KITS Forum, 3/27/2017

Charge, Spin and Thermal Transport in Topological Insulators: Some New Surprises

Yong P. Chen, *Quantum Matter and Devices (QMD)*
Physics, ECE & Birck Nanotechnology Center & Purdue Quantum Center
Purdue University, West Lafayette IN 47907
http://www.physics.purdue.edu/quantum

Work by J. Tian, Y. Xu, L. Jauregui, H Cao, I. Miotkowski…;
Colleagues: L. Rokhinson, S. Datta, X. Xu (Purdue);
L. Shi (UT Austin), MZ Hasan (Princeton),…

$$: DARPA, NSF, INTEL, Purdue PCTM & Birck Center,…

Outline: transport phenomena/signatures *unique* to (3D) topological insulators?

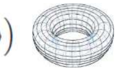
- Quick overview
- **Charge transport [of "intrinsic" topological insulator]**
  - Topological conduction via surface state *Y.Xu et al. Nature Phys.* ***10****, 956 (2014); Y.Xu et al. Nature Comm. 7, 11434 (2016)*
  - "half-integer" quantum Hall effect (QHE) [½ e^2/h from each surface]
  - "half-integer" Aharonov-Bohm oscillation (ABO) [TI nanowire]

  L.A.Jauregui et al., Nature Nanotech. 11, 345 (2016)

- **Spin transport**
  - Current-induced electron spin polarization (helical spin-momentum locking of TSS) [measured by spin potentiometry] *J. Tian et al. Sci. Rep. 5, 14293, (2015)*
  - **Current-induced persistent electron & nuclear [?] spin polarization** ***J. Tian et al. in press (2017)***
- **Thermal transport**
  - **Large enhancement of Lorenz number (violates Wiedemann-Franz)** ***Z. Luo & J. Tian et al. arXiv:1702.01716***
  - Topological thermal transport?

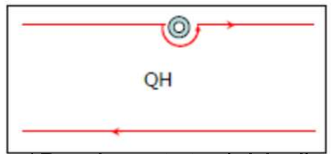
From Quantum Hall Effect (QHE) to Topological Insulator (TI)

$$K = \frac{i}{2\pi} \times \int_{BZ} d^2k \left(\left\langle \frac{\partial \Phi_0}{\partial k_x} \middle| \frac{\partial \Phi_0}{\partial k_y} \right\rangle - \left\langle \frac{\partial \Phi_0}{\partial k_y} \middle| \frac{\partial \Phi_0}{\partial k_x} \right\rangle \right)$$

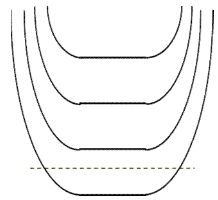


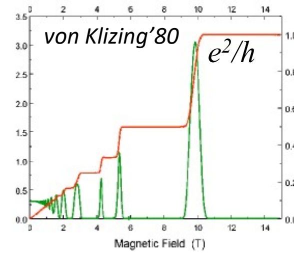
Thouless

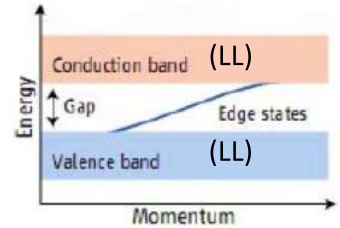
2D Quantum Hall
[*time-reversal breaking*: external B≠0]



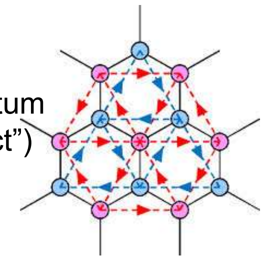
1D edge state (chiral)

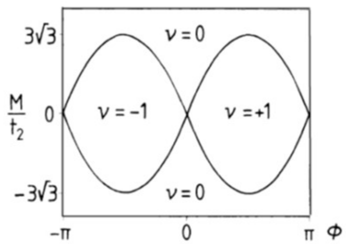


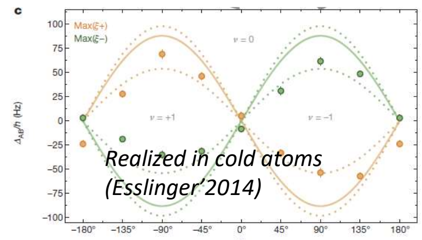




Haldane Model '88
(2D "Chern insulator"/"quantum anomalous Hall (QAH) effect")
[time-reversal breaking;
B=0 (no LL)]

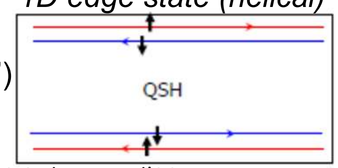






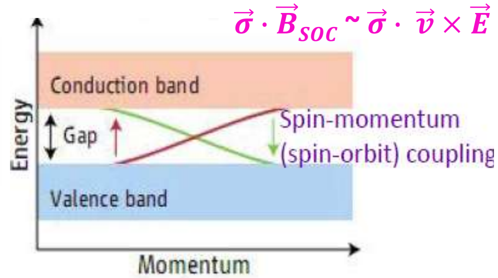
2D Quantum Spin Hall
("2D topological insulator")
[*time-reversal invariant*: B=0] (2D TI)

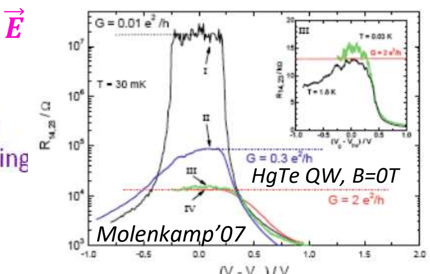
1D edge state (helical)



Kane-Mele'05; S.C.Zhang et al'06

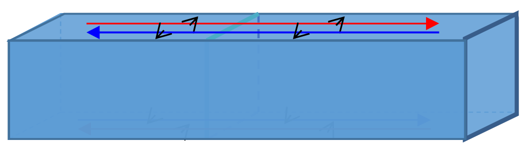
$\vec{\sigma} \cdot \vec{B}_{SOC} \sim \vec{\sigma} \cdot \vec{v} \times \vec{E}$



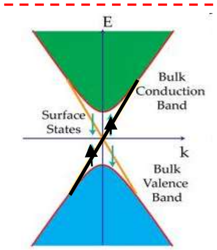


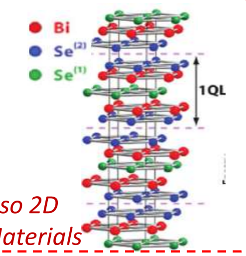
3D (strong)
Topological Insulator
[*time-reversal invariant*: B=0]

Fu-Kane'07;Moore-Balents'07;Roy'09;Qi-Zhang'08...



2D surface state ("spin-helical Dirac fermion")

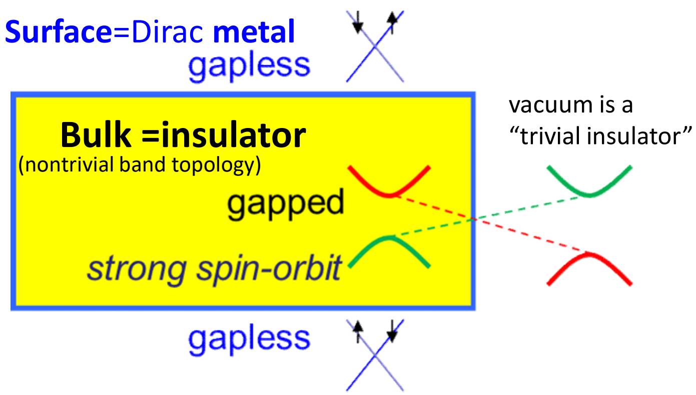


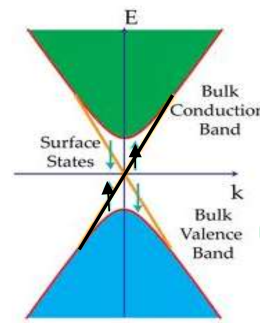


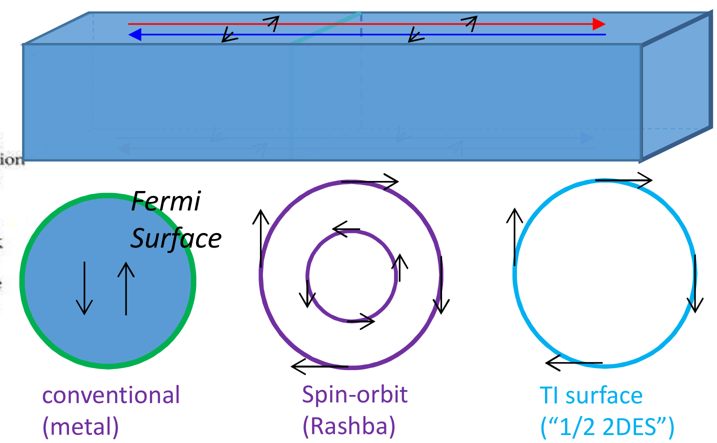
also 2D Materials

(3D) Topological Insulator & Topological Surface State

actually a "topological" metal







General refs: Hasan/Kane, RMP '11; Qi/Zhang, RMP'11

Key Properties *(inter-related)*	***Benefits/Potential Device Applications***
Topological Protection (reduce backscattering) [assuming time-reversal symmetry]	High mobility/conductivity (*FET*) [in absence of magnetic impurities]
Dirac fermions (linear E-k dispersion) $H(\mathbf{q}) = \hbar v_F \mathbf{q} \bullet \vec{\sigma} \times \hat{n}$ *real spin* [odd # Dirac cones]	"graphene-like" physics & devices (eg. *Klein tunneling; electron "optics" etc.*)
Spin-momentum locking (in-plane polarized) $\vec{S} \sim \vec{k} \times \hat{n} \sim \hat{n} \times \vec{j}$ [Berry phase, real & k space]	Spin-polarized surface current (*spintronics: all-electric spin injection etc.*)
"Axion" electrodynamics $\Delta\mathcal{L} = \theta(e^2/2\pi h)\mathbf{E}\cdot\mathbf{B}$ (topological magneto-electric effect)	E-field controlled magnetism (*magnetoelectric & spintronic devices etc.)*

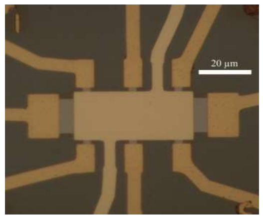
Bulk insulating + surface (only & always) conducts

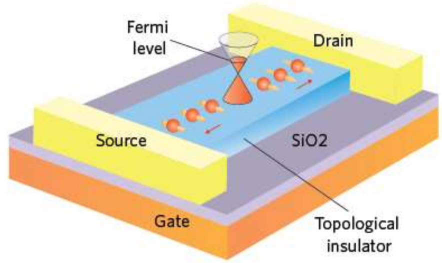
Chen, Proc. SPIE **8373**, 83730B (2012)

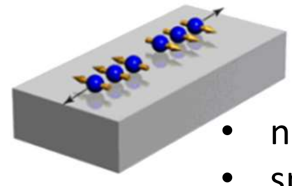
Many other exotic/rich physics & novel devices (electronic/spintronic/photonic/thermoelectric/quantum...) predicted!

