KEK 素核宇・物性連携研究会 2021年3月31日

トポロジカル絶縁体ヘテロ構造における
アクシオン電磁気応答

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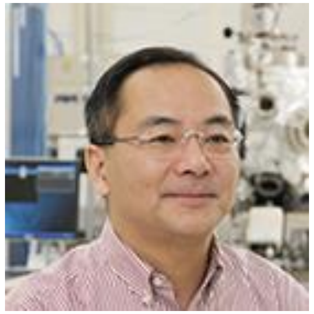
東京大学 THE UNIVERSITY OF TOKYO

APPLIED PHYSICS THE UNIVERSITY OF TOKYO



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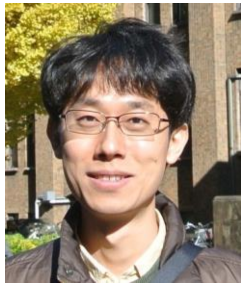

森本 高裕

TOHOKU UNIVERSITY Research

塚崎 敦

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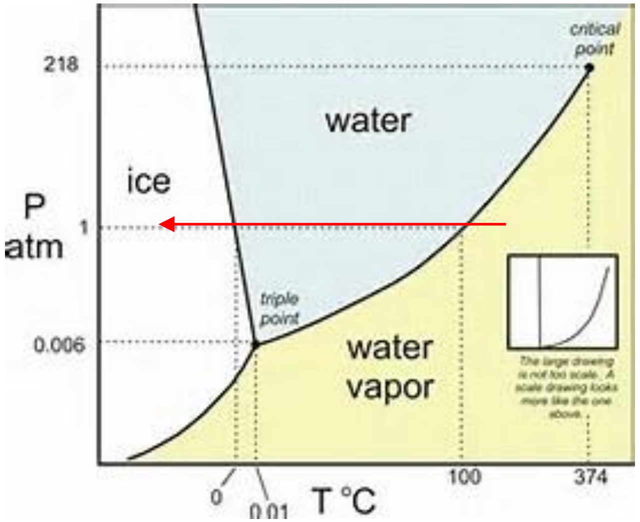
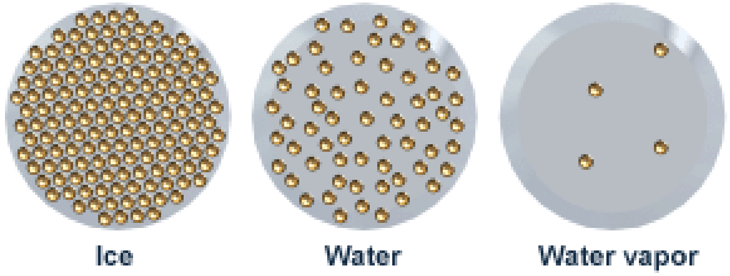
産総研 白川 直樹

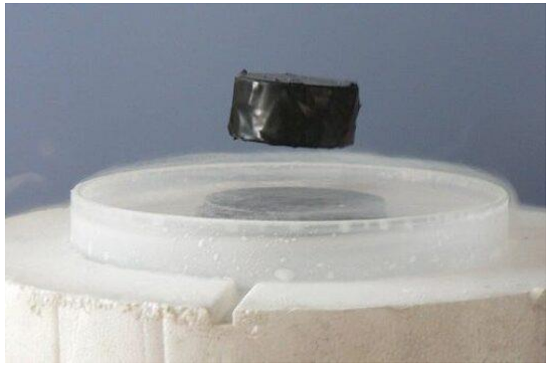
物質の相と対称性の破れ



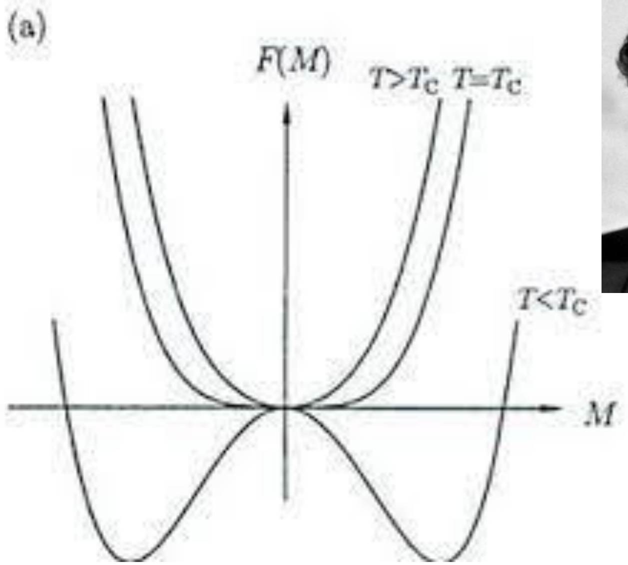


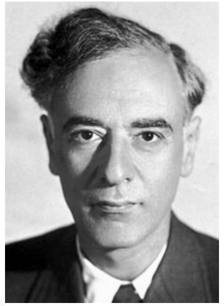
並進対称性

回転対称性



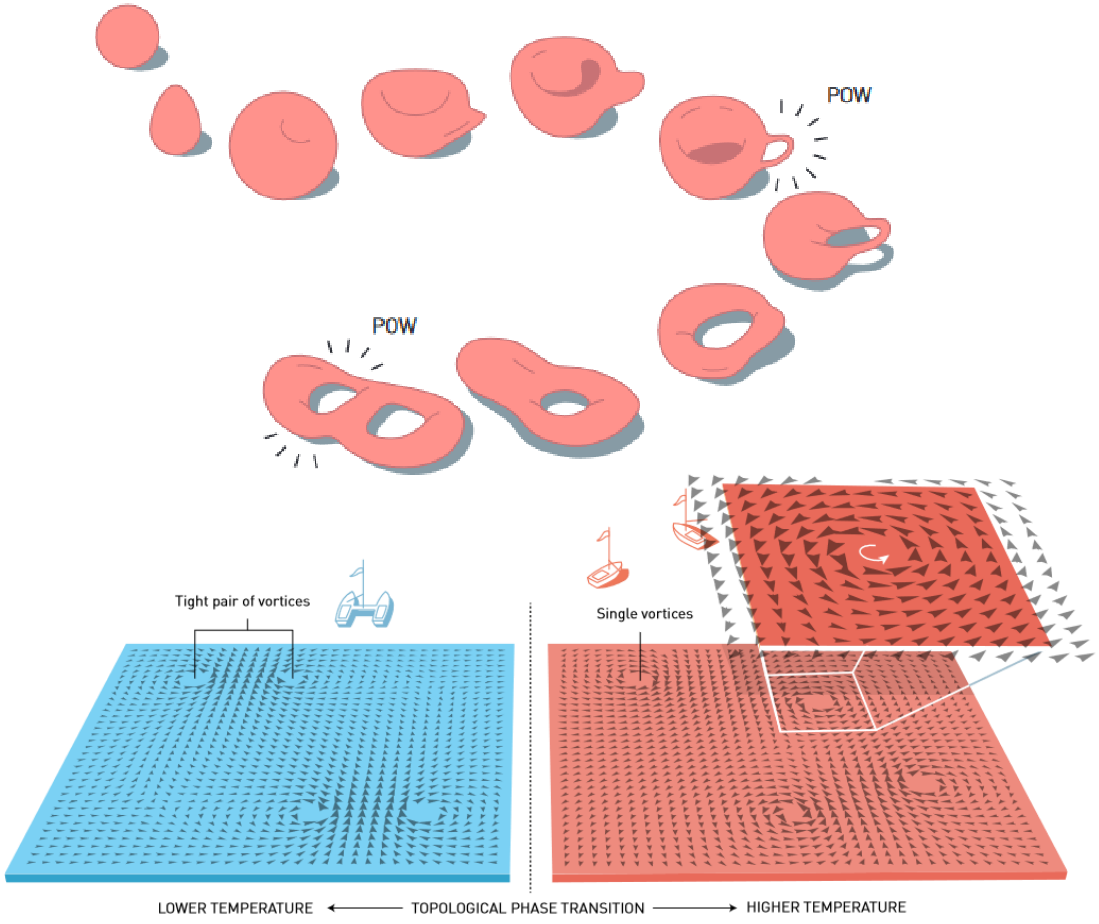
ゲージ対称性



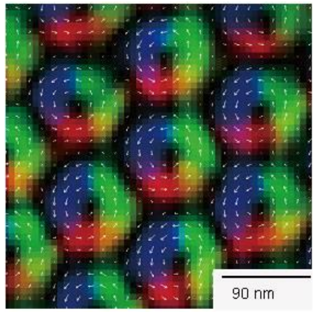


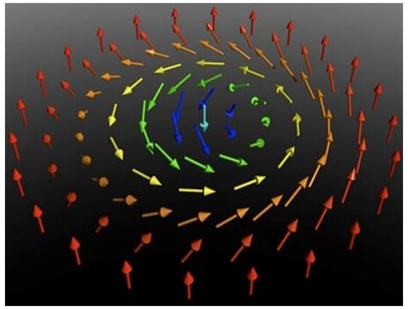
物質のトポロジカル相

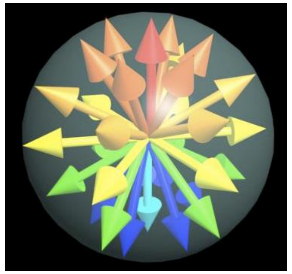
Nobel prize for Kosteritz, Thouless, Haldane (2016)



nobelprize.org

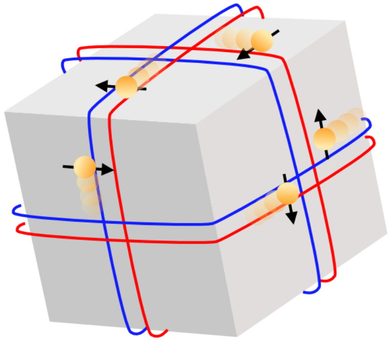


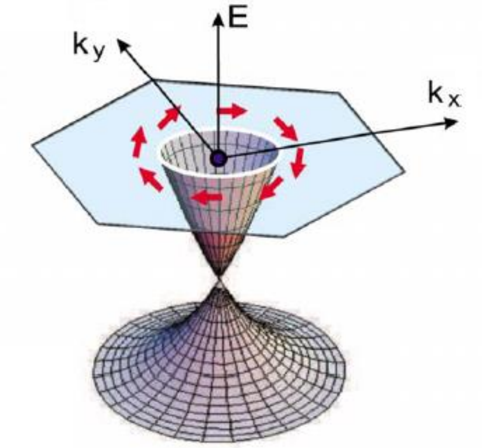




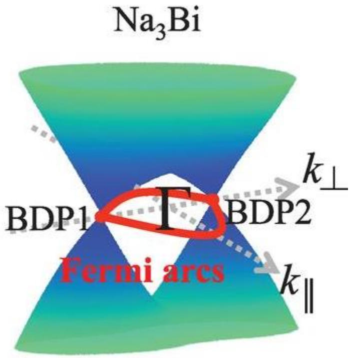
X. Z. Yu *et al.*,
Nature (2010)

トポロジカル物質





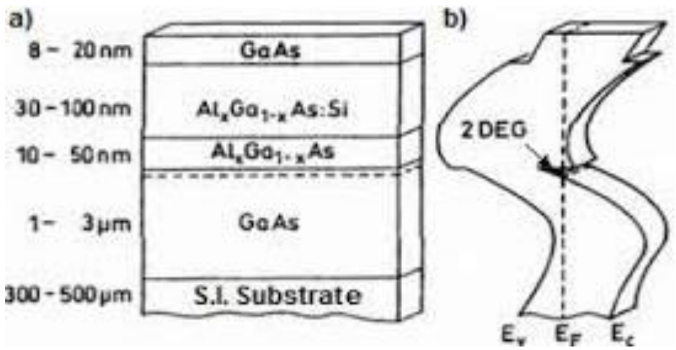
D. Hsieh *et al.*,
Nature (2010).



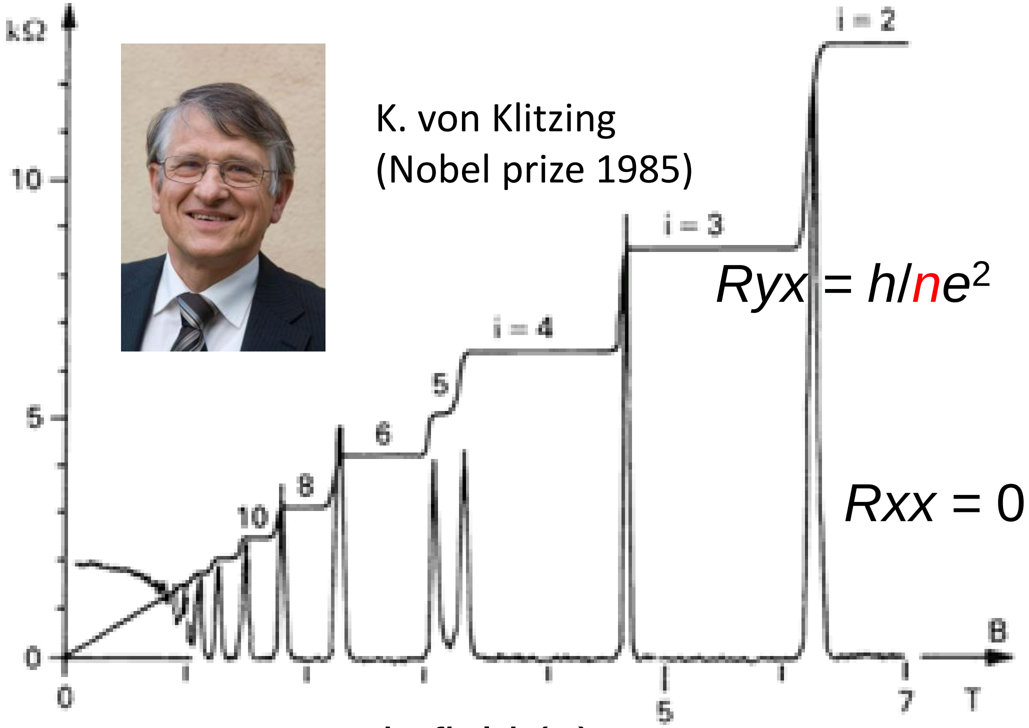
S.-Y. Xu *et al.*,
Science (2015).

