

Chapter 7

Topological Spintronics

韩伟

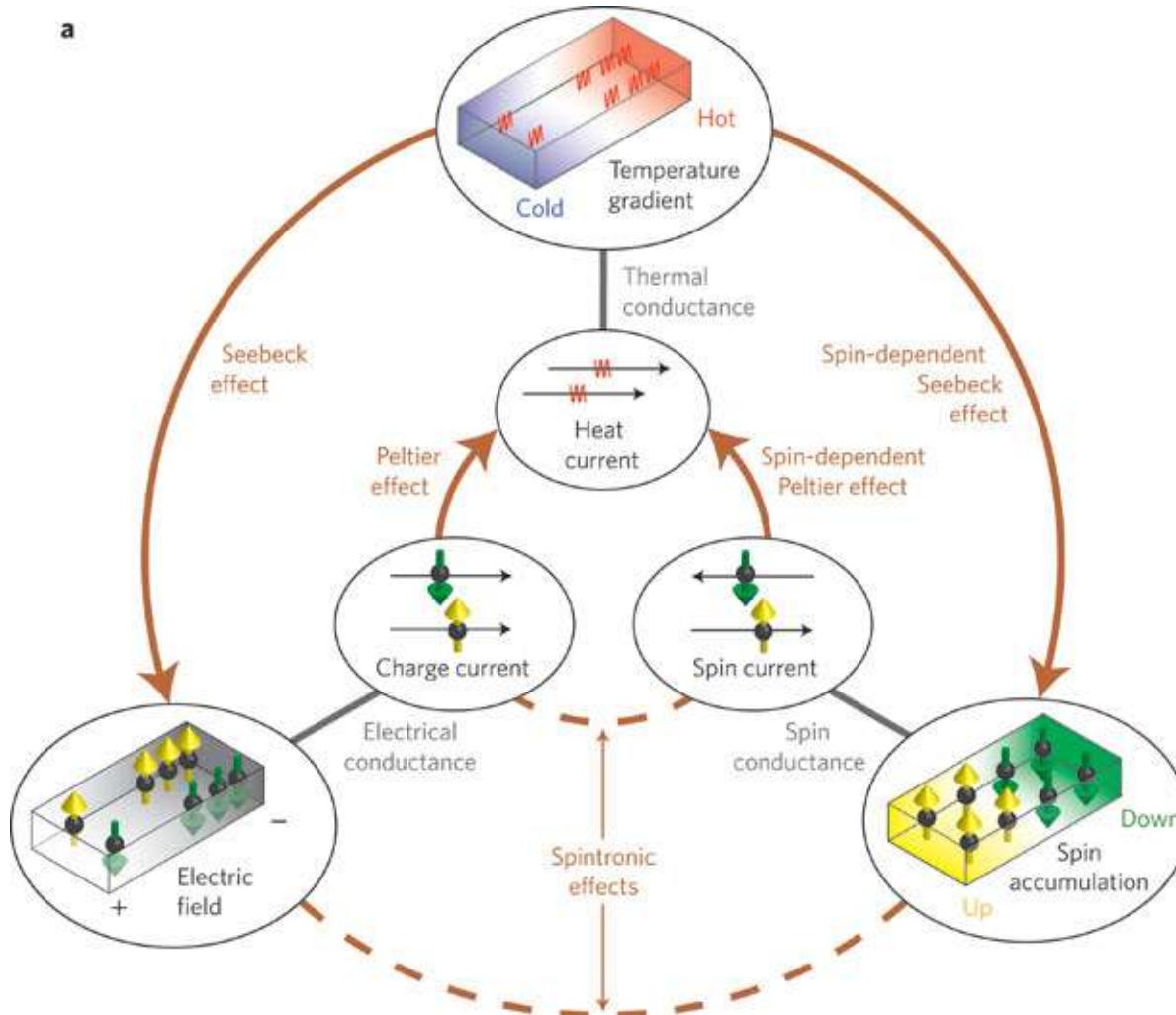
量子材料科学中心

2016年11月29日

Review of last class

- 1. Seebeck and Peltier effect**
- 2. Spin Seebeck effect**
- 3. Spin Peltier effect**
- 4. Thermal spin injection**
- 5. Thermal spin torque**
- 6. Spin energy**

Review of last class

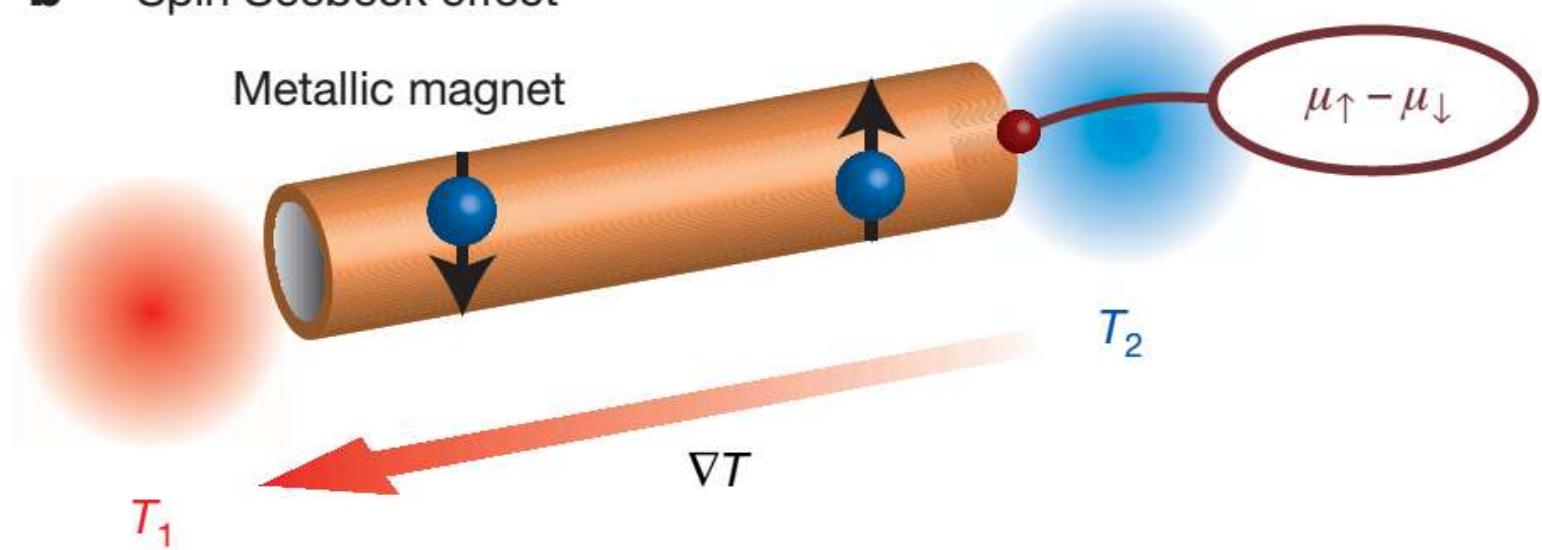


Goennenwein & Bauer, Nature Nanotech. (2012)

Review of last class

2. Spin Seebeck effect

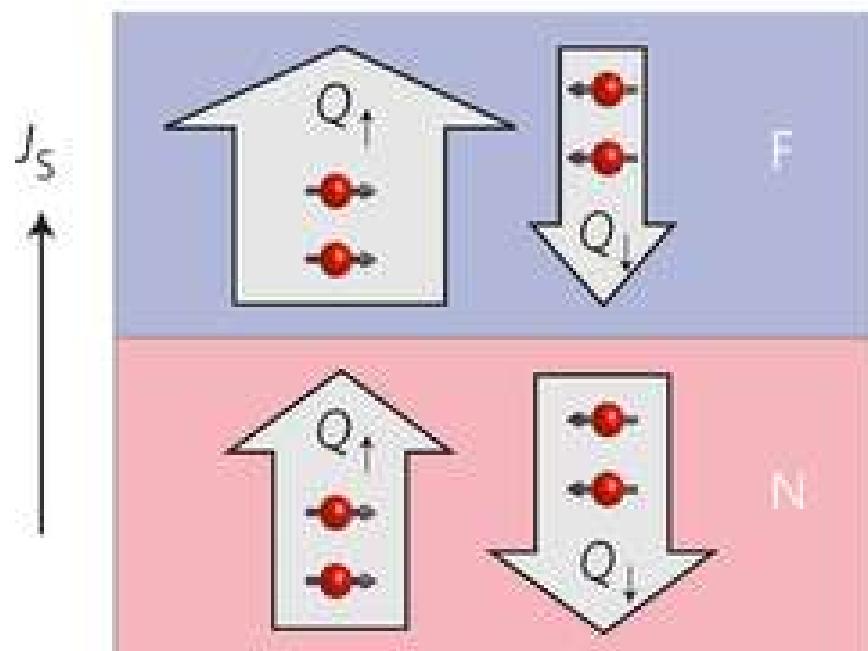
b Spin Seebeck effect



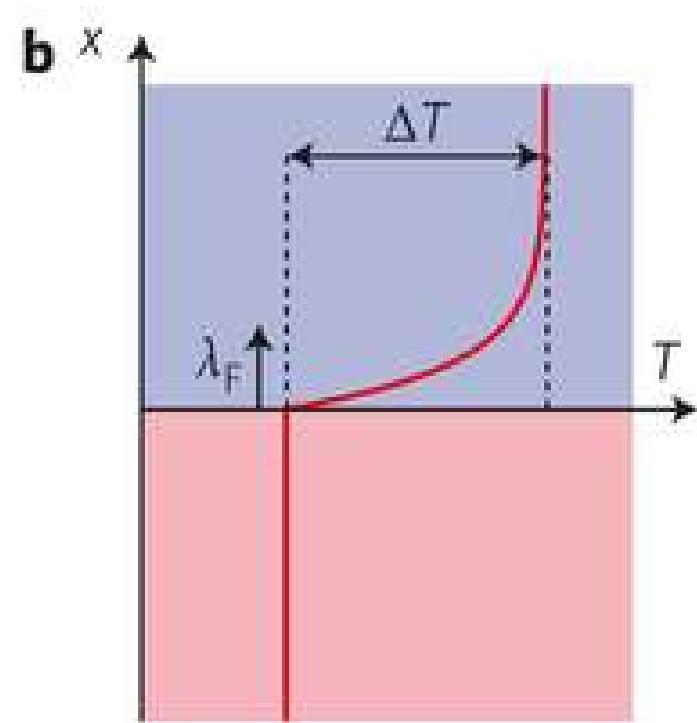
Review of last class

3. Spin Peltier effect

a

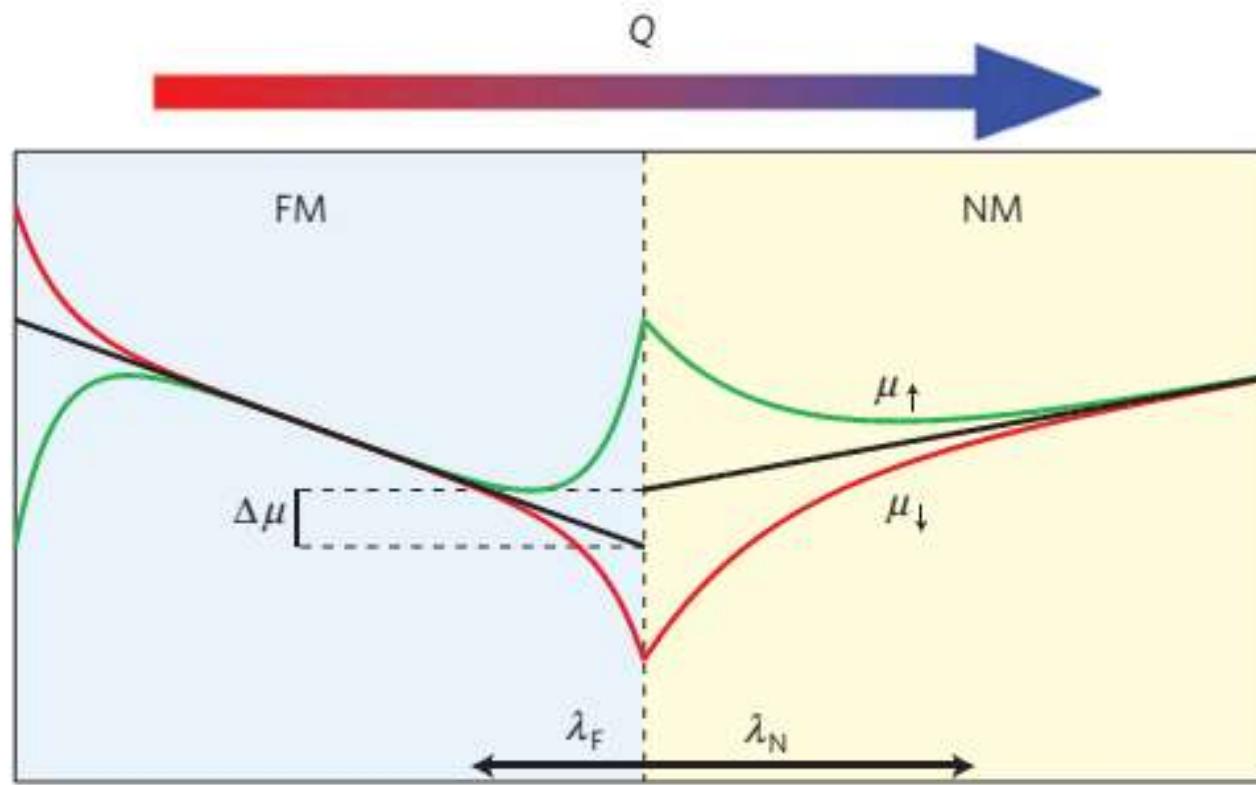


b



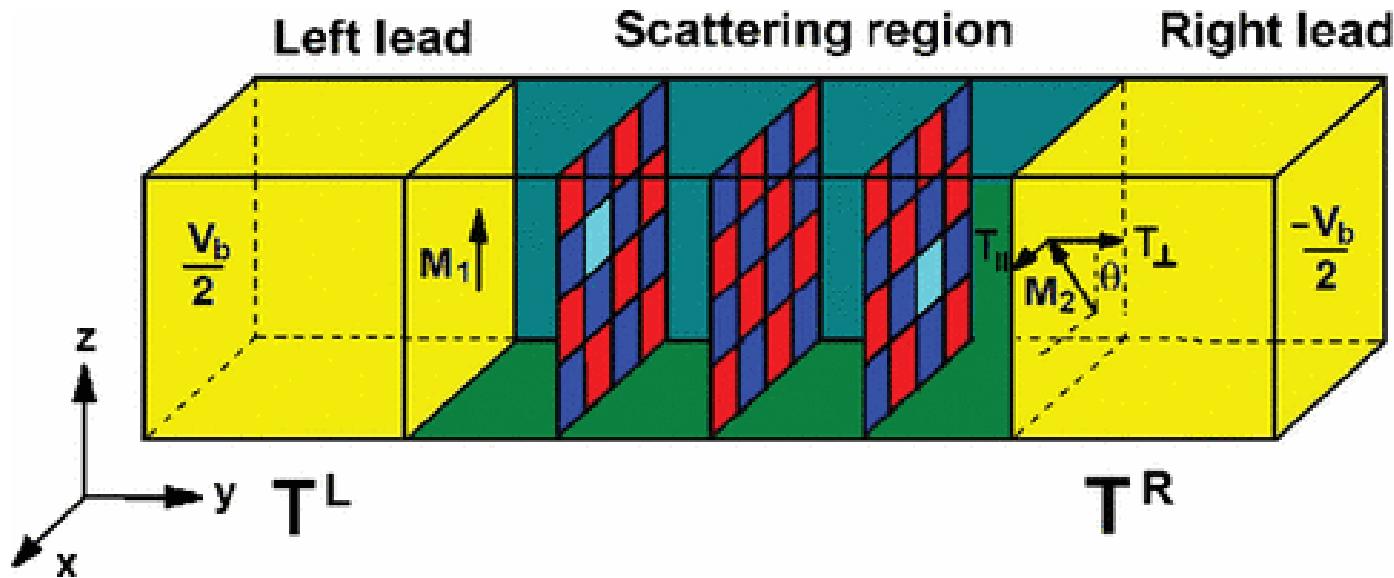
Review of last class

4. Thermal spin injection



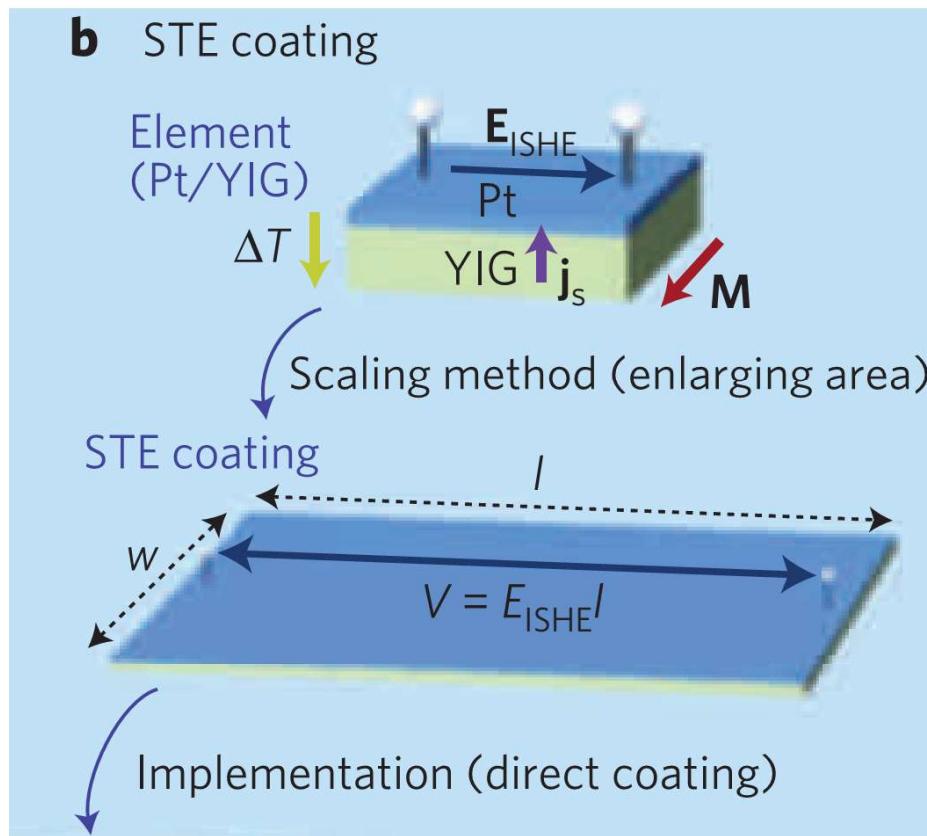
Review of last class

5. Thermal spin torque



Review of last class

6. Spin energy



Outline

1. Topology

2. Quantum anomalous Hall effect

3. Skyrmions

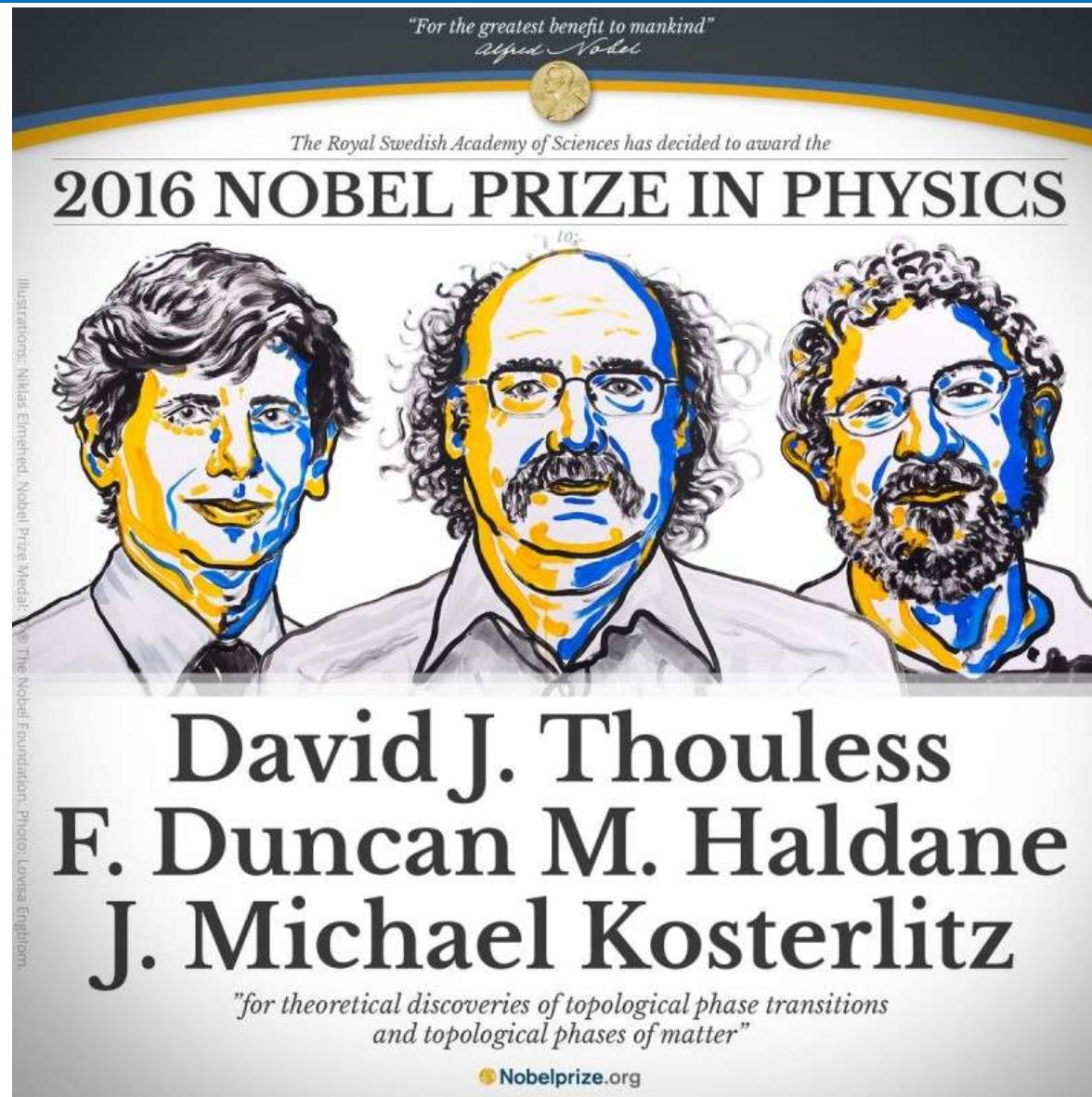
4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**

Outline

1. Topology

Topology



Topology

”for theoretical discoveries of topological phase transitions and topological phases of matter”

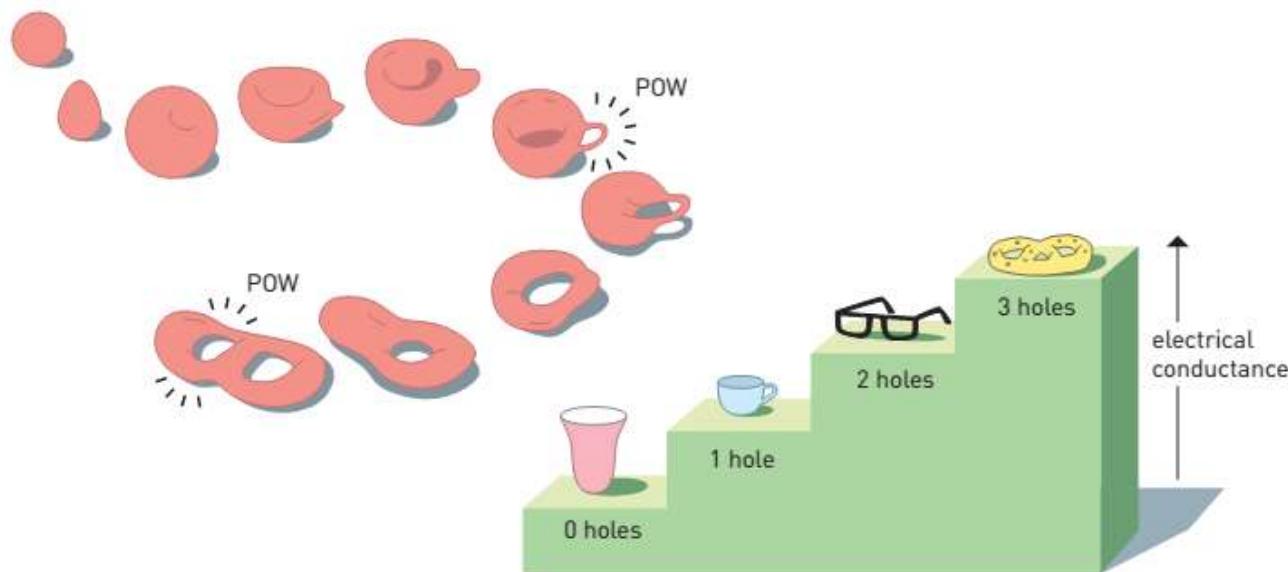
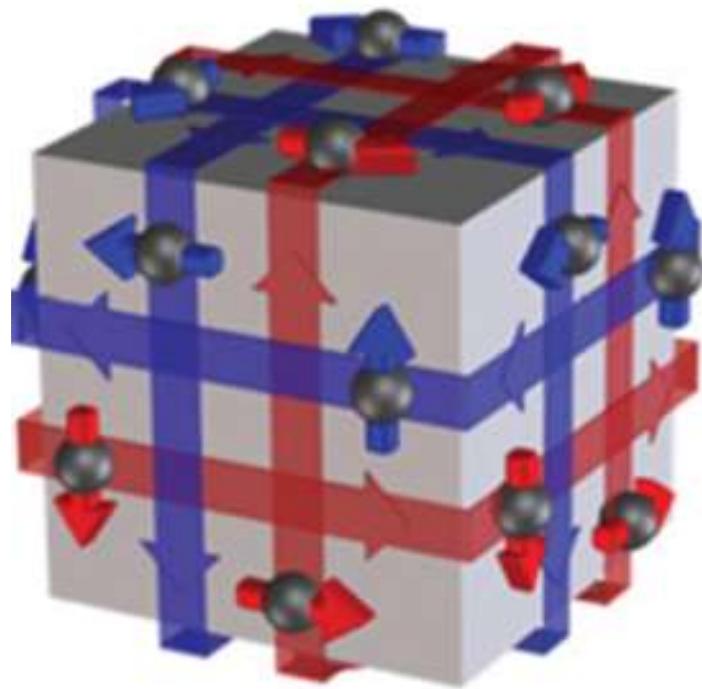


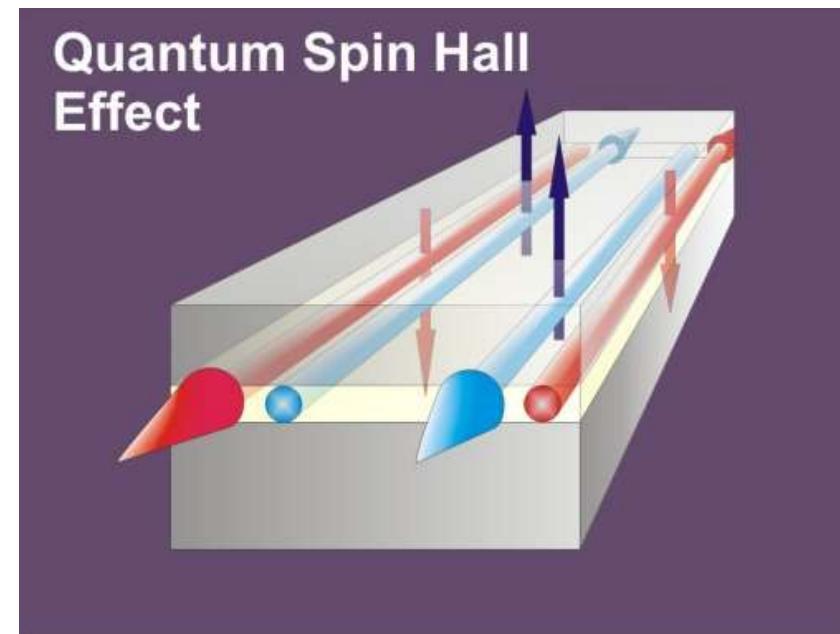
Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Topological insulator

3D Topological insulator

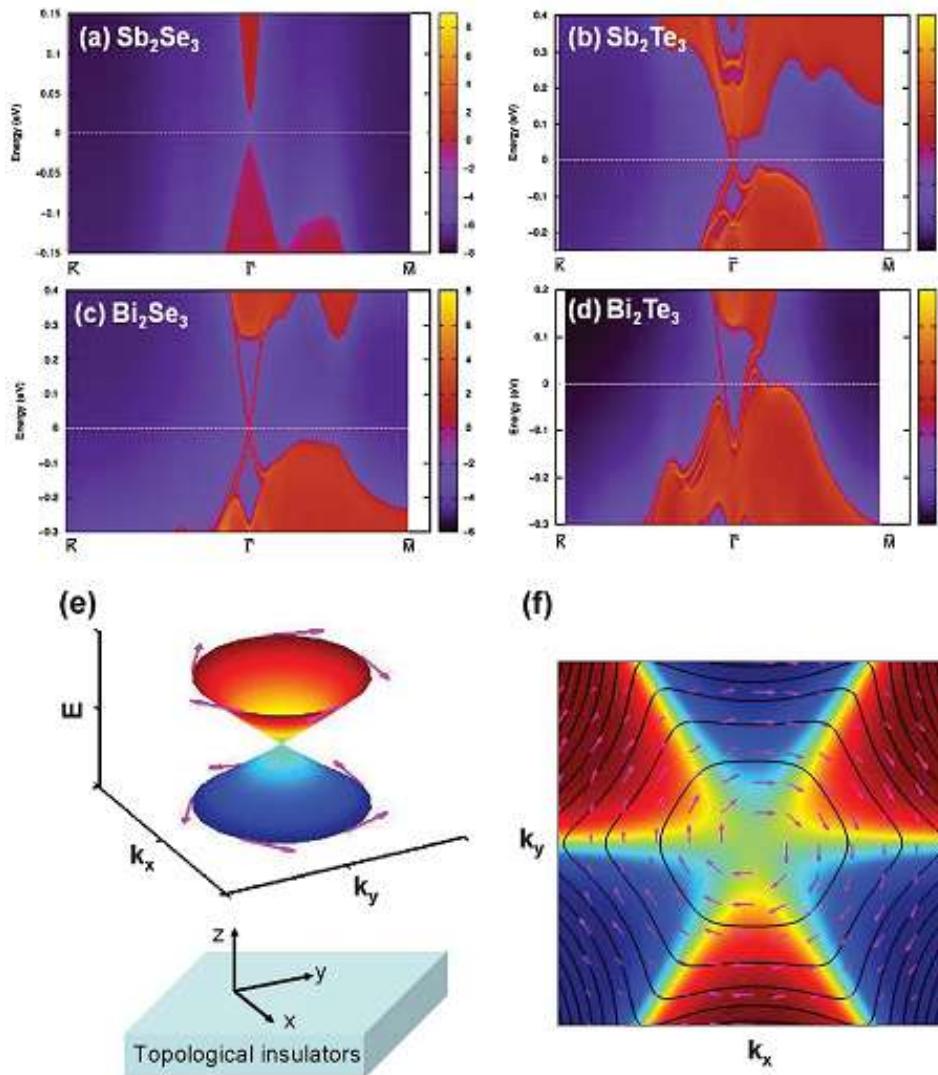


2D Topological insulator

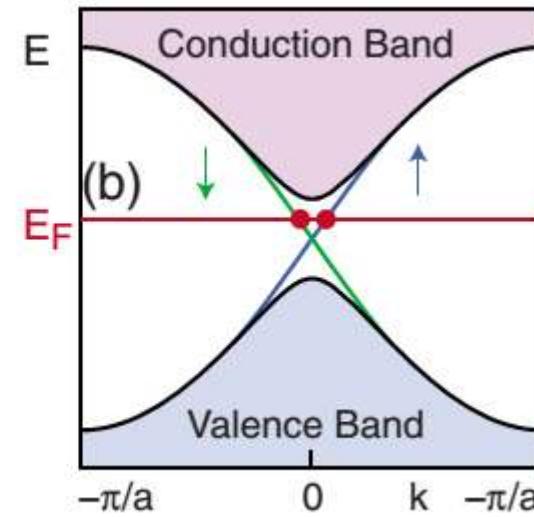
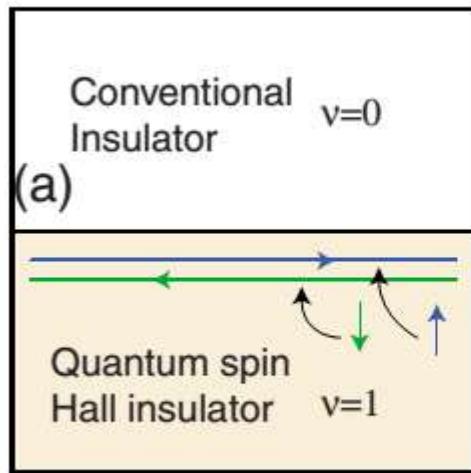
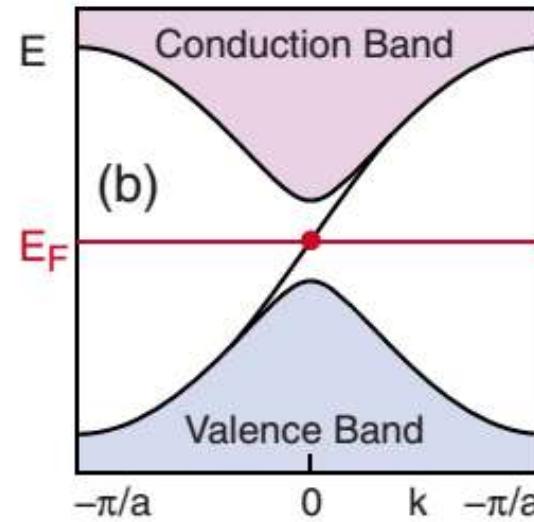
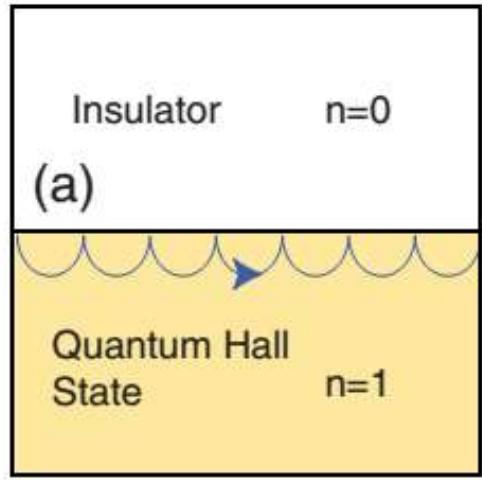


Hasan & Kane, Rev Mod Phys (2009)
Qi & Zhang, Rev Mod Phys (2011)

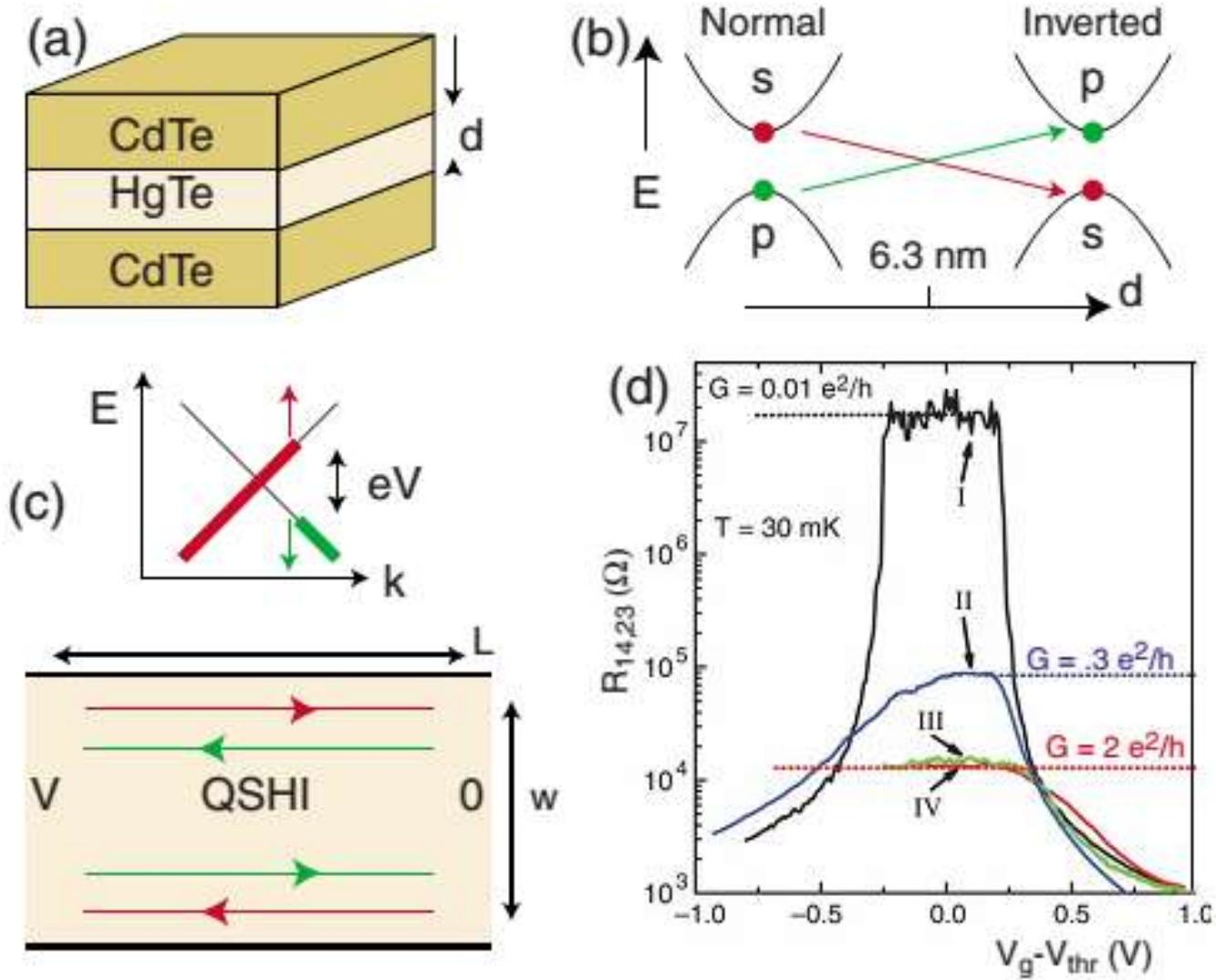
3D Topological insulator



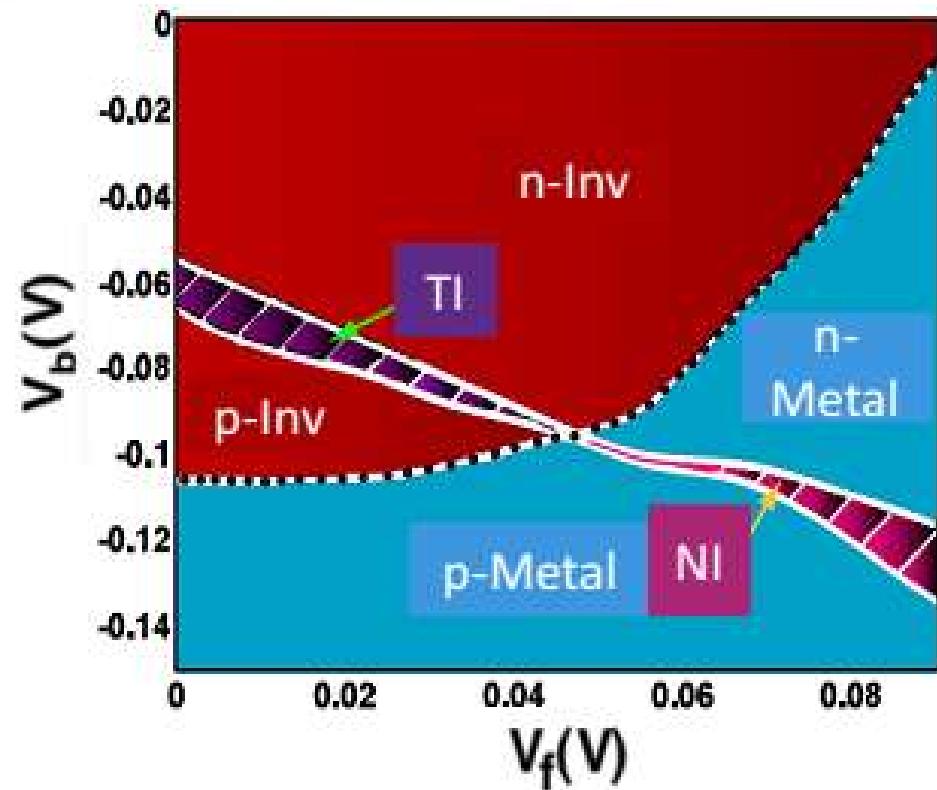
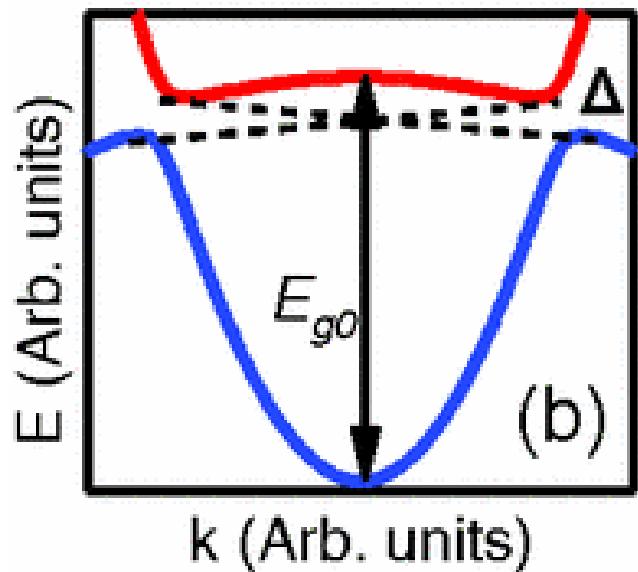
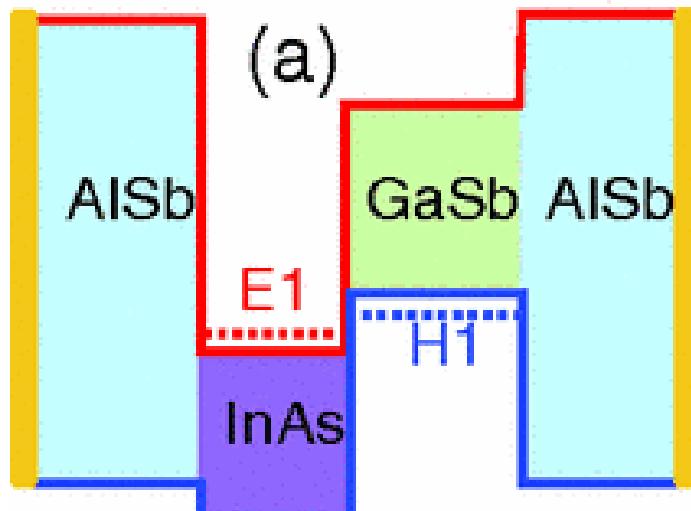
2D Topological insulator



