Quantum anomalous Hall effect in magnetic topological insulator

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MBE, STM, and ARPES

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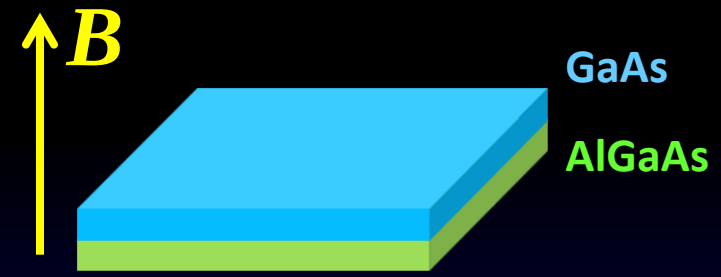
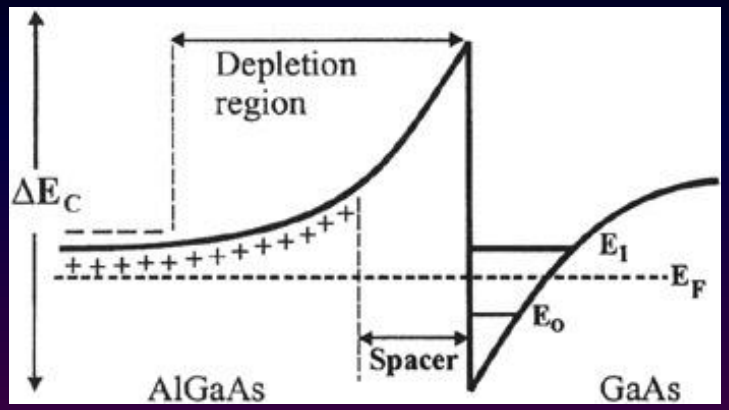
Theory & Calc.

Xi Dai, Zhong Fang **IOP**

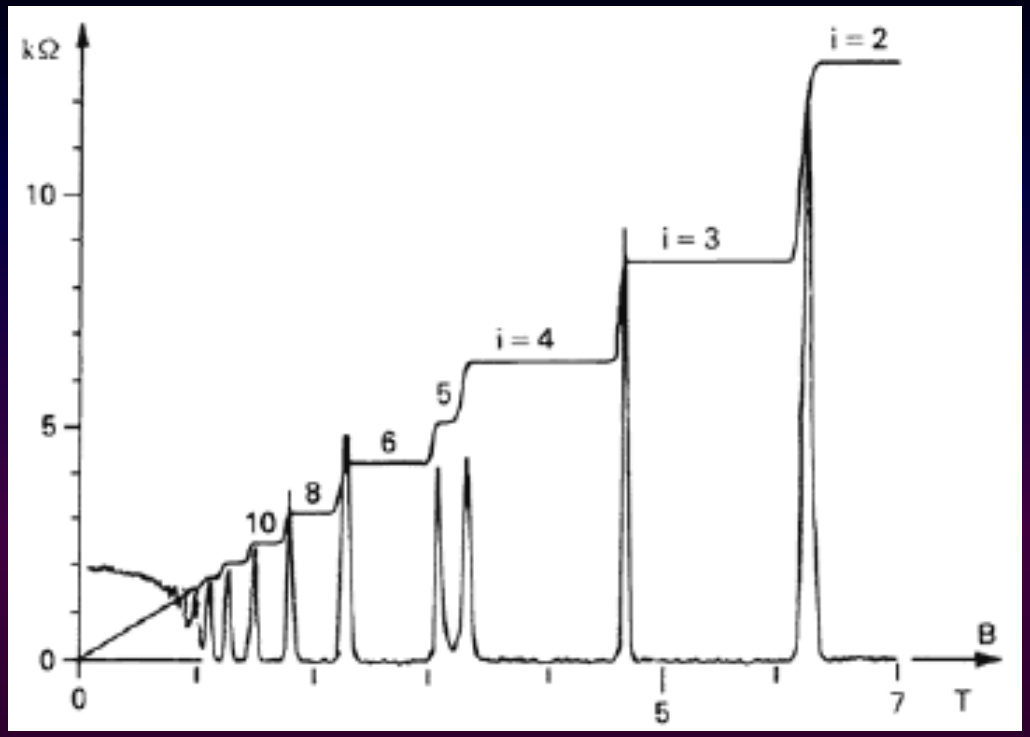
X.-L. Qi, S.-C. Zhang **Stanford**

Quantum Hall Effect





Two dimensional electron gas



Klaus Von Klitzing

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

Topological origin of QHE

$\chi = 2$

$\chi = 0$

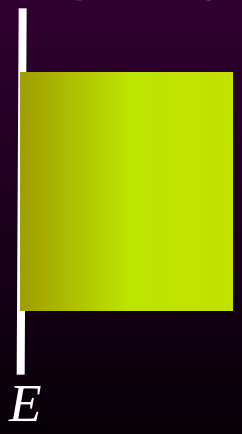
$$\frac{1}{2\pi}\oint_S K dA = \chi$$

K: Gauss curvature

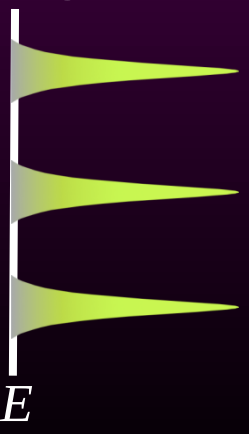
χ: Euler characteristic

Gauss-Bonnet Theorem

$C = 0$



$C = 1$

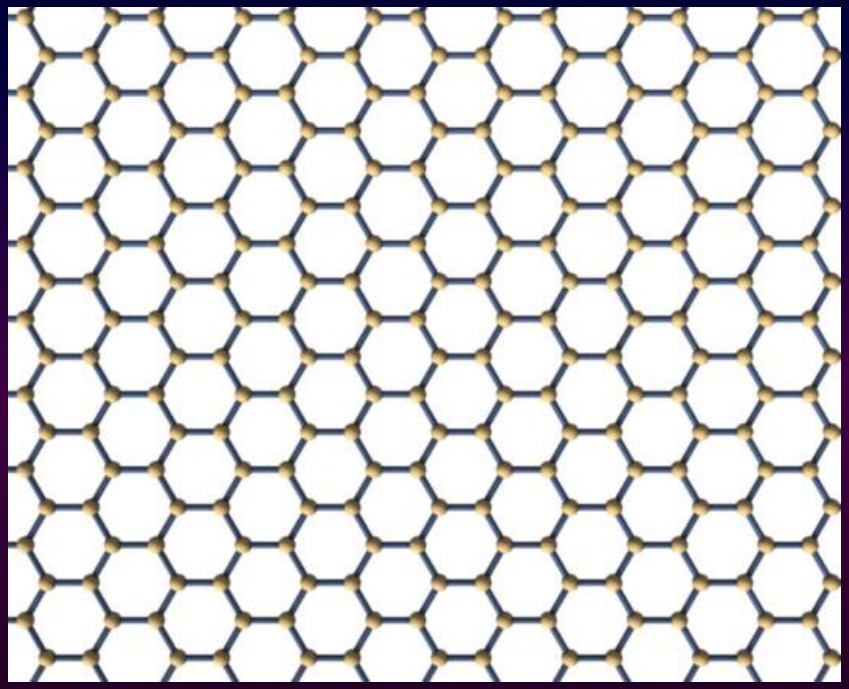


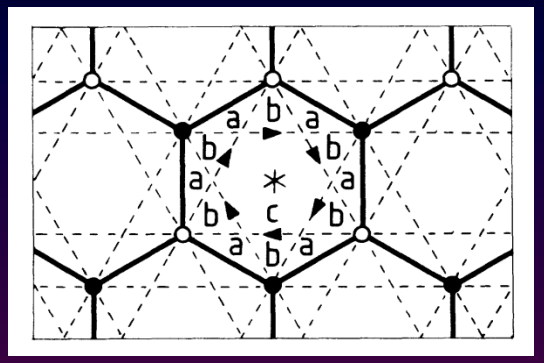
$$\frac{1}{2\pi}\oint_{BZ} \Omega d\vec{k} = C$$

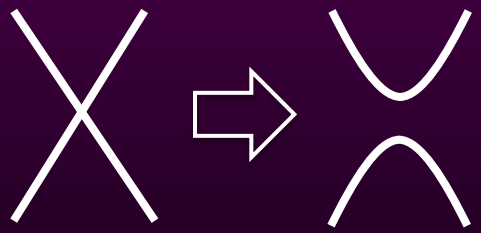
Ω: Berry curvature

C: Chern number

Can we obtain QHE without Landau levels?

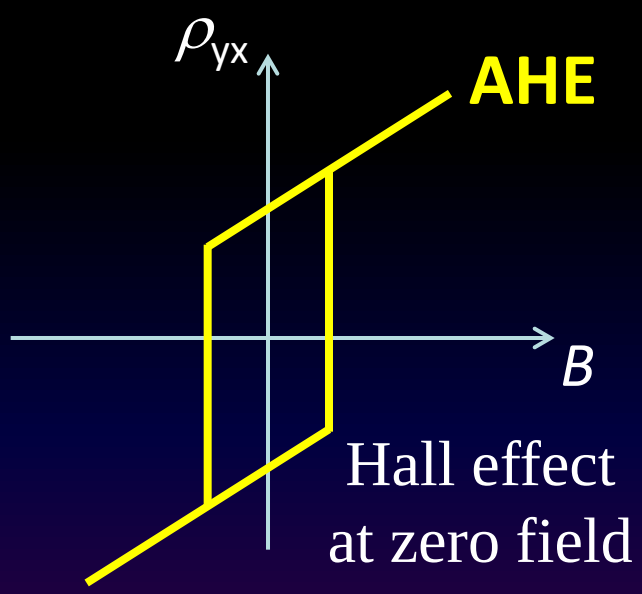


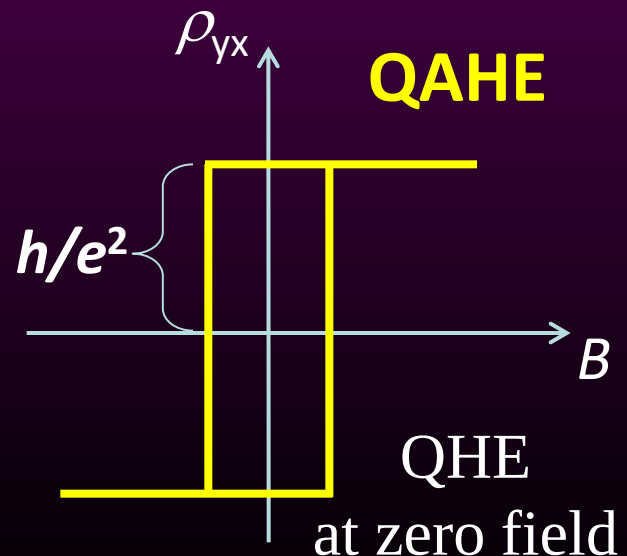




Graphene with periodic magnetic field but without net flux

Haldane PRL 61, 2015 (1988)





Quantized AHE

Extrinsic: induced by impurities

- **Skew scattering**
  Smit, Physica 1958
- **Side jump**
  Berger, PRB 1970

Intrinsic: induced by energy band

Karplus & Luttinger, Phys. Rev. 1954

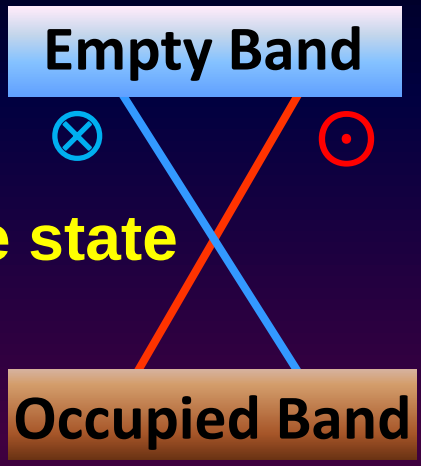
$$\sigma_{xy} = \frac{e^2}{h} \sum_{occupied} \frac{1}{2\pi} \oint_{BZ} \Omega d\vec{k}$$

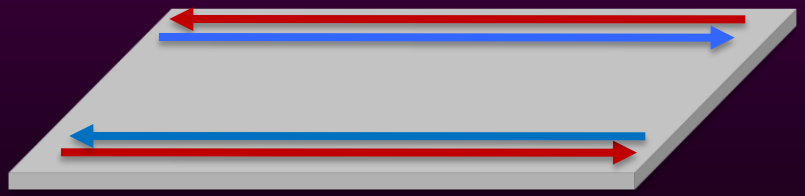
Chang & Niu PRB 1996, Sundaram & Niu PRB 1999, Fang et al., Science 2003

can be quantized in a ferromagnetic insulator with $C \neq 0$ (Chern insulator)

