Physics in two dimensions in the lab

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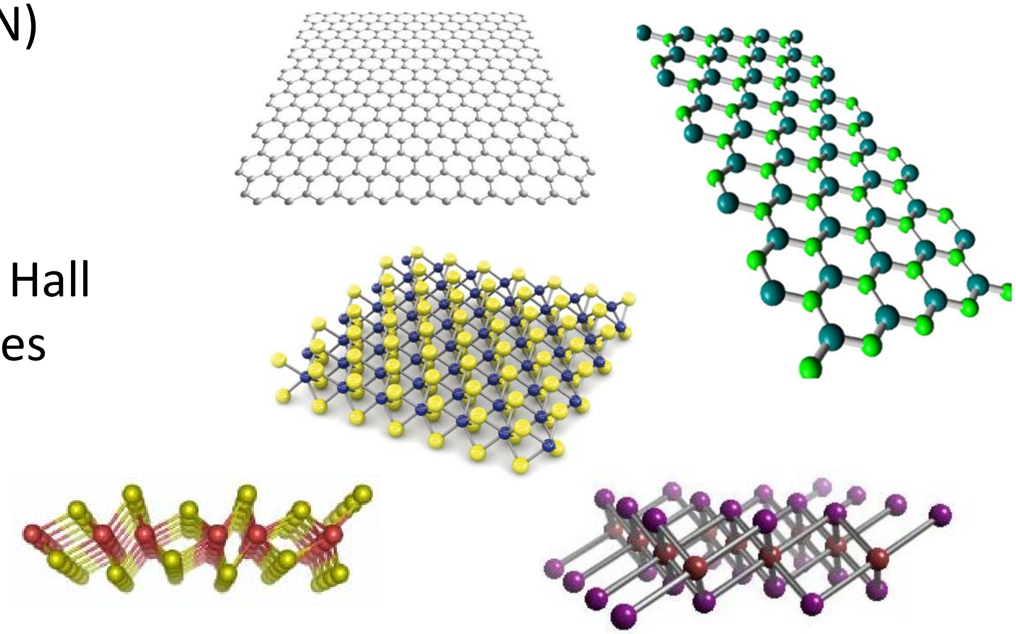
Xiaodong Xu (Nanoscale Optoelectronics Lab)
Jiun-Haw Chu (Quantum Materials Lab)
Theorists: Anton Andreev, Boris Spivak, Marcel den Nijs
Elsewhere: Josh Folk (UBC), Neil Wilson (Warwick), Yongtao Cui (UC Riverside)

Nutshell history of 2D:

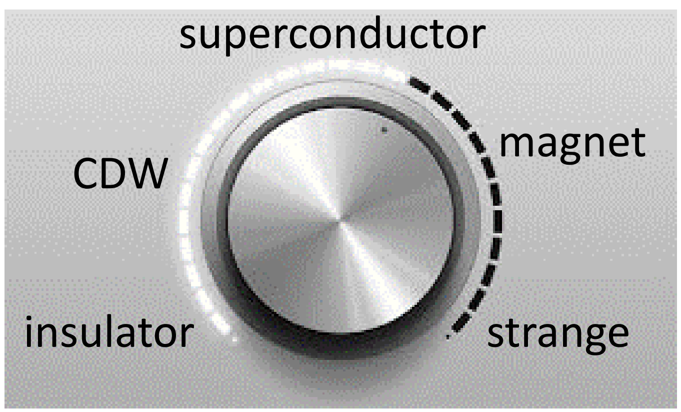
- Electrons on surfaces, eg of He (1950s)
- Thin metal films (1950s)
- Atoms/molecules adsorbed on surfaces (1960s)
- Silicon/oxide interface (1970s)
- Semiconductor heterojunctions (1980s)
- Graphene (2004)
- Surfaces of topological insulators (2006)
- Other layered materials: MoS_2, CrI_3, WTe_2, hBN, ...

Some electronic states found in 2D monolayer materials

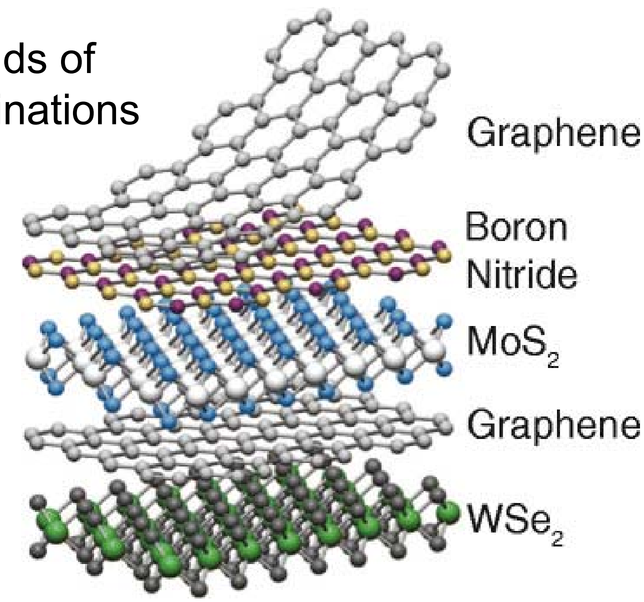
- Good old-fashioned insulators (hBN)
- Semimetals (graphene)
- Semiconductors
- Charge density waves
- Quantum Hall, fractional quantum Hall
- Wigner crystal, stripe/bubble phases
- Superconductivity
- Magnetism (various kinds)
- Ferroelectricity
- 2D topological insulator
- Topological superconductor
- Excitonic insulator
- Anomalous metals
- Plain metals … ?



Wouldn't it be nice if we could switch between them electrically?

