Weak Localization and Universal Conductance Fluctuations in Twisted Bilayer Graphene

D. Mallick[1], A.H. Chen[1], S. Talkington[2*], B.F. Mead[2], S.J. Yang[3], C.J. Kim[3], S. Adam[2,4,5], E.J. Mele[2], L. Wu[2], M. Brahlek[1]

1. Oak Ridge National Laboratory, 2. University of Pennsylvania, 3. Pohang University, 4. National University of Singapore, 5. Washington University in St. Louis

We acknowledge funding and support from the Army Research Office (ARO), National Science Foundation (NSF), Department of Energy (DOE), Sloan Foundation, Korean Institute for Basic Science (IBS), and Singapore National Research Foundation (SNRF) and from our host institutions.

Penn UNIVERSITY of PENNSYLVANIA

EP2DS-26 2025 ST. LOUIS MSS-22

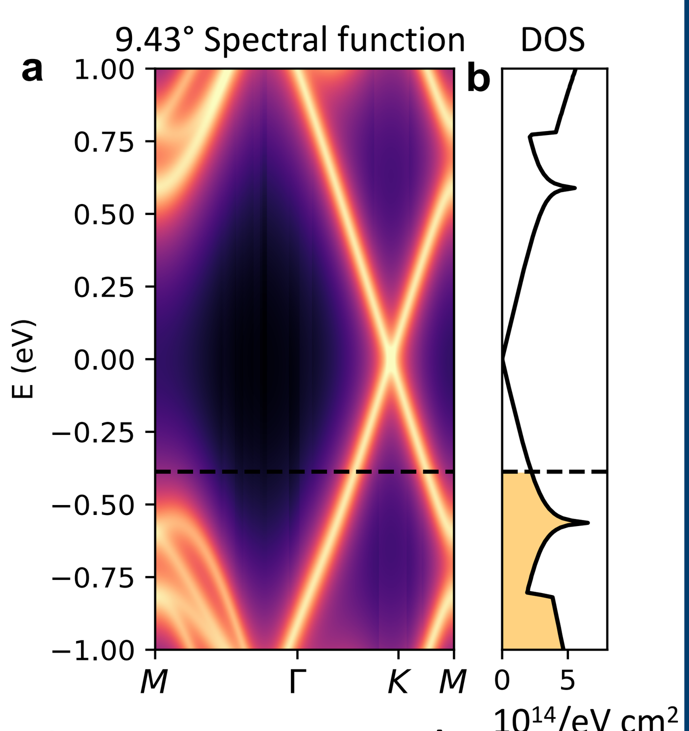
Abstract

We study diffusive magnetotransport in highly p-doped large-area twisted bilayer graphene as a function of twist angle, crossing from below to above the van Hove singularity in 1° and 20° samples with 7° and 9° samples near the van Hove singularity. We observe a crossover from weak localization dominated transport to fluctuation dominated transport as a function of twist angle with an intervening regime of universal conductance fluctuations near the van Hove singularity.