TI electronic transport: Rich physics and Potential Device Applications

Want: Topological Surface State (TSS) Transport (spin –helical Dirac fermion)







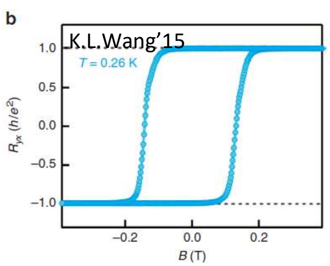
- nanoelectronics
- spintronics
- Thermoelectrics …

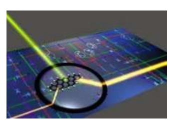
TI surface state (Dirac fermion, spin polarized)

TI + magnetism
Quantum Anomalous Hall
[QK.Xue et al'13]
Topological magnetoelectric
"*axion*" eletrodynamics
Topological Phase Transition

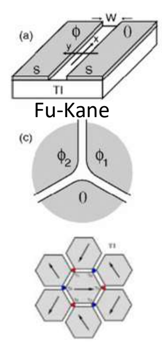
TI + superconductor
(*Majorana* fermions)
Non-Abelian statistics (1D/2D)

TI + TI
(Excitonic condensate)
[electronic superfluid]

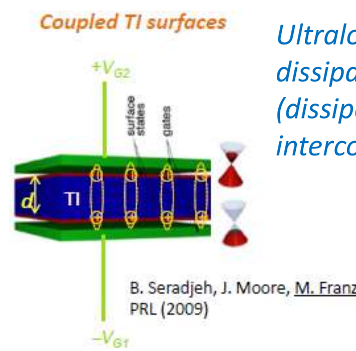




Ultralow power dissipation (dissipationless) interconnect/FFIT



Topological quantum computing



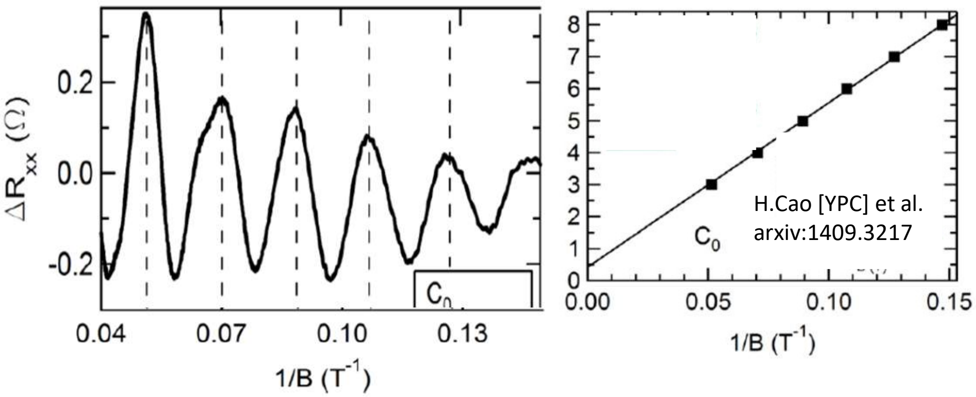
Ultralow power dissipation (dissipationless) interconnect/BiSFET

Which one is from Topological Insulator?

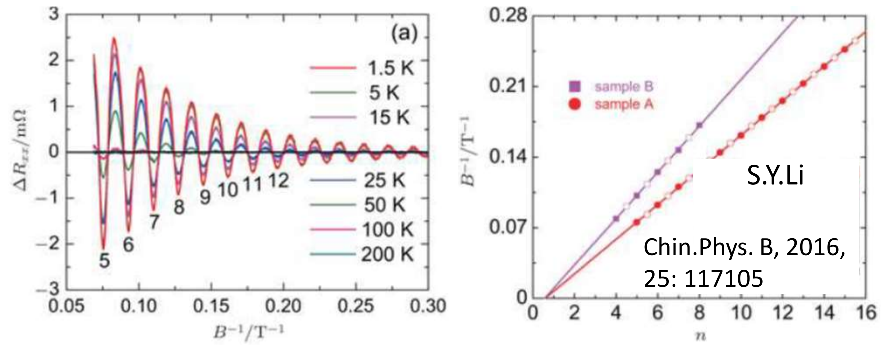
Desire:
"***Forensic***-grade"
transport signatures?

Quantum Oscillations (e.g. SdH in resistance) – "1/2" Landau Level intercept ("pi" Berry phase of Dirac fermions)

Topological insulator (Bi_2Te_2Se)

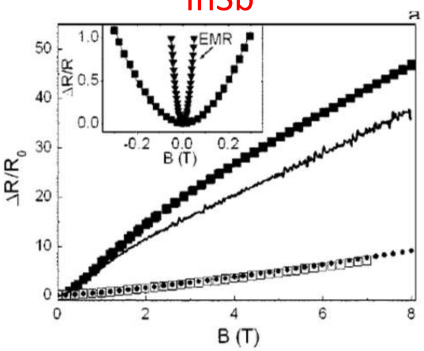


Dirac Semimetal (Cd_3As_2)

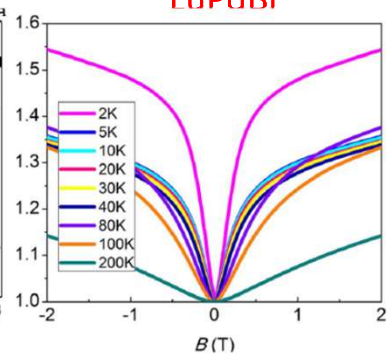


Weak-antilocalization and "linear" magnetoresistance

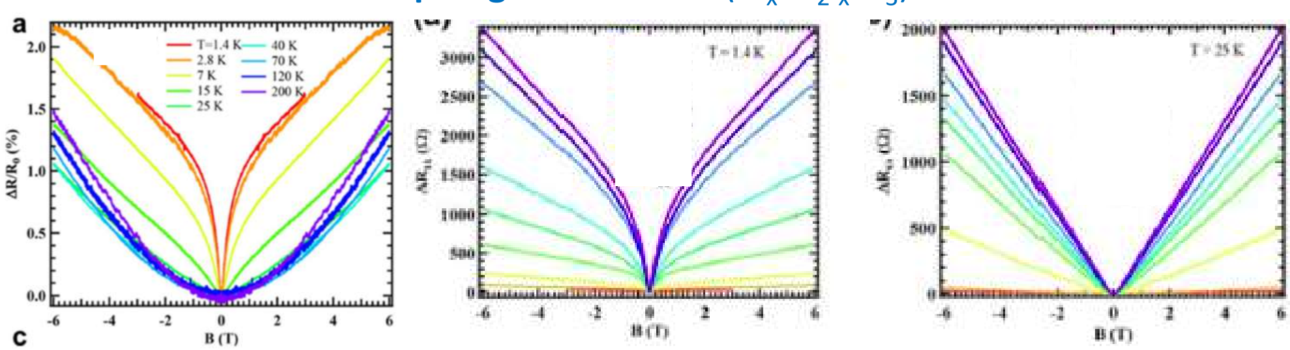
InSb



LuPdBi



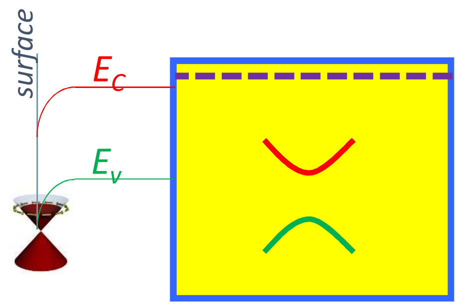
Topological insulator ($Bi_xSb_{2-x}Te_3$)

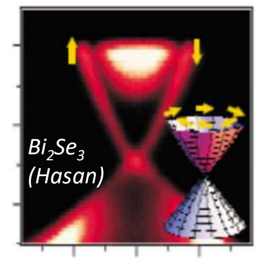


Need “clean” TI materials that would show anambiguous “topological” transport signatures of TSS (spin-helical Dirac fermions)?

Experimental Challenge:
Real TI can have ***multiple conduction channels***

- **Bulk** (doped)
- **Surface 2DES (Rashba)**
- **Topological SS**



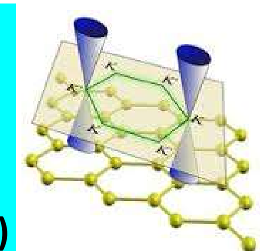


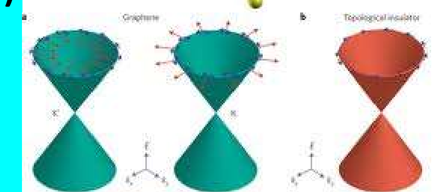
How to distinguish TI (TSS) from

- **Other conducting channels within real TI materials:**
  Bulk (strong SOC) & **Surface 2DES (strong Rashba SOC)**
- **Other 2DES with narrow gap or strong SOC**
- **Other 2D Dirac fermion system: graphene (4-species Dirac *pseudo-spin*)**

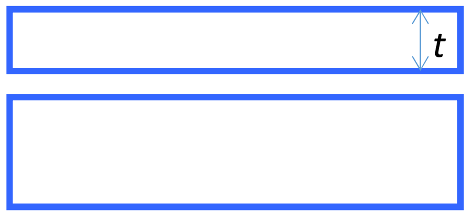
Can I just look at some transport data which will “immediately” tell us we are measuring a TI (TSS) rather than any of the above?

