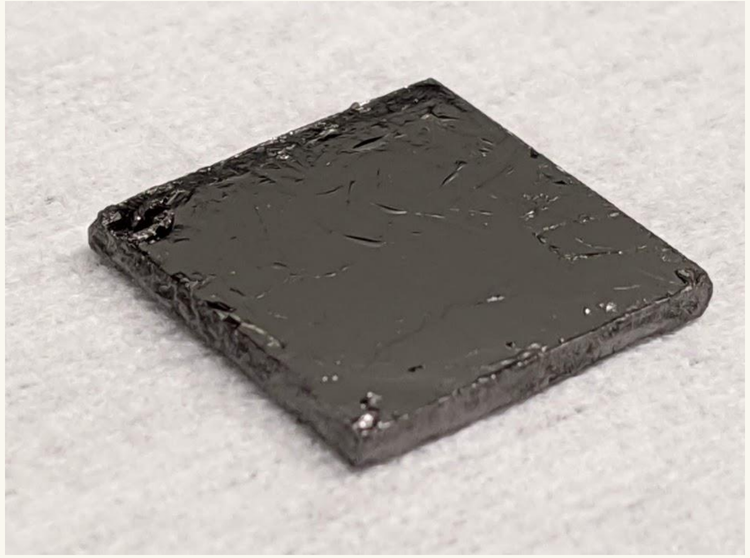
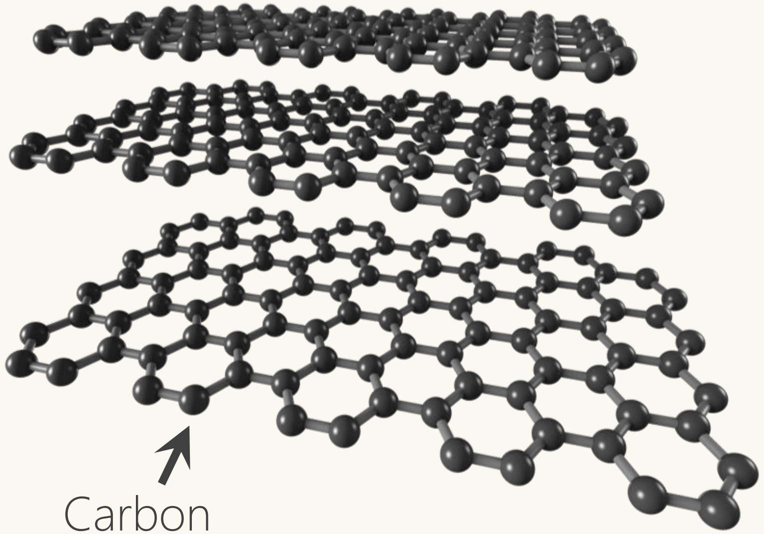
Ferromagnetism in twisted bilayer graphene

Aaron Sharpe

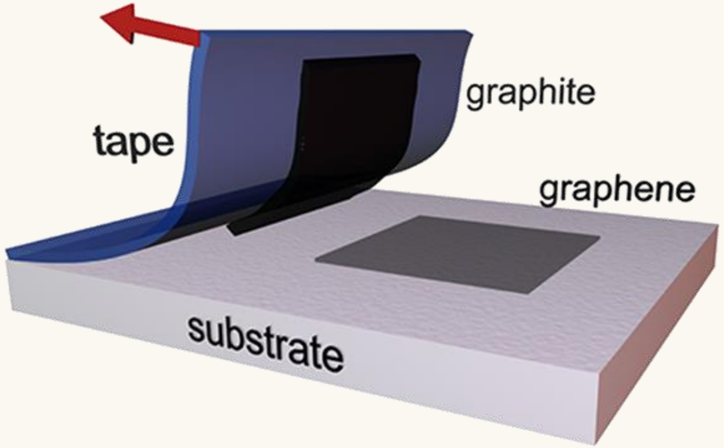
Thesis Defense

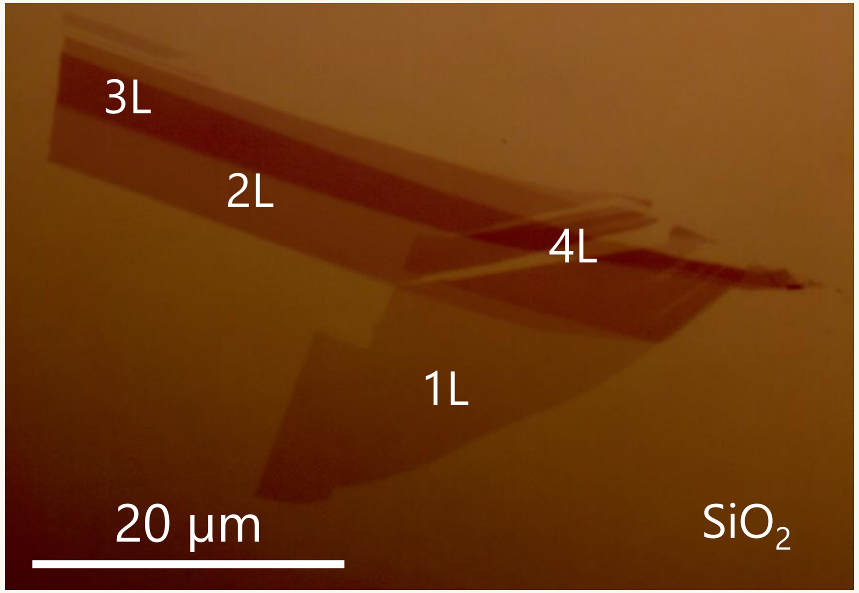
Graphene



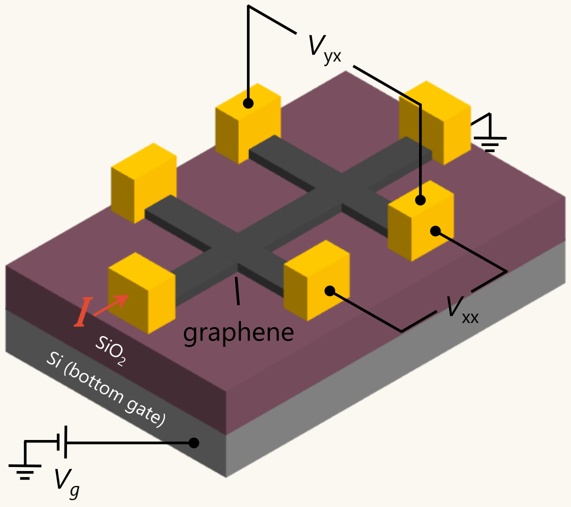


Graphene: Exfoliate with Scotch Tape

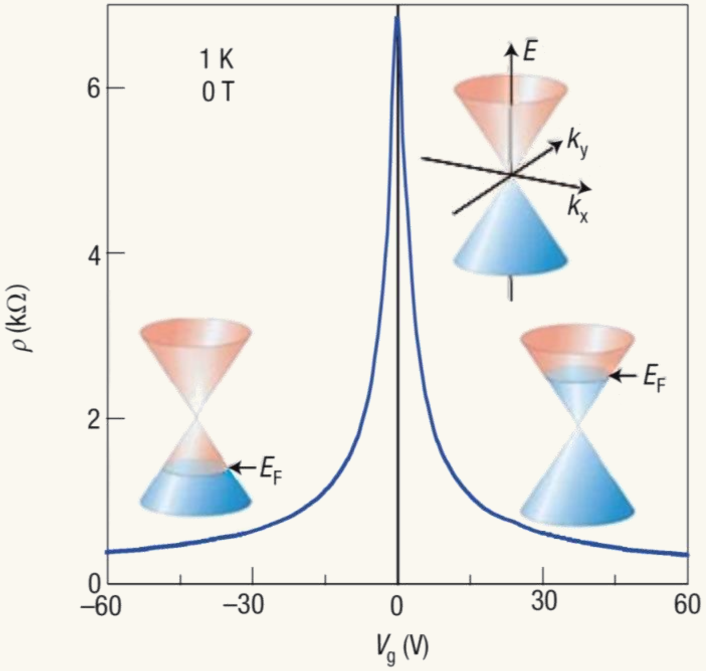




Graphene: Transport Properties

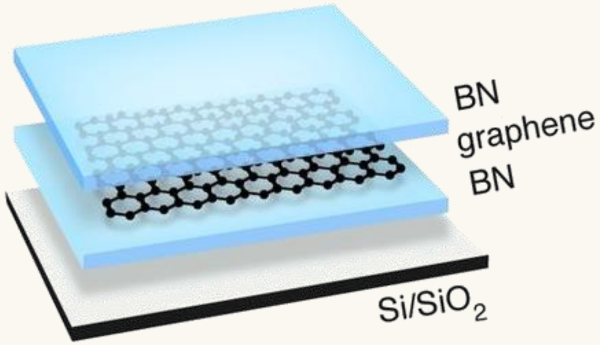


$$R_{xx} = V_{xx}/I$$
$$R_{yx} = V_{yx}/I$$
$$n = CV_g/eA$$

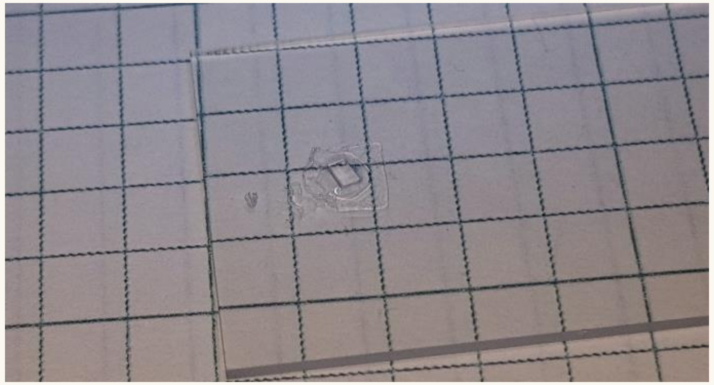


Geim and Novoselov, Nat. Mat. (2007)
Wang et al., Science (2013)

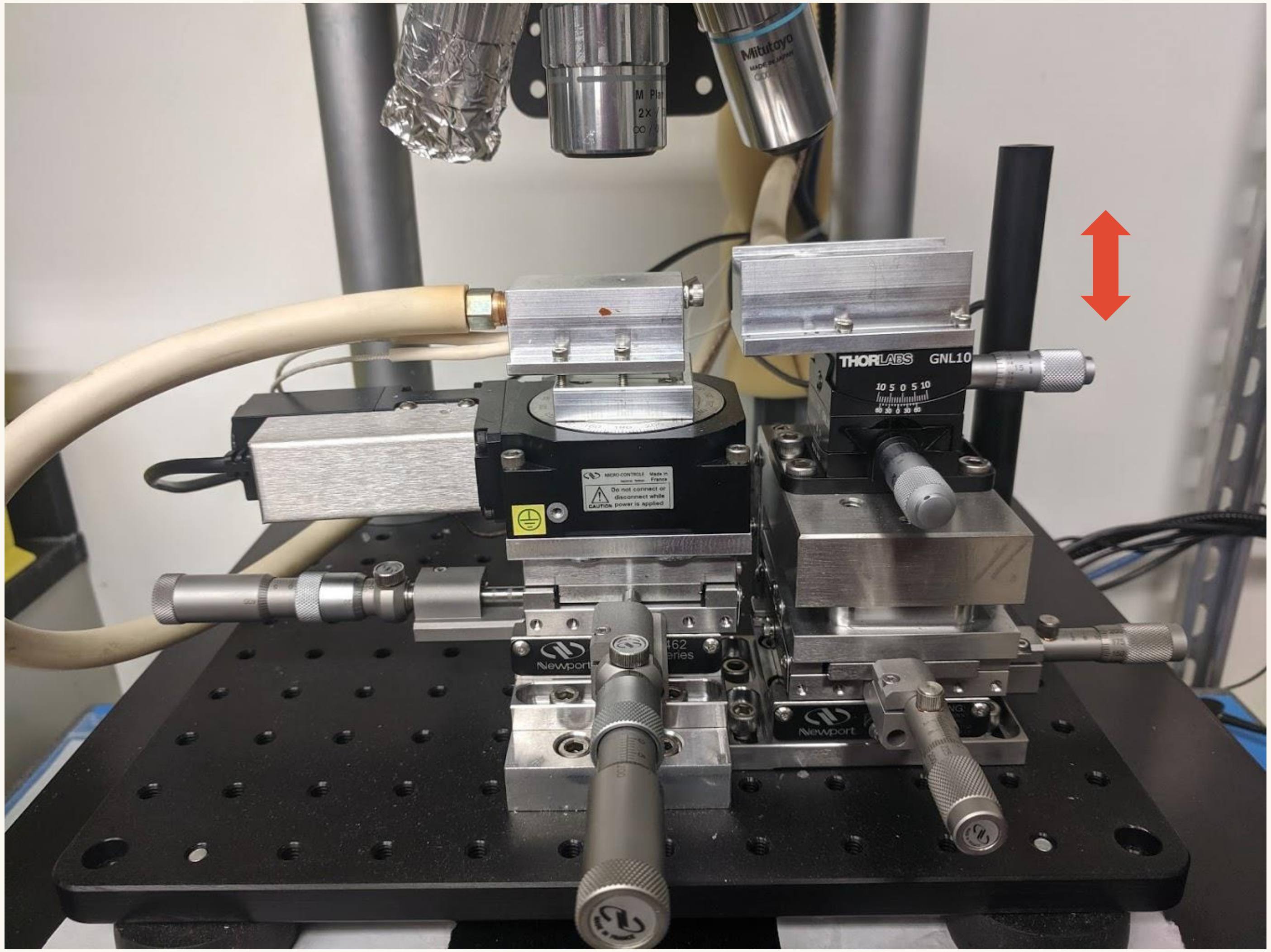
Transferring 2D Materials



Stamp

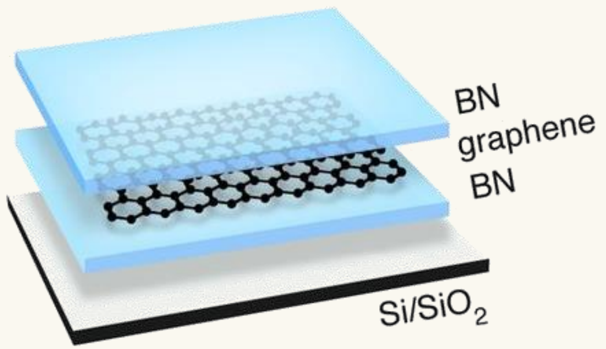


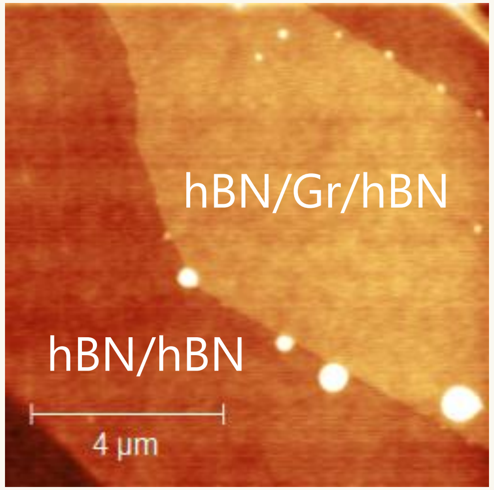
PC/PDMS/Glass

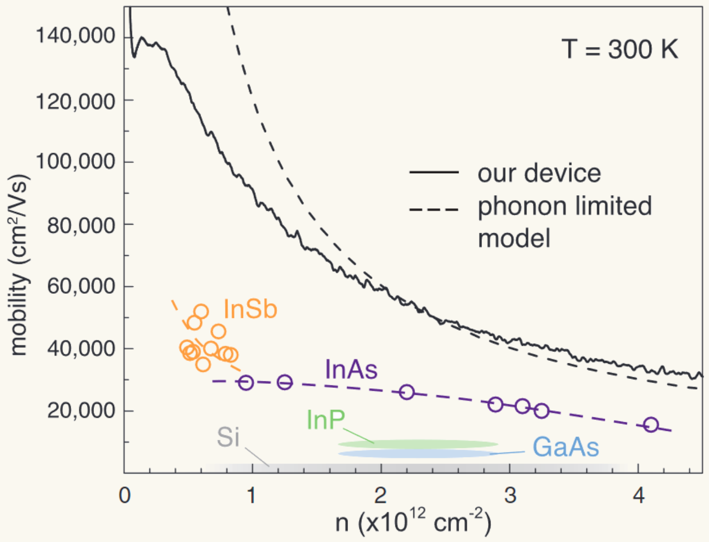


Wang et al., Science (2013)

Designer Atomically Clean Heterostructures



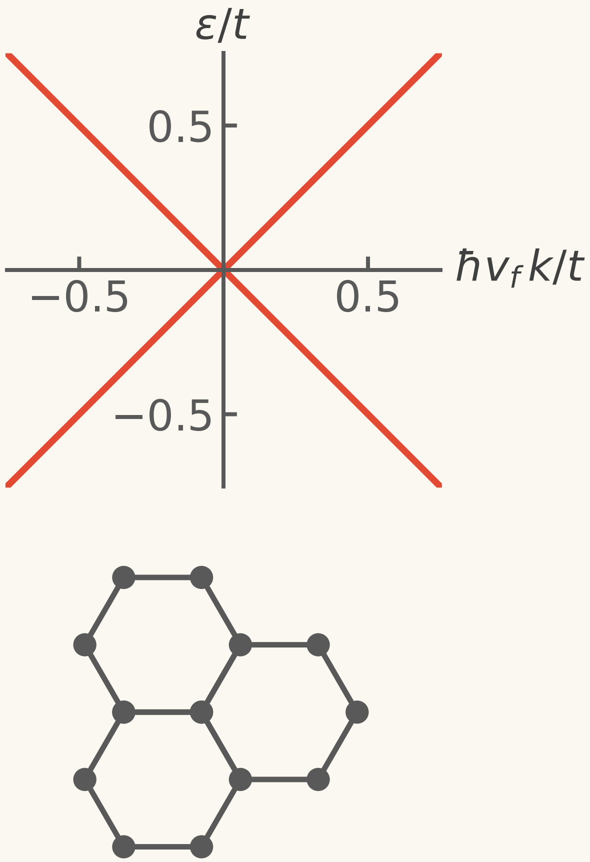




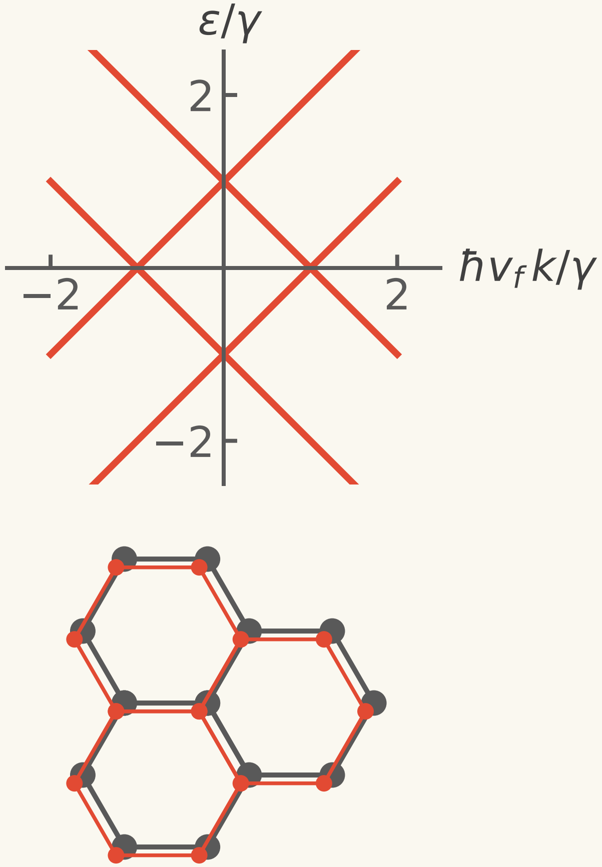
Wang et al., Science (2013)

