Emergent ferromagnetism near three-quarters filling in twisted bilayer graphene

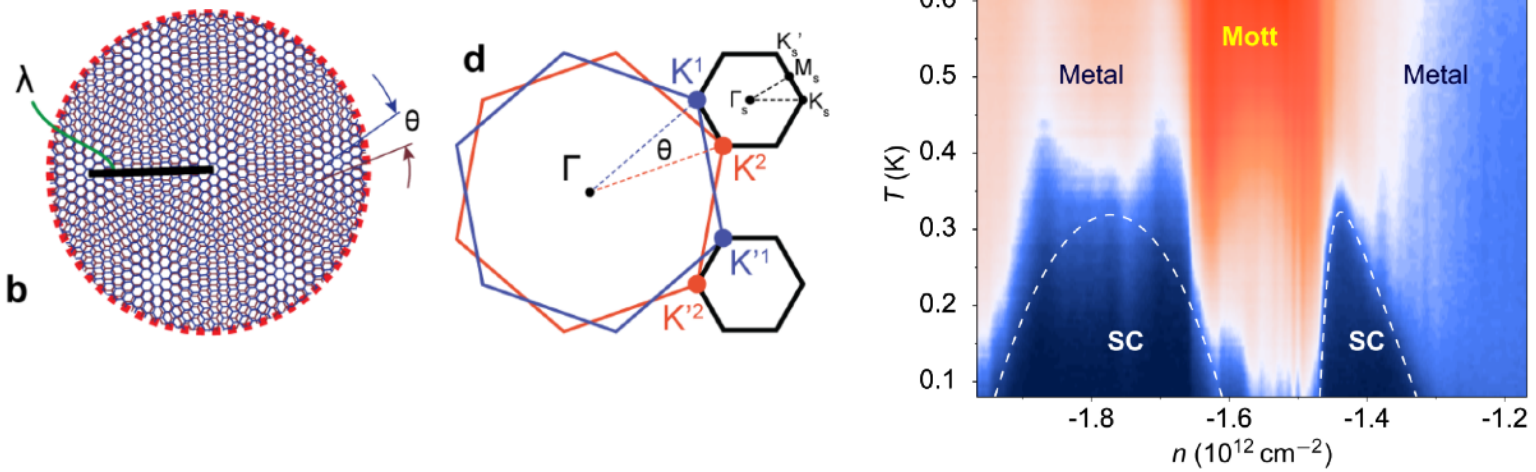
David Goldhaber-Gordon

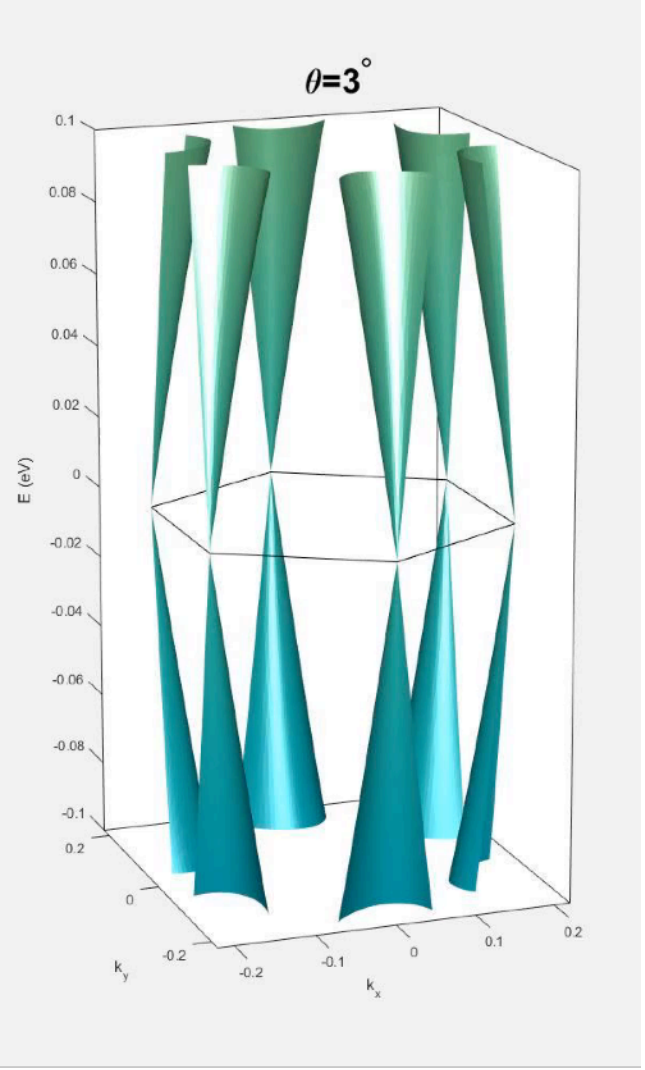
KITP 1/14/2019

arXiv 1901.03520

Strong Correlations

Twisted layer graphene and hBN provide unprecedented control of correlations in 2D electron systems

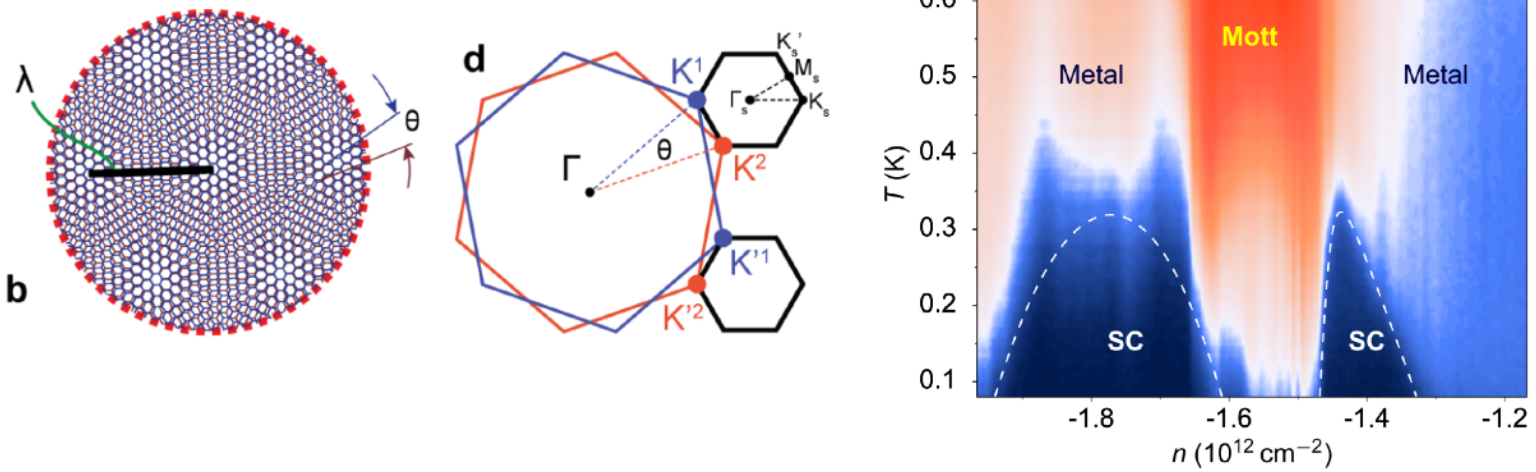


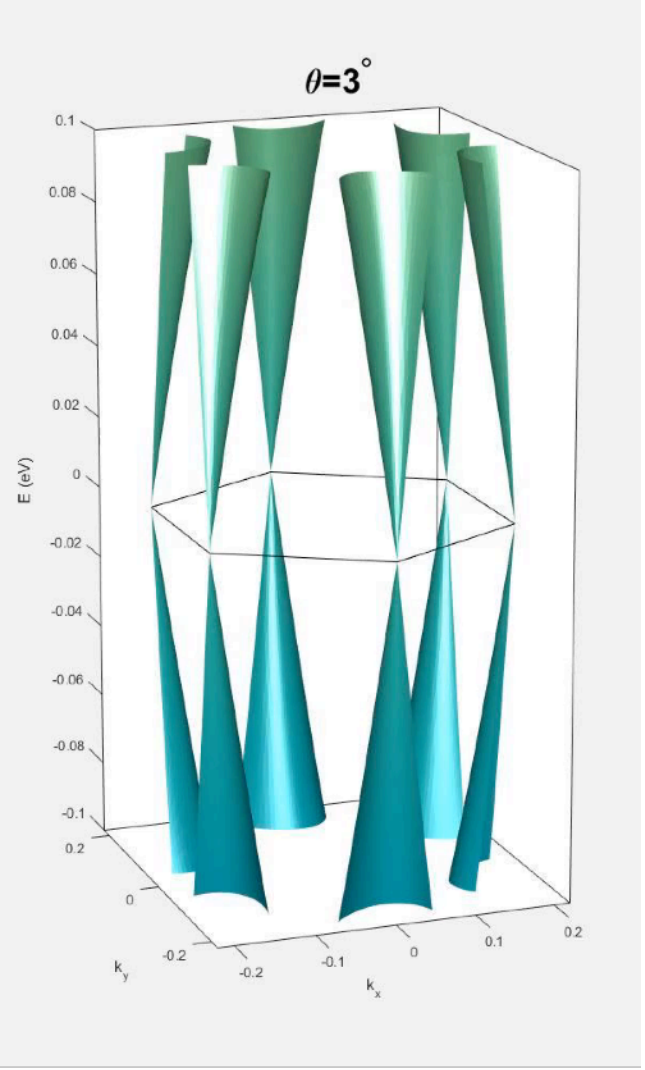


Cao, *Nature* (2018)
cf Nam, Koshino PRB (2017)
Morell (2010)
Bistritzer (2011)
…

Strong Correlations

Twisted layer graphene and hBN provide unprecedented control of correlations in 2D electron systems

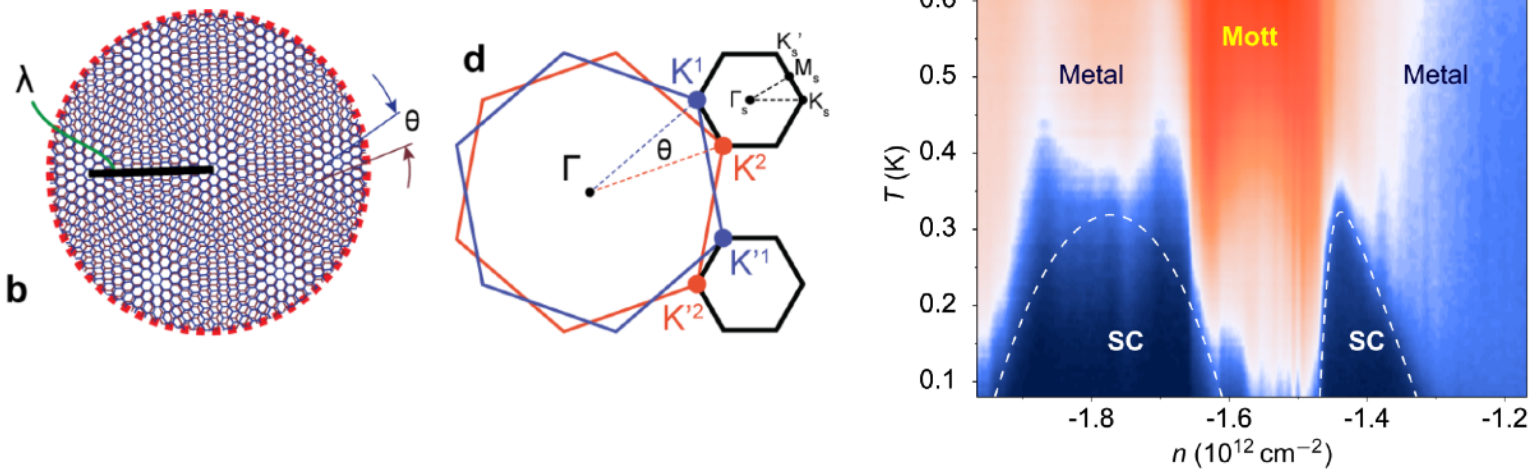


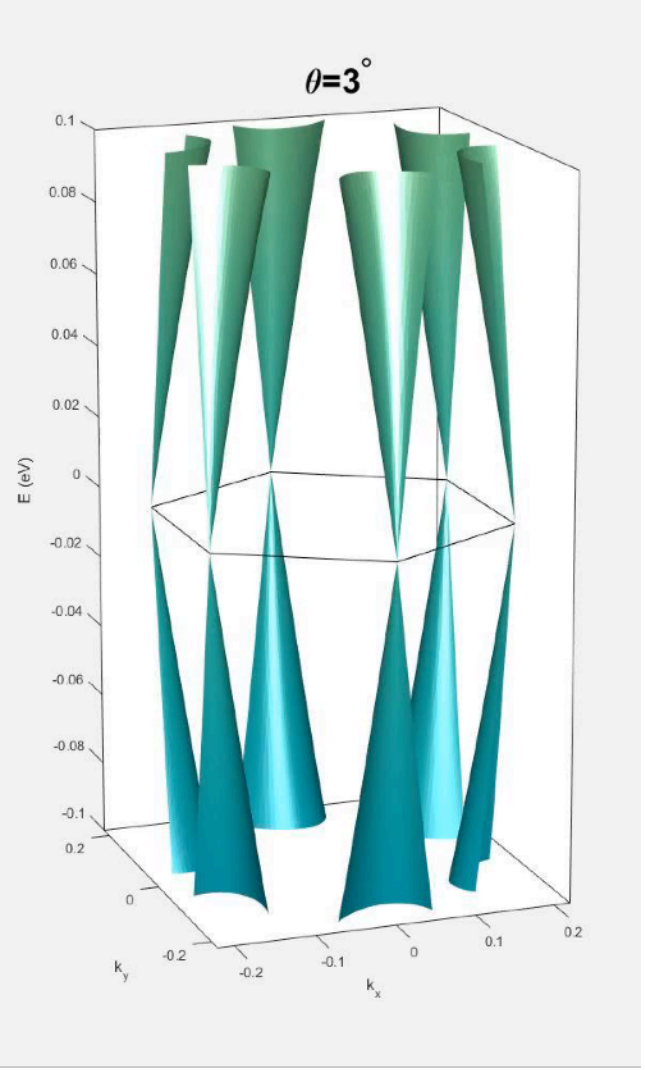


Cao, *Nature* (2018)
cf Nam, Koshino PRB (2017)
Morell (2010)
Bistritzer (2011)
…

Strong Correlations

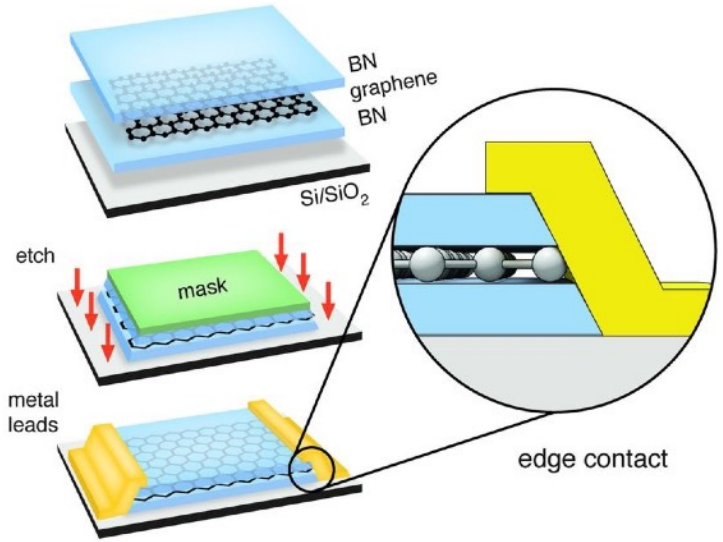
Twisted layer graphene and hBN provide unprecedented control of correlations in 2D electron systems



