

Dioidic order in graphene multilayers

A study of the nonreciprocal superconducting and normal state

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J.-X. Lin, et al., *Nature Physics*, 18, 10 (2022)

N. J. Zhang, et al., *arXiv:2209.12964* (2022)

J.-X. Lin, et al., *arXiv:2302.04261* (2023)



Outline

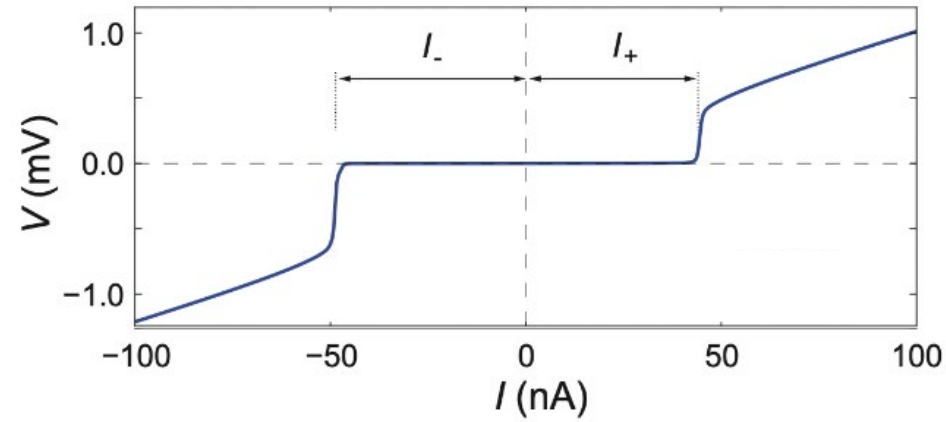
- Introduction: superconducting diode effect (SDE)
- Zero-field SDE in twisted trilayer graphene
- Diodic order in normal state in multilayer graphene
- Valley and momentum polarization

Outline

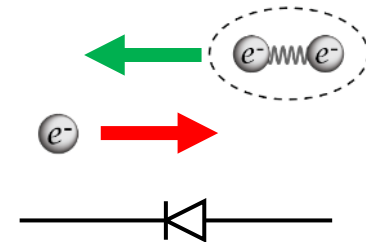
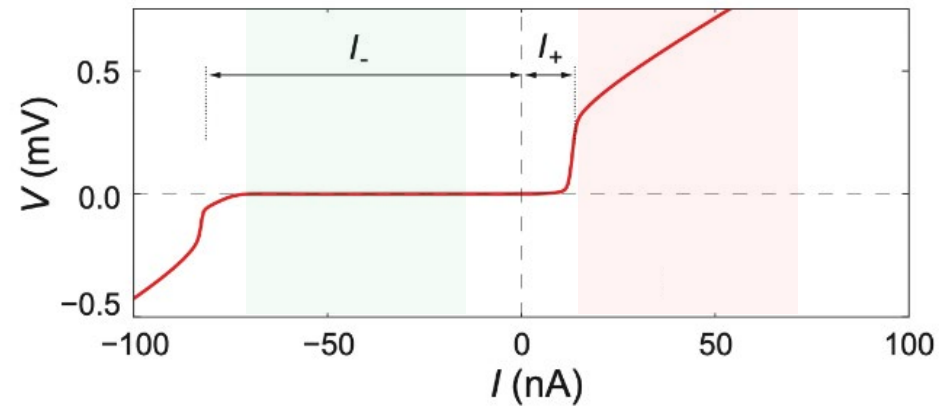
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Superconducting diode effect (SDE)

Regular superconductor

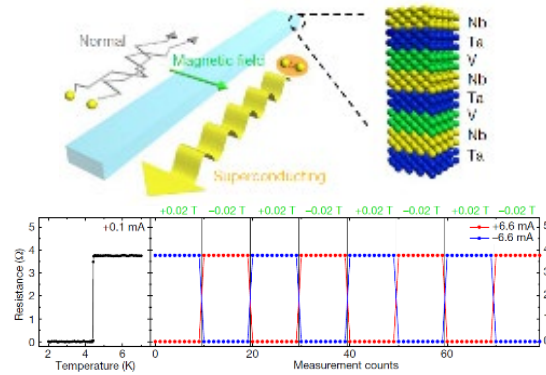


Nonreciprocal superconductor
(Superconducting diode effect)

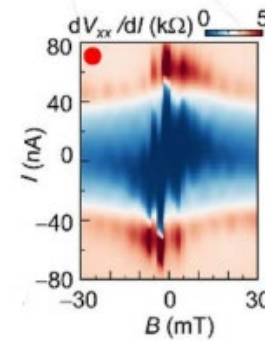
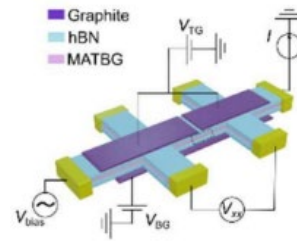


Superconducting diode effect (SDE)

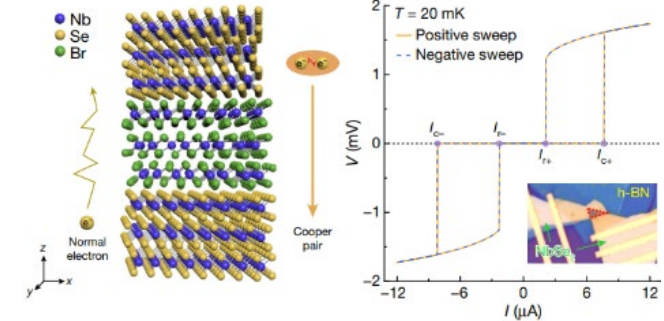
Examples of SDE:



F. Ando, et al, Nature (2020)

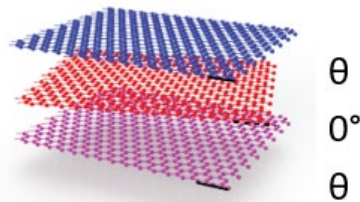


J. Diez-Merida, et al, arXiv (2021)

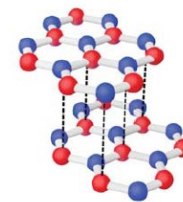


H. Wu, et al, Nature (2022)

Our systems:



