Graphene's divergent orbital diamagnetism at the Dirac point

Jorge Vallejo Bustamante

Mesoscopic Physics group LPS

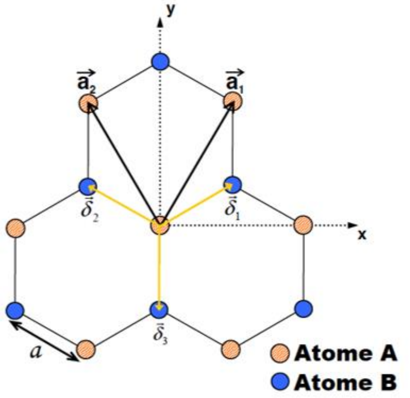
PhD advisors:

Helene Bouchiat

Meydi Ferrier

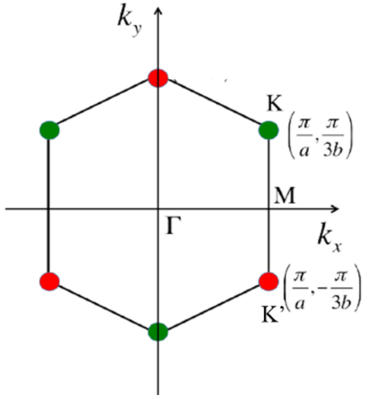
Why graphene?

Real space Honeycomb lattice

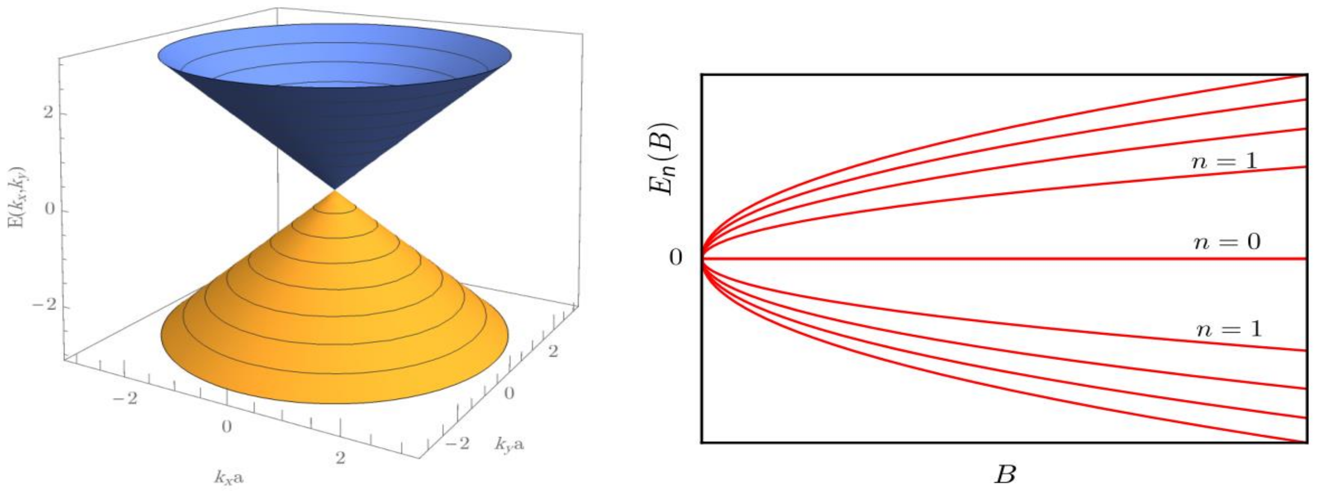


Lecture notes. D Mayou.
University Grenoble Alpes

Reciprocal space

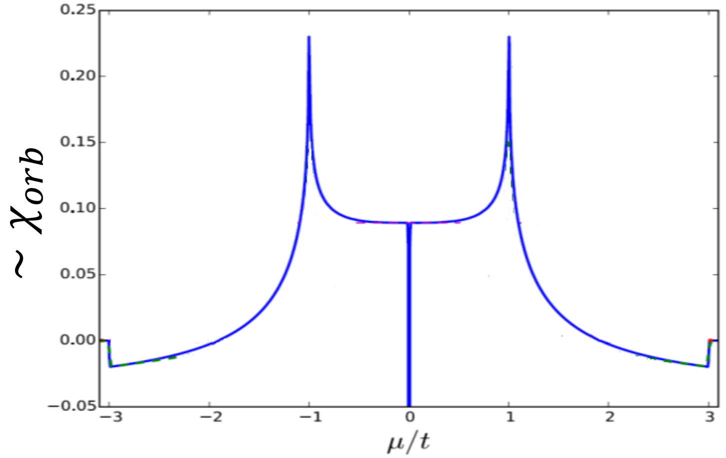


Lecture Notes on Graphene. D Ninno.
University of Naples



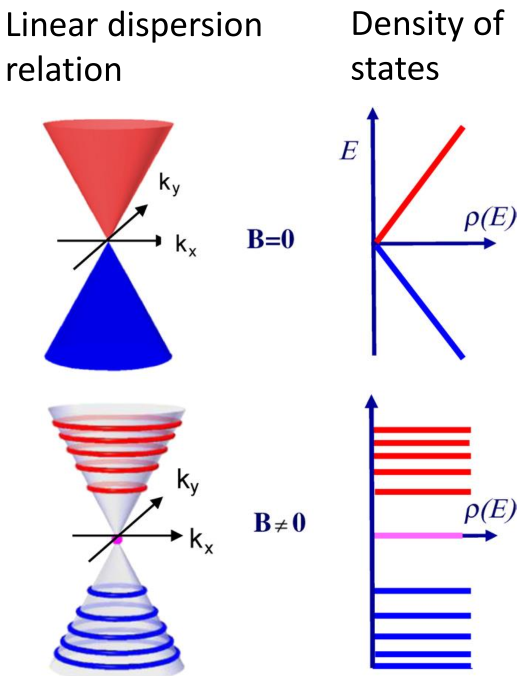
Raoux A. Thèse doctorale. UParis-Saclay, 2017. Français.

Graphene's orbital magnetic susceptibility



Raoux A. *et al Phys. Rev. B* 91, 085120 2015

Diamagnetic orbital currents in graphene

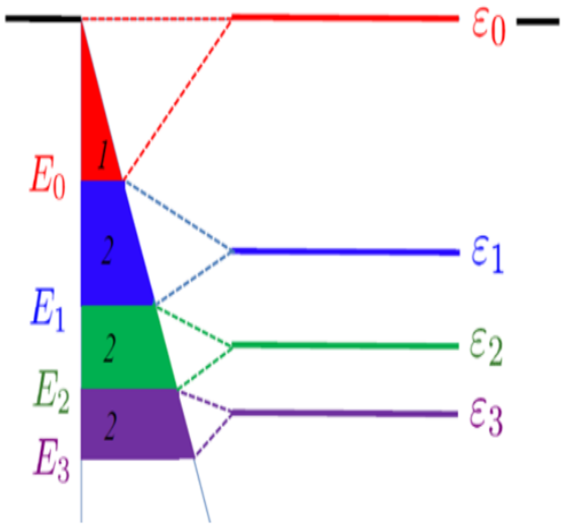


Eva Y Andrei *et al* 2012
Rep. Prog. Phys. **75** 056501

Condensation of states from B=0 to the Landau levels.

Energy of occupied states close to the Dirac point increases with B

$$E_k = \hbar v_F k \xrightarrow{B} \varepsilon_B(N) = \sqrt{2 e {v_F}^2 \hbar B |N|}$$



Raoux A. Thèse doctorale. UParis-Saclay, 2017. Français.

