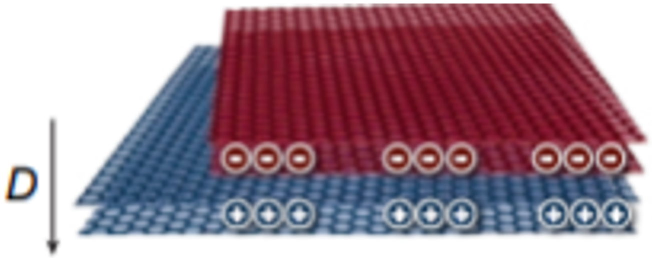

Density-Wave States in Twisted Double-Bilayer Graphene

Peter Rickhaus,[1,*] Folkert K. de Vries,[1] Jihang Zhu,[2] Elías Portolés,[1] Giulia Zheng,[1] Michele Masseroni,[1] Annika Kurzmann,[1] Takashi Taniguchi,[3] Kenji Wantanabe,[3] Allan H. MacDonald,[2] Thomas Ihn,[1] and Klaus Ensslin[1]

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(Dated: May 20, 2020)

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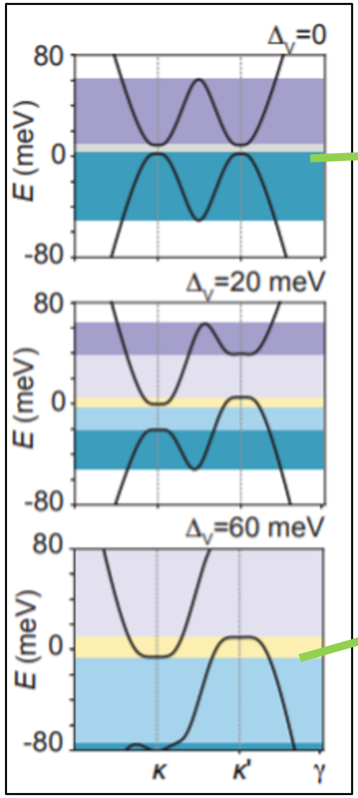
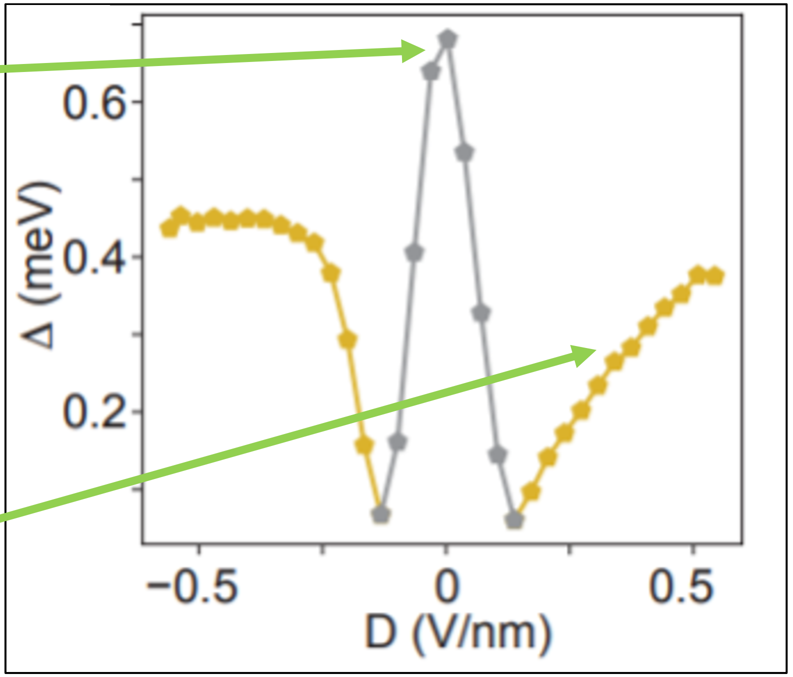
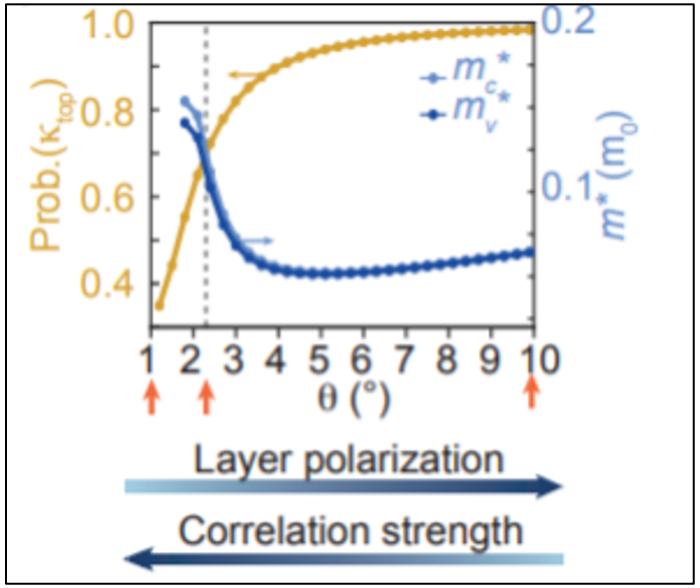
Results



Δ_V=0
80
0
-80
E (meV)
Δ_V=20 meV
Δ_V=60 meV
κ
κ'
γ



0.6
0.4
0.2
Δ (meV)
−0.5
0
0.5
D (V/nm)

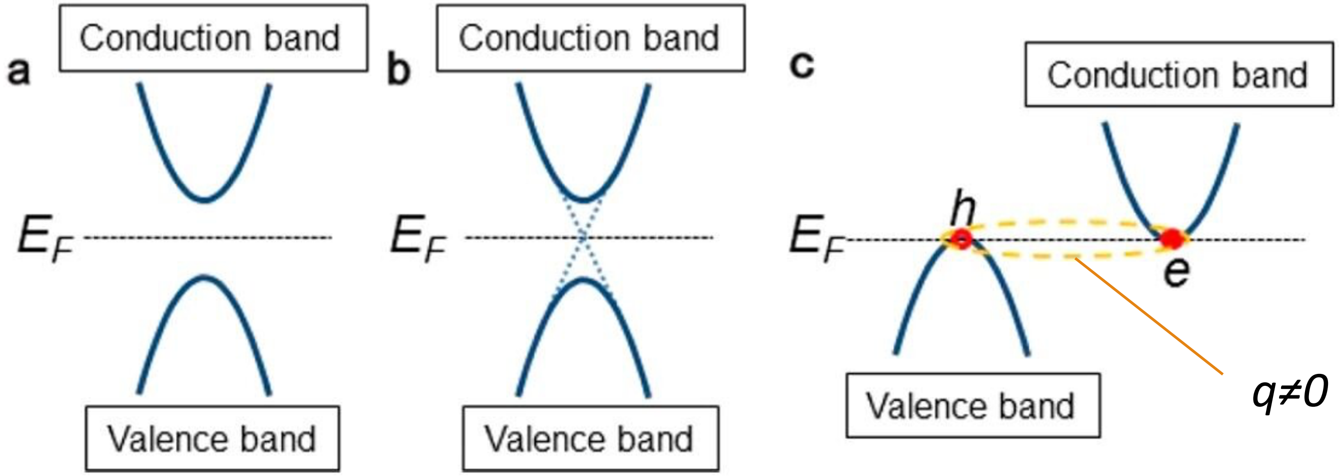


1.0
0.8
0.6
0.4
Prob.(κ_top)
0.2
0.1
m* (m_0)
m_c*
m_v*
1 2 3 4 5 6 7 8 9 10
θ (°)
Layer polarization
Correlation strength

Outline

- Background on excitonic insulators and twisted 2D heterostructures
- Methods and sample preparation
- Appearance of a gap with displacement field
- Effects of magnetic fields
- Open questions

