NONTRIVIAL QUANTUM OSCILLATION GEOMETRIC PHASE SHIFT IN A TRIVIAL BAND

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Datta et al. Science Advances 5, eaax6550 (2019).
Datta et al. Physical Review Letters 121, 056801 (2018),

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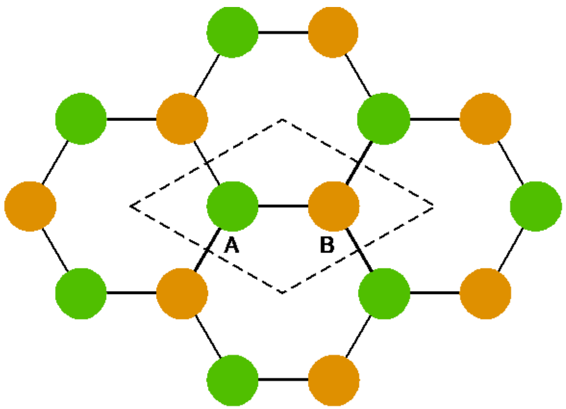
Outline

- Few layers of graphene – why are they interesting?
- Trilayer ABA graphene
- Measuring quantum oscillations
- Berry’s phase in a multiband system

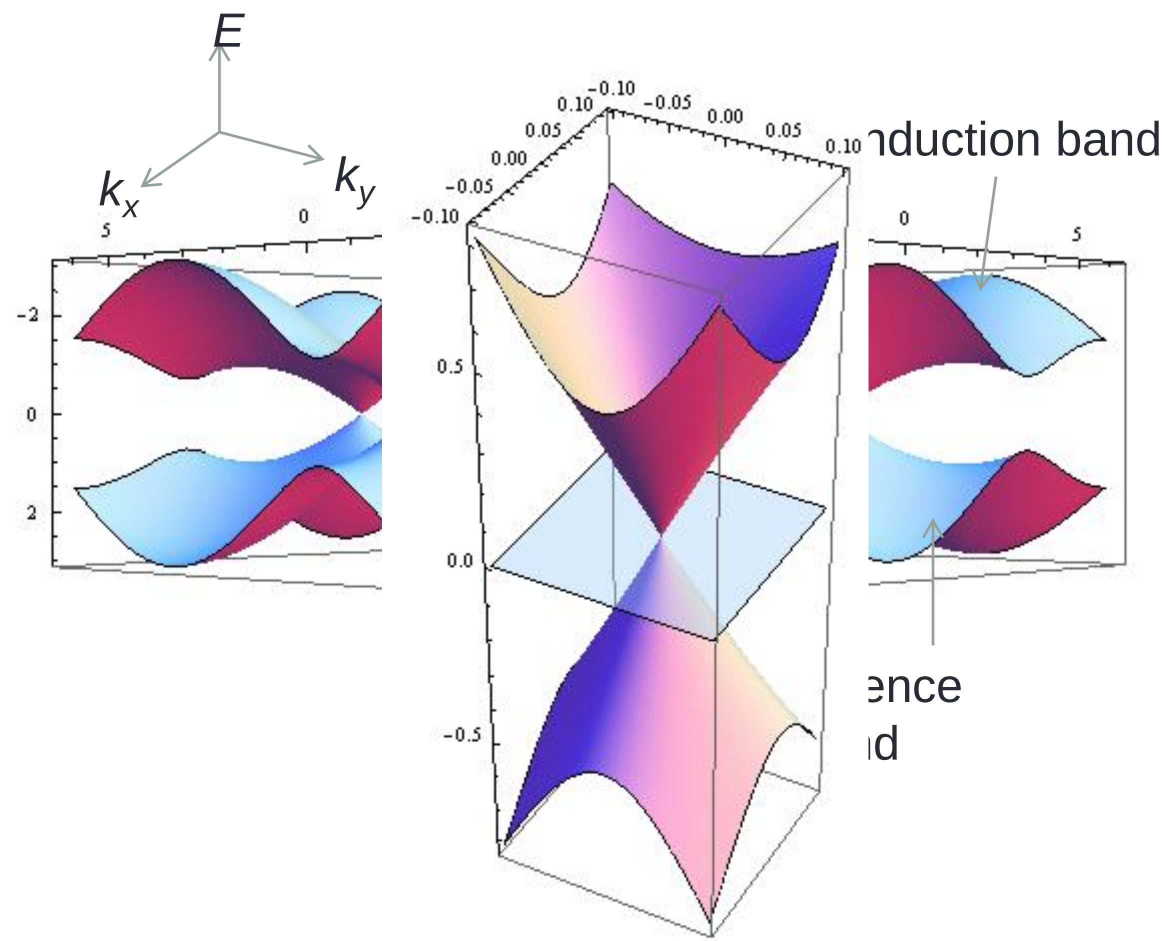
Graphene basics



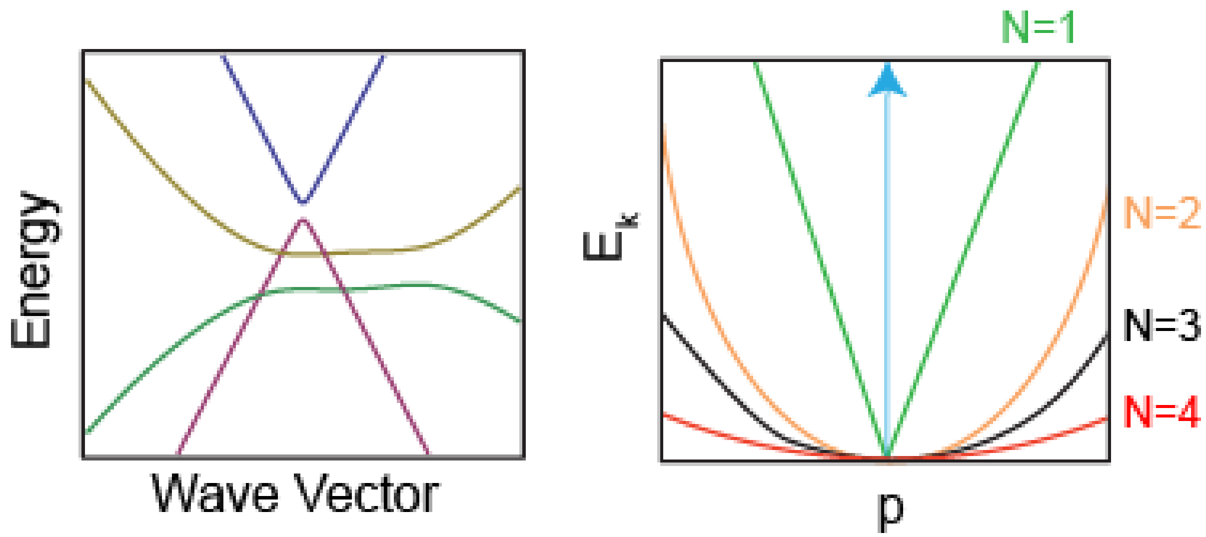
