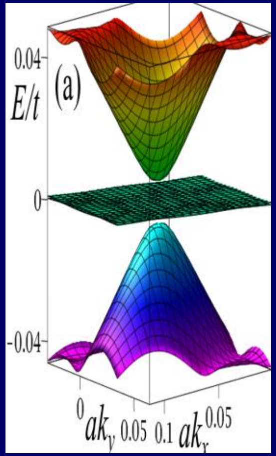
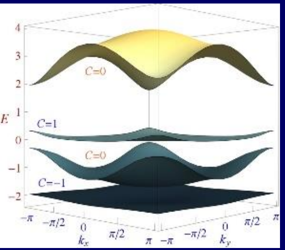
Lecture 2 - Magic Angle Twisted bilayer graphene

- Magic angle Twisted bilayer graphene
  - Van Hove singularities
  - MA-TBG and HTC superconductors
  - Nematicity
  - Chern insulators

Flat bands enhance correlation effects

- Flat band $\mapsto$ Quenched kinetic energy + divergent DOS





Fermi energy in flat band

↓

Enhanced correlation effects

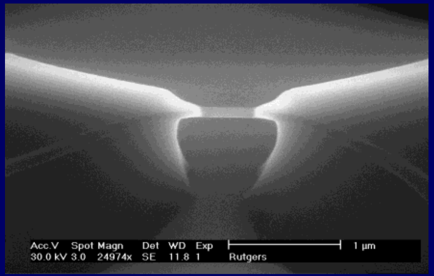
↓

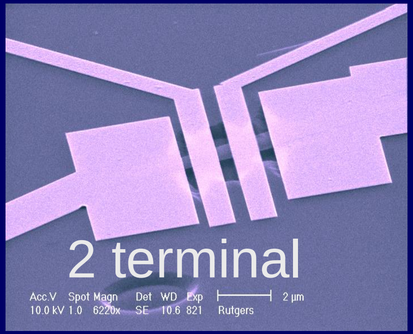
- Ferromagnetism
- Mott Insulator
- Charge Density Waves
- Fractional Quantum Hall Effect
- Superconductivity

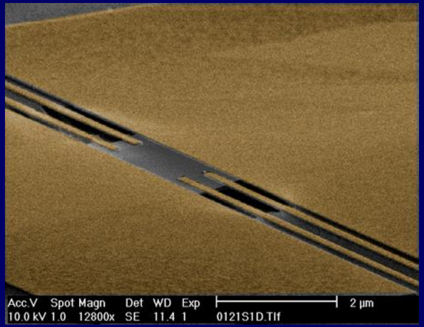
V.A. Khodel and V.R. Shaginyan JETP Lett. (1990).
Volovik 1991
Volovik, Lect.Notes Phys. (2007)
D. Green et al Phys. Rev. B (2010)
T.T. Heikkila, N.B. Kopnin , G.E. Volovik, (2011)

increase DOS by chemical doping
- Graphite: Ca doping $T_c \sim 6K$
- WS_2 , MoS_2 : ionic liquid doping $T_c \sim$ 2-15 K

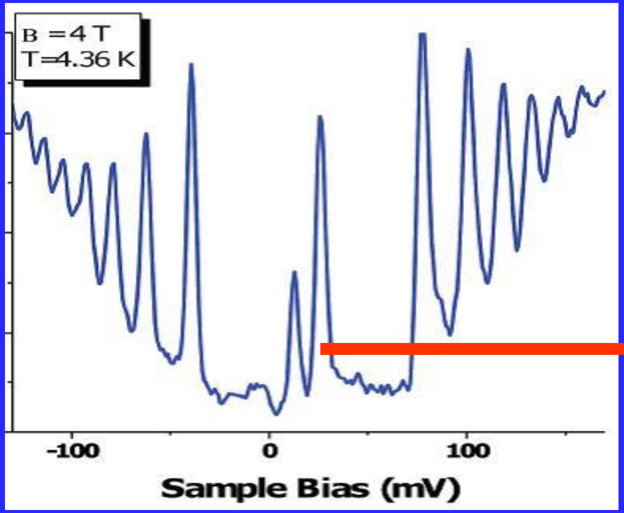
Landau levels – The quintessential flat bands





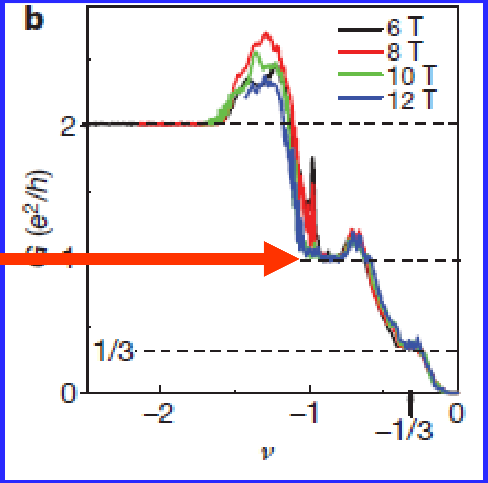


Landau levels



G. Li, A. Luican, E.Y.A, PRL, 102, (2009)
G. Li, E.Y.A., Nat. Phys , 3 (2007), 623

Fractional QHE,



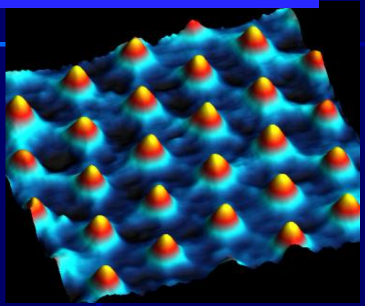
X. Du,..EYA, et al, Nature 462 (2009), 192
K.I. Bolotin , et al, Nature 462 (2009), 196

Can we create Flat bands without braking TRS?

E.Y. Andrei

Flat bands without breaking TRS?

Periodic strain

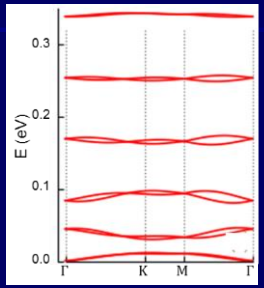


Pseudo-magnetic field

$$\vec{B}_{K,K'} = \pm \vec{\nabla} \times \vec{A}$$

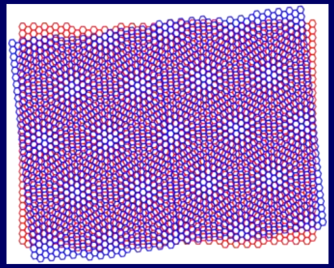
Strain induced Gauge field

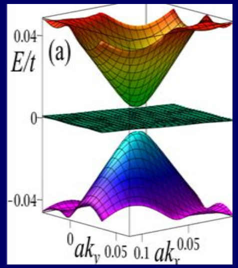
Pseudo Landau levels



J. Mao.. EYA et al Nature, **584**, *215* (2020)

Magic angle twisted graphene
- Moire period
- fine-tuning hopping parameters





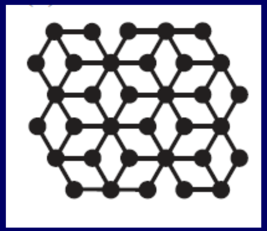
Moire lattice

Magic angle:

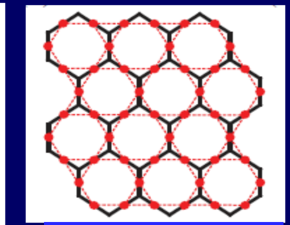
$$\theta \approx \frac{\sqrt{3}}{\pi}\frac{t_{\perp}}{t}$$

G. Li, EYA, et al Nat. Phys. **6**, 109 (2010)

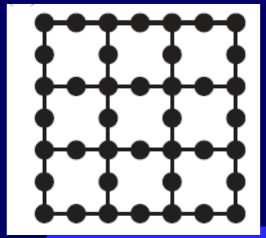
- Line-graph lattices
- symmetry protected chiral flat bands
- Superpositions of degenerate Bloch waves
- ➢ Compact localized states



Dice lattice



Kagome



Lieb

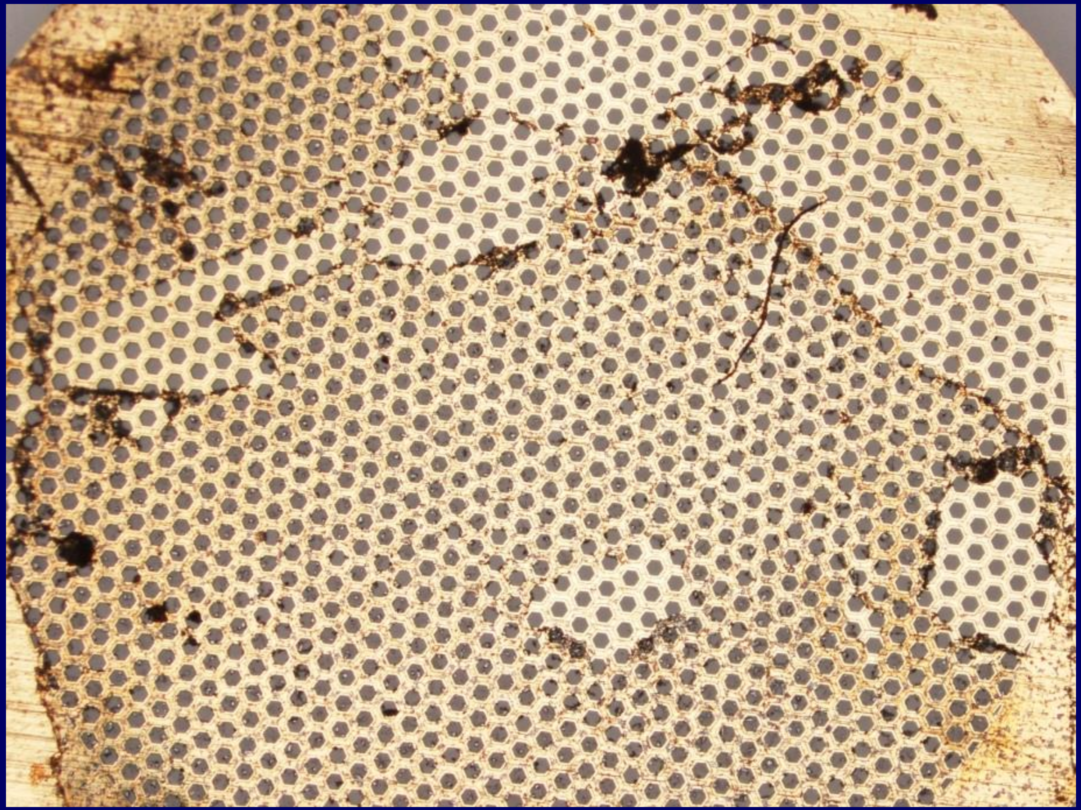
B. Sutherland (1986)
E.H. Lieb (1989)
R. Shen et al (2010)
V. Apaja et al, (2010)

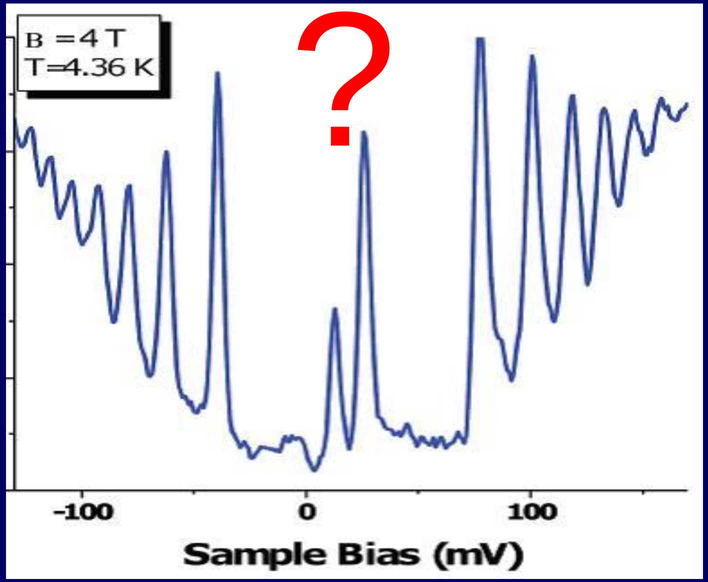
Twisted bilayer graphene

G. Li, EYA, *et al* Nat. Phys. on-line 2009, **6**, 109 (2010)

Guohong Li

- CVD graphene on Ni + electron microscope grid





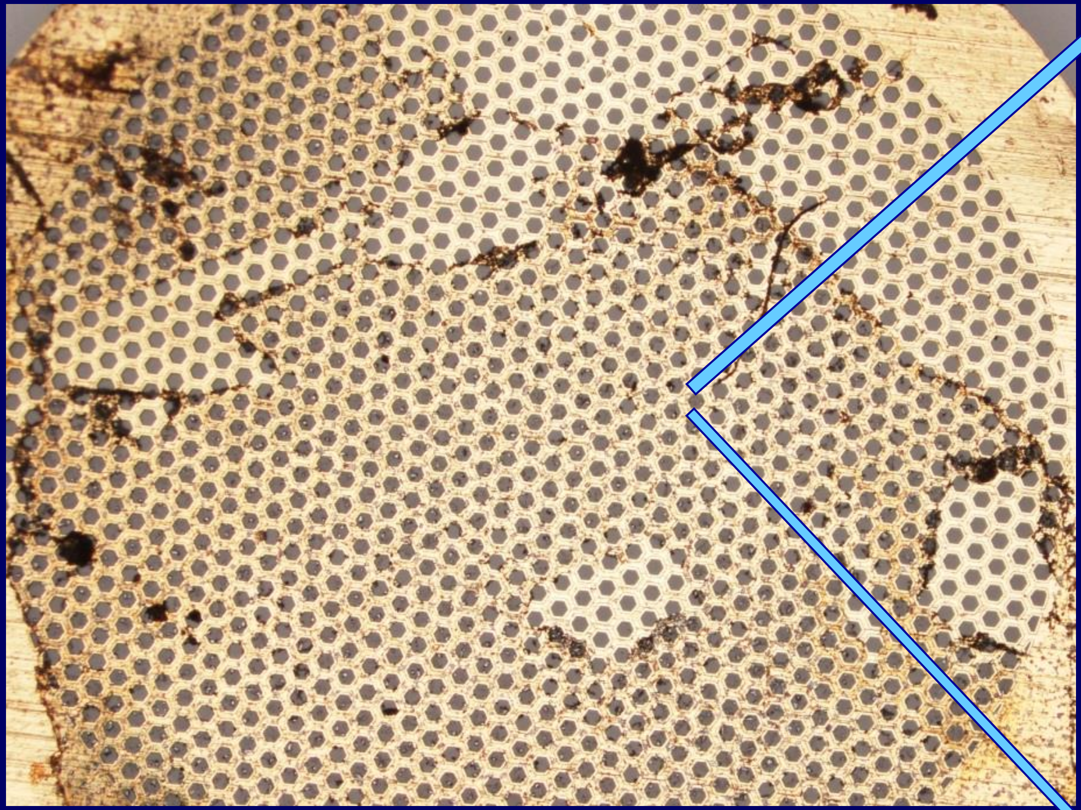
Collaborators:
Jing Kong, Konstantin Novoselov

