Observation of Van Hove Singularities in twisted graphene layers

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LETTERS

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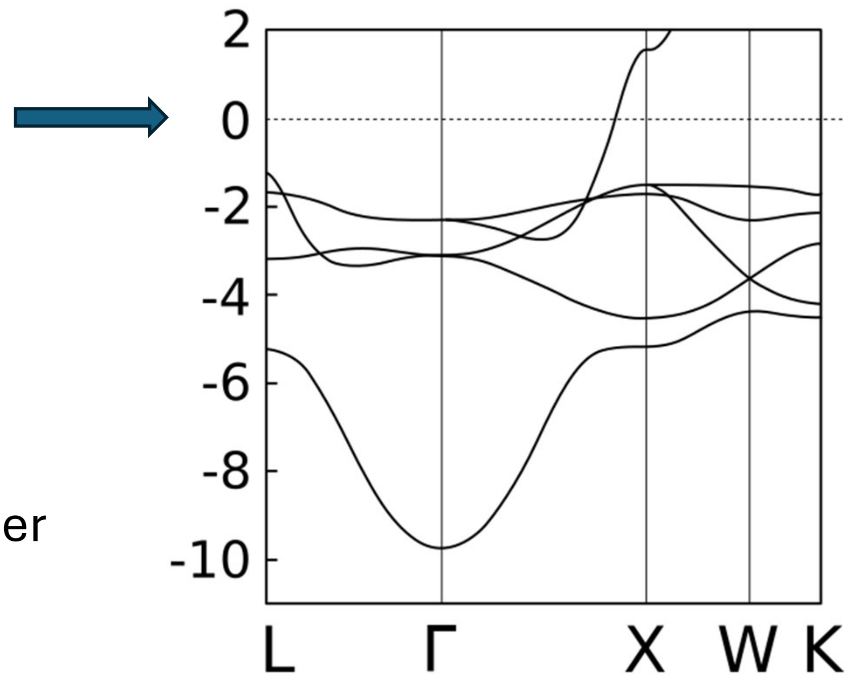
Observation of Van Hove singularities in twisted graphene layers

Guohong Li[1], A. Luican[1], J. M. B. Lopes dos Santos[2], A. H. Castro Neto[3], A. Reina[4], J. Kong[5] and E. Y. Andrei[1]*

Background

Band Structure 101

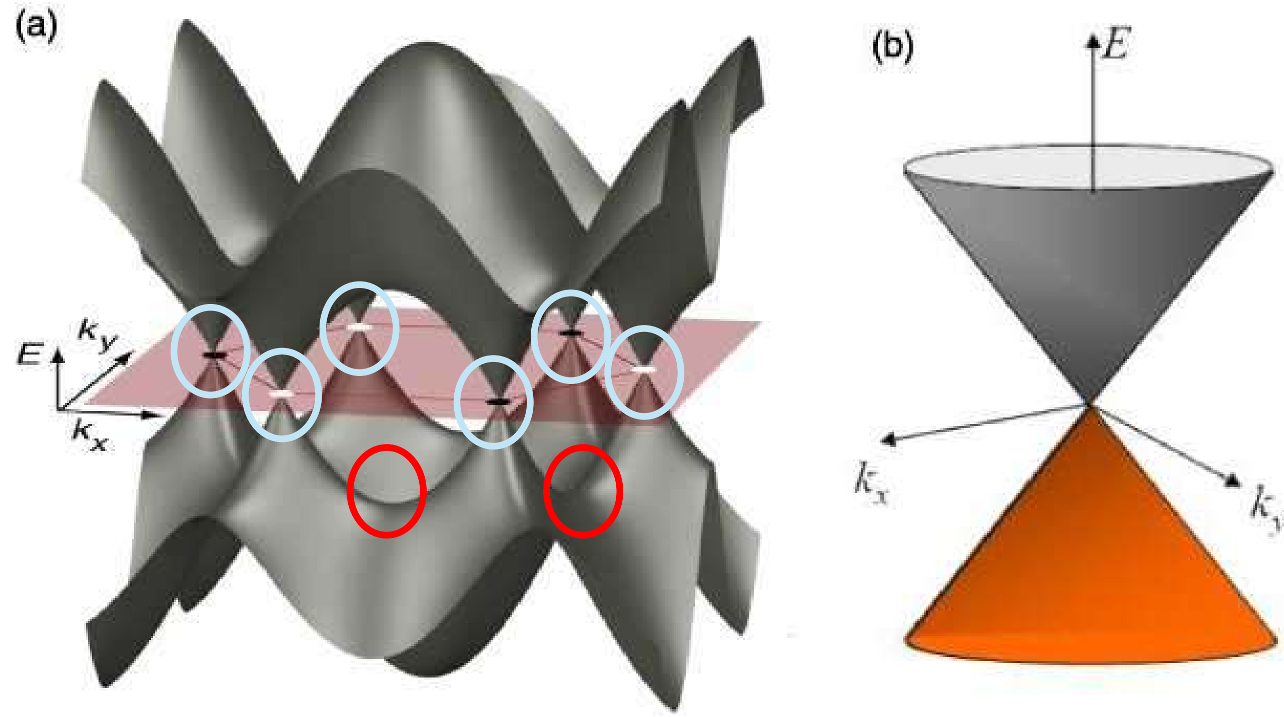
- Dispersion relation of electrons in material
  - X axis is momentum
  - Y axis is energy
- Density of states (DOS) - the number of different states electrons can occupy at a particular energy level
- Fermi level: energy where there is a mix of filled and empty energy levels



Band Structure and Density of States for Cu. Fermi Level Shown.
Copied from Wikipedia

