Transport Properties of 3D Topological Insulators and a Candidate for Magnetic Weyl Semimetals

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http://nano.iphy.ac.cn/N08

ICAM Summer School, Beijing, July 21, 2015

Part I: Localization phenomena in three-dimensional topological insulators

I. Introduction to localization
II. Gate voltage tuning of chemical potential in TI
III. Weak antilocalization in TI (perpendicular fields)
IV. Weak antilocalization in TI (parallel fields)
V. Electron-electron interaction effects
VI. Crossover from 3D to 2D & observation of Anderson localization
VII. Summary and outlook

J. Chen et al., **PRL** 105,176602 (2010); **PRB** 83, 241304 (R) (2011);
C. J. Lin et al., **PRB** 88, 041307 (R) (2013); J. Liao et al., **PRL** 114, 216601 (2015).

Collaborators

- Jun Chen, Tong Guan, Jian Liao, Chaojing Lin, Wenmin Yang
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  Surface Physics Lab, *IOP-CAS*
- Yunbo Ou, Xiao Feng, **Ke He**, Xucun Ma, **Qi-Kun Xue**
  Tsinghua University

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  Alexander Mirlin, *University of Karlsruhe*
  Xi Dai & Zhong Fang, *IOP-CAS*
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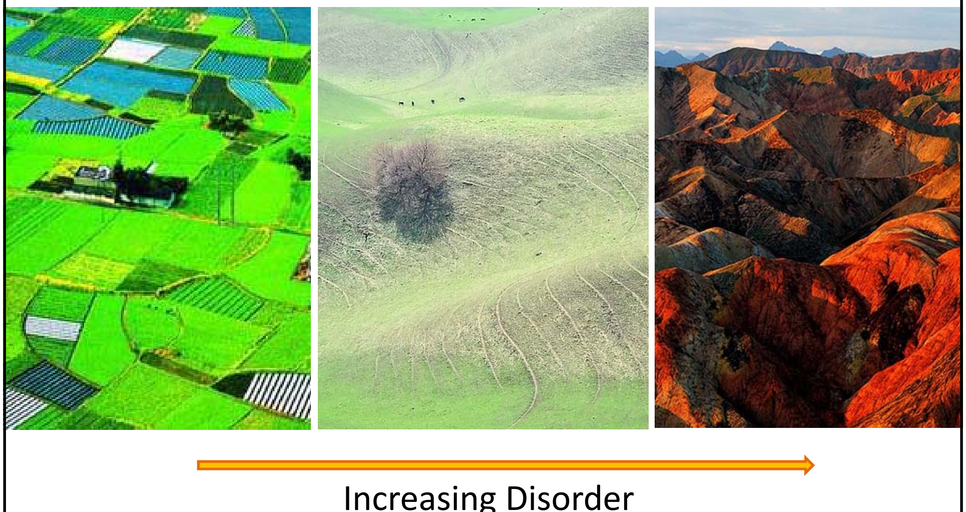
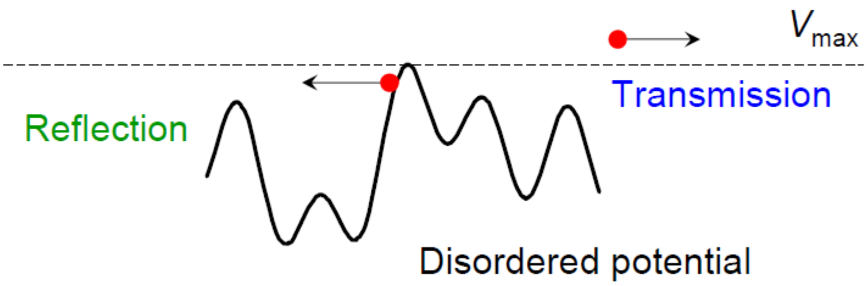
  Li Lv et al., *IOP-CAS*
  Jurgen Smet & **K. von Klitzing**, *MPI-Stuttgart*

I. Introduction to localization



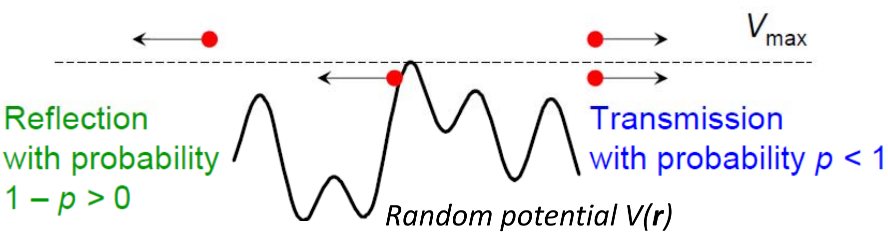
Increasing Disorder

Transport of a Classical Particle

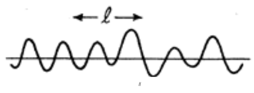


No prorogation occurs when particle's kinetic energy E_k is lower than V_{max}

Quantum Particles ~ Waves

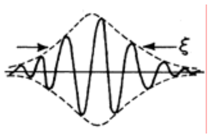


Diffusion ⇔ ***extended*** **waves**



vs.

Absence of transport ⇔ ***localized*** **waves**

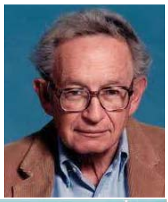


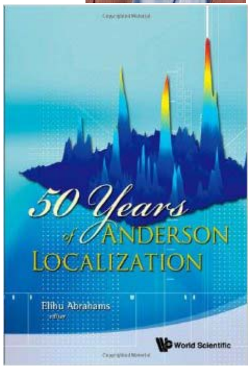
Anderson Localization

PHYSICAL REVIEW VOLUME 109, NUMBER 5 MARCH 1, 1958

Absence of Diffusion in Certain Random Lattices

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received October 10, 1957)



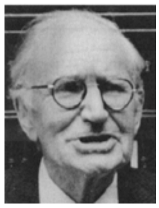


1) light, microwave, acoustic wave …
Classical waves

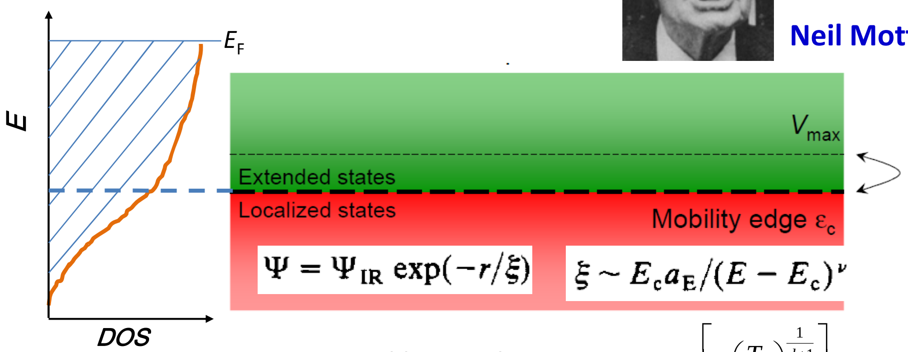
2) Electrons, spin wave, cold atoms …
Quantum waves

Complicated by interactions

Mobility Edge



Neil Mott



Variable range hopping: $\sigma \propto \exp\left[-\left(\frac{T_0}{T}\right)^{\frac{1}{d+1}}\right]$ *d*=2,3

N. F. Mott, *Adv. Phys.* ***16*** *,49 (1967)*
N. F. Mott & E. A. Davis, *Electronic Processes in Non-Crystalline Materials* (1979, Oxford)

1977 Nobel Prize

Philip W. Anderson

Nevill F. Mott

John H. Van Vleck

Official press release: **…. for their fundamental theoretical investigations of the electronic structure of magnetic and disordered systems.**

Scaling Theory of electron localization

VOLUME 42, NUMBER 10 PHYSICAL REVIEW LETTERS 5 MARCH 1979

Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions

E. Abrahams
Serin Physics Laboratory, Rutgers University, Piscataway, New Jersey 08854

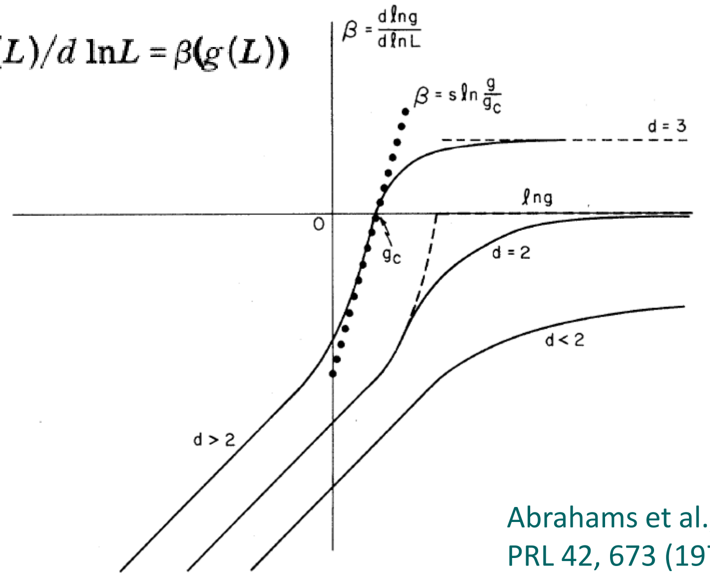
and

P. W. Anderson,[a] D. C. Licciardello, and T. V. Ramakrishnan[b]
Joseph Henry Laboratories of Physics, Princeton University, Princeton, New Jersey 08540
(Received 7 December 1978)

Arguments are presented that the $T=0$ conductance G of a disordered electronic system depends on its length scale L in a universal manner. Asymptotic forms are obtained for the scaling function $\beta(G)=d\ln G/d\ln L$, valid for both $G \ll G_c \simeq e^2/\hbar$ and $G \gg G_c$. In three dimensions, G_c is an unstable fixed point. In two dimensions, there is no true metallic behavior; the conductance crosses over smoothly from logarithmic or slower to exponential decrease with L.

Scaling Theory: No true metallic states in 2D

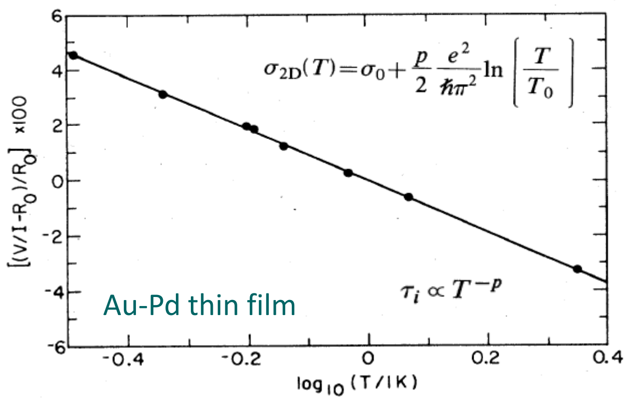
$$d \ln g(L)/d \ln L = \beta(g(L))$$



Abrahams et al.,
PRL 42, 673 (1979)

Weak Localization in 2D

$$(d \ln g / d \ln L) = -a/g \Rightarrow g(L) = g_0 - \frac{e^2}{\hbar\pi^2} \ln\left|\frac{L}{l}\right|$$

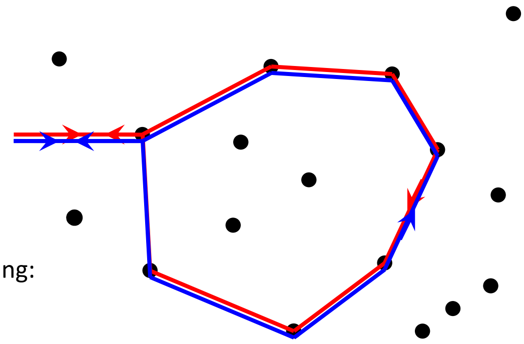


Dolan & Osheroff, PRL (1979)

Weak Localization: a precursor to Anderson Localization

At low T,

$l_\phi >> l_e$



Without spin-orbit coupling:

$$\varphi_{\mathrm{CW}} = \varphi_{\mathrm{CCW}}$$

Quantum backscattering probability: $|A_{\mathrm{CW}} + A_{\mathrm{CCW}}|^2 = 4A_0^2$

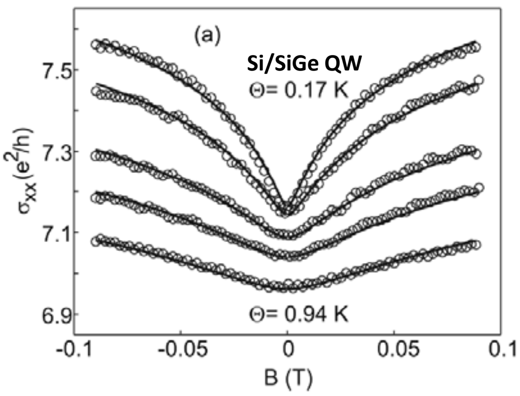
Classical backscattering probability: $A_{\mathrm{CW}}{}^2 + A_{\mathrm{CCW}}{}^2 = 2A_0^2$

Consequence of Weak Localization

Temperature dependence: $\Delta\sigma^{WL} \sim \ln T$

Magnetic field dependence:

$$\Delta\sigma^{WL}(B) = \frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_\varphi}{B}\right)-\psi\left(\frac{1}{2}+\frac{B_e}{B}\right)+\ln\left(\frac{B_e}{B_\varphi}\right)\right]$$

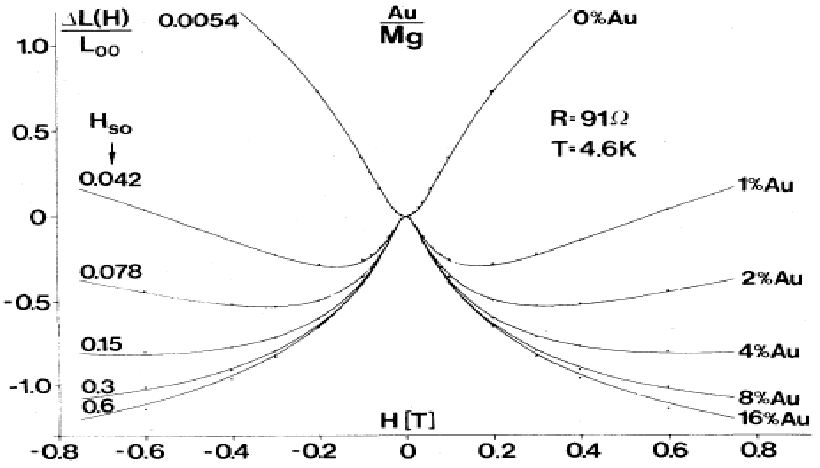


B. L. Altshuler et al., PRB 22, 5142(1980)

T. Heizel, *Mesoscopic Electronics in Solid State Nanostructures*, p229 (Wiley VCH, 2007)

Spin-Orbit Coupling:

