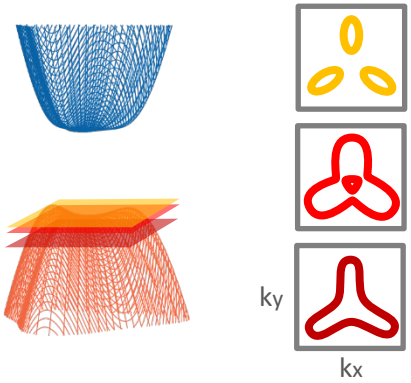
Correlated phases in the vicinity of tunable van Hove singularities in Bernal bilayer graphene



Anna M. Seiler

Nils Jacobsen, Martin Statz, Fabian R. Geisenhof, Felix Winterer, Isabell Weimer, Noelia Fernandez, Francesca Falorsi, Kenji Watanabe, Takashi Taniguchi, Tianyi Xu, Zhiyu Dong, Leonid S. Levitov, Fan Zhang, R. Thomas Weitz

Geneva, 17.05.2024

Electronic correlations

- The behavior of an electron is dependent on the behavior of the others
- Electron-electron correlations can induce spontaneous symmetry breaking

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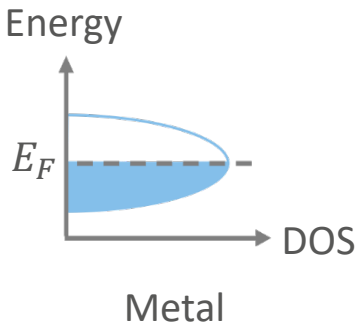

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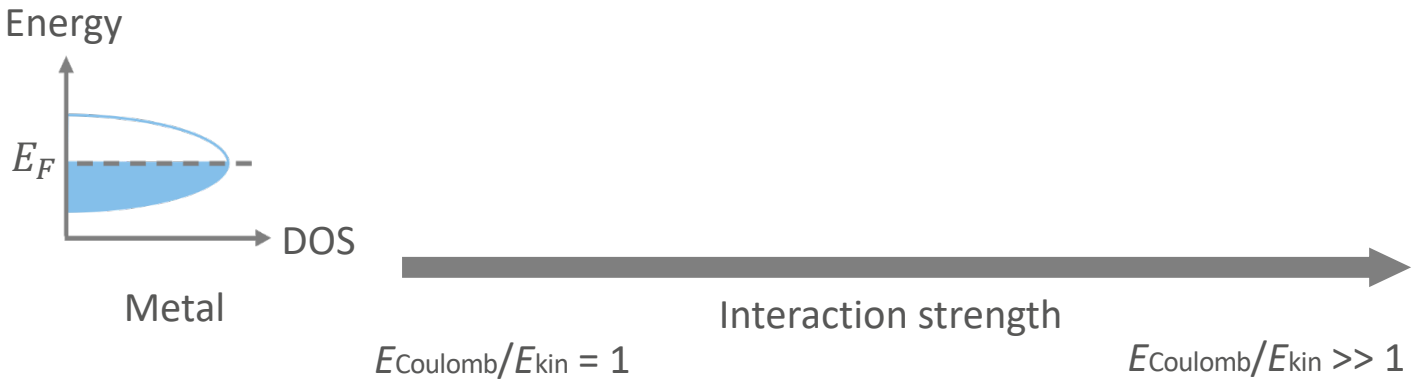

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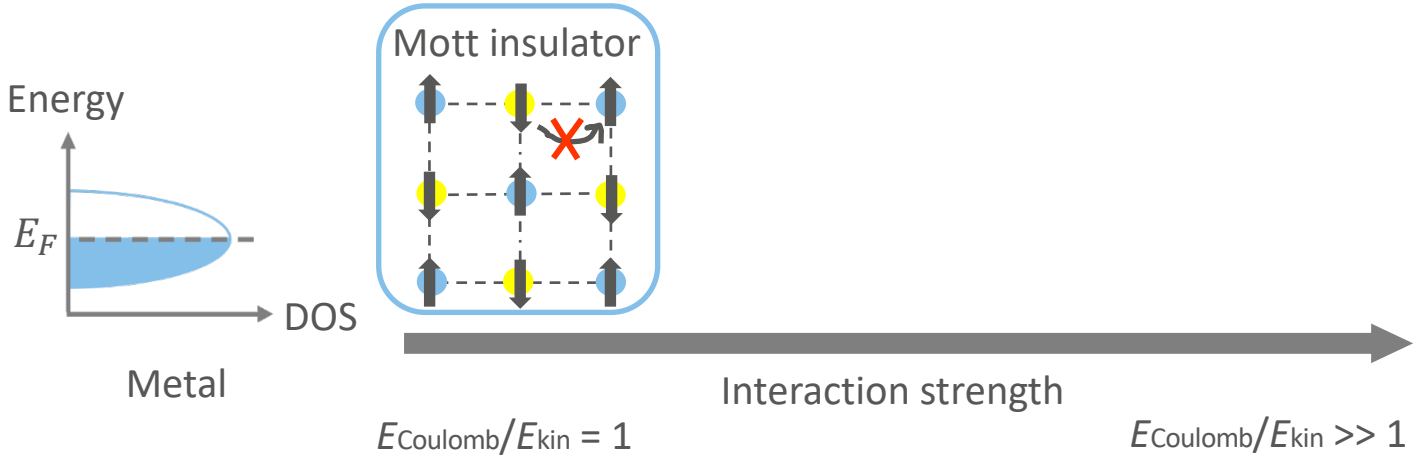

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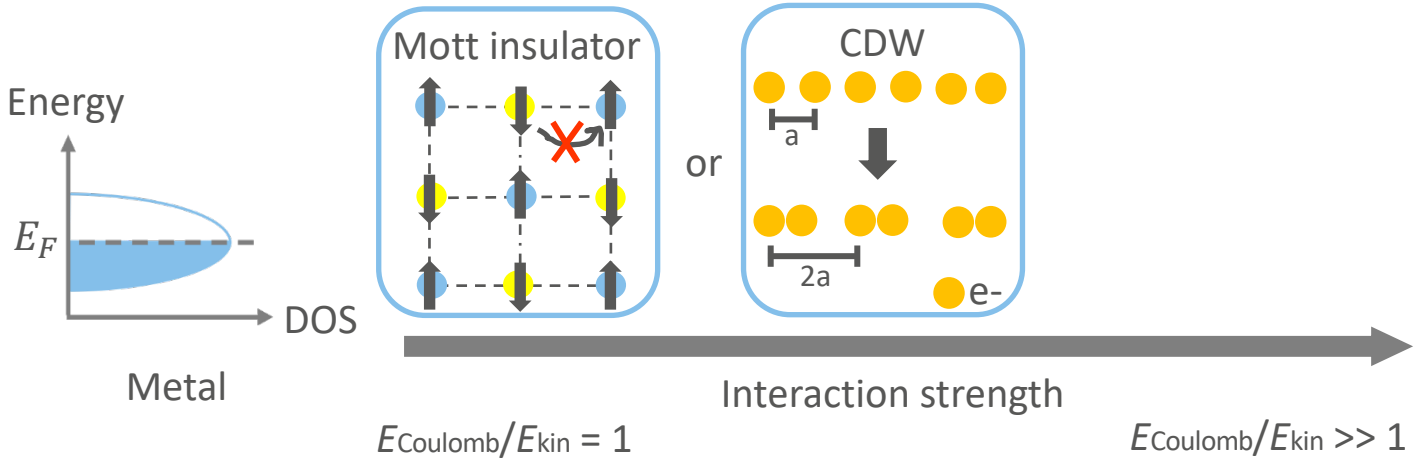

Electronic correlations

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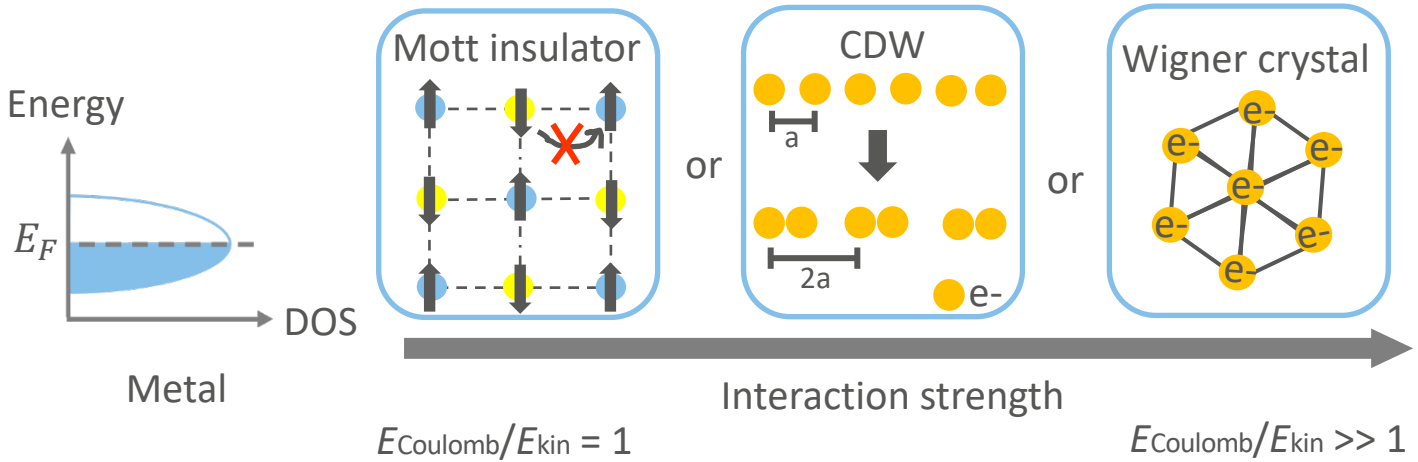

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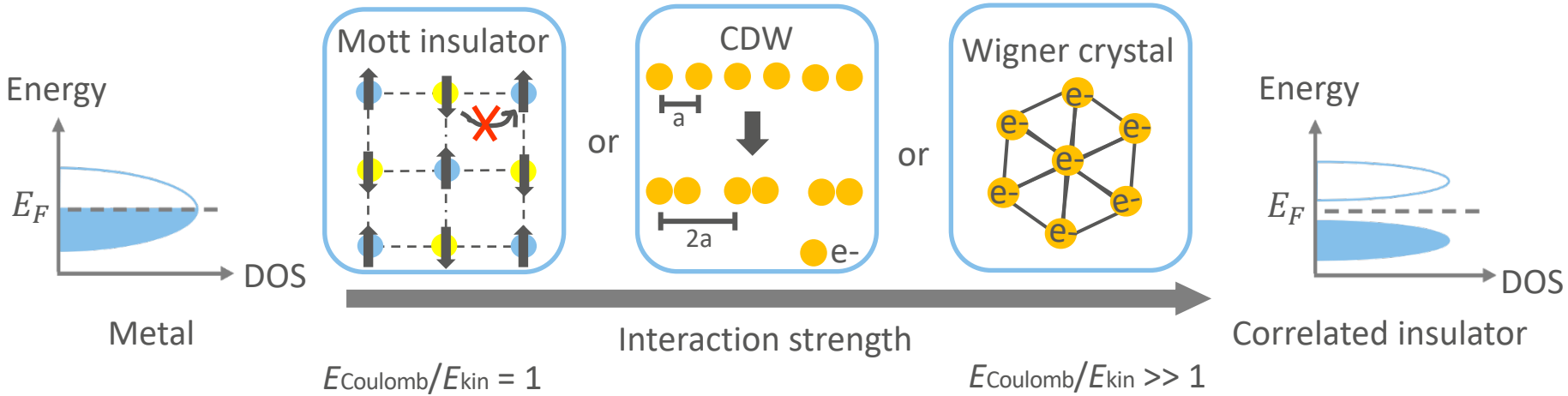
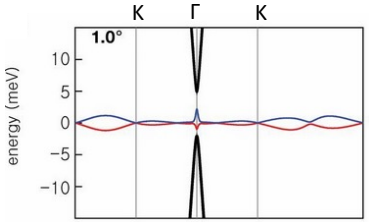
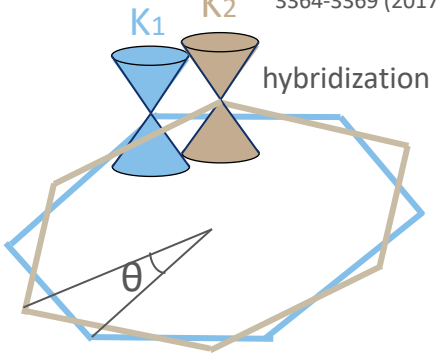


Magic-angle twisted bilayer graphene



K. Kim et al., *PNAS* **114**, 3364-3369 (2017)



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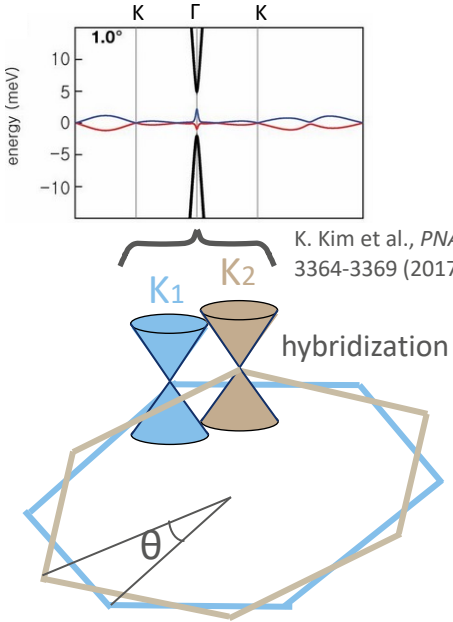

