The State University of New Jersey
Rutgers
Department of Physics and Astronomy

Seminar in physics

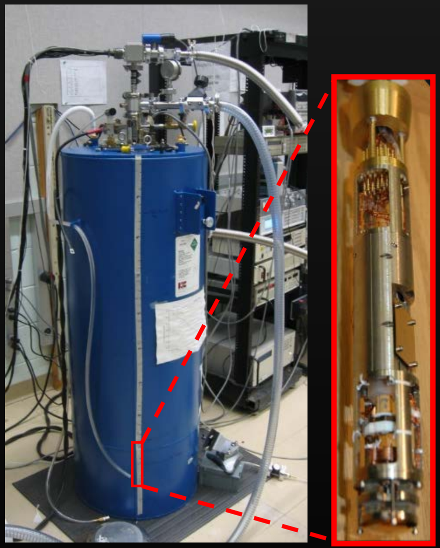
SPM lab

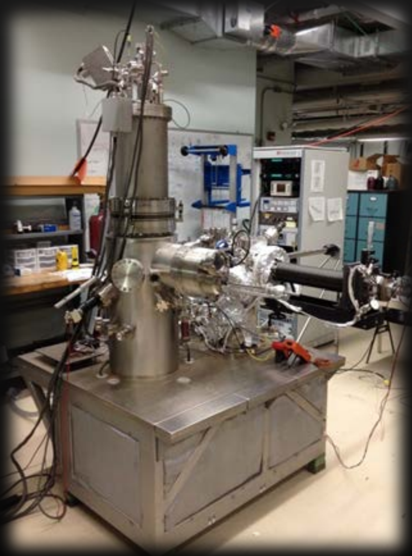
Magnetic and spectroscopic imaging of topological quantum materials

Weida Wu

Department of Physics & Astronomy, Rutgers University

Magnetic Force Microscopy

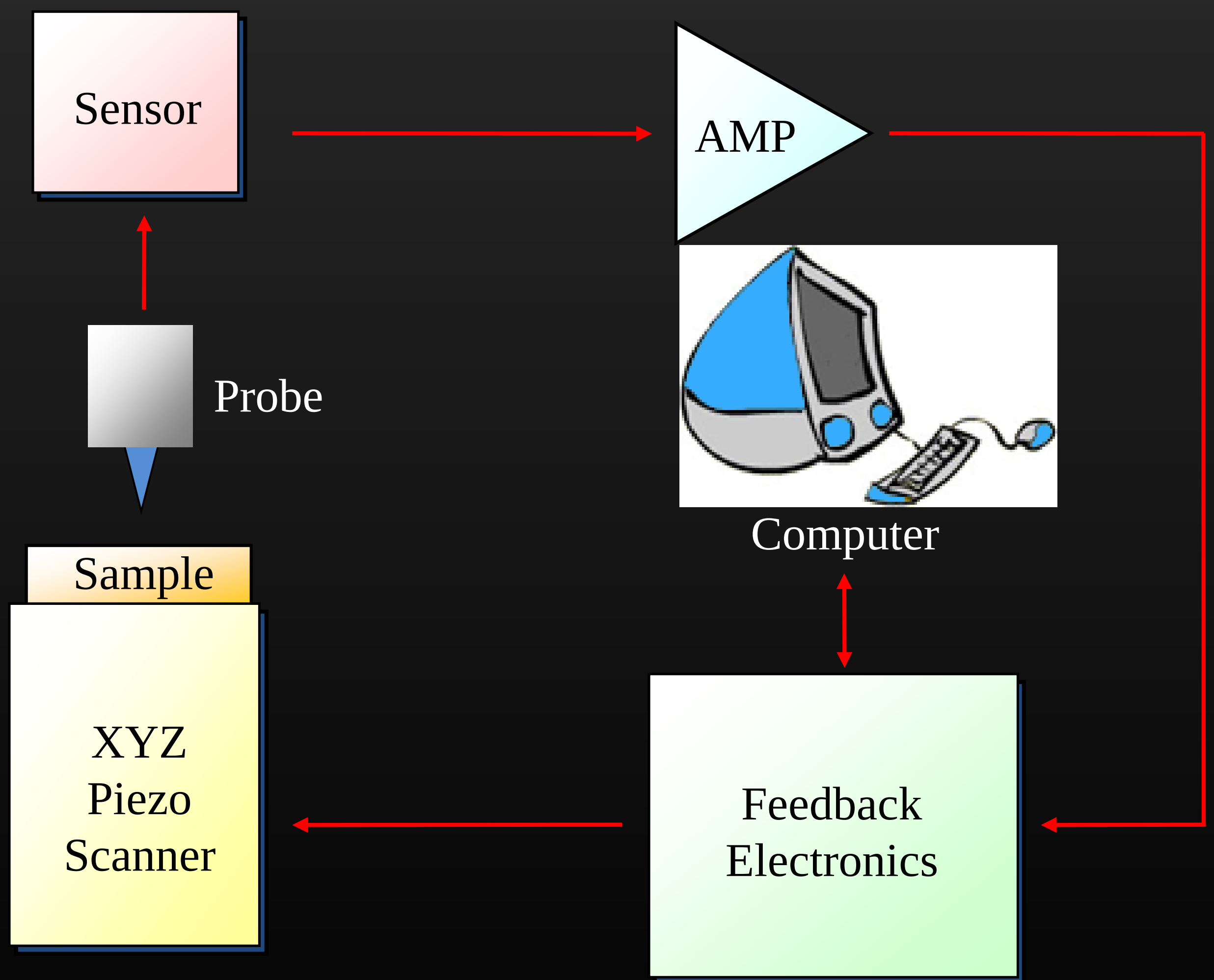




Scanning Tunneling Microscopy

09/07/2021

Scanning Probe Microscopy (SPM)



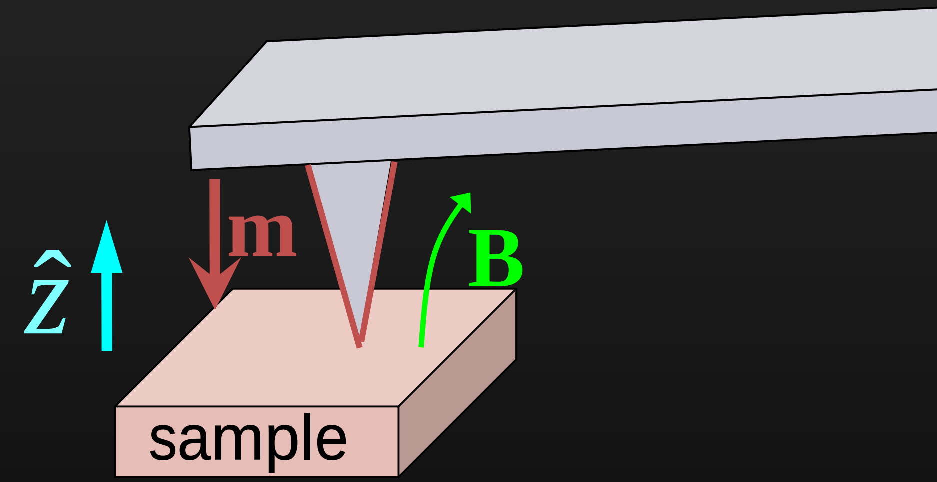
Probe signal: tunneling, force, optical, thermal, capacitance …

Magnetic force microscopy (MFM)

- Ferromagnetic material on sharp tip attached to cantilever

- Magnetic force gradient causes effective change of spring constant *k*

- Drive cantilever at resonance, measure frequency shift as sample is scanned



$$U = -\mathbf{m}\cdot\mathbf{B}$$

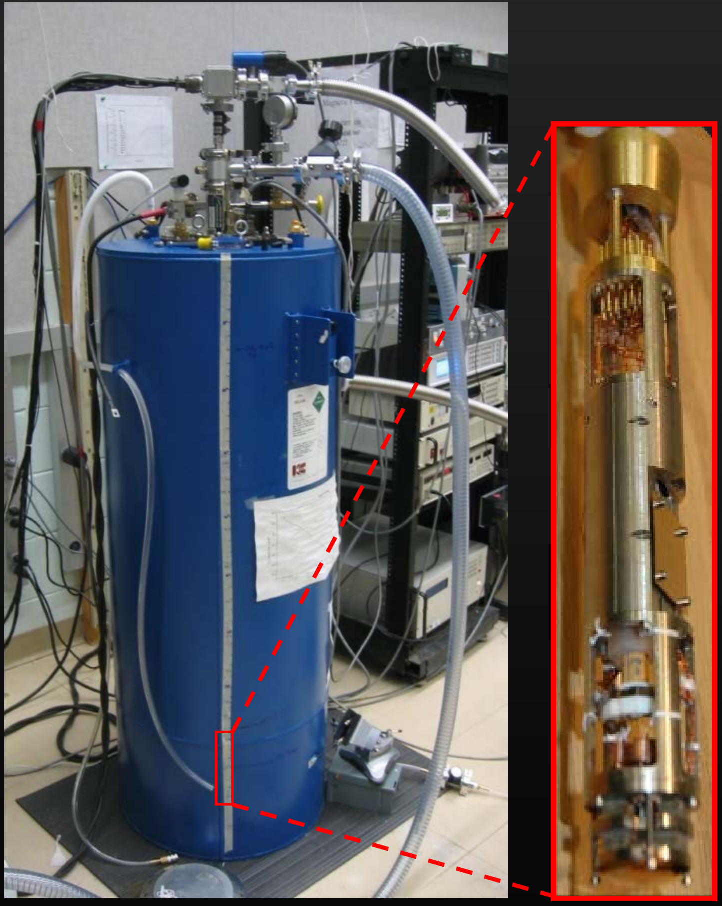
$$\mathbf{F} = -\nabla U$$

$$f = f_0 \left(1 - \frac{F'_z}{k}\right)^{\frac{1}{2}} \rightarrow \frac{\Delta f}{f_0} = -\frac{1}{2k} F'_z \rightarrow \frac{\Delta f}{f_0} = -\frac{m_z}{2k}\frac{\partial^2 B_z}{\partial z^2}$$

Homemade Variable Temperature-MFM

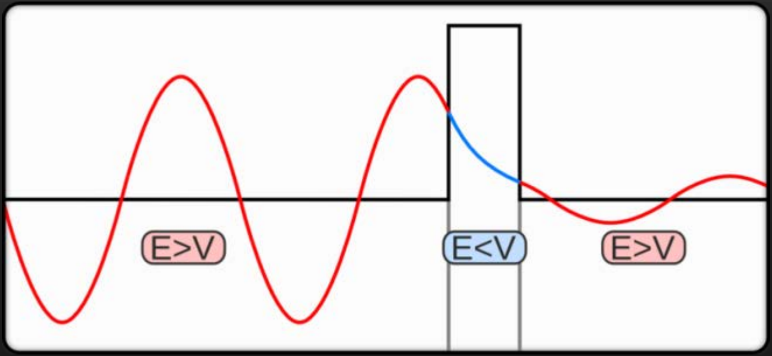
- Var. *T* (**2 – 200 K**) & high *H* (**8 T**)
- High vacuum (<1E-6 mbar)
- High resolution (20-50 nm)
- High sensitivity (~10^5 μ_B)
  - Weak ferromagnets.
  - Domain walls in antiferromagnets
- ***in-situ* high voltage (1 kV)**
  - Magnetoelectric Force Microscopy **(MeFM)**
  - Gating
- ***in-situ* transport**
  - Quantum anomalous Hall effect **(QAHE)**
  - Topological Hall effect **(THE)**