Crossover from **weak localization** to **weak antilocalization**



G. Bergman,
PRL **48**, 1046 (1982)

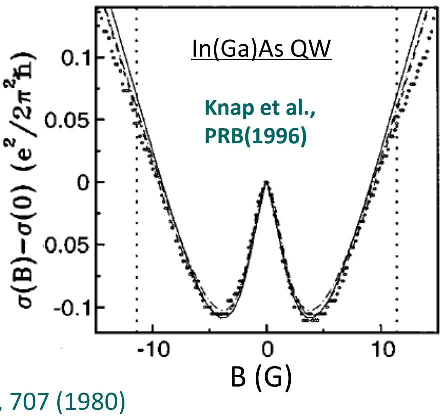
Hikami-Larkin-Nagaoka theory

$$\Delta\sigma(B) = -\frac{e^2}{\pi h}\left[\Psi\left(\frac{1}{2}+\frac{B_e}{B}\right)-\frac{3}{2}\Psi\left(\frac{1}{2}+\frac{B_i+4/3B_{SO}}{B}\right)+\frac{1}{2}\Psi\left(\frac{1}{2}+\frac{B_i}{B}\right)\right]$$

B_e: elastic scattering
B_i: inelastic scattering
B_{so}: spin-orbital coupling

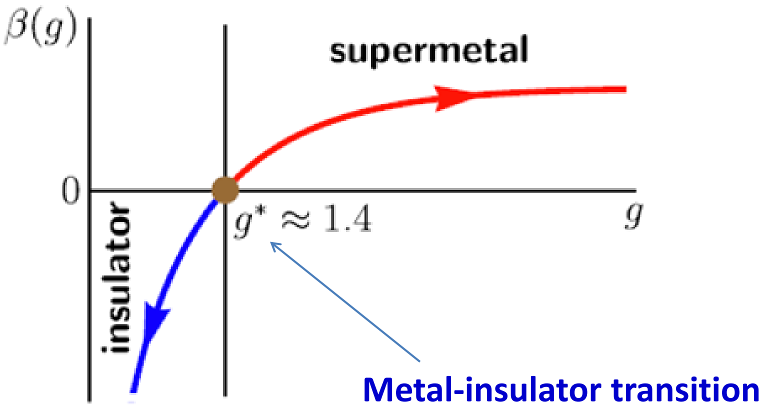
$$B_\beta = \frac{\hbar}{4De\tau_\beta}$$

D: diffusion constant
τ: scattering time



Hikami et al., Prog. Theor. Phys. **63**, 707 (1980)
Bergmann, Phys. Rep. **107**, 1 (1984)

Non-interacting 2D electron system with SOC



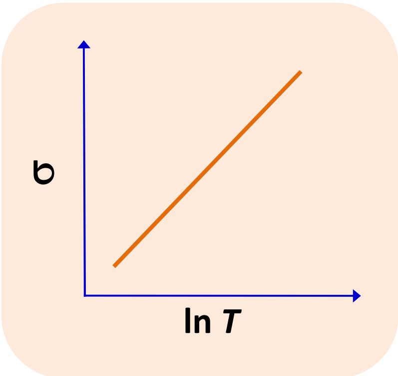
VOLUME 44, NUMBER 19 PHYSICAL REVIEW LETTERS 12 MAY 1980

Interaction Effects in Disordered Fermi Systems in Two Dimensions

B. L. Altshuler and A. G. Aronov
Leningrad Nuclear Physics Institute, Gatchina, Leningrad 188 350, U.S.S.R.

and

P. A. Lee
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 11 February 1980)

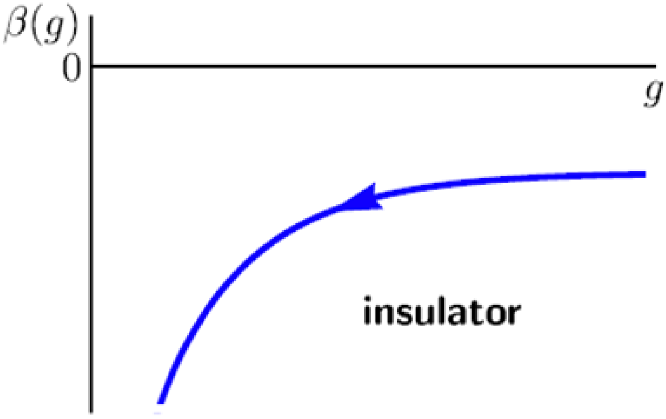


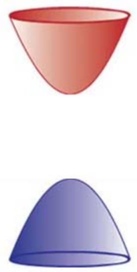
e-e interaction effects:

$$\delta\sigma = \frac{e^2}{\hbar}\frac{1}{4\pi^2}\left(2 - \tfrac{3}{2}\tilde{F}_\sigma\right)\ln(T\tau)$$

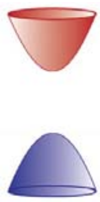
Review: Lee & Ramakrishnan,
Rev. Mod. Phys. **57**, 287 (1985)

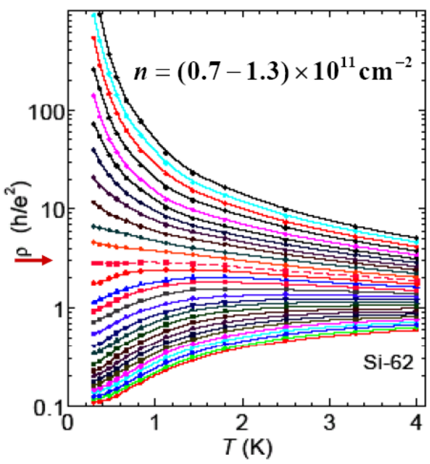
Interacting 2D electron system with *SOC*





Strongly interacting 2D electron systems





Low disorder

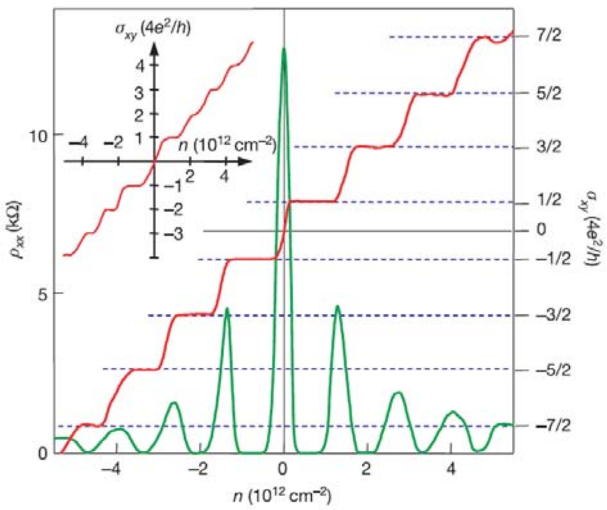
Low density $\Rightarrow r_s >> 1$

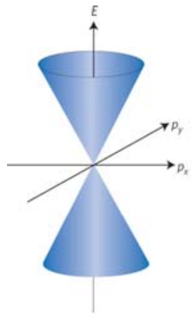
$$r_s \equiv 1/\sqrt{\pi n (a_B)^2}$$

Metal-insulator transition

Kravchenko et al. Phys. Rev. B **50**, 8039 (1994)
Spivak et al., Rev. Mod. Phys. **82**, 1743 (2010)

2D Dirac electron systems





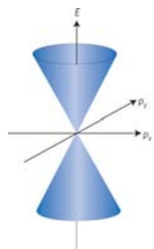
π Berry's phase

Also leading to
weak antilocalization
(WAL)

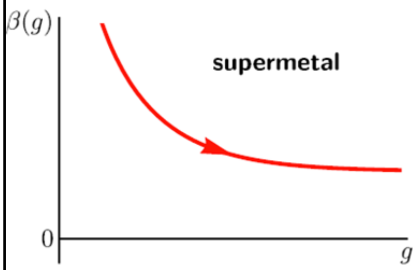
T. Ando et al.,
J. Phys. Soc. Jpn.
67, 2857 (1998)

Novoselov & Geim et al., Nature **438**, 197 (2005)
Also reported by Y. B. Zhang et al., Nature **438**, 201 (2005)

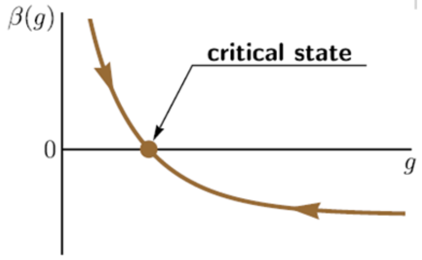
Scaling behavior in 2D Dirac Fermion Systems



Non-interacting



Interacting

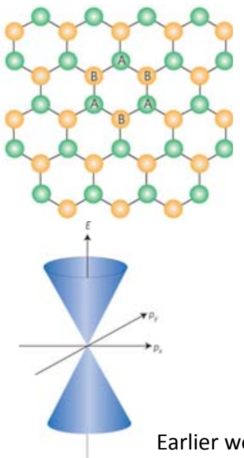


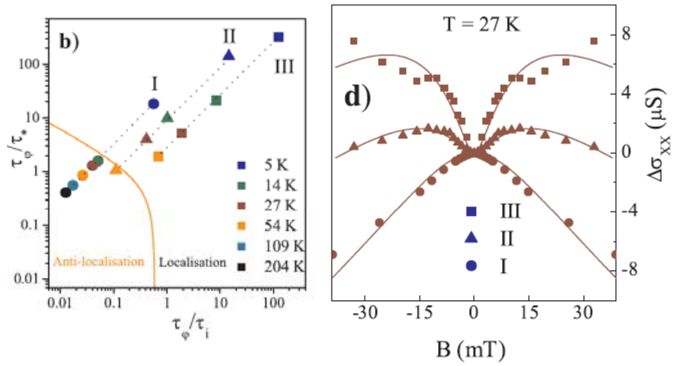
Ostrovsky,Gornyi & Mirlin, PRL **105**, 036803 (2010)
See also: Ostrovsky et al, PRL (2007); Ryu et al., PRL (2007);
Fu & Kane, PRL (2012); Konig et al., PRB (2012).

PRL 103, 226801 (2009) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2009

Transition between Electron Localization and Antilocalization in Graphene

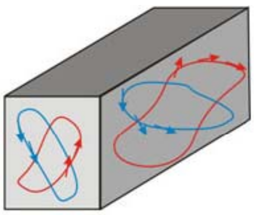
F. V. Tikhonenko, A. A. Kozikov, A. K. Savchenko, and R. V. Gorbachev
School of Physics, University of Exeter, EX4 4QL Exeter, United Kingdom
(Received 16 July 2009; published 23 November 2009)





Earlier work: **only weak localization**, e.g. **X. S. Wu et al., PRL 98, 136801 (2007)**

3D Topological Insulators

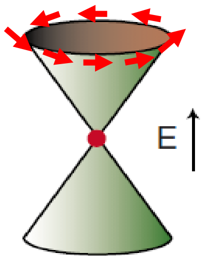


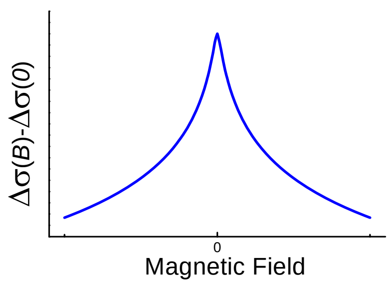
Spin-momentum locking ⇒
Berry's phase π

⬇

Weak antilocalization (WAL)

T. Ando et al, J. Phys. Soc. Jpn. **67**,2857 (1998);
Suzuura & Ando,PRL **89**, 266603 (2002)

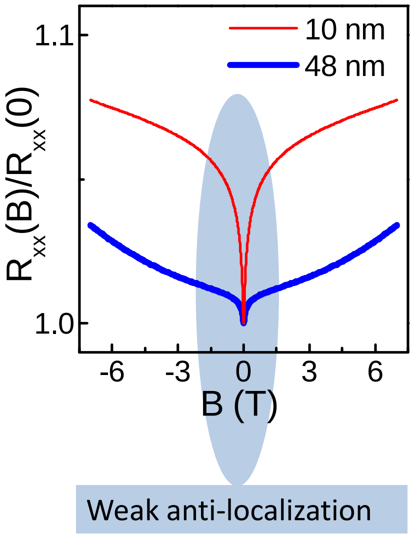


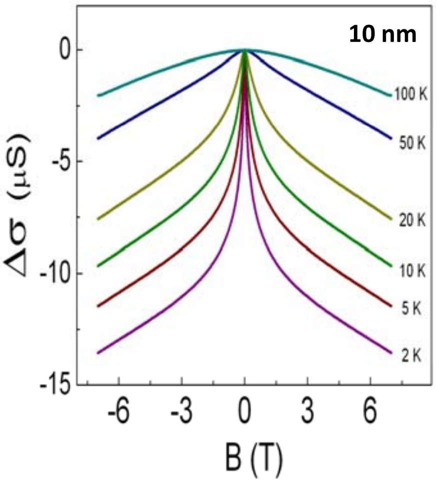


Bi_2Se_3, Bi_2Te_3, ….. Single Dirac cone

Hasan & Kane, Rev. Mod. Phys. (2010); Qi & Zhang, Rev. Mod. Phys. (2011)

