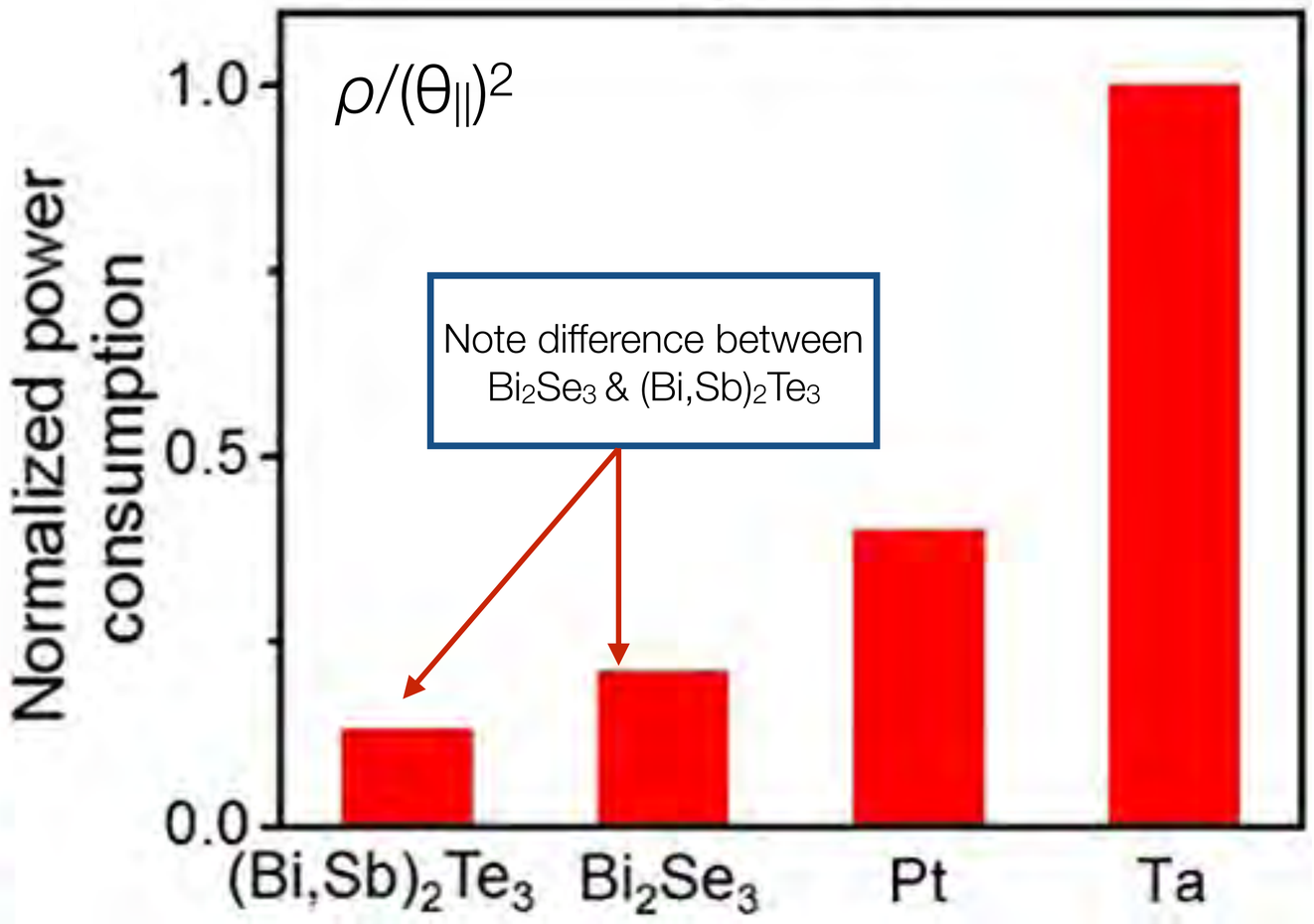
Topological vs. conventional spin torque devices

TI-based devices generate a more efficient spin torque with larger spin torque ratio and lower normalized power consumption compared with heavy metals.



Han *et al.*, *PRL* **119** 077702 (2017)

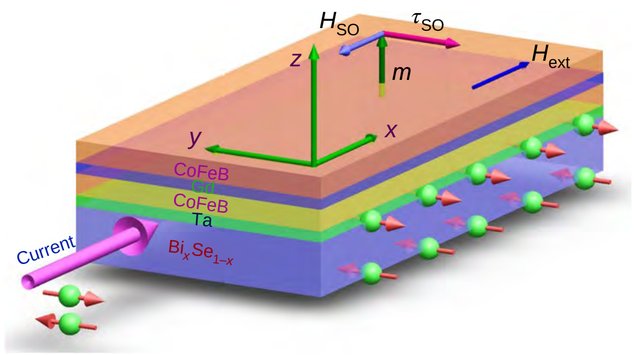
2D Crystal Consortium
NSF Materials Innovation Platform

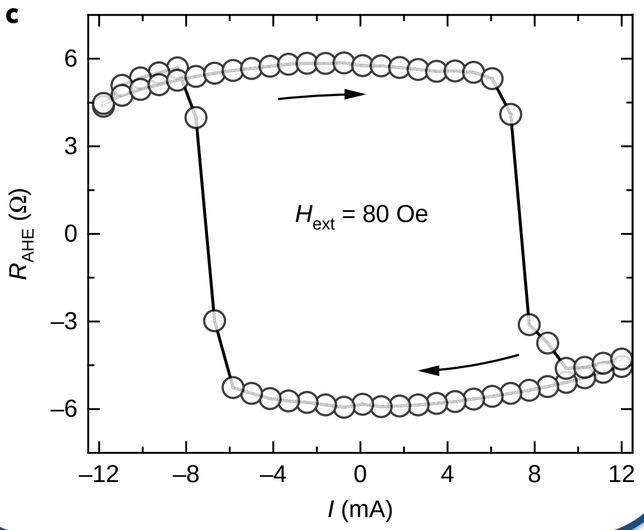
Direct spin torque switching in TI/FM devices

Sputtered
Bi_2Se_3
+ Ta/CoFeB

$\theta_{||}$ ~ 20
J_C ~ 0.4 MA/cm^2

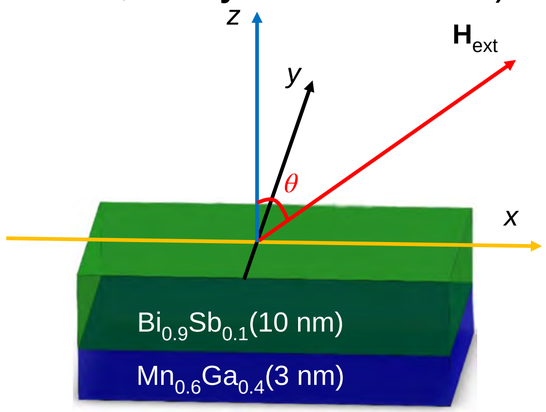
(JP Wang, Minnesota)

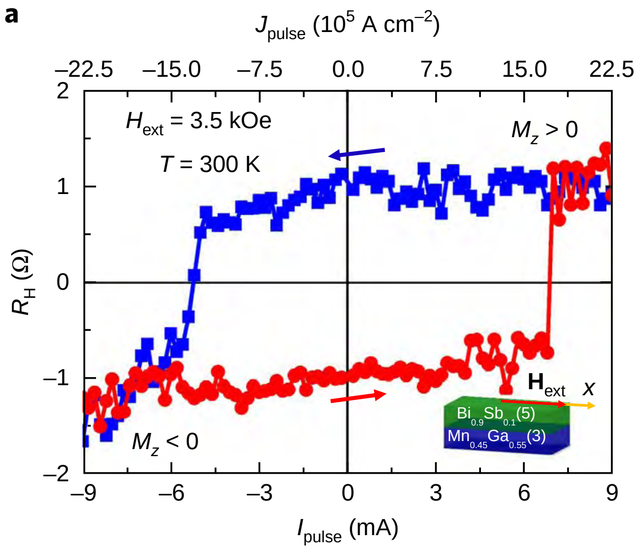




Mahindra *et al.*, *Nat. Mater.* **18** 800 (2018)

(PN Hai, Tokyo Inst. Tech.)





Khang *et al.*, *Nat. Mater.* **18** 808 (2018)

MBE:
$Bi_{0.9}Sb_{0.1}$
+ MnGa

$\theta_{||}$ ~ 50
J_C ~ 1.5 MA/cm^2

Topological spintronics: so we succeeded?

- Measurements of spin-charge conversion (spin Hall angle) show that this is higher in Bi_2Se_3 (and also $(Bi,Sb)_2Te_3$, $Bi_{1-x}Sb_x$) compared with heavy metals.

- Measurements of spin torque devices shows that these materials are also more energy efficient (e.g. MIT/Penn State, Minnesota).

- Looks attractive for technology — but have we understood the physics? Are there any holes in the story you just heard?

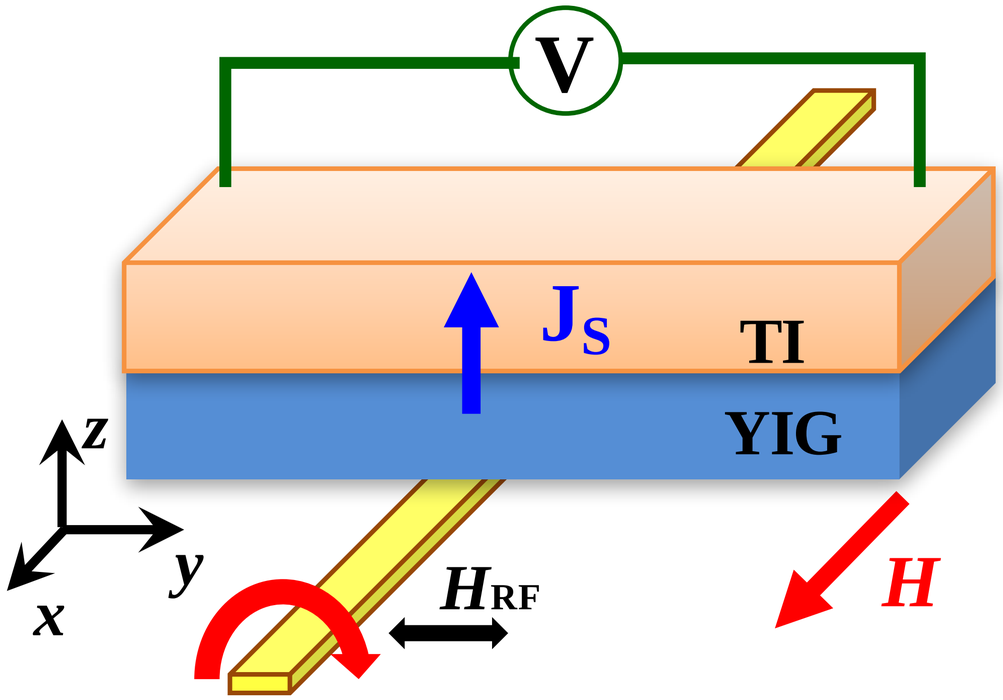
Topological spintronics: questions

- When a topological insulator surface is interfaced with a ferromagnetic metal, are the spin textured surface states unperturbed? Do they even exist at a TI/FM metal interface? [Zhang *et al*., *Phys. Rev. B* **94**, 014435 (2016)

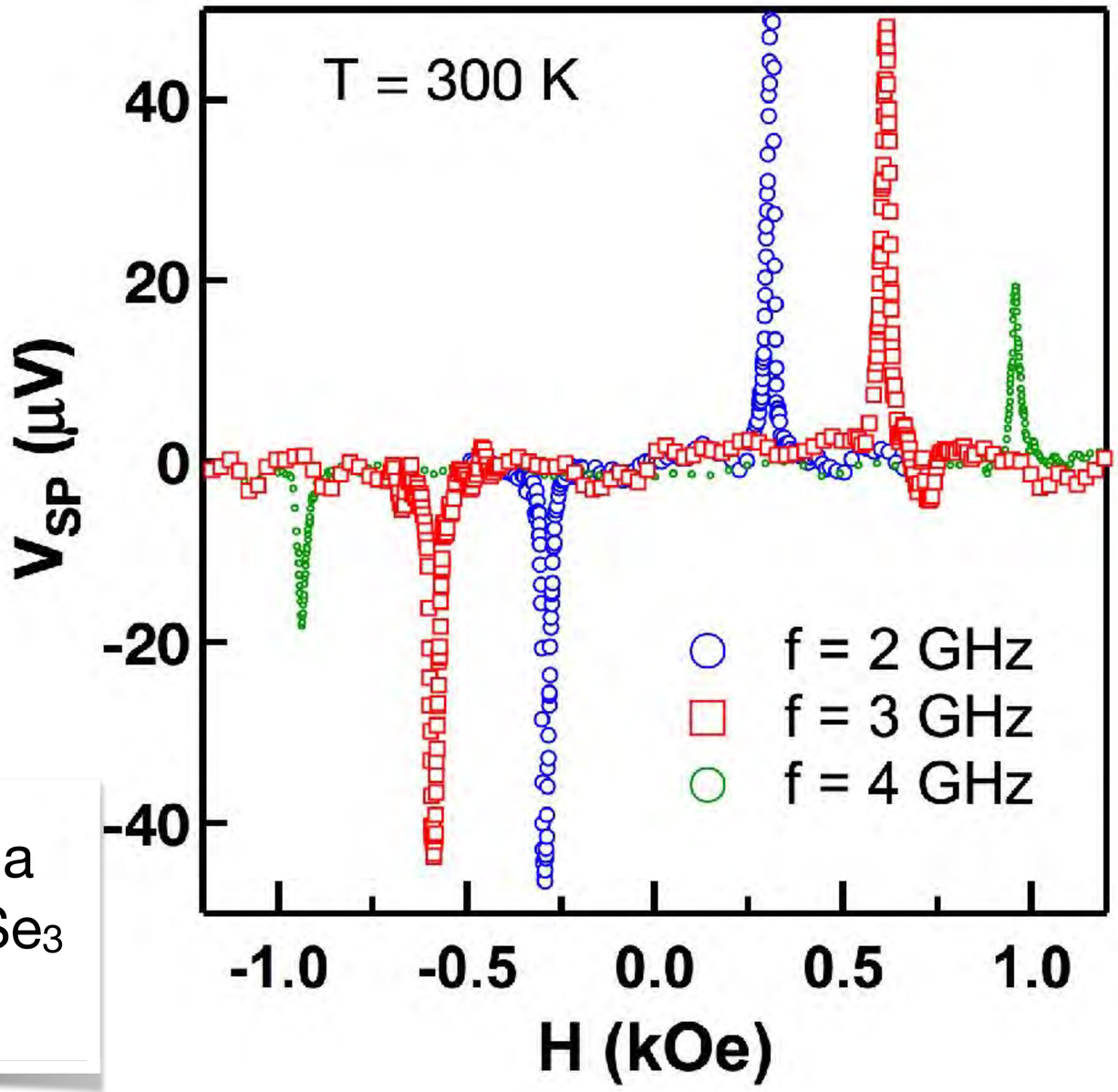
- In all the reported measurements of spin-charge conversion, where is the chemical potential (Fermi energy) located? [In most experiments so far, E_F is the bulk conduction band.]