$$H_{\boldsymbol{K}} = v_F \boldsymbol{\sigma} \cdot \boldsymbol{p}$$

$$H_{\boldsymbol{K}'} = -H_{\boldsymbol{K}}$$

- ❑ Bravais lattice with two carbon atom basis



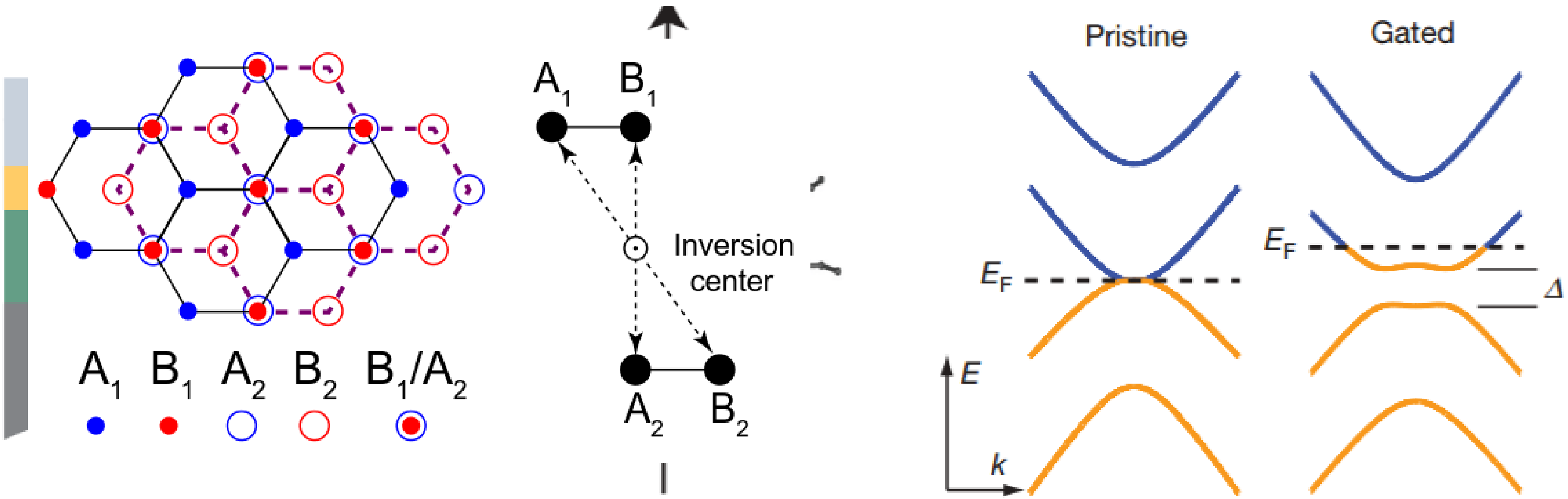
Why few layers of graphene are interesting?



- Interactions become more important for multiple layers due to flatter bands
- Tunable symmetries
- Possibility of studying non-Abelian quantum Hall states

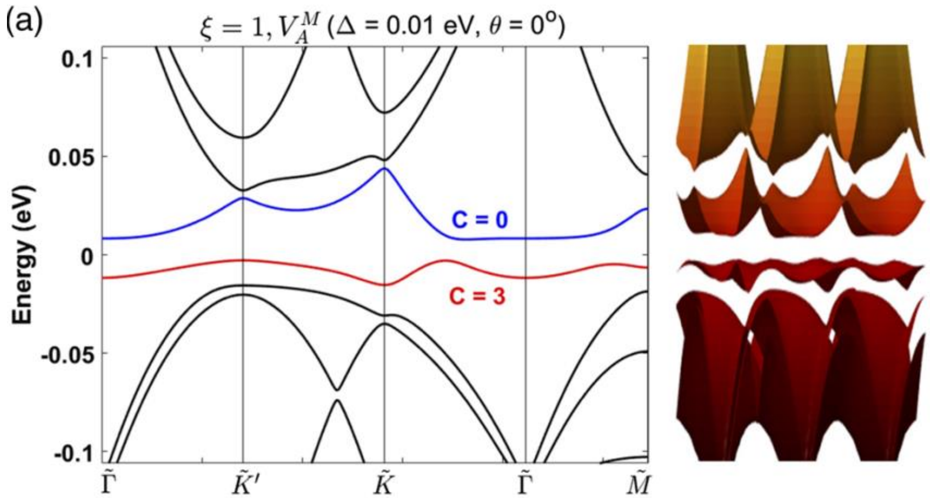
Breaking inversion symmetry in bilayer graphene opens up a bandgap

Bilayer graphene



Zhang et al. Nature 459, 820 (2009).

