Kavli Workshop on Topological Matter and Quantum Computing, May 4-6, 2018, Beijing

New progress in quantum anomalous Hall effect

Qi-Kun Xue

Department of Physics, Tsinghua University

Acknowledgements

Tsinghua: MBE, STM and ARPES

Yunbo Ou, Gaoyuan Jiang, Xiao Feng, Li-Guo Zhang, Li-Li Wang, Wei Li, Can-Li Song, Ding Zhang, Ke He, Xu-Cun Ma

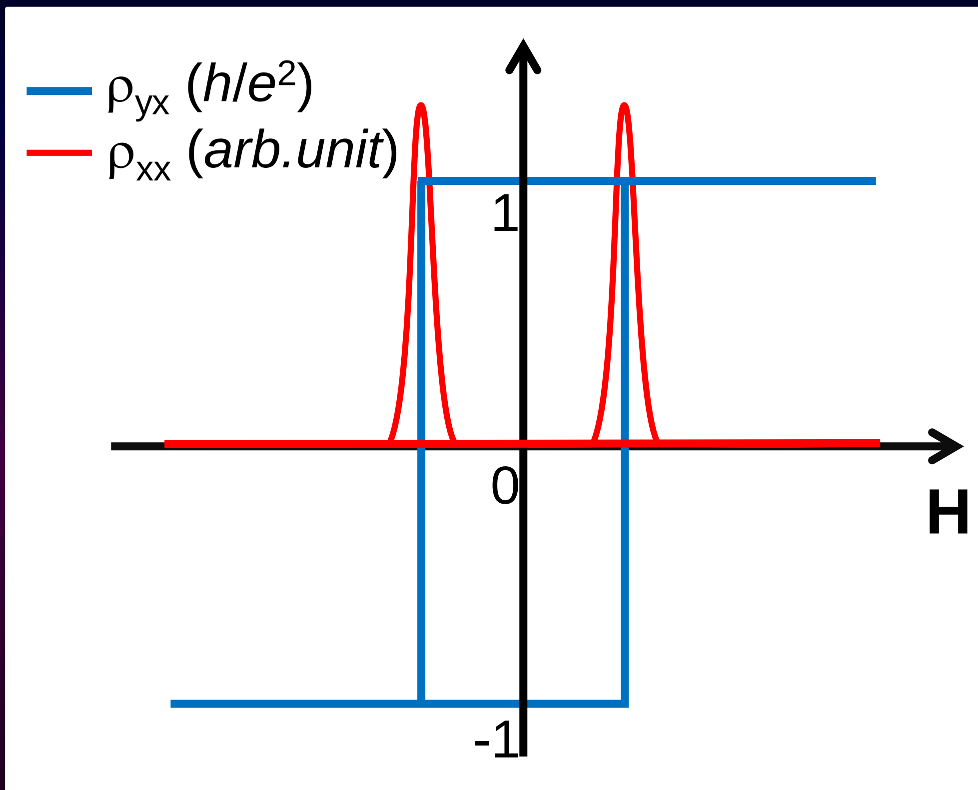
Tsinghua: Transport

Yang Feng, Weixiong Wu, Chang Liu, Shaorui Li, Yaoxin Li, and Yayu Wang

Rutgers: MFM Wenbo Wang, Weida Wu

IOP, CAS: TEM Qinghua Zhang, Xiaozhi Liu, Lin Gu

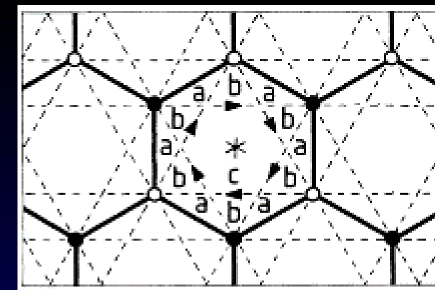
Quantum Anomalous Hall Effect (QAHE)



