character significantly in enhanced field

Still no SdH oscillations

# Magnetoresistance of gapped Bi2Se3

Checkelsky *et al.*, PRL '09

Giant, quasi-periodic, retraceable conductance fluctuations



# Magneto-fingerprints

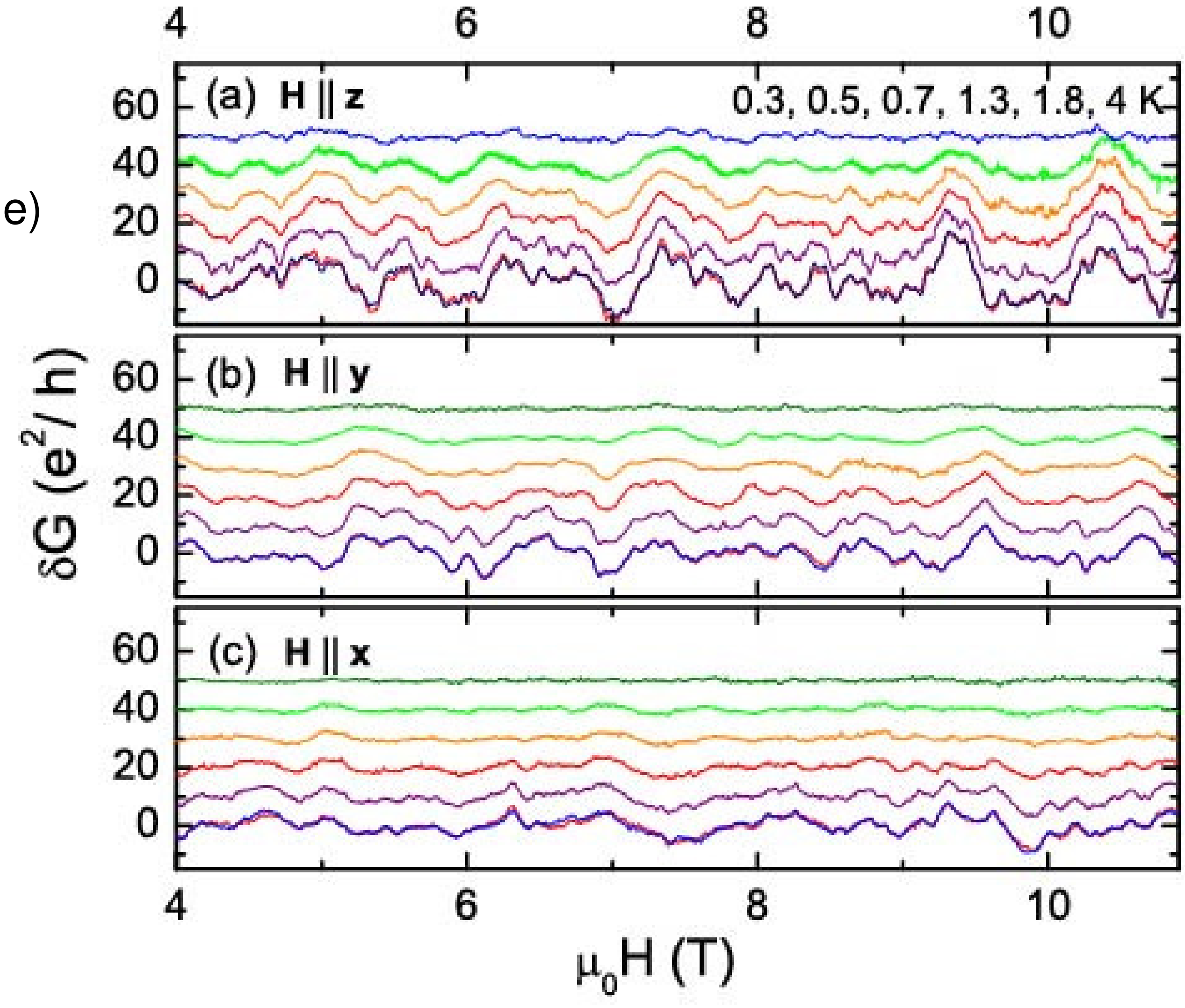
Checkelsky *et al.*, PRL ‘09

**Fluctuations** **retraceable**

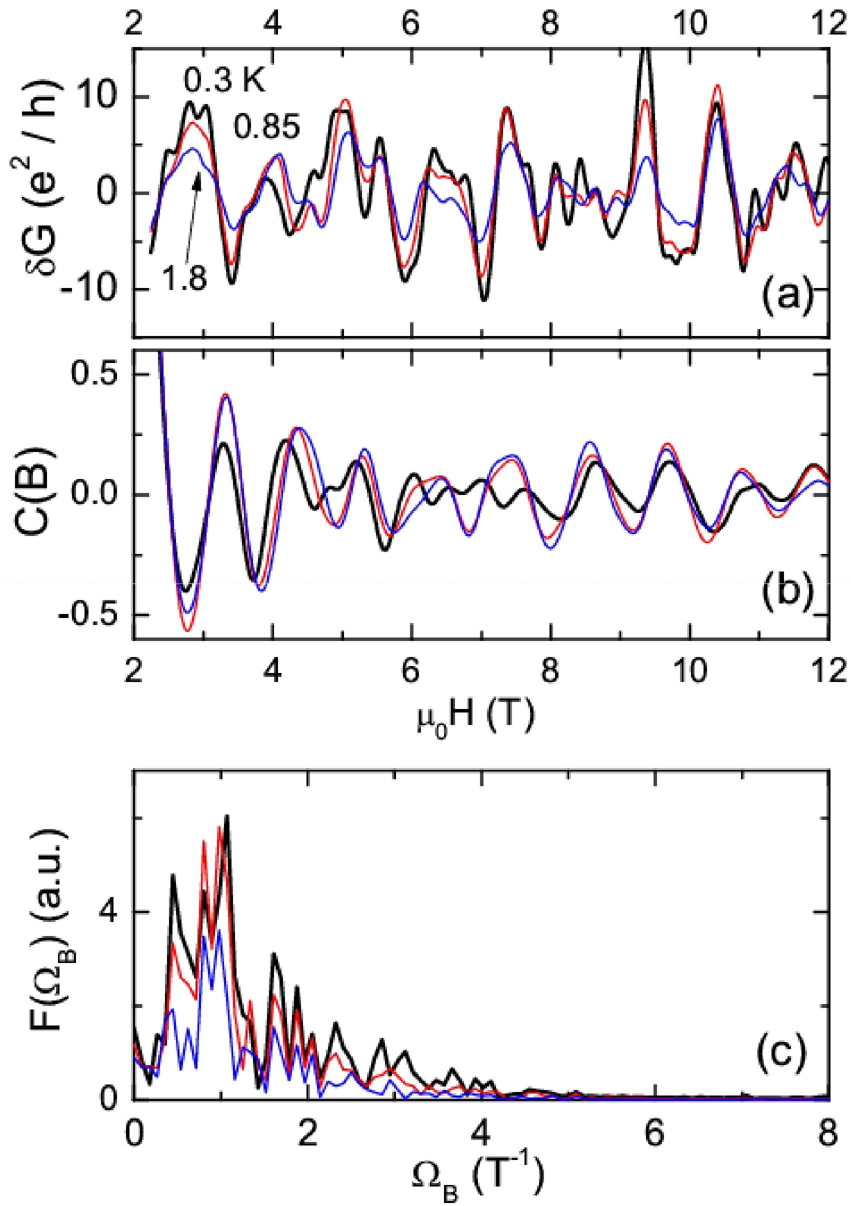
Giant amplitude
(200-500 X too large)

Retraceable
(fingerprints)

Spin degrees
Involved in
fluctuations



# Quasi-periodic fluctuations




Background removed with T = 10 K trace (checked with smoothing)

