Tunable Correlated Phenomena in Trilayer Graphene on hBN Moiré Superlattice

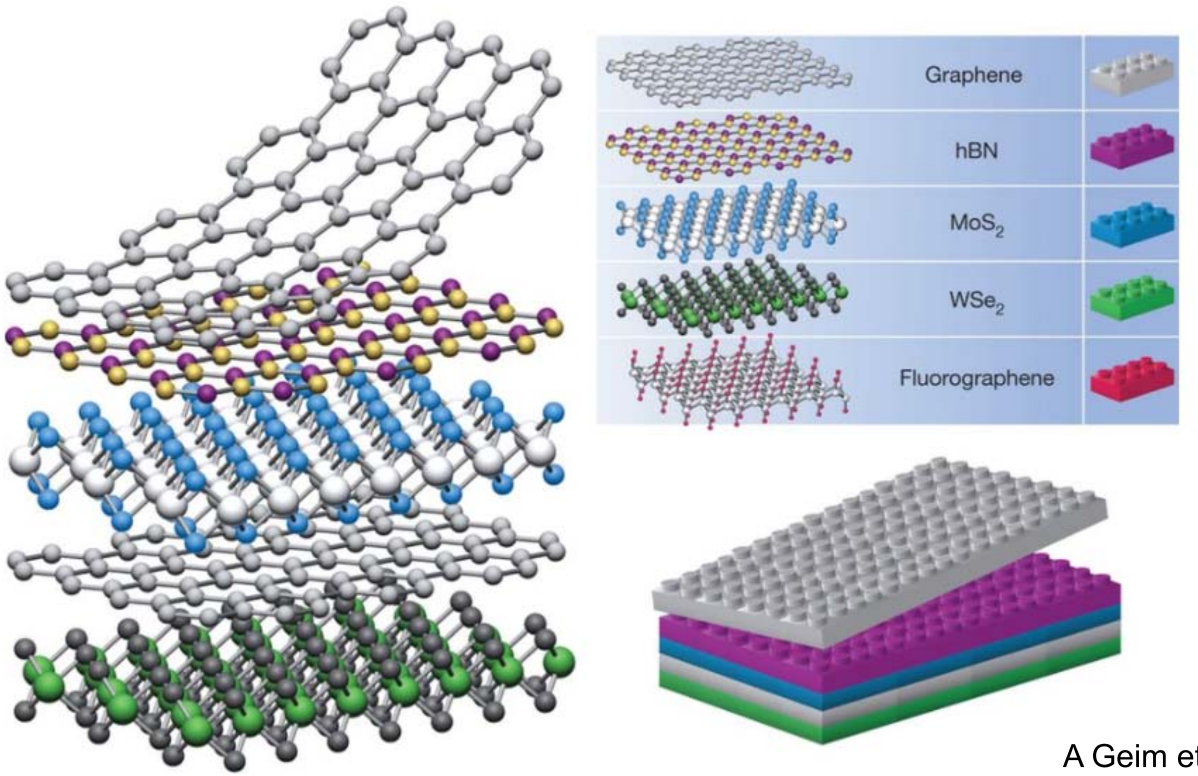
Guorui Chen

Lawrence Berkeley National Laboratory
Department of Physics, UC Berkeley

Berkeley
UNIVERSITY OF CALIFORNIA

5/2/2019, Santa Fe

Van der Waals heterostructures



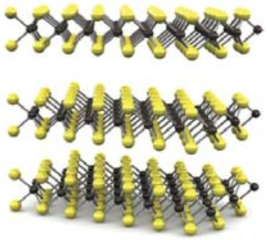
A Geim et al, Nature (2013)

Atomically thin layers: Electrons exposed at interface

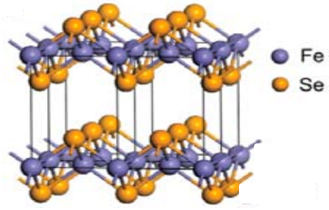
Van der Waals stacking: clean interface, no lattice matching requirement.

Van der Waals heterostructures

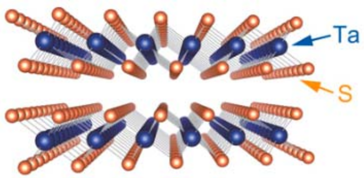
-- Novel materials and emerging phenomena



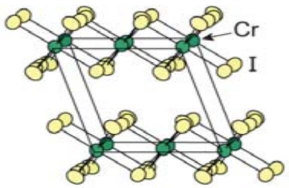
MoS_2
(semiconductor)



FeSe
(superconductor)



1T-TaS_2
(CDW)



CrI_3
(magnet)

- **Integrating vastly different materials together:**

2D semiconductors, metals, superconductors, magnet
(no constraint of lattice matching)