- Berry phase of π
- Electron-hole symmetry
- Interband transitions

$$M = -\frac{\partial(\Omega_B - \Omega_0)}{\partial B},$$

$$\chi = \lim_{B \to 0} \frac{\partial M}{\partial B}$$

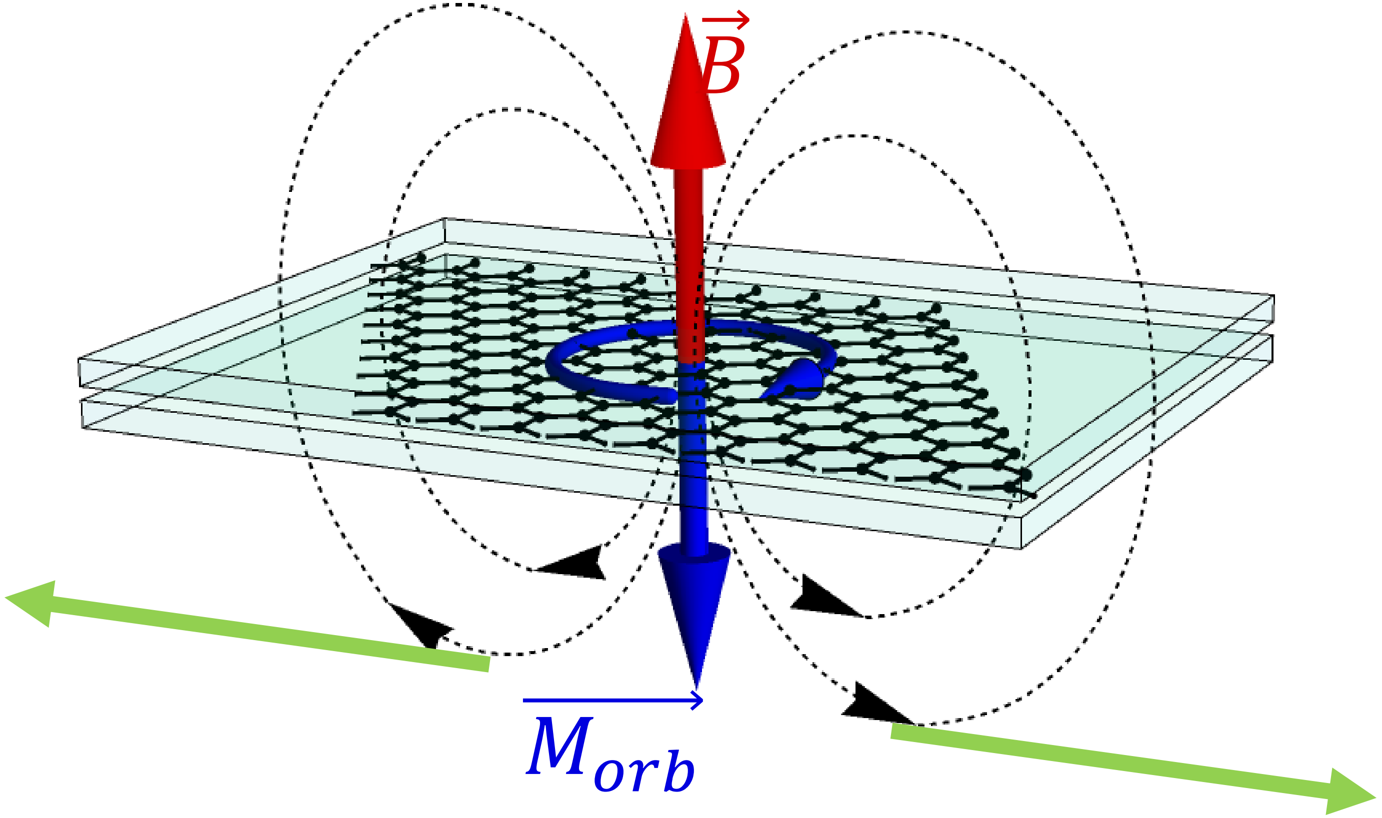
$$\chi_{McC} = -\frac{2e^2 v_F^2}{3\pi} \delta(\mu),$$

