Recent Progress on Quantum Anomalous Hall Effects

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Outline

1. Introduction
   - Graphene
   - Band gap engineering

2. Quantum anomalous Hall effect (QAHE) in graphene

   Progress on QAHE in graphene from ideal to realistic materials

3. Exploration of high-temperature QAHE in topological insulators and graphene

4. Anderson localization from Berry-curvature interchange in QAHE systems

5. Summary

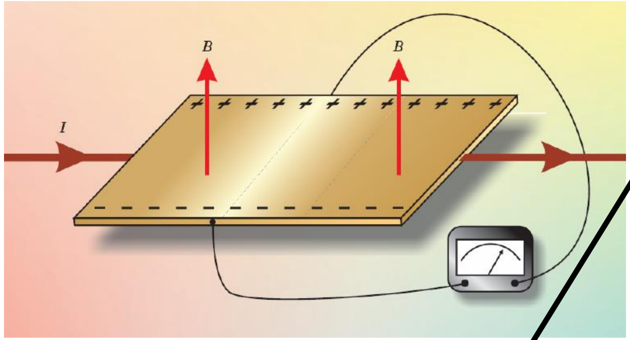
ABCs about Hall Effects

Edwin Herbert Hall

3D Hall Effect ← *1879* → 3D Anomalous Hall Effect

(*B* field, Lorenz force)

(Ferromagnetic material)



Spin-Hall Effect

1975 | 1980

1971 | 2004

Quantum Valley Hall Effect (QVHE)

Quantum Hall Effect

(2D, Low T, Landau Quantization)

2005 | 2007

Quantum Spin-Hall Effect/ 2D Topological Insulators (TI)

1988 | 2013

Quantum Anomalous Hall Effect (QAHE)

ABCs about Hall Effects

2D Topological Insulators

↓

3D Topological Insulators

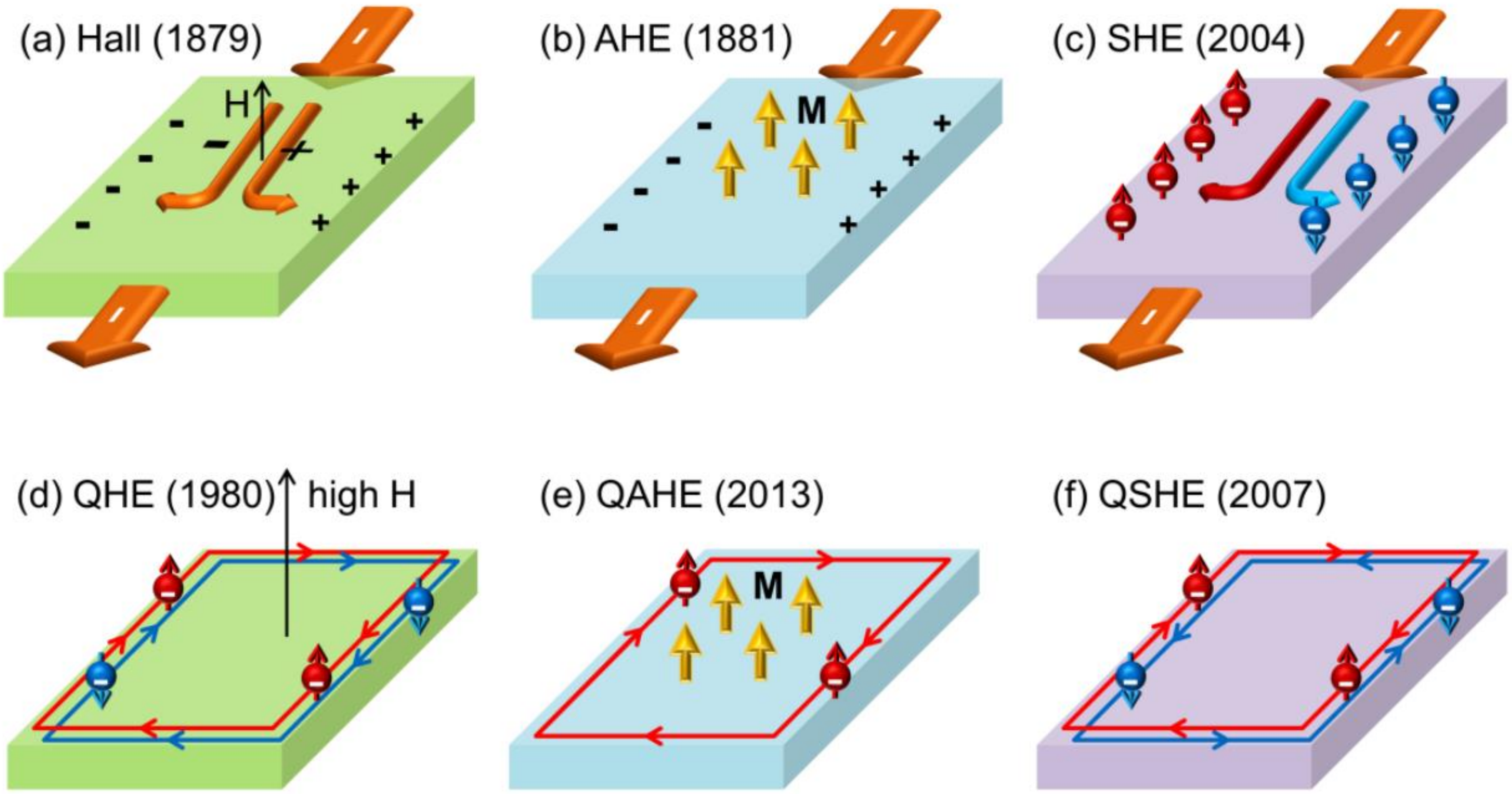
↓

3D quantum Hall effect
(2019 Experiment)

↑

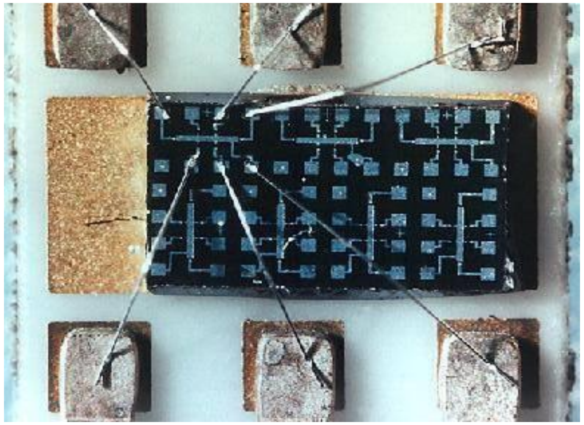
3D quantum Hall effect
(1987 theory)

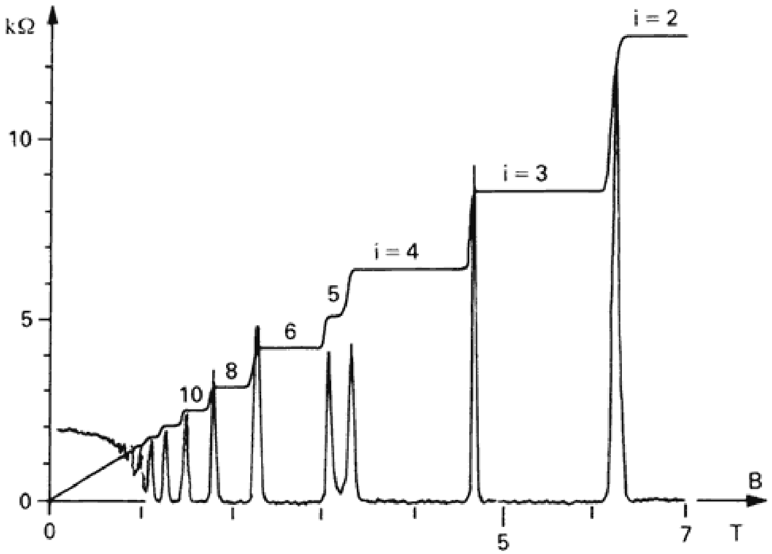
Members of Hall family



Quantum Hall Effect

In the 2D limit, Landau-level quantization from strong magnetic field leads to ***quantized Hall conductance*** --- zero longitudinal resistance.

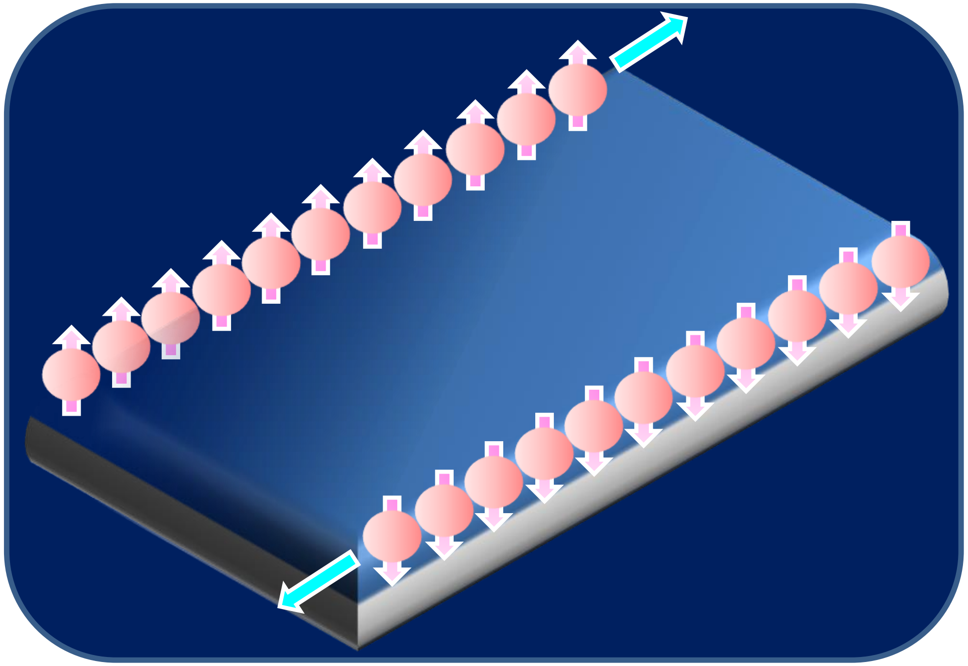


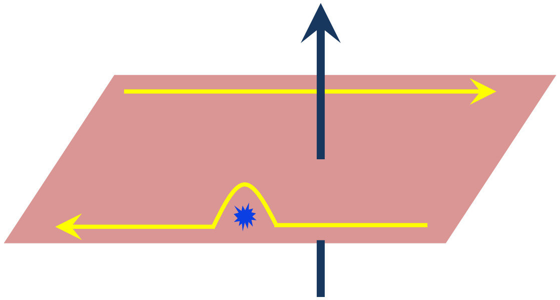


Edge States of Quantum Hall Effect

Characters of QHE

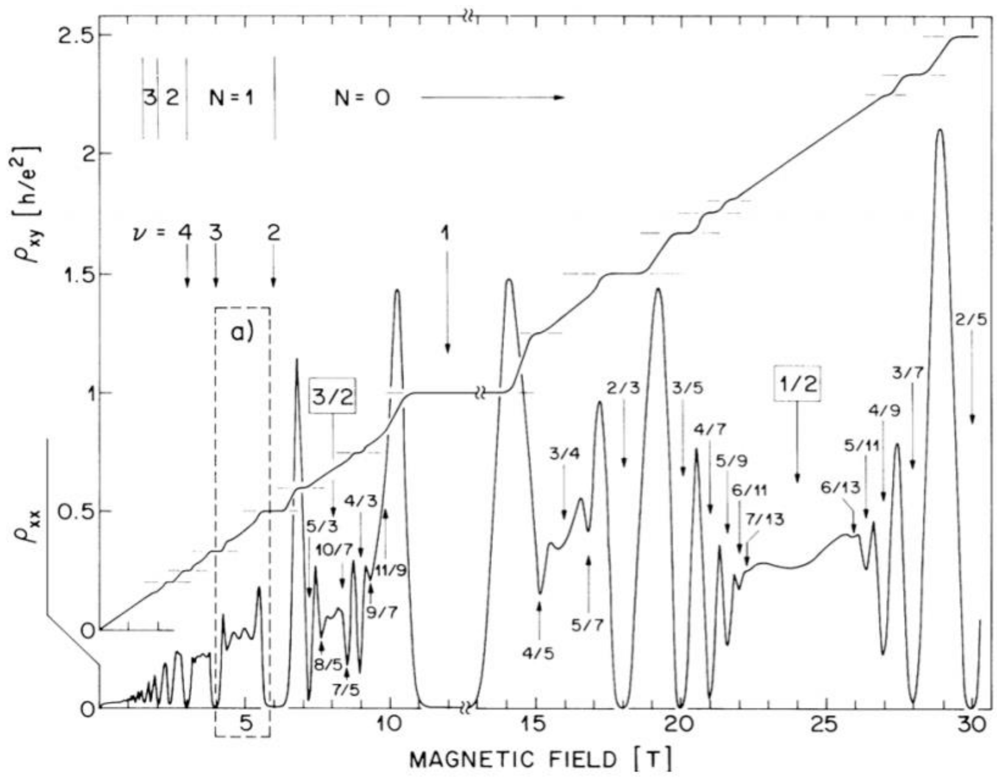
- Strong magnetic field
- Insulating bulk
  -- Landau level
- Real topological state
  -- Robust edge state
  -- Backscattering forbidden
- High-precision determination of fine structure constant
  -- IQHE: $\alpha^{-1} = 137.0360037(27)$
  -- CODATA-2010: $\alpha^{-1} = 137.035999074(44)$





Back-scattering is forbidden!

Fractional Quantum Hall Effect



$$\sigma_{xy} = n\,e^2/h$$

n=1/3, 2/3, 1/5, …

D.C. Tsui, *et al.*, PRL (1982)

- Electron-electron interaction
- Landau quantization
- A topological quantum phase of composite fermions with broken time-reversal symmetry

Nobel Prize in Quantum Hall Effect

The Nobel Prize in Physics 1985

Photo from the Nobel Foundation archive.

Klaus von Klitzing

Prize share: 1/1

The Nobel Prize in Physics 1985 was awarded to Klaus von Klitzing "for the discovery of the quantized Hall effect."

The Nobel Prize in Physics 1998

Photo from the Nobel Foundation archive.

Robert B. Laughlin

Prize share: 1/3

Photo from the Nobel Foundation archive.

Horst L. Störmer

Prize share: 1/3

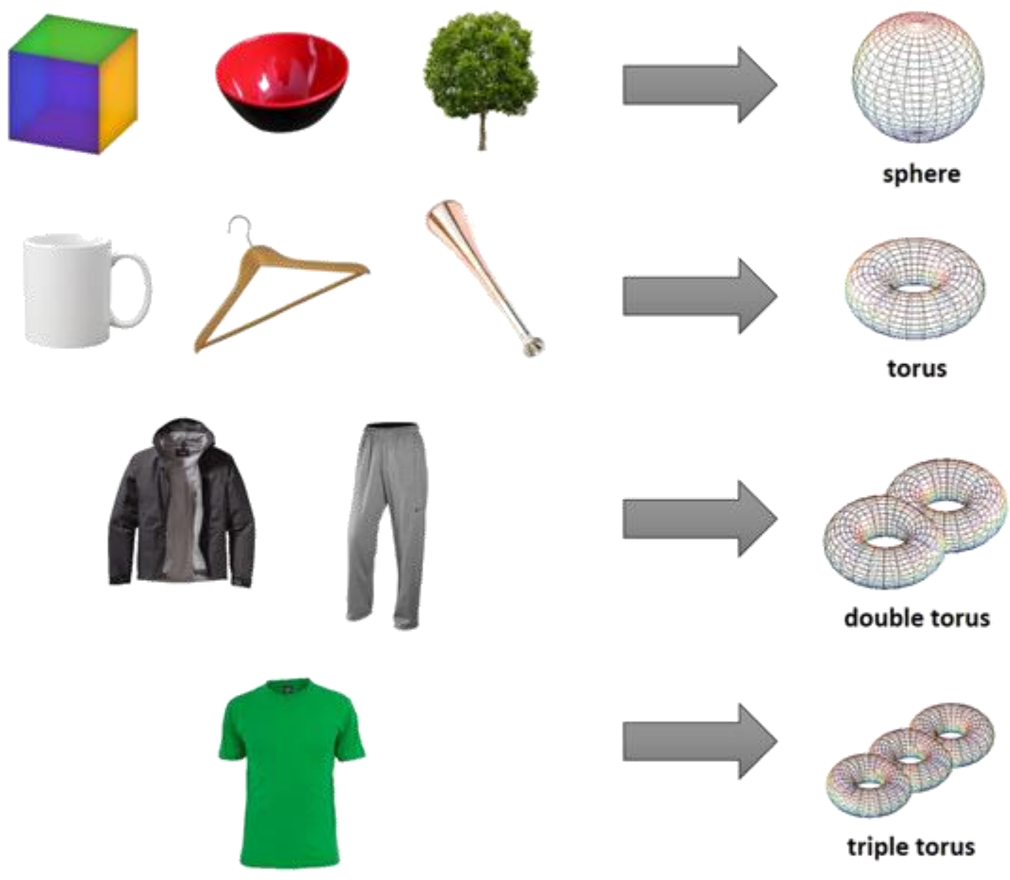
Photo from the Nobel Foundation archive.

Daniel C. Tsui

Prize share: 1/3

The Nobel Prize in Physics 1998 was awarded jointly to Robert B. Laughlin, Horst L. Störmer and Daniel C. Tsui "for their discovery of a new form of quantum fluid with fractionally charged excitations."

