# Ferromagnetism near three-quarters filling in twisted bilayer graphene

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Rencontres de Moriond
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# Acknowledgements

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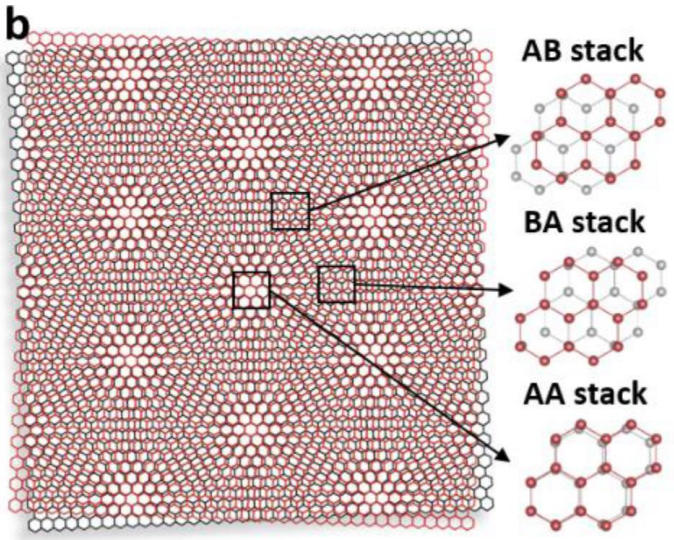
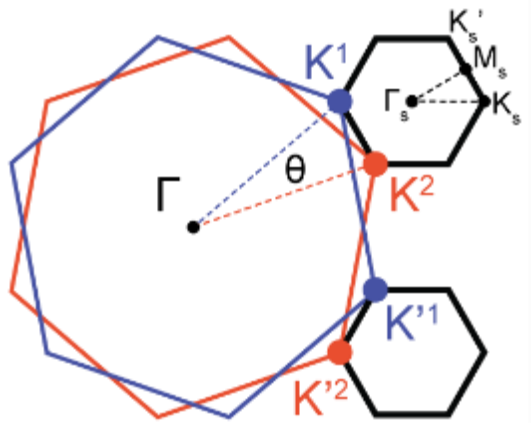
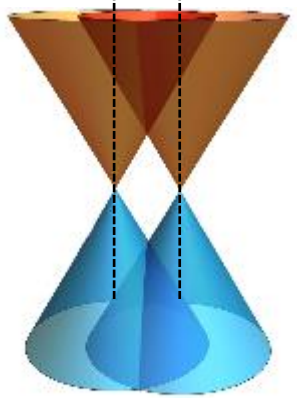
# Twisted Bilayer Graphene

## Engineering bandstructure

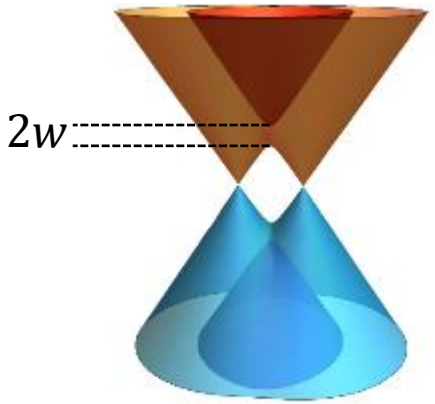


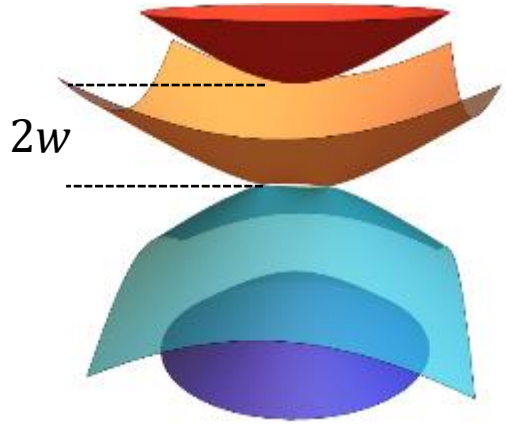

$k_\theta \approx K\theta$



$w$: Inter-layer interaction




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

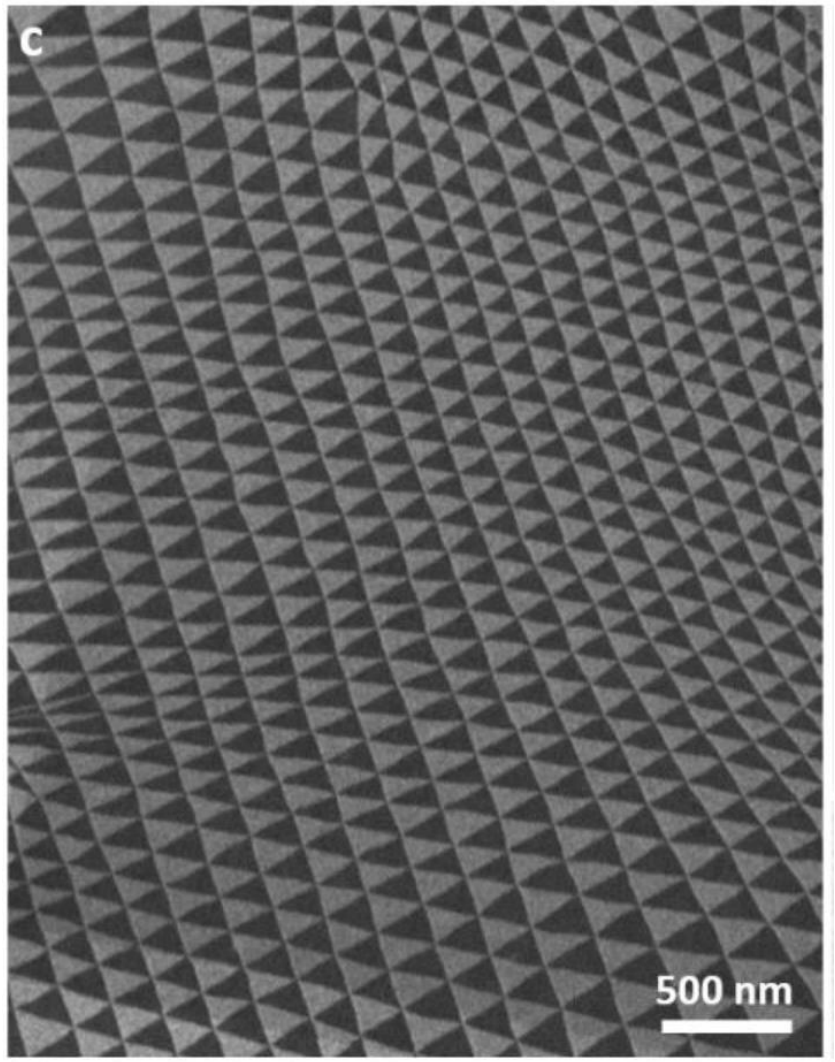



$2w \approx v_{F0}k_\theta$

***Decreasing Twist Angle***

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

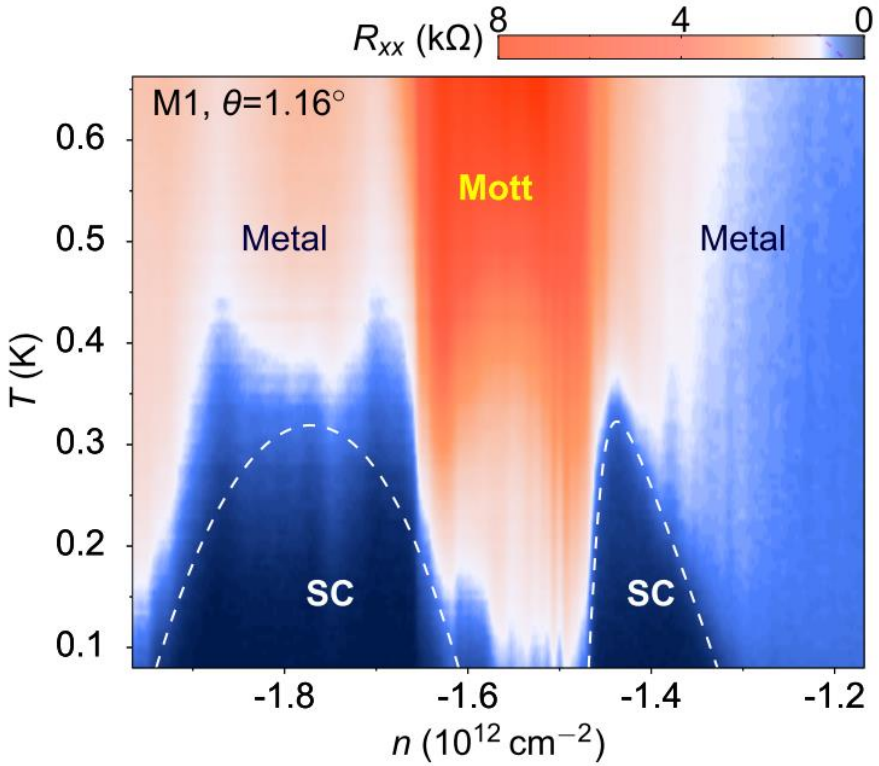
# Variations in Local Twist Angle



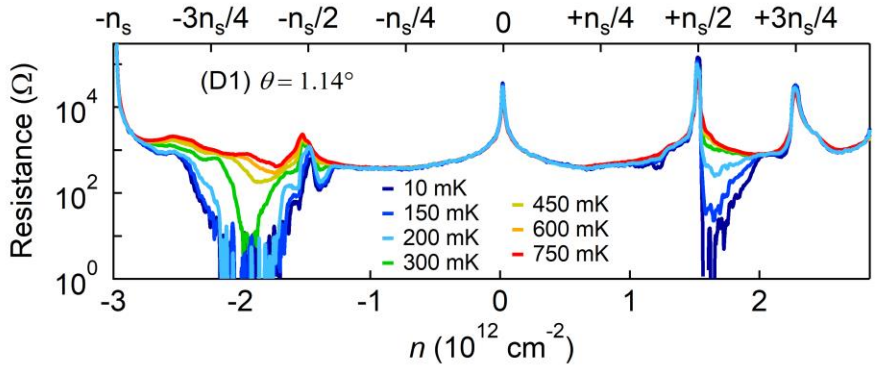

Yoo, *arXiv:*1804.03806

# Strong Correlations

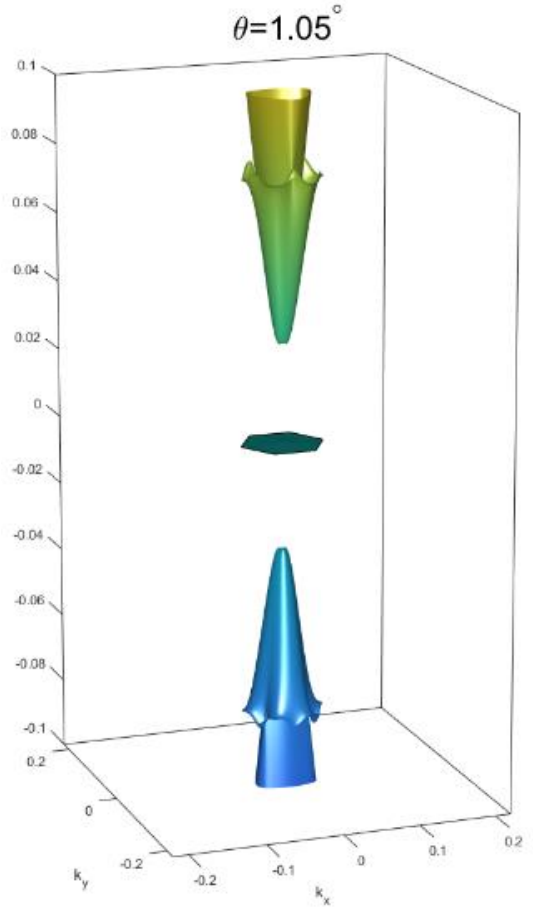
## Twisted bilayer graphene provides unprecedented control of correlations in 2D electron systems




