Topology and Correlations in Monolayer Crystals

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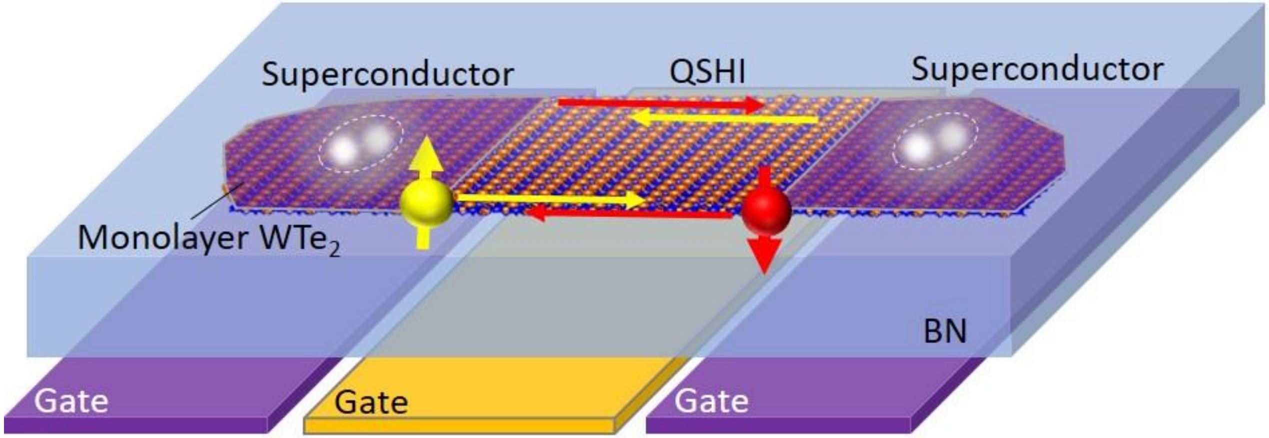
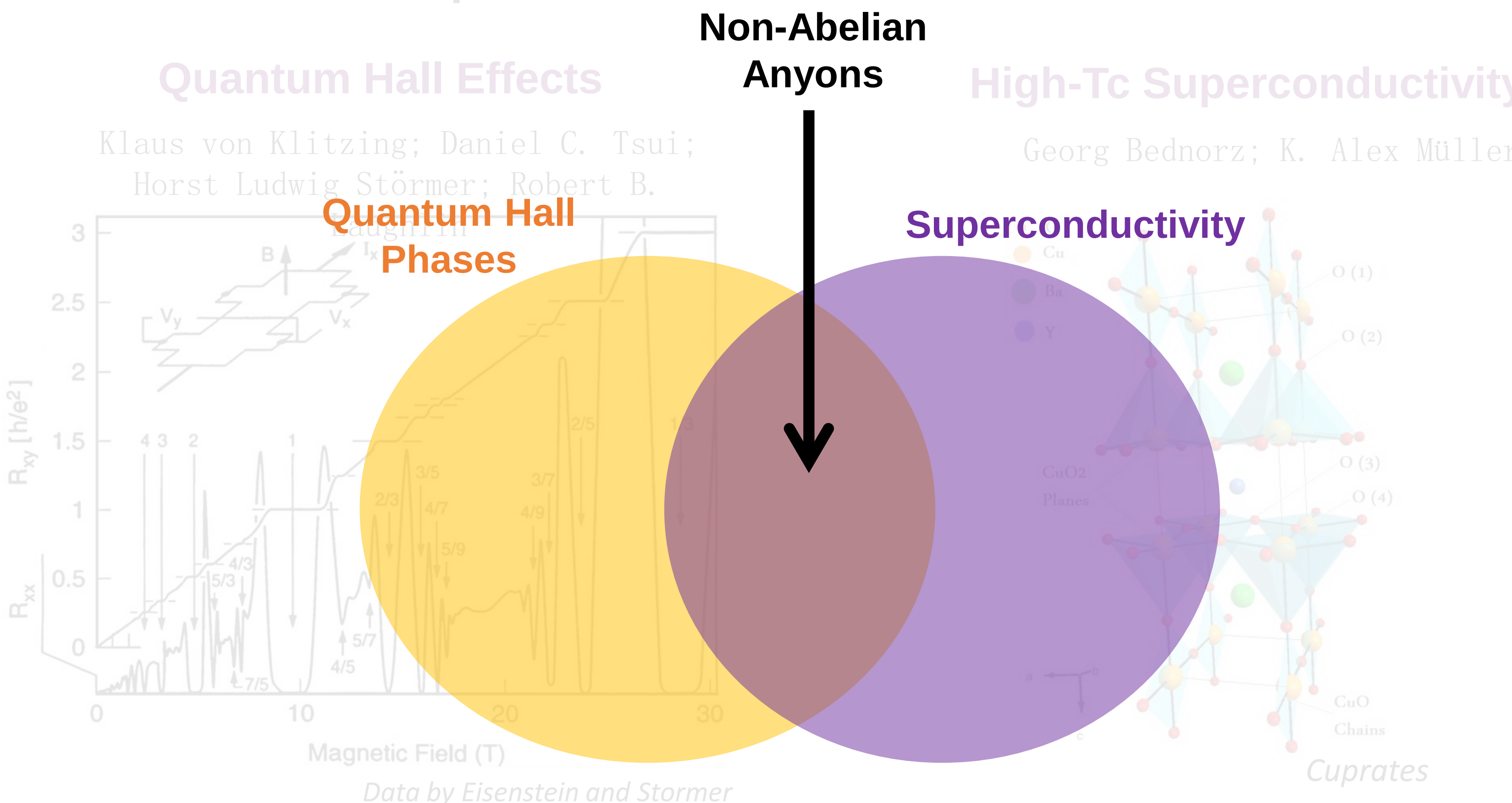
Department of Physics, MIT

12/25/2017
@ UCAS



Topology and Correlations

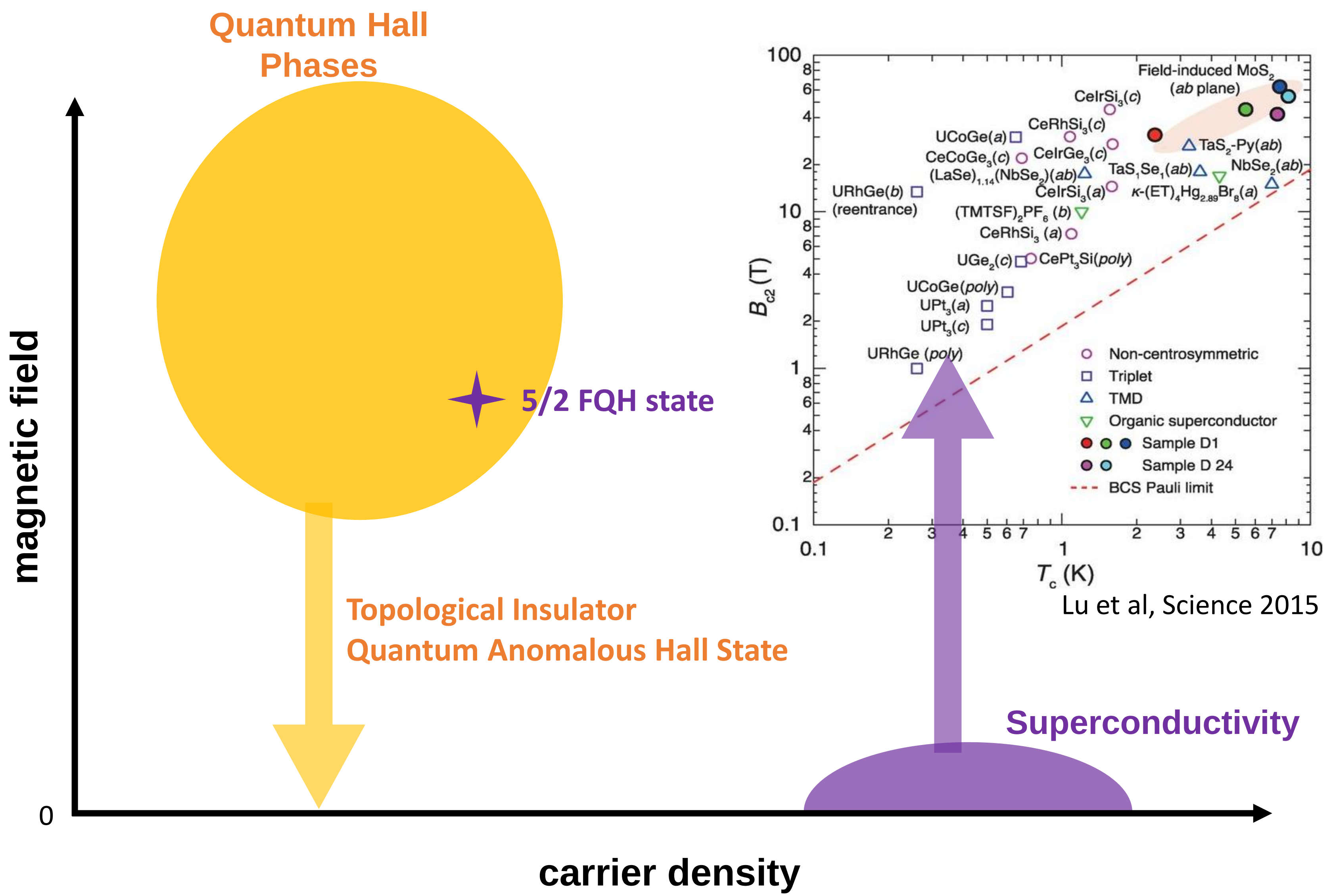
Experimental milestones in 1980s:



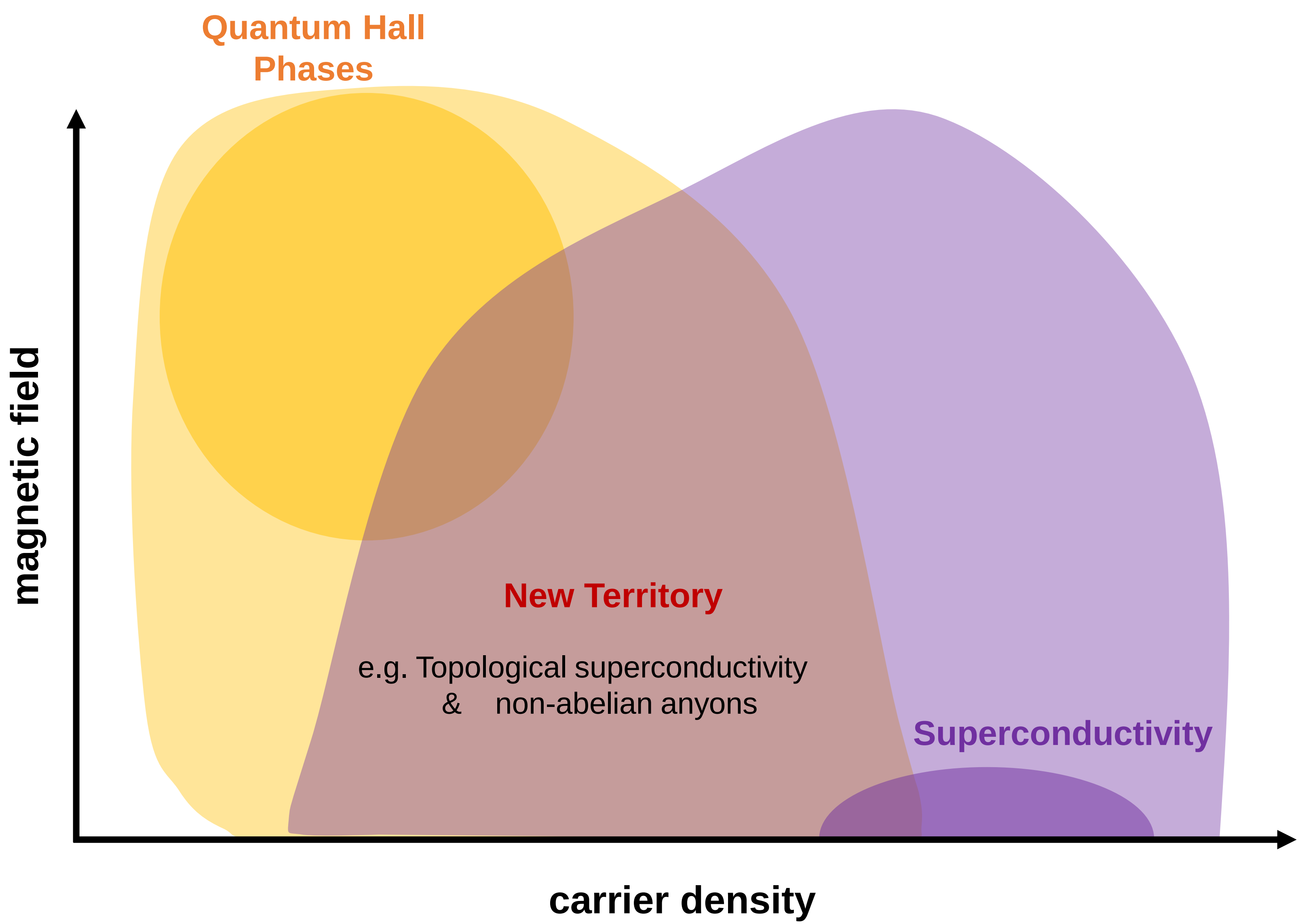
Topological Quantum States

Correlated Quantum States

Topology and Correlations



Topology and Correlations

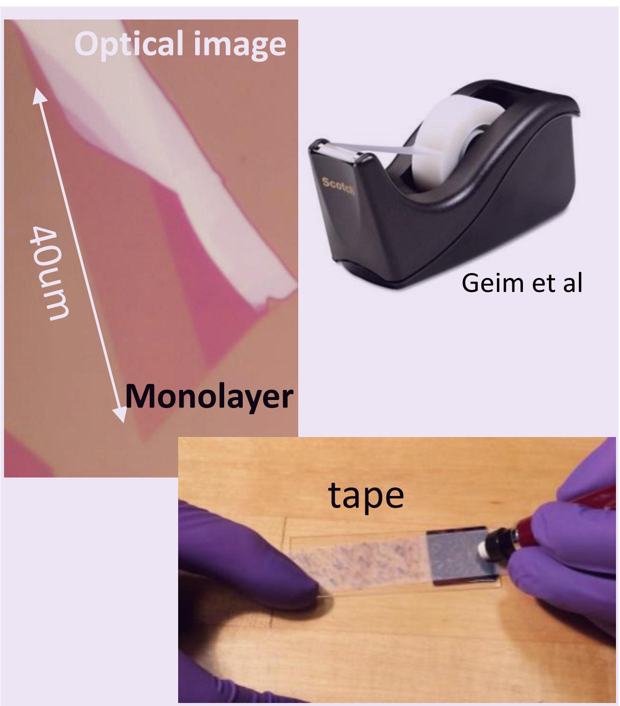


Monolayer Crystals and Heterostructures

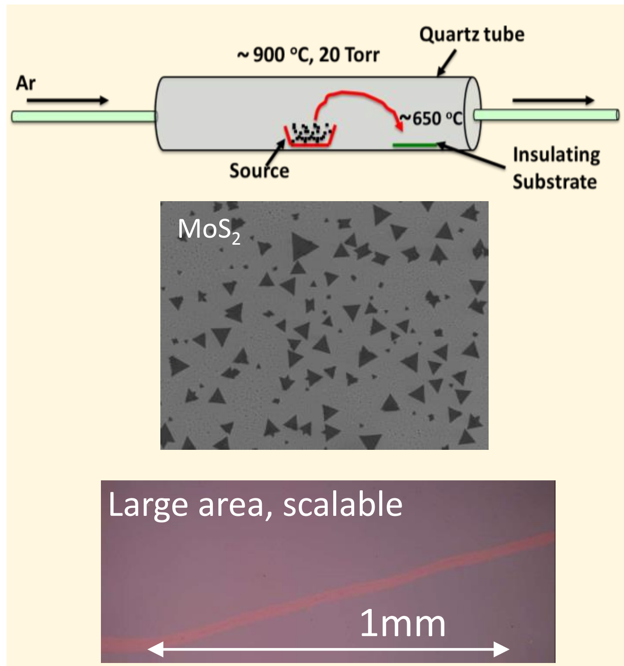
The simplest materials hosting 2D electrons:

(Isolated) Crystalline Atomic Monolayers

Mechanical Exfoliation

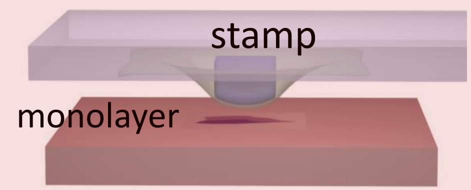


MBE/CVD/PVD Growth



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

Heterostructures



Van der Waals Heterostructure

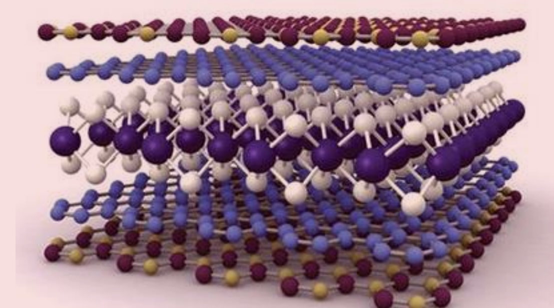
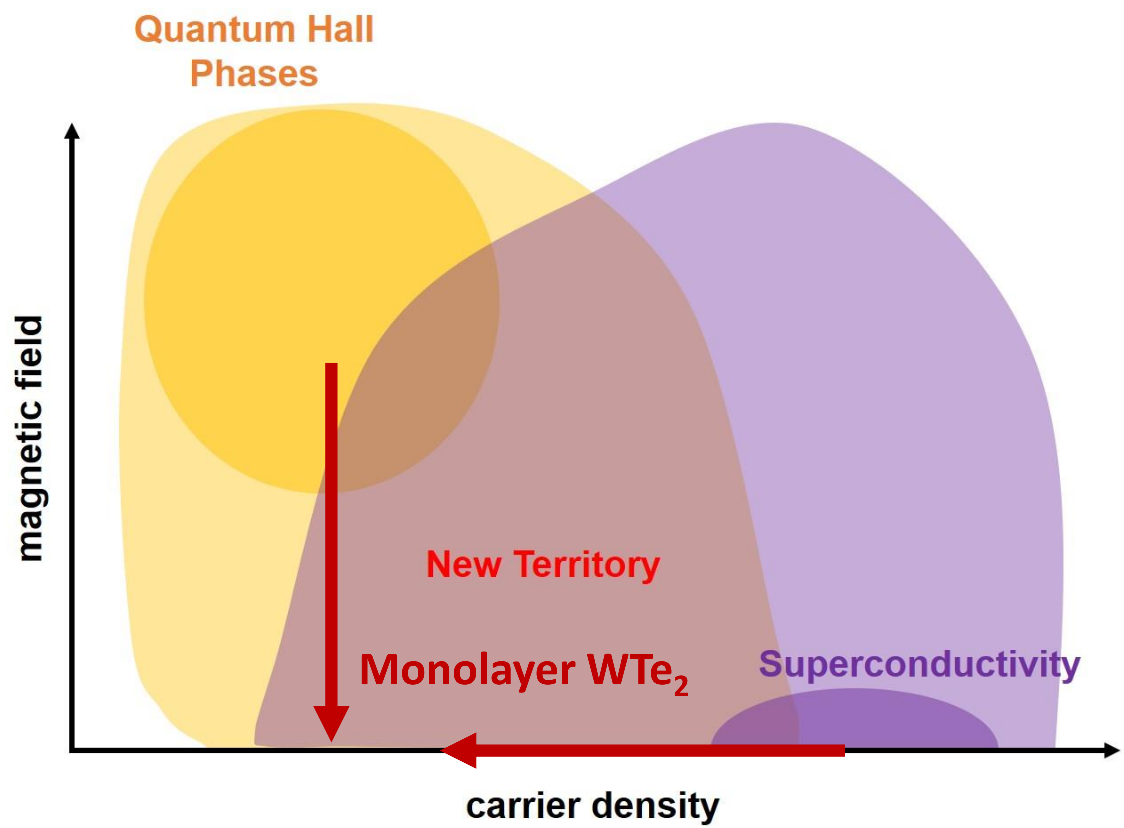