Onoda & Nagaosa, PRL 2003
Onoda, Sugimoto & Nagaosa, PRL 2006

TRS Invariant Topological Insulators

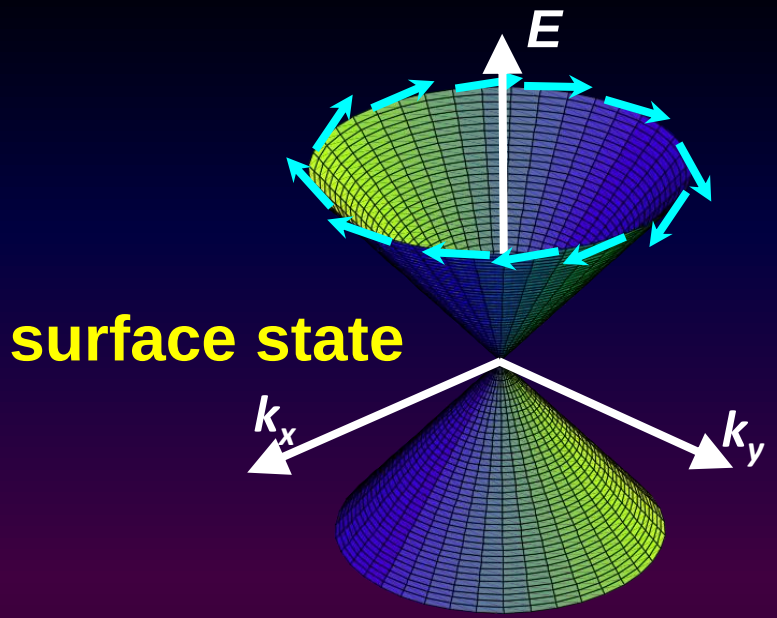


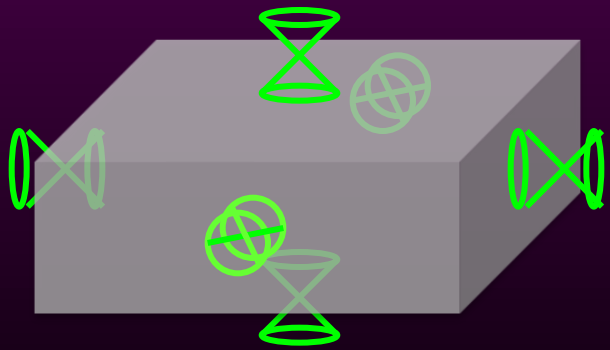


2D TI (Quantum Spin Hall effect)

Mele & Kane, PRL 2005

Bernevig & Zhang, PRL 2006



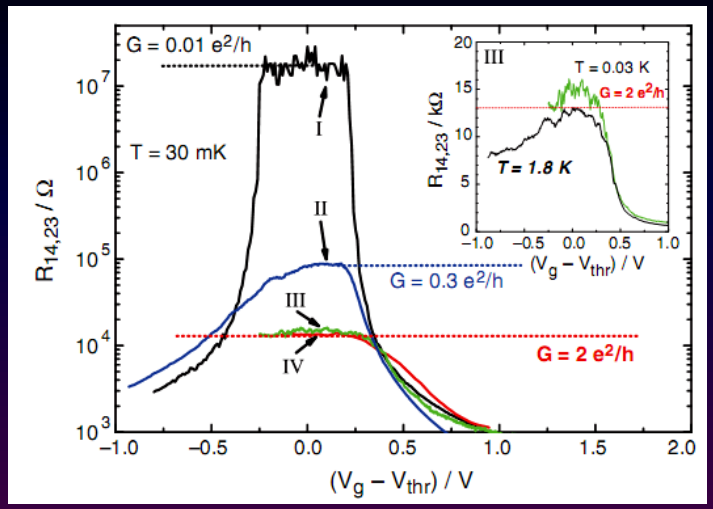


3D TI

Fu, Kane, & Mele, PRL 2007

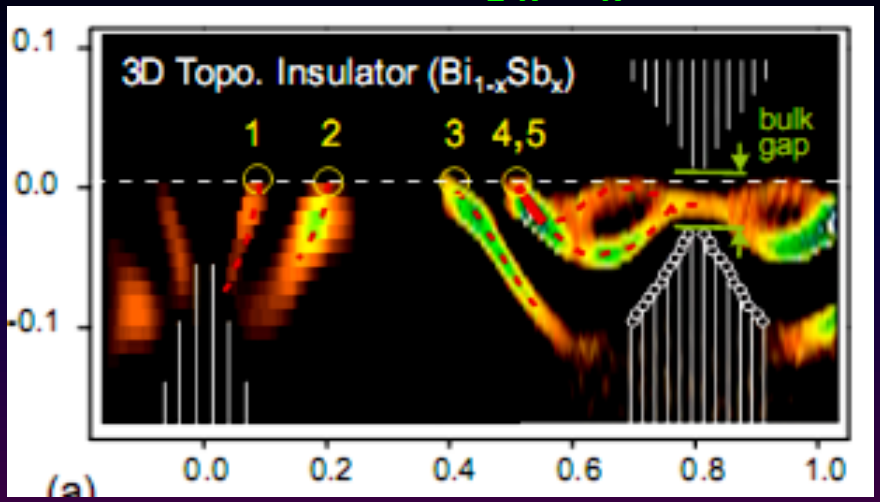
Real TI Materials

2D TI: HgTe Quantum Well

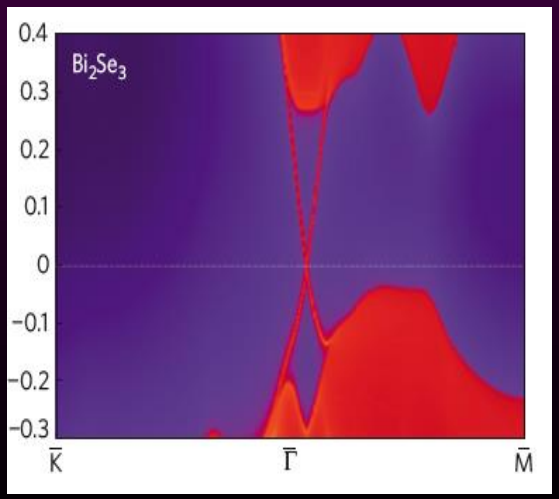


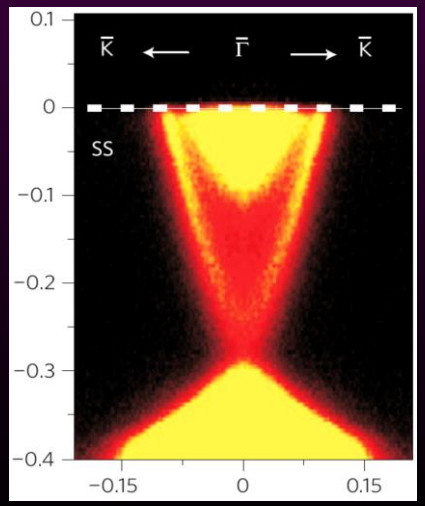
Bernevig, Hughes & Zhang, Science 2006
Konig et al., Science 2007

3D TI: $Bi_{1-x}Sb_x$



Fu & Kane Phys. Rev. B 2007
Hsieh et al., Nature 2008





H. Zhang et al., Nature Phys. 2009

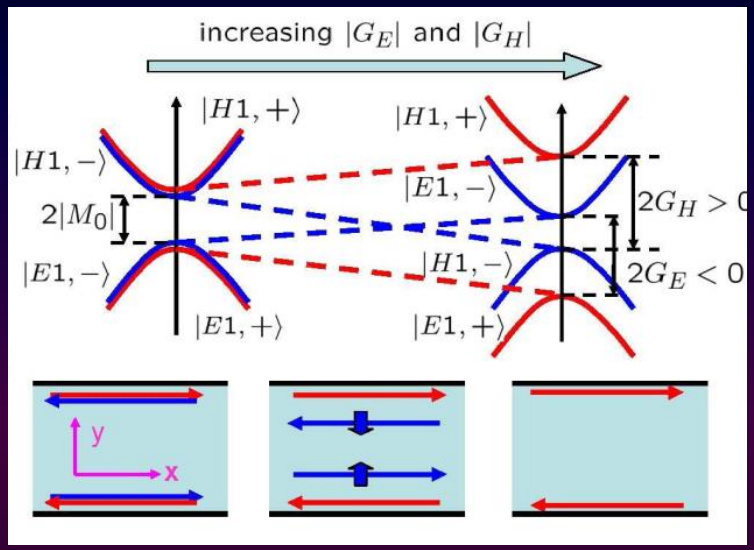
Y. –L. Chen et al., Science 2009

Y. Xia et al., Nature Phys. 2009

3D TI: Bi_2Se_3 Family (Bi_2Se_3, Bi_2Te_3, Sb_2Te_3,)

QAHE in magnetic TIs

2D TI

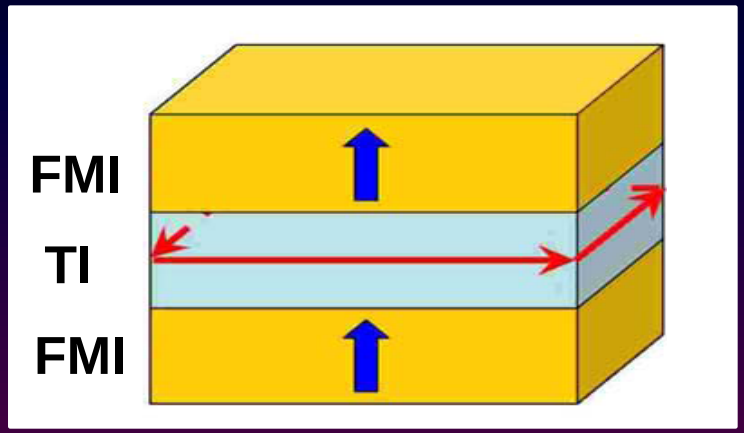


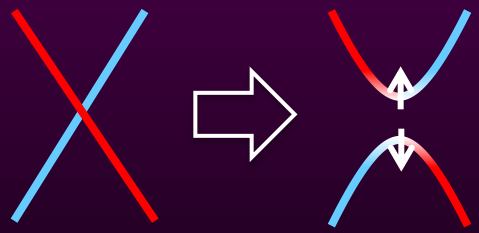
X. -L. Qi, Y. S. Wu & S. -C. Zhang, PRB 2006

C. -X. Liu et al., PRL 2008

R. Yu et al., Science 2010

3D TI





X. -L. Q & S. -C. Zhang, PRL 2008

K. Nomra & N. Nagaosa, PRL 2011

To observe QAHE in a TI

- Thin film with appropriate thickness

  ➔ MBE growth

- FM insulator phase with perpendicular magnetic anisotropy

  ➔ Magnetic doping

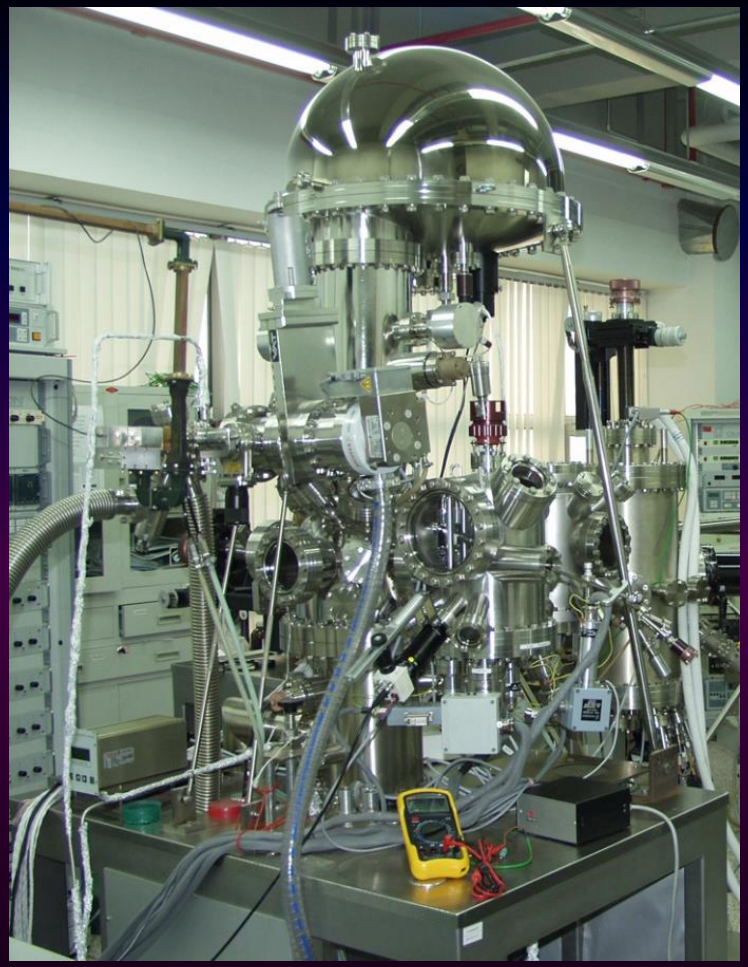
- Tunable chemical potential (carriers)