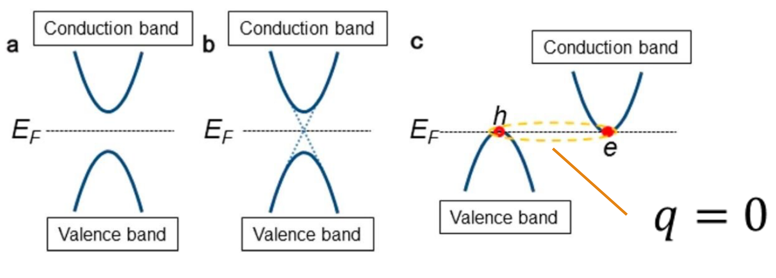
Excitonic insulators



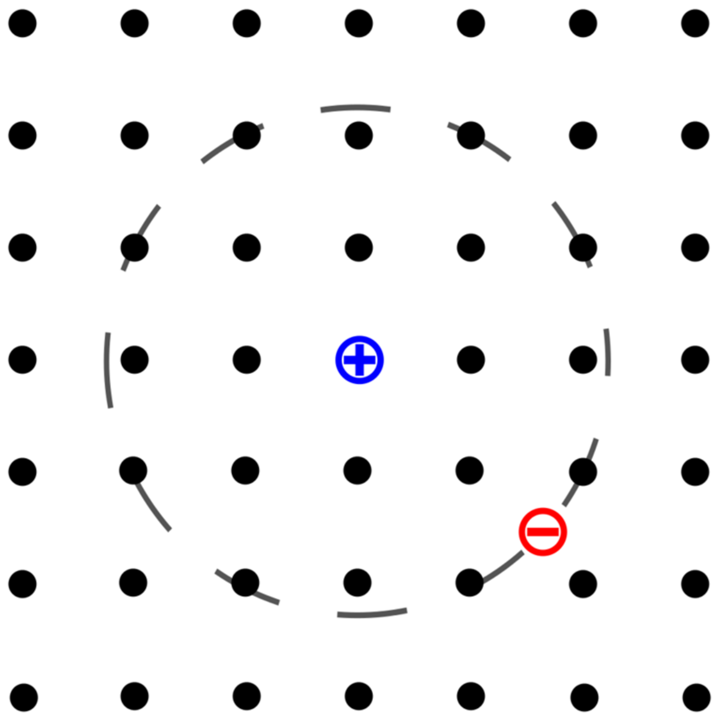
Zhi Li et al, *Possible Excitonic Insulating Phase in Quantum-Confined Sb Nanoflakes*

- Interaction between electrons/holes in conducting/valence bands
- Correlated wave function formed analogous to superconductors (or Peierl's transition)
- Band nesting → strong coherence

Excitonic insulators



Zhi Li et al, *Possible Excitonic Insulating Phase in Quantum-Confined Sb Nanoflakes*



Wannier-Mott exciton

$$\epsilon_b = \frac{\mu^*}{m_e}\frac{1}{\epsilon^2}\text{Ryd},$$

$$a_b = \frac{m_e}{\mu^*}\epsilon a_B,$$

$$\mu^* = \frac{m_e^* m_h^*}{m_e^* + m_h^*}$$

*Length scale of excitons much larger than lattice

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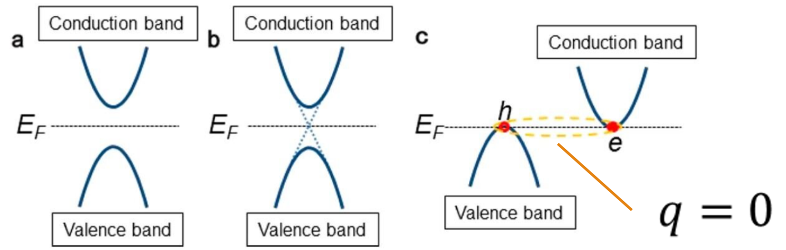
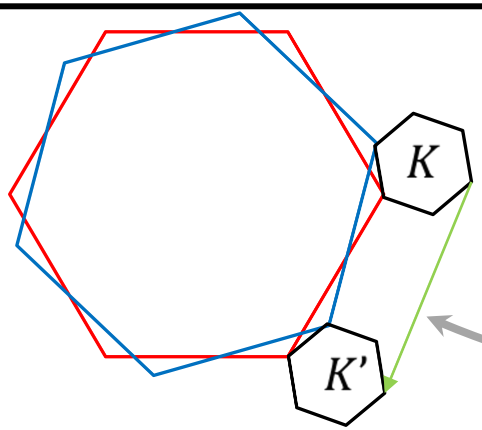
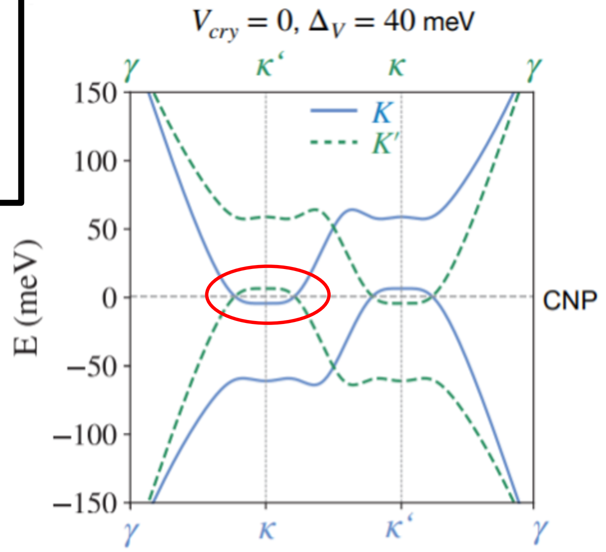
Excitonic insulators

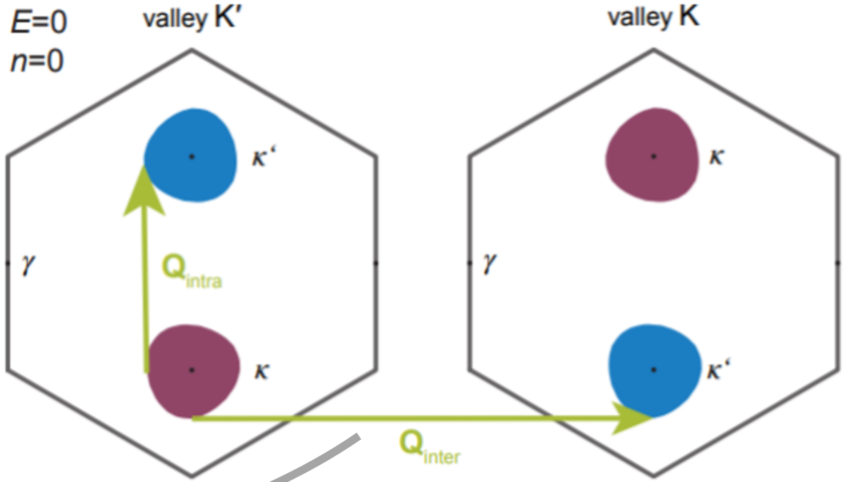


Zhi Li et al, *Possible Excitonic Insulating Phase in Quantum-Confined Sb Nanoflakes*

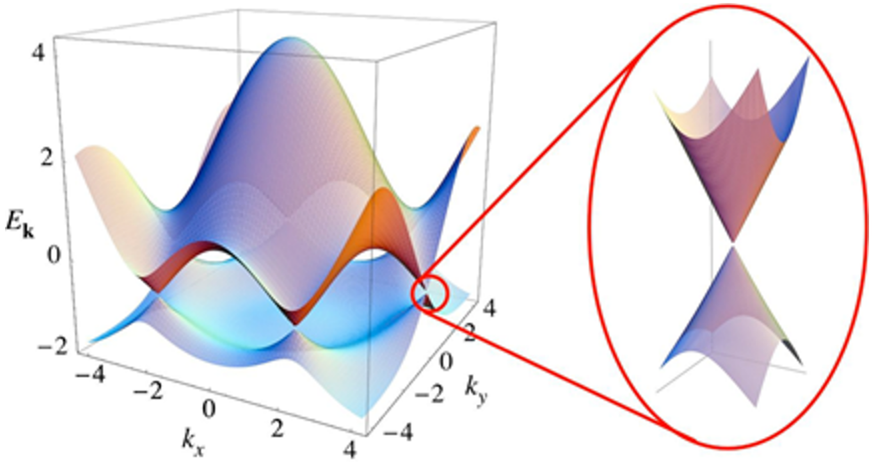


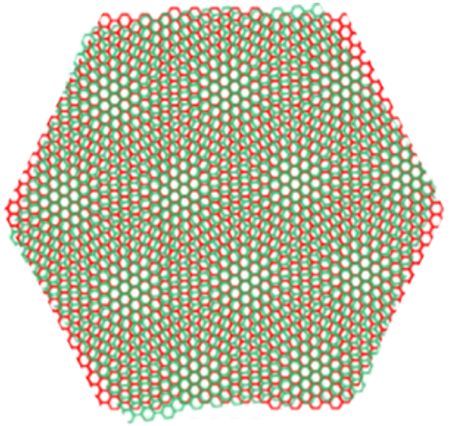
Nested Fermi surfaces lead to strongest correlations
→ DW state correlated by Q_{inter}