Ω = Grand canonical potential

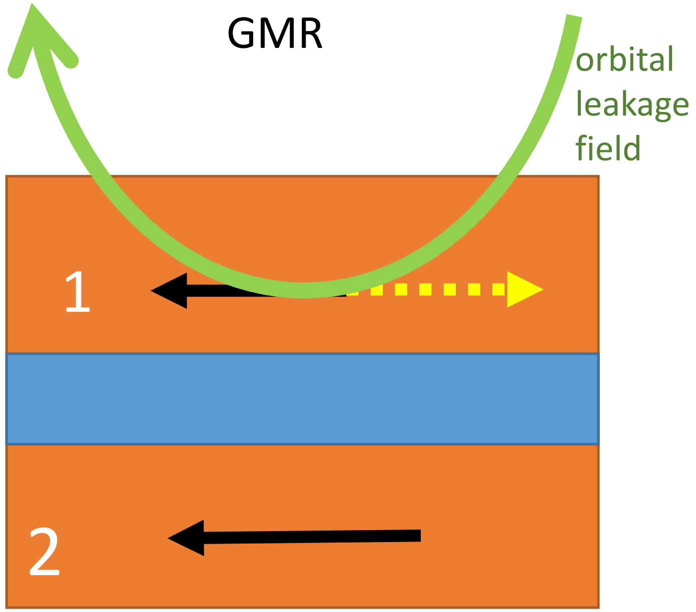
Measuring principle

B: applied vertical magnetic field

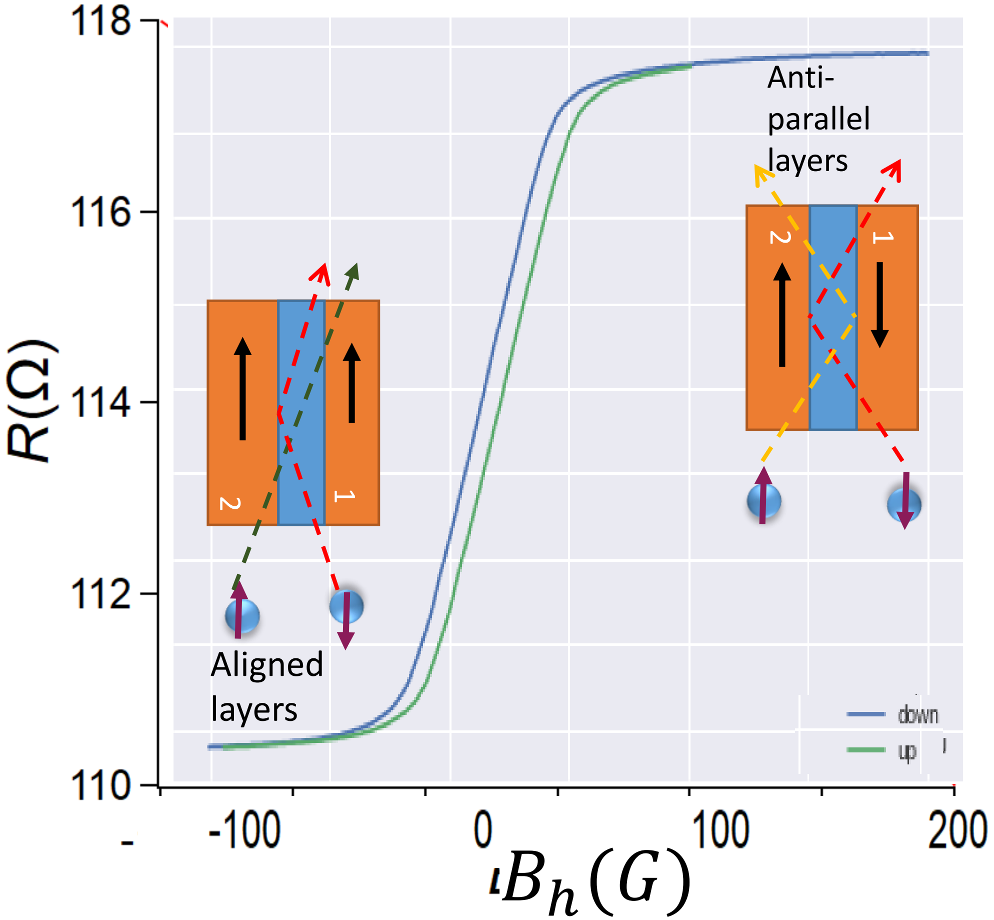
Morb: diamagnetic response of graphene

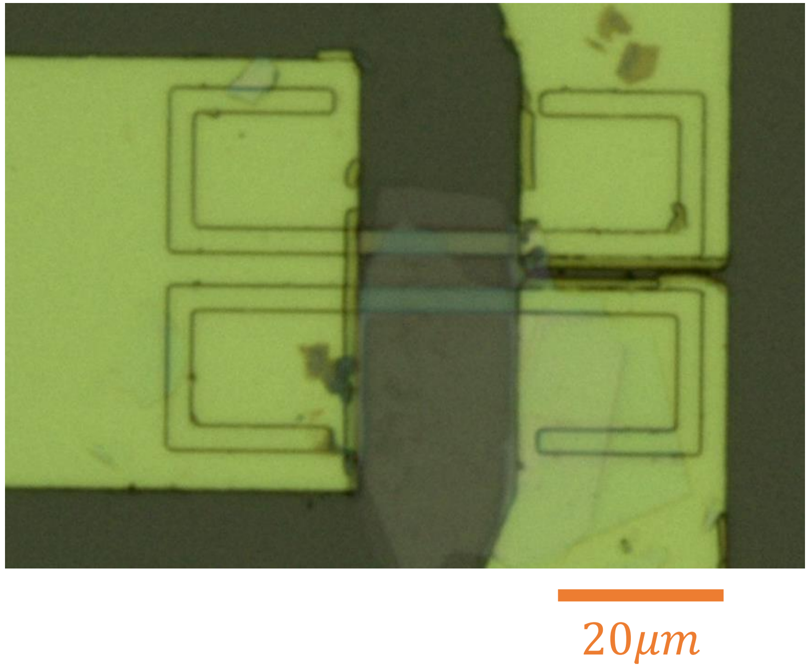


Giant magnetoresistance sensors



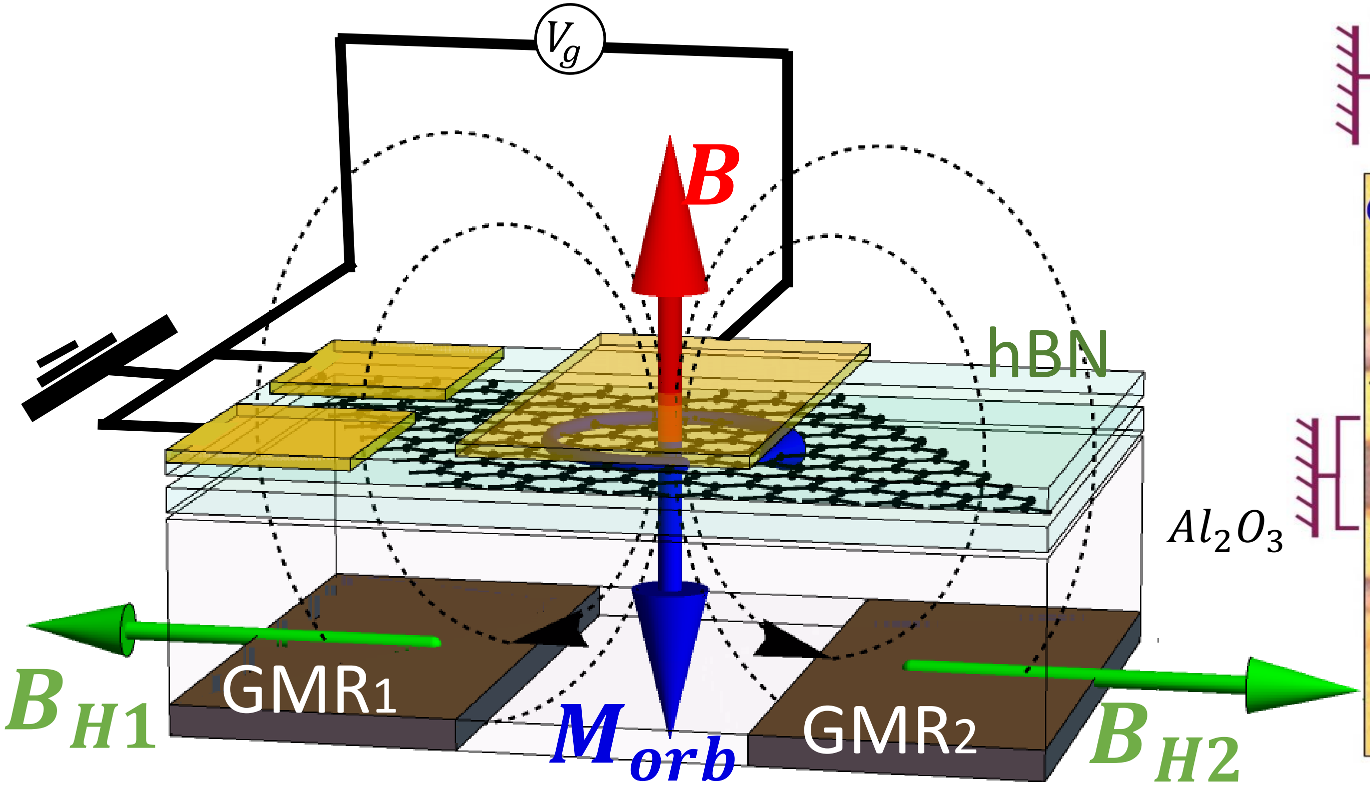
1) Soft ferromagnetic which can align with Bh
2) Hard ferromagnetic, pinned in one direction

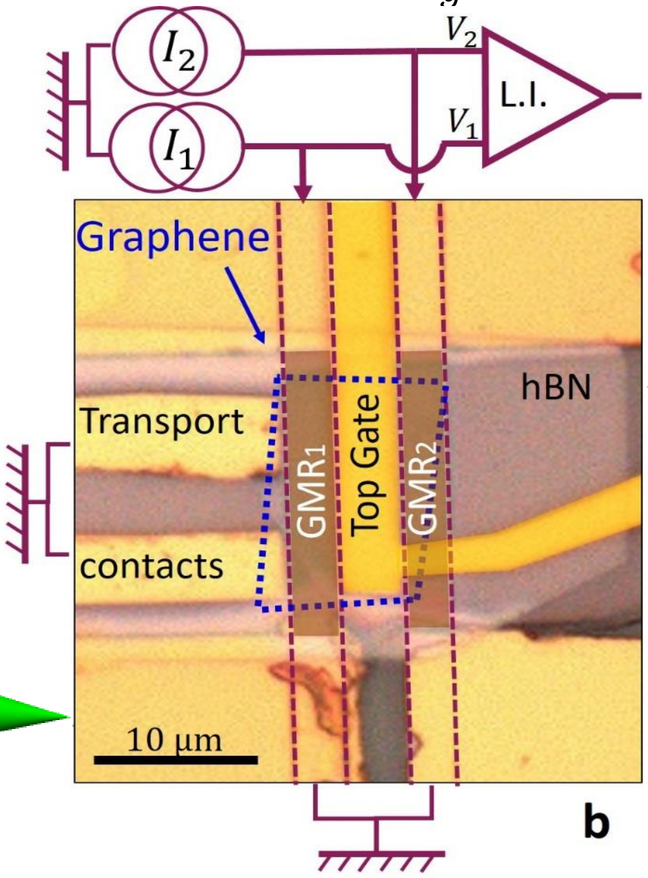




High sensitivity: GMRs and Gate modulation

- Sensors: GMRs probes insensitive to perpendicular B. Collaboration: C Fermon et M Pannetier-Lecoeur, CEA
- Gate modulation $V_g = V_{DC} + \delta V_g \cos \omega t, \quad \delta V_g \to 0$ <u>(only signal dependent on V_g)</u>



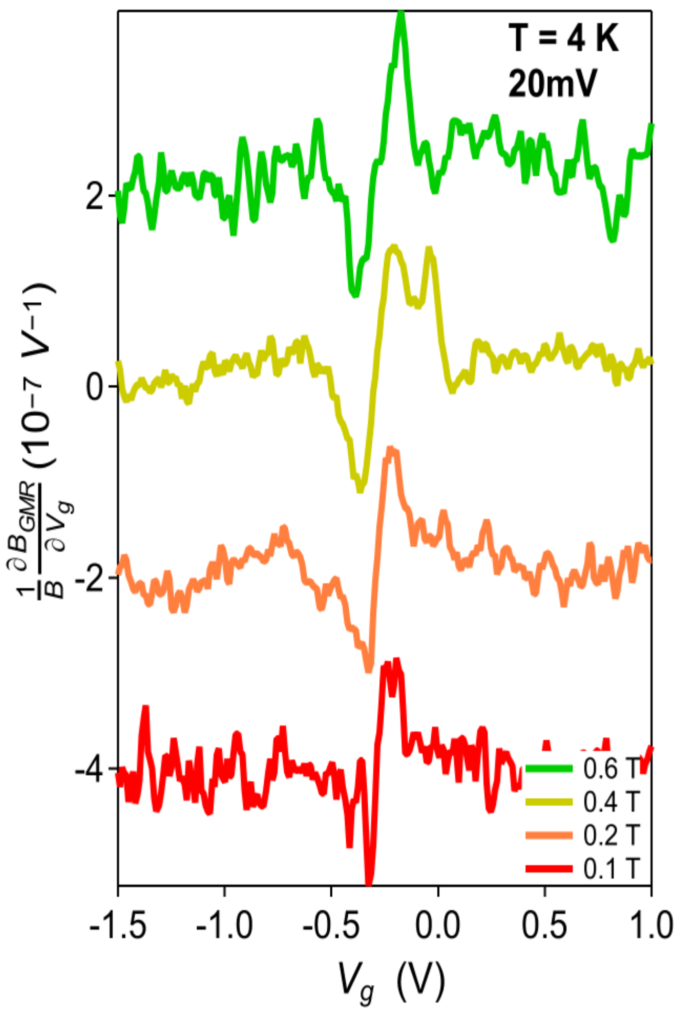


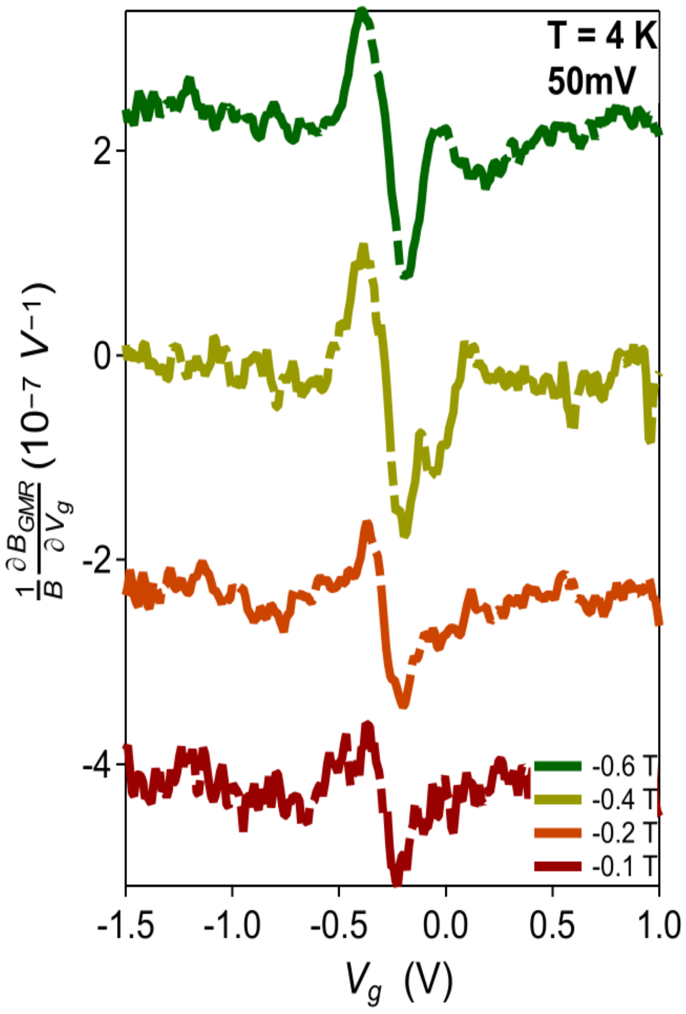
Encapsulated graphene:
BN-G-BN stack
100nm Au top gate
1 μm Alumina

$$B_1 - B_2 \propto V_1(\omega) - V_2(\omega) \propto \frac{\delta M_{Orb}}{\delta V_g}$$