量子ホール効果

磁場



K. von Klitzing
(Nobel prize 1985)

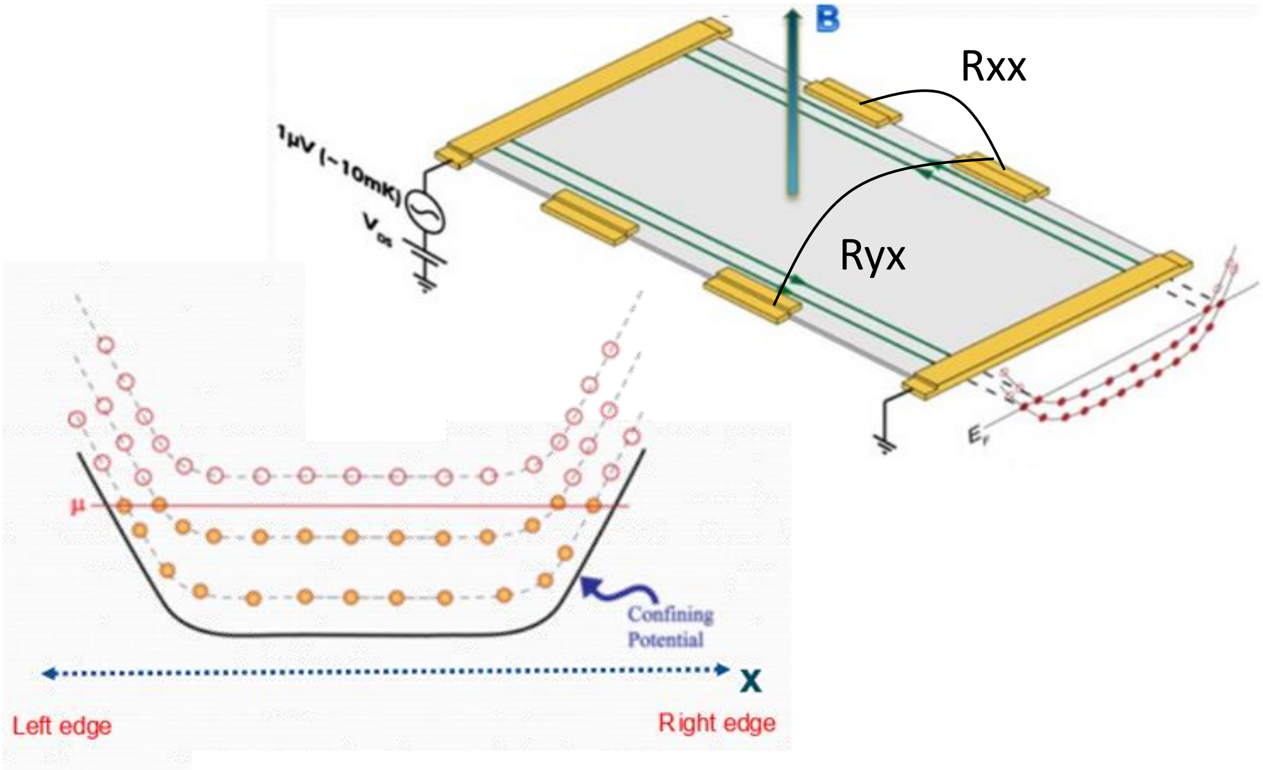


Ryx = *h*/*n**e*^{2}

Rxx = 0

Magnetic field (T)

nobelprize.org



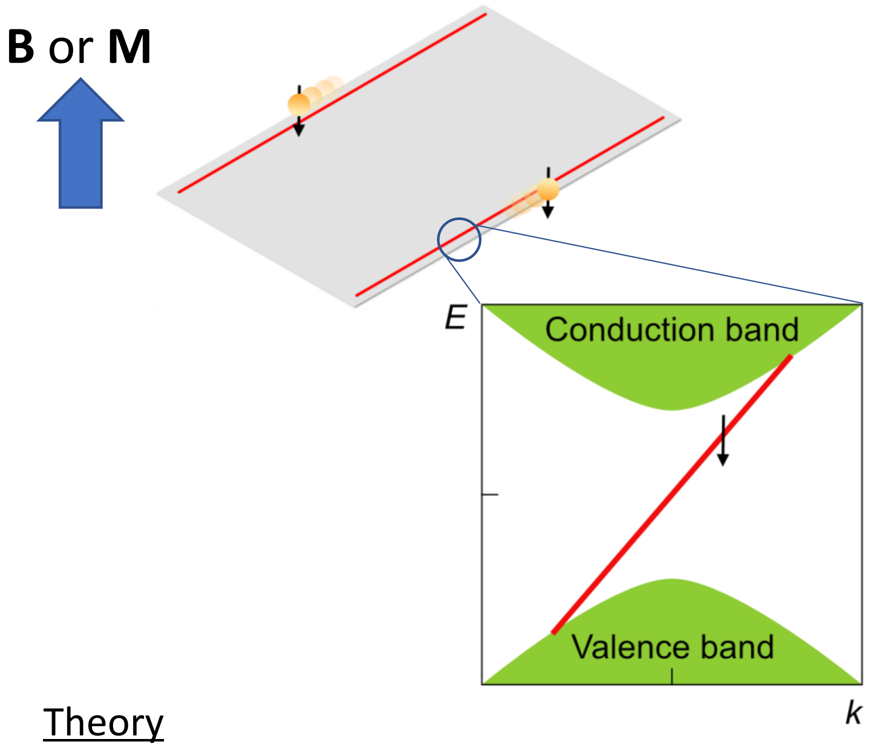
$$n_j = \frac{i}{2\pi}\int_{BZ} d^2k \left(\left\langle \partial_{k_y} u_j \middle| \partial_{k_x} u_j \right\rangle - \left\langle \partial_{k_x} u_j \middle| \partial_{k_y} u_j \right\rangle \right)$$

$$\sigma_{xy} = \frac{e^2}{h} \sum_{j \in occ} n_j = \frac{e^2}{h} C_1.$$ **チャーン数**

Thouless, 甲元, Nightingale, den Nijs (TKNN)

二次元トポロジカル絶縁体

量子（異常）ホール効果
(時間反転対称性無し)



<u>Theory</u>

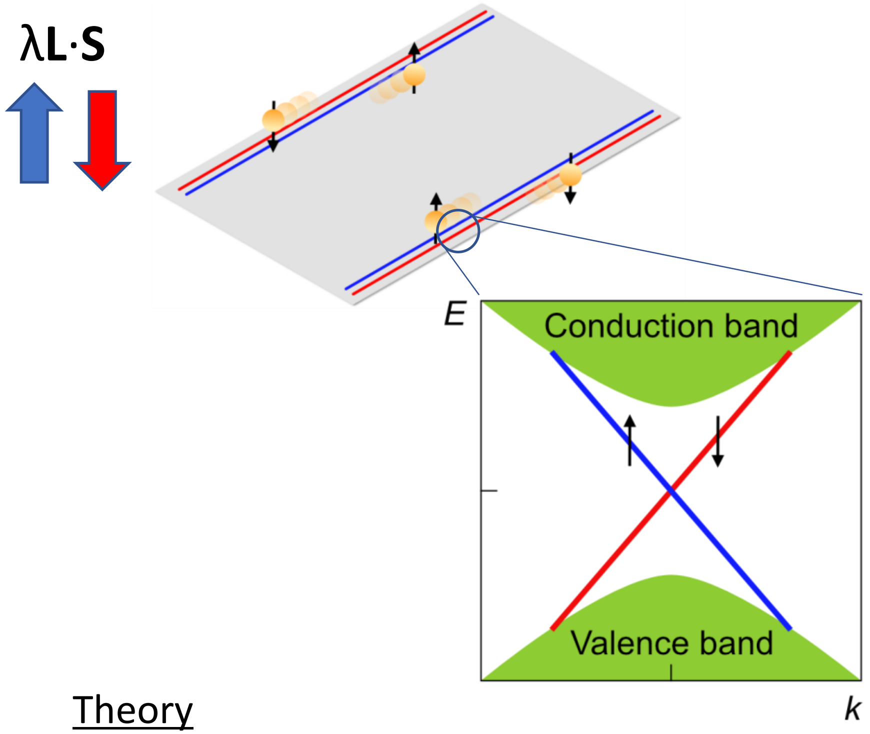
Honeycomb lattice (Haldane 1988)

Magnetically doped TI (Yu, Fang et al. 2010)

<u>Experiment</u>

Cr-doped $(Bi,Sb)_2Te_3$ (Chang, Xue et al. 2013)

量子スピンホール効果 (2D TI)
(時間反転対称性あり)



<u>Theory</u>

Honeycomb lattice (Kane and Mele 2005)

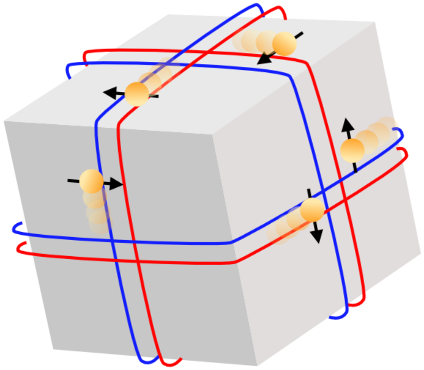
HgTe/CdTe (Bernevig, Hughes, Zhang 2006)

<u>Experiment</u>

HgTe/CdTe (Konig, Molenkamp et al. 2007)

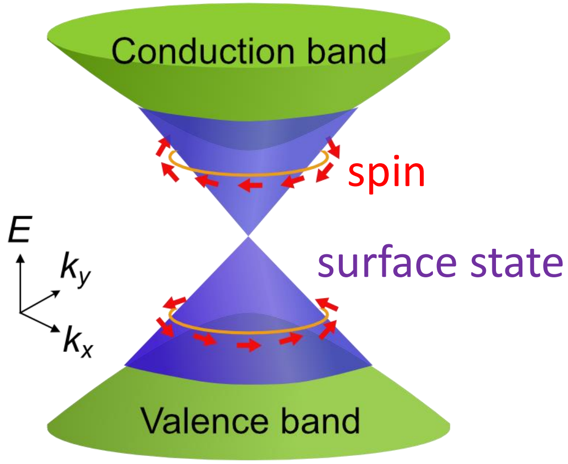
三次元トポロジカル絶縁体

実空間



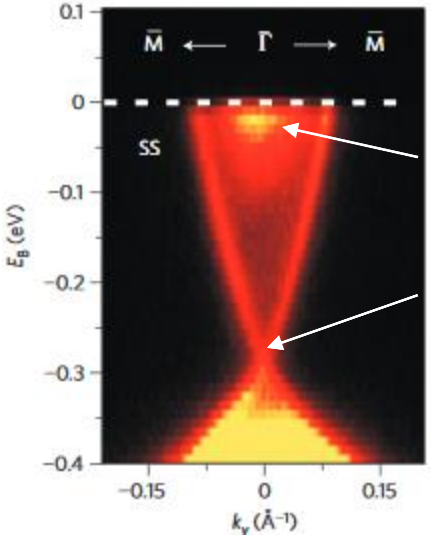
Fu and Kane (2006)
Moore and Balents (2006)
Roy (2006)

運動量空間



$$H_0(k_x, k_y) = \hbar(\sigma_x k_y - \sigma_y k_x)$$

Bi_2Se_3 の角度分解光電子分光(ARPES)



← フェルミ準位

バルク状態

ディラック点

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

- Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, **$(Bi,Sb)_2Te_3$**
- $Bi_{1-x}Sb_x$
- $GeSb_2(Se,Te)_4$
- etc.

トポロジカル場の理論

- 物質の詳細に依らない低エネルギー応答を場の理論（ラグランジアン、作用）によって記述

- 量子ホール効果のトポロジカル応答は、(2+1)次元の有効作用で記述できる(TKNN公式と一致)

$$S_{\mathrm{eff}}^{\mathrm{2D}} = \frac{C_1}{4\pi}\int \mathrm{d}^2x \int \mathrm{d}t\ \varepsilon^{\mu\nu\tau} A_\mu \partial_\nu A_\tau \qquad j^\mu = \frac{C_1}{2\pi}\varepsilon^{\mu\nu\tau}\partial_\nu A_\tau$$

Zhang, Int. J. Mod. Phys. B (1992)

- 三次元トポロジカル絶縁体は、(4+1)次元量子ホール系 -> 次元縮小化によって記述される

$$S_{\mathrm{eff}}^{\mathrm{3D}} = \frac{1}{4\pi}\int \mathrm{d}^3x \int \mathrm{d}t\ \varepsilon^{\mu\nu\sigma\tau}\theta(\mathbf{x},t)\partial_\mu A_\nu \partial_\sigma A_\tau \ \Rightarrow\ L_{\mathrm{TI}} = \frac{\theta e^2}{2\pi h}\boldsymbol{E}\cdot\boldsymbol{B}$$

アクシオン項

$$\theta = -\frac{1}{4\pi}\int_{\mathrm{BZ}} \mathrm{d}^3k\ \varepsilon^{\mu\nu\sigma}\mathrm{tr}\left[a_\mu \partial_\nu a_\sigma - \frac{2i}{3}a_\mu a_\nu a_\sigma\right]$$

Qi, Hughes, Zhang, PRB (2008)

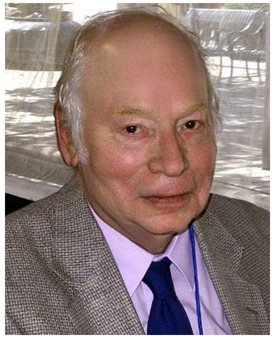
物質におけるアクシオン電磁気学（歴史）

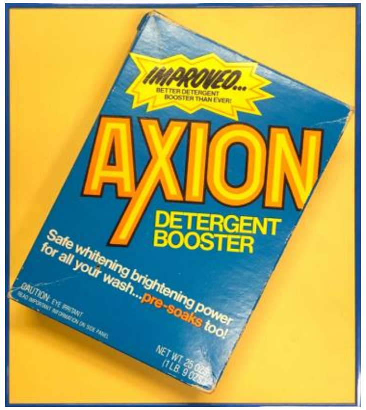
- “アクシオン”は強い相互作用におけるCP対称性に関する問題において生まれた概念
- Peccei-Quinn 理論 によって解決できる（アクシオン場(θ)の導入） (1977年)
- アクシオン粒子はアクシオン場の南部-Goldstone モードに対応 (1978年)


Roberto Peccei


Helen Quinn


Frank Wilczek


Steven Weinberg



Quanta Magazine (2016)

- Wilczek 教授が1987年に物質中でのアクシオン応答の存在を予言

F. Wilczek, PRL (1987)

トポロジカル絶縁体でのアクシオン電磁気学

$$L_{\mathrm{TI}} = \frac{\theta e^2}{2\pi h} \boldsymbol{E} \cdot \boldsymbol{B}$$

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

$$\theta = -\frac{1}{4\pi} \int_{\mathrm{BZ}} d^3k\, \epsilon_{ijk} \mathrm{Tr}\left[A_i \partial_j A_k - i \frac{2}{3} A_i A_j A_k \right]$$

1. トポロジカル状態の分類

L_{TI} による作用は $\theta \rightarrow \theta + 2\pi$ に対して不変

$\theta = 0$: 通常の絶縁体

$\theta = \pi$: トポロジカル絶縁体

(時間反転対称性)

2. マクスウェル方程式の変更

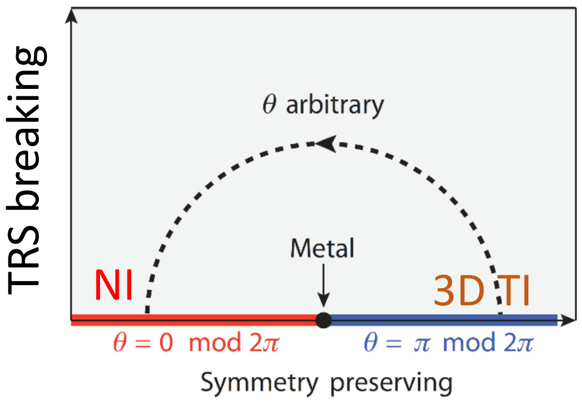
$$\nabla \cdot \boldsymbol{E} = \frac{e^2}{2\varepsilon_0 h} \nabla \left(\frac{\theta}{\pi} \right) \cdot \boldsymbol{B}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