*---- want: “**1/2**” quantum number!*
[2 examples: “1/2 QHE”; “1/2 ABO”]



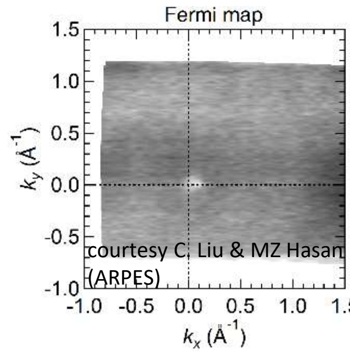


Topological transport: surface (always) conduction & bulk insulating



Usual conductor:
"G→G/2+G/2"

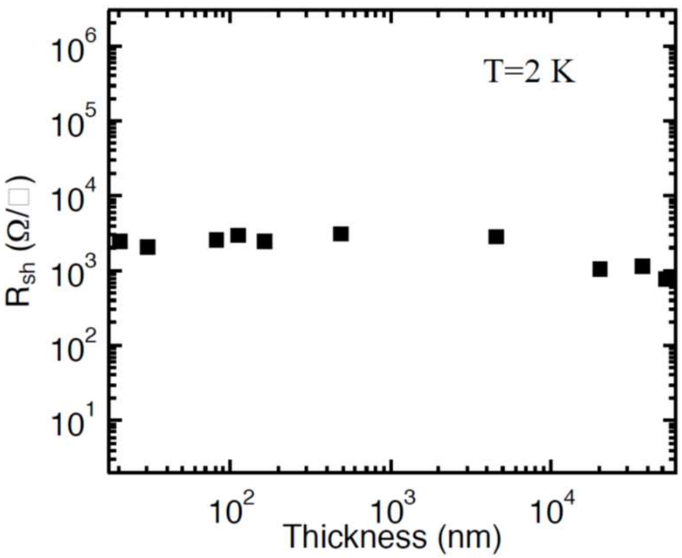
Topological:
"G→G+G"

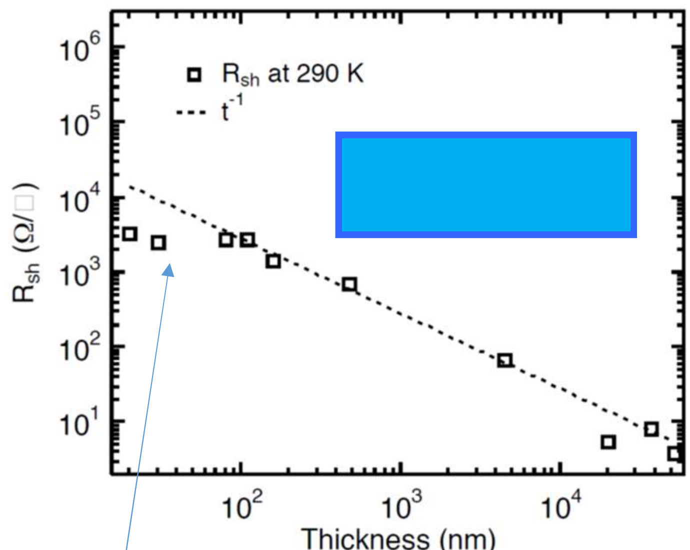


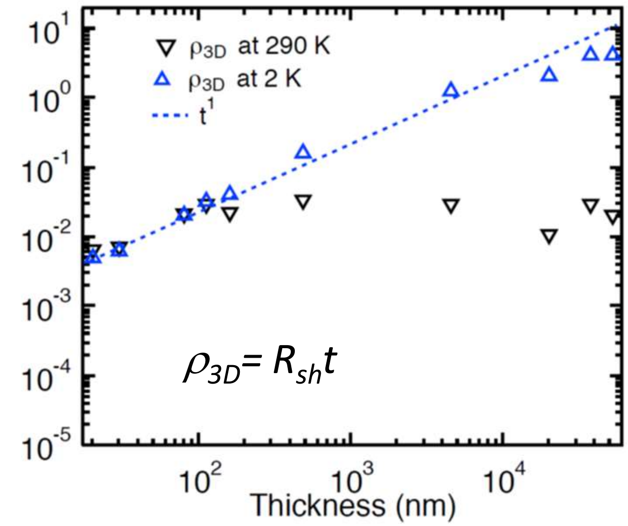
TI=BiSbTeSe_2 ("BSTS") -- one of the *"cleanest" TI* (no bulk conduction)

- **3D (intrinsic) TI**
  – R~const.; "ρ" ∝ t

- 3D conductor (doped 3D TI)
  -- R ∝ 1/t; ρ~const. ;







Surface-dominated conduction even at 300K (thin samples <100nm)

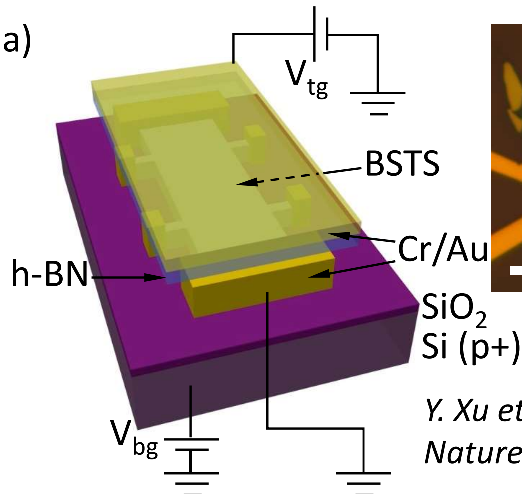
02:57

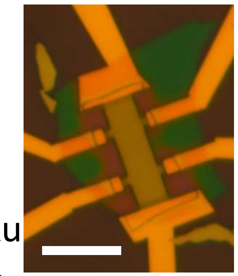
Yang Xu et al. Nature Physics **10**, 956 (2014);

Double-gated TI thin film

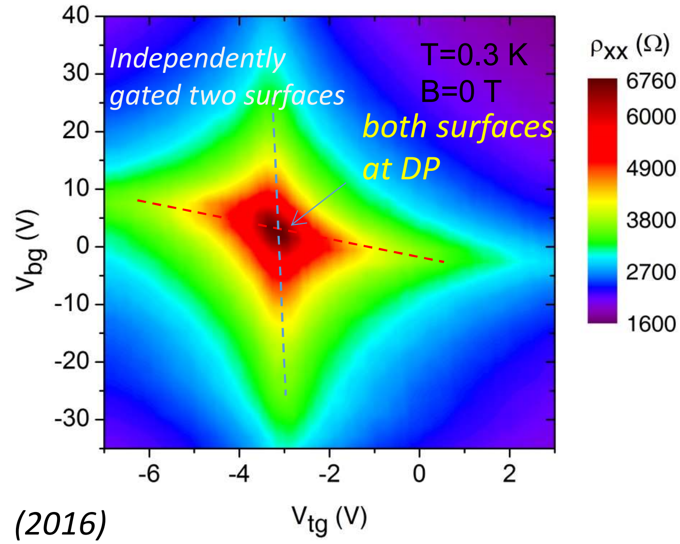
TI=$BiSbTeSe_2$ ("BSTS")

(a)

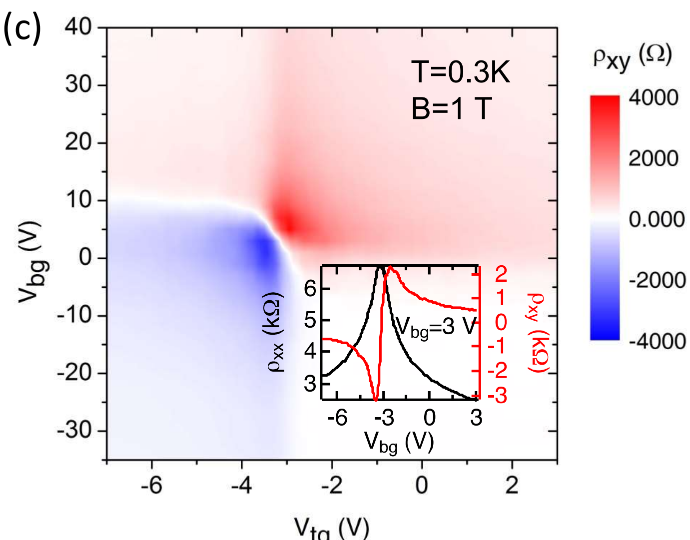




Y. Xu et al.
Nature Comm 7, 11434 (2016)

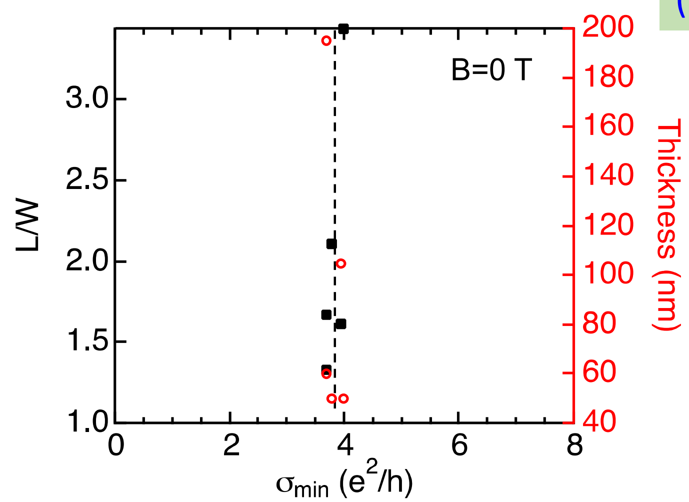


(c)



~universal minimum conductivity of Dirac fermion in TSS?

(~$2e^2/h$ per surface?!)

