Chapter 7

Topological Spintronics

韩伟

量子材料科学中心

2018年12月7日

Review of last class

1. Seebeck and Peltier effect

2. Spin Seebeck effect

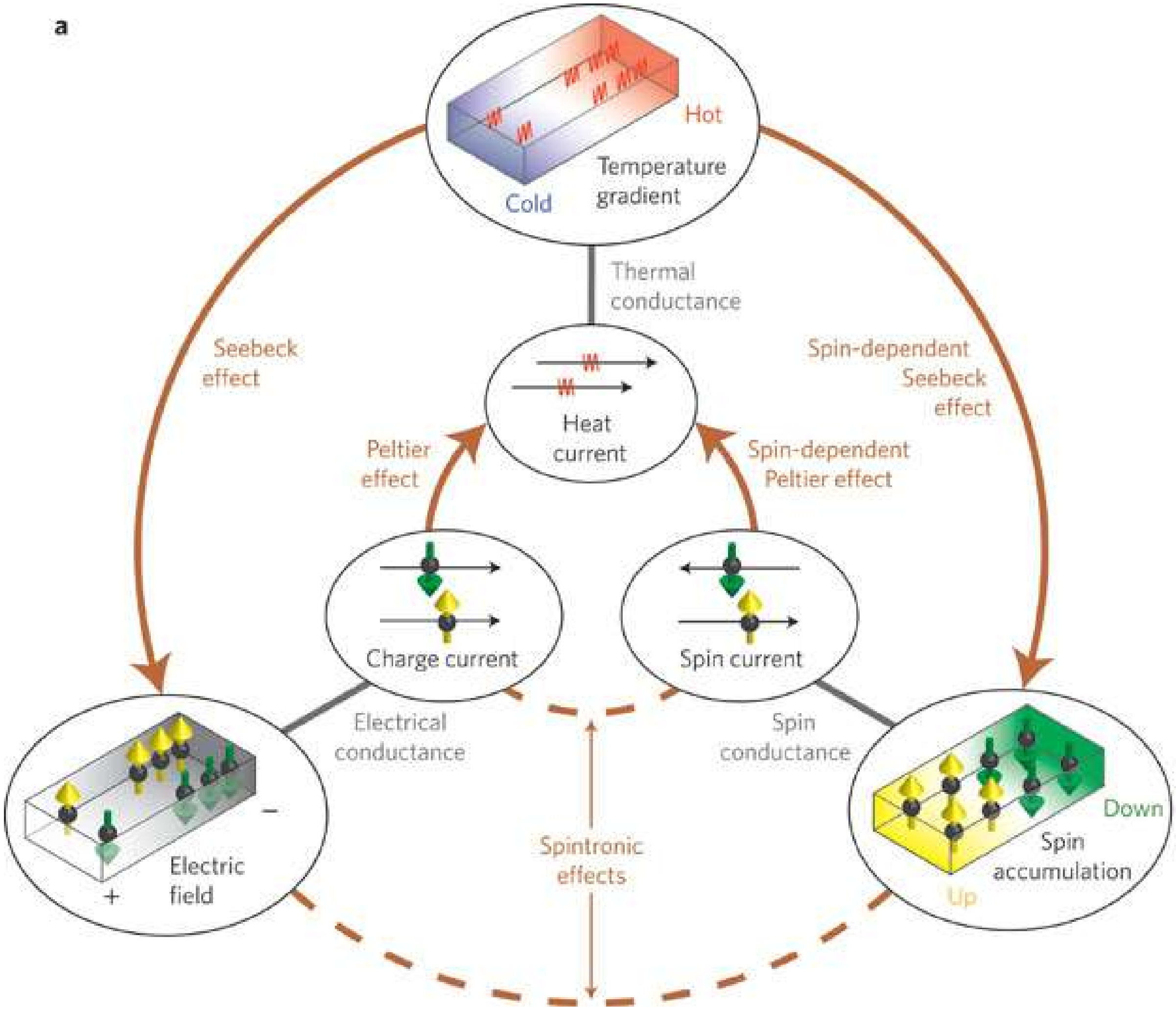
3. Spin Peltier effect

4. Thermal spin injection

5. Thermal spin torque

6. Spin energy

Review of last class



Goennenwein & Bauer, Nature Nanotech. (2012)

Outline

1. Topology

2. Quantum anomalous Hall effect

3. Skyrmions

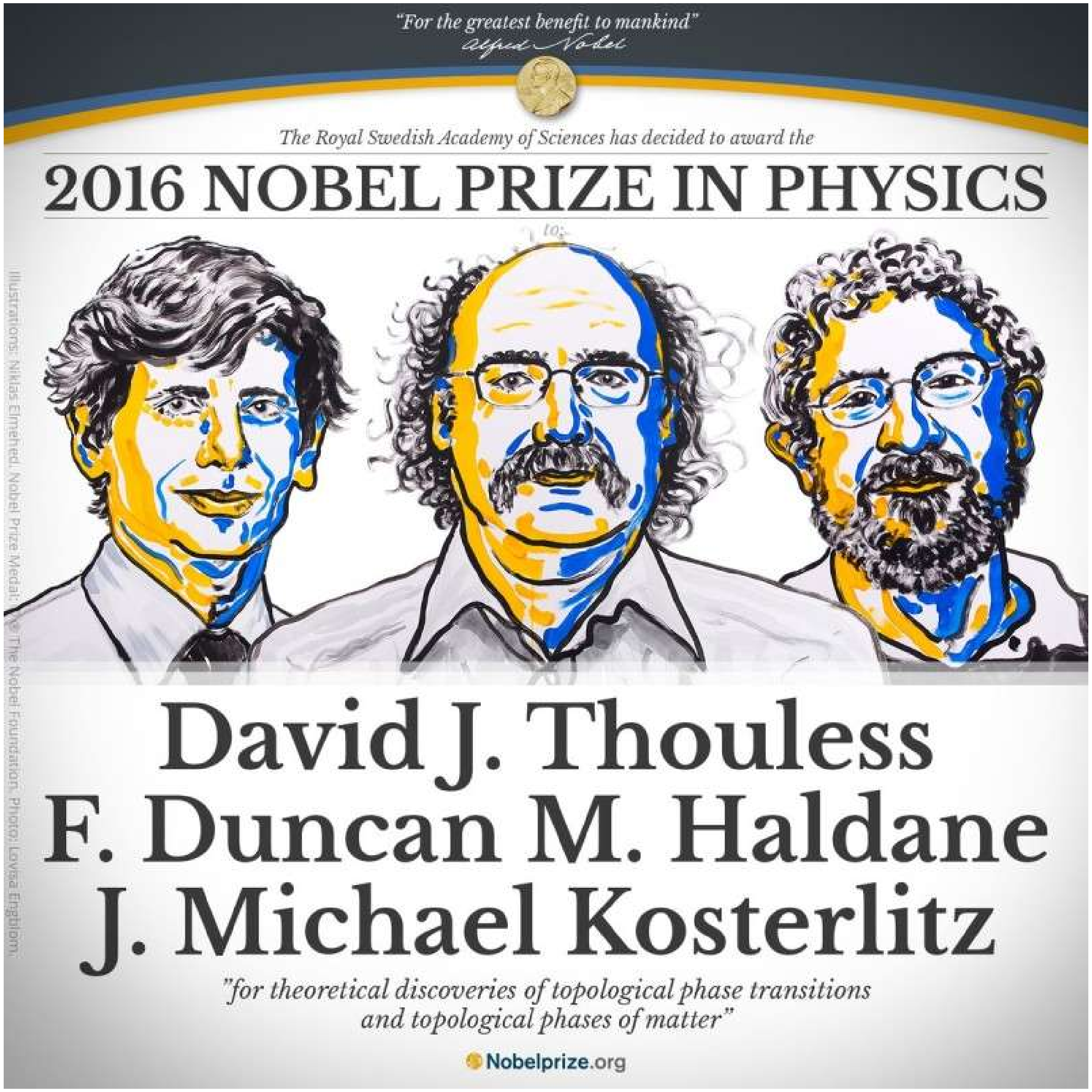
4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**
- **Spin Seebeck effect**

Outline

1. Topology

Topology



"For the greatest benefit to mankind"
The Royal Swedish Academy of Sciences has decided to award the
2016 NOBEL PRIZE IN PHYSICS
to:
David J. Thouless
F. Duncan M. Haldane
J. Michael Kosterlitz
"for theoretical discoveries of topological phase transitions and topological phases of matter"
Nobelprize.org

Topology

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

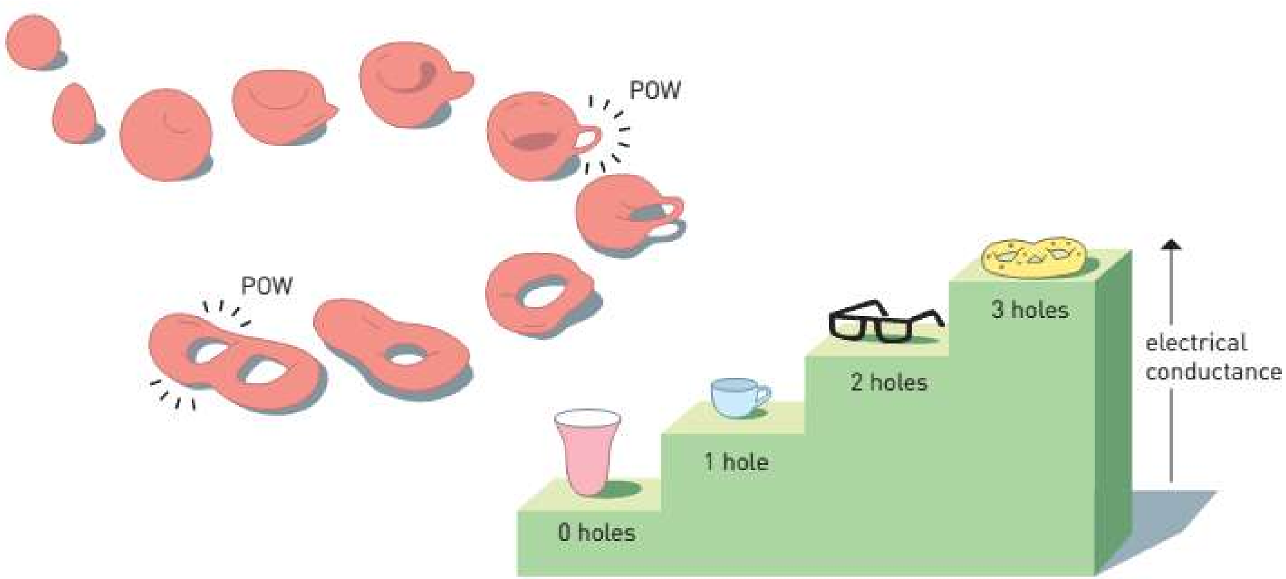
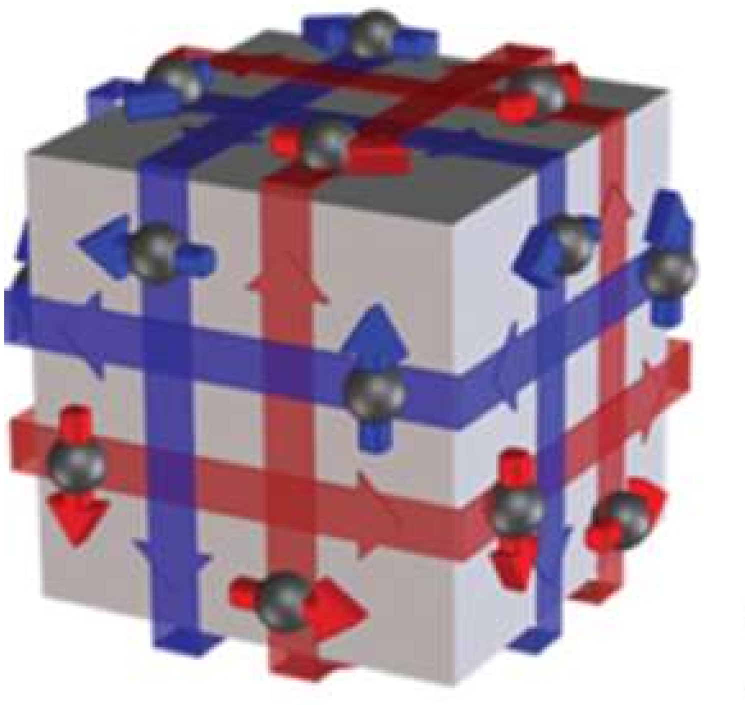


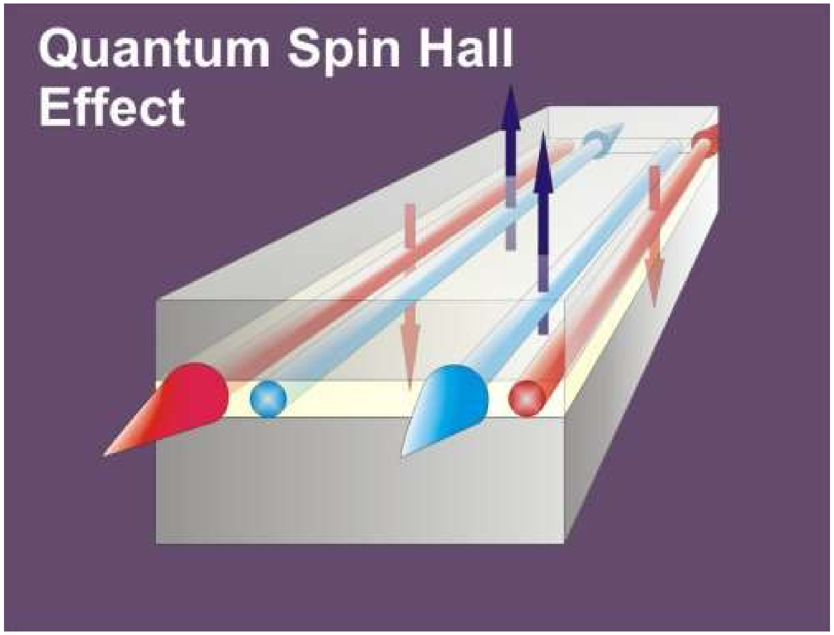
Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

Topological insulator

3D Topological insulator

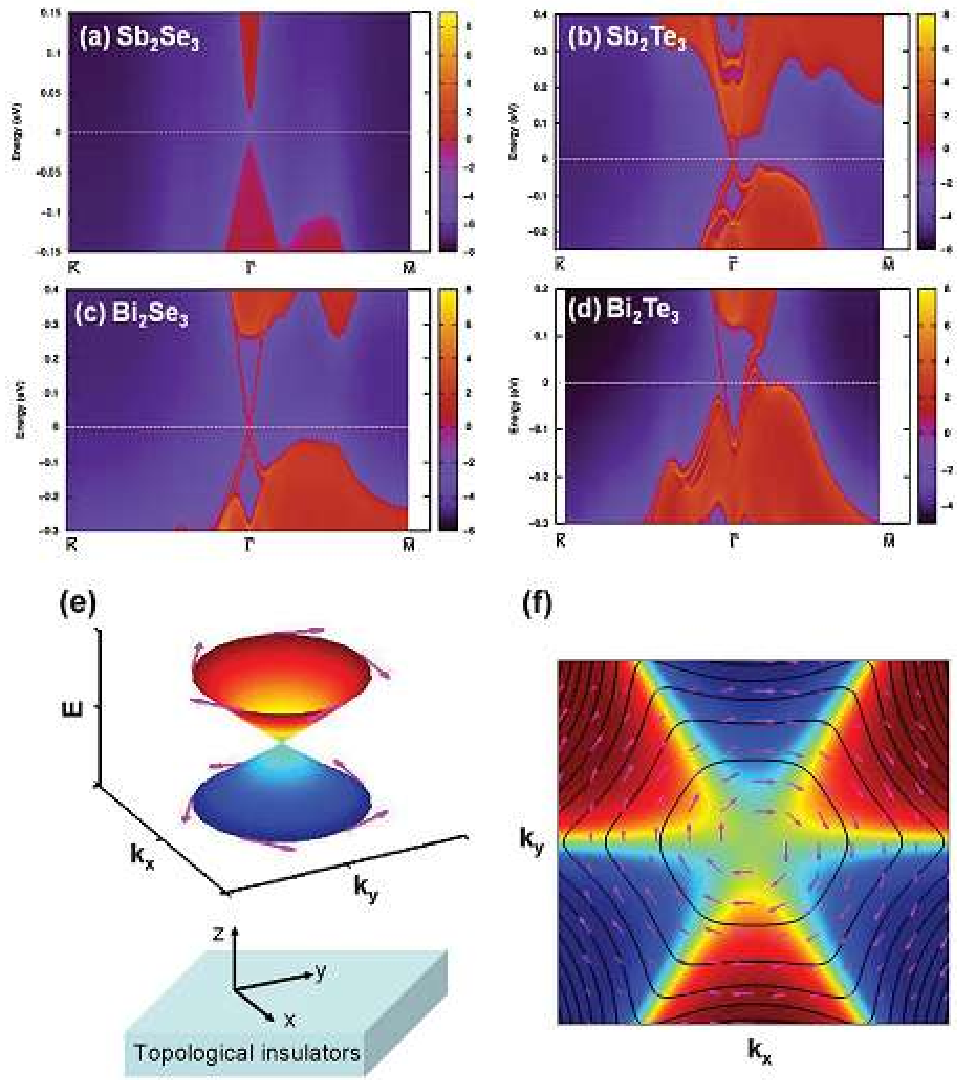


2D Topological insulator

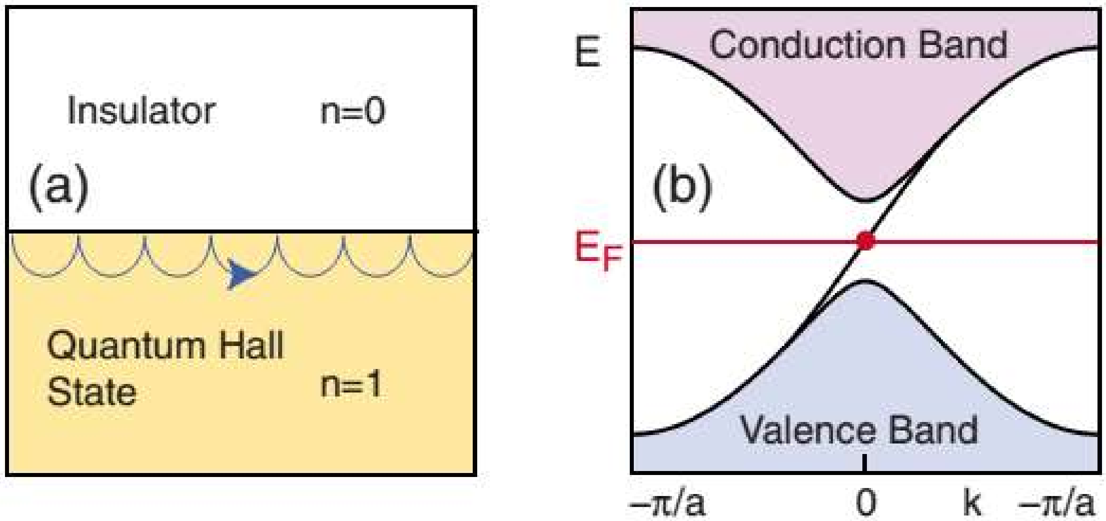


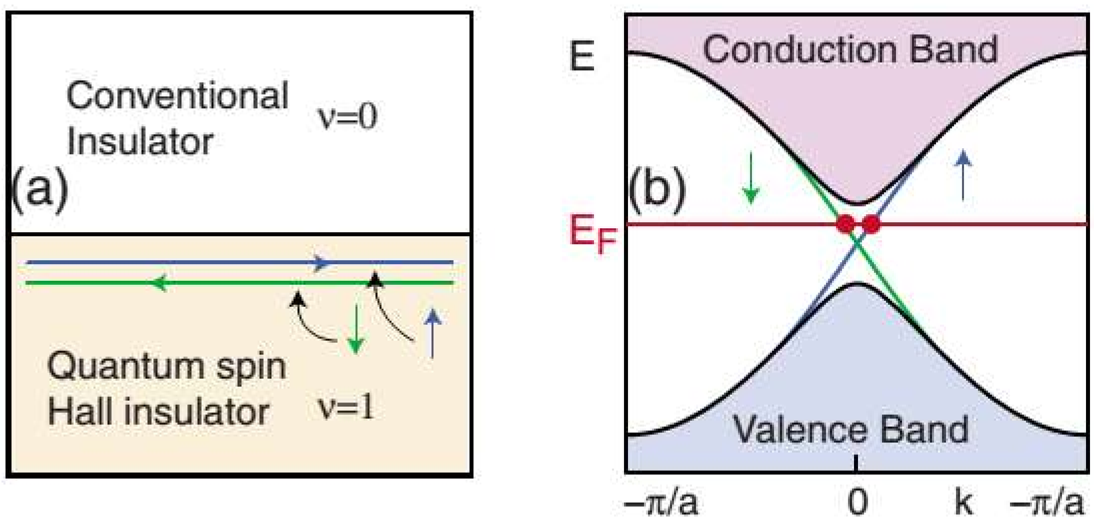
Hasan & Kane, Rev Mod Phys (2009)
Qi & Zhang, Rev Mod Phys (2011)

3D Topological insulator

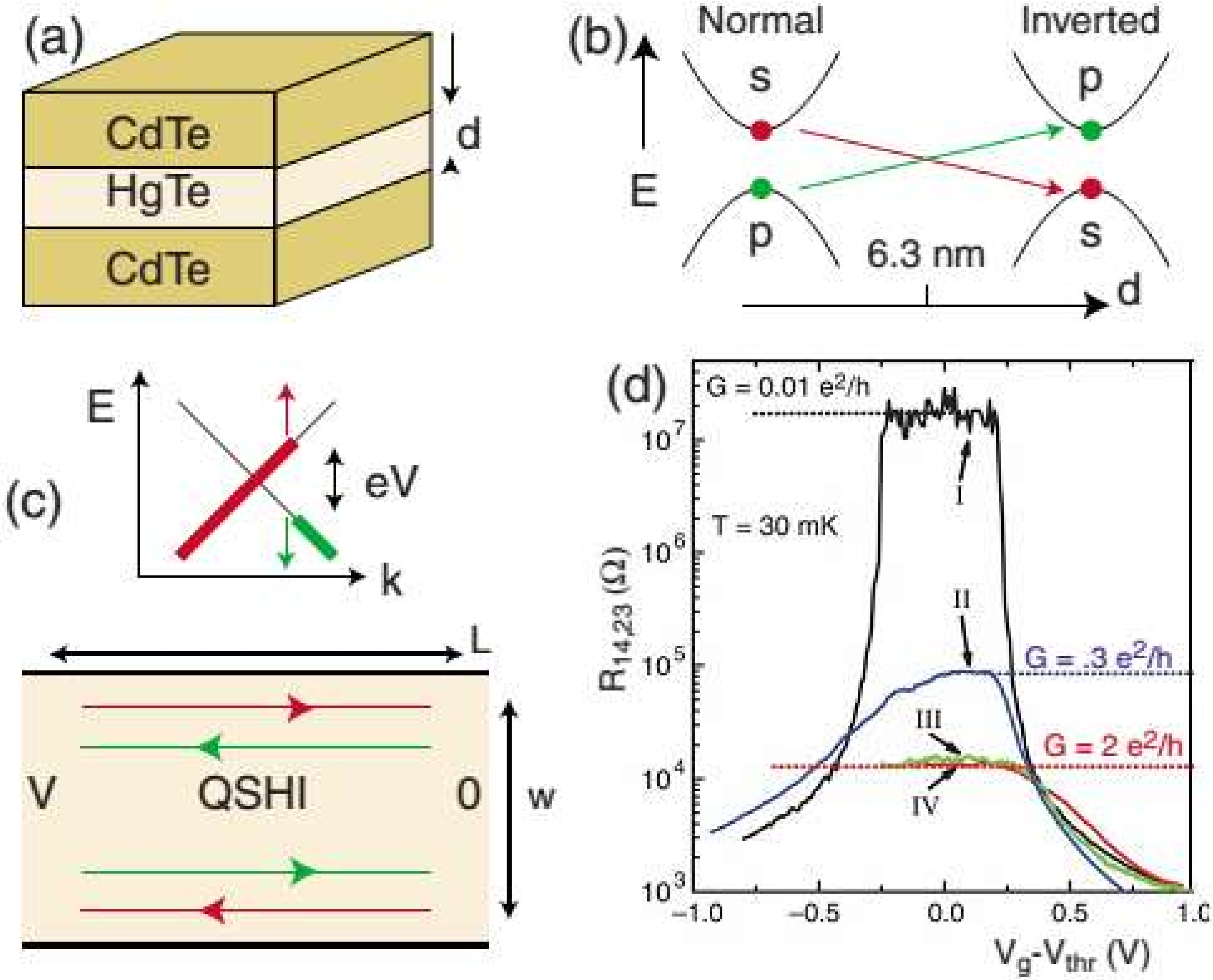


2D Topological insulator

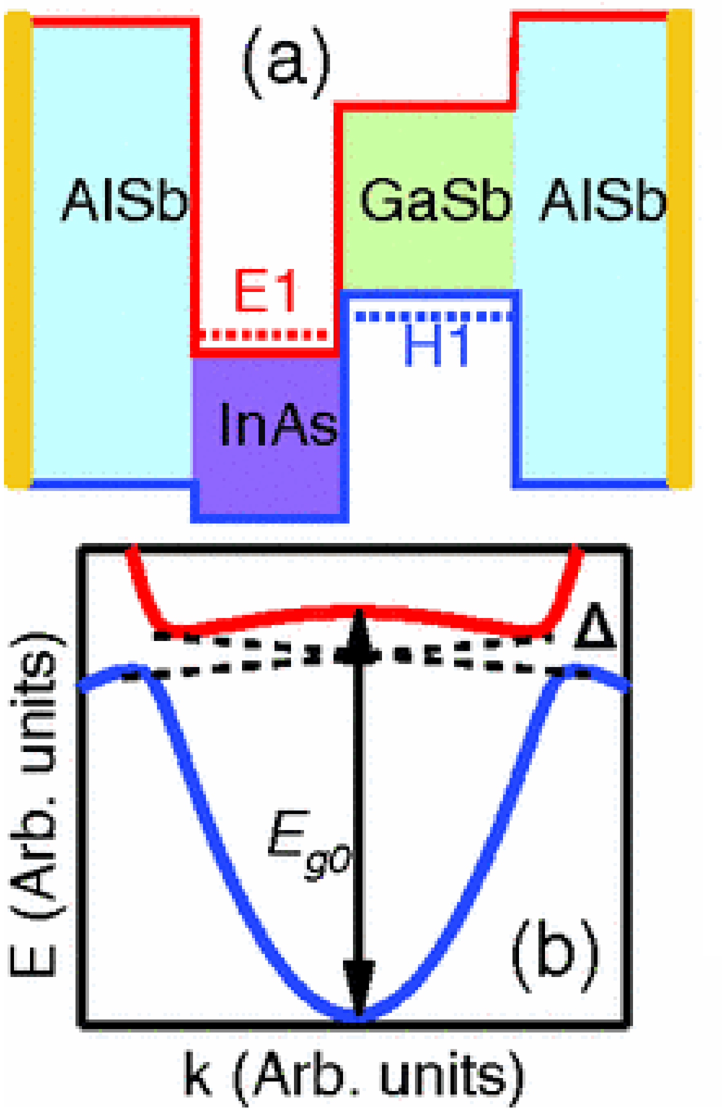


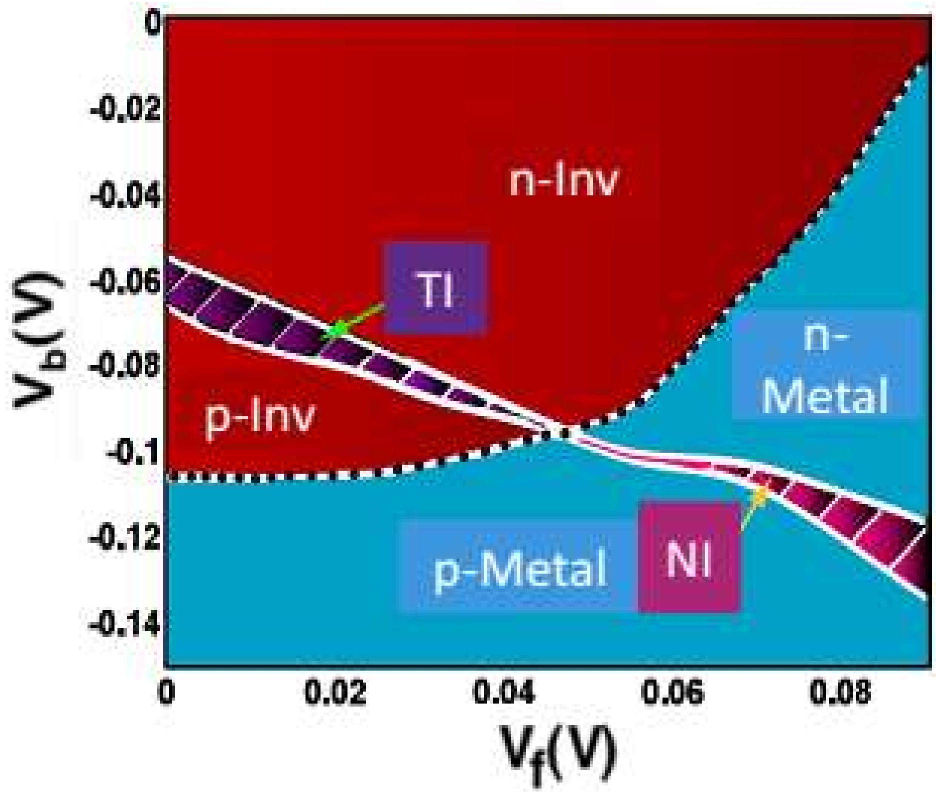


2D Topological insulator



2D Topological insulator

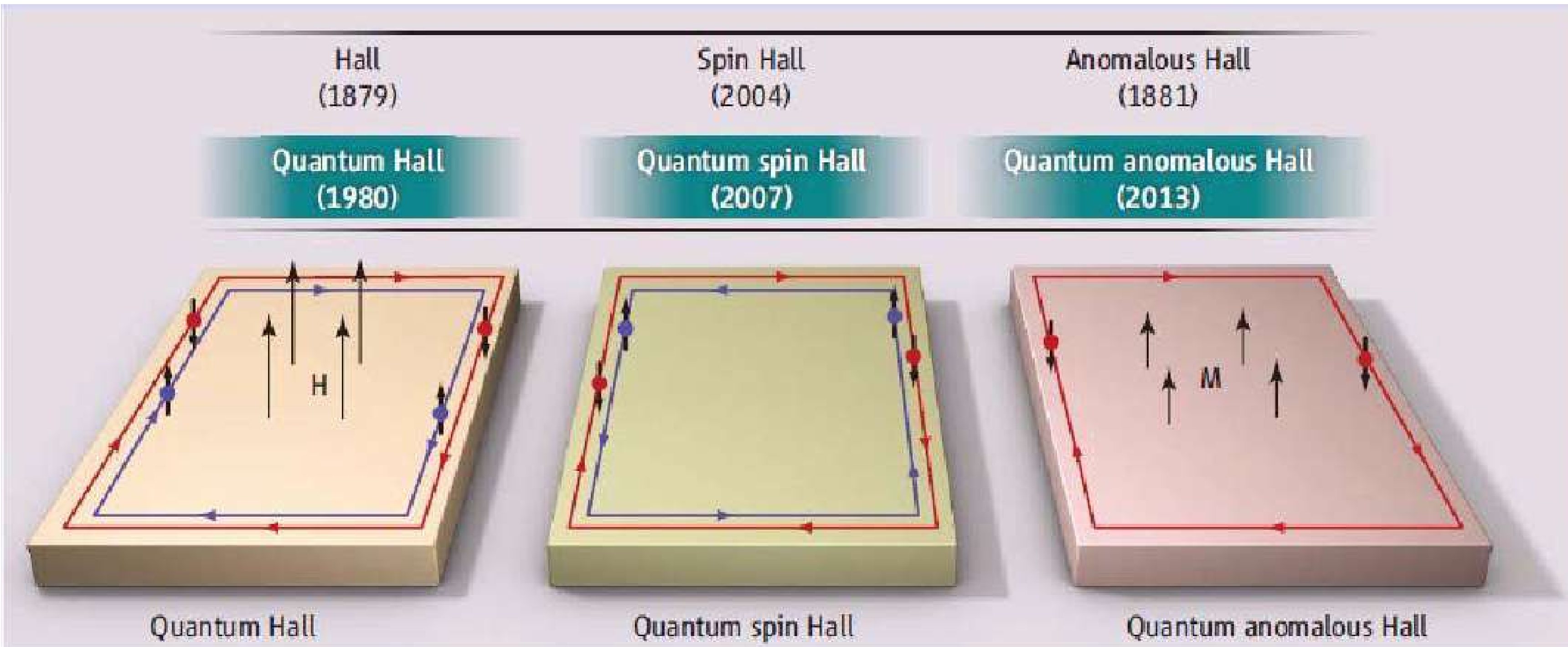




From Prof. Du Ruirui

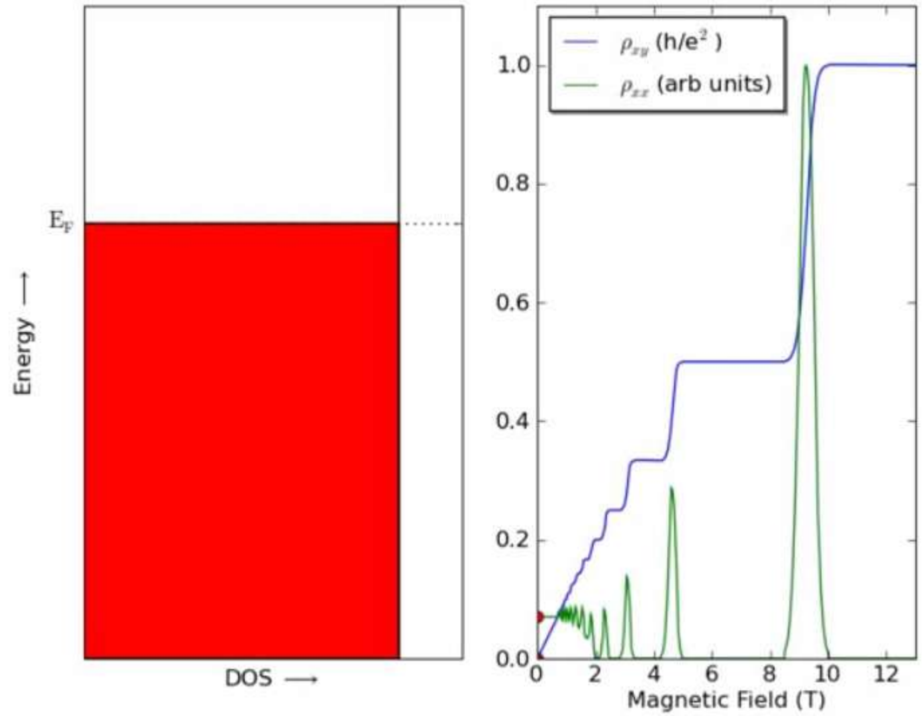
2. Quantum anomalous Hall effect

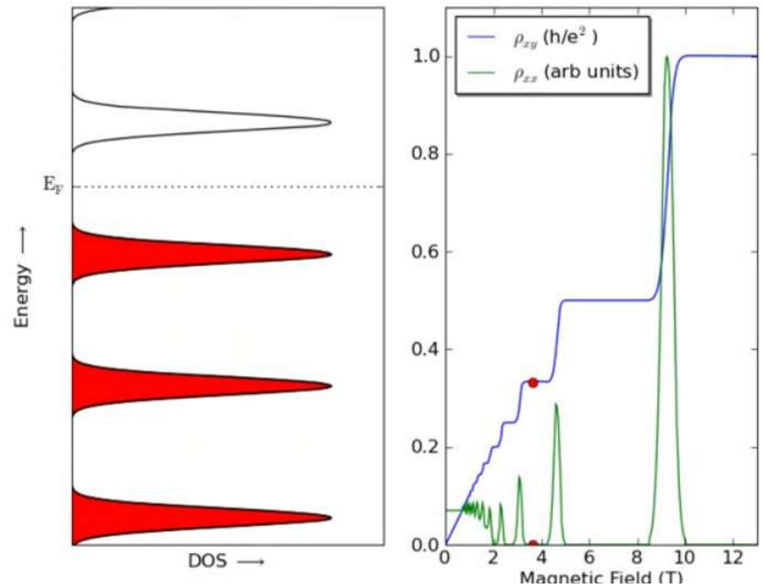
Hall effect

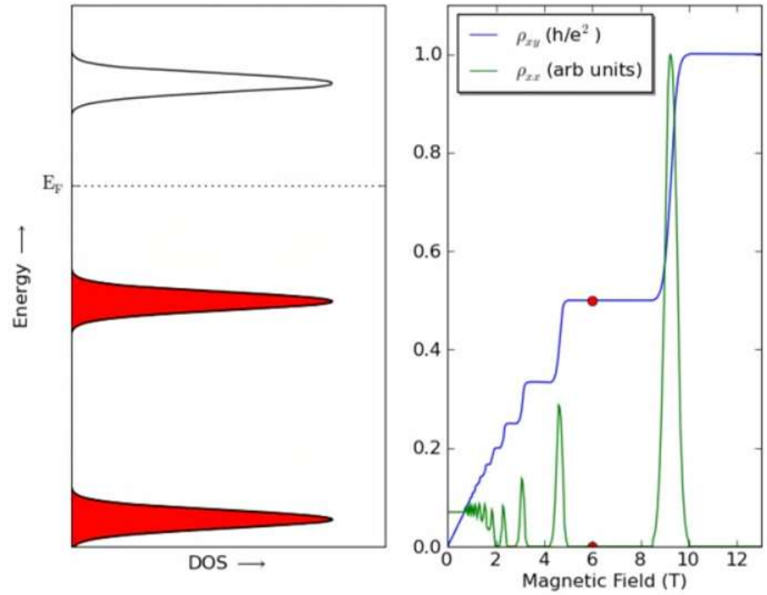


Hall
(1879)
Spin Hall
(2004)
Anomalous Hall
(1881)
Quantum Hall
(1980)
Quantum spin Hall
(2007)
Quantum anomalous Hall
(2013)
H
M
Quantum Hall
Quantum spin Hall
Quantum anomalous Hall