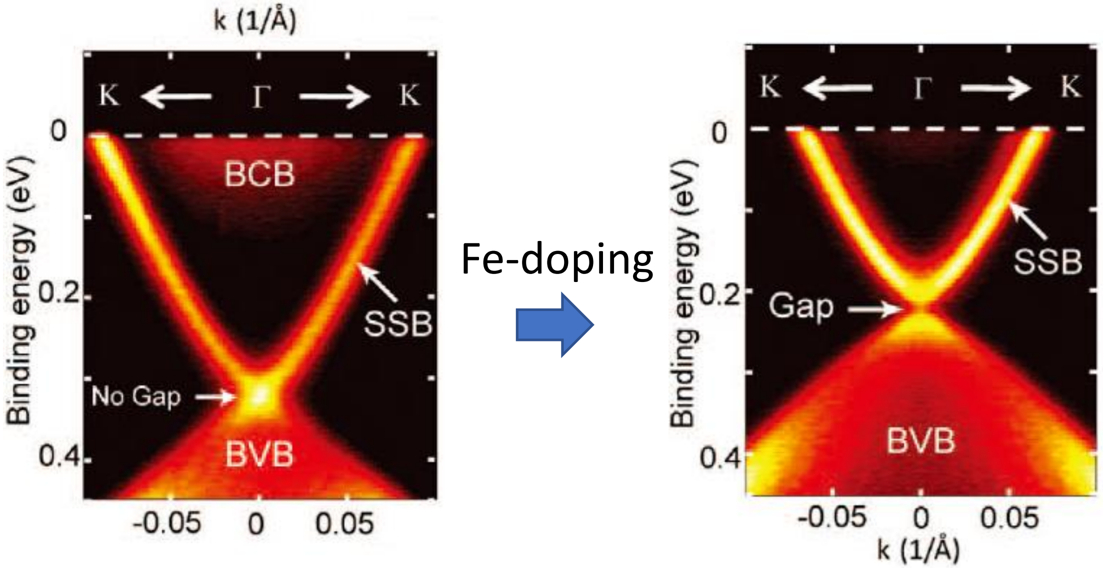
$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c^2} \frac{\partial \boldsymbol{E}}{\partial t} + \frac{\mu_0 e^2}{2h} \nabla \left(\frac{\theta}{\pi} \right) \times \boldsymbol{E} + \frac{\mu_0 e^2}{2h} \frac{\dot{\theta}}{\pi} \boldsymbol{B}$$

時間反転対称性の破れたトポロジカル絶縁体



S. Coh, D. Vanderbilt *et al.*, PRB **83**, 085108 (2011).



Y. L. Chen et al., Science (2010)

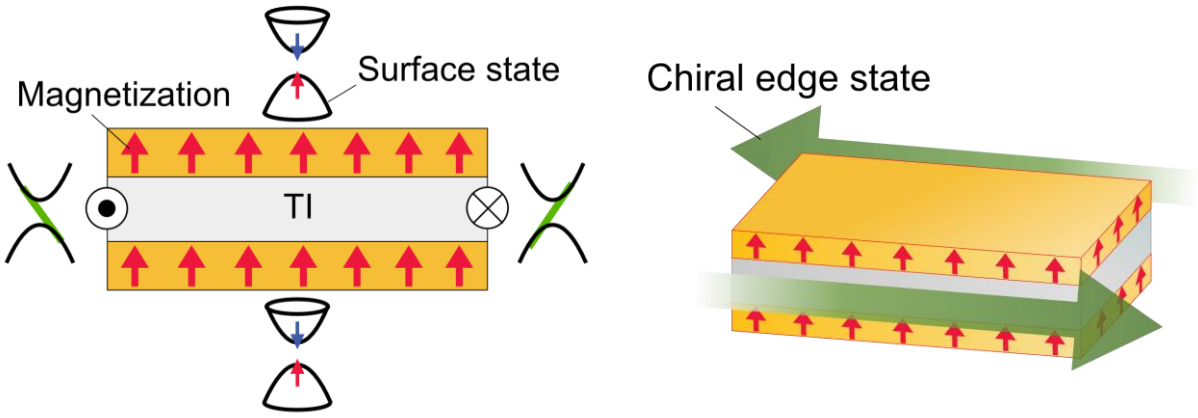
$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \frac{\mu_0 e^2}{2h}\nabla\left(\frac{\theta}{\pi}\right)\times \boldsymbol{E}$$

$$= \mu_0\,\mathbf{j}$$

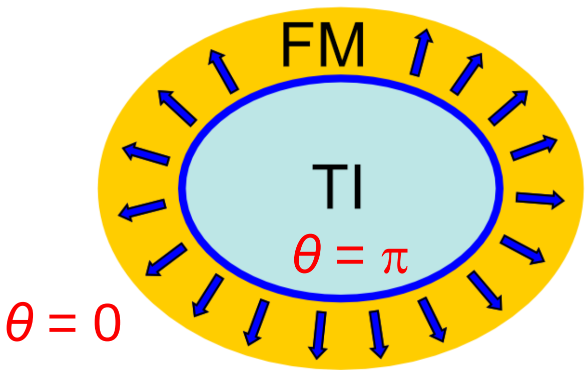
$$j_y = e^2/(2\mathrm{h})E_x$$

半整数量子化ホール電流

量子異常ホール効果



アクシオン絶縁体、トポロジカル電気磁気効果

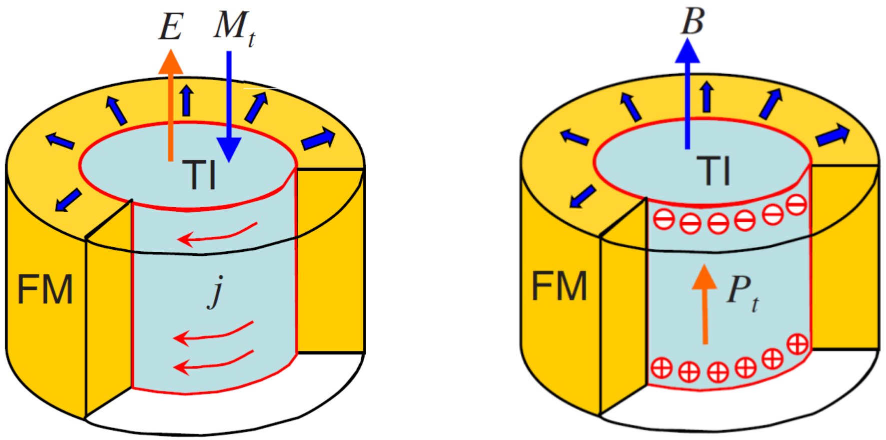


$$\mathcal{L}_\theta = \theta \frac{e^2}{2\pi h} \boldsymbol{E} \cdot \boldsymbol{B}$$

➡ **量子化電気磁気効果**

$$\boldsymbol{P} = \frac{e^2}{2h}\frac{\theta}{\pi}\boldsymbol{B}, \quad \boldsymbol{M} = \frac{e^2}{2h}\frac{\theta}{\pi}\boldsymbol{E}$$

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



"アクシオン絶縁体"

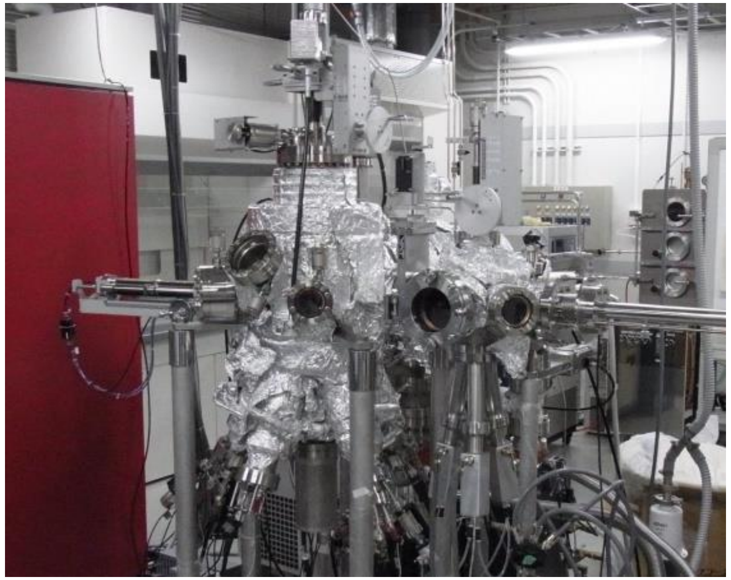
どうやって∇θを空間的に
制御するか?

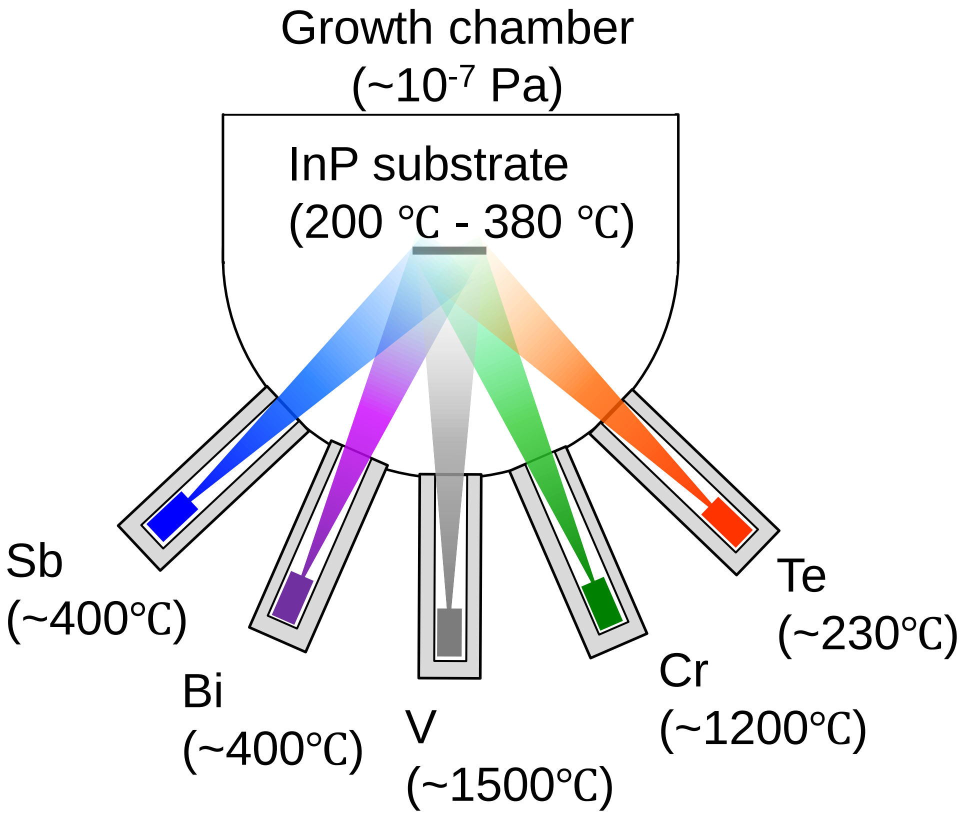
概要

- トポロジカル絶縁体ヘテロ構造
- アクシオン絶縁体状態の作成
- 半整数量子ホール効果の観測
- まとめと展望

MBEによるトポロジカル絶縁体薄膜作製

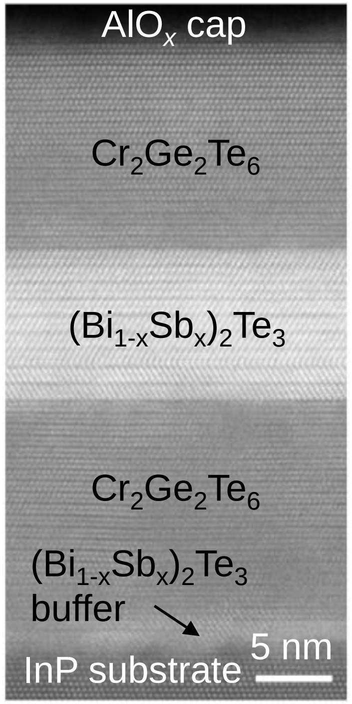
分子線エピタキシー装置 (Molecular Beam Epitaxy, MBE)





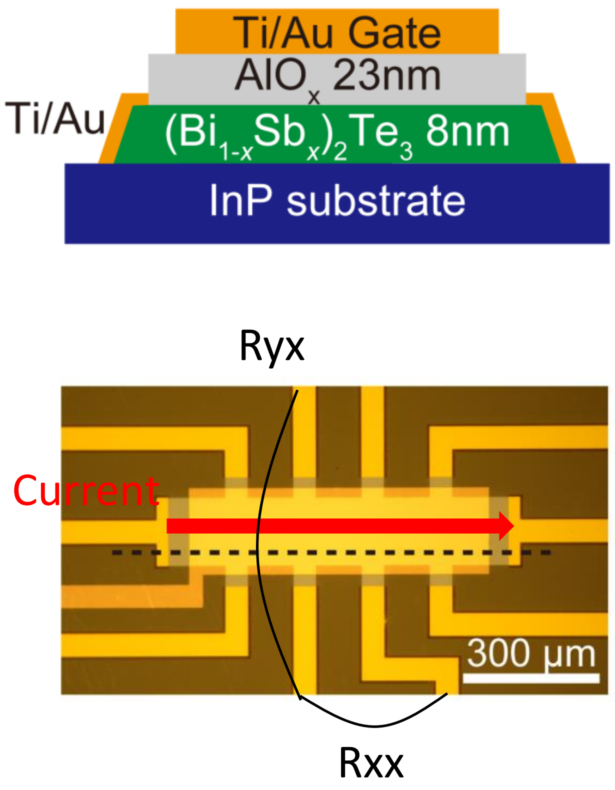
- 膜厚制御性 (< 1nm)
- 組成制御性 (~ 1%)
- ヘテロ構造エンジニアリング