B: applied vertical magnetic field
Bh: compensation horizontal magnetic field
$B_{1,2}$: **Measured field**

Magnetization: $\frac{1}{B}\frac{\partial B_{GMR}}{\partial V_g}$ vs $V_g, (T = 4.2K)$

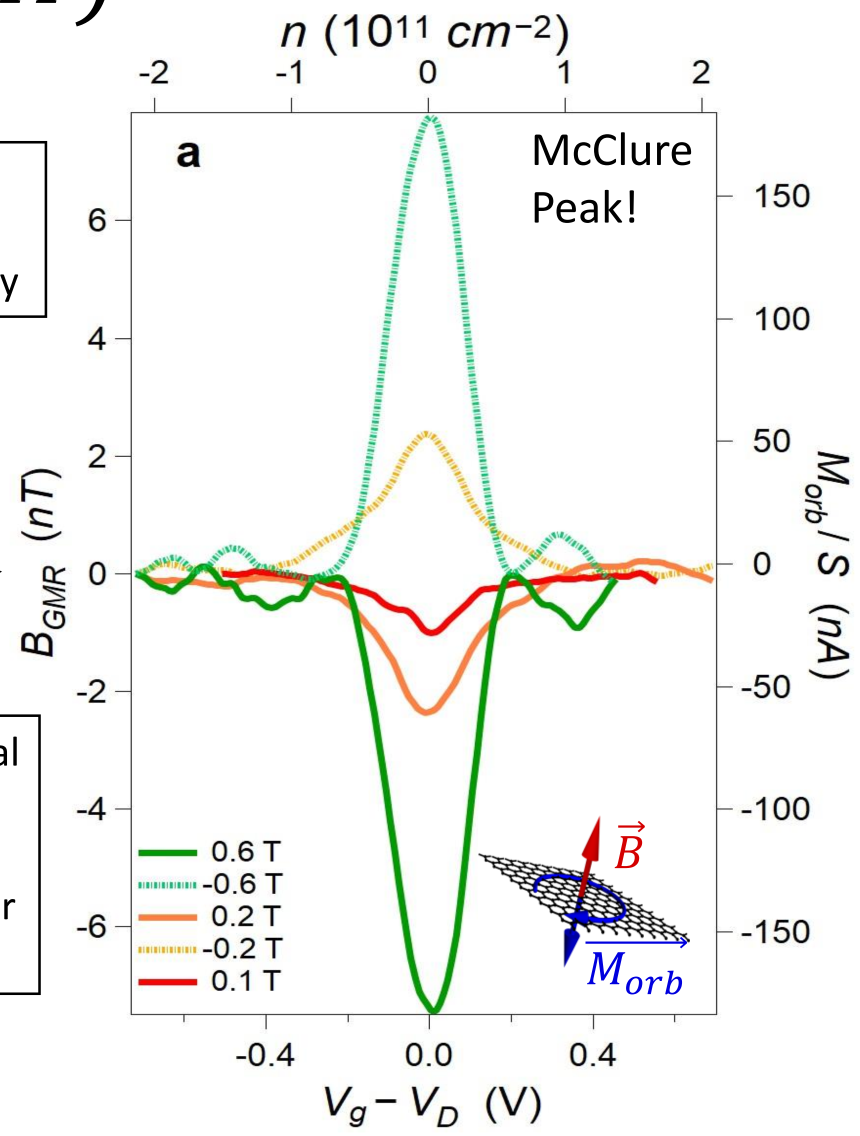




Sign determined independently

Numerical Integration

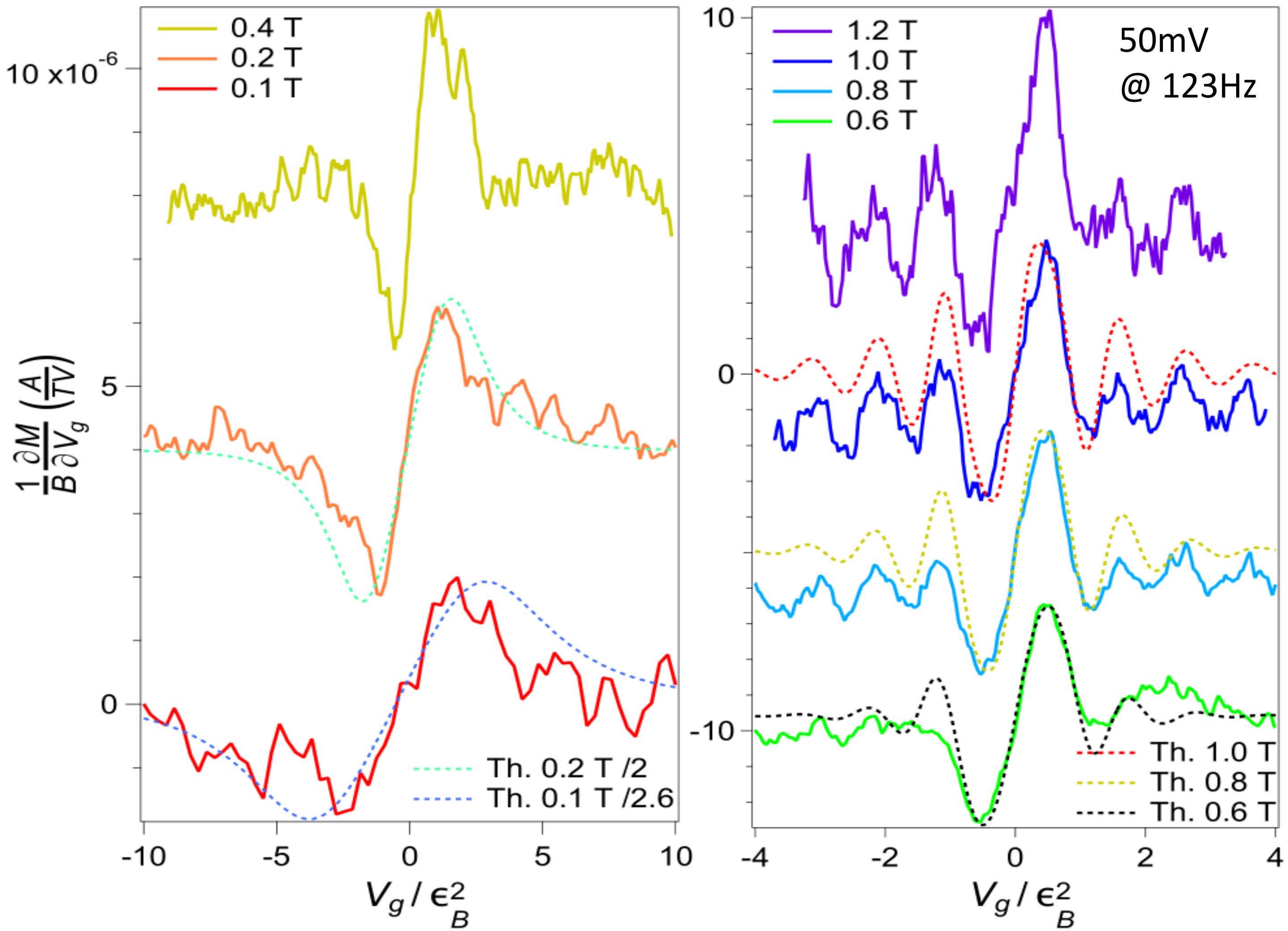
Model: Orbital current carried by rectangular loop (gate)



About **1 nT** for an external field of **0.1 T**

Science, 2021, vol. 374, no 6573, p. 1399-1402.

