Title: Can you make a magnet out of carbon?

Speakers: David Goldhaber-Gordon

Series: Colloquium

Date: September 23, 2020 - 2:00 PM

URL: http://pirsa.org/20090007

Abstract: In most materials, electrons fill bands, starting from the lowest kinetic energy states. The Fermi level is the boundary between filled states below and empty states above. This is the basis for our very successful understanding of how metals and semiconductors work. But what if all the electrons within a band had the same kinetic energy (this situation is called a "flat band")? Then electrons could arrange themselves so as to minimize their Coulomb repulsion, giving rise to a wide variety of possible states including superconductors and magnets. Until recently, flat bands were achieved only by applying large magnetic fields perpendicular to a 2D electron system; in this context they are known as Landau levels. Fractional quantum hall effects result from Coulomb-driven electron arrangement within a Landau level. Recently, Pablo Jarillo-Herrero of MIT and coworkers demonstrated flat minibands in graphene-based superlattices, discovering correlated insulators and superconductors at different fillings of these minibands. We have now discovered dramatic magnetic states in such superlattice systems. Specifically, in magic-angle twisted bilayer graphene which is also aligned with a hexagonal boron nitride (hBN) cladding layer, we observe a giant anomalous Hall effect as large as 10.4 kÎ©, and signs of chiral edge states. This all occurs at zero magnetic field, in a narrow density range around an apparent insulating state at 3 electrons (1 hole) per moirÃ© cell in the conduction miniband [1]. Remarkably, the magnetization of the sample can be reversed by applying a small DC current. Although the anomalous Hall resistance is not quantized, and dissipation is significant, we suggest that the system is essentially a "Chern insulator", a type of topological insulator similar to an integer quantum Hall state. In a quite different superlattice system, ABC-trilayer graphene aligned with hBN, again near 3 electrons (1 hole) per moirÃ© cell a Chern insulator emerges [2]. This time the flat band is a valence miniband, and a magnetic field of order 100 mT is needed to quantize the anomalous hall signal. This trilayer system can be tuned in-situ to display superconductivity instead of magnetism [3]. We will discuss possible magnetic states, complementary probes to examine which state actually emerges as the ground state in each system, and what one might do with such states.

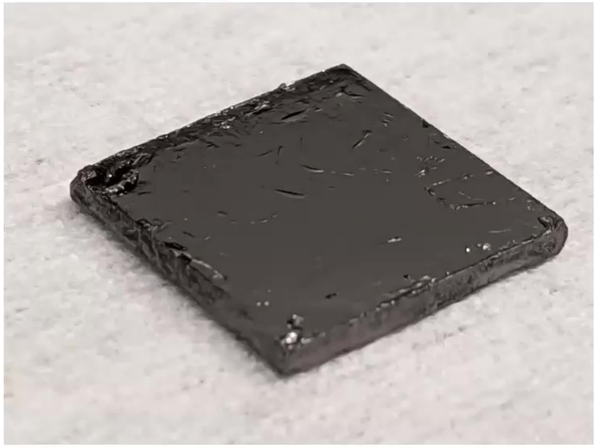
[1] A.L. Sharpe et al., â€œEmergent ferromagnetism near three-quarters filling in twisted bilayer grapheneâ€•, Science 365, 6453 (2019).
[2] G. Chen et al., â€œTunable Correlated Chern Insulator and Ferromagnetism in Trilayer Graphene/Boron Nitride Moire Superlatticeâ€•, Nature 579, 56 (2020)
[3] G. Chen et al., â€œSignatures of tunable superconductivity in a trilayer graphene moirÃ© superlatticeâ€•, Nature 572, 215 (2019).

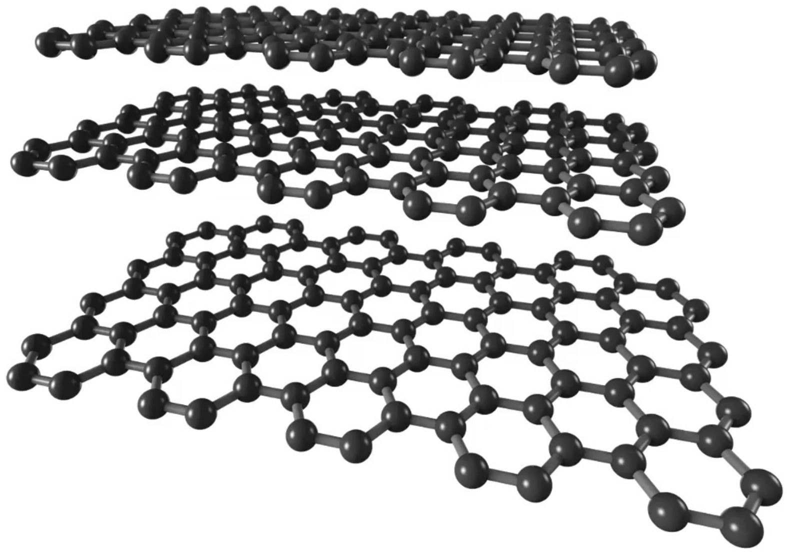
Can you make a magnet out of carbon?

David Goldhaber-Gordon
Stanford University

Perimeter Institute September 23, 2020

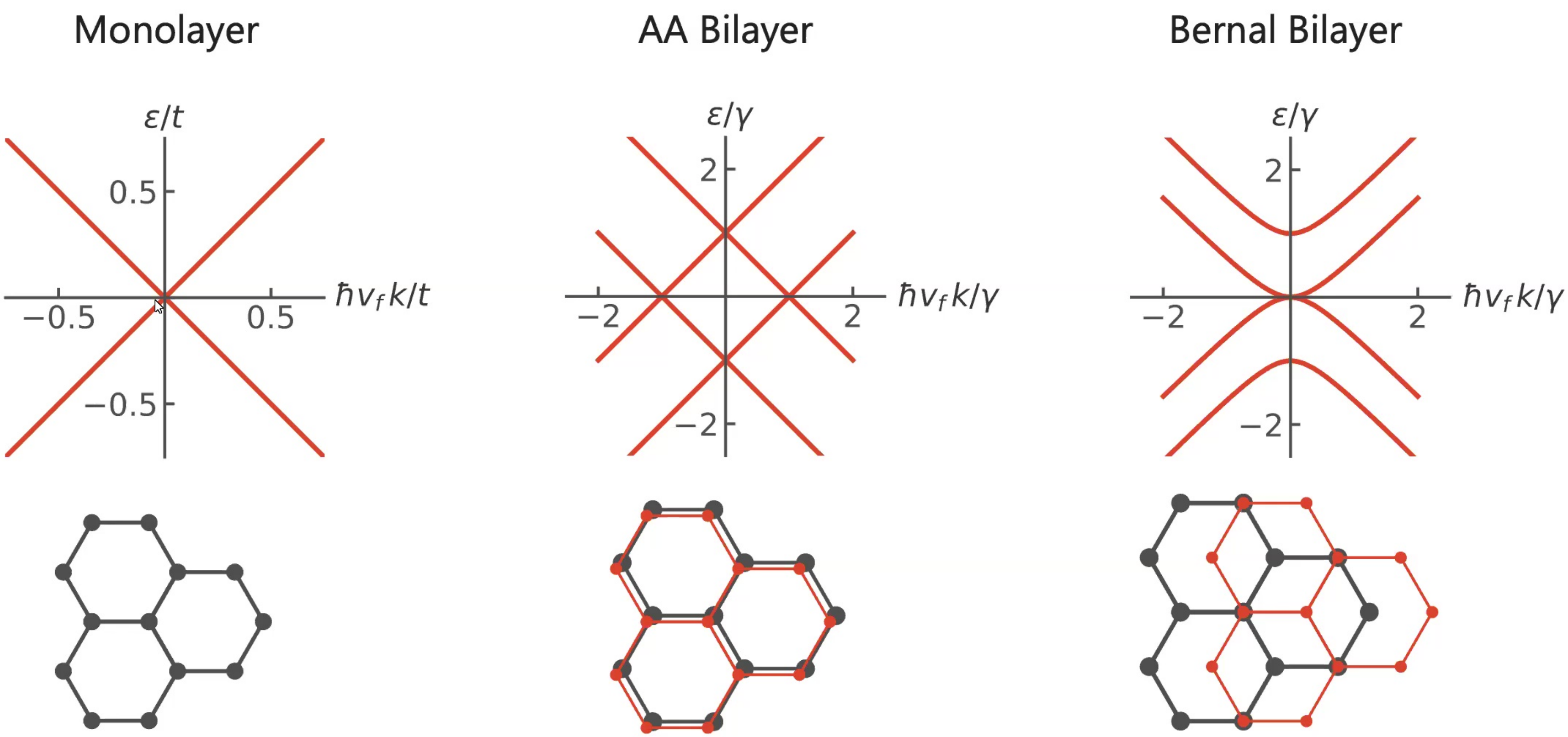
Graphene





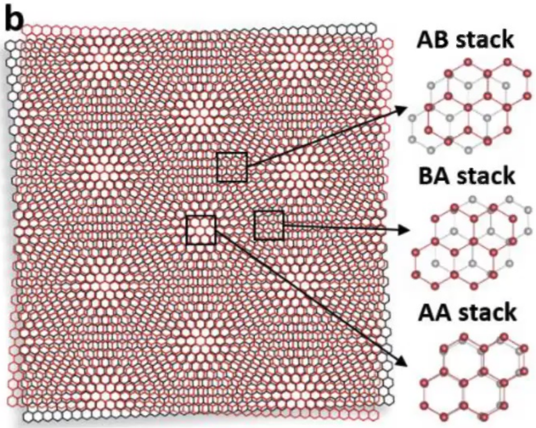
nisenet.org

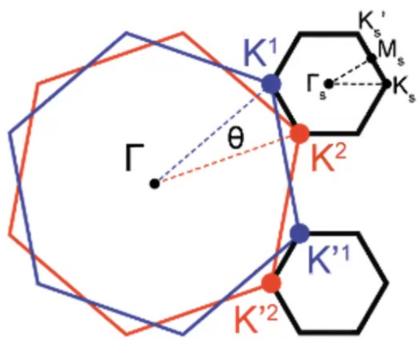
Layer Dependent Properties

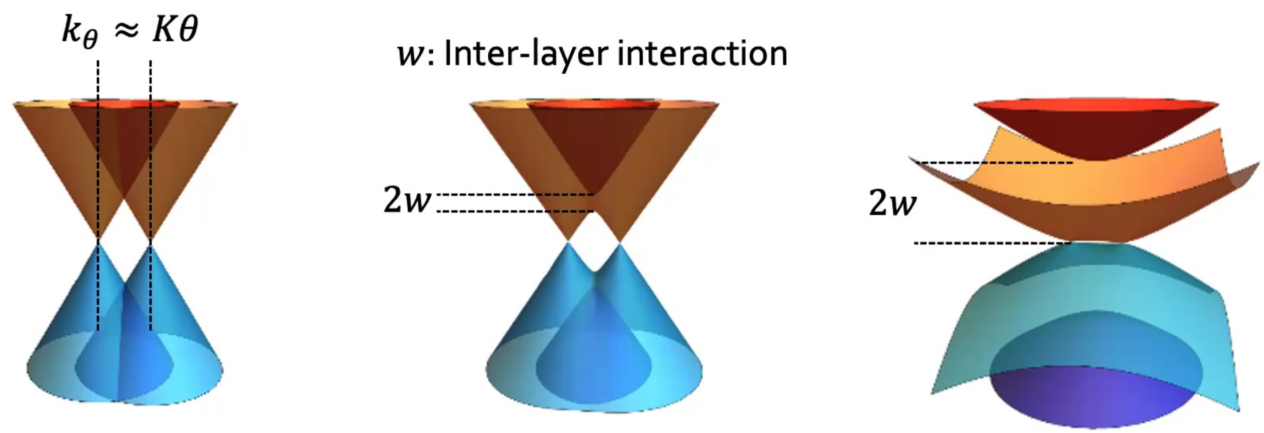


Twisted Bilayer Graphene

Engineering bandstructure







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

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

Decreasing Twist Angle

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

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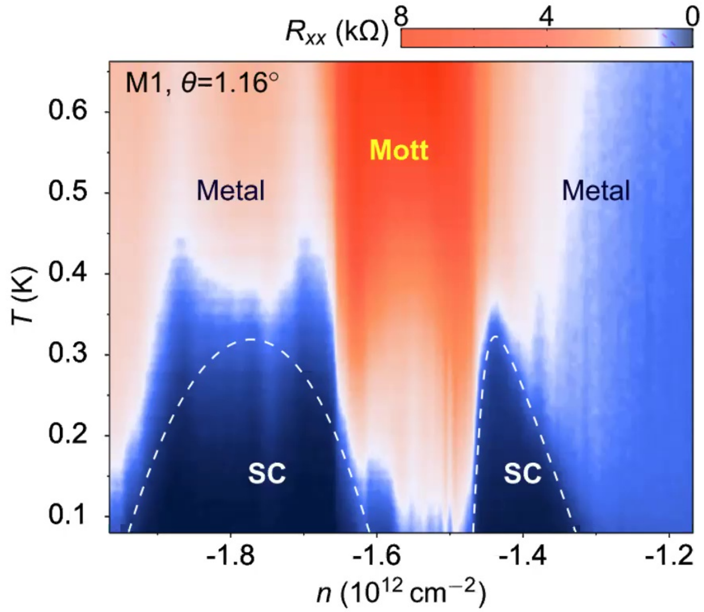
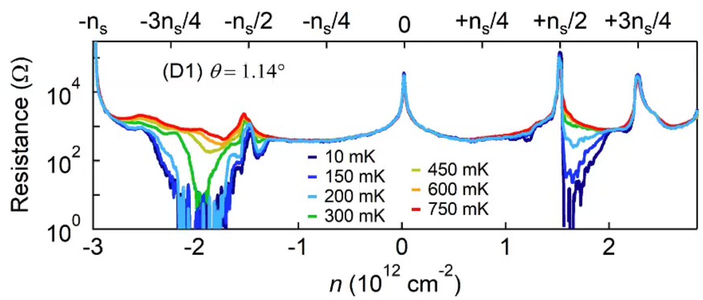
Strong Correlations