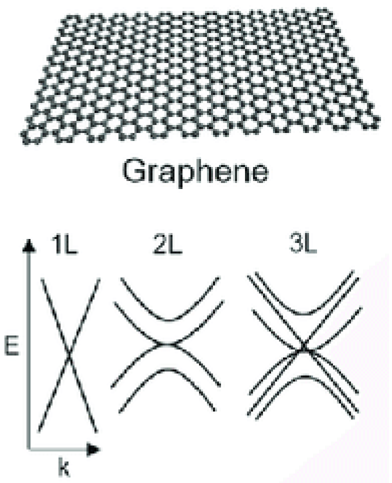
	MoS_2	$NbSe_2$	TaS_2	FeSe	CrI3	…
MoS_2	S	S/M	S/CDW	S/S.C.	S/MA	
$NbSe_2$	ME/S	M	M/CDW	M/S.C	M/MA	
TaS_2	CDW/S	CDW/M	CDW	CDW/S.C	CDW/ MA	
FeSe	S.C./S	S.C./M	S.C./CDW	S.C.	S.C./M A	
CrI3	MA/S	MA/M	MA/CDW	MA/S.C	MA	
…						

Tremendous new opportunities!

Berkeley
UNIVERSITY OF CALIFORNIA

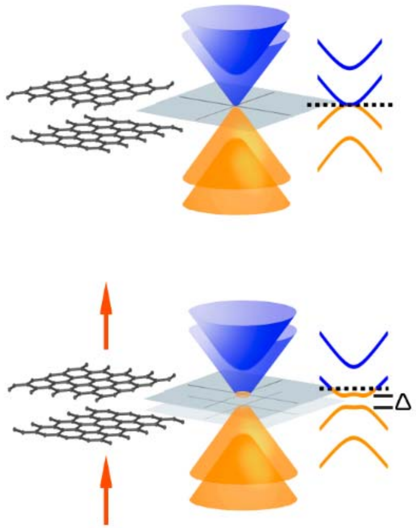
Tunable band structure

Layer-Layer interactions



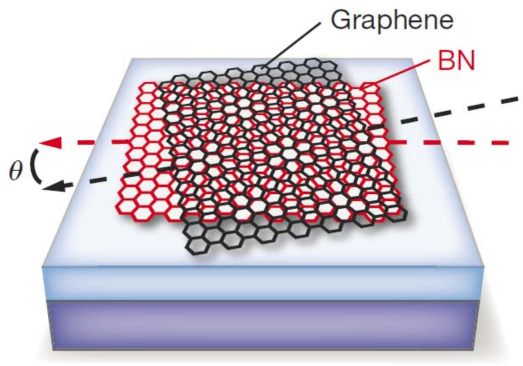
Number of layers

Electrical Field



Field effect devices

Superlattice

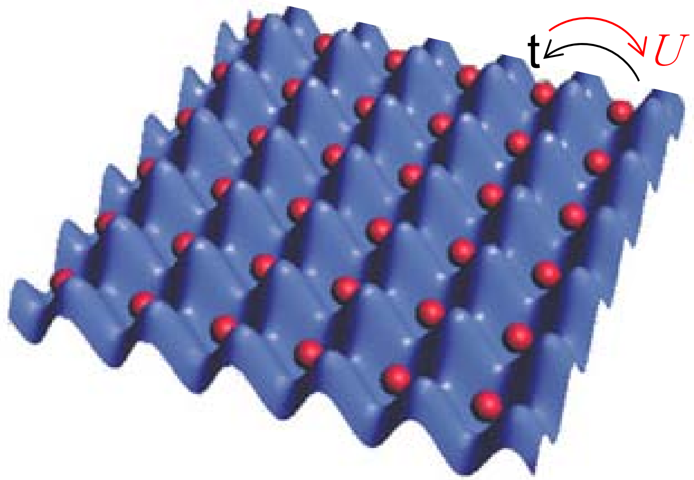


Graphene/Boron Nitride heterostructure

Engineer correlated electron phenomena in 2D materials?

Mott insulator: Hubbard model

Real space



One electron per unit cell.