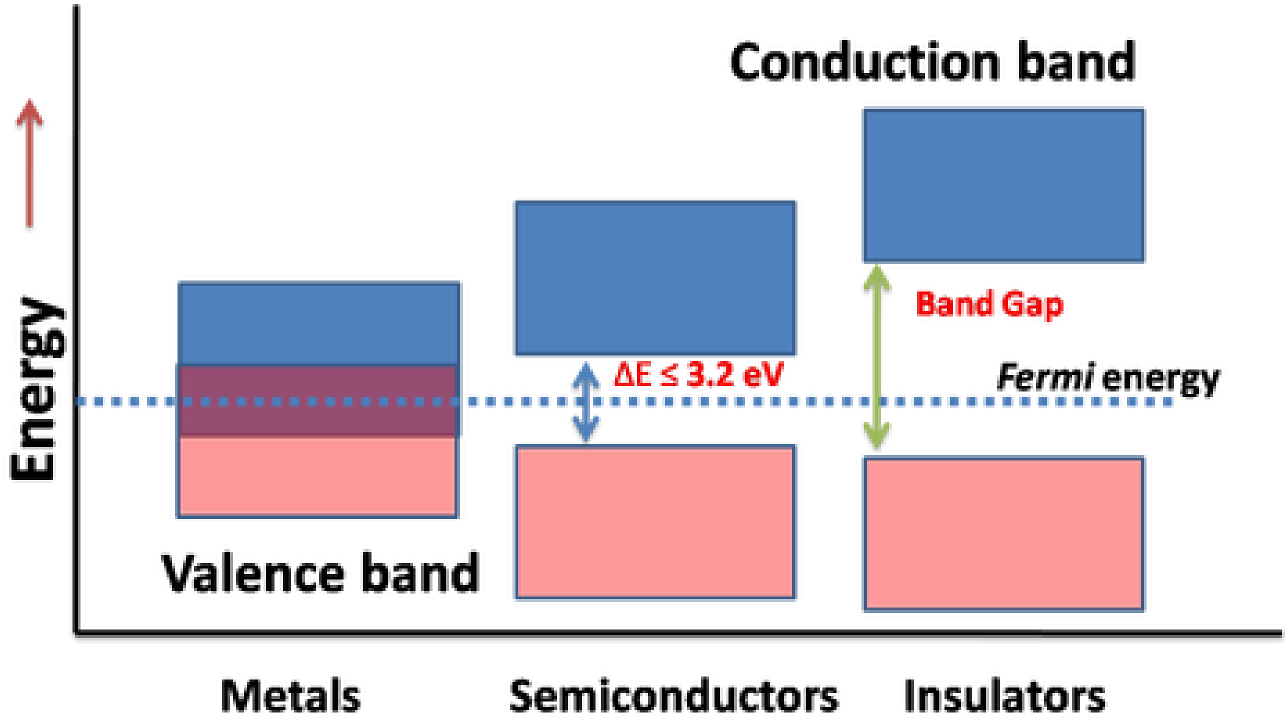
Continuous deformation

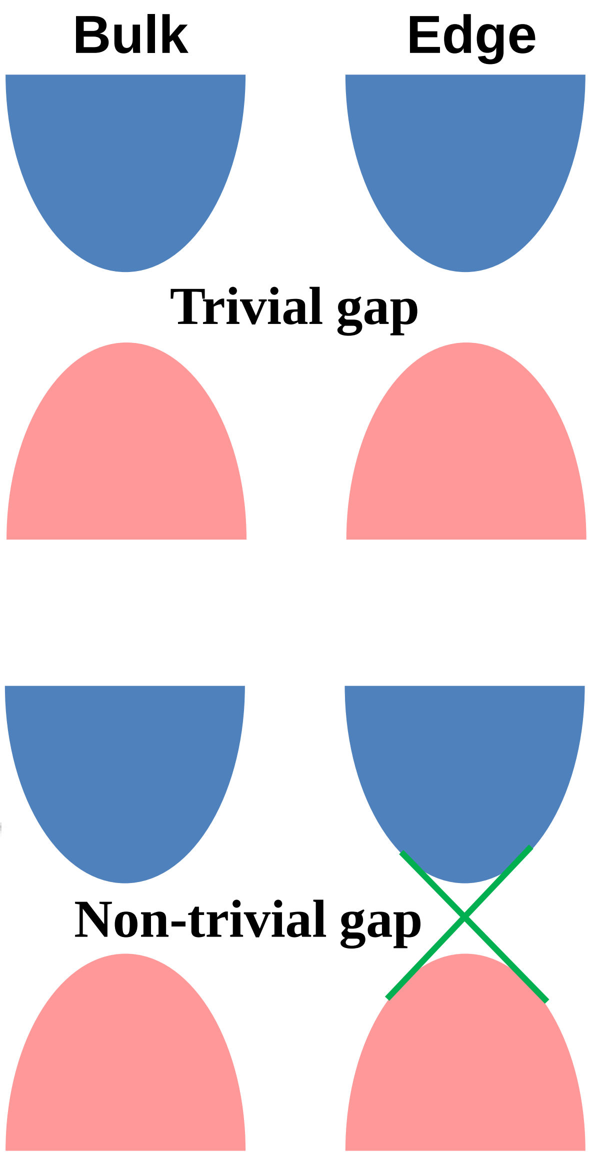


Möbius strip

Topology in Condensed Matter Physics

Material classification





Topology in Condensed Matter Physics

Kubo formula: TKNN number / Chern number

$$\sigma_H = \frac{ie^2}{A_0 \hbar} \sum_{\epsilon_\alpha < E_F} \sum_{\epsilon_\beta > E_F} \frac{(\partial \hat{H}/\partial k_1)_{\alpha\beta} (\partial \hat{H}/\partial k_2)_{\beta\alpha} - (\partial \hat{H}/\partial k_2)_{\alpha\beta} (\partial \hat{H}/\partial k_1)_{\beta\alpha}}{(\epsilon_\alpha - \epsilon_\beta)^2}$$

D. J. Thouless *et al*., PRL 1982

Berry curvature:

$$\Omega_n(\boldsymbol{k}) = -\sum_{n' \neq n} \frac{2\,\mathrm{Im}\langle \psi_{n\boldsymbol{k}} | v_x | \psi_{n'\boldsymbol{k}} \rangle \langle \psi_{n'\boldsymbol{k}} | v_y | \psi_{n\boldsymbol{k}} \rangle}{(\omega_{n'} - \omega_n)^2}$$

Induce anomalous velocity perpendicular to external electric filed!

Chern number:

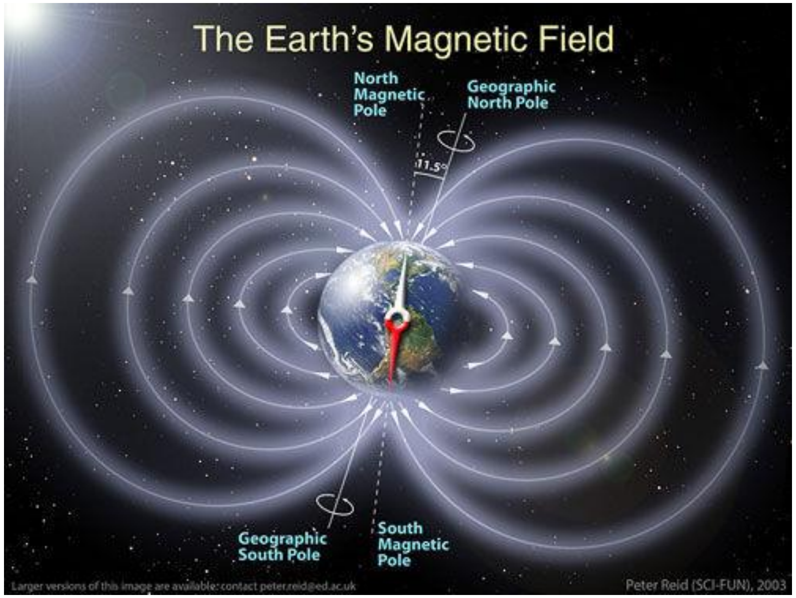
$$\mathcal{C} = \frac{1}{2\pi} \sum_n \int_{\mathrm{BZ}} d^2k\, \Omega_n \quad \longrightarrow \quad \sigma_H = \mathcal{C} \frac{e^2}{h}$$

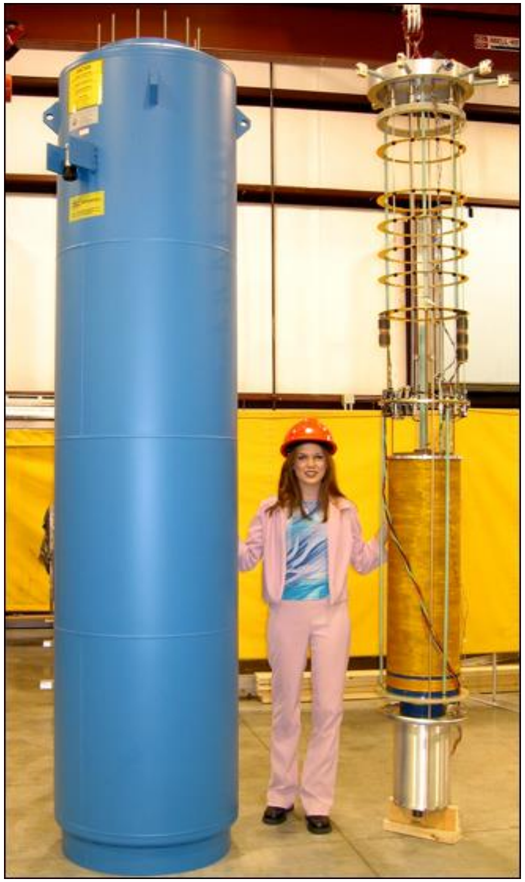
M. C. Chang and Q. Niu, PRL 1995; PRB 1996

The Disadvantage of QHE: Strong B field

QHE: 10000 Gauss

Earth: 0.5 Gauss



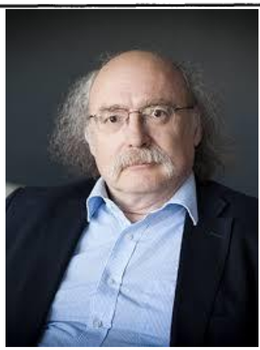


Quantum Hall Effect

Goal of both condensed matter physics and materials physics:

Quantum Hall effect ***without magnetic field***

Quantum anomalous Hall Effect



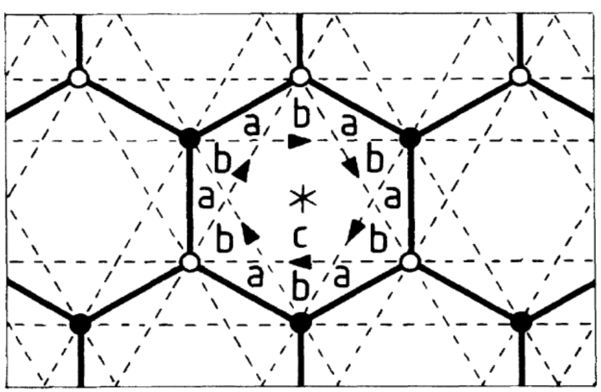
Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the "Parity Anomaly"

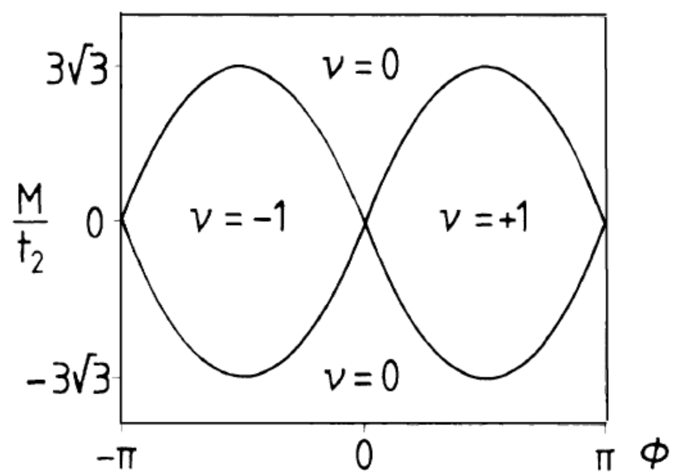
F. D. M. Haldane

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

(Received 16 September 1987)

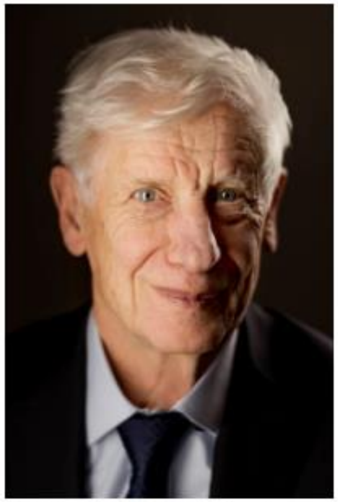
A two-dimensional condensed-matter lattice model is presented which exhibits a nonzero quantization of the Hall conductance σ^{xy} in the *absence* of an external magnetic field. Massless fermions *without spectral doubling* occur at critical values of the model parameters, and exhibit the so-called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





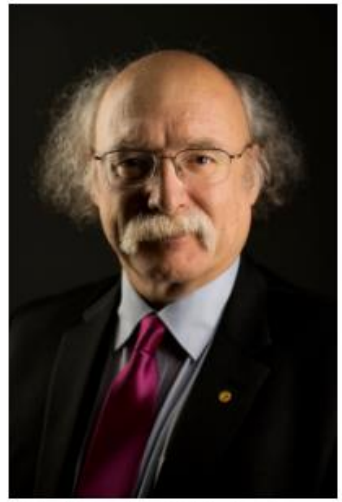
Nobel Prize in Physics 2016

The Nobel Prize in Physics 2016



David J. Thouless

Prize share: 1/2



F. Duncan M. Haldane

Prize share: 1/4

J. Michael Kosterlitz

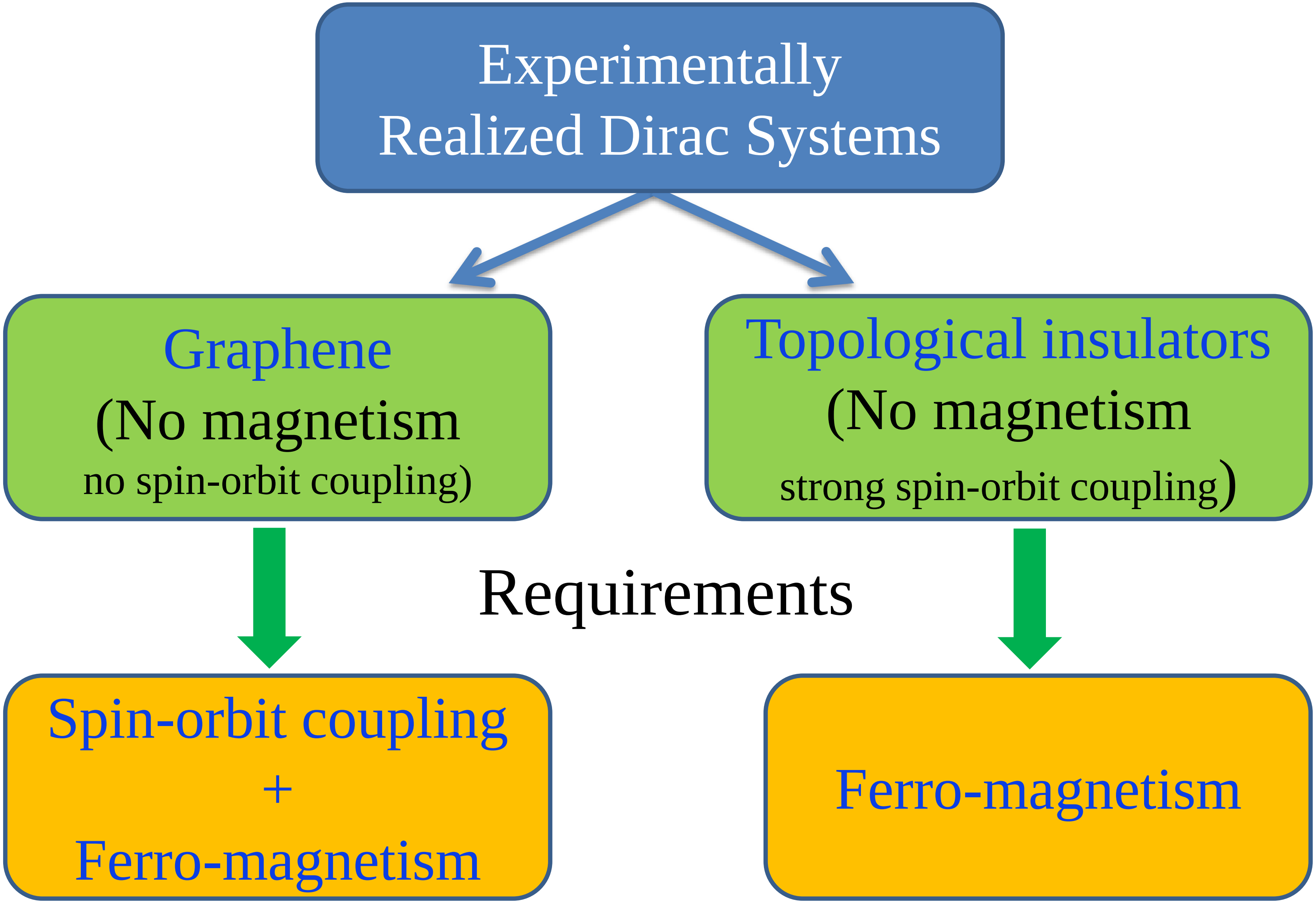
Prize share: 1/4

The Nobel Prize in Physics 2016 was divided, one half awarded to David J. Thouless, the other half jointly to F. Duncan M. Haldane and J. Michael Kosterlitz "for theoretical discoveries of topological phase transitions and topological phases of matter."

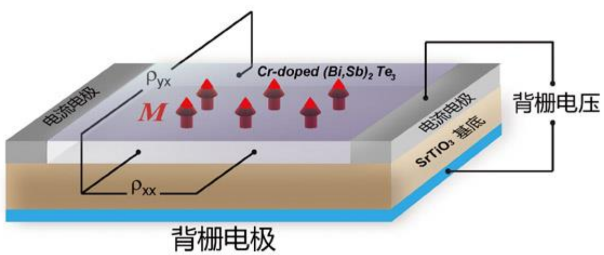
Proposals for realizing QAHE

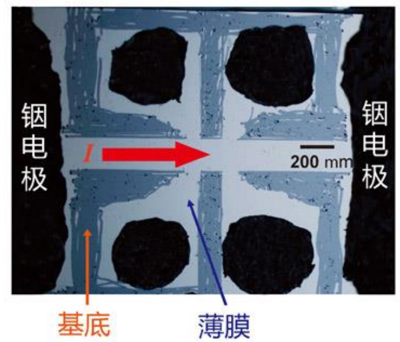
(a) Disordered honeycomb system	**Onoda et al., PRL 90, 206601 (2003)**
(b) HgTe quantum wells	**Liu et al., PRL 101, 146802 (2008)**
(c) Cold-atom system	**Wu, PRL 101, 186807 (2008)**
(d) Topological insulators	**Yu et al., Science 329, 61 (2010)**
(e) *Graphene*	**Qiao et al., PRB 82, 161414 (2010)**
(f) Silicene	**Ezawa, PRL 109, 055502 (2012)**
(g) Kagome lattices	**Zhang, JPCM 23, 365801 (2011)**
(h) Thin layers containing heavy elements	**Garrity et al., PRL 110, 116802 (2013)**
(i) Organic molecules	**Wang et al., PRL 110, 196801 (2013)**
(j) ……	

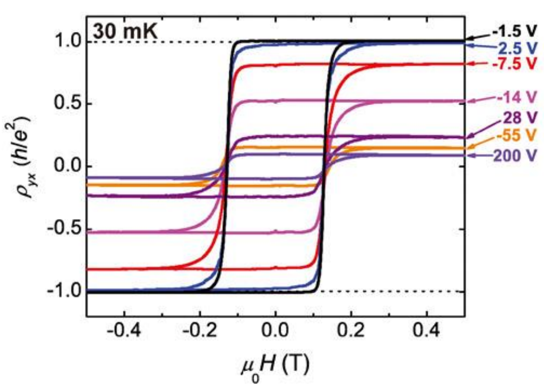
General QAHE Materials

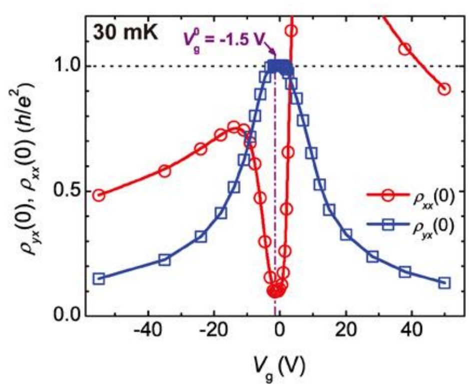


Short summary of magnetic topological insulator based quantum anomalous Hall effect







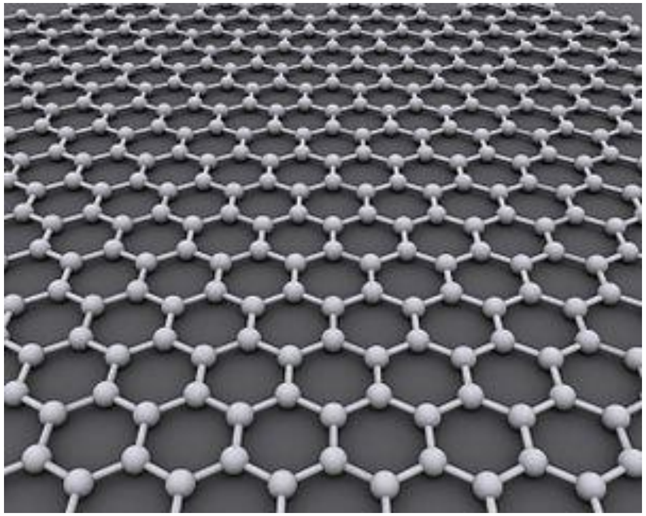


2010年，方忠、戴希团队理论首次提出；

2013年，由薛其坤教授领衔的国际联合团队首次实验观测到；

2018年，薛其坤教授团队获得国家自然科学一等奖

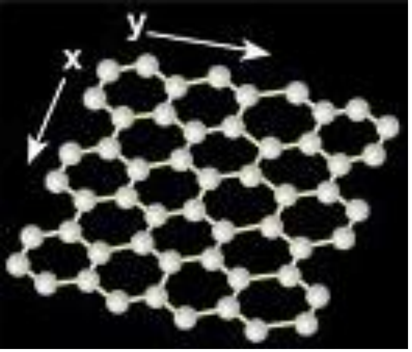
Why graphene? Era of 2D Materials



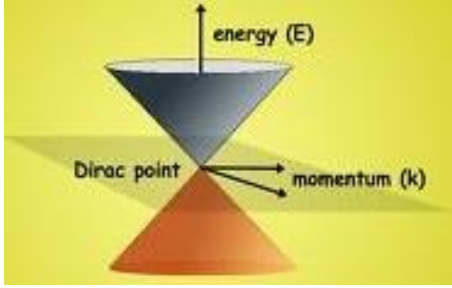
SEM

2004: the beginning of 2D materials

Graphene-hBN-Silicene-MoS2… …



Why graphene?