Weak antilocalization in Bi_2Se_3 thin films





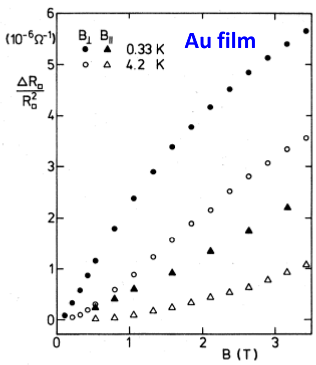
Magnetoconductivity due to Weak Anti-localization

$$\Delta\sigma(B) \simeq -\alpha \cdot \frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right)-\ln\left(\frac{B_\phi}{B}\right)\right]$$

α=1/2 for

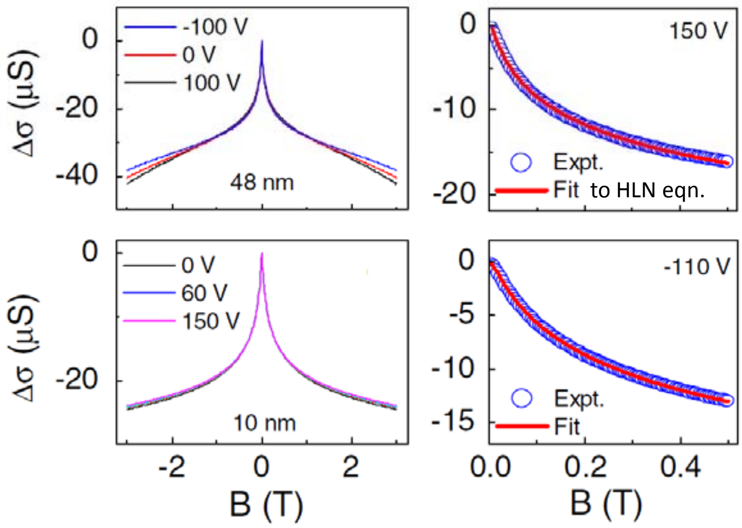
- **One surface of TI**
- **Traditional 2D systems with strong SOC**

  e.g. Au thin films, …



Hoffmann, PRB (1982)

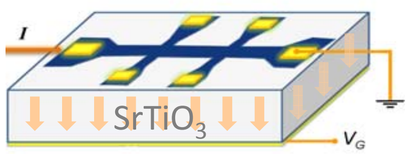
Magnetoconductivity in Bi_2Se_3 thin films

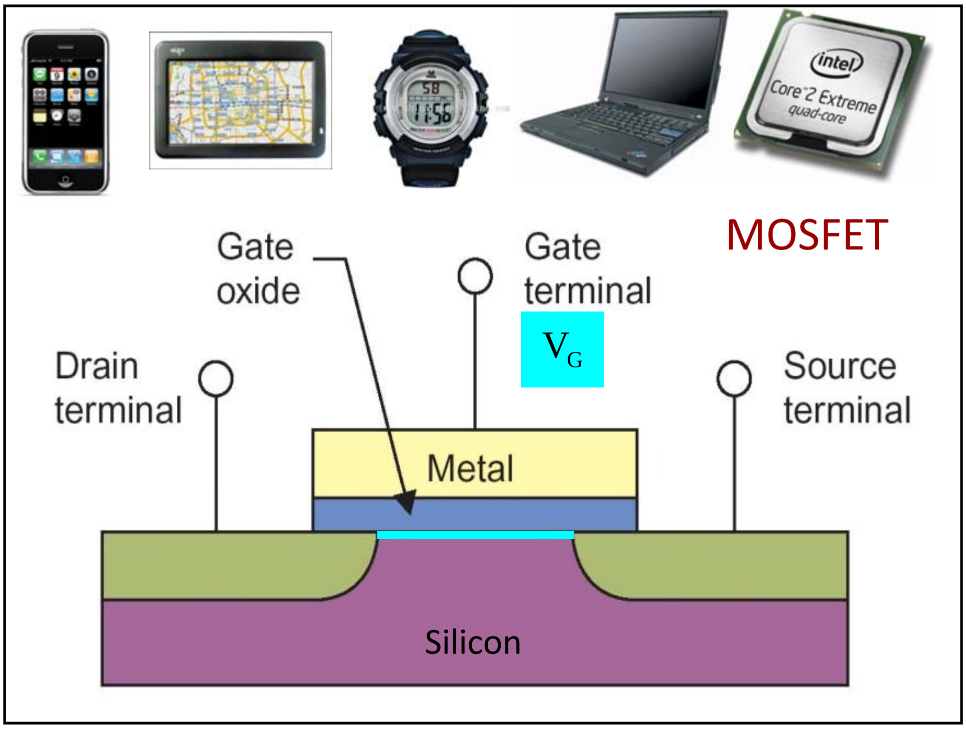


Bi_2Se_3 thin films (>4 nm), α~1/2

J. Chen et al.,
PRL **105**,176602 (2010)

II. Gate voltage control of chemical potential



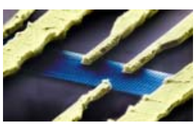


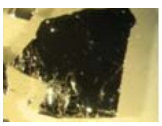
Field effect tuning of chemical potential

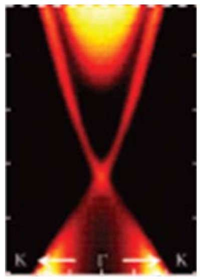
Gate voltage tuning of chemcial potential

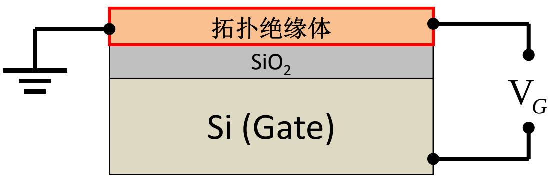
- Si, InAs, Graphene： ~ 10^{12} cm^{-2}
- GaAs： ~10^{11} cm^{-2}

Challenge: $\Delta n_s > 2\times 10^{13}$ cm^{-2}



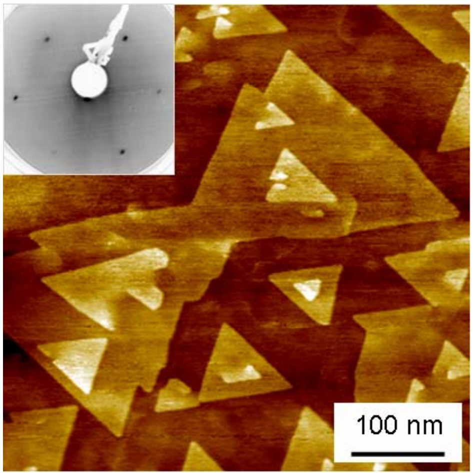


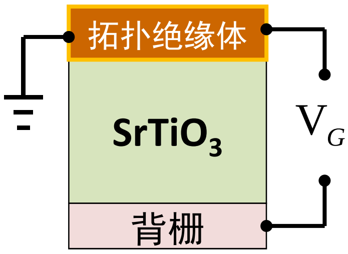


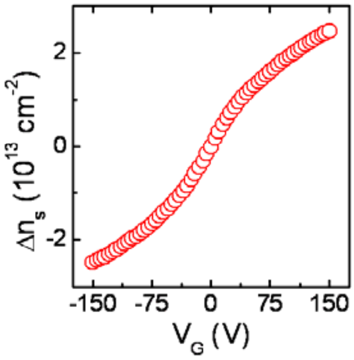


SiO_2: $\Delta n_s < 1\times 10^{13}$ cm^{-2}， and not suitable for epitaxial growth

Bi_2Se_3 single crystalline films grown on $SrTiO_3$ (111)

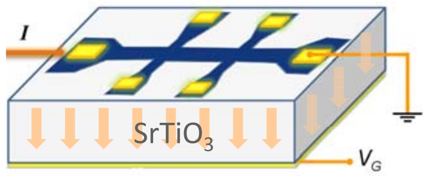


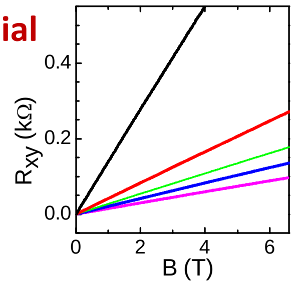


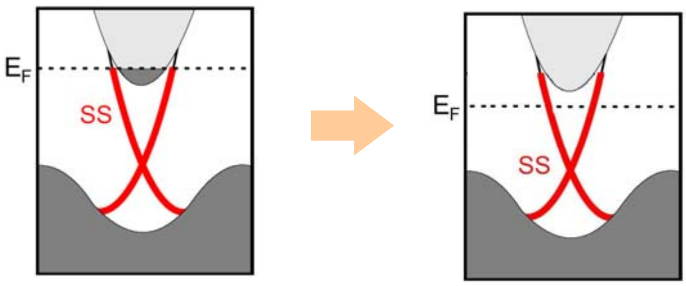


J. Chen et al., PRL 105, 176602 (2010)

Field effect tuning of chemical potential

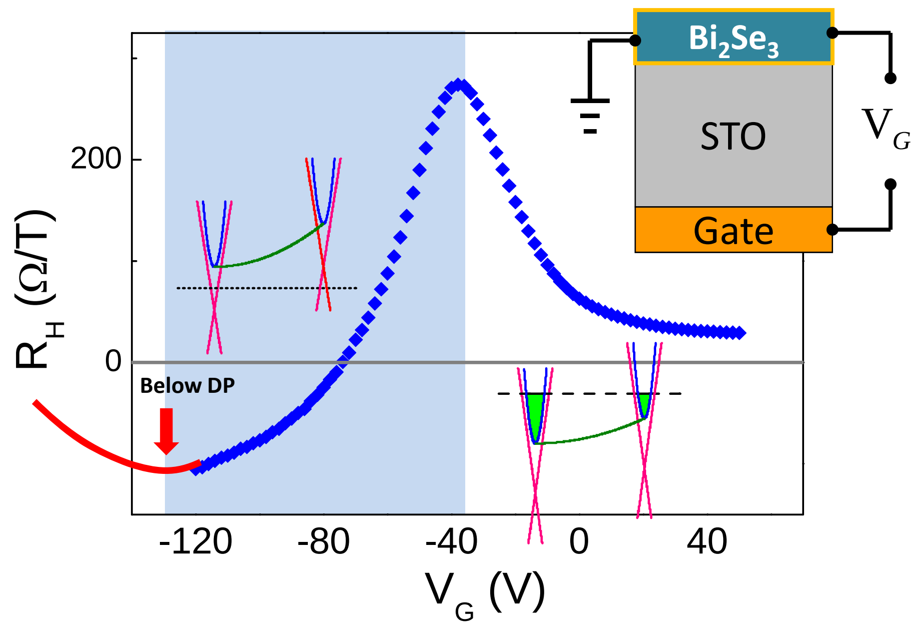






J. Chen et al., PRL 105, 176602 (2010)

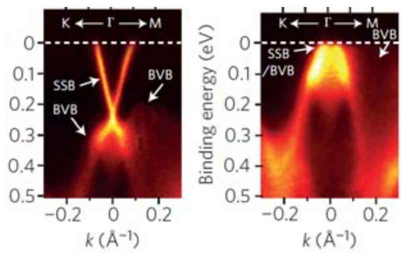
Ambipolar transport obtained by gating



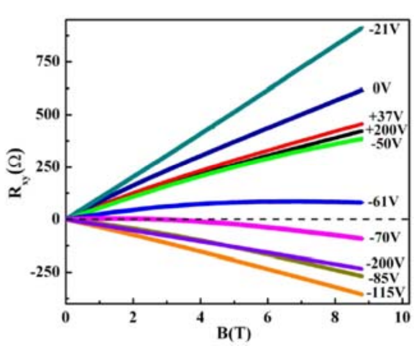
$(Bi_{1-x}Sb_x)_2Te_3$ thin films

Wang/Xue groups , Nat. Commun. (2011)
Y. Cui group, Nat. Nano. (2011)

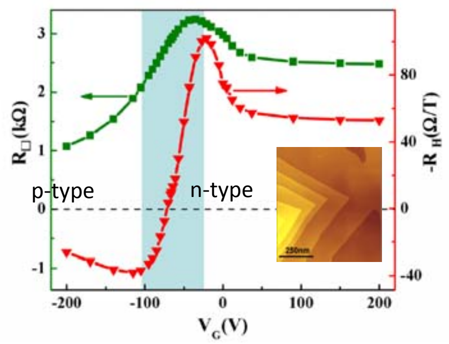
Bi_2Te_3, n-type; **Sb_2Te_3**, p-type



⇒ Full-range tuning of chemical potential by a back-gate:



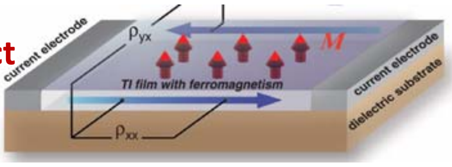
$(Bi,Sb)_2Te_3$ film on $SrTiO_3$

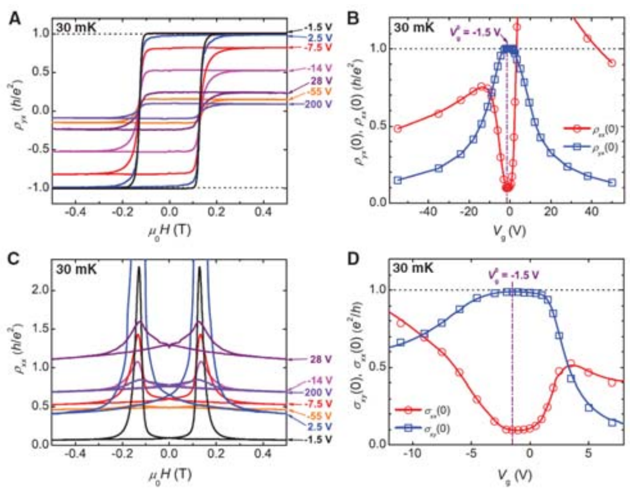


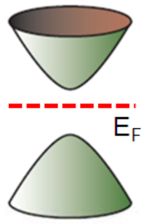
X. Y. He et al., APL **101**, 123111 (2012)

