Ferromagnetism near three-quarters filling in twisted bilayer graphene

Aaron Sharpe

Caltech

February 11th, 2020

10.1126/science.aaw3780

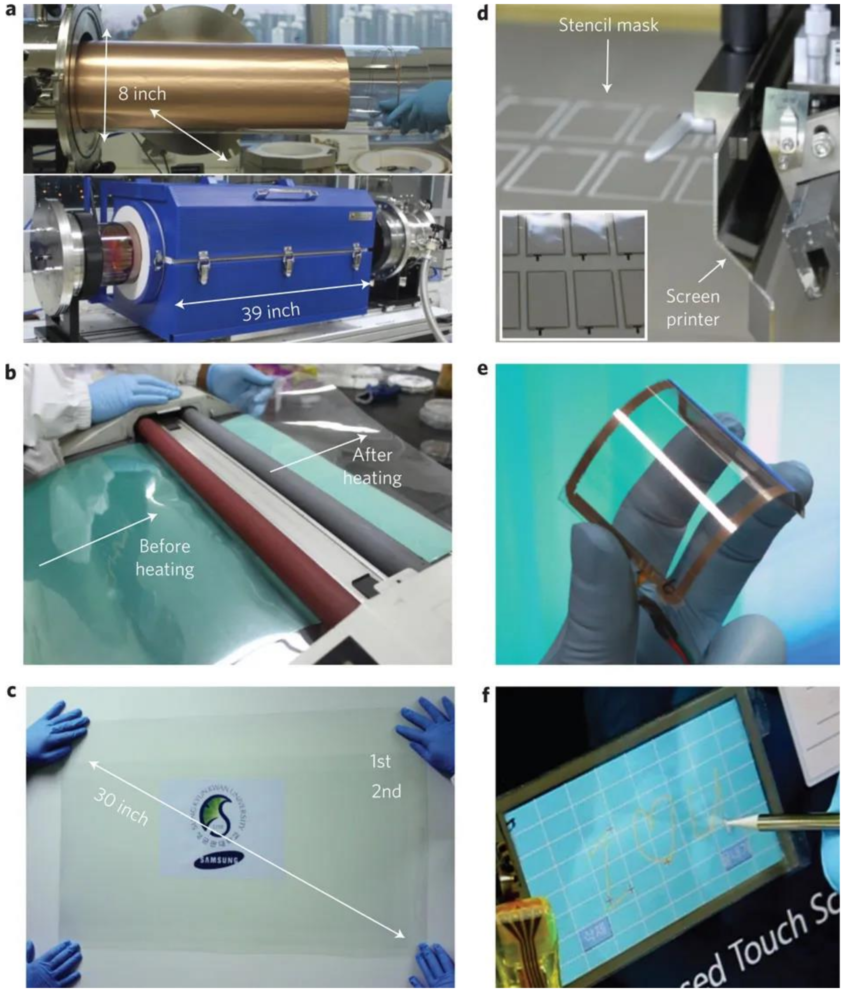
Acknowledgements

Stanford University
Eli Fox
Arthur Barnard
Joe Finney
Marc Kastner
David Goldhaber-Gordon

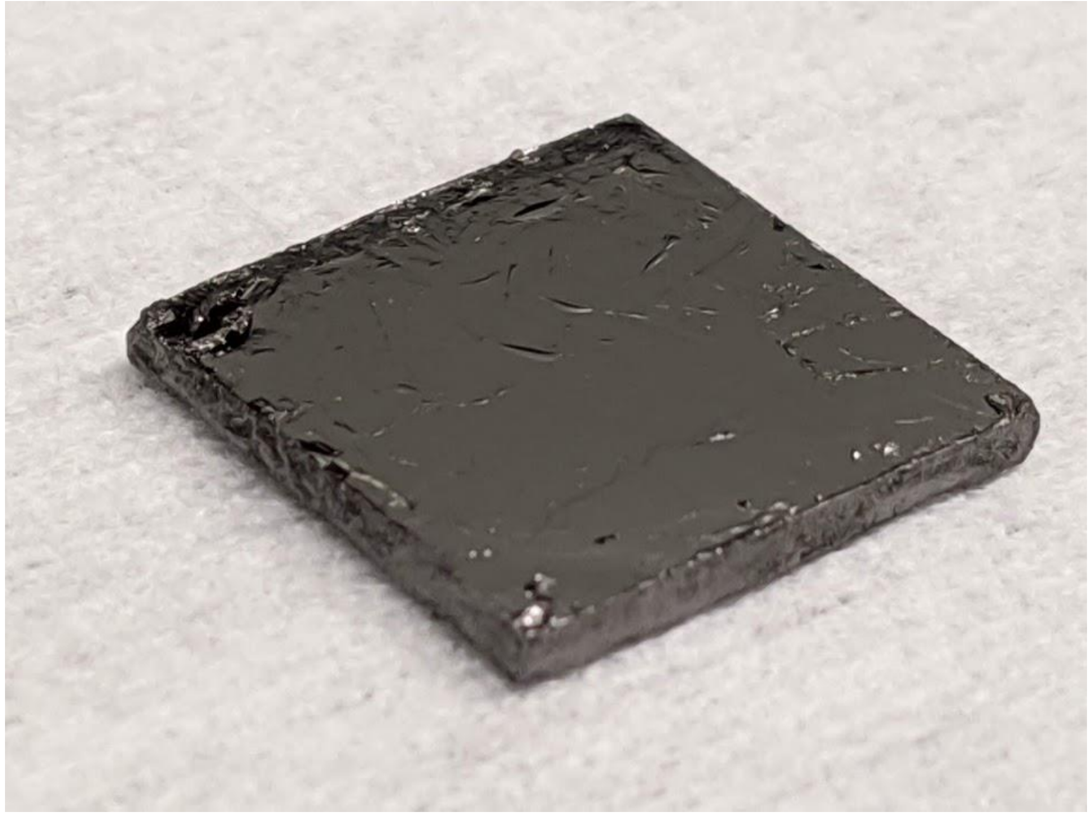
National Institute for Materials Science
Kenji Watanabe
Takashi Taniguchi

Thanks
Rupini Kamat, Hava Schwartz, Sungyeon Yang, Anthony Chen, Patrick Gallagher, Allan MacDonald, Ming Xie, Michael Zaletel, Nick Bultinck, Todadri Senthil, Steve Kivelson, Yoni Schattner, Feng Wang, Guorui Chen, Matt Yankowitz, Yuan Cao, Pablo Jarillo-Herrero

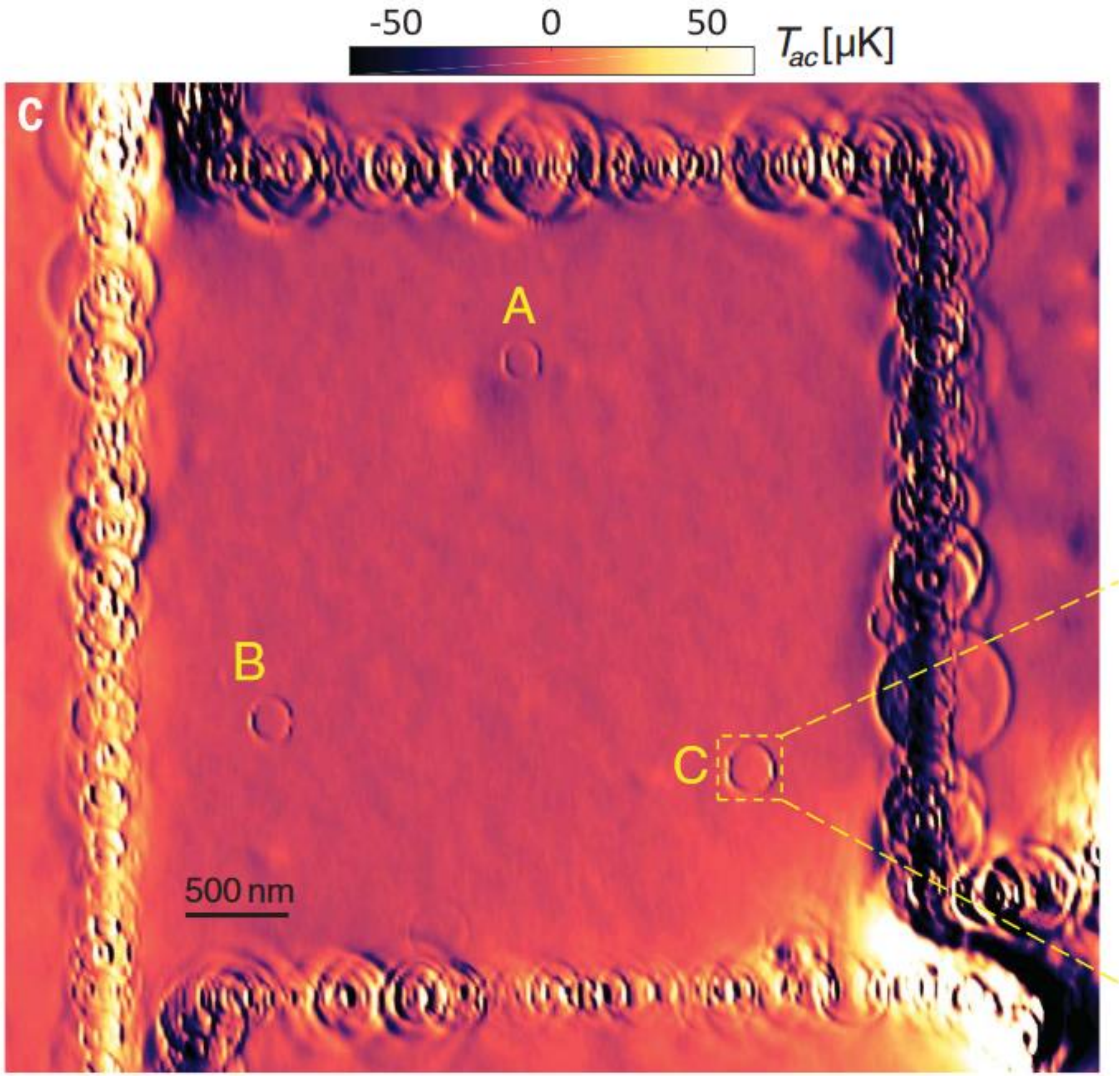
Graphene: Scotch Tape Still King



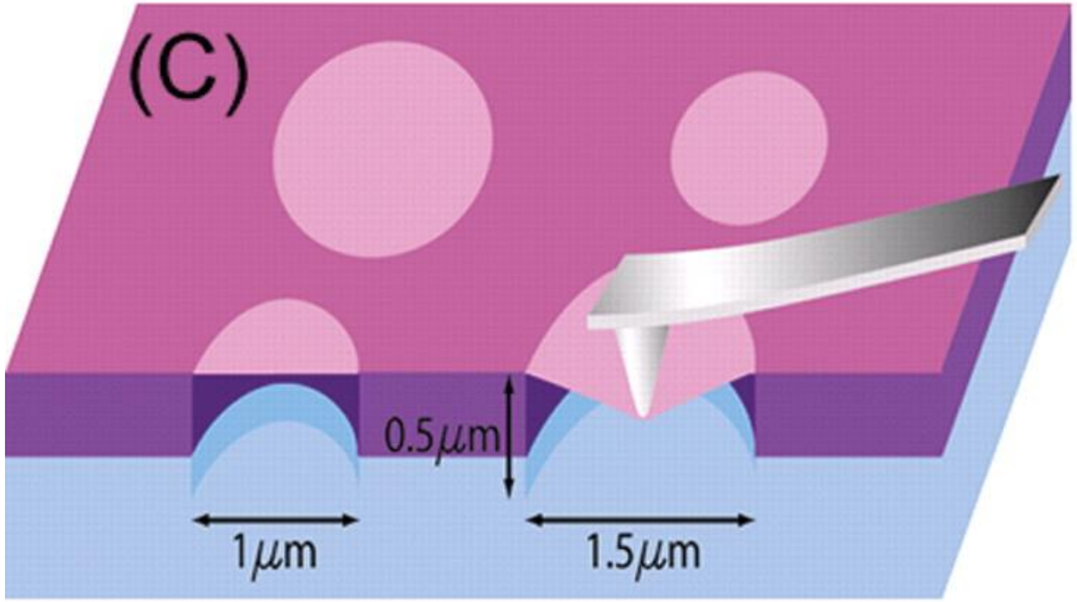
Bae, *et. al. Nat. Nanotech* (2010)



Graphene: Truly 2D and Defect Free

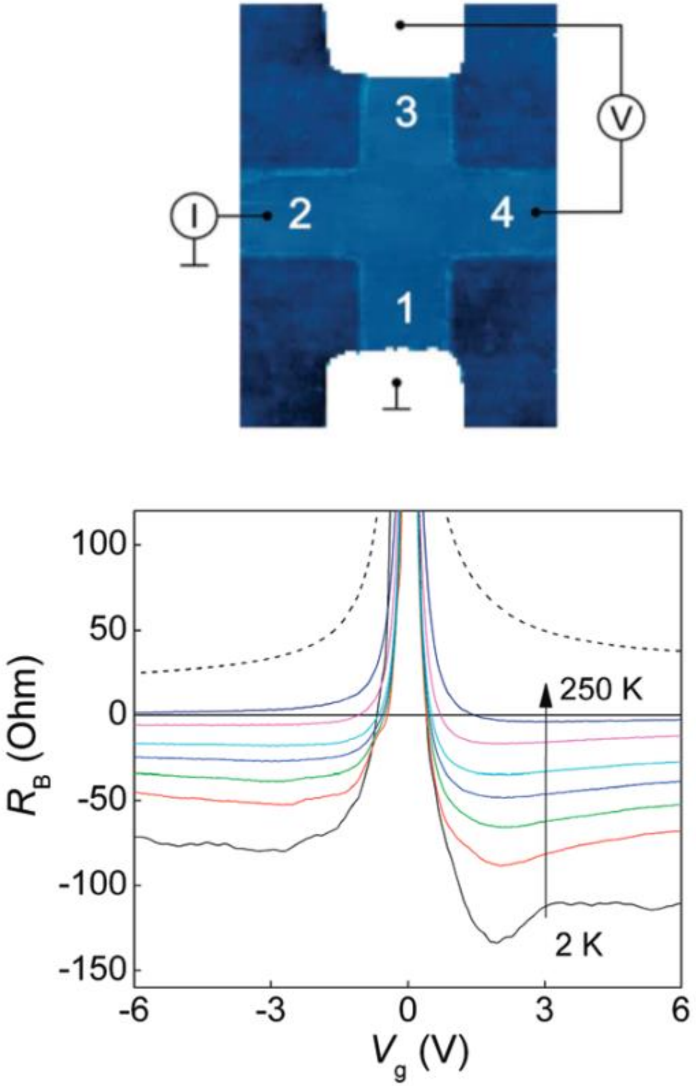


Halbertal, *et. al.* Science (2017)



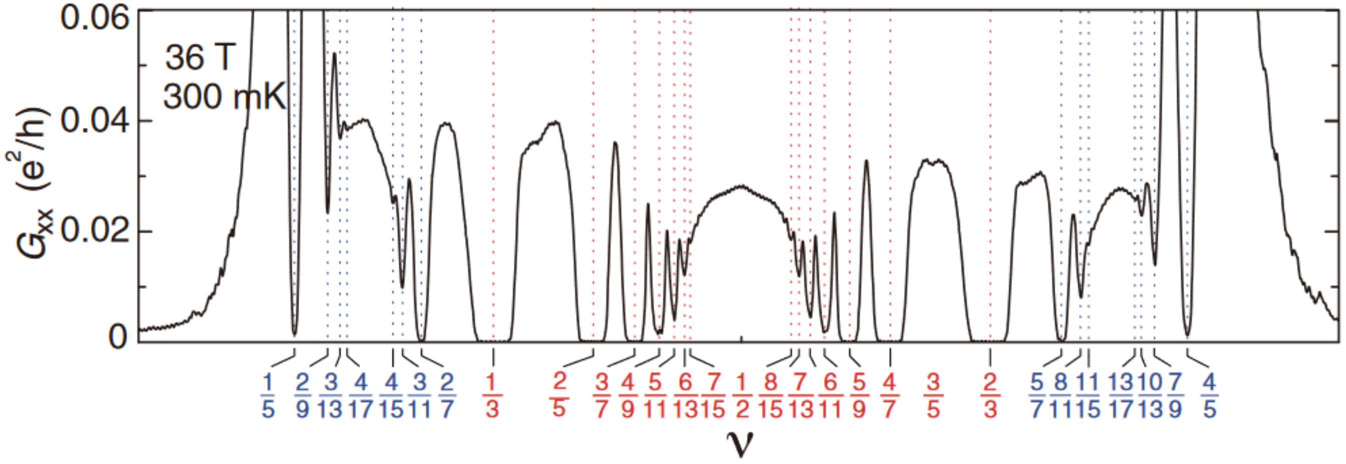
Lee, *et. al.* Science (2008)

Ballistic Transport



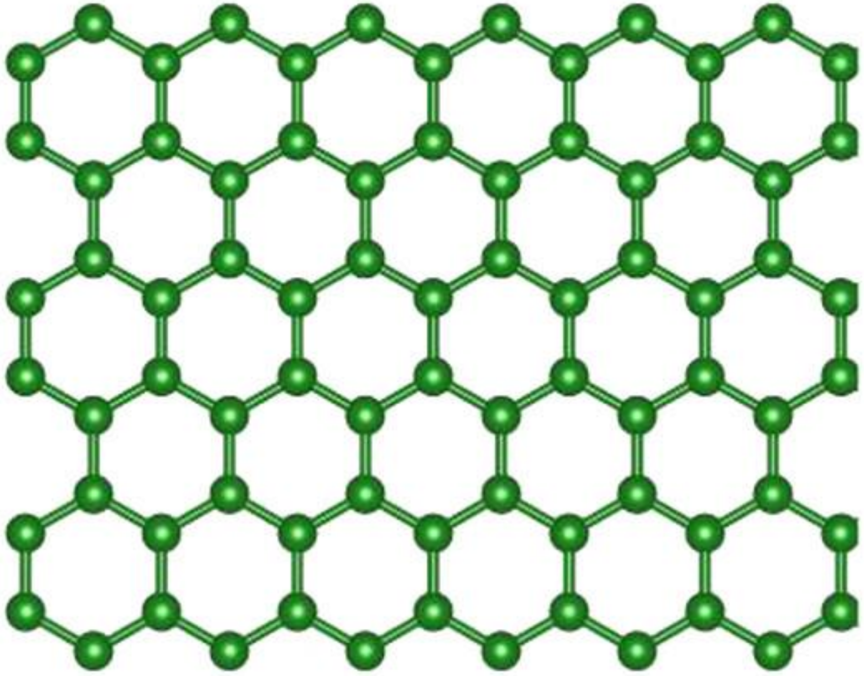
AS Mayorov, *et al.* Nanoletters (2011)

Fractional Quantum Hall

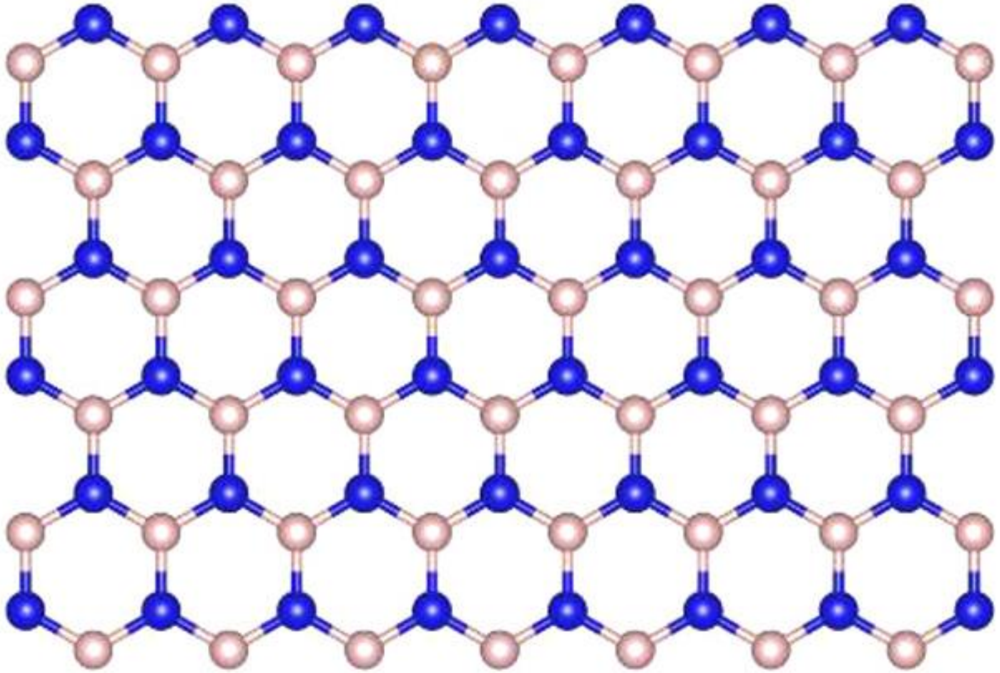


Zeng, *et. al.* PRL (2019)