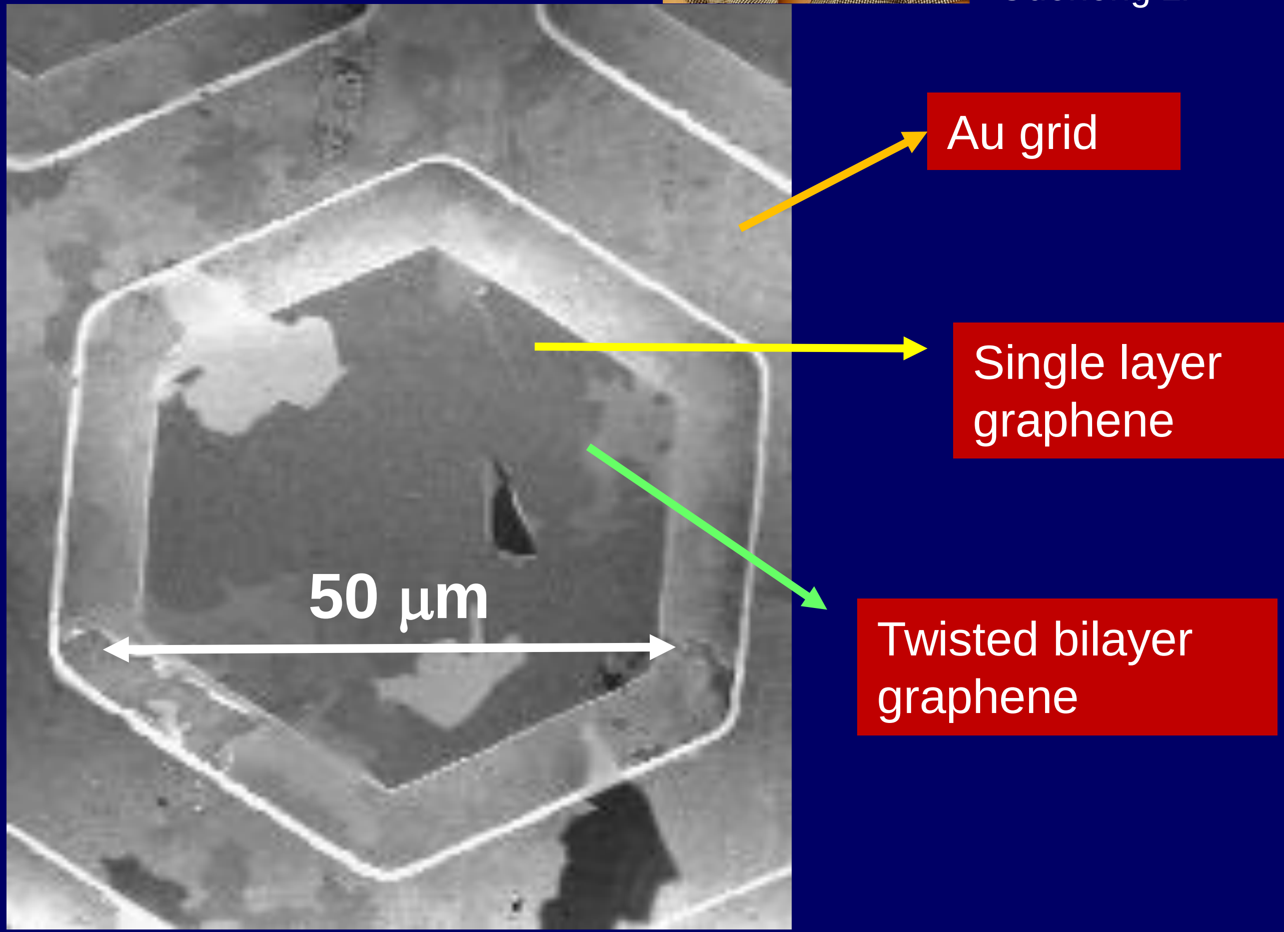
Twisted bilayer graphene

G. Li, EYA, et al Nat. Phys. on-line 2009, **6**, 109 (2010)

Guohong Li

- CVD graphene on Ni + electron microscope grid

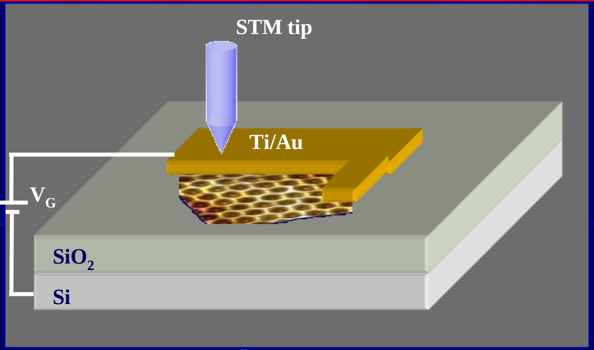




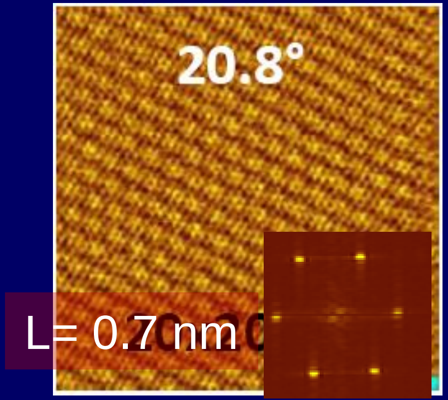
Collaborators:
Jing Kong, Konstantin Novoselov

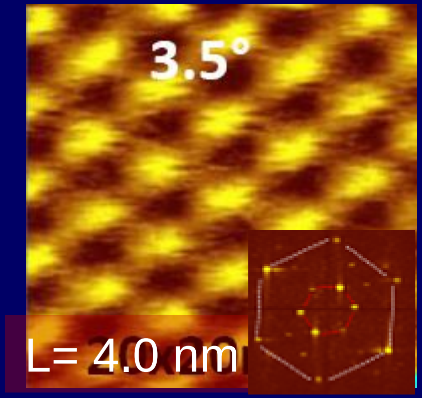
Observation of Van Hove singularities twisted graphene

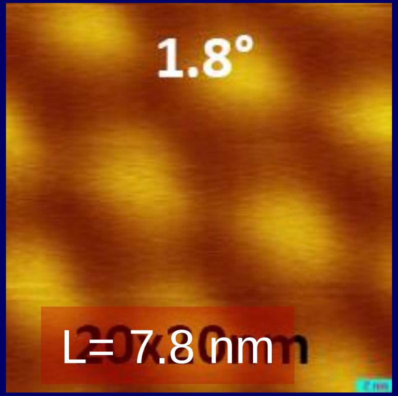
G. Li, EYA, et al Nat. Phys. **6**, 109 (2010)

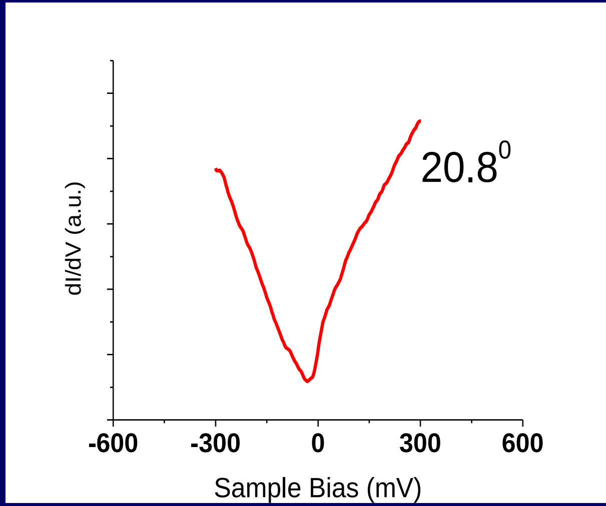


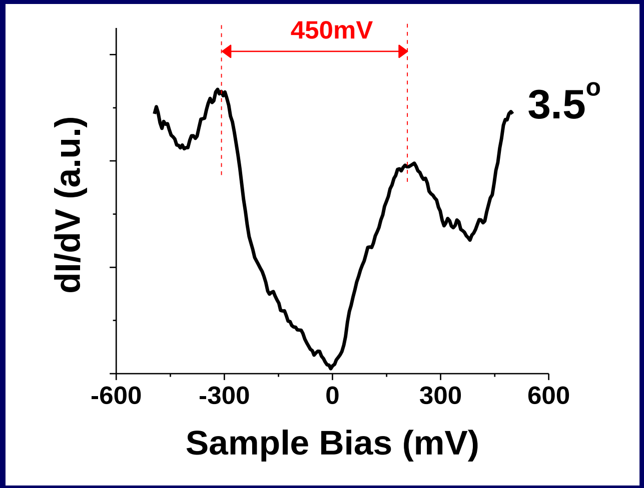
Reducing θ

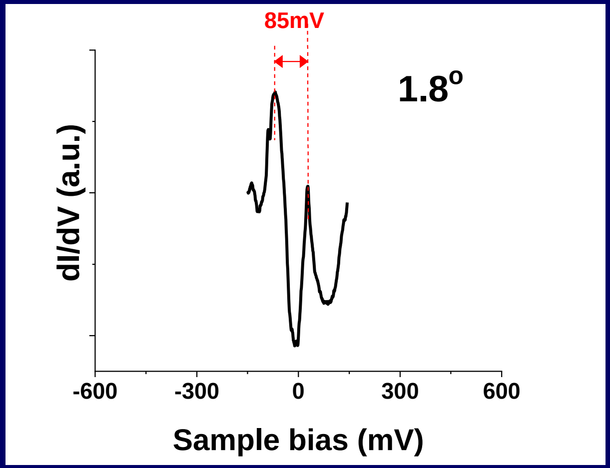






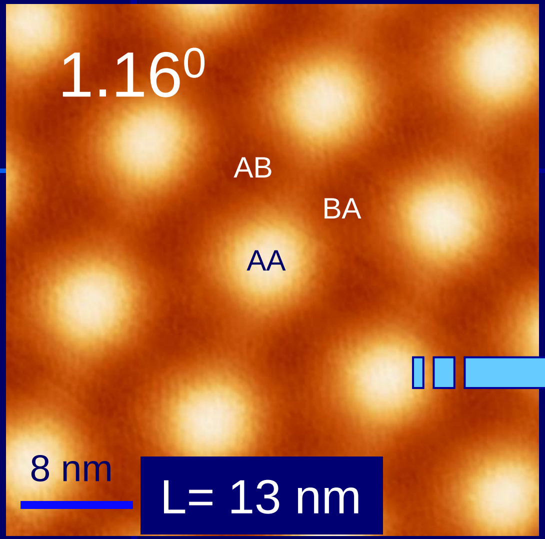




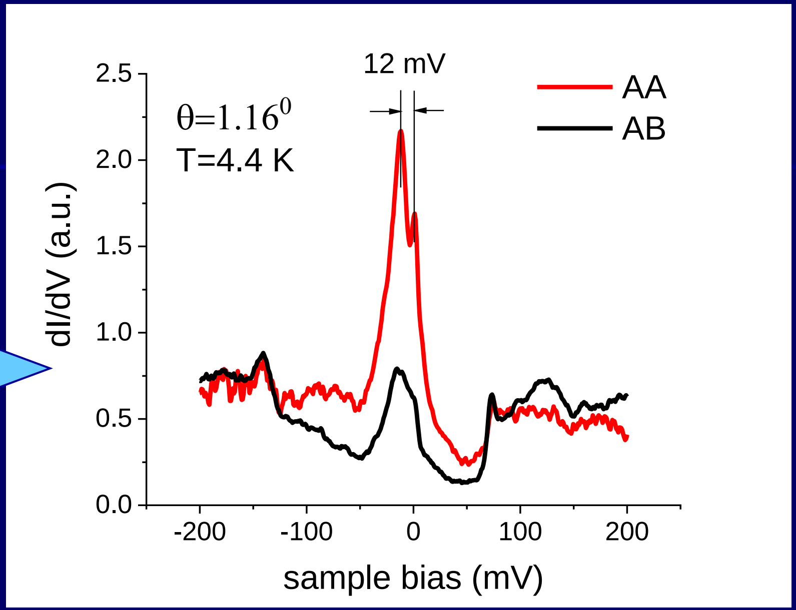


Merging Van Hove singularities

G. Li, EYA et al Nature Physics **6**, 109 (2010



~13,000 atoms per moire cell !!



$\theta \sim 1.1^0$

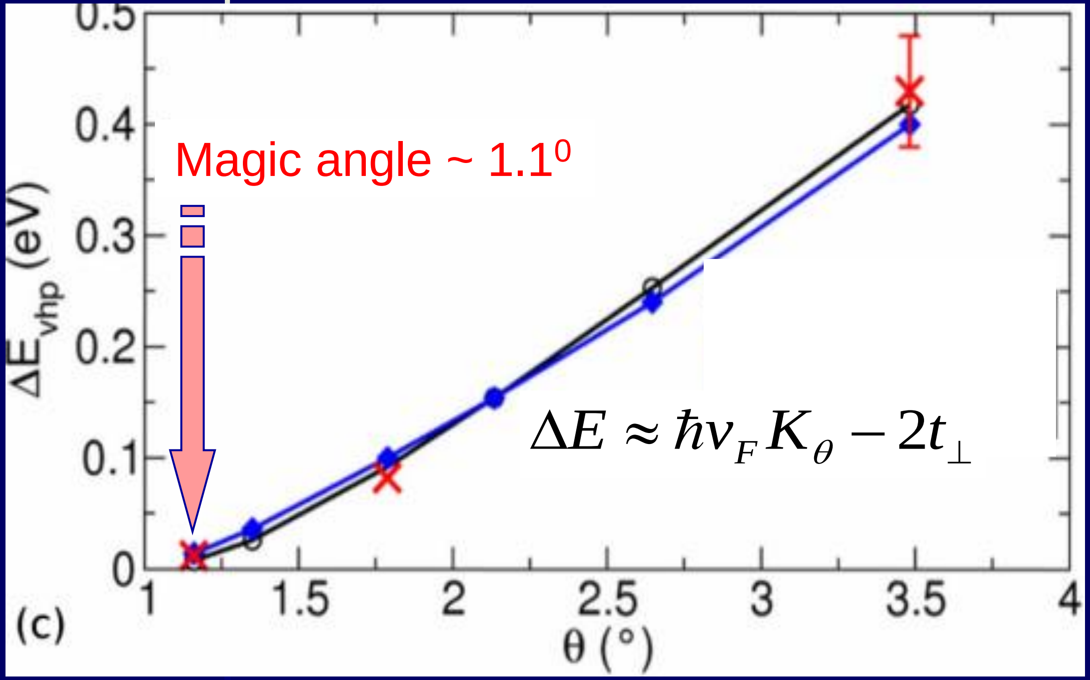
- vHS merged $\mapsto$ flat band
- 12mV Gap at E_F

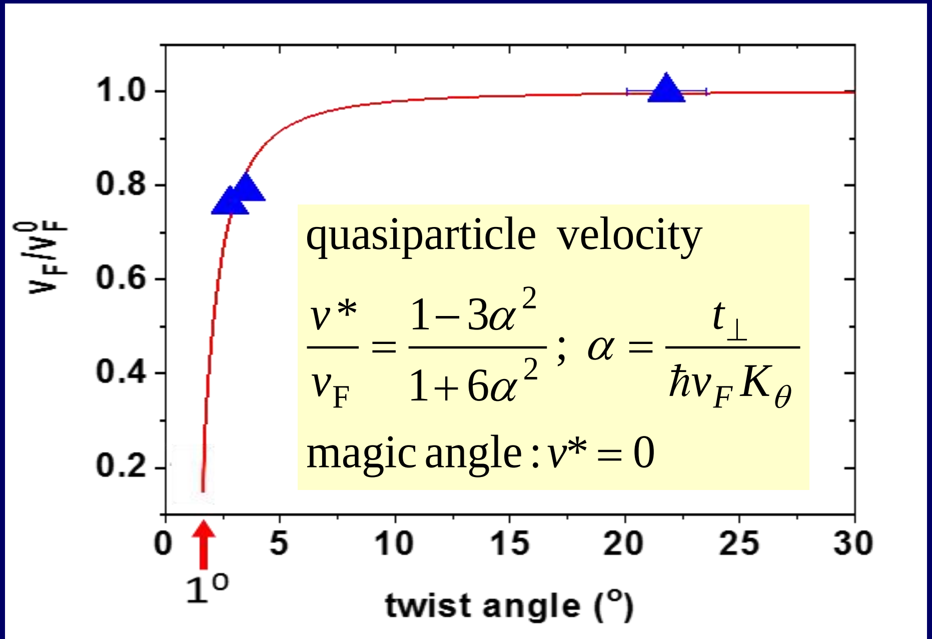
Magic angle : flat band and slow down of carriers