Tuning topological properties



ABC trilayer, Chittari et al. PRL 122, 016401 (2019)

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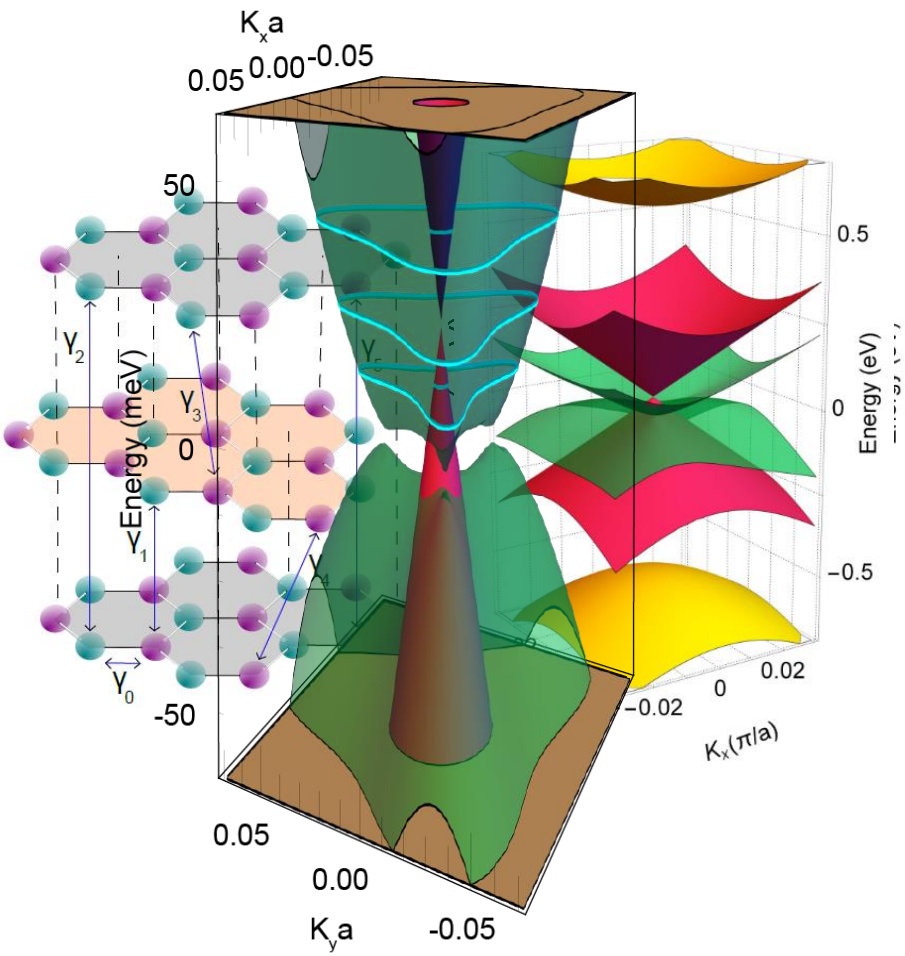
ABA-Trilayer Graphene: Crystal and Band Structure

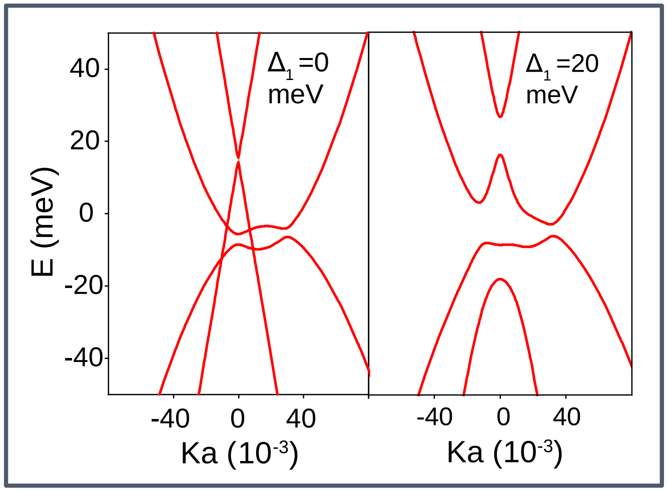


Monolayer graphene (MLG)-like and bilayer graphene (BLG)-like bands

Bands do not hybridize at the crossing points due to mirror symmetry protection

Some states are polarized in mirror symmetric and anti-symmetric basis

Effect of Electric Field on the Band Structure

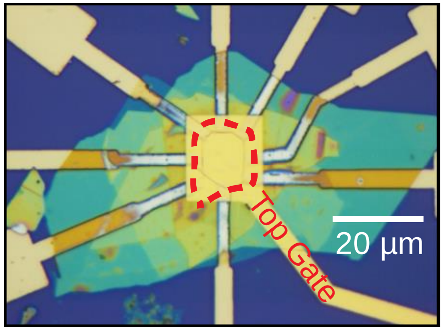


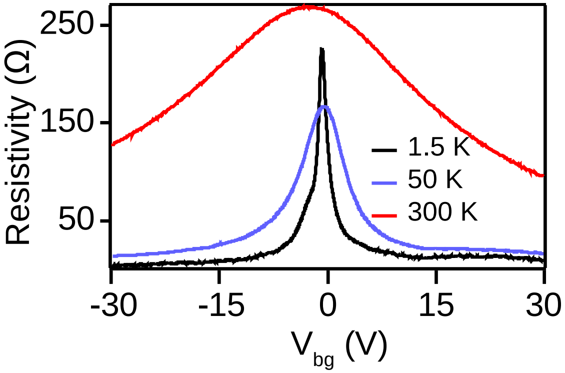
Basis: $\frac{A_1 - A_3}{\sqrt{2}}$, $\frac{B_1 - B_3}{\sqrt{2}}$, $\frac{A_1 + A_3}{\sqrt{2}}$, B_2, A_2, $\frac{B_1 + B_3}{\sqrt{2}}$