- When we make bilayer lateral transport devices with a topological insulator and a ferromagnetic metal, where does most of the current flow? [Resistivity of FM metals << resistivity of Bi_2Se_3]

Spin pumping from FM insulator into Bi_2Se_3

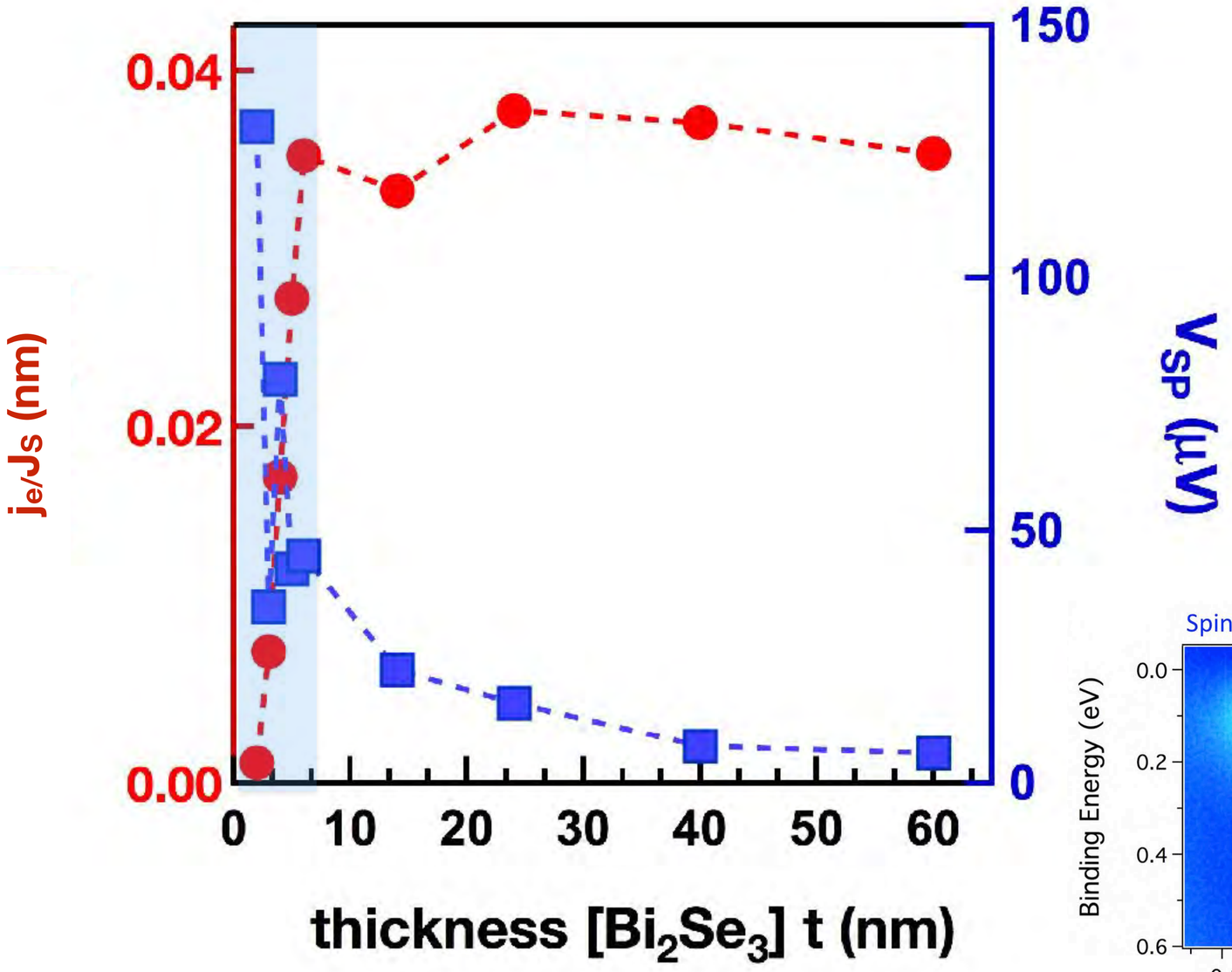


Hailong Wang *et al.*, PRL **117**, 076601 (2016).



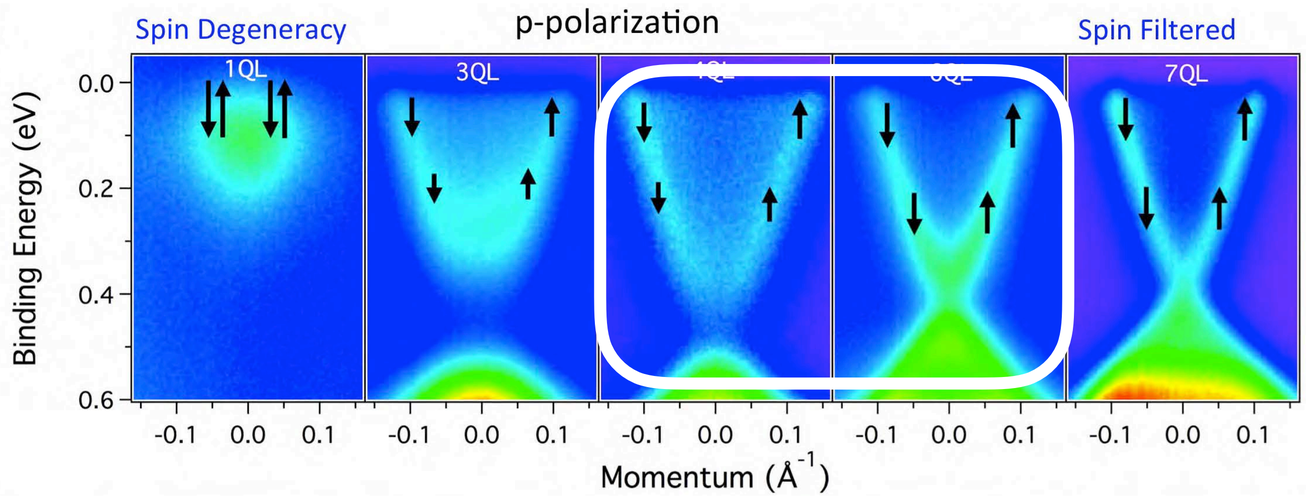
Spin pumping observed at 300 K from a **ferrimagnetic insulator** (YIG) into Bi_2Se_3 thin films.

Spin pumping from FM insulator into Bi_2Se_3

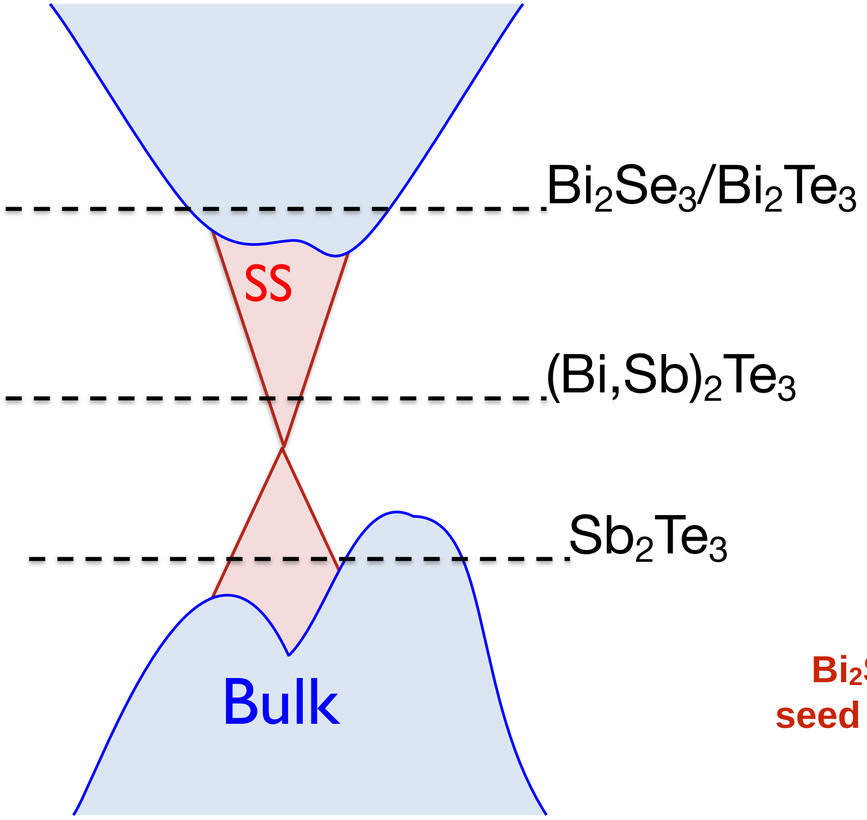


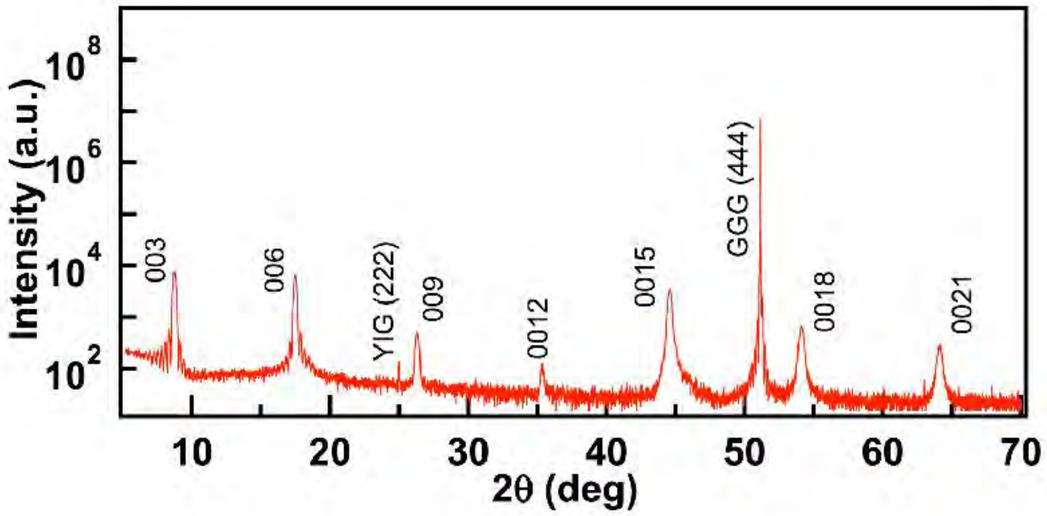
Hailong Wang *et al.*, PRL **117**, 076601 (2016).

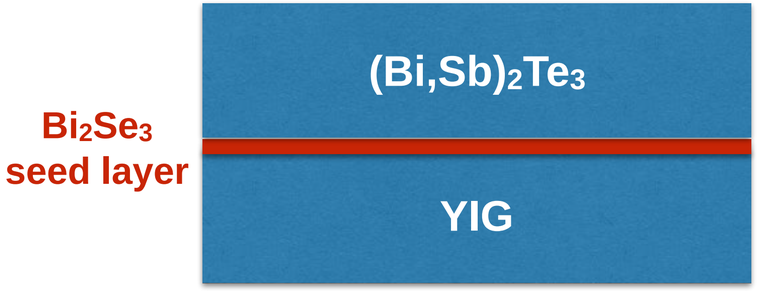
Bi_2Se_3 thickness dependence of spin pumping signal from YIG suggests dominant role of interface or surface states. But, we still have bulk conduction…!

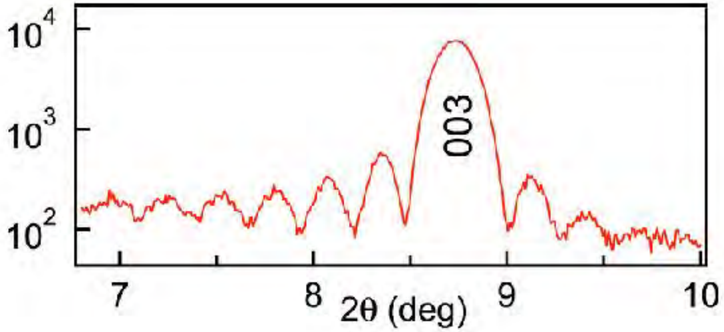


Probing spin pumping as a function of chemical potential



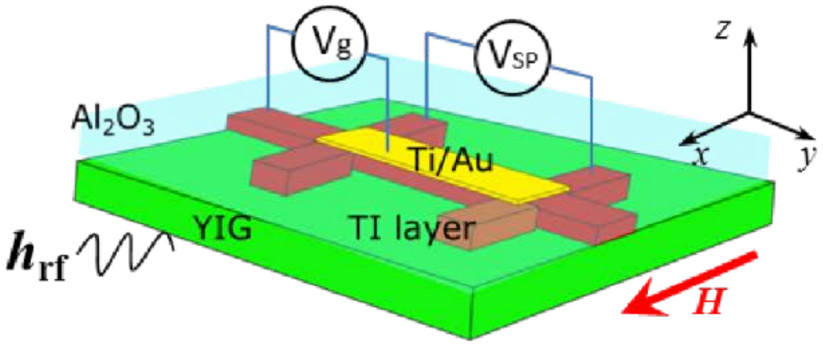






Use $(Bi_xSb_{1-x})_2Te_3$ either with gating or varying composition.
As grown films have low enough carrier density to allow gating across Dirac point.
Caveat: films grown on YIG with 1QL seed layer of Bi_2Se_3
Varying composition takes films from p-type (Sb_2Te_3) to n-type (Bi_2Te_3).

Spin-charge conversion vs. chemical potential



$$j_e / J_S = \lambda_{\mathrm{IREE}}$$

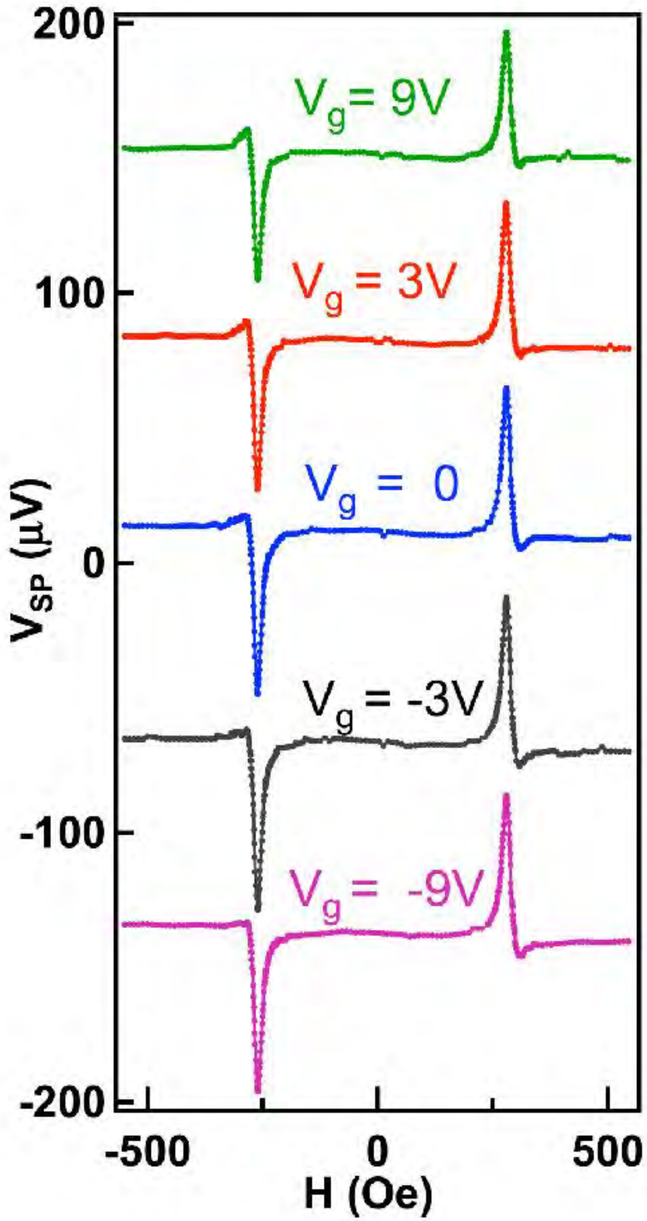
$$J_S = f\left(\omega, g_{\uparrow\downarrow}, \Delta H_{pp}, M_S, h_{RF}\right)$$

$$j_e = V_{SP} / Rw$$

For convenience, focus on:

$$\frac{V_{SP}}{R} \propto \frac{j_e}{J_S} = \lambda_{IREE}$$

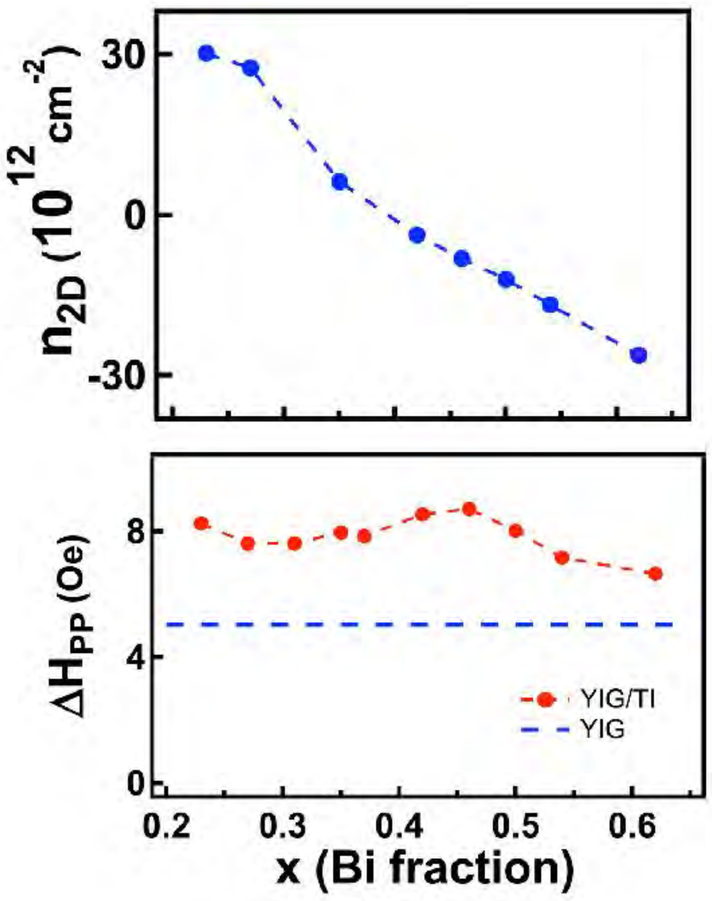
Chemical potential in YIG/$(Bi,Sb)_2Te_3$ bilayers varied through Dirac point using a top gate.