G. Li, et al Nature Physics, 6 (2010)109

A. Luican et al PRL106, (2011) 126802

Landau level spectroscopy



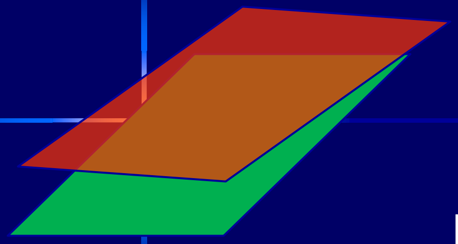


Van Hove Singularities merge

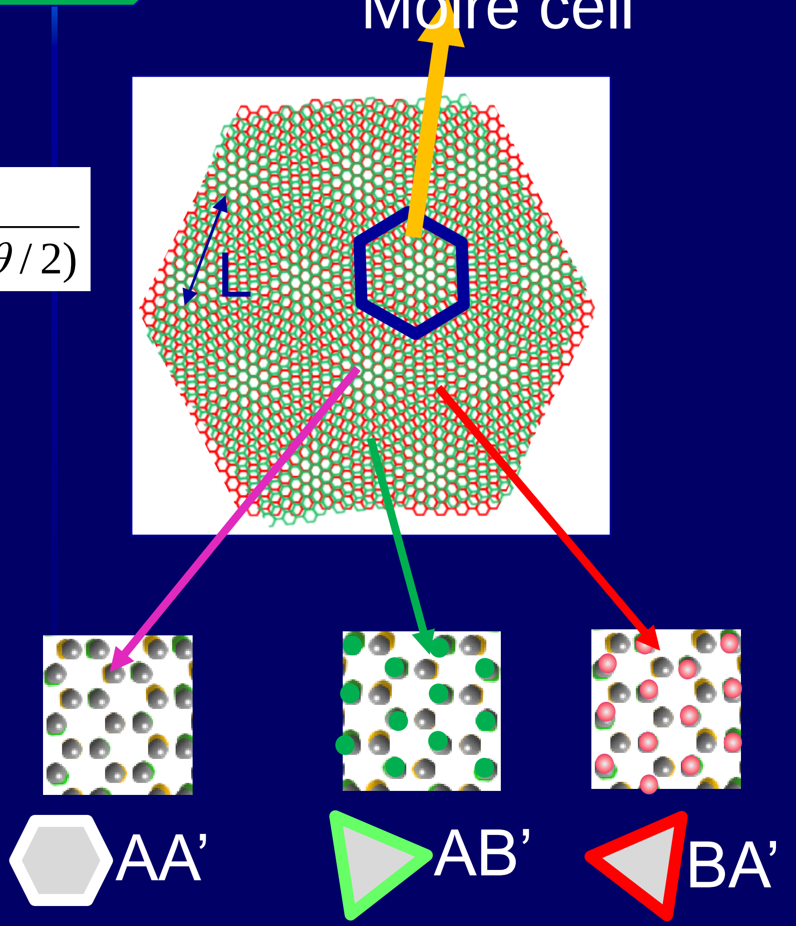
Electrons slow down ↦ Enhanced interactions

Twisted Bilayer Graphene and Lattice Relaxation

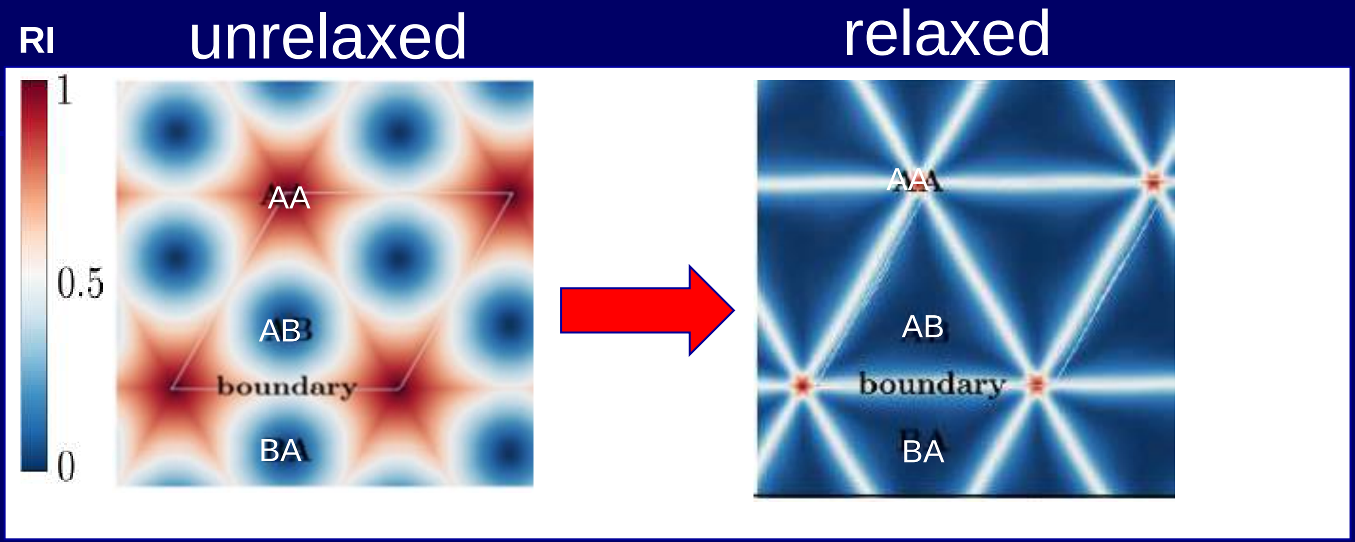
Twist between layers $\mapsto$ Moiré pattern:



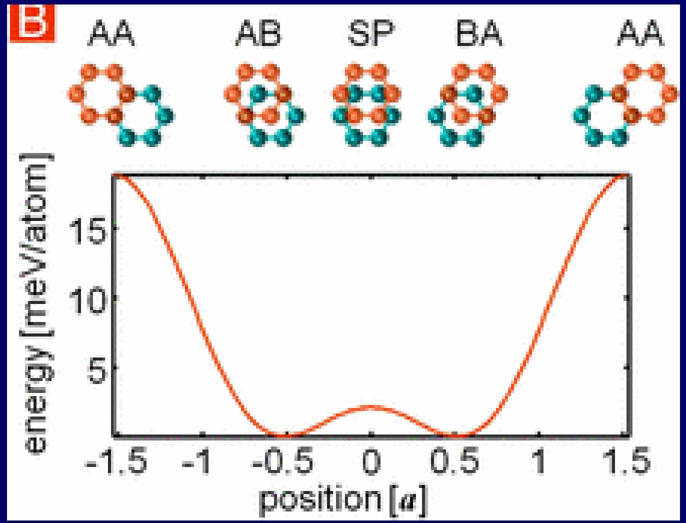
$$L = \frac{a}{2\sin(\theta/2)}$$



Twist angle: 0.3^0

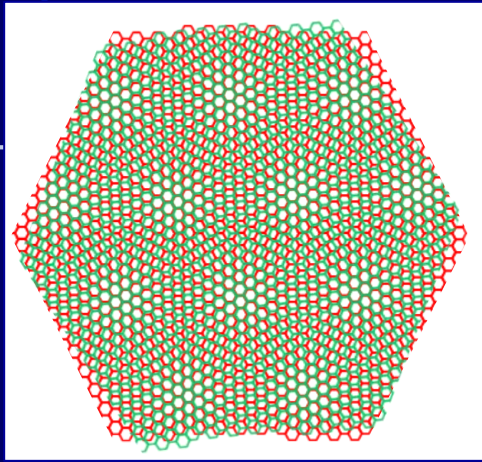


RI – registry index =1 for AA, 0 for AB/BA

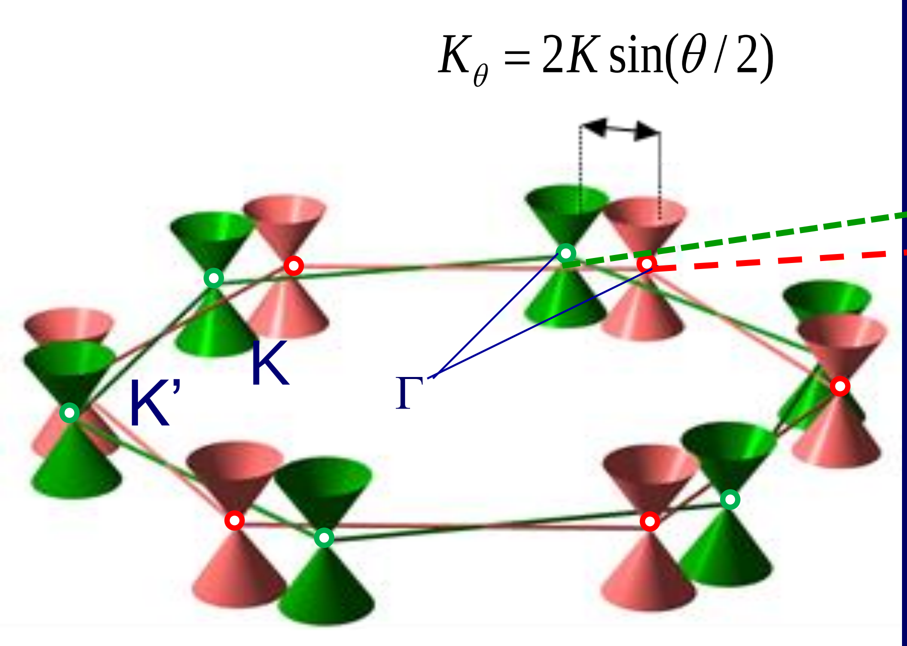


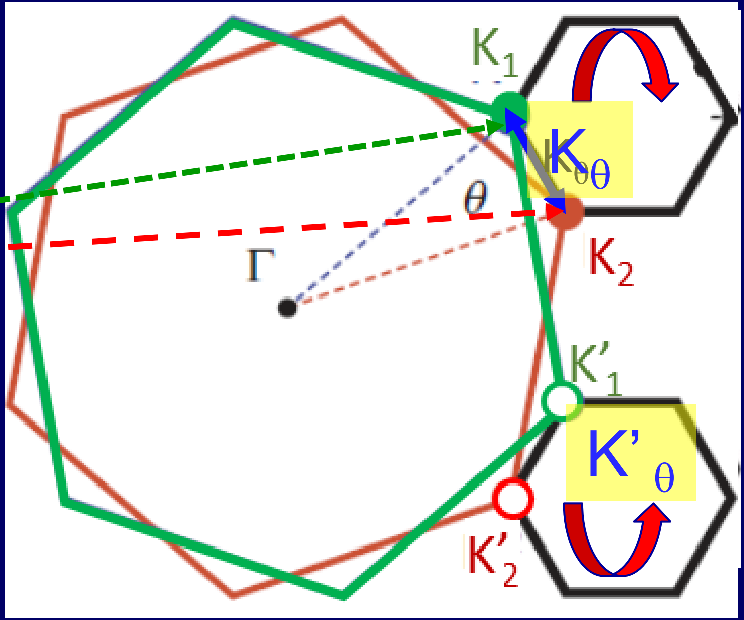
Mini Brillouin zone

Lopes dos Santos, Castro-Neto et al (2007)
Suarez Morel et al PRB (2010)
Bistritzer, MacDonald, PNAS (2011)



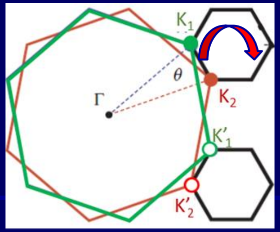
Two mini-BZ with opposite chirality
8 orbitals per moiré cell:
2Valley x 2layer x 2spin



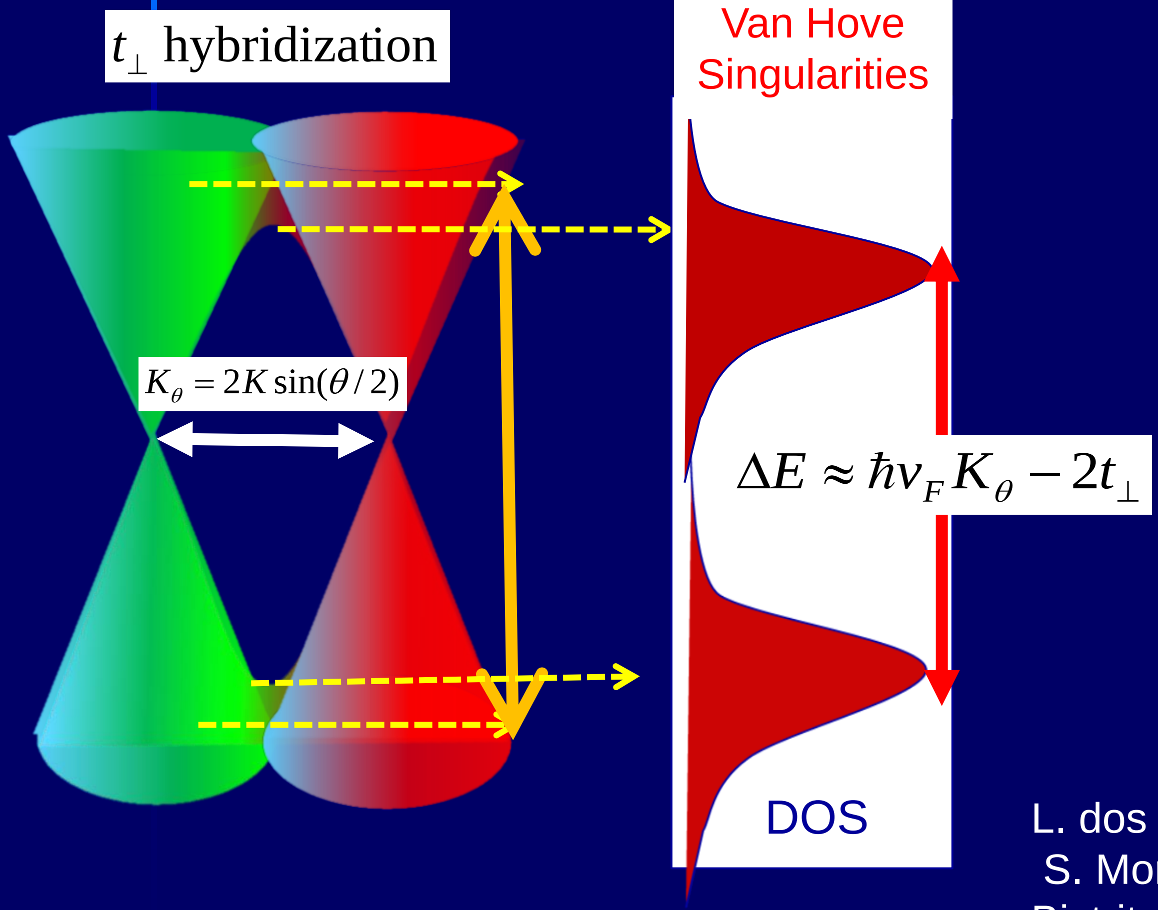


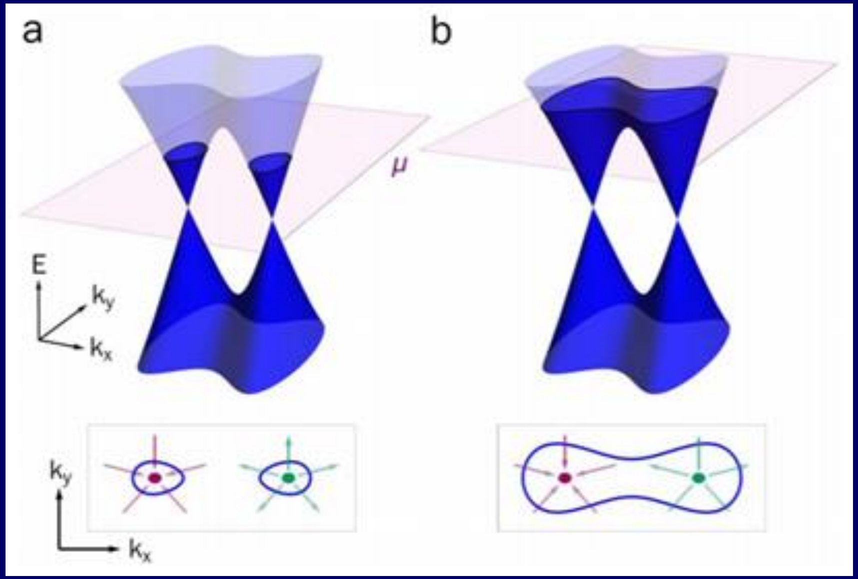
Van Hove singularities

$$H_K = v_F \begin{pmatrix} \vec{\sigma}_{\theta/2}.\vec{p} & \\ & \vec{\sigma}_{-\theta/2}.\vec{p} \end{pmatrix}$$



- VHS : Divergent DOS $\mapsto$ enhanced correlations
- Lifshitz transition - Fermi surface topology change





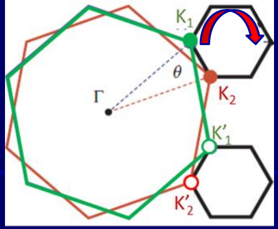
K. A. Modic, et al., Sci. Rep.(2018)