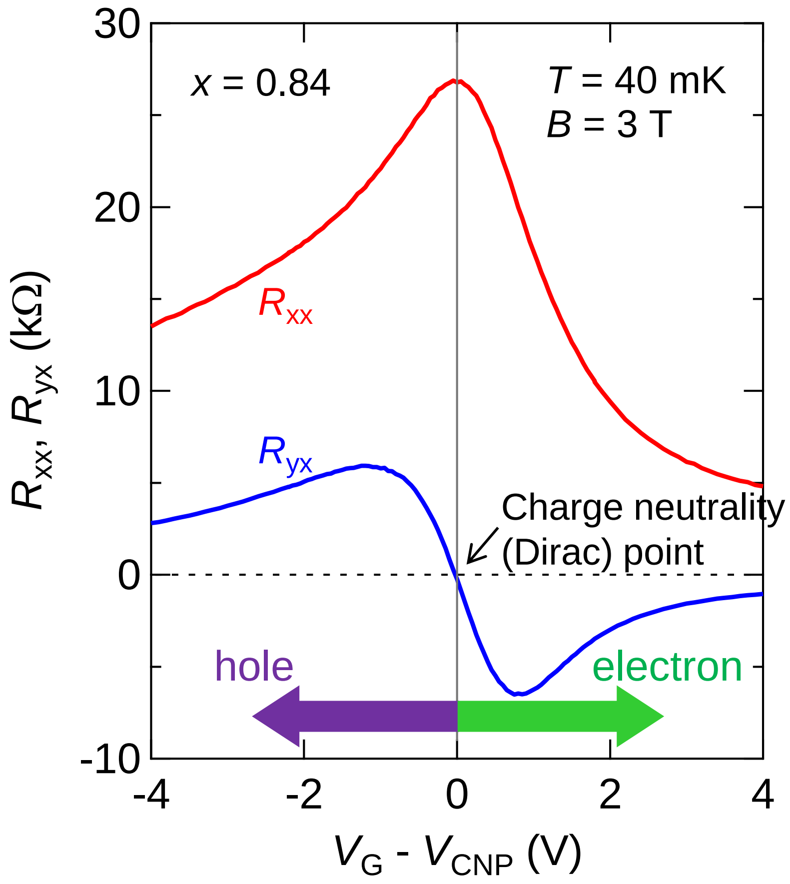
作製例

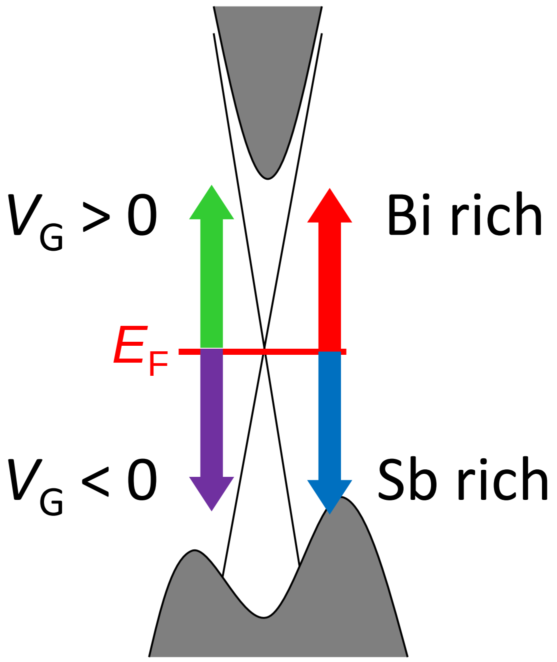


M. Mogi *et al.*, PRL **123**, 016804 (2019)

薄膜ホール素子によるフェルミ準位制御







R. Yoshimi, *et al.*,
Nature Commun. **6**, 6627 (2015)

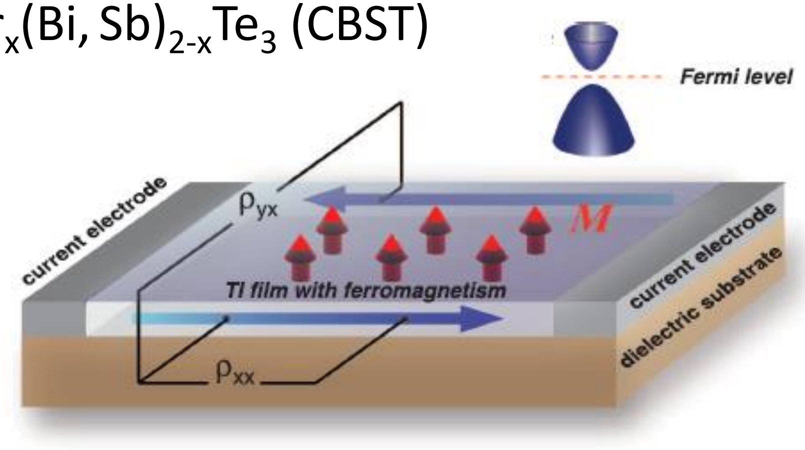
量子異常ホール効果(QAHE)の観測

REPORTS

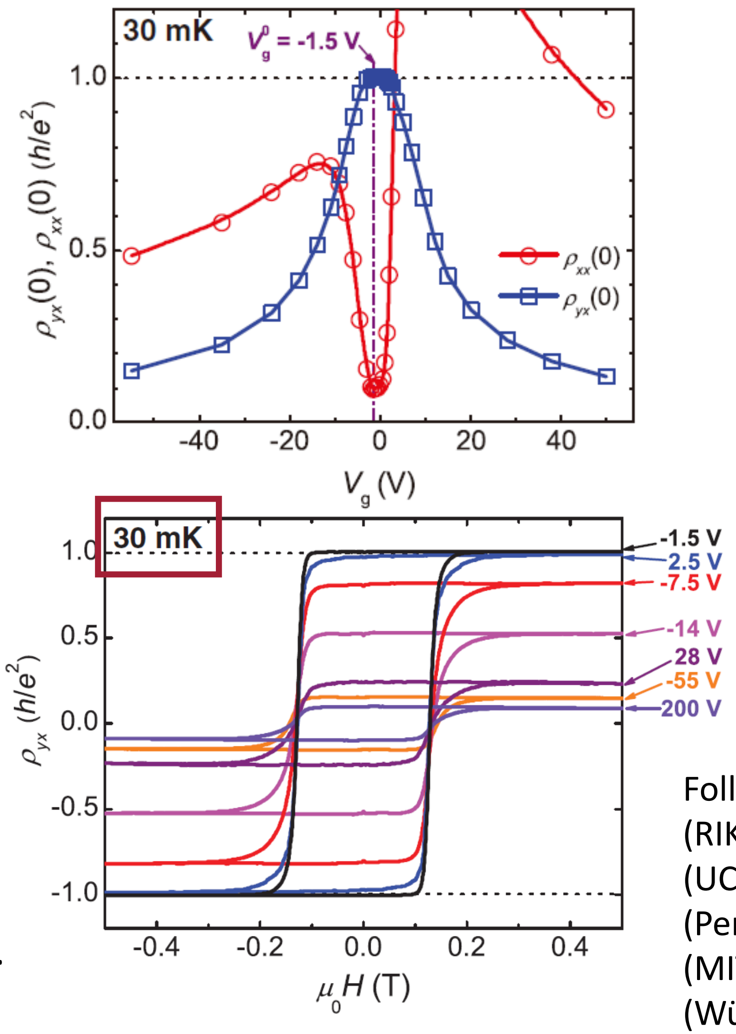
Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator

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†]

$Cr_x(Bi,Sb)_{2-x}Te_3$ (CBST)



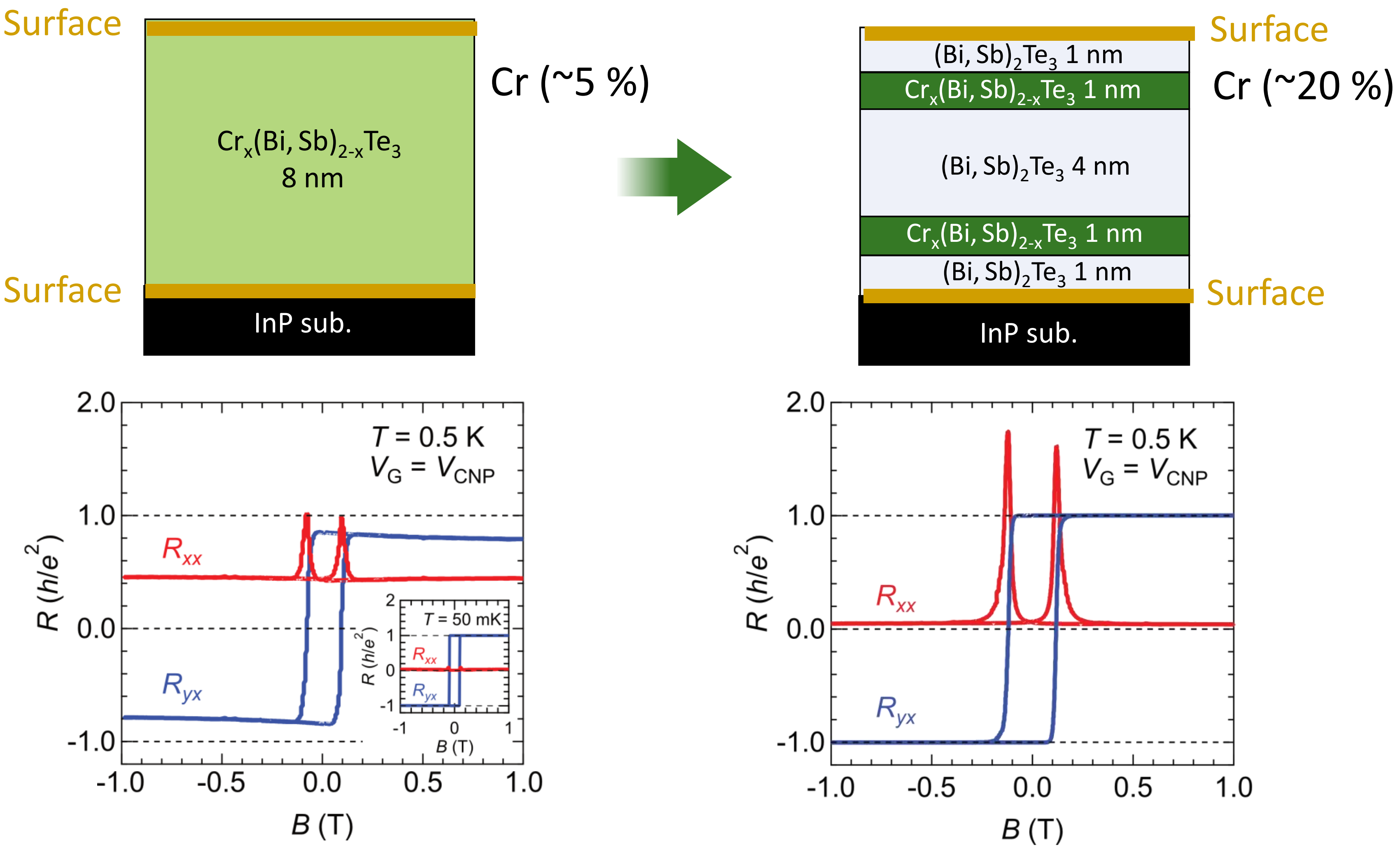
C. Z. Chang, Q. K. Xue *et al.*, Science **340**, 167 (2013).



$$R_{yx} = \frac{h}{e^2} \quad (25.8\ \mathrm{k\Omega})$$

Following works (2014-2015):
(RIKEN) J. G. Checkelsky *et al.*, Nat. Phys. (2014)
(UCLA) X. Kou *et al.*, PRL (2014)
(Penn State) A. Kandala *et al.*, Nat. Commun. (2015)
(MIT) C. Z. Chang *et al.*, Nat. Mater. (2015)
(Würzburg) S. Grauer *et al.*, PRB (2015)