Cao, *Nature* (2018)

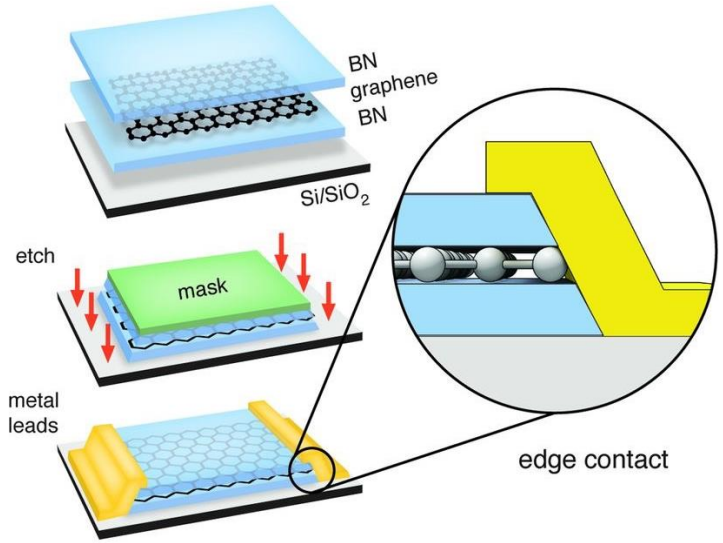



Yankowitz, *Science* (2019)

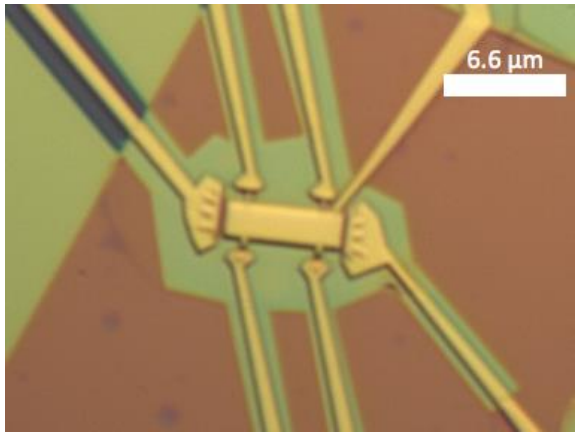


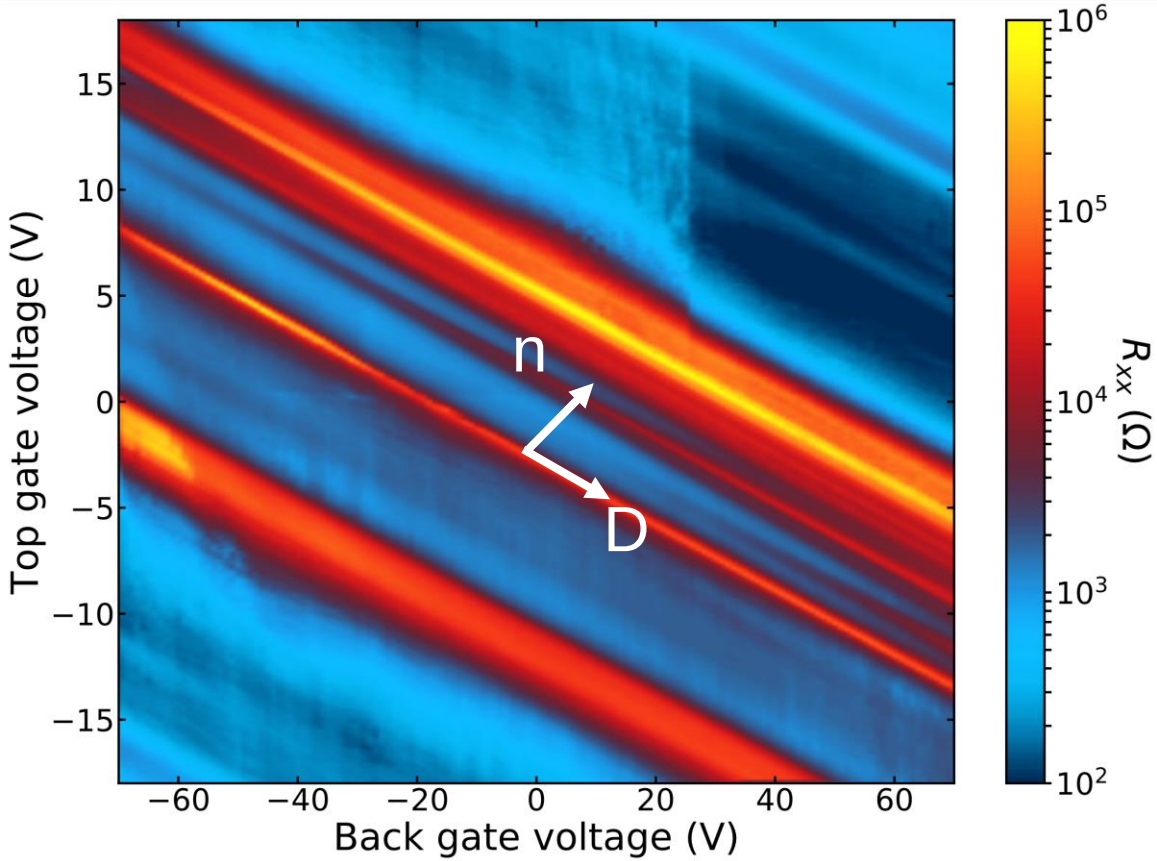

Jarillo-Herrero and Kaxiras groups

# Strong Correlations: Twisted bilayer near magic angle




Wang, *Science* (2013)