  ➔ Chemical doping

  ➔ Field effect

MBE-STM-ARPES Combo System

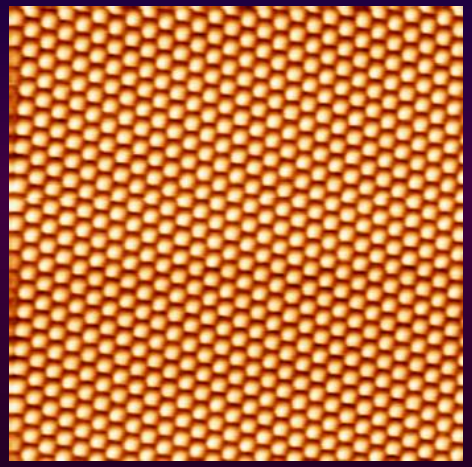
Omicron

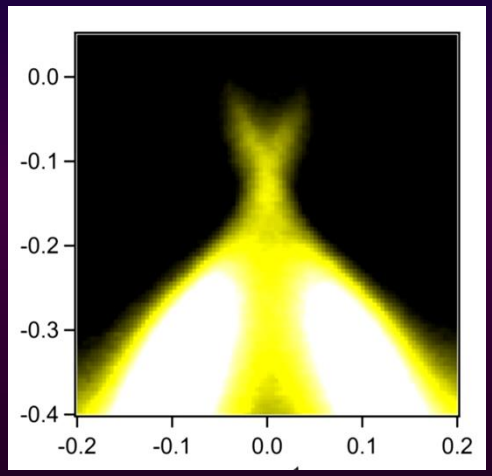


MBE: Sample preparation

ARPES: Band structure

STM: Atomic arrangement





@ Qi-Kun Xue's group Tsinghua-IOP

Facility for Transport Experiments

Oxford

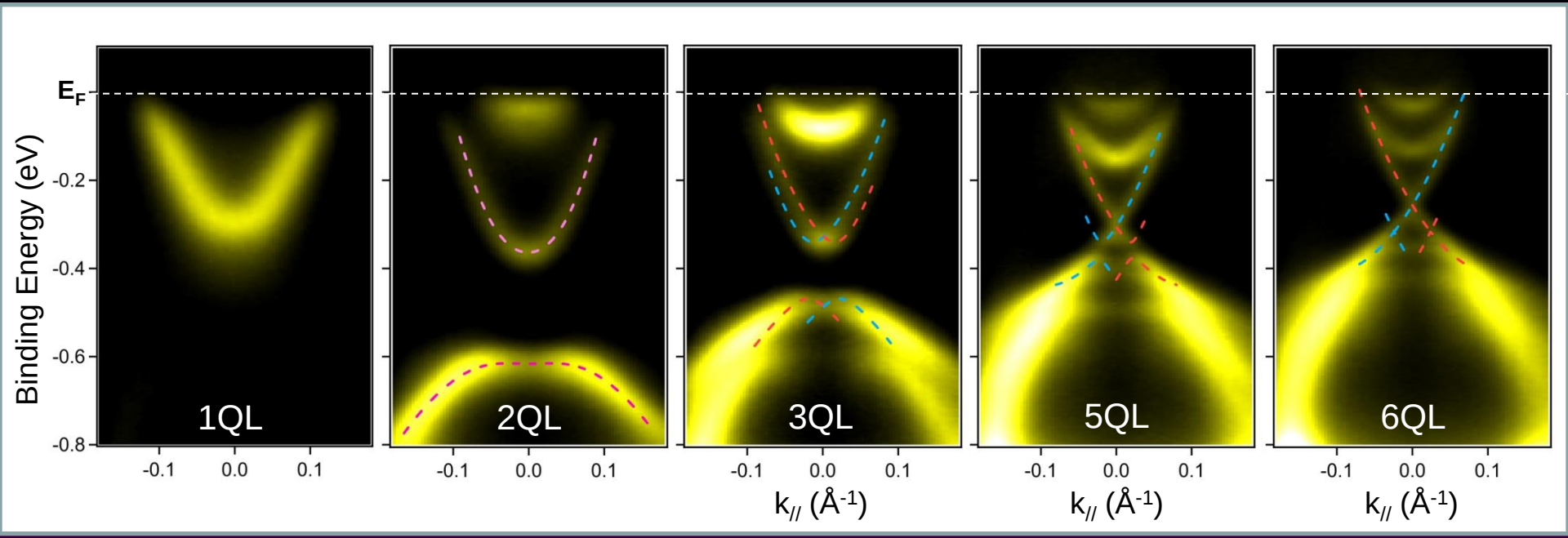
250 mK, 15 Tesla

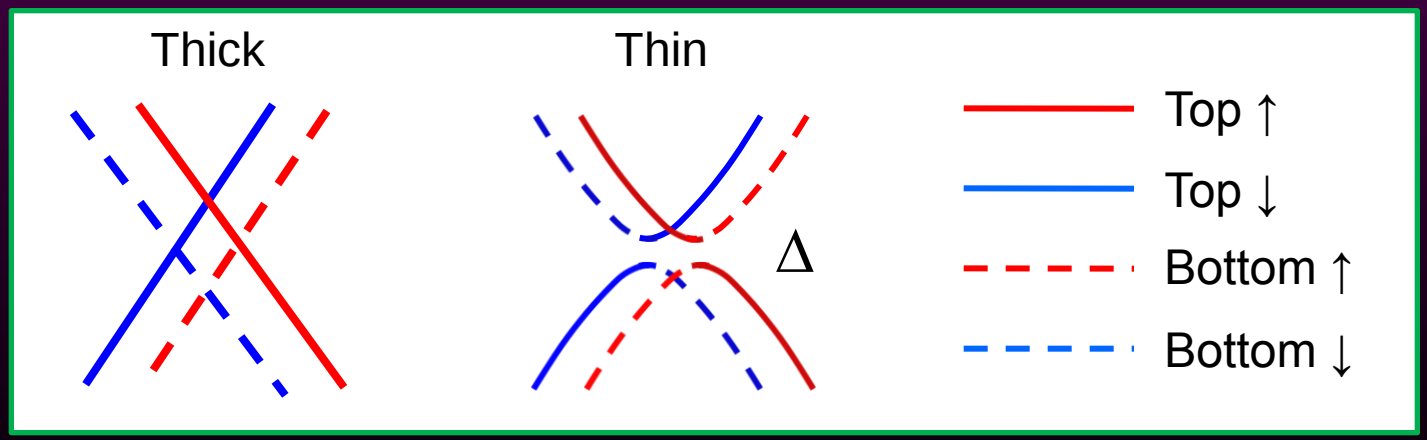
@ Yayu Wang's Group (Tsinghua)

30 mK, 18 Tesla

@ Li Lu's Group (IOP)

MBE-grown Bi_2Se_3 thin films



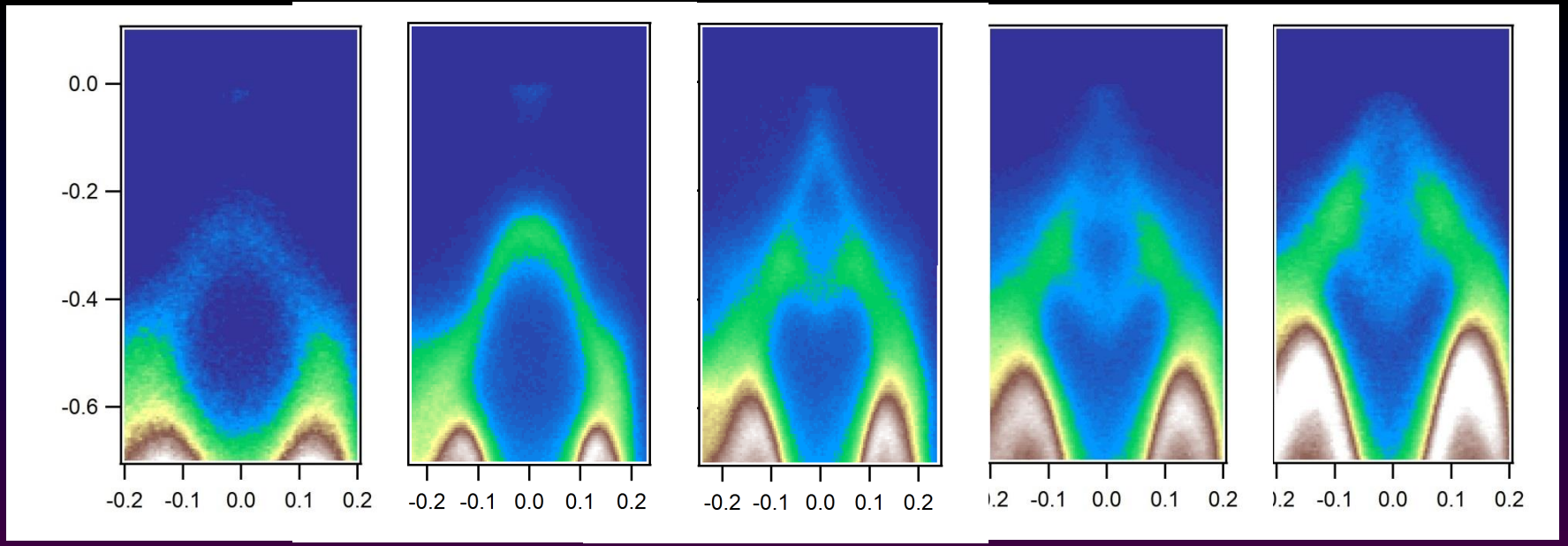


For QAHE,

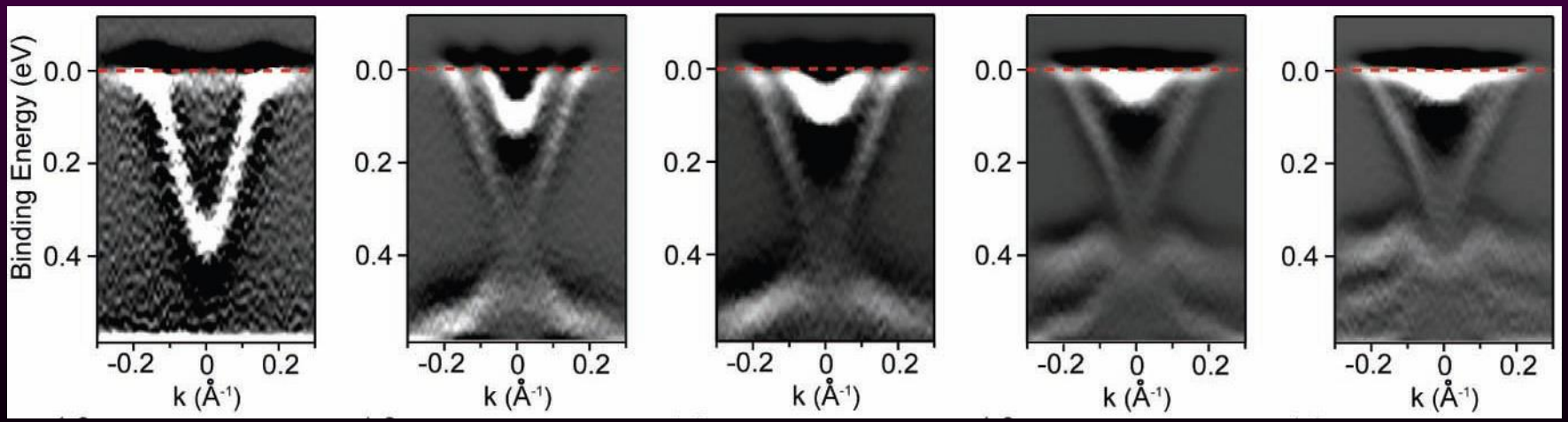
$\Delta < E_{exchange}$

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

MBE-grown Sb_2Te_3 and Bi_2Te_3 thin films

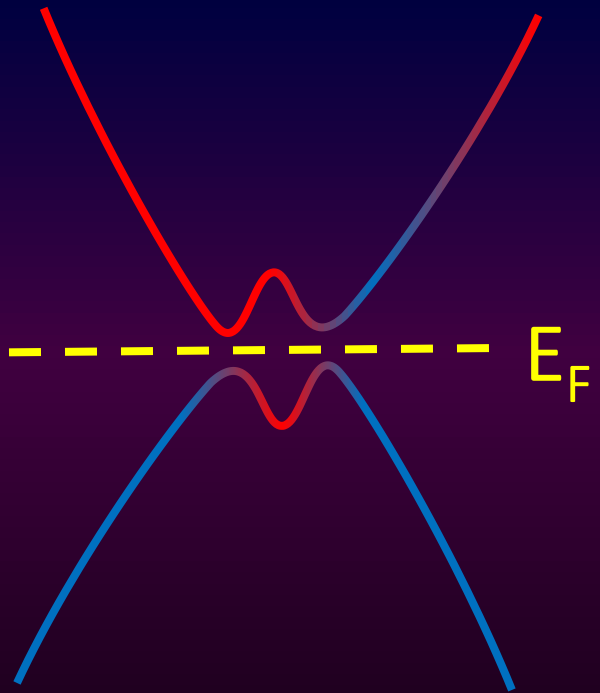


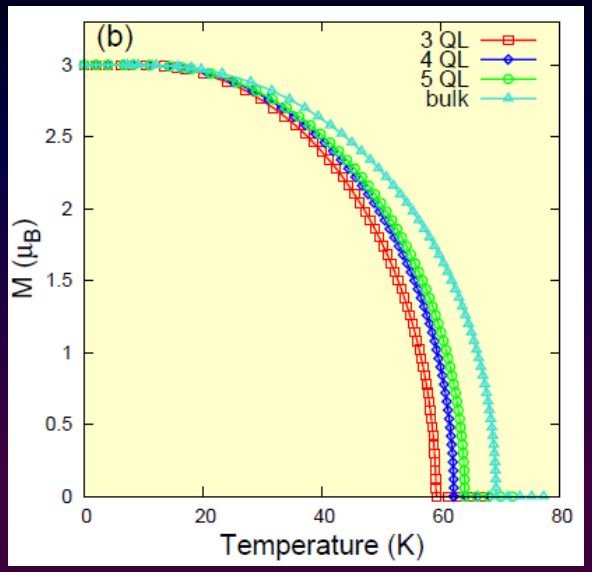
G. Wang et al., Nano Res. 3, 874 (2010).