Dirac Cones & Van Hove Singularities

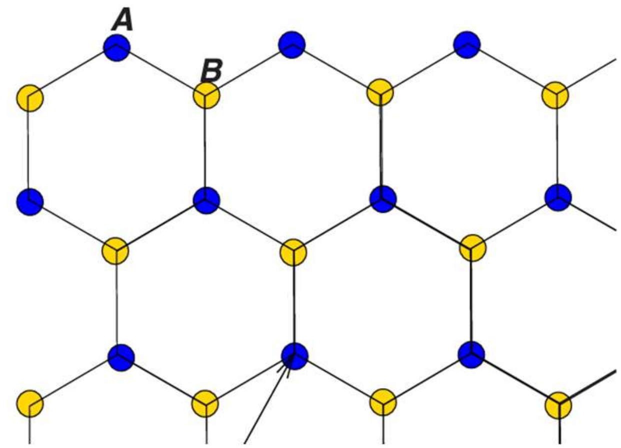
- Dirac Cones
  - Conical surfaces of valence and conduction bands, meet in Dirac point
- Van Hove Singularities
  - Flat part / saddle point in band
  - Infinite DOS
  - E_F close to VHS = magnified interactions
    - New phases of matter, advantageous properties

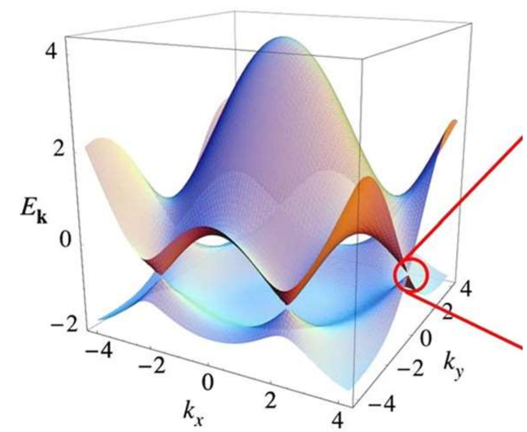


Previous work

VHS in Monolayer Graphene

- Graphene is made of C atoms in a honeycomb lattice.
- Band structure contains Dirac points and van Hove singularities
- However, van Hove singularities are far away from the typical Fermi level

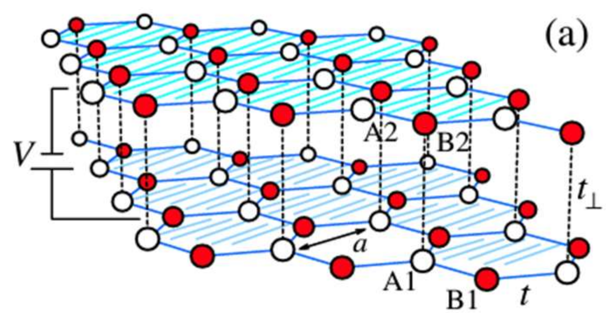


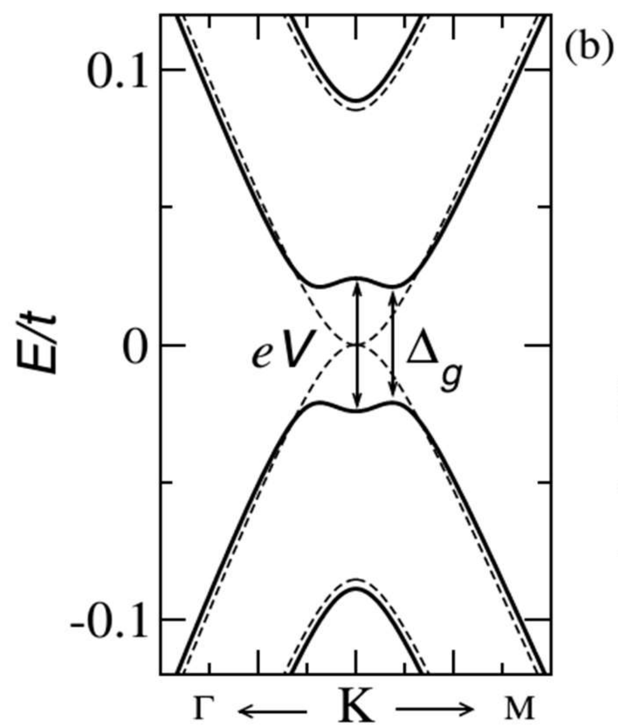


Copied from AH Castro Neto et al. (2009)

No VHS in untwisted bilayer Graphene

- Stack layers in alternating structure.
- No Dirac point. Bands touch quadratically.
- No van Hove singularity.





Copied from EV Castro et al. (2007)

Twisted Bilayer Graphene

The first paper describing the electronic properties of twisted graphene bilayers

PRL **99**, 256802 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

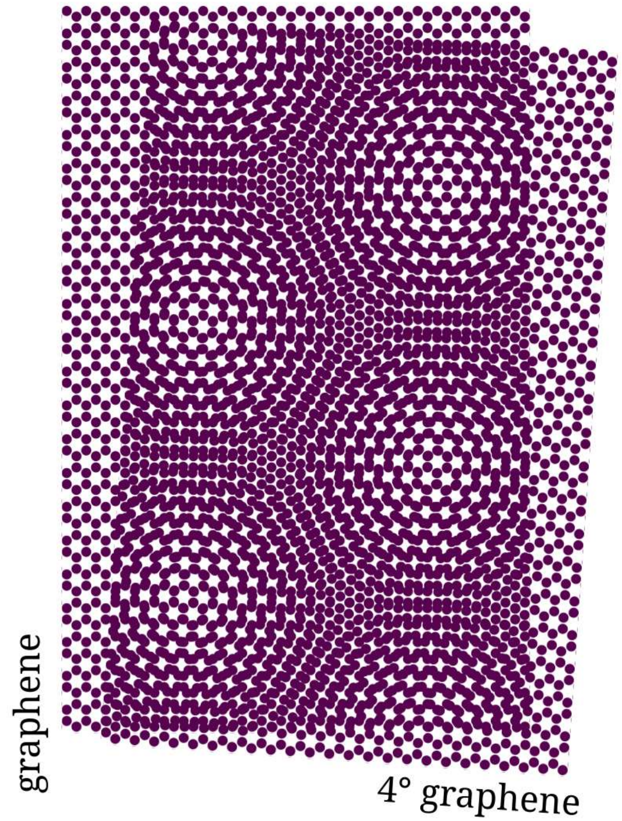
Graphene Bilayer with a Twist: Electronic Structure