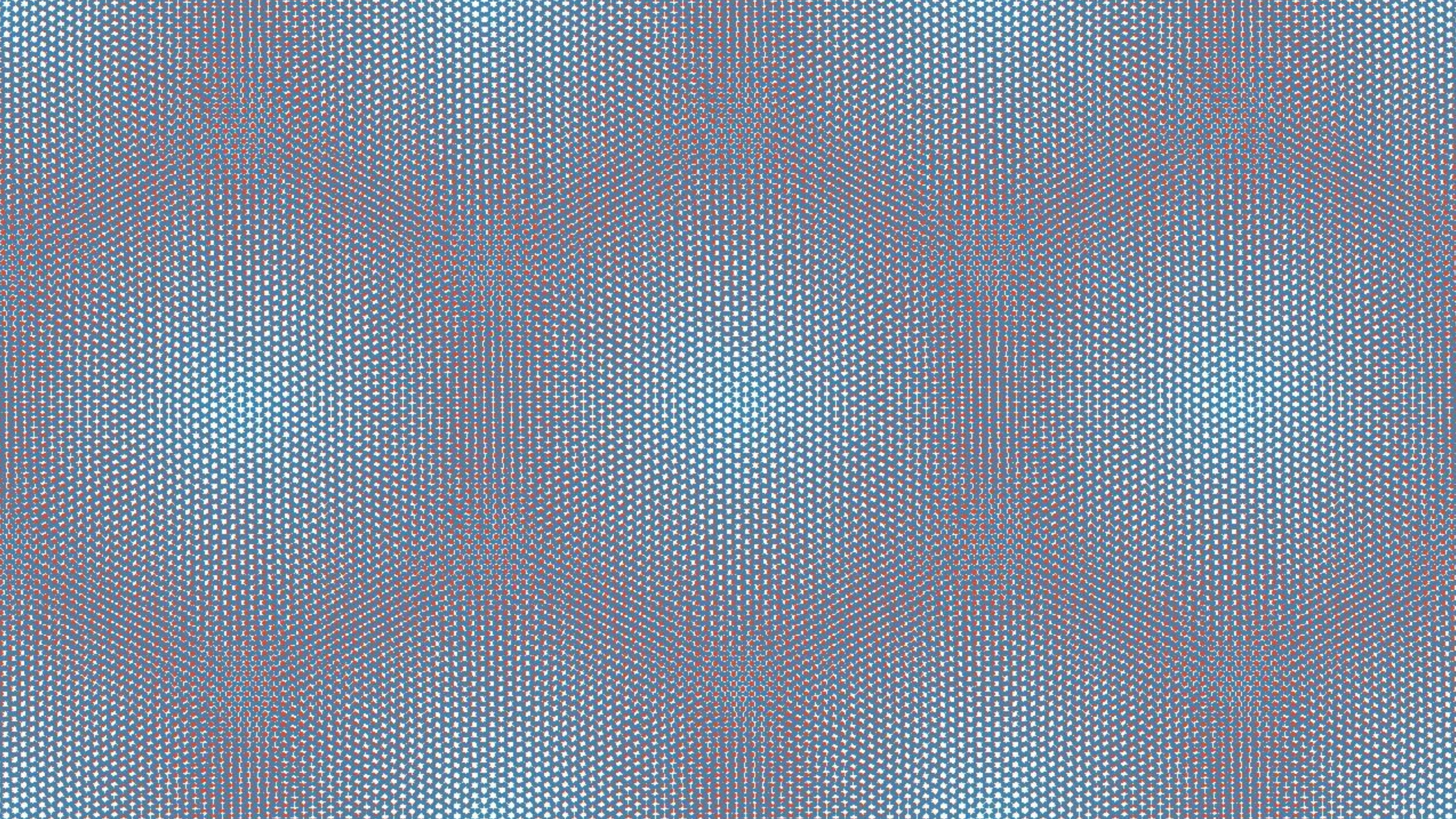
Graphene



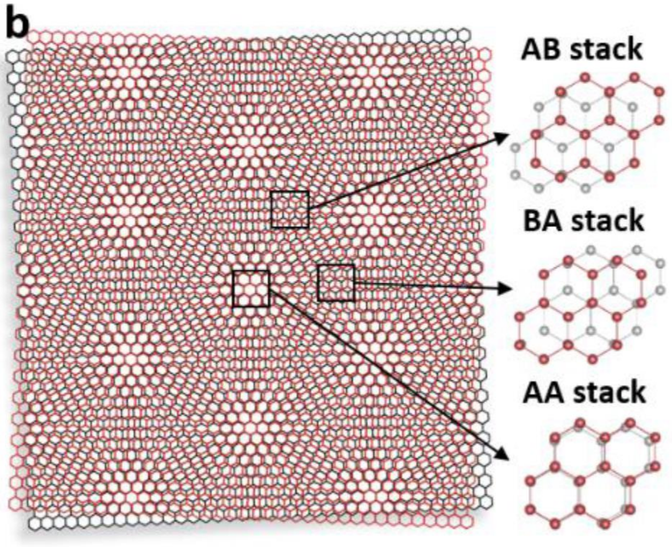
Hexagonal Boron Nitride (hBN)

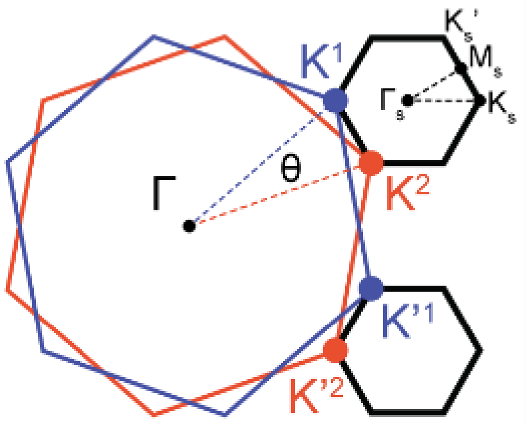


Jin et al., Chem. Rev. (2018)



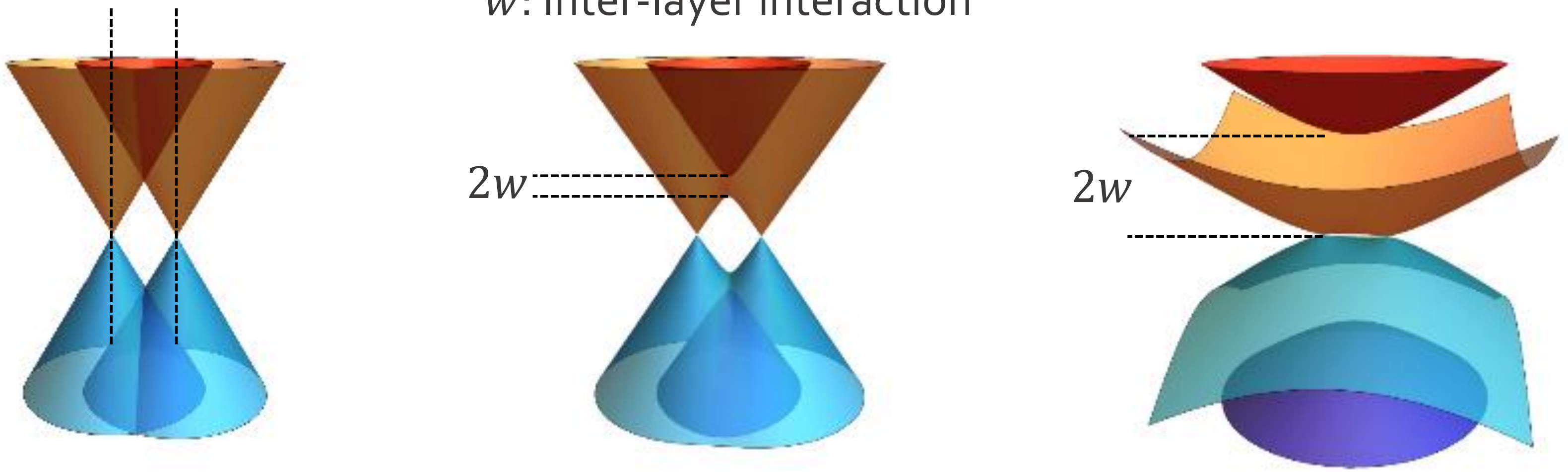
Twisted Bilayer Graphene





$k_\theta \approx K\theta$

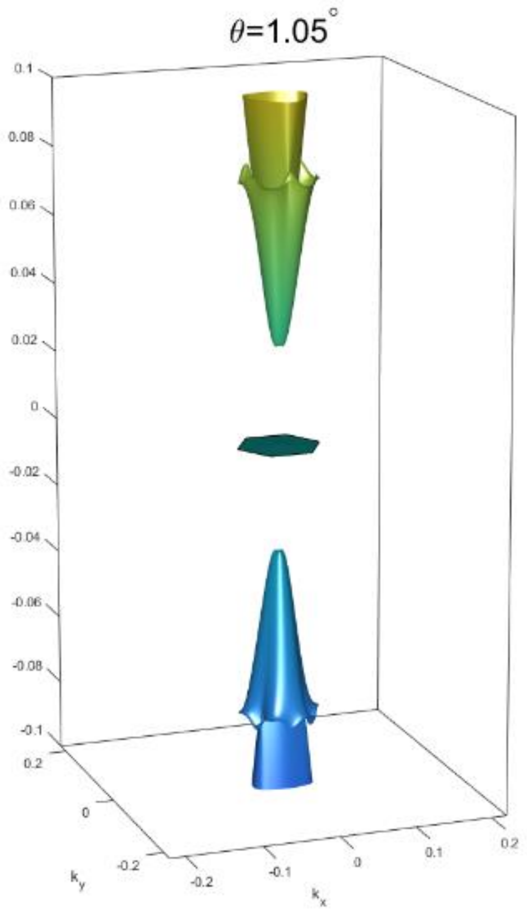
w: Inter-layer interaction



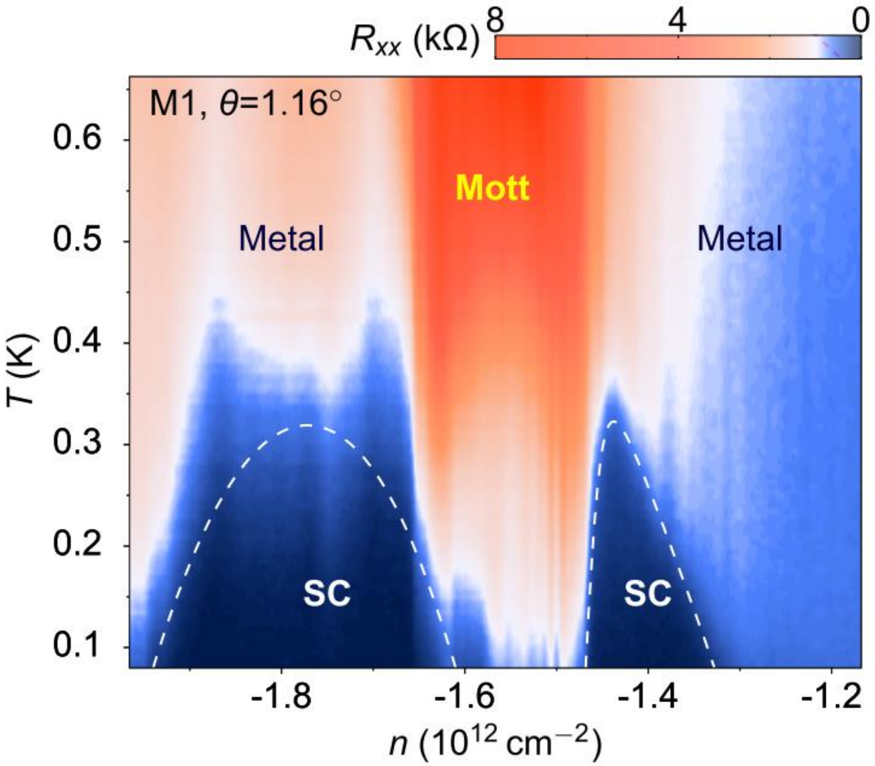
$2w \ll v_{F0} k_\theta$ $\qquad$ $2w \approx v_{F0} k_\theta$

Decreasing Twist Angle

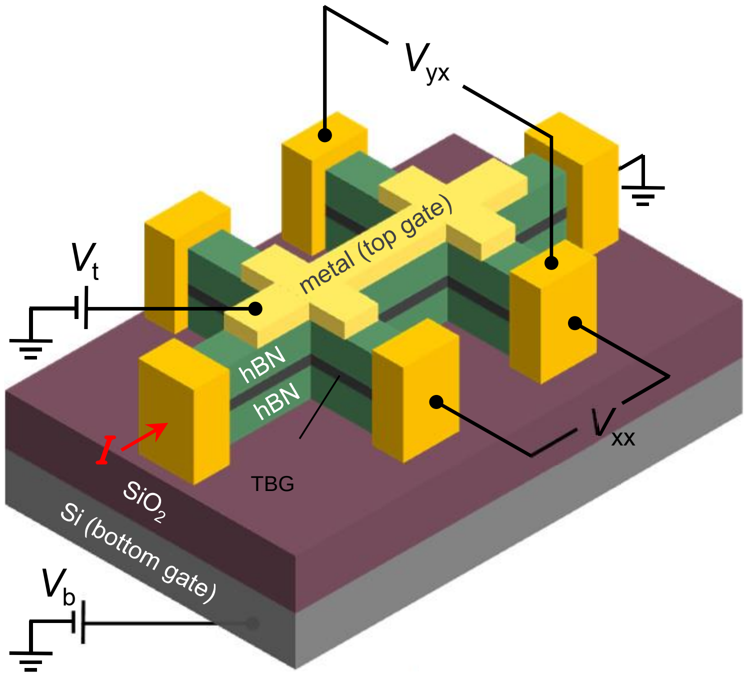
Yoo, *arXiv:*1804.03806
Cao, *Nature* (2018)

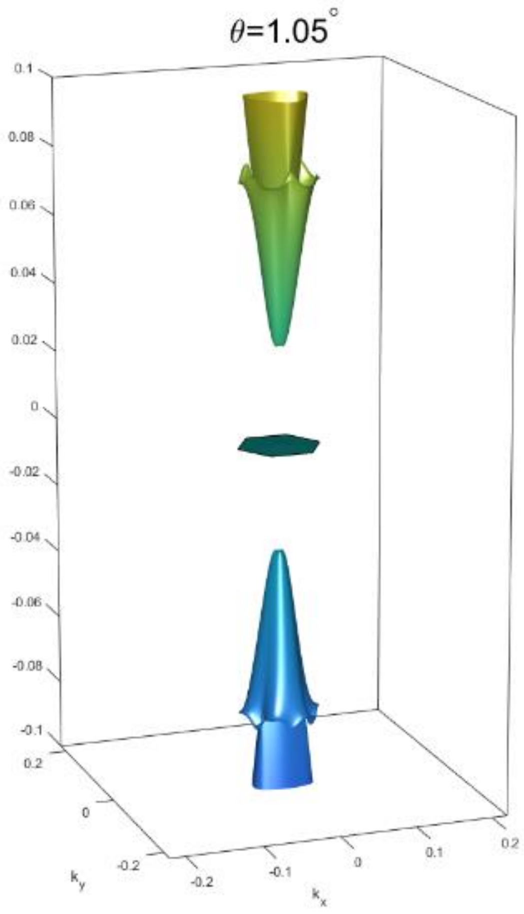


Jarillo-Herrero and
Kaxiras groups

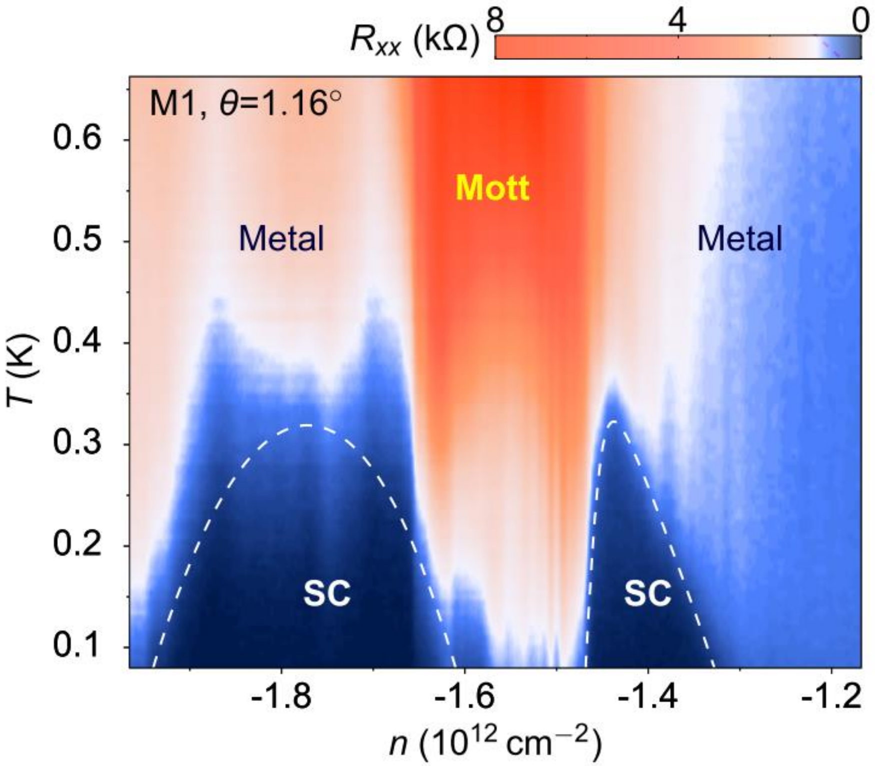


Cao, *Nature* (2018)

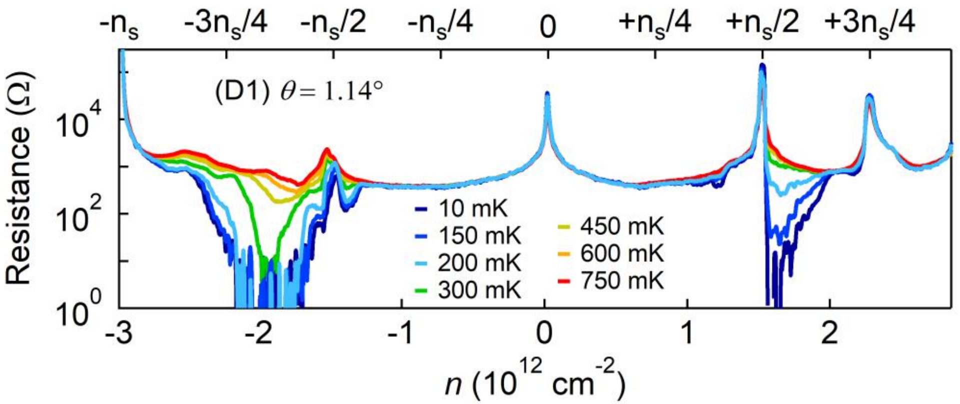




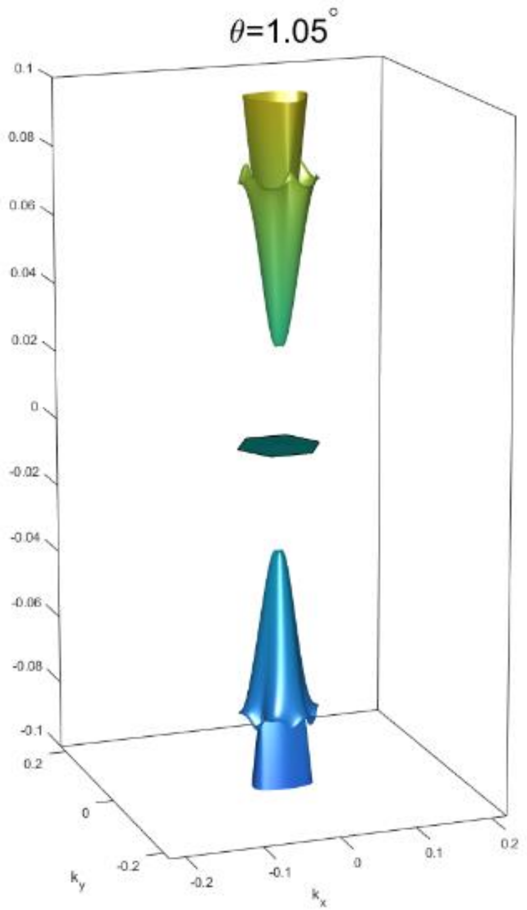
Jarillo-Herrero and
Kaxiras groups



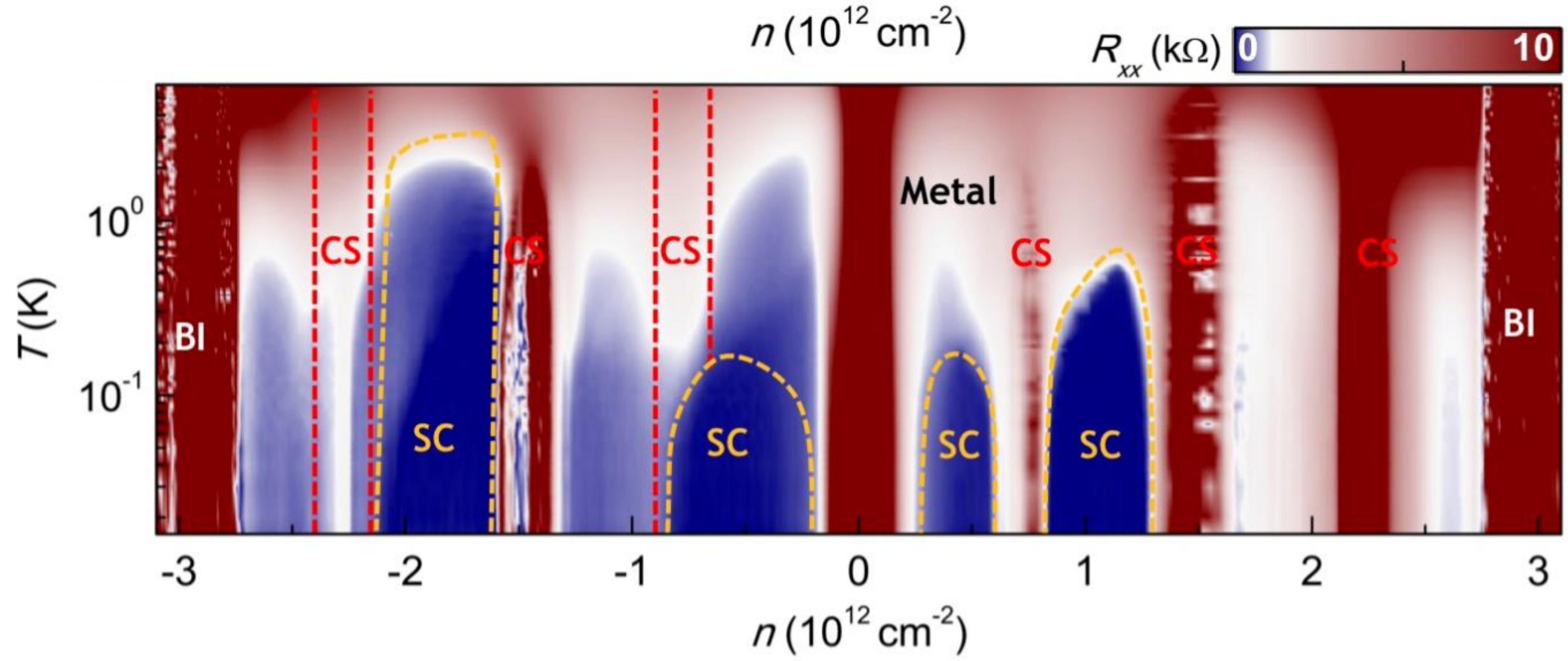
Cao, *Nature* (2018)