Layer Dependent Properties

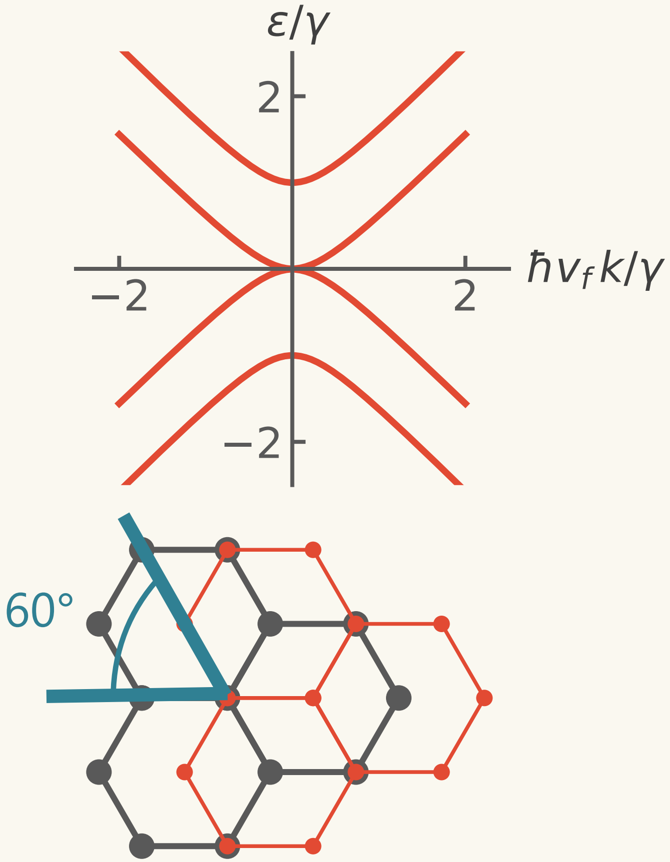
Monolayer

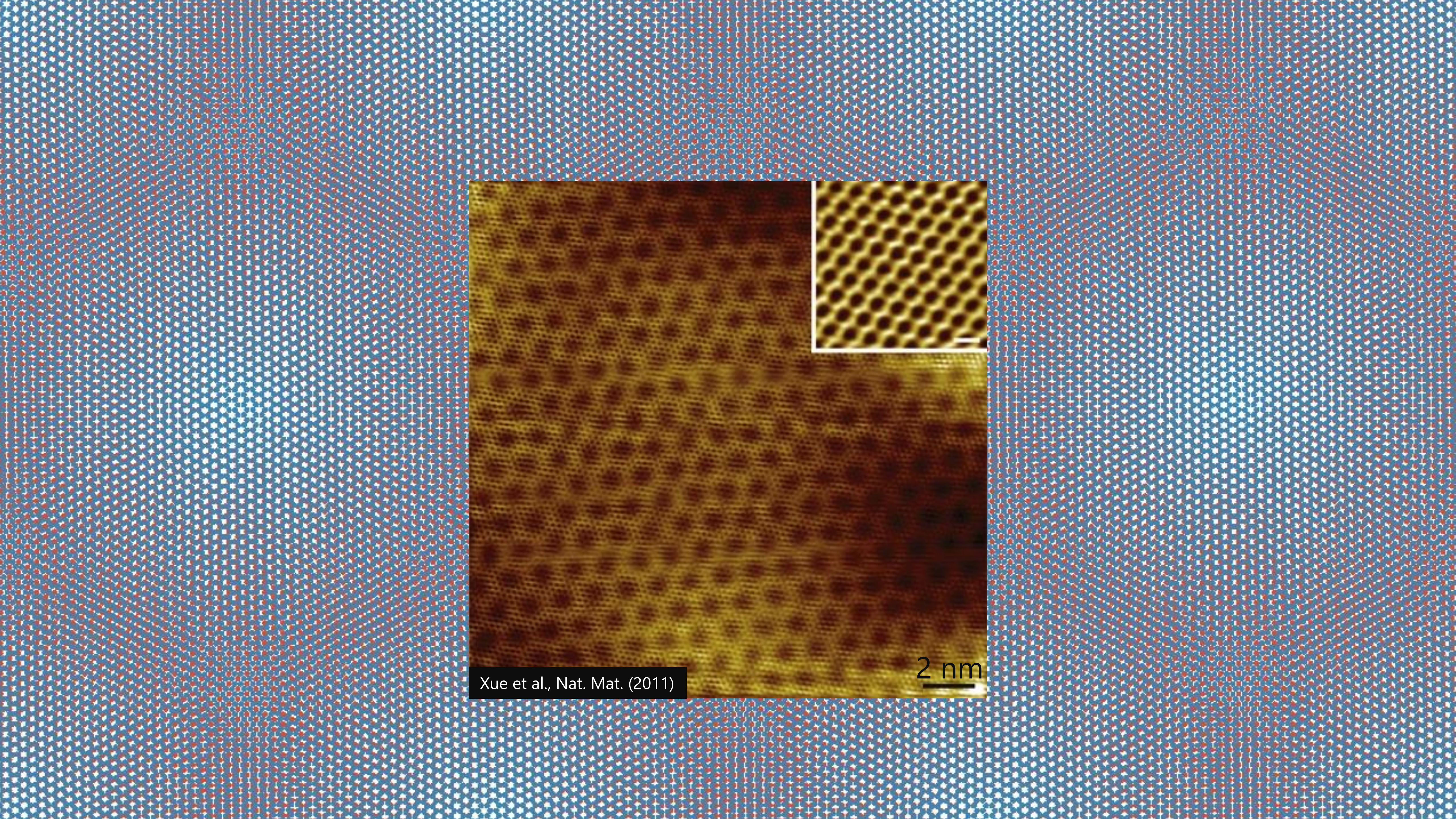


AA Bilayer

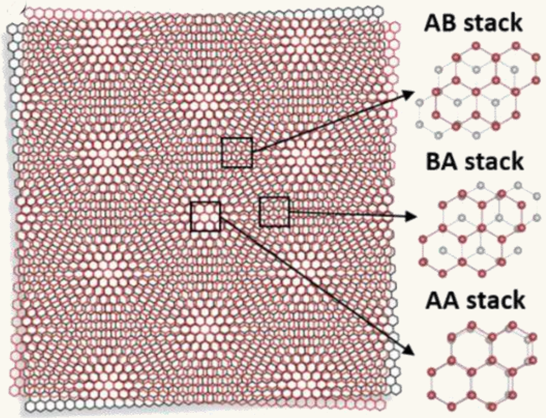


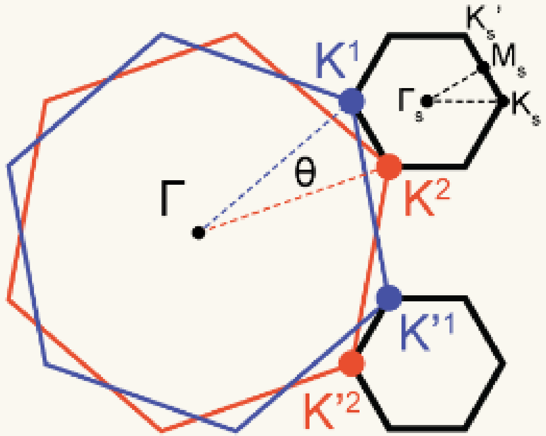
Bernal Bilayer



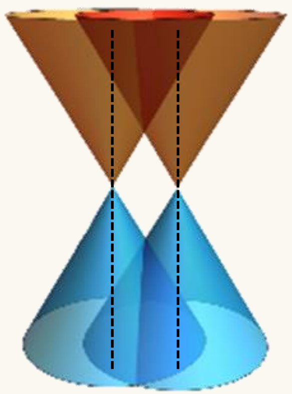

2 nm
Xue et al., Nat. Mat. (2011)

Twisted Bilayer Graphene



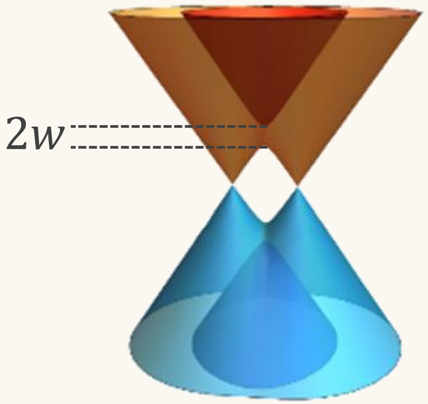


$k_\theta \approx K\theta$

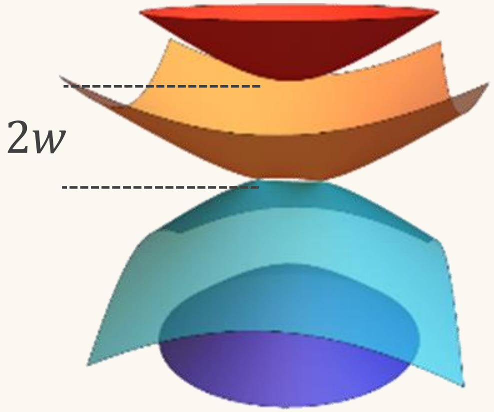


4-fold degenerate

w: Inter-layer interaction



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



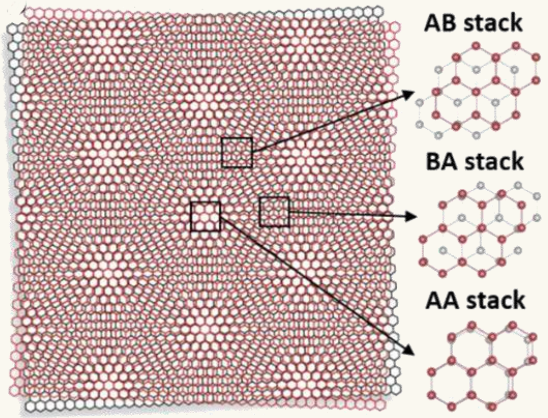
$2w \approx v_{F0} k_\theta$

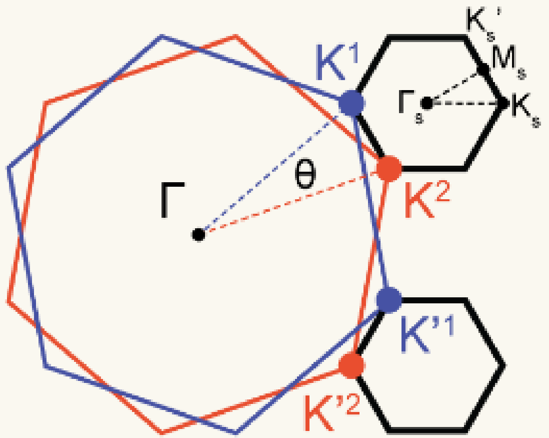
Decreasing twist angle

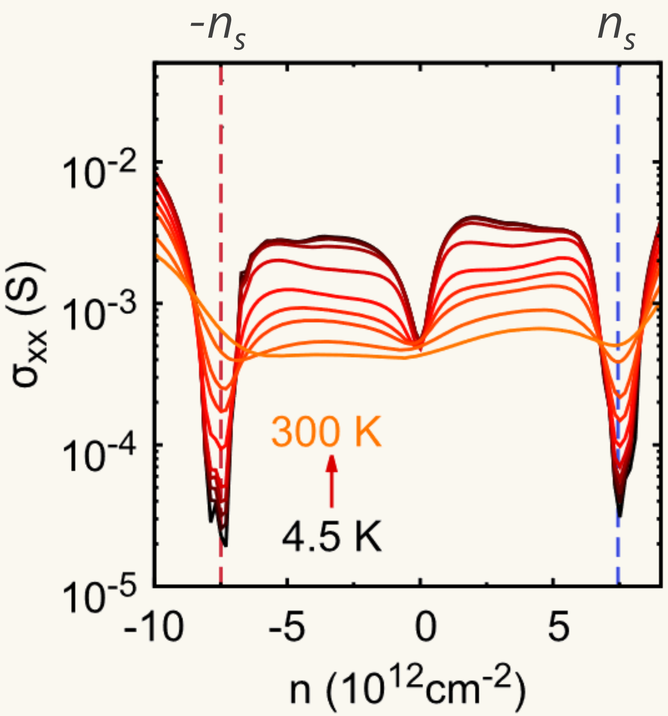
A new knob:
twist angle!

Yoo et al., Nat. Mater. (2019)
Cao et al., Nature (2018)
motorsandcontrol.com

Twisted Bilayer Graphene



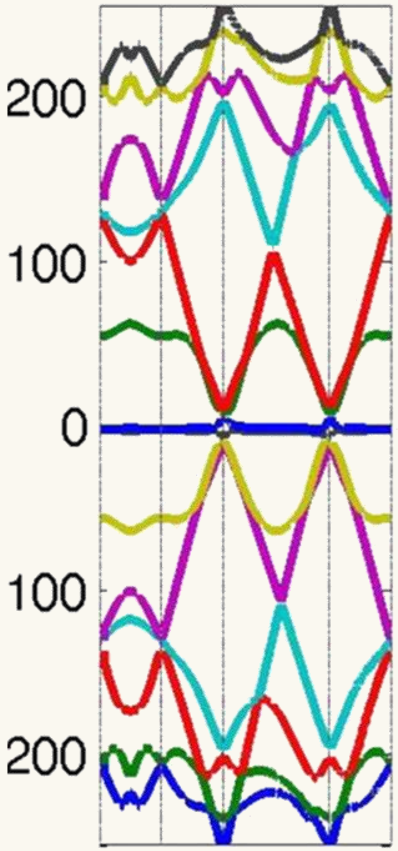


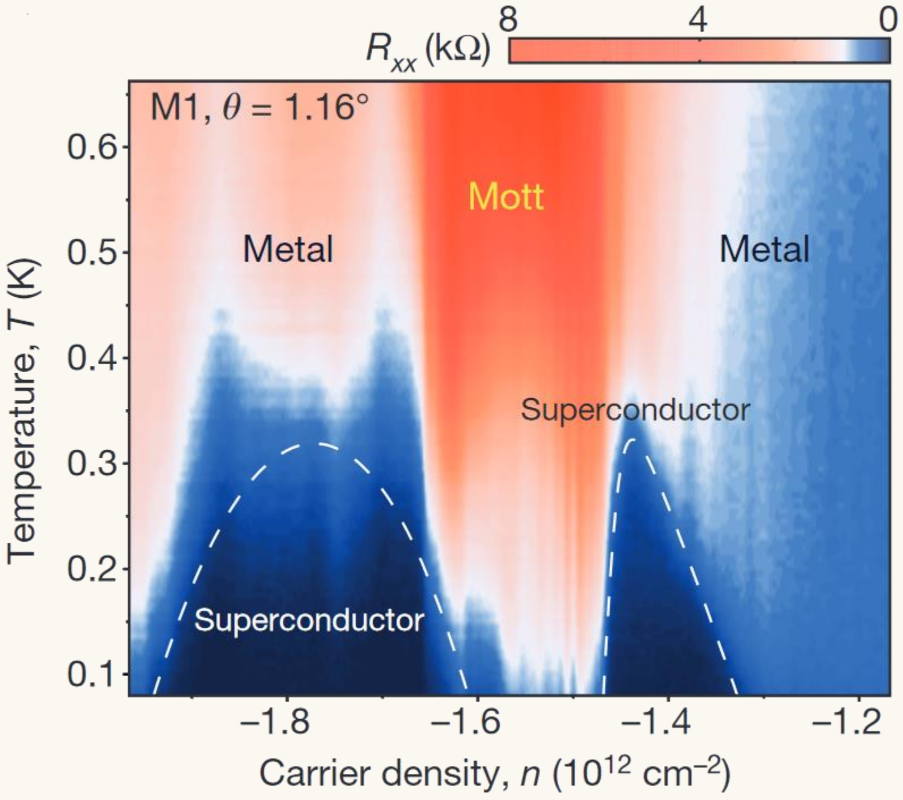


Yoo et al., Nat. Mater. (2019)
Cao et al., PRL (2016)