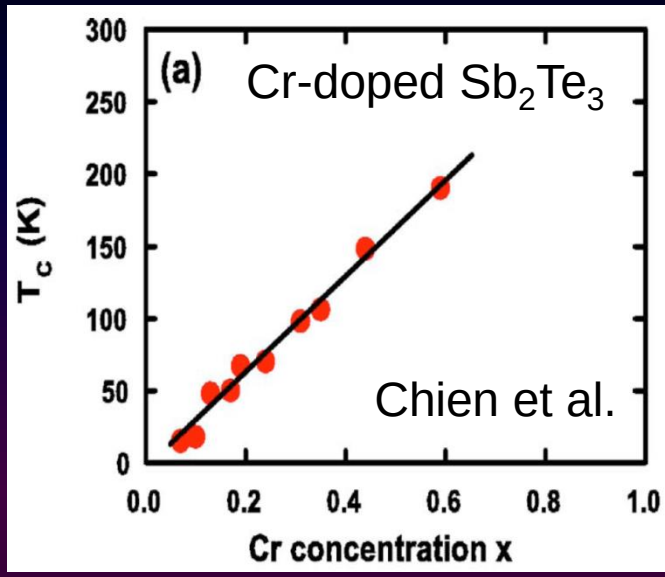


Y. –Y, Li et al., Adv. Mater. 22, 4002 (2010).

Magnetically doped Bi_2Se_3 family TIs: FM of van Vleck mechanism







$$F_{\text{total}} = \frac{1}{2}\chi_L^{-1}M_L^2 + \frac{1}{2}\chi_e^{-1}M_e^2 - J_{\text{eff}}M_L M_e - (M_L + M_e)H$$

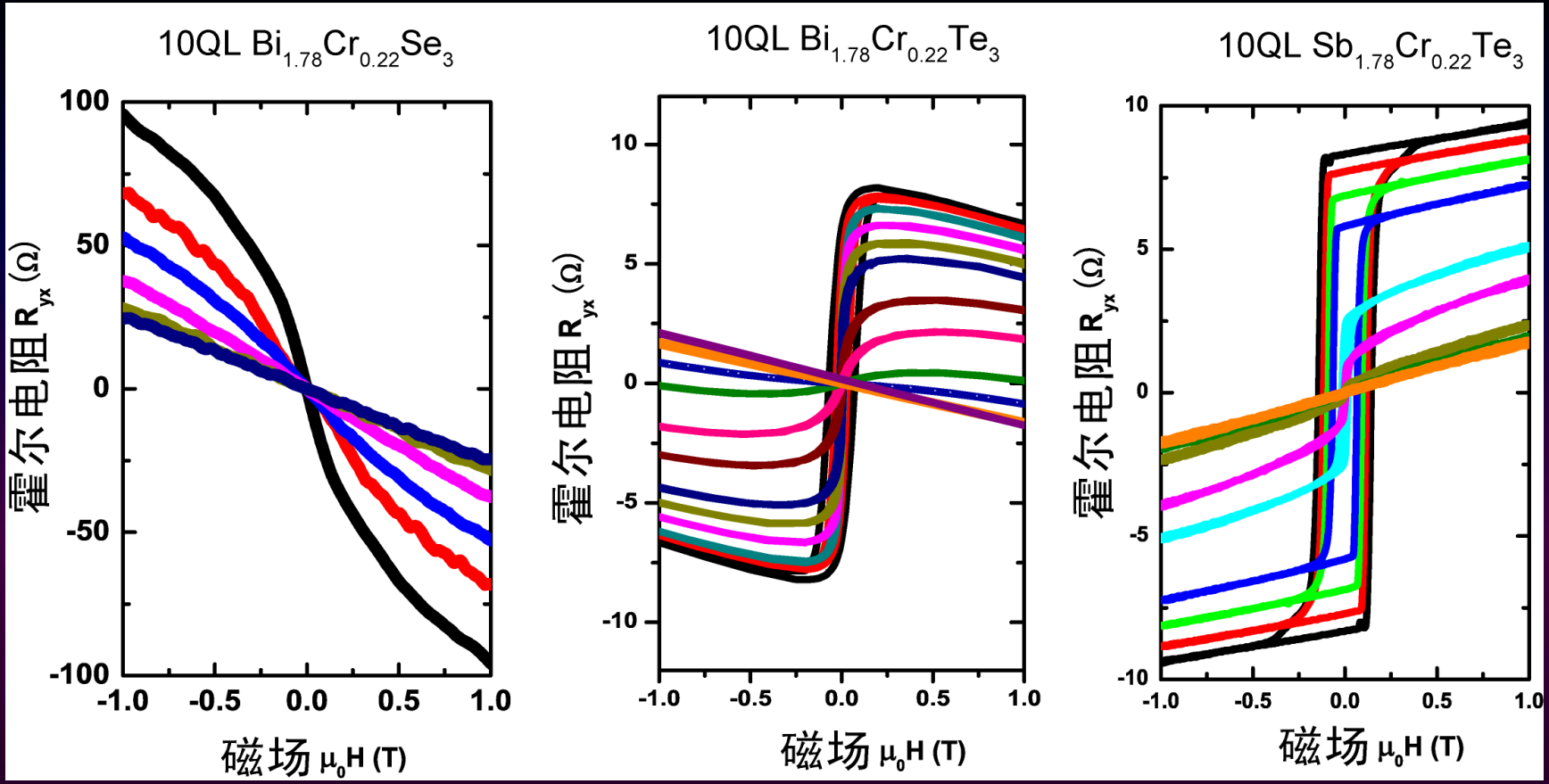
$$J_{eff}^2 - \chi_L^{-1}\chi_e^{-1} > 0$$

$$\chi_L = x\mu_J^2/(3k_BT)$$

$$\chi_e^{zz} = \sum_{E_{nk}<\mu;E_{mk}>\mu} 4\mu_0\mu_B^2 \frac{\langle nk|\hat{S}_z|mk\rangle\langle mk|\hat{S}_z|nk\rangle}{E_{mk}-E_{nk}}.$$

R. Yu et al., Science 329, 61 (2010).

Cr-doped Bi_2Se_3 group TIs



No long range FM order

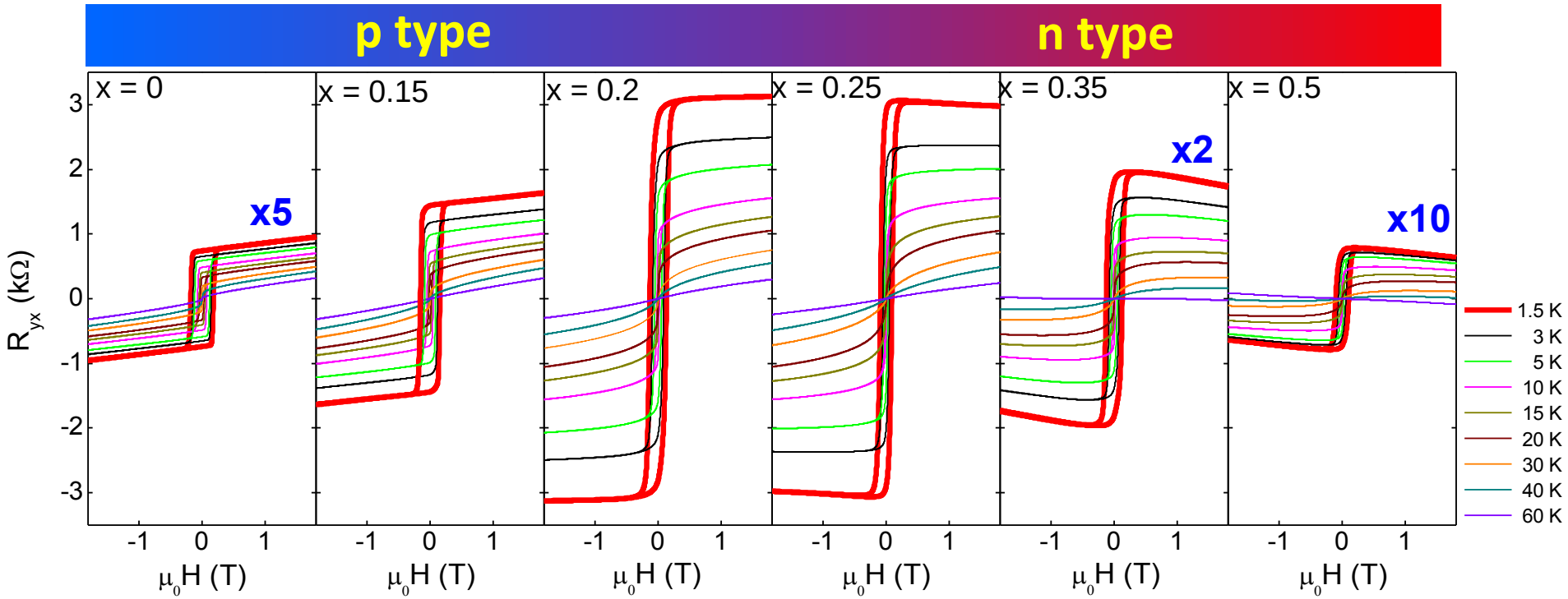
Long range FM order

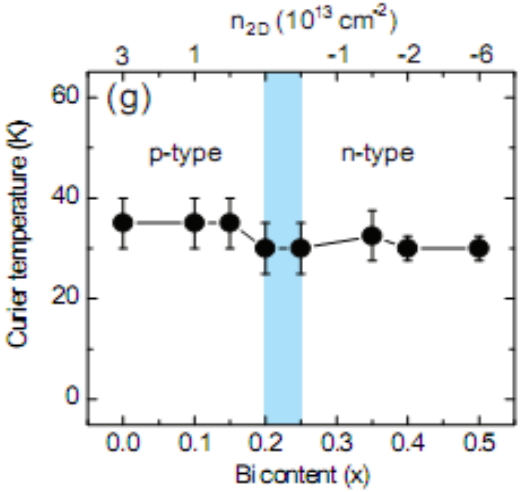
M. Liu et al., PRL **108**, 036805 (2012)

J. Zhang et al., Science 339, 1582 (2013)

C. -Z. Chang et al., PRL 112, 056801 (2014)

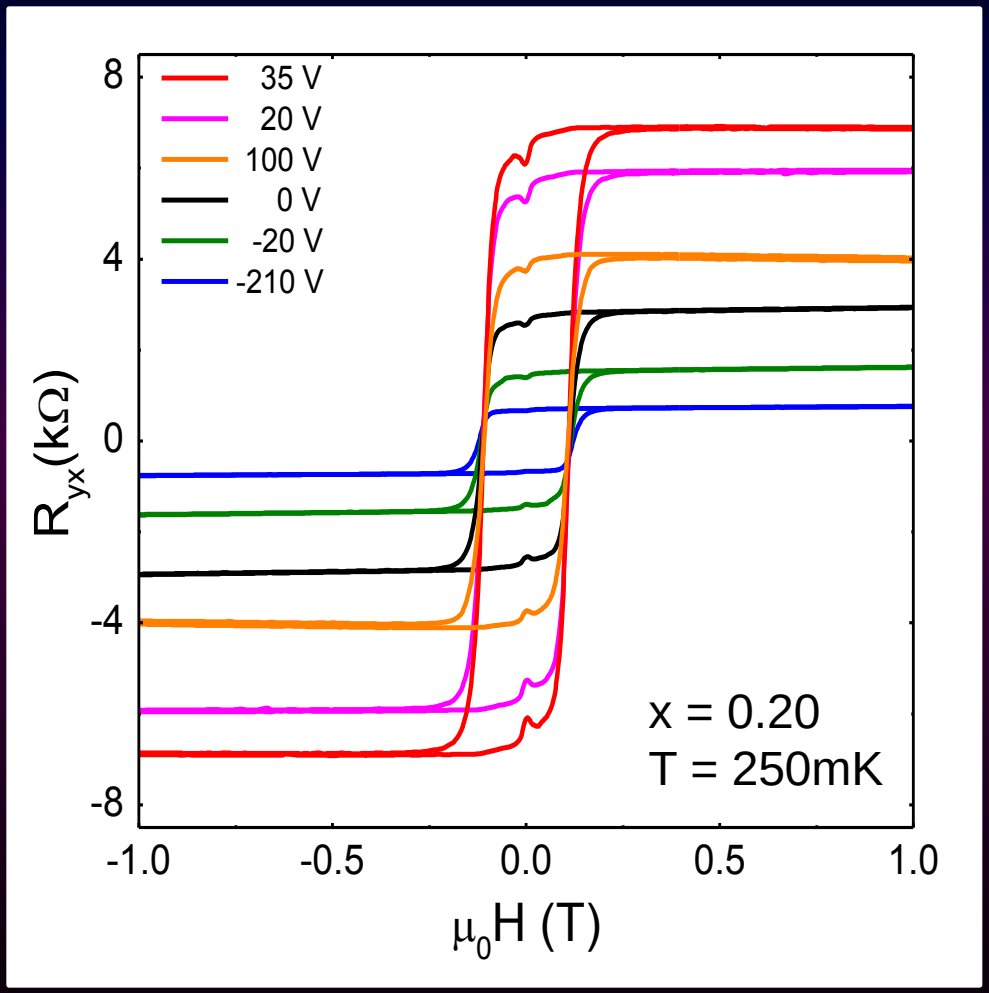
Magnetism of $Cr_{0.22}(Bi_xSb_{1-x})_2Te_3$

