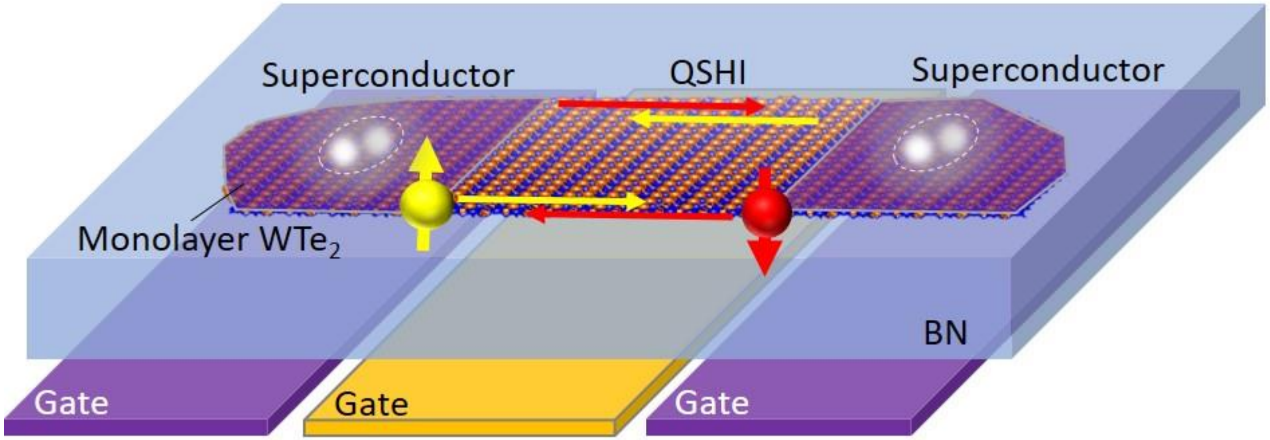
Topology and Correlations in Monolayer Crystals

Sanfeng Wu
Department of Physics, MIT
12/25/2017
@ UCAS



Topology and Correlations

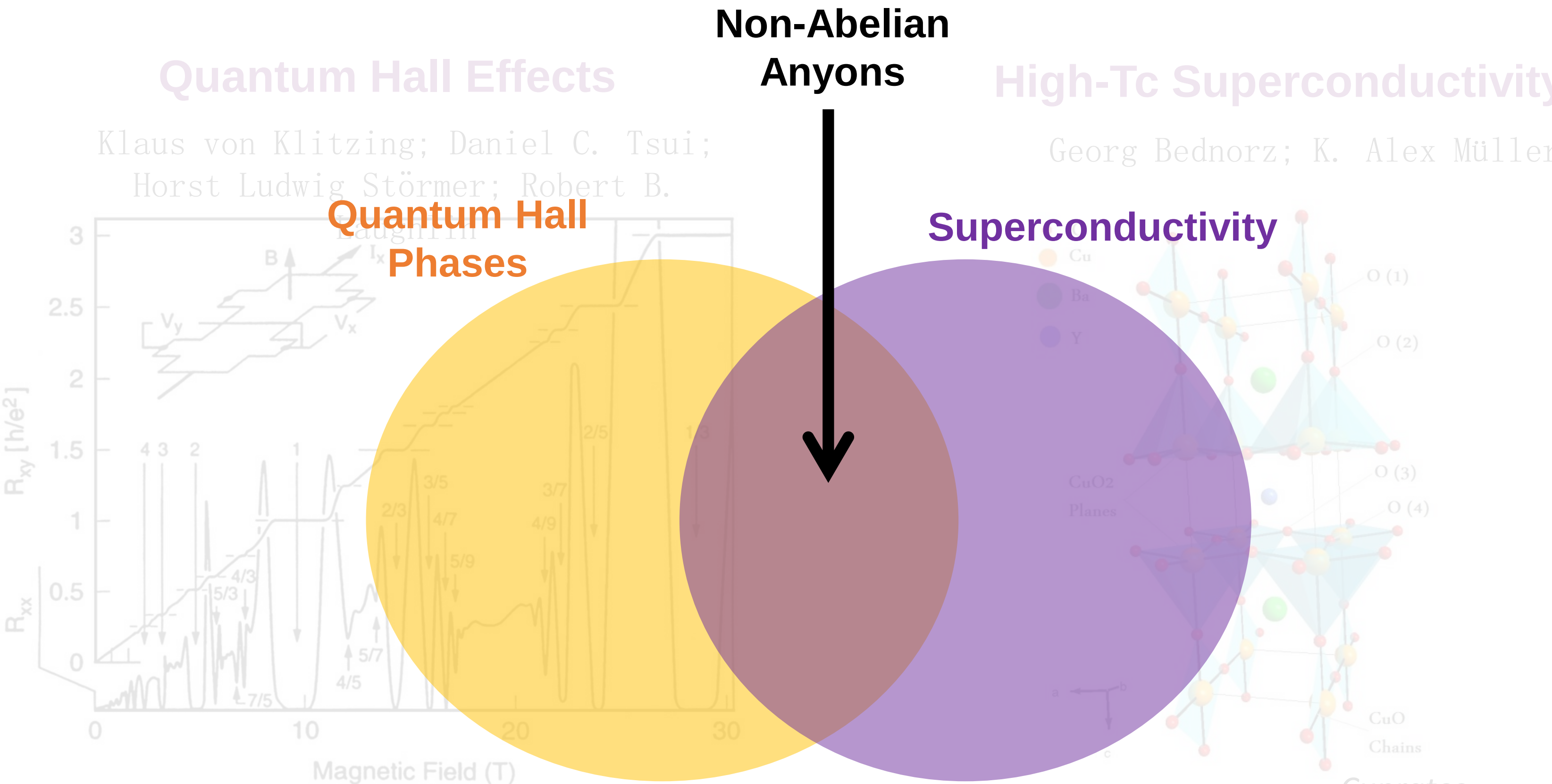
Experimental milestones in 1980s:

Quantum Hall Effects

Klaus von Klitzing; Daniel C. Tsui; Horst Ludwig Störmer; Robert B. Laughlin

High-Tc Superconductivity

Georg Bednorz; K. Alex Müller



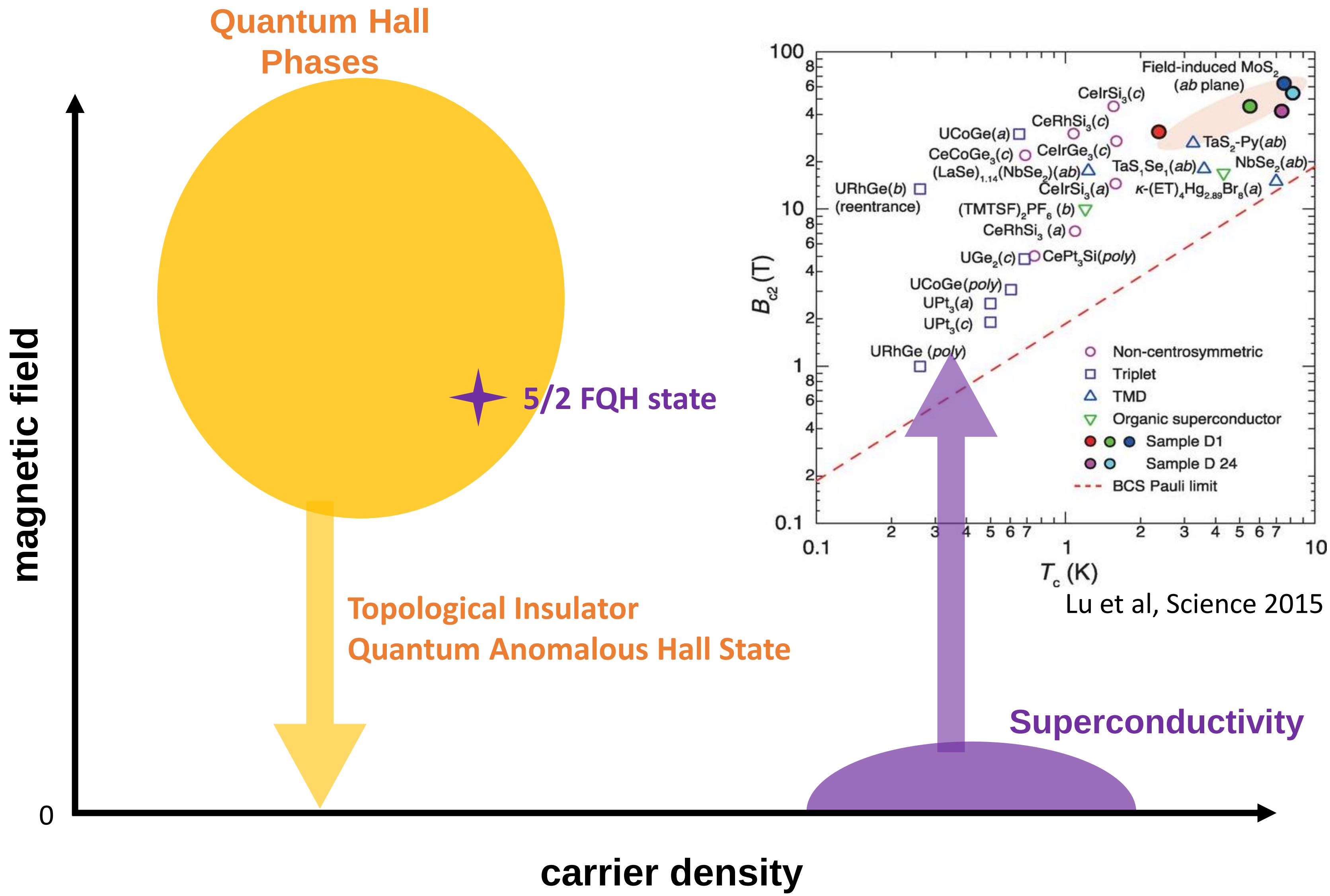
Data by Eisenstein and Stormer

Cuprates

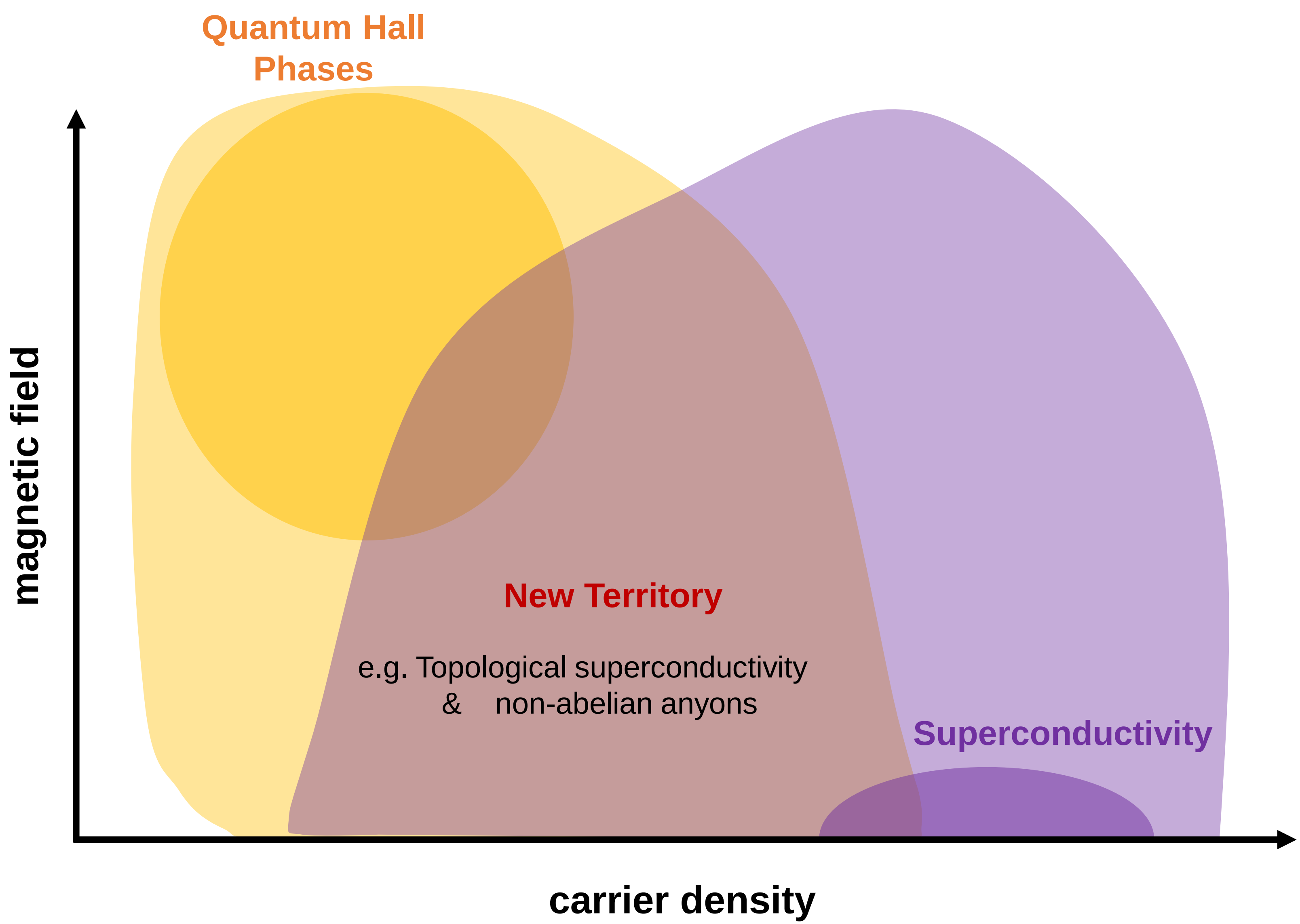
Topological Quantum States

Correlated Quantum States

Topology and Correlations



Topology and Correlations

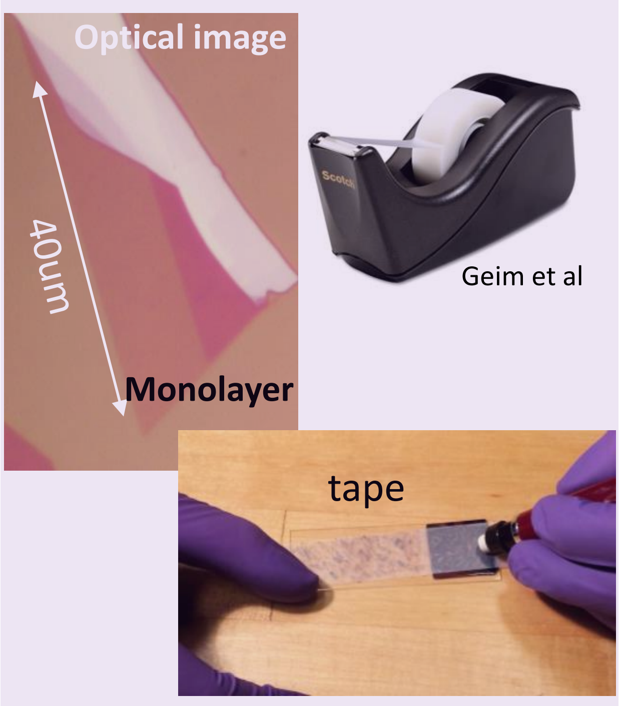


Monolayer Crystals and Heterostructures

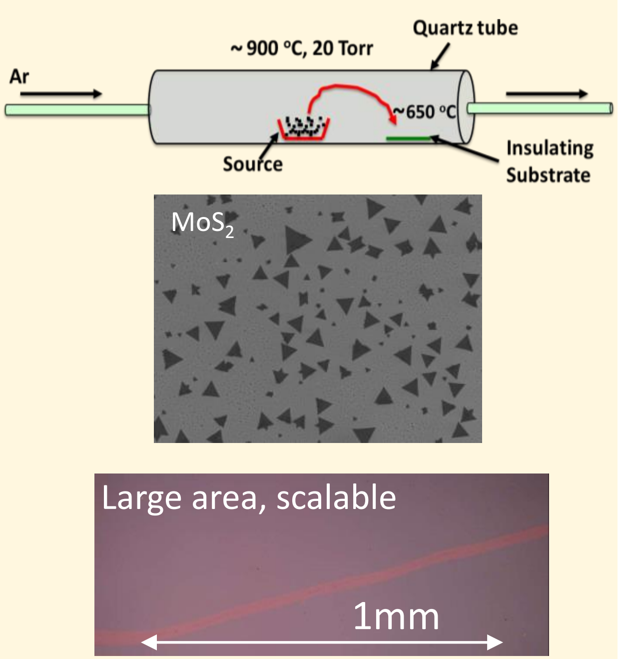
The simplest materials hosting 2D electrons:

<u>(Isolated) Crystalline Atomic Monolayers</u>

Mechanical Exfoliation



MBE/CVD/PVD Growth



Wu*, Huang*, et al, ASC Nano (2013)

Heterostructures

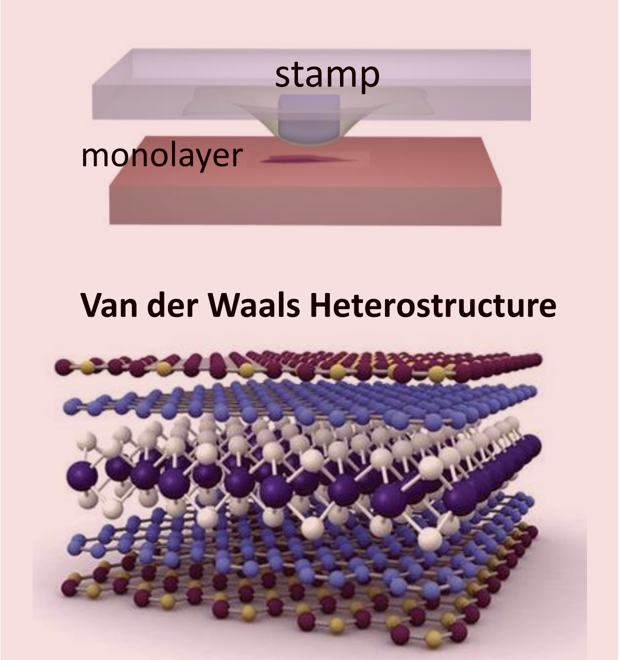
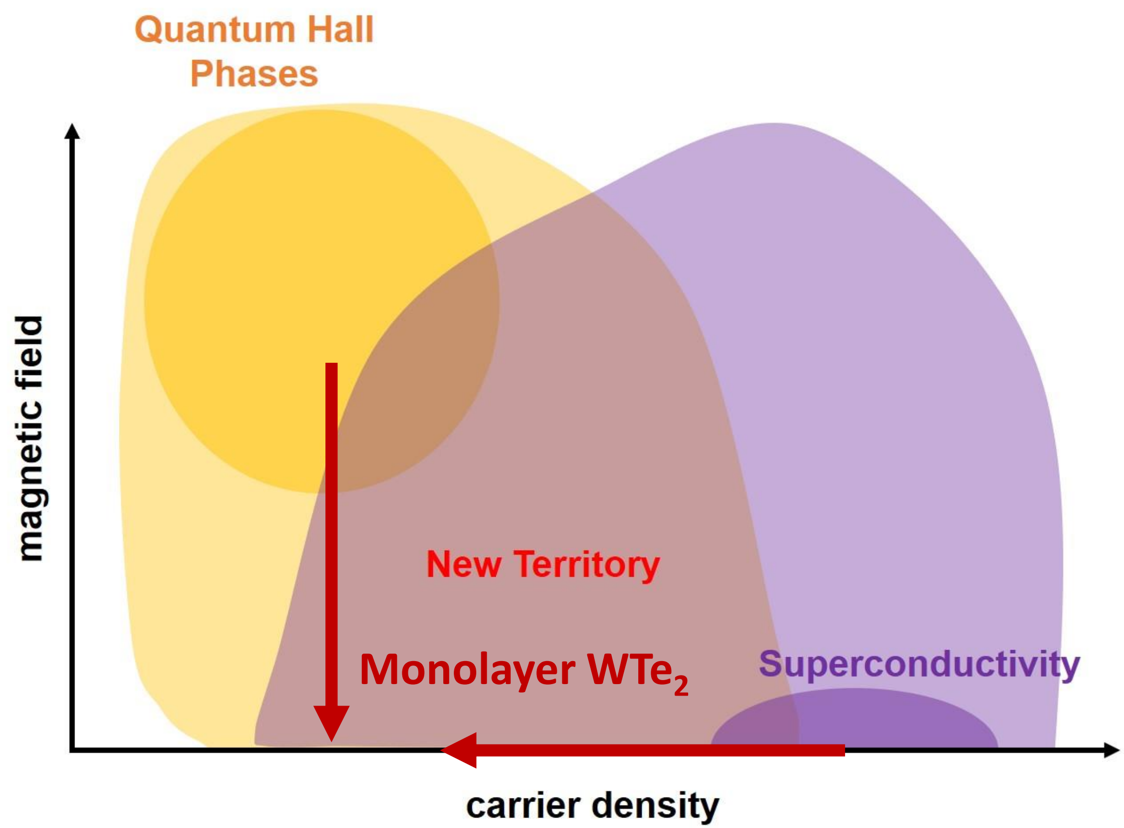


Image: Novoselov et al, Science (2016)