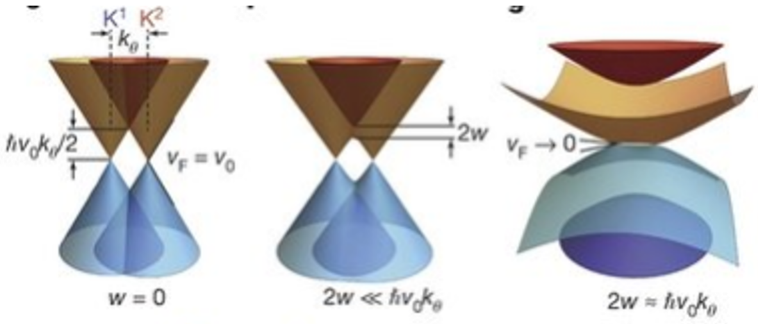


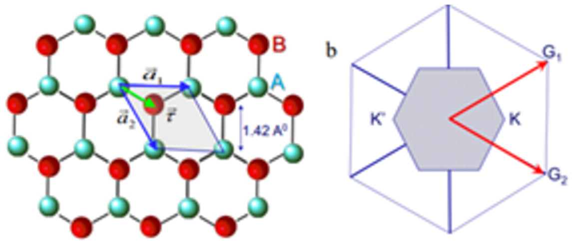


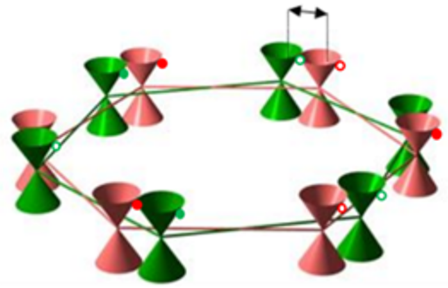
Twisted bilayer graphene



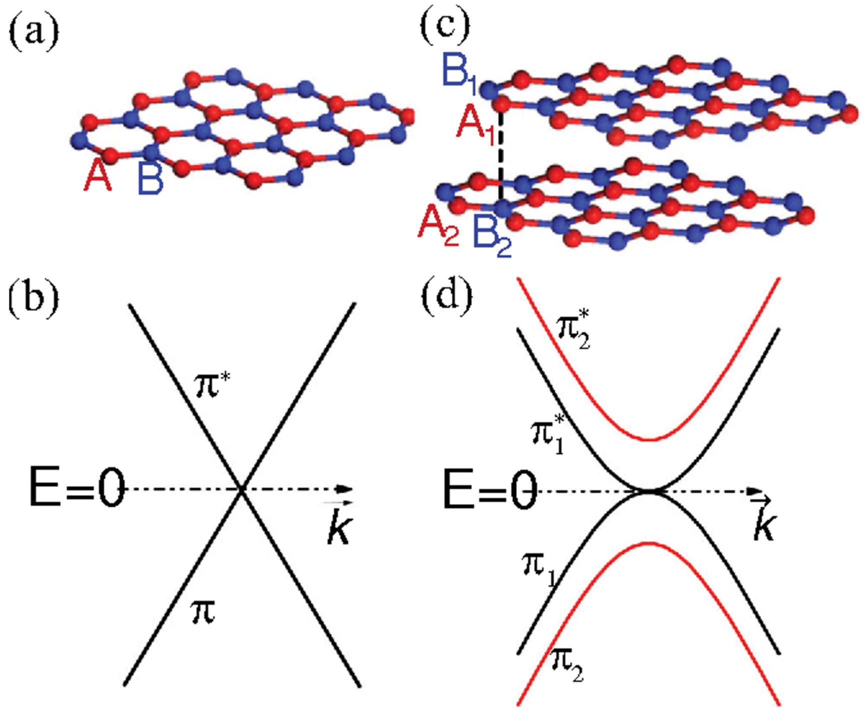


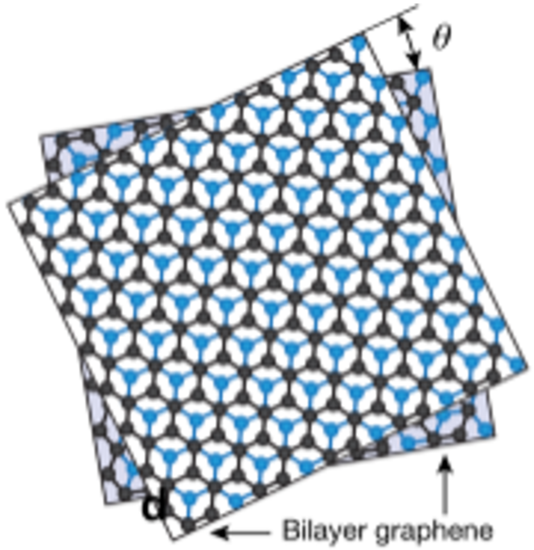


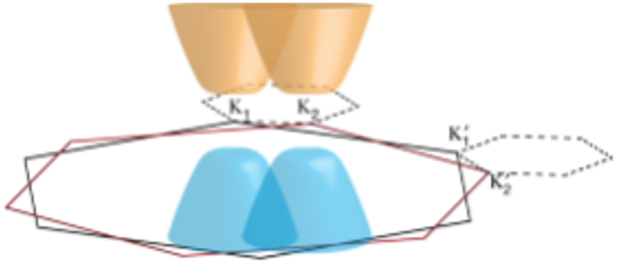




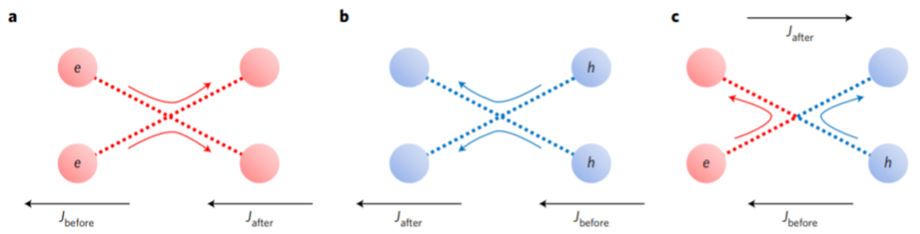
Twisted double bilayer graphene





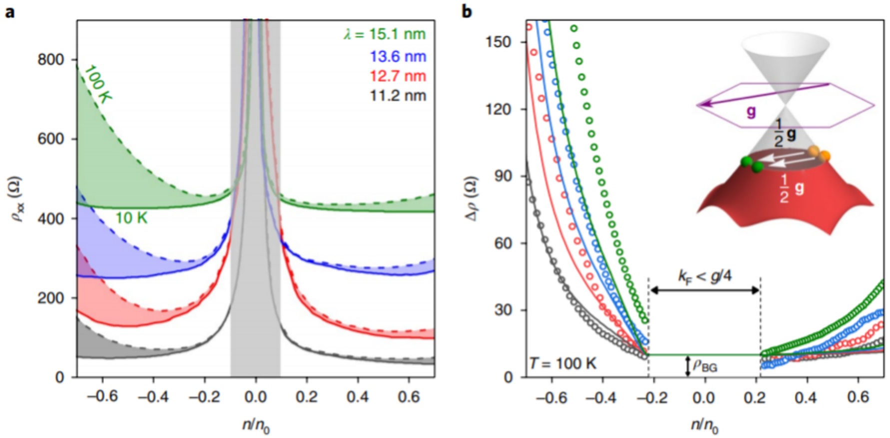


Scattering processes

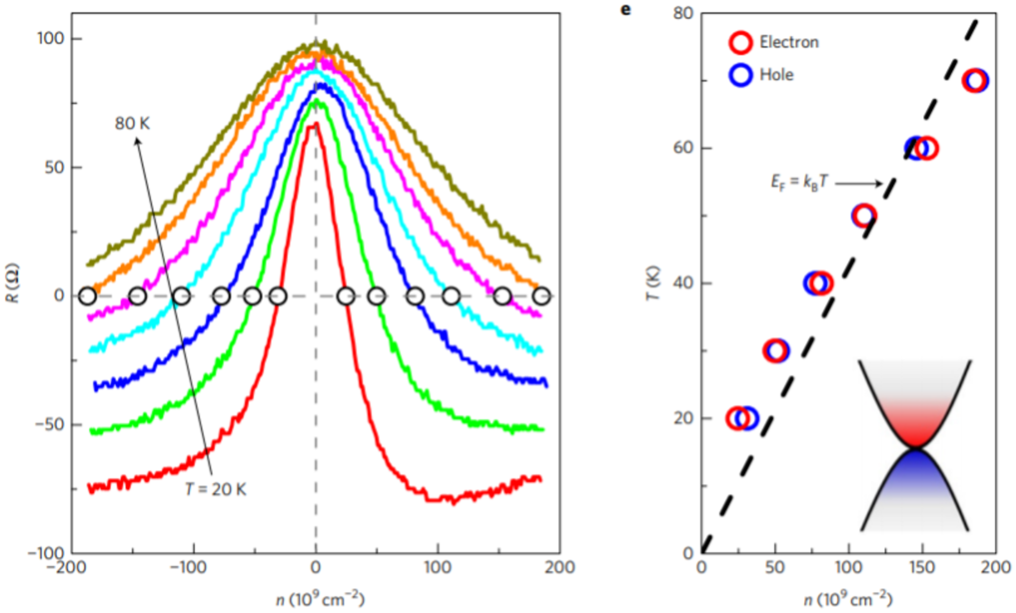


Umklapp scattering in e-e or h-h interactions

Carrier-phonon interactions



$E_F<k_BT$ near charge neutrality



Limits on current due to scattering processes between electrons and holes (Relaxation of relative momentum)