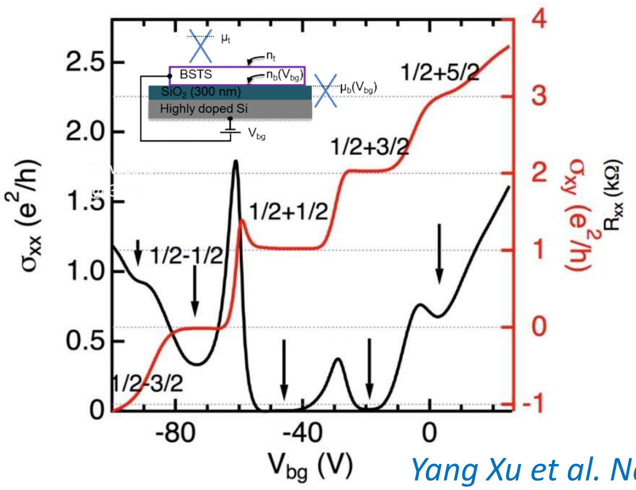


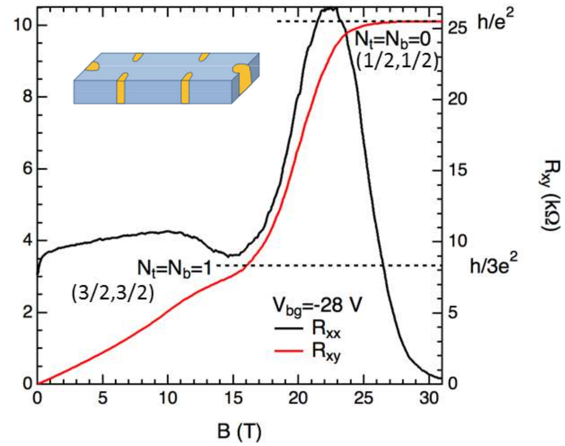
Prev studied in graphene eg. Geim'05; Kim'05

Fingerprint#1:

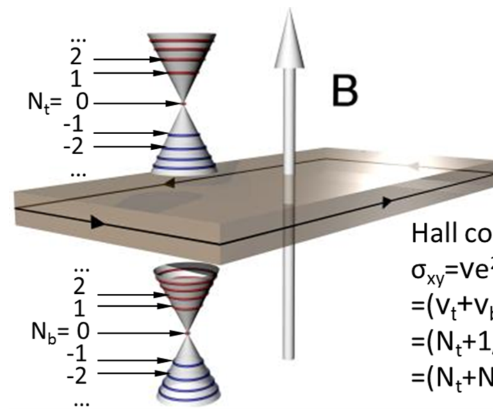
"Half-integer" QHE --- of two-component (surface) Dirac fermions

Each surface: σ_{xy}=(1/2)e^2/h
---*"1/4-graphene"*



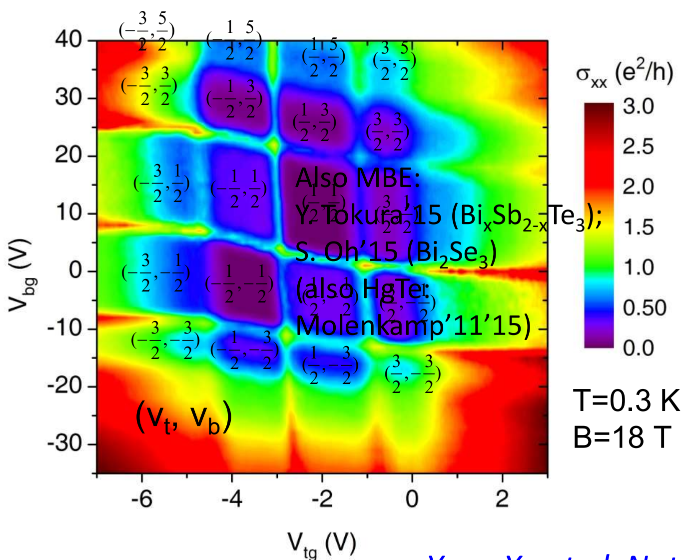


Yang Xu et al. Nature Physics **10**, 956 (2014);



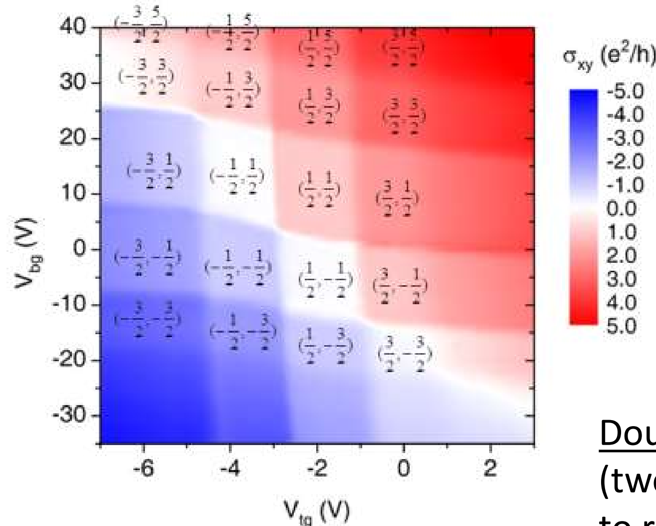
$v_t=N_t+1/2$
$v_b=N_b+1/2$

Hall conductivity:
$\sigma_{xy}=ve^2/h$
$=(v_t+v_b)e^2/h$
$=(N_t+1/2+N_b+1/2)\ e^2/h$
$=(N_t+N_b+1)\ e^2/h$



Also MBE:
Y. Tokura'15 ($Bi_xSb_{2-x}Te_3$);
S. Oh'15 (Bi_2Se_3)
(also HgTe:
Molenkamp'11'15)

T=0.3 K
B=18 T

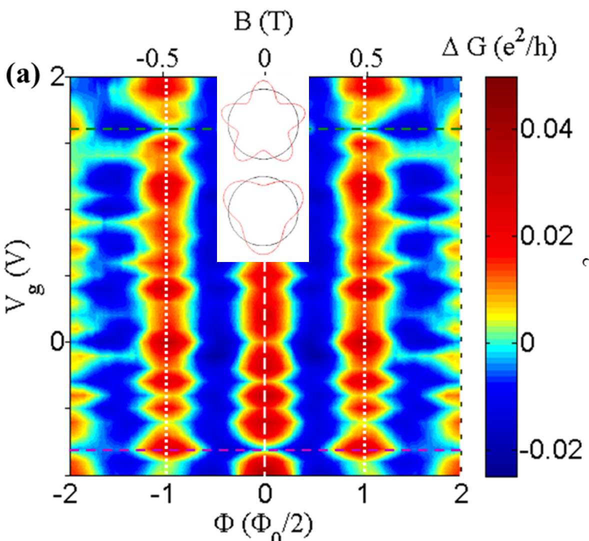


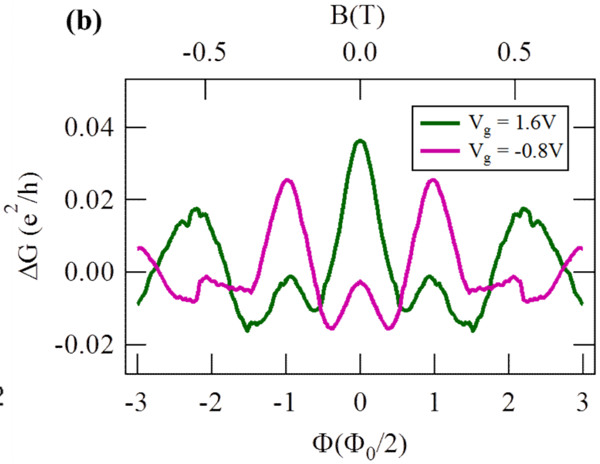
Yang Xu et al. Nature Comm. 7, 11434 (2016)

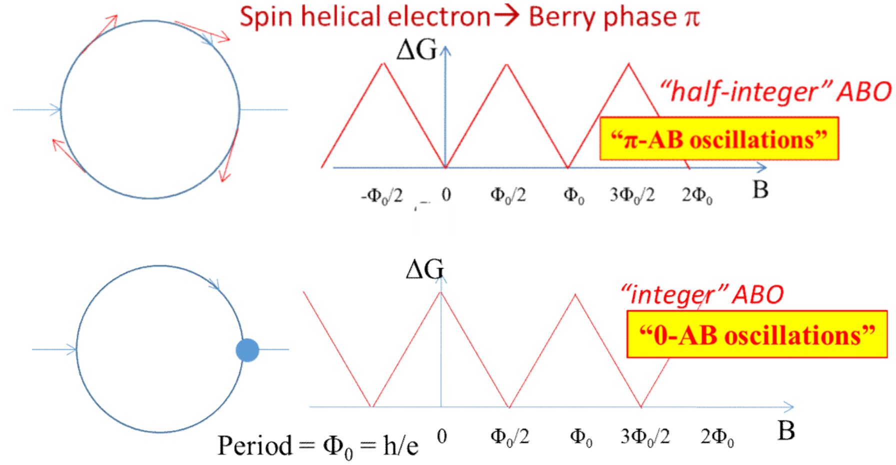
Dirac fermions: $\sigma_{xy}=g(N+1/2)e^2/h$
g=4 for graphene
g=1 for a TI surface

<u>Double Gated</u> TI QHE
(two surfaces independently gated to resolve its contribution)

Fingerprint#2: "half-integer" Aharonov-Bohm oscillations (ABO)



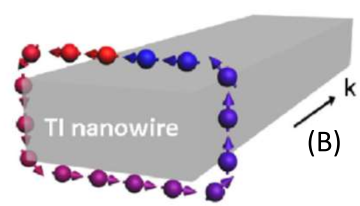


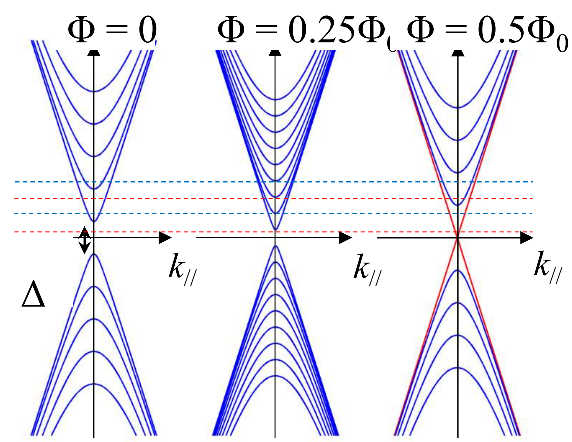


Luis Jauregui, et al. Nature Nanotechnology 11, 345 (2016)

Theories in TINW:
J. H. Bardarson, et al. PRL 105, 156803 (2010)
Y. Zhang, et al. PRL 105, 206601 (2010)
A. Cook, et al 2012 & 2011

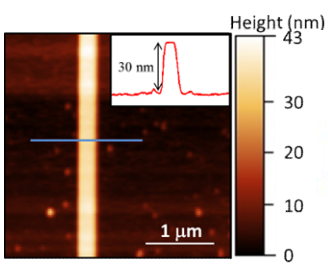
***alternating 0-ABO/pi-ABO periodic in k_F** due to*
quantized TSS sub-bands and B field driven topological transitions