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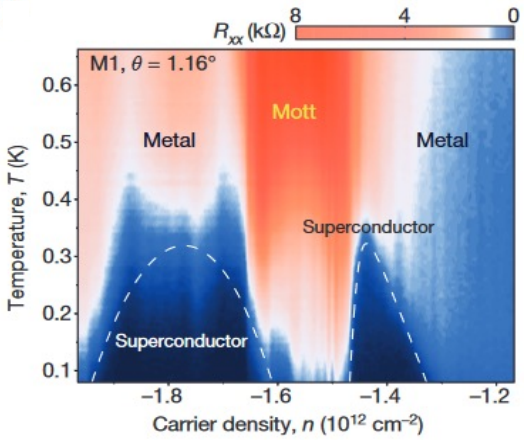

Y. Cao et al., *Nature* **556**, 43-50 (2018)

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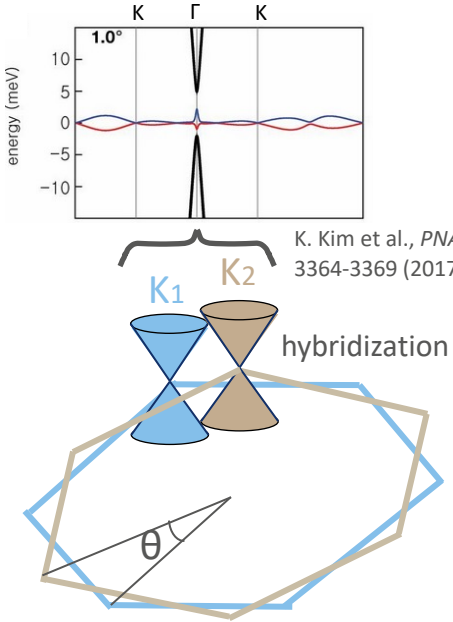

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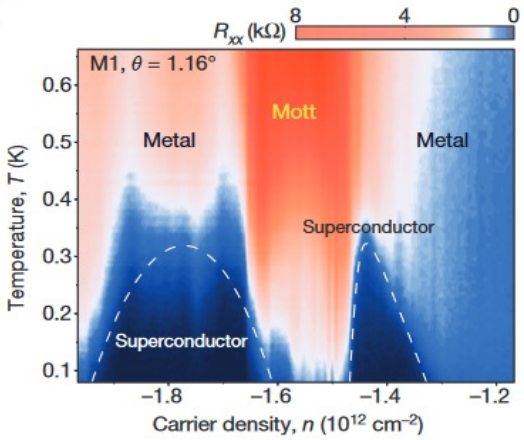
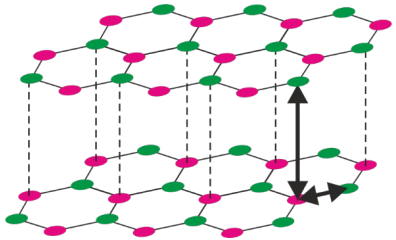


Y. Cao et al., *Nature* **556**, 43-50 (2018)

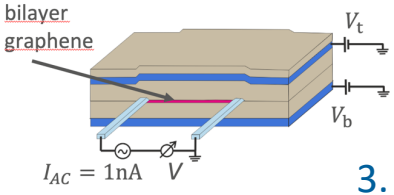
Are there similar correlated phases in natural bilayer graphene?

Outline

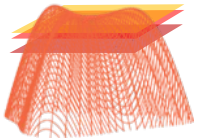
1. Bernal bilayer graphene



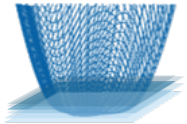
2. Transport measurements



3. Correlated phases at hole-doping



4. Correlated phases at electron-doping



Outline

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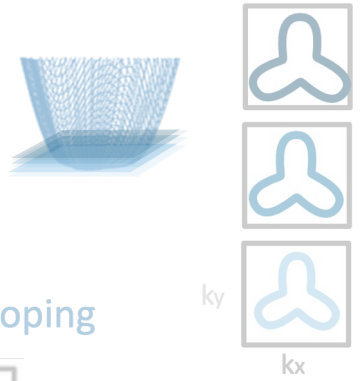

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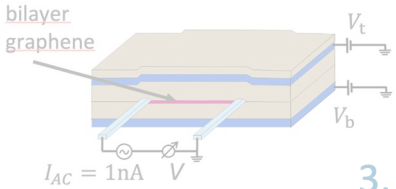

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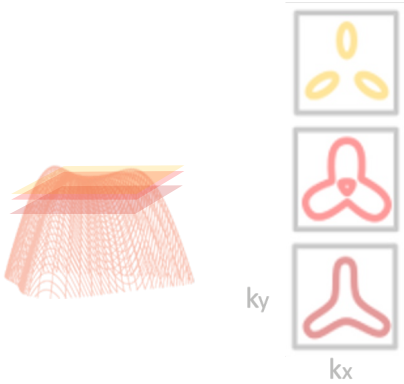

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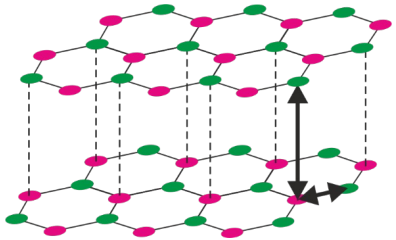
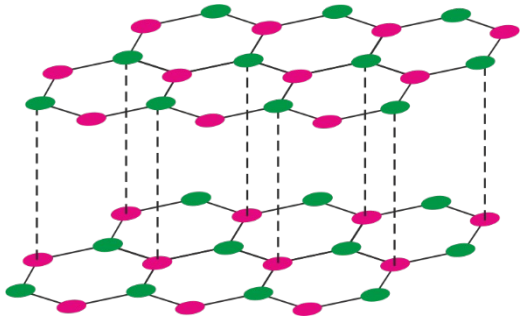
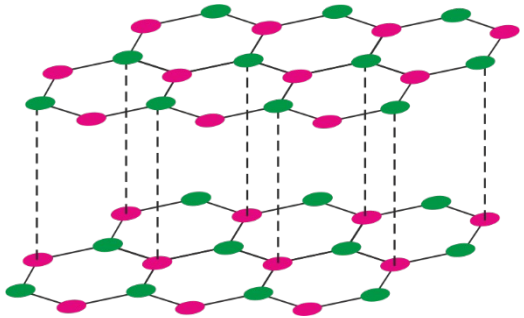


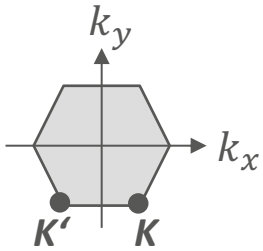
Bernal bilayer graphene



- Sublattice A and B

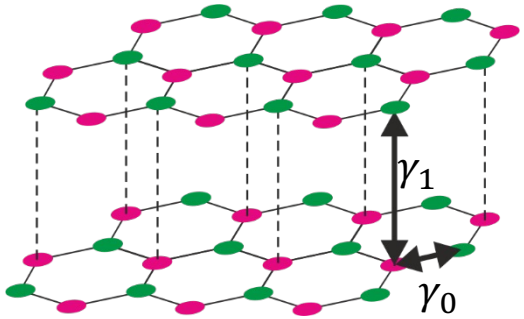
Bernal bilayer graphene

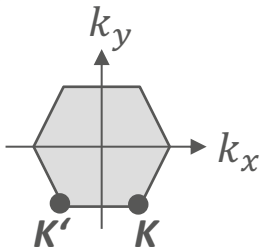


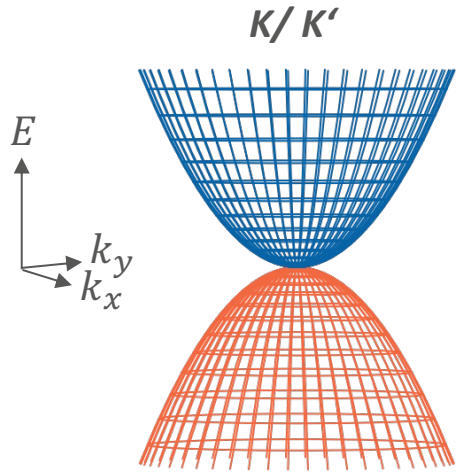


- Sublattice A and B
- 4-fold degeneracy: **valley** and **spin** degrees of freedom

Bernal bilayer graphene







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Parabolic band structure!

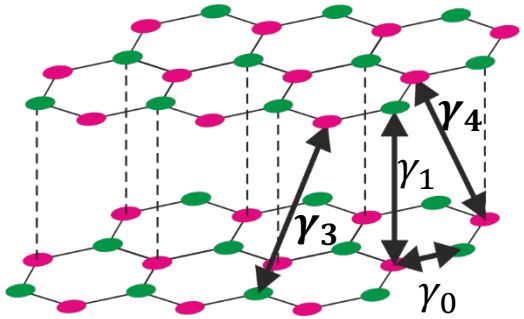
consistent with

K. S. Novoselov et al. *Nature Physics* **2**, 177-180 (2006)
R. T. Weitz et al. *Science* **330**, 812-816 (2010)
J. I. A. Li et al. *Science* **358**, 648-652 (2017)
F. R. Geisenhof et al. *Nature* **598**, 53-58 (2021)
and many others…

Band structure calculations done by Nils Jacobsen

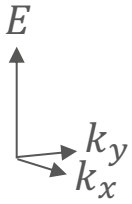
A. M. Seiler, N. Jacobsen, M. Statz, N. Fernandez, F. Falorsi, K. Watanabe, T. Taniguchi, Z. Dong, L. S. Levitov and R. T. Weitz, *Nat. Commun*. **15**, 3133 (2024)

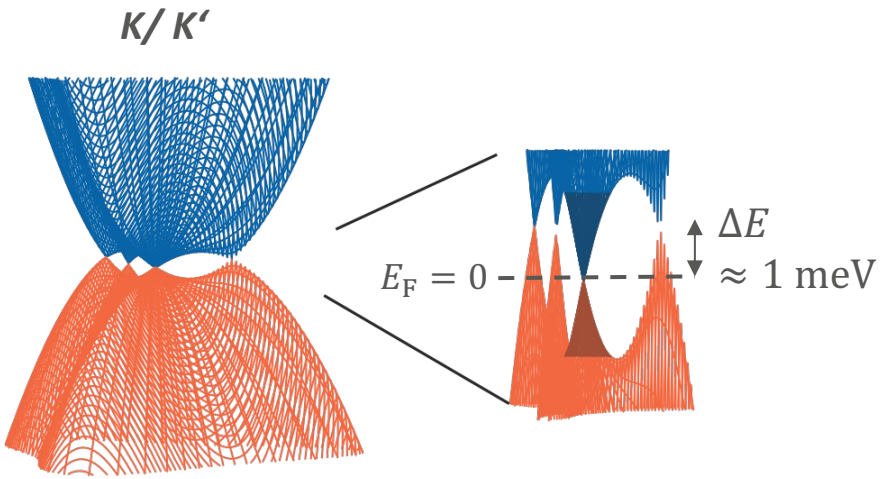
Bernal bilayer graphene



γ_3 → trigonal warping

γ_4 → electron-hole asymmetry





- Sublattice A and B
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Band structure calculations done by Nils Jacobsen

see also: E. McCann and V. I. Fal‘ko. *PRL* **96**, 086805 (2006) and others

A. M. Seiler, N. Jacobsen, M. Statz, N. Fernandez, F. Falorsi, K. Watanabe, T. Taniguchi, Z. Dong, L. S. Levitov and R. T. Weitz, *Nat. Commun*. **15**, 3133 (2024)

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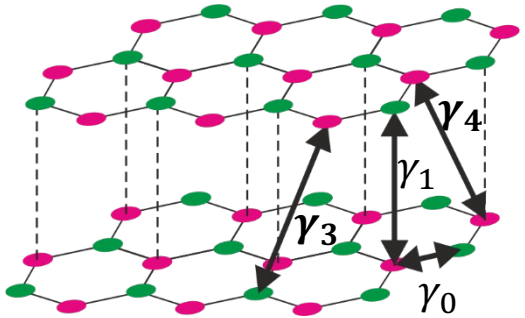
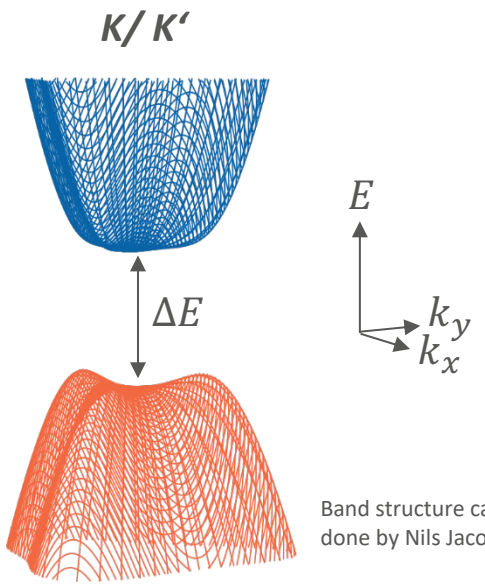


Electric displacement field *D*

breaks inversion symmetry



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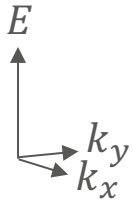
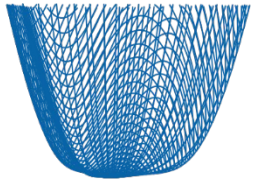
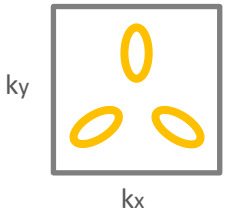
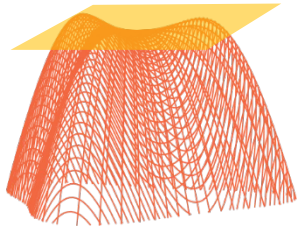
see also: E. McCann and V. I. Fal'ko. *PRL* **96**, 086805 (2006) and others
A. Varlet et al. *PRL* **113**, 116602 (2014)