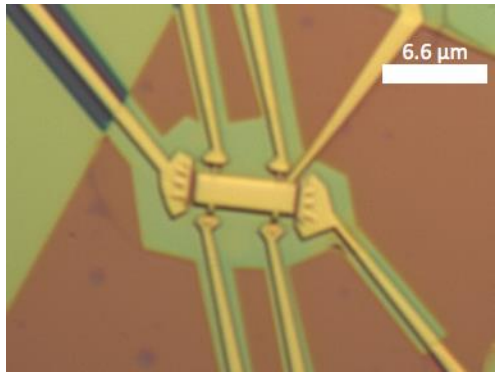


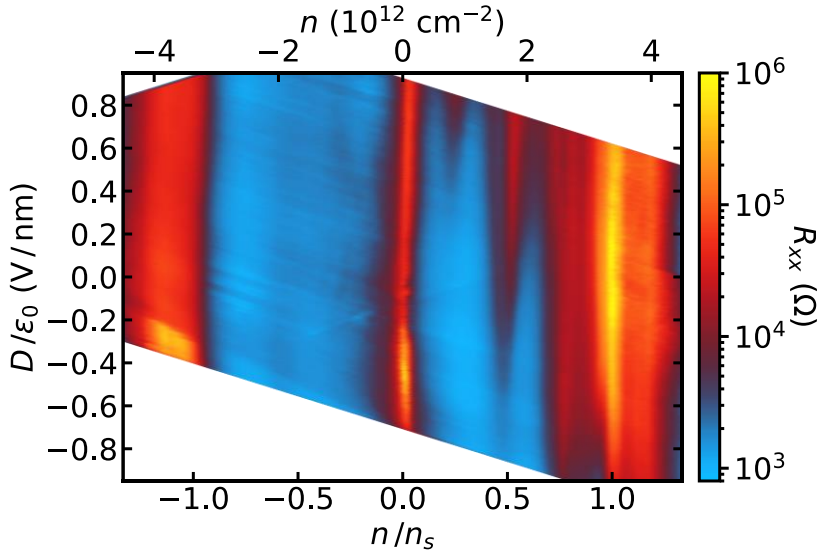

Angle 1.20+/-0.01°. Target 1.17°

# Impact of Alignment with hBN

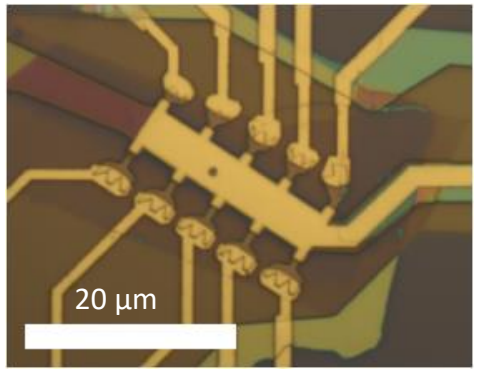
Device 1: aligned hBN



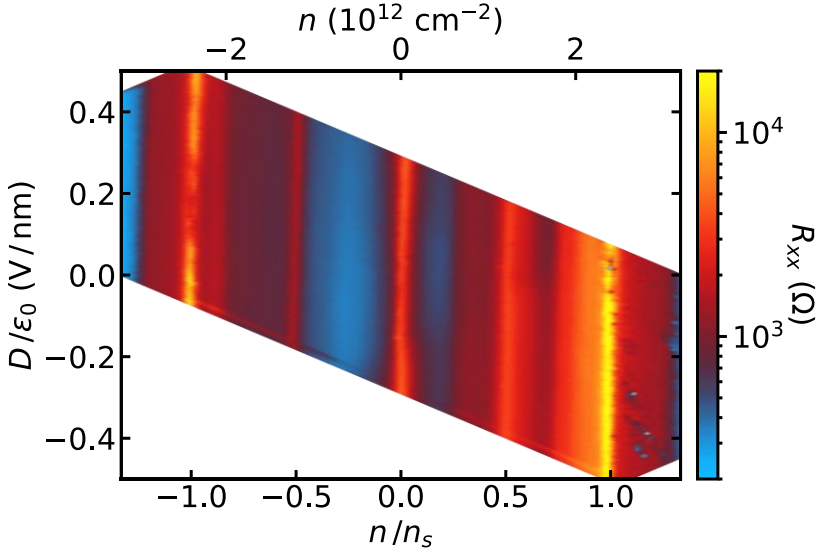

Graphene twist: 1.20 +/- 0.01°
Twist to one hBN: 0.81° +/- 0.02°




Device 2: misaligned hBN

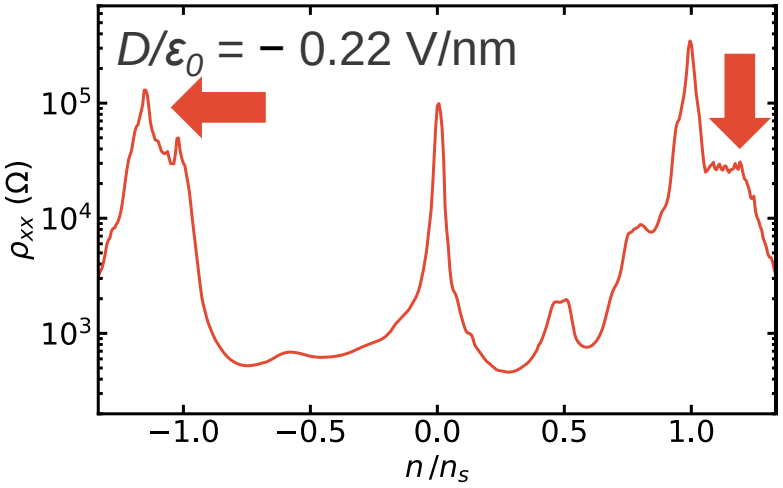


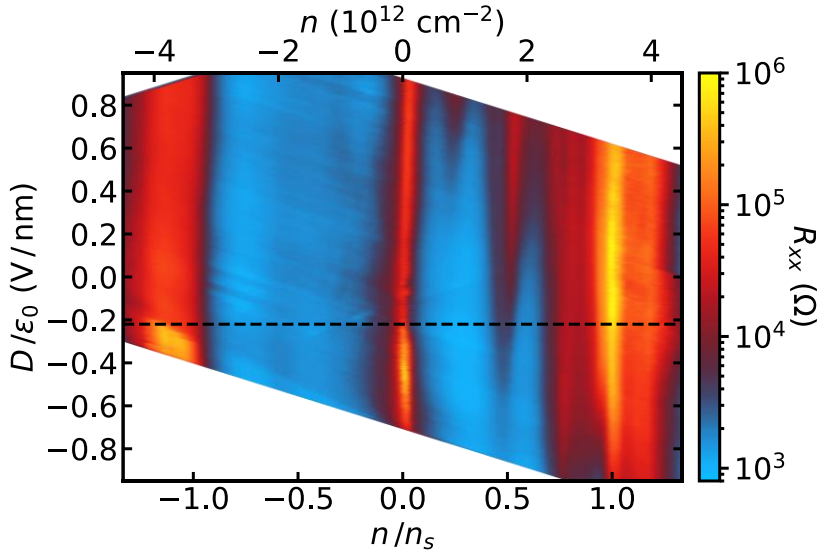

Graphene twist: 1.05 +/- 0.01°
Twist to hBN: large