$$\rho_{yx}(H=0) = h / ie^2$$
$$\rho_{xx}(H=0) = 0$$

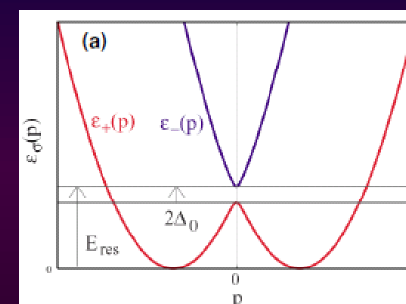
TRS-broken graphene

Haldane, PRL 1988



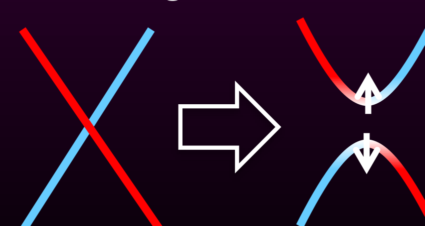
2D FM system with SOC

Onoda & Nagaosa, PRL 2003



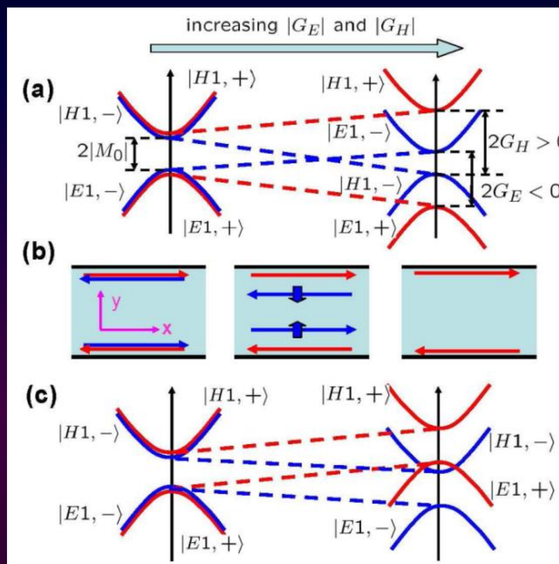
Magnetic topological insulator

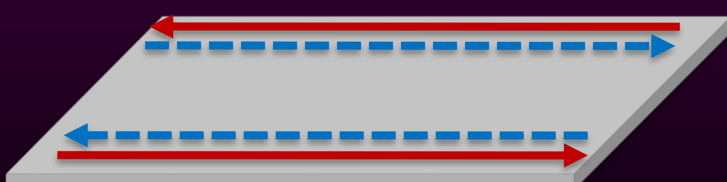
SC Zhang et al., since 2006



QAHE in magnetic TIs

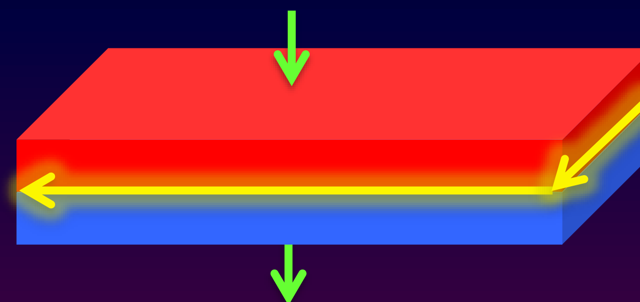
2D TI + FM

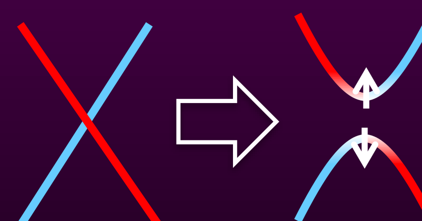




Qi, Wu & Zhang., PRB 2006
C. -X. Liu et al., PRL 2008

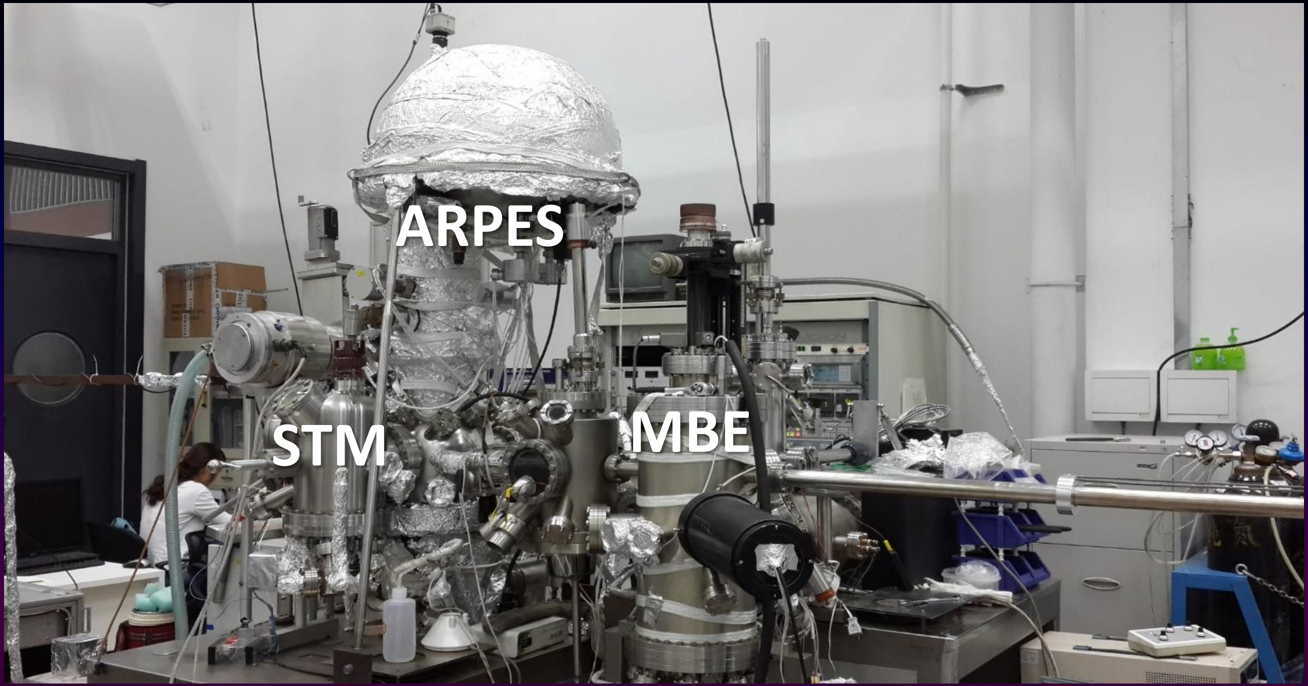
3D TI + FM

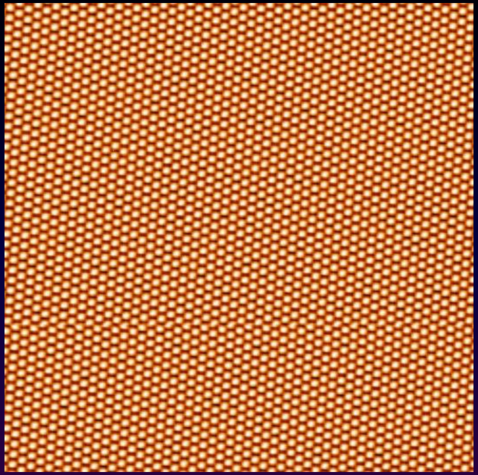


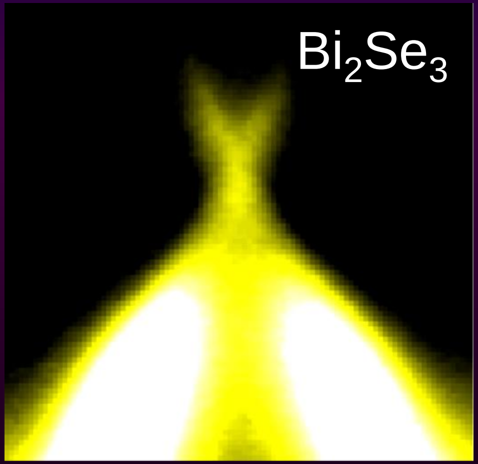


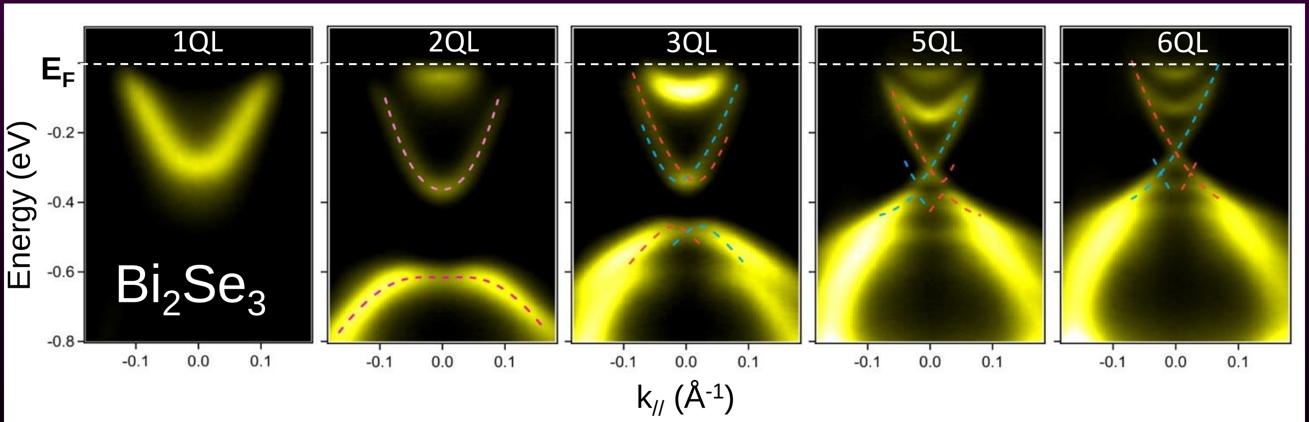
Qi, Hughes & Zhang PRB 2008
Yu et al., Science 2010

MBE + STM + ARPES for TI studies





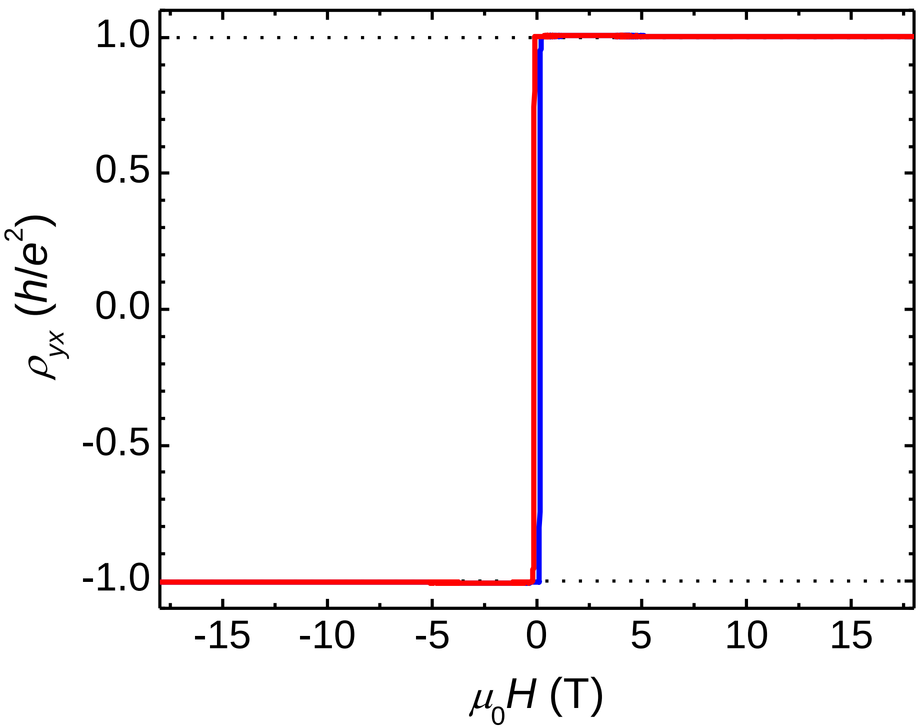


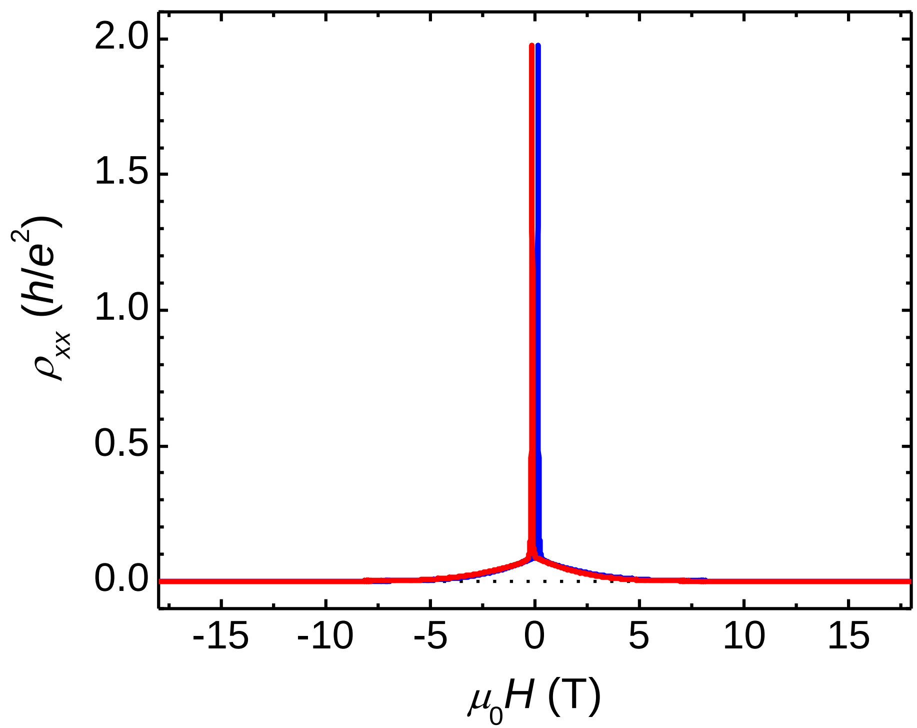


Adv. Mater. 22, 4002 (2010)
Nat. Phys. 6, 584 (2010)

QAHE observed in Cr-doped $(Bi,Sb)_2Te_3$

@ 30 mK





with Li Lv (IOP)

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

Confirmation of QAHE

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]

2014.08: Tokyo/RIKEM

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,†]

2014.09: 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*]

2015.03: 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,*]

2015.05: 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*]

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under a
NonCom
10.1126/

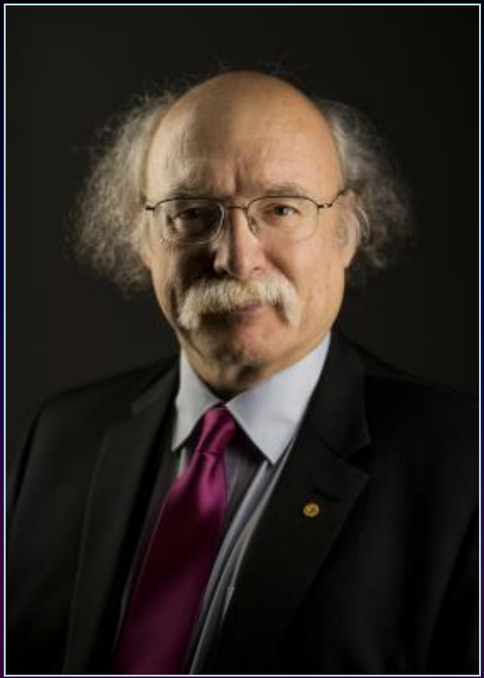
2016.06: Princeton

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

2017.06: Wurzburg

Nobel Lecture by F. D. M. Haldane



REVIEWS OF MODERN PHYSICS, VOLUME 89, OCTOBER–DECEMBER 2017

Nobel Lecture: Topological quantum matter*

F. Duncan M. Haldane
Department of Physics, Princeton University, Princeton, New Jersey 08544-0708, USA

(published 9 October 2017)

Nobel Lecture, presented December 8, 2016, Aula Magna, Stockholm University. I will describe the history and background of three discoveries cited in this Nobel Prize: The "TKNN" topological formula for the integer quantum Hall effect found by David Thouless and collaborators, the Chern insulator or quantum anomalous Hall effect, and its role in the later discovery of time-reversal-invariant topological insulators, and the unexpected topological spin-liquid state of the spin-1 quantum antiferromagnetic chain, which provided an initial example of topological quantum matter. I will summarize how these early beginnings have led to the exciting, and currently extremely active, field of "topological matter."

DOI: 10.1103/RevModPhys.89.040502

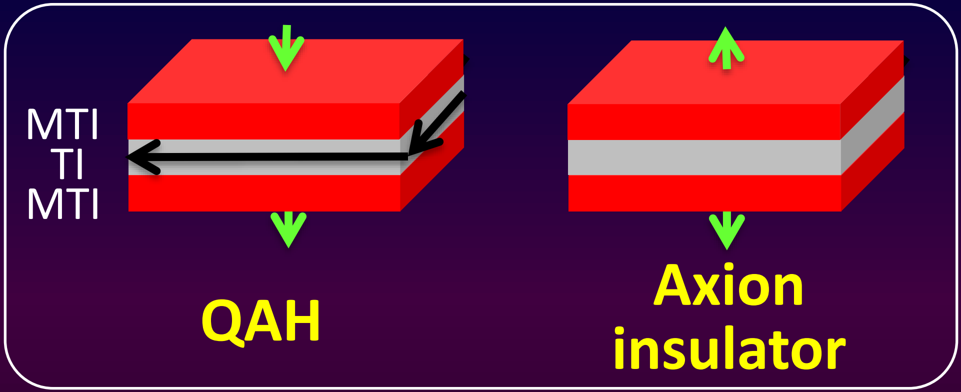
QAHE is among the most important physics effects discovered in topological insulators.

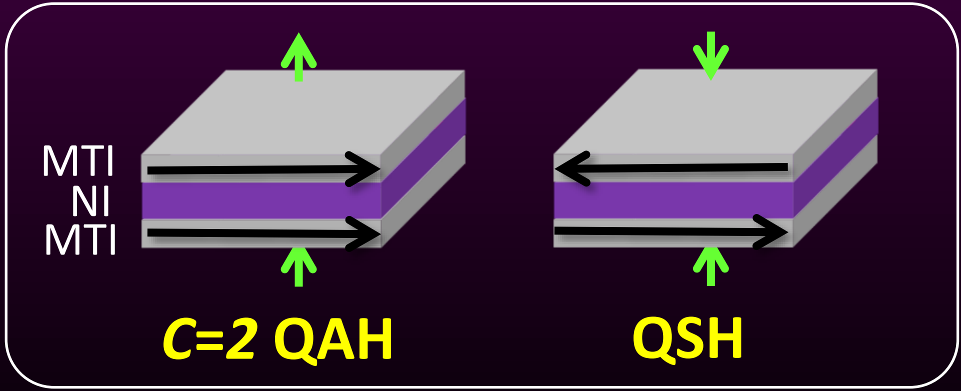
discovery of the 3D time-reversal-invariant topological insulators (TI). This finally led to the reported experimental realization (Chang *et al.*, 2013) by QiKun Xue's group at Tsinghua University, Beijing, of the quantum anomalous Hall effect in thin films of TRI TI's which had been doped with magnetic material.

