TUNABLE SYMMETRIES AND BERRY'S PHASE IN FEW LAYER GRAPHENE

Mandar M. Deshmukh
DCMP and MS
TIFR, Mumbai, India

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ICTS, Bengaluru
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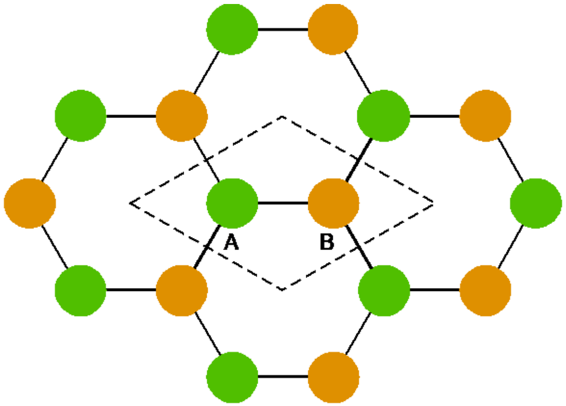
Collaborators

Biswajit Datta, Pratap Chandra Adak, Hitesh Agarwal, Li-kun Shi (NTU Singapore), **Justin Song (NTU Singapore)**, Abhisek Samanta (DTP), Amulya Ratnakar (DTP), **Rajdeep Sensarma (DTP), Kenji Watanabe (NIMS, Japan), Takashi Taniguchi (NIMS Japan)**

Outline

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

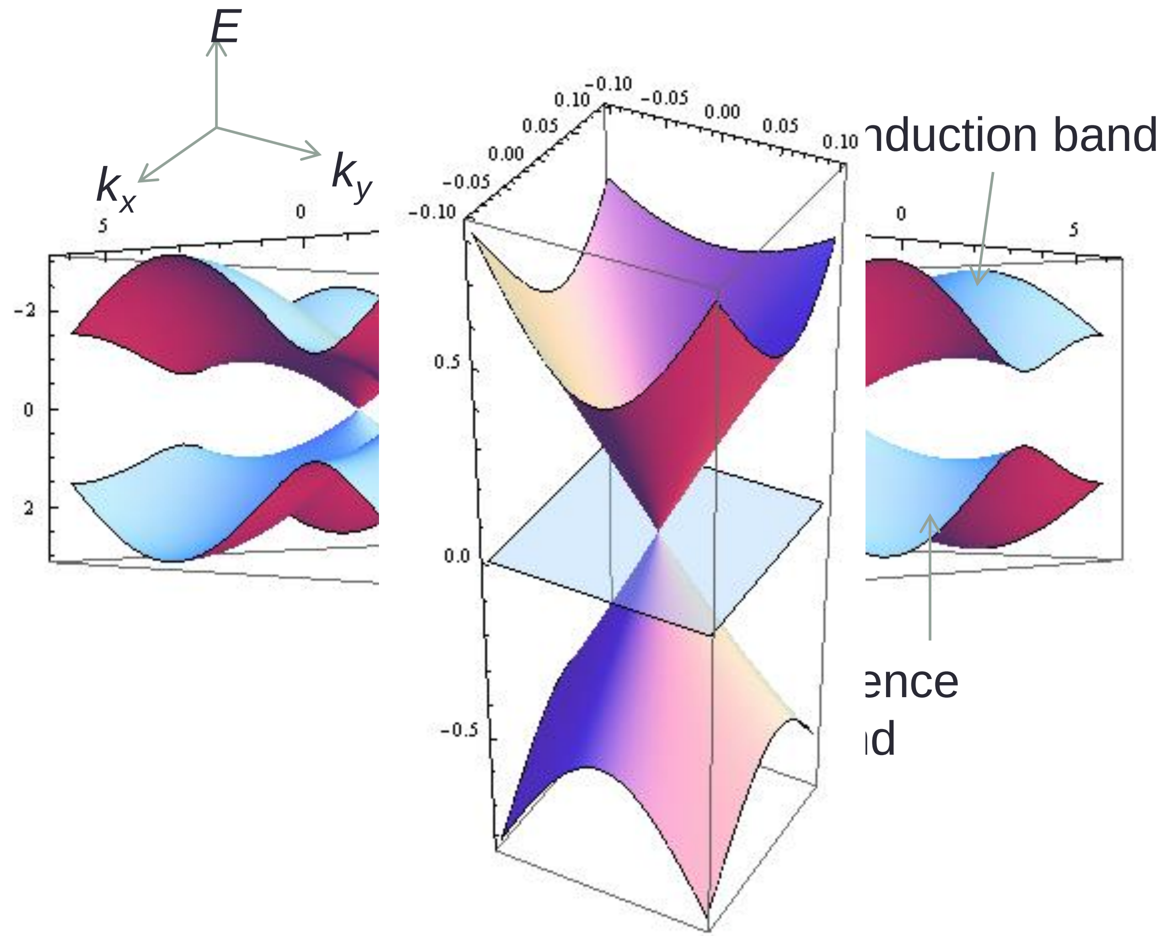
Graphene basics



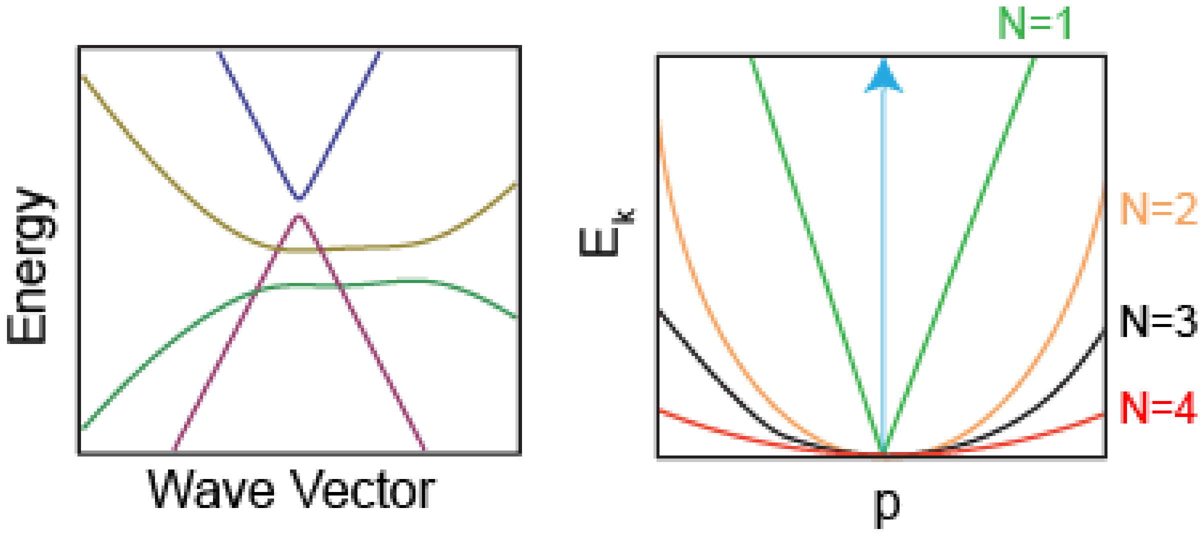
$$H_{\boldsymbol{K}} = v_F \boldsymbol{\sigma} \cdot \boldsymbol{p}$$