L. dos Santos, Castro-Neto et al PRL(2007)
S. Morel et al PRB (2010)
Bistritzer, MacDonald, PNAS (2011)

Magic Angle

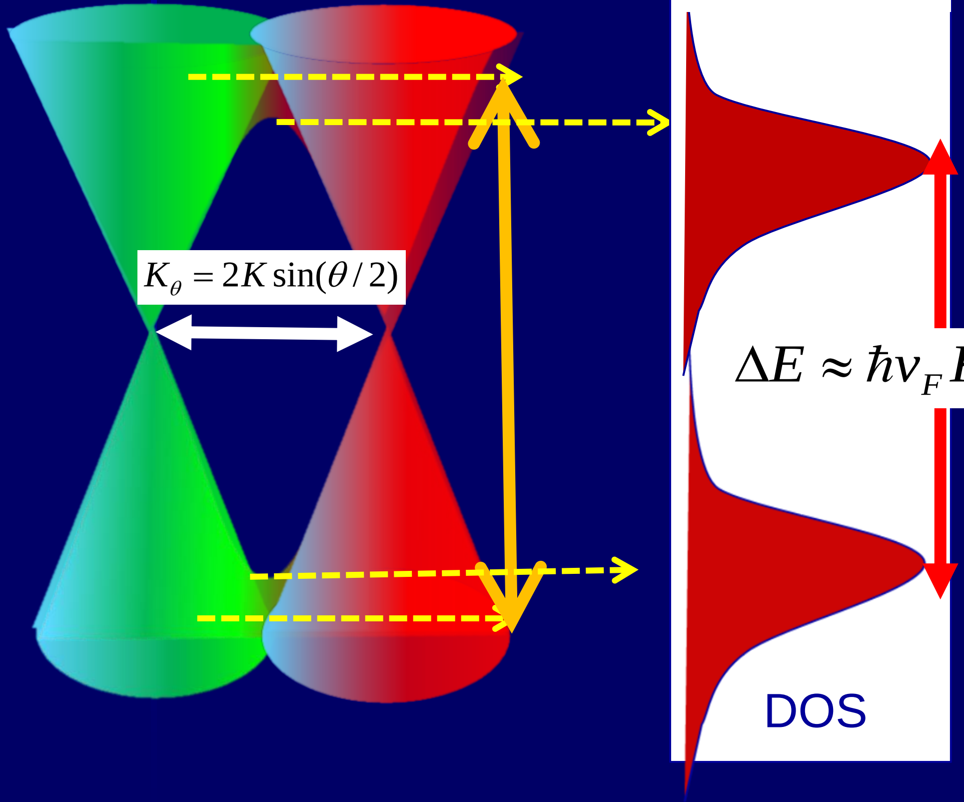
Layer basis

$$H_K = v_F \begin{pmatrix} \vec{\sigma}_{\theta/2}.\vec{p} & U(t_\perp) \\ U^+(t_\perp) & \vec{\sigma}_{-\theta/2}.\vec{p} \end{pmatrix} \begin{pmatrix} 1A \\ 1B \\ 2A \\ 2B \end{pmatrix}$$



$t_\perp$ hybridization

Van Hove Singularities



$K_\theta = 2K\sin(\theta/2)$

$$\Delta E \approx \hbar v_F K_\theta - 2t_\perp$$

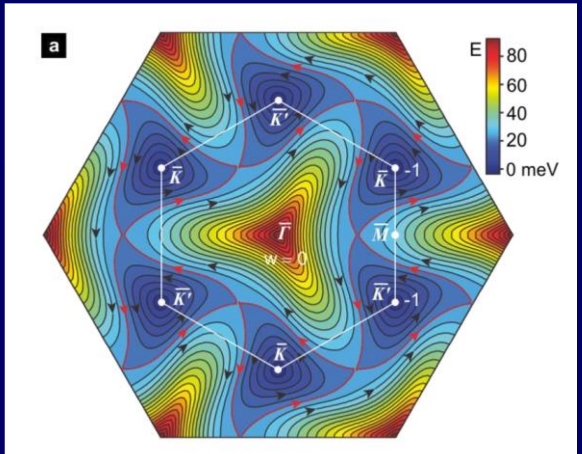
VHS merge ↦ Flat Band

$$\Delta E \to 0$$

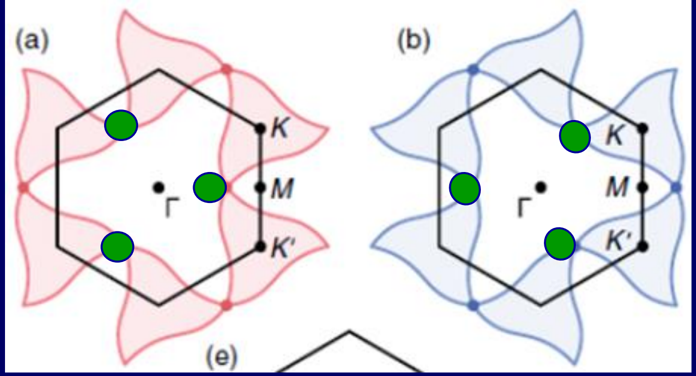
Magic angle:

$$\theta_M \approx \frac{\sqrt{3}}{\pi}\frac{t_\perp}{t} \sim 1^0$$

Moire traversal time ~ tunneling time



Y. Kim et al Nano Lett. 2016, 16, 8, 5053



VHS at half filled band

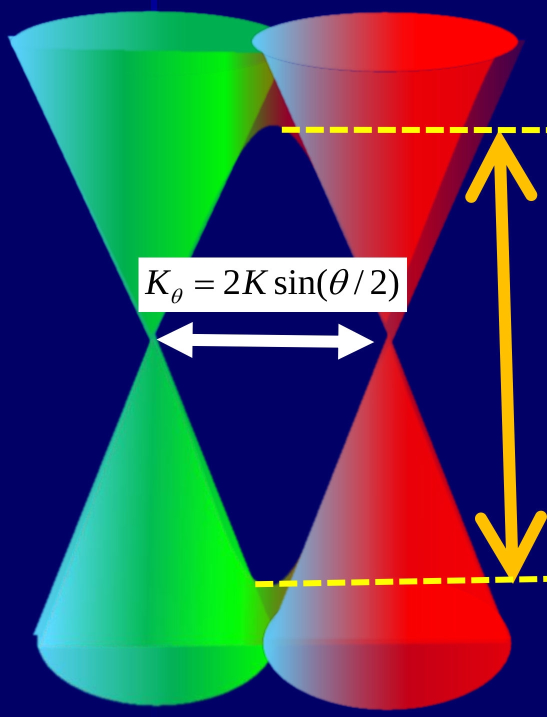
Hiroki Isobe, Noah F. Q. Yuan, and Liang Fu
Phys. Rev. X **8**, 041041 – Published 5 December 2018

E.Y. Andrei

Van Hove singularities

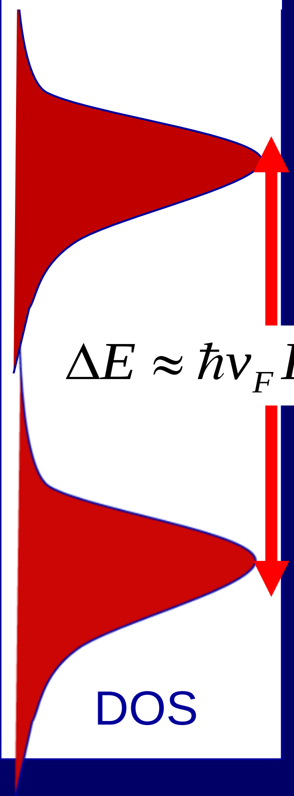
$$H_K = v_F \begin{pmatrix} \vec{\sigma}_{\theta/2}\cdot\vec{p} & U(t_\perp) \\ U^+(t_\perp) & \vec{\sigma}_{-\theta/2}\cdot\vec{p} \end{pmatrix}$$

$t_\perp$ hybridization



$K_\theta = 2K\sin(\theta/2)$

Van Hove Singularities



$\Delta E \approx \hbar v_F K_\theta - 2t_\perp$

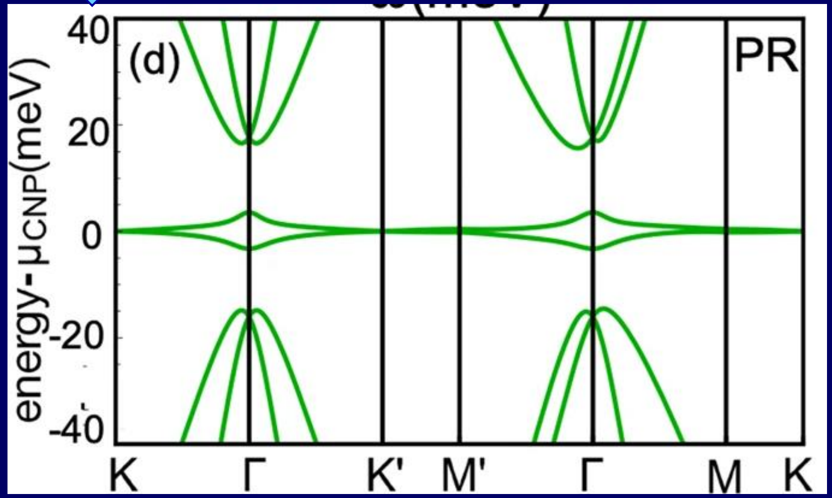
VHS merge $\mapsto$ Flat Band

$\Delta E \rightarrow 0$

Magic angle:

$$\theta_M \approx \frac{\sqrt{3}}{\pi}\frac{t_\perp}{t} \sim 1^0$$

Moire cell traversal time
~ tunneling time



Lattice relaxation

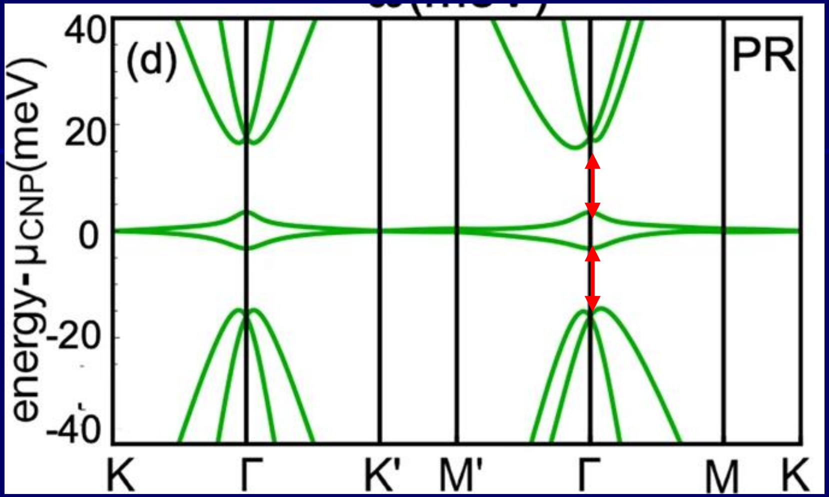
"Flat" band: 8 orbitals per moire cell

G. Li… EYA, Nature Phys. **6**, 109 (2010)

E.Y. Andrei

Lattice relaxation opens gap

Lattice relaxation $\mapsto$ gap



Isolated flat band:
8 fold degenerate states

Degeneracy protected by C_2T symmetry

Band Filling notations:

# of carriers /moire cell

$$n_0 = \frac{\text{one carrier}}{\text{moire cell}}$$

$\mathrm{n} = 0$ charge neutrality

Electrons $n/\mathrm{n}_0 = 1,2,3,4$

Holes $n/\mathrm{n}_0 = -1,-2,-3,-4$

Fraction of band filled

$\nu = 0$ charge neutrality

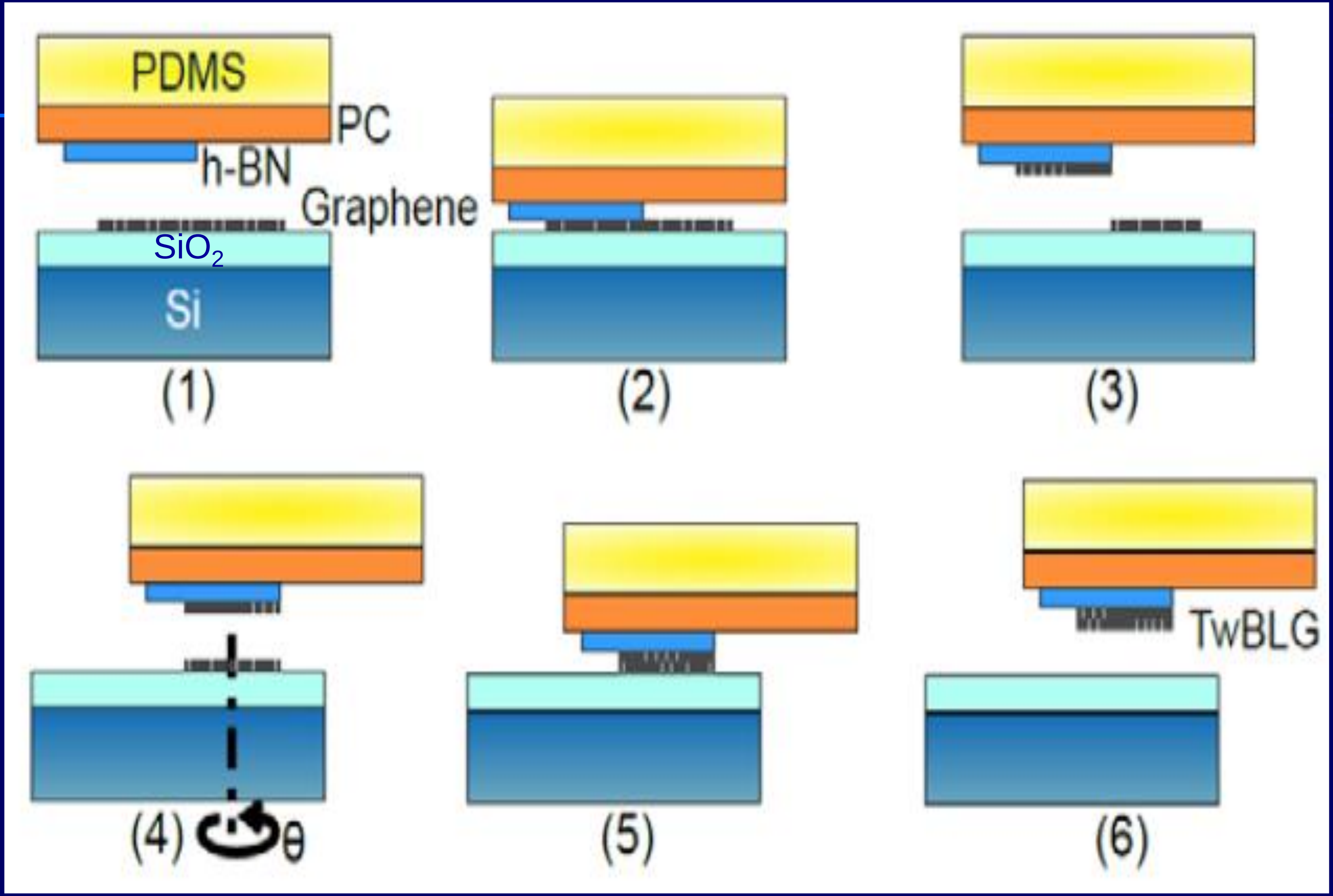
Electrons $\nu = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1$

Holes $\nu = -\frac{1}{4}, -\frac{1}{2}, -\frac{3}{4}, -1$

- Magic angle Twisted bilayer graphene
  - Van Hove singularities
  - MA-TBG and HTC superconductors
  - Nematicity
  - Chern insulators

Controlling the Twist-angle

Kim, K. *et al.* *Nano Letters* **16**, 1989, (2016)



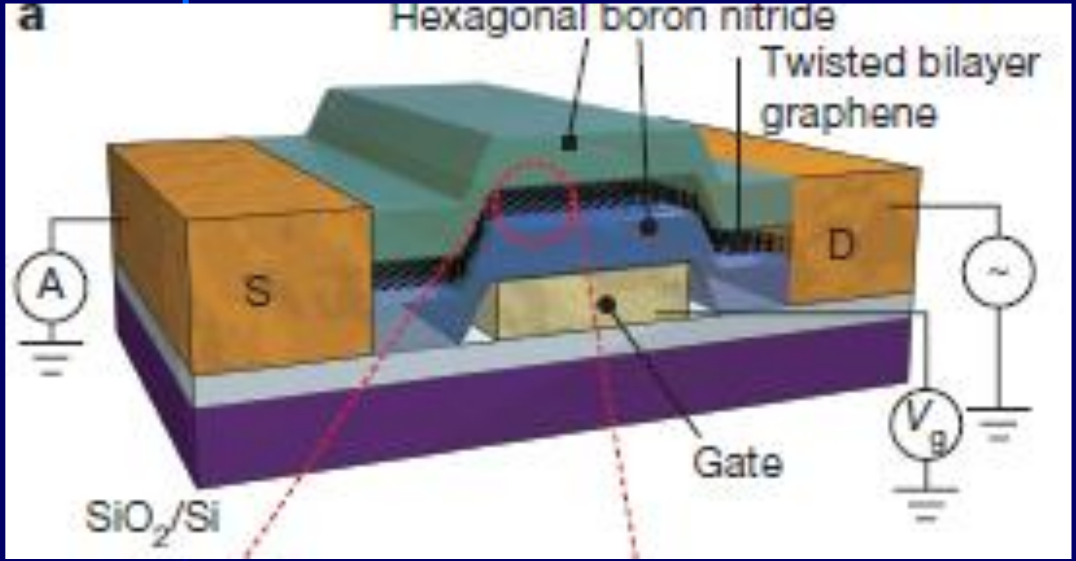
Controlling the Twist-angle and Carrier Density