VLS-grown TI (Bi_2Te_3)
Nanoribbon (NR)

in collab:
M. Pettes/L.Shi (UT Austin);
L. Rokhinson (Purdue)



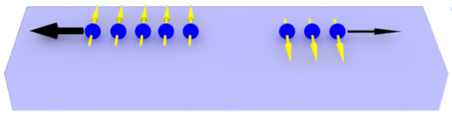
$$E_{kl} = \pm \upsilon_F \hbar \sqrt{k^2 + \frac{(l+1/2-\Phi/\Phi_0)^2}{R^2}}$$

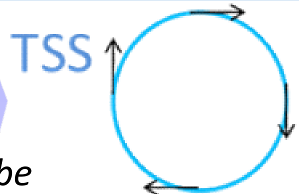
Berry-phase
(real space
rotation)--
not in CNT!

$$\vec{S} \sim \vec{k} \times \hat{n}$$

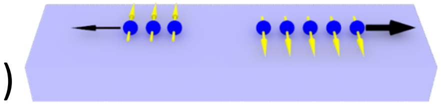
See also Bi_2Se_3: N. Mason'15 (exfoliated); Y. Cui'13 (VLS)

Spin potentiometry: measure *out-of-equilibrium* electron spin polarization ($\mu_\uparrow - \mu_\downarrow$)



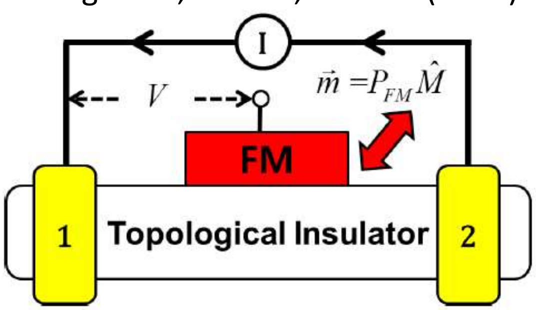


Current induced (helical) electron ***spin polarization*** (ESP)



Ferromagnet (FM): *spin-sensitive voltage probe*
[measures $\mu_\uparrow$ or $\mu_\downarrow$ depending on magnet spin orientation (controlled by B)]

Theory: Hong et al., PRB 86, 085131 (2012)



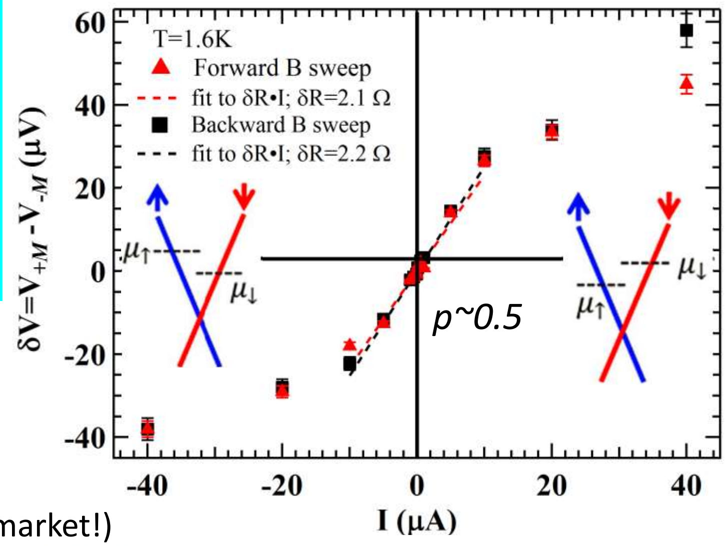
Valid from ballistic to diffusive regime

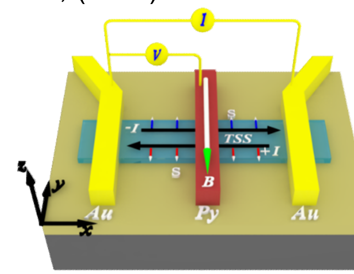
$$\Delta V = V(\vec{M}) - V(-\vec{M})$$
$$= I R_B \vec{p} \cdot \vec{m}$$
$$\frac{1}{R_B} = \frac{e^2}{h} \cdot \frac{k_F W}{\pi}$$

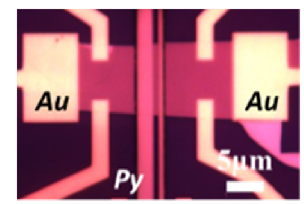
"Direction" ("sign") of step signal measures direction of channel spin polarization S!

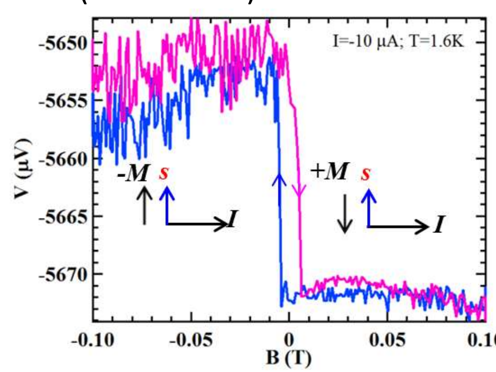
Dr. Jifa Tian (on market!)

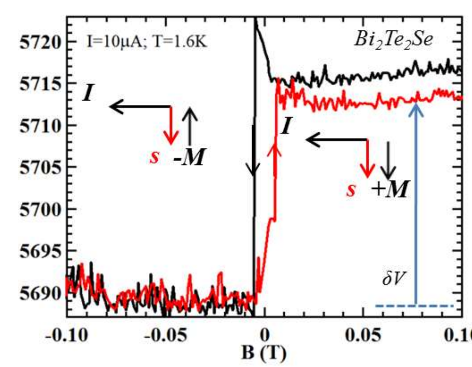
Experiment: J. Tian et al. *Sci. Rep.* 5, 14293, (2015)









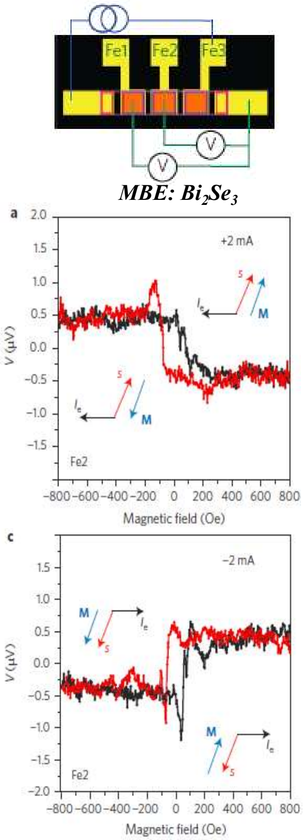


TI : **Bi_2Te_2Se** (BTS221) bulk-Insulating

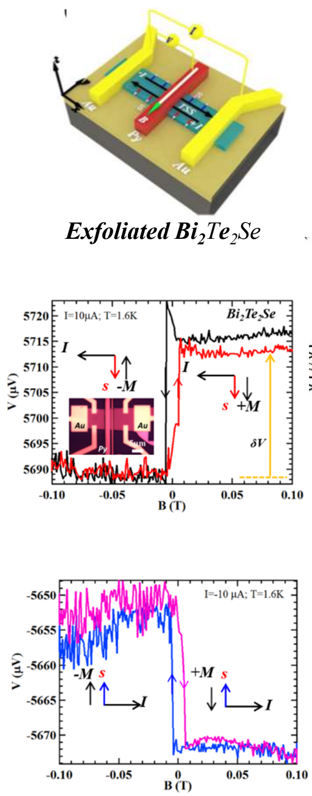
Exfoliated flakes (~40nm thick)

(0th order agreement)

Various spin transport/potentiometry measurements in TIs: current-induced electron spin polarization [*spin-momentum-locking*]

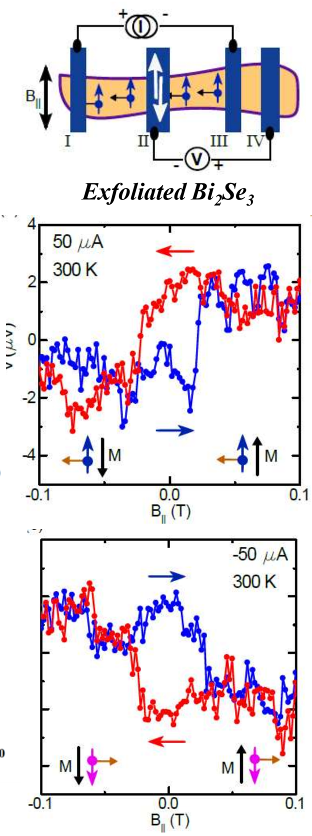


Li et al. *Nat. Nano* 9, 218–224 (2014)

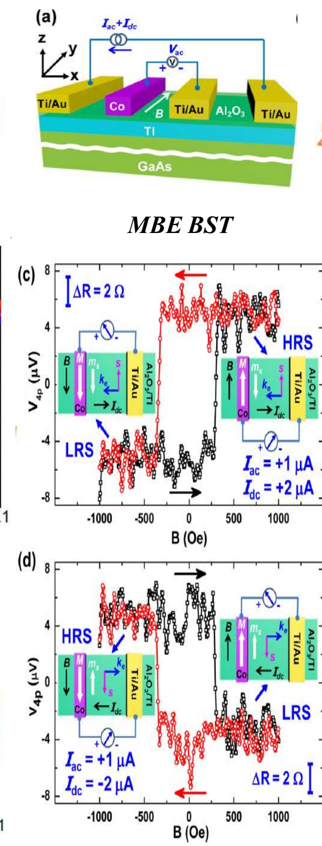


J. Tian et al. Sci. Rep. 5, 14293, (2015)

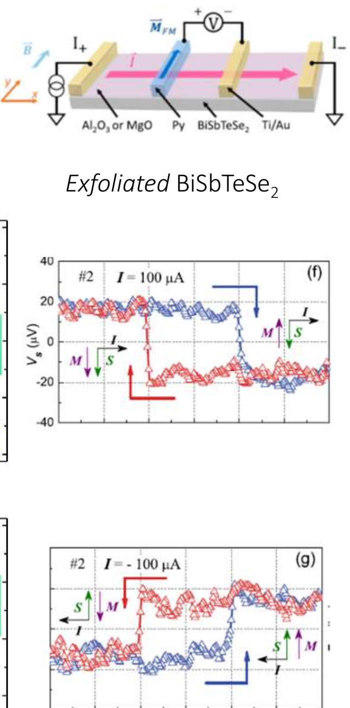
J. Tian et al. Sol. Sta. Comm.191, 1 (2014)