Outline

- Background on excitonic insulators and twisted 2D heterostructures
- Methods and sample preparation
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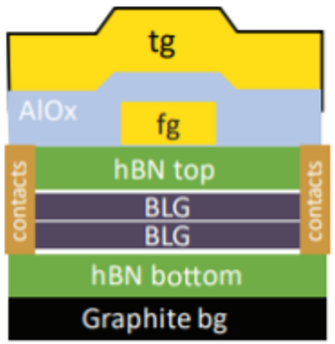
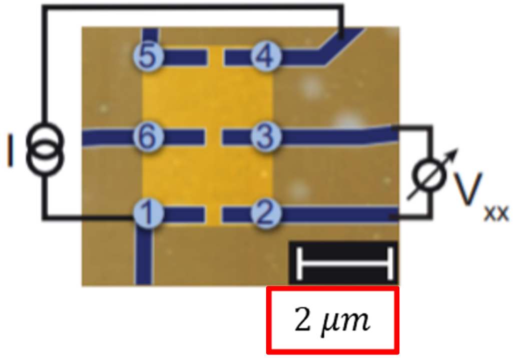
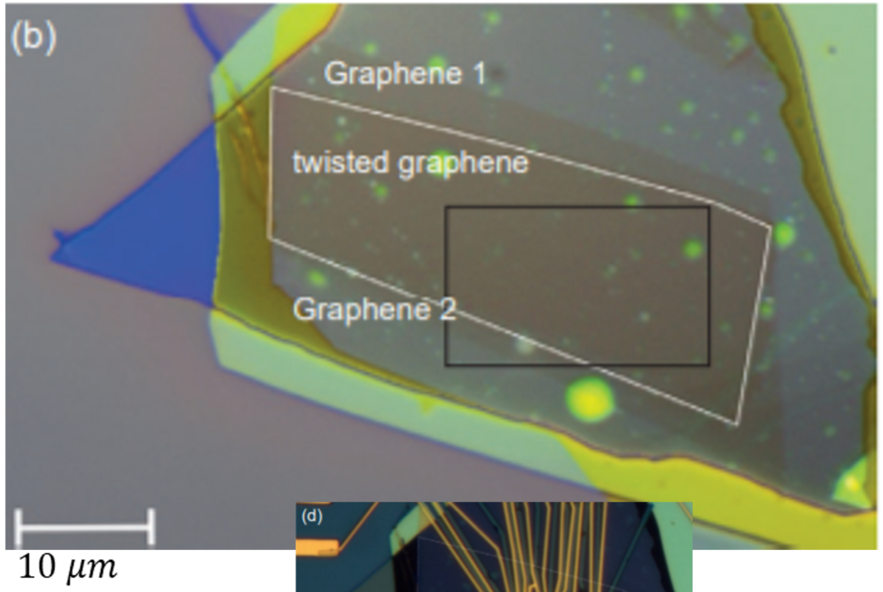
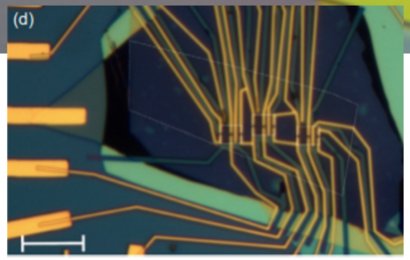
Device design



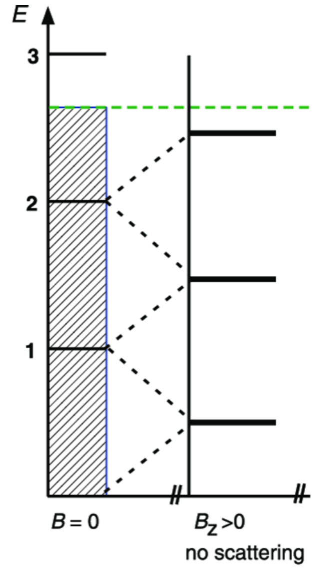


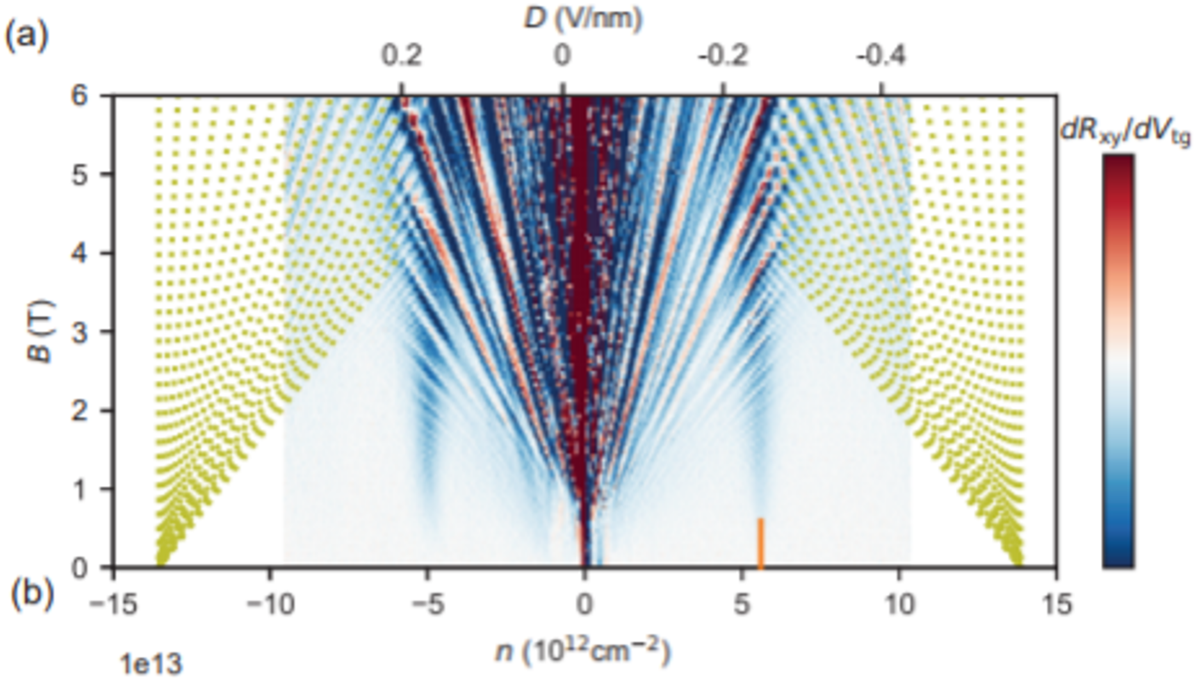




- Three twist angles: 1.2°, 2.37°, and 10°
- Tear-and-stack technique for double bilayer
- 3 sets of leads attached to the same device
  - All measurements done at 100mK
  - $R_{xx} = \frac{V_{23}}{I_{14}}$ where I_{14} is an AC current