TBG: Emergent Properties

$\theta = 1.05°$

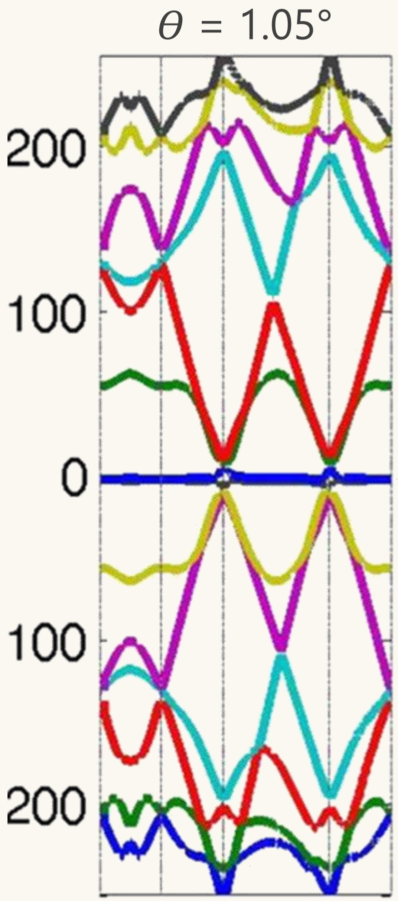


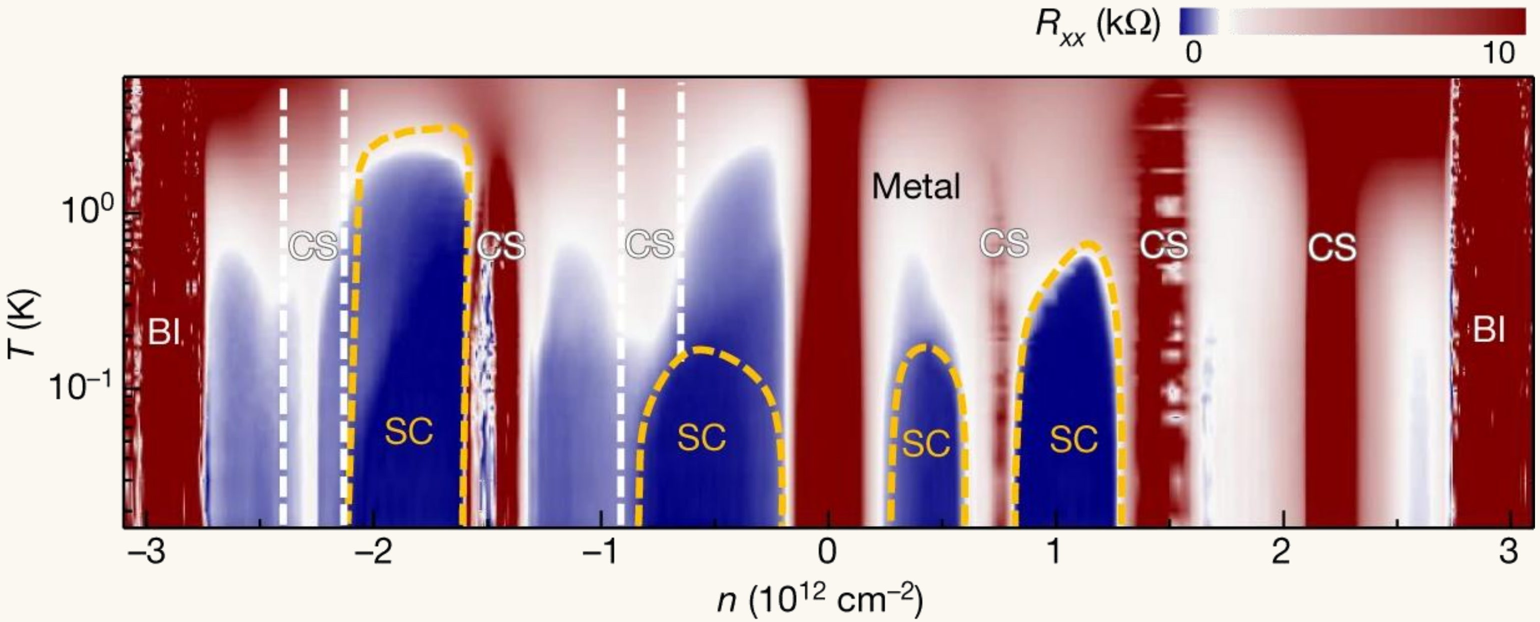


$n_s/2$

Bistritzer et al., PNAS (2011)
Cao et al., Nature (2018)

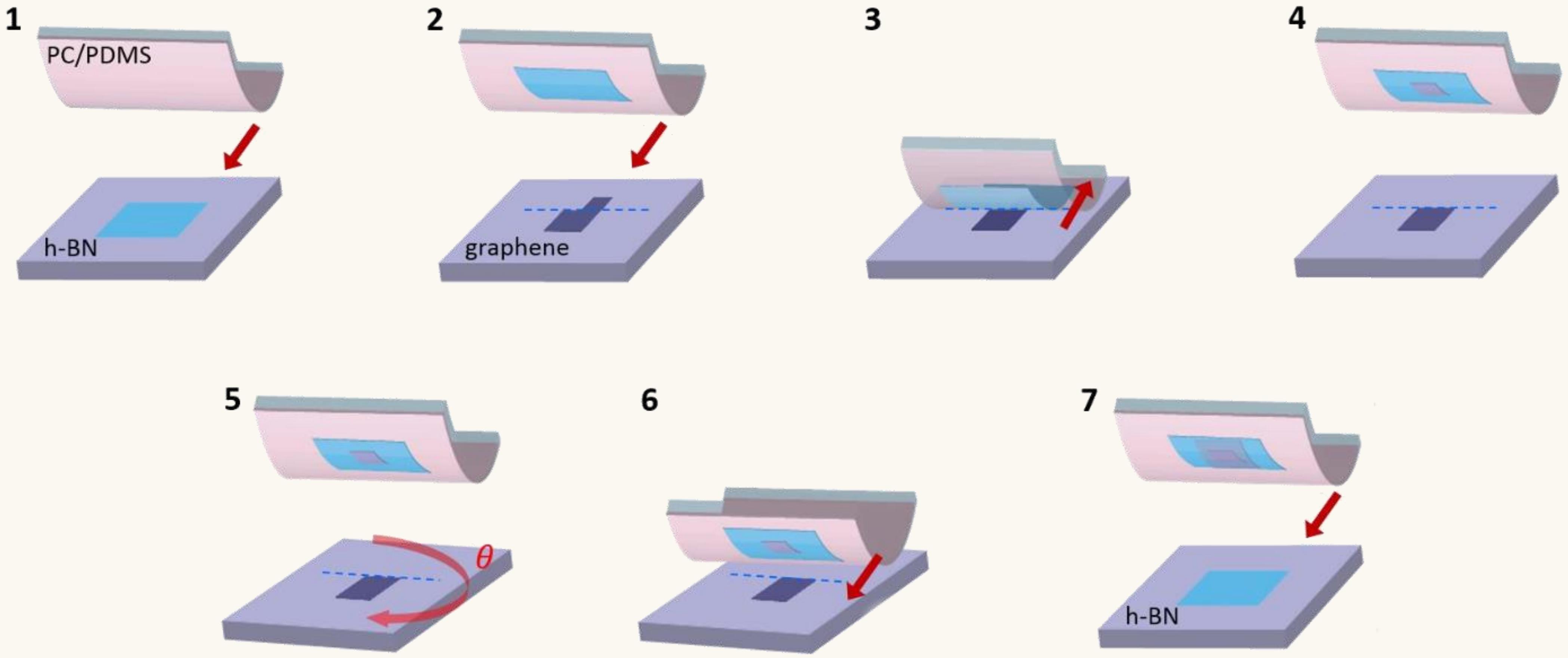
TBG: Emergent Properties



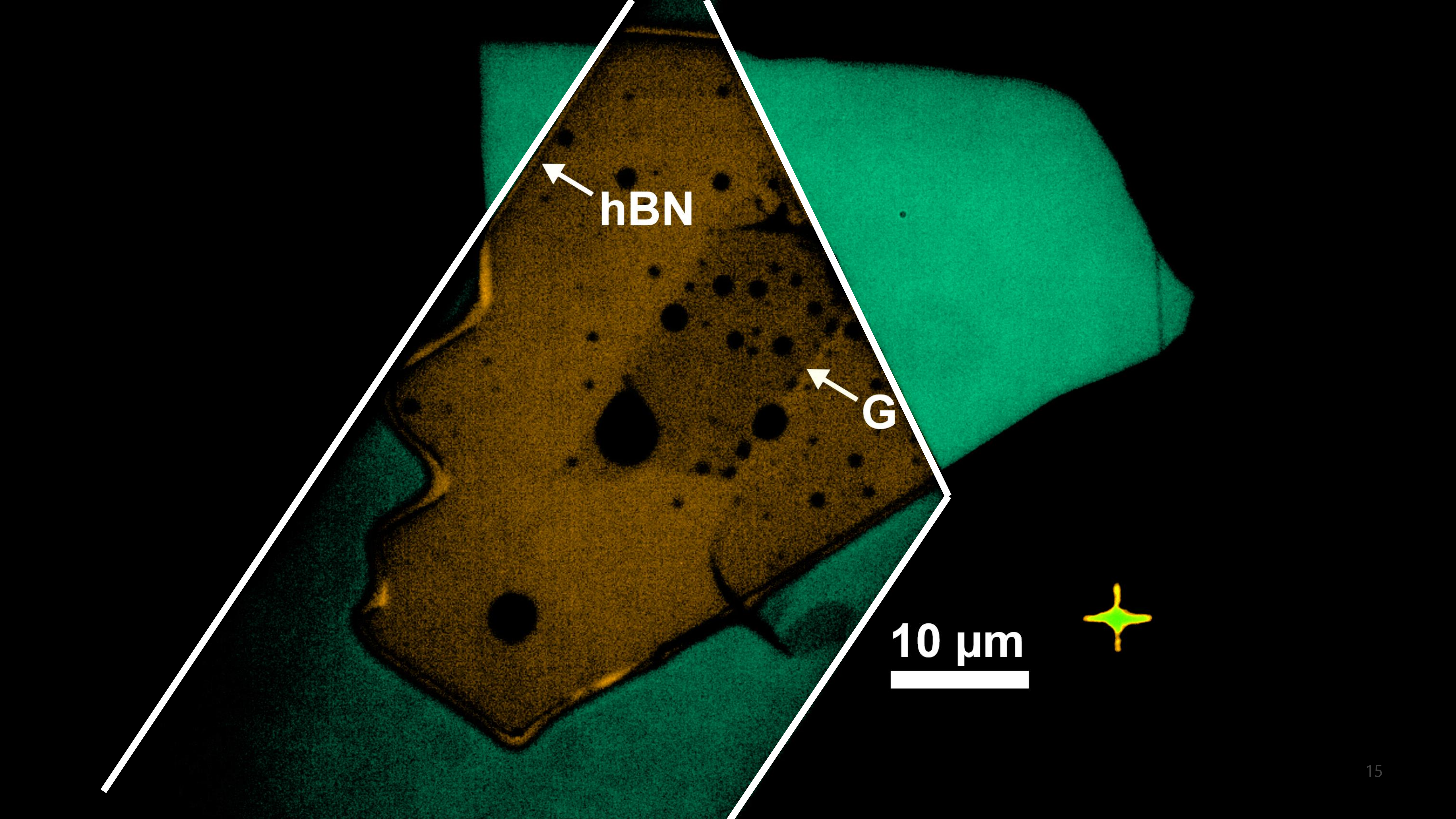


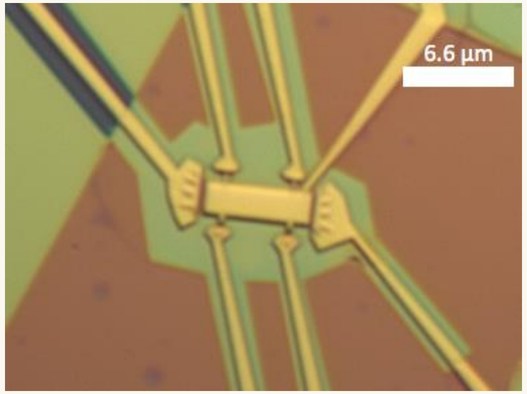
Bistritzer et al., PNAS (2011)
Lu et al., Nature (2019)

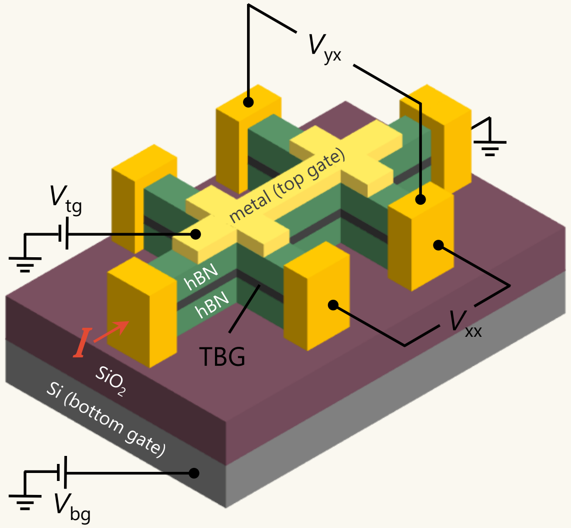
Fabricating TBG

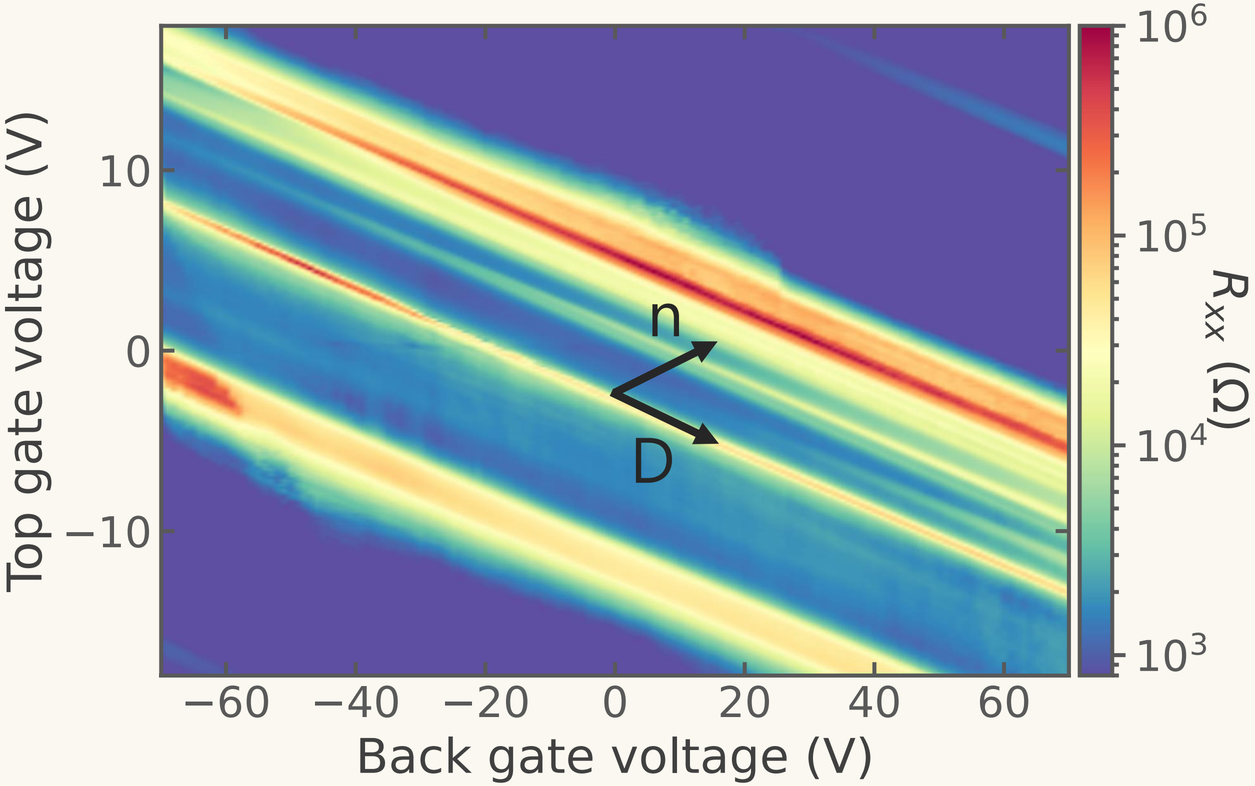


Yoo et al., Nat. Mat. (2019)

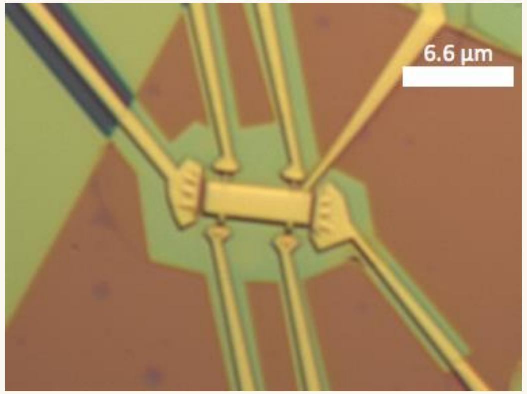

hBN
G
10 µm

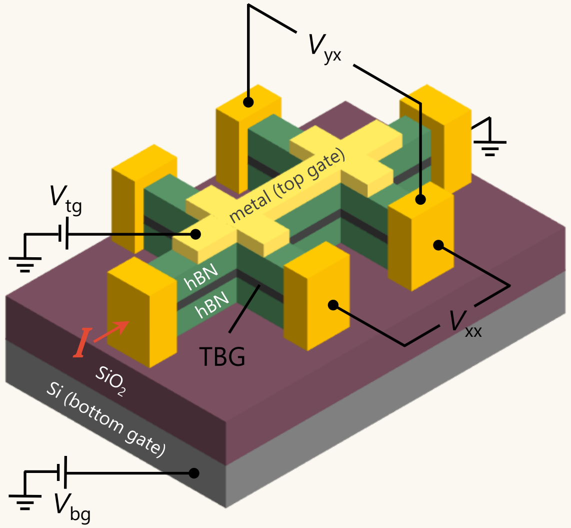


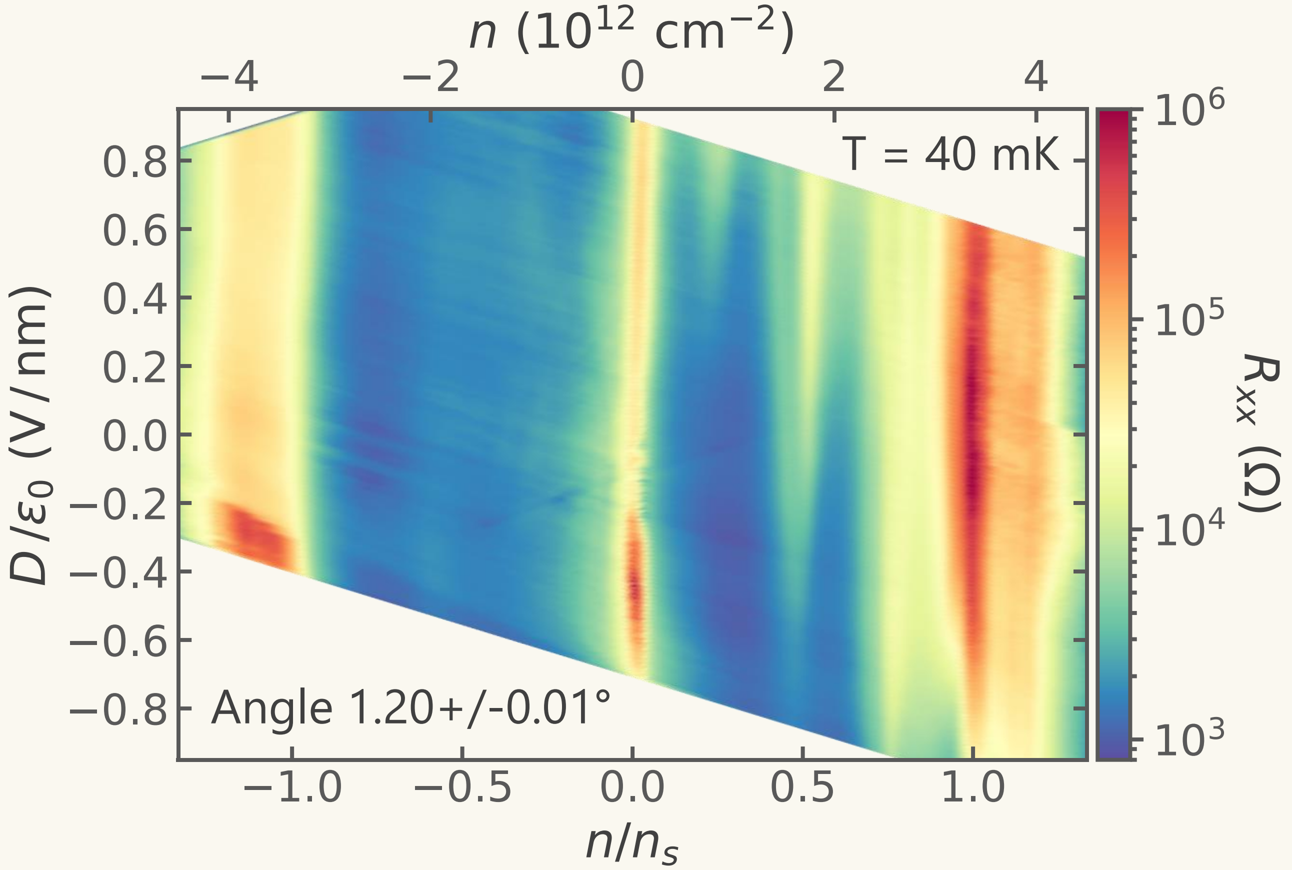




Sharpe et al., Science (2019)