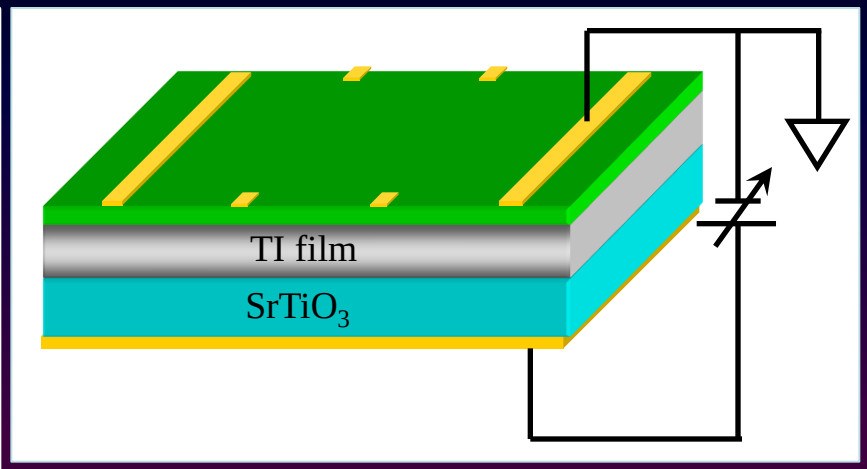




Long-range ferromagnetic order independent of carriers (probably van Vleck-type)

Gate-doping $Cr_{0.22}(Bi_xSb_{1-x})_{1.78}Te_3$ film with $SrTiO_3$ substrate





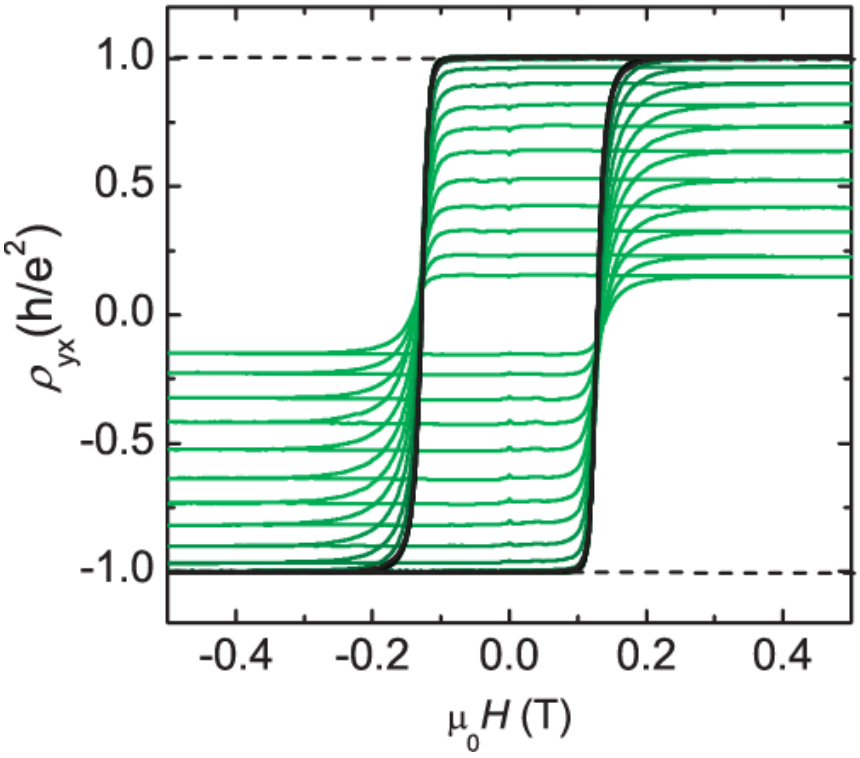
- **FM order is little influenced**
- **ρ_{yx} up to ¼ h/e^2**

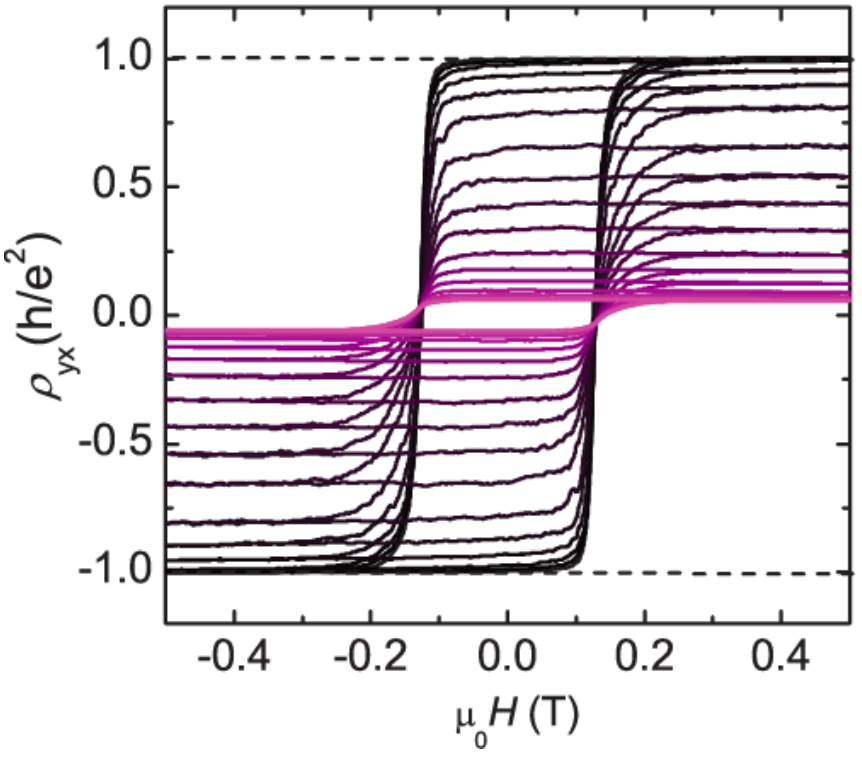
C. –Z. Chang et al., Adv. Mater. 25, 1065 (2013).

After one and half a year...

ρ_{yx}-B at different gate voltages

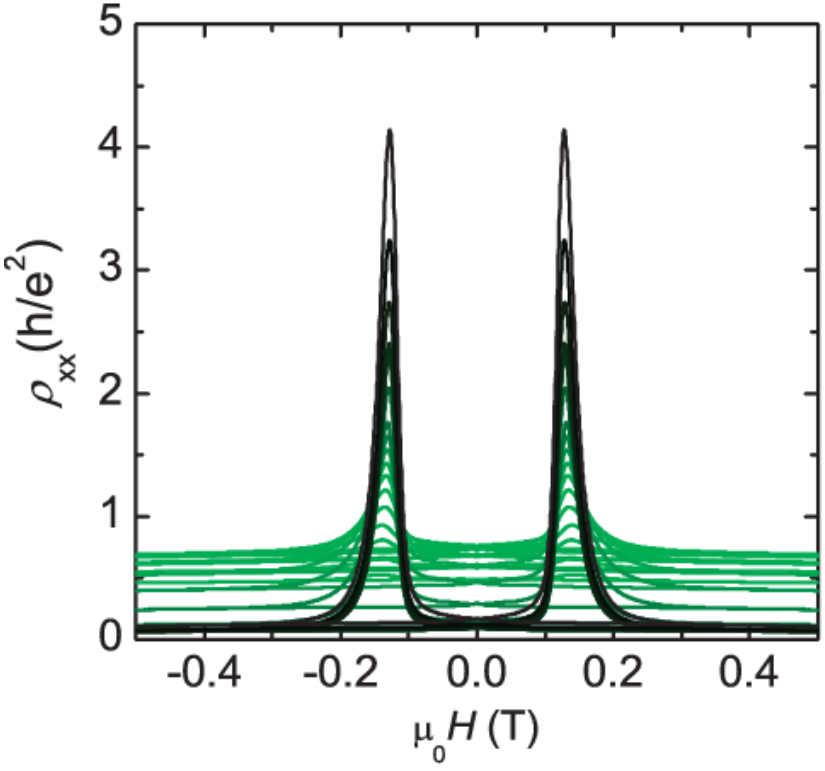
5QL $Cr_{0.15}(Bi_xSb_{1-x})_{1.85}Te_3$ on $SrTiO_3$ (111)

