Stockholm, June 21, 2019

Topological Insulators and Quantum Anomalous Hall Effect

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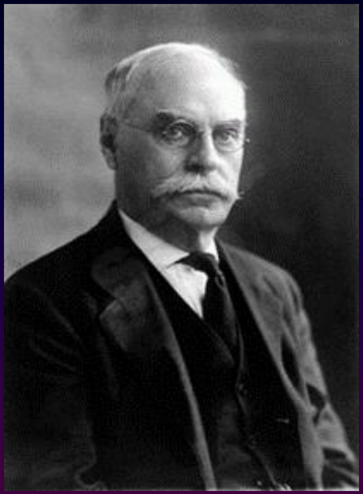
Tsinghua University

OUTLINE

- Introduction
- MBE-STM-ARPES of topological insulators
- Realization of Quantum Anomalous Hall Effect
- Summary

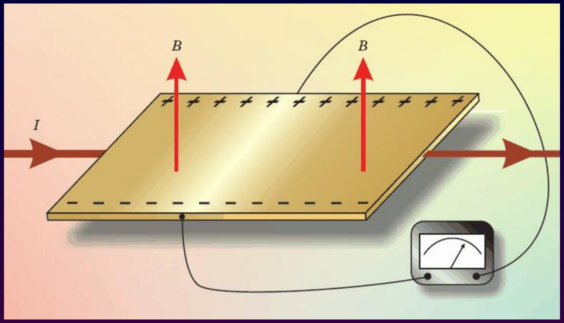
Hall Effect and Anomalous Hall Effect

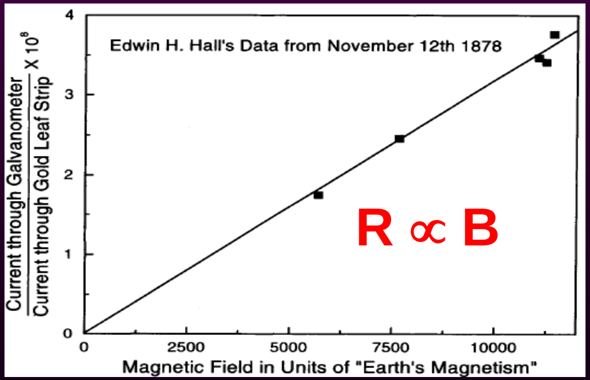


Edwin H. Hall

Hall Effect: 1879

(non-magnetic materials)

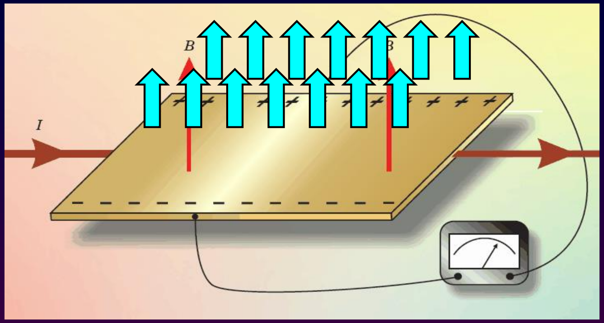


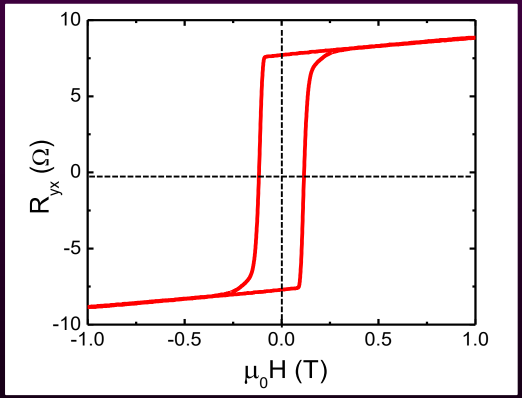


Linear dependence

Anomalous Hall Effect: 1881

(magnetic materials)





Magnetic property

Anomalous Hall Effect: Mechanism

Nagaosa, Sinova, Onoda, MacDonald, Ong,
Review of Modern Physics 2009

$$\sigma_{\rm AH} = (\sigma_{\rm int} + \sigma_{\rm sk} + \sigma_{\rm sj})$$

Spin-orbit coupling： intrinsic

R. Karplus, J. M. Luttinger, Phys. Rev. 95, 1154 (1954)

$$\rho_{\rm int} \propto \rho_{xx}^2$$

Skew scattering： extrinsic

J. Smit, Physica 24, 39 (1958)

$$\rho_{\rm sk} \propto \rho_{xx}$$

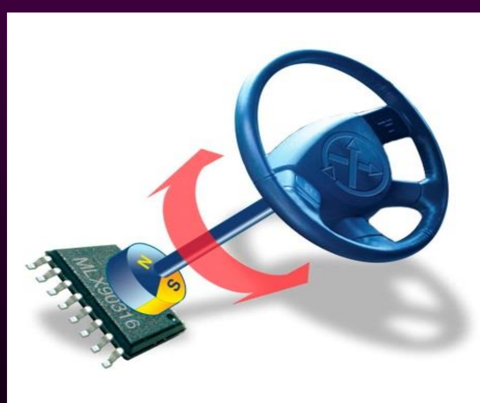
Side jump： extrinsic

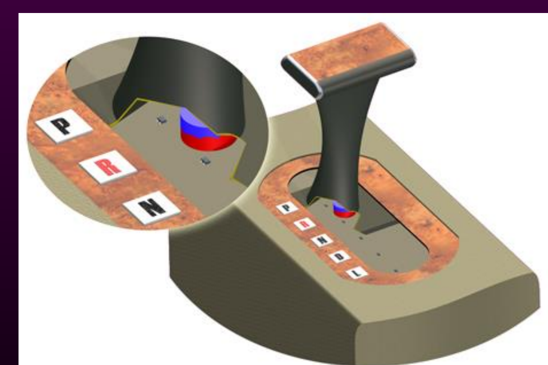
L. Berger, Phys. Rev. B2, 4559 (1970)

$$\rho_{\rm sj} \propto \rho_{xx}^2$$

Applications

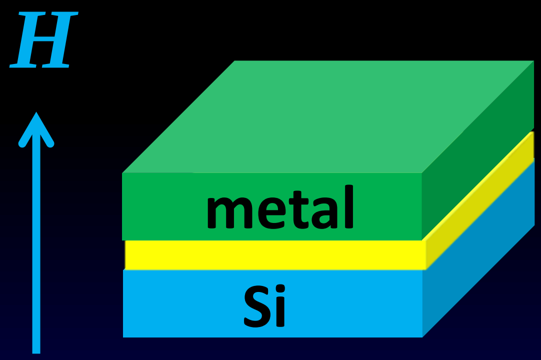
Hall effect
+ IC





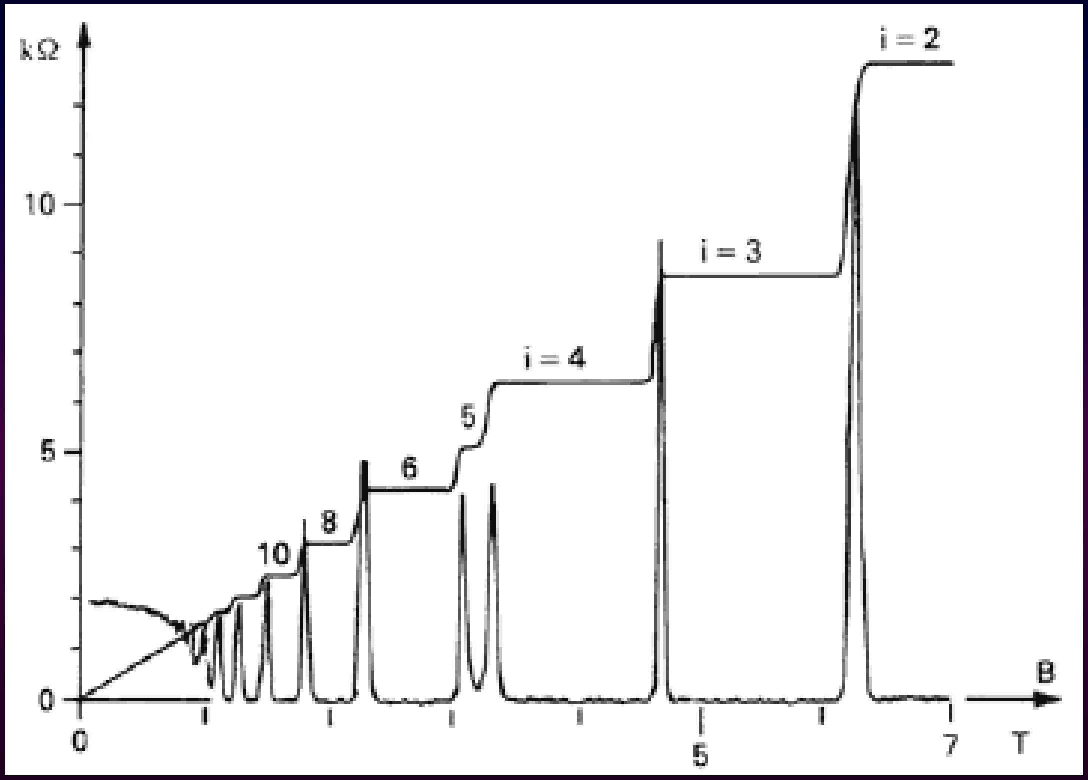
Integer Quantum Hall Effect

(1980)



2D electron gas

Klaus von Klitzing



$$\rho_{\mathrm{xy}} = h / ie^2$$
$$\rho_{xx} = 0$$

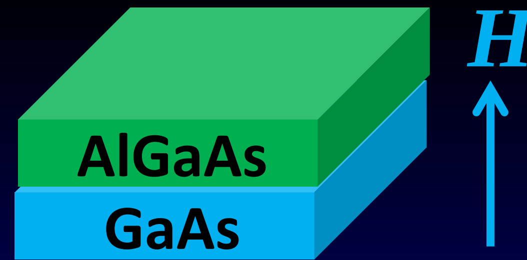
Fractional Quantum Hall Effect
(1982)

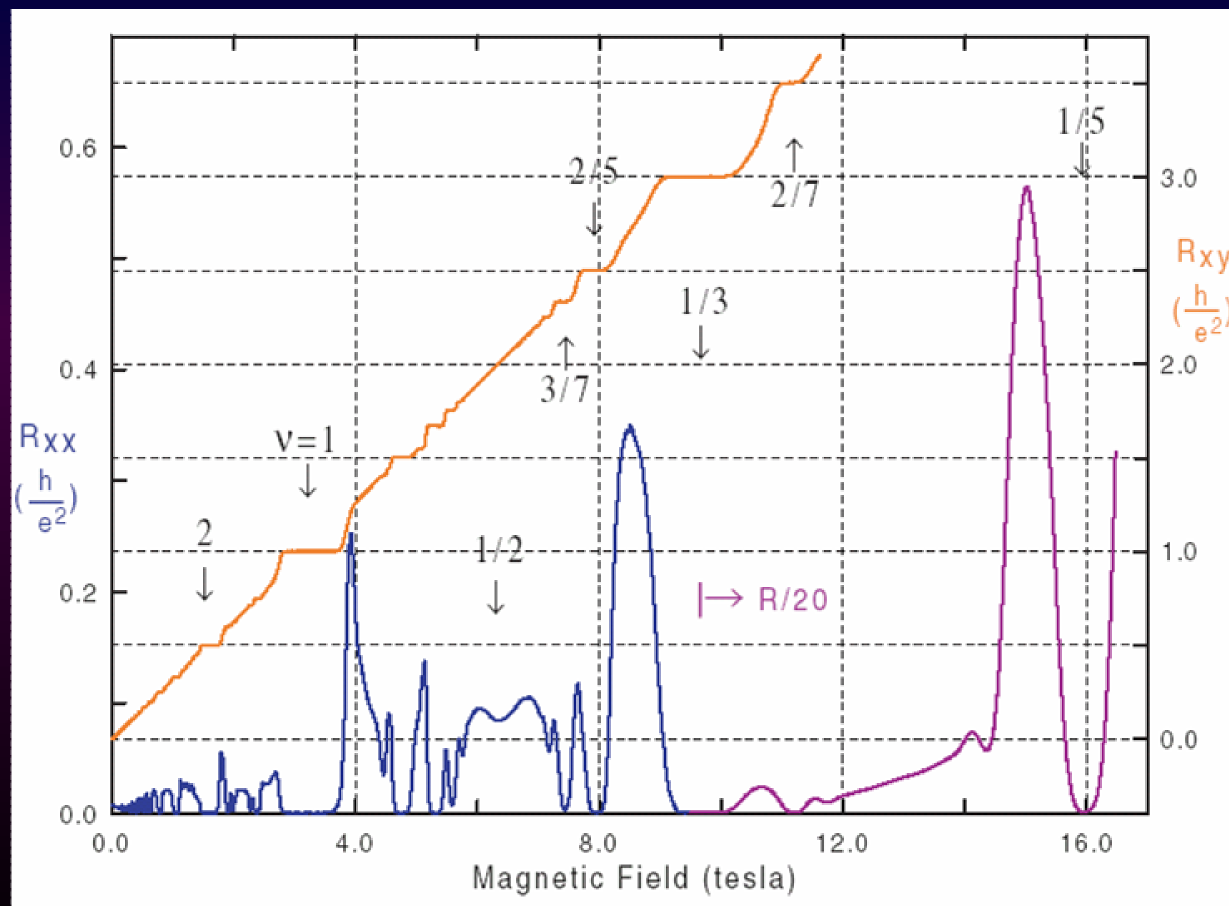
Tsui

Stormer

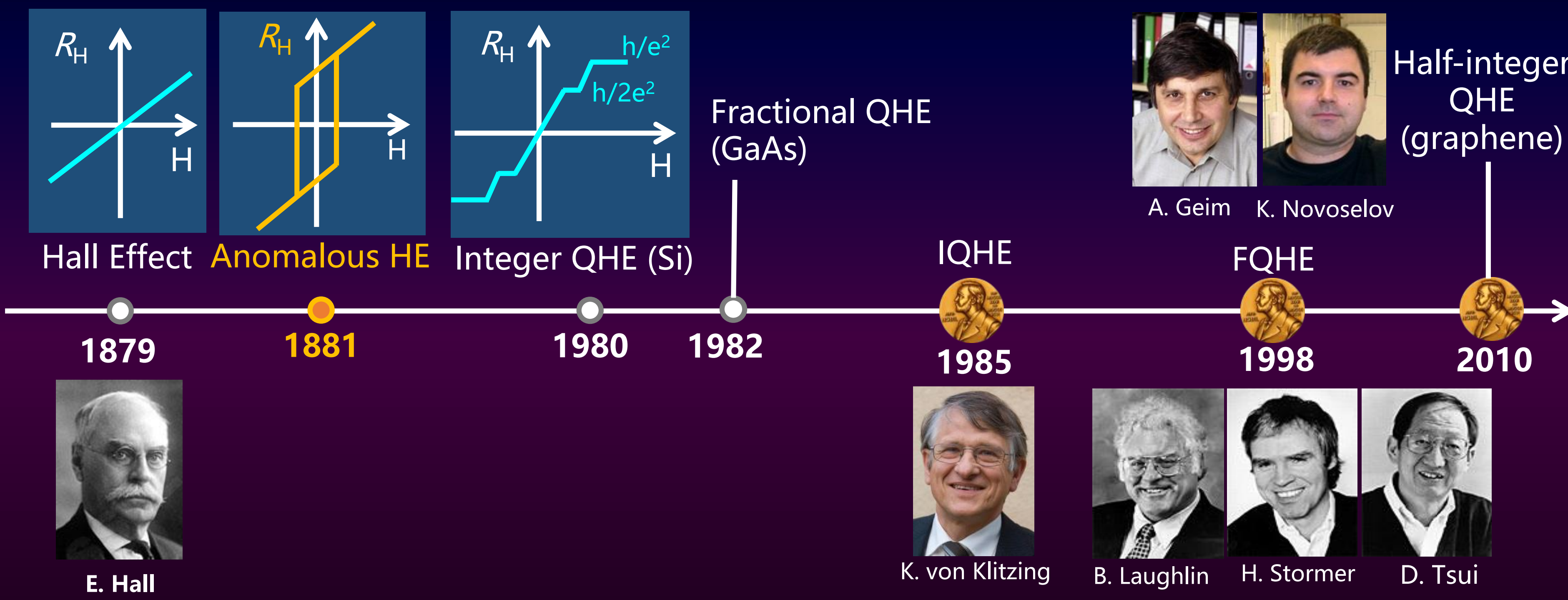
Laughlin

2DEG

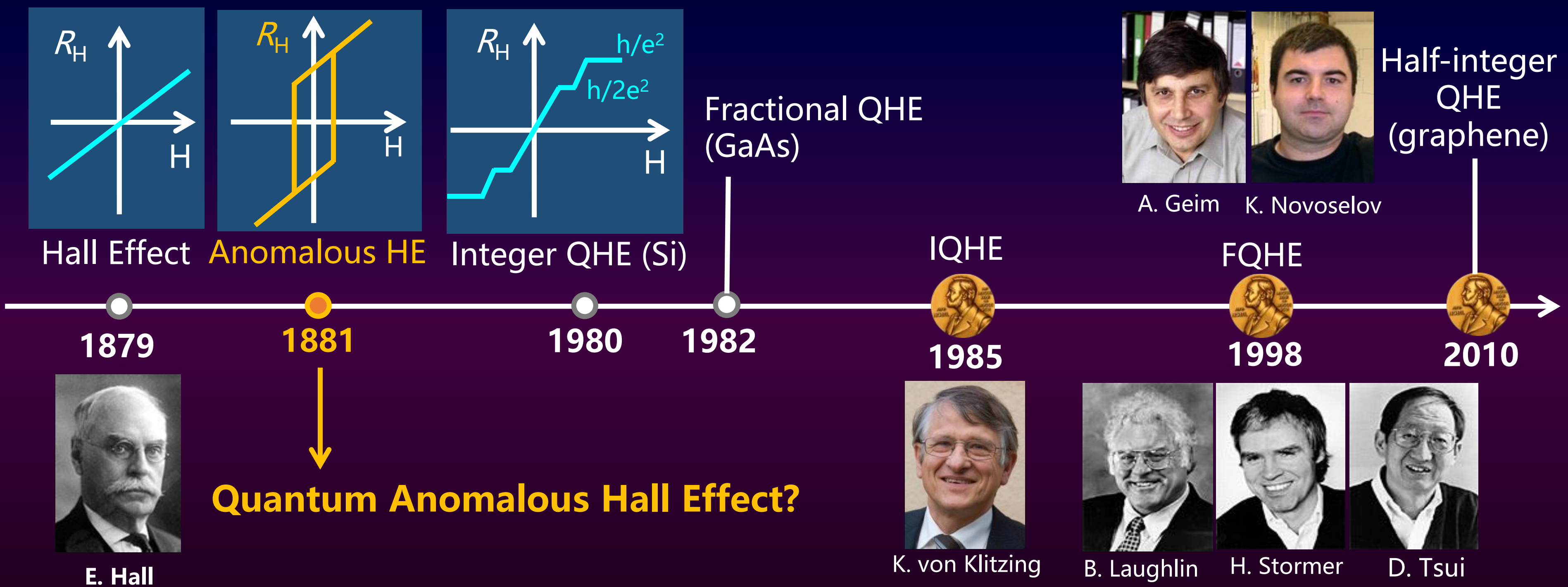




From Hall Effect to Quantum Hall Effects (QHE)