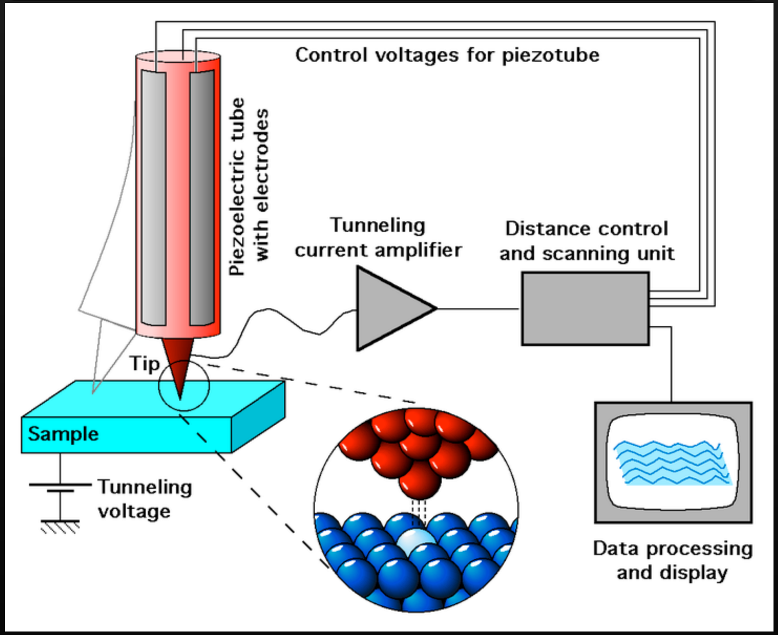
VT-MFM



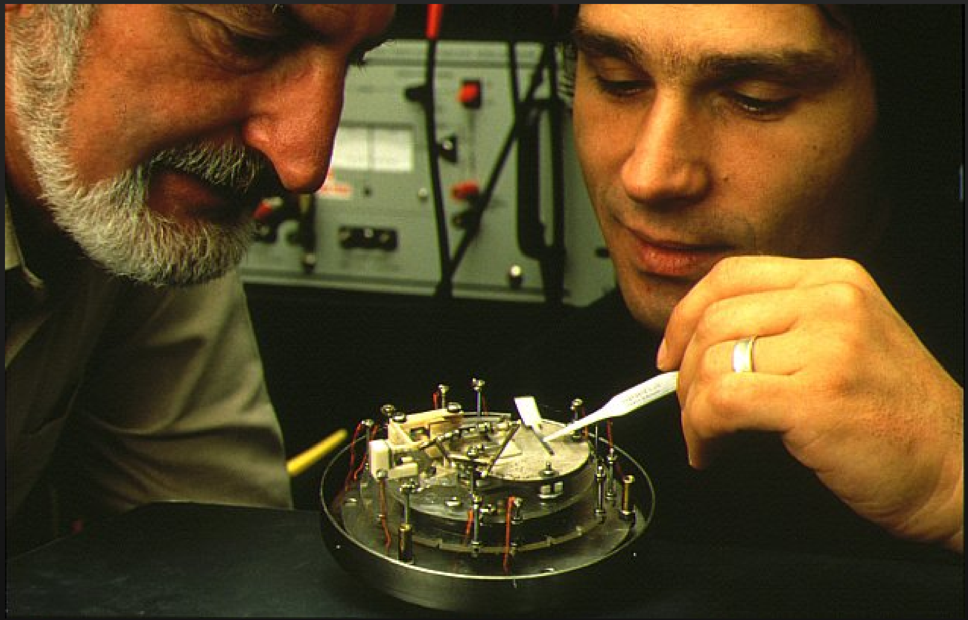
Under construction: 300 mK/14 T MFM

Scanning Tunneling Microscopy (STM)





$$\frac{dI}{dV} \propto \rho_S(E_F - eV)$$



Rohrer and Binnig with STM

- Nobel Prize in 1986
- “See” individual atoms
- Manipulate atoms
- Spectroscopy (LDOS)

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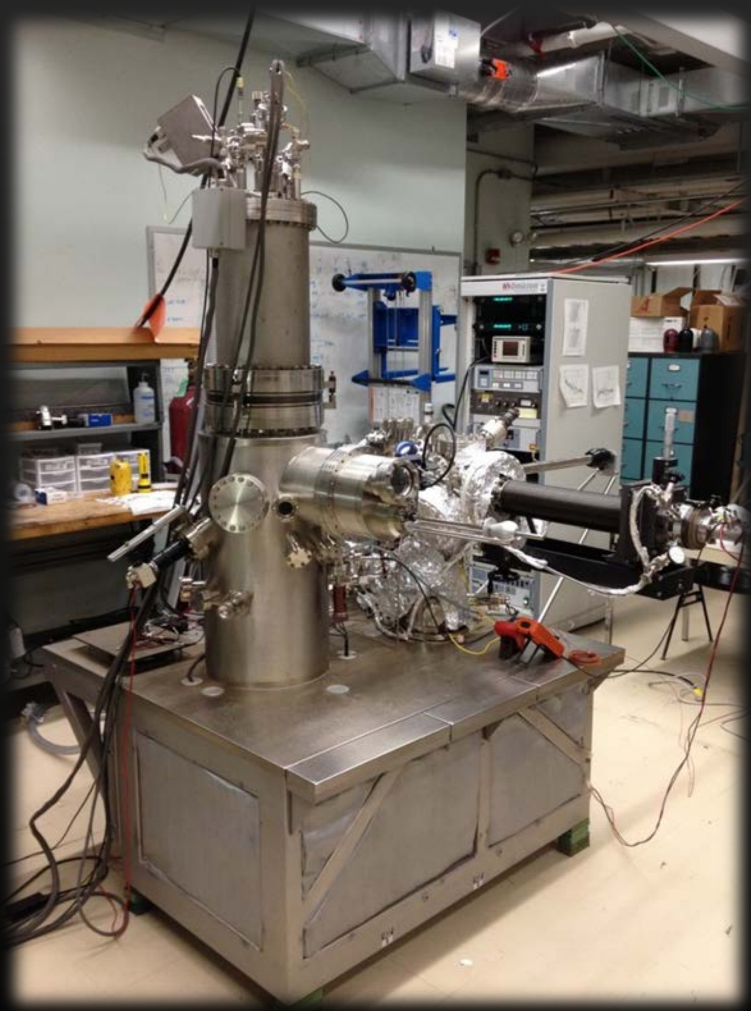
UHV-LT-STM in SPM lab

SPM lab



UHV: $P_{base} \sim 1\times10^{-11}$ mbar

T : 4.5 – 300 K

z-noise: ~ 1-2 pm

SP-STM

In-situ tip/sample prep

Sample heater

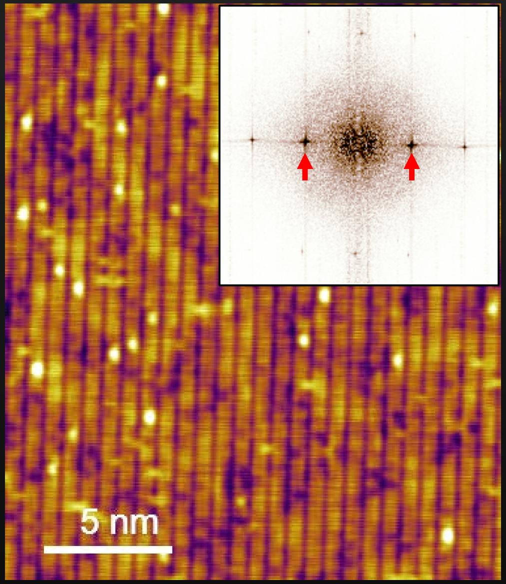
Ion sputtering

E-beam evaporators

In-situ cleavage

Se/Te decapping low temperature

$Fe_{1+y}Te$



Enayat, M. et al, Science **345**, 653 (2014).

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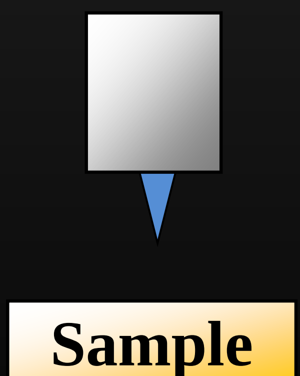
Research Overview

Materials Science

Topological insulators/semimetals/magnets, Topological spin texture and Hall effects, Multiferroics and Magnetoelectrics, CMR manganites, Superconducting vortices, …

Scanning Probe Microscopy (SPM)



- Magnetic Force Microscopy (MFM)
  - ➢ Magnetoelectric Force Microscopy (MeFM)
- Piezo-response Force Microscopy (PFM)
- …
- Scanning Tunneling Microscopy (STM)
  - ➢ Spectroscopy-imaging STM (SI-STM)
  - ➢ Spin-polarized STM (SP-STM)

supported by

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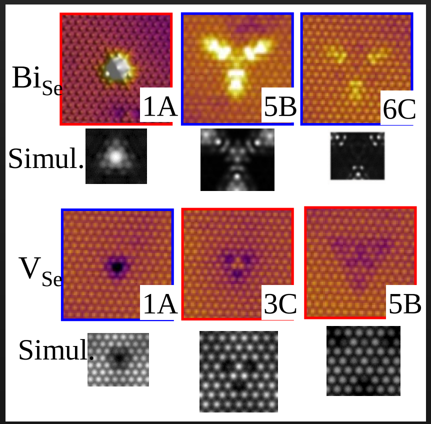
Recent works in my group

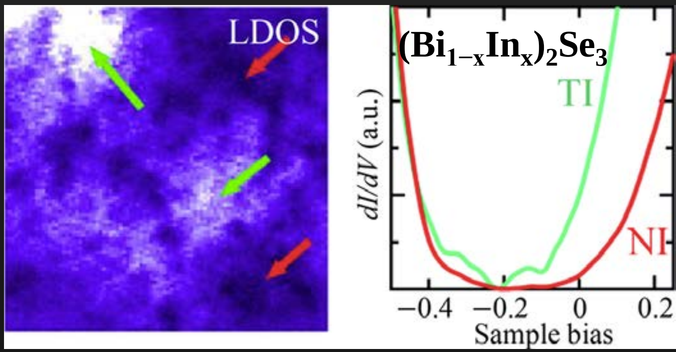
Geng, et al, Nature Mater., **13**, 163 (2014).