Magnetization: $\frac{1}{B}\frac{\partial B_{GMR}}{\partial V_g}$ vs $V_g, (T = 4.2K)$



Gaussian μ

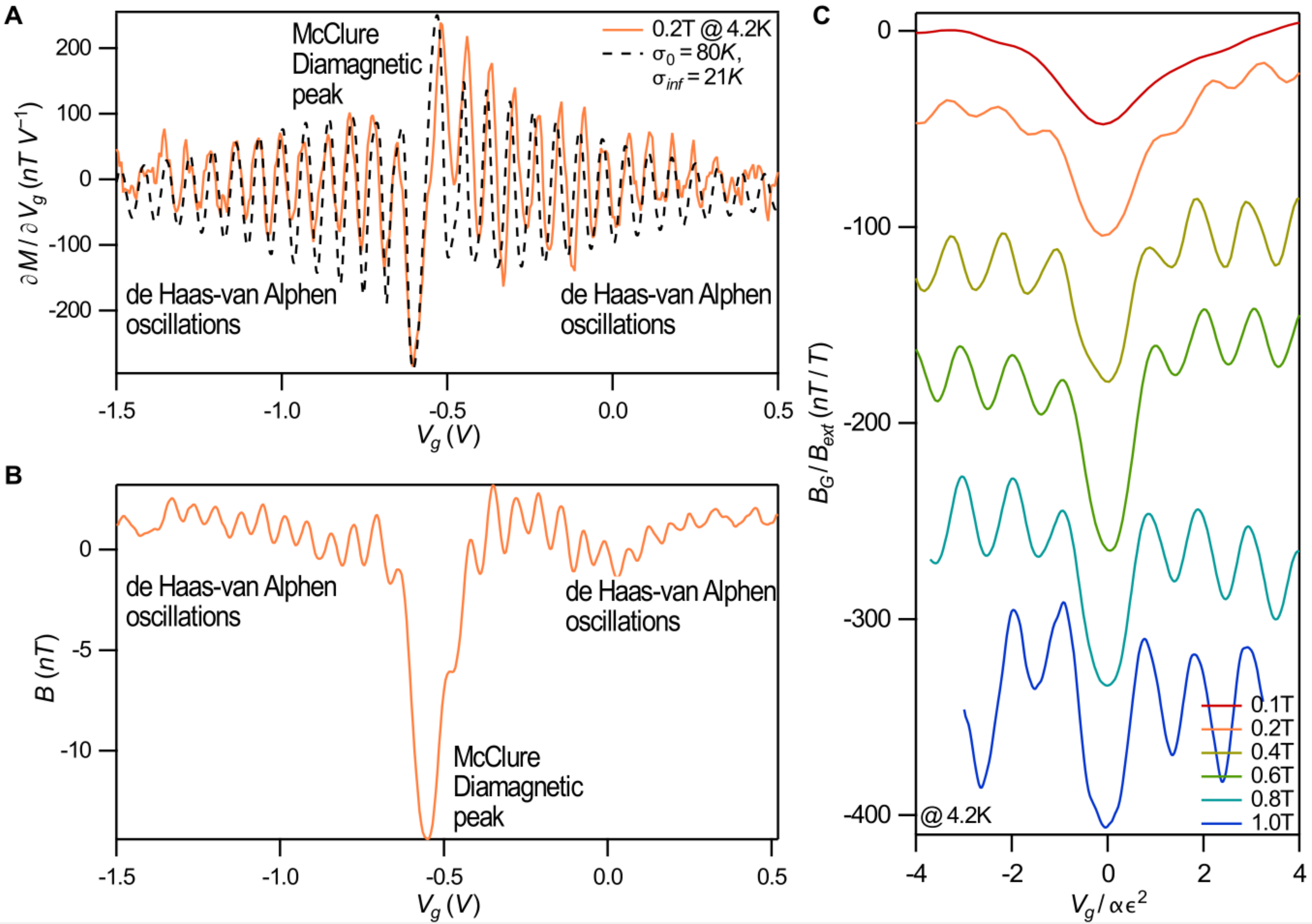
$$P(\mu_D) = \frac{1}{\sqrt{2\pi}\sigma(\mu)} exp\left[-\frac{\mu_D^2}{2\sigma^2(\mu)}\right]$$

$$\chi(\mu) = -\frac{e^2 v_F^2}{6\pi}\int P(\mu_D)\,\delta(\mu - \mu_D) d\mu_D$$

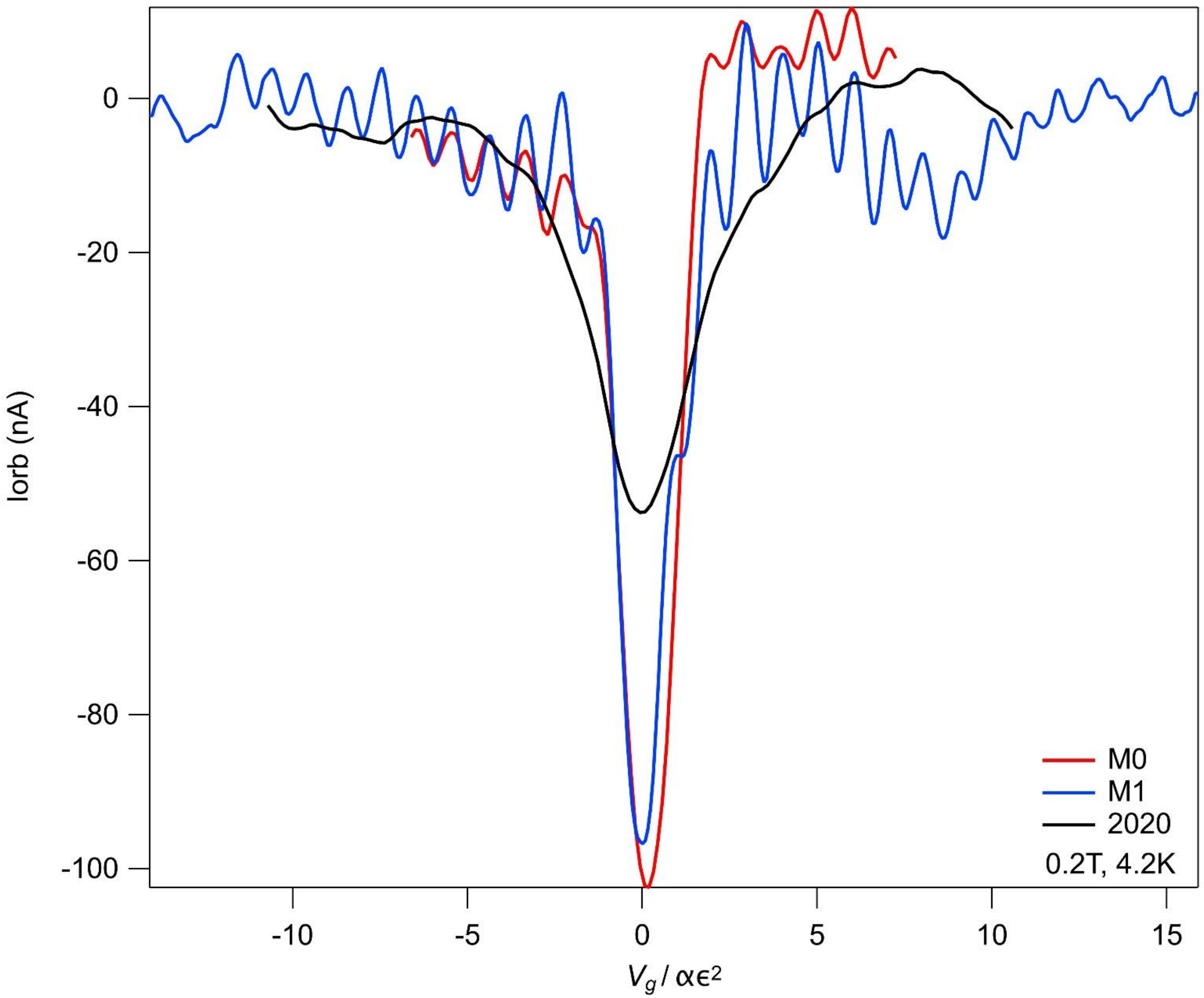
Collaboration G. Montambaux, LPS

Science, 2021, vol. 374, no 6573, p. 1399-1402.

Cleaner sample



Comparison 3 samples at 0.2T



In new samples, graphene is aligned with BN

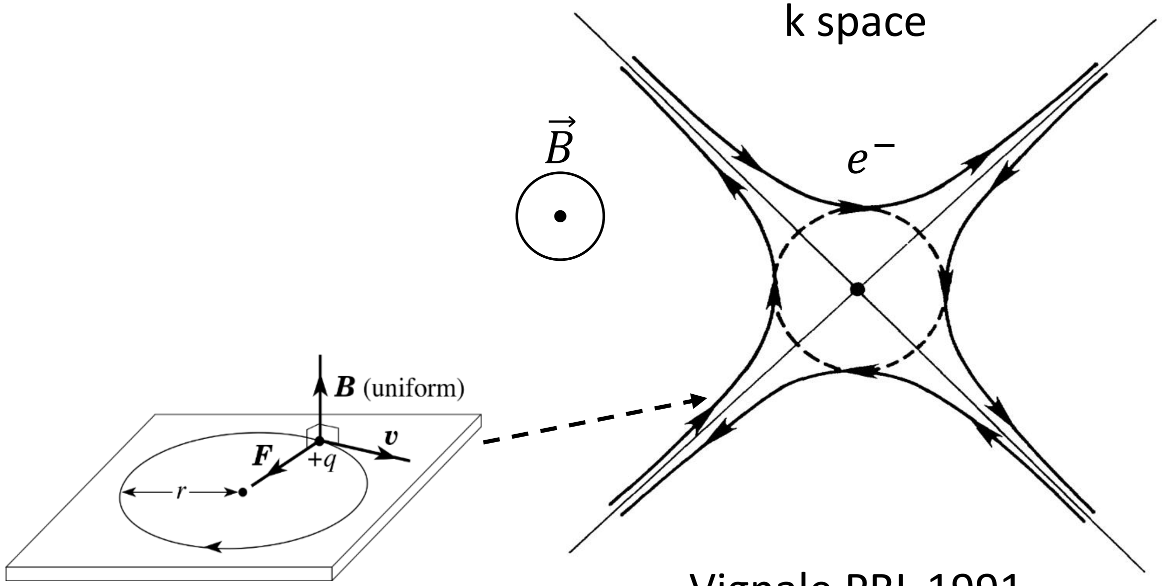
Orbital paramagnetism in 2D crystals

2D lattice: susceptibility is **positive** and **diverges logarithmically** near a van Hove singularity (vHs).

