Correlated Insulator and Unconventional Superconductivity in Magic-angle Graphene Superlattice

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Cao Y et al. Nature, 2018, 556(7699): 43.
Cao Y et al. Nature, 2018, 556(7699): 80.

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Moiré Pattern in Twisted Bilayer Graphene

Two layers of lattice with a twist angle generate Moiré pattern and gives rise to superlattice.

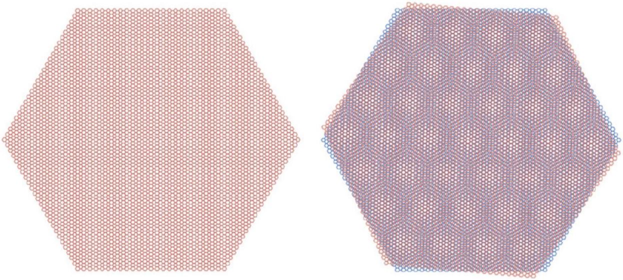

Figure: Pablo Jarillo-Herrero (MIT) at APS March Meeting 2018

Left: Untwisted bilayer graphene retains lattice structure of single layer graphene.
Right: Moiré pattern in Twisted bilayer graphene generates an extra superlattice.

Band Structure of Twisted Bilayer Graphene

Low-energy bands become flat when twist angle is close to the magic angles, which leads to localized profile in position space.

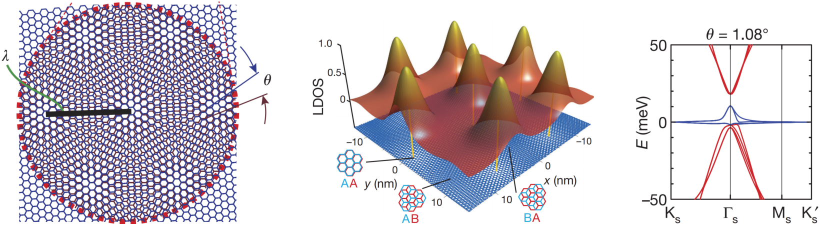

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Left: Superlattice constant $\lambda = a/[2\sin(\theta/2)]$ where a is the graphene lattice constant and θ the twist angle.
Middle: Normalized local density of states calculated for the flat band showing localized profile.
Right: The band energy of MA-TBG calculated using an *ab initio* tight-binding method.

Flat Band Created by Interlayer Hybridization

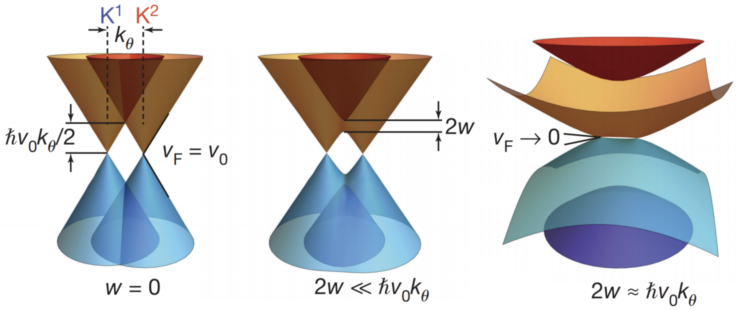

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Left: Large twist angle, no interlayer hybridization.
Middle: Large twist angle, hybridization energy w much smaller than the height of crossing.
Right: Small twist angle, hybridization energy comparable to crossing height, band flatterns.

Band Structure of Twisted Bilayer Graphene

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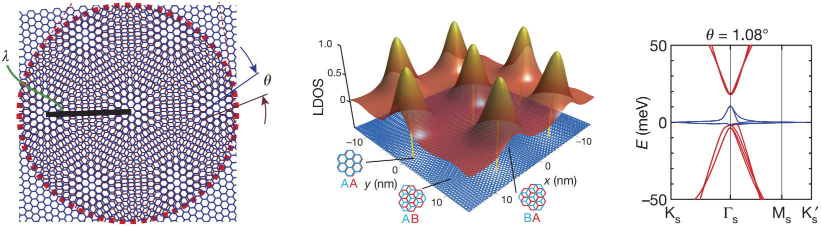

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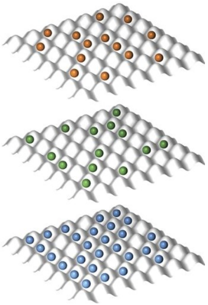
Lattice Platforms for Strong Correlated Physics