Twisted trilayer graphene

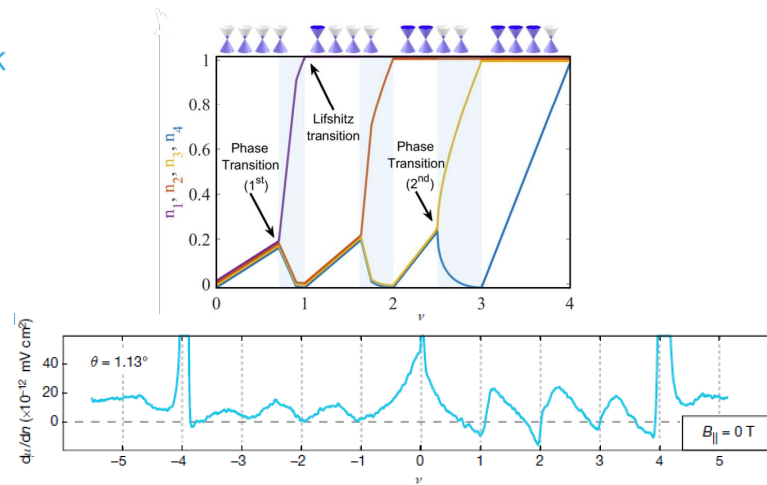
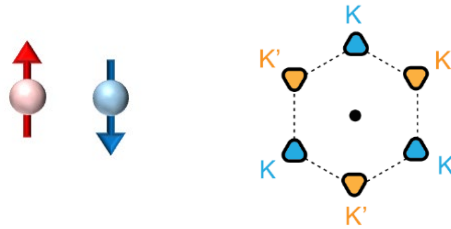


Bernal (AB stacking) bilayer graphene

Graphene multilayers with flat band

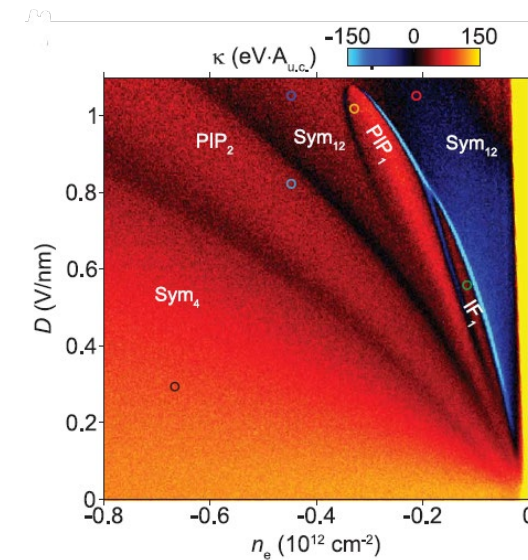
- Flat energy band
- Superconductivity

Degrees of freedom:



Dirac revival (moiré)

U. Zondiner, et al., *Nature*, 582 (2020)



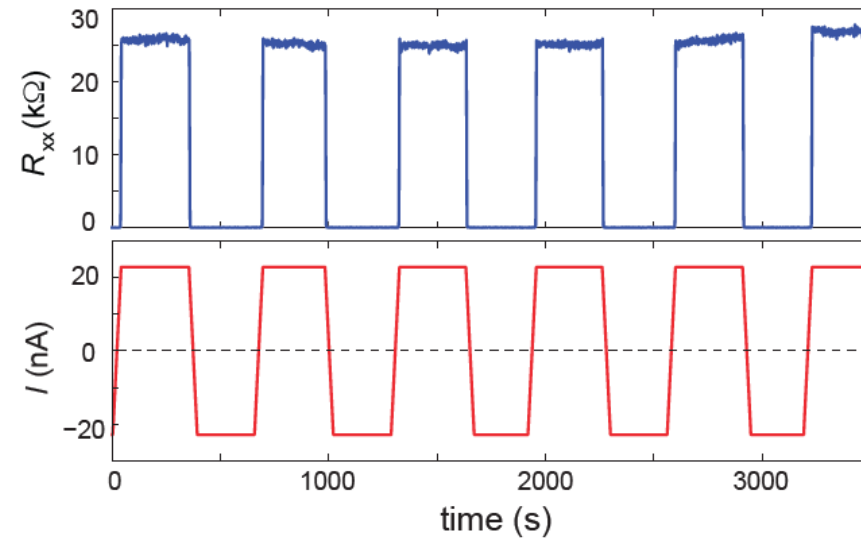
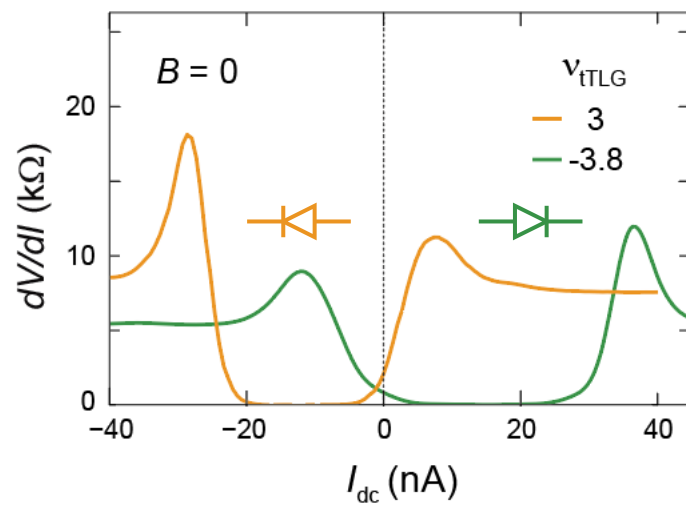
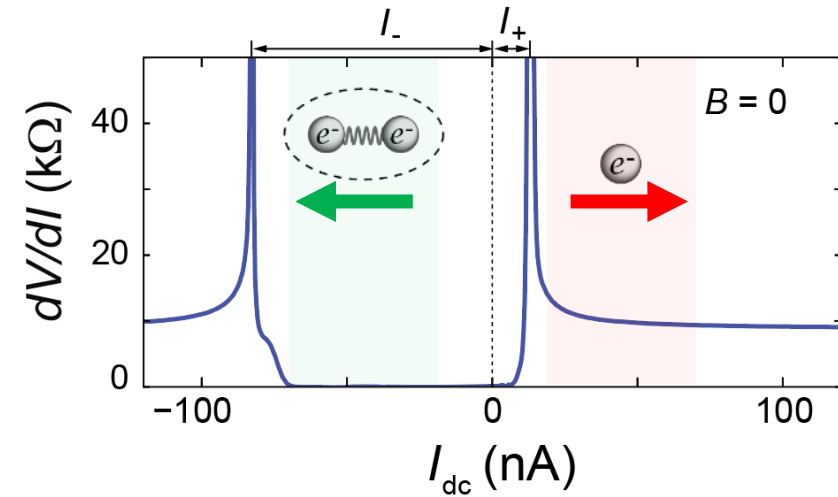
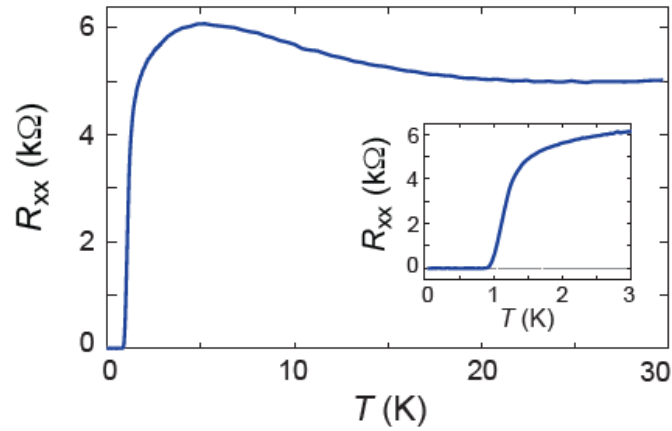
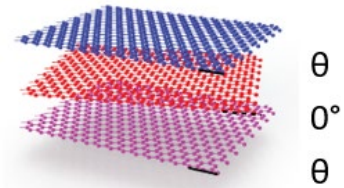
Half- and quarter-metal (moiré-less)