Quantum Hall effect







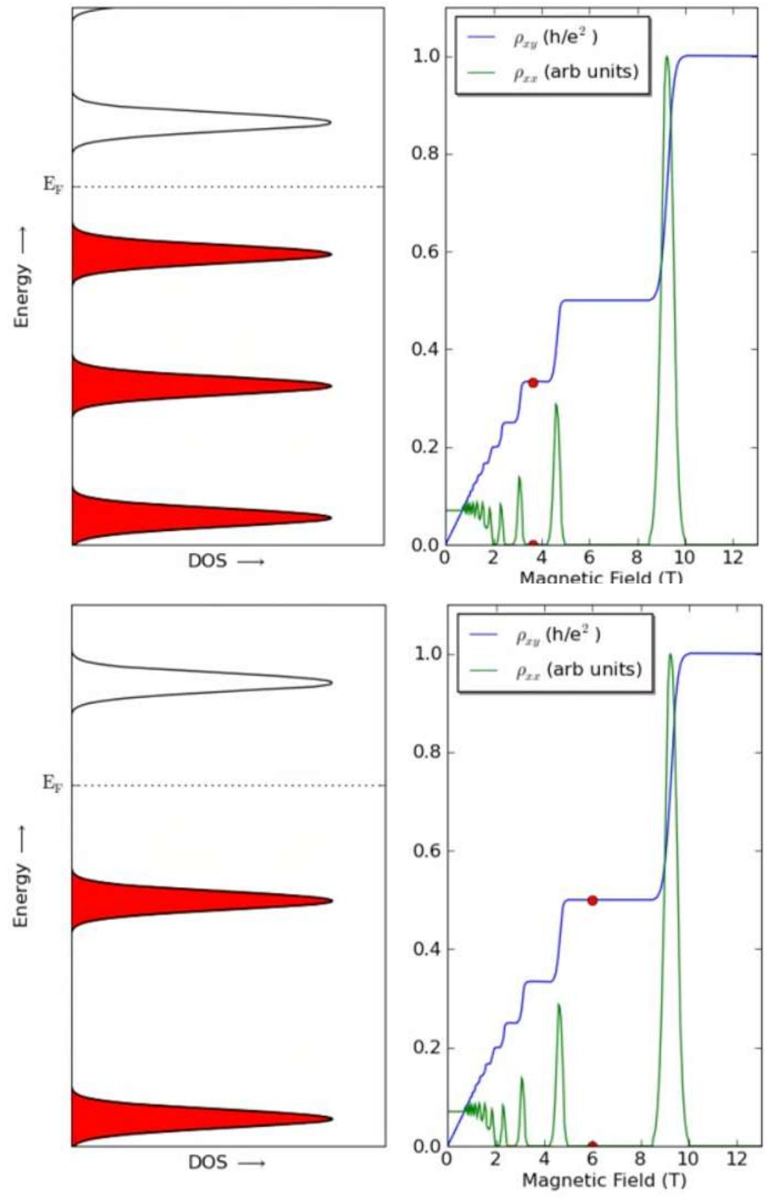
Wikipedia

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

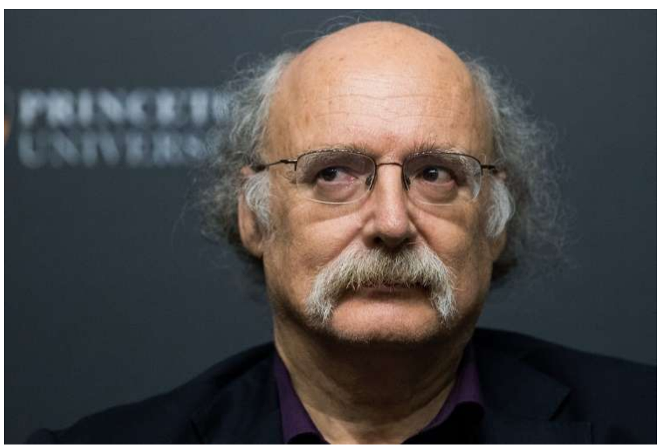
Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly"

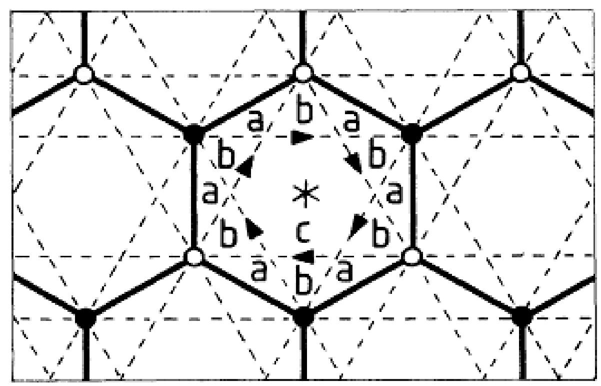
F. D. M. Haldane

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

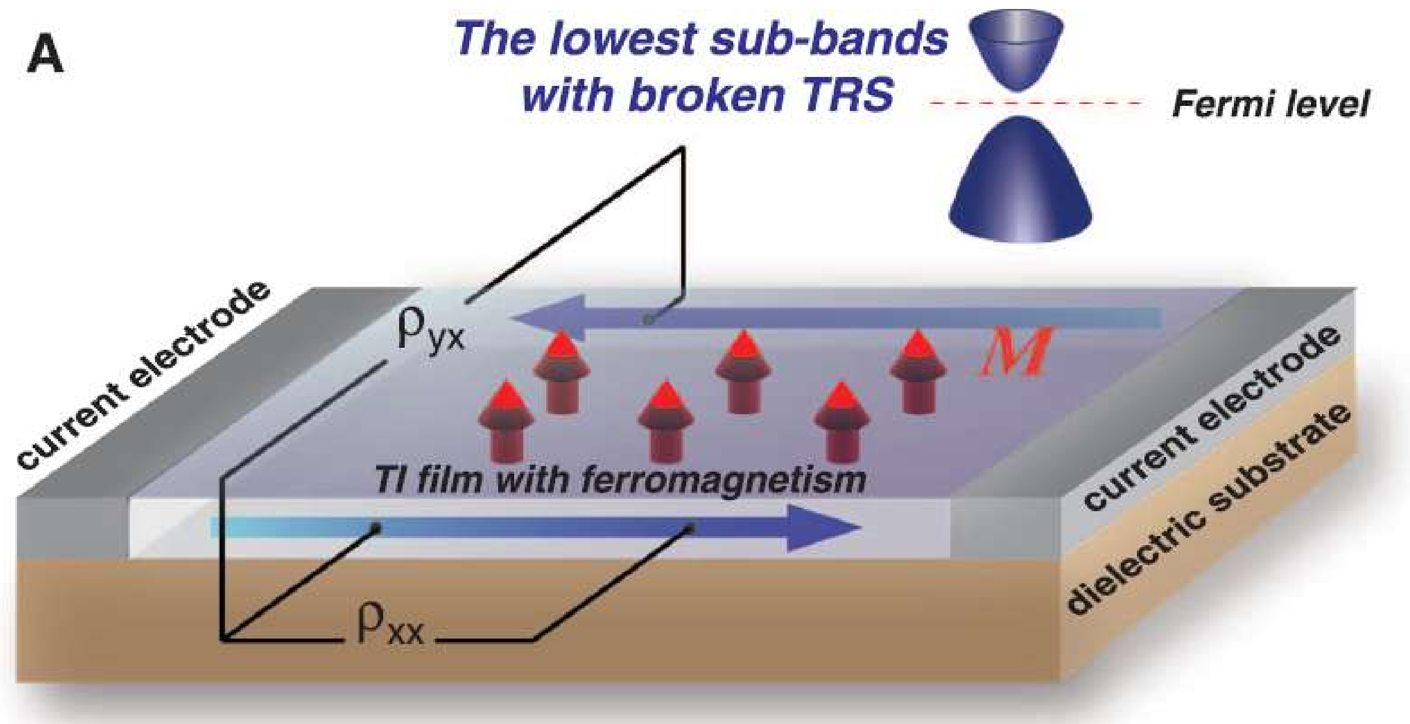
(Received 16 September 1987)

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.



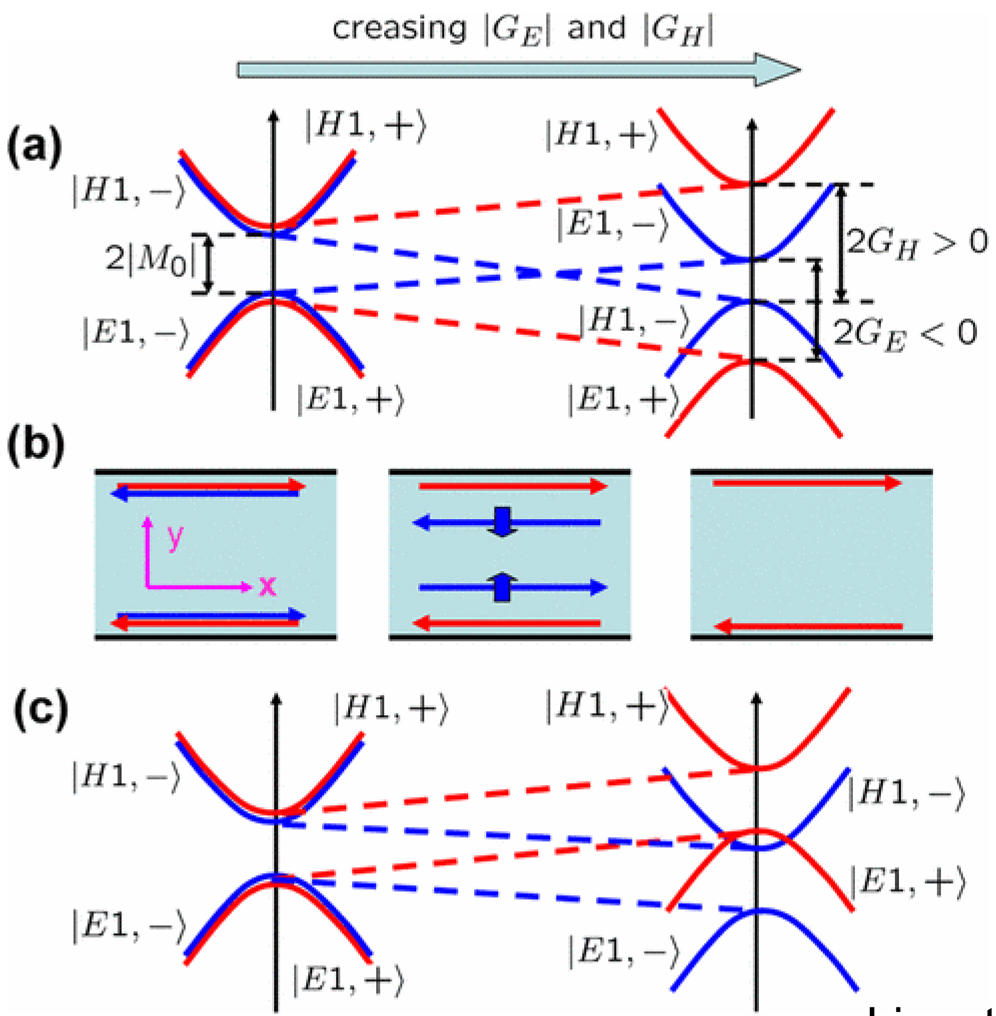


Quantum Hall effect



Quantum anomalous Hall effect

$Hg_{1-y}Mn_yTe$ Quantum Wells



Liu, et al, PRL (2008)

Quantum anomalous Hall effect

$Hg_{1-y}Mn_yTe$ Quantum Wells

PRL 101, 146802 (2008) PHYSICAL REVIEW LETTERS week ending 3 OCTOBER 2008

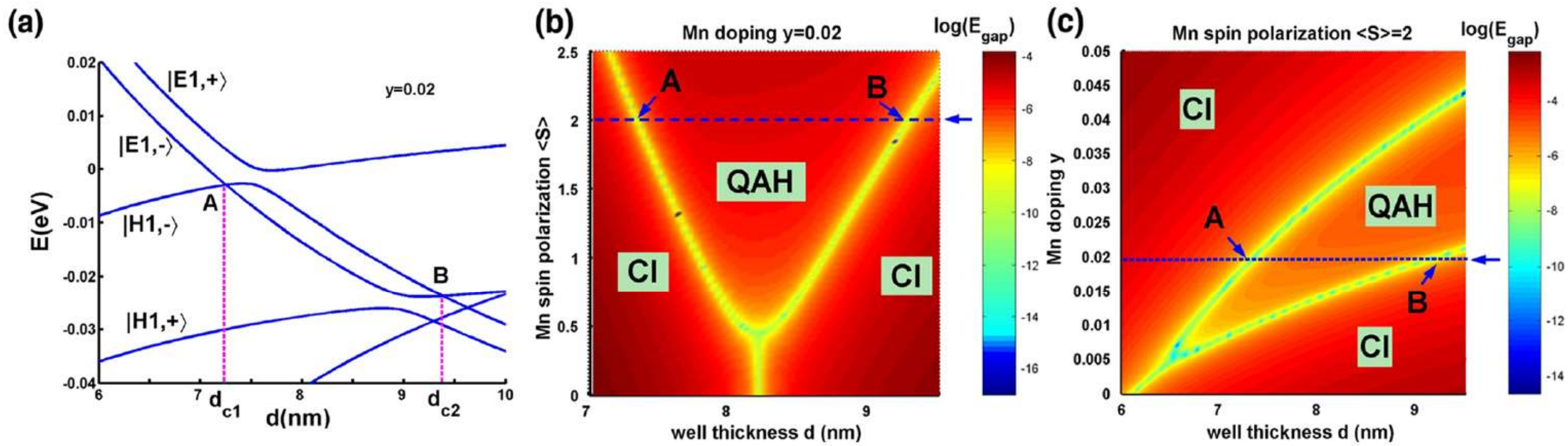
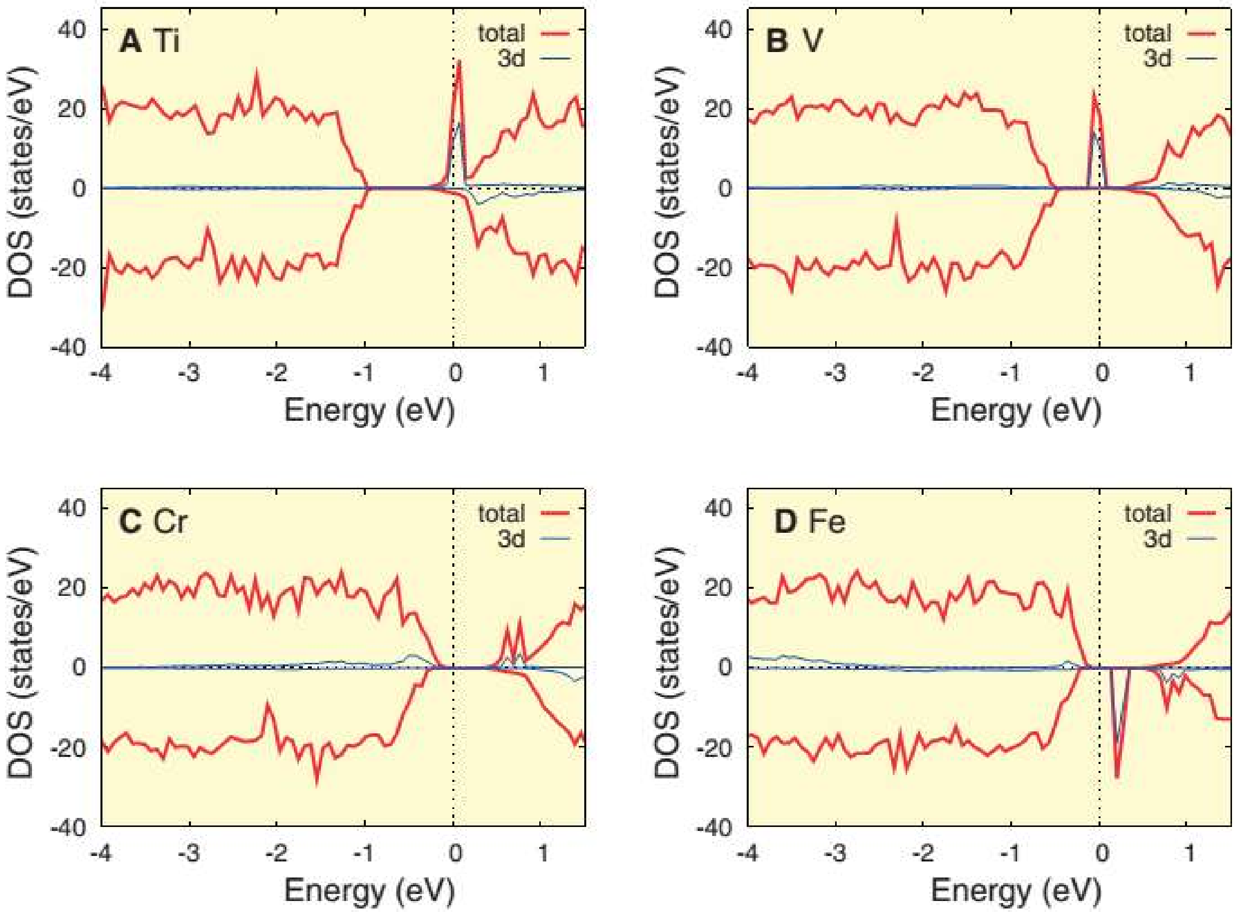


FIG. 2 (color online). (a) The energy levels for $|E1, \pm\rangle$ and $|H1, \pm\rangle$ are plotted as a function of the QW thickness. Two crossing points (A and B) are labeled in the figure. The energy gap ($\log(E_{\mathrm{gap}})$ used here) is plotted as a function of the well thickness d versus 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

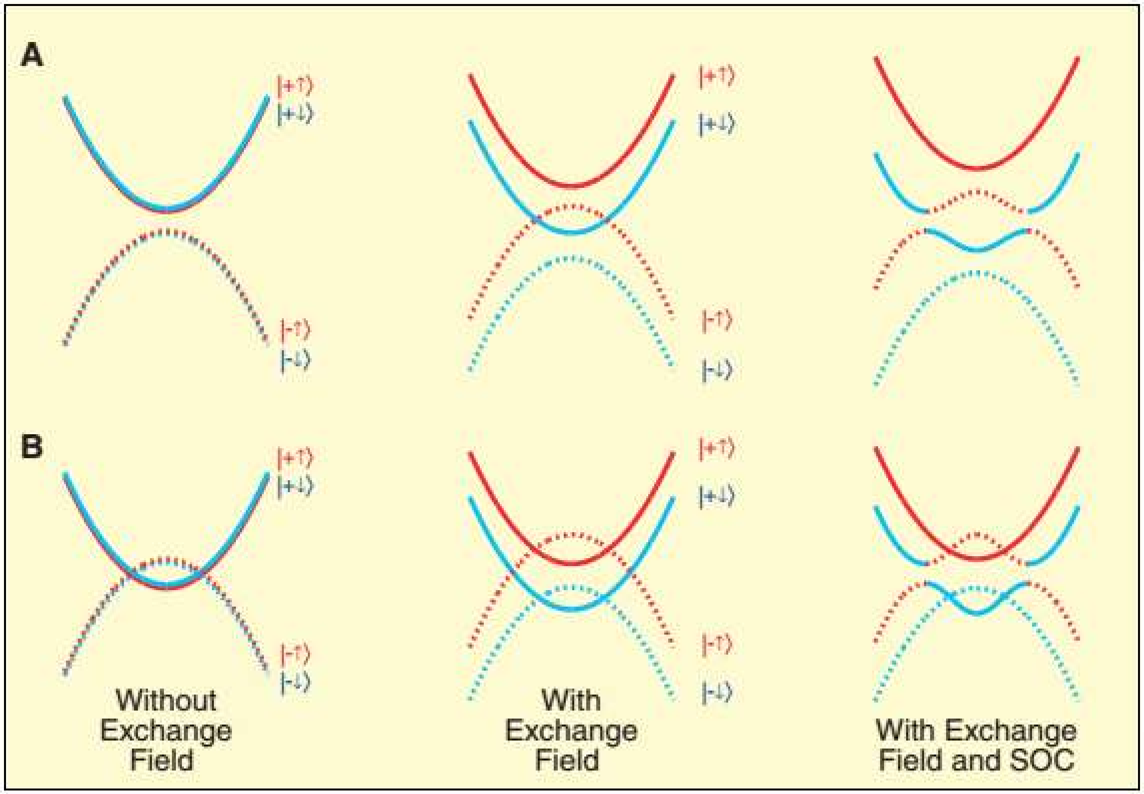
FM doped BiSeTe

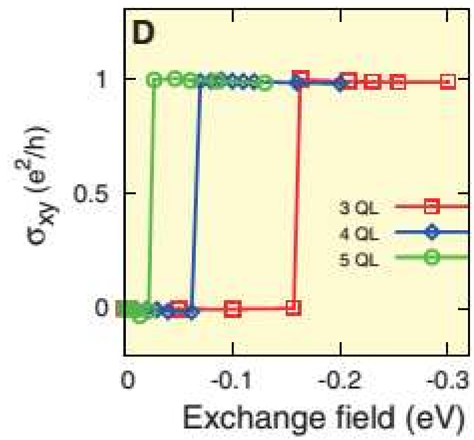


Yu, et al, Science (2010)

Quantum anomalous Hall effect

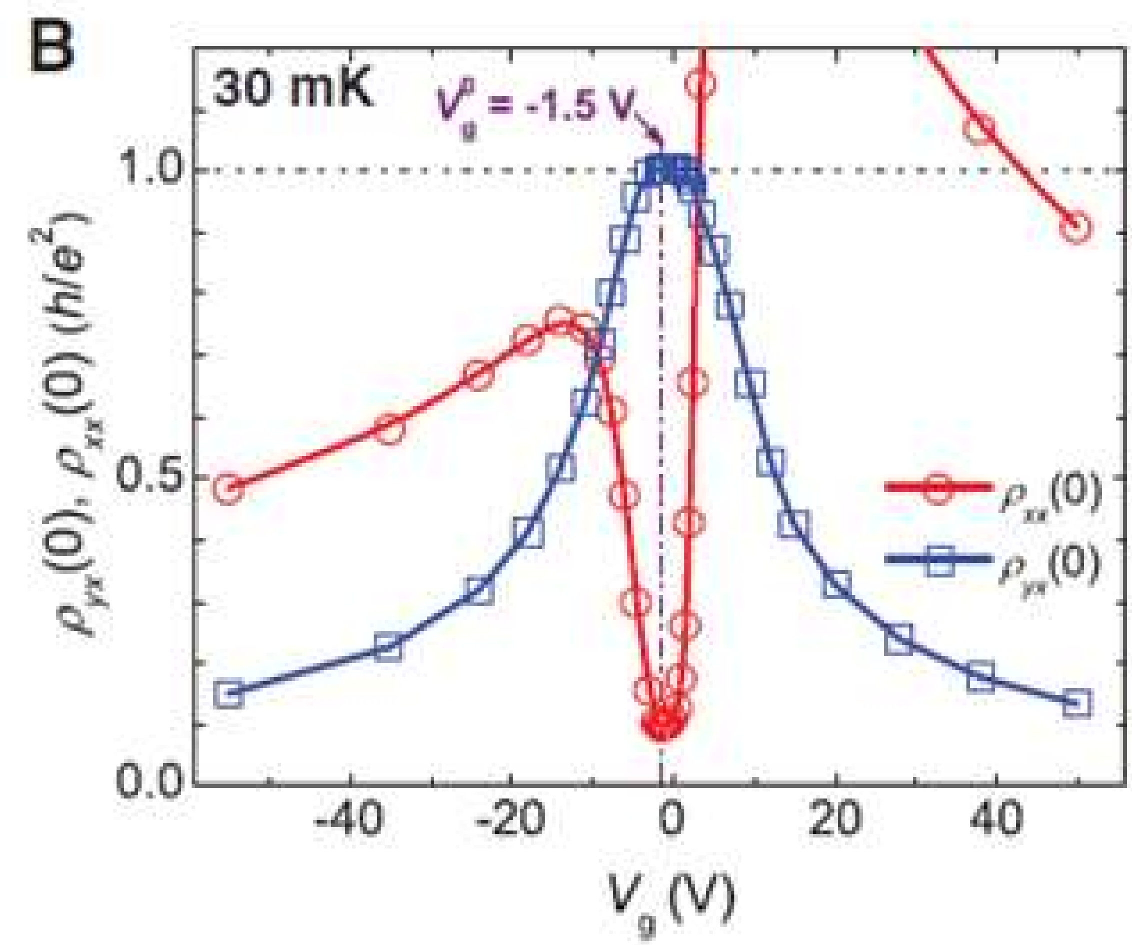
FM doped BiSeTe





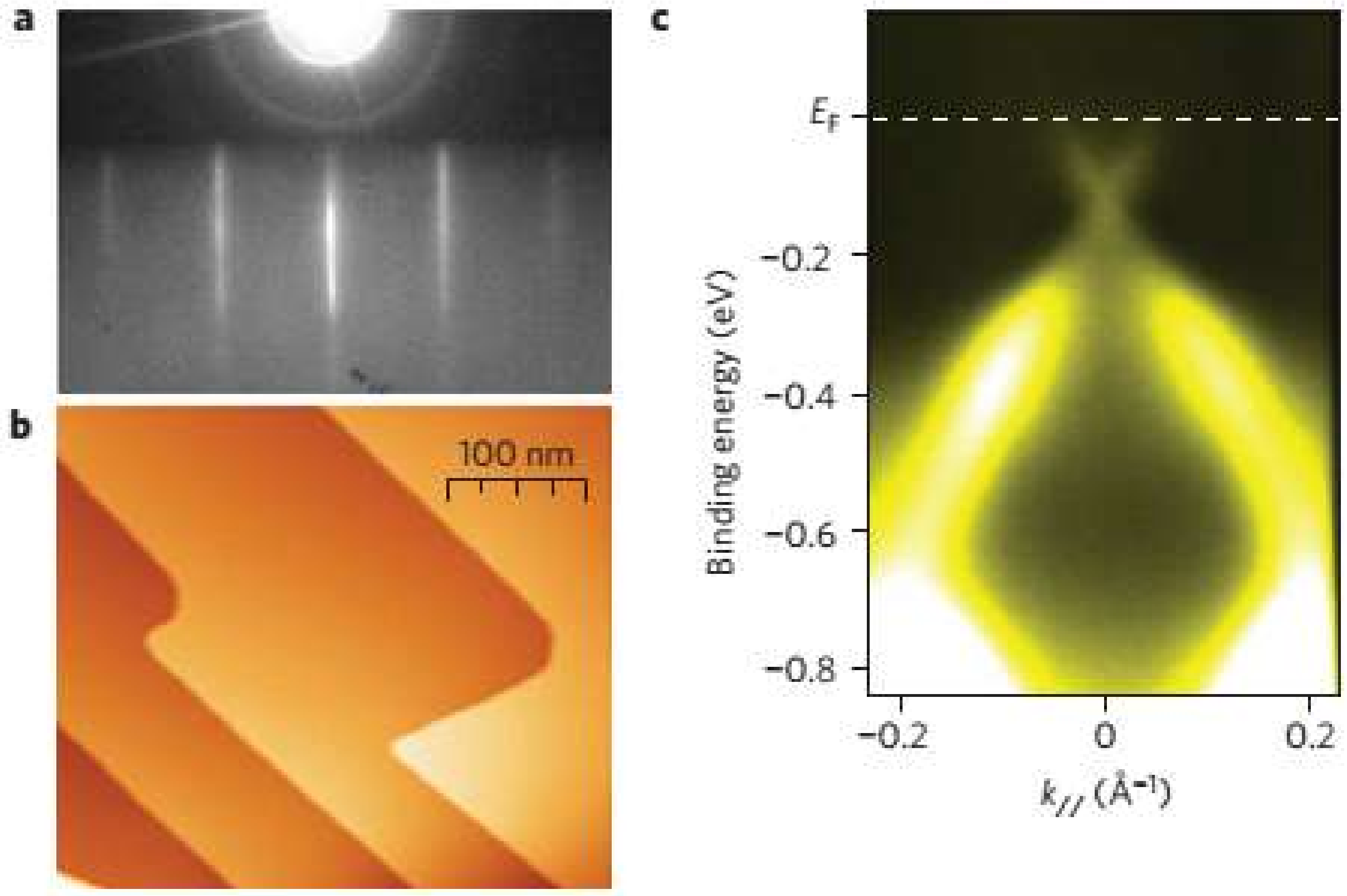
FM droped TI
@FM order lead Hall conductance quantized in units of e2/h;
open energy gap at Dirac point;

Quantum anomalous Hall effect



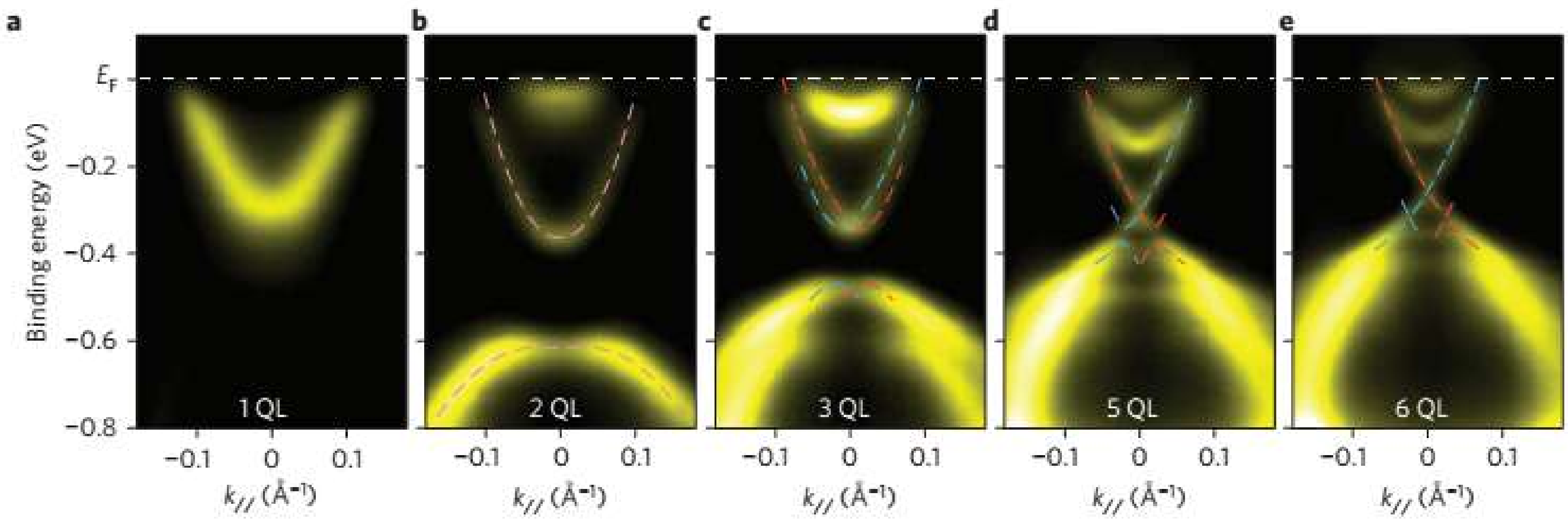
Chang, et al, Science (2013)

Bi2Se3 -- TI



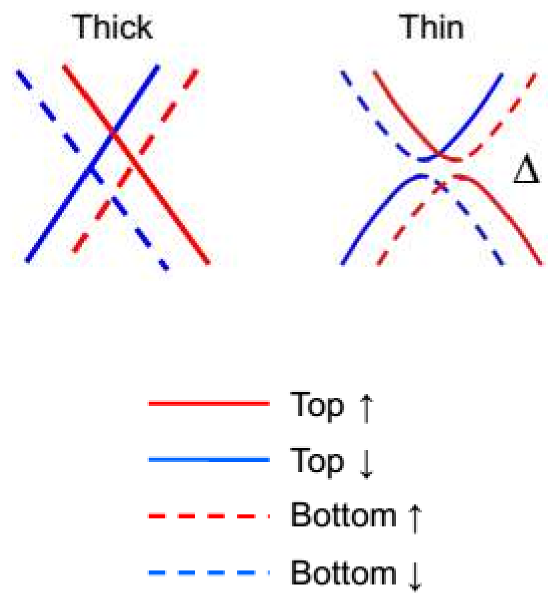
Zhang, et al, Nature Physics (2010)

