Discovery of QAH (2013)

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

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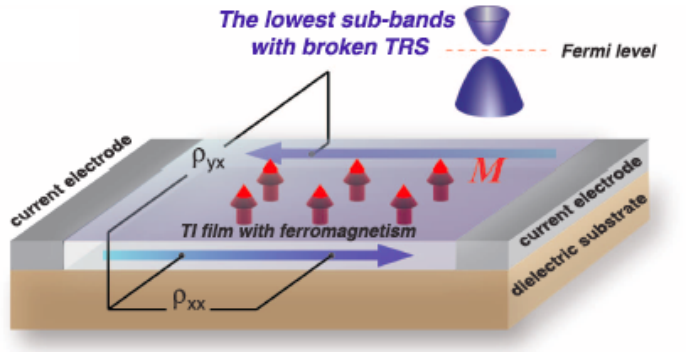
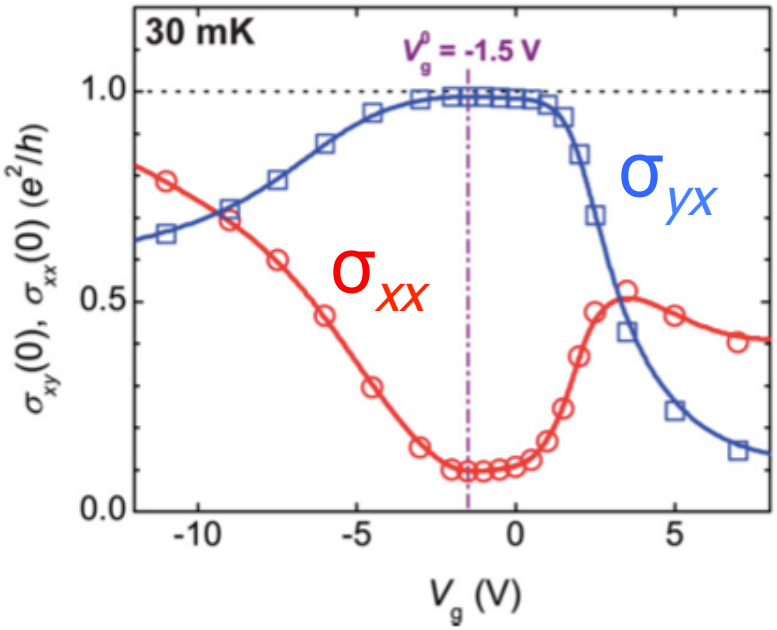