J. M. B. Lopes dos Santos,[1] N. M. R. Peres,[2] and A. H. Castro Neto[3]

Twisted Bilayer Graphene - Moiré lattice

- Crystal is now periodic with superlattice instead of regular lattice

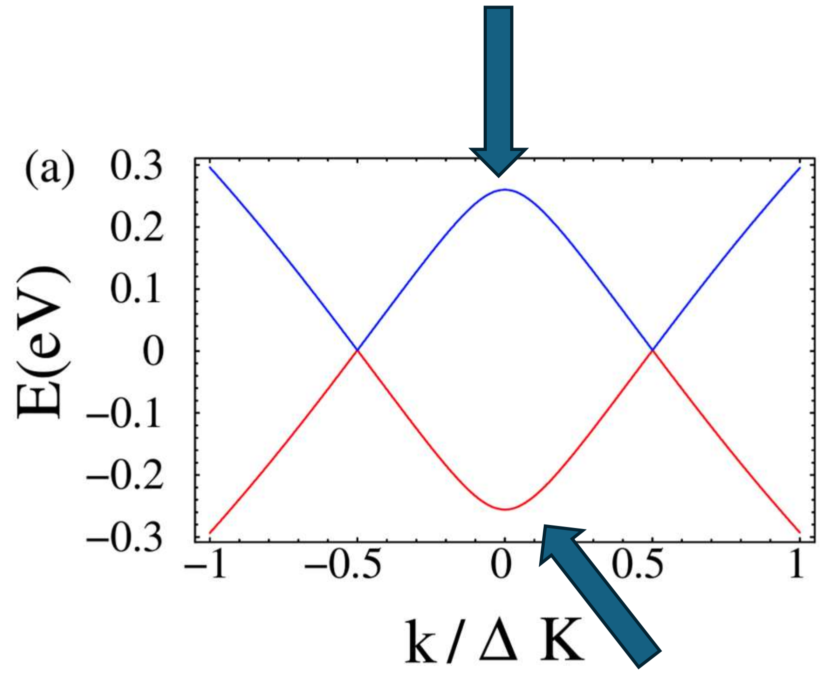
- Moiré superlattice introduces new twist angle dependent length scale.



Moiré Pattern
Copied from Wikipedia

Energy Bands in Twisted Bilayer

- Expect two Dirac cones in lowest energy states of twisted bilayer graphene.
- Leads to two Van Hove singularities in between the Dirac cones



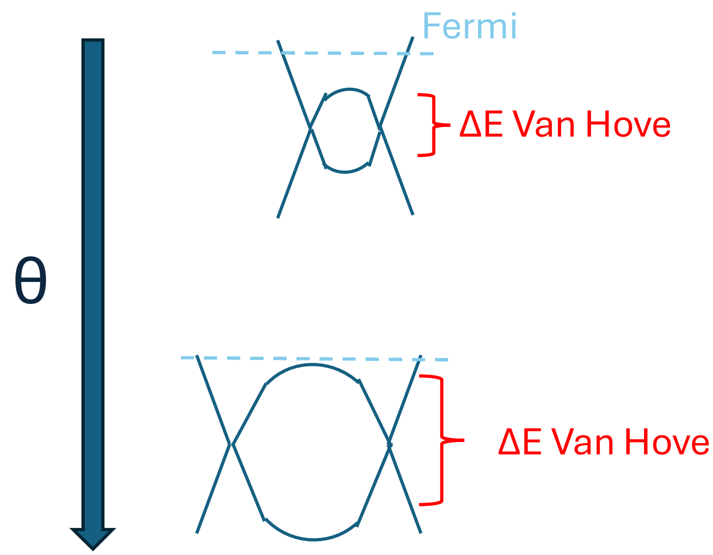
Copied from JMB Lopes dos Santos, NMR Peres, AH Castro Neto (2007)

VHS Gap in Twisted Bilayer

- For small angles, increasing twist angle increases distance between Dirac cones in momentum space

- Results in larger energy gap between Van Hove singularities

- Upper van Hove singularity is closer to Fermi energy!