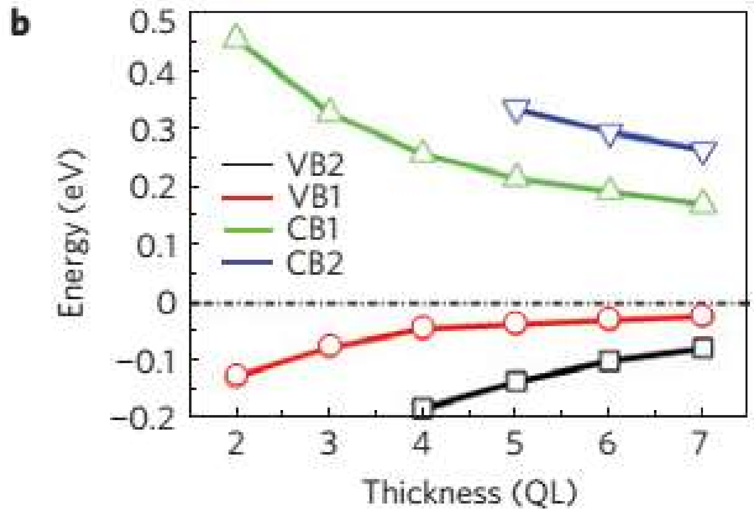
Bi2Se3 -- TI

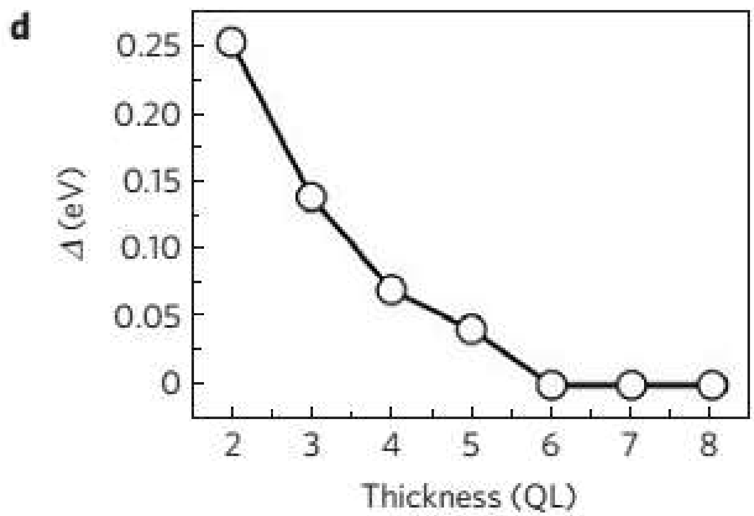


a
b
c
d
e
E_F
Binding energy (eV)
−0.2
−0.4
−0.6
−0.8
1 QL
2 QL
3 QL
5 QL
6 QL
−0.1
0
0.1
$k_{//}$ (Å^{-1})

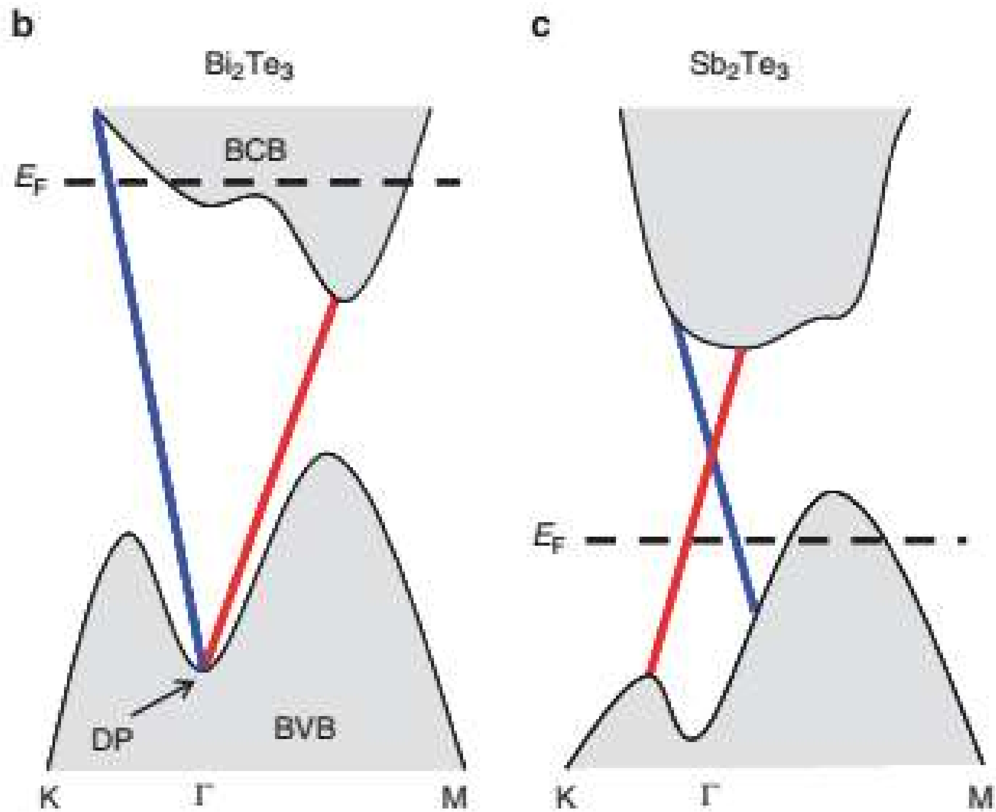
Bi2Se3 -- TI


Thick
Thin
Δ
Top ↑
Top ↓
Bottom ↑
Bottom ↓


b
Energy (eV)
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
VB2
VB1
CB1
CB2
2
3
4
5
6
7
Thickness (QL)

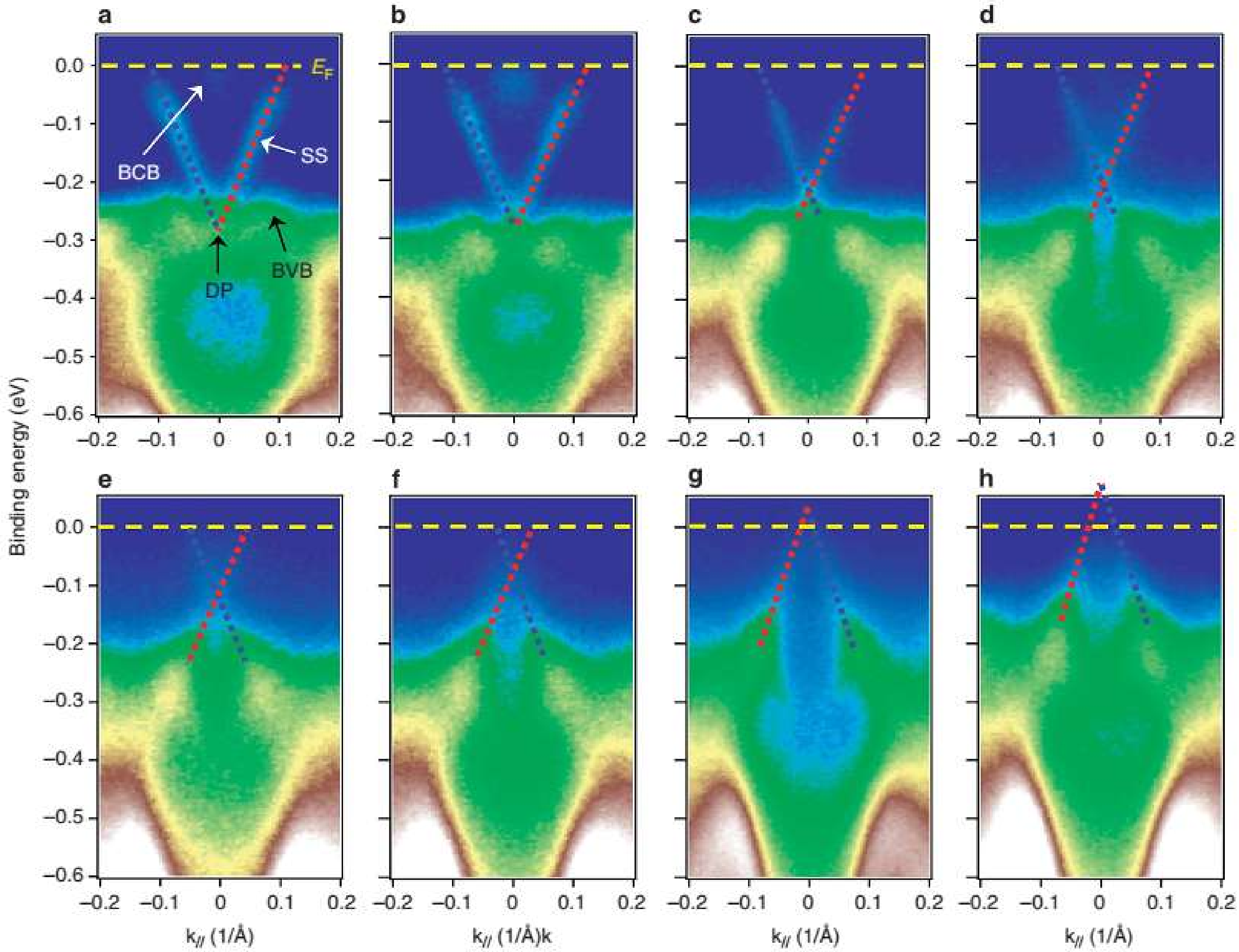

d
Δ (eV)
0.25
0.20
0.15
0.10
0.05
0
2
3
4
5
6
7
8
Thickness (QL)

Tuning Fermi Level TI



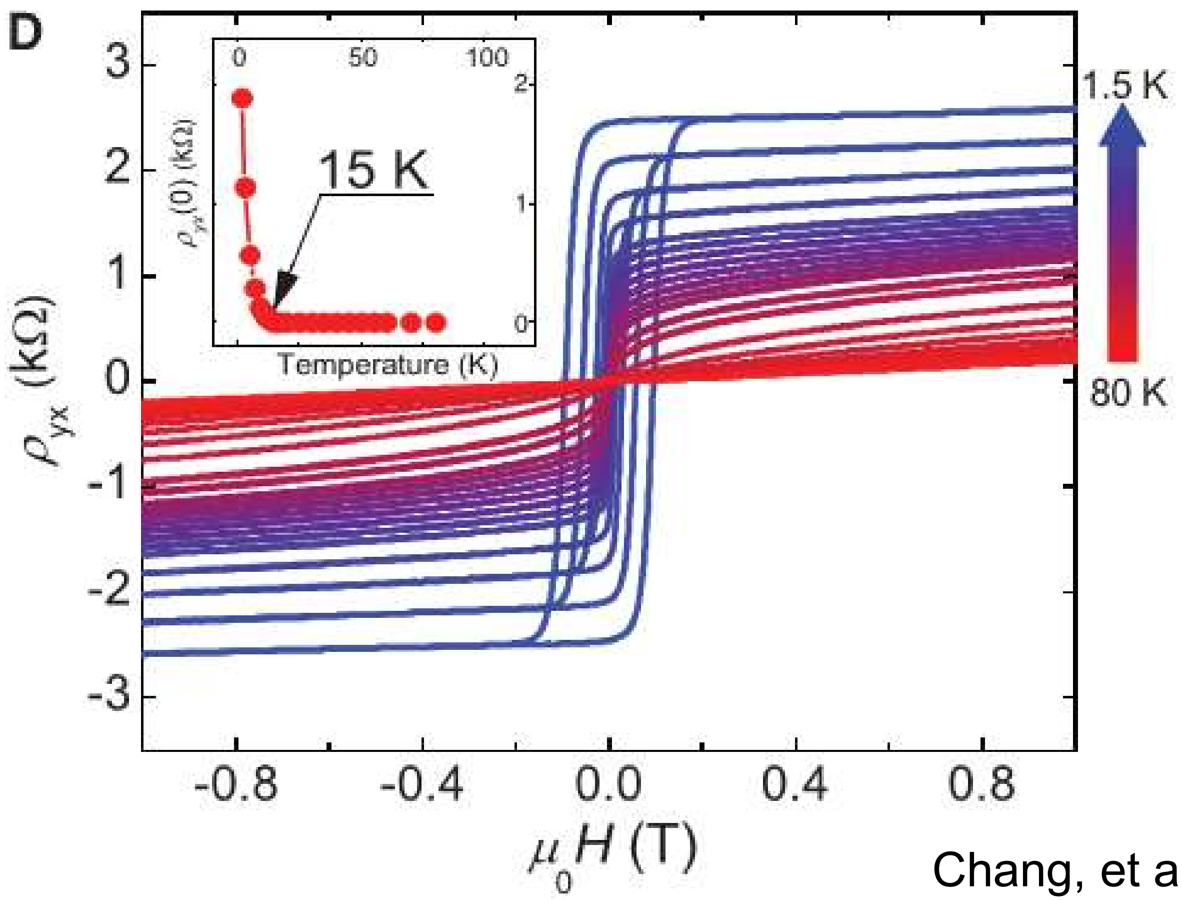
Zhang, et al, Nature Communications (2011)

Tuning Fermi Level TI



Quantum anomalous Hall effect

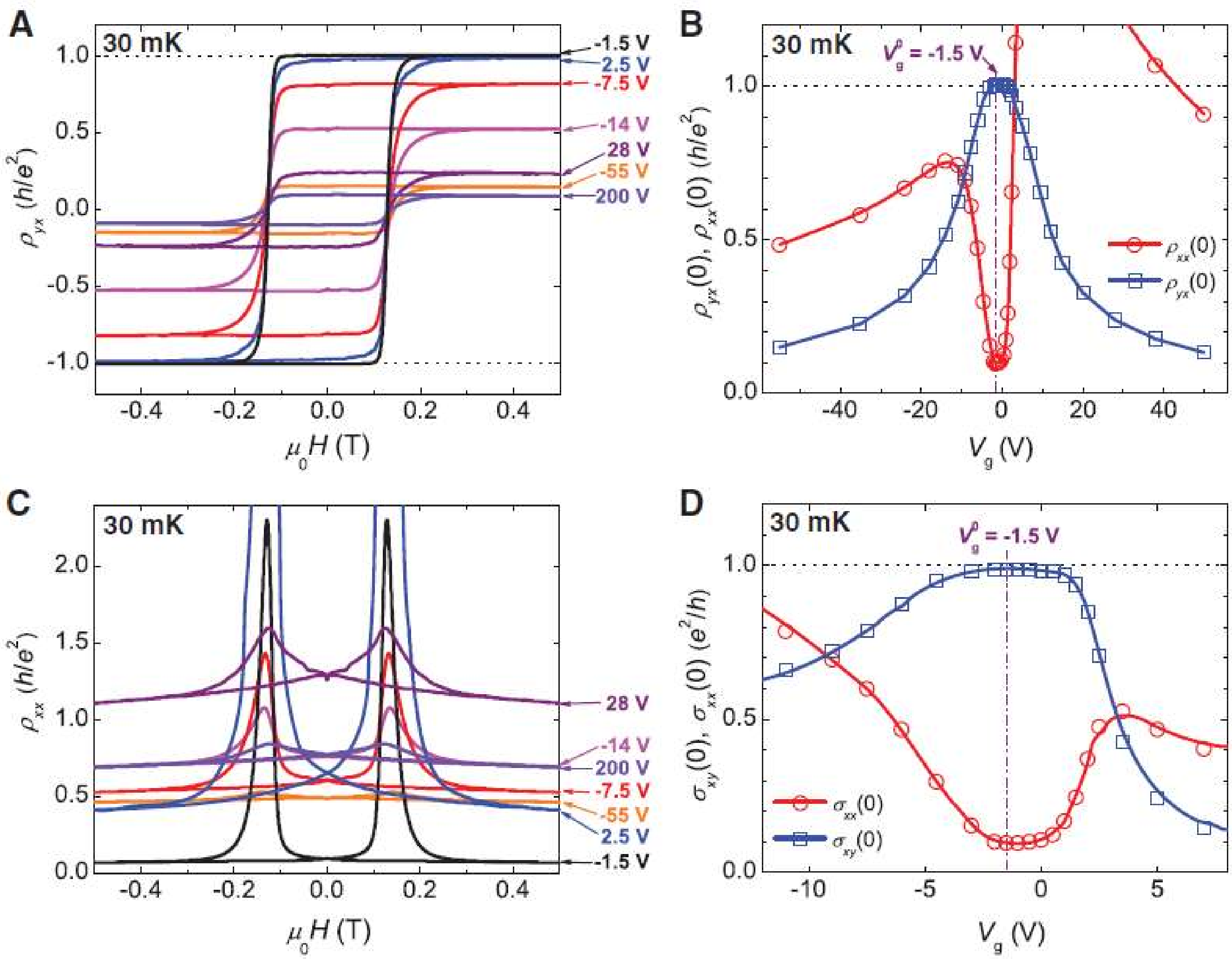
Cr doped $(Bi,Sb)Te_3$



Chang, et al, Science (2013)

Quantum anomalous Hall effect

Cr doped $(Bi,Sb)Te_3$

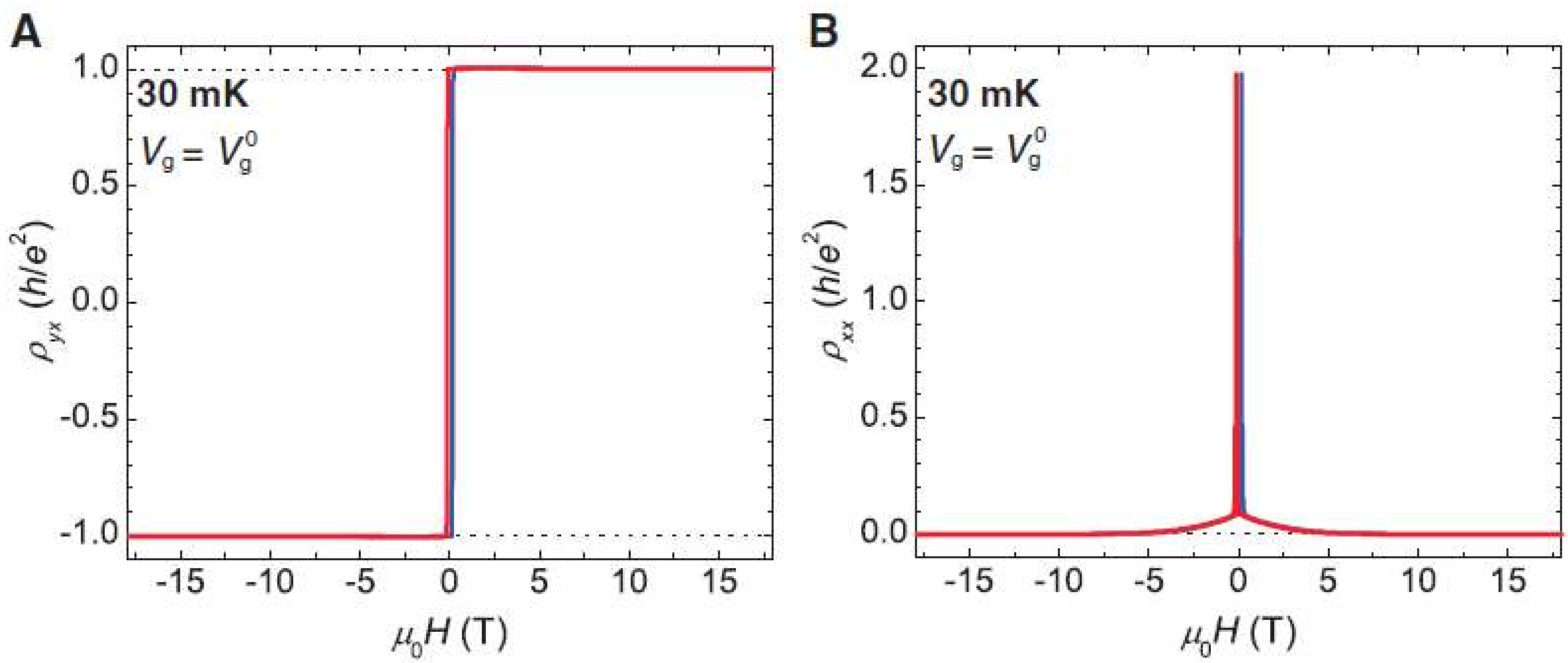


0.098 h/e^2

0.987 e^2/h

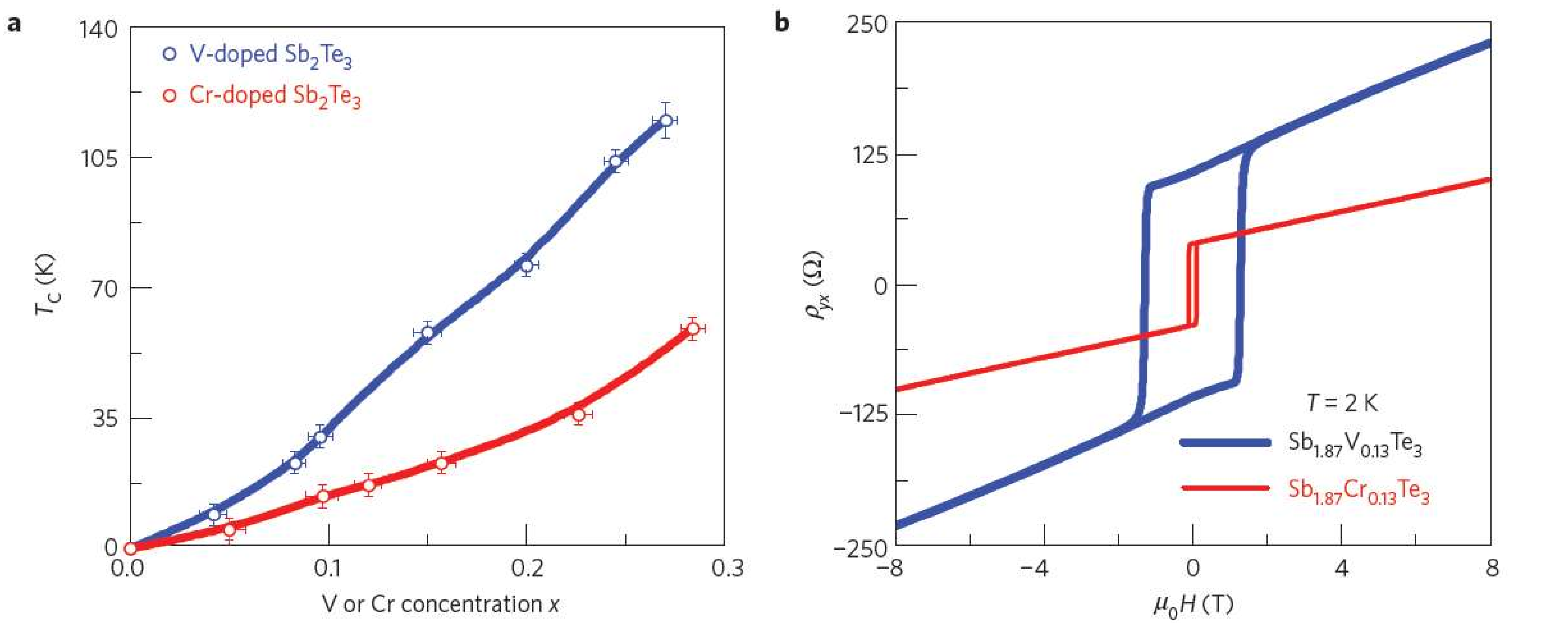
Quantum anomalous Hall effect

Cr doped $(Bi,Sb)Te_3$



Quantum anomalous Hall effect

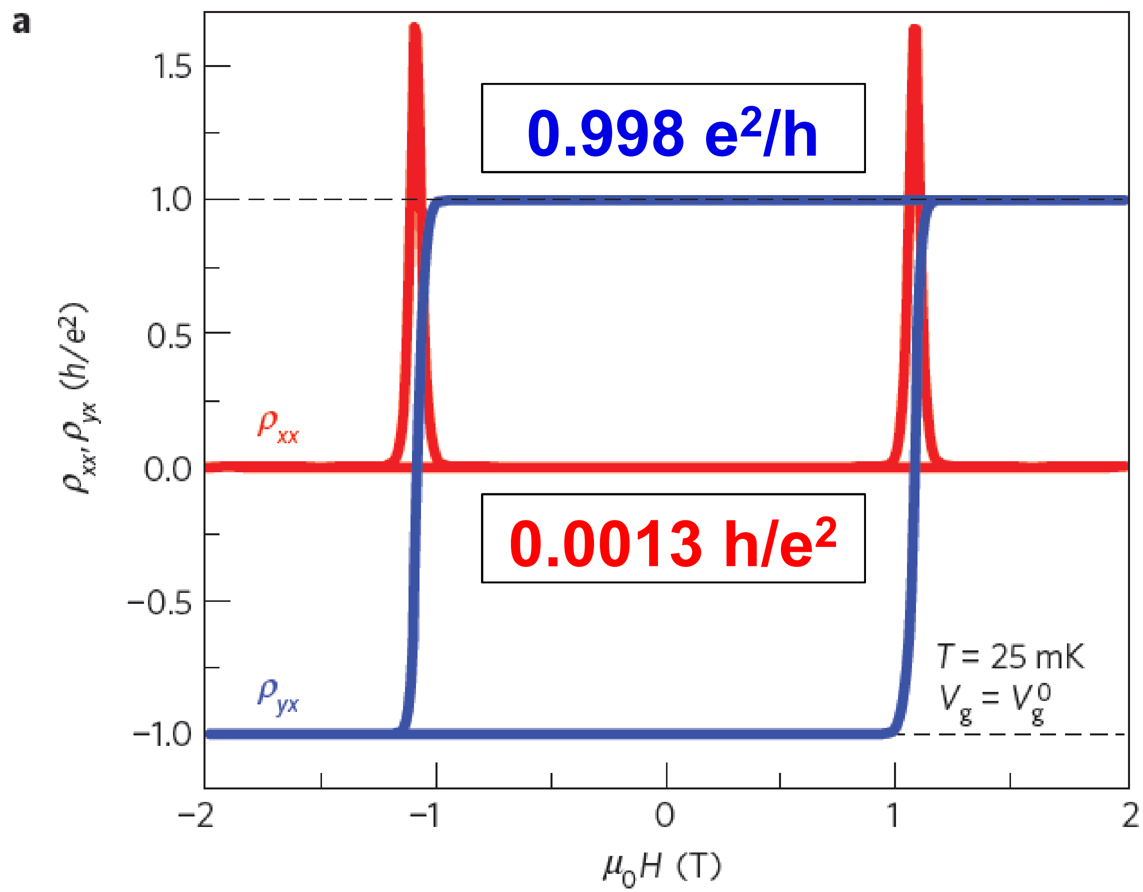
V doped $(Bi,Sb)Te_3$



Higher T_C, larger anisotropy

Quantum anomalous Hall effect

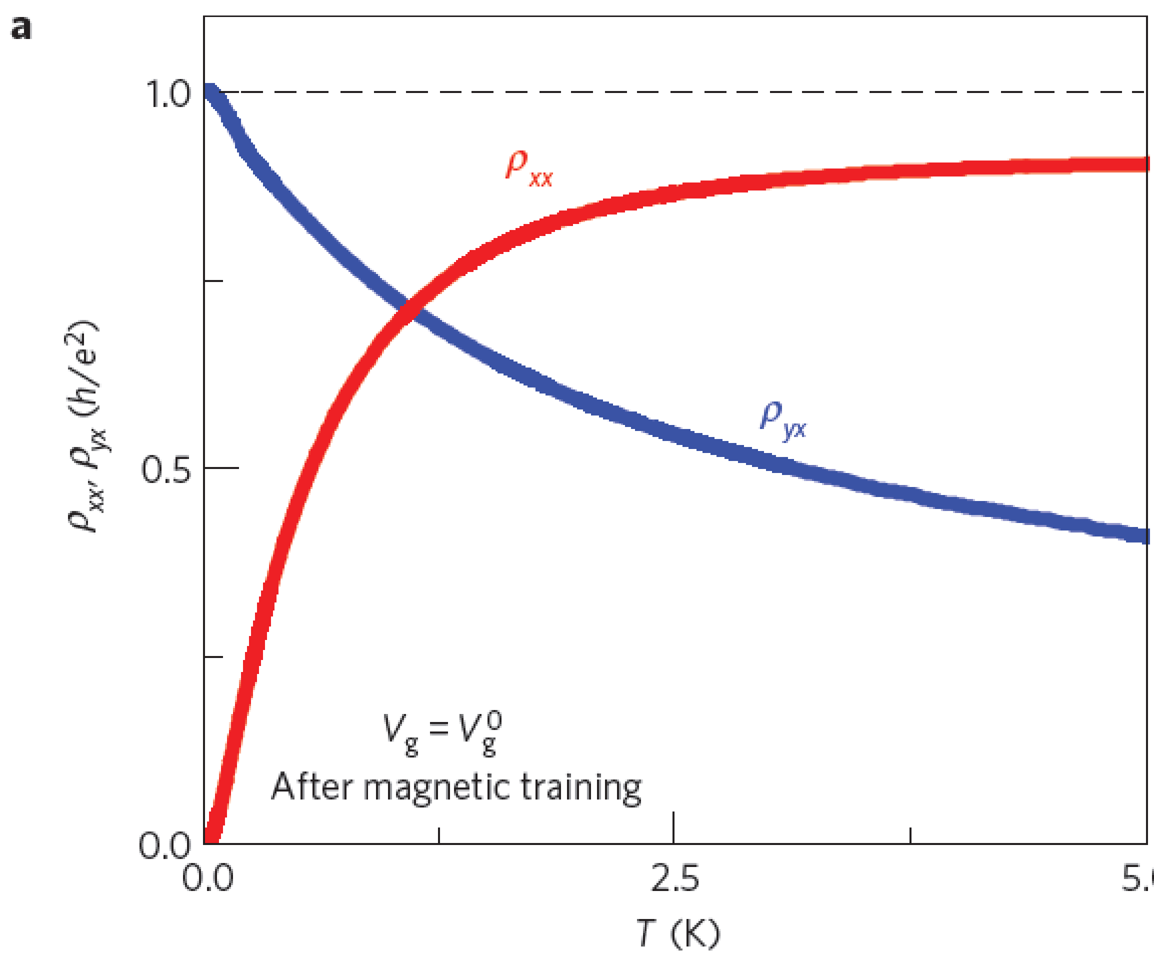
V doped $(Bi,Sb)Te_3$



Chang, et al, Nature Materials (2015)

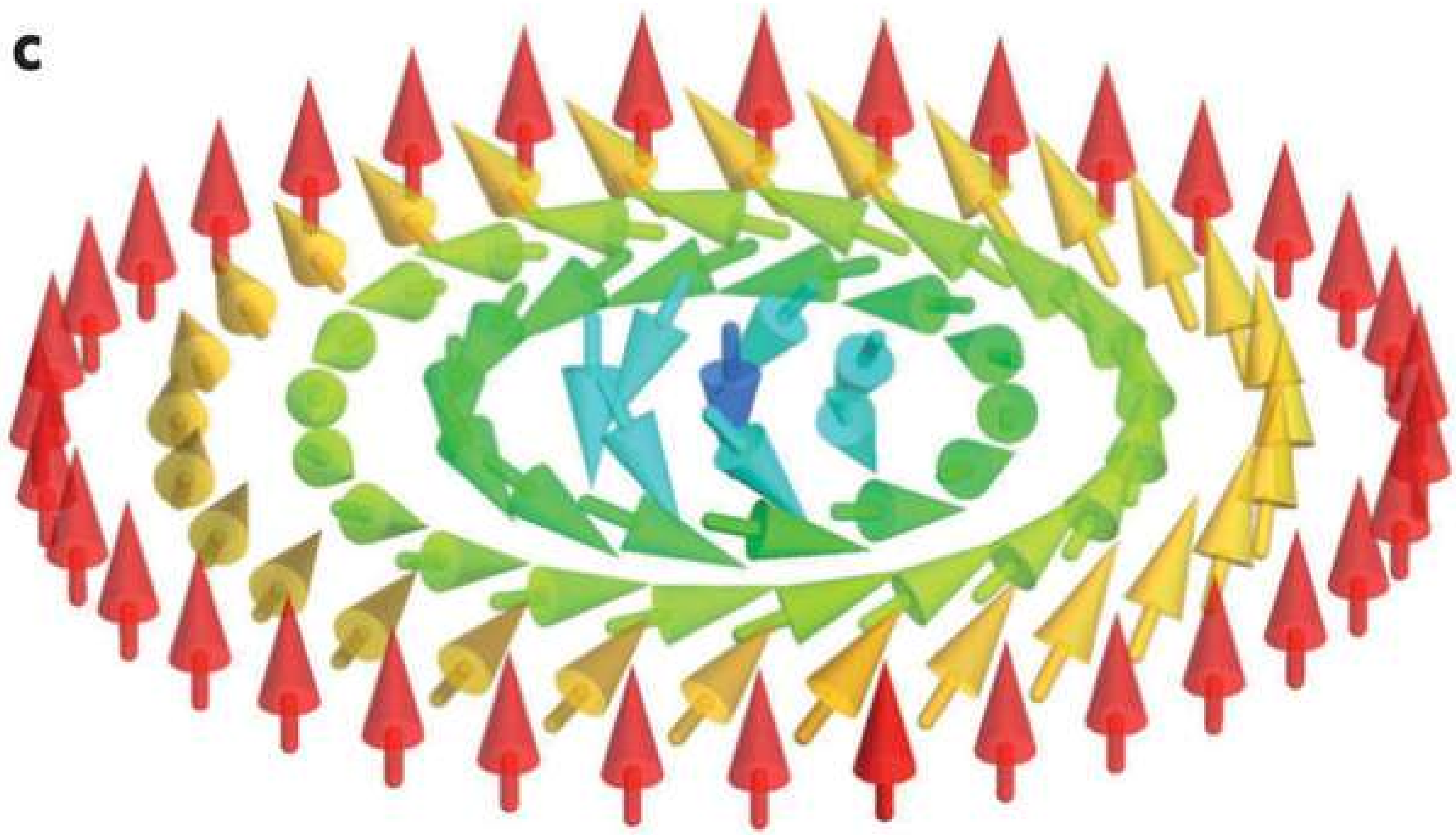
Quantum anomalous Hall effect

V doped $(Bi,Sb)Te_3$



3. Skyrmions

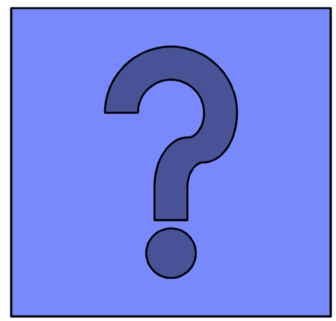
Topology in real space



Questions?