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

- ❑ Bravais lattice with two carbon atom basis



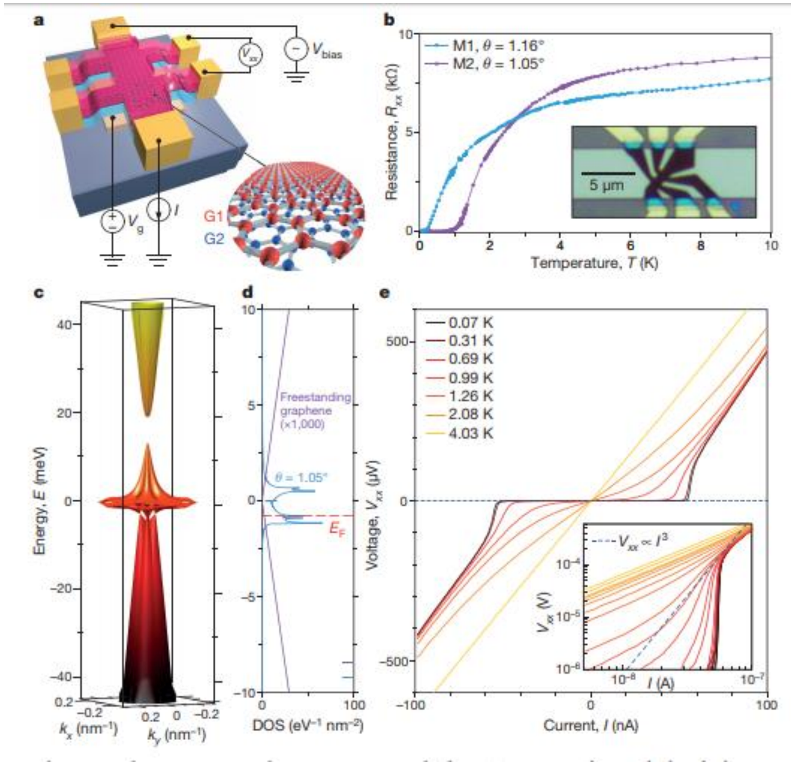
Why few layers of graphene are interesting?

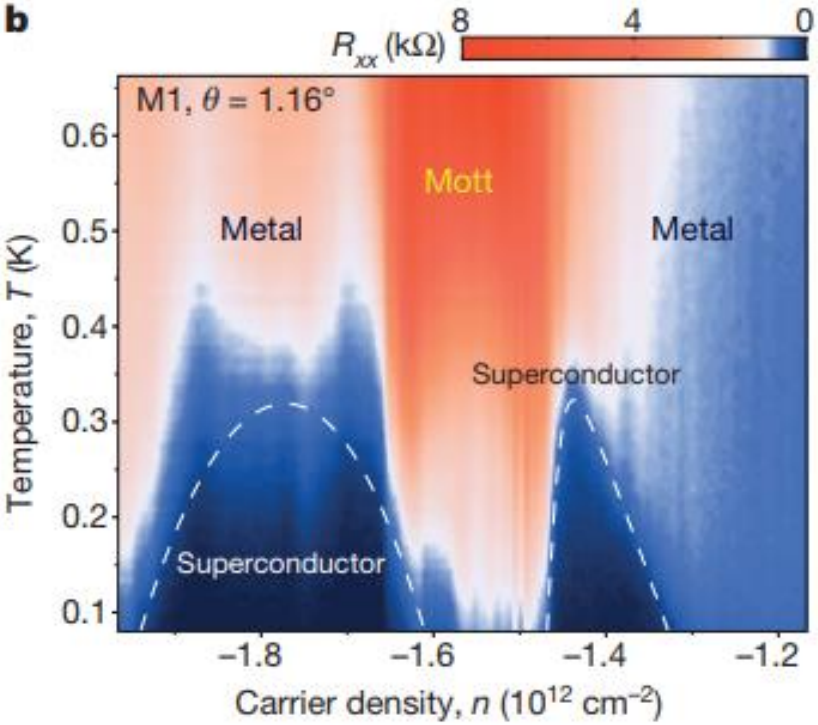


- Interactions become more important for multiple layers due to flatter bands
- Tunable symmetries
- Possibility of studying non-Abelian states quantum Hall states

our past work on interaction physics Biswajit Datta, et al. Nature Communications 8, 14518 (2017).

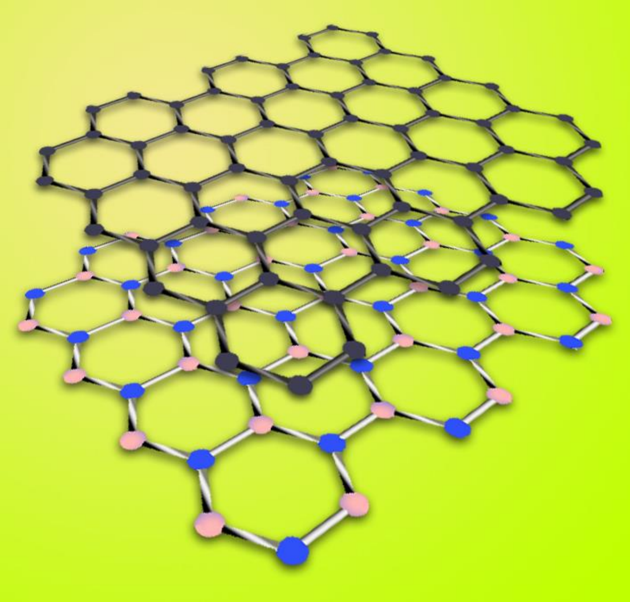
Superconductivity in magic-angle graphene superlattices





Cao et al. Nature, 556, 43 (2018)

Breaking symmetry in monolayer graphene – going from a semimetal to an insulator



https://phys.org/

Graphene

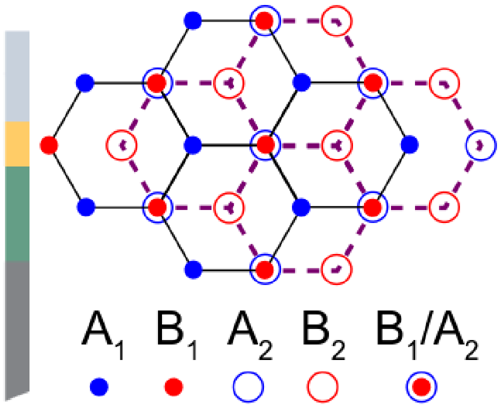
$$H_{\mathbf{K}} = v_F \boldsymbol{\sigma} \cdot \boldsymbol{p}$$