Summary of Paper

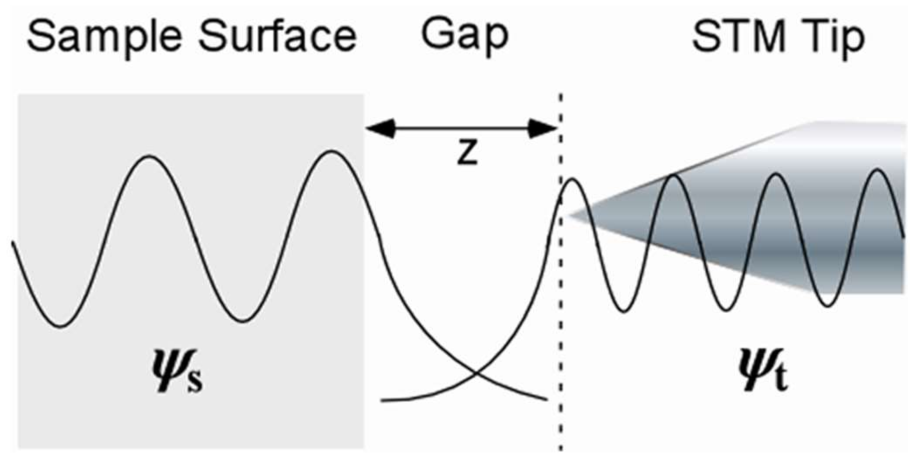
Motivation

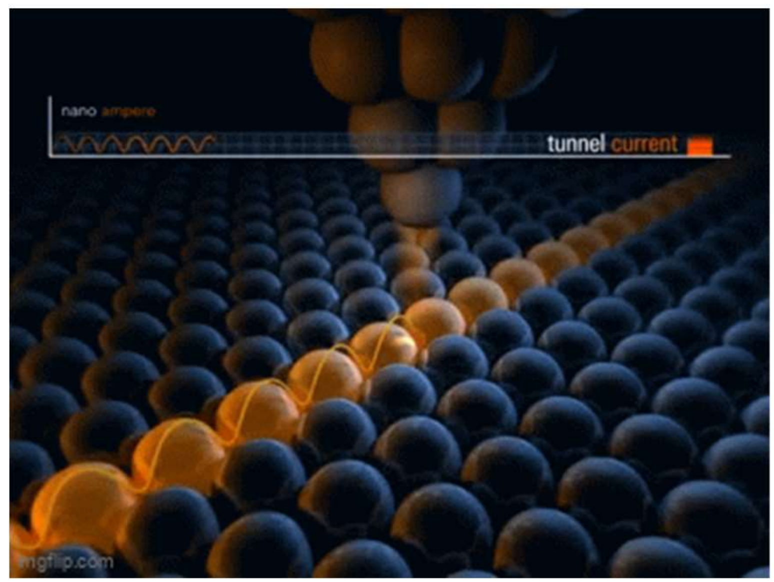
Being able to change the energy level of a van Hove singularity is very useful.

Should try to replicate this theoretical result experimentally.

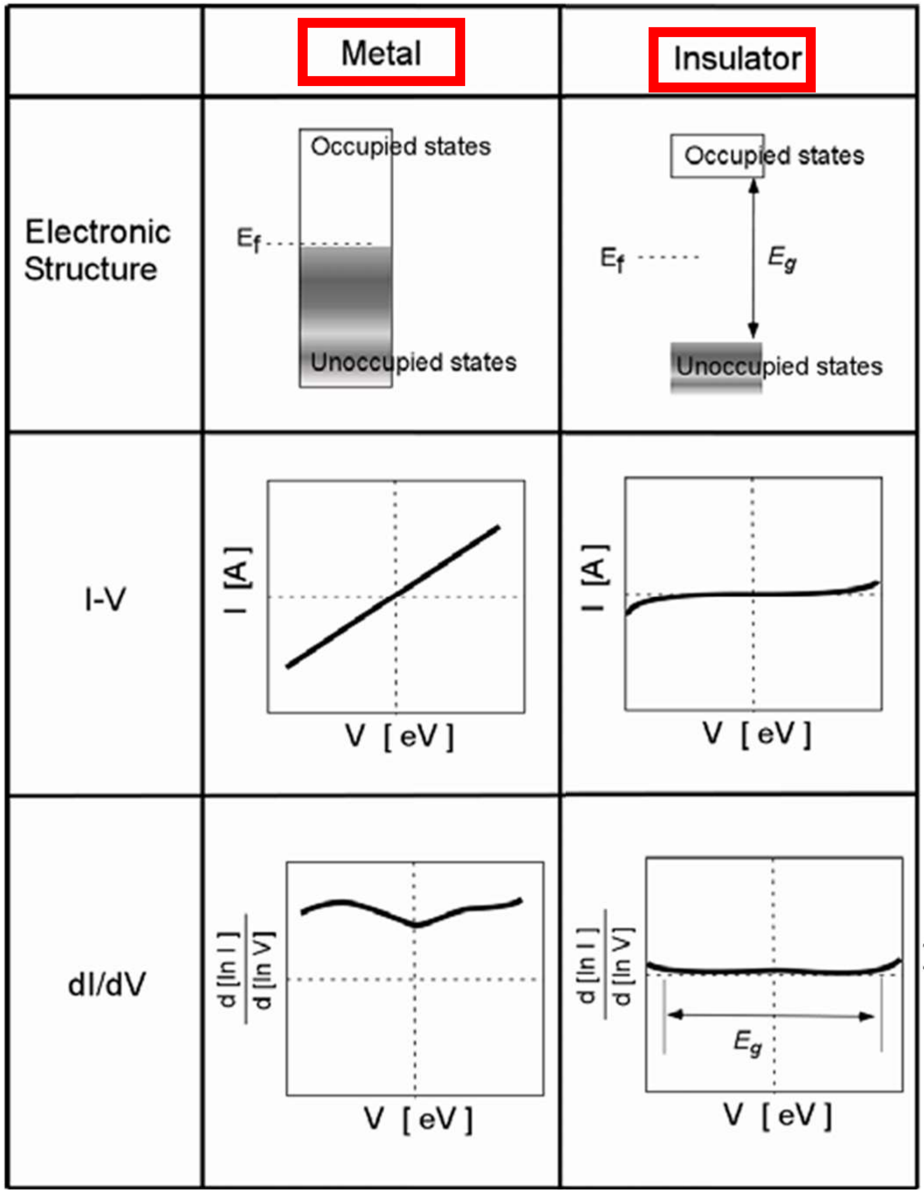
This is precisely what Eva Andrei's lab did using Scanning Tunneling Spectroscopy (STS), leading to the paper we are discussing.