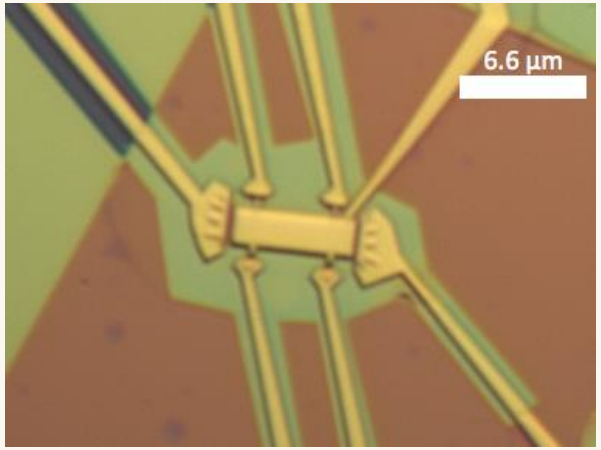




Sharpe et al., Science (2019)

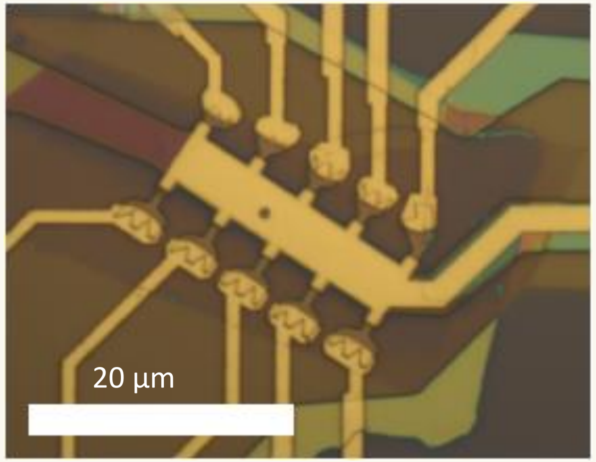
Device 1

Graphene twist: 1.20 +/- 0.01°



Device 2

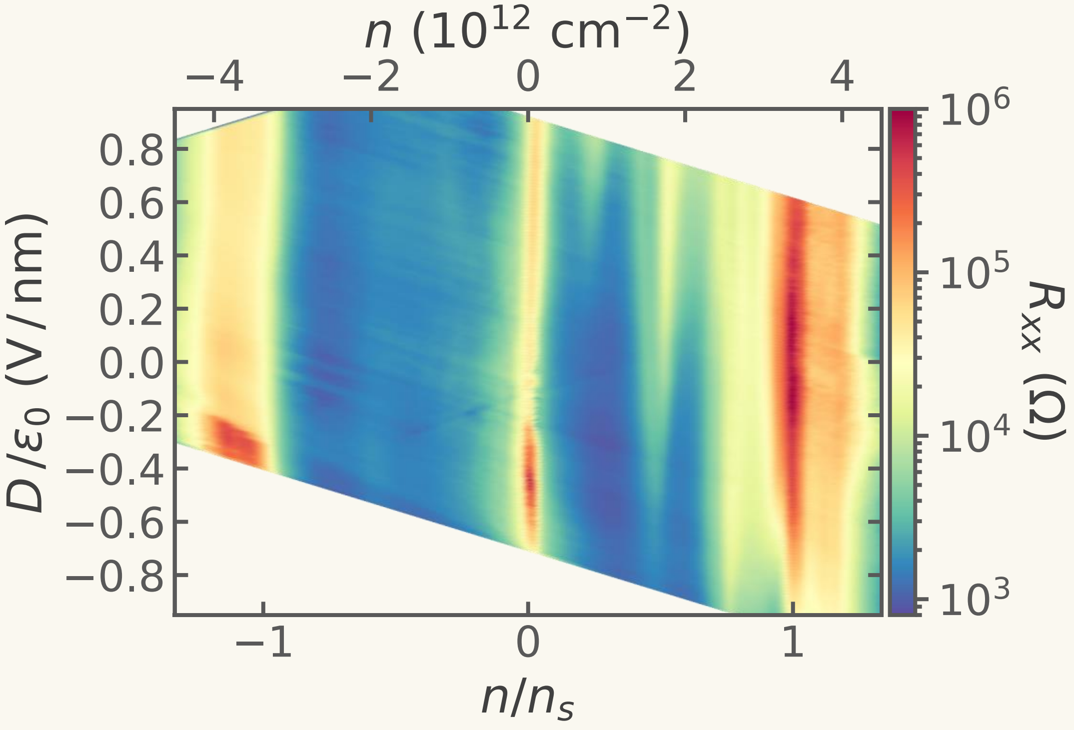
Graphene twist: 1.05 +/- 0.01°



Sharpe et al., Science (2019)

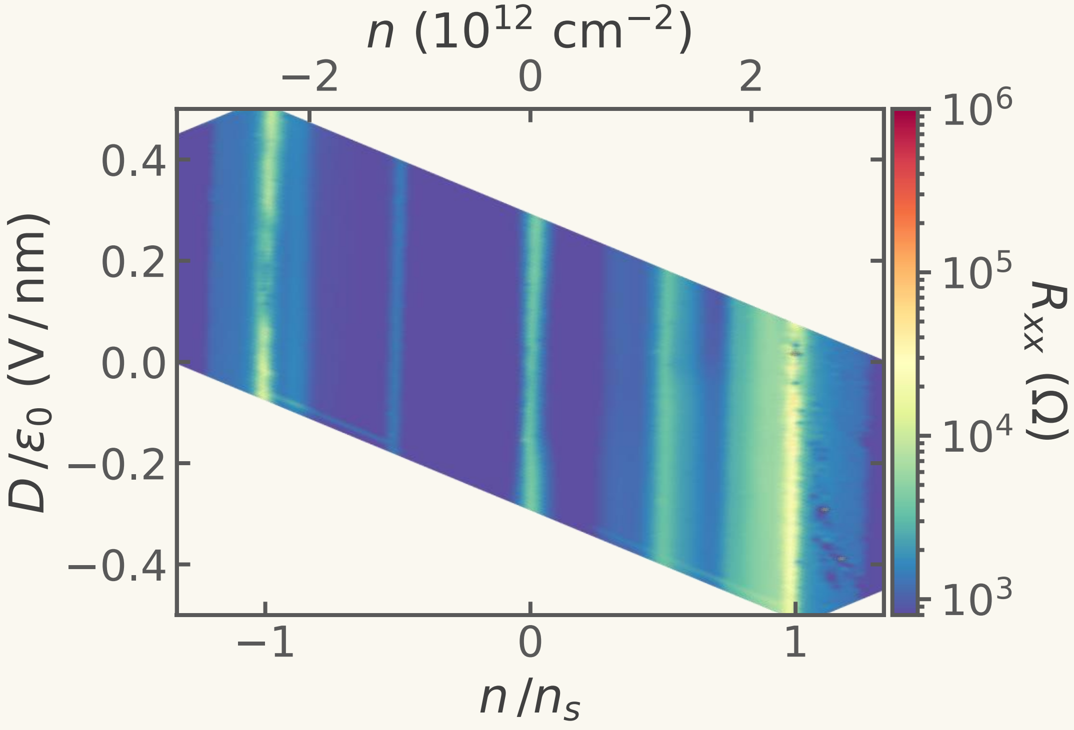
Device 1

Graphene twist: 1.20 +/- 0.01°



Device 2

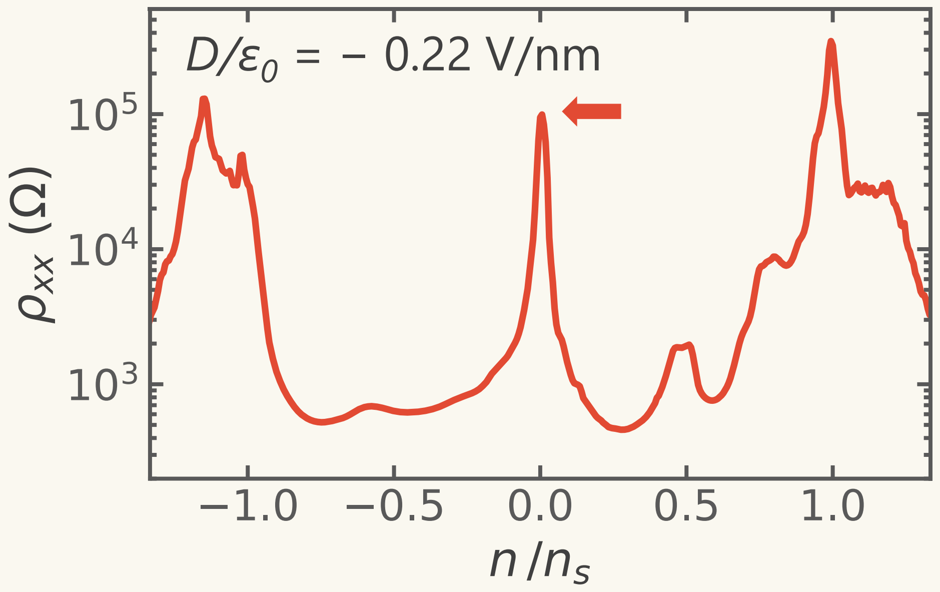
Graphene twist: 1.05 +/- 0.01°



Sharpe et al., Science (2019)

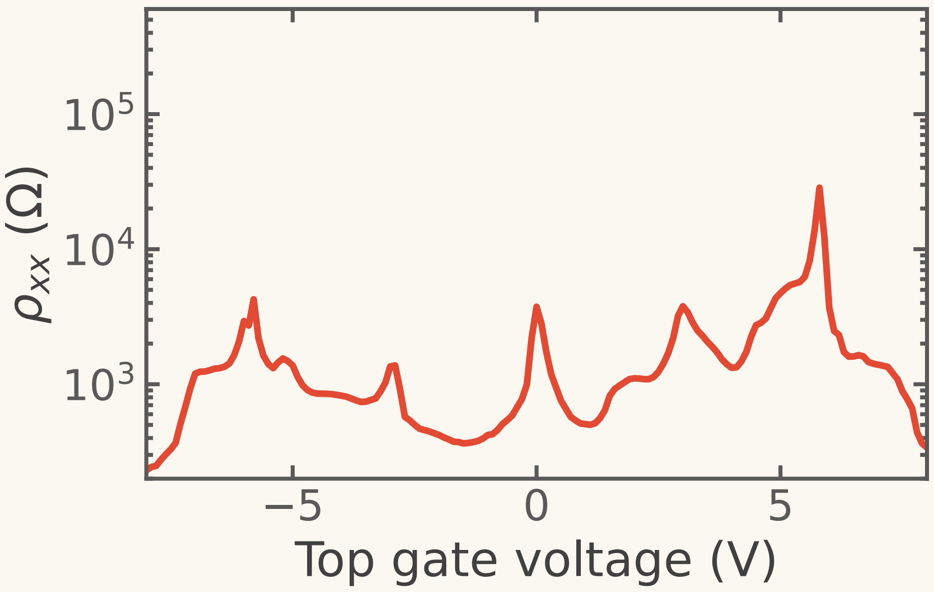
Device 1

Graphene twist: 1.20 +/- 0.01°

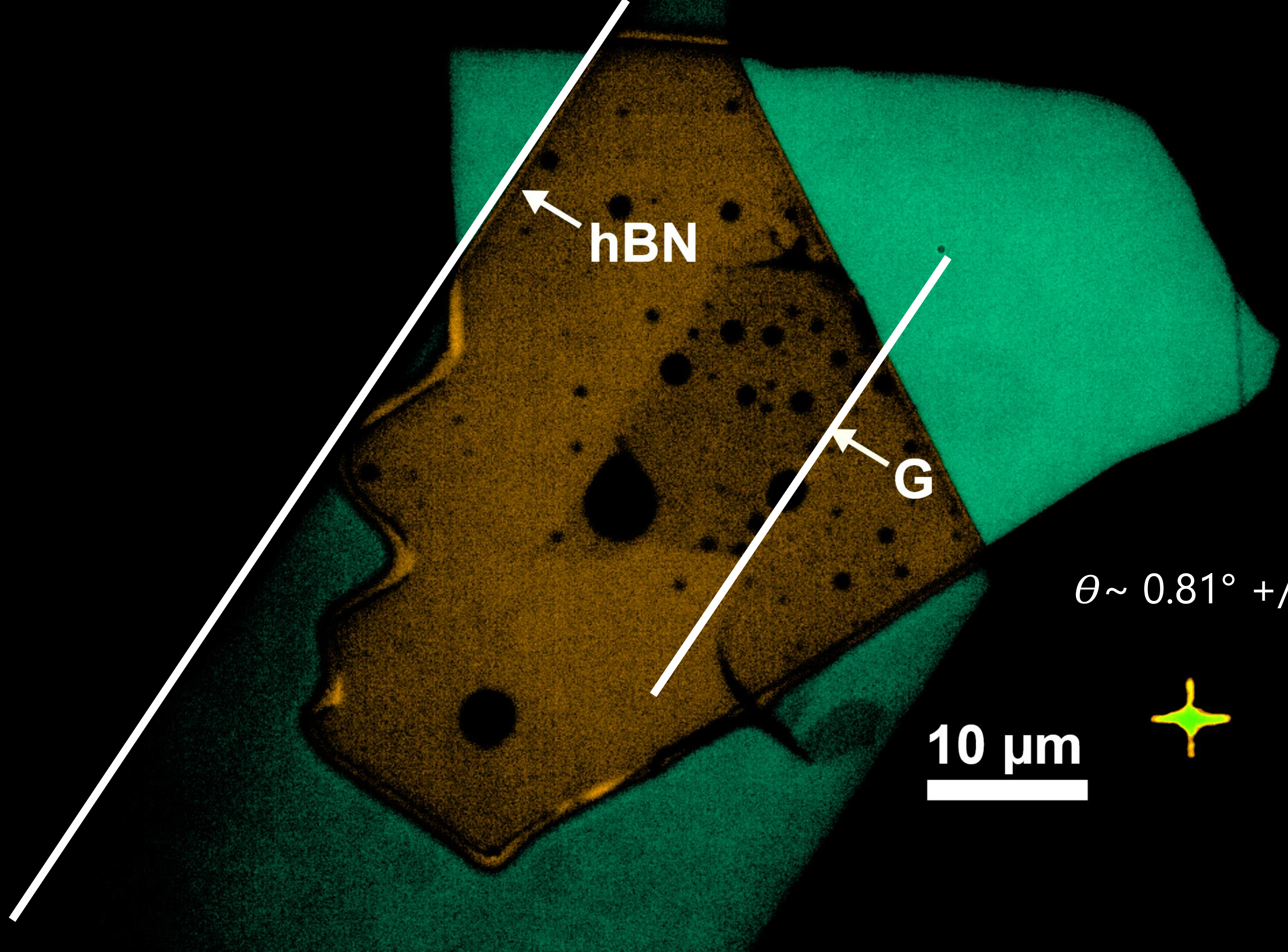


Device 2

Graphene twist: 1.05 +/- 0.01°

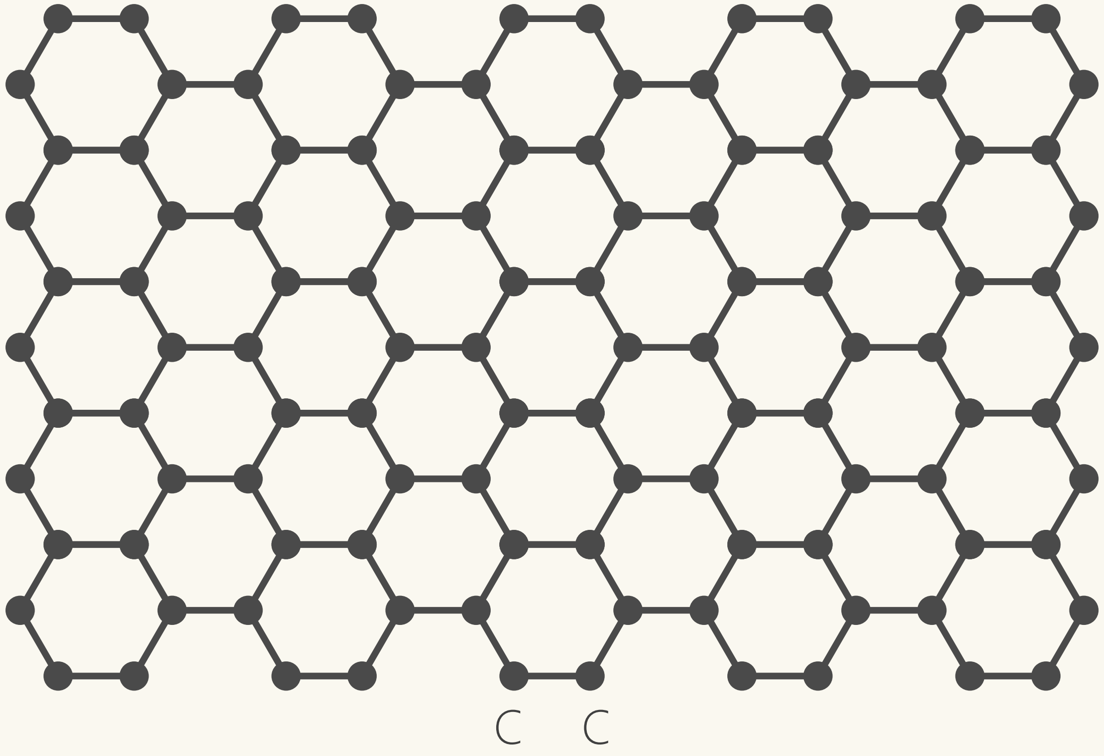


Sharpe et al., Science (2019)