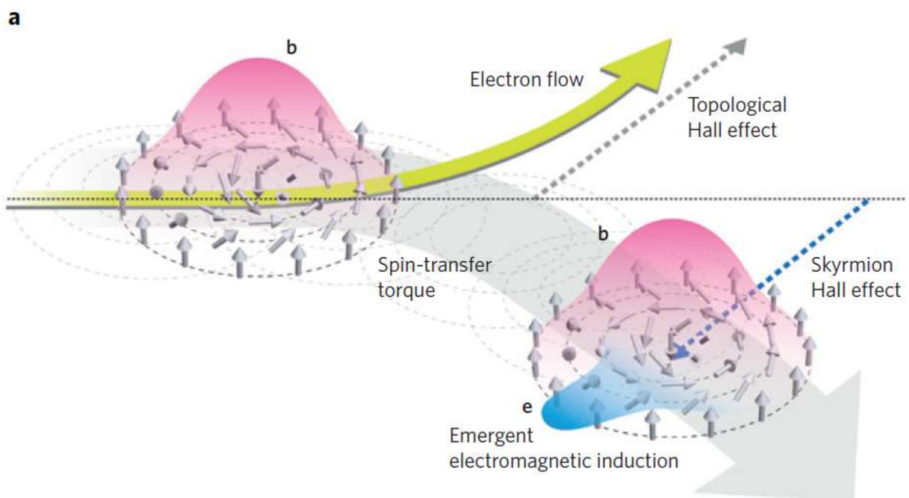
Topology in momentum space

+

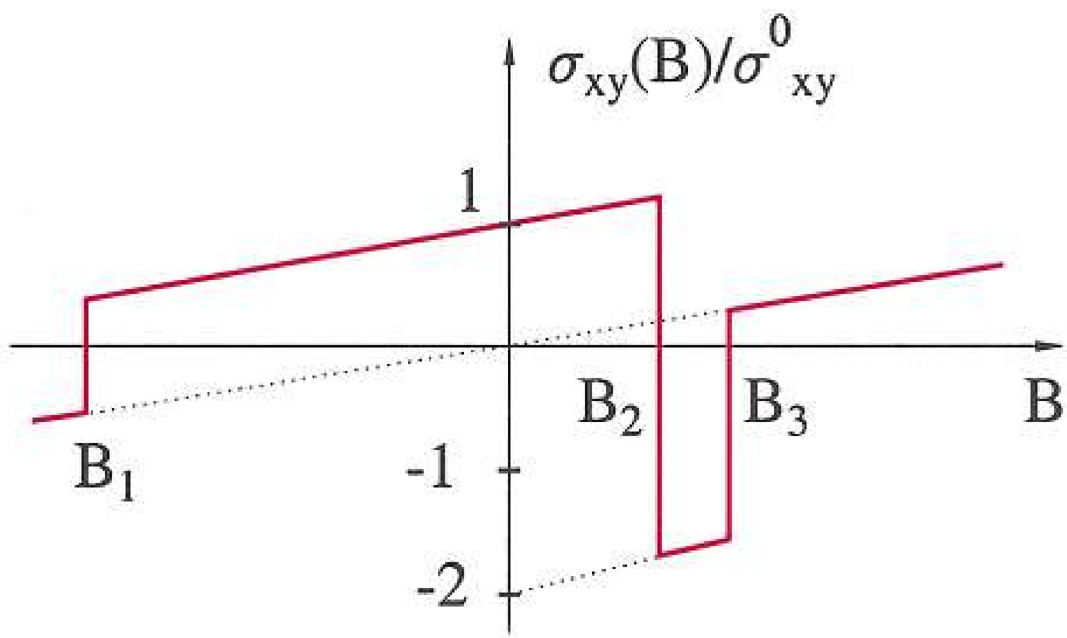


Topology in real space

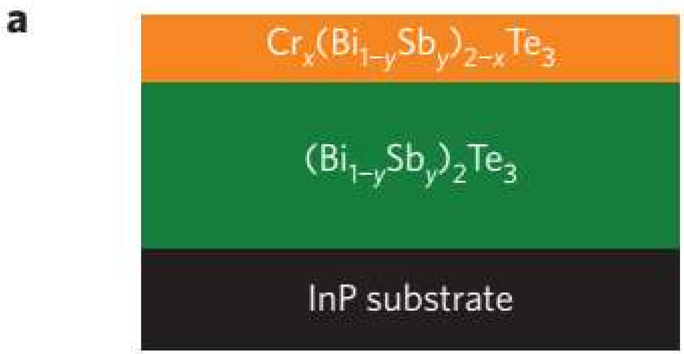
Topological Hall effect

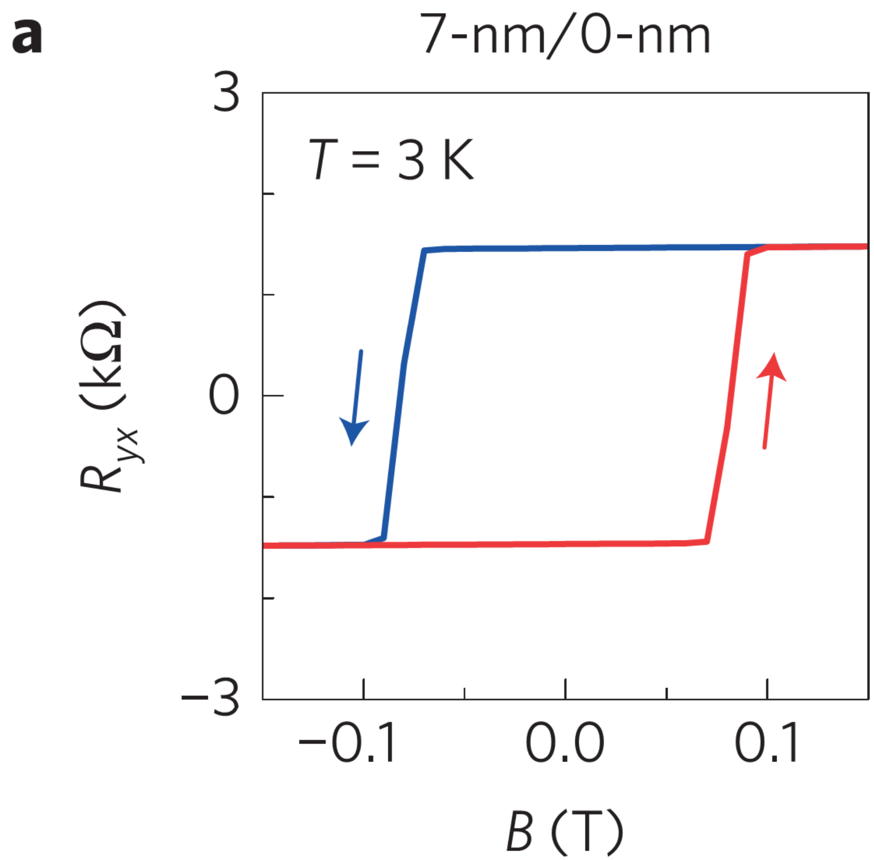


conduction electrons & localized spins



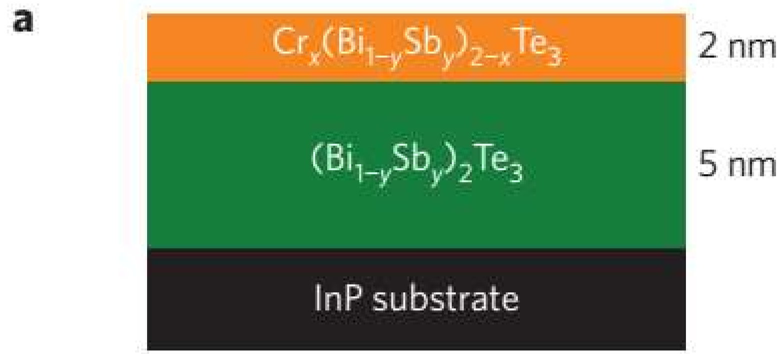
Topological Hall effect

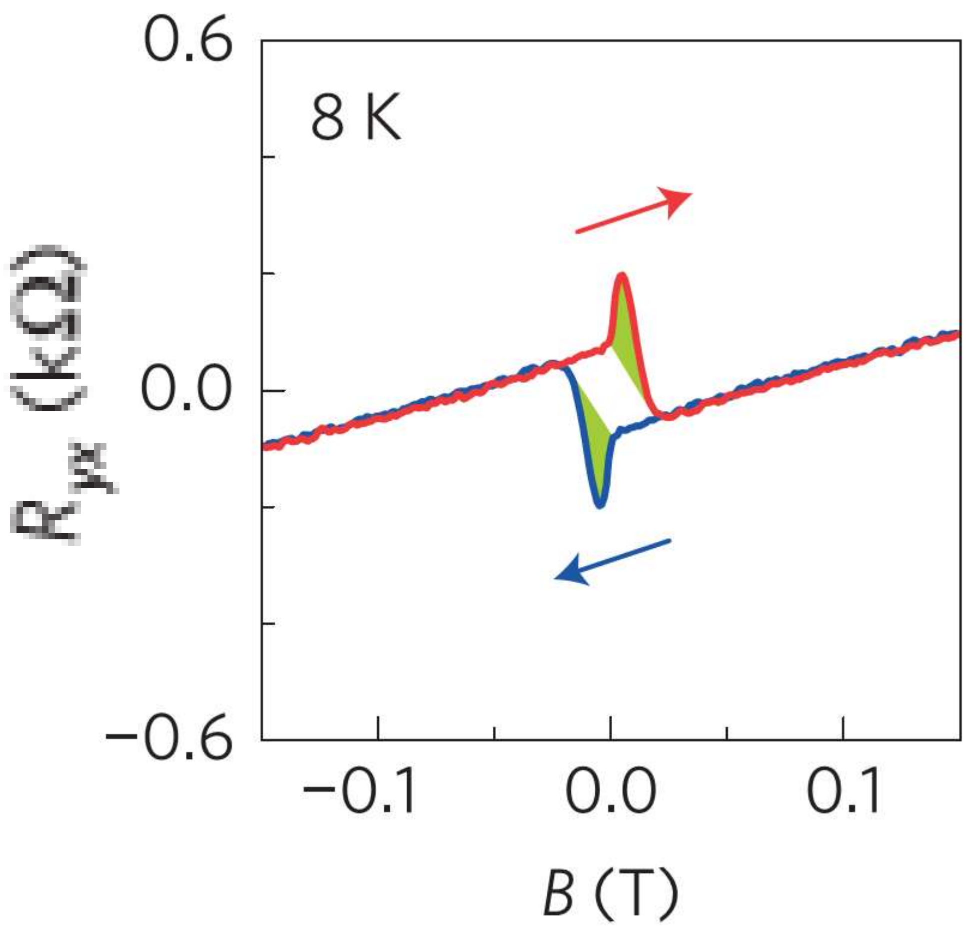




Yasuda, et al, Nature Physics (2016)

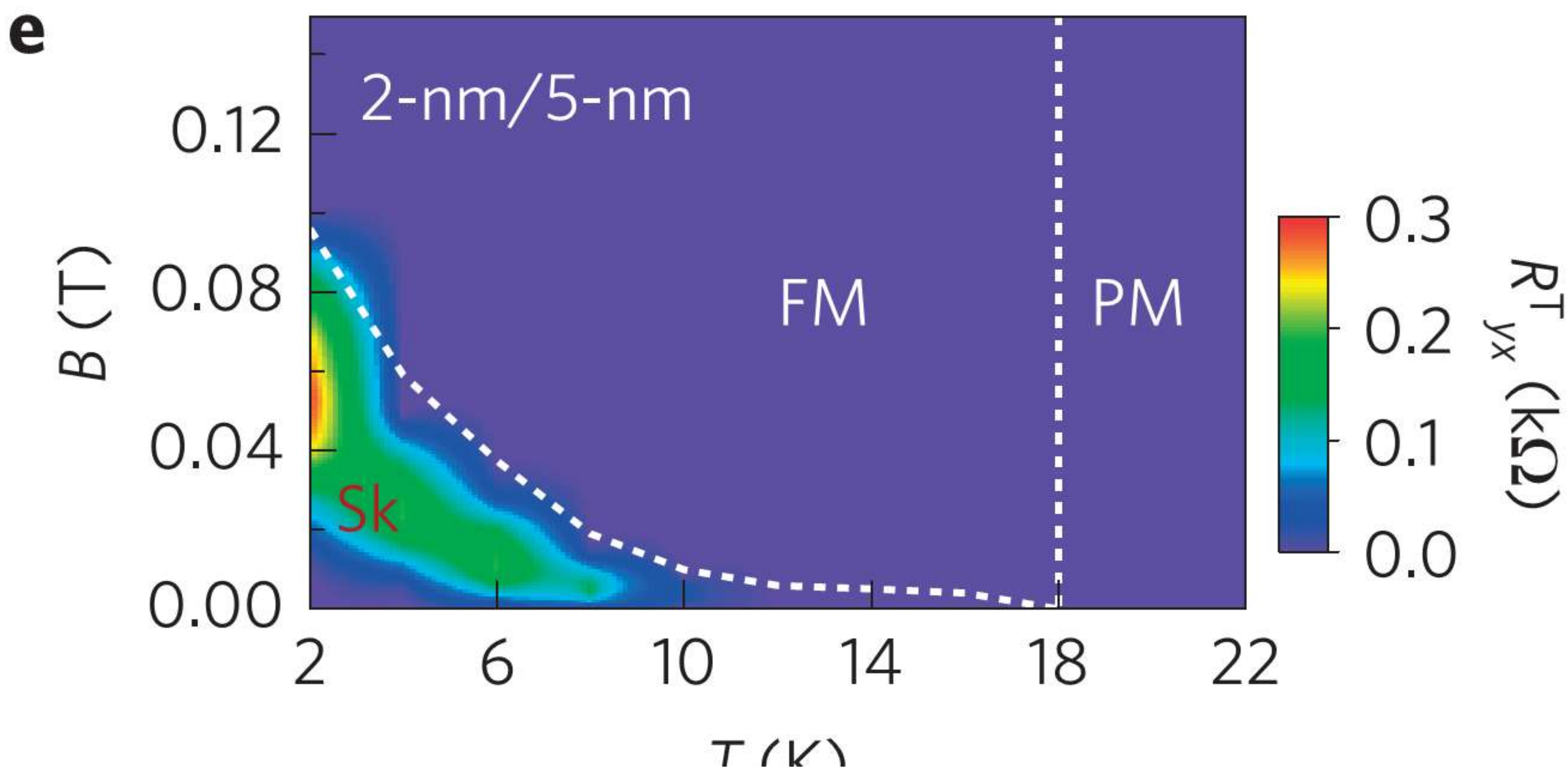
Topological Hall effect





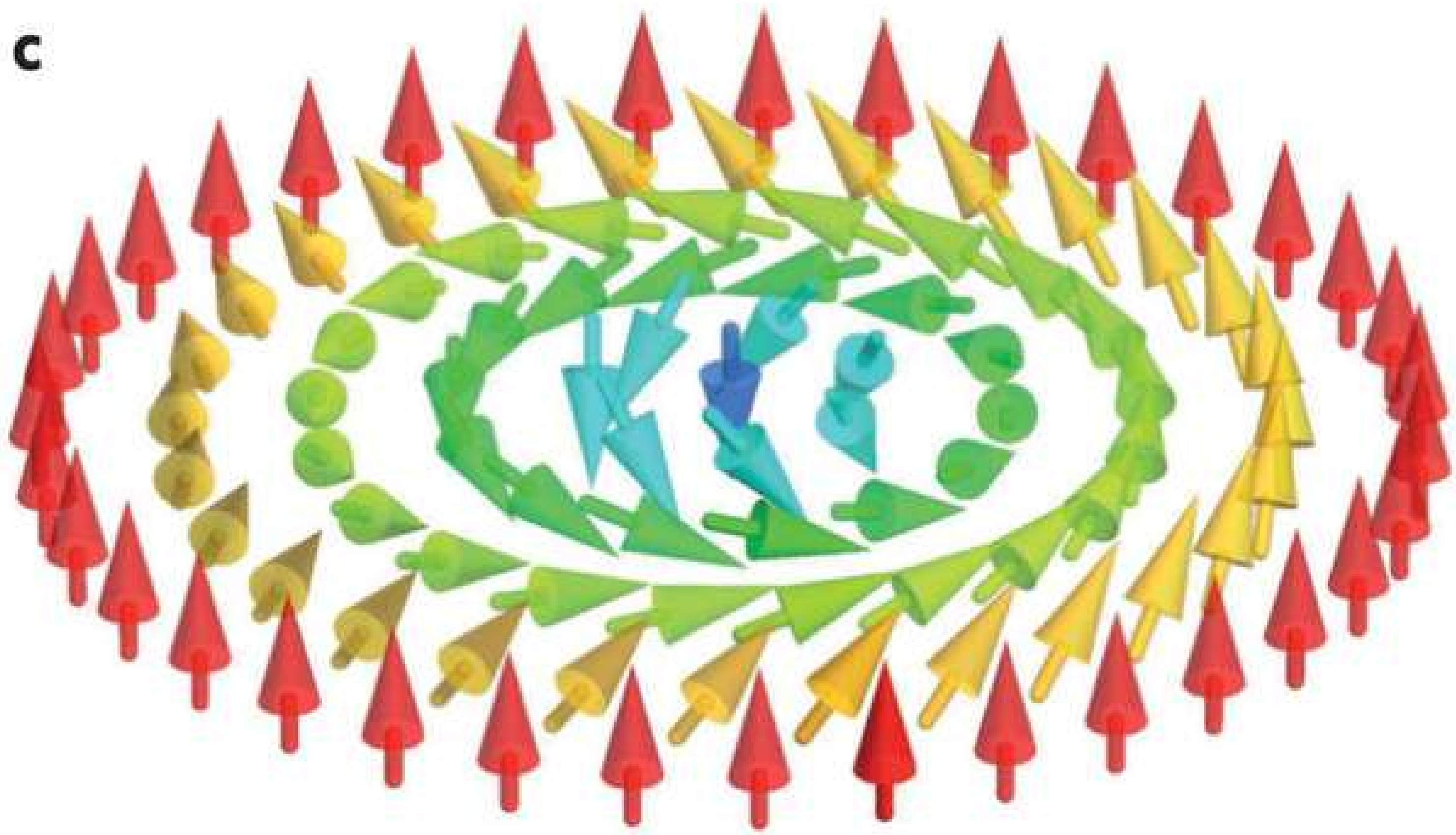
Yasuda, et al, Nature Physics (2016)

Topological Hall effect



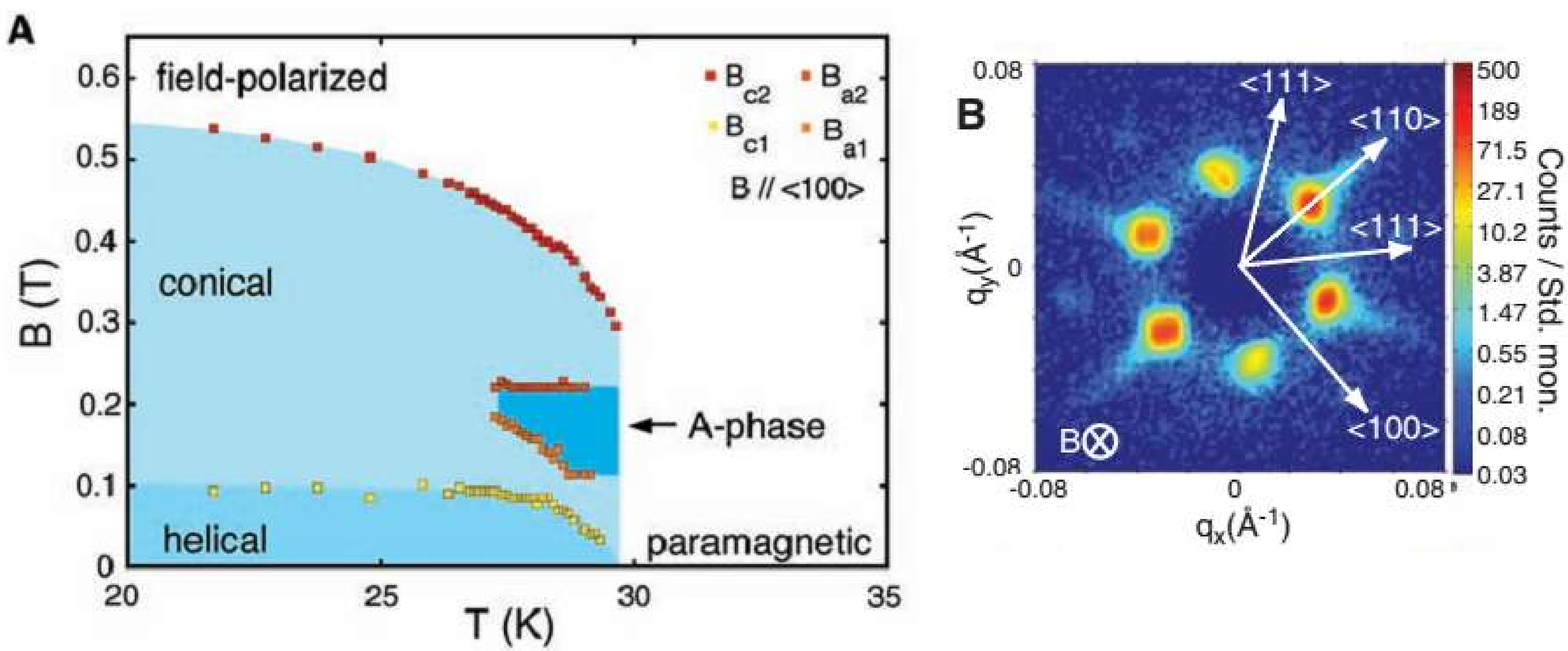
休息10分钟

Topology in real space



Observation

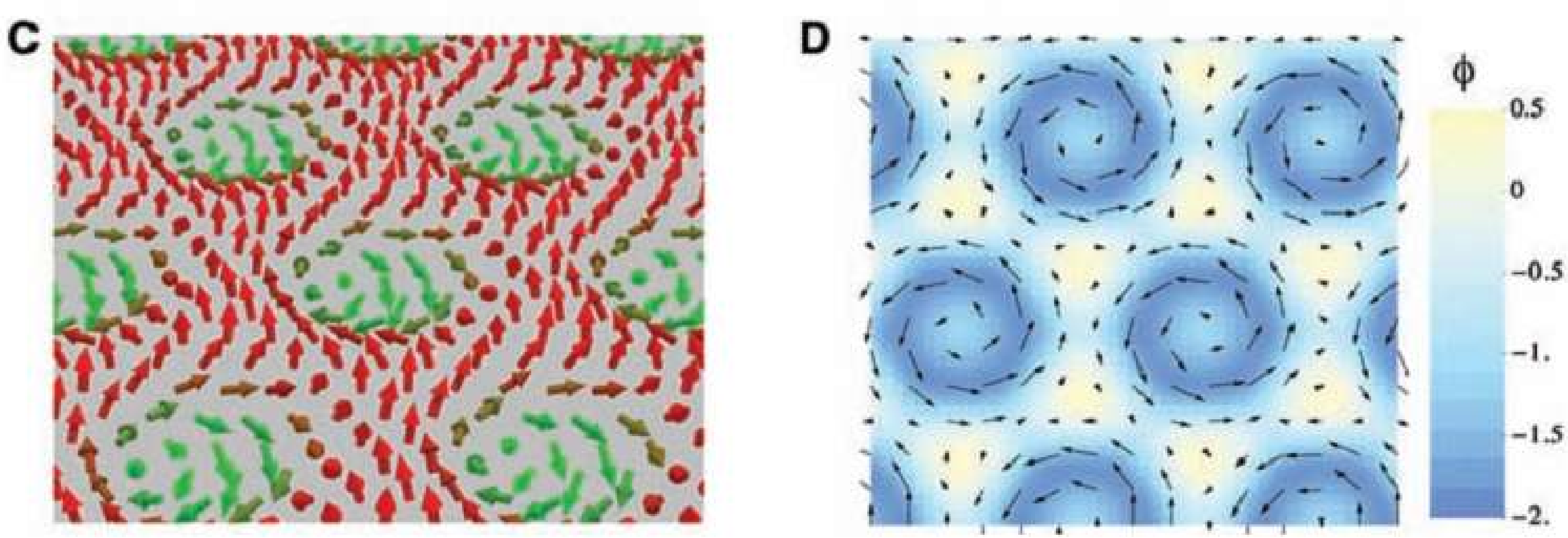
Neutron Scattering: MnSi



Muhlbauer, et al, Science (2009)

Observation

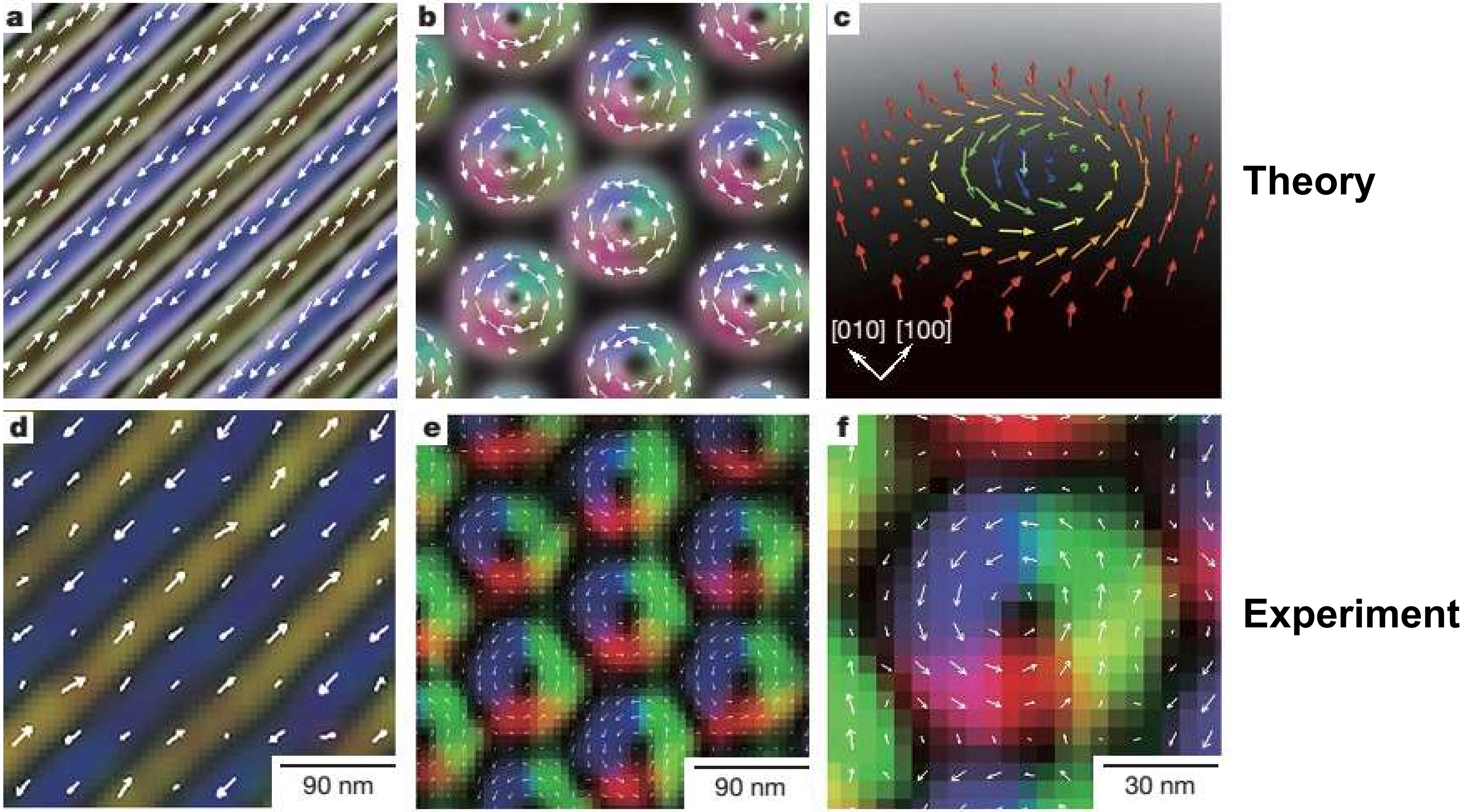
Neutron Scattering



Muhlbauer, et al, Science (2009)

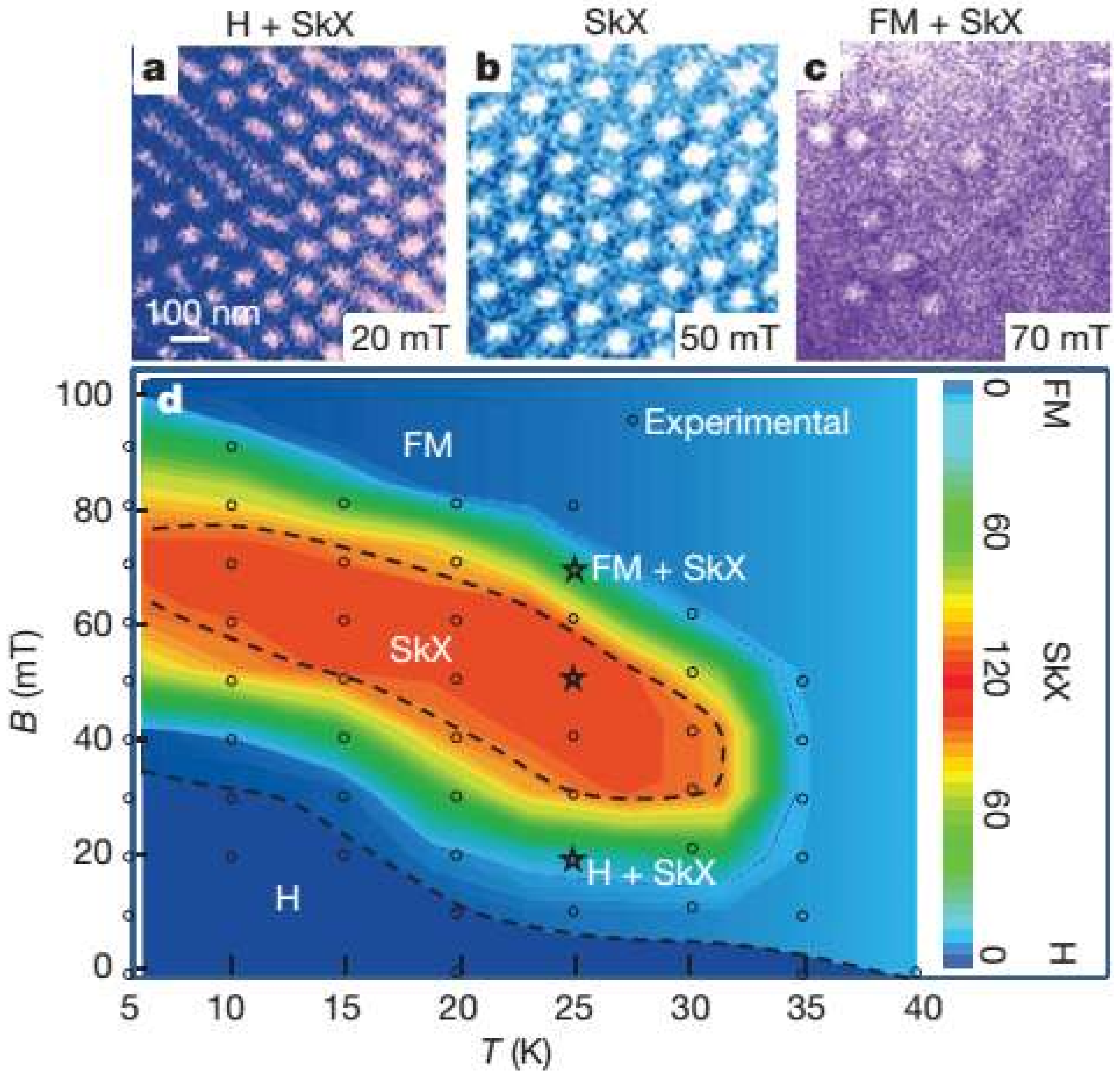
Observation

Lorentz TEM： $Fe_{0.5}Co_{0.5}Si$



Observation

Lorentz TEM： $Fe_{0.5}Co_{0.5}Si$



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.

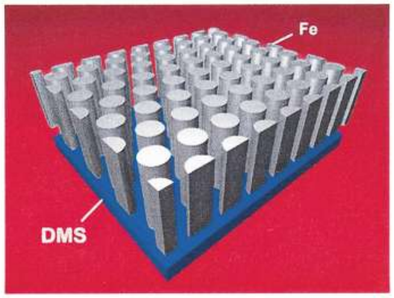
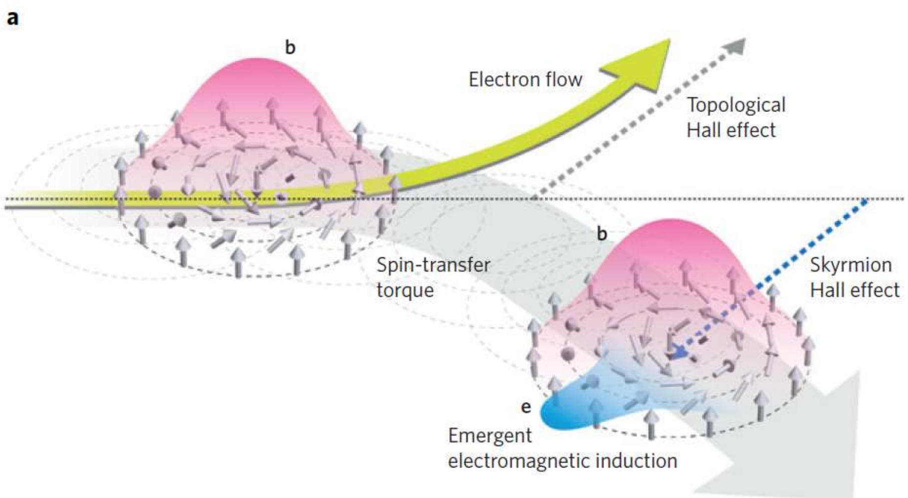
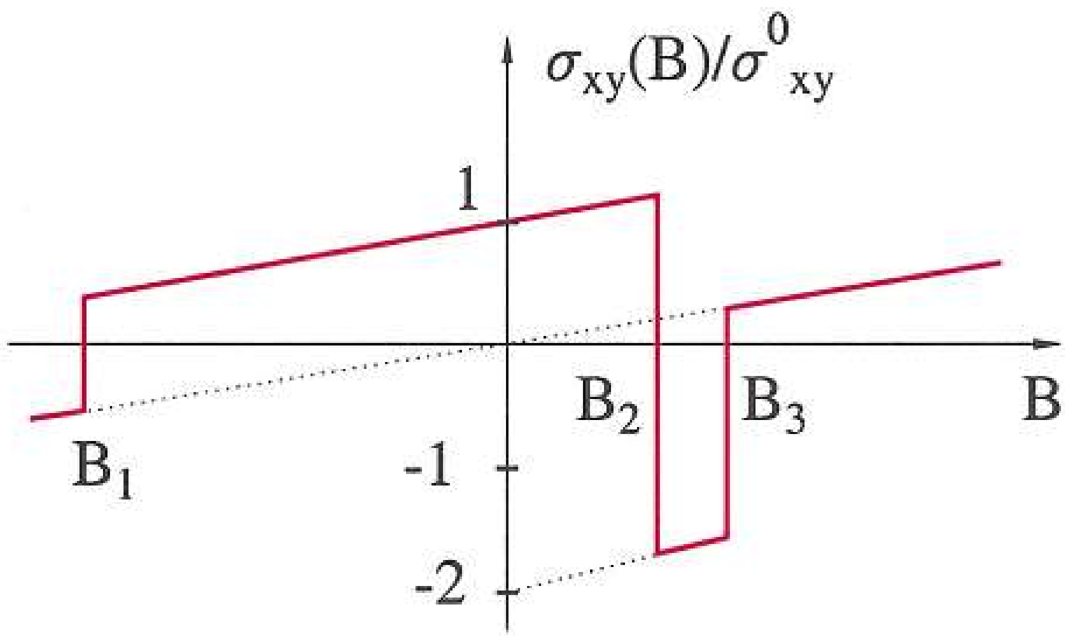


FIG. 1 (color). The proposed structure consisting of a triangular lattice of magnetic nanocylinders on top of 2D diluted magnetic semiconductor.