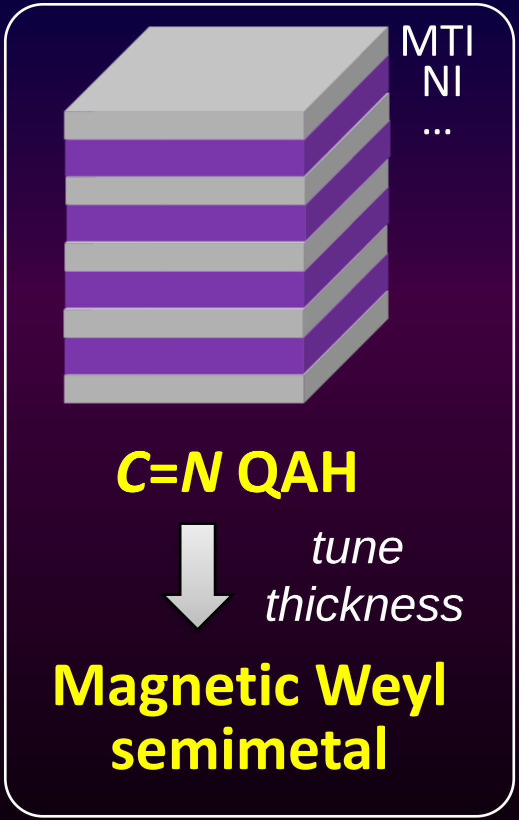
I now turn to the other (1981) discovery recognized by this Nobel prize: the novel quantum spin-liquid states of the one-

Recent progresses in QAHE

- **Higher temperature:** **Cr+V co-doped $(Bi,Sb)_2Te_3$**
- **Other novel topological states of matter**

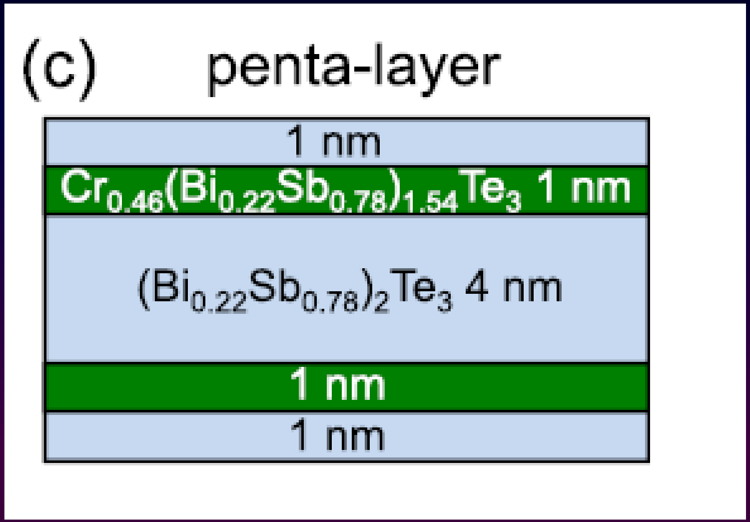


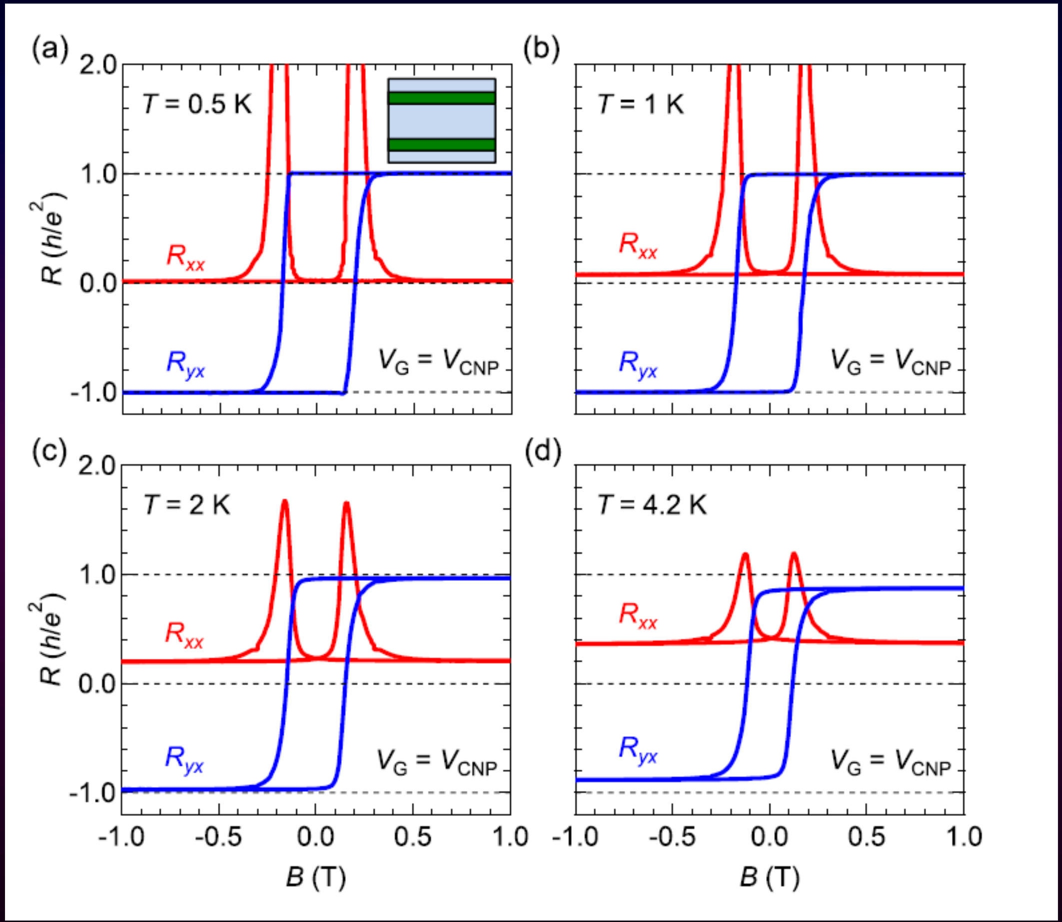




"Penta-layer" Cr-doped $(Bi,Sb)_2Te_3$

Y. Tokura: APL 107, 182401 (2015)





Good quantization at 0.5 K and zero field

Quantized Anomalous Hall Effect in V-Sb_2Te_3

nature materials

LETTERS

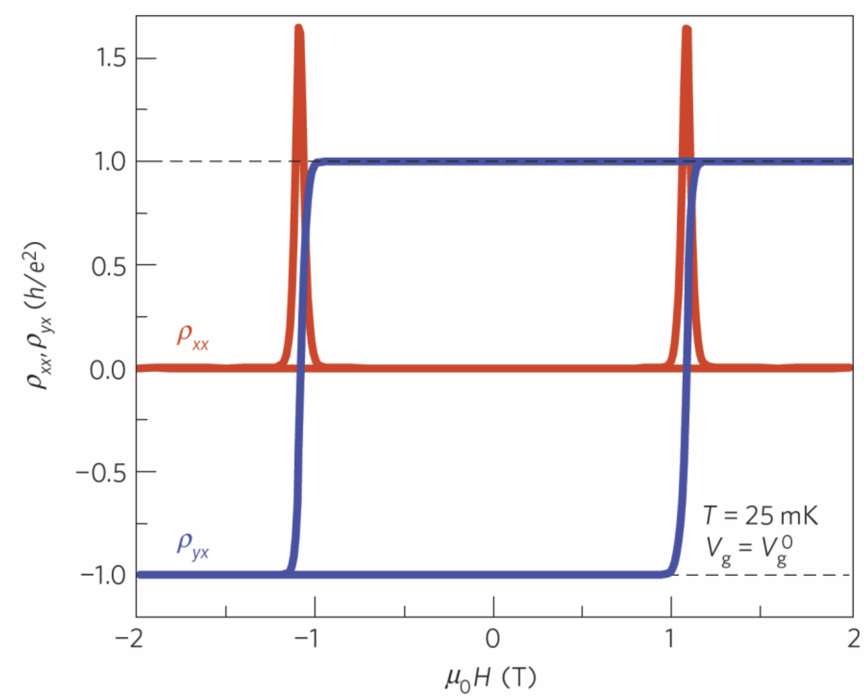
PUBLISHED ONLINE: 2 MARCH 2015 | DOI: 10.1038/NMAT4204

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

MIT/PSU/Stanford

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*]

V-doped Sb_2Te_3 (~4%)

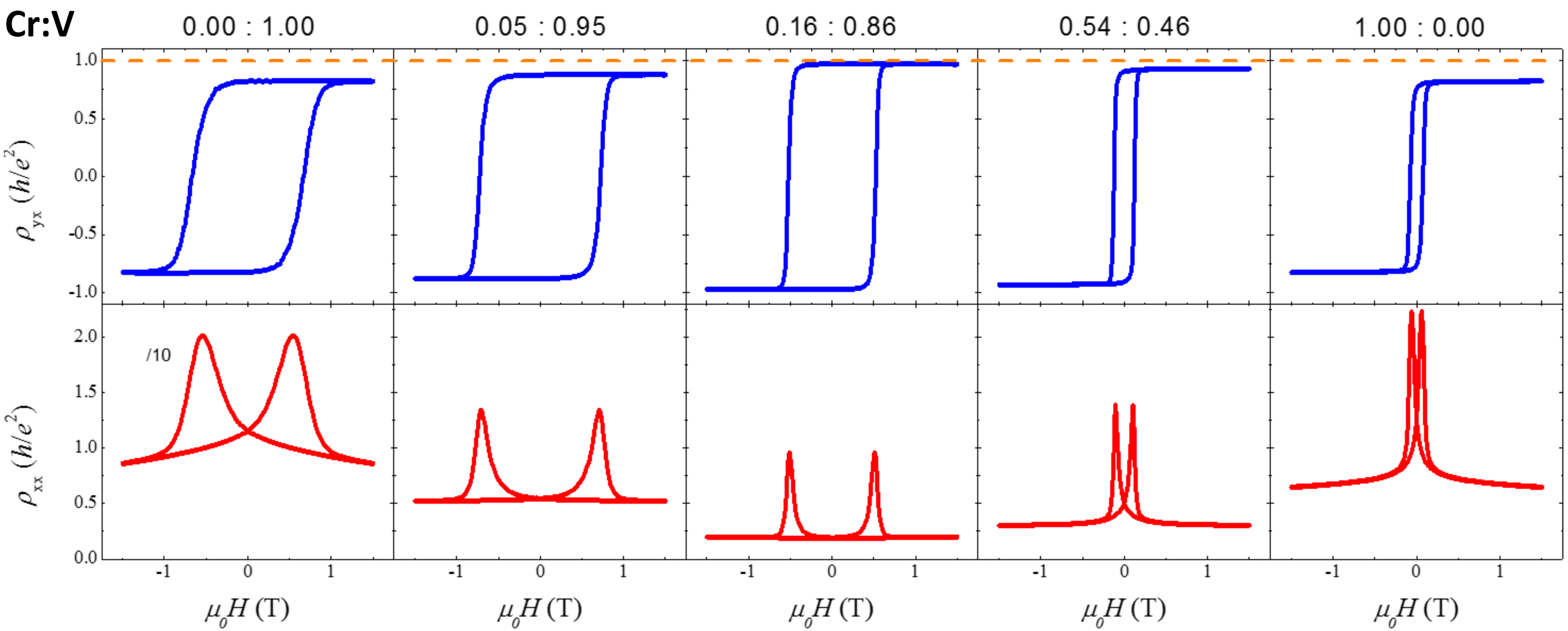


Dr. Chang and Prof. Moodera (MIT)

