Recent progress of 2D topological insulators in both experiments and theories

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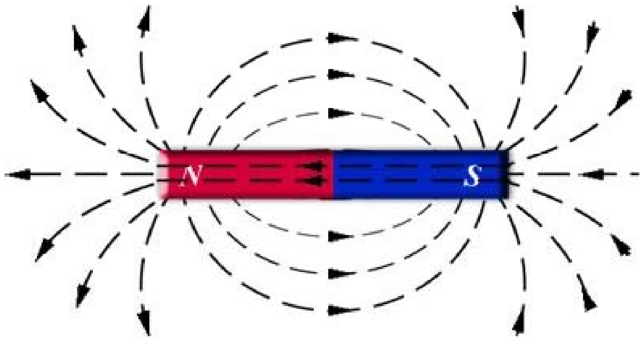
Outline

- Background
  - The family of Hall effects
- 2D topological insulators in theories and experiments
  - Quantum Wells type
  - Graphene type
  - 2D limit from 3D topological insulators
- Outlook
- Summary

New states of matter in condensed matter physics

We have known many kinds of fundamental states of matter, including metals, insulators, superconductors, magnets,…
And most of them can be differentiated by breaking symmetries.

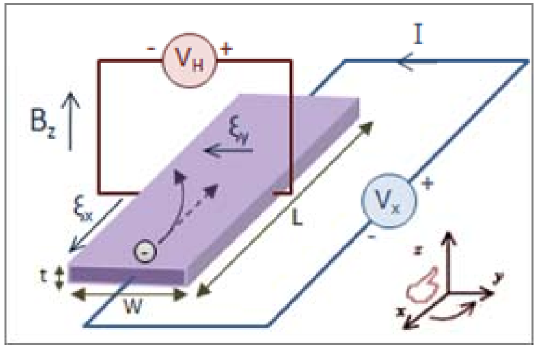


Crystal: break the translation symmetry

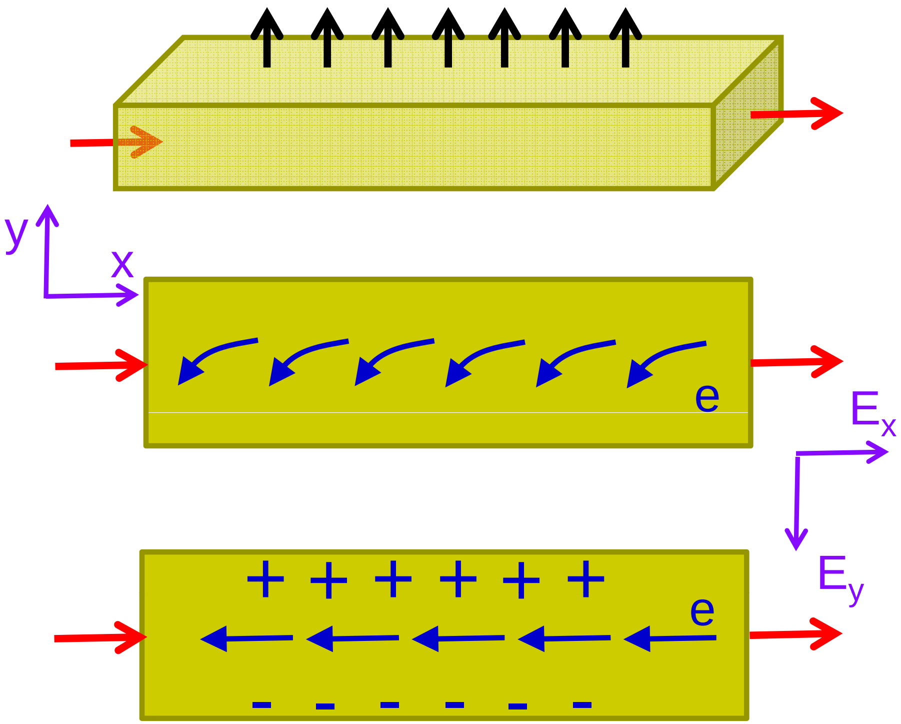
Superconductors: break the U(1) gauge symmetry

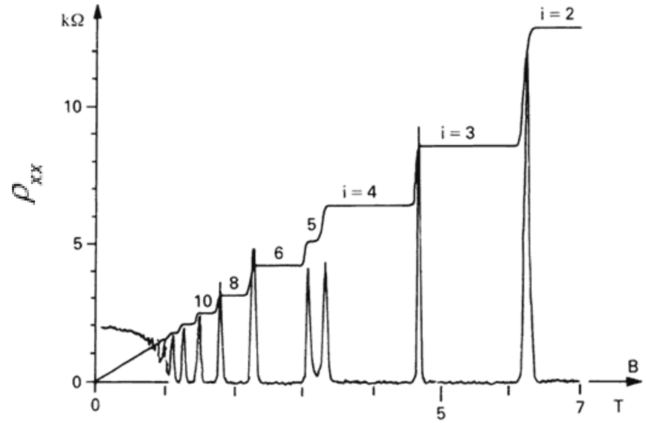
Magnets: break the rotation symmetry

The Hall effect and quantum Hall effect



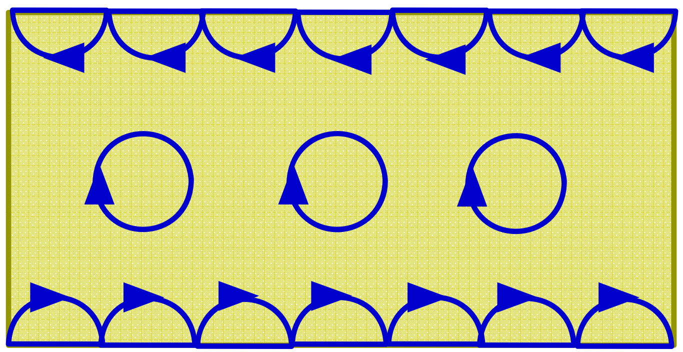
$$R_H = \frac{E_y}{j_x B}$$



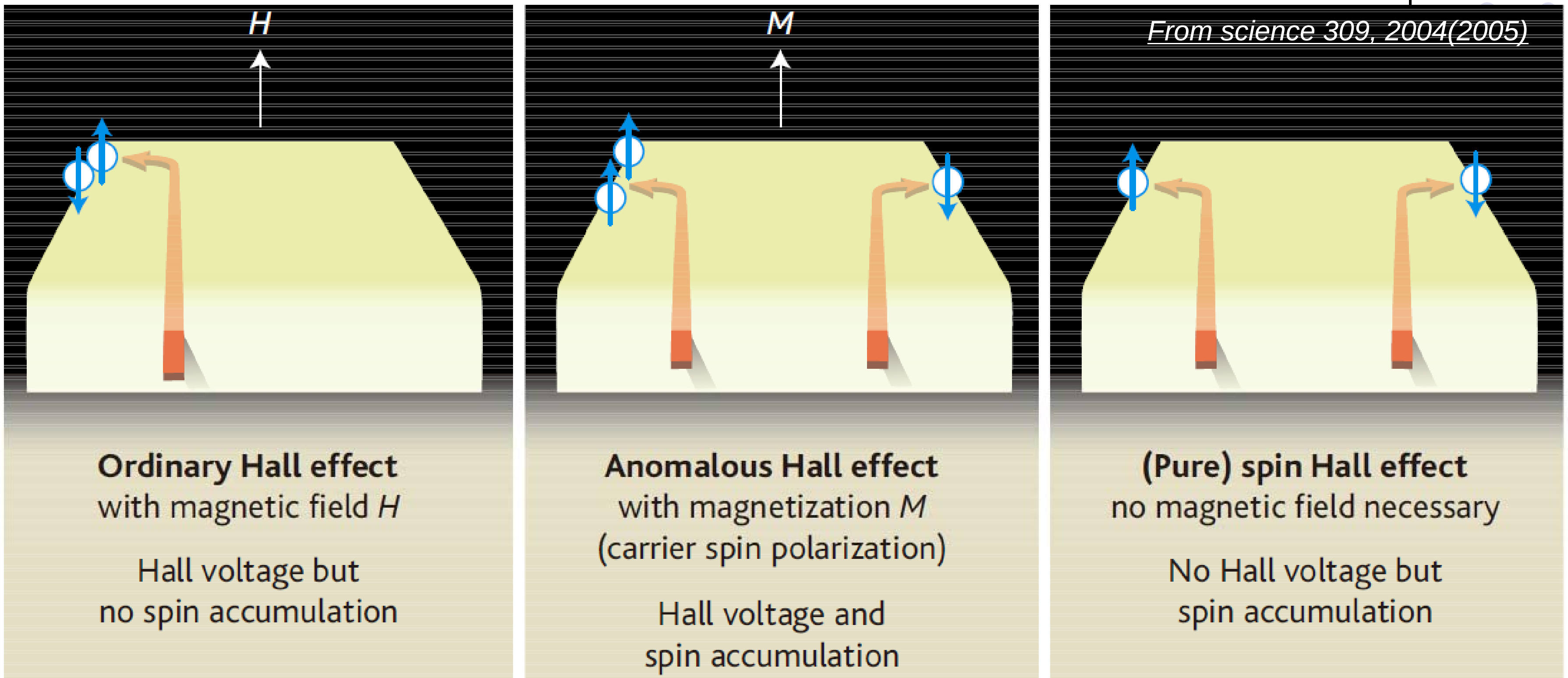


$$\sigma = \nu \frac{e^2}{h}$$

In mathematics, known as the first Chern number, related to Berry's phase.