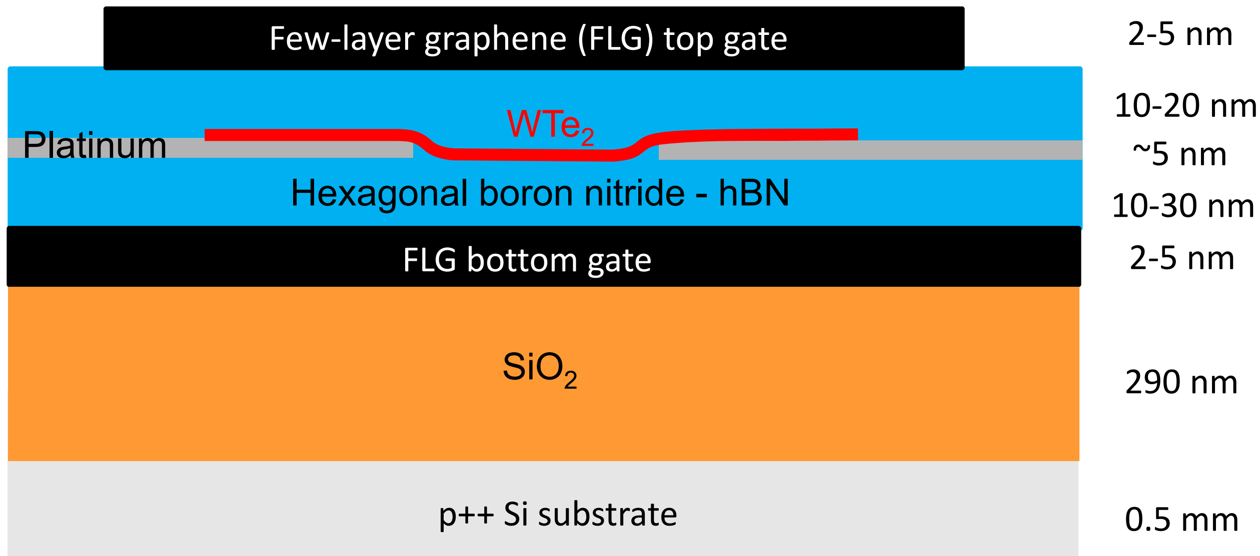


All kinds of combinations

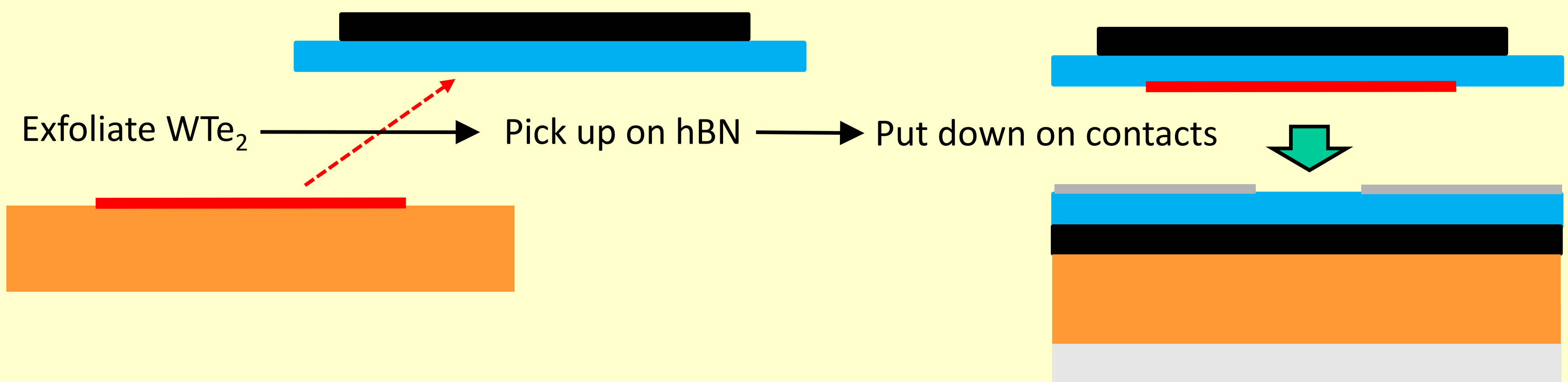


Example of device fab

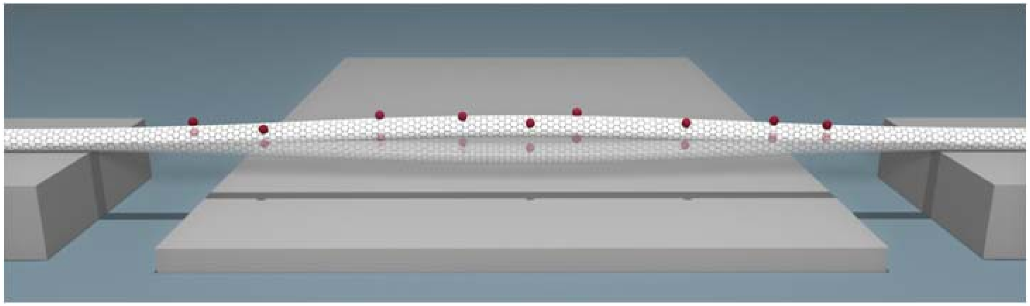
Dry transfer technique - Zomer P et al. *Appl Phys Lett* **105**, 013101 (2014)

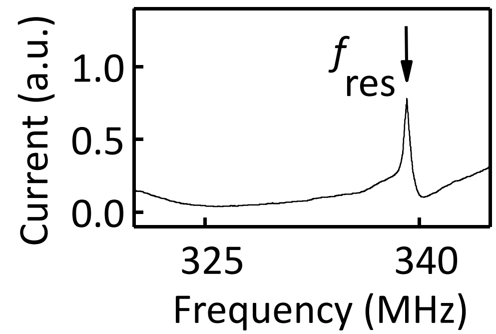


In the glove box, <0.5 ppm O_2 and H_2O



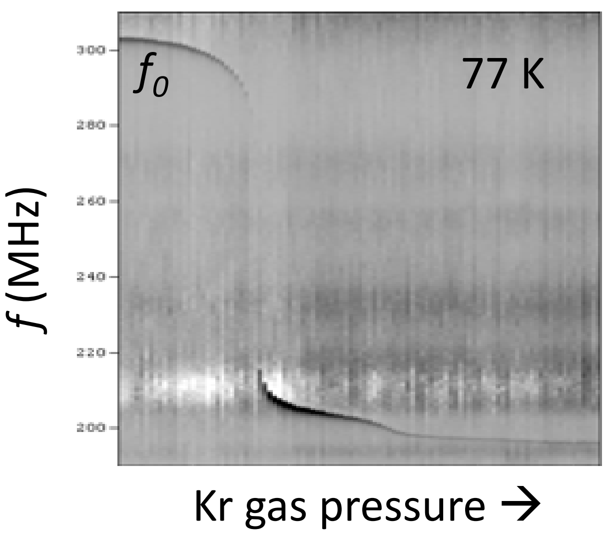
Nanotube nanoguitar – the most sensitive mass balance



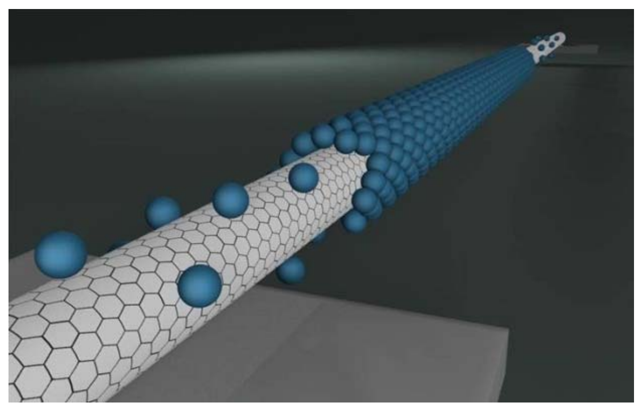


$$f_{res} \propto \left(\frac{\text{mass}}{\text{unit length}}\right)^{-\frac{1}{2}}$$

$$\text{adsorbed molecules per C atom} = \frac{m_c}{m_{ads}}\left[\left(\frac{f_0}{f_{res}}\right)^2 - 1\right]$$

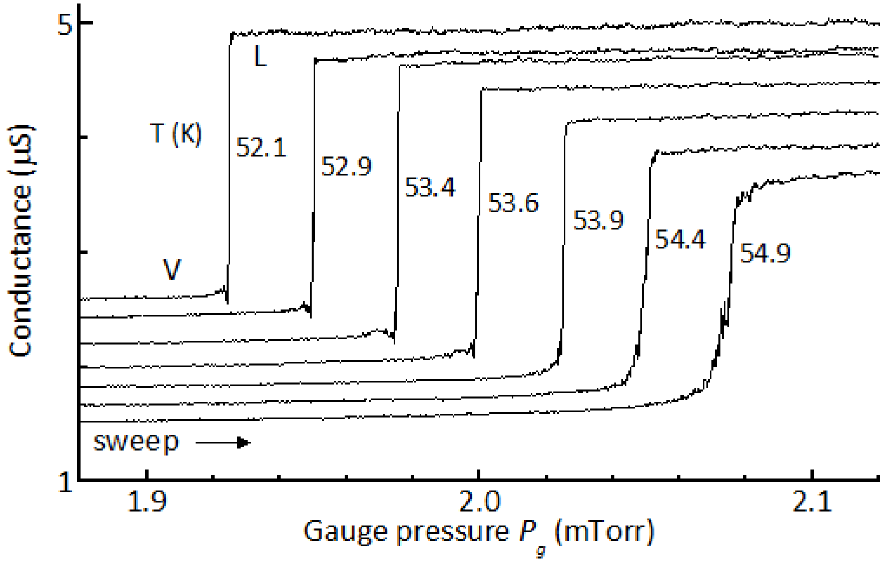


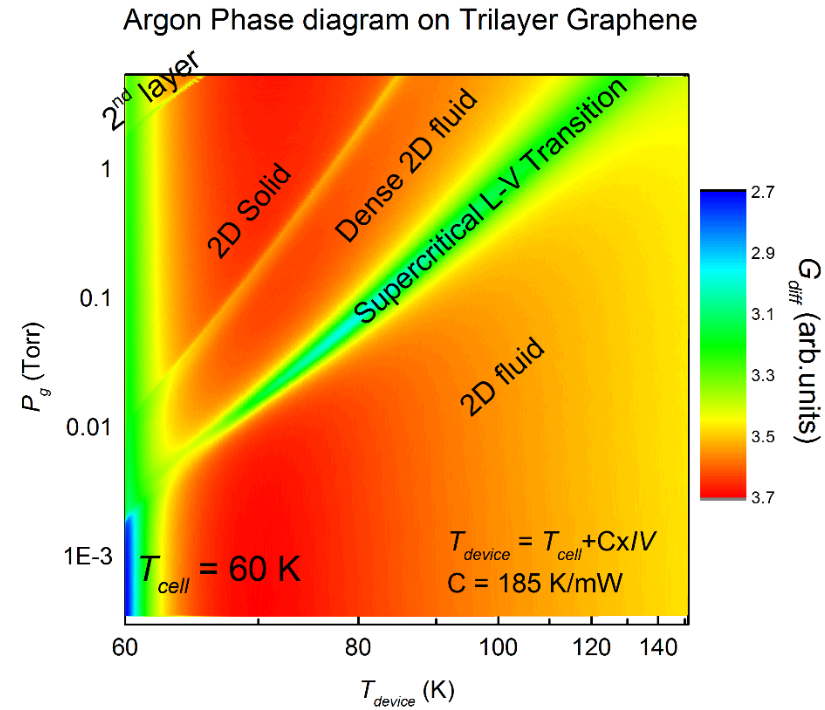
Precision ~ 1 atom, << 1 electron

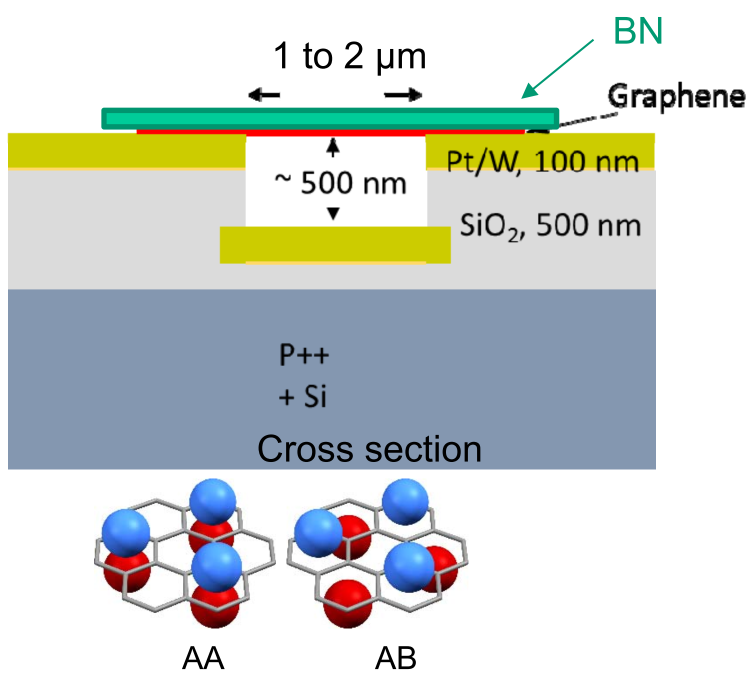


Adsorption can also be detected via the conductance …

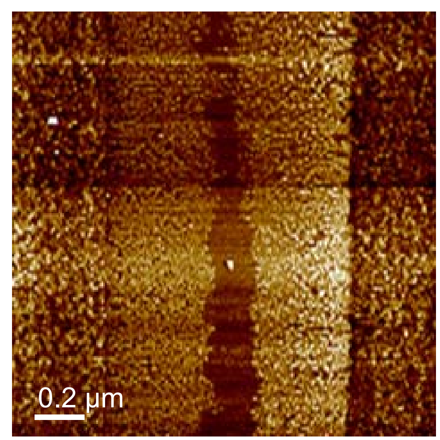
"Conductance isotherms": studying 2D phase transitions