My Research Interests & Today's Topic

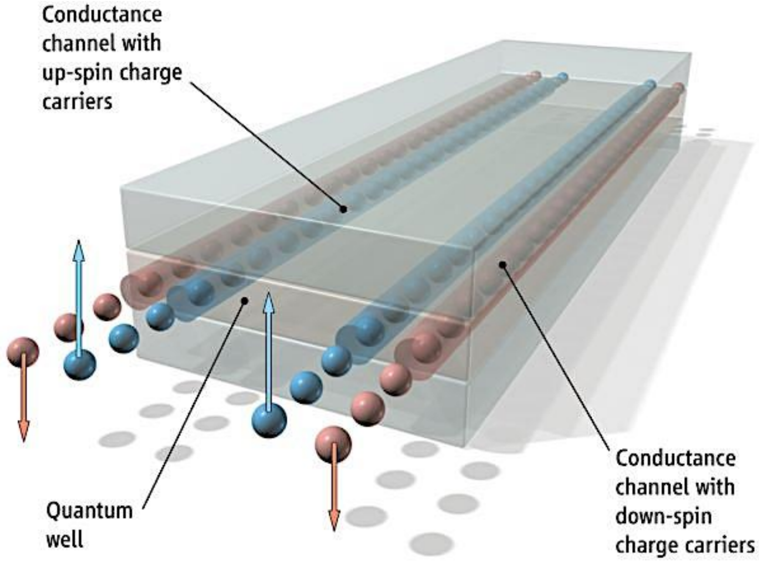


- Quantum spin Hall effect in monolayer WTe_2
- Superconductivity in monolayer WTe_2

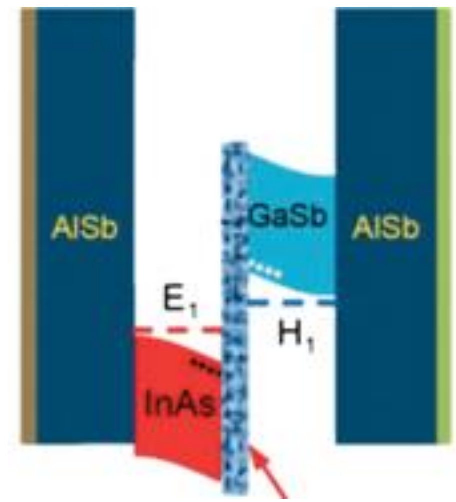
Experimental Quantum Spin Hall Effect

2D time-reversal invariant topological insulators

Semiconductor Heterostructures



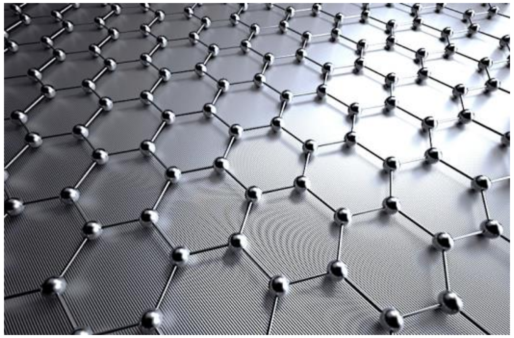
Molenkamp & Zhang et al (HgTe, 2007)



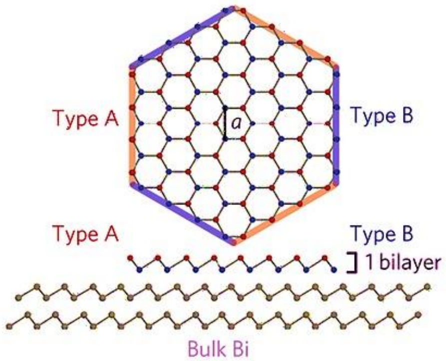
Du et al (InAs/GaSb, ~ 2015)

Low Temperature Phenomena:
Near Liquid Helium Temperature (< 10 K)

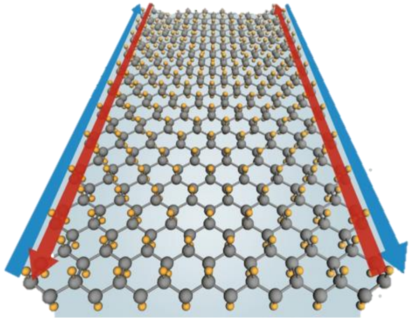
Monolayer QSH Systems



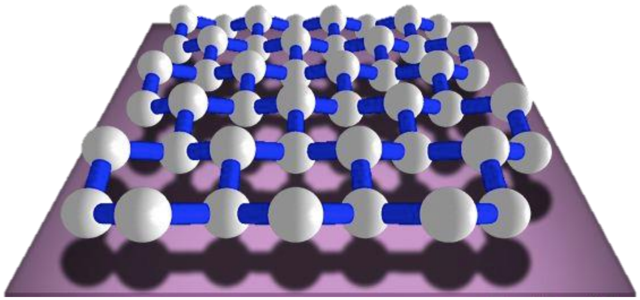
Spin-orbit coupled Graphene, 2005
Kane&Mele



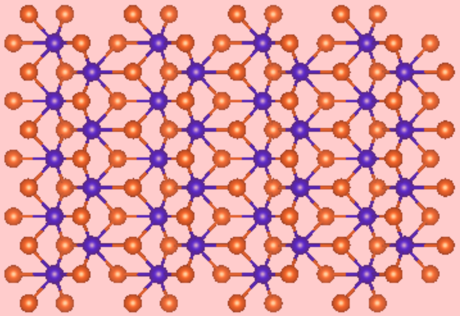
Bismuth Bilayer, 2006
Yazdani, Murakami, Palacios etc



Stanene, 2013
S.C. Zhang et al



Silicene and Germanium, 2011
Y. Yao et al



Transition Metal Dichalcogenides
Qian, Liu, Fu and Li, Science (2014)

Others:
$GaBiCl_2$
BiX/SbX
ZrBr
$ZrTe_5$
Bi_4F_4
Bi_4Br_4
TaCX (X=Cl, Br, I)
MC (M = Zr, Hf)
....

Monolayer Transition Metal Dichalcogenides

REPORT

Quantum spin Hall effect in two-dimensional transition metal dichalcogenides

Xiaofeng Qian[1,*], Junwei Liu[2,*], Liang Fu[2,†], Ju Li[1,†]

+ Author Affiliations

†Corresponding author. E-mail: liangfu@mit.edu (L.F.); liju@mit.edu (J.L.)

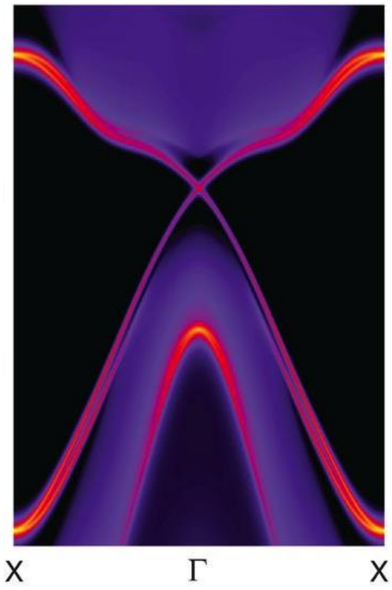
* These authors contributed equally to this work.

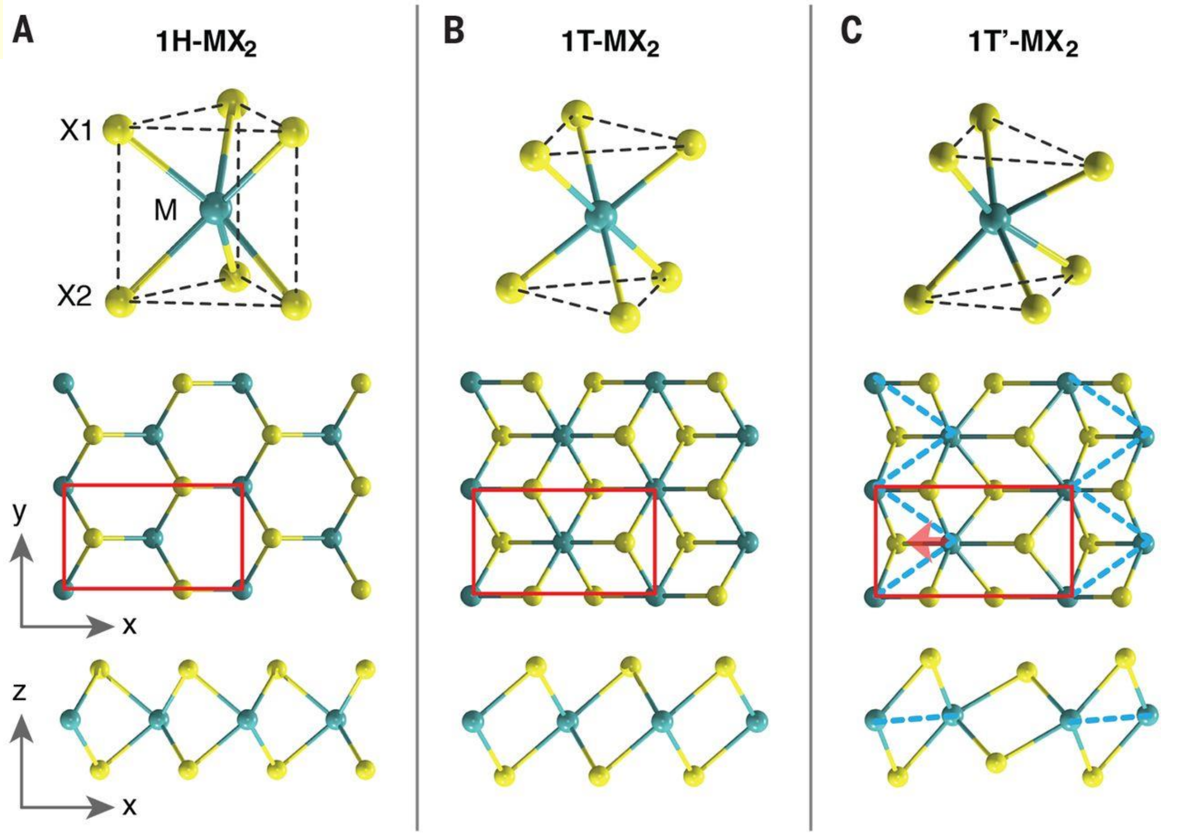
Science 20 Nov 2014:

DOI: 10.1126/science.1256815

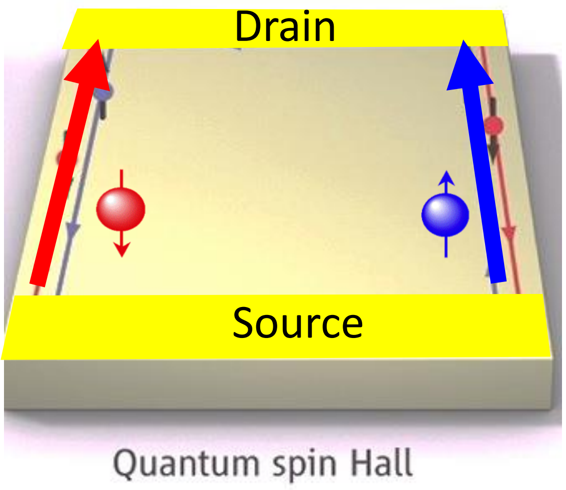
M = Mo, W;
X = S, Se, Te.