Autocorrelation C should polynomial decrease for UCF yielding

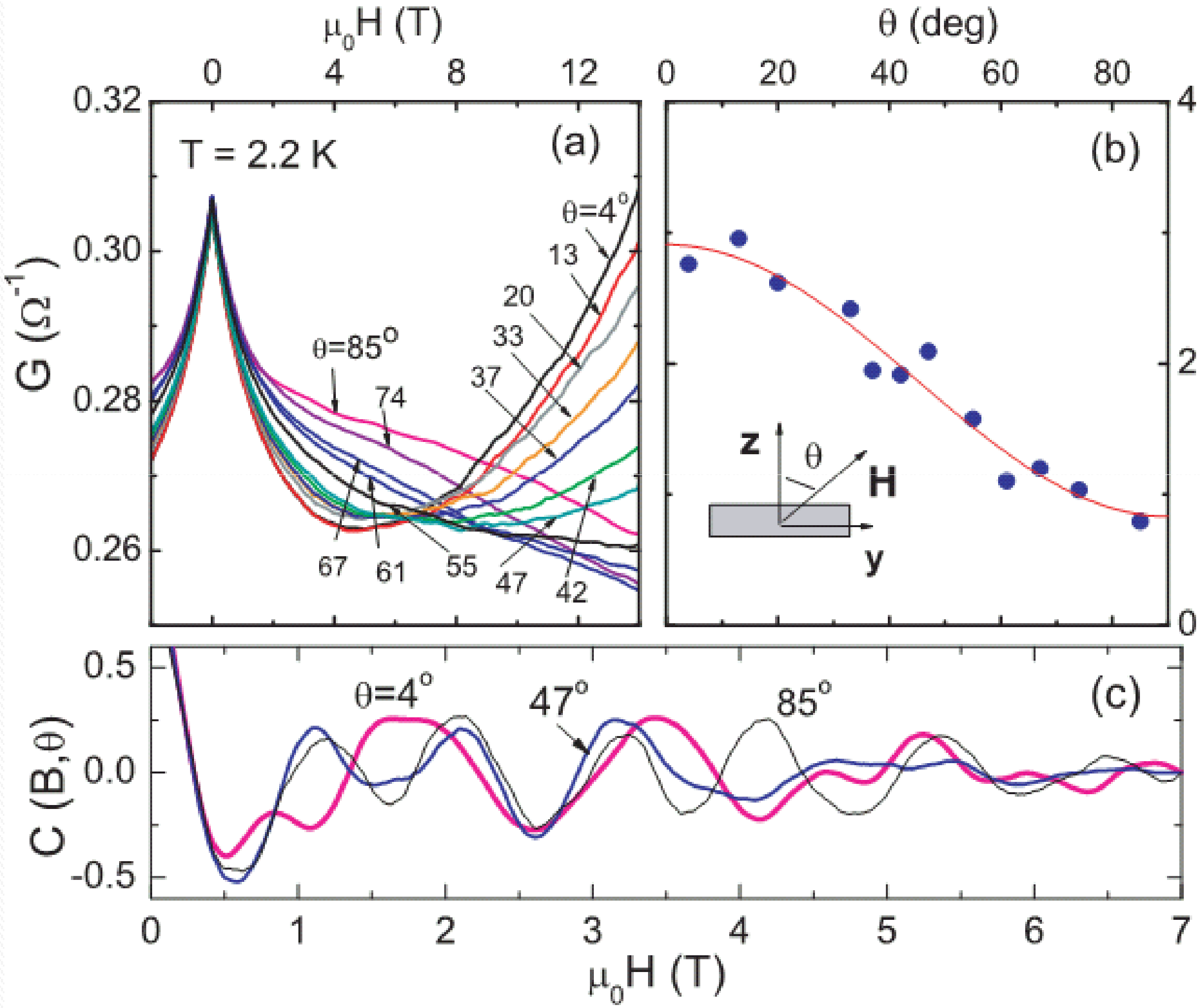
$$B_c \sim \phi_0 / L_T^2$$

If interpreted as Aharonov-Bohm effect, Fourier components yield

$$\sqrt{\phi_0 / B_p} \sim 600\ \text{Å}$$

# Angular Dependence of R(H) profile Cont.

Checkelsky *et al.*, PRL '09




For δG, 29% spin term

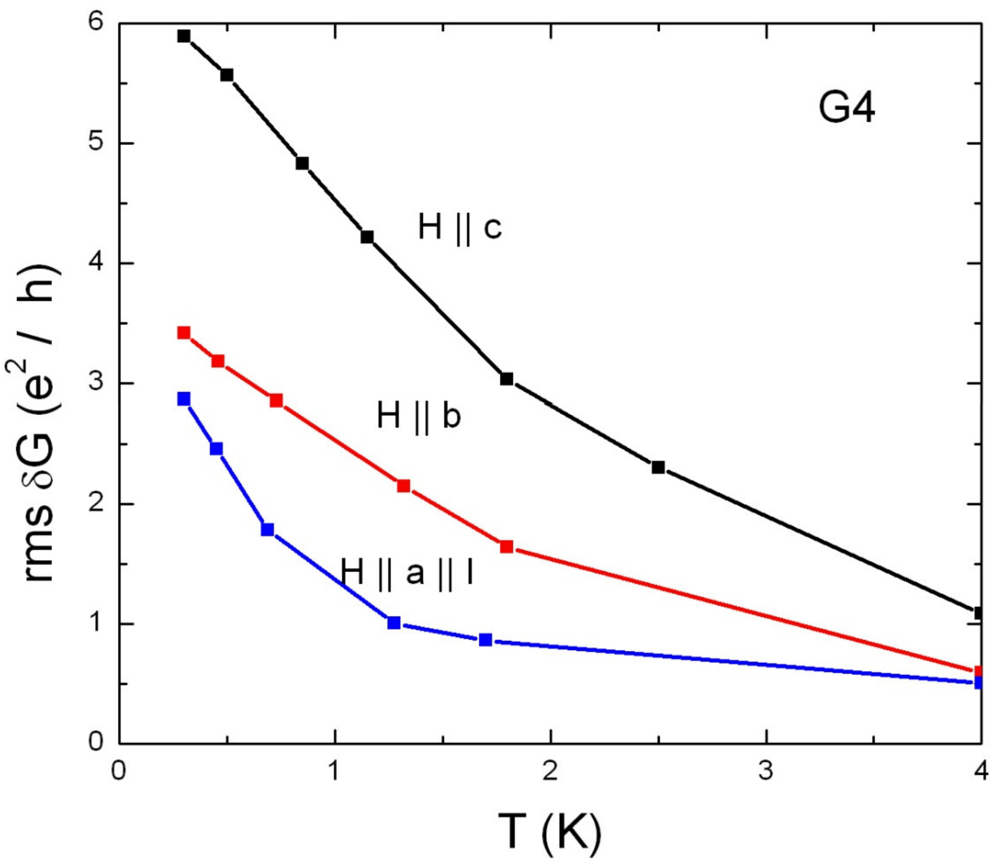
For ln H, 39% spin term (~200 $e^2/h$ total)

$$-\frac{e^2}{h}\left[A_{orb} + A_{spin}\right] \ln H$$

Theory predicts both to be ~ 1/2π

(Lee & Ramakrishnan), (Hikami, Larkin, Nagaoka)

# Quasi-periodic fluctuations vs T




Fluctuation falls off quickly with temperature

For UCF, expect slow power law decay $\sim T^{-1/4}$ or $T^{-1/2}$

AB, AAS effect exponential in $L_T/P$

→ Doesn't match!