ヘテロ構造による量子化温度の高温化



QAHE below 0.1 K

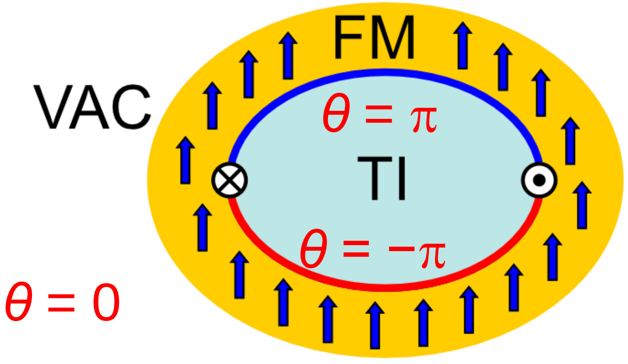
Realization of QAHE up to **2 K**

M. Mogi *et al.*, APL **107**, 182401 (2015).

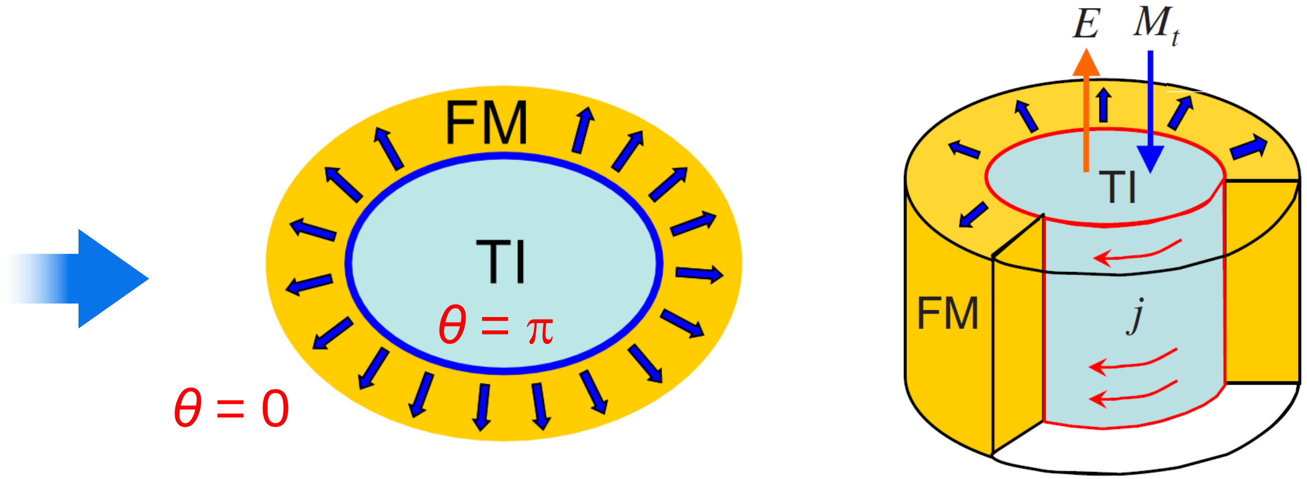
アクシオン絶縁体状態の設計

量子異常ホール絶縁体

アクシオン絶縁体



平行磁化

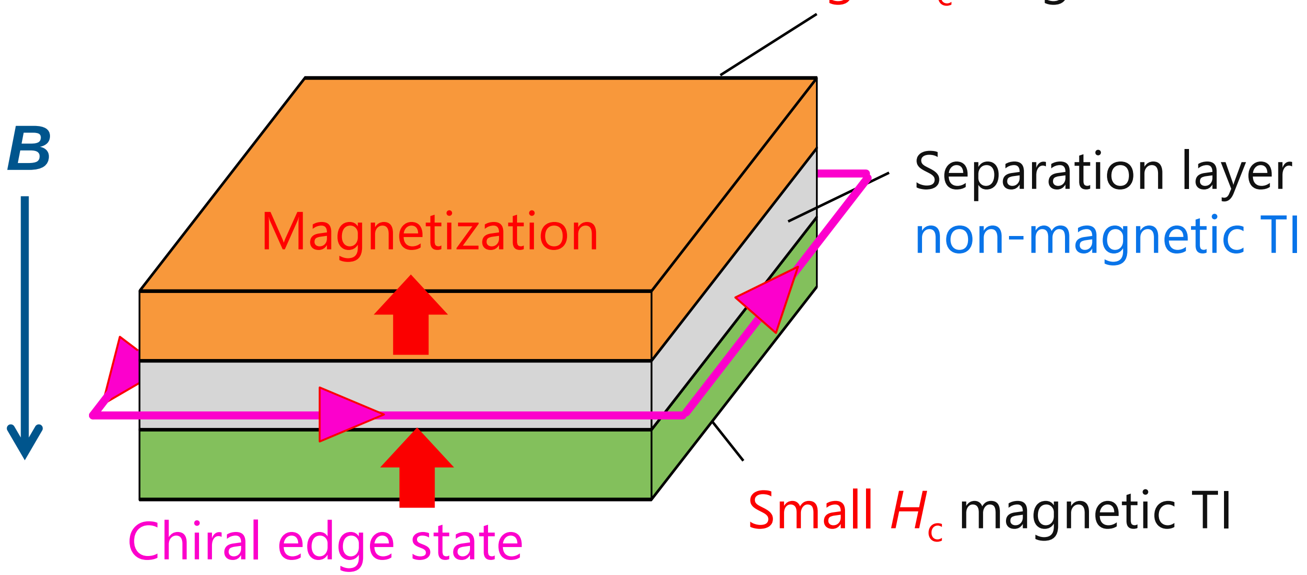


反平行磁化

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

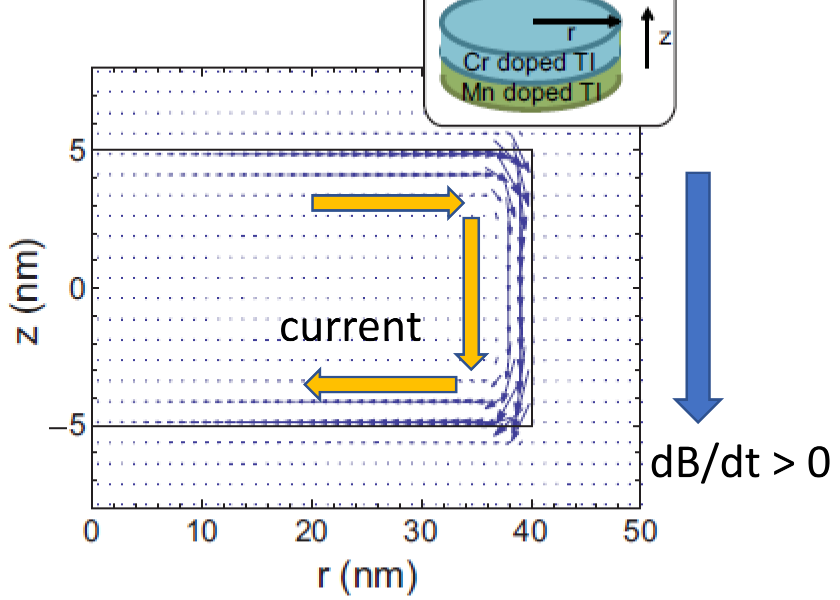
磁気サンドイッチ構造

Our idea



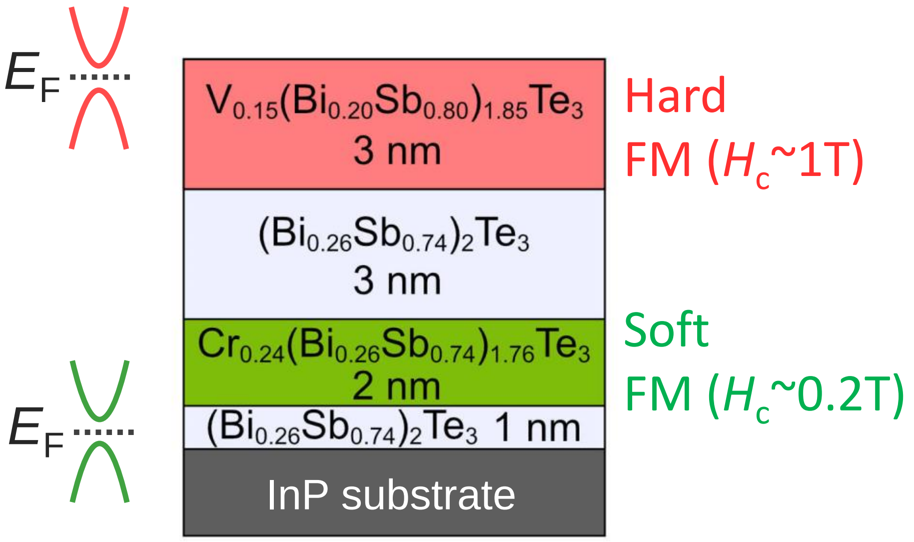
M. Mogi, M. Kawamura et al., Nat. Mater. 16, 516 (2017)

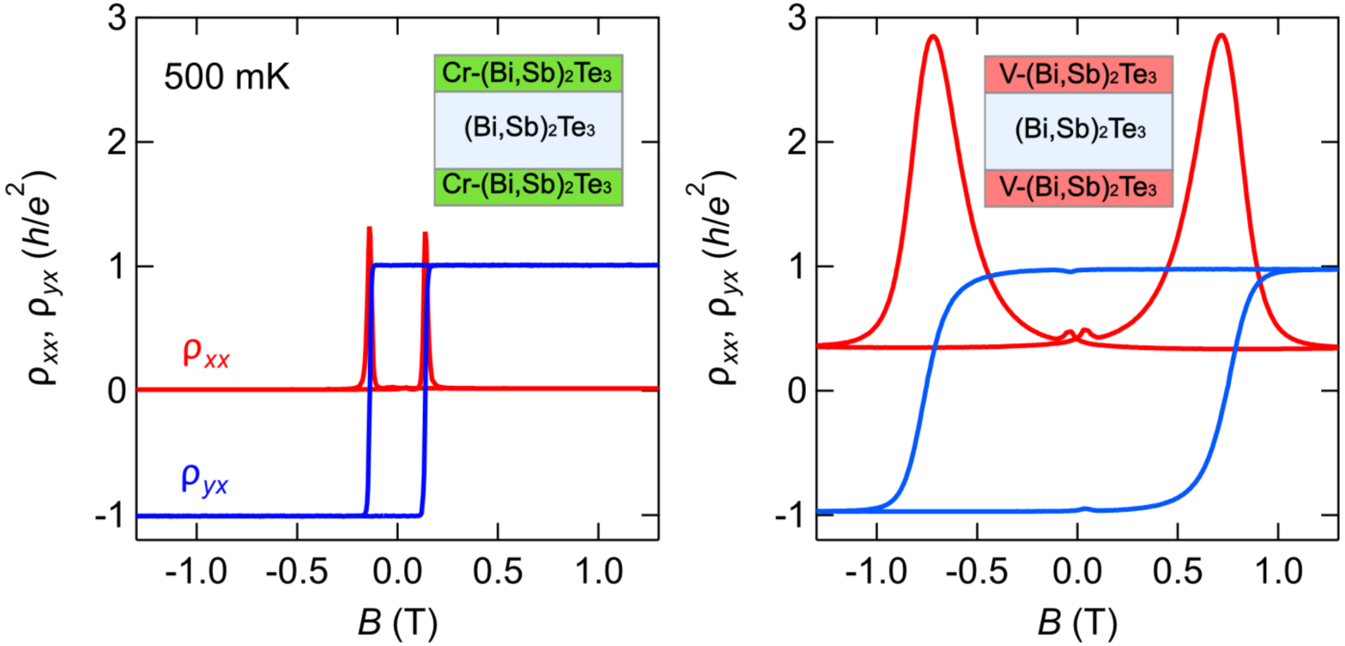
Theory



T. Morimoto *et al.*, PRB **92**, 085113 (2015)
J. Wang *et al.*, PRB **92**, 081107 (2015)

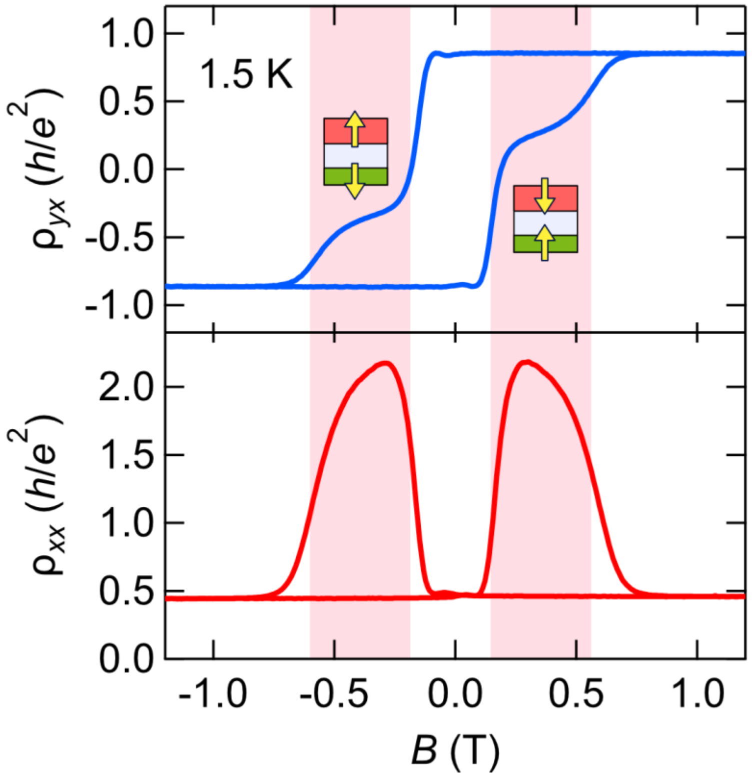
QAH サンドイッチ構造





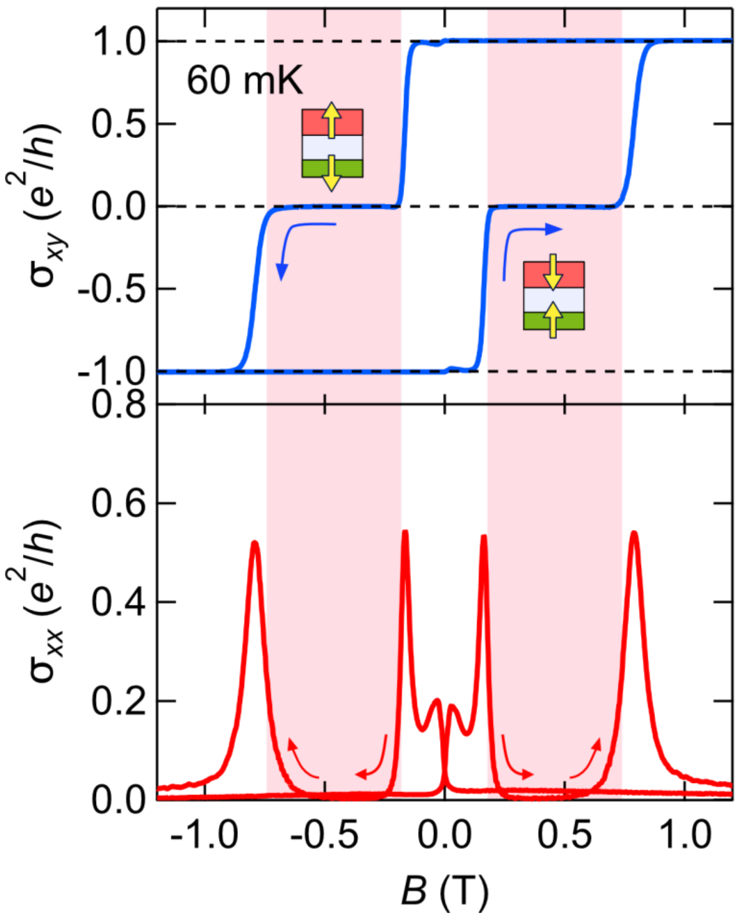
cf. QAHE in V-doped BST:
C.-Z. Chang *et al.*, Nat. Mater. **14**, 473 (2015).

ゼロホール伝導度プラトーの観測

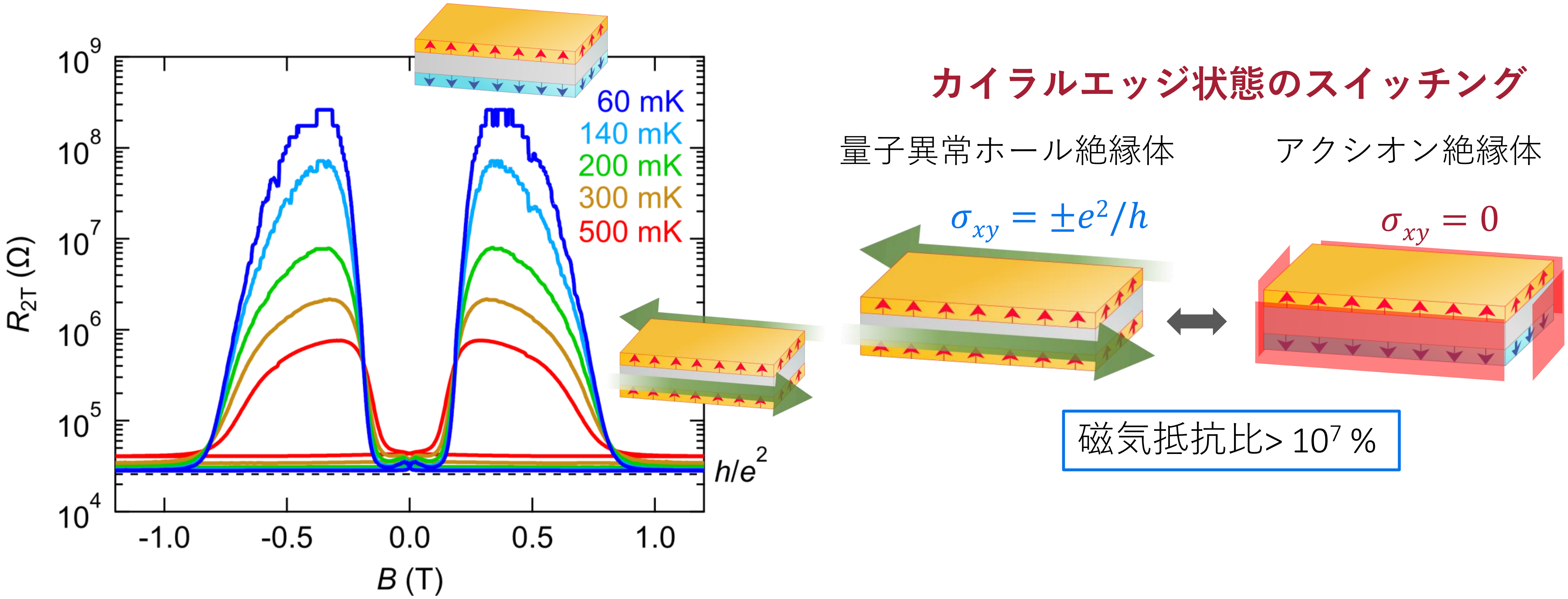


$J = \sigma E$

$\sigma = \rho^{-1}$



アクシオン-QAH転移による巨大磁気抵抗効果



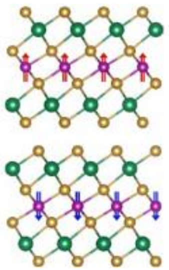
磁気抵抗比> 10^7 %

M. Mogi et al., Sci. Adv. 3, eaao1669 (2017)

Other axion insulators, proposals, reviews

LETTERS
https://doi.org/10.1038/s41563-019-0573-3
nature materials

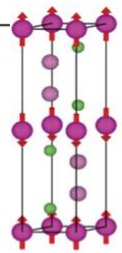
MnBi$_2$Te$_4$



Robust axion insulator and Chern insulator phases in a two-dimensional antiferromagnetic topological insulator

Chang Liu[1,8], Yongchao Wang[2,8], Hao Li[3,4,8], Yang Wu[4,5], Yaoxin Li[1], Jiaheng Li[1], Ke He[1,6], Yong Xu[1,6,7*], Jinsong Zhang[1,6*] and Yayu Wang[1,6*]

PHYSICAL REVIEW LETTERS 122, 256402 (2019)



Higher-Order Topology of the Axion Insulator EuIn$_2$As$_2$

Yuanfeng Xu,[1,2,3] Zhida Song,[1,2,4] Zhijun Wang,[1,2] Hongming Weng,[1,2,5,6,*] and Xi Dai[7,†]
[1]*Beijing National Laboratory for Condensed Matter Physics, and Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*
[3]*Max Planck Institute of Microstructure Physics, Halle 06120, Germany*
[4]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[5]*CAS Center for Excellence in Topological Quantum Computation, University of Chinese Academy of Sciences, Beijing 100190, China*
[6]*Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China*
[7]*Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon 999077, Hong Kong*

(Received 1 April 2019; published 25 June 2019)

nature physics
ARTICLES
https://doi.org/10.1038/s41567-019-0457-0

Symmetry-enforced chiral hinge states and surface quantum anomalous Hall effect in the magnetic axion insulator Bi$_{2-x}$Sm$_x$Se$_3$

Changming Yue[1,2], Yuanfeng Xu[1,2], Zhida Song[1,2], Hongming Weng[1,2,3,4,5], Yuan-Ming Lu[6], Chen Fang[1,3,4,5,7] and Xi Dai[8*]

PHYSICAL REVIEW B 100, 075303 (2019)

Magnetic resonance induced pseudoelectric field and giant current response in axion insulators