Quantum anomalous Hall effect

Cr doped $(Bi,Sb)_2Te_3$ thin films



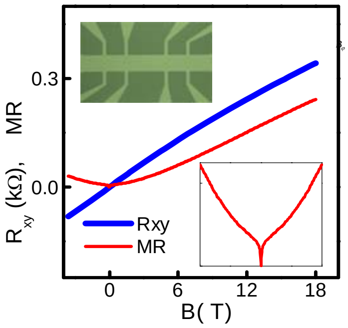


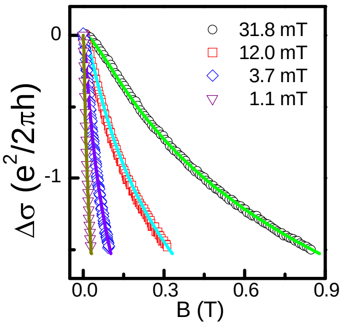


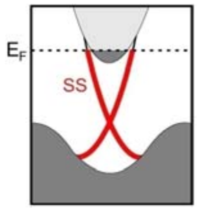
C. Z. Chang *et al.*, **Science (2013)**
Tsinghua/IOP

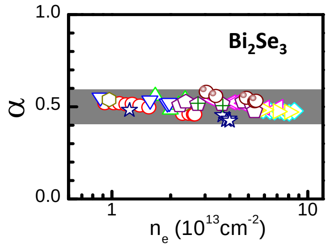
III. Probe surface transport with weak antilocalization effect

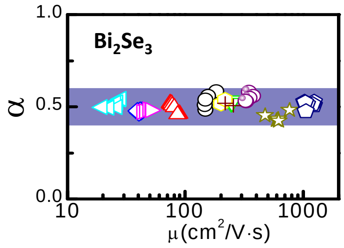
Samples with High Electron-densities: $0.8-8.6\times10^{13}\ \mathrm{cm}^{-2}$









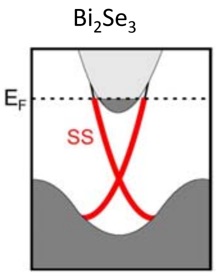


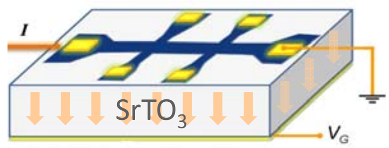
$$\alpha \approx \frac{1}{2}$$

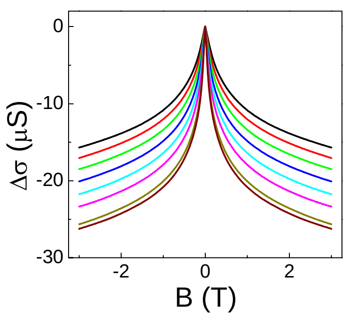
J. Chen et al., PRB (2011)

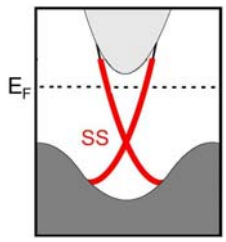
$$\Delta\sigma(B) \simeq -\alpha \cdot \frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right) - \ln\left(\frac{B_\phi}{B}\right)\right]$$

Gate-voltage Tuning of Chemical Potential



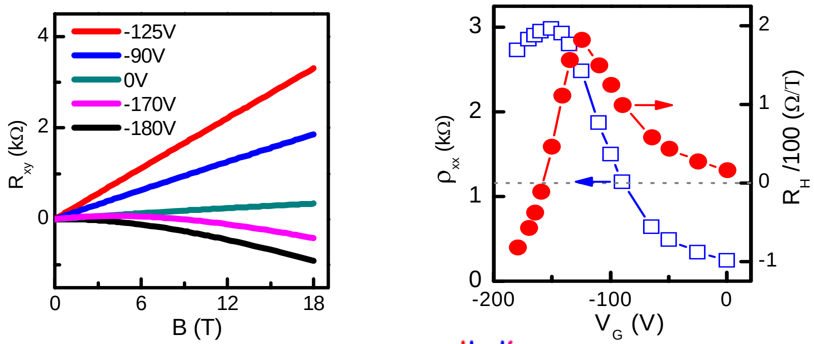


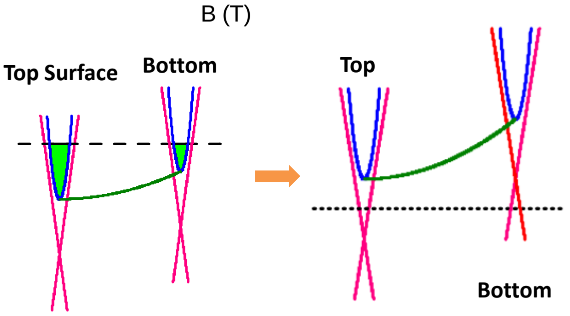




J. Chen et al.,
PRL 105, 176602 (2010);
PRB 83, 241304(R) (2011)

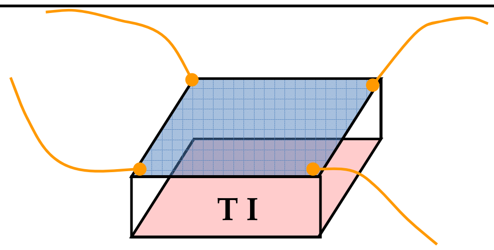
Example of gate-voltage tuning: 10 nm thick Bi_2Se_3 thin film





Ambipolar regime

electrons
Depleted bulk
holes

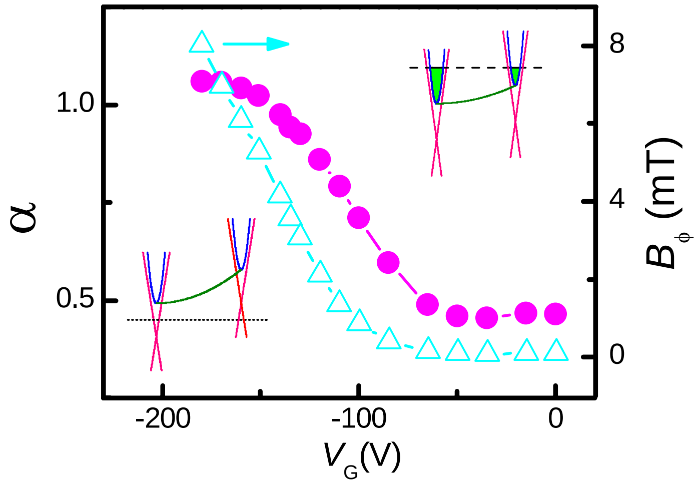


$$\Delta\sigma(B) = \sum_{i=1}^{2} -\frac{e^2}{2\pi h}\left[\psi\left(\frac{1}{2}+\frac{B_{\phi,i}}{B}\right)-\ln\left(\frac{B_{\phi,i}}{B}\right)\right]$$

If $B_{\phi,1} = B_{\phi,2}$ and the bulk is insulating,

$$\Delta\sigma(B) = -\alpha\frac{e^2}{\pi h}\left[\psi\left(\frac{1}{2}+\frac{B_{\phi}}{B}\right)-\ln\left(\frac{B_{\phi}}{B}\right)\right], \alpha = 1$$

Tuning toward decoupled surface-dominating transport

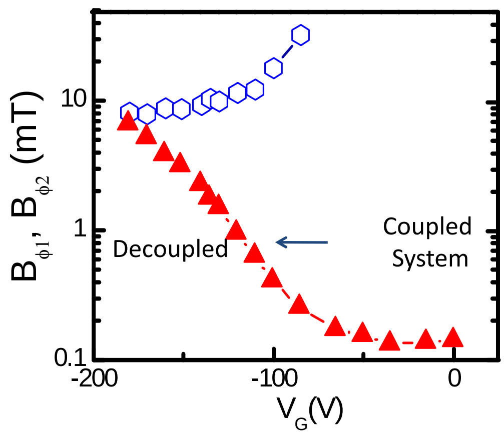


$$\Delta\sigma(B) \simeq -\alpha \cdot \frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right) - \ln\left(\frac{B_\phi}{B}\right)\right]$$

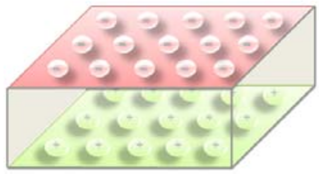
Hikami-Larkin-Nagaoka equation (1981)

Fit with two-component HLN equation:

$$\Delta\sigma(B) = \sum_{i=1}^{2}\frac{e^2}{2\pi h}\left[\psi\left(\frac{1}{2}+\frac{B_{\phi,i}}{B}\right) - \ln\left(\frac{B_{\phi,i}}{B}\right)\right]$$



Top surface： electrons



Bottom: holes

Theory **e–h pair**

↓

Topological exicton condensation

Quantized vortex: ±e/2 charge

Seradjeh, Moore, Franz, PRL (2009)

Journal Club for Condensed Matter Physics
A Monthly Selection of Interesting Papers by Distinguished Correspondents

Whispers in Bedlam: Detecting the Dirac metal at a surface of a topological insulator by means of weak localization

Electrically tunable surface-to-bulk coherent coupling in topological insulator thin films.
arXiv:1104.1404 (2011)
Authors: H. Steinberg, J.-B. Laloë, V. Fatemi, J. S. Moodera, P. Jarillo-Herrero
and
Tunable surface conductivity in Bi_2Se_3 revealed in diffusive electron transport
Phys. Rev. B **83**, 241304/1-4 (2011)
Authors: J. Chen, X. Y. He, K. H. Wu, Z. Q. Ji, L. Lu, J. R. Shi, J. H. Smet, and Y. Q. Li

Recommended with a Commentary by Leonid Glazman, Yale University

Garate-Glazman Theory

WAL in two coupled channels:

$$\Delta\sigma_\perp = -\frac{e^2}{4\pi^2\hbar}\left[f\left(\frac{B_a}{B}\right) + f\left(\frac{B_b}{B}\right)\right]$$

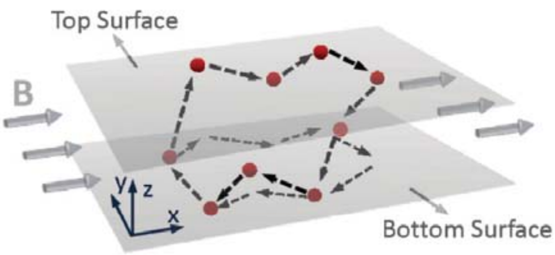
$$B_a = B_\phi, \quad B_b = B_\phi\left(1 + 2\frac{\tau_\phi}{\tau_s}\right)$$

$$f(z) = \Psi(1/2 + z) - \ln(z)$$

Coherent **surface-bulk scattering** $\Rightarrow$ α=1/2

Garate & Glazman, PRB **86**, 035422 (2012)

IV. Manifestation of WAL in parallel magnetic field transport

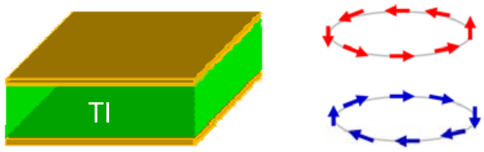


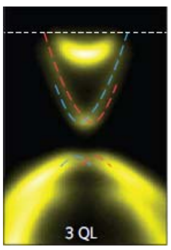
Motivation

Effort on making the bulk of the TI truly insulating: Bi_2Te_2Se, $(Bi, Sb)_2Te_3$, $(Bi,Sb)_2(Se,Te)_3$, ...

resistivity up to several Ω·cm

Ando et al., JPSJ (2010)





Y. Zhang et al., Nature Phys. (2010)

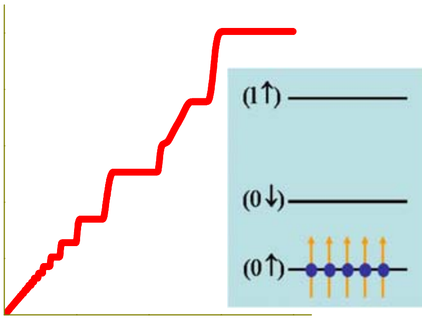
New challenges:

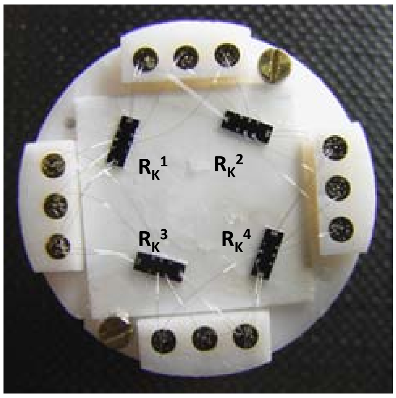
How to detect weak couplings between the top and bottom surfaces or between the surfaces and the bulk?

von Klitzing constant:

$$R_K = \frac{h}{e^2} = 25812.807\,\Omega$$

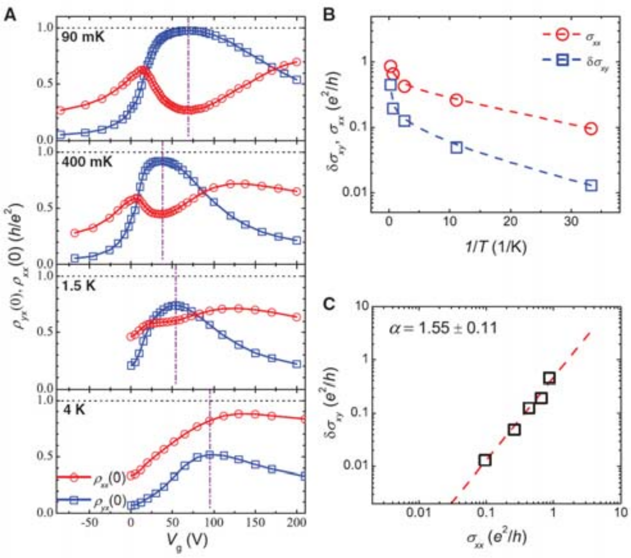
$R_K^{1,2,3,4}$ identical within an accuracy of some parts in 10^{11}

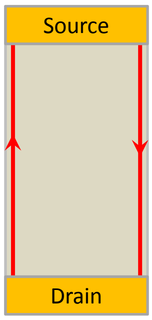




F. Schopfer, (2006)

QAH resistance： not as accurate





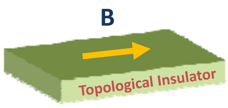
Conducting bulk?