**Features of anomalous magneto-fingerprint**

1. Observed in mm-sized xtals – not UCF

2. RMS value very large 1-10 $e^2/h$

3. Modulated by in-plane (spin degrees play role)

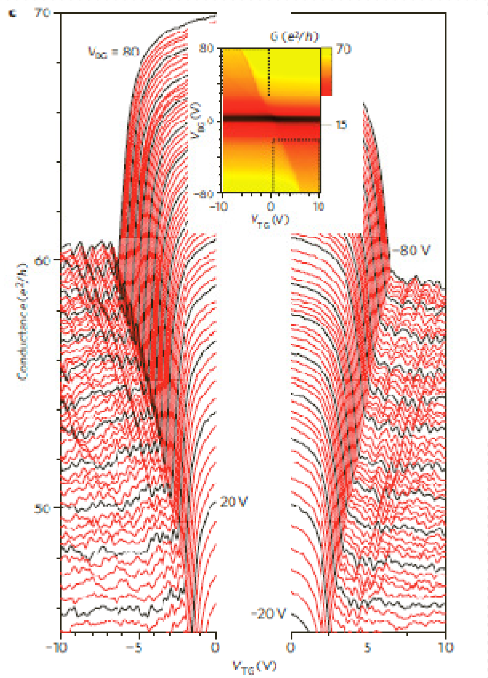
4. T dependence steeper than UCF

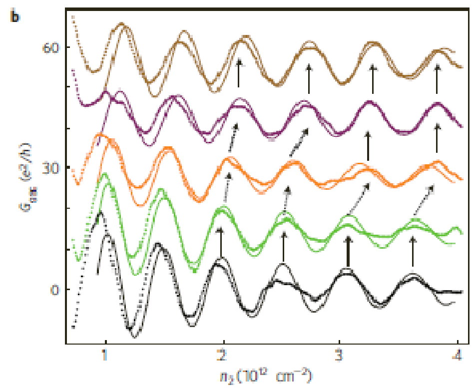
LETTERS
PUBLISHED ONLINE: 1 FEBRUARY 2009 | DOI: 10.1038/NPHYS1198
nature physics

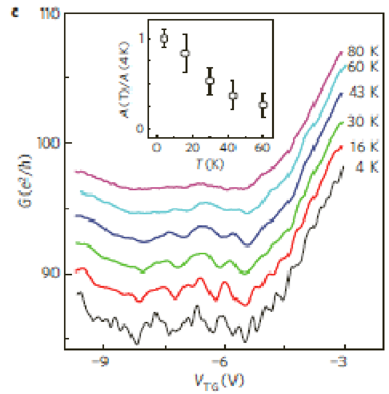
# Quantum interference and Klein tunnelling in graphene heterojunctions

Andrea F. Young and Philip Kim*

Young & Kim, Nat. Phys 2008



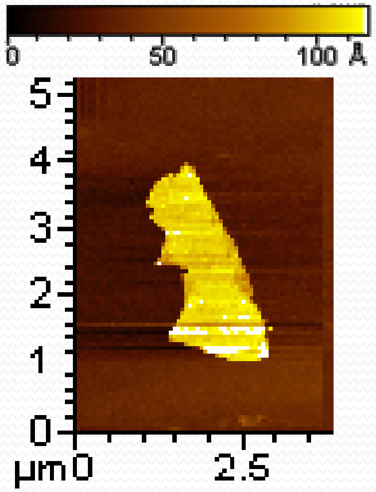



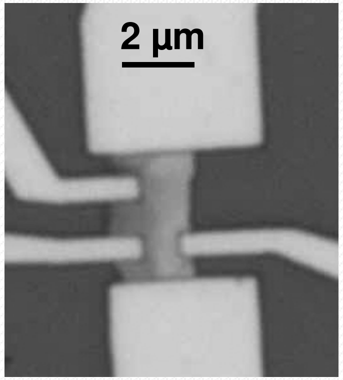



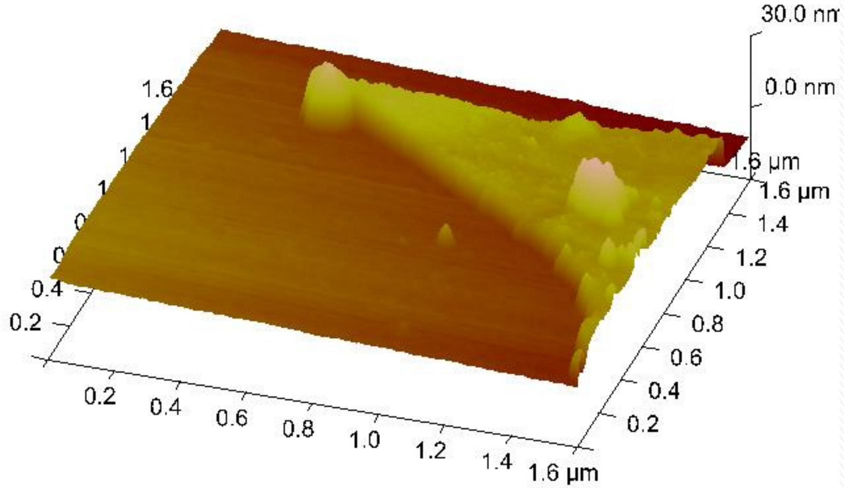

Fabry-Perot resonances produce cond. oscillationsof amplitude 5-10 $e^2/h$

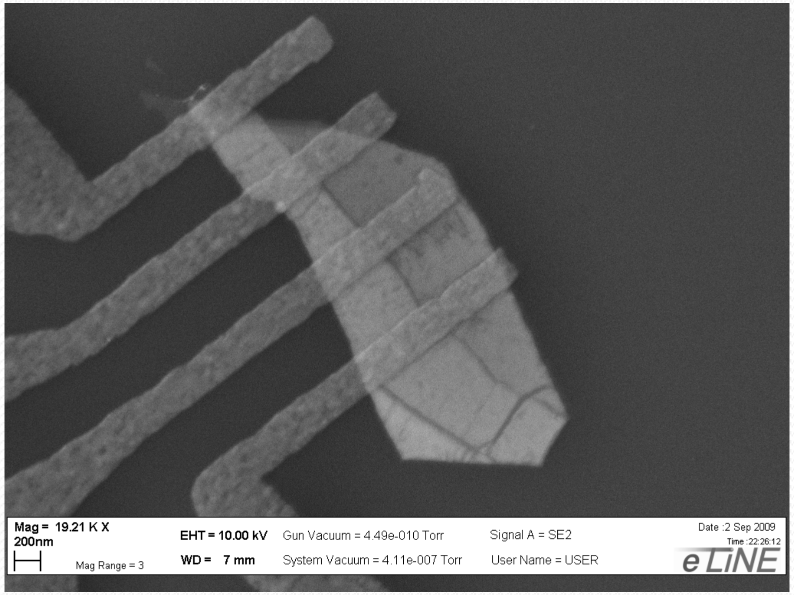
# Tuning the Chemical Potential by Gate Voltage