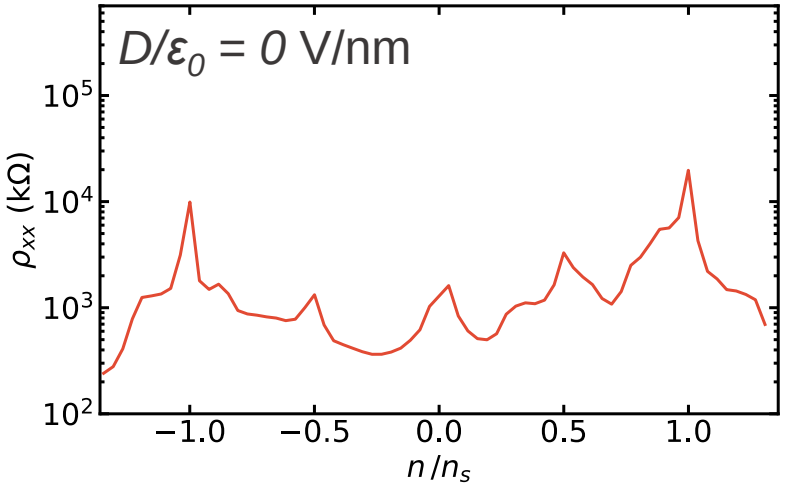
# Impact of Alignment with hBN

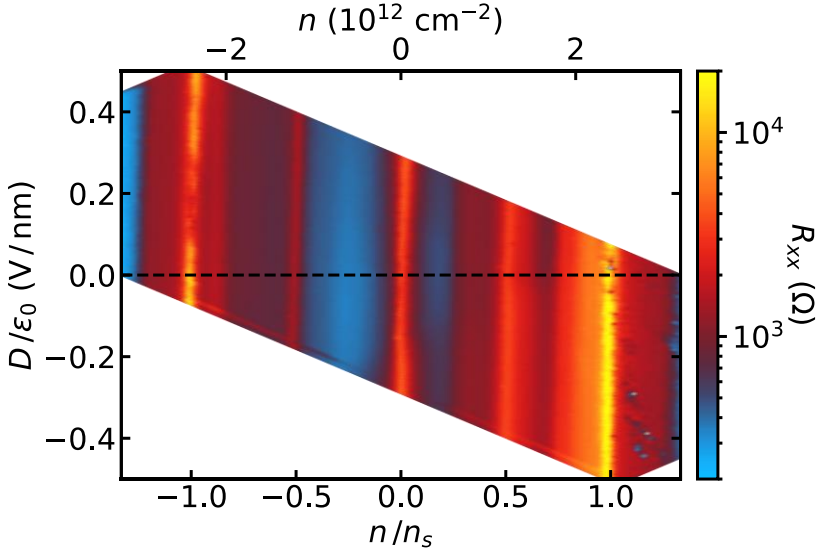
Device 1: aligned hBN



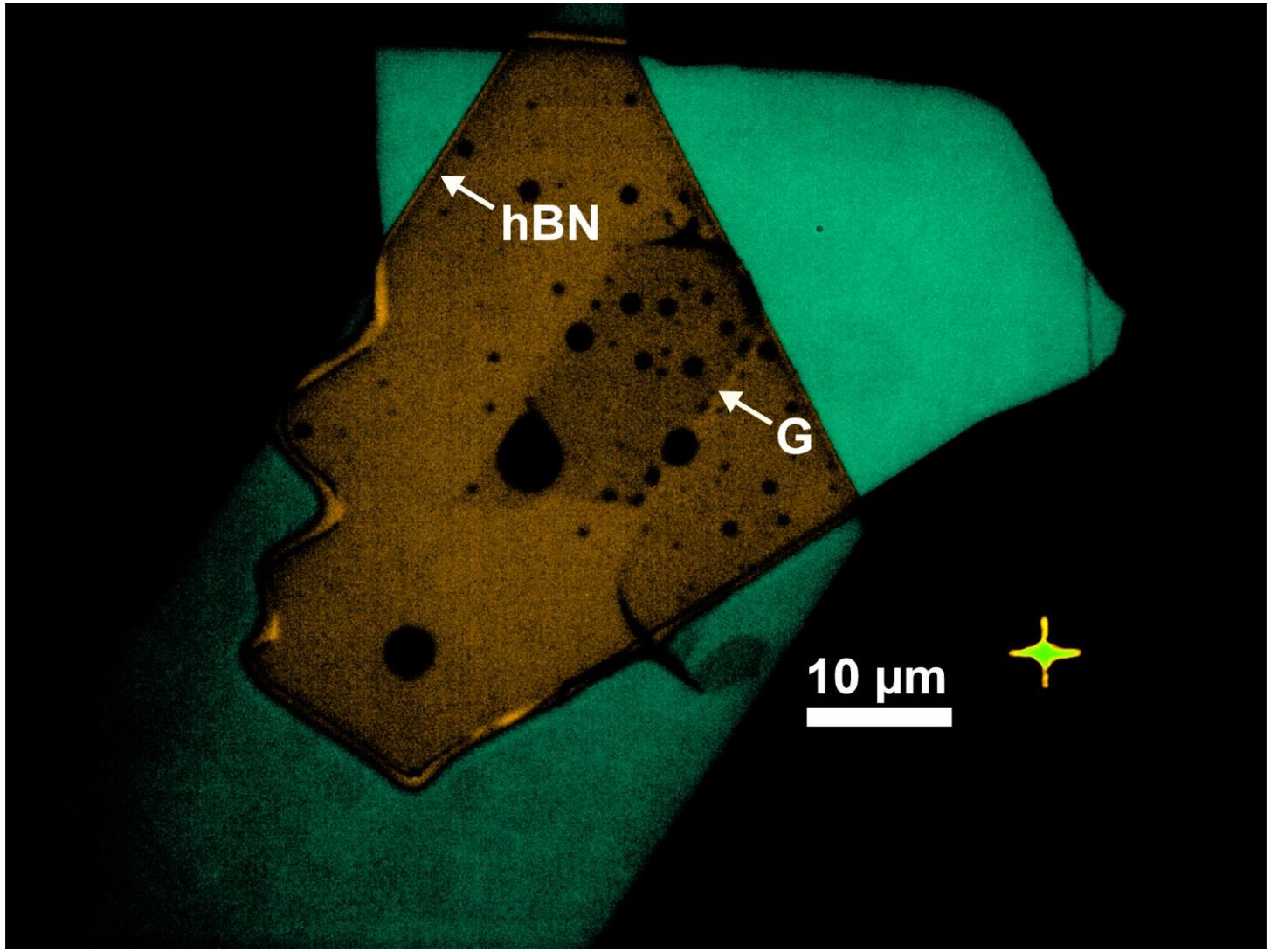




Device 2: misaligned hBN



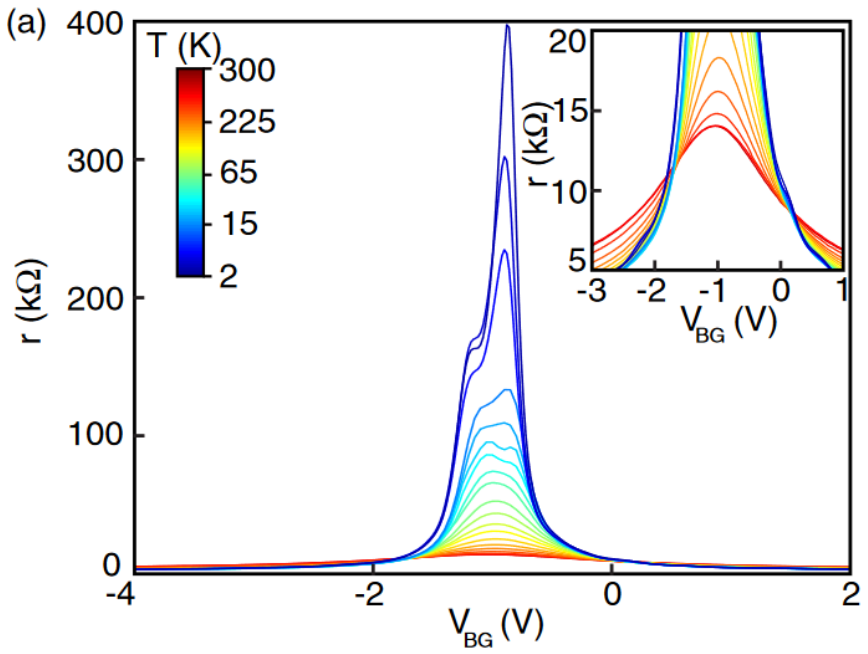



# Visual hBN Alignment



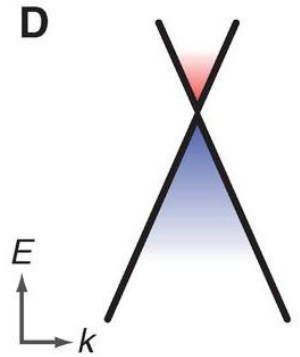
# Alignment with hBN

## Opens a gap at charge neutrality

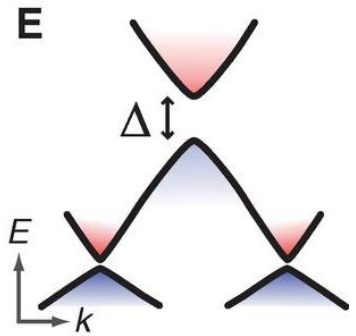


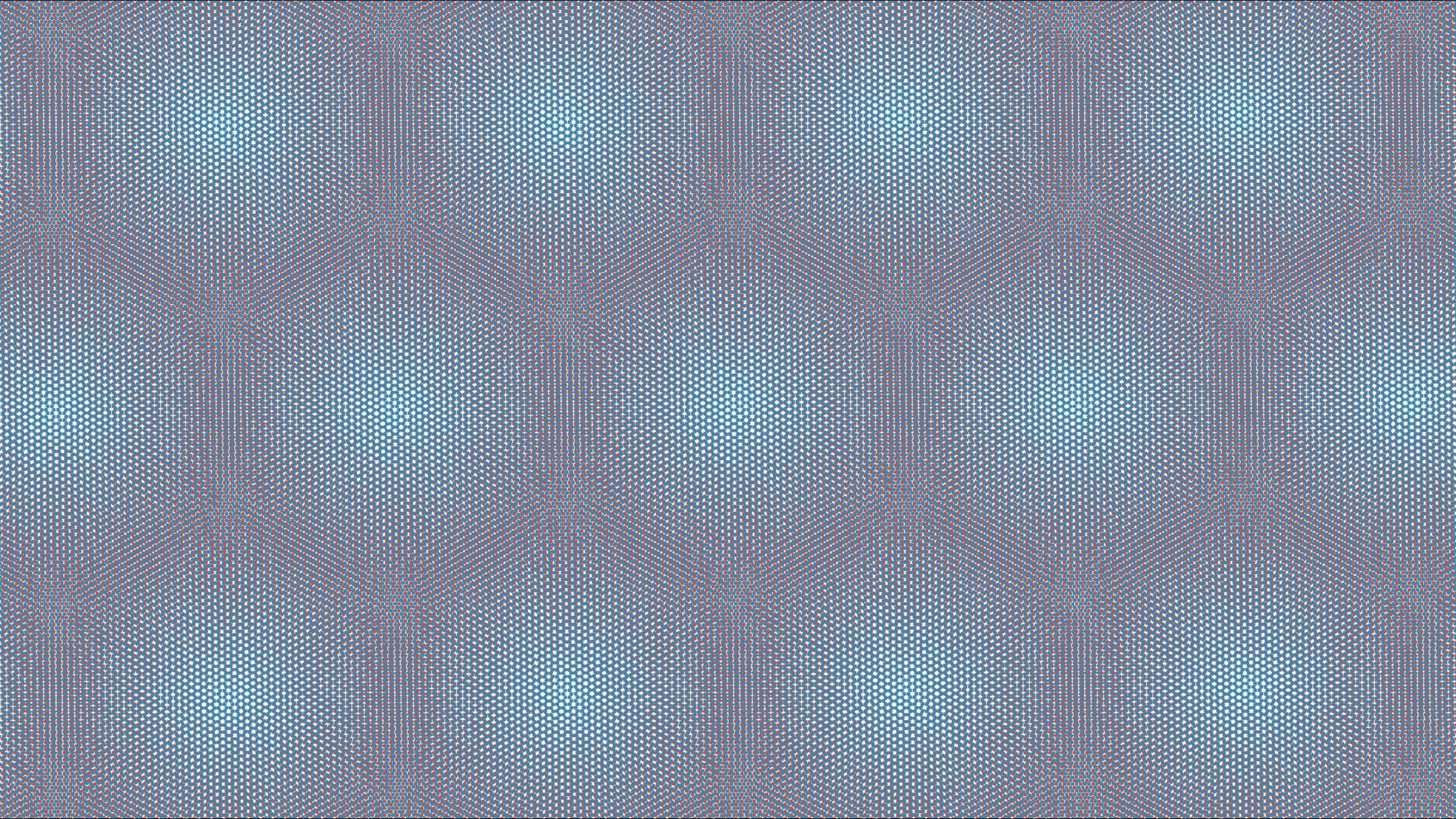

Amet, *PRL* (2013)
Hunt, *Science* (2013)