Hubbard model:

$$\hat{H} = -t \sum_{\langle i,j \rangle,\sigma} (\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \hat{c}^{\dagger}_{j,\sigma}\hat{c}_{i,\sigma}) + U \sum_{i=1}^{N} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

Two competing energies:

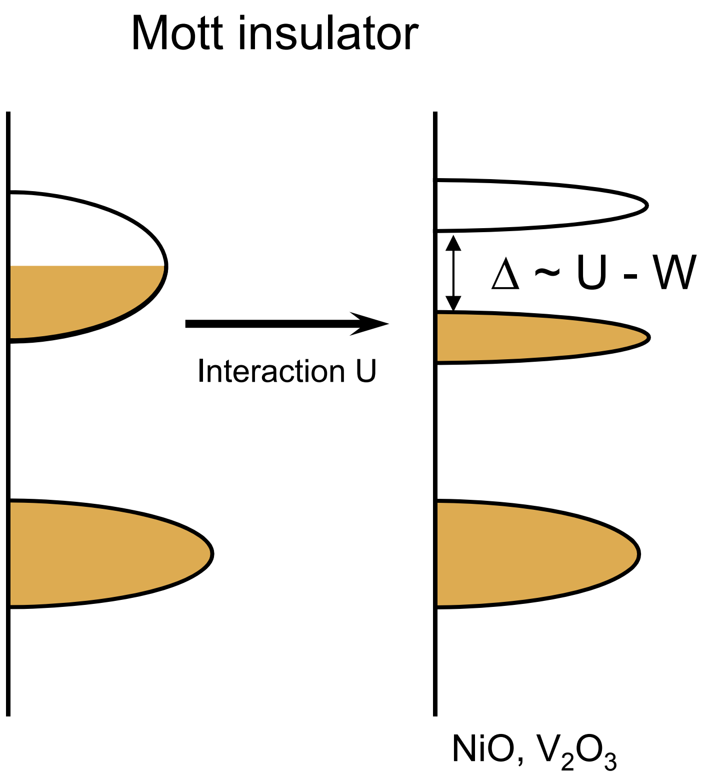
<u>inter-site hopping t</u> vs. <u>on-site repulsion U</u>

(Kinetic energy) (Coulomb energy)

Strong correlation:

U > W

Mott insulator: Hubbard model



Mott gap opens at 1/2 filling.
Correlated phenomena.

Hubbard model:

$$\hat{H} = -t \sum_{\langle i,j \rangle,\sigma} (\hat{c}^\dagger_{i,\sigma}\hat{c}_{j,\sigma} + \hat{c}^\dagger_{j,\sigma}\hat{c}_{i,\sigma}) + U \sum_{i=1}^{N} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

Two competing energies:
<u>inter-site hopping t</u> vs. <u>on-site repulsion U</u>

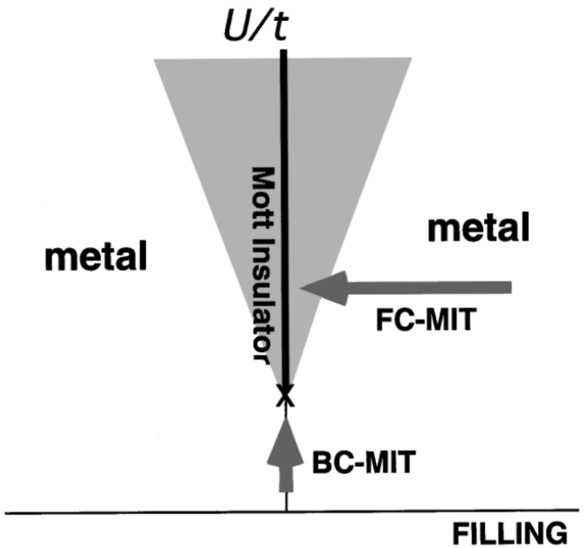
(Kinetic energy) (Coulomb energy)

Strong correlation:

$U > W$

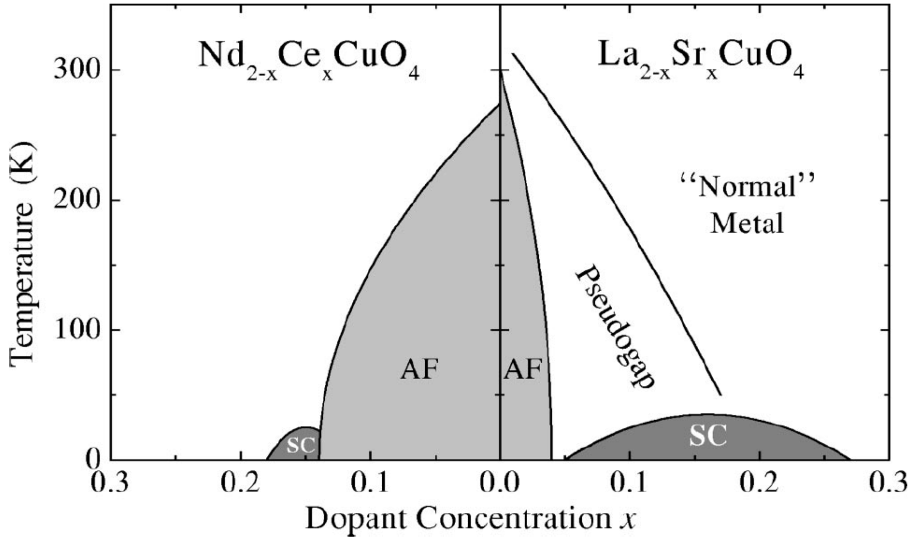
Many mysteries around Mott insulator

Metal-Insulator transitions:



Challenging describe to the MIT region

High T_c superconductor:
Doped Mott insulator



Unconventional cooper pairs
Quantum critical point
Strange metal, quantum spin liquid …

Many outstanding questions after many decades!