Cr-doped $(Bi,Sb)_2Te_3$ thin films ρ_{xx}~15 kΩ @ T=1.5 K

Magnetoresistance of thin films and of wires in a longitudinal magnetic field

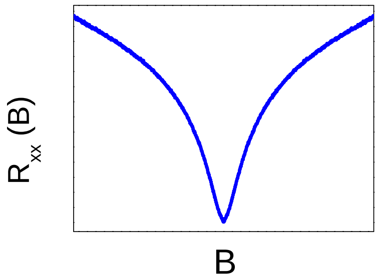
B. L. Al'tshuler and A. G. Aronov
B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR

(Submitted 2 April 1981)
Pis'ma Zh. Eskp. Teor. Fiz. **33**, No. 10, 515–518 (20 May 1981)



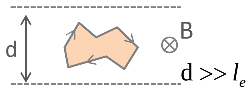
$$\Delta\sigma_{\parallel}(B) = -\frac{e^2}{4\pi^2\hbar}\ln(1+bB^2)$$

$$b = \beta\frac{ew^2}{4\hbar B_{\phi}}, \quad \beta = \frac{1}{3}$$

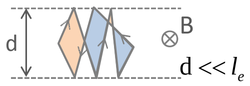


Mechanisms for magnetoresistance in parallel fields

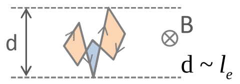
***T*-dependence of β**



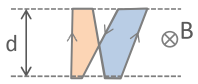
Altshuler-Arnonv (AA) β=1/3 — **weak**



Dugaev-Khmelitskii (DK) β=(1/16)·(d/l_e)<<1 — **weak**

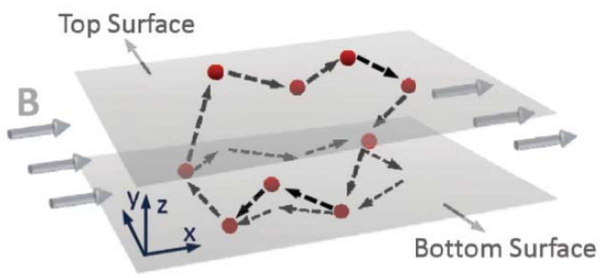


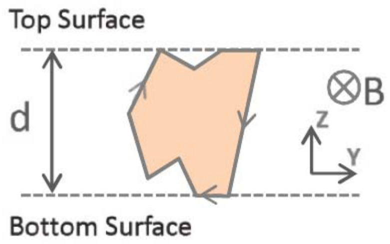
Beenakker-von Houten (BvH) **(1/16)·(d/l_e)< β<1/3** — **weak**



Raichev-Vasilpoulos (RV) 0<β<1 — **strong**

$$\Delta\sigma_{\parallel}(B) = -\frac{e^2}{4\pi^2\hbar}\ln(1+bB^2), \quad b = \beta\frac{ed^2}{4\hbar B_{\phi}}$$

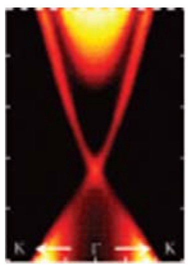


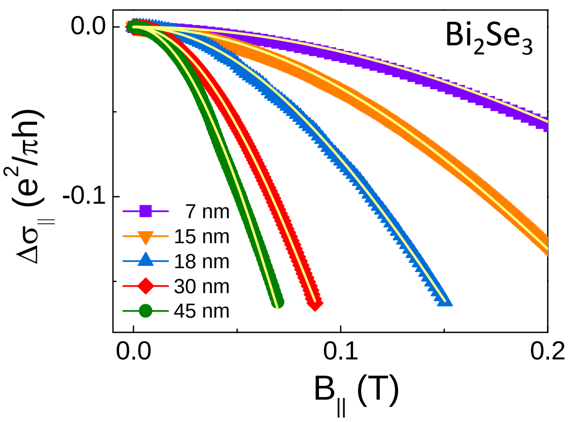


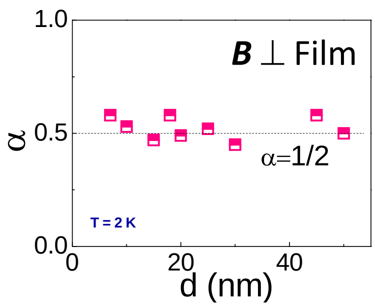
Ideal thick TI films ⇔
weakly coupled bilayer, $\beta \sim 0$

Ideal ultra thin TI films ⇔
strongly coupled bilayer, $\beta \sim 1$

$$\Delta\sigma_{\parallel}(B) = -\frac{e^2}{4\pi^2\hbar}\ln(1+bB^2), \quad b = \beta\frac{ed^2}{4\hbar B_{\phi}}$$

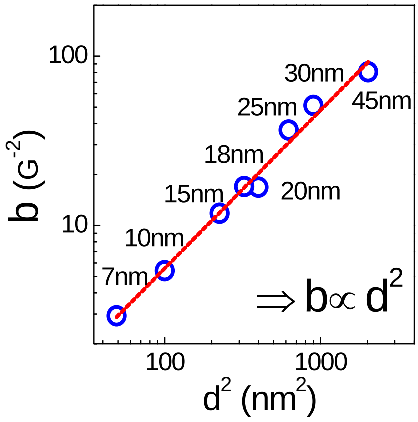


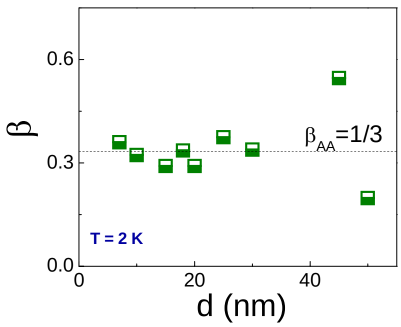




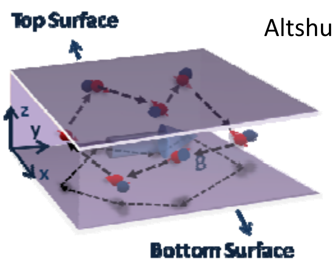
Parallel field Magnetoconductivity in Bi_2Se_3 thin films

$$\Delta\sigma_{\parallel}(B) = -\frac{e^2}{4\pi^2\hbar}\ln(1+bB^2),\quad b=\beta\frac{ed^2}{4\hbar B_\phi}$$





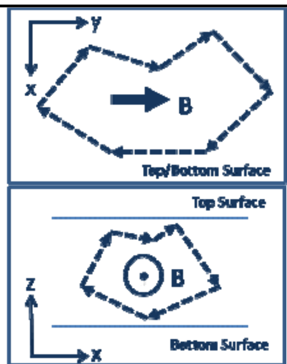
Topological trivial metal films



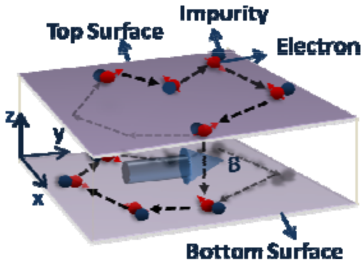
Altshuler-Aronov regime:

$$d >> l_e$$

$$\beta = \frac{1}{3}$$



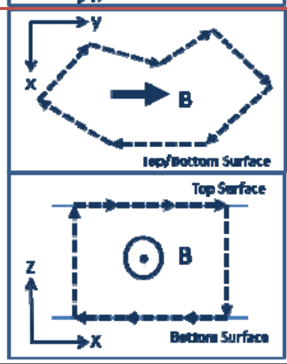
Topological insulator thin films



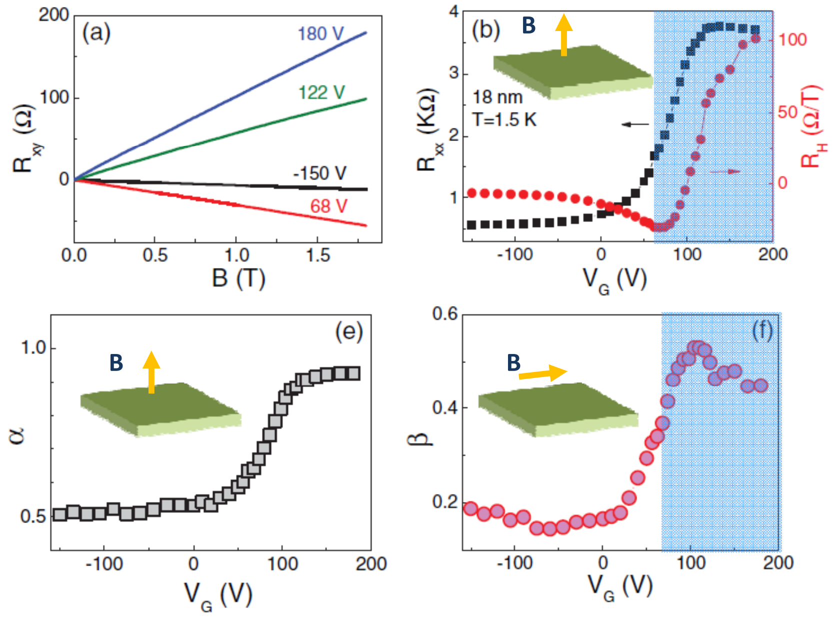
(RV regime)

$$0 \le \beta \le 1$$

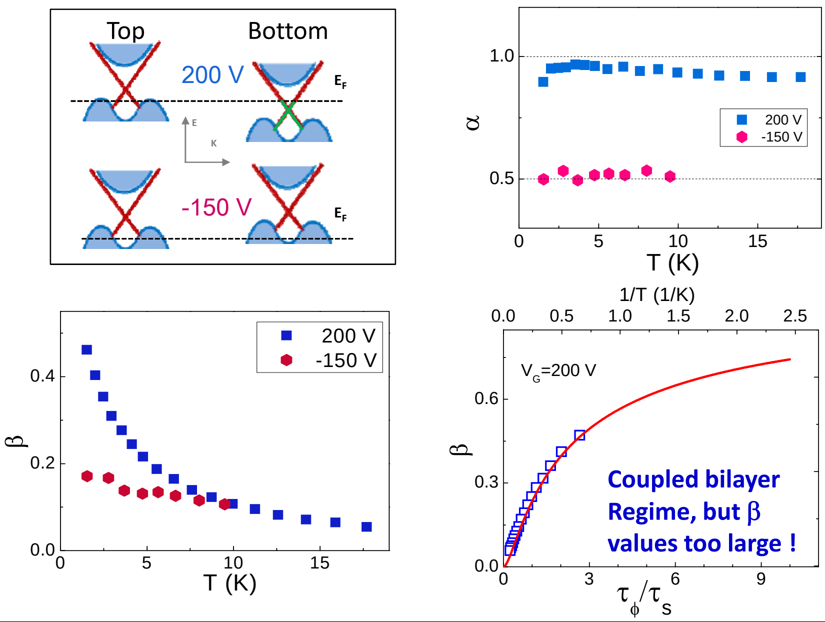
$$s = \frac{\tau_\phi}{\tau_s}$$



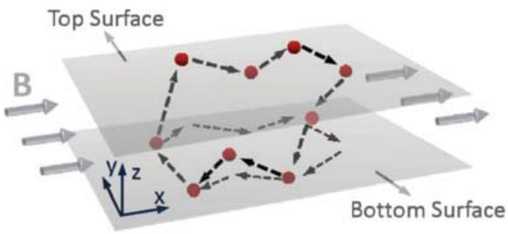
How perfect are the $(Bi,Te)_2Te_3$ thin films?



$(Bi_{1-x}Sb_x)_2Te_3$ thin films: T-dependence of β



Quantum diffusive transport in parallel fields



β parameter: A new figure of merit for 3D TIs?

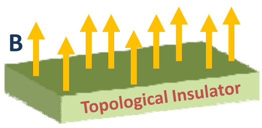
$\beta \rightarrow 0$ for ideal TIs

An ultrasensitive probe for intersurface and surface-bulk couplings: $1/\tau_s \sim 10^9\ s^{-1}$

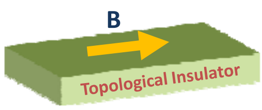
Chaojing Lin et al., PRB **88**, 041307 (R) (2013)

Summary on the WAL part

- **Detecting surface state transport with perpendicular field transport**
  α parameter



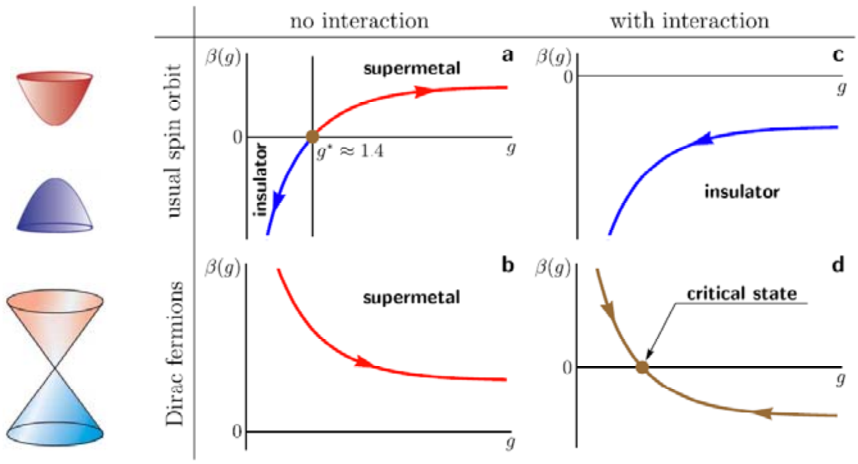
- **Probing inter-surface couplings with parallel field transport**
  β parameter



Jun Chen et al., PRB 83, 241307 (R) (2011)
Chaojing Lin et al., PRB **88**, 041307 (R) (2013)

V. Temperature dependence of conductivity

— Manifestation of e-e interaction effects



Ostrovsky,Gornyi & Mirlin, PRL **105**, 036803 (2010)

PRL 112, 146601 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

Finite-Temperature Conductivity and Magnetoconductivity of Topological Insulators