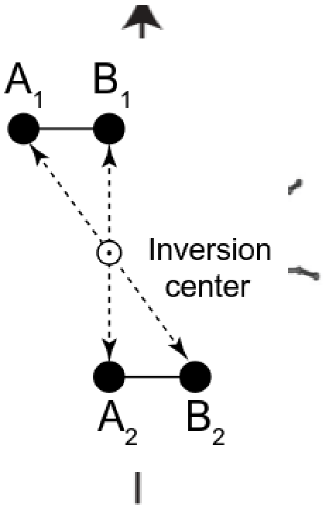
Boron Nitride or MoS_2

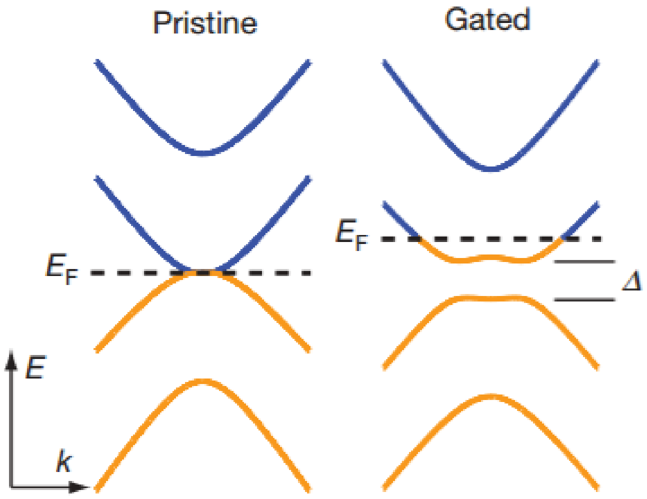
$$H_{\mathbf{K}} = v_F \boldsymbol{\sigma} \cdot \boldsymbol{p} \quad + \Delta\, \sigma_z$$

Breaking inversion symmetry in bilayer graphene opens up a bandgap

Bilayer graphene

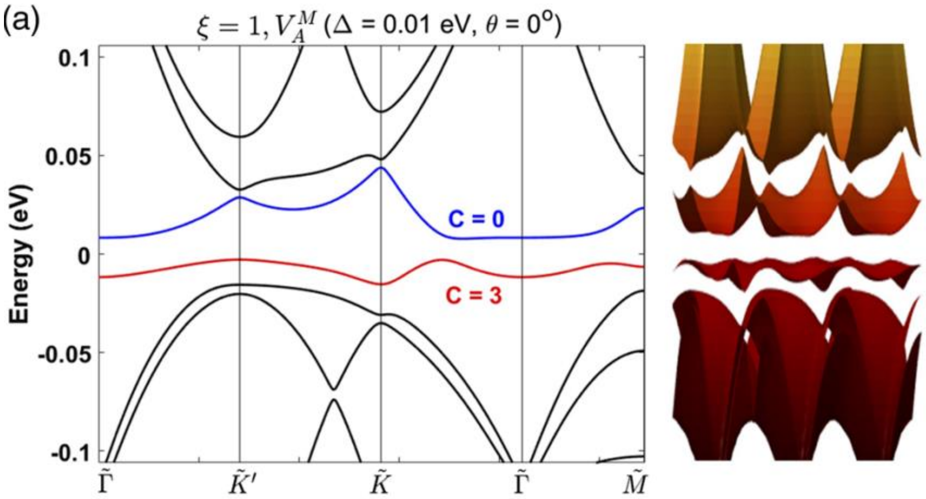






Zhang et al. Nature 459, 820 (2009).

Tuning topological properties



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

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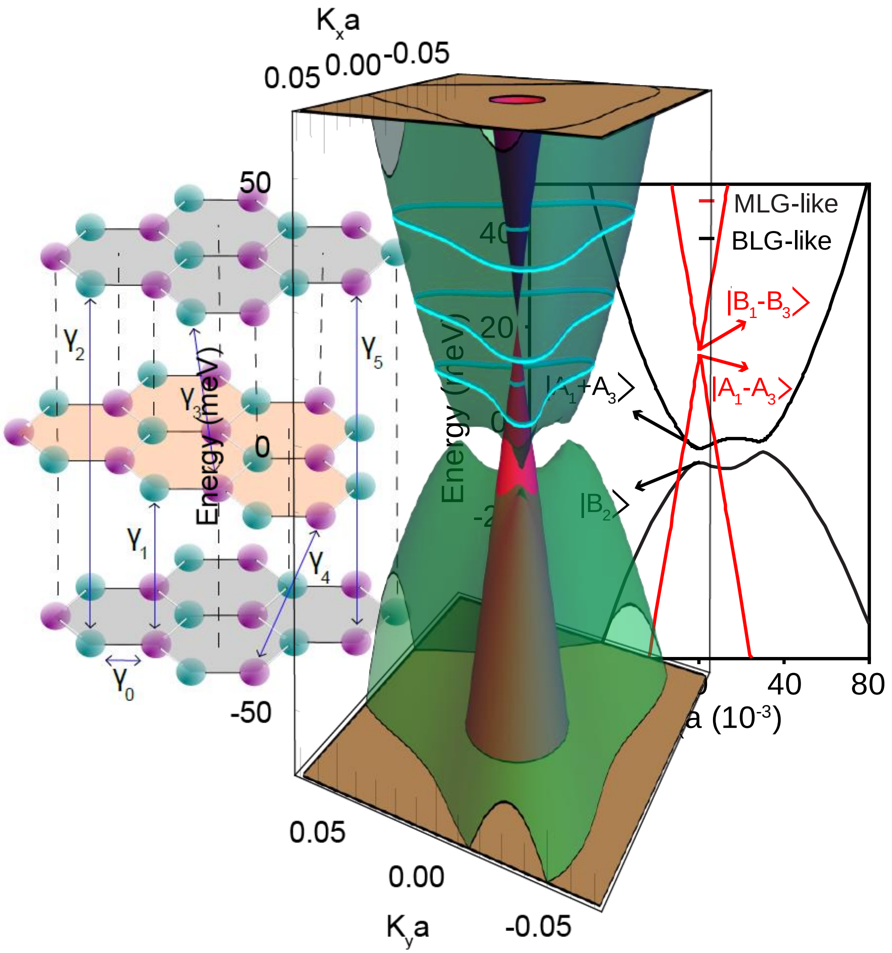
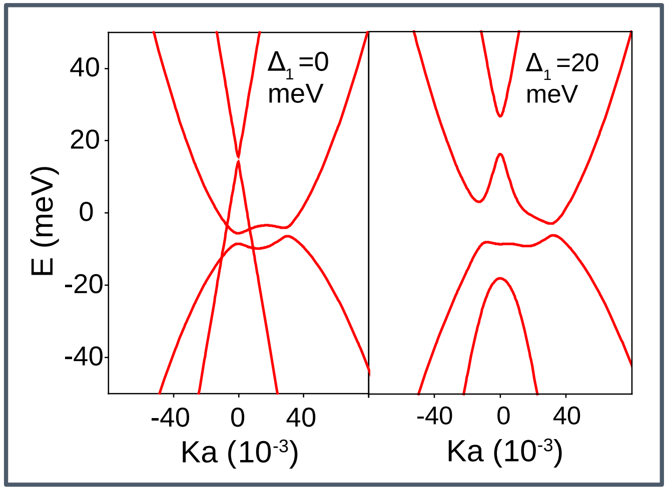
ABA-Trilayer Graphene: Crystal and Band Structure



- 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

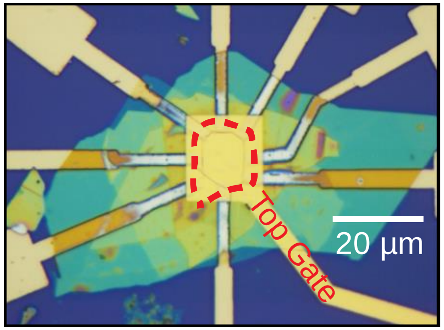
Effect of Electric Field on the Band Structure