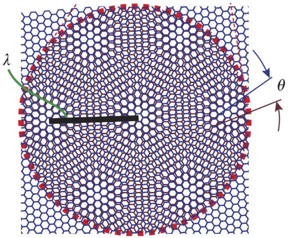
Cold Atom Optical Lattice Scale

$\sim$ 1 micron



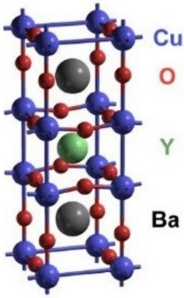
Magic-angle Graphene Superlattice Scale

$\sim$ 10 nm



Quantum Materials Lattice Scale

$\sim$ few $\AA$



New Platform Based on MA-TBG Superlattice

Magic-angle Twisted Bilayer Graphene is highly tunable:

- Electrostatic control of charge density
- Mechanical control of twist angle
- Pressure control of interlayer coupling (and hence magic angle and lattice constant)
- Usual control knobs (voltage, current, temperature, magnetic field ...)
- All the technologies that come with 2D device nanofabrication

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Insulating Behaviour at Full-filling

When the twist angle is larger than the first magic angle, the system behaves normally.

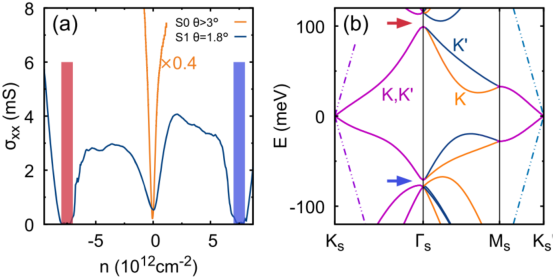

Figure: Cao Y, et al. Physical review letters, 2016, 117(11): 116804.

Left: Dependence of conductance on the charge density. Observe insulating states at full-filling.
Right: Band structure at twist angle 1.8°. No flat bands occur.

Insulating Behaviour at Half-filling

When twist angle approaches the first magic angle, two new insulating states occur at half-filling.

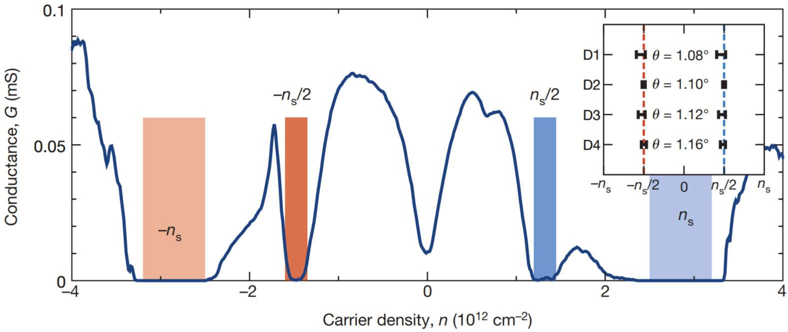

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Dependence of conductance on the charge density of magic-angle TBG.
Observe abnormal insulating states at half-filling.

Metal-insulator Behaviour in Magic-angle TBG

Insulating states only occur at low temperature, which resembles the correlated Mott insulator.

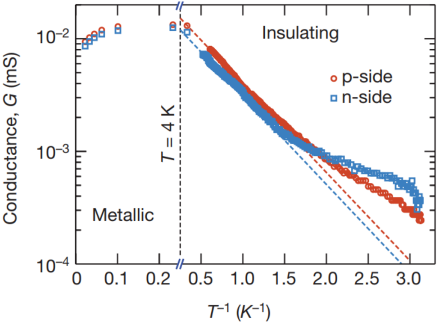

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Dependence of conductance on inverse temperature. Observe insulating states below temperature 4K.

Response to Perpendicular Magnetic Field

The insulating state starts conducting after applying a magnetic field (especially when the field is perpendicular).

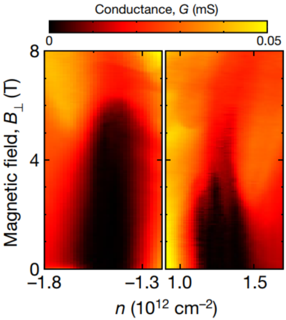

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Dependence of conductance on perpendicular magnetic field on (Left) p-side and (Right) n-side.

Response to Perpendicular Magnetic Field

The electron-electron interaction creates band gap and thus the insulating states. The magnetic field provides Zeeman energy which closes the band gap.

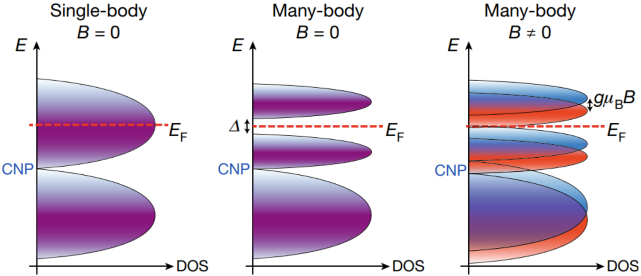

Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Schematics of the density of states (DOS) in different scenarios. CNP, charge neutrality point. The shape is purely illustrative.