Van Hove singularities in bilayer graphene at $D >> 0$





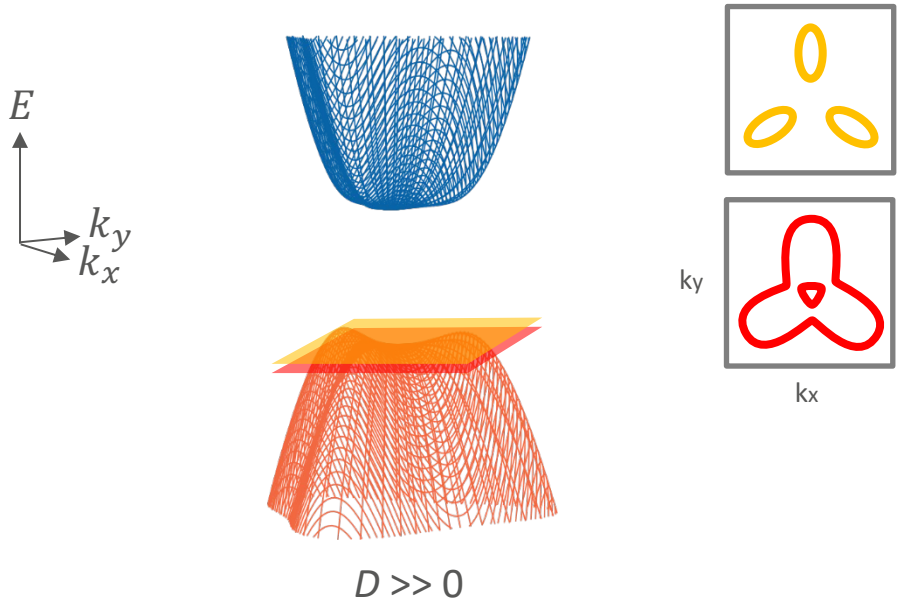




$D >> 0$

Band structure calculations done by Nils Jacobsen

Van Hove singularities in bilayer graphene at $D >> 0$



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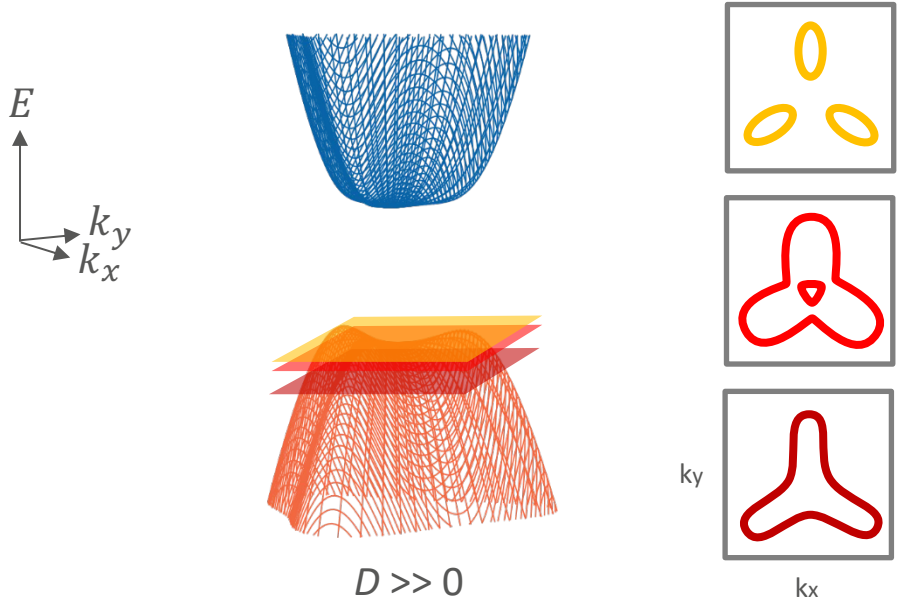
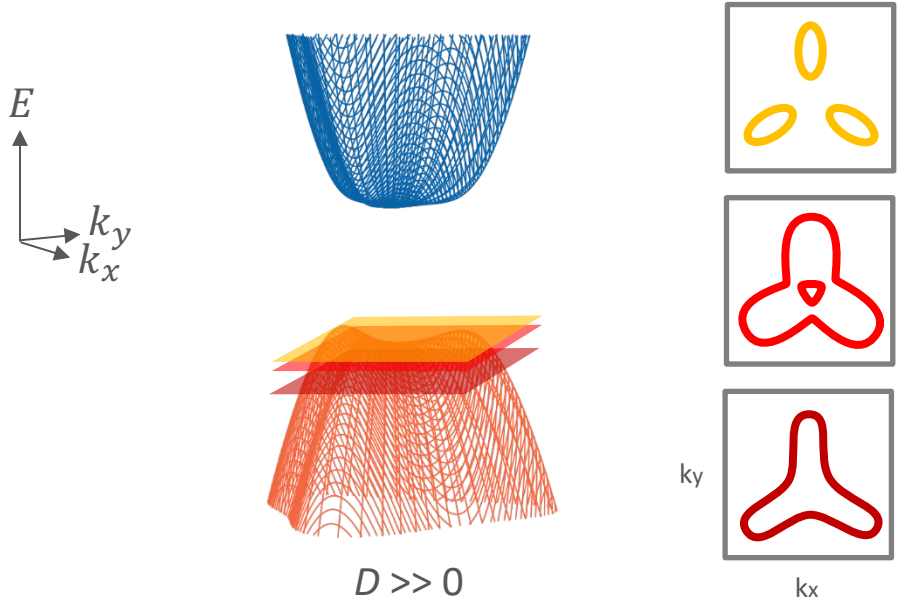
Band structure calculations done by Nils Jacobsen

Van Hove singularities in bilayer graphene at $D >> 0$



Band structure calculations done by Nils Jacobsen

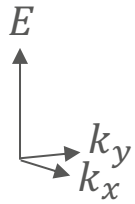
Van Hove singularities in bilayer graphene at $D >> 0$

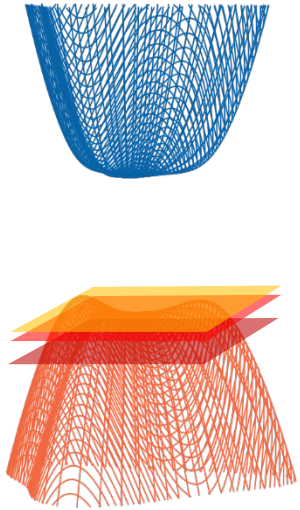


- Lifshitz transitions

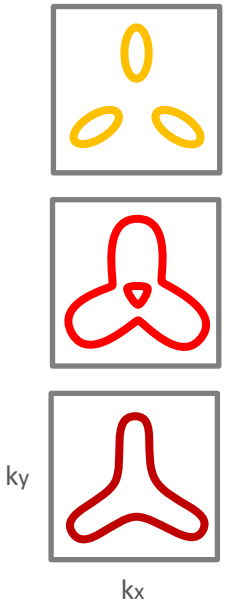
Band structure calculations done by Nils Jacobsen

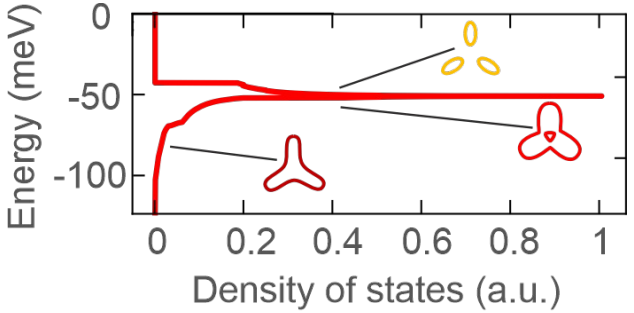
Van Hove singularities in bilayer graphene at $D >> 0$





$D >> 0$

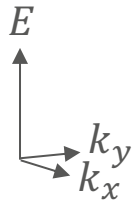


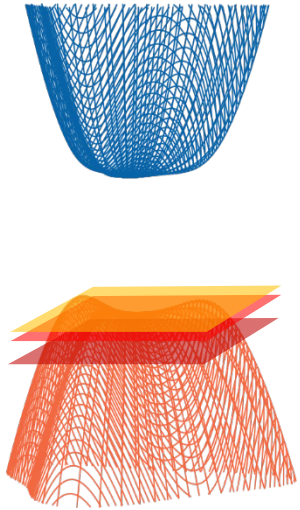


- Lifshitz transitions
- Van Hove singularities

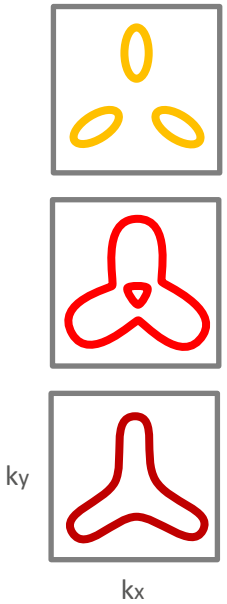
Band structure and DOS calculations done by Nils Jacobsen

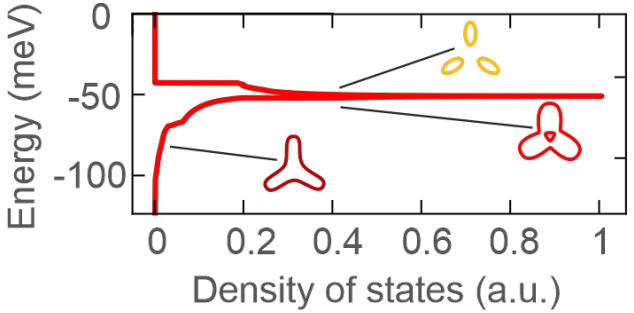
Van Hove singularities in bilayer graphene at $D >> 0$





$D >> 0$



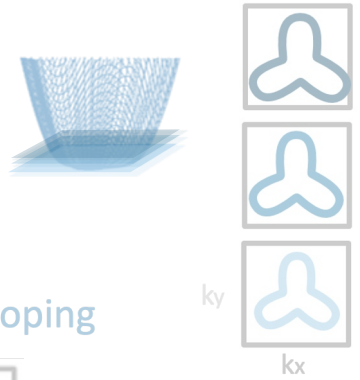


- Lifshitz transitions
- Van Hove singularities
- Interaction effects!

Band structure and DOS calculations done by Nils Jacobsen

Outline

4. Correlated phases at electron-doping



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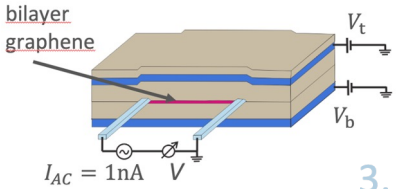
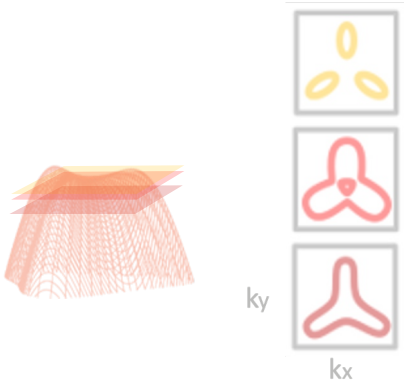
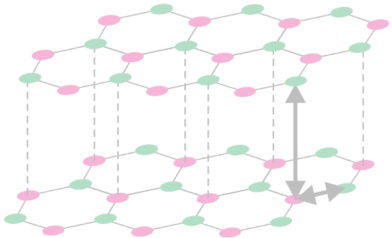


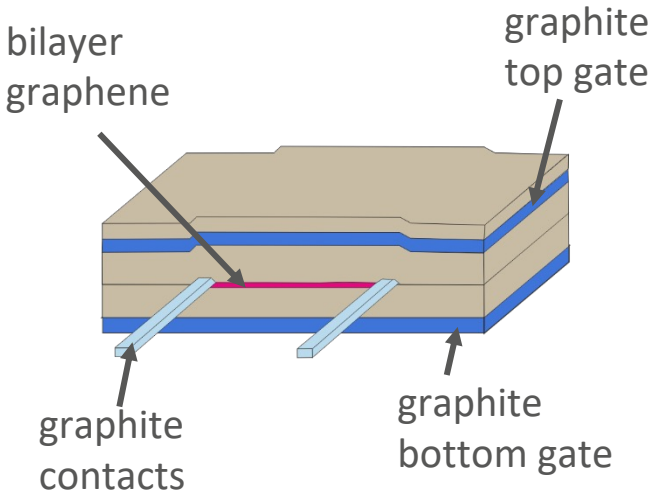
3. Correlated phases at hole-doping



1. Bernal bilayer graphene



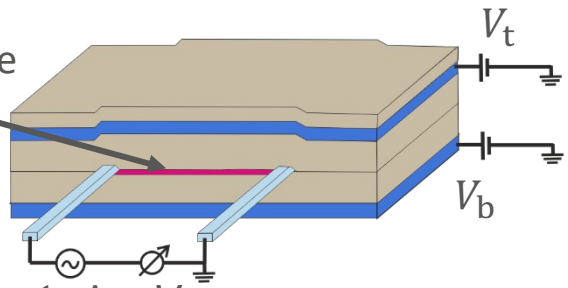
Fabrication of bilayer graphene heterostructures



hexagonal boron nitride (hBN)