2D Topological insulator



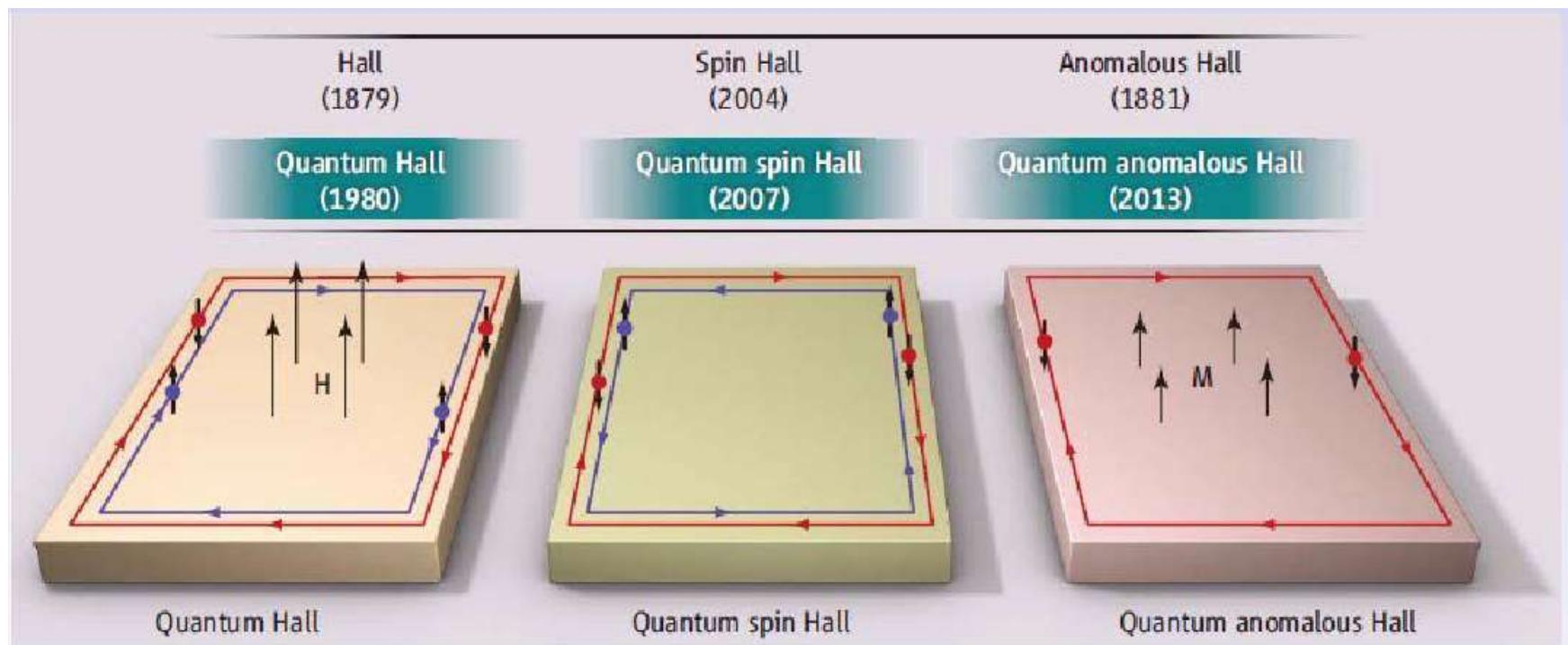
2D Topological insulator



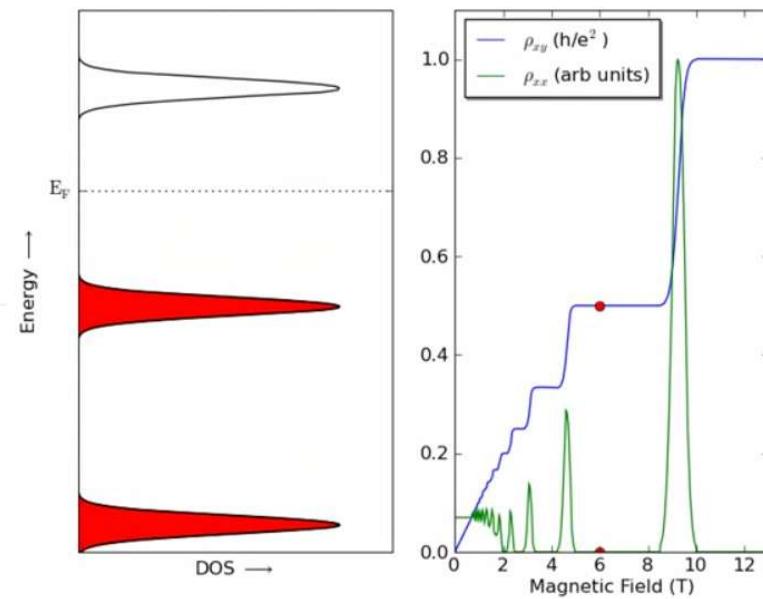
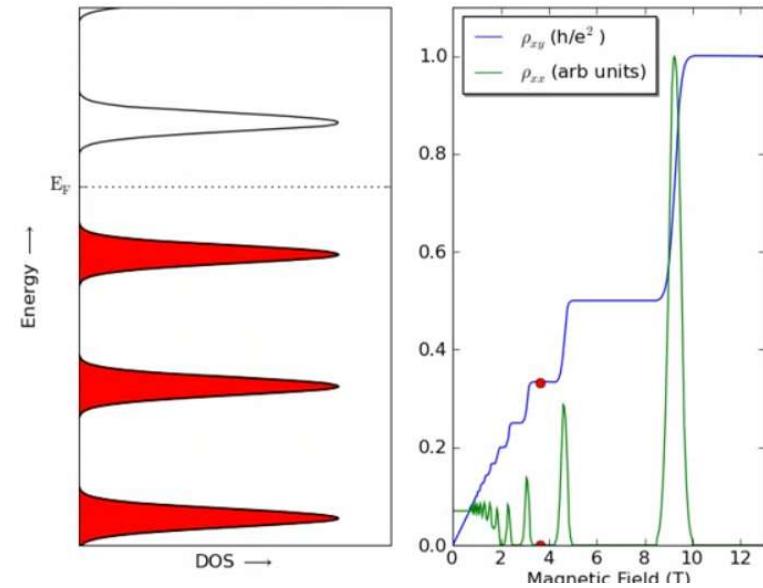
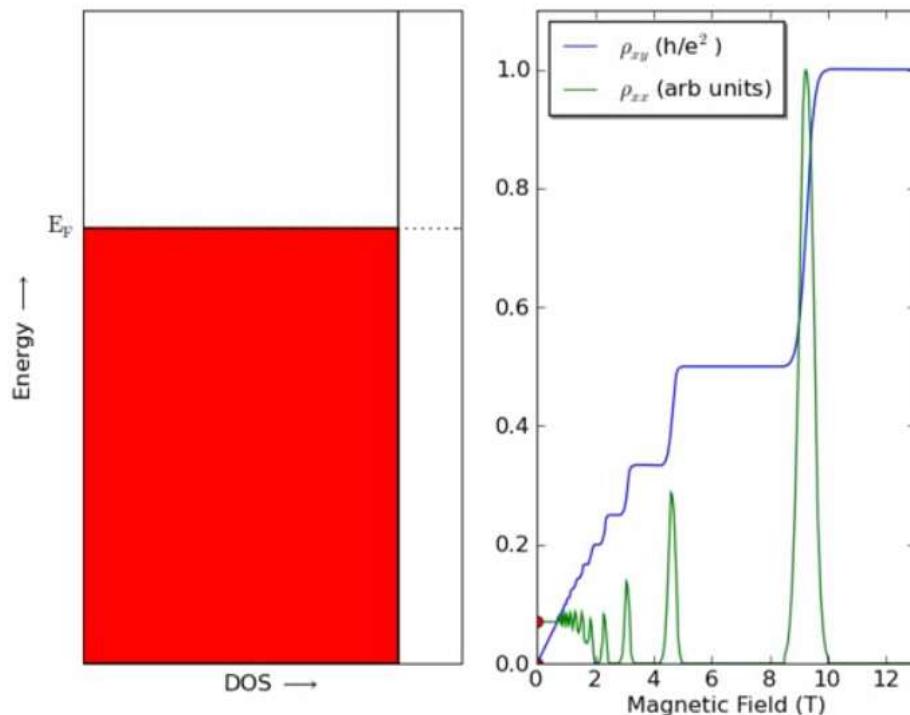
Outline

2. Quantum anomalous Hall effect

Hall effect



Quantum Hall effect



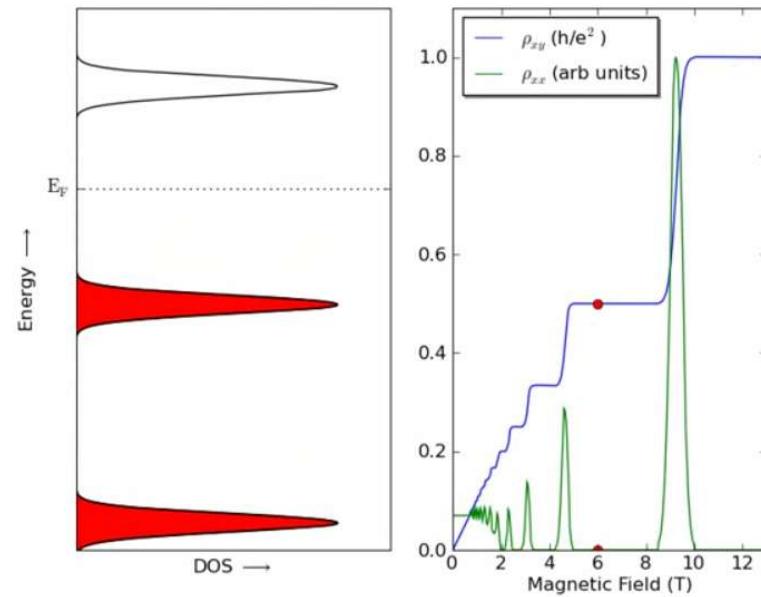
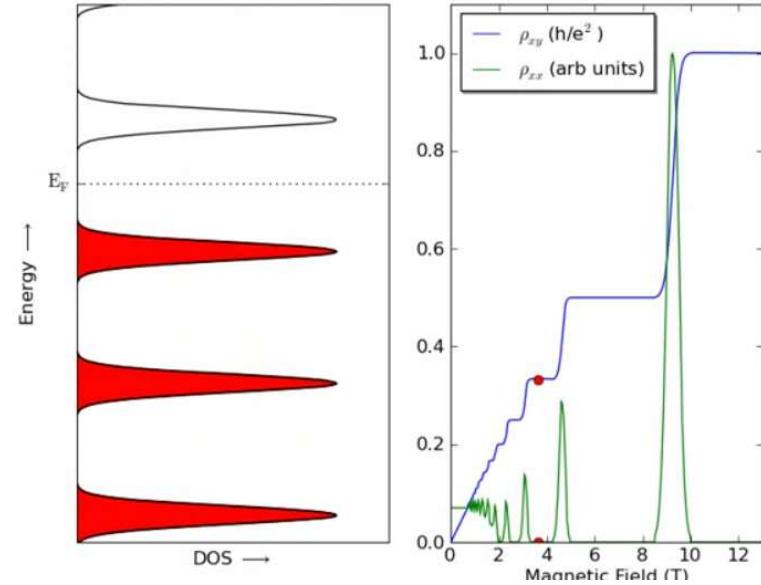
Wikipedia

Quantum Hall effect

A Strong magnetic field is needed!

Whether a magnetic field is necessary?

YES!



Quantum Hall effect

VOLUME 61, NUMBER 18

PHYSICAL REVIEW LETTERS

31 OCTOBER 1988

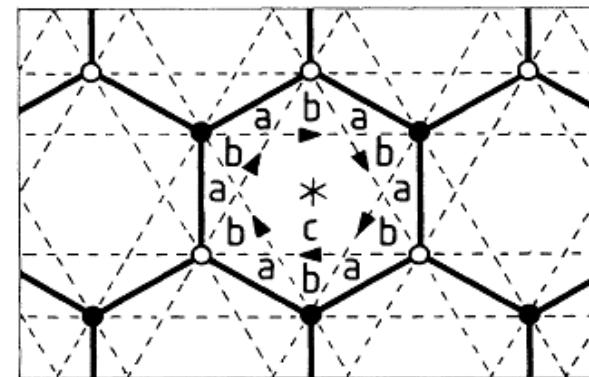
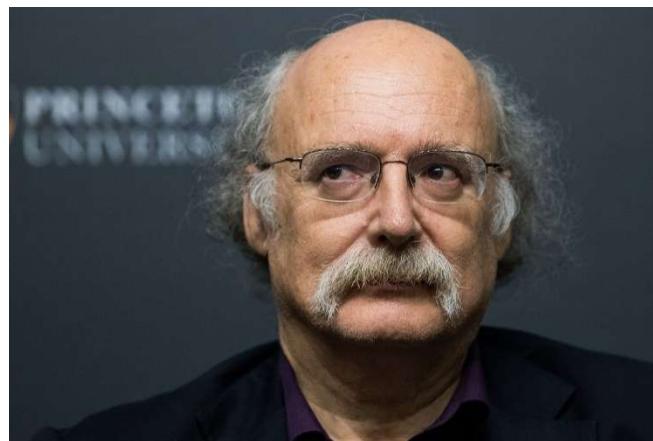
Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the “Parity Anomaly”

F. D. M. Haldane

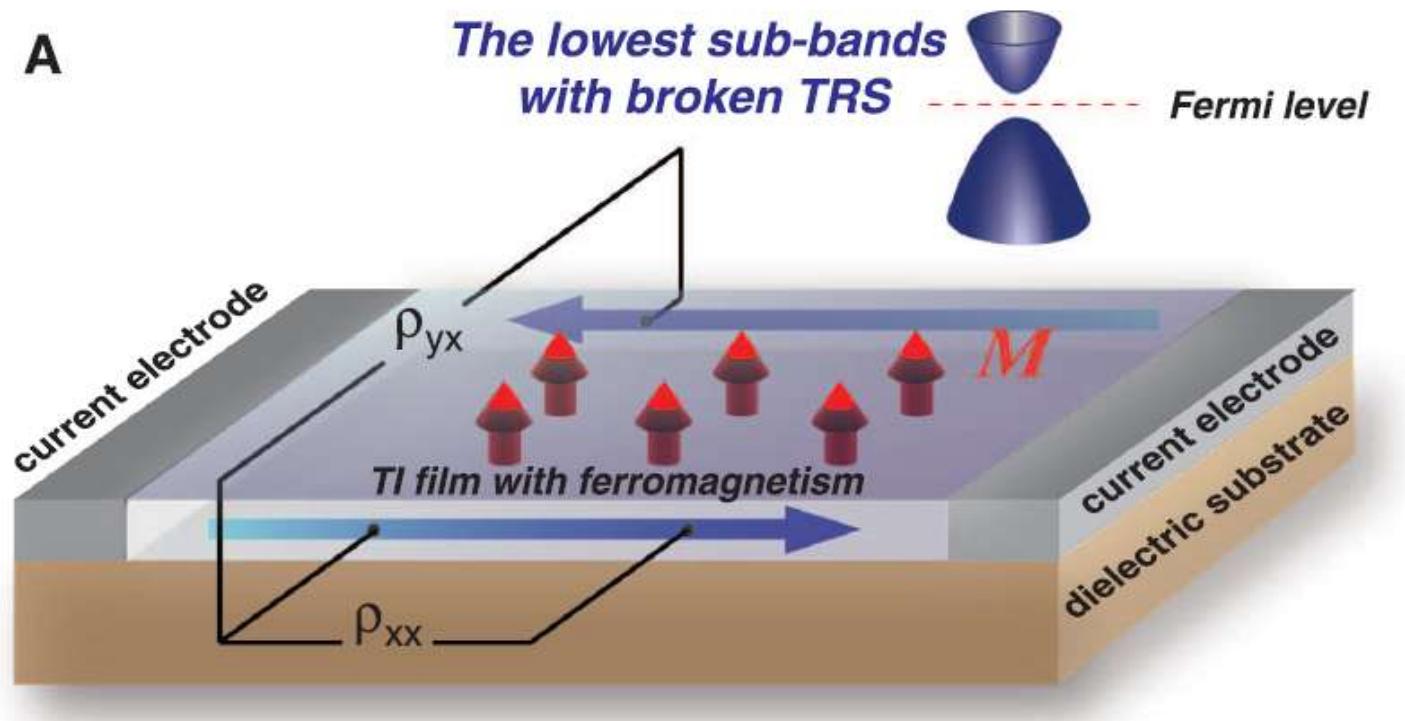
Department of Physics, University of California, San Diego, La Jolla, California 92093

(Received 16 September 1987)

A two-dimensional condensed-matter lattice model is presented which exhibits a nonzero quantization of the Hall conductance σ^{xy} in the *absence* of an external magnetic field. Massless fermions *without spectral doubling* occur at critical values of the model parameters, and exhibit the so-called “parity anomaly” of (2+1)-dimensional field theories.

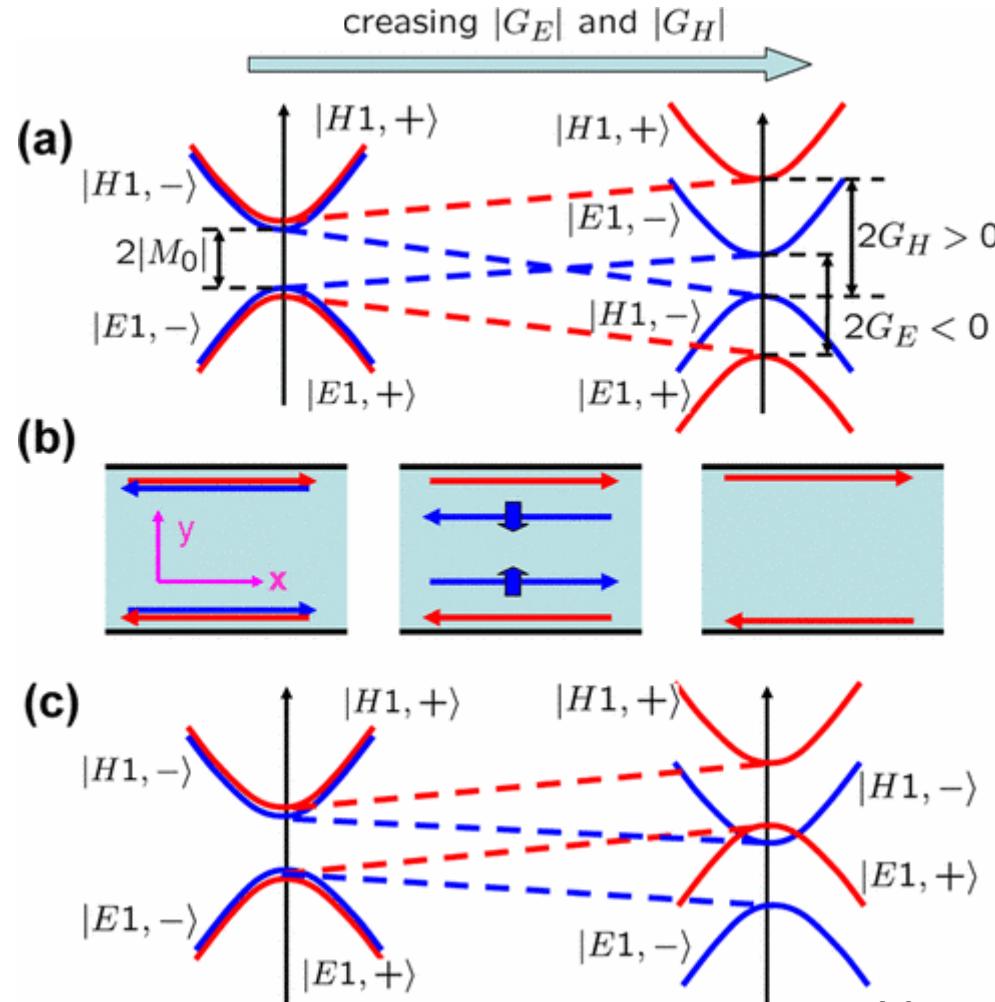


Quantum Hall effect



Quantum anomalous Hall effect

$\text{Hg}_{1-y}\text{Mn}_y\text{Te}$ Quantum Wells



Quantum anomalous Hall effect

$\text{Hg}_{1-y}\text{Mn}_y\text{Te}$ Quantum Wells

PRL 101, 140802 (2008)

PHYSICAL REVIEW LETTERS

week ending
3 OCTOBER 2008

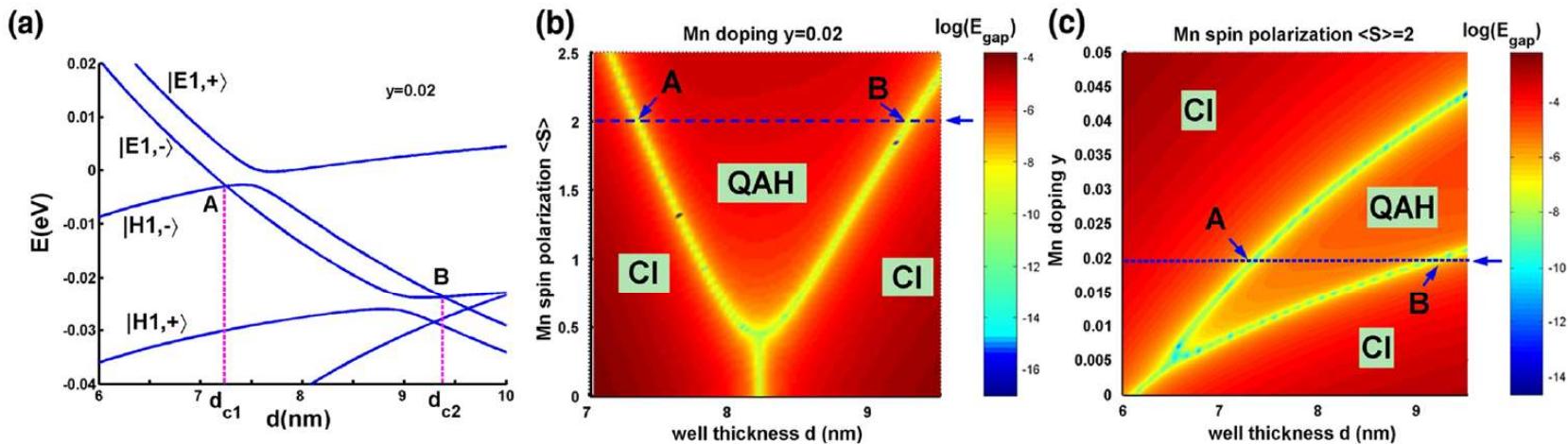
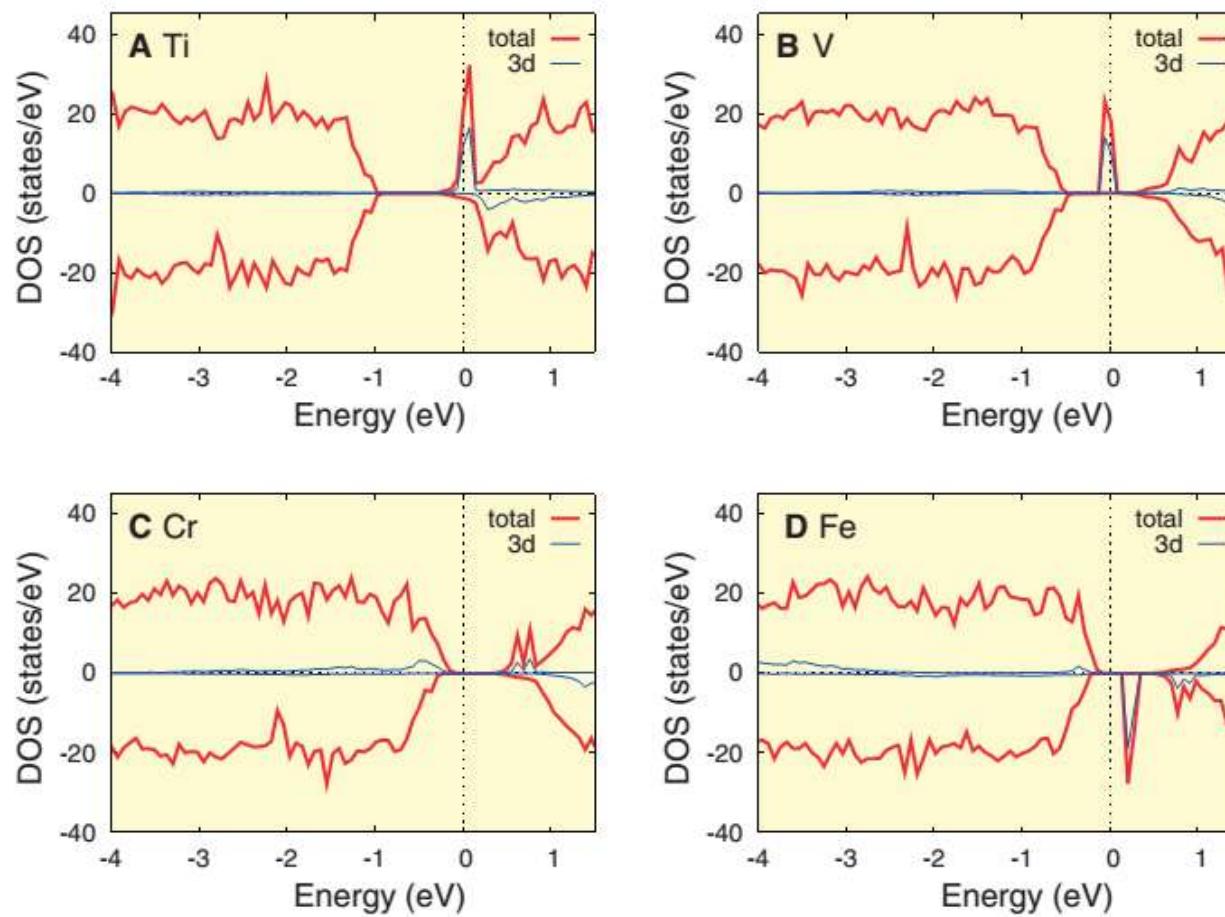


FIG. 2 (color online). (a) The energy levels for $|E1, \pm\rangle$ and $|H1, \pm\rangle$ are plotted as a function of the QW thickness. Two crossing points (A and B) are labeled in the figure. The energy gap ($\log(E_{\text{gap}})$ used here) is plotted as a function of the well thickness d versus the Mn magnetic moment $\langle S \rangle$ in (b), versus the Mn doping concentration y in (c). Dashed blue line in (b) or (c) refers to the line along which (a) is plotted. The points “A” and “B” correspond to the two Dirac-type crossing points. Two different phases, conventional insulator (CI) with $\sigma_H = 0$ and QAH state with $\sigma_H = -e^2/h$, are separated by the gap closing line in the figures.

Liu, et al, PRL (2008)

Quantum anomalous Hall effect

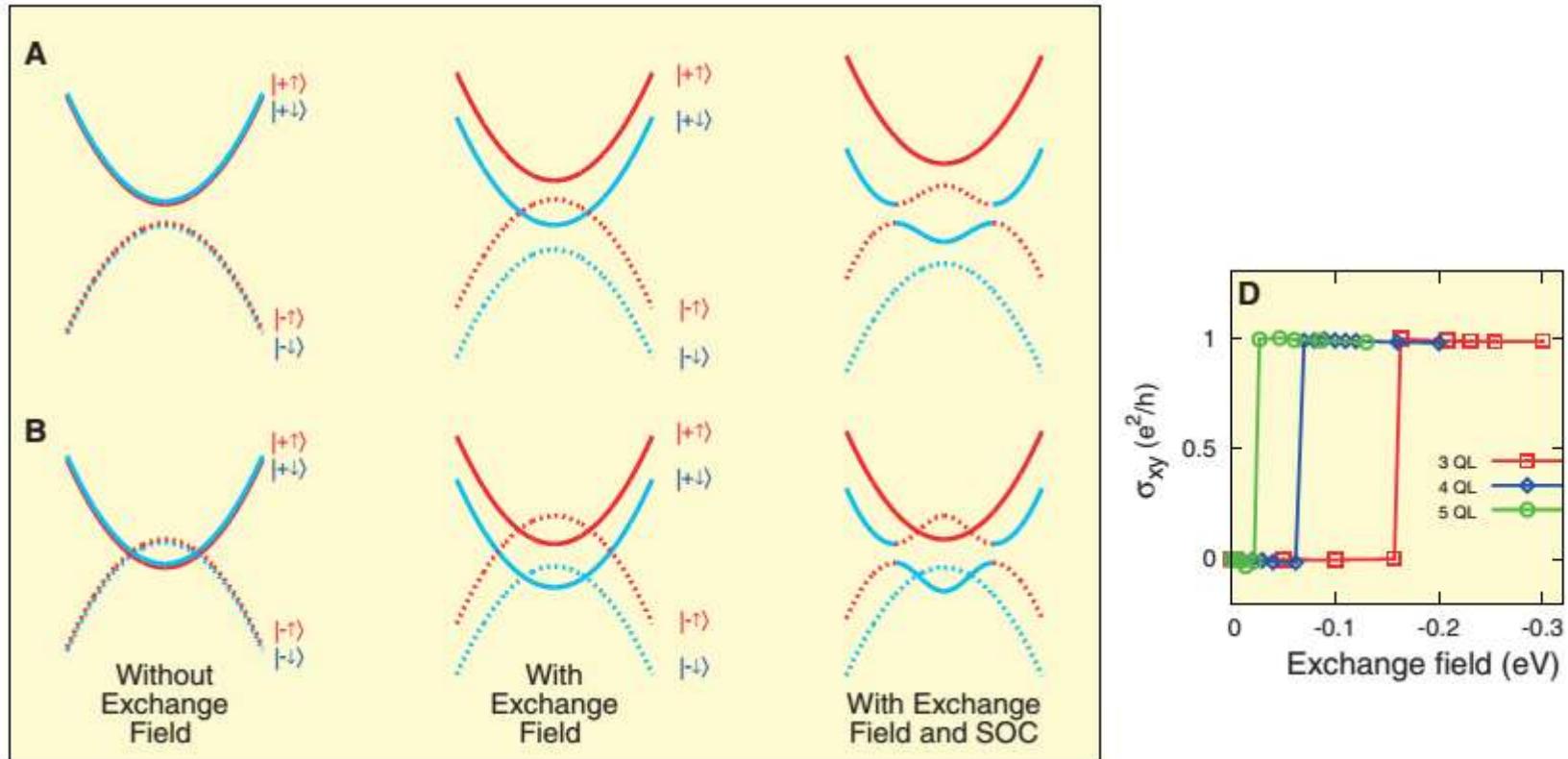
FM doped BiSeTe



Yu, et al, Science (2010)

Quantum anomalous Hall effect

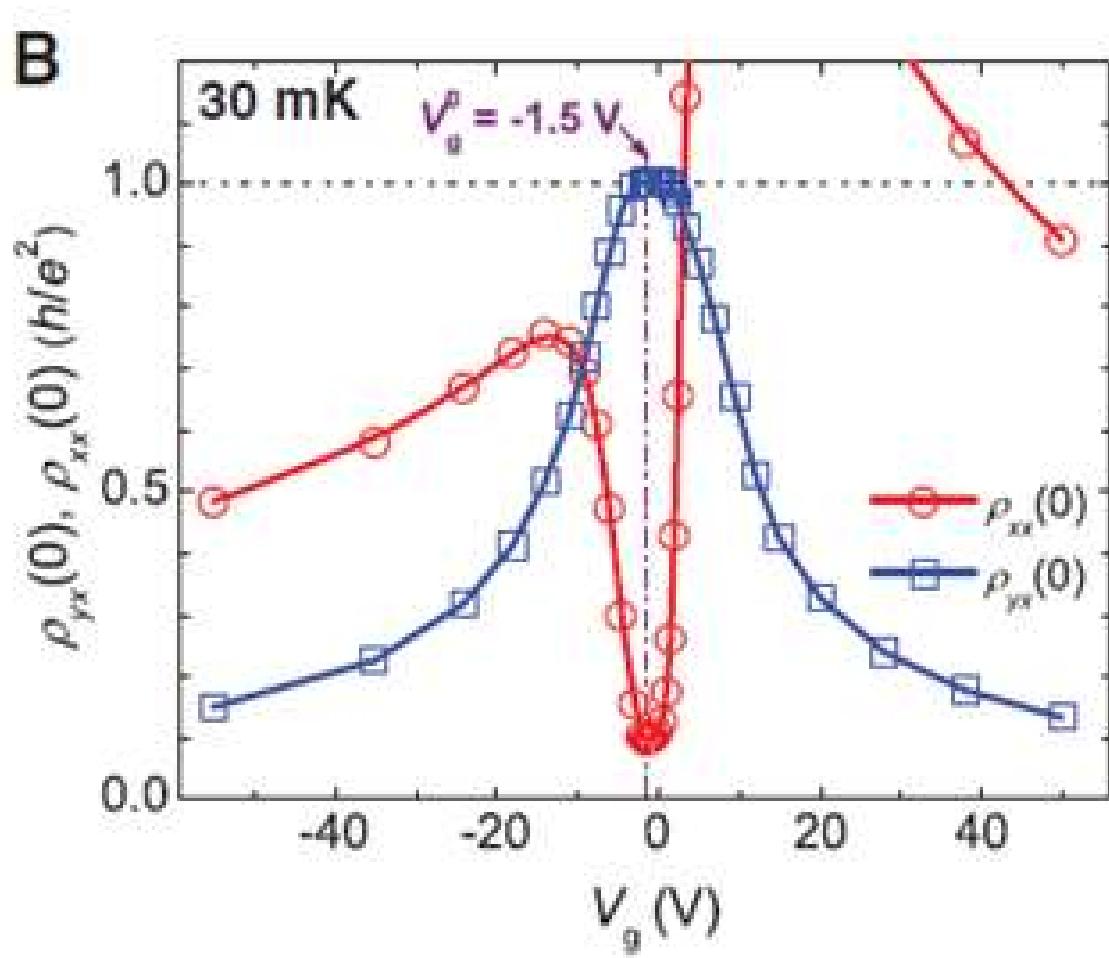
FM doped BiSeTe



FM doped TI

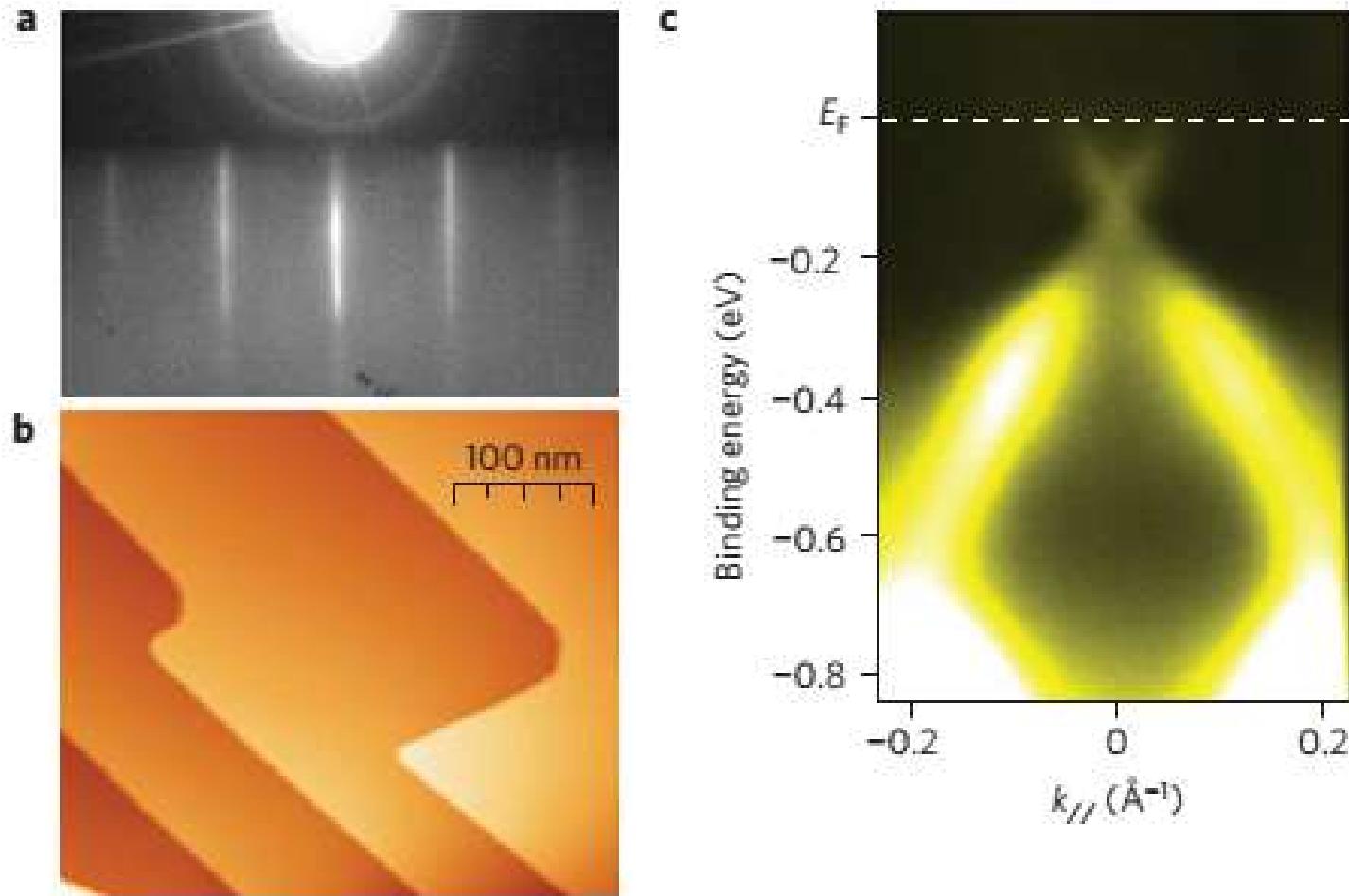
@FM order lead Hall conductance quantized in units of e^2/h ;
open energy gap at Dirac point;

