nature physics

LETTERS

PUBLISHED ONLINE: 17 FEBRUARY 2013 | DOI: 10.1038/NPHYS2549

# Electrically tunable transverse magnetic focusing in graphene

Thiti Taychatanapat[1,2], Kenji Watanabe[3], Takashi Taniguchi[3] and Pablo Jarillo-Herrero[2]*

FAM

June 2, 2017

Mirko Rehmann

# Outline

- Motivation and Introduction
- General concepts of transverse magnetic focusing (TMF)
- TMF in monolayer (MLG), bilyer (BLG) and trilayer (TLG) graphene
- TMF as a ballistic electron spectroscopy method
- Temperature dependence of the TMF spectra
- Summary and conclusions

# Motivation and Introduction

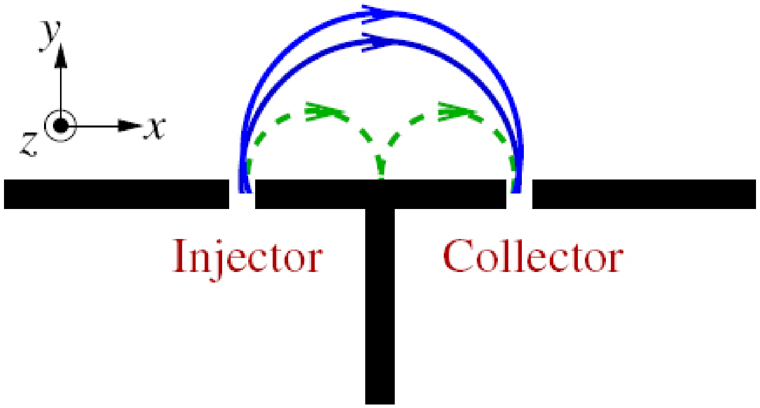
Ballistic motion of electrons over macroscopic distances → Focusing of electrons with a transverse magnetic field

<u>TMF used to study:</u>

- Fermi surface of metals [1]
- and semiconductor heterostructures [2]
- Andreev reflection [1]
- Spin-orbit interaction [3]
- Detection of composite fermions [4, 5]

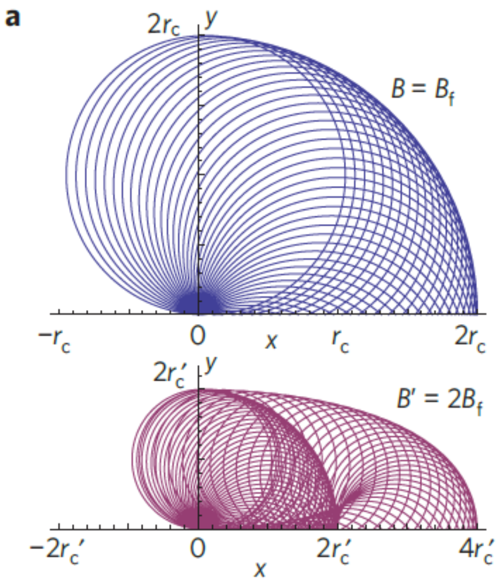
<u>And the quality of graphene edges:</u>

- Exploring the graphene edges with coherent electron focusing [6]
- Boundary scattering in ballistic graphene [7]




[1] Tsoi et al., Rev. Mod. Phys. **71**, 1641 (1999)
[2] Van Houten et al., Phys. Rev. B **39**, 8556 (1989)
[3] Rokhinson et al., Phys. Rev. Lett. **93**, 146601 (2004)
[4] Goldman et al., Phys. Rev. Lett. **72**, 2065 (1994)
[5] Smet et al., Phys. Rev. Lett. **77**, 2272 (1996)
[6] Rakyta et al., Phys. Rev. B **81**, 115411 (2010)
[7] Masubuchi et al., Phys. Rev. Lett. 109, 036601 (2012)