Higher QAHE temperature in Cr & V co-doped $(Bi,Sb)_2Te_3$ films

5 QL $(Cr_yV_{1-y})_{0.19}(Bi_xSb_{1-x})_{1.81}Te_3$

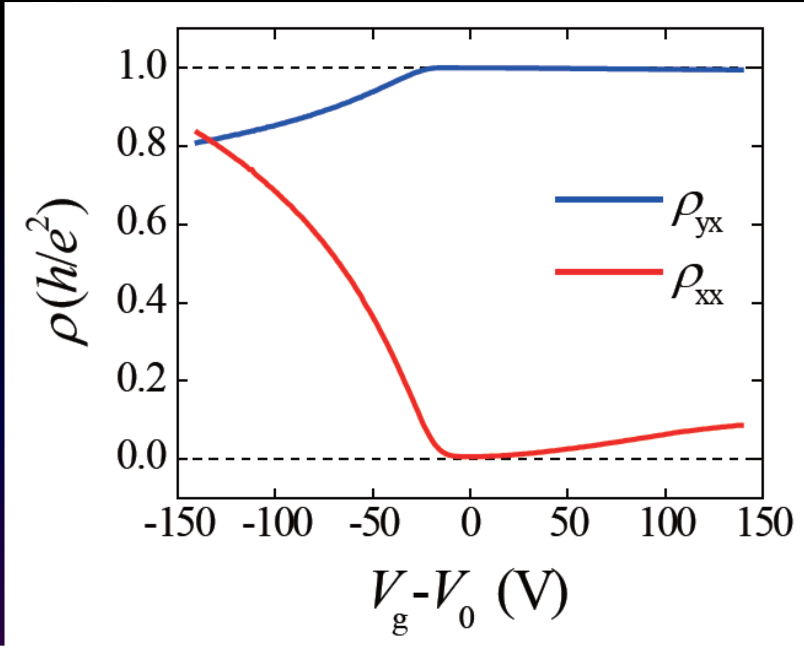
0.97 h/e^2 @ 1.5 K

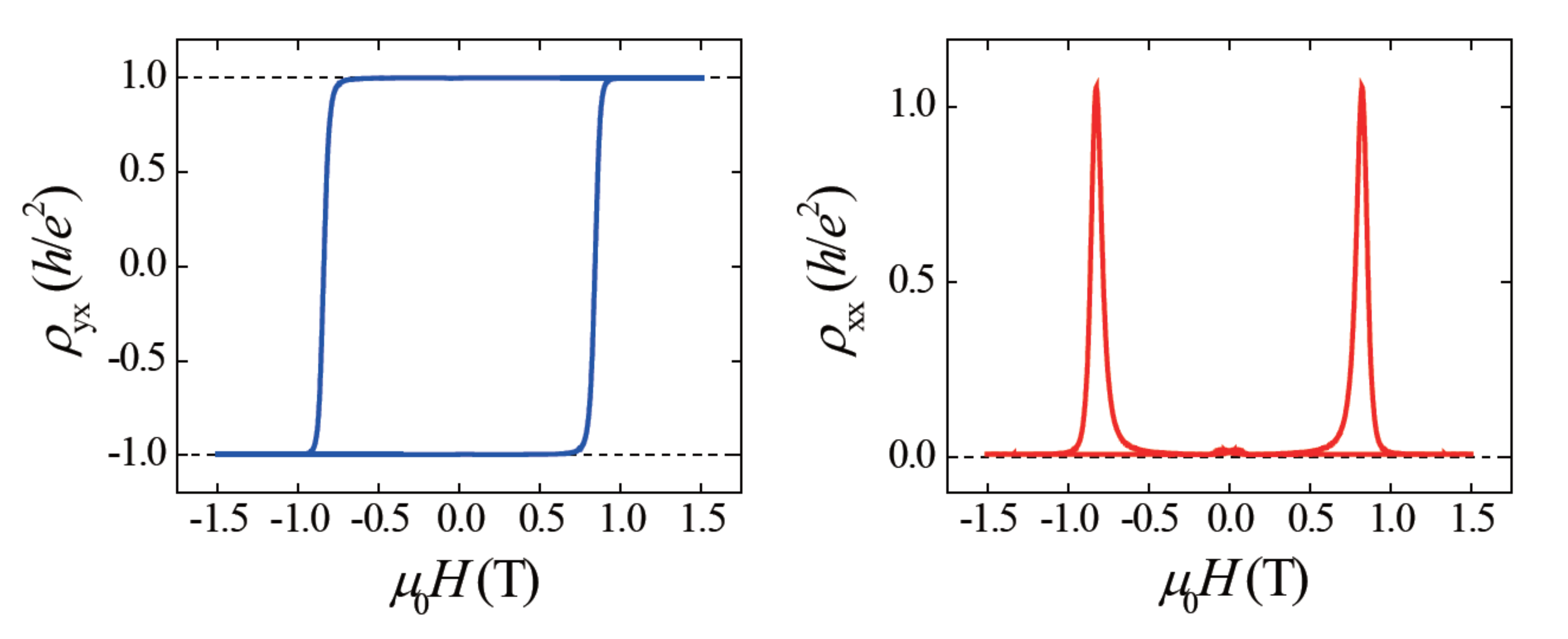


Y. Ou et al., Adv. Mater. (2018)

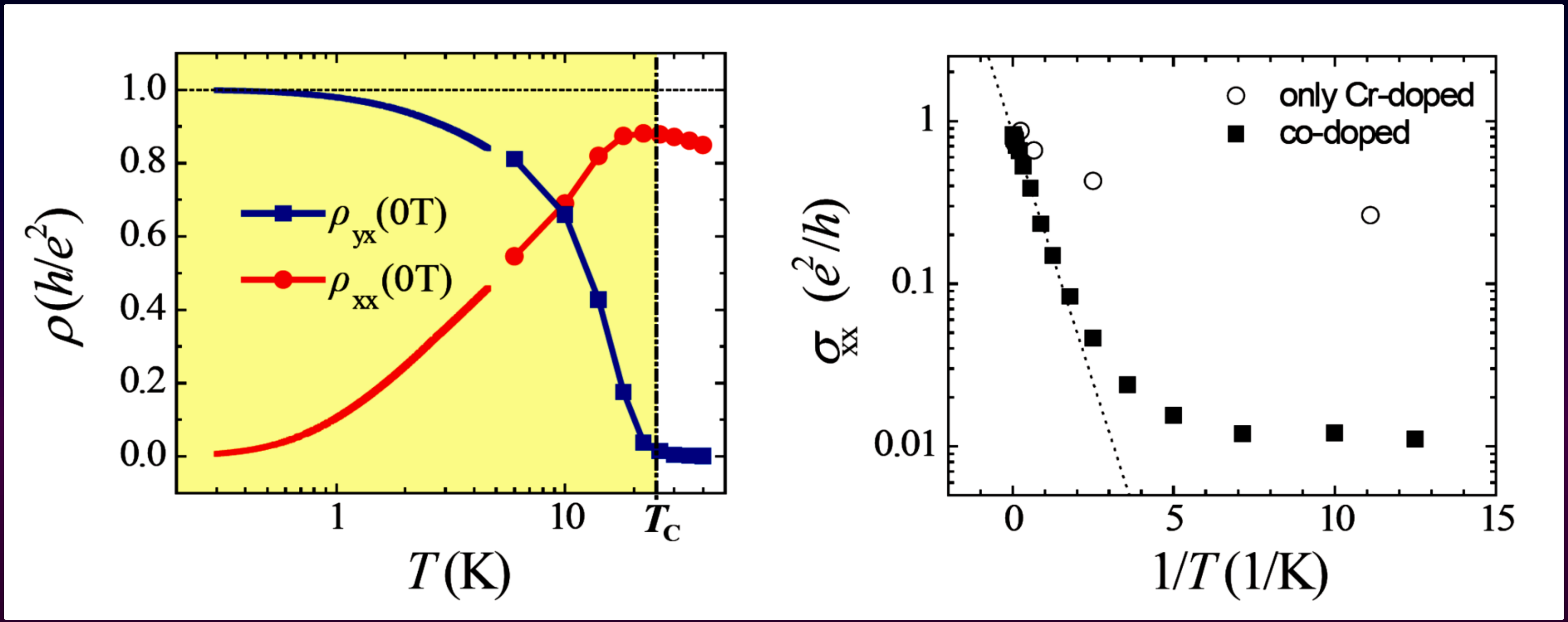
Full quantization at 0.3 K

Y. Ou et al., Adv. Mater. (2018)





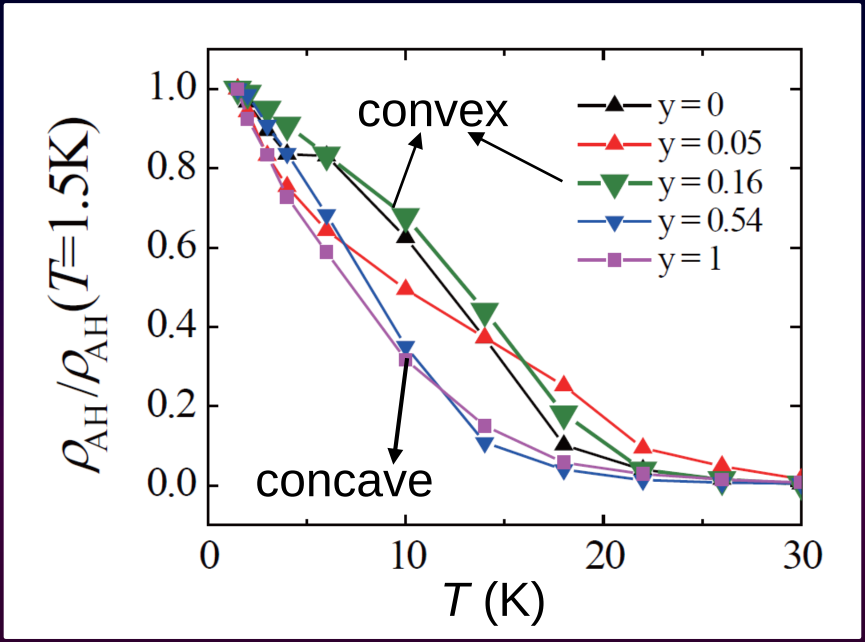
Temperature dependence



Activation gap ~ 1.4 K

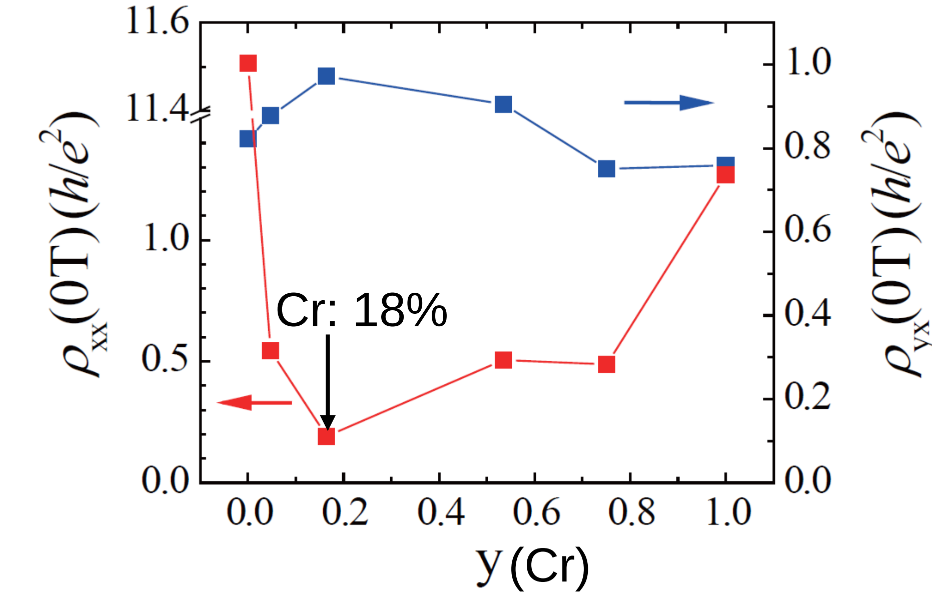
Y. Ou et al., Adv. Mater. (2018)

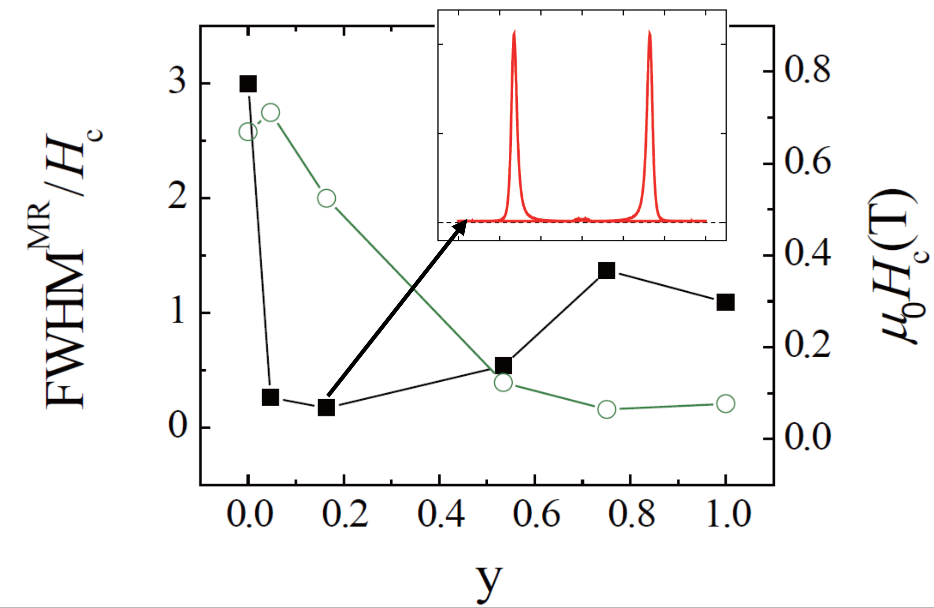
Why co-doped samples do better?