Monolayer graphene

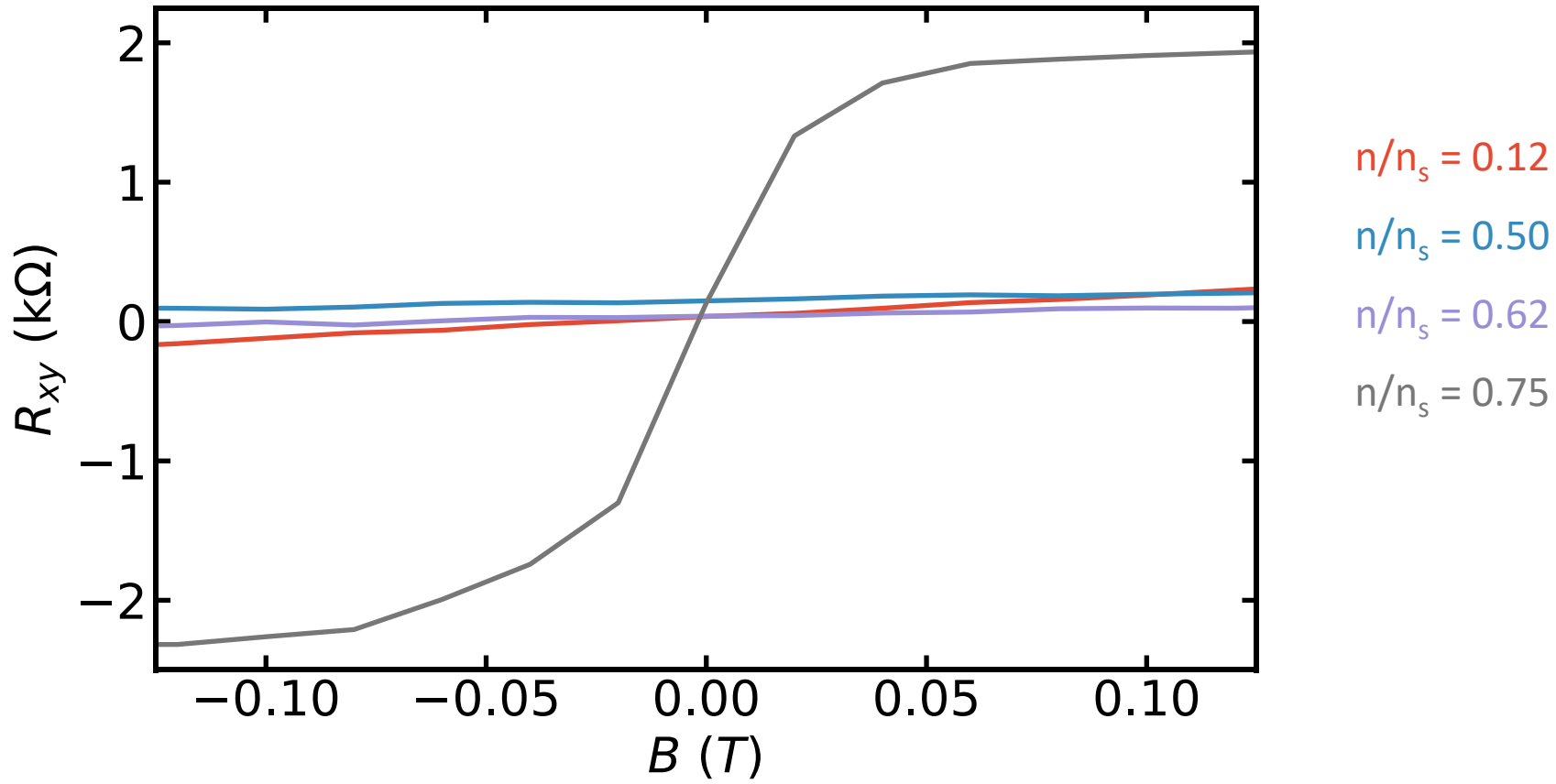



Monolayer graphene + hBN

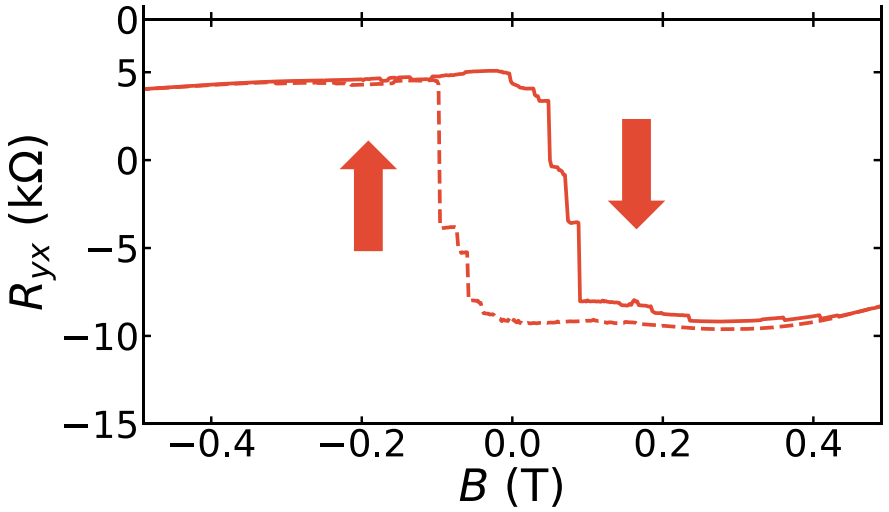


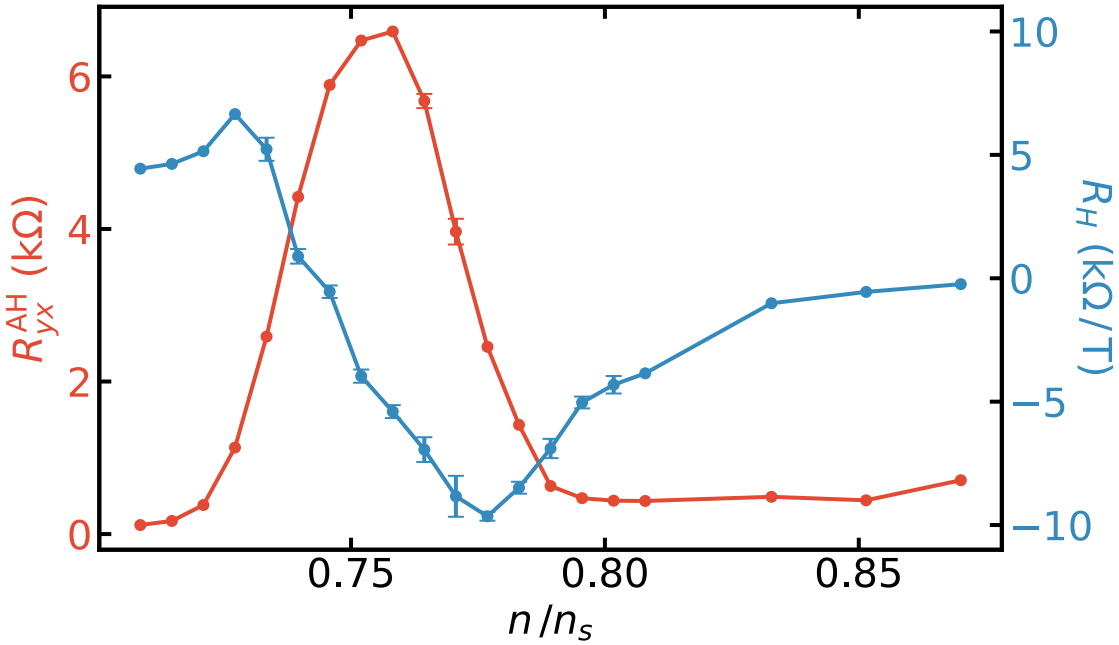


# Measuring Hall Slope Density Dependence

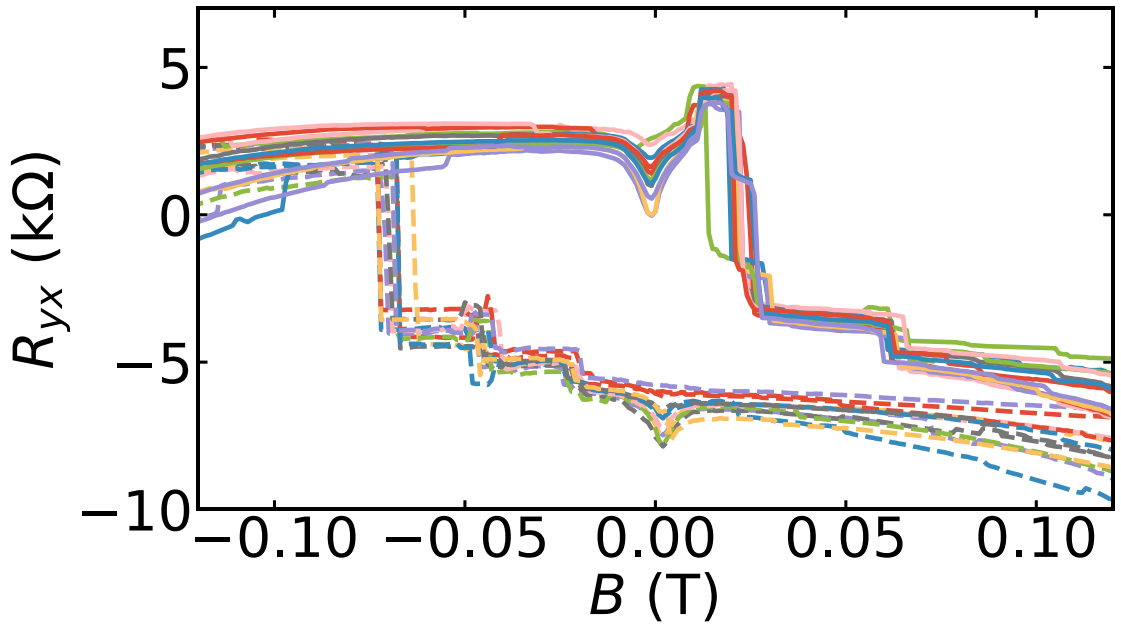


# Emergent Ferromagnetism at ¾ Filling

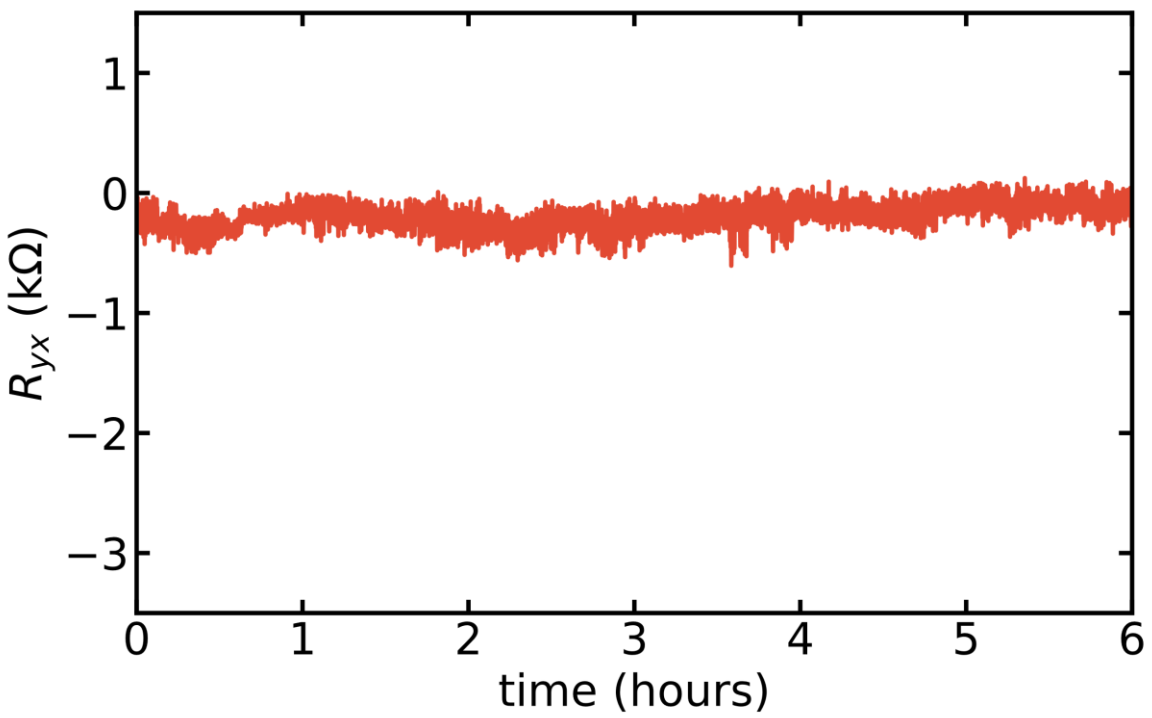


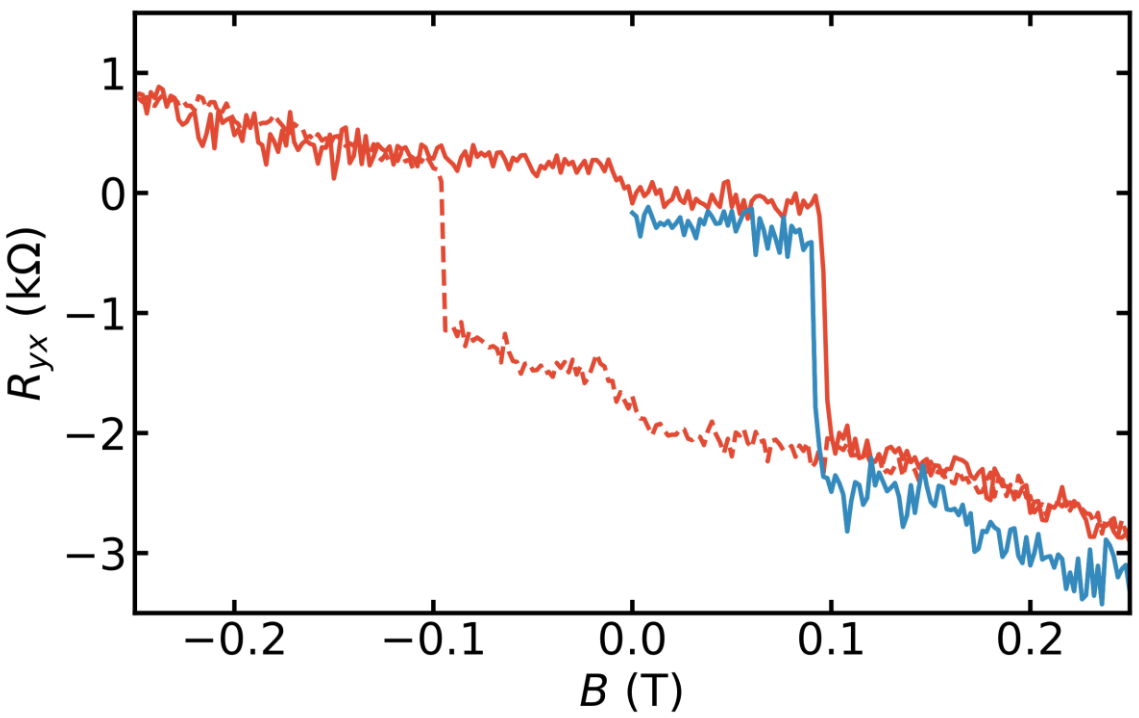



# Repeatable Hysteresis Fine Structure in Field

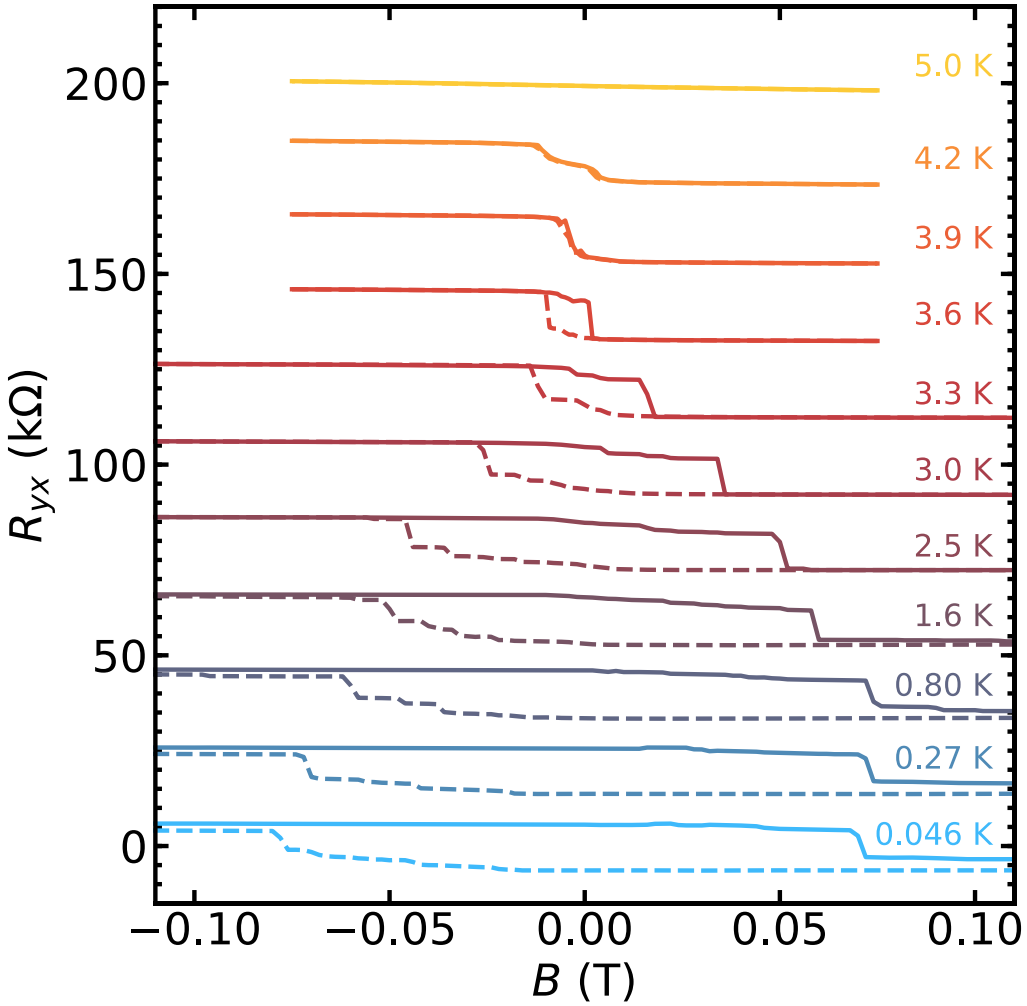


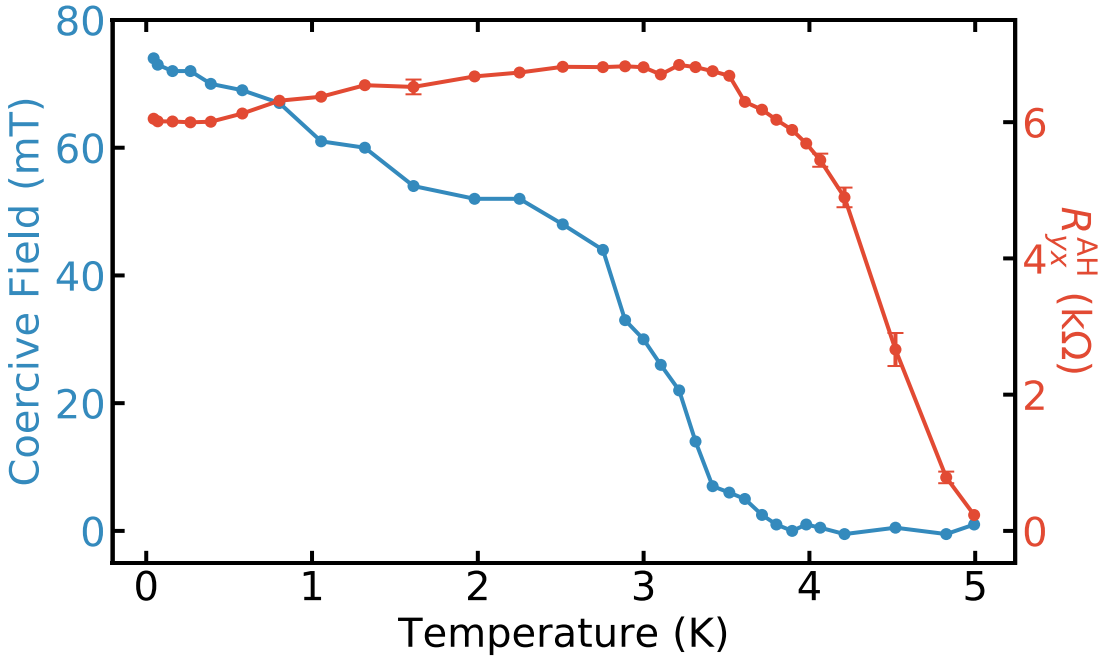