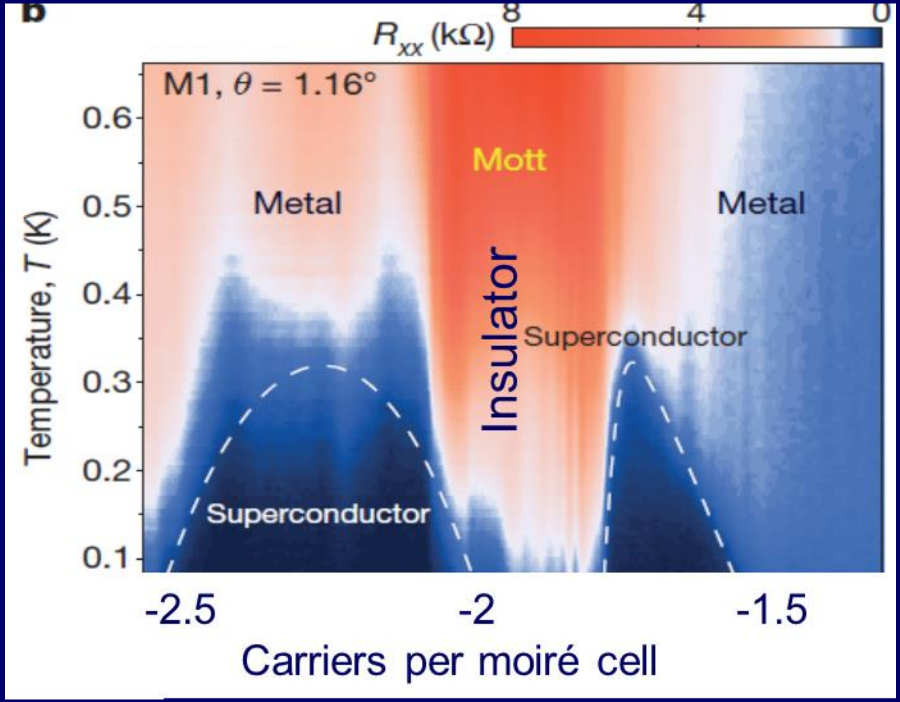
ARTICLE 2018

doi:10.1038/nature26160

Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Shiang Fang[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4] & Pablo Jarillo-Herrero[1]





- Sample protected by hBN encapsulation
- Density controlled with gate voltage

Magic angle superconductivity – why the excitement ?

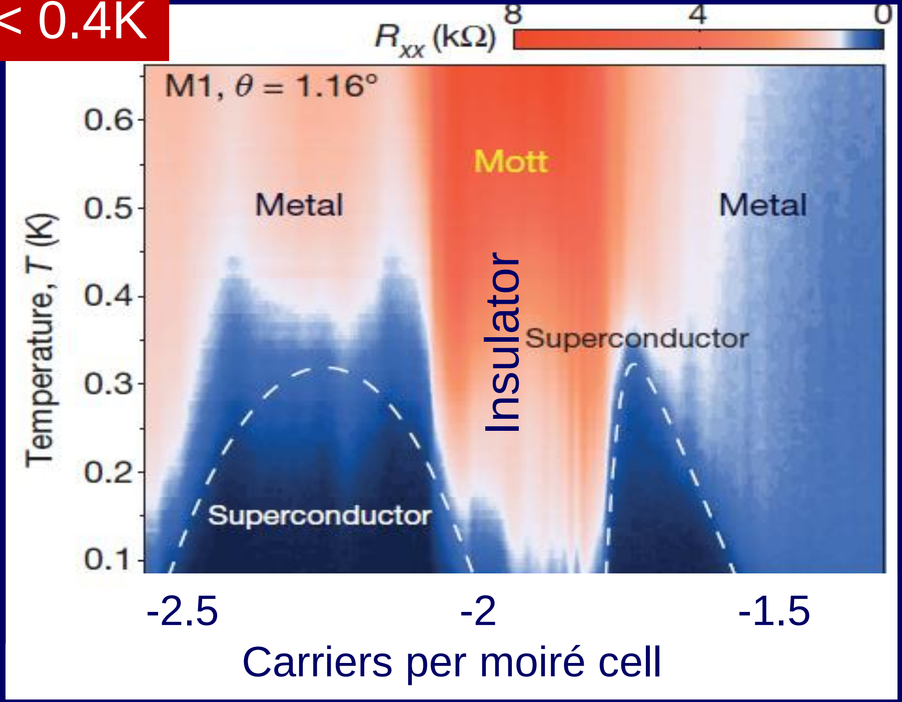
✓ Insulating phase flanked by superconducting domes

? $T_c/T_F > 10^{-2} \mapsto$ strong coupling

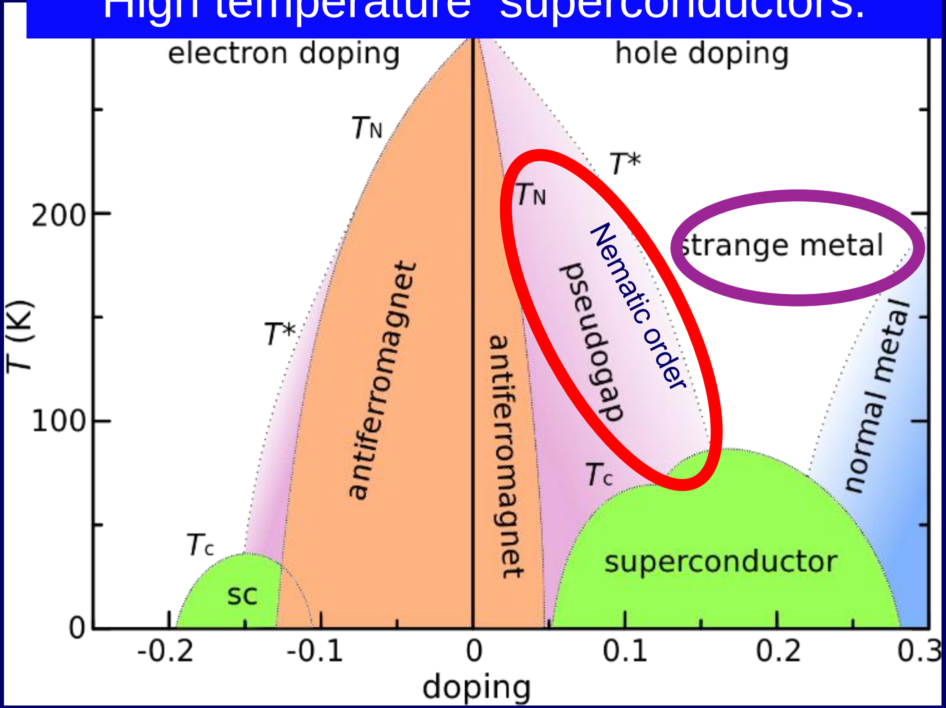
? Pseudogap phase ?
? Nematic Order ?

? Strange metal : "Planckian" dissipation ?

$T_c < 0.4K$



High temperature superconductors:



- ➢ Doping by electrostatic gating
- ➢ Entire Phase diagram in single sample!

- ➢ Chemical doping

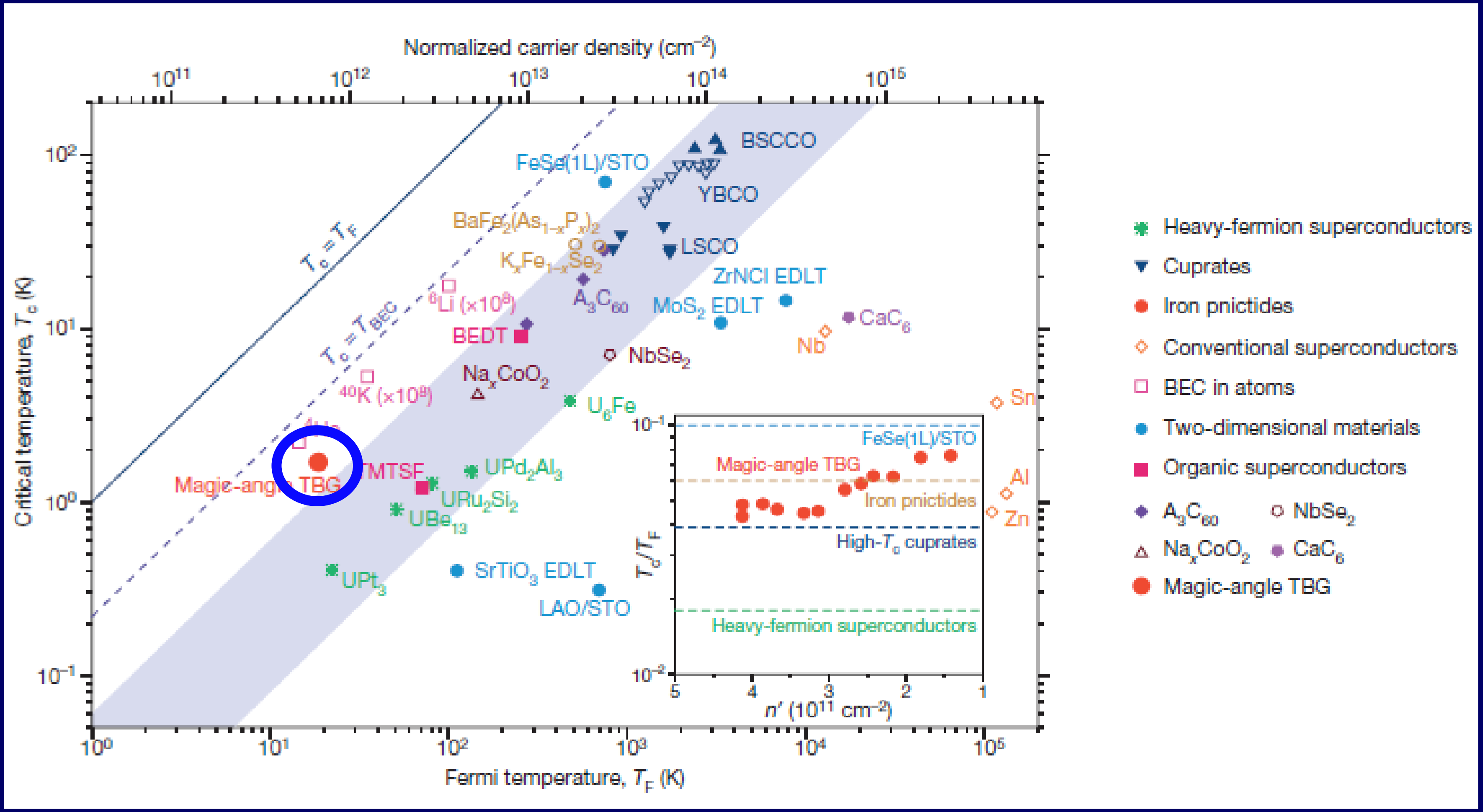
E.Y. Andrei

Magic angle superconductivity – strong coupling

- ✓ Insulating phase flanked by superconducting domes
- ✓ $T_c/T_F \sim 10^{-1} \mapsto$ strong coupling

- ? Pseudogap phase ?
- ? Nematic Order ?

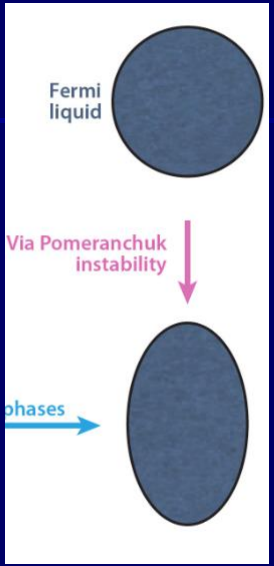
- ? Strange metal : “Planckian” dissipation ?

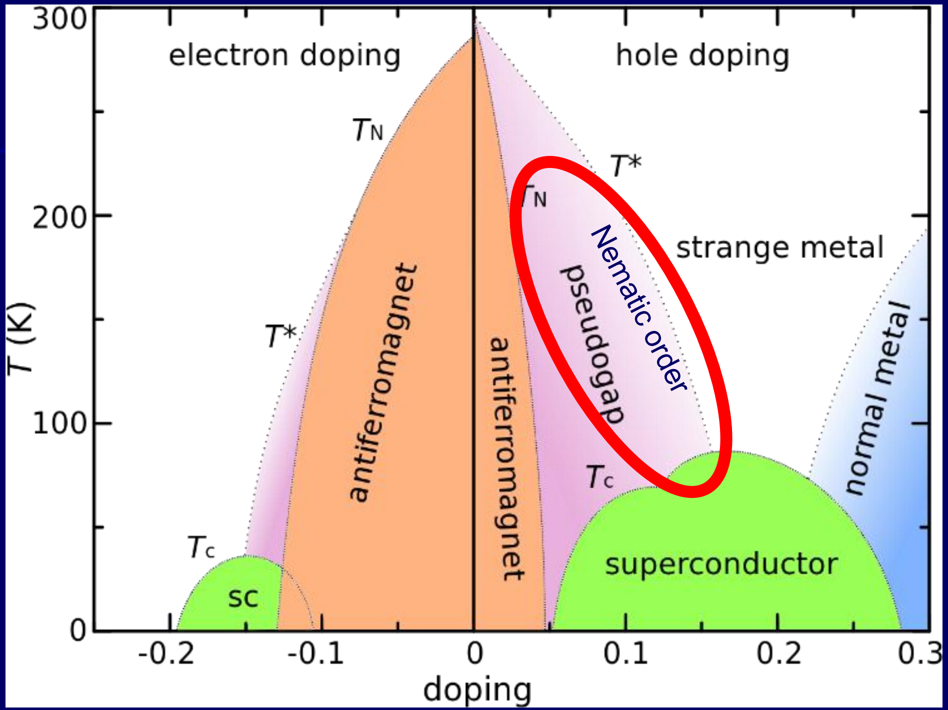


E.Y. Andrei

Nematicity

- Nematicity : discrete rotational symmetry of the lattice is spontaneously broken due to electron correlations, while lattice translational and time-reversal symmetries are preserved .