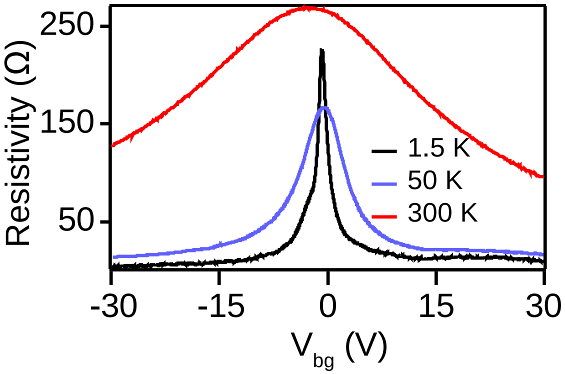


$$H_{\mathrm{TLG}} = \begin{array}{cccccc|c} \frac{A_1-A_3}{\sqrt{2}} & \frac{B_1-B_3}{\sqrt{2}} & \frac{A_1+A_3}{\sqrt{2}} & B_2 & A_2 & \frac{B_1+B_3}{\sqrt{2}} & \\ \Delta_2-\frac{\gamma_2}{2} & v_0\pi^\dagger & \Delta_1 & 0 & 0 & 0 & \frac{A_1-A_3}{\sqrt{2}} \\ v_0\pi & \Delta_2+\delta-\frac{\gamma_5}{2} & 0 & 0 & 0 & \Delta_1 & \frac{B_1-B_3}{\sqrt{2}} \\ \Delta_1 & 0 & \Delta_2+\frac{\gamma_2}{2} & \sqrt{2}v_3\pi & -\sqrt{2}v_4\pi^\dagger & v_0\pi^\dagger & \frac{A_1+A_3}{\sqrt{2}} \\ 0 & 0 & \sqrt{2}v_3\pi^\dagger & -2\Delta_2 & v_0\pi & -\sqrt{2}v_4\pi & B_2 \\ 0 & 0 & -\sqrt{2}v_4\pi & v_0\pi^\dagger & \delta-2\Delta_2 & \sqrt{2}\gamma_1 & A_2 \\ 0 & \Delta_1 & v_0\pi & -\sqrt{2}v_4\pi^\dagger & \sqrt{2}\gamma_1 & \Delta_2+\delta+\frac{\gamma_5}{2} & \frac{B_1+B_3}{\sqrt{2}} \end{array}$$

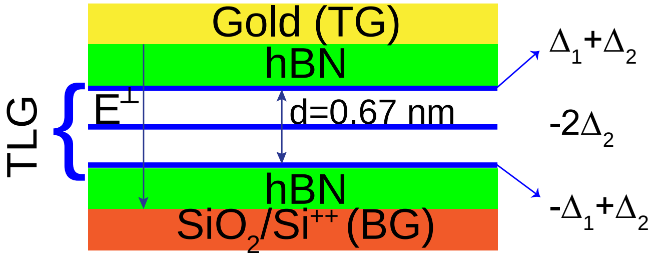
- Electric field increases the band gap of MLG-like bands
- 0_M^+ LL originates from the bottom of the MLG-like conduction band and 0_M^- LL originates from the top of the MLG-like valence band

Understanding our experimental system

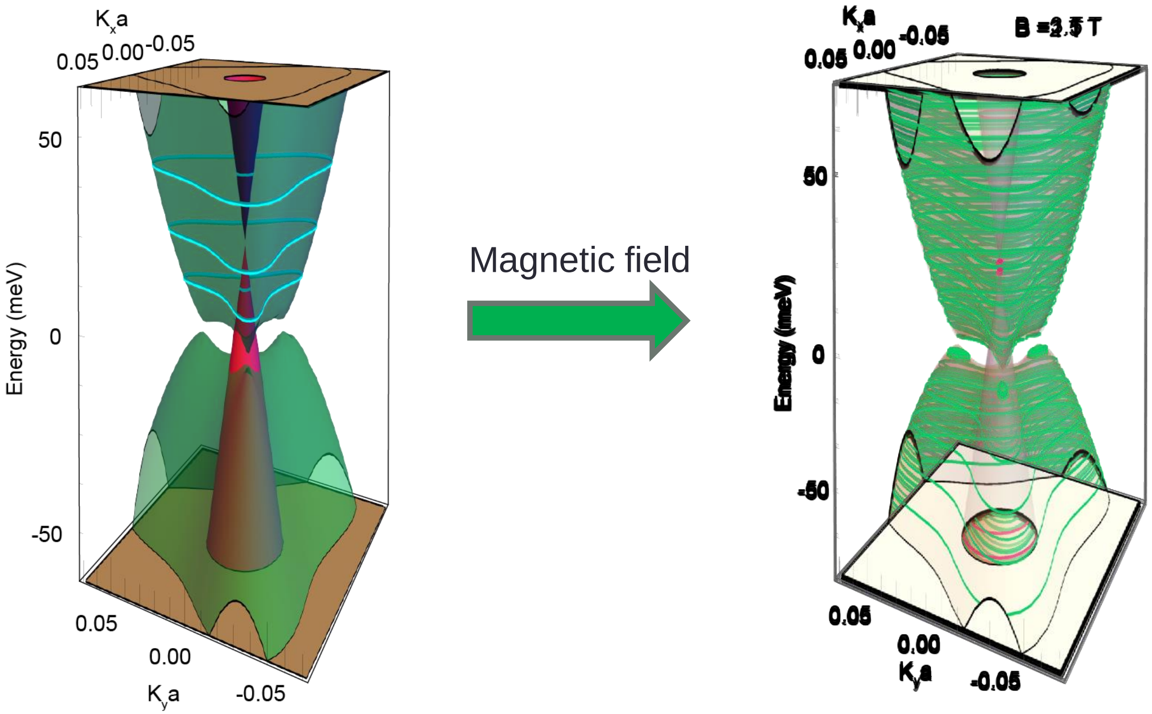


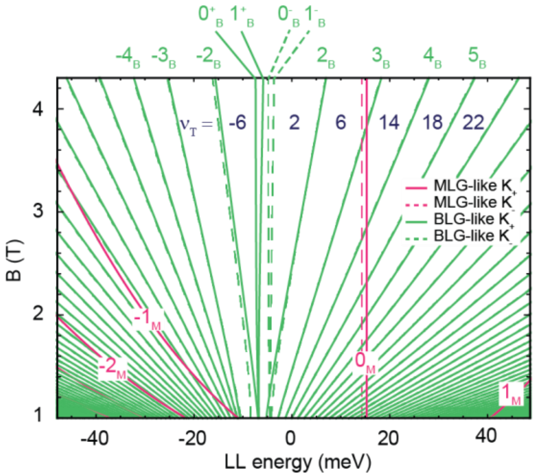


- Mobility ~ 800,000 $cm^2 V^{-1} s^{-1}$
- Mean free path ~ 10 µm
- Average $E^{\perp}=2\Delta_1/d$ (e)