Yankowitz, *Science* (2019)



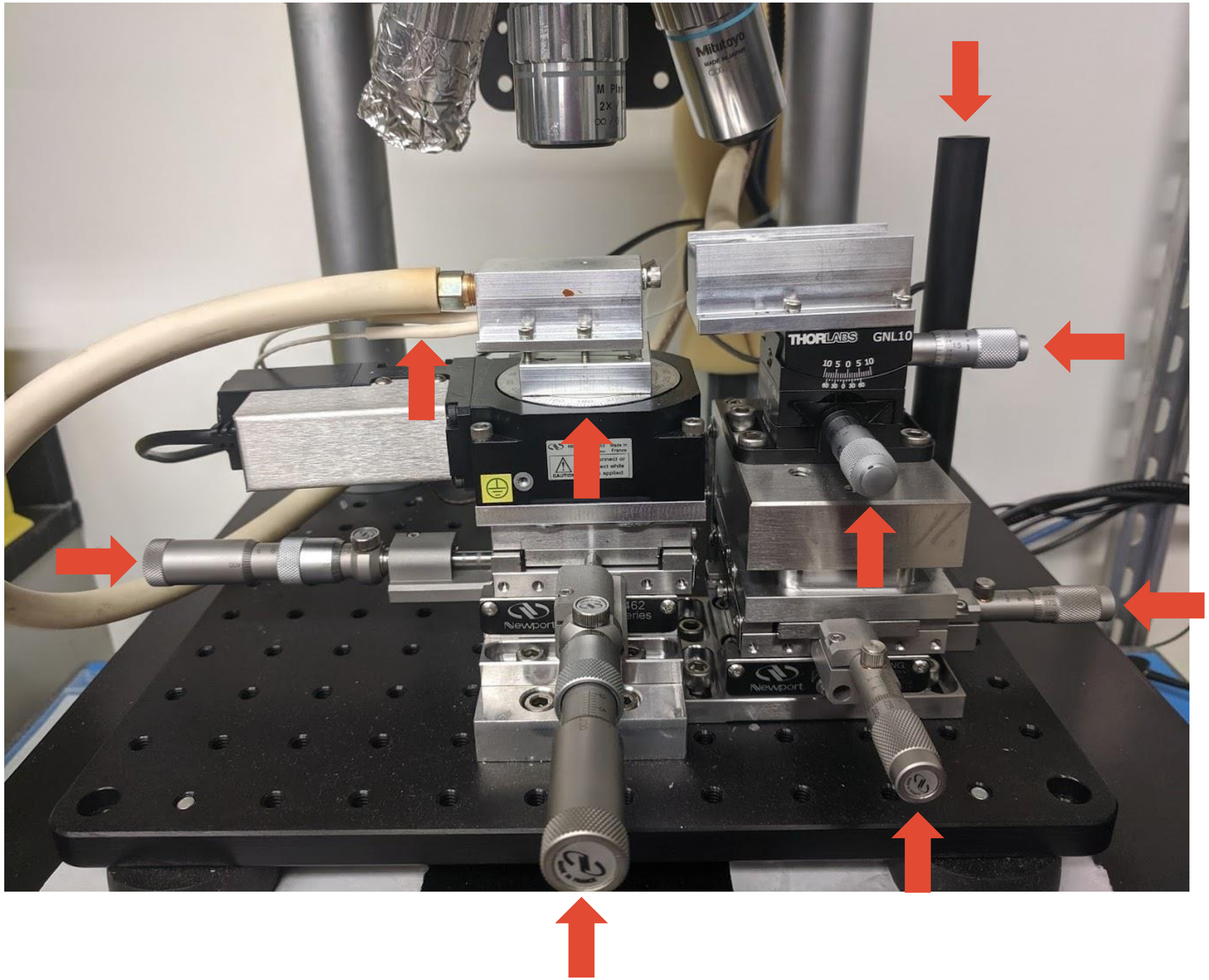
Jarillo-Herrero and
Kaxiras groups



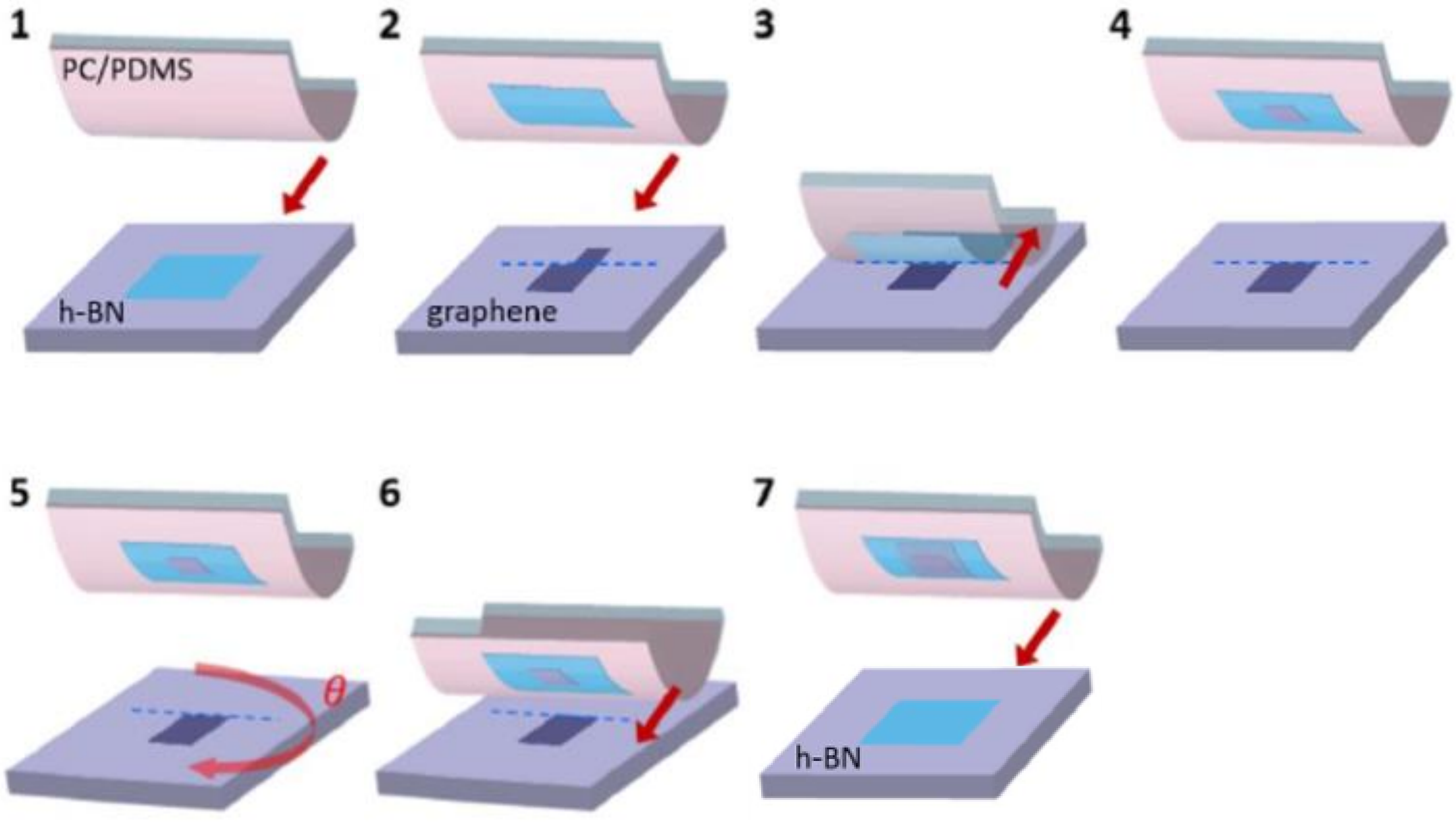
Twisted bilayer graphene provides unprecedented control of correlations in 2D electron systems

Lu et al. arXiv:1903.06513

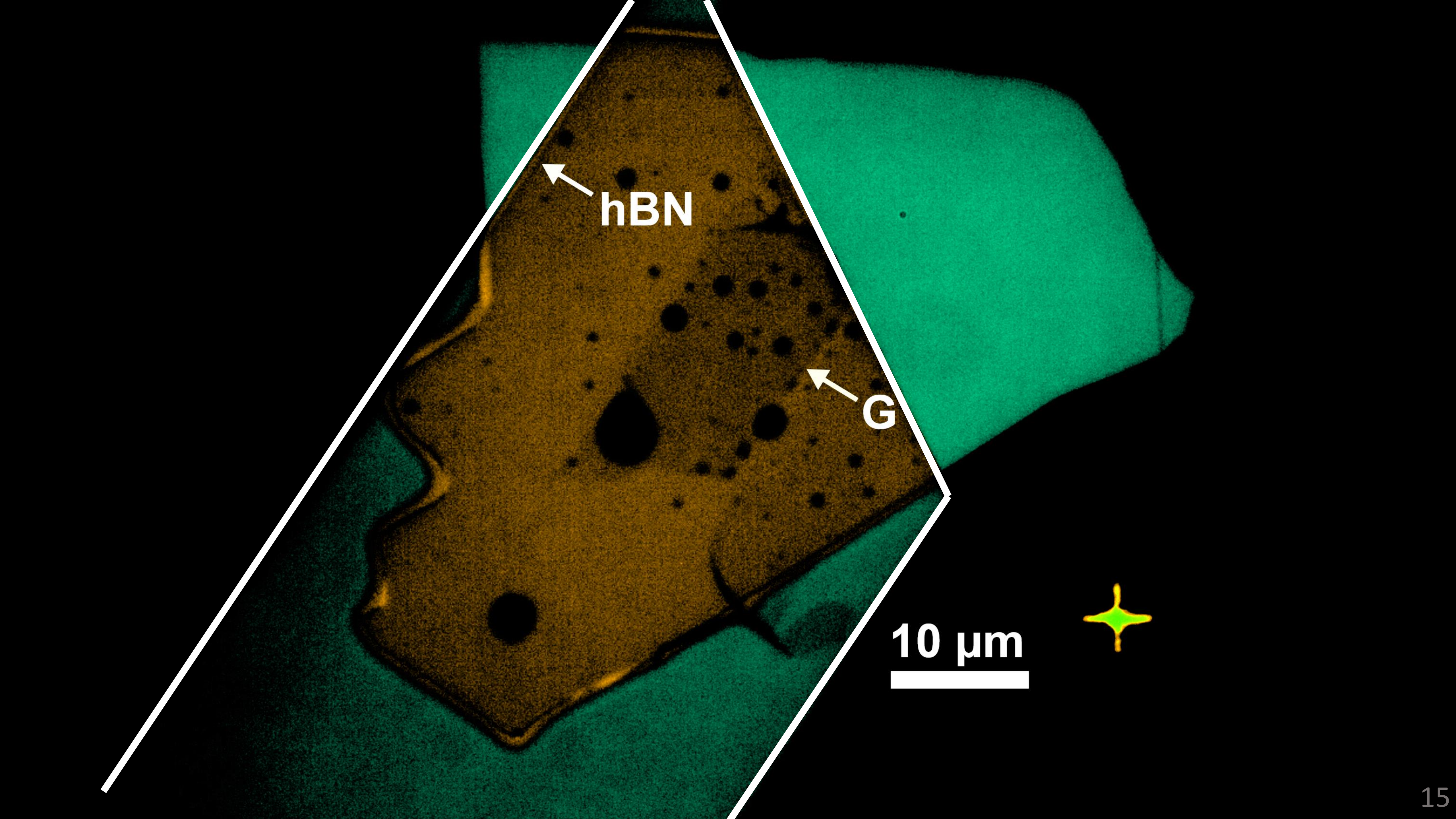
Transferring 2D Materials

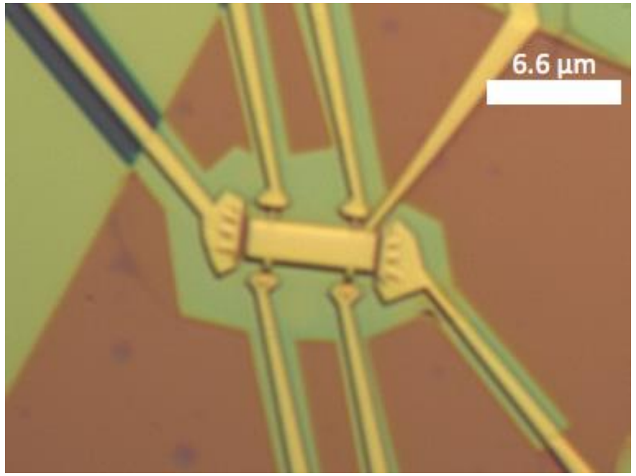


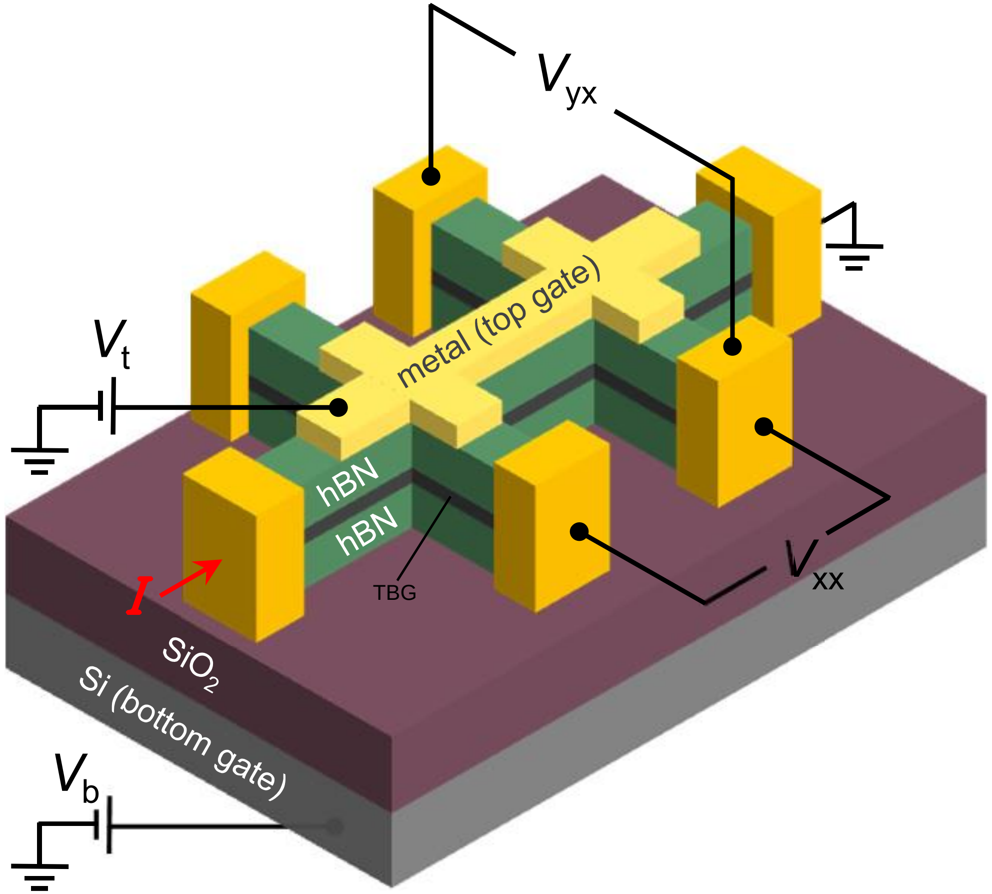
Transferring 2D Materials

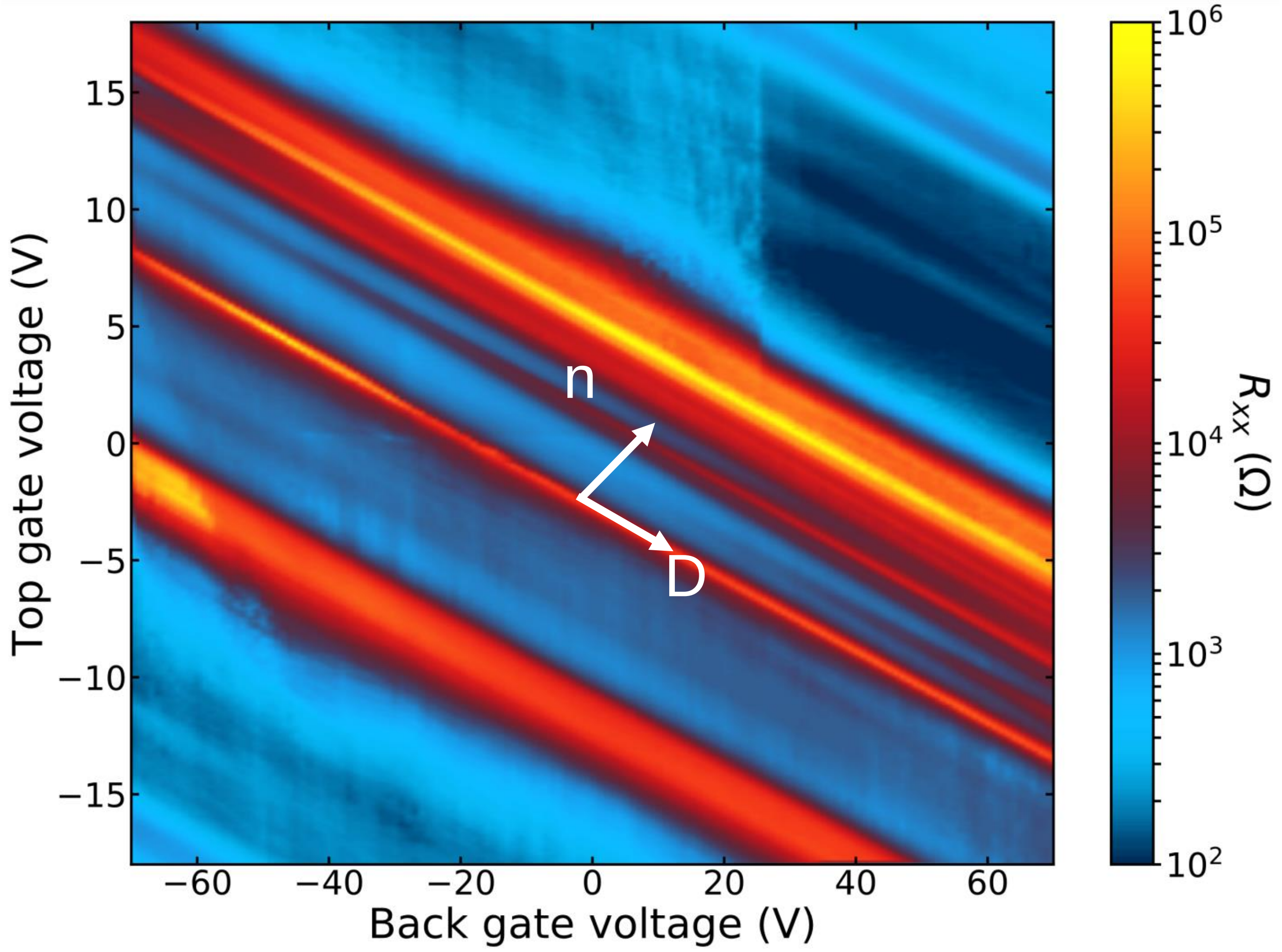


Yoo et al., *Nat. Mat.* (2019)