Dankert et al. Nano Lett'15



Tang et al. *Nano Lett.* 14, 5423–5429 (2014)



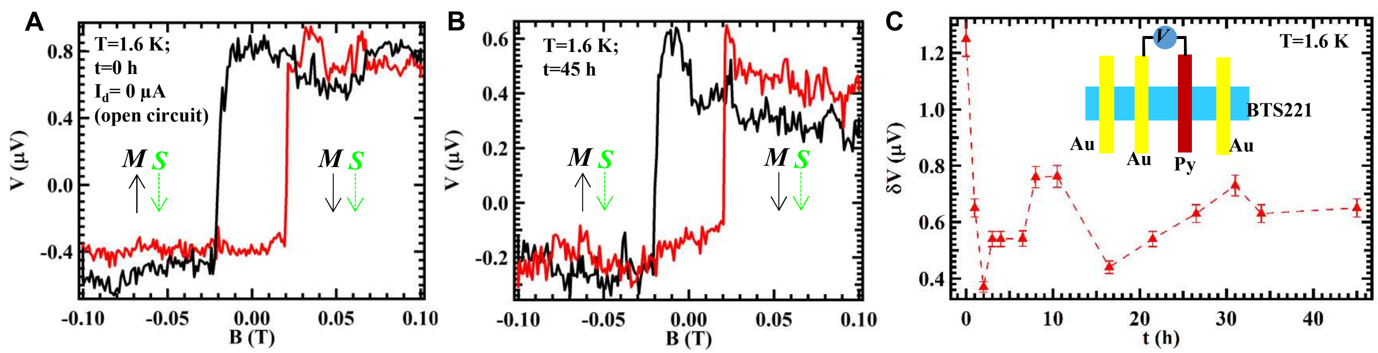
Yang et al. PRB 94 075304 (2016)

MBE Bi_2Se_3 & BST: Liu et al. PRB **91**, 235437 (2015) Lee et al. PRB 92, 155312 (2015)

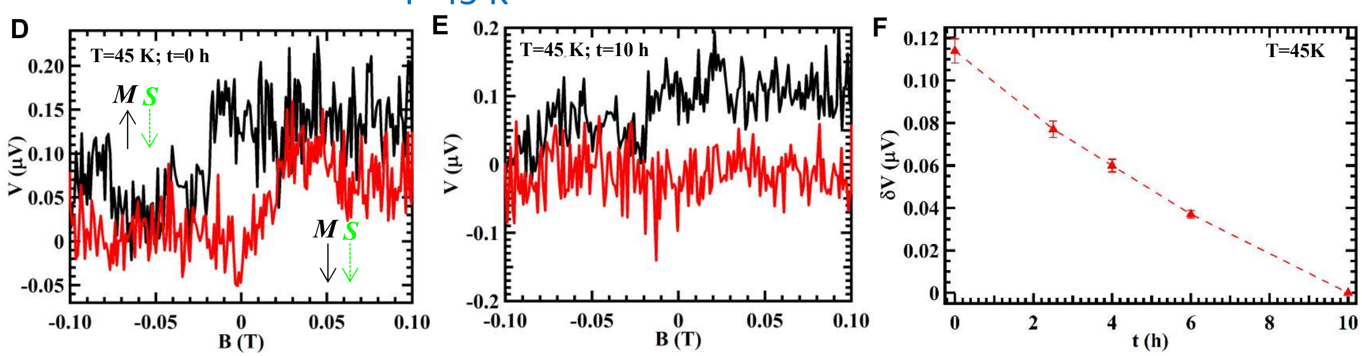
Persistent (days!) Spin Polarization/Potential even after current (I_d) is turned off --- spin battery/memory

Open circuit spin signal: T=1.6 K

lifetime > *45 h*



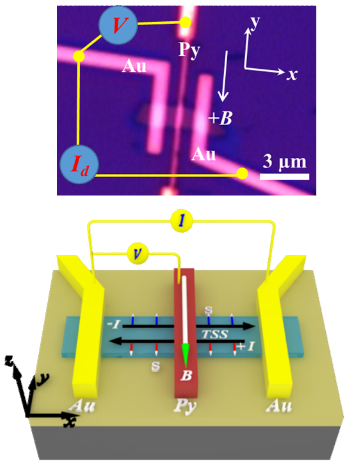
T=45 K

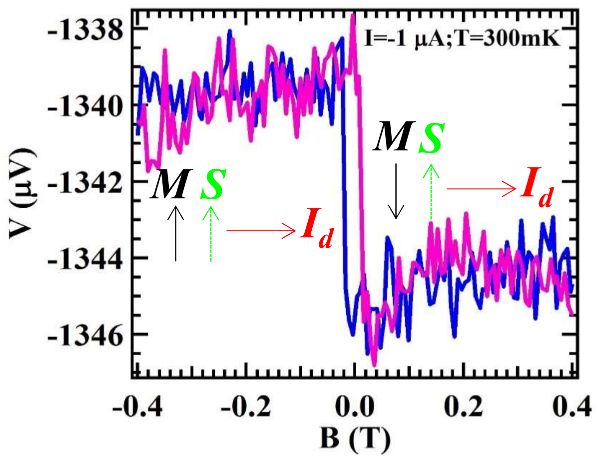


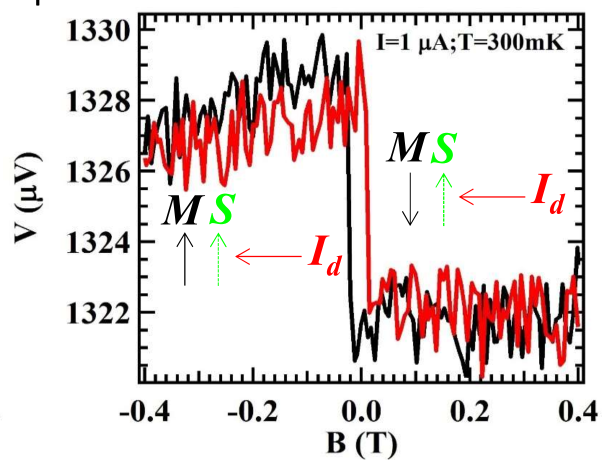
J. Tian et al. in press (2017)

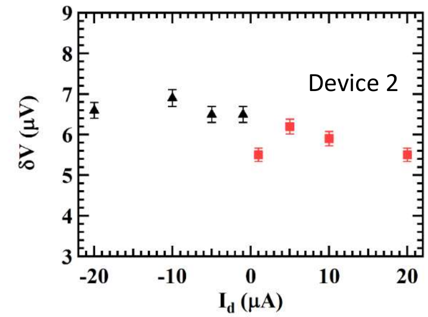
Spin polarization *independent* of (small) current I_d

current experiment





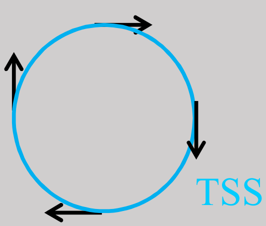


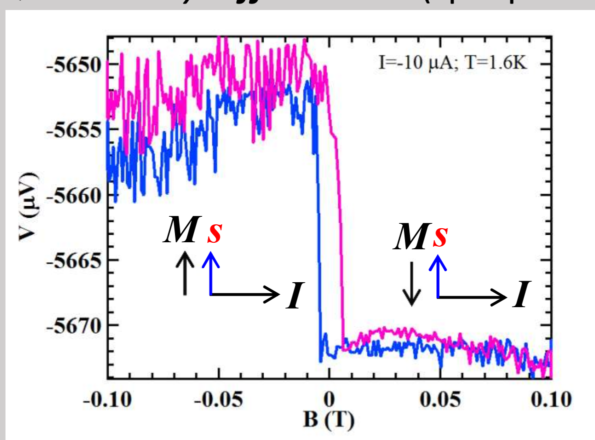


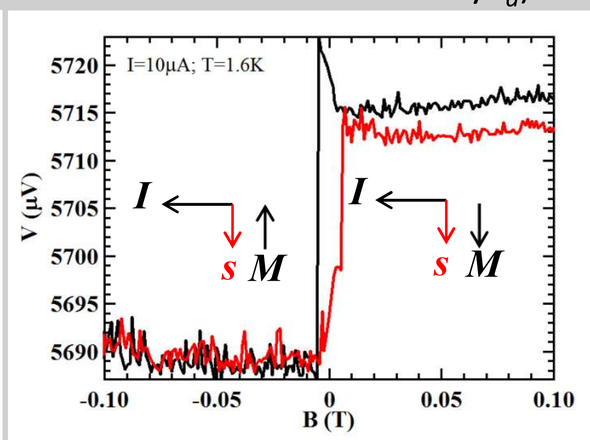
J. Tian et al. in press (2017)

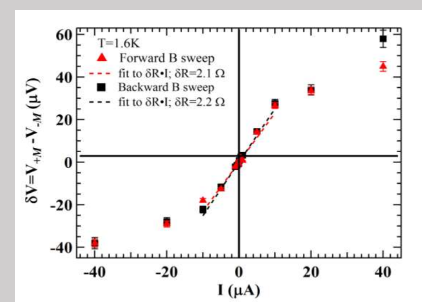
previous experiments

*Qualitatively **different**!* (spin polarization induced & reversible by I_d)!







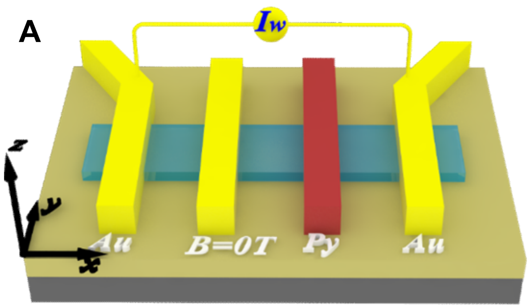


*J.Tian et al. Sci. Rep. **5**, 14293 (2015)*

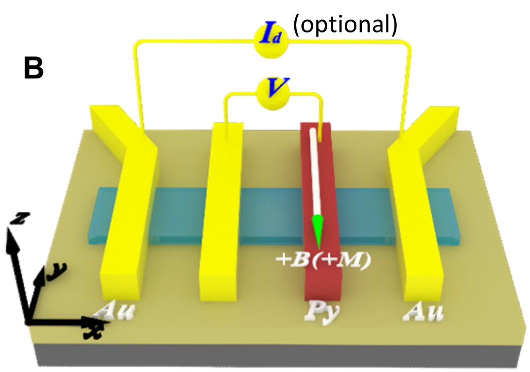
It’s a *rechargeable* (spin) battery!