Cr-doped $(Bi,Sb)_2Te_3$ films



98% of e^2/h at 30mK

Slightly Higher *T*

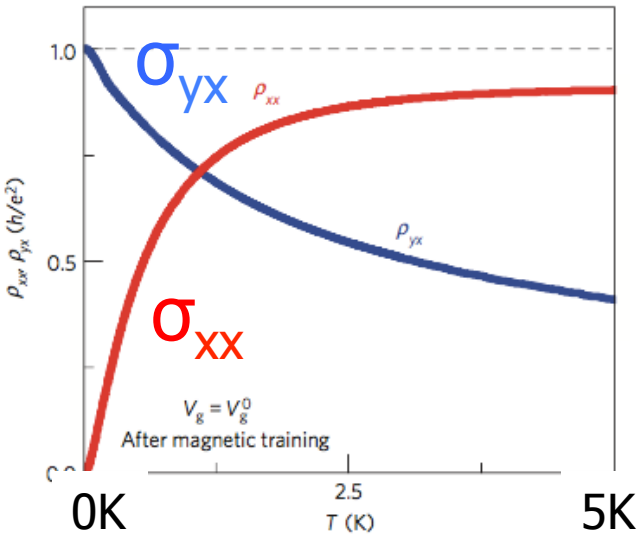
nature materials

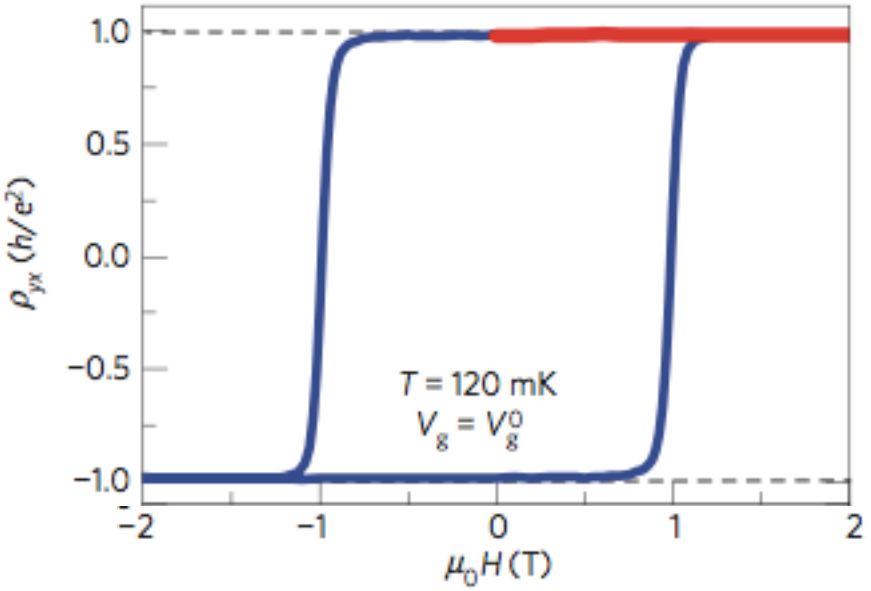
March 2015

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]*

V-doped $(Bi,Sb)_2Te_3$ films





97% of e^2/h at 200mK

99.98% of e^2/h at 25mK

QAH in twisted bilayer graphen

Science

REPORT

Intrinsic quantized anomalous Hall effect in a moiré heterostructure

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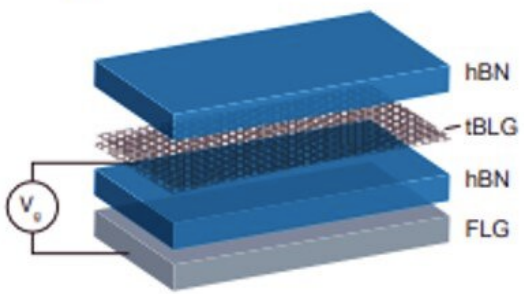
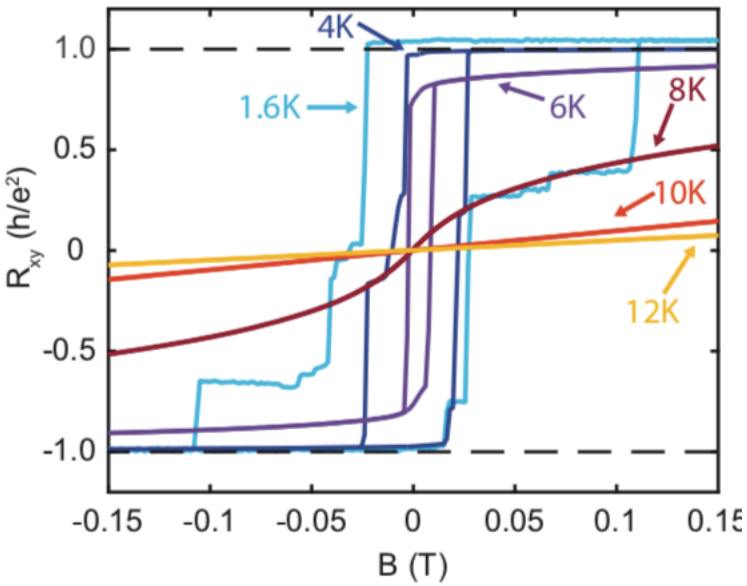
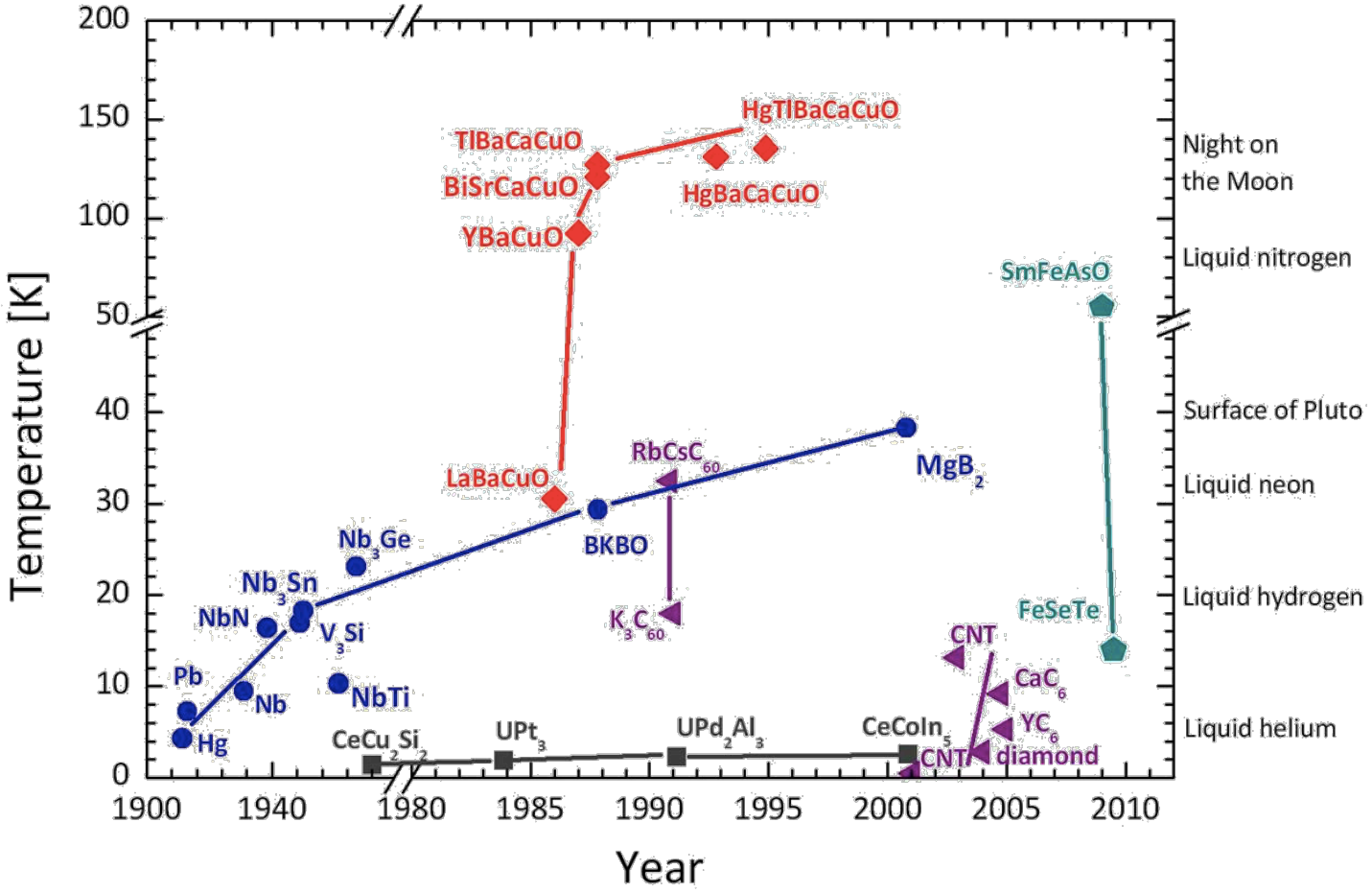