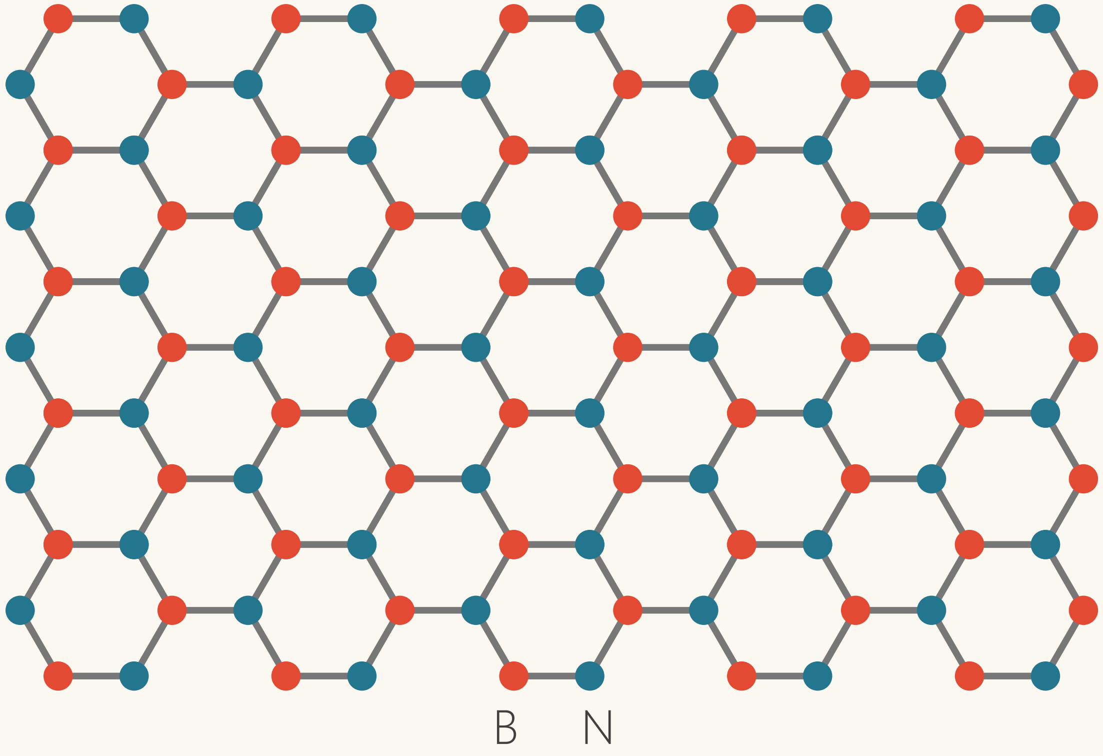


$\theta \sim 0.81° +/- 0.02°$

Graphene

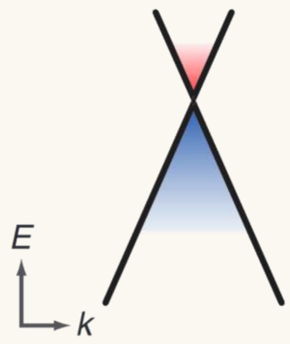


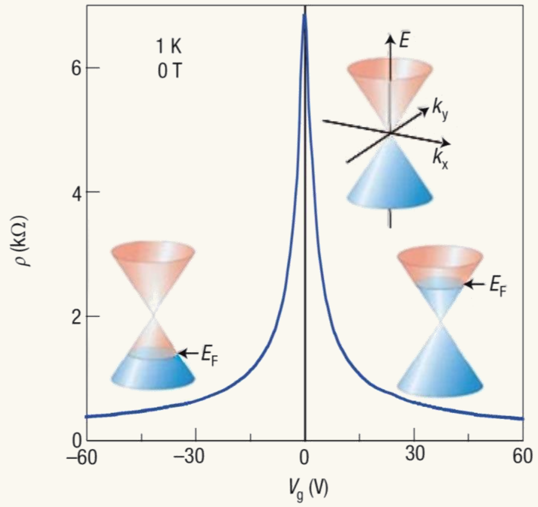
Hexagonal Boron Nitride (hBN)



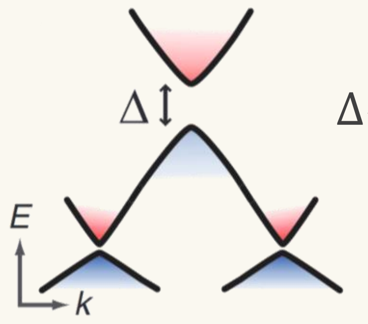
Alignment with hBN

Monolayer graphene

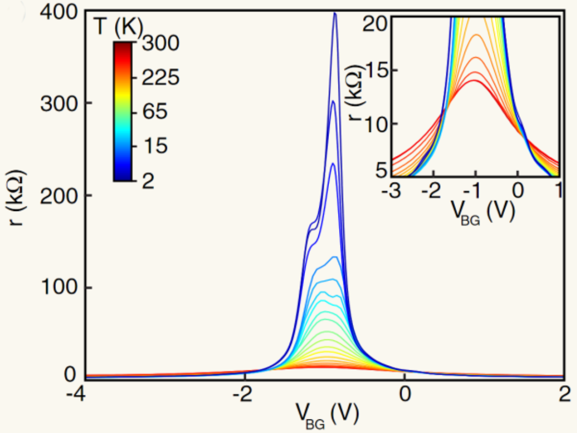




Monolayer graphene + hBN

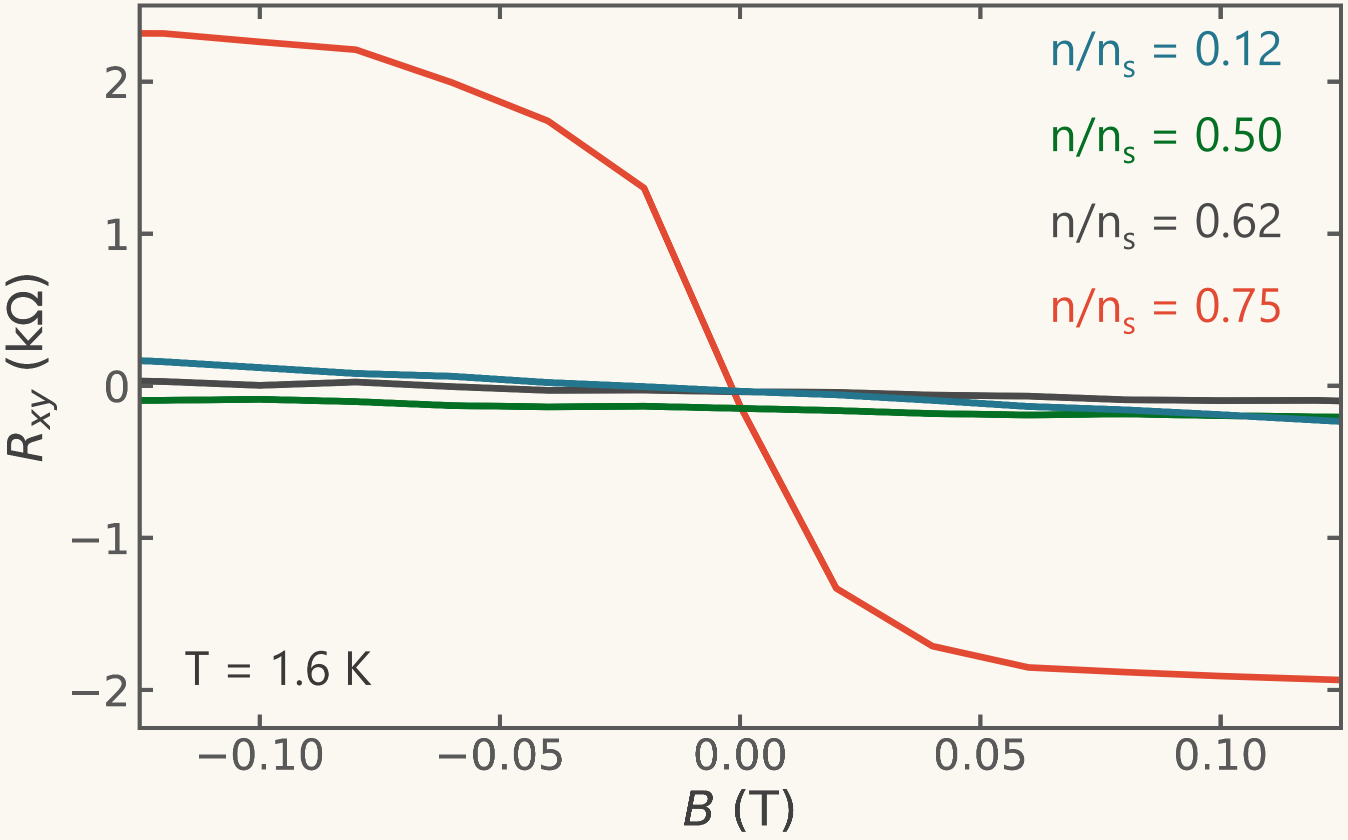


$\Delta \sim 16 - 28$ meV*



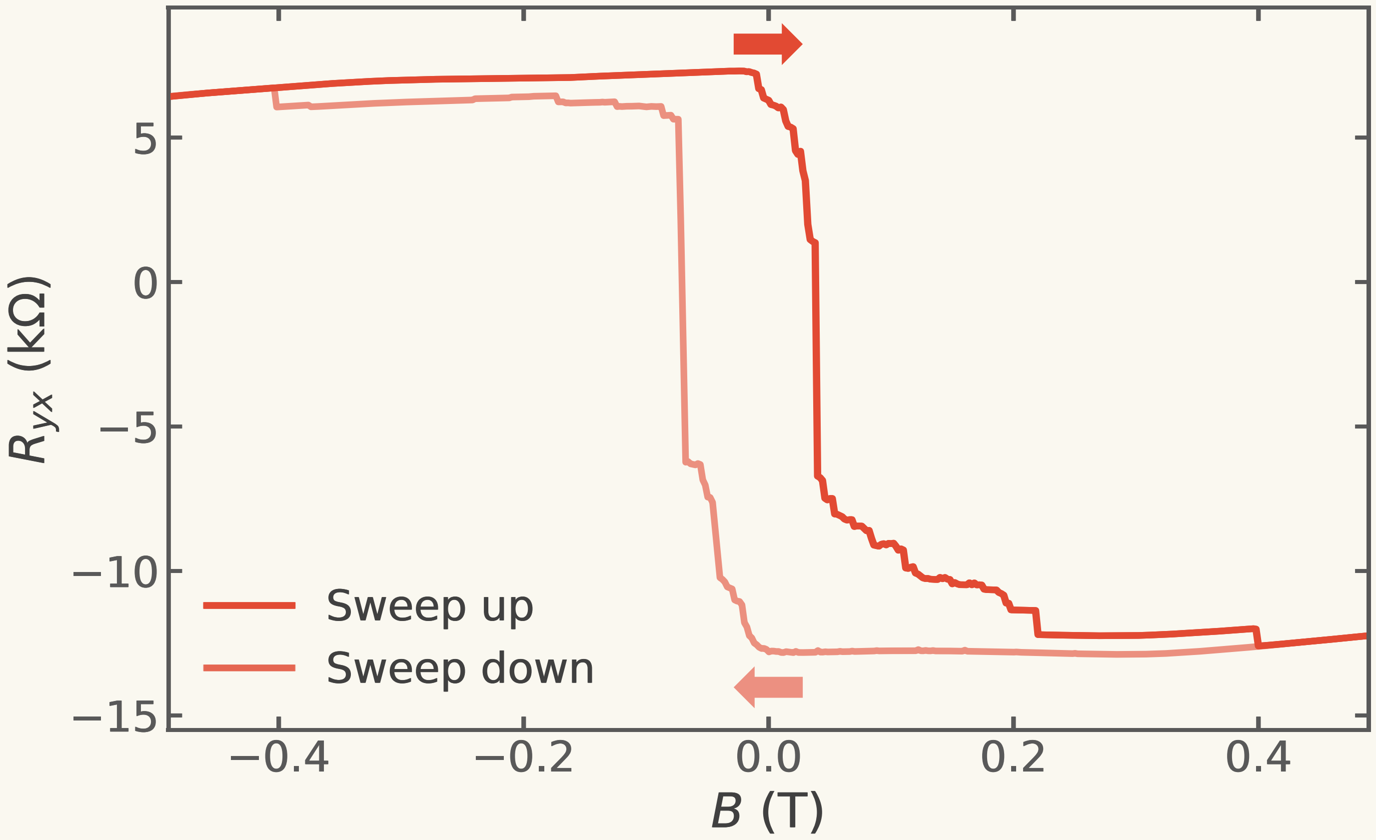
Amet et al., PRL (2013)
Hunt et al., Science (2013)
Geim and Novoselov, Nat. Mat. (2007)

Measuring Hall Slope Density Dependence



Classical Hall: $R_{xy} = \frac{V_H}{I} = -\frac{B}{ne}$

Anomalous Hall Signal Can Be Really Large!

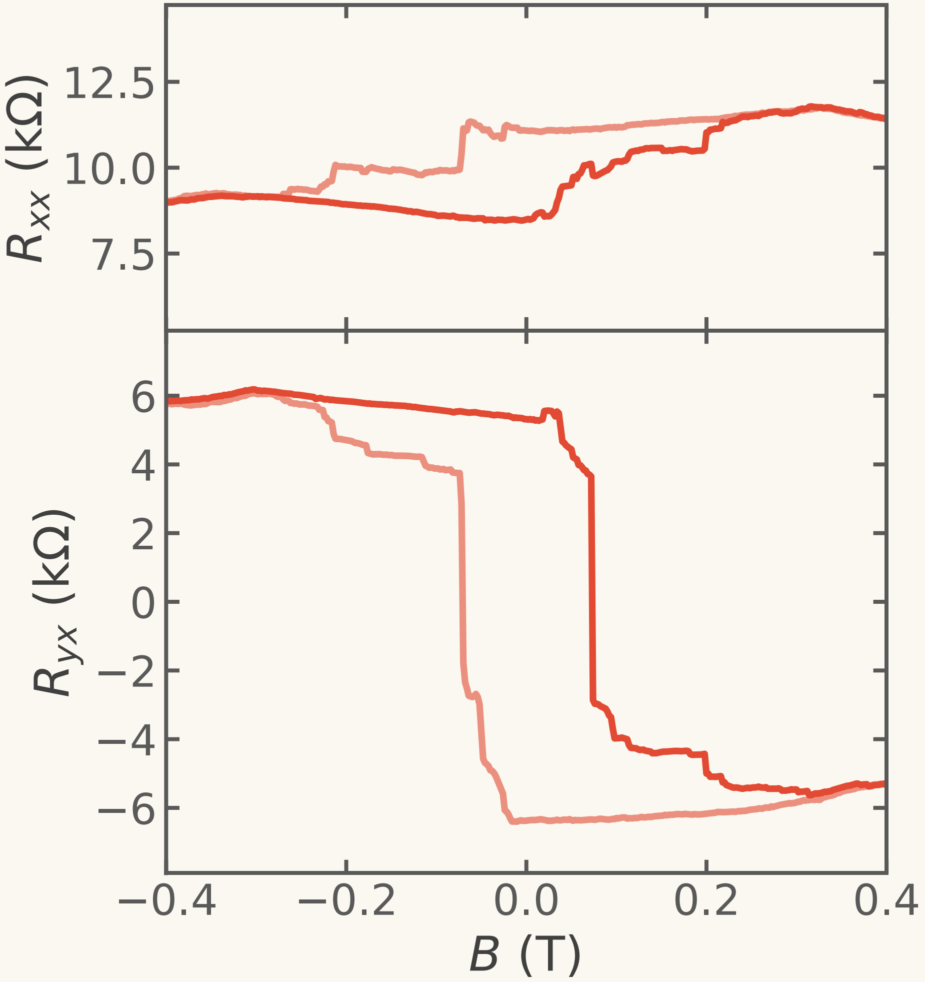


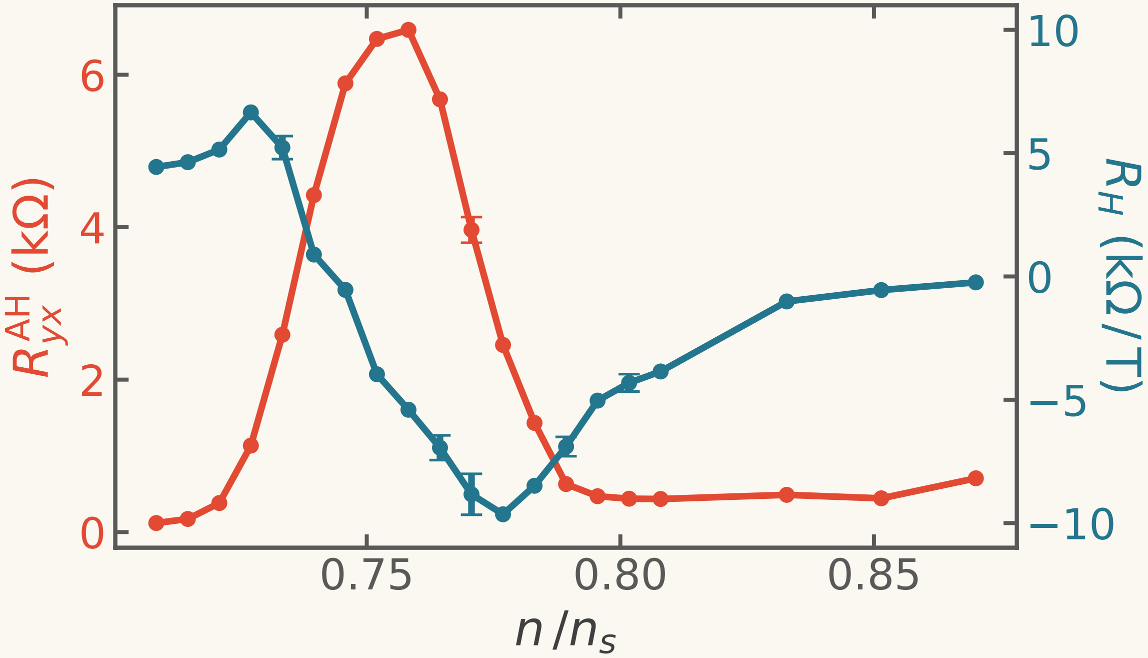
$R_q = h/e^2 \approx 26\ \text{k}\Omega$

n/n_s=0.775, T = 2.1 K

Sharpe et al., Science (2019)