Topological insulators



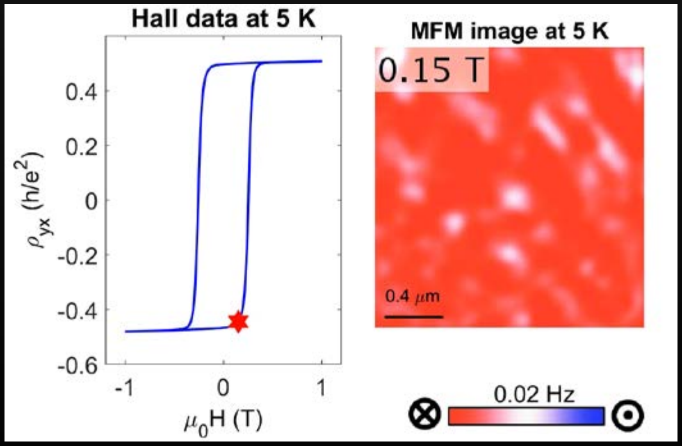
Dai, et al, PRL, **117**, 106401 (2016)

TI/NI transition



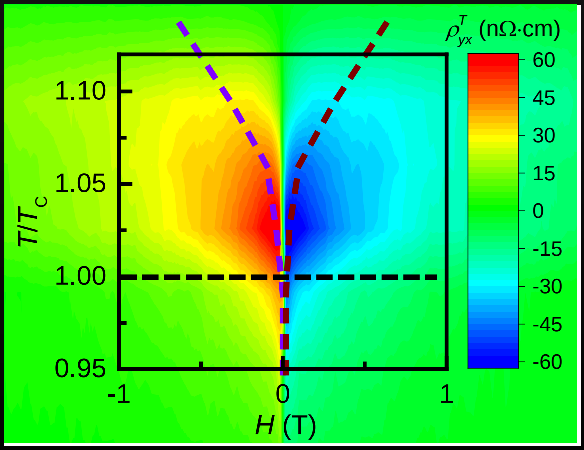
Zhang, et al, Nano Lett., **18**, 2677 (2018).

Robust FM→ enhanced QAHE



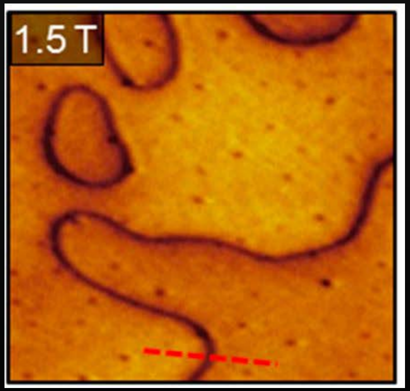
Wang, et al, Nature Phys., **14,** 791 (2018).

Chiral fluct. driven THE



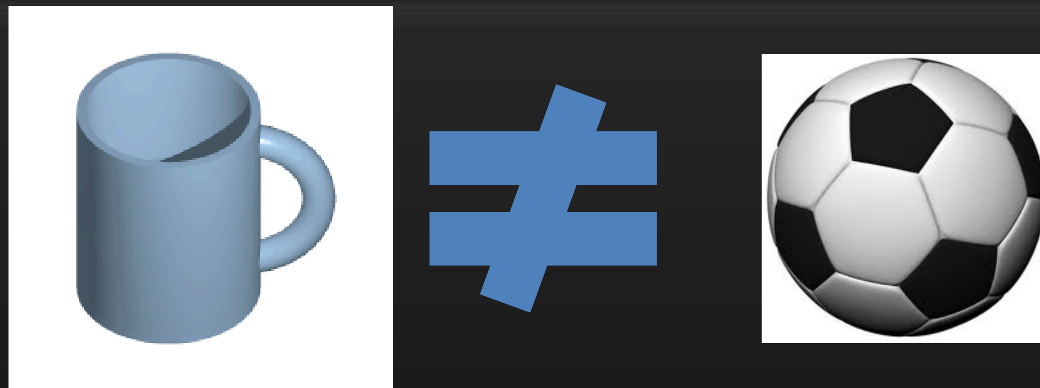
Wang, et al, Nature Mater. 18, 1054 (2019).

Domain walls in AFM-TI



Sass, et al, Nano Lett., **20**, 2609 (2020).

Topology is pervasive in physics



- Topological defects (spontaneous symmetry breaking)
  - Dislocation, Vortex, Domain wall, Solitons, Monopoles, Strings, …
- Topological phase transitions (e.g. KT transition)
- Quantum Hall effect (Topological Landau bands)
- Topological insulators, Weyl/Dirac semimetals
- QAHE, axion insulators, high order topological insulators
- …

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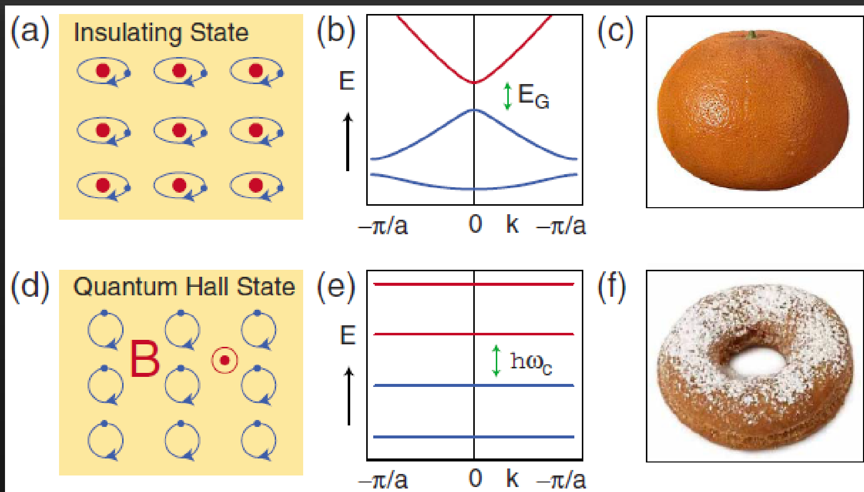
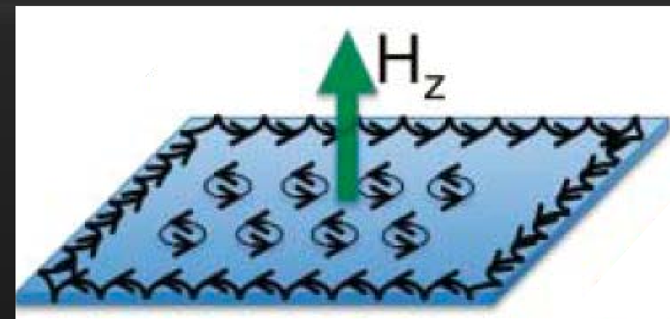
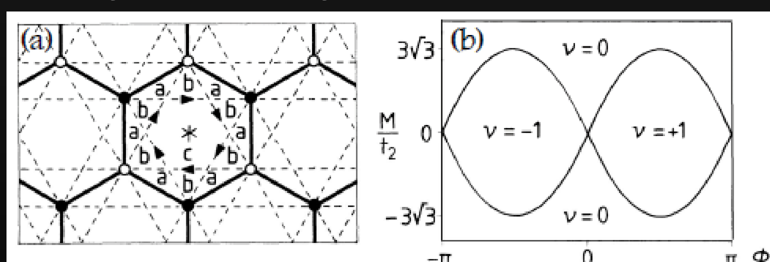
QH states: the first topologically non-trivial insulator!

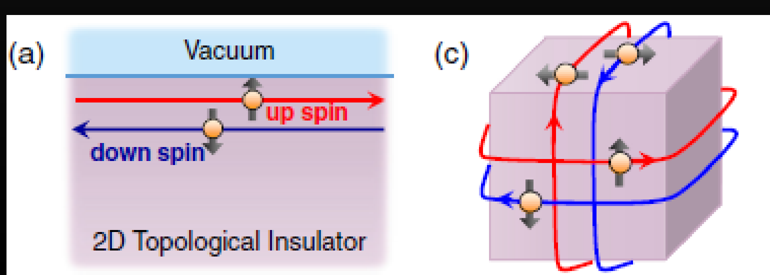




Dissipationless conduction electronic highway

QAHE: QHE without *H*

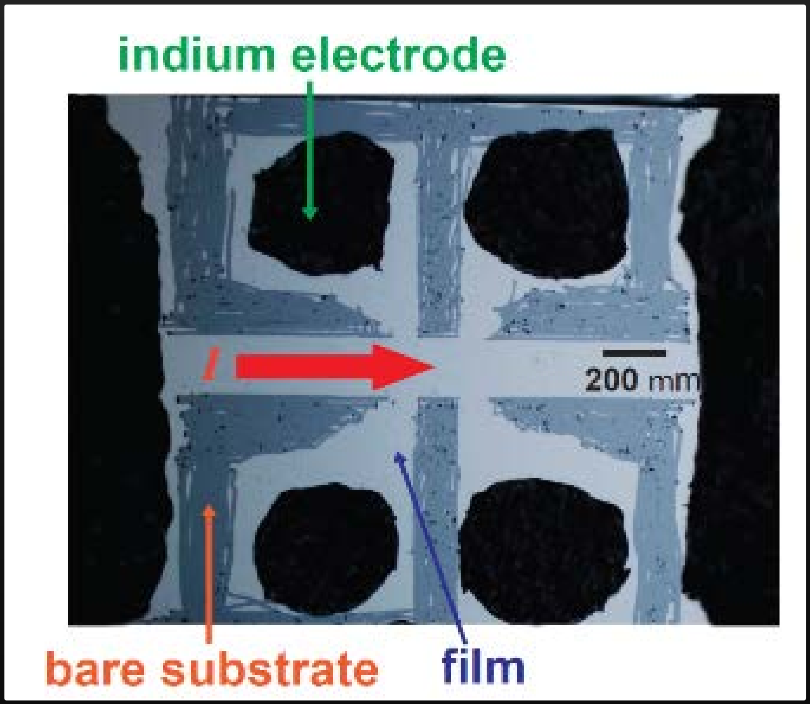




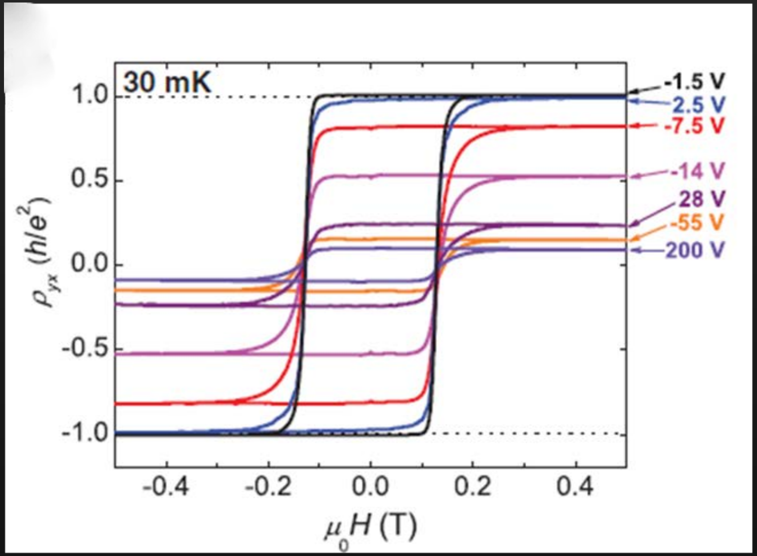
K. v. Klitzing et al, PRL **45,** 494 (1980)
TKNN, PRL **49**, 405 (1982)
Haldane, PRL 61, 2015 (1988)
Kane & Mele PRL, (2005).
Bernevig, Hughes, Zhang, Science (2006).
Fu, Kane & Mele PRL (2007).
Hasan, Kane, RMP (2010).