From Hall Effect to Quantum Hall Effects (QHE)



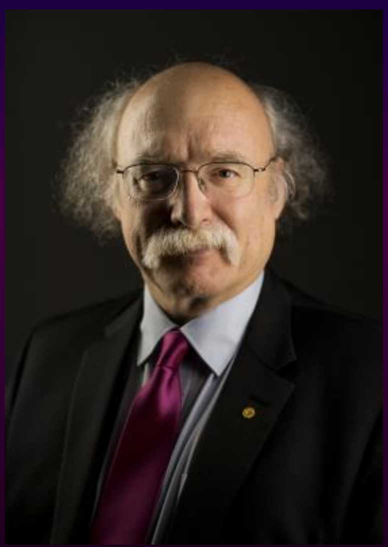
The first Theoretical Proposal for Quantum Hall Effect without Magnetic Field

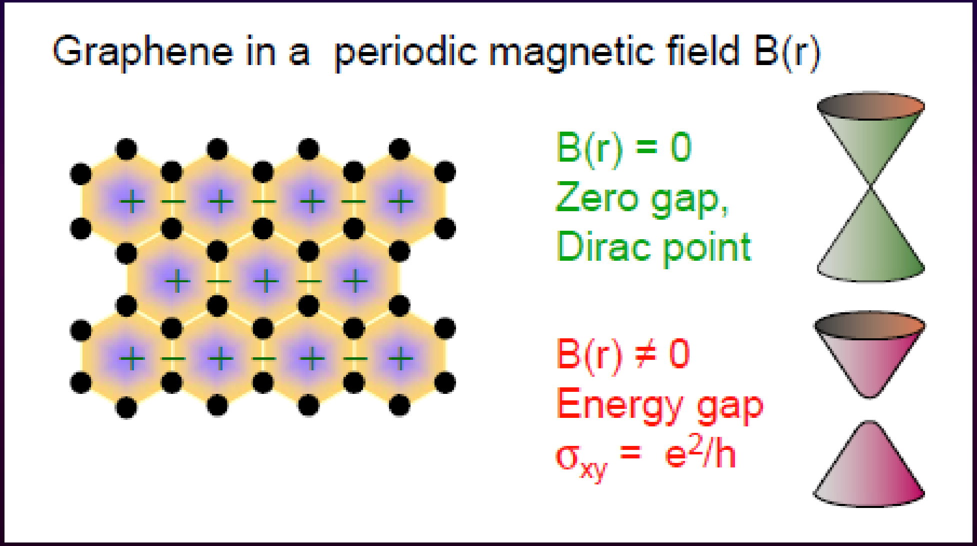
VOLUME 61, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1988

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

F. D. M. Haldane

Graphene with broken TRS

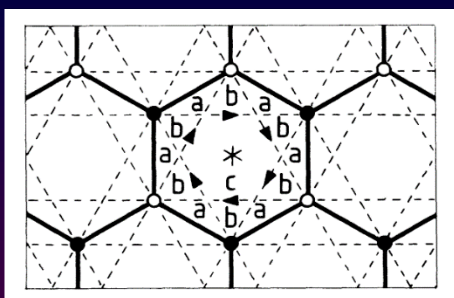


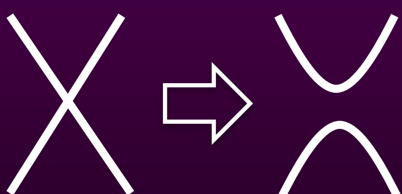


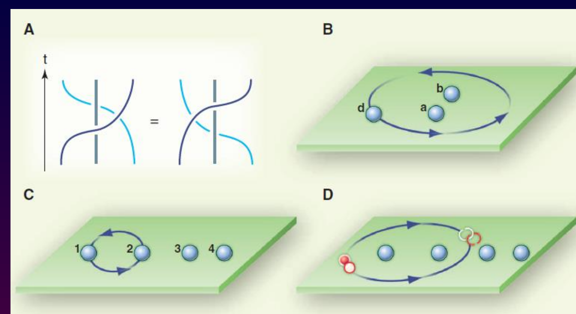
- Haldane conceived a model that will show QHE in zero magnetic field, it is now called the "Chern insulator"
- It is very abstract and way ahead of its time, but it is highly influential about 20 years later in the field of topological insulators

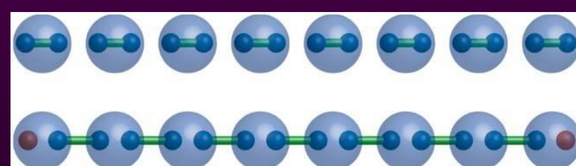
Topological States of Matter

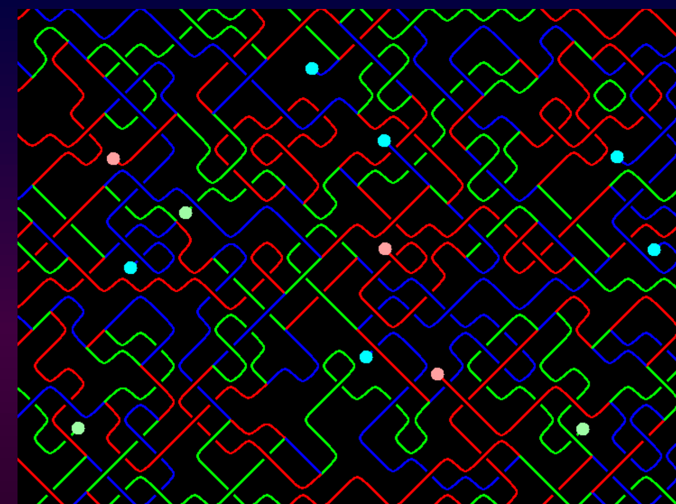
Quantum anomalous Hall effect, Haldane phase, Non-abelion anyons, Topological order, String-net condensation……











Zoo of quantum-topological phases of matter

X. –G. Wen Rev. Mod. Phys. 89, 041004 (2017)


Haldane


X.-G. Wen


S. –C Zhang


Kitaev


Moore


Read

…

Topology

$\chi = 2$

$\chi = 0$

$$\frac{1}{2\pi}\oint_S K d\mathbf{A} = \chi$$

K: Gauss curvature

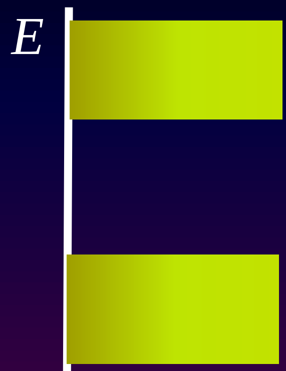
χ: Euler number

Gauss-Bonnet theorem

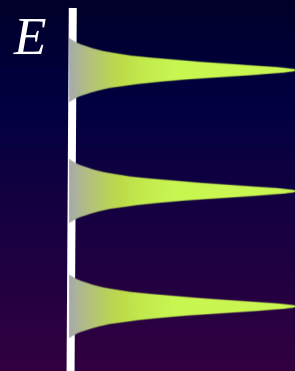
Gauss

Bonnet

Topological property of the electronic structure of a 2D insulator



$C = 0$



$C = 1$

$$\frac{1}{2\pi}\oint_{BZ}\Omega d\mathbf{k} = C$$

Ω: Berry's curvature

C: Chern number

"TKNN"

T: Thouless

Nobel laureate in Physics 2016

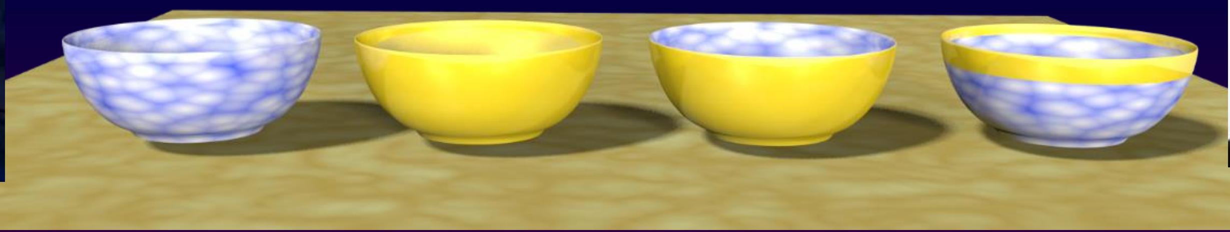
Berry

Chern

2005: Topological Insulators

Topological Insulators (2005—)

Hasan & Kane: Rev. Mod. Phys. 2010
Qi & Zhang: Rev. Mod. Phys. 2011



Quantum Anomalous Hall Effect

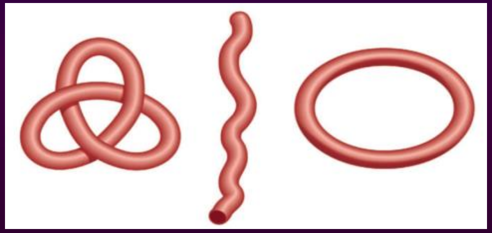
Quantum Spin Hall Effect

Majorana Fermions

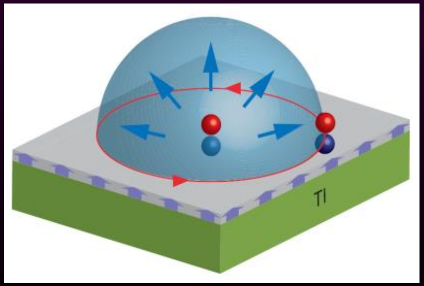
Magnetic Monopole and Dyon

TME Effect and Axion

………………

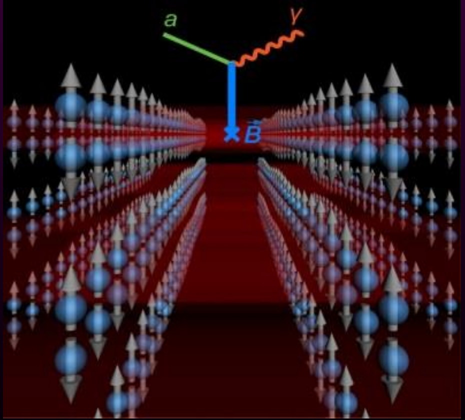


J. Moore, Nature 2010



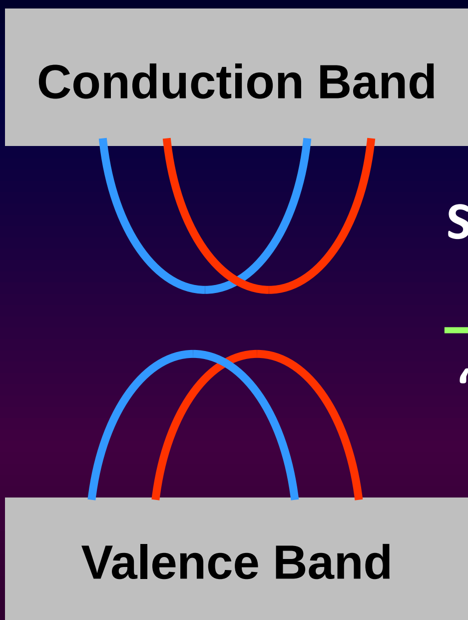
Qi & Zhang, Science 2009

Dark matter on desktop
Wilczek, Nature 2009



Ordinary versus Topological Insulators

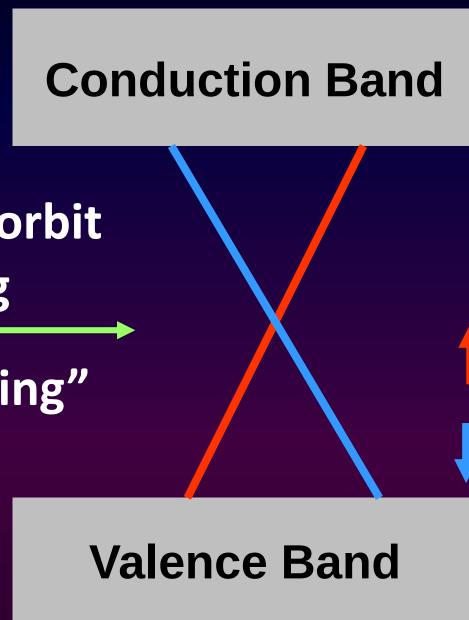
Ordinary Insulator



Strong spin-orbit coupling

"band twisting"

Topological Insulator

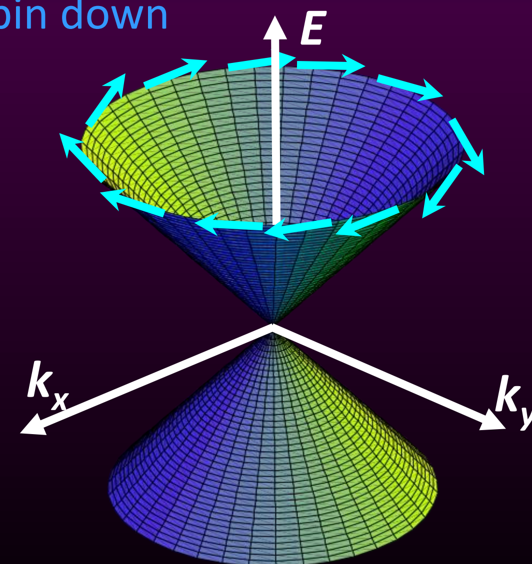


$$H = c\vec{\alpha} \bullet \vec{p} + mc^2\beta$$

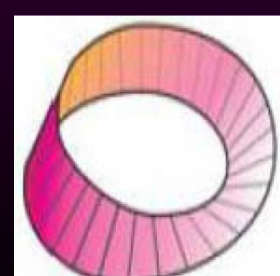
$$H = c\vec{\sigma} \bullet \vec{p} \quad (\text{m=0})$$

↑ Spin up

↓ Spin down



Rashba Spin-Orbit Splitting of Surface States



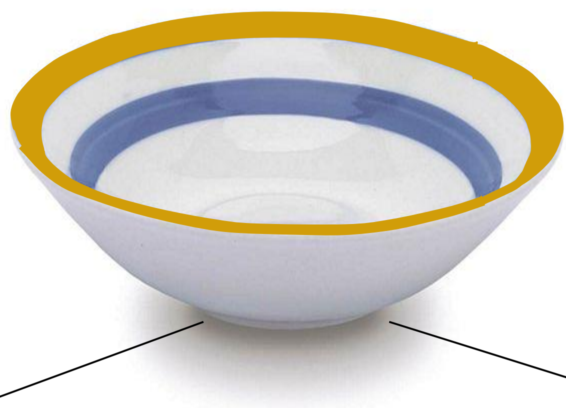
Time reversal symmetry, Strong S-O coupling

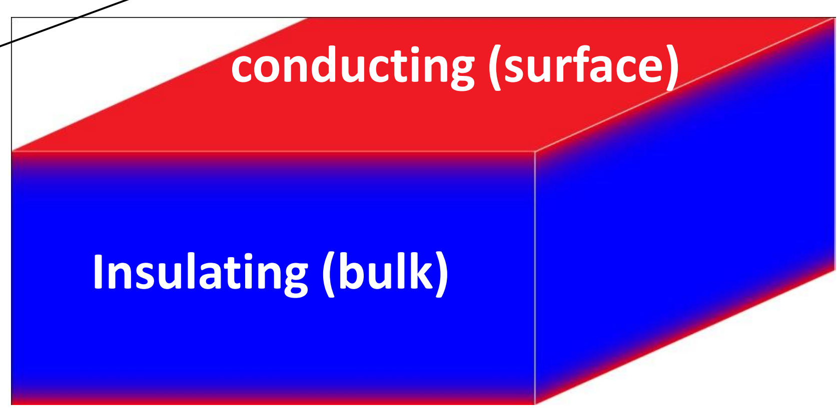
Classification of Materials (new)