Landau levels



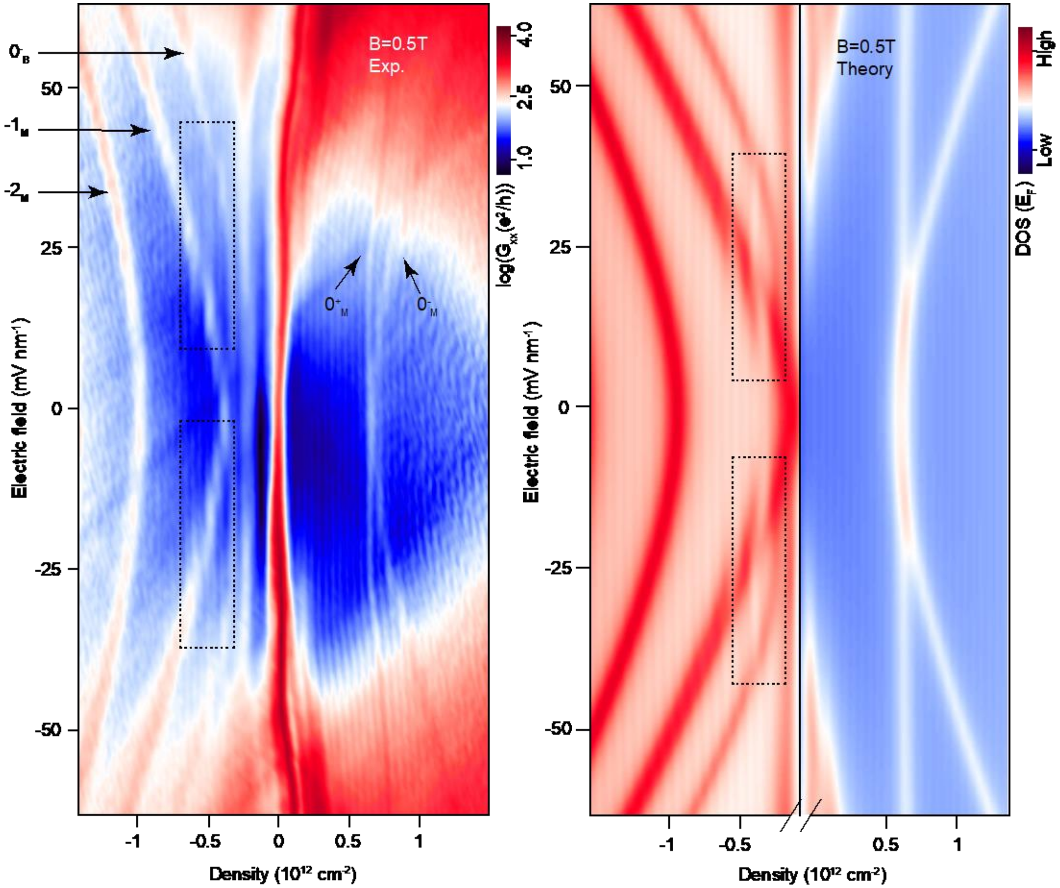


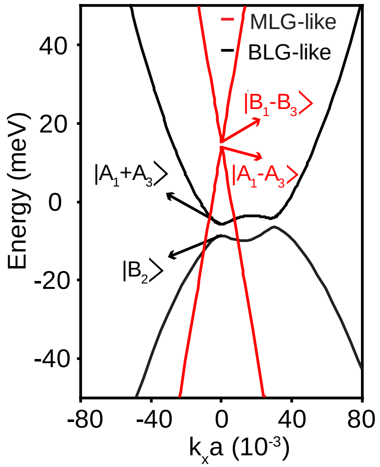
$$E_{MLG}(B,N) \sim \pm\sqrt{BN}, N = 0,1,2\ldots$$

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

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

Tuning Band Gap Between Monolayer-like Graphene Bands – electric field induced symmetry breaking





- Valley gap of N_M=0 LL is same as the band gap of MLG-like bands
- At $E^{\perp}$= 0 for a disorder ~1 meV there is no valley gap of N_M=0 LL meaning the band gap is ~ 1 meV

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

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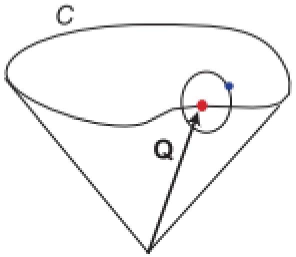
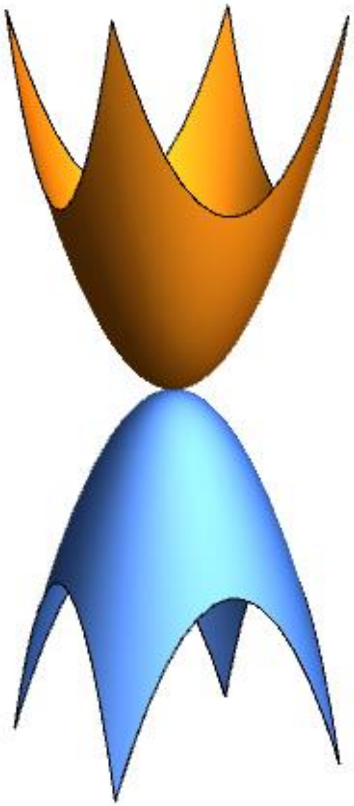
Berry’s phase

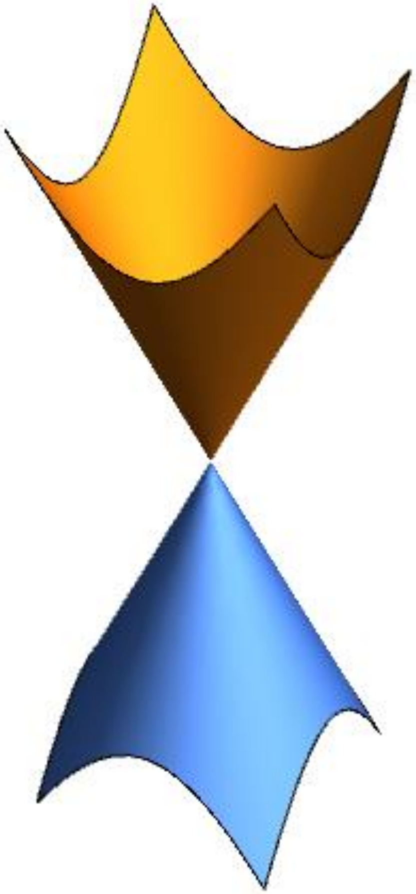


- First version of this for optics proposed by Panchratnam
- A geometric phase
- The flux enclosed by the closed loop due to the Berry’s curvature
- In a periodic lattice depends on symmetry of the lattice

Berry’s phase for different bands?