# Magnetism is Stable with No Applied Field



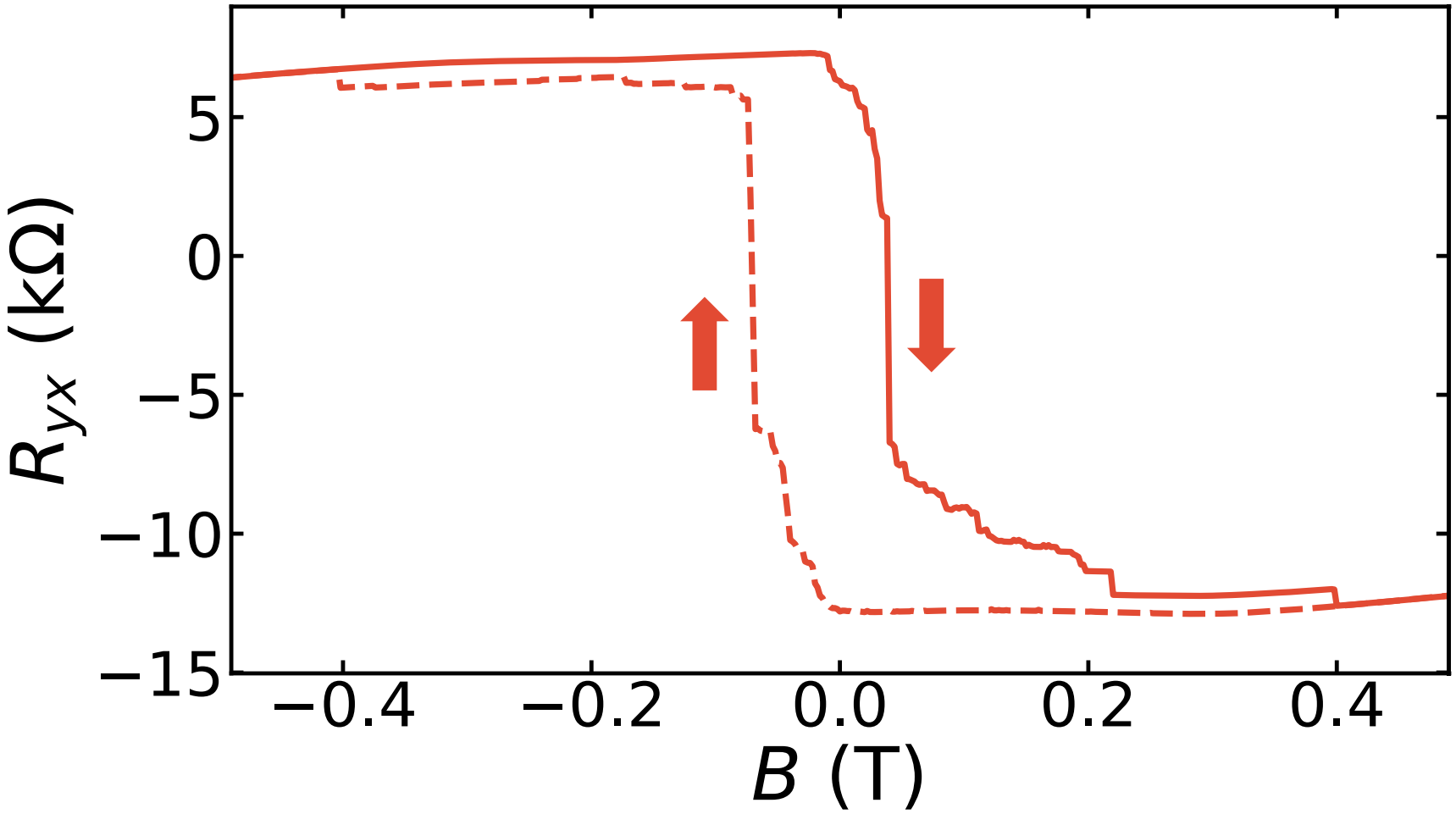



# Temperature Dependence of Ferromagnetism at ¾ Filling



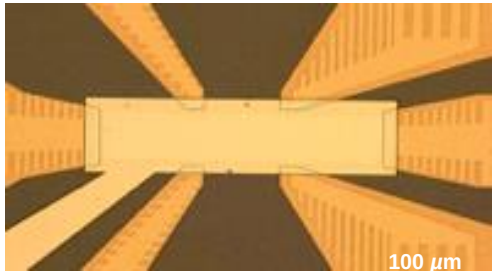



# Anomalous Hall Signal Can Be Really Large!




$n/n_s$=0.775, T=2.1K

# Comparison: Quantum Anomalous Hall in $(Cr,Bi,Sb)_2Te_3$




**Material & device:**

6 QL $Cr_{0.24}(Bi_{0.3}Sb_{0.7})_{1.76}Te_3$

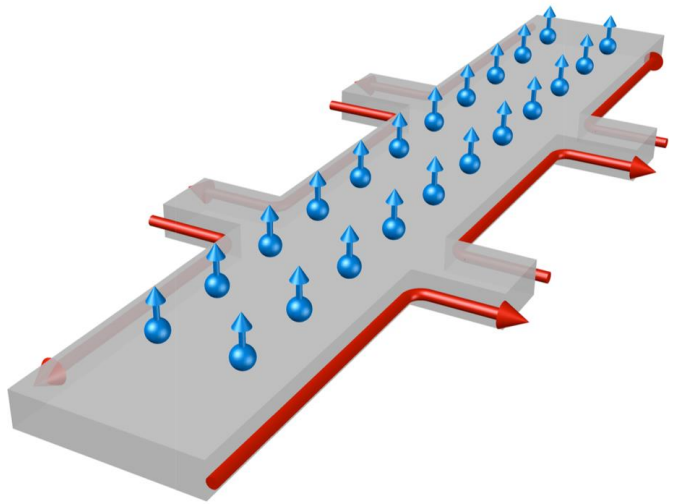
GaAs substrate

Ti/Au contacts

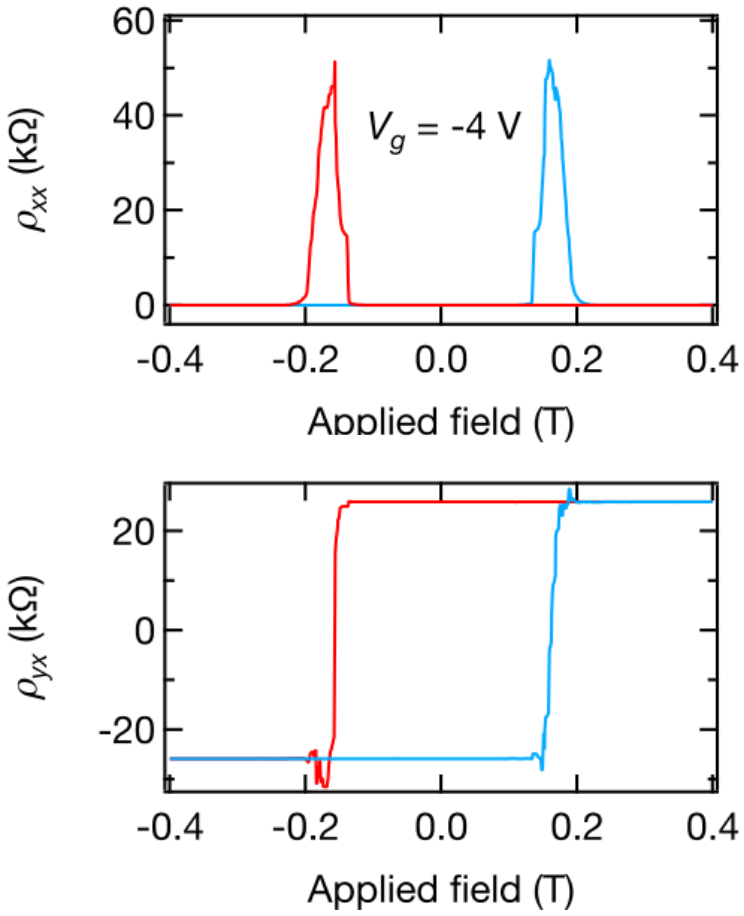
Top gate

Ideally:

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

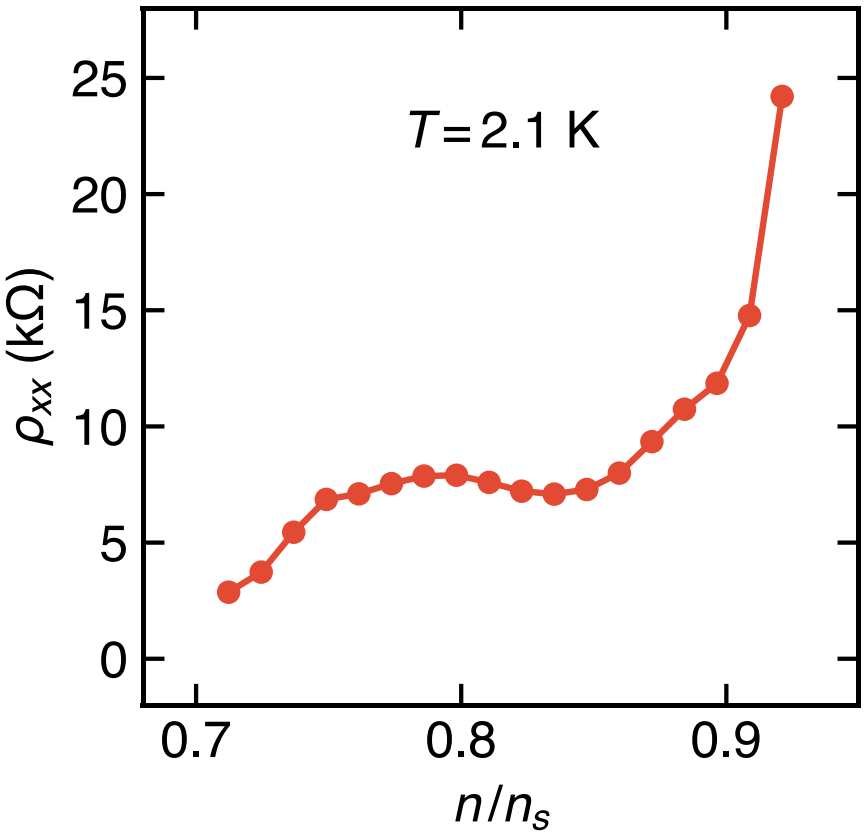


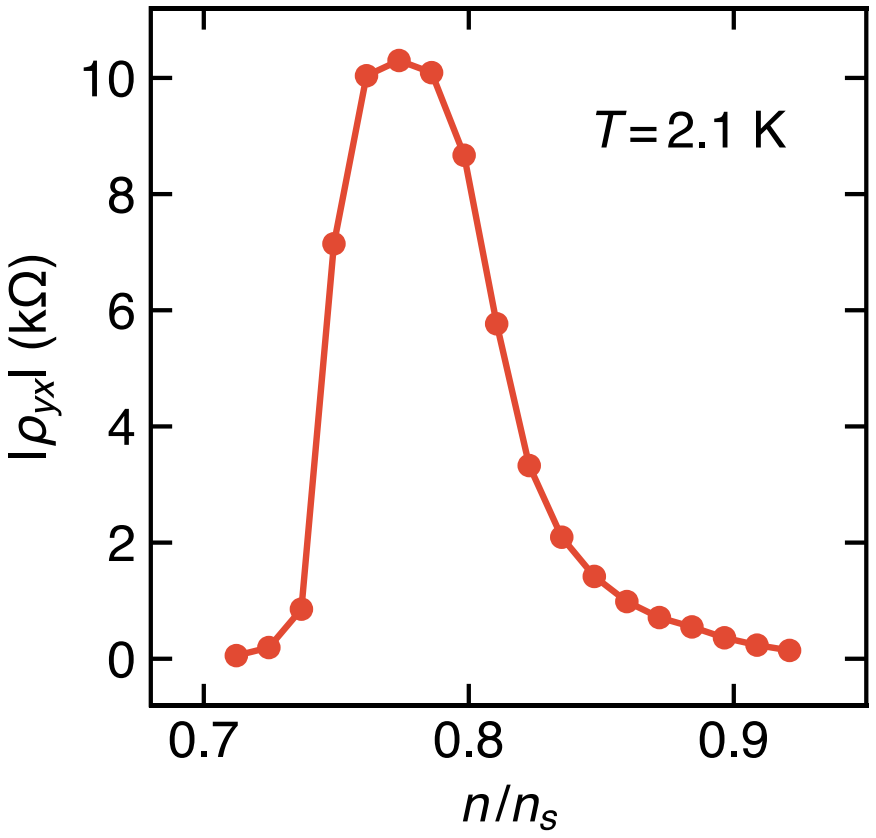
Near optimal gate voltage



# Comparison: Anomalous Hall in TBG

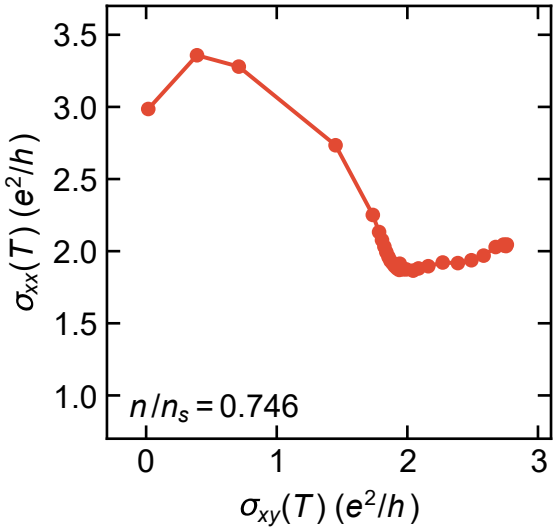
## Far from quantization

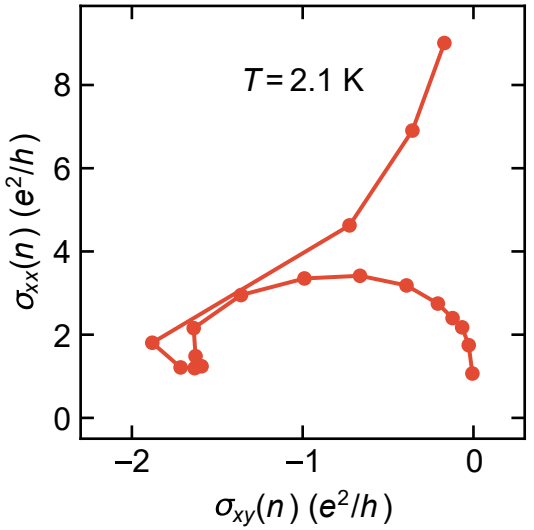


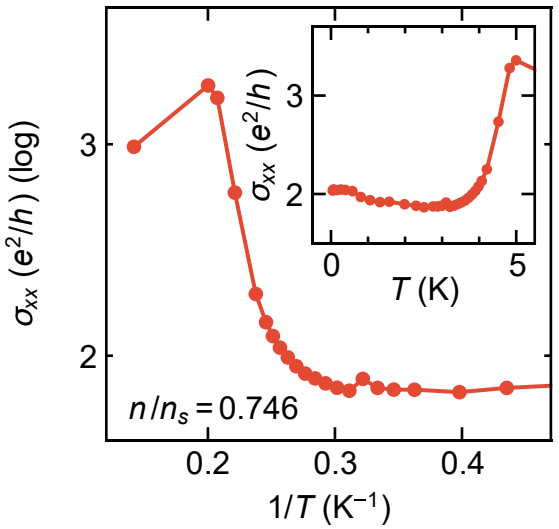



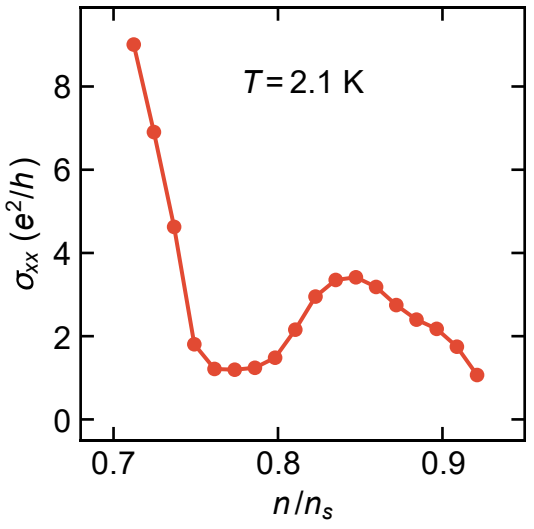
# Nature of Emergent Ferromagnetism

## Intrinsic vs. extrinsic anomalous Hall mechanisms



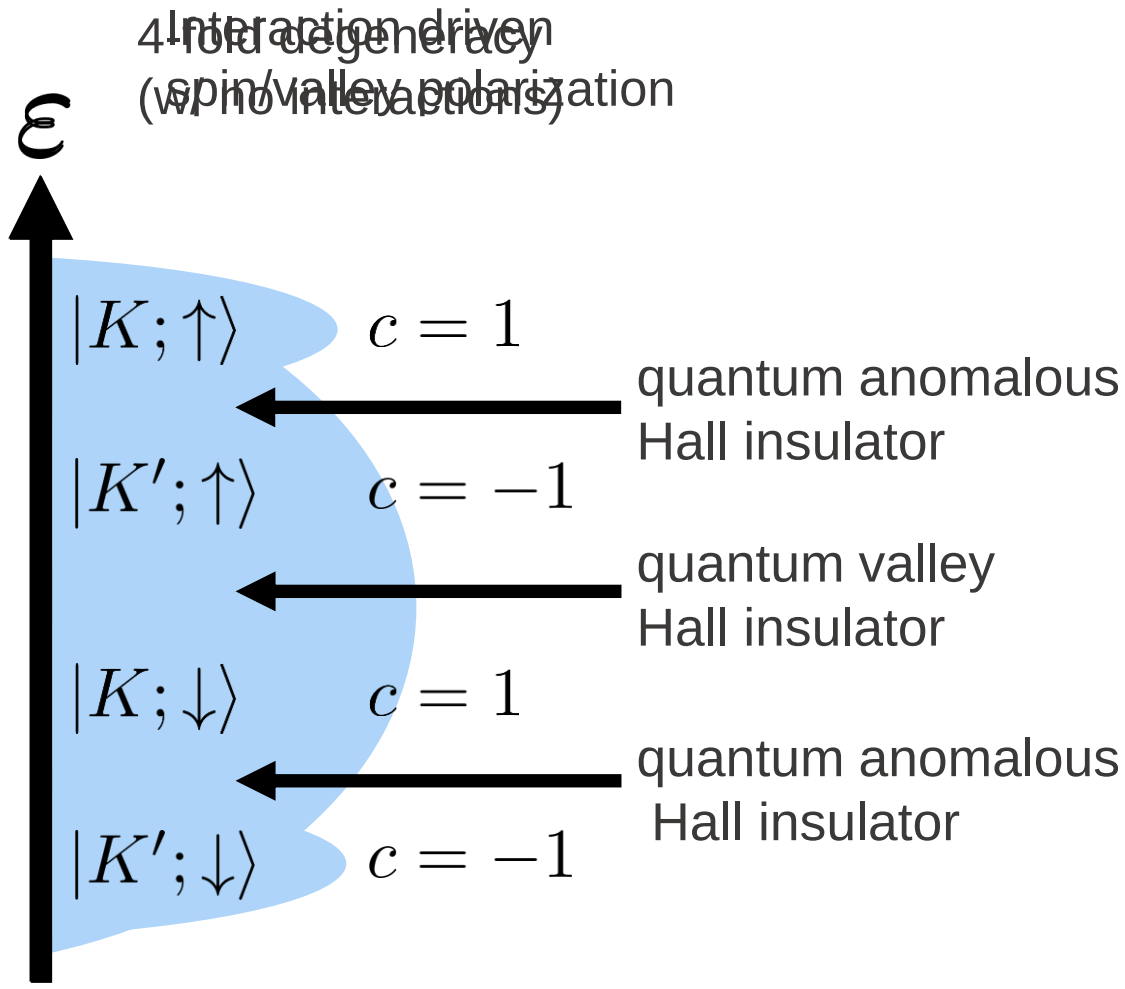



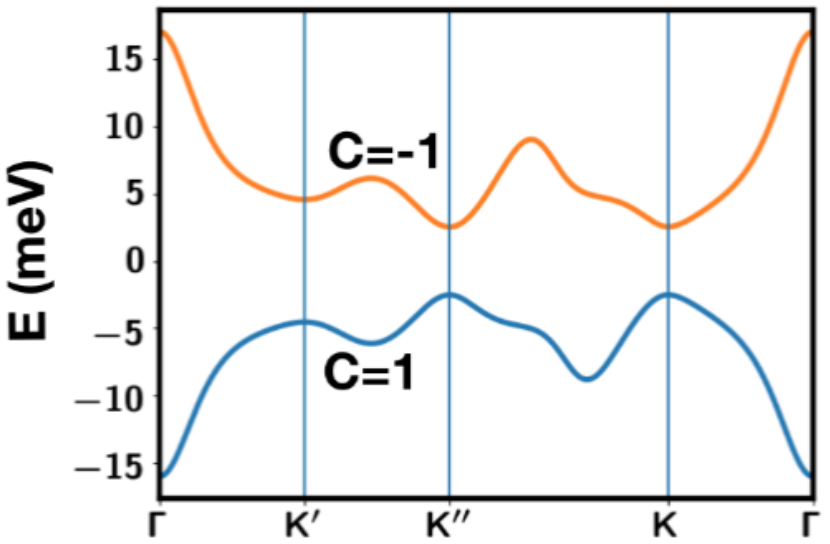



# Nature of Emergent Ferromagnetism at ¾ Filling?

## Simplistic band diagram: what *might* be happening…



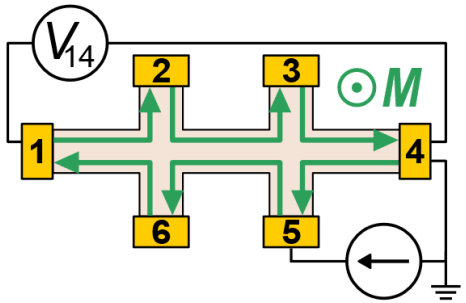