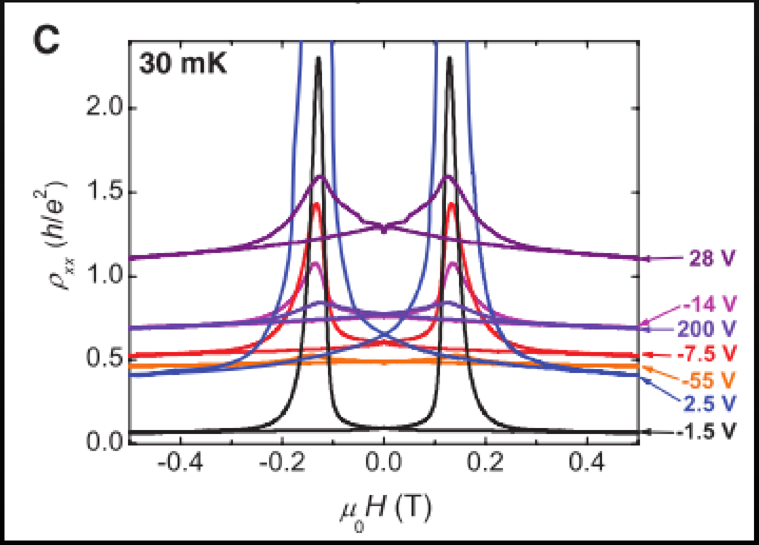
Demonstration of QAHE in magnetic TI thin films

Cr-doped $Sb_{2-x}Bi_xTe_3$ thin film

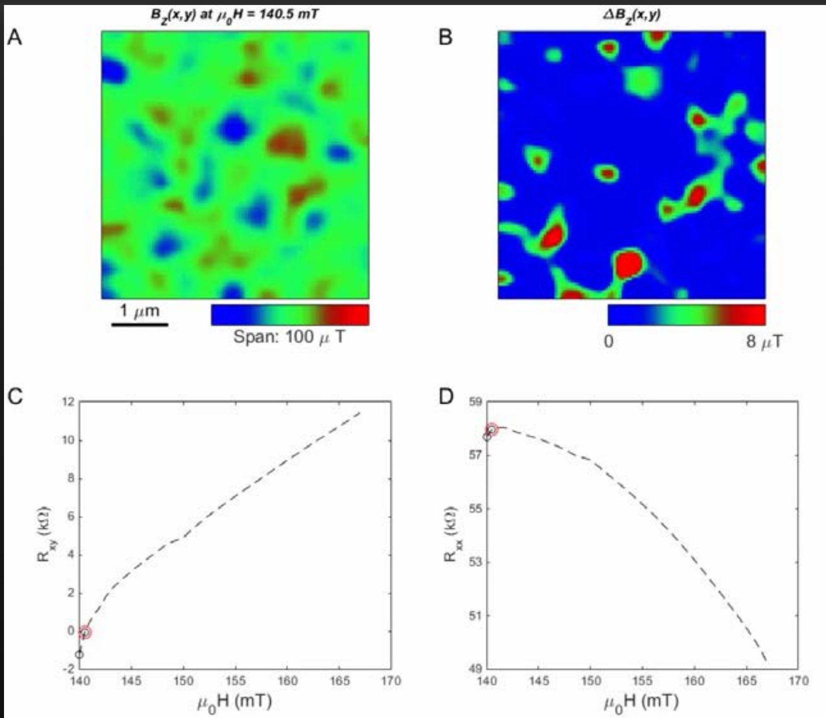


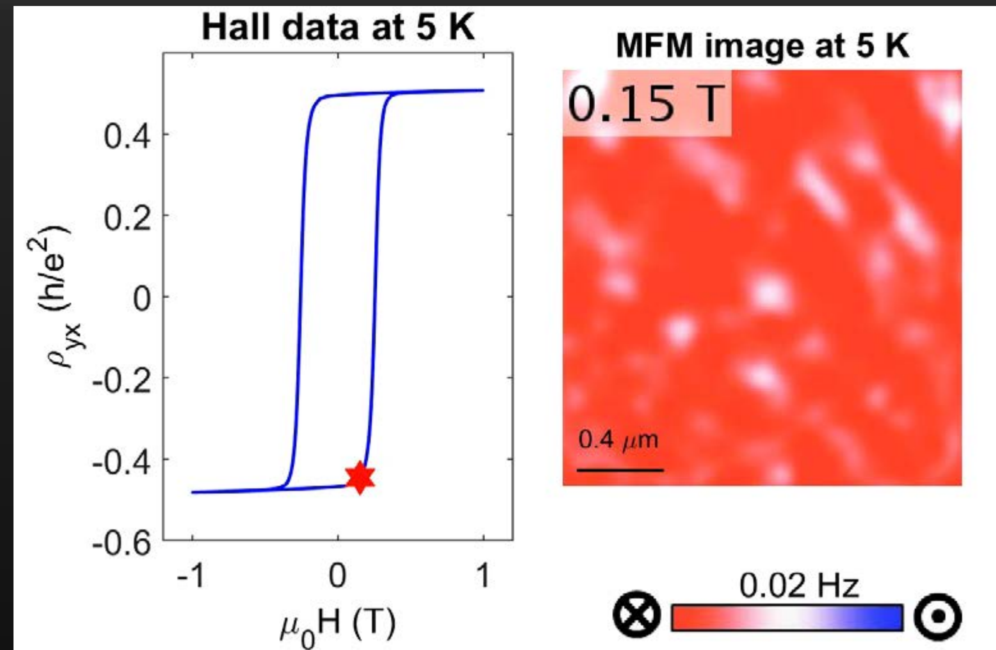
C.-Z. Chang et al., Science **340**, 167 (2013).
J. G. Checkelsky et al., Nat. Phys. **10**, 731(2014).
X. Kou et al., PRL, **113**, 137201 (2014).
Bestwick, et al, PRL, **114**, 187201 (2015)





FM domain behavior → long range order



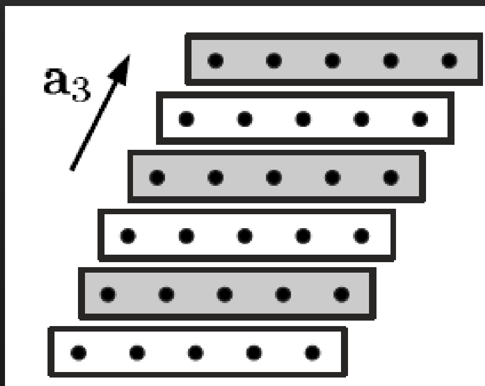


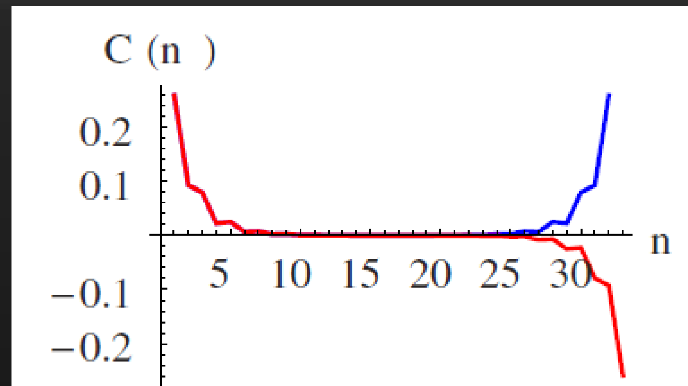
Lachman et al., *Sci. Adv.* 1, e1500740 (2015)

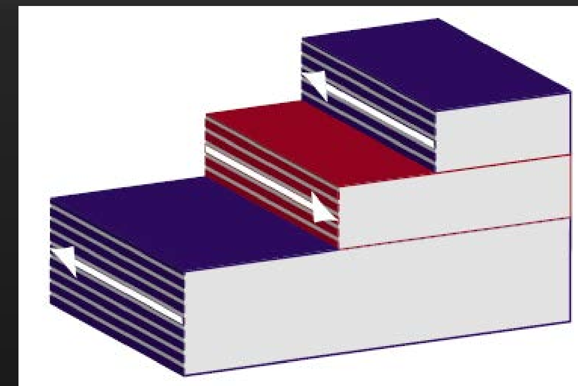
Wang et al, *Nature Phys.* **14**, 795, (2018)

Robust ferromagnetism → enhanced QAH Temperature

AFM + TI → AFTI (Z_2)

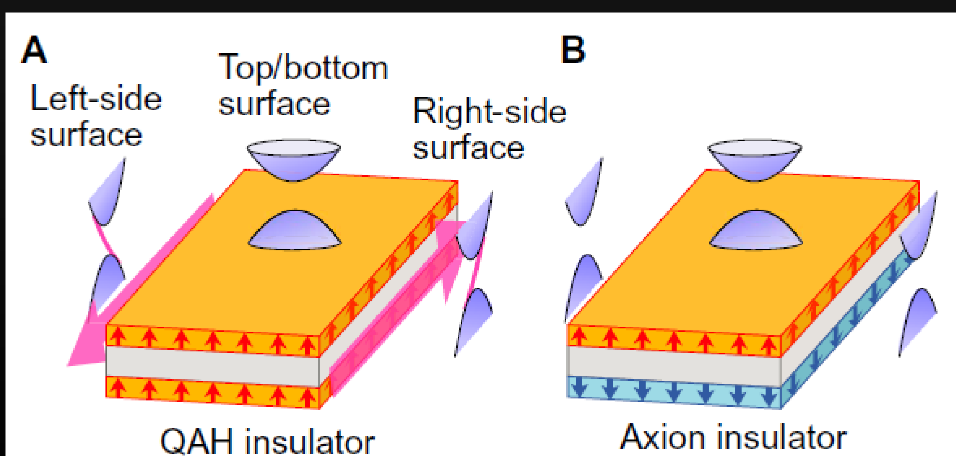




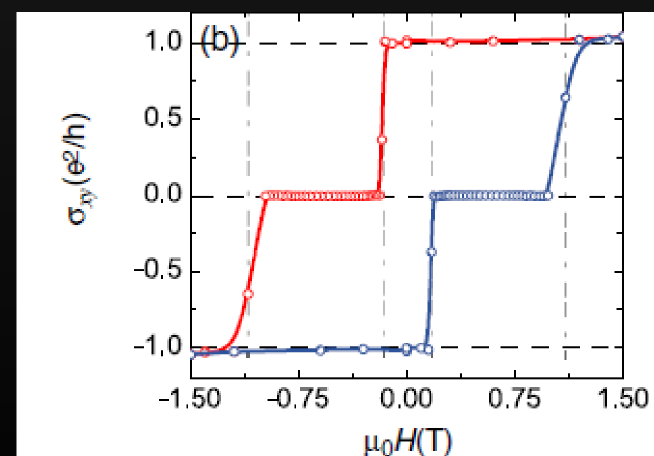


Mong et al, PRB, **81**, 245209 (2010).