Electrical transport measurements

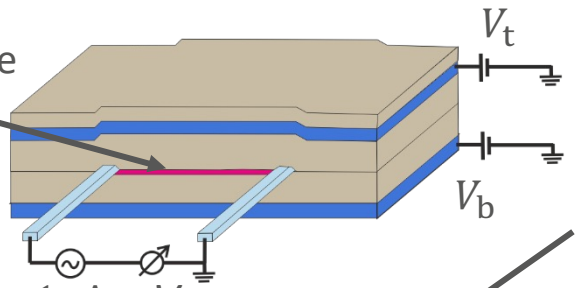
bilayer graphene



$$R = V/I_{AC}$$
$$G = 1/R$$

Electrical transport measurements

bilayer graphene



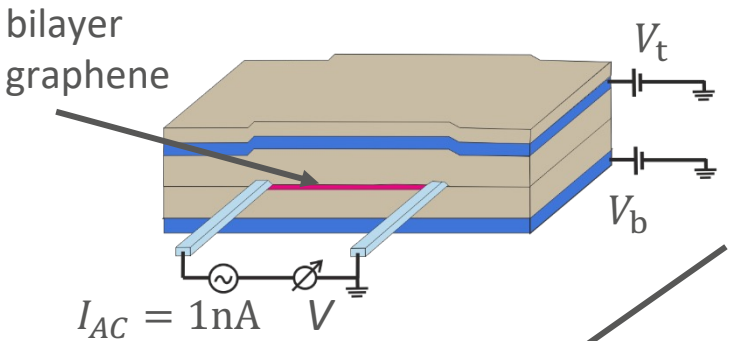
Charge carrier density ~ Fermi energy

$R = V/I_{AC}$
$G = 1/R$

$n \sim V_t + V_b$
$D \sim V_t - V_b$

Electric displacement field

Electrical transport measurements



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Charge carrier density
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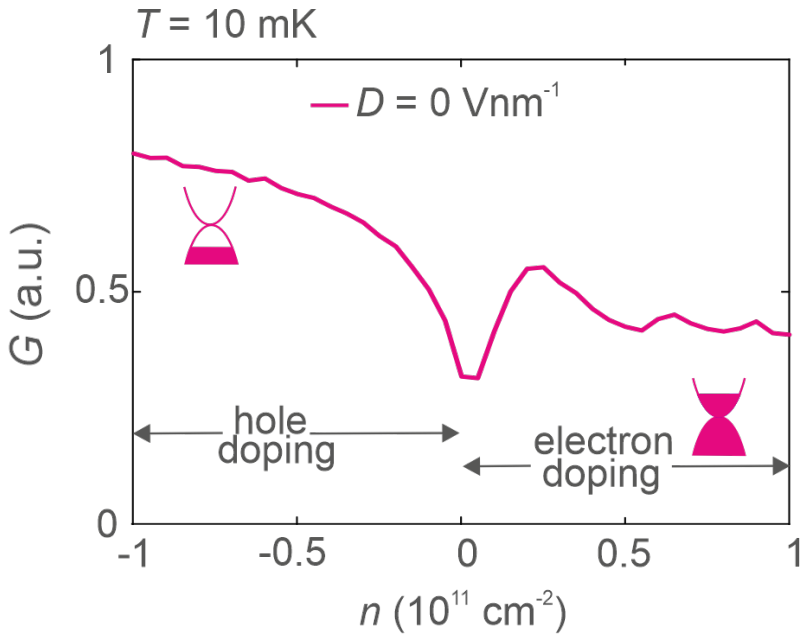
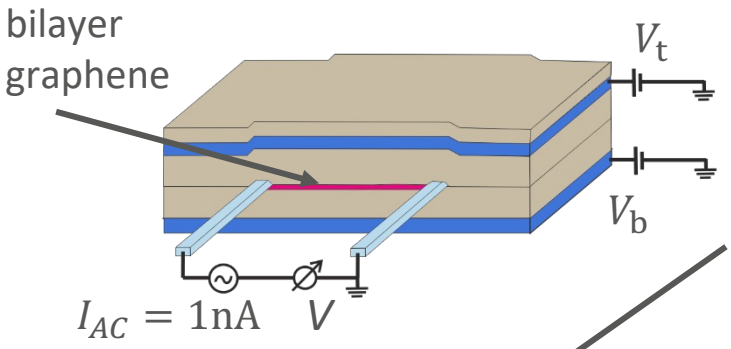
Electric displacement field



Electrical transport measurements



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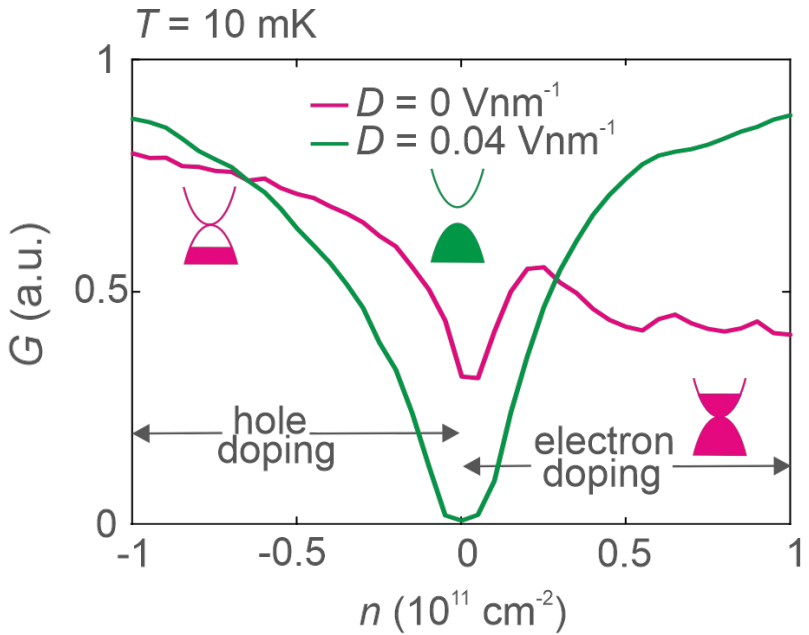
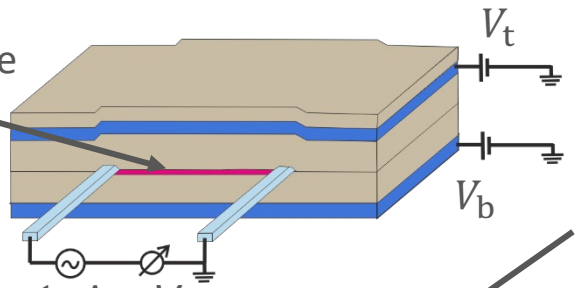


Electrical transport measurements

bilayer graphene



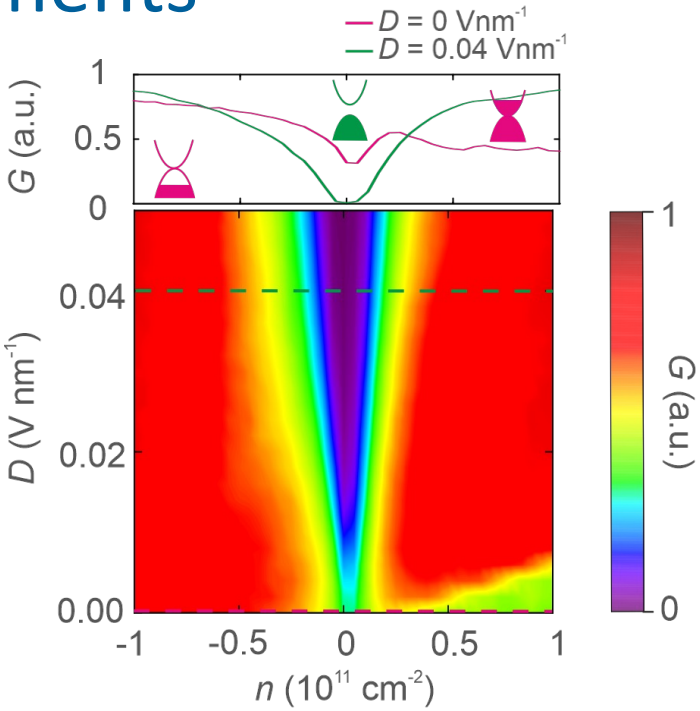
$I_{AC} = 1\text{nA}$ V

$R = V/I_{AC}$
$G = 1/R$

Charge carrier density
~ Fermi energy

$n \sim V_t + V_b$
$D \sim V_t - V_b$

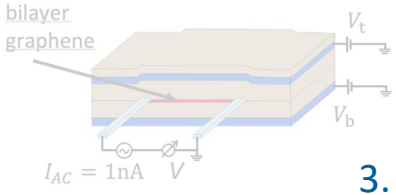
Electric displacement field



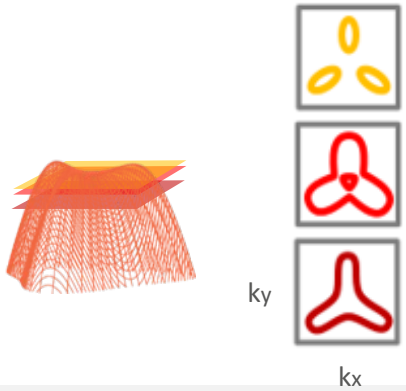
Outline

4. Correlated phases at electron-doping

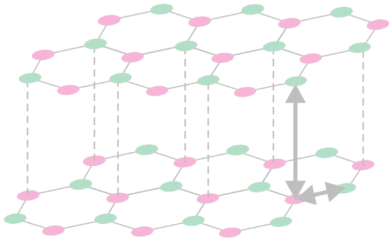
2. Transport measurements



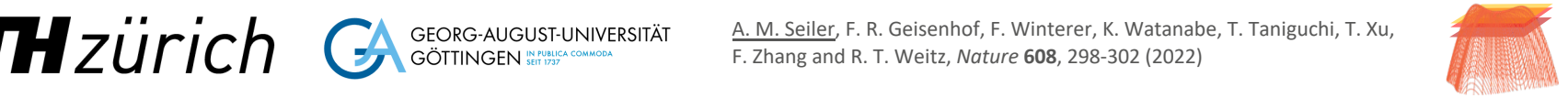
3. Correlated phases at hole-doping



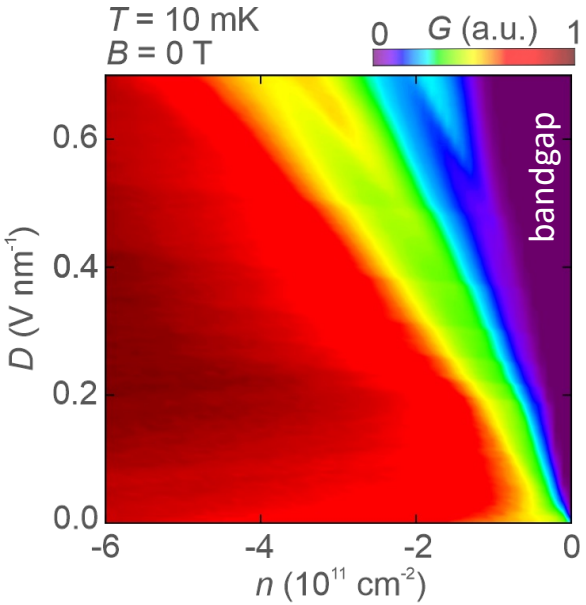
1. Bernal bilayer graphene



A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)



Correlated phases in hole-doped bilayer graphene



A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

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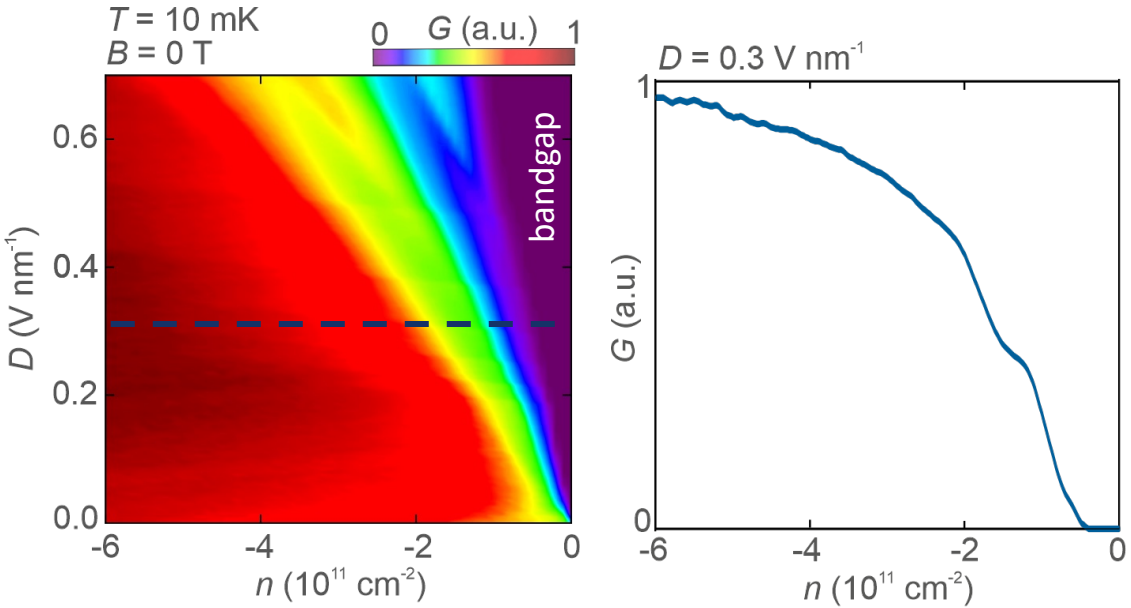

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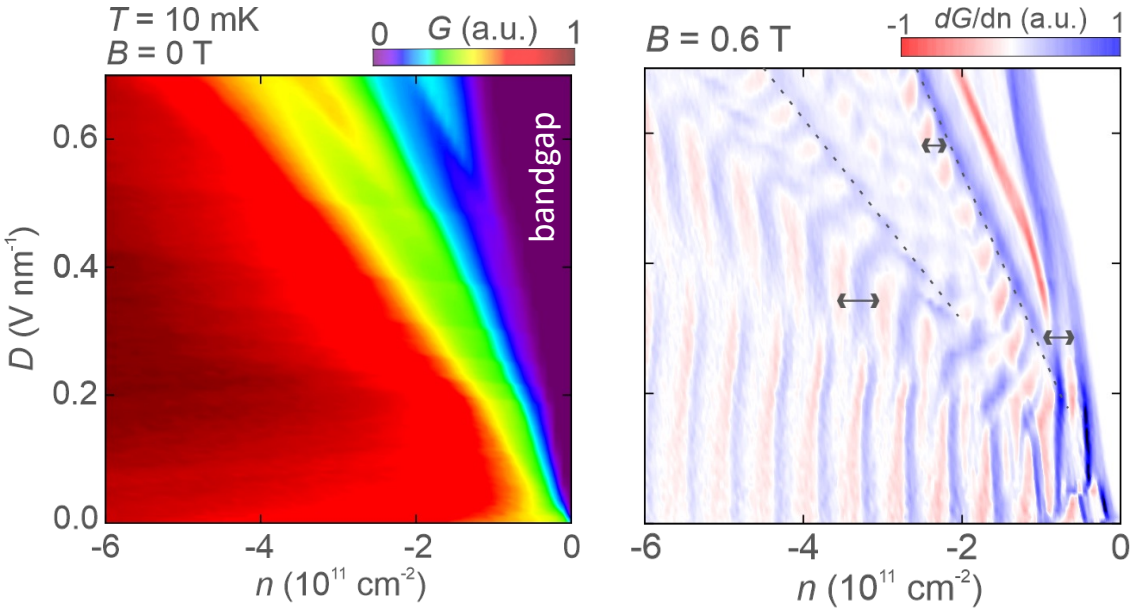