Twisted Bilayer Graphene

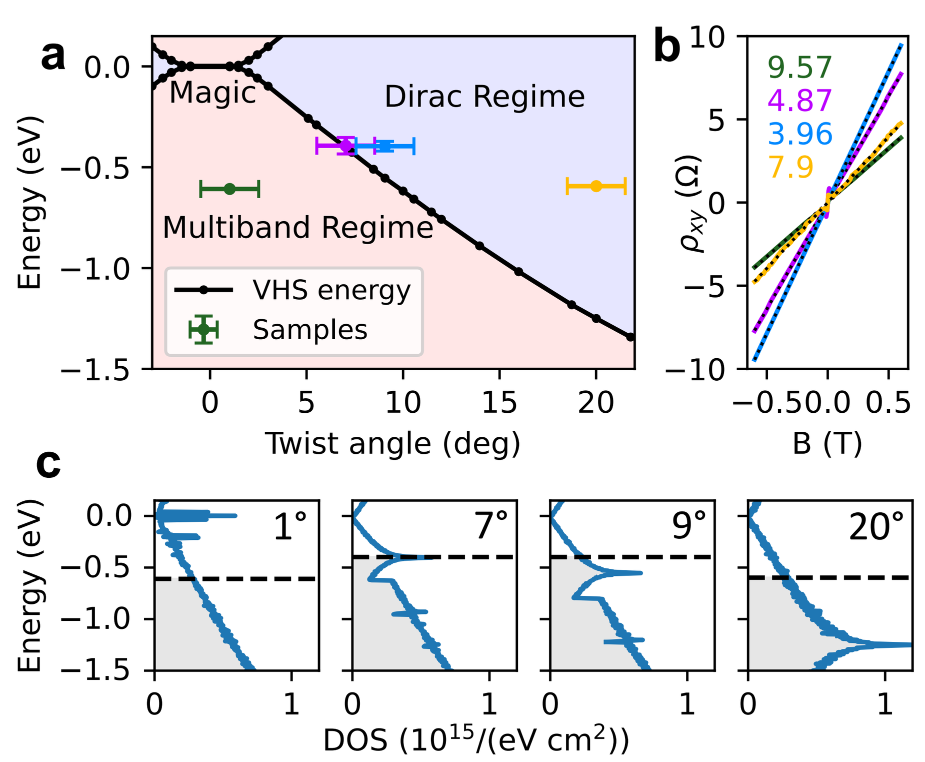
Dirac Fermions

At twist angles ≥ 3°, the low energy electronic structure of twisted bilayer graphene (TBG) has linear crossings at the K and K′ points (Dirac points) of the Brillouin zone. The low energy excitations are massless Dirac fermions and an electron making a loop around a Dirac point acquires a π Berry phase.



Van Hove Singularities

At higher energies multiple bands are present, and the symmetry of Dirac fermions is broken. Explicitly, the crossover is at the van Hove singularity (VHS). When the VHS in reaches 0 energy exotic correlated physics is seen [1] We cross the VHS at fixed chemical potential.



Weak Localization

Theory of Weak (Anti)Localization

In disordered 2D systems, magnetoresistance's (MR) sign diagnoses the symmetries of the system [2]. Weak (anti)-localization was found in monolayers [3].

Valley SU(2)	Berry	Interference	MR	Localization
Preserved	π	Destructive	+	Weak anti.
Broken	0	Constructive	–	Weak

In either scenario the Hikami-Larkin-Nagaoka fit is [4]

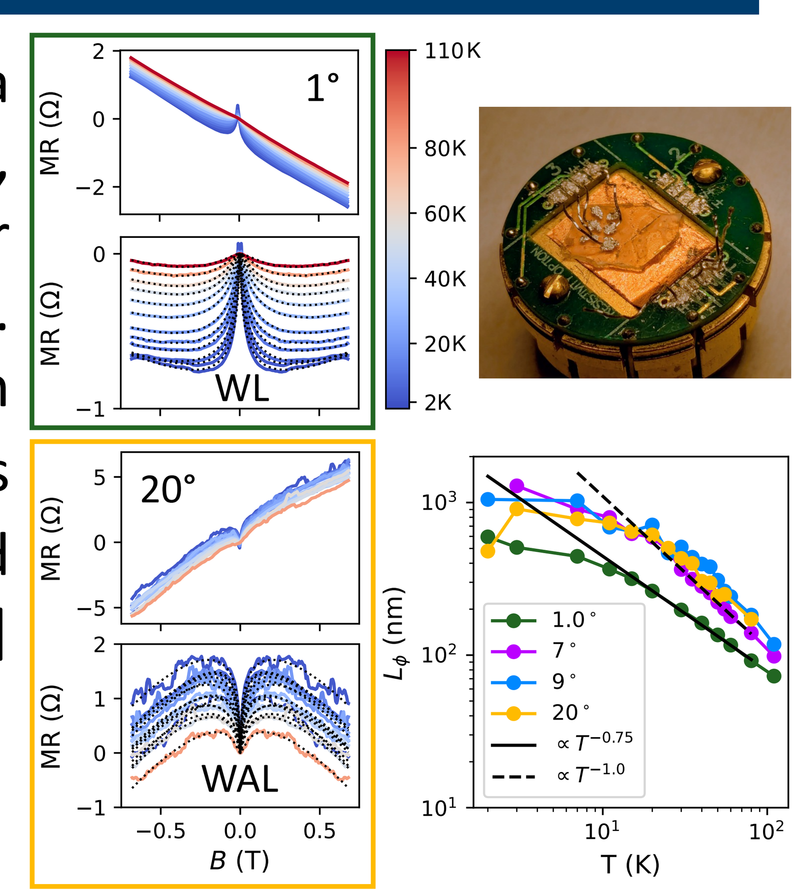
$$\mathrm{MR} = c_{\mathrm{cl}}B^2 + c_{\mathrm{q}}\left(F\left(\frac{B}{B_\phi}\right) - 3F\left(\frac{B}{B_\phi + 2B_{\mathrm{iv}}}\right)\right)$$

with T-independent "classical" c_{cl} and "quantum" coefficients c_{q}. $F(z) = \ln(z) + \mathrm{digamma}(1/z + 1/2)$.