Artificial AFTI: topological axion insulator

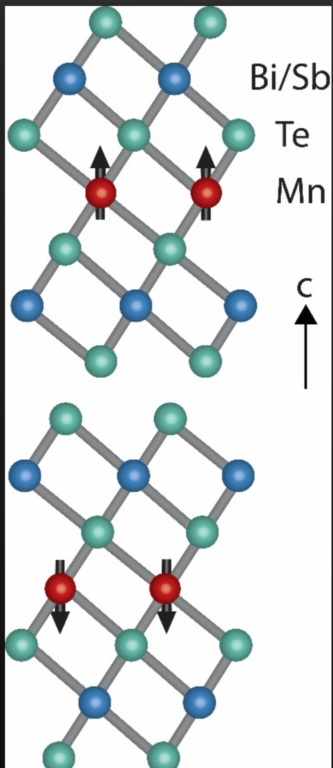


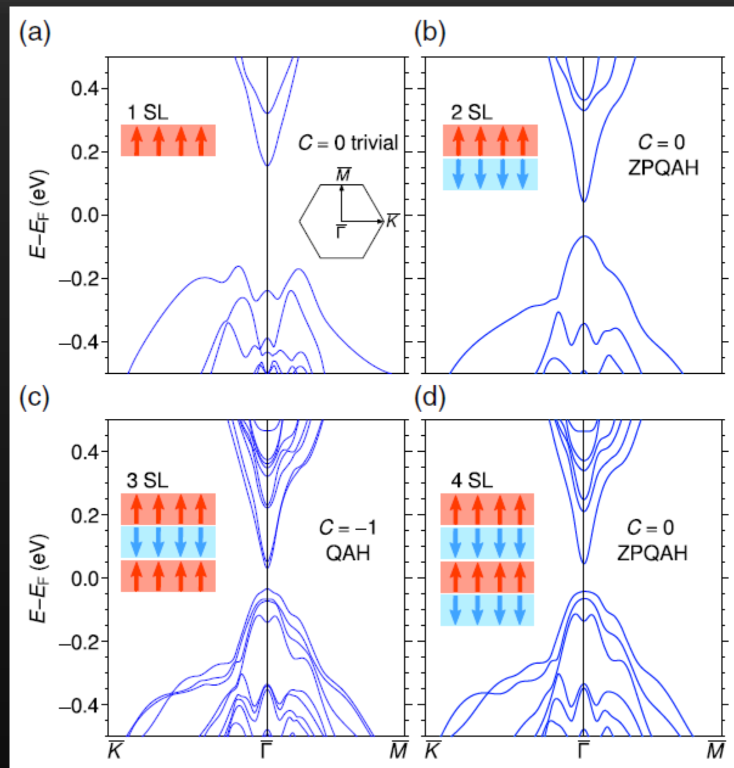
Tokura, Nature Rev. Phys., **1**, 126 (2019).

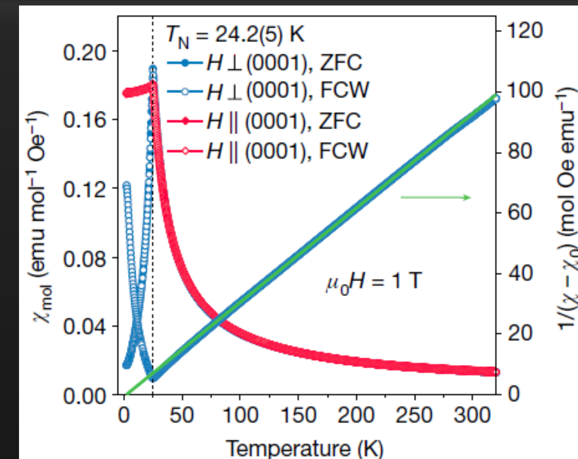


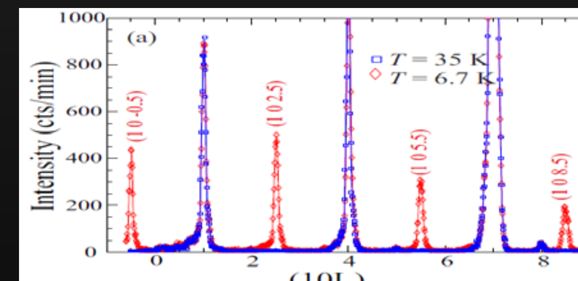
Xiao et al, PRL, **120**, 056801 (2018)
Mogi et al, Sci. Adv., **3:** eaao1669 (2017).

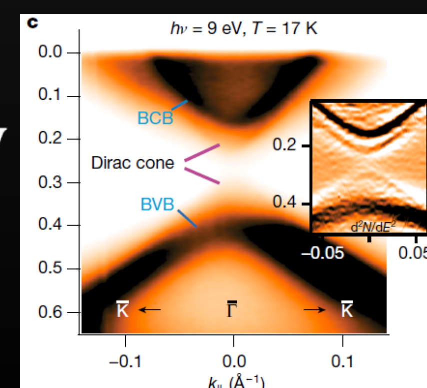
$MnBi_2Te_4$: the first AFM-TI











$\Delta_D \sim 70$ meV

Mong et al, PRB, **81**, 245209 (2010).
Lee et al, CrystEngComm., **15**, 5532 (2013).
Otrokov et al, PRL, **122**, 107202 (2019).
Gong et al, Chin. Phys. Lett. **36**, 076801 (2019).
Otrokov et al, Nature, **576**, 417 (2019).
Yan, et al, PR Mater., **3**, 064202 (2019)

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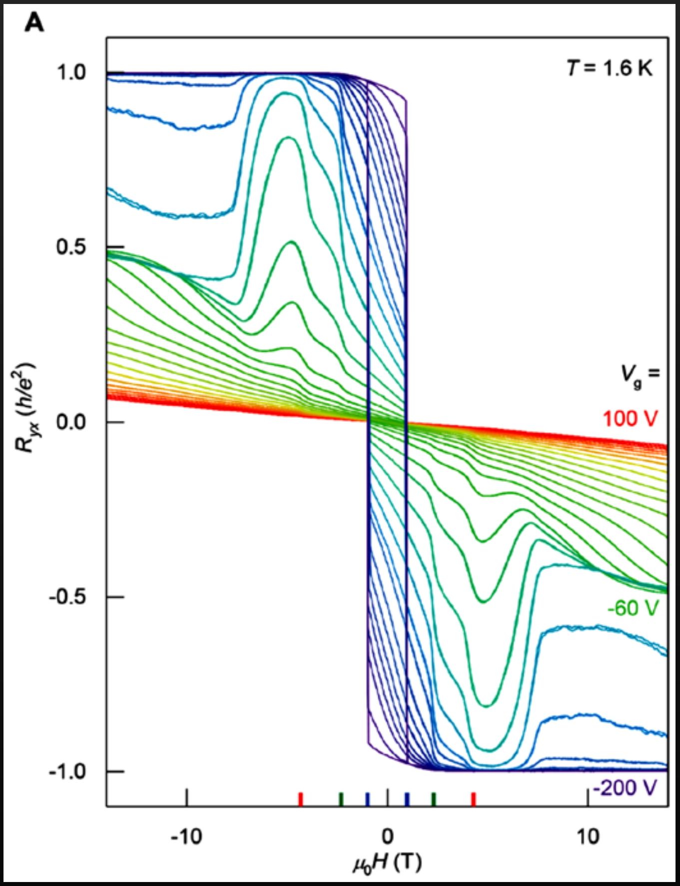
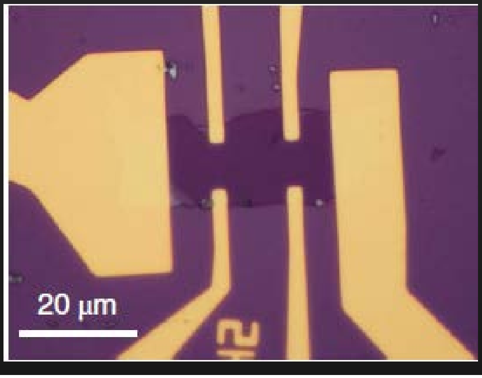
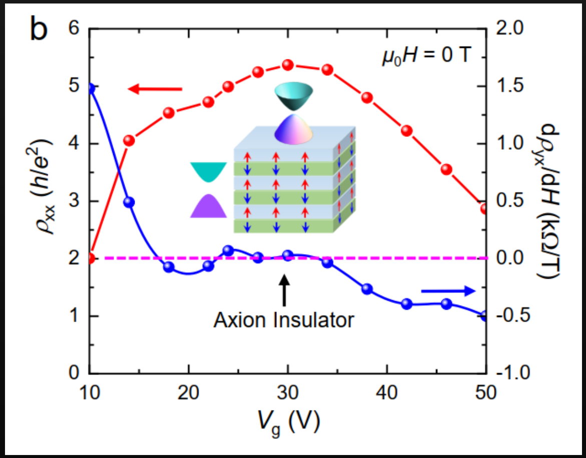
Quantized transport in MBT flakes

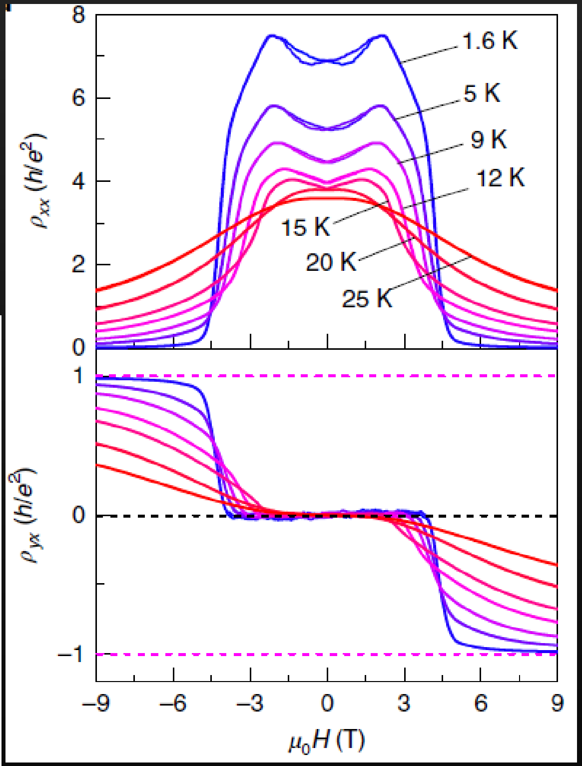
5 SL flake



6 SL flake



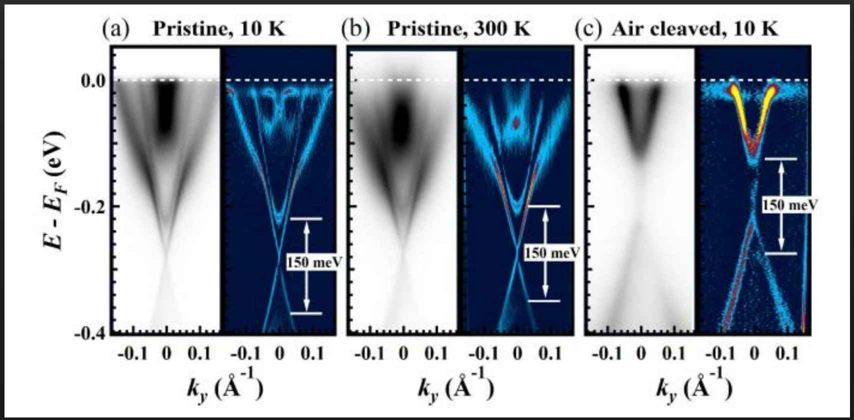


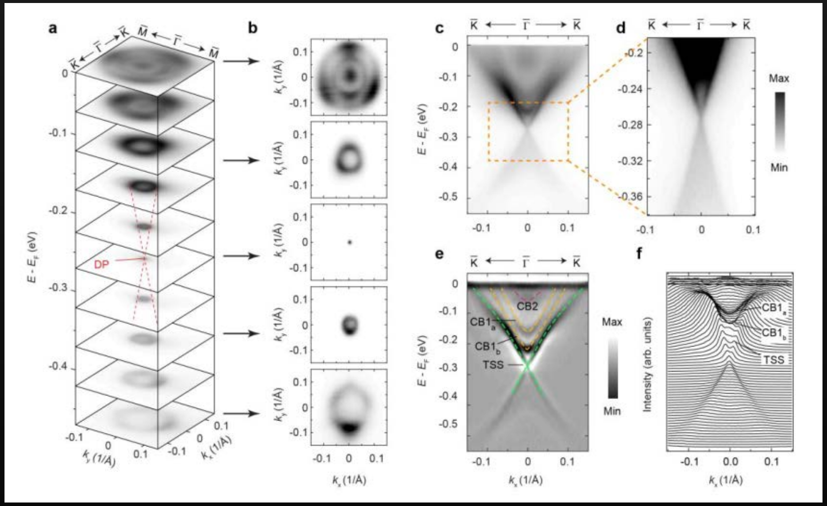


Deng et al, Science, **376**, 895 (2020)