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First Glimpse Towards MA-TBG Superconductivity

The conductivity near the hole-doping insulating states tends to increase with decreasing temperature.

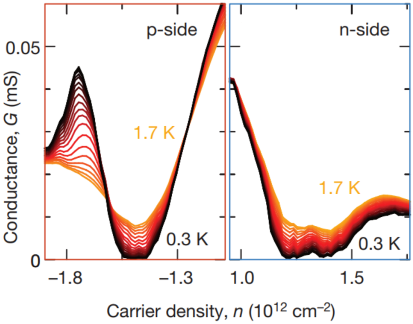
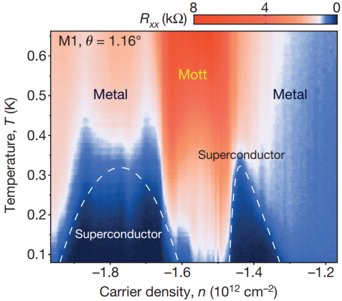


Figure: Cao Y et al. Nature, 2018, 556(7699): 80.

Temperature-dependent conductance for temperatures from about $0.3\mathrm{K}$ (black) to $1.7\mathrm{K}$ (orange) near (Left) p-side and (Right) n-side.

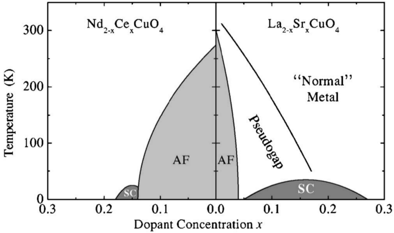
Unconventional Superconductivity in MA-TBG

Carrier density much lower than conventional superconductor.
Phase diagram resembles that of high-T_c superconductor.



Cao Y et al. Nature, 2018, 556(7699): 43.

Resistance measured near half-filling densities versus temperature. Two superconducting domes are observed next to the half-filling state.



Lee, Nagaosa & Wen. Rev mod phys, 2006, 78(1): 17.

Schematic phase diagram of high-T_c superconductors showing (right) hole doping and (left) electron doping.

Magnetic Field Response of Superconductivity

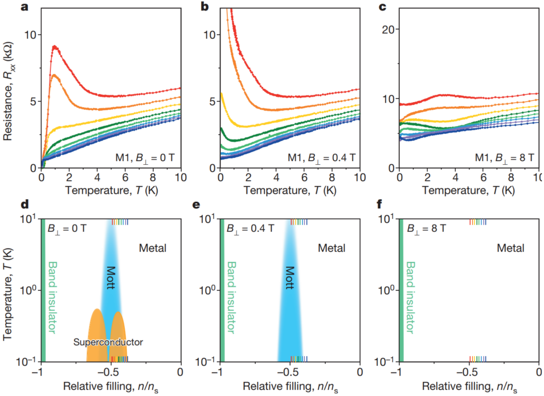


Figure: Cao Y et al. Nature, 2018, 556(7699): 43.

Above: Resistence-Temperature curve at different densities and magnetic fields.
Below: Temperature–density phase diagrams of magic-angle TBG at different magnetic fields.

How Strong is MA-TBG Superconductivity

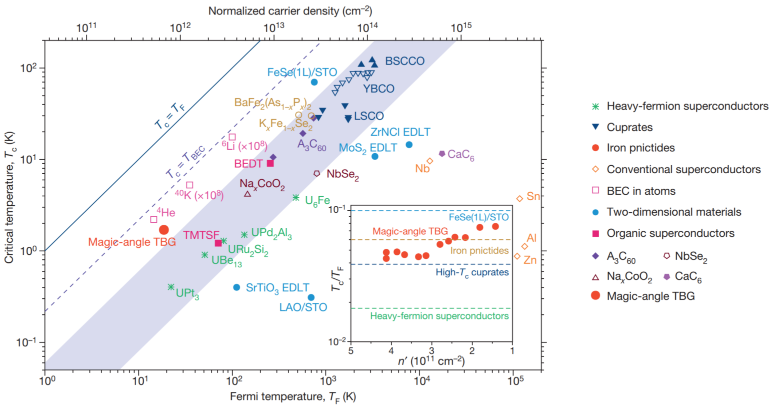


Figure: Cao Y et al. Nature, 2018, 556(7699): 43.

Logarithmic plot of critical temperature T_c versus Fermi temperature T_F for various superconductors
MA-TBG Superconductivity is among the strongest unconventional superconductivity.

Summary

- Magic-angle graphene superlattices ⇒ System with flat bands in electronic structure
- Highly-tunable platform for correlated electrons physics:
    - Control over carrier density, lattice constants, temperature, magnetic field, etc.
    - Correlated insulating at half-filling
    - Superconducting dome (resembling high-T_c superconductivity)
- Magic-angle concept can be more general ⇒ Many new magic-angle 2D material superlattices waiting to explore!