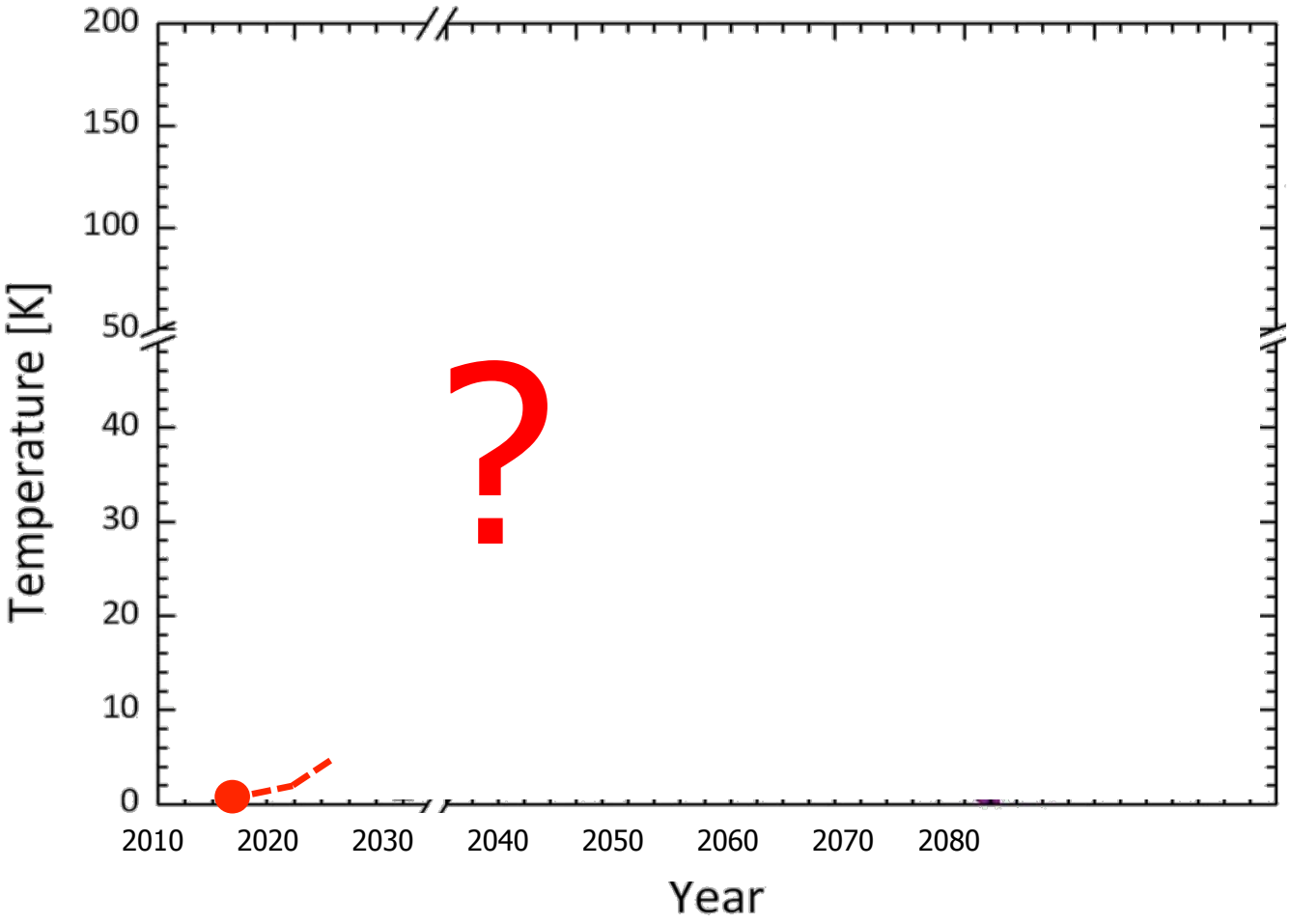
High-T_c?

High-Tc superconductors



High-T_c?