Identifying twist angle





Tracing Landau fan to density at full-fulling

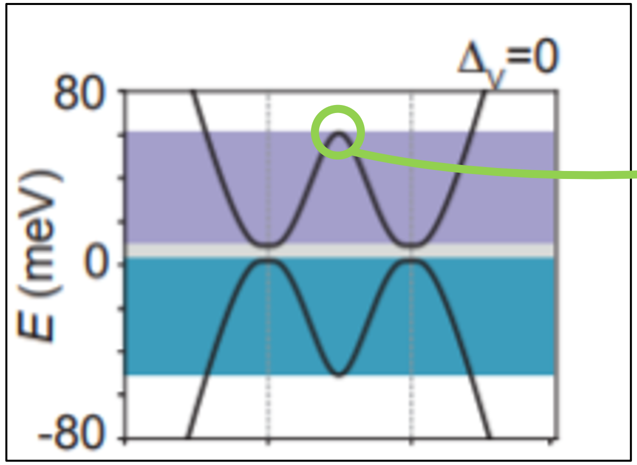
$$n_s = 1.35 \times 10^{13}\ cm^{-2}$$

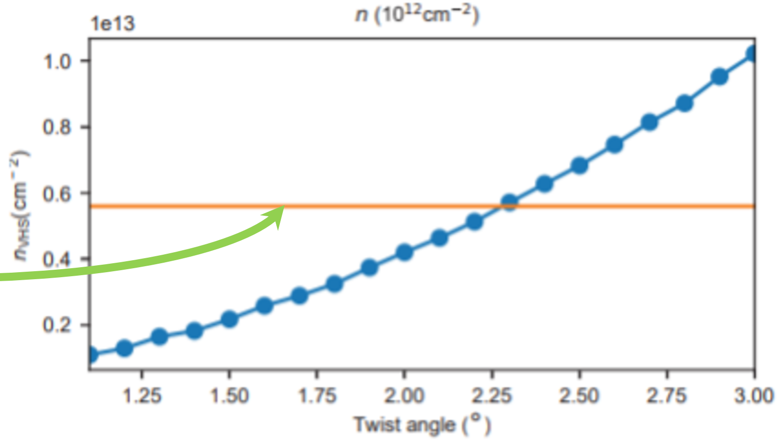
$$\frac{8}{n_s} = A_{Moire}$$

$$\rightarrow \boldsymbol{\theta \approx 2.4^\circ}$$

Identifying twist angle

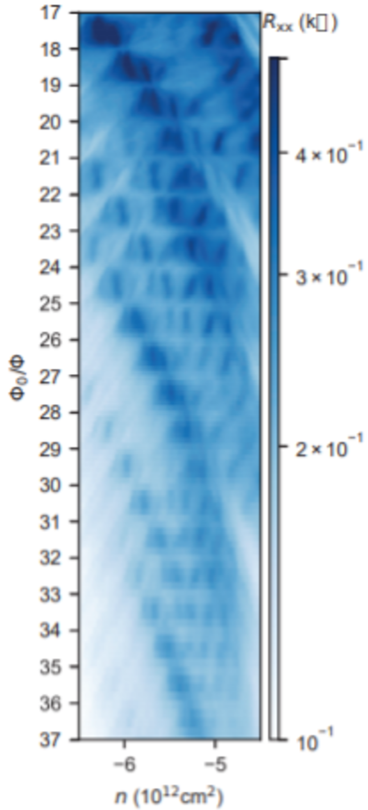
Theory calculations of van Hove singularity location





F. K. de Vries et al, *Combined minivalley and layer control in twisted double bilayer graphene*

$\rightarrow \boldsymbol{\theta = 2.3^{\circ}}$



Hofstadter butterfly spectrum

Setting ϕ so that resonances of R_{xx} (LL) happen at integer multiples of $\frac{\phi_0}{\phi}$

$$\phi = BA \rightarrow A = 30.5\ nm^2$$

$$\rightarrow \boldsymbol{\theta = 2.37^{\circ}}$$

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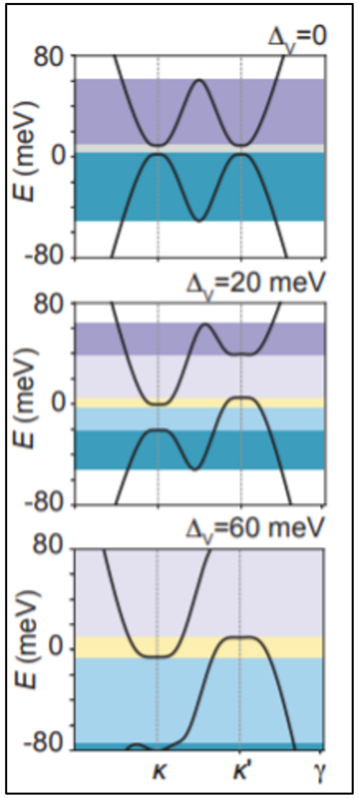
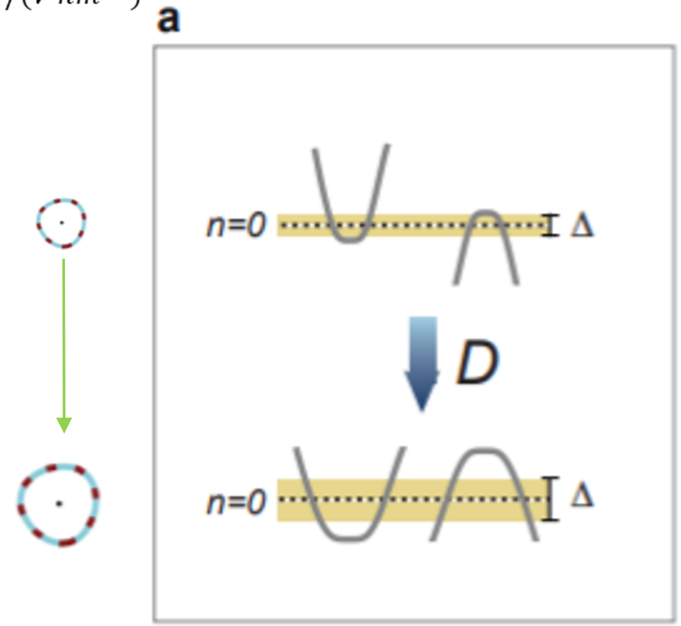
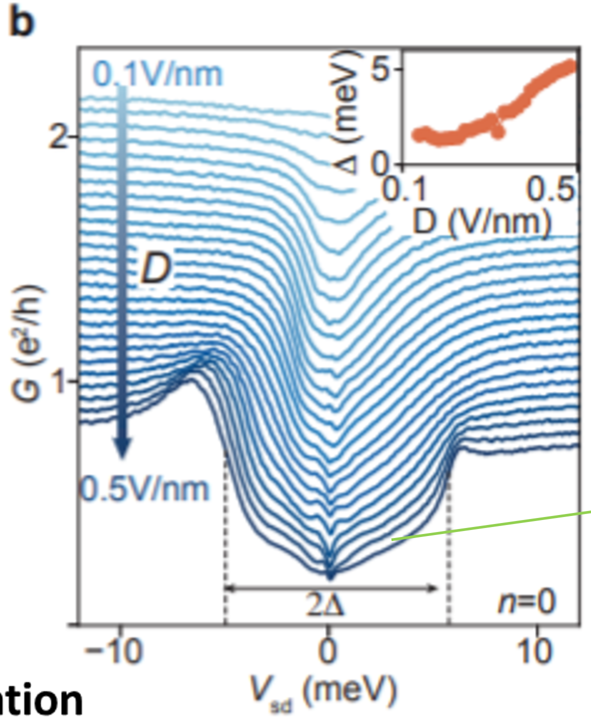
Displacement field effects