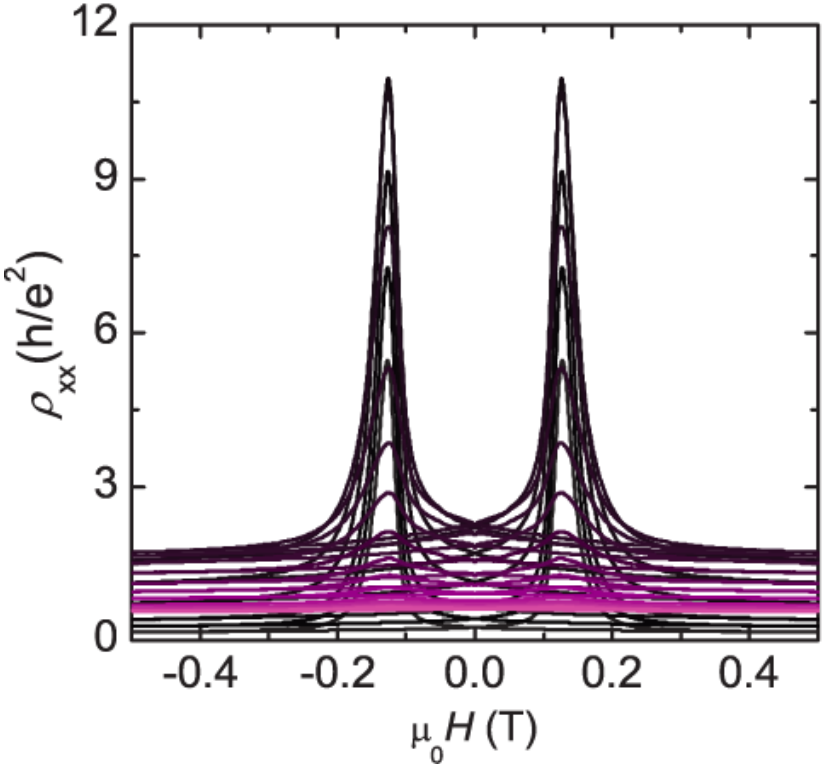




-55 V **0 V** **220 V**

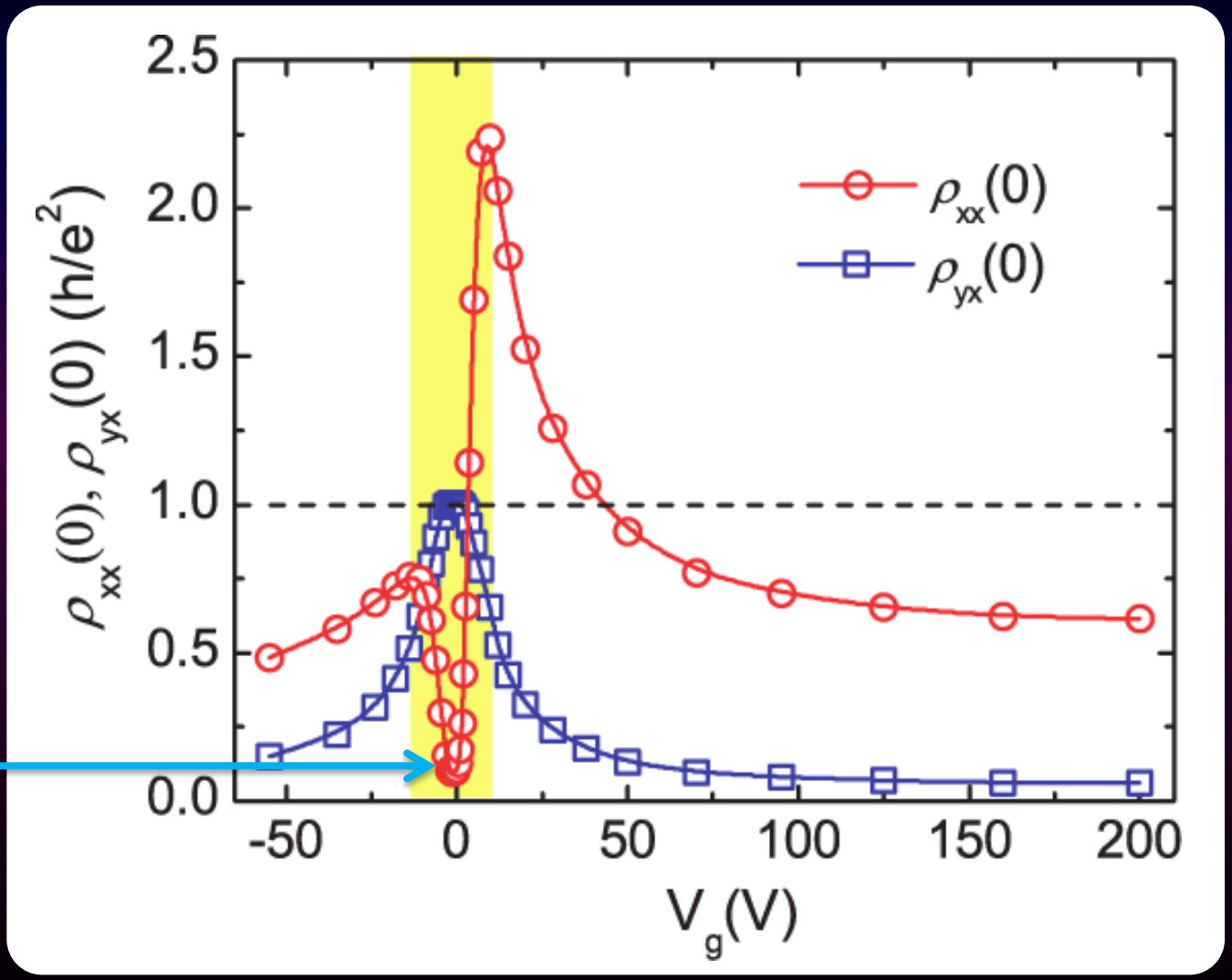
ρ_{xx}-B at different gate voltages





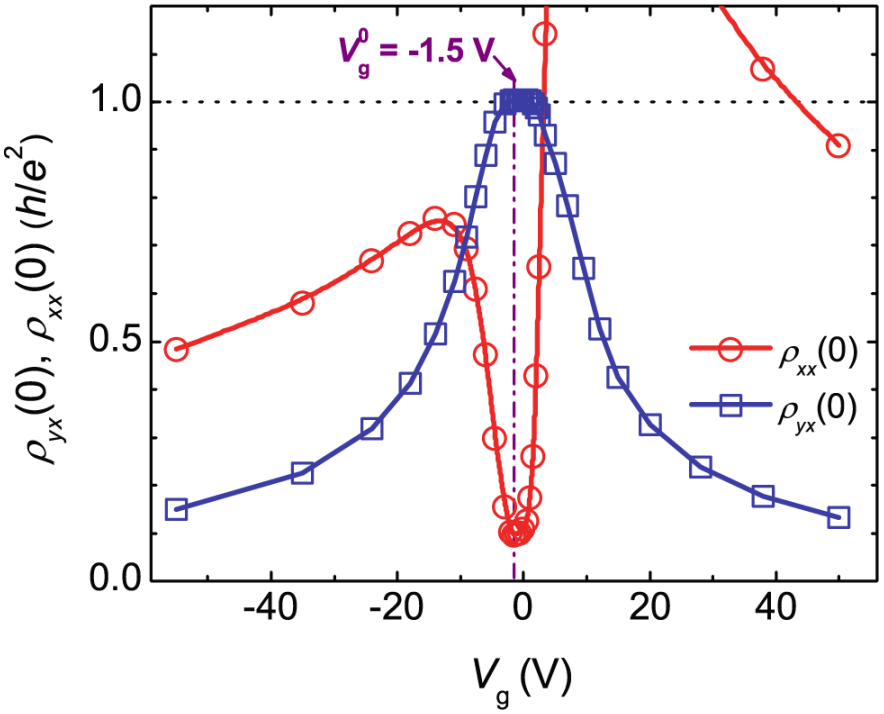
-55 V **0 V** **220 V**

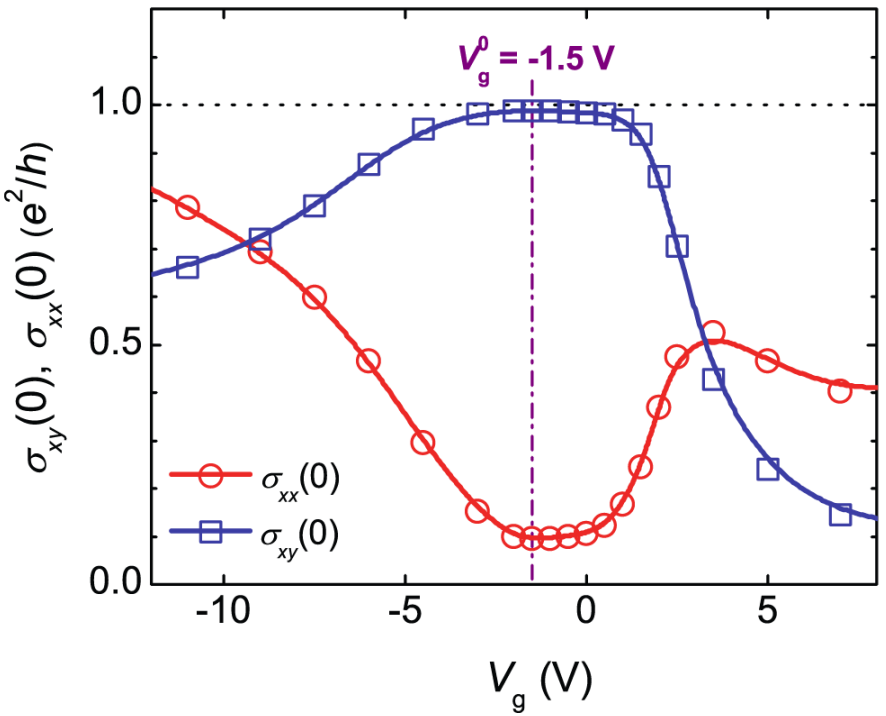
V_g dependent zero field ρ_{xx} and ρ_{yx}



ρ_{xx} dip

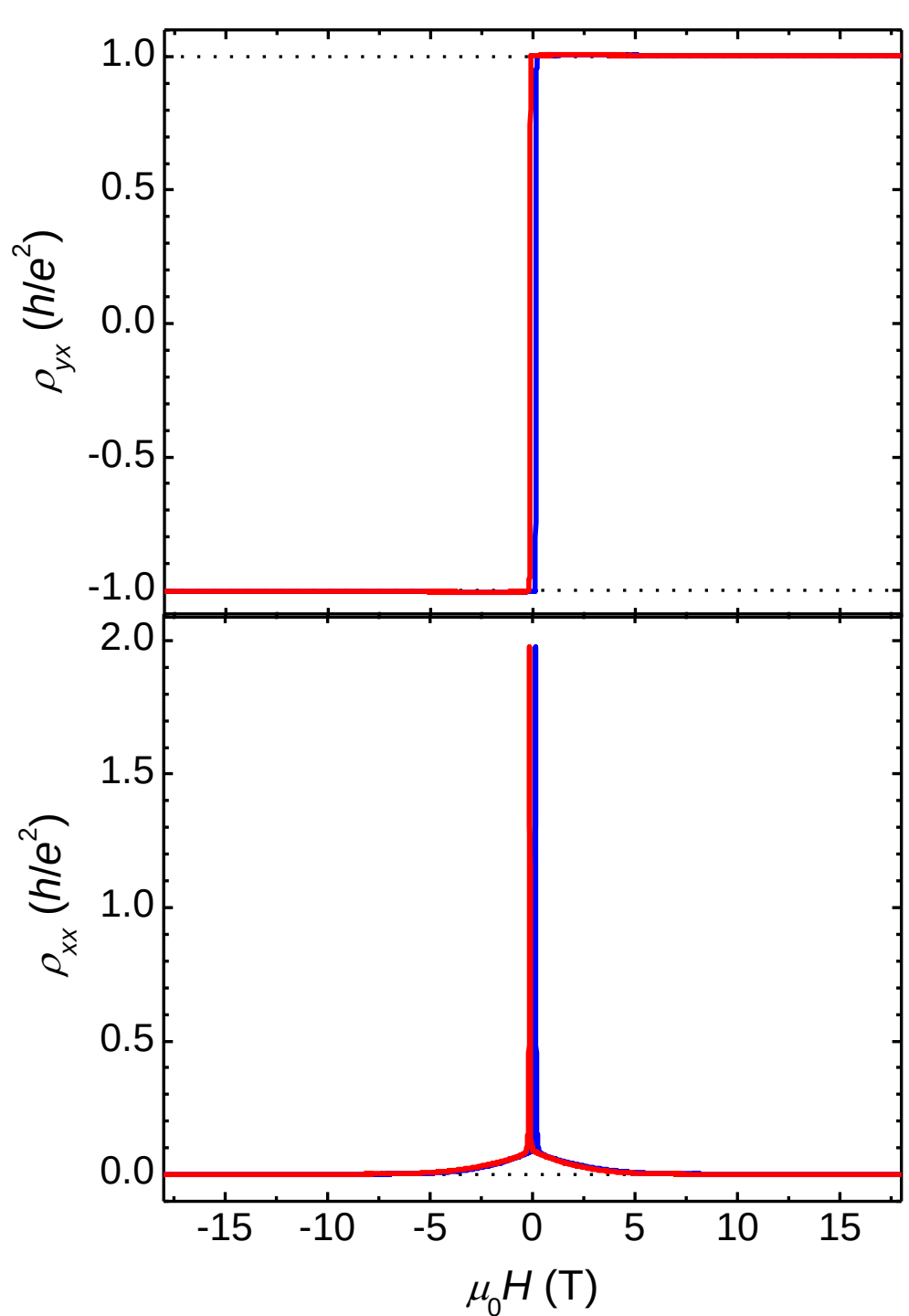
Quantum plateau observed





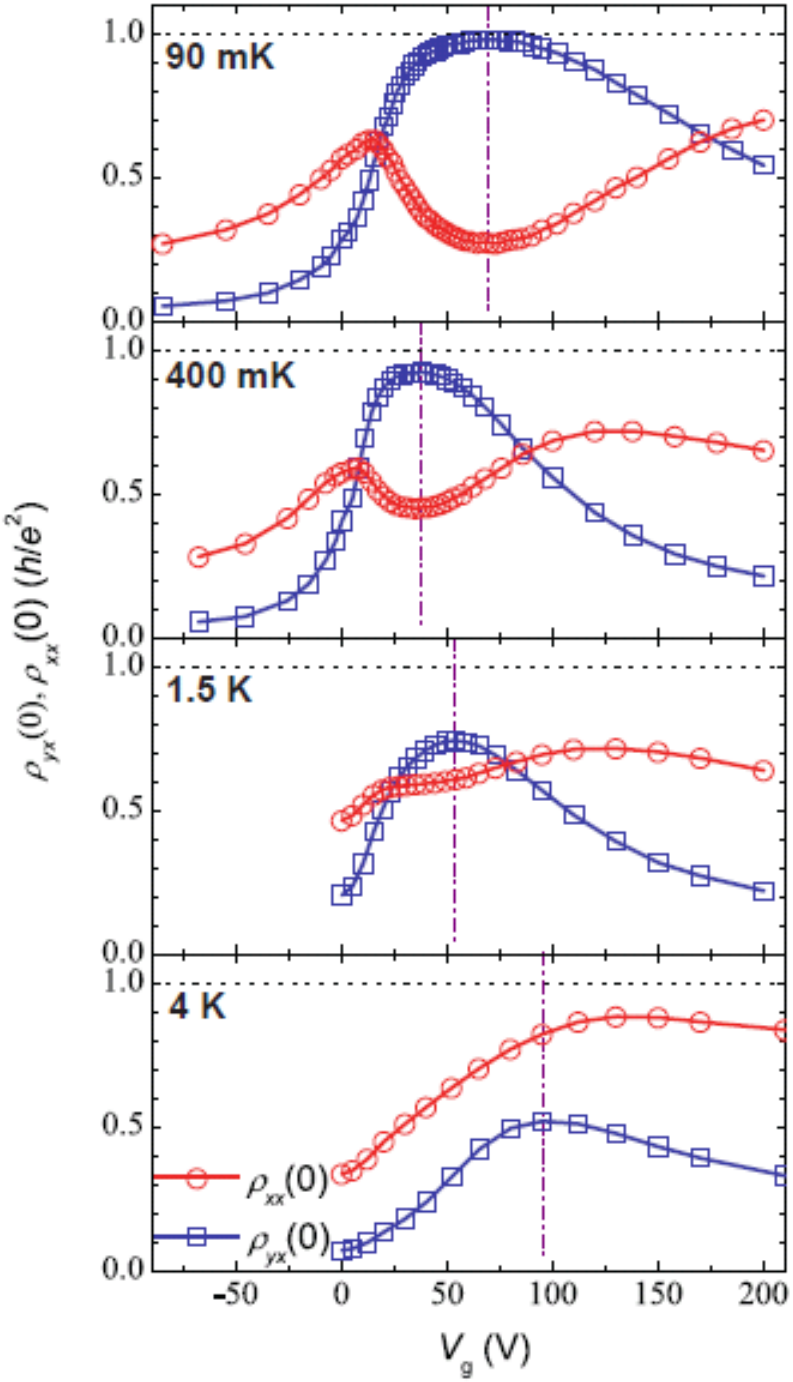
1 (h/e^2)

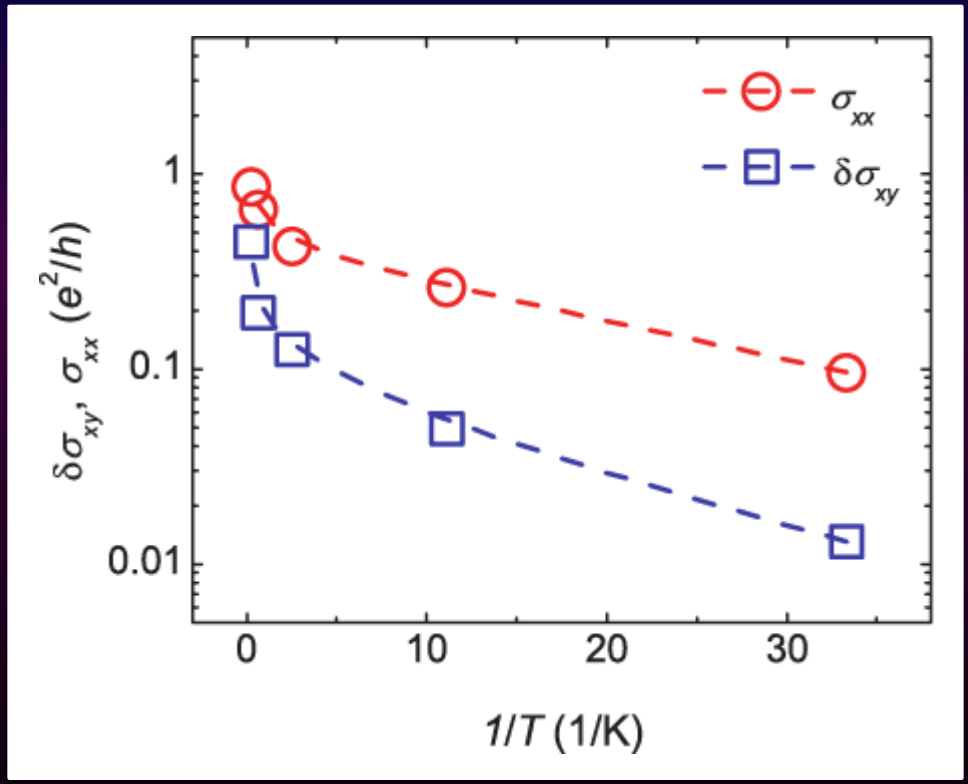
0.99 (e^2/h)