H. Zhou, et al., *Science*, 375 (2022)

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SDE in twisted trilayer graphene

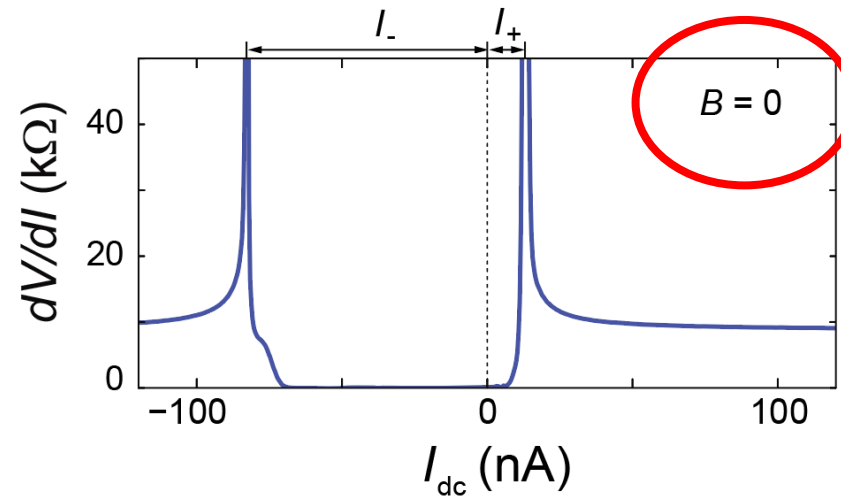


Symmetry requirement of SDE

- SDE requires breaking time reversal symmetry
- SDE requires breaking inversion/ C_2 symmetry
- finite momentum pairing

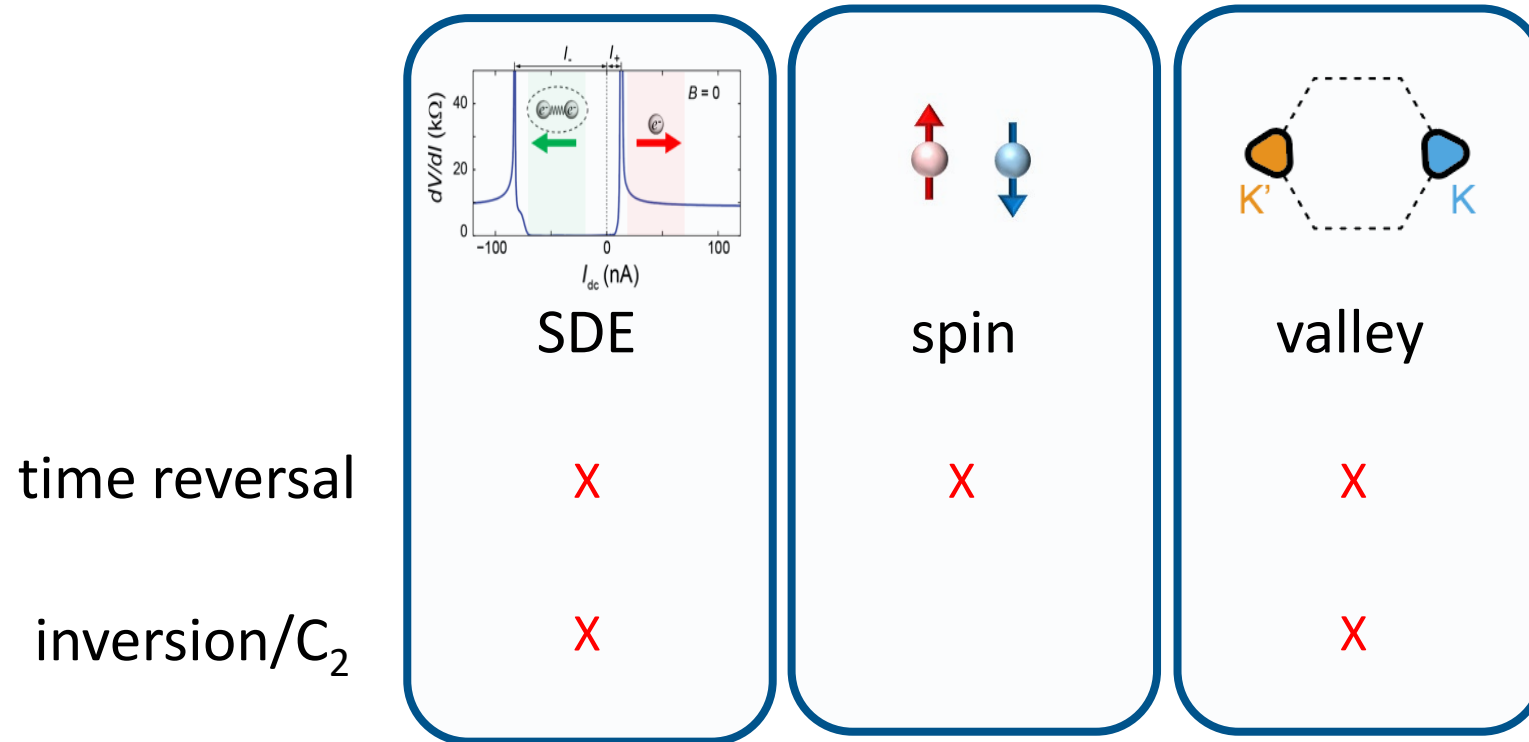
} spontaneous

N. F. Q. Yuan, et al, *PNAS* (2022), A. Daido, et al, *PRL* (2022), J. J. He, et al, *New J. Phys* (2022), H. D Scammell, et al, *2D Materials* (2022), ...

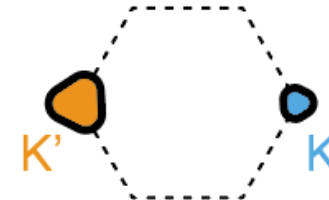


What is the origin of the zero field SDE?

Symmetry analysis



Hypothesis: SDE originates from a valley imbalance in charge occupation.

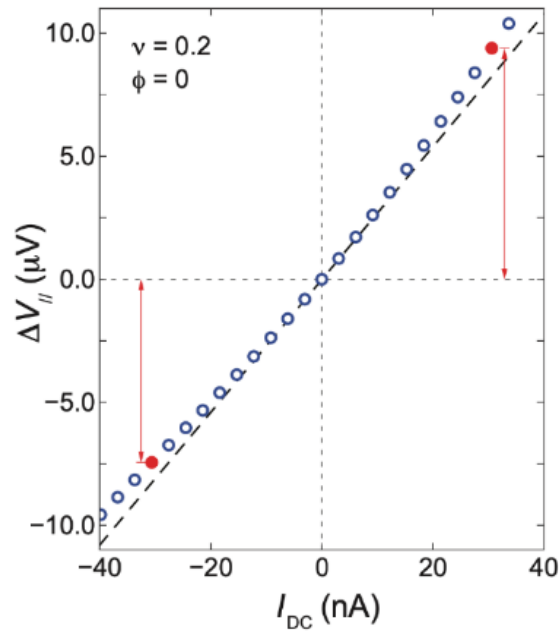


- Is this order intrinsic to SC? Or inherit from normal state?
- How to detect valley isospin order?