Nematic Fermi Fluids in Condensed Matter Physics

Annual Review of Condensed Matter Physics

Vol. 1:153-178 (Volume publication date 2010)

nature physics

REVIEW ARTICLE

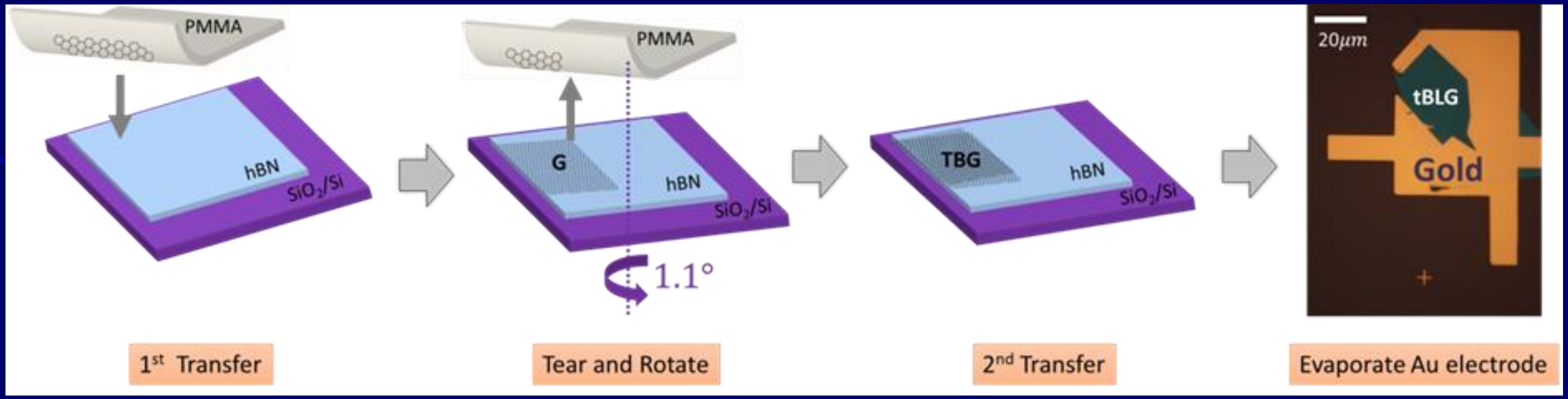
PUBLISHED ONLINE: 31 JANUARY 2014 | DOI: 10.1038/NPHYS2877

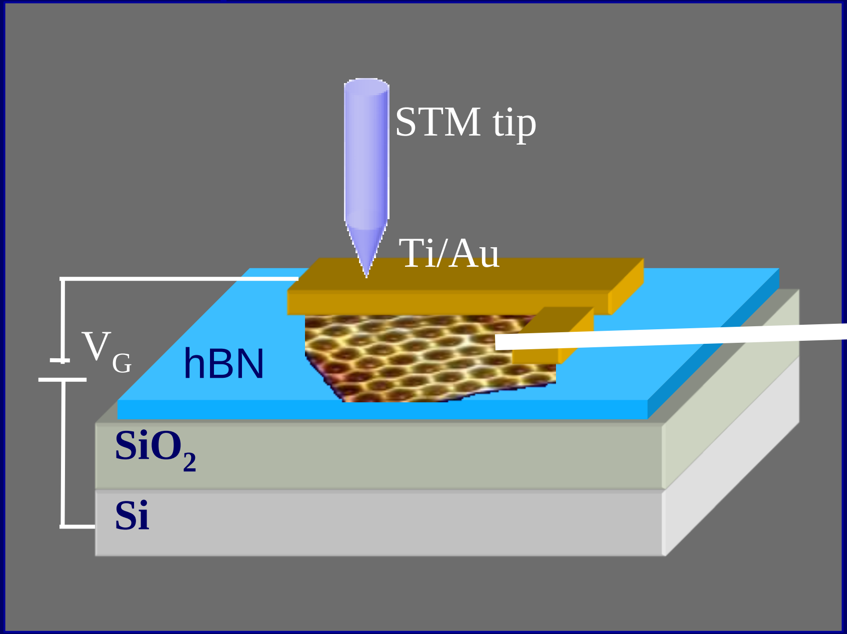
What drives nematic order in iron-based superconductors?

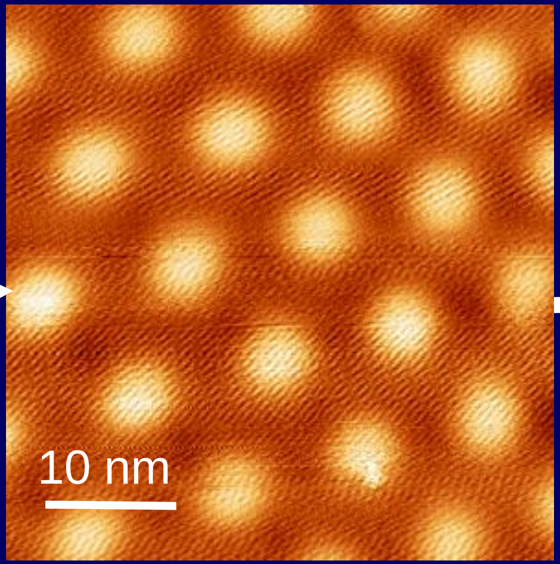
R. M. Fernandes[1]*, A. V. Chubukov[2]* and J. Schmalian[3]*

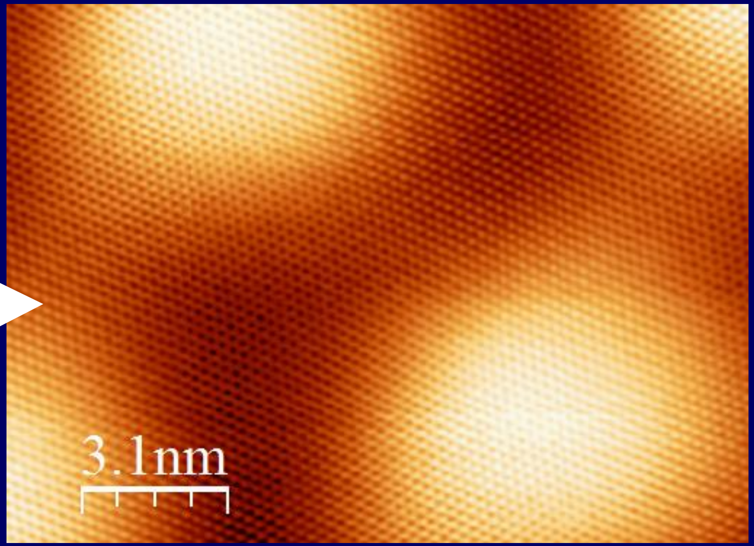
STM measurements on magic angle twisted graphene

"Tear & Stack"
Prepared in Ar glovebox





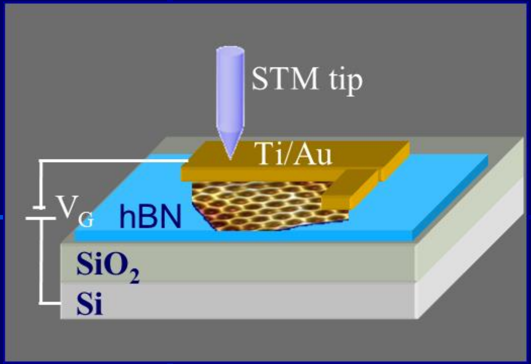




$\theta = 1.07^0$

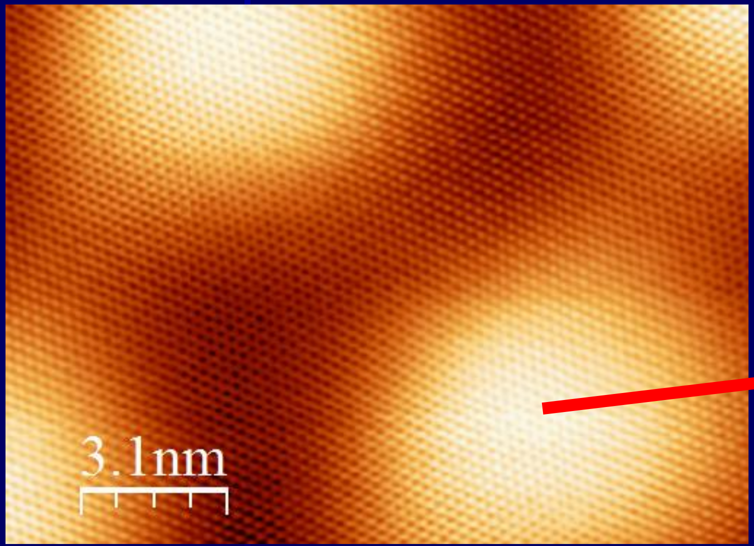
Y. Jiang, .. ,EYA, Nature **573,** 91 (2019)

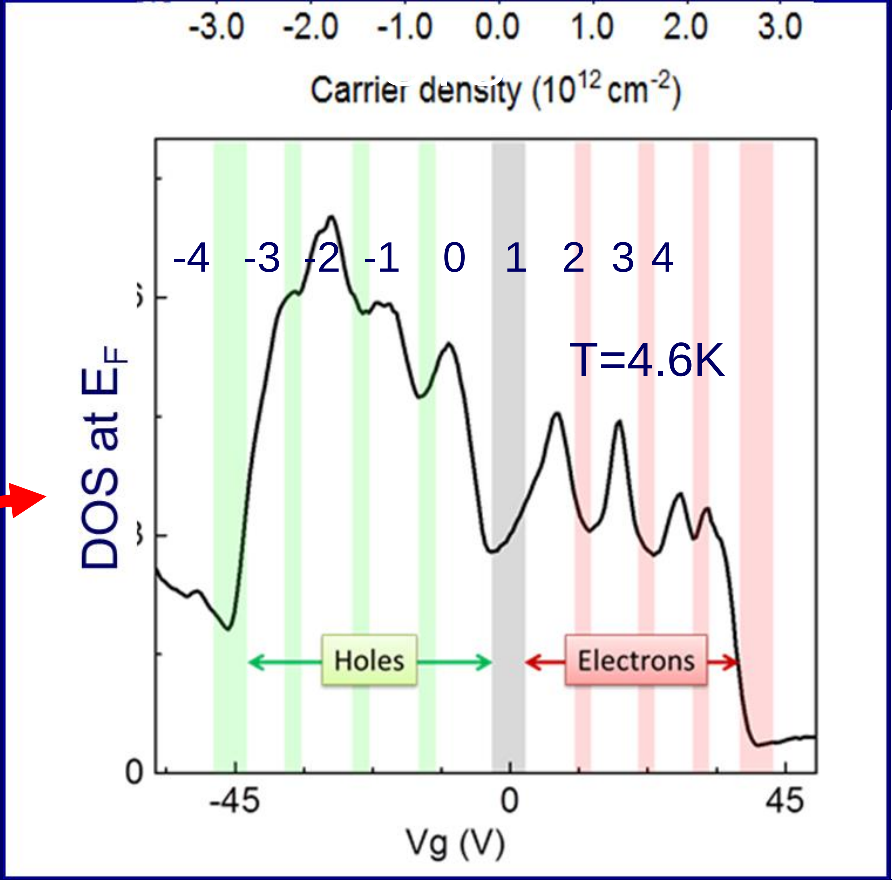
Flat band and correlated states: STS and transport



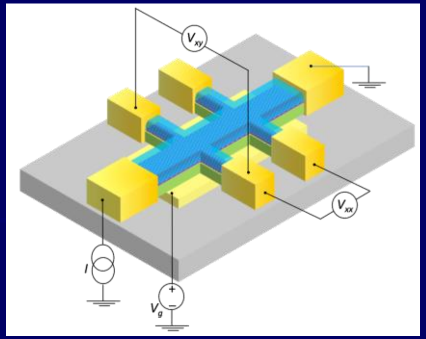
Mimic transport measurement:

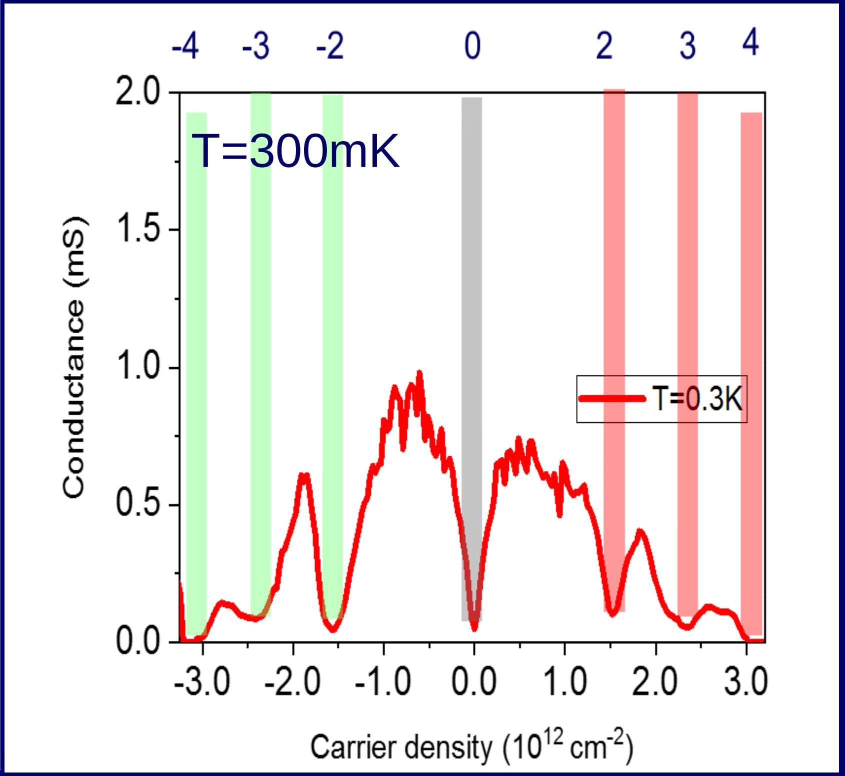
$V_b = 0 \mapsto E_F(\text{tip}) = E_F(\text{sample})$





transport



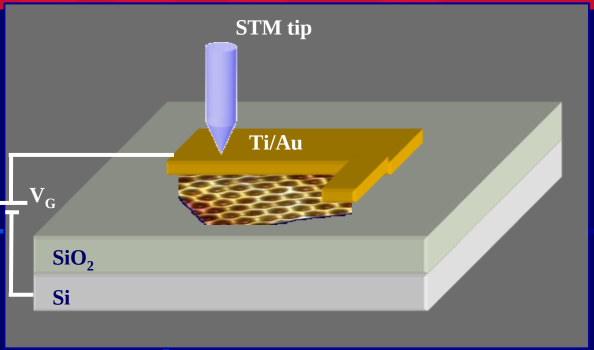


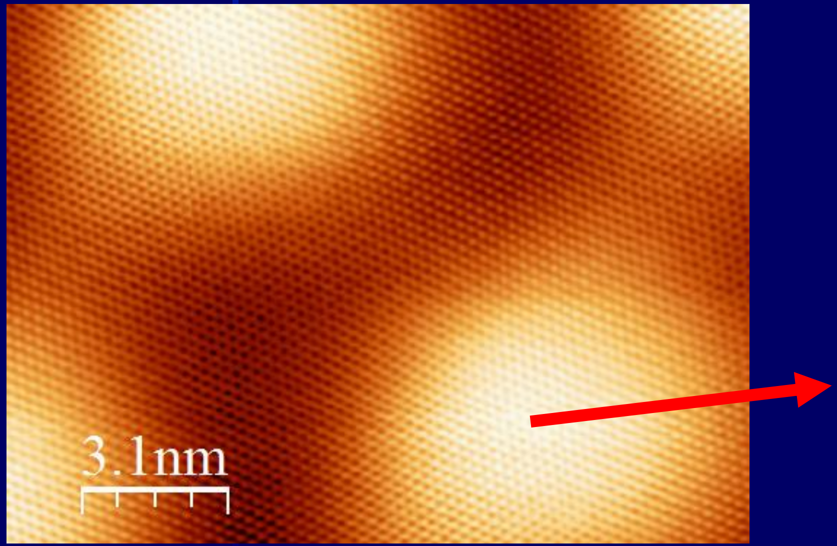
Y. Jiang,.. EYA, et al Nature 573, 91 (2019)