石墨烯：拓扑态的理想载体

石墨烯材料的优势

1、材料特性：

线性Dirac色散关系引起的

优异的电学、光学特性

2、制备基础：

实验及工业上已经可制备

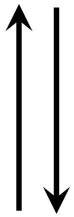
大面积高质量的石墨烯

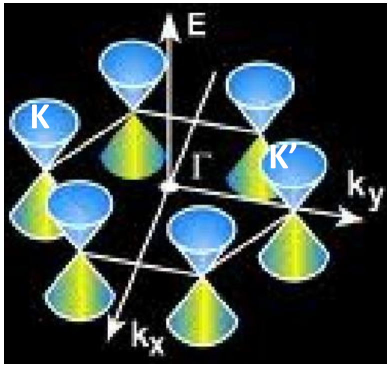
多种可调自由度

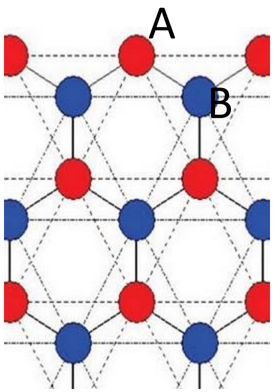
自旋

谷

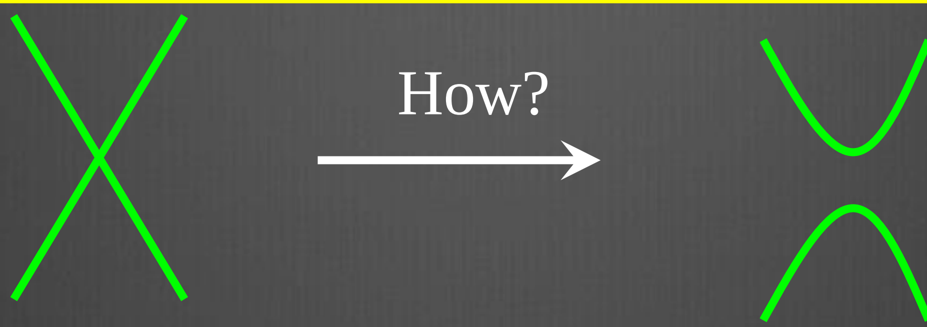
子晶格





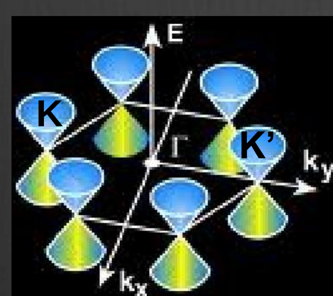


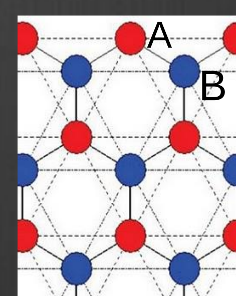
Engineering band gaps

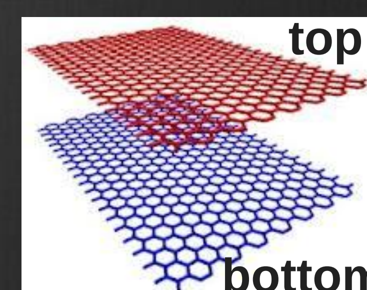


Degrees of freedom

- Real spin
- Valleys
- Sublattices
- Layers



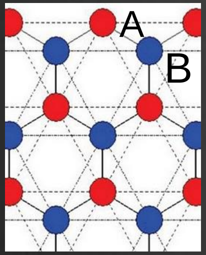




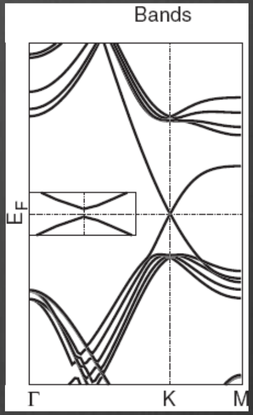
Gap opening mechanism (1)

- Breaking inversion symmetry.

(a) Placing graphene on top of hexagonal boron nitride:

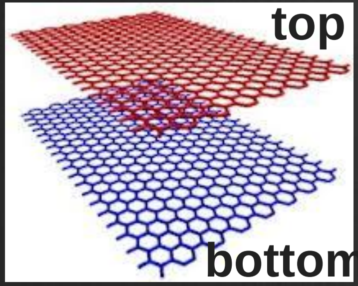


G. Giovannetti et al., PRB 76, 073103 (2007)

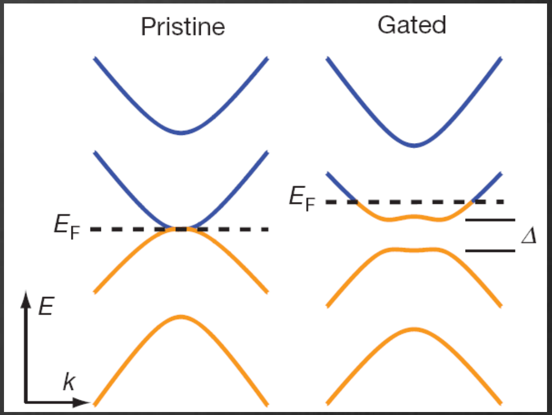


53 meV

(b) Applying an interlayer potential difference in AB-stacking bilayer graphene:



Y. Zhang et al., Nature 459, 820 (2008)



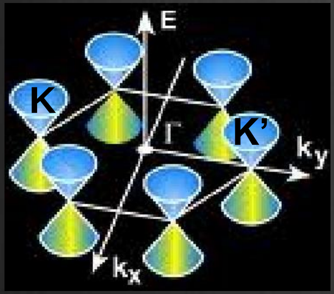
Tunable band gap

Supporting quantum valley-Hall state

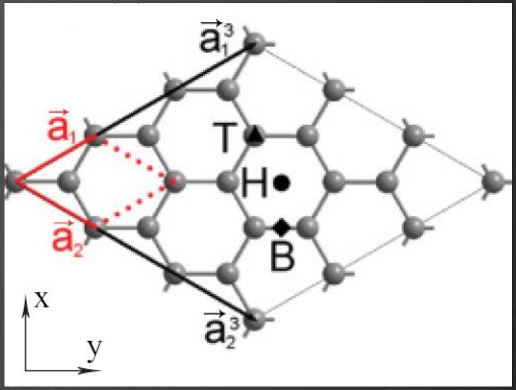
Gap opening mechanism (2)

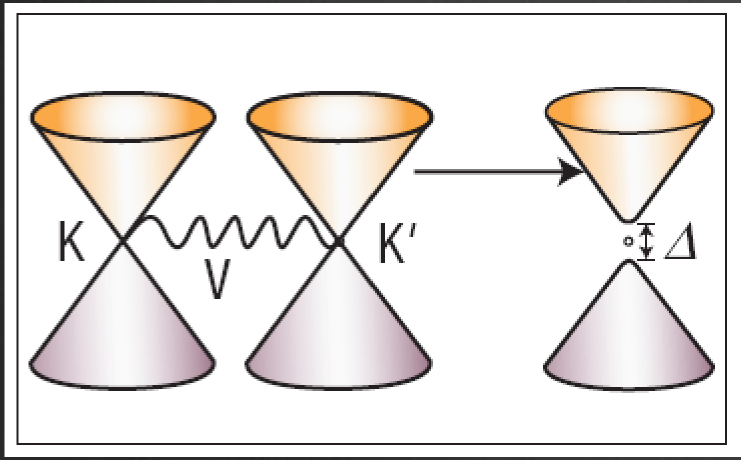
- Intervalley scattering.

Doping in 3*3 supercell of graphene.

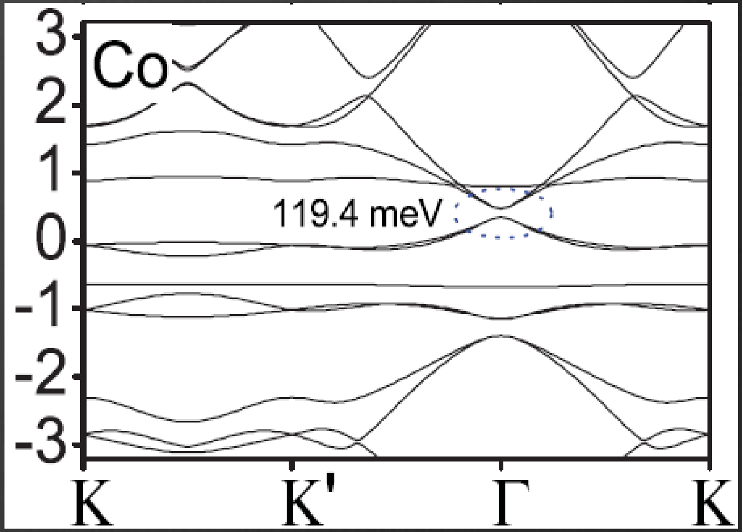


J. Ding, Z. Qiao* et al., PRB 84,195444 (2011)
Z. Qiao, H. Jiang et al., PRB 85,115439 (2012)
Y. Ren, X. Deng et al, PRB 91,245415 (2015)





Co doping



Gap opening mechanism (3)

■ Intrinsic spin-orbit coupling

Kane-Mele model

$\mathbf{V_{SO} >> V_r}$

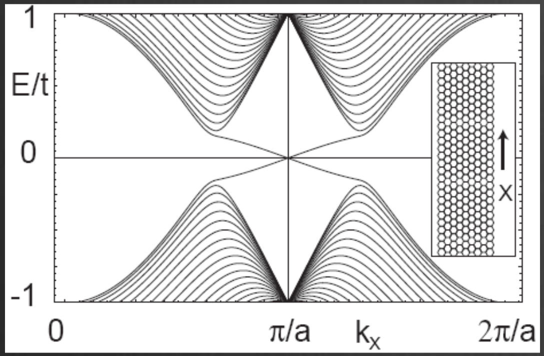
$$H = -t\sum_{\langle ij\rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle\langle ij\rangle\rangle} c_i^\dagger \sigma \cdot (\mathbf{d}_{kj} \times \mathbf{d}_{ik}) c_j$$

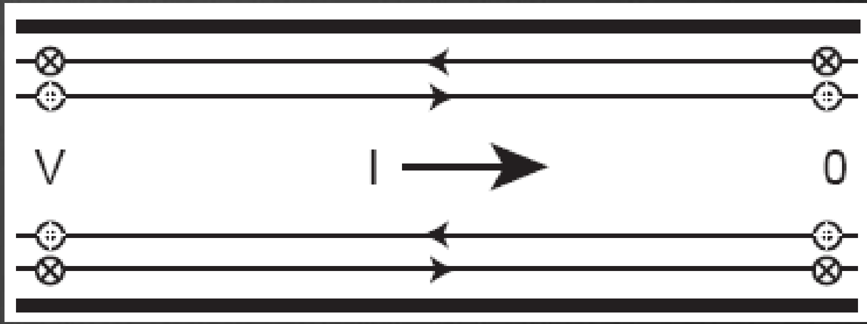
Intrinsic SOC

$$+ iV_r \sum_{\langle ij\rangle} c_i^\dagger \hat{\mathbf{e}}_z \cdot (\sigma \times \mathbf{d}_{ij}) c_j$$

Rashba SOC

Quantum spin-Hall effect





C. Kane et al., PRL 95, 146802 (2005)

Extremely weak intrinsic SOC!

Y. Yao et al., PRB 75, 041401 (2007)
H. Min et al., PRB 74, 165310 (2006)

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    - Graphene
    - Band gap engineering

2. Quantum anomalous Hall effect (QAHE) in graphene

    Progress on QAHE in graphene from ideal to realistic materials

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4. Anderson localization from Berry-curvature interchange in QAHE systems

5. Summary

The rise of QAHE in graphene

Modified Kane-Mele model

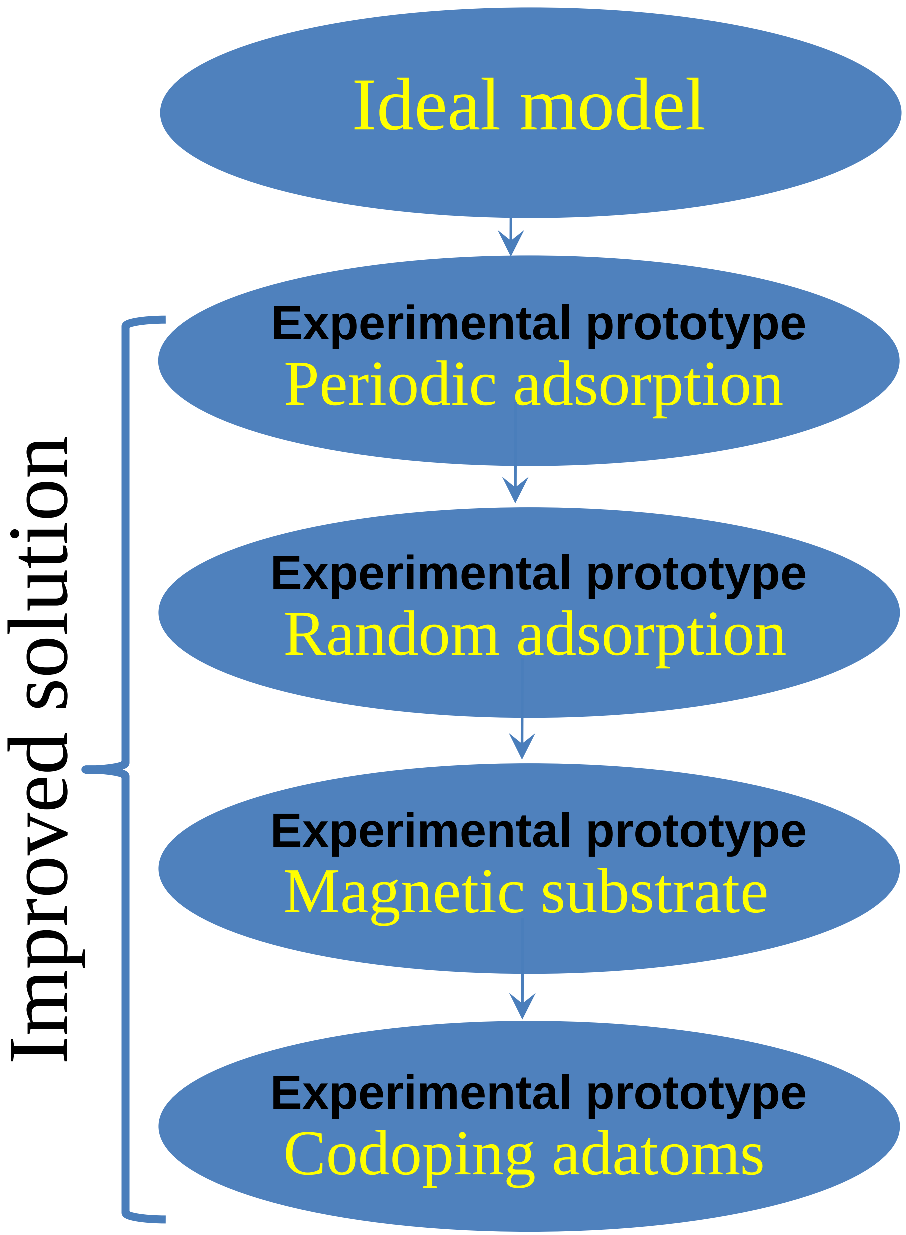
$$H = -t\sum_{\langle ij\rangle} c_i^\dagger c_j + \frac{2i}{\sqrt{3}} V_{SO} \sum_{\langle\langle ij\rangle\rangle} c_i^\dagger \sigma \cdot (\mathbf{d}_{kj} \times \mathbf{d}_{ik}) c_j$$

$$+ iV_r \sum_{\langle ij\rangle} c_i^\dagger \hat{\mathbf{e}}_z \cdot (\sigma \times \mathbf{d}_{ij}) c_j + \lambda \sum_{i\alpha} c_{i\alpha}^\dagger \sigma_z c_{i\alpha}$$

Zeeman field

Quantum anomalous-Hall effect

Roadmap of QAHE in graphene



Qiao, Yang *et al*,
PRB 82, 161414 (2010)

Ding, Qiao* *et al*.,
PRB 84,195444 (2011)

Jiang*, Qiao* *et al*.,
PRL 109,116803 (2012)

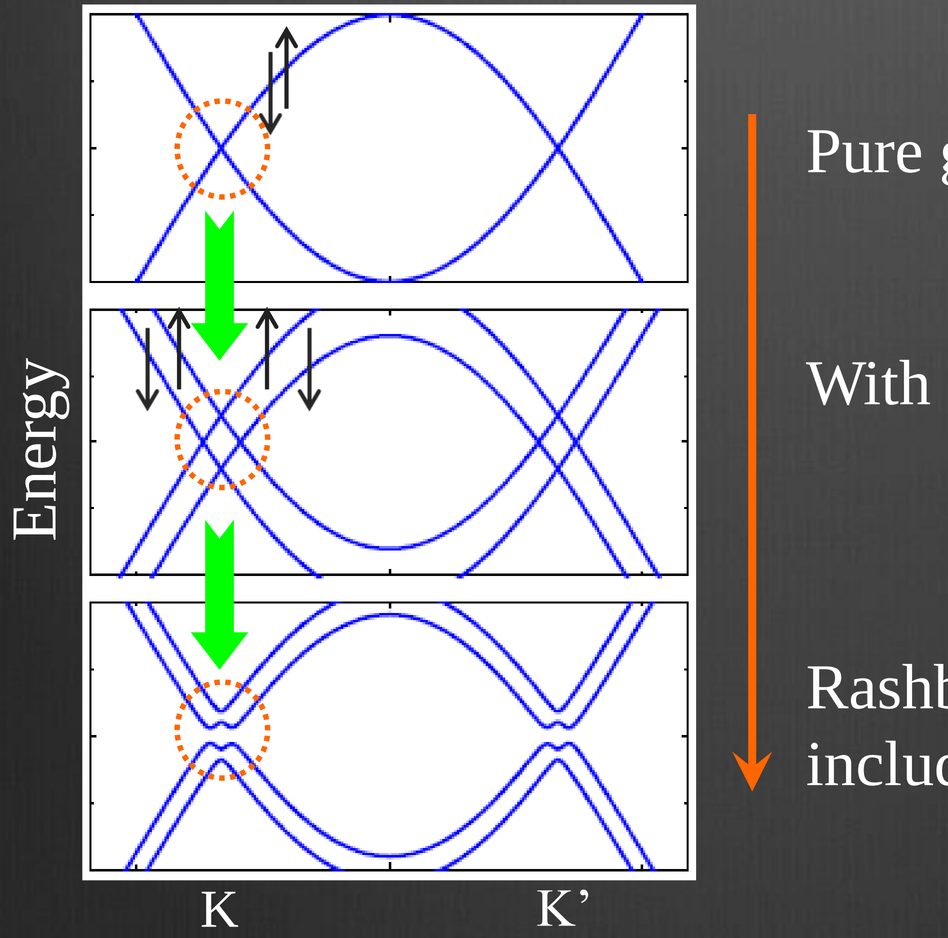
Qiao, Ren *et al*.,
PRL 112,116404 (2014)