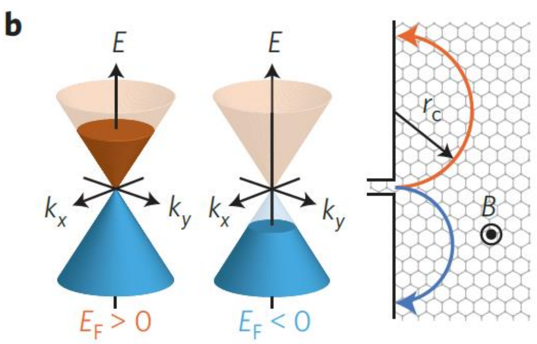
# General concepts of TMF




Magnetic field $B_f$ is required to focus electrons at a distance L:

$$B_f^{(p)} = \left(\frac{2\hbar k_F}{eL}\right)p = \left(\frac{2\hbar\sqrt{\pi n}}{eL}\right)p$$

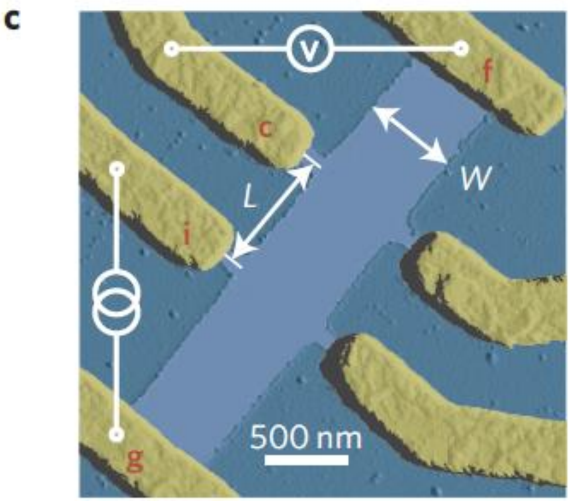
p-1: # of reflections off the edge

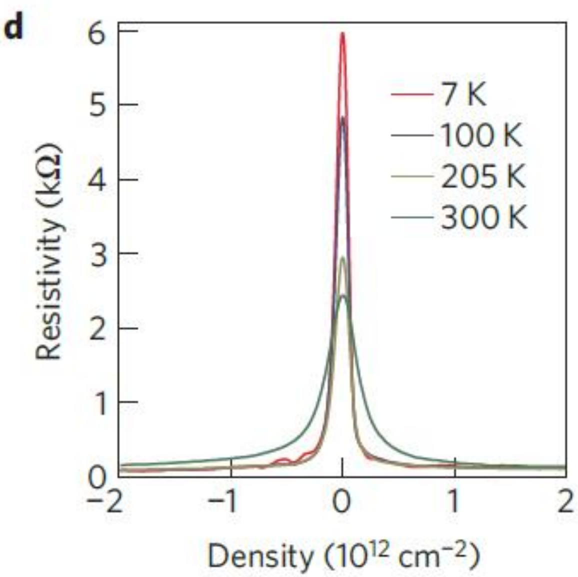



In graphene the density can be tuned continously from the hole to the elctron regime

For negative density (holes) the sign of $B_f$ changes as well!