Topological Hall effect



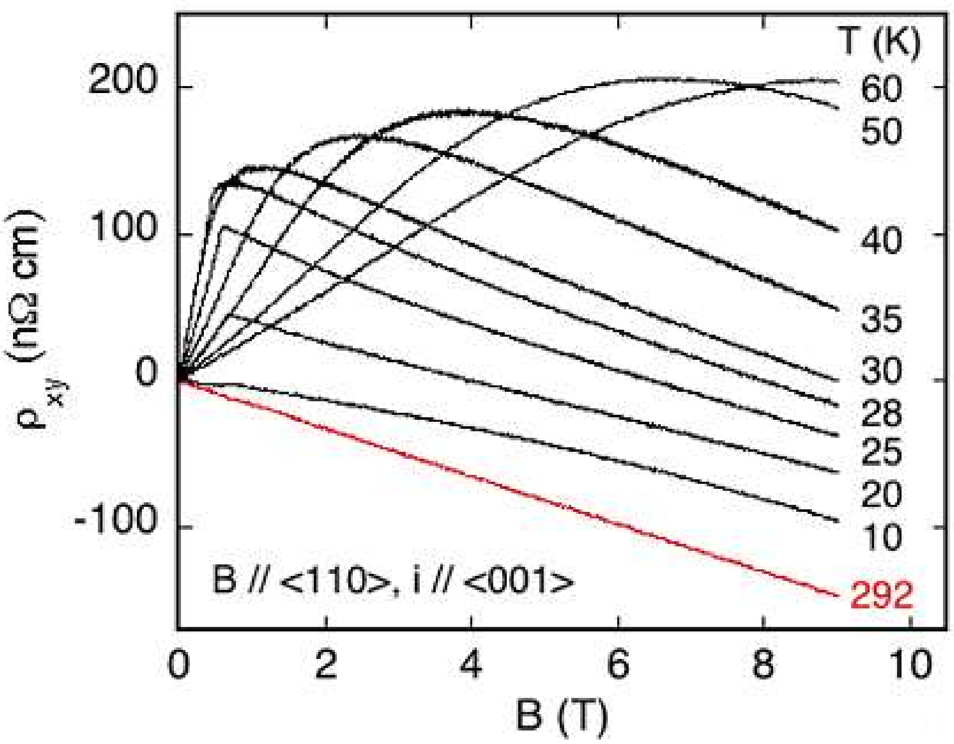
conduction electrons & localized spins



Observation

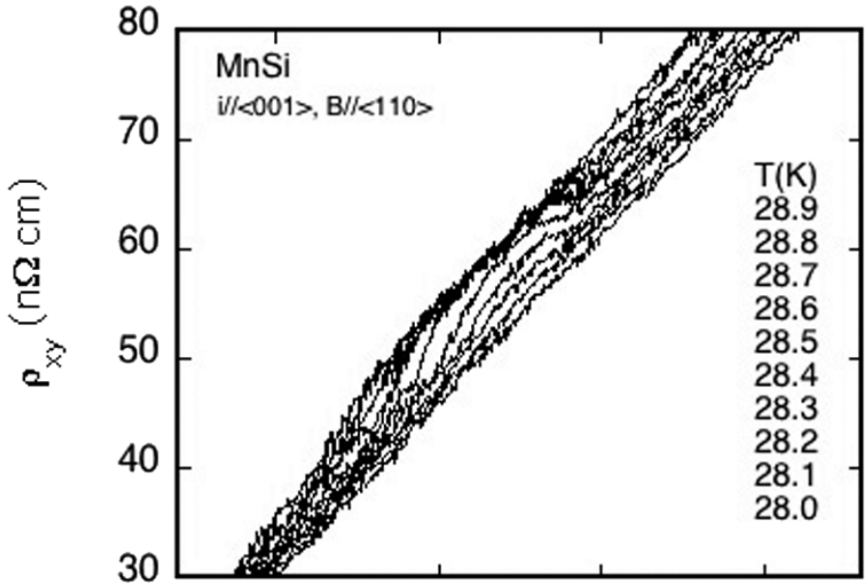
Topological Hall effect: MnSi

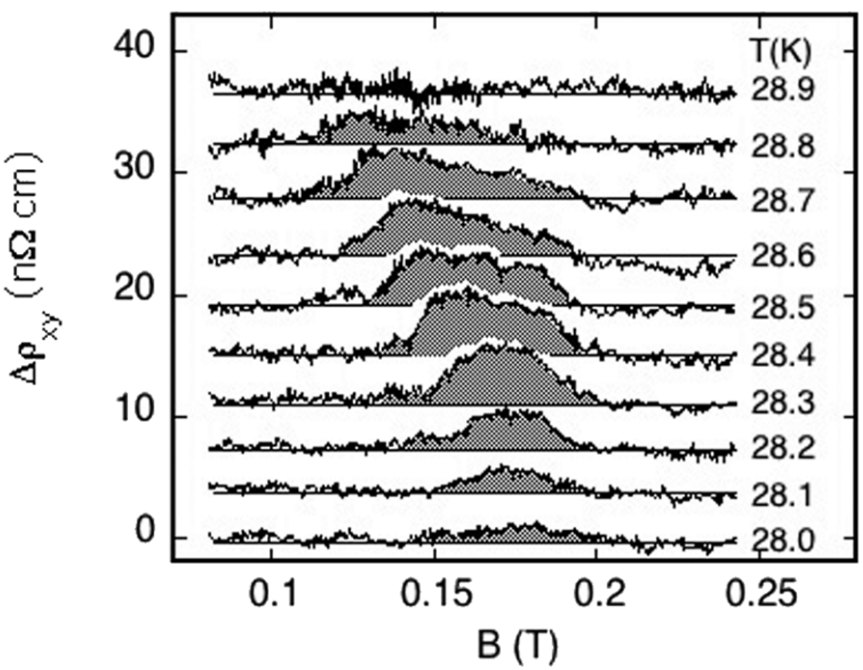
AHE



Observation

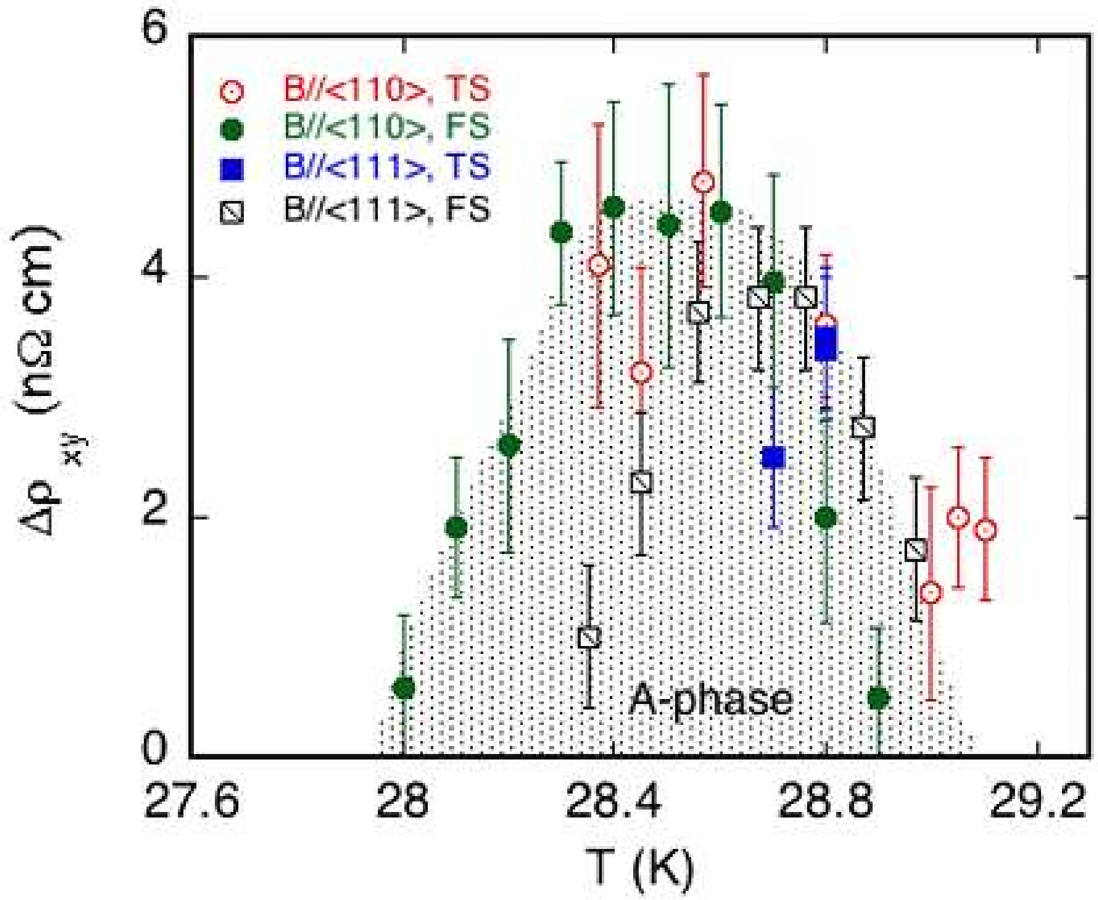
Topological Hall effect: MnSi



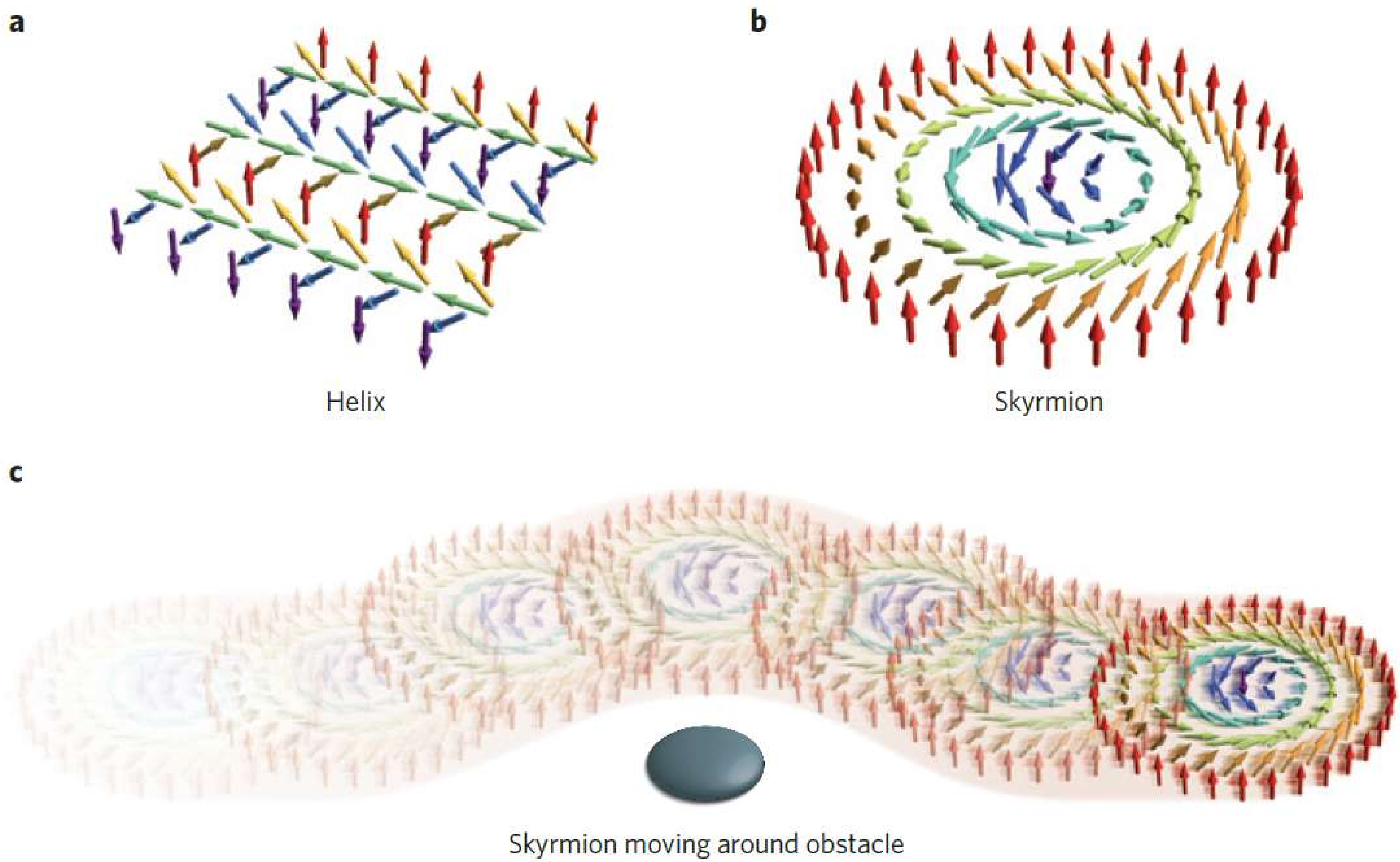


Observation

Topological Hall effect: MnSi

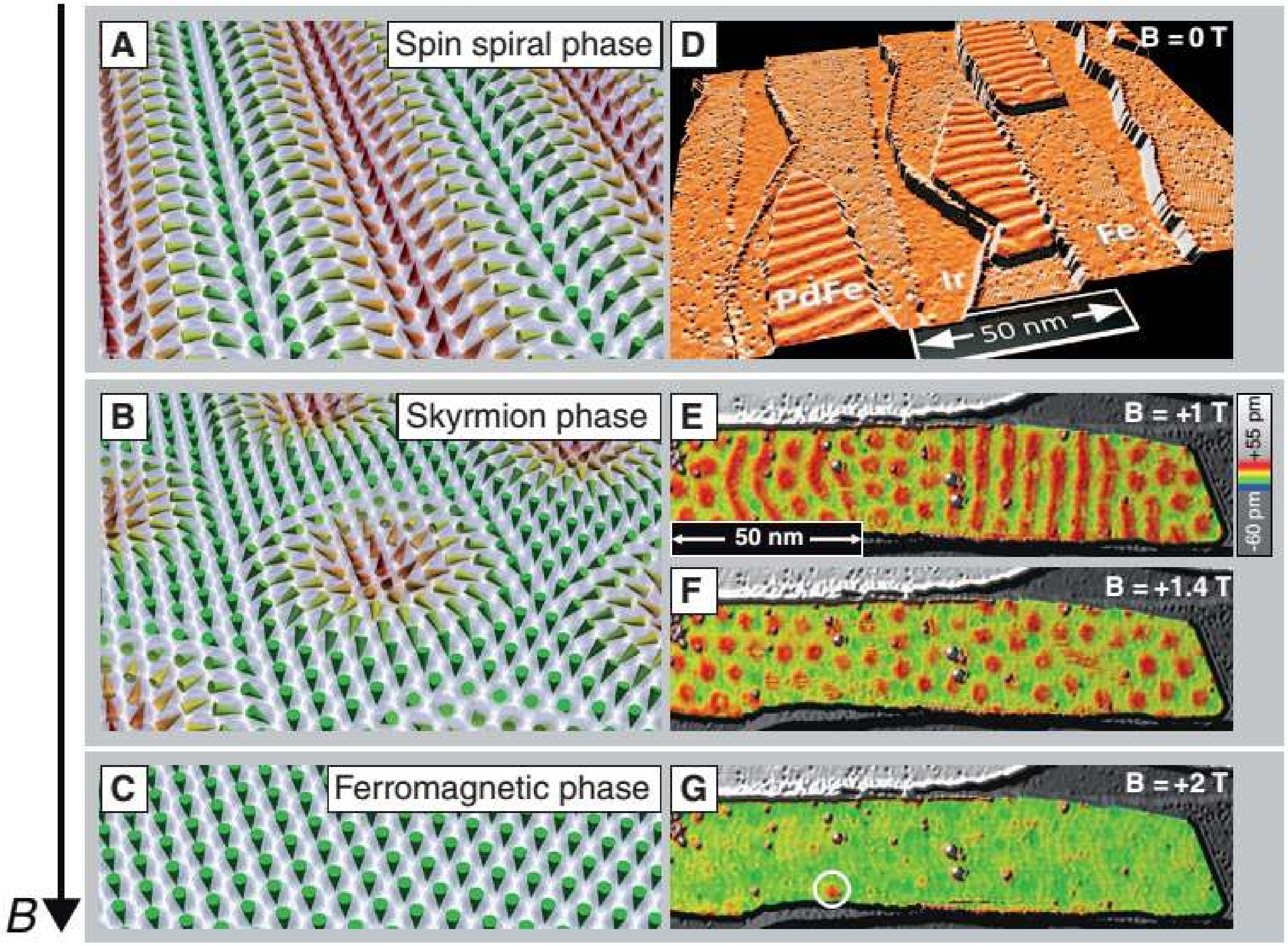


Skyrmion



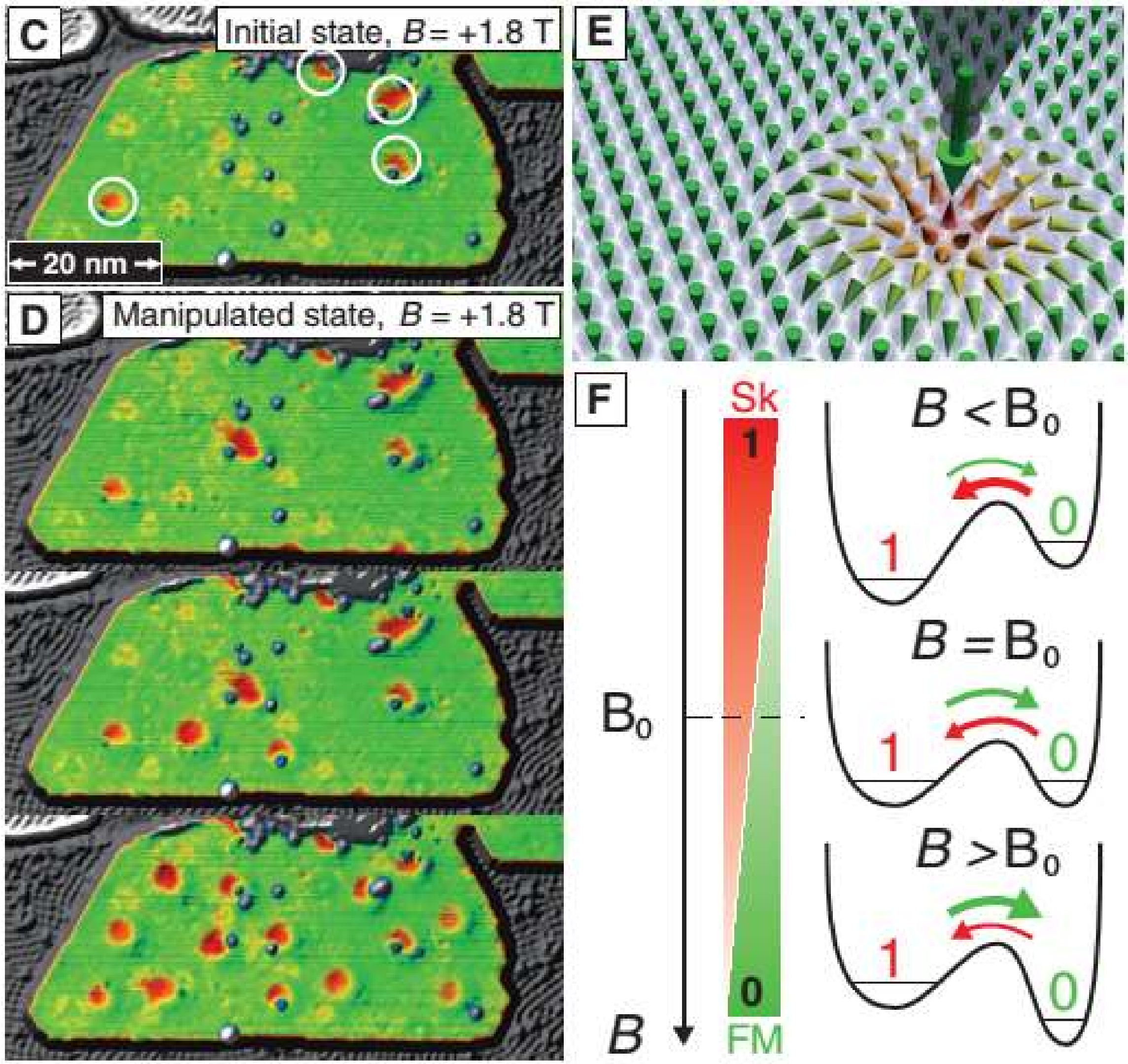
Rosch, et al, Nature Nanotechnology (2013)

Write a skyrmion

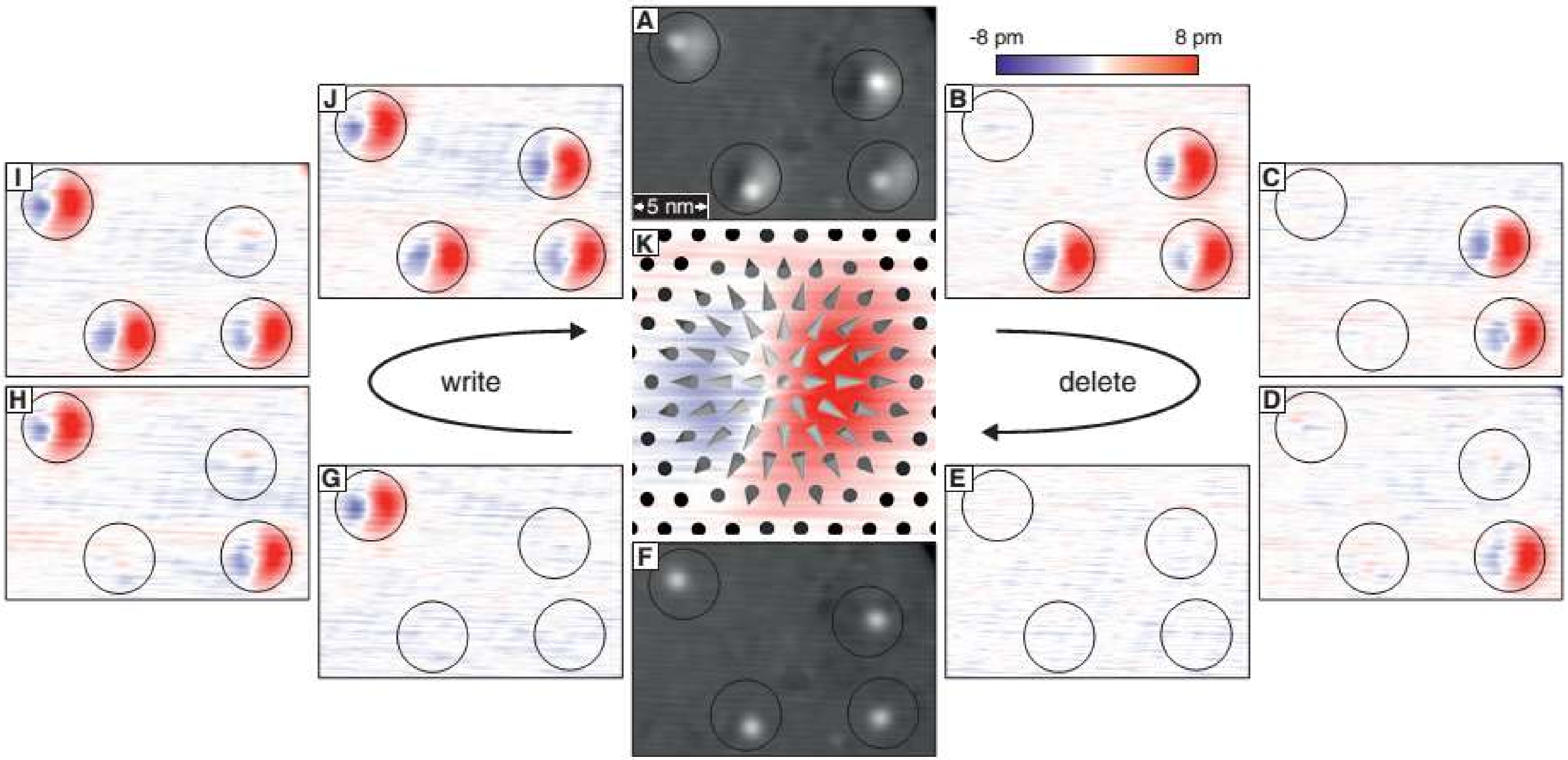


Romming, et al, Science (2013)

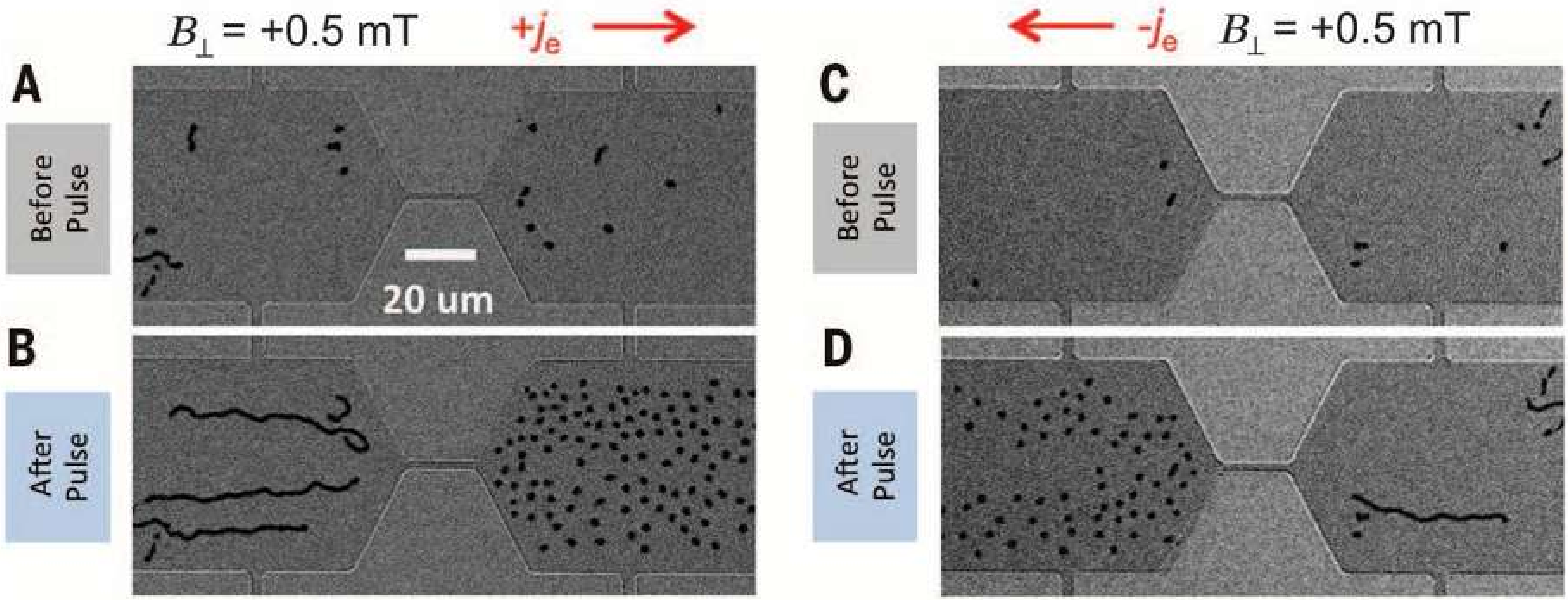
Write a skyrmion



Write and delete a skyrmion



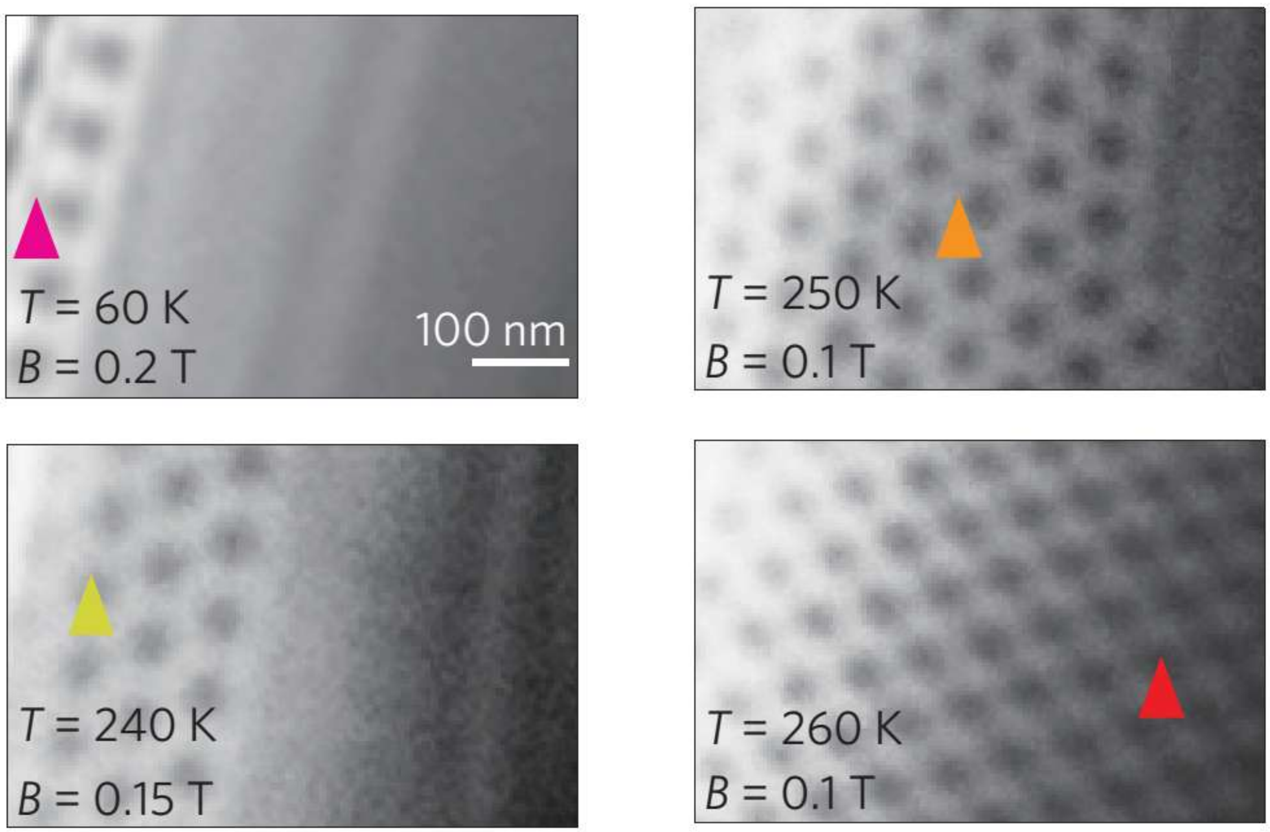
Create a skyrmion



Jiang, et al, Science (2015)

Near Room temperature Skyrmion

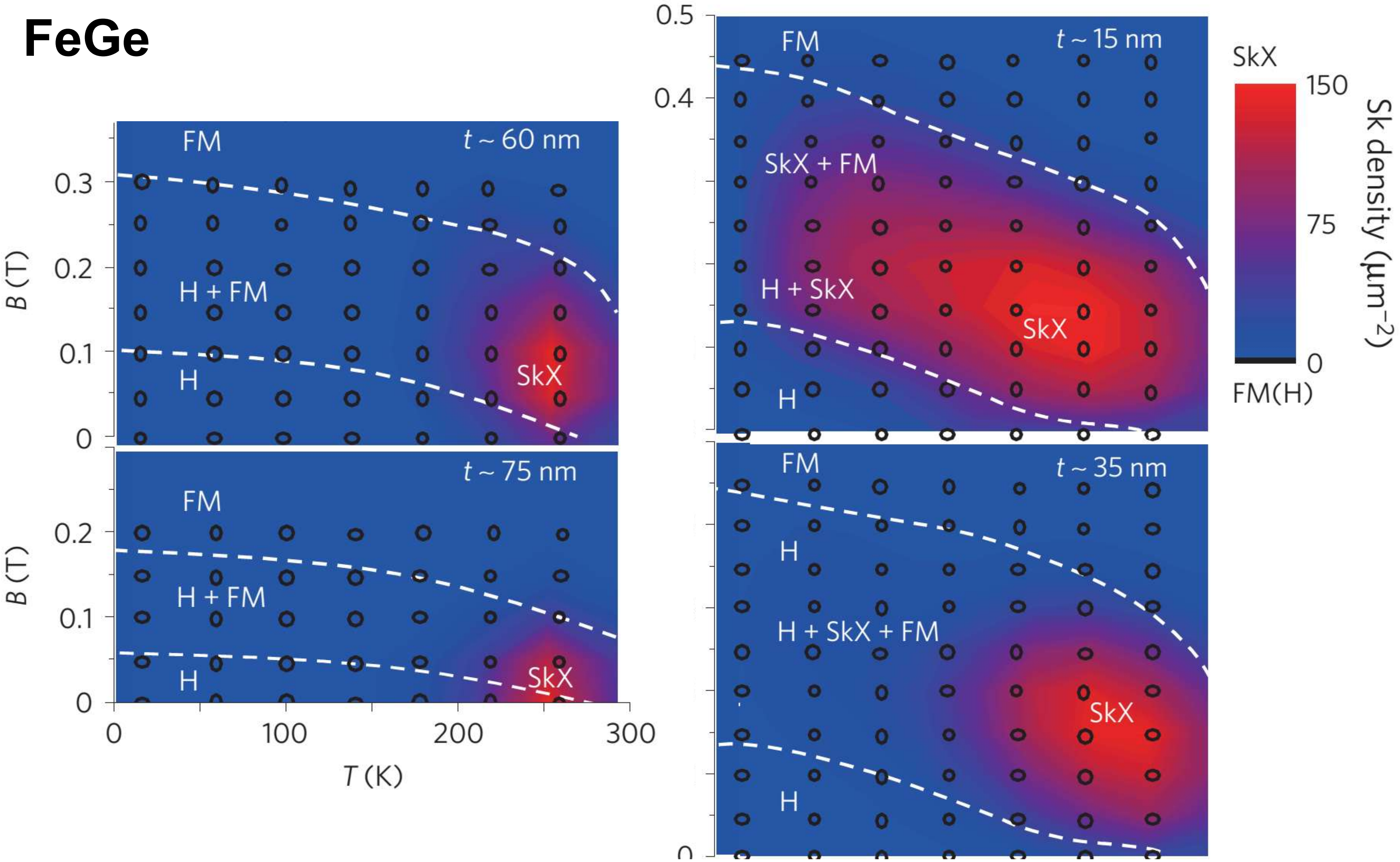
FeGe: 10 nm



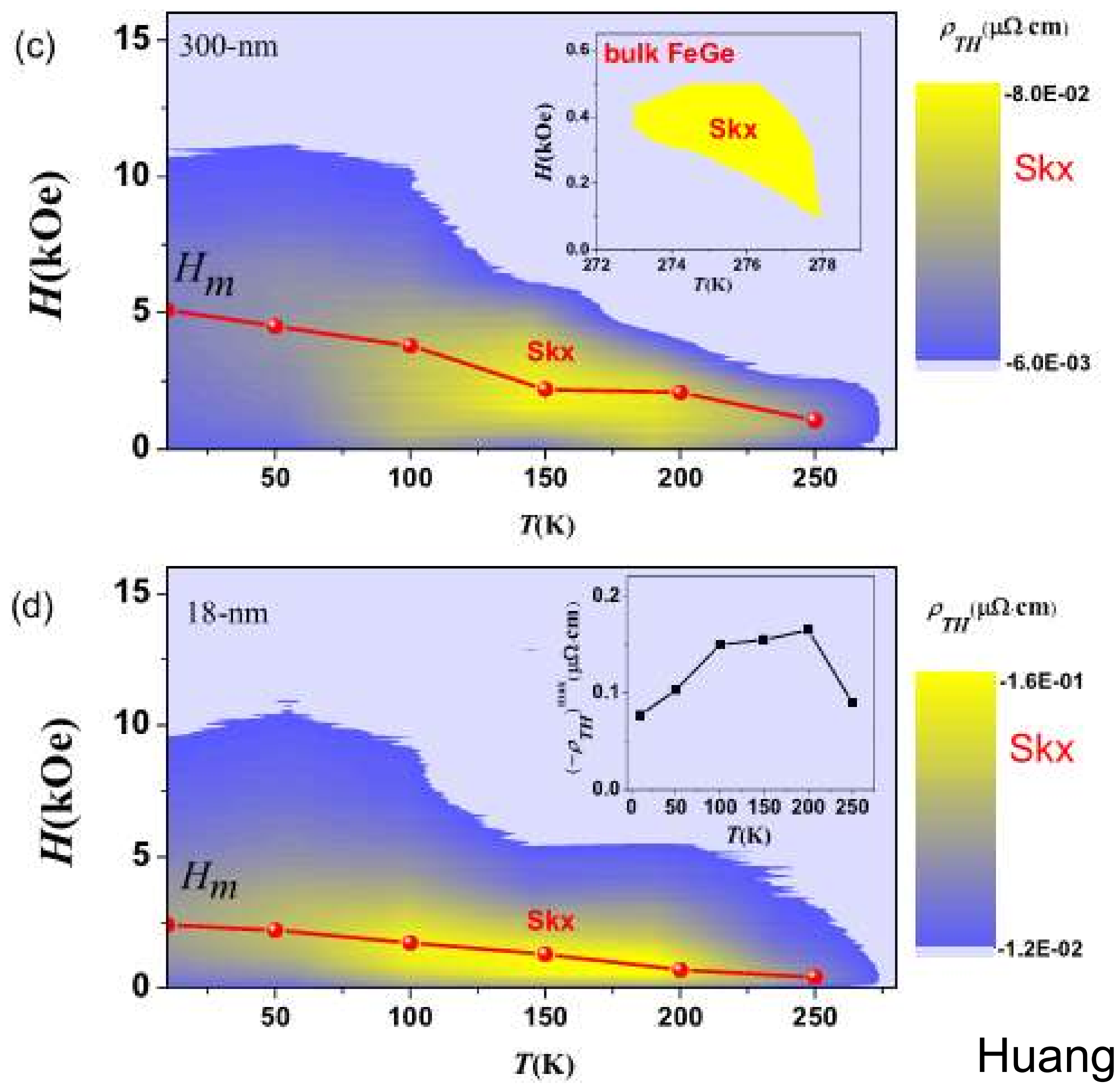
Yu, et al, Nature Materials (2010)