Conductor

Topological Insulator

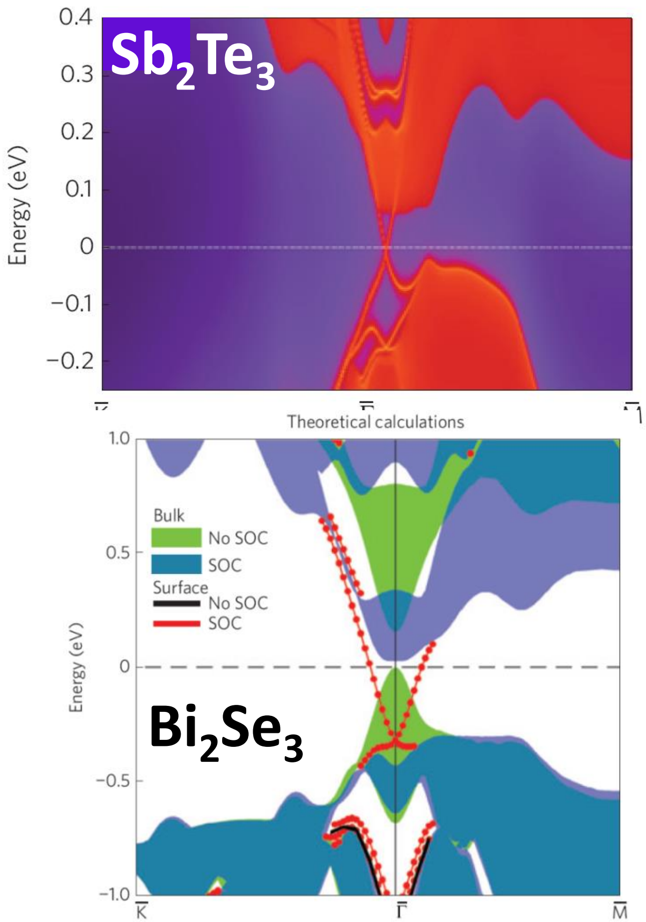
Insulator





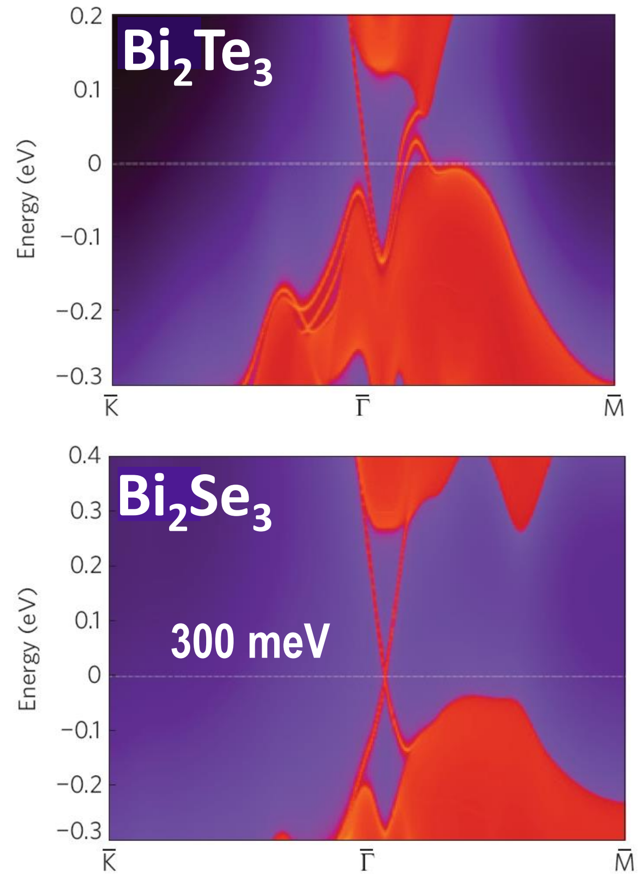
Spin-Orbital Coupling

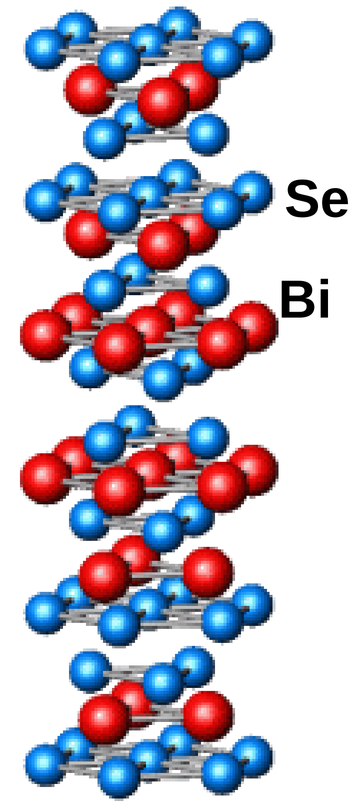
3D Topological Insulators: Bi_2Se_3, Bi_2Te_3, Sb_2Te_3



Xia et al., Nat. Phys. 5, 398 (2009)

Hasan group





Zhang et al., Nat. Phys. 5, 438 (2009)

Shoucheng Zhang group

Electron Band Structure of 3D TI by ARPES

Bi_2Te_3

Fisher (Stanford)

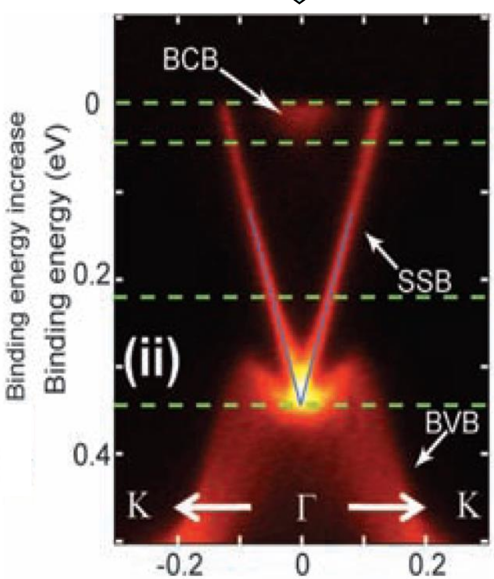
Bi_2Se_3

Cava (Princeton)

n-type conductor

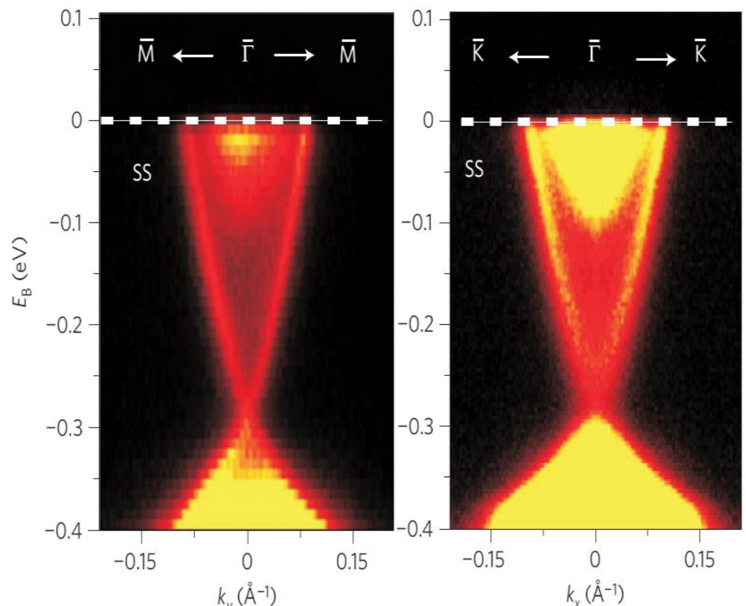
(Se vacancies)

(Similar to that in ZnO)



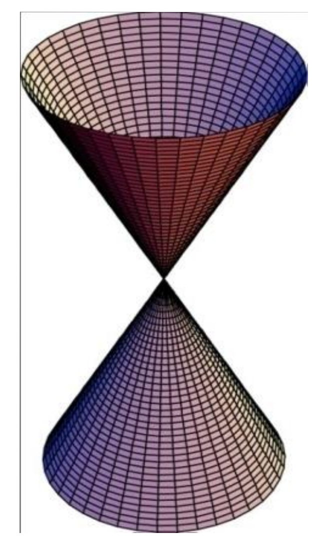
Chen et al., Science 2009

Zhixun Shen (Stanford)



Xia et al., Nat. Phys. 2009

Hasan (Princeton)



Dirac Cone

Topological Insulator Material

"insulator" by definition: Bulk insulating
Surface metallic (2D)

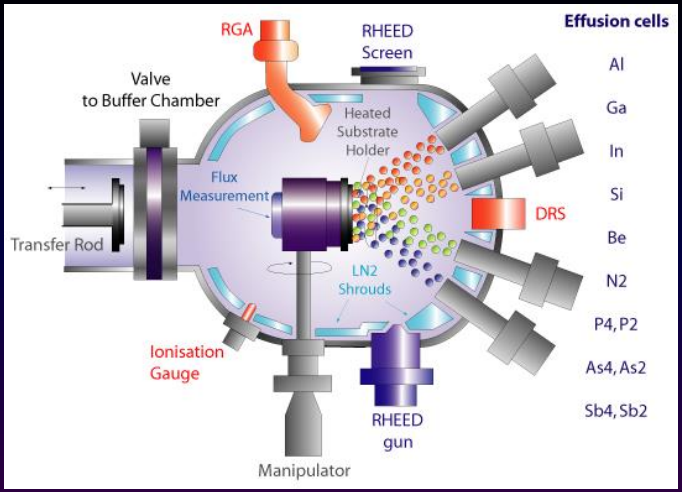
(real space)

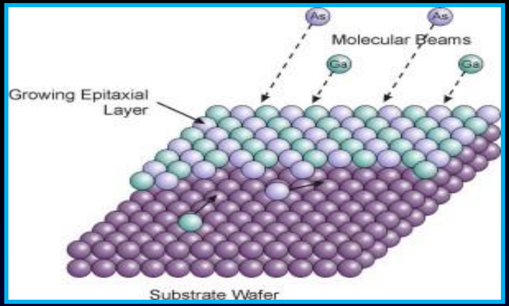
If the bulk is conducting, it is difficult to measure the transport property of its surface with exotic topological property.

↓

High quality:
low defect/impurity density

Molecular Beam Epitaxy (MBE)
(Cho & Arthur, 1970)



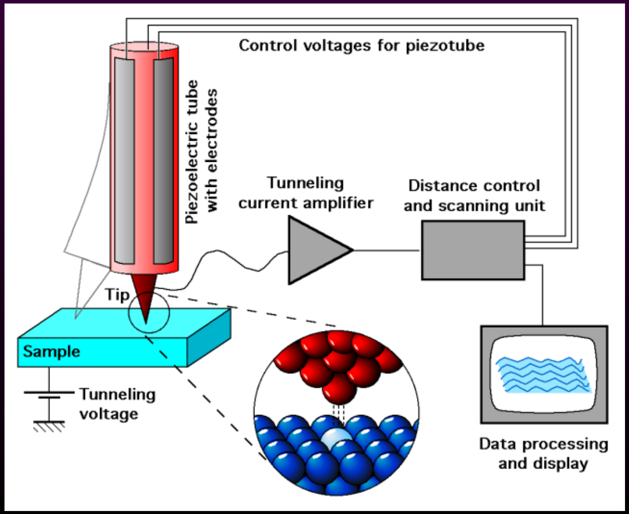


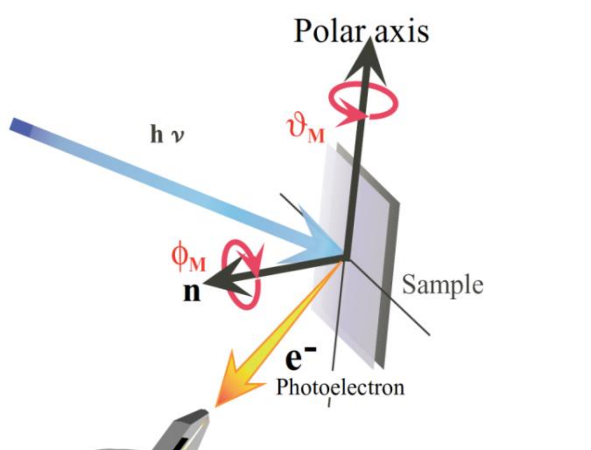
Atomic-Level

+

Angle-Resolved Photoemission Spectroscopy (ARPES)

Scanning Tunneling Microscope (STM)
(Binnig & Rohrer, 1981)



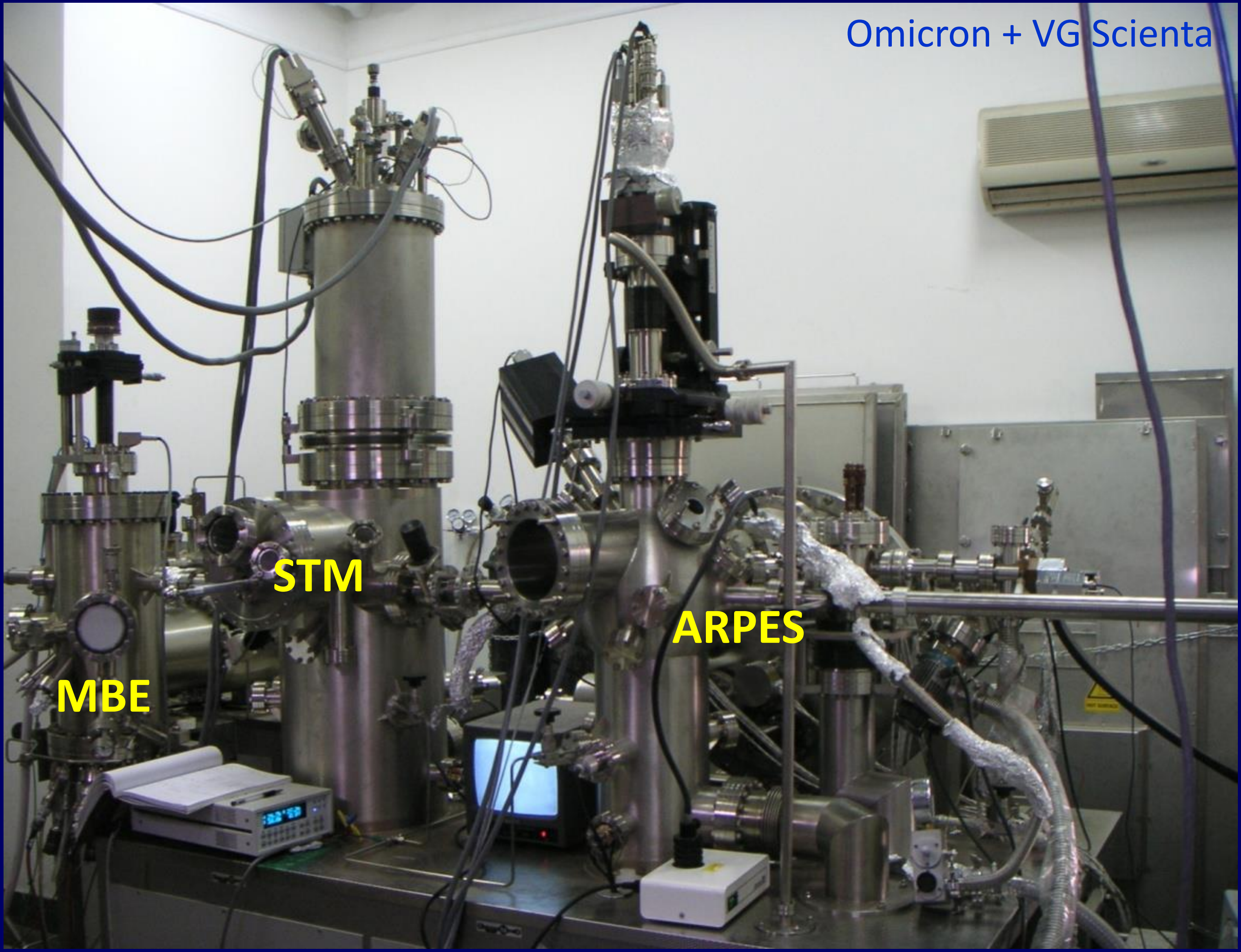


$$E_k = h\upsilon - W - E\,(k_{//})$$

E_k : kinetic energy
$h\upsilon$: photon energy
W : work function

$E(k_{//})$: band dispersion

MBE-STM-ARPES



OUTLINE

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Establishment of MBE growth conditions

Y. Y. Li et al., Adv. Mater. 2010

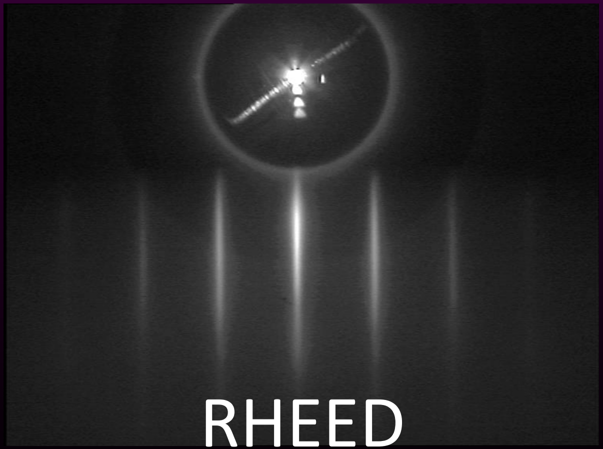
Growth rules:

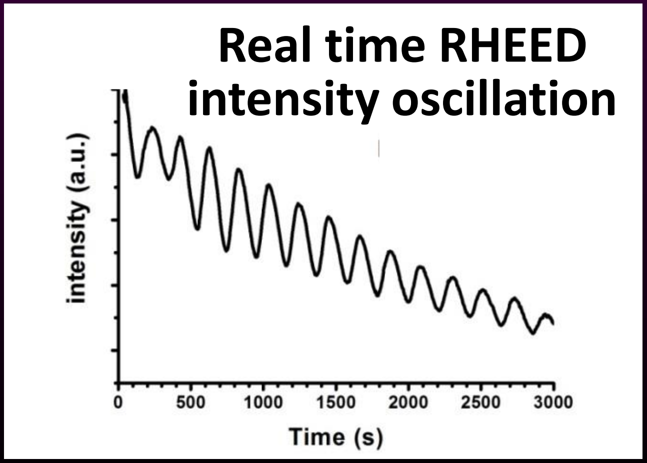
High VI (Te/Se) flux

$T_{Bi} >> T_{Sub} > T_{Te/Se}$

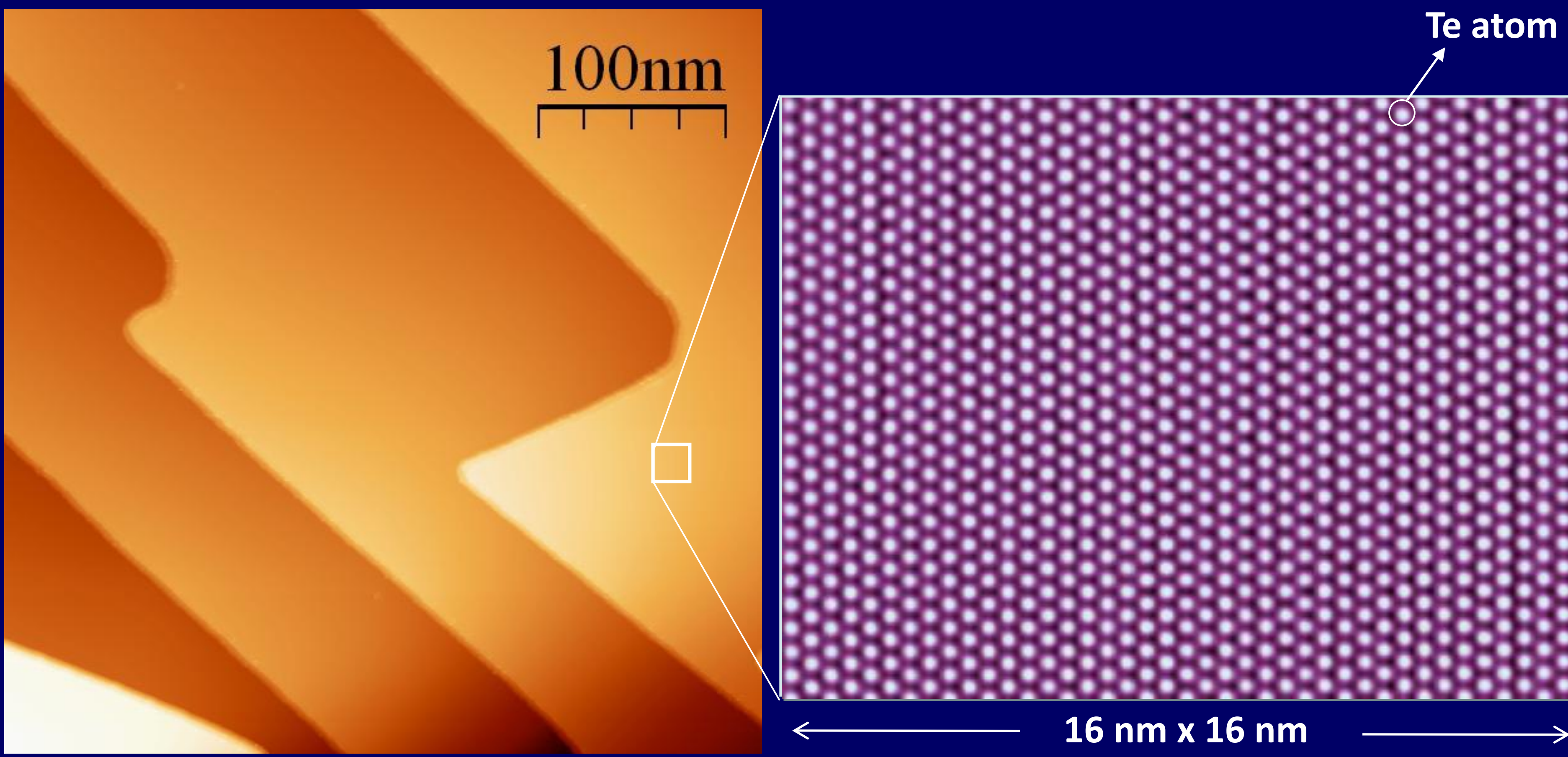
(1) Stoichiometric: low impurities

(2) Layer-by-layer: flat & single crystalline



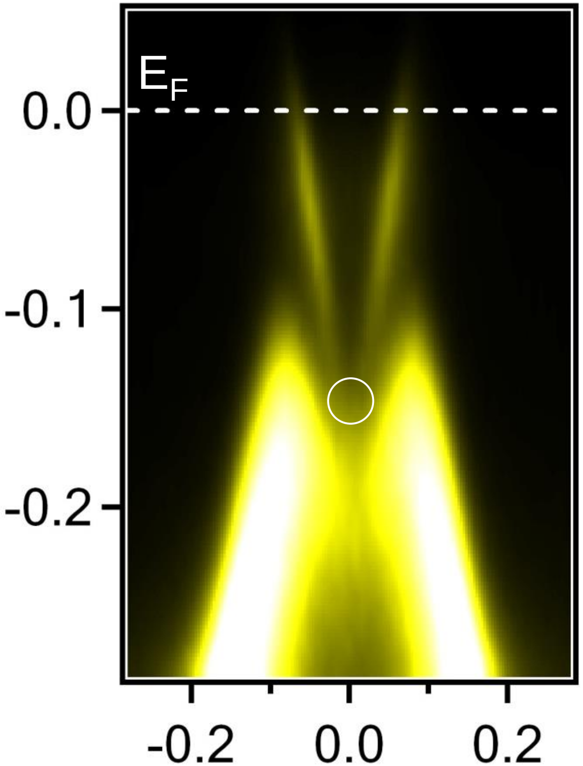


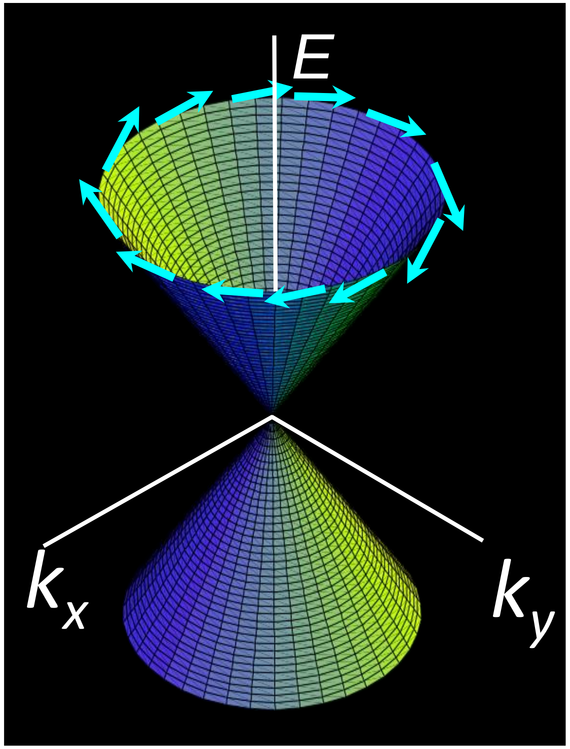
Atomically flat Bi_2Te_3 films by MBE



Y. Y. Li et al., Adv. Mater. (2010)
G. Wang et al., Adv. Mater. (2011)
X. Chen et al., Adv. Mater. (2011)

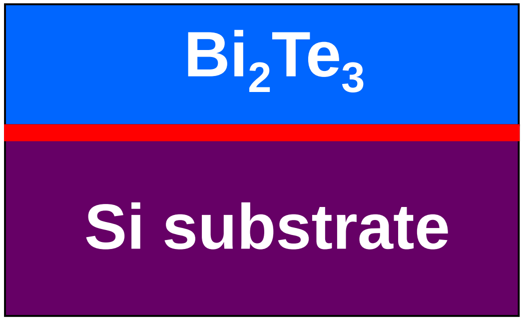
ARPES: Bi_2Te_3 band structure





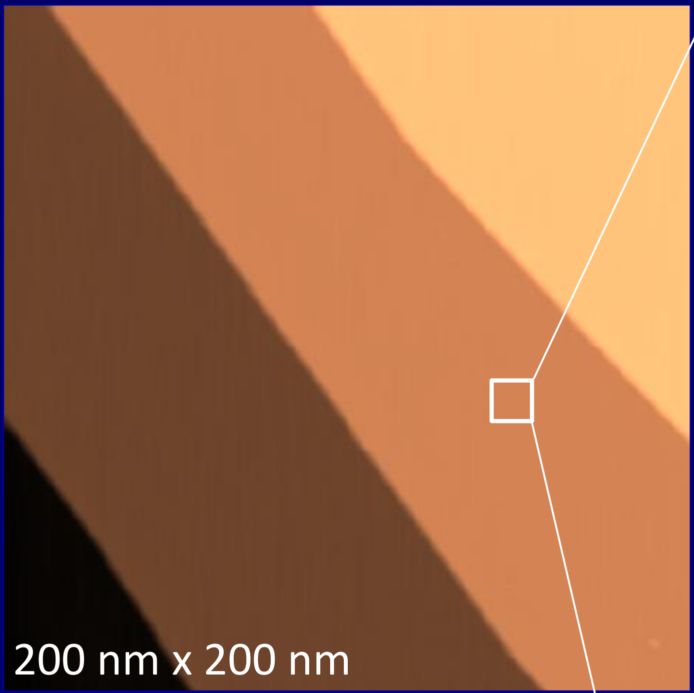
Experimentally confirmed:

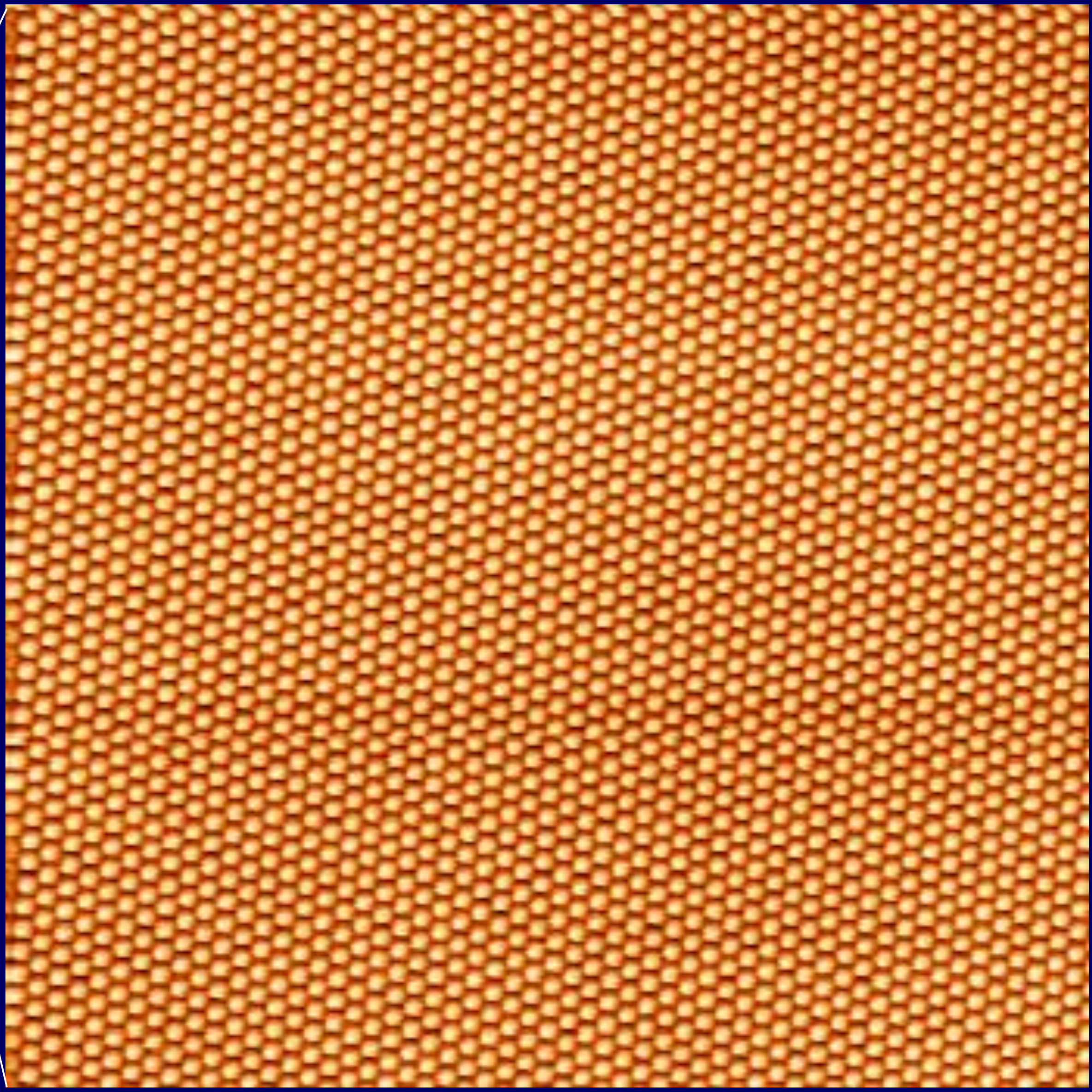
Massless Dirac Cone

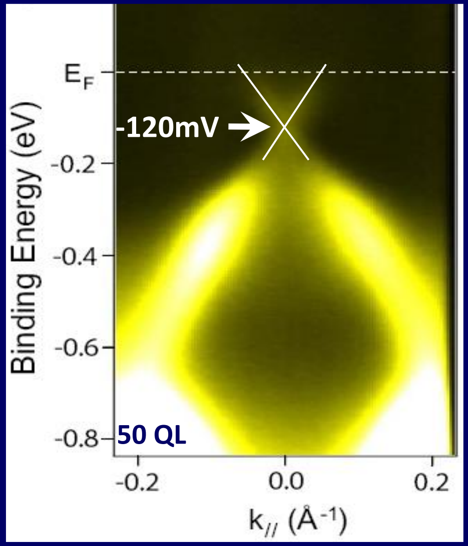


Insulating topological insulator

Atomically flat Bi_2Se_3 films on graphene by MBE



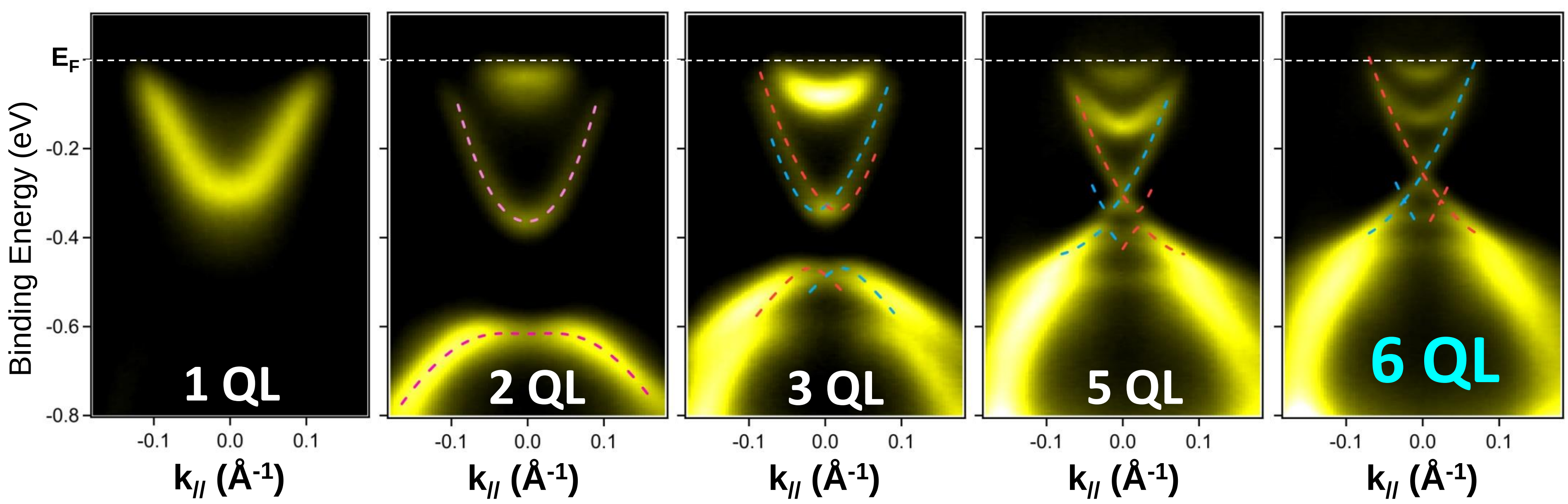




Yi Zhang et al., Nature Physics 6, 584 (2010)

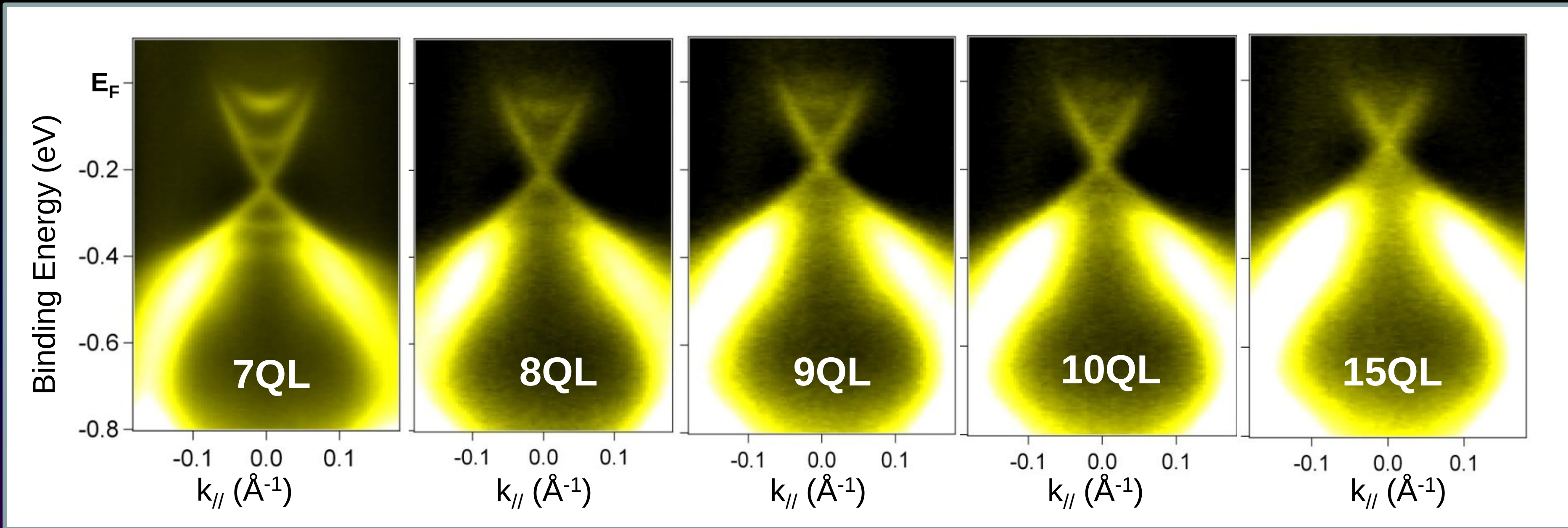
Bi_2Se_3 Band Structure: layer-by-layer

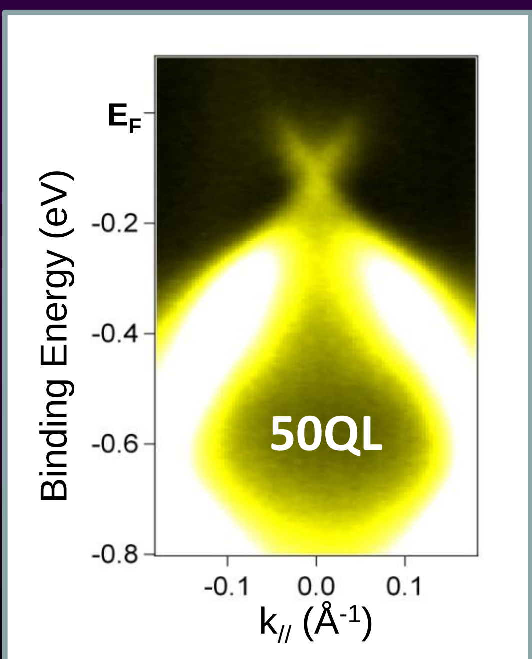
Yi Zhang et al., Nature Phys. ***6****, 584 (2010)*