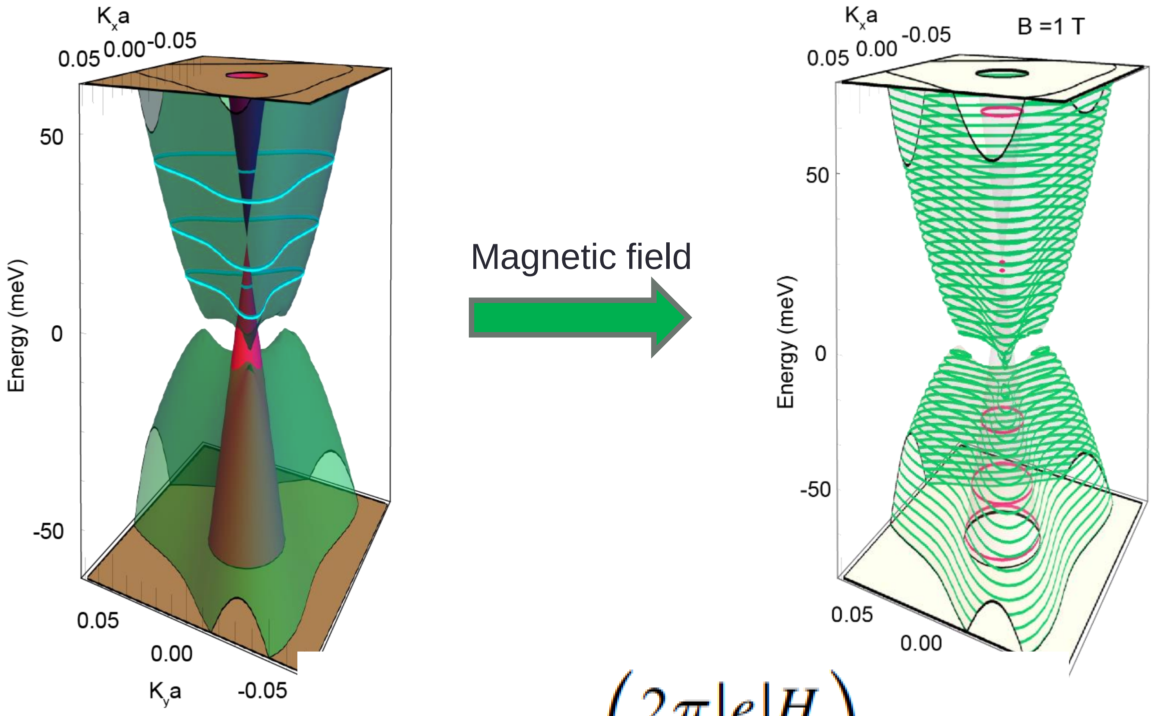


Berry’s phase = $2\pi = 0$ (modulo 2π)



Berry’s phase = π (modulo 2π)

Semiclassical quantization and Berry’s phase



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

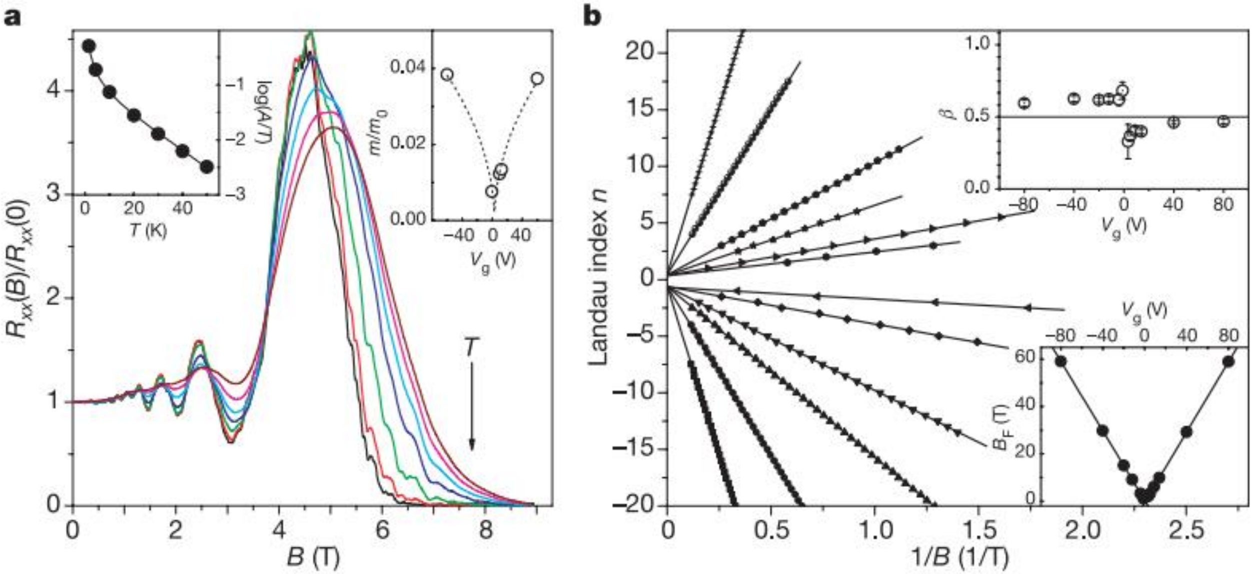
$$\gamma - \frac{1}{2} = -\frac{1}{2\pi} \oint_{\Gamma} \mathbf{\Omega}\, d\mathbf{k}$$

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

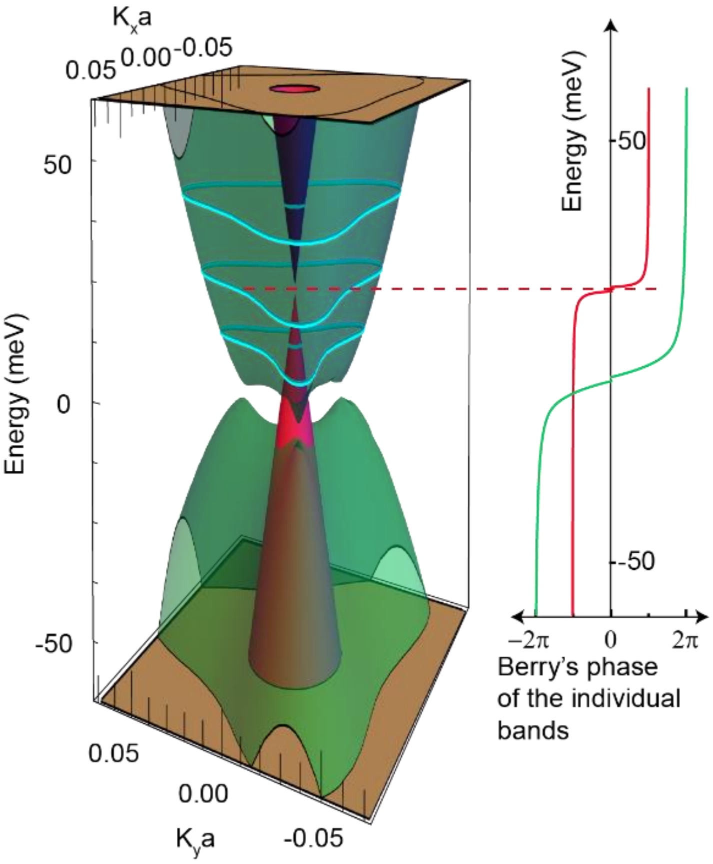
$$\Delta R_{xx} = R(B,T)\cos[2\pi(B_F/B + 1/2 + \beta)]$$