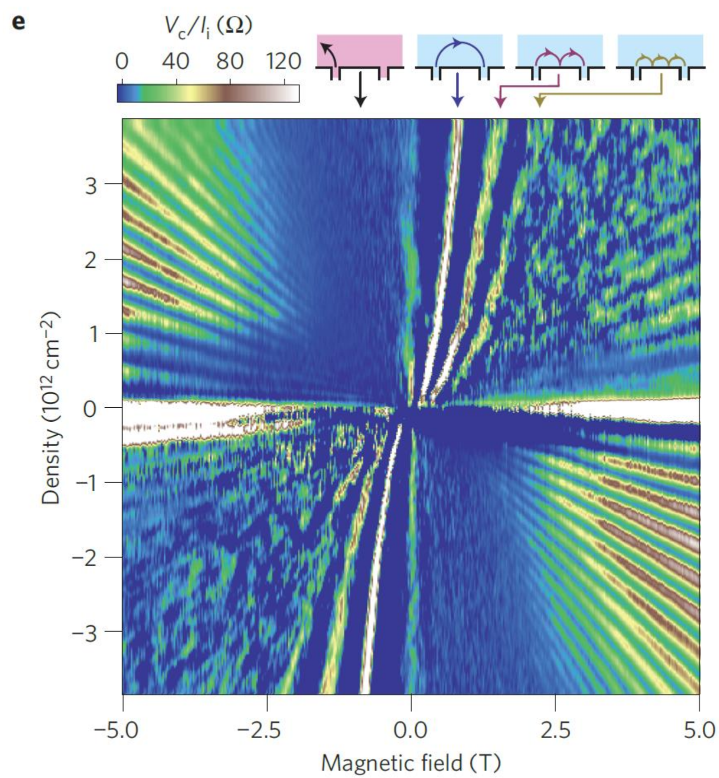
# Investigated Hall bar devices



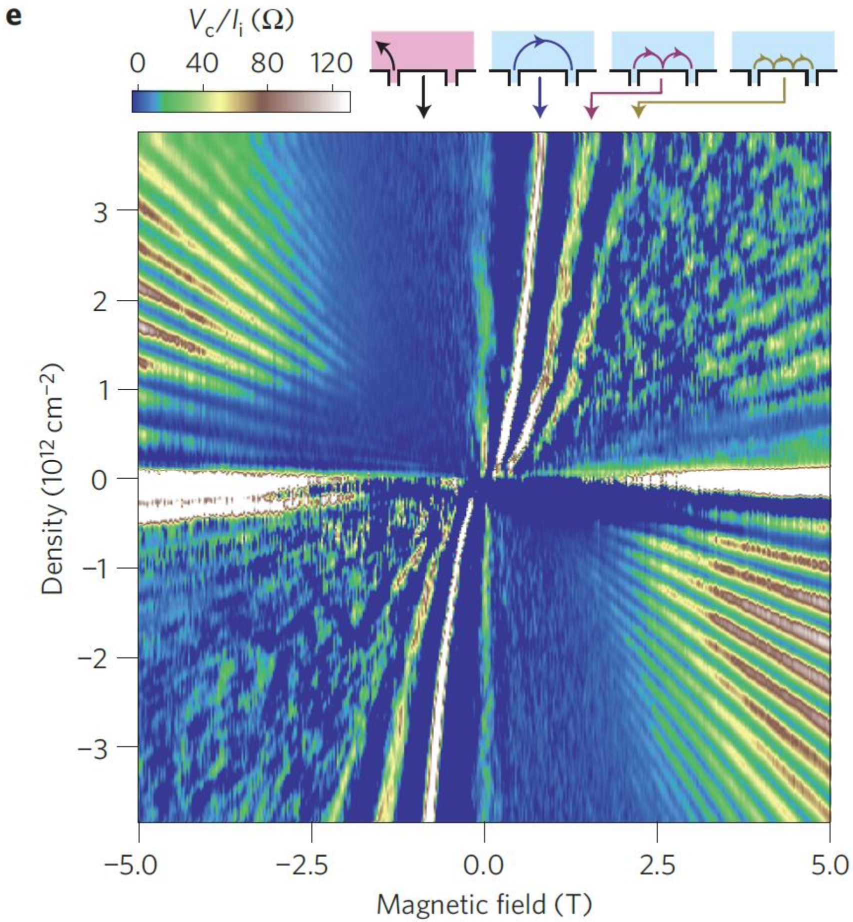




- hBN-supported MLG, BLG and TLG
- Field-effect mobility = 100’000 cm$^2$/Vs
- mfp = 1um

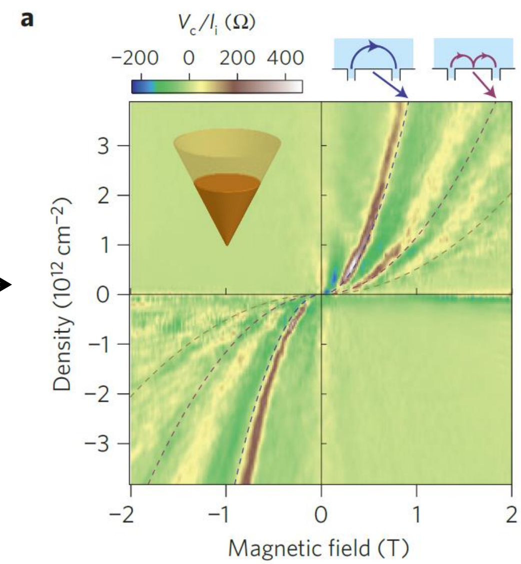
High mobility and low disorder enables TMF