Image: Novoselov et al, Science (2016)

My Research Interests & Today's Topic

A Large Family of Monolayer Crystals

(many to be explorec

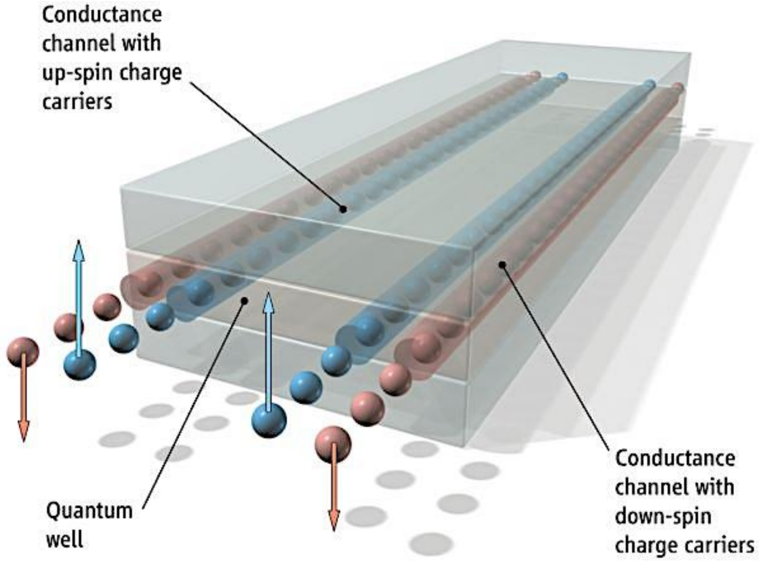


- Quantum spin Hall effect in monolayer WTe_2
- Superconductivity in monolayer WTe_2

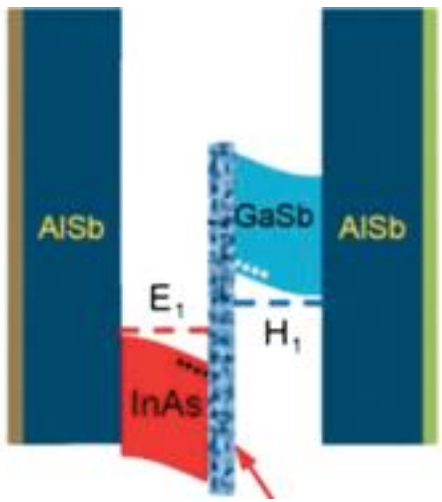
Experimental Quantum Spin Hall Effect

2D time-reversal invariant topological insulators

Semiconductor Heterostructures



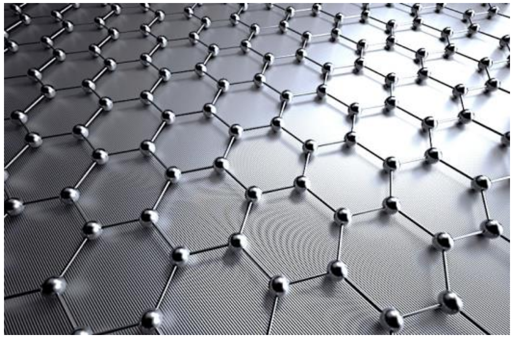
Molenkamp & Zhang et al (HgTe, 2007)



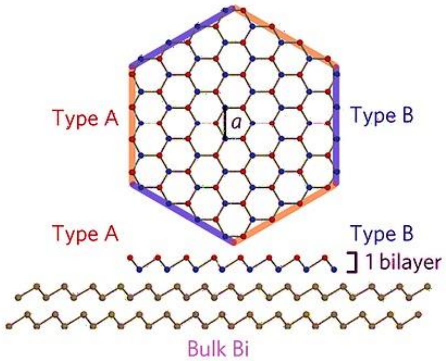
Du et al (InAs/GaSb, ~ 2015)

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

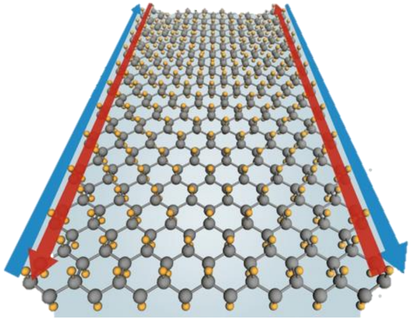
Monolayer QSH Systems



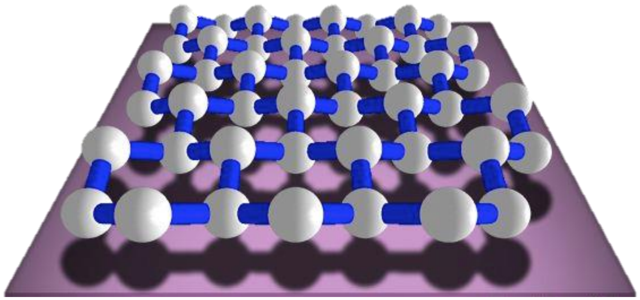
Spin-orbit coupled Graphene, 2005
Kane&Mele



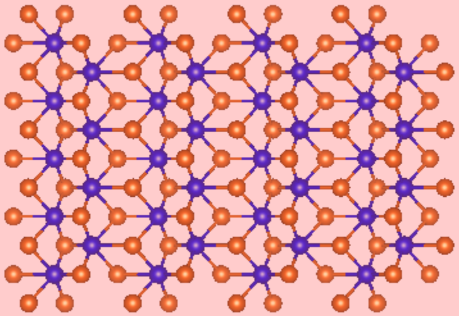
Bismuth Bilayer, 2006
Yazdani, Murakami, Palacios etc



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.)

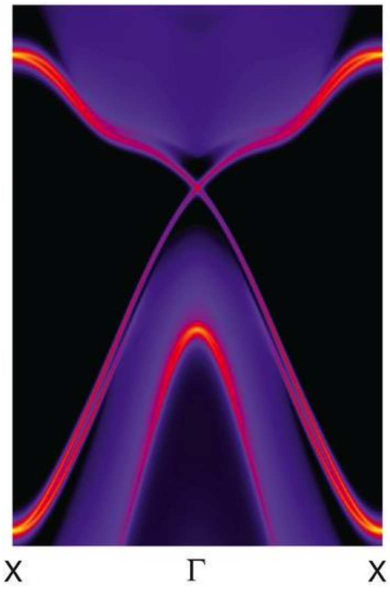
* These authors contributed equally to this work.

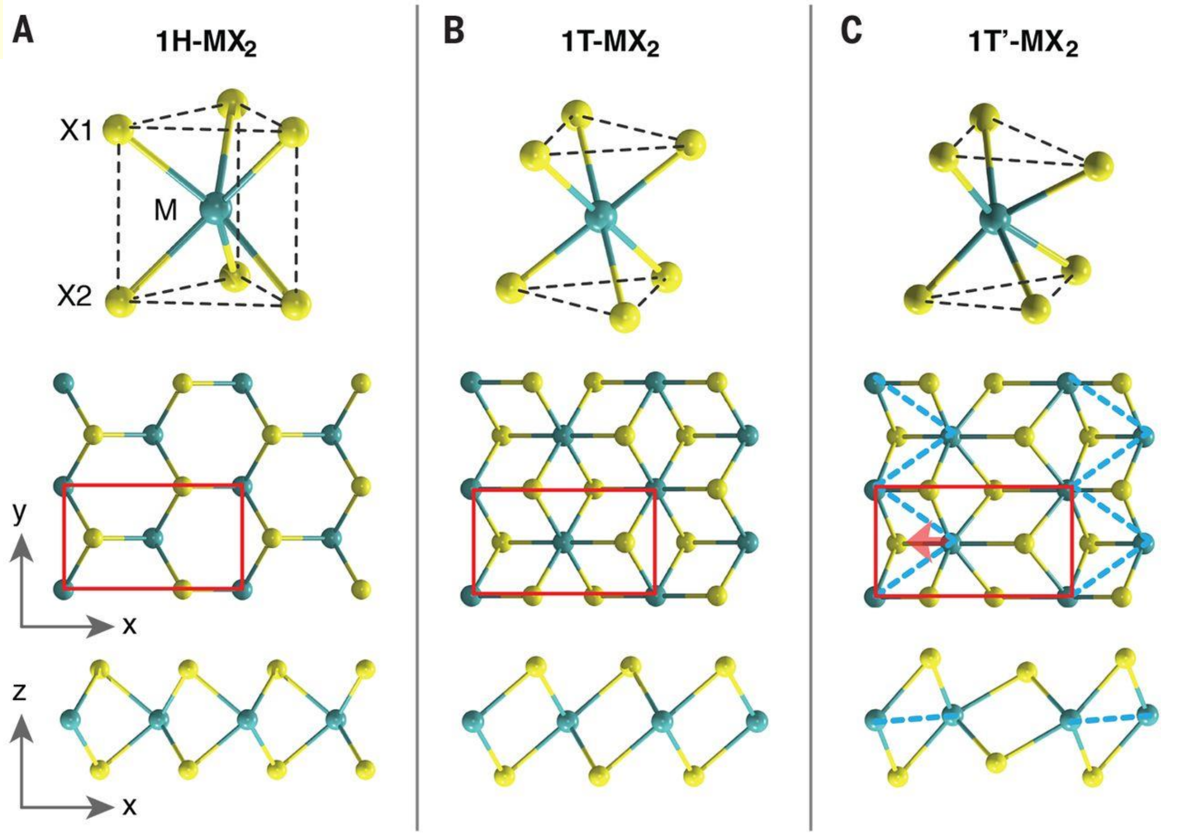
Science 20 Nov 2014:

DOI: 10.1126/science.1256815

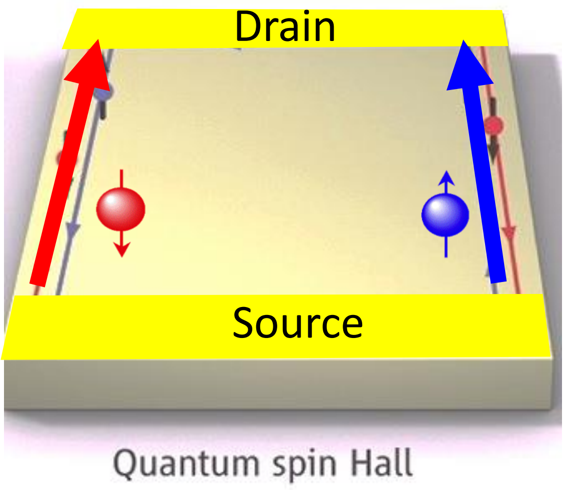
M = Mo, W;
X = S, Se, Te.

1T' TMD Monolayer

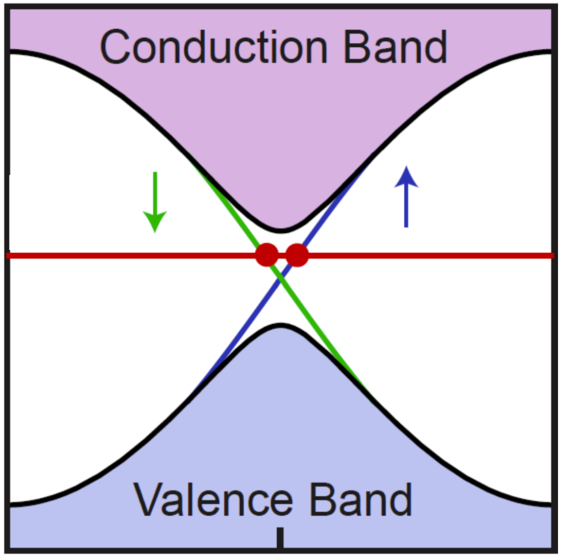




Signatures of QSHE in a 2D time reversal invariant TI



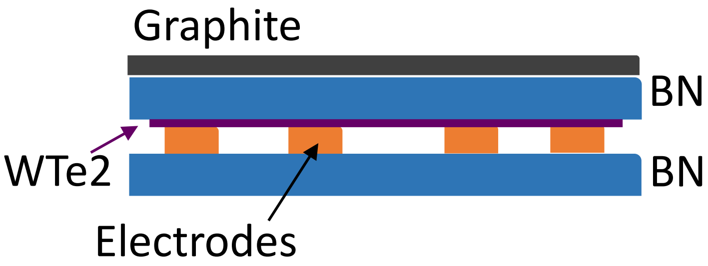
- ✓ **Helical edge mode of a insulator**
- ✓ **Topological protection allowed by TR symmetry**

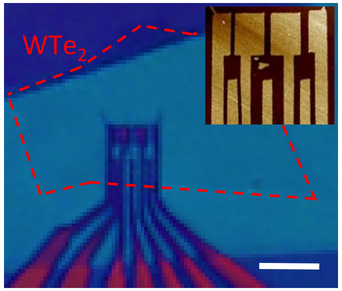


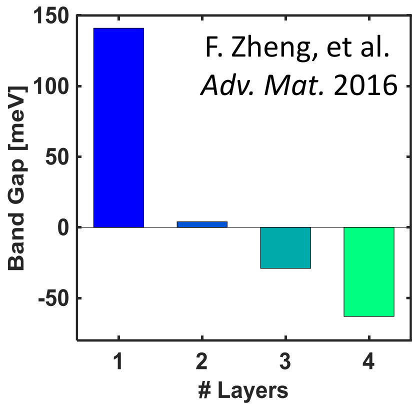
Expected QSH Transport Signatures:

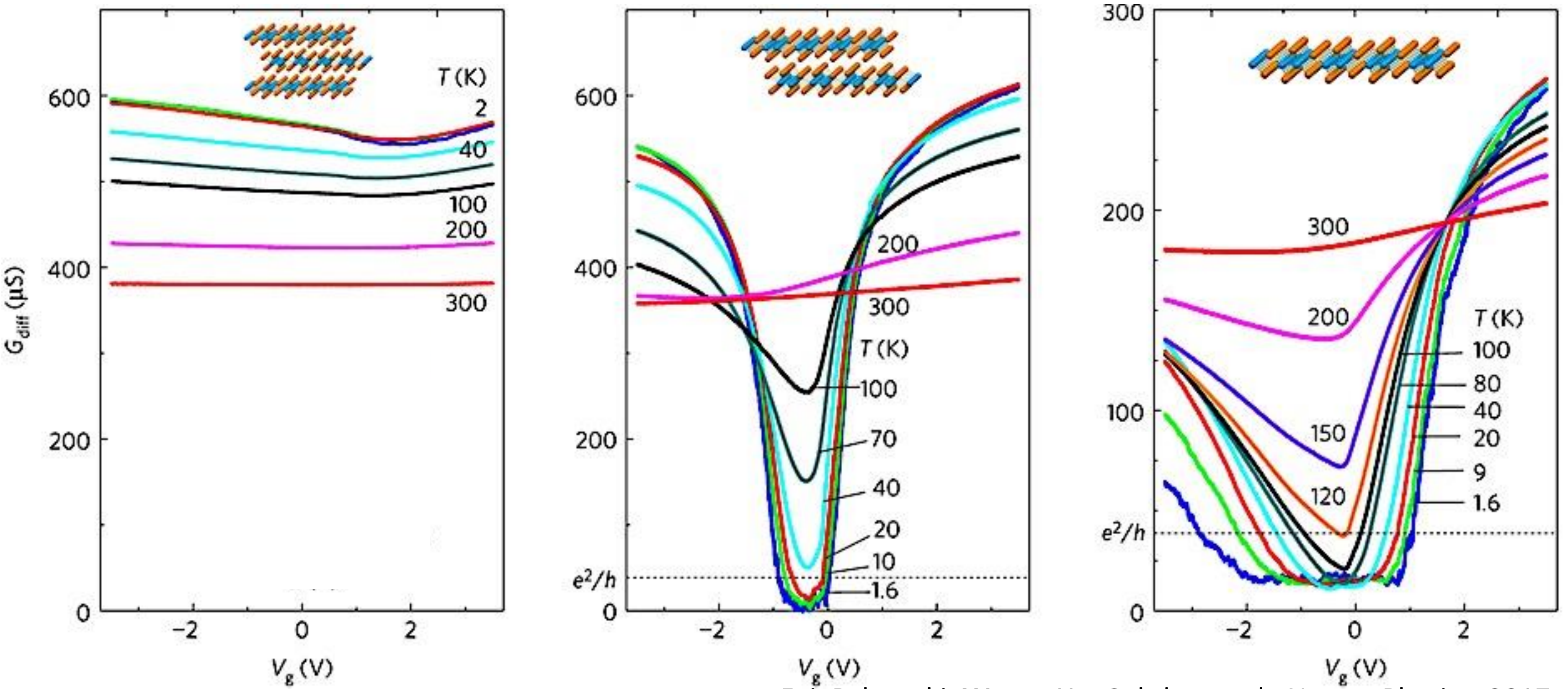
- Bulk insulating + edge conducting
- Quantized conductance, ~ e^2/h per edge
- Conductance saturates in the short-edge limit
- Quantization destroyed under broken TR symmetry
- (Zeeman gap opening at the Dirac point)
- … …

Quantum Transport in Atomically Thin WTe_2





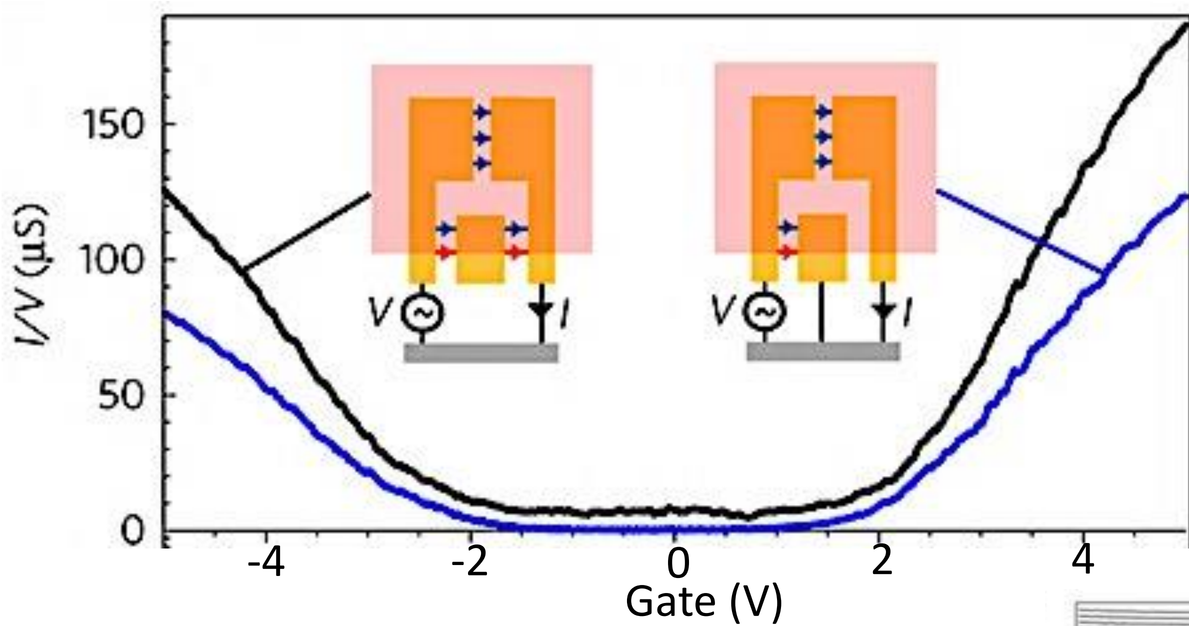




Fei, Palomaki, **Wu**, …, Xu, Cobden et al, Nature Physics, 2017

Edge Conduction in Monolayer WTe_2

Distinguish Edge Conduction from the Bulk Contribution



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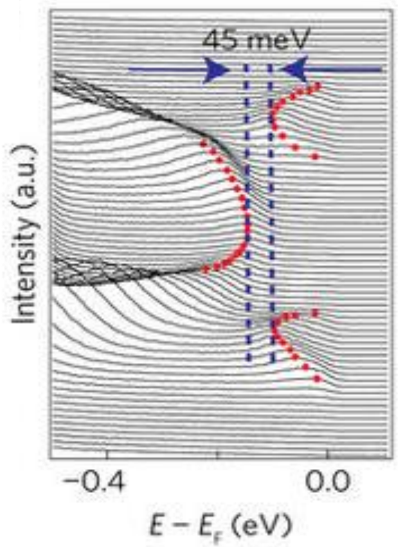
- (Zeeman gap opening at the Dirac point)