Theoretically challenging. Systematic experimental studies needed.

Create model correlated systems in 2D

Strong correlation: Coulomb energy *U* > Bandwidth *W*

A 2D crystal with lattice constant *L*:

$$U \sim \frac{e^2}{\varepsilon L} \qquad\qquad W \sim \frac{\hbar^2 k^2}{2m_e} \propto \frac{1}{m_e} \cdot \frac{1}{L^2}$$

$$\frac{U}{W} \propto m_e \cdot L$$

Correlated 2D system:
Large effective mass + large lattice constant

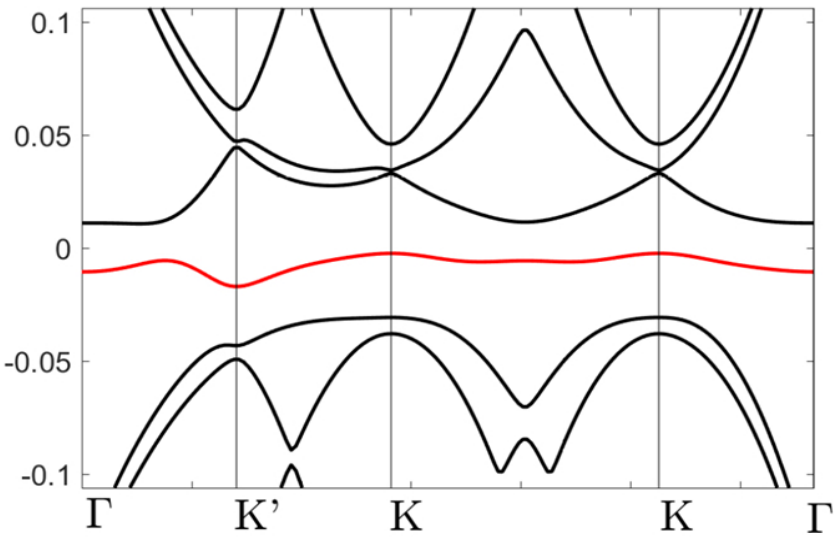
$\frac{U}{W} \sim 1$ at $m_e = 1\ m_0$, $L \sim 1\text{nm}$

$m_e = 0.1\ m_0$, $L \sim 10\text{nm}$

Flatband engineering in 2D heterostructures

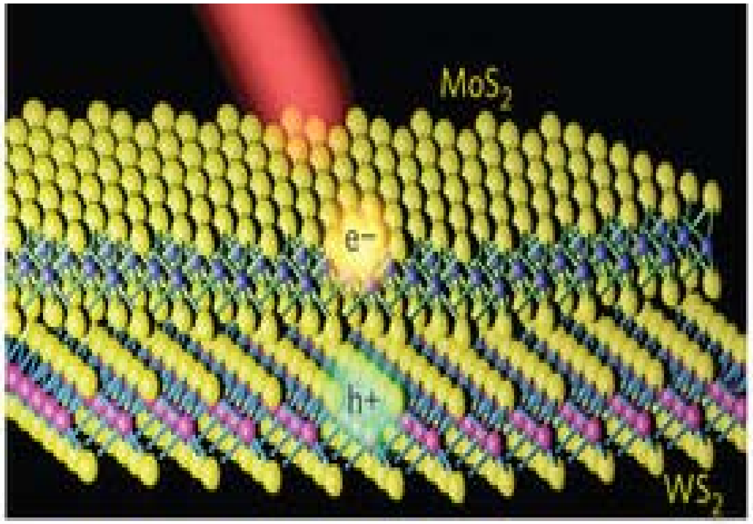
(*U* > *W*)