Quantum anomalous Hall effect



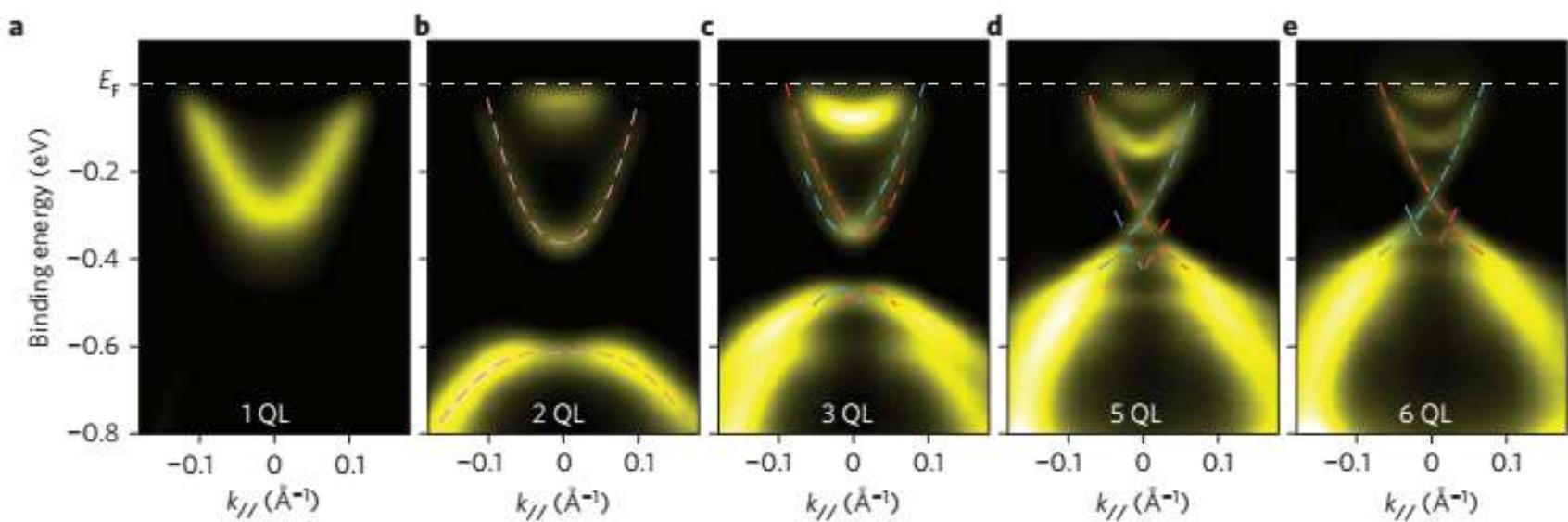
Chang, et al, Science (2013)

Bi₂Se₃ -- TI

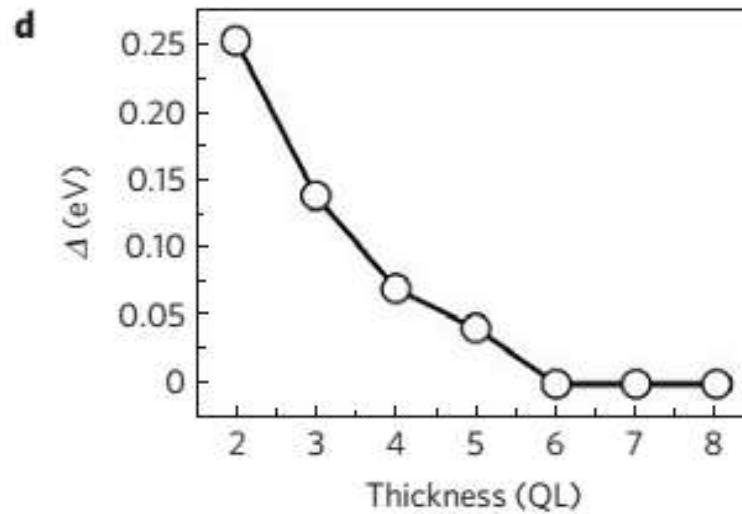
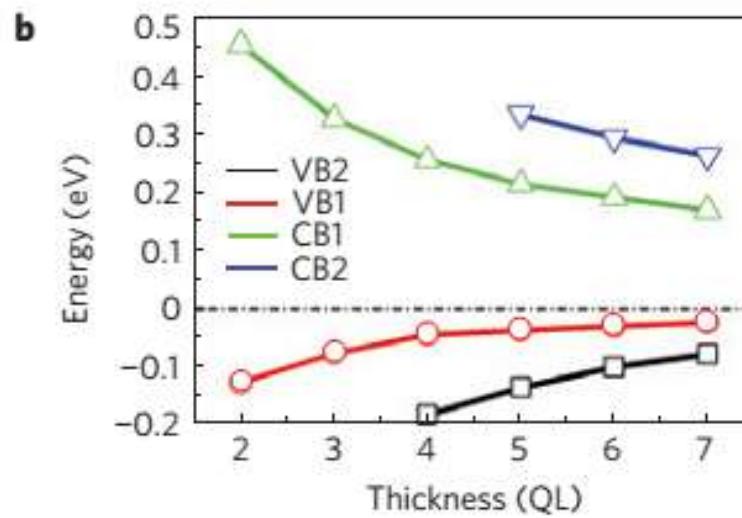
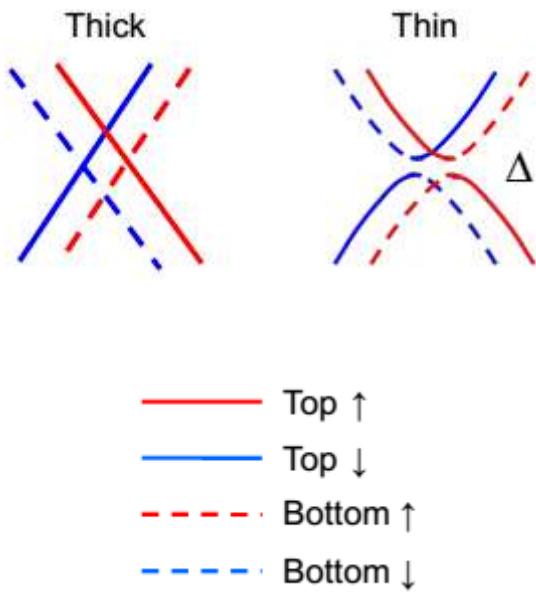


Zhang, et al, Nature Physics (2010)

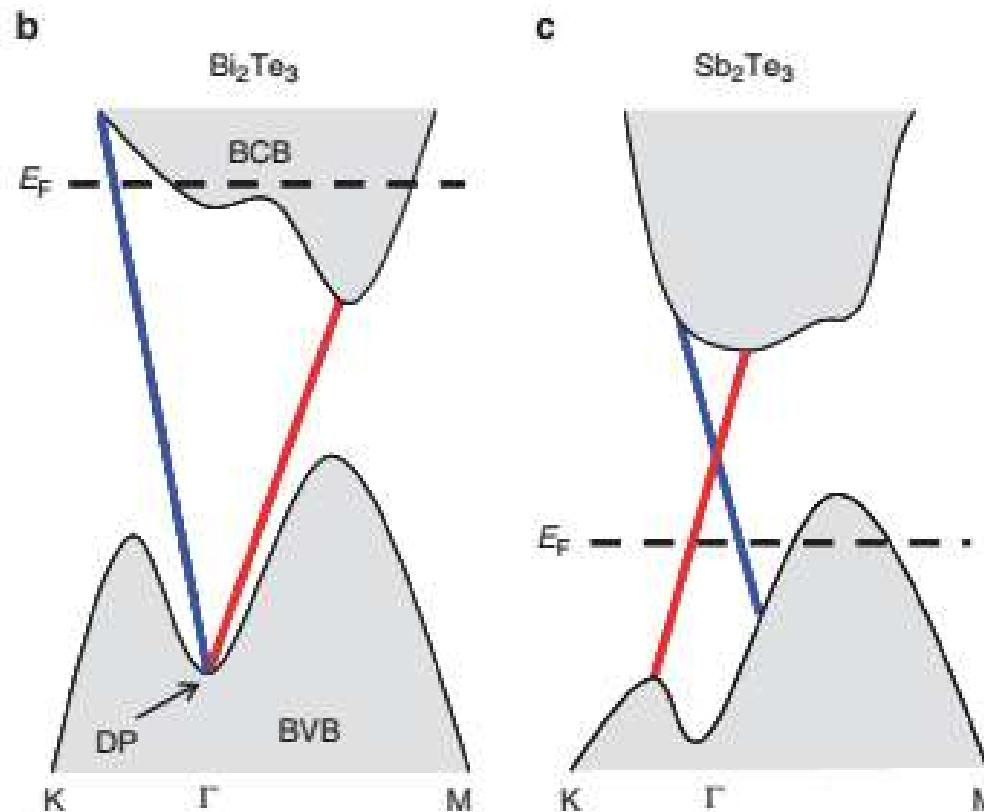
Bi₂Se₃ -- TI



Bi₂Se₃ -- TI

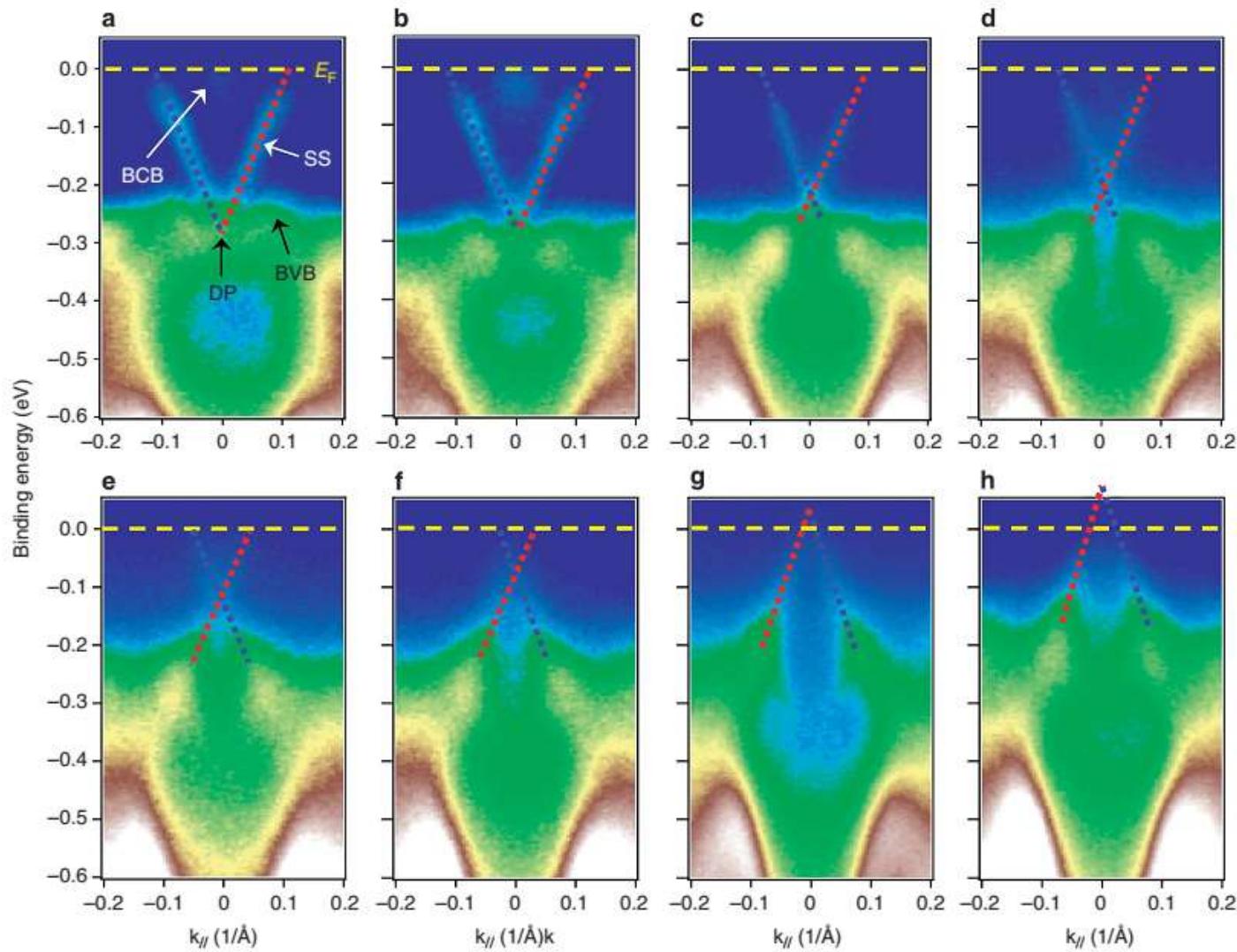


Tuning Fermi Level TI



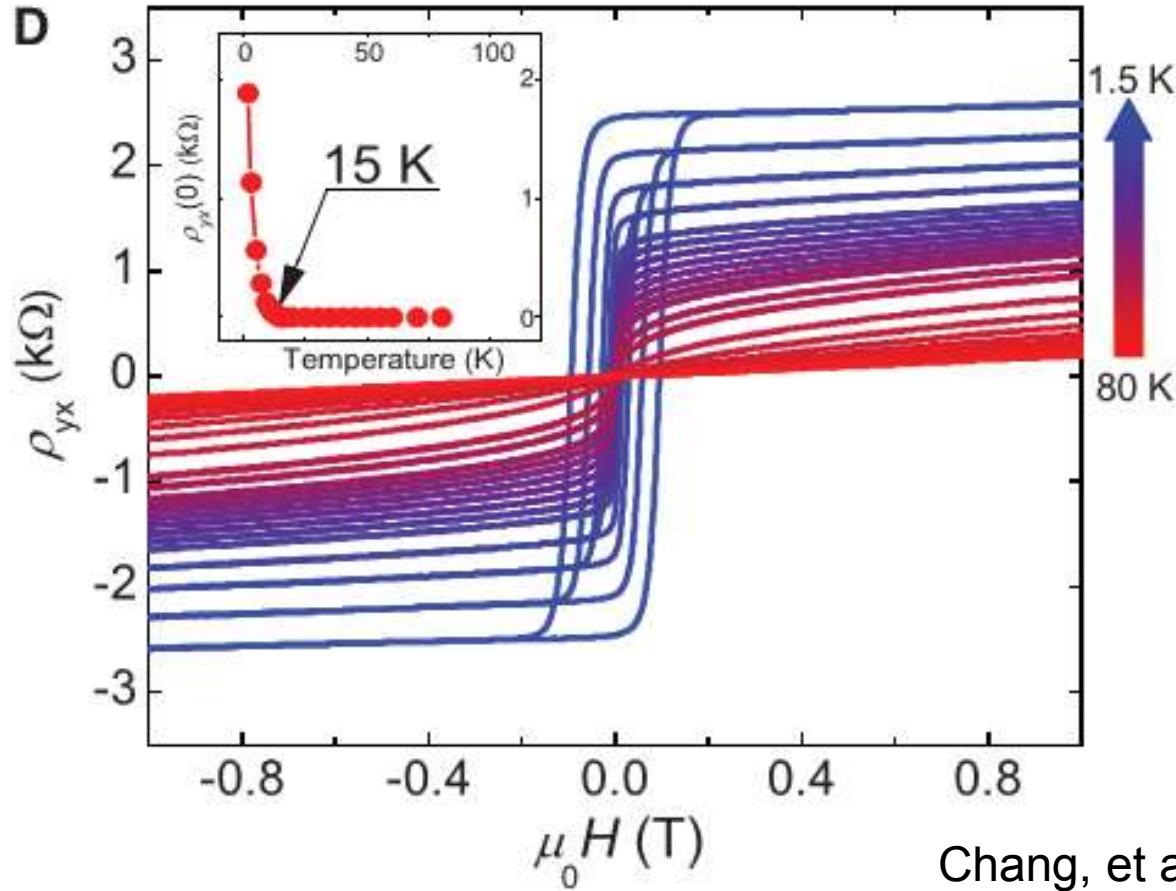
Zhang, et al, Nature Communications (2011)

Tuning Fermi Level TI



Quantum anomalous Hall effect

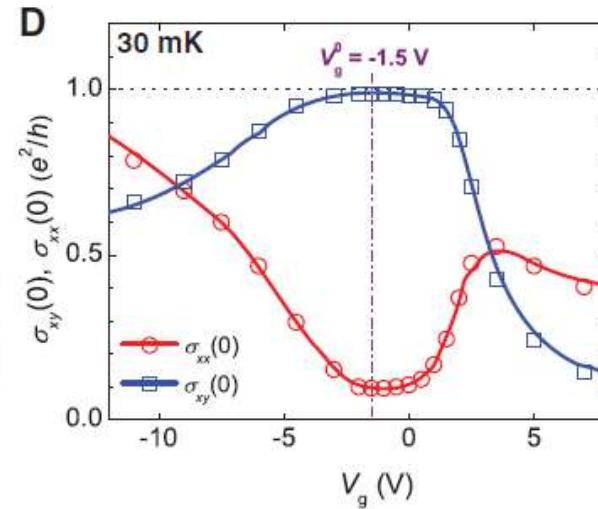
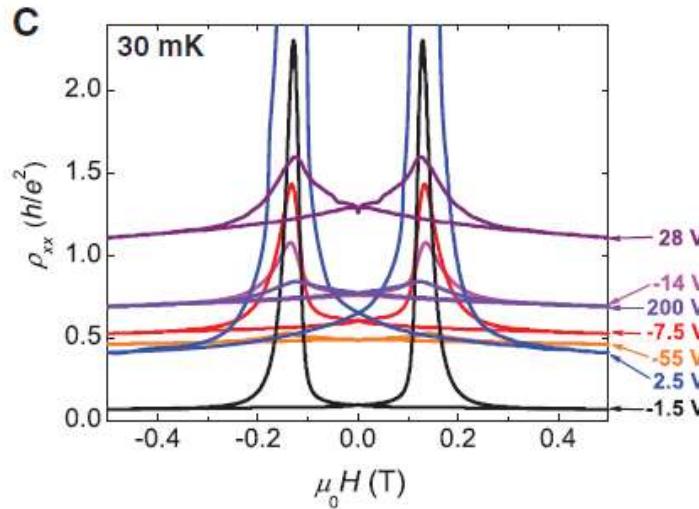
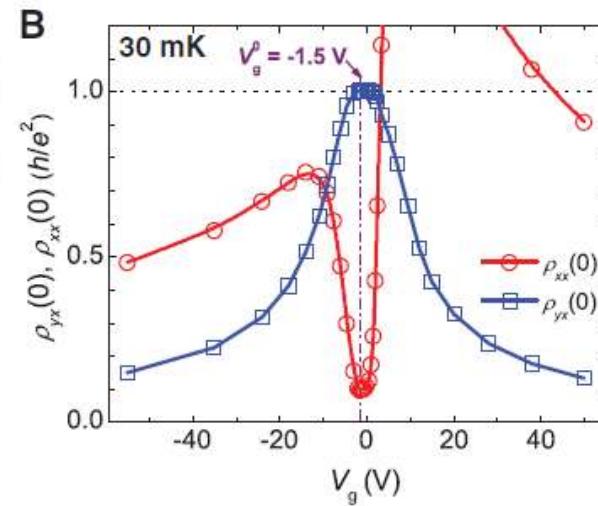
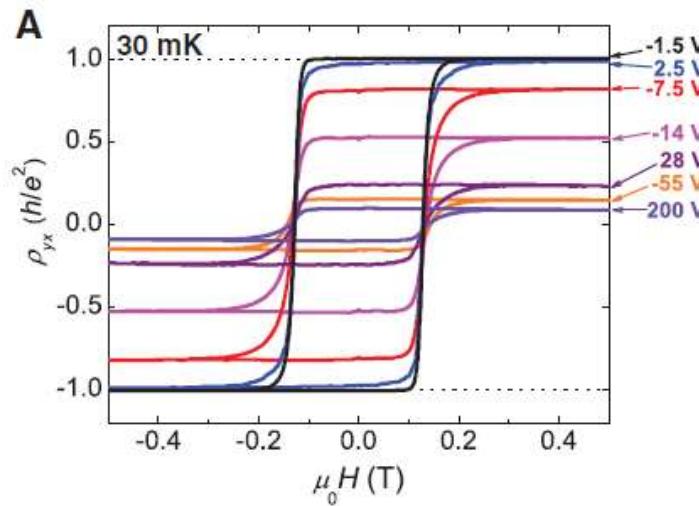
Cr doped (Bi,Sb)Te₃



Chang, et al, Science (2013)

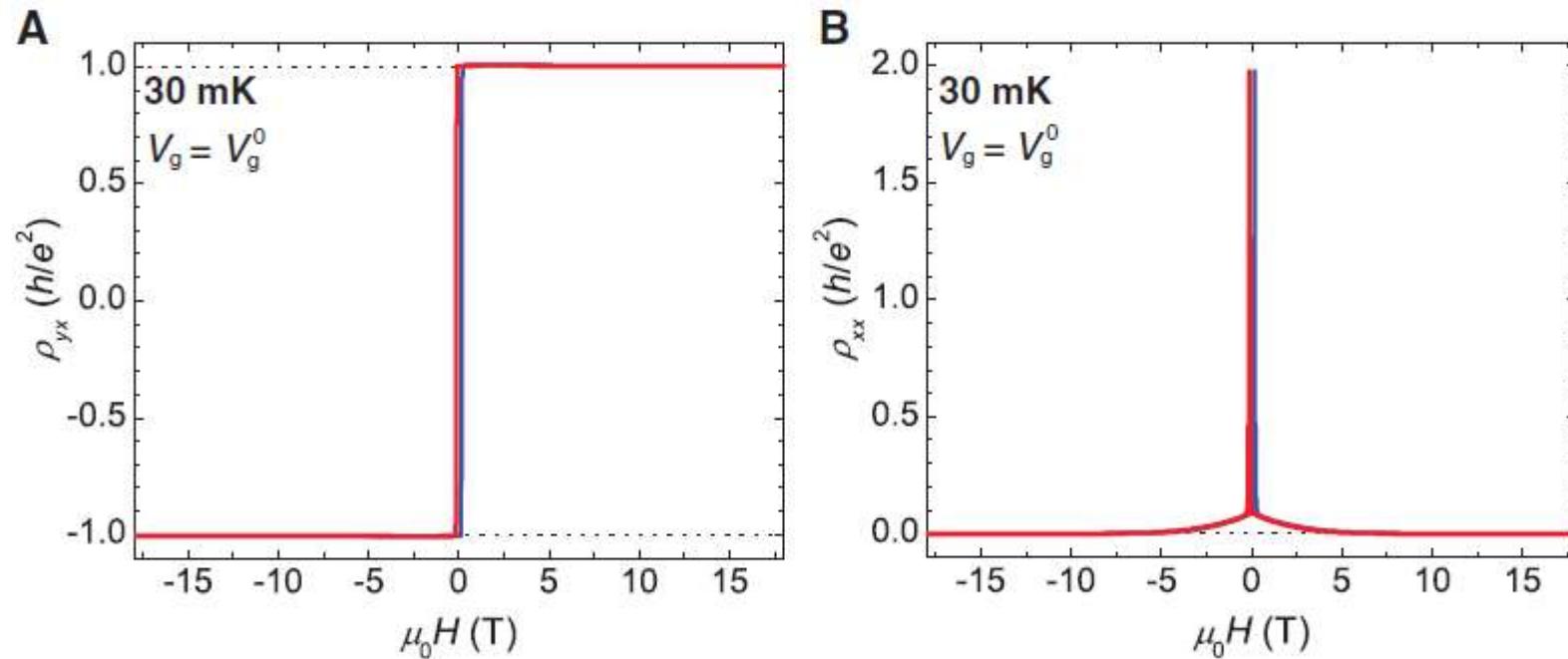
Quantum anomalous Hall effect

Cr doped (Bi,Sb)Te₃



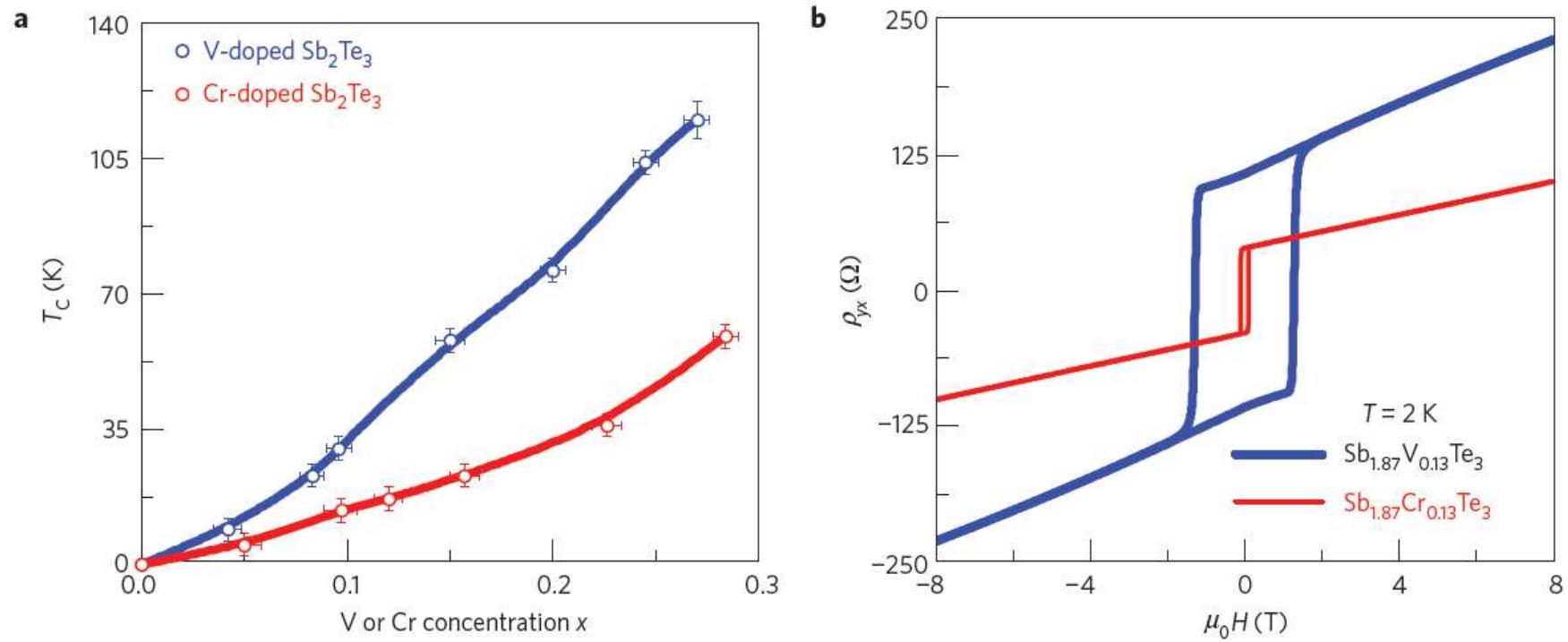
Quantum anomalous Hall effect

Cr doped (Bi,Sb)Te₃



Quantum anomalous Hall effect

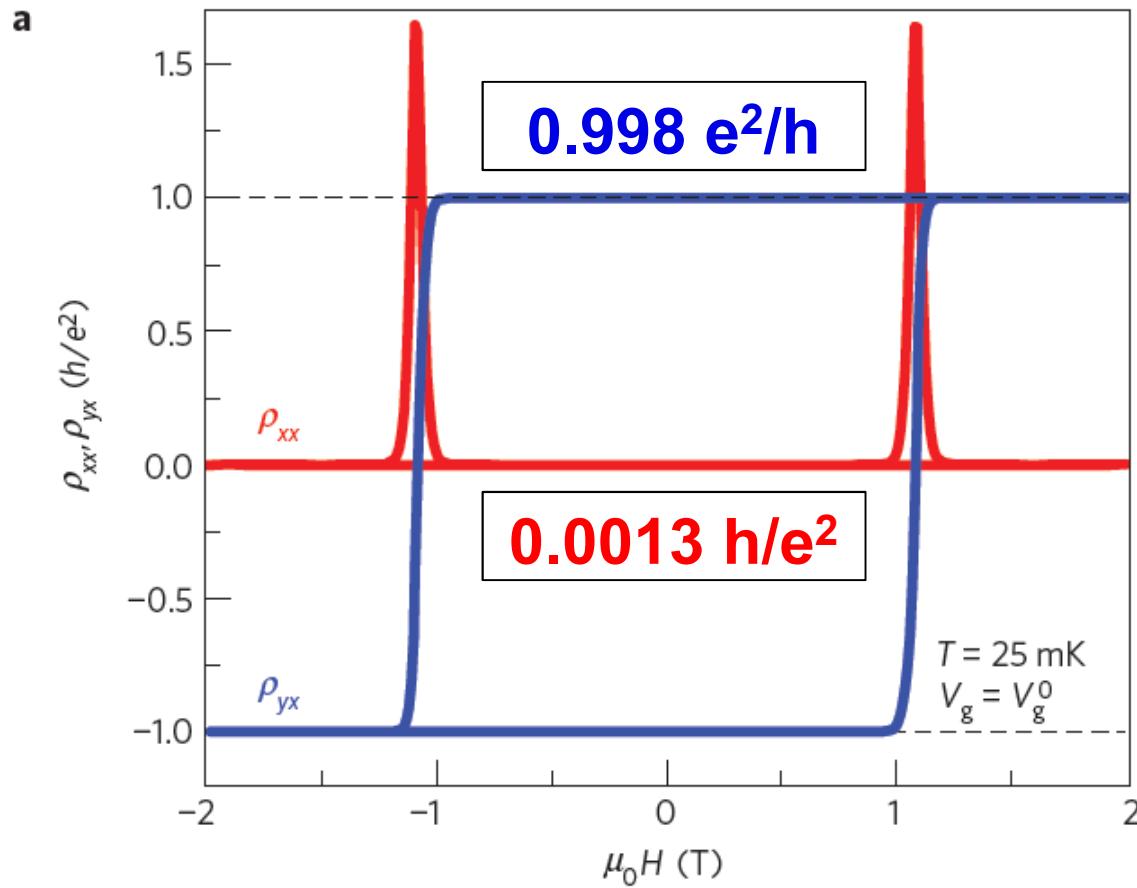
V doped (Bi,Sb)Te₃



Higher T_C , larger anisotropy

Quantum anomalous Hall effect

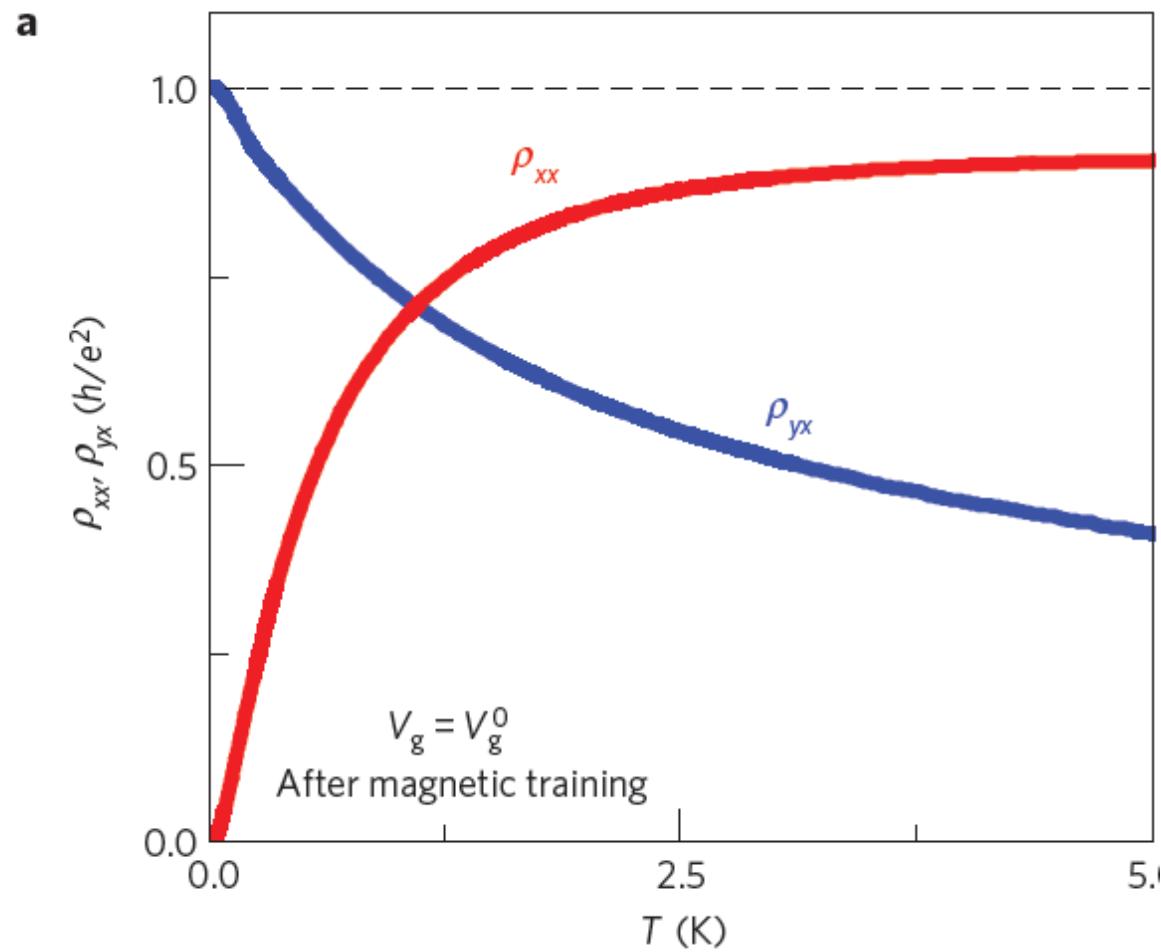
V doped (Bi,Sb)Te₃



Chang, et al, Nature Materials (2015)

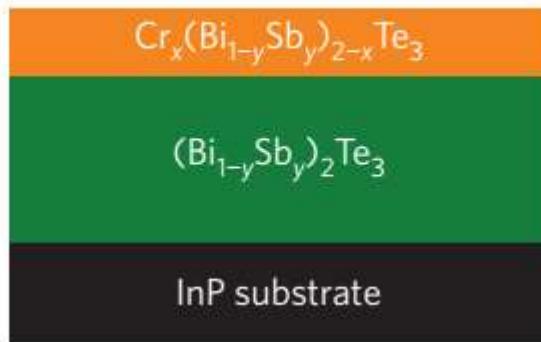
Quantum anomalous Hall effect

V doped (Bi,Sb)Te₃

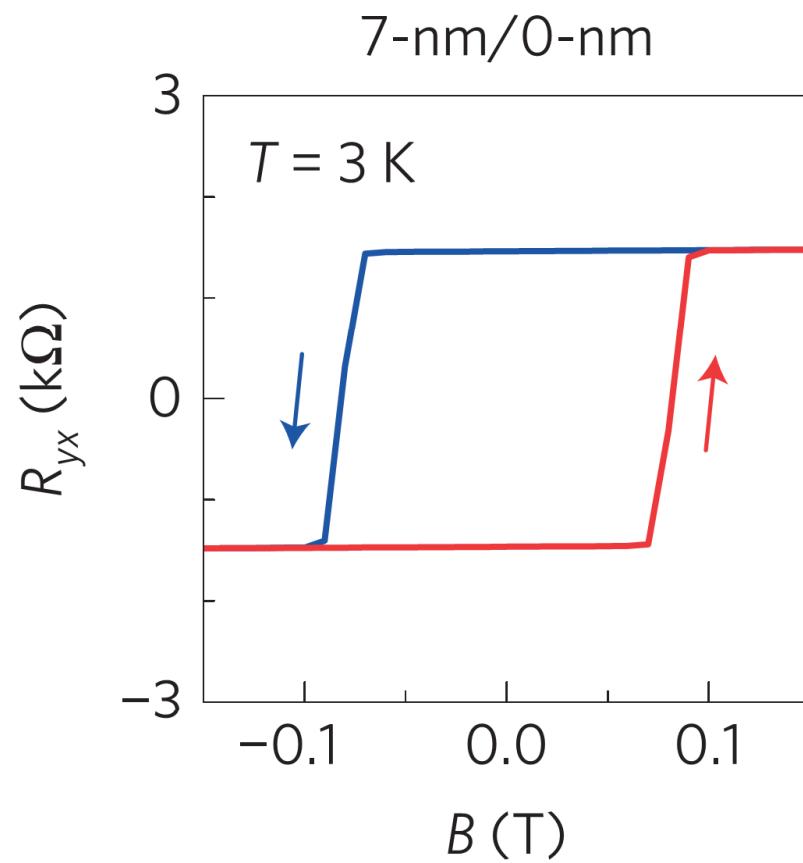


Topological Hall effect

a



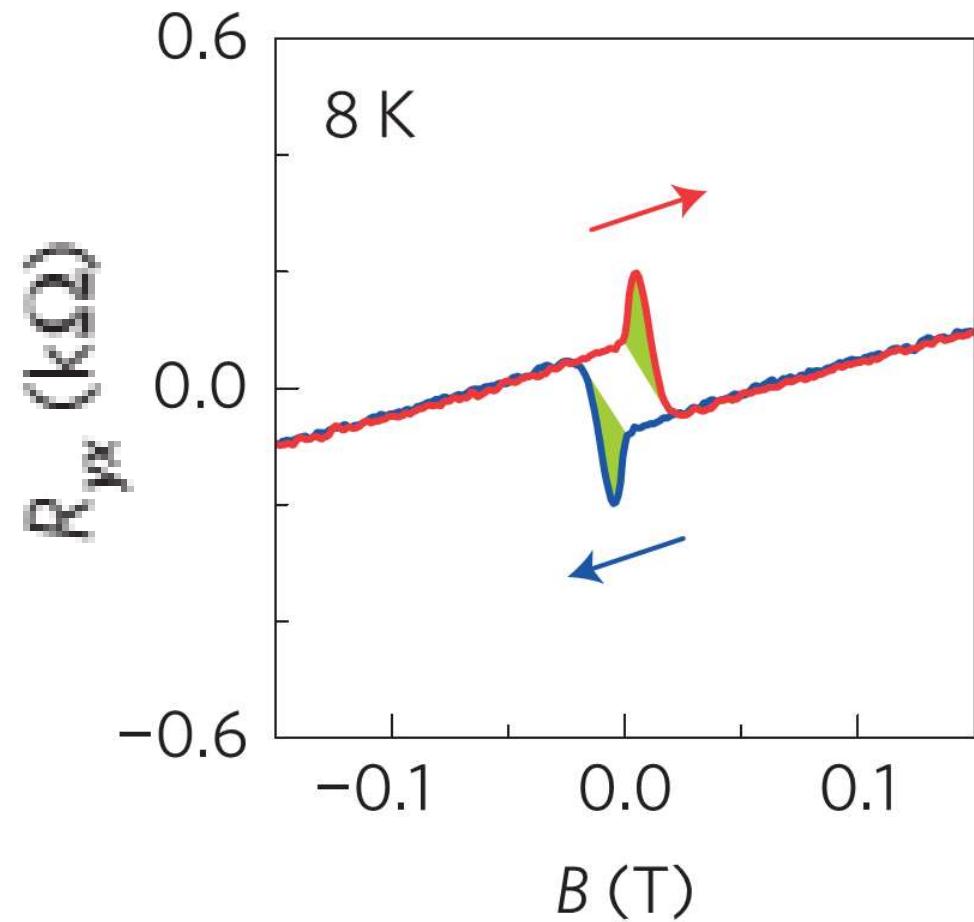
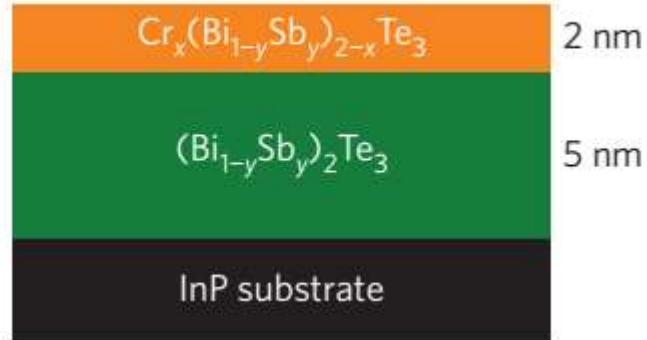
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Yasuda, et al, Nature Physics (2016)