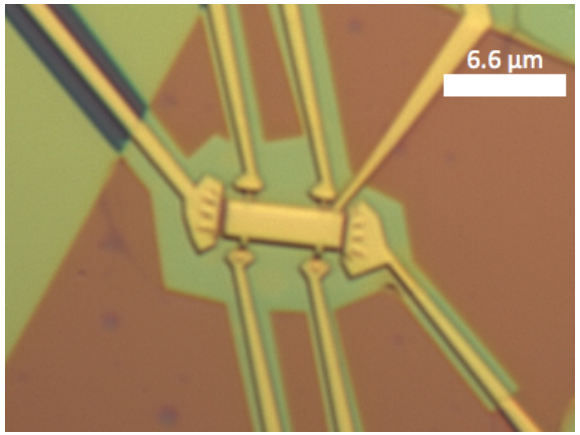


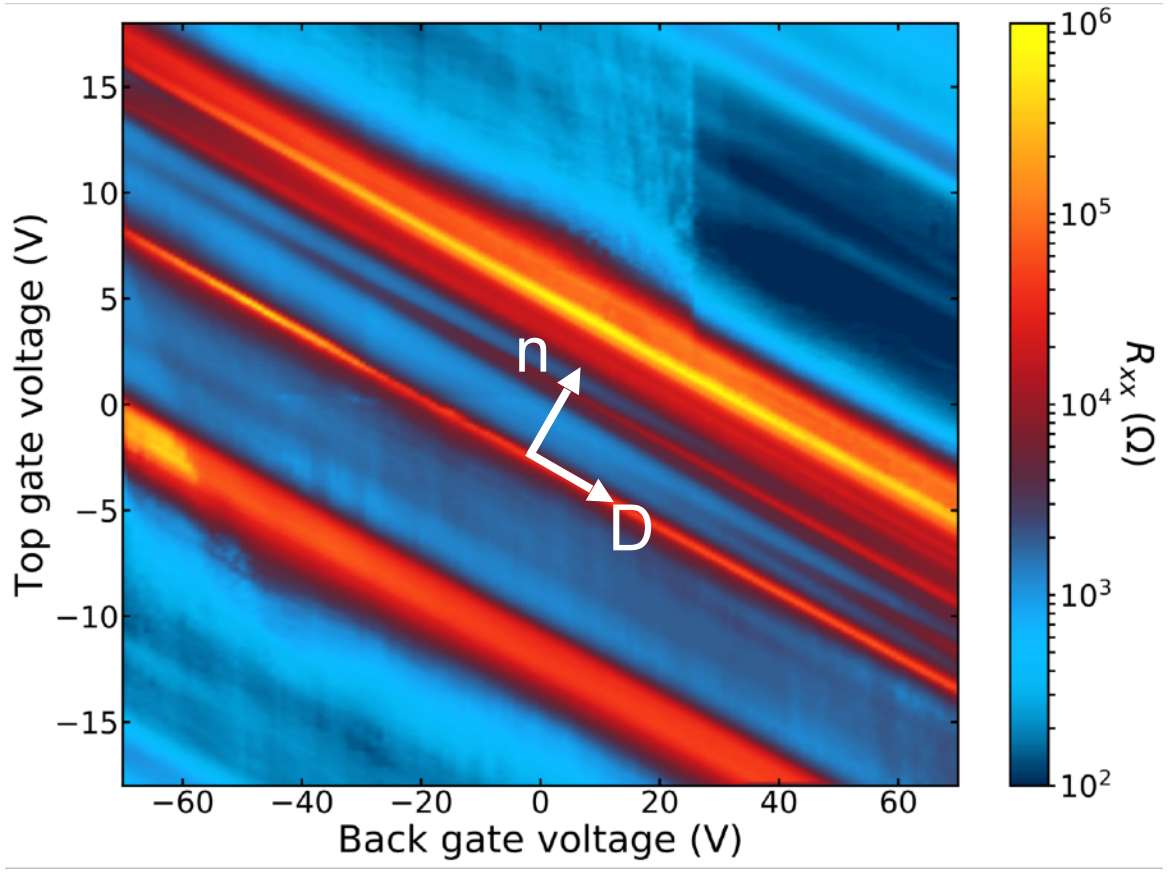
Cao, *Nature* (2018)
cf Nam, Koshino PRB (2017)
Morell (2010)
Bistritzer (2011)
…

Strong Correlations: Twisted bilayer near magic angle



Wang, *Science* (2013)

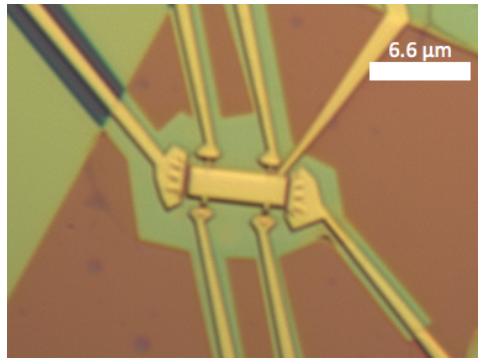




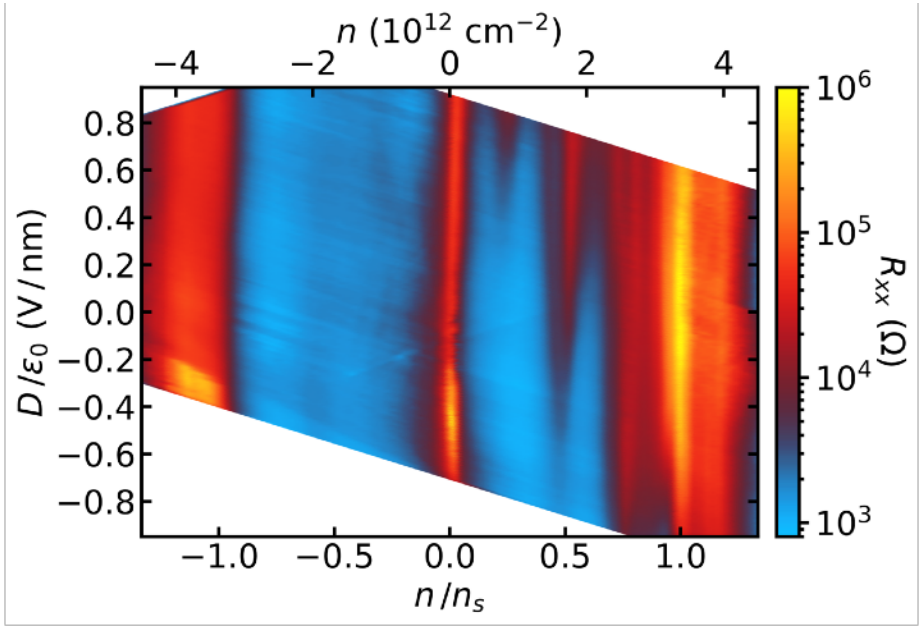
Angle 1.20+/-0.01°. Target 1.17°

Alignment with hBN matters?

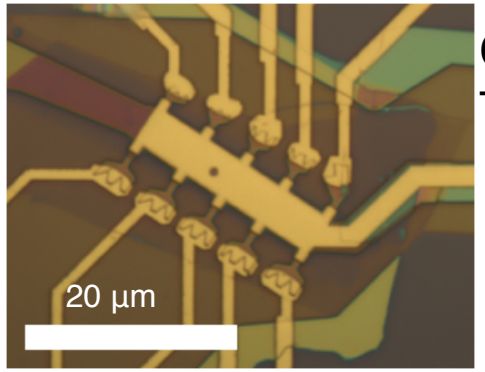
Device 1: aligned hBN



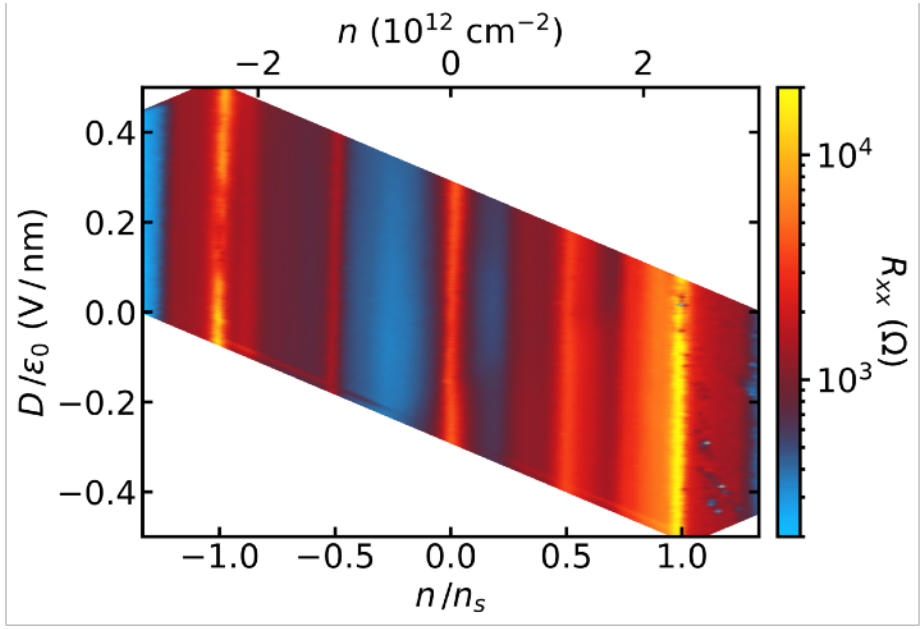
Graphene twist 1.20+/-0.01°
Twist to one hBN 0.81°+/-0.02°



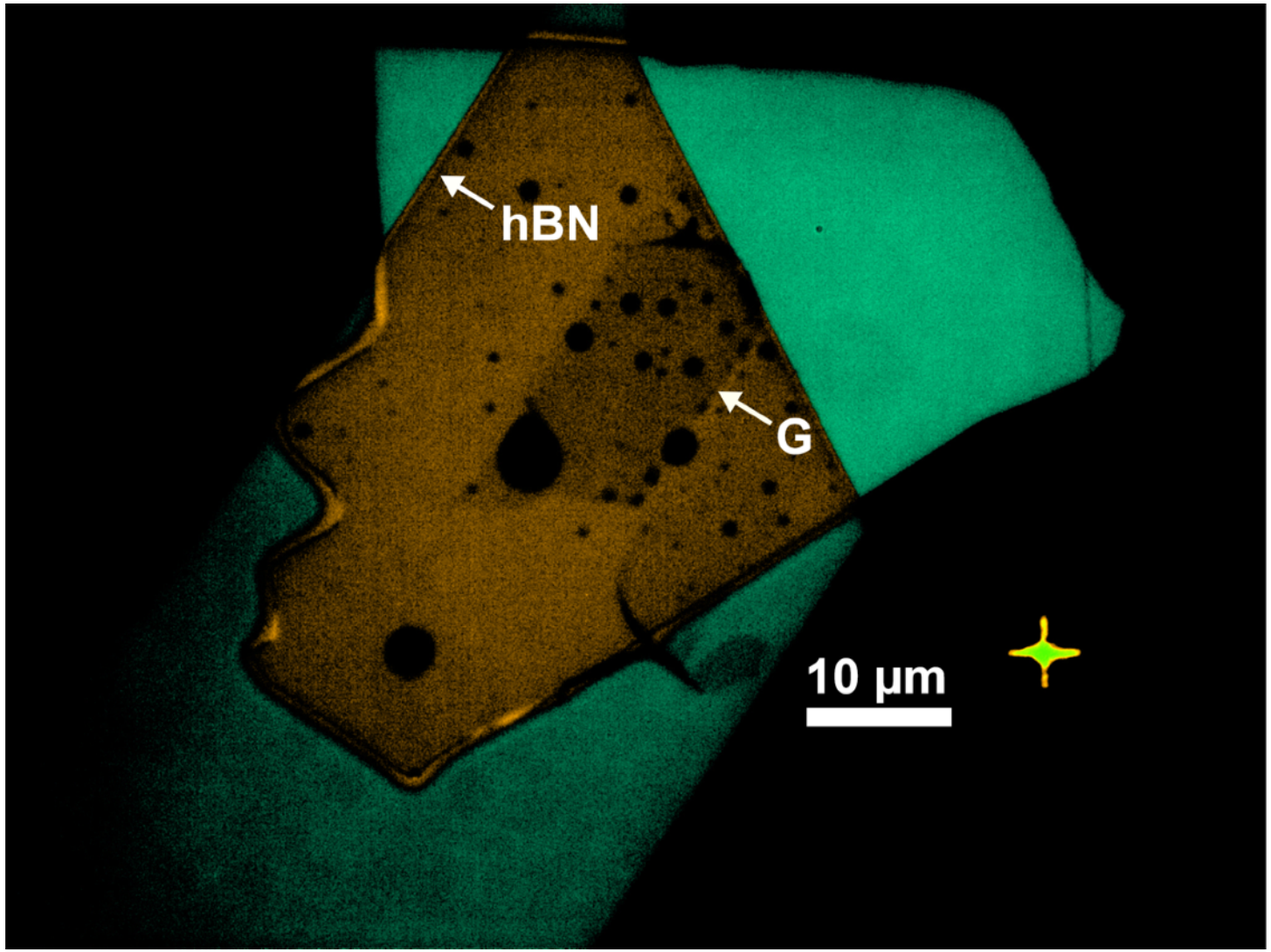
Device 2: misaligned hBN



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

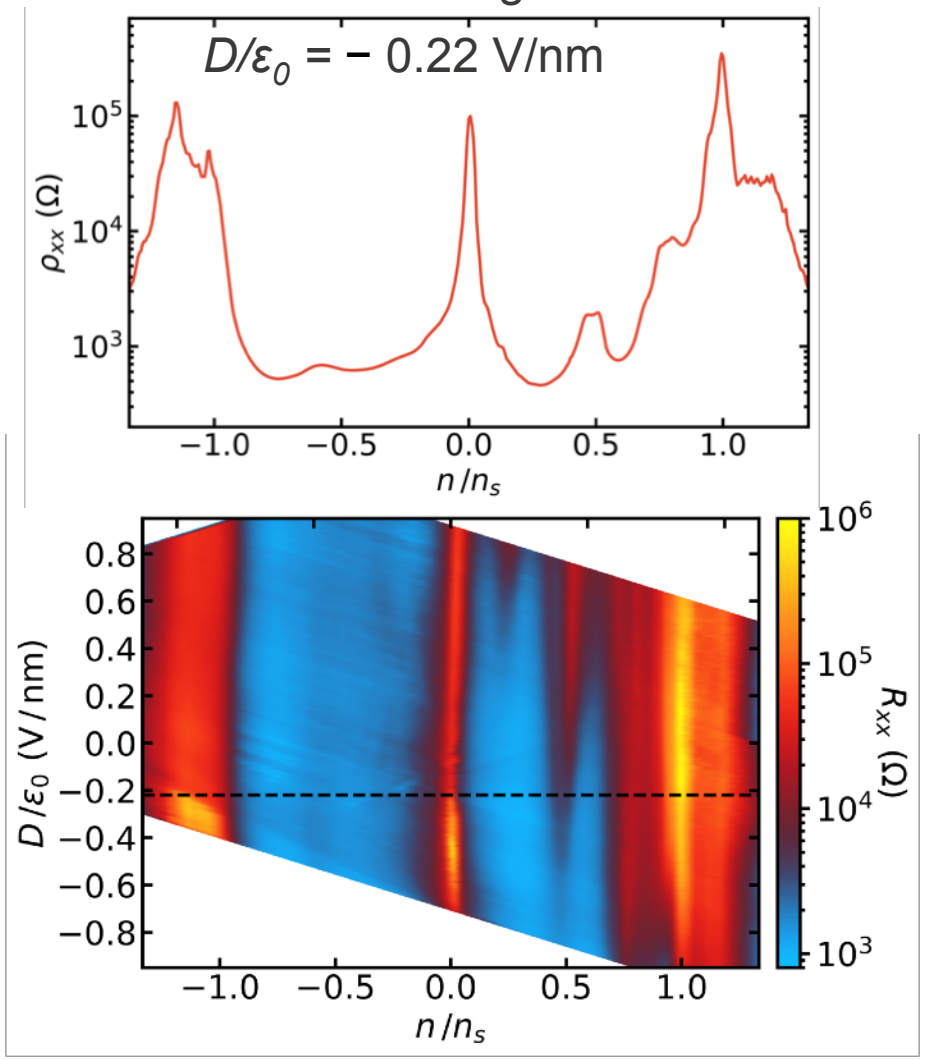


Visual hBN Alignment

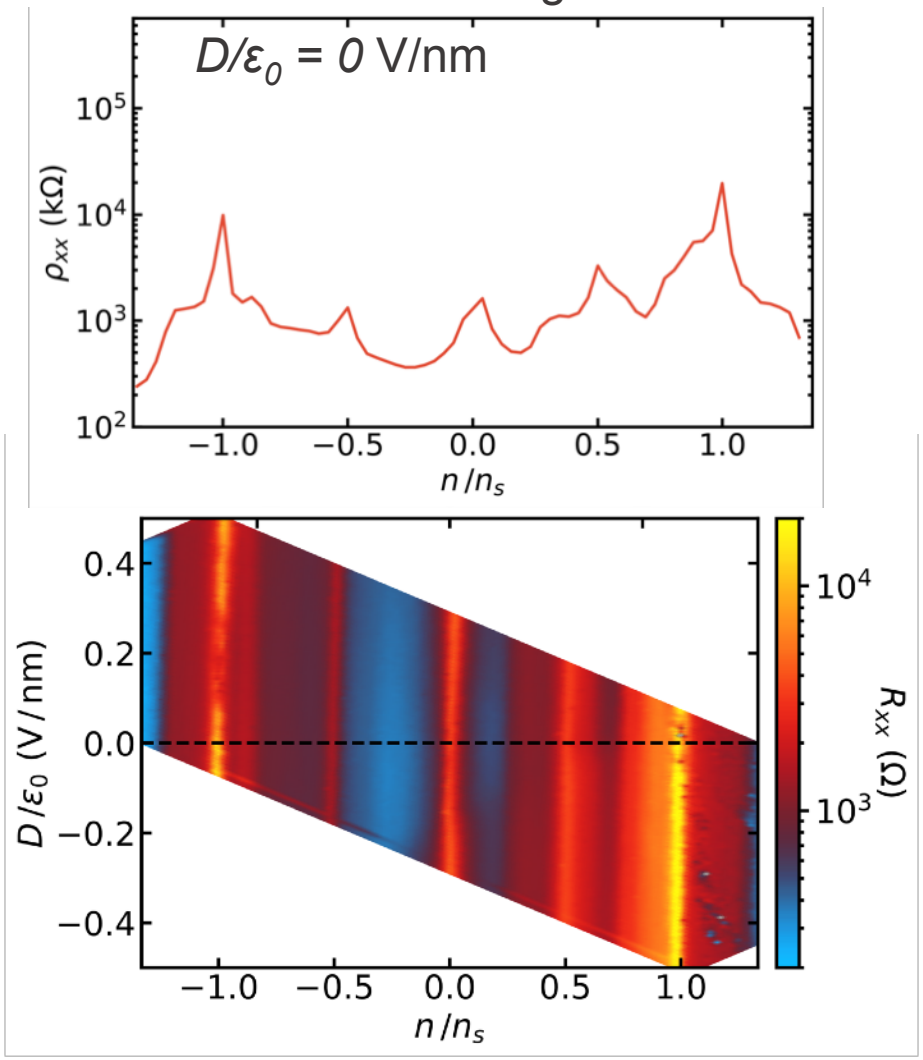


Alignment with hBN matters?