ABC trilayer graphene/hBN



L ~ 15 nm
$m_e \sim 0.1\ m_0$

TMD heterostructure

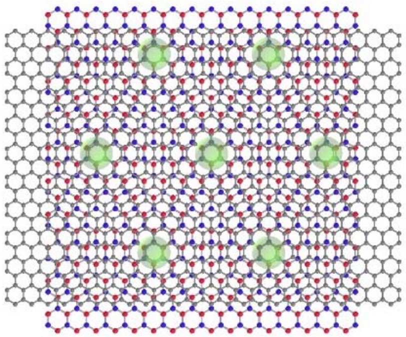


L ~ 10 nm
$m_e \sim 0.5\ m_0$

Outline

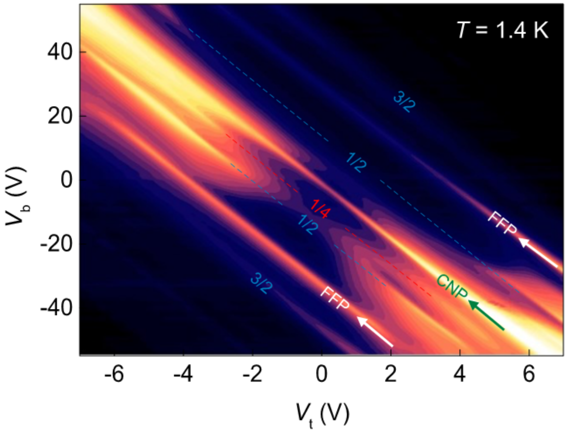
- Tunable Mott insulator in TLG/hBN

TLG

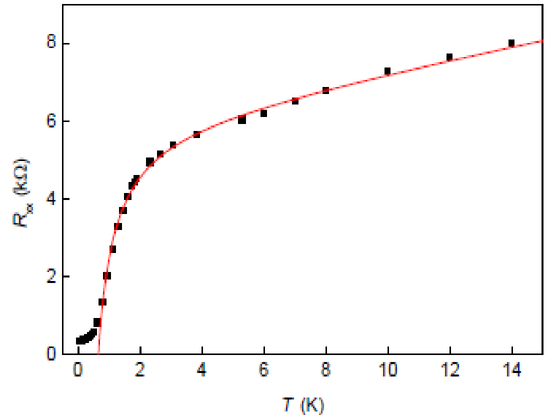


hBN

- Correlated quantum transport

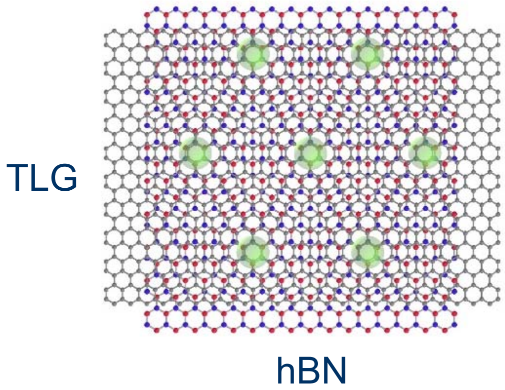


- Signatures of superconductivity

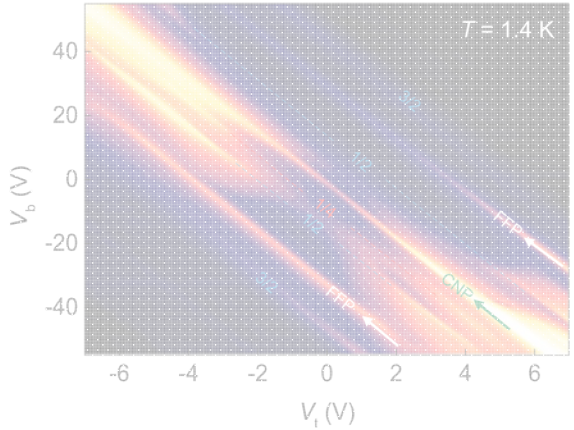


Outline