More mean-field-like
ρ_{AH}-T curve

Improved FM order

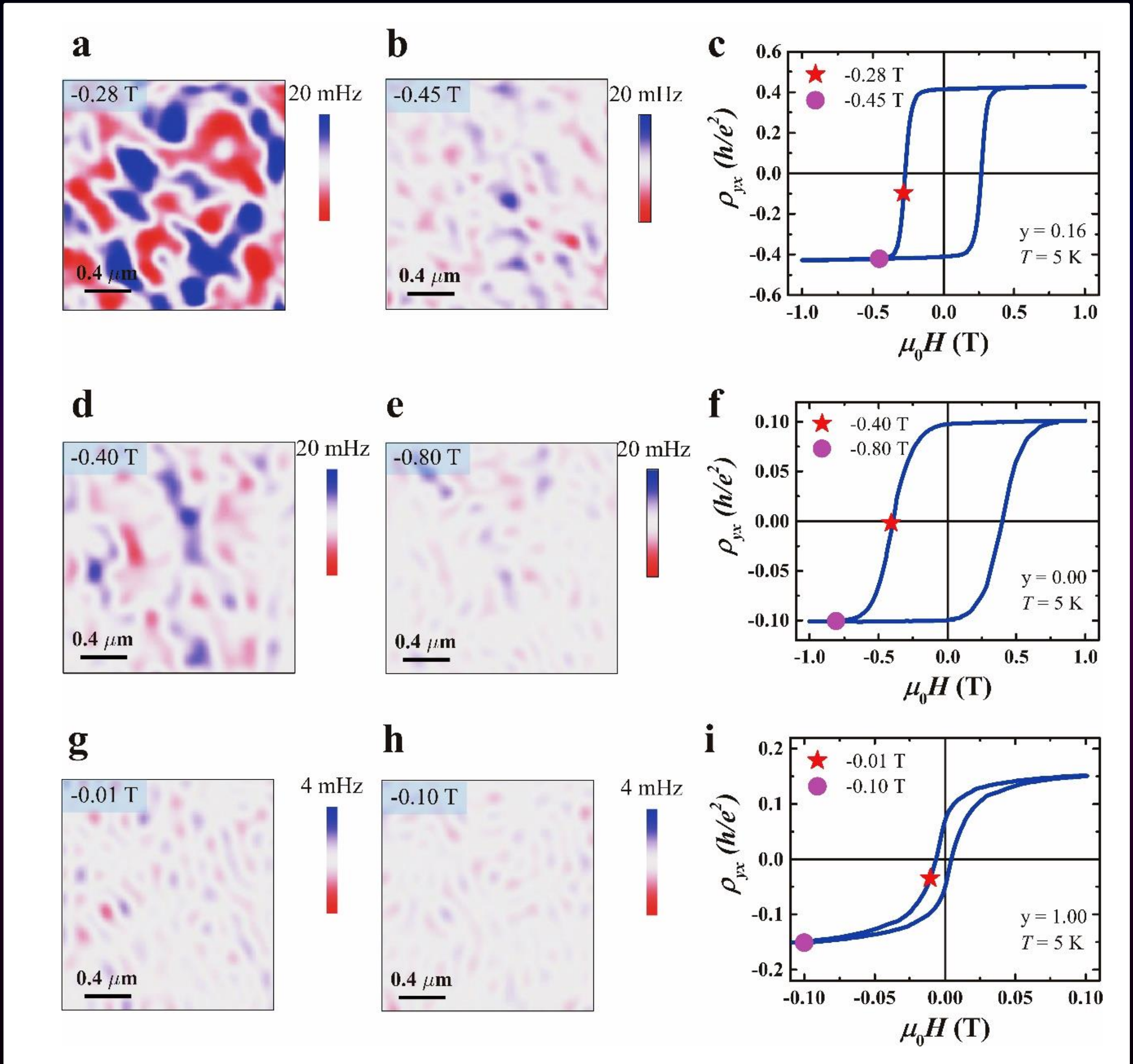




sharper magnetization reversal

Direct evidence by magnetic force microscopy

Weida Wu, Rutgers
Nat. Phys. (in press)

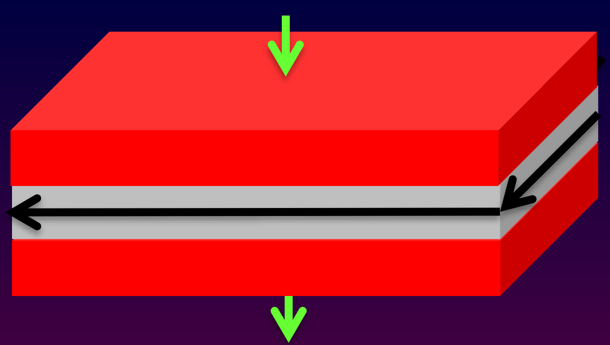


Cr+V co-doped

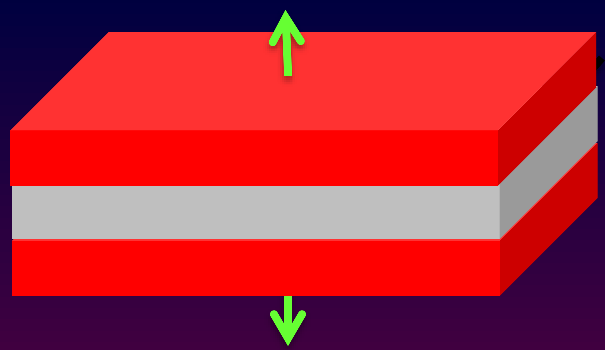
V-doped

Cr-doped

"Spin valve" based on QAH edge states in Cr+V co-doped $(Bi,Sb)_2Te_3$ films



QAH insulator



Axion insulator:

Topological magnetoelectric effect

⇩

Collinear electric and magnetic fields

X. -L. Qi, T. L. Hughes & S. -C. Zhang, PRB 78, 195424 (2008)

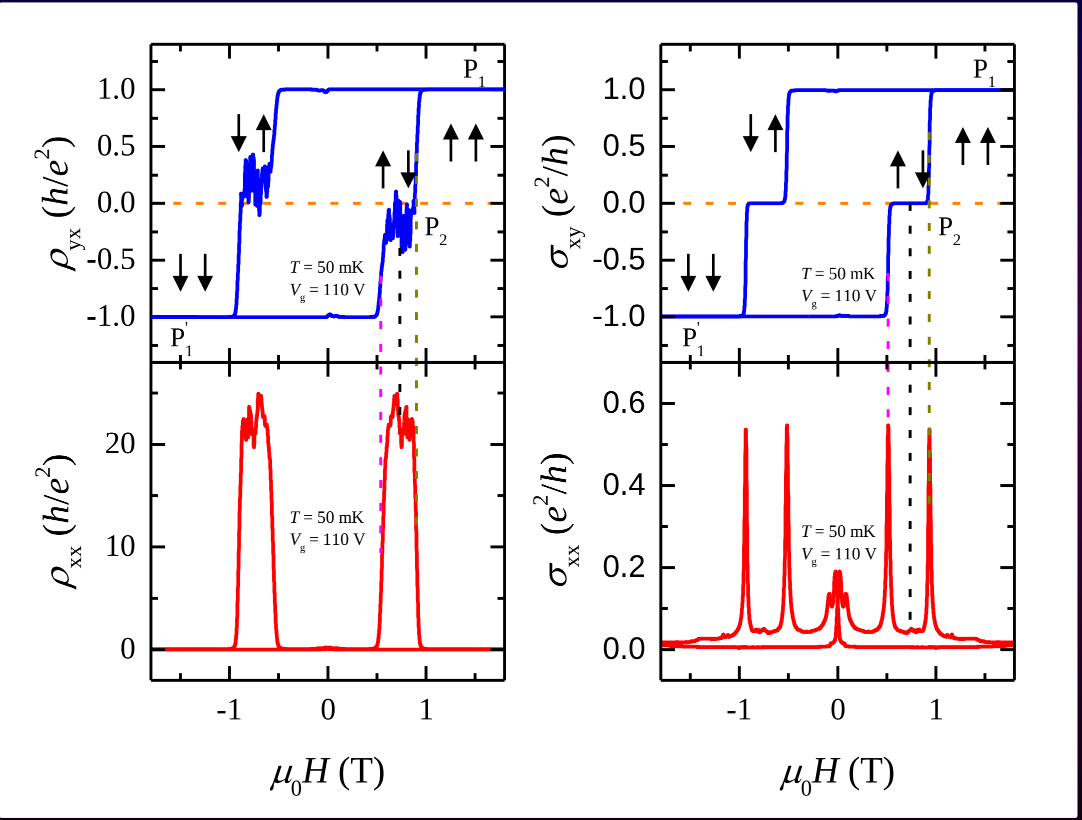
“Spin valve” for QAH edge states

Sample Structure

CVBST (Cr/V: 0.16/0.84—larger coercivity)
BST (non-magnetic)
CVBST (Cr/V: 0.4/0.6—smaller coercivity)

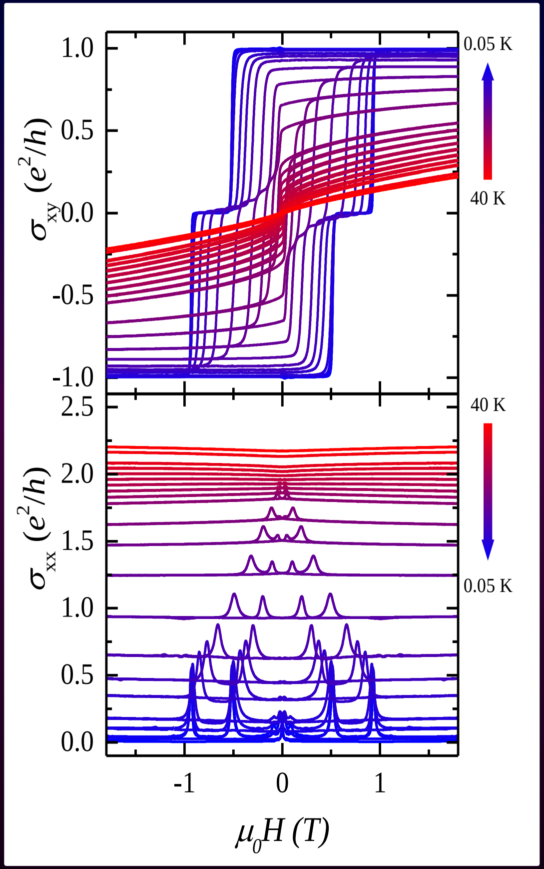
- When the magnetization directions of the top and bottom layers are parallel, QAH ($\rho_{xx}=0$, $\rho_{xy}= h/e^2$).
- Its longitudinal resistance becomes very large ($\rho_{xx}> 20\ h/e^2$) when anti-parallel.