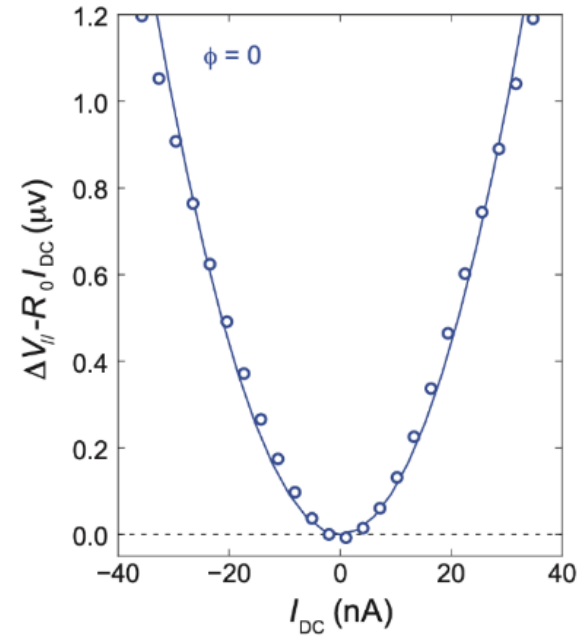
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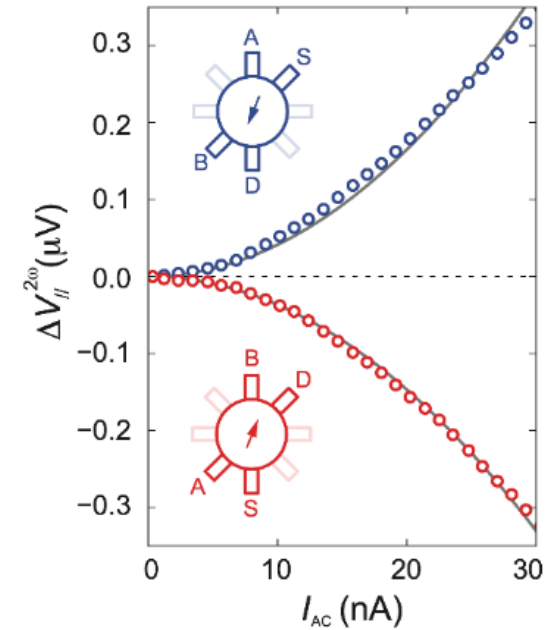
Normal state nonreciprocity and nonlinear measurement



subtract
linear
background



Nonlinear response:
measure V at $2f$

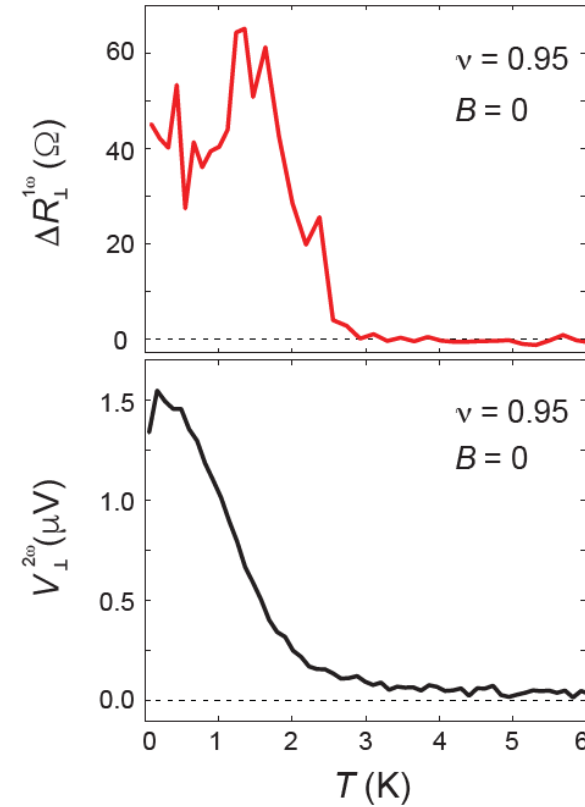
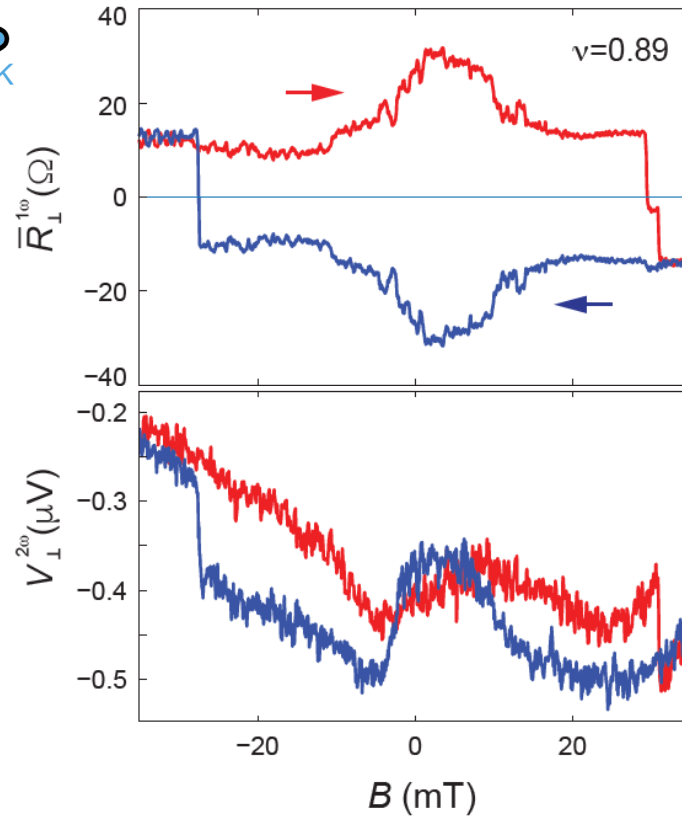
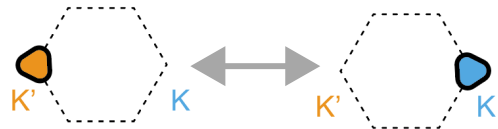


Nonreciprocity



Nonlinear response at the
second-harmonic frequency

Normal state nonreciprocity and nonlinear measurement



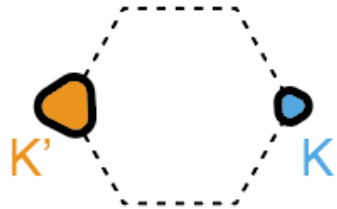
nonreciprocity
(nonlinear response)



valley isospin order

Angular-resolved nonlinear transport measurement

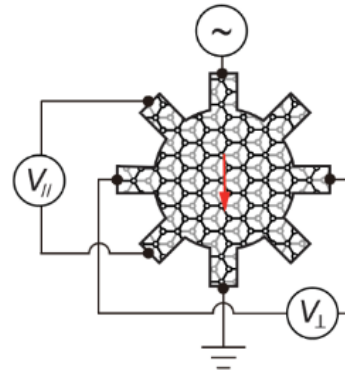
nonlinear response:
fermi surface imbalance