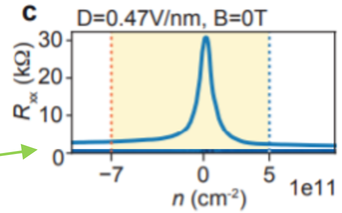


Layer on-site energy difference Δ_v

$\Delta_V = bD,\, b = 59\, meV/(V\, nm^{-1})$



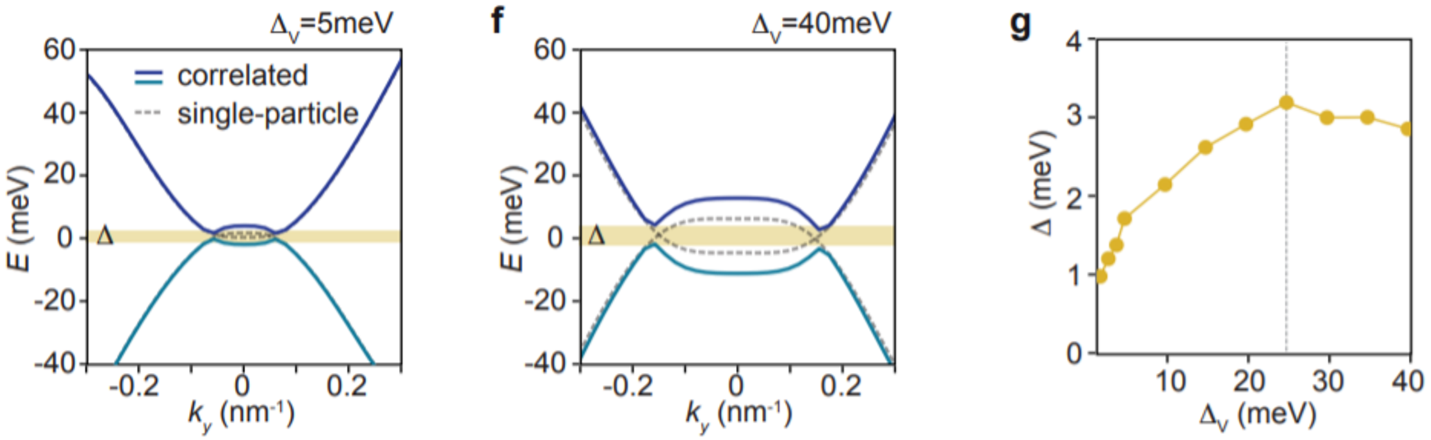


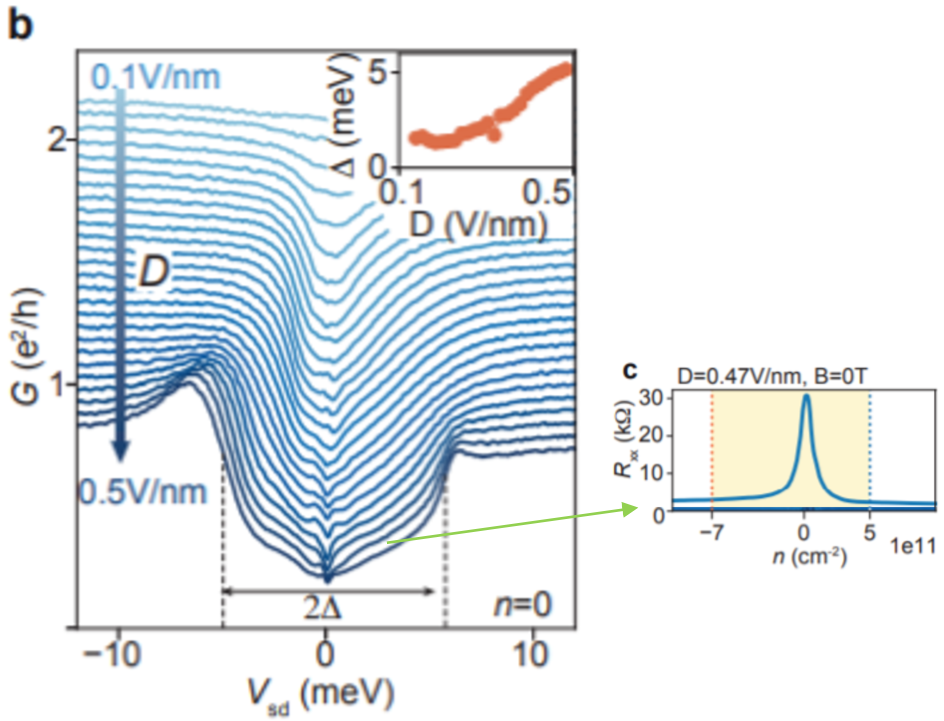


Increasing size of Fermi surface → better correlation

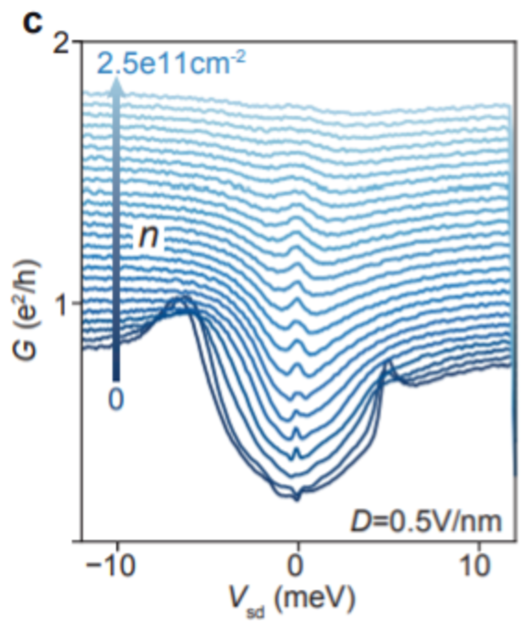
Displacement field effects

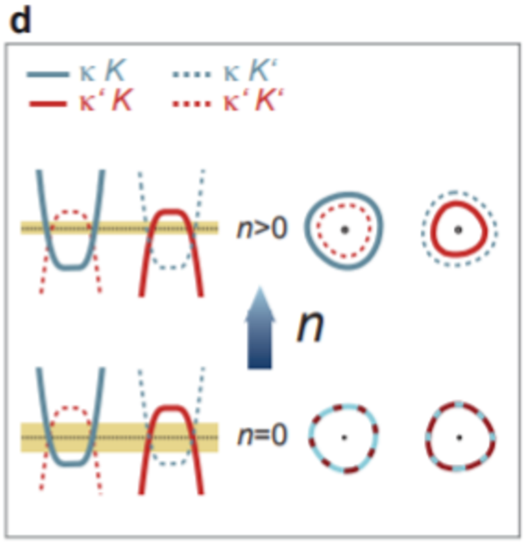
Layer on-site energy difference Δ_v
$\Delta_V = bD, b = 59\ meV/(V\ nm^{-1})$

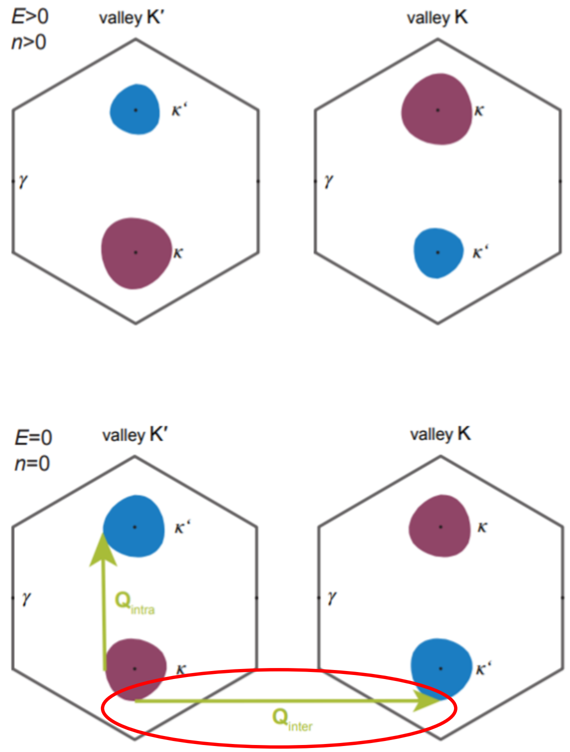




Charge density effects







Increasing discrepancy between Fermi surfaces → weaker correlation

Outline

- Background on excitonic insulators and twisted 2D heterostructures
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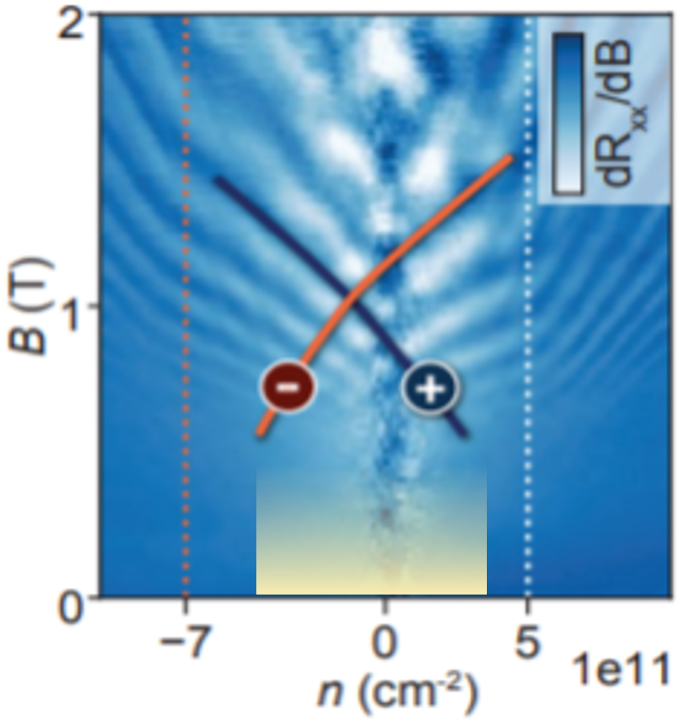
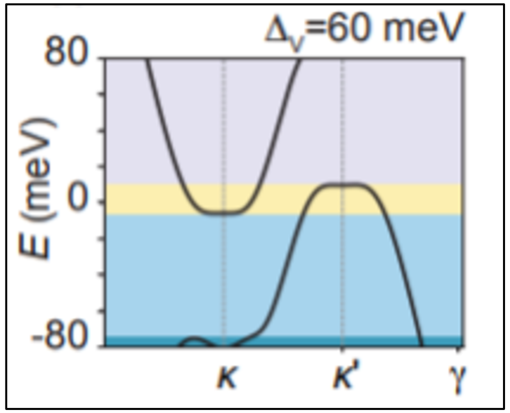
- Open questions