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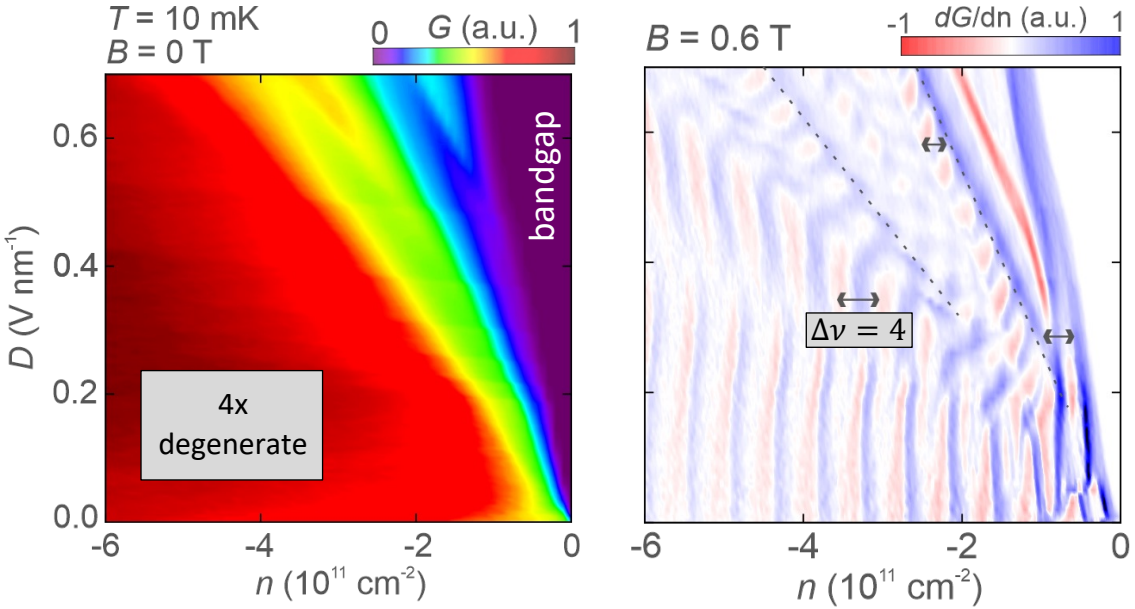
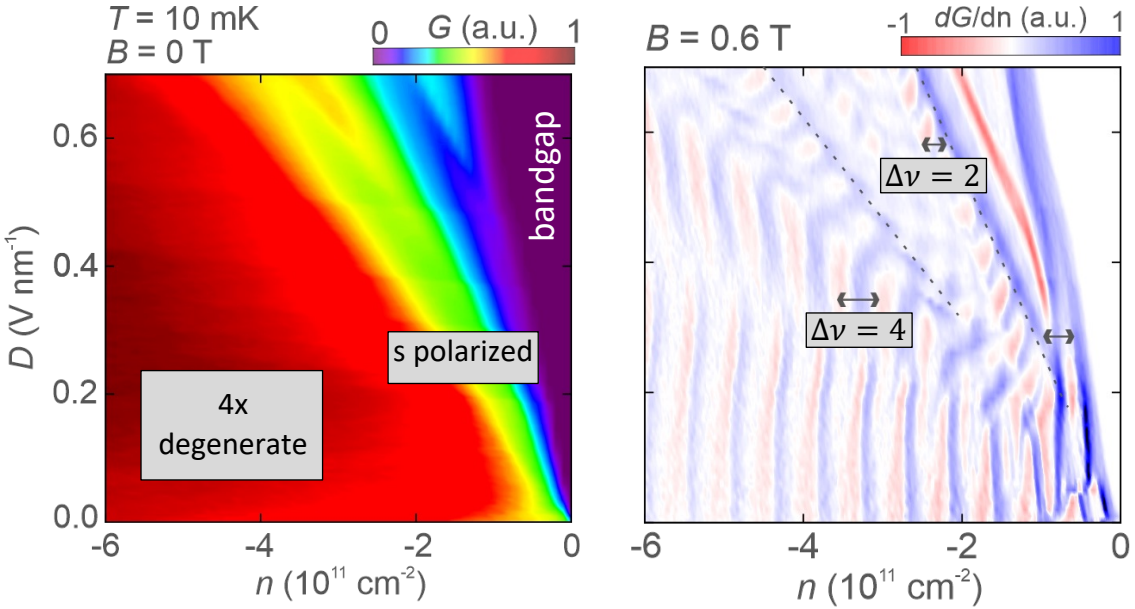
Correlated phases in hole-doped bilayer graphene



- 4x degenerate/ non-polarized phase -> full metal

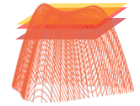
A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

Correlated phases in hole-doped bilayer graphene

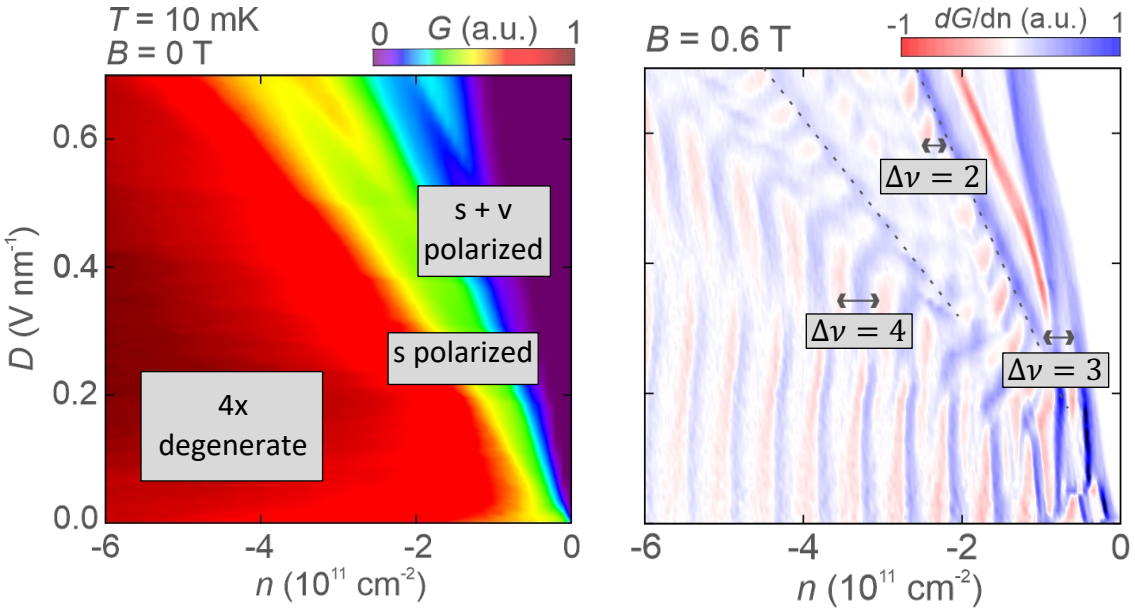


- 4x degenerate/ non-polarized phase -> full metal
- Spin (s) polarized phase -> Stoner half metal

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

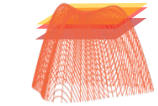


Correlated phases in hole-doped bilayer graphene

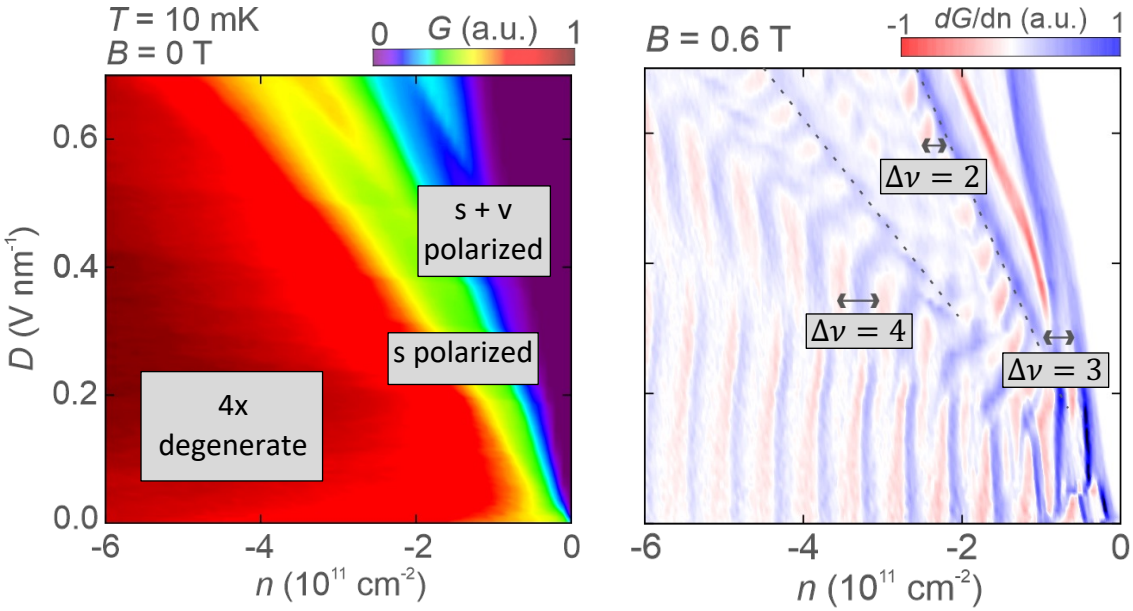


- 4x degenerate/ non-polarized phase -> full metal
- Spin (s) polarized phase -> Stoner half metal
- Spin (s) and valley (v) polarized phase -> Stoner quarter metal

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)



Correlated phases in hole-doped bilayer graphene



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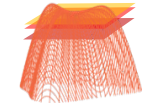
- Spin (s) and valley (v) polarized phase -> Stoner quarter metal

Consistent with

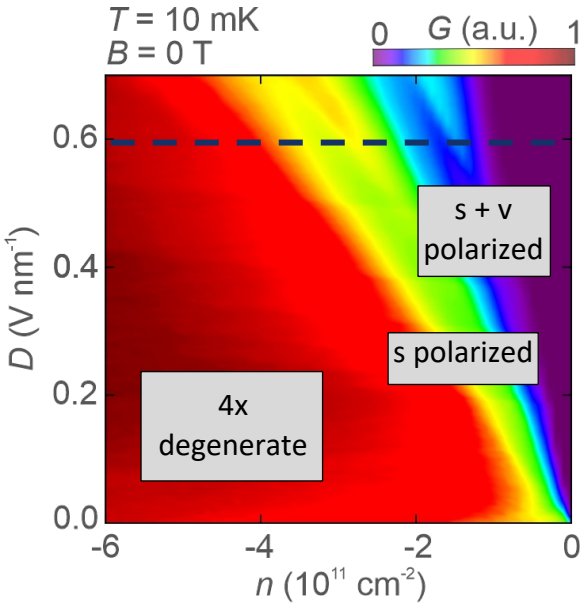
H. Zhou et al., *Science* **375**, 6582 (2022)

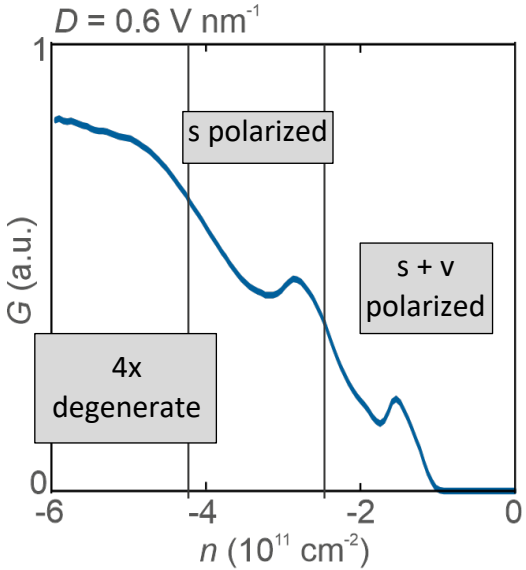
S. C. de la Barrera et al., *Nature Physics* **18**, 771-775 (2022)

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)