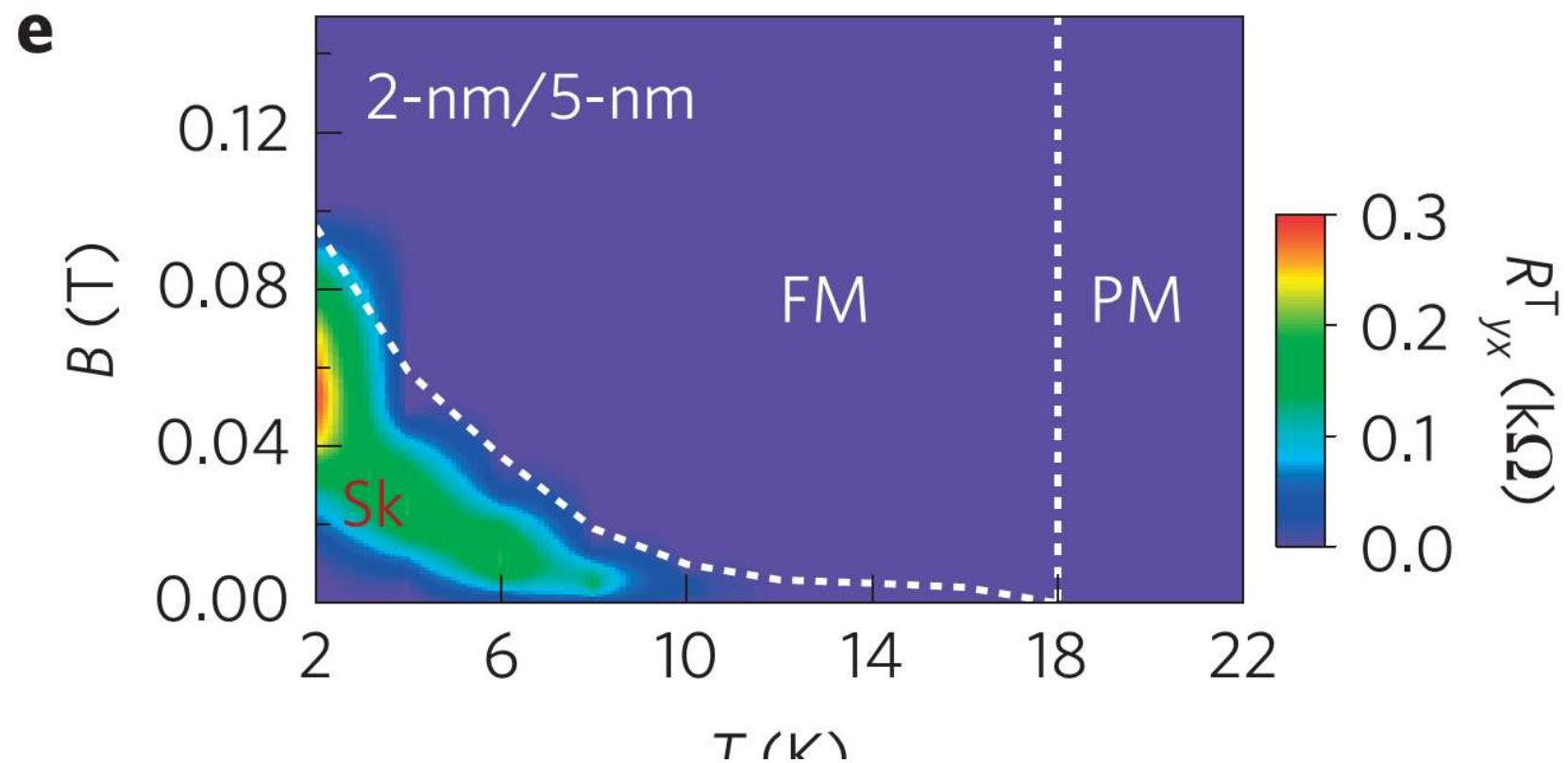
Topological Hall effect

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Yasuda, et al, Nature Physics (2016)

Topological Hall effect

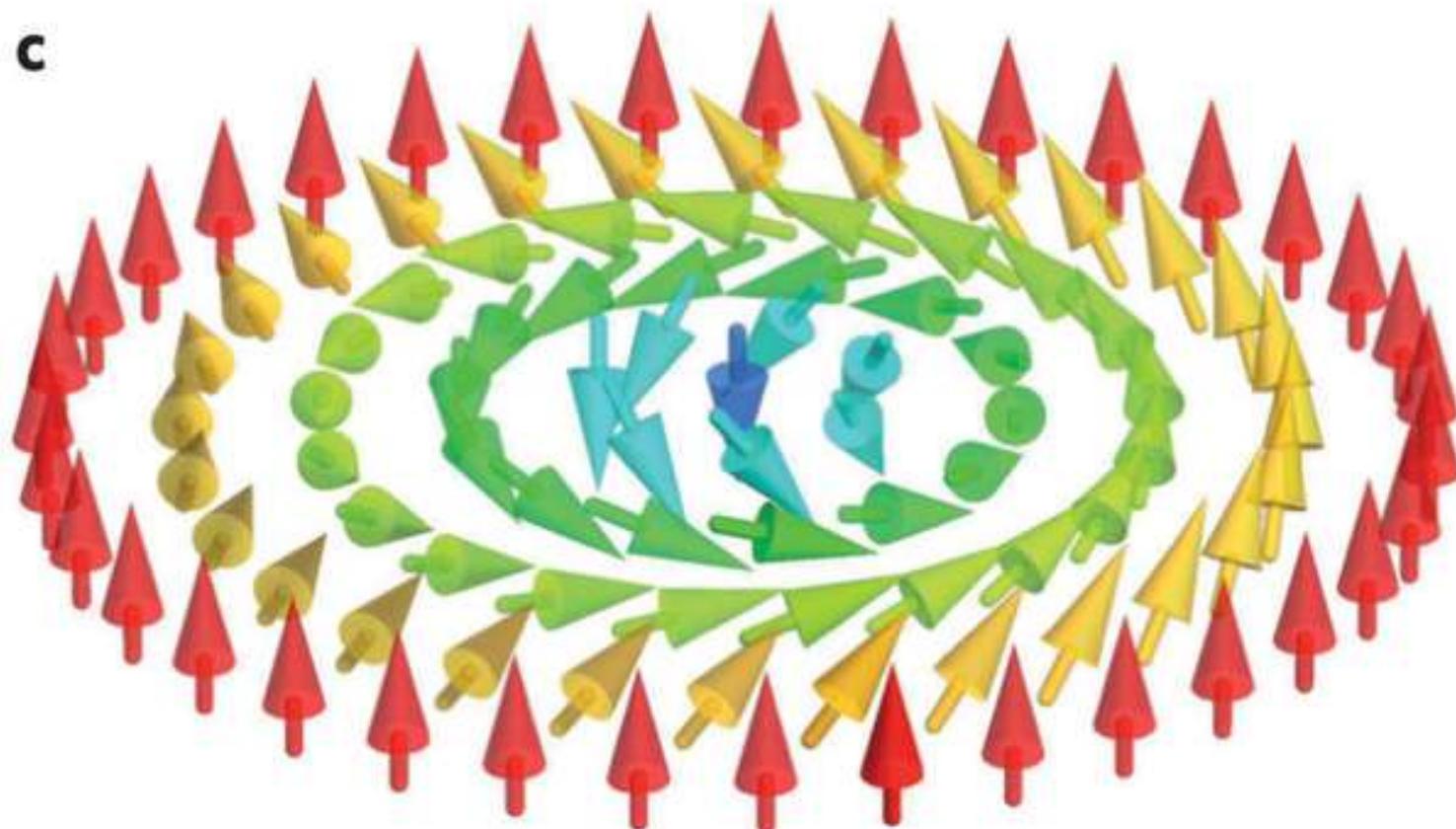


休息10分钟

Outline

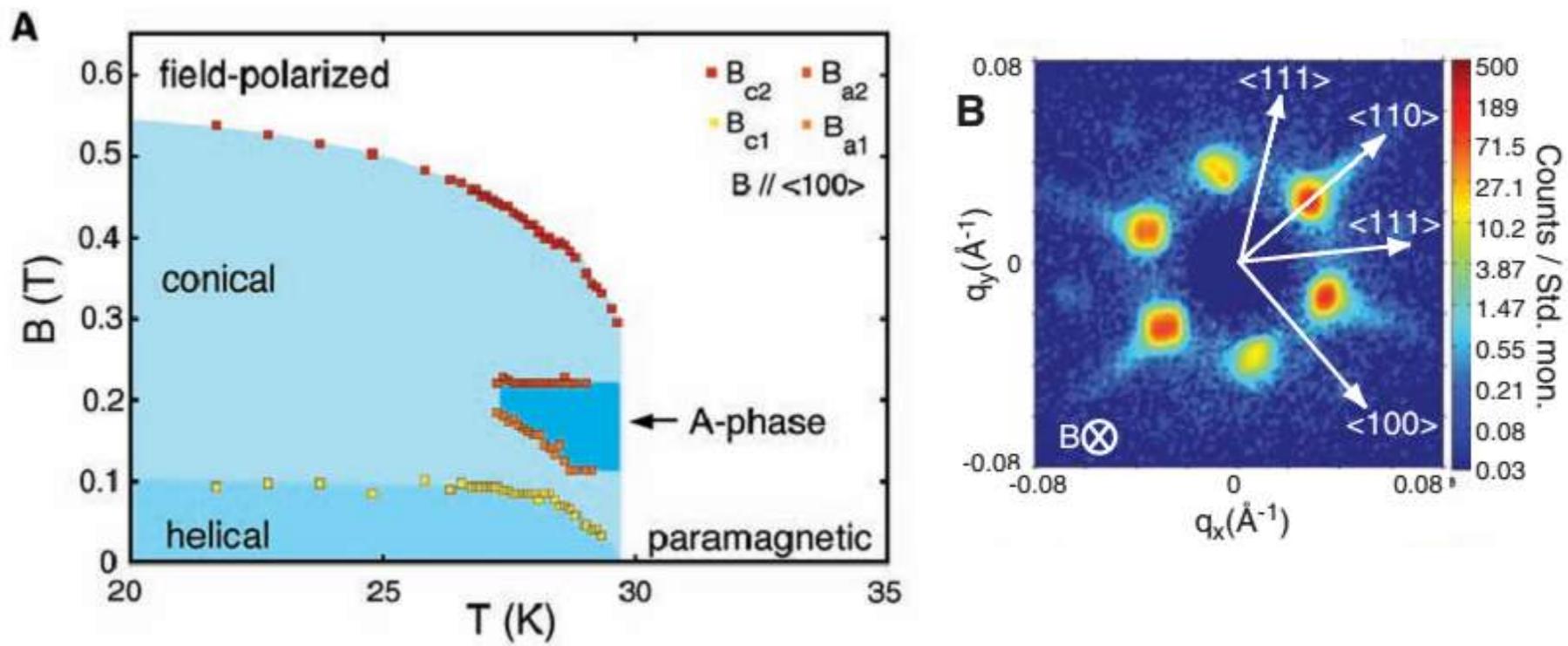
3. Skyrmions

Topology in real space



Observation

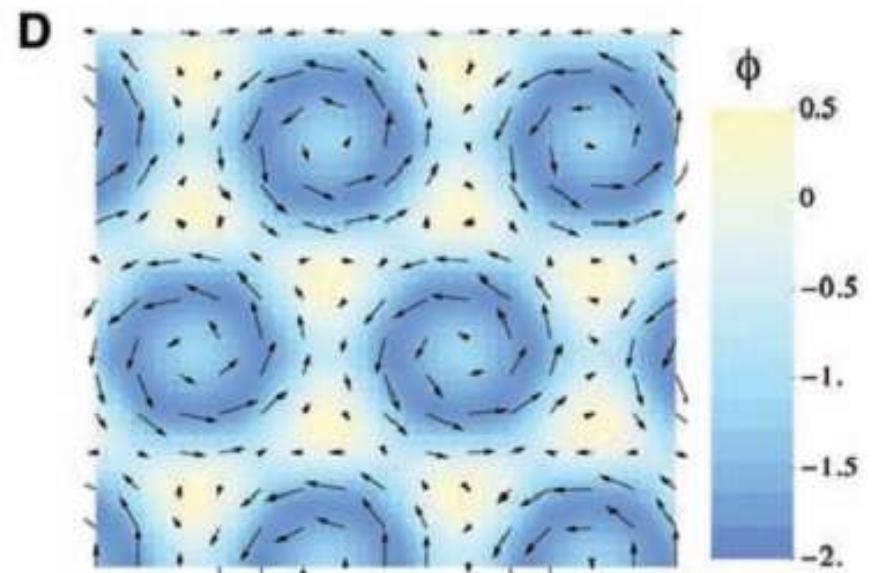
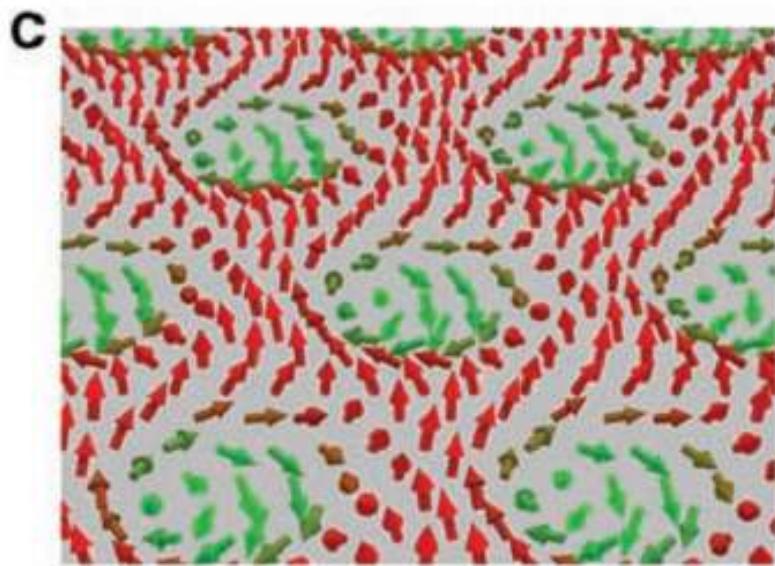
Neutron Scattering: MnSi



Muhlbauer, et al, Science (2009)

Observation

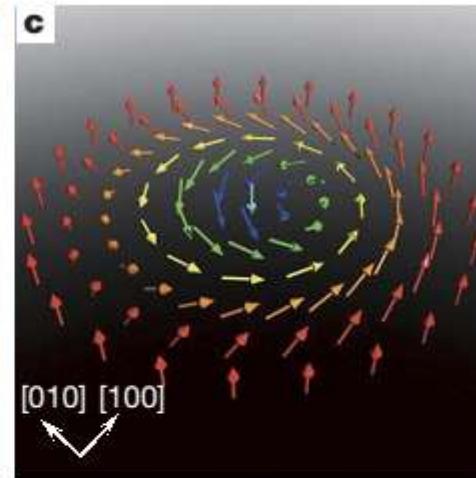
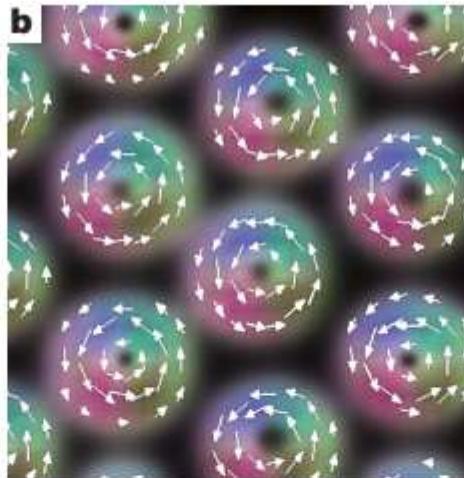
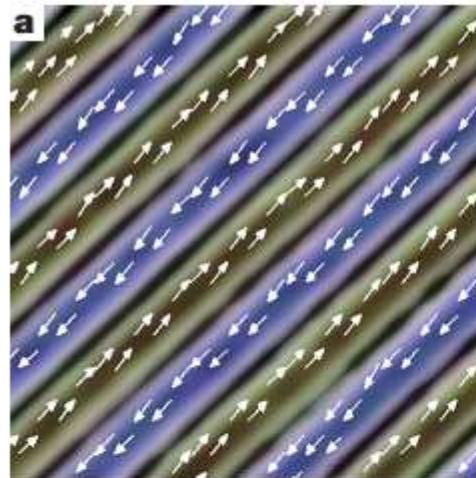
Neutron Scattering



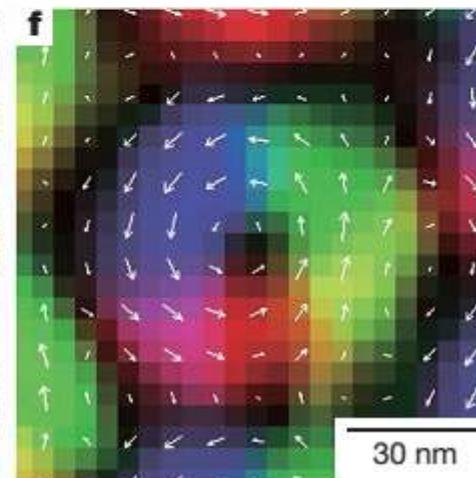
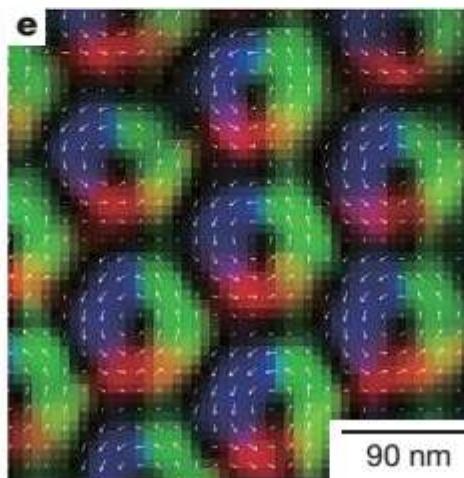
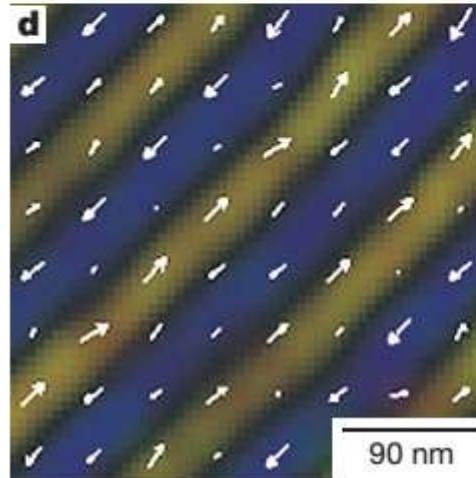
Muhlbauer, et al, Science (2009)

Observation

Lorentz TEM: $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$



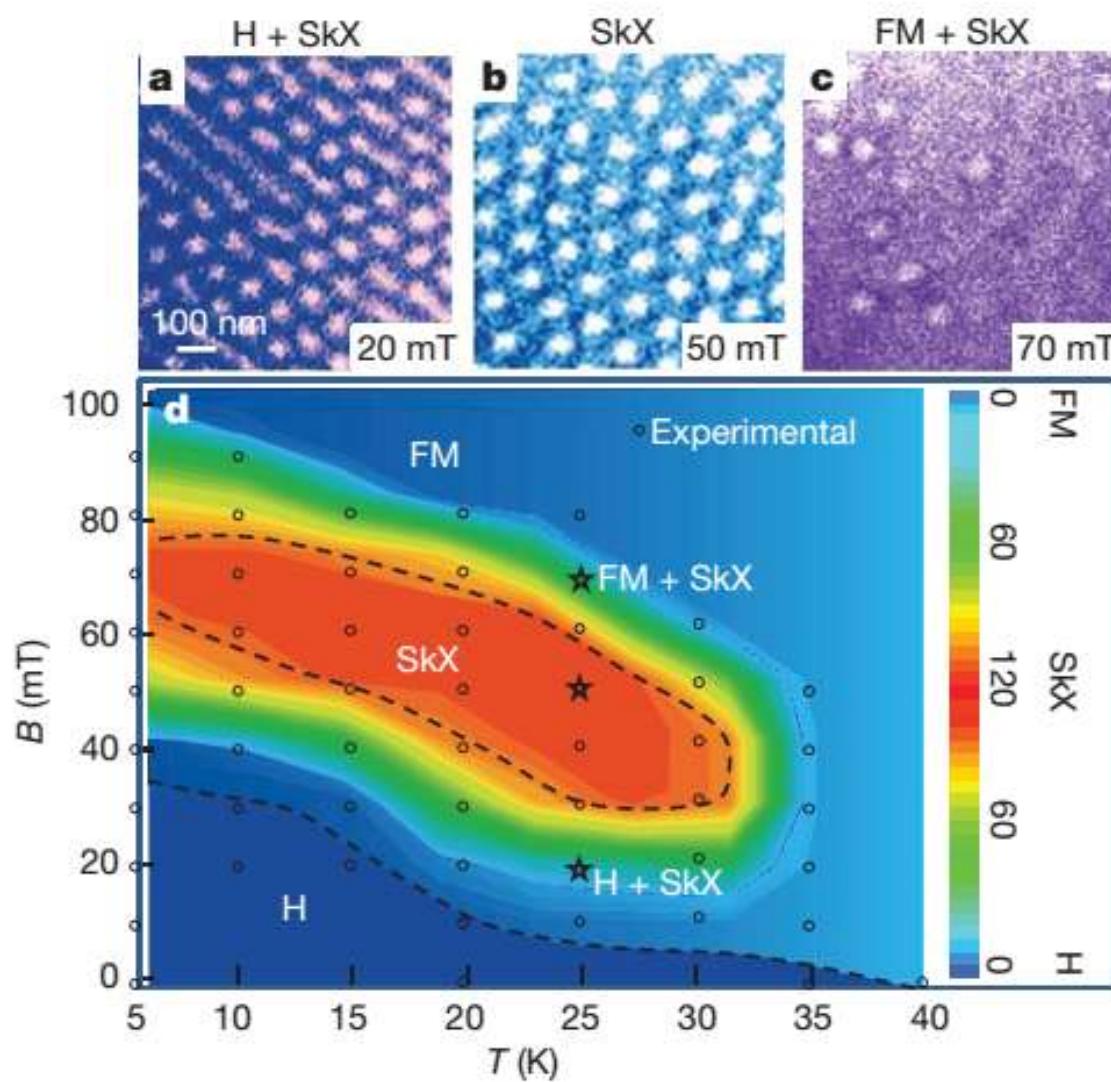
Theory



Experiment

Observation

Lorentz TEM: $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$



Topological Hall effect

VOLUME 93, NUMBER 9

PHYSICAL REVIEW LETTERS

week ending
27 AUGUST 2004

Topological Hall Effect and Berry Phase in Magnetic Nanostructures

P. Bruno,¹ V. K. Dugaev,^{1,2} and M. Taillefumier^{1,3}

¹*Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, 06120 Halle, Germany*

²*Institute for Problems of Materials Science, NASU, Vilde 5, 58001 Chernovtsy, Ukraine*

³*Laboratoire Louis Néel, CNRS, Boite Postale 166, 38042 Grenoble CEDEX 09, France*

(Received 21 October 2003; published 27 August 2004)

We discuss the anomalous Hall effect in a two-dimensional electron gas subject to a spatially varying magnetization. This topological Hall effect does not require any spin-orbit coupling and arises solely from Berry phase acquired by an electron moving in a smoothly varying magnetization. We propose an experiment with a structure containing 2D electrons or holes of diluted magnetic semiconductor subject to the stray field of a lattice of magnetic nanocylinders. The striking behavior predicted for such a system (of which all relevant parameters are well known) allows one to observe unambiguously the topological Hall effect and to distinguish it from other mechanisms.

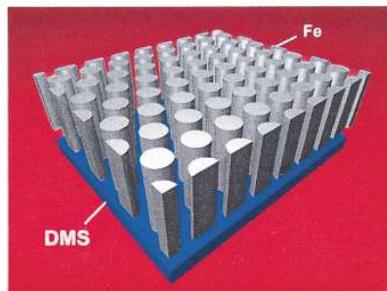
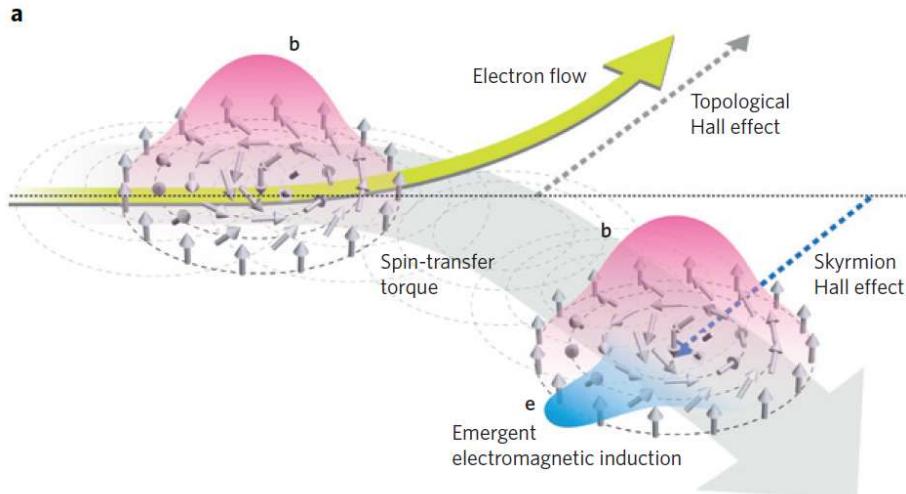
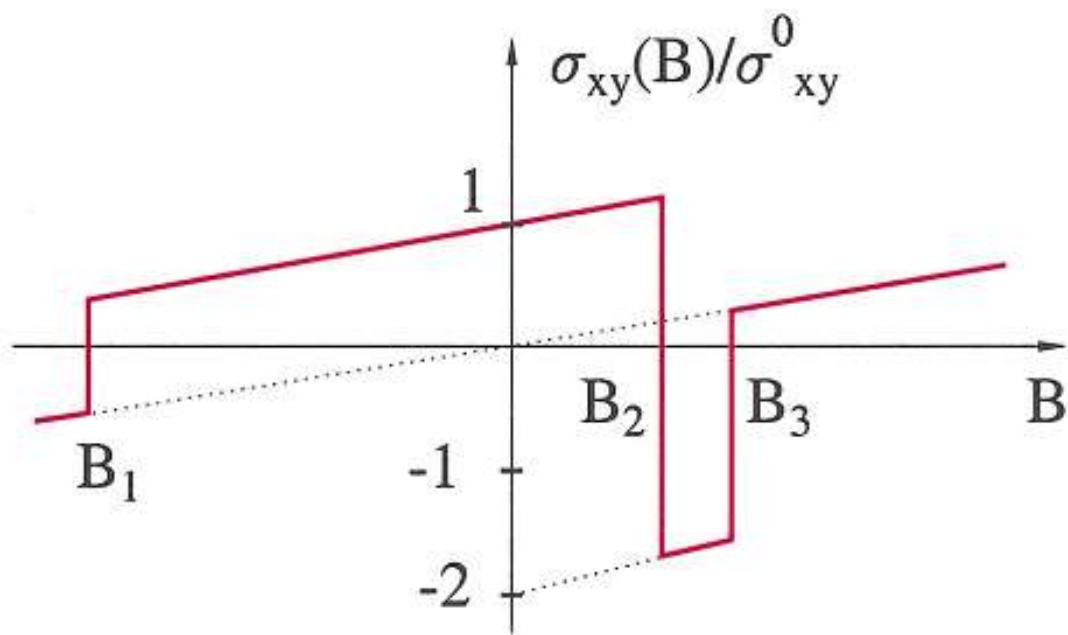


FIG. 1 (color). The proposed structure consisting of a triangular lattice of magnetic nanocylinders on top of 2D diluted magnetic semiconductor.

Topological Hall effect

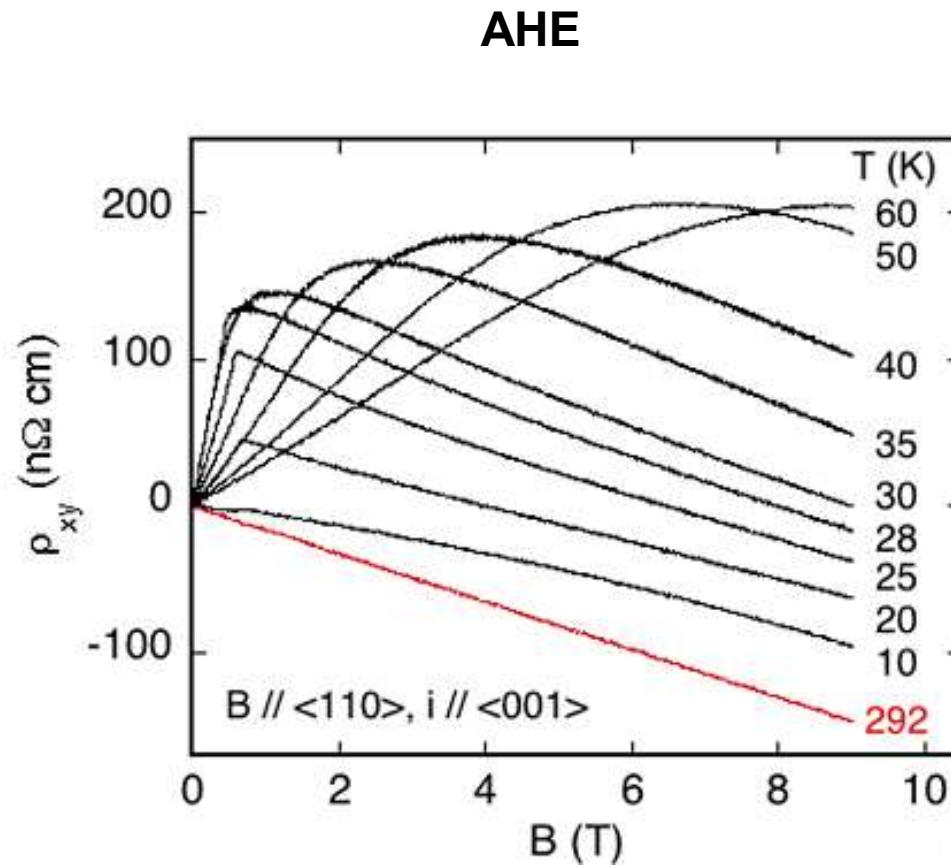


conduction electrons & localized spins



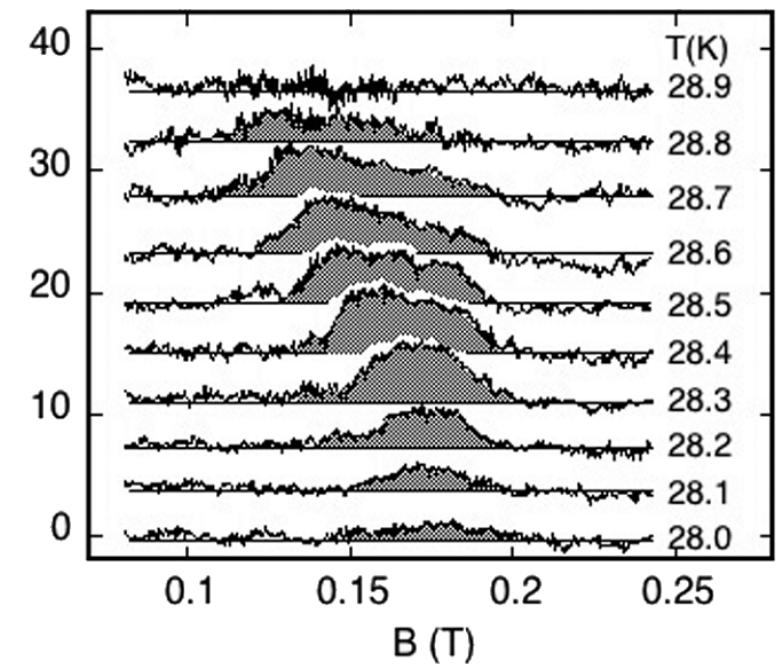
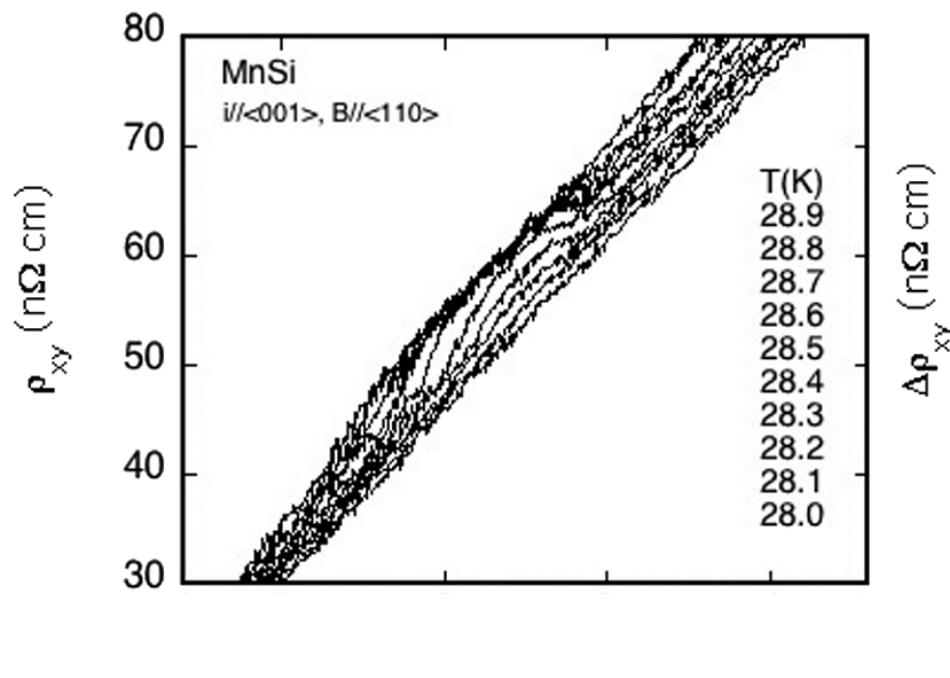
Observation