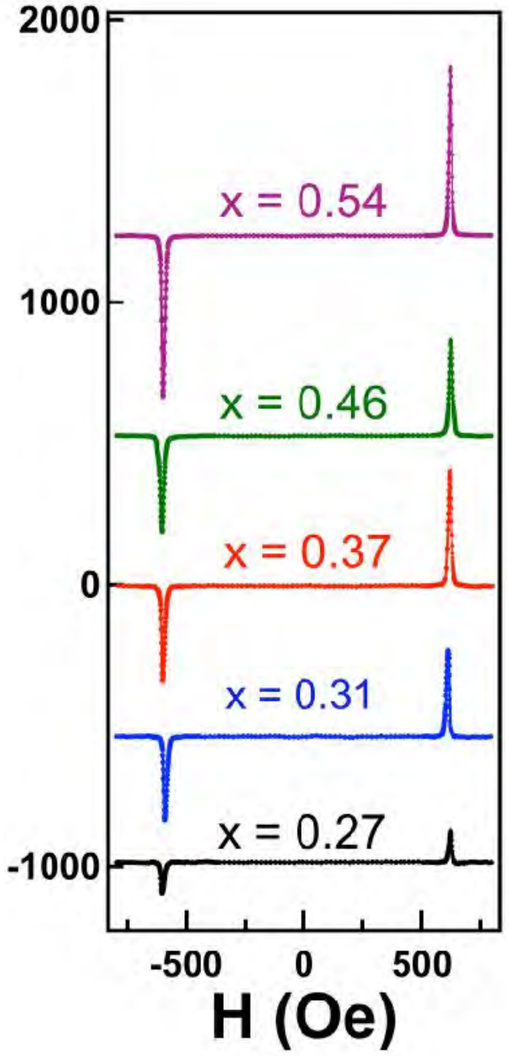


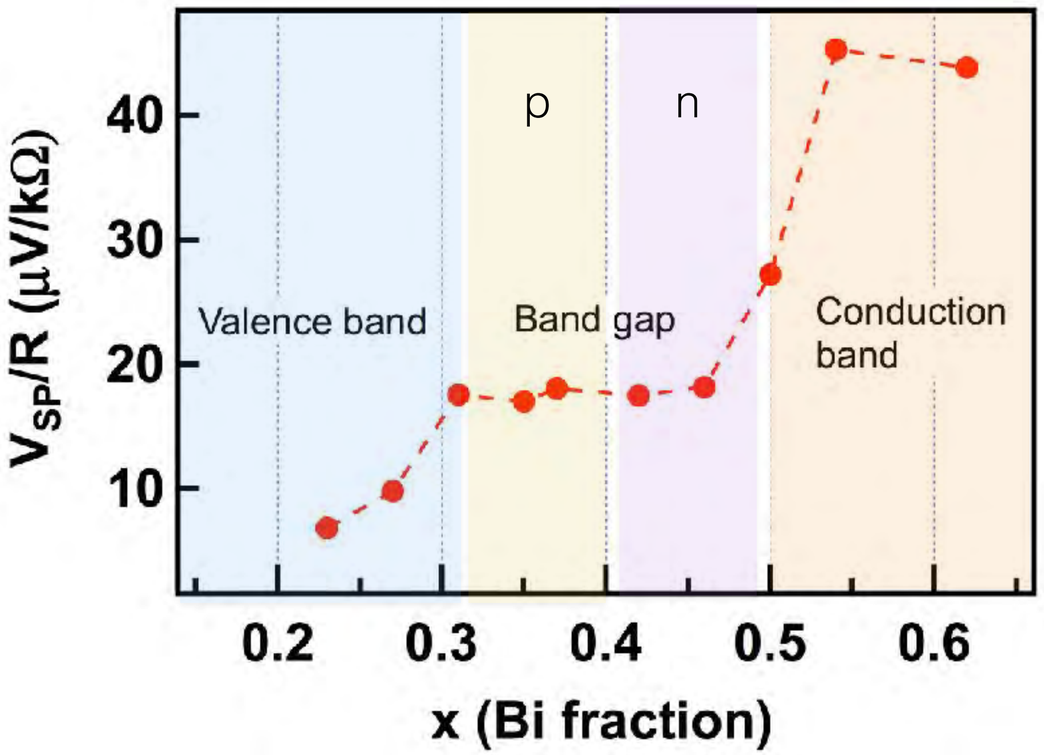
Hailong Wang *et al, submitted*

Spin-charge conversion vs. chemical potential

Hailong Wang *et al, submitted*







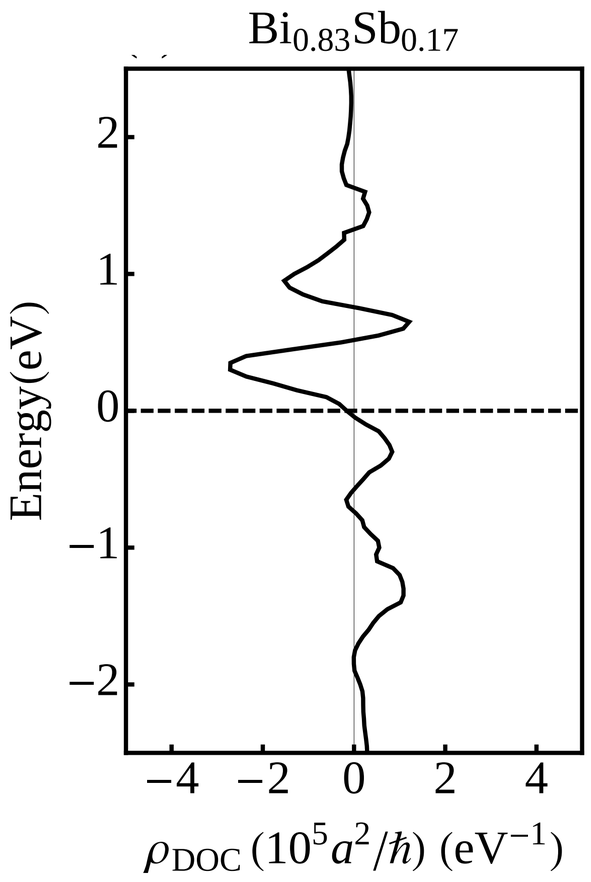
Systematic measurements of spin pumping in YIG/$(Bi,Sb)_2Te_3$ bilayers as a function of chemical potential. Chemical potential varied using either gate voltage or sample composition (extrinsic unintentional doping). *Spin-to-charge conversion efficiency is independent of chemical potential within surface states.*

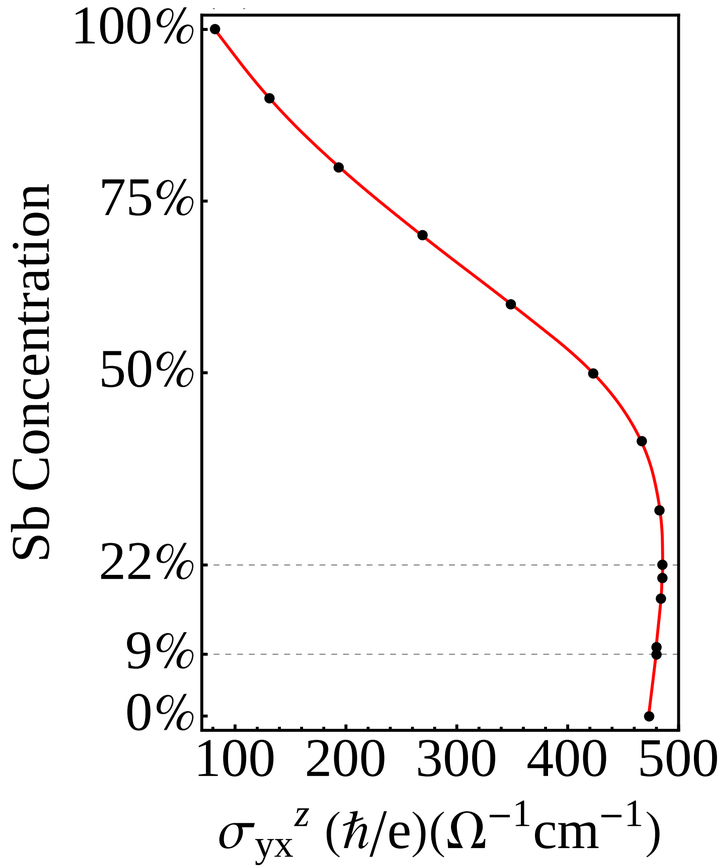
Calculation of spin Hall conductivity in TIs

$$\sigma_{\parallel} = \frac{e\hbar}{V}\sum_{\vec{k}}\sum_{n} f_{\vec{k}n}\Omega_n^z\left(\vec{k}\right)$$

$$\Omega_n\left(\vec{k}\right) = \sum_{n\neq n'}\frac{\left\langle u_{n\vec{k}}\middle|j_y\middle|u_{n'\vec{k}}\right\rangle\left\langle u_{n\vec{k}}\middle|\hat{v}_x\middle|u_{n'\vec{k}}\right\rangle}{\left(E_{n\vec{k}}-E_{n'\vec{k}}\right)^2}$$

$$\sigma_{\parallel} = \frac{e\hbar}{V}\int_{-\infty}^{\infty} f\left(\varepsilon\right)\rho_{\mathrm{DOC}}\left(\varepsilon\right)d\varepsilon$$

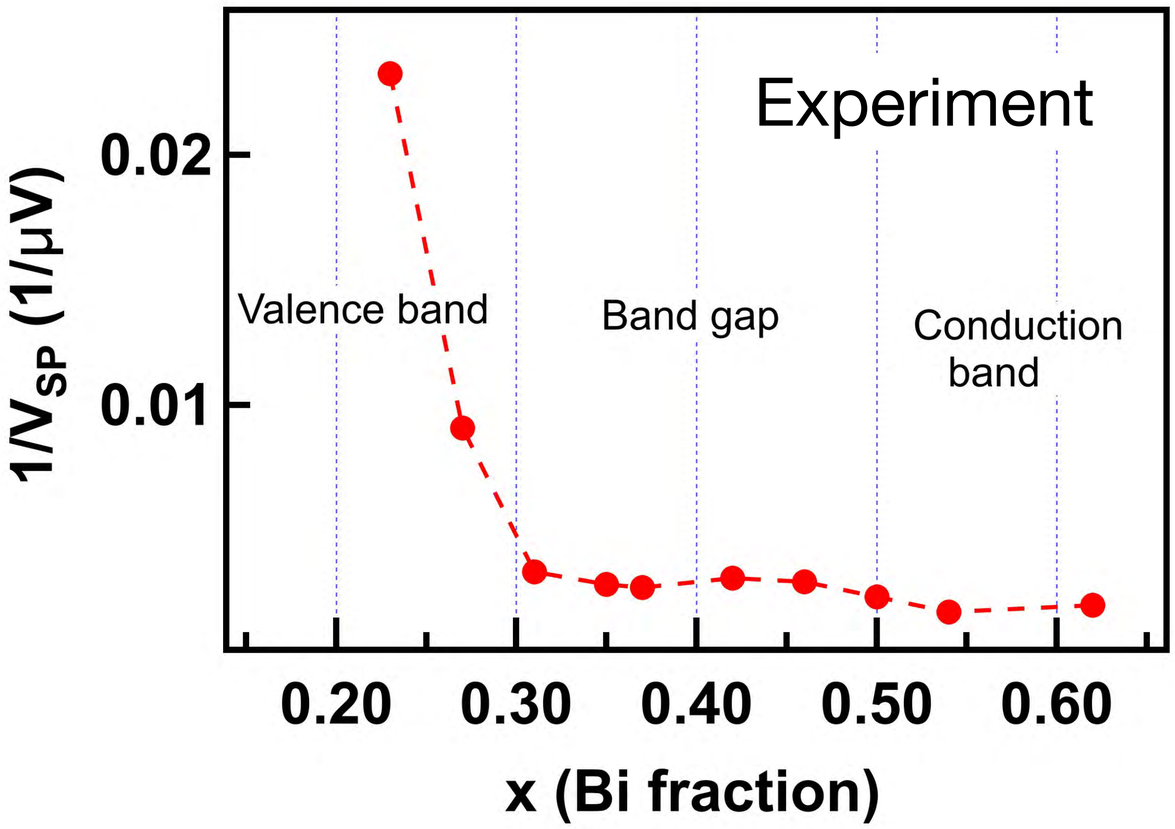




Sahin & Flatte, *PRL* **114**, 107201 (2015)

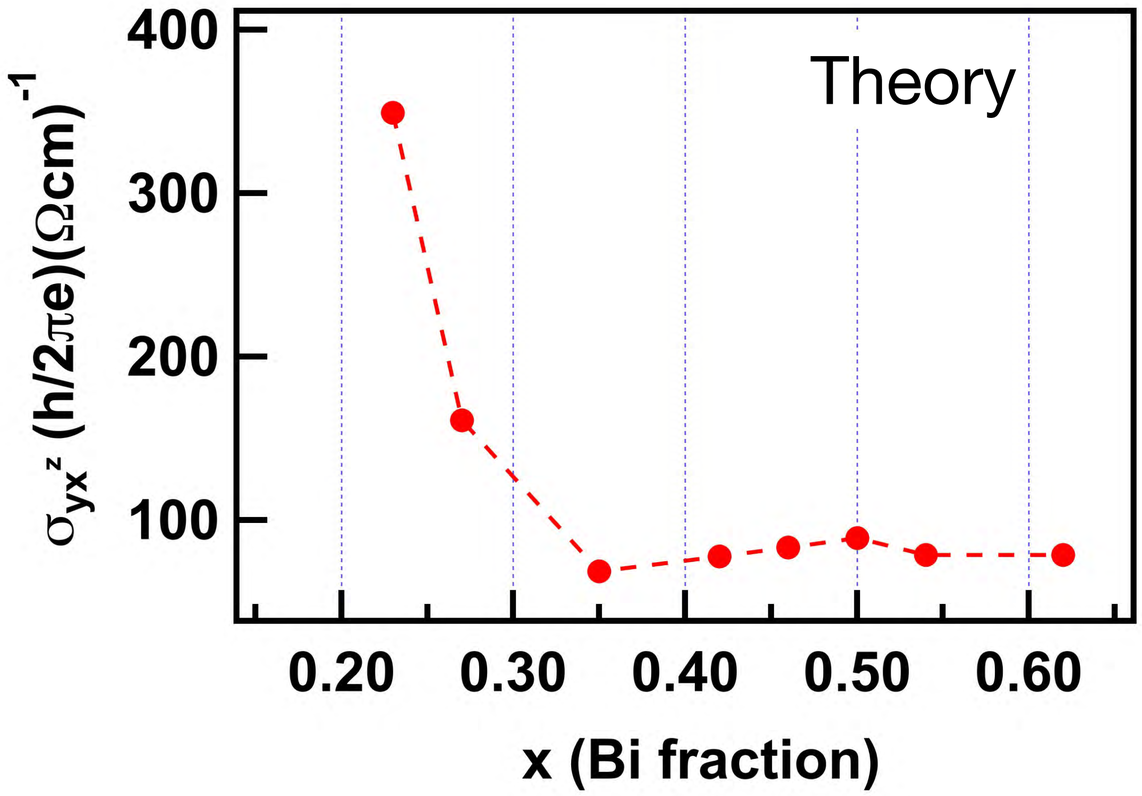
Spin Hall conductivity calculated using bulk states in $Bi_{1-x}Sb_x$ (strong TI for $0.07 < x < 0.22$)
Kubo formula relates $\sigma_{\parallel}$ to 'density of Berry curvature.'
Bulk-edge correspondence: spin-orbit coupling of bulk states yields same $\sigma_{\parallel}$ as surface states.