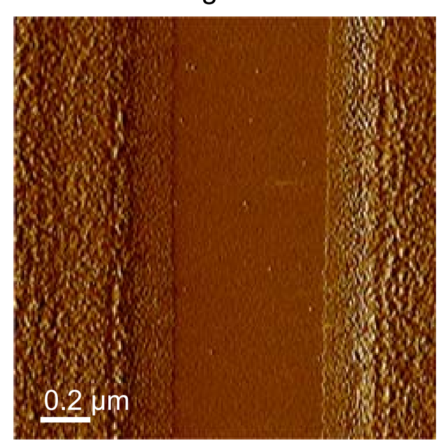




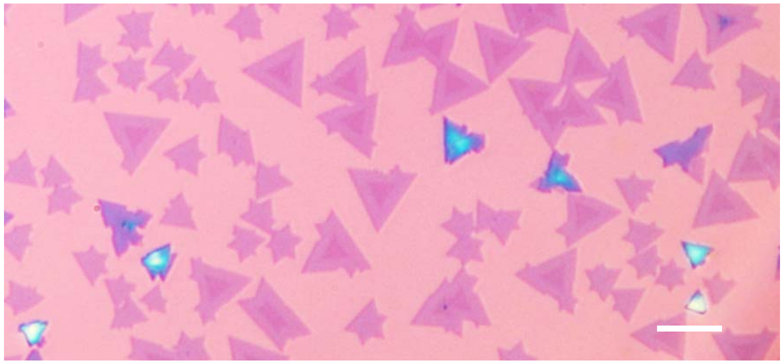
After low V anneal



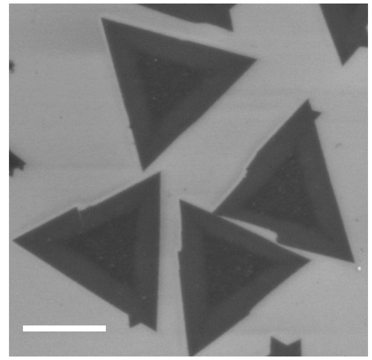
After high V anneal



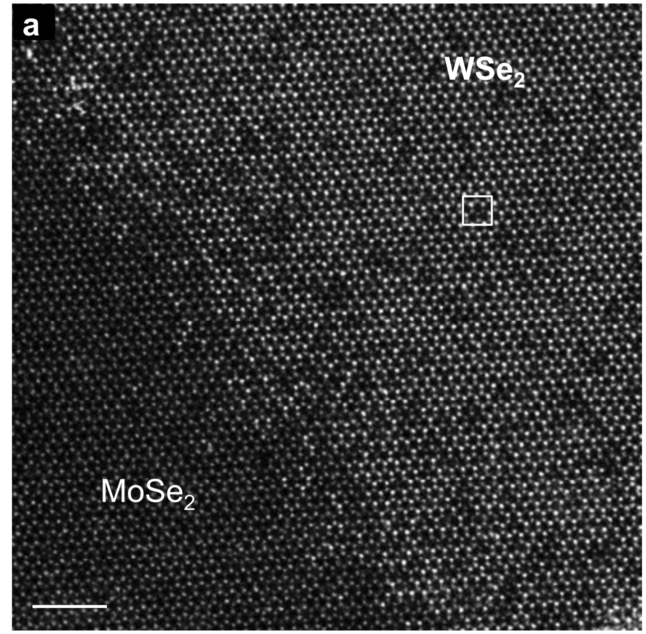
2D semiconductor heterojunctions



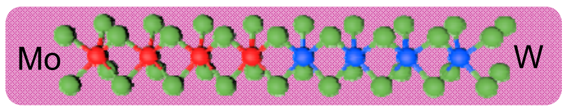
Optical



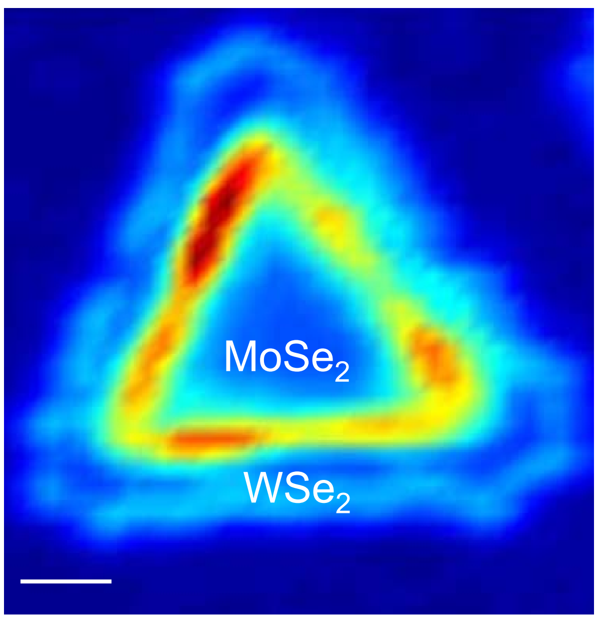
SEM

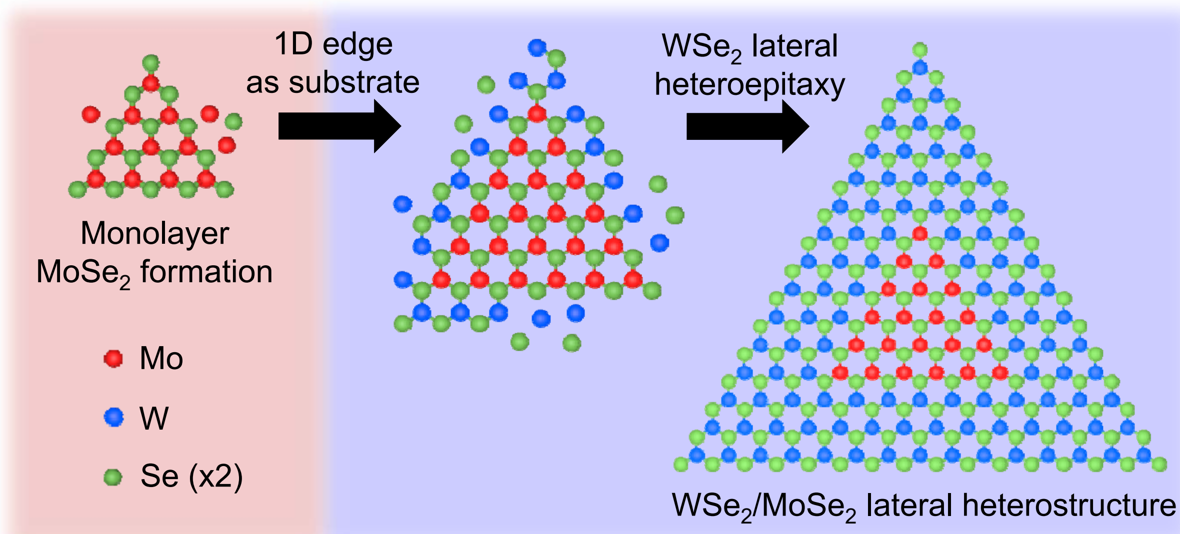


TEM

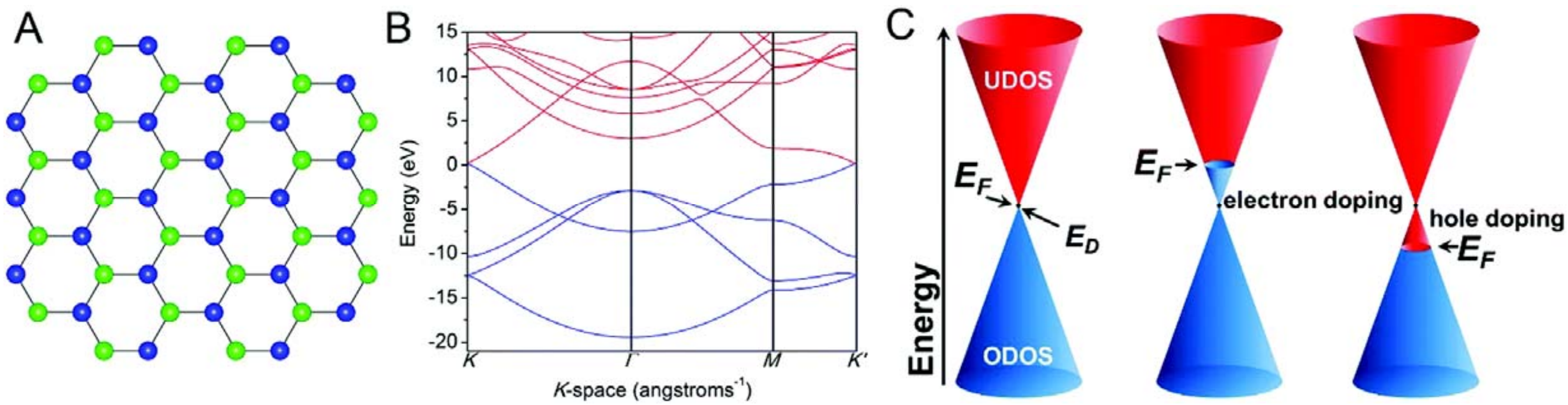


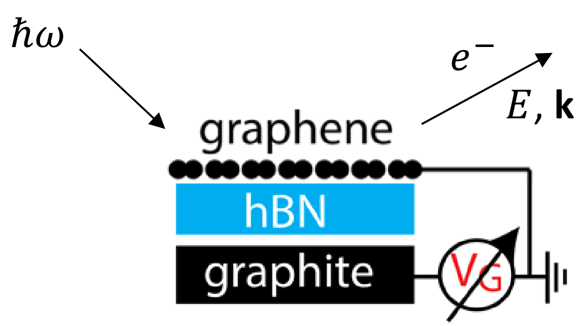
Photoluminescence