$$H_{\mathrm{TLG}} = \begin{pmatrix} \Delta_2 - \frac{\gamma_2}{2} & v_0\pi^\dagger & \Delta_1 & 0 & 0 & 0 \\ v_0\pi & \Delta_2 + \delta - \frac{\gamma_5}{2} & 0 & 0 & 0 & \Delta_1 \\ \Delta_1 & 0 & \Delta_2 + \frac{\gamma_2}{2} & \sqrt{2}v_3\pi & -\sqrt{2}v_4\pi^\dagger & v_0\pi^\dagger \\ 0 & 0 & \sqrt{2}v_3\pi^\dagger & -2\Delta_2 & v_0\pi & -\sqrt{2}v_4\pi \\ 0 & 0 & -\sqrt{2}v_4\pi & v_0\pi^\dagger & \delta - 2\Delta_2 & \sqrt{2}\gamma_1 \\ 0 & \Delta_1 & v_0\pi & -\sqrt{2}v_4\pi^\dagger & \sqrt{2}\gamma_1 & \Delta_2 + \delta + \frac{\gamma_5}{2} \end{pmatrix}$$

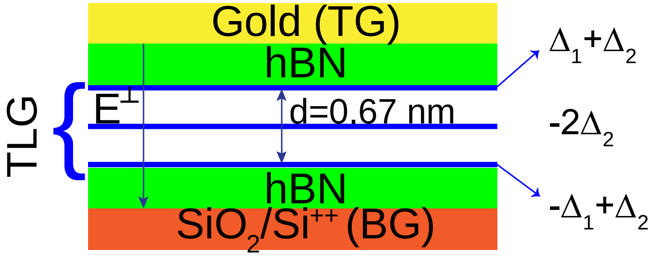
- Electric field increases the band gap of MLG-like bands

Understanding our experimental system

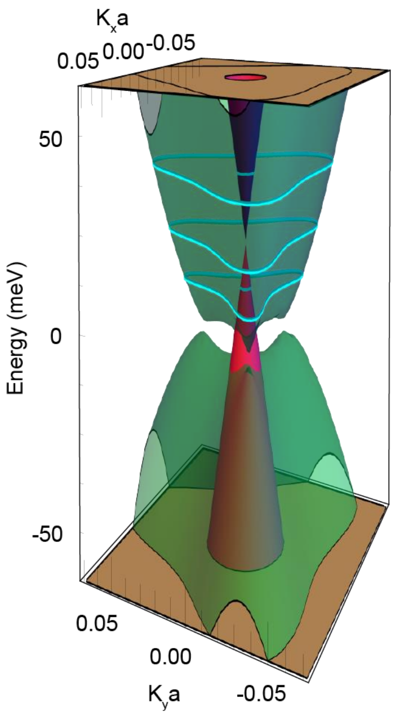




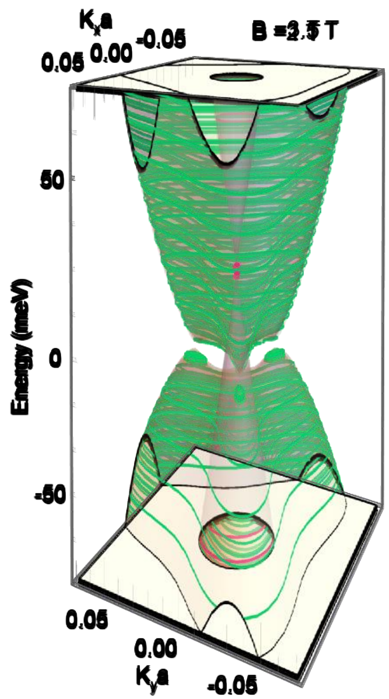
- Mobility ~ 800,000 $cm^2 V^{-1} s^{-1}$
- Mean free path ~ 10 µm
- Average $E^{\perp}=2\Delta_1/d$ (e)

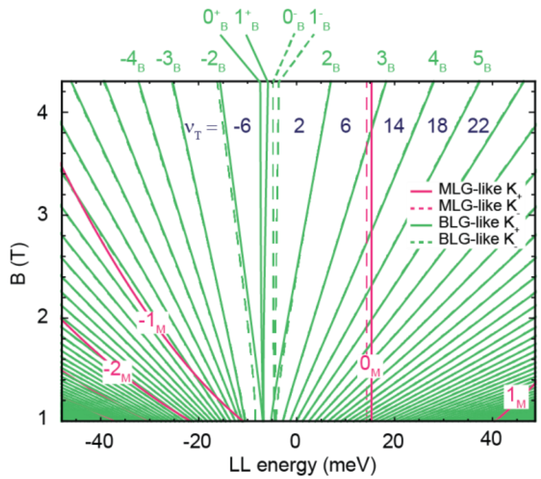


Landau levels



Magnetic field





$$E_{MLG}(B,N) \sim \pm\sqrt{BN},\, N = 0,1,2\ldots$$

$$E_{BLG}(B,N) \sim \pm B\sqrt{N(N-1)},\, N = 0,1,2\ldots$$

- Monolayer-like Landau Level gaps are much larger than bilayer-like bands
- Zeroth Monolayer-like Landau Level does not disperse with magnetic field