Spin-charge conversion vs. chemical potential



Hailong Wang *et al, submitted*

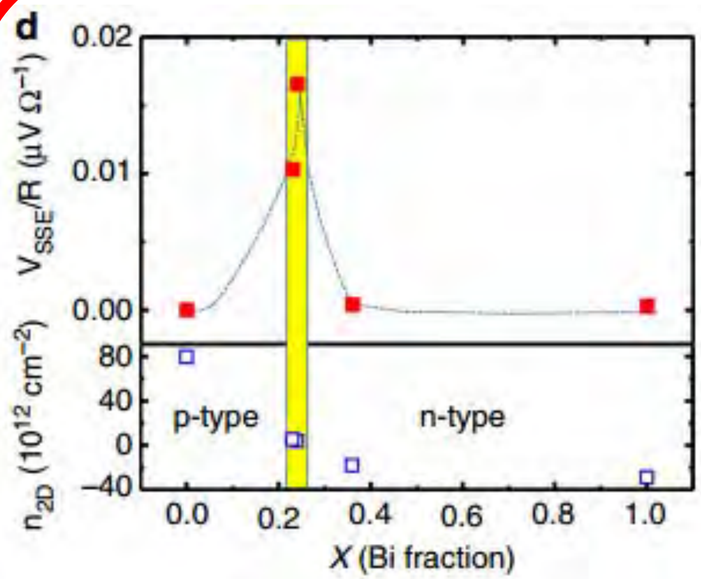
Do only surface states matter?
New experiments + theory indicate that the answer is more subtle & deeper…

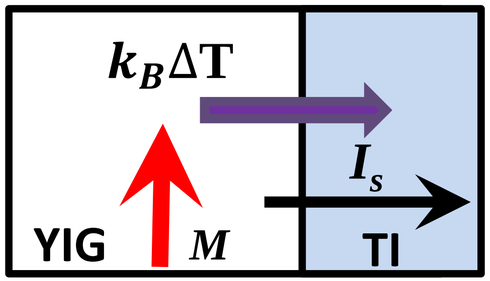


'Bulk-surface correspondence' suggests that bulk states & surface states both contribute to spin Hall conductivity

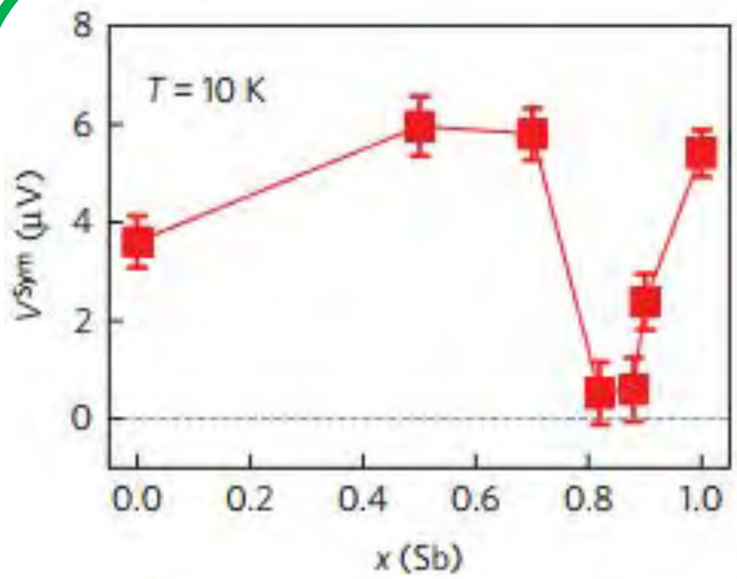
Spin-charge conversion variation with E_F: an alternate picture

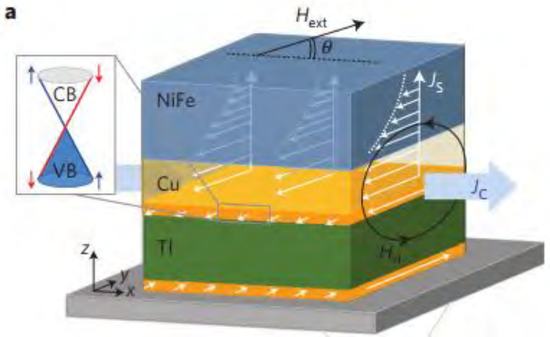
J. Shi
(UC Riverside)
$(Bi,Sb)_2Te_3$ + YIG





Nature Comm. **7**, 11458 (2016)



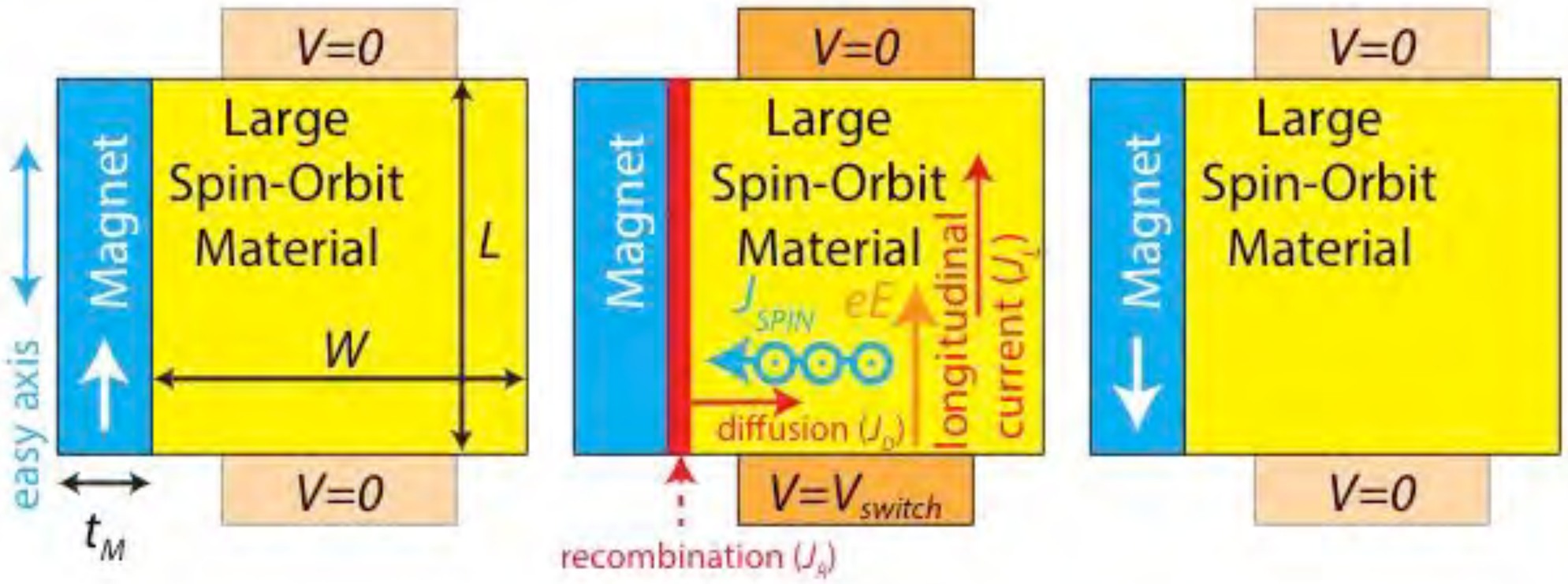


Nature Physics (2016) doi:10.1038/nphys3833

Otani
(Tokyo)

A unique topological spintronic device proposal

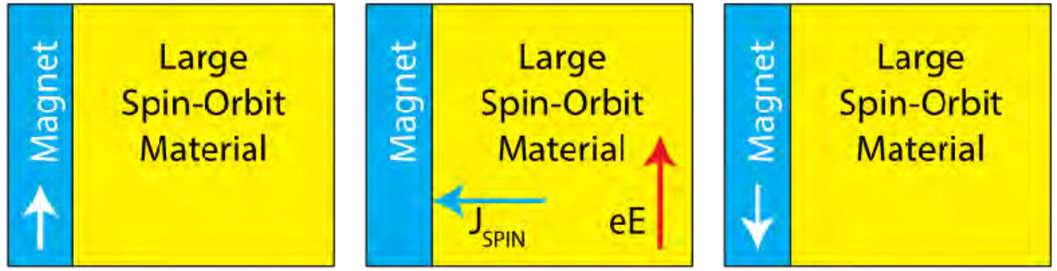
- Spin-charge conversion at topological insulator/ferromagnetic insulator interfaces for a “voltage-driven topological spin switch”
- Relies on the “global” effects of spin-orbit coupling in entire topological insulator band structure, not just surface states.

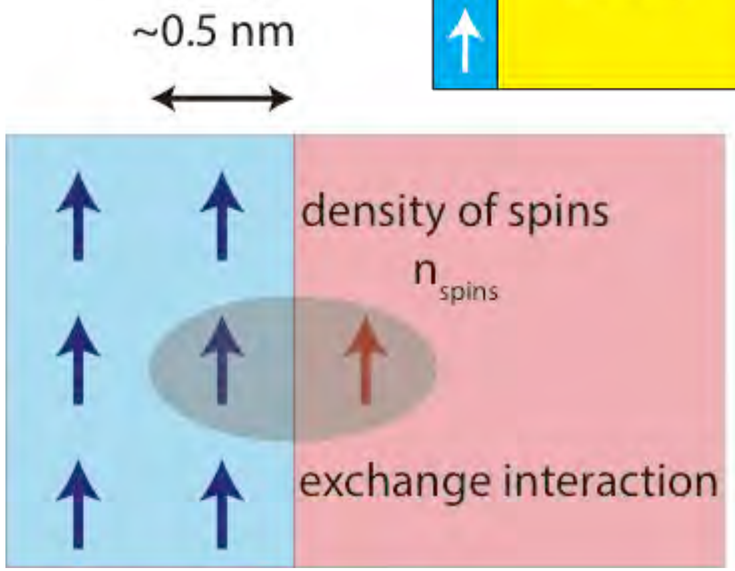


A ‘synthetic multiferroic’ for spin-based logic or memory that uses strong SO coupling in insulating bulk of TI.

Flatte, AIP Advances **7**, 055923 (2017)

VTSS: Predicted Performance





$$\frac{dn_{spins}}{dt} = \frac{\sigma_{SHC}}{\hbar/2}\frac{V_{switch}}{L} = \frac{200\mathrm{THz}}{\mathrm{nm}^2}\frac{V_{switch}}{\mathrm{Volts}}$$

$$\nu_{switch} = 600\mathrm{GHz}\left(\frac{V_{switch}}{\mathrm{Volts}}\right)^{1/2}$$

$$E = \frac{1}{2}CV_{switch}^2 = \frac{\epsilon_0\epsilon_r A V_{switch}^2}{L}$$

Assuming a switching voltage of 50 mV ⇒100 GHz switching rate &

10 meV switching energy: energy-delay product ~3 x 10^{-32} J.s.

C-SPIN

Flatte, AIP Advances **7**, 055923 (2017)

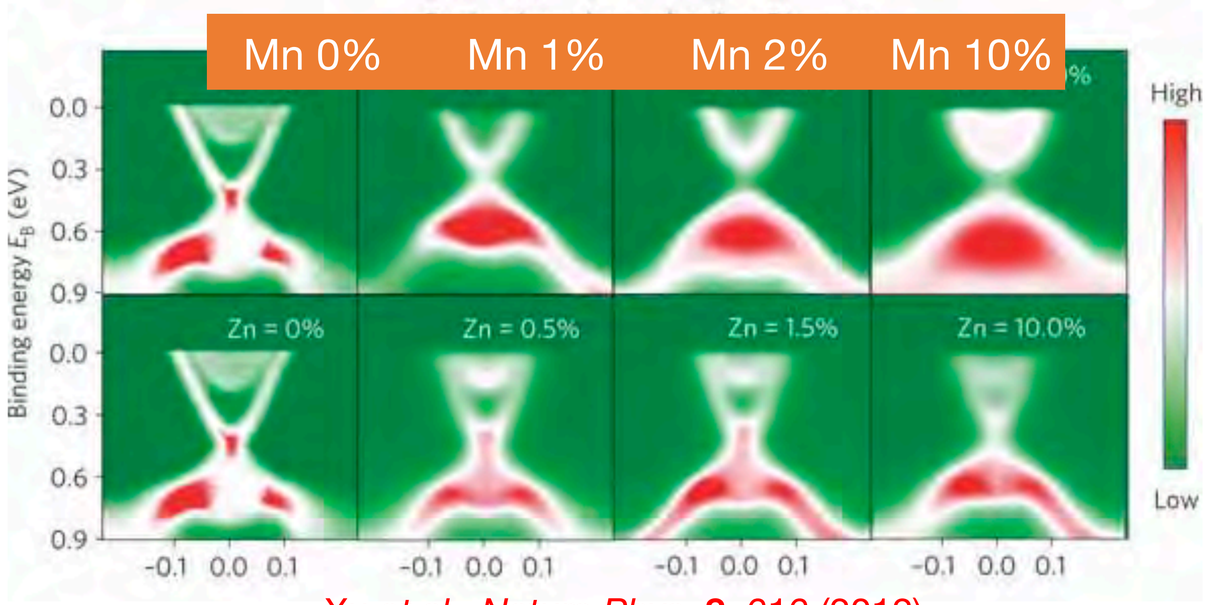
STARnet

VTSS: Topological surface states as leakage

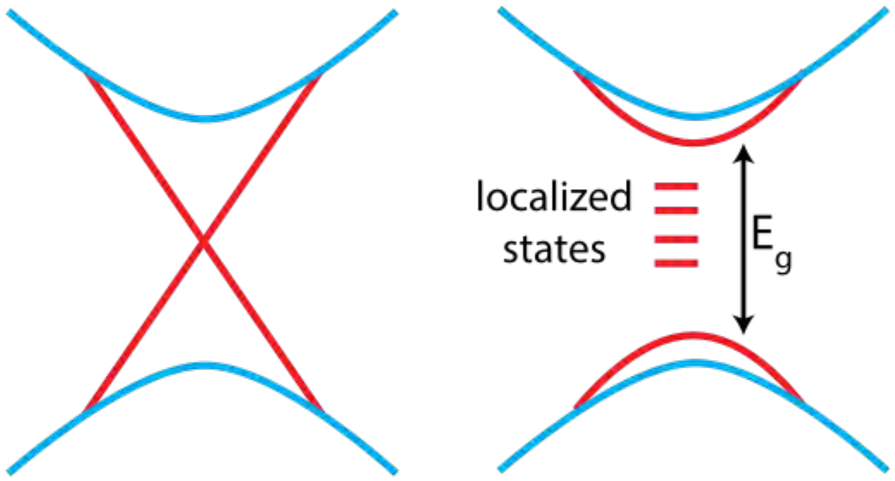
Sources of dissipation:

- Charge transport in bulk
- Charge transport in surface states
- Spin recombination current at interface
- Spin diffusion current into bulk.

$$H = v\left[k_x\sigma_y - k_y\sigma_x\right] + b_z\sigma_z$$



Xu *et al.*, *Nature Phys.* **8**, 616 (2012)
Sanchez-Barriga *et al.*, *Nature Comm.* **7**, 10559 (2016)



Flatte: use magnetic doping of TI to gap the surface states and electrical gating to place chemical potential into gap..

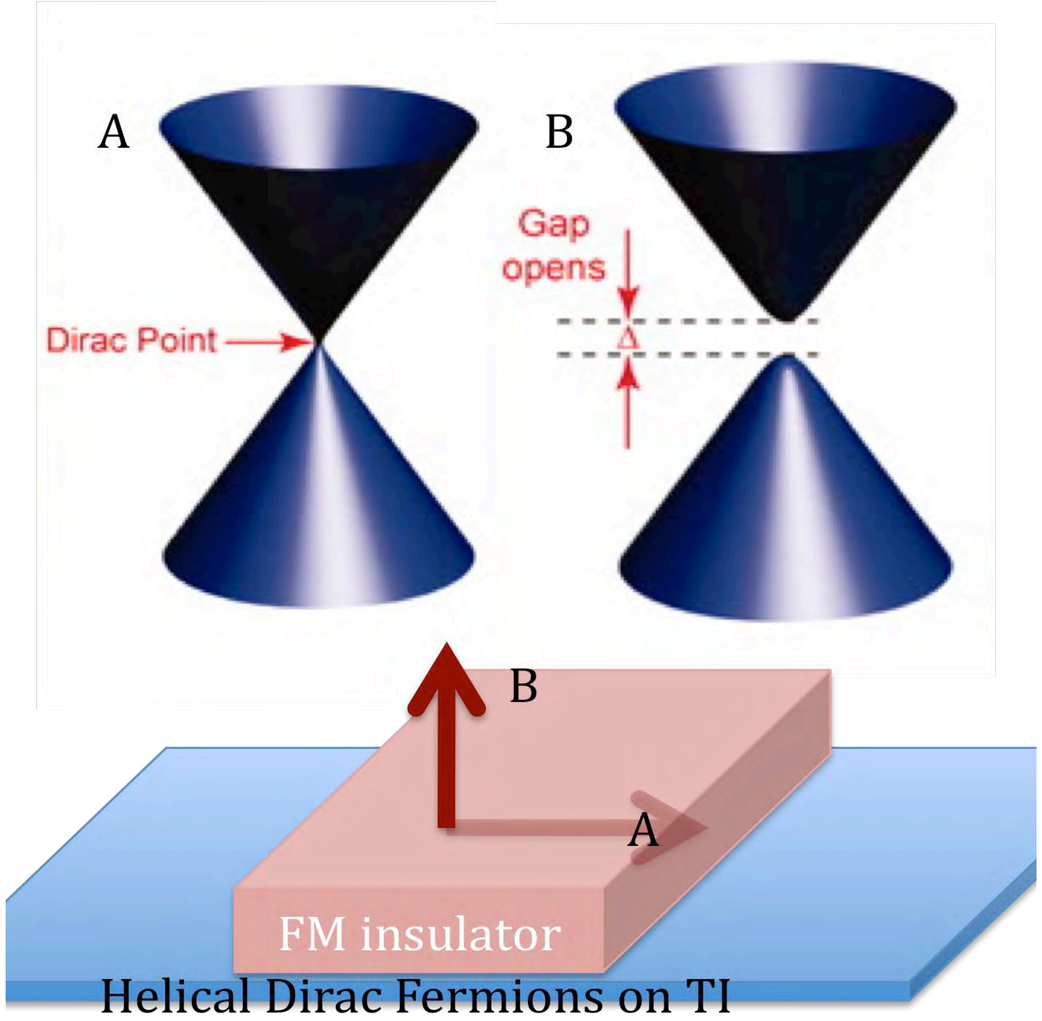
Caveat: experimentally observed "gaps" vary by orders magnitude, 25-100 meV [ARPES], 100-200 μeV [transport].