# TMF in monolayer graphene




- For |B| ≥ 2.5 T SdHOs are visible
- No SdHOs in quadrants 1 and 3 due to interference of different trajectories
- For |B| ≤ 2.5 T three unusual peaks are visible (TMF)



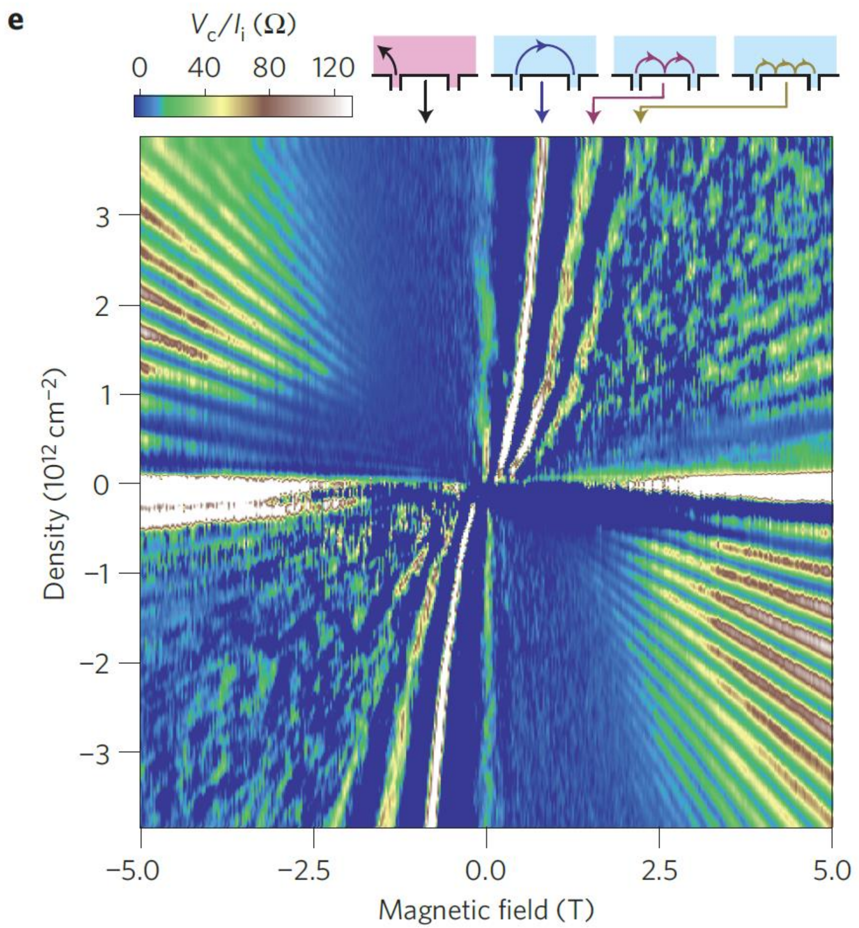

$$B_f^{(p)} = \left(\frac{2\hbar k_F}{eL}\right)p = \left(\frac{2\hbar\sqrt{\pi n}}{eL}\right)p$$

L = 500 nm

n known from QH

- Discrepancy between calculation and experiment
  - Finite width of injector and collector
  - Charge accumulation at the edges
  - Density fluctuations and small angle scattering