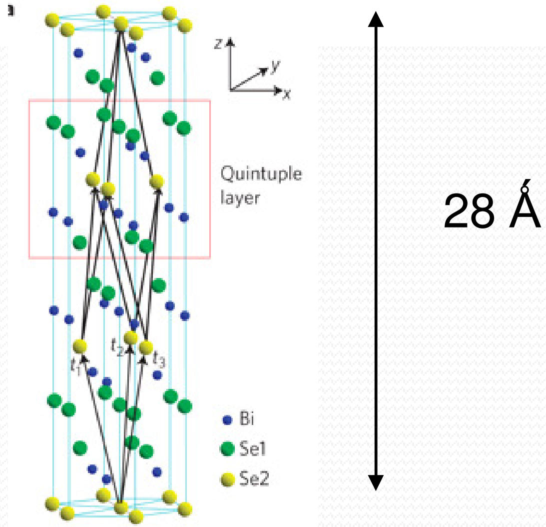
# Cleaved Crystals



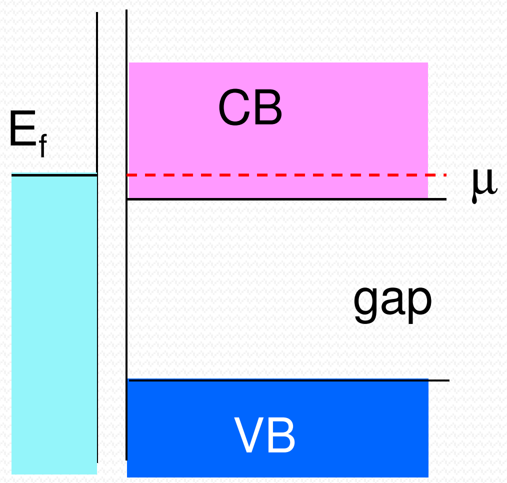



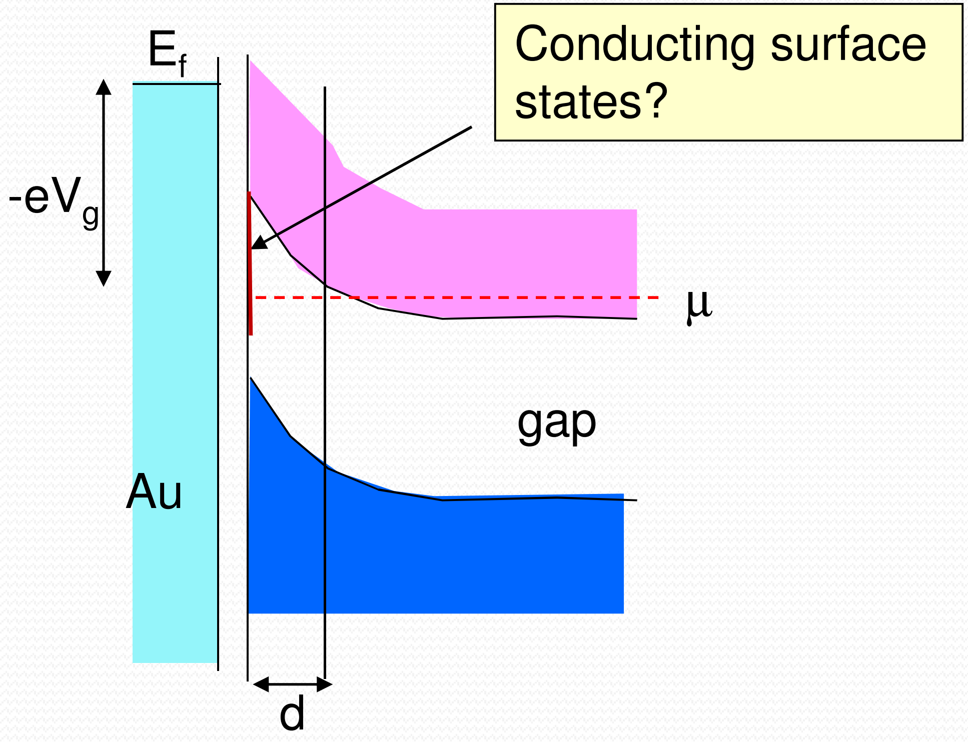



# Gating approach to Topological Insulators




Flat band case

Chemical potential
In the cond. band

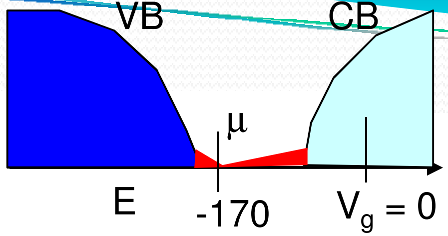



Negative gate bias

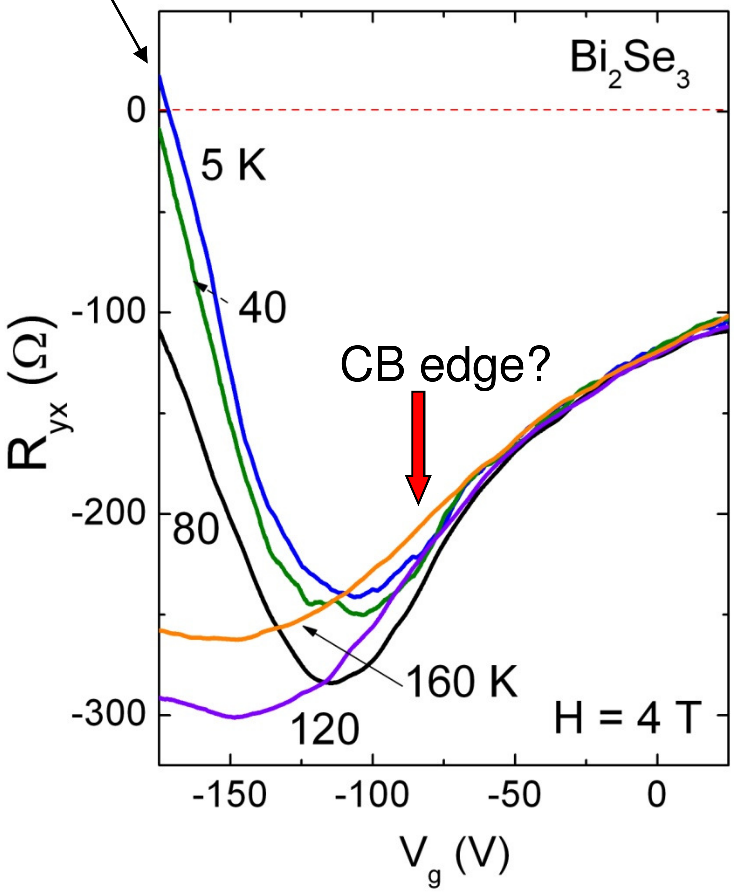
In thin sample, μ moves inside gap

# Gating thin crystal of $Bi_2Se_3$ into gap (*d* ~ 20 nm)

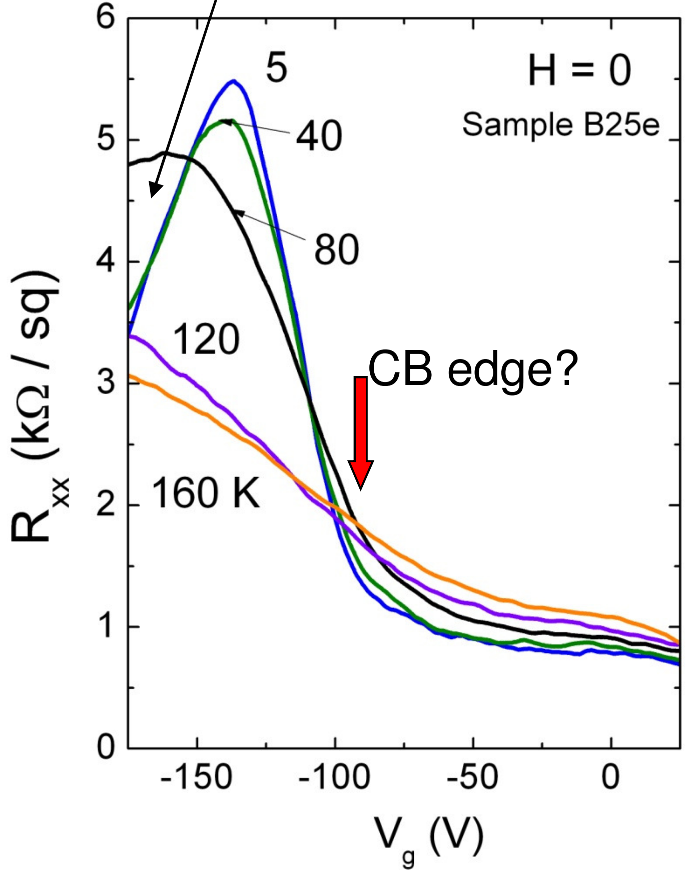
Checkelsky et al. unpub

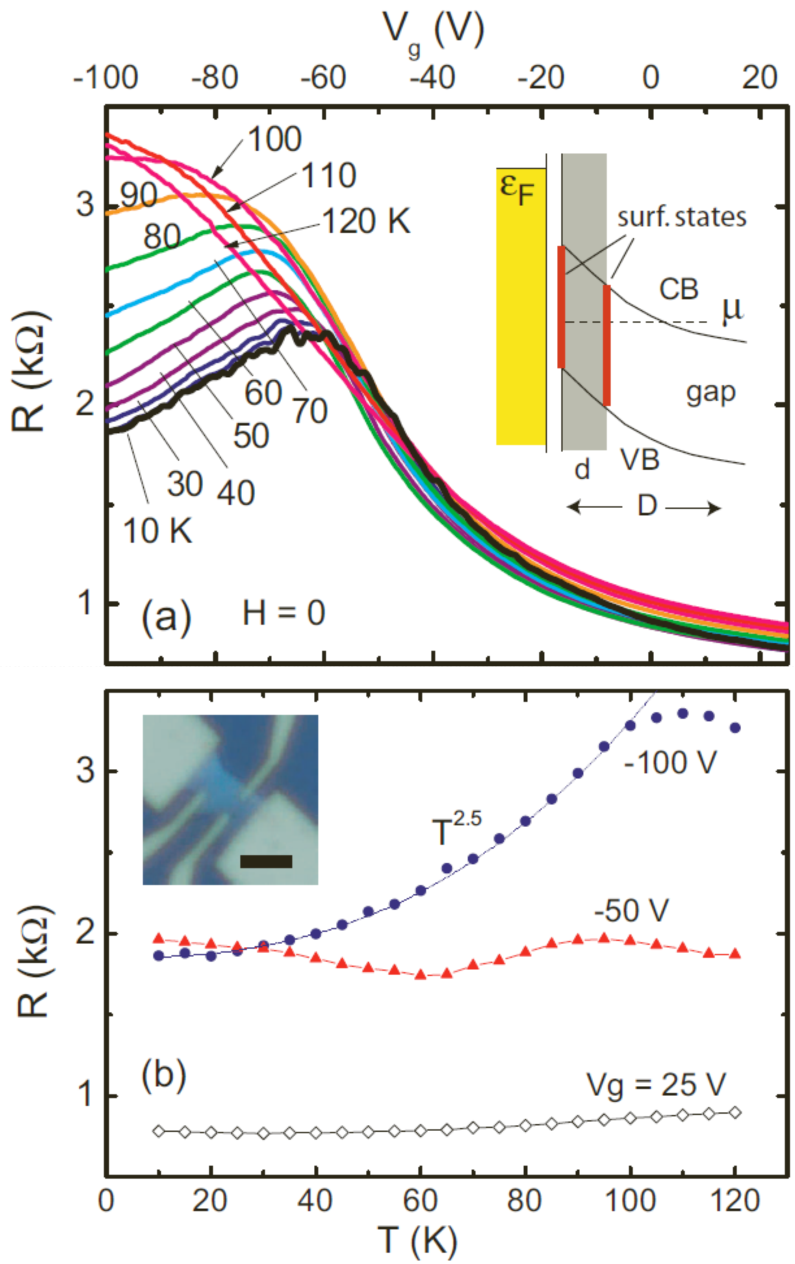



Hall changes sign!