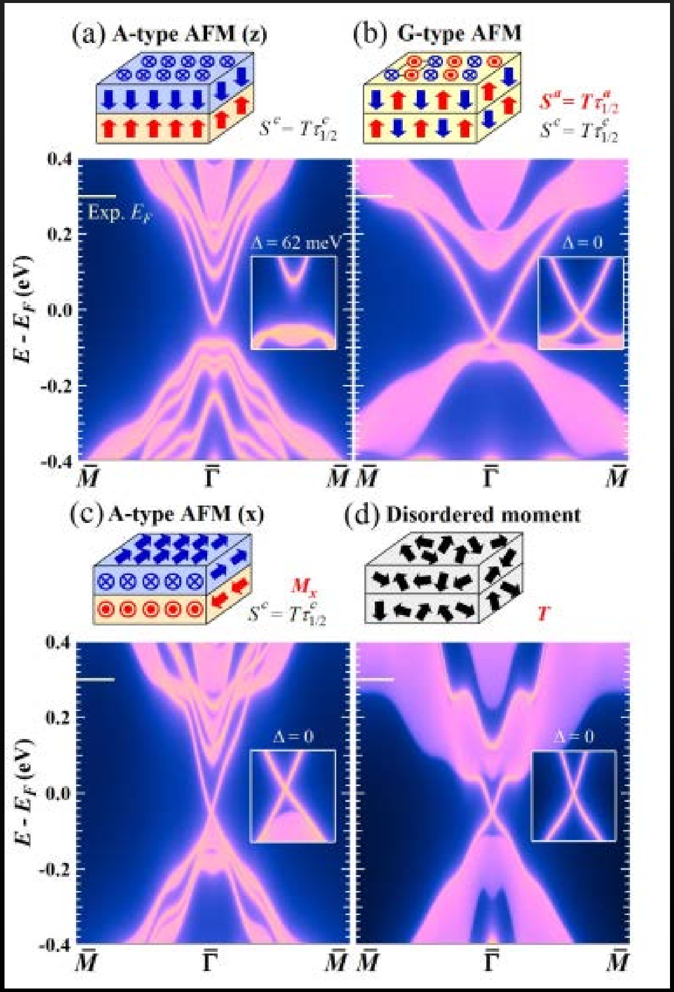
Liu et al, Nat. Mater., **376**, 895 (2020)

Gap or no gap? → nano domains or surface relaxation?



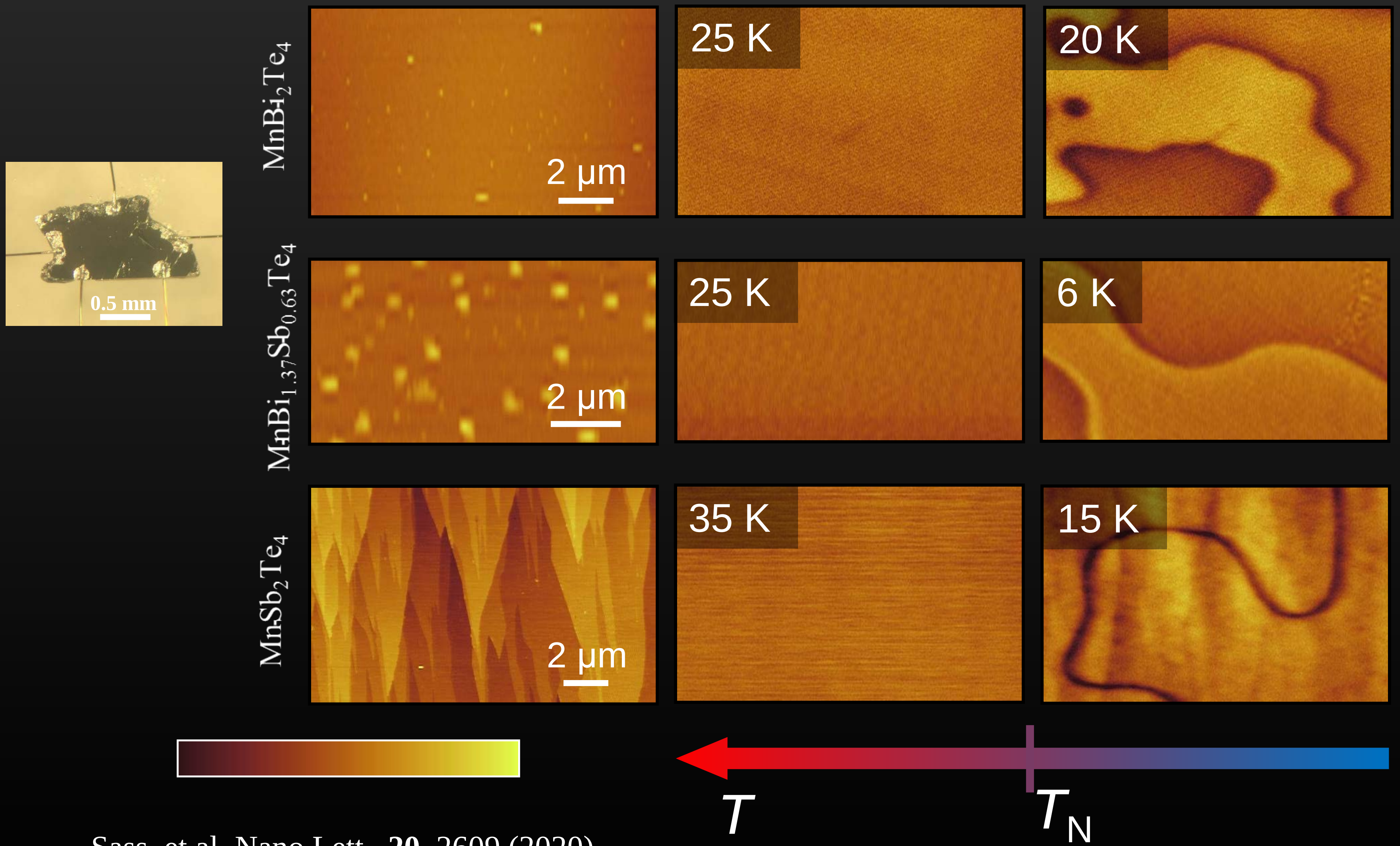


Dense AFM domain walls (?)
Surface relaxation (?)



Hao *et al. Phys. Rev. X* **9**, 041038 (2019).
Li *et al. Phys. Rev. X* **9**, 041039 (2019).
Chen *et al. Phys. Rev. X* **9**, 041040 (2019).
Swatek *et al*, *Phys. Rev. B* **101**, 161109 (2020)

MFM imaging of $MnBi_{2-x}Sb_xTe_4$



Sass, et al, Nano Lett., **20**, 2609 (2020).