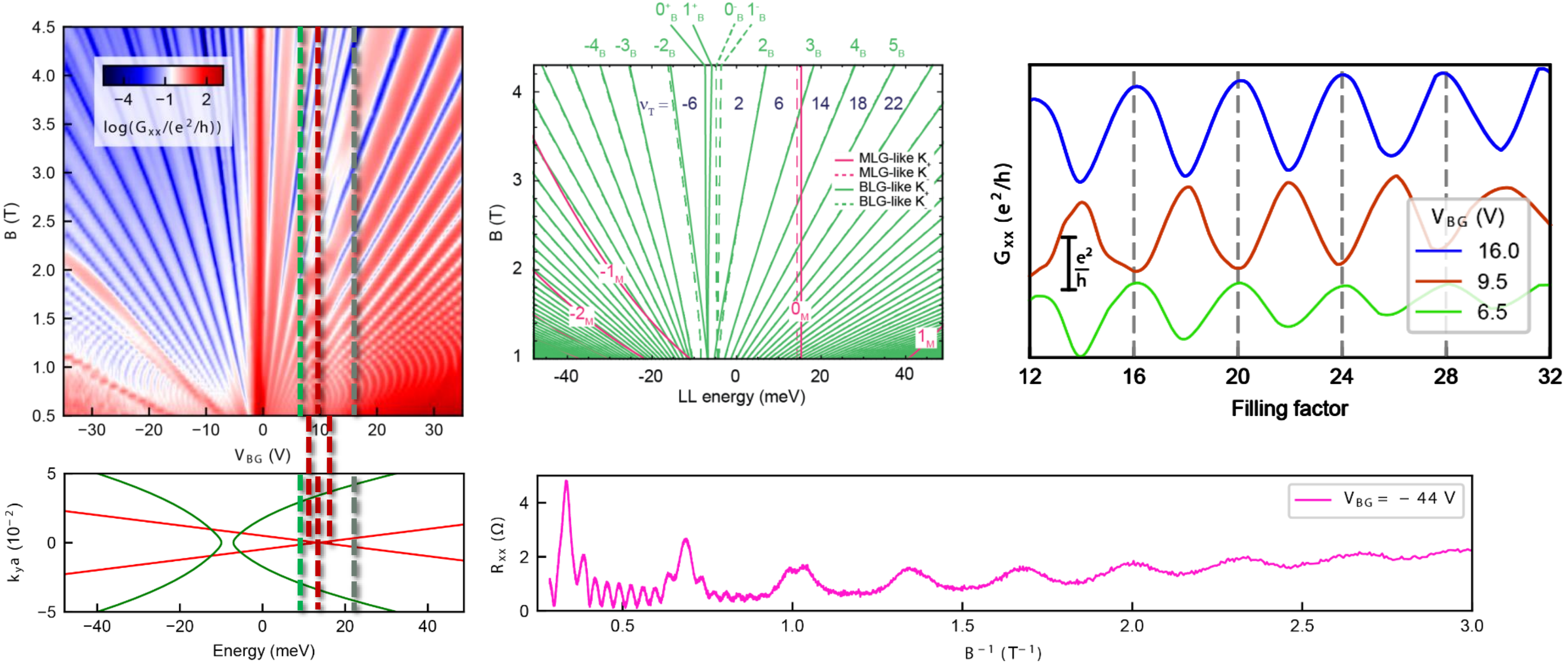
Zhang et al. Nature **438**, 201 (2005).

Connection to trilayer physics

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

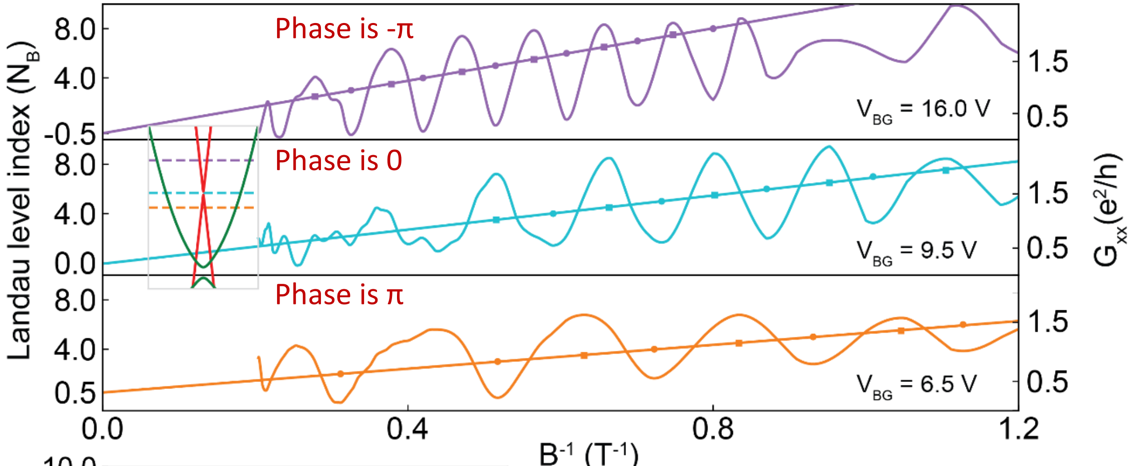


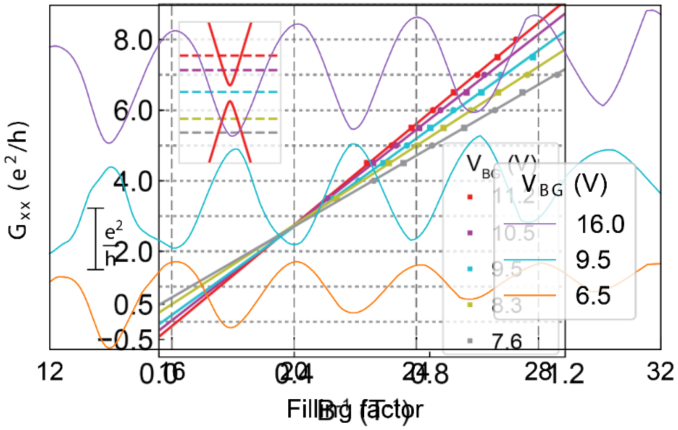
Multiband magnetotransport

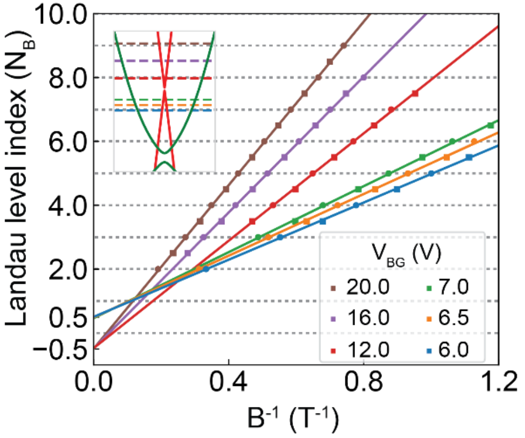


- Two SdH frequency results from two Fermi surfaces
- Phase of the BLG-like oscillations depend on the MLG-like band gap!
- Changing phase is not Berry's phase of the bilayer band

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?