+ angular dependence



ARNTM

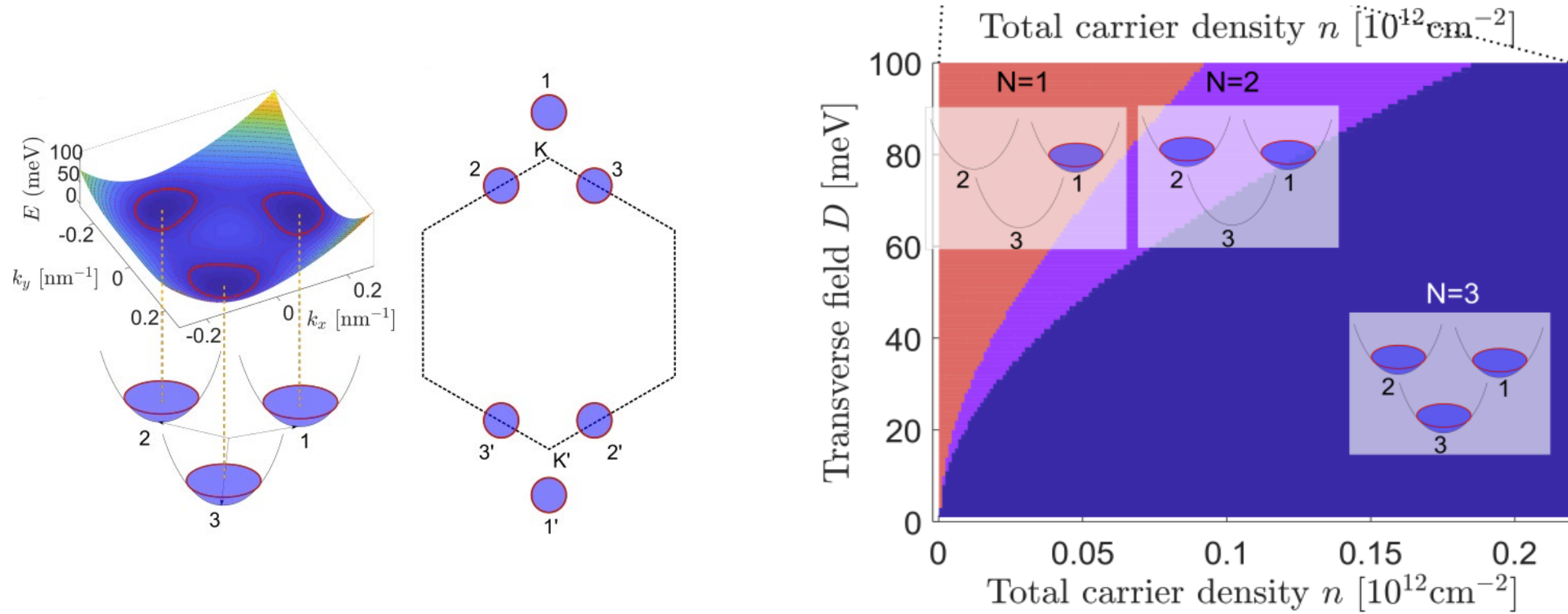


Imbalance in different directions
→ Map out fermi surface contour

Outline

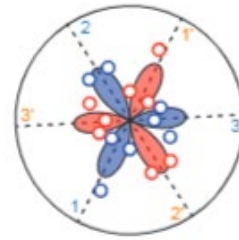
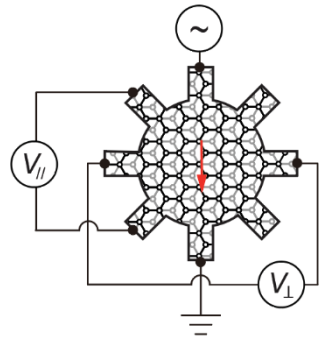
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Coulomb-driven momentum polarization

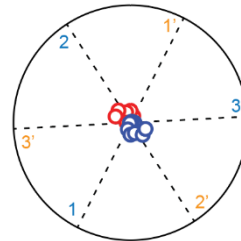
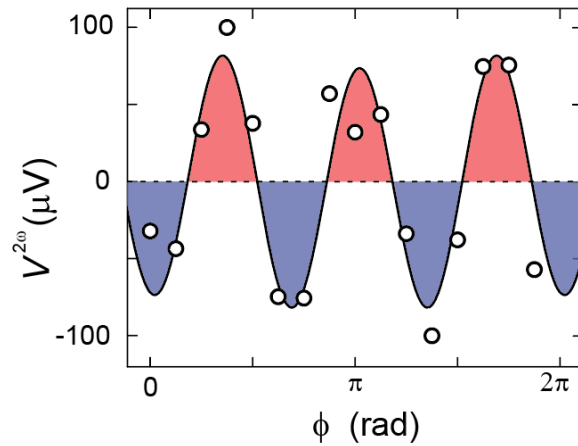
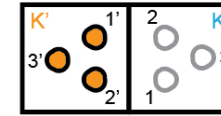
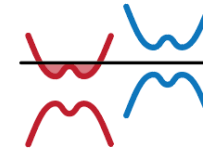


Z. Dong, et al., *Phys. Rev. B*, 107, 075108 (2023)

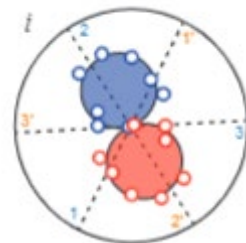
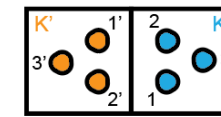
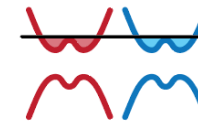
ARNTM – in Bernal bilayer graphene



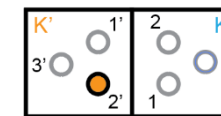
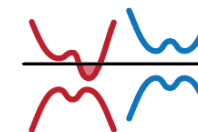
C_3 ✓ T, C_2 ✗