1T' TMD Monolayer

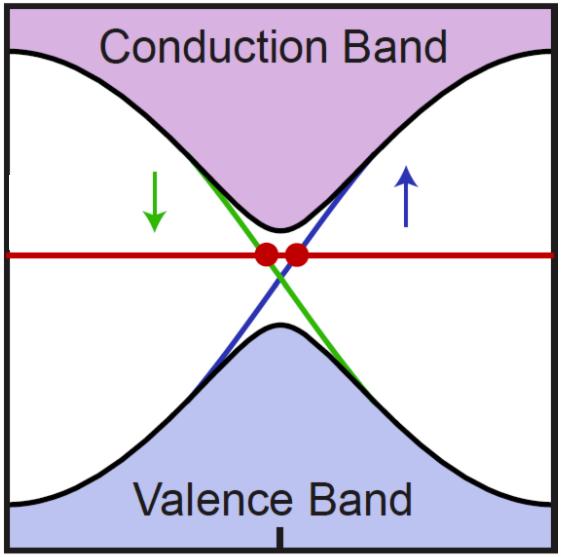




Signatures of QSHE in a 2D time reversal invariant TI



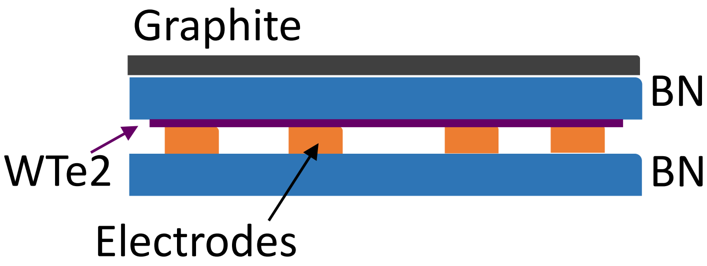
- ✓ **Helical edge mode of a insulator**
- ✓ **Topological protection allowed by TR symmetry**

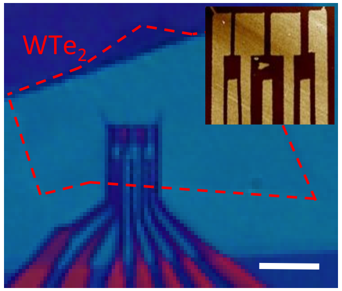


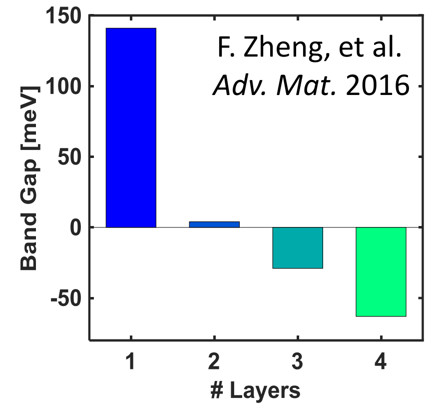
Expected QSH Transport Signatures:

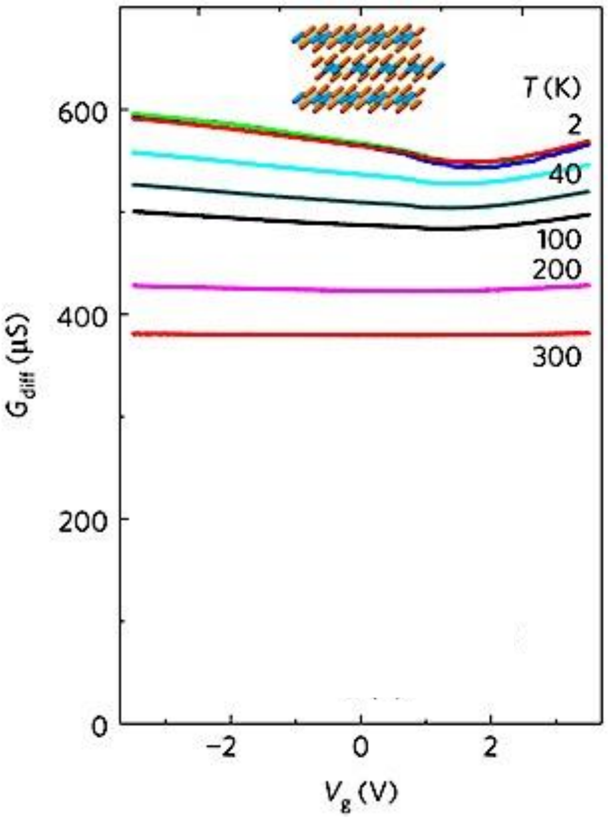
- Bulk insulating + edge conducting
- Quantized conductance, ~ e^2/h per edge
- Conductance saturates in the short-edge limit
- Quantization destroyed under broken TR symmetry
- (Zeeman gap opening at the Dirac point)
- … …

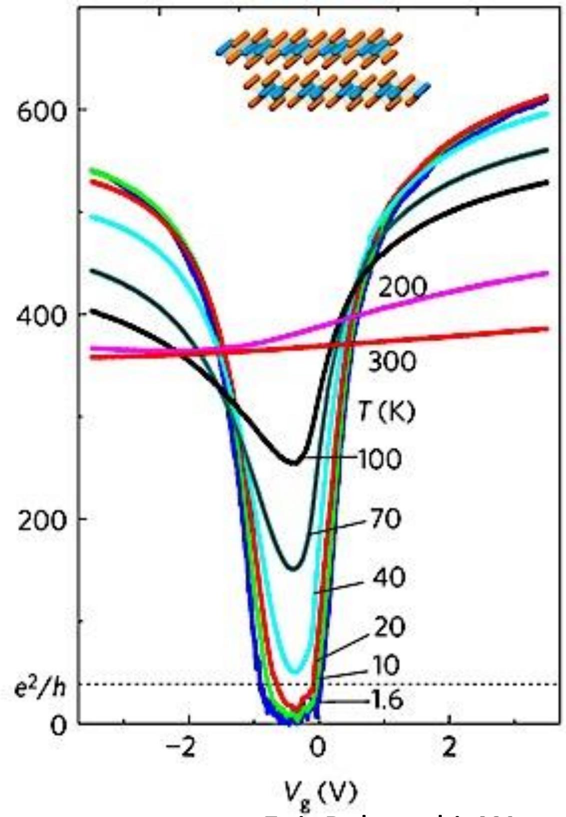
Quantum Transport in Atomically Thin WTe_2