Hai-Zhou Lu and Shun-Qing Shen
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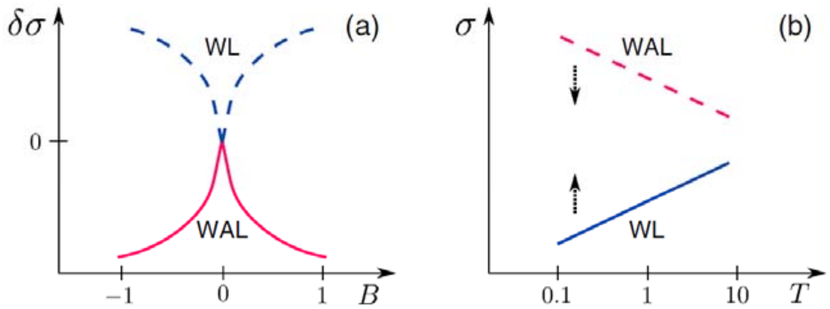
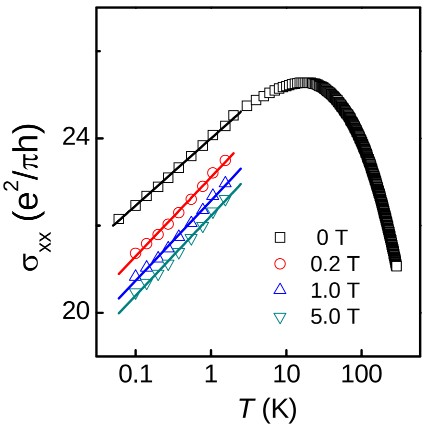
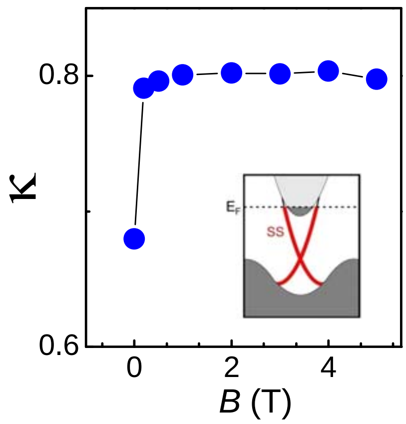
(Received 5 December 2013; published 7 April 2014)



Temperature Dependence Measurements



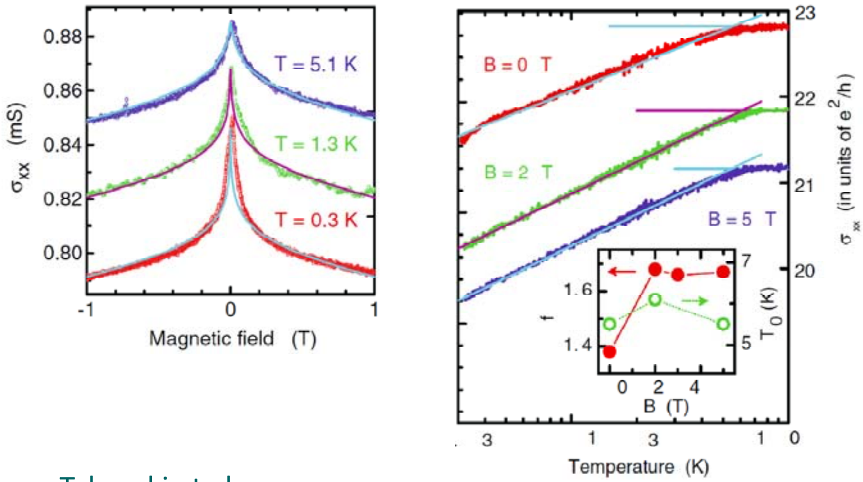


Manifestation of **electron-electron interaction**

$$\kappa \equiv \frac{\pi h}{e^2}\frac{\partial \sigma}{\partial \ln T}$$

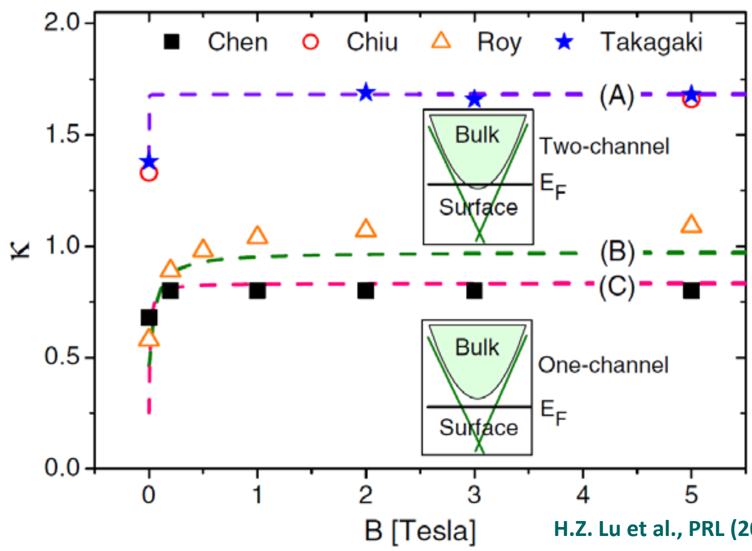
J. Chen et al., PRB (2011)
J. Wang et al., PRB (2011); M. H. Liu et al., PRB (2011)

Similar measurements by other groups



Takagaki et al.,
PRB **85**, 115314 (2012)

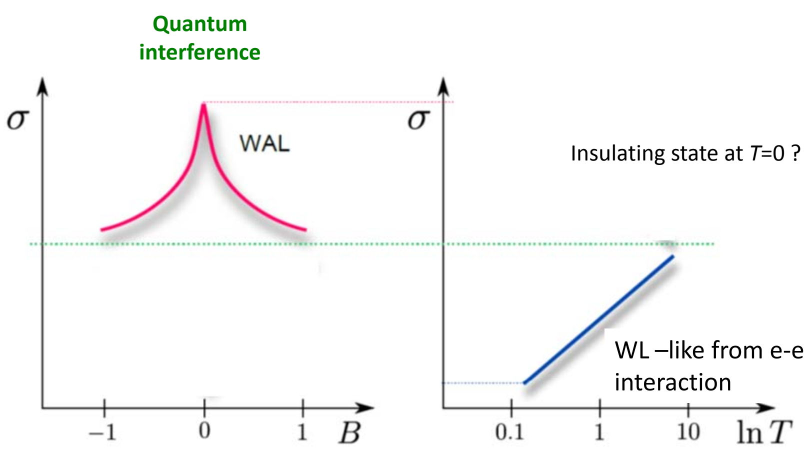
Summary of the lnT dependence of conductivity in TI thin films



H.Z. Lu et al., PRL (2014)

Chen et al, PRB (2012), Takagaki et al., PRB (2012), Chiu et al., PRB (2013); Roy et al., APL (2013)

Puzzling temperature dependence of conductivity



Graph from
H. Z. Lu & S. Q. Shen

Open question:
Eventual fate as $T \rightarrow 0$

PHYSICAL REVIEW B 85, 195130 (2012)

Metal-insulator transition in two-dimensional random fermion systems of chiral symmetry classes

E. J. König,[1,2] P. M. Ostrovsky,[3,4] I. V. Protopopov,[3,4] and A. D. Mirlin[1,2,3,5]
[1]*Institute für Theorie der kondensierten Materie, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany*
[2]*DFG Center for Functional Nanostructures, Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany*
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(Received 30 January 2012; published 15 May 2012)

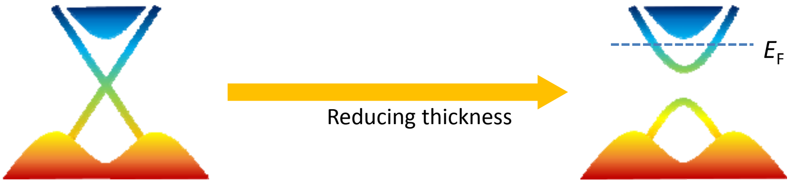
Disordered Dirac fermions in graphene in the absence of valley mixing and **surface states of disordered topological insulators** and superconductors are characterized by sigma models with Wess-Zumino or ϑ *terms, ensuring a* topological protection from localization.

Ongoing experimental efforts, but challenges from residue bulk conductivity, weak e-e interactions, …

VI. Taking a Different Route: Ultrathin TI films

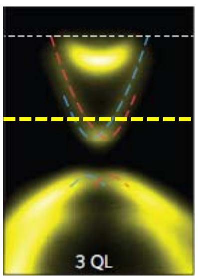
Gap opening due to hybridization:

H. Z. Lu et al., PRB (2010);
C. X. Liu et al., PRB (2010).



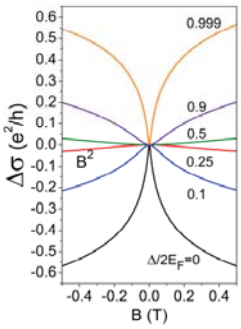
1. Transition from 3D TI to 2D TI or topologically trivial insulator
2. Anderson localization of surface states?
3. Crossover between weak antilocalization and weak localization

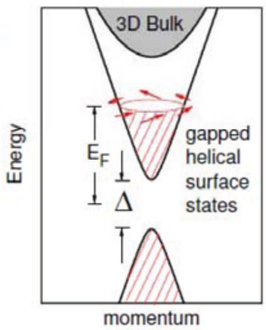
Predicted crossover between WAL and WL



Evidence for a surface state hybridization gap from ARPES

Y. Zhang et al., Nature Phys. (2010)



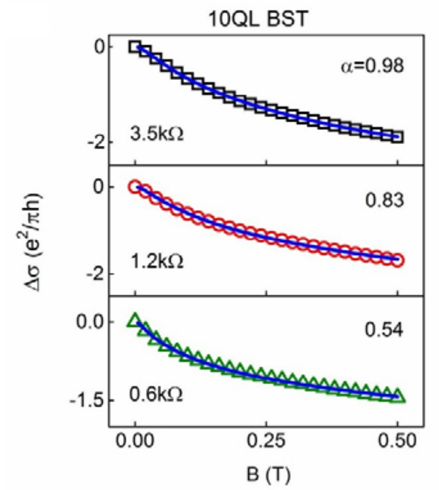


Modified Berry's phase: $\pi\left(1-\frac{\Delta}{2E_F}\right)$

H.-Z. Lu, J. R. Shi & S.-Q. Shen, PRL (2011)

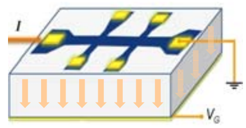
But only valid at the diffusive regime, i.e. $k_F l \ll 1$

More reliable tuning of the phase coherent transport



$\alpha \approx 1$

Nearly two independent surfaces



$\alpha \approx 1/2$

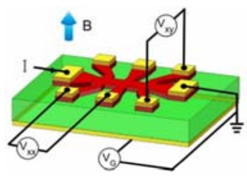
Strong couplings between surface & bulk states

$$\Delta\sigma(B) \simeq -\alpha \cdot \frac{e^2}{2\pi^2\hbar}\left[\psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right)-\ln\left(\frac{B_\phi}{B}\right)\right]$$

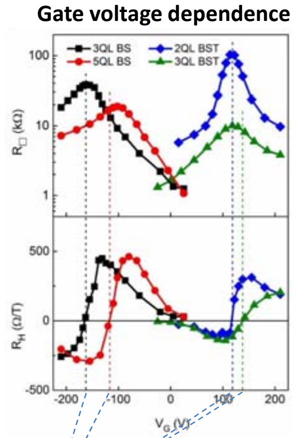
Hikami-Larkin-Nagaoka (1981)

$(Bi,Sb)_2Te_3$ and Bi_2Se_3 Thin Films with Highly Tunable Chemical Potential

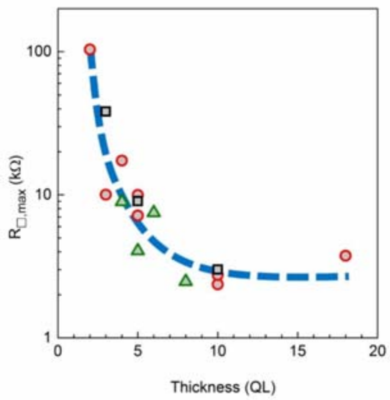
Device

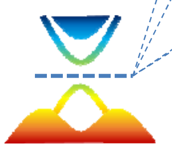


Gate voltage dependence

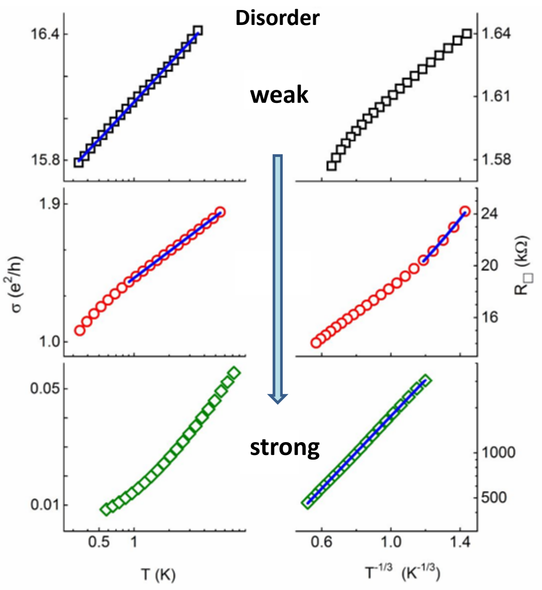


Thickness dependence of Resistance





Temperature Dependence of Longitudinal Resistance



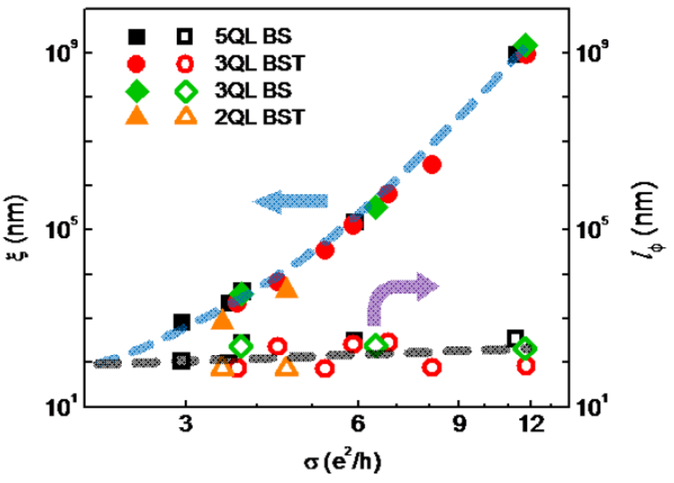
R□<<h/e²
Weak antilocalization
$\Delta\sigma \sim \ln T$