Topological Hall effect: MnSi



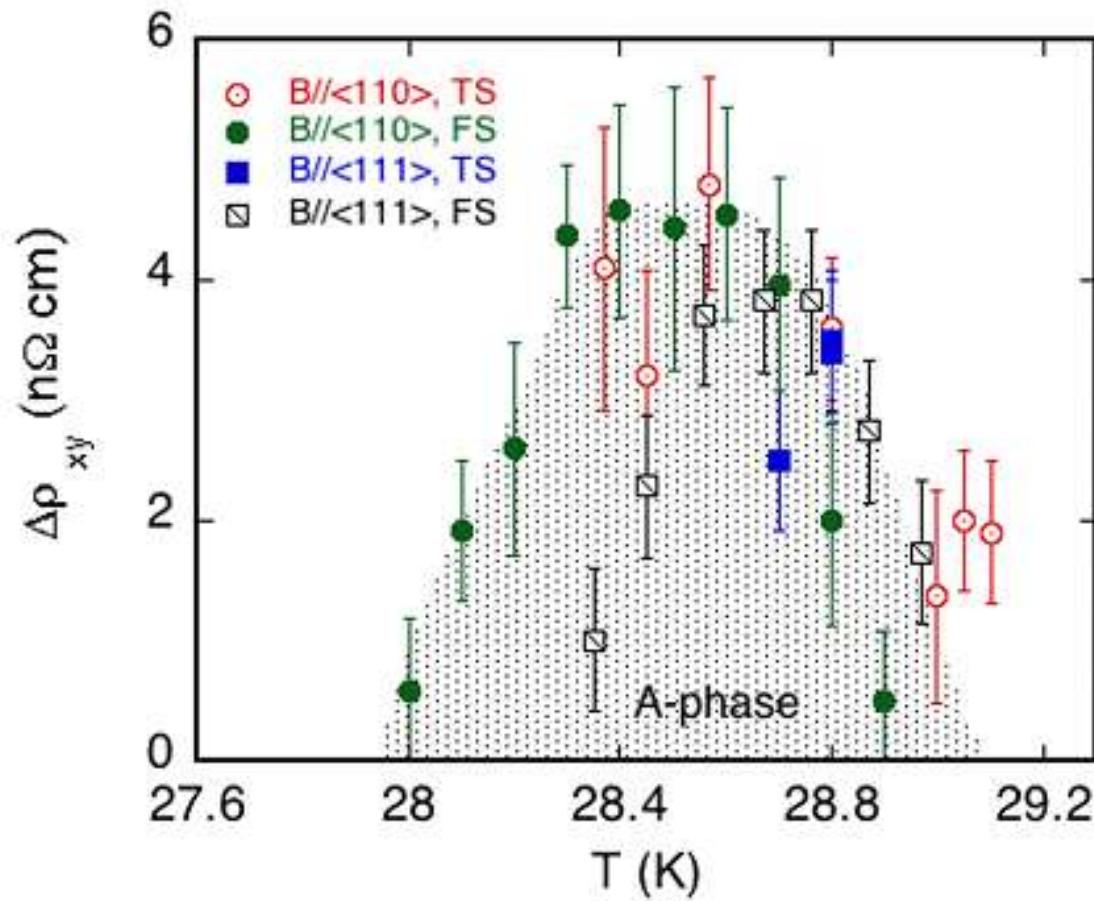
Observation

Topological Hall effect: MnSi

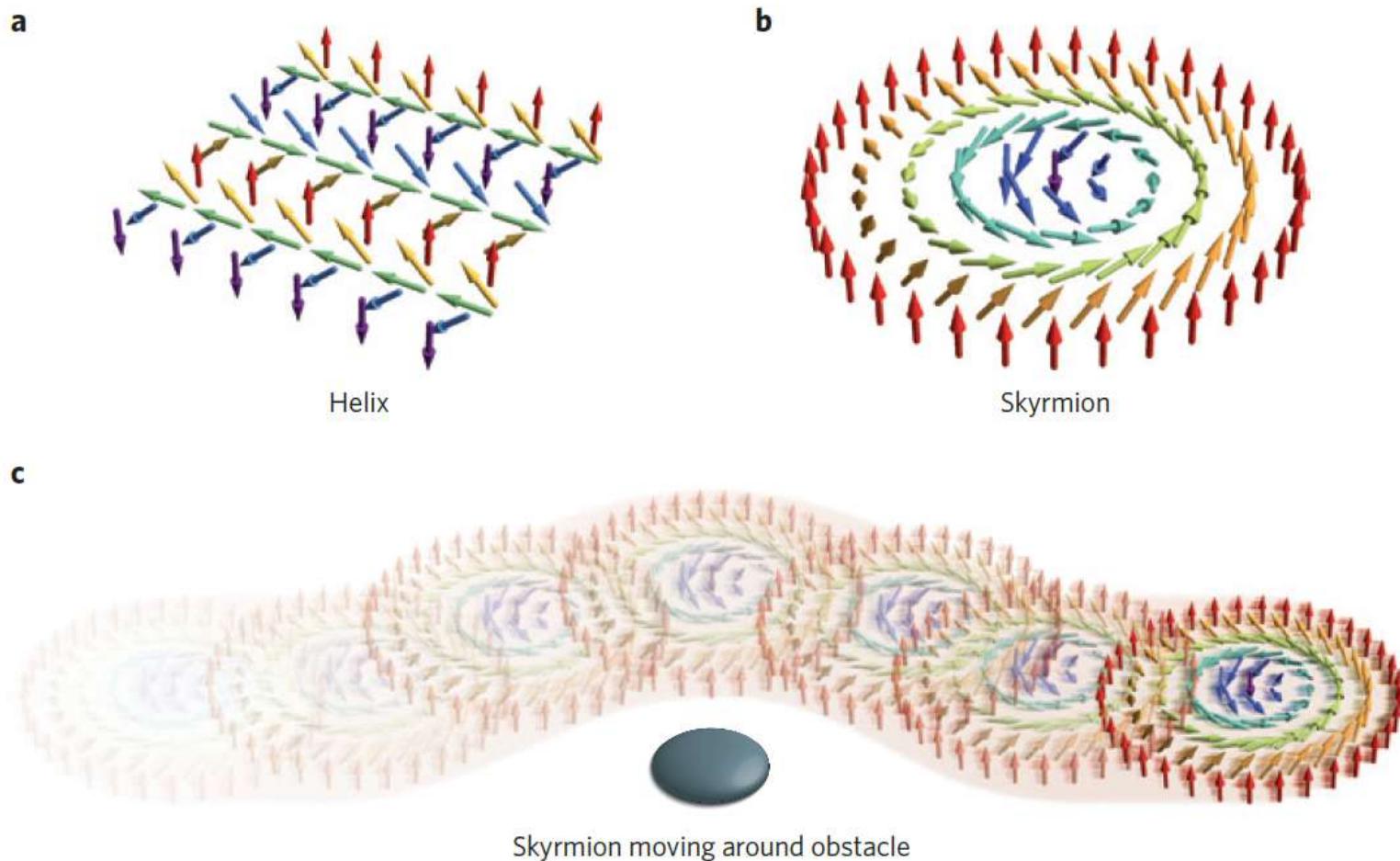


Observation

Topological Hall effect: MnSi

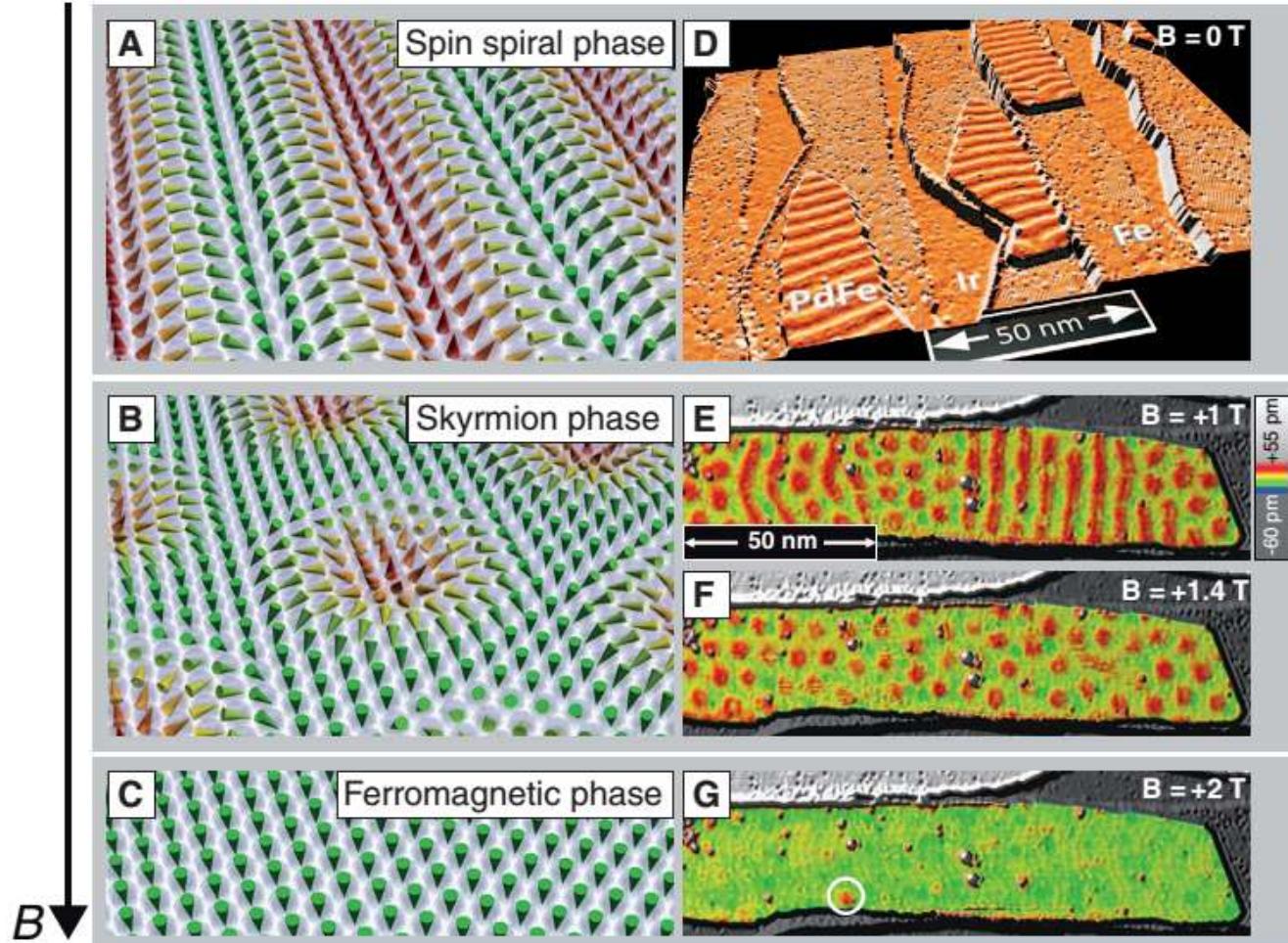


Skyrmion



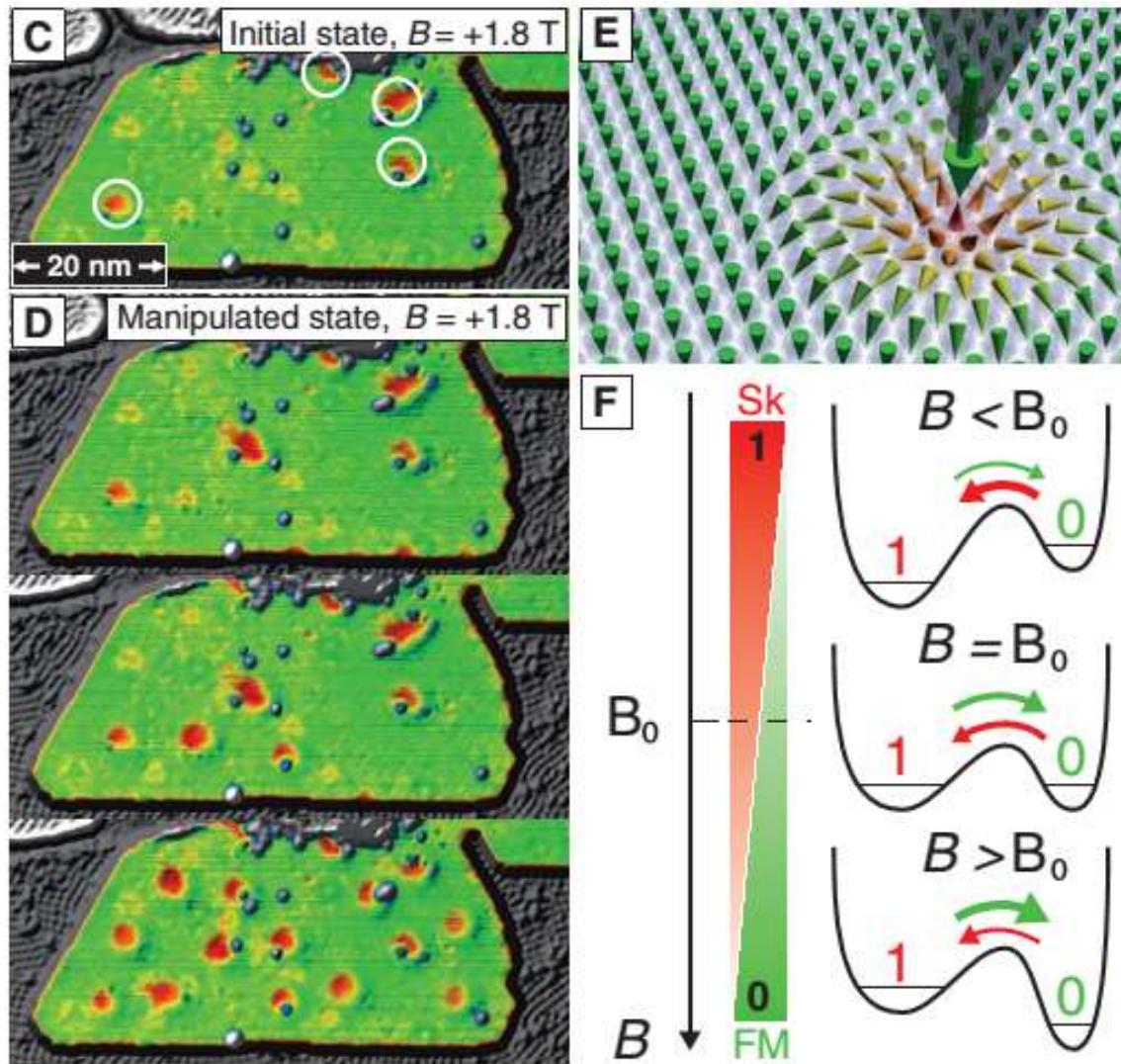
Rosch, et al, Nature Nanotechnology (2013)

Write a skyrmion

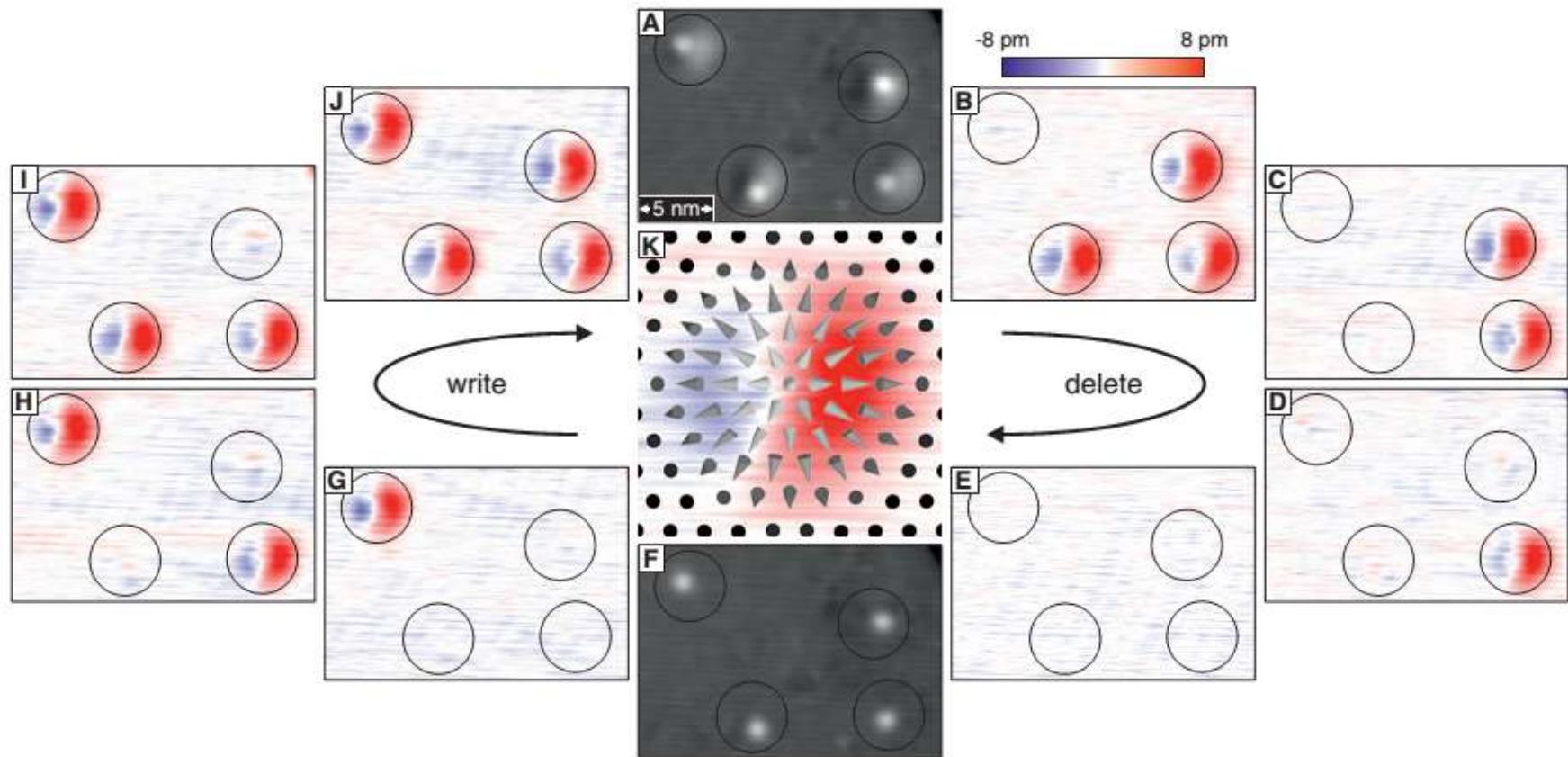


Romming, et al, Science (2013)

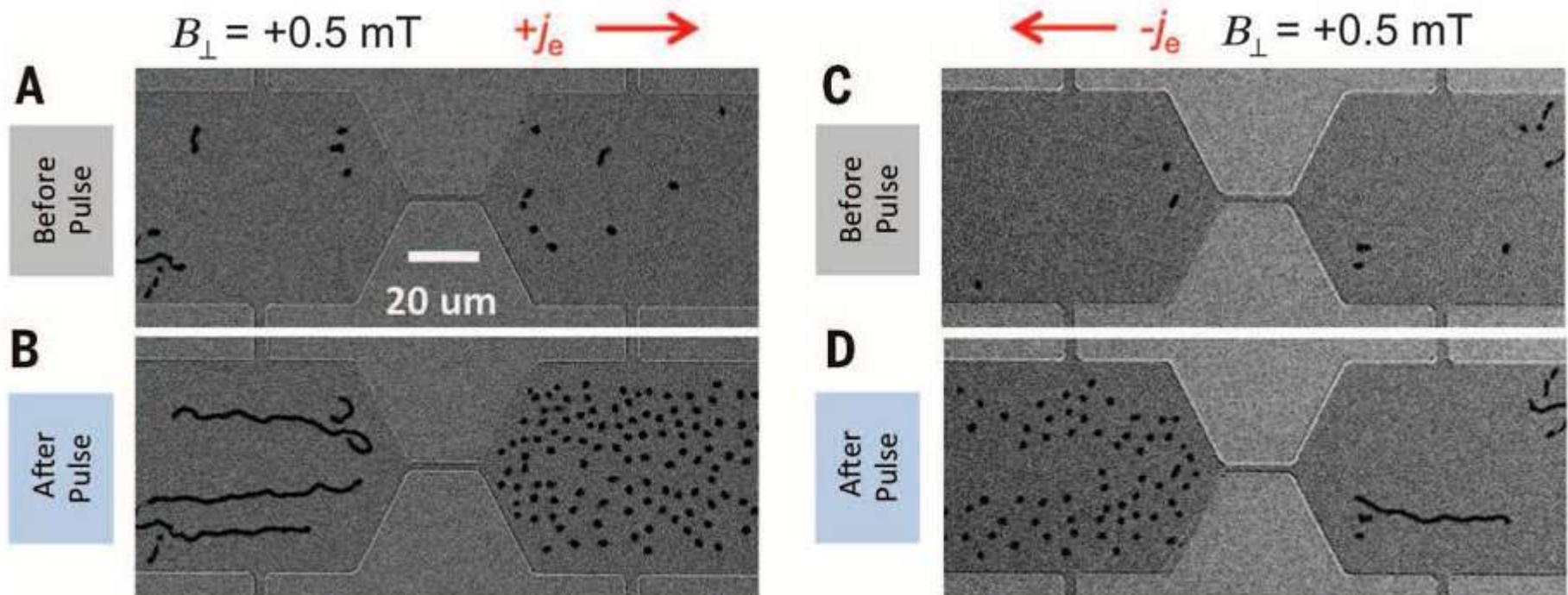
Write a skyrmion



Write and delete a skyrmion



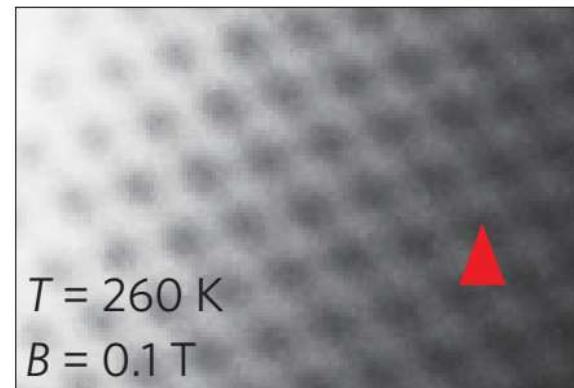
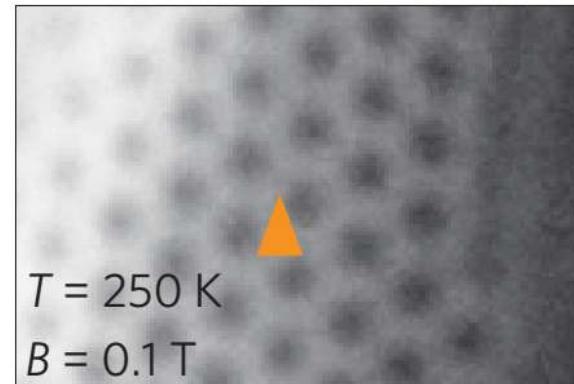
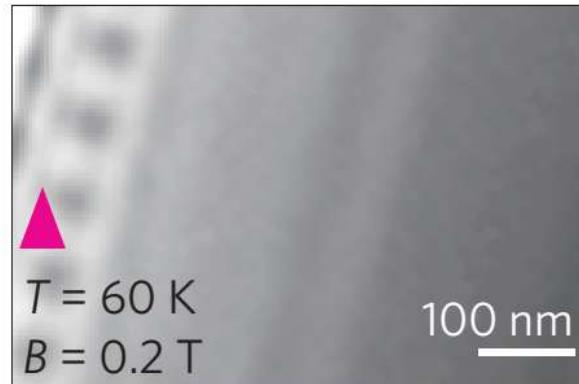
Create a skyrmion



Jiang, et al, Science (2015)

Near Room temperature Skyrmion

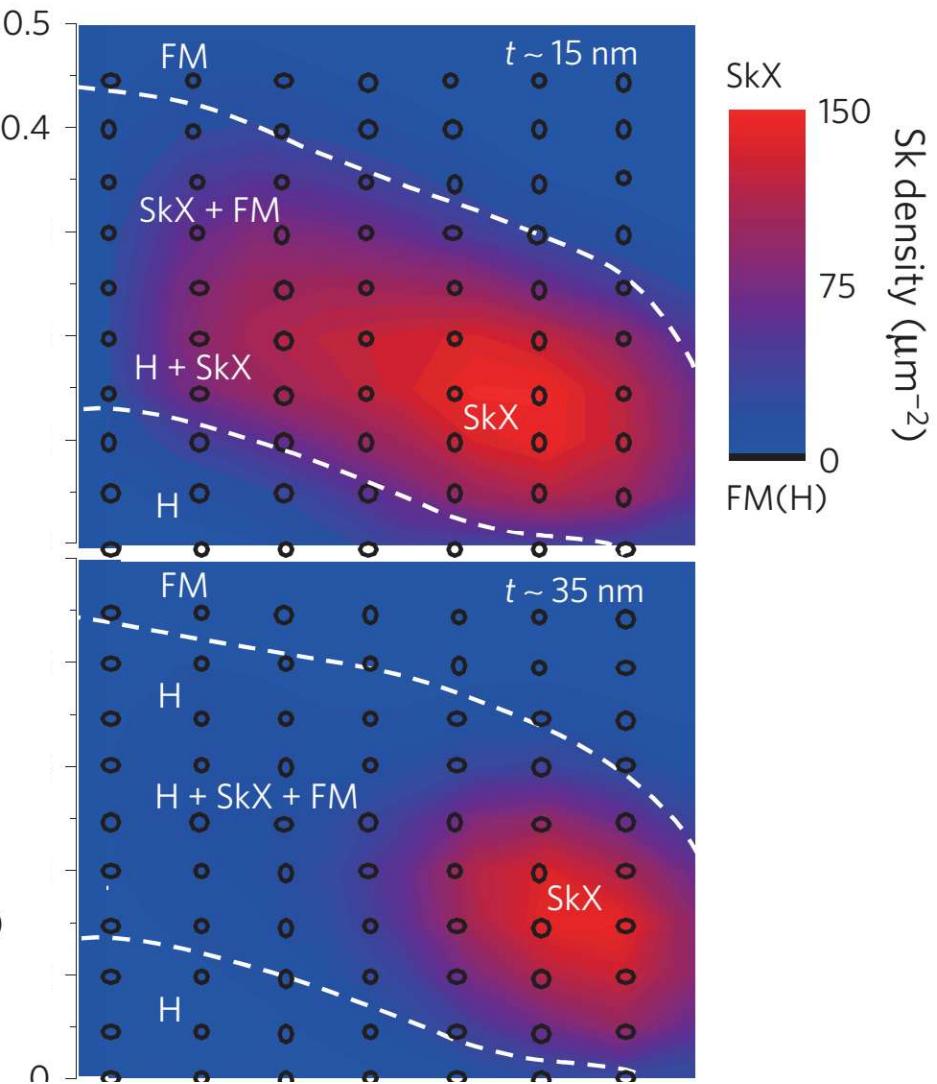
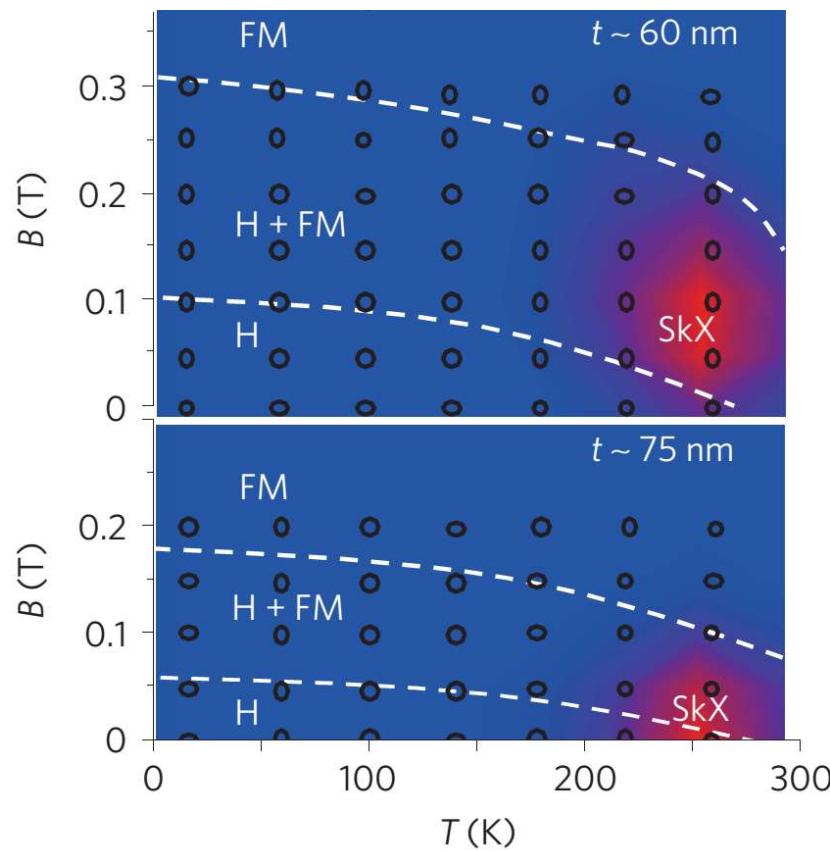
FeGe: 10 nm



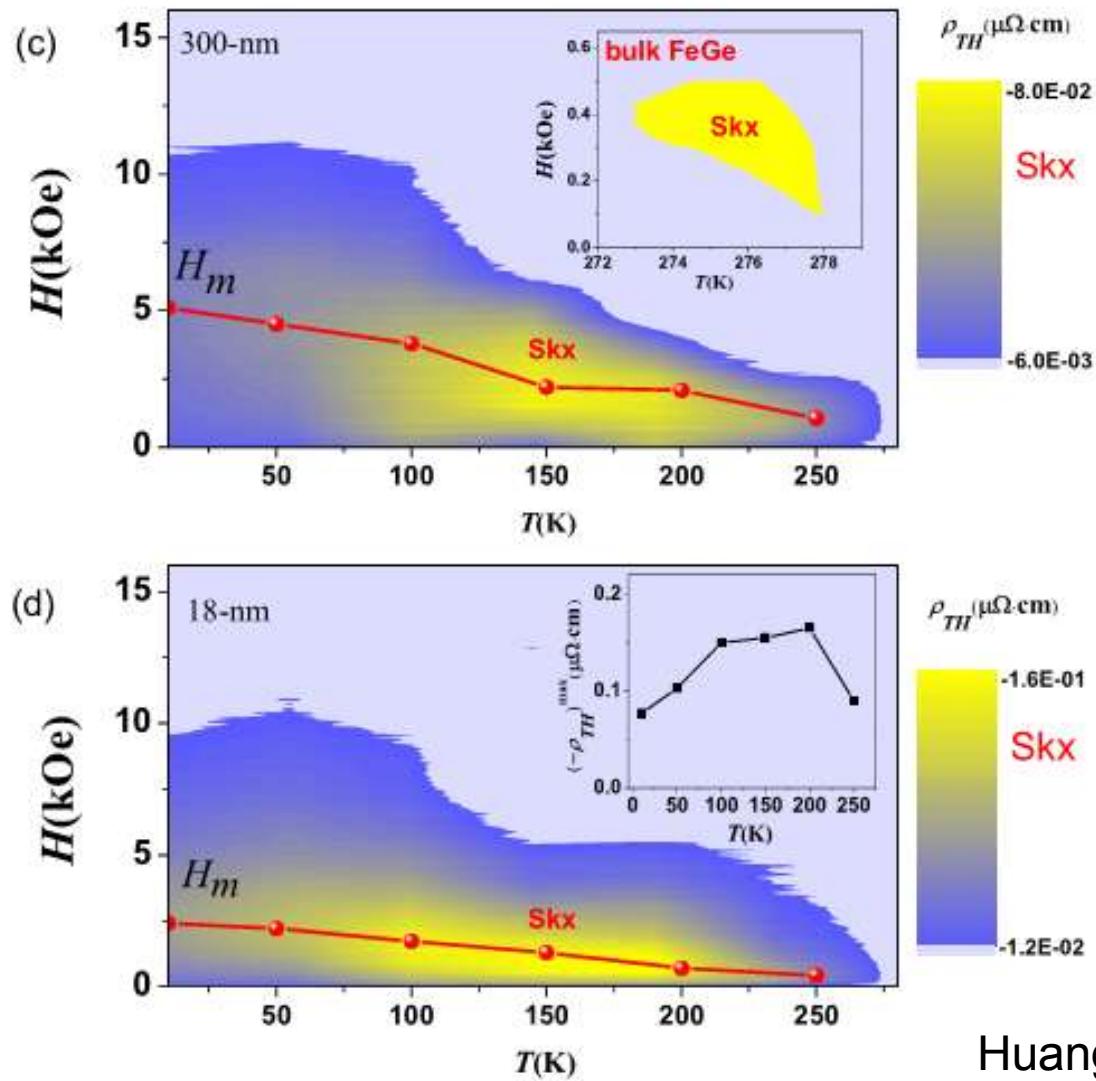
Yu, et al, Nature Materials (2010)

Near Room temperature Skyrmion

FeGe

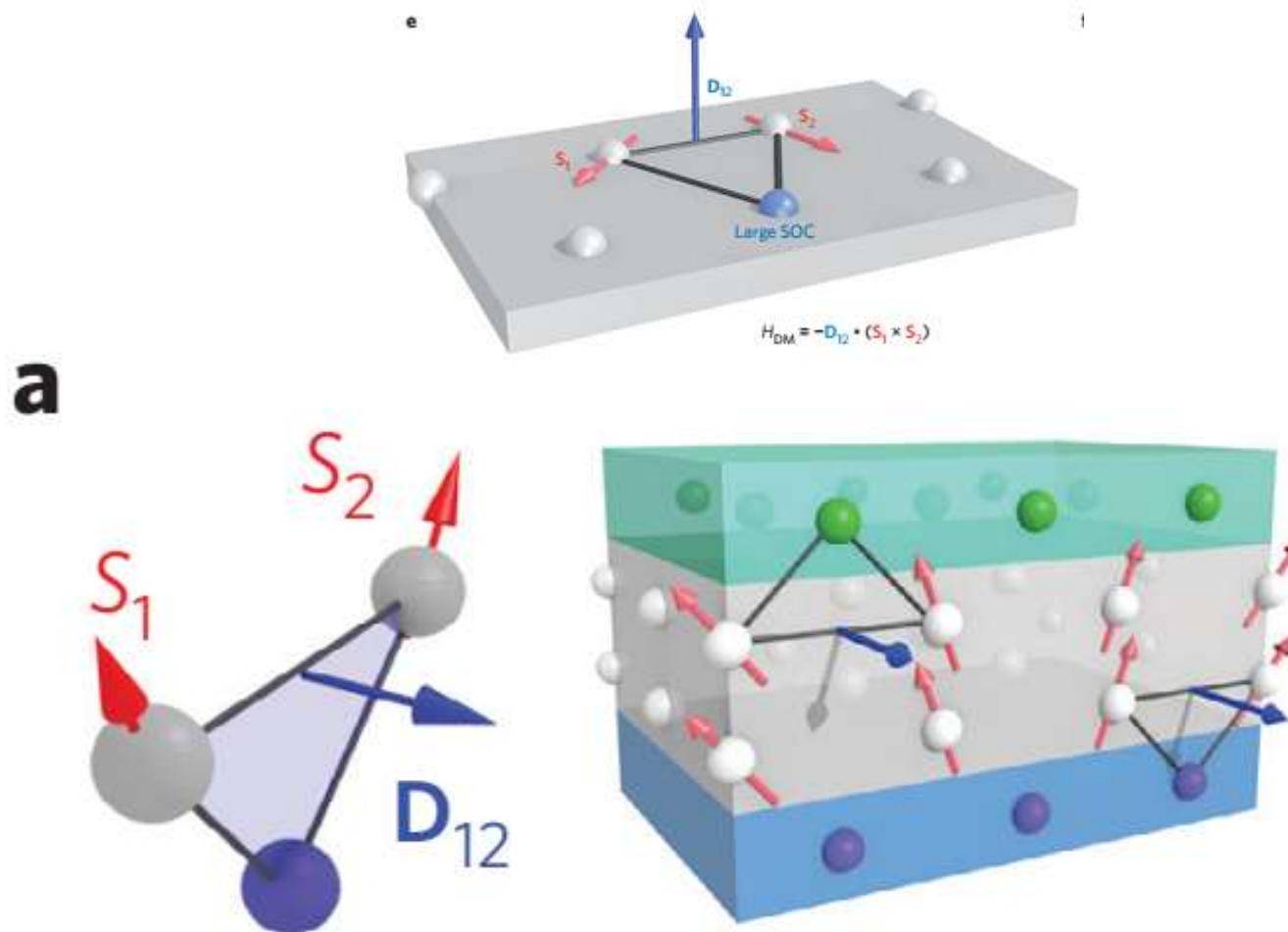


Room temperature Skyrmion



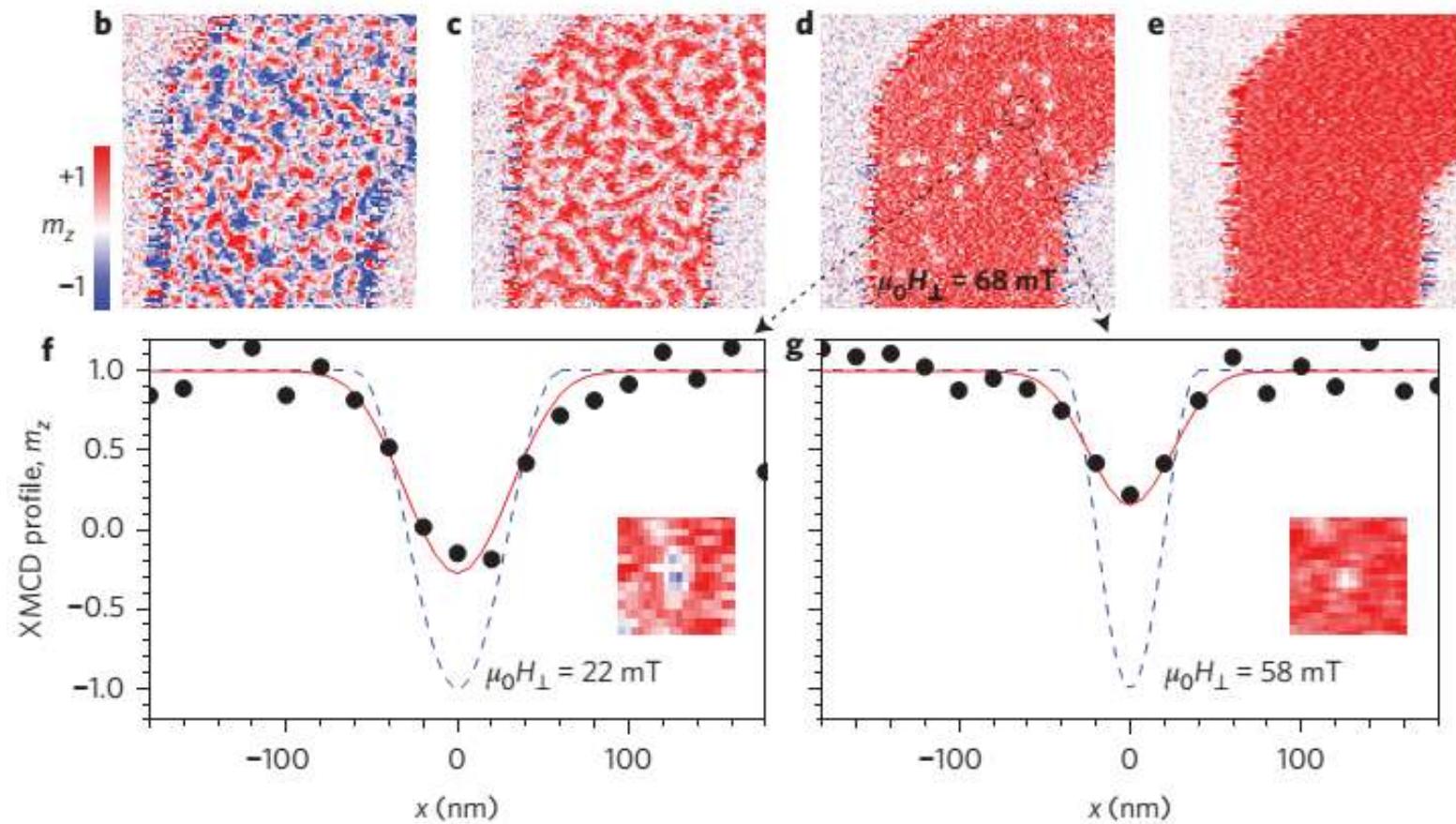
Huang, et al, PRL (2012)