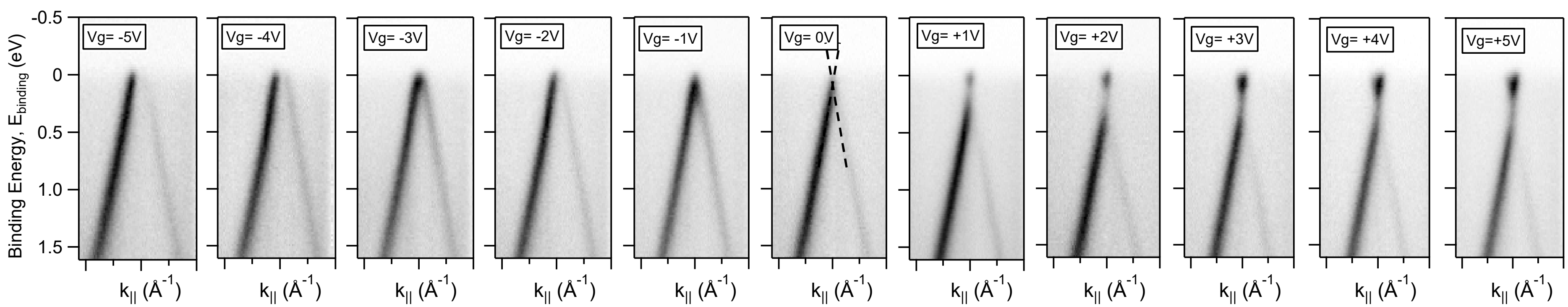




Directly measuring electronic bands –
Angle-resolved photoemission spectroscopy

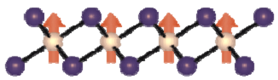


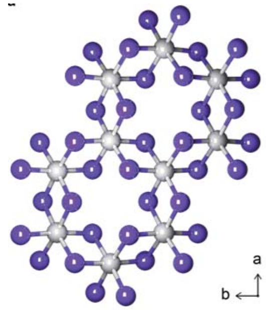




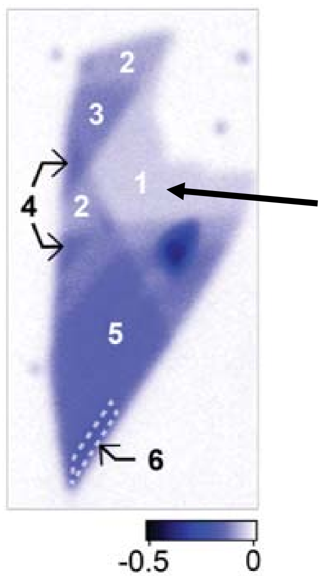
2D magnetism in monolayers

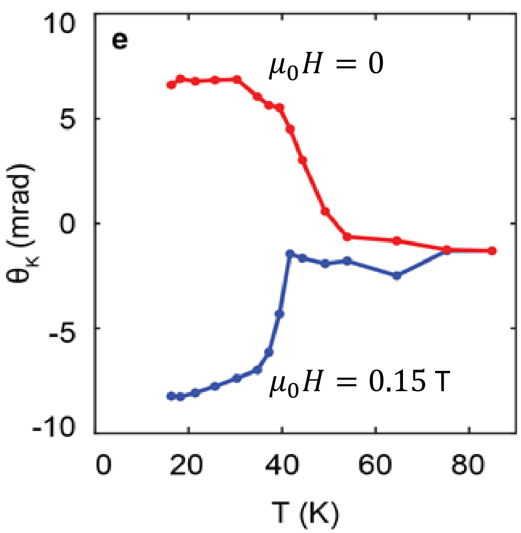
CrI_3

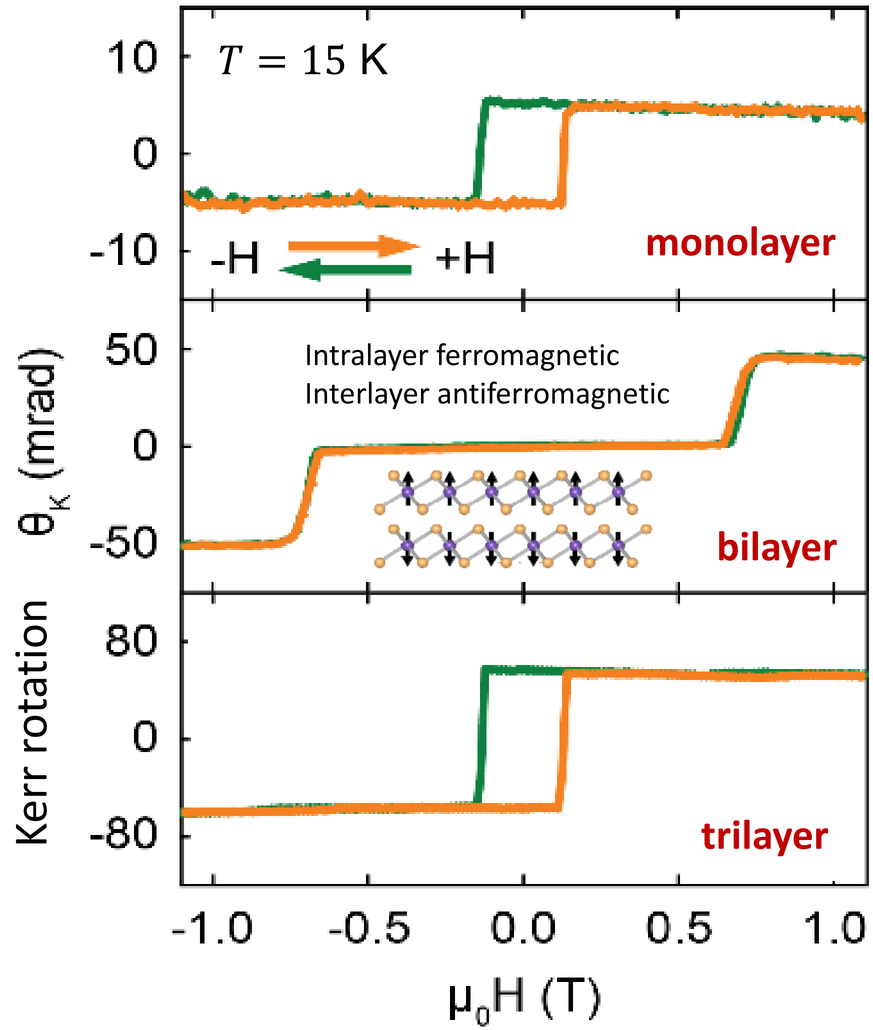




bulk $T_C = 61$ K



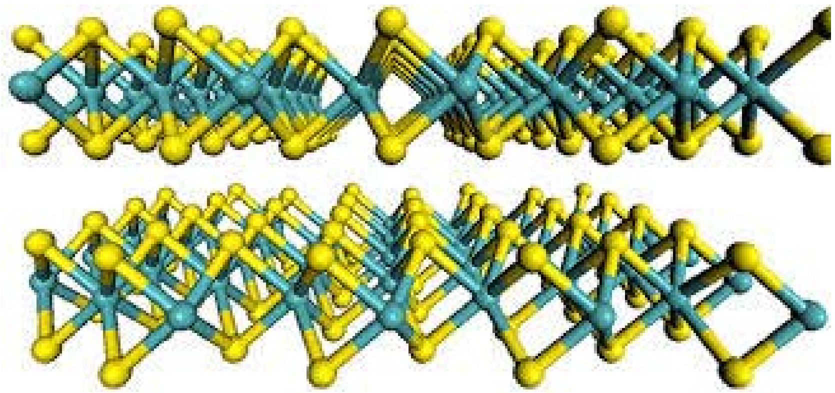




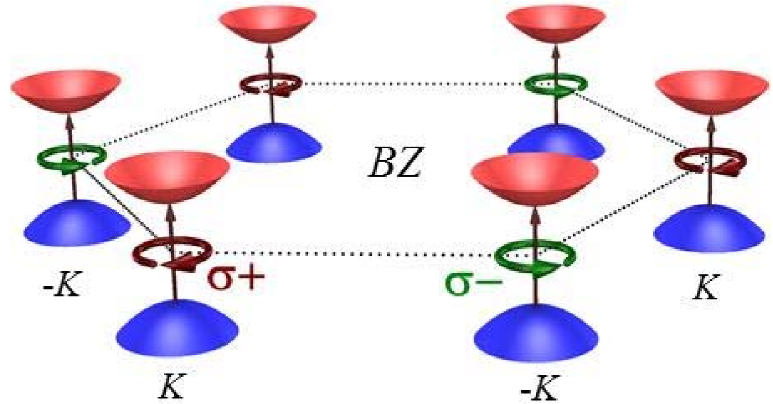
Electric field/strain tunable?