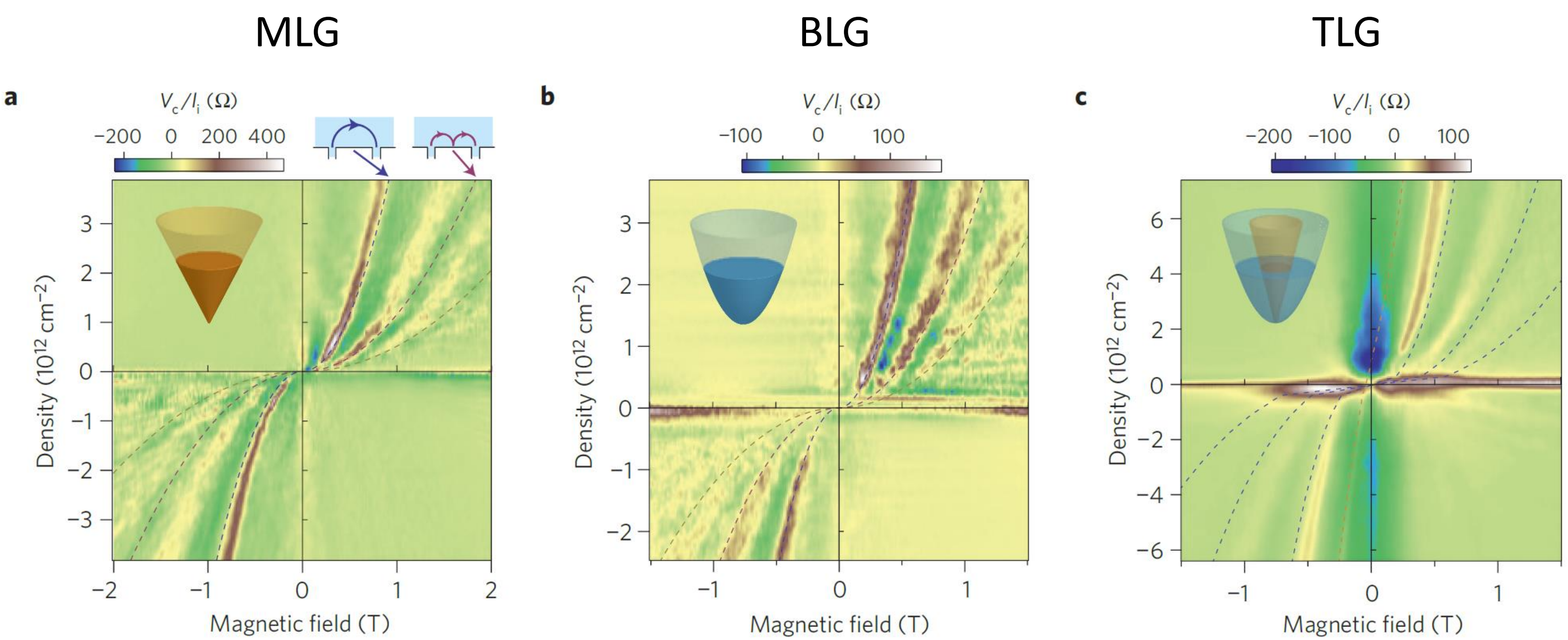
# Specularity at the edge




- Multiple focusing peaks observed in all investigated devices
- Significant fraction of charge carriers gets specularly reflected at the edges
- Measured specularity defined as ratio between amplitudes of second and first peaks
- For this experiment 0.2 – 0.5
- < 1 for focused-ion-beam-etched devices
- > 1 for electrostatically defined edges