Device 1: aligned hBN

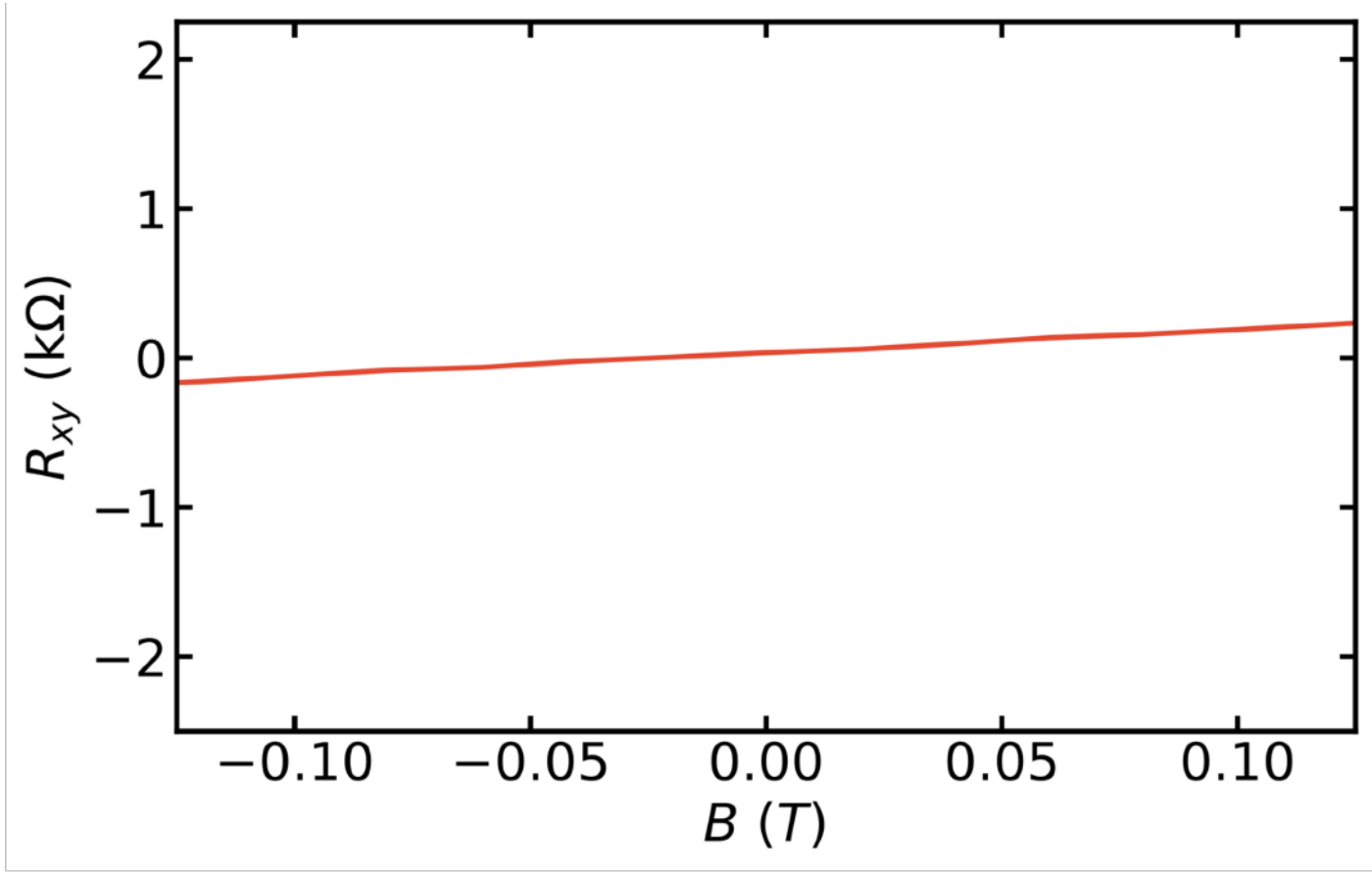


Device 2: misaligned hBN



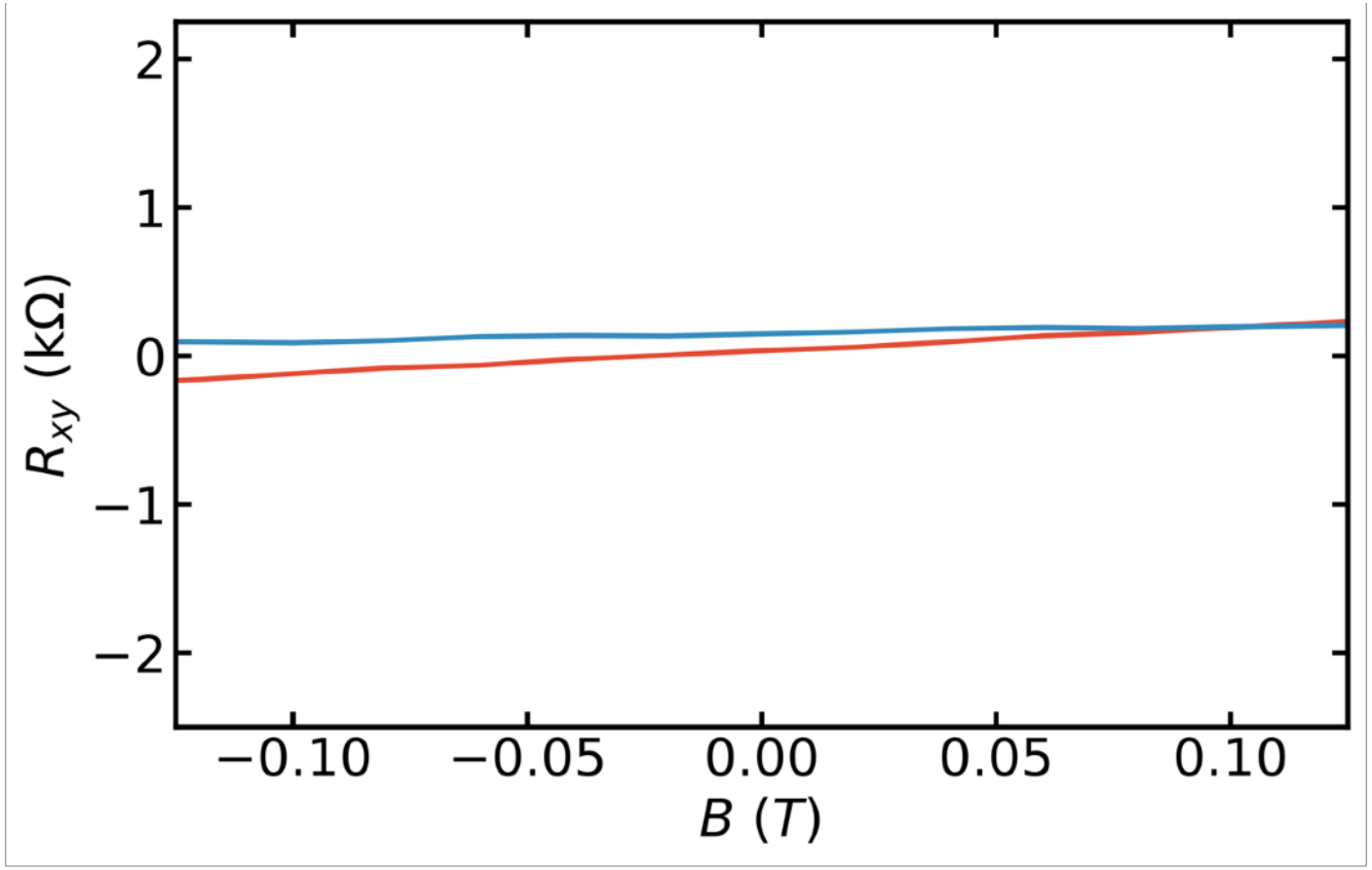
For insulating behavior a charge neutrality for graphene on hBN see Amet PRL 110.216601 Hunt Science 1237240 (2013)