T, C_2 ✓



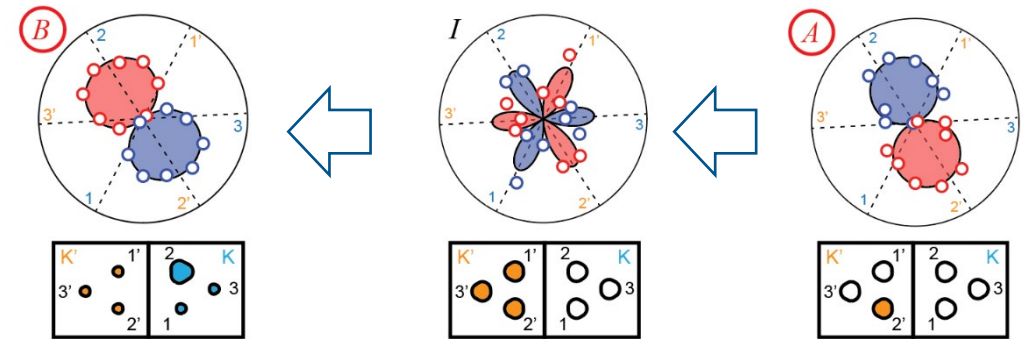
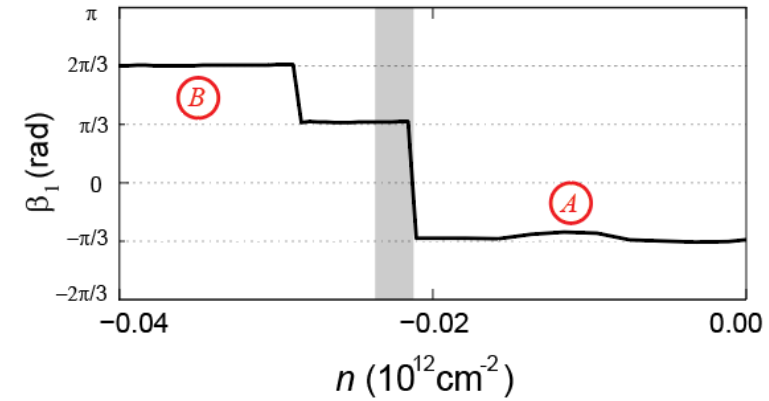
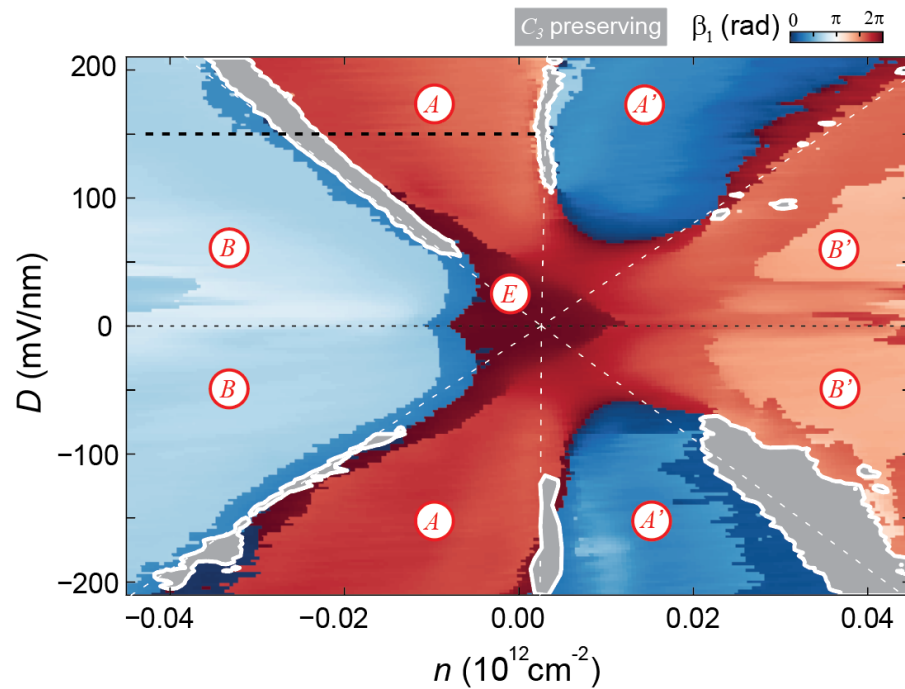
T, C_2 ✗ C_3 ✗



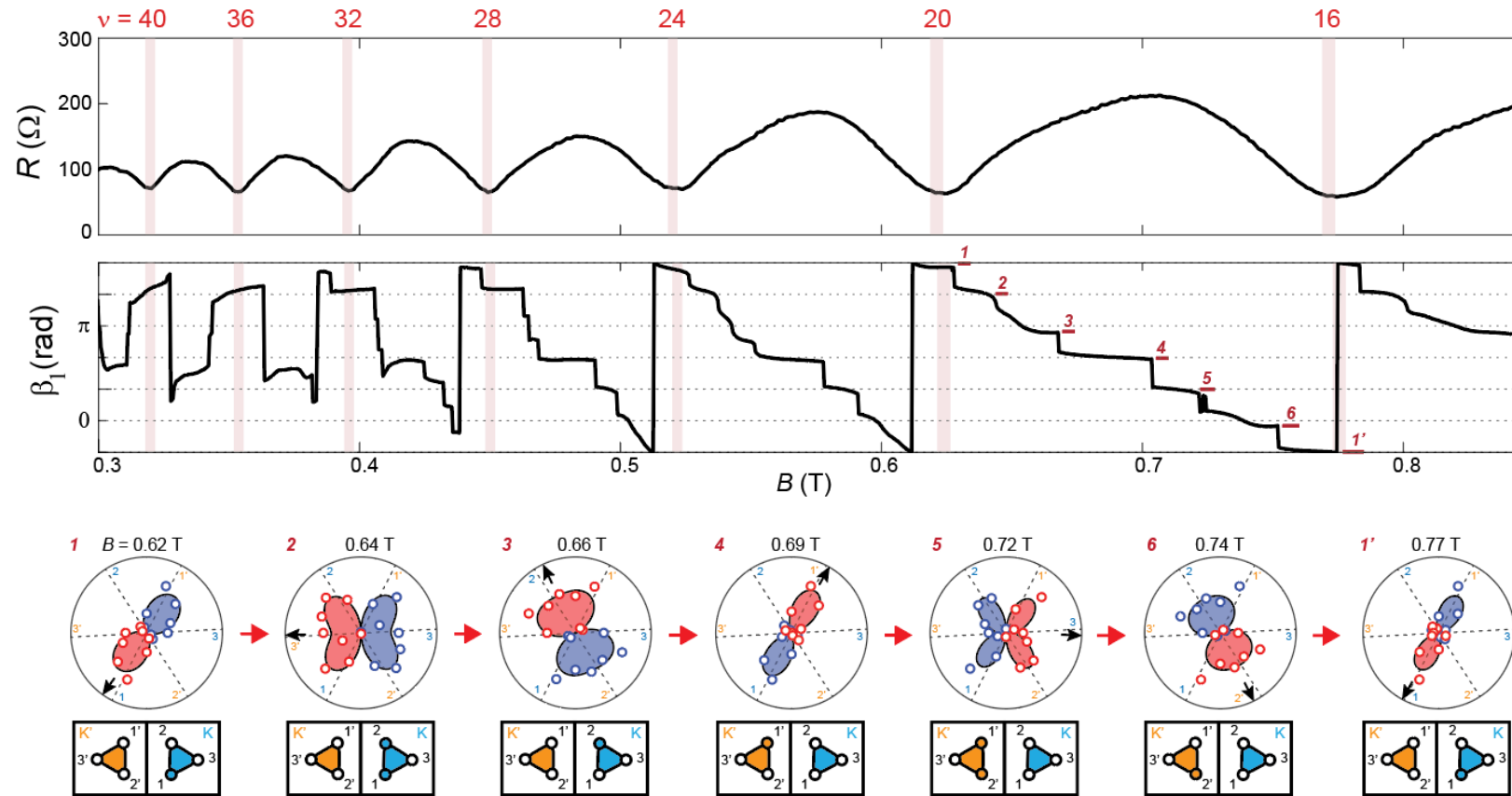
Valley and momentum polarized

ARNTM – in Bernal bilayer graphene

$$V_{\parallel}^{2\omega}(\phi) = V_1 \cos(\phi - \beta_1) + V_3 \cos(3(\phi - \beta_3))$$