The family of Hall effects



Quantum Hall effect 1980

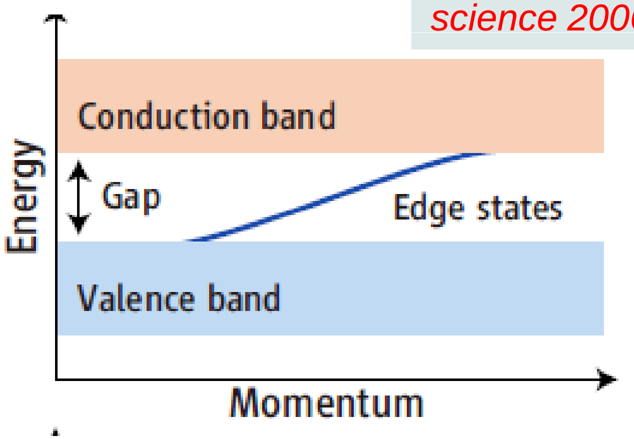
Quantum Anomalous Hall effect 2013

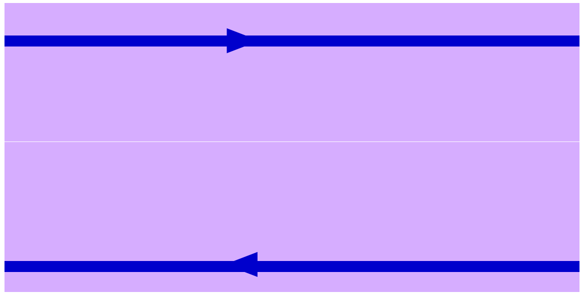
Quantum Spin Hall effect 2007

The quantum anomalous Hall (QAH) states

✓No external magnetic field

science 2006

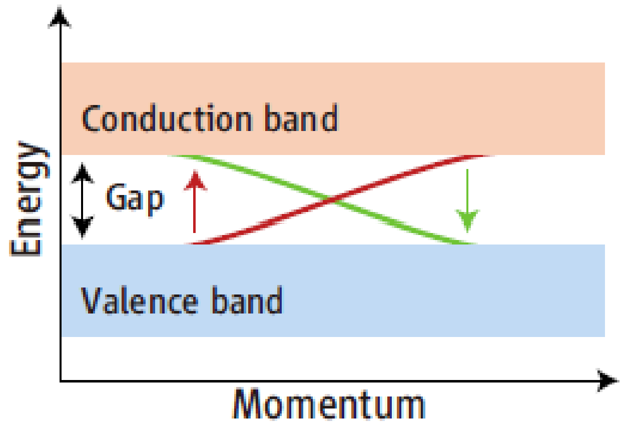




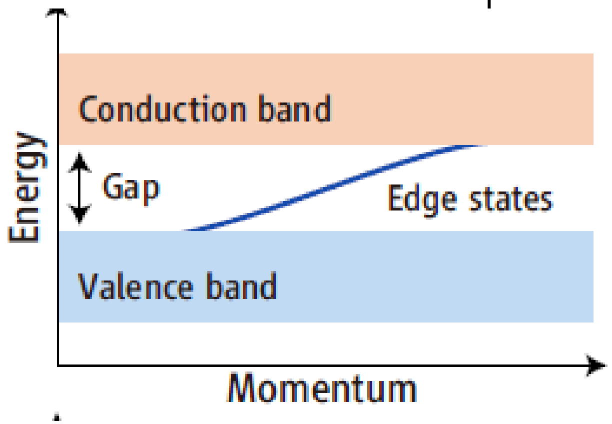
Dissipationless charge current!

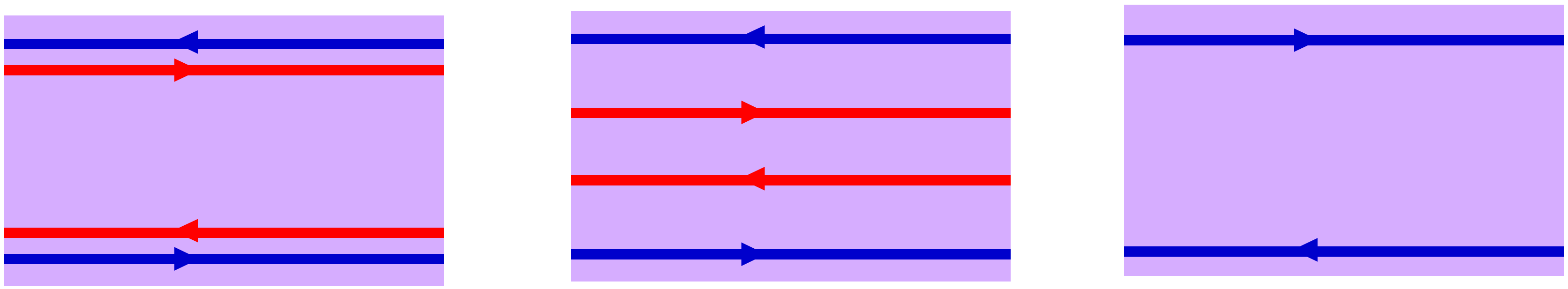
In QAH systems, electrons move just like cars on a highway!

QAH states could get born in quantum spin Hall (QSH) states



Time reversal symmetry breaking



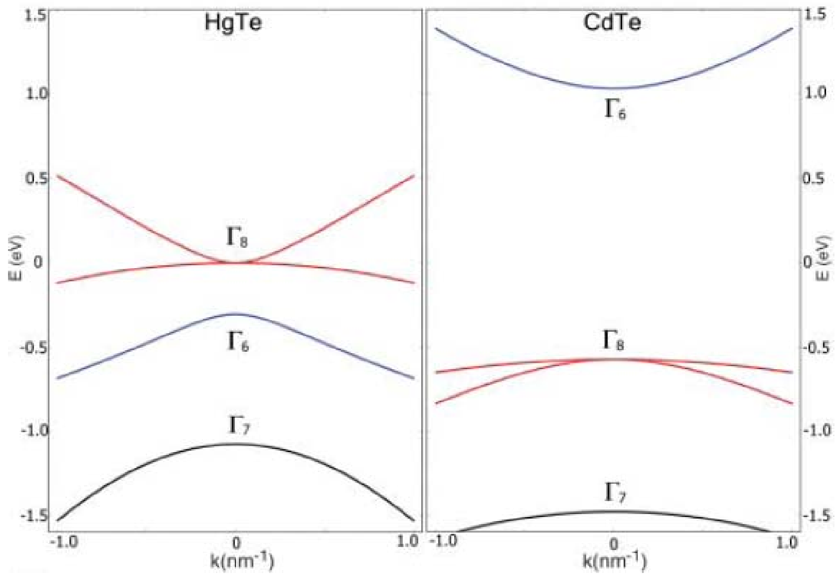


Time reversal symmetry

Time reversal Symmetry breaking

2D topological insulators in quantum Wells

HgTe/CdTe Quantum Wells

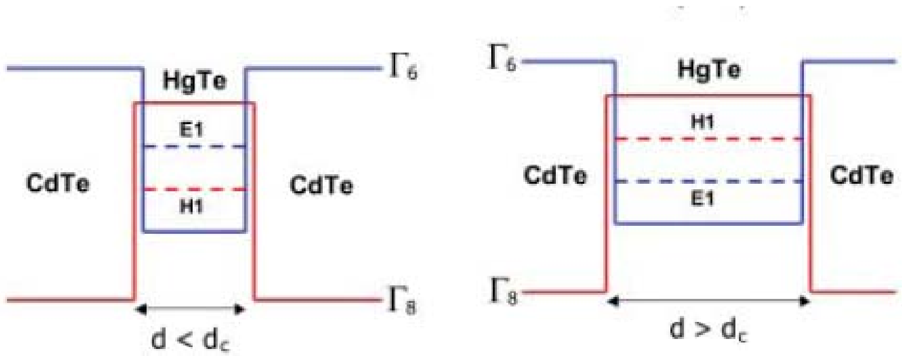


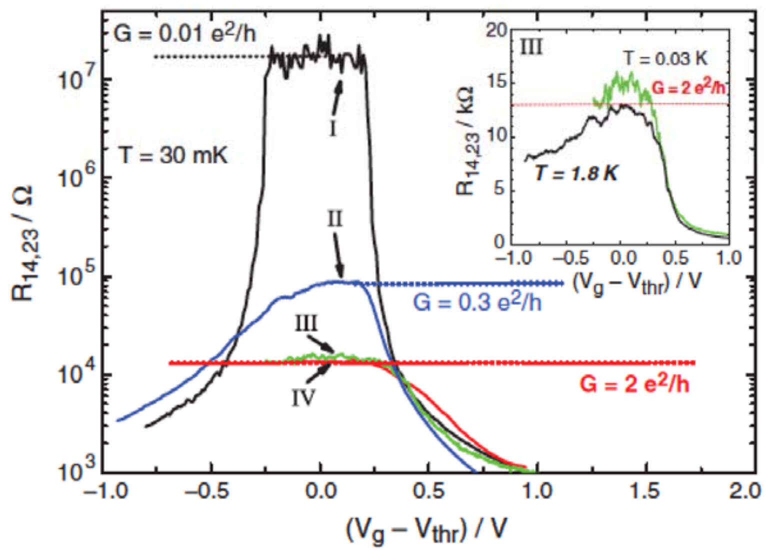
$$H_{\rm eff}(k_x, k_y) = \begin{pmatrix} H(k) & 0 \\ 0 & H^*(-k) \end{pmatrix},$$