High-Tc QAH insulators

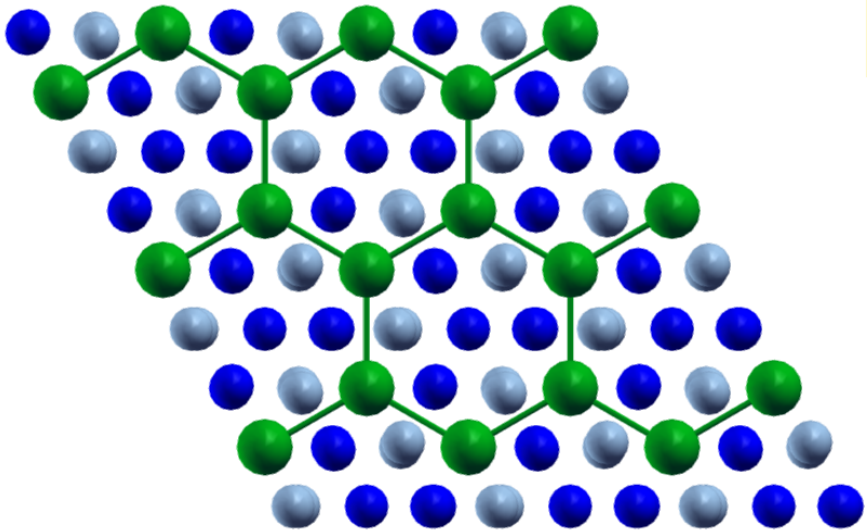


QAH insulators

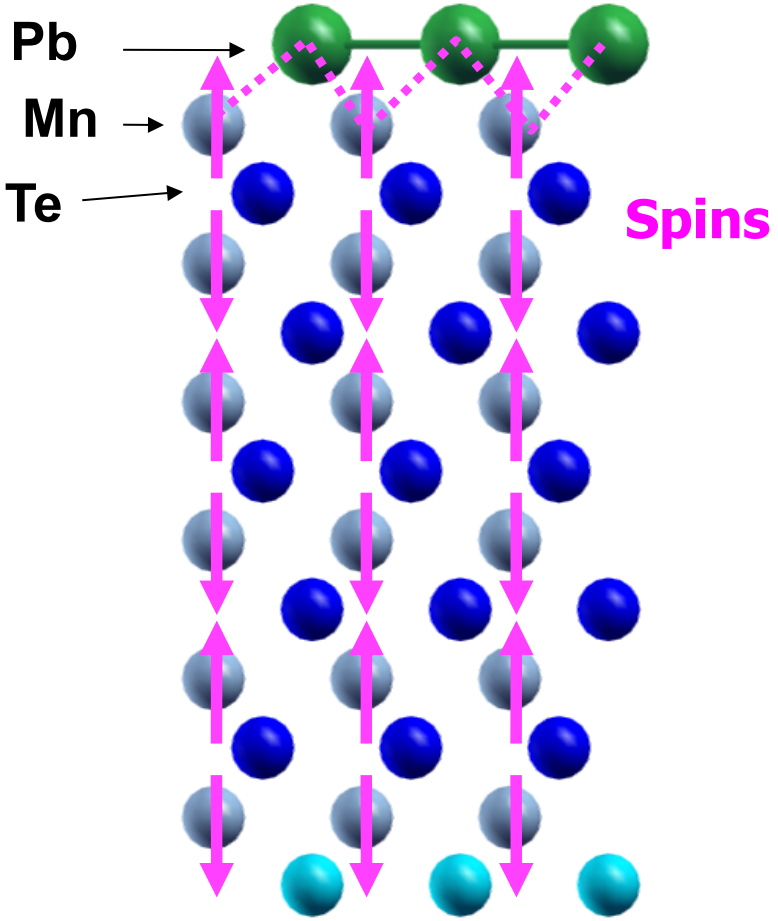
- "QAH insulator" = "Chern insulator"
- Usefulness:
  - Precision measurement?
  - Dissipationless "wires" for microelectronics?
  - Magnetoelectric coupling?
- Needed:
  - 2D ferromagnetic insulator
  - Strong spin-orbit coupling