Dissipationless transport in magnetic field (@ 30 mK)

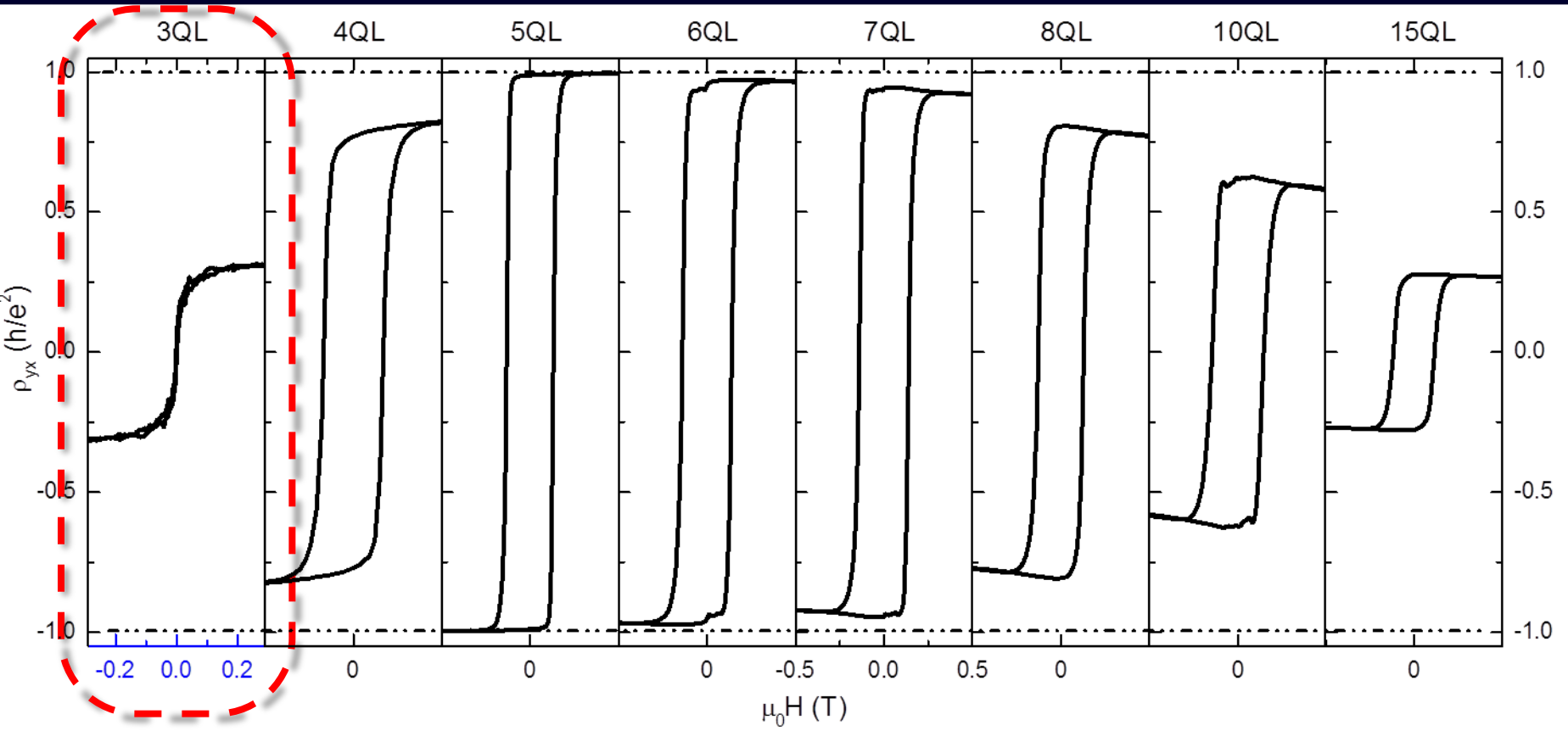
Temperature dependence





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

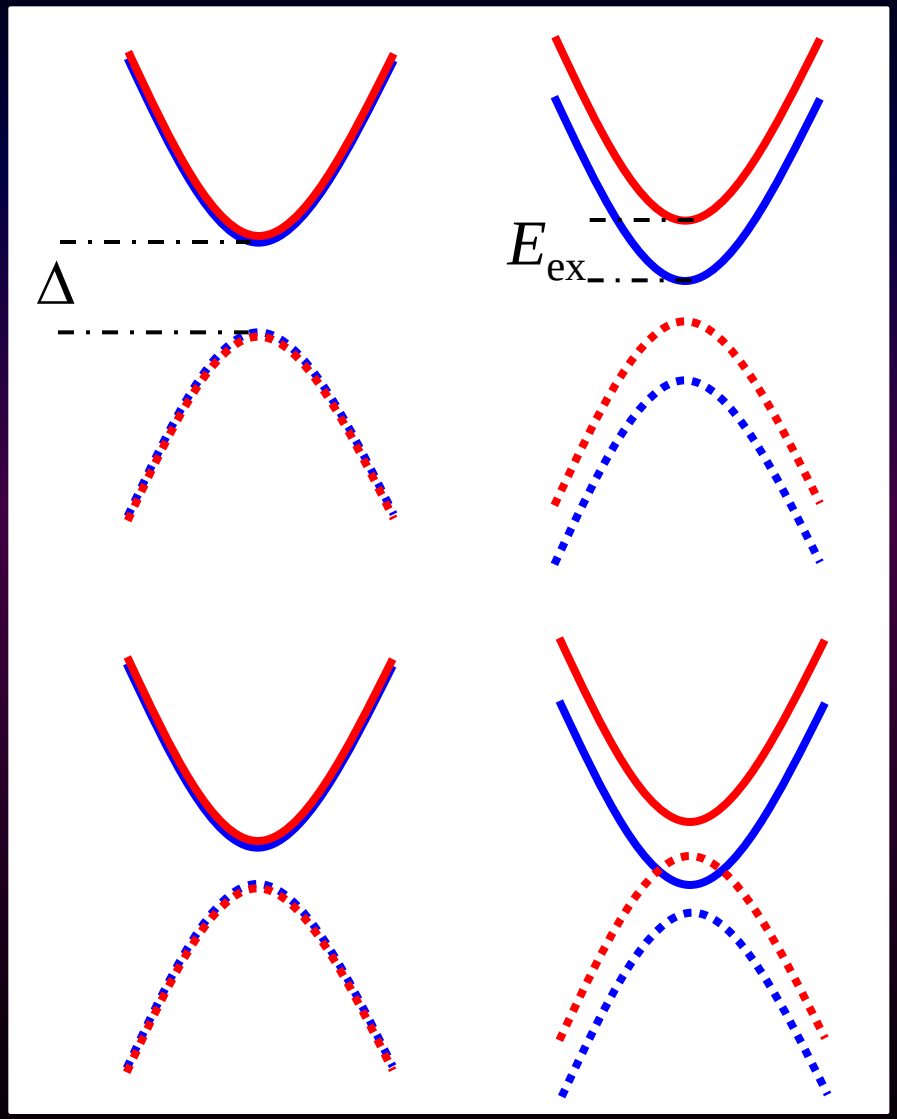
Thickness dependence of the QAHE in Cr-doped $(Bi,Sb)_2Te_3$ film (low field)



@5 K

@30 mK

Lower thickness limit of a QAH film



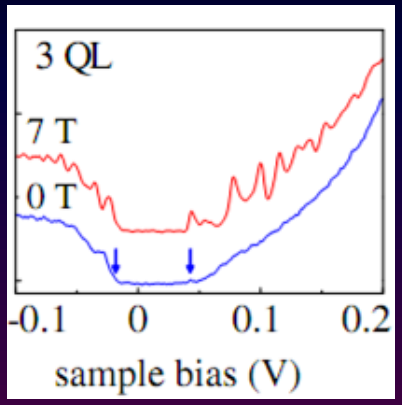
$\Delta > E_{ex}$: trivial

$\Delta < E_{ex}$: QAH

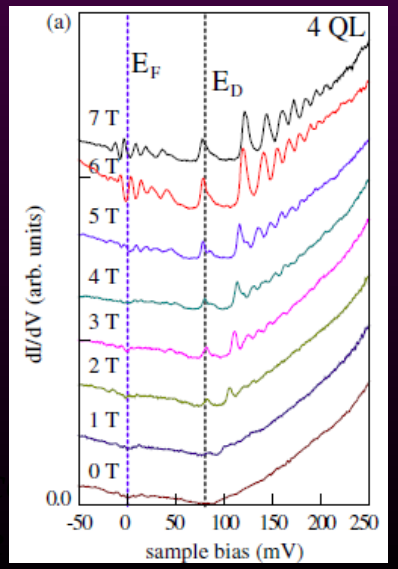
Landau levels of the SSs of Sb_2Te_3

Y. Jiang et al., PRL 2012

3 QL : Δ ~ 50 meV

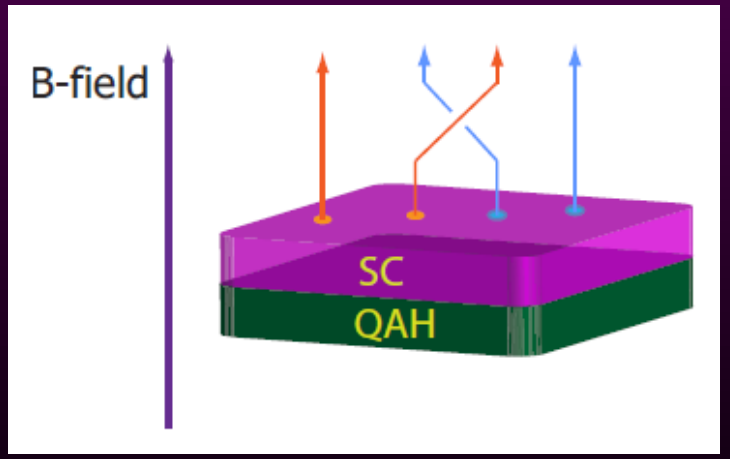


4 QL : Δ < 1 meV



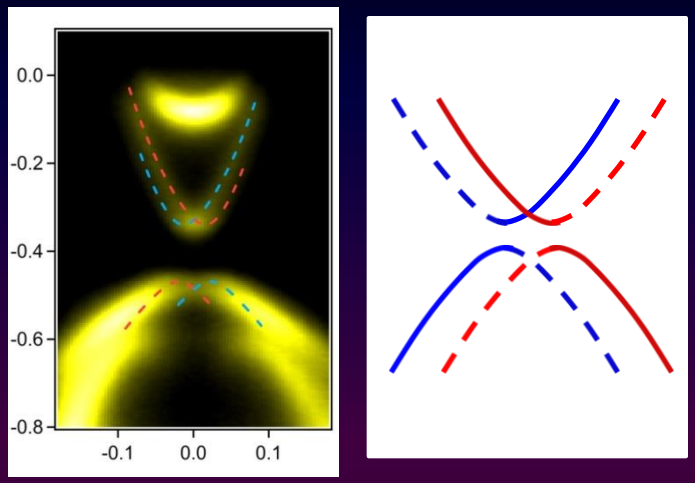
Outlook

- QAHE at higher temperature
- High order QAHE (Jing Wang, PRL 2008)
- QAH-based topological superconductors (X.–L. Qi, PRB 2010)
- ……