Correlated phases beyond Stoner physics





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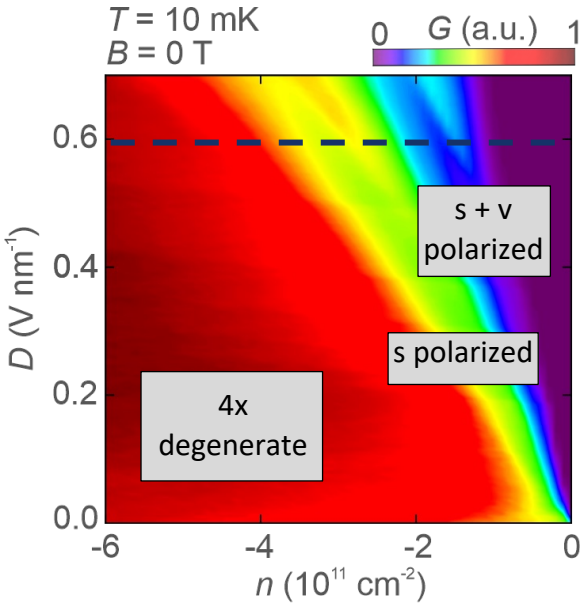
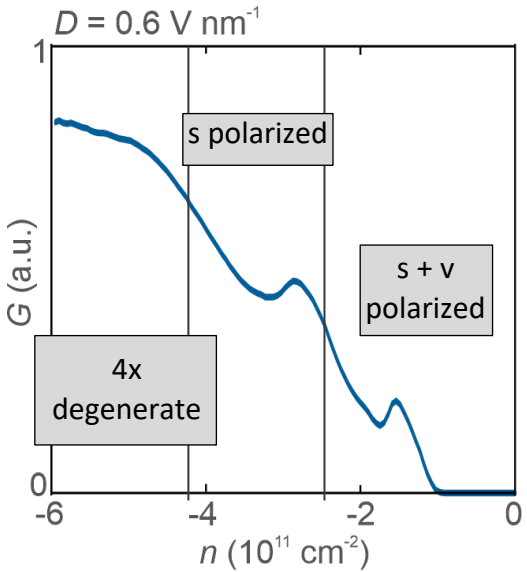
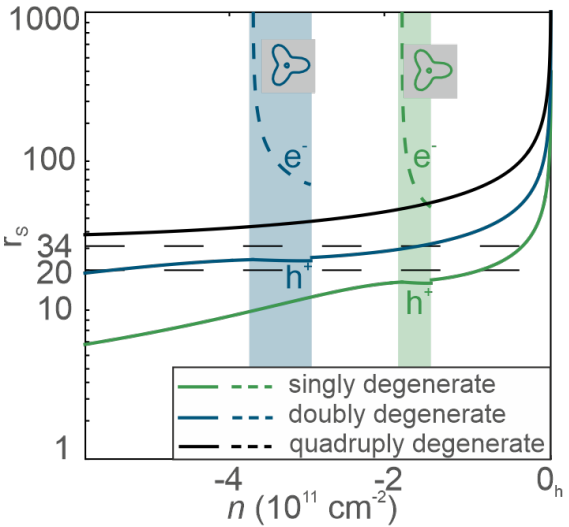
Correlated phases beyond Stoner physics





Theory:



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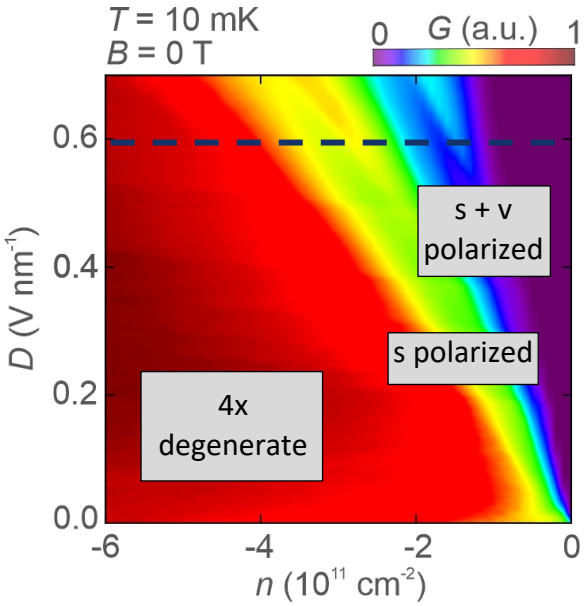
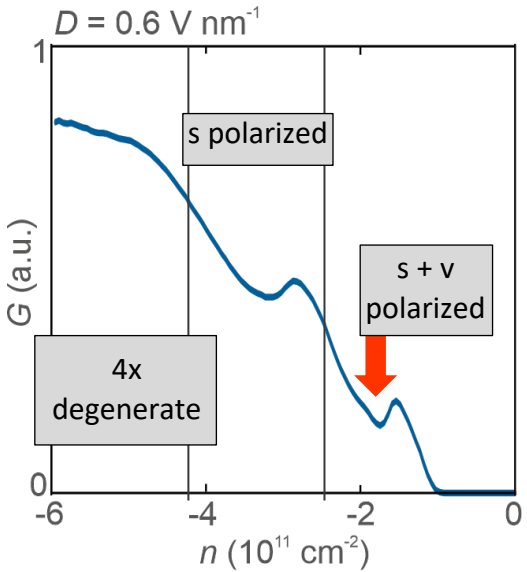
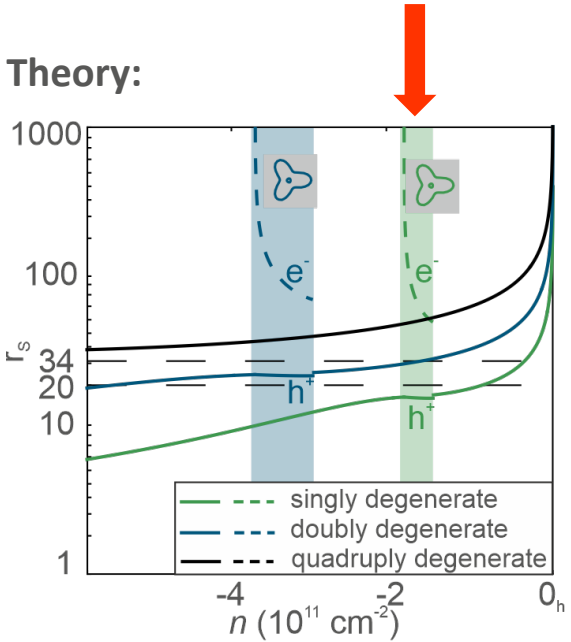
Correlated phases beyond Stoner physics







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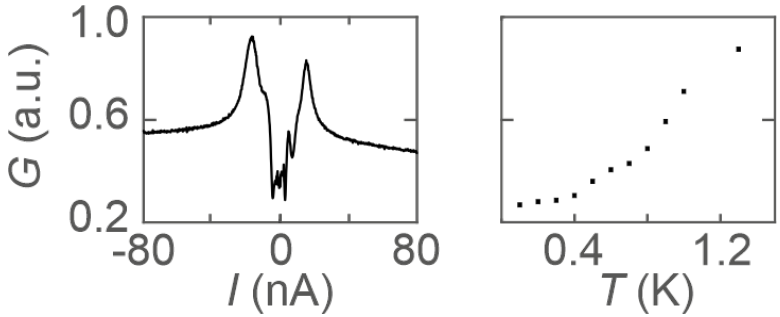
Insulating phase at $B = 0$ T



- Non-linear bias-current dependence
- Insulating temperature dependence

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

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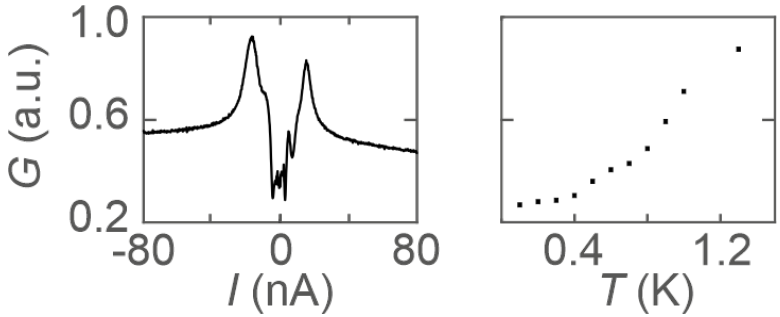
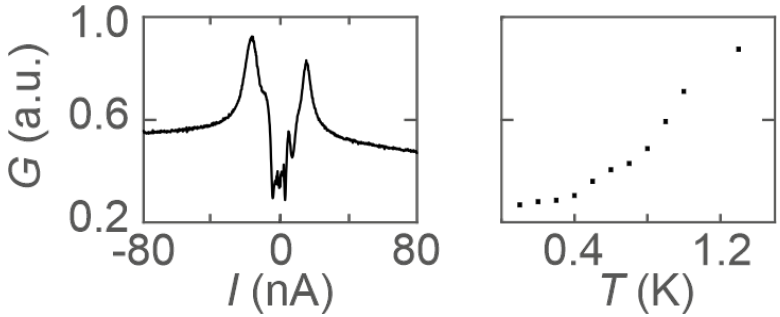


- Non-linear bias-current dependence
- Insulating temperature dependence

➡ **Consistent with Wigner crystal**

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

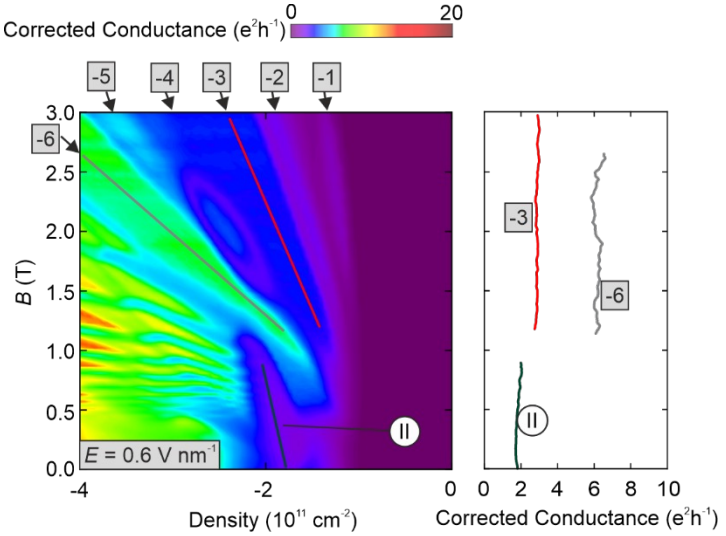
Insulating phase at B = 0 T



- Non-linear bias-current dependence
- Insulating temperature dependence

Consistent with Wigner crystal

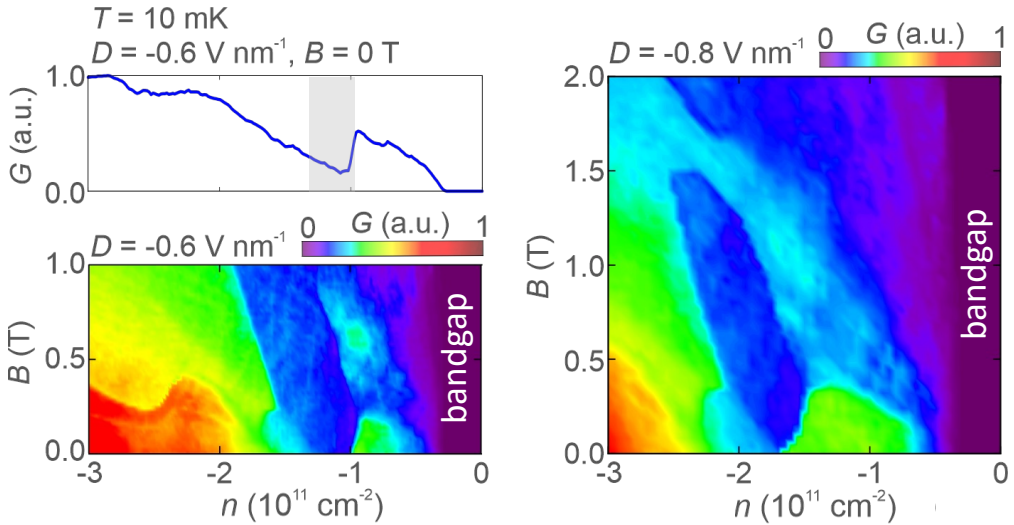
D = 0.6 V/nm



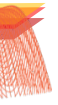
$G \approx 2e^2/h$

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

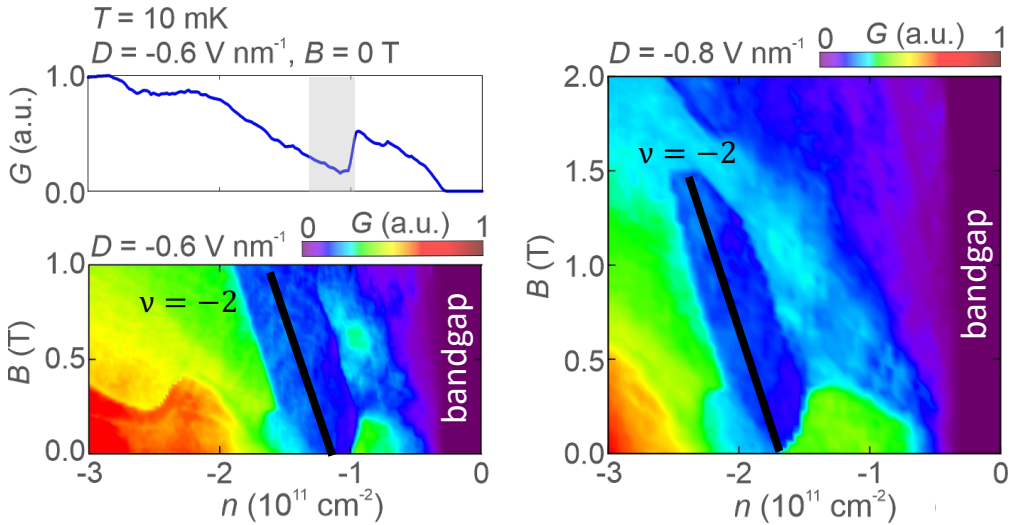
Applying an out-of-plane magnetic field



A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

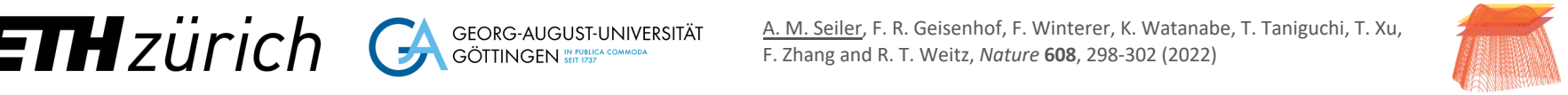


Applying an out-of-plane magnetic field



- Slope in the magnetic field (ν= -2)