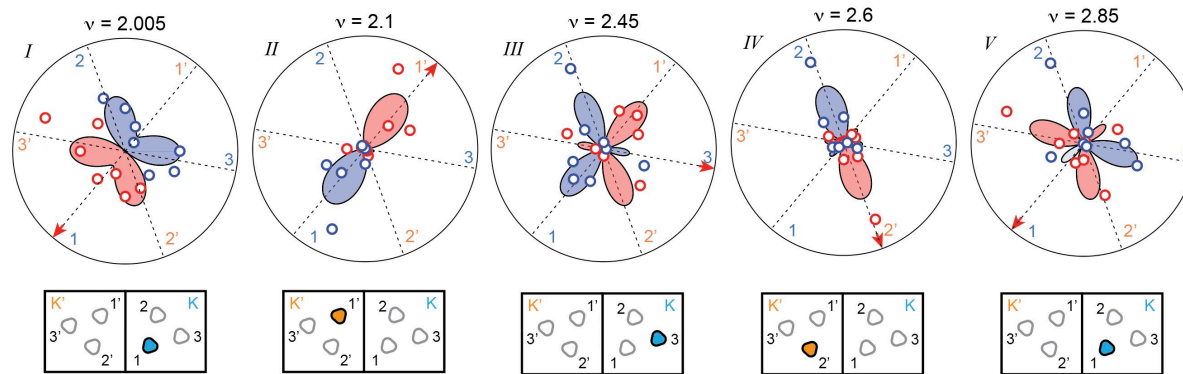
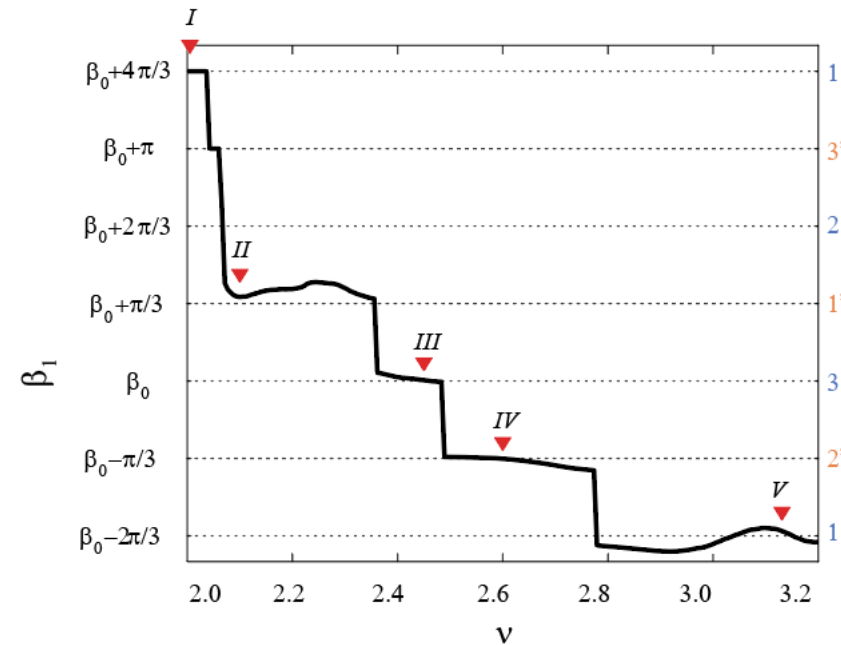
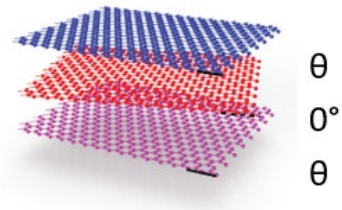