Measuring Hall Slope Density Dependence



$n/n_s = 0.12$

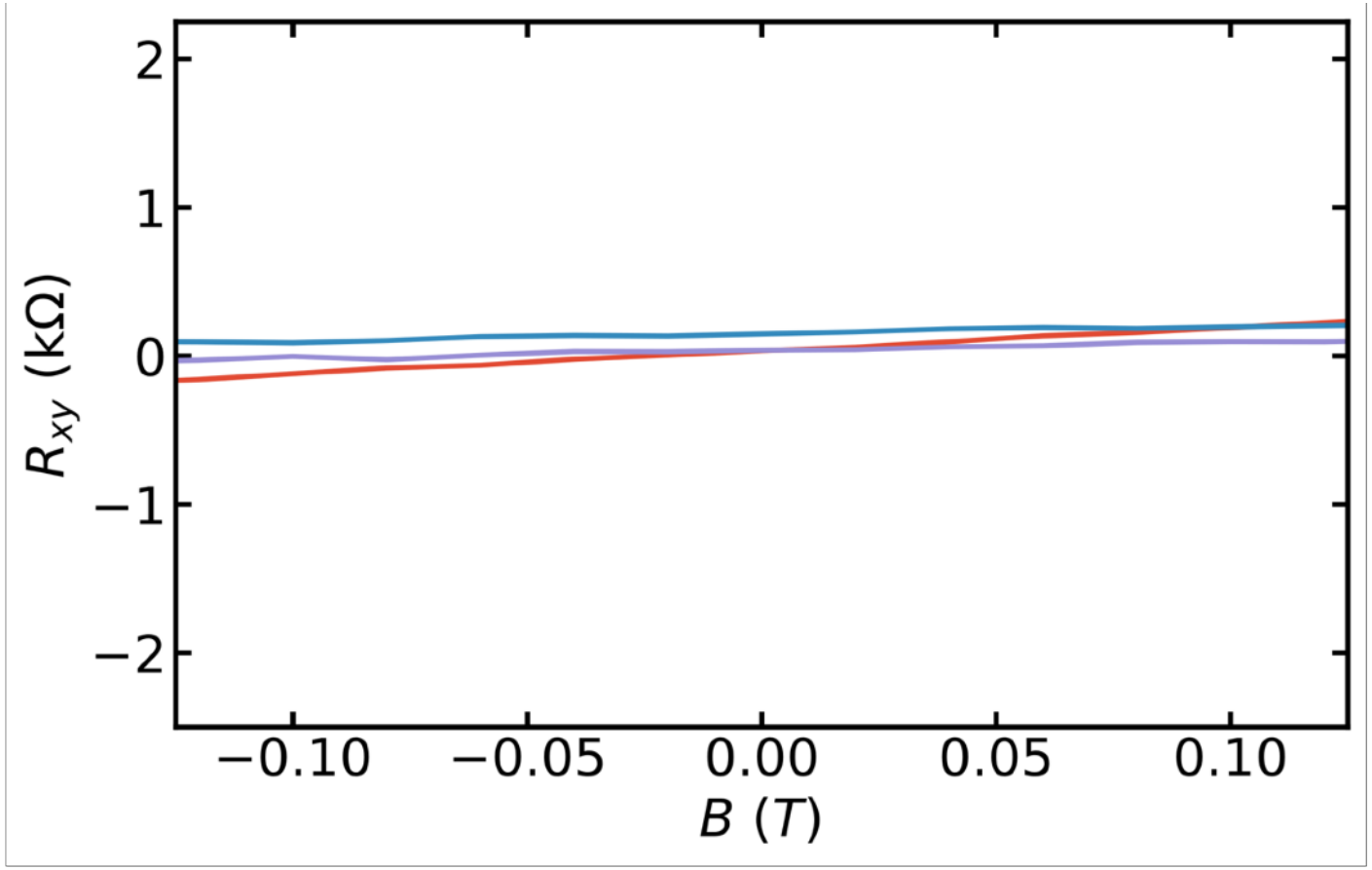
Measuring Hall Slope Density Dependence



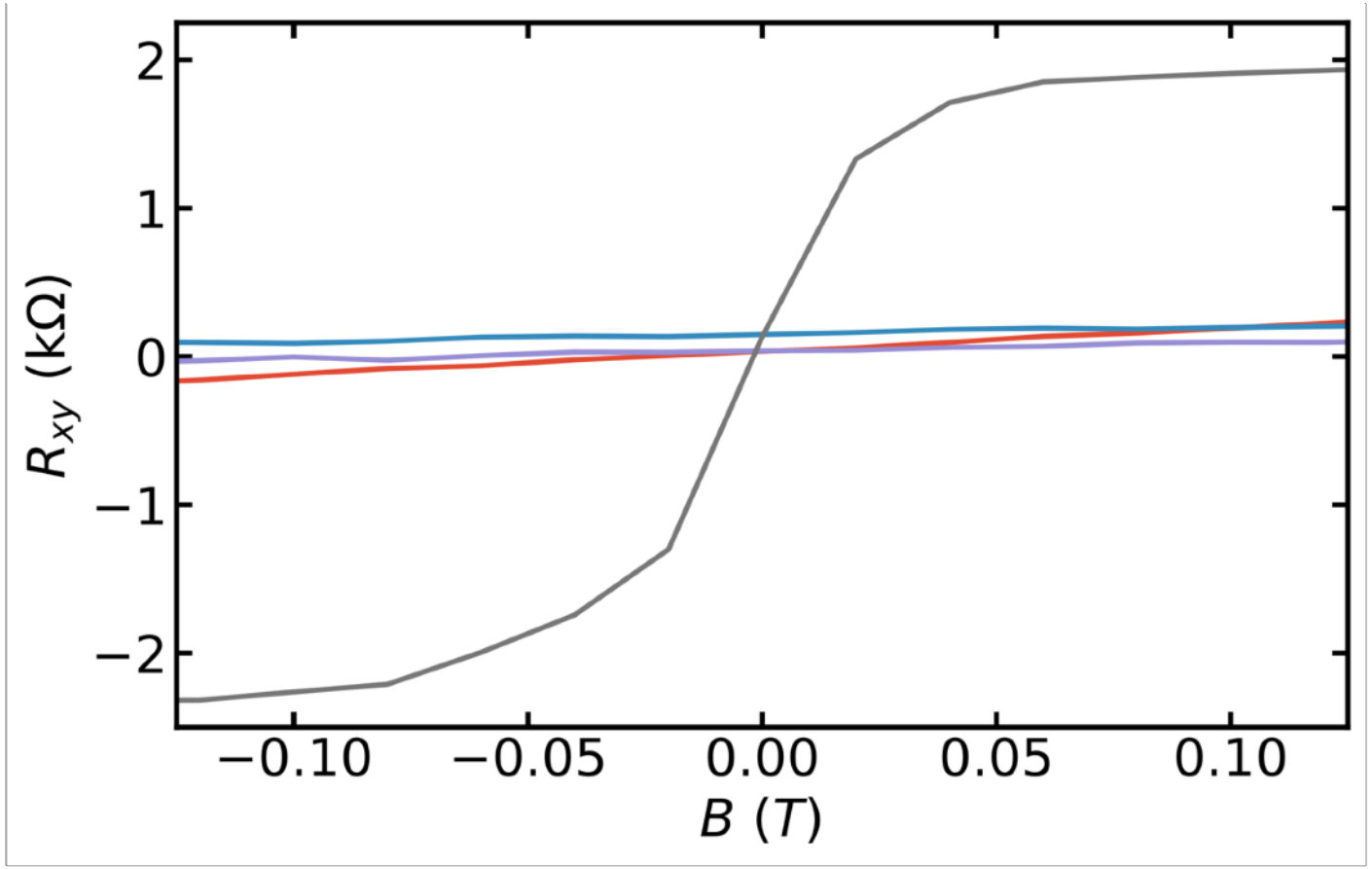
$n/n_s = 0.12$

$n/n_s = 0.50$

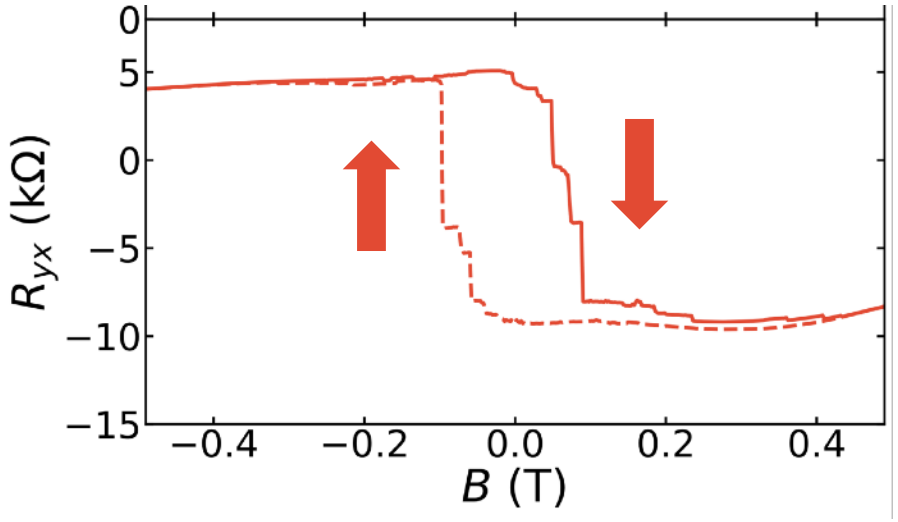
Measuring Hall Slope Density Dependence



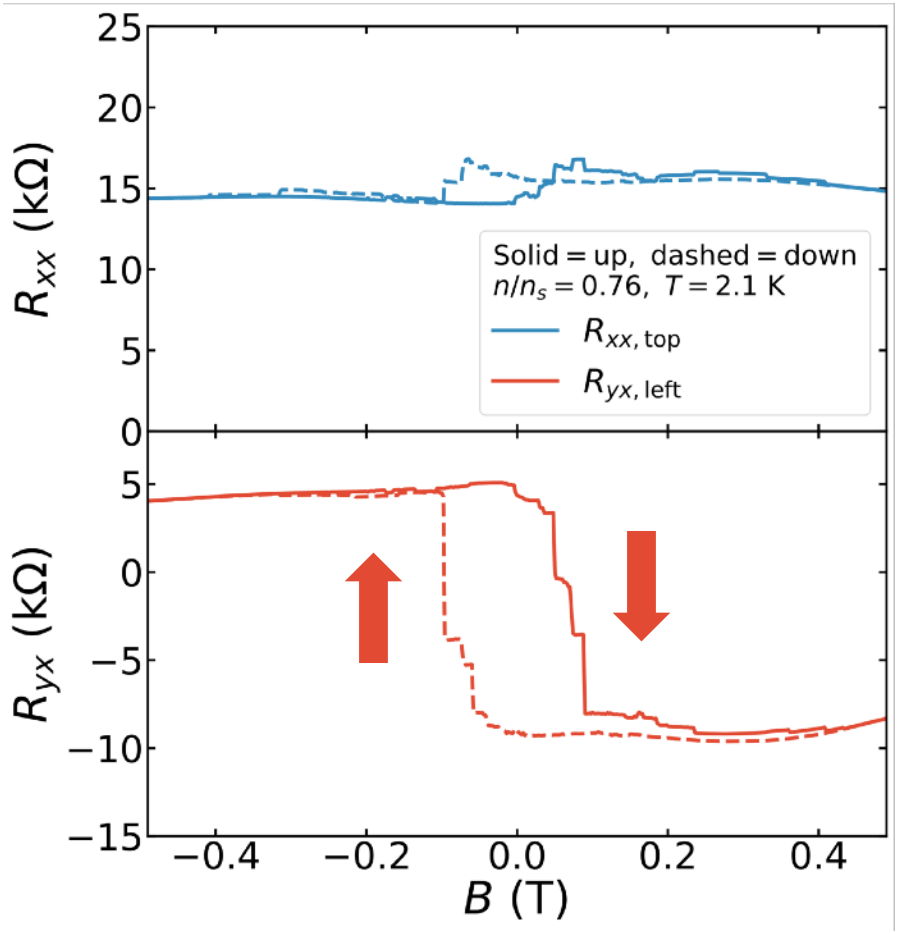
Measuring Hall Slope Density Dependence



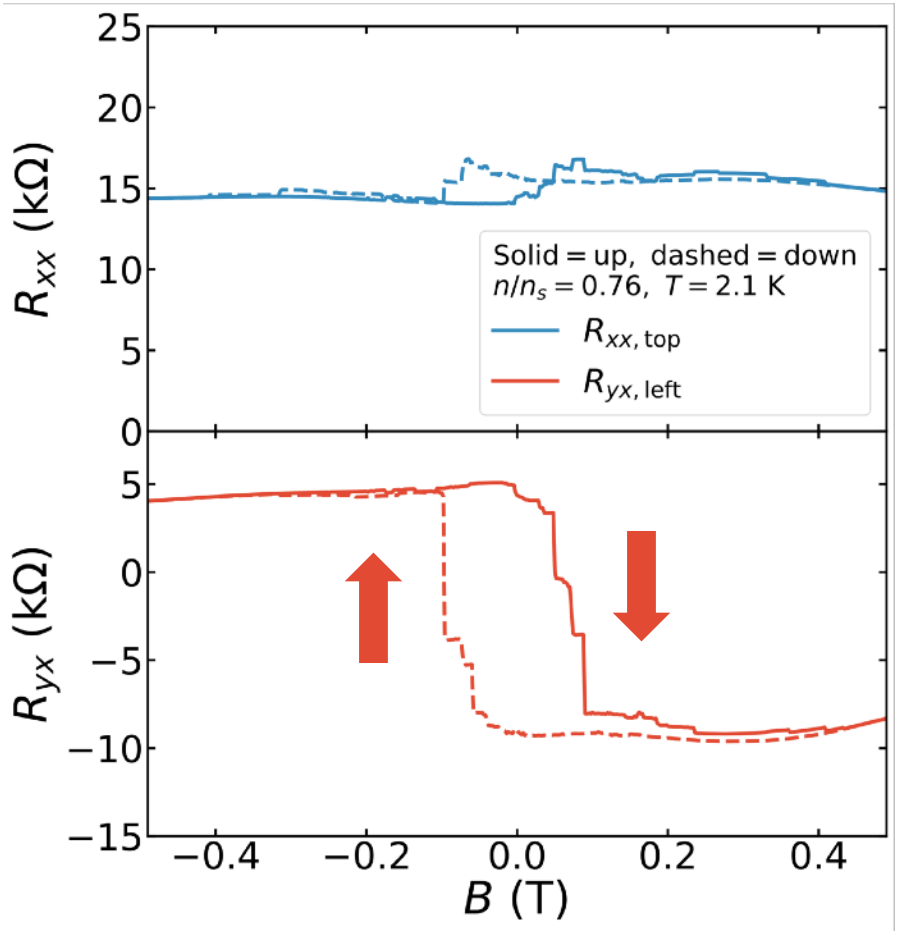
Emergent Ferromagnetism at ¾ Filling

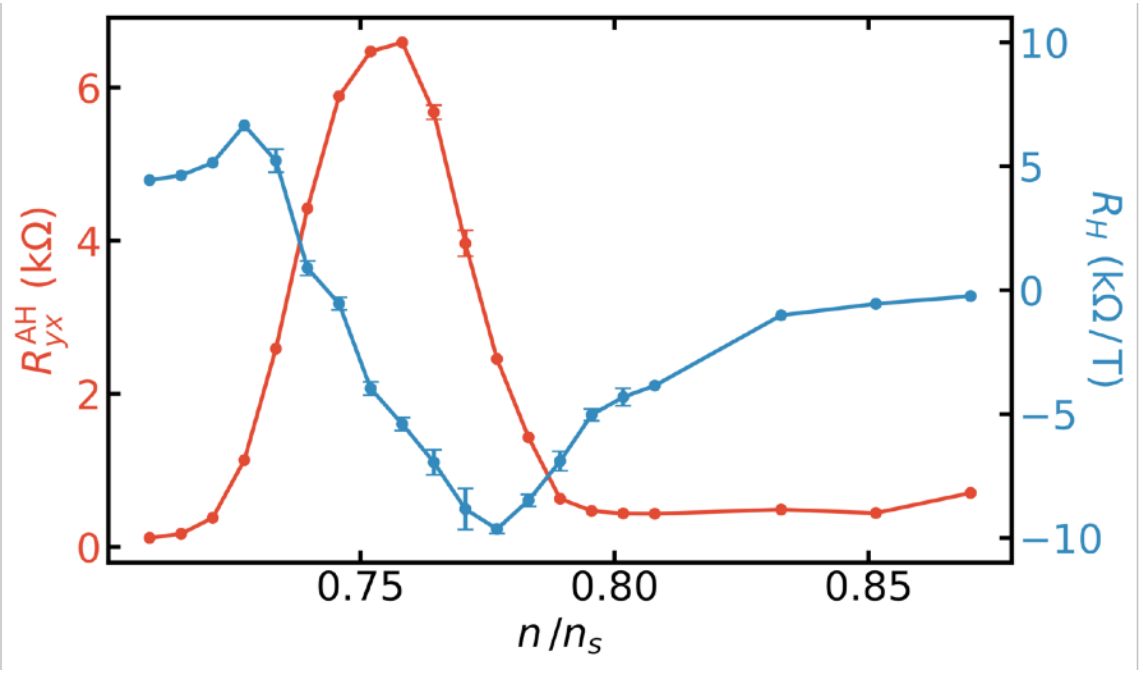


Emergent Ferromagnetism at ¾ Filling

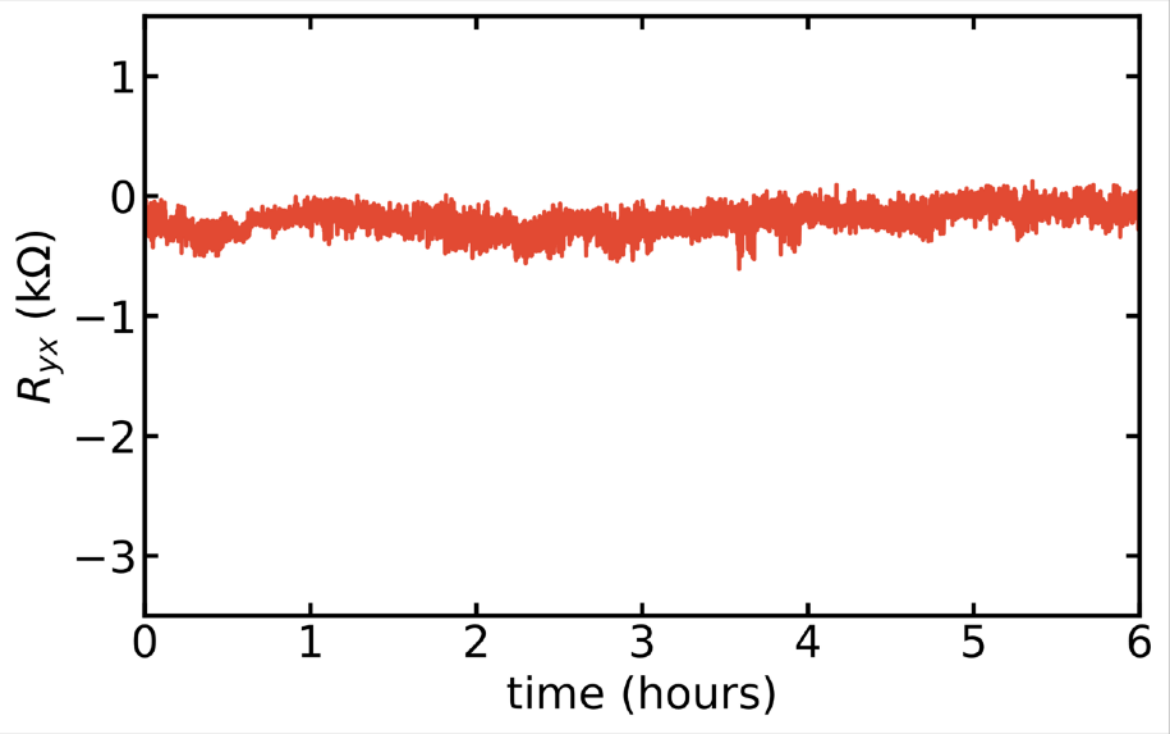


Emergent Ferromagnetism at ¾ Filling