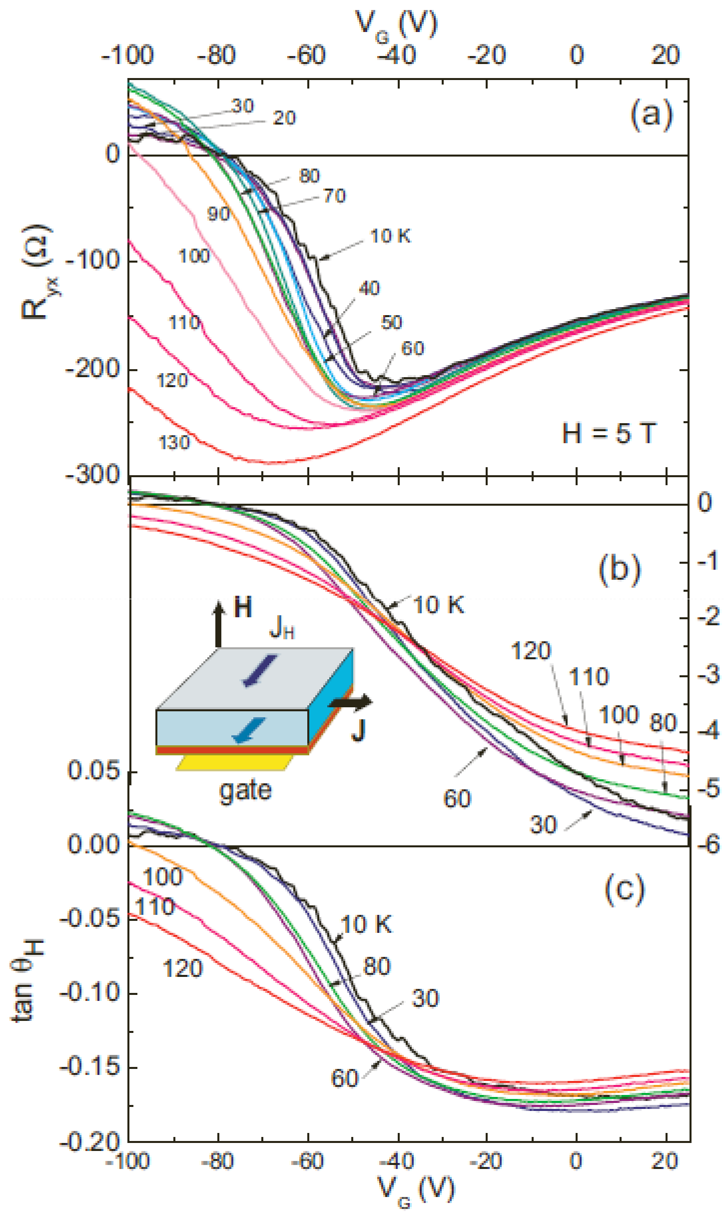



Metallic surface state

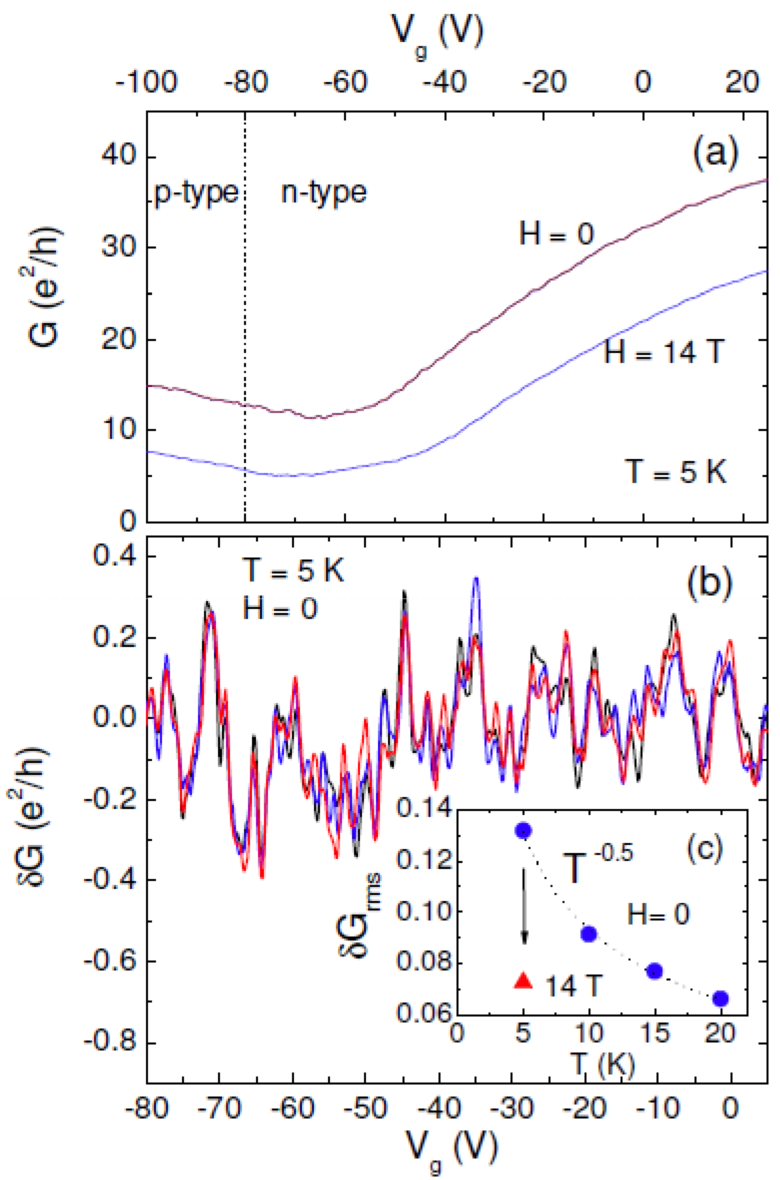




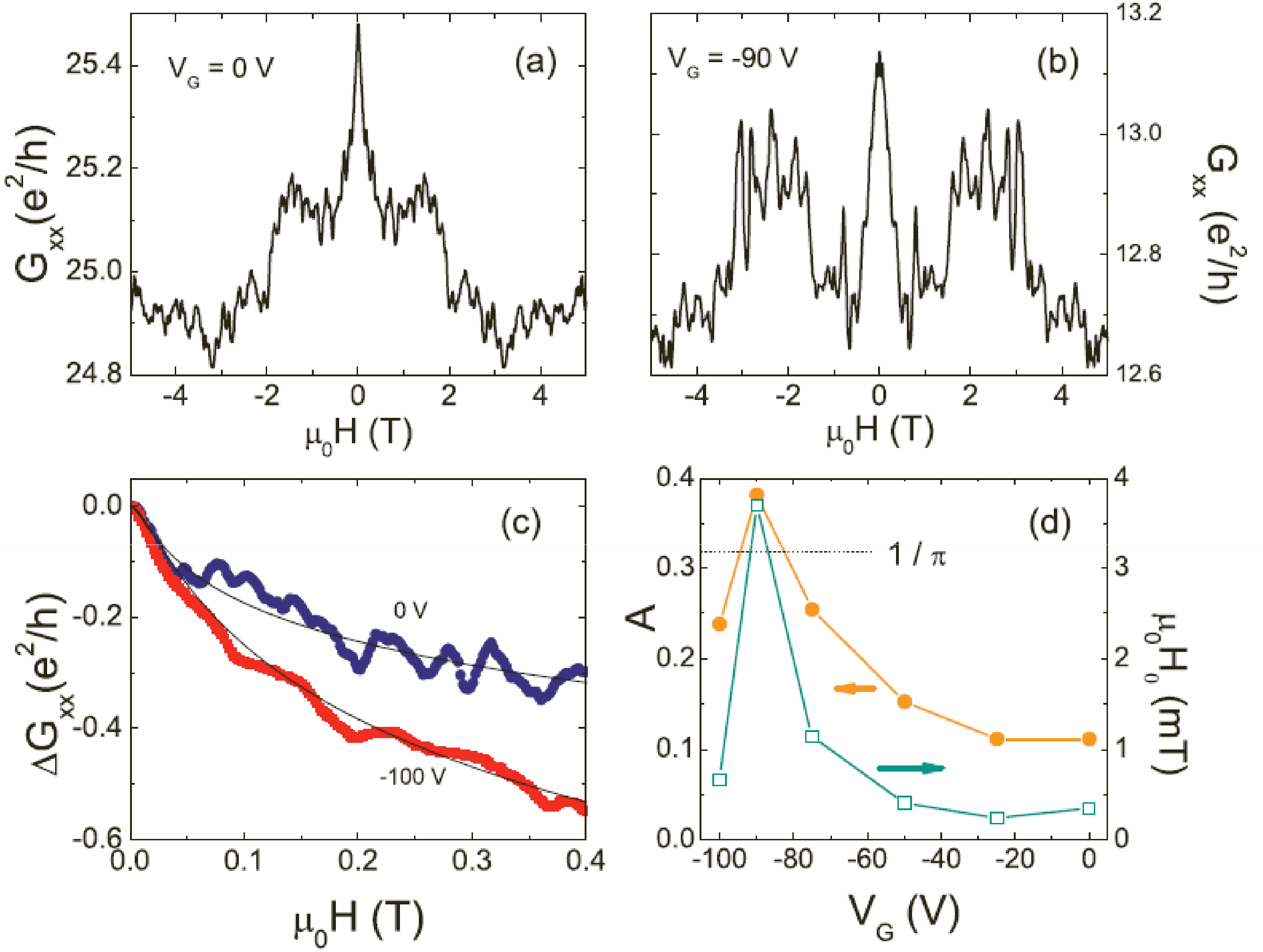
V_g (V)
-100
-80
-60
-40
-20
0
20
R (kΩ)
1
2
3
100
110
120 K
90
80
60
70
50
30
40
10 K
(a)
H = 0
ε_F
surf. states
CB
μ
gap
VB
d
D
R (kΩ)
1
2
3
-100 V
T^2.5
-50 V
(b)
Vg = 25 V
0
20
40
60
80
100
120
T (K)



V_G (V)
-100 -80 -60 -40 -20 0 20
(a)
R_yx (Ω)
0
-100
-200
-300
30
20