Idea #1: Heavy atoms on magnetic substrate

Top view

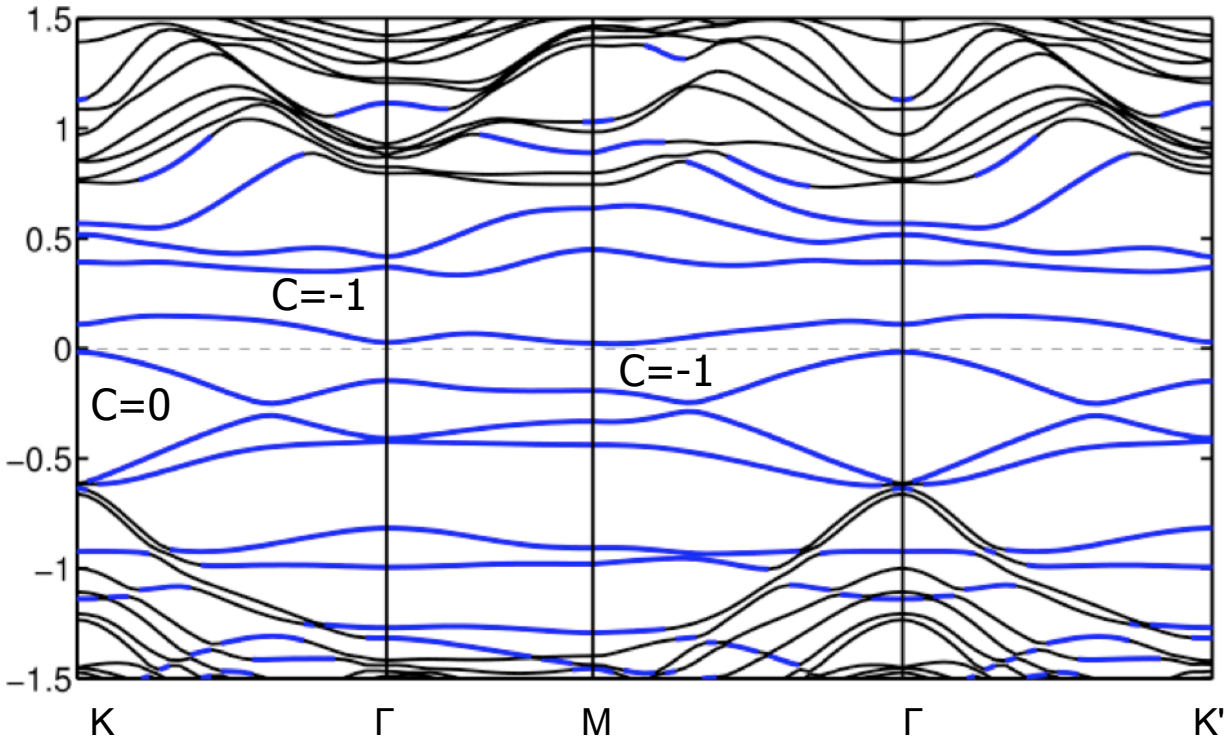


Side view



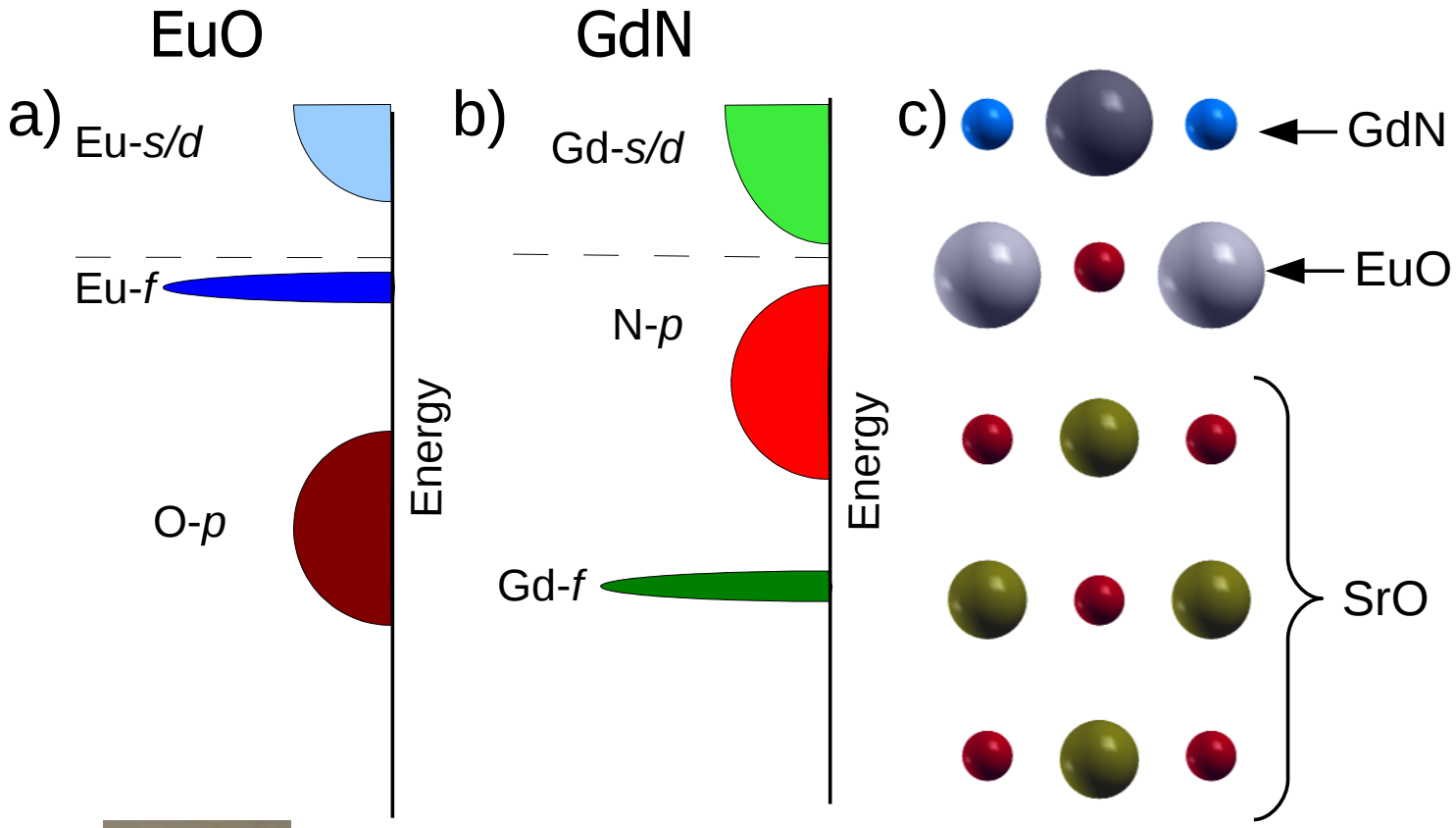
Kevin Garrity
NIST
Washington, DC

Honeycomb Pb on MnTe



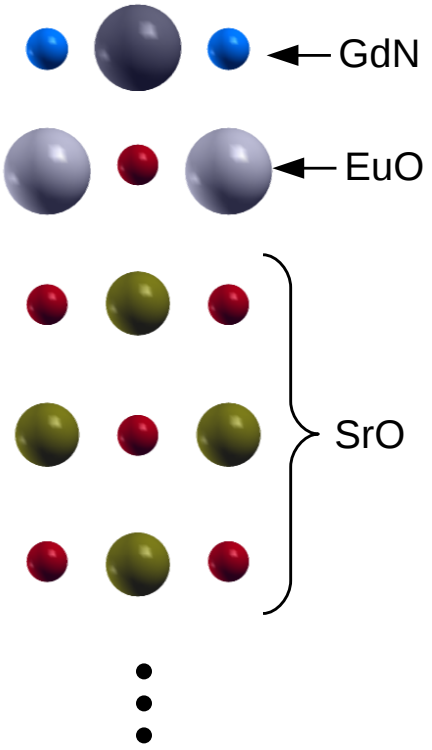
- E_F is in gap of 36 meV with C=-1
- This is a QAH insulator!
- Even larger minimum direct gap (>0.2eV above)