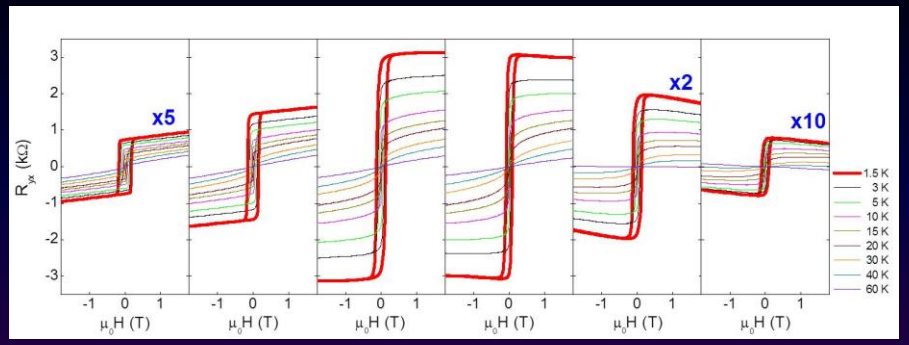


Summary

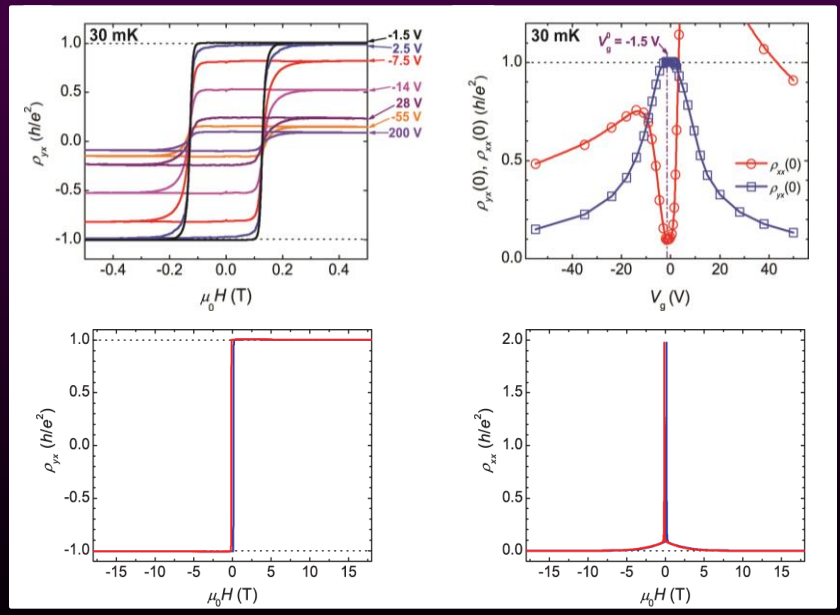
- **MBE-grown TI thin films**



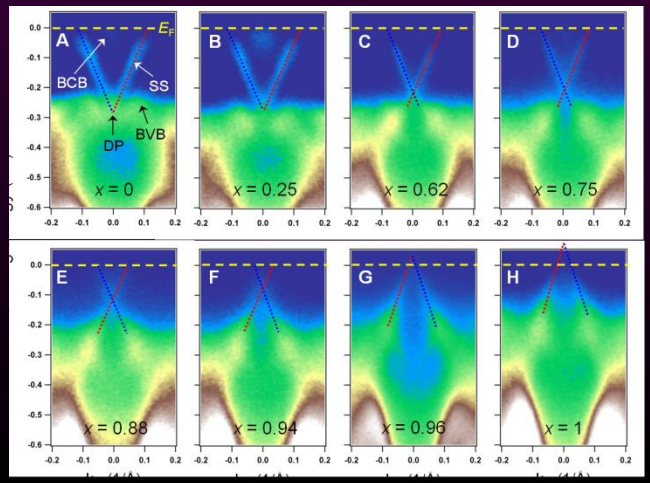
- **Magnetically doped TI thin films**



- **QAHE**

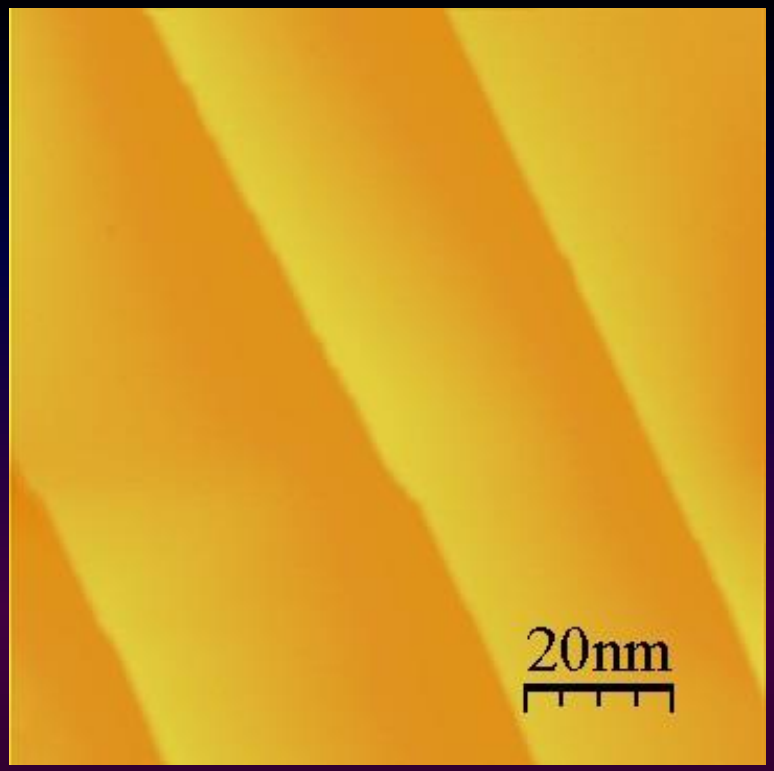


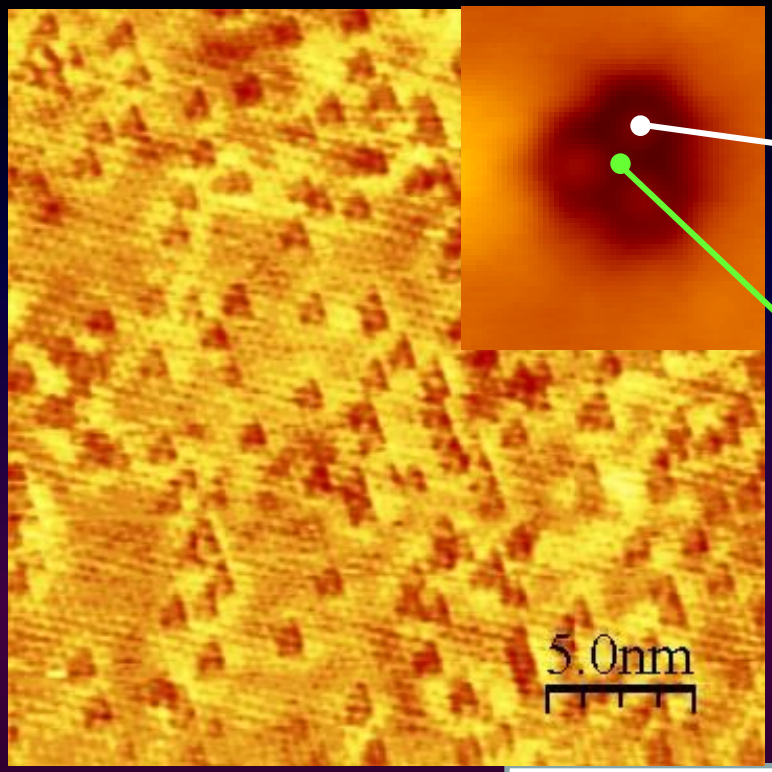
- **Chemical potential tuning**



Thank you for your attention !

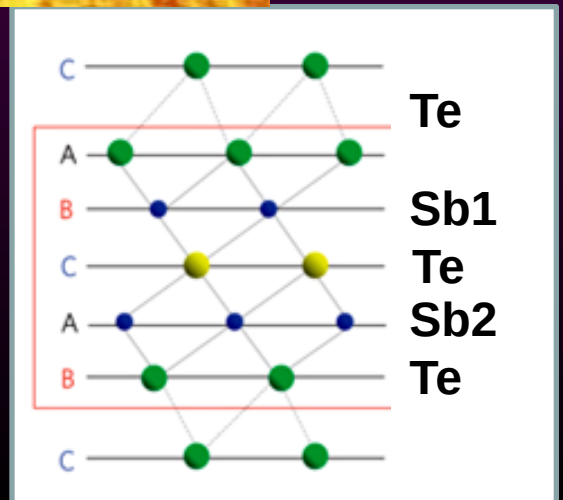
STM of Cr doped Sb_2Te_3



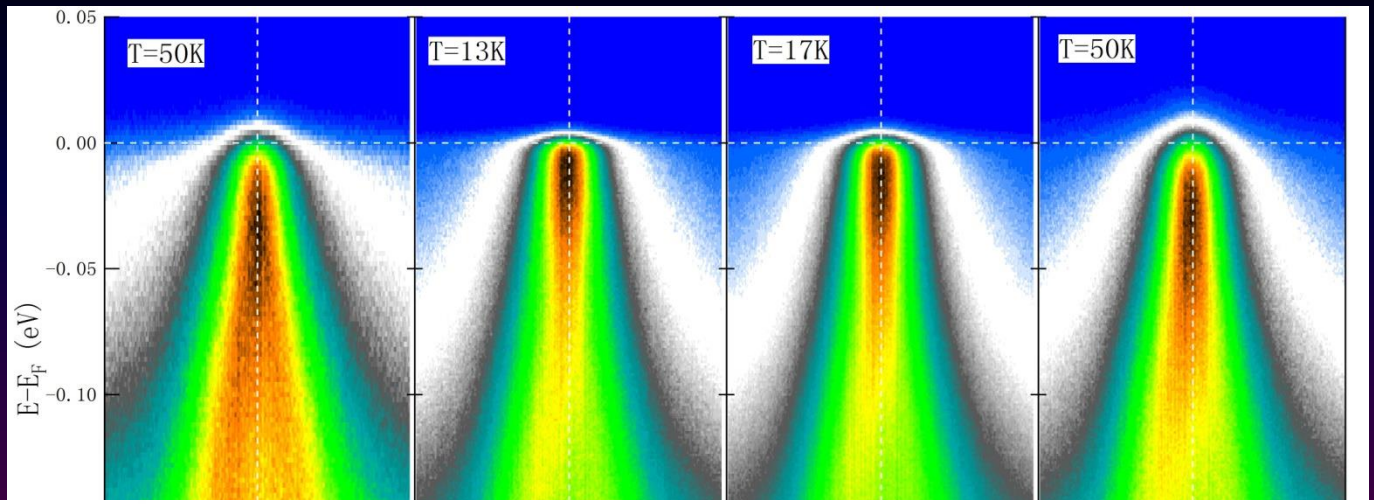


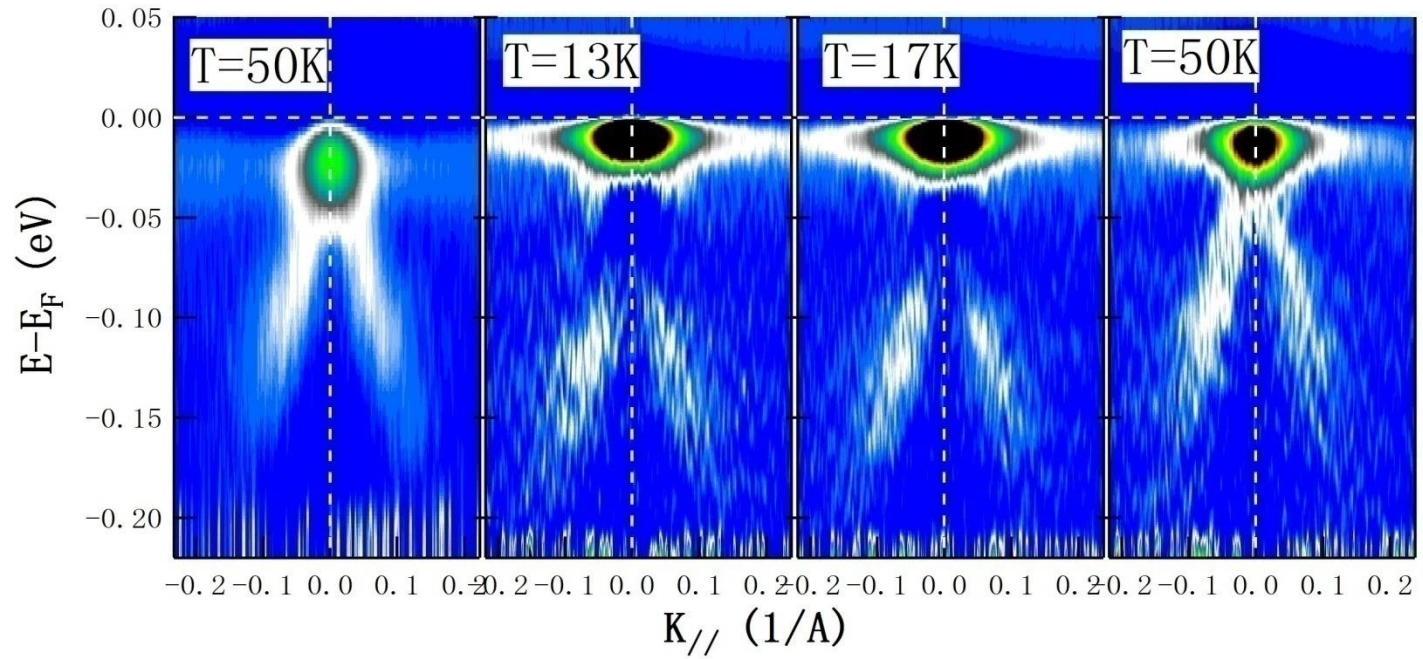
Cr atoms

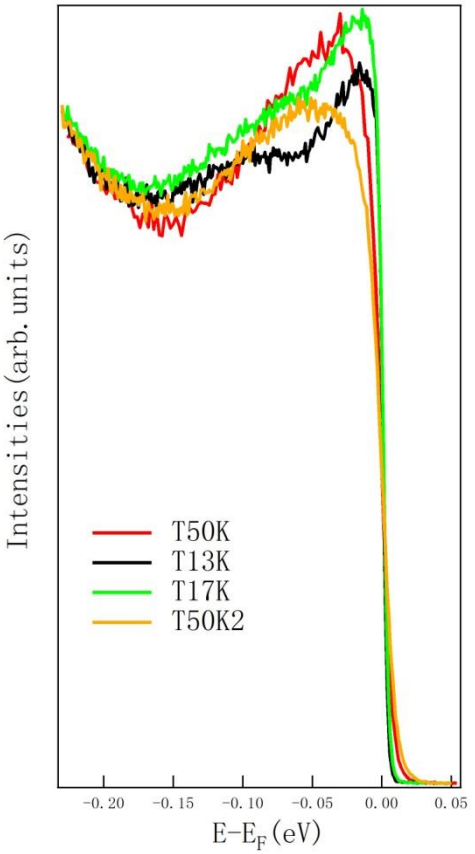
- No Clustering
- Occupying Sb sites!



LT-ARPES in Xingjiang Zhou's Lab (IOP)







Cr-doped $(Bi_{0.5}Sb_{0.5})_2Te_3$
Tc ~ 40K