Flatte, AIP Advances **7**, 055923 (2017)

C-SPIN

STARnet

Breaking time-reversal symmetry in 3D TI



2D Dirac equation for massive free electrons breaks time-reversal symmetry:

$$i\hbar\frac{\partial}{\partial t}\psi = \left[\left(-p_x\sigma_y + p_y\sigma_x\right)c + \sigma_z mc^2\right]$$

Similarly, on the surface of a 3D TI, breaking time reversal symmetry should create a "mass" or a gap:

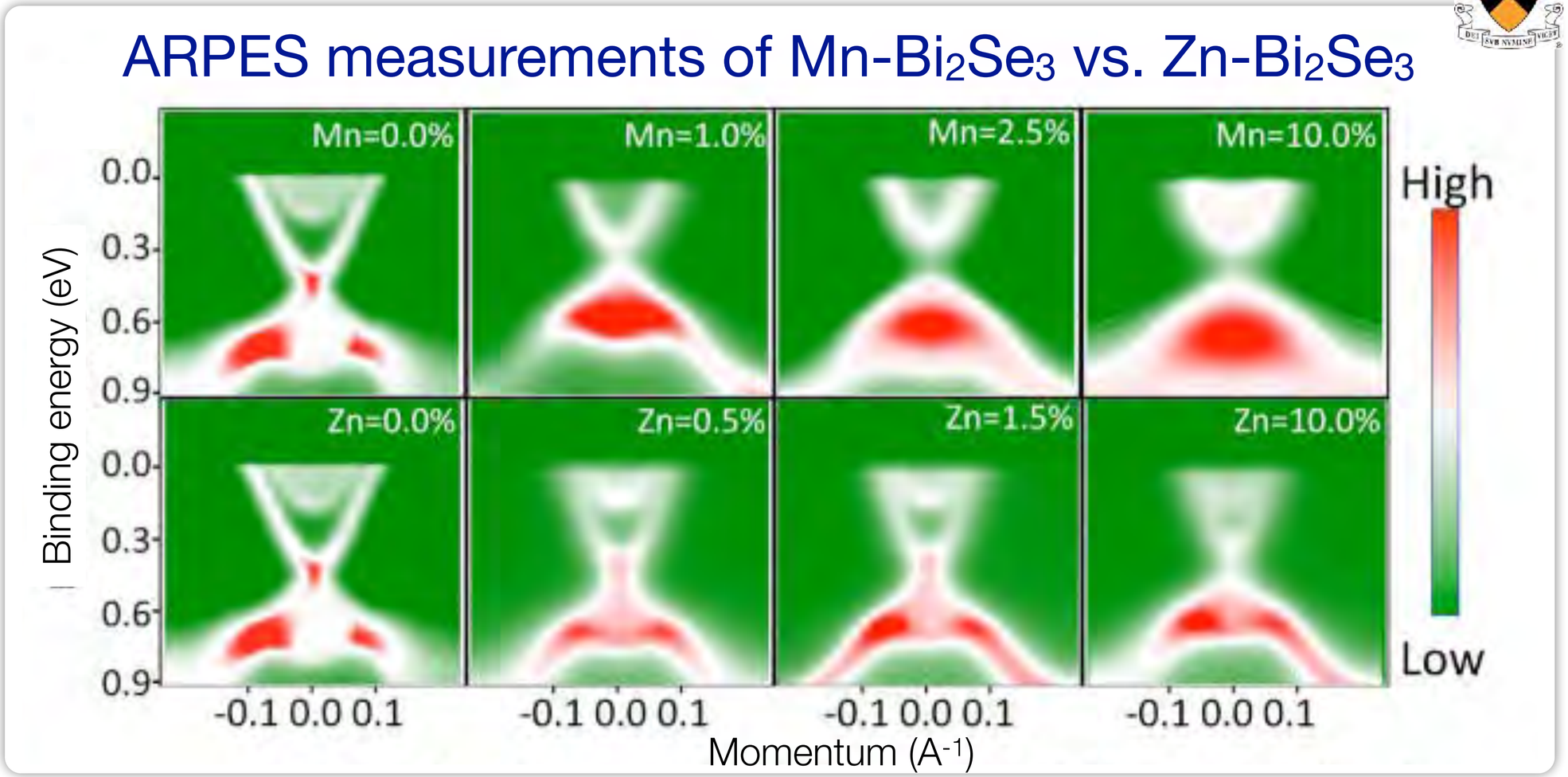
$$H = v\left[k_x\sigma_y - k_y\sigma_x\right] + b_z\sigma_z$$

Can we detect this gap? How does it affect the properties of a topological insulator?

Broken time-reversal symmetry: magnetic gap?

Xu *et al*., Nature Phys. **8**, 616 (2012)
Also: Yulin Chen *et al.*, Science 329, **659** (2010)

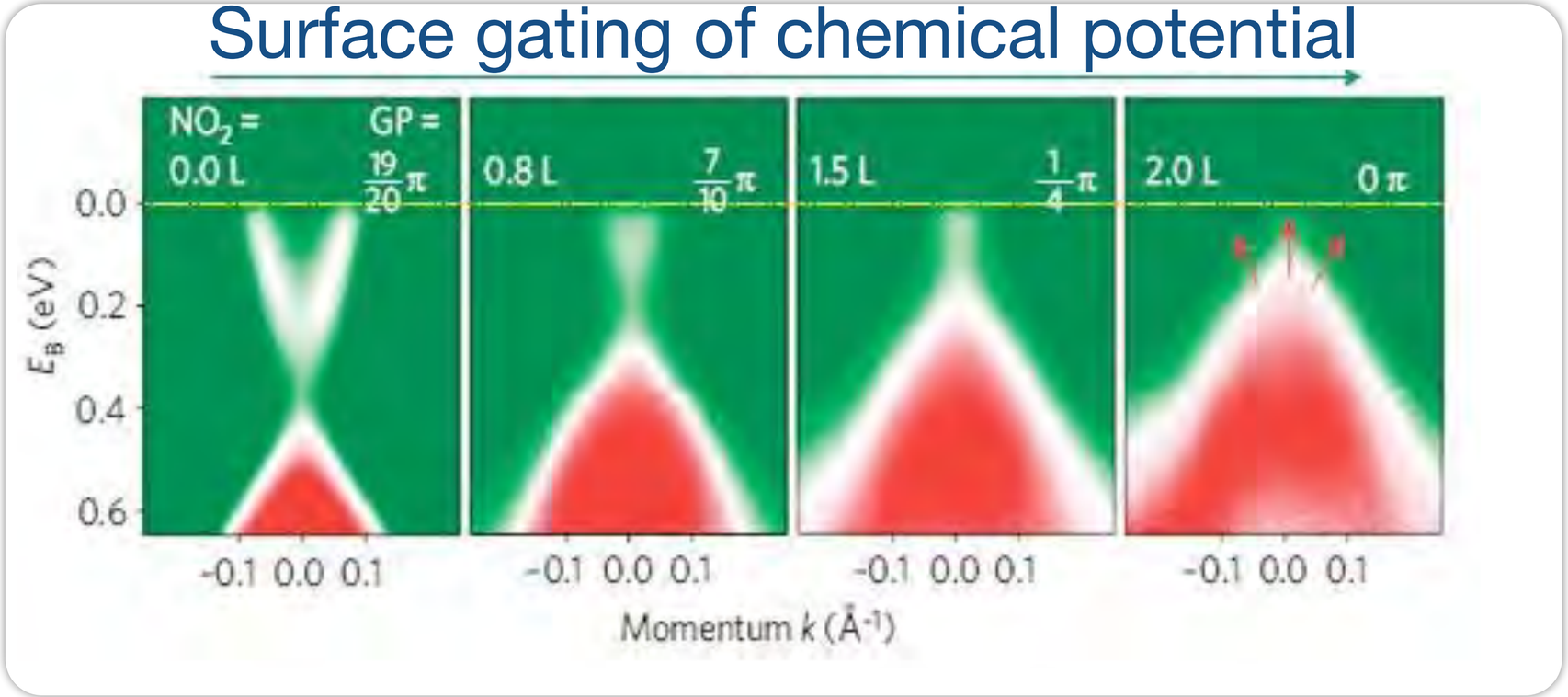
Alternative interpretation: Sanchez-Barriga *et al.,* Nature Communications **7**, 10559 (2016).



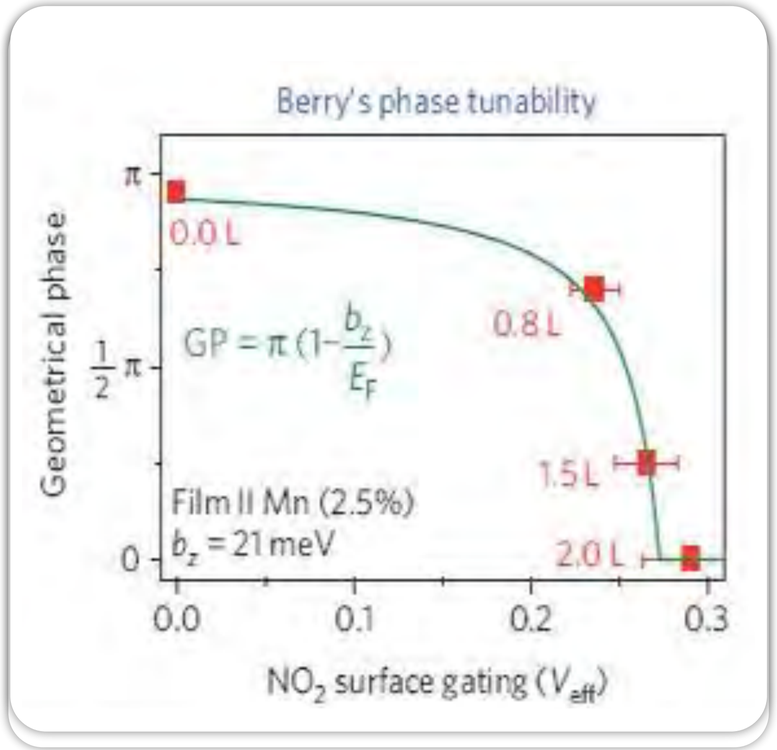
ARPES measurements of ferromagnetic (magnetically-doped) TI thin films suggest the formation of a gap. But this is complicated by disorder & controversial. Other mechanisms for getting a ‘non-magnetic’ gap.

Broken time-reversal symmetry: spin textures

Xu *et al*., Nature Phys. **8**, 616 (2012)

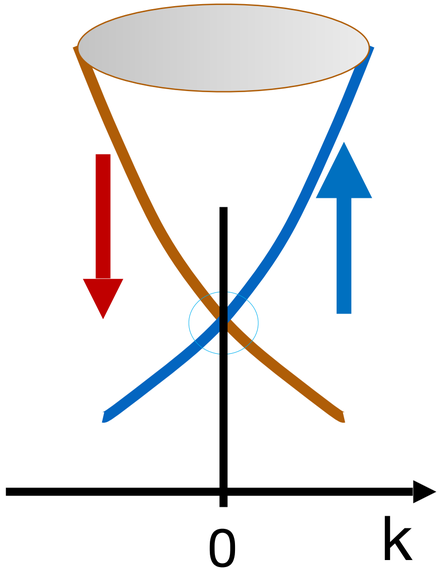


$$\text{Geometric Phase} = \pi\left[1 - \frac{vk\tan\theta}{E_F}\right]$$



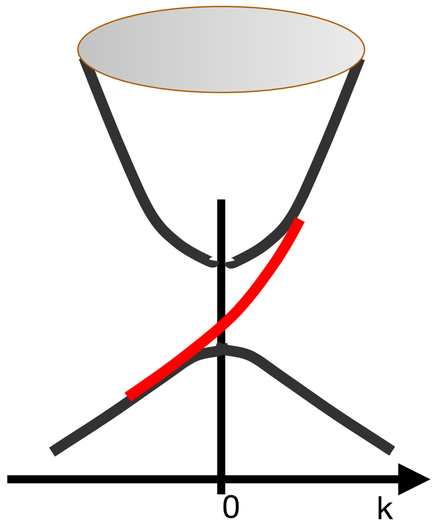
- Creation of "hedgehog spin texture"
- Dosing with NO_2 allows "chemical gating" of geometric phase

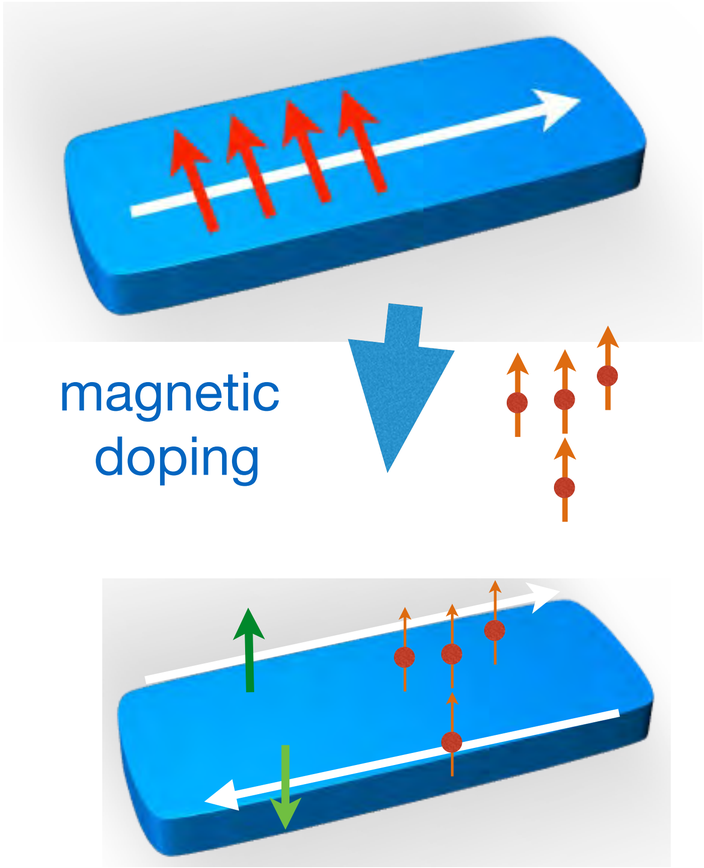
Broken time-reversal symmetry: Chiral edge states



$$\sigma_{xy} = \frac{e^2}{h}$$

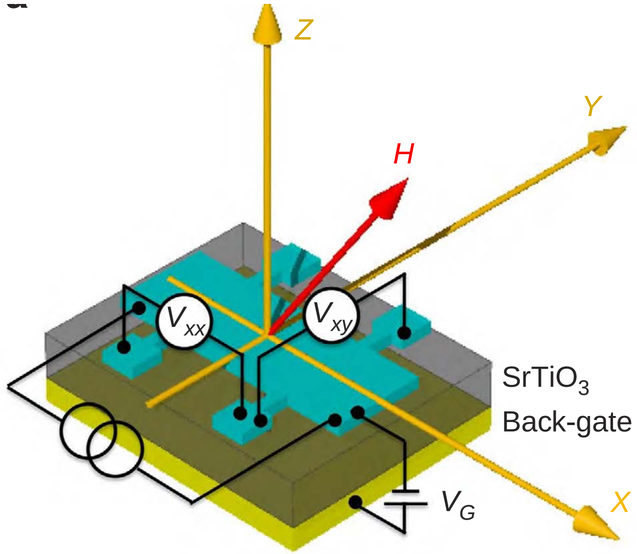
$$\sigma_{xx} = 0$$

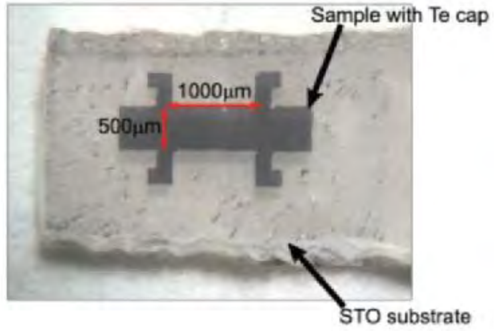




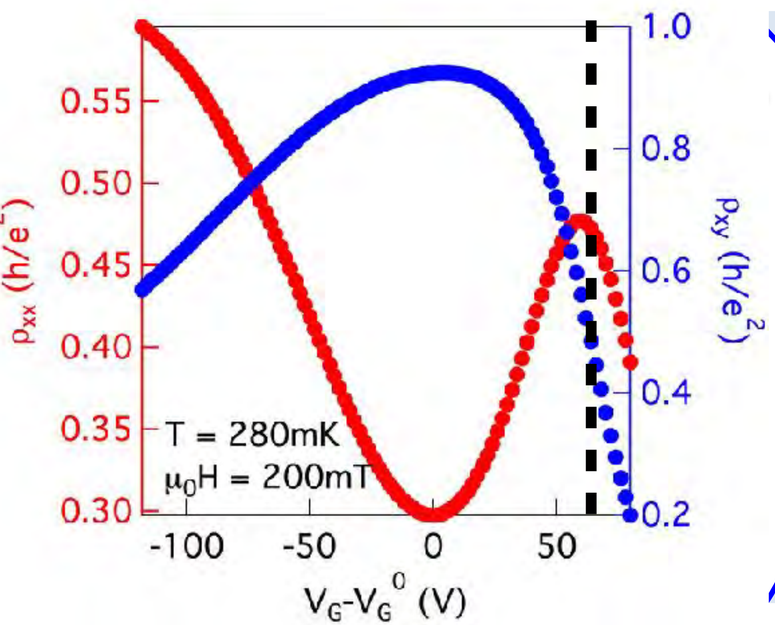
Yu *et al* (Science **329**, 61, 2010): ferromagnetic order in a topological insulator transforms helical Dirac surface states into chiral edge states with quantized Hall conductance and zero longitudinal conductance at B = 0. This is known as a "quantum anomalous Hall insulator."