Domain walls in finite magnetic field

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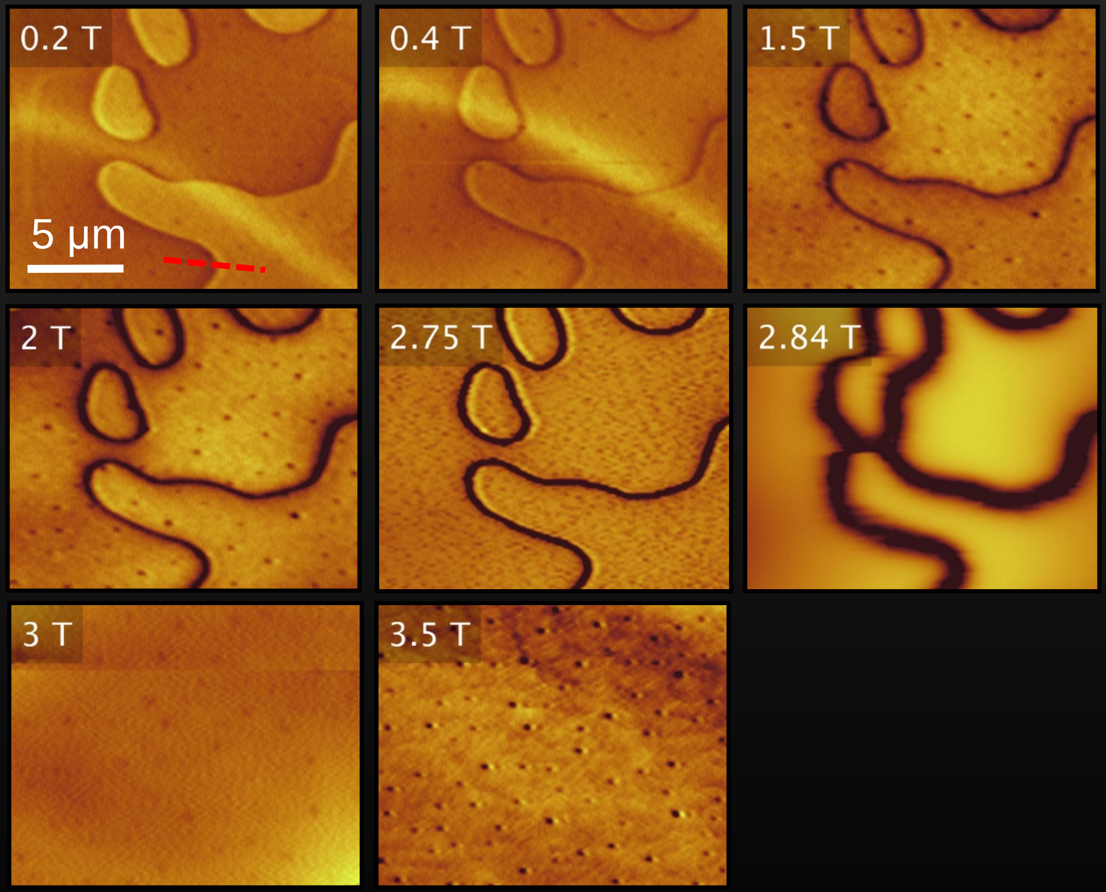
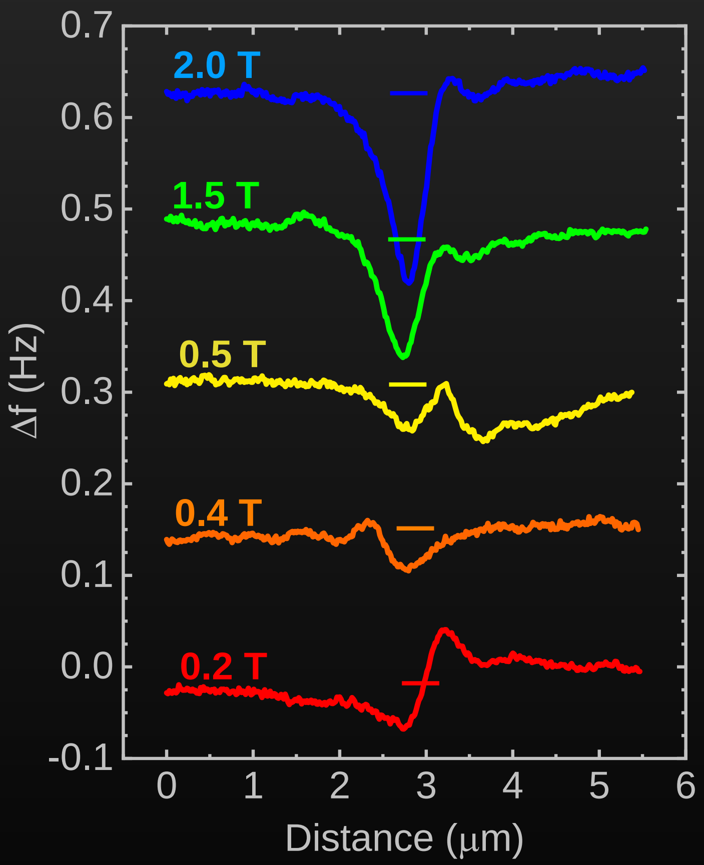
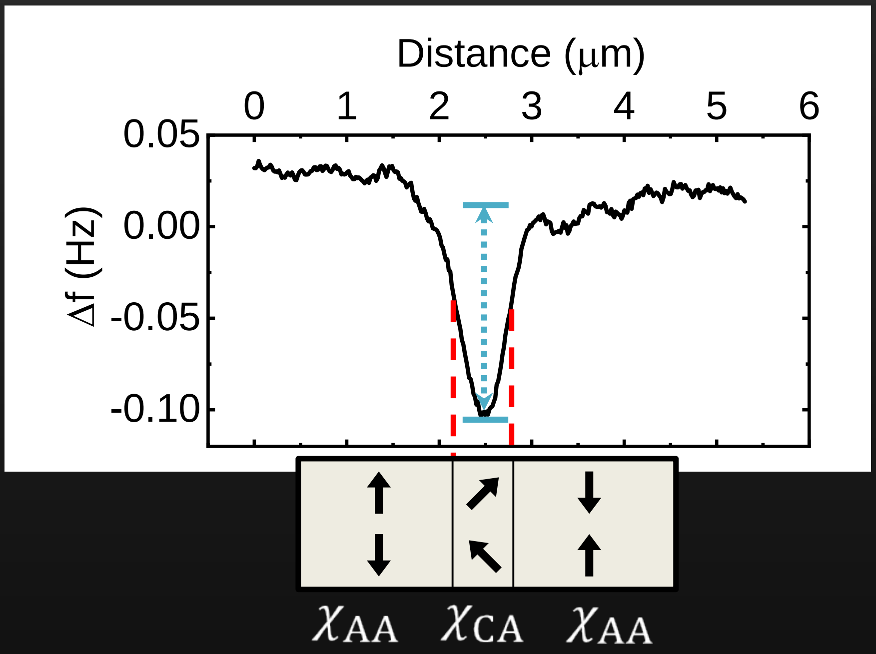
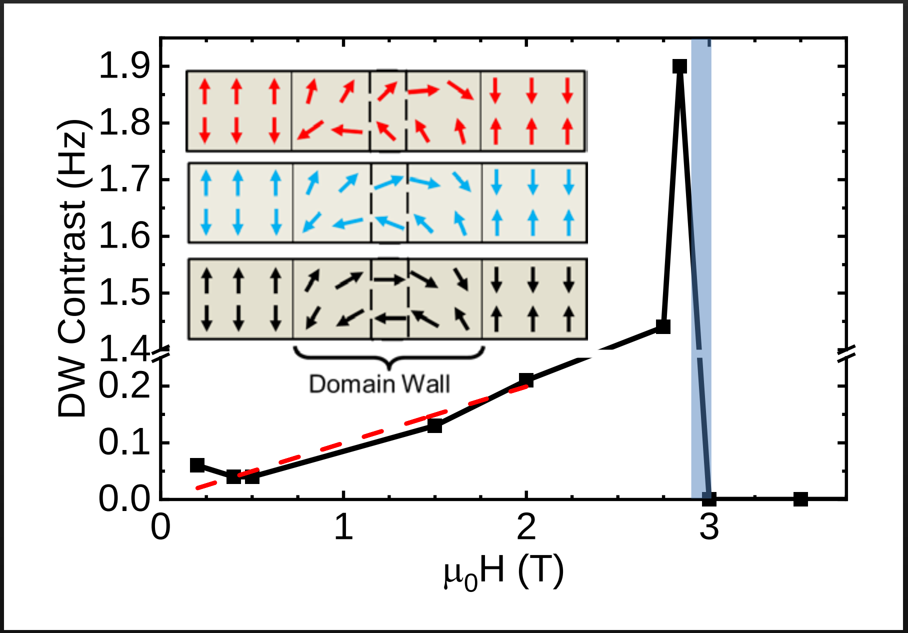
$MnBi_{1.37}Sb_{0.63}Te_4$



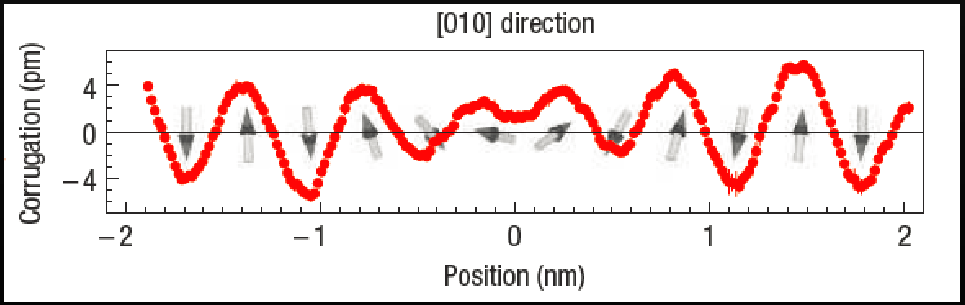


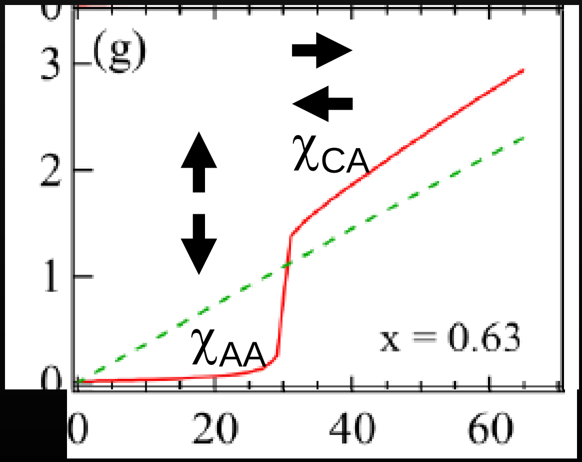
Susceptibility contrast mechanism





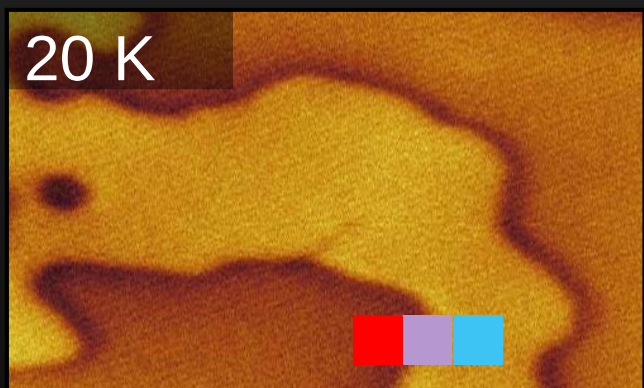
SP-STM of ML Fe/W(001)

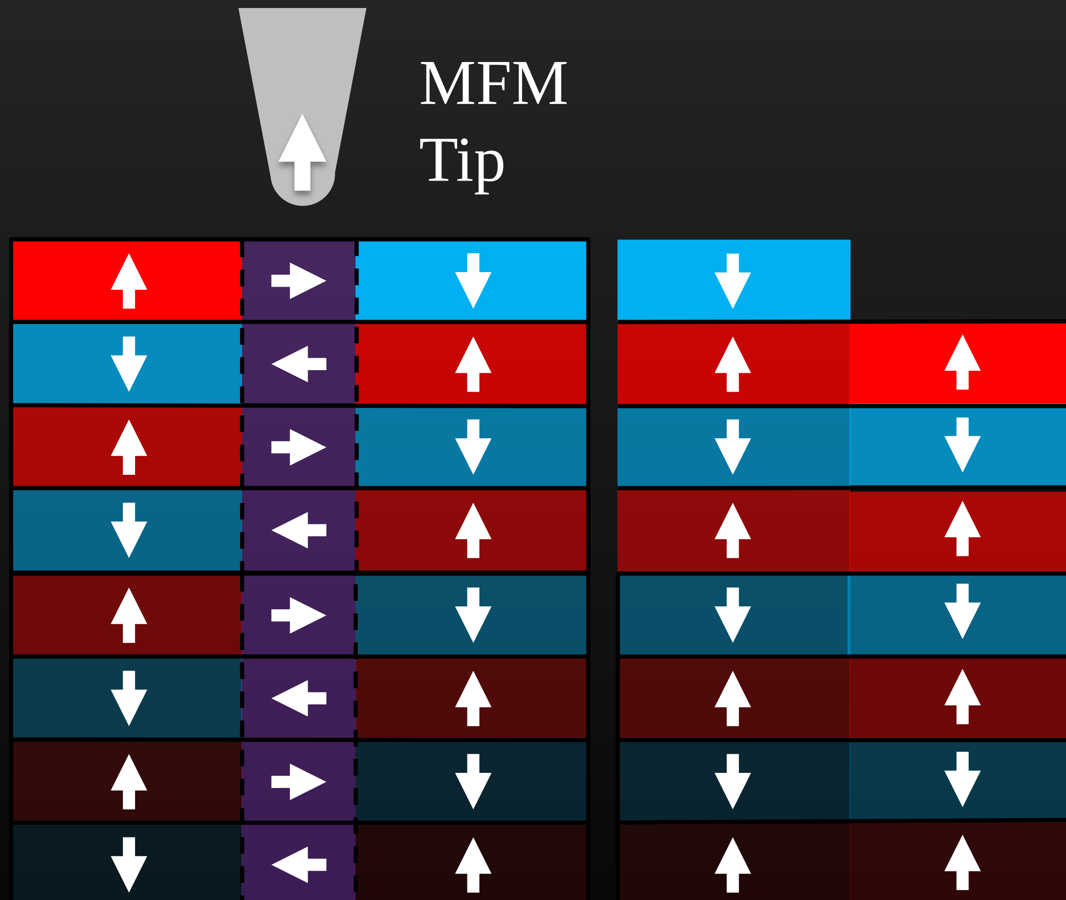




Bode, et al, Nat. Mater., **5**, 477 (2006).