Edge quality influences the specularity

# TMF in MLG, BLG and TLG

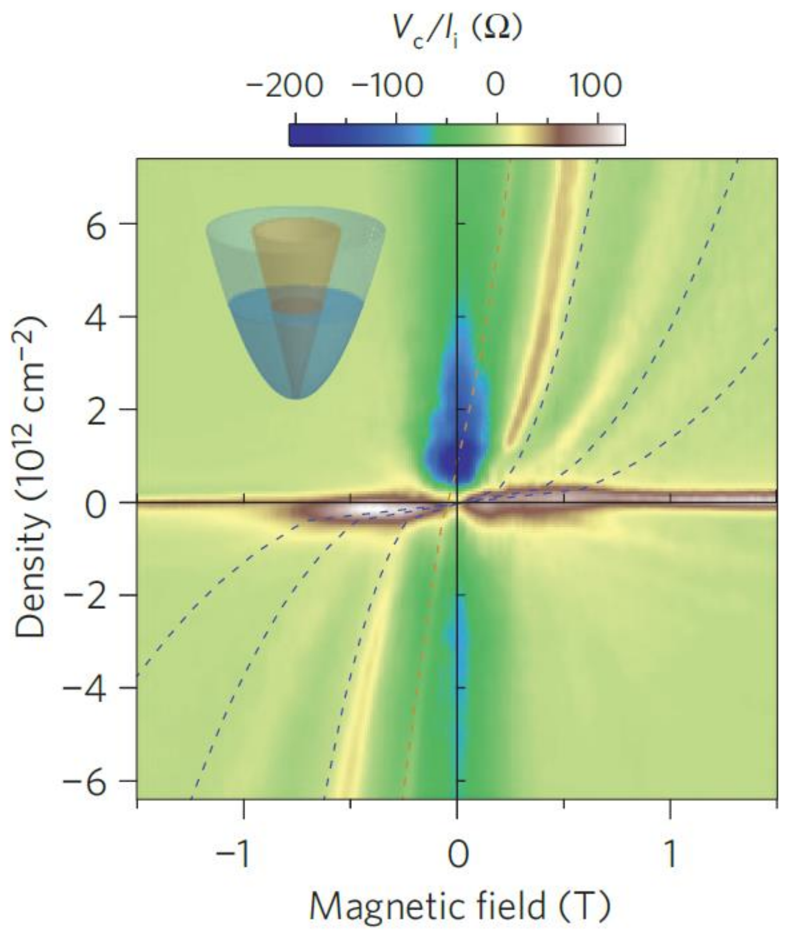



- TMF spectra very similar (despite the different band structures)
- Both have a circular Fermi surface, resulting in the same circular orbit and $\sqrt{n}$ - dependence of $k_F$

TMF spectrum of TLG remarkably different (multiband character of its band structure)

# TMF as a ballistic electron spectroscopy method

c




- Band structure: massless MLG-like and massive BLG-like subbands
- Both subbands give rise to their own TMF spectra
- No higher order peaks from MLG-like subband, masked by the stronger peaks from the BLG-like subband

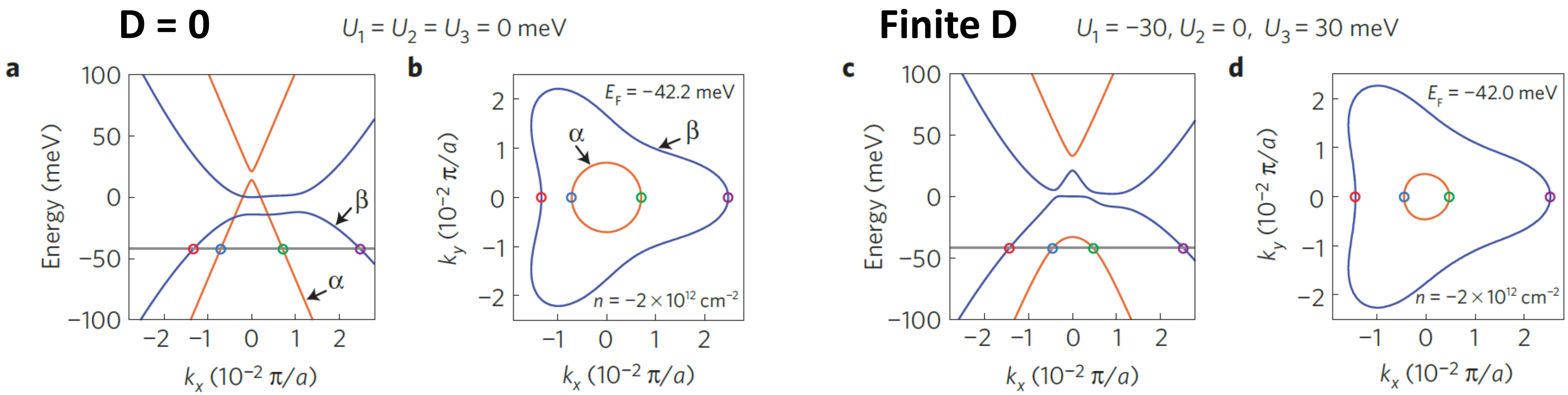
---

- TLG band structure can be tuned and controlled by a transverse electric displacement field D
- TMF is sensitive to the occupation of each of the TLG subbands