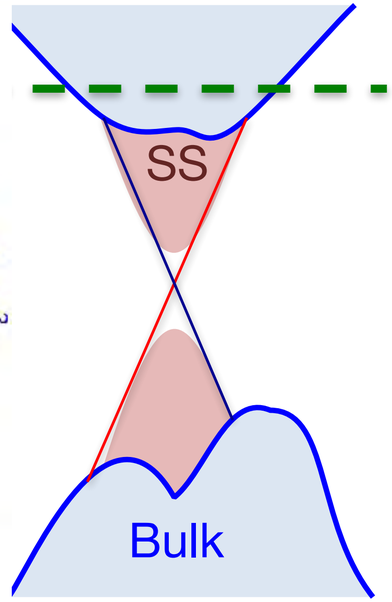
The quantum anomalous Hall effect





Four probe measurements of the Hall effect & the longitudinal resistance in large (mm scale) samples as a function of external magnetic field and temperature.

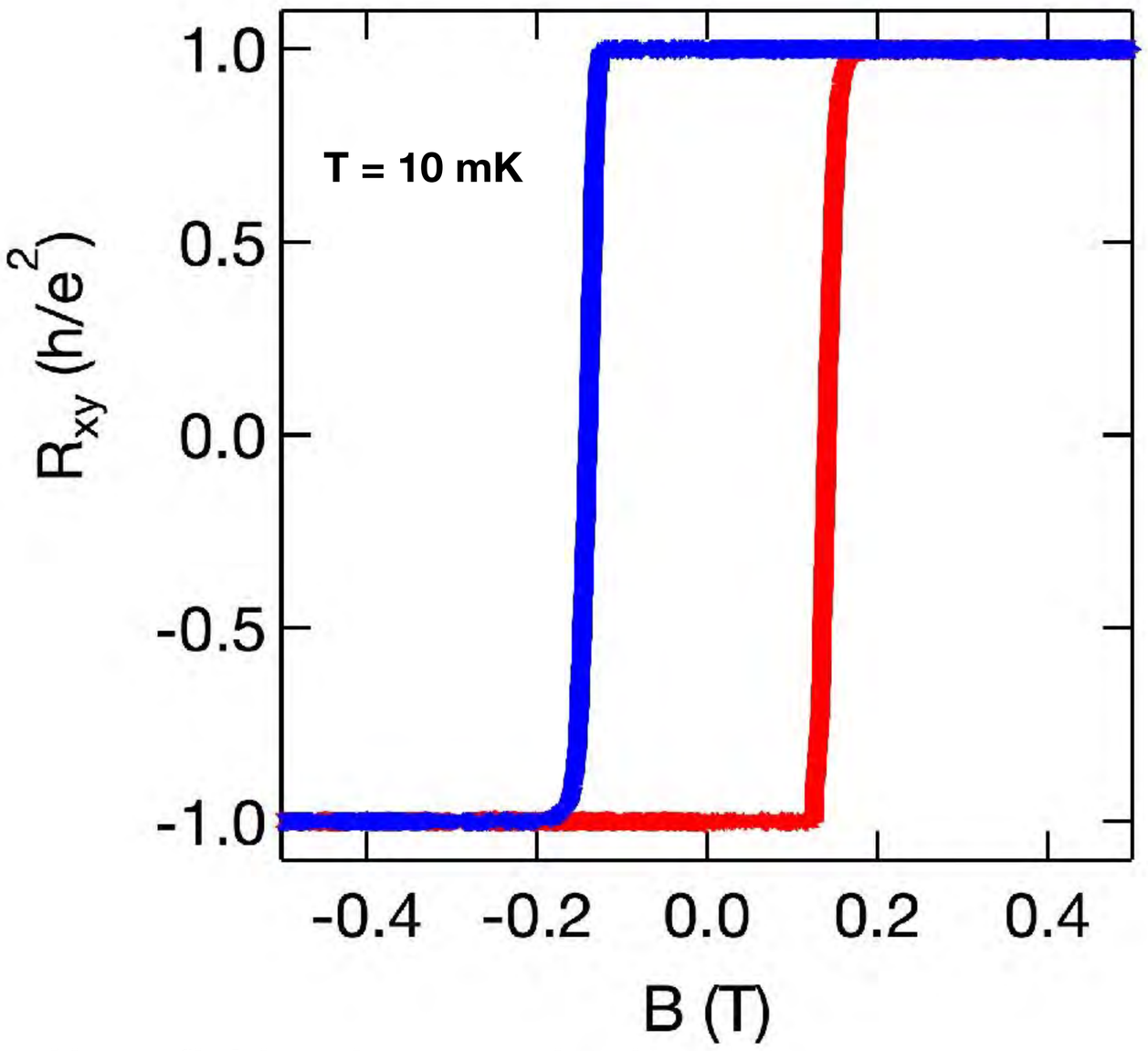




Thin films are grown on a $SrTiO_3$ substrates that serves as the dielectric of a capacitor.

Back gate voltage allows tuning of the chemical potential (Fermi energy)

Fully quantized edge transport at B = 0



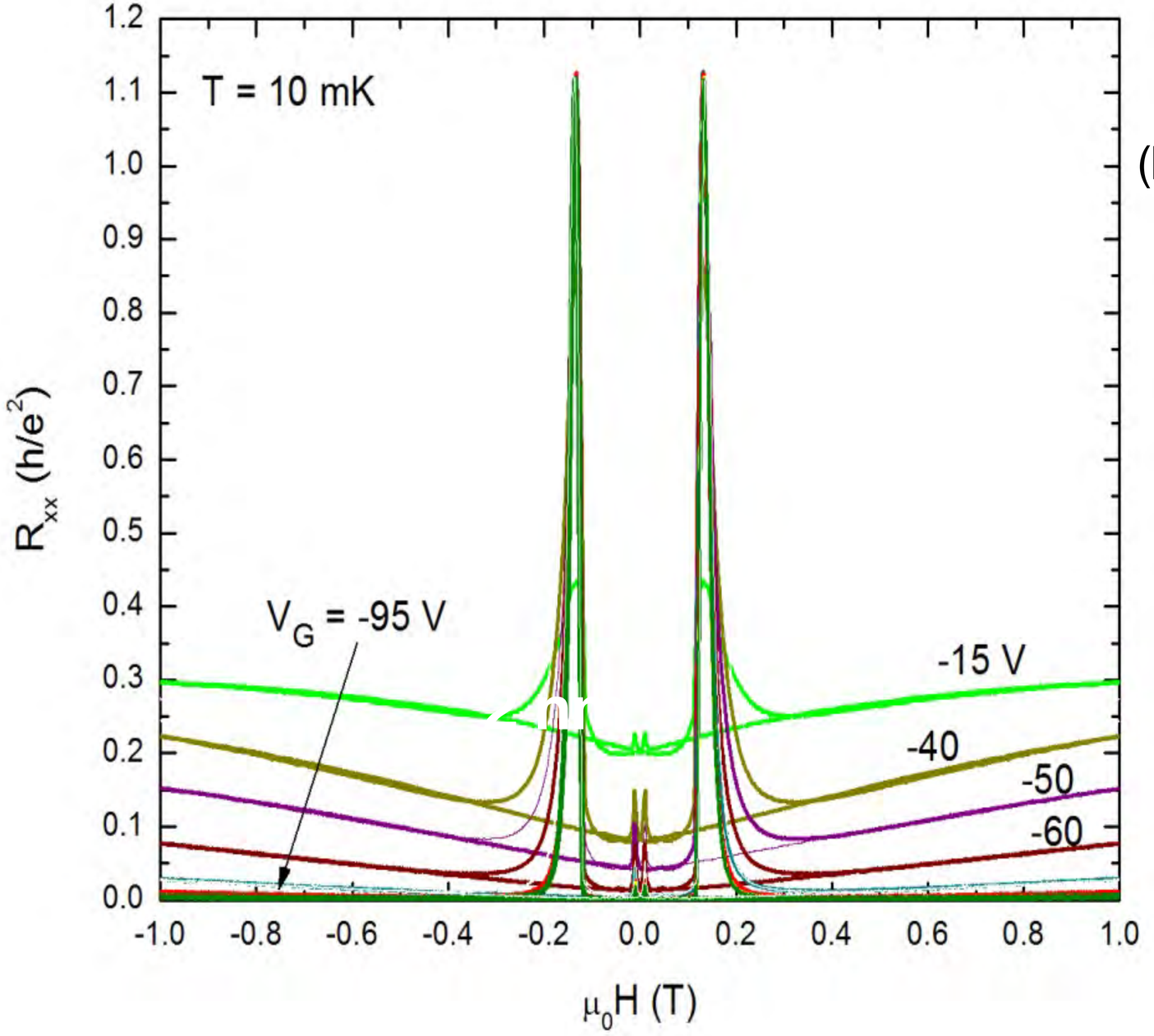
Note: field antisymmetrized

Hall quantization at 4 parts in 10^4
Minhao Liu, Wong, Richardella, Kandala, Yazdani, Samarth, Ong,
Science Advances **2**, e1600167 (2016)

First demonstration: Chang *et al.*, *Science* **340**, 167 (2013)
Followed by:
Checkelsky *et al.*, *Nature Physics* **10**, 731 (2014)
Kou *et al,*, *Phys. Rev. Lett.* **113**, 137201 (2014)
Chang *et al.*, *Nature Materials* **14**, 473 (2015)
Bestwick *et al.*, *Phys. Rev. Lett.* **114**, 187201 (2015)
Kandala *et al.*, *Nature Communications*,**6**, 7434 (2015).
Kou *et al.*, *Nature Communications*, **6**, 8474 (2015)

Note: Gotz *et al.*, Appl. Phys. Lett. **112**, 072102 (2018):
Precision of measurement 0.17 ppm

Dissipation free edge transport at B = 0



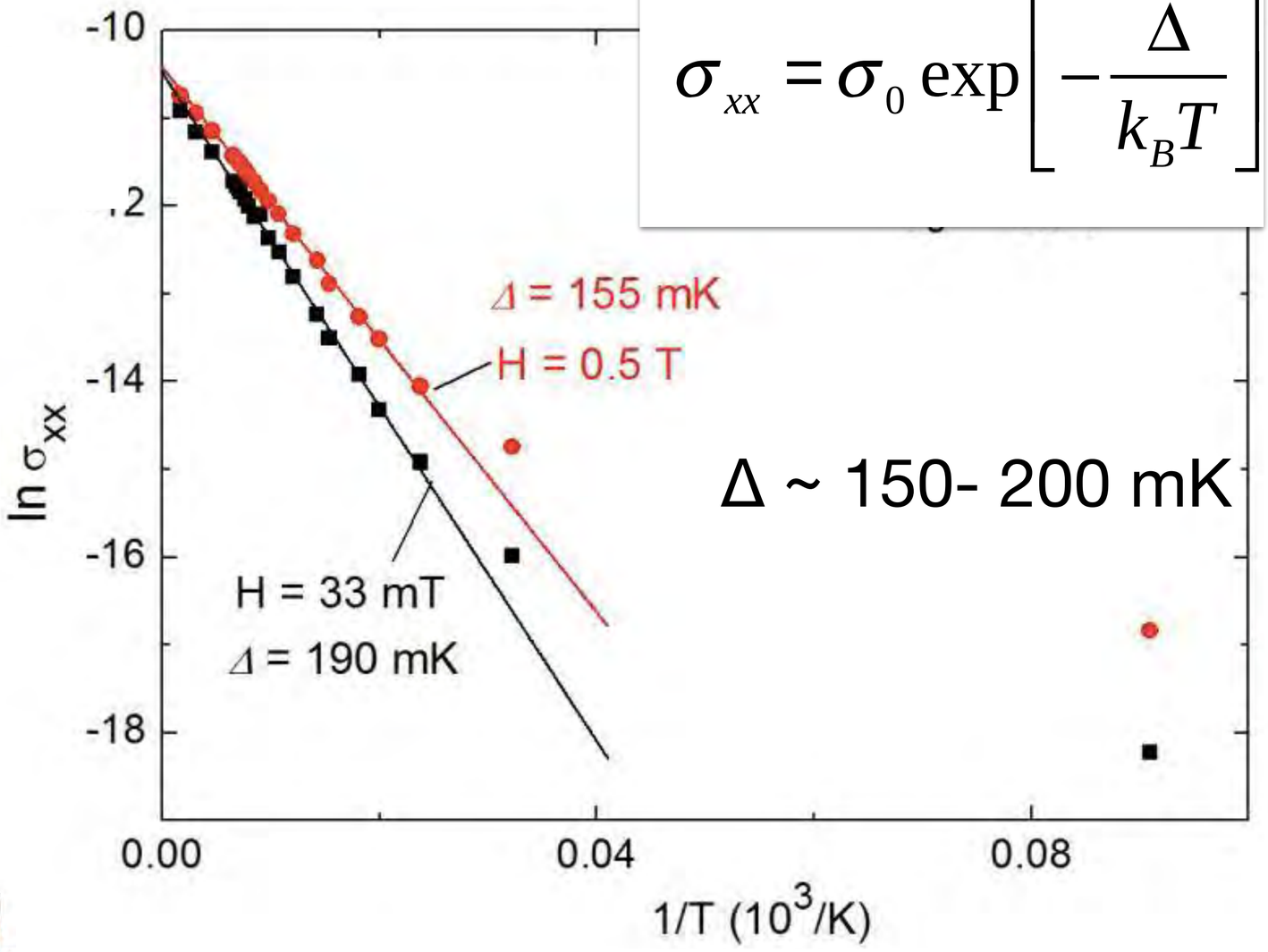
Nearly dissipation free edge transport (Minhao Liu, Wong, Richardella, Kandala, Yazdani, Samarth, **N. P Ong,** *Science Advances* **2**, e1600167 **(**2016)

R_{xx} ~ 3 x 10^{-4} h/e^2

Contrast with quantum Hall effect: mobility in quantum anomalous Hall effect samples is only ~ 150 cm^2/v.s

Activation of edge transport across gap

$$\sigma_{xx} = \sigma_0 \exp\left[-\frac{\Delta}{k_B T}\right]$$



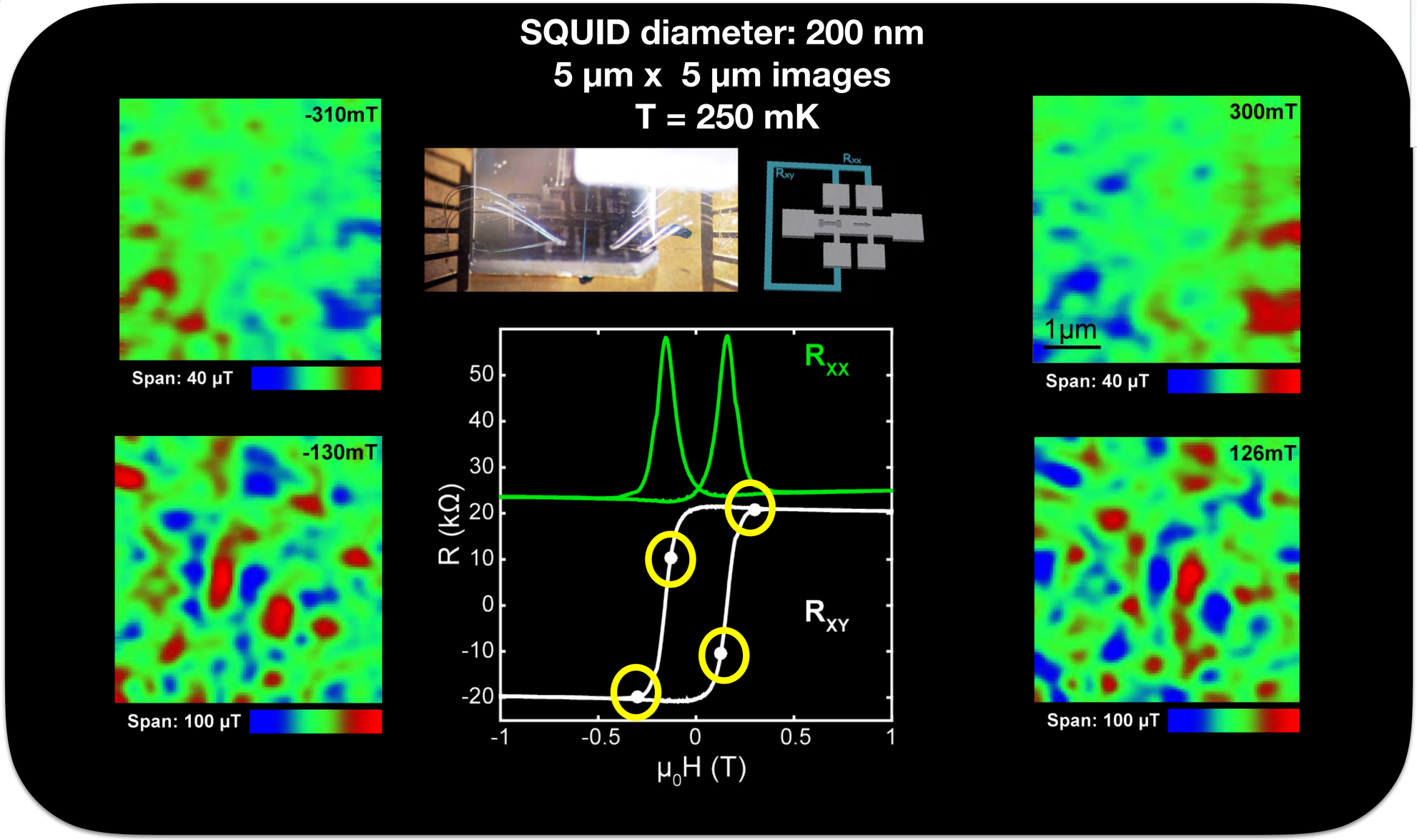
Ferromagnetic ordering temperature T_C ~ 15 K.