Spin valve

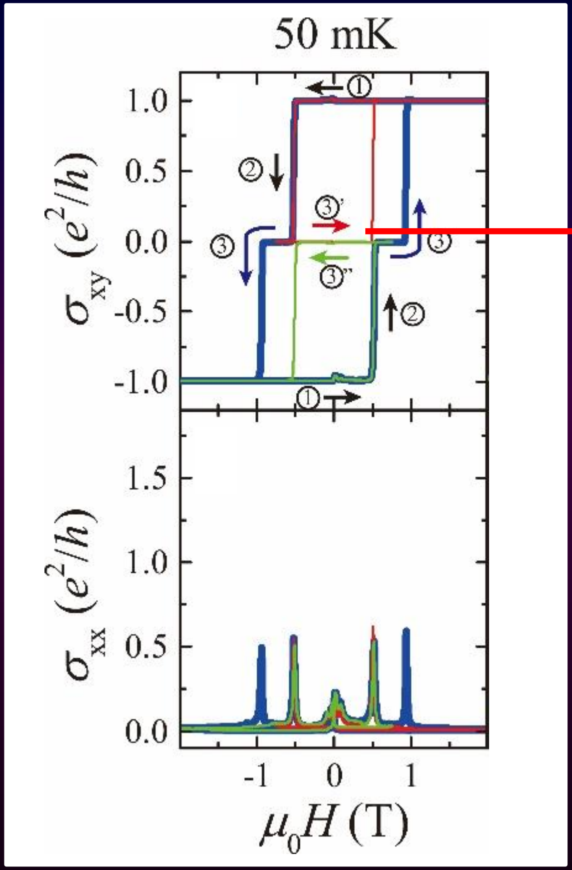


"Spin valve" for QAH edge states

Persistent up to 300 mK

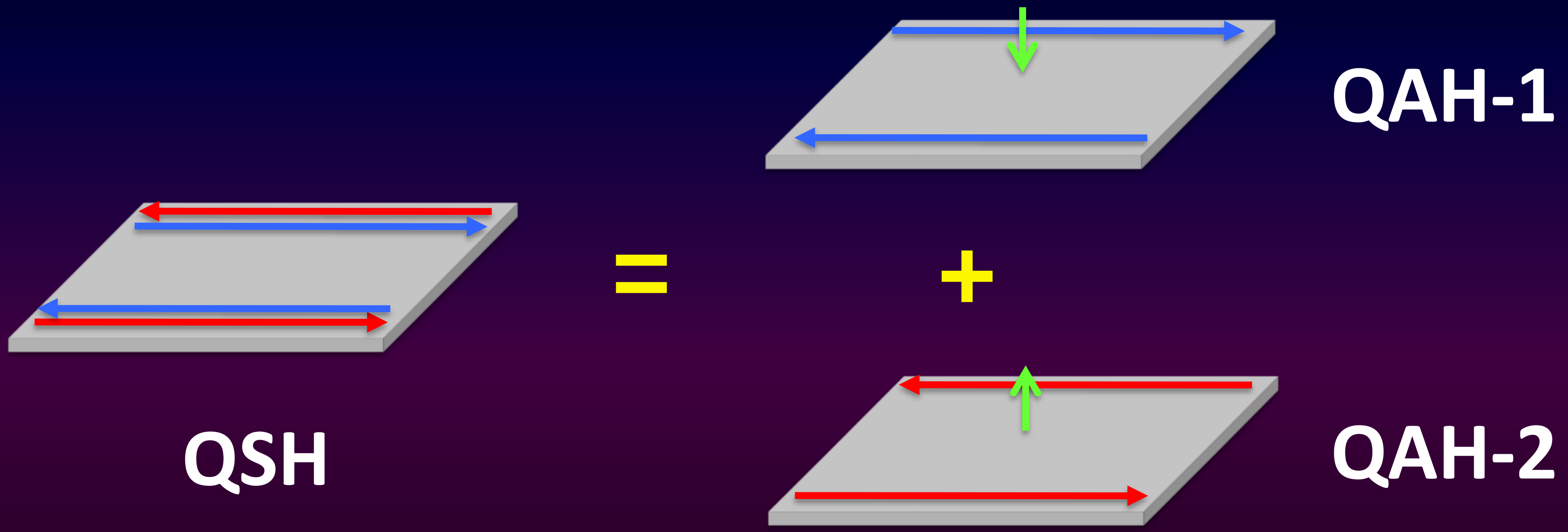


Robust



At zero plateau,
when we switch off the magnetic field,
the system stays at Axion insulator state (stable).

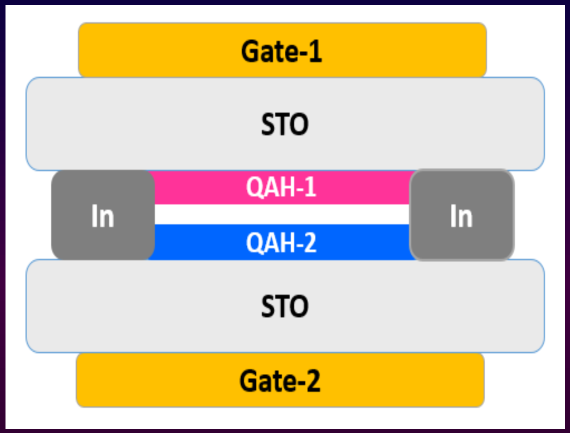
Synthetic Quantum Spin Hall System



Helical edge states = a pair of counter-propagating QAH chiral edge states

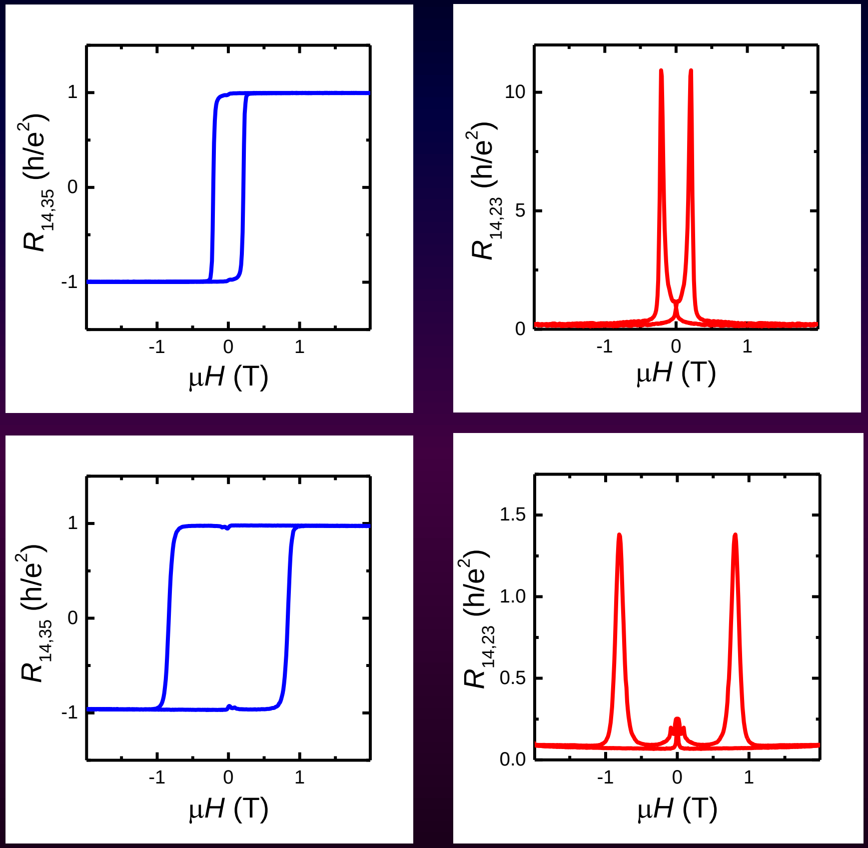
Qi, Wu & Zhang., PRB 2006

Synthetic Quantum Spin Hall System

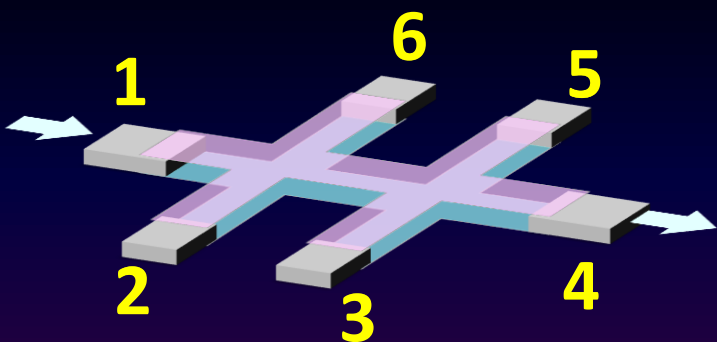


QAH-1
(less V)

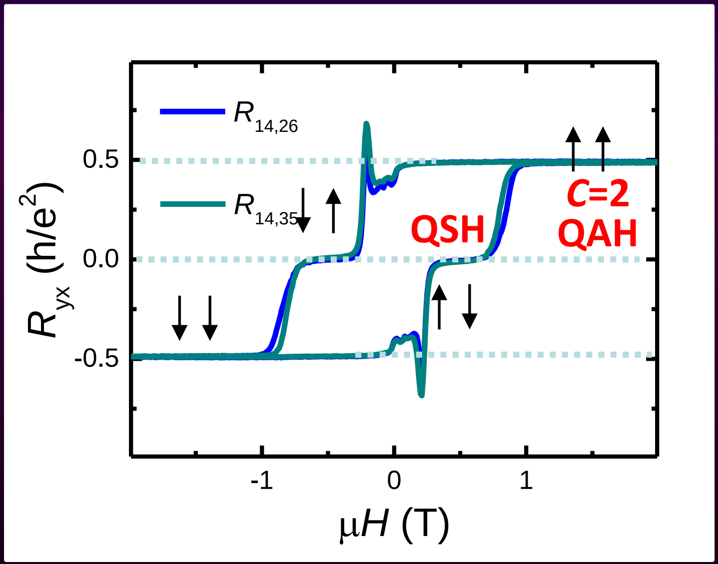
QAH-2
(more V)