Our Samples

We measured R_{xx} as a function of B and T, symmetrize and fit for the parameters c_i, B_i. Phase coherence length $L_\phi = \sqrt{\hbar/4eB_\phi}$ scales with power law T^{-p} and reveals the scattering [5]

- $p = 0.5$: e-e diffusive
- $p = 1$: e-e ballistic
- $p = 1.5$ - 2: e-phonon



Universal Conductance Fluctuations (UCF)

UCF, or fluctuations in σ_{xx} the order of e^2/h occur in mesoscale systems and serves as a reproducible signature of the sample disorder [6]. Near the VHS in the 9° sample, we see behaviors consistent with UCF. Converting R to σ

$$\sigma_{xx} = R_{xx}^{\mathrm{sym}} / [(R_{xx}^{\mathrm{sym}})^2 + (R_{xy}^{\mathrm{asym}})^2]$$

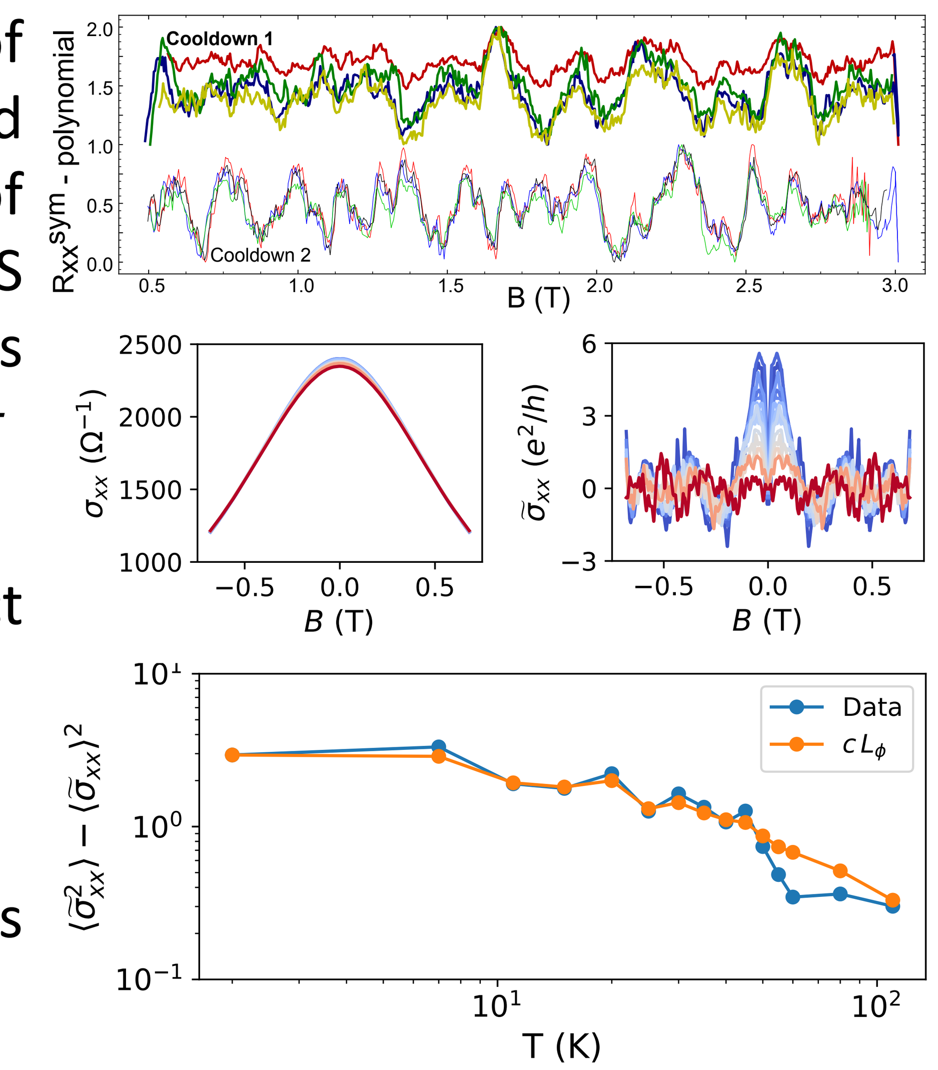
To capture fluctuations we subtract

$$\tilde{\sigma}_{xx} = \sigma_{xx} - (c_0 + c_2B^2 + \cdots c_{2n}B^{2n})$$

Now, we can fit the fluctuations using

$$\langle \tilde{\sigma}_{xx}^2 \rangle - \langle \tilde{\sigma}_{xx} \rangle^2 = c\, L_\phi$$

for fixed c. Extended electron puddles may make the sample act mesoscopic.



My Other Works

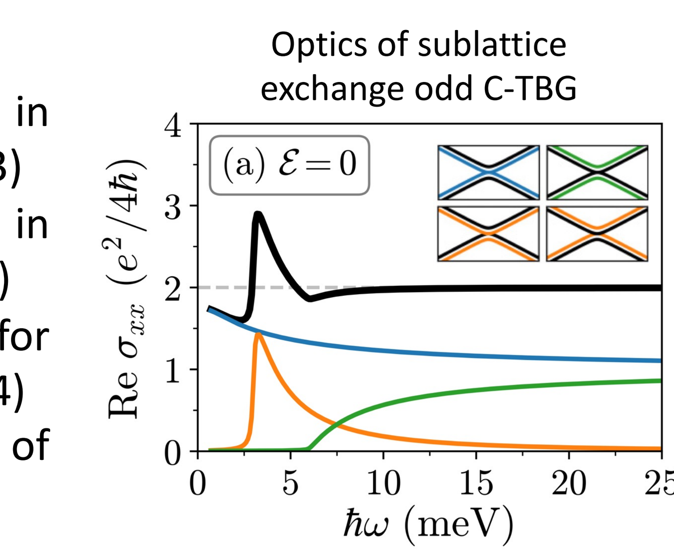
I am a theorist with interests in materials and their responses

[1] Talkington and Mele, "Electric Field Tunable Band Gap in Commensurate Twisted Bilayer Graphene", PRB **107**, 041408 (2023)