$$H(k) = \varepsilon(k) + d_i(k)\sigma_i \qquad (2)$$

$$|E1, m_J = 1/2\rangle, |H1, m_J = 3/2\rangle,$$

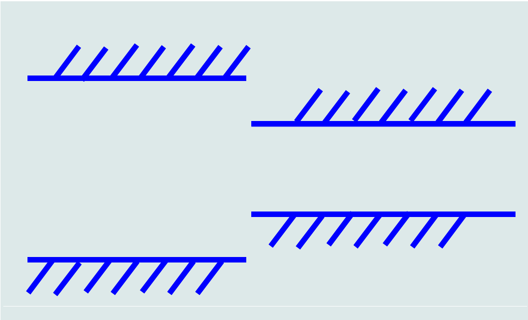
$$|E1, m_J = -1/2\rangle, |H1, m_J = -3/2\rangle$$

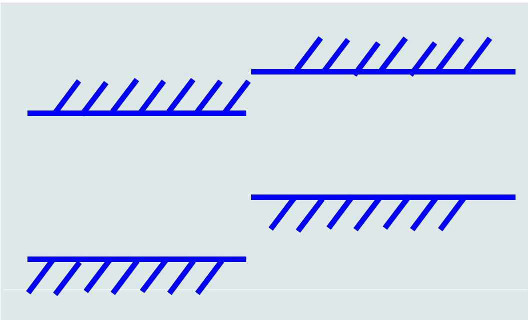


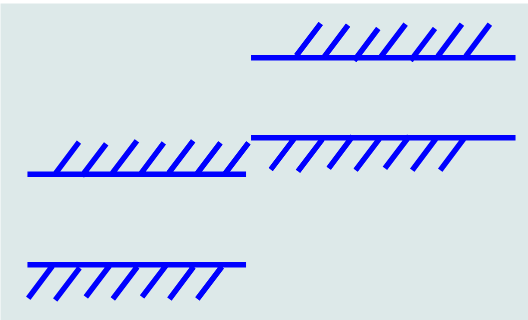


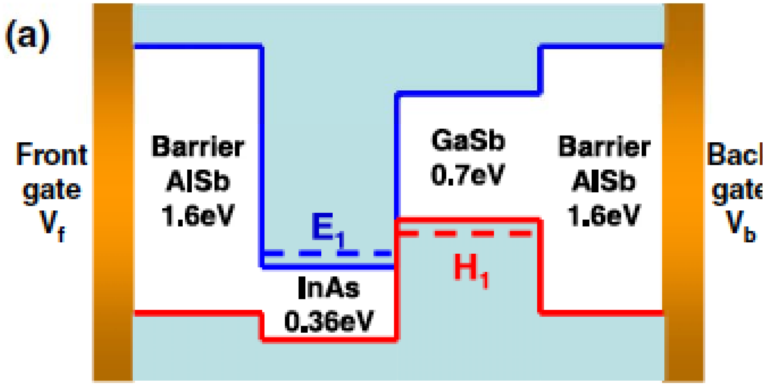
Bernevig et al. Science 2006; Markus et al. Science 2007