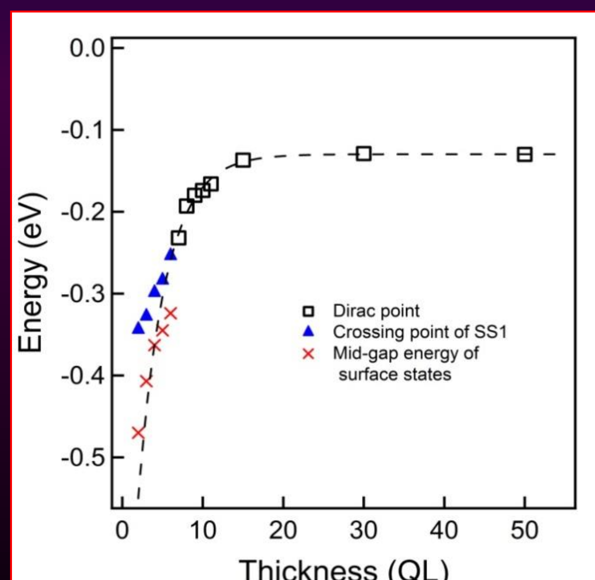


Critical thickness

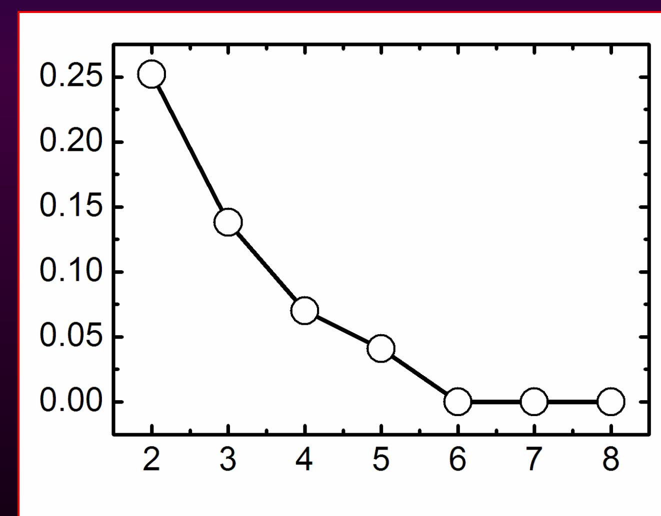
- The thickness and band structure can be controlled with atomic-layer precision by MBE
- Applied to FeSe, $MoSe_2$ and other layered materials





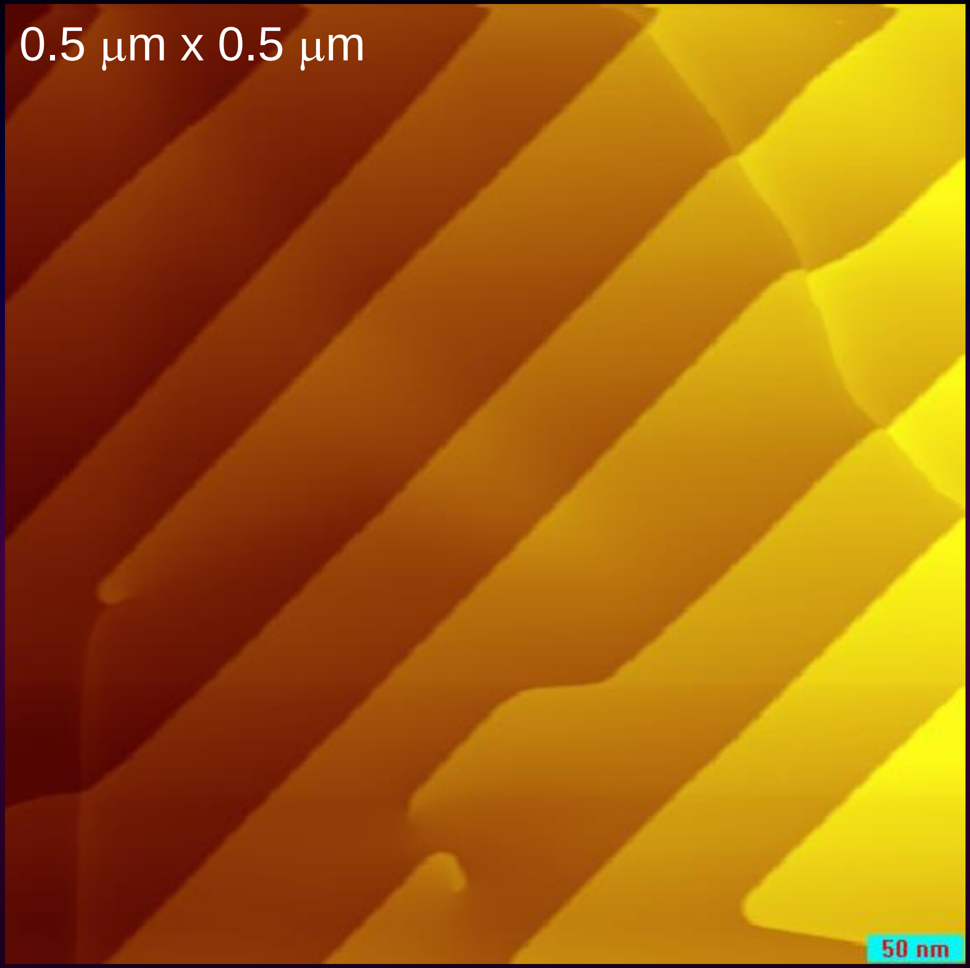


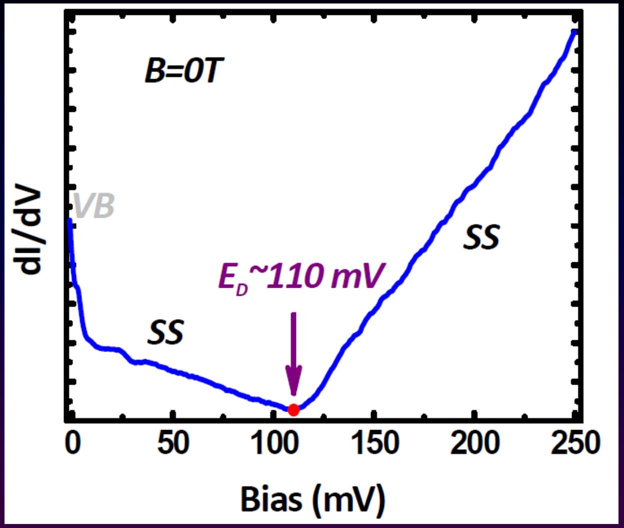
Position of Dirac Point

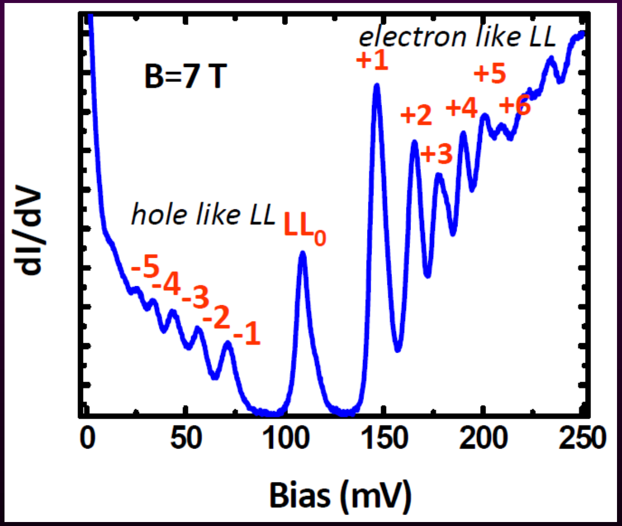


Gap size

Sb_2Te_3



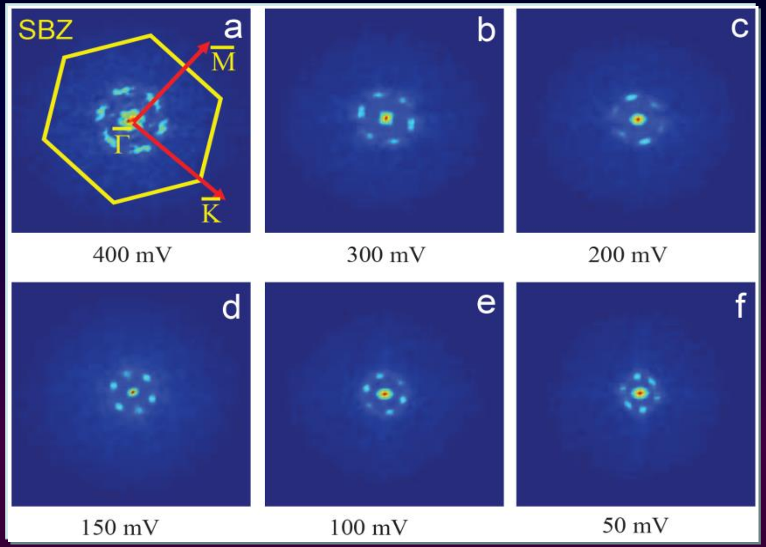


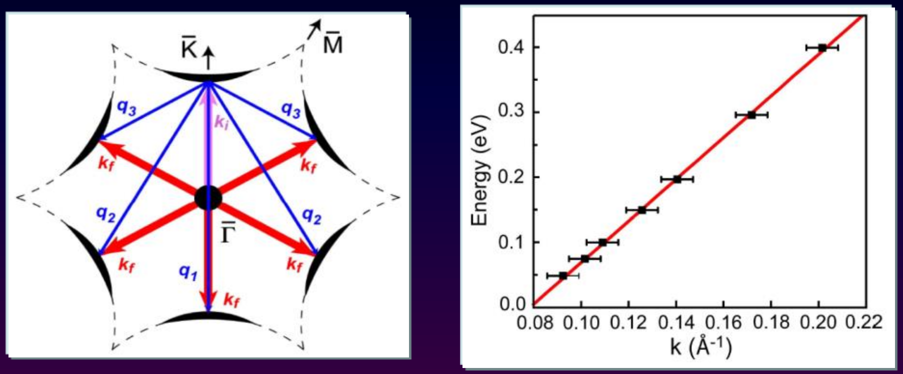


Y. P. Jiang, PRL 108, 016401 (2012)
Y. P. Jiang PRL 108, 066809 (2012)

STM study of fundamental properties of TIs

Quantum Interference ⇨ Absence of backscattering



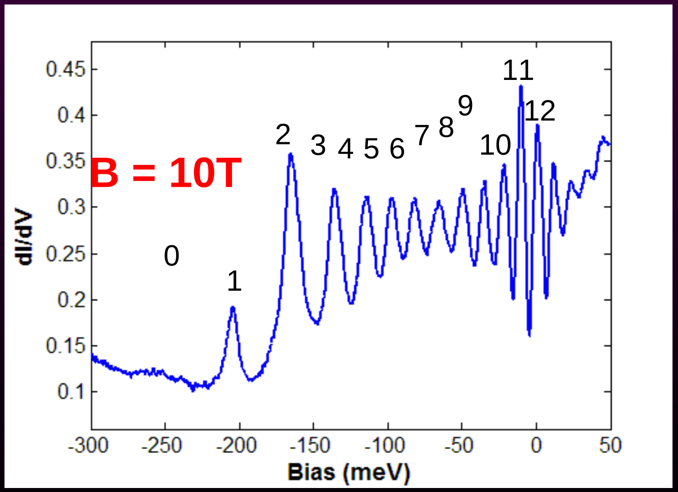


Zhang et al., PRL 103, 266803 (2009)
Jiang et al., PRL 108, 016401 (2012)

Massless Dirac fermion (Landau Quantization)

Cheng et al., PRL 105, 076801 (2010)
Jiang et al., PRL 108, 066809 (2012)

Chang et al., PRL 115, 066809 (2015)
Song et al., PRL 114, 176602 (2015)



With MBE-STM, we are able to prepare high quality epitaxial thin films and demonstrate their exotic electronic structure…

New Effect or Law!

OUTLINE

- Introduction
- MBE-STM-ARPES of topological insulators
- Realization of Quantum Anomalous Hall Effect
- Summary

QAHE in magnetic topological insulator

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

Quantum Anomalous Hall Effect in $Hg_{1-y}Mn_yTe$ Quantum Wells

Chao-Xing Liu,[1,2] Xiao-Liang Qi,[2] Xi Dai,[3] Zhong Fang,[3] and Shou-Cheng Zhang[2]

[1]*Center for Advanced Study, Tsinghua University, Beijing, 100084, China*

Chaoxing Liu et al. proposed that a 2D topological insulator with ferromagnetic order, but this compound cannot be made ferromagnetic

Journal of the Physical Society of Japan
Vol. 71, No. 1, January, 2002, pp. 19–22
©2002 The Physical Society of Japan

Term: QAHE

Topological Nature of Anomalous Hall Effect in Ferromagnets

Masaru ONODA* and Naoto NAGAOSA[1,†]

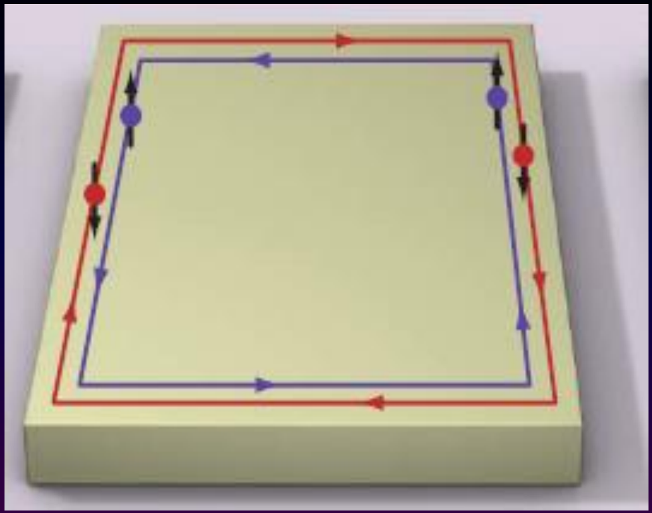
Quantized Anomalous Hall Effect in Magnetic Topological Insulators

Rui Yu,[1] Wei Zhang,[1] Hai-Jun Zhang,[1,2] Shou-Cheng Zhang,[2,3] Xi Dai,[1]* Zhong Fang[1]*

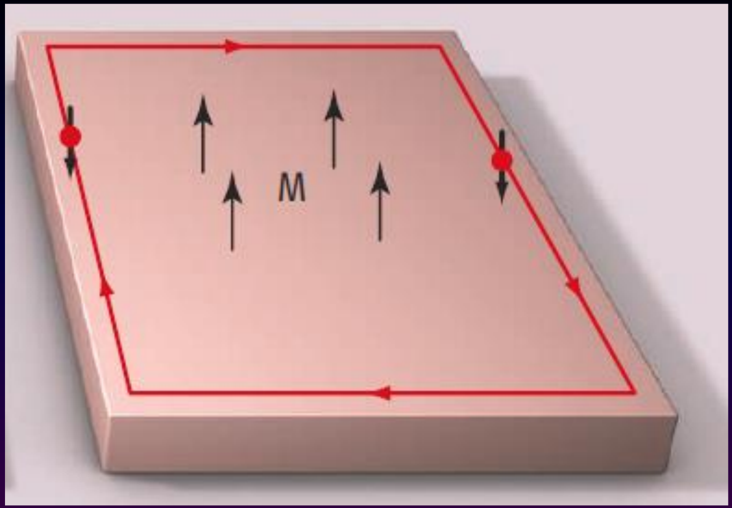
Science (2010)

- TI could remain ferromagnetic when it is insulating (van Vleck mechanism)
- The Bi_2Se_3 family topological insulator was proposed to be perfect candidate