Ren, Qiao, Niu,
Rep. Prog. Phys. 112,116404 (2014)

Deng, Qi, Xu, and Qiao*,
PRB *95*, *121410* (2017)

Band structure: ideal model

Evolution of bulk band structure (Tight-binding):



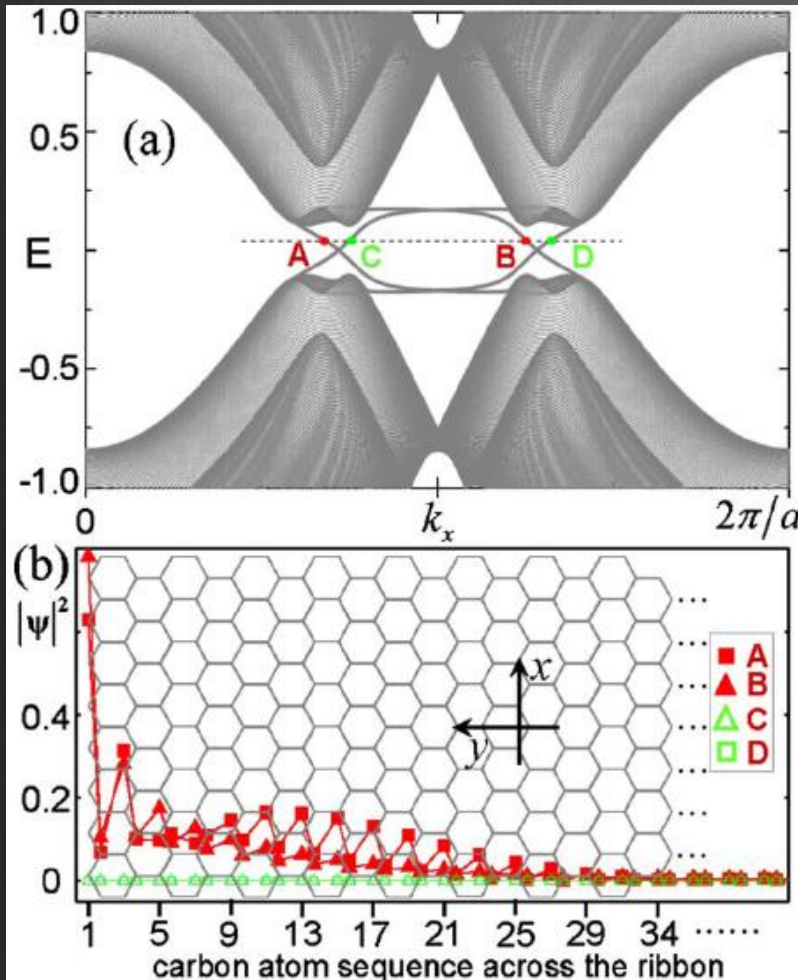
Pure graphene

With Zeeman field

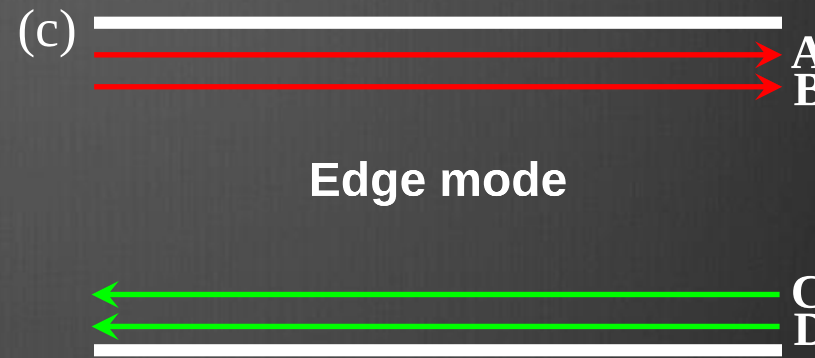
Rashba SOC is further included

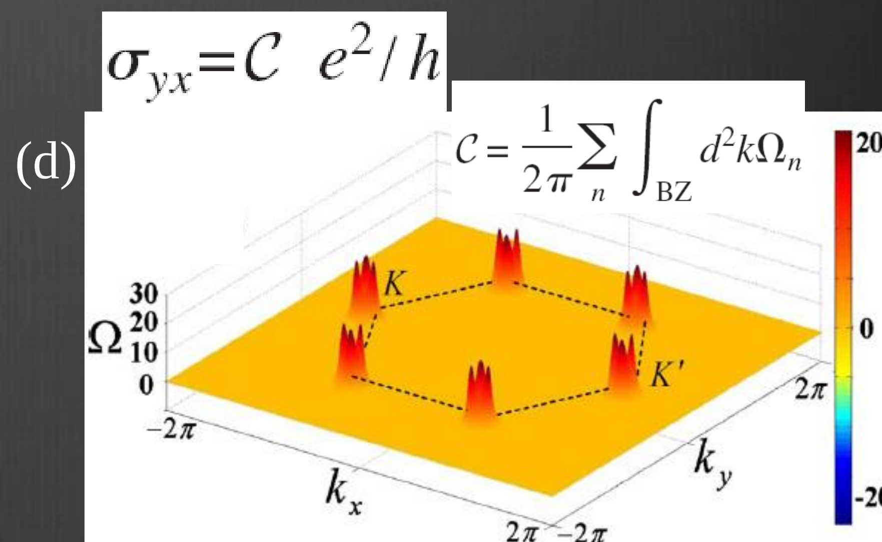
Z. Qiao et al., PRB 82, 161414(R) (2010)

Edge mode & Berry curvature



Gapless edge mode

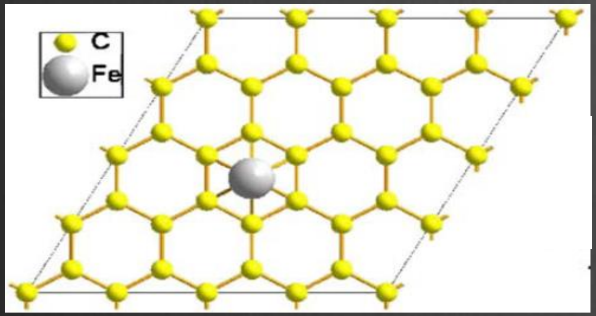




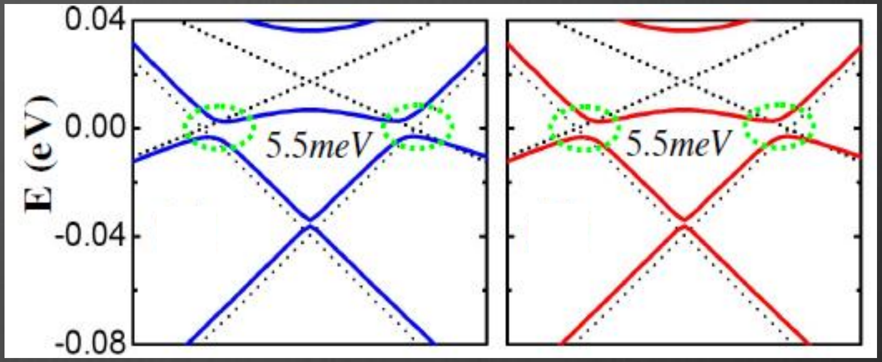
Berry curvature distribution

Z. Qiao et al., PRB 82, 161414(R) (2010)

QAHE in graphene: periodic adsorption



Band structure

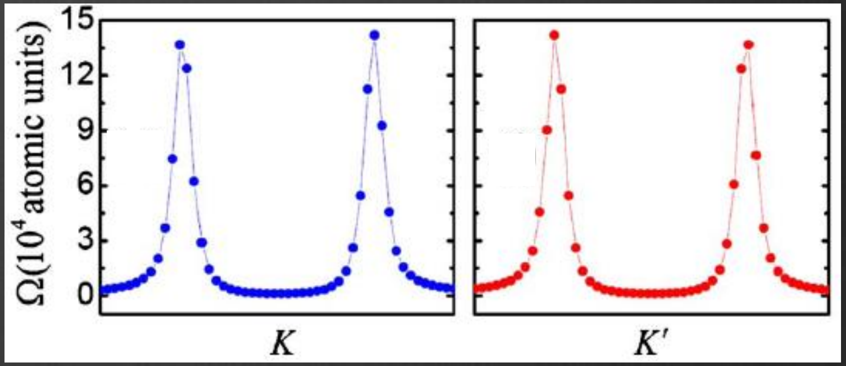


K K’

Adatoms：

Sc, Ti, V, Cr, Mn, Fe, Co

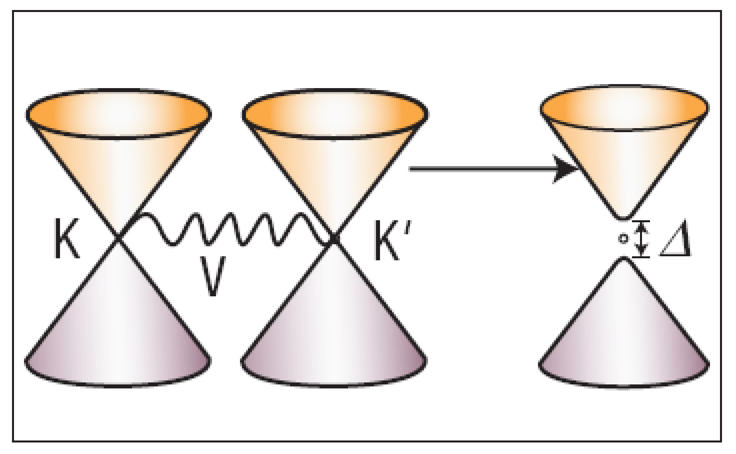
Berry curvature



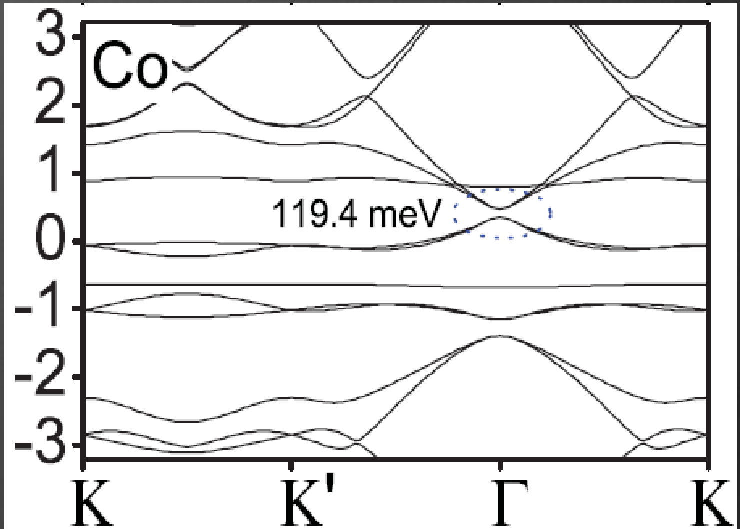
Z. Qiao et al., PRB 82, 161414(R) (2010)
J. Ding, Z. Qiao* et al., PRB 84,195444 (2011)

Difficulties of periodic adsorption

3N*3N supercell



Co doping



Experimental difficulty：

(1) Precise control

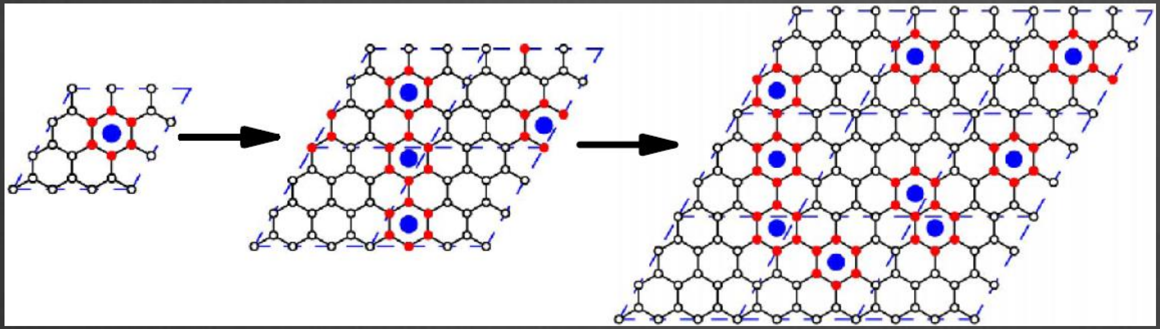
(2) Intervalley scattering

Z. Qiao, H. Jiang et al., PRB 85,115439 (2012)

J. Ding, Z. Qiao* et al., PRB 84,195444 (2011)

Random adsorption

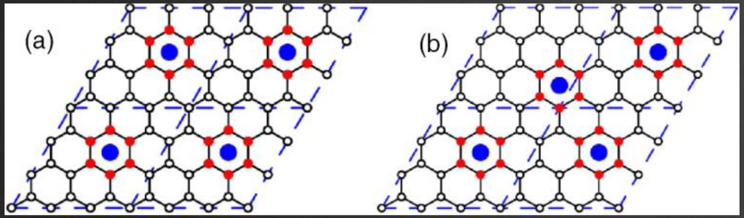
Finite size scaling



n=1 n=2 n=3

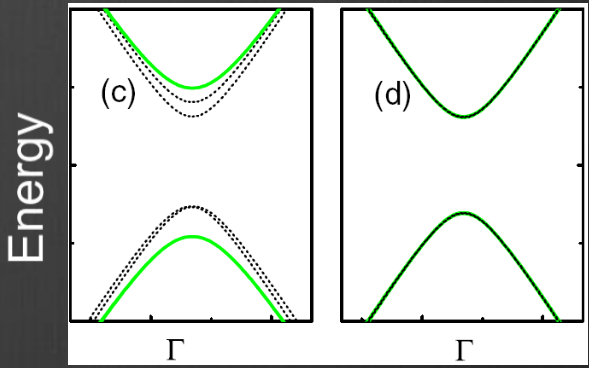
n^2 adatoms in a 3n*3n supercell

Influence of random :



3*3 supercell 6*6 supercell

Slight change

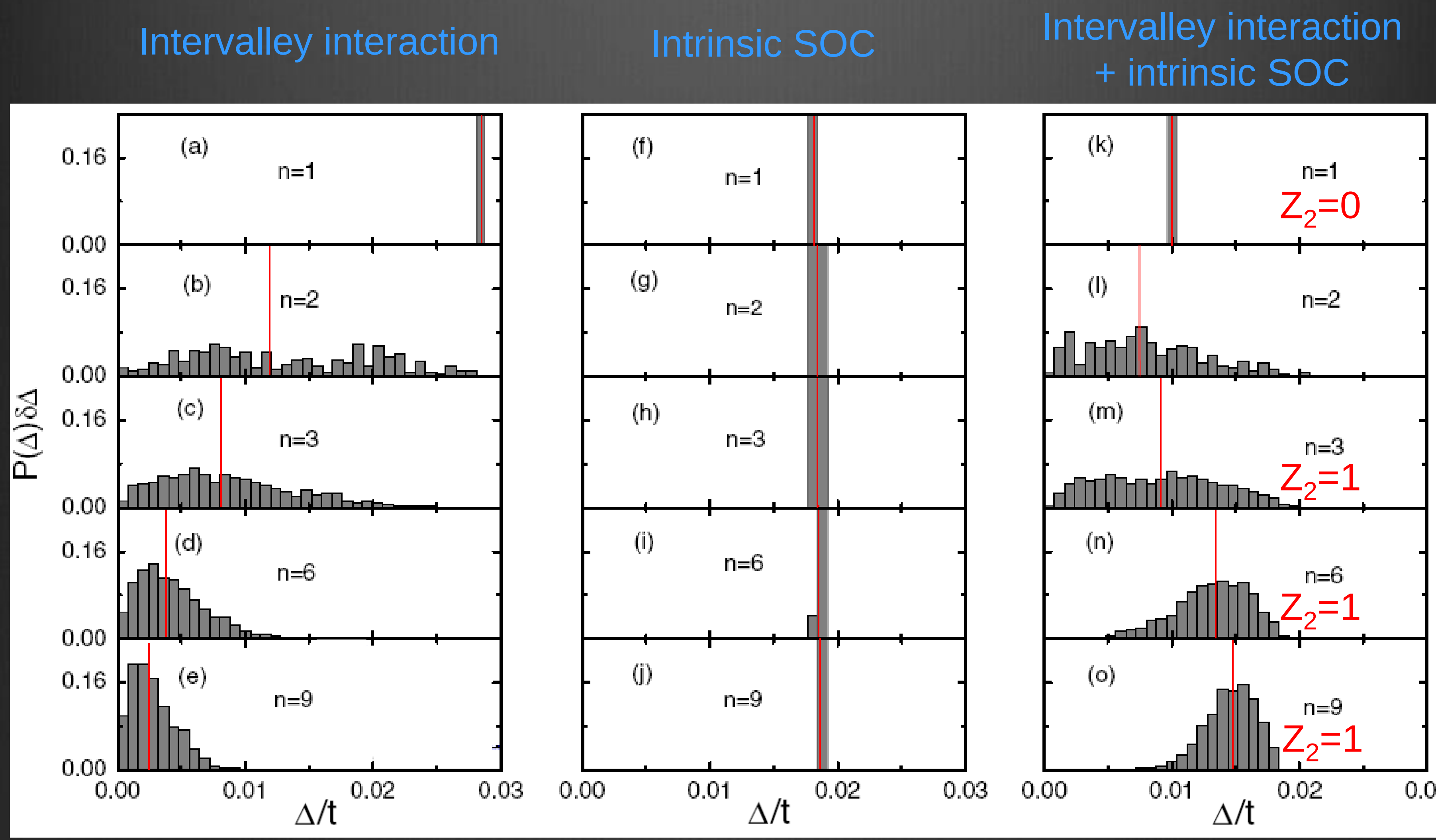


Only intervalley interaction

Only intrinsic SOC

H. Jiang, Z. Qiao* et al., PRL 109,116803 (2012)

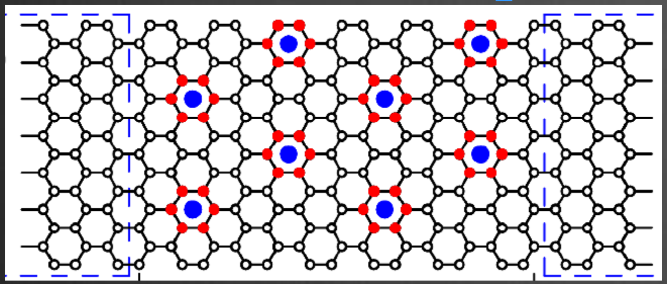
Random adsorption



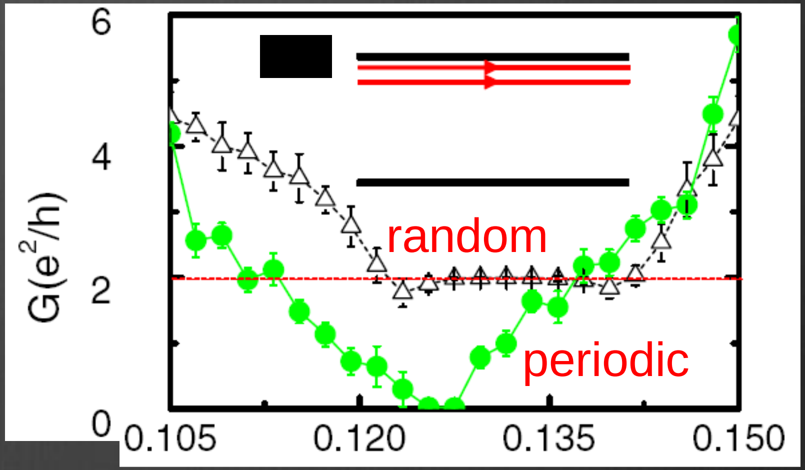
H. Jiang, **Z. Qiao*** et al., PRL 109,116803 (2012)

Random adsorption

Periodic adsorption

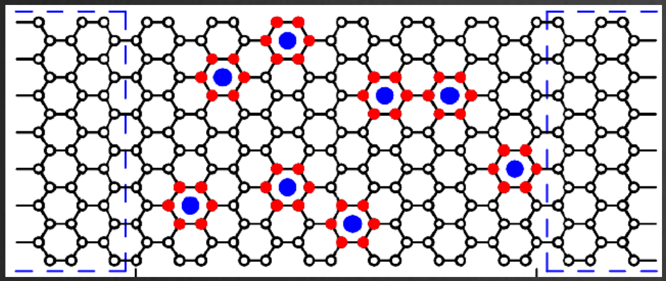


Two-terminal conductance vs. energy



Energy

Random adsorption



L

Central Scattering

R

Topological states are the ground states!