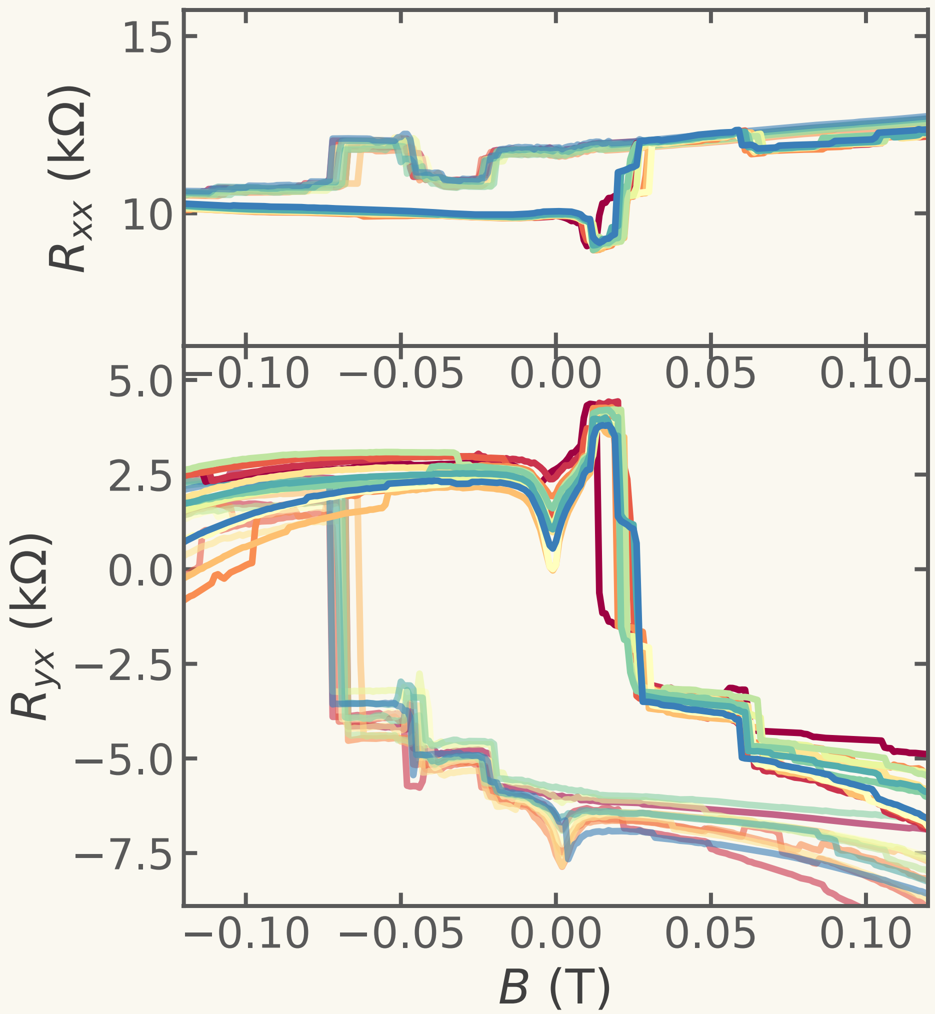
Emergent Ferromagnetism at ¾ Filling





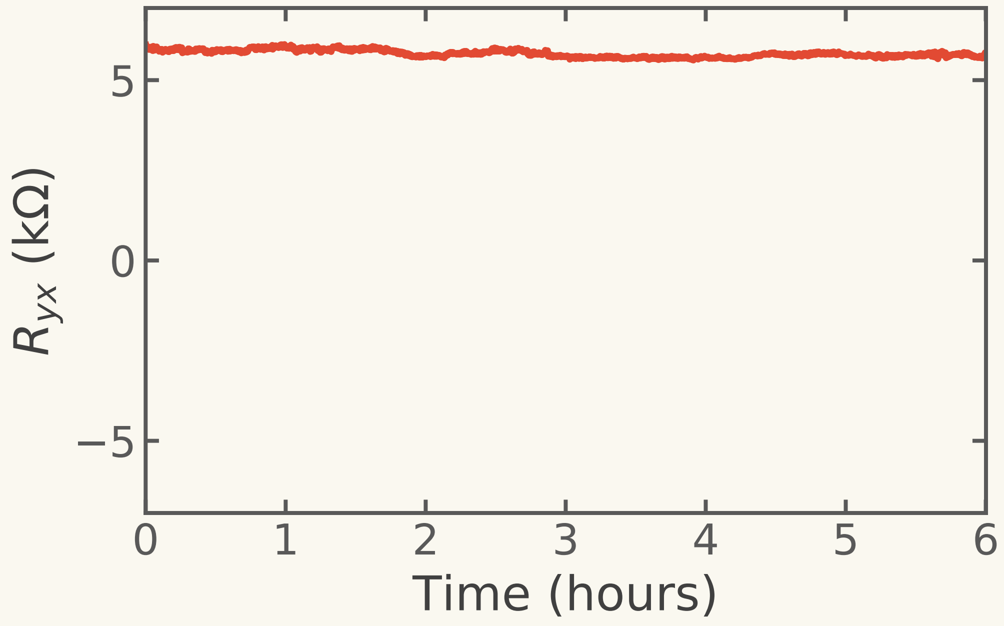
Sharpe et al., Science (2019)

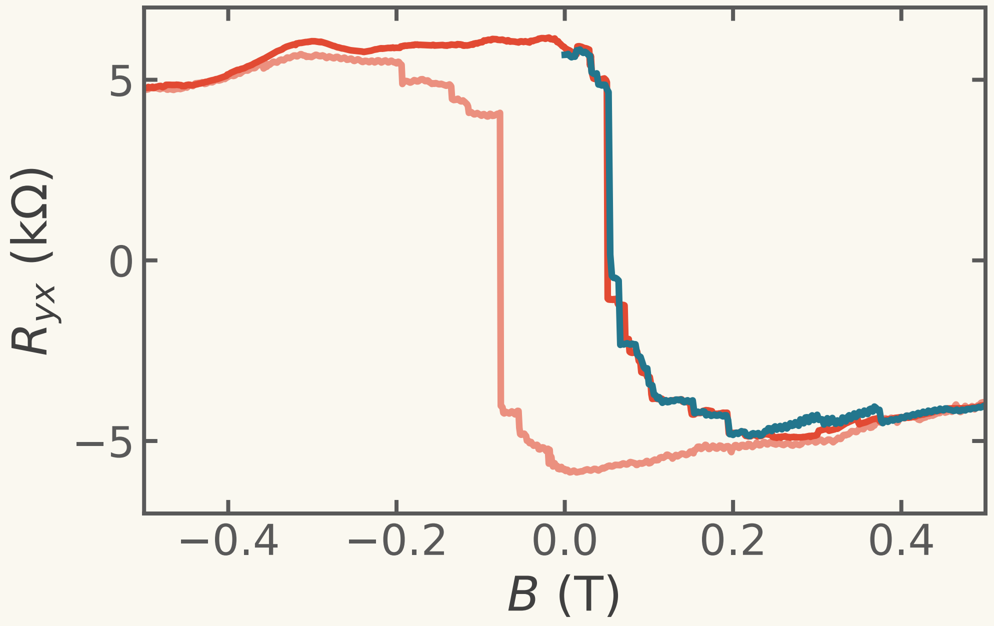
Repeatable Fine Structure



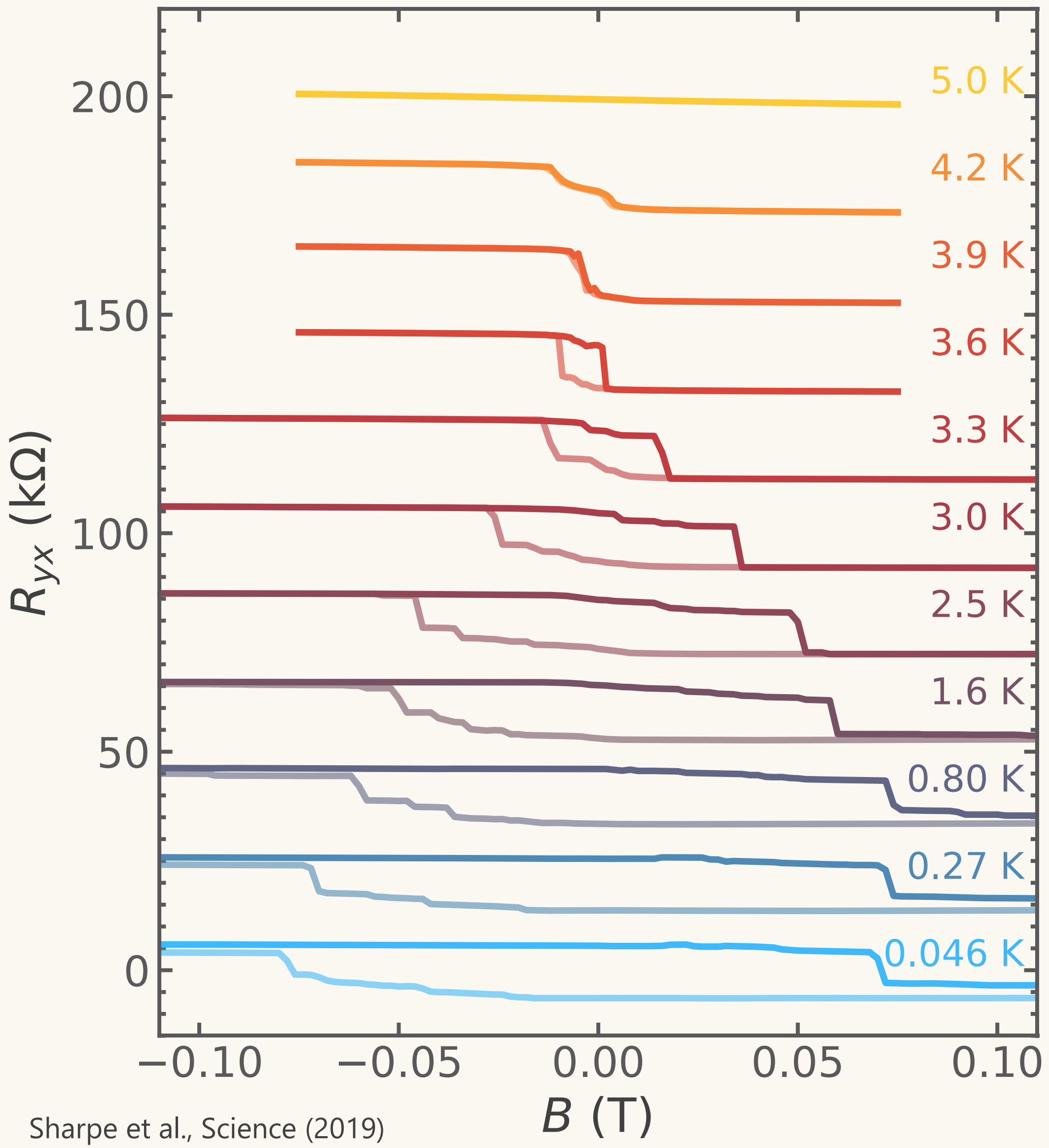
Sharpe et al., Science (2019)

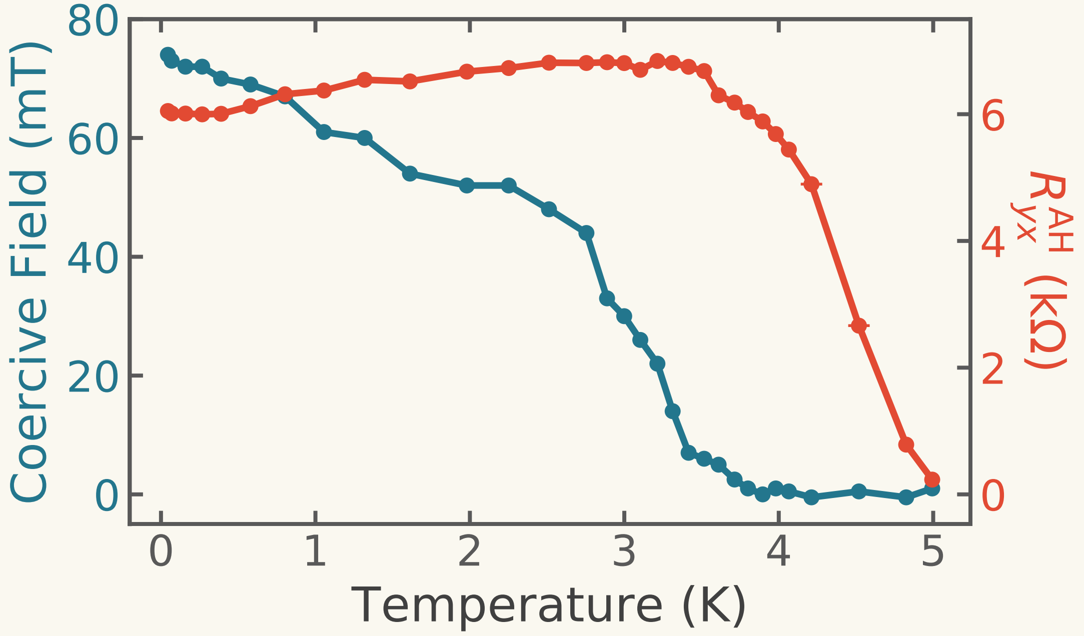
Magnetism is Stable in Zero Applied Field





Sharpe et al., Science (2019)





Sharpe et al., Science (2019)

Large anomalous Hall

Apparent insulating state

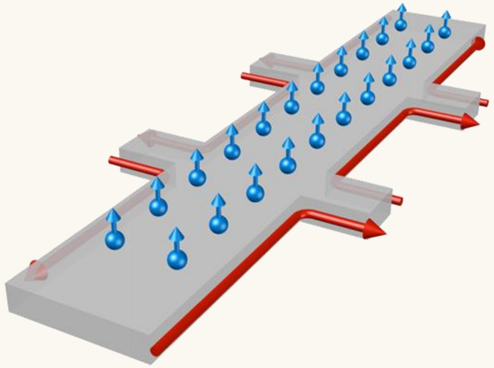
Evidence of domains

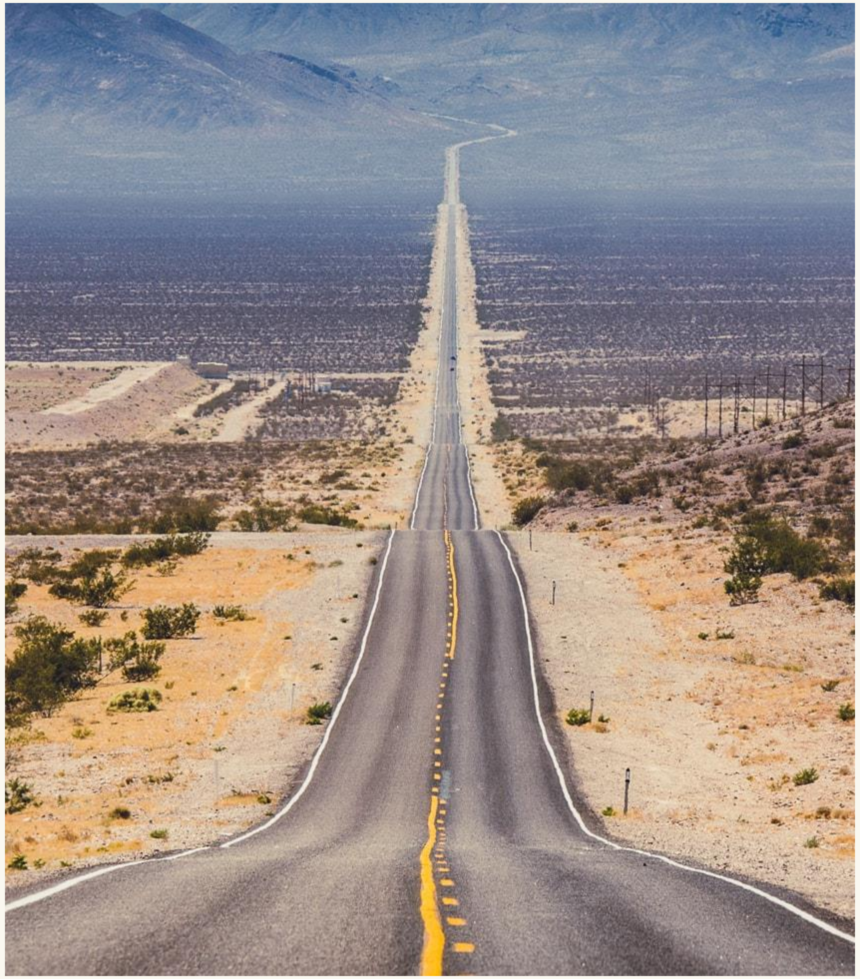
Reminiscent of early Magnetic TIs

Chern insulator?