80
70
90
10 K
100
40
50
110
60
120
130
H = 5 T
(b)
G_xy (e²/h)
0 -1 -2 -3 -4 -5 -6
10 K
120
110
100
80
60
30
H
J_H
J
gate
(c)
tan θ_H
0.05
0.00
-0.05
-0.10
-0.15
-0.20
100
110
120
10 K
80
30
60
-100 -80 -60 -40 -20 0 20
V_G (V)



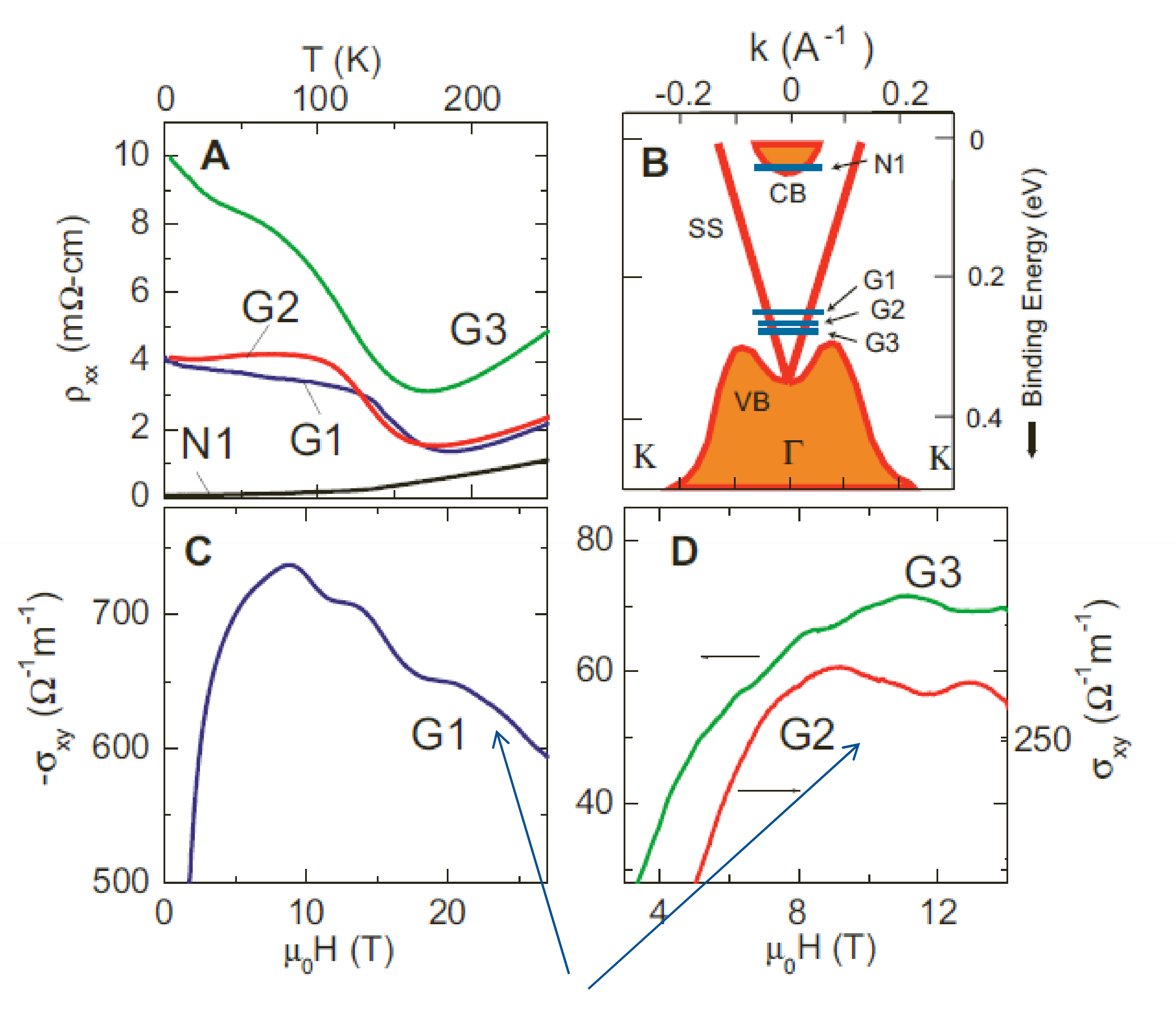
V_g (V)
-100
-80
-60
-40
-20
0
20
(a)
p-type
n-type
H = 0
H = 14 T
T = 5 K
G (e^2/h)
T = 5 K
H = 0
(b)
δG (e^2/h)
T^-0.5
(c)
H= 0
14 T
δG_rms
T (K)
V_g (V)