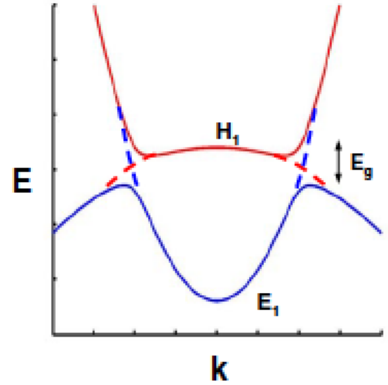
Type-II quantum wells

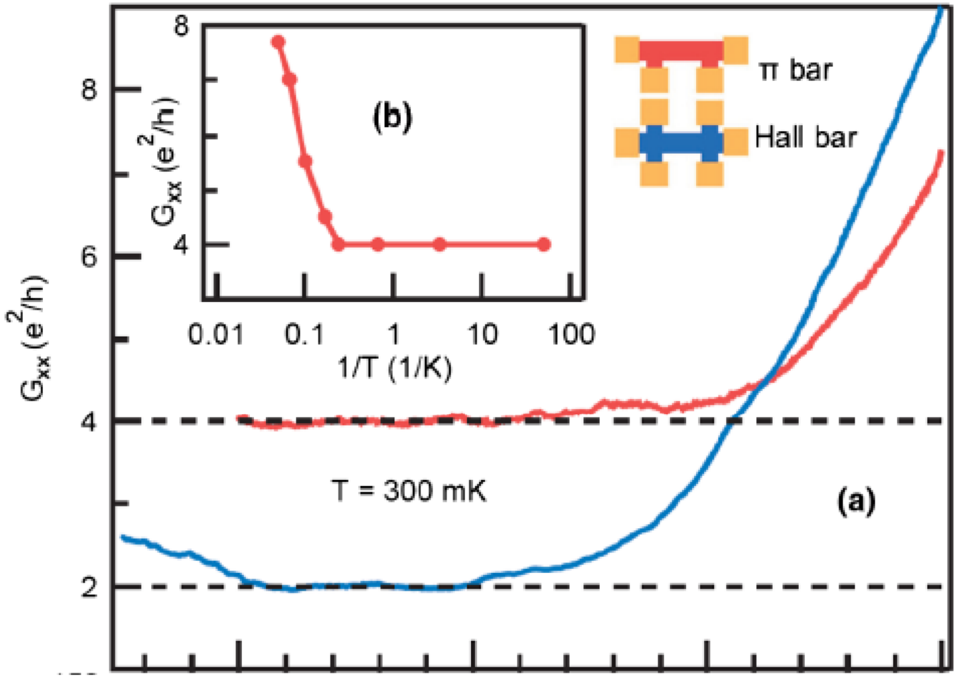






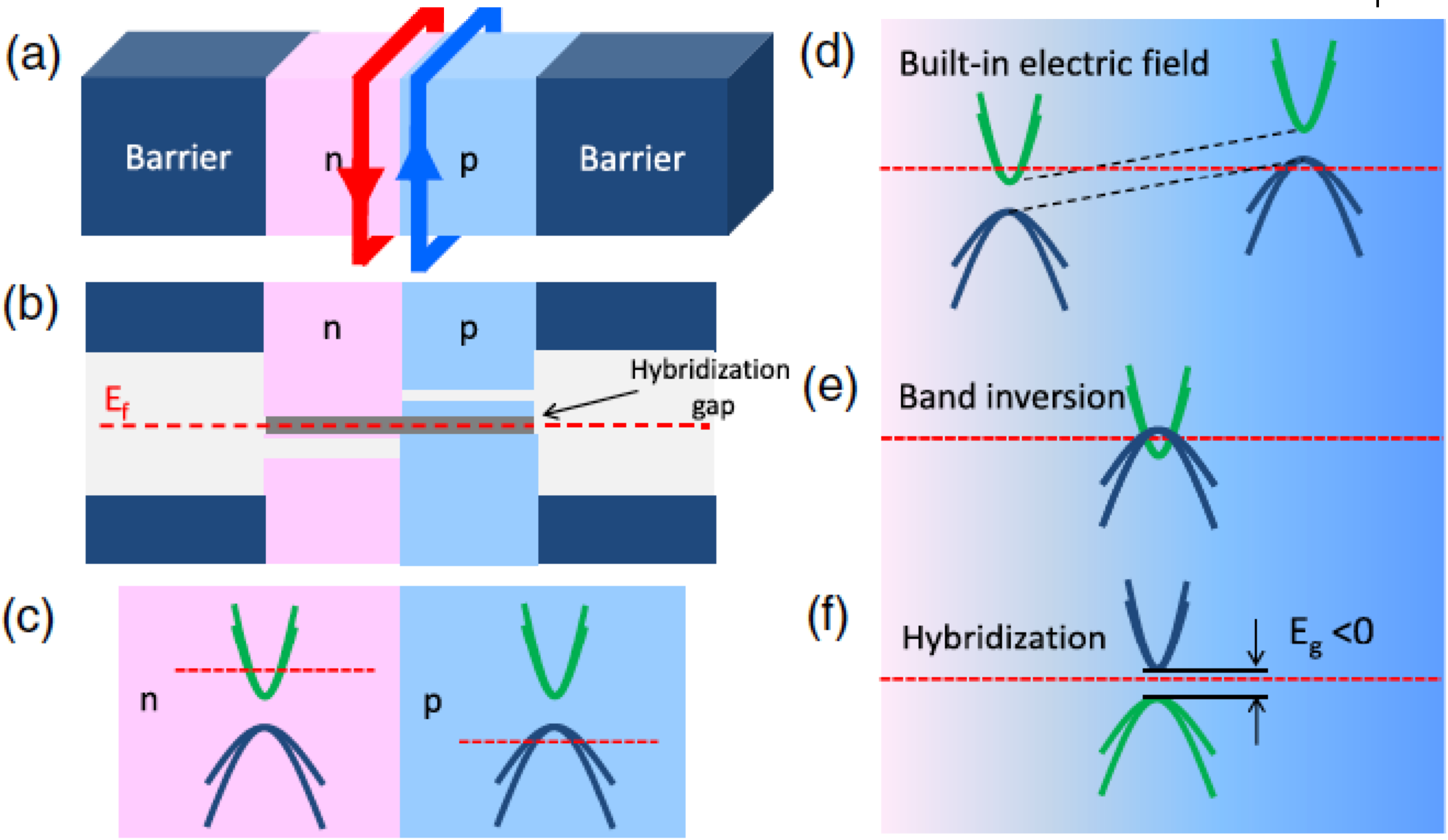






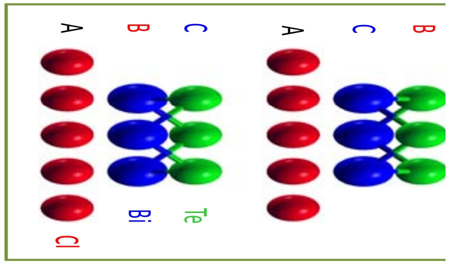
Liu et al. PRL 2008; Du et al. PRL 2013

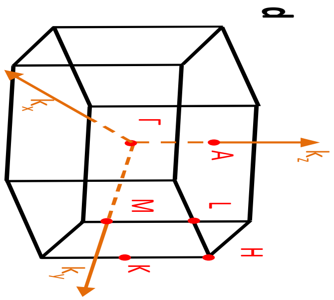
pn doping to make type-II quantum Wells

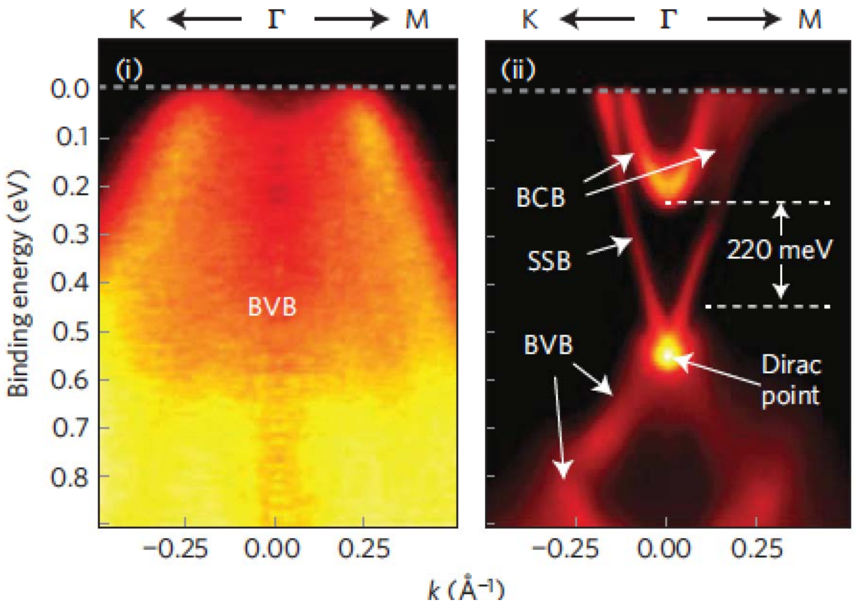


Zhang et al. PRL 2014

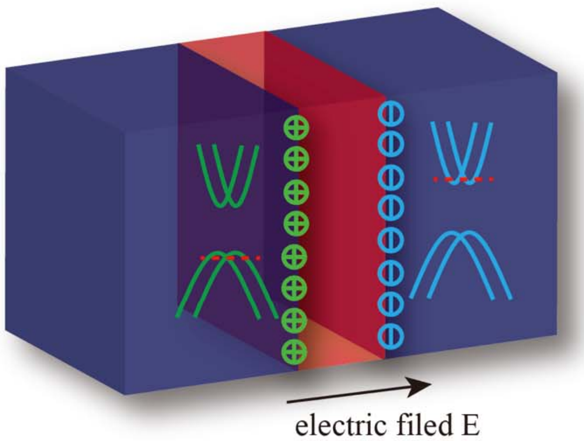
Polar quantum Wells

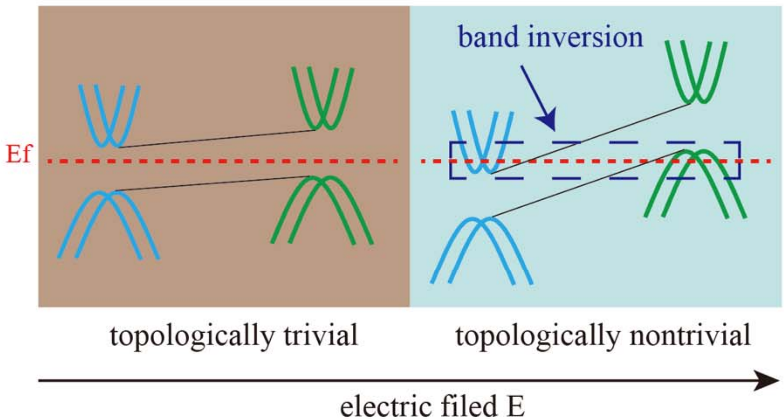






Chen et al. Nature Physics 2013





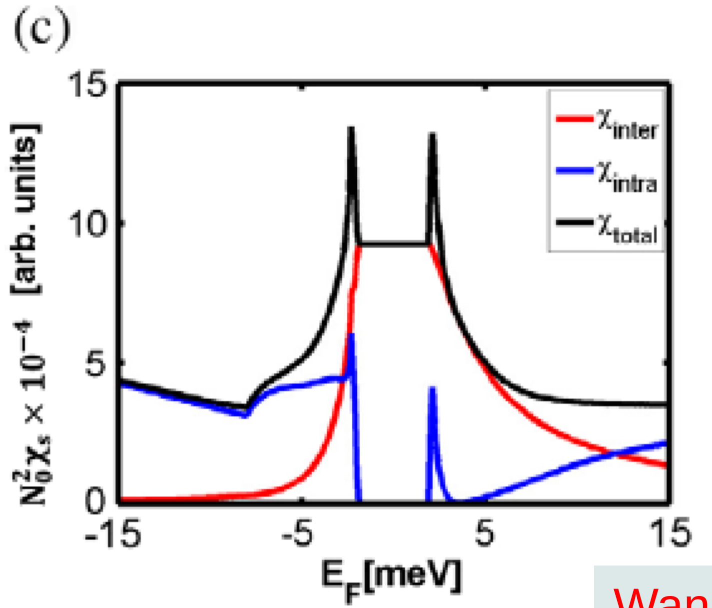
Be prepared

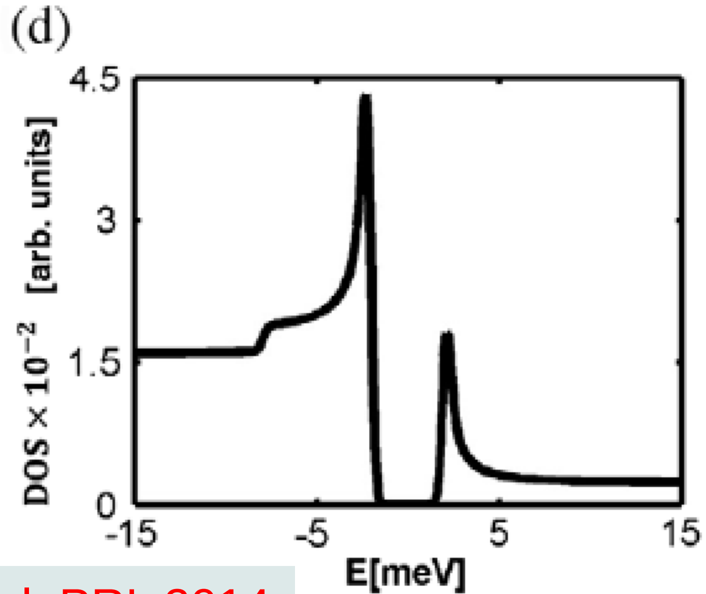
Magnetic doping in type-II quantum Wells

$$H = H_0 + H_{\mathrm{BIA}} + H_{\mathrm{SIA}} + H_{\mathrm{ex}}.$$

$$H_{\mathrm{ex}} = \sum_{\vec{R}_n} \mathbf{S}_M(\vec{R}_n) \cdot \tilde{\mathbf{s}},$$

$$\tilde{\chi}_s = \lim_{q\to 0} \mathrm{Re}\left[\sum_{i,j,\sigma,\sigma',\vec{k}} \frac{|\langle u_{i\sigma,\vec{k}}|\tilde{s}|u_{j\sigma',\vec{k}+\vec{q}}\rangle|^2 [f_{i\sigma}(\vec{k}) - f_{j\sigma'}(\vec{k}+\vec{q})]}{E_{j\sigma'}(\vec{k}+\vec{q}) - E_{i\sigma}(\vec{k}) + i\Gamma} \right]$$