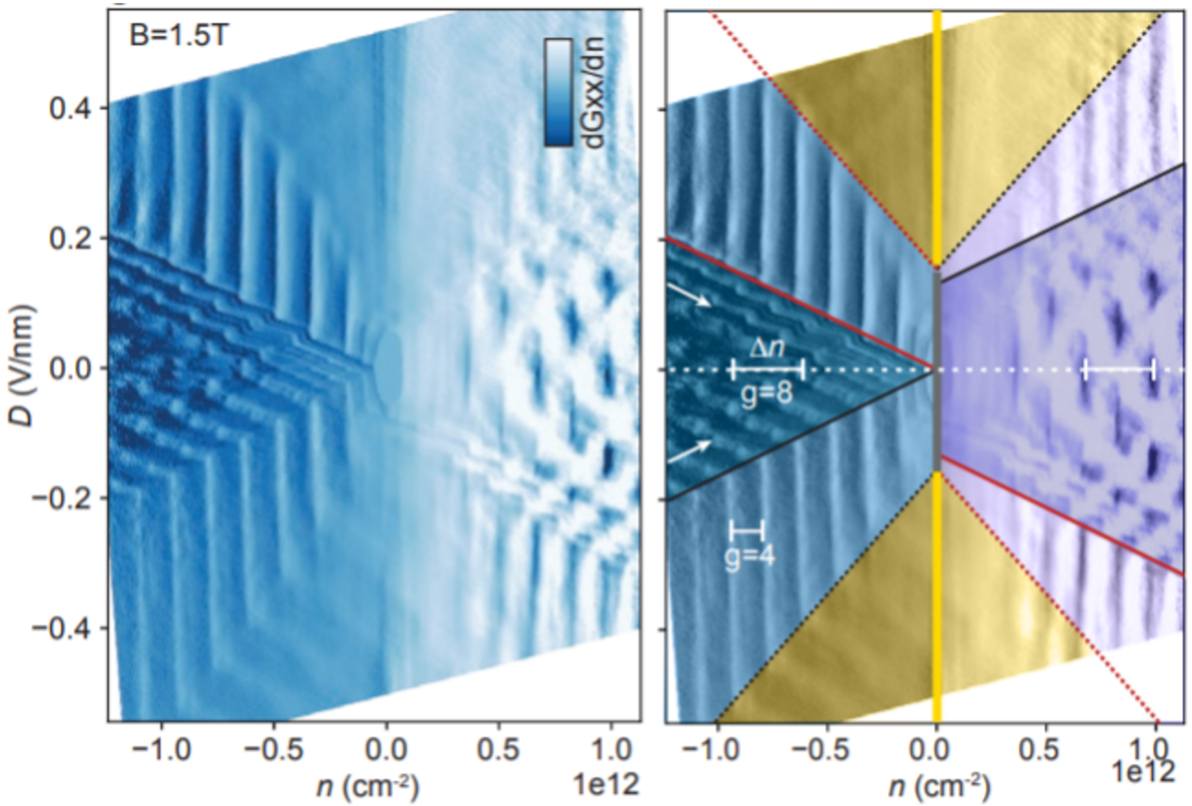
SdH oscillations with low field

$D = 0.47\ V/nm$





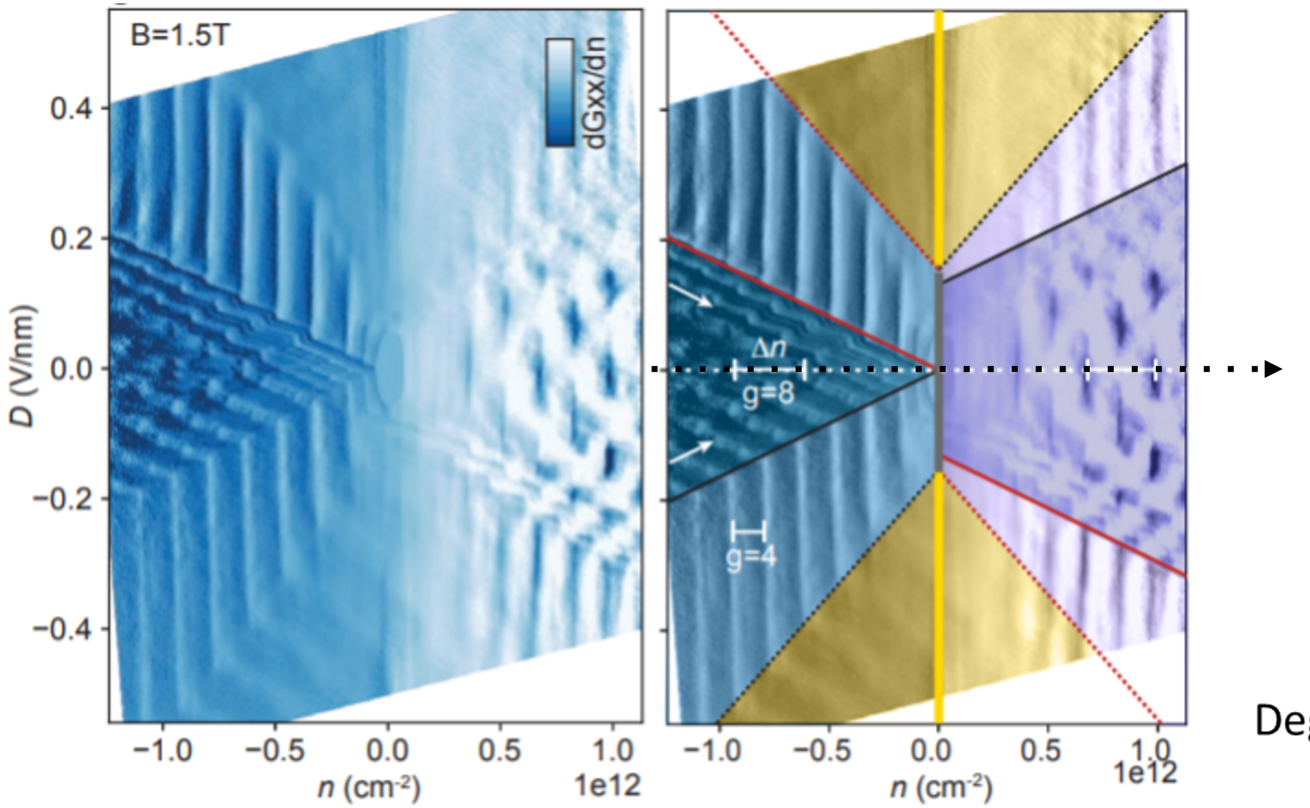
SdH oscillations with low field

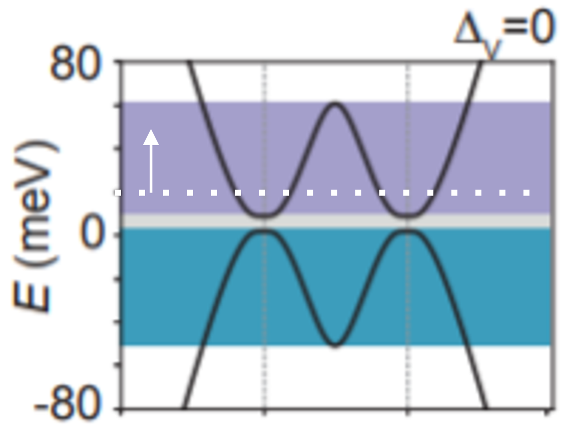


SdH oscillation behavior distinguishes regions in n vs D

$\frac{dG_{xx}}{dn}$ selected for visual convenience

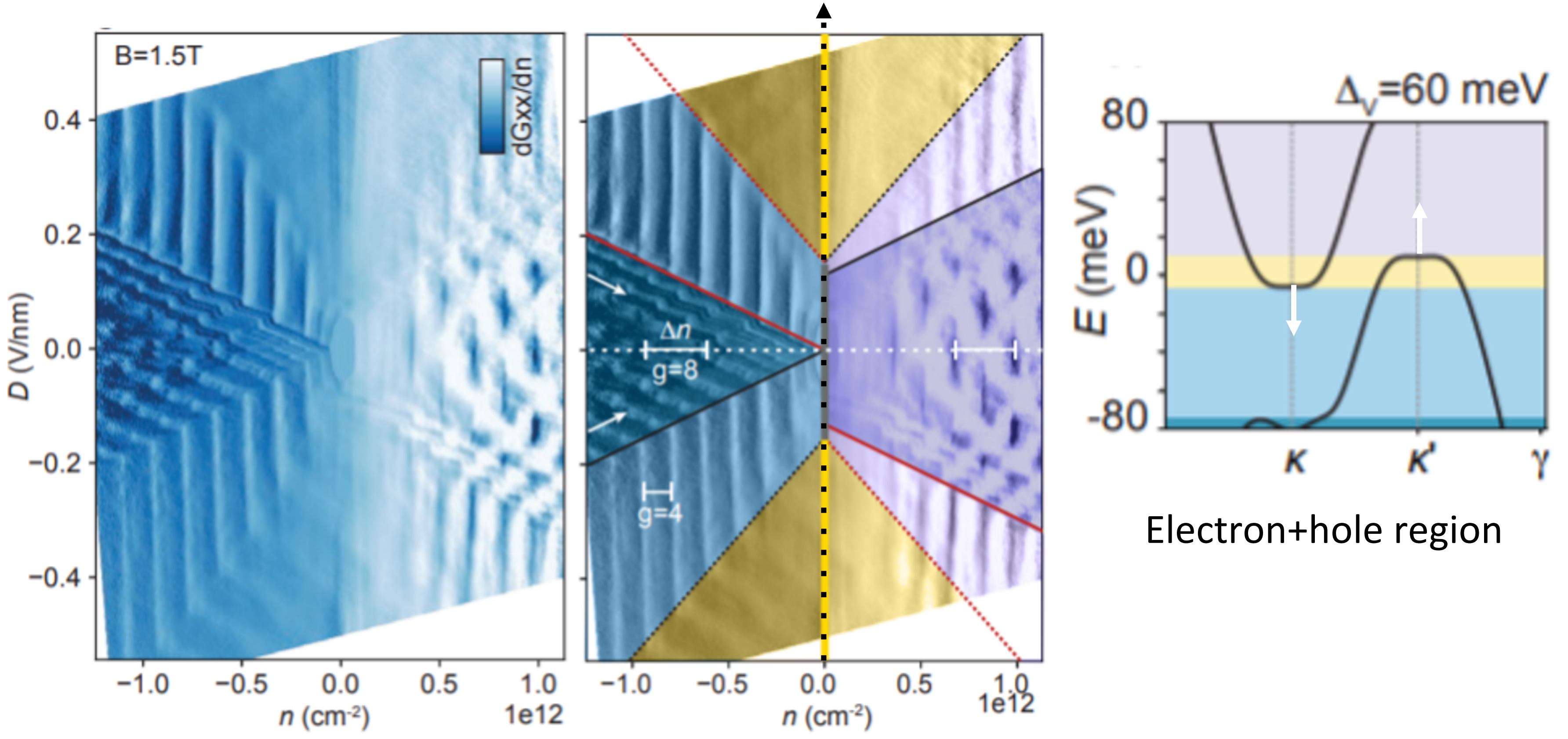
SdH oscillations with low field





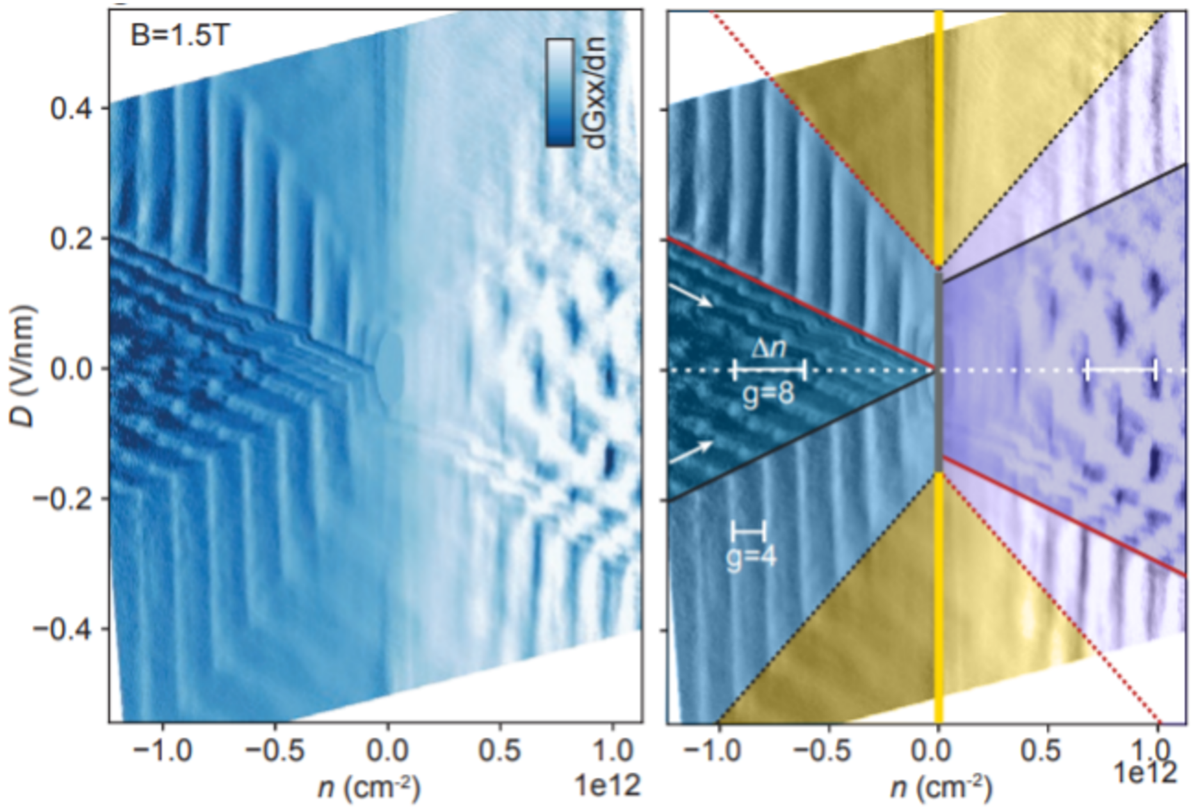
Degeneracy $g = 2\ valleys\ \times 2\ spins\ \times 2\ layers = 8$

SdH oscillations with low field



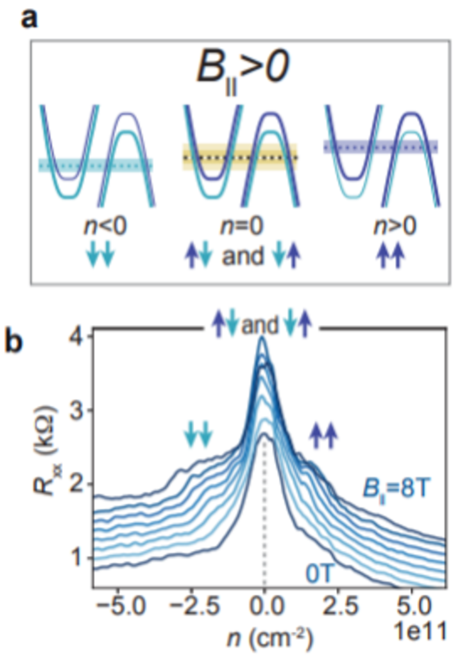
Electron+hole region

SdH oscillations with low field

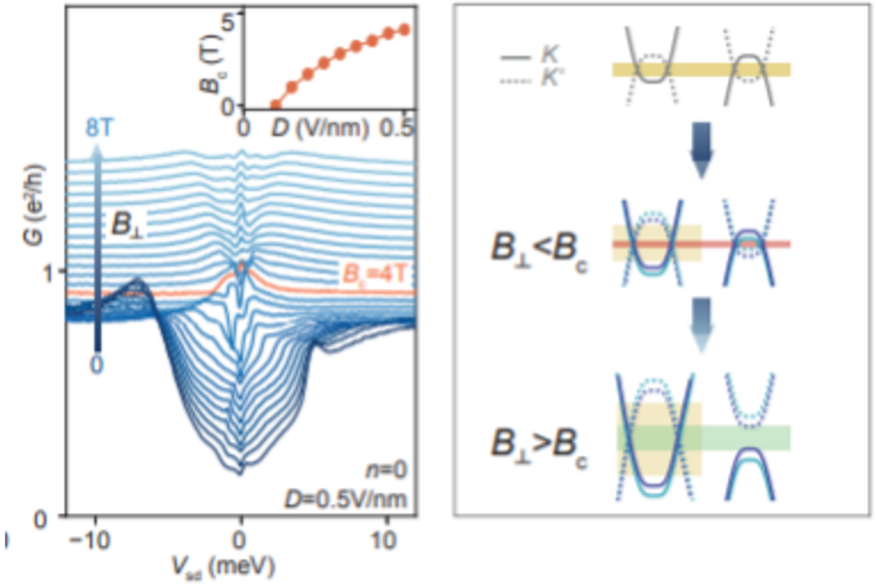


- Transitions between these regions match parabolic band theory calculations
- Asymmetry between hole and electron density
  - Intrinsic asymmetry from tight-binding model
  - Some effects from crystal field
  - Potential lattice relaxation effects

Magnetic field effects



Zeeman splitting creates new nesting possibilities
→ Correlated insulating states at higher n



Valley-Zeeman effect dominates
→ Weaker gap

Questions

- Possible competition with other correlated states? (spin states, nematic state, superconductivity)
- How much does scattering contribute to effects when turning carrier density?
- Origins of zero-bias peak with perpendicular magnetic field
- Effects of Landau levels on perpendicular magnetic field effects
- How resilient is the DW state with the application of strain?
- Phase of excitonic insulator—does it form a crystal-like lattice?
  - Can this be measured in either transport or STM?