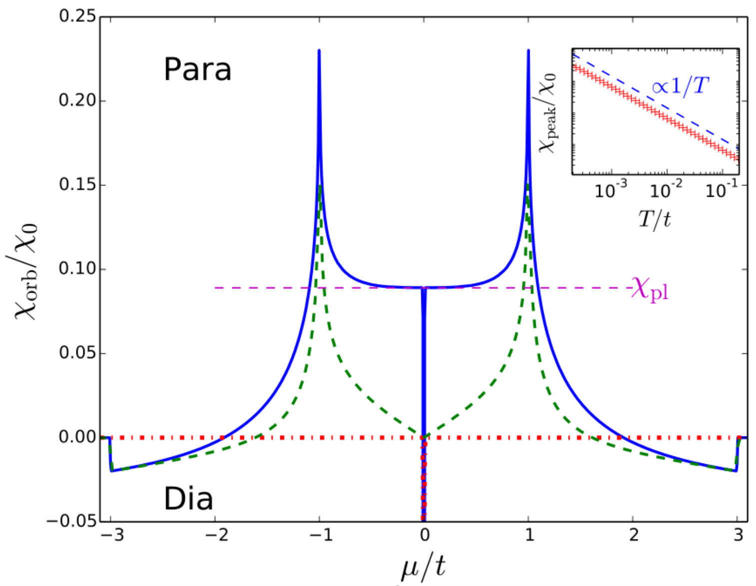
Quasi-classical e⁻ in B field follow trajectories with constant energy, hyperbolic open orbits following Lorentz law: diamagnetic.

Near vHs, tunneling appears, electrons jump between orbits, resulting orbit in opposed direction

➡ Orbital paramagnetism



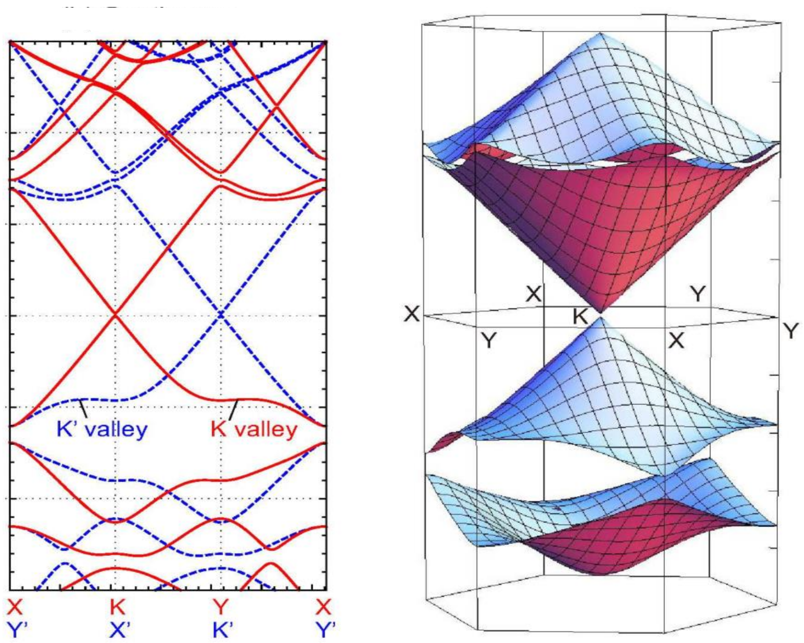
Vignale PRL 1991



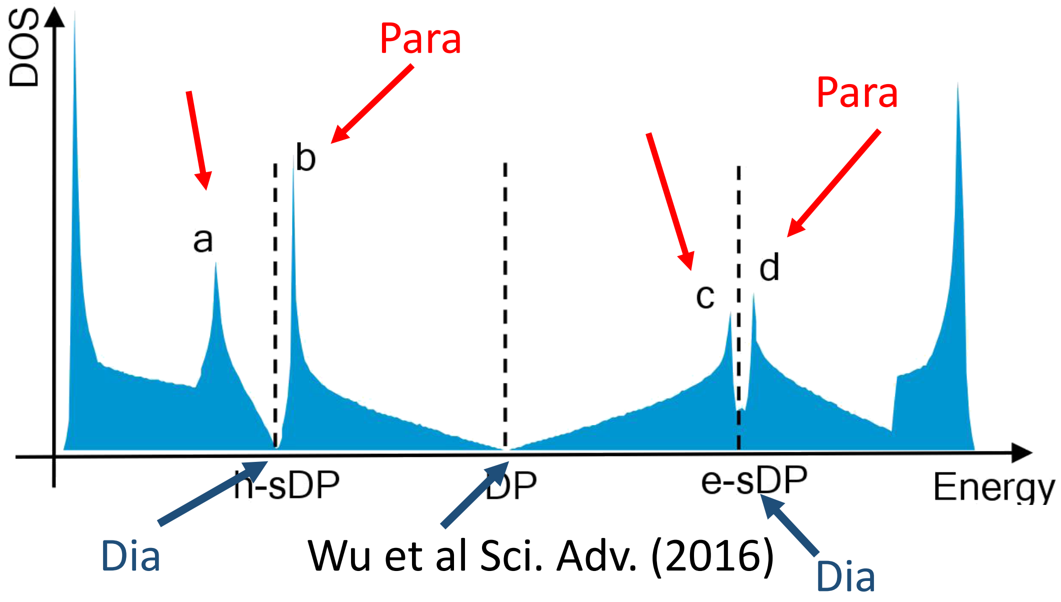
Raoux, et al. PRB. 2015.

Why graphene/BN moiré?

- Van Hove singularities in graphene not possible for this experiment ($\sim 10^3 V$).
- Moiré superpotential: satellite Dirac peaks appear at higher energies. Surrounding these peaks, 2 vHs per peak also appear.
- These satellite peaks can be achieved experimentally.
- Moriya et al, Nat. Com. (2020): indirect measurement of enhanced magnetism at vHs.



Moon, Koshino, Phys. Rev. B 90, 155406 (2014)



Wu et al Sci. Adv. (2016)

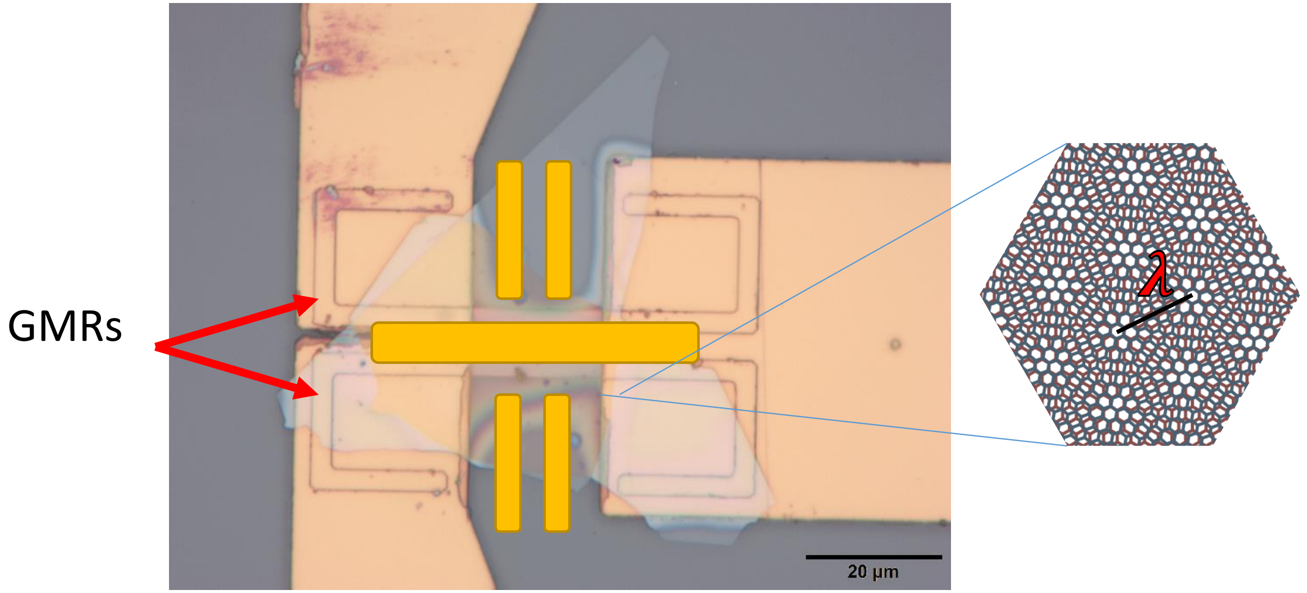
System

2 samples encapsulated graphene: hBN/G/hBN. Collaboration Rebeca Ribeiro-Palau C2N.