R□~h/e²

R□>>h/e²
Strong localization
R□ ∝exp(T^-1/3)

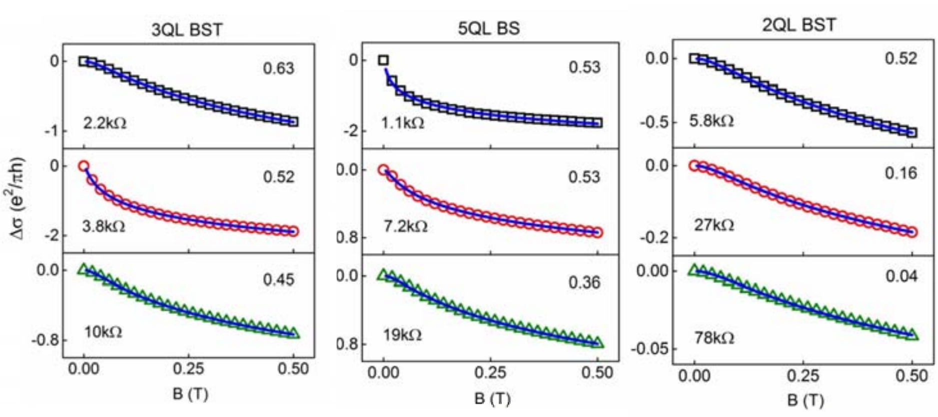
Anderson localization

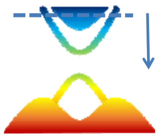
Crossover from weak (anti)localization to strong localization



Localization length ξ vs. **Dephasing length l_ϕ**

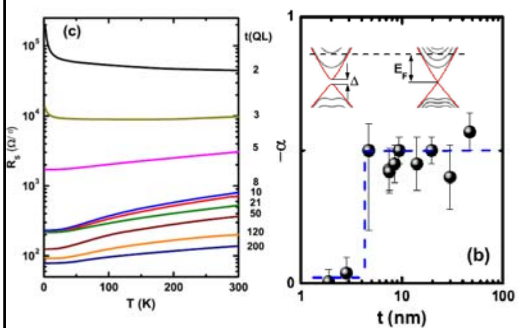
Suppression of WAL in ultrathin films



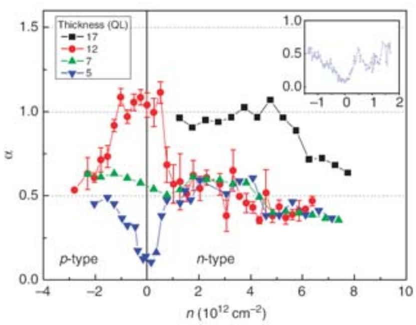


- All MC data can be fitted to HLN equation
- As $R_\square$ increases, $\alpha \to 0$: crossover from WAL to WL ?

Other observation of Suppression of WAL



Ando group @ Osaka
PRL 109, 066803 (2012)

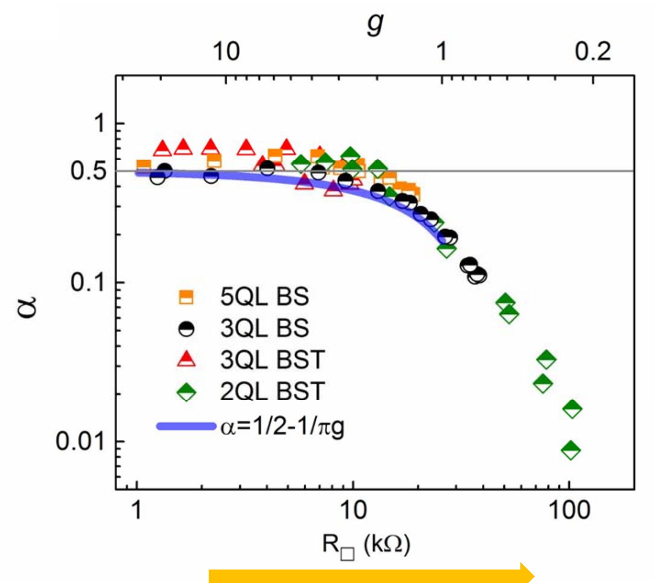


Fuhrer group @ Maryland
Nat. Commun. 4, 2040 (2013)

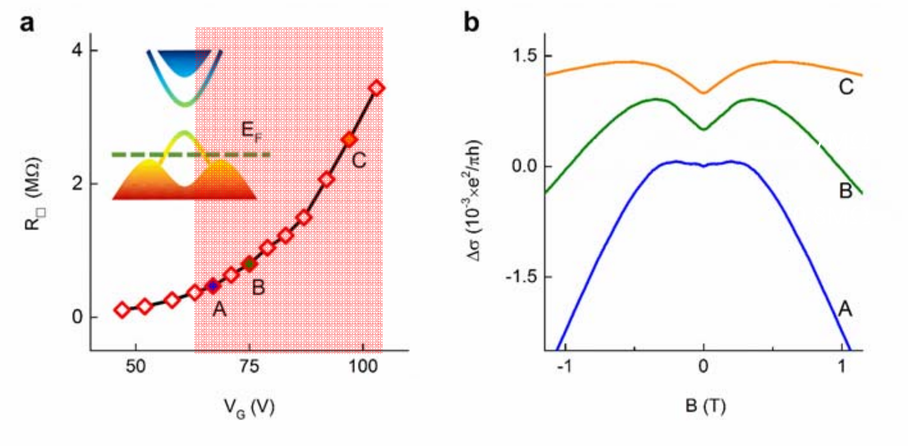
See also: K. L. Wang group, Nano Lett. 13, 48 (2013); S. Oh group, PRB 84, 073109 (2011)

But none of these observations were made in the well-defined *diffusive* regime

Correlation between α and $R_\square$



Magnetoconductivity in the Strong Localization Regime

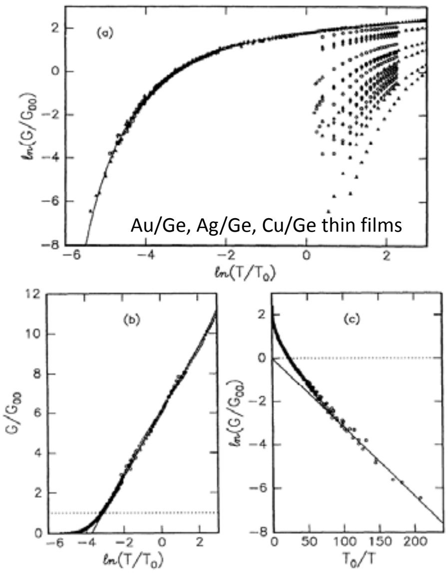


Hopping transport in zero-fields **Positive MC**

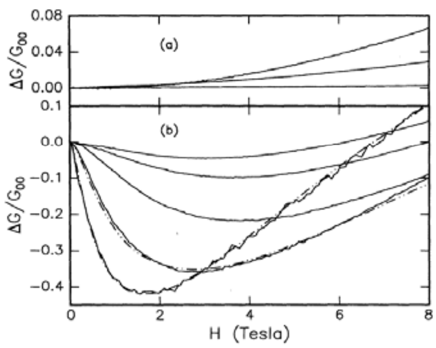
⇒ Crossover to Anderson insulator instead of QSH insulator

Samples from Yunbo Ou, Ke He & Q.-K. Xue @ Tsinghua

Crossover from WAL to strong localization in traditional systems



diffusive | hopping

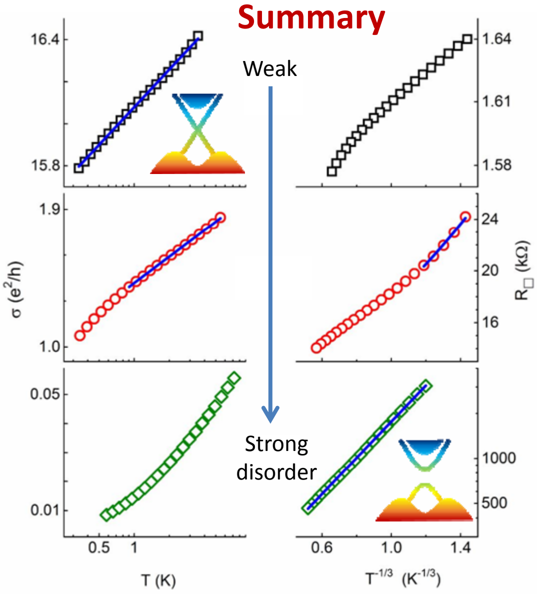


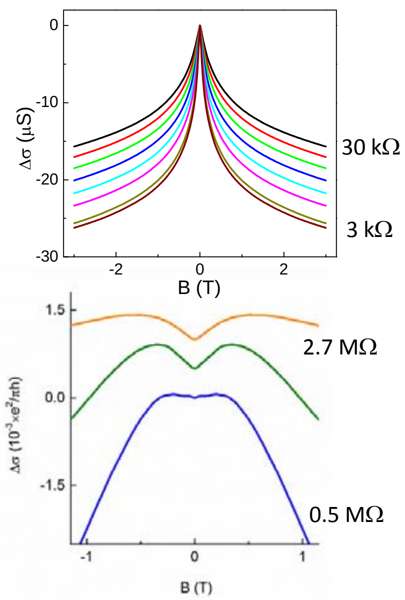
Magnetoconductivity changes sign at $G \sim e^2/(\pi h)$

Well Defined Transition from WAL to Strong Localization

Hsu & Valles, PRL **74**, 2331 (1995)

Summary





J. Liao, Y. B. Ou, X. Feng, S. Yang, C. J. Lin, W. M. Yang, K. H. Wu, K. He, X. C. Ma, Q.-K. Xue, and Y. Q. Li, Phys. Rev. Lett. **114**, 216601 (2015)

Summary & outlook

- **Truly 3D TI thin films:**
  - Only WAL-like magnetoconductivity has been observed
  - Low T conductivity only shows weakly insulating behavior due to overwhelming e-e interactions
- **Ultrathin 3D TI films:**
  - Transport in both WAL and SL regimes
  - No evidence available for transition to QSH phase

Many open questions still exist regarding the electron transport in topological insulators.

Part Two:

Evidence for half-metallicity in n-$HgCr_2Se_4$

Collaborators:

Tong Guan, Chaojing Lin, Chongli Yang, **Youguo Shi**, Cong Ren, Hongming Weng, Xi Dai, Zhong Fang, *IOP-CAS*

Peng Xiong, Florida State University

Shishen Yan, Shandong University

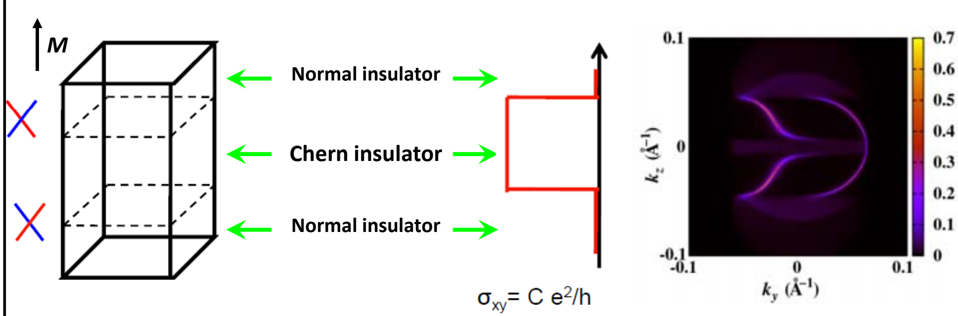
T. Guan et al., arXiv: 1503.03190, accepted by Phys. Rev. Lett.

Topological States of Matter

	2D	3D
Time-reversal symmetry	Quantum Spin Hall Insulator HgTe/CdTe QW	Topological Band/Crystalline/Kondo /Anderson/Mott Insulator
TR-symmetry broken	Quantum Hall states; Quantum Anomalous Hall States Cr-doped $(Bi,Sb)_2Te_3$	? Magnetic Weyl semimetal

Xiangang Wan et al., PRB (2010) $A_2Ir_2O_7$

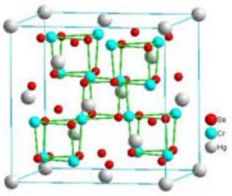
A Candidate for Magnetic Wey Semimetals

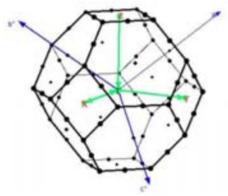


- ***Fermi arcs*** on surfaces
- ***Quantum anomalous Hall effect*** from the quantum well structure

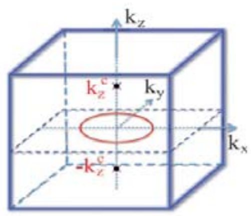
G. Xu et al., PRL **107**, 186806 (2011)

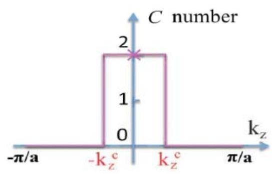
Crystalline & Band Structures of $HgCr_2Se_4$

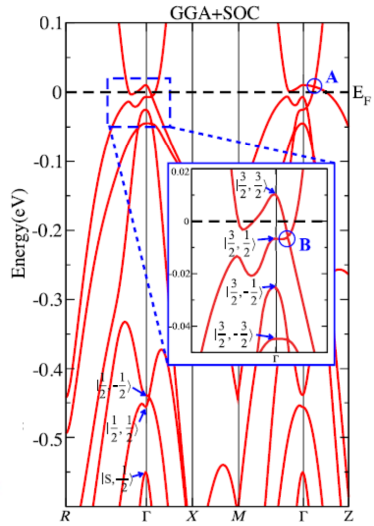




Zinc blend structure (HgX)