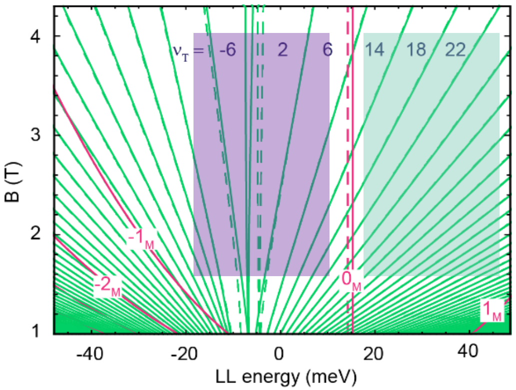
$$\Delta G_{XX} = G_M \cos\left[2\pi\left(\frac{B_{FM}}{B}+\Upsilon_M\right)\right] + G_B \cos\left[2\pi\left(\frac{B_{FB}}{B}+\Upsilon_B\right)\right]$$

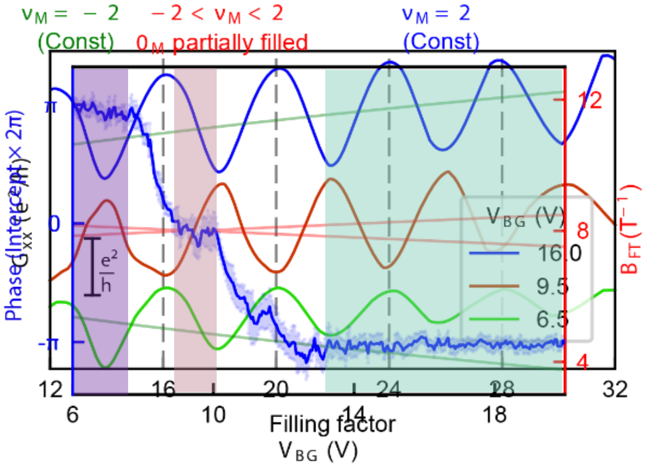
$$B_{FM} = \frac{n_M\, h}{4e} \qquad B_{FB} = \frac{n_B\, h}{4e}$$

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

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

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





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

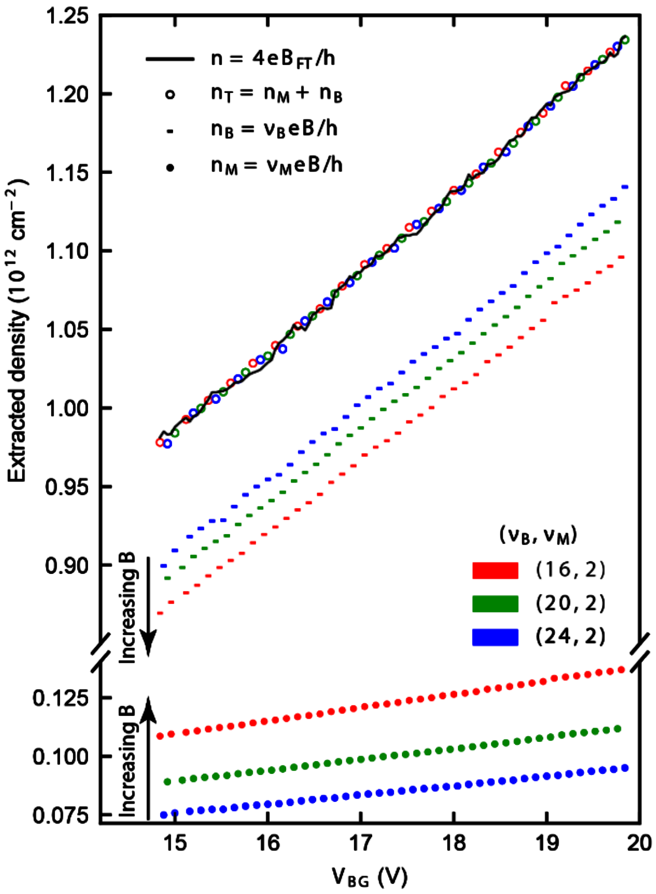
$$\Delta G_{XX} \approx G_B \cos\left[2\pi\left(\frac{B_{FB}}{B}+\Upsilon_B\right)\right]$$

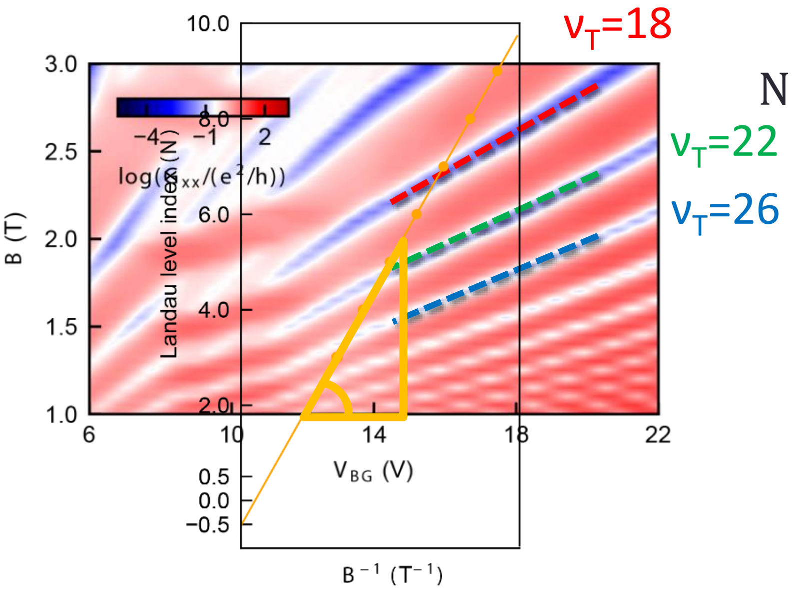
Above the gap ν_M= 2

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

Datta et al. arXiv:1902.04264 (2019).

SdH frequency -- area of Fermi Surface and filling enforcement

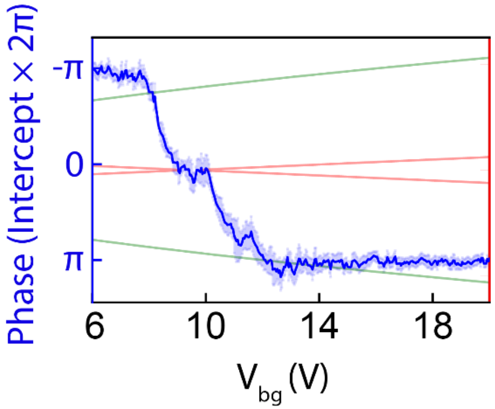


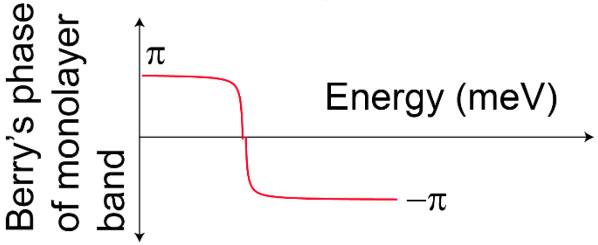


$$\mathrm{N} = \frac{B_{FT}}{B_N} + \frac{\Phi_B}{2\pi} - \frac{\nu_M}{4}$$

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

Extracting phase across band edge





Summary

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- Berry’s phase in a multiband system -- key role of filling enforcement in pickup of non-trivial phase in a trivial band

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