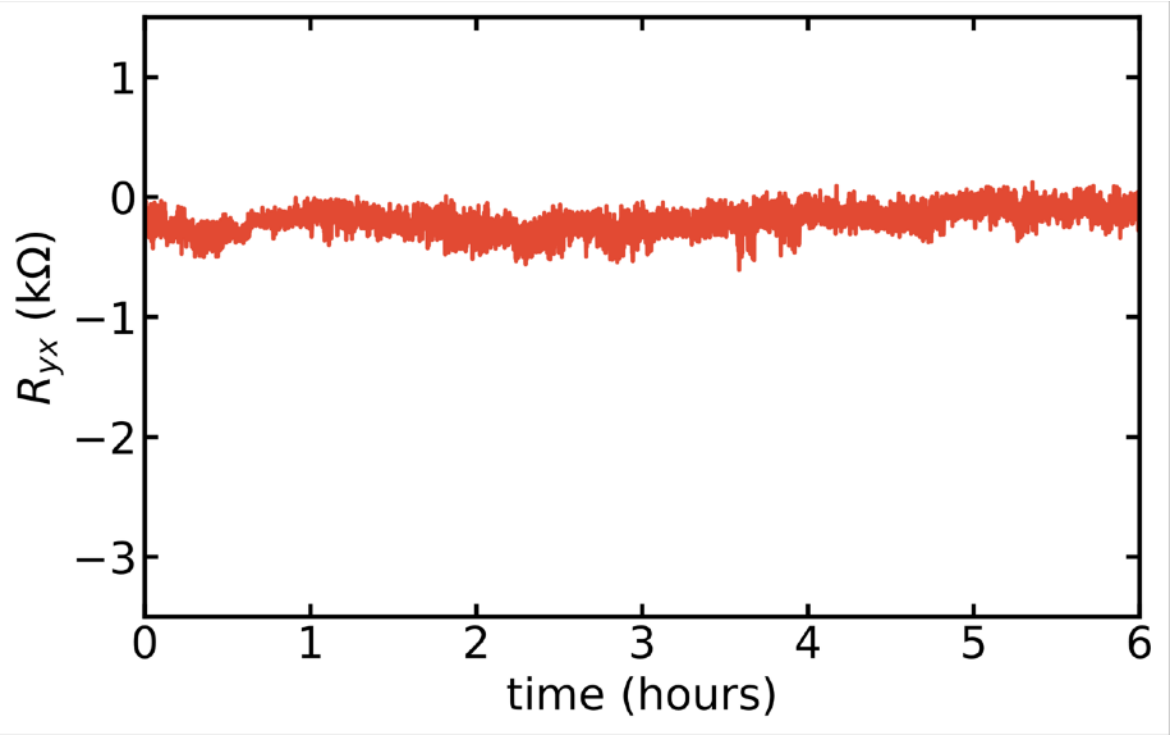


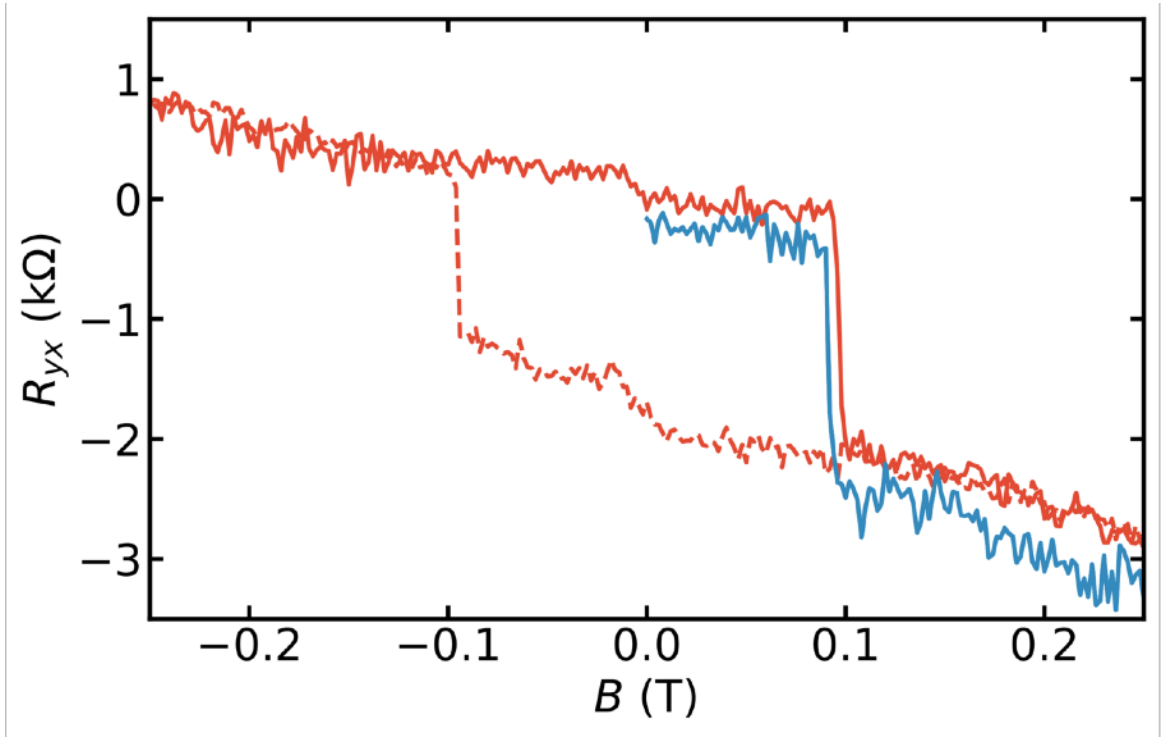


Magnetism is Stable with No Applied Field

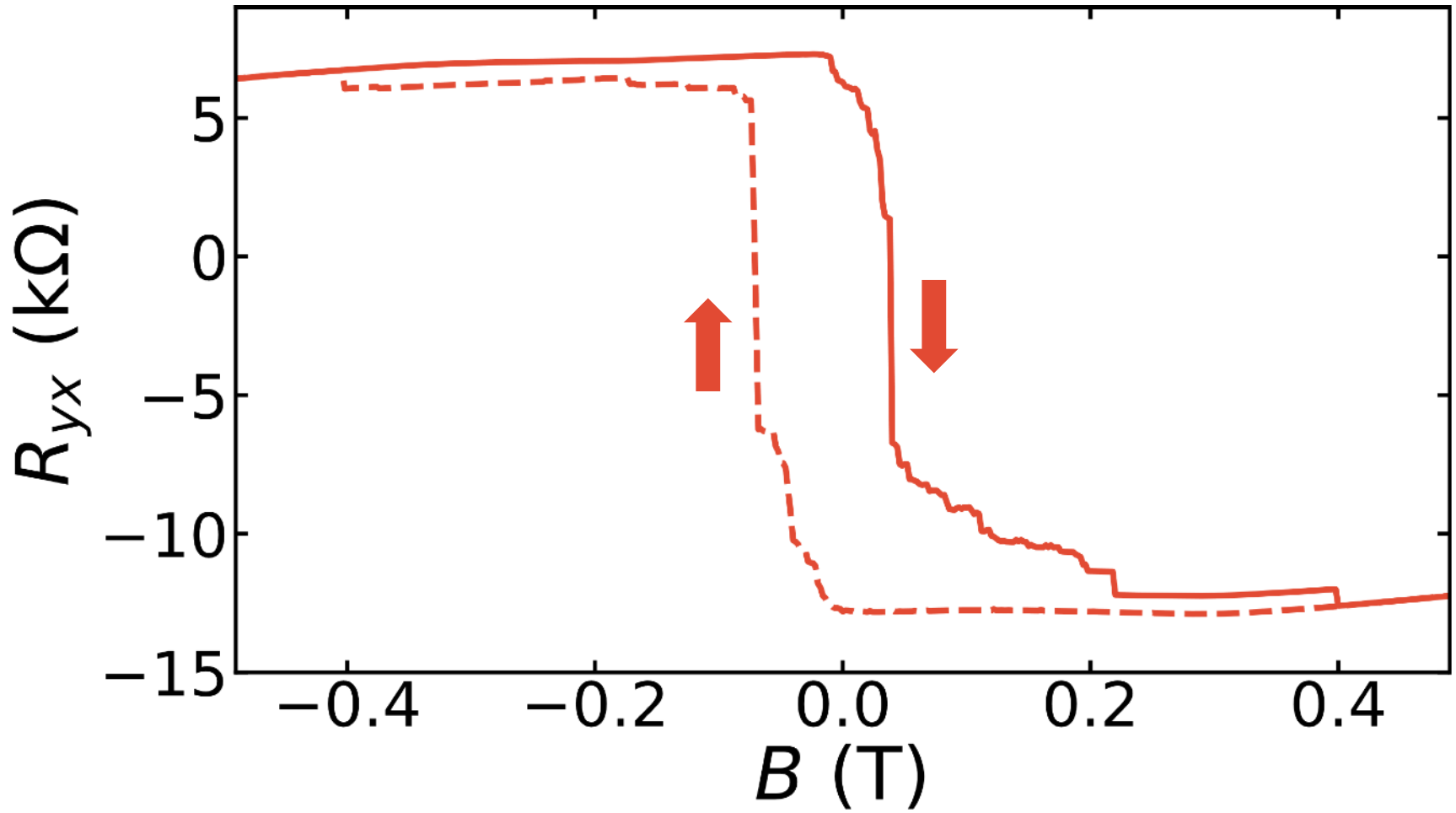


Magnetism is Stable with No Applied Field



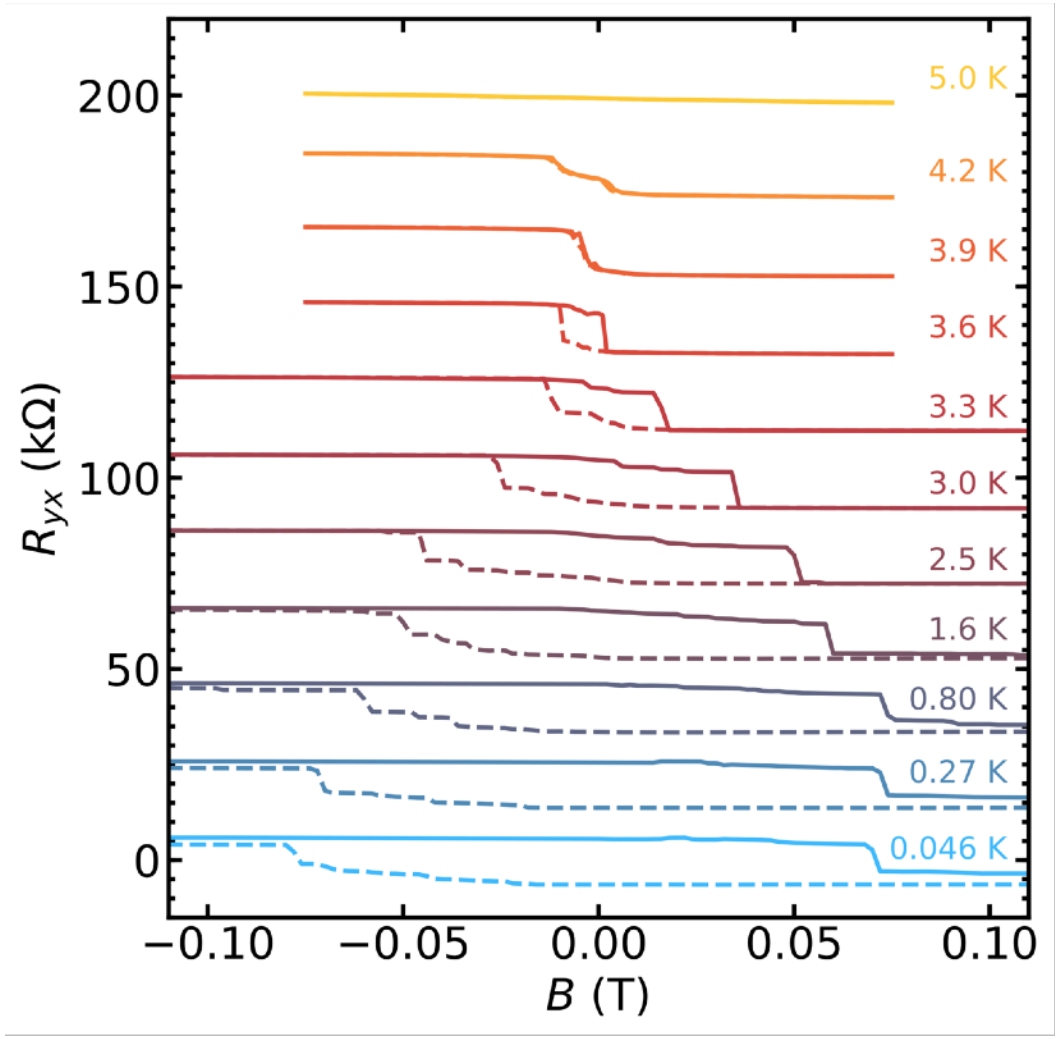


Anomalous Hall Signal Can Be Really Large!

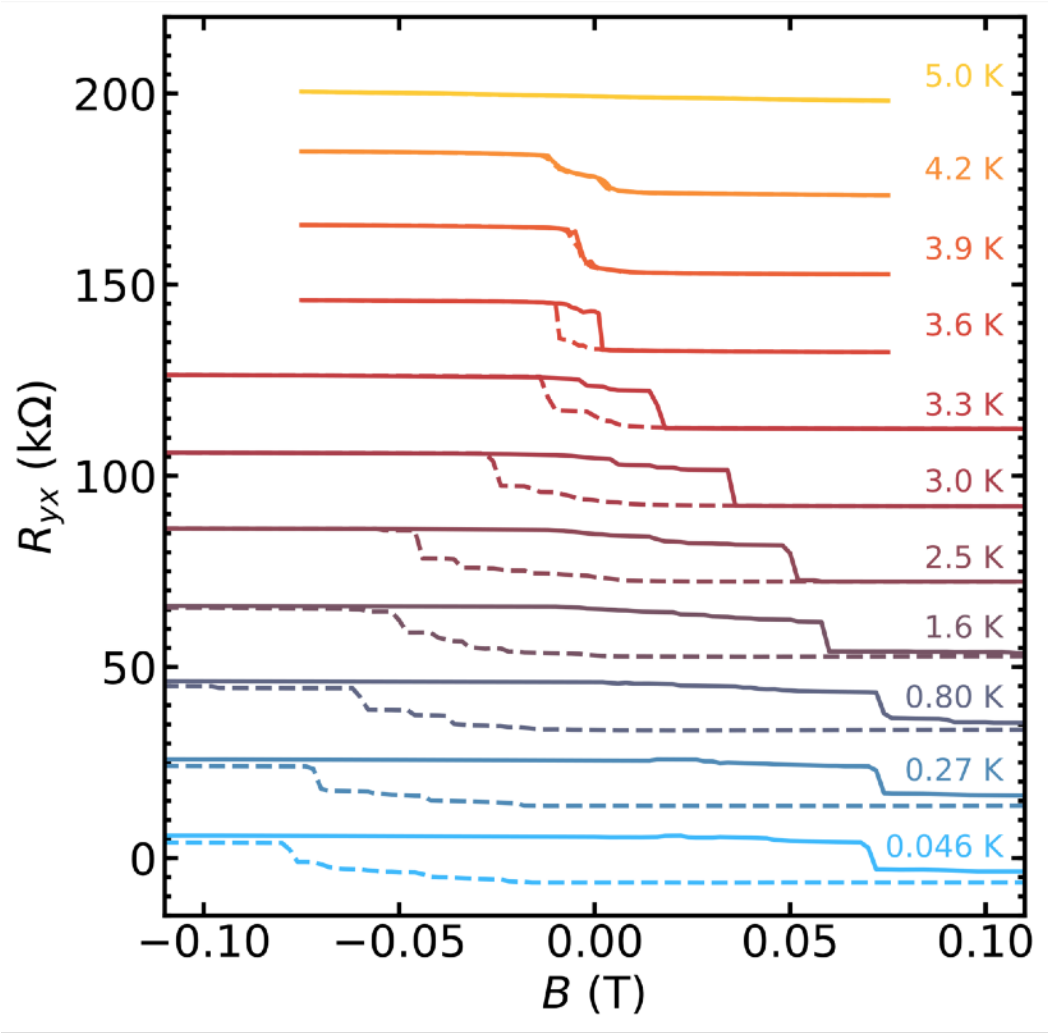


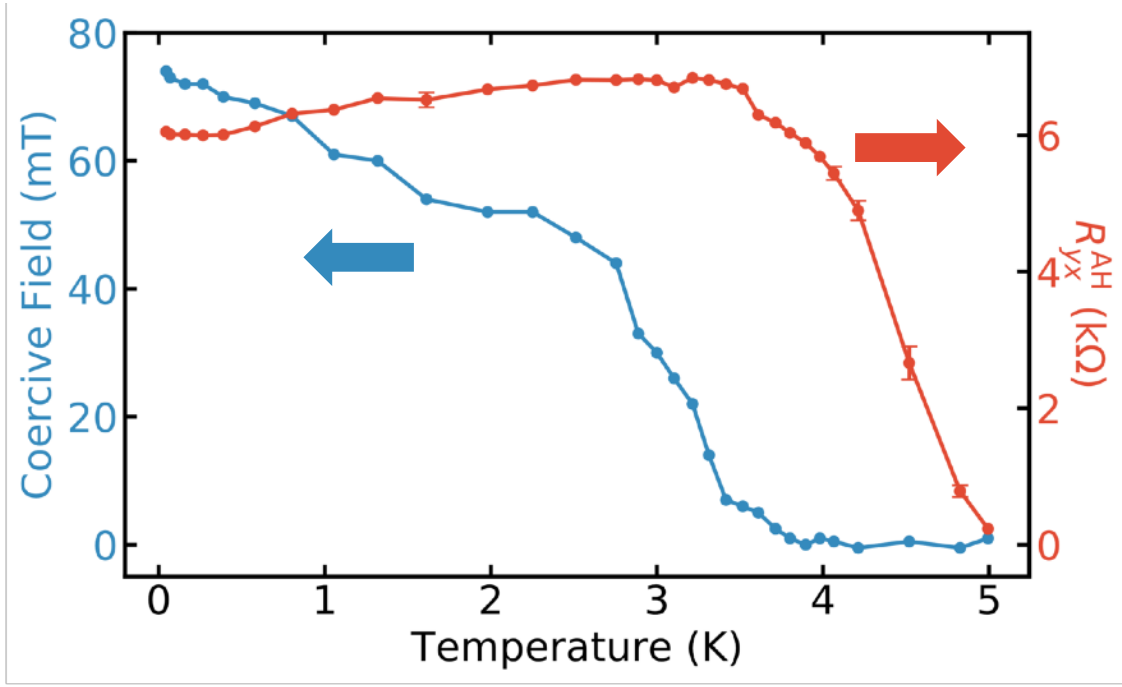
n/n_s=0.775, T=2.1K

Temperature Dependence of Emergent Ferromagnetism at ¾ Filling

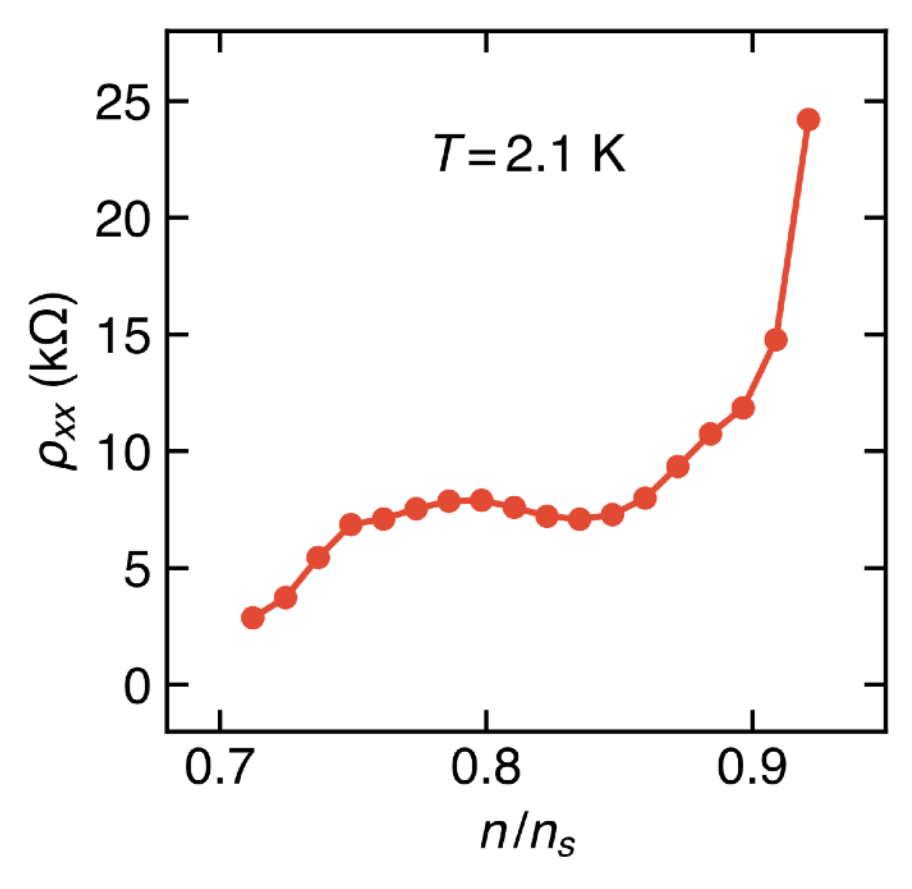


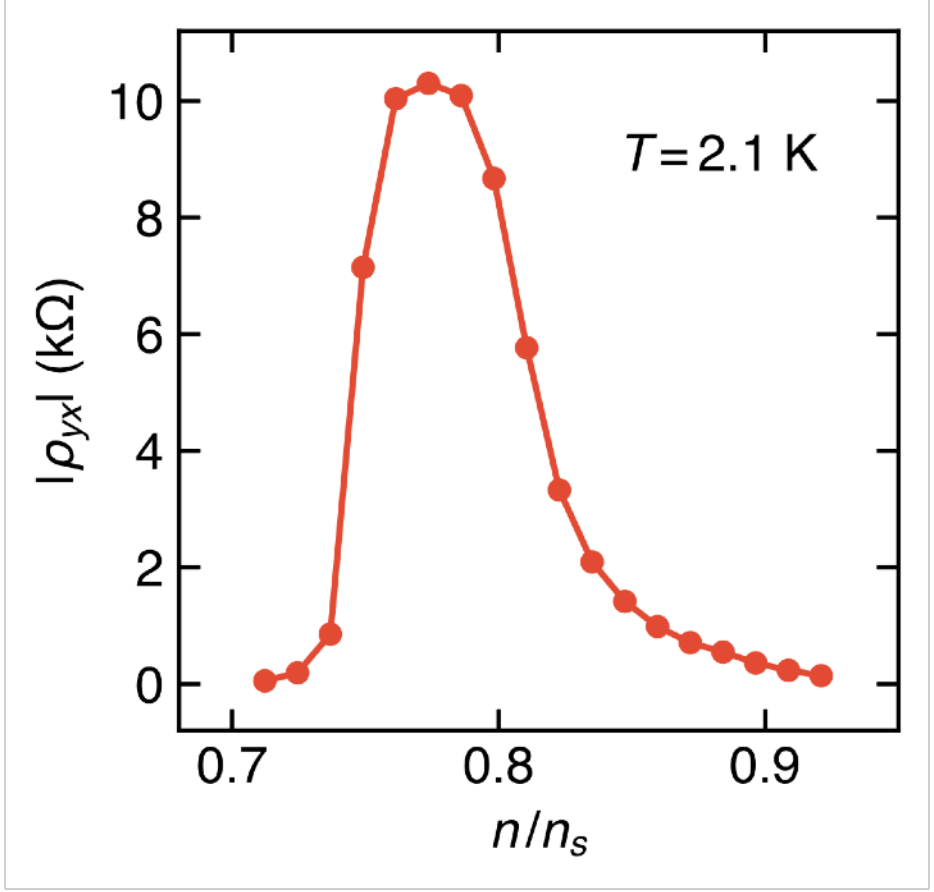
Temperature Dependence of Emergent Ferromagnetism at ¾ Filling