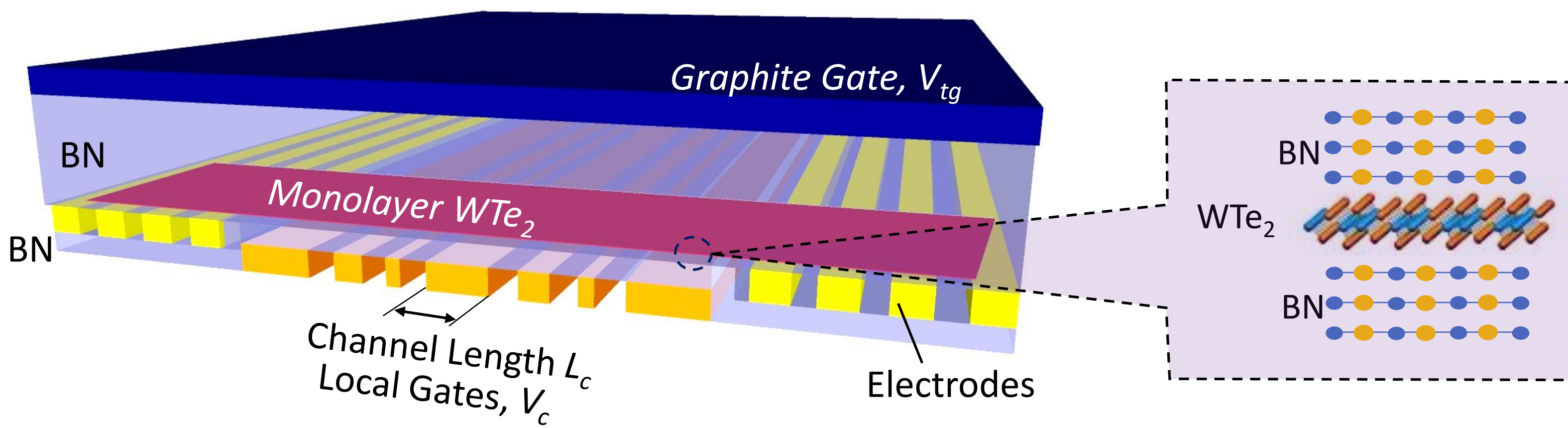


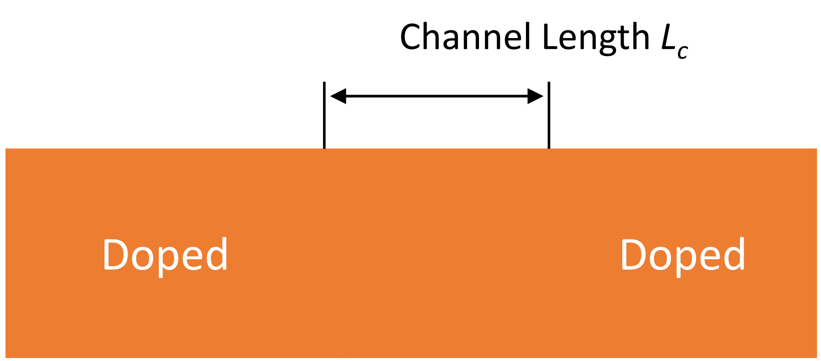
Tang et al, *Nature Physics* (2017)

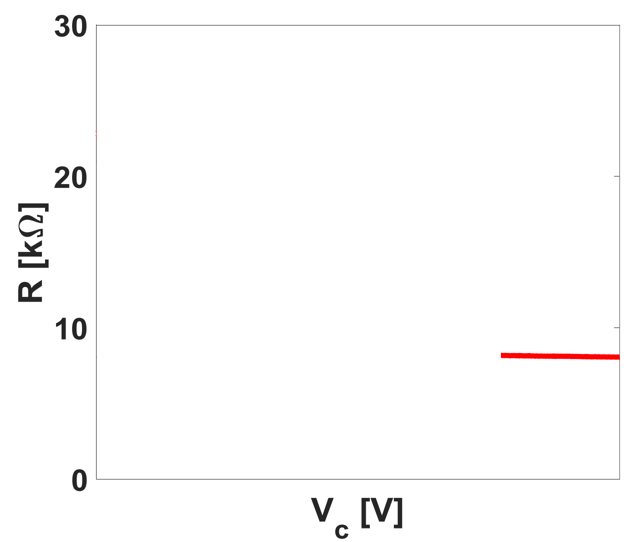
Is It Really a QSH Insulator?

Difficulties

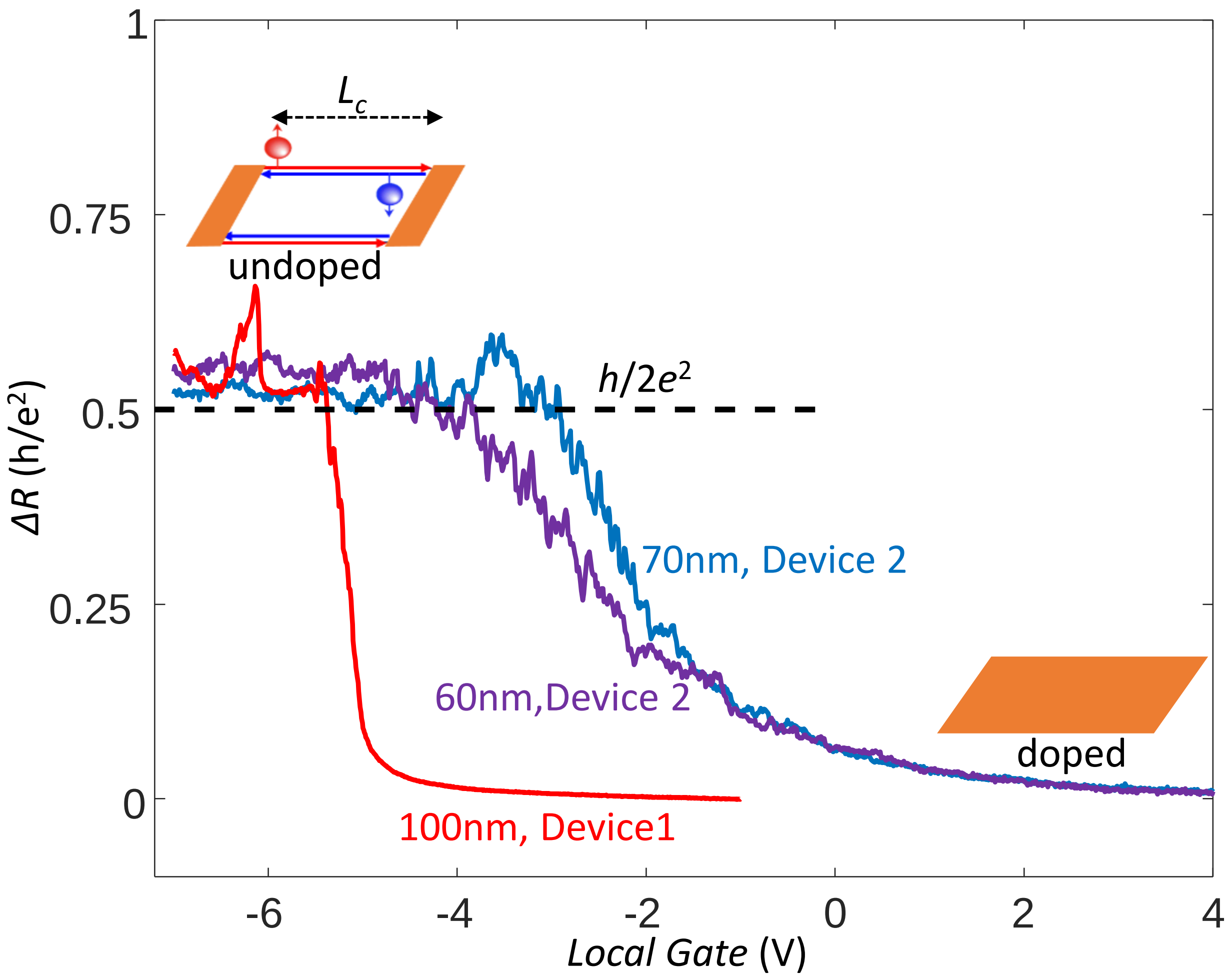
- **Good Contact?**
- **High Quality Devices?**
- **How to do length dependence properly?**



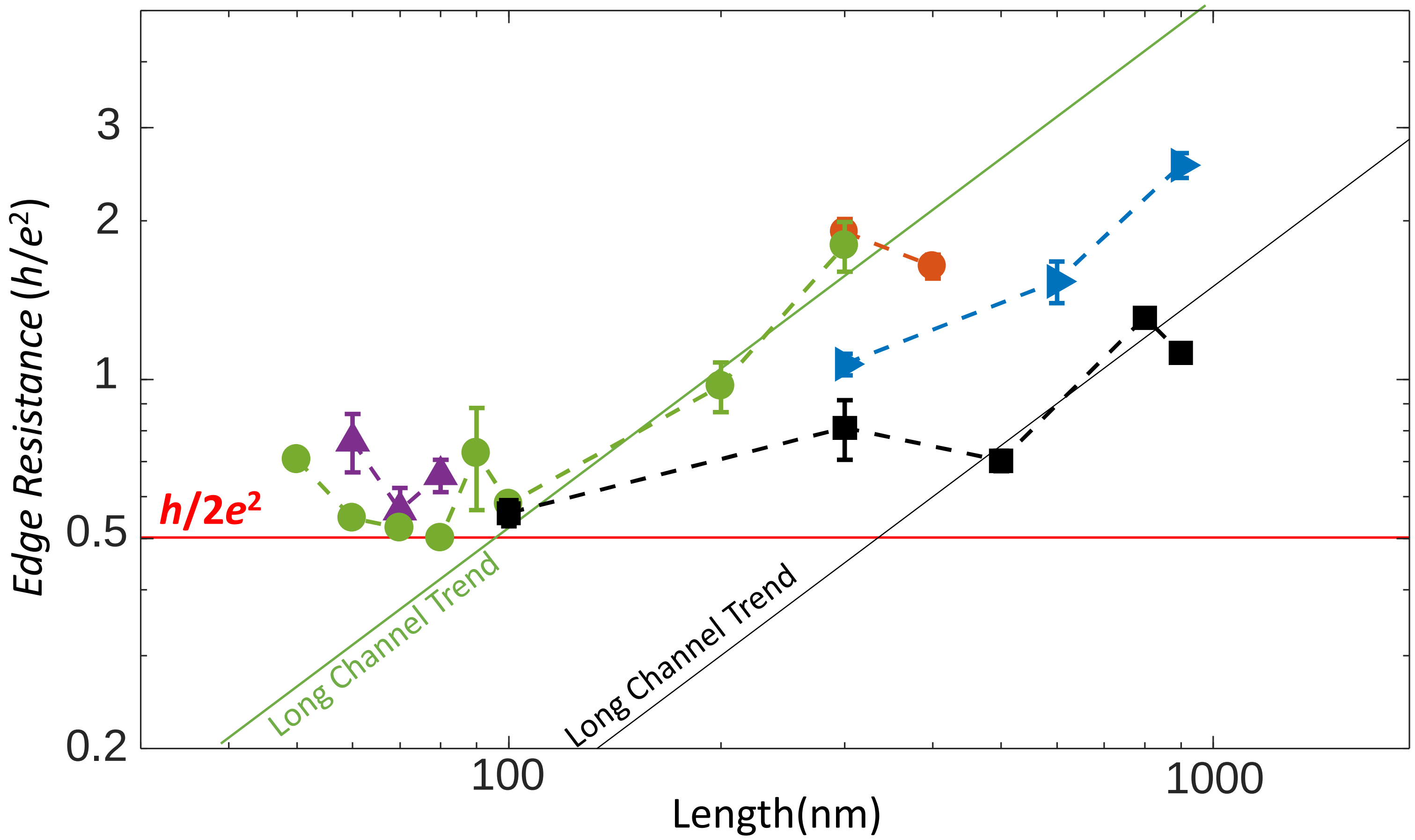




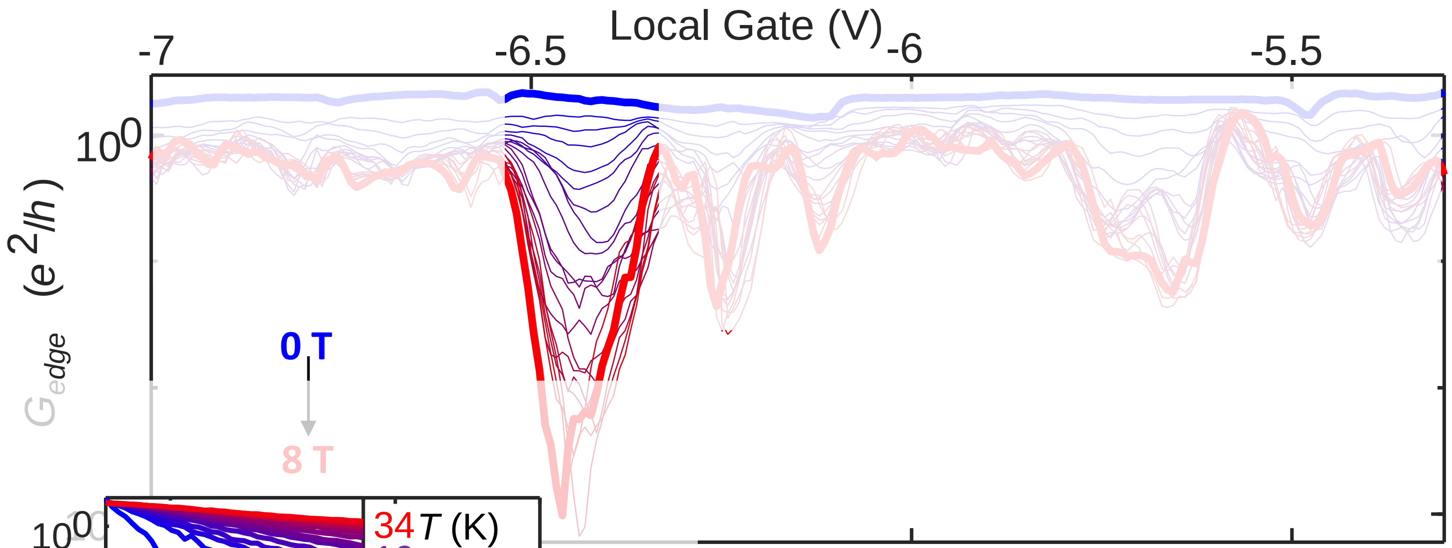
Helical Edge Mode: Conductance Quantization

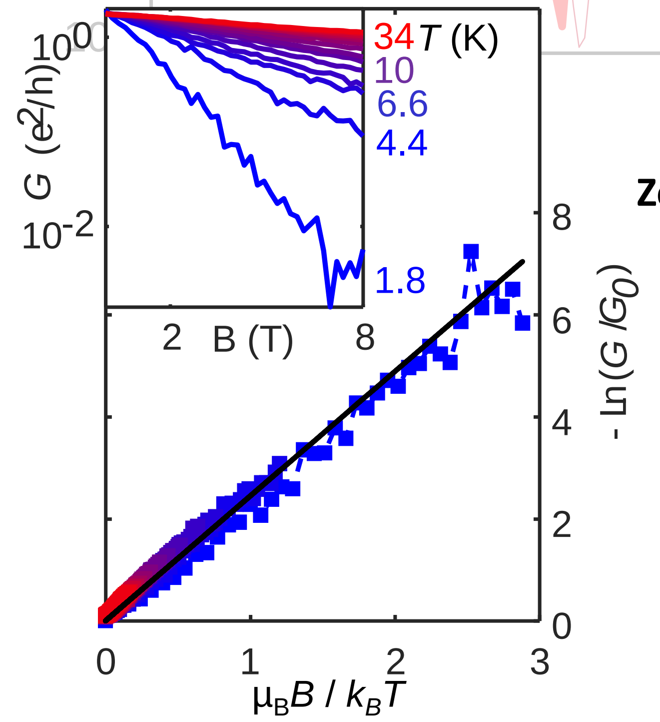


Helical Edge Mode: Length Dependence



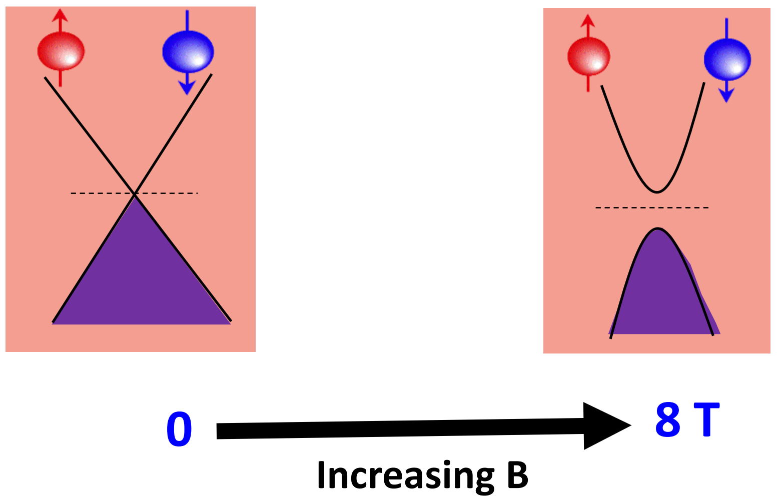
Helical Edge Mode: Breaking Time-Reversal Symmetry