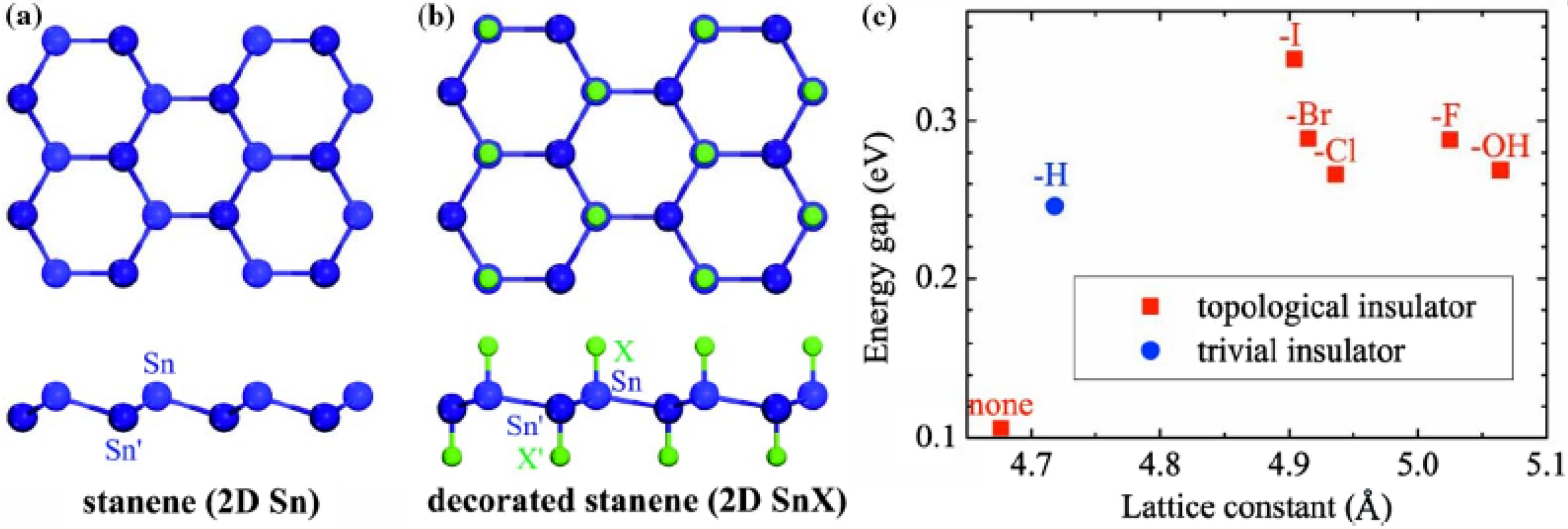


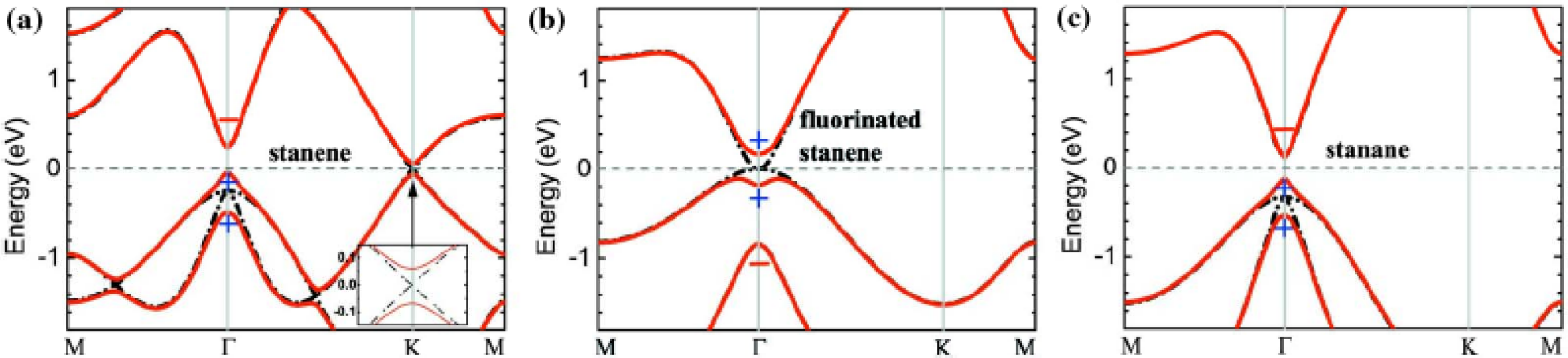


Wang et al. PRL 2014

2D topological insulators in Graphene type compounds

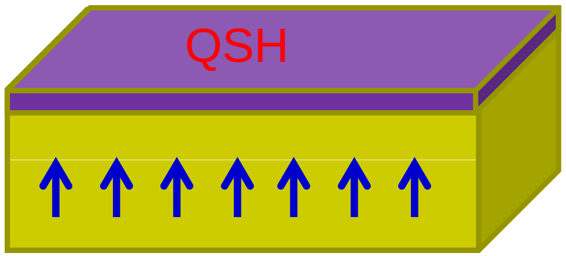
Graphene-type QSH states



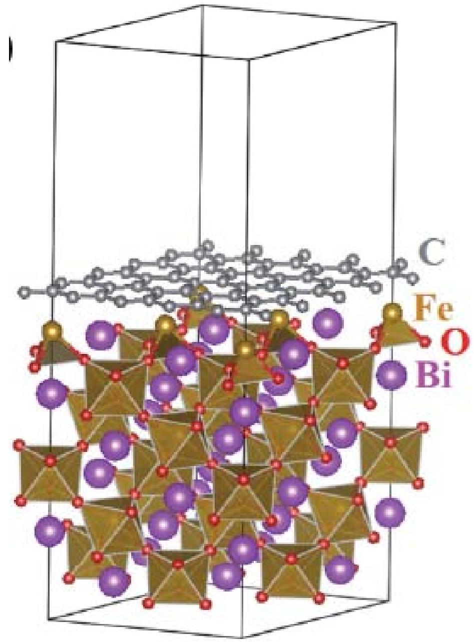


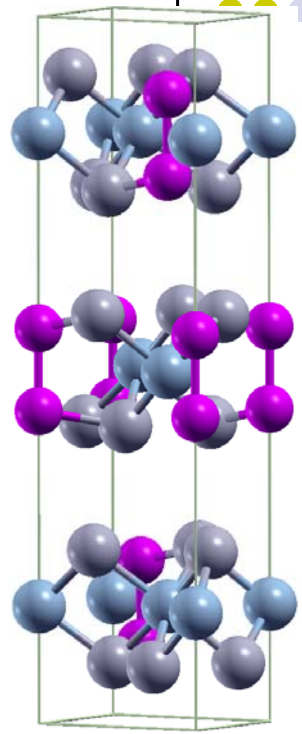
Xu et al. PRL 2013

Magnetic proximity in Graphene-type QSH states



FM insulators
Or
AFM insulators





Difficulty:
1)Out of plane magnetic moment at the interface
2)Strong magnetic proximity
3)Charge transfer