Domain contrast: A-type order





Domain magnetic contrast of $MnBi_2Te_4$

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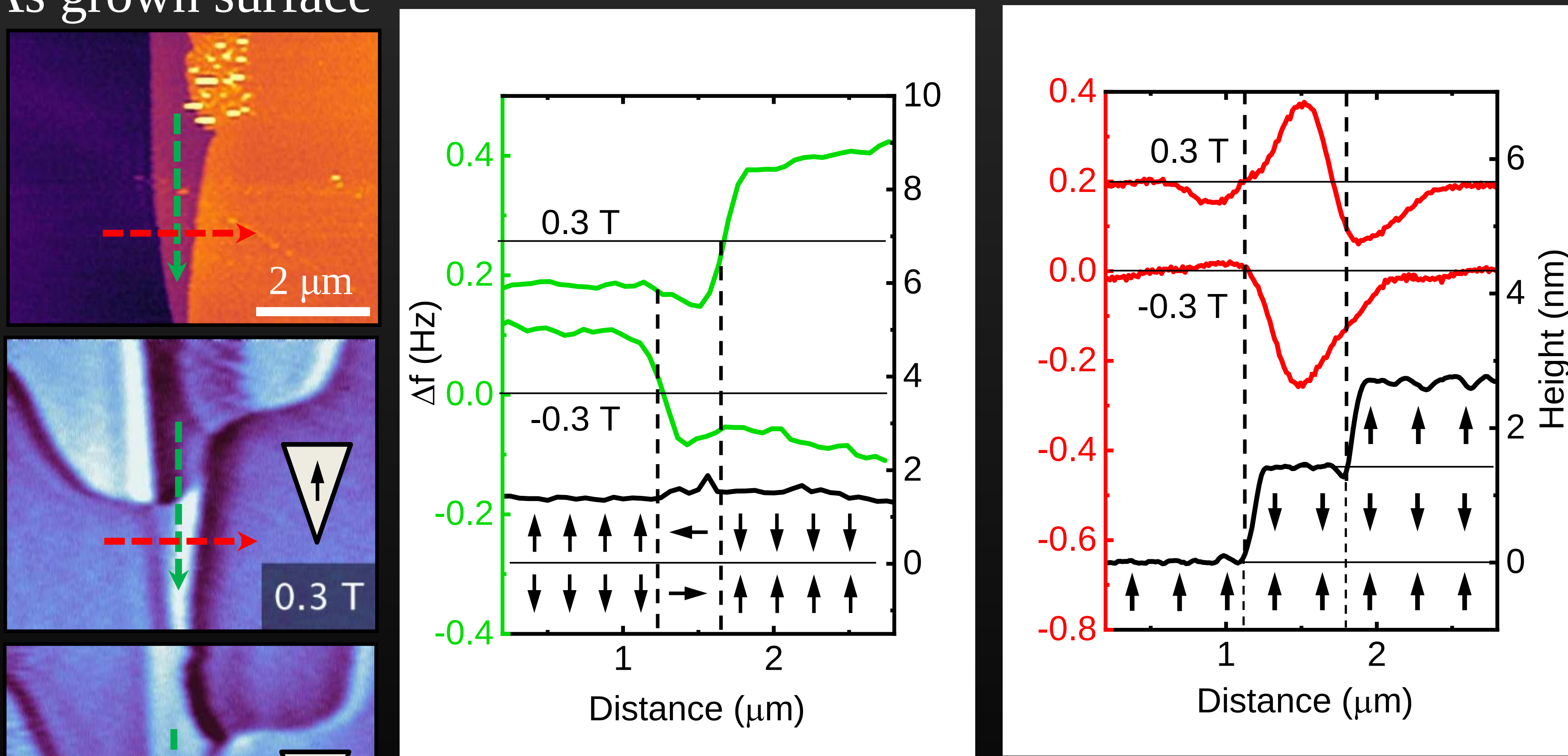
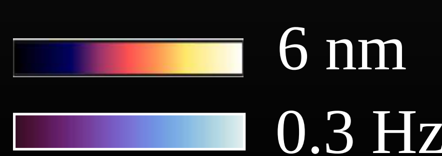
As grown surface

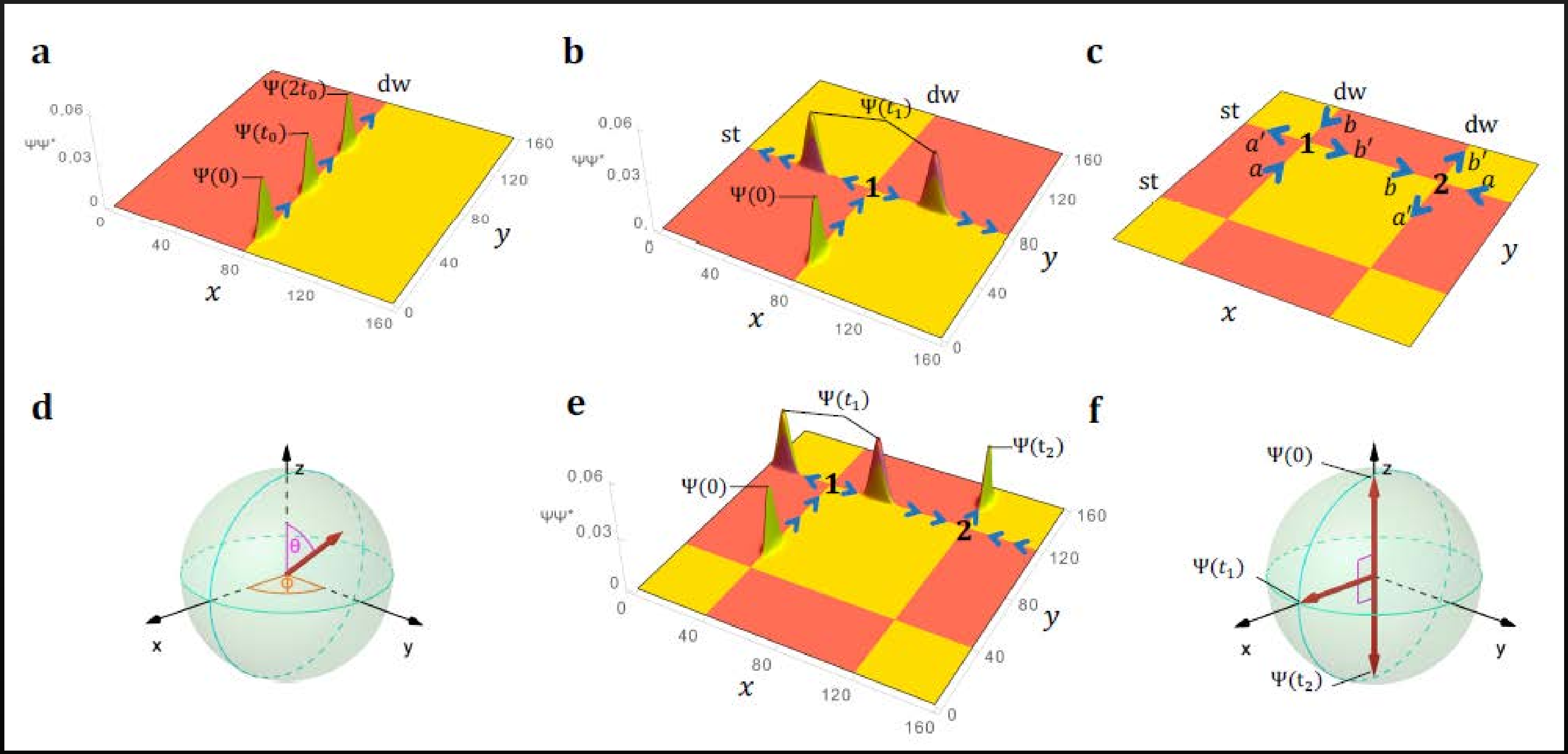




Termination dependent magnetic contrast → A-type AFM order

Quantum computing using chiral edge states

Controlling a quantum point junction on the surface of an antiferromagnetic topological insulator

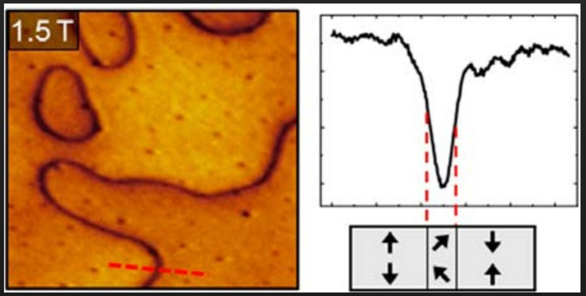


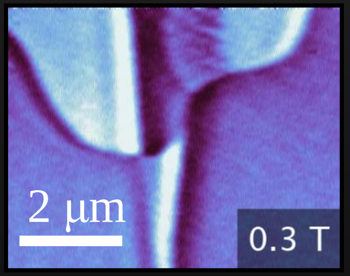
Varnava, Wilson, Pixley, and Vanderbilt, Nature Comm. (2021).

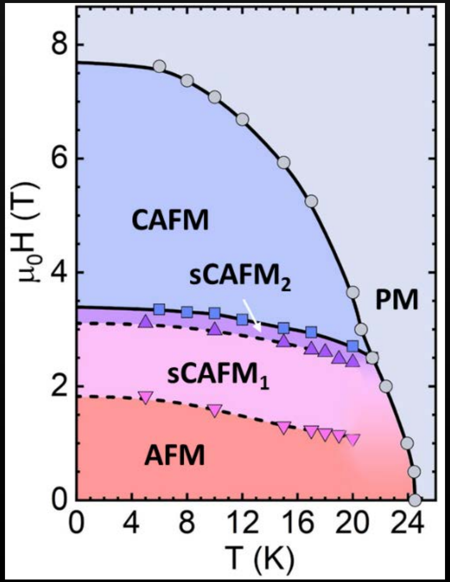
Summary of magnetic imaging of MBT

Magnetic imaging of $MnBi_2Te_4$ family

- Curvilinear domain walls
- low DW density
- Susceptibility contrast mechanism
  - ➢ Uniaxial AFMs (Cr_2O_3, MnF_2, CrI_3, $EuMnBi_2$, …)
- Persistence of A-type order on the surface of $MnBi_2Te_4$
  - ➢ No soft surface magnetic order
- Surface spin-flop transitions
  - ➢ SSF in other AFMs?







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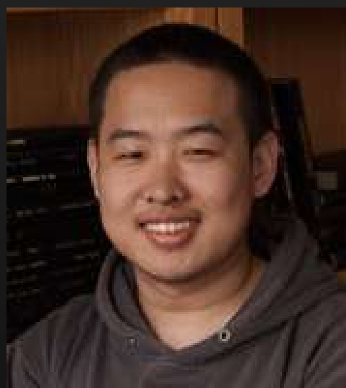
DE-SC0018153

The State University of New Jersey
Rutgers
Department of Physics and Astronomy

Group members

Graduate students



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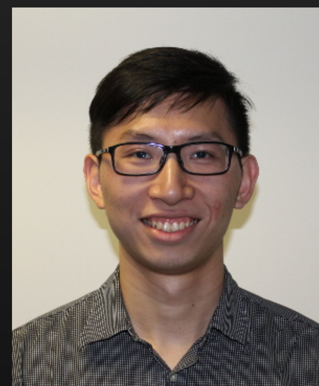

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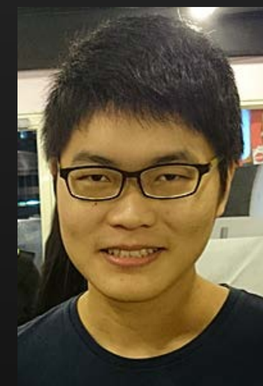

Ying-ting Chan

All are supported by grant.

Four golden lessons

- that no one knows everything, and you don't have to.
- to go for the messes — that's where the action is.
- to forgive yourself for wasting time.
- learn something about the history of science, or at a minimum the history of your own branch of science.

Steven Weinberg, Nature **426**, 389 (2003)

Thank you !

Contact info

wdwu@physics.rutgers.edu
8751 (Office) 117 W
8759 (Lab) 132 W