Jiabin Yu,[1] Jiadong Zang,[2] and Chao-Xing Liu[1,*]
[1]*Department of Physics, Pennsylvania State University, University Park, Pennsylvania 16802, USA*
[2]*Department of Physics and Astronomy, University of New Hampshire, Durham, New Hampshire 03824, USA*

(Received 3 April 2019; published 27 August 2019)

PHYSICAL REVIEW LETTERS 123, 121601 (2019)

Proposal to Detect Dark Matter using Axionic Topological Antiferromagnets

David J. E. Marsh,[1,*] Kin Chung Fong,[2] Erik W. Lentz,[1] Libor Šmejkal,[3,4,5] and Mazhar N. Ali[6]
[1]*Institut für Astrophysik, Georg-August Universität, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany*
[2]*Raytheon BBN Technologies, Quantum Engineering and Computing, Cambridge, Massachusetts 02138, USA*
[3]*Institut für Physik, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany*
[4]*Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnická 10, 162 53 Praha 6 Czech Republic*
[5]*Faculty of Mathematics and Physics, Charles University in Prague, Ke Karlovu 3, 121 16 Prague 2, Czech Republic*
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(Received 13 August 2018; published 17 September 2019; corrected 16 October 2019)

REVIEWS

Axion physics in condensed-matter systems

Dennis M. Nenno[1,2✉], Christina A. C. Garcia[2], Johannes Gooth[1,3], Claudia Felser[1,2] and Prineha Narang[2✉]

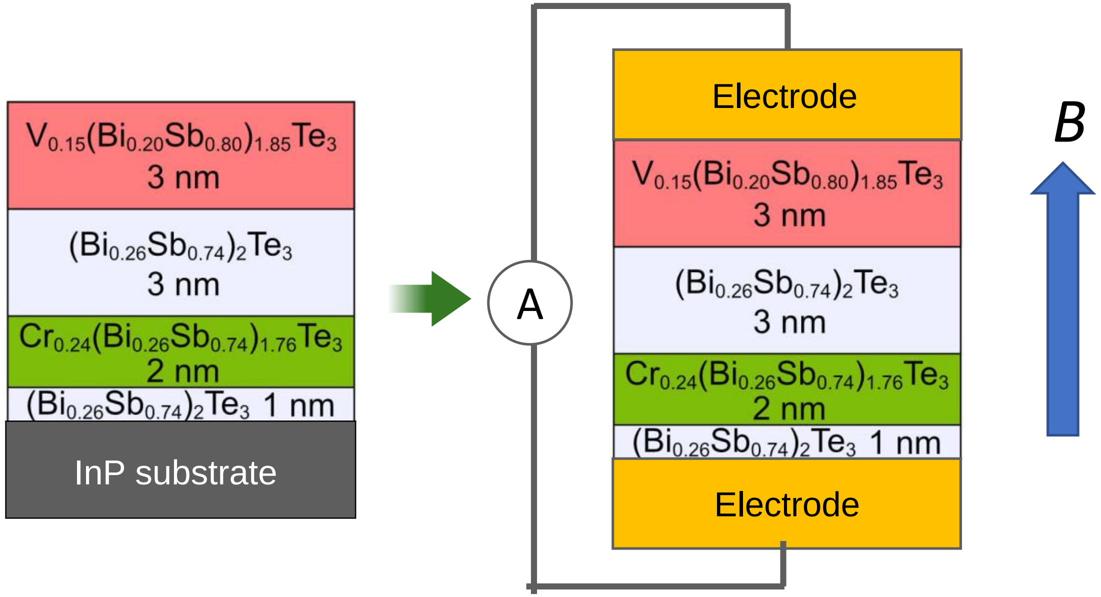
Abstract | Axions are hypothetical particles that were proposed to solve the strong charge–parity problem in high-energy physics. Although they have long been known in quantum field theory, axions have so far not been observed as elementary particles in nature. Yet, in condensed-matter systems, axions can also emerge as quasiparticles in certain materials such as strong topological insulators. The corresponding axion field is expected to lead to exciting physical phenomena in condensed-matter systems, such as a fractional quantum anomalous Hall effect, the chiral anomaly, exotic Casimir–Lifshitz repulsion and a linear magnetoelectric response quantized in units of the fine-structure constant. First signatures of electronic states that permit axion dynamics have been reported in condensed-matter systems. In this Review, we explore the concepts that introduce axion fields in condensed-matter systems and present experimental findings. We discuss predicted and realized material systems, the prospects of using axion electrodynamics for next-generation devices and the search for axions as a possible constituent of dark matter.

Axion electrodynamics in topological materials

Akihiko Sekine[1, a)] and Kentaro Nomura[2]
[1)]*RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan*
[2)]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

(Dated: 30 November 2020)

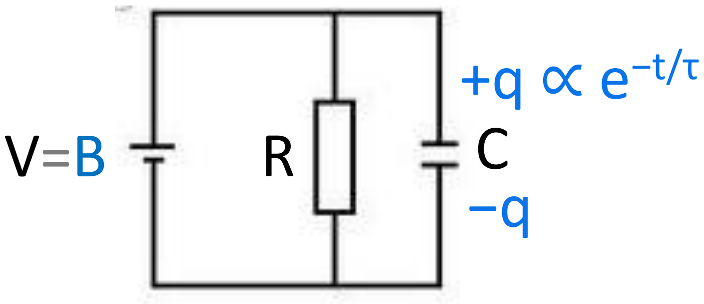
電気磁気効果の観測に向けて



$$P_z \cong 24.3(\mu C m^{-2} T^{-1}) \times B_z(T)$$

cf. Cr_2O_3: 0.7-1.6 ($\mu Cm^{-2}T^{-1}$)

Equivalent circuit



$R_\perp$ = 1GΩ/(100μm/10nm) ~ 10^5 Ω
C = 24.3×10^{-14} F

⇒ τ = RC = 2.4×10^{-8} s

⇒ ω > 100 MHz

概要

- トポロジカル絶縁体ヘテロ構造
- アクシオン絶縁体状態の作成
- 半整数量子ホール効果の観測
- まとめと展望

Another manifestation of axionic responses

$$\nabla \cdot \boldsymbol{E} = \frac{e^2}{2\varepsilon_0 h} \nabla \left(\frac{\theta}{\pi}\right) \cdot \boldsymbol{B}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \underline{\frac{\mu_0 e^2}{2h} \nabla \left(\frac{\theta}{\pi}\right) \times \boldsymbol{E}}$$

$$= \mu_0 \mathbf{j}$$

$$j_y = e^2/(2h)E_x$$

半整数量子化ホール電流

二次元場の理論におけるパリティ異常 (1983~)

VOLUME 51, NUMBER 23 PHYSICAL REVIEW LETTERS 5 DECEMBER 1983

Axial-Anomaly–Induced Fermion Fractionization and Effective Gauge-Theory Actions in Odd-Dimensional Space-Times

A. J. Niemi
The Institute for Advanced Study, Princeton, New Jersey 08540,[a] *and Research Institute for Theoretical Physics, University of Helsinki, SF-00170 Helsinki 17, Finland*

and

G. W. Semenoff
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 2 September 1983)

PHYSICAL REVIEW D VOLUME 29, NUMBER 10 15 MAY 1984

Fractional charge and zero modes for planar systems in a magnetic field

R. Jackiw
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute for Technology, Cambridge, Massachusetts 02139
(Received 9 January 1984)

PHYSICAL REVIEW LETTERS

VOLUME 53 24 DECEMBER 1984 NUMBER 26

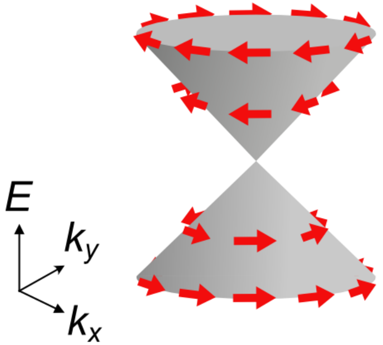
Condensed-Matter Simulation of a Three-Dimensional Anomaly

Gordon W. Semenoff
The Institute for Advanced Study, Princeton, New Jersey 08540, and Department of Physics,[a] *University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada*
(Received 4 September 1984)

Parity anomaly of "single" Dirac fermion

Massless Dirac fermion

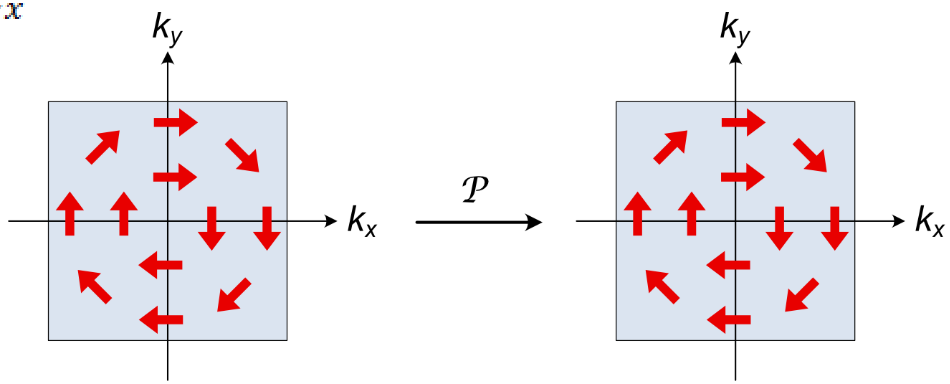
$$H_0(k_x, k_y) = \hbar(\sigma_x k_y - \sigma_y k_x)$$



Parity operator

$k_x \to -k_x$

$\mathcal{P} = i\sigma_x$

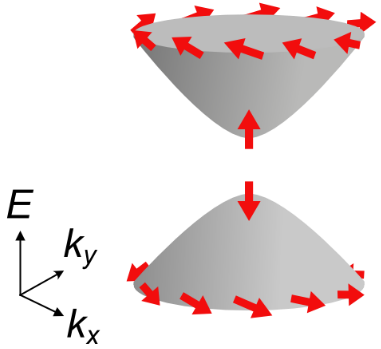


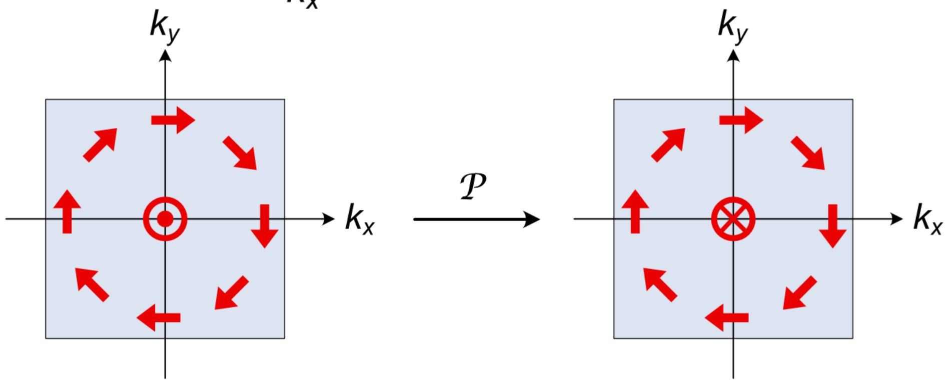
$$\mathcal{P}(\sigma_x, \sigma_y, \sigma_z)\mathcal{P}^{-1} = (\sigma_x, -\sigma_y, -\sigma_z)$$

$$\mathcal{P}H_0(-k_x, k_y)\mathcal{P}^{-1} = H_0(k_x, k_y)$$

Massive Dirac fermion

$$H_m(k_x, k_y, m) = \hbar(\sigma_x k_y - \sigma_y k_x) + m\sigma_z$$





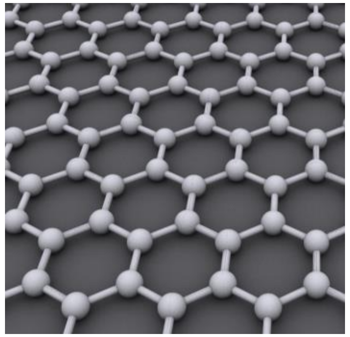
$$\mathcal{P}H_m(-k_x, k_y, m)\mathcal{P}^{-1} = H_m(k_x, k_y, -m) \neq H_m(k_x, k_y, m)$$

Parity and time-reversal symmetries are broken

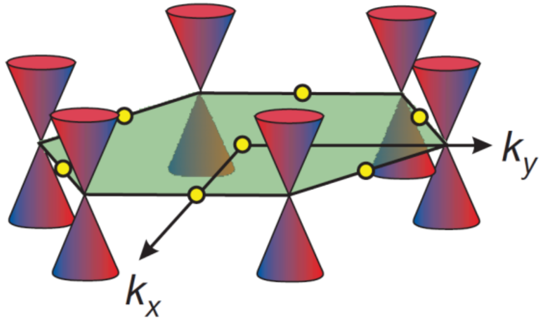
Dirac fermions “in pairs”

2D lattices

Graphene



wikipedia



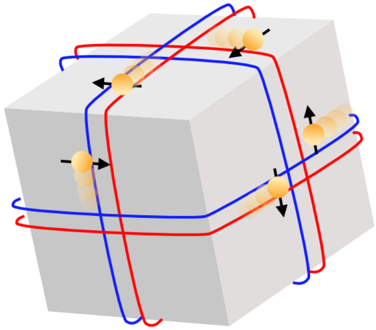
Dirac cones must be in pairs

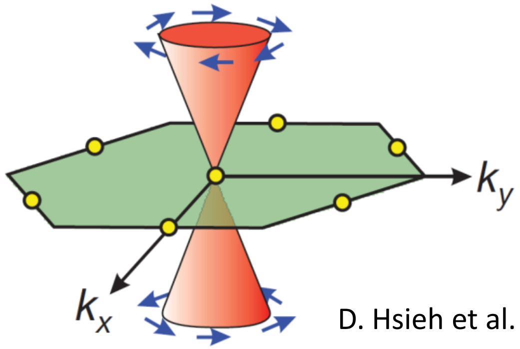
⇔ fermion doubling theorem

⇒ Parity anomaly is cancelled out

N. B. Nielsen, M. Ninomiya, Nucl. phys. **B185**, 20 (1981).

3D TI





D. Hsieh et al. Nature (2009)

“Single” Dirac cone at each surface

by Z_2 topological nature in **3D** bulk

L. Fu, C. L. Kane, E. J. Mele, PRL **98**, 106803 (2007).

Proposals for half-quantization in 3D TI

PHYSICAL REVIEW B **76**, 045302 (2007)

Topological insulators with inversion symmetry

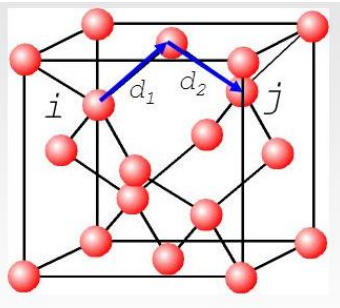
Liang Fu and C. L. Kane
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
(Received 14 November 2006; revised manuscript received 17 January 2007; published 2 July 2007)

The surface of the strong topological insulator is thus unique in that it can generate a single Dirac fermion *without* violating time-reversal symmetry and, in principle, exhibits the half quantized quantum Hall effect.