Near Room temperature Skyrmion

FeGe

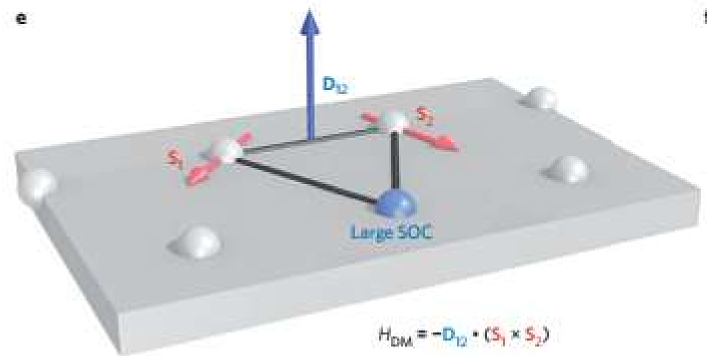


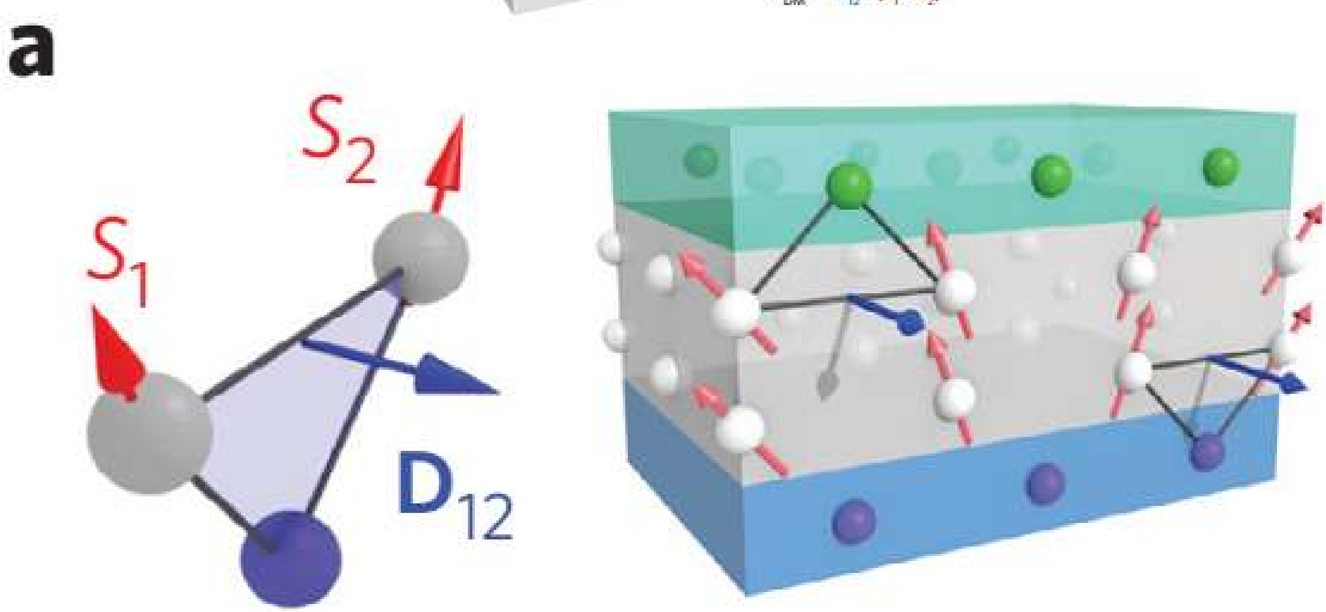
Room temperature Skyrmion



Huang, et al, PRL (2012)

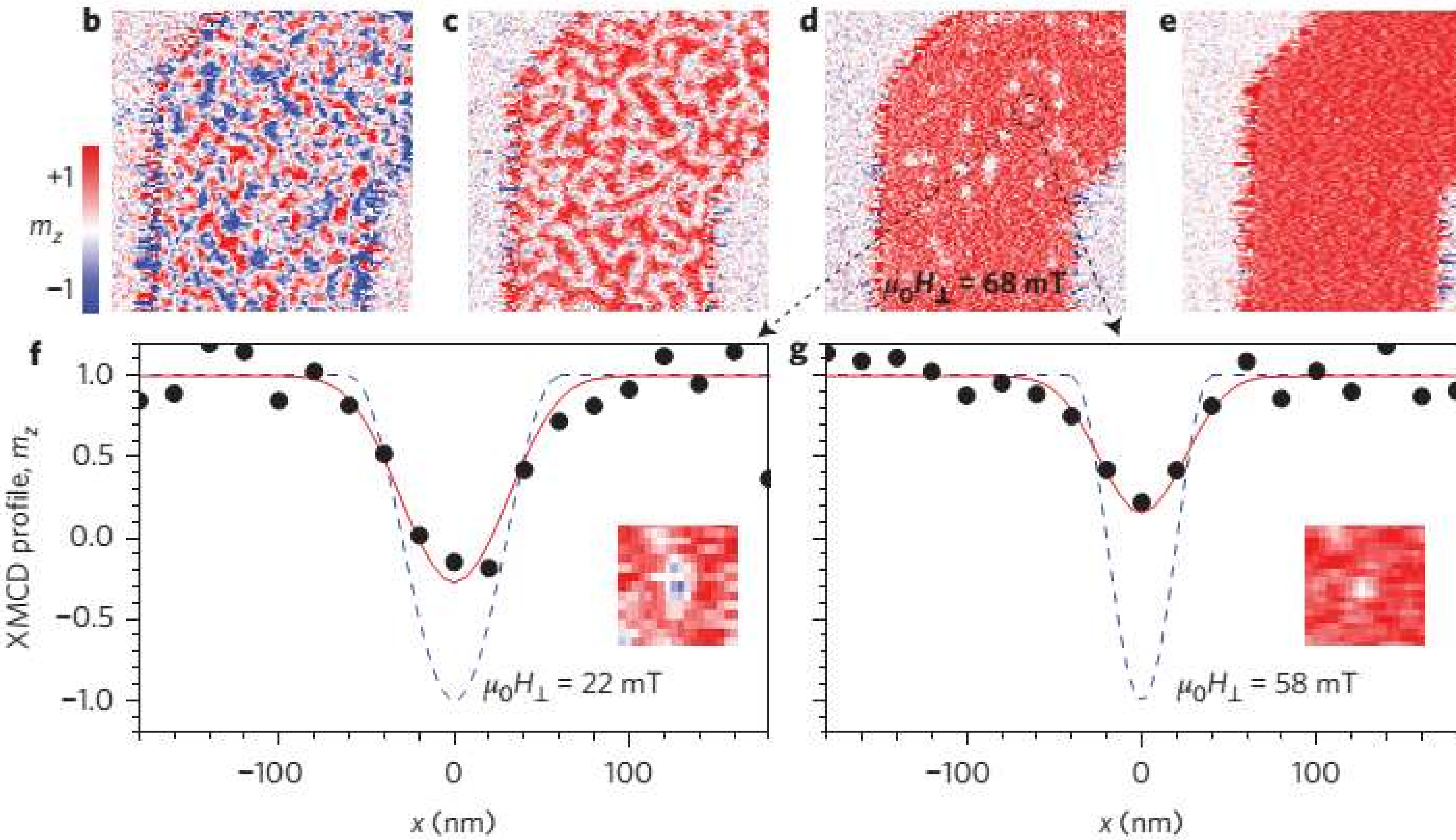
Room temperature Skyrmion



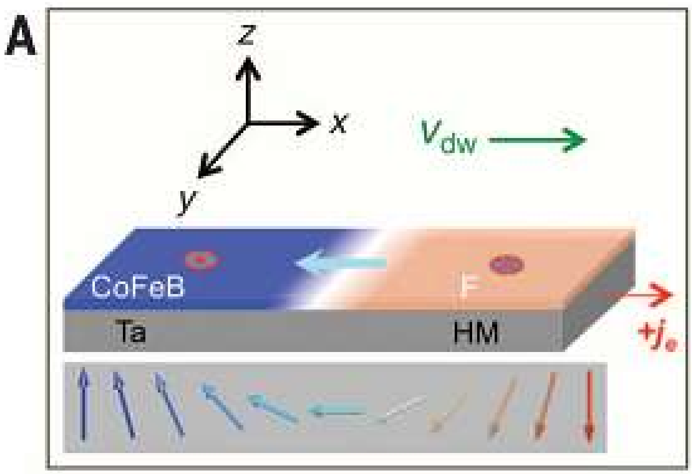


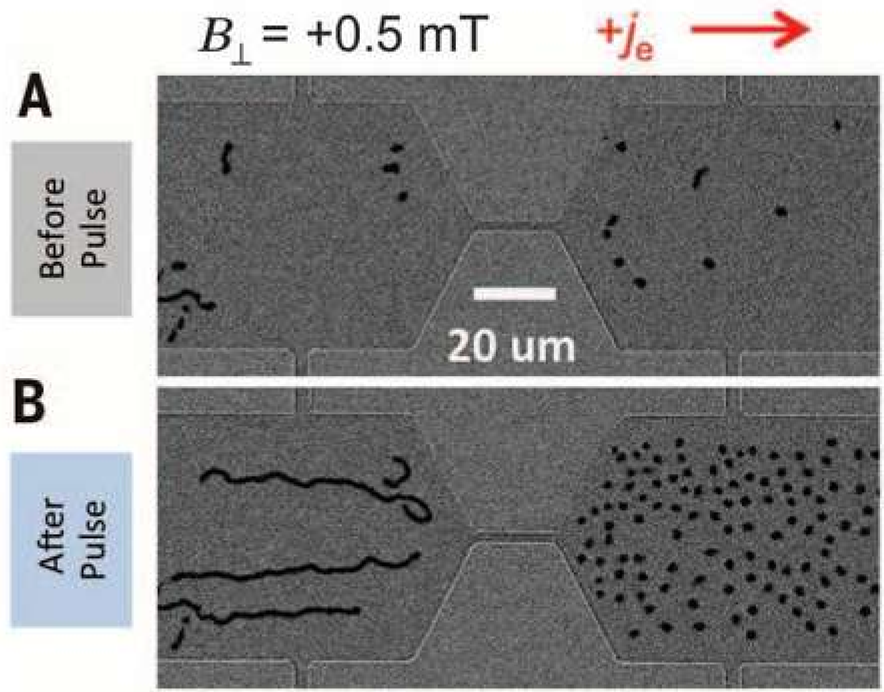
Moreau-Luchaire, et al, Nature Nano (2016)

Room temperature Skyrmion



Room temperature Skyrmion

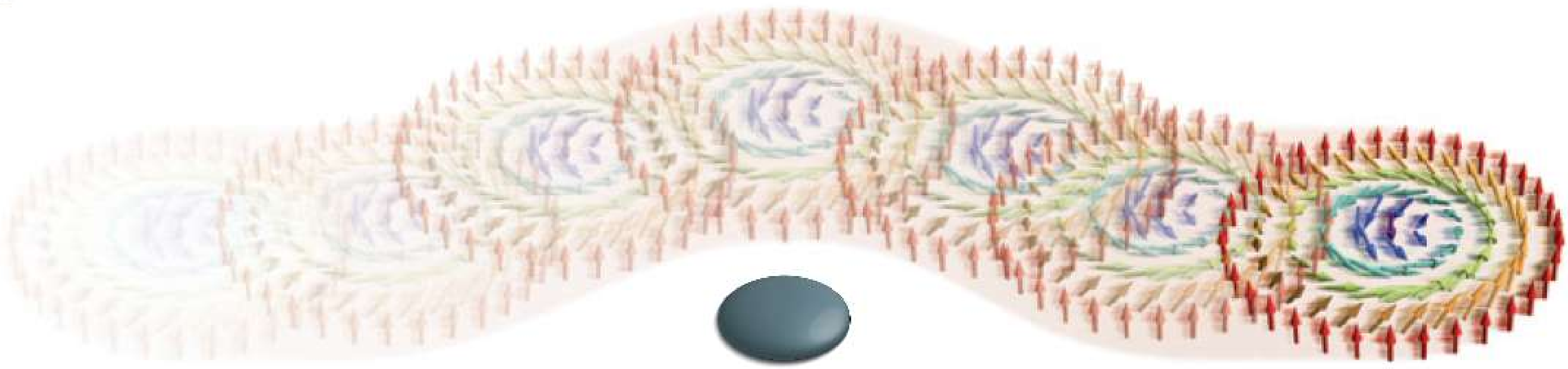




Jiang, et al, Science (2015)

Move a skyrmion

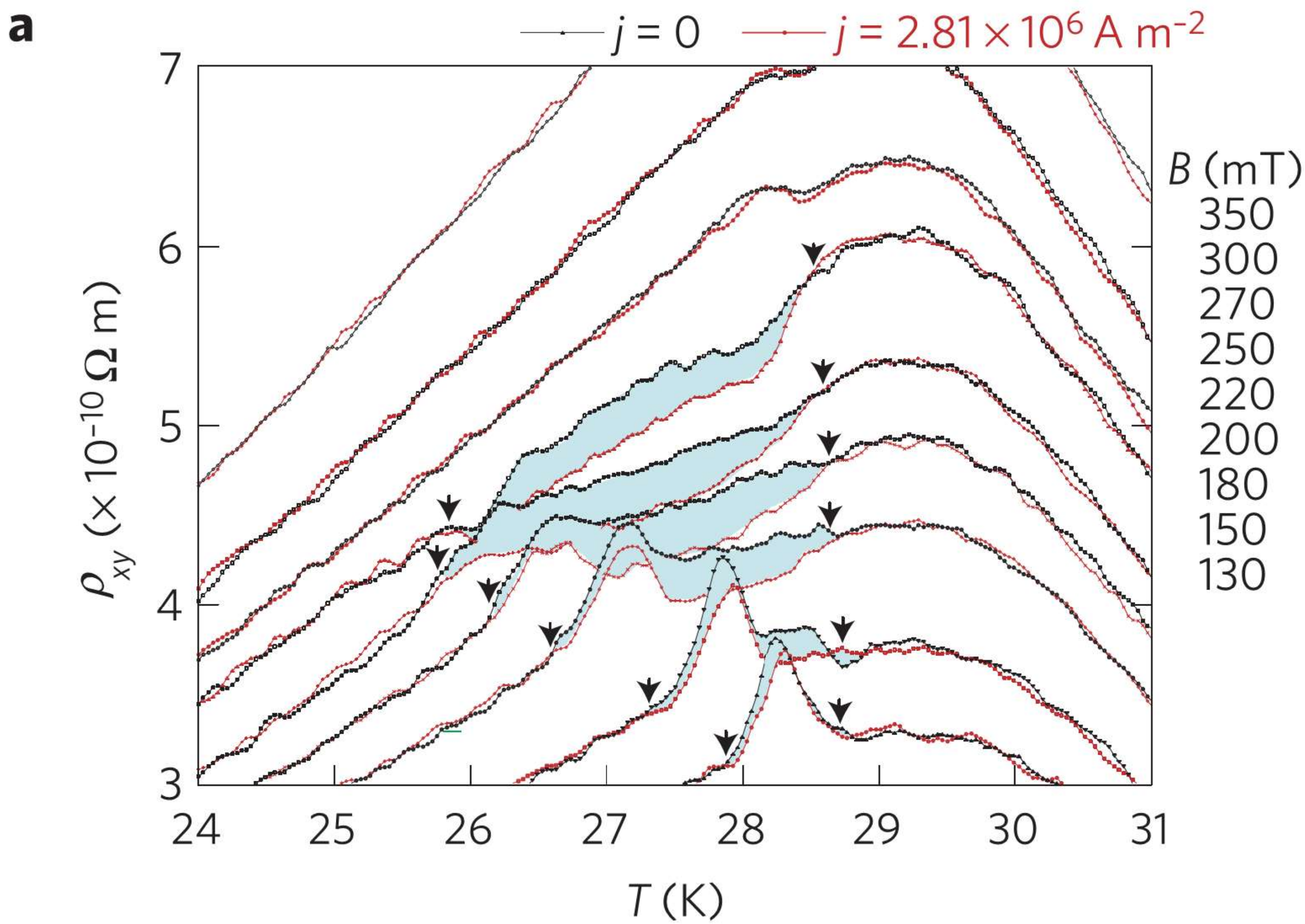
c



Skyrmion moving around obstacle

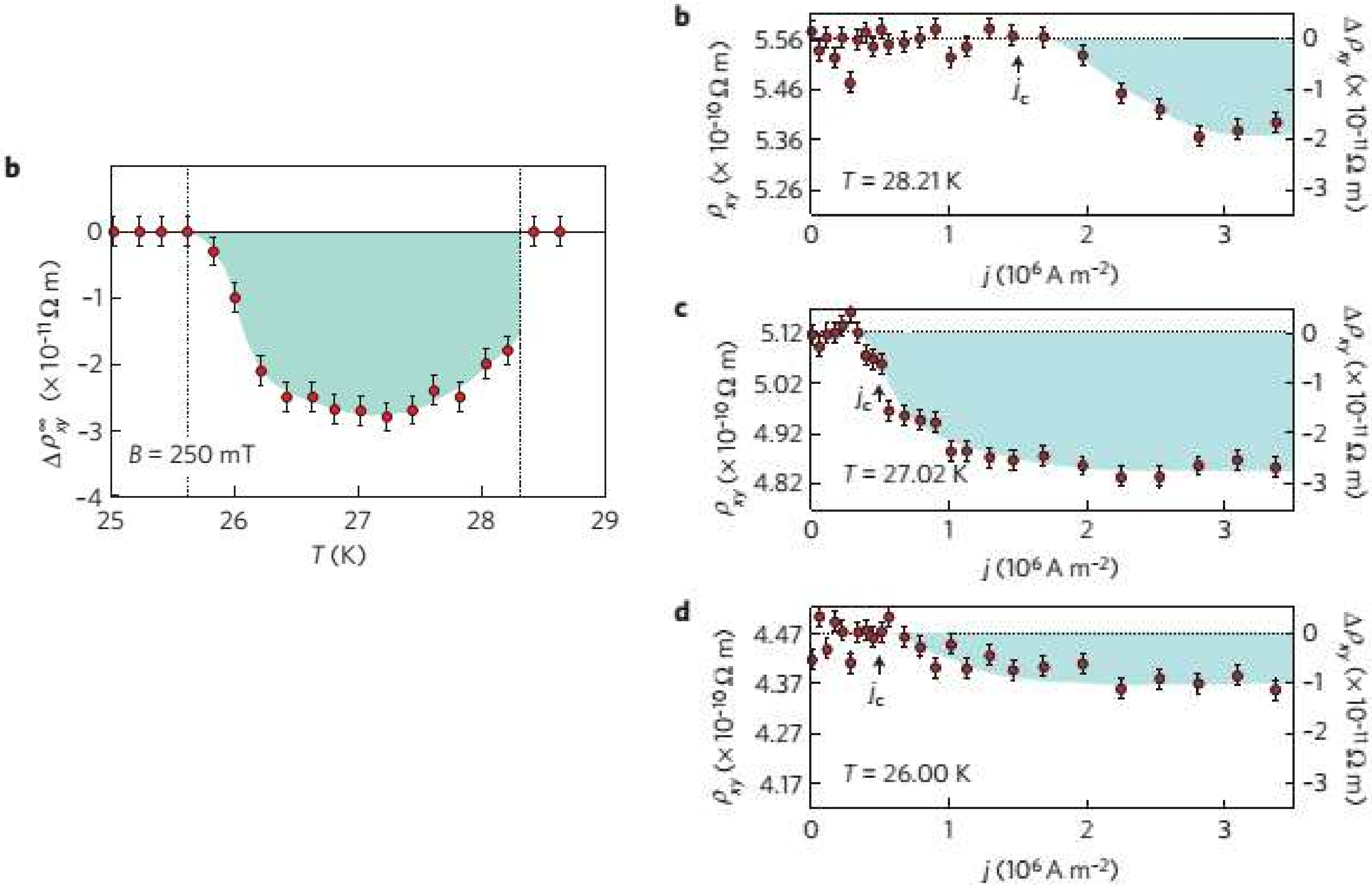
Rosch, et al, Nature Nano (2013)

Move a skyrmion



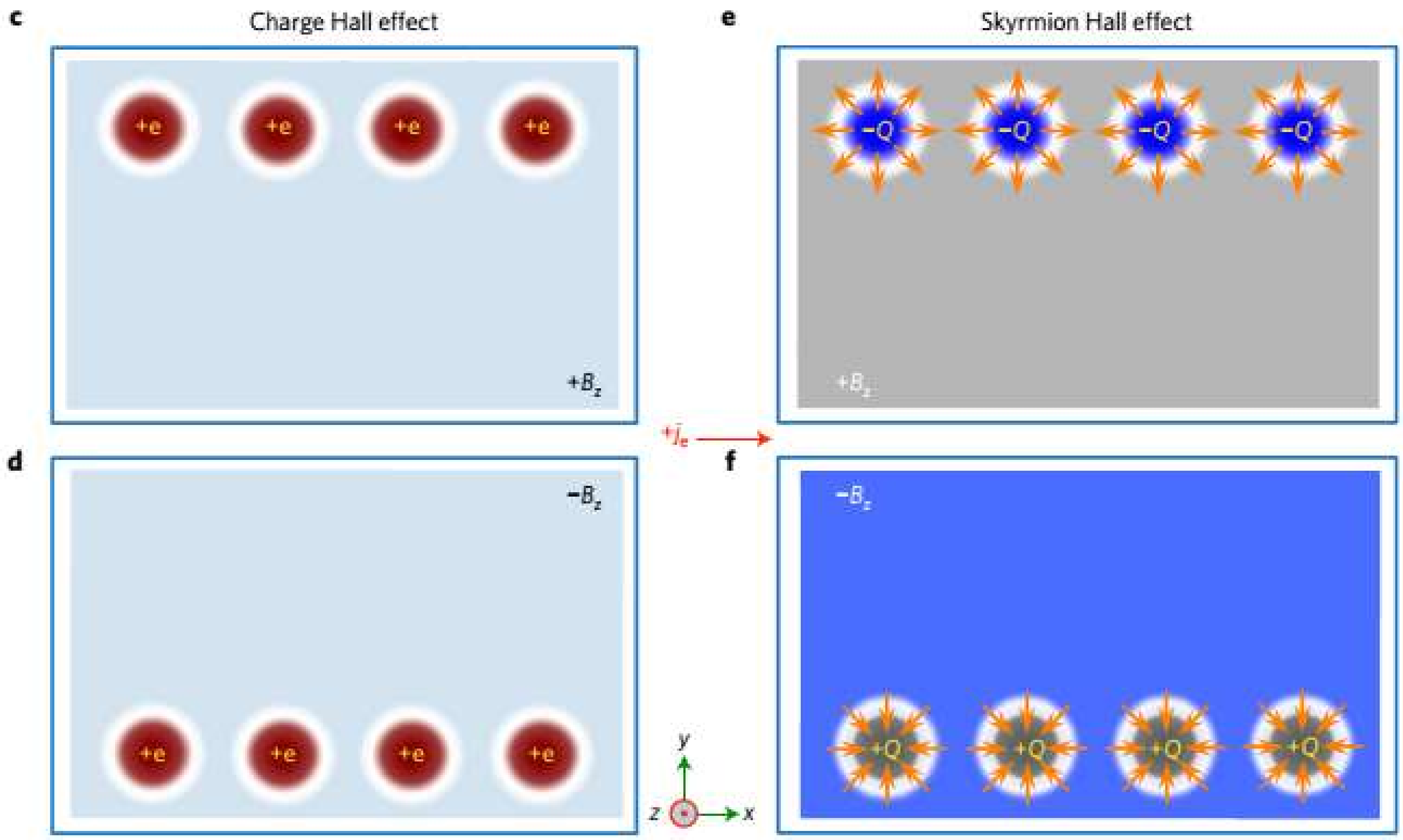
Schulz, et al, Nature Physics (2012)

Move a skyrmion

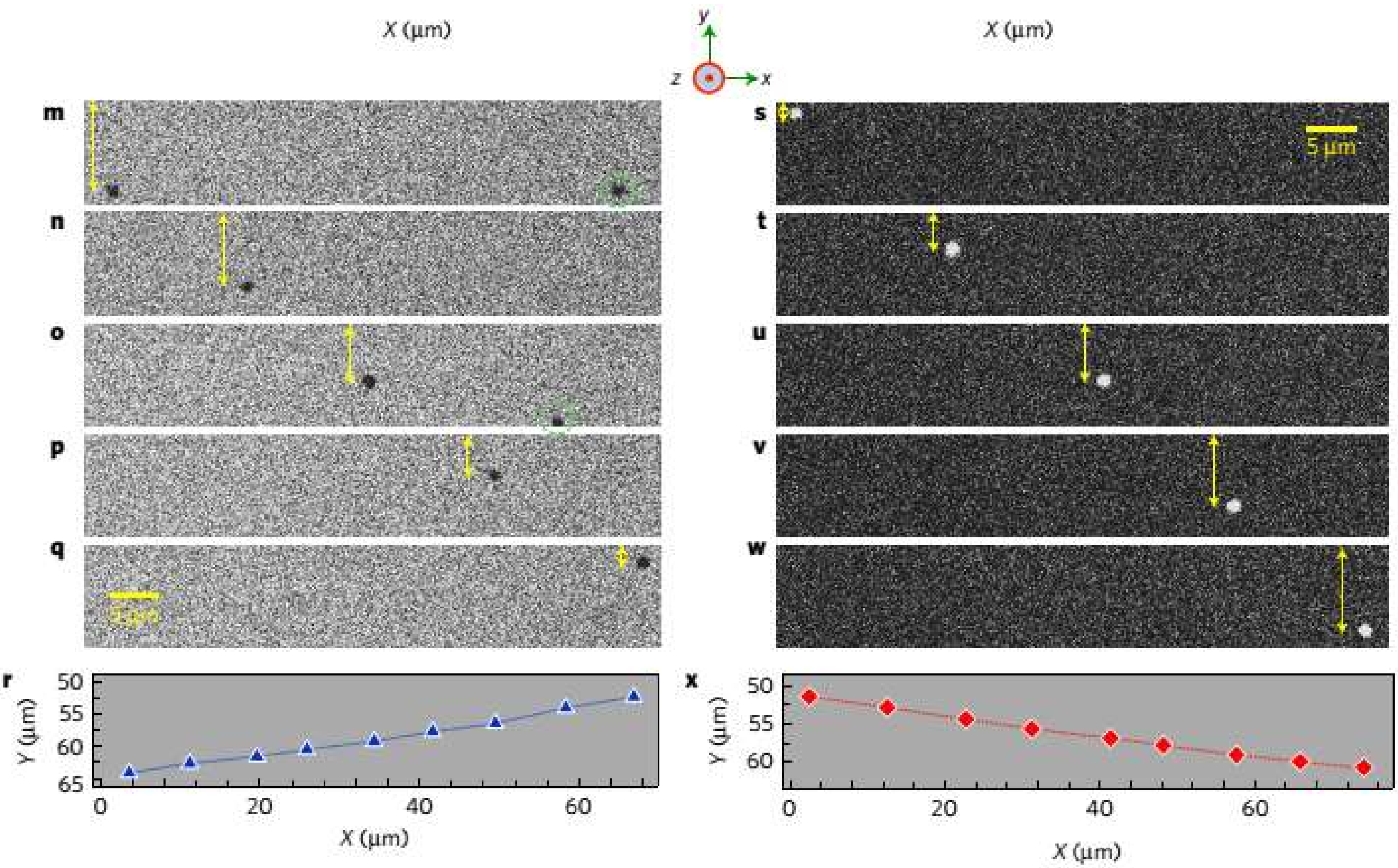


Schulz, et al, Nature Physics (2012)

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)

Outline

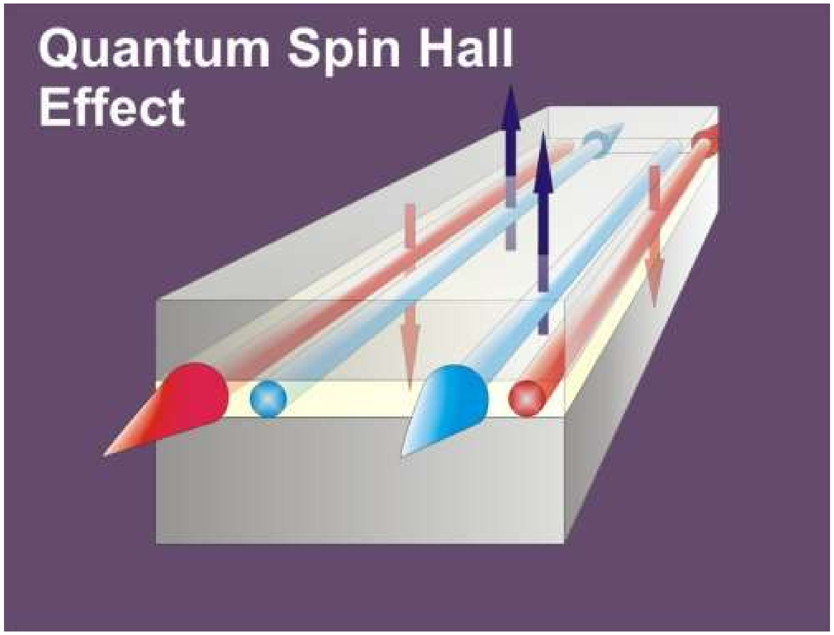
4. Spin-momentum locking of 3D TI

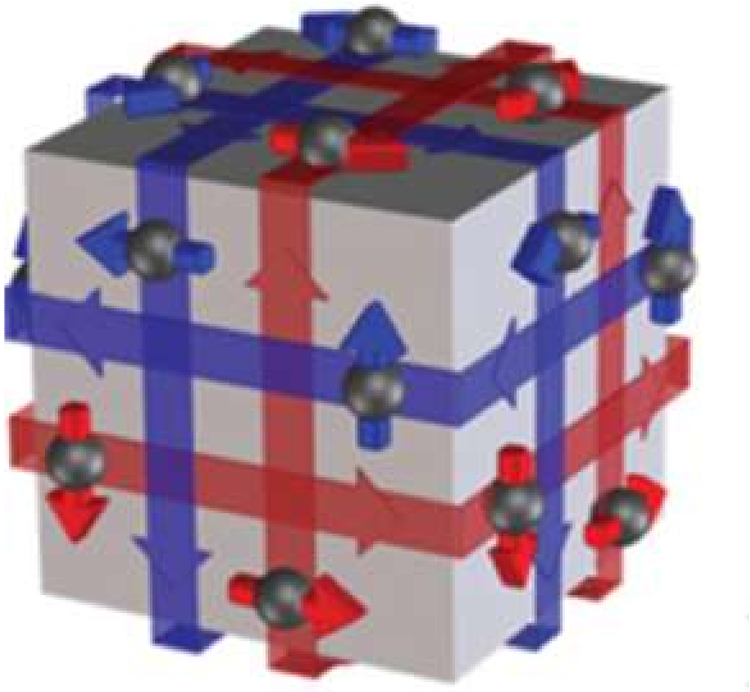
- **Spin injection**
- **Spin orbit torque**
- **Spin Seebeck effect**