$BiFeO_3$
Multiferroic materials
G-type antiferromagnet
T_N=653K

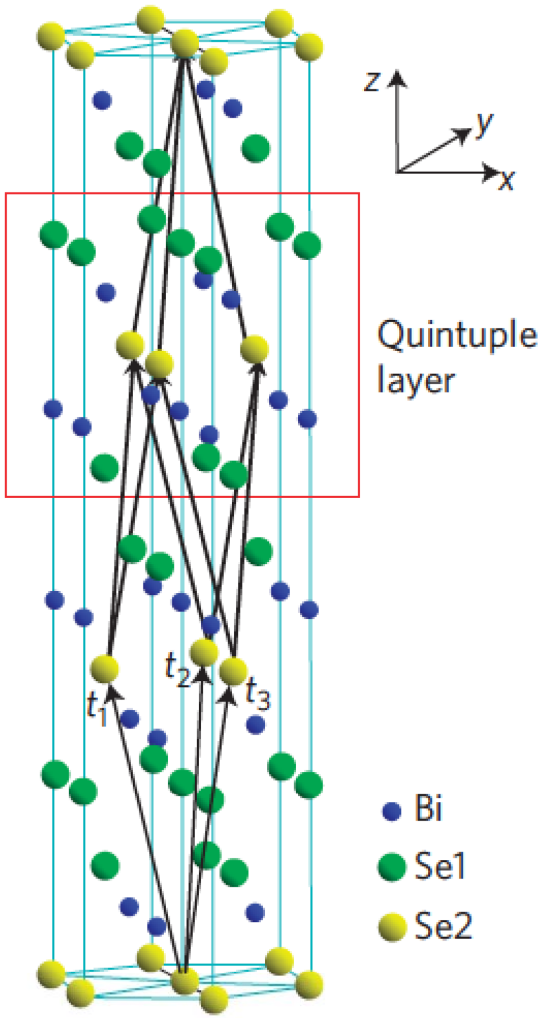
Qiao et al. PRL 112, 116404 (2014)

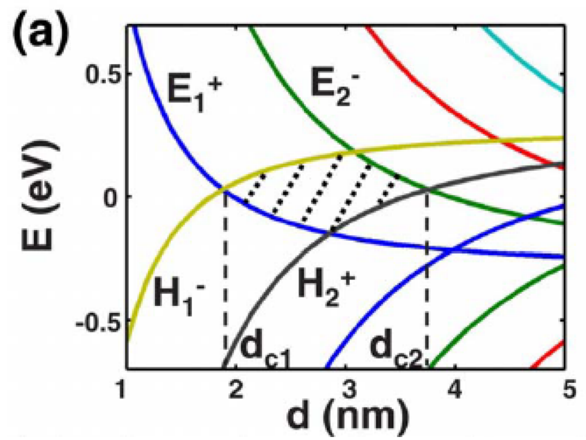
$CrGeTe_3$
Ferromagnetic Insulator.
Out of plane.

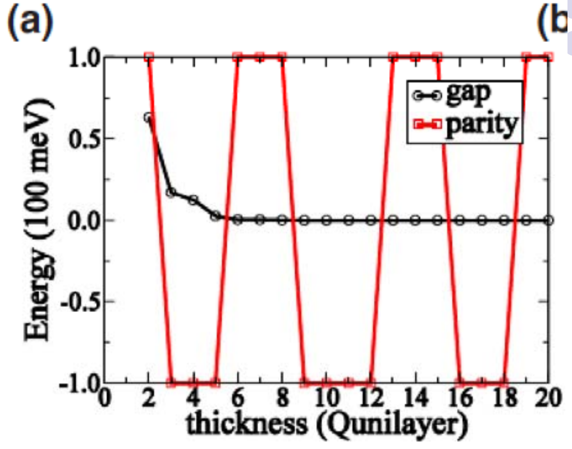
Be prepared

2D topological insulators from the 2D limit of 3D topological insulators

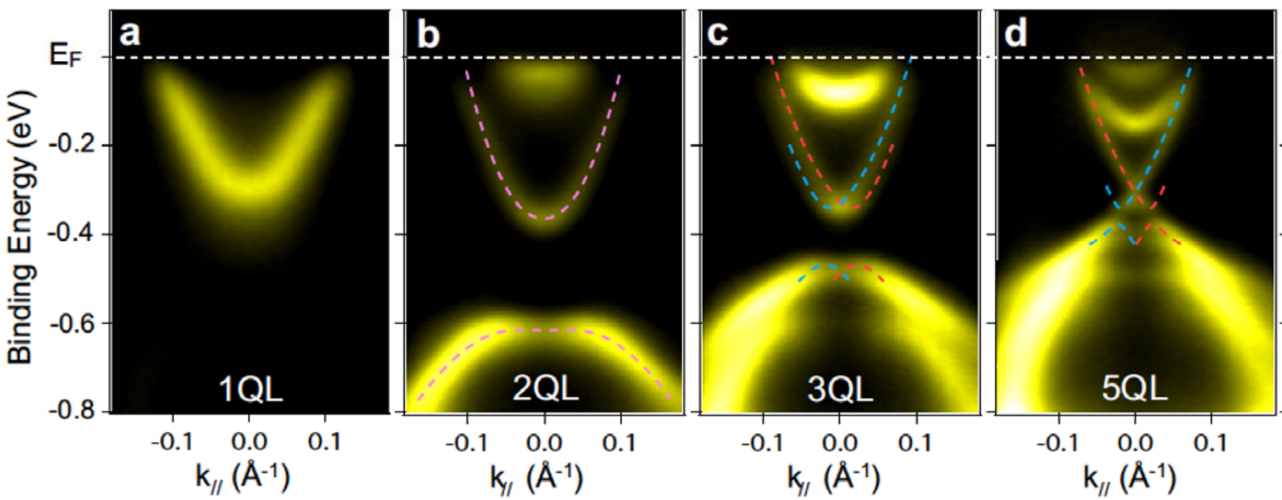
From 3D topological insulators







Liu et al. PRB 2010



Zhang et al. Nature Physics 2010

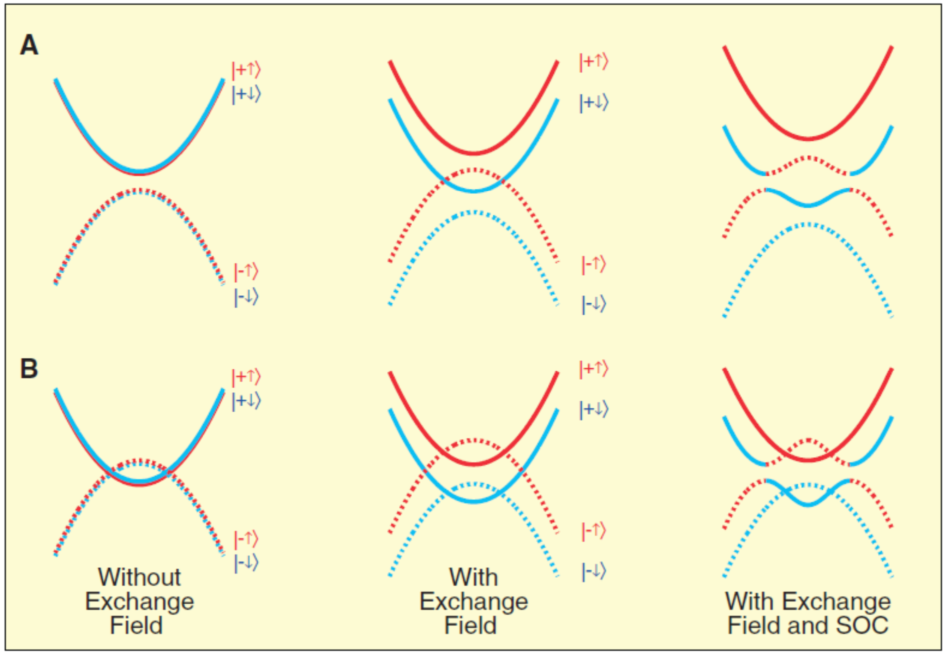
Magnetic impurity doping in QSH states

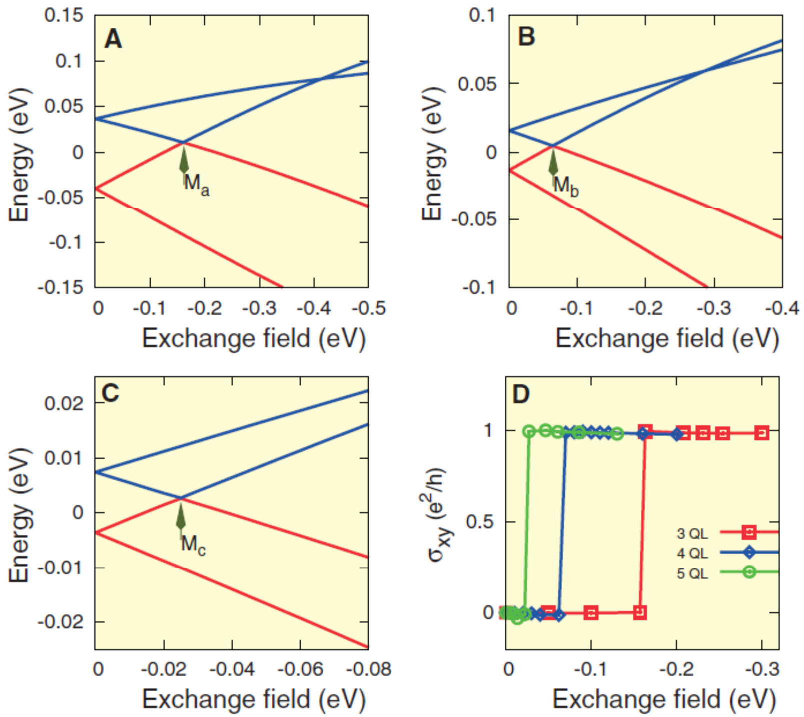
$$H = H_{sf} + H_{Zeeman}$$

$$= \begin{pmatrix} m_k + gM & iv_F k_- & 0 & 0 \\ -iv_F k_- & -m_k - gM & 0 & 0 \\ 0 & 0 & m_k - gM & -iv_F k_- \\ 0 & 0 & iv_F k_- & -m_k + gM \end{pmatrix}$$