Layer-resolved Hall conductivity calculation

$$H_{\rm FKM} = \sum_{\langle ij\rangle} t_{ij} c_i^\dagger c_j + i\frac{4\lambda_{\rm SO}}{a^2}\sum_{\langle\langle ij\rangle\rangle} c_i^\dagger \boldsymbol{\sigma}\cdot(\boldsymbol{d}_{ij}^1\times\boldsymbol{d}_{ij}^2)c_j$$
$$+\ \boldsymbol{h}\cdot\left(\textstyle\sum_{i\in A} c_i^\dagger\boldsymbol{\sigma}c_i - \sum_{i\in B} c_i^\dagger\boldsymbol{\sigma}c_i\right)$$

Essin, Moore, Vanderbilt, PRL (2009)



diamond lattice

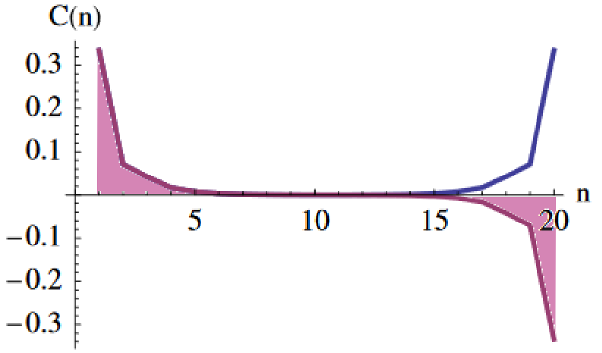
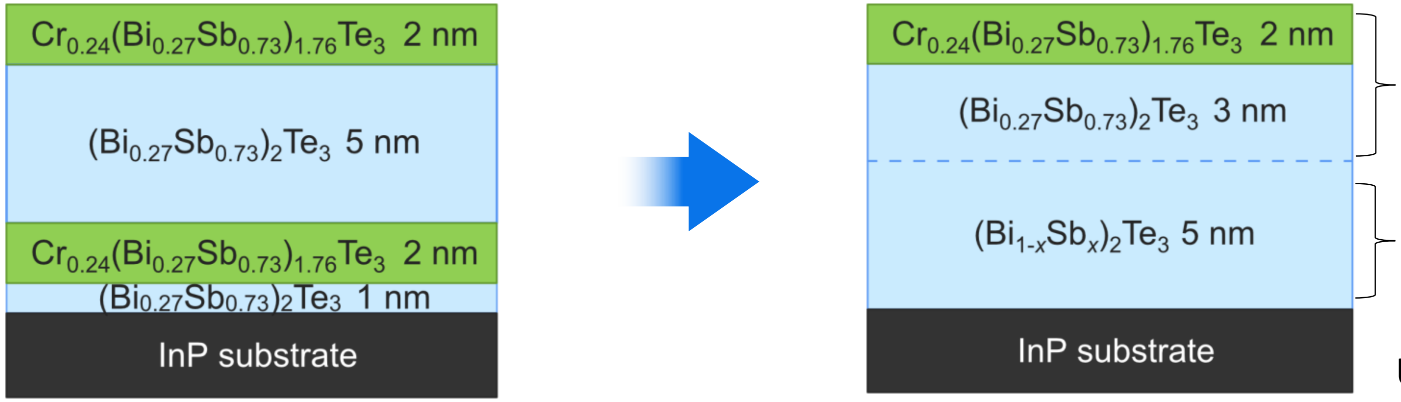


FIG. 2 (color online). The layer-resolved Hall conductivity (in units of e^2/h) at $\beta = \pi$ in a slab of 20 layers, with $m = t/2$ and $\lambda_{SO} = t/4$, terminated in $(\bar{1}11)$ planes.

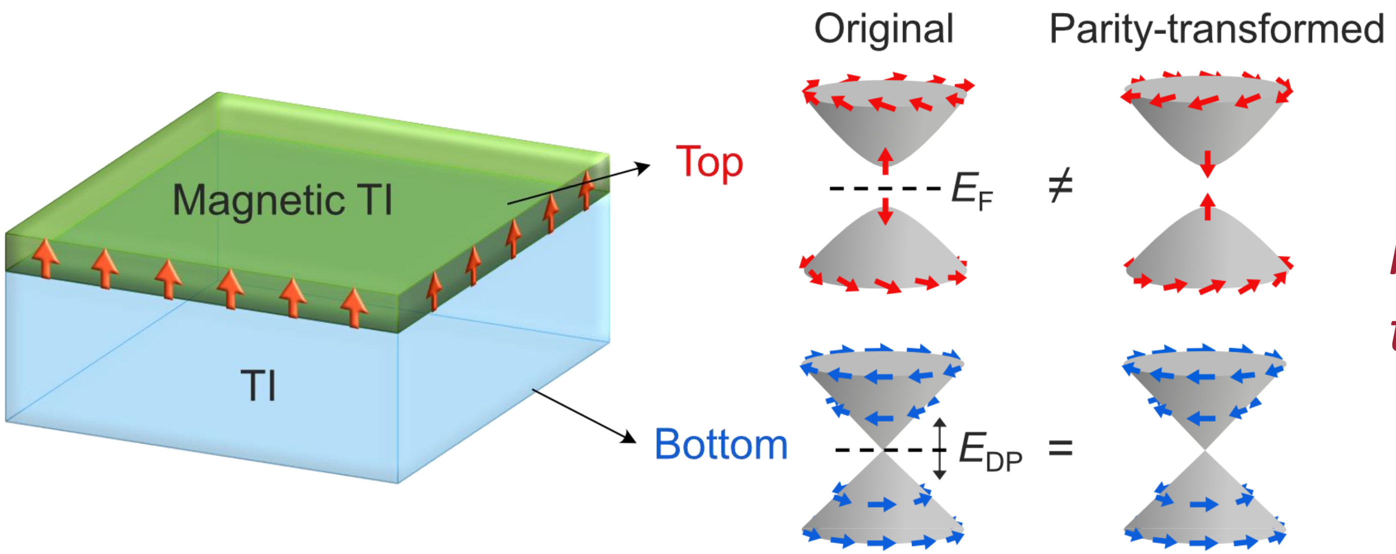
Parity anomaly in semi-magnetic TI



QAH composition

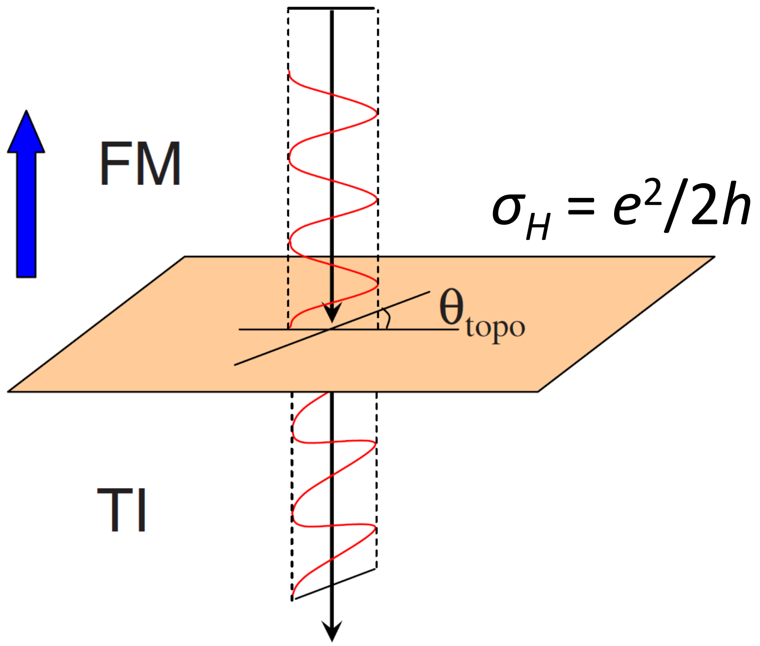
E_F within bulk gap

Updated from R. Yoshimi, K. Yasuda et al. Nat. Commun. (2015)



How to measure only the top surface contribution?

Quantization of magneto-optical effects



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

$\hbar\omega \ll 2|m|$: exchange gap (> 10 meV)

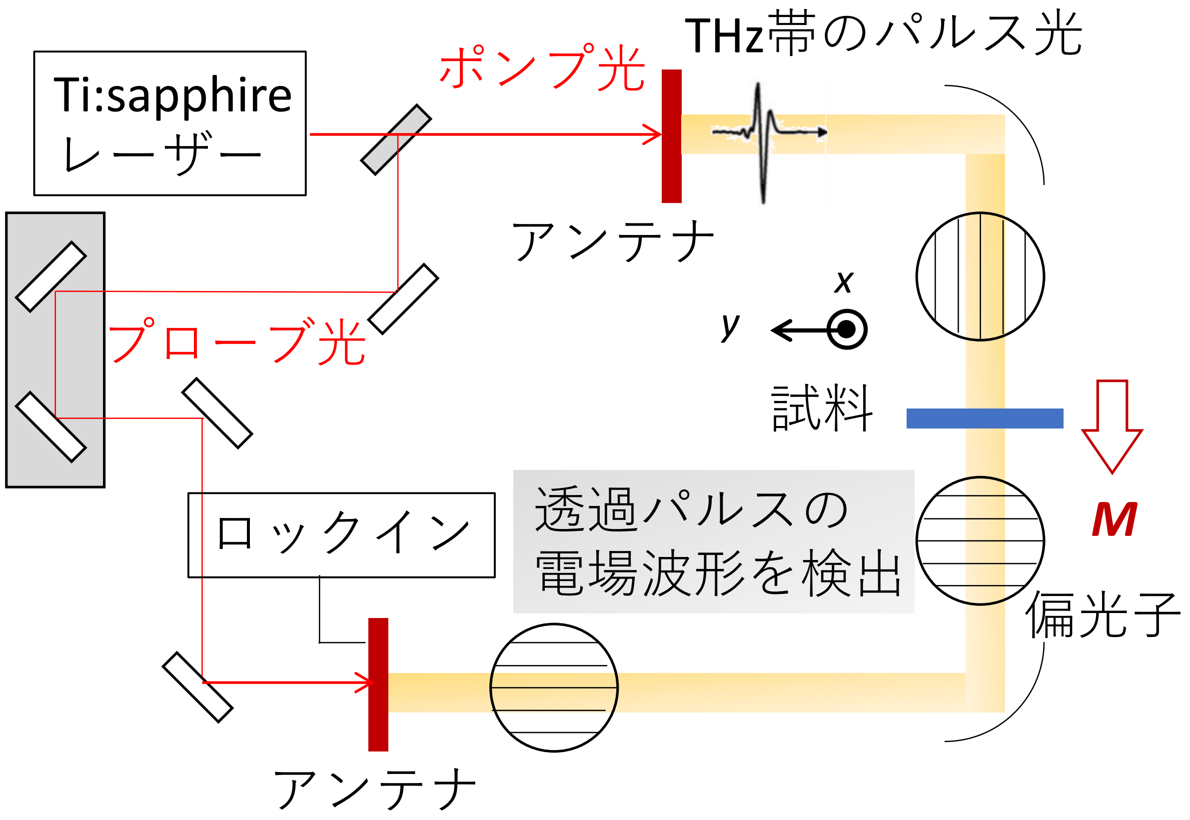
$$\begin{cases} \hat{n} \times (\boldsymbol{E}_{\mathrm{TI}} - \boldsymbol{E}_{\mathrm{vac}}) = 0 \\ \hat{n} \times (\boldsymbol{H}_{\mathrm{TI}} - \boldsymbol{H}_{\mathrm{vac}}) = \boldsymbol{j}_{\mathrm{Hall}} = \sigma_H \boldsymbol{E}_{\mathrm{TI}} \end{cases}$$

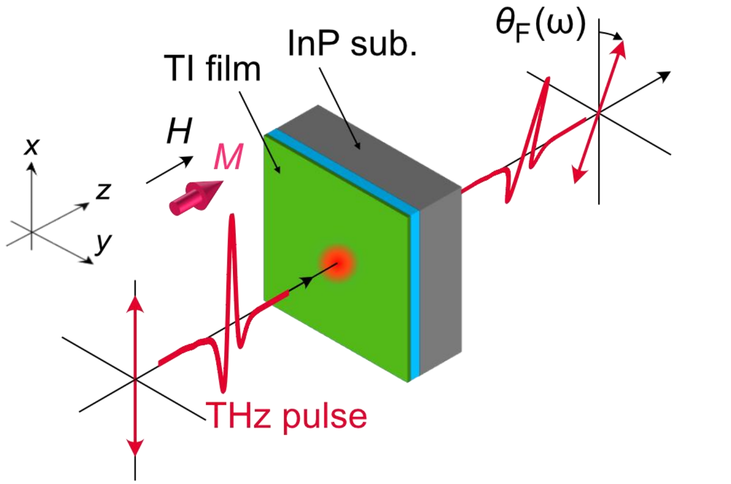
$$\theta_{\mathrm{F}} = \tan^{-1}\frac{\alpha}{1+n_{\mathrm{TI}}} \approx \frac{\alpha}{1+n_{\mathrm{TI}}}$$

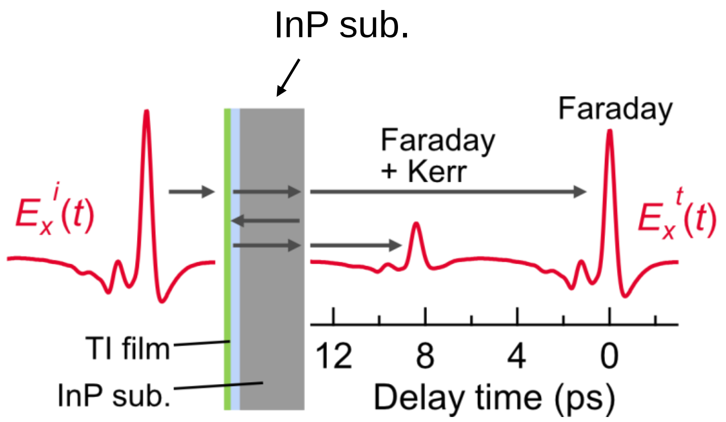
$$\left(\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}\right)$$

Time-domain THz magneto-optical spectroscopy

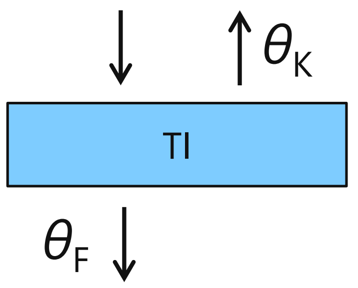
東大物工　高橋研究室との共同研究







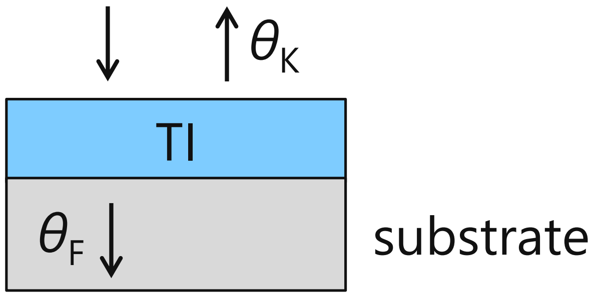
Geometries for Faraday & Kerr measurements



$$\theta_{\mathrm{F}} = \alpha(\nu_{\mathrm{T}} + \nu_{\mathrm{B}})$$

$$\theta_{\mathrm{K}} = \pi/2$$

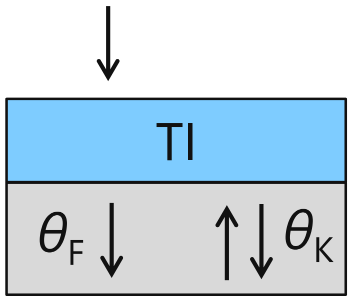
W.-K. Tse, A. H. MacDonald,
PRL **105**, 057401 (2010).



$$\theta_{\mathrm{F}} = \frac{2\alpha(\nu_{\mathrm{T}} + \nu_{\mathrm{B}})}{1 + n_{\mathrm{s}}}$$

$$\theta_{\mathrm{K}} = \frac{4\alpha(\nu_{\mathrm{T}} + \nu_{\mathrm{B}})}{{n_{\mathrm{s}}}^2 - 1}$$

J. Macicjko et al.,
PRL **105**, 166803 (2010).



σ_{xy} = $\boldsymbol{\nu}_{\mathbf{T}} e^2/h$

σ_{xy} = $\boldsymbol{\nu}_{\mathbf{B}} e^2/h$

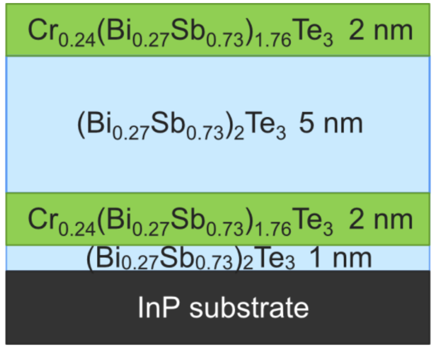
$$\theta_{\mathrm{F}} = \frac{2\alpha(\boldsymbol{\nu_T} + \boldsymbol{\nu_B})}{1 + n_{\mathrm{s}}}$$

$$\theta_{\mathrm{K}} = \frac{4n_{\mathrm{s}}\alpha(\boldsymbol{\nu_T} + \boldsymbol{\nu_B})}{{n_{\mathrm{s}}}^2 - 1}$$

present study

InP substrate: n_s = 3.46

Quantized Faraday & Kerr rotations from QAHE



Updated from K. N. Okada, Y. Takahashi, M. Mogi *et al.*, Nat. Commun. **7**, 12245 (2016).