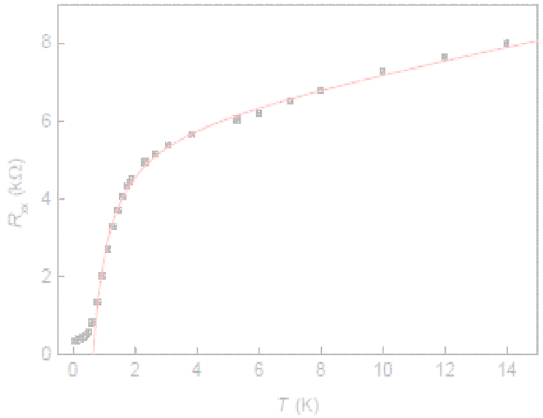
◆ Tunable Mott insulator in TLG/hBN



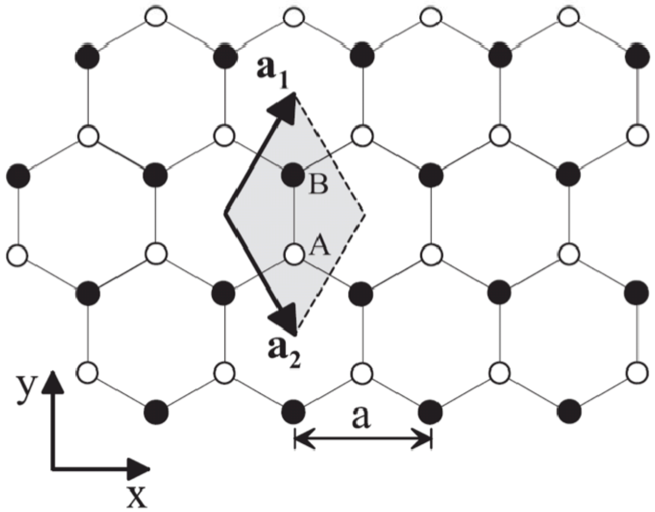
◆ Correlated quantum transport

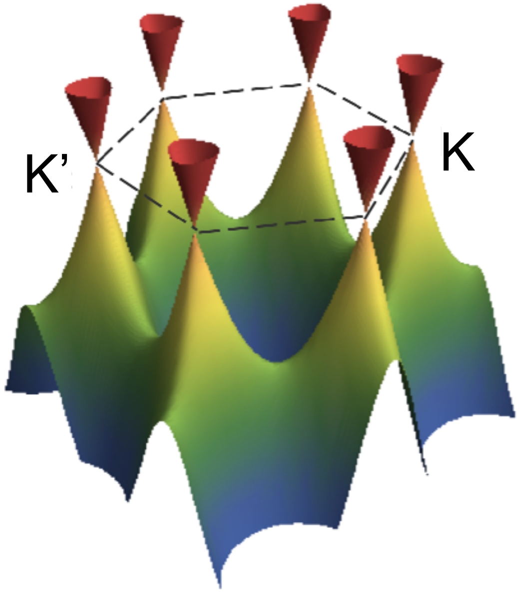


◆ Signatures of superconductivity



Monolayer graphene

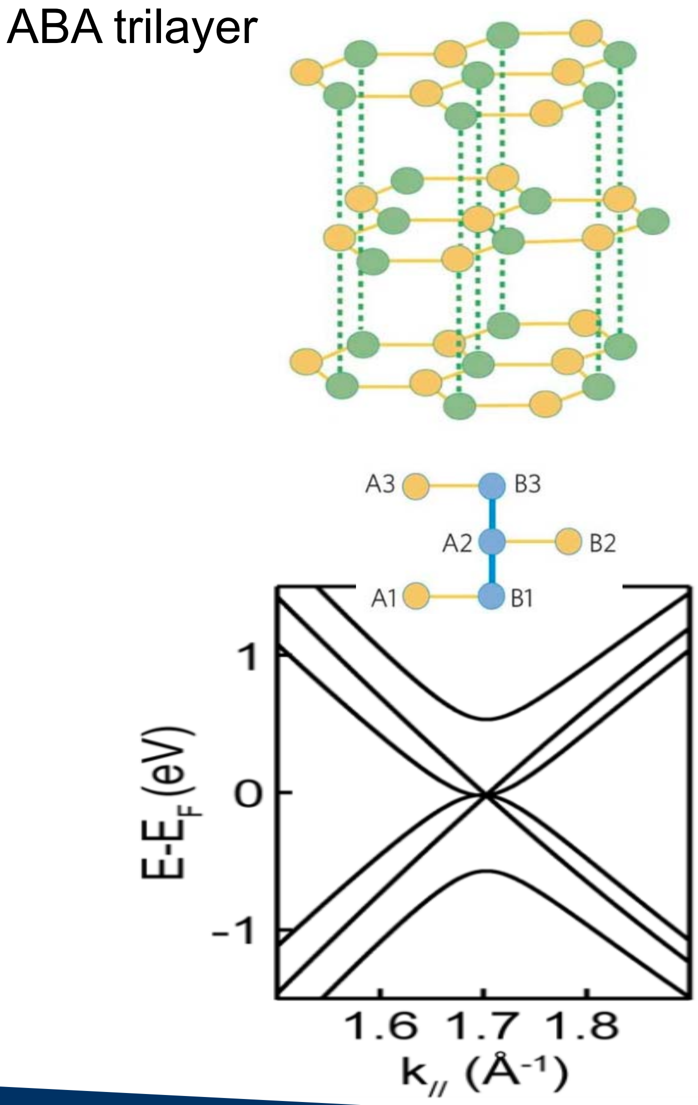


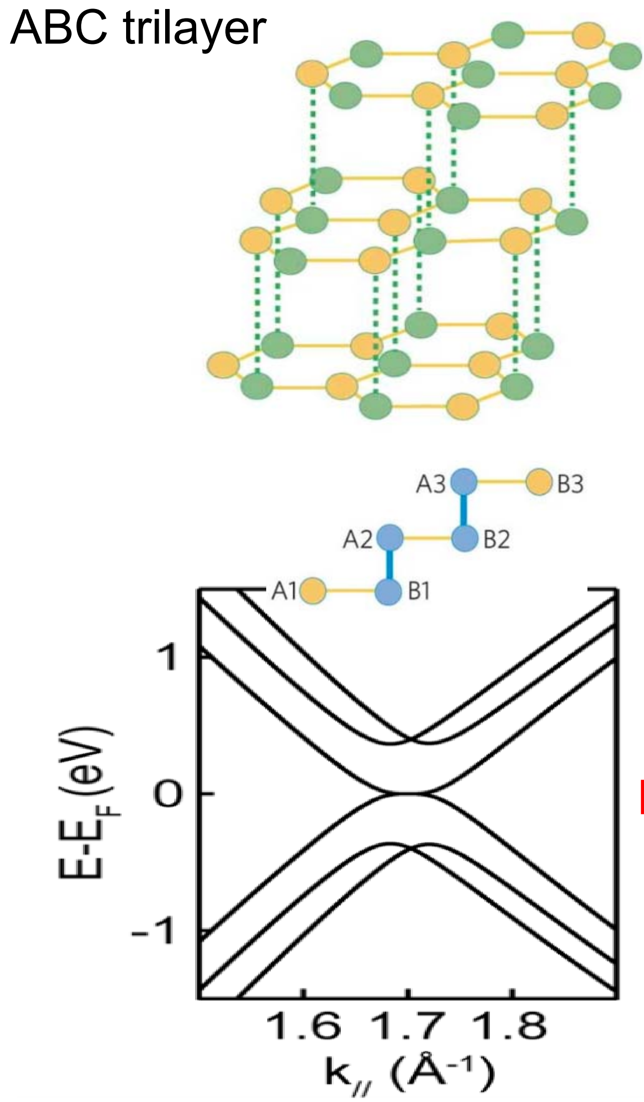


$$\varepsilon(\boldsymbol{\kappa}) = \pm v_F |\boldsymbol{\kappa}|$$

Linear band at low energy.
Zero mass like photons!