See Huang et al, Nature (2017)

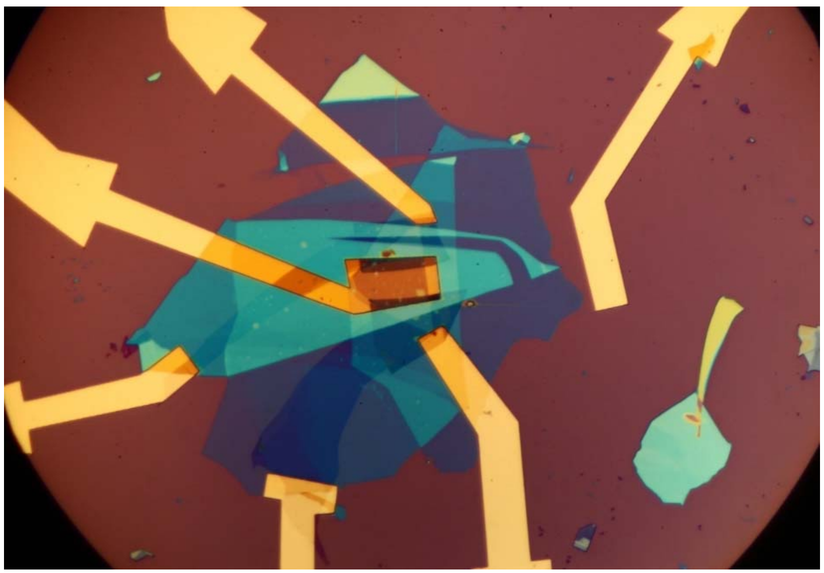
2D monolayer semiconductors



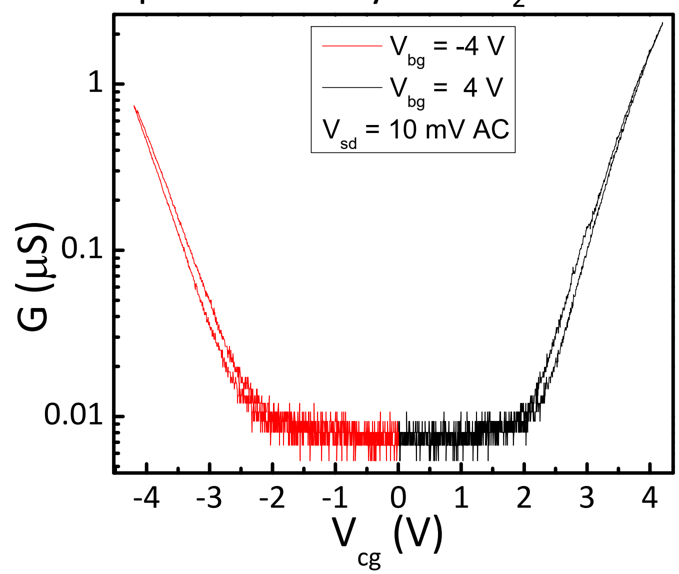
MoS_2, WSe_2 …



Electrons are massive Dirac particles with added valley pseudospin

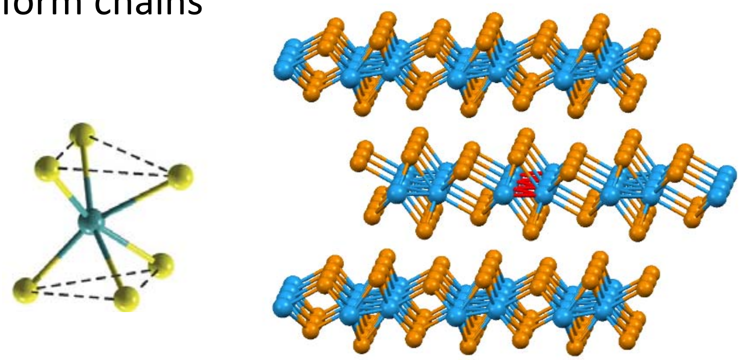


Ambipolar monolayer WSe_2 transistor



3D WTe_2 – a van der Waals layered topological semimetal

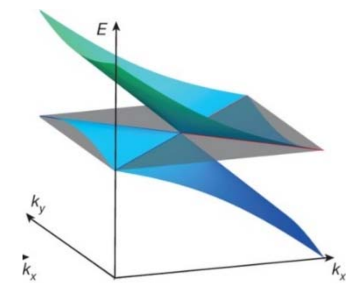
Orthorhombic "T_d" structure
W form chains



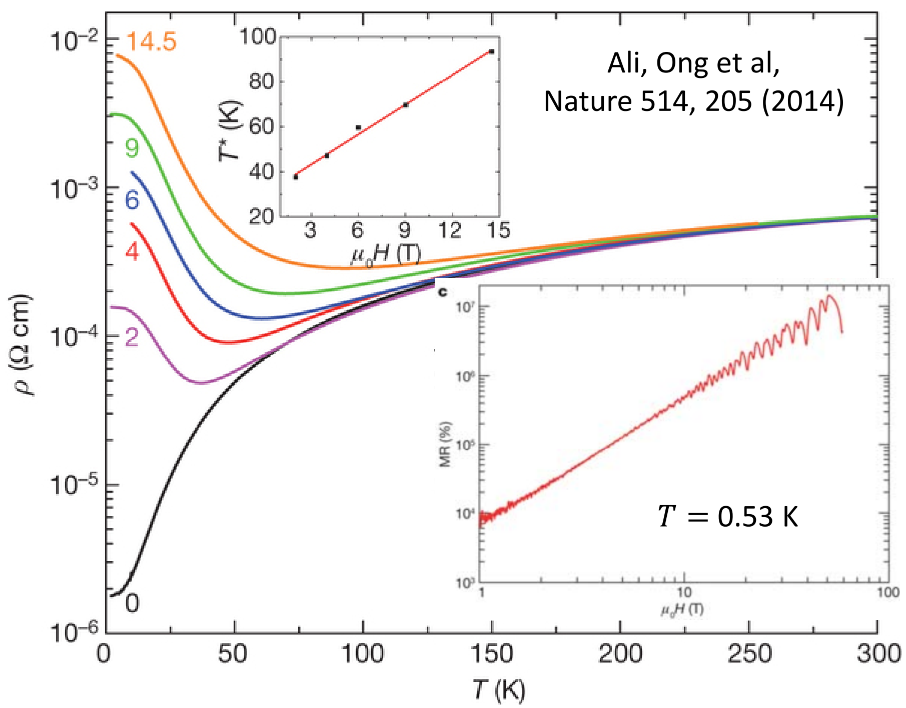
Theory:

Type-II Weyl points

Soluyanov et al. Nature 527, 495 (2015)

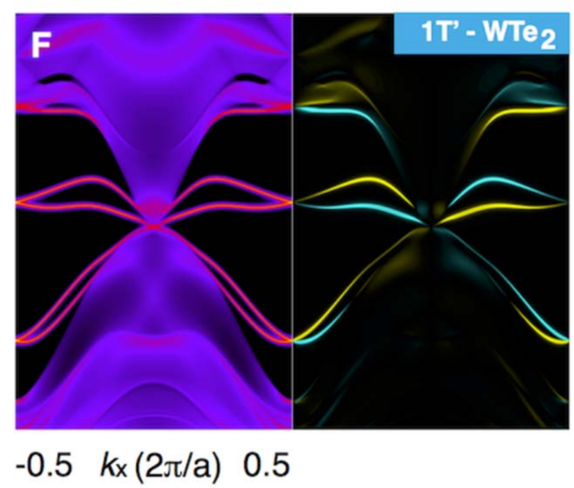


Huge nonsaturating magnetoresistance at low *T*



Monolayer is quantum-spin Hall candidate

Qian, Junwei Liu, Fu, Li (Science, 2014)



The quantum spin Hall (QSH) effect

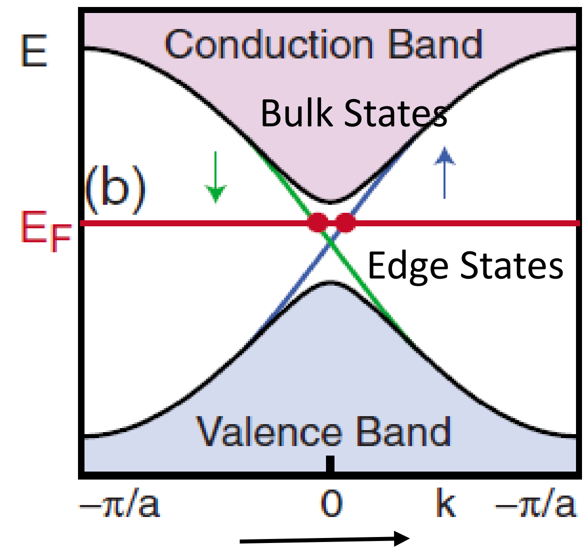
A 2D insulator is topologically nontrivial if Z_2 invariant $\nu = 1$