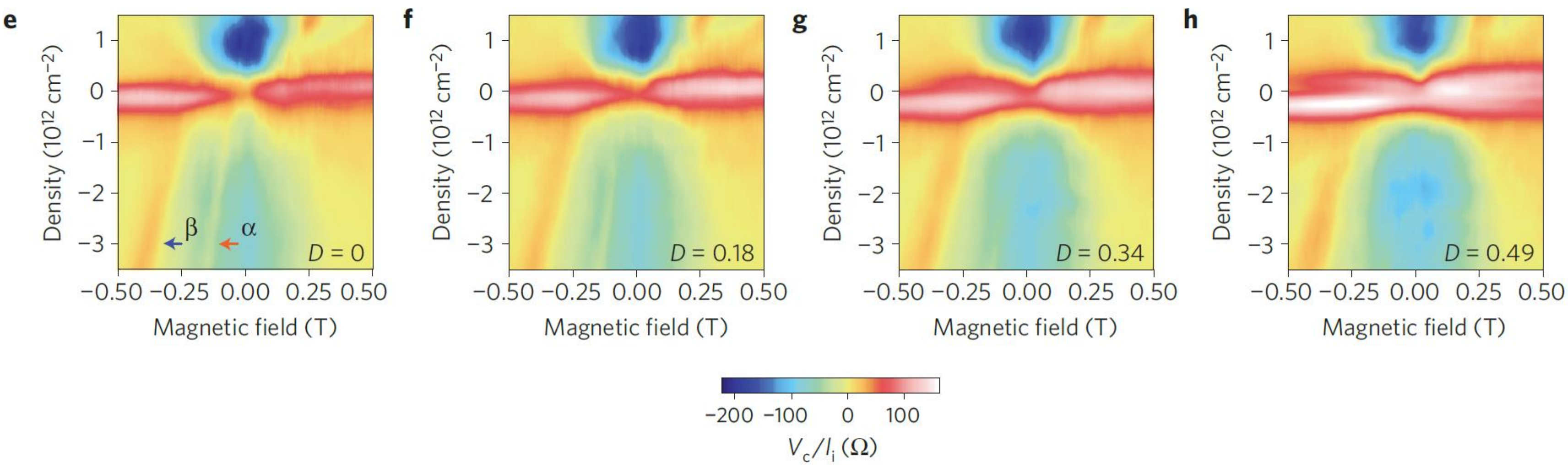
↓

Enables the use of TMF as a probe of the change in the bandstructure

# TMF as a ballistic electron spectroscopy method

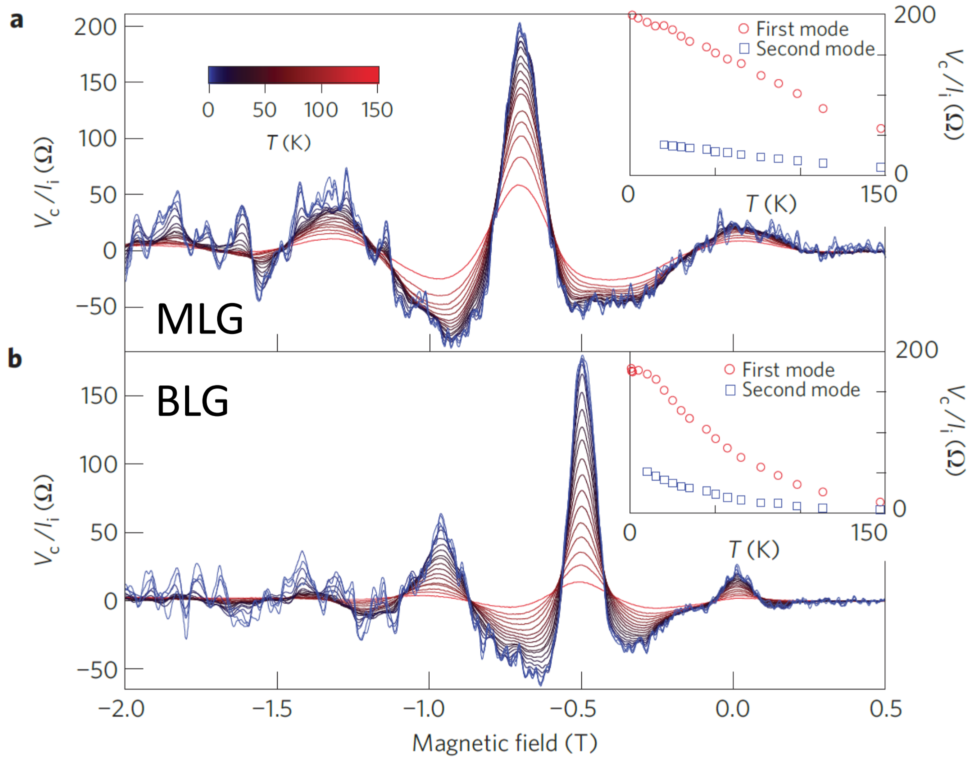



A finite D induces a potential difference between the layers
→ hybridization MLG-like and BLG-like subbands