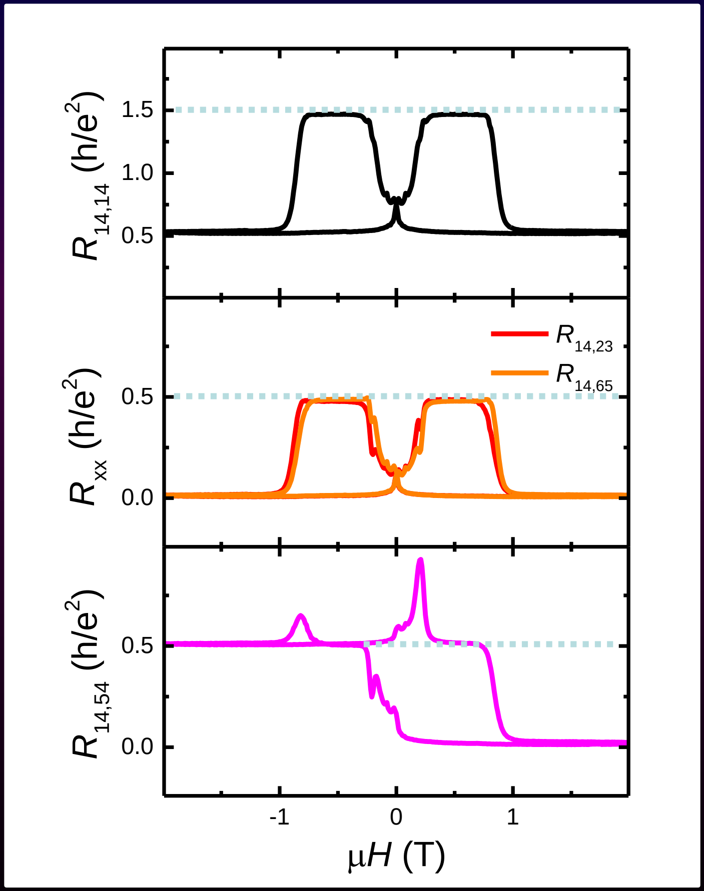


Synthetic Quantum Spin Hall System



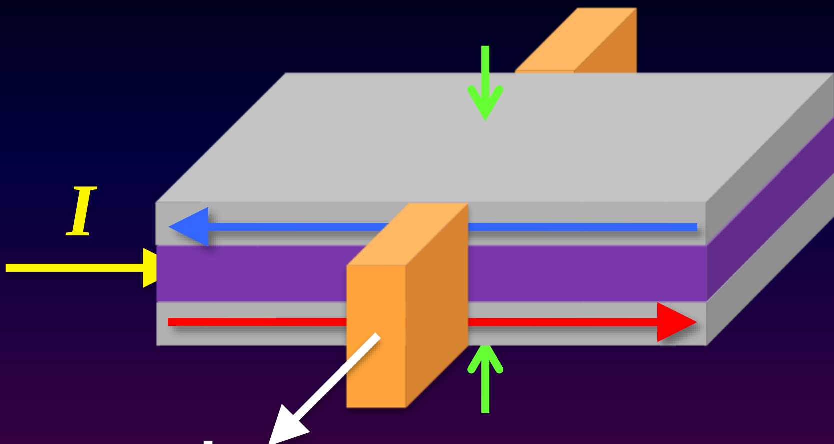
- When two QAH sub-systems have the same magnetization direction (strong field), the system become a QAH insulator with Chern number 2.
- In the case of opposite magnetization, it becomes a QSH system.





The synthetic QSH system could be useful

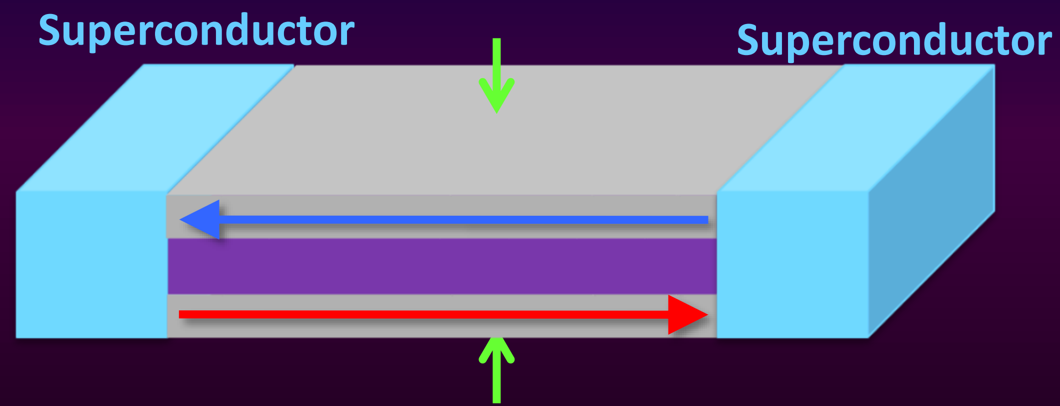
However, the two QAH systems
are separated too much:
the space is > coherent length



spin current

Brüne et al., Nat. Phys. 8, 485 (2012)

Q. L. He et al., Science 357, 294 (2017)

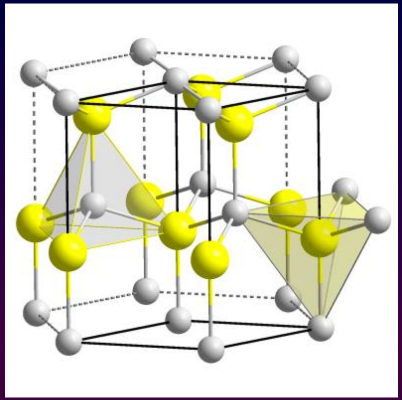


perfect Andreev reflection
(Majorana mode)

Knez, Du, Sullivan, Phys. Rev. Lett. 109, 186603 (2012)

Normal insulator spacing layer

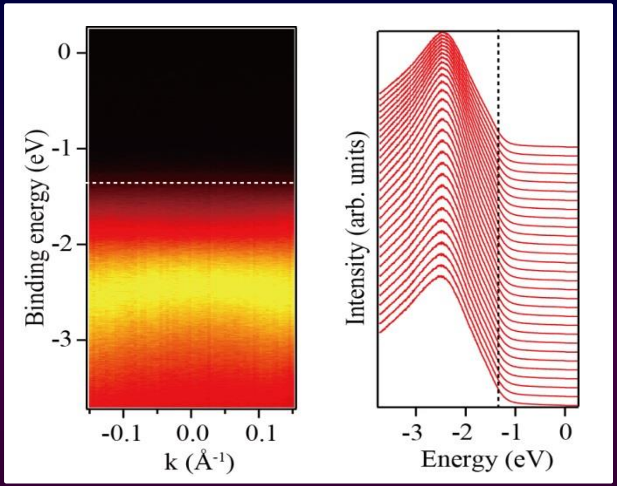
CdSe

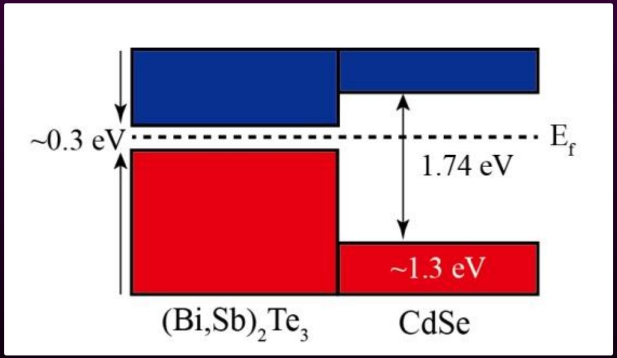


	CdSe	Bi_2Te_3	Sb_2Te_3
Lattice constant (Å)	4.30	4.43	4.26

Bandgap: ~1.74 eV

TI-CdSe Band alignment



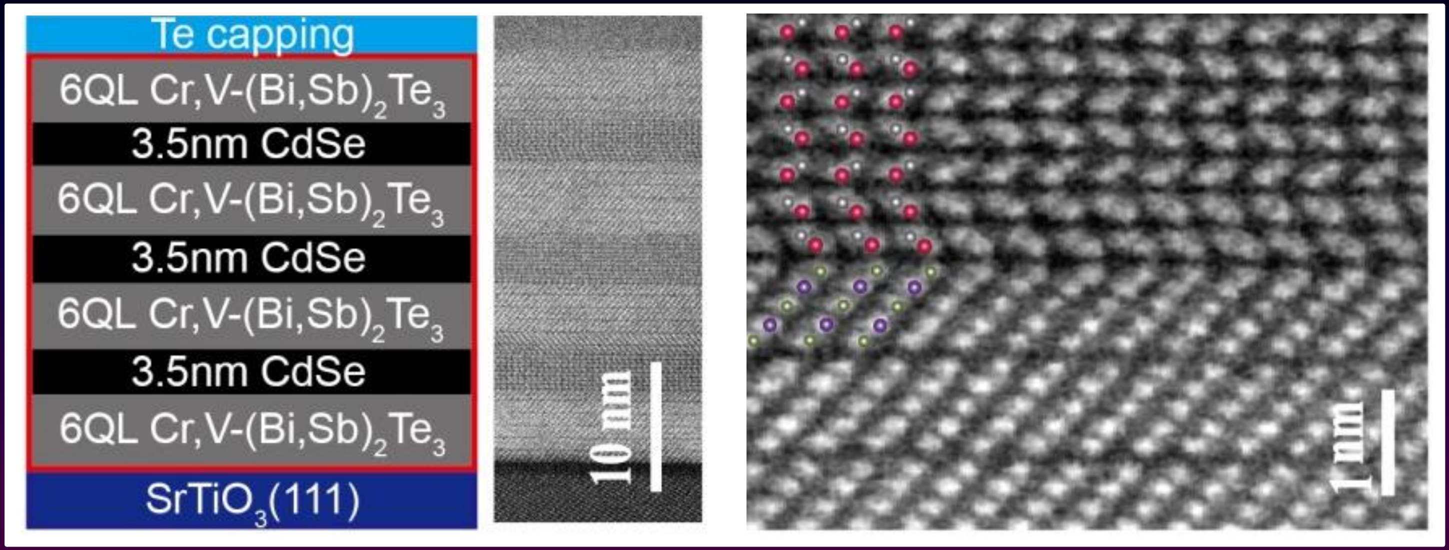


Type-I QW structure

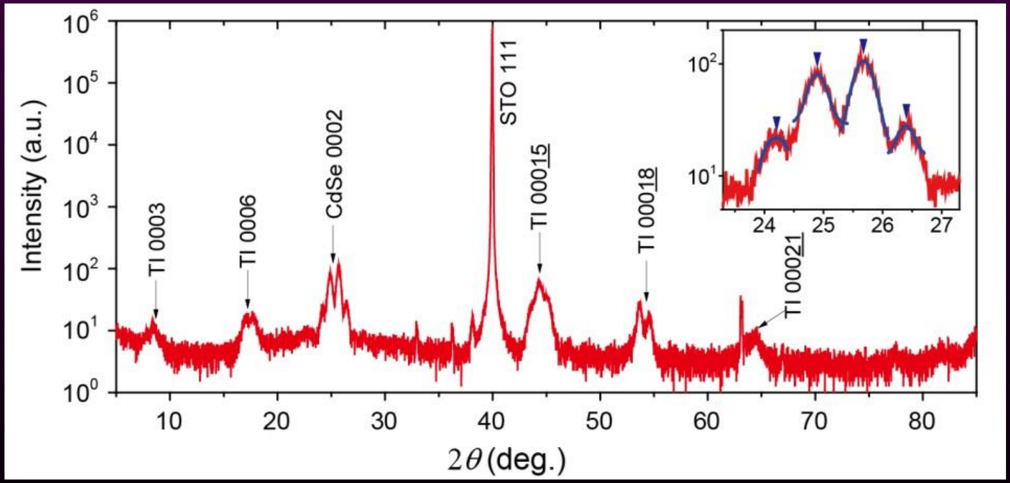
G. Jiang et al., (unpublished)

Superlattice of CVBST and CdSe

TEM



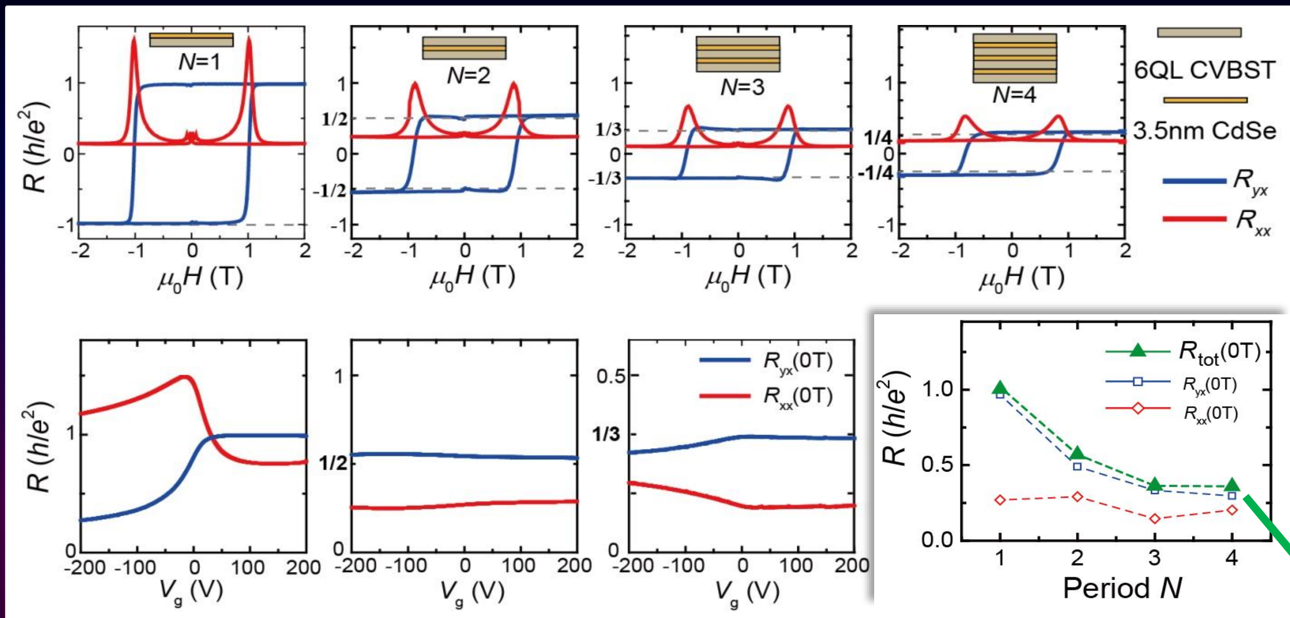
XRD



Super-lattice peaks

G. Jiang et al., (unpublished)

QAH multilayers



With increasing space layer number (N), the Hall resistance follows *h/Ne²*.