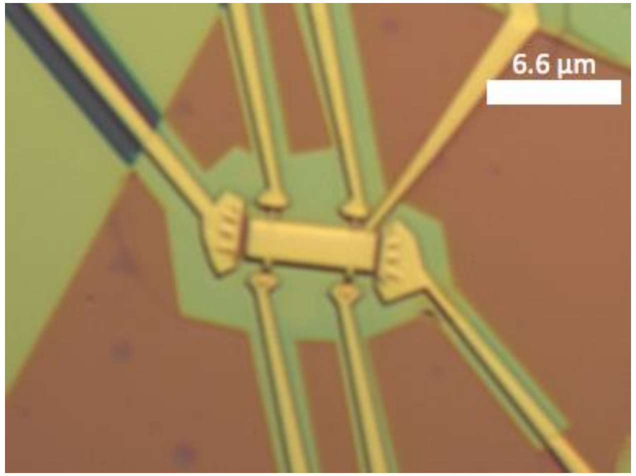

hBN
G
10 µm

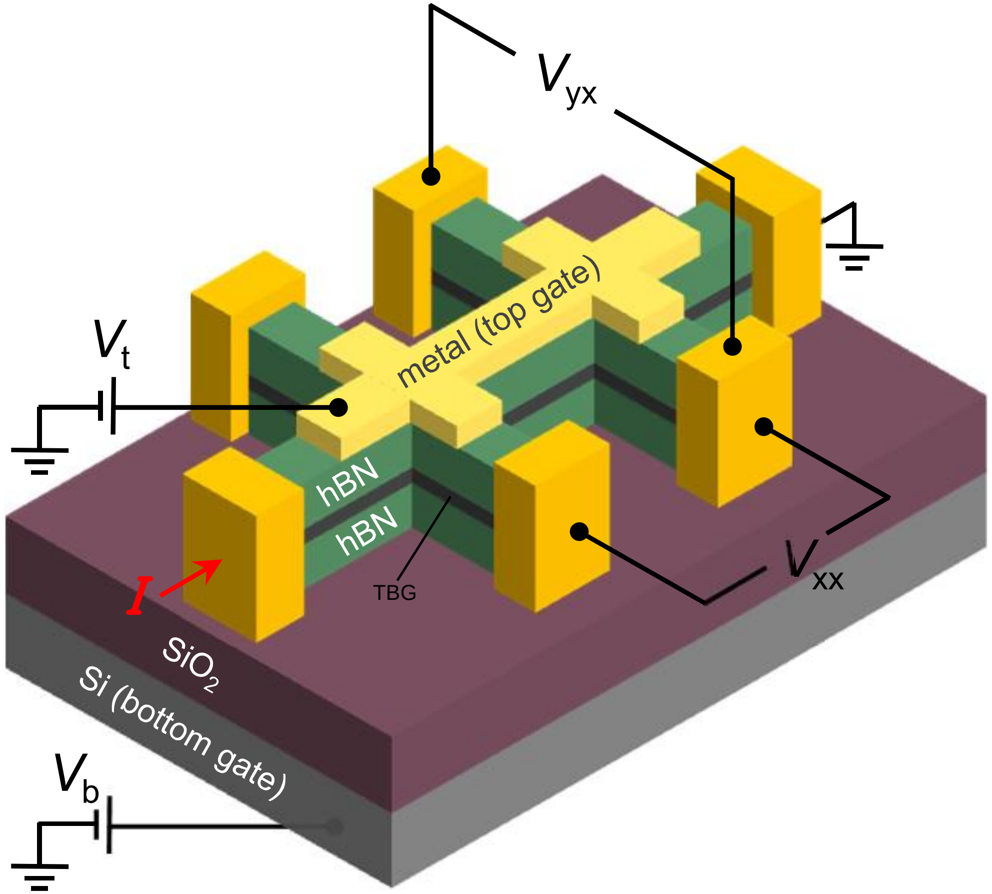


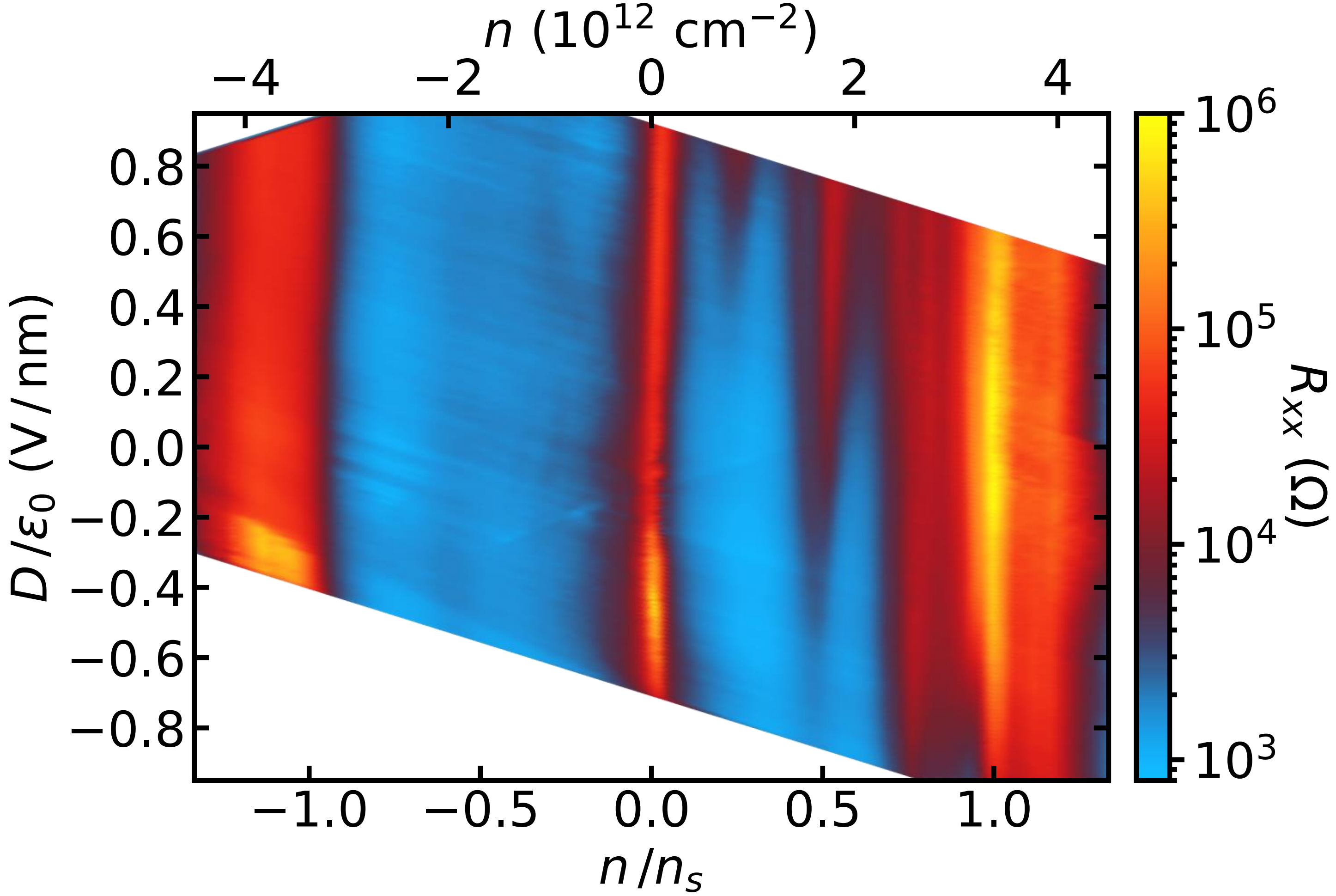




Angle 1.20+/-0.01°. Target 1.17°
T = 40 mK





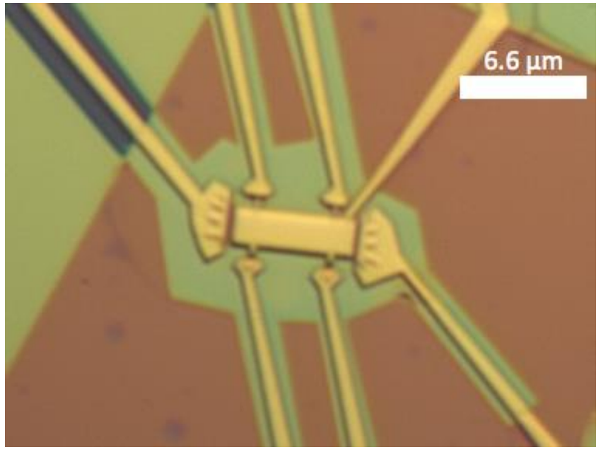


Angle 1.20+/-0.01°. Target 1.17°

T = 40 mK

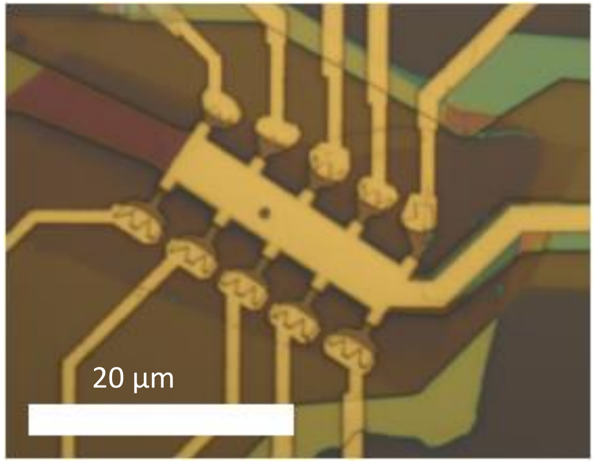
Device 1: ferromagnetic sample w/ aligned hBN

Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°



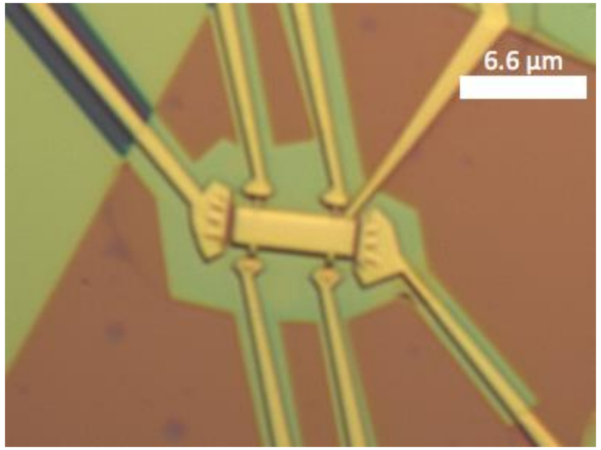
Device 2: superconducting sample w/ misaligned hBN

Graphene twist: 1.05 +/- 0.01°
Twist to hBN: large



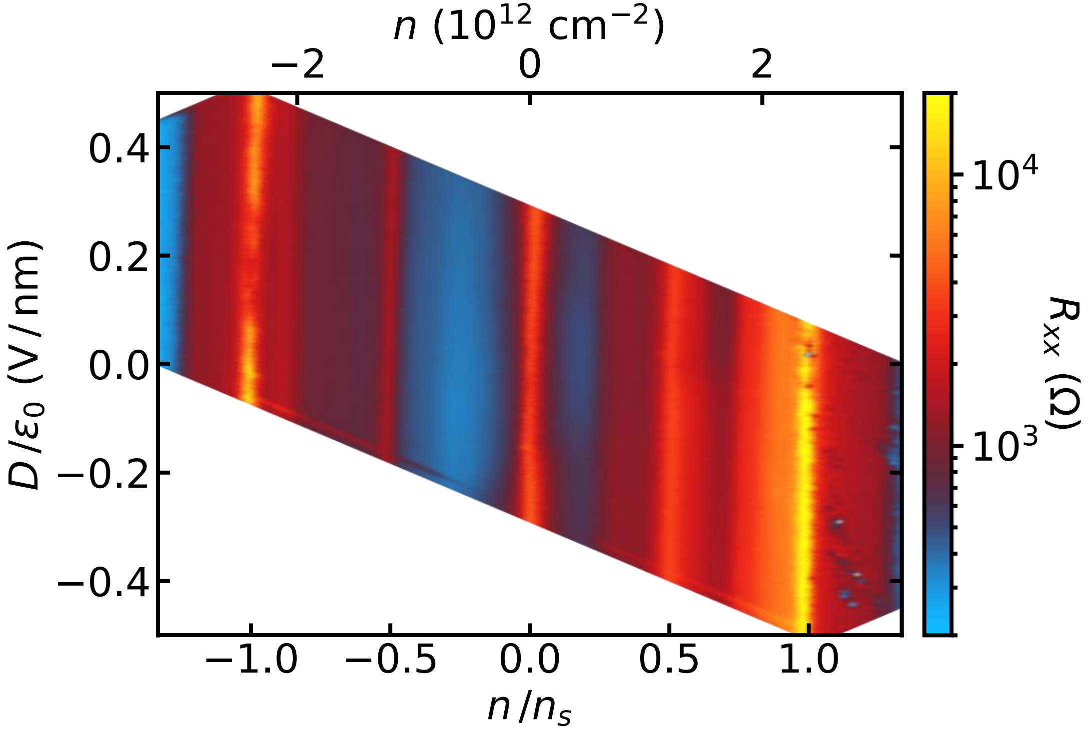
Device 1: ferromagnetic sample
w/ aligned hBN

Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°



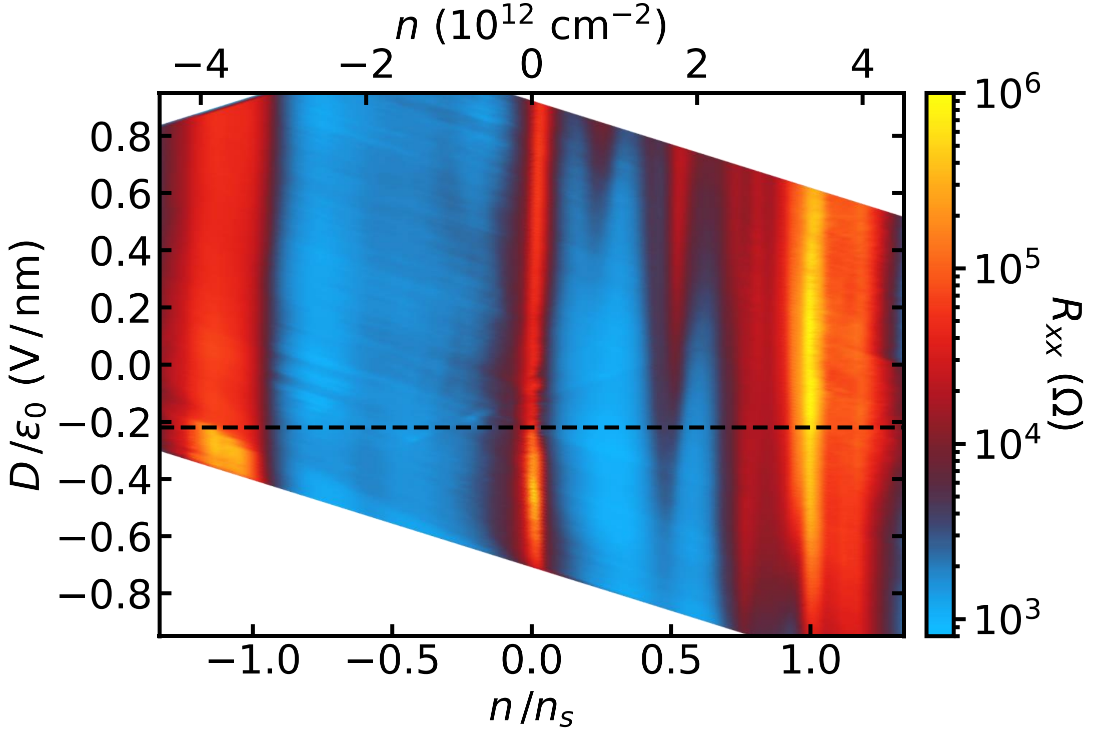
Device 2: superconducting sample
w/ misaligned hBN

Graphene twist: 1.05 +/- 0.01°
Twist to hBN: large



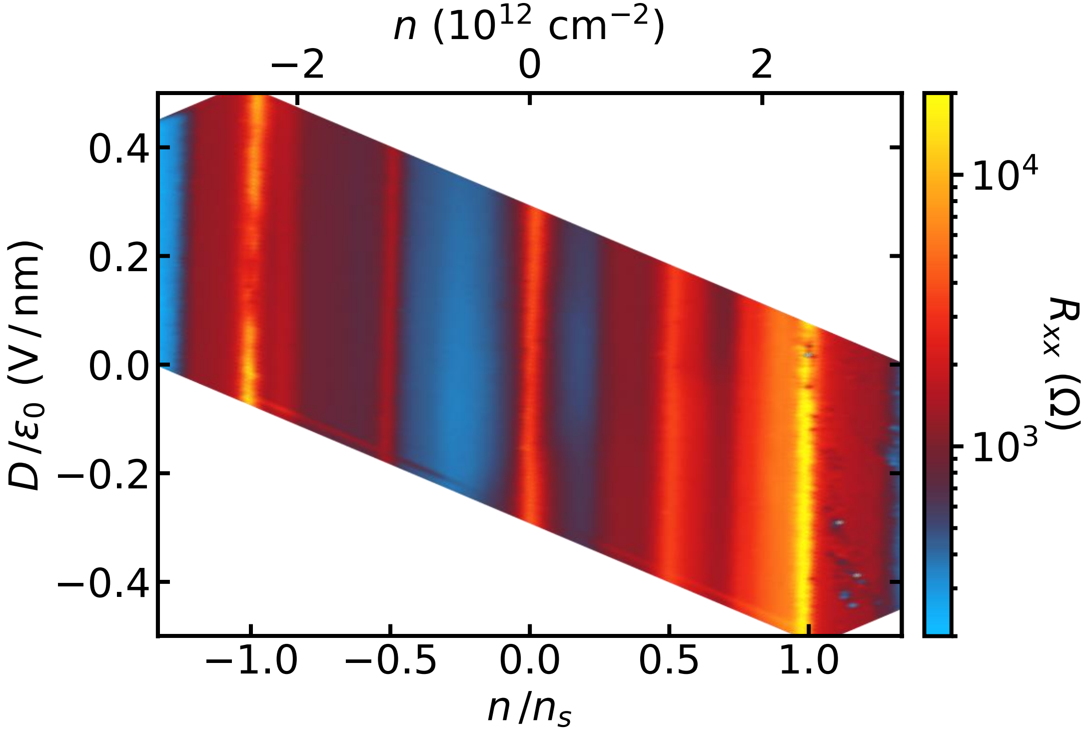
Device 1: ferromagnetic sample
w/ aligned hBN

Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°



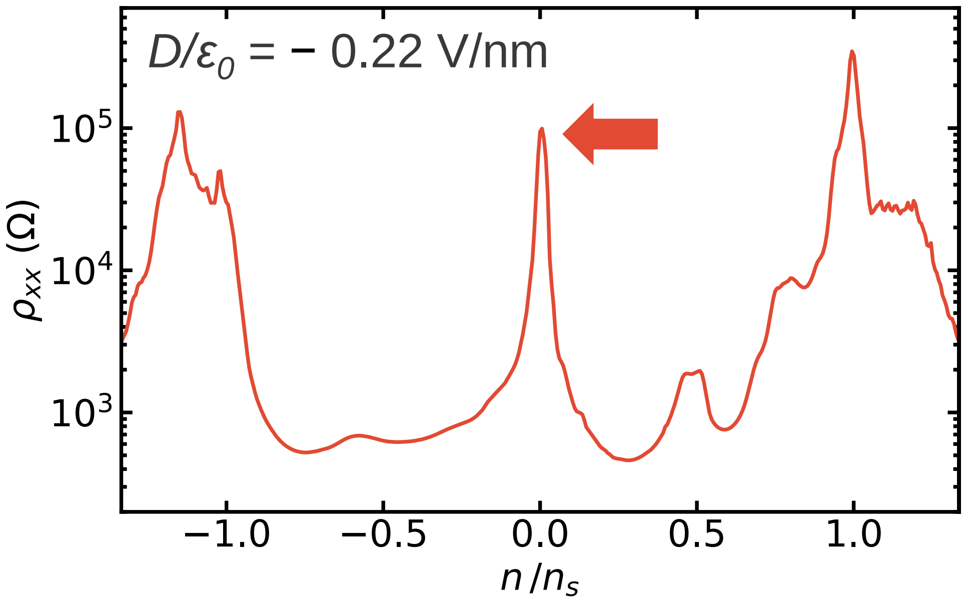
Device 2: superconducting sample
w/ misaligned hBN

Graphene twist: 1.05 +/- 0.01°
Twist to hBN: large



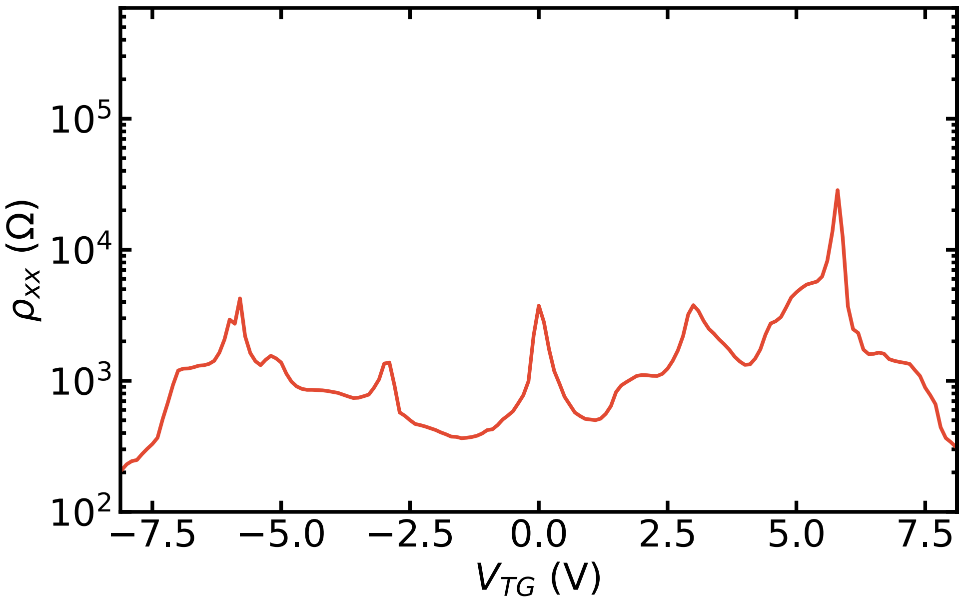
Device 1: ferromagnetic sample
w/ aligned hBN

Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°



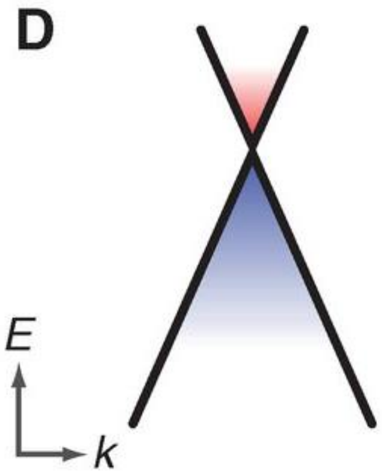
Device 2: superconducting sample
w/ misaligned hBN