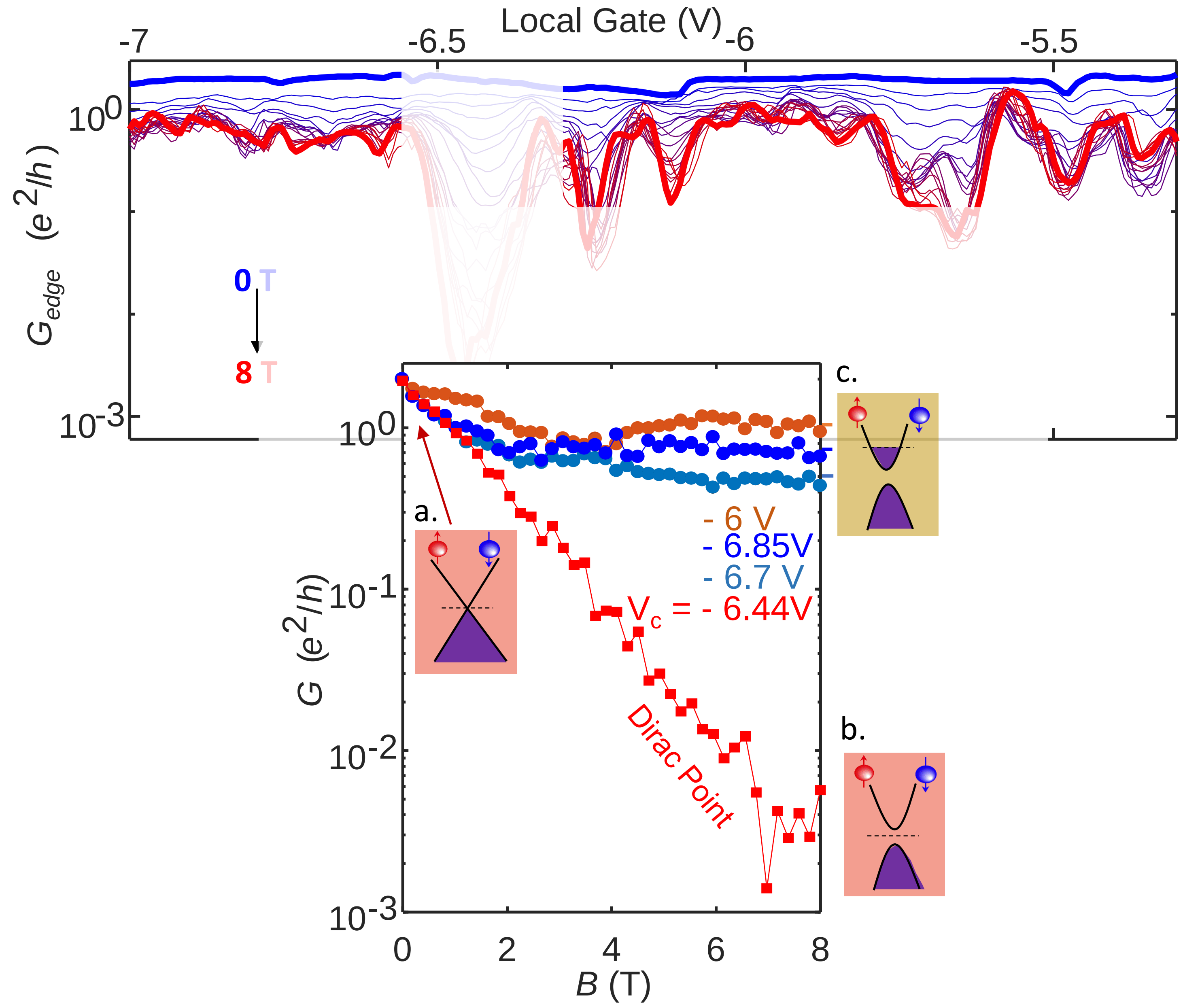


$G = G_0 \exp(-g\, u_B B/2K_B T)$, $g \sim 4.8$

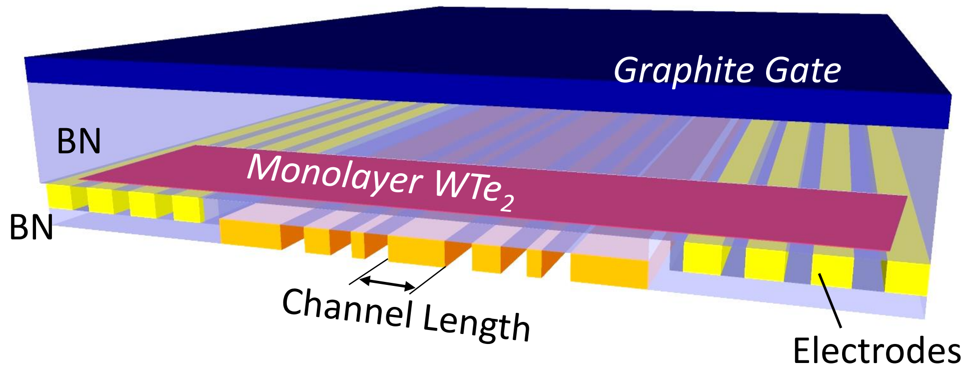
Zeeman Gap Opening at the Kramers point (Dirac Point)



Helical Edge Mode: Breaking Time-Reversal Symmetry



Observation of the QSHE in Monolayer WTe_2



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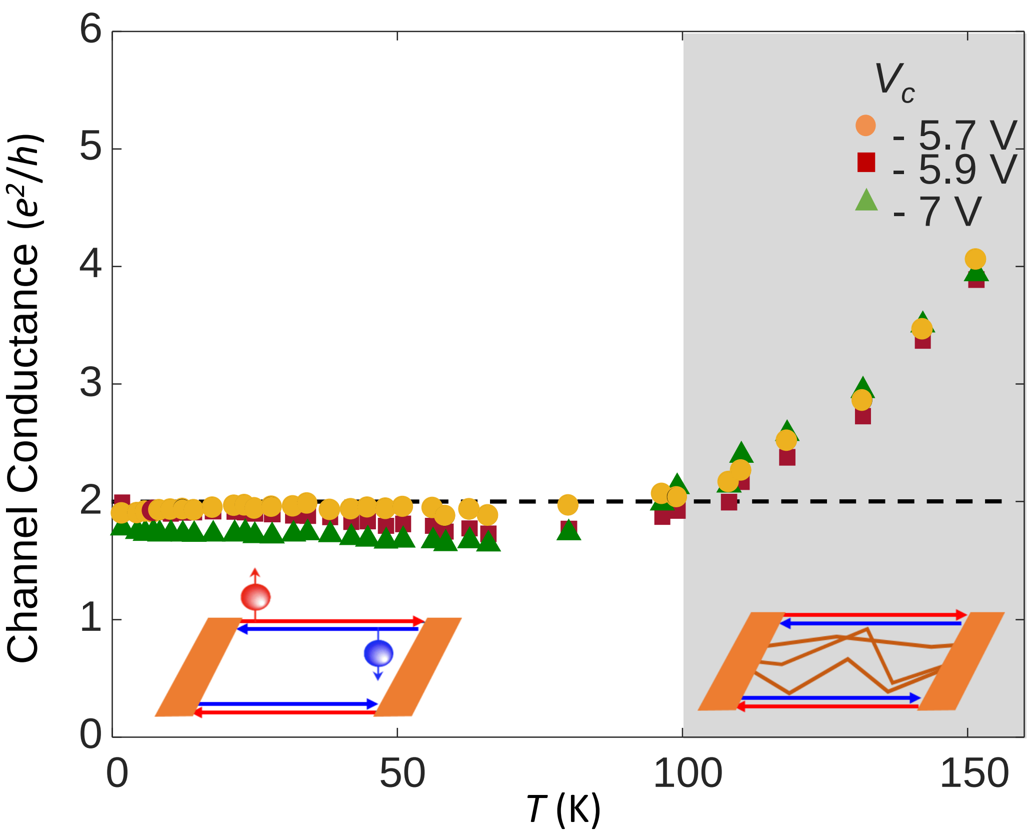
- Quantized conductance, ~ e^2/h per edge ✓
- Conductance saturates in the short-edge limit ✓
- Quantization destroyed under broken TR symmetry ✓
- (Zeeman gap opening at the Dirac Point) ✓

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

The High Temperature QSHE

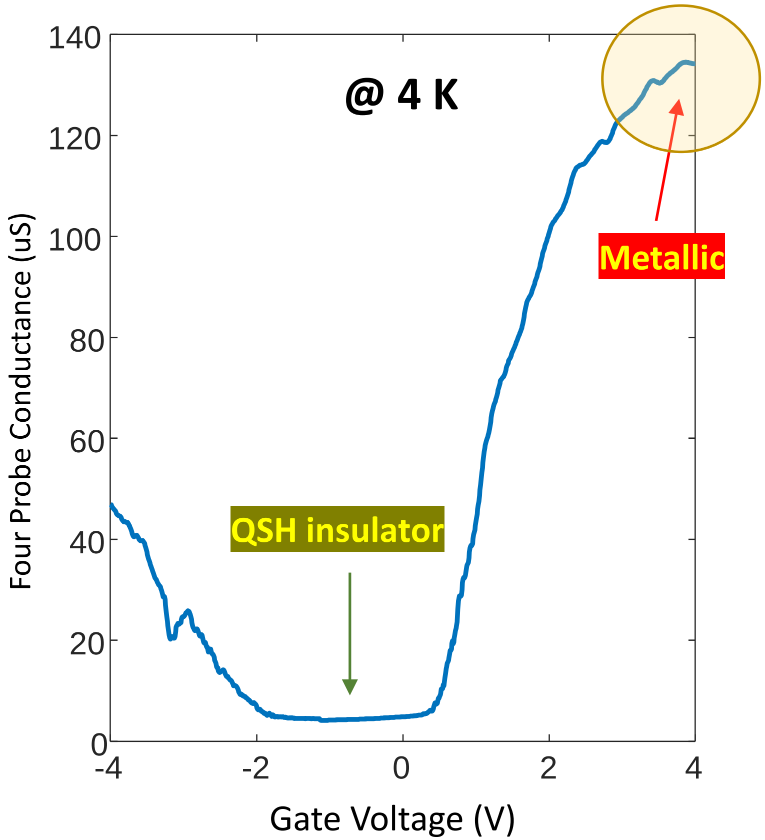


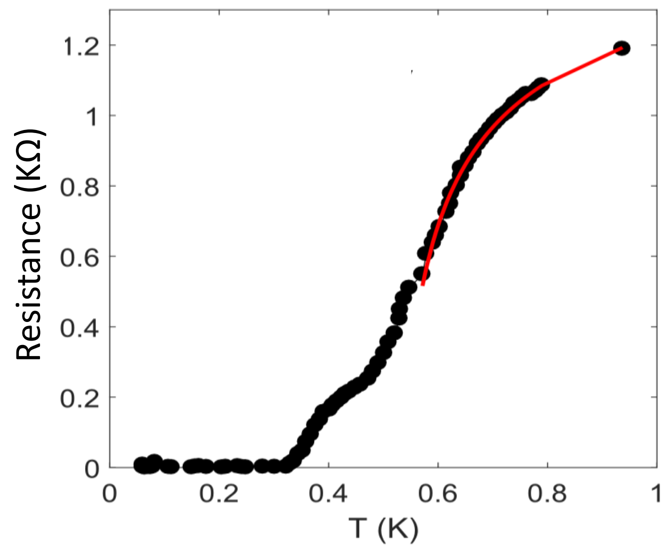
- **12** years after the prediction of QSHE in graphene, **we report strong evidences of QSHE in a monolayer crystal**.
- 10 years after the first QSH experiment, we observed the expected **Dirac-point** behavior.
- We achieved the **QSHE at high temperatures.**

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

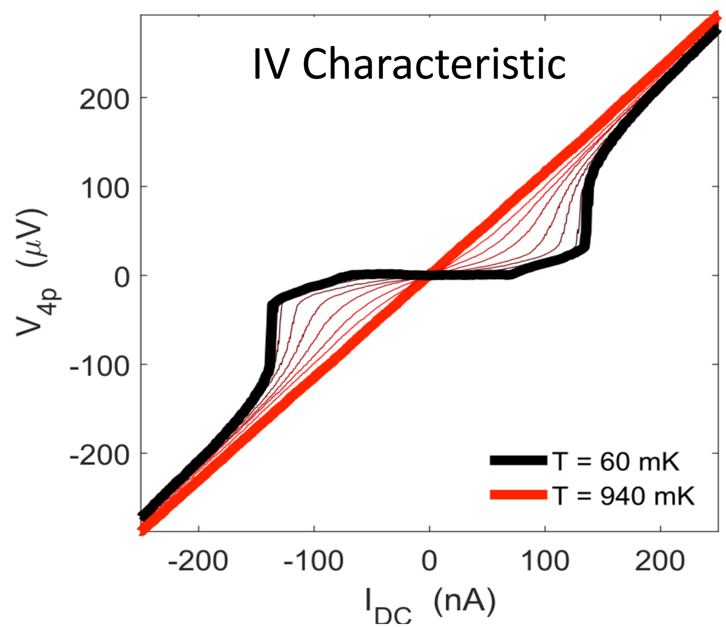
Recent ARPES/STM Measurements: **45 meV** gap in the bulk
Tang et al, *Nature Physics* (2017); Jia et al, *PRB (2017)*

Superconductivity in Electrostatically Doped Monolayer WTe_2





T_c ~ 1K for highest gate voltage

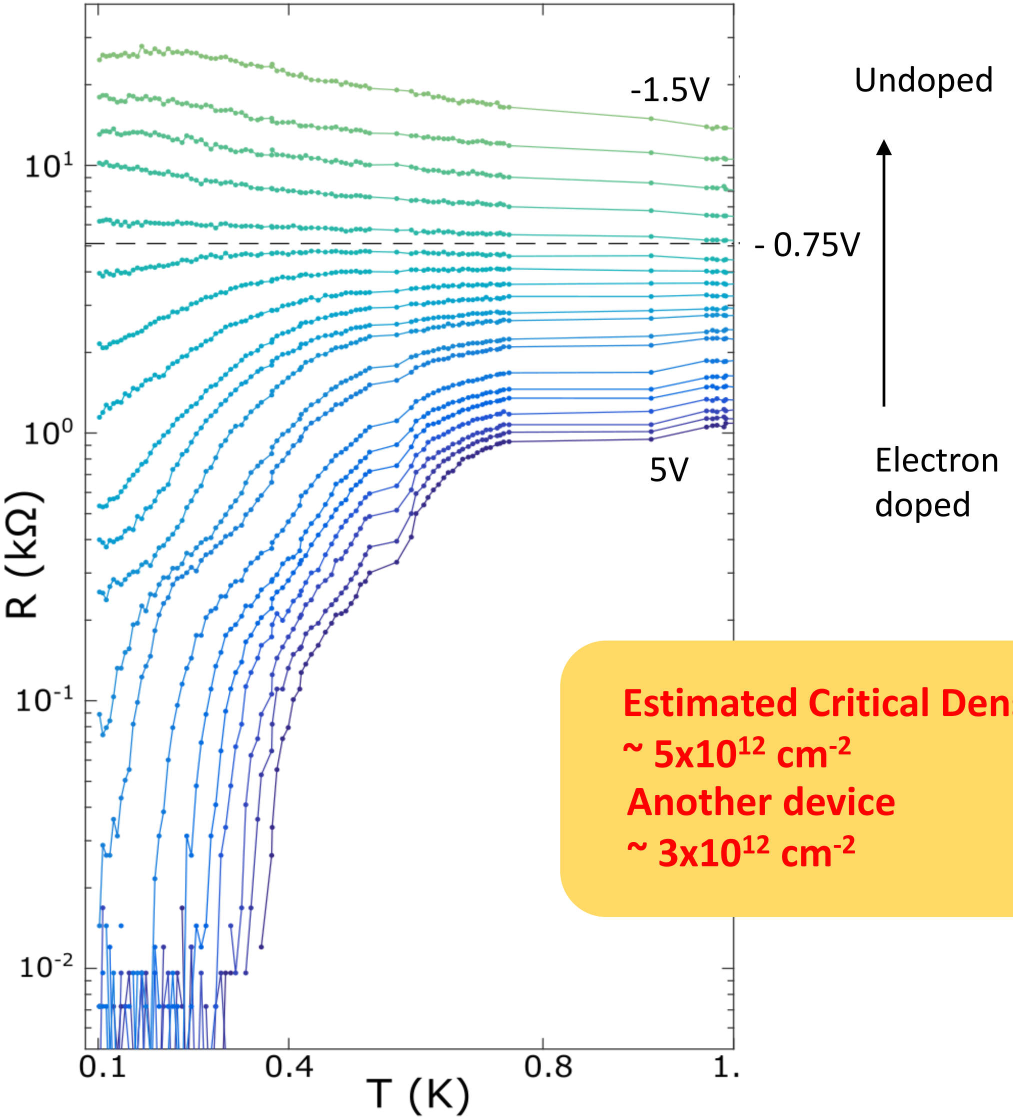


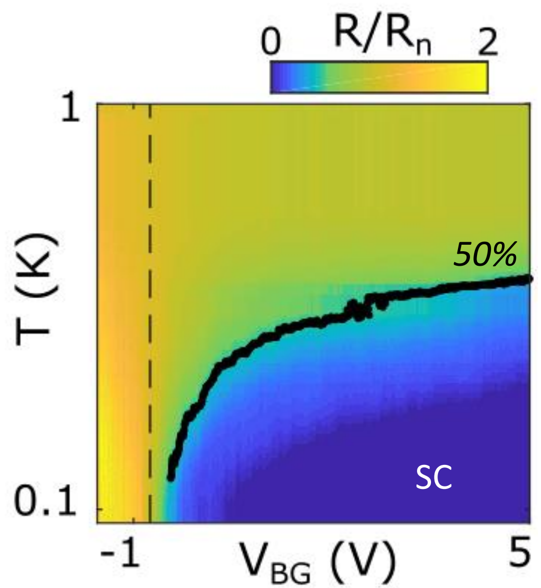
Bulk WTe_2: Tc ~ 6.5 K under high pressure

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

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

Gate Tunable Superconductivity



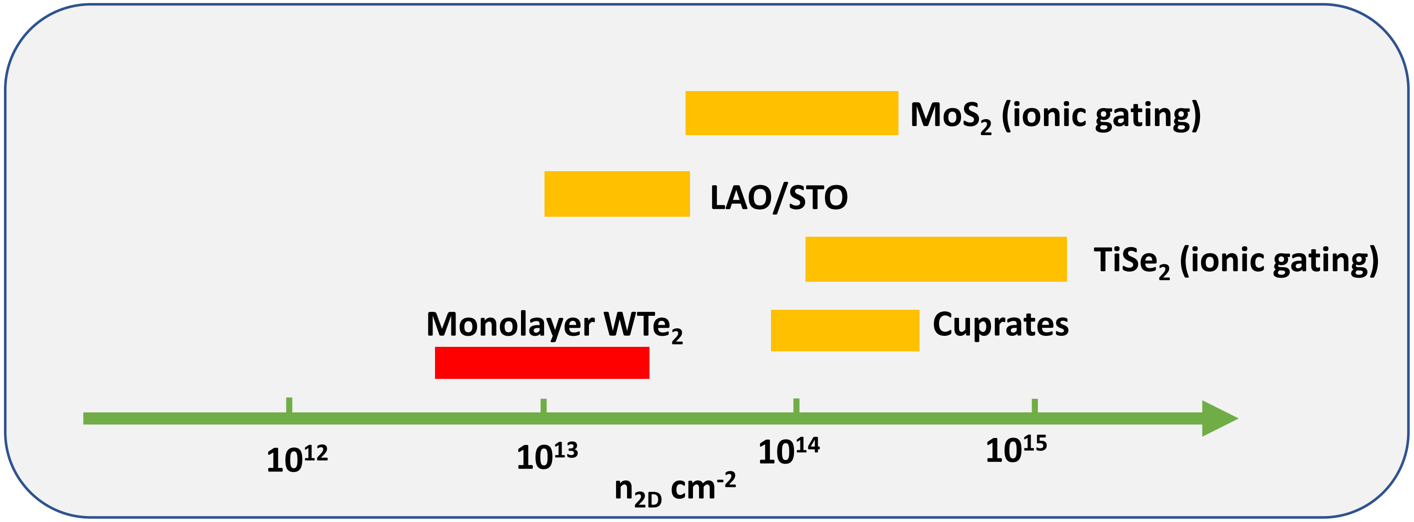


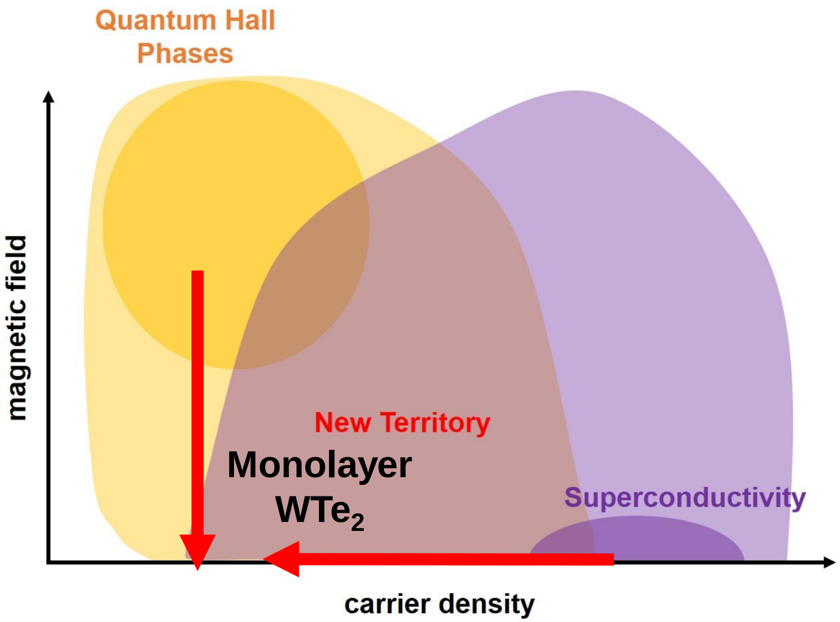
Estimated Critical Density:
~ 5×10^{12} cm^{-2}
Another device
~ 3×10^{12} cm^{-2}

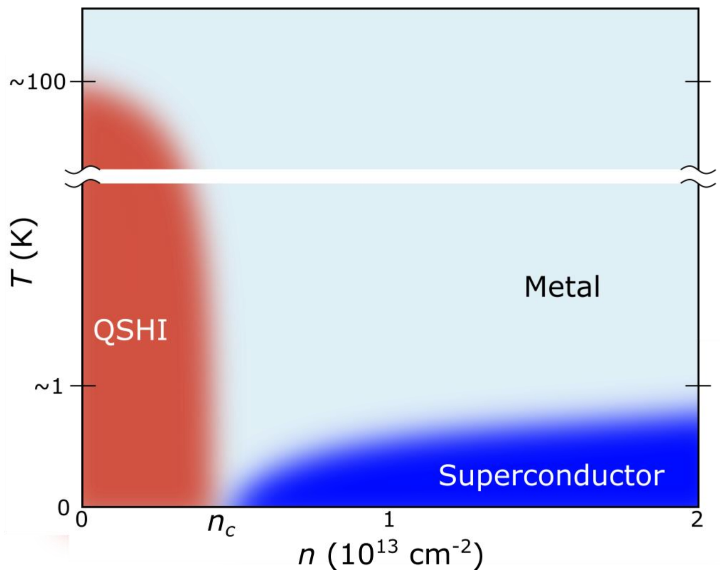
Fatemi*, **Wu*,#**, Cao, Bretheau, Gibson, Watanabe, Taniguchi, Cava, and Jarillo-Hererro#
Submitted (2017)

Monolayer WTe_2: A Low Density Superconductor

2D Superconductors and their carrier densities.