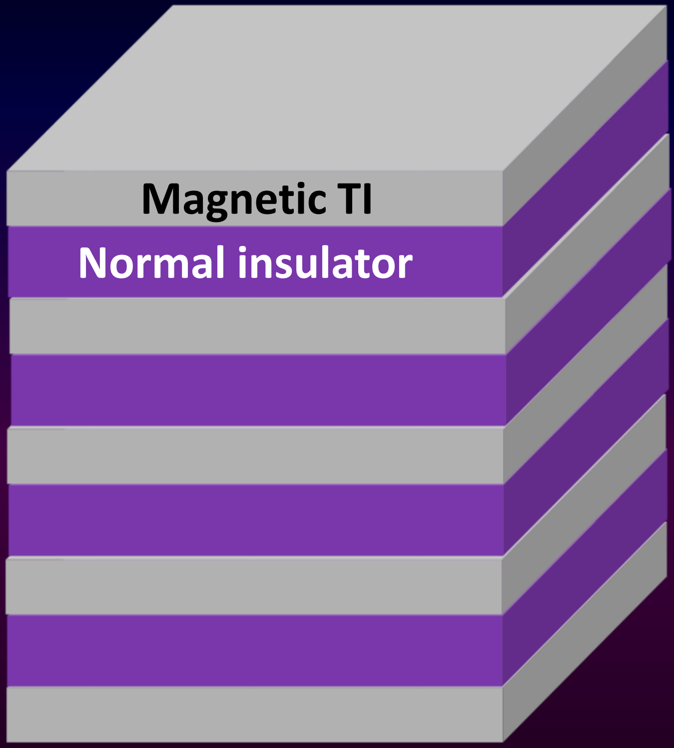
Effective high Chern number QAHE

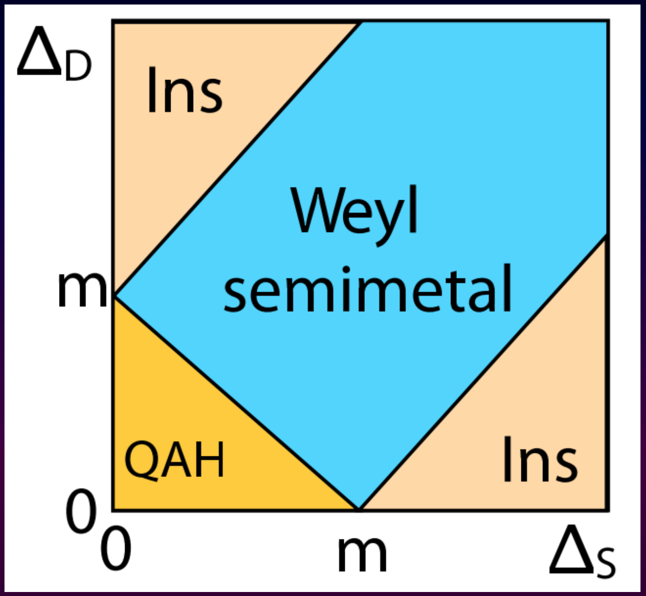
The two-terminal resistance decreases with increasing N

Applications

G. Jiang et al., (unpublished)

QAH multilayers: magnetic Weyl semimetals



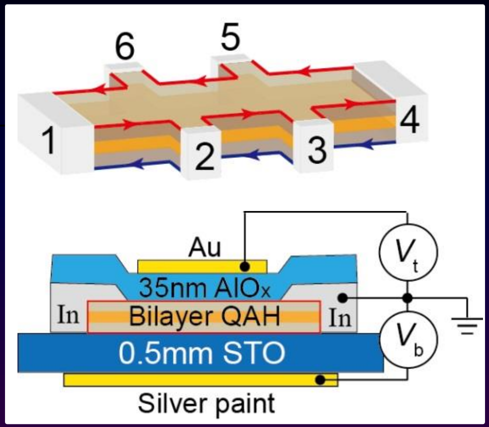


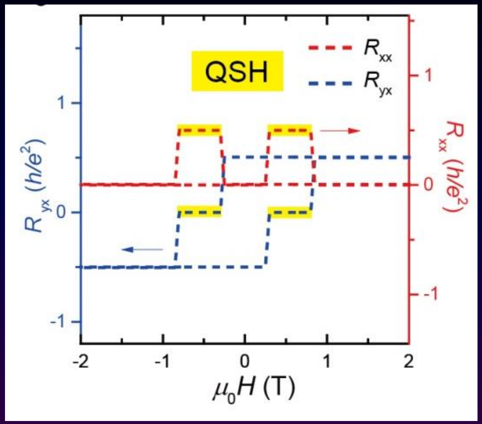
Δ_D: **Hybridization between the SSs of two MTI layers**

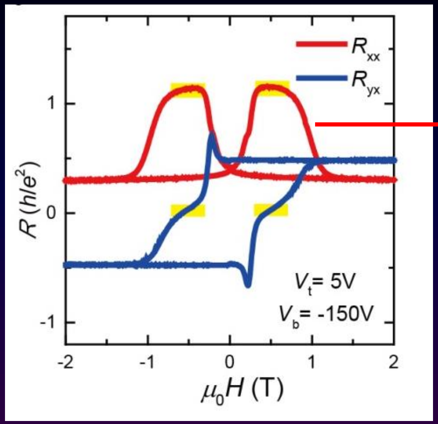
Δ_S: **Hybridization between the SSs of a MTI layer**

Burkov & Balents, PRL 107, 127205 (2011)

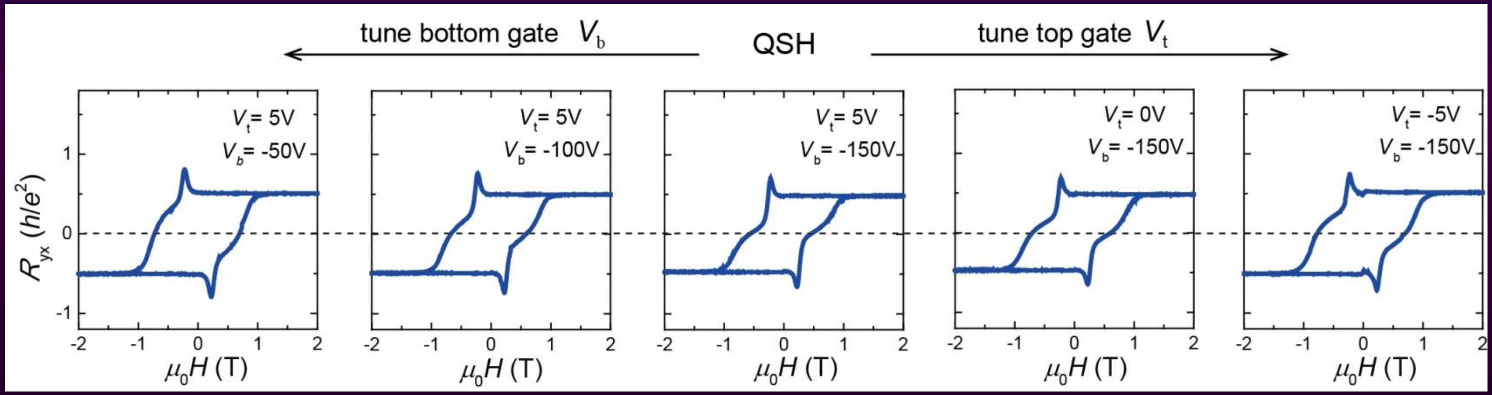
MBE-grown Effective QSH system







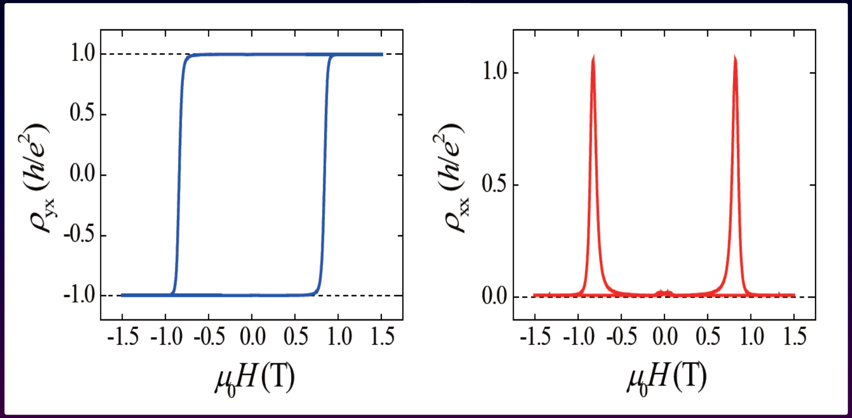
$R_{xx} > h/e^2$



In the "QSH" phase, $R_{xx} > h/2e^2$, which suggests scattering between the two chiral edge channels.

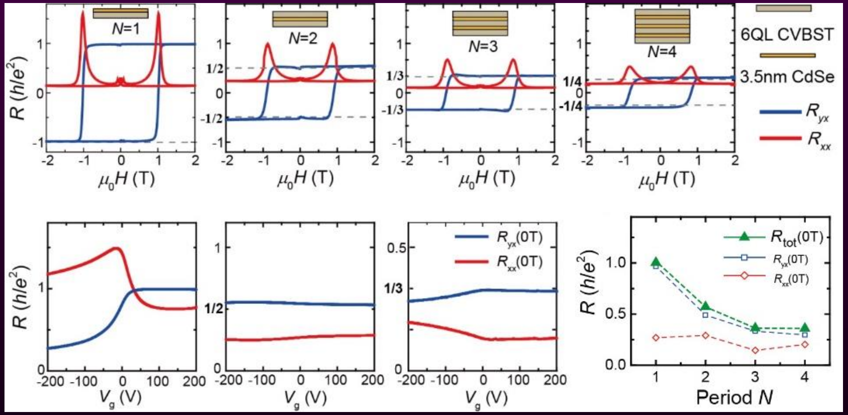
G. Jiang et al., (unpublished)

Summary



- **Cr+V co-doped $(Bi,Sb)_2Te_3$ shows improved QAHE and ferromagnetism.**

- **The improved material enables us to make interesting structures based on QAH systems.**



Thank you for your attention !

Synthetic Quantum Spin Hall System