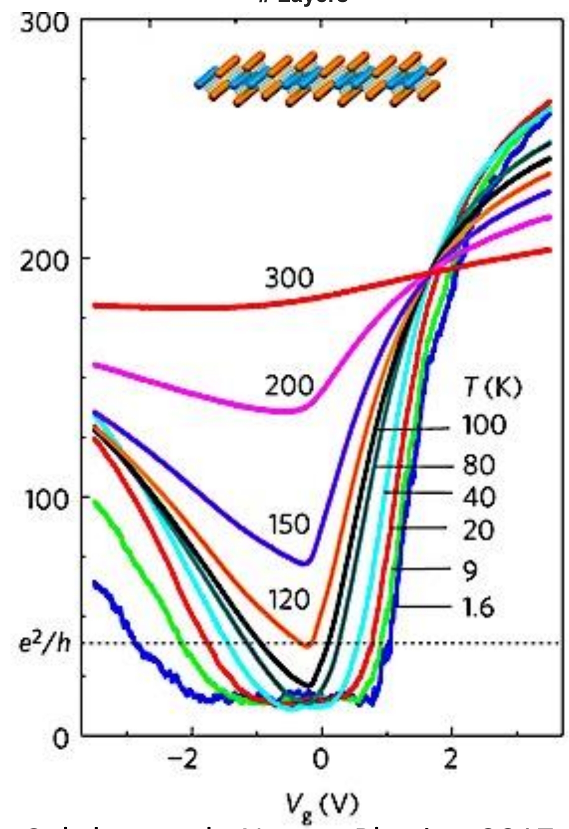








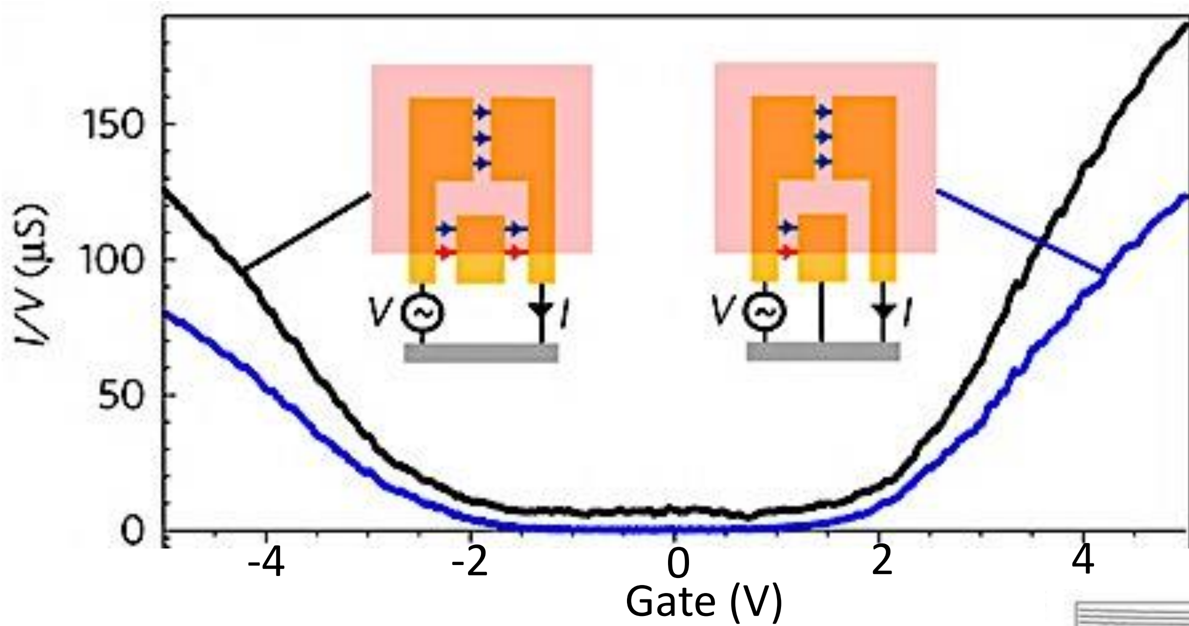




Fei, Palomaki, **Wu**, …, Xu, Cobden et al, Nature Physics, 2017

Edge Conduction in Monolayer WTe_2

Distinguish Edge Conduction from the Bulk Contribution



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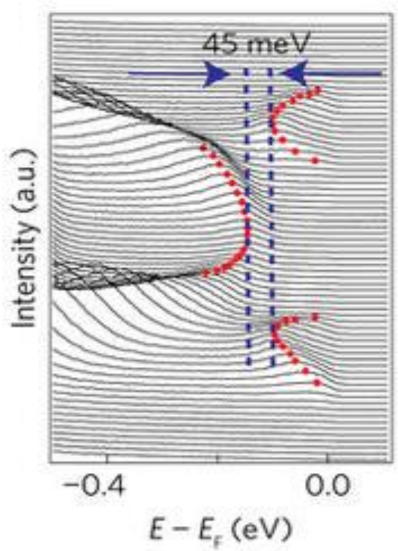
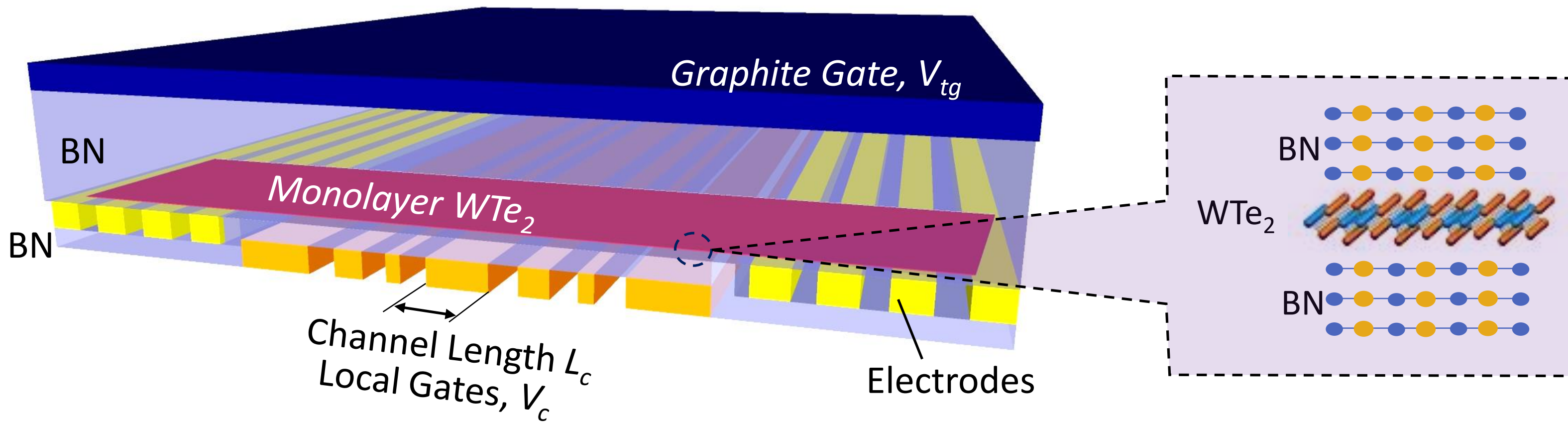


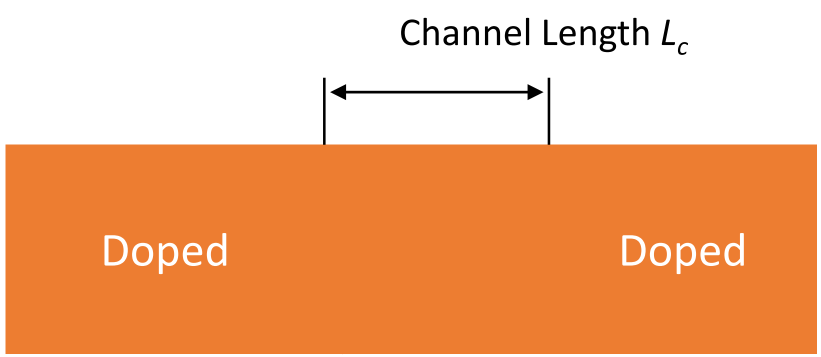
Tang et al, *Nature Physics* (2017)

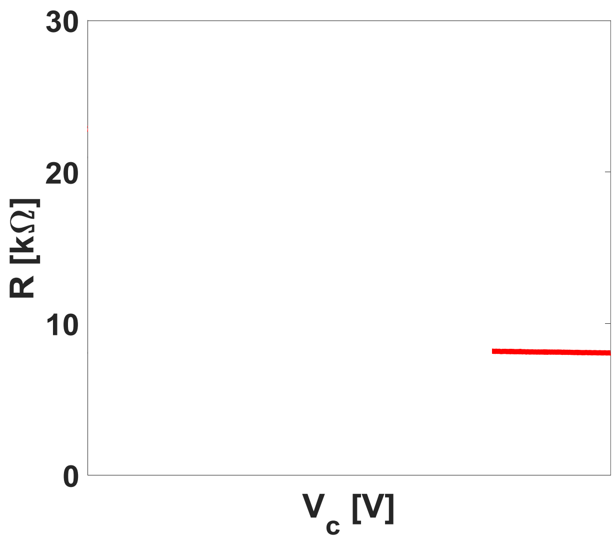
Is It Really a QSH Insulator?

Difficulties

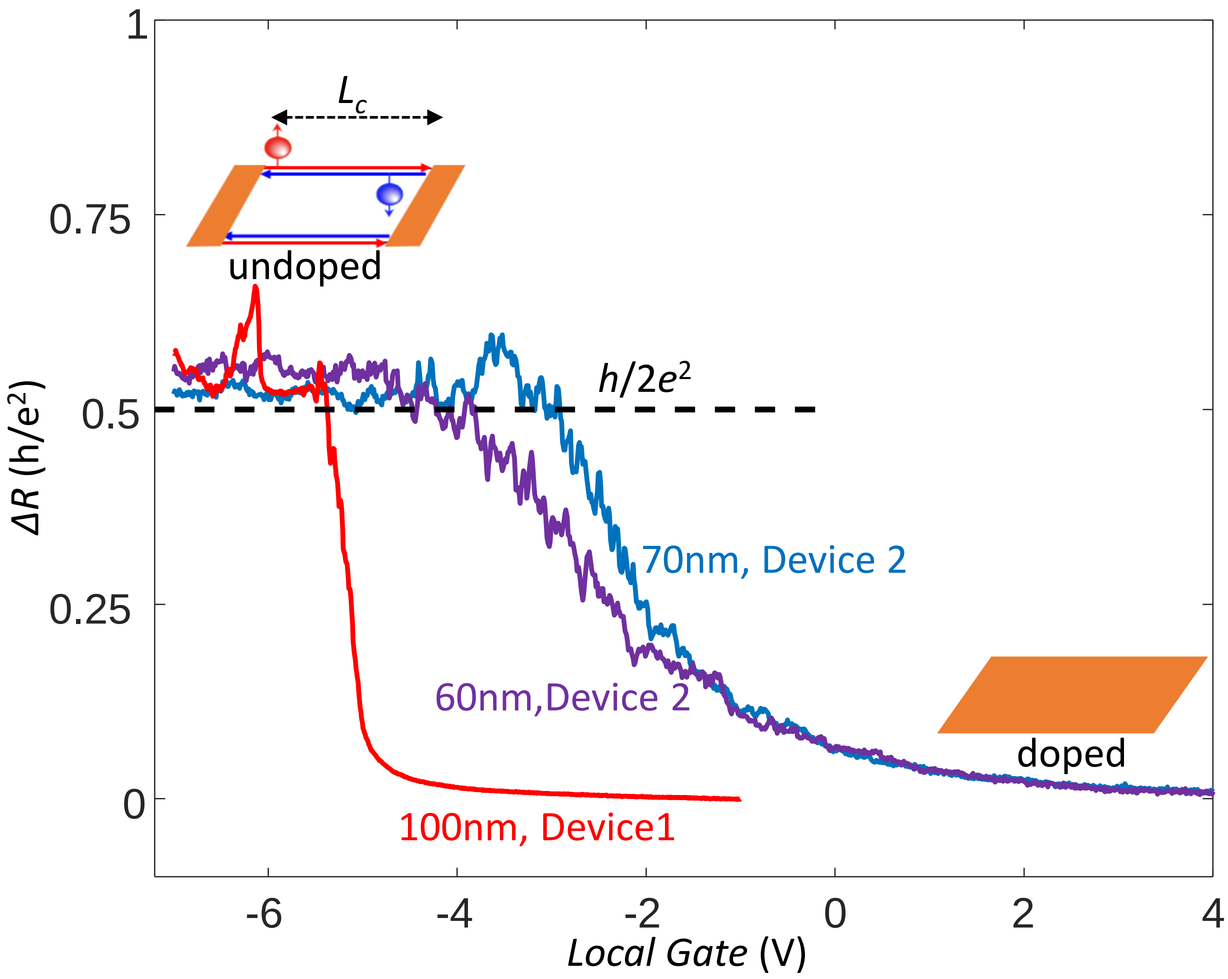
- **Good Contact?**
- **High Quality Devices?**
- **How to do length dependence properly?**