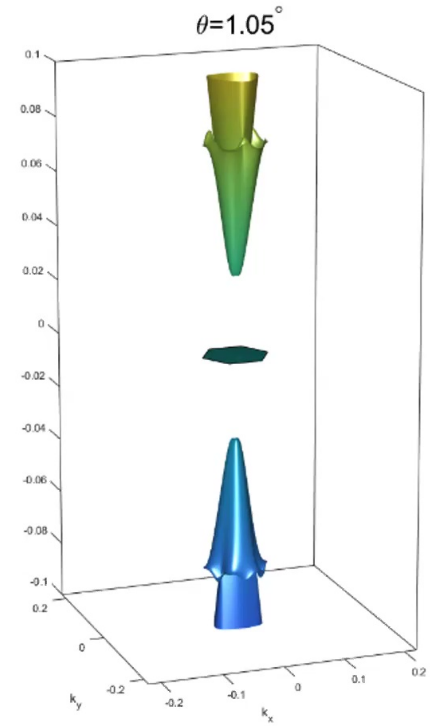
Twisted bilayer graphene provides unprecedented control of correlations in 2D electron systems



Cao, *Nature* (2018)



Yankowitz, *Science* (2019)



Jarillo-Herrero and Kaxiras groups

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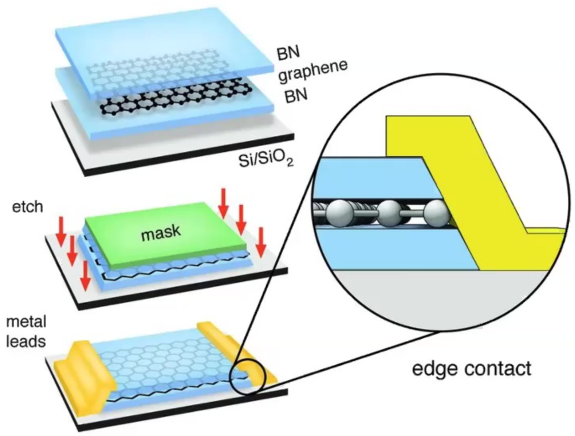
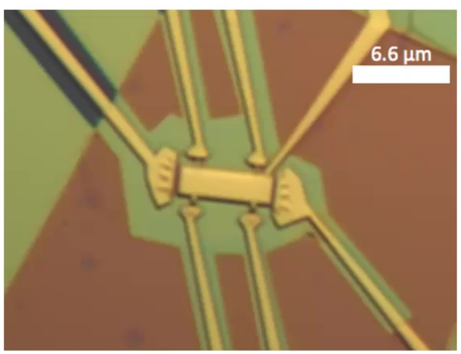
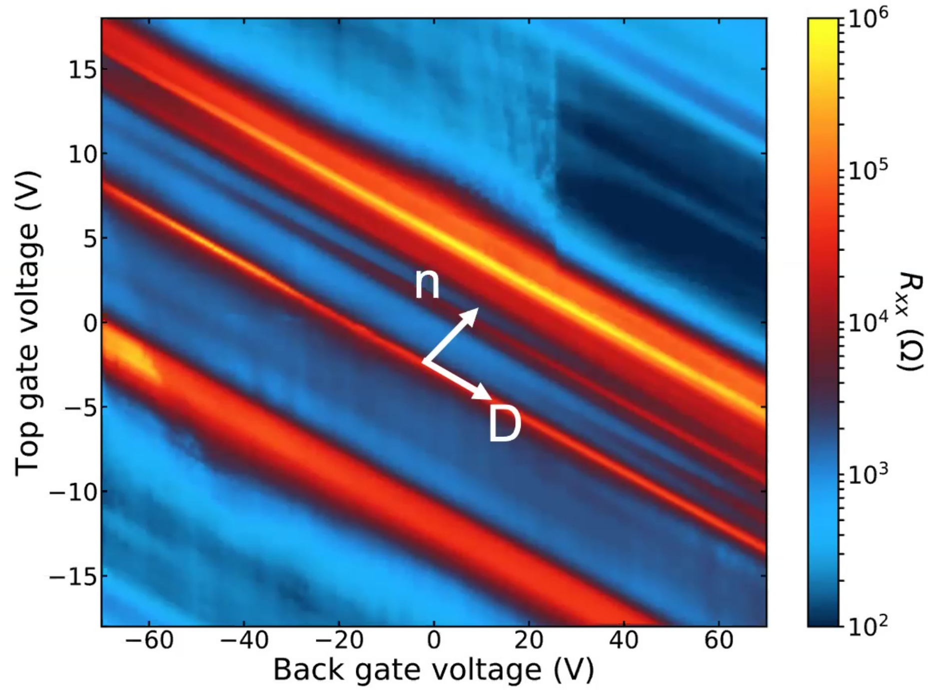
Strong Correlations: Twisted bilayer near magic angle



Wang, *Science* (2013)

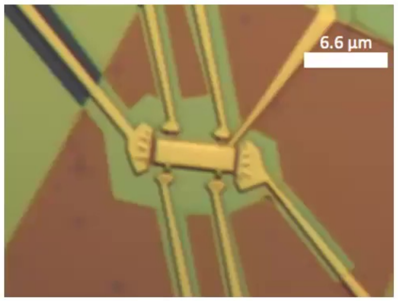




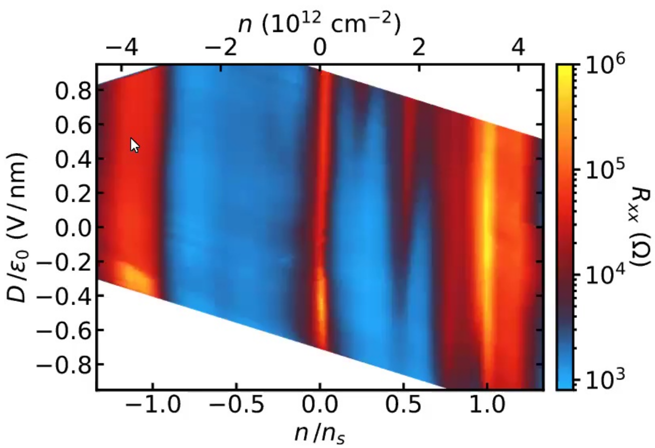
Angle 1.20+/-0.01°. Target 1.17°

Impact of Alignment with hBN

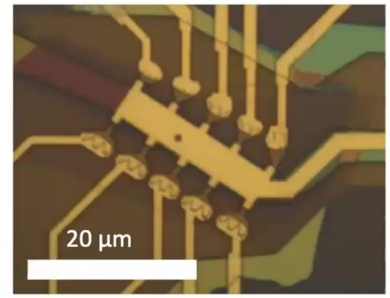
Device 1: aligned hBN



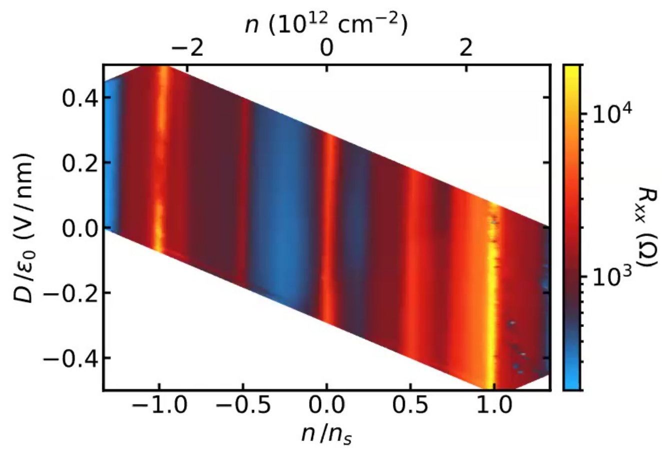
Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°



Device 2: misaligned hBN



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



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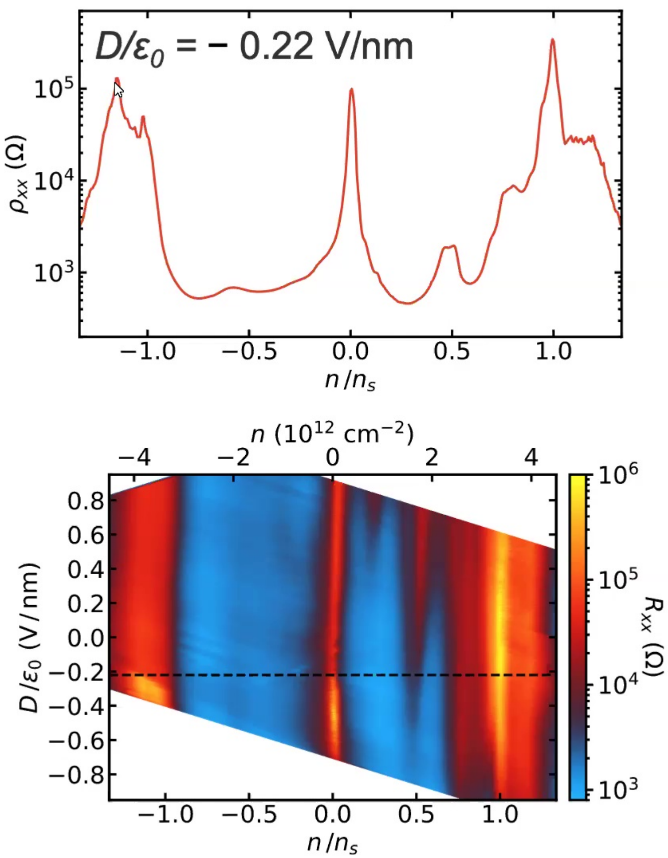
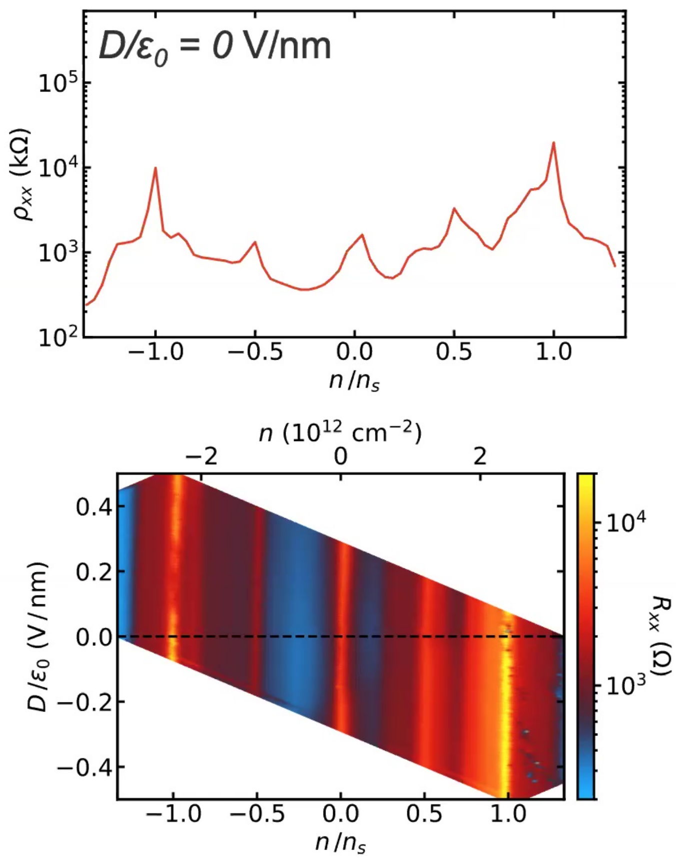
Impact of Alignment with hBN