[2] Talkington and Mele, "Terahertz Circular Dichroism in Commensurate Twisted Bilayer Graphene", PRB **108** 085421 (2023)

[3] De Beule, Gassner, Talkington, Mele, "Floquet-Bloch theory for nonperturbative response to a static drive" PRB **109**, 235421 (2024)

[4] Talkington and Claassen, "Linear and non-linear response of quadratic Lindbladians", npj Quantum Materials **9**, 104 (2024)



References

[1] Cao, *et al* Nature **556**, 43 (2018);
Yankowitz, *et al* Science **363**, 1059 (2019);
Andrei, *et al* Nat. Materials **19**, 1265 (2020)

[2] Abrahams, *et al* PRL **42**, 673 (1979);
Beenakker, RMP **69**, 731 (1997)

[3] Morozov, *et al* PRL **97**, 016801 (2006);
Wu, *et al* PRL **98**, 136801 (2007);
Tikhonenko, *et al* PRL **100**, 057802 (2008)

[4] Hikami, *et al* Prog. Th. Phys. **63**, 707 (1980);
McCann, *et al* PRL **97**, 146805 (2006);
Das Sarma, *et al* RMP **83**, 407 (2009)

[5] Altshuler, *et al* J. Phys. C **15**, 7367 (1982);
Chakravarty, *et al* Phys. Rep. **140**, 193 (1986)

[6] Lee, *et al* PRL **55**, 1622 (1985)
Lee, *et al* PRB **35**, 1039 (1987)

[7] Mead, Talkington, *et al*, "Terahertz Landau level spectroscopy of Dirac fermions in millimeter-scale twisted bilayer graphene", PRB **112** 205116 (2025)

[8] Talkington, Mallick, *et al*, "Weak localization and universal conductance fluctuations in large area twisted bilayer graphene", arXiv: 2511.07334 (2025)