Kane & Mele; Kane & Fu, PRL 2005-7

$$(-1)^{\nu} = \prod_{a=1}^{4} \delta_a \qquad \delta_a = \prod_m \xi_m(\Lambda_a)$$

Time-reversal invariant points — occupied bands — Parity $\xi_m(\Lambda_a) = \pm 1$

$\nu = 1$ implies “band inversion”

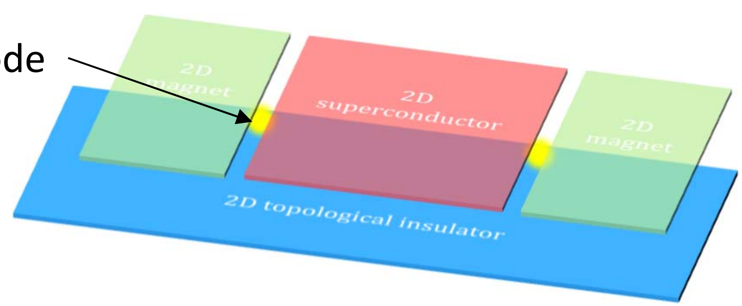


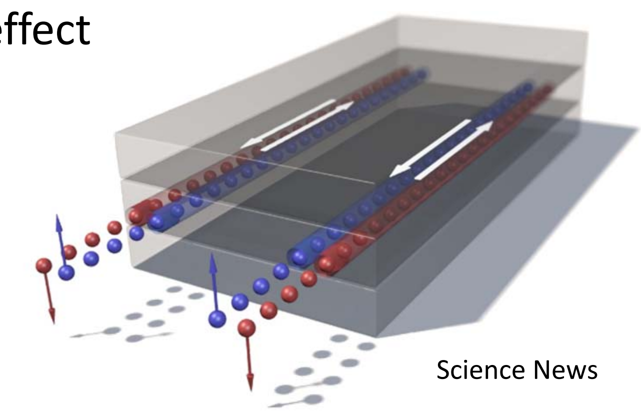
Momentum along edge

- If $\nu = 1$ there exists at least one gapless mode on the edge
- +k and –k not mixed by time-symmetric perturbations
  → possible e^2/h quantization
- Mode is *helical* (spin locked to **k**) → quantum spin Hall effect

First evidence for QSH reported in HgCdTe (Konig et al, Science 2007)

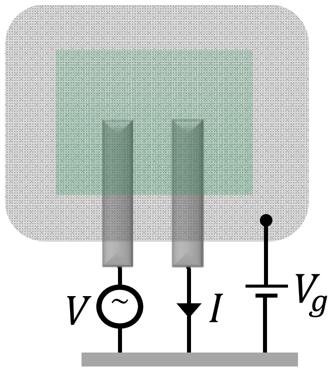
Majorana mode





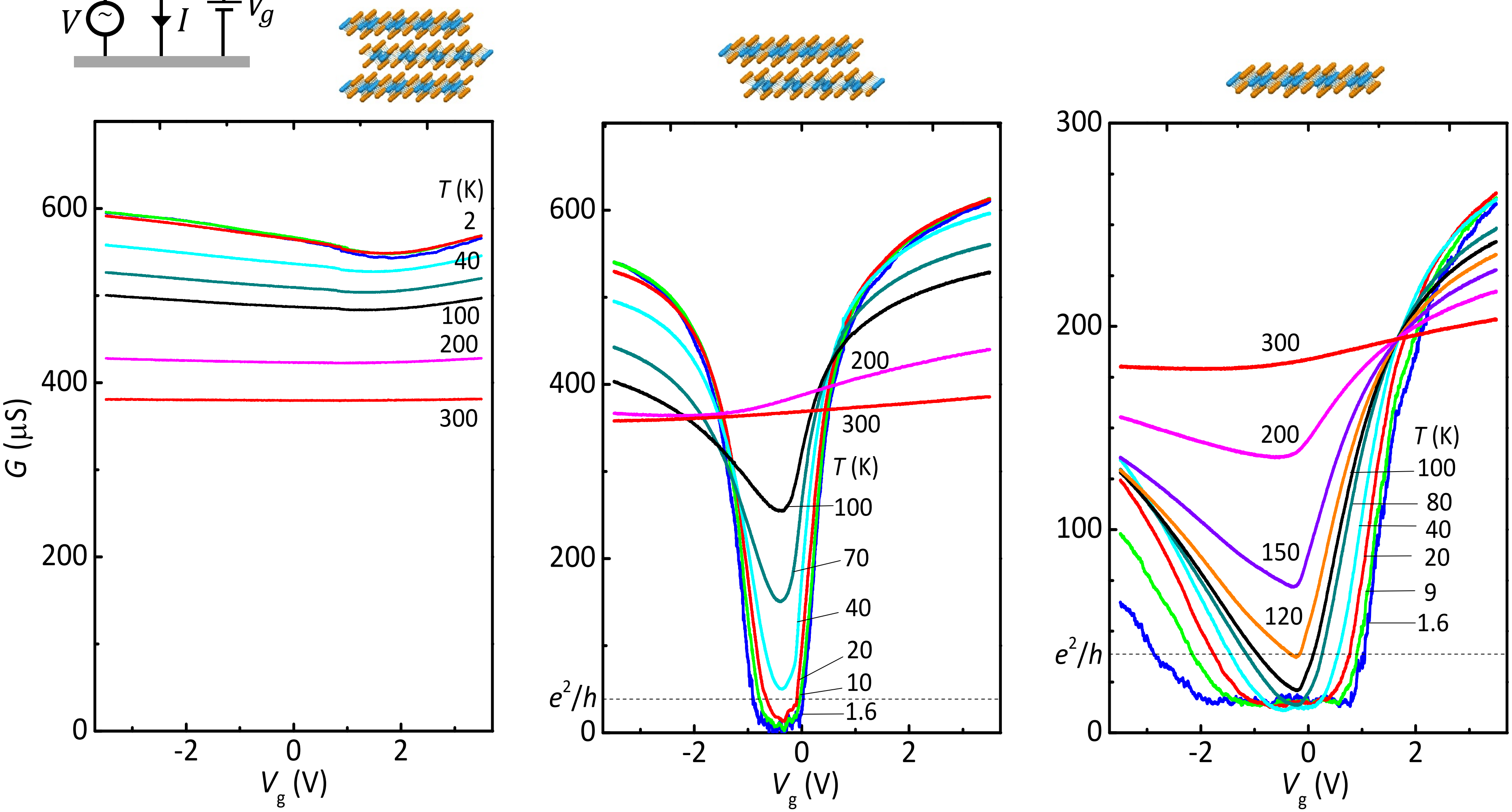
Science News

Few-layer WTe_2 devices

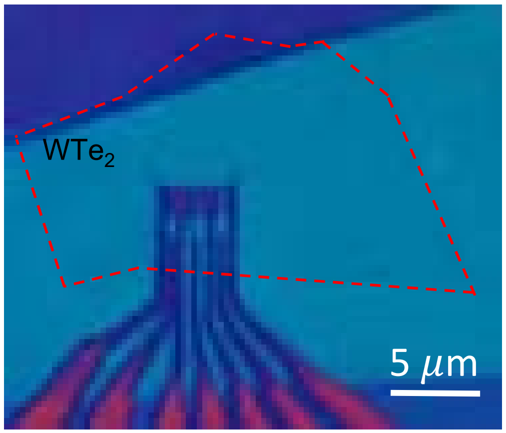


The first 2D semimetal to be studied

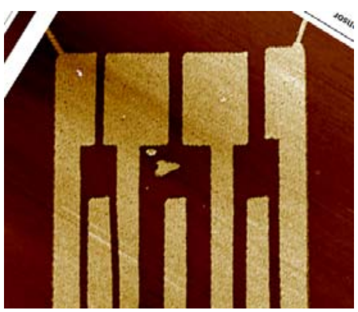
Z. Fei et al, *Nature Physics (10 April 2017)*