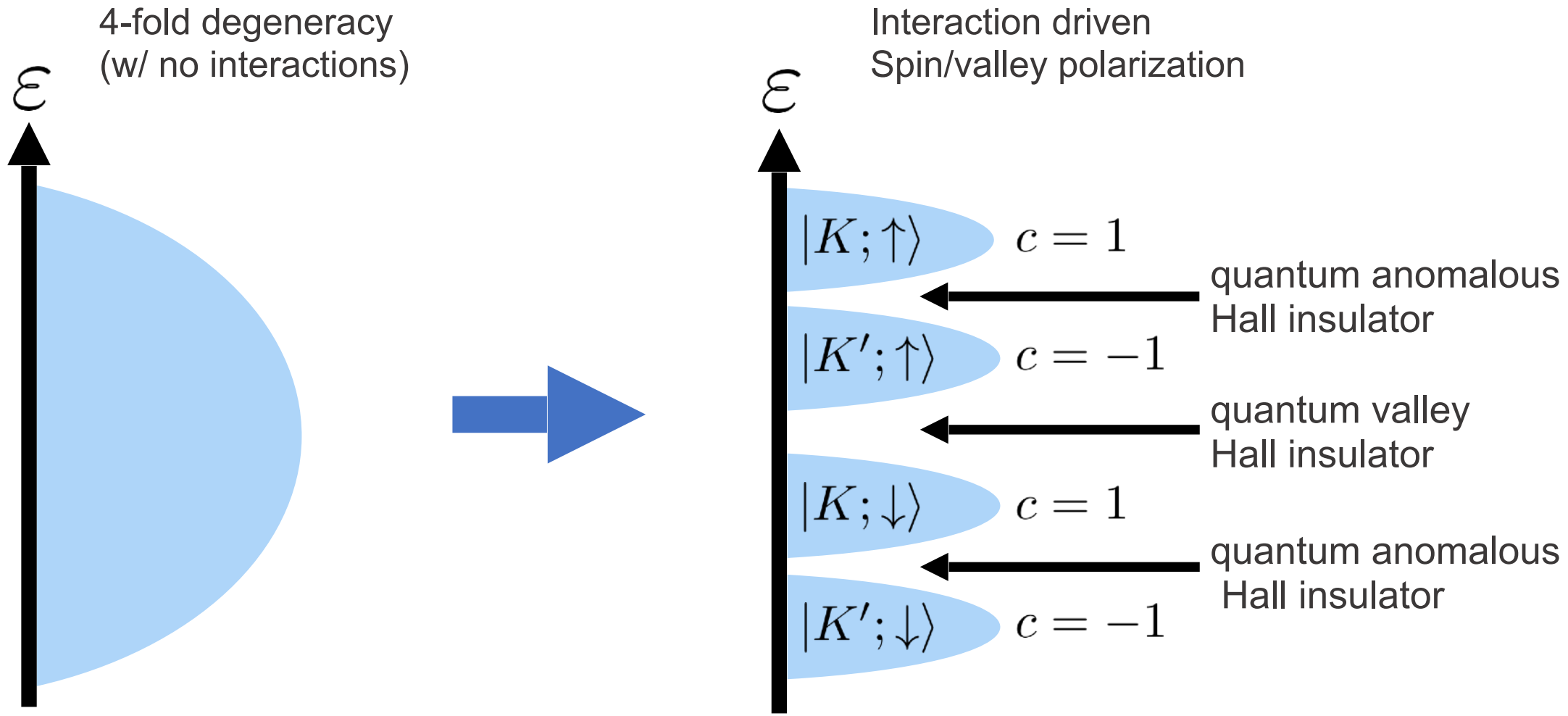
Resistivity: no strong feature at 3/4





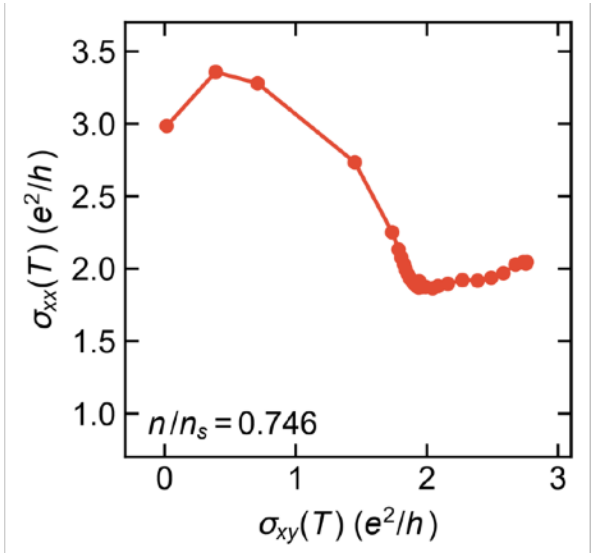
Nature of Emergent Ferromagnetism at ¾ Filling?

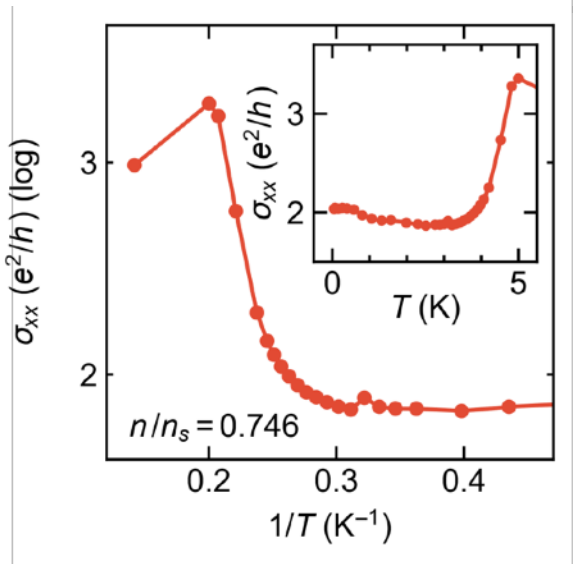
Simplistic band diagram: What *might* be happening…



Nature of Emergent Ferromagnetism

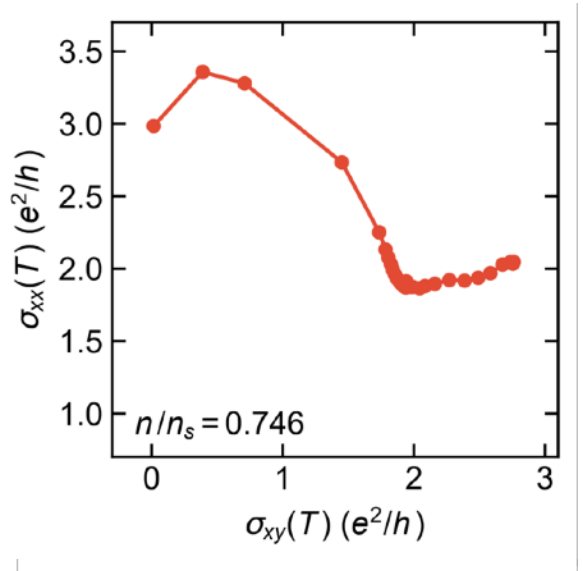
Intrinsic vs. extrinsic anomalous Hall mechanisms

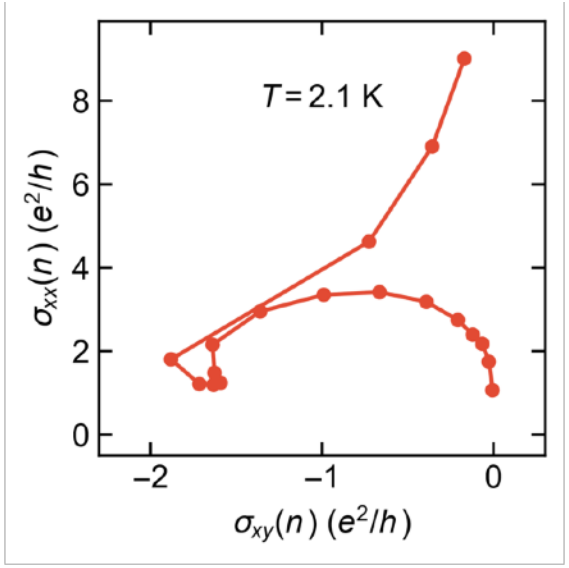


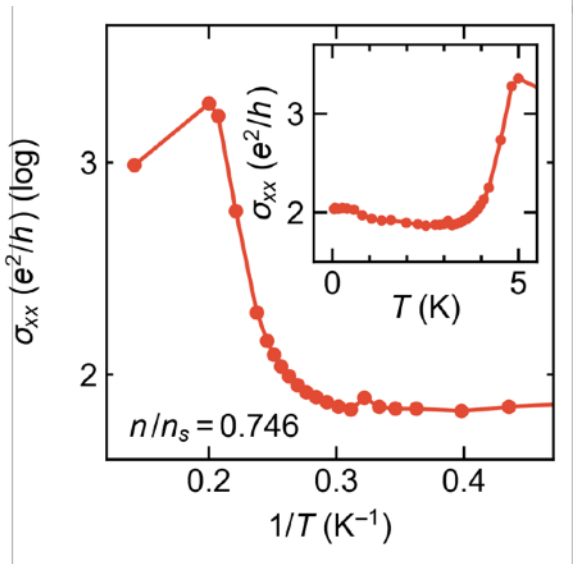


Nature of Emergent Ferromagnetism

Intrinsic vs. extrinsic anomalous Hall mechanisms

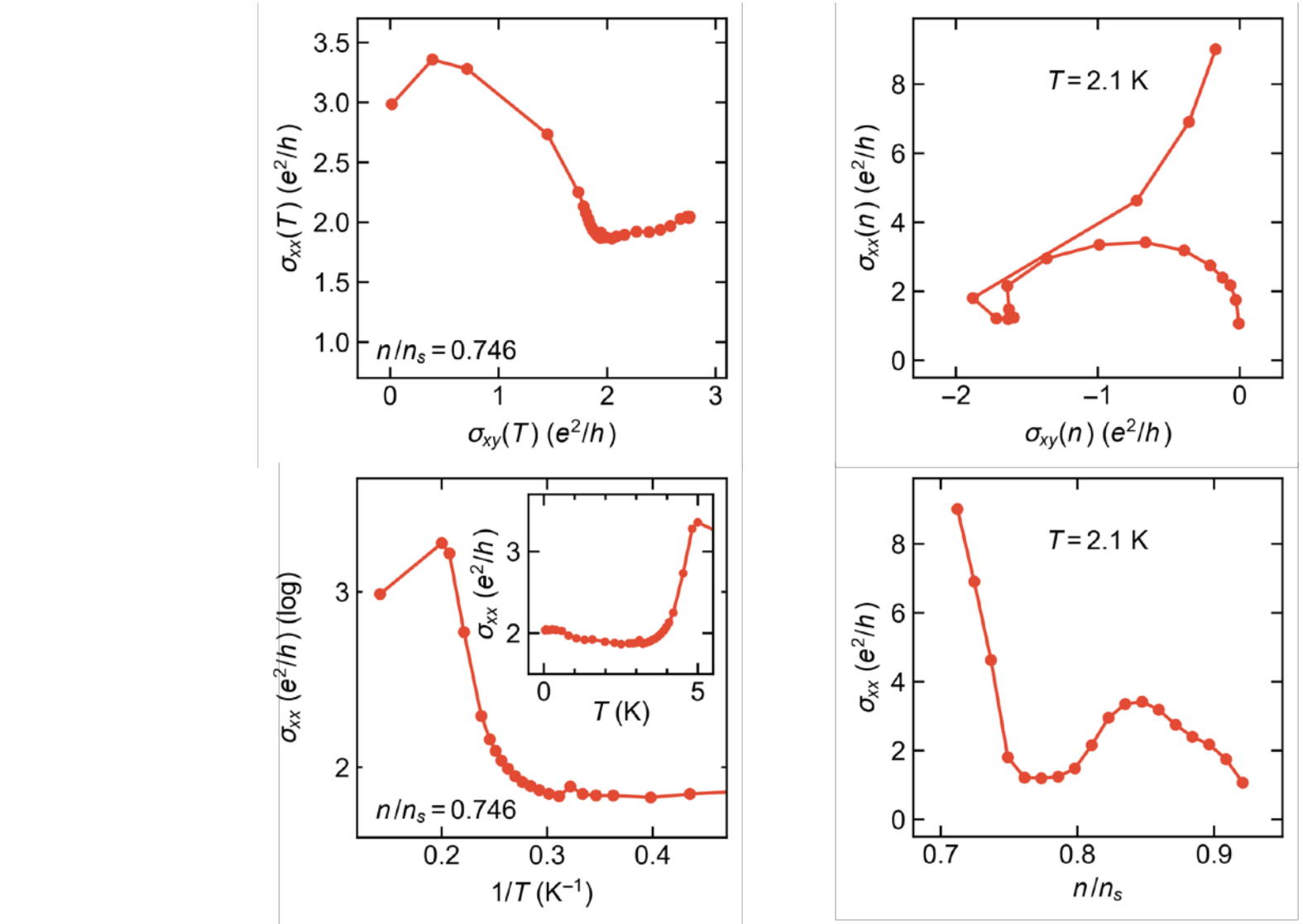




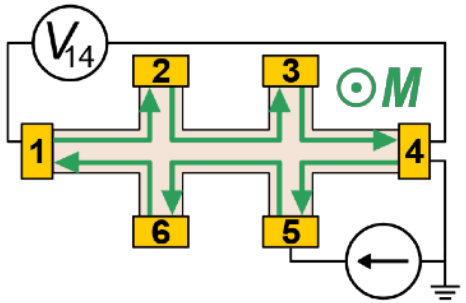


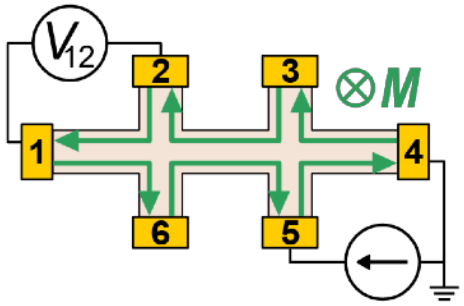
Nature of Emergent Ferromagnetism

Intrinsic vs. extrinsic anomalous Hall mechanisms

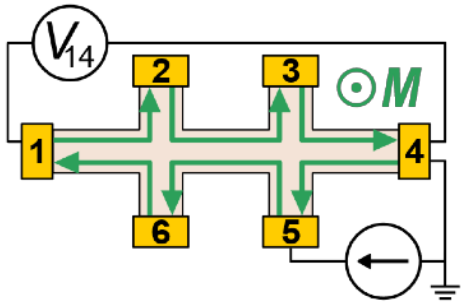


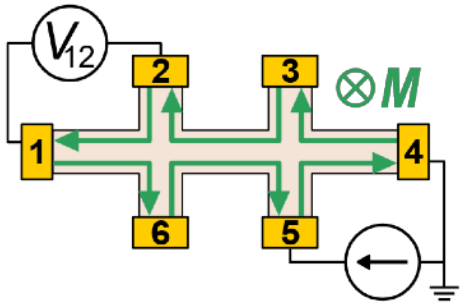
3- and 4-Terminal Nonlocal Transport at ¾ Filling