S. Wu,,.. EYA, Nature Materials 20, 488 (2021)

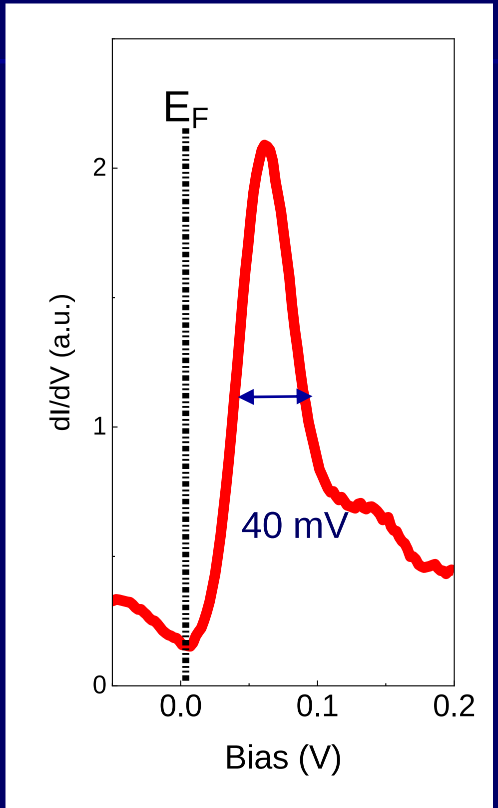
E.Y. Andrei

Magic angle: Flat Band

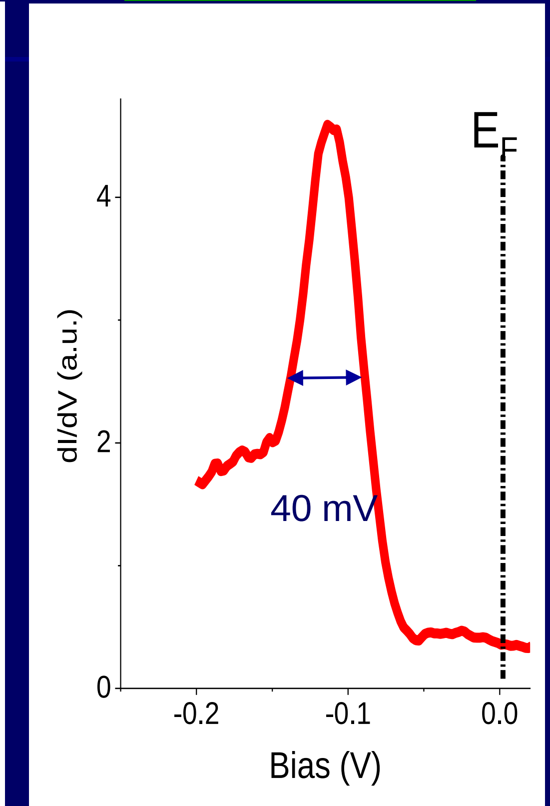




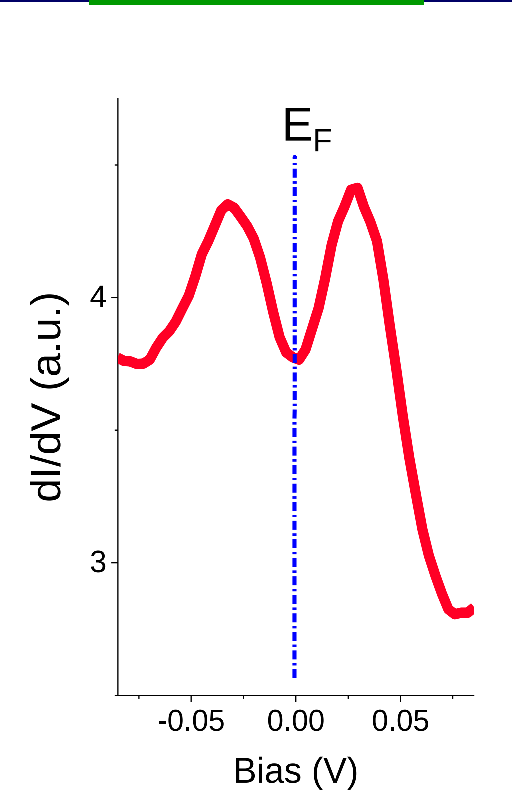
V_g=-55V
Flat band empty



V_g=+55V
Flat band full



V_g= 0V
Half full band



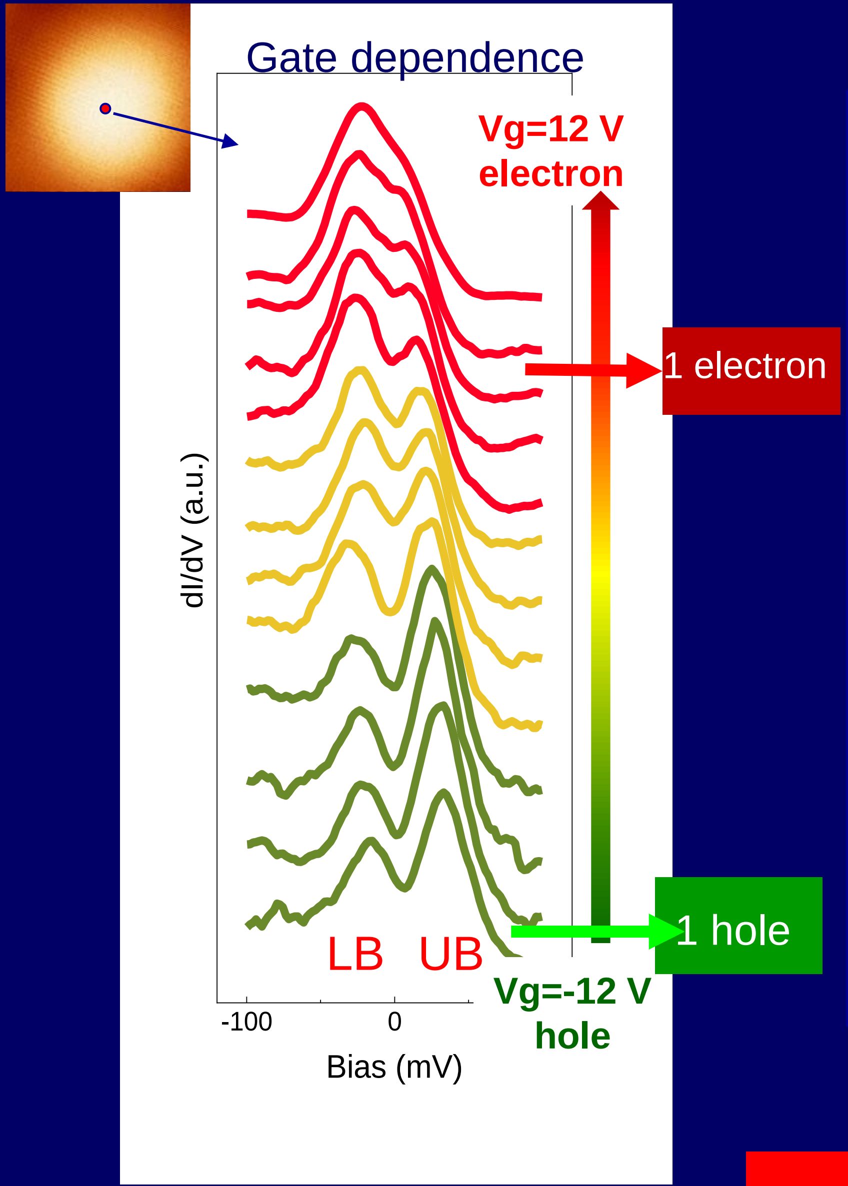
No gap feature in full or empty band

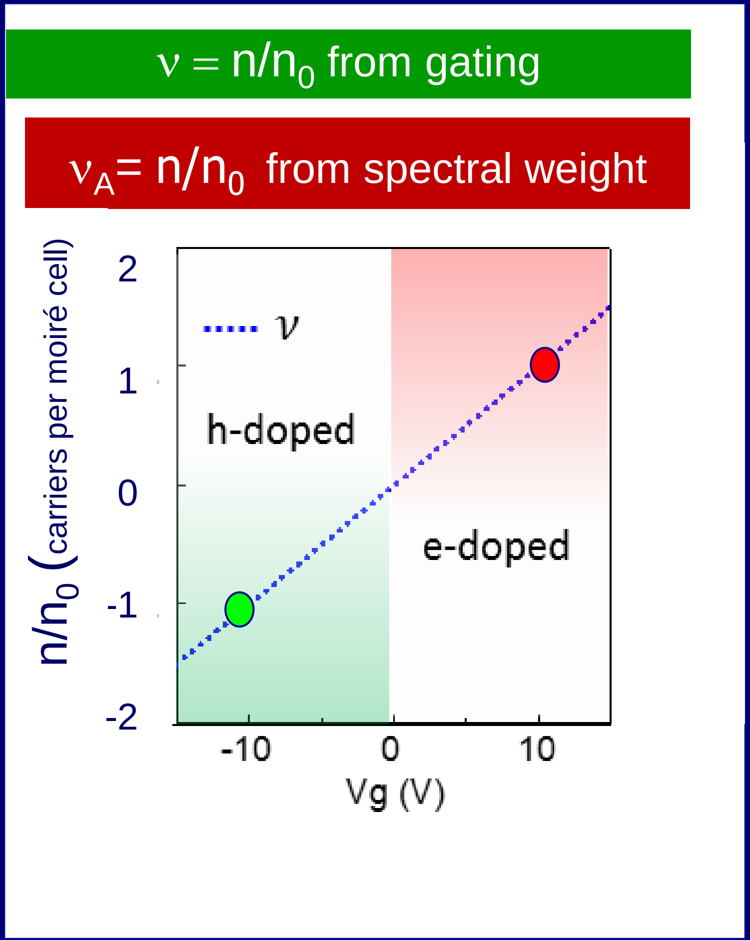
Correlation induced pseudo gap

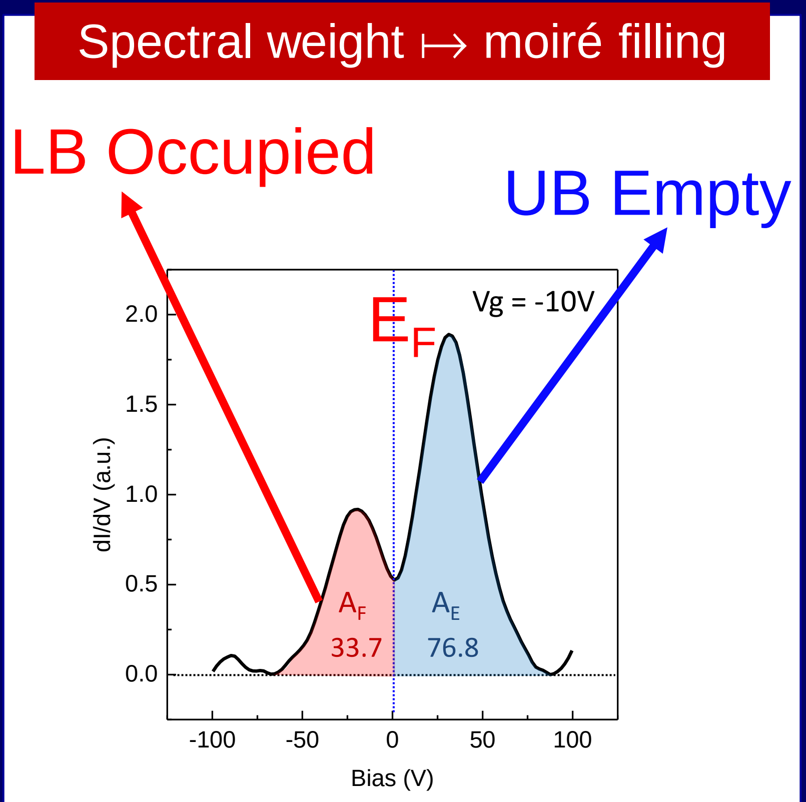
Kerelsky, *et al. Nature* **572**, 95-100, (2019).
Xie, Y. *et al. Nature* **572**, 101-105 (2019)
Choi, Y. et al. Nature Physics (2019)

Y. Jiang, .. ,EYA, Nature **573** (2019) 91

Charge spectroscopy in the flat band





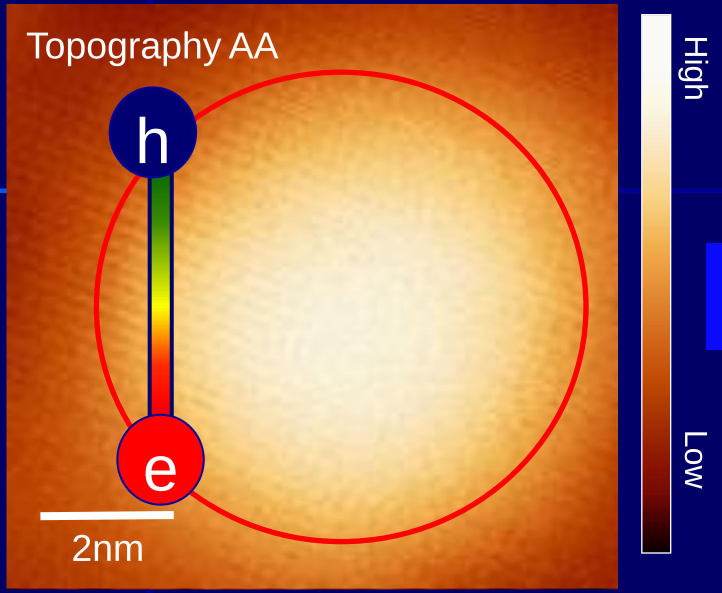


$$\frac{n}{n_0} = \frac{A_F}{A_{tot}} - \frac{1}{2}$$

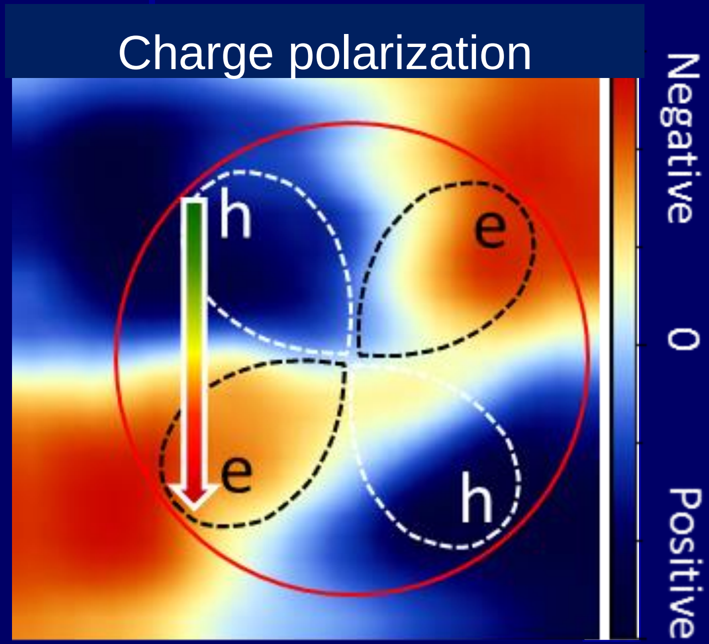
Spectral weight redistribution → Local Charge