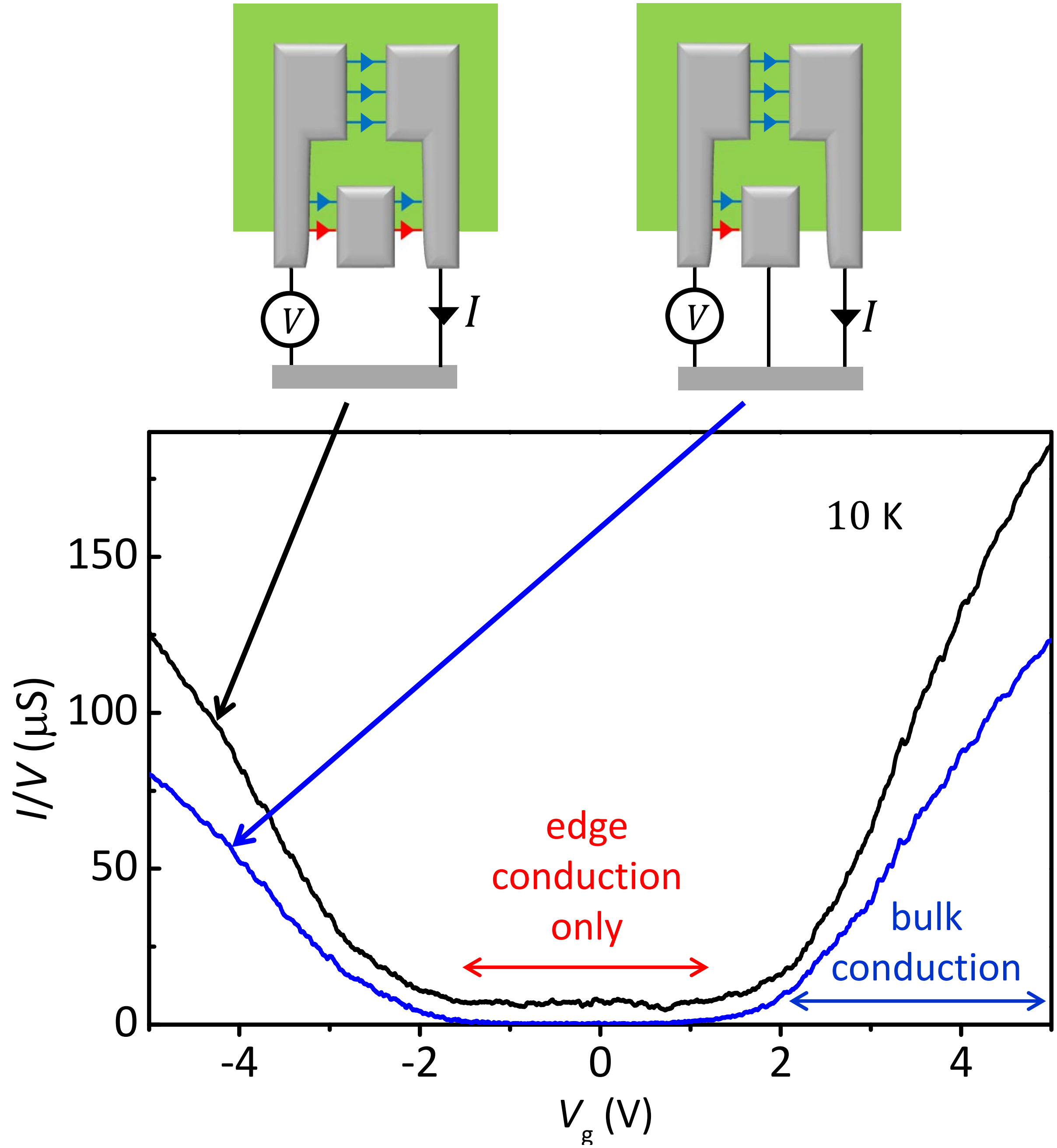
Differentiating edge and bulk conduction



optical image

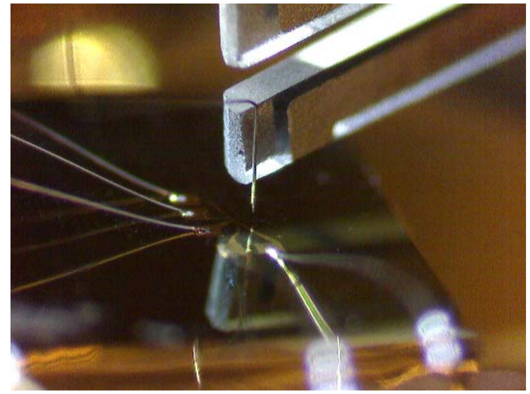


AFM image



Seeing the edge - scanning microwave impedance microscopy

Measurements by Yongtao Cui,
Stanford and UC Riverside
Technique: *Rev Sci Instr* 87, 063711 (2016)