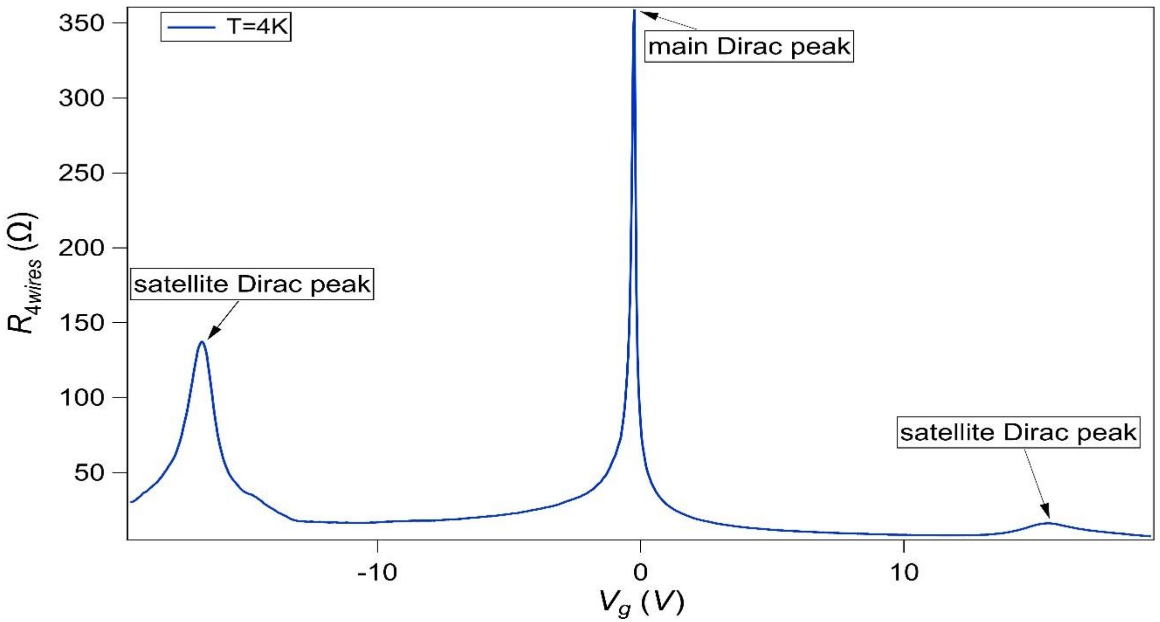
BN and graphene aligned (M0 ~ 0.5° and M1 ~ 1.5°)

Moiré pattern: satellite Dirac peaks (sPp) at high energy (doping) in addition to the main Dirac point (mDp).