m_k	a finite mass
g	the effective factor
M	the exchange field along z direction

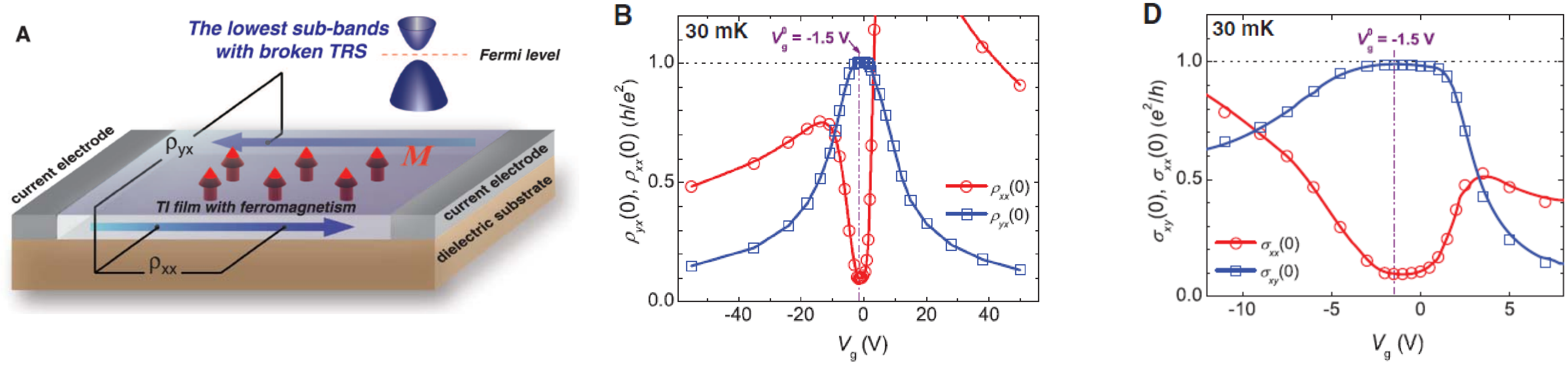
Yu et al. Science 2010
Liu et al. PRL 101, 146802 (2008)
Zhang et al. PRL 112, 216803 (2014)

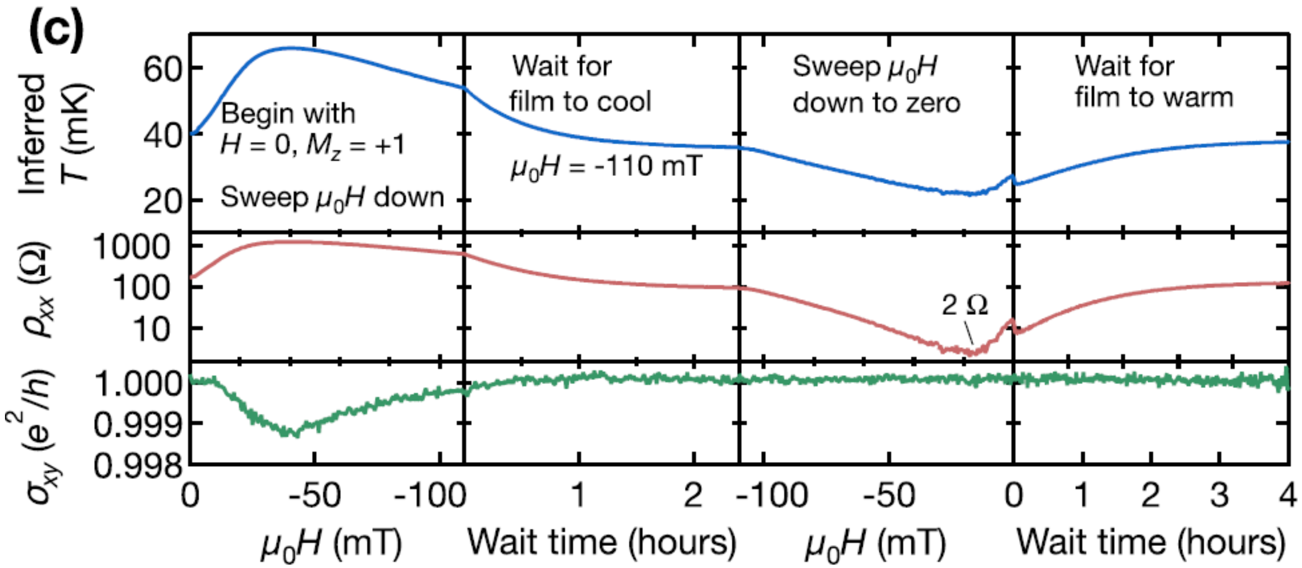




Really observed QAH Effect in experiments

30mK





$\sigma_{xy} \sim 1.0e^2/h;\ \rho_{xx} \sim 2\Omega$

Chang et al. Science 2013
Kou et al. PRL 2014
Checkelsky Nat. Phys. 2014

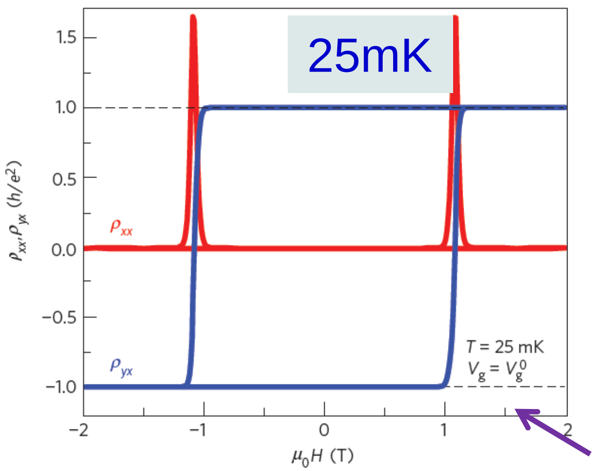
Further optimize the Position of the chemical position for 0 ρ_{xx} ?

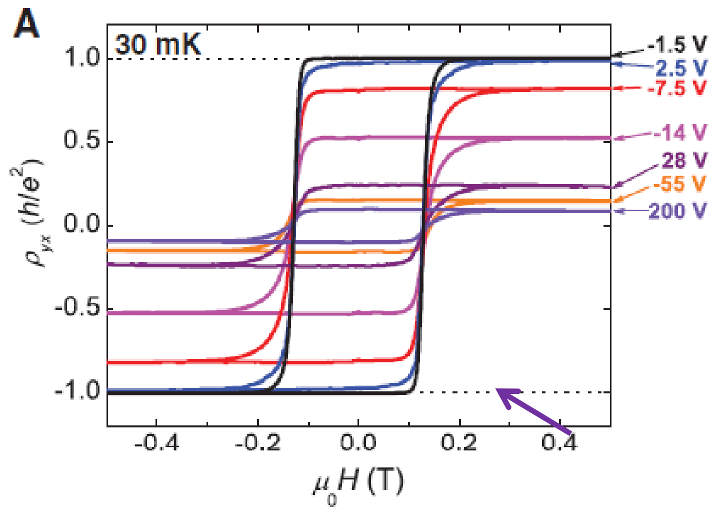
Bestwick et al
PRL 114, 187201 (2015)

Precise quantization of the QAH effect—V-doped case

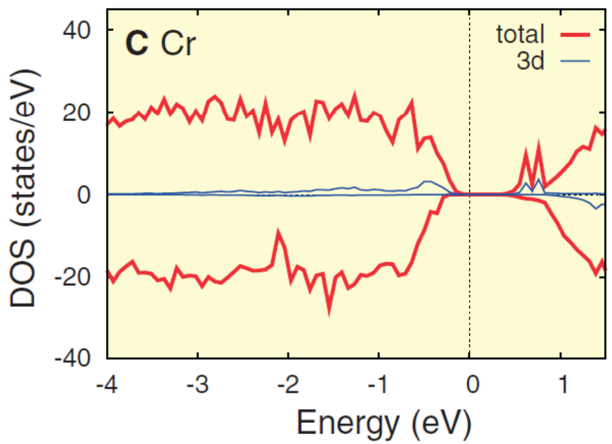
4 QL $V_{0.11}(Bi_{0.29}Sb_{0.71})_2Te_3$

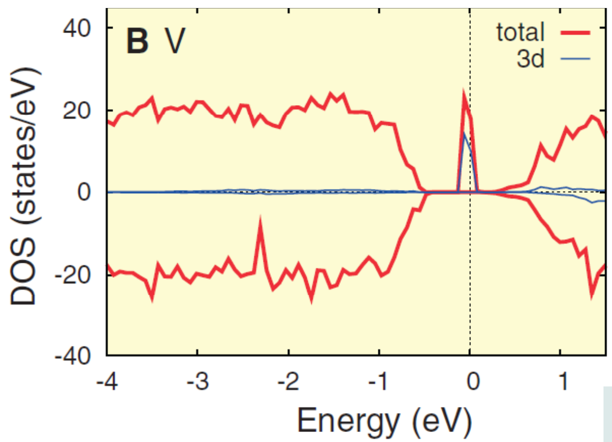
$\sigma_{xy} \sim 0.9998e^2/h;\ \rho_{xx} \sim 3.3\Omega$





1) Self-driven, without magnetic training
2) A large coercive field H_c





1) Impurity bands and the QAH effect
2) Exchange mechanism

Chang et al. Nat. Materials 2015

Outlook

- How to understand the ‘surprised’ observation?
- How to improve the working temperature to K or ten K level?
- Can we realize the QAH effect in much cheaper systems?
- Superconductor + the QAH effect?