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)



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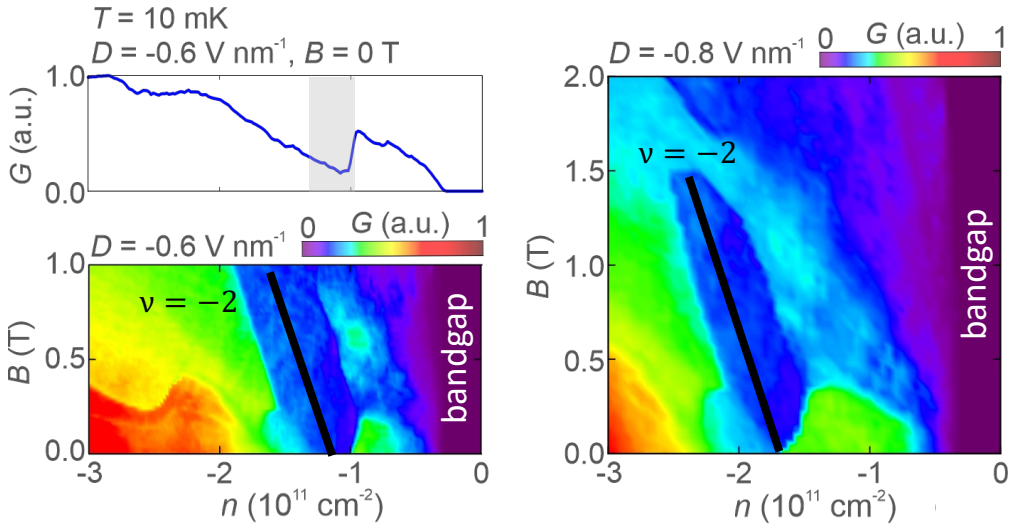
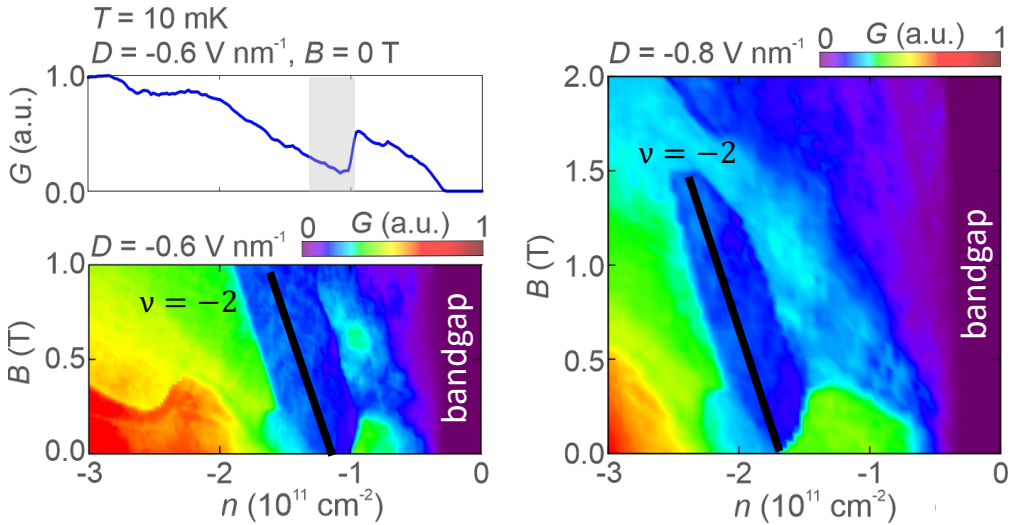


- Slope in the magnetic field (ν= -2)
- Starts at finite density
- No moiré pattern

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)

Applying an out-of-plane magnetic field



- Slope in the magnetic field (ν= -2)
- Starts at finite density
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→ **Consistent with a Wigner Hall crystal**

See also:

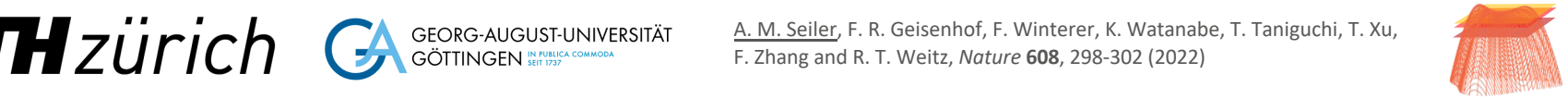
Z.Tešanović, Françoise Axel, and B. I. Halperin, *Phys. Rev. B* **39**, 8525 (1989)

J. Dong et al., arXiv:2311.05568 (2023)

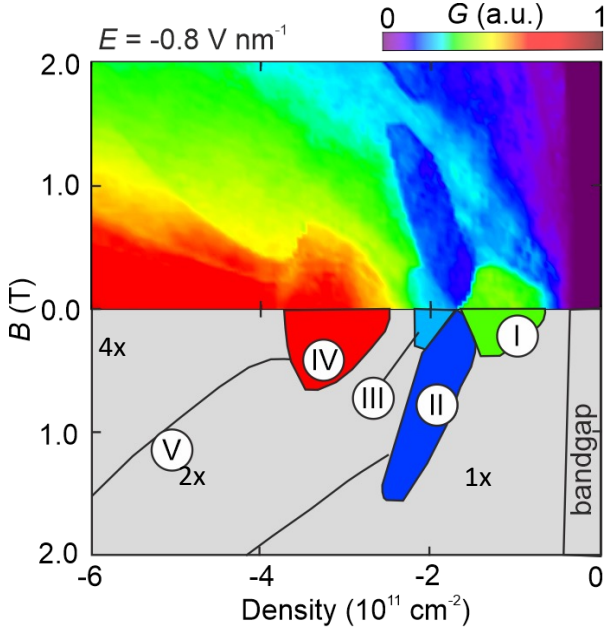
B. Zhou et al., arXiv:2311.04217 (2023)

Z. Lu et al., *Nature* **626**, 759–764 (2024)

A. M. Seiler, F. R. Geisenhof, F. Winterer, K. Watanabe, T. Taniguchi, T. Xu, F. Zhang and R. T. Weitz, *Nature* **608**, 298-302 (2022)



Cascade of correlated phases

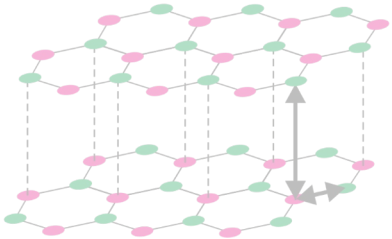


More correlated phases including:

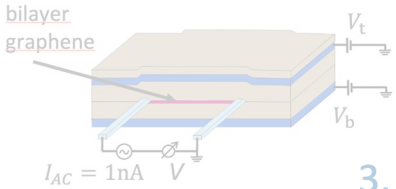
- Correlated metals
- Topologically-trivial correlated insulator

Outline

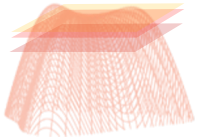
1. Bernal bilayer graphene



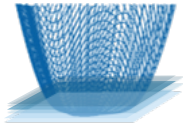
2. Transport measurements



3. Correlated phases at hole-doping



4. Correlated phases at electron-doping



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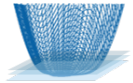
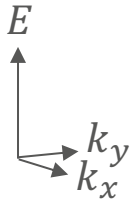
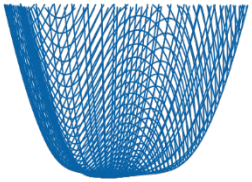
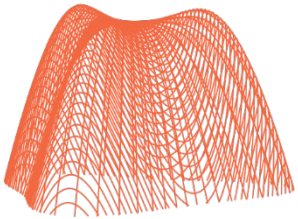


Trigonal warping in the conduction band







$D >> 0$

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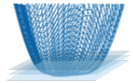
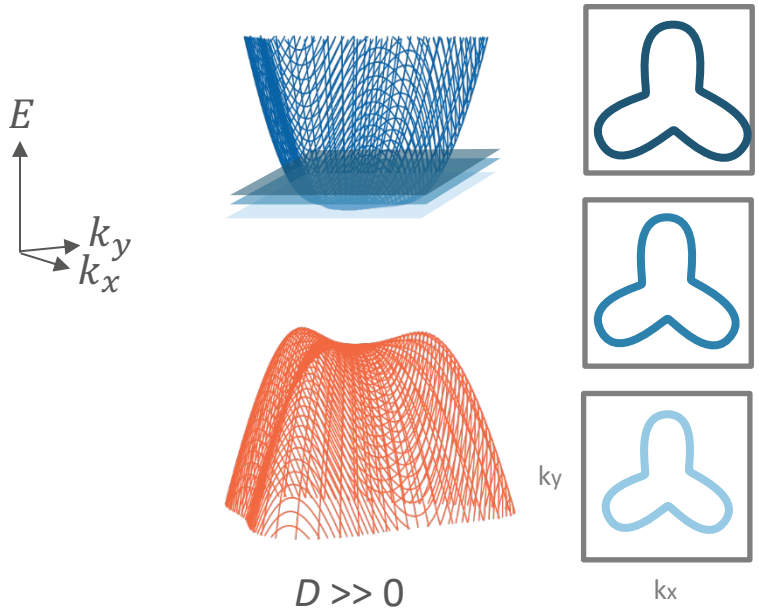


Trigonal warping in the conduction band



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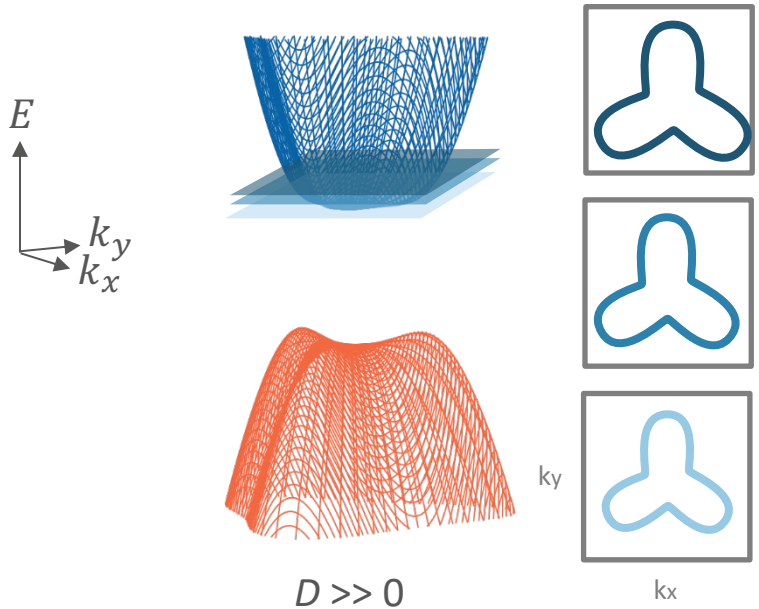

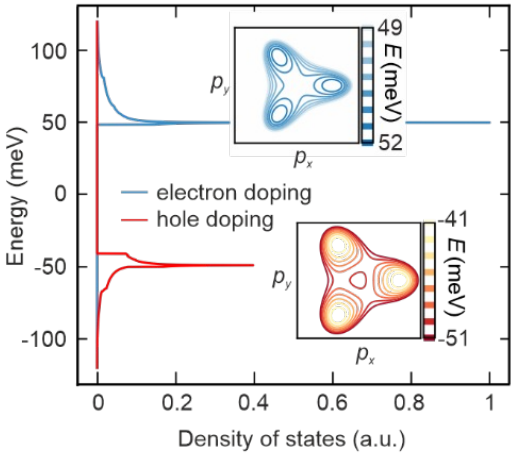

- Flat bands
- Van Hove singularity at the band edge
- High DOS

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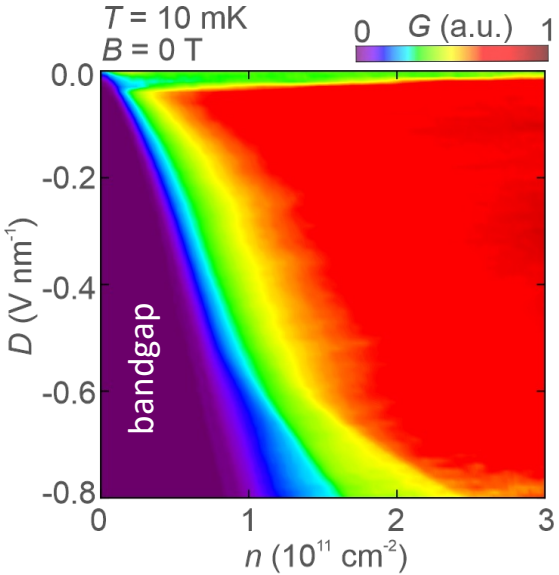
Correlated phases in electron-doped bilayer graphene



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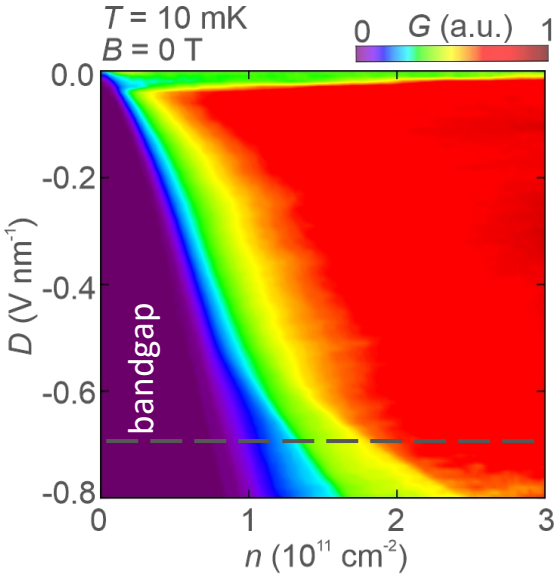