Graphene twist: 1.05 +/- 0.01°
Twist to hBN: large

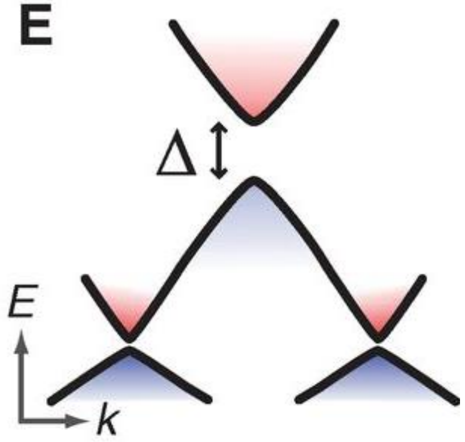


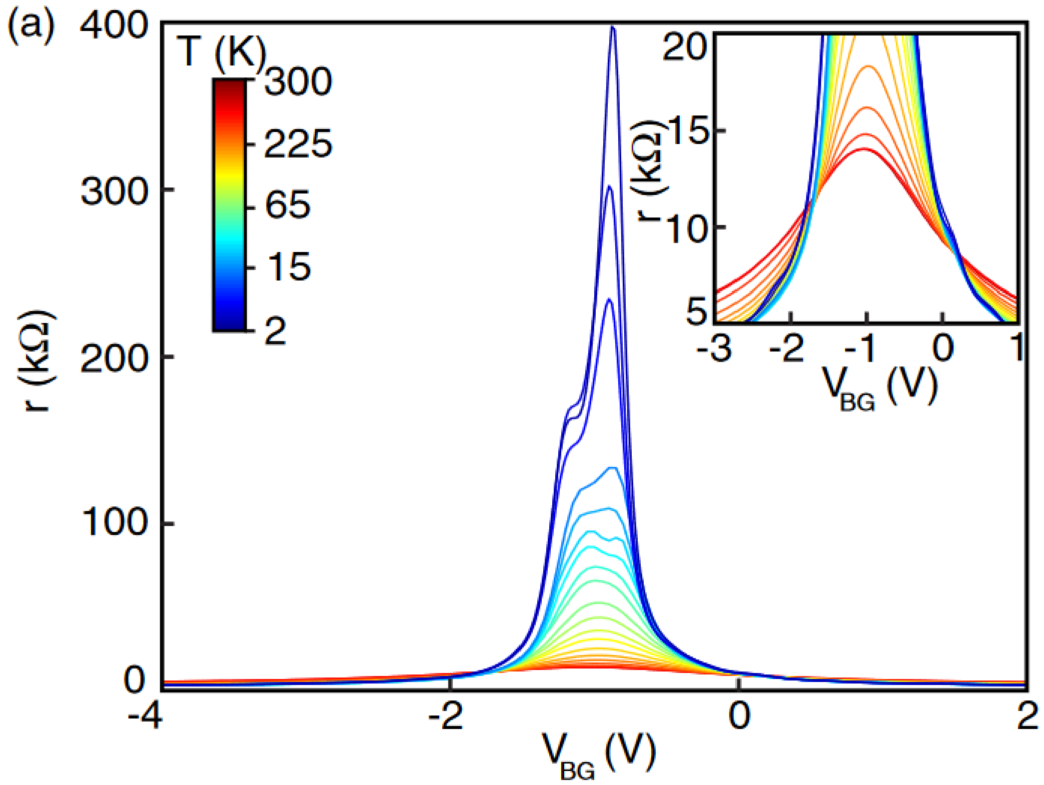
Alignment with hBN

Monolayer graphene



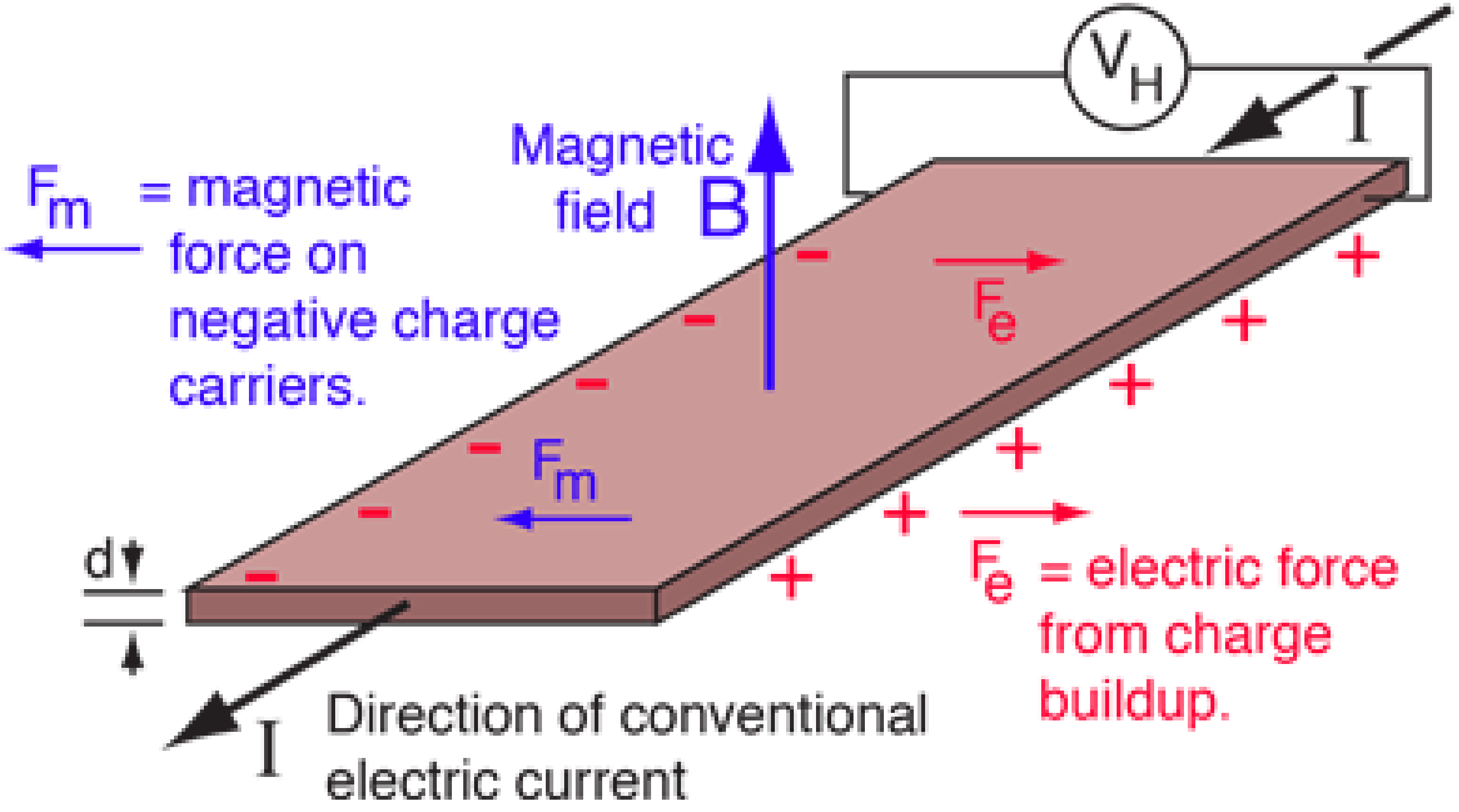
Monolayer graphene + hBN





Amet et al., *PRL* (2013)
Hunt et al., *Science* (2013)

Classical Hall Effect: Calibrate Capacitance



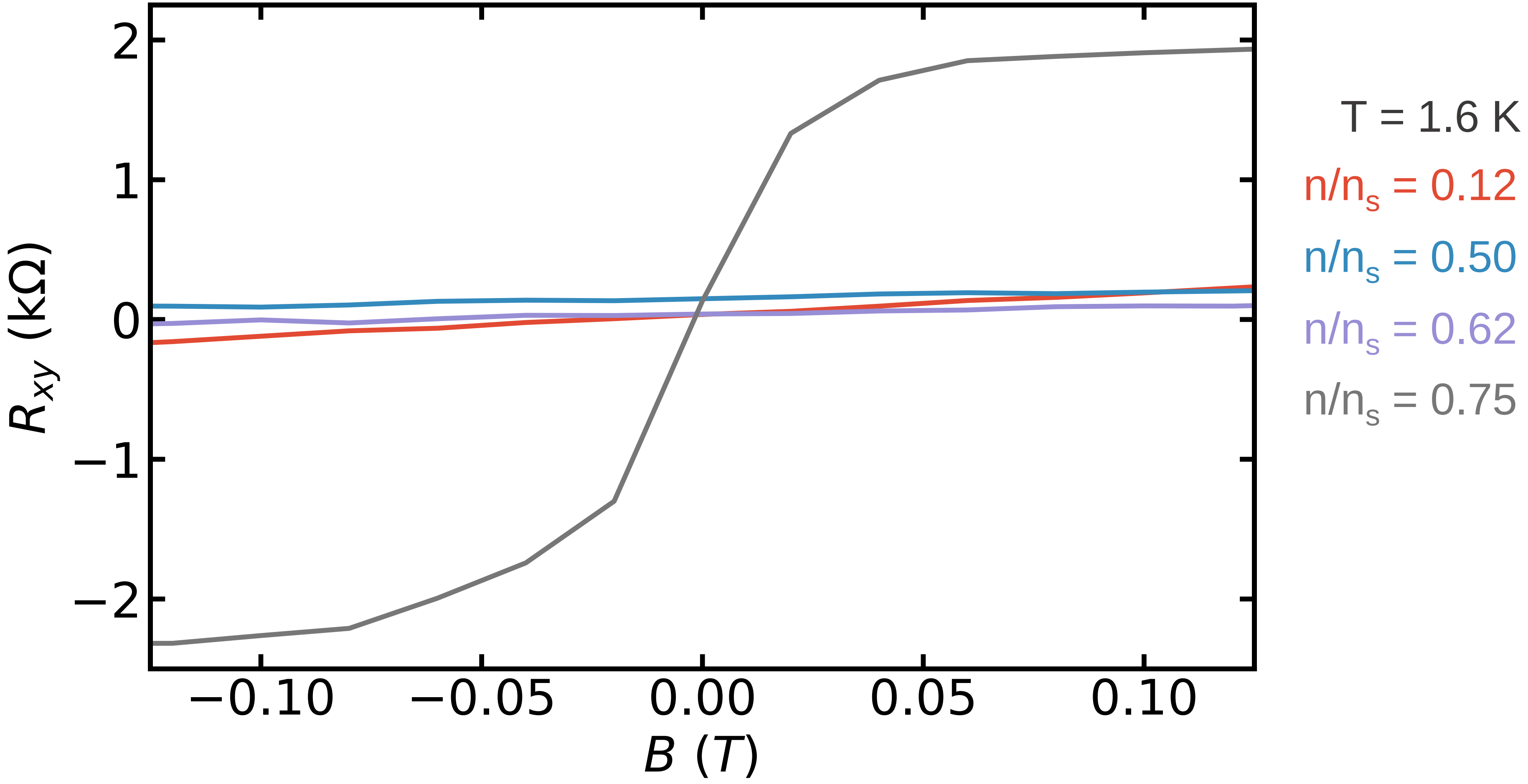
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\boxed{R_{\mathrm{xy}} = \frac{V_{\mathrm{H}}}{I} = -\frac{B}{ne}}$$

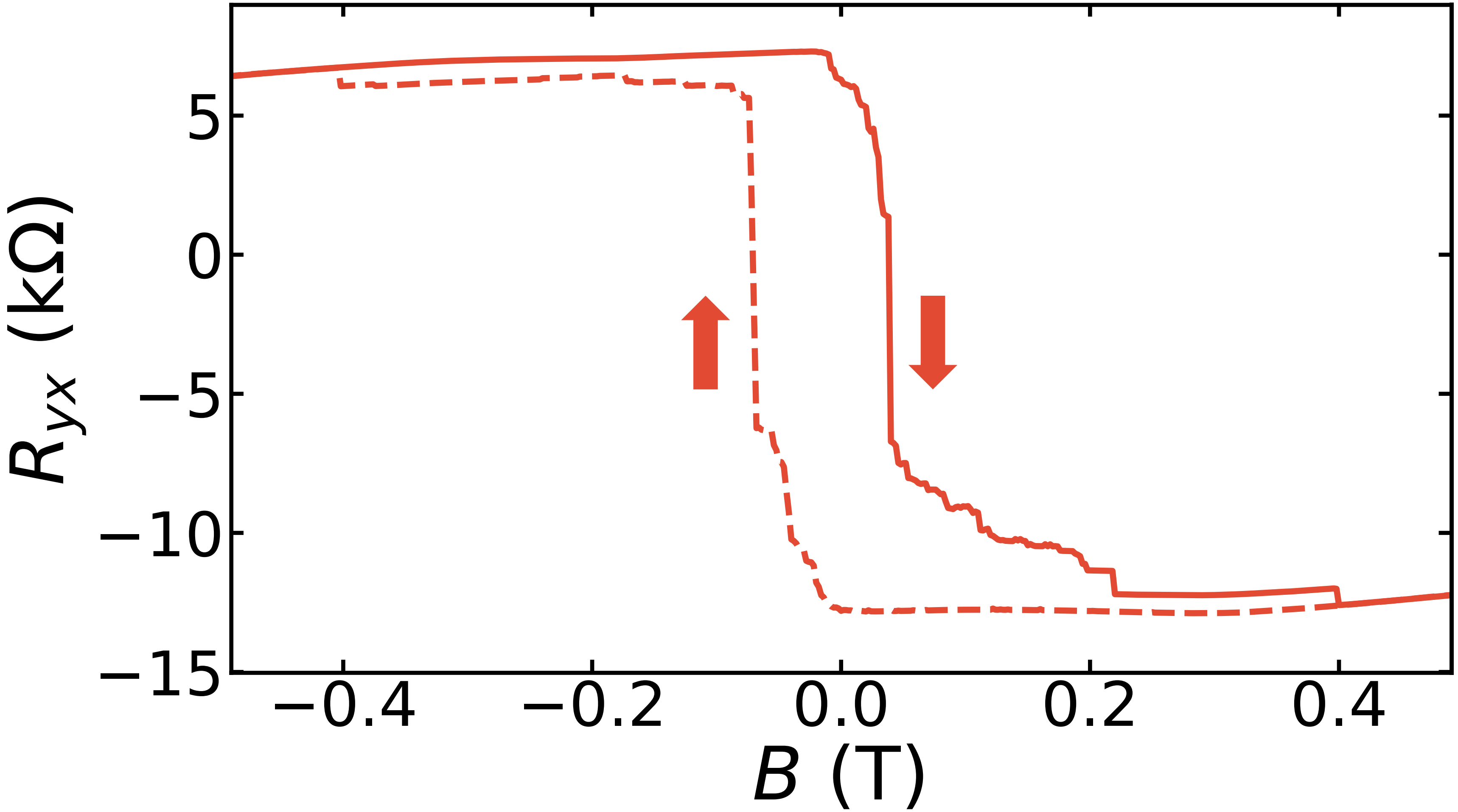
$$n = \frac{C}{eA} V_{\mathrm{gate}}$$

http://hyperphysics.phy-astr.gsu.edu/

Measuring Hall Slope Density Dependence

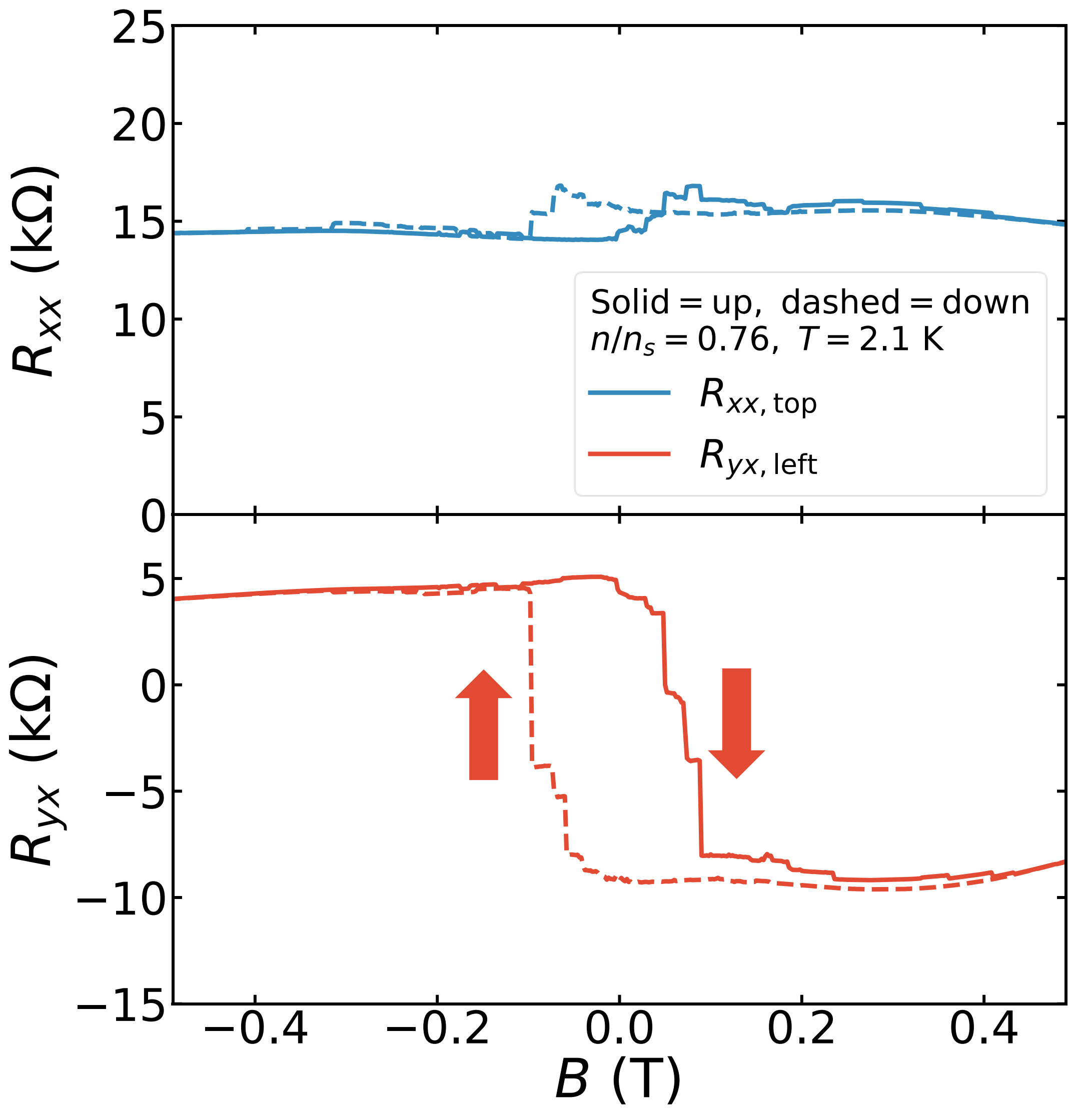


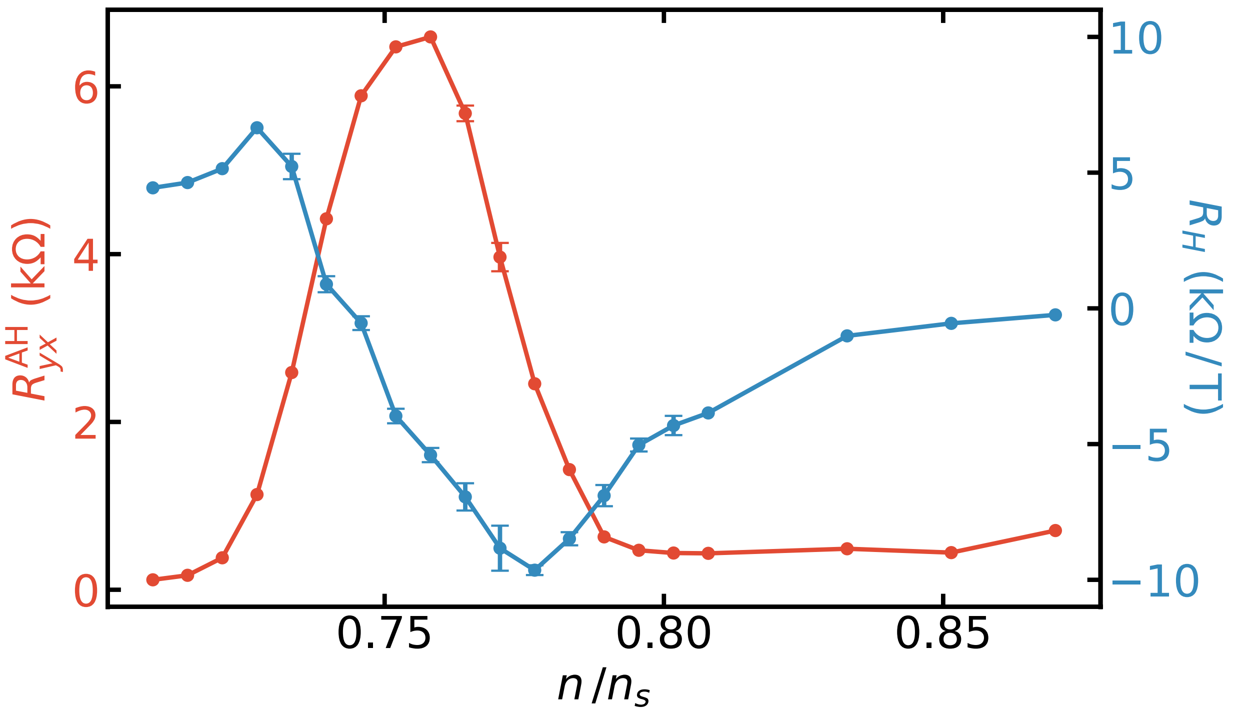
Anomalous Hall Signal Can Be Really Large!