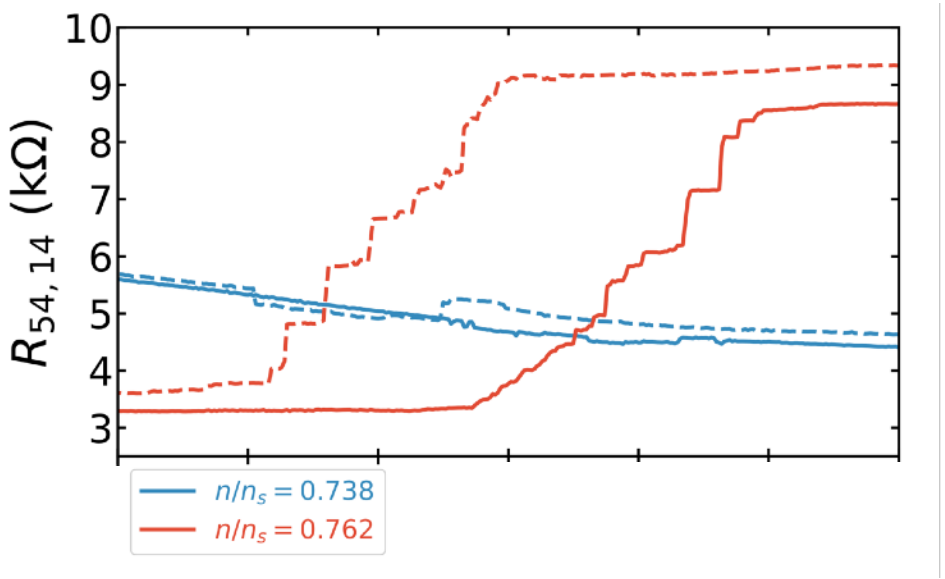




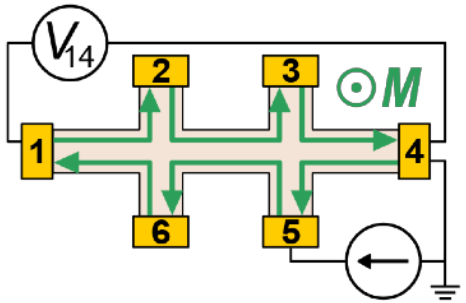
3- and 4-Terminal Nonlocal Transport at ¾ Filling

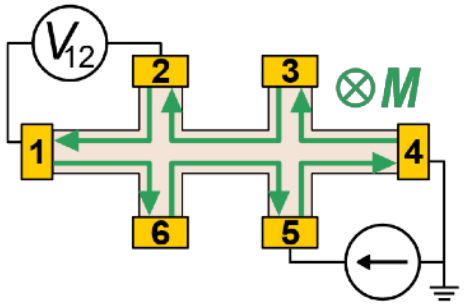


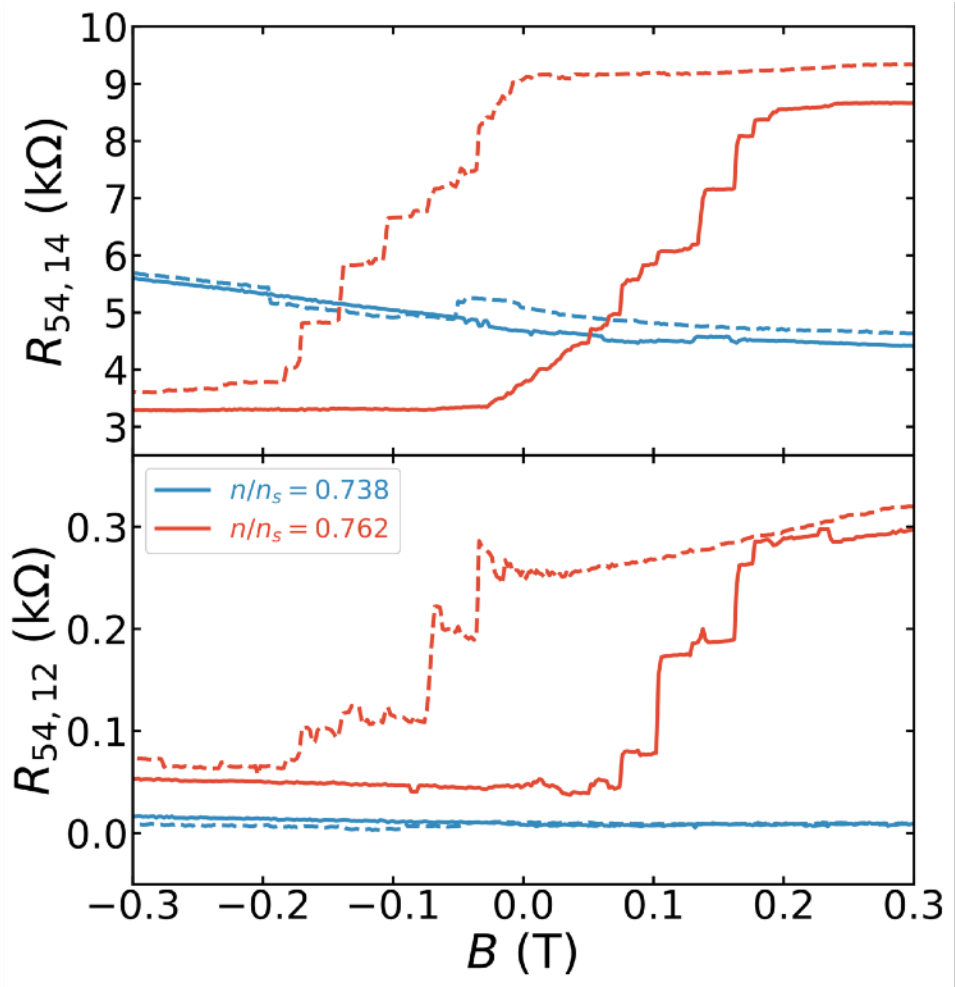




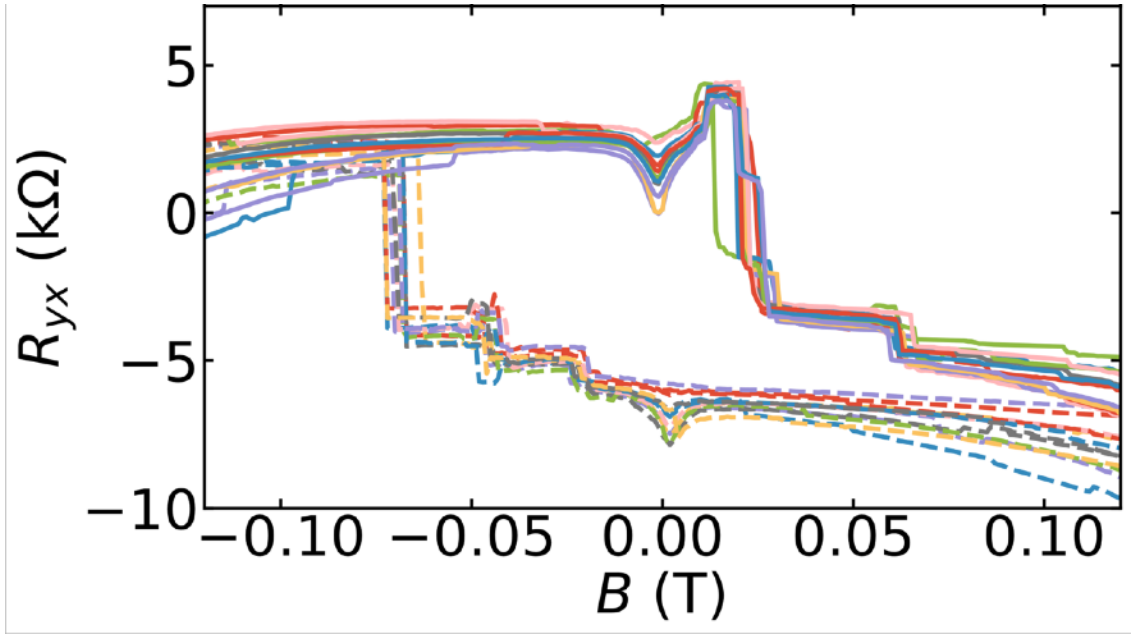
3- and 4-Terminal Nonlocal Transport at ¾ Filling



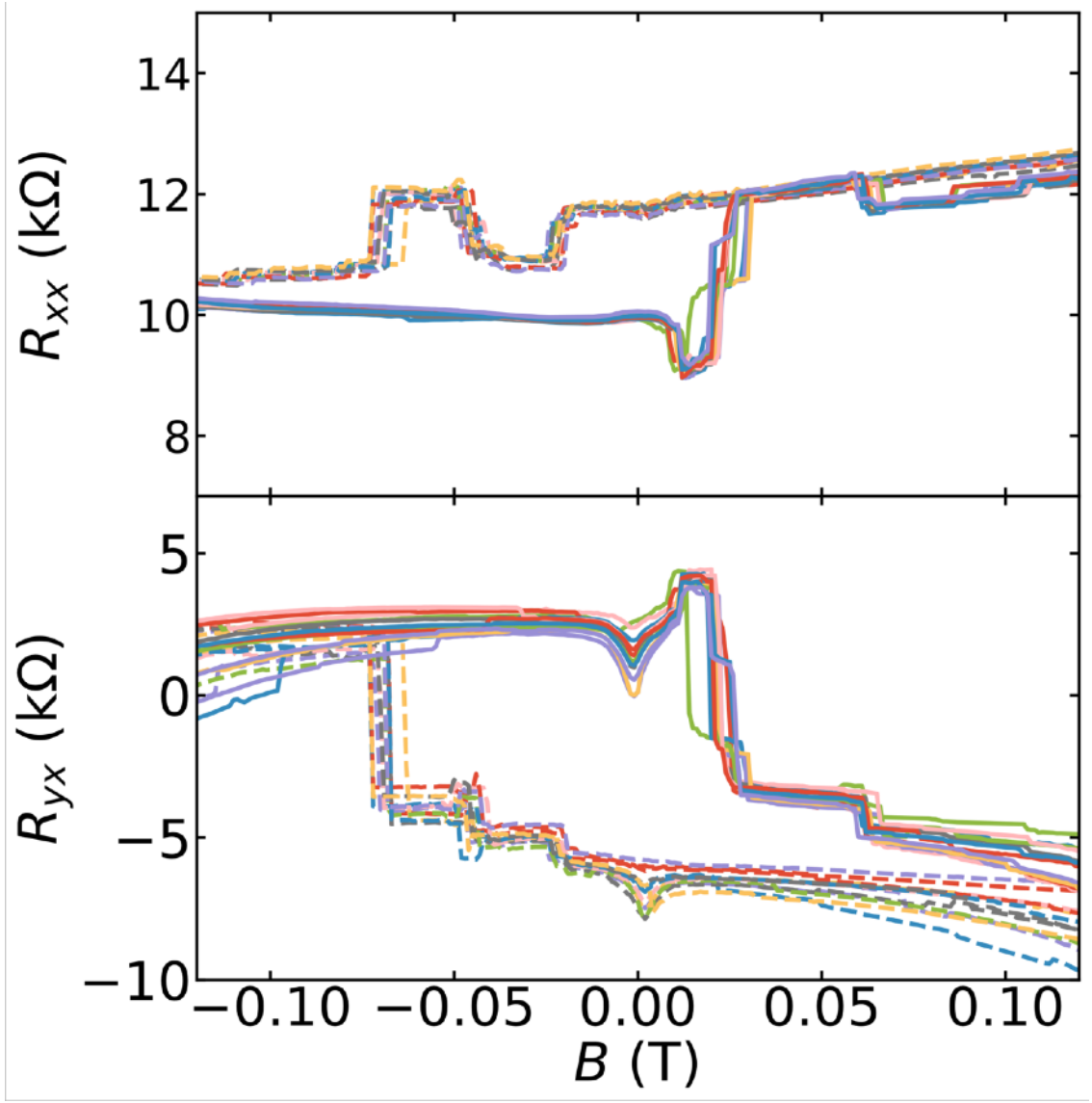




Repeatable Hysteresis Fine Structure in Field

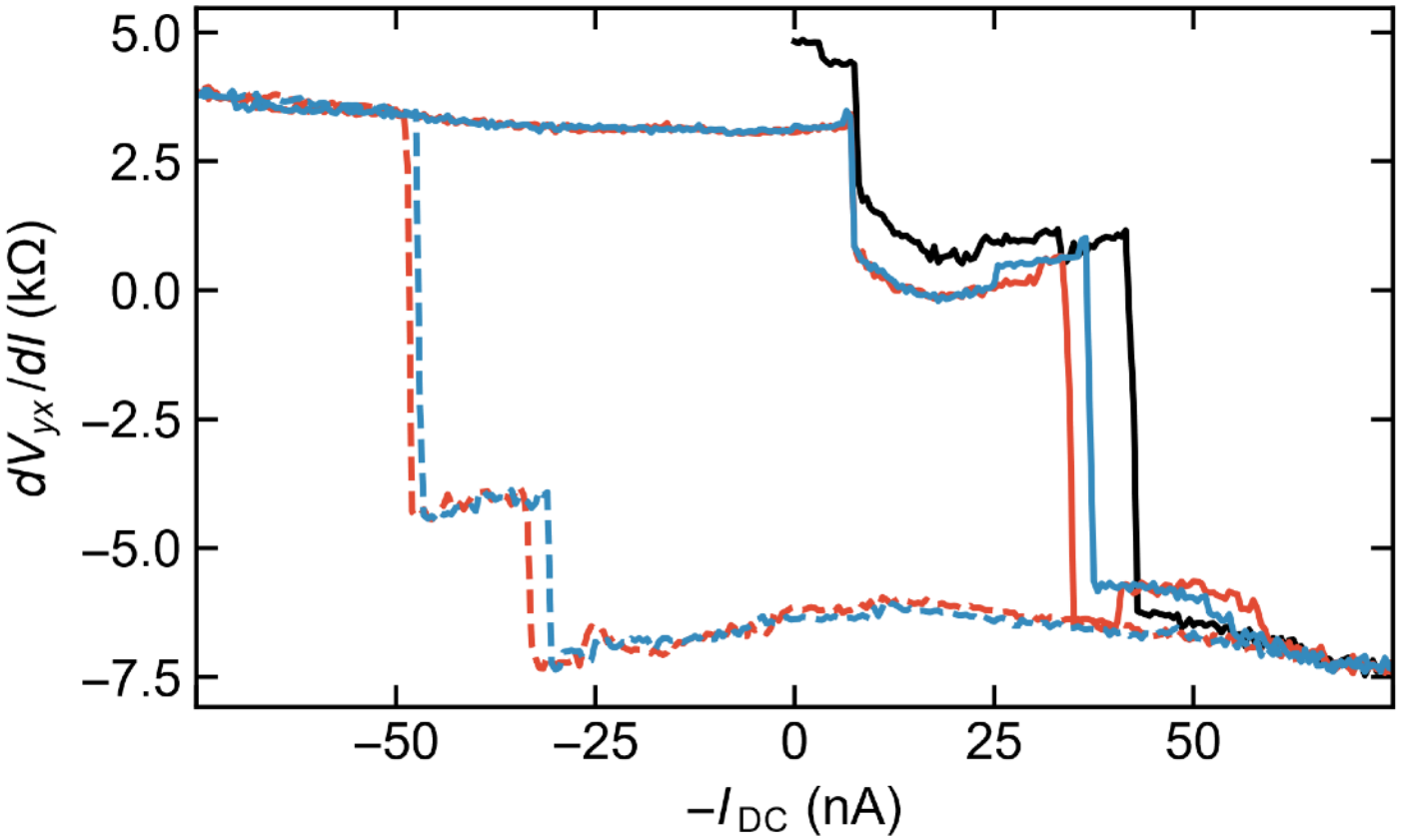


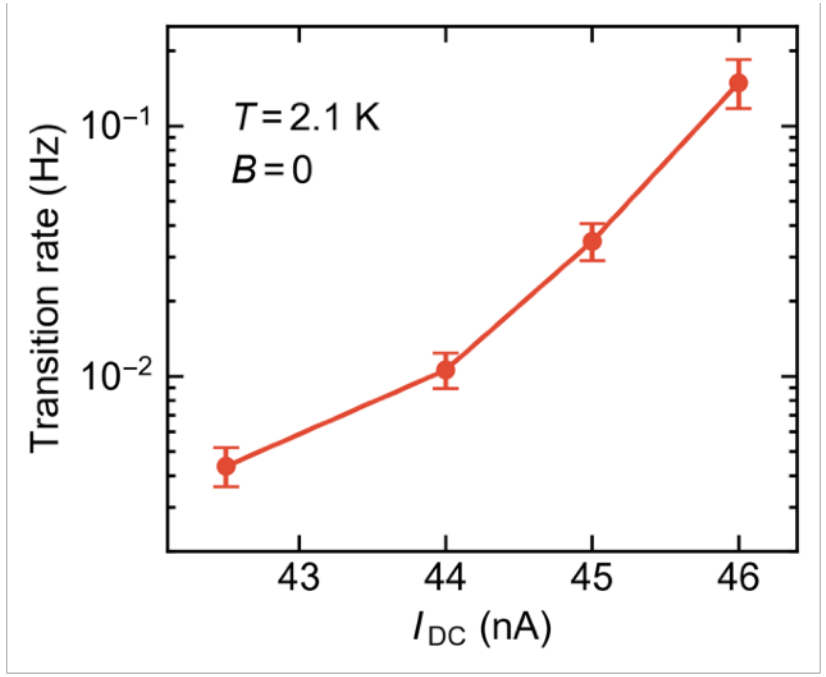
Repeatable Hysteresis Fine Structure in Field