Biswajit Datta *et al. Physical Review Letters 121, 056801 (2018).*

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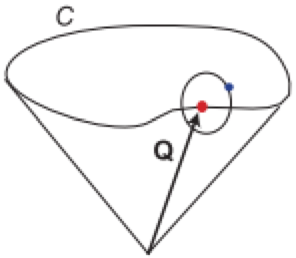
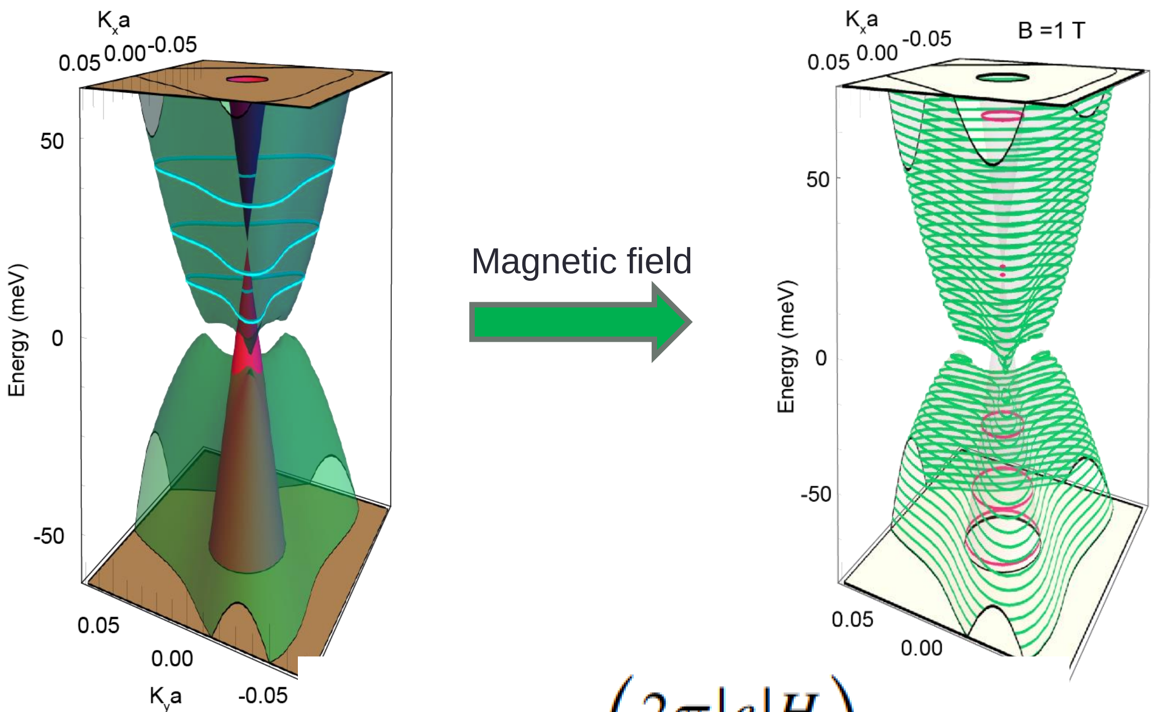
Berry's phase



- A version of this for optics proposed by Panchratnam
- The flux enclosed by the closed loop due to the Berry's curvature
- In a periodic lattice depends on symmetry of the lattice

Semiclassical quantization and Berry's phase



$$S(\varepsilon, k_z) = \left(\frac{2\pi|e|H}{\hbar c}\right)(n + \gamma)$$

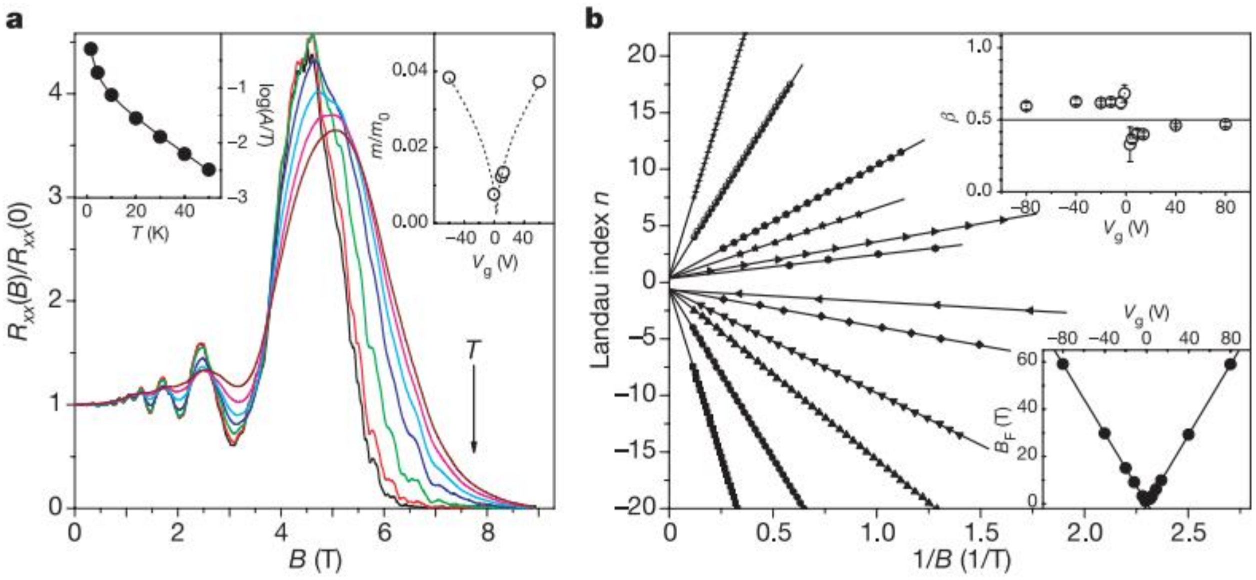
$$\gamma - \frac{1}{2} = -\frac{1}{2\pi}\oint_{\Gamma} \mathbf{\Omega}\, d\mathbf{k}$$