Scanning Tunneling Microscopy (STM)





- Sharp (thin) conductive tip, penetrates conductive barriers with electrons emitting from it
- Bias voltage applied to observe current *I* of electrons
  - Spectroscopy (ramped up bias) used in this case

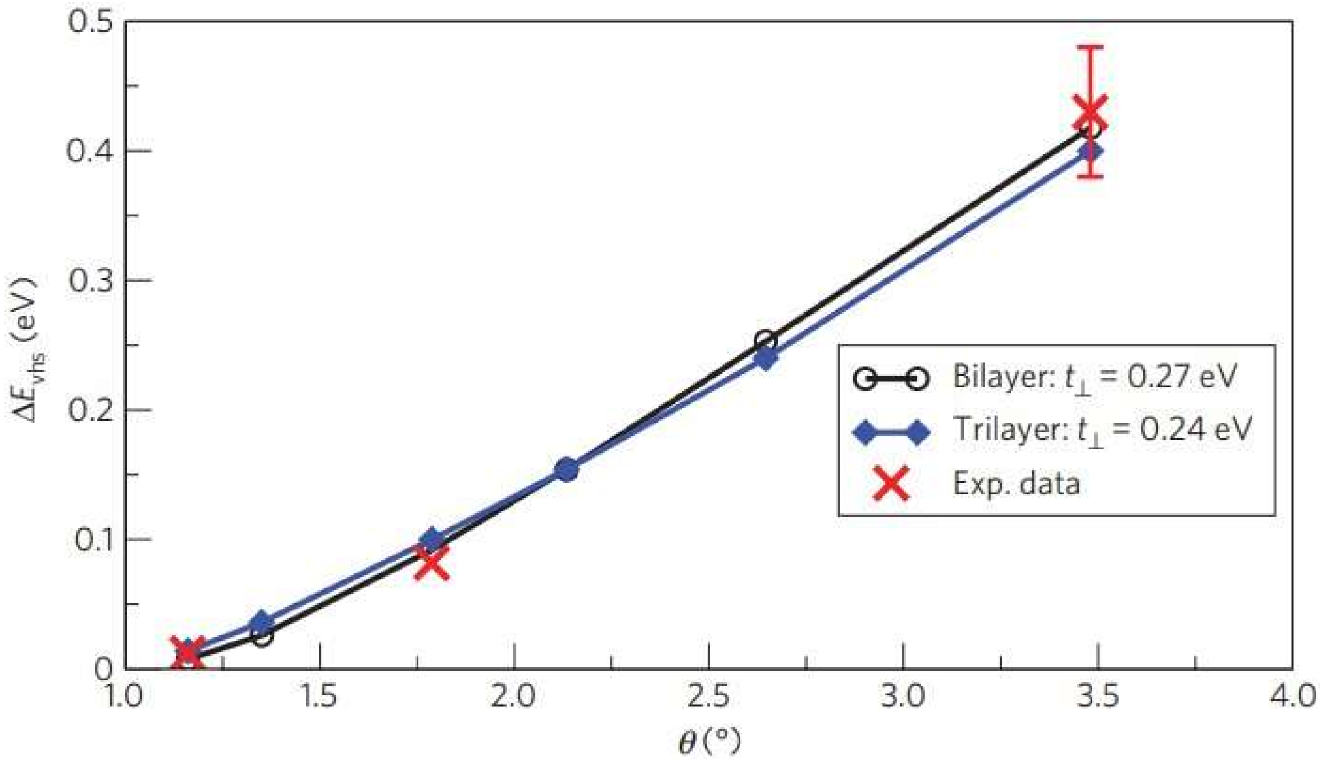

Metal
Insulator
Electronic Structure
Occupied states
Ef
Unoccupied states
Occupied states
Ef
Eg
Unoccupied states
I-V
I [A]
V [eV]
I [A]
V [eV]
dI/dV
d [ln I] / d [ln V]
V [eV]
d [ln I] / d [ln V]
Eg
V [eV]

py

Results & Conclusions

Main Conclusion:

The Van Hove singularity can be moved closer to the Fermi level by twisting it



Critical Analysis

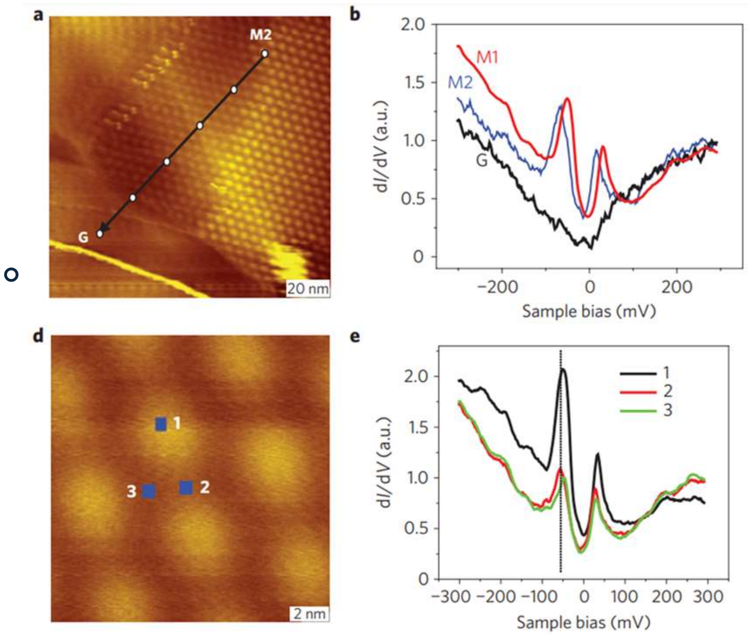
Critical Analysis

- Showed observation of VHS at different locations

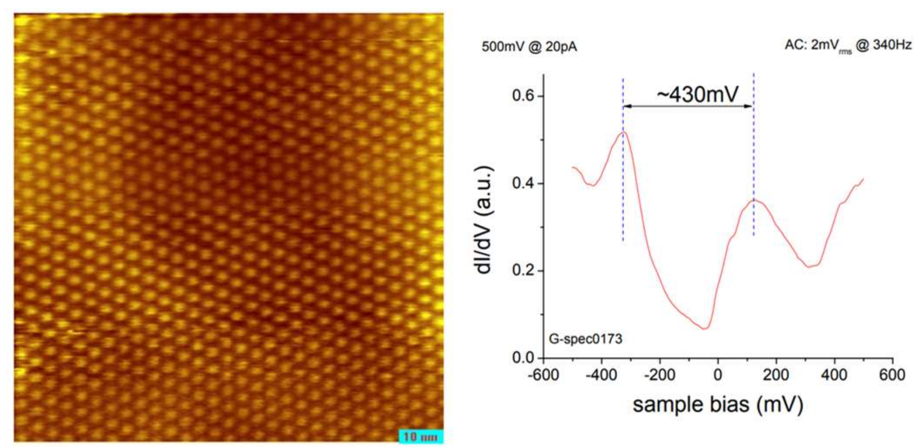
- Showed clear correspondence between angle of rotation and ΔE_{vhs}

- Tunability of suggests new ways of engineered electronic phases

θ=1.79°



θ=3.48°
(From supplement)

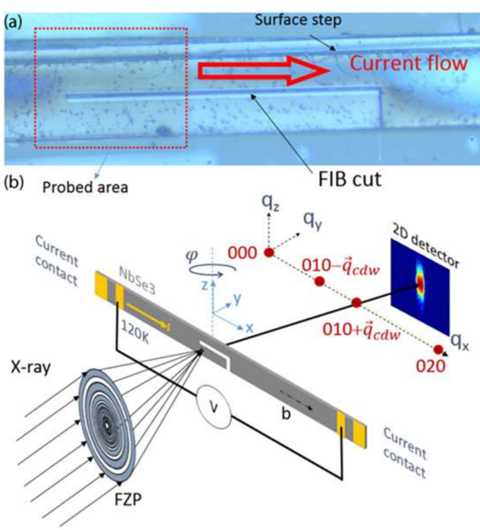


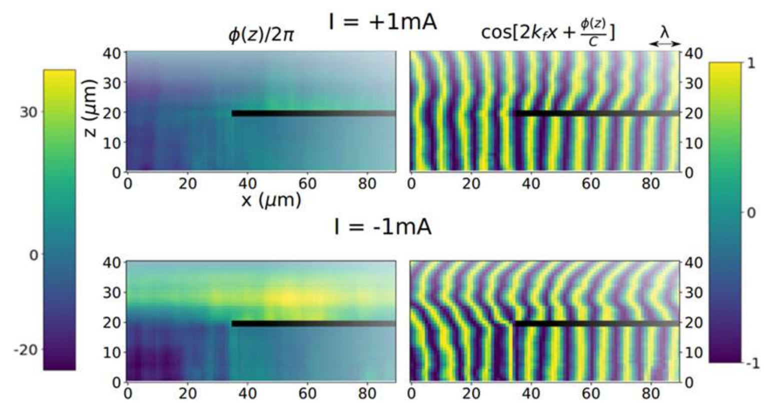
Critical Analysis

Drawbacks:

1. Evidence of new phases from tuning of ΔE_{vhs} is not direct

Charge density wave observed via x-ray microdiffraction showing lattice distortion

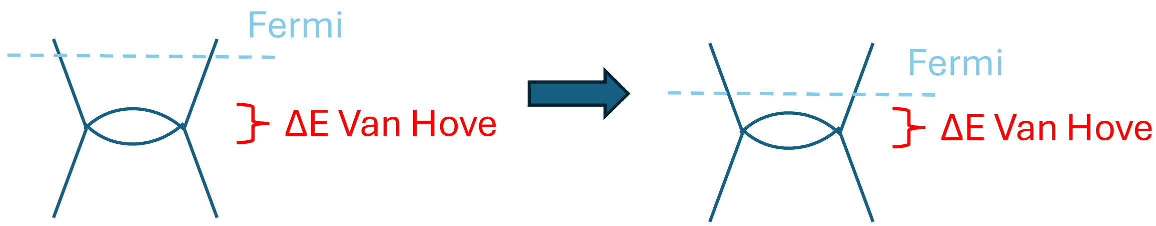




Evidence of charge density wave transverse pinning by x-ray microdiffraction E. Bellec, I. Gonzalez-Vallejo, V. L. R. Jacques, A. A. Sinchenko, A. P. Orlov, P. Monceau, S. J. Leake, and D. Le Bolloc'h Phys. Rev. B 101, 125122 (2020)

Critical Analysis

- Experiment done at fixed E_f
- Should also demonstrate tuning E_f by more conventional and accessible method such as doping and adjusting temperature