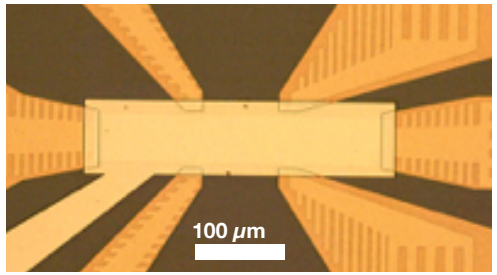
Repeatable Hysteresis in Current

Dynamics of transition appear memoryless

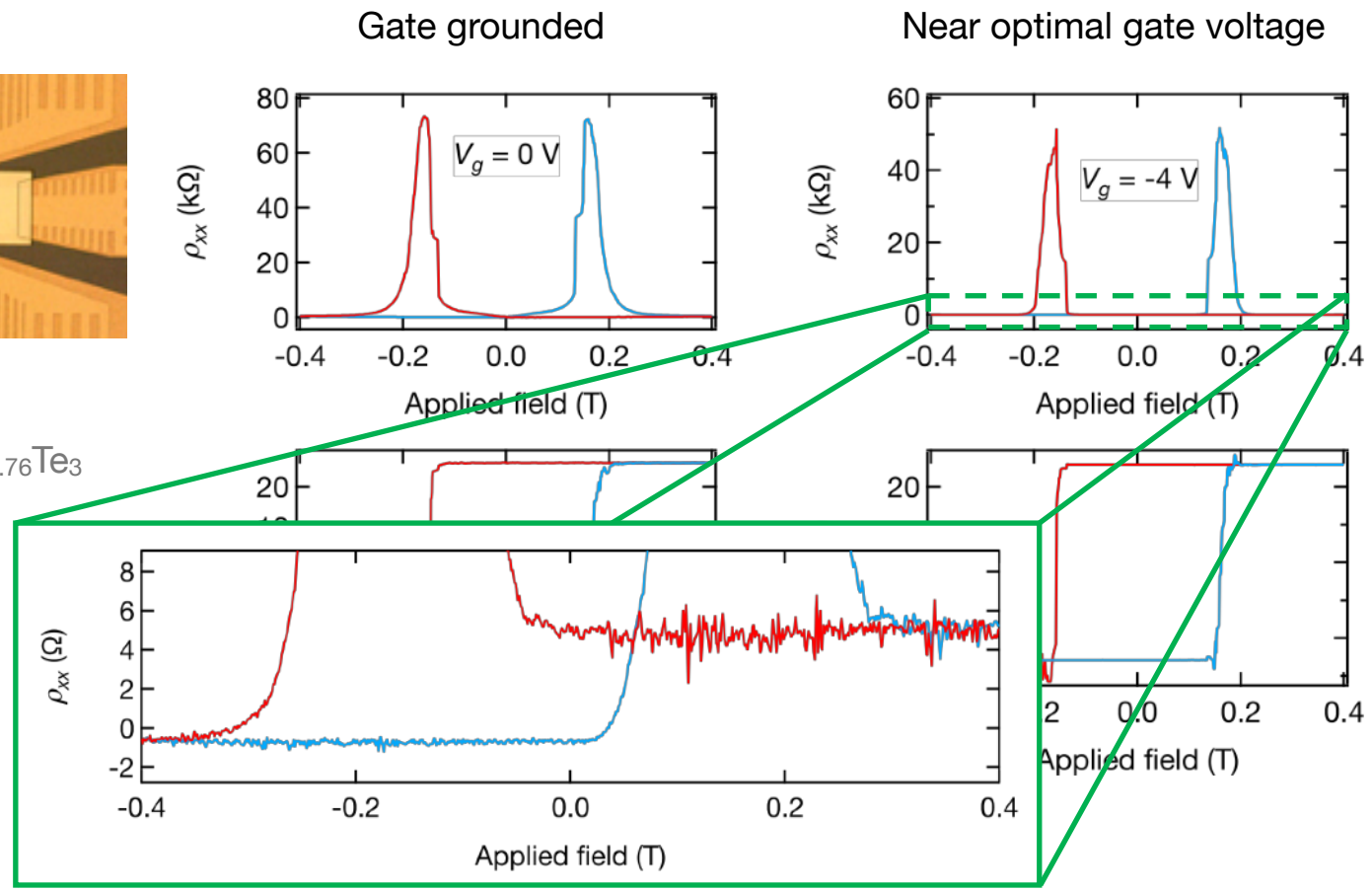




Comparison: Quantum Anomalous Hall in $(Cr,Bi,Sb)_2Te_3$

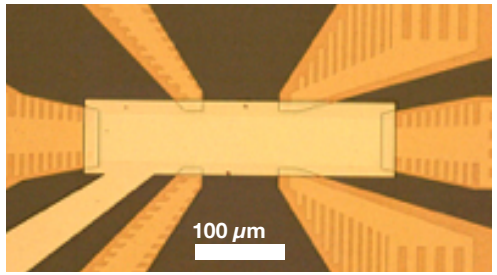


Material & device:
6 QL $Cr_{0.24}(Bi_{0.3}Sb_{0.7})_{1.76}Te_3$
GaAs substrate
Ti/Au contacts
Top gate

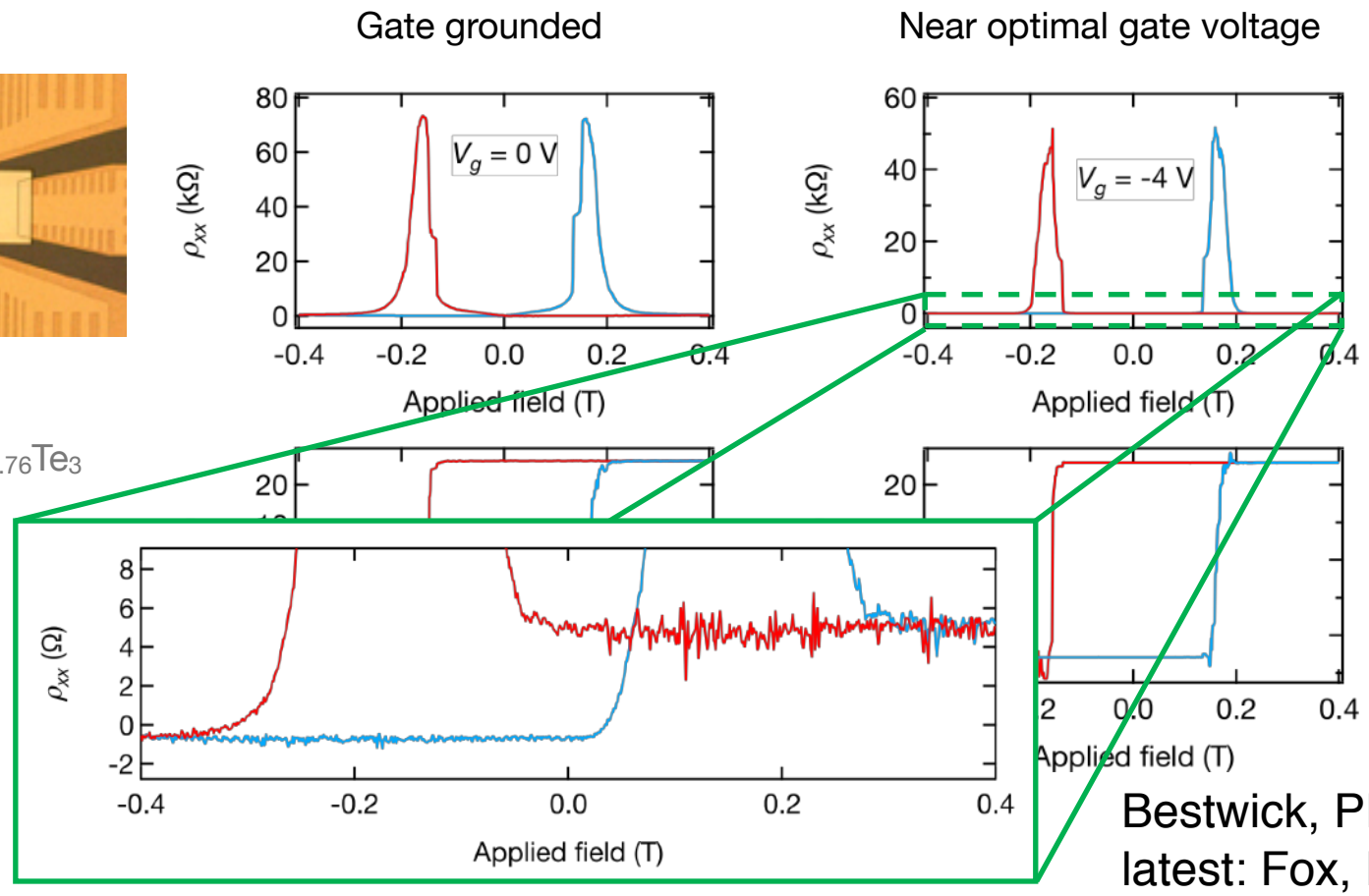


Systematic offsets due to finite input impedance of voltage preamplifiers

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



Systematic offsets due to finite input impedance of voltage preamplifiers

Bestwick, PRL 114, 187201 (20
latest: Fox, PRB 98.075145 (20
Rex 2 parts in 10 million
Rhoxy 20 millohm

Acknowledgements

DGG Group @ Stanford
Aaron Sharpe
Eli Fox
Ilan Rosen
Andrew Bestwick

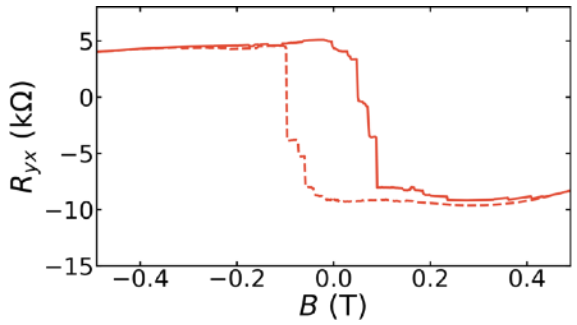
UCLA (Magnetic TIs)
Kang Wang
Xufeng Kou
Lei Pan

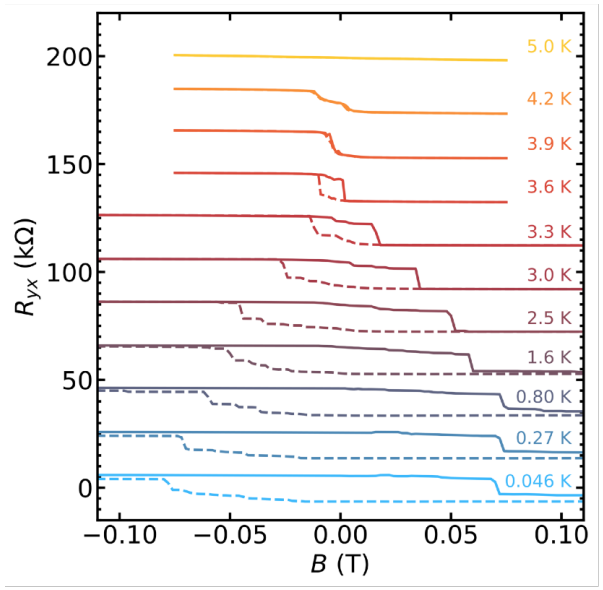
DOE: SIMES Spin Physics and Nanoscale Probes FWP
Marc Kastner

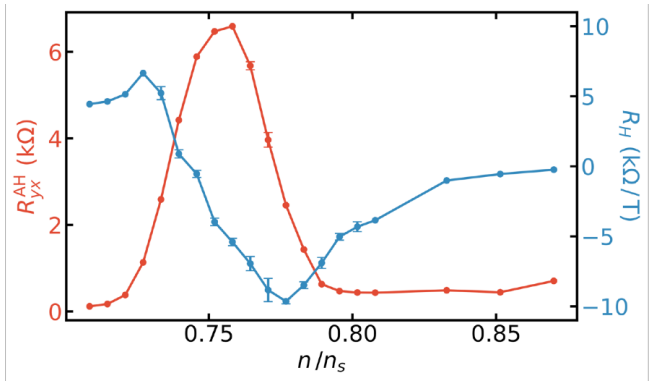
Thanks
Arthur Barnard, Joe Finney, Hava Schwartz, Sungyeon Yang, Anthony Chen, Patrick Gallagher, Allan MacDonald, Ming Xie, Michael Zaletel, Nick Bultinck, Todadri Senthil, Steve Kivelson, yoni Schattner, Feng Wang, Guorui Chen, Matt Yankowitz, Yuan Cao, Pablo Jarillo-Herrero

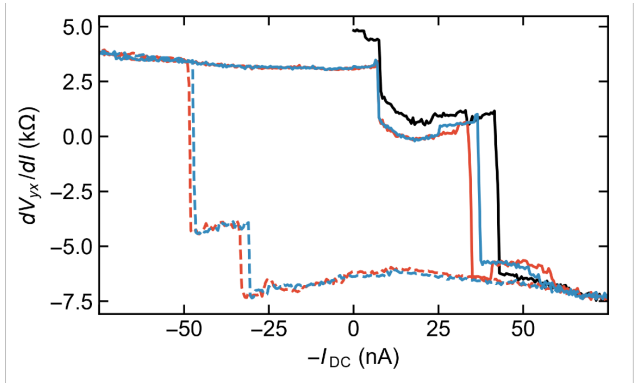
arXiv: Sharpe et al., 1901.03520 (just now!)

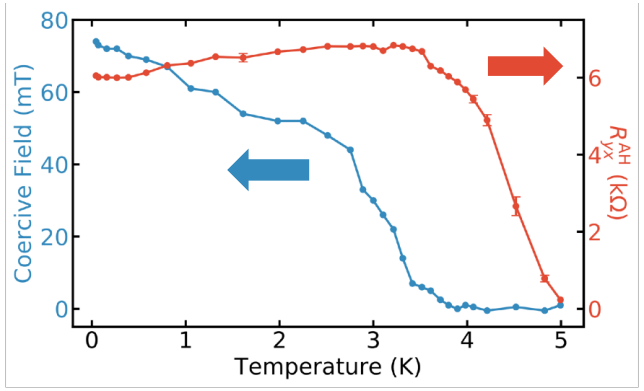
Questions?

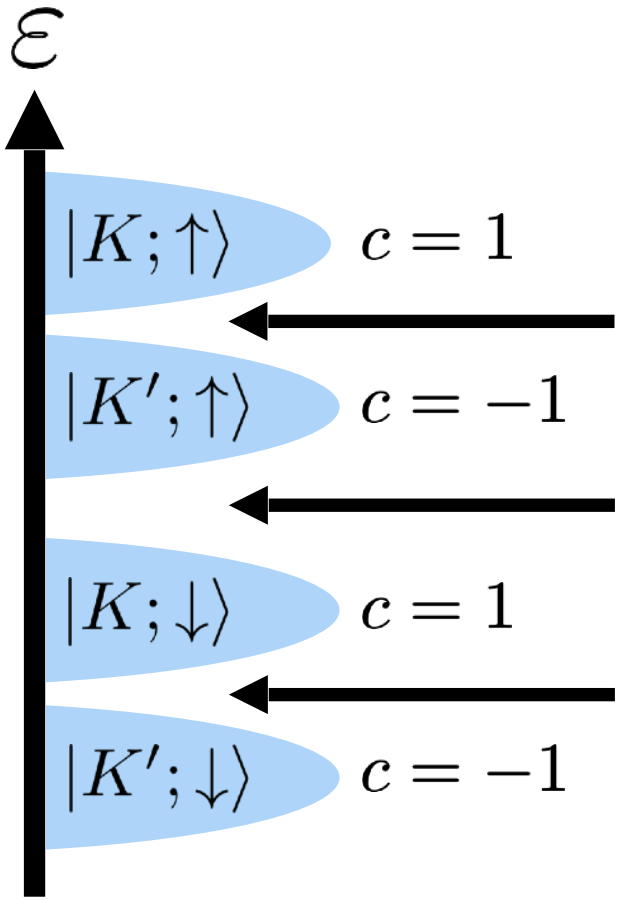

R_{yx} (kΩ)
B (T)

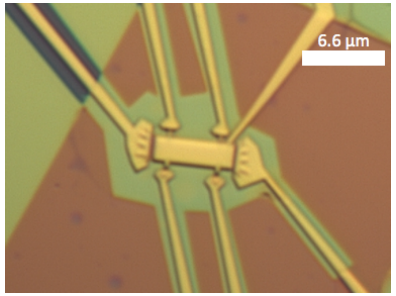

5.0 K
4.2 K
3.9 K
3.6 K
3.3 K
3.0 K
2.5 K
1.6 K
0.80 K
0.27 K
0.046 K
R_{yx} (kΩ)
B (T)


R_{yx}^{AH} (kΩ)
R_H (kΩ/T)
n/n_s


dV_{yx}/dI (kΩ)
$-I_{DC}$ (nA)


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


$\mathcal{E}$
$|K;\uparrow\rangle$
$c = 1$
$|K';\uparrow\rangle$
$c = -1$
$|K;\downarrow\rangle$
$c = 1$
$|K';\downarrow\rangle$
$c = -1$


6.6 µm