Ideally: $\rho_{xx} = 0$

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





flightnetwork.com/blog/road-trip-on-route-66/

Large anomalous Hall

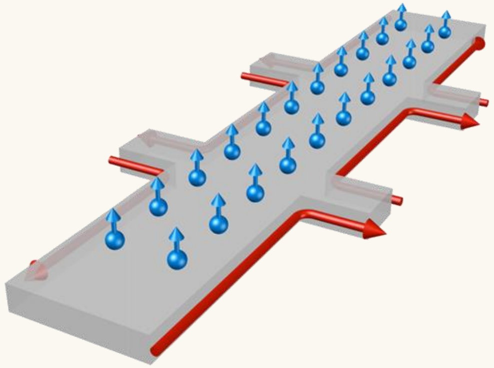
Apparent insulating state

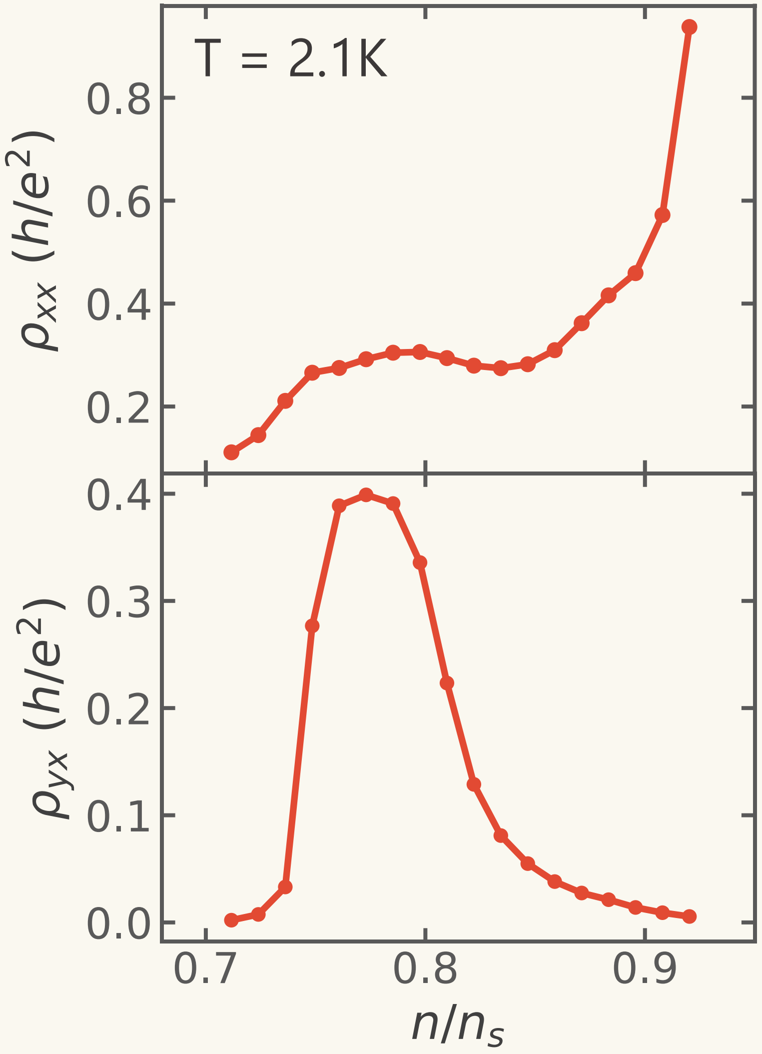
Evidence of domains

Reminiscent of early Magnetic TIs

Chern insulator?

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





Sharpe et al., Science (2019)

Large anomalous Hall

Apparent insulating state

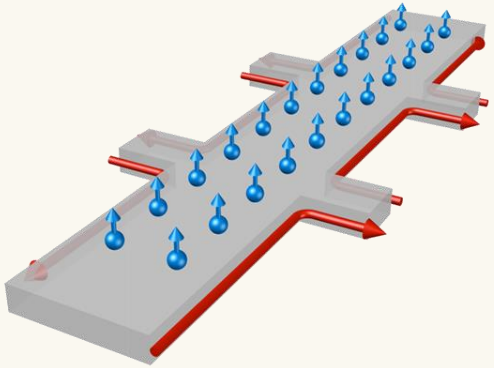
Evidence of domains

Reminiscent of early Magnetic TIs

Chern insulator?

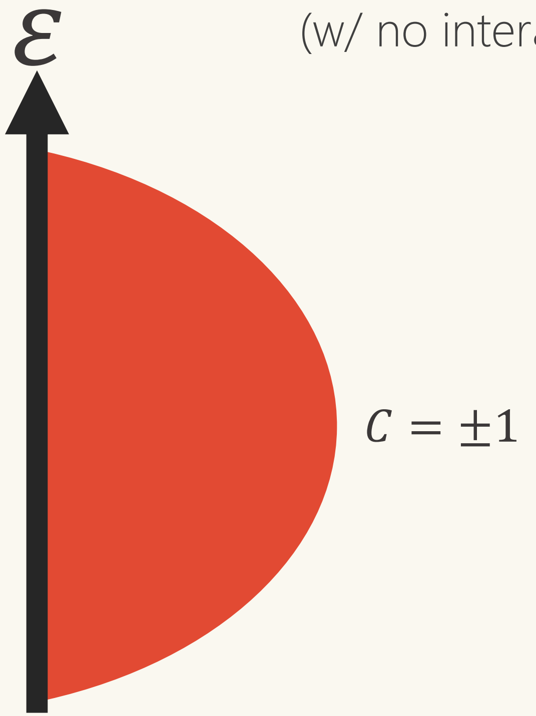
Ideally: $\rho_{xx} = 0$

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



4-fold degeneracy

(w/ no interactions)



TBG + hBN:

Zhang et al., PRR (2019)

Bultinck et al., PRL (2020)

Spontaneously Gapped:

Xie et al., PRL (2020)

Large anomalous Hall

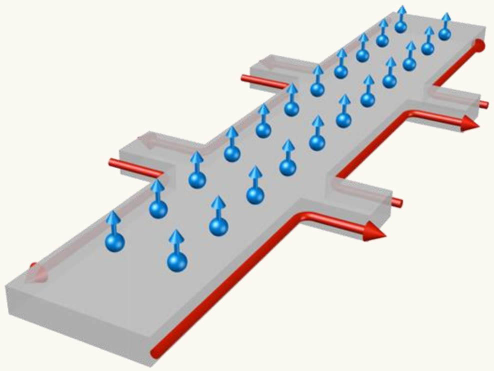
Apparent insulating state

Evidence of domains

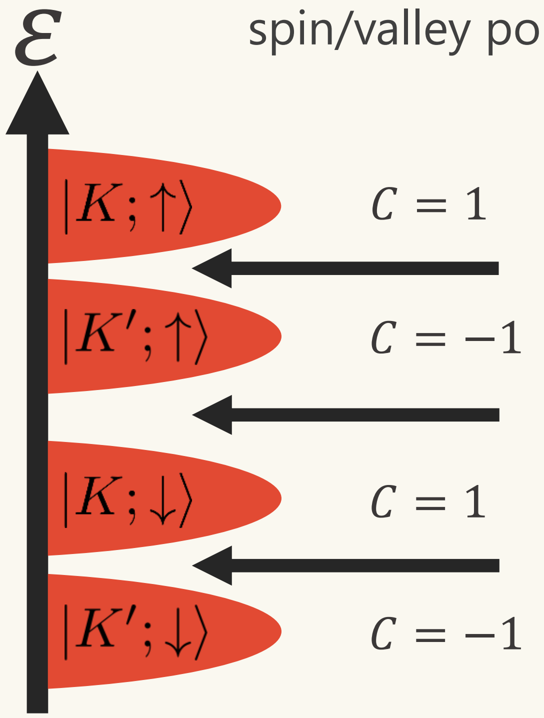
Reminiscent of early Magnetic TIs

Chern insulator?

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



Interaction driven
spin/valley polarization



quantum anomalous
Hall insulator

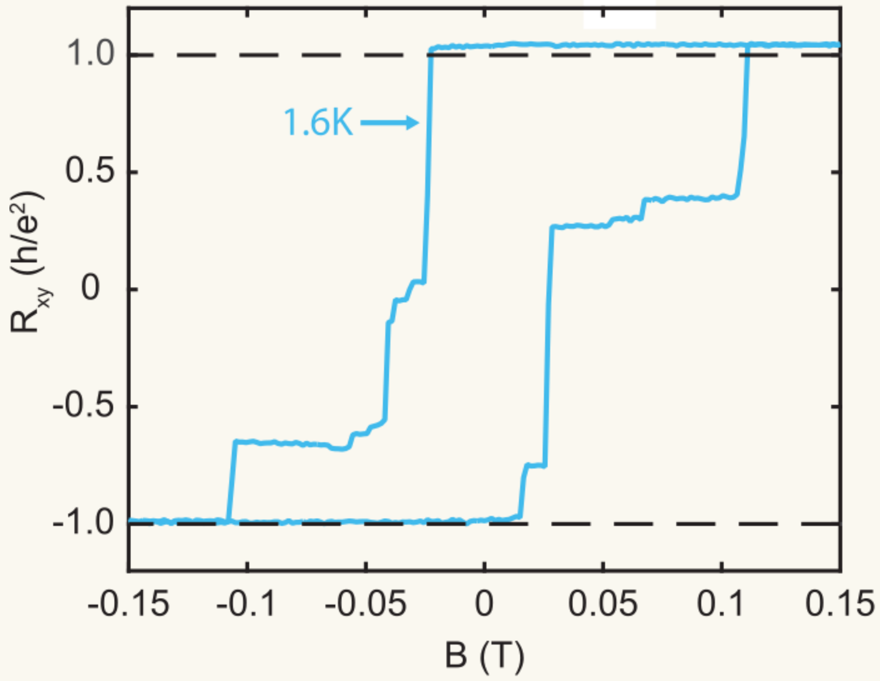
quantum valley
Hall insulator

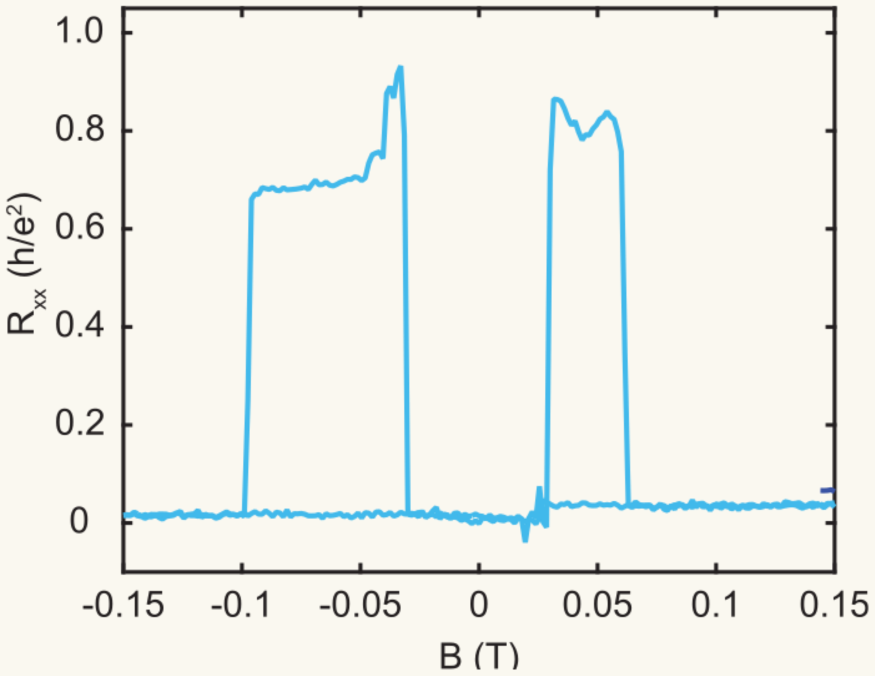
quantum anomalous
Hall insulator

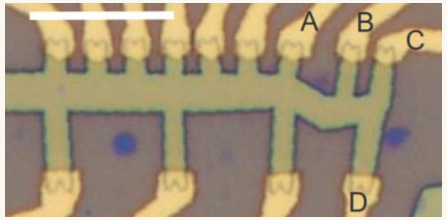
TBG + hBN:
Zhang et al., PRR (2019)
Bultinck et al., PRL (2020)

Spontaneously Gapped:
Xie et al., PRL (2020)

Quantum Anomalous Hall in TBG

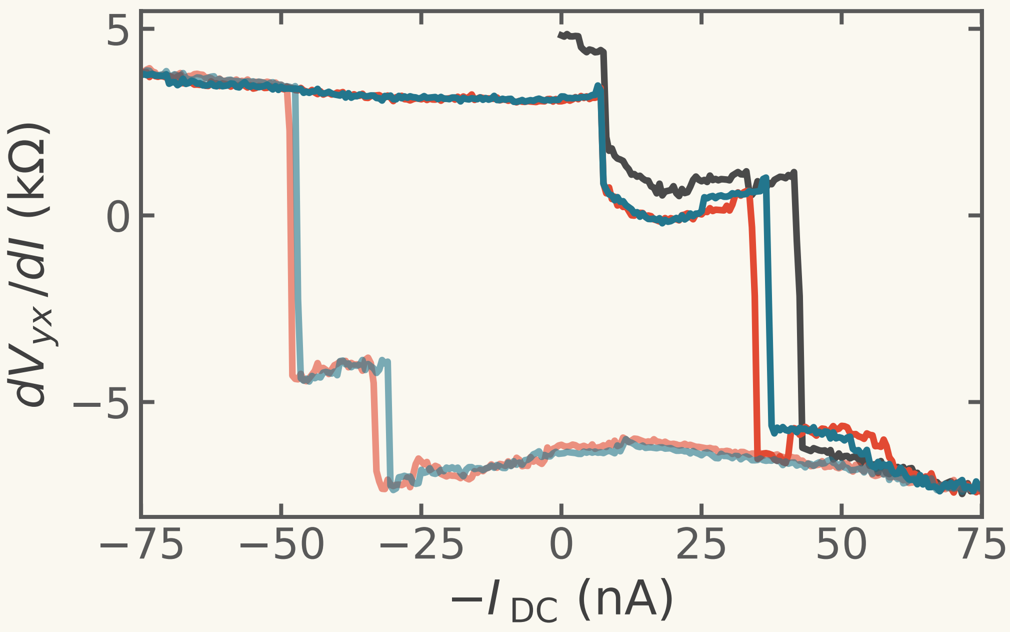






Serlin et al., Science (2019)

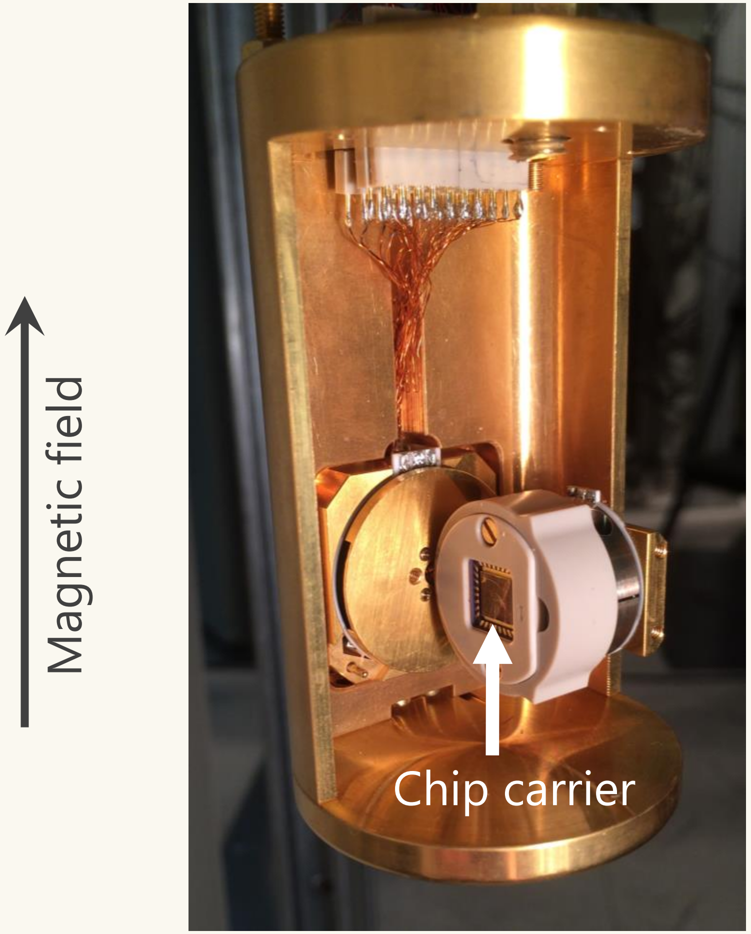
Repeatable Hysteresis in DC Current

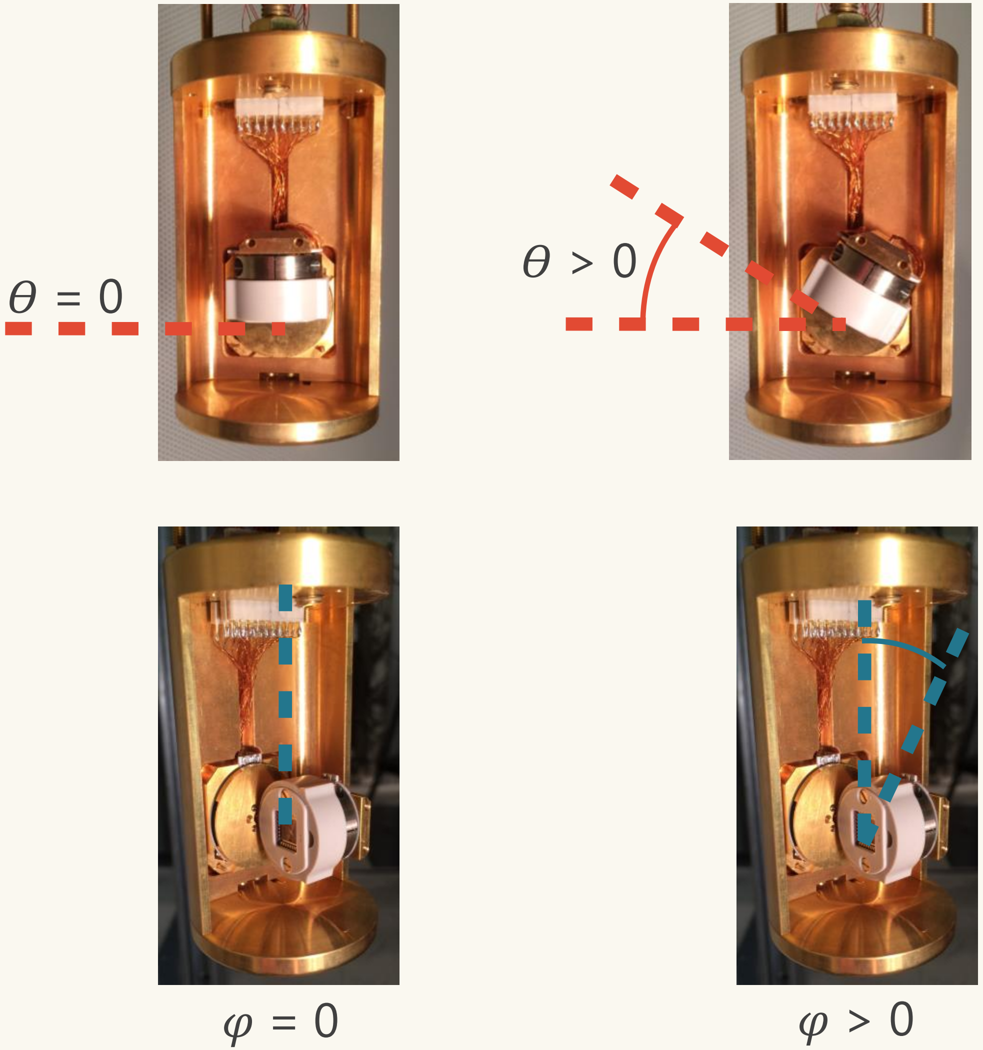


Relevant theory:
Su and Lin, arXiv:2002.02611
He et al., Nat. Comms. (2020)
Upadhyaya et al., PRB (2016)