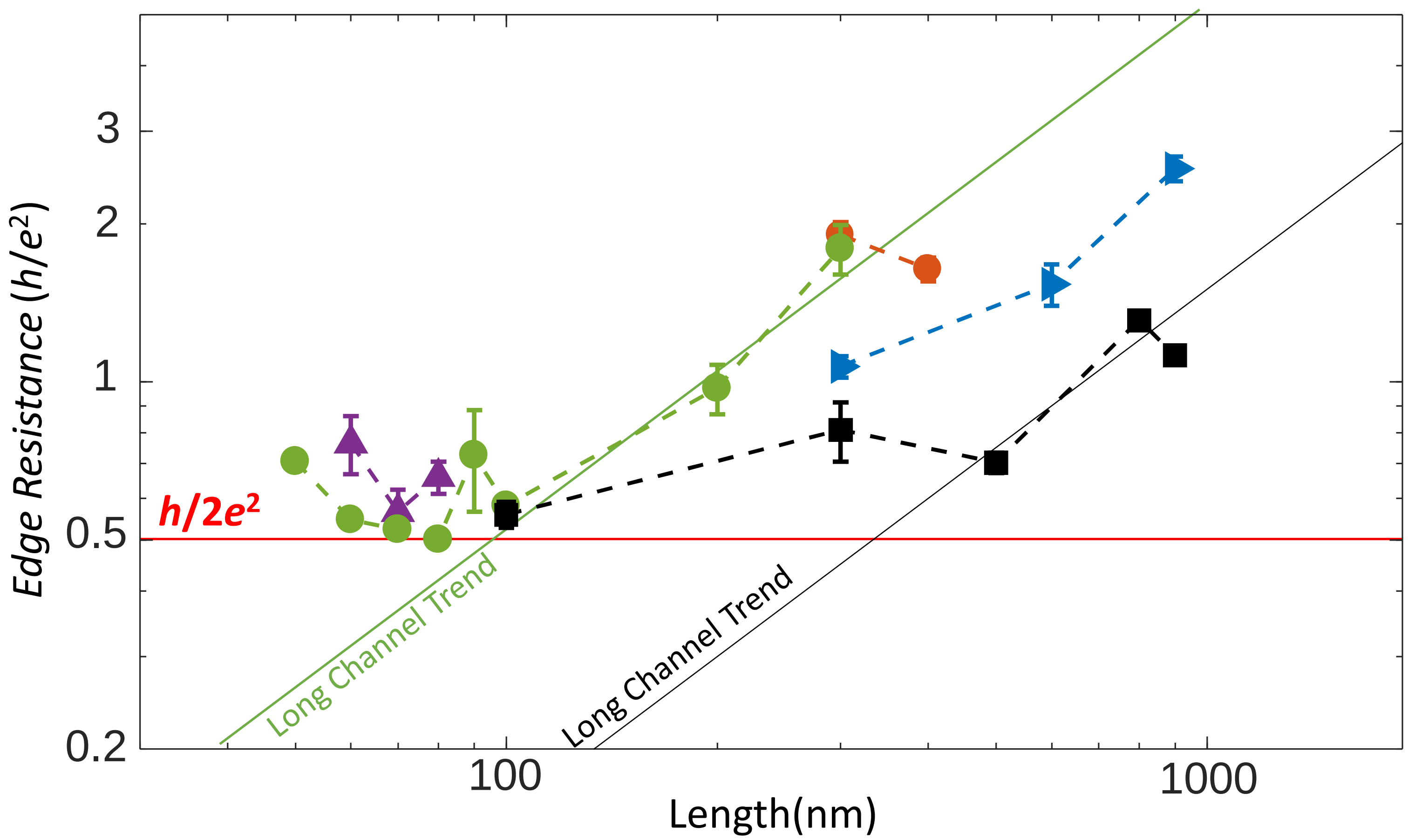




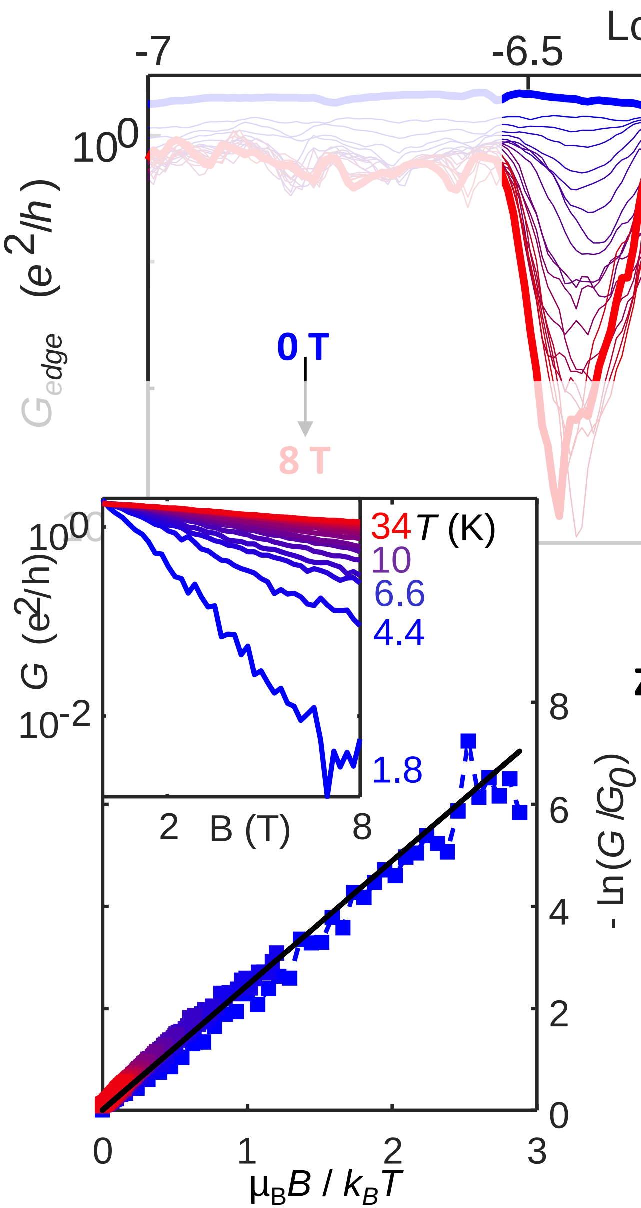
Helical Edge Mode: Conductance Quantization



Helical Edge Mode: Length Dependence

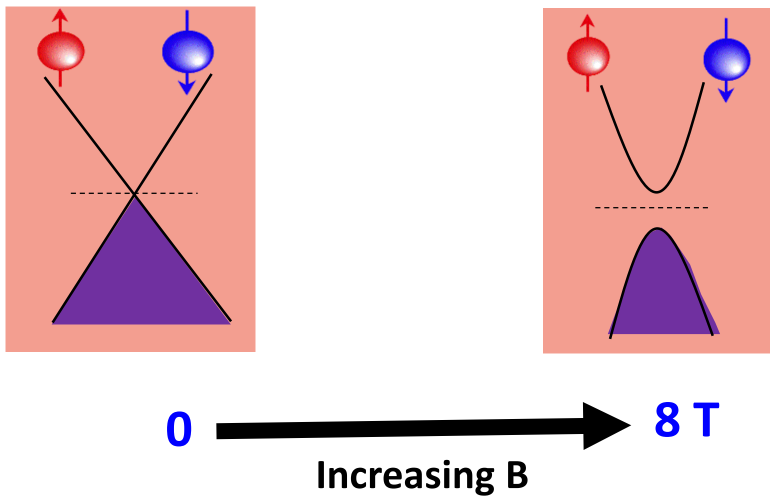


Helical Edge Mode: Breaking Time-Reversal Symmetry



$G = G_0 \exp(- g\, u_B B/2K_B T)$, $g \sim 4.8$

Zeeman Gap Opening at the Kramers point (Dirac Point)



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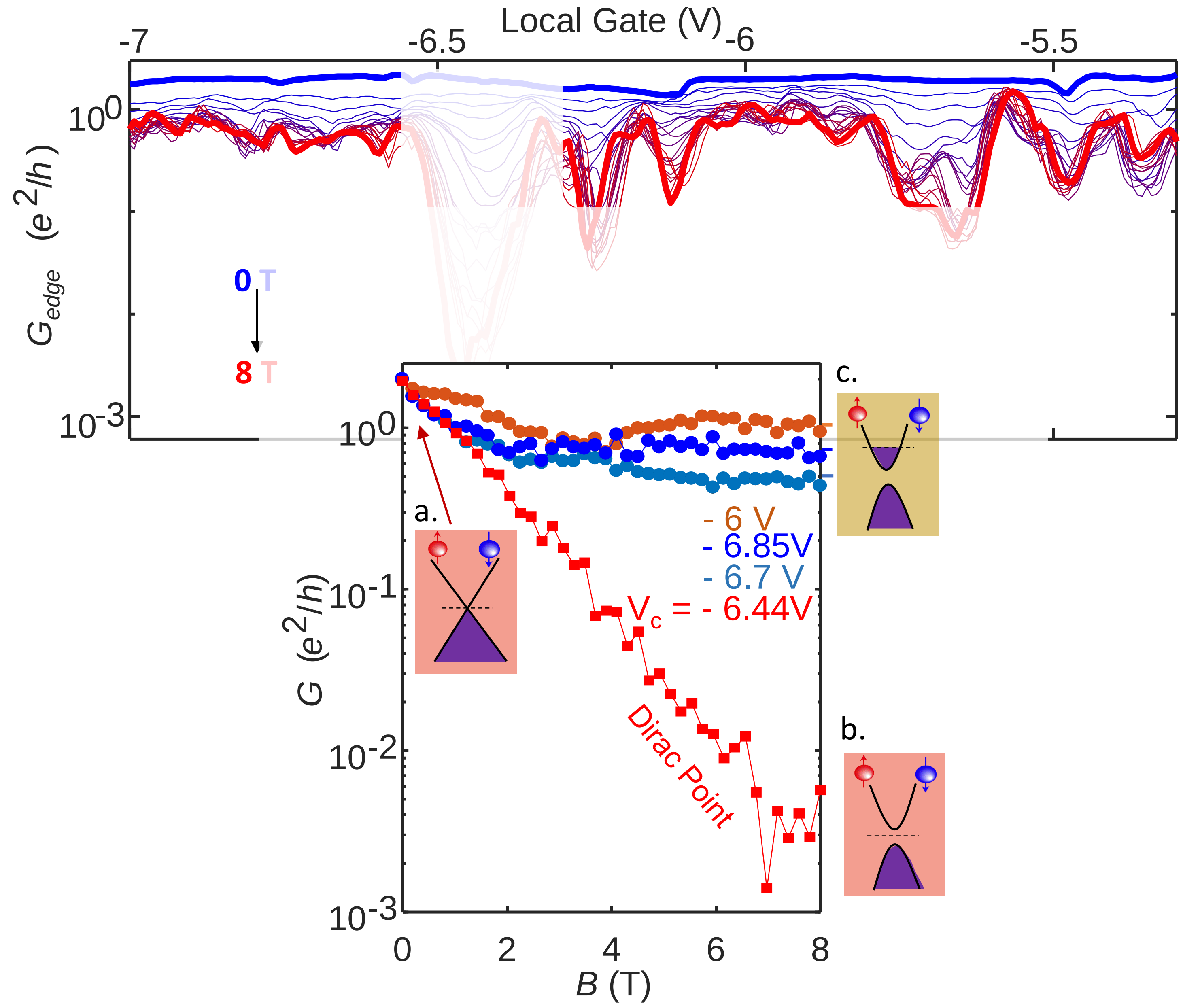
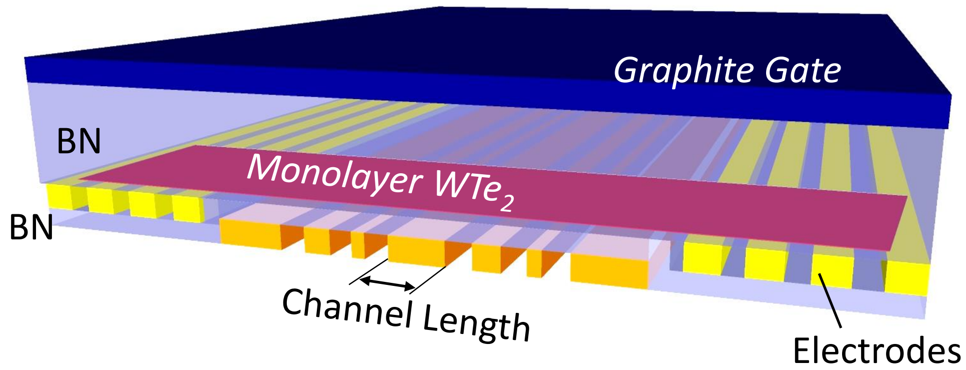