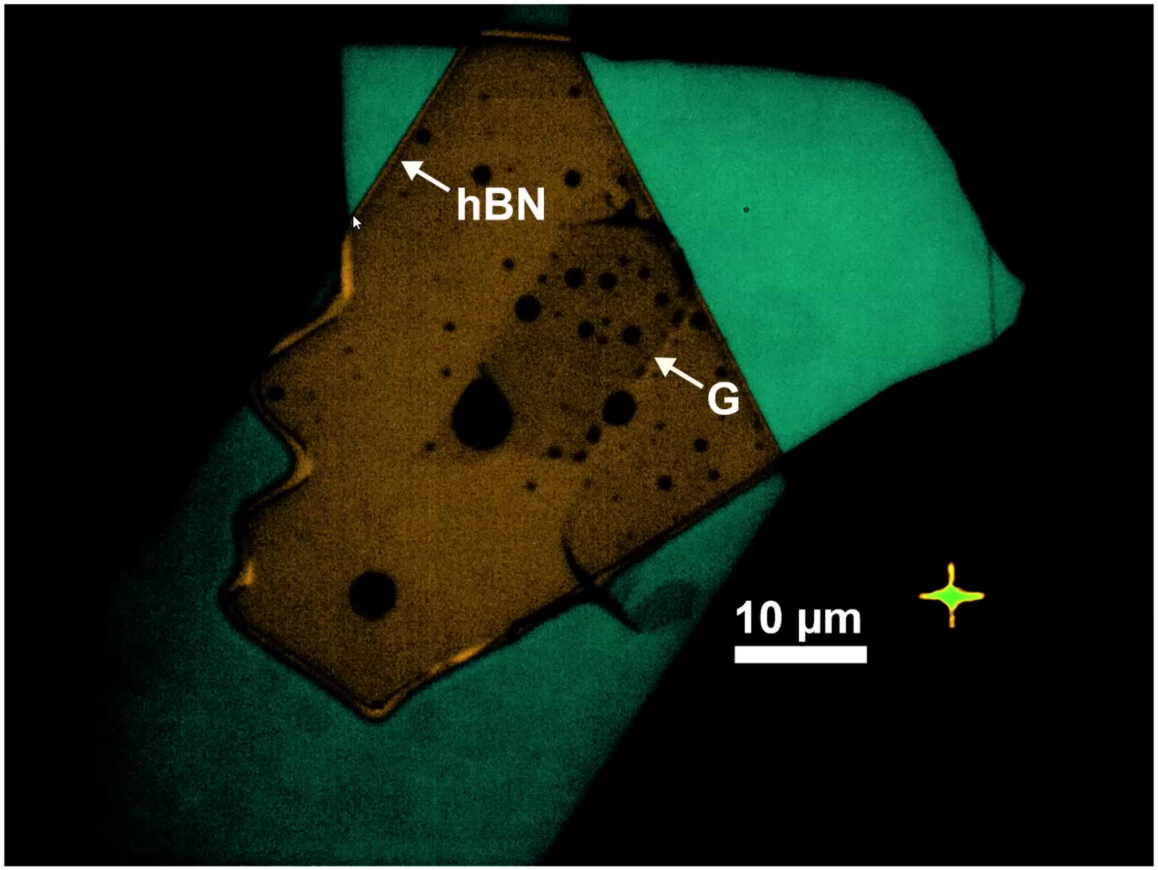
Device 1: aligned hBN



Device 2: misaligned hBN



Visual hBN Alignment



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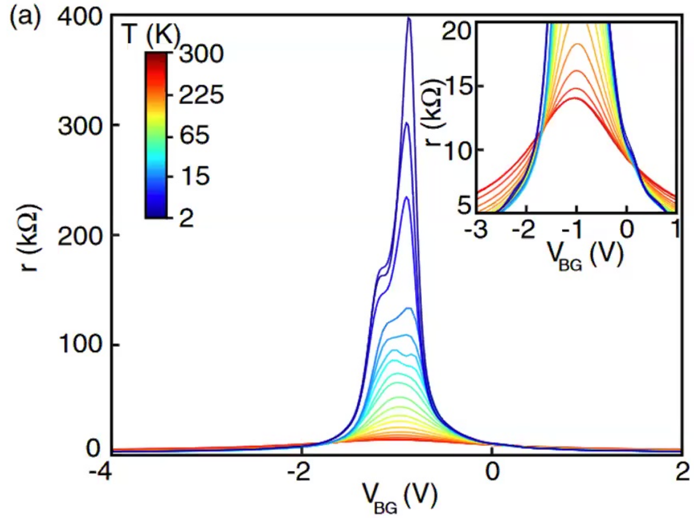
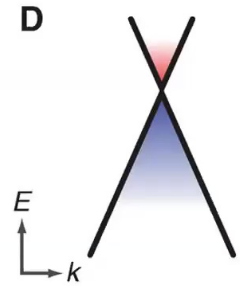
Alignment with hBN

Opens a gap at charge neutrality

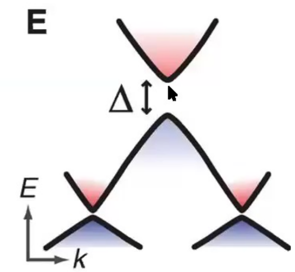


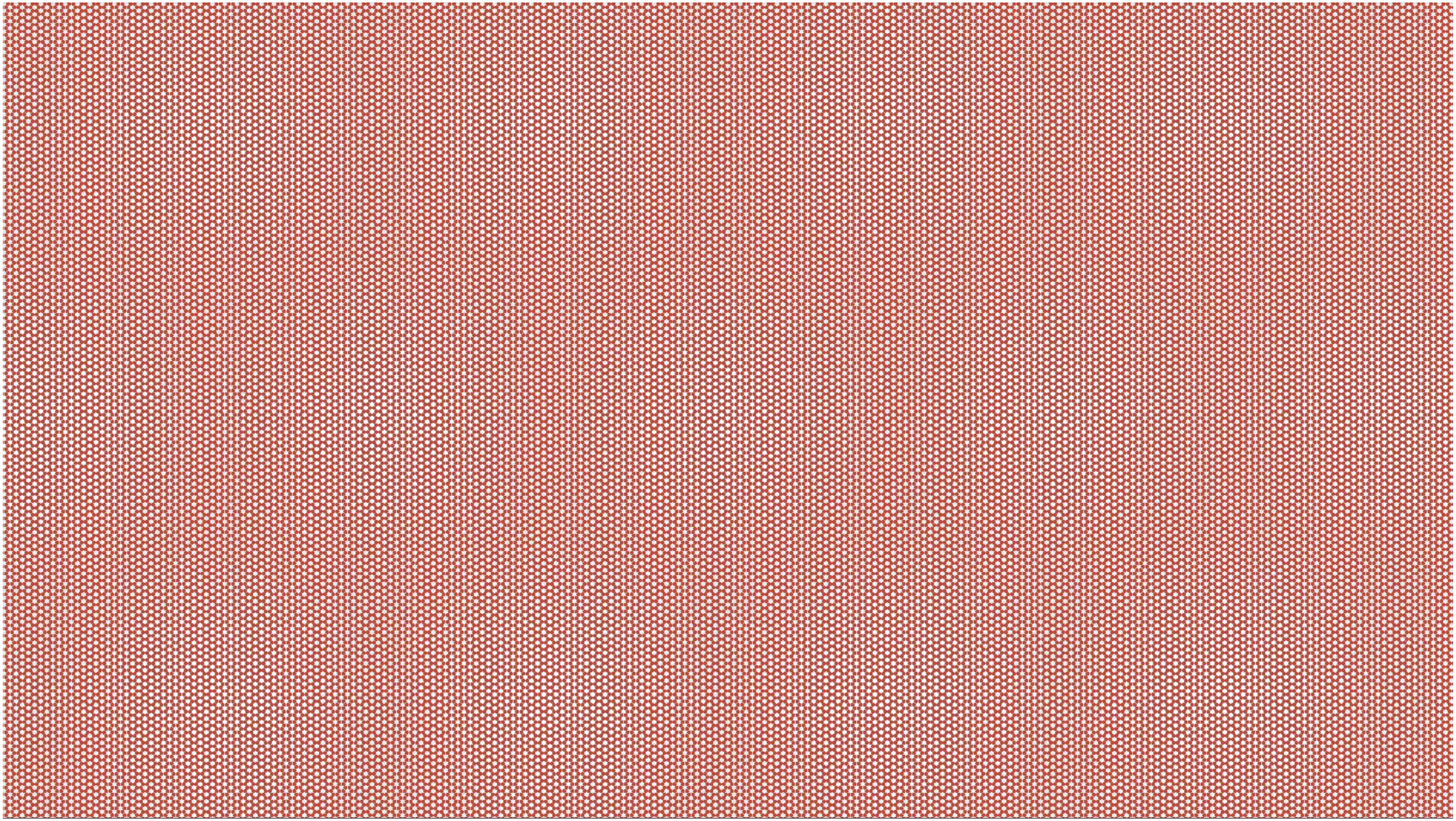
Amet, *PRL* (2013)
Hunt, *Science* (2013)