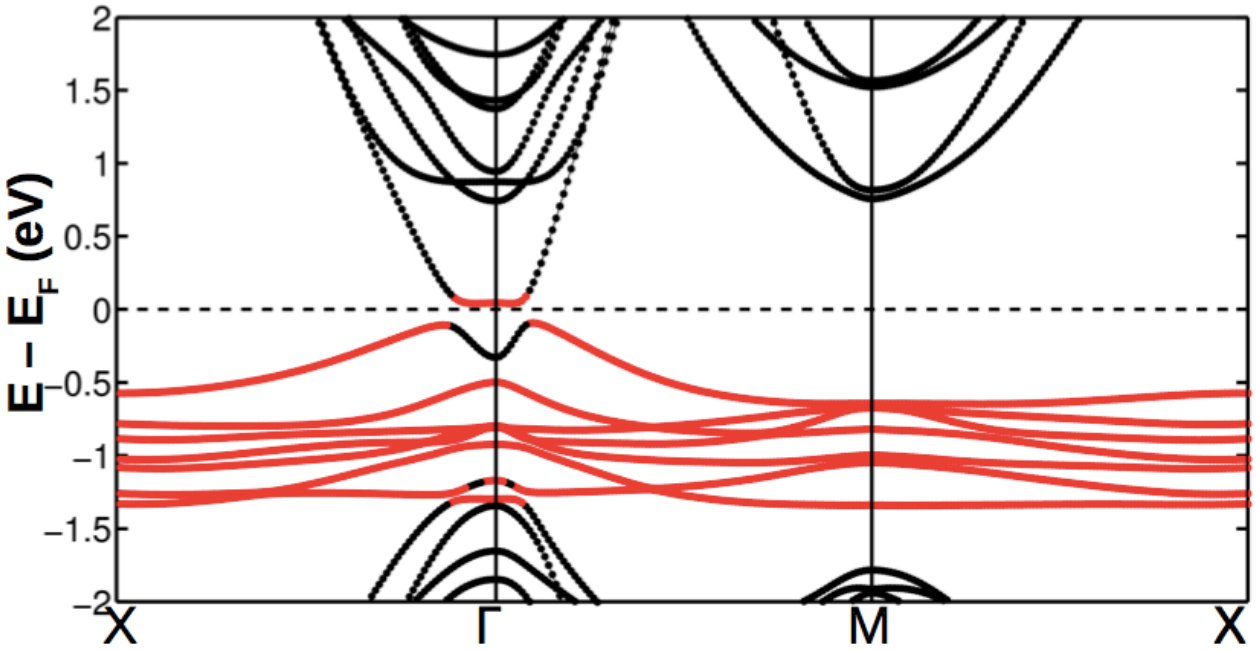
Idea #2: Rocksalt EuO/GdN



Kevin Garrity and D.V.
Chern insulators from a magnetic rocksalt interface
Phys. Rev. B **90**, 121103 (2014)