Spin momentum locking

2D Topological insulator

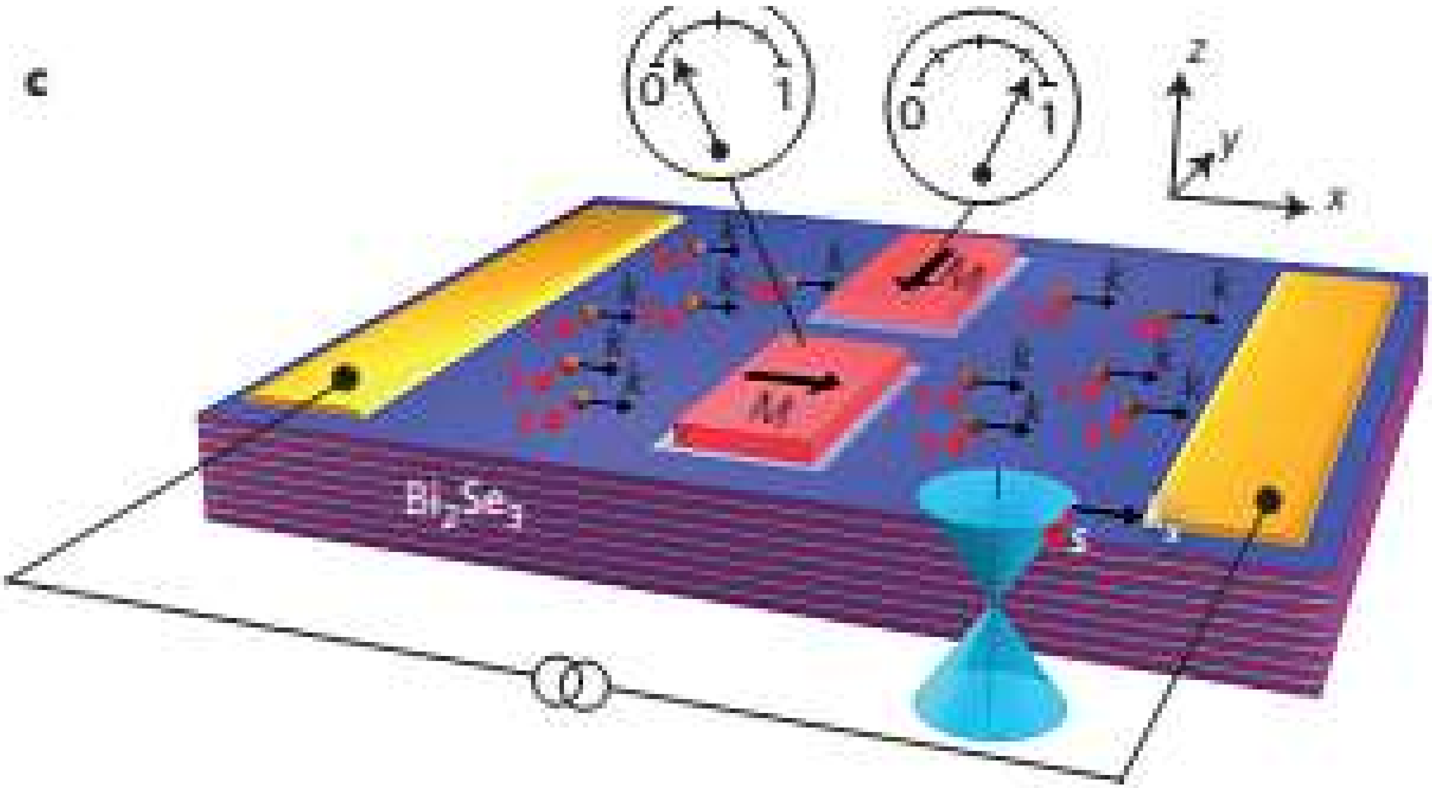
3D Topological insulator





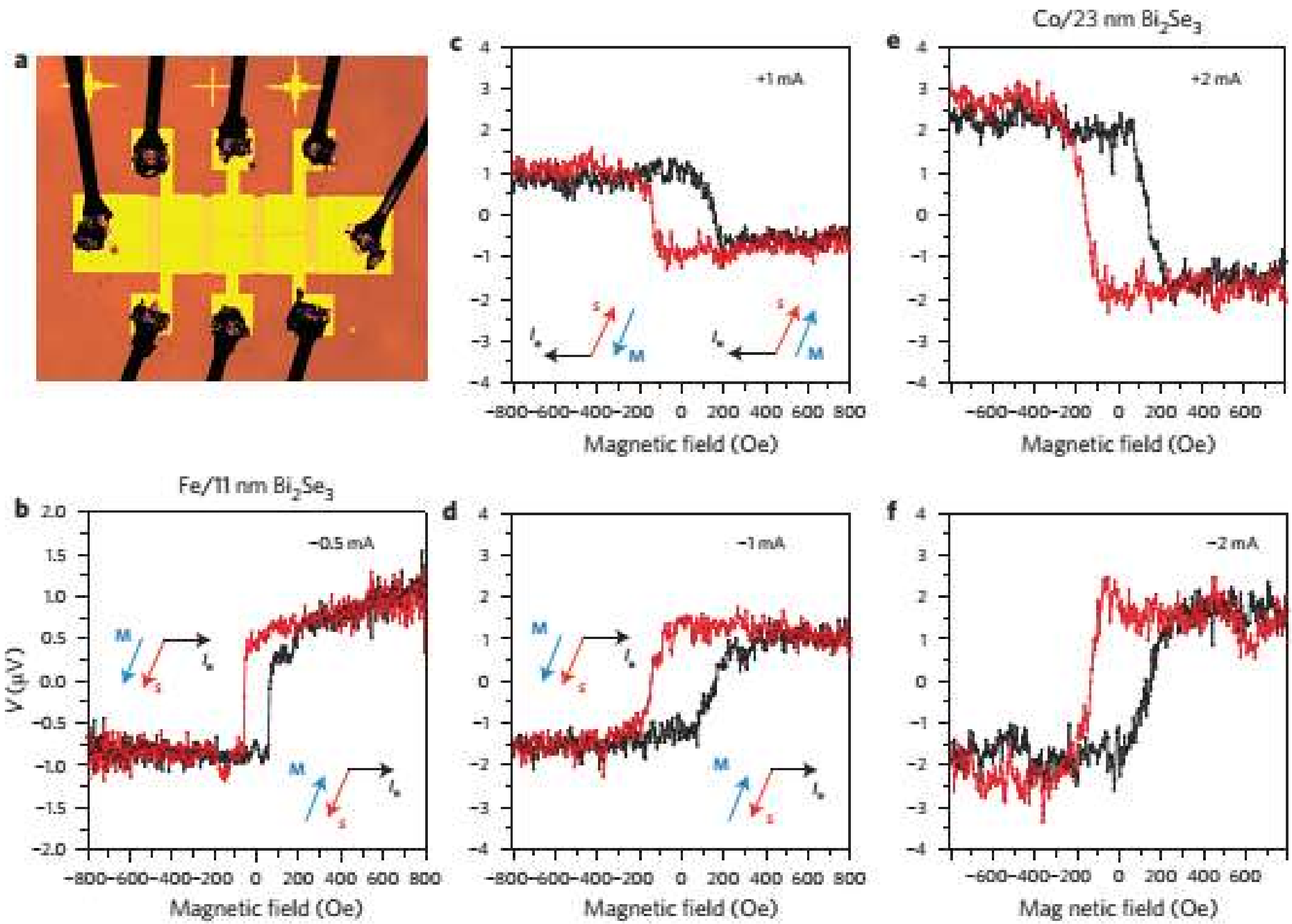
Hasan & Kane, Rev Mod Phys (2009)
Qi & Zhang, Rev Mod Phys (2011)

Spin momentum locking



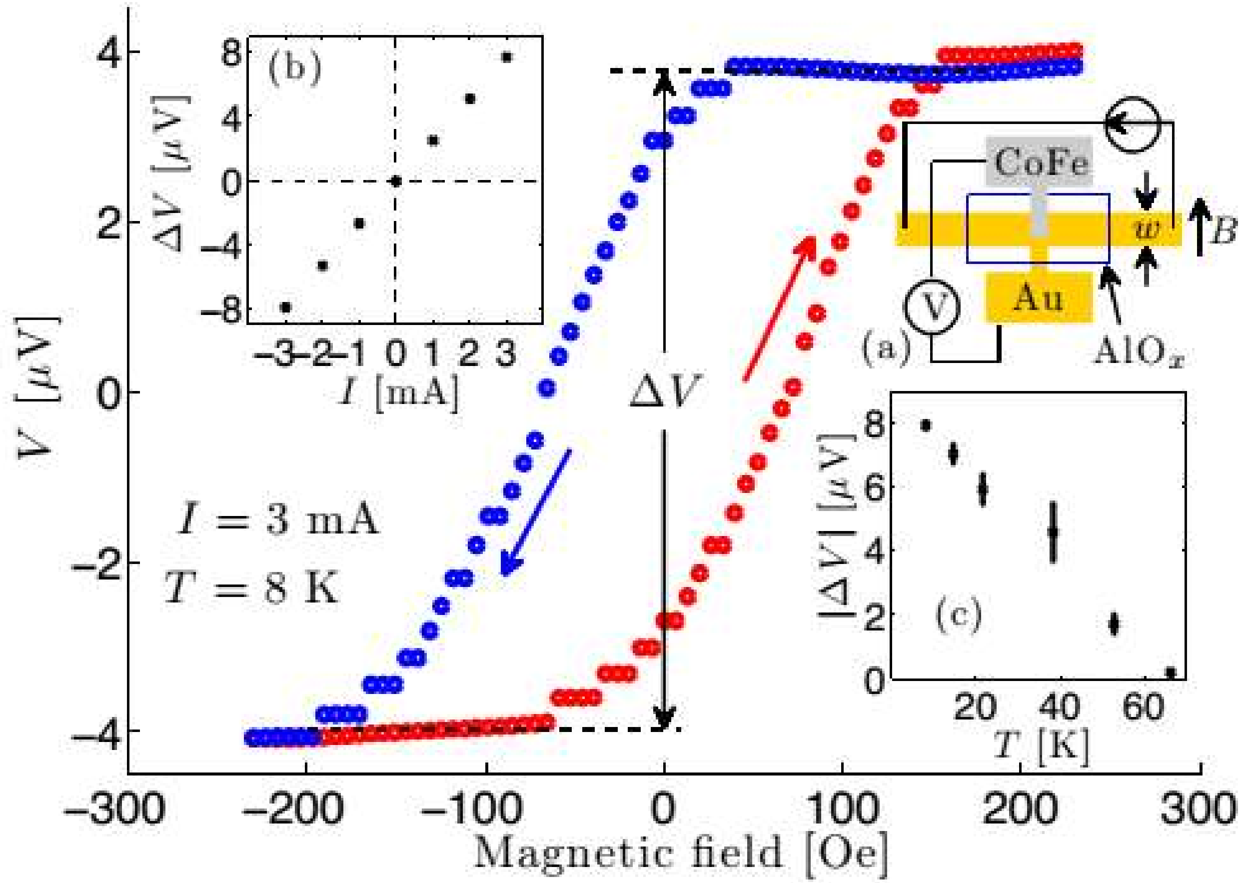
Li, et al, Nature Nanotechnology (2014).

Spin momentum locking



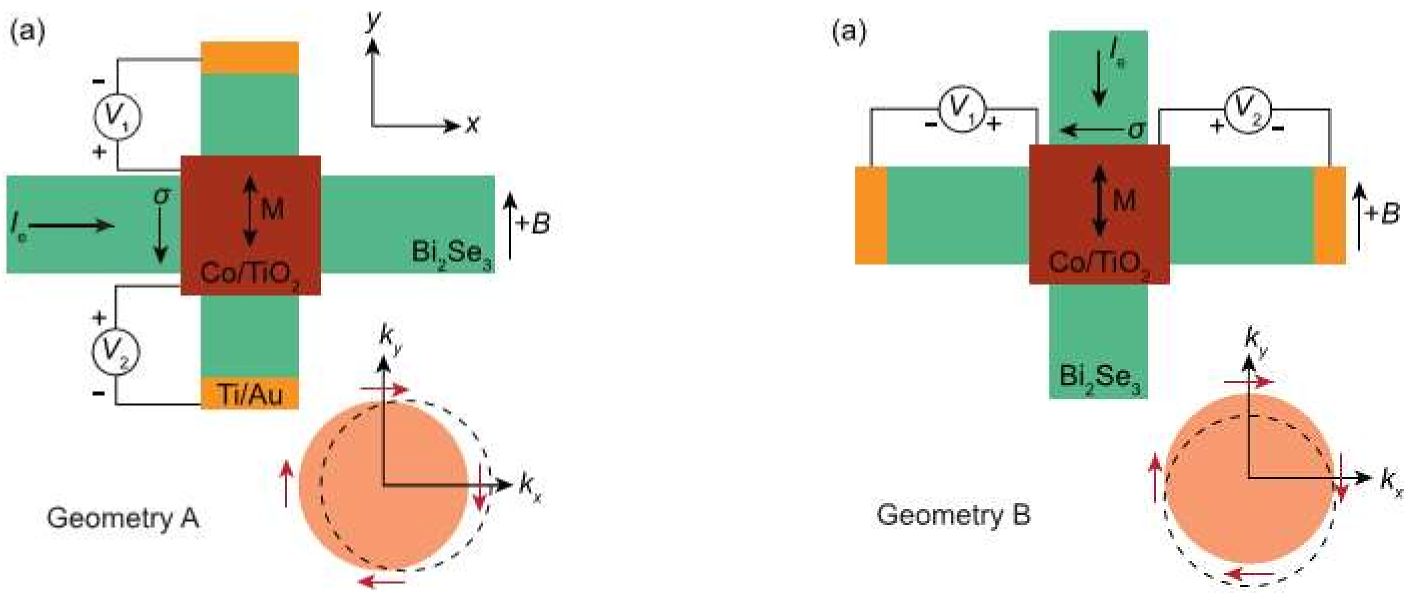
Spin momentum locking

Real spin or not?



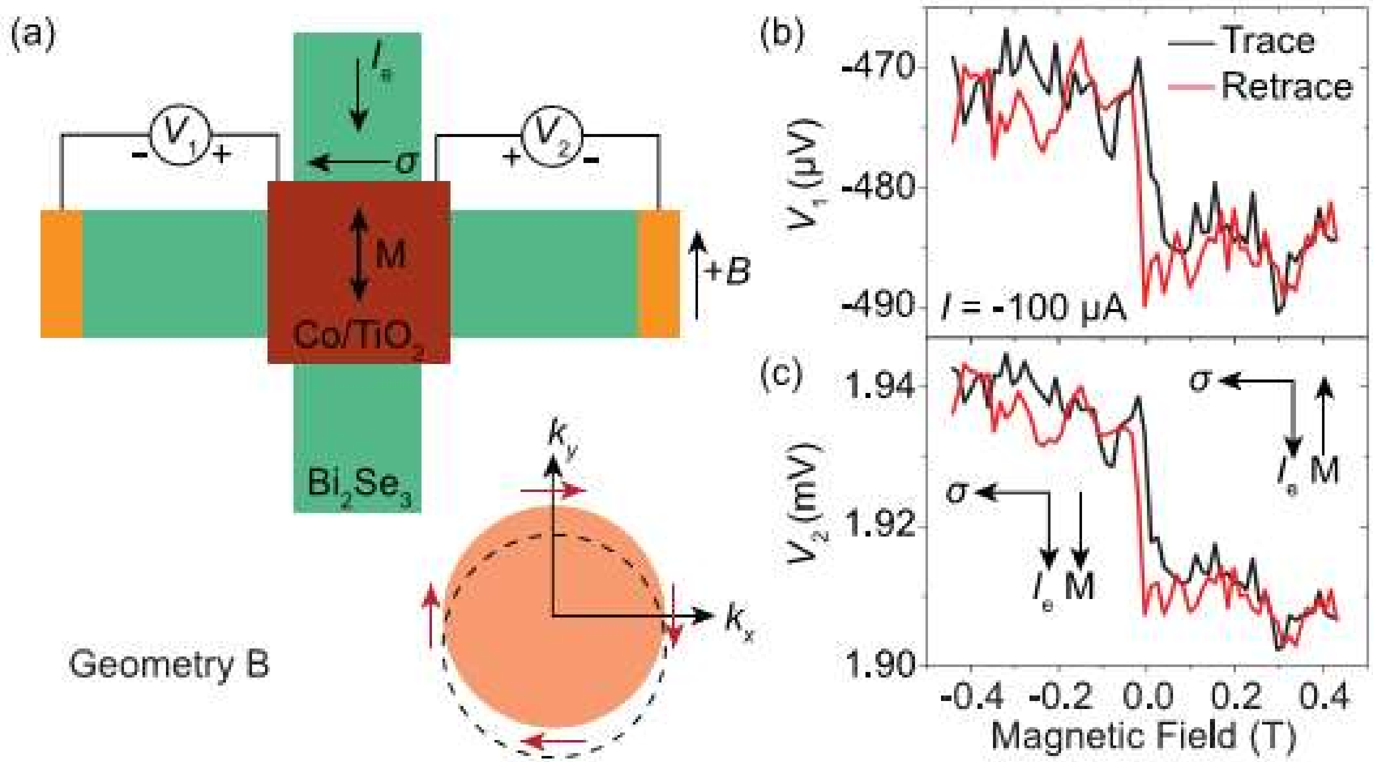
Li & Appelbaum, PRB (2016)

Spin momentum locking



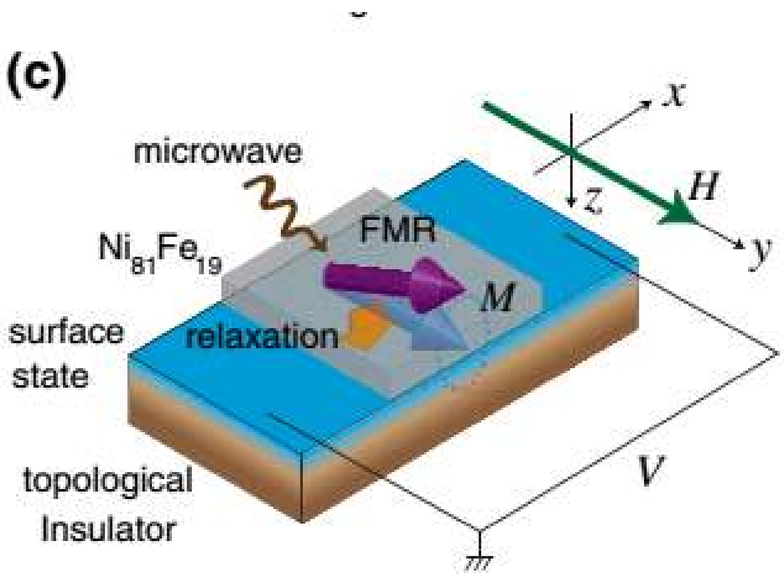
Vries, et al, PRB (2015)

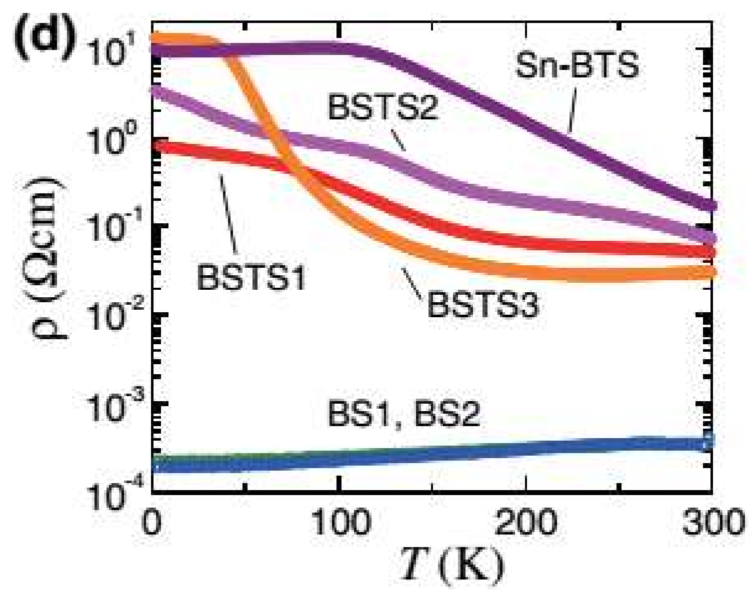
Spin momentum locking



Signal not from the TI surface states !!

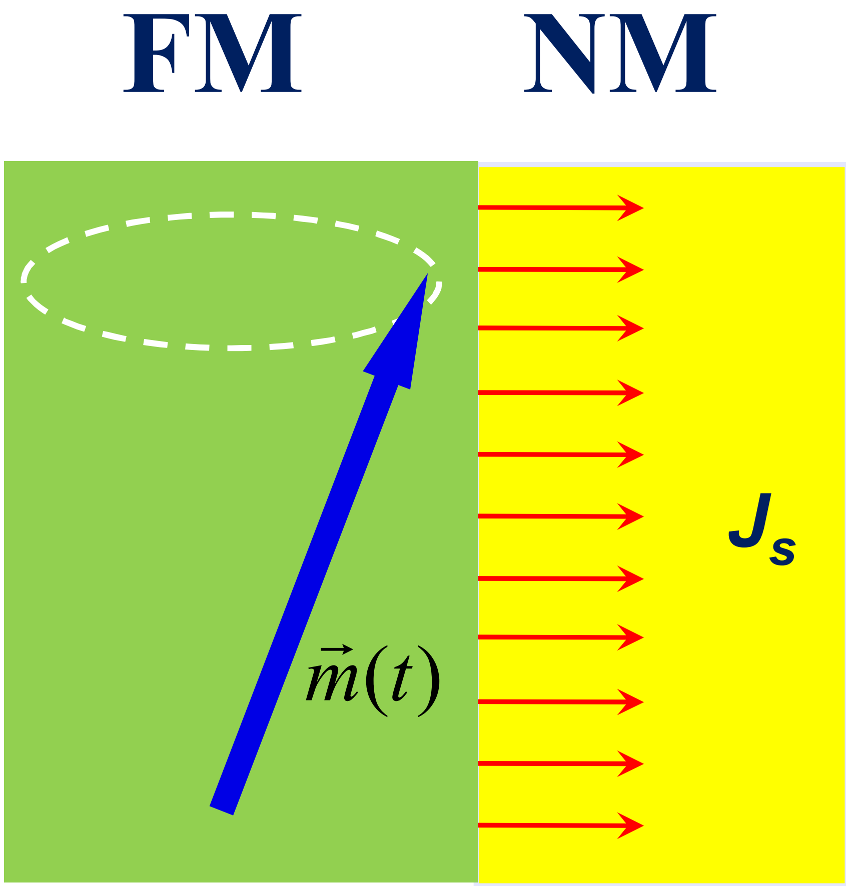
Spin momentum locking





Shiomi, et al, PRL (2014)

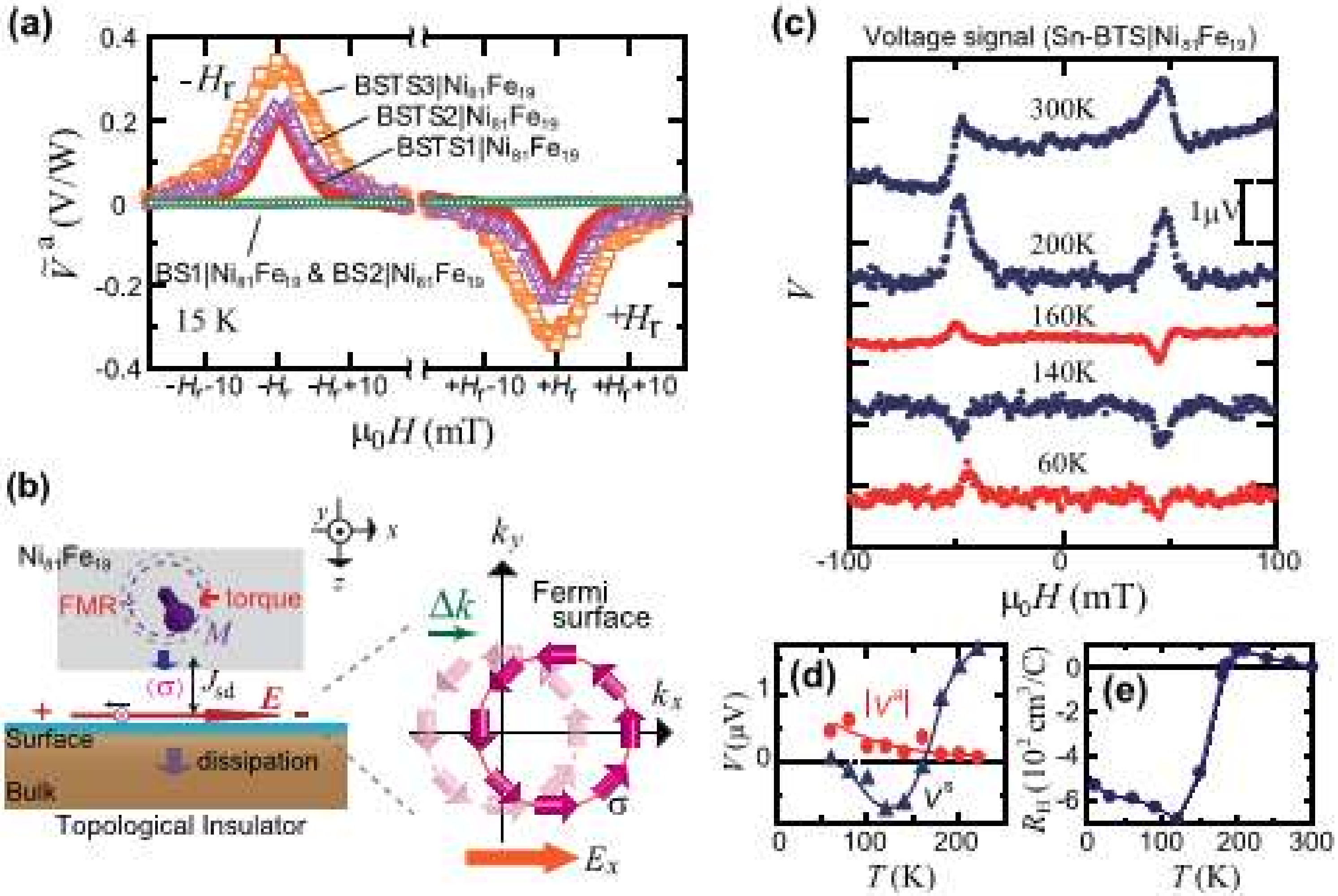
Spin momentum locking



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

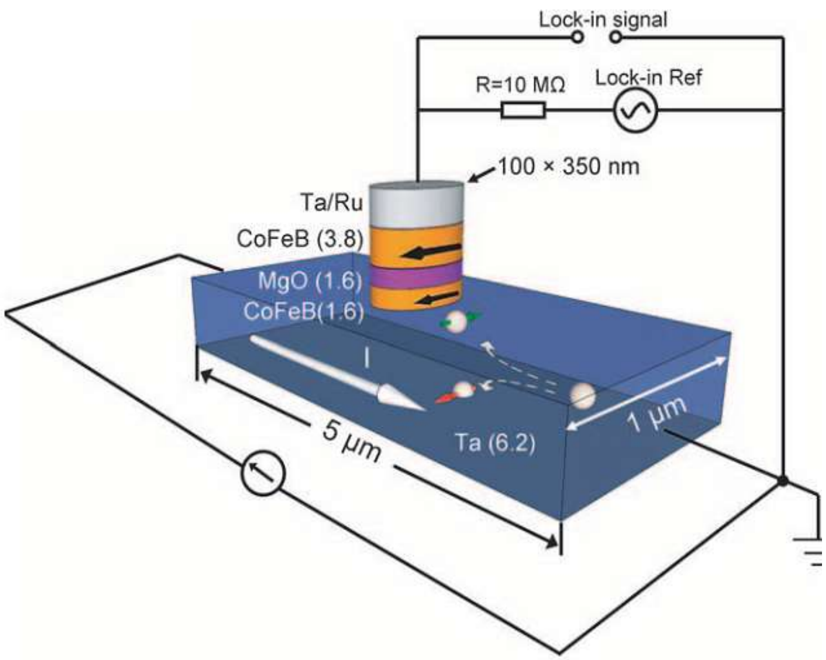
Precessing magnetization in FM layer pump spin current into NM layer (Angular momentum conservatoin)

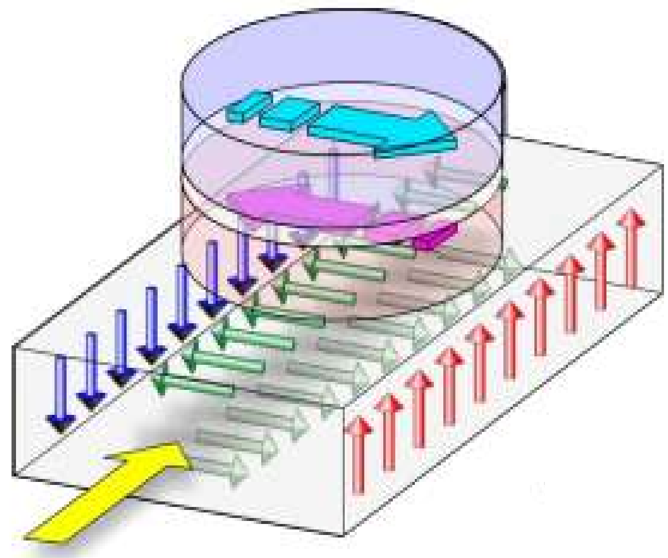
Spin momentum locking



Shiomi, et al, PRL (2014)

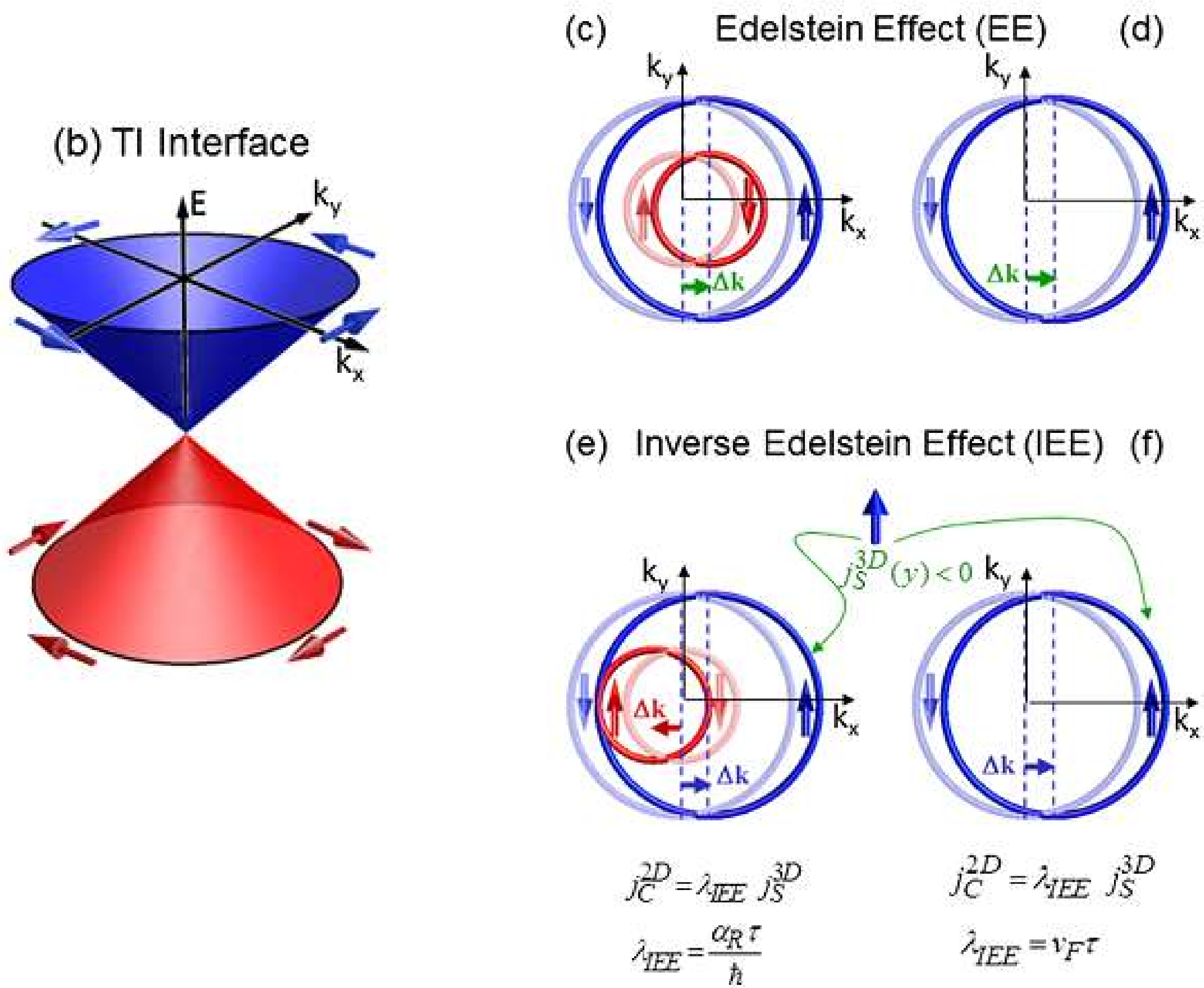
Spin orbit torque



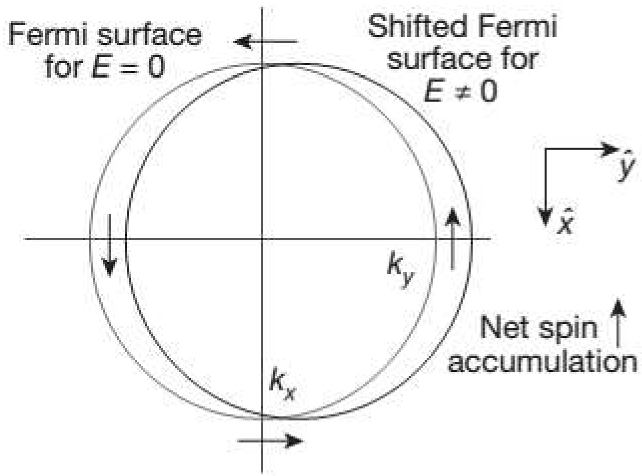


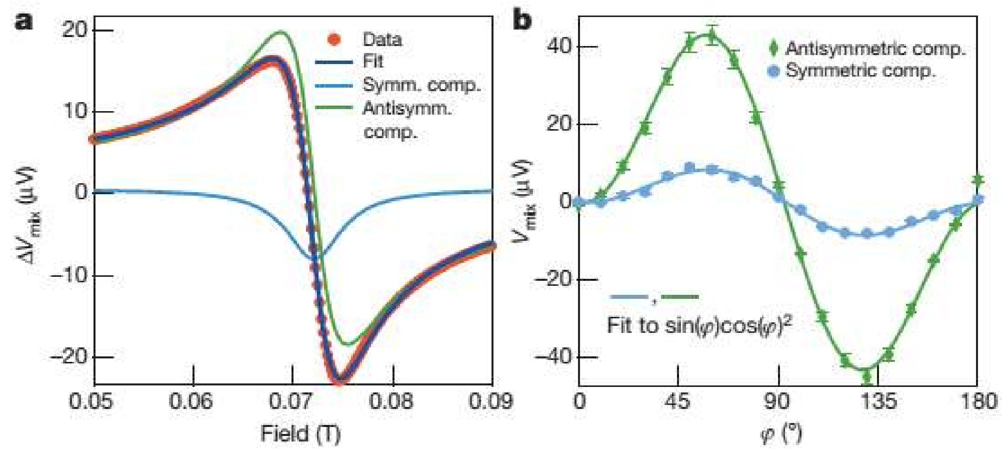
Liu, et al, Science (2012)

Spin orbit torque



Spin orbit torque





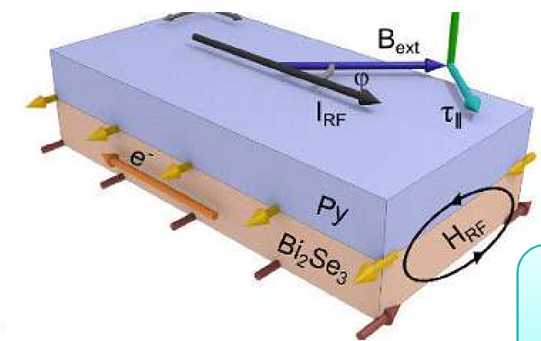


Table 1 | Comparison of room-temperature $\sigma_{s,\|}$ and $\theta_{s,\|}$ for Bi_2Se_3 with other materials

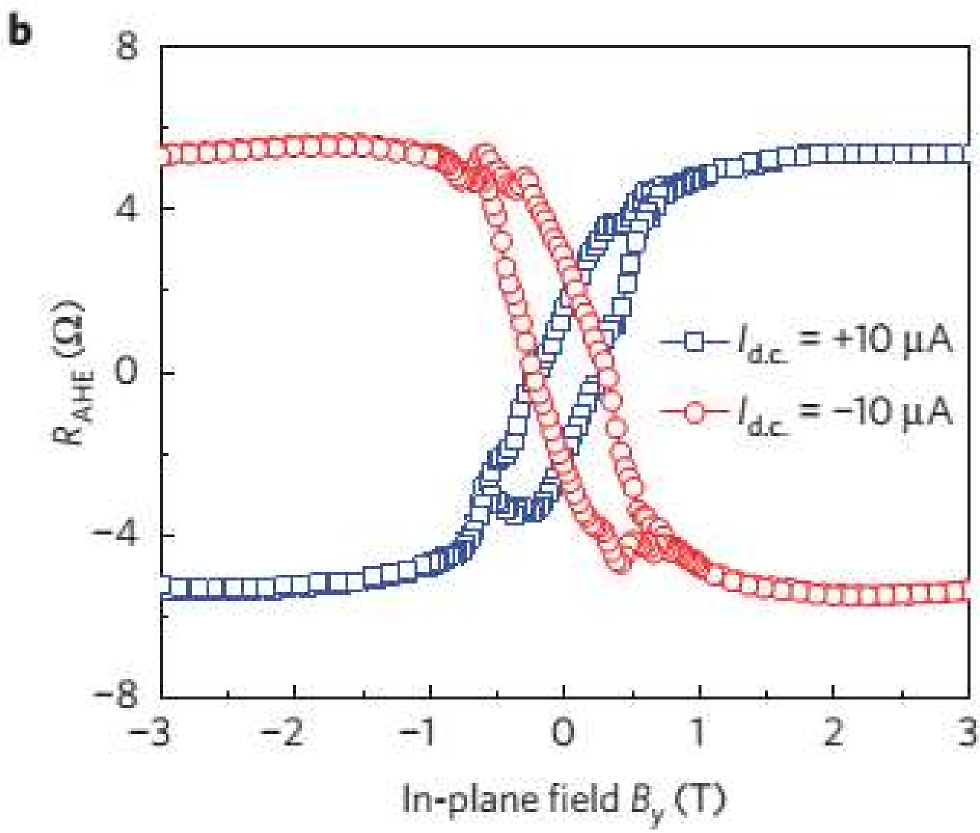
Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
	2.0–3.5	0.08	0.15	0.24	0.3
					1.8

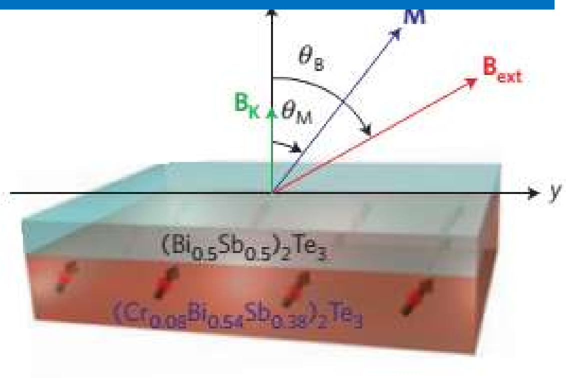
Spin Hall angle: 2.0-3.5

Mellink, et al. Nature (2014)

Spin orbit torque

$(Bi_{0.5}Sb_{0.5})_2Te_3$





T=1.9 K

SHA > 100

Fan, et al, Nature Mater. (2014)

Spin orbit torque

$(Bi_{0.5}Sb_{0.5})_2Te_3$

SHA > 100??