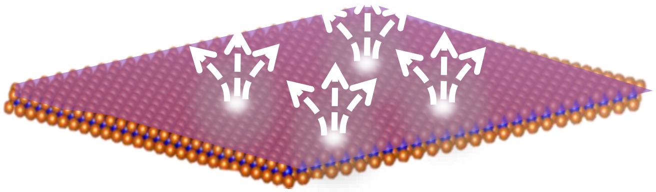




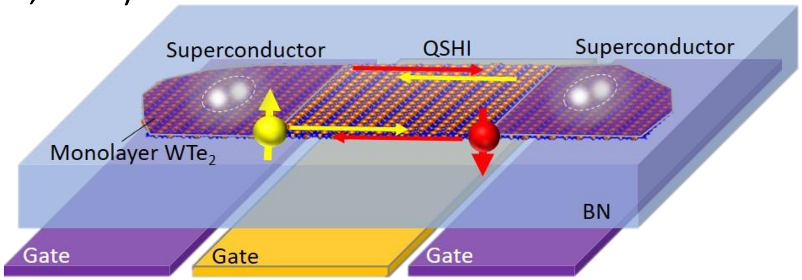


A Route to Monolayer Topological Superconductor

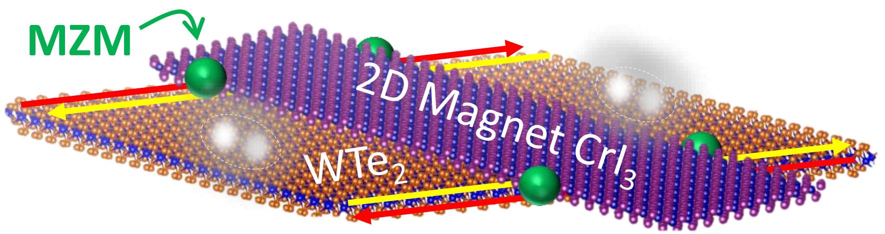
- **Understand the nature of the monolayer superconductivity**
  - -- Is it unconventional/topological?
  - -- Is there spontaneous symmetry breaking?



- **Create topological Josephson Junctions** (Fu & Kane, 2008)
  - -- Interference pattern?
  - -- Current-phase relation?
  - -- ac Josephson effect?



- **Engineer Majorana Zero Mode (MZM)**
  - -- Zero bias tunneling peak?
  - -- Reading and Braiding?



A Route to Engineering Superconducting Tc

- **What is the optimal Tc of the WTe_2 monolayer superconductivity?**

-- Will there be a dome in the phase diagram?

-- Can monolayer Tc be higher than bulk (under high pressure)?

Tc	bulk	Bulk under Pressure	monolayer	Engineered Monolayer
FeSe	~ 9 K	~ 27 K	< 2.2 K (on SiC)	65 or 109 K (on STO)
WTe_2	Not Found	~ 6.5 K	0 (Insulator)	~ 1 K (BN gated)

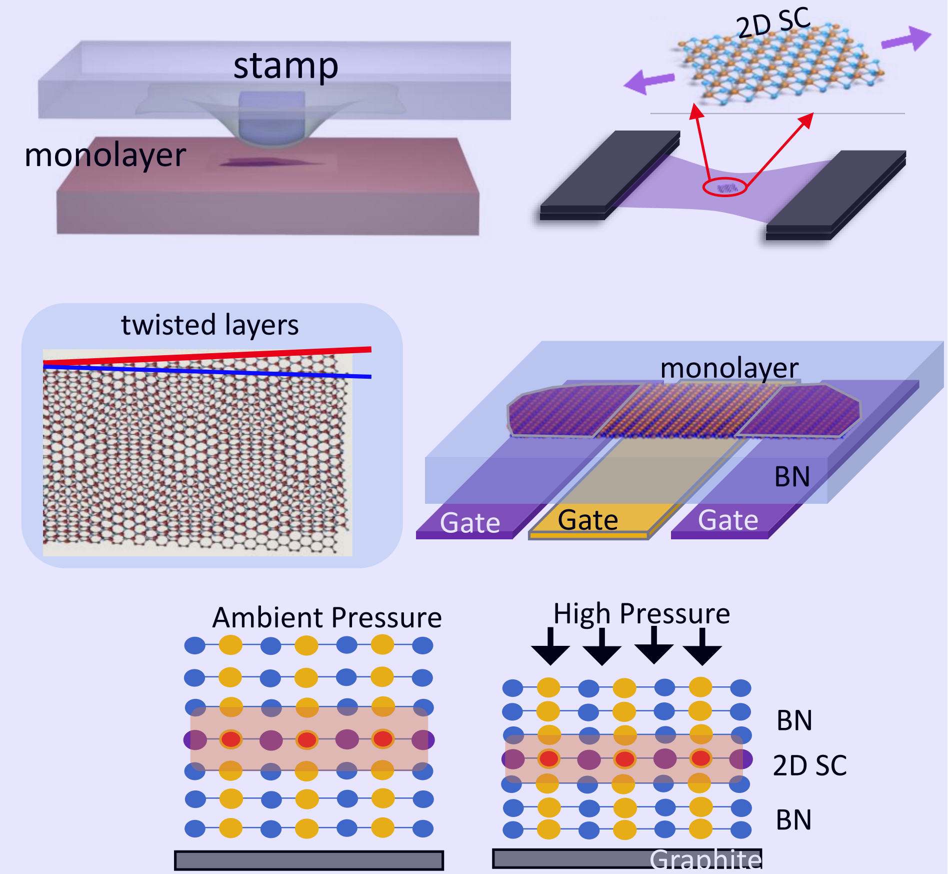
- **Can we develop a tool box for engineering monolayer Tc?**

-- The effect of substrate, strain, pressure, twist angle, and electric field

-- What is the effect of combining them?

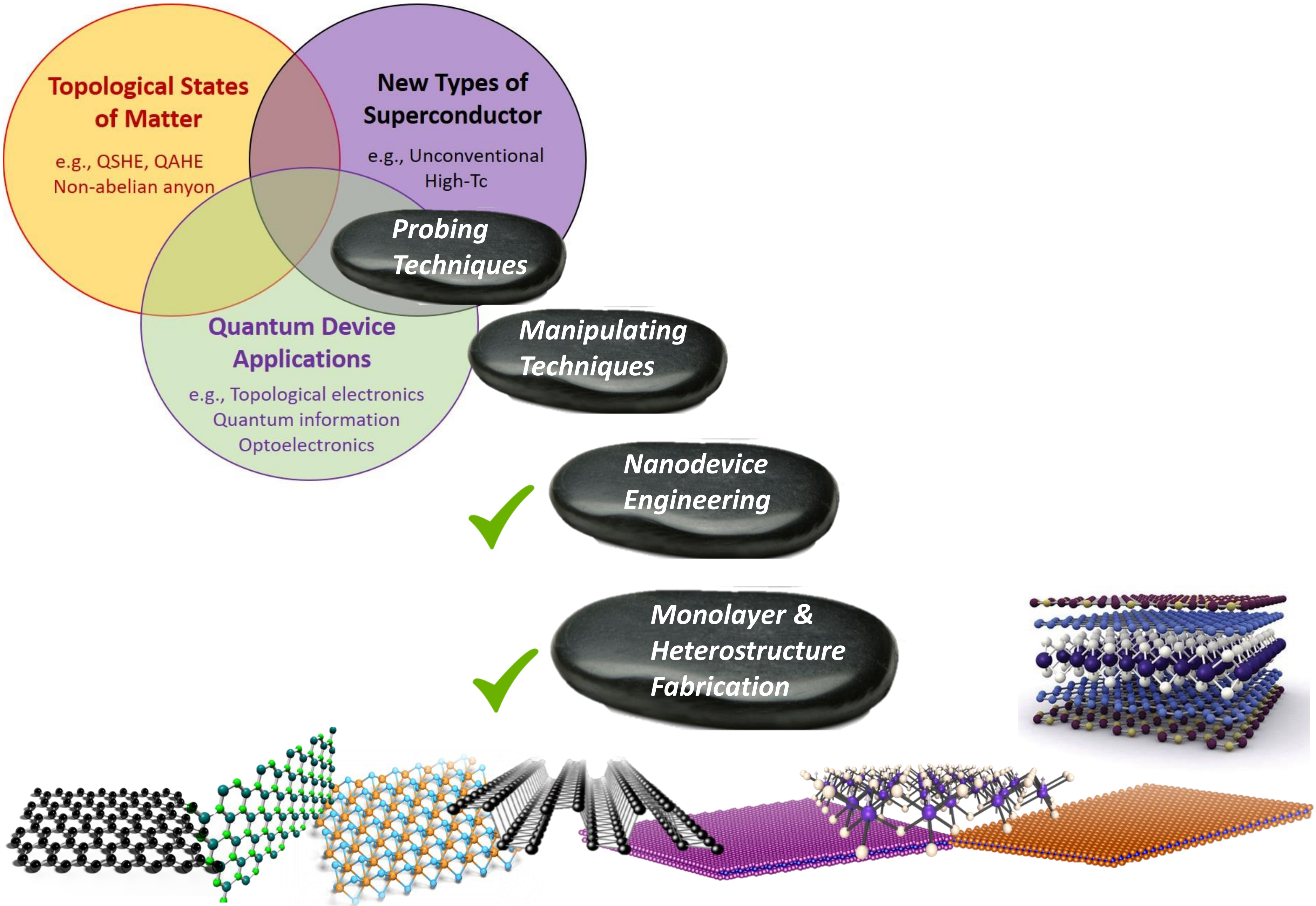
- **New High Tc SC in monolayer form?**

-- other monolayers?

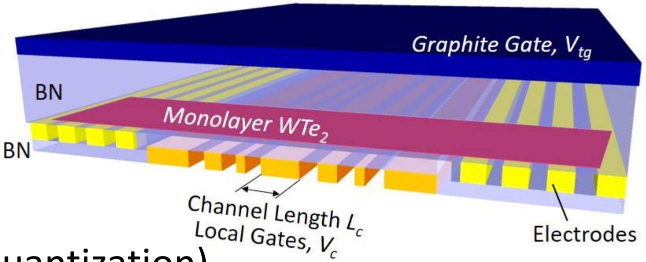


Monolayer Tc-Engineering Tool Box

Experimental Tools To Be Developed

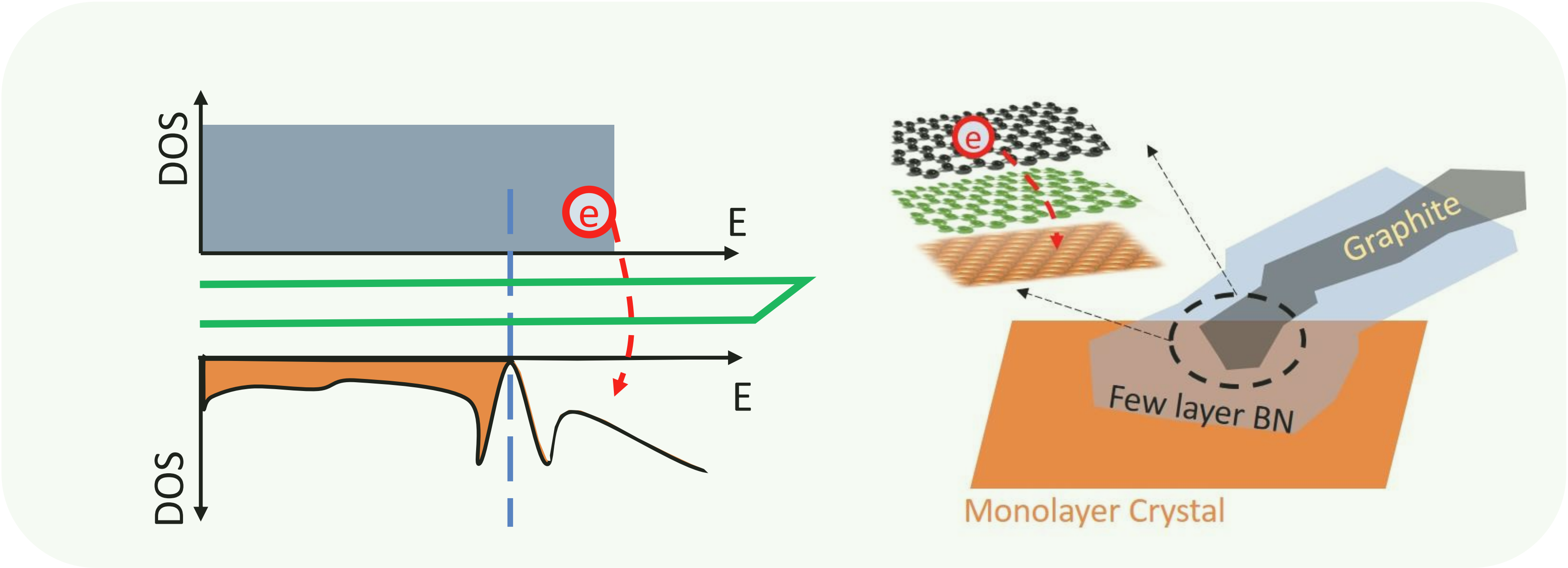


Monolayer Quantum Electronics



- **Quantum Transport**
  -- Electron dissipation/dissipation-less transport
  -- Characteristic conductance (T-dependence, B-dependence, Quantization)

- **Electron Tunneling Spectroscopy**
  -- DOS near fermi surface
  -- Van der Waals Tunneling

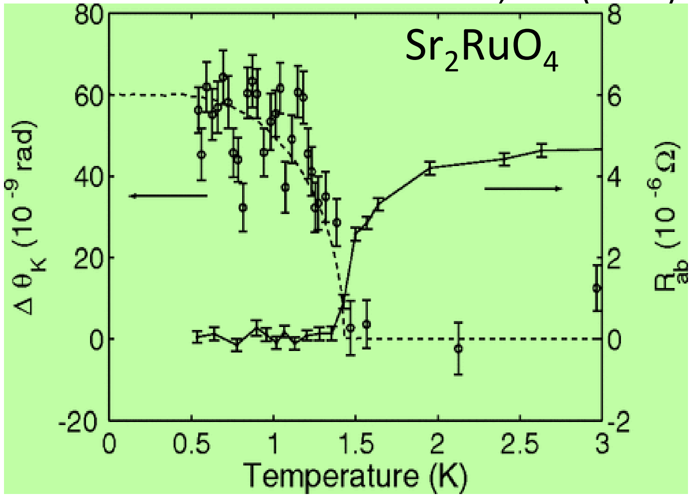


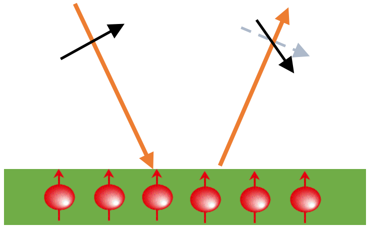
Monolayer Optical Spectroscopy and Microscopy

- ➢ **Symmetry Breaking**
- ➢ **Spin information**
- ➢ **Time Resolution (dynamics)**
- ➢ **Space Resolution (microscope)**

- **Optical Probe**

Xia et al, PRL (2016)





Selection of My PhD Work

2D Nanophotonics

Wu et al, 2D Materials (2014)
Wu et al, Nature (2015)

2D Nonlinear Optics

Wu et al, Nano Letters (2012)
Seyler,…, Wu, et al, Nat. Nanotech. (2015)

2D Magneto-photocurrent

Wu et al, Science Advances (2016)
Wu et al, in preparation, (2016)

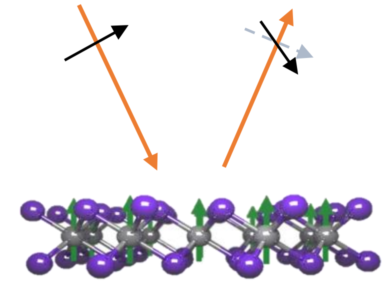
2D Valley-Optoelectronics

Wu et al, Nature Physics (2013)
Ross*, Wu*, et al, Nat. Comm. (2013)
Jones, …, Wu, et al, Nat. Nanotech. (2013)
Yuan, …, Wu, et al, Nat. Phys. (2013)
Singh, …, Wu, et al, PRL (2014)
Chu, …, Wu, et al, PRB (2014)
Rivera, …, Wu, et al, Nat. Comm. (2015)

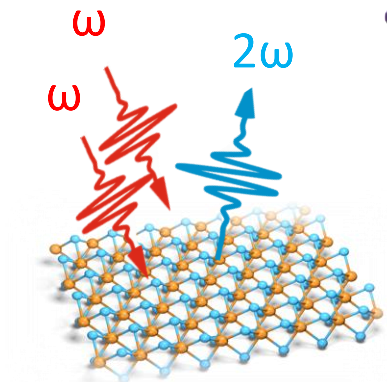
Monolayer Optical Spectroscopy and Microscopy

Optical Tools for Probing and Manipulating Correlated and Topological Electronic Phases

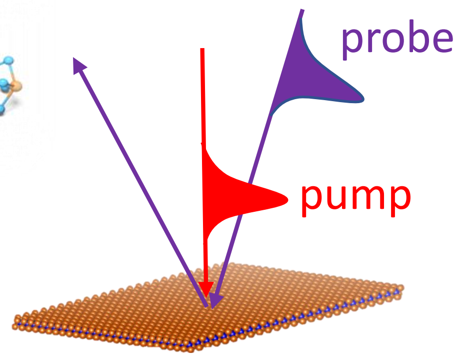
- **Magneto-Optical Spectroscopy**
  - --- Faraday/Kerr rotation
  - --- ***Time reversal symmetry breaking***
  - --- Vortex/spin polarization



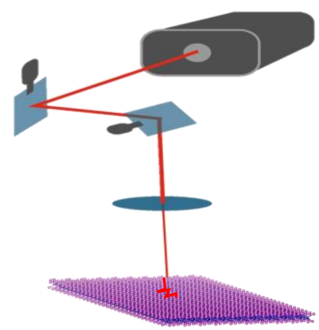
- **Nonlinear Optics**
  - -- Second harmonic generation
  - -- ***Inversion symmetry breaking***
  - -- Lattice or electronic symmetries