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Save all to author list

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[c] Department of Physics, Boston University, Boston, MA 02215, 590 Commonwealth Avenue, United States
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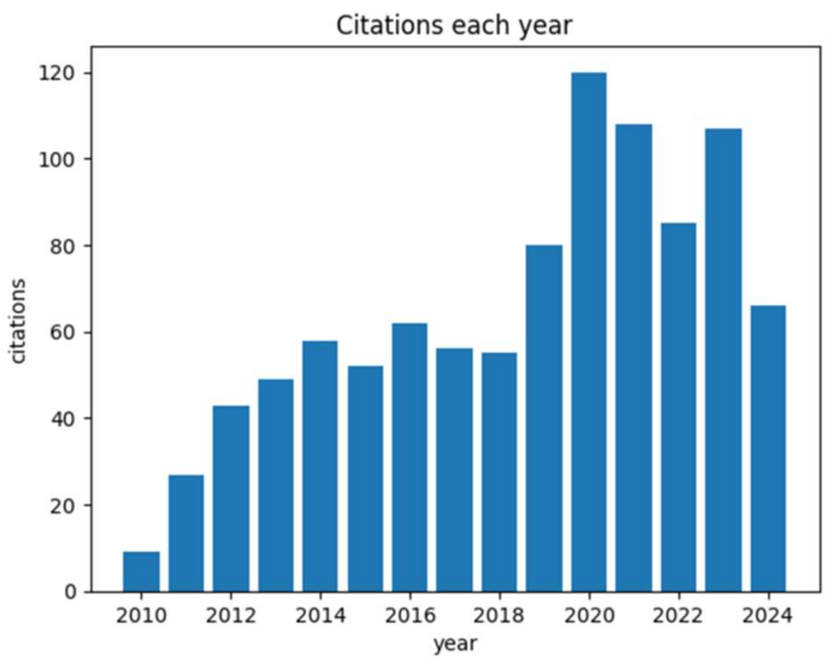
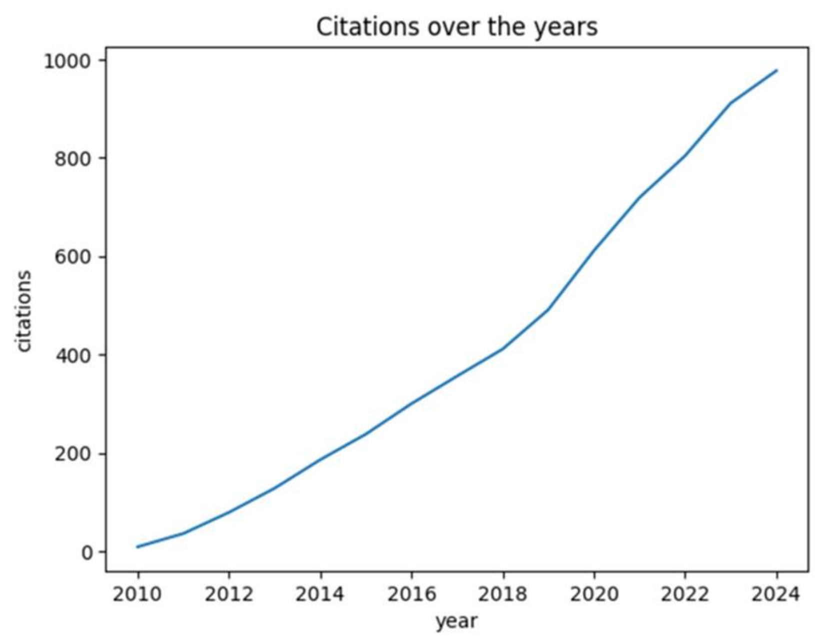
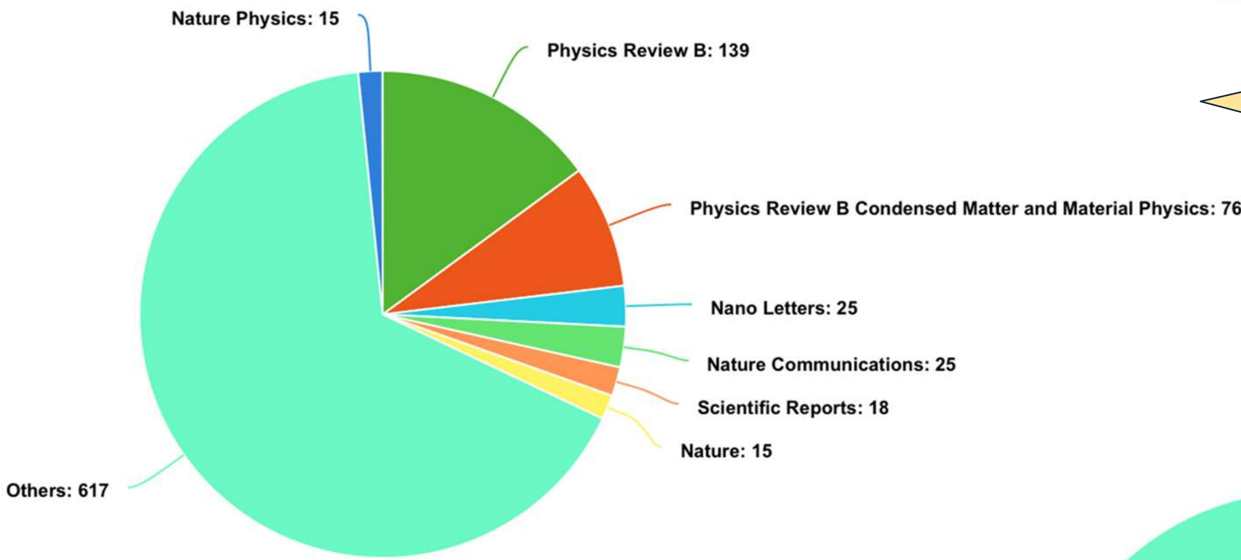
Citation over the years