Sharpe et al., Science (2019)

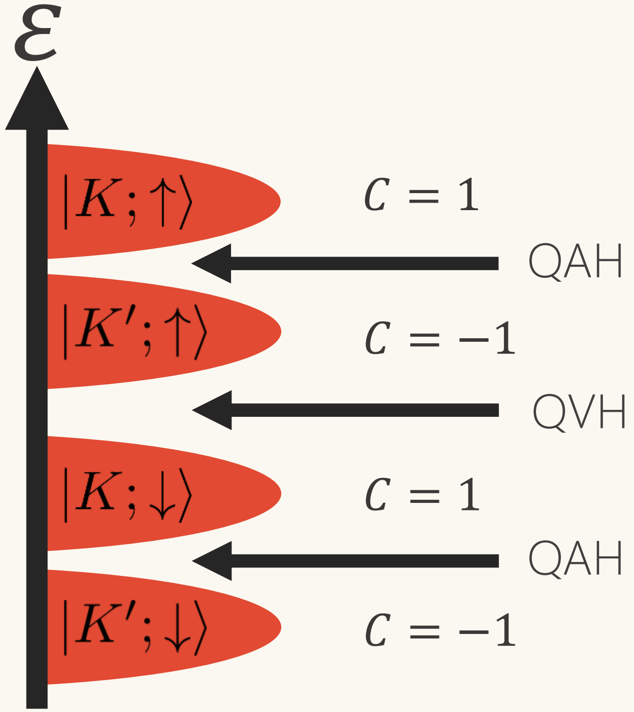
Probing Nature of Magnetism





Possible Scenarios and in-plane response:

Interaction driven spin/valley polarization

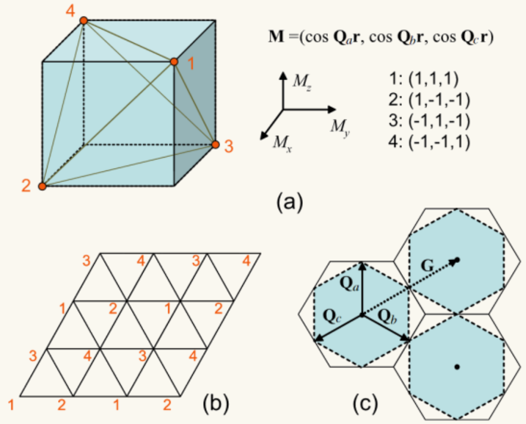


Valley-polarized, spin-unpolarized composite Fermi liquid

similar to FQHE

Non-coplanar chiral spin order at 3/4 filling of an individual band

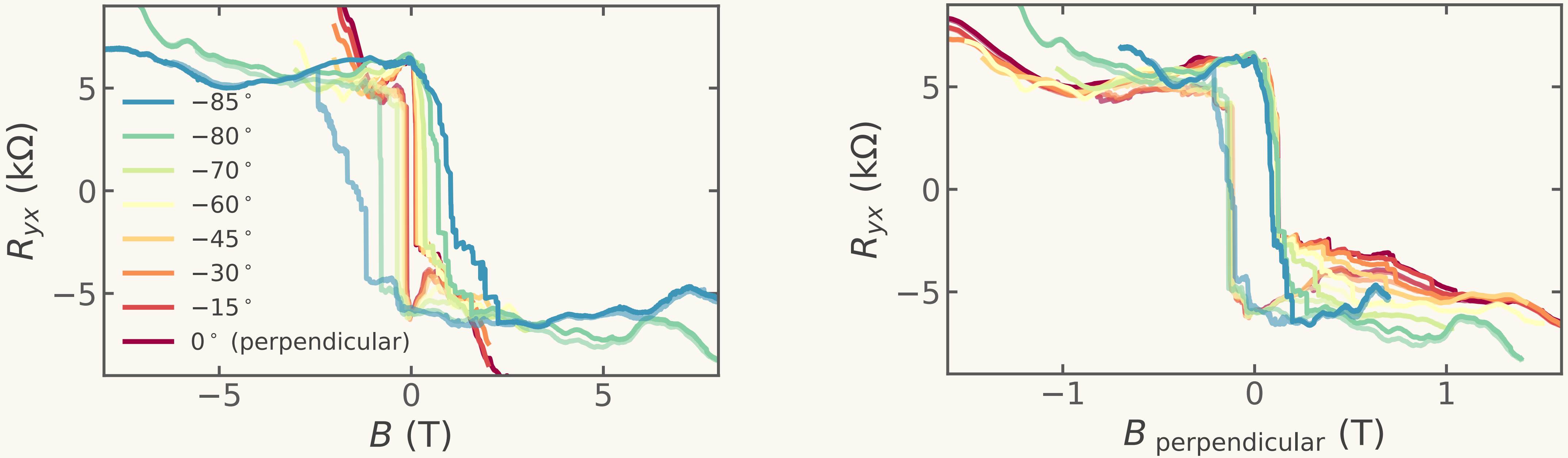
(two copies from valley)



Xie et al., PRL (2020)
Zhang et al., PRR (2019)
Bultinck et al., PRL (2020)
Zhang et al., PRR (2019)
Martin et al., *PRL* (2008)
Lee et al., Nat. Comms. (2019)

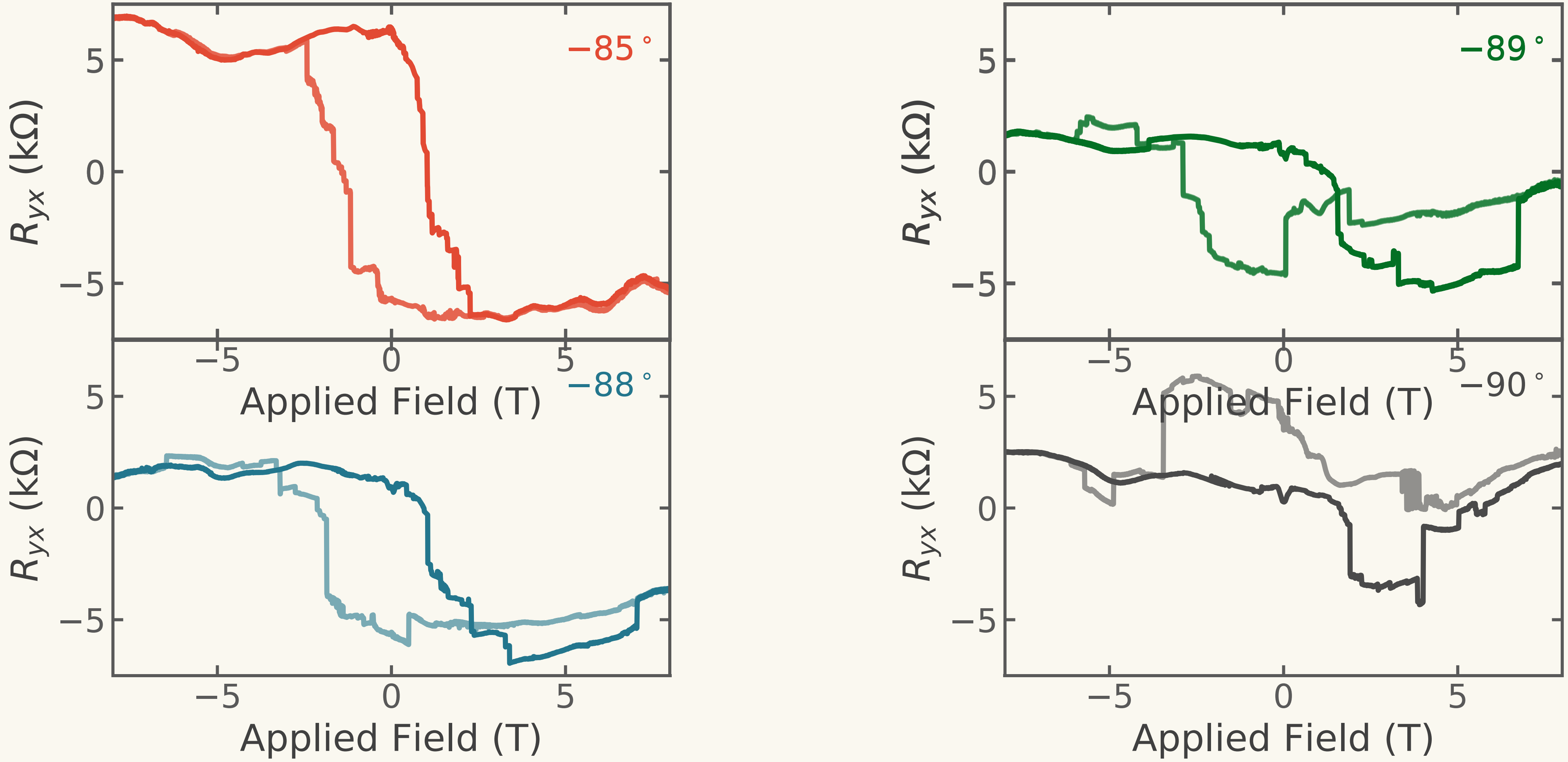
In-plane field can couple to valley!

Hysteresis Loops in Tilted Field

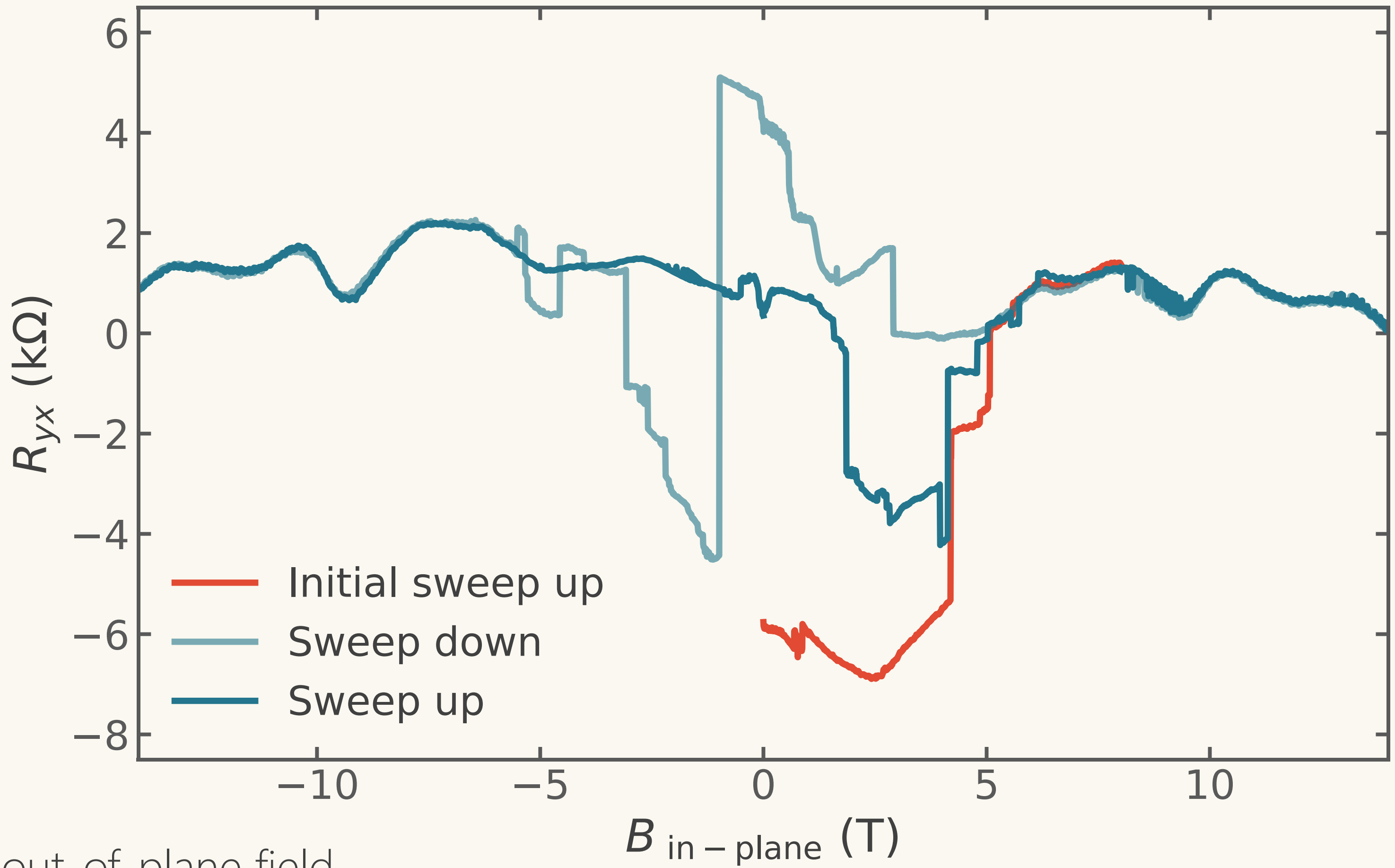


Mostly sensitive to perpendicular component!

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

Conclusions

Twist angle is a new knob

TBG is a Chern insulator near ¾ filling

No magnetic dopants needed

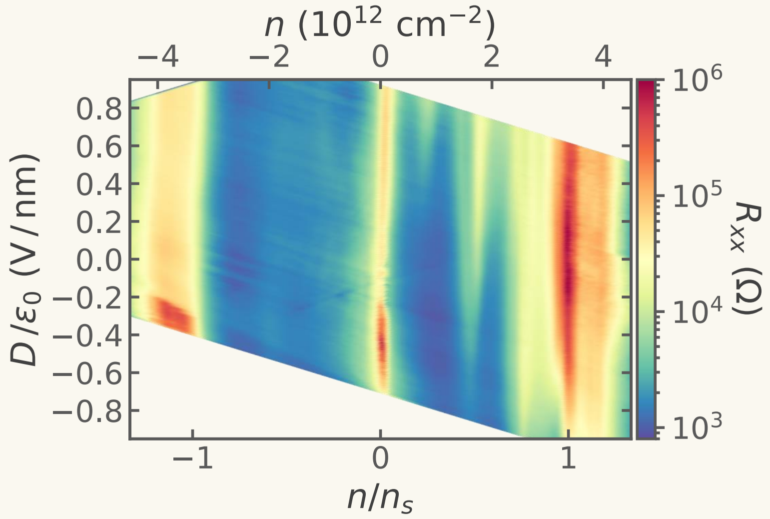
Aligned hBN may be crucial to open topologically nontrivial gap

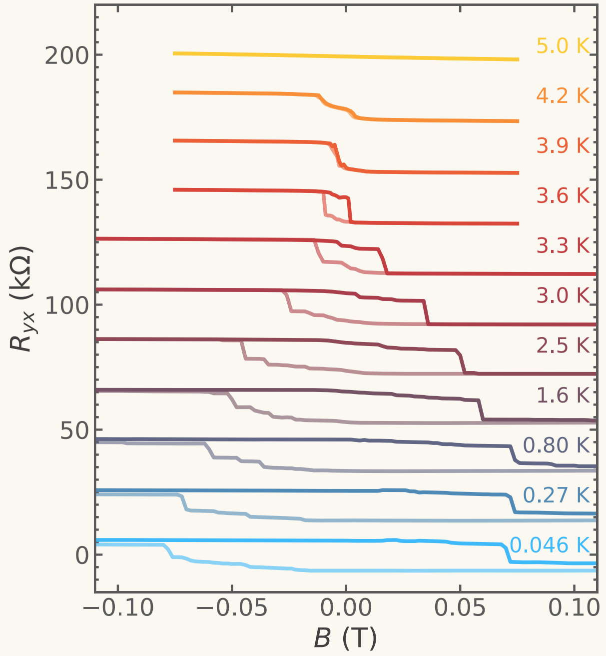
Orbital ferromagnet

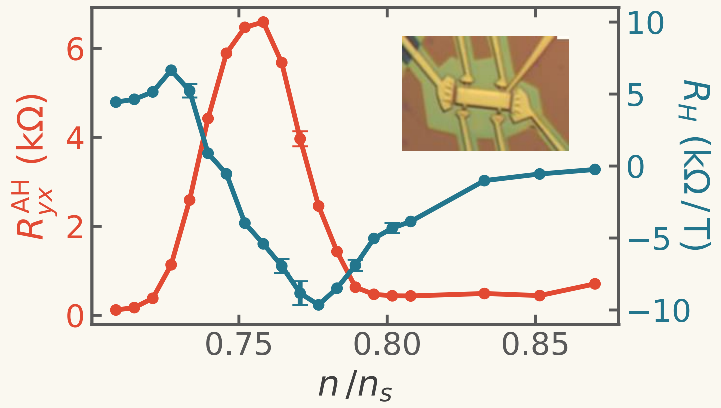
High degree of anisotropy

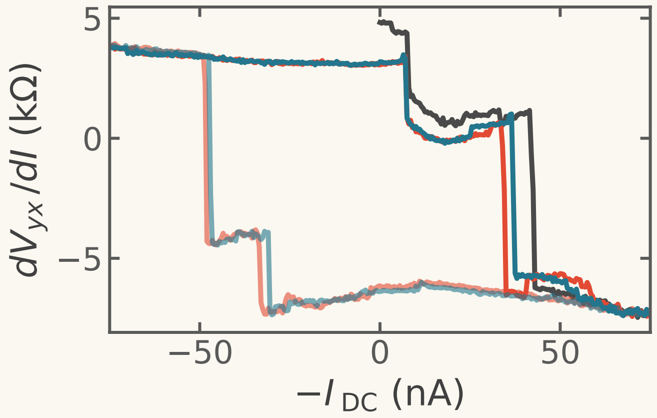
Sufficiently large in-plane field kills magnetization

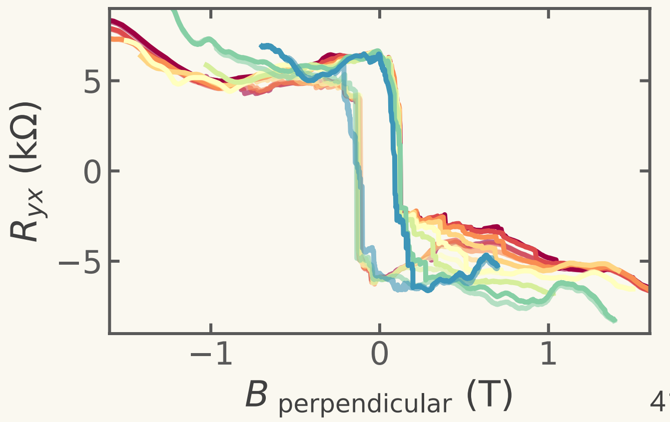
In-plane field is coupling to either spin or valley











10.1126/science.aaw3780