QAHE in 2D magnetic TIs



2D TI: helical edge states



QAHE: chiral edge state

Requirements for QAHE: 2D Ferromagnetic Topological Insulator

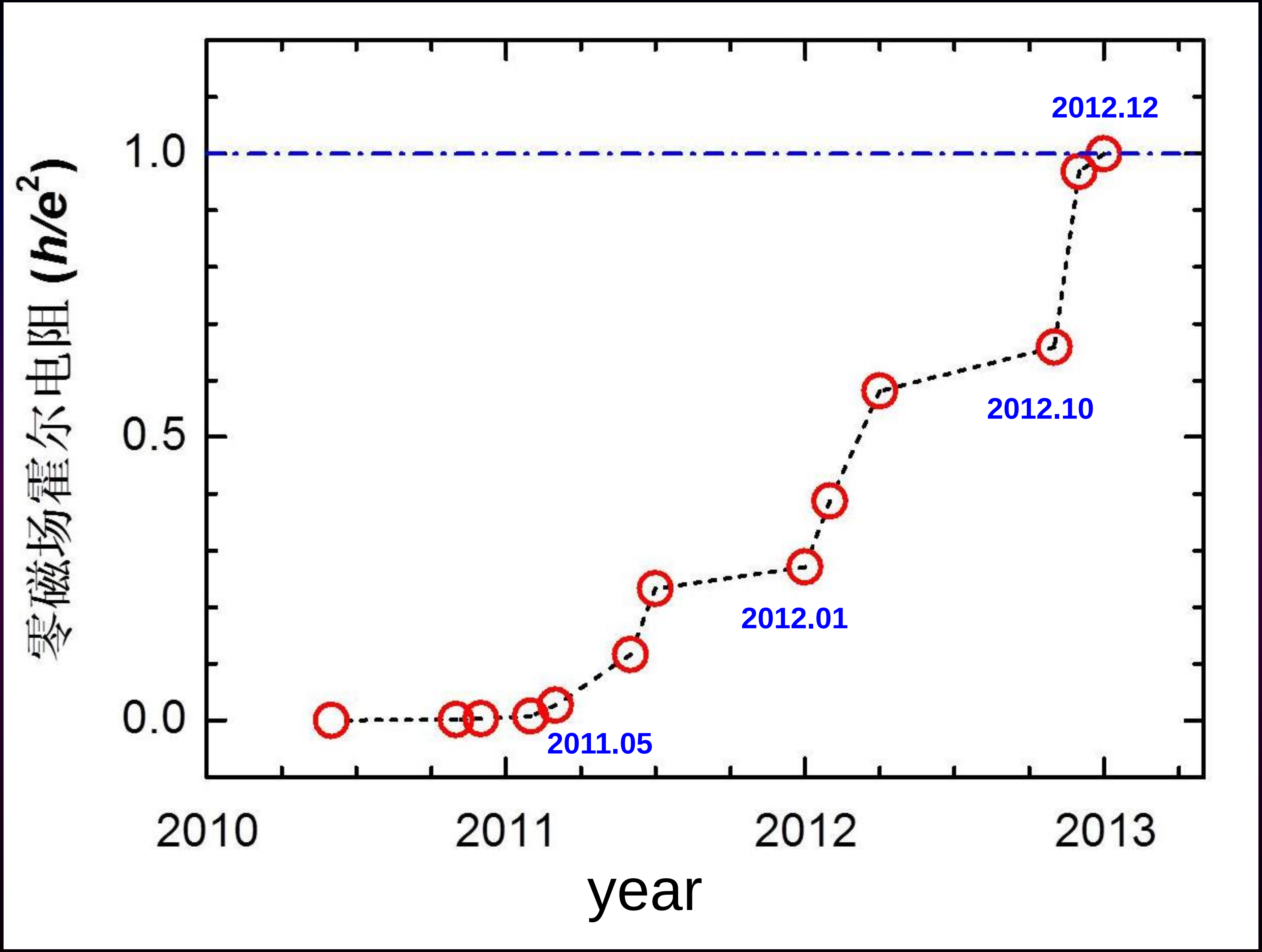
- It must be *magnetic*, so there is anomalous Hall effect at $B = 0$
- It must be *topological*, so there are spontaneous edge states
- It must be *insulating*, so there is only edge state transport

QAHE in 2D magnetic TIs

The QAHE puts stringent requirements for materials:

- Most ferromagnetic materials are metallic
- Magnetic order is difficult to realize in 2D
- Magnetism and topology may be against each other

$$R_H = h/e^2 = 25812.807449\ \Omega$$

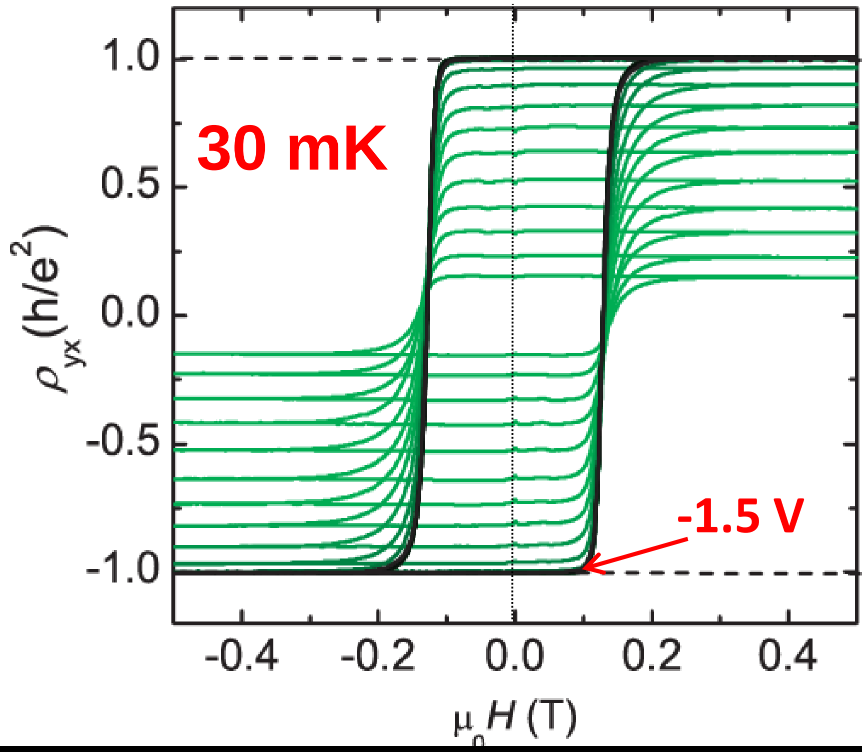


- Sharpen your tools
- Work hard

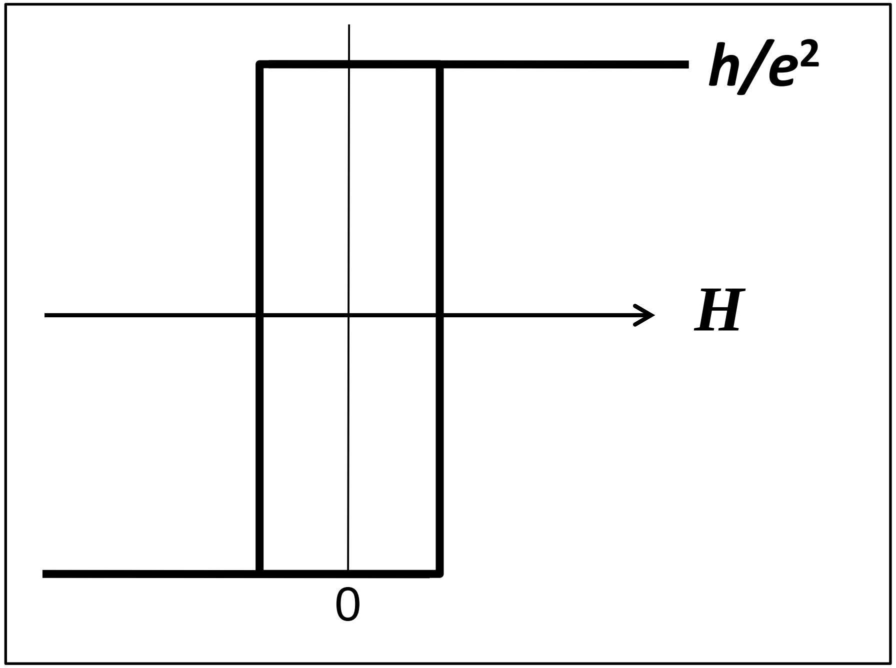
Quantum Anomalous Hall Effect in $Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

C. Z. Chang et al., Science 340, 167 (2013)

experiment



theory



- 20 samples at T = 1.5 K
- 6 samples at T = 90 mK (zero-field ρ = 0.87 to 0.98 h/e^2)
- 2 samples at T = 30 mK (full quantization at h/e^2)

QAHE by other groups

nature physics LETTERS
PUBLISHED ONLINE: 17 AUGUST 2014 | DOI: 10.1038/NPHYS3053

Trajectory of the anomalous Hall effect towards the quantized state in a ferromagnetic topological insulator

J. G. Checkelsky[1*†], R. Yoshimi[1], A. Tsukazaki[2], K. S. Takahashi[3], Y. Kozuka[1], J. Falson[1], M. Kawasaki[1,3] and Y. Tokura[1,3]

Y. Tokura (Tokyo/RIKEN)

PRL 113, 137201 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2014

Scale-Invariant Quantum Anomalous Hall Effect in Magnetic Topological Insulators beyond the Two-Dimensional Limit

Xufeng Kou,[1] Shih-Ting Guo,[2] Yabin Fan,[1] Lei Pan,[1] Murong Lang,[1] Ying Jiang,[3] Qiming Shao,[1] Tianxiao Nie,[1] Koichi Murata,[1] Jianshi Tang,[1] Yong Wang,[3] Liang He,[1] Ting-Kuo Lee,[2] Wei-Li Lee,[2,*] and Kang L. Wang[1,†]

K. L. Wang (UCLA)

nature materials LETTERS
PUBLISHED ONLINE: 2 MARCH 2015 | DOI: 10.1038/NMAT4204

High-precision realization of robust quantum anomalous Hall state in a hard ferromagnetic topological insulator

Cui-Zu Chang[1*], Weiwei Zhao[2*], Duk Y. Kim[2], Haijun Zhang[3], Badih A. Assaf[4], Don Heiman[4], Shou-Cheng Zhang[3], Chaoxing Liu[2], Moses H. W. Chan[2] and Jagadeesh S. Moodera[1,5*]

J. Moodera (MIT)

Selected for a Viewpoint in *Physics*
PRL 114, 187201 (2015) PHYSICAL REVIEW LETTERS week ending 8 MAY 2015

Precise Quantization of the Anomalous Hall Effect near Zero Magnetic Field

A. J. Bestwick,[1,2] E. J. Fox,[1,2] Xufeng Kou,[3] Lei Pan,[3] Kang L. Wang,[3] and D. Goldhaber-Gordon[1,2,*]

D. Gordhaber-Gondon (Stanford)

QUANTUM MECHANICS

Large discrete jumps observed in the transition between Chern states in a ferromagnetic topological insulator

Minhao Liu,[1] Wudi Wang,[1] Anthony R. Richardella,[2] Abhinav Kandala,[2] Jian Li,[1] Ali Yazdani,[1] Nitin Samarth,[2] N. Phuan Ong[1*]

N. Sarmath (Penn State)

N. P. Ong (Princeton)

PRL 118, 246801 (2017) PHYSICAL REVIEW LETTERS week ending 16 JUNE 2017

Scaling of the Quantum Anomalous Hall Effect as an Indicator of Axion Electrodynamics

Scientific Background on the Nobel Prize in Physics 2016

TOPOLOGICAL PHASE TRANSITIONS AND TOPOLOGICAL PHASES OF MATTER

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

D. Thouless

F. Haldane

J. Kosterlitz

The great importance of the Thouless *et al.* result is that it opens up the possibility of having a Hall conductance even in the absence of a magnetic field. It would, however, be another six years before this conceptually very important step was taken by Haldane [22], who realized that the important thing is to break the invariance under time-reversal and have an energy band,

This phase of matter described by Haldane is now called a *Chern insulator*, and twentyfive years later, in 2013, a quantized Hall effect was observed in thin films of Cr-doped $(Bi,Sb)_2Te_3$ at zero magnetic field, thus providing the first experimental detection of this phase of matter [15]. In Fig. 6 we see a clear plateau in the Hall resistance ρ_{yx} at a density (regulated by the gate voltage) corresponding to a filled band. The later development of *topological band theory* will be discussed in the concluding section.

Topological Insulators (2005—present)

(Dirac/Weyl semimetals)