Room temperature Skyrmion

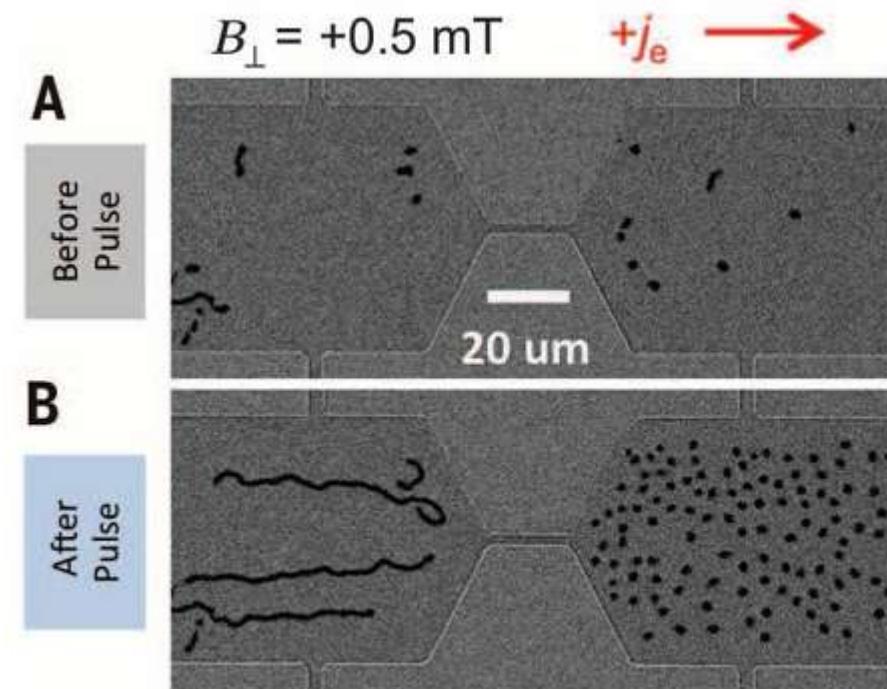
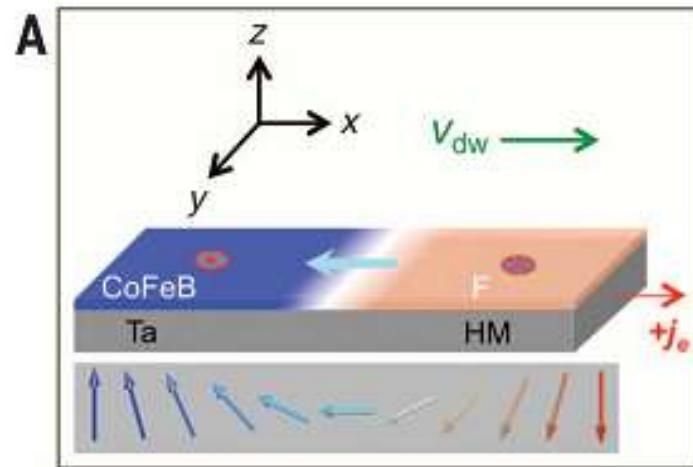


Moreau-Luchaire, et al, Nature Nano (2016)

Room temperature Skyrmion



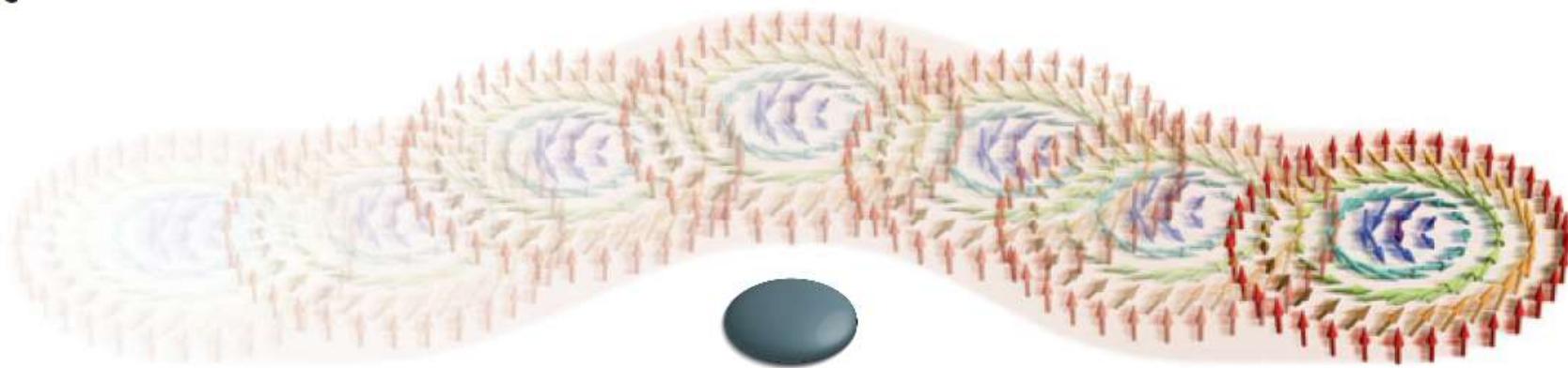
Room temperature Skyrmion



Jiang, et al, Science (2015)

Move a skyrmion

c

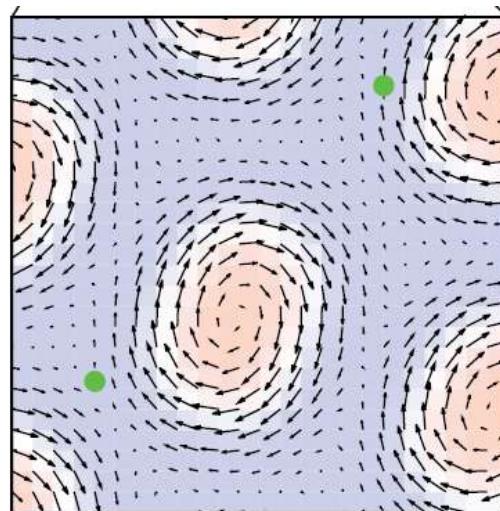
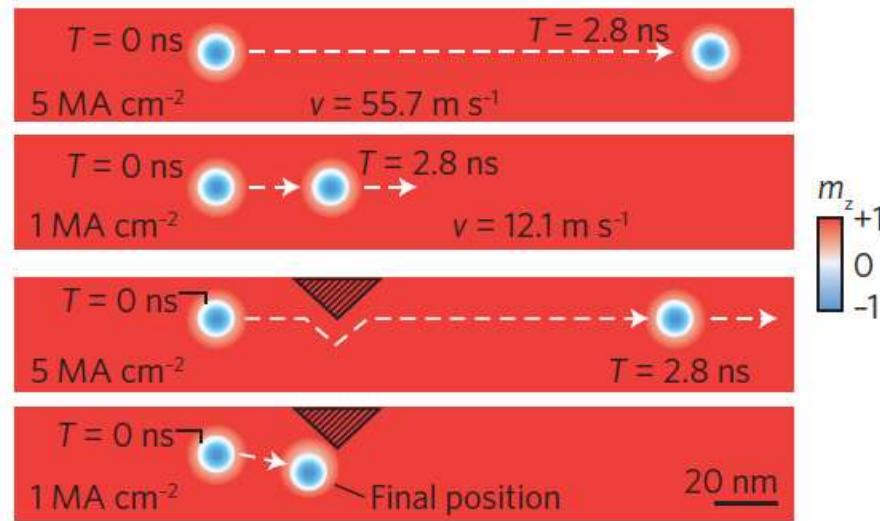


Skyrmion moving around obstacle

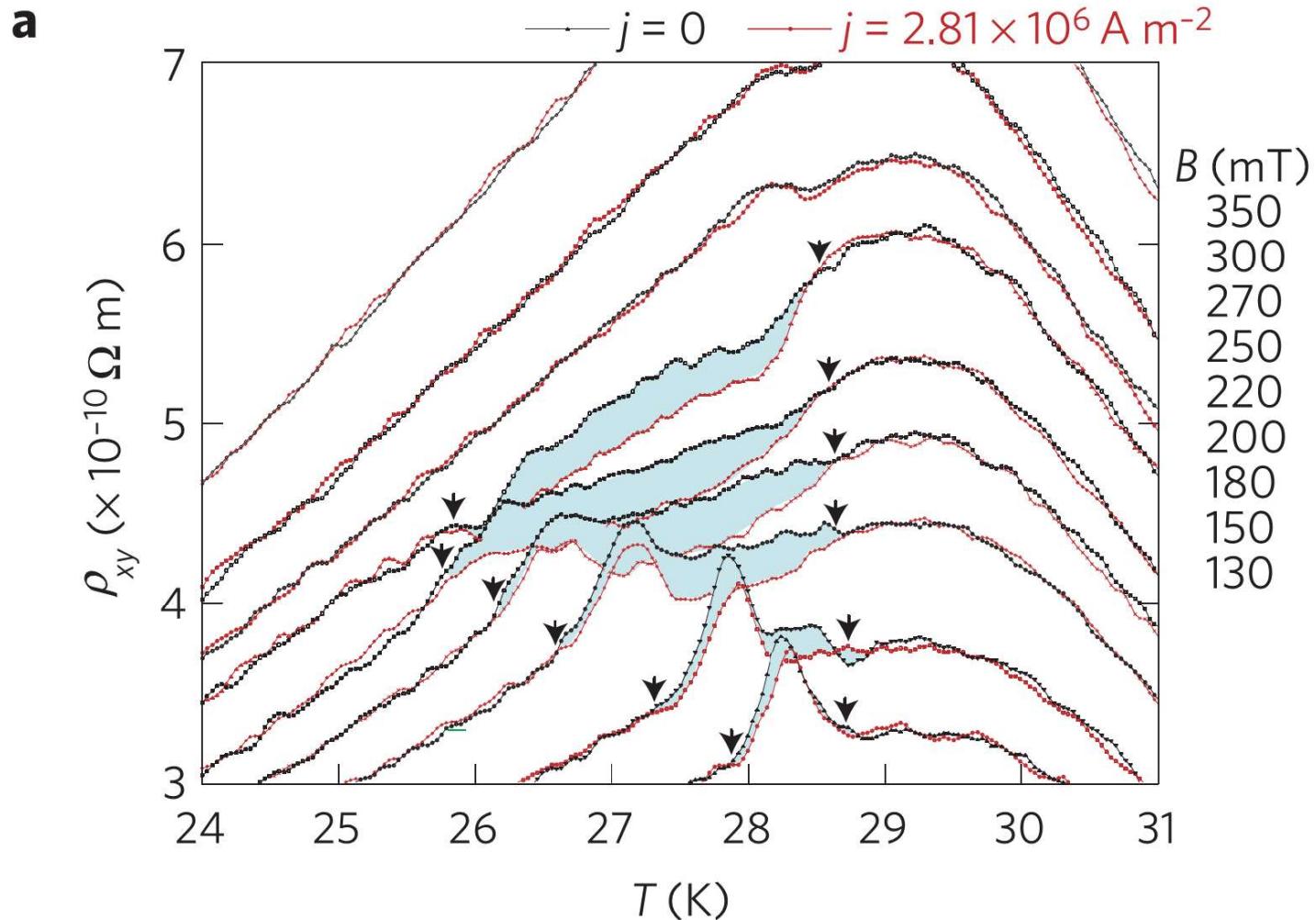
Rosch, et al, Nature Nano (2013)

Move a skyrmion

d

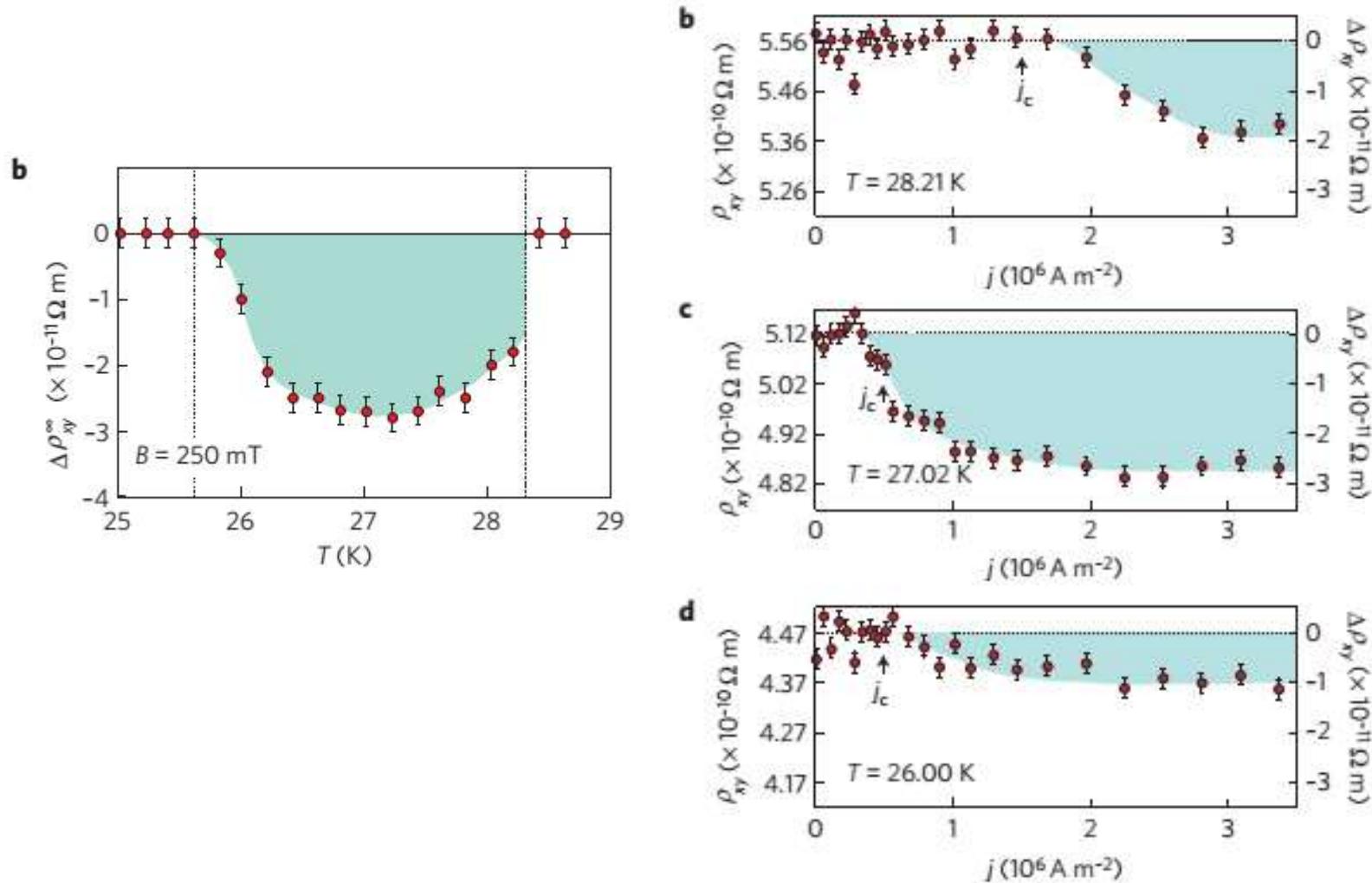


Move a skyrmion



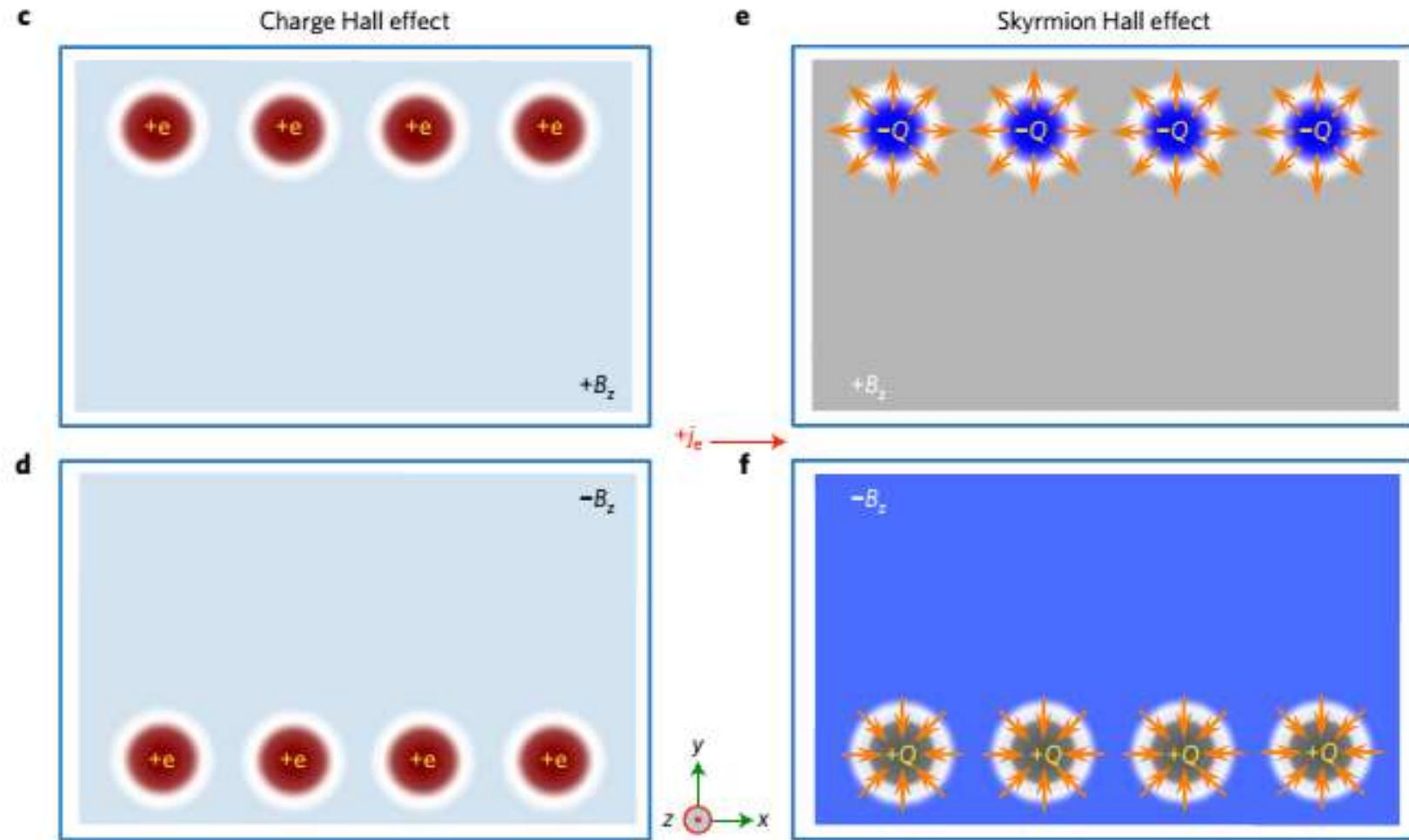
Schulz, et al, Nature Physics (2012)

Move a skyrmion

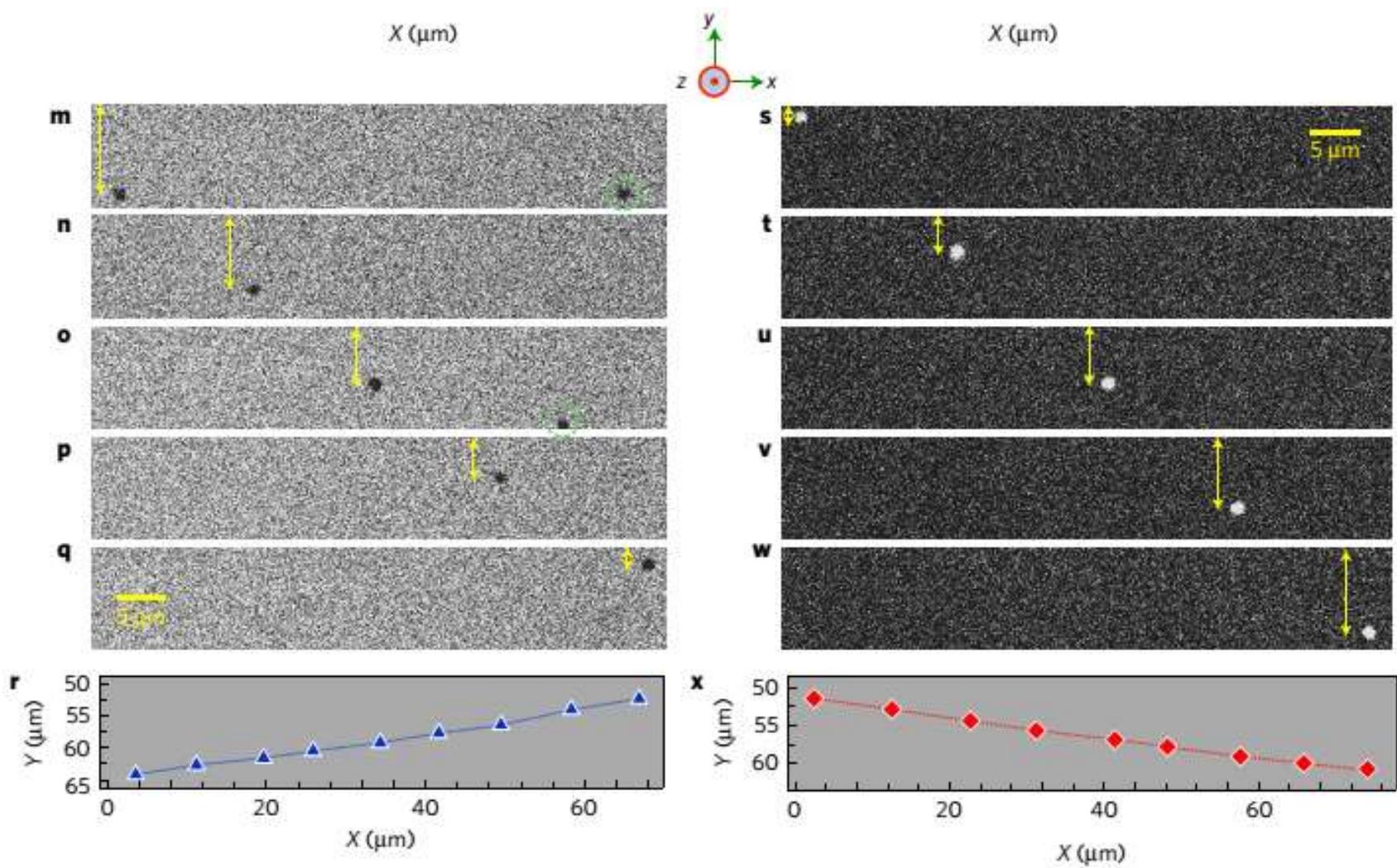


Schulz, et al, Nature Physics (2012)

Skyrmion Hall effect



Skyrmion Hall effect



Jiang, et al, Nature Physics (2016)

Skyrmion Materials

Table 1 | List of transition temperatures (T_N) and helical periods (λ) of helimagnets.

Material		T_N (K)	λ (nm)	Reference
MnSi	Bulk	30	18	23
	Epitaxial thin film	45	8.5	51
$Mn_{1-x}Fe_xSi$	$x=0.06$	16.5	12.5	25
	$x=0.08$	10.6	11	25
	$x=0.10$	6.8	10	25
$Fe_{1-x}Co_xSi$	$x=0.10$	11	43	29,33
	$x=0.5$	36	90	29,33
	$x=0.6$	24	174	29,33
	$x=0.7$	7	230	29,33
MnGe	$T=20$ K	170	3	50
	$T=100$ K	-	3.4	50
	$T=150$ K	-	5.5	50
$Mn_{1-x}Fe_xGe$	$x=0.35$	150	4.7	38
	$x=0.5$	185	14.5	38
	$x=0.7$	210	77	38
	$x=0.84$	220	220	38
FeGe	Bulk	278	70	34
Cu_2OSeO_3	Bulk	59	62	76
	Thinned plate	-	50	86

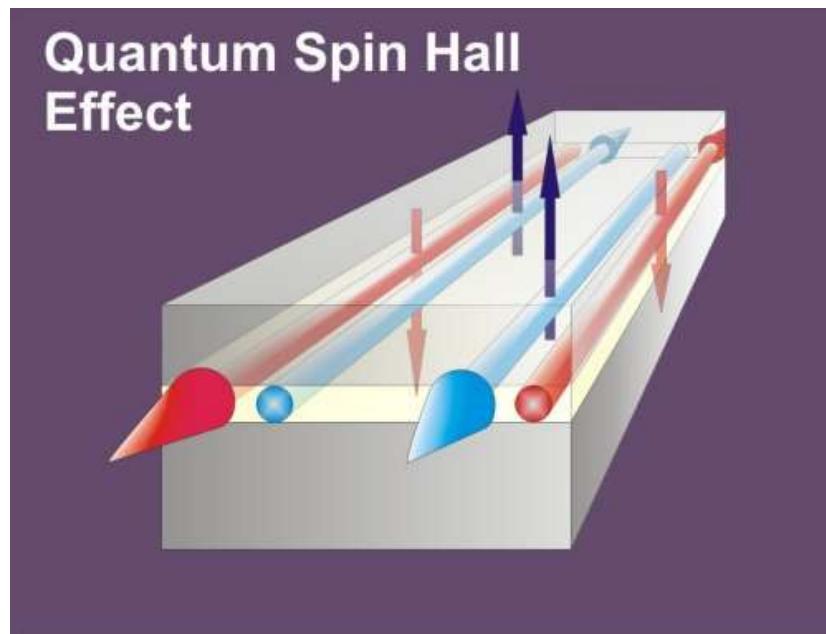
Nagaosa & Tokura,
Nature Nano (2013)

4. Spin-momentum locking of 3D TI

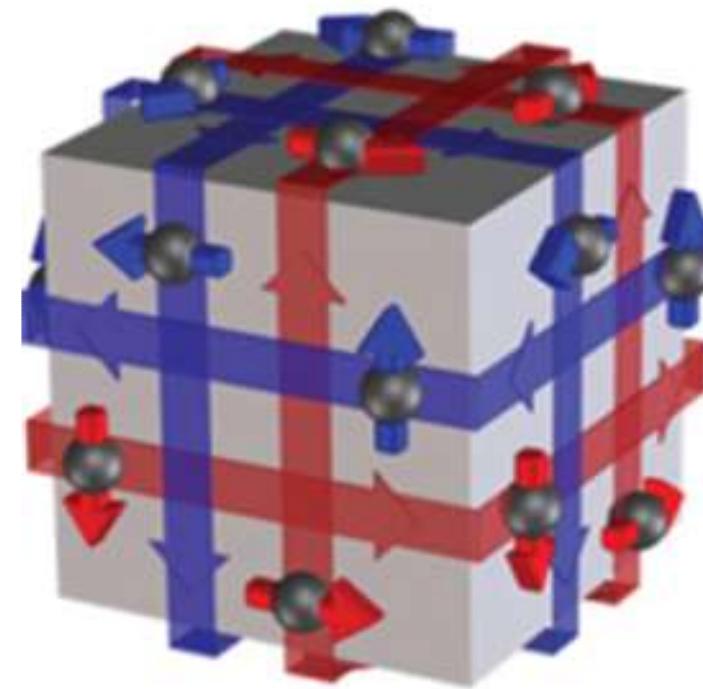
- Spin injection
- Spin orbit torque

Spin momentum locking

2D Topological insulator

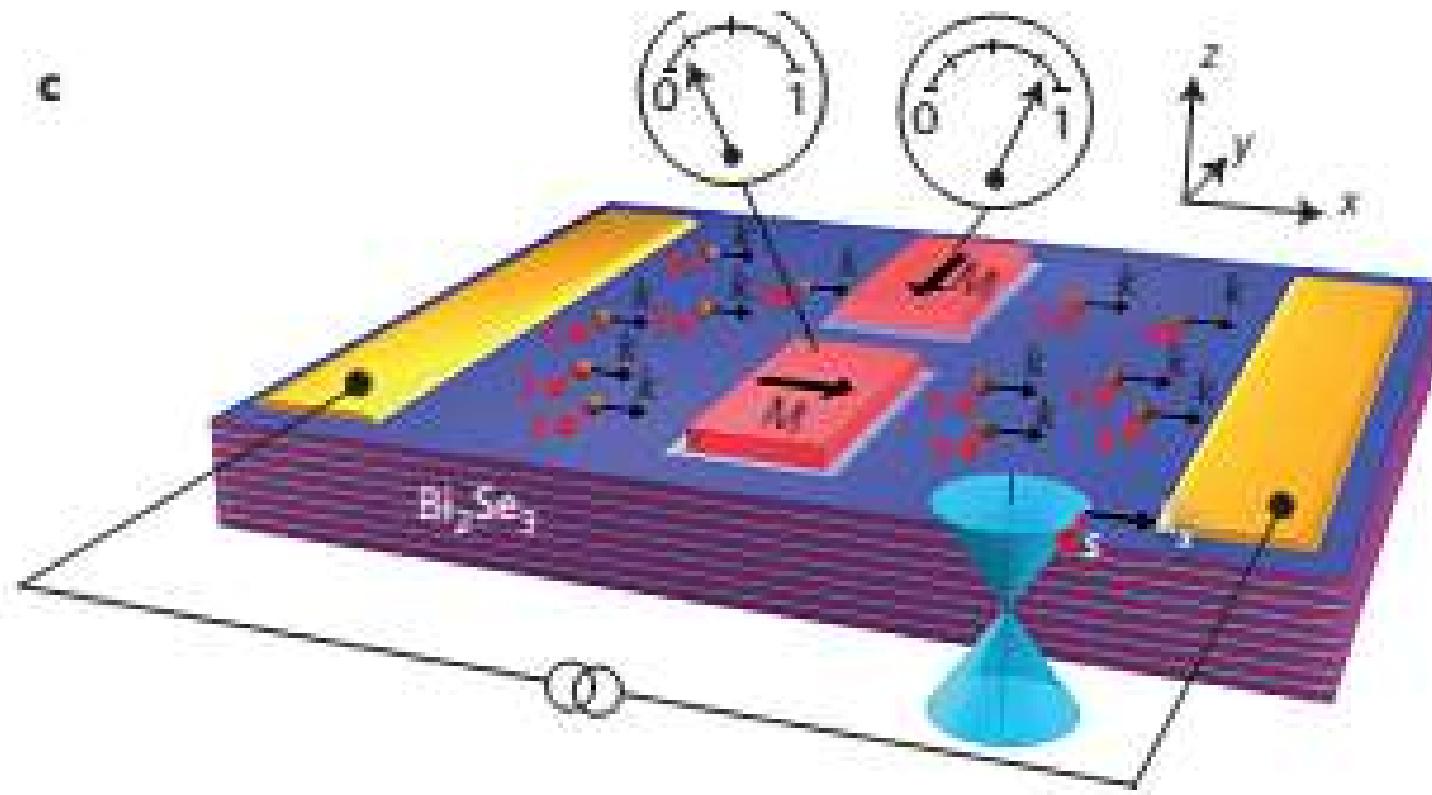


3D Topological insulator



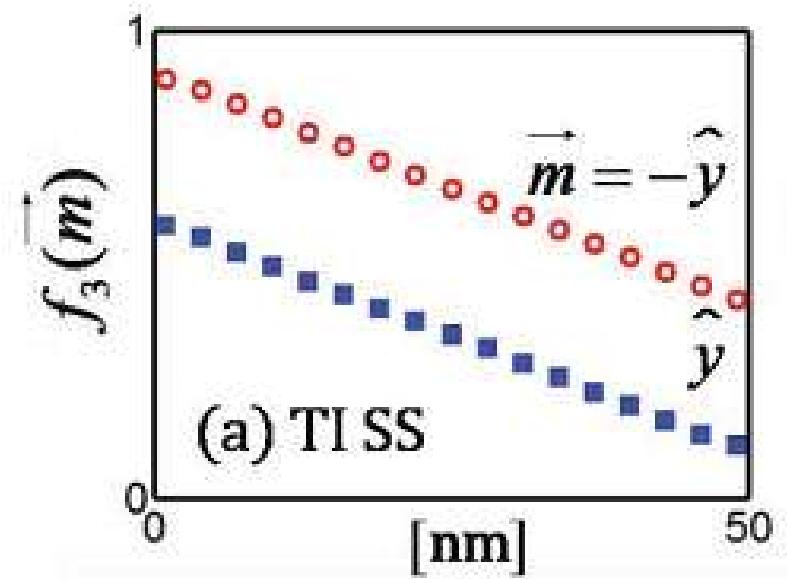
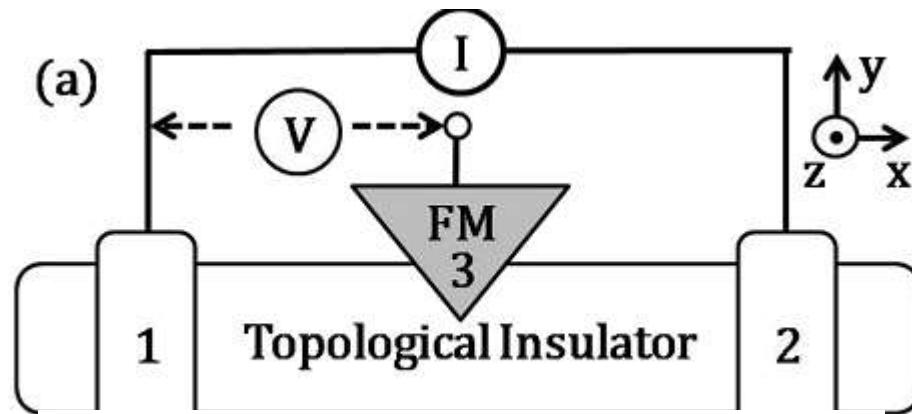
Hasan & Kane, Rev Mod Phys (2009)
Qi & Zhang, Rev Mod Phys (2011)

Spin momentum locking



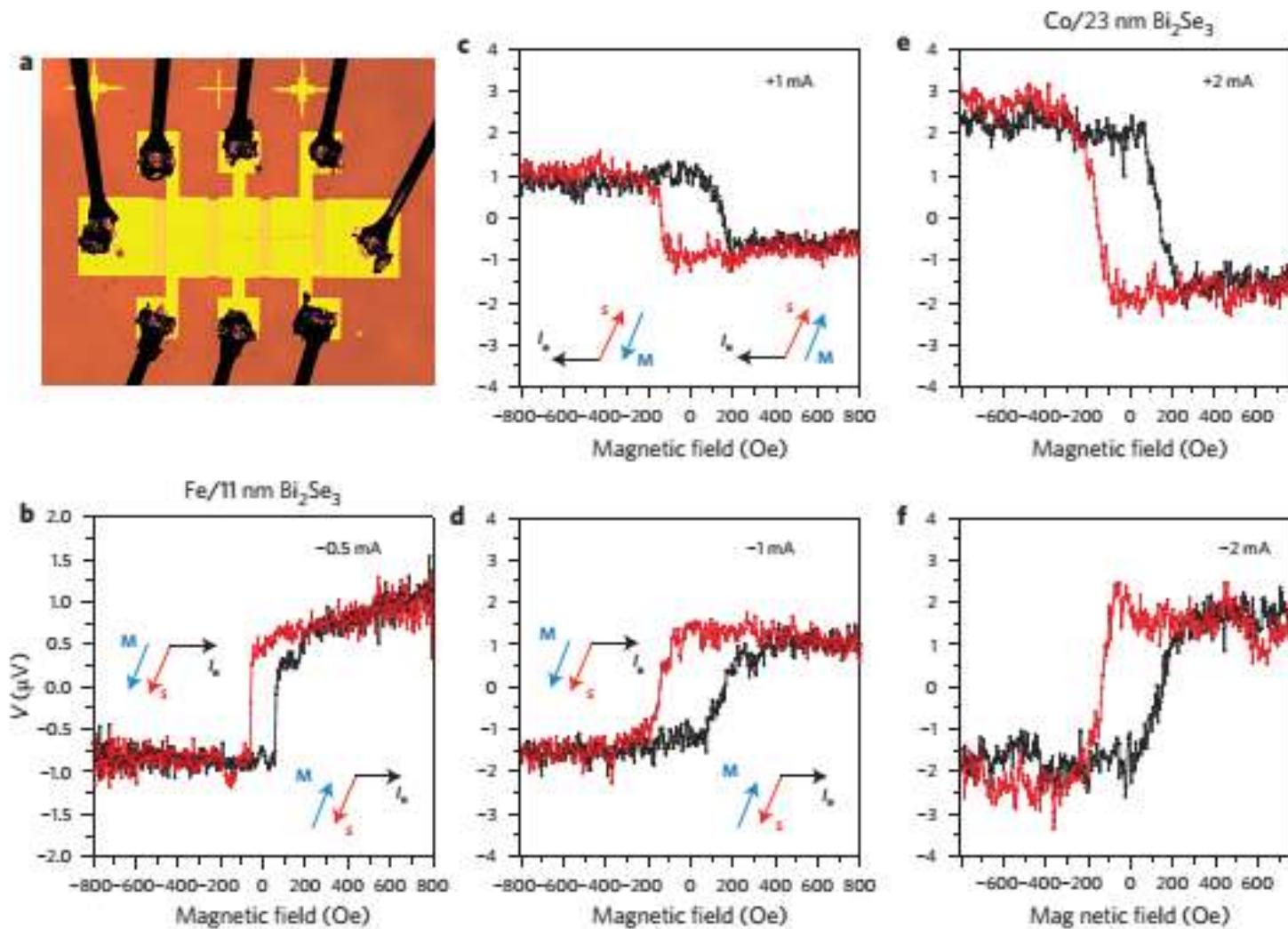
Li, et al, Nature Nanotechnology (2014).

Spin momentum locking



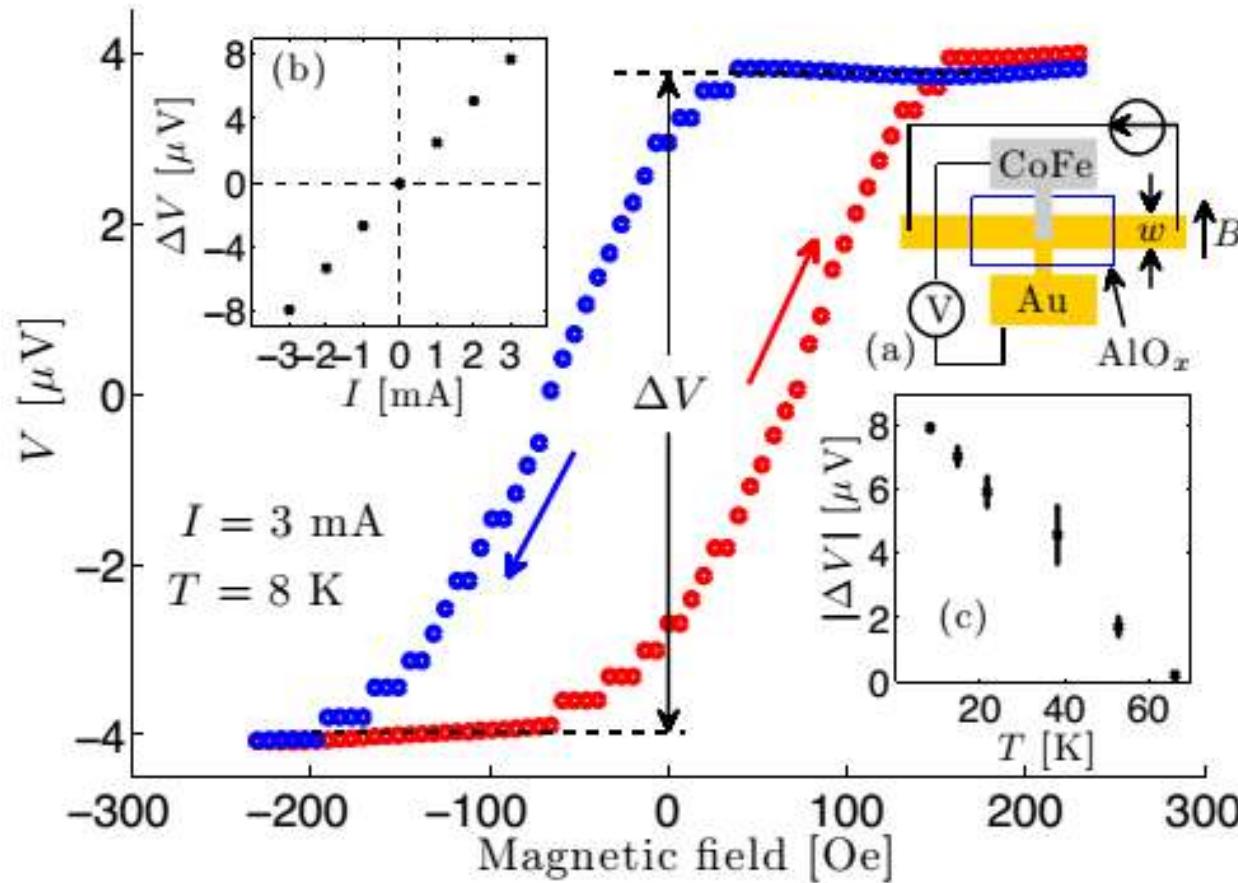
Hong, et al, PRB (2012)

Spin momentum locking



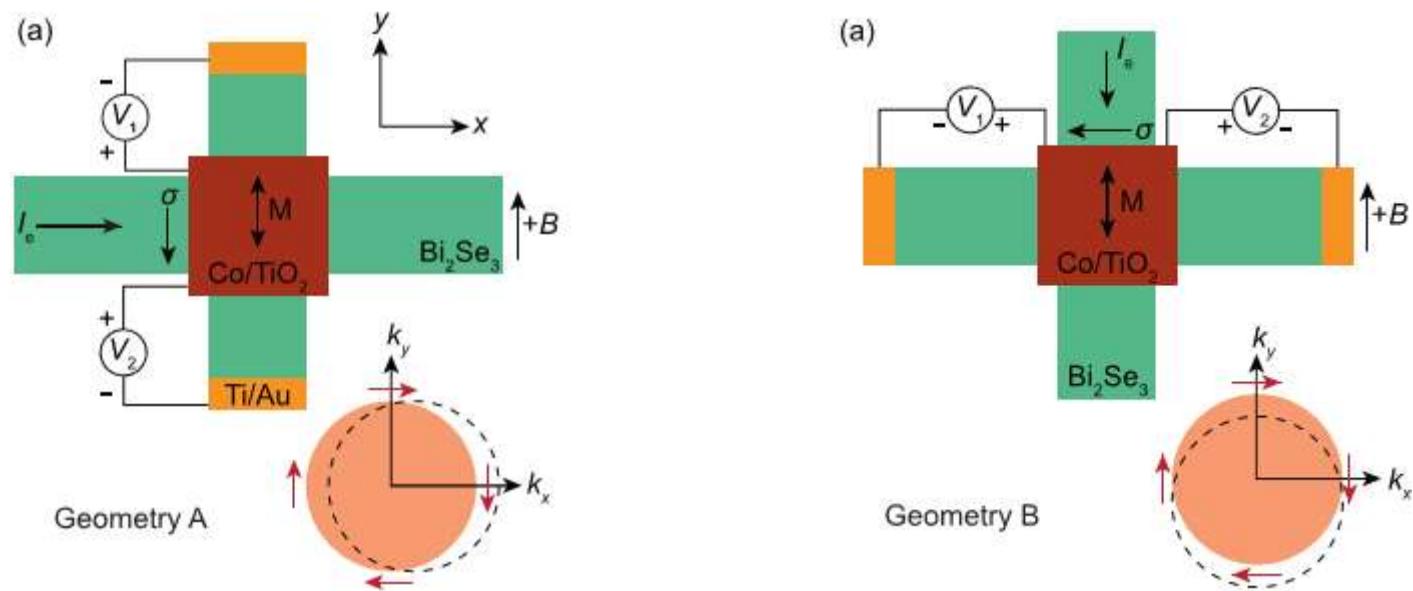
Spin momentum locking

Real spin or not?