ABC trilayer graphene: larger m_e

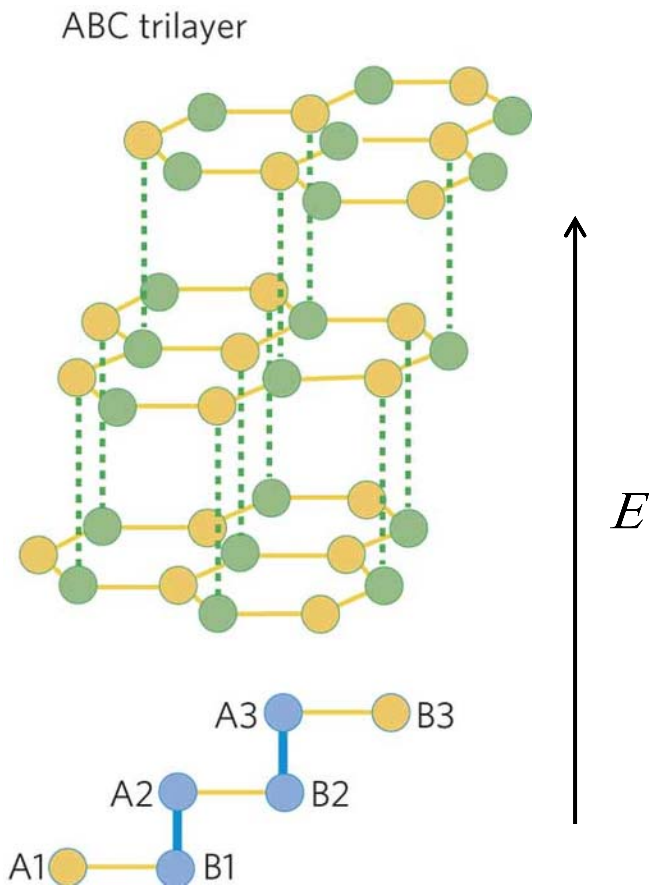


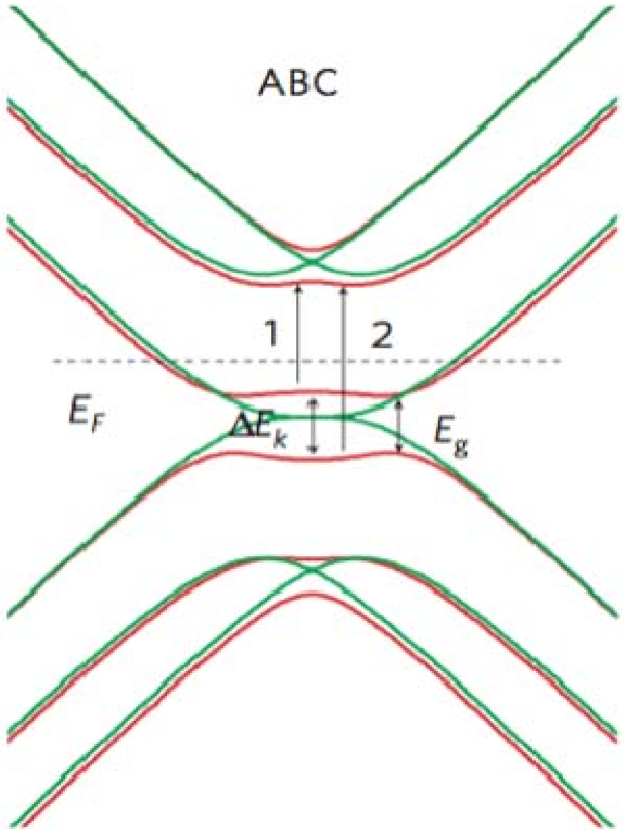


$E \sim k^3$

Large mass

Trilayer graphene: tunable band gap