But dissipation free transport is activated by a gap Δ ~ 150- 200 mK!

Is the gap induced by breaking of time reversal symmetry?
Or is it a mobility gap due to disorder?

Minhao Liu, *et al.* *Science Advances* **2**, e1600167 (2016)

Imaging the magnetic disorder in quantum anomalous Hall insulators



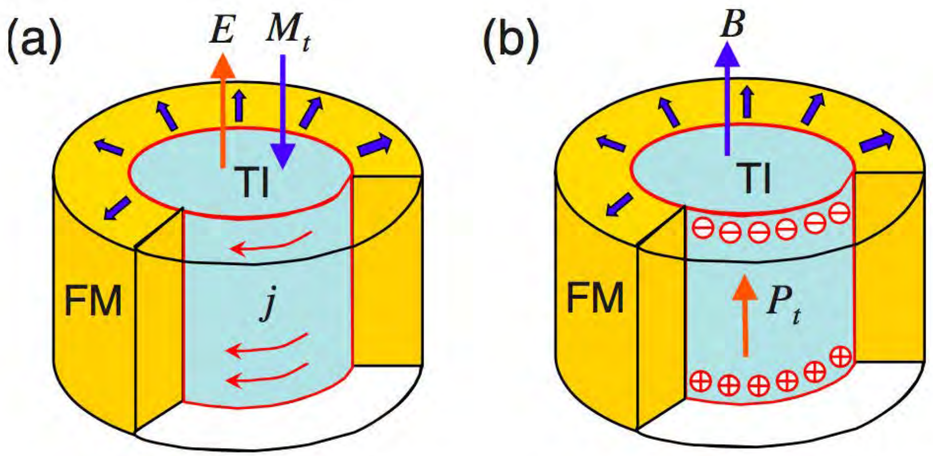
Lachman *et al.*, *Science Advances* **1**, e1500740 (2015)

[with E. Zeldov & Andrea Young]

Topological insulators & axion electrodynamics

Topological field theory: topological insulators can be regarded as magnetoelectrics

$$L_\theta = 2\alpha\sqrt{\frac{\epsilon_0}{\mu_0}}\frac{\theta}{2\pi}\vec{E}\cdot\vec{B}$$

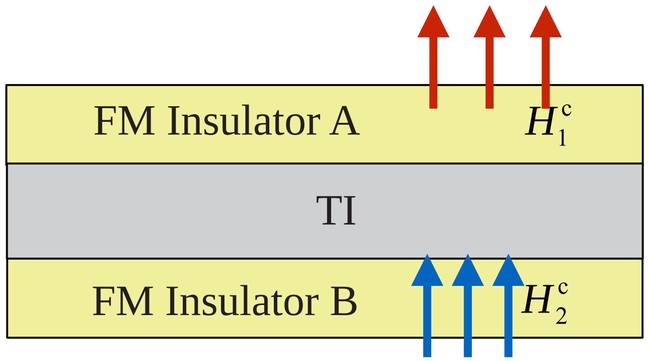


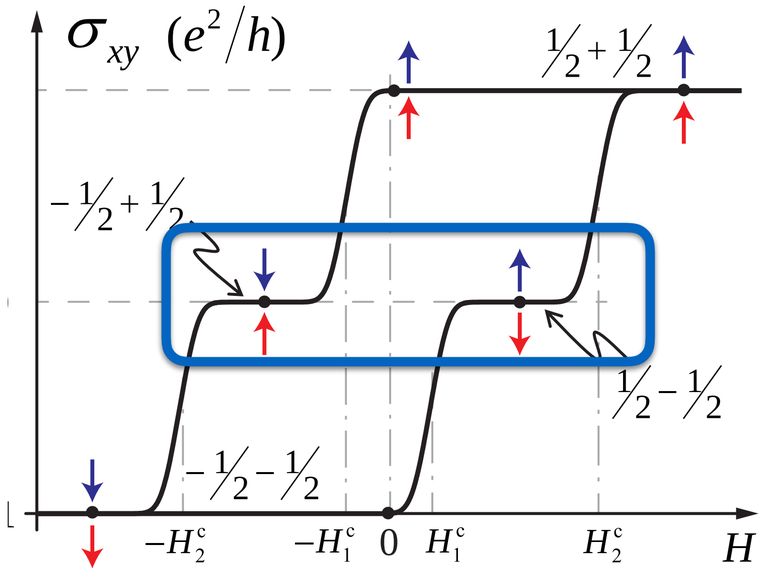
'Axion angle' θ = π in time-reversal invariant topological insulators leads to half-quantized surface Hall conductance: $\sigma_{xy} = e^2/2h$.

Qi, Hughes, Zhang, PRB **78**, 195424 (2008)
Qi *et al*., *Science* **323**, 1184 (2009)
Wu *et al*., *Science* **354**, 1124 (2016)

See Armitage & Wu: arXiv:1810.0123 for recent perspective

Making an ‘axion insulator’





Jing Wang *et al*., PRB **92**, 081107(R) (2015)

$$L_\theta = 2\alpha\sqrt{\frac{\epsilon_0}{\mu_0}}\frac{\theta}{2\pi}\vec{E}\cdot\vec{B}$$

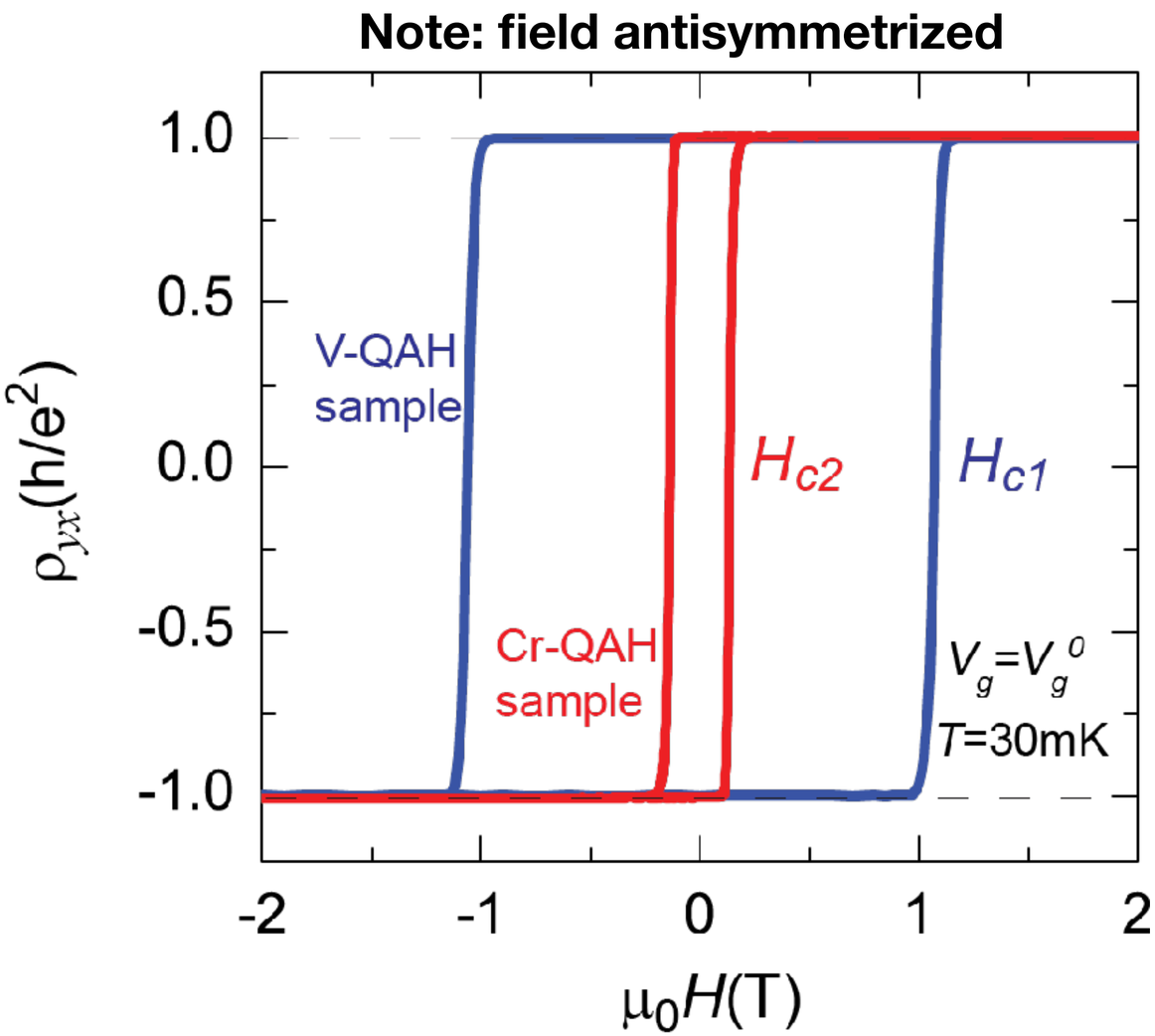
‘Axion angle’ θ = π in time-reversal invariant topological insulators leads to half-quantized surface Hall conductance: $\sigma_{xy} = e^2/2h$.

Observation requires:

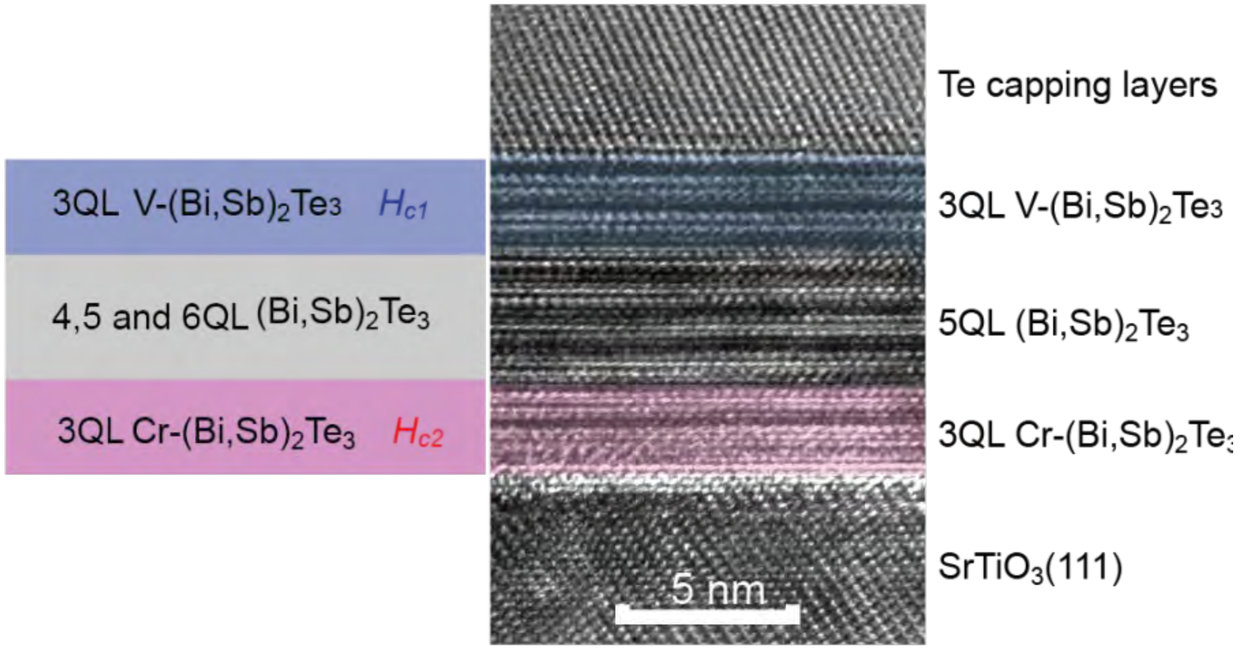
A. All surfaces gapped from broken time-reversal symmetry with E_F in gap.
B. Topological insulator should be in 3D regime to avoid finite size effect (hybridization gap)
C. Interior of topological insulator should still obey time-reversal symmetry

See Armitage & Wu: arXiv:1810.0123 for recent review

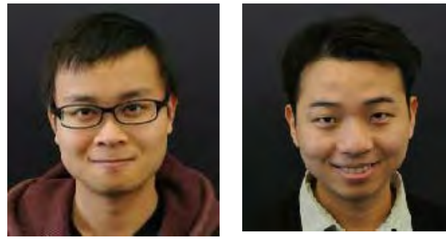
Heterostructure for axion insulator



Di Xiao, Jue Jiang *et al*., Phys. Rev. Lett. **120**, 056801 (2018)

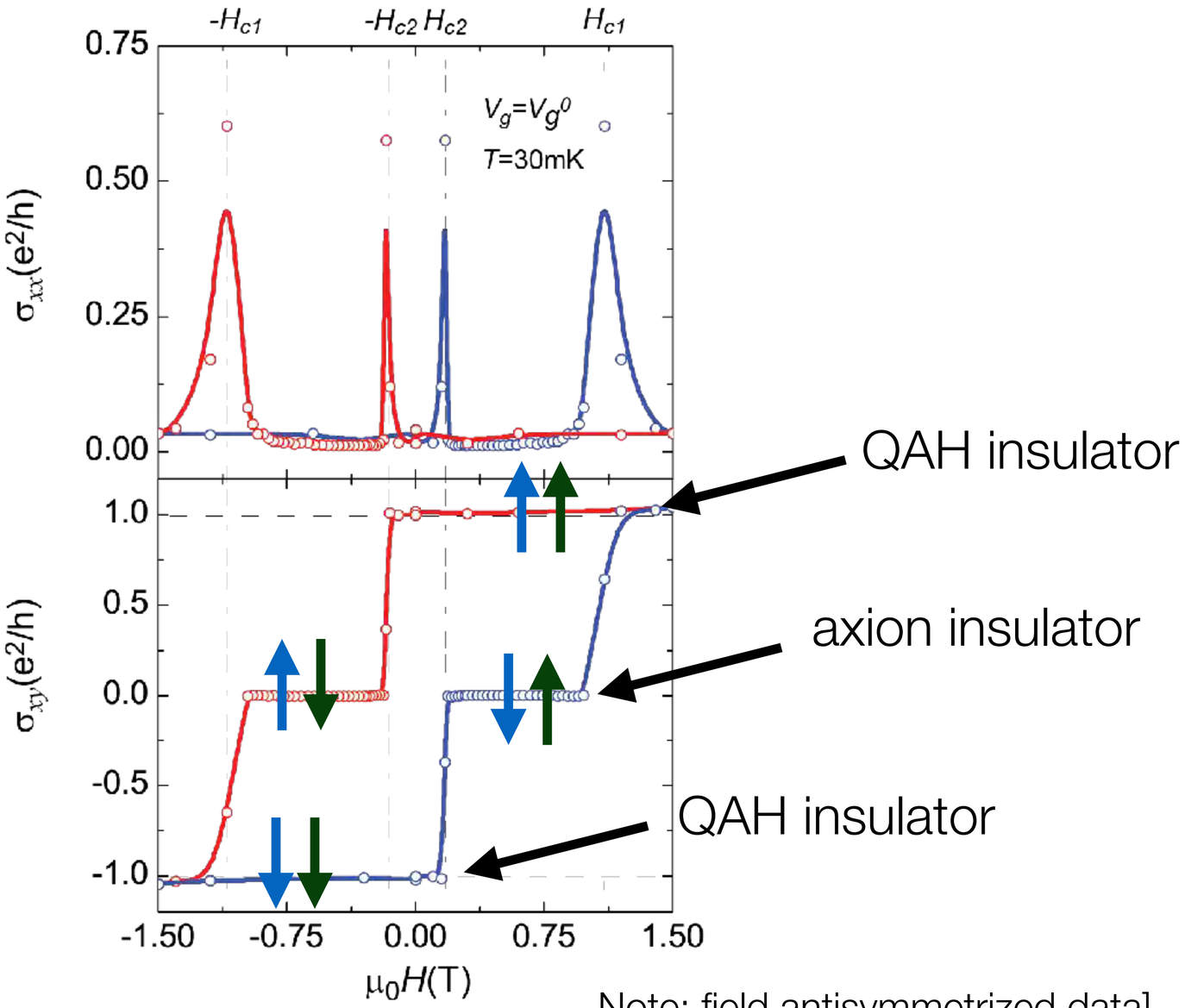


See also:
Mogi *et al*., *Science Advances* **3,** eaao1669 (2017).