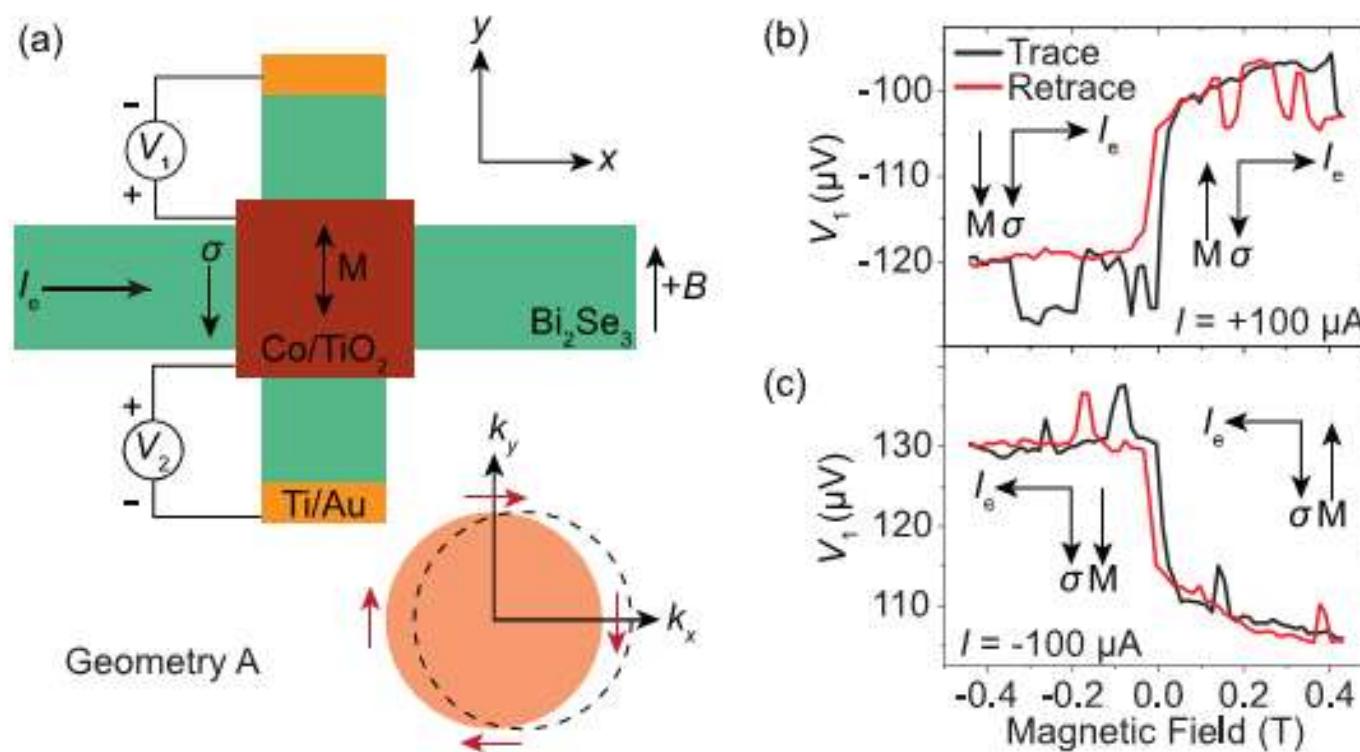


Li & Appelbaum, PRB (2016)

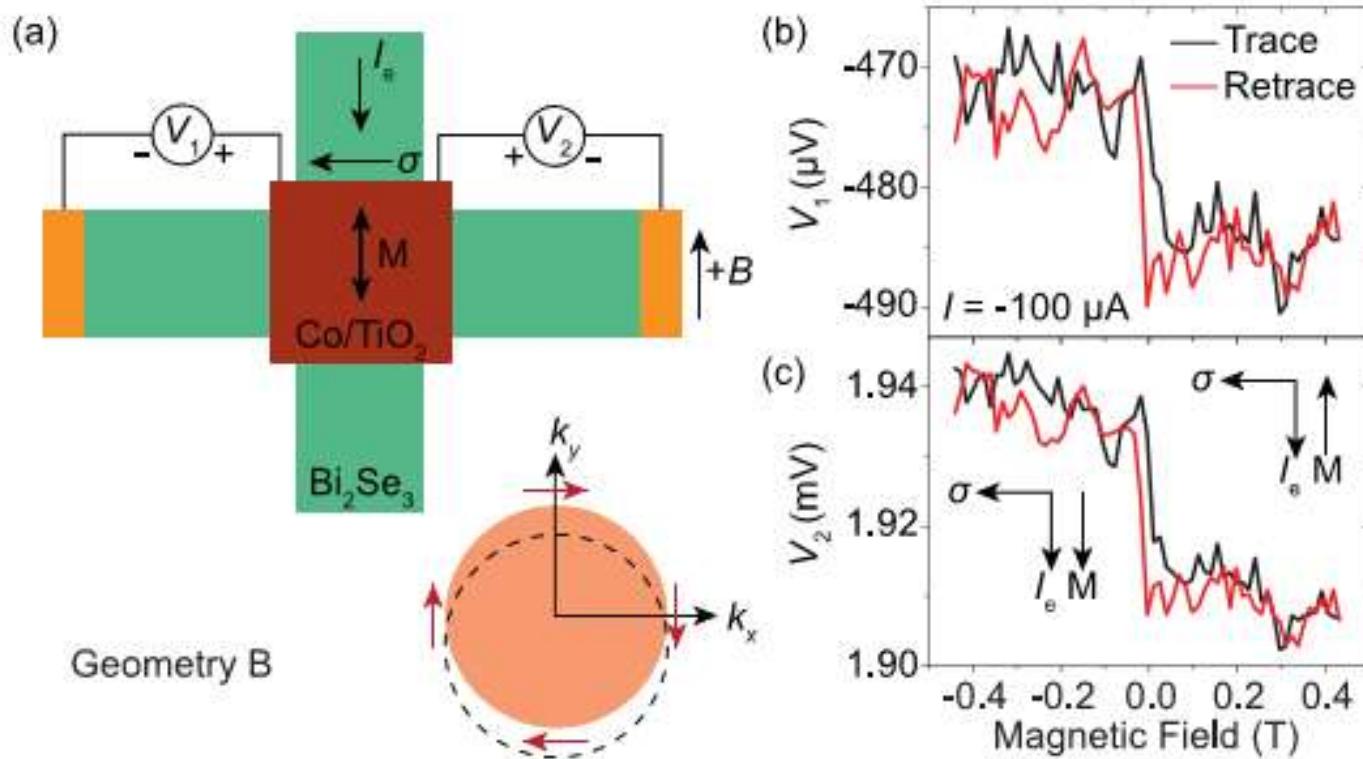
Spin momentum locking



Spin momentum locking

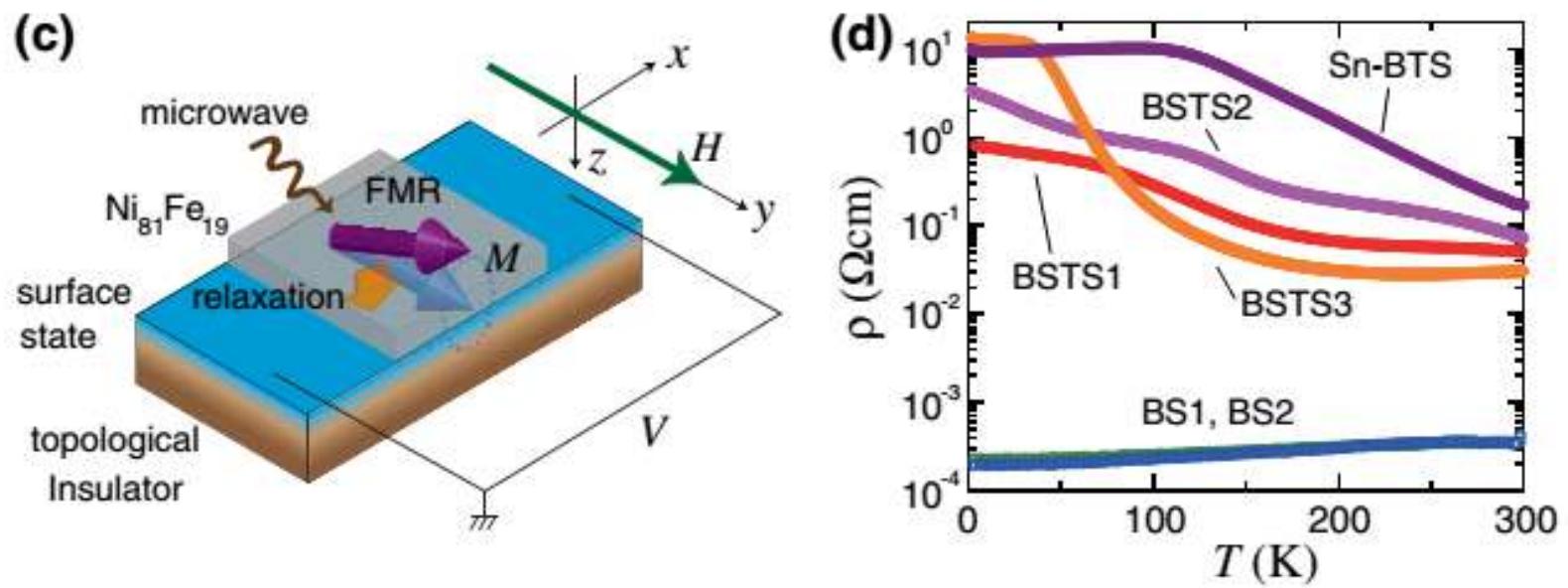


Spin momentum locking



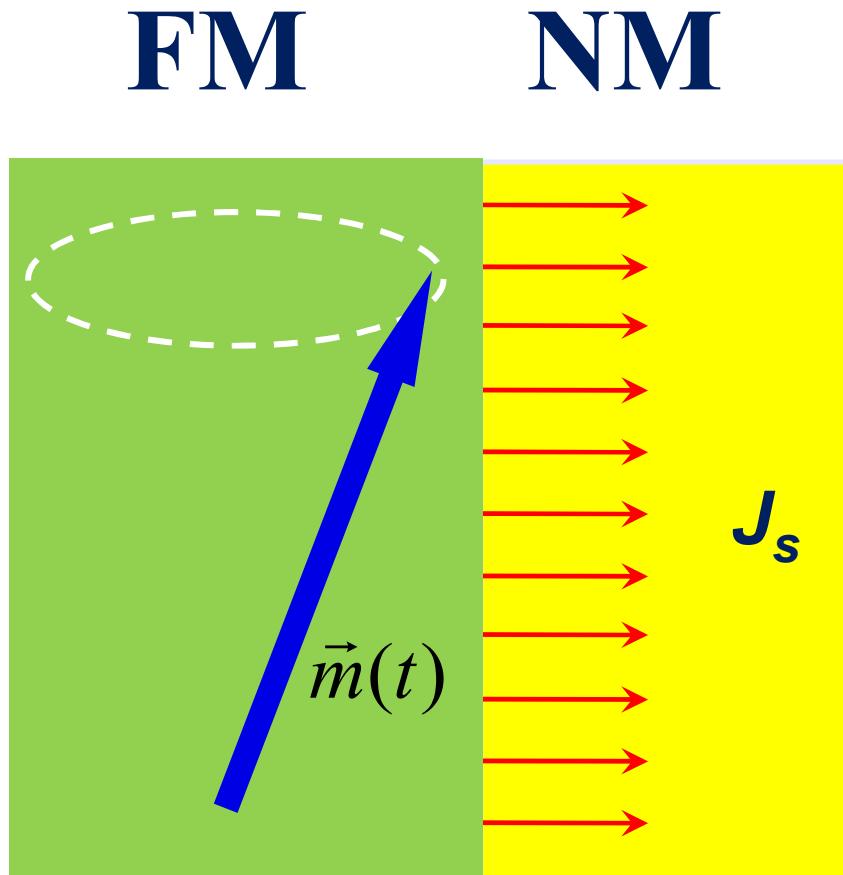
Signal not from the TI surface states !!

Spin momentum locking



Shiomi, et al, PRL (2014)

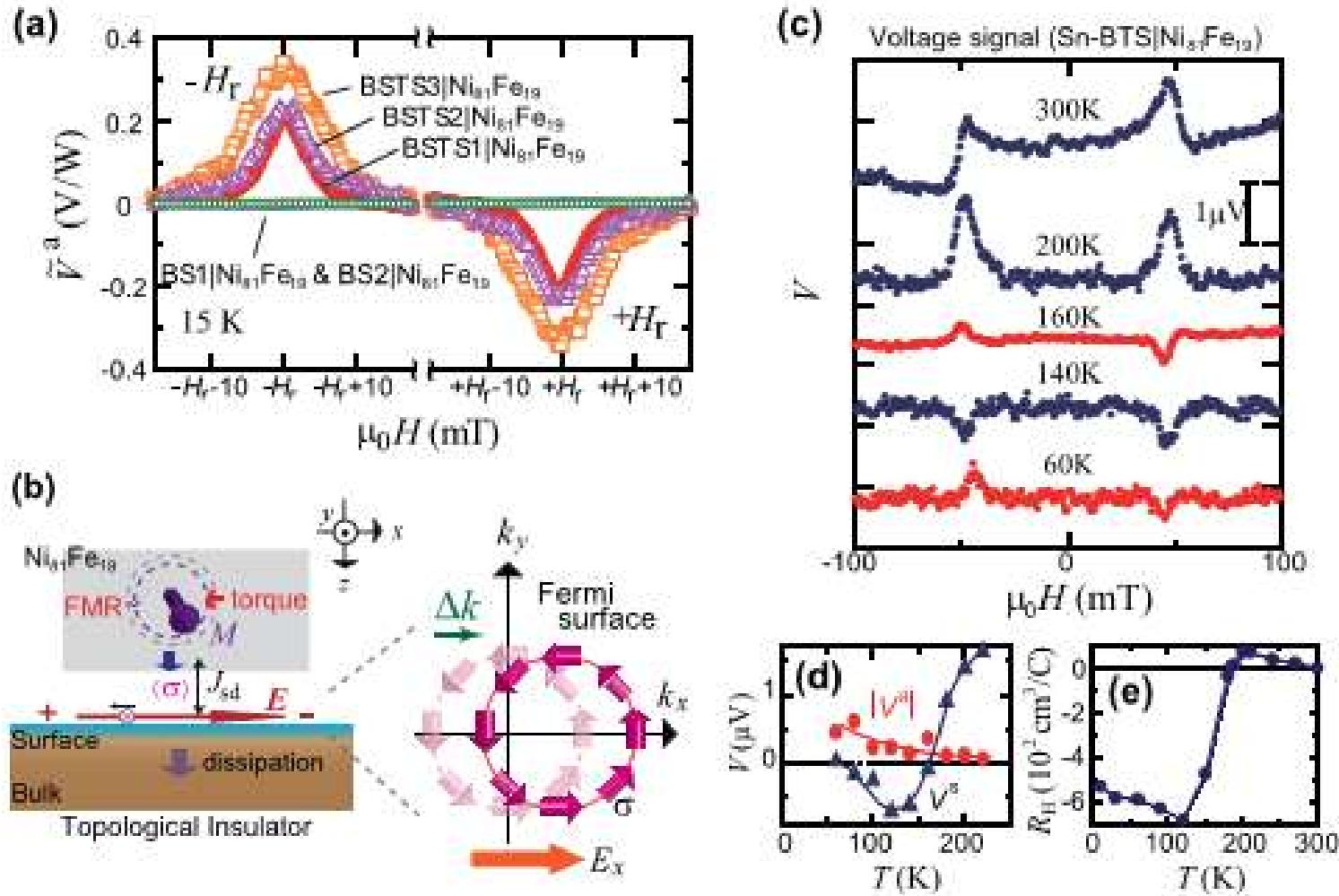
Spin momentum locking



$$\vec{J}_s = \frac{\hbar g_r^{\uparrow\downarrow}}{4\pi M^2} \left(\vec{M} \times \frac{\partial \vec{M}}{\partial t} \right)$$

Precessing **magnetization** in
FM layer pump **spin current**
into NM layer
(Angular momentum
conservation)

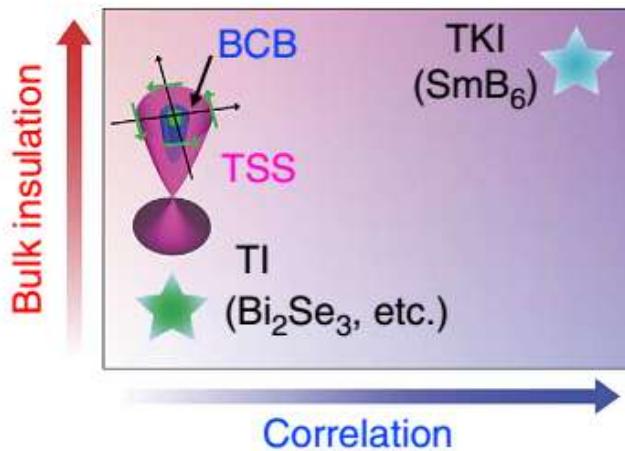
Spin momentum locking



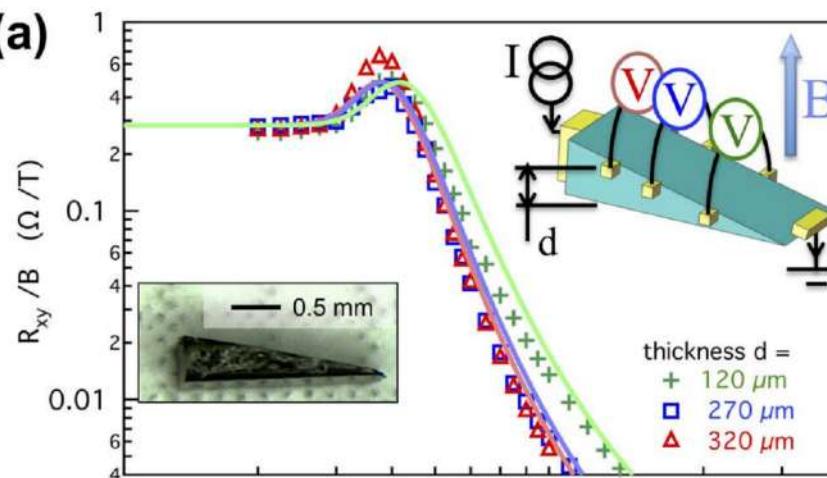
Shiomi, et al, PRL (2014)

Spin momentum locking

b



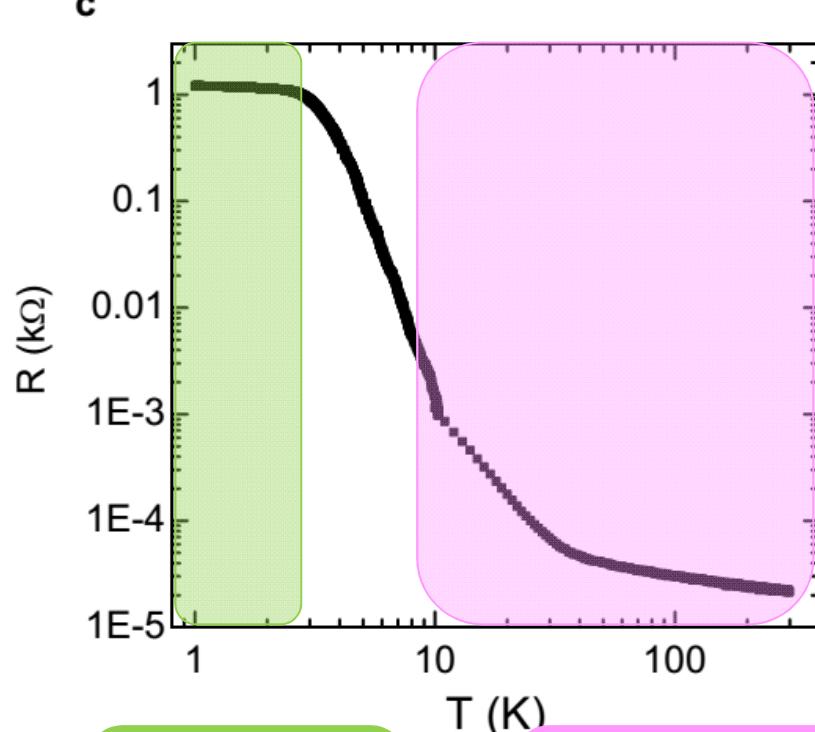
(a)



Kim et al, Scientific Reports (2013)

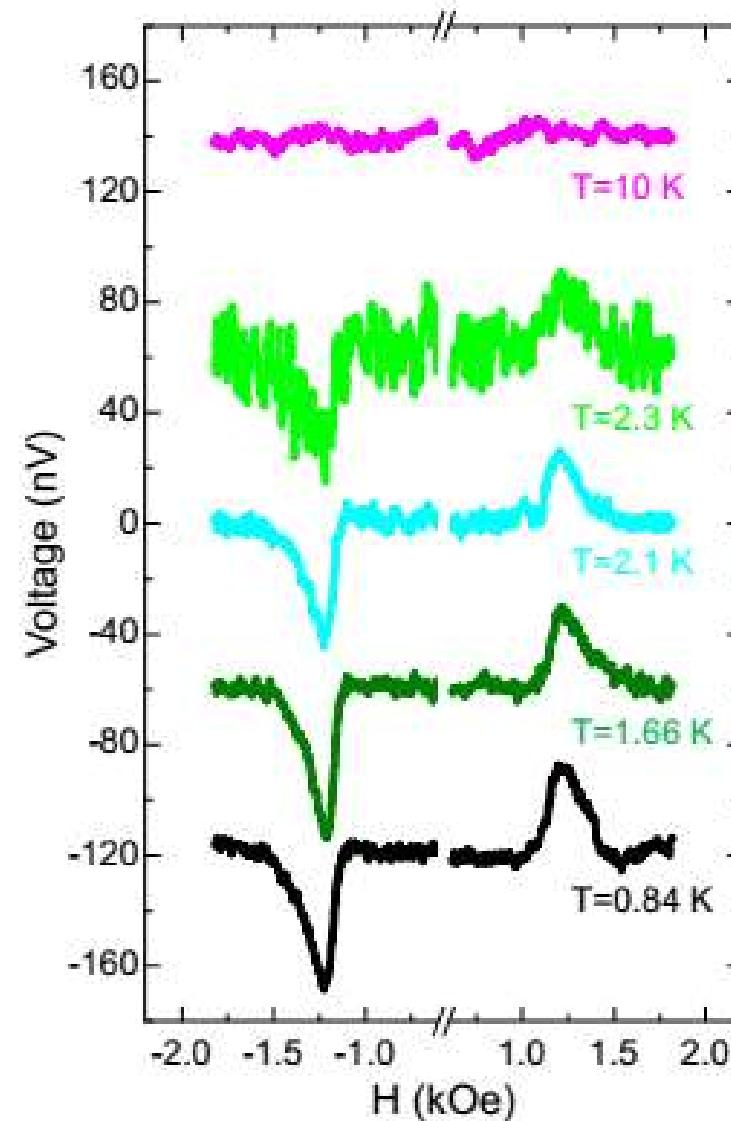
Spin momentum locking

Temperature dependence

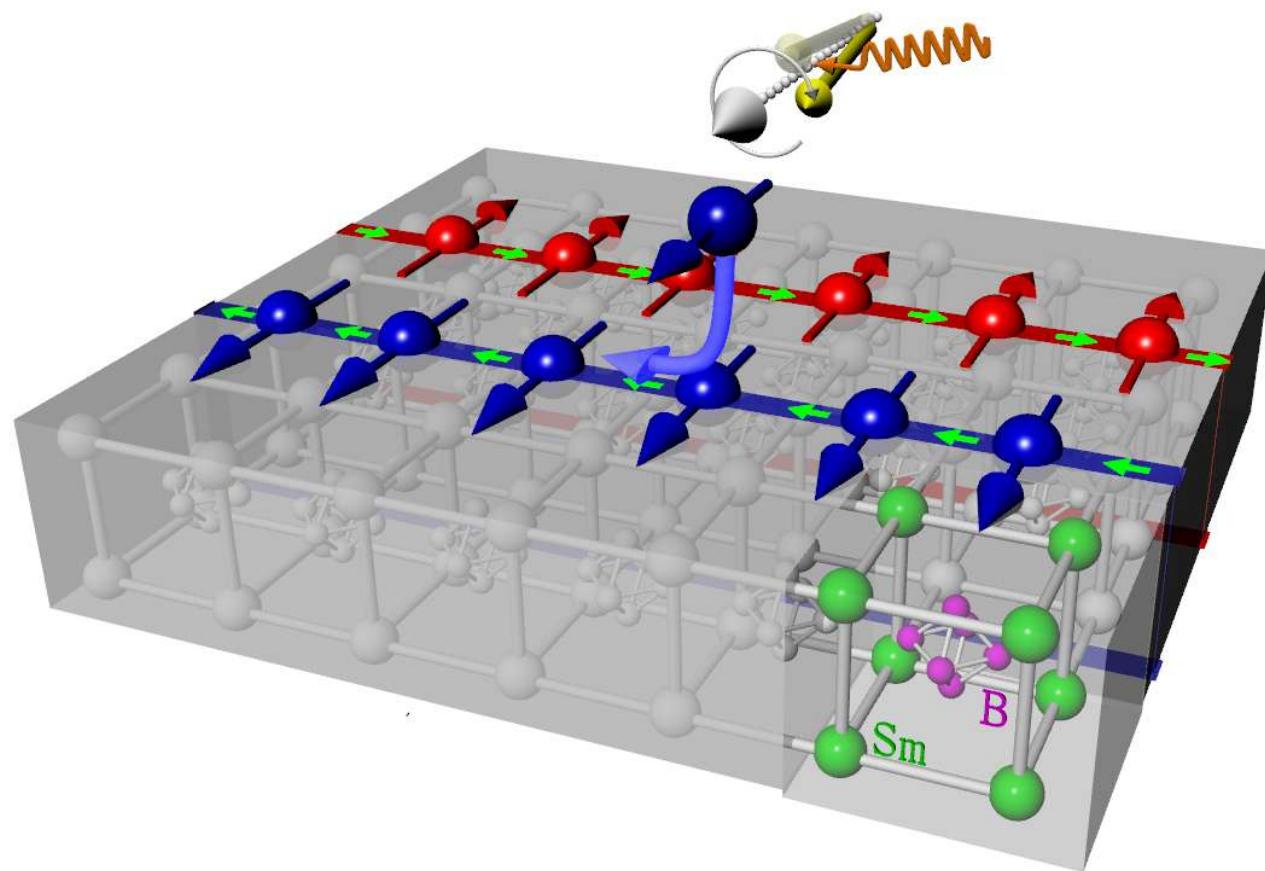


Surface
states

Bulk
states

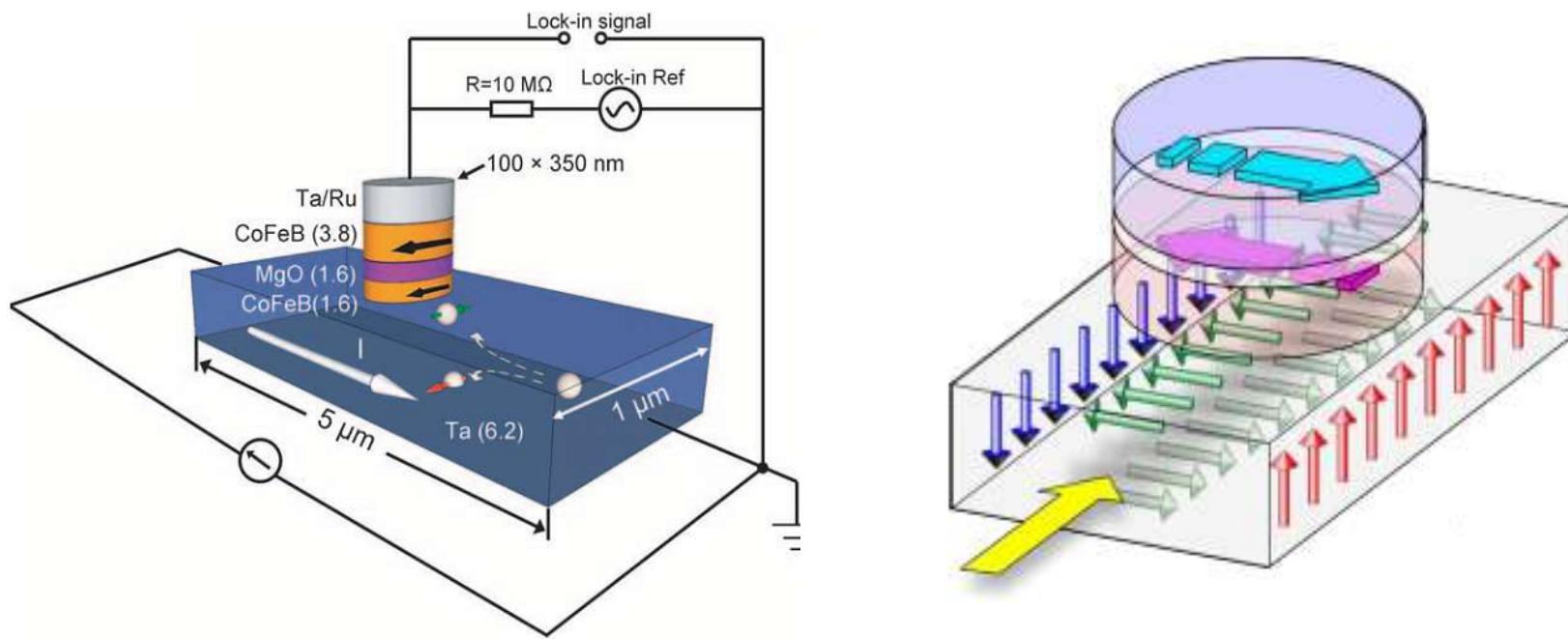


Spin momentum locking



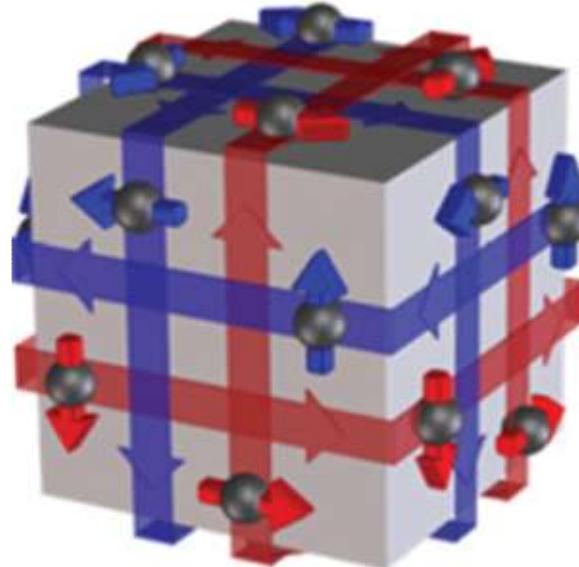
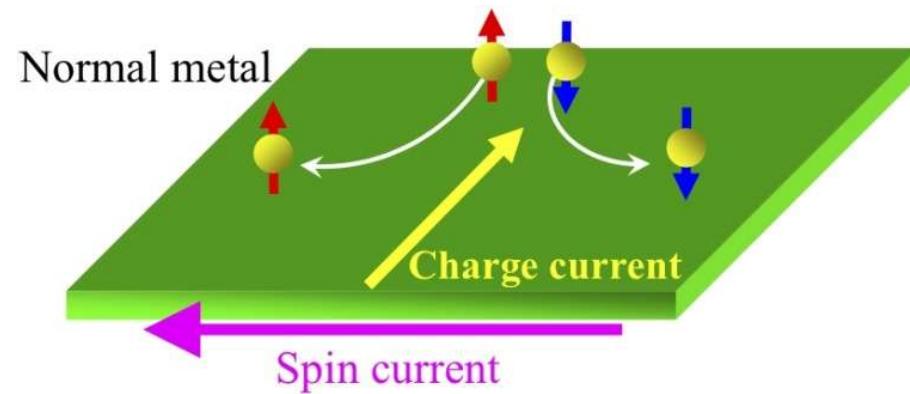
Song, et al, Nature Commun. (2016)

Spin orbit torque

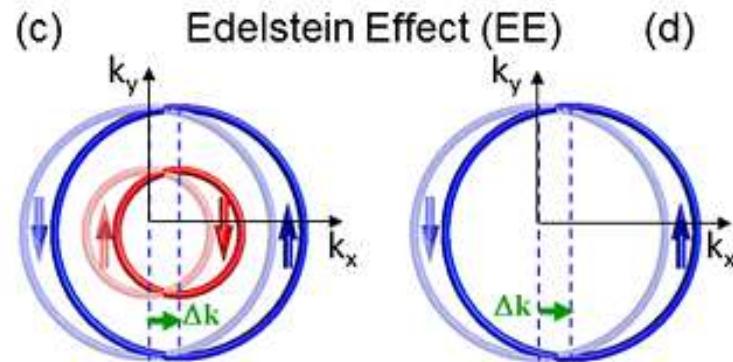
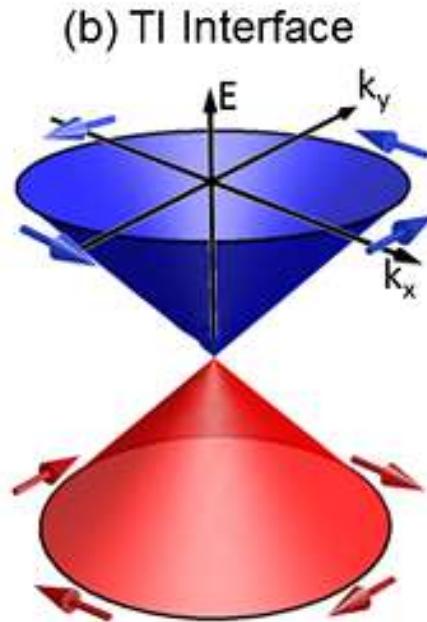


Liu, et al, Science (2012)

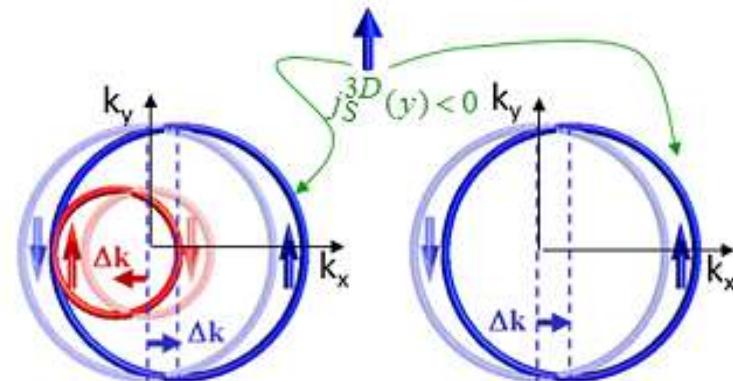
Spin orbit torque



Spin orbit torque



(e) Inverse Edelstein Effect (IEE) (f)



$$j_C^{2D} = \lambda_{IEE} j_S^{3D}$$

$$\lambda_{IEE} = \frac{\alpha_R \tau}{\hbar}$$

$$j_C^{2D} = \lambda_{IEE} j_S^{3D}$$

$$\lambda_{IEE} = v_F \tau$$

Spin orbit torque

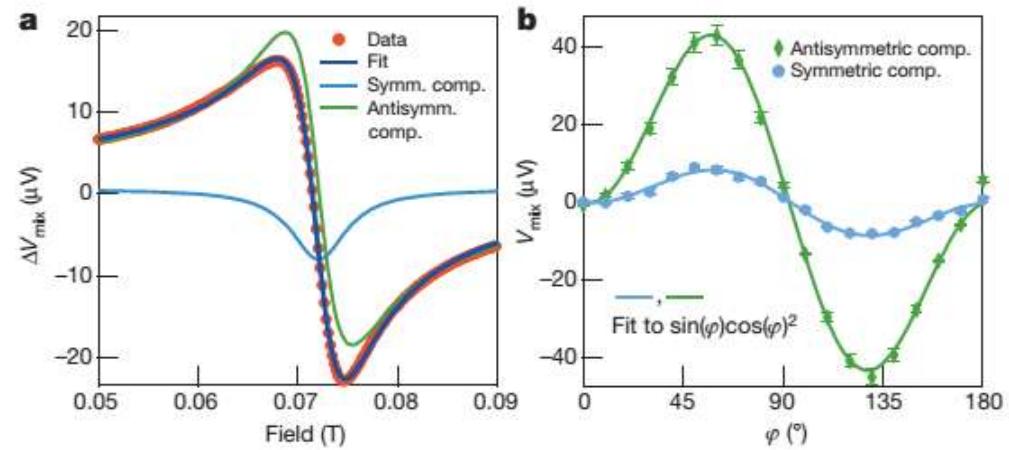
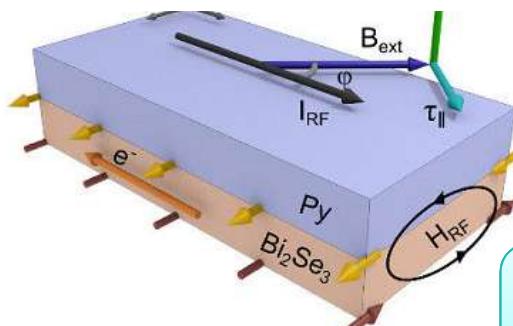
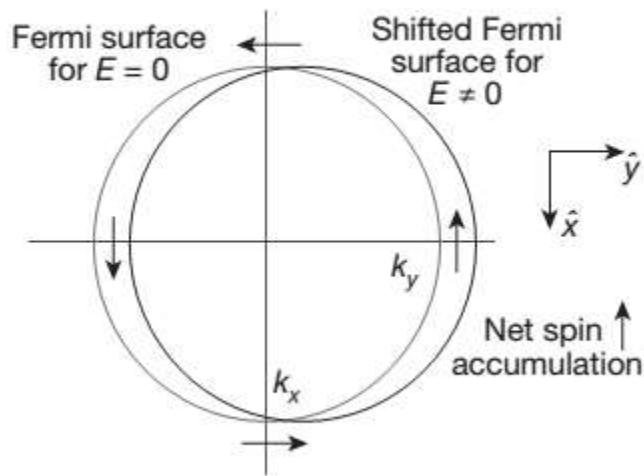