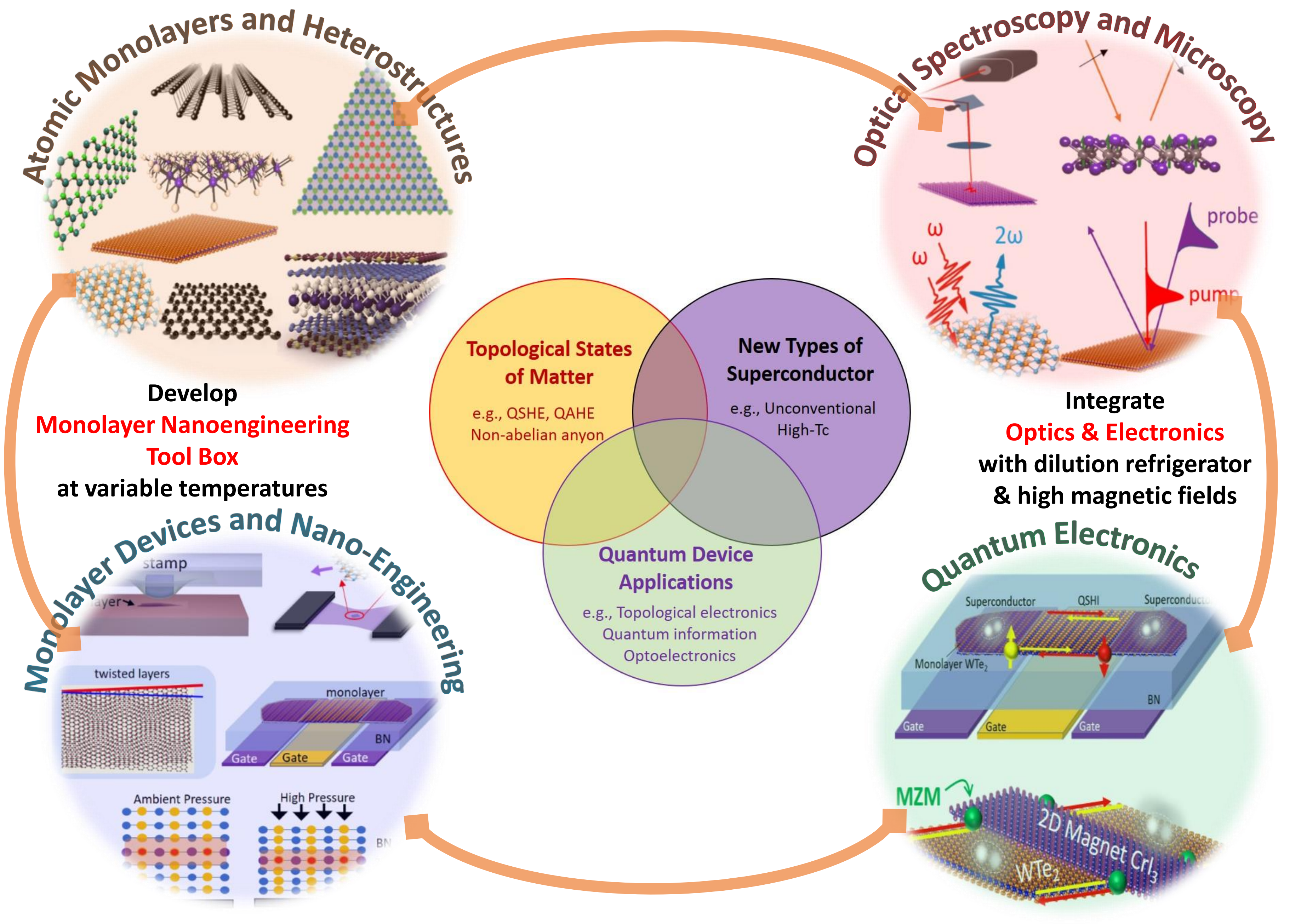
- **Ultrafast Pump Probe Spectroscopy**
  - -- Ultrafast time domain information
  - -- ***Dynamics of spin, charge, orbit, and lattice***
  - -- Lifetimes & hidden metastable states



- **Microscopic Imaging**
  - -- Kerr rotation microscope
  - -- SHG microscope
  - -- Scanning photocurrent microscope



A Laboratory for Correlated and Topological States in Atomic Monolayers

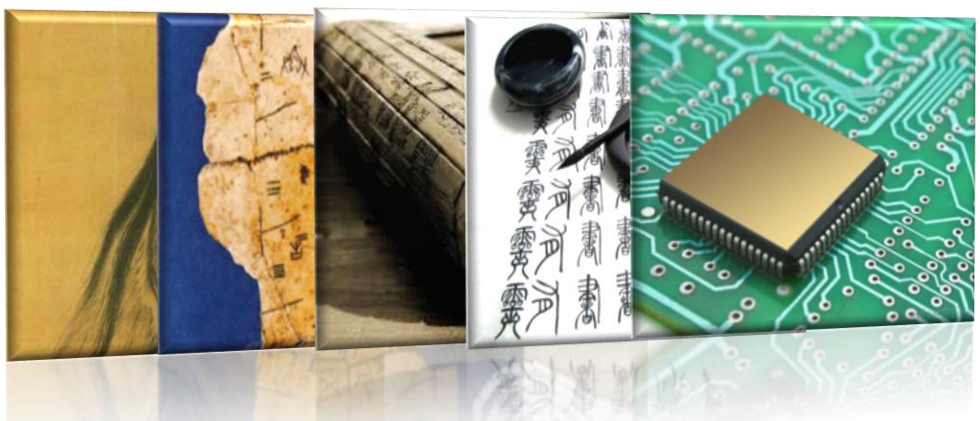


History and the Future of History

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

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Kenji Watanabe & Takashi Taniguchi (NIMS)
Liang Fu (MIT)

GORDON AND BETTY MOORE FOUNDATION

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE

NSF

U.S. DEPARTMENT OF ENERGY | Office of Science

Work at UW

UNIVERSITY OF WASHINGTON 1861

Xu Lab
Nanoscale Optoelectronics Laboratory at the University of Washington

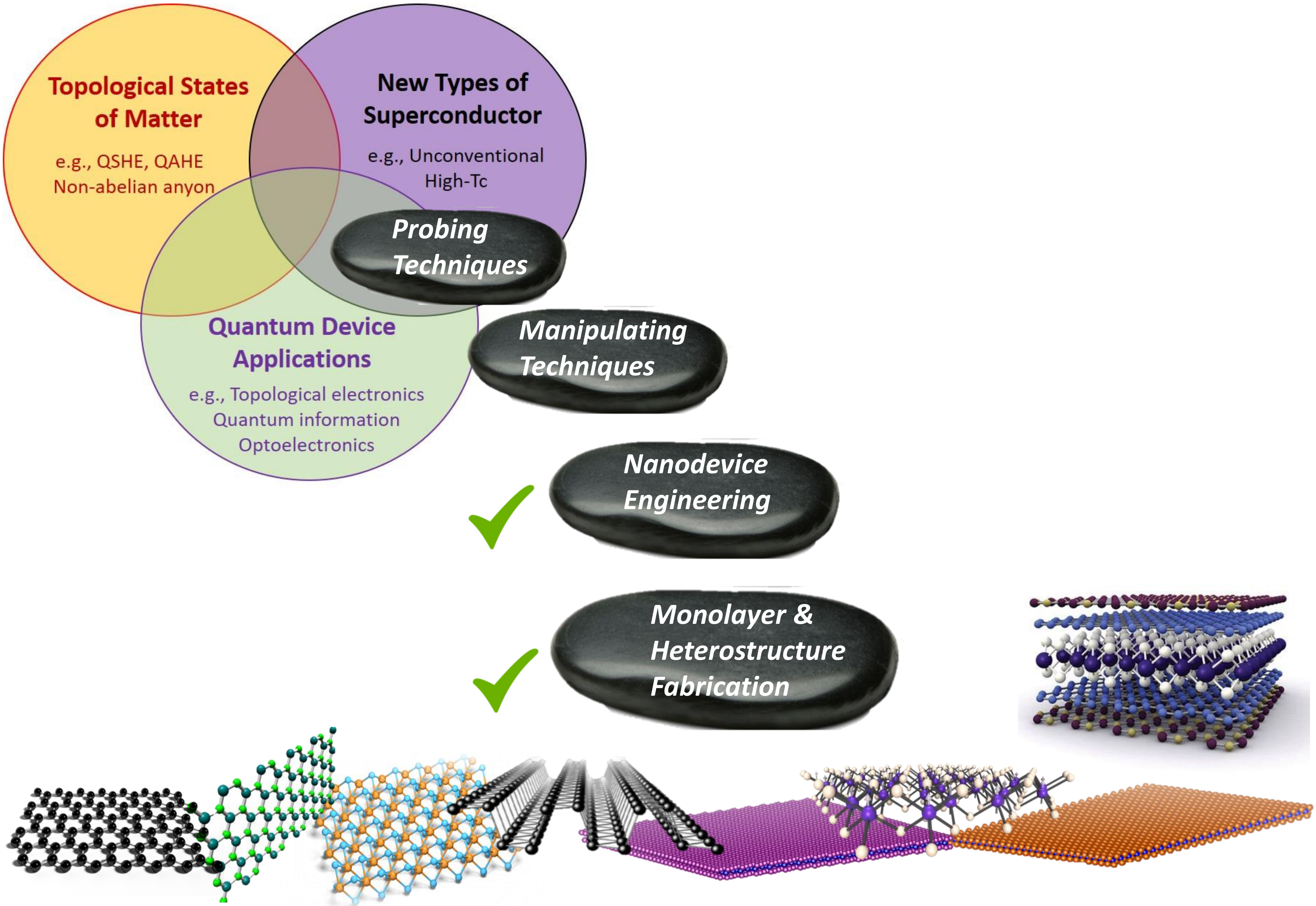
CLEAN ENERGY INSTITUTE

Xiaodong Xu

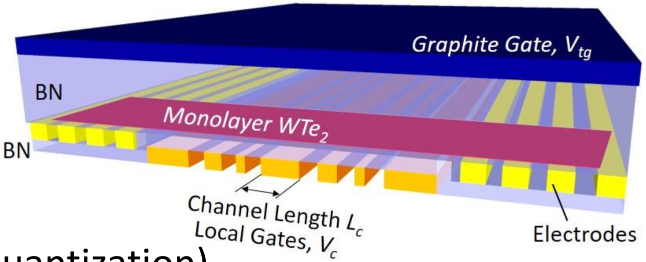
David Cobden (UW)
Zaiyao Fei (UW)
Wang Yao (HKU)
Di Xiao (CMU)
Jiaqiang Yan & David Mandrus (ORNL)

Additional Information

Experimental Tools To Be Developed

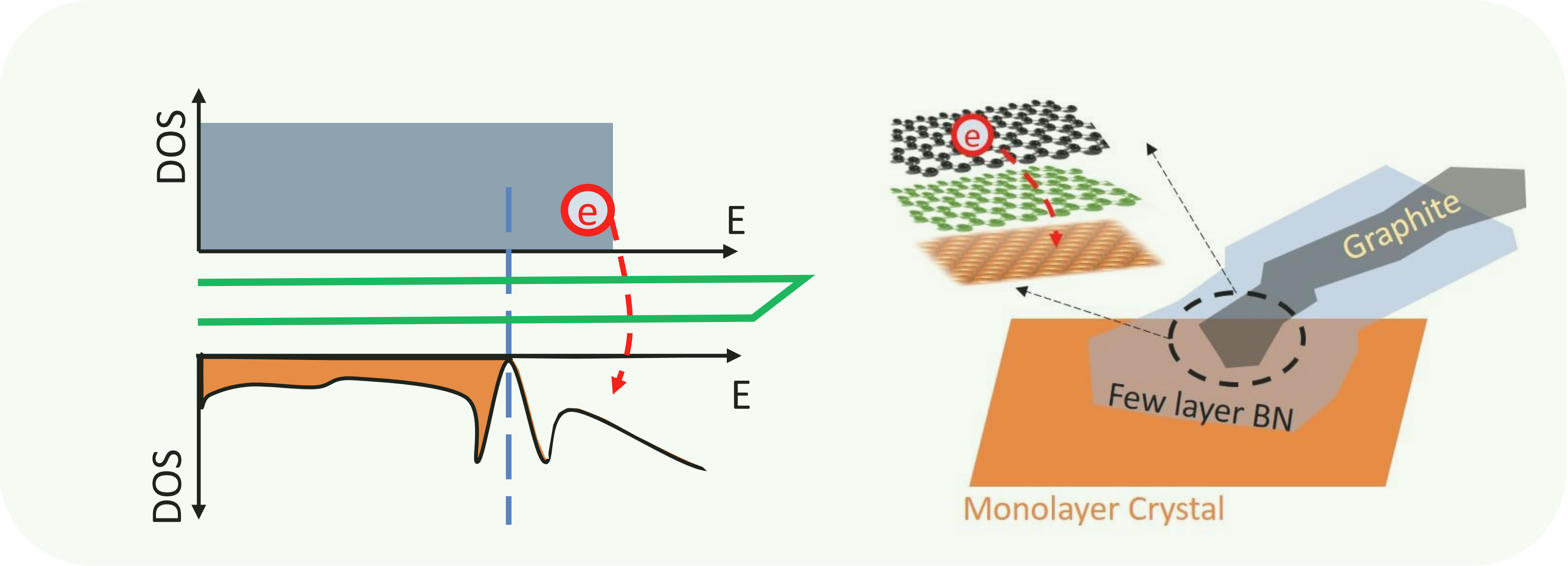


Monolayer Quantum Electronics



- **Quantum Transport**
  -- Electron dissipation/dissipation-less transport
  -- Characteristic conductance (T-dependence, B-dependence, Quantization)

- **Electron Tunneling Spectroscopy**
  -- DOS near fermi surface
  -- Van der Waals Tunneling

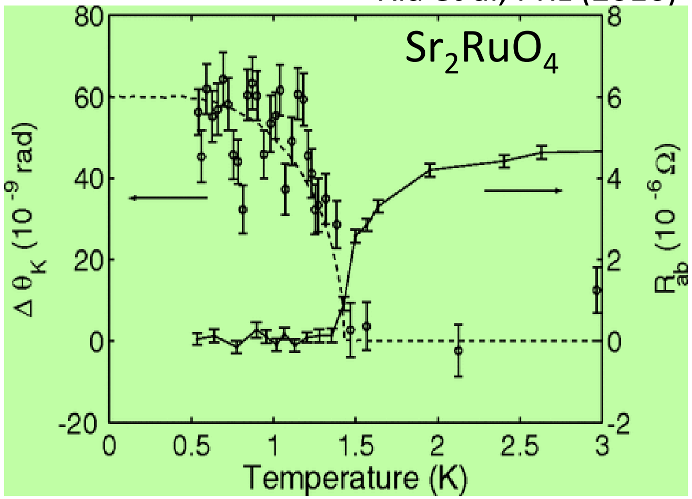


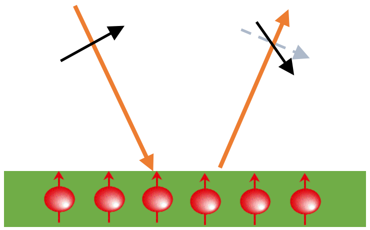
Monolayer Optical Spectroscopy and Microscopy

- ➢ **Symmetry Breaking**
- ➢ **Spin information**
- ➢ **Time Resolution (dynamics)**
- ➢ **Space Resolution (microscope)**

- **Optical Probe**

Xia et al, PRL (2016)





Selection of My PhD Work

2D Nanophotonics

Wu et al, 2D Materials (2014)
Wu et al, Nature (2015)

2D Nonlinear Optics

Wu et al, Nano Letters (2012)
Seyler,…, Wu, et al, Nat. Nanotech. (2015)

2D Magneto-photocurrent

Wu et al, Science Advances (2016)
Wu et al, in preparation, (2016)

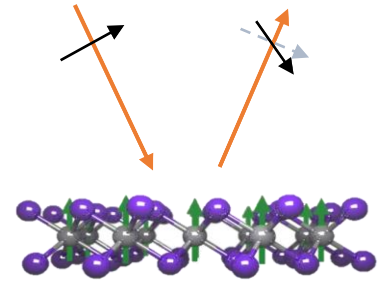
2D Valley-Optoelectronics

Wu et al, Nature Physics (2013)
Ross*, Wu*, et al, Nat. Comm. (2013)
Jones, …, Wu, et al, Nat. Nanotech. (2013)
Yuan, …, Wu, et al, Nat. Phys. (2013)
Singh, …, Wu, et al, PRL (2014)
Chu, …, Wu, et al, PRB (2014)
Rivera, …, Wu, et al, Nat. Comm. (2015)

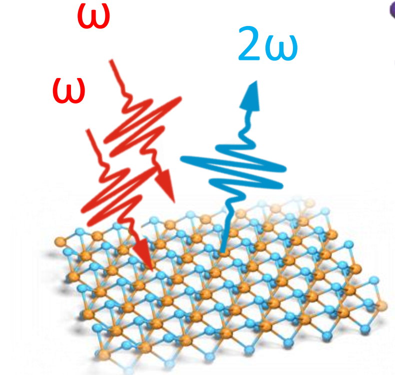
Monolayer Optical Spectroscopy and Microscopy

Optical Tools for Probing and Manipulating Correlated and Topological Electronic Phases

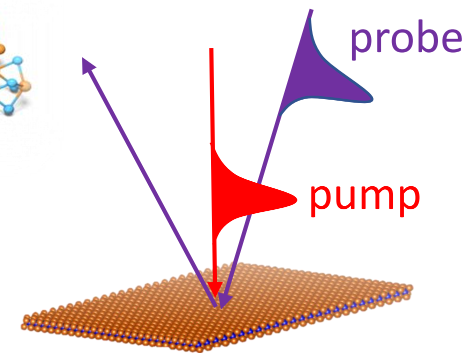
- **Magneto-Optical Spectroscopy**
  - --- Faraday/Kerr rotation
  - --- ***Time reversal symmetry breaking***
  - --- Vortex/spin polarization



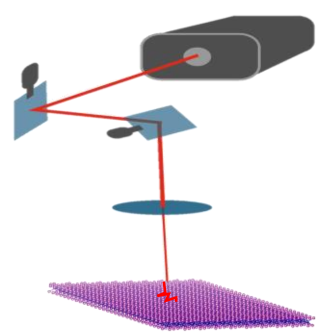
- **Nonlinear Optics**
  - -- Second harmonic generation
  - -- ***Inversion symmetry breaking***
  - -- Lattice or electronic symmetries