Mikitik and Sharlai
Phys. Rev. Lett. 82 2147 (1999)

SdH Oscillations

- Magnetoresistance oscillations reflecting density of states oscillations
- de Haas van Alphen can be used as it is essentially the same physics

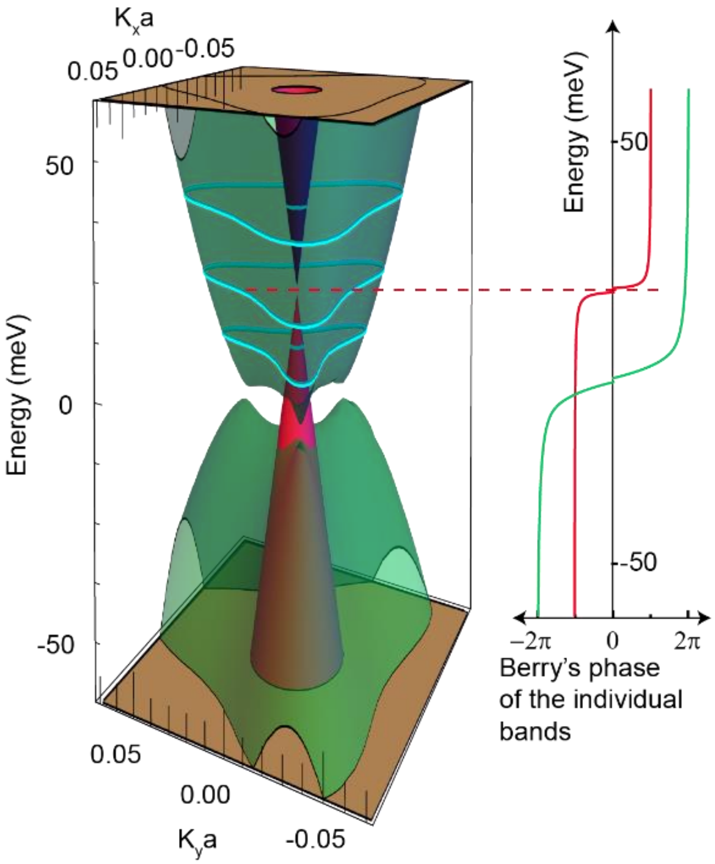
$$\Delta R_{xx} = R(B,T)\cos[2\pi(B_F/B + 1/2 + \beta)]$$



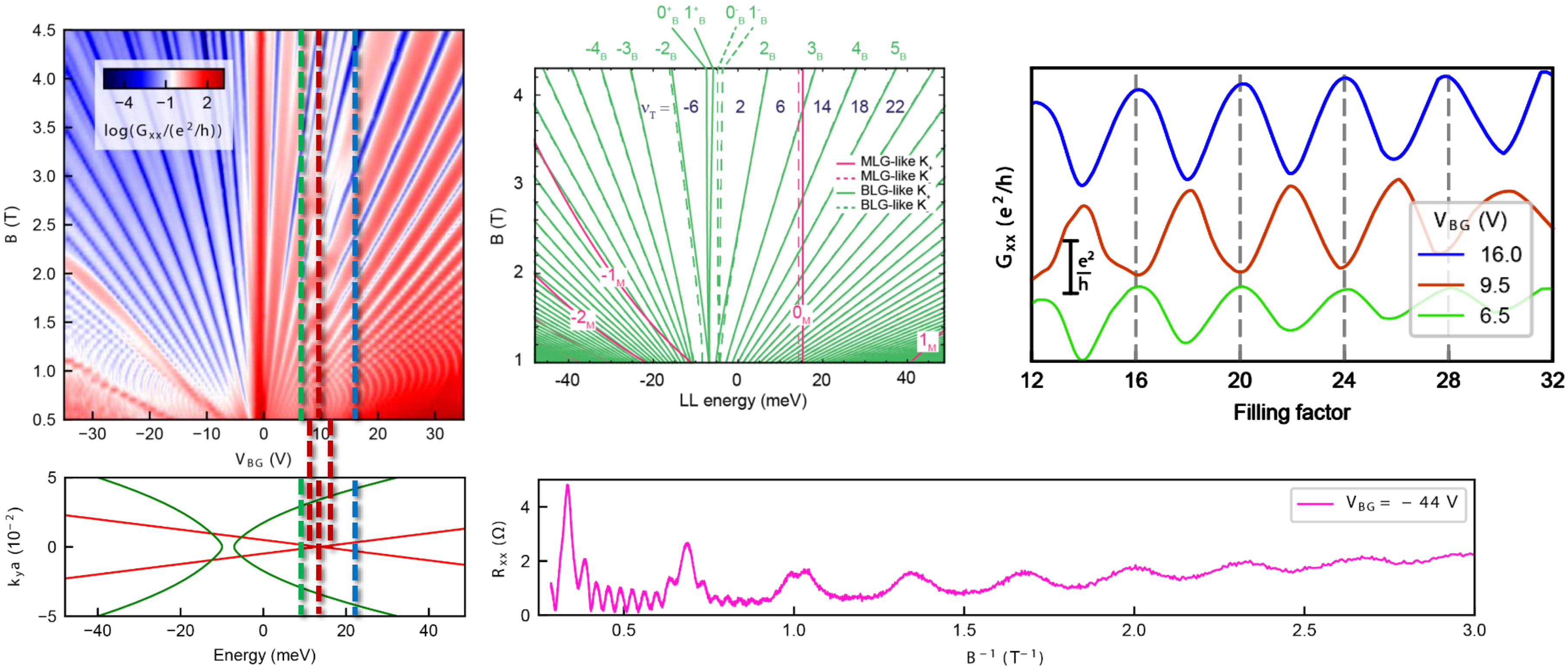
Zhang et al. Nature **438**, 201 (2005).