Reviews: Qi & Zhang: Phys. Today 2009

Hasan & Kane: Rev. Mod. Phys. 2010
Qi & Zhang: Rev. Mod. Phys. 2011

Quantum Anomalous Hall Effect

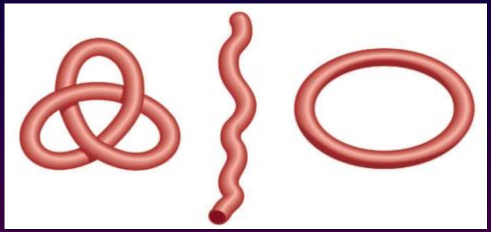
Quantum Spin Hall Effect

Majorana Fermions

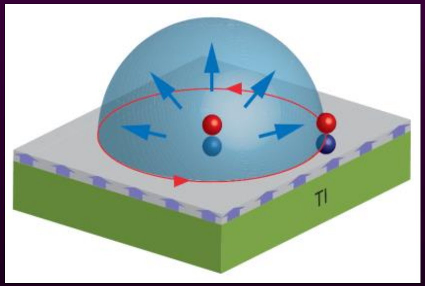
Magnetic Monopole and Dyon

TME Effect and Axion

………………

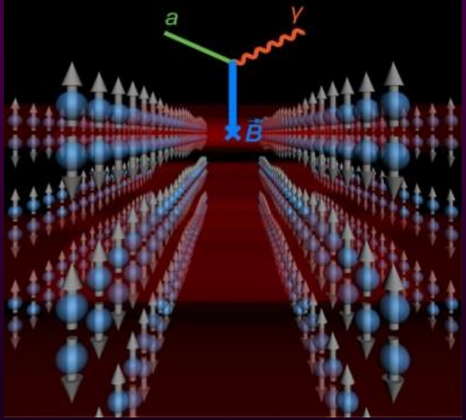


J. Moore, Nature 2010



Qi & Zhang, Science 2009

Dark matter on desktop
Wilczek, Nature 2009



Anomalous Hall Effect: Mechanism

Nagaosa, Sinova, Onoda, MacDonald, Ong,
Review of Modern Physics 2009

$$\sigma_{AH} = (\sigma_{int} + \sigma_{sk} + \sigma_{sj})$$

Spin-orbit coupling: intrinsic

R. Karplus, J. M. Luttinger, Phys. Rev. 95, 1154 (1954)

$$\rho_{int} \propto \rho_{xx}^2$$

Skew scattering: extrinsic

J. Smit, Physica 24, 39 (1958)

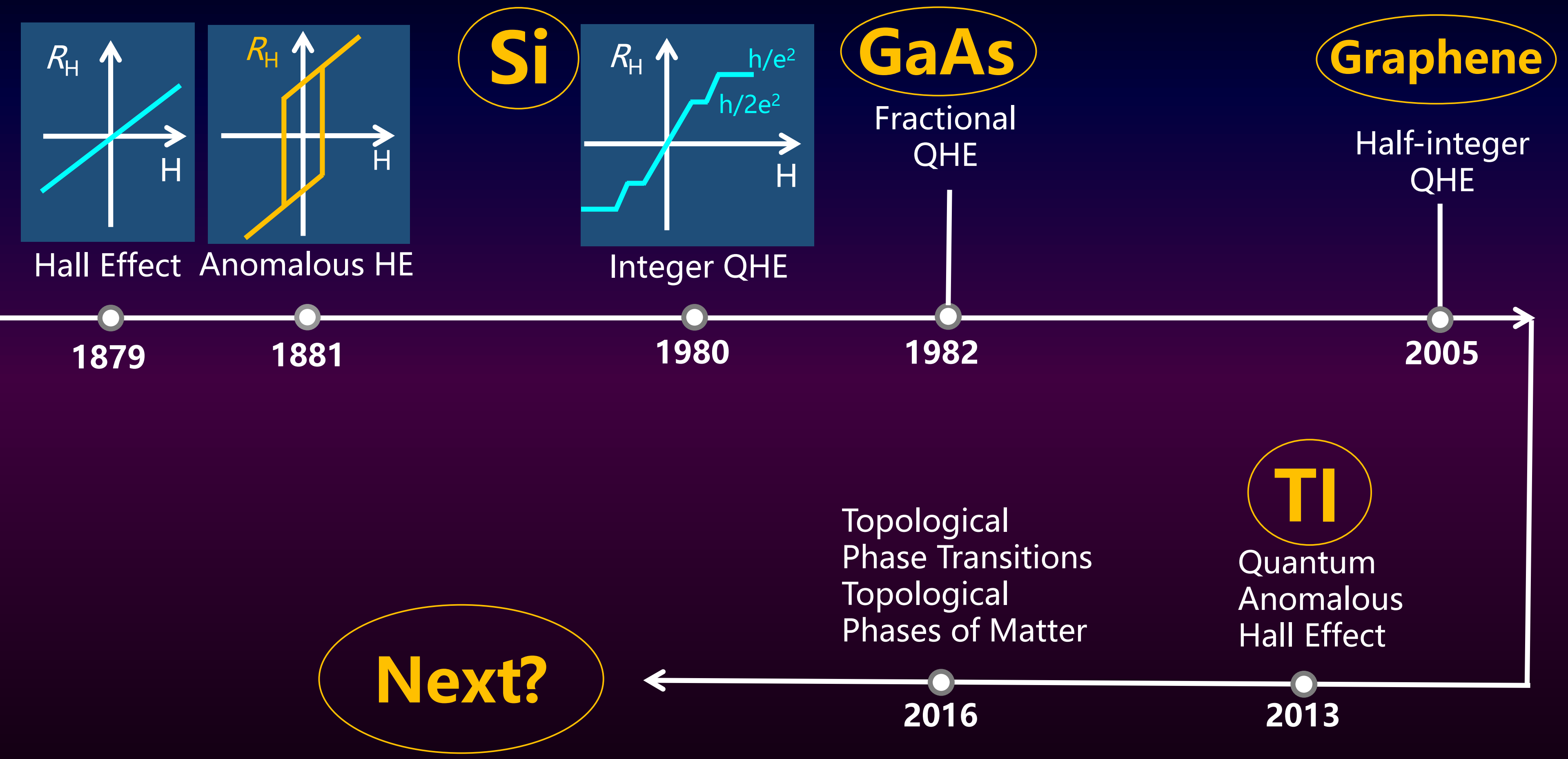
$$\rho_{sk} \propto \rho_{xx}$$

Side jump: extrinsic

L. Berger, Phys. Rev. B2, 4559 (1970)

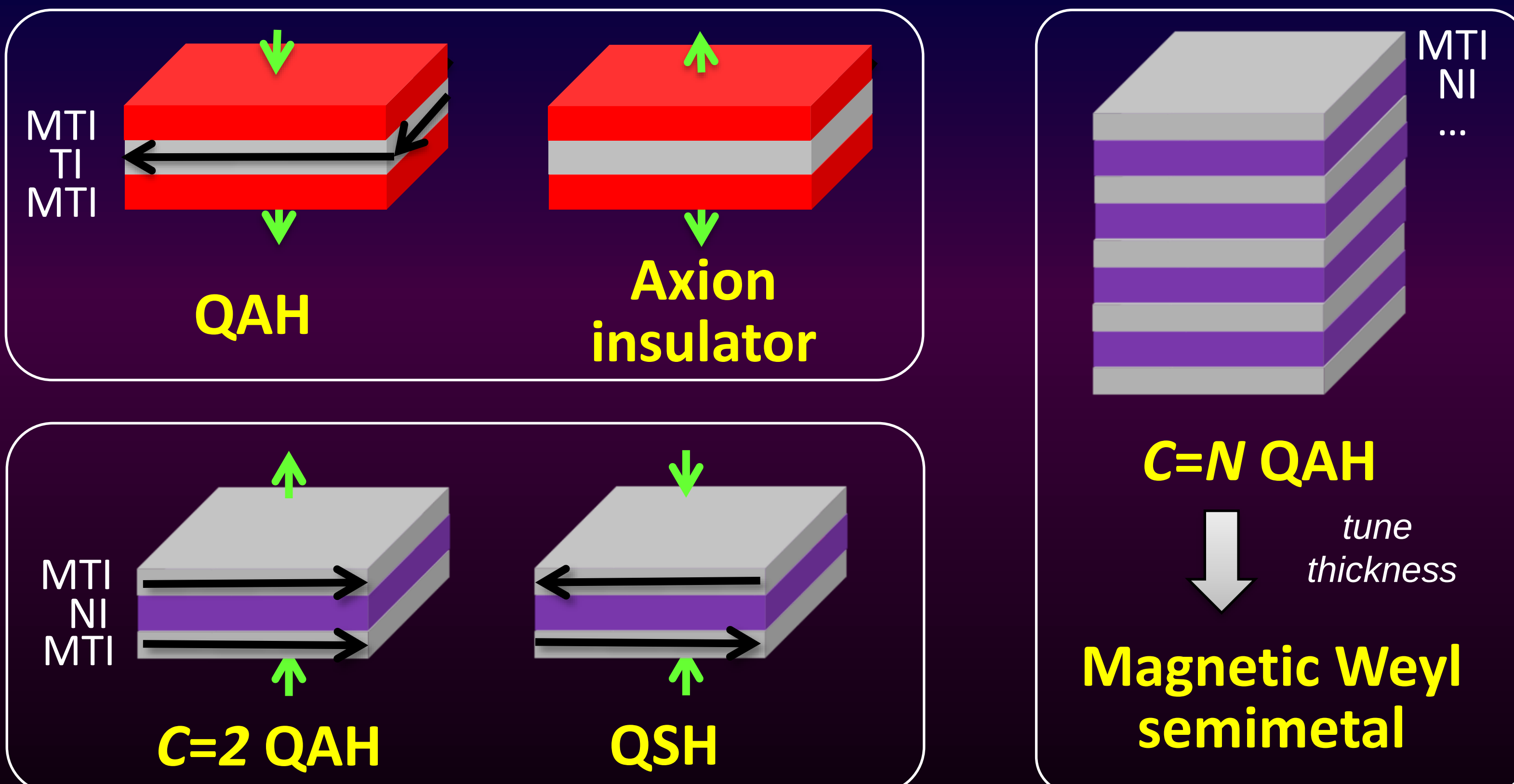
$$\rho_{sj} \propto \rho_{xx}^2$$

Material Driven Discoveries

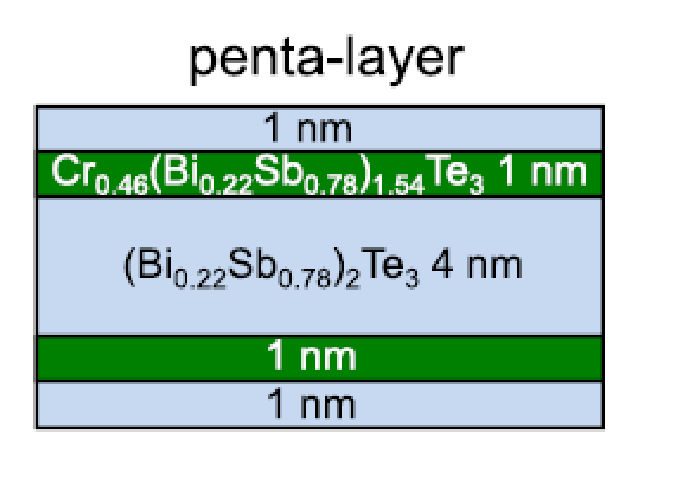


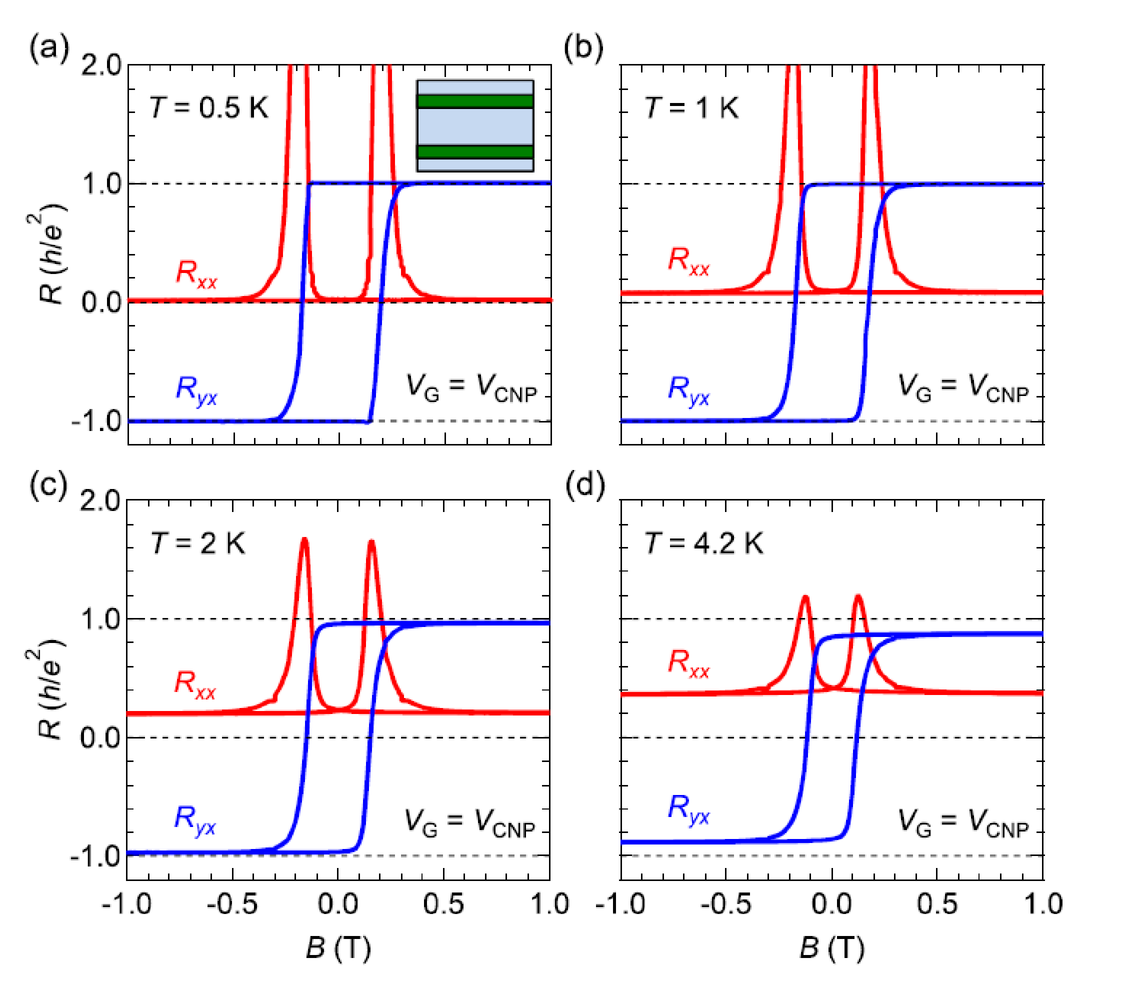
New progresses in QAHE

- QAHE at higher temperatures
- Other novel topological states of matter



"Penta-layer" Cr-doped $(Bi,Sb)_2Te_3$





Perfect quantization at 0.5 K and zero field

Tokura Group: APL 107, 182401 (2015)

Quantized Anomalous Hall Effect in V-Sb_2Te_3

nature materials

LETTERS

PUBLISHED ONLINE: 2 MARCH 2015 | DOI: 10.1038/NMAT4204

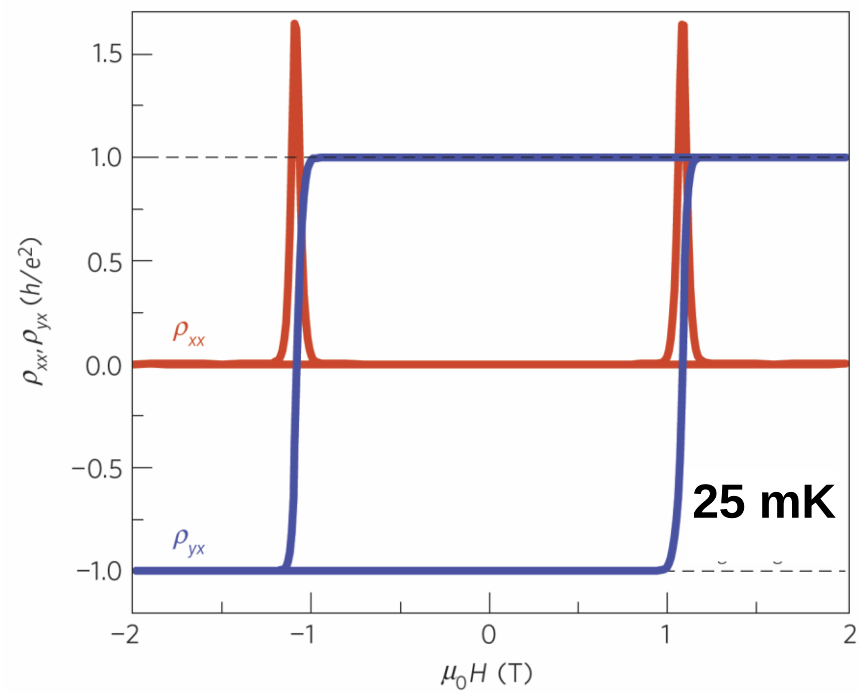
High-precision realization of robust quantum anomalous Hall state in a hard ferromagnetic topological insulator

Cui-Zu Chang[1]*, Weiwei Zhao[2]*, Duk Y. Kim[2], Haijun Zhang[3], Badih A. Assaf[4], Don Heiman[4], Shou-Cheng Zhang[3], Chaoxing Liu[2], Moses H. W. Chan[2] and Jagadeesh S. Moodera[1,5]*

MIT/PSU/Stanford

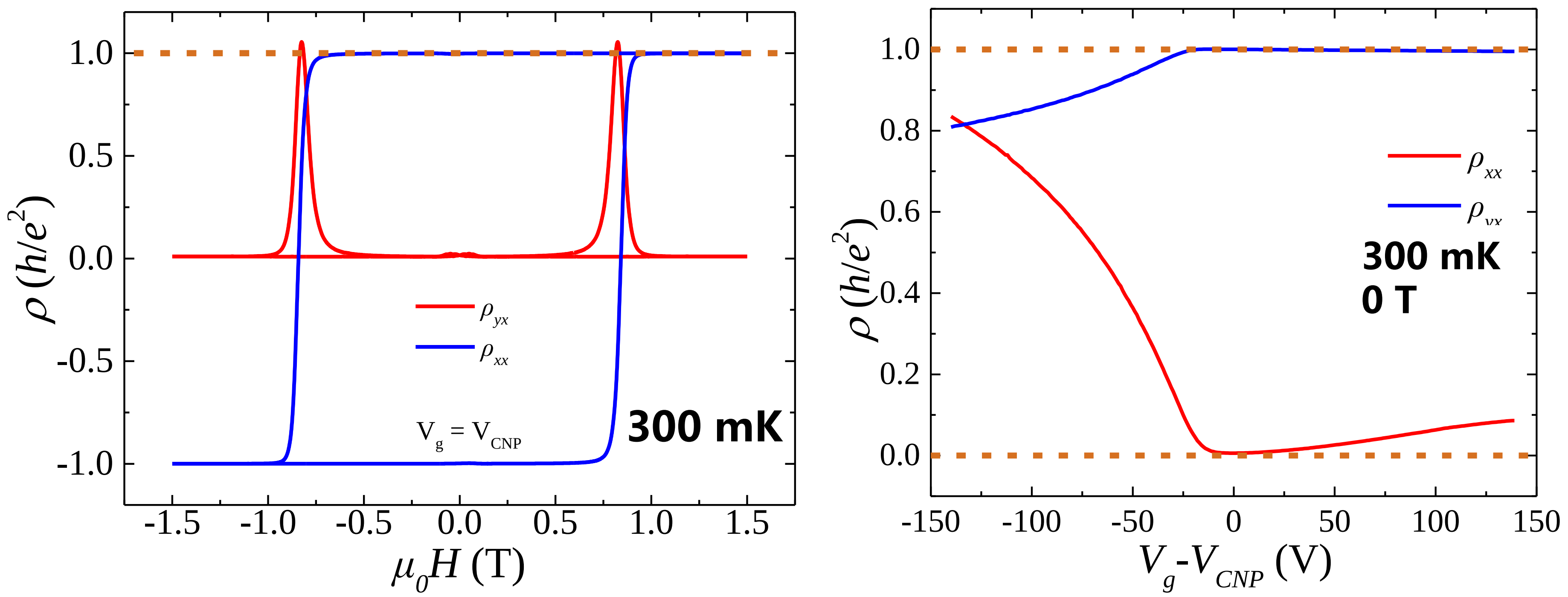
V-doped Sb_2Te_3 (~4%)

Moodera Group (MIT)



QAHE at higher T

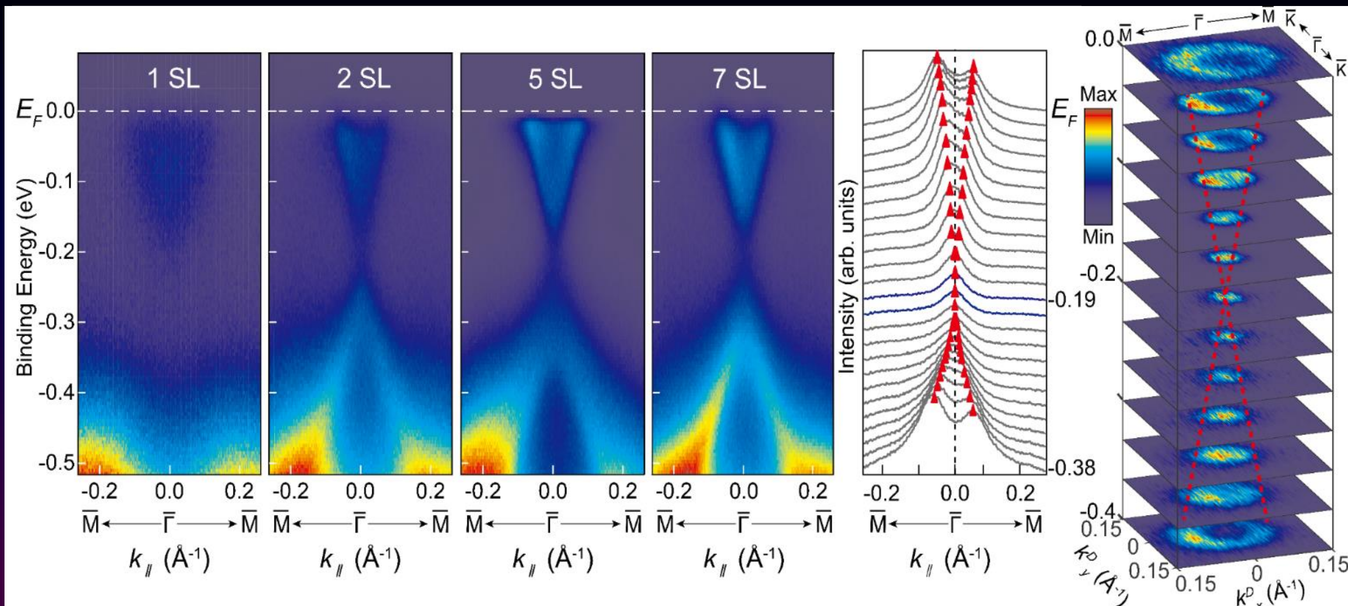
Cr+V co-doped $(BiSb)_2Te_3$



Perfect quantization at **T = 300 mK**

Y. B. Ou et al., APL Materials ***4****, 086101 (2016)*

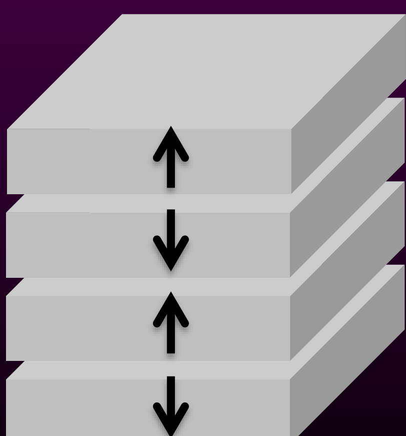
$MnBi_2Te_4$: 3D TI by MBE

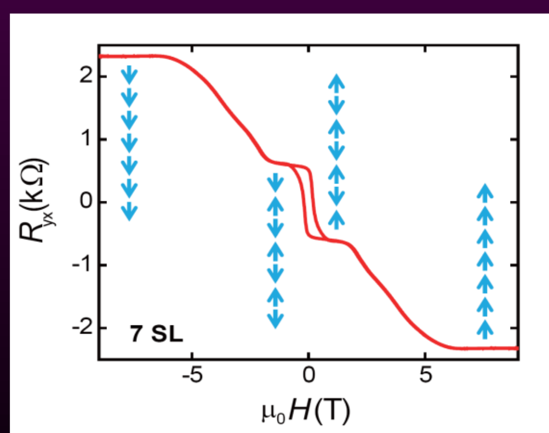


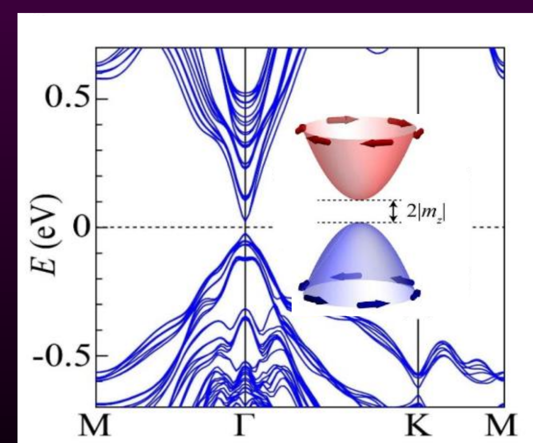
5SL $MnBi_2Te_4$:

- Chern No. =1
- Gap: ~52meV

QAHE

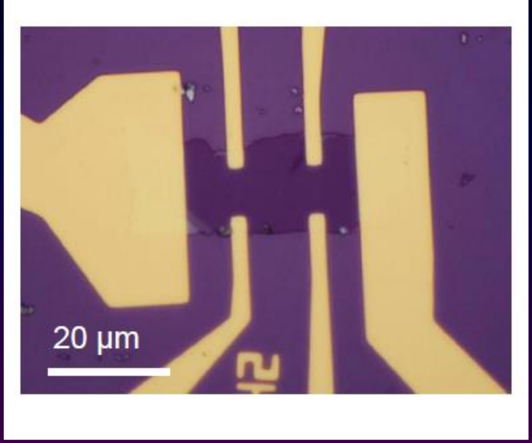


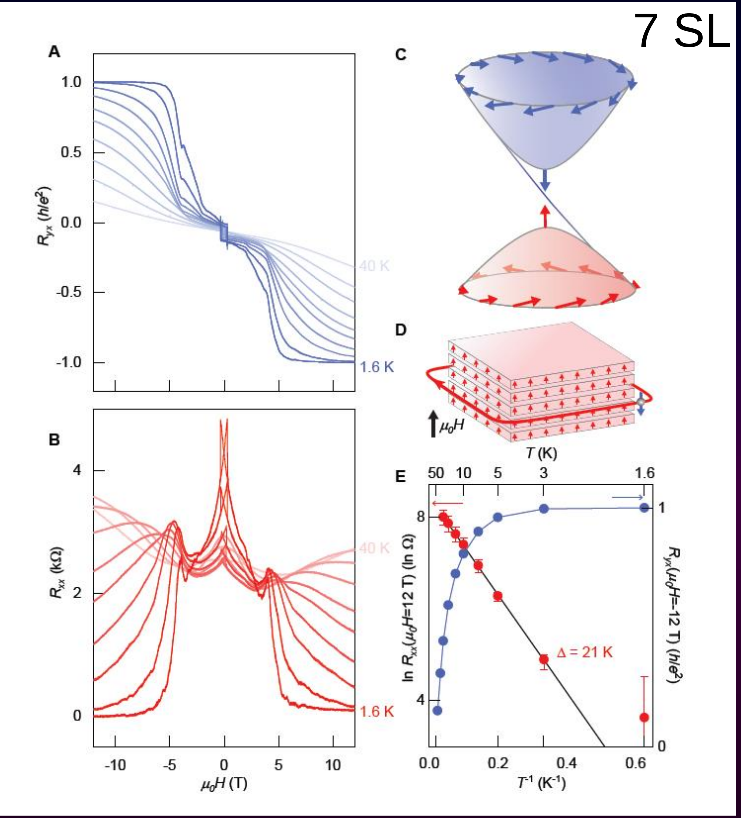


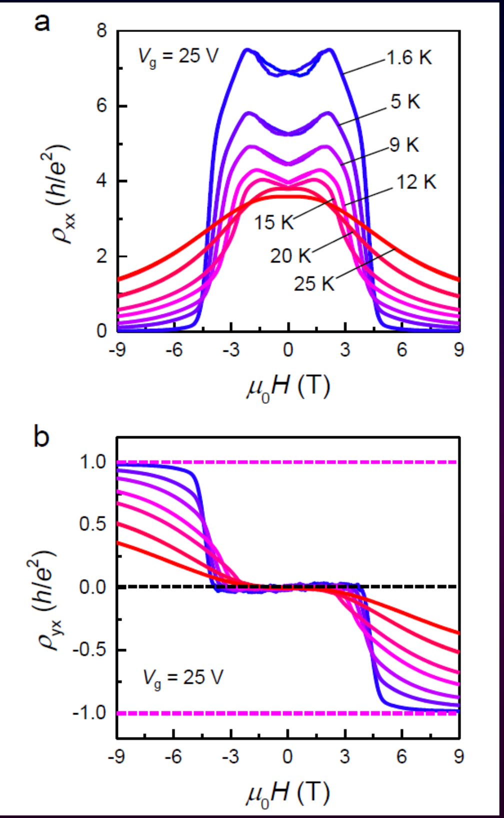


Y. Gong et al., ***Chin. Phys. Lett. 36****, 076801 (2019) (June 2, 2019)*

QAHE in single crystal flakes of $MnBi_2Te_4$







Requires a strong magnetic field

Xianhui Chen (USTC) and Yuanbo Zhang (Fudan): arXiv: 1904.11468
Yayu Wang (Tsinghua): arXiv: 1905.00715

"Spin valve" based on QAH edge states

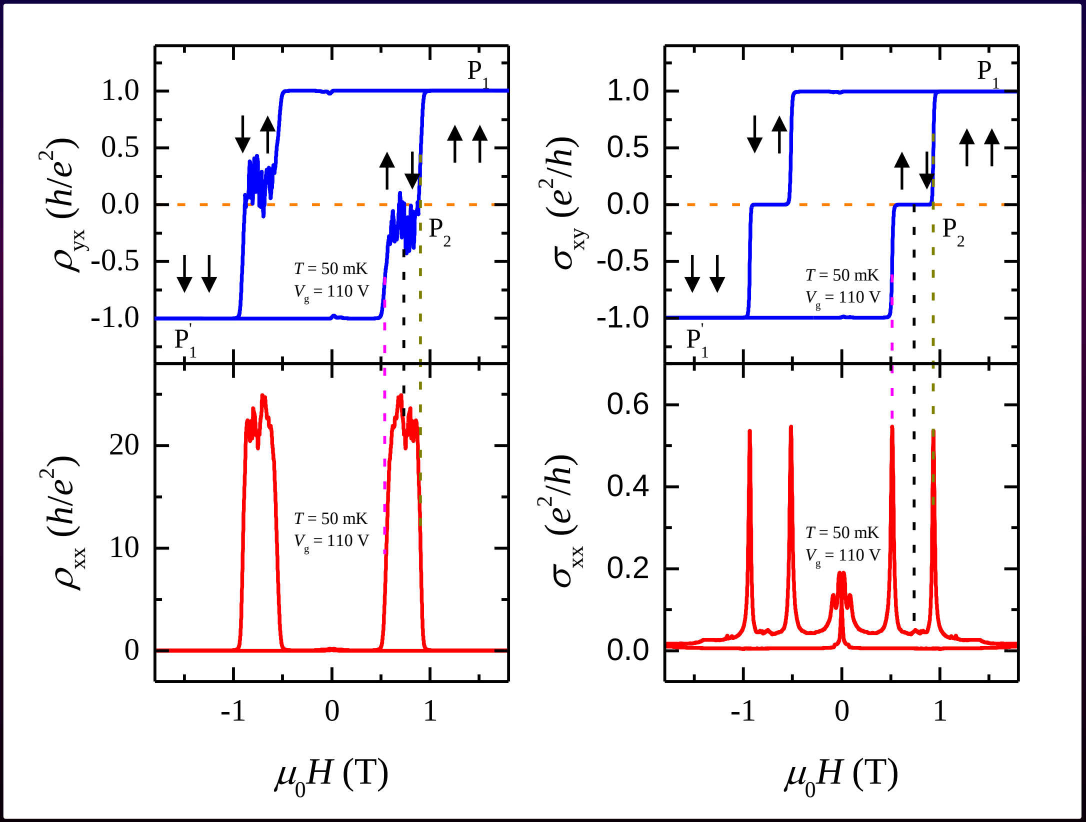
Sample Structure

5 QL	MTI (Cr/V: 0.16/0.84—larger coercivity)
3 QL	TI (non-magnetic)
5 QL	MTI (Cr/V: 0.4/0.6—smaller coercivity)

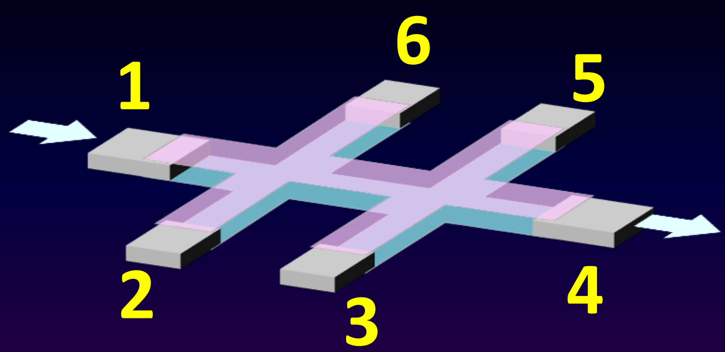
- When the magnetization directions of the top and bottom layers are parallel, QAH ($\rho_{xx}=0$, $\rho_{xy}= h/e^2$).
- Its longitudinal resistance becomes very large ($\rho_{xx}> 20\ h/e^2$) when anti-parallel.

⇩

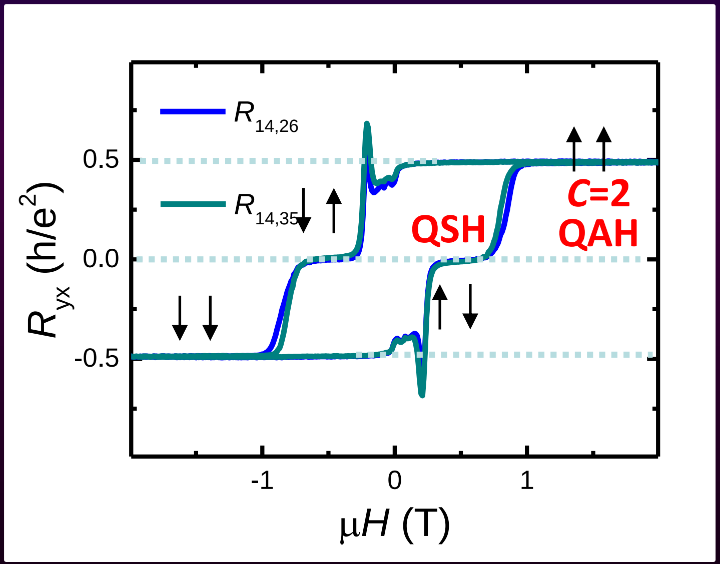
Spin valve

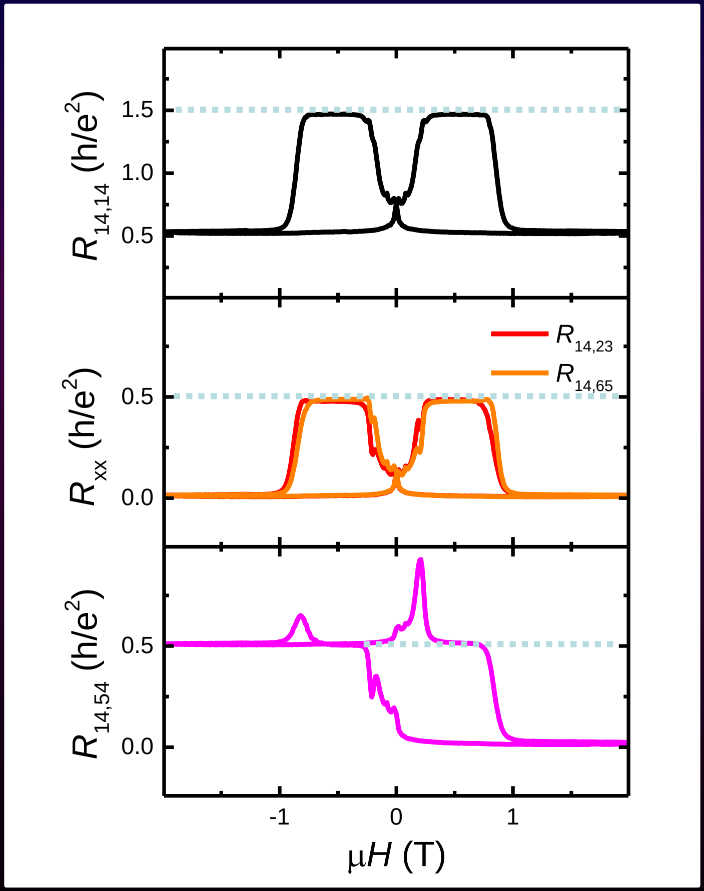


Synthetic Quantum Spin Hall Effect



- When two QAH sub-systems have the same magnetization direction (strong field), the system become a QAH insulator with Chern number 2.
- In the case of opposite magnetization, it becomes a QSH system.





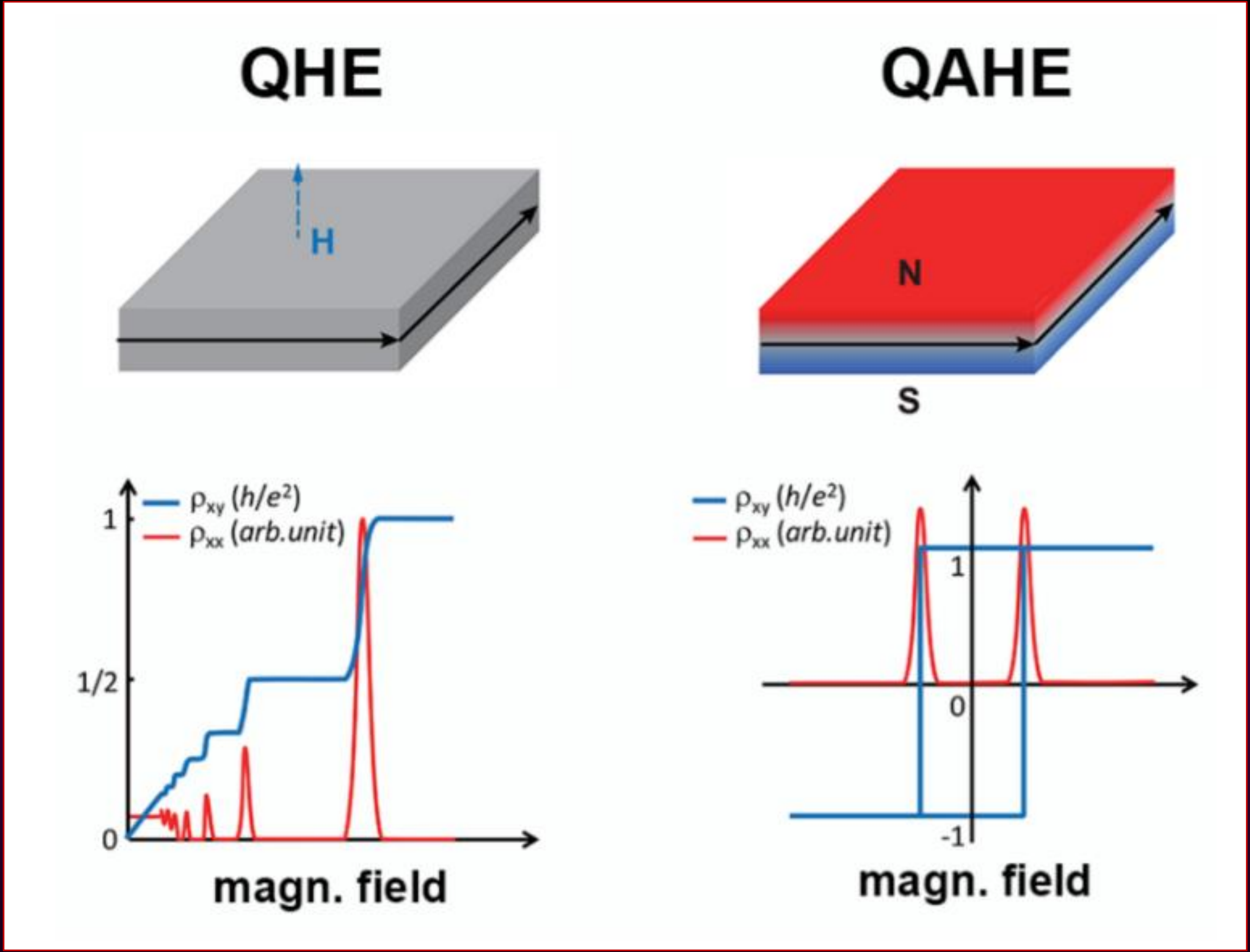
Summary

- QAHE is well-established quantum state of matter, independently realized by many groups.
- QAHE forms a platform for other exotic states of matter.

Hall Effect 1879	Anomalous Hall Effect 1881
IQHE 1980 FQHE 1982	QAHE 2013

⇧ with Magnetic Field

⇧ w/o Magnetic Field



science is art

Acknowledgements

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Ke He, Xucun Ma, Xi Chen, Lili Wang, S. H. Ji (Tsinghua/IOP)
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Theory: **Shoucheng Zhang (Stanford)**

Bangfen Zhu, Wenhui Duan (Tsinghua), Zhong Fang, Xi Dai (IOP),
X. L. Qi (Stanford), C. X. Liu (Penn State), Shengbai Zhang (RPI),
X. C. Xie (PKU), S. Q. Shen (Hong Kong), Feng Liu (Utah)

$$$: NSF, MOST, MOE of China

Thank you very much!