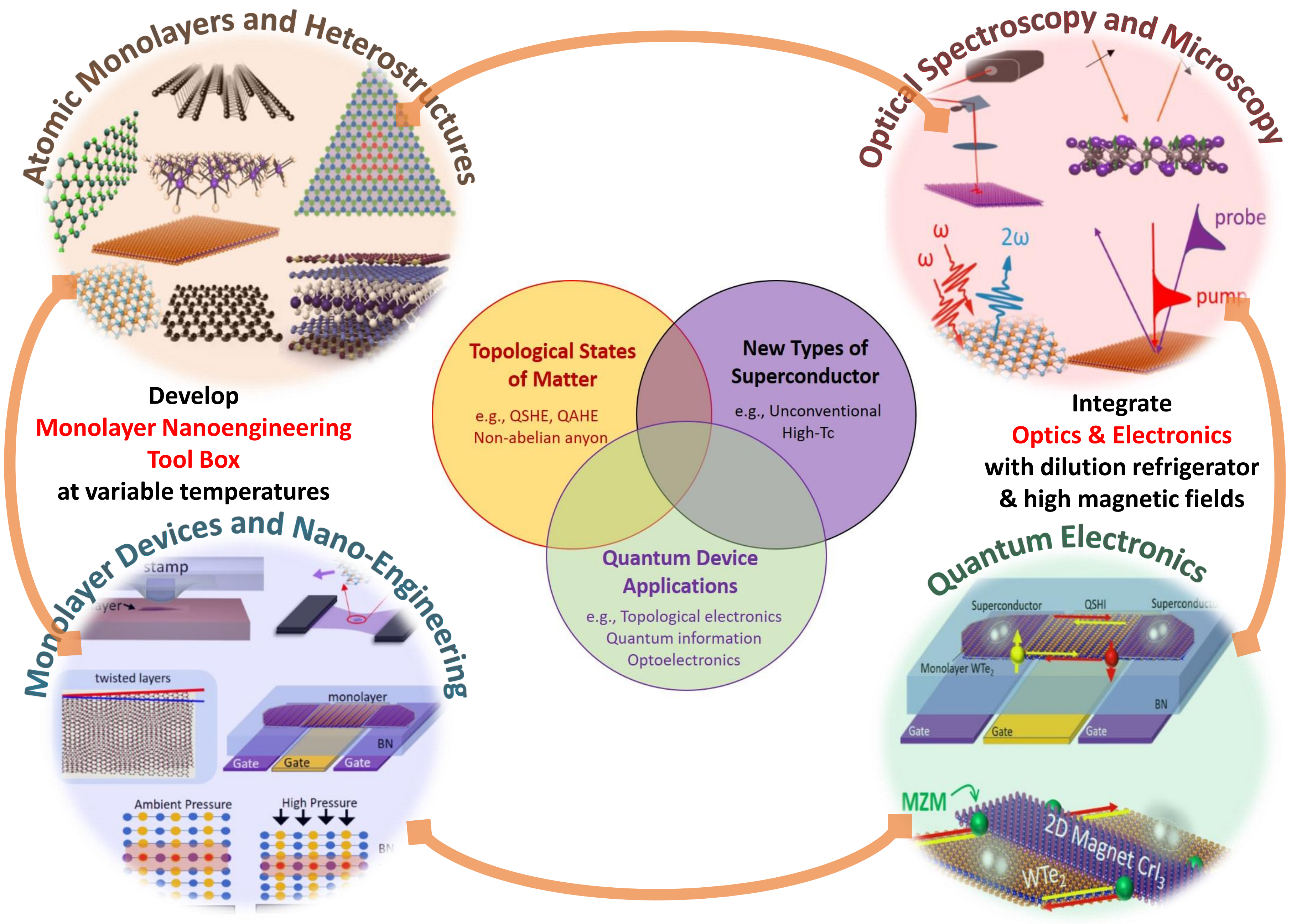
- **Ultrafast Pump Probe Spectroscopy**
  - -- Ultrafast time domain information
  - -- ***Dynamics of spin, charge, orbit, and lattice***
  - -- Lifetimes & hidden metastable states



- **Microscopic Imaging**
  - -- Kerr rotation microscope
  - -- SHG microscope
  - -- Scanning photocurrent microscope

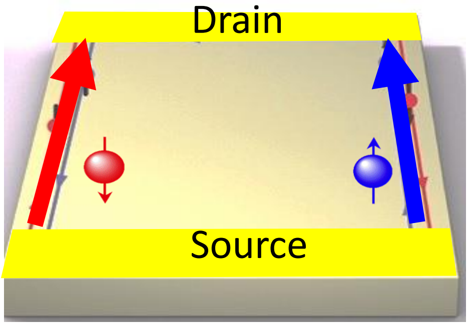


A Laboratory for Correlated and Topological States in Atomic Monolayers

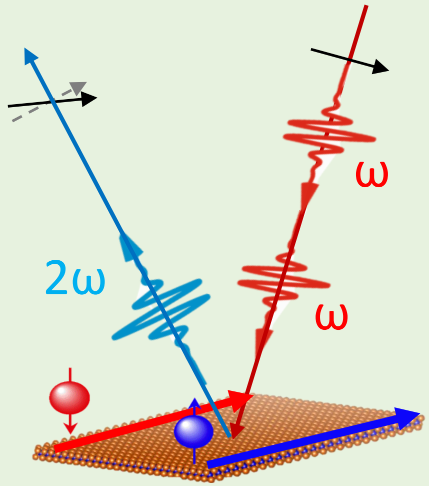


Probing Spin Polarization in Monolayer QSHE

Spin-Polarized Current



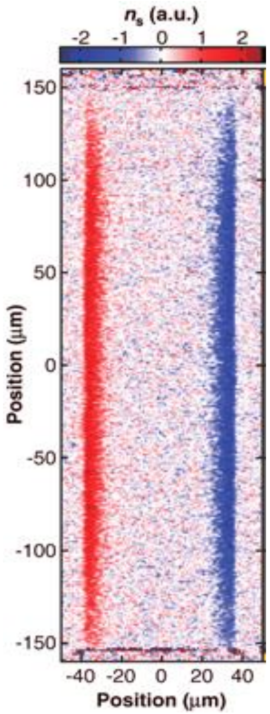
QSHE in Monolayer WTe_2 (inversion symmetric)



Scanning Nonlinear Kerr Rotation Microscope

SHG selects only edge
Kerr effect detects spin polarization

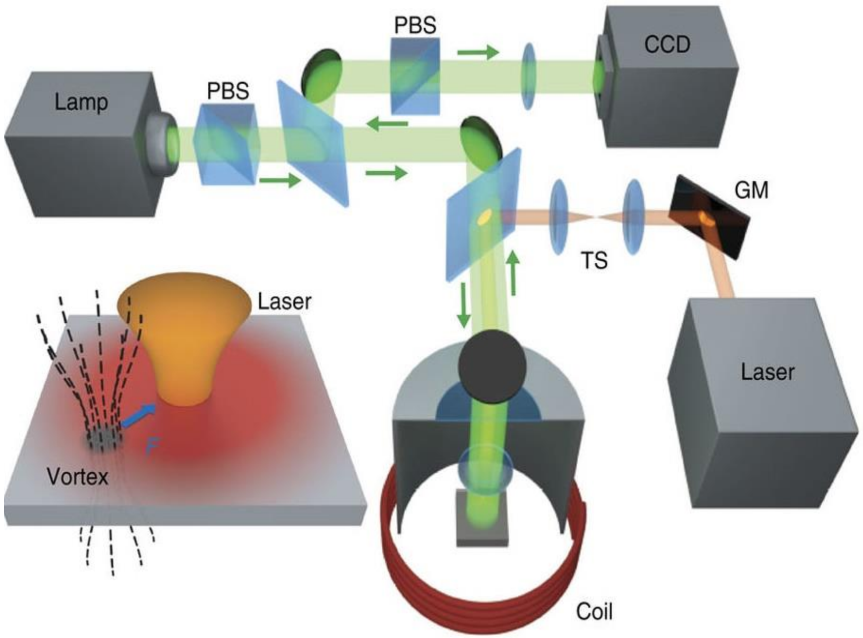
Scanning Kerr Rotation Microscope

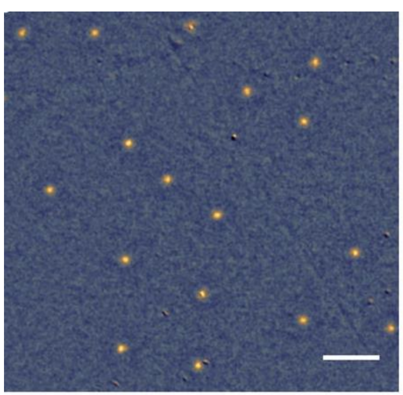


Spin Hall Effect in Semiconductors
Kato et al, Science 2014

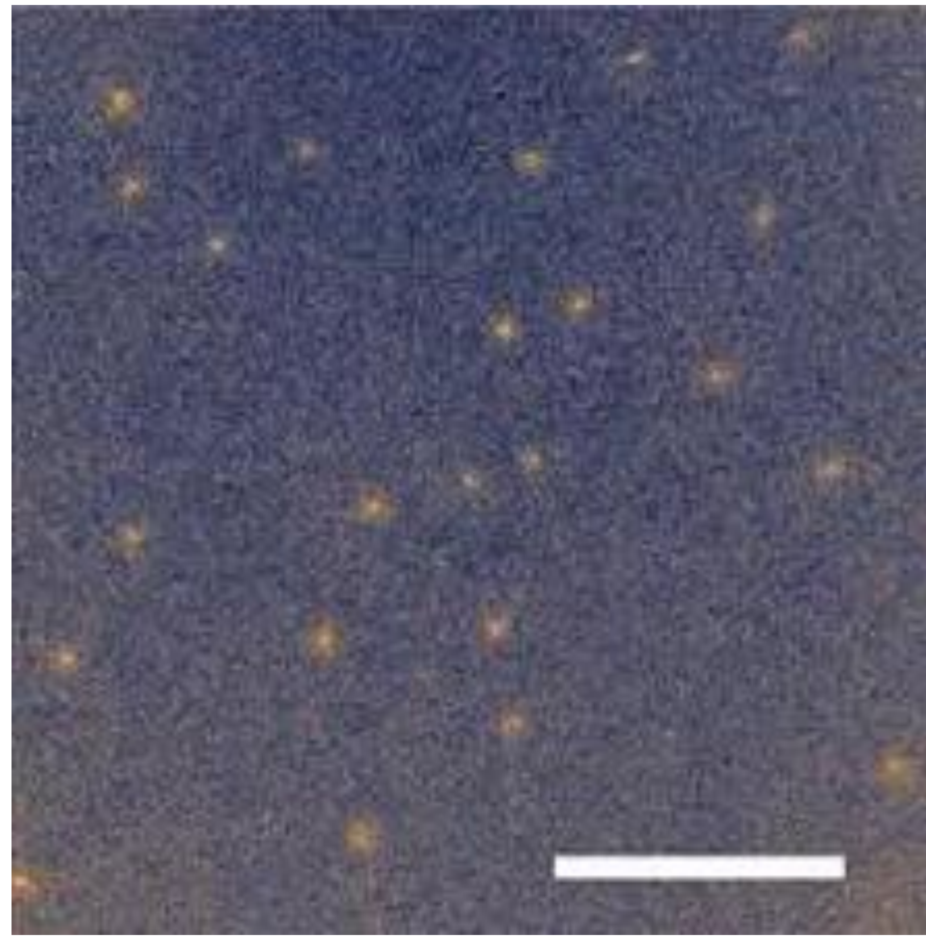
Magneto-optics and Laser Manipulation of Single Vortex

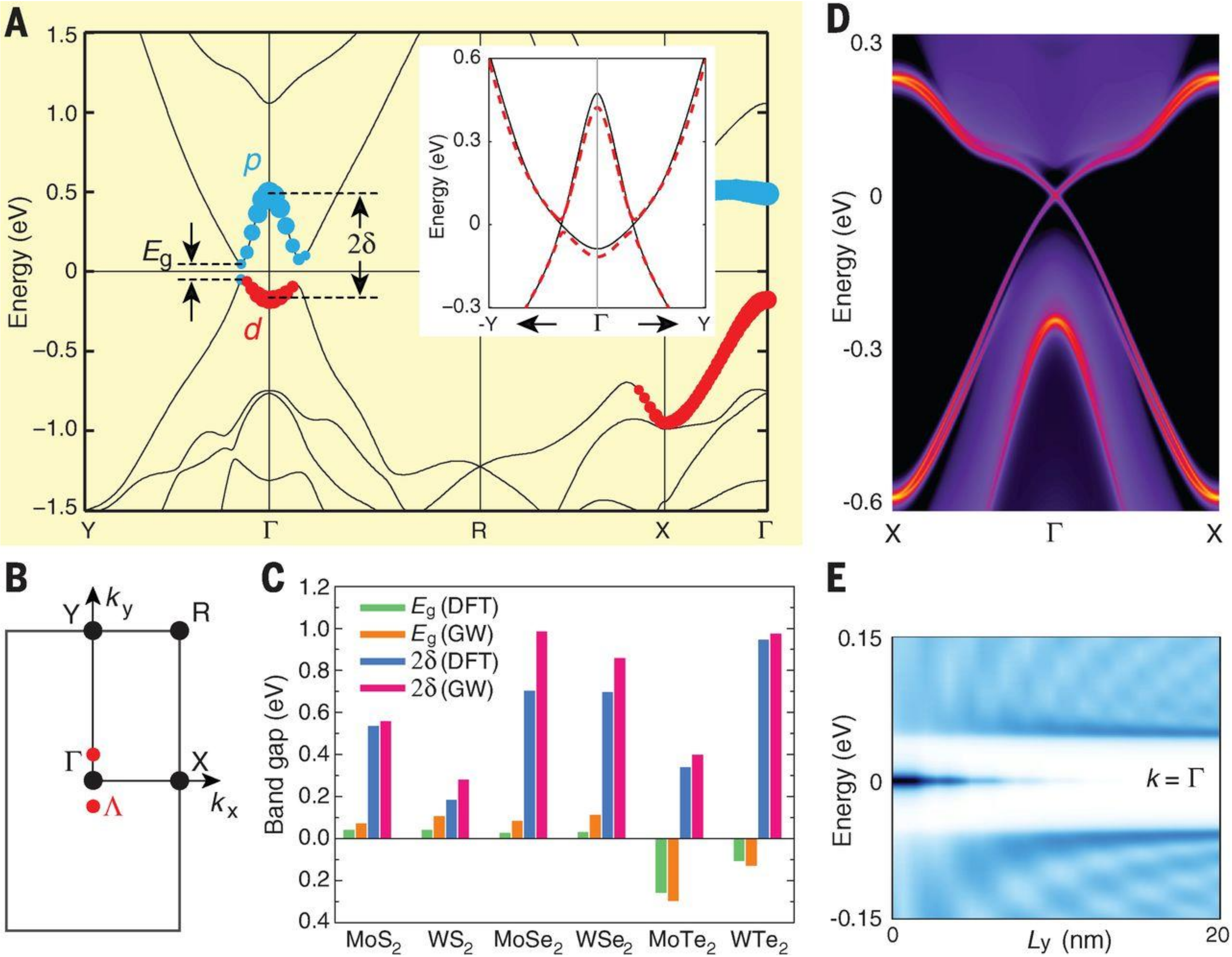
Optical manipulation of single flux quanta
I.S. Veshchunov, W. Magrini, S.V. Mironov, A.G. Godin, J.-B. Trebbia, A.I. Buzdin, Ph. Tamarat & B. Lounis *Nature Communication* (2016)



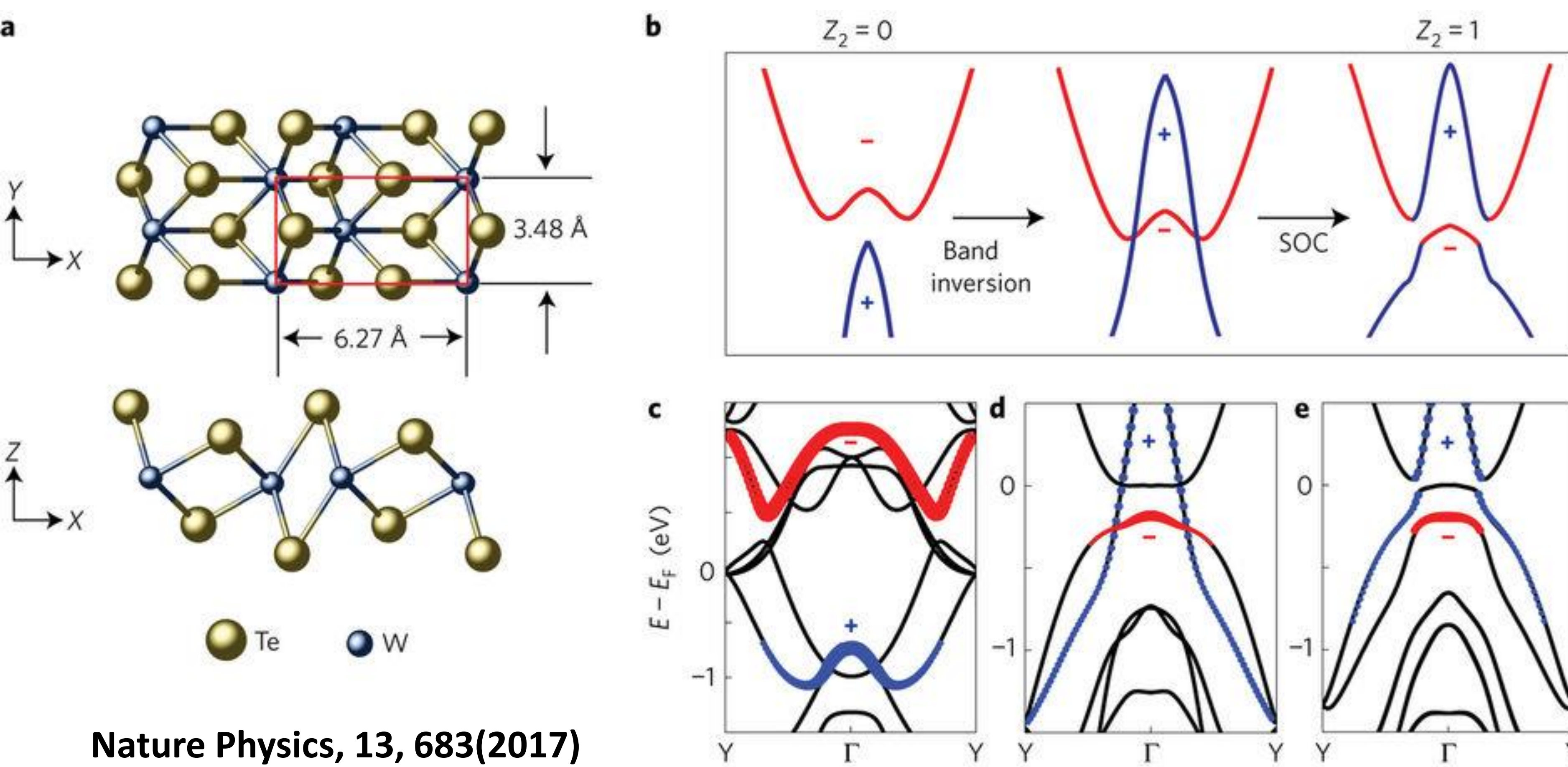


“**A**”brikosov “**V**”ortices





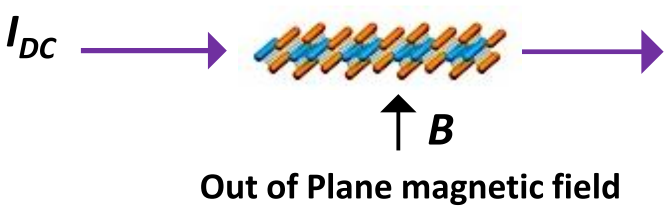
A
Energy (eV)
1.5
1.0
0.5
0
−0.5
−1.0
−1.5
Y
Γ
R
X
Γ
p
d
E_g
2δ
0.6
0.3
0
−0.3
-Y
Γ
Y
B
k_y
Y
R
Γ
X
Λ
k_x
C
E_g (DFT)
E_g (GW)
2δ (DFT)
2δ (GW)
Band gap (eV)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.4
MoS_2
WS_2
$MoSe_2$
WSe_2
$MoTe_2$
WTe_2
D
0.3
0
-0.3
-0.6
X
Γ
X
E
0.15
0
-0.15
$k = Γ$
L_y (nm)
0
20