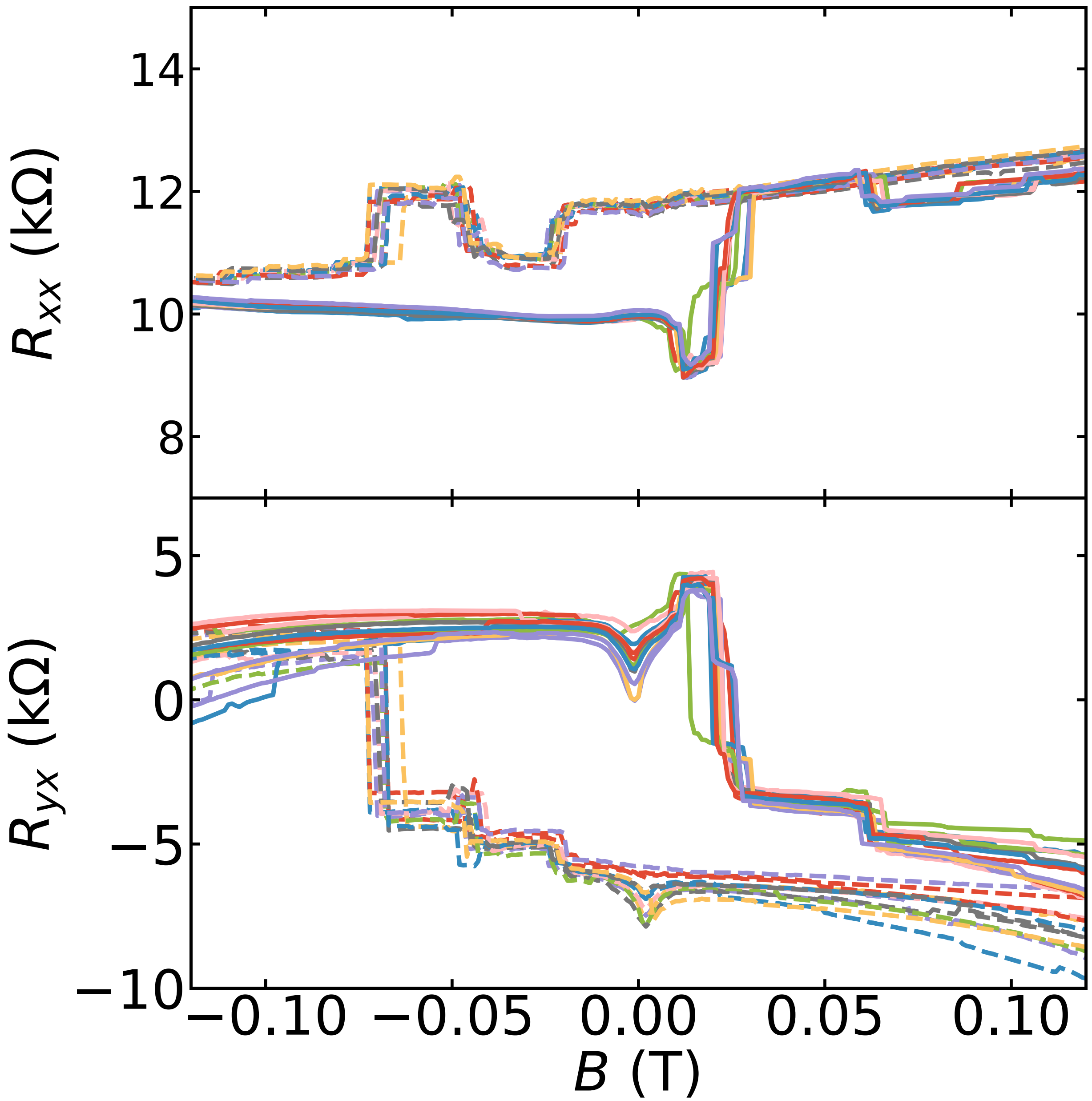
n/n_s=0.775, T = 2.1K

Emergent Ferromagnetism at ¾ Filling

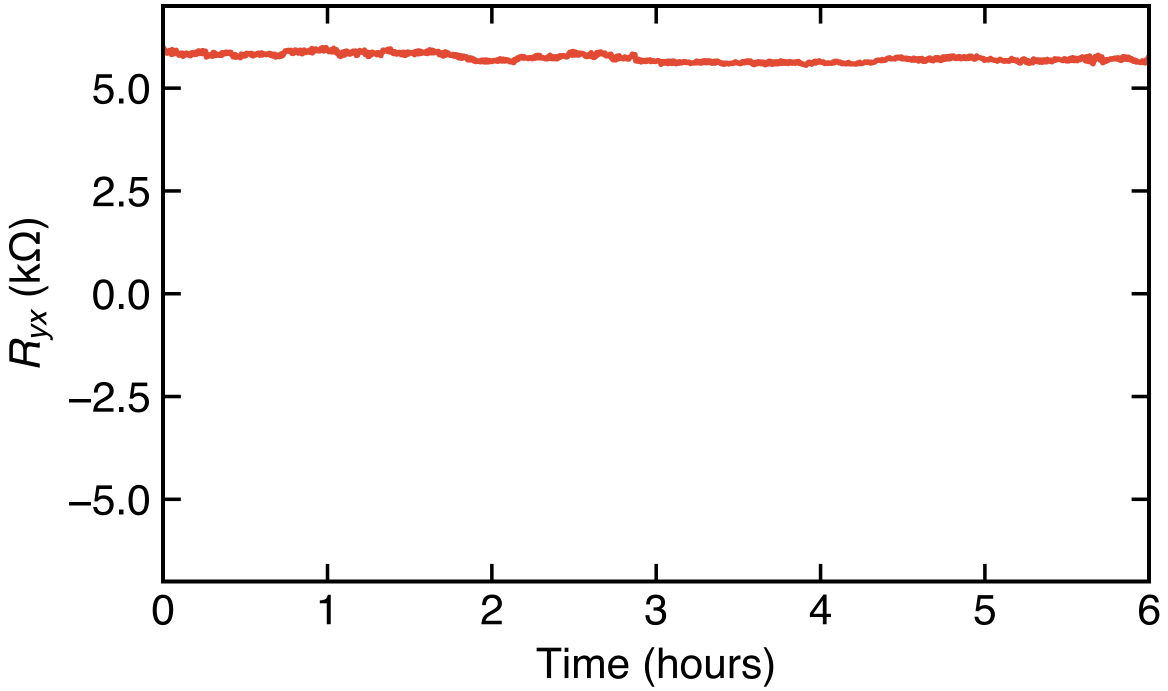


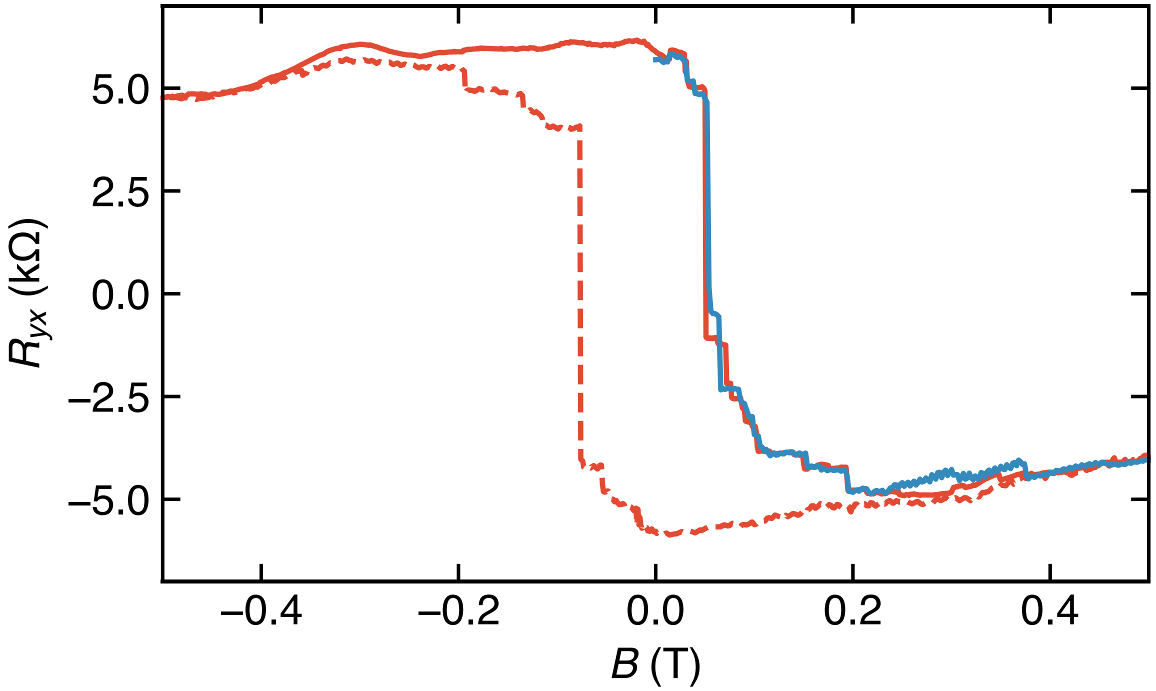


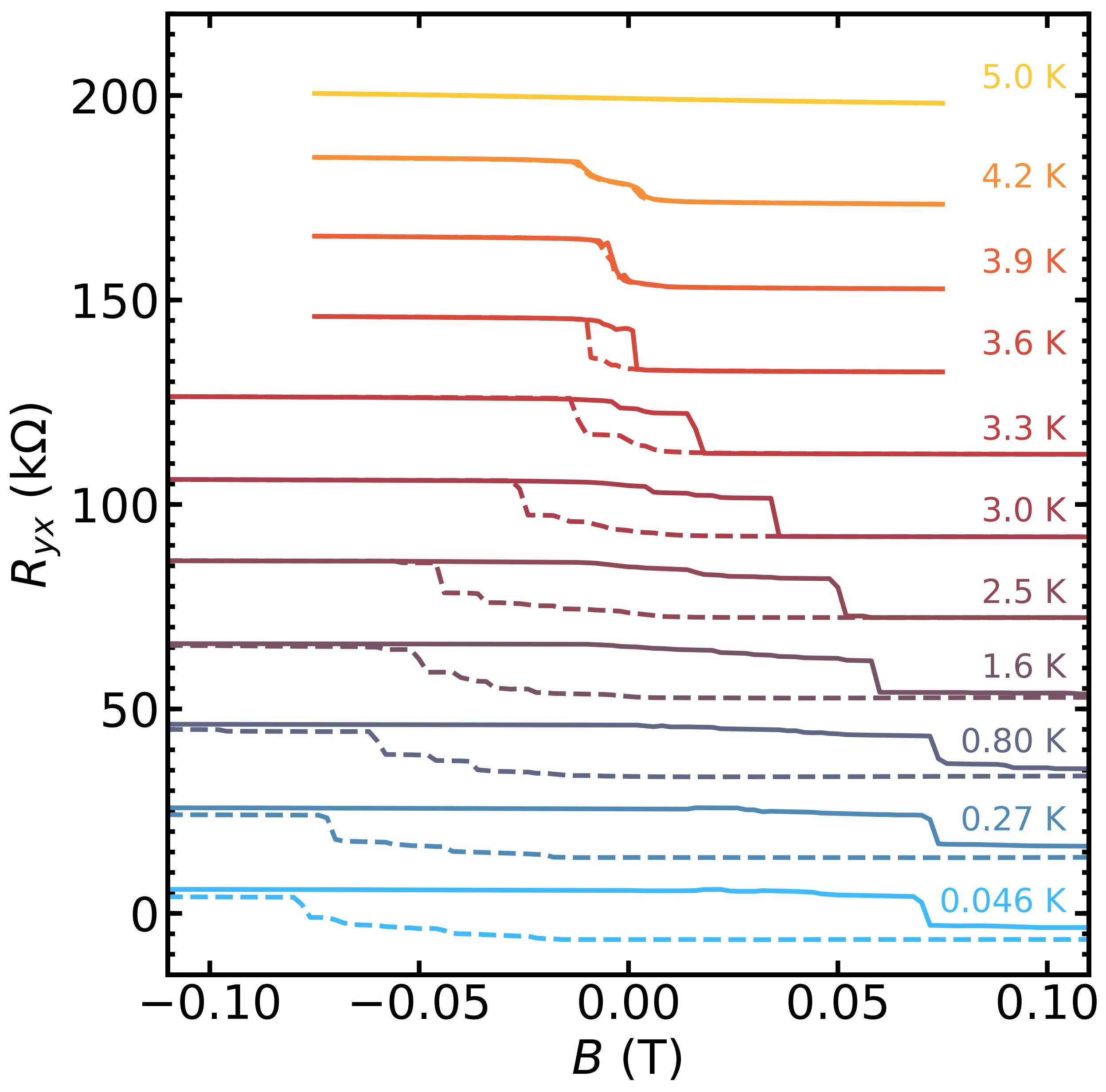
Repeatable Fine Structure

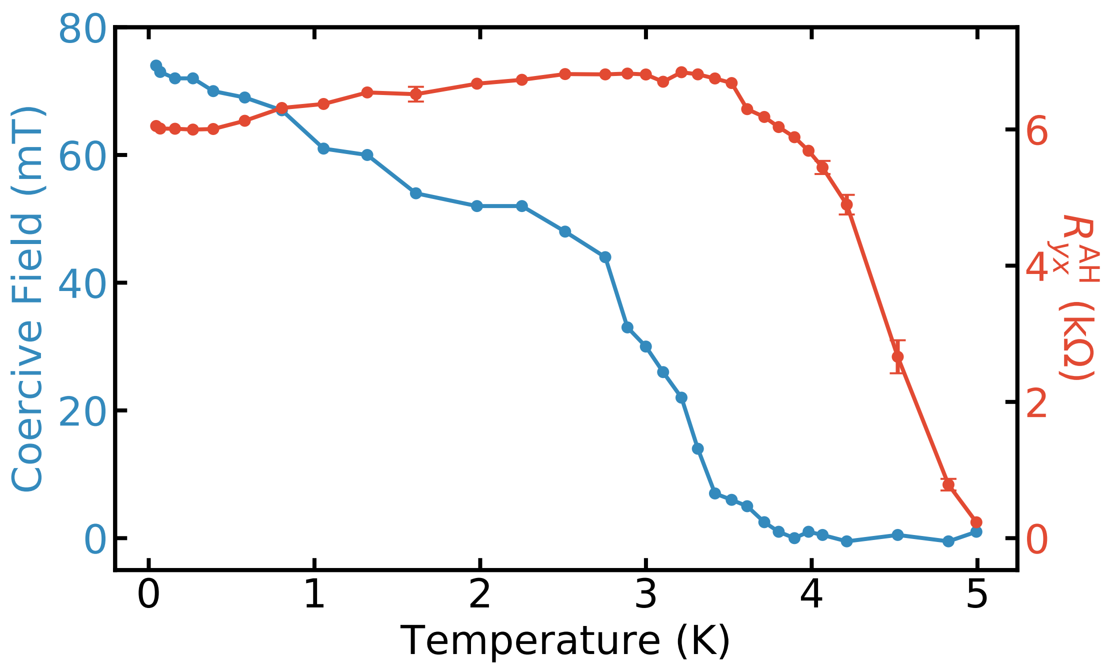


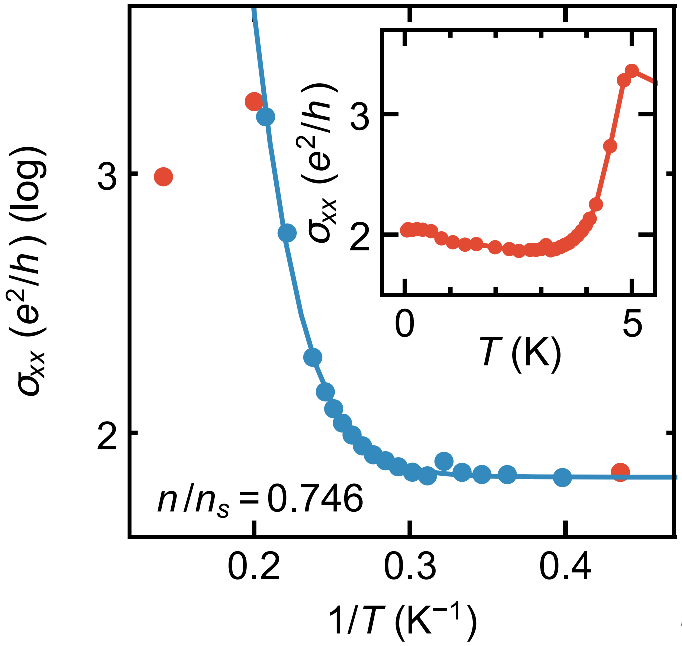
Magnetism is Stable in Zero Applied Field






5.0 K
4.2 K
3.9 K
3.6 K
3.3 K
3.0 K
2.5 K
1.6 K
0.80 K
0.27 K
0.046 K
R_{yx} (kΩ)
B (T)


Coercive Field (mT)
R_{yx}^{AH} (kΩ)
Temperature (K)


σ_{xx} (e^2/h) (log)
$1/T$ (K^{-1})
$n/n_s = 0.746$
σ_{xx} (e^2/h)
T (K)

$\Delta = 86$ K

Large anomalous Hall in apparent insulating state

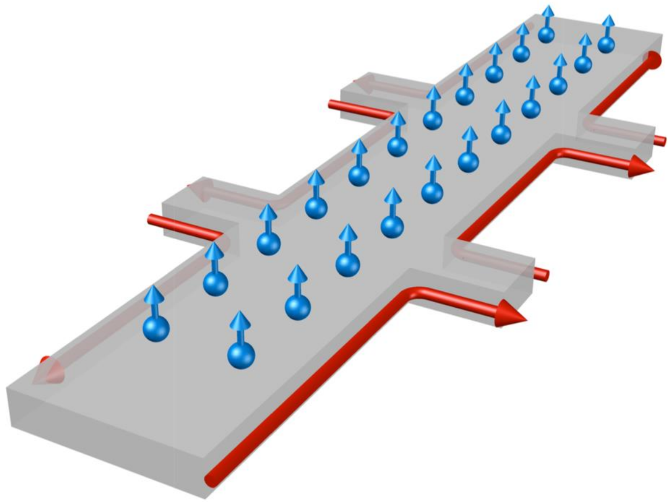
Evidence of domains

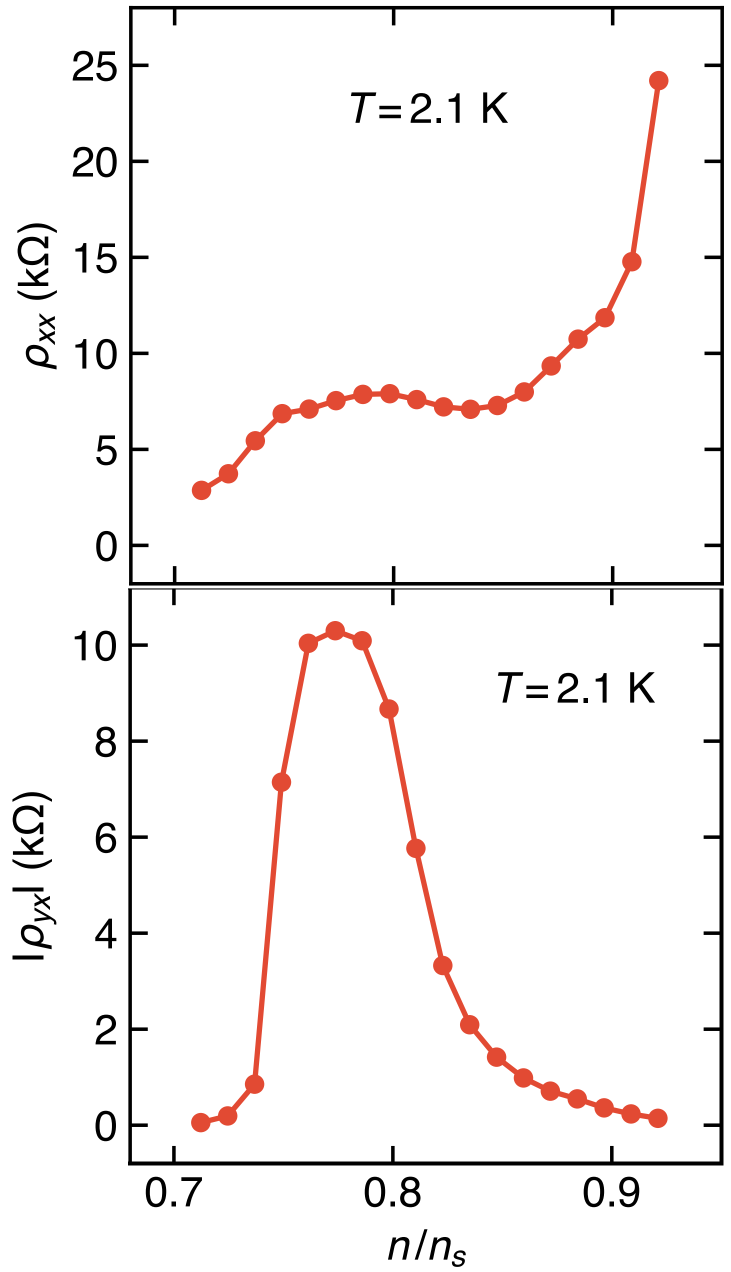
Reminiscent of early Magnetic TIs

Chern insulator?

Ideally:

$$\rho_{xx} = 0$$
$$\rho_{yx} = h/e^2 \approx 26\ \mathrm{k\Omega}$$





Large anomalous Hall in apparent insulating state

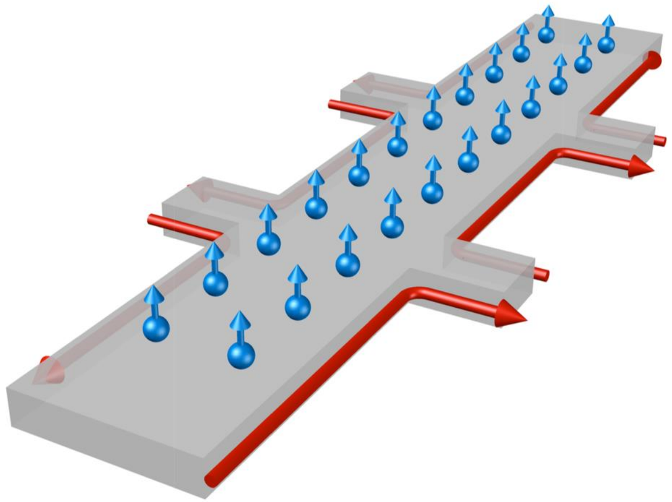
Evidence of domains

Reminiscent of early Magnetic TIs

Chern insulator?