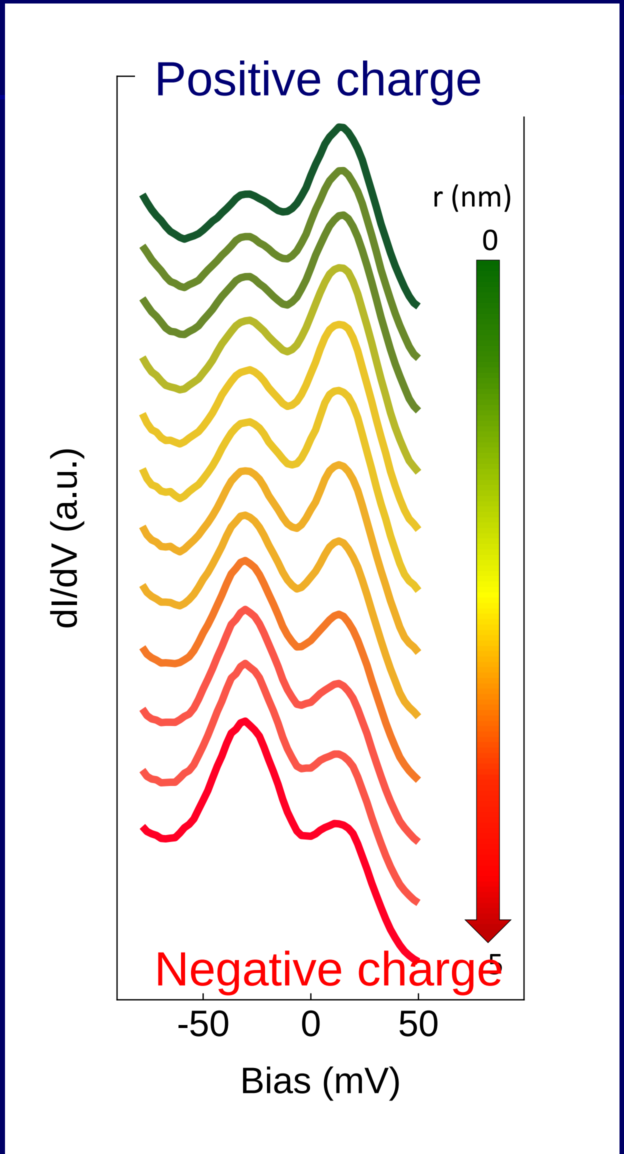
E.Y. Andrei

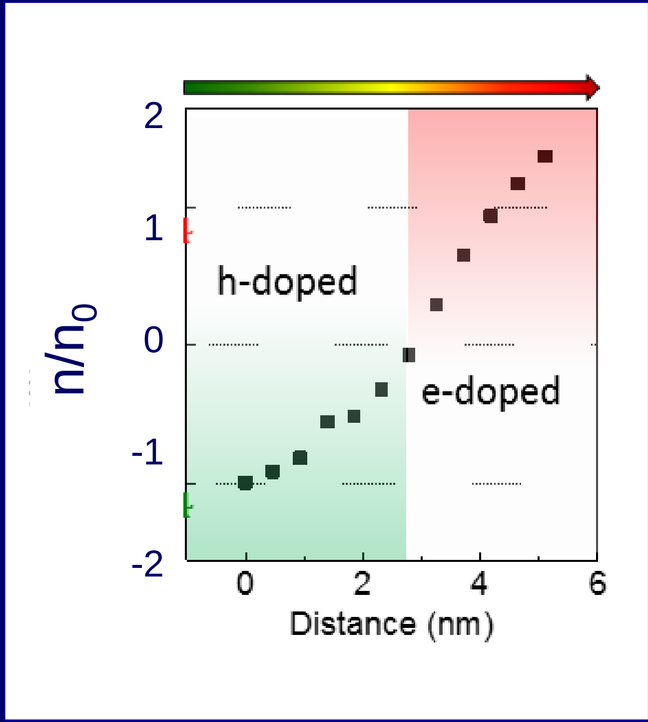
Spontaneous charge polarization



$V_g=0$



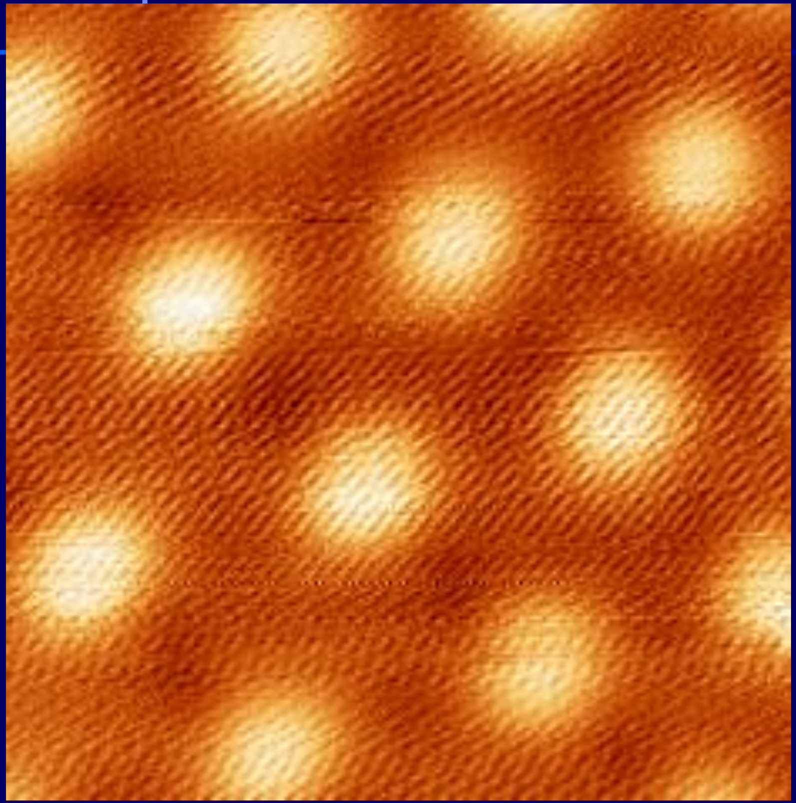




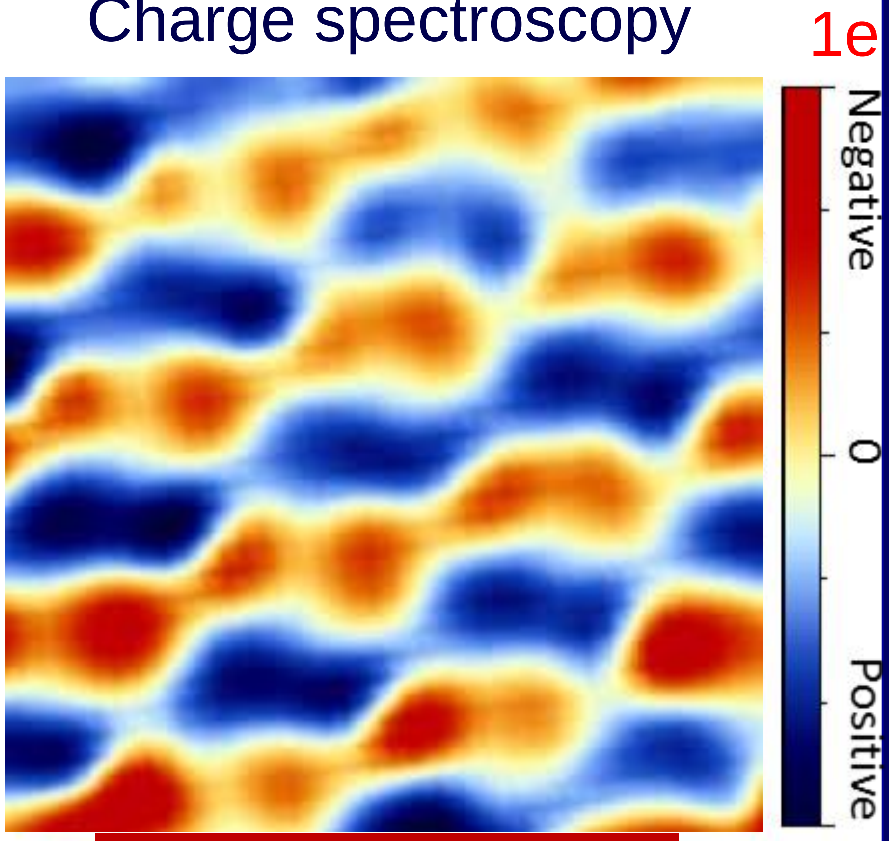
E.Y. Andrei

Nematic Charge order

Six fold symmetry



Charge spectroscopy



Nematic Charge order

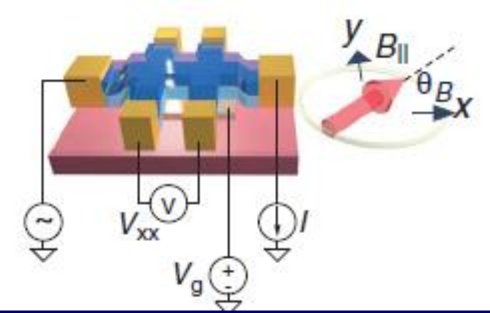
Y. Jiang, .. ,EYA, Nature **573** (2019) 91

Nematicity in Superconducting state

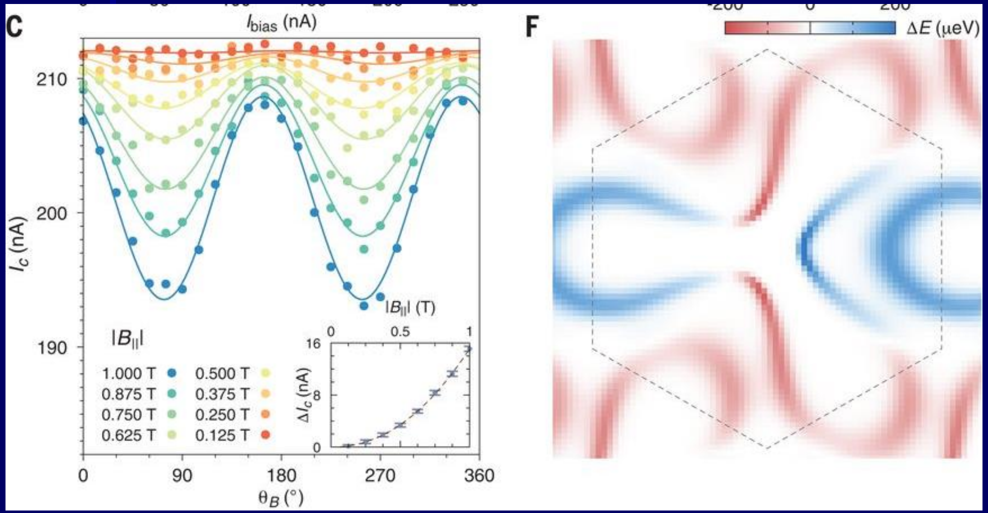
Nematicity and competing orders in superconducting magic-angle graphene

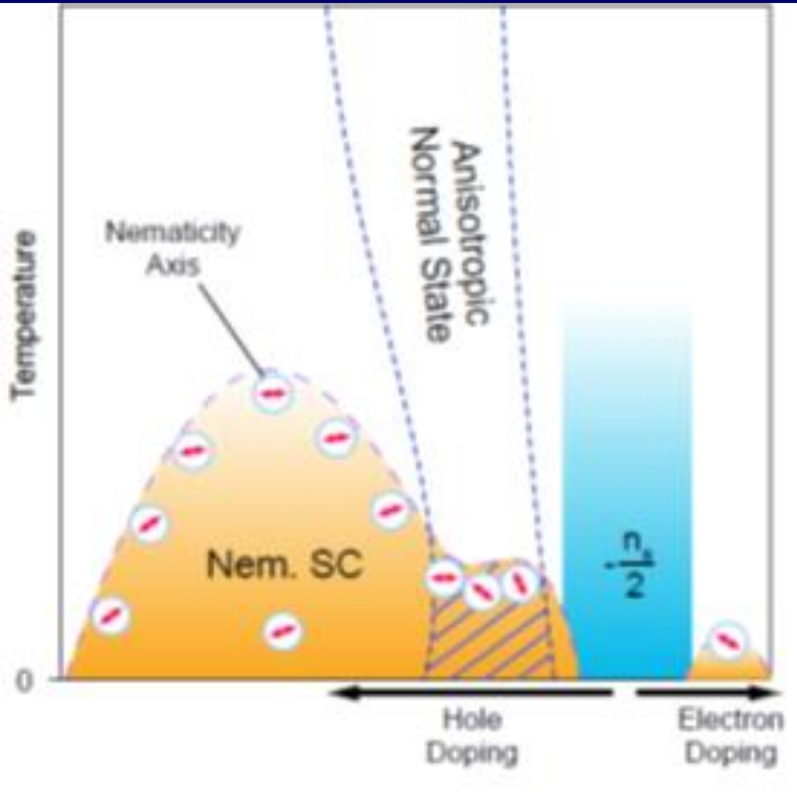
YUAN CAO, DANIEL RODAN-LEGRAIN, JEONG MIN PARK, NOAH F. Q. YUAN, KENJI WATANABE, TAKASHI TANIGUCHI, RAFAEL M. FERNANDES, LIANG FU, AND PABLO JARILLO-HERRERO Authors Info & Affiliations

SCIENCE • 16 Apr 2021 • Vol 372, Issue 6539 • pp. 264-271 • DOI: 10.1126/science.abc2836

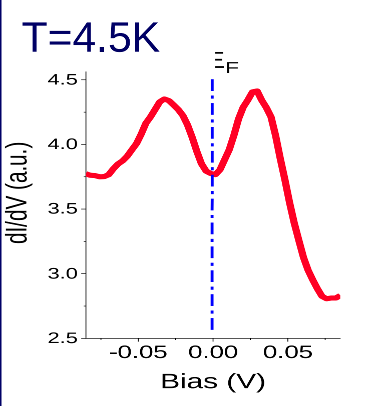


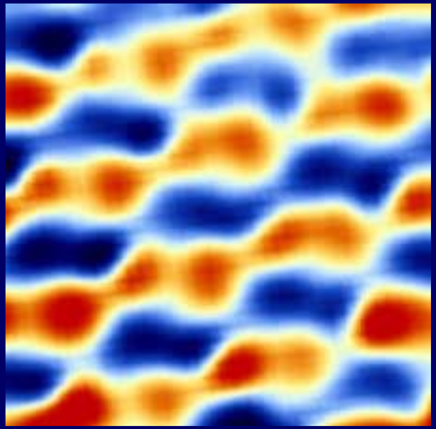
In the superconducting state : nematicity, manifested in its response to in-plane magnetic fields.





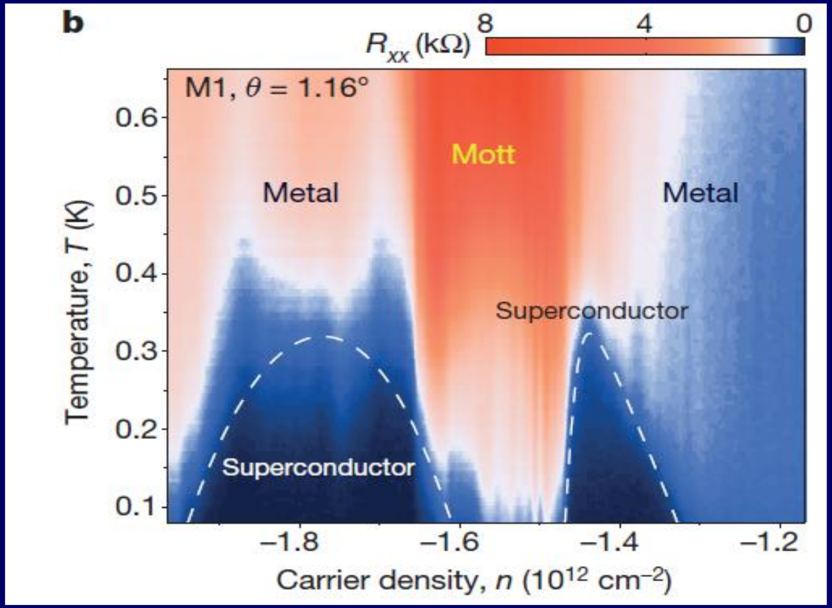
Compare with high temperature superconductors

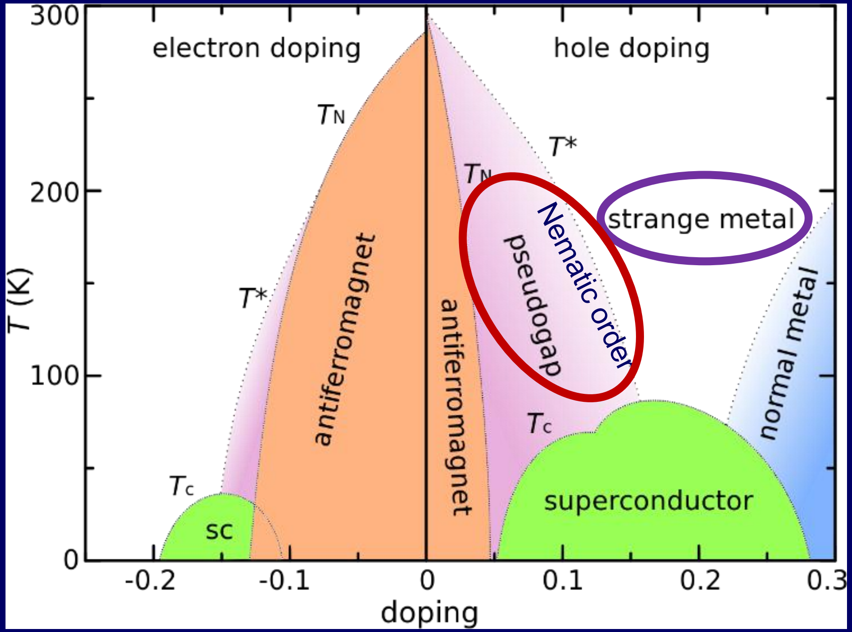




- ✓ Insulating phase flanked by superconducting domes
- ✓ $T_c/E_F \sim 10^{-1} \mapsto$ strong coupling

- ✓ Pseudogap phase
- ✓ Nematic Order
- ✓ Strange metal : “Planckian” dissipation





E.Y. Andrei

Beyond high temperature superconductors

New results

- Chern insulators
- Van Hove singularities
- Multiple superconducting domes

Chern insulators, van Hove singularities and topological flat bands in magic-angle twisted bilayer graphene

Shuang Wu, Zhenyuan Zhang, K. Watanabe, T. Taniguchi & Eva Y. Andrei

Nature Materials **20**, 488–494 (2021) | Cite this article

Superconductors, orbital magnets and correlated states in magic-angle bilayer graphene

Xiaobo Lu, Petr Stepanov, Wei Yang, Ming Xie, Mohammed Ali Aamir, Ipsita Das, Carles Urgell, Kenji Watanabe, Takashi Taniguchi, Guangyu Zhang, Adrian Bachtold, Allan H. MacDonald & Dmitri K. Efetov

Nature **574**, 653–657 (2019) | Cite this article

32k Accesses | **519** Citations | **169** Altmetric | Metrics

Cascade of phase transitions and Dirac revivals in magic-angle graphene

U. Zondiner, A. Rozen, D. Rodan-Legrain, Y. Cao, R. Queiroz, T. Taniguchi, K. Watanabe, Y. Oreg, F. von Oppen, Ady Stern, E. Berg, P. Jarillo-Herrero & S. Ilani

Nature **582**, 203–208 (2020) | Cite this article

Evidence for unconventional superconductivity in twisted bilayer graphene

Myungchul Oh, Kevin P. Nuckolls, Dillon Wong, Ryan L. Lee, Xiaomeng Liu, Kenji Watanabe, Takashi Taniguchi & Ali Yazdani

Nature **600**, 240–245 (2021) | Cite this article

Strongly correlated Chern insulators in magic-angle twisted bilayer graphene

Kevin P. Nuckolls, Myungchul Oh, Dillon Wong, Biao Lian, Kenji Watanabe, Takashi Taniguchi, B. Andrei Bernevig & Ali Yazdani