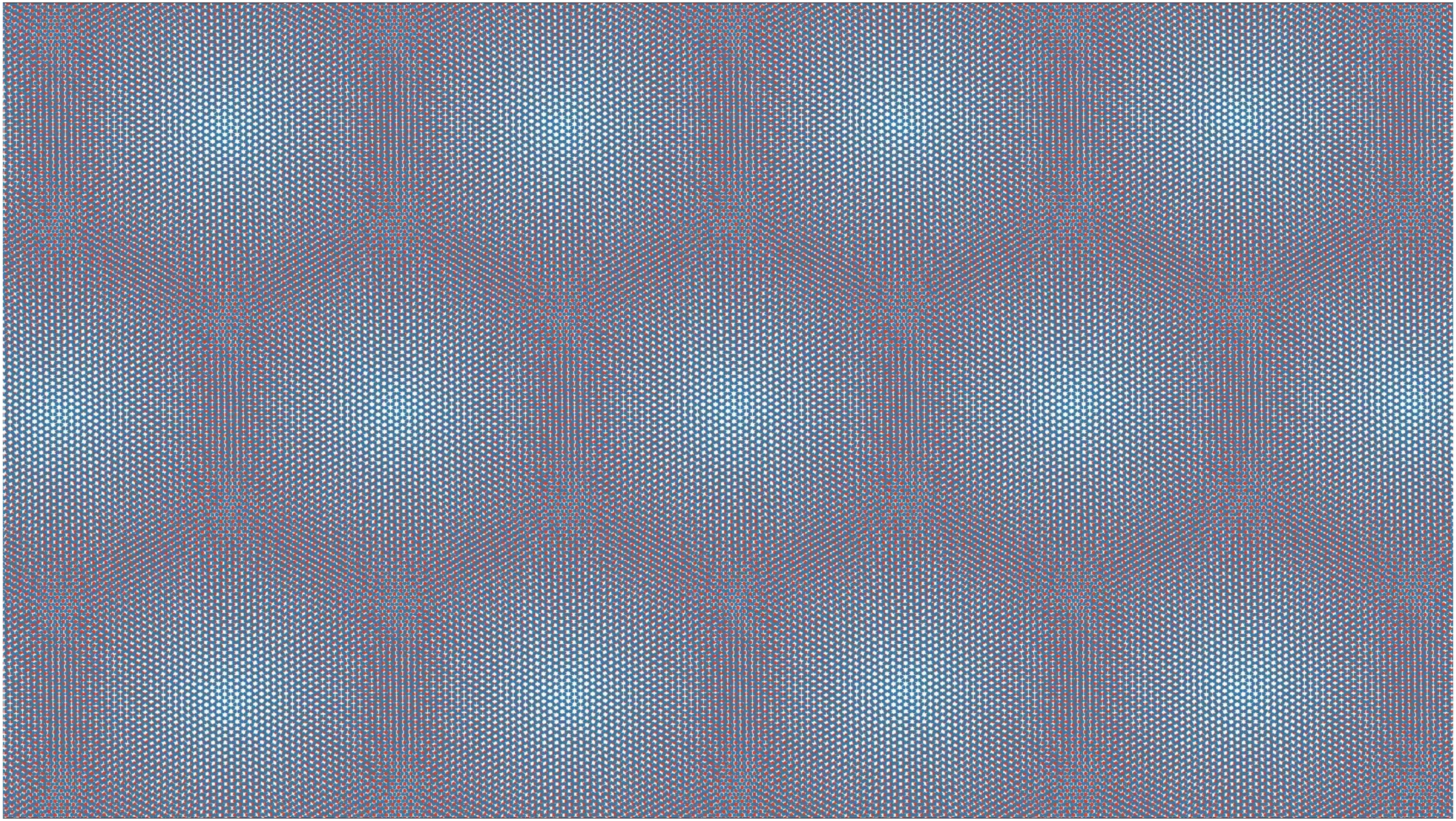
Monolayer graphene

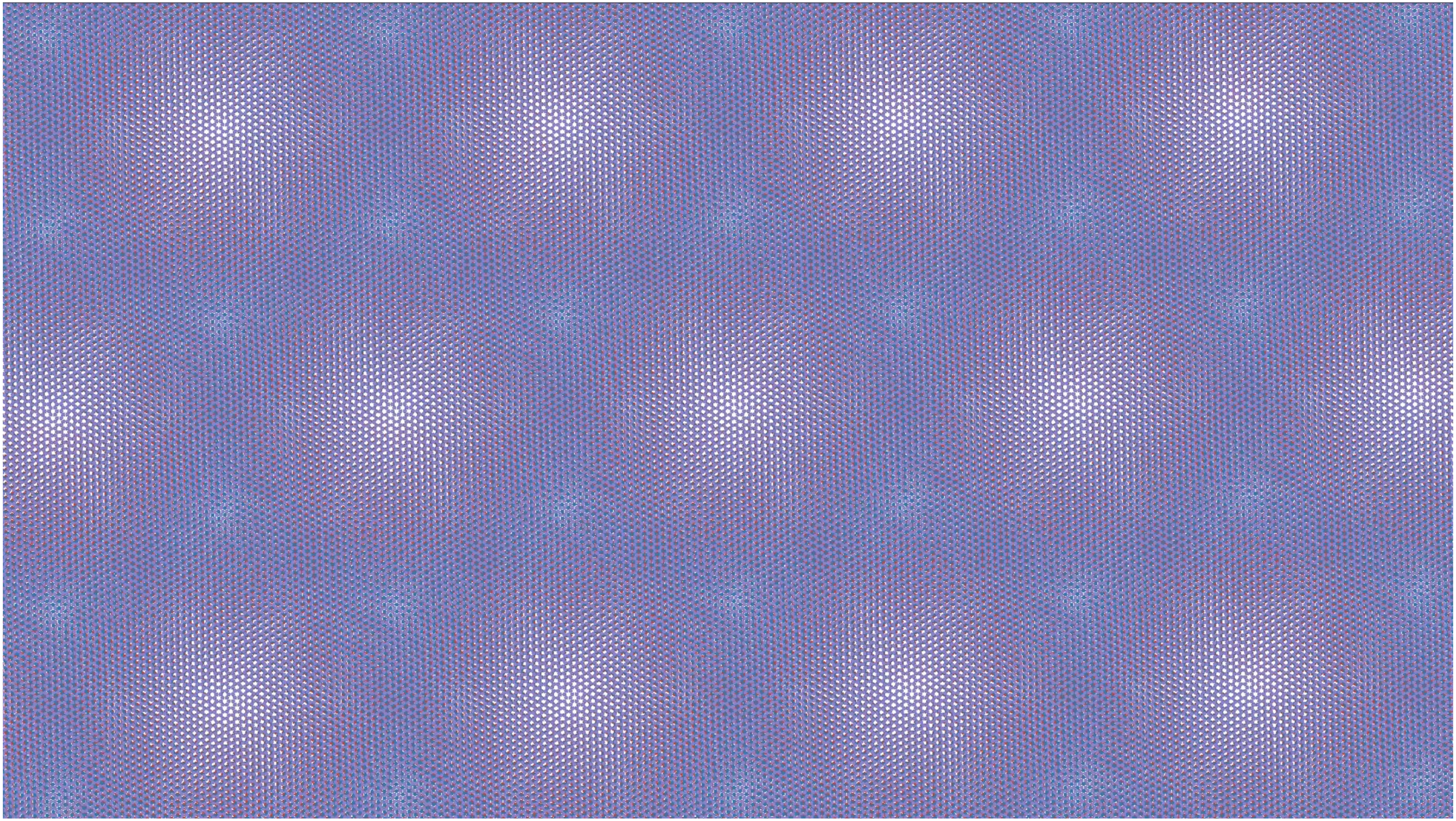


Monolayer graphene + hBN

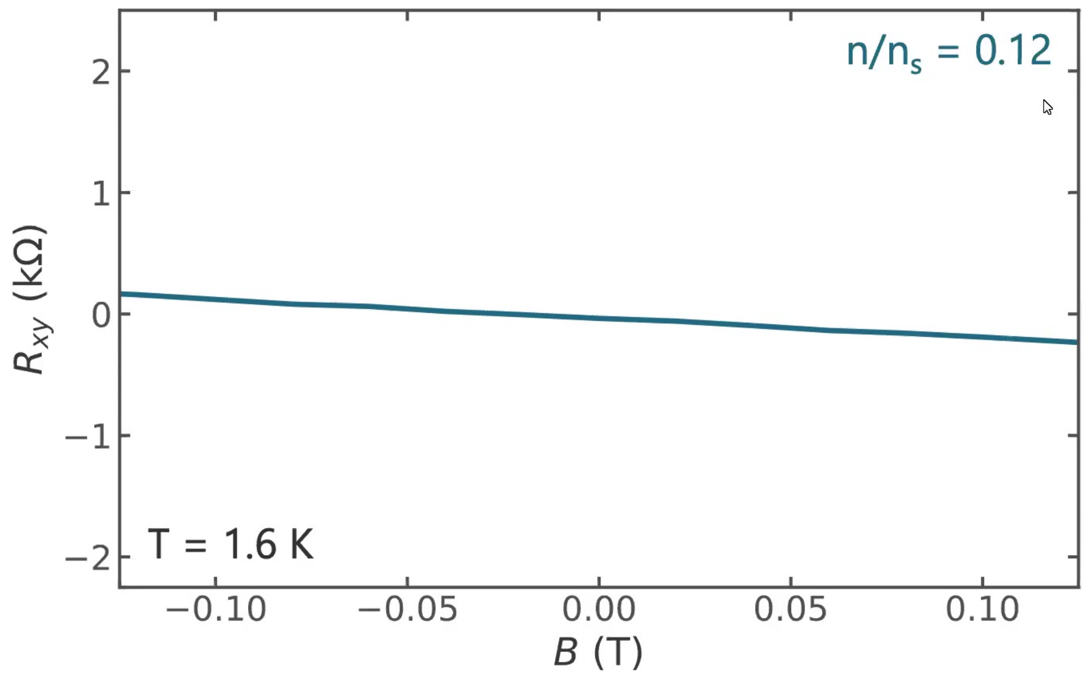






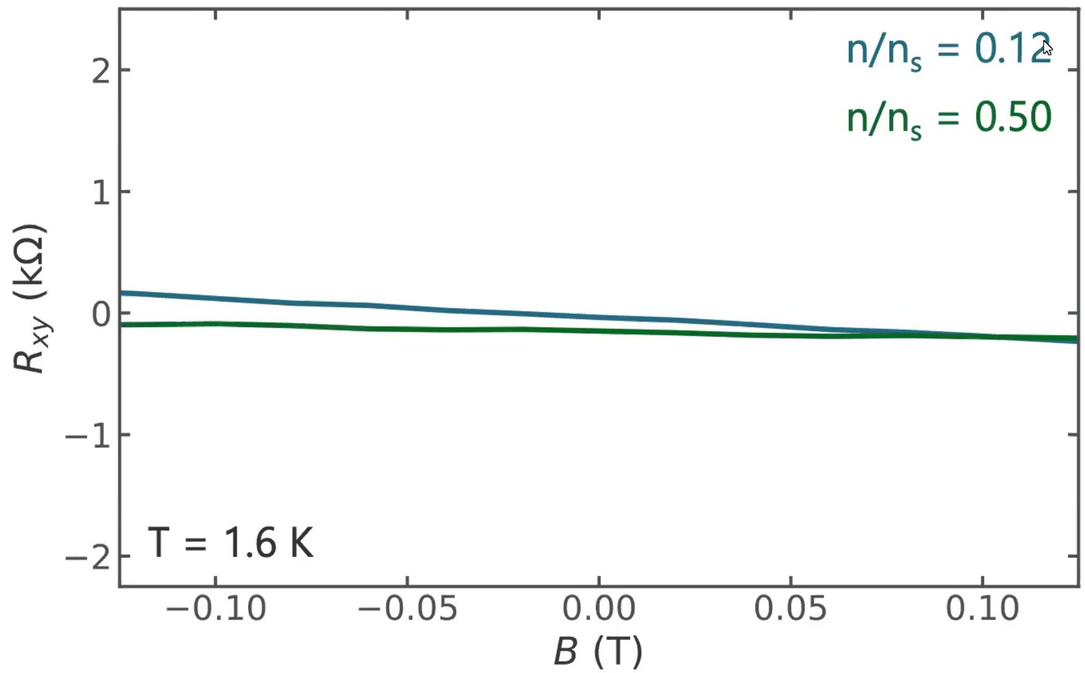


Measuring Hall Slope Density Dependence



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

Measuring Hall Slope Density Dependence



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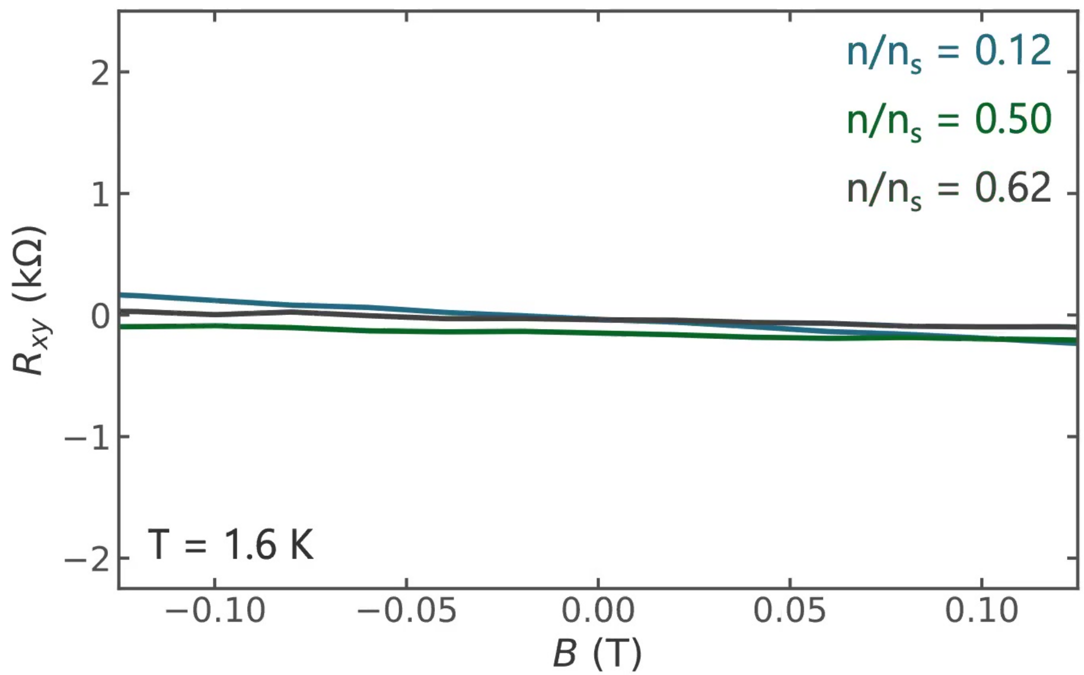