Acknowledgement

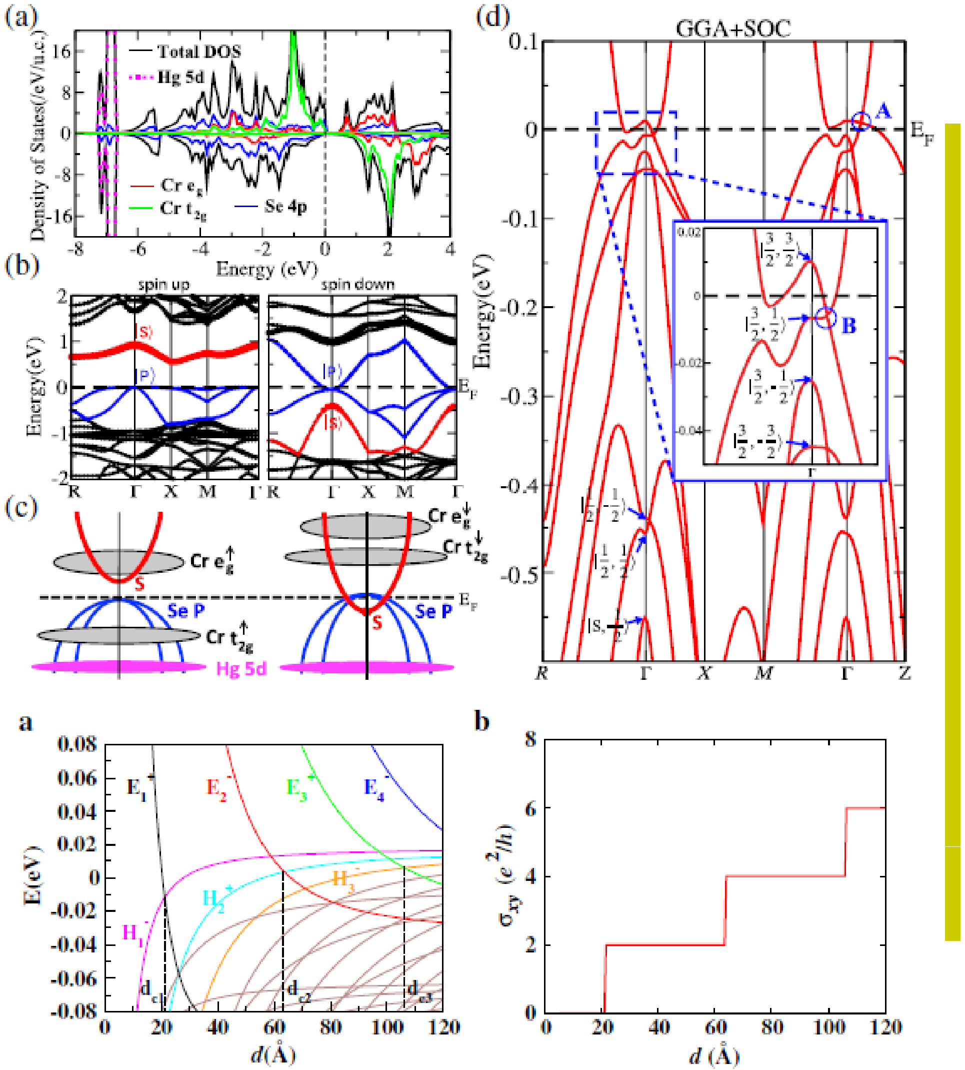
- ✓ Yong Xu, Gang Xu, Jing Wang, Shou-Cheng Zhang
- ✓ Chaoxing Liu
- ✓ Cui-zu Chang
- ✓ Hong Yao, Zhong Wang

Summary

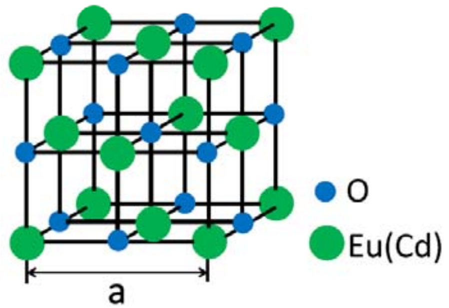
- Background
- Design 2D topological insulators
  - Type-II Quantum Wells, polar Quantum Wells
  - Graphene, Silience, Stanene et al.
  - 2D limit from 3D topological insulators
- Outlook

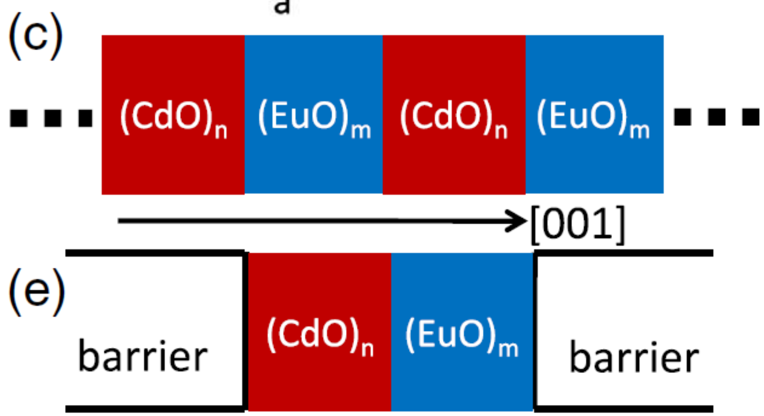
Thank you for your attention!

Intrinsic magnetic insulators



Intrinsic FM insulators
+
Type-II Quantum Wells structure





Xu et al. PRL 107, 186806 (2011)

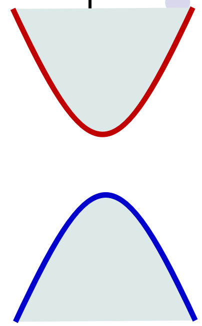
Zhang et al. PRL 112, 096804 (2014)

The toy model of the QAH effect

$$H = \sum_{\vec{k}} H(\vec{k})$$
$$H(\vec{k}) = \epsilon(\vec{k}) + V d_\alpha(\vec{k})\sigma^\alpha$$

$$E_\pm(\vec{k}) = \epsilon(\vec{k}) \pm V\sqrt{\sum_\alpha d_\alpha^2(\vec{k})}$$

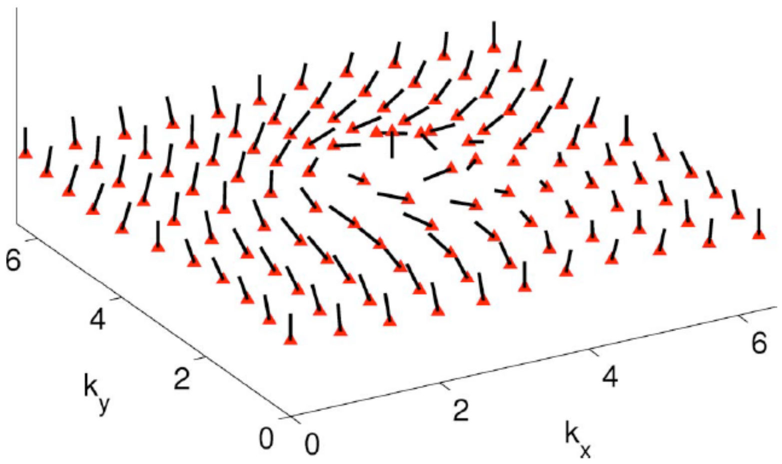
$$\min_{k\in BZ} E_+(\vec{k}) > \max_{k\in BZ} E_-(\vec{k})$$



The Hall conductivity:

$$\sigma_{xy} = -\frac{1}{8\pi^2}\int\int_{FBZ} dk_x dk_y \hat{d}\cdot\partial_x\hat{d}\times\partial_y\hat{d}$$
$$= -\frac{n}{2\pi}$$

with
$$\hat{d}_\alpha(\vec{k}) = d_\alpha(\vec{k})/\sqrt{\sum_\alpha d_\alpha^2(\vec{k})}$$



Quantized conductivity without the Landau levels!