H. Jiang, Z. Qiao* et al., PRL 109,116803 (2012)

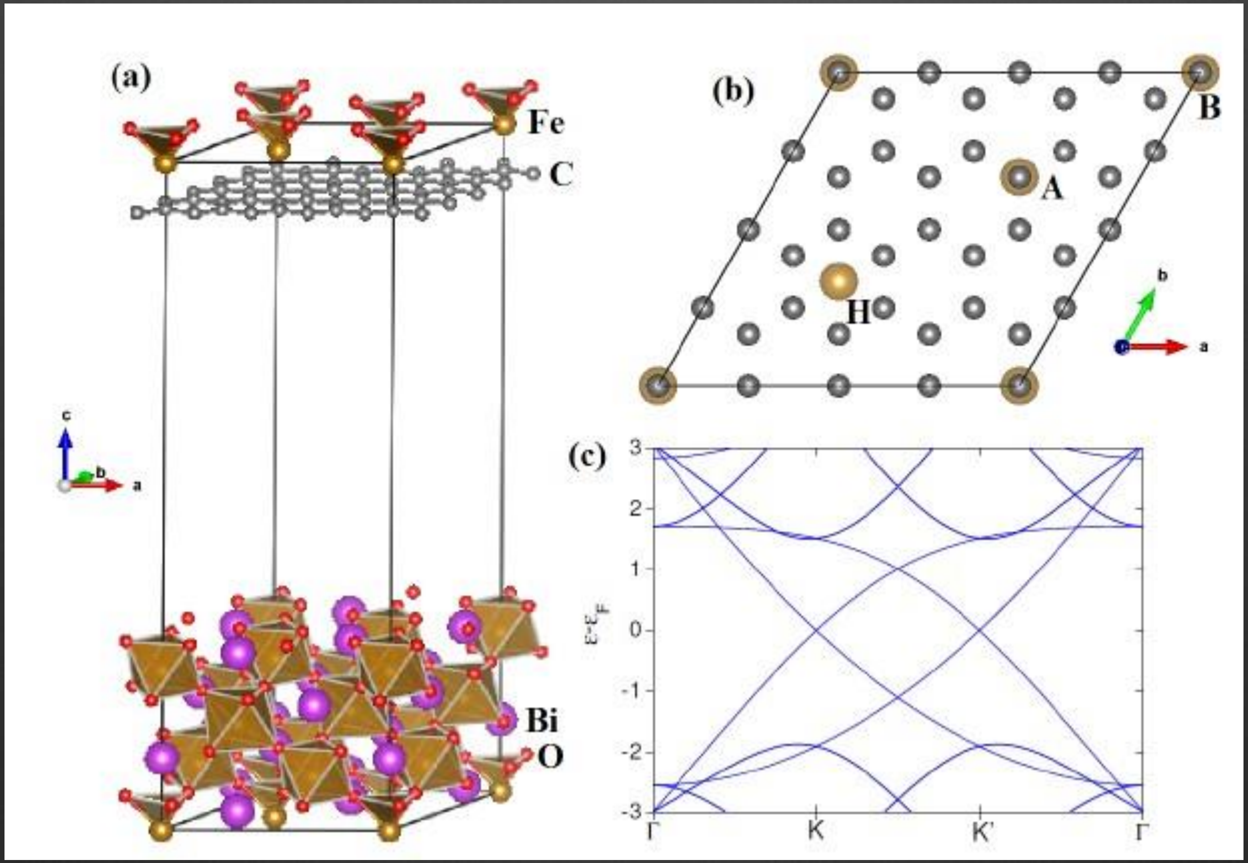
Adatom difficulty

Adatoms → Clusters

Exploring easily realized substrate.

Graphene/magnetic insulator

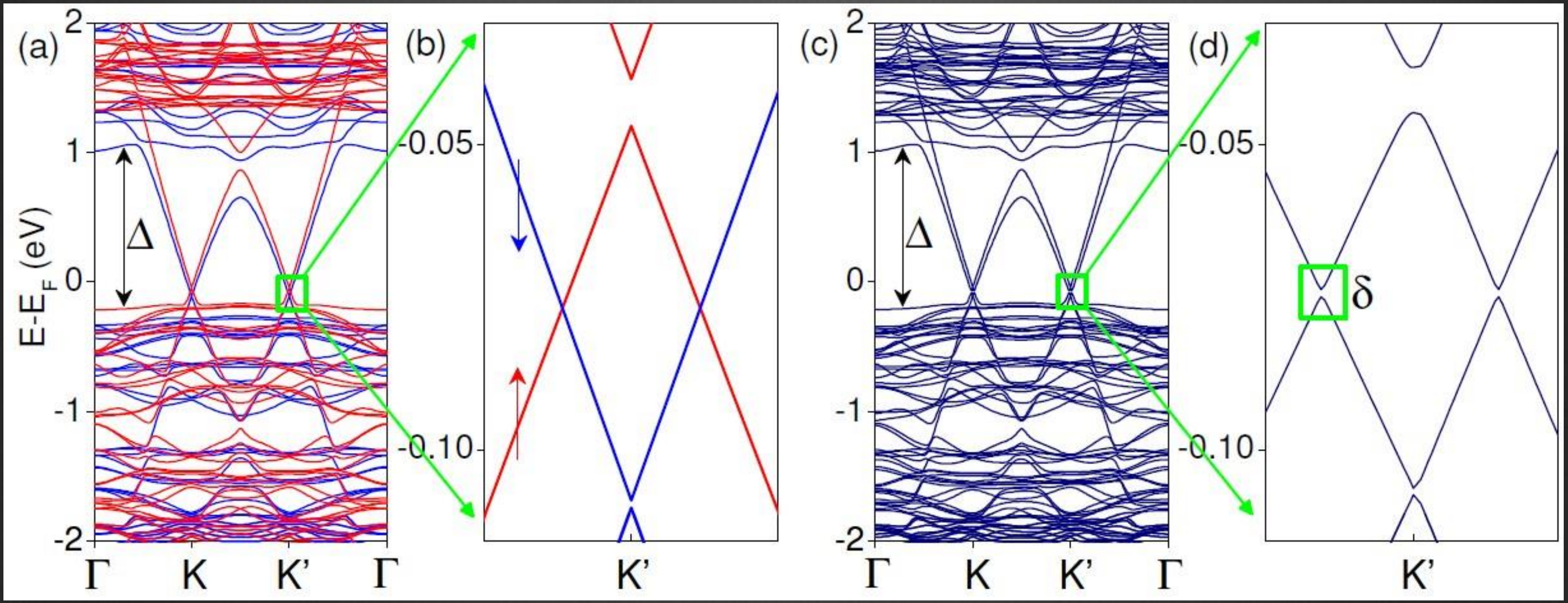
Graphene on top of BiFeO3



Z. Qiao, W. Ren et al., PRL 112, 116404 (2014)

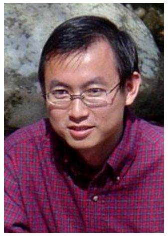
Graphene/magnetic insulator

Band structure

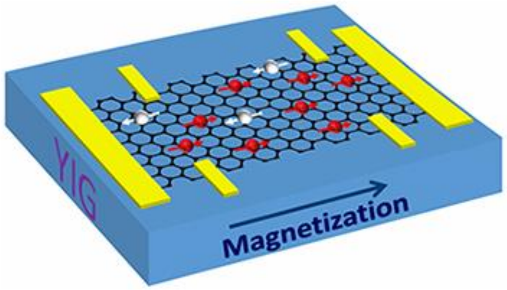


Z. Qiao, W. Ren et al., PRL 112, 116404 (2014)

Experimental progresses



USTC
Changgan Zeng's group



APPLIED PHYSICS LETTERS **105**, 133111 (2014)

Graphene in proximity to magnetic insulating $LaMnO_3$

Guanghui Cheng,[1] Laiming Wei,[1,a)] Long Cheng,[1] Haixing Liang,[1] Xiaoqiang Zhang,[1] Hui Li,[1] Guolin Yu,[2] and Changgan Zeng[1,3,4,a)]

tric layers to apply gate voltages. Interesting low-temperature transport behaviors have also been revealed, including asymmetrical longitudinal magnetoresistivity and nonlinear Hall effect. The present work may provide a clue to stabilize nontrivial quantum phases in graphene via proximity coupling.

Proximity induced ferromagnetism

UC Irvine
Jing Shi's group

PRL **114**, 016603 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

Proximity-Induced Ferromagnetism in Graphene Revealed by the Anomalous Hall Effect

Zhiyong Wang, Chi Tang, Raymond Sachs, Yafis Barlas, and Jing Shi
Department of Physics and Astronomy, University of California, Riverside, California 92521, USA
(Received 28 May 2014; revised manuscript received 12 September 2014; published 7 January 2015)

We demonstrate the anomalous Hall effect (AHE) in single-layer graphene exchange coupled to an atomically flat yttrium iron garnet (YIG) ferromagnetic thin film. The anomalous Hall conductance has magnitude of $\sim 0.09(2e^2/h)$ at low temperatures and is measurable up to ~300 K. Our observations indicate not only proximity-induced ferromagnetism in graphene/YIG with a large exchange interaction, but also enhanced spin-orbit coupling that is believed to be inherently weak in ideal graphene. The proximity-induced ferromagnetic order in graphene can lead to novel transport phenomena such as the quantized AHE which are potentially useful for spintronics.

Large ferromagnetism and weak spin-orbit coupling

Experimental progresses

UC Irvine
Jing Shi's group

APL MATERIALS **6**, 026401 (2018)

Approaching quantum anomalous Hall effect in proximity-coupled YIG/graphene/h-BN sandwich structure

Chi Tang,[1] Bin Cheng,[1] Mohammed Aldosary,[1] Zhiyong Wang,[1] Zilong Jiang,[1] K. Watanabe,[2] T. Taniguchi,[2] Marc Bockrath,[1,3] and Jing Shi[1,a]
[1]*Department of Physics and Astronomy, University of California, Riverside, California 92521, USA*
[2]*Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Ibaraki 305-0044, Japan*
[3]*Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*

(Received 23 August 2017; accepted 10 October 2017; published online 2 November 2017)

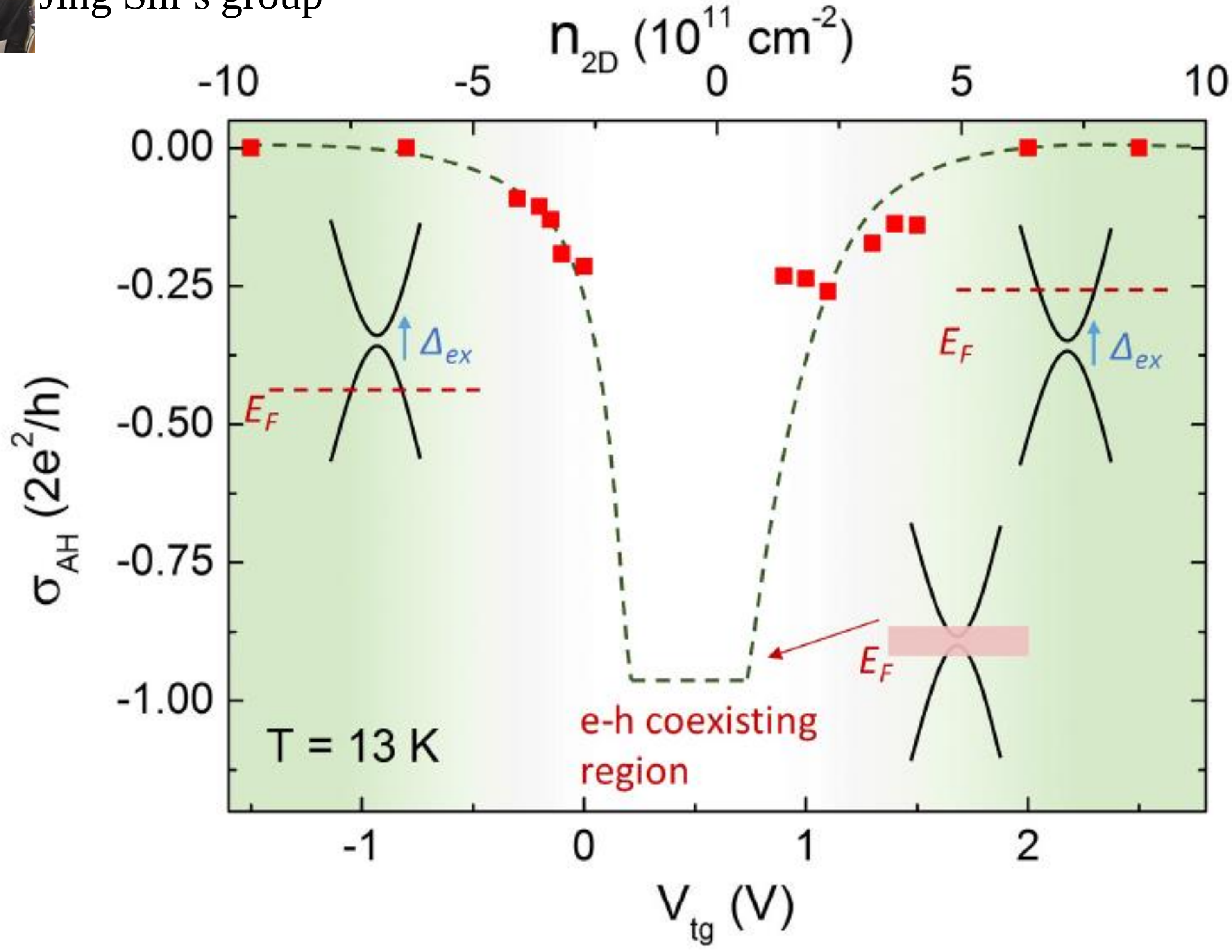
Experimental progresses

UC Irvine
Jing Shi's group

Quantum anomalous Hall state is expected to emerge in Dirac electron systems such as graphene under both sufficiently strong exchange and spin-orbit interactions. In pristine graphene, neither interaction exists; however, both interactions can be acquired by coupling graphene to a magnetic insulator as revealed by the anomalous Hall effect. Here, we show enhanced magnetic proximity coupling by sandwiching graphene between a ferrimagnetic insulator yttrium iron garnet (YIG) and hexagonal-boron nitride (h-BN) which also serves as a top gate dielectric. By sweeping the top-gate voltage, we observe Fermi level-dependent anomalous Hall conductance. As the Dirac point is approached from both electron and hole sides, the anomalous Hall conductance reaches ¼ of the quantum anomalous Hall conductance $2e^2/h$. The exchange coupling strength is determined to be as high as 27 meV from the transition temperature of the induced magnetic phase. YIG/graphene/h-BN is an excellent heterostructure for demonstrating proximity-induced interactions in two-dimensional electron systems. https://doi.org/10.1063/1.5001318

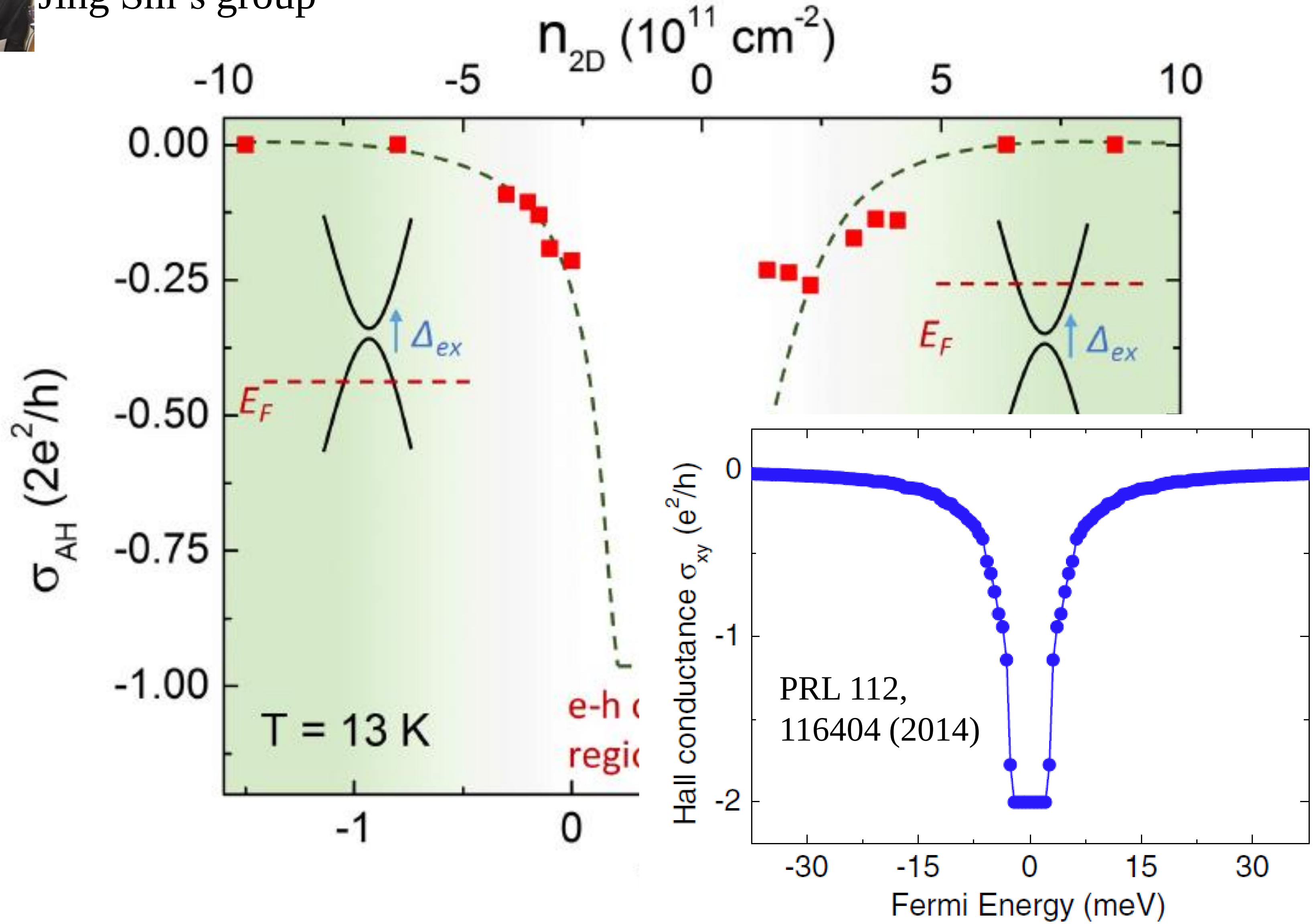
Experimental progresses

UC Irvine
Jing Shi's group



Experimental progresses

UC Irvine
Jing Shi's group



PRL 112, 116404 (2014)