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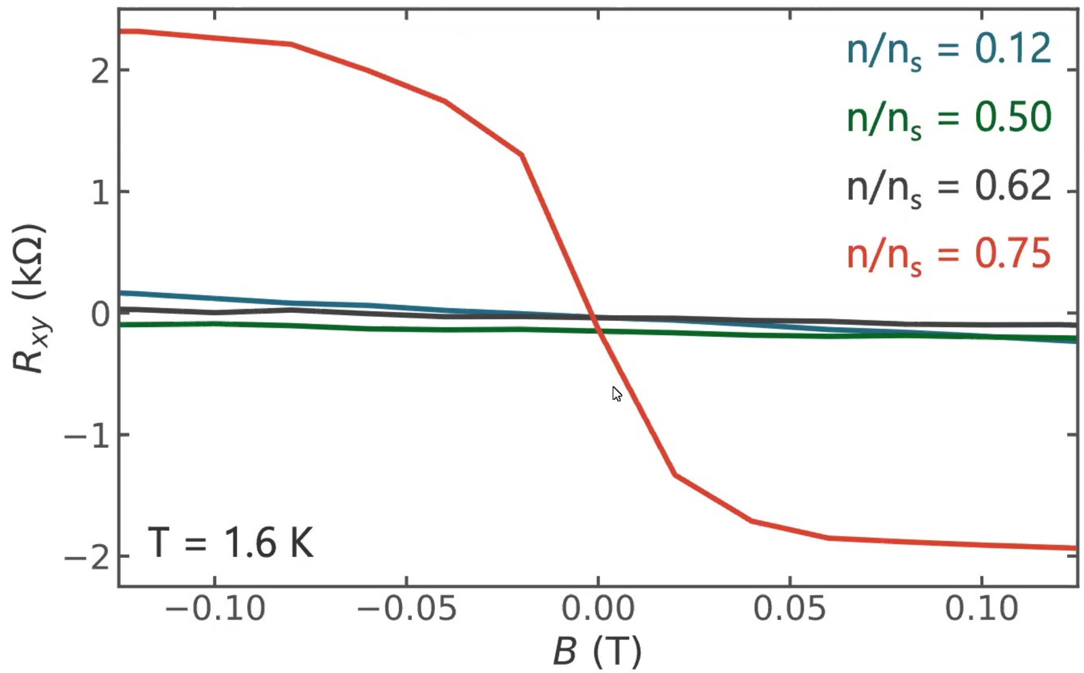
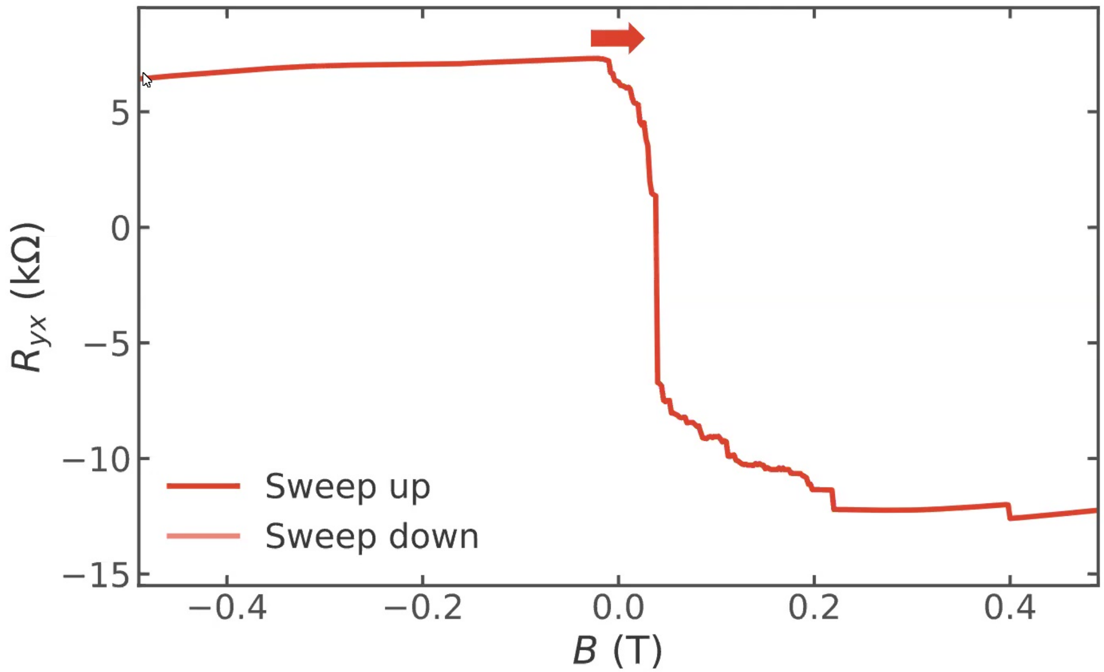
Measuring Hall Slope Density Dependence



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

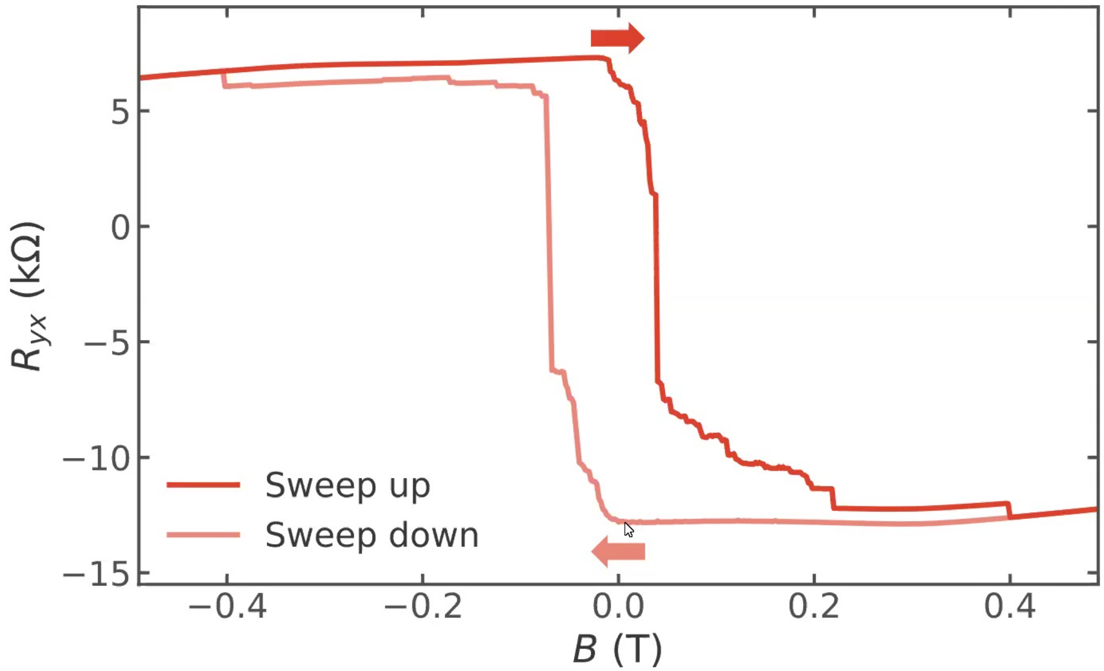
Anomalous Hall Signal Can Be Really Large!



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

n/n_s=0.775, T = 2.1K

Anomalous Hall Signal Can Be Really Large!



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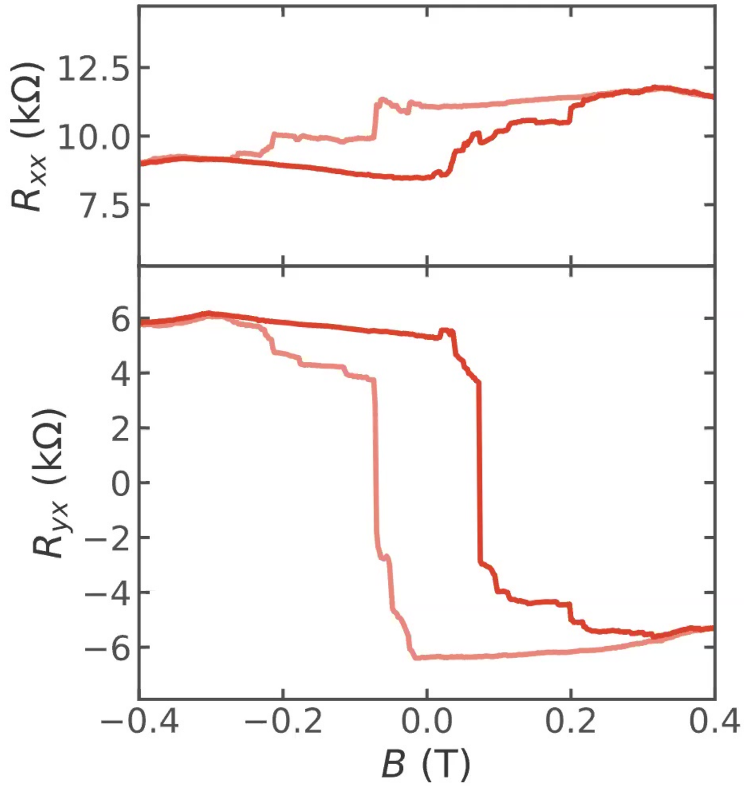
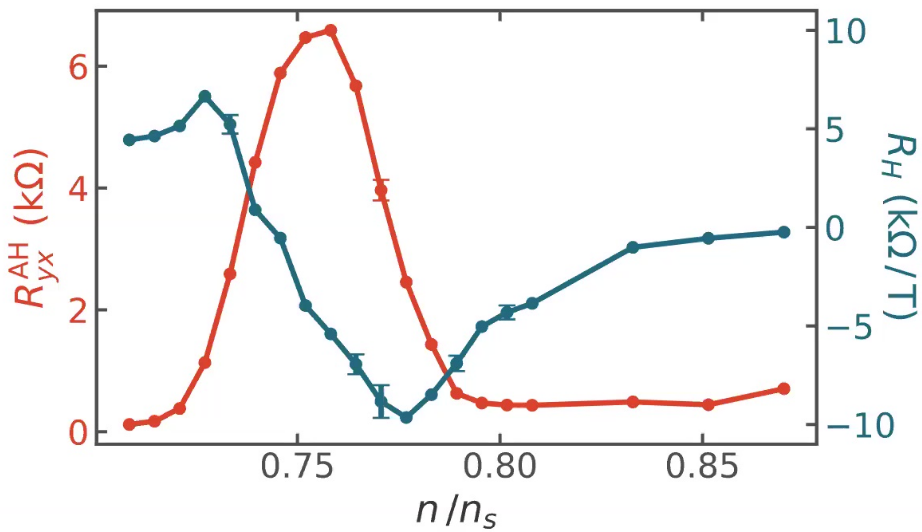
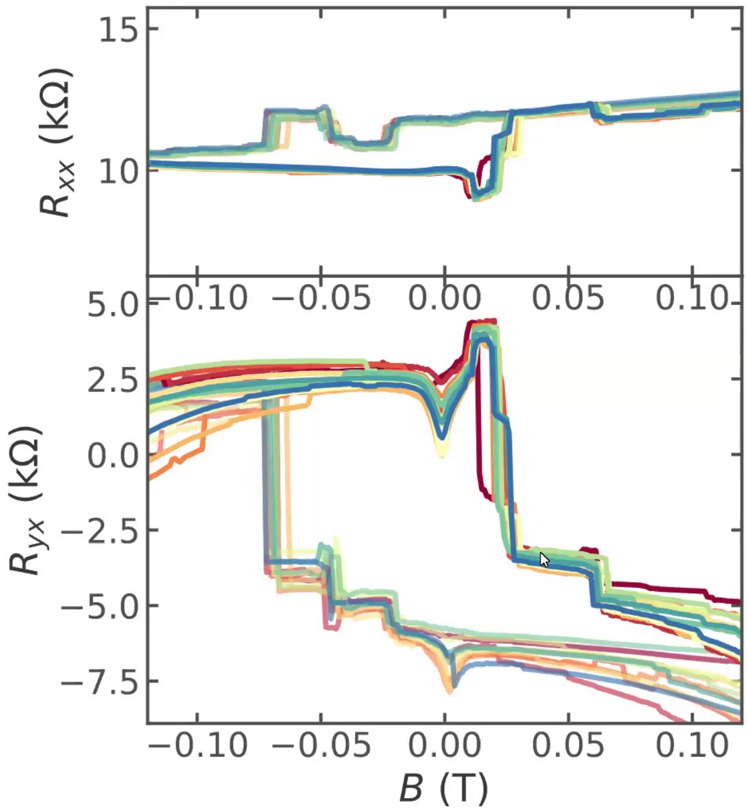
n/n_s=0.775, T = 2.1K