(a)
V_G = 0 V
G_xx (e^2/h)
μ_0H (T)
(b)
V_G = -90 V
G_xx (e^2/h)
μ_0H (T)
(c)
0 V
-100 V
ΔG_xx (e^2/h)
μ_0H (T)
(d)
1 / π
A
μ_0H_0 (mT)
V_G (V)

Measurement of surface mobility, $k_F\ell$, velocity in bulk crystals of $Bi_2Te_3$

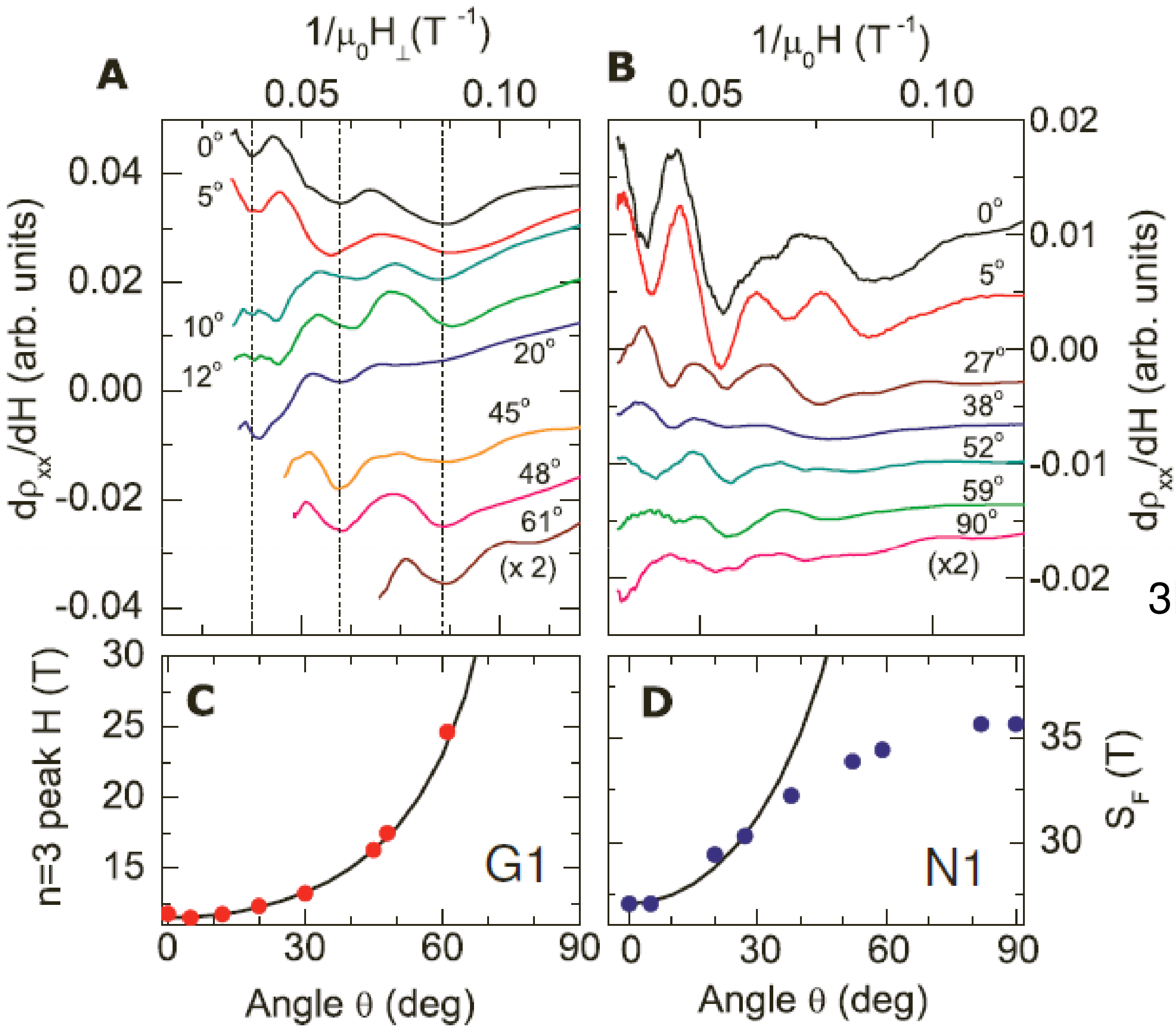
# Mobility of surface state in bulk, non-metallic $Bi_2Te_3$




Quantum oscill.
in Hall conductivity

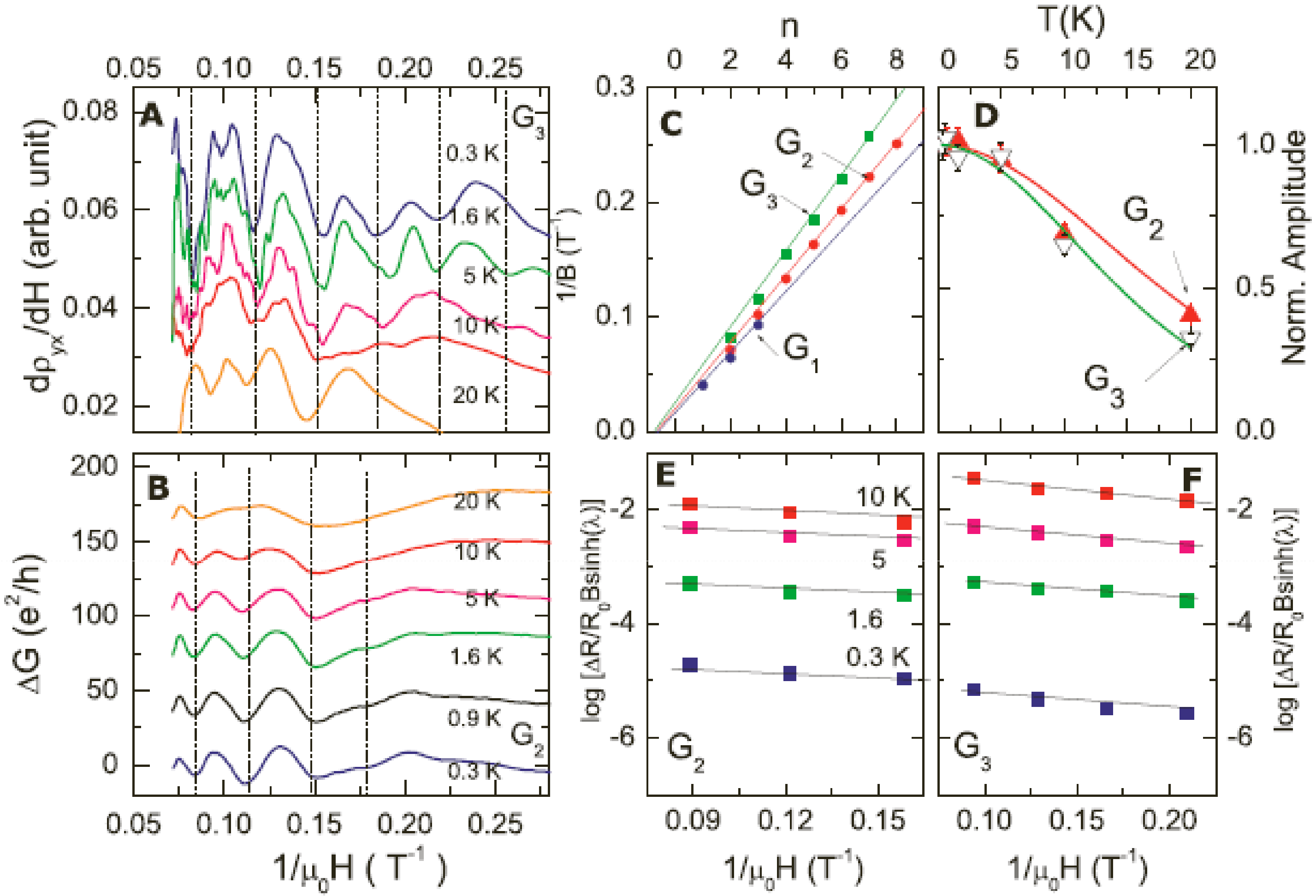
# 2D vs 3D Shubnikov de Haas period in bulk $Bi_2Te_3$