Observation of the QSHE in Monolayer WTe_2

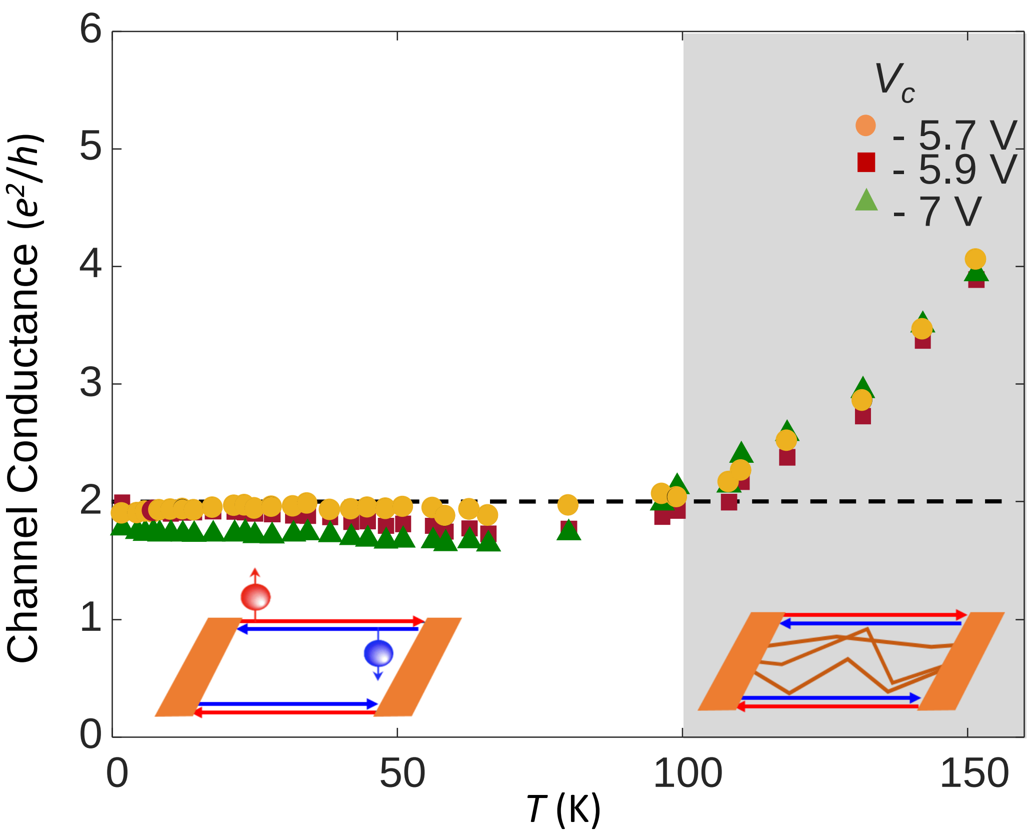


Expected QSH Transport Signatures:

- Bulk insulating + edge conducting ✓
- Quantized conductance, ~ e^2/h per edge ✓
- Conductance saturates in the short-edge limit ✓
- Quantization destroyed under broken TR symmetry ✓
- (Zeeman gap opening at the Dirac Point) ✓

- Spin-polarized edge transport
- Non-local quantum transport
- Exotic phenomena allowed by QSHE

The High Temperature QSHE

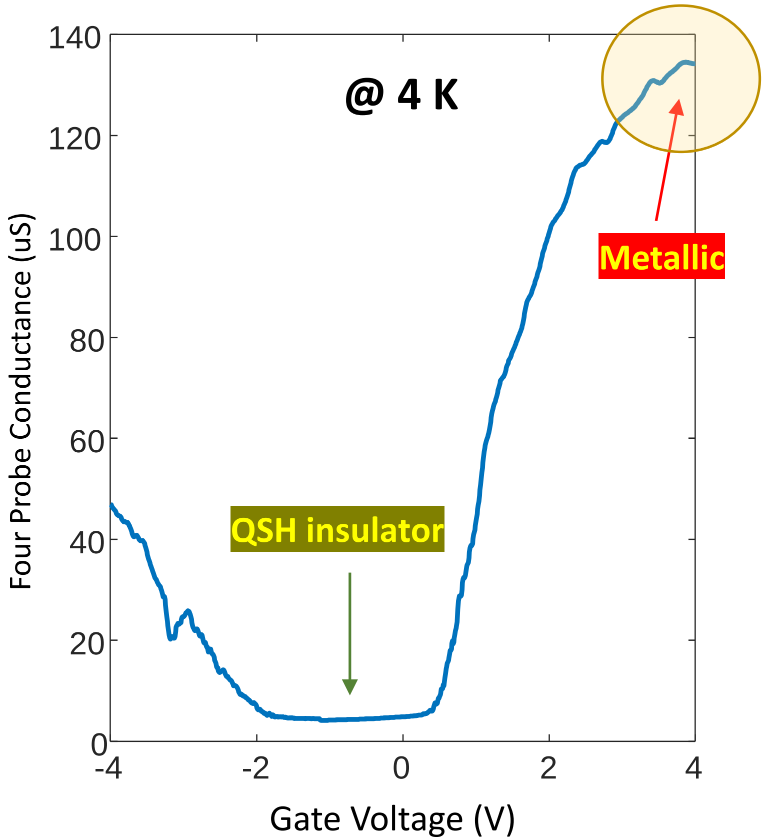


- **12** years after the prediction of QSHE in graphene, **we report strong evidences of QSHE in a monolayer crystal**.
- 10 years after the first QSH experiment, we observed the expected **Dirac-point** behavior.
- We achieved the **QSHE at high temperatures.**

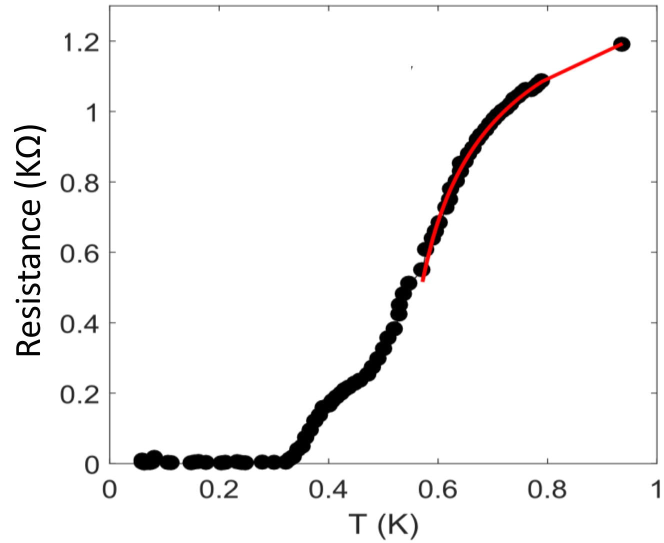
Wu*,#, Fatemi*,#, Gibson, Watanabe, Taniguchi, Cava, and Jarillo-Hererro#
to appear in **Science** (2017)

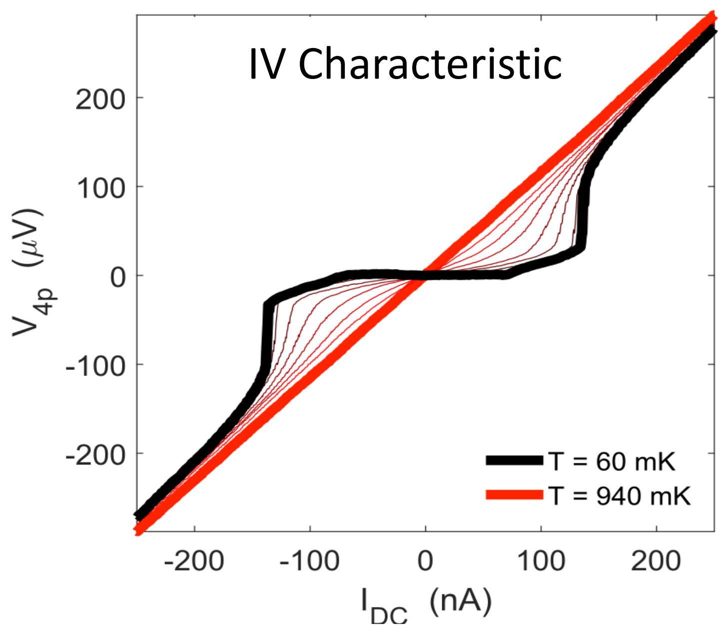
Recent ARPES/STM Measurements: **45 meV** gap in the bulk
Tang et al, *Nature Physics* (2017); Jia et al, *PRB (2017)*