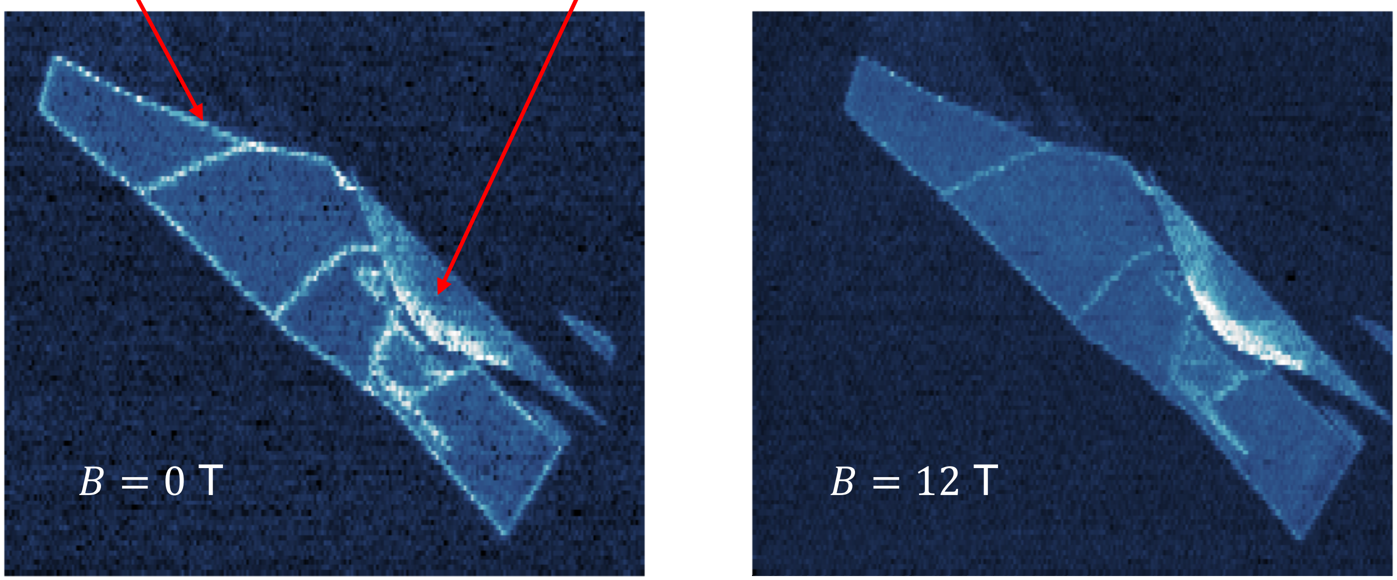


9 GHz 300 mK

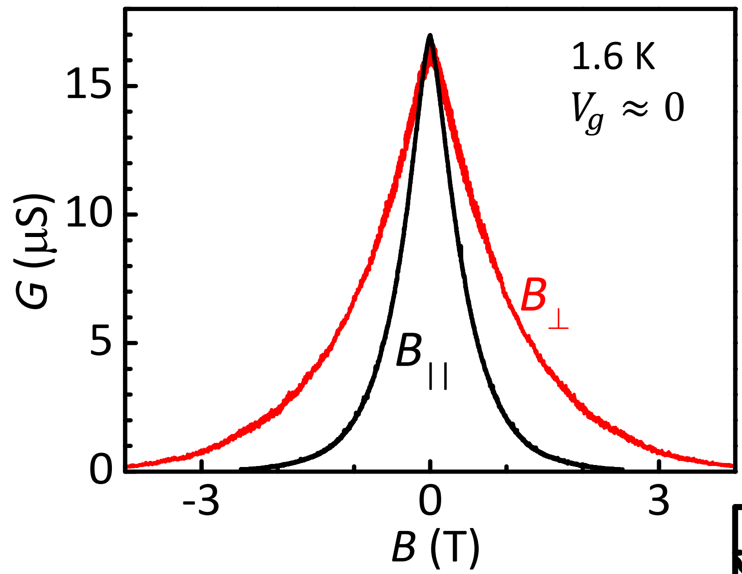
Brighter = higher conductivity

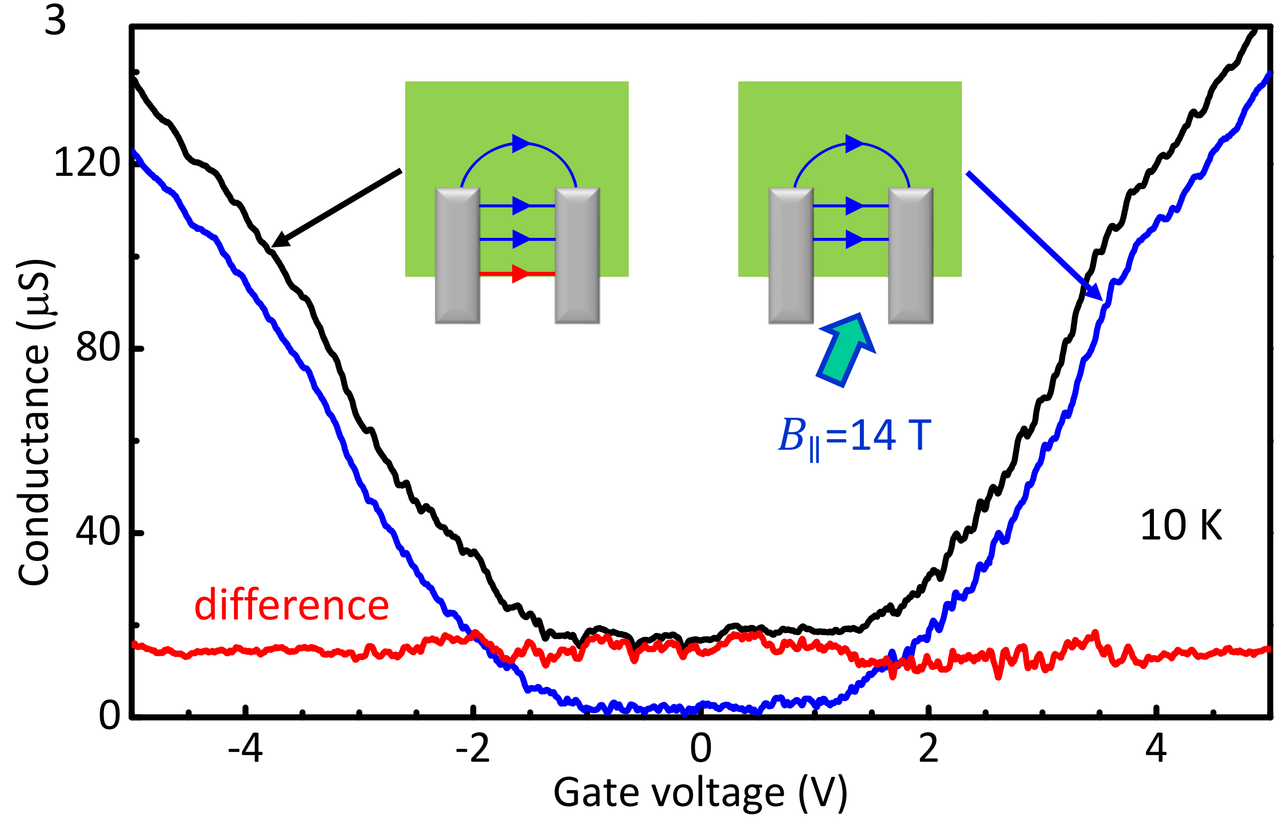
conducting edge

Bilayer region



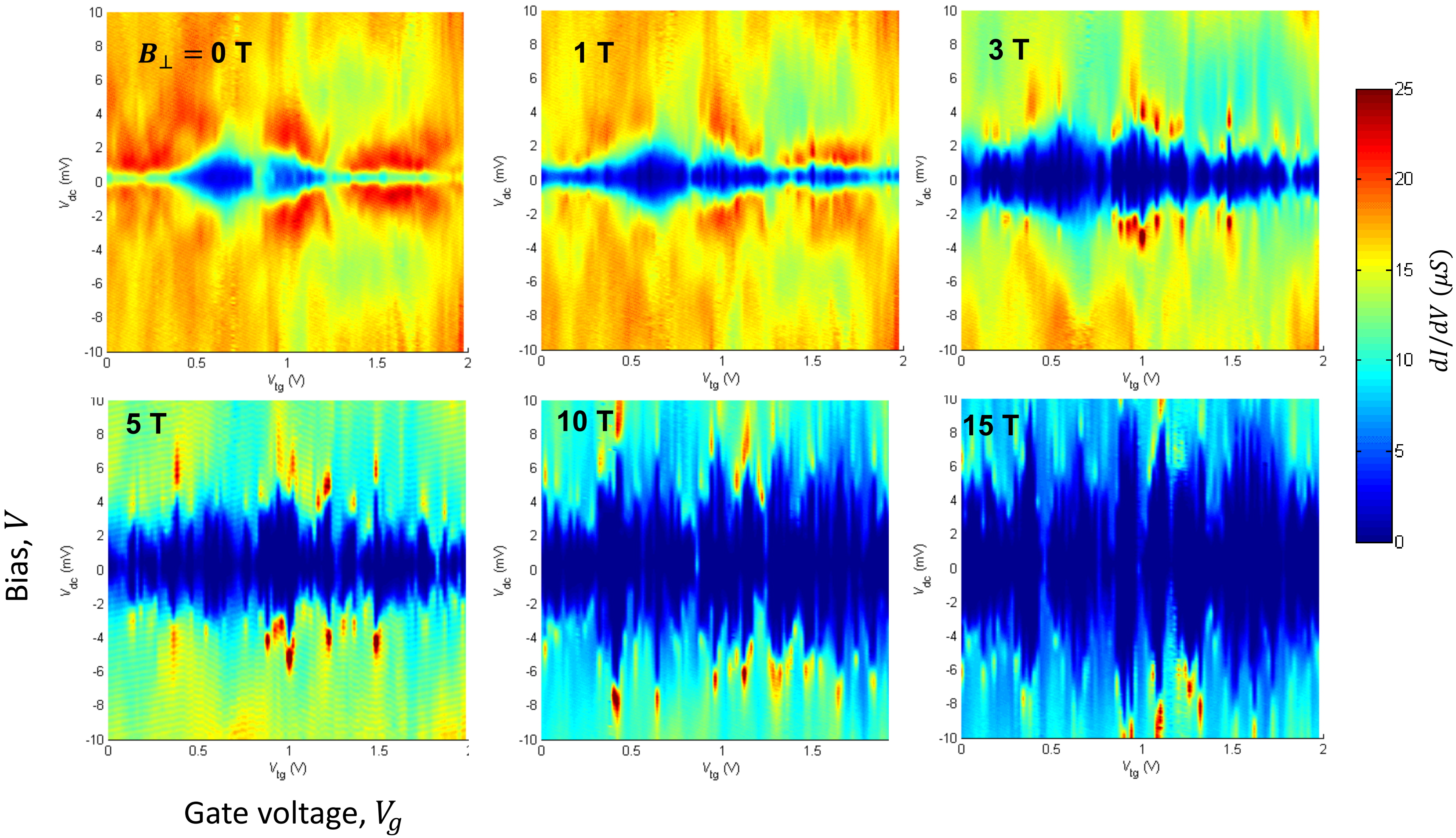
B-field suppresses edge conduction – characteristic of QSH



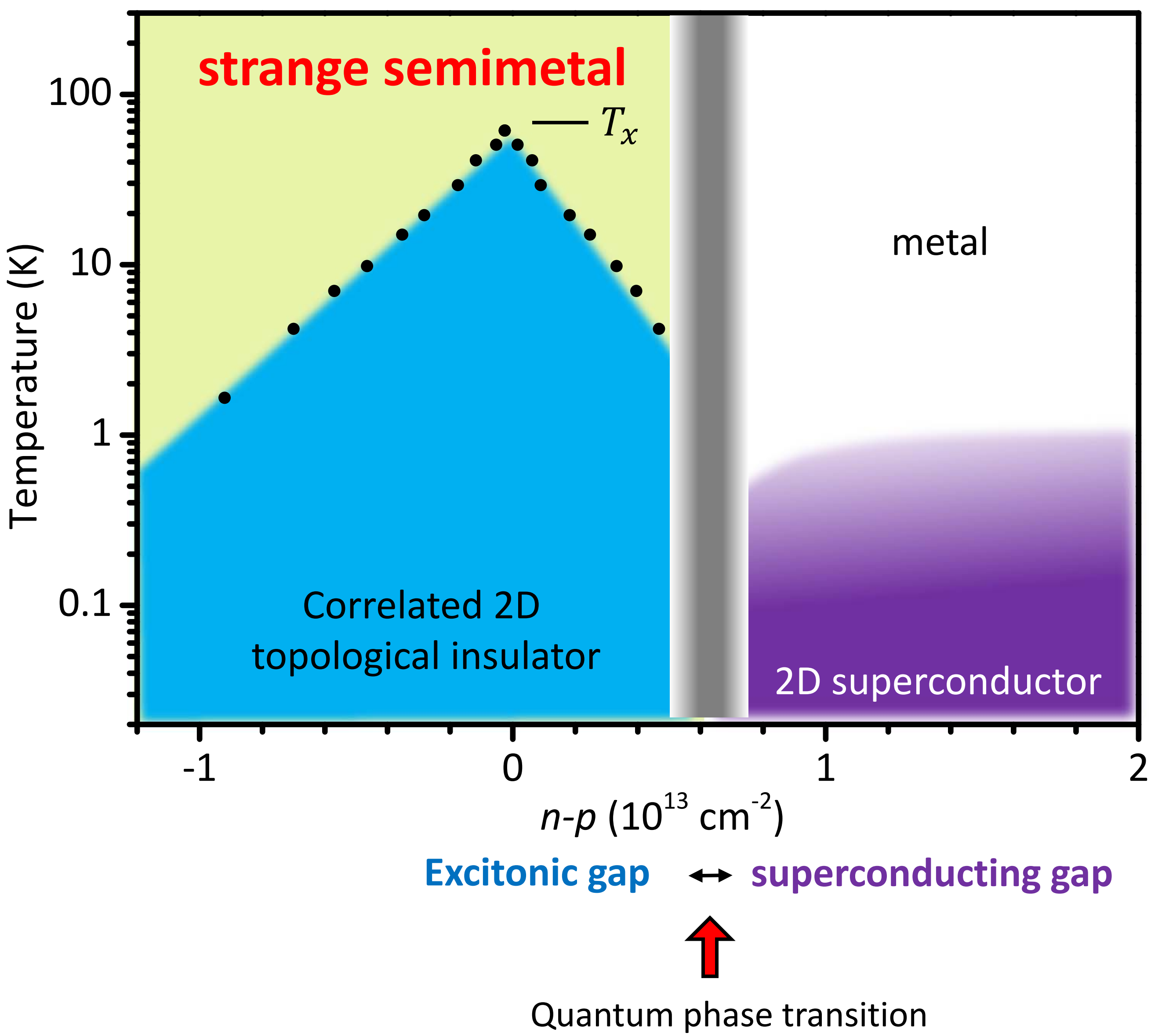


Weird and wonderful properties of edge conduction

T = 1.6 K, L = 150 nm



Phase diagram of monolayer WTe_2 (under construction)



Unpublished data deleted

CONCLUSION

2D physics in the lab is going places!