Connection to trilayer physics

Gapped monolayer like levels and gapped bilayer like levels exist in trilayer ABA graphene

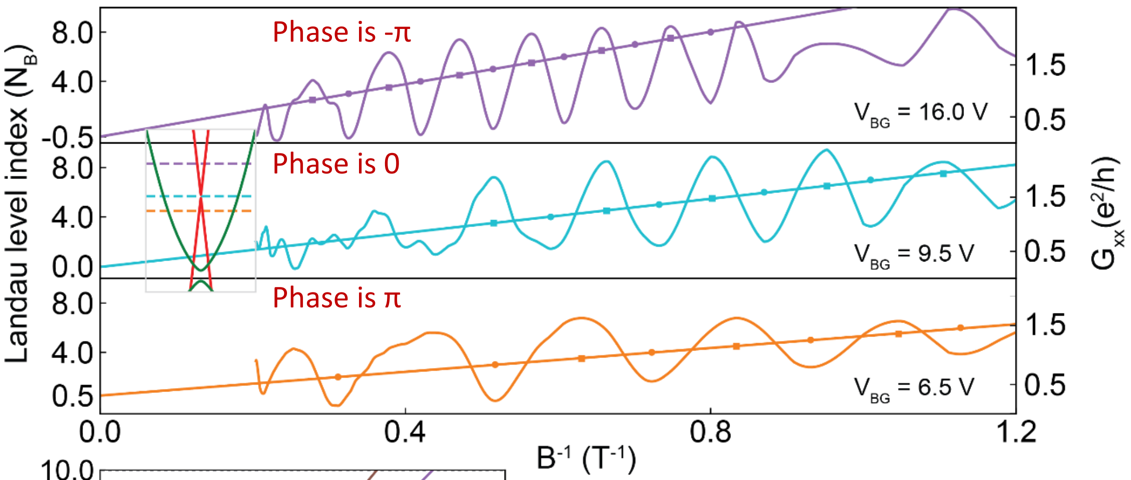


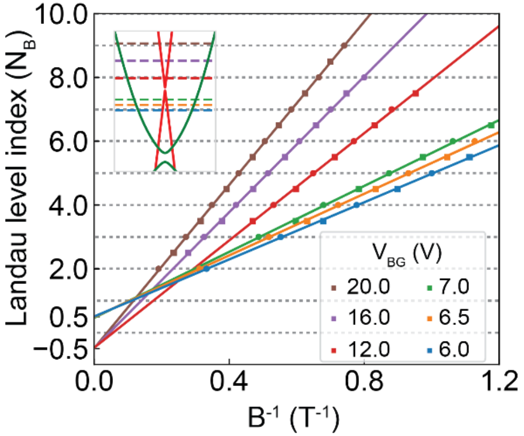
Multiband magnetotransport

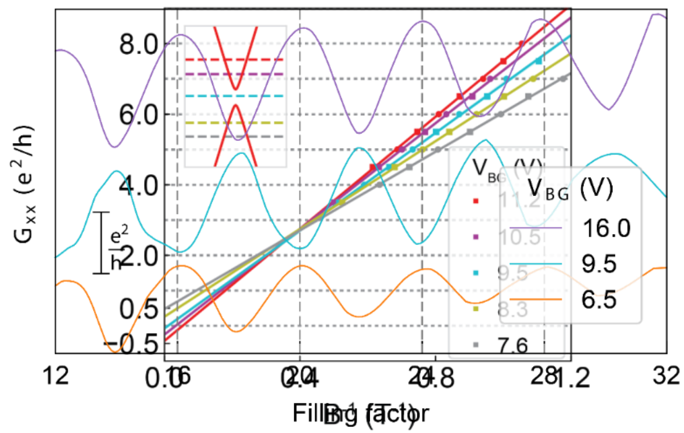


- Two SdH frequency results from two Fermi surfaces
- Phase of the BLG-like oscillations depend on the MLG-like band gap!
- Changing phase is not Berry's phase of the bilayer band

Anomalous SdH phase shift measured in trivial band







- Phase changes continuously close to the band gap!

How does one understand the anomalous SdH phase shift?

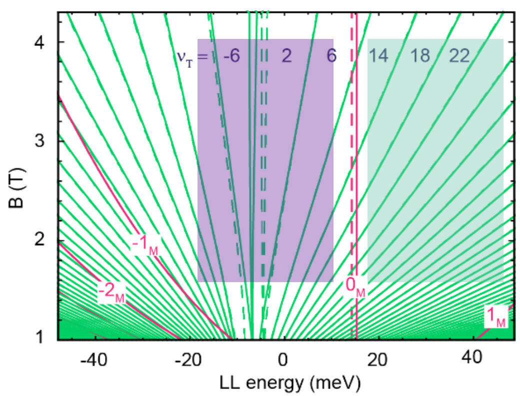
$$\Delta G_{XX} = G_M \cos\left[2\pi\left(\frac{B_{FM}}{B} + \Upsilon_M\right)\right] + G_B \cos\left[2\pi\left(\frac{B_{FB}}{B} + \Upsilon_B\right)\right]$$