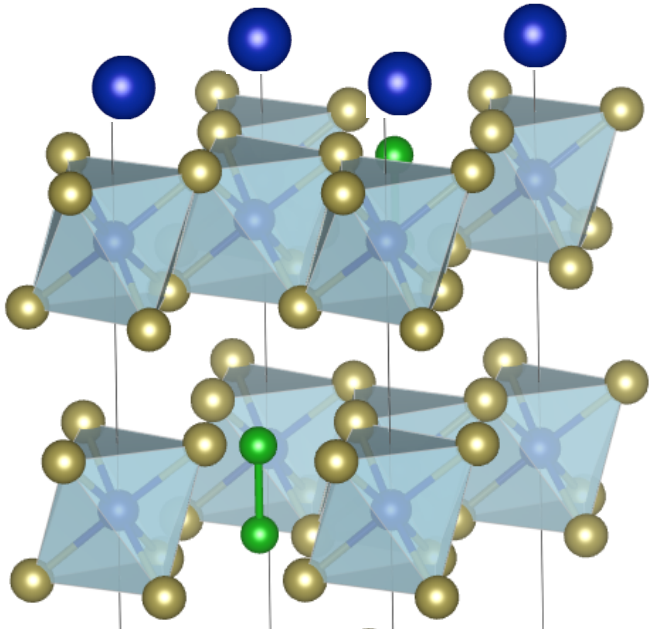
Idea #2: Rocksalt EuO/GdN

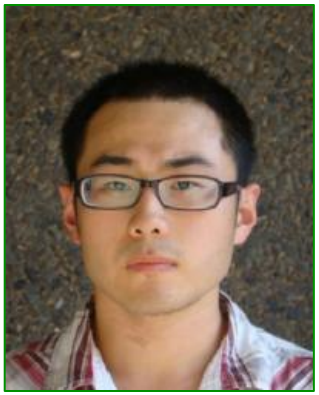




C = -1 Gap = 130 meV

Idea #3: Adatoms on $CrSiTe_3$ or $CrGeTe_3$





Jianpeng Lui

E_g ~1 eV

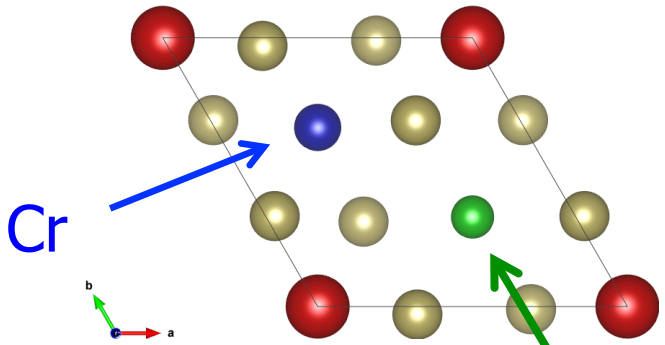
FM, T_c ~32K

Magnetization ⊥ surface

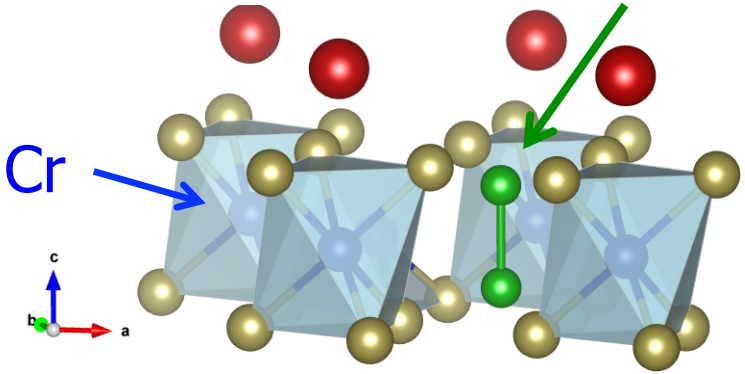
Non-polar surfaces

Adatoms on $CrSiTe_3$ or $CrGeTe_3$

Top view



Side view



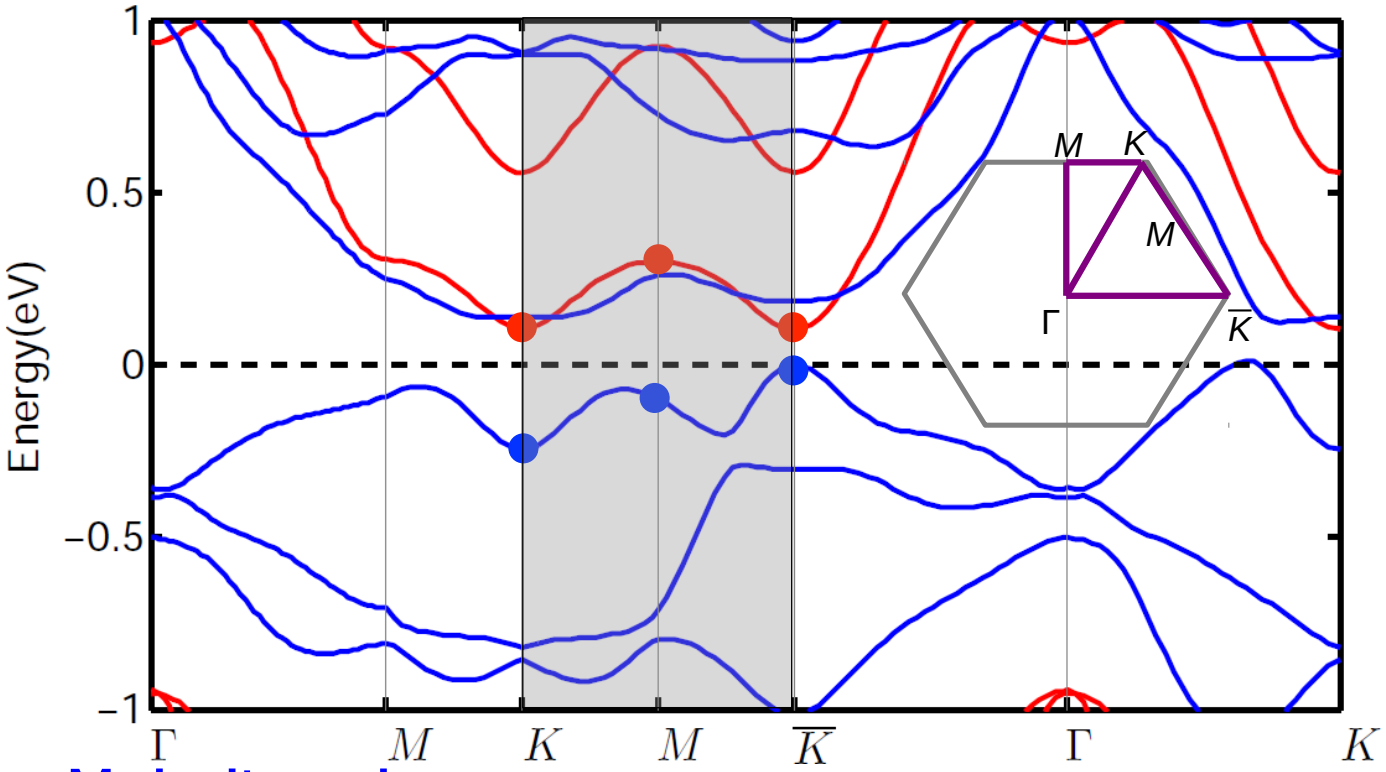
Adatoms:

- Bi, Pb, Tl, Hg, Au, In, Sb, Sn
  - *No luck*
- Rare earths: La, Lu
  - *Bizarre result:*
    - Found QAH state
    - Turned off SOC
    - It survived!

Substrate:
Single-layer $CrSiTe_3$ or $CrGeTe_3$

Bizarre result for $CrGeTe_3$:Lu

Hybrid functional calculation (without SOC)