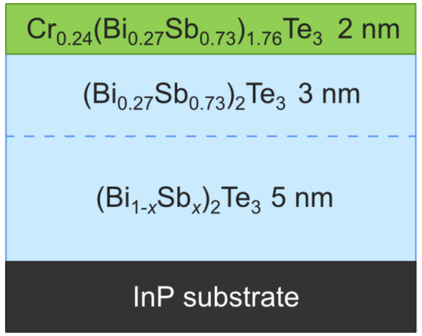
非公開

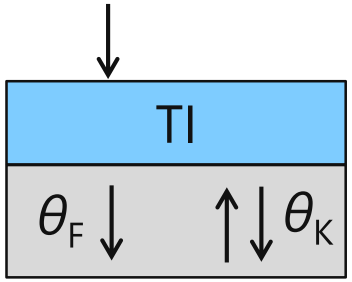
Related studies
GaAs, Graphene: Shimano group
3DTI: Armitage group, Molenkamp group
(QHE states under magnetic fields)

$$\theta_{\mathrm{F}} = \frac{2\alpha(1/2+1/2)}{1+n_{\mathrm{s}}} = 3.26\ \mathrm{mrad}$$

$$\theta_{\mathrm{K}} = \frac{4n_{\mathrm{s}}\alpha(1/2+1/2)}{{n_{\mathrm{s}}}^2-1} = 9.21\ \mathrm{mrad}$$

Half quantized magneto-optical rotations





$$\sigma_{xy} = \boldsymbol{\nu_T} e^2/h$$

$$\sigma_{xy} = \boldsymbol{\nu_B} e^2/h$$

$$\theta_F = \frac{2\alpha(\boldsymbol{\nu_T} + \boldsymbol{\nu_B})}{1 + n_s}$$

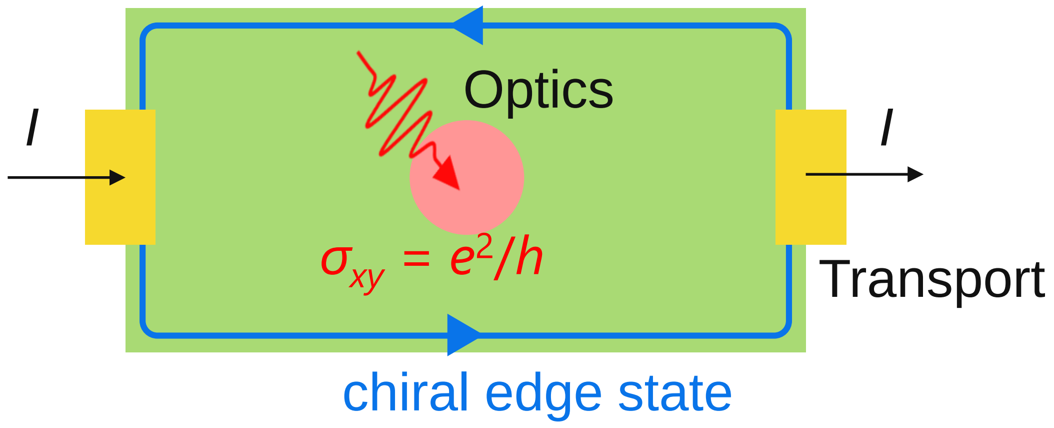
$$\theta_K = \frac{4 n_s \alpha(\boldsymbol{\nu_T} + \boldsymbol{\nu_B})}{{n_s}^2 - 1}$$

What about at zero-frequency limit (dc transport)?

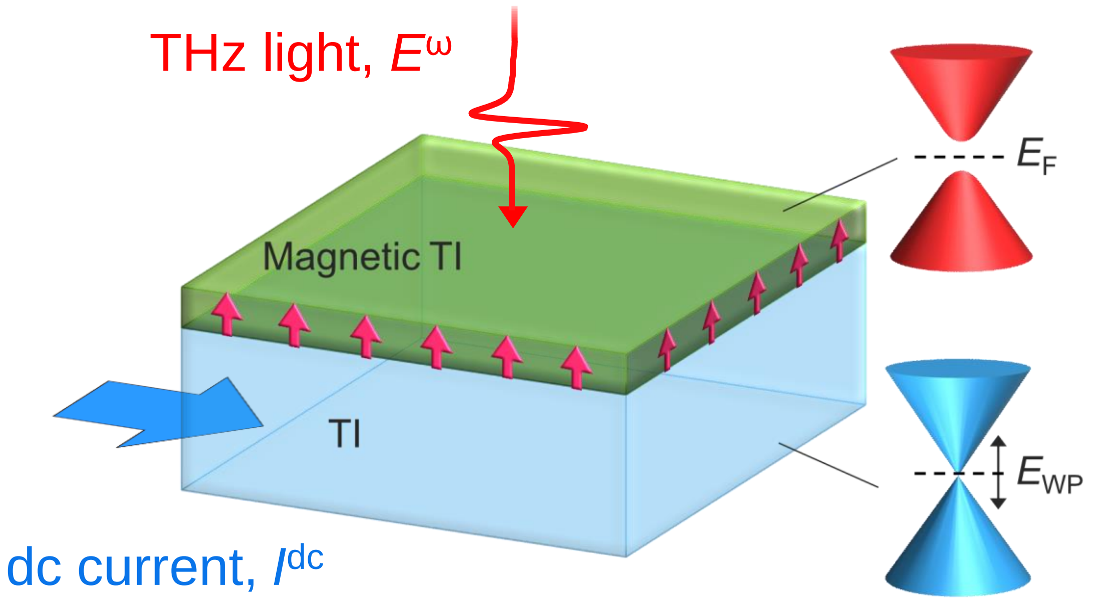
非公開

Comparison: magneto-optics and transport

QAH insulator



Semi-magnetic TI



Experimental confirmation of bulk (optics) – edge/surface (transport) correspondence

Half-integer quantization in transport

非公開

$J = \sigma E$

$\sigma = \rho^{-1}$

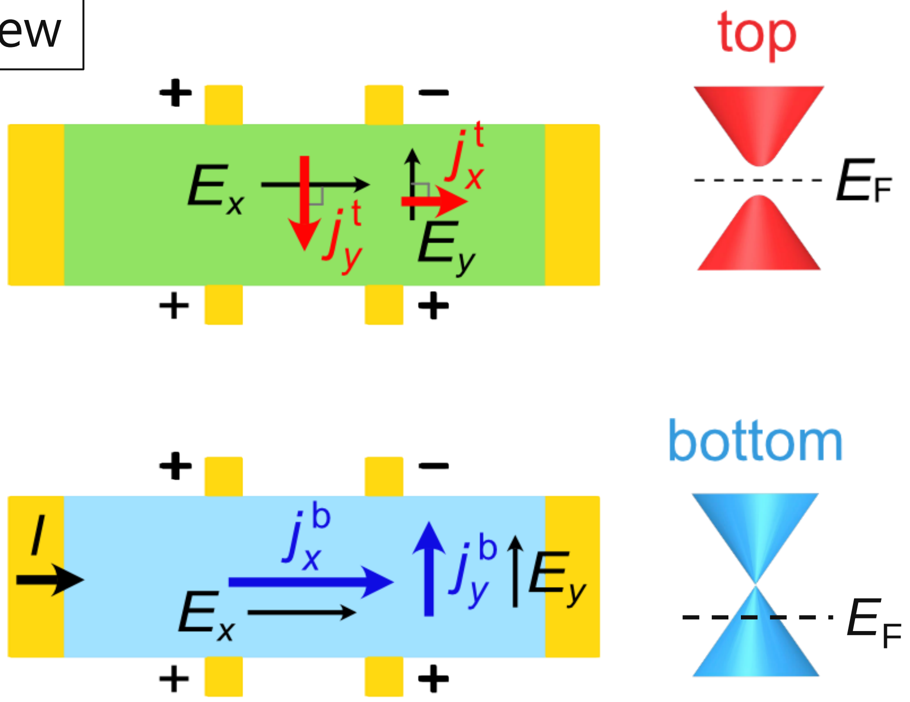
非公開

Current distribution of half-quantized state

top view

$\sigma_{xy}{}^{t} = e^2/2h$
$\sigma_{xx}{}^{t} = 0$

$\sigma_{xy}{}^{b} = 0$
$\sigma_{xx}{}^{b} \neq 0$



$$j_y^{\mathrm{t}} + j_y^{\mathrm{b}} = 0$$

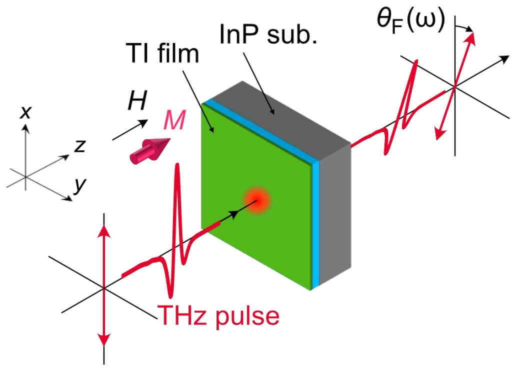
$$I = (j_x^{\mathrm{t}} + j_x^{\mathrm{b}})W$$

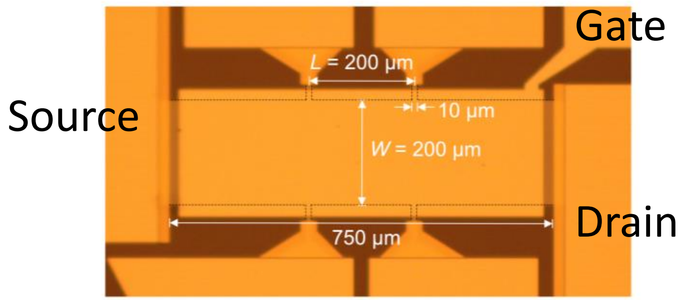
Bottom surface j^{b} causes dissipation (voltage)

$$\rho_{xx}^{\mathrm{meas}} = E_x/(I/W)$$
$$\rho_{yx}^{\mathrm{meas}} = E_y/(I/W)$$

$$\sigma_{xy}^{\mathrm{meas}} = \frac{\rho_{yx}^{\mathrm{meas}}}{(\rho_{xx}^{\mathrm{meas}})^2 + \left(\rho_{yx}^{\mathrm{meas}}\right)^2} = \sigma_{xy}^{\mathrm{t}} = \frac{e^2}{2h}$$, irrespective of σ_{xx}^{b}

Summary of our findings





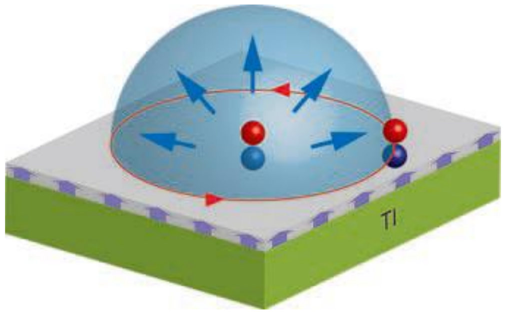
非公開

- Our THz magneto-optical measurement directly and firstly demonstrates the half quantization
- Well defined Hall bars allow highly accurate conversion to conductance
- Quantitatively consistent data of THz and transport certify the bulk-surface correspondence

M. Mogi et al. under review

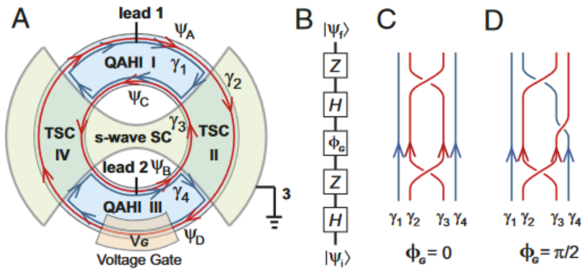
展望

分数電気磁気応答による磁気単極子像
（Witten効果)

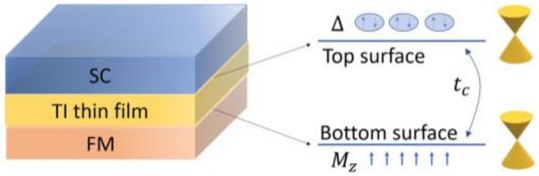


X.-L. Qi et al.
Science (2009)

カイラルマヨラナフェルミオンモード
を利用した量子コンピューティング



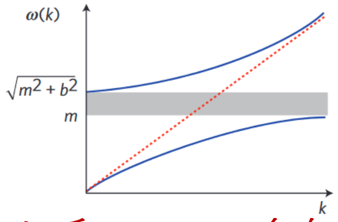
B. Lian et al. PNAS (2018)



J.J. He et al. Commun. Phys. (2019)

アクシオンダイナミクス (dθ/dt項)

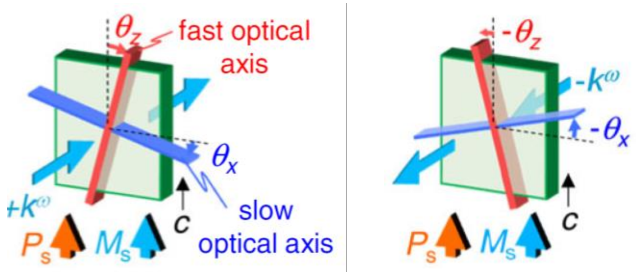
- 反強磁性トポロジカル絶縁体



例: $MnBi_2Te_4$

R. Li et al.
Nat. Phys. (2010)

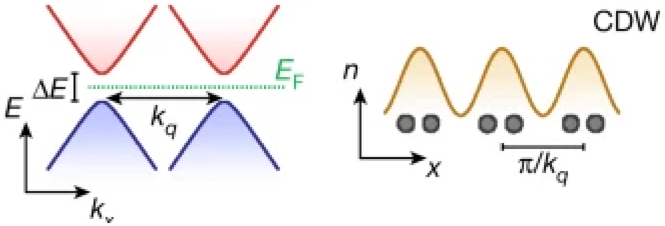
- マルチフェロイクス、エレクトロマグノン



例: $(Fe,Zn)_2Mo_3O_8$

T. Kurumaji et al.
PRL (2017)

- 電荷密度波とワイル半金属の相関



例: $(TaSe_4)_2I$

J. Gooth et al.
Nature (2019)