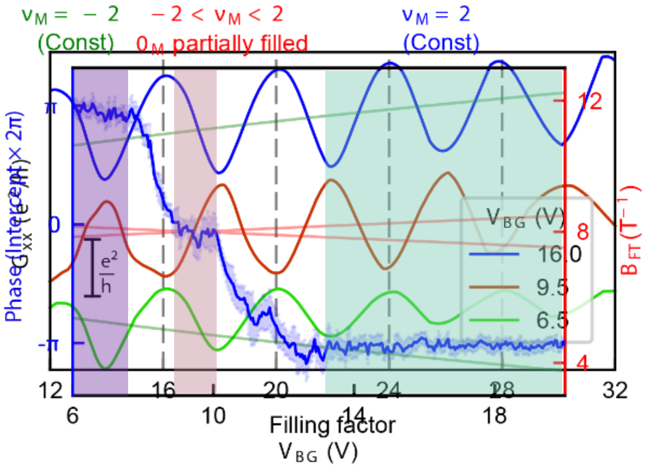
$$B_{FM} = \frac{n_M\, h}{4e} \qquad B_{FB} = \frac{n_B\, h}{4e}$$

$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FB}}{B} + \Upsilon_B\right)\right]$$

$$B_{FB} = \frac{n_B\, h}{4e} = \frac{(n_T - n_M)\, h}{4e} = B_{FT} - \frac{\nu_M B}{4}$$

$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FT}}{B} + \Upsilon_B - \frac{\nu_M}{4}\right)\right]$$





Below the gap ν_M= -2

$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FT}}{B} + \Upsilon_B - \frac{1}{2}\right)\right]$$

In the gap ν_M= 0

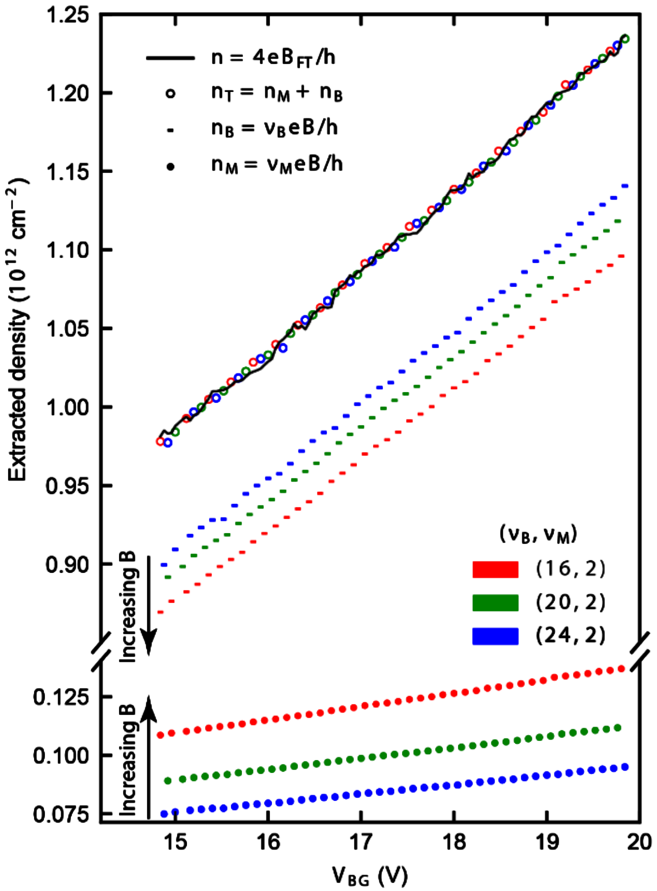
$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FB}}{B} + \Upsilon_B\right)\right]$$

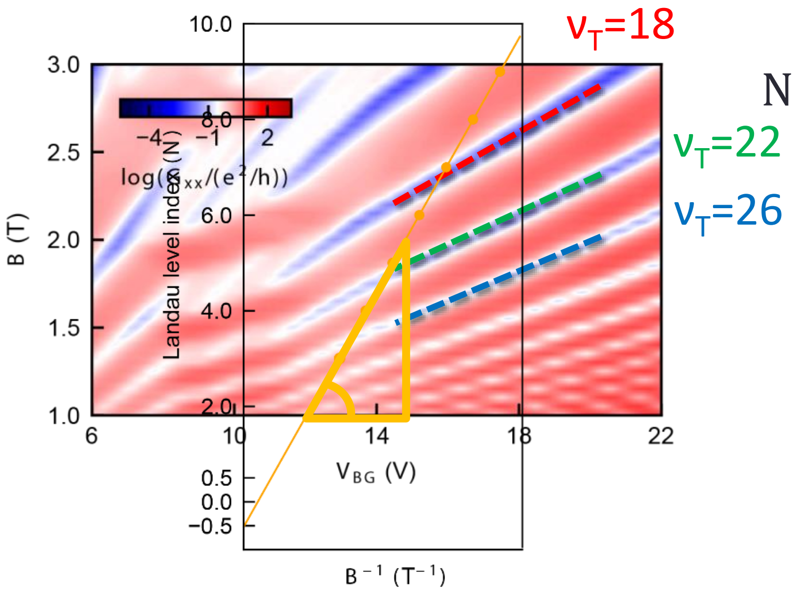
Above the gap ν_M= 2

$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FT}}{B} + \Upsilon_B + \frac{1}{2}\right)\right]$$

Datta et al. arXiv:1902.04264 (to appear in Science Advances).

SdH frequency -- area of Fermi Surface and filling enforcement





$$N = \frac{B_{FT}}{B_N} + \frac{\Phi_B}{2\pi} - \frac{\nu_M}{4}$$

$$B_{FT} = \frac{n_T\, h}{4e}$$

Independent corroboration of the phase shift from the measurement of Fermi surface area

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