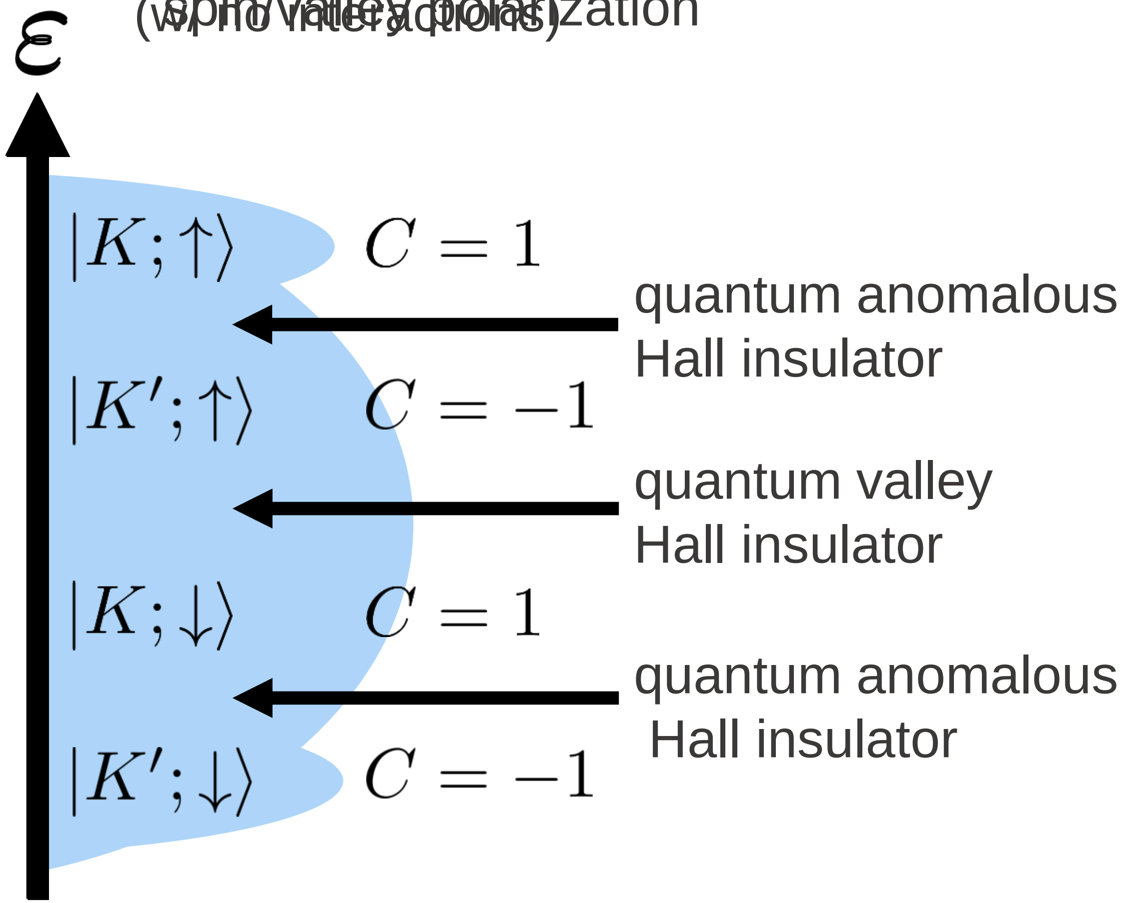
Ideally:

$$\rho_{xx} = 0$$
$$\rho_{yx} = h/e^2 \approx 26\ \mathrm{k}\Omega$$



Interaction driven spin/valley polarization

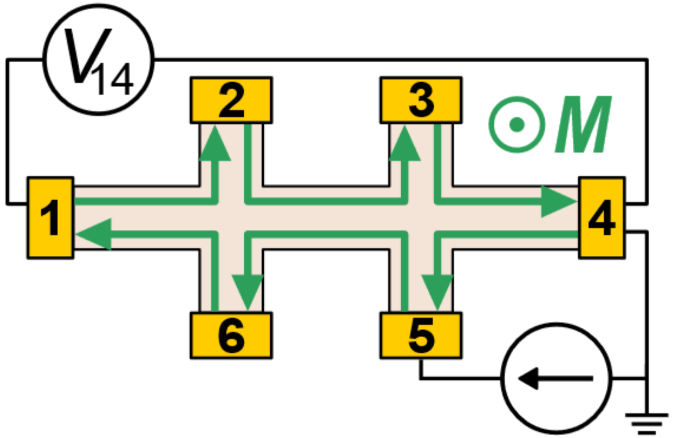
4-fold degeneracy (w/ no interactions)

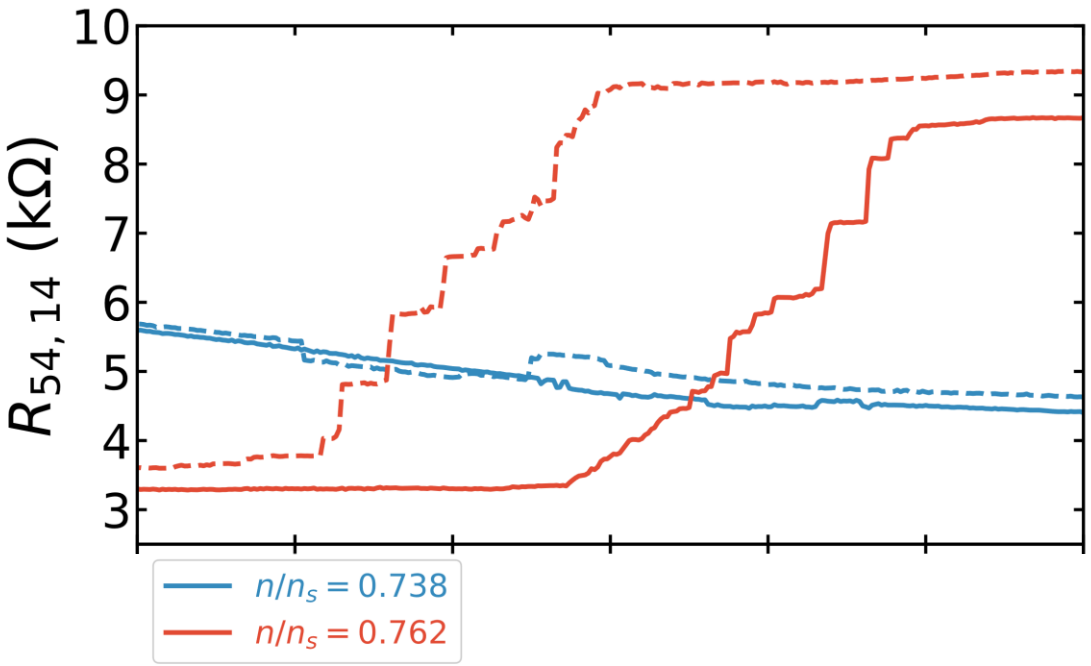


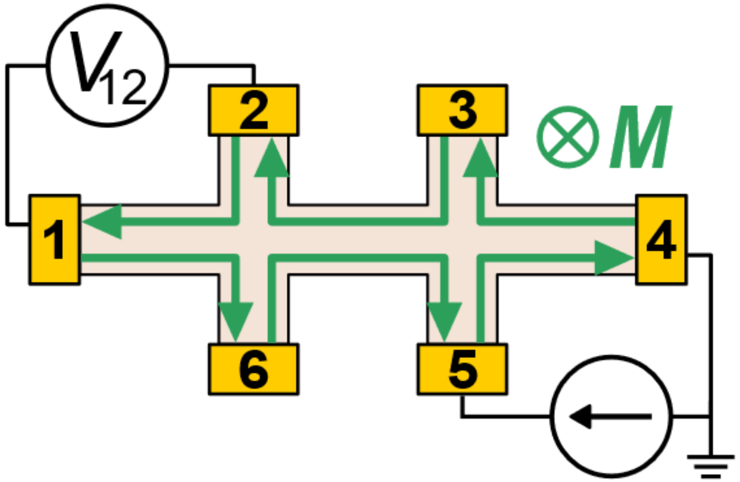
Zhang et al. *arXiv:1901.08209*
Bultinck et al. *arXiv:1901.08110*

Gap may open spontaneously:
Xie et al. *arXiv:1812.04213*

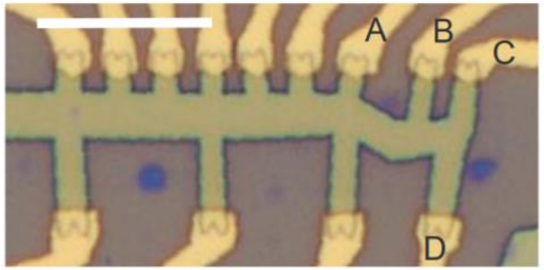
3- and 4- Terminal Nonlocal Transport

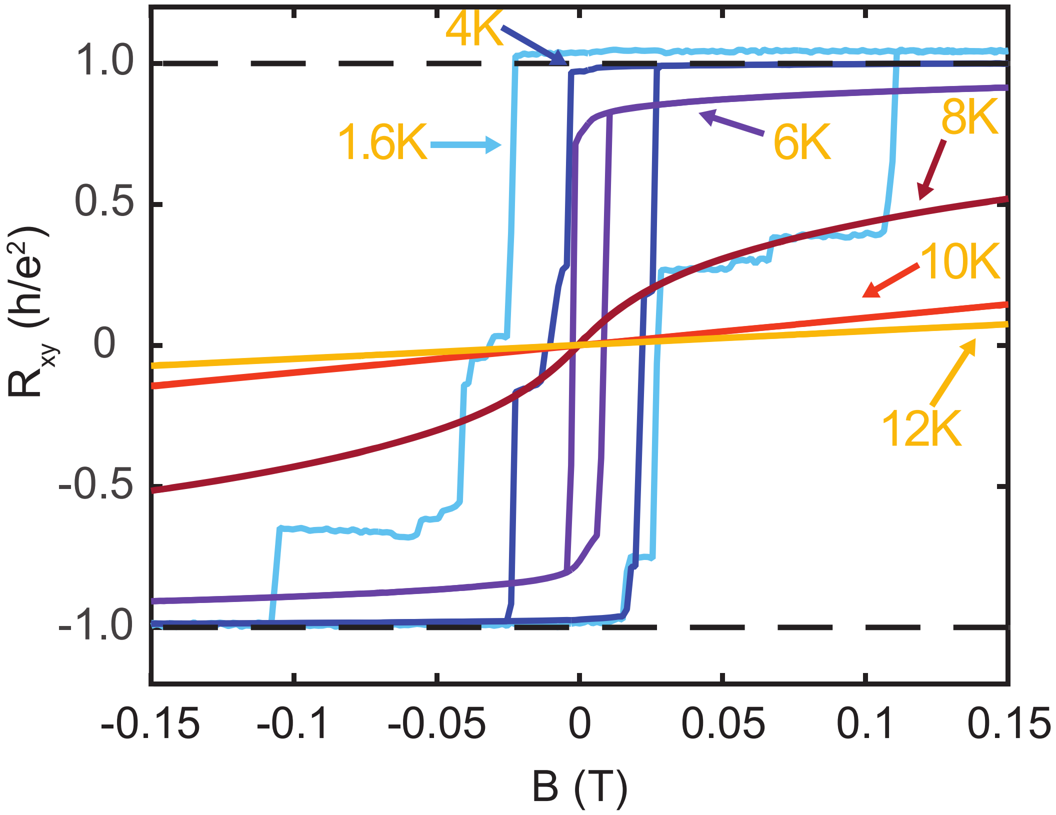


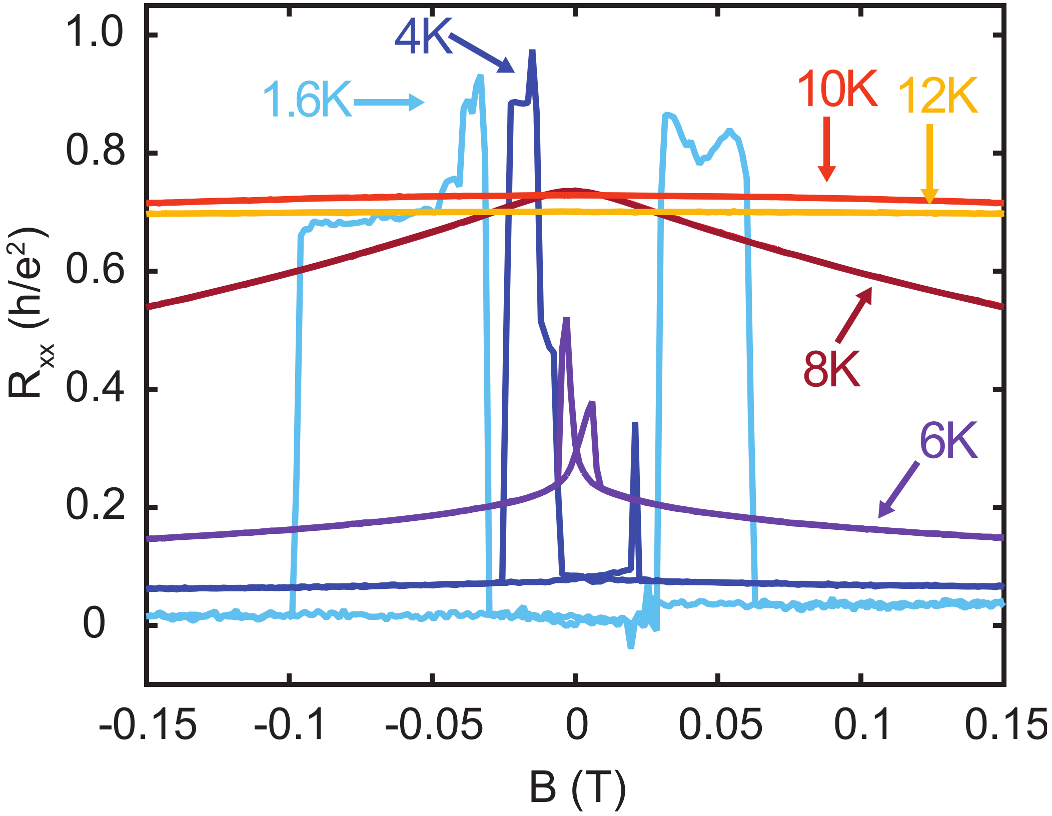




Quantum Anomalous Hall in TBG

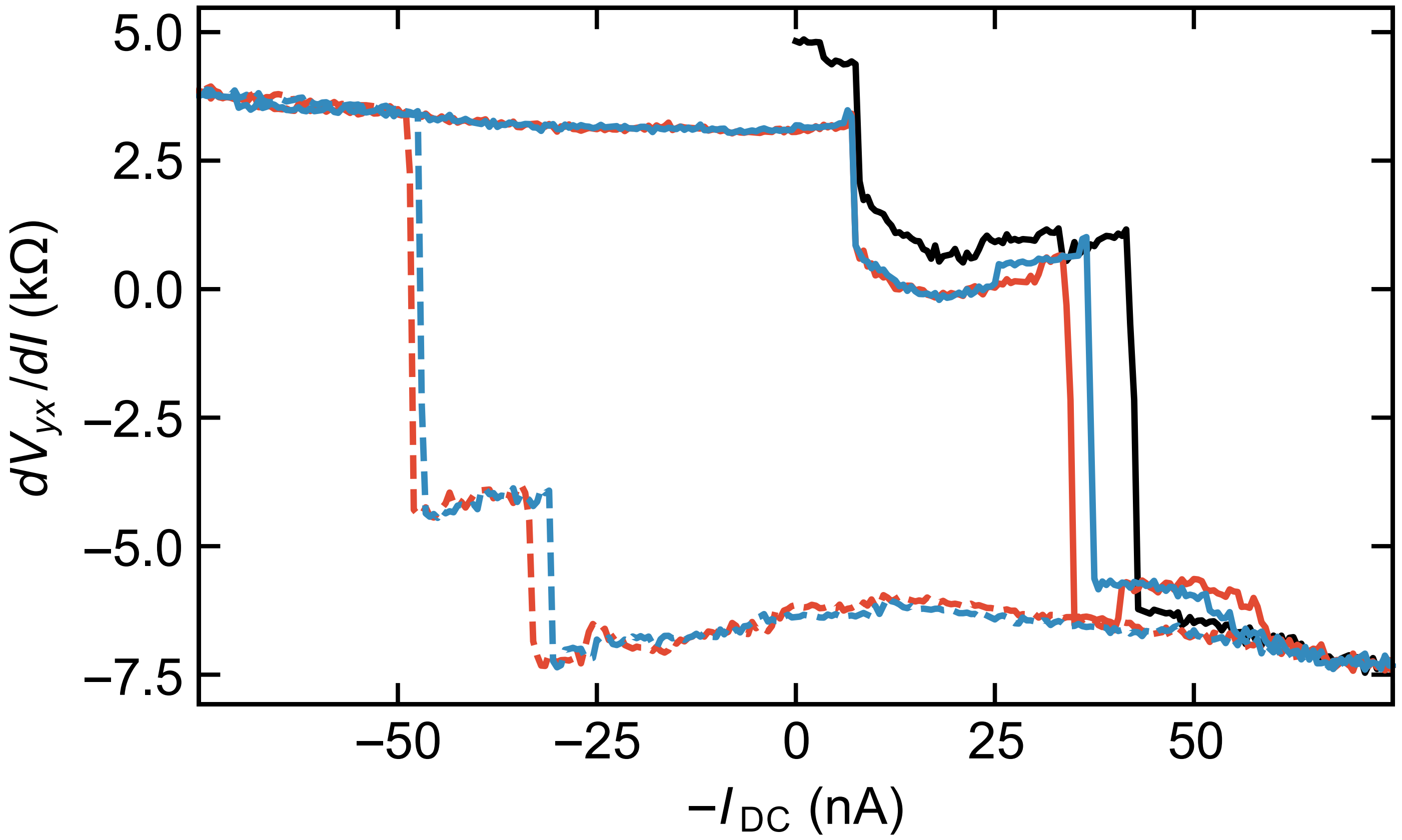


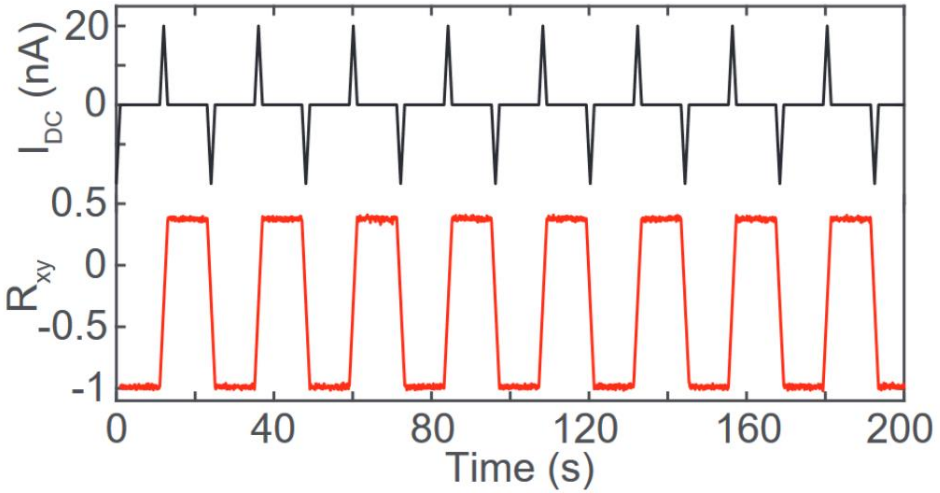




Serlin et al. arXiv:1907.00261

Repeatable Hysteresis in DC Current





Serlin et al. arXiv:1907.00261

Toward Understanding the Nature of the Magnetism

Possible scenarios:

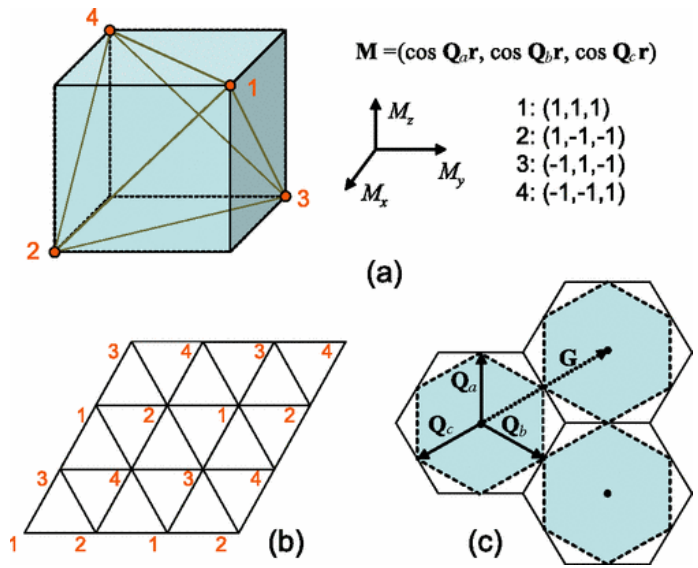
Spin/valley polarization — like our simple picture

$$E_{\text{valley}-\text{Zeeman}} = g_v \mu_B H_z \tau_z / 2$$

Orbital moment from gapped Dirac cones

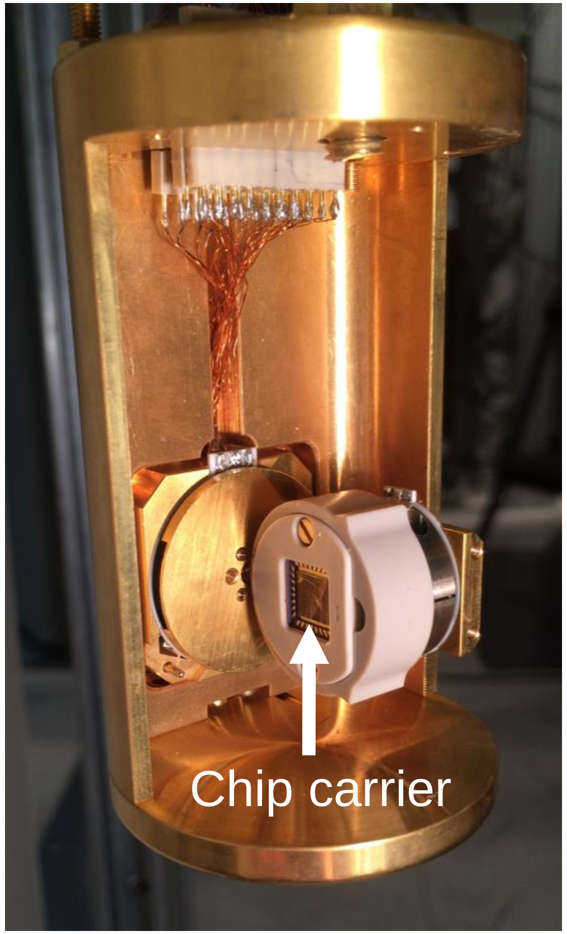
Valley-polarized, spin-unpolarized composite Fermi liquid state — similar to FQHE