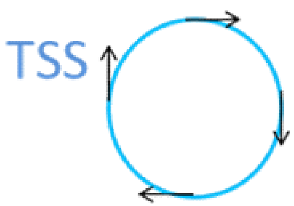
By a <u>large</u> “writing” current (I_w)

Current “Writing”

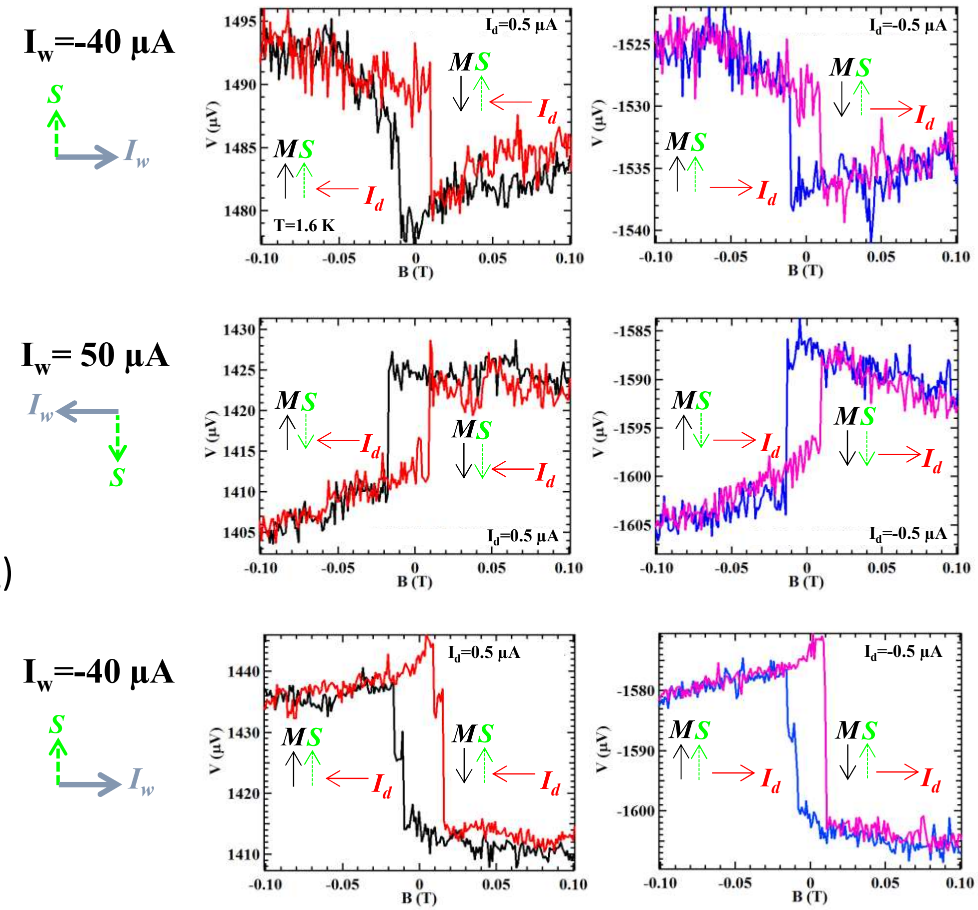


Spin potentiometry



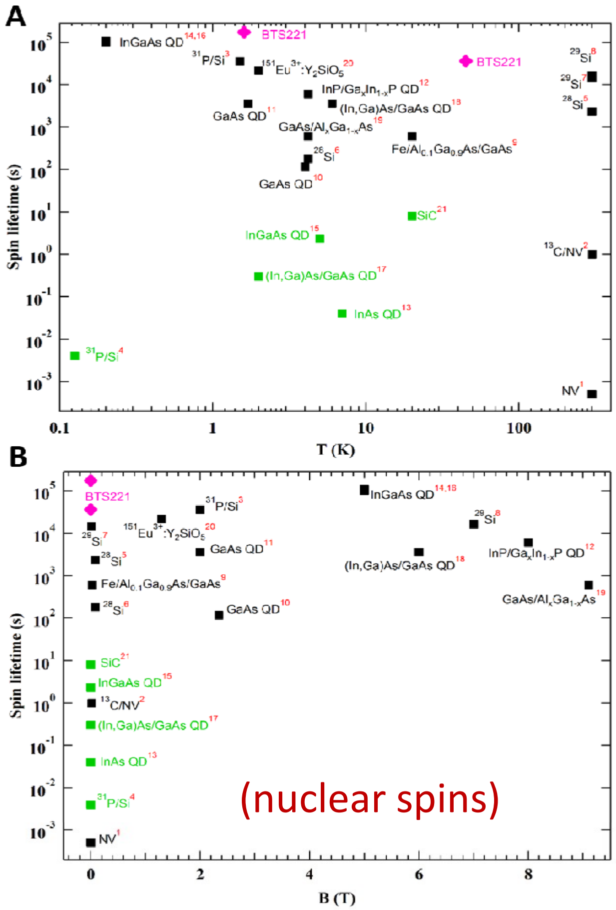


(locked to I_{write})
[via TSS]



J. Tian et al. in press (2017)

Why such extraordinarily long-lived spin polarization?

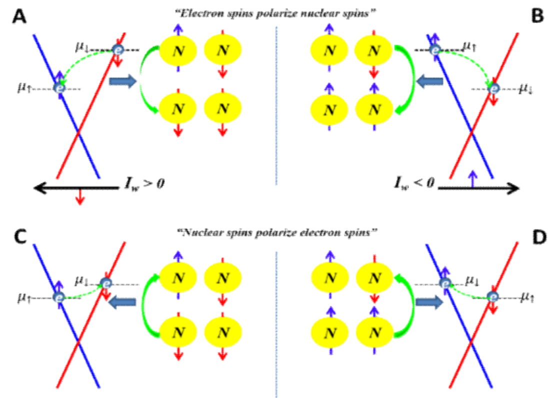


(spin helical) current induced Nuclear spin polarization?

dynamical nuclear polarization

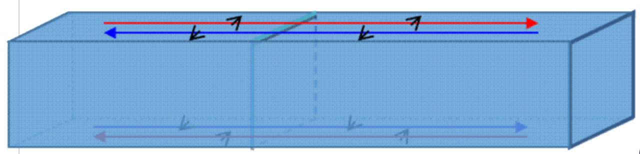
Nuclear spin polarization induces electron spin polarization?

(nuclear spin) powered spin battery



"charging battery"

"battery output"



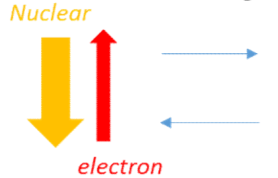
How do nuclear spins relax ?

(*unique physics involving* ***TSS spin-helical electrons****?*
different from conventional metal/semiconductors?
gradient from surface to bulk?)

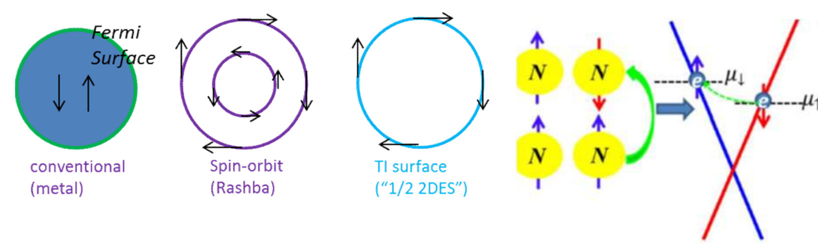
Coupled/locked nuclear spin – helical TSS electron spins?

$\vec{I} \cdot \vec{S}$

- *weakly breaks e-TRS*
- *gives N-e spin flops*



$\vec{k} \times \vec{S} \cdot \vec{n} + \vec{I} \cdot \vec{S}$



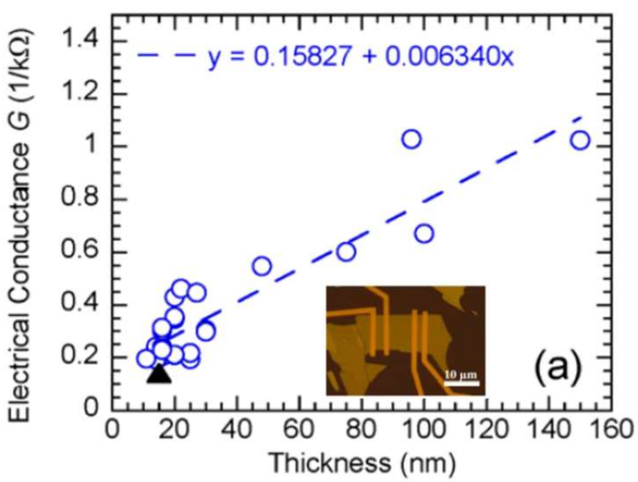
J. Tian et al. in press (2017)

Electronic & *Thermal* Conductance vs. Thickness

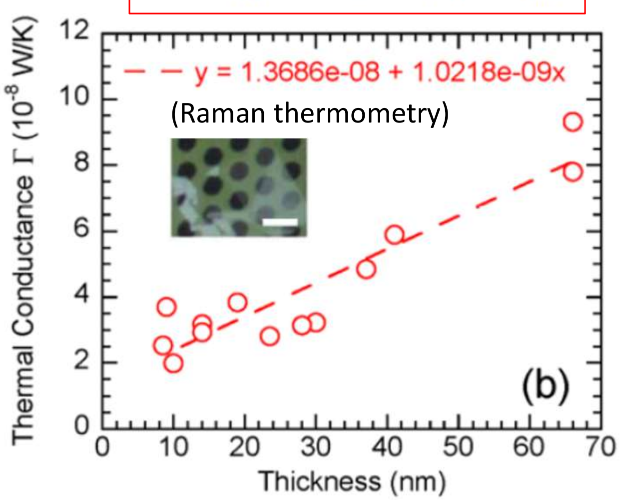
Z.Luo & J. Tian et al.
arXiv:1702.01716 (2017)
[collab: Xianfan Xu (Purdue ME)]