Emergent Ferromagnetism at ¾ Filling

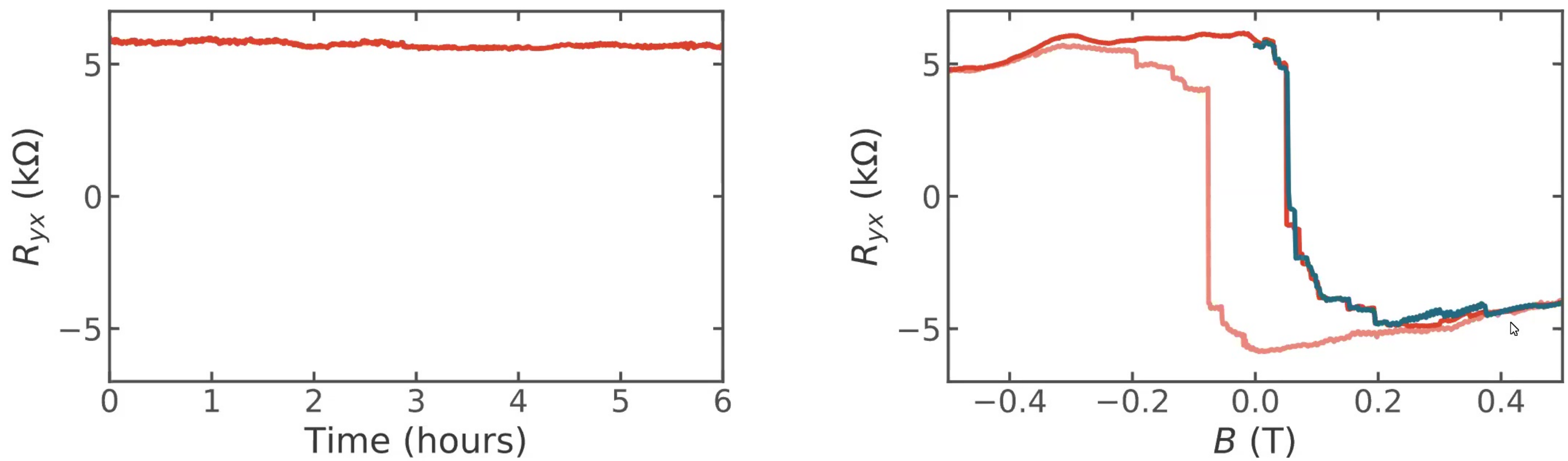


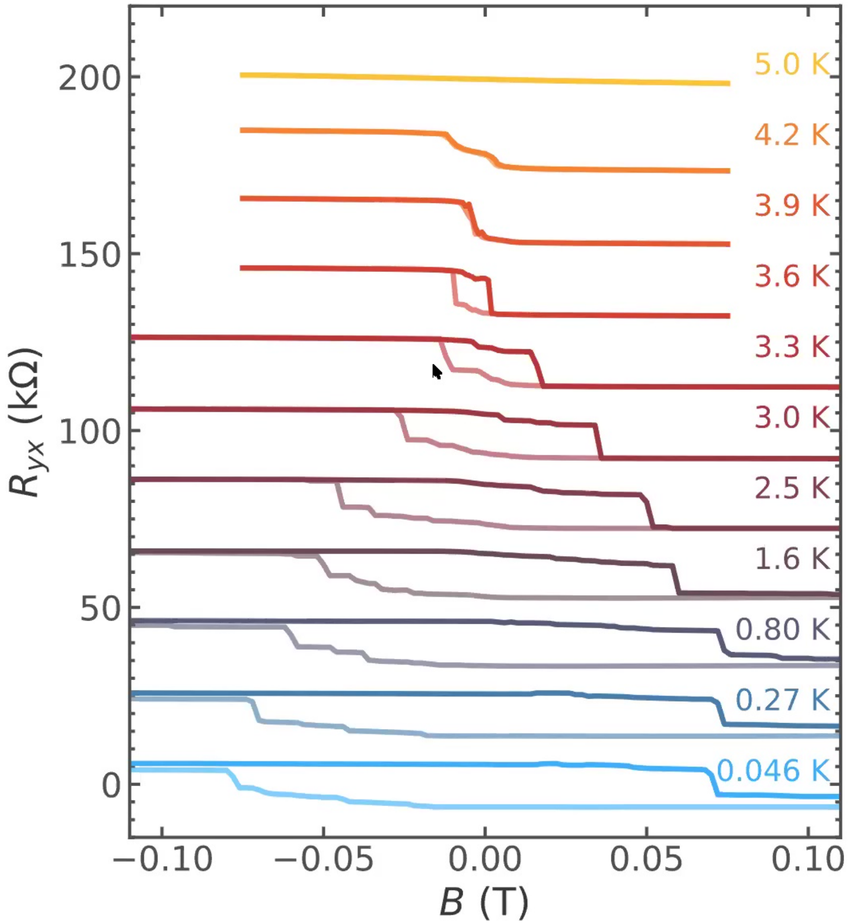


Repeatable Fine Structure

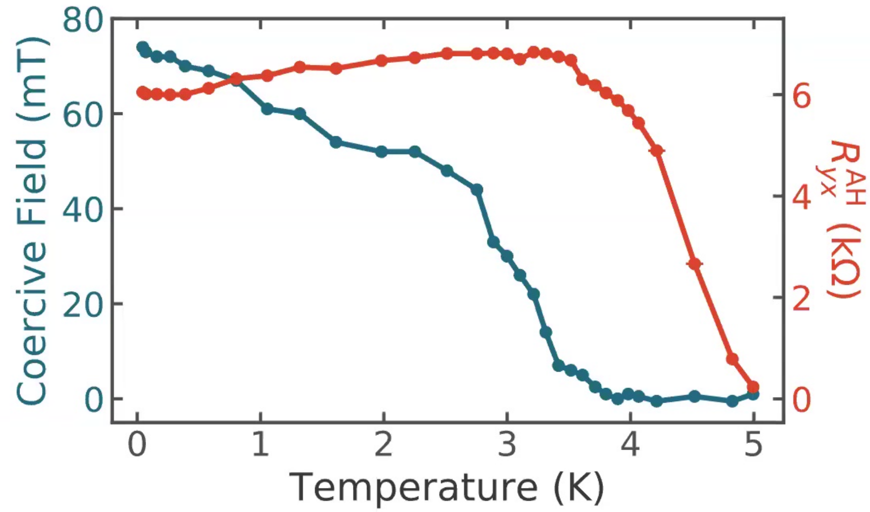


Magnetism is Stable in Zero Applied Field





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)

Large anomalous Hall

apparent insulating state

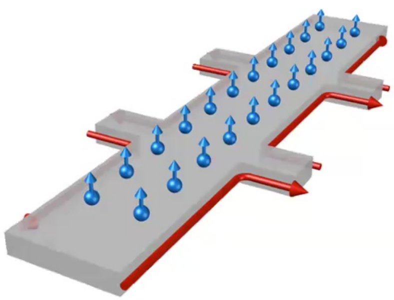
Evidence of domains

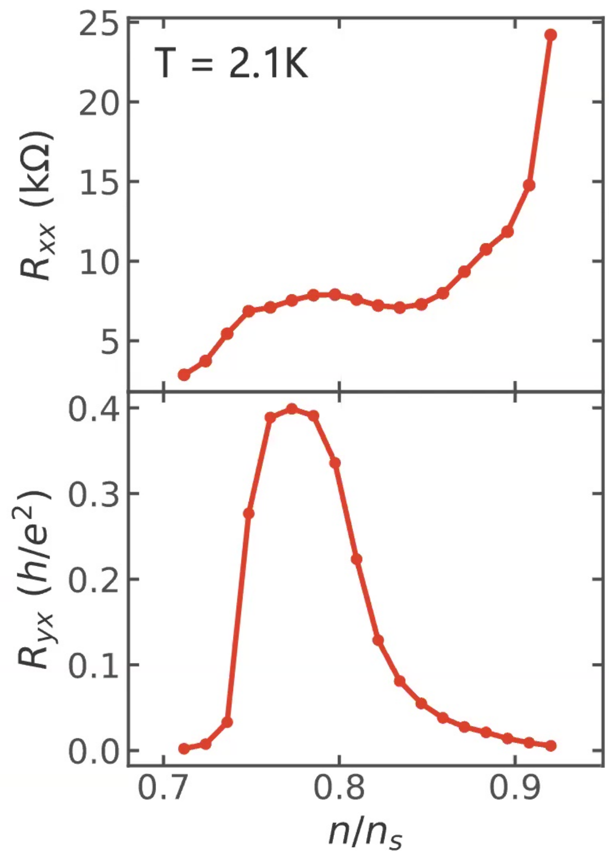
Reminiscent of early Magnetic TIs

Chern insulator?

Ideally: $\rho_{xx} = 0$

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





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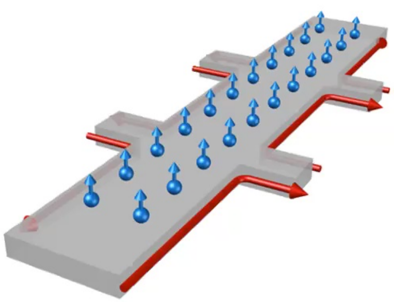

flightnetwork.com/blog/road-trip-on-route-66/

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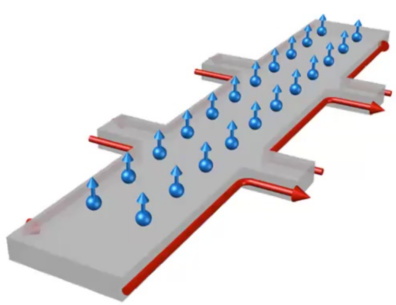

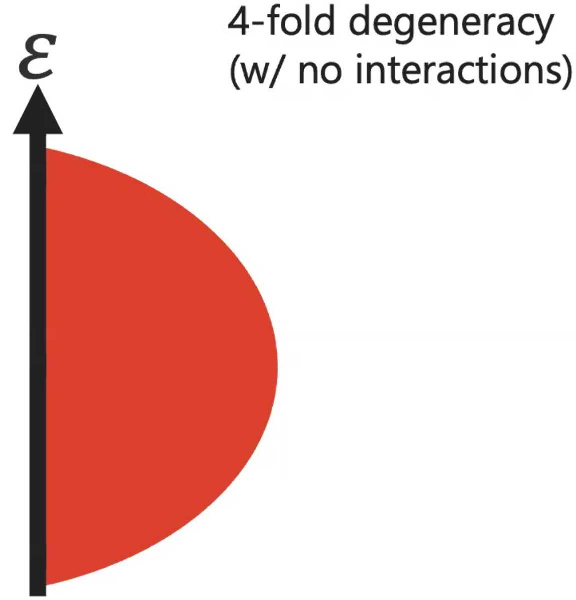

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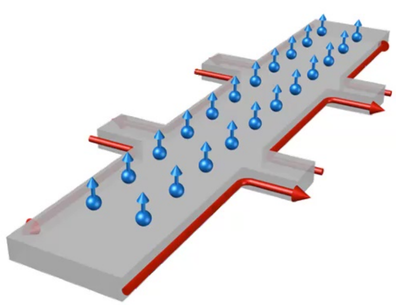
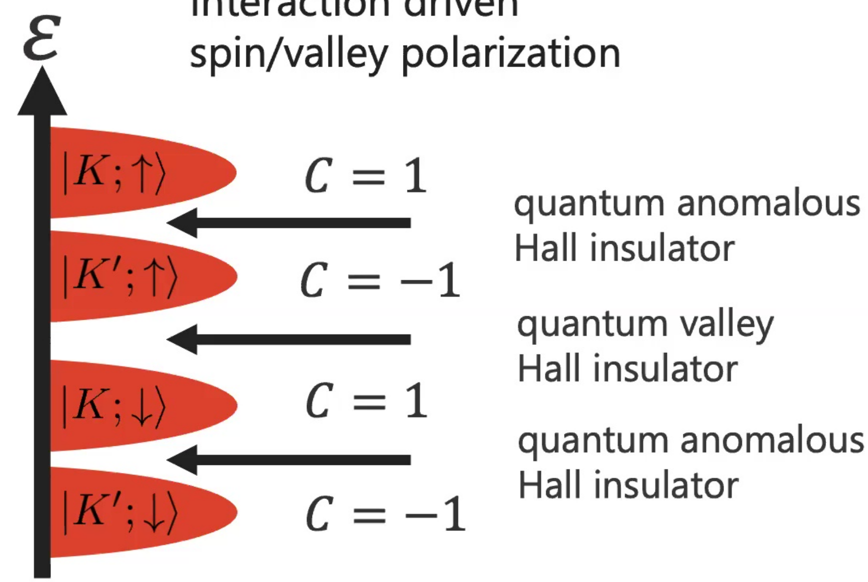


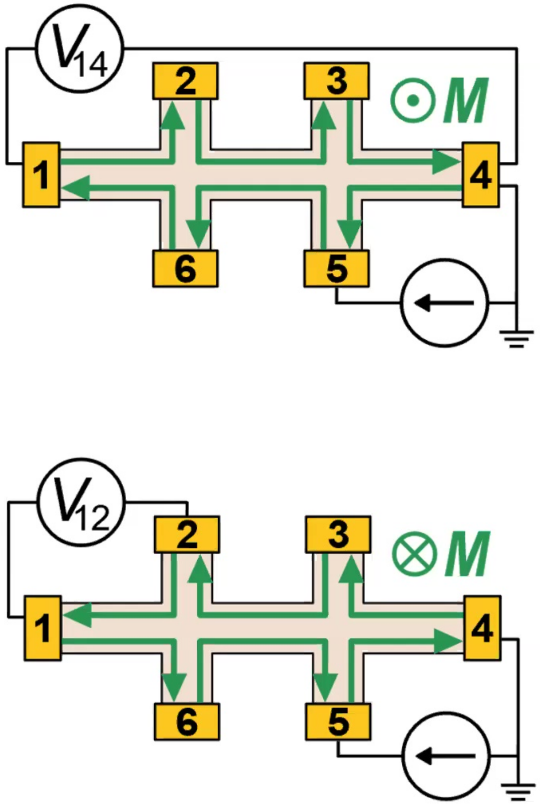
Interaction driven spin/valley polarization