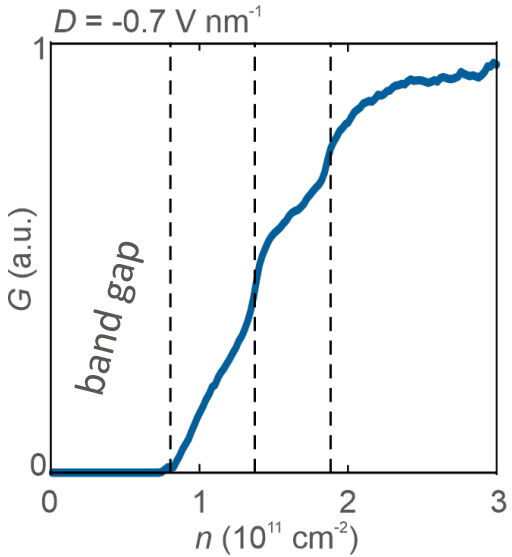

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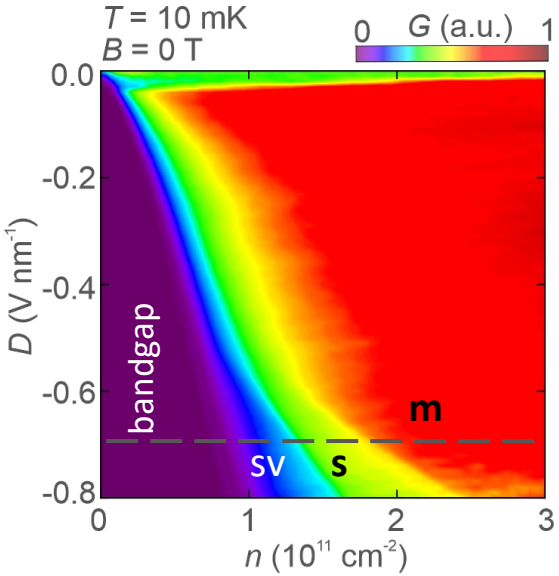

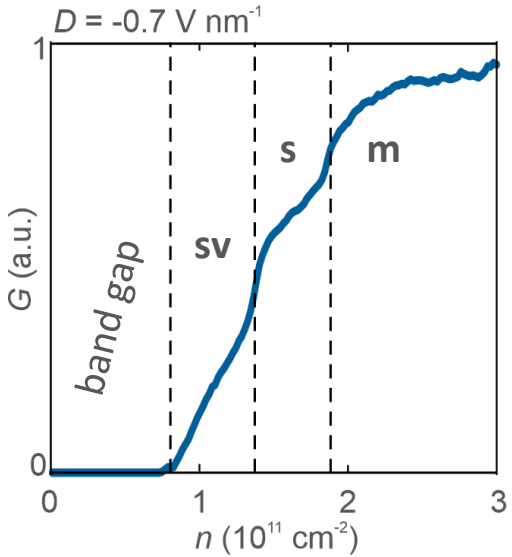

sv: spin and valley polarized

s: spin polarized

m: four-fold degenerate (not polarized)

Consistent with S. C. de la Barrera et al., *Nature Physics* **18**, 771-775 (2022)

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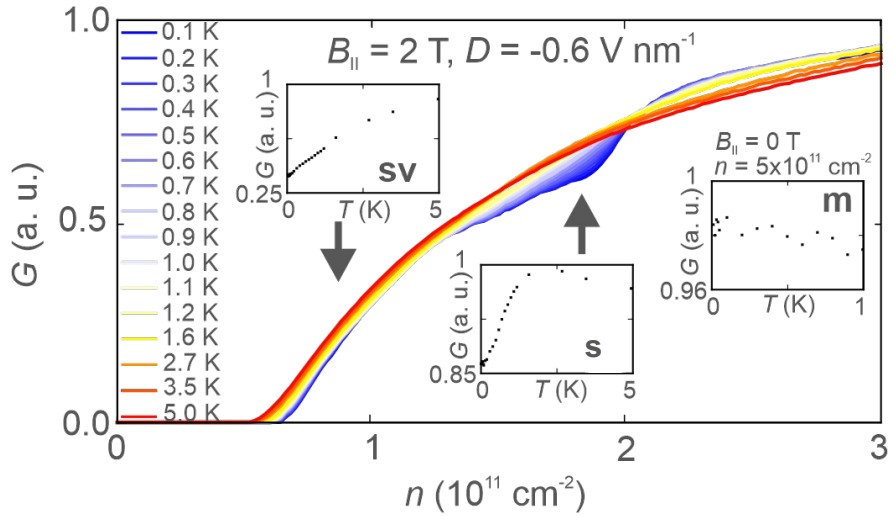
Insulating temperature dependence



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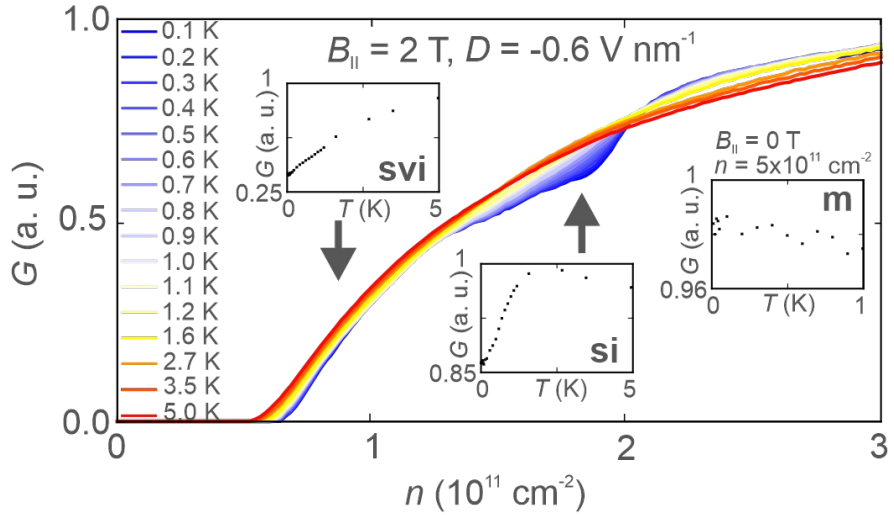

svi: spin and valley polarized (quasi-) insulator

si: spin polarized (quasi-) insulator

m: metal

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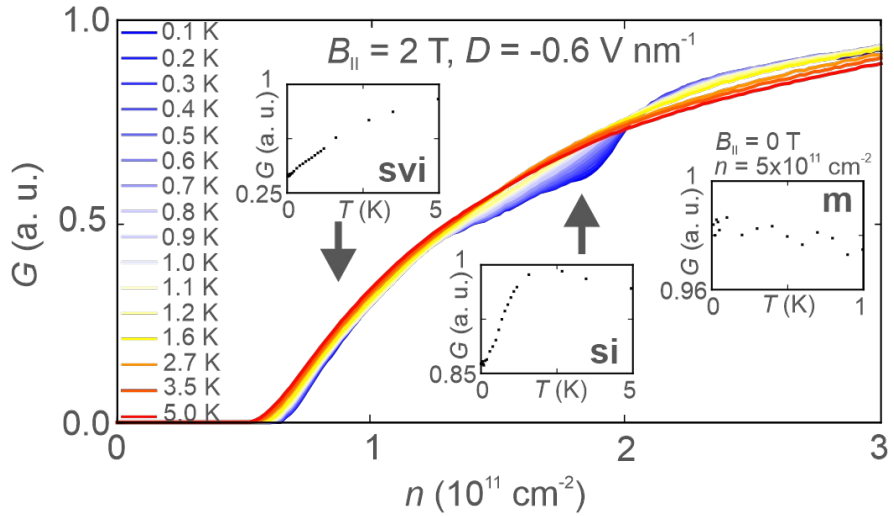

svi: spin and valley polarized (quasi-) insulator

si: spin polarized (quasi-) insulator

m: metal

Consistent with a charge density wave or Wigner crystal

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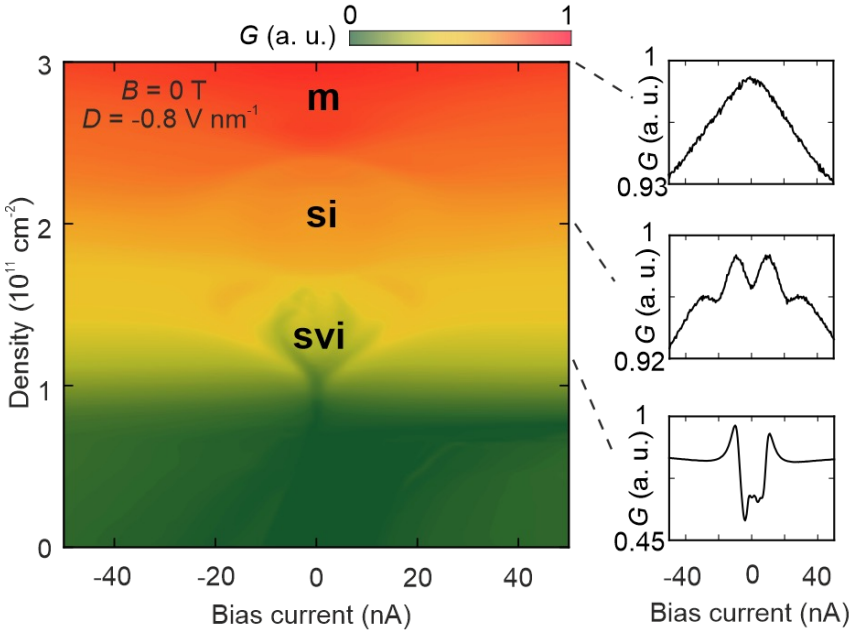
Non-linear bias current



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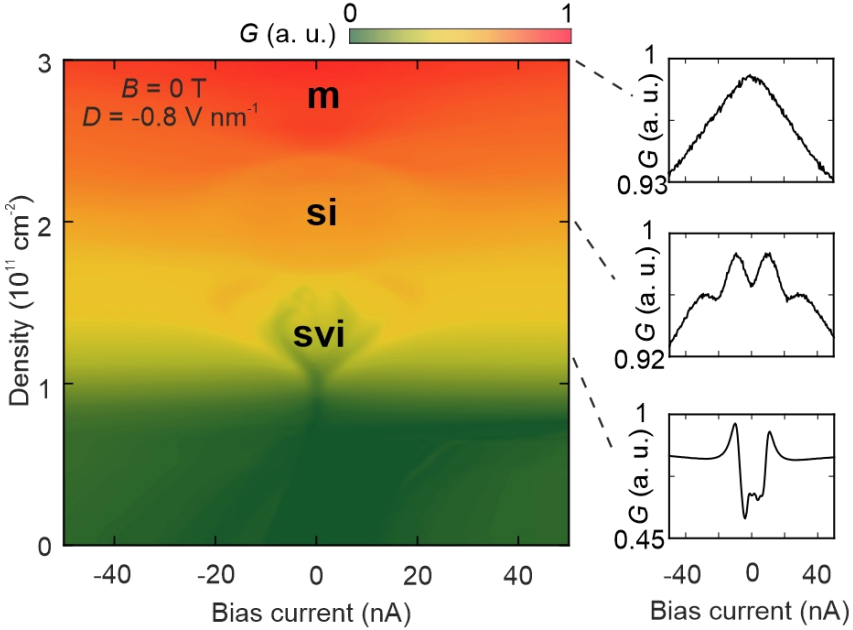
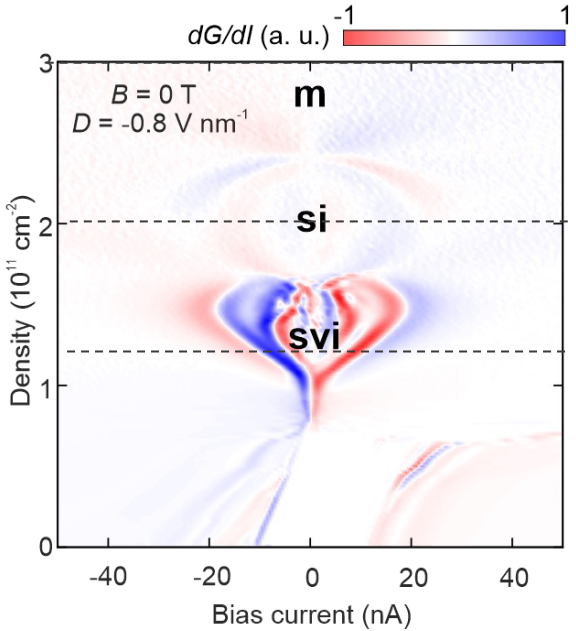
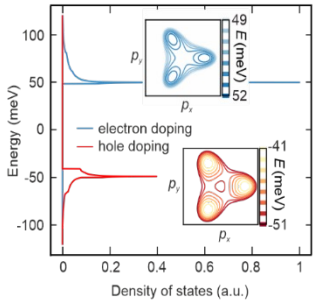


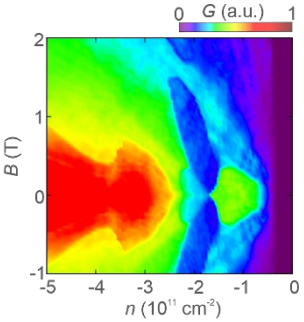


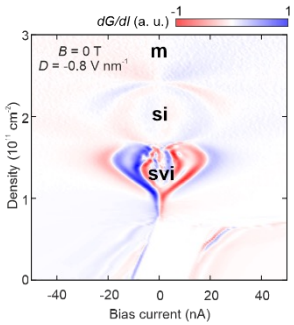
Summary

Cascade of correlated phases in hole- and electron-doped bilayer graphene

- One correlated insulating state is consistent with a Wigner Hall crystal state
- Strong electron-hole asymmetry







Nat. Commun. **15**, 3133 (2024)
Nature **608**, 298-302 (2022)
arXiv:2308.00827 (2023)

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