Twisted bilayer graphene + hBN

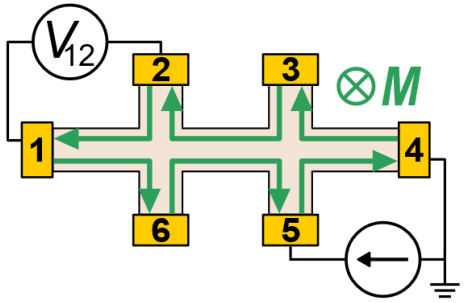


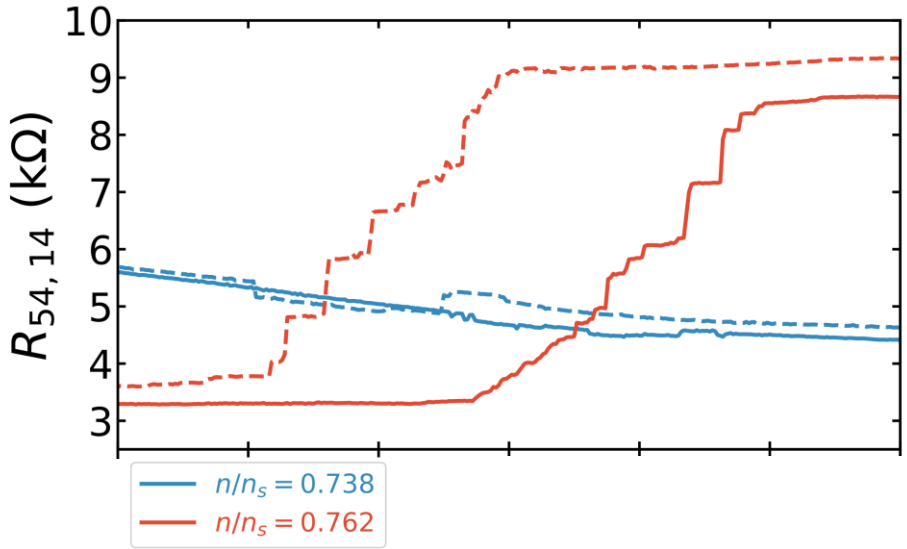

Zhang, *arXiv:1901.08209*
Bultinck, *arXiv:1901.08110*

Gap may open spontaneously:
Xie, *arXiv:1812.04213*

# 3- and 4-Terminal Nonlocal Transport at ¾ Filling

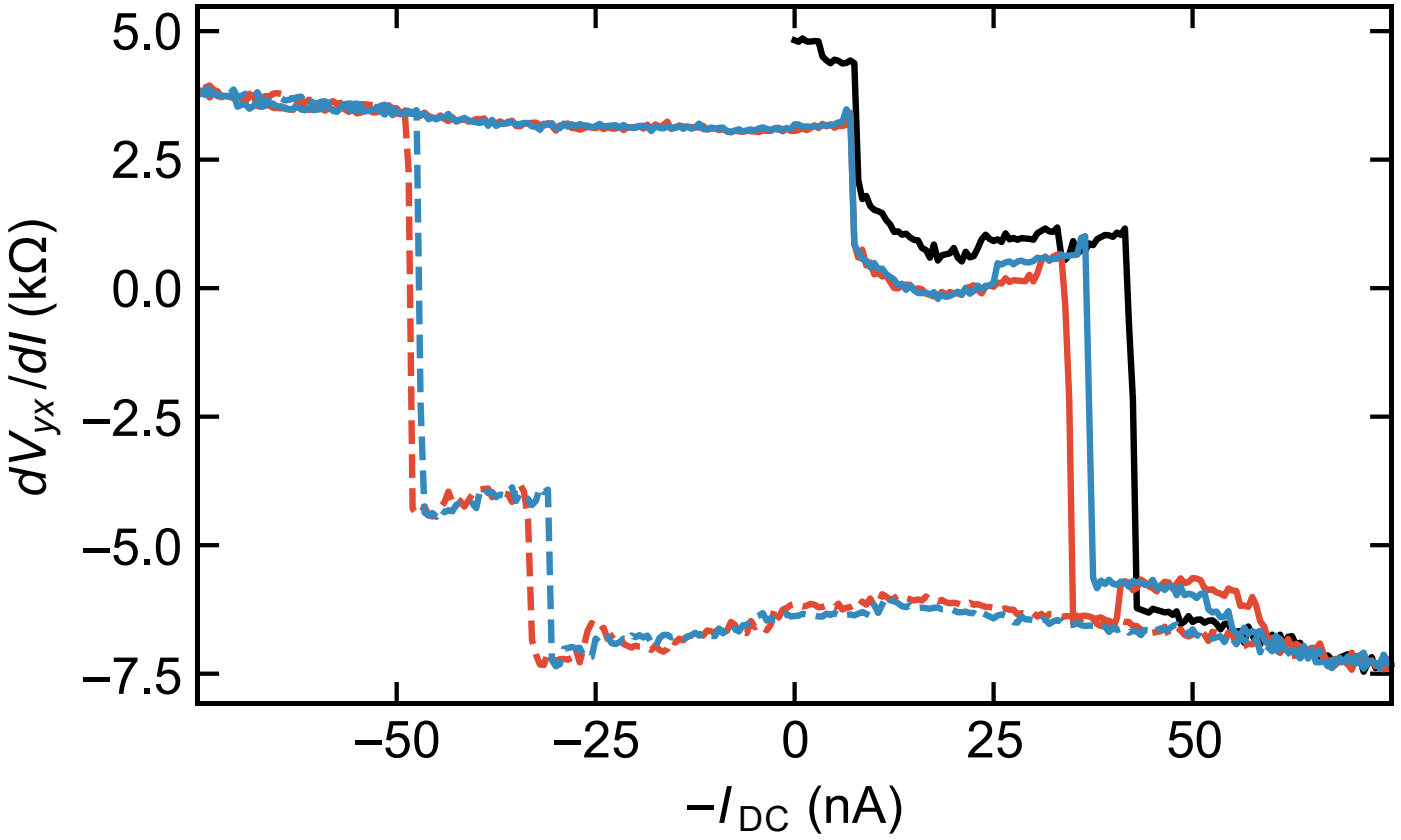


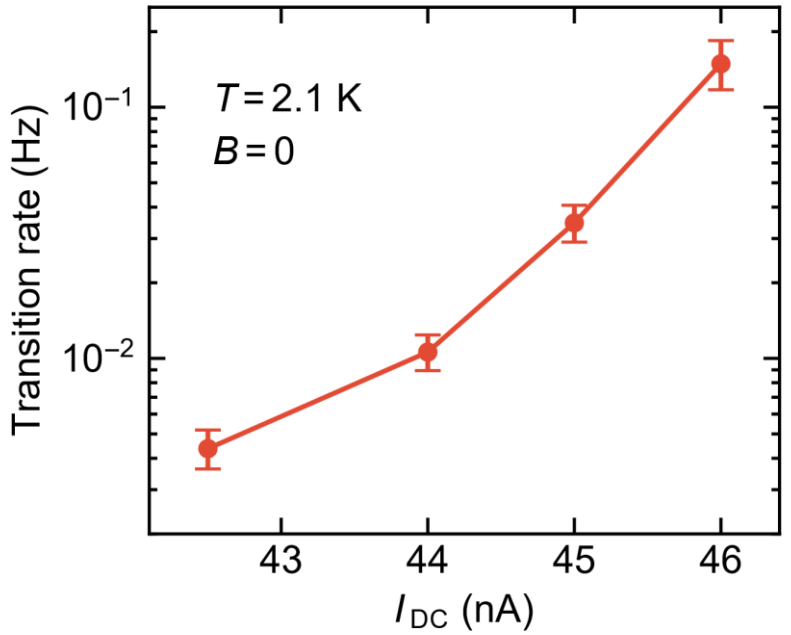



# Repeatable Hysteresis in Current

## Another TBG Mystery



# Questions?

TBG becomes ferromagnetic near ¾ filling up to 5 K!

Alignment to hBN may be crucial

At optimal doping
$\rho_{xy}$ = 10.4 kΩ
$\rho_{xy}/\rho_{xx}$ = 1.4

Evidence for edge conduction

Small DC current can flip magnetization

arXiv: 1901.03520