PRL **119,** 137204 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Current-Nonlinear Hall Effect and Spin-Orbit Torque Magnetization Switching in a Magnetic Topological Insulator

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[1]*Department of Applied Physics and Quantum-Phase Electronics Center (QPEC), University of Tokyo, Tokyo 113-8656, Japan*

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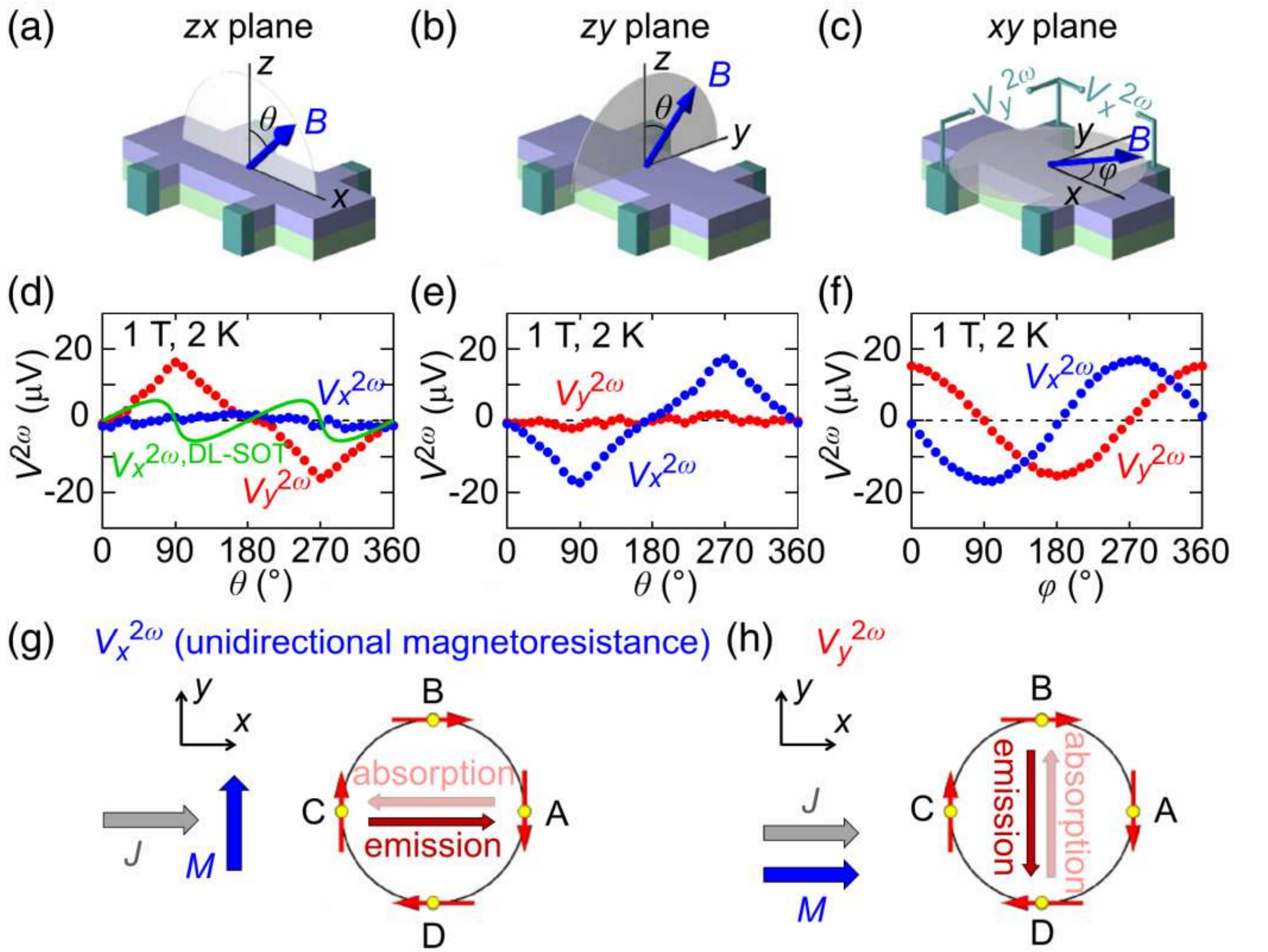
The current-nonlinear Hall effect or second harmonic Hall voltage is widely used as one of the methods for estimating charge-spin conversion efficiency, which is attributed to the magnetization oscillation by spin-orbit torque (SOT). Here, we argue the second harmonic Hall voltage under a large in-plane magnetic field with an in-plane magnetization configuration in magnetic-nonmagnetic topological insulator (TI) heterostructures, $Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3/(Bi_{1-y}Sb_y)_2Te_3$, where it is clearly shown that the large second harmonic voltage is governed not by SOT but mainly by asymmetric magnon scattering without macroscopic magnetization oscillation. Thus, this method does not allow an accurate estimation of charge-spin conversion efficiency in TI. Instead, the SOT contribution is exemplified by current pulse induced nonvolatile magnetization switching, which is realized with a current density of 2.5×10^{10} A m^{-2}, showing its potential as a spintronic material.

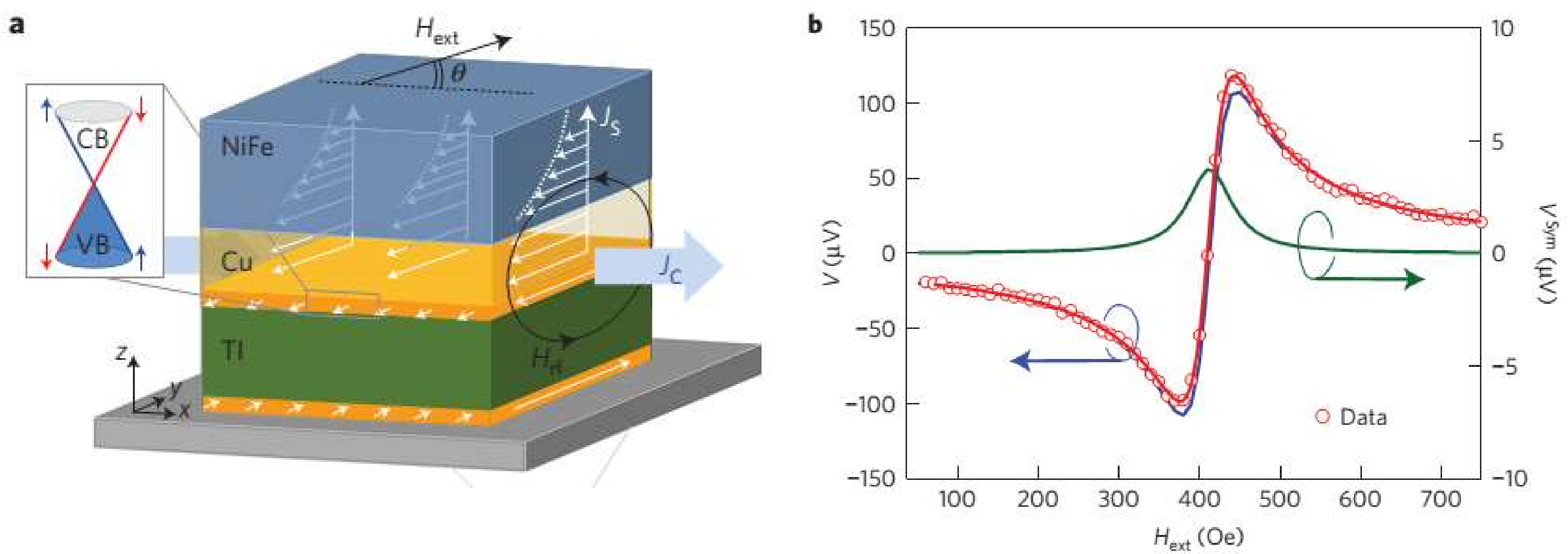
Yasuda, et al, PRL (2017)

Spin orbit torque

$(Bi_{0.5}Sb_{0.5})_2Te_3$

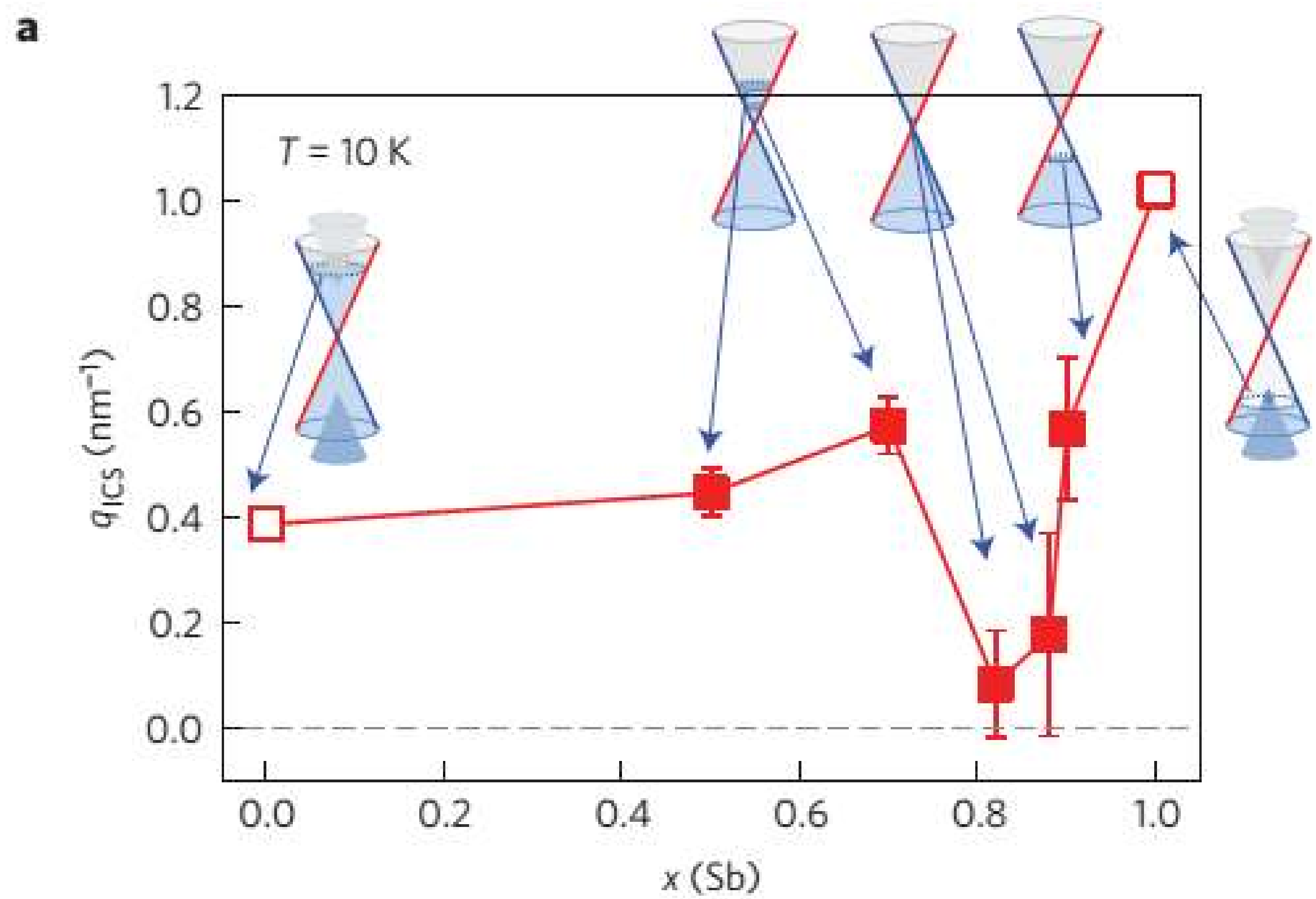


Gate tunable spin orbit torque

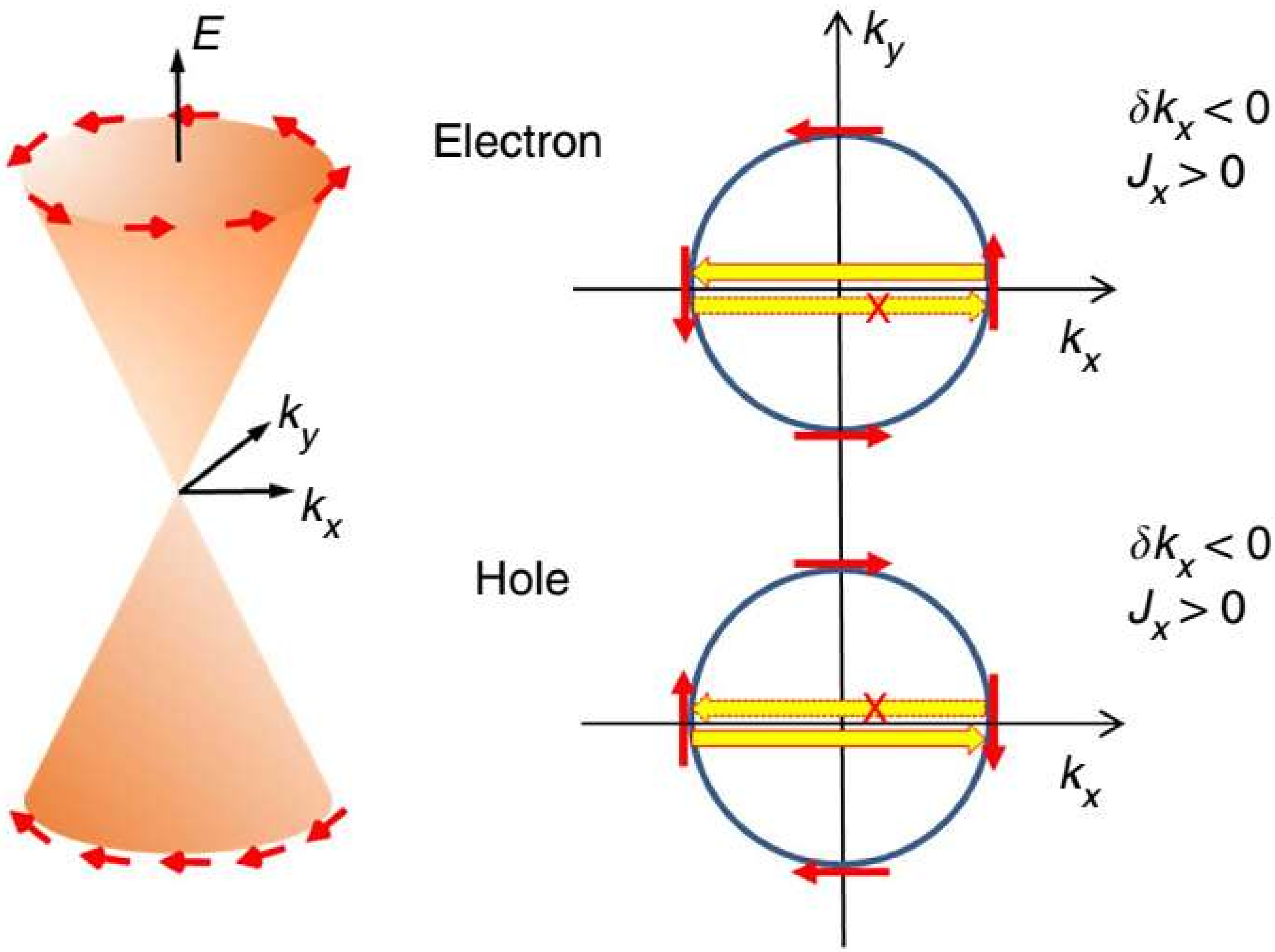


Kondou, et al, Nature Physics (2016)

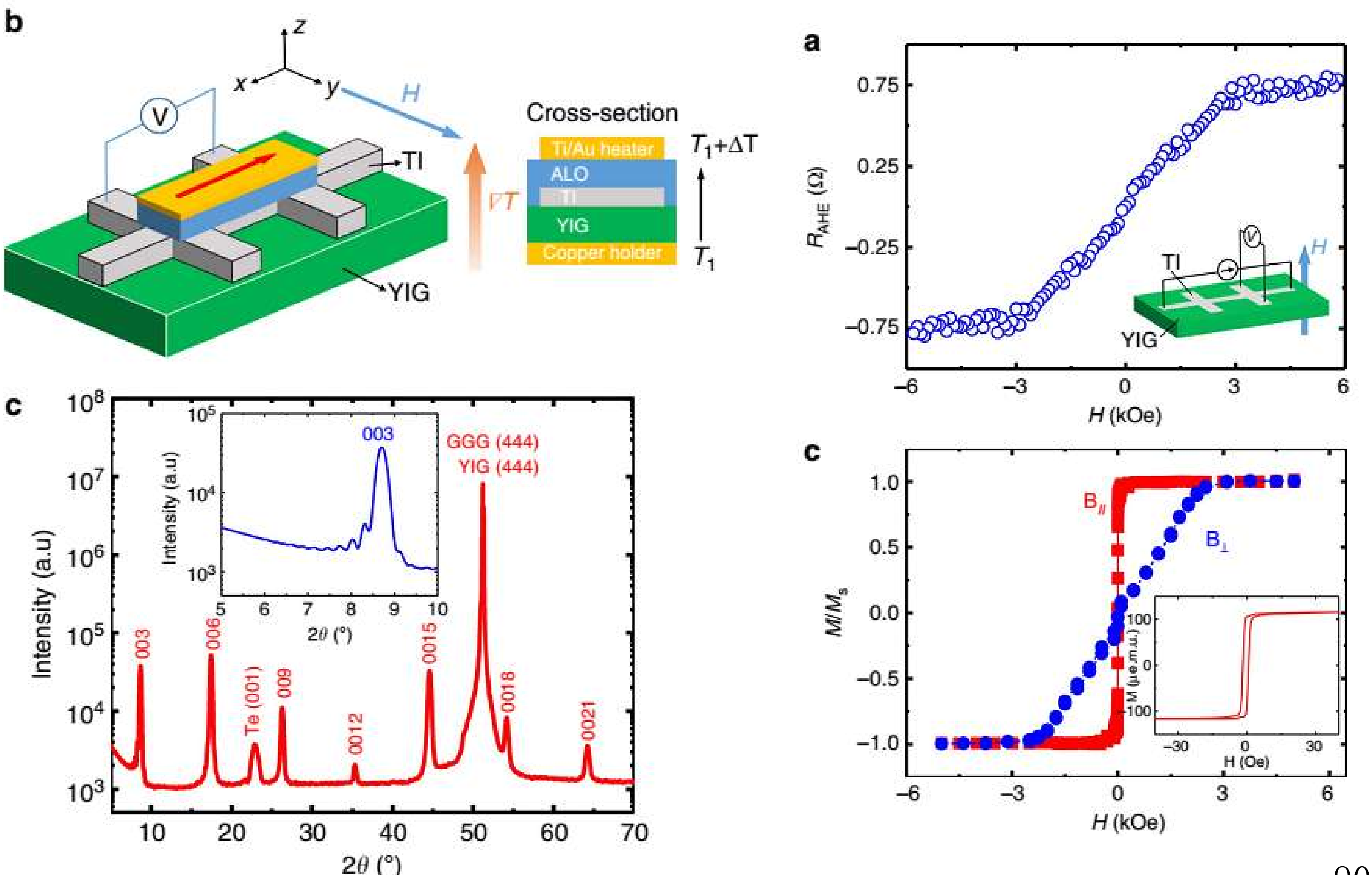
Gate tunable spin orbit torque



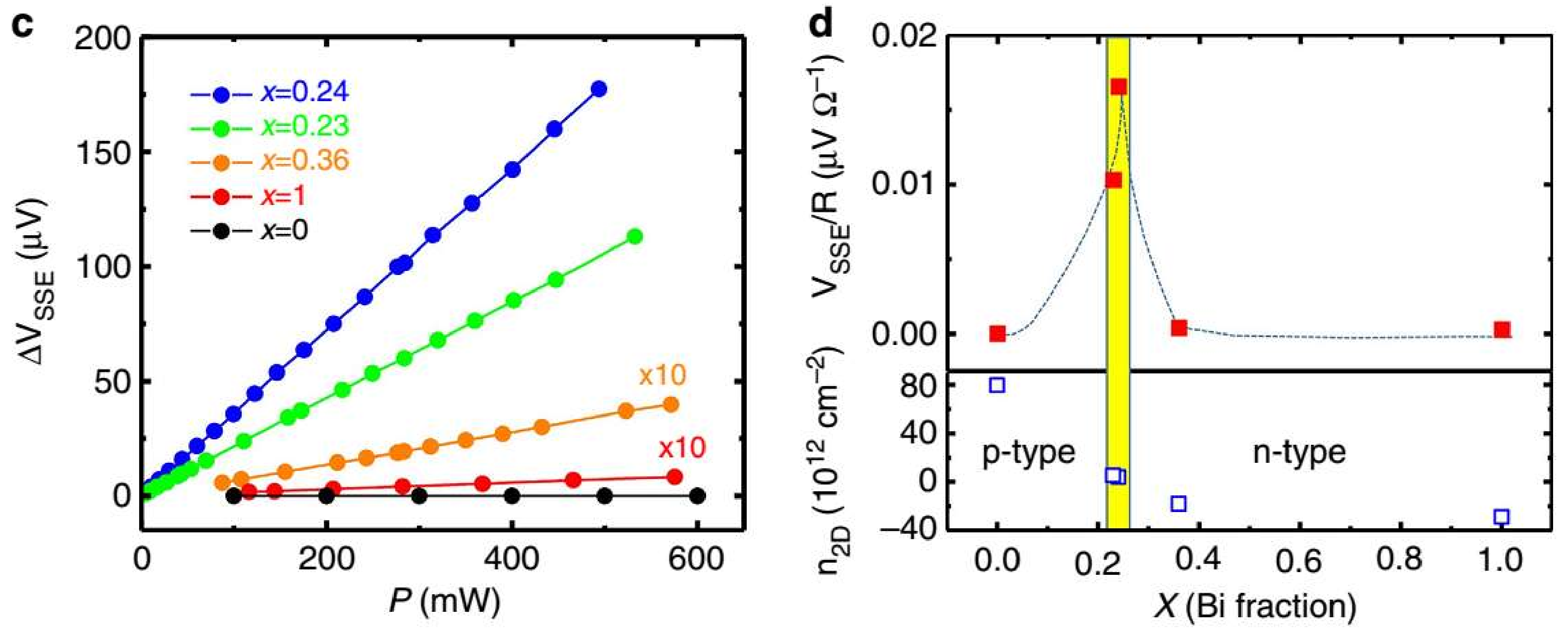
Spin Seebeck effect



Spin Seebeck effect



Spin Seebeck effect



Jinag, et al, Nature Commun. (2016)

Summary

1. Topology

2. Quantum anomalous Hall effect

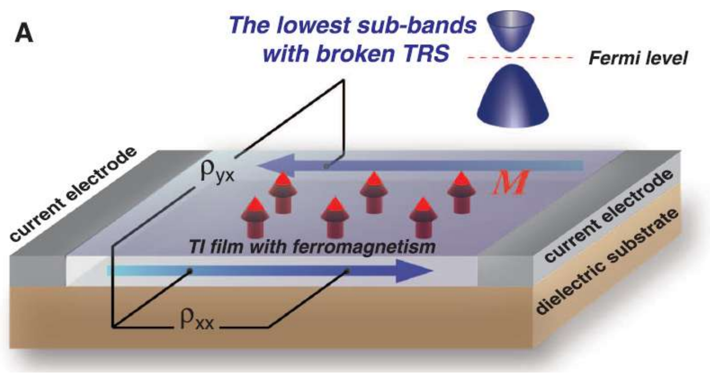
3. Skyrmions

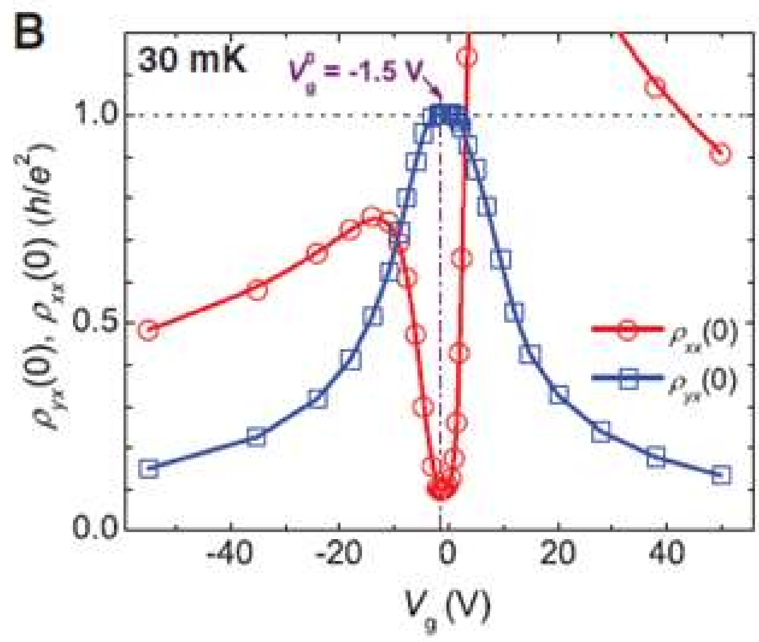
4. Spin-momentum locking of 3D TI

- **Spin injection**
- **Spin orbit torque**
- **Spin Seebeck effect**

Summary

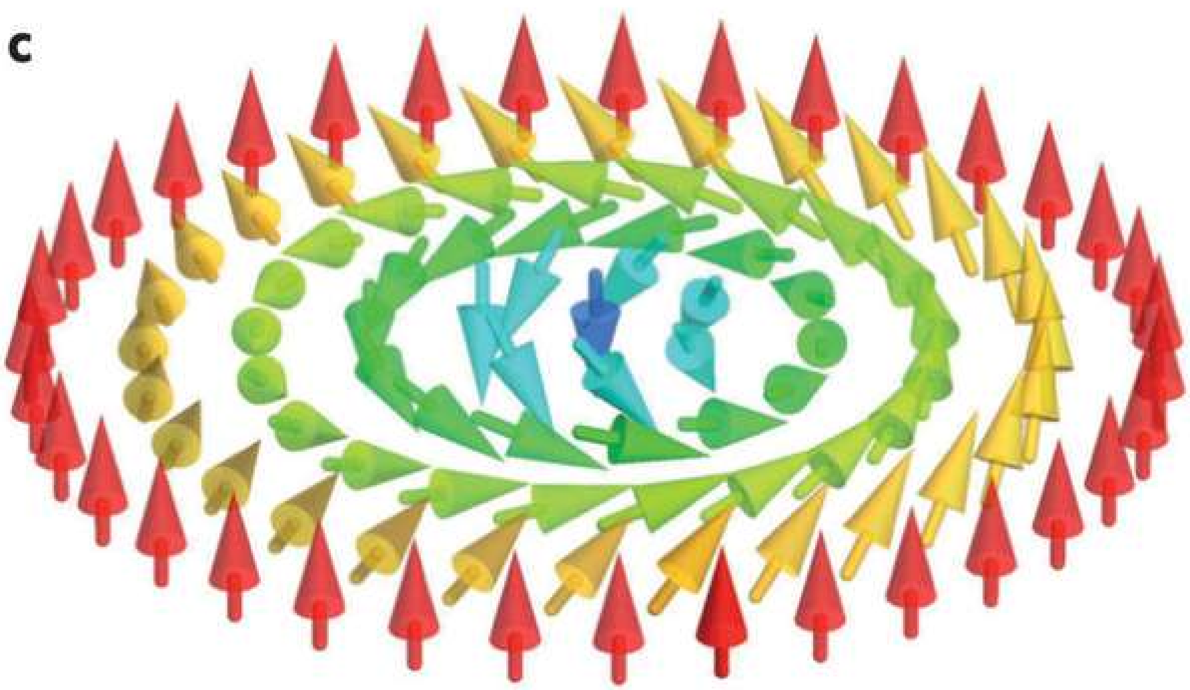
2. Quantum anomalous Hall effect



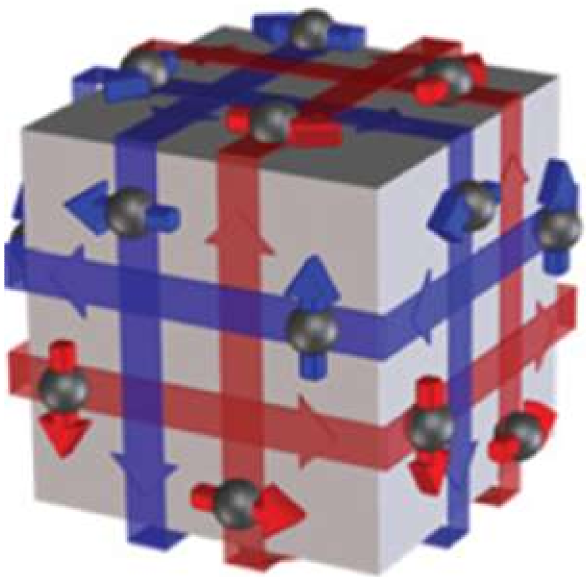


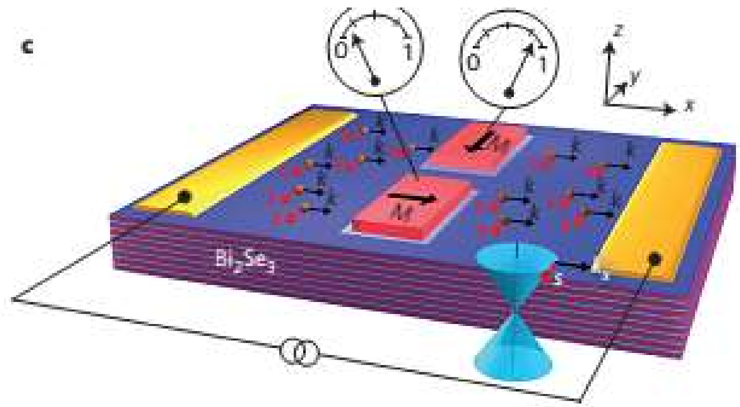
Summary

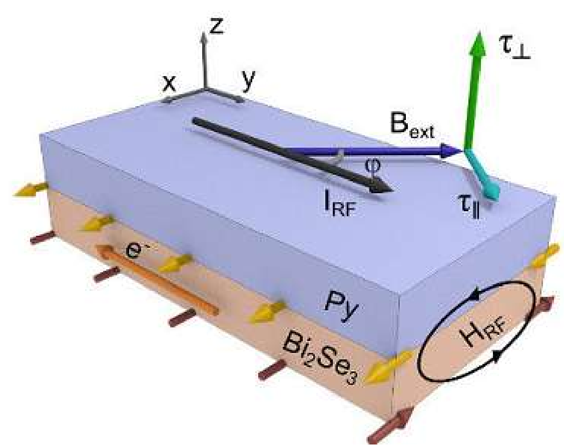
3. Skyrmions



4. Spin-momentum locking of 3D TI







最后两节课: Dec. 21th

Date	Group
Dec. 21st 10:10 am- 11:00 am	Topic: Magnon BEC 何梦云、李思衡、李娜、孙慧敏、陈文杰
Dec. 21st 11:10 am- 12:00 pm	Topic: Spin FET 张仕雄、丁石磊、梁栋、杨洁、朱鹏飞、赵嘉佶

最后两节课: Dec. 28th

Date	Group
Dec. 28th 10:10 am- 11:00 am	Topic: Quantum Spin liquids 吉源　孙恺伟　尚念梓　王一帆
Dec. 28th 11:10 am- 12:00 pm	Topic: Anomalous hall effect/spin hall effect 赵利利，王善，闫姣婕，齐少勉，李龙飞，刘震

下一节课: Dec. 14th

Chapter 8: AFM Spintronics

课件下载：
http://www.phy.pku.edu.cn/~LabSpin/teaching.html