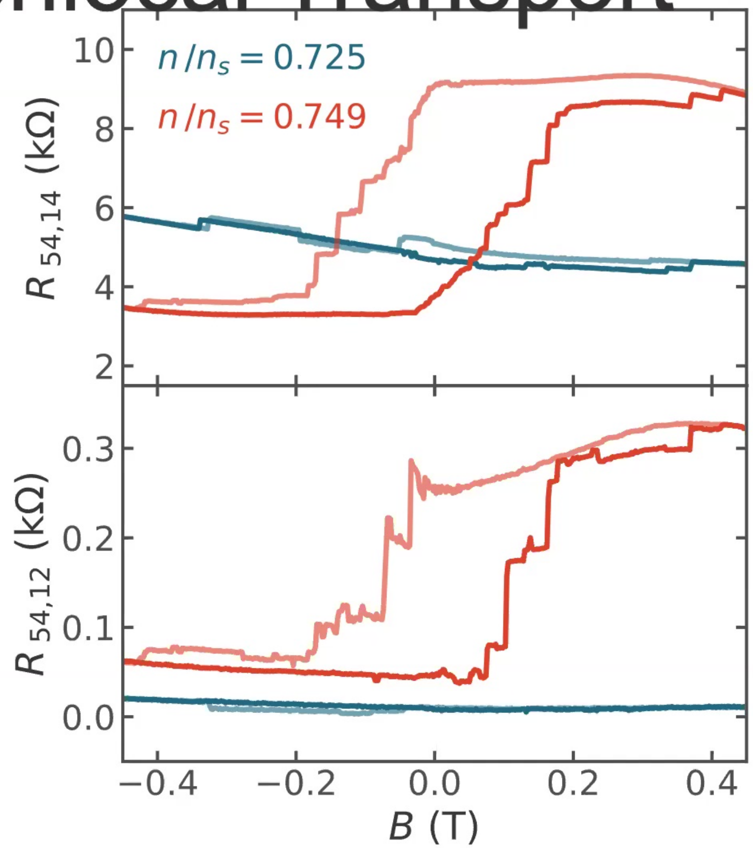


TBG + hBN:
Zhang et al., PRR (2019)
Bultinck et al., PRL (2020)

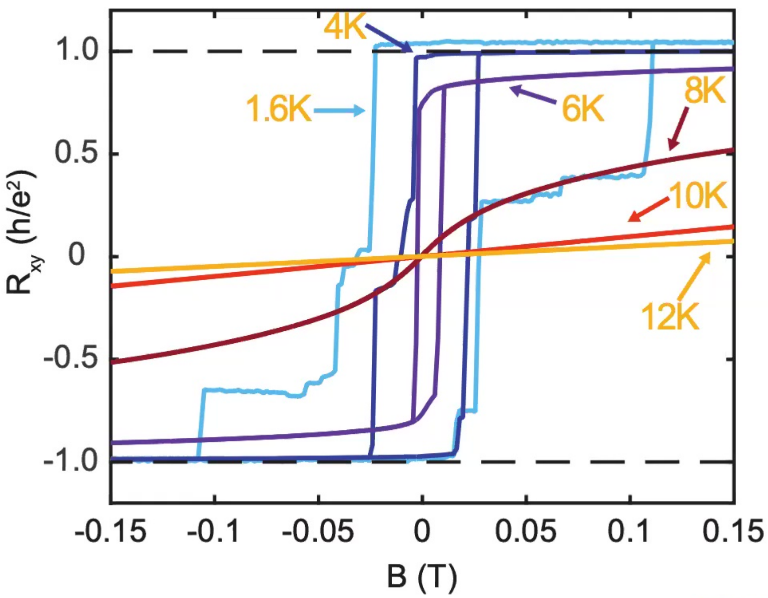
Spontaneously Gapped:
Xie et al., PRL (2020)

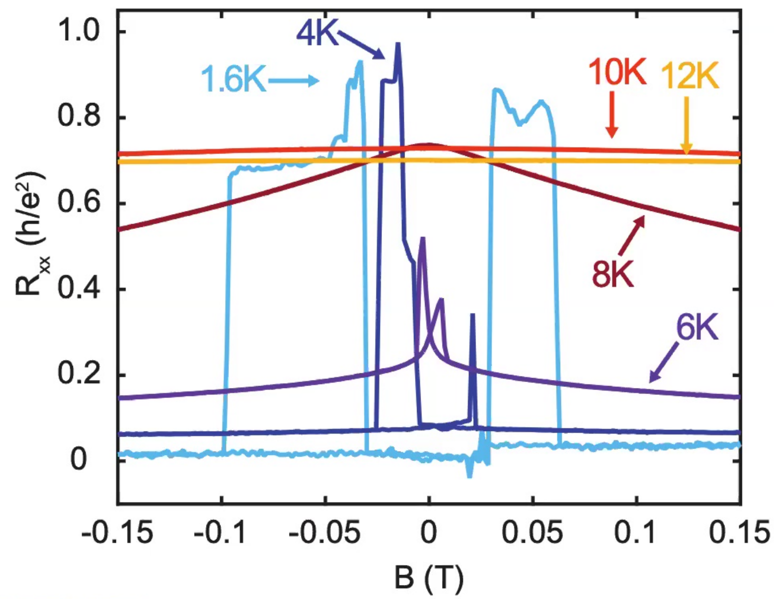
3- and 4- Terminal Nonlocal Transport

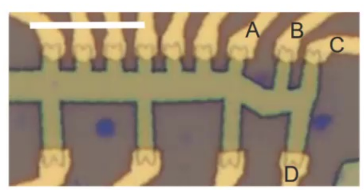




Quantum Anomalous Hall in TBG

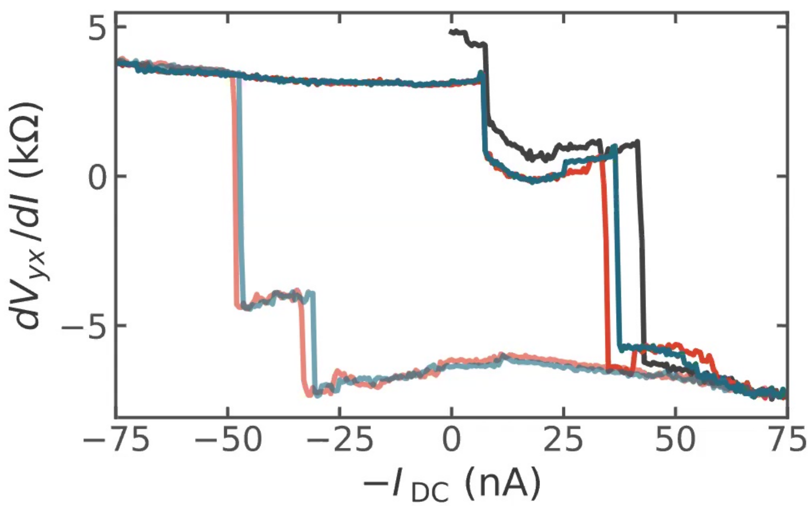


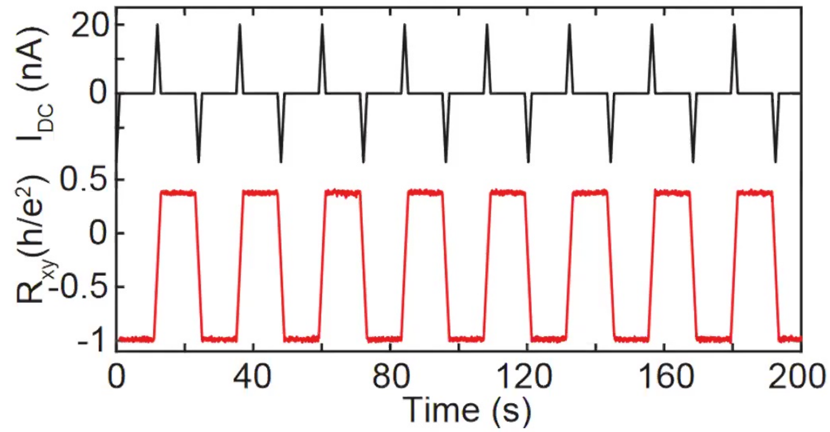




Serlin et al., Science (2019)

Repeatable Hysteresis in DC Current





Serlin et al., Science (2019)

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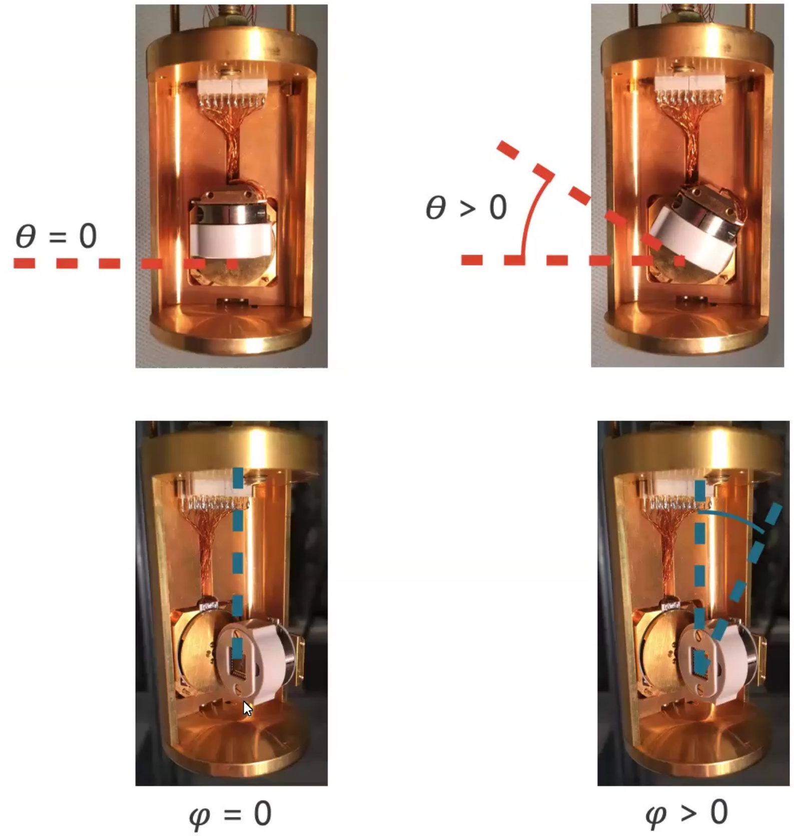
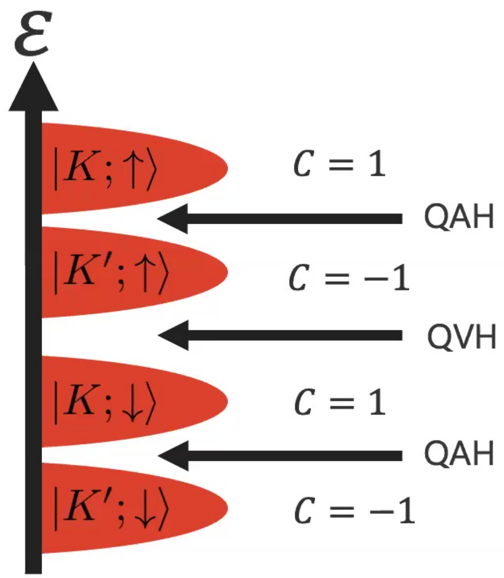
Probing Nature of Magnetism



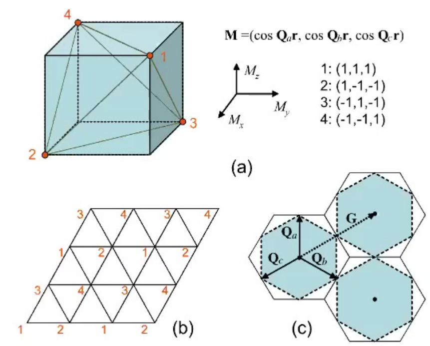
Possible Scenarios and in-plane response:

Interaction driven spin/valley polarization



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

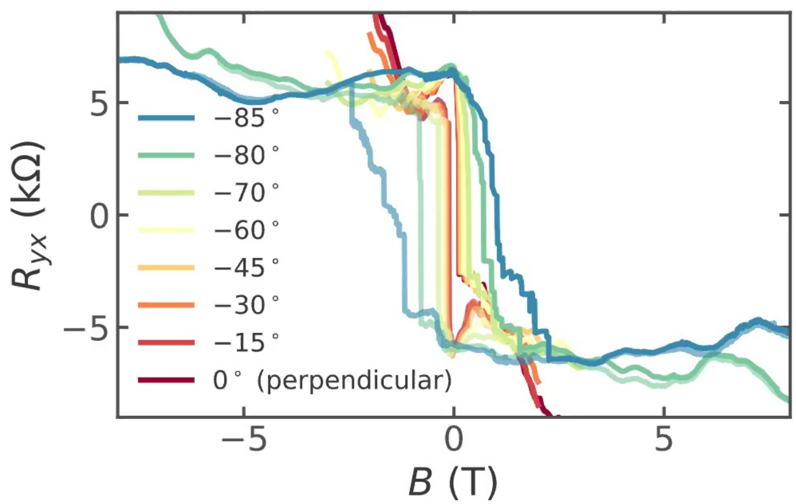
Non-coplanar chiral spin order at 3/4 filling of an individual band (two copies from valley)