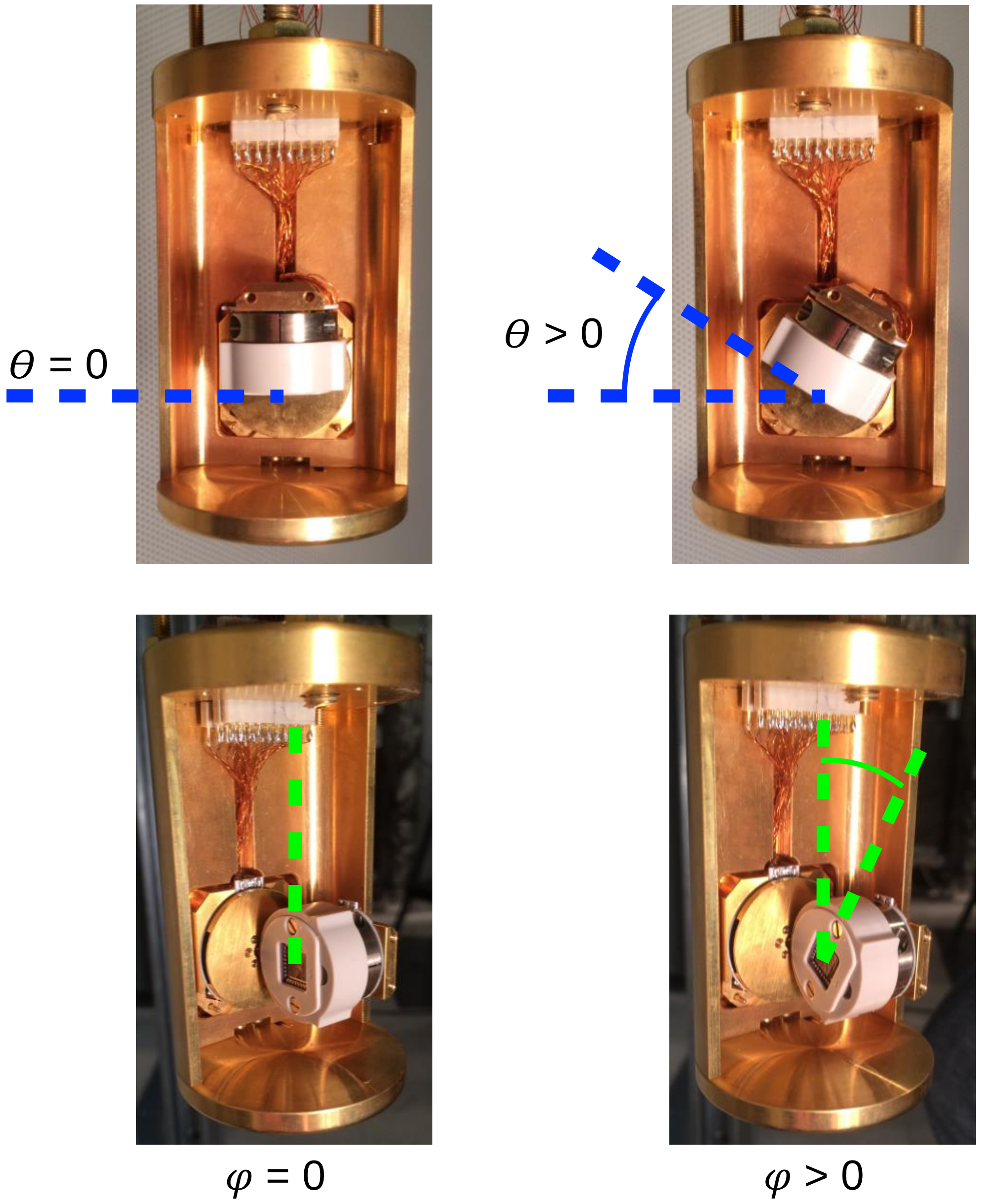
Non-coplanar chiral spin order at 3/4 filling of an individual band (two copies from valley)



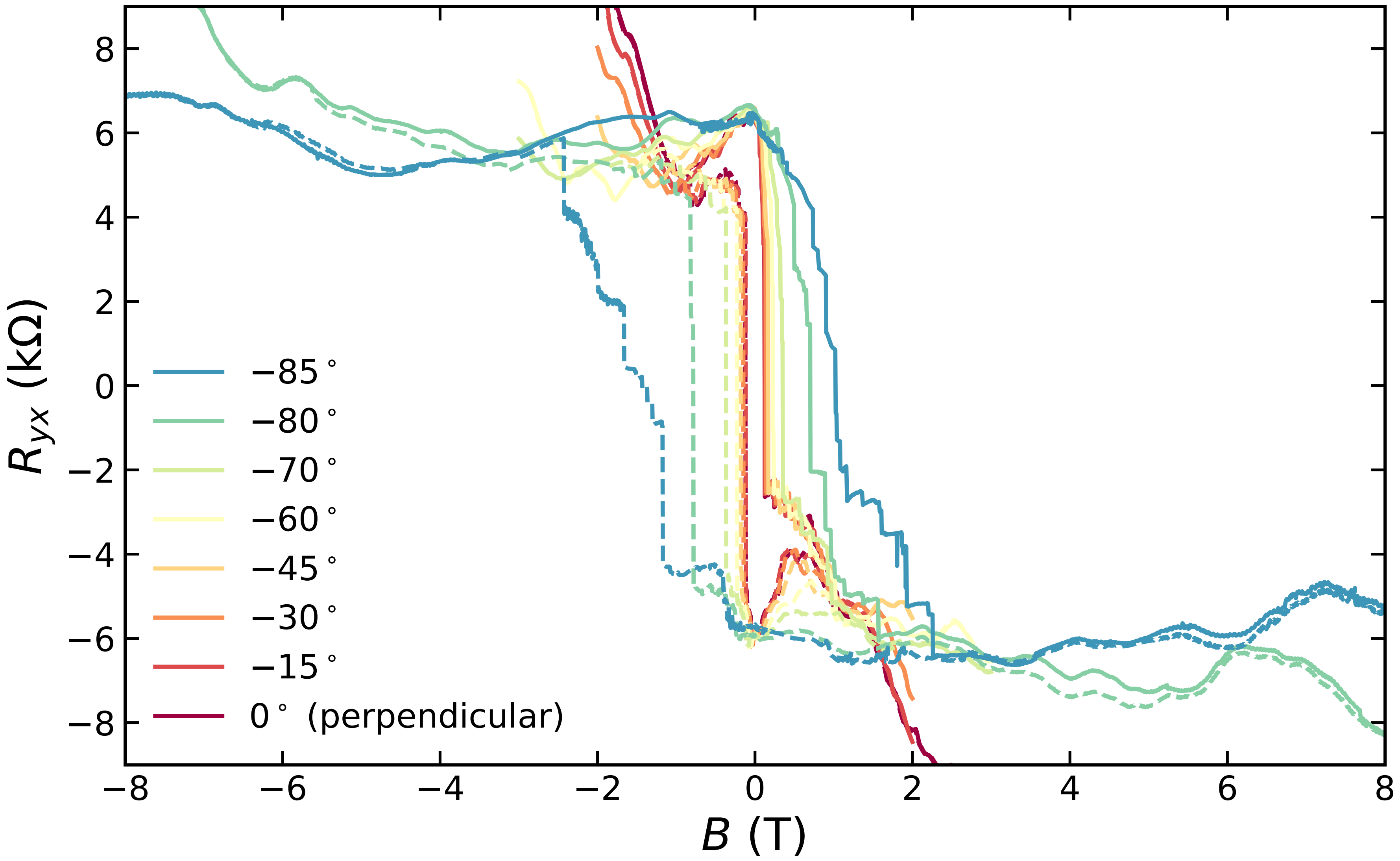
Martin et al. PRL 2008

Probing nature of magnetism

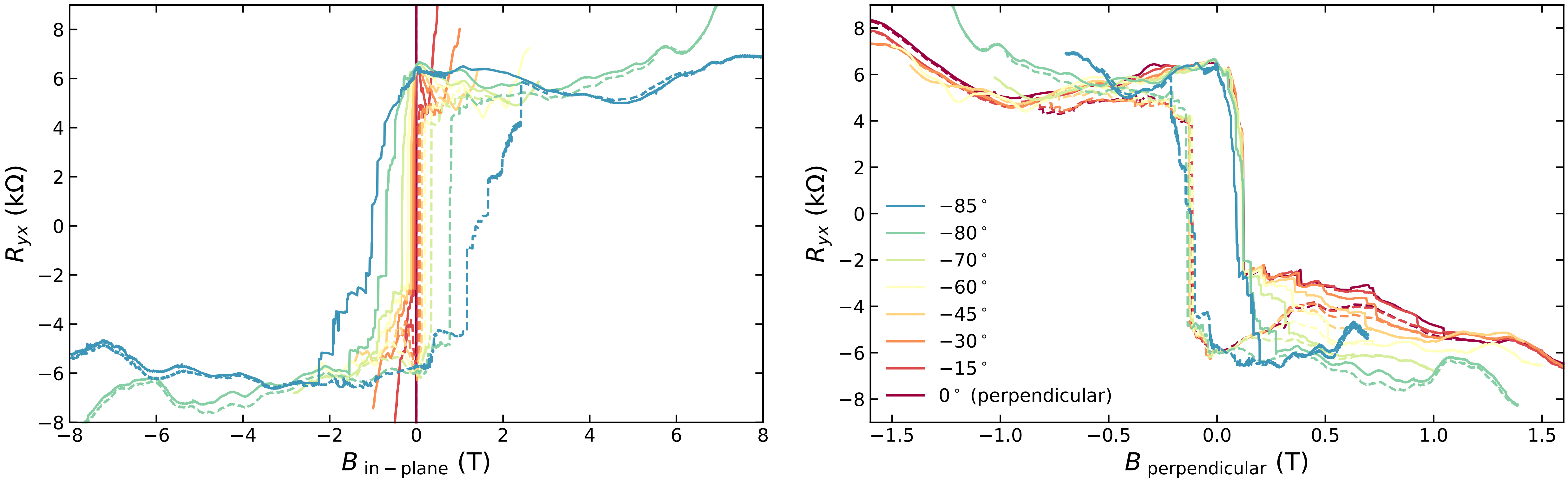




Hysteresis loops in tilted filed

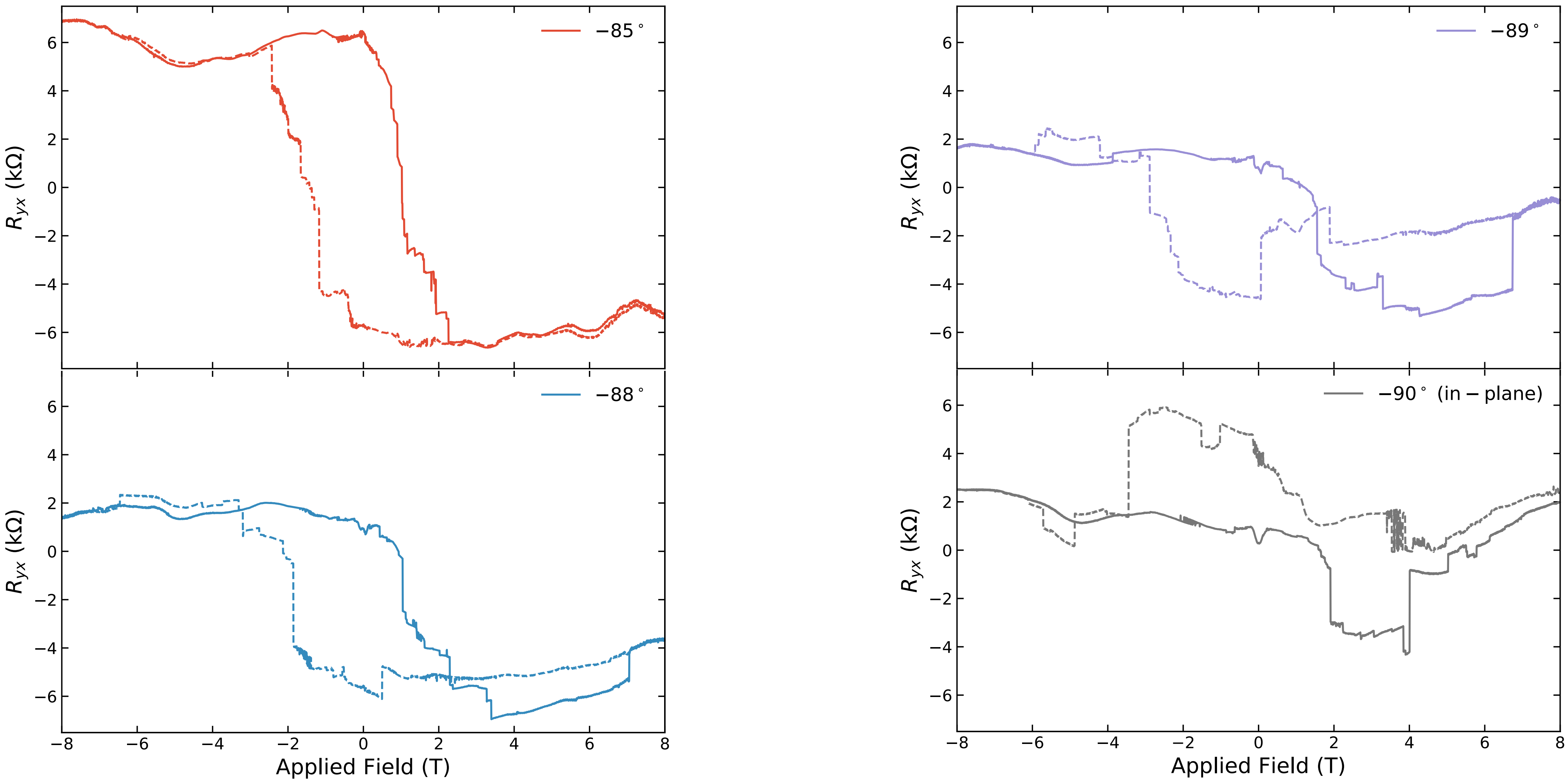


Hysteresis loops in tilted filed

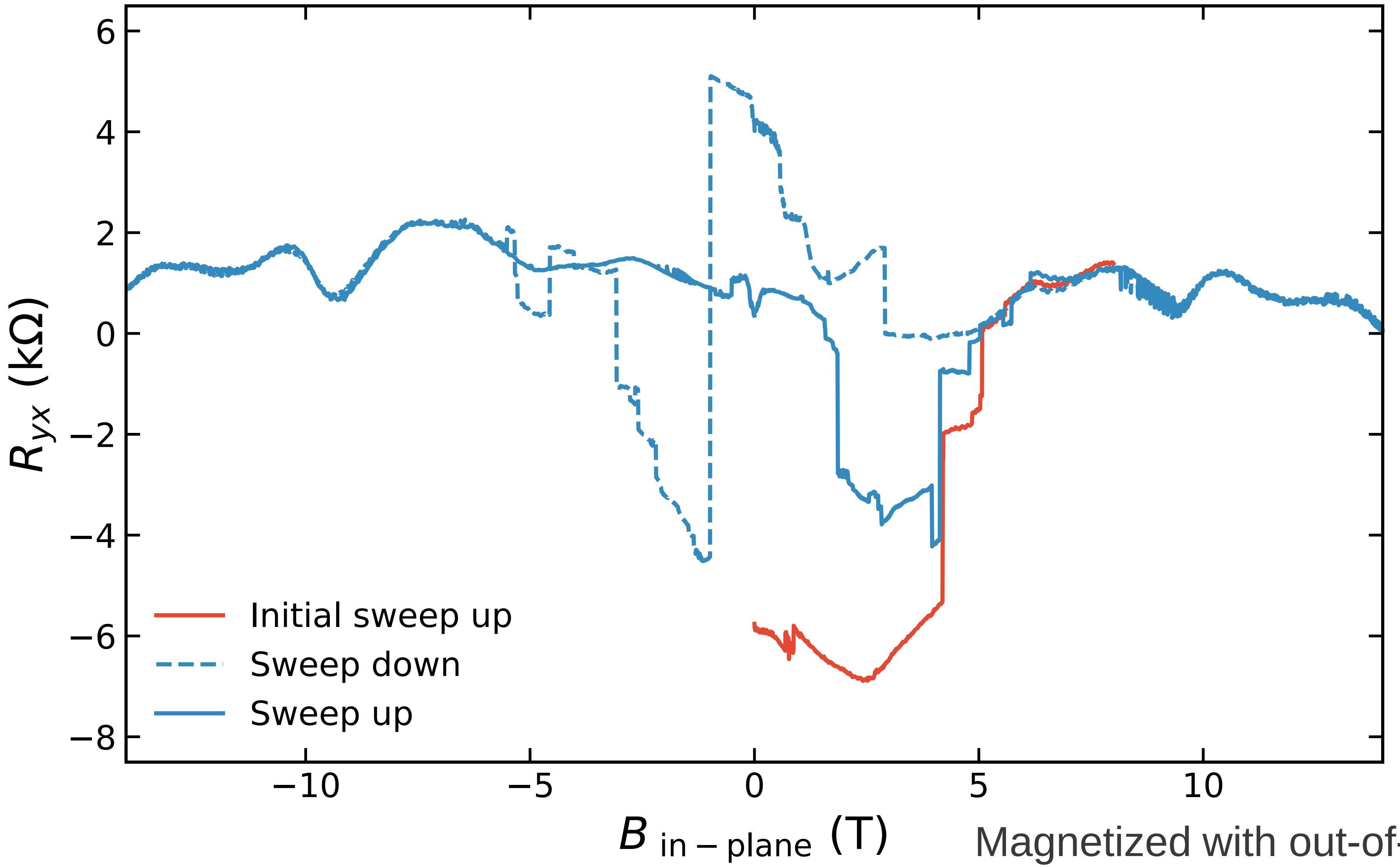


Mostly sensitive to perpendicular component!

Behavior near in-plane field



Applying in-plane field to a magnetized state



Magnetized with out-of-plane field
Rotated to in-plane in zero field

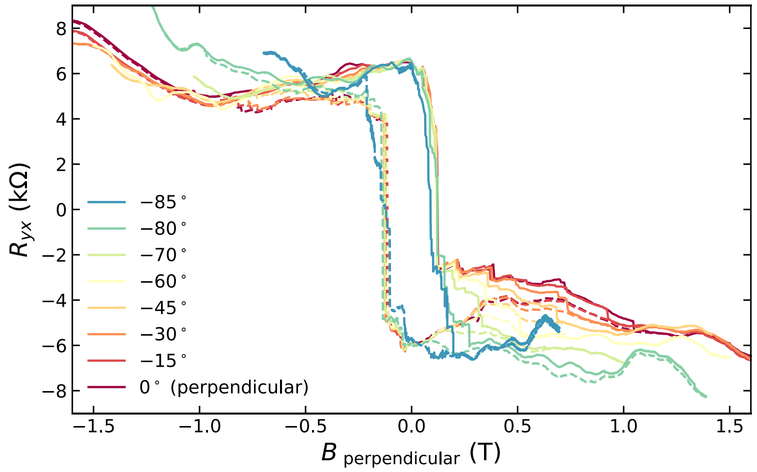
TBG is a Chern insulator near ¾ filling!

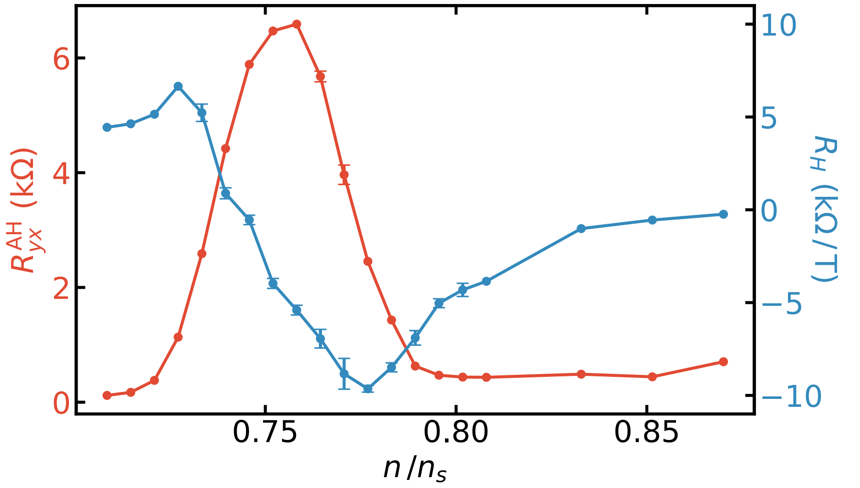
Alignment to hBN appears crucial to open topologically nontrivial gap

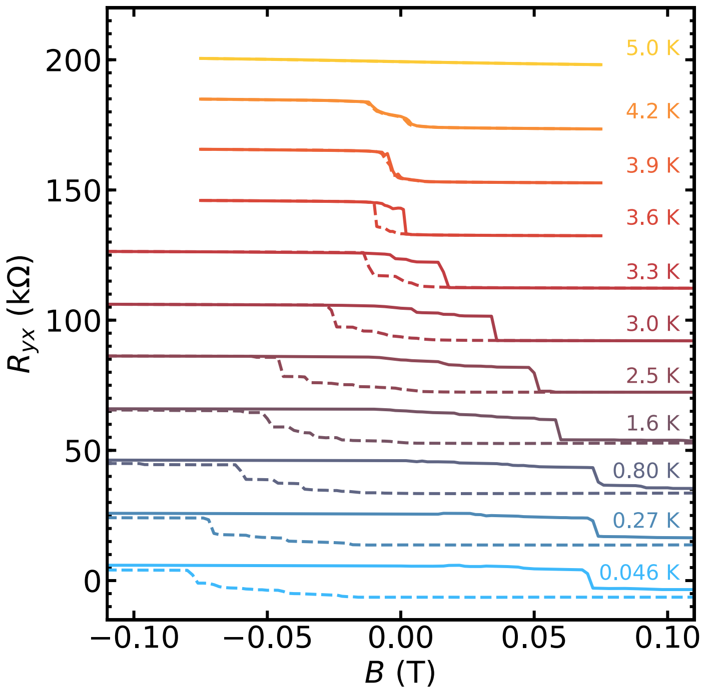
Small DC current can flip magnetization, potentially useful for magnetic memory

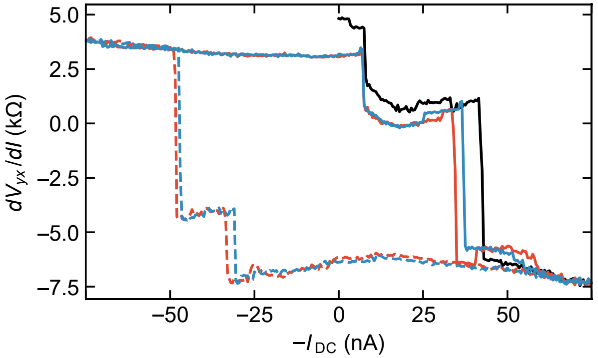
Orbital ferromagnet: high degree of anisotropy

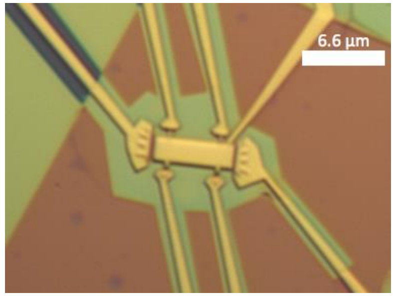
Sufficiently large in-plane field kills magnetization











10.1126/science.aaw3780