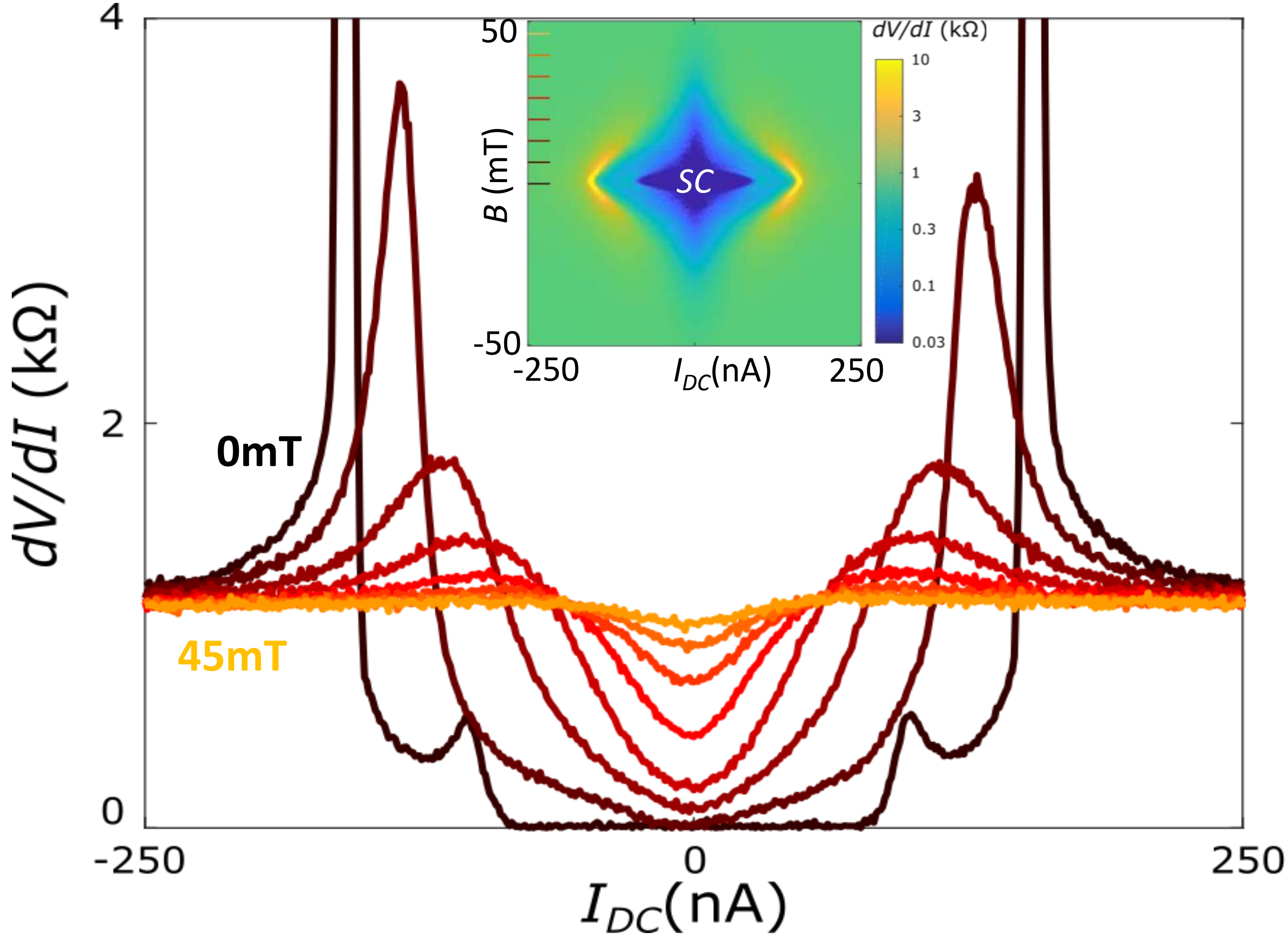


Nature Physics, 13, 683(2017)

a, Crystal structure of 1T'-WTe_2. The doubled period due to the spontaneous lattice distortion from 1T phase is indicated by the red rectangle. **b**, Schematic diagram to show the bulk band evolution from a topologically trivial phase, to a non-trivial phase, and then to a bulk band opening due to SOC. **c**–**e**, Calculated band structures for WTe_2 to show the evolution from 1T-WTe_2 along the Γ–Y direction (**c**), 1T'-WTe_2 without SOC (**d**) and 1T'-WTe_2 with SOC (**e**). Red and blue dotted bands highlight the two bands involved in band inversion, which mainly contain the $5d_{z^2}$ and $5d_{xz}$ orbital contents, respectively. + and − signs denote the parity of the Bloch states at the Γ point

Superconductivity: Magnetic Field Effect





Monolayer Crystals and Heterostructures

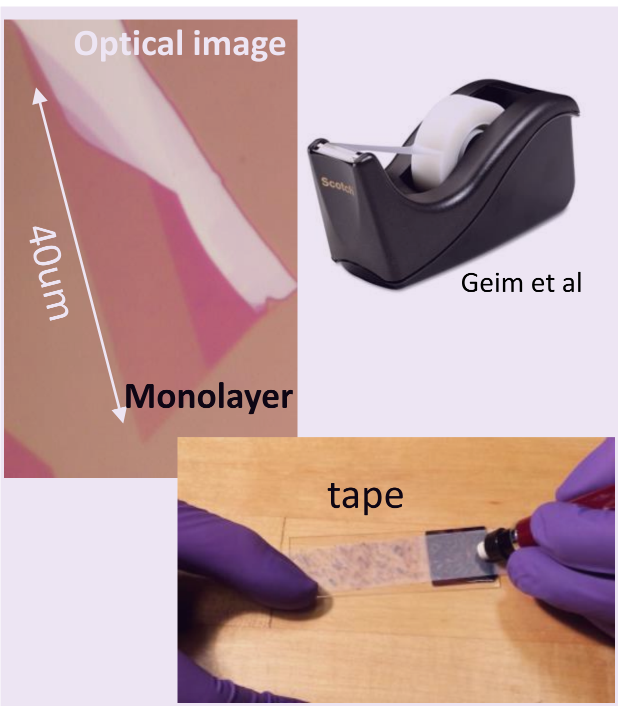
2D electron

Atomic Heterostructures

Hidden (Buried), Complex

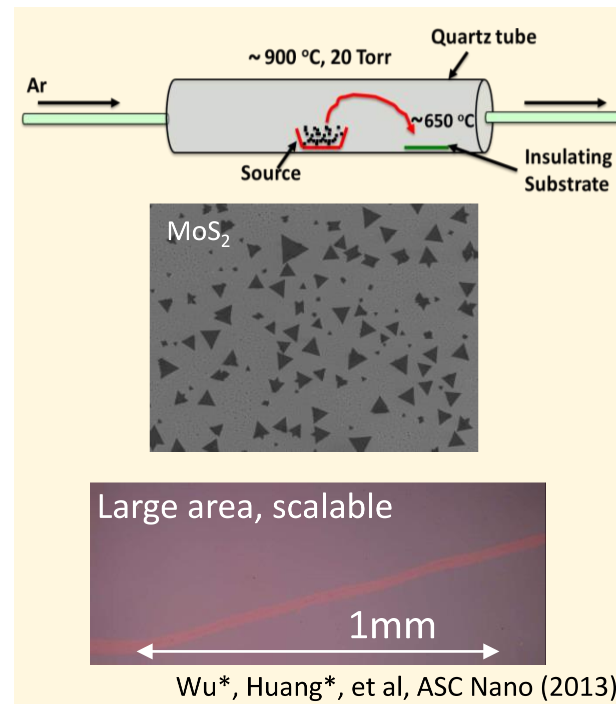
(Isolated) Crystalline Atomic Monolayers

Mechanical Exfoliation



MBE Growth

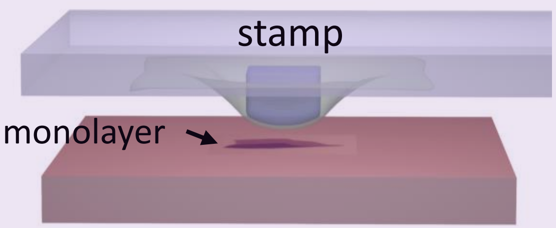
CVD/PVD Growth



Version 3.0 ?

Monolayer Heterostructures

Vertical Stacking



Van der Waals Heterostructure

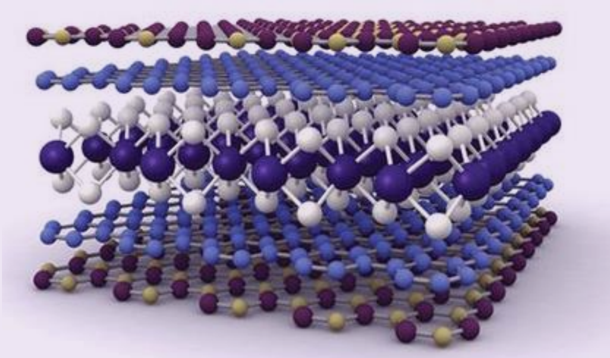
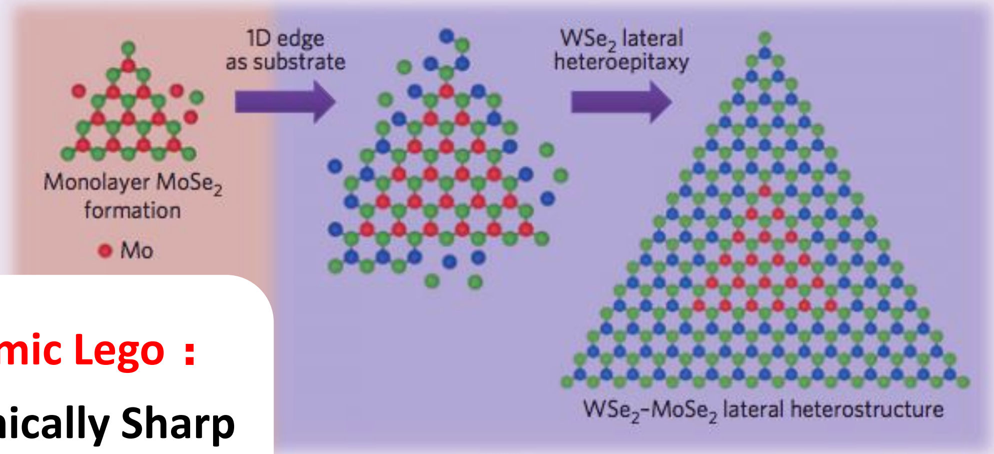


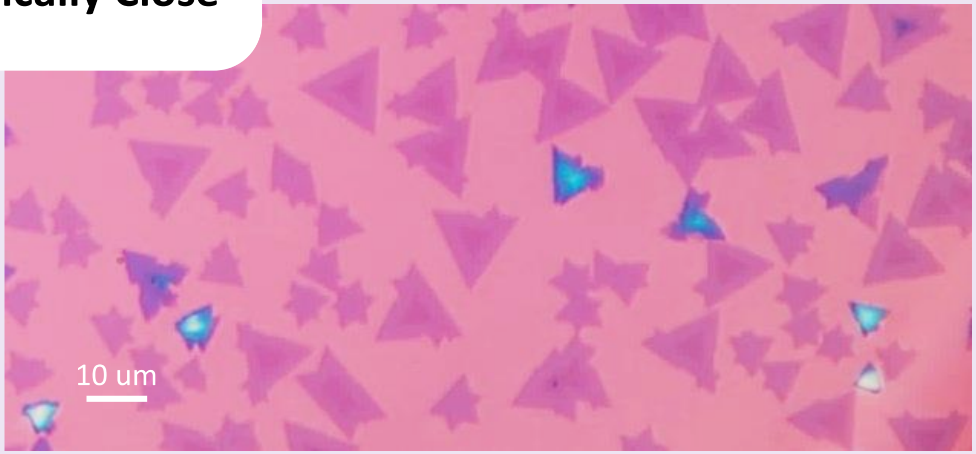
Image Credit: Novoselov et al, Science (2016)

Lateral Sticking



Atomic Lego :

Atomically Sharp
Atomically Close



Huang*, Wu*,#, Sanchez*,#, et al, Nature Materials (2014)

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:

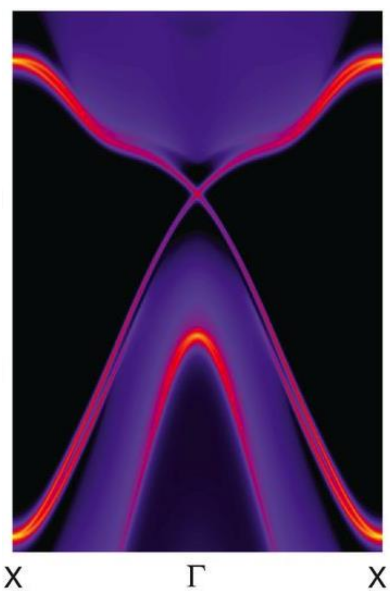
DOI: 10.1126/science.1256815

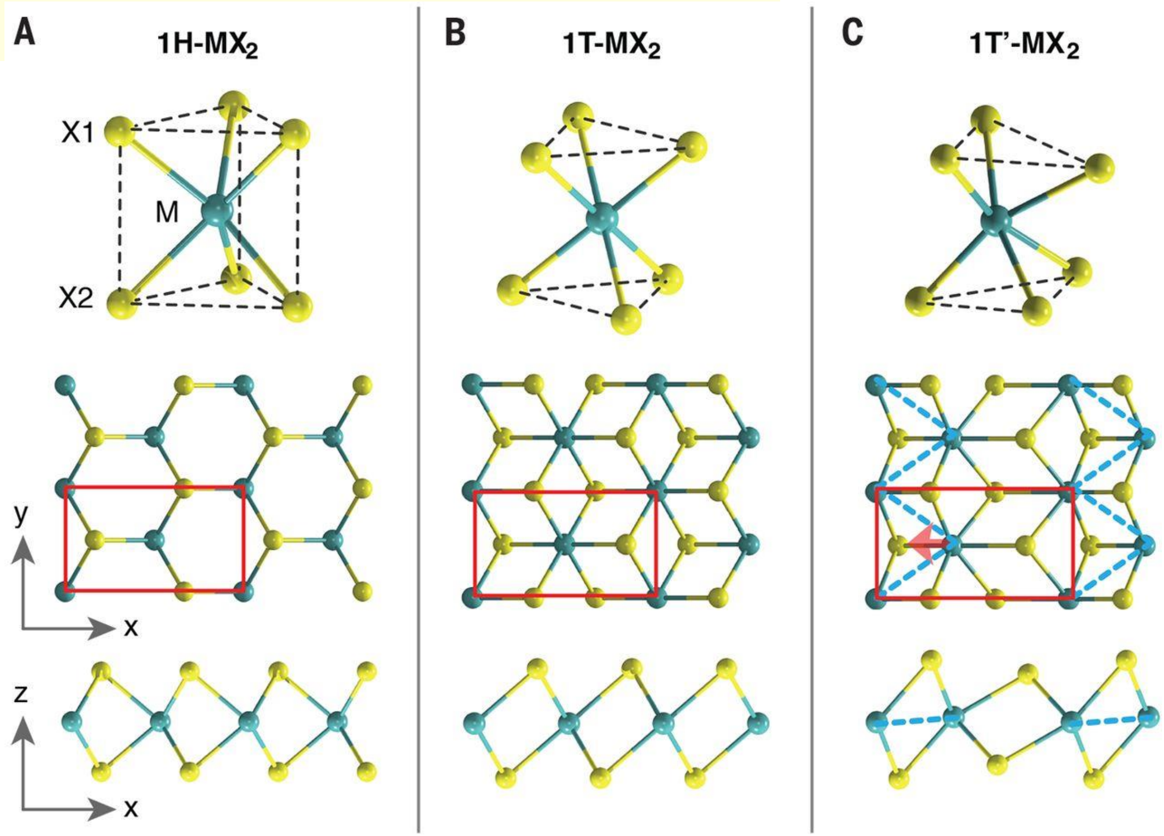
M = Mo, W;
X = S, Se, Te.

Semiconductors

Semimetal

1T’ TMD Monolayer



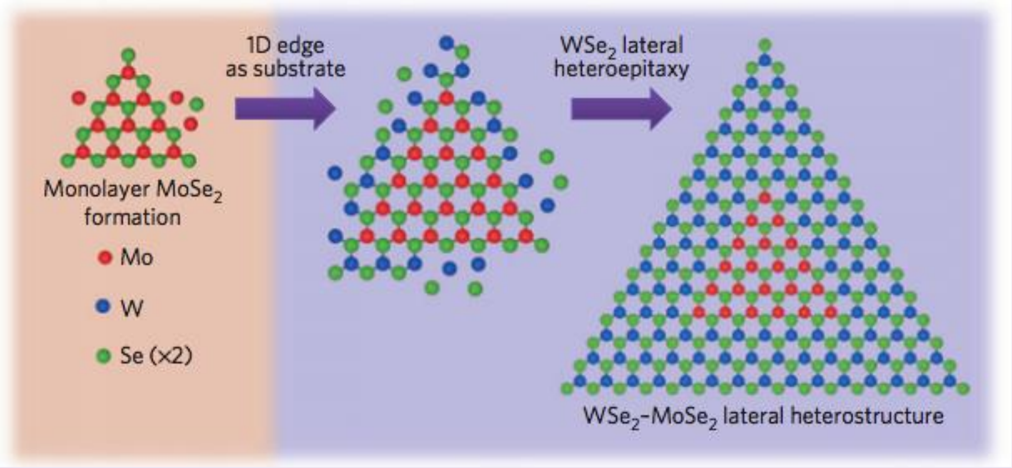


Version 3.0 ?

Monolayer Heterostructures

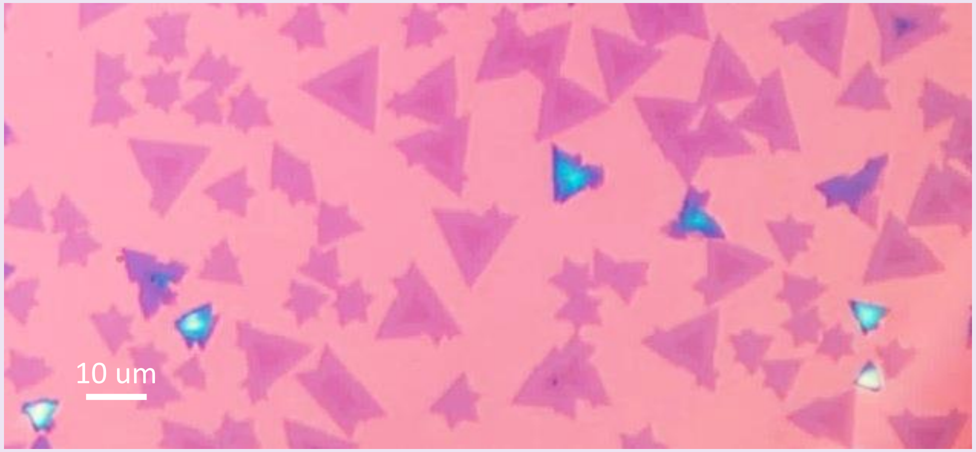
Vertical

Lateral



2D Atomic Lego :

Atomically Sharp
Atomically Close



Huang*, Wu*,#, Sanchez*,#, et al, Nature Materials (2014)

Existing Semiconductor Heterostructure Systems

Received 3 Feb 2015 | Accepted 20 Apr 2015 | Published 26 May 2015 DOI: 10.1038/ncomms8252 OPEN

Unexpected edge conduction in mercury telluride quantum wells under broken time-reversal symmetry

"Surprisingly, the edge conduction persists up to 9 T with little change"

Eric Yue Ma[1,2], M. Reyes Calvo[1,2], Jing Wang[1,3], Biao Lian[1,3], Mathias Mühlbauer[1,4], Christoph Brüne[4], Yong-Tao Cui[1], Keji Lai[1,2,5], Worasom Kundhikanjana[1,2], Yongliang Yang[1], Matthias Baenninger[1,3], Markus König[1,3], Christopher Ames[4], Hartmut Buhmann[4], Philipp Leubner[4], Laurens W. Molenkamp[4], Shou-Cheng Zhang[1,3], David Goldhaber-Gordon[1,3], Michael A. Kelly[1] & Zhi-Xun Shen[1,2,3]

PRL **114**, 096802 (2015) PHYSICAL REVIEW LETTERS 6 MARCH 2015

Robust Helical Edge Transport in Gated InAs/GaSb Bilayers

"The quantized conductance persist to a 12 T applied in-plane field"

Lingjie Du,[1] Ivan Knez,[1,2] Gerard Sullivan,[3] and Rui-Rui Du[1,*]

Expected QSH Transport Signatures:

- Bulk insulating + edge conducting ✓
- Quantized conductance, ~ e^2/h per edge ✓
- Conductance saturates in the short-edge limit No report
- Quantization destroyed under broken TR symmetry No
- (Zeeman gap opening at the Krammers Point)

Low Temperature Phenomena:

Near Liquid Helium Temperature (< 8 K)