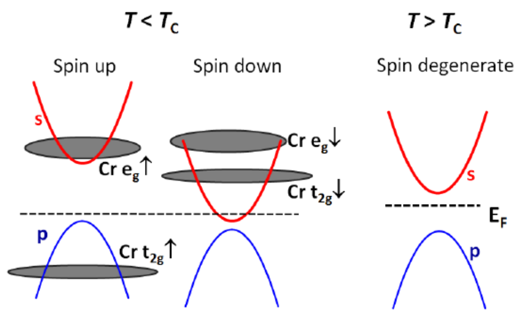


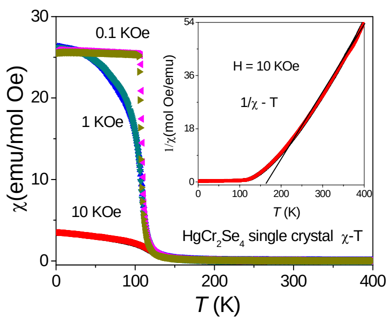


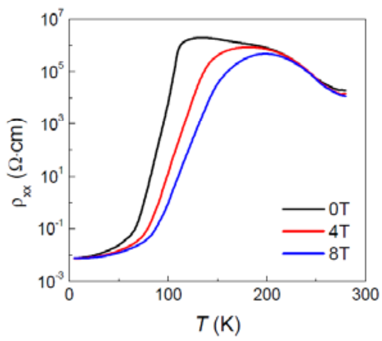
G. Xu et al., PRL (2011)

$HgCr_2Se_4$

Ferromagnet-paramagnet transition
&
Metal-insulator transition

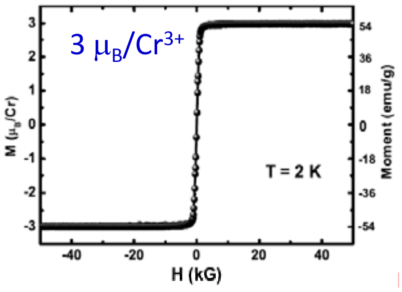




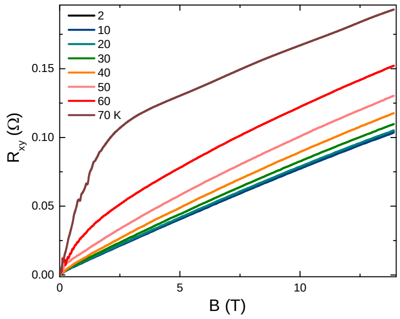


Ferromagnetic ground states of *n*-$HgCr_2Se_4$

Magnetism



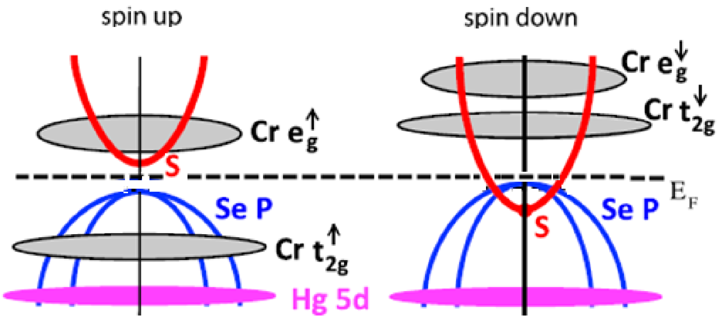
Transport



Integer Bohr magneton/unit cell:
Indication for **half-metallicity**

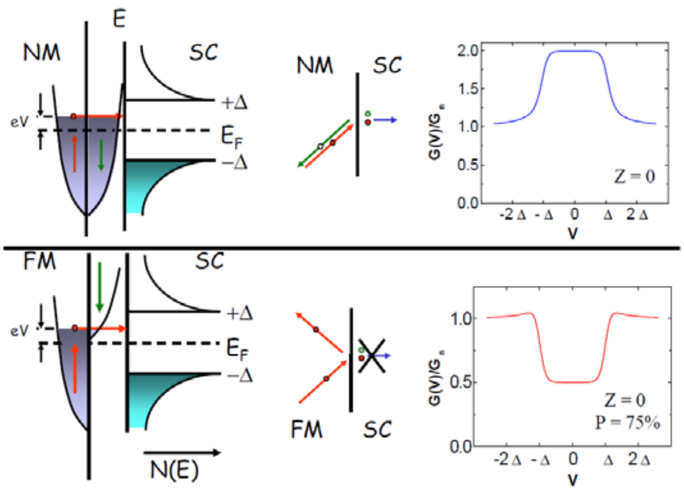
Anomalous Hall effect

Spin polarization in *n*-$HgCr_2Se_4$: 100%?



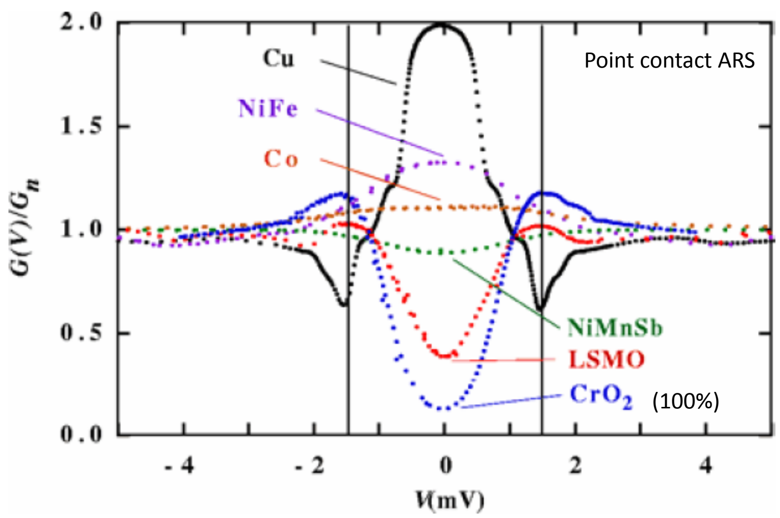
T< T_C, half-metallic ferromagnet
T> T_C, paramagnet

Andreev reflection spectroscopy



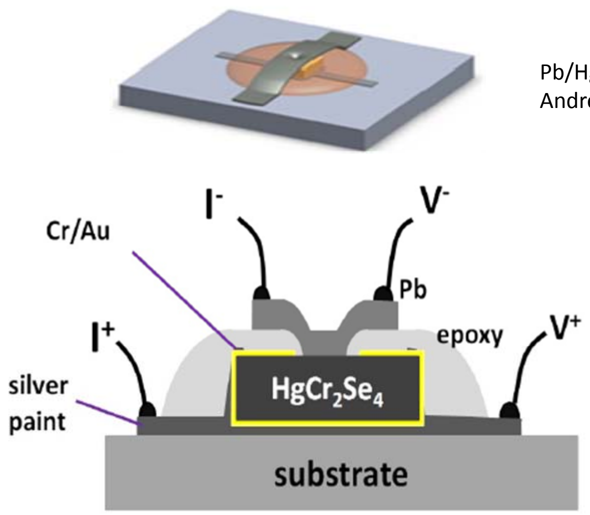
A. F. Andreev. Sov. Phys. JETP **19**, 1228 (1964)
Courtesy of J. S. Parker & P. Xiong

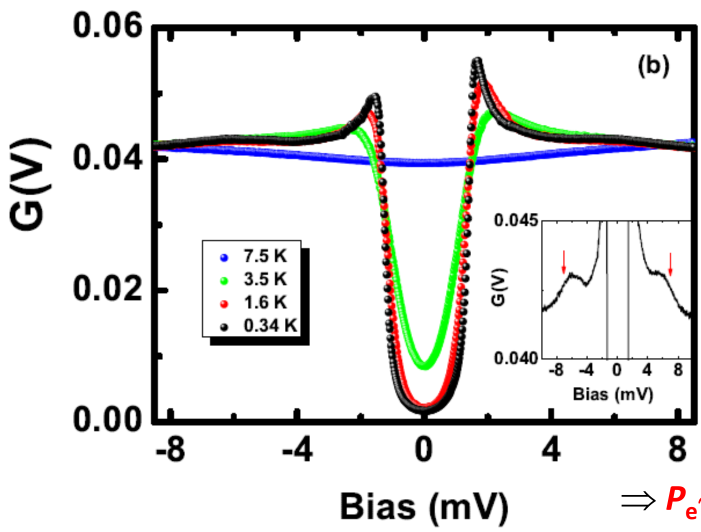
Applications of Andreev reflection spectroscopy



R.J. Soulen et al., Science **282**, 85 (1998)

Planar junctions for Andreev reflection

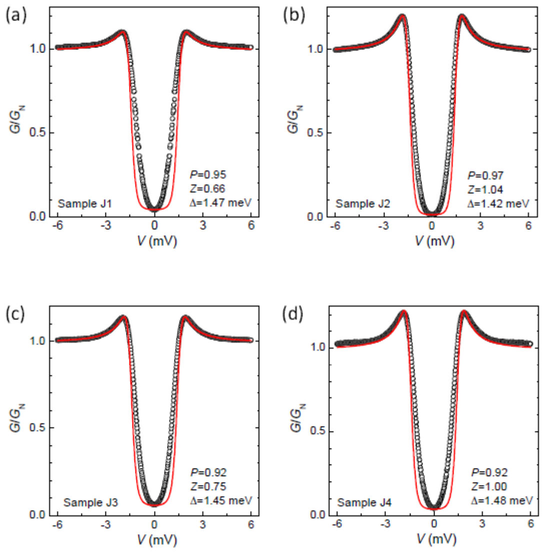




⇒ P_e~100%

n-$HgCr_2Se_4$: **low** electron density, **half-metallic** magnetic semiconductor

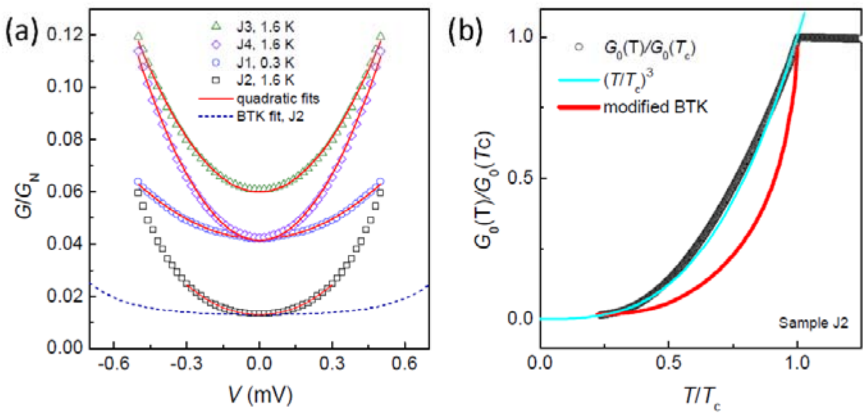
Fits with modified BTK theory



P=92-97%

T. Guan et al.,
arXiv:1503.03190
To appear in PRL

Finite conductance near zero-bias



T. Guan et al., arXiv: 1503.03190, accepted by PRL (2015)

PRL 105, 207001 (2010) PHYSICAL REVIEW LETTERS week ending 12 NOVEMBER 2010

Is CrO_2 Fully Spin Polarized? Analysis of Andreev Spectra and Excess Current

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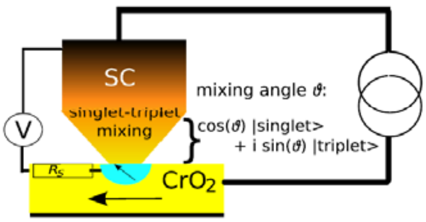
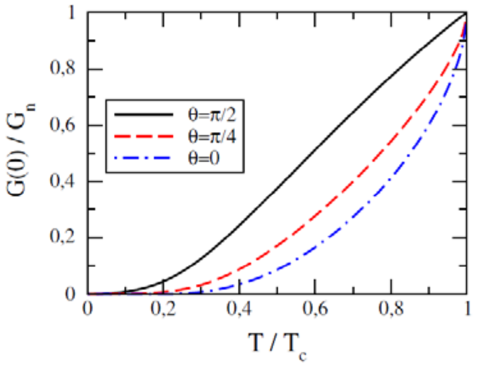
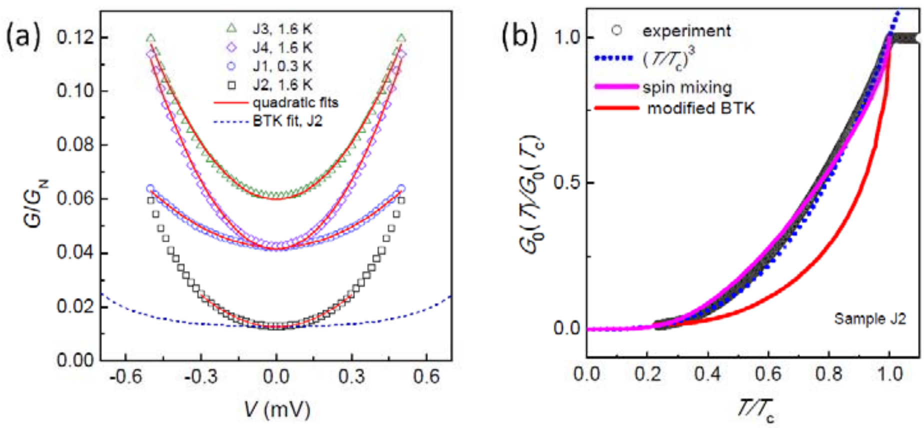
[3]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany
(Received 19 July 2010; published 10 November 2010)

Spin active scattering model



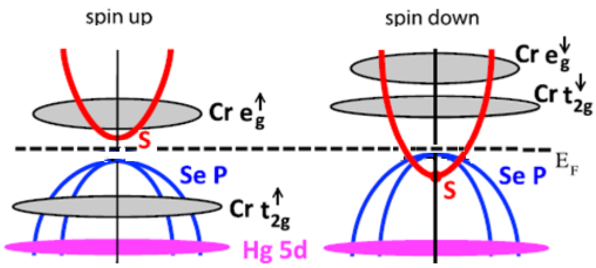


Differential conductance of *n*-$HgCr_2Se_4$



T. Guan et al., arXiv: 1503.03190, accepted by PRL (2015)

n-$HgCr_2Se_4$: s-band half-metal



Other half-metallic materials:

CrO_2, NiMnSb, (La,Sr)MnO_3: 3*d* electrons

EuO, EuS, … 5*d* electrons

(Ga,Mn)As, only *p*-type

Outlook: Spintronics, unconventional superconductivity, high-*T* quantum anomalous Hall effect