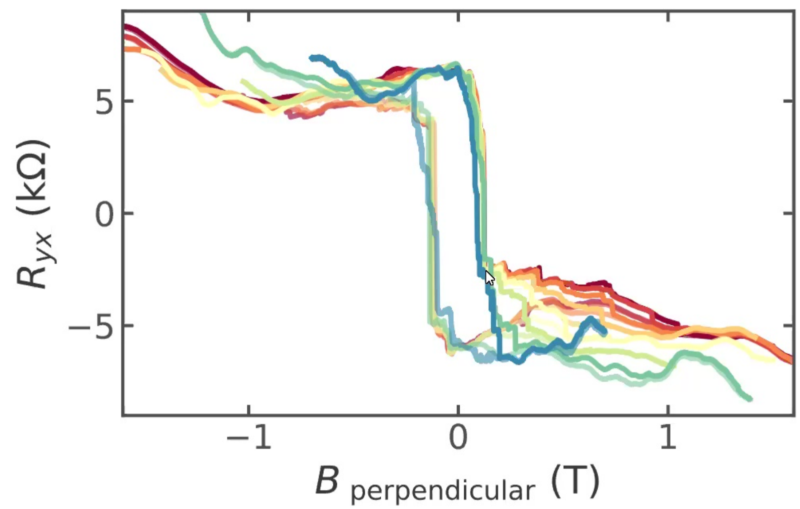


Xie et al., PRL (2020)
Zhang et al., PRR (2019)
Bultinck et al., PRL (2020)
Zhang et al., PRR (2019)
Martin et al., *PRL* (2008)
Lee et al., Nat. Comms. (2019)

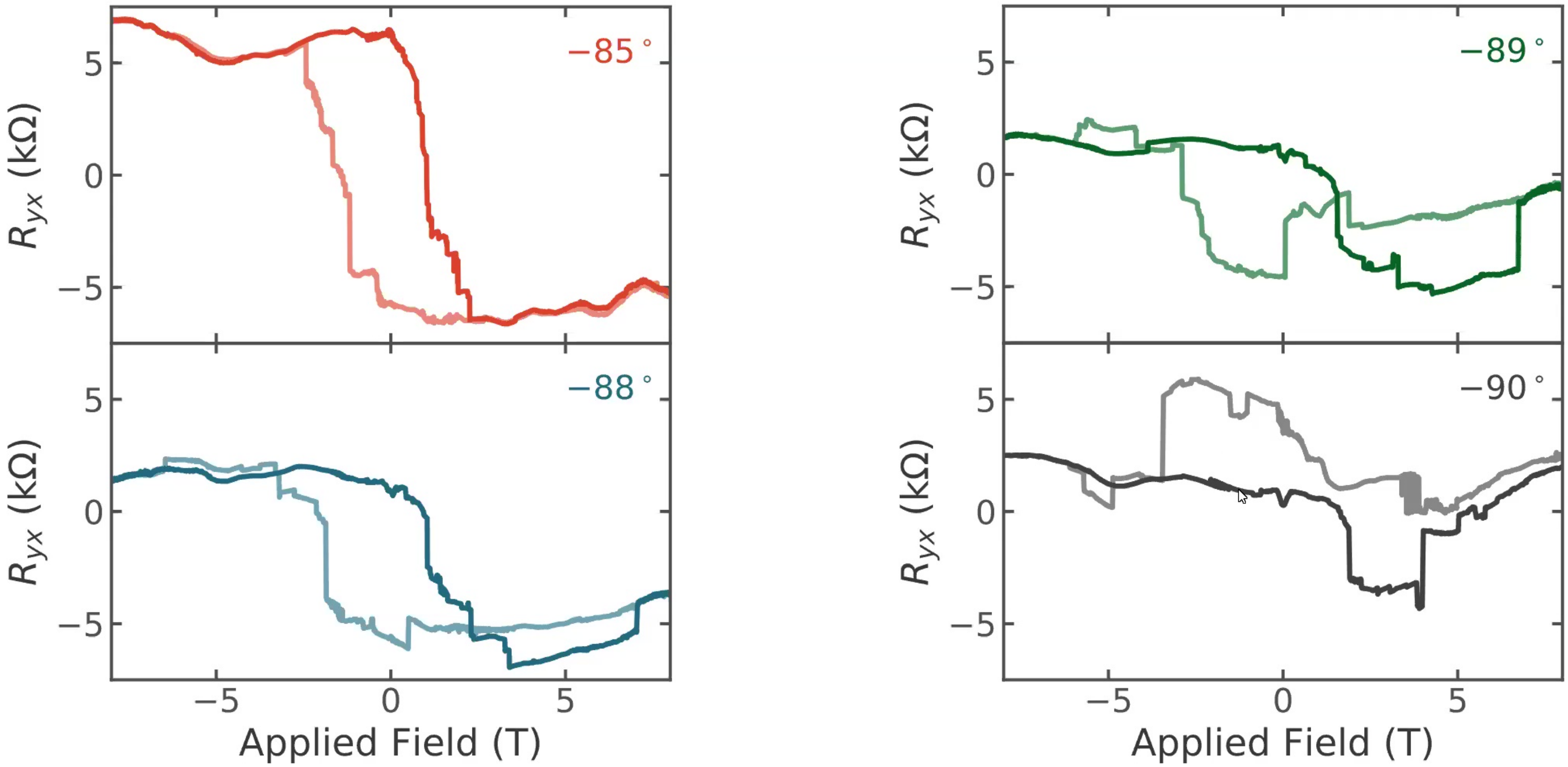
In-plane field can couple to valley!

Hysteresis Loops in Tilted Filed

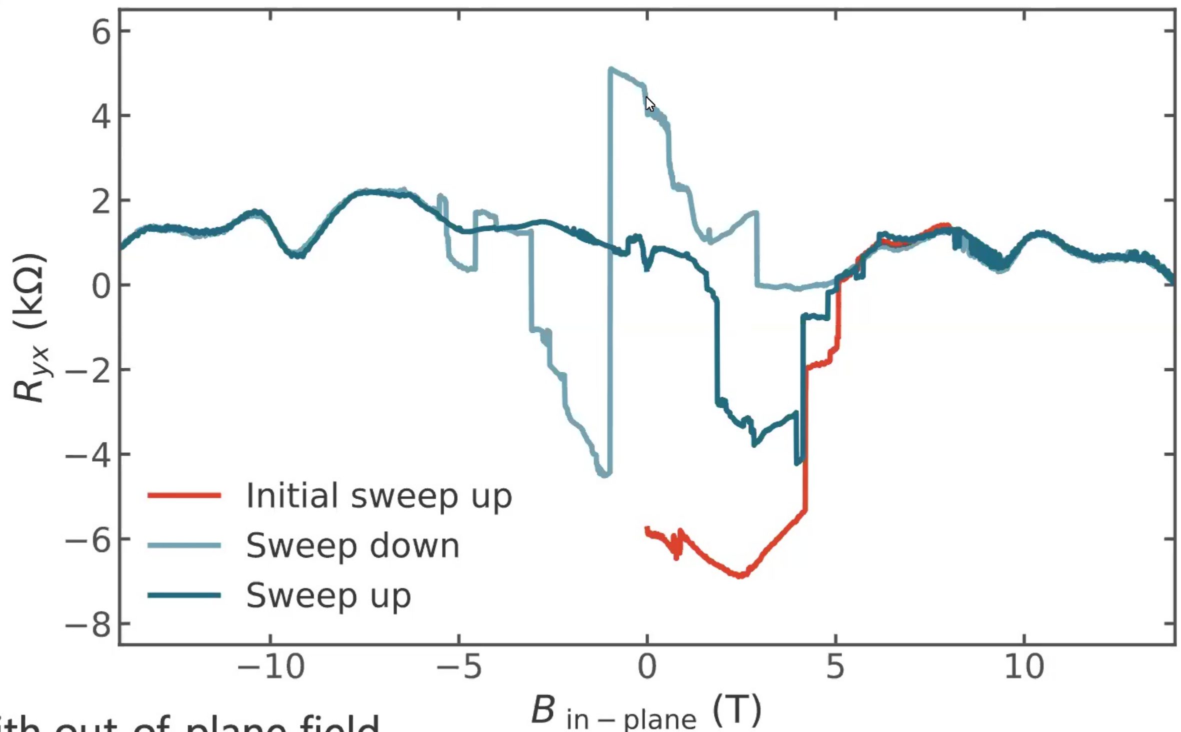




Behavior Near In-Plane Field



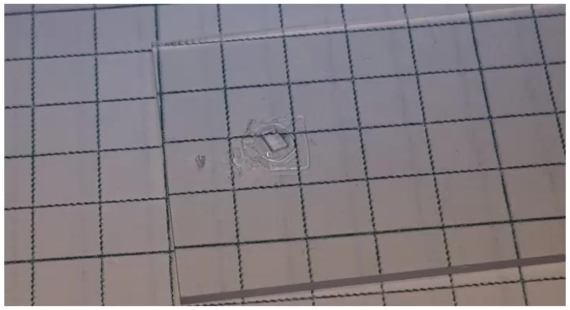
Applying In-Plane Field to a Magnetized State



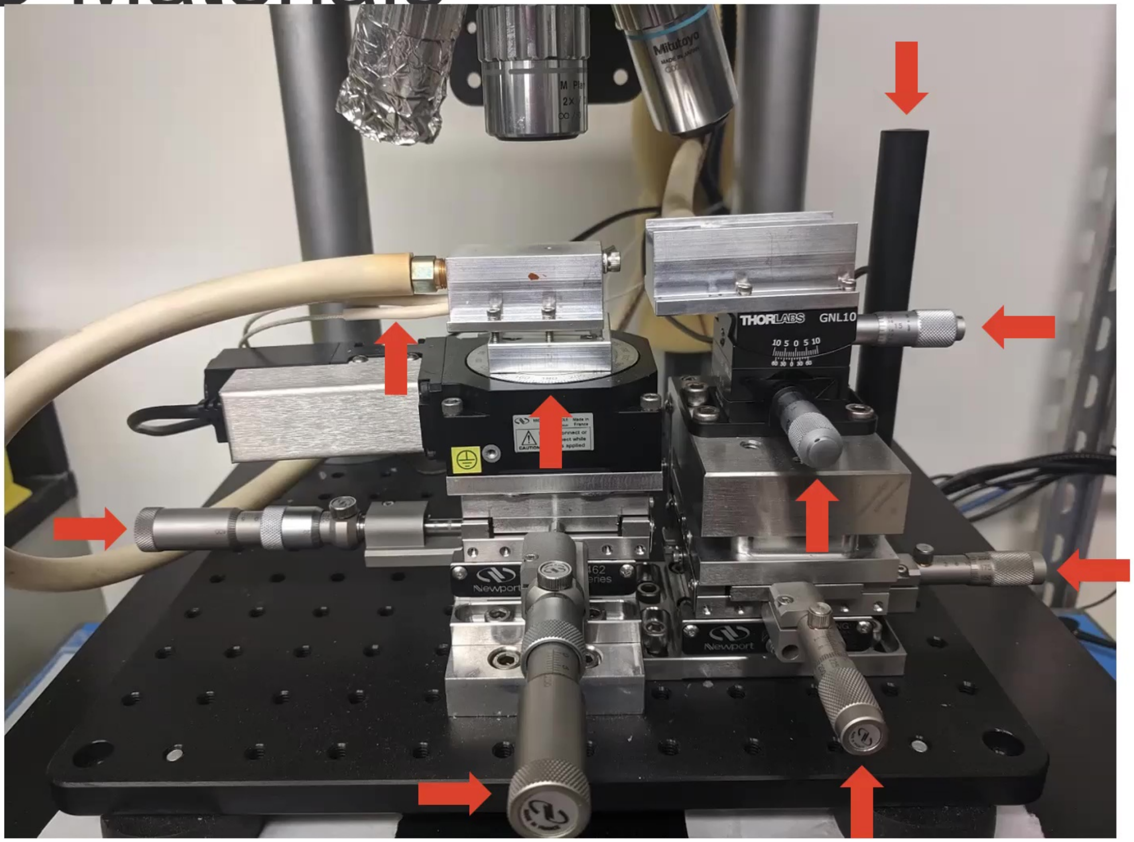
Magnetized with out-of-plane field
Rotated to in-plane in zero field

Transferring 2D Materials

Stamp



PC/PDMS/Glass



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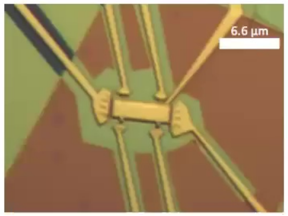
TBG is a Chern insulator near ¾ filling!



Alignment to 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

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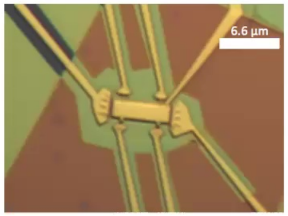

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