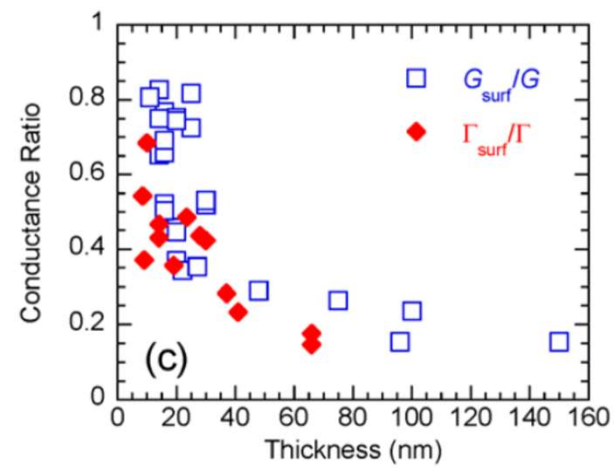
Material: Bi_2Te_2Se (BTS221)
@ **Room T** (300K)

$$G = G_{surf} + G_{bulk} = G_{surf} + \sigma_{bulk} t$$



$$\Gamma = \Gamma_{surf} + \Gamma_{bulk} = \Gamma_{surf} + k_{bulk} t$$





$$k_e/\sigma = \Gamma/G = LT.$$

$$L_0 = (\pi^2/3)(k_B/e)^2 = 2.45 \times 10^{-8}\ \mathrm{W{\cdot}\Omega{\cdot}K^{-2}}$$

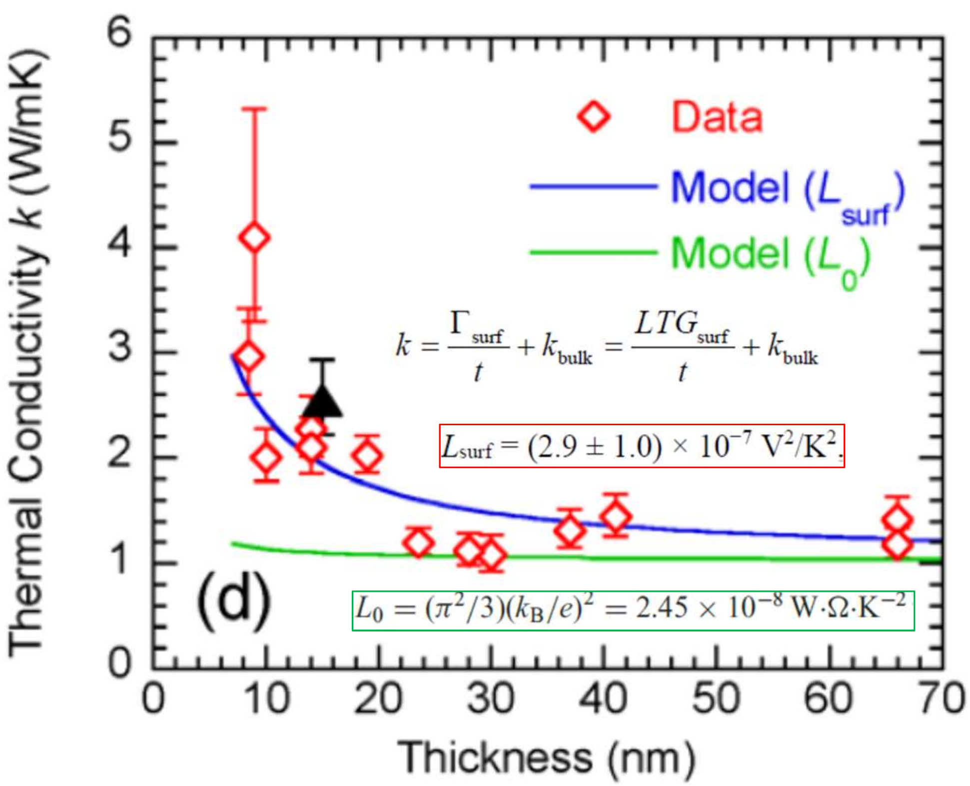
$$\Gamma_{surf}/G_{surf} = L_{surf} T$$

$$L_{surf} = (2.9 \pm 1.0) \times 10^{-7}\ \mathrm{V^2/K^2}.$$

Surprise: Large (~10X) enhancement of Lorenz number (violation of Wiedemann-Franz law)

~10 times!

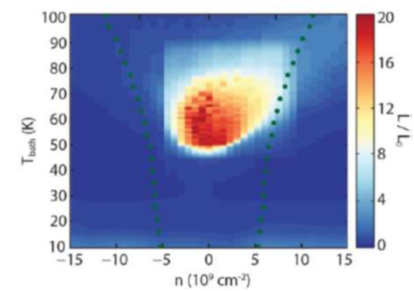
Large enhancement of Lorenz number (violation of Wiedemann-Franz law)



Z.Luo & J. Tian et al. arXiv:1702.01716 (2017)

Possible reasons:

- "Dirac fluid"?



Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] Kin Chung Fong[5*]

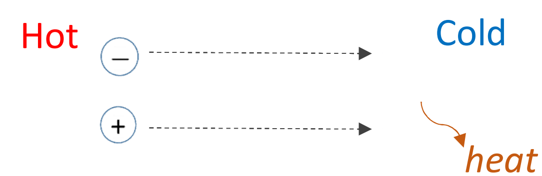
- "Bipolar diffusion"?

Significant Enhancement of Electronic Thermal Conductivity of Two-Dimensional Zero-Gap Systems by Bipolar-Diffusion Effect

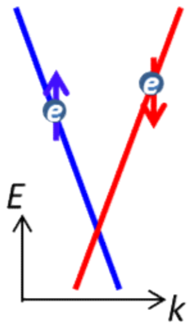
Journal of the Physical Society of Japan 84, 024601 (2015)

Harukazu Yoshino* and Keizo Murata

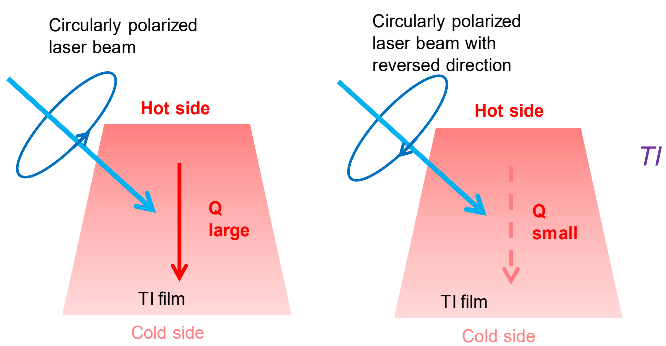
- ???

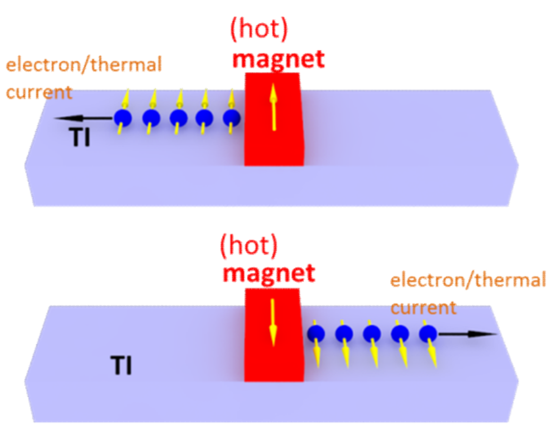


Can we have Topological Thermal Transport?: *spin-momentum-locked heat carriers*

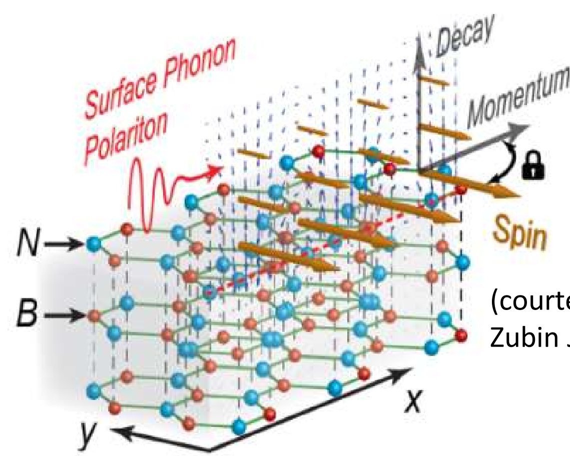


topological insulator (TI) surface **electrons**



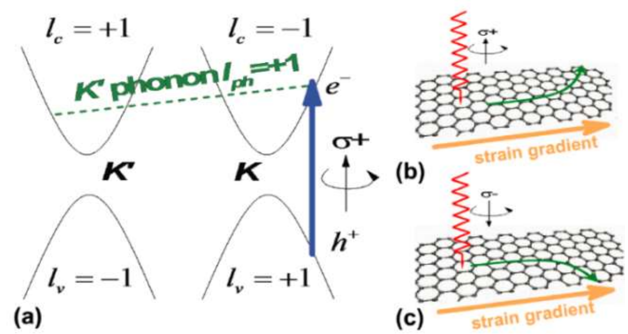


phonon-photon **polaritons**



(courtesy Zubin Jacob)

chiral **phonons**



Valley phonon Hall effect (courtesy Qian Niu)

NSF EFRI "NewLaw" (2016): Yong P. Chen, Xianfan Xu, Zubin Jacob (Purdue) & Qian Niu (UT Austin)

Summary: transport phenomena/signatures *unique* to (3D) topological insulators?

- **Charge transport [of "intrinsic" topological insulator]**
  - Topological conduction via surface state
  - "half-integer" quantum Hall effect (QHE) [½ e^2/h from each surface]
  - "half-integer" Aharonov-Bohm oscillation (ABO) [TI nanowire]

Y.Xu et al. Nature Phys. ***10****, 956 (2014);*
Y.Xu et al. Nature Comm. 7, 11434 (2016)

L.A.Jauregui et al., Nature Nanotech. 11, 345 (2016)

- **Spin transport**
  - Current-induced electron spin polarization (helical spin-momentum locking of TSS) [measured by spin potentiometry] *J. Tian et al. Sci. Rep. 5, 14293, (2015)*
  - **Current-induced persistent electron & nuclear [?] spin polarization** ***J. Tian et al. in press (2017)***
- **Thermal transport**
  - **Large enhancement of Lorenz number (violates Wiedemann-Franz)** ***Z. Luo & J. Tian et al. arXiv:1702.01716***
  - Topological thermal transport?