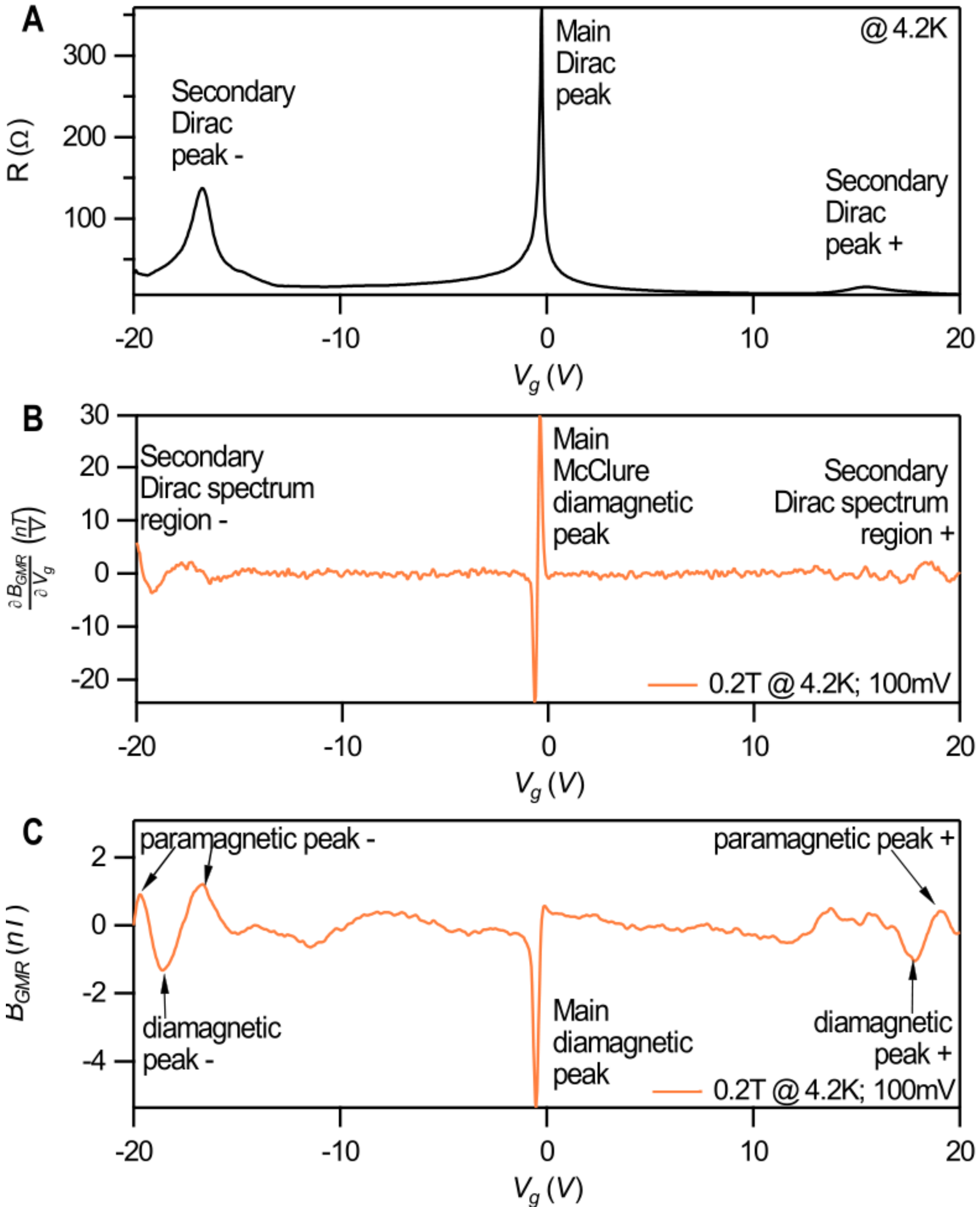
M1 sample



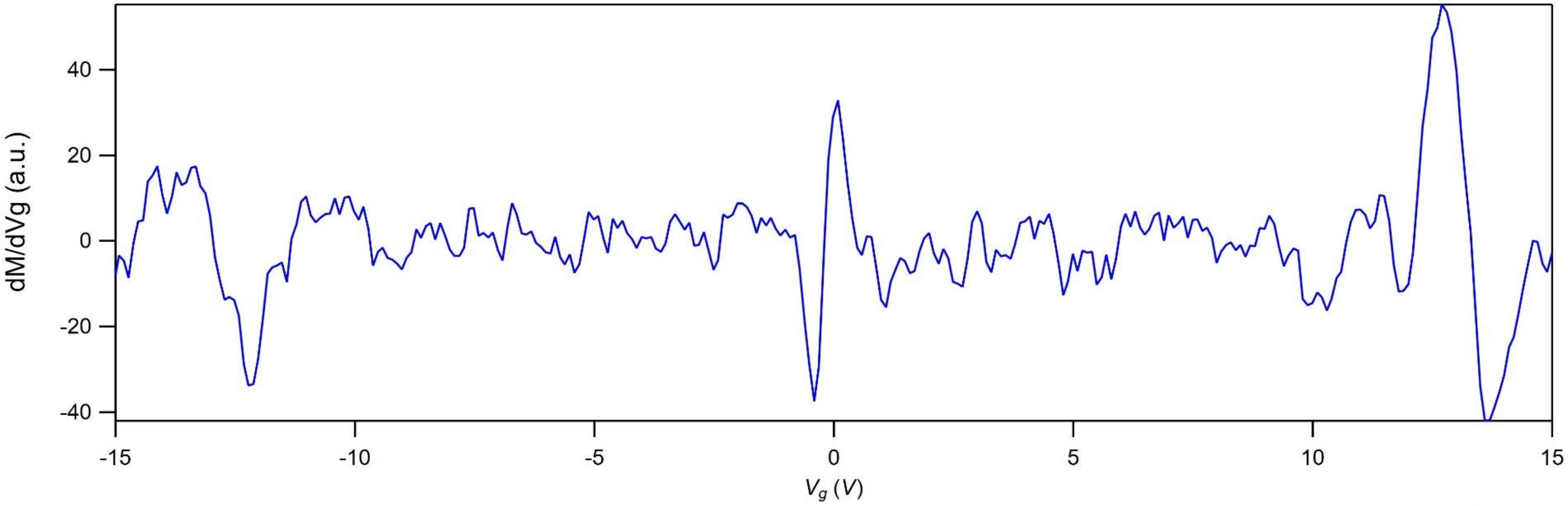
M1 four wires resistance

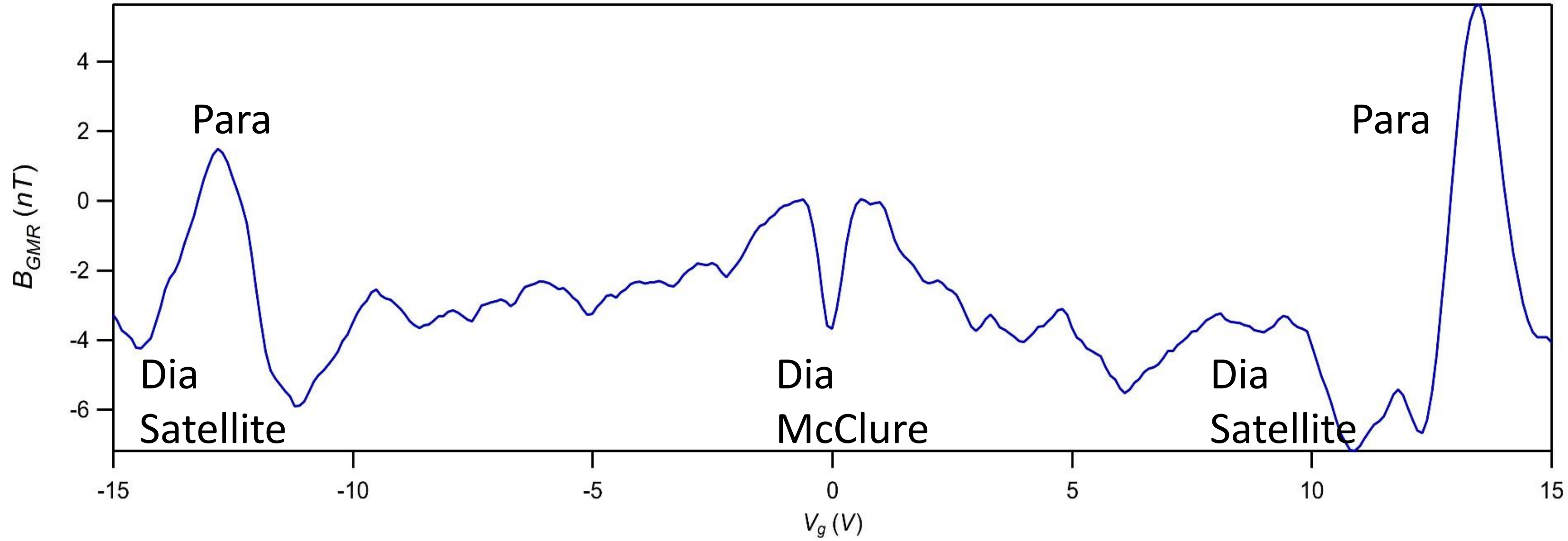


Results: high doping regime M1 at 0.2T (in preparation)

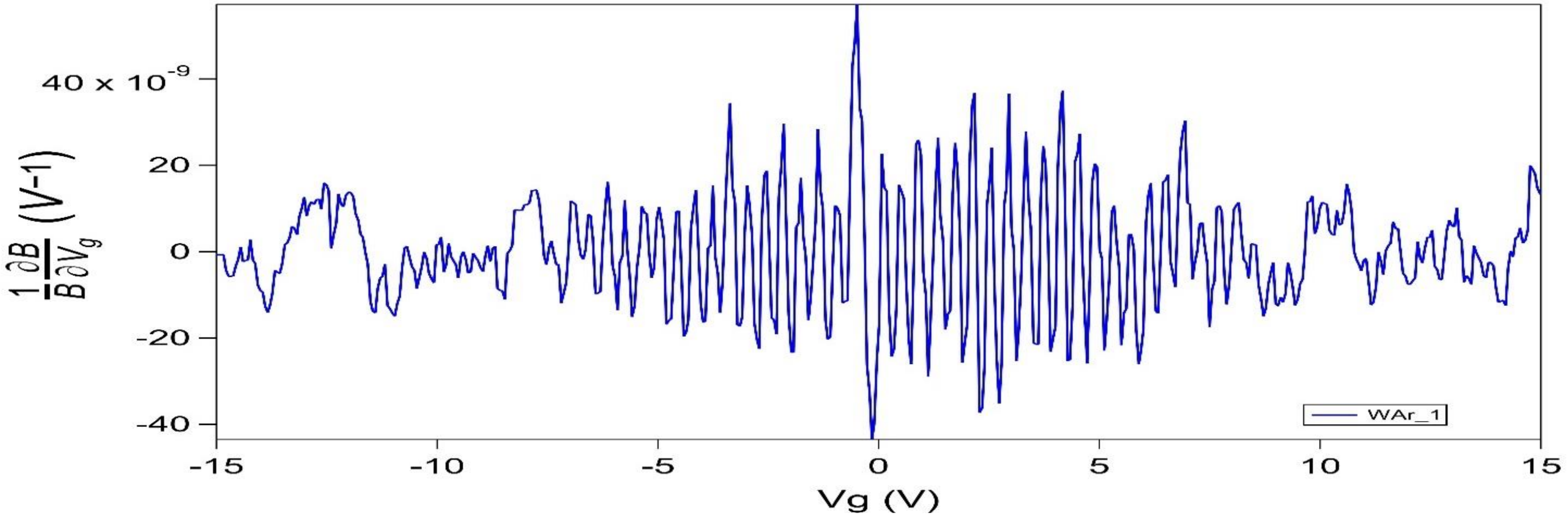


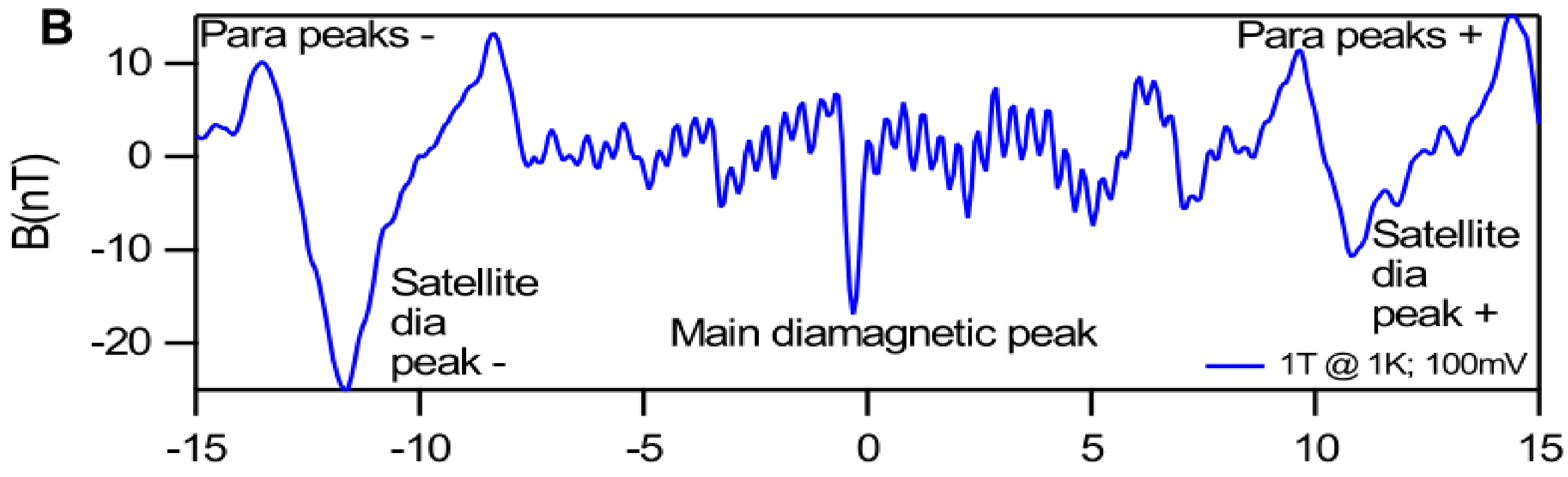
Results: high doping regime M0 at 0.2T





Results: high doping regime M0 at 1T

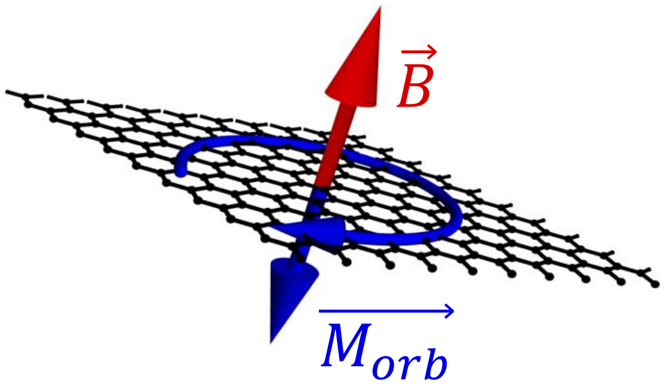




Conclusions

- McClure diamagnetic peak measured for single flake graphene. ***Science*, 2021, vol. 374, no 6573, p. 1399-1402.**
- Effects of high fields as de Haas- van Alphen oscillations in graphene.
- Reproduced McClure diamagnetic peak for 2 additional (cleaner) samples.
- Close to the position of the secondary Dirac points: Diamagnetic peaks (secondary McClure peaks).
- Surrounding the secondary McClure peaks, opposed sign peaks appear. They must be paramagnetic and are located close to the expected position of the vHs.

Dirac points



Van Hove singularities in moiré