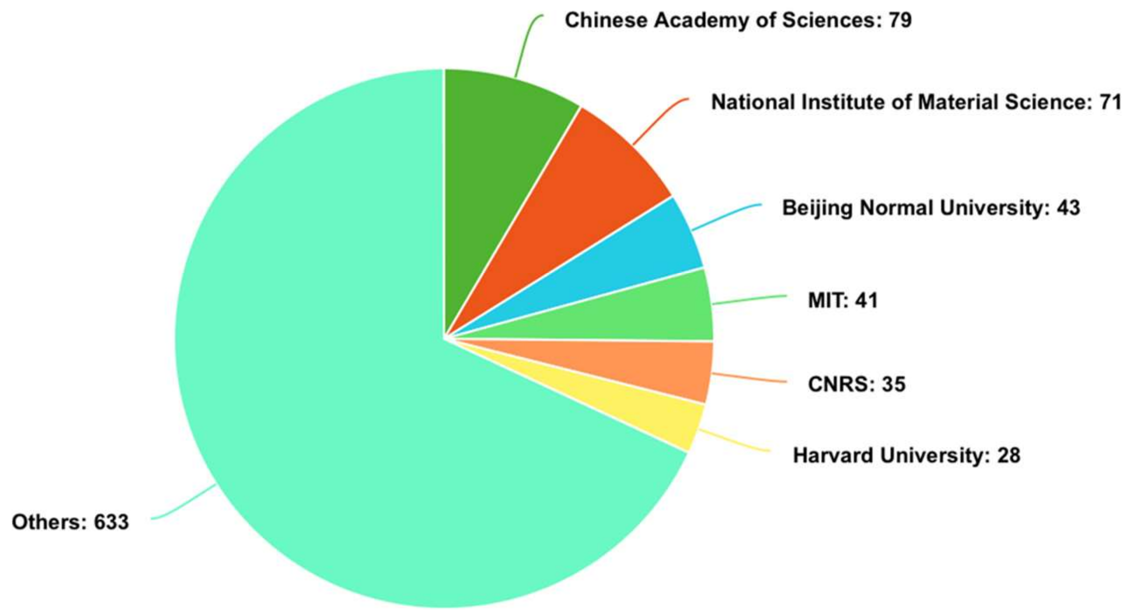
- Steady growth over the years, with a peak in 2020.
- It crossed 100 citations within three years of being published.

Who cited the paper?



Cited by top journals multiple times

Popular among top institutes

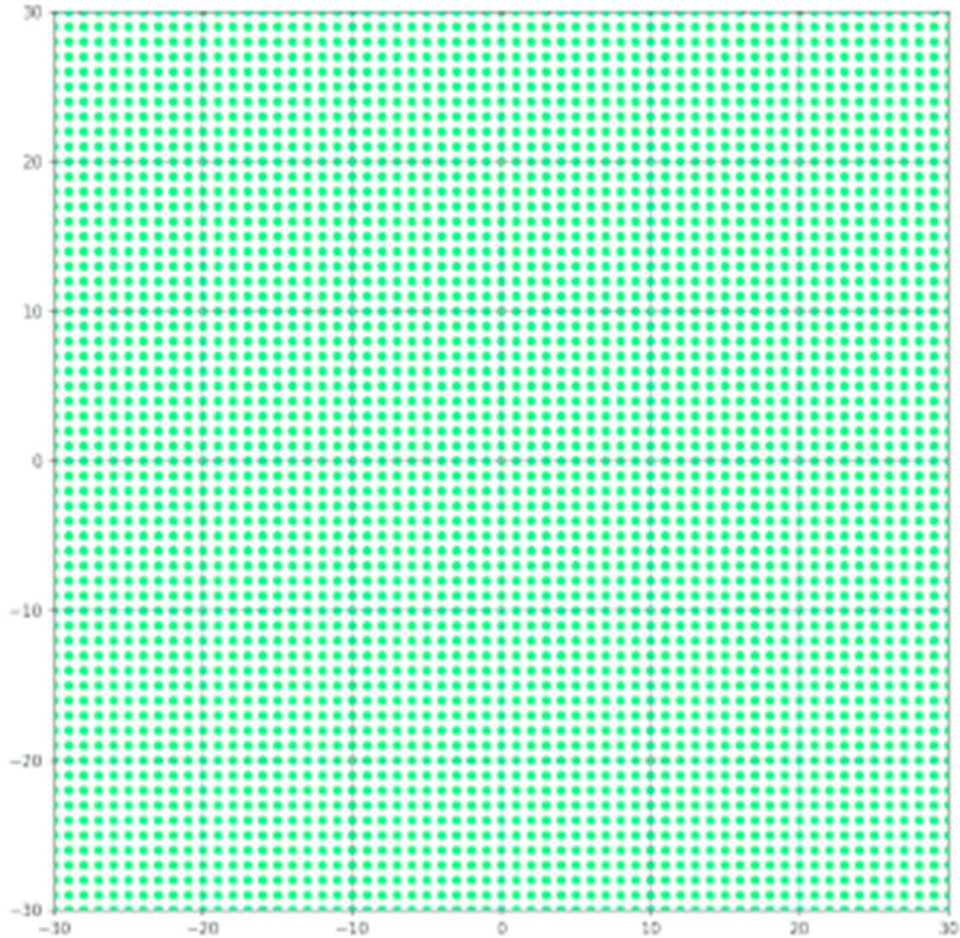


DK0

Emergence of a new field : Twistronics

The paper inspired investigations into angle dependent electronic properties of twisted 2D materials.

Moire Pattern changes with changing angle between graphene layers



Source - Wikipedia

Slide 27

DK0 https://meetings.aps.org/Meeting/MAR24/Session/G09
Danesh, Kaeshav, 2024-12-05T22:46:46.497

DK0

Evolution of the field

ARTICLE

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]

Developments on “magic angle“

Discovery of Superconductivity in Twisted Bilayer Graphene

Slide 28

DK0 maybe mention the term twistronics
Danesh, Kaeshav, 2024-12-05T16:11:00.383

DS0 0 ok
Das, Swadhina, 2024-12-05T20:08:22.424

Thank you

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