Superconductivity in Electrostatically Doped Monolayer WTe_2



T_c ~ 1K for highest gate voltage



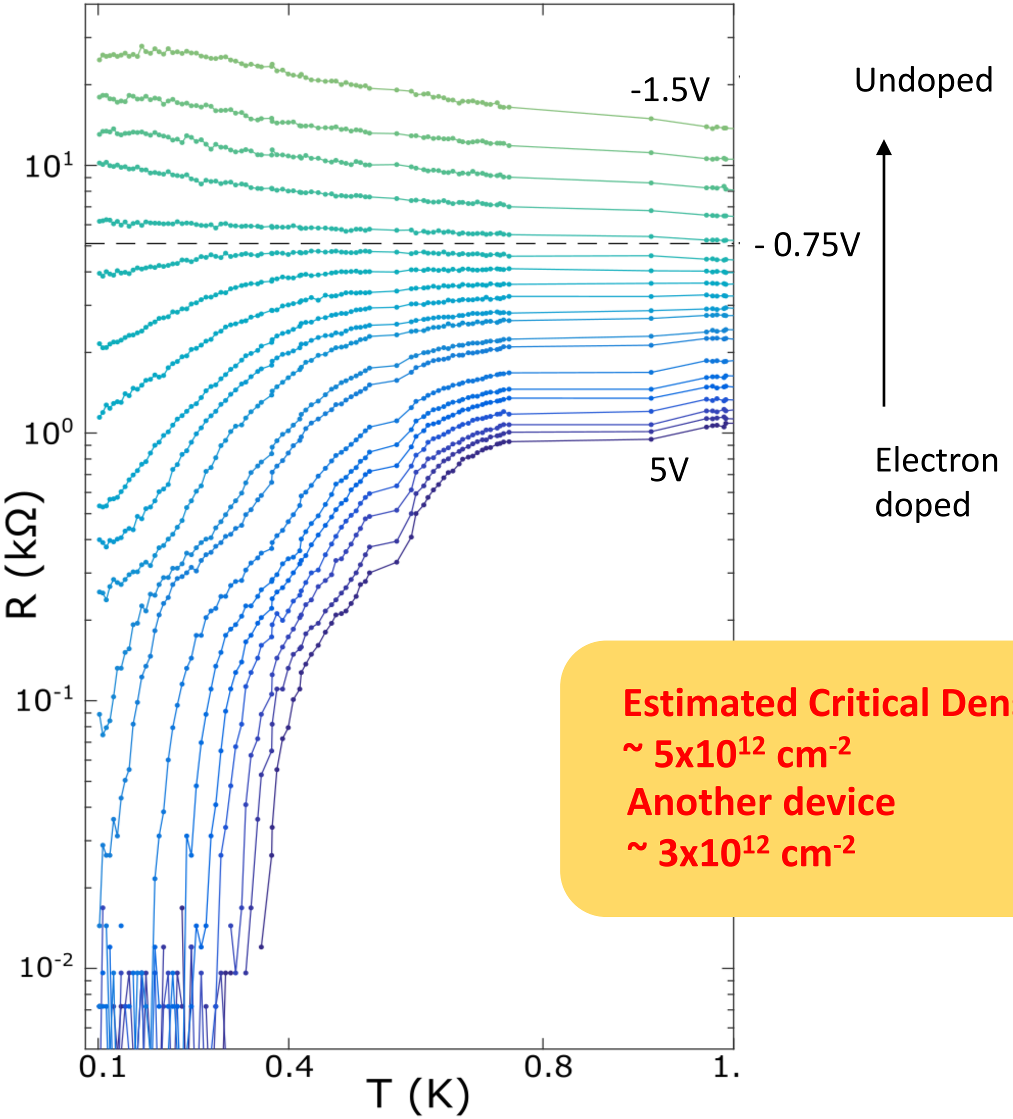


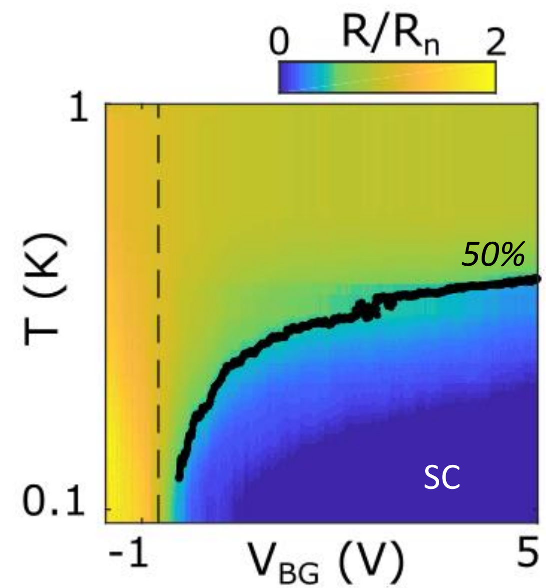
Bulk WTe_2: Tc ~ 6.5 K under high pressure

Kang et al, *Nat. Commun.* **6**, 8804 (2015)

Pan et al, *Nat. Commun.* **6**, 8805 (2015)

Gate Tunable Superconductivity



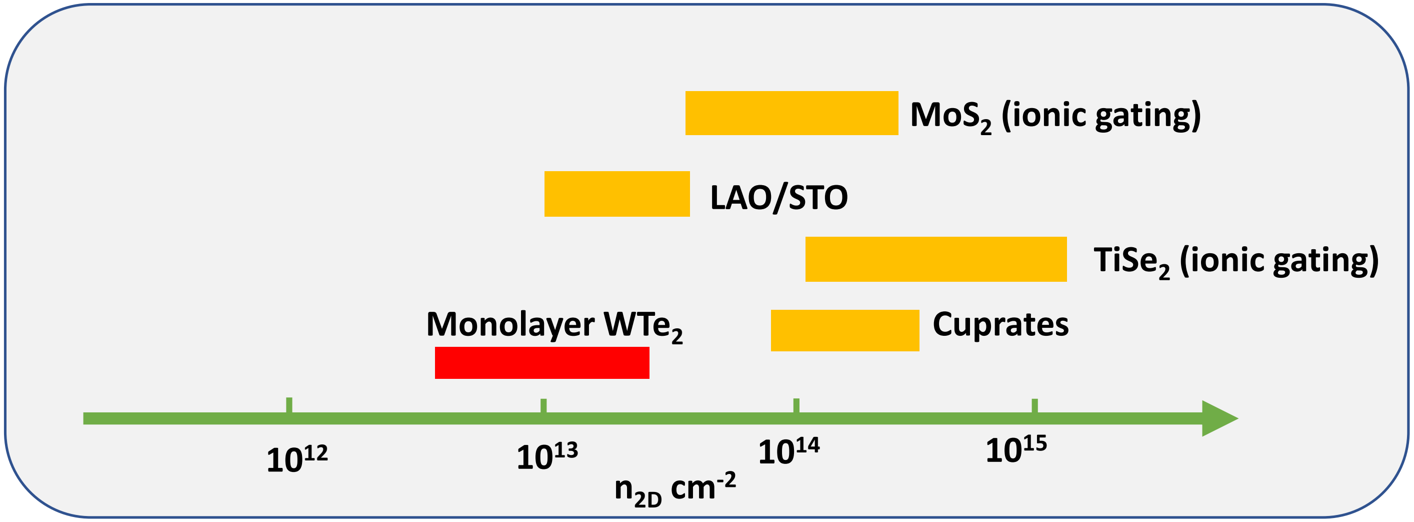


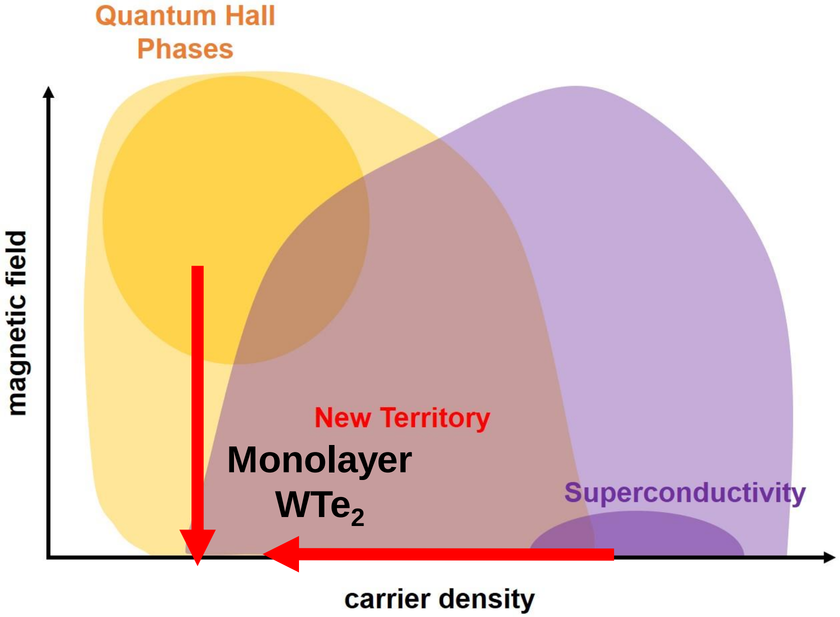
Estimated Critical Density:
~ 5×10^{12} cm^{-2}
Another device
~ 3×10^{12} cm^{-2}

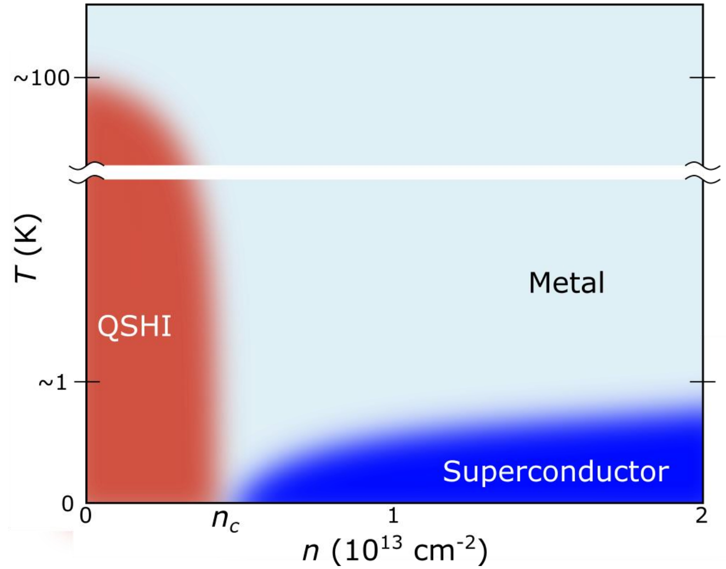
Fatemi*, **Wu*,#**, Cao, Bretheau, Gibson, Watanabe, Taniguchi, Cava, and Jarillo-Hererro#
Submitted (2017)

Monolayer WTe_2: A Low Density Superconductor

2D Superconductors and their carrier densities.







History and the Future of History

1000 - 200 B.C.E

“上古结绳而治，后世圣人易之以书契”

中国历史

伏羲 (3000 ~ 5000 B.C.E)

2017 C.E

“The Knotting Age”

结绳记事

“The Scratching Age”

刻划记事

“A New Knotting Age” ?

量子结绳记事？

Acknowledgements

Work at MIT

Jarillo-Herrero Group
Quantum Nanoelectronics @ MIT

Pappalardo Fellowships in Physics

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

GORDON AND BETTY MOORE FOUNDATION

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH — UNITED STATES AIR FORCE

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

Pablo Jarillo-Herrero

Valla Fatemi (MIT)
Quinn Gibson & Robert J. Cava (Princeton)
Kenji Watanabe & Takashi Taniguchi (NIMS)
Liang Fu (MIT)

Work at UW

UNIVERSITY OF WASHINGTON · 1861

Xu Lab
Nanoscale Optoelectronics Laboratory at the University of Washington

CLEAN ENERGY INSTITUTE

Xiaodong Xu

David Cobden (UW)
Zaiyao Fei (UW)
Wang Yao (HKU)
Di Xiao (CMU)
Jiaqiang Yan & David Mandrus (ORNL)