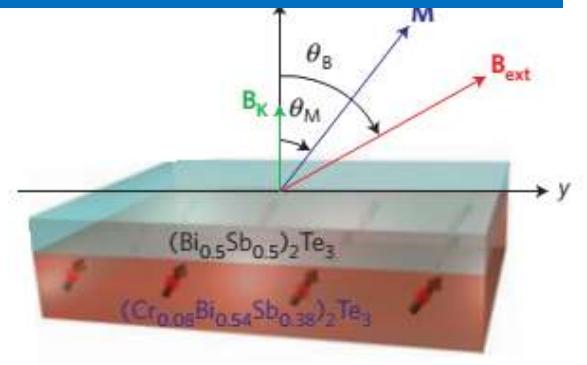
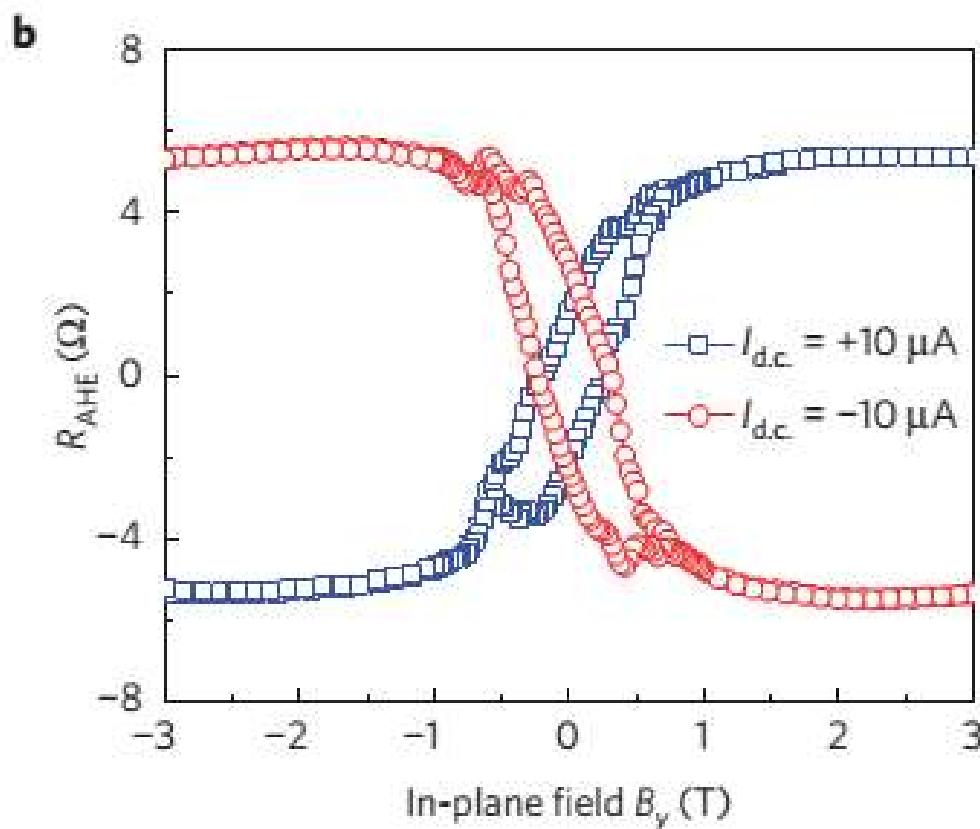
Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for Bi_2Se_3 with other materials

Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	$\beta\text{-Ta}$ (ref. 6)	Cu(Bi) (ref. 23)	$\beta\text{-W}$ (ref. 24)
θ_s	2.0–3.5	0.08	0.15	0.24	0.3 1.8

Spin Hall angle: 2.0–3.5

Spin orbit torque

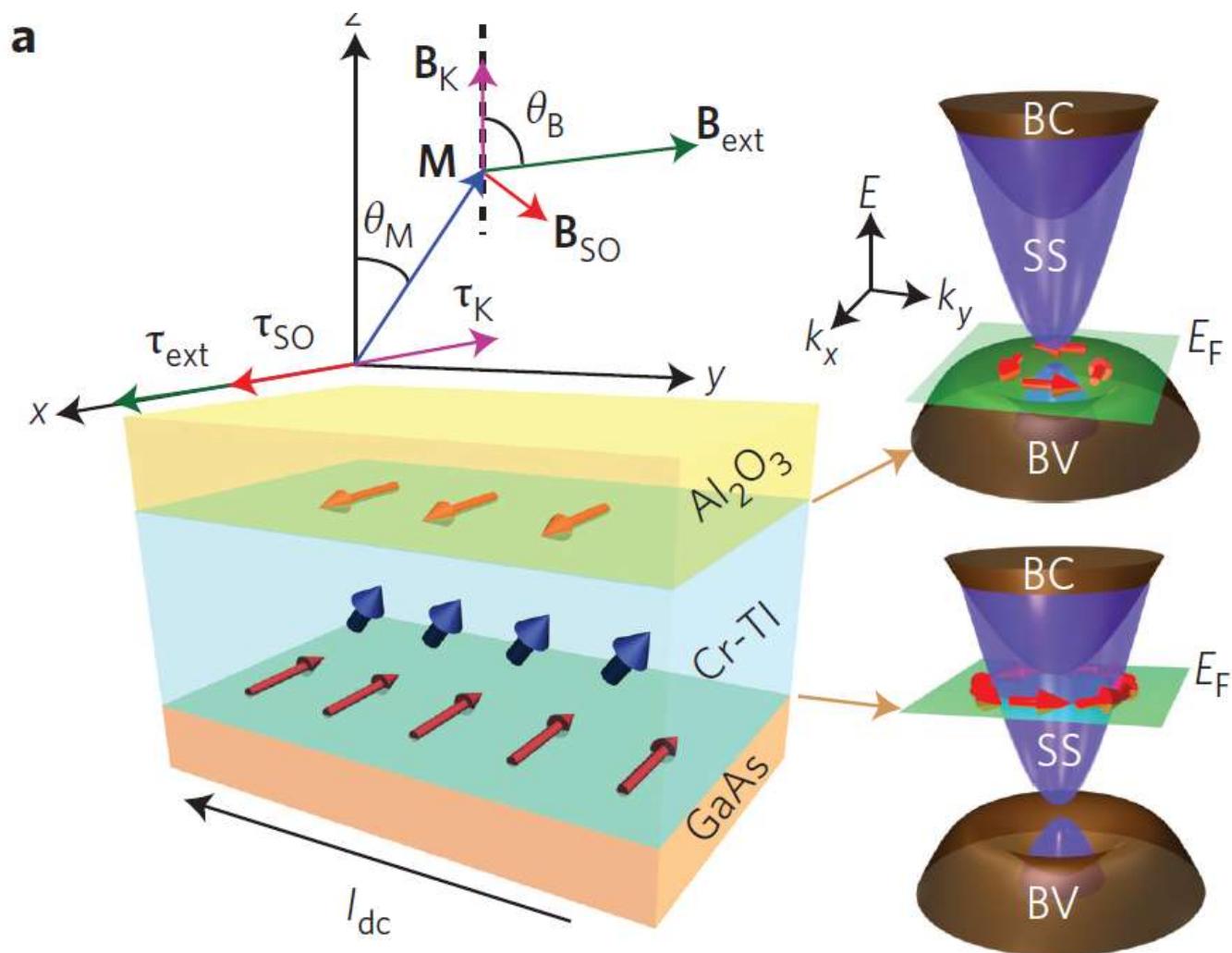
$(\text{Bi}_{0.5}\text{Sb}_{0.5})_2\text{Te}_3$



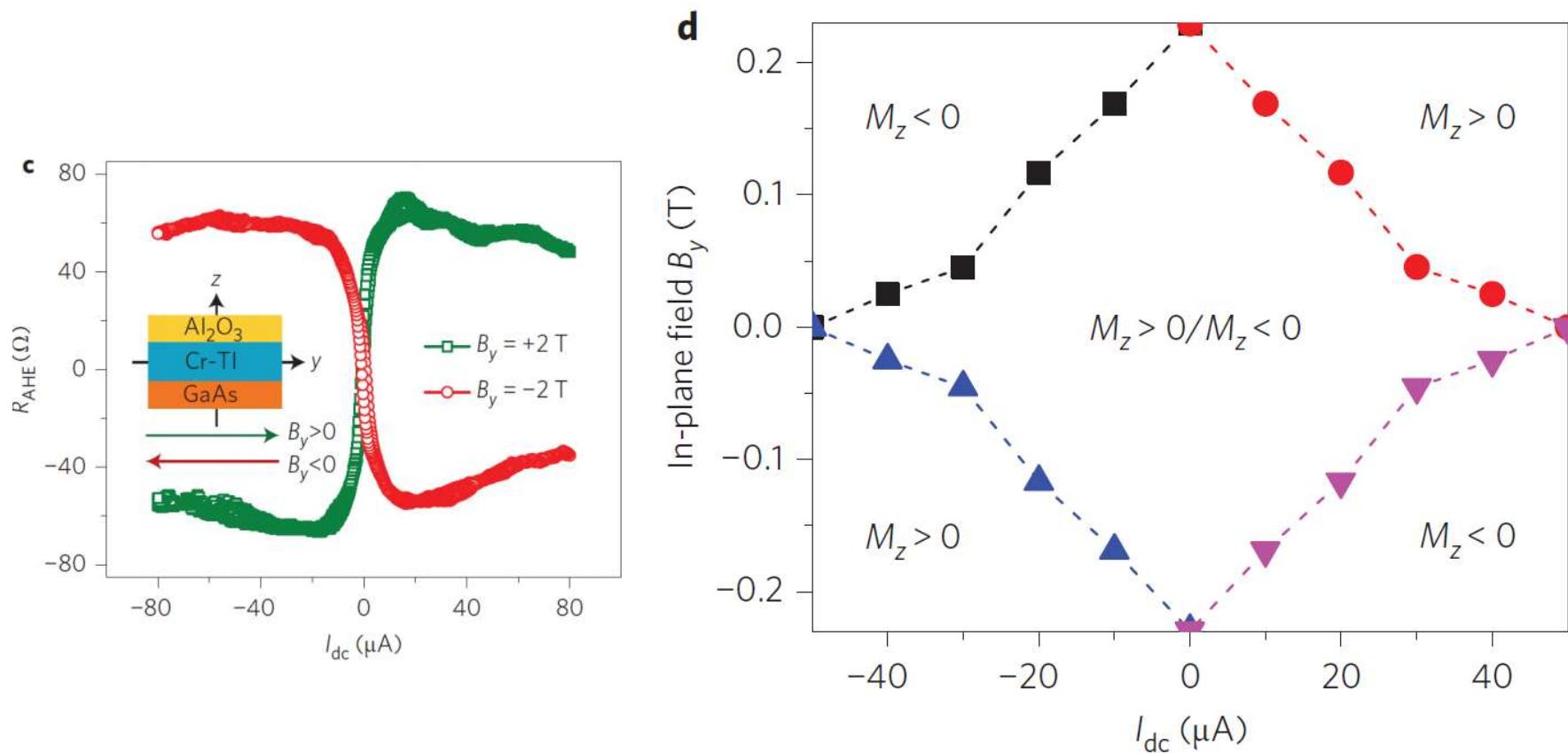
T=1.9 K
SHA > 100

Fan, et al, Nature Mater. (2014)

Spin orbit torque

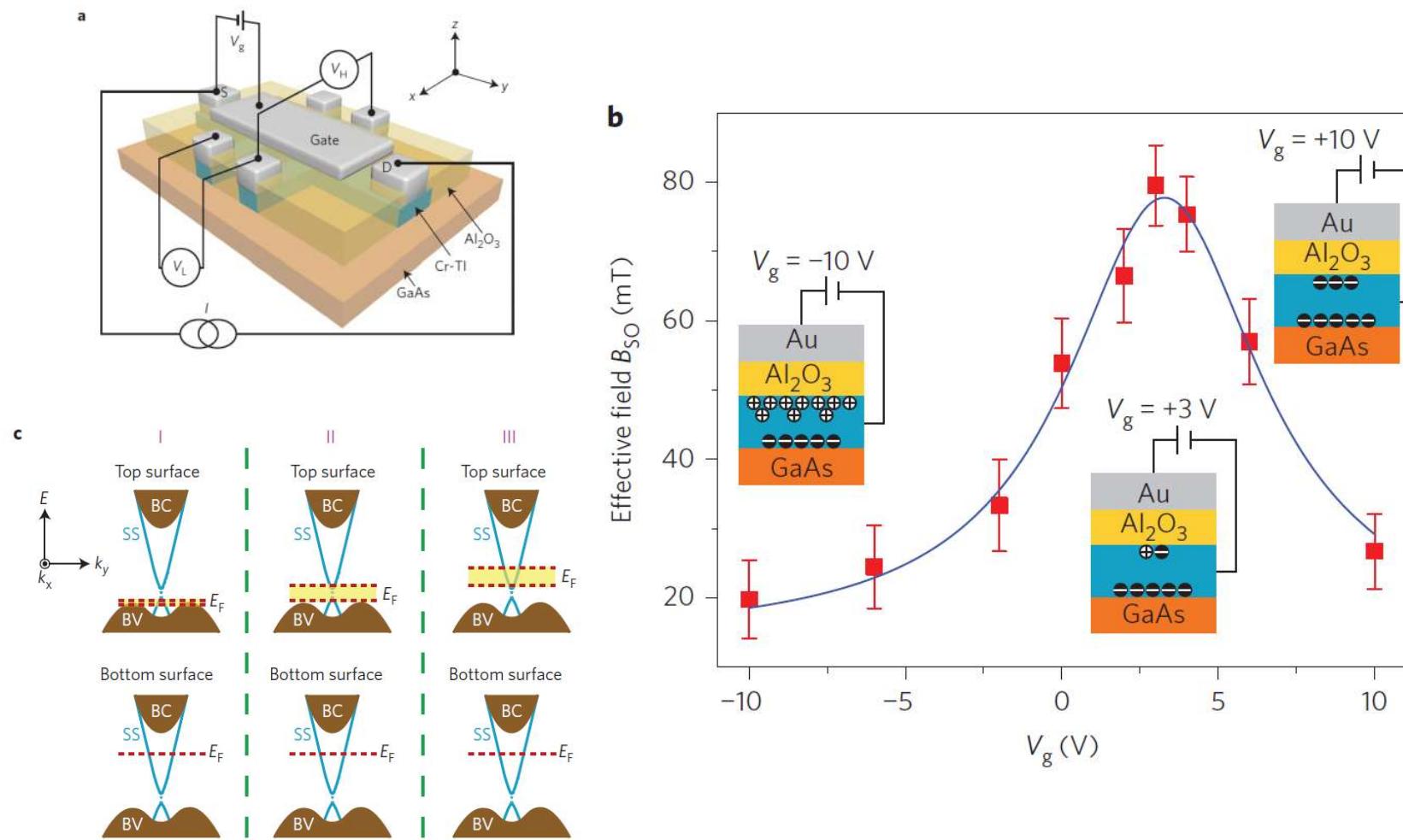


Spin orbit torque

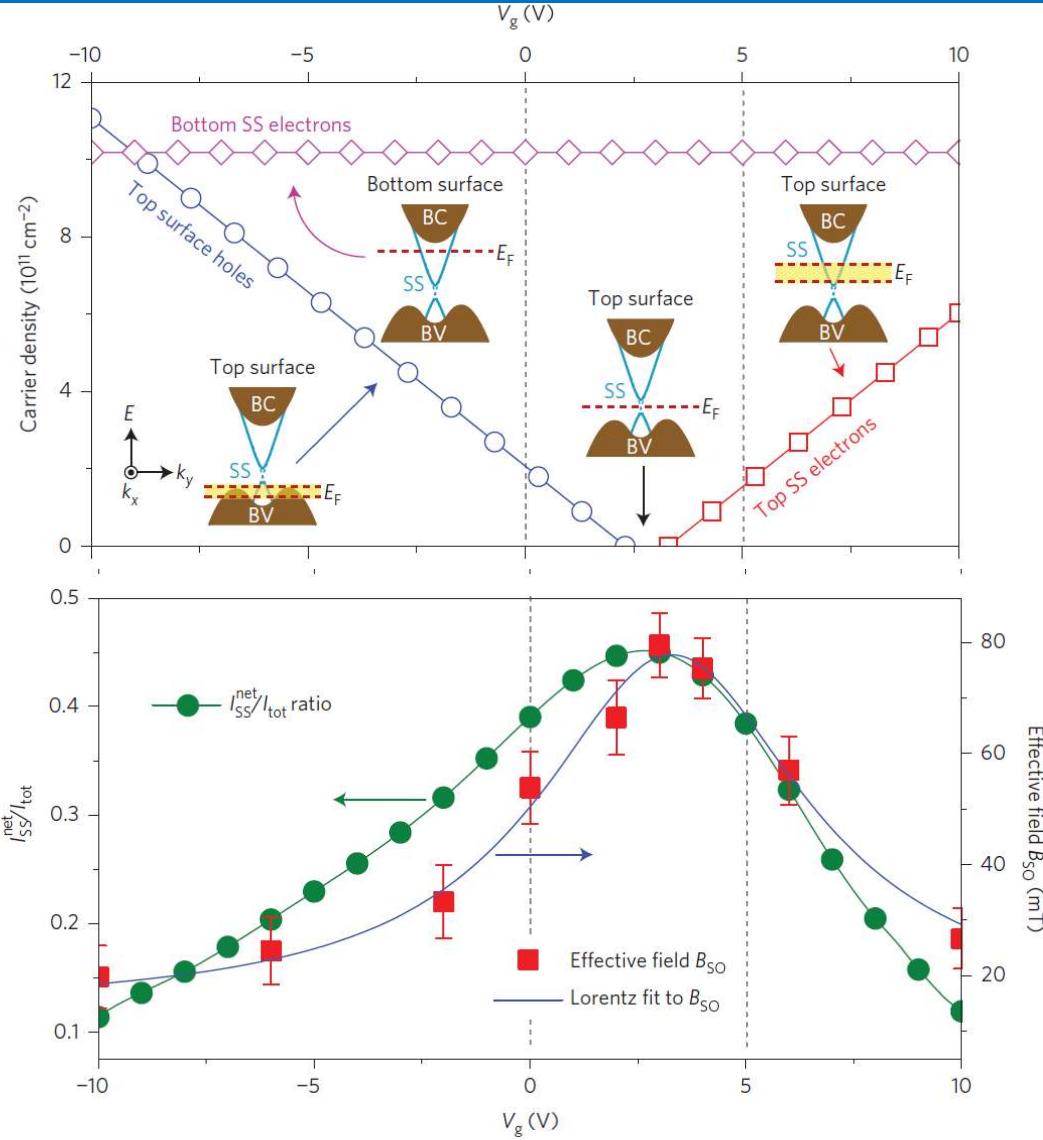


Fan, et al, Nature Nanotech. (2016)

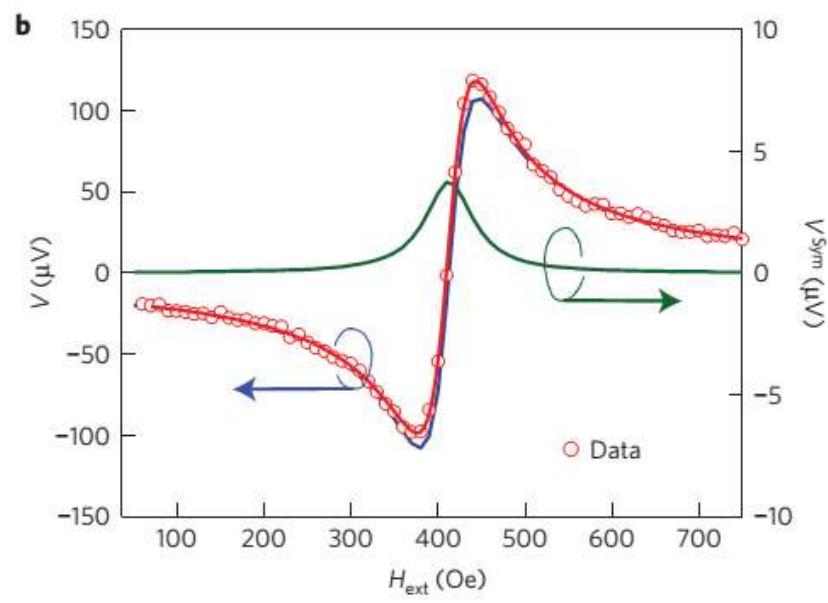
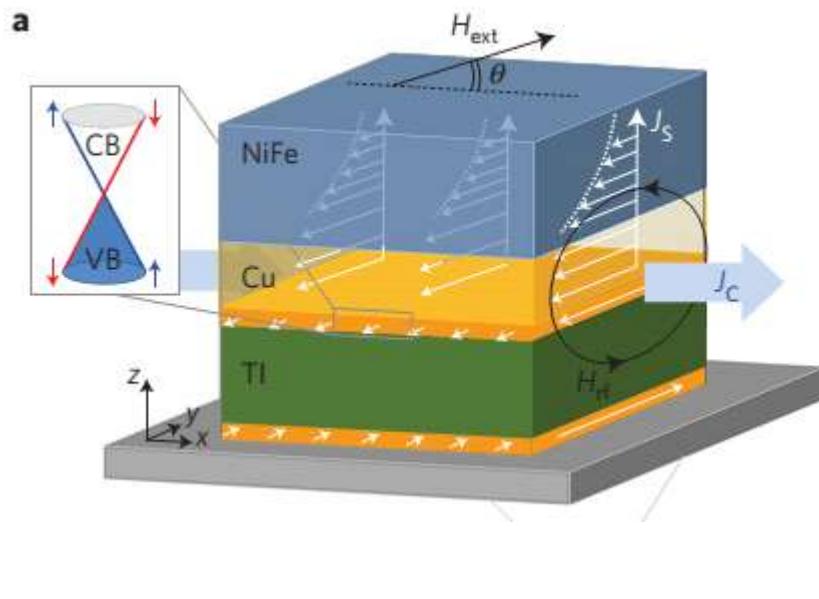
Gate tunable spin orbit torque



Gate tunable spin orbit torque

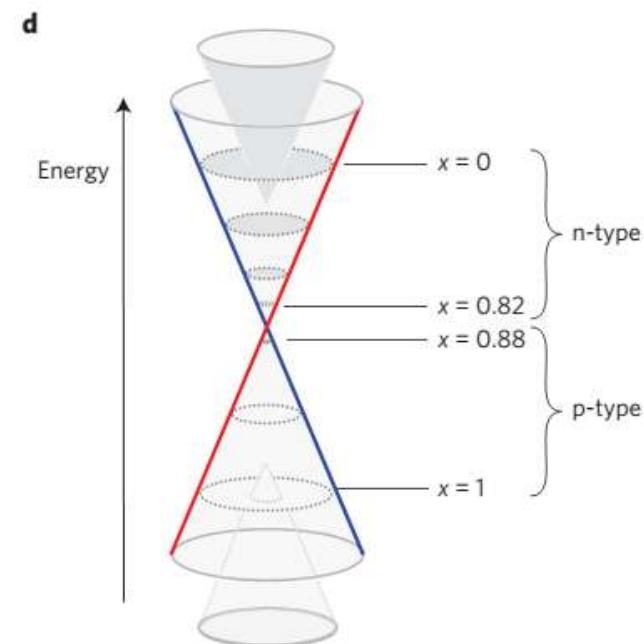
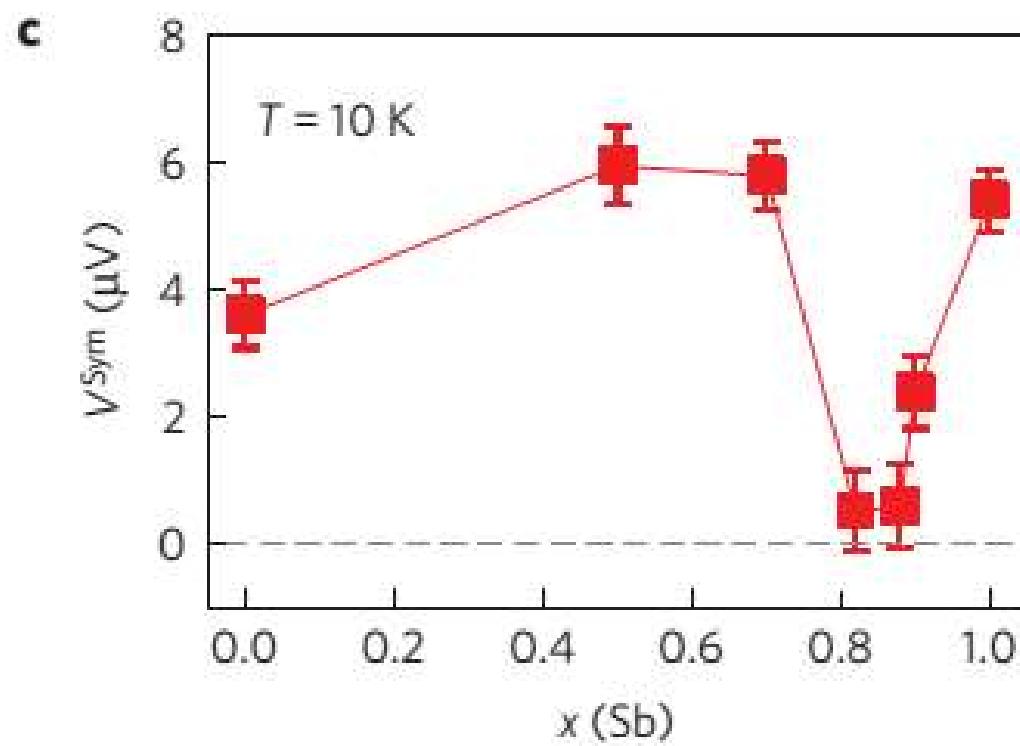


Gate tunable spin orbit torque



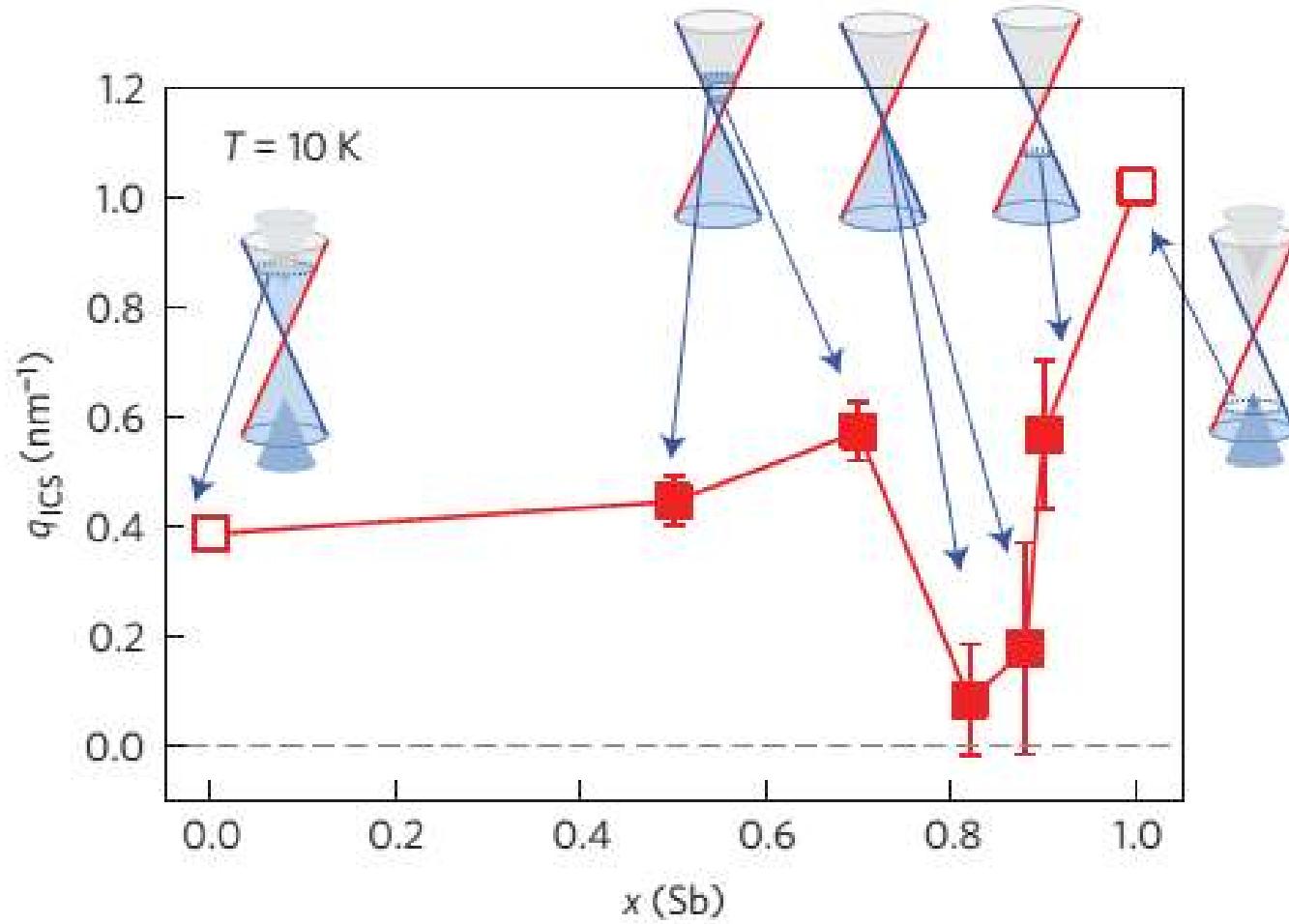
Kondou, et al, Nature Physics (2016)

Gate tunable spin orbit torque



Gate tunable spin orbit torque

a



Summary

1. Topology

2. Quantum anomalous Hall effect

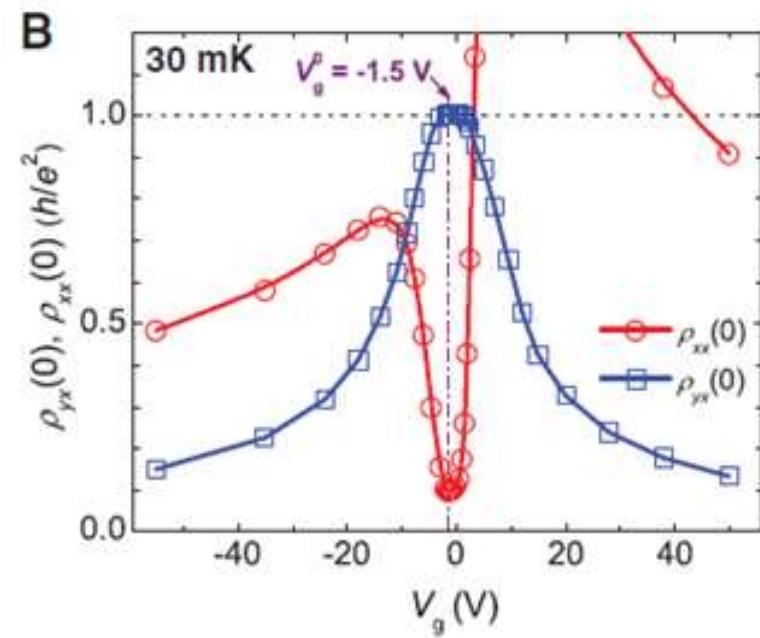
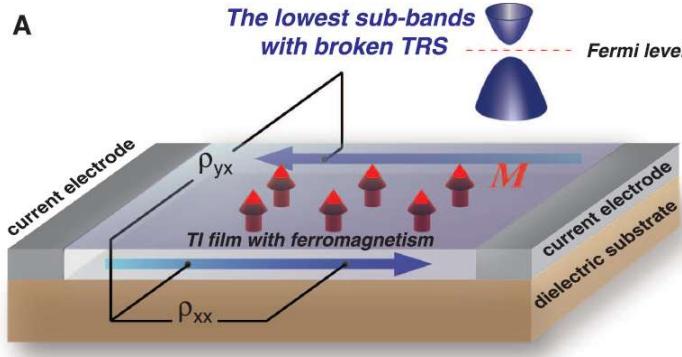
3. Skyrmions

4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**

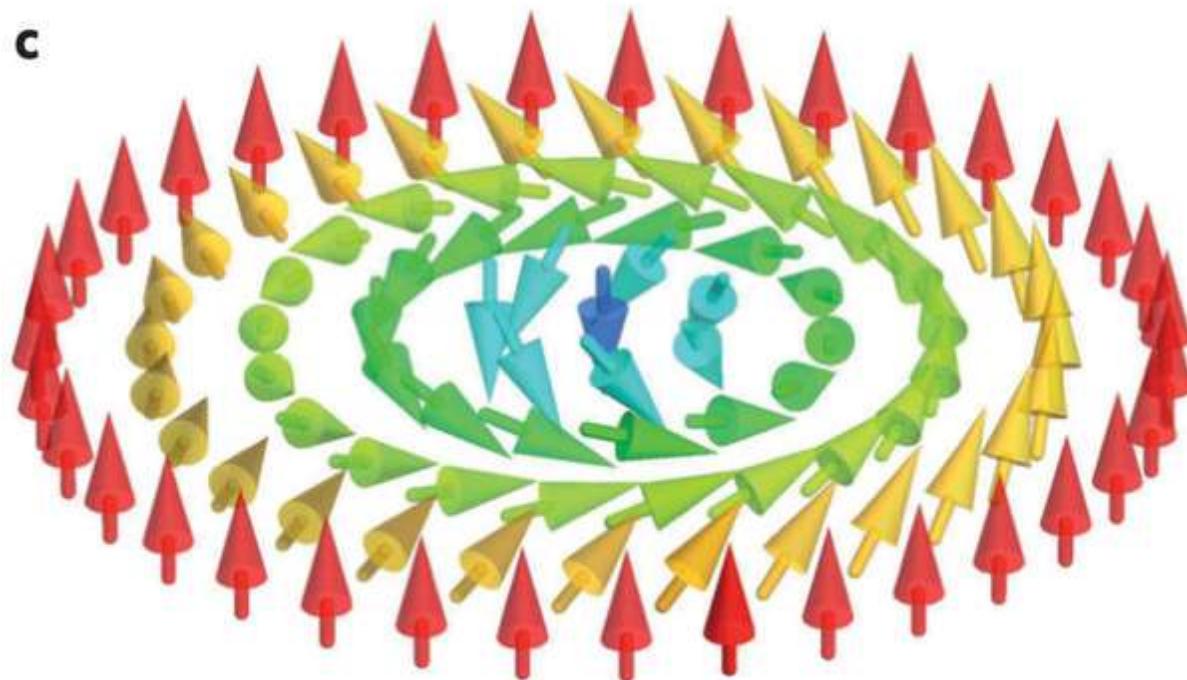
Summary

2. Quantum anomalous Hall effect



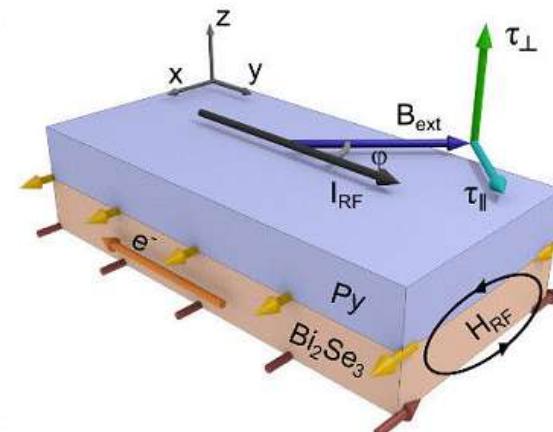
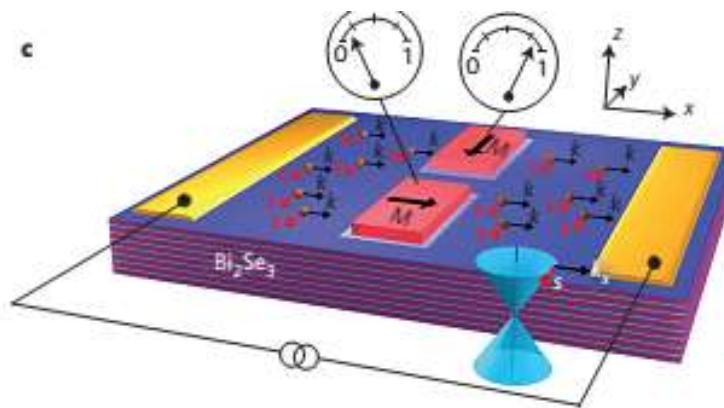
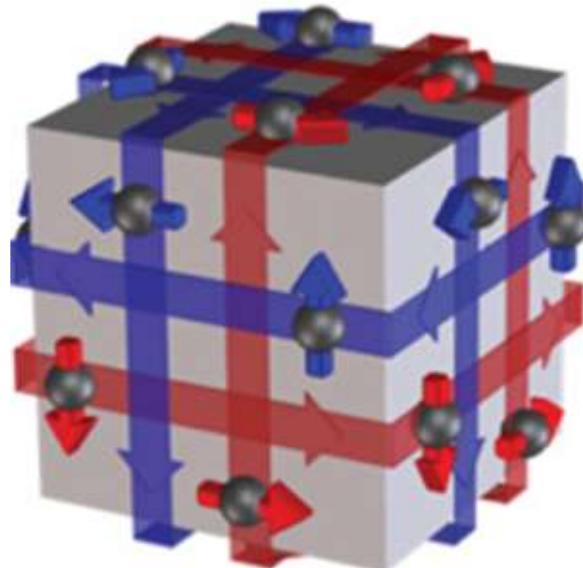
Summary

3. Skyrmions



Summary

4. Spin-momentum locking of 3D TI



Final Exam

Due date:

2016 12-27 (1:00 PM)

Student Presentations

Dec. 13th, 20th, 27th

20 mins/ Per person

15 mins talk + 5 mins questions

Student Presentations

Date	Names
Dec. 13 th	陈阳阳; 邢文字; 刘林; 刘雅卉; 刘彦昭
Dec. 20th	马扬; 孙健; 唐维; 谢志坚; 薛海鹏
Dec. 27th	姚云焱; 张晓玥; 李金培 ; 张雅文

下一节课: Dec. 13th

Chapter 8: AFM Spintronics

课件下载 :

<http://www.phy.pku.edu.cn/~LabSpin/teaching.html>

谢谢！