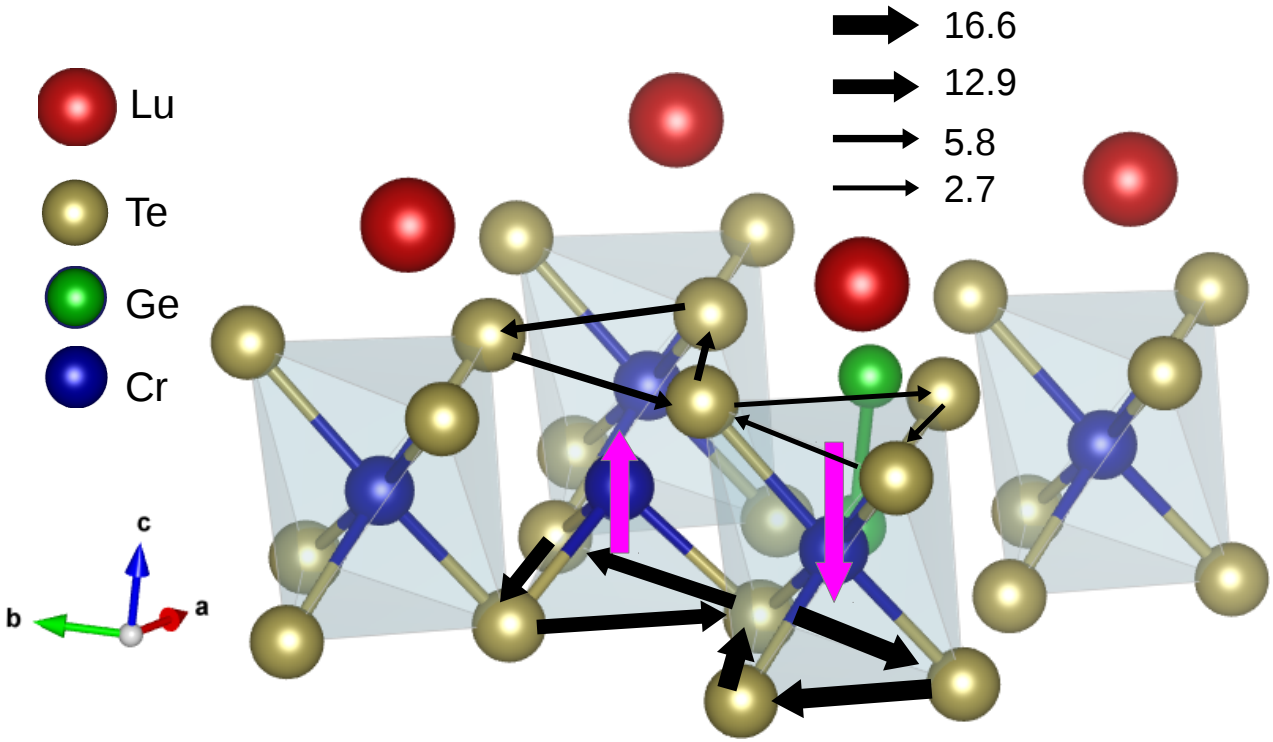


Blue: Majority spin

Red: Minority spin

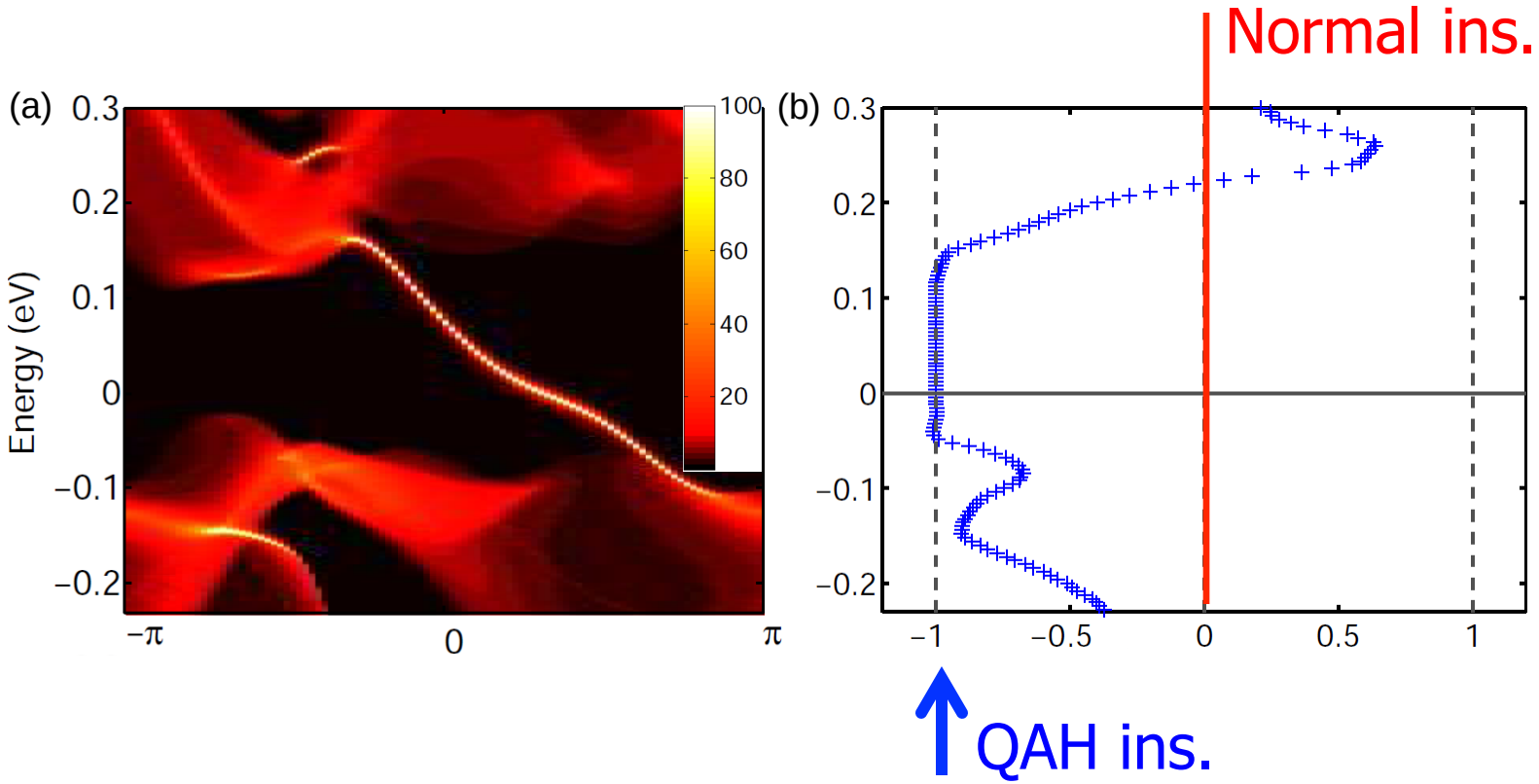
Spontaneously broken time reversal!

Orbital currents: "Flux state"



Orbital currents and orbital moments for $CrGeTe_3$:Lu

QAH insulator, C=-1



Edge bandstructure and anomalous Hall conductivity for $CrGeTe_3$:Lu