Codoped Graphene

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **95**, 121410(R) (2017)

Realization of quantum anomalous Hall effect in graphene from *n*-*p* codoping-induced stable atomic adsorption

Xinzhou Deng,[1,2] Shifei Qi,[1,3] Yulei Han,[1,2] Kunhua Zhang,[1,2] Xiaohong Xu,[3,*] and Zhenhua Qiao[1,2,†]

[1]*ICQD, Hefei National Laboratory for Physical Sciences at Microscale, and Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics, and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[3]*School of Chemistry and Materials Science, Shanxi Normal University, Linfen, Shanxi 041004, China*

(Received 22 September 2016; revised manuscr

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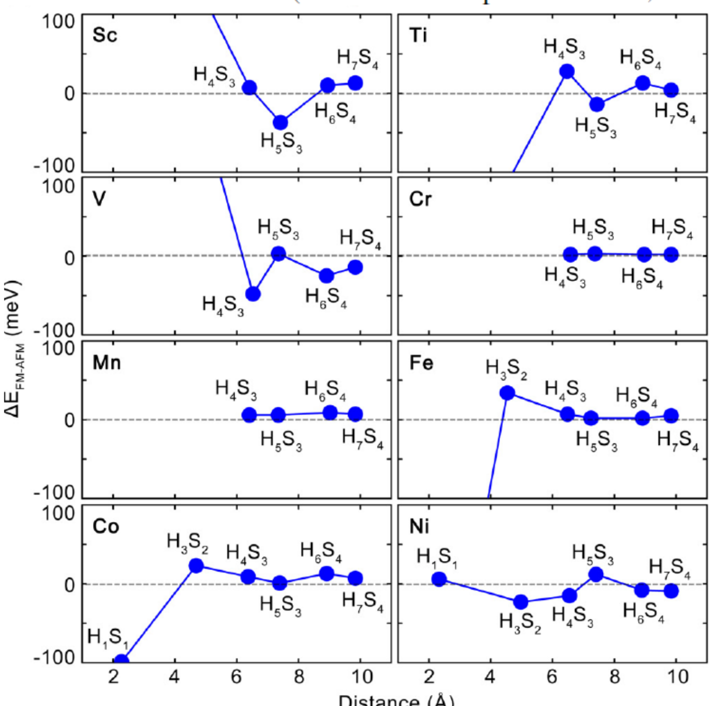
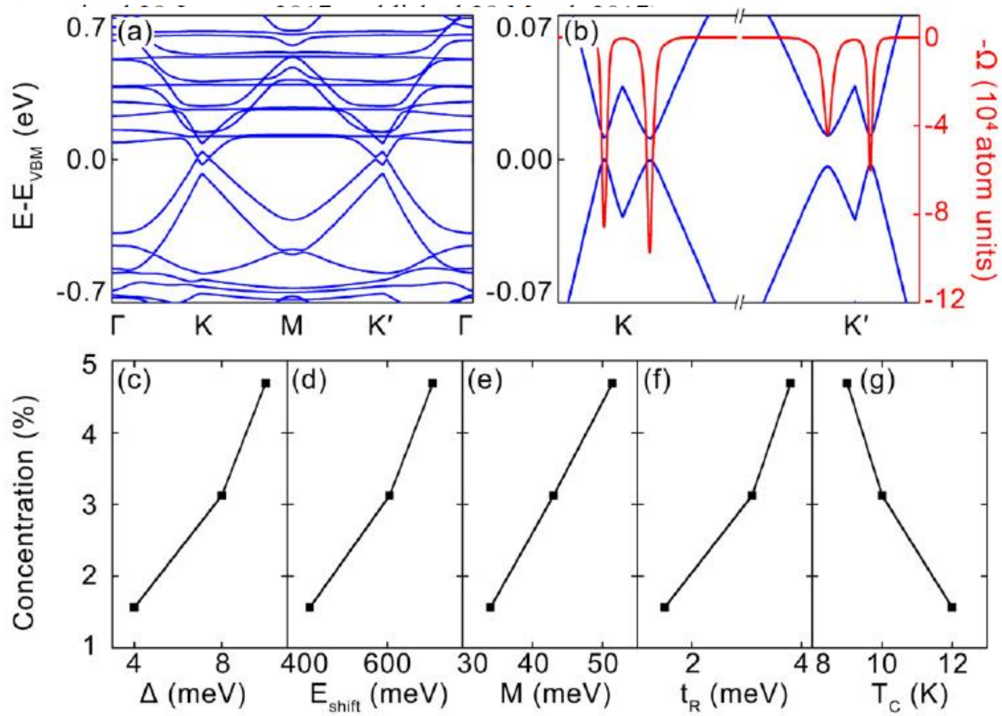




RAPID COMMUNICATIONS

PHYSICAL REVIEW B **96**, 241103(R) (2017)

In-plane magnetization-induced quantum anomalous Hall effect in atomic crystals of group-V elements

Peichen Zhong,[1,2] Yafei Ren,[1,2] Yulei Han,[1,2] Liyuan Zhang,[3,*] and Zhenhua Qiao[1,2,†]

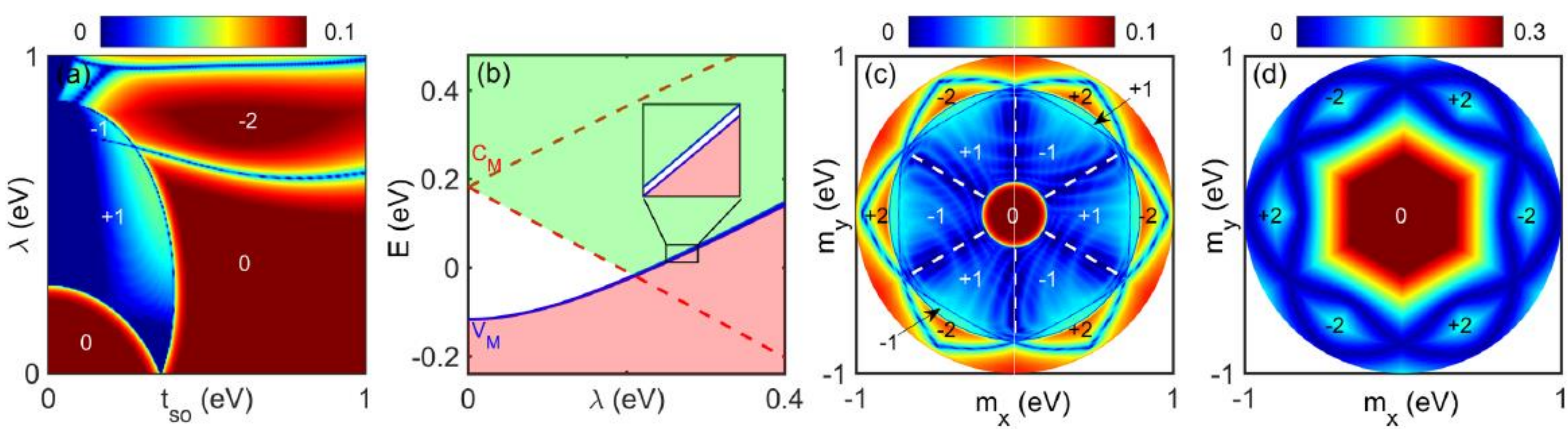
[1]*ICQD, Hefei National Laboratory for Physical Sciences at Microscale, and Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[2]*CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics, and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[3]*Department of Physics, South University of Science and Technology of China, Shenzhen, Guangdong 518055, China*

(Received 6 June 2017; revised manuscript received 31 October 2017; published 14 December 2017)

We theoretically demonstrate that the in-plane magnetization-induced quantum anomalous Hall effect (QAHE) can be realized in the atomic crystal layers of group-V elements with a buckled honeycomb lattice. Based on sp^3 tight-binding models with parameters being extracted from first-principles results, we show that for weak and strong spin-orbit couplings, the systems harbor QAHEs with Chern numbers of $\mathcal{C} = \pm 1$ and ± 2, respectively. For $\mathcal{C} = \pm 1$ phases, we find the critical magnetization to realize QAHE can be extremely small by tuning the spin-orbit coupling strength. For $\mathcal{C} = \pm 2$ phases, we find that although the critical magnetization is larger, it can be decreased effectively by strain. Moreover, the band gap is large enough for a room-temperature observation. These features suggest that it is experimentally feasible to realize high-temperature QAHEs from in-plane magnetization in the atomic crystal layers of group-V elements.



0
0.1
(a)
-2
-1
+1
0
0
λ (eV)
t_so (eV)
(b)
C_M
V_M
E (eV)
λ (eV)
0.4
-0.2
(c)
-2
+2
+1
-1
+2
-2
0
m_y (eV)
m_x (eV)
(d)
0.3

Outline

1. Introduction
    - Graphene
    - Band gap engineering

2. Quantum anomalous Hall effect (QAHE) in graphene

    Progress on QAHE in graphene from ideal to realistic materials

3. Exploration of high-temperature QAHE in topological insulators and graphene

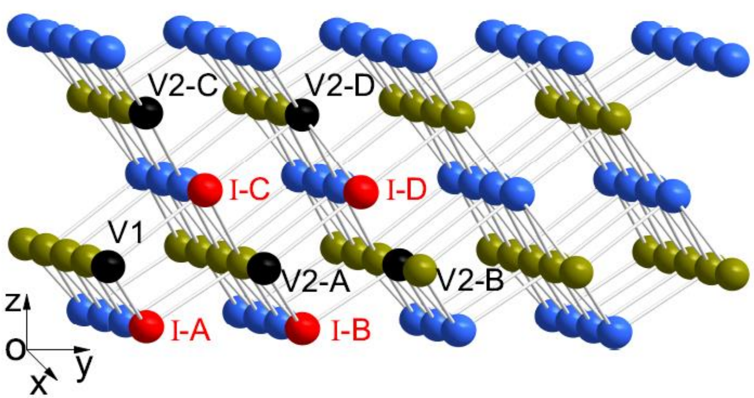
4. Anderson localization from Berry-curvature interchange in QAHE systems

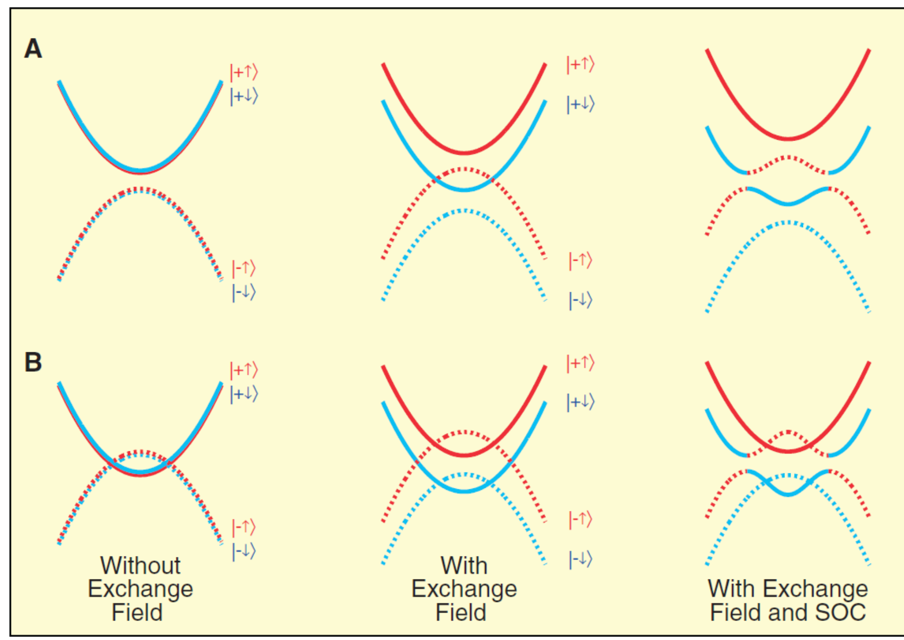
5. Summary

Topological Insulator Based QAHE: Theory

Magnetic TIs---Zhong Fang and Xi Dai's group (IOP, CAS 2010)

Quantized Anomalous Hall Effect in Magnetic Topological Insulators
Rui Yu *et al.*
Science **329**, 61 (2010);
DOI: 10.1126/science.1187485





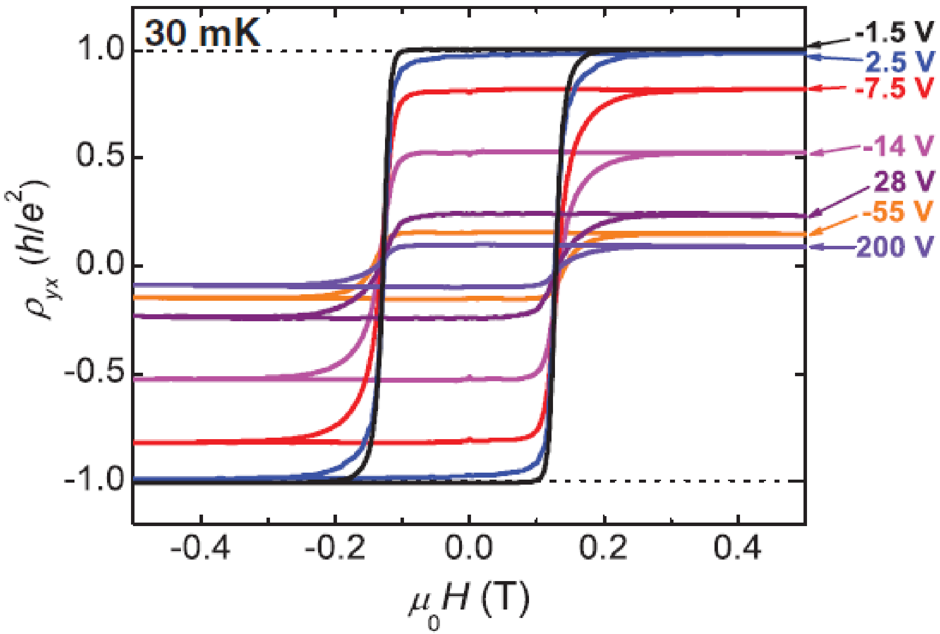
Topological Insulator Based QAHE: Experiment

Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator

Cui-Zu Chang,[1,2]* Jinsong Zhang,[1]* Xiao Feng,[1,2]* Jie Shen,[2]* Zuocheng Zhang,[1] Minghua Guo,[1] Kang Li,[2] Yunbo Ou,[2] Pang Wei,[2] Li-Li Wang,[2] Zhong-Qing Ji,[2] Yang Feng,[1] Shuaihua Ji,[1] Xi Chen,[1] Jinfeng Jia,[1] Xi Dai,[2] Zhong Fang,[2] Shou-Cheng Zhang,[3] Ke He,[2]† Yayu Wang,[1]† Li Lu,[2] Xu-Cun Ma,[2] Qi-Kun Xue[1]†

Science AAAS

Prof. Q.-K. Xue
Tsinghua Univ.



Topological Insulator Based QAHE: Experiment

PRL **113,** 137201 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 201

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,†]

[1]*Department of Electrical Engineering, University of California, Los Angeles, California 90095, USA*

[2]*Institute of Physics, Academia Sinica, Taipei 11529, Taiwan*

[3]*Center for Electron Microscopy and State Key Laboratory of Silicon Materials, Department of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, China*

(Received 26 May 2014; revised manuscript received 28 July 2014; published 26 September 2014)

We investigate the quantum anomalous Hall effect (QAHE) and related chiral transport in the millimeter-size $(Cr_{0.12}Bi_{0.26}Sb_{0.62})_2Te_3$ films. With high sample quality and robust magnetism at low temperatures, the quantized Hall conductance of e^2/h is found to persist even when the film thickness is beyond the two-dimensional (2D) hybridization limit. Meanwhile, the Chern insulator-featured chiral edge conduction is

Topological Insulator Based QAHE: Experiment

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★]

Topological Insulator Based QAHE: Experiment

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

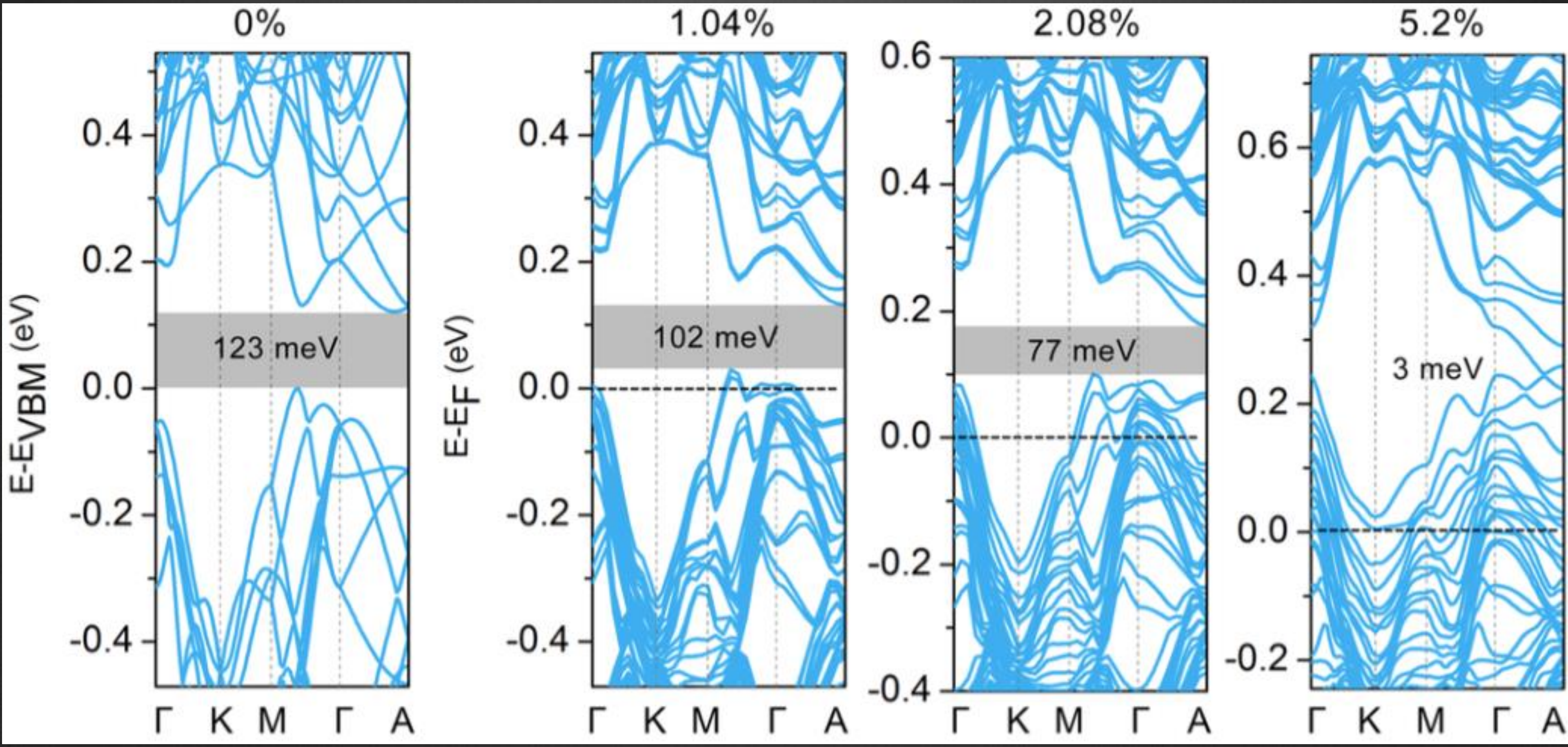
J. G. Checkelsky[1*†], R. Yoshimi[1], A. Tsukazaki[2], K. S. Takahashi[3], Y. Kozuka[1], J. Falson[1], M. Kawasaki[1,3] and Y. Tokura[1,3]

Dependence of Realization Temperature

1. Surface band gap of magnetic TI thin films
2. Spatial inhomogeneity of dopants
3. Ferromagnetic Curie temperature

Why T is so small in the conventional magnetic doping?