As D increases the α-peak starts to shift downward and eventually disappears at low density

# Temperature dependence of TMF spectra



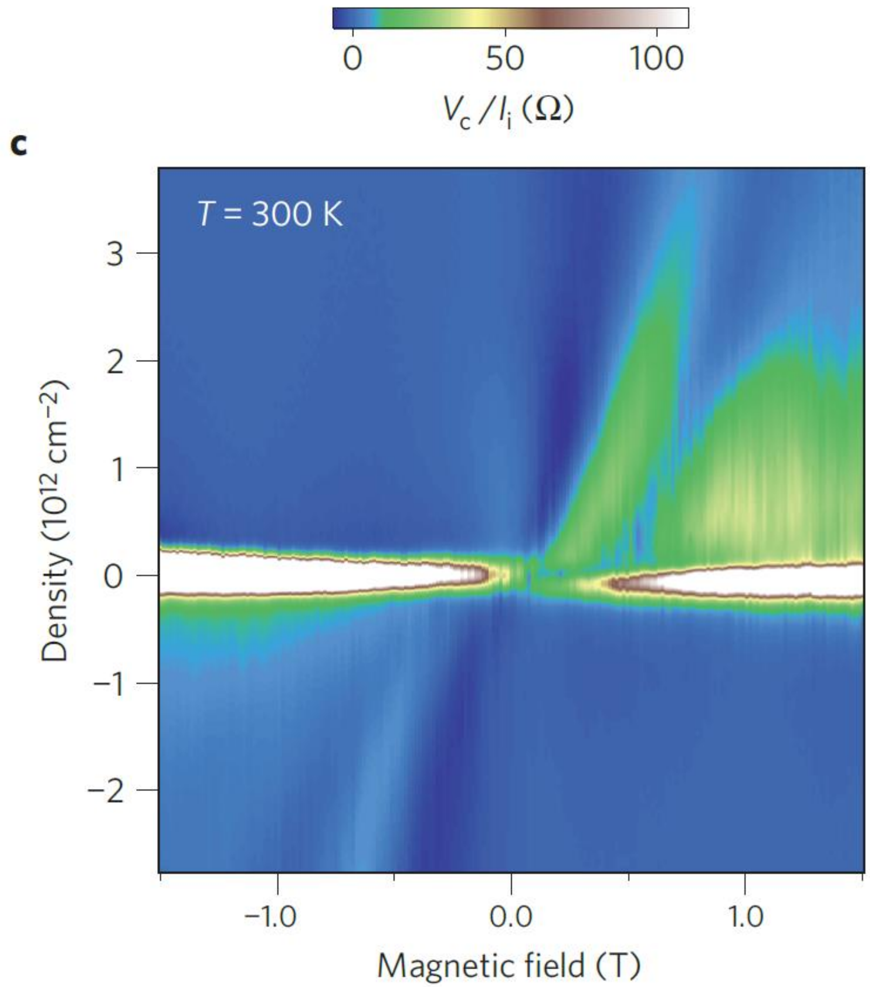

Two effects of temperature:

1. Increase in dephasing
2. Loss of ballistic transport due to new scattering channels

- Finestructure at low T due to interference between different paths travelling to the collector
- If broadening of $k_F$ is on the order of 1/L the interference is washed out
- Should appear at T = 15 K

- Decreasing focusing peak amplitudes with T (linear for MLG and saturating for BLG)
- A potential scattering mechanism includes longitudinal acustic phonons which give rise to a linear T-dependence of the scattering rate
- More theoretical work is needed to understand the temperature dependence!

# Remarkable robustness of TMF in graphene




- First mode clearly visible indicating room-T ballistic transport well into the μ-regime
- T three times higher than in semiconductor heterostructures
- Lack of remote interfacial phonon scattering from hBN

# Summary

- Observation of TMF in MLG, BLG and TLG
- The use of TMF as a ballistic electron spectroscopy method to investigate controlled changes in the electronic structure
- TMF in graphene survives up to 300 K

---

# Conclusions

- Could we design an experiment to study the edge quality of H-plasma defined edges by TMF?

Thank you for your attention!