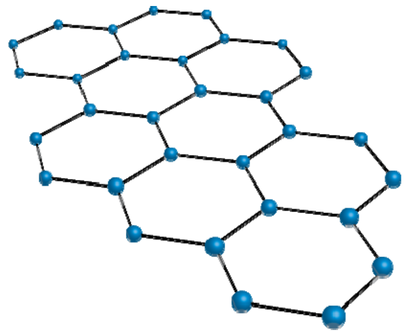




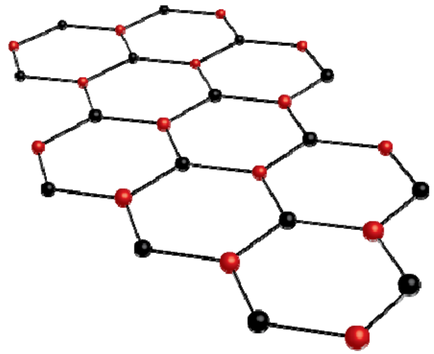
Lui et al, Nature Physics 7, 944 (2011)

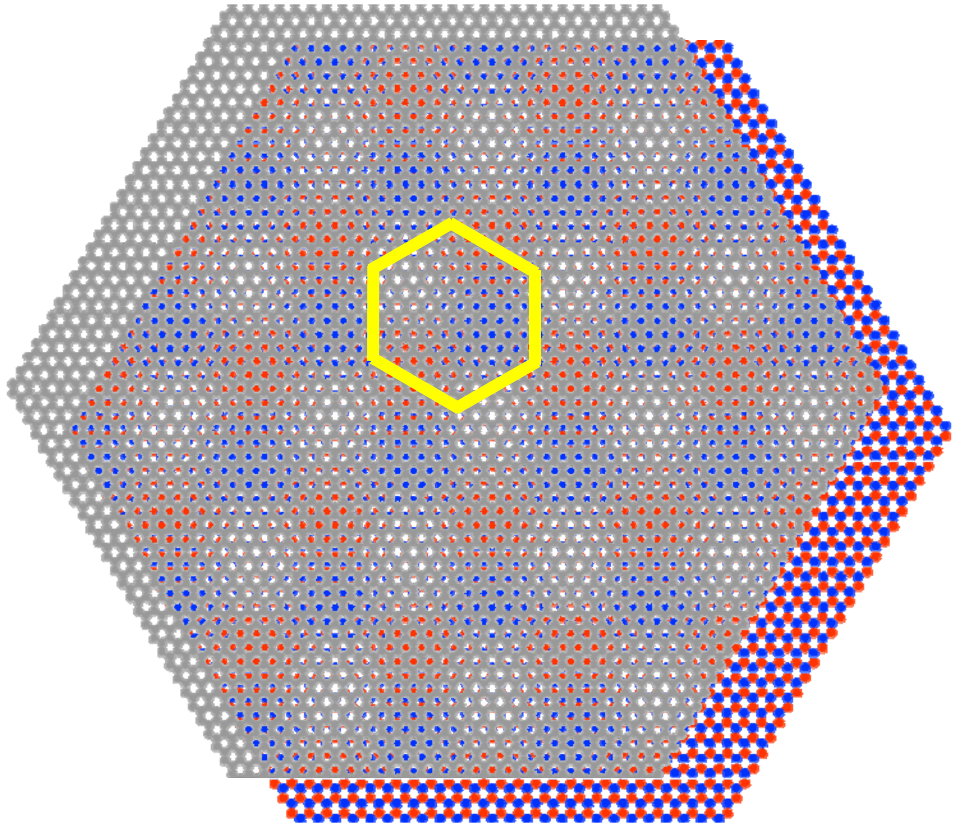
Moiré superlattice: large lattice constant

Graphene



hBN