Let’s take the example of doping V atoms in Sb_2Te_3



Why N-P Codoping?

1. Charge compensation, keeping the system an insulator.

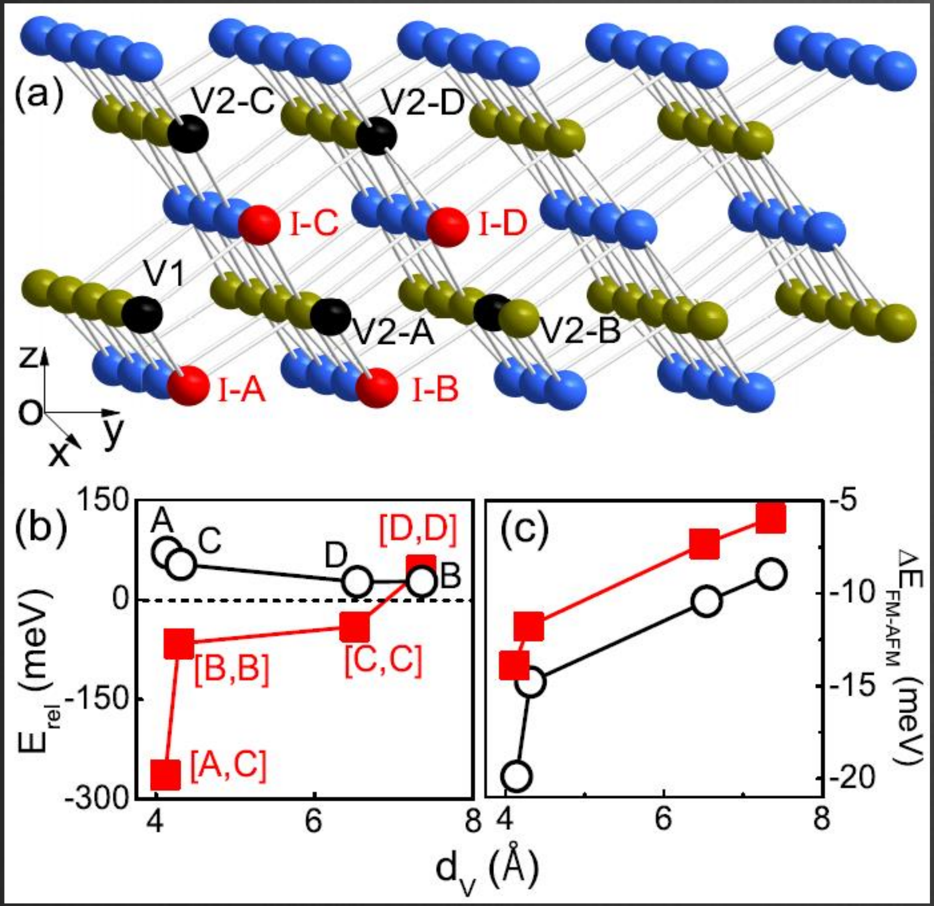
2. Tune band gaps of some materials.

Xu et al., NJP 8, 135 (2006)
Chen et al., PRB 79, 235202 (2009)
Zhu et al., PRL 100, 027205 (2008)
Zhu et al., PRL 103, 226401 (2009)

V-I Codoped Sb_2Te_3

Vanadium (V) --------- p-doping and introducing Ferromagnetism

Iodine (I) -------- n-doping and enhancing spin-orbit coupling



V ← → Sb

I ← → Te

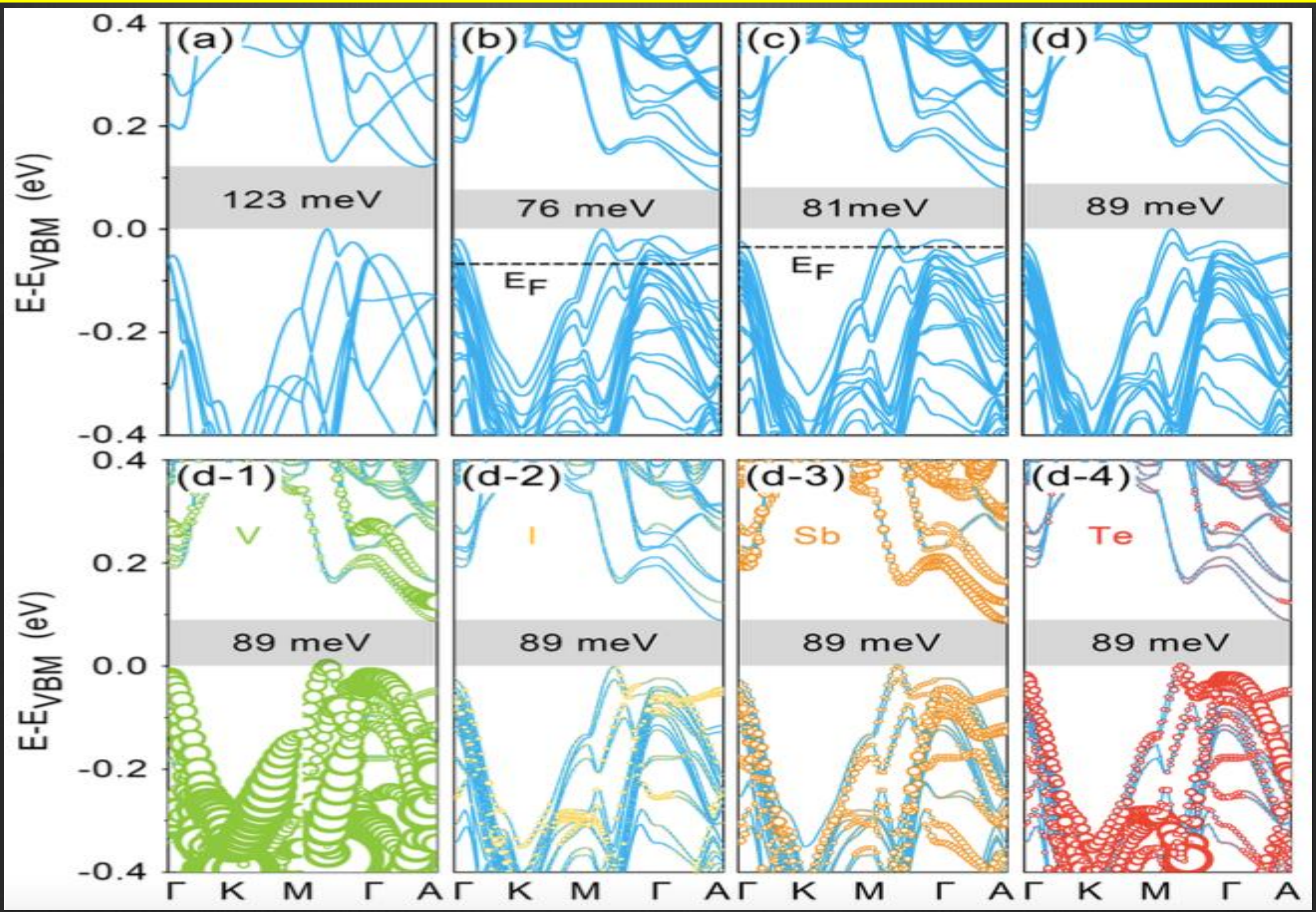
V doping: dilute distribution. (More V doping is required to get a large ferromagnetism)

V-I codoping: attractive. (Less doping is required to get a large ferromagnetism)

Both give rise to ferromagnetism.

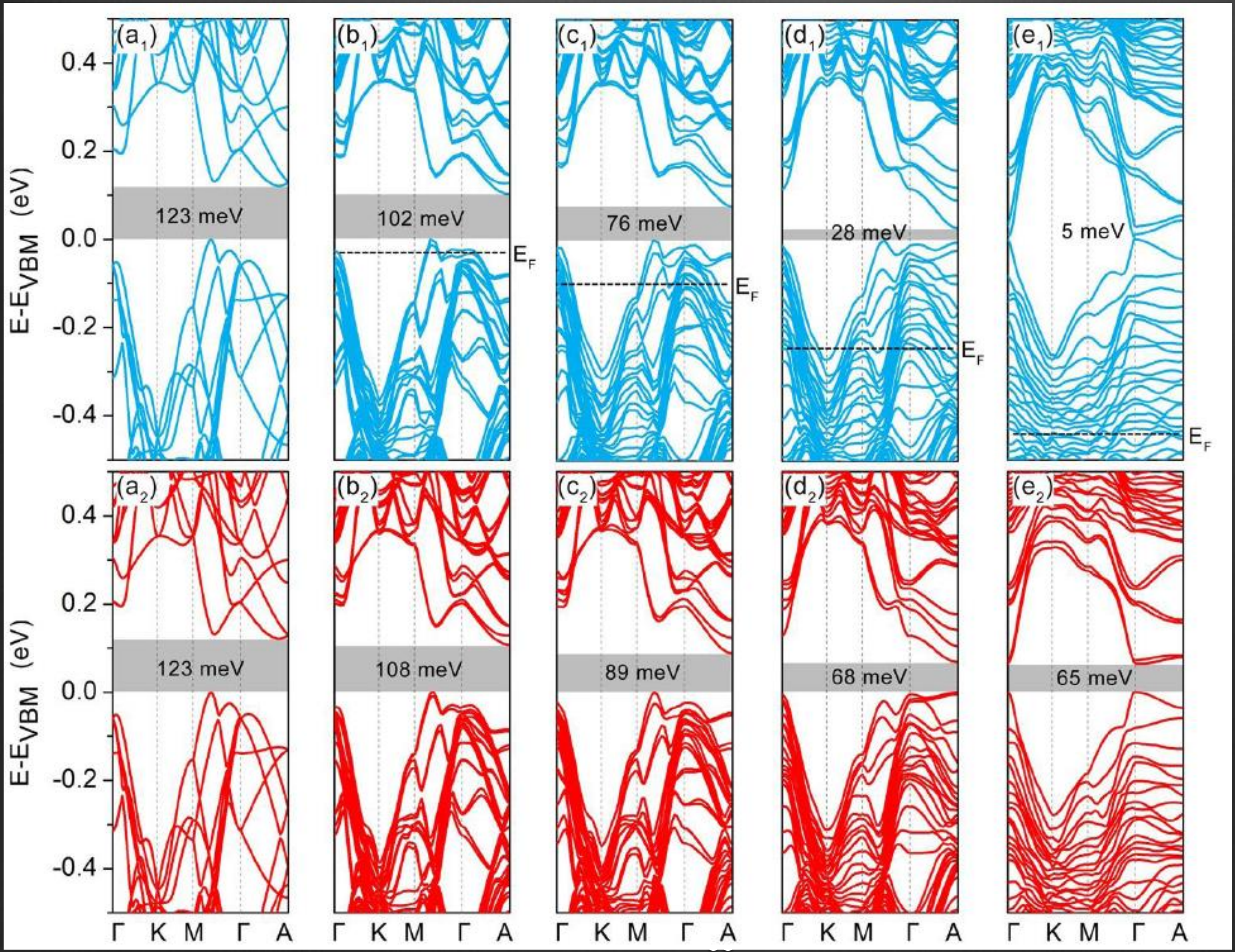
S. Qi*, Z. Qiao* et al., arXiv:1507.03218 (2015)

Band Structures of V-I Codoped Sb_2Te_3



S. Qi*, Z. Qiao* et al., arXiv:1507.03218 (2015)

Comparison between V and V-I Codoped Sb_2Te_3



V-doped

V-I codoped

Ideal Platform for Large Band Gap QAHE

1. Large spin-orbit coupling

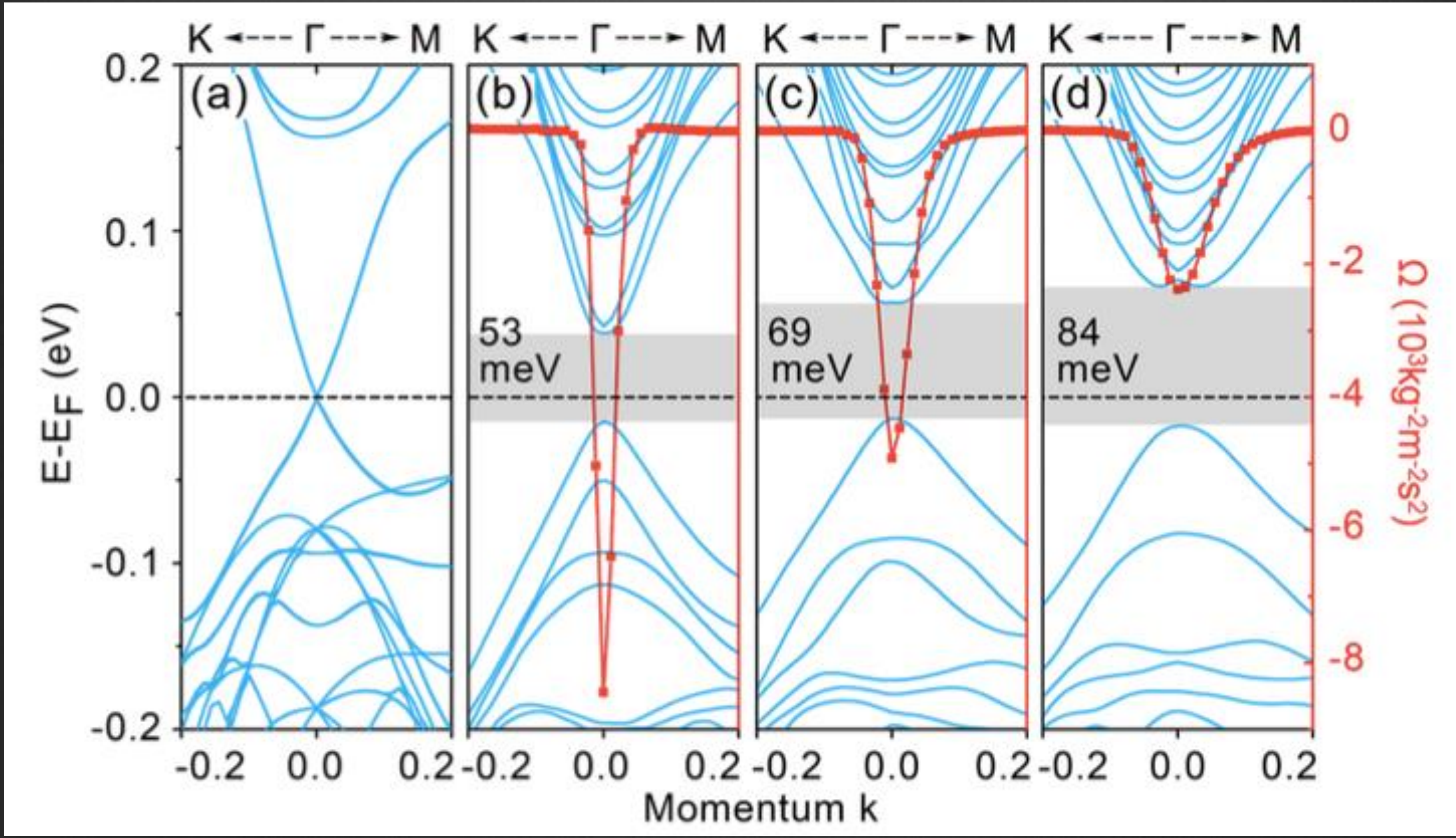
2. Ferromagnetic system

3. Insulator

4. Large bulk band gap

S. Qi*, Z. Qiao* et al., arXiv:1507.03218 (2015)

Realization of QAHE in V-I codoped Sb2Te3 thin films



S. Qi*, Z. Qiao* et al., arXiv:1507.03218 (2015)

Outline

1. Introduction
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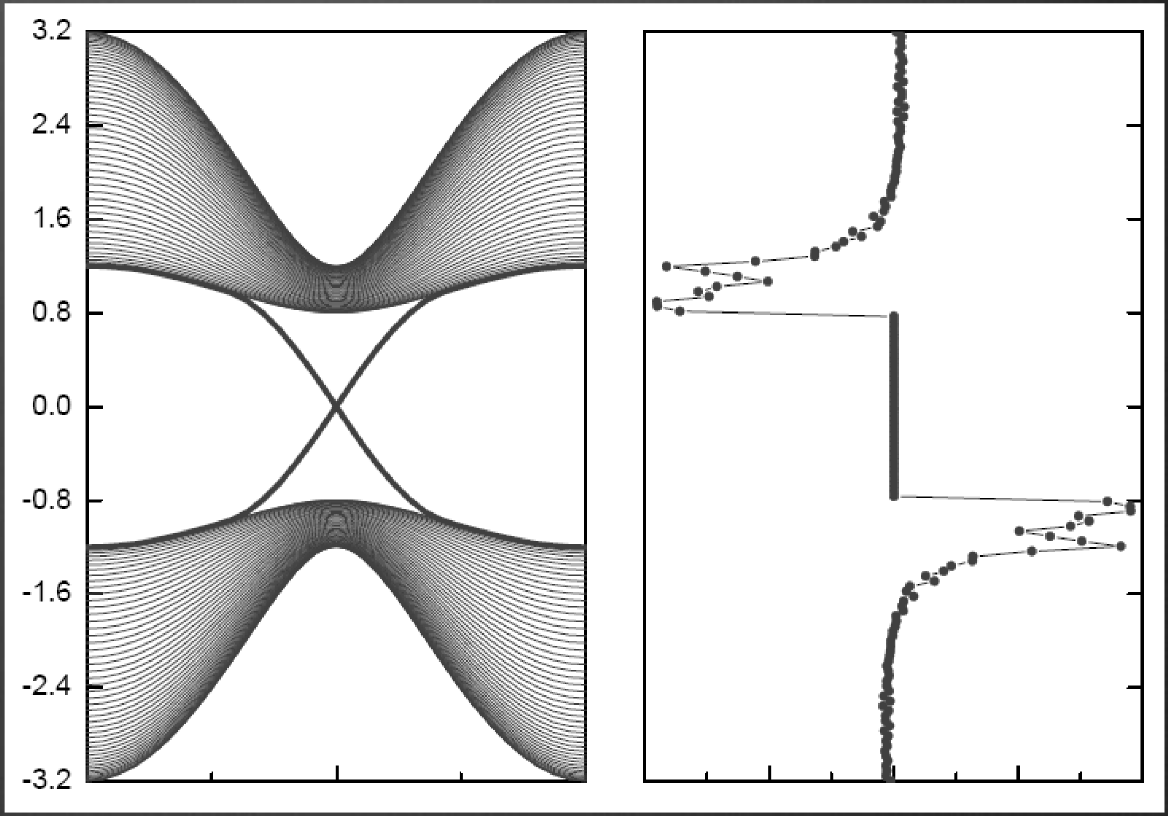
How will the QAHE be destroyed in the presence of disorders?