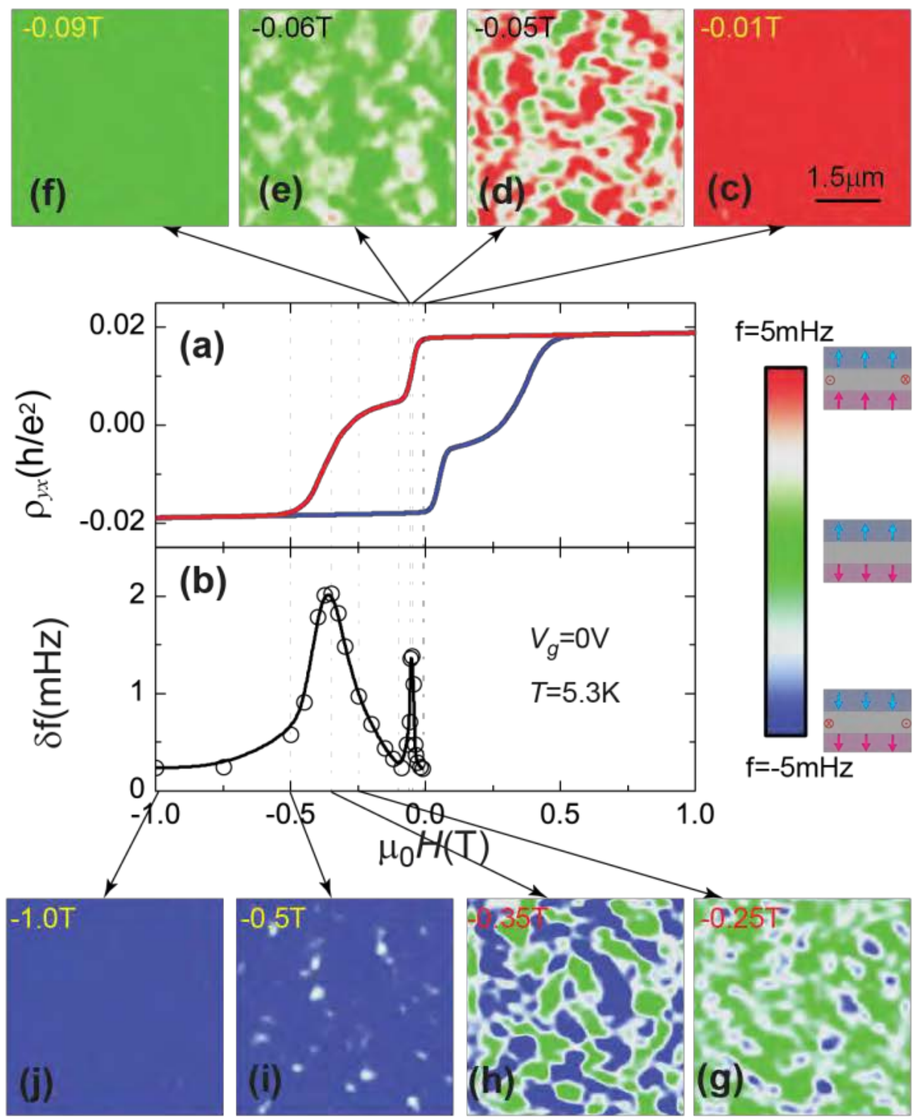


Cr-doped and V-doped (Bi,Sb)$_2$Te$_3$ thin films: dramatically different coercive fields.
Opportunity to create novel quantum anomalous Hall insulator configurations.

Observation of the axion insulator



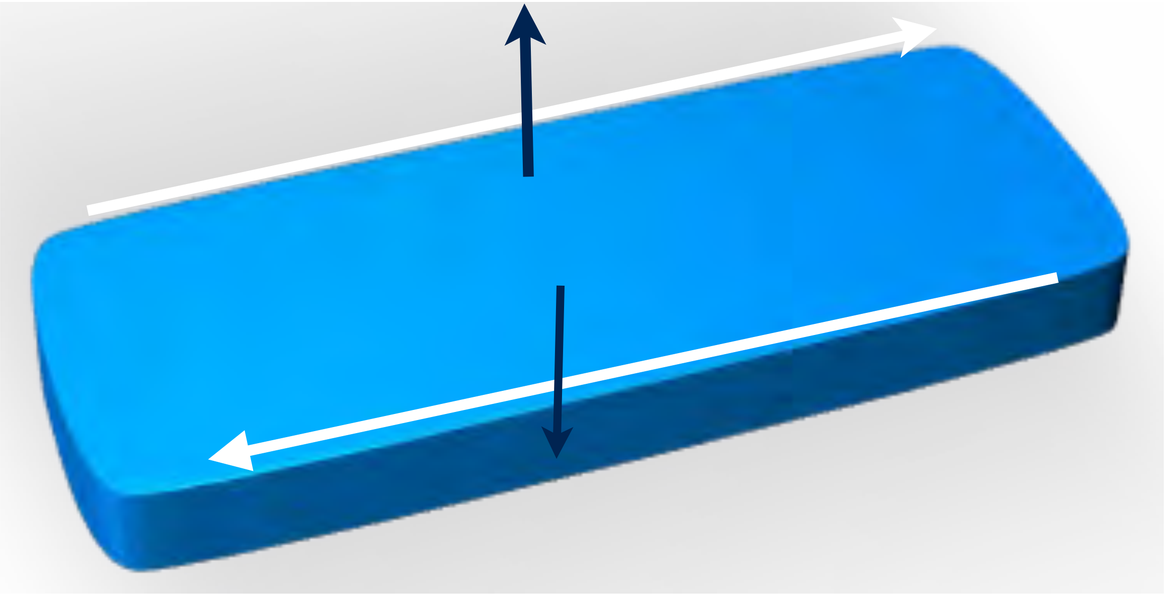
Note: field antisymmetrized data]



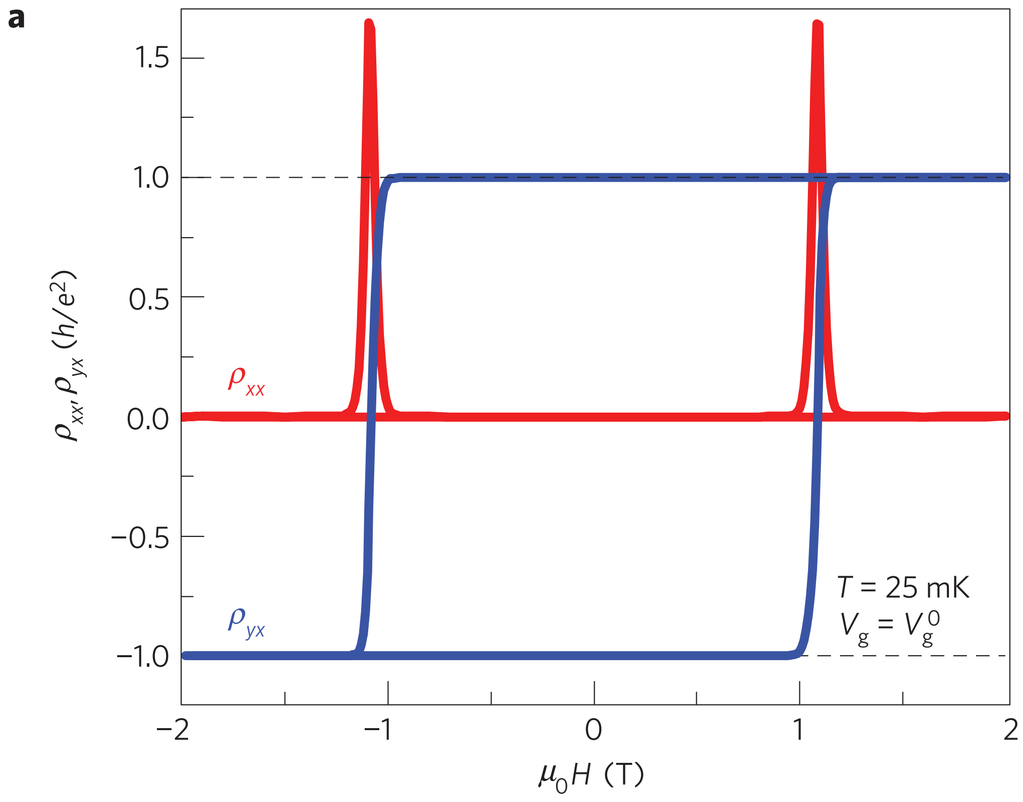
Low temperature MFM proves opposite magnetization in top and bottom magnetic layers (Weida Wu)

Di Xiao *et al*., Phys. Rev. Lett. **120**, 056801 (2018)

Quantum anomalous Hall edges: useful for spintronics?



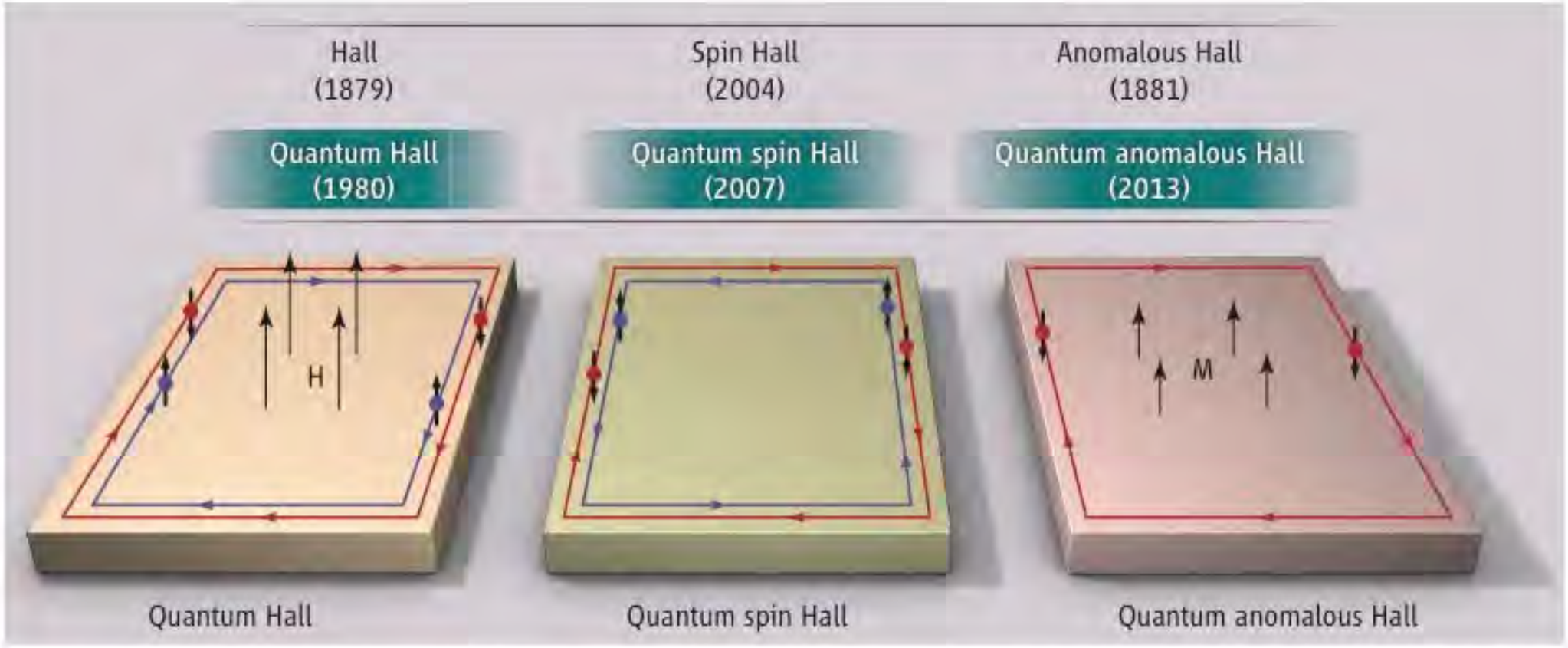
Chang *et al.*, *Nature Materials* **14**, 473 (2015)



- Dissipationless charge flow without a magnetic field is potentially “useful” but…
- Can the temperature at which this effect is observed be raised to a technologically relevant range? [Mogi *et al*., *Appl. Phys. Lett*. **107**, 182401 (2015)].
- What is the spin polarization of the edge states and can it be used for devices? [Zhang *et al*., *Phys. Rev. B* **93**, 235315 (2016)]

Quantum anomalous Hall effect: outlook

Can we increase temperature scale for observation?
What is the spin polarization of edge states?
Effect of interactions? Going beyond $C_n = \pm 1$?
Interplay between superconductivity & quantum anomalous Hall edges?
Can we directly observe axion term through topological magnetoelectric effect?



graphic: S. Oh, Science (2013)

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- **Colorado State:** Yang Lv, **Mingzhong Wu**
- **Princeton:** Su-Yang Xu, Madhab Neupane, Minhao Liu, **Zahid Hasan, Phuan Ong, Ali Yazdani**
- **UCSB:** **Andrea Young**
- **Weizmann:** Ella Lachman, **Eli Zeldov**



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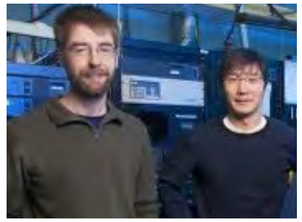

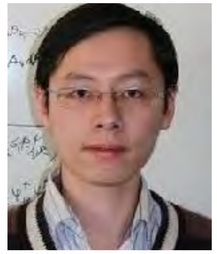

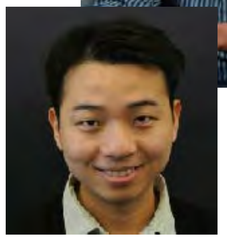








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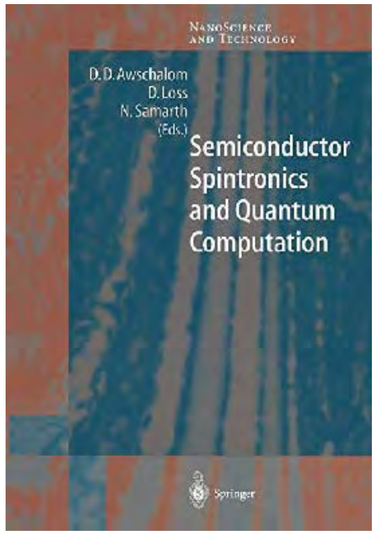

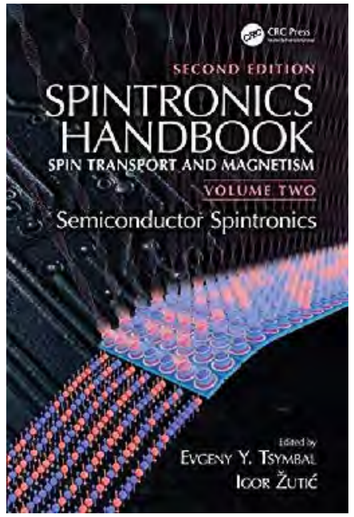

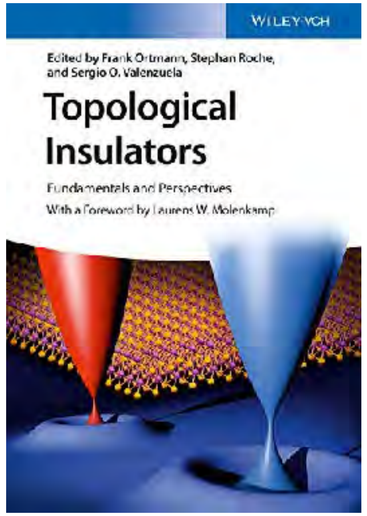

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