ARNTM – in Bernal bilayer graphene

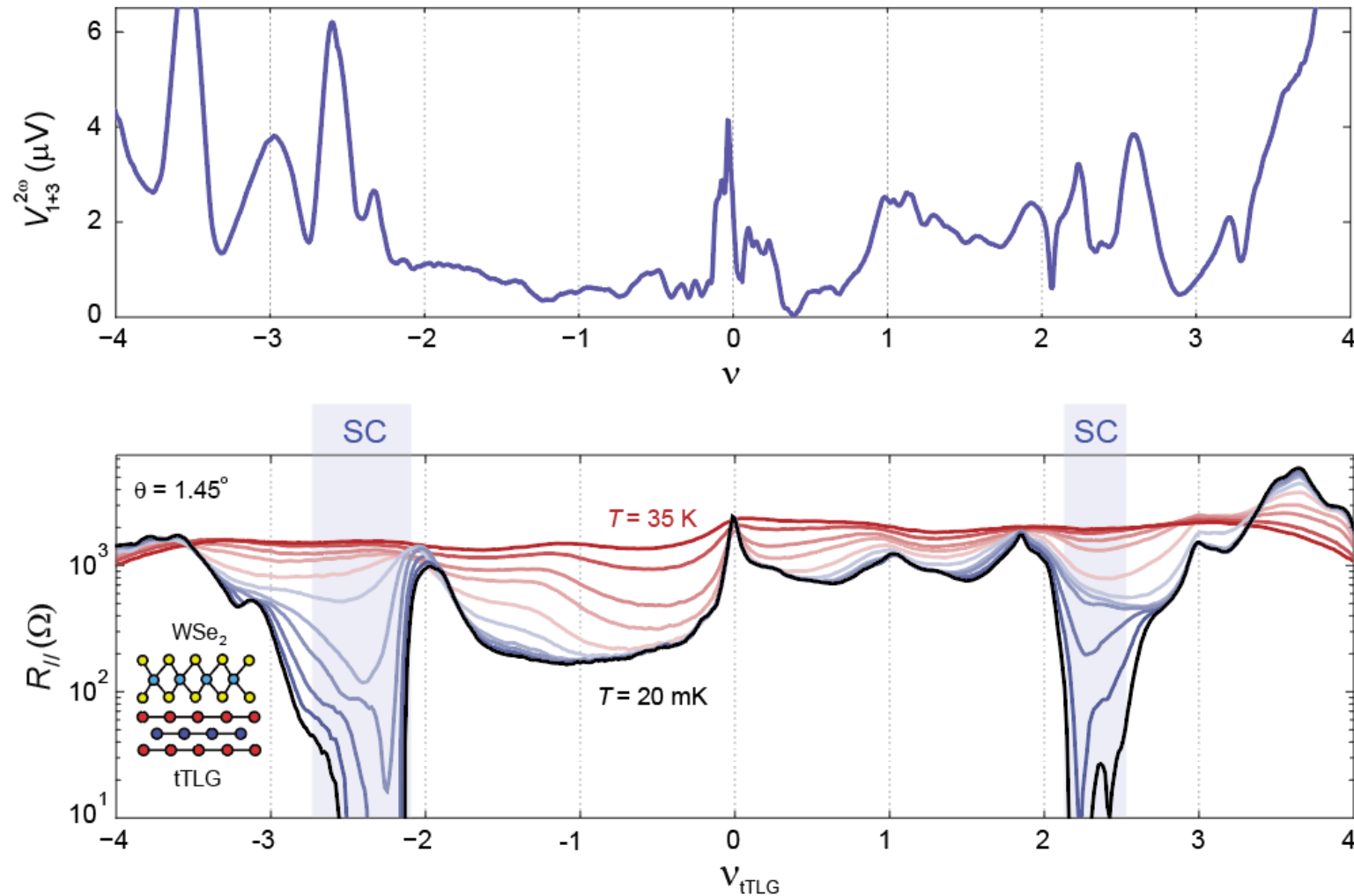


- Not artifact
- Momentum polarization is a universal phenomena
- ARNTM is a sensitive probe

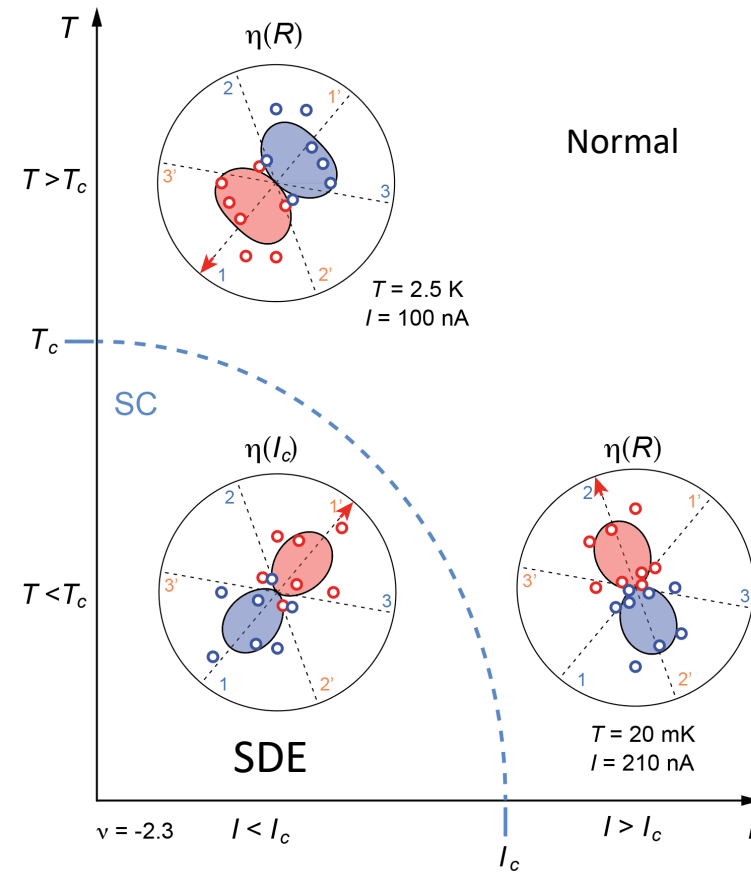
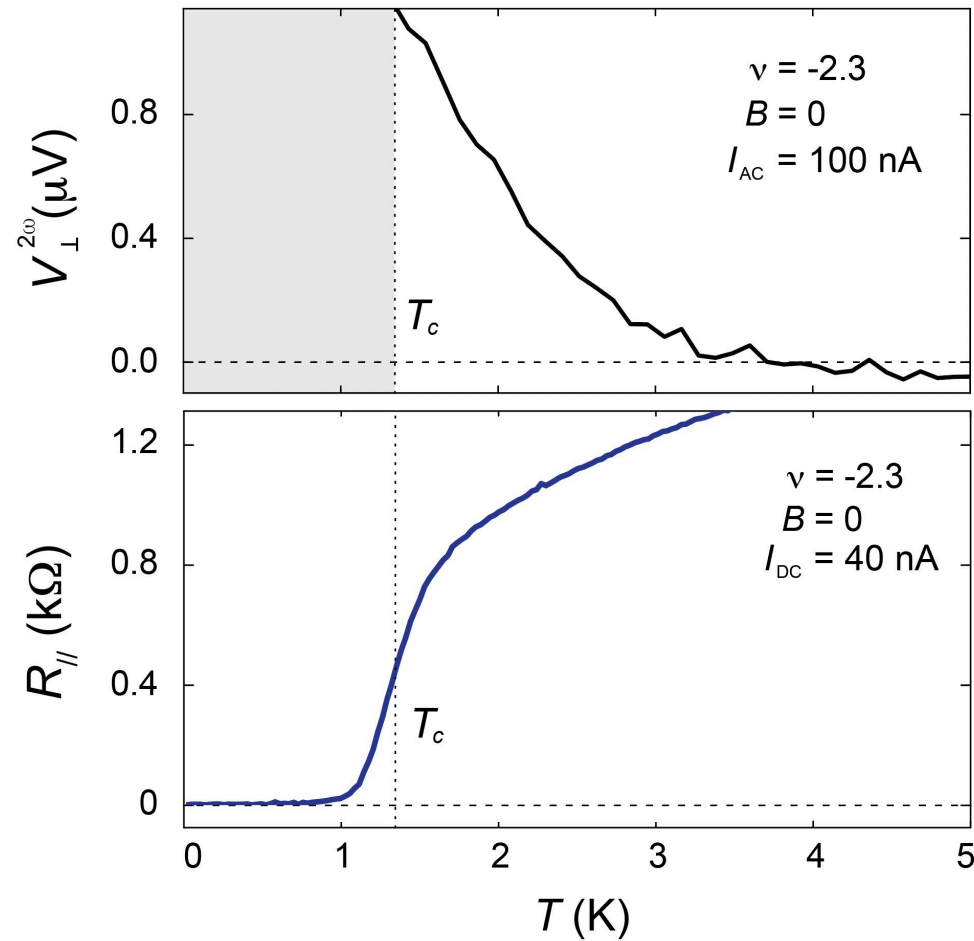
tTLG: normal state valley and momentum polarization



tTLG: normal state valley and momentum polarization



Dioidic order at superconducting transition



Summary

- Zero-field superconducting diode effect
- Dioidic order in normal state, arising from valley and momentum polarization

Acknowledgement

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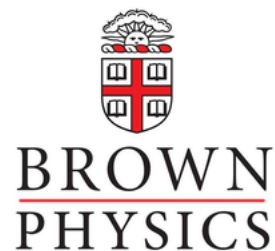
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NIMS, Japan

Kenji Watanabe, Takashi Taniguchi