Single Dirac-cone model

MODEL

Lattice model of a single Dirac-cone system:

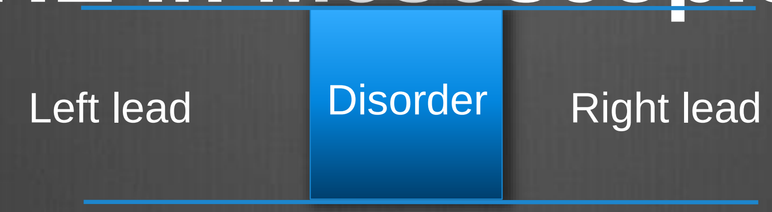
Chern number = 0.5+0.5



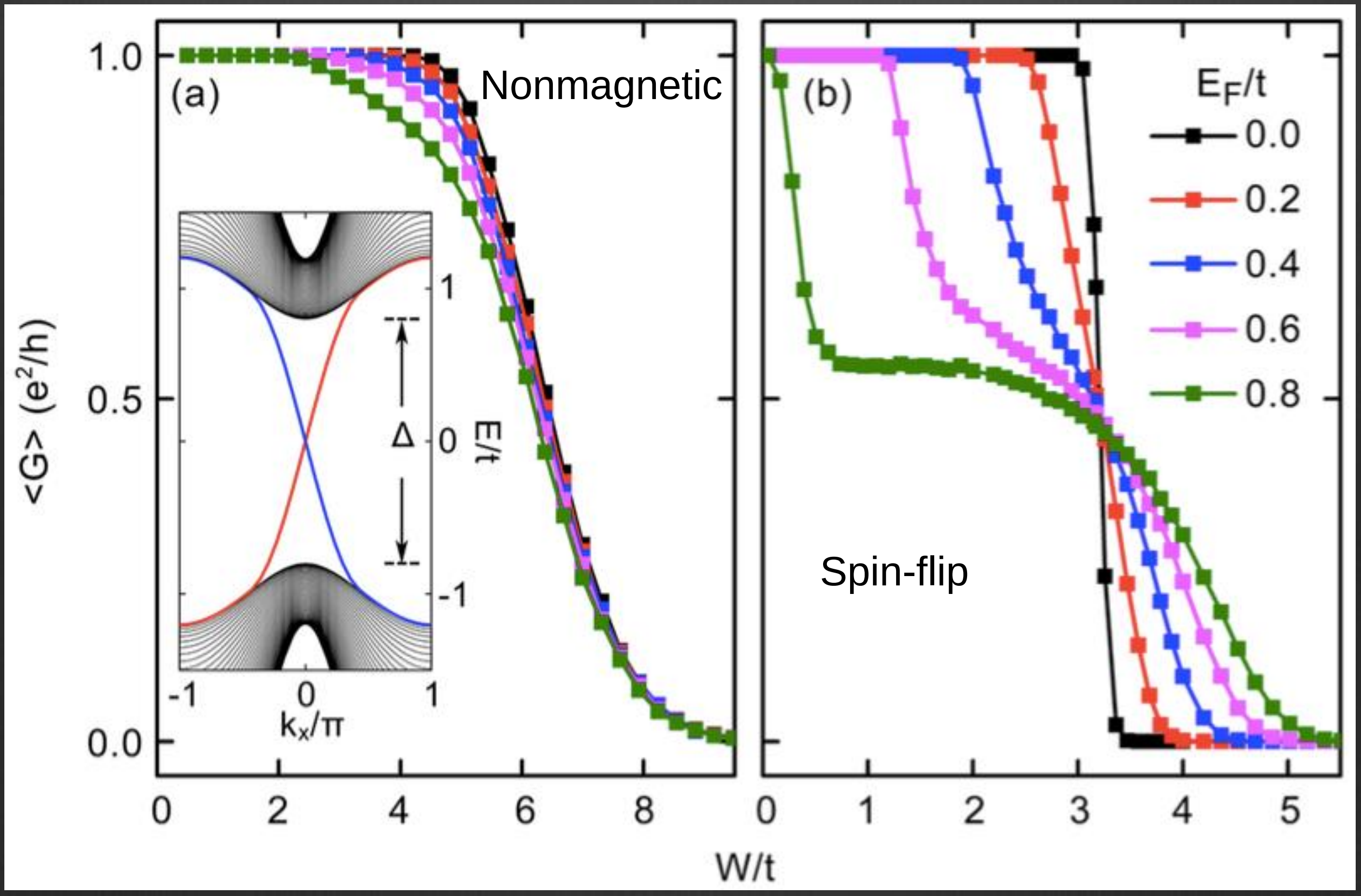
(a) Band structure of a ribbon

(b) Berry curvature distribution

Disorder Effect on Transport Properties of QAHE in Mesoscopic Regime



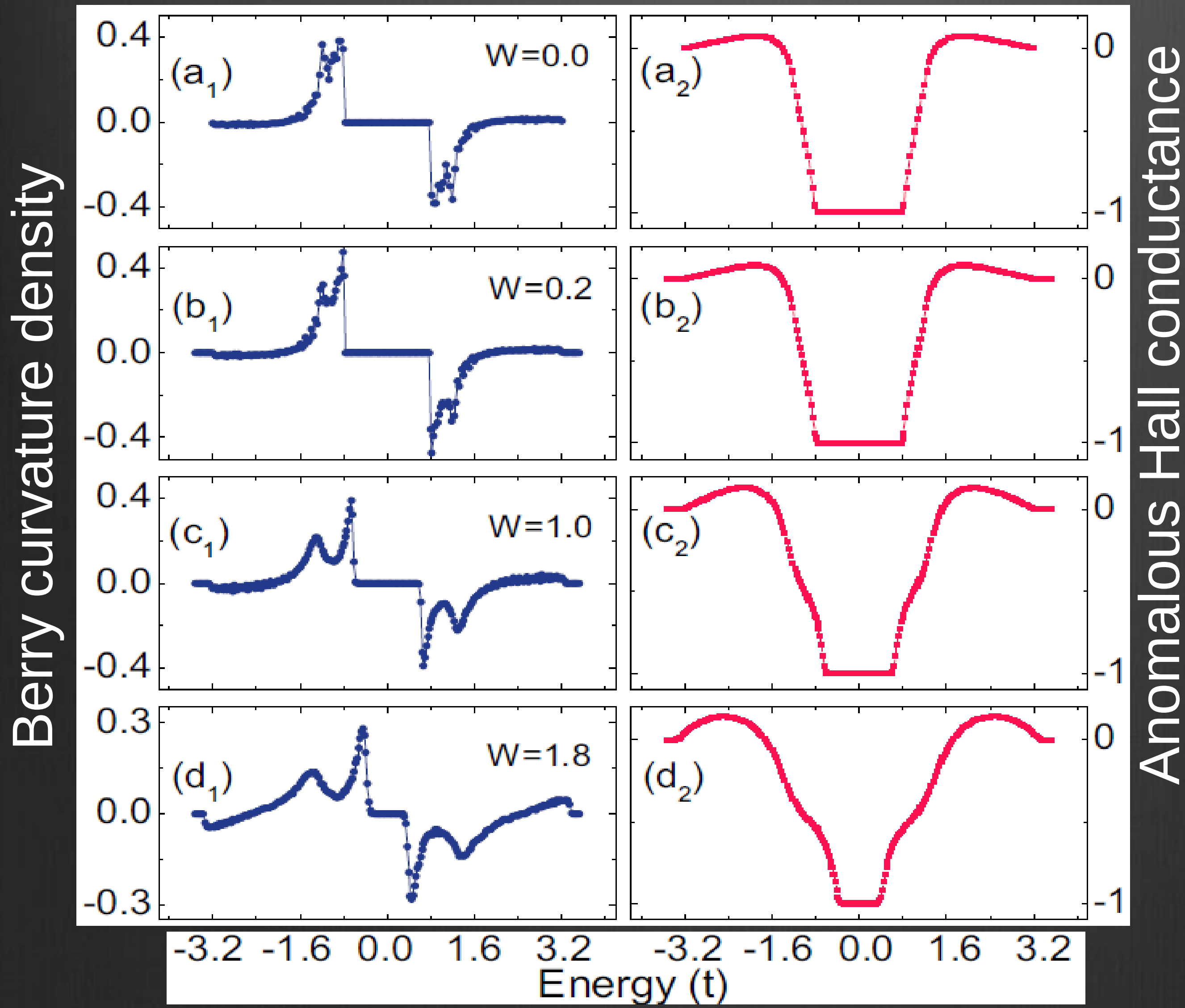
80*80



Berry curvature and Hall conductance analysis

Spin-flip disorder

50*50

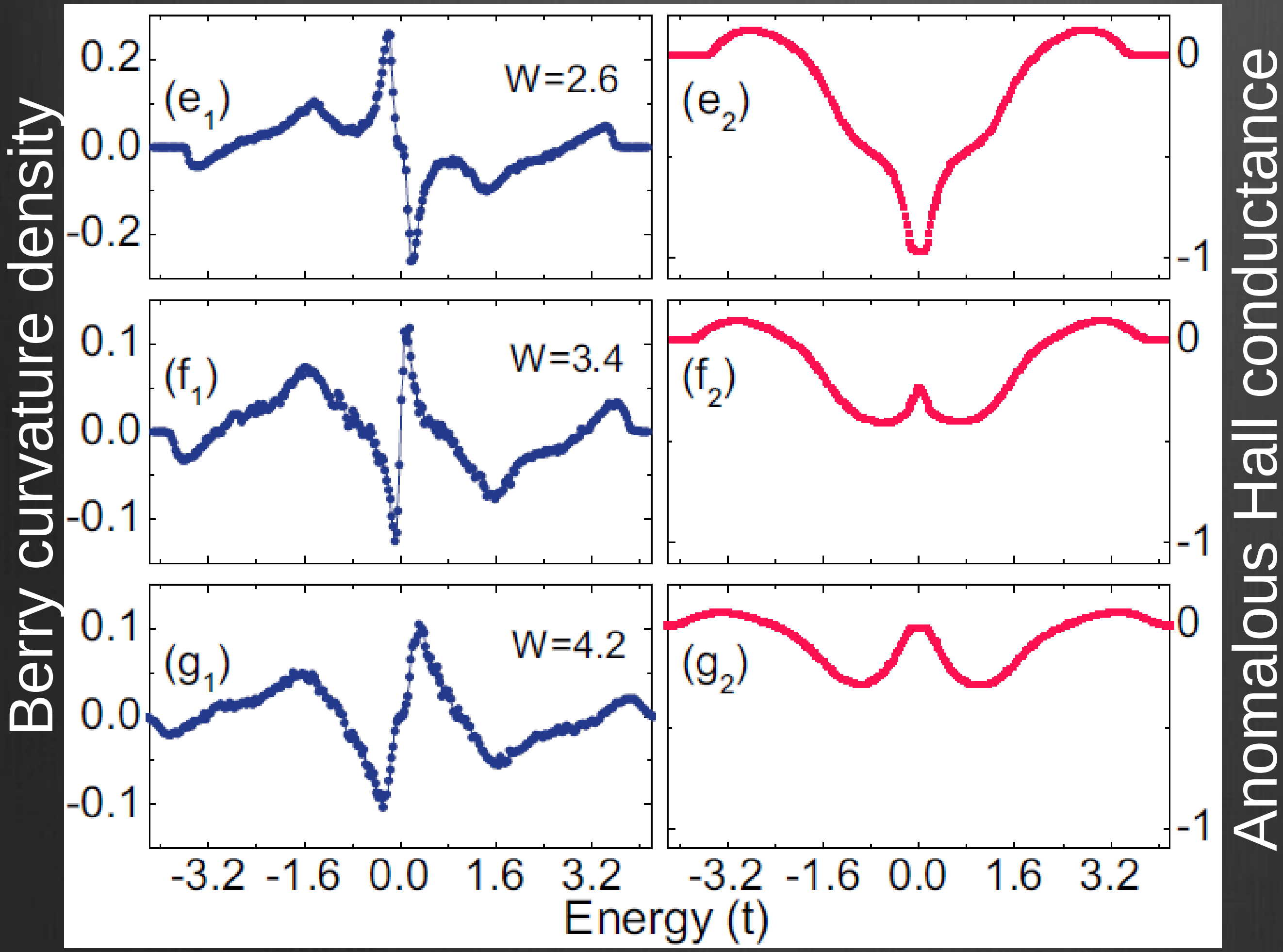


1. Shrinking band gap;

2. Separating Berry curvature peaks

Berry curvature and Hall conductance analysis

Spin-flip disorder

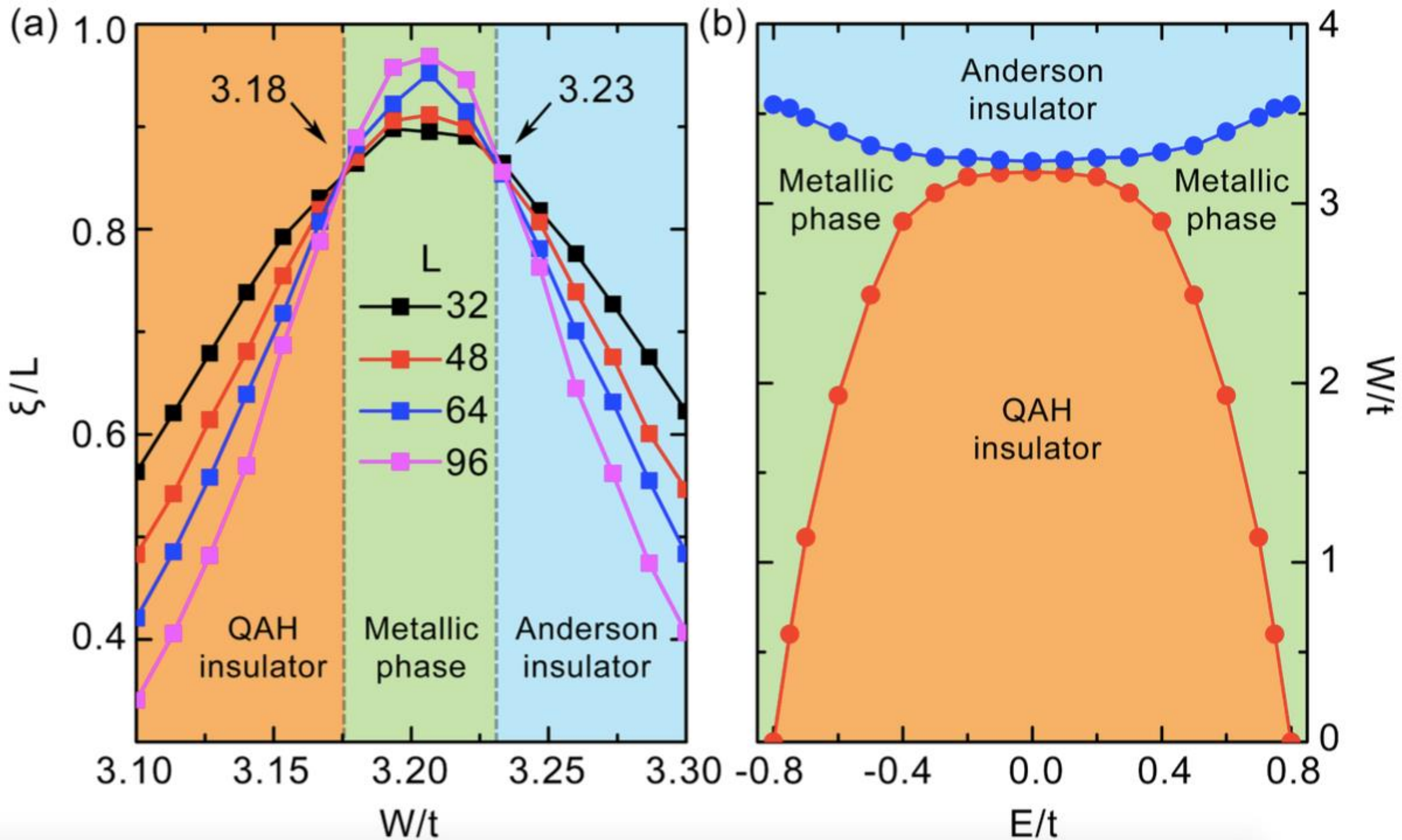


1. Gap closing and reopening;

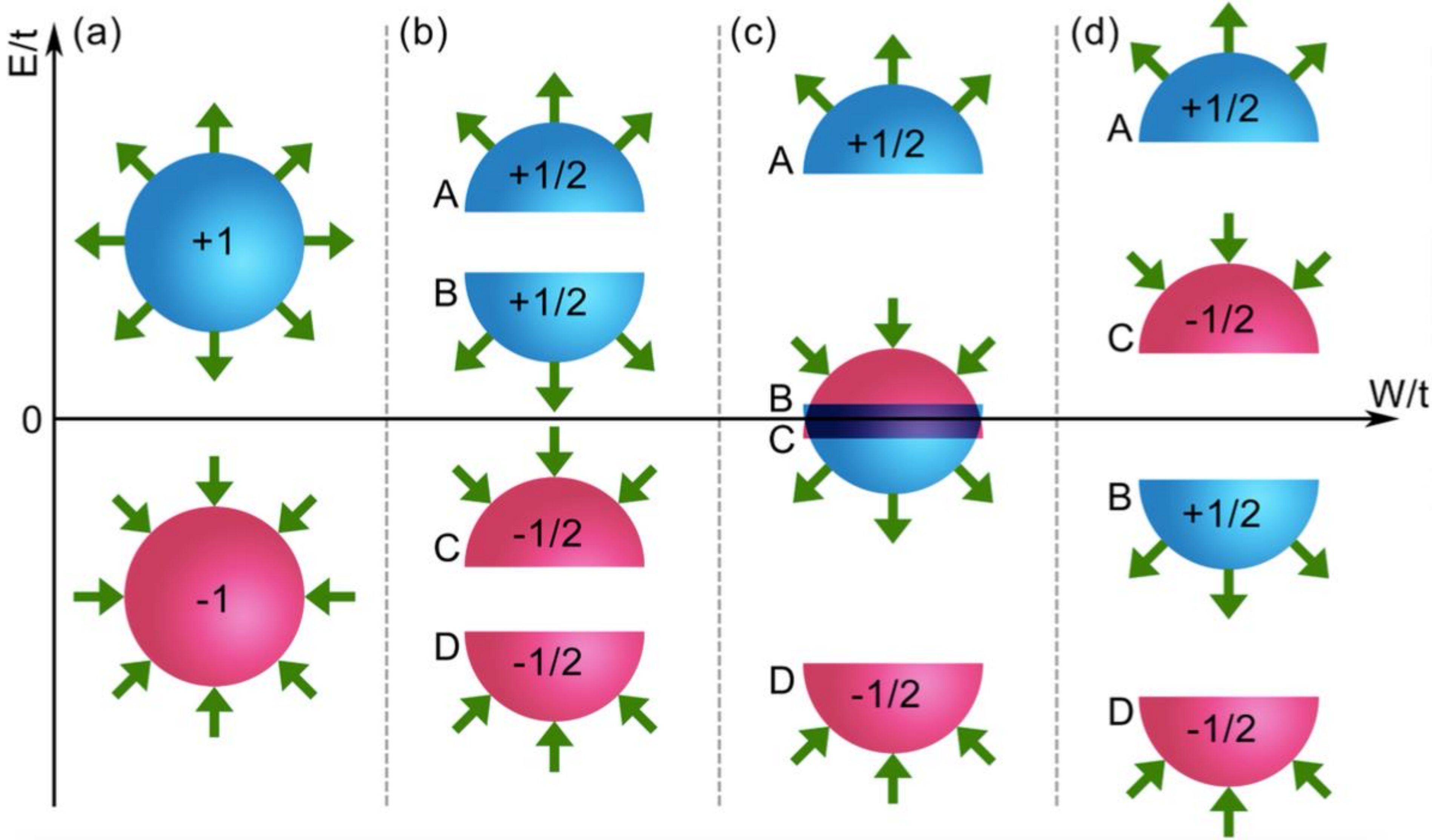
2. Berry curvature exchange between valence and conduction bands;

3. The Hall conductance at the center changes quickly.

Phase-diagram



Phenomenological understanding------ From topological charge aspect



SUMMARY

(1) Brief review of the progress on QAHE in graphene

(2) Pursuing high-temperature QAHE in TI

(3) Localization mechanism of QAHE in the presence of spin-flip disorders