2D SdH




3D SdH

# Analysis of T and H dependences of SdH amplitude

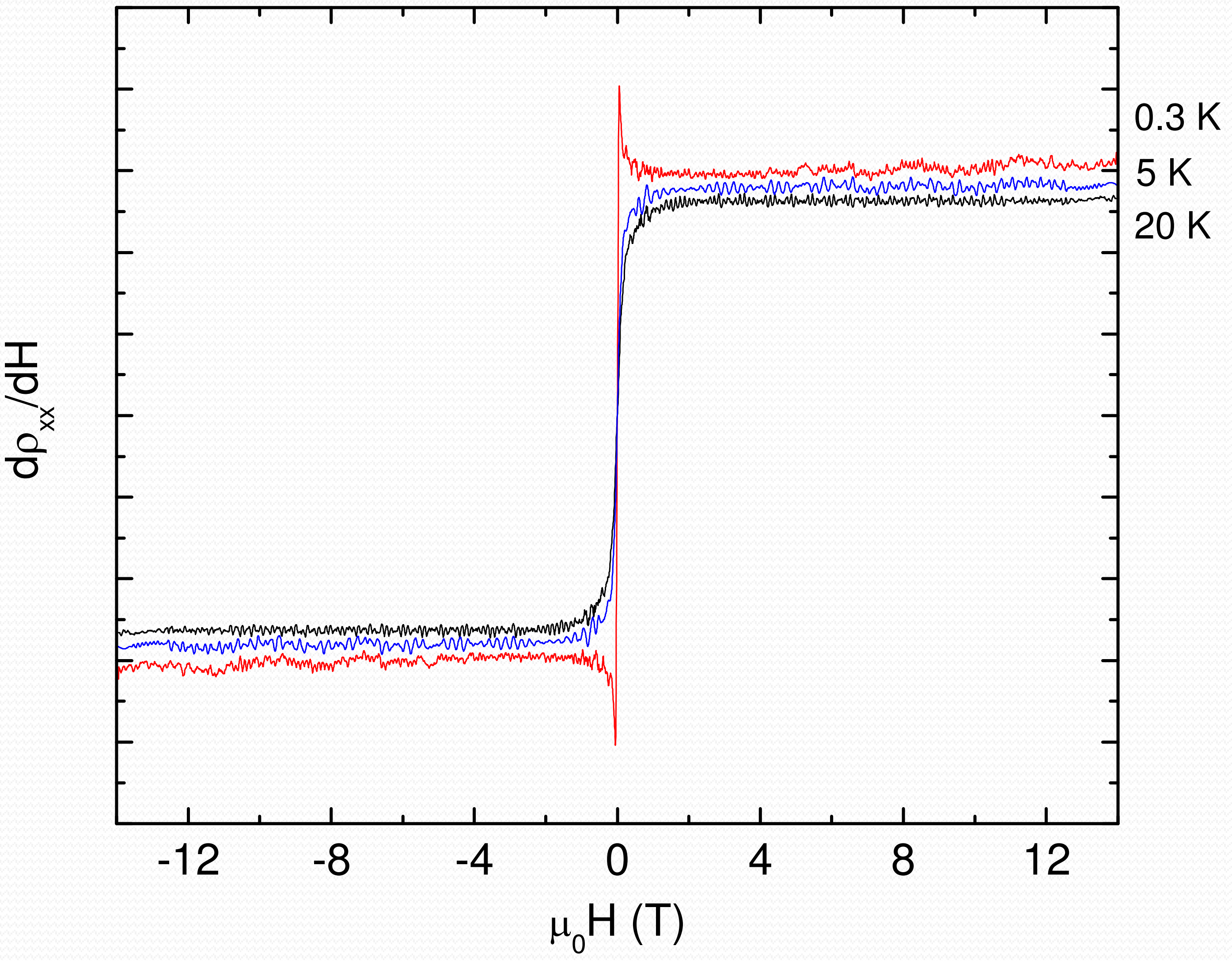



SdH period → $k_F$ = 0.035 Å$^{-1}$

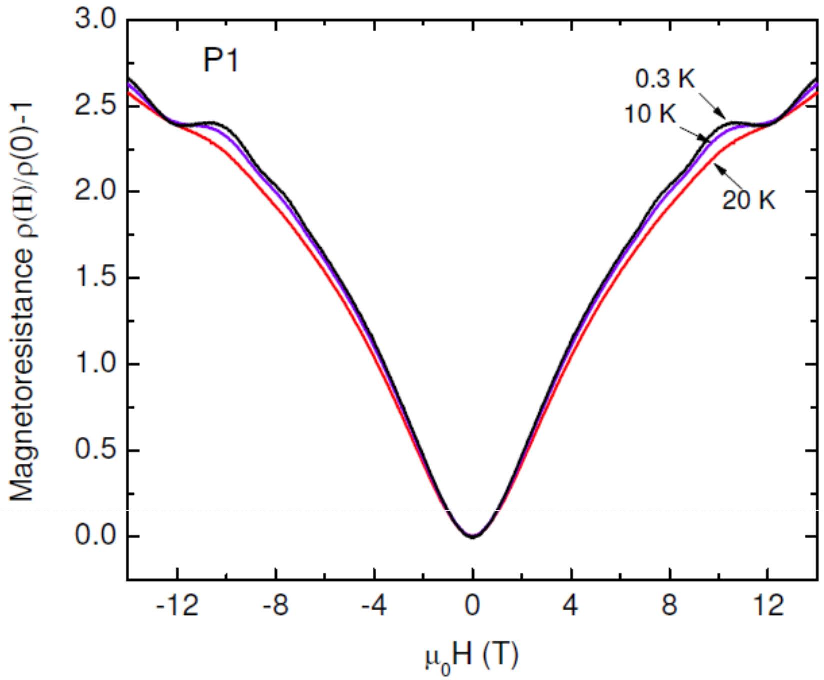
*T* dependence of amplitude → $v_F$ = 4 x 10$^5$ m/s

*H* dependence of amplitude → mfp ℓ = 2,000 Å, $k_F\ell$ = 70

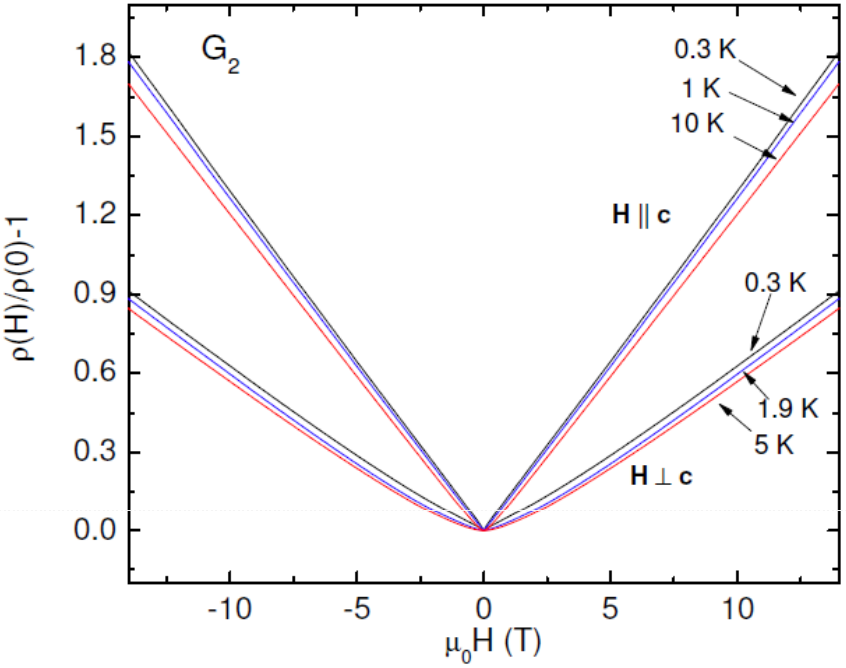
Samle Q0



## Metallic p-type Bi2Te3




## Non-metallic Bi2Te3



# Summary

Transport evidence for surface state in Bi2Se3 and Bi2Te3

1. Cleaved xtals of Bi2Se3 can be gated to reveal surface conduction
2. In bulk xtals of Bi2Te3, detected surface SdH oscillations
3. FS Caliper and velocity consistent with ARPES results
4. First measurement of surface mobility $\mu$ = 10,000 $cm^2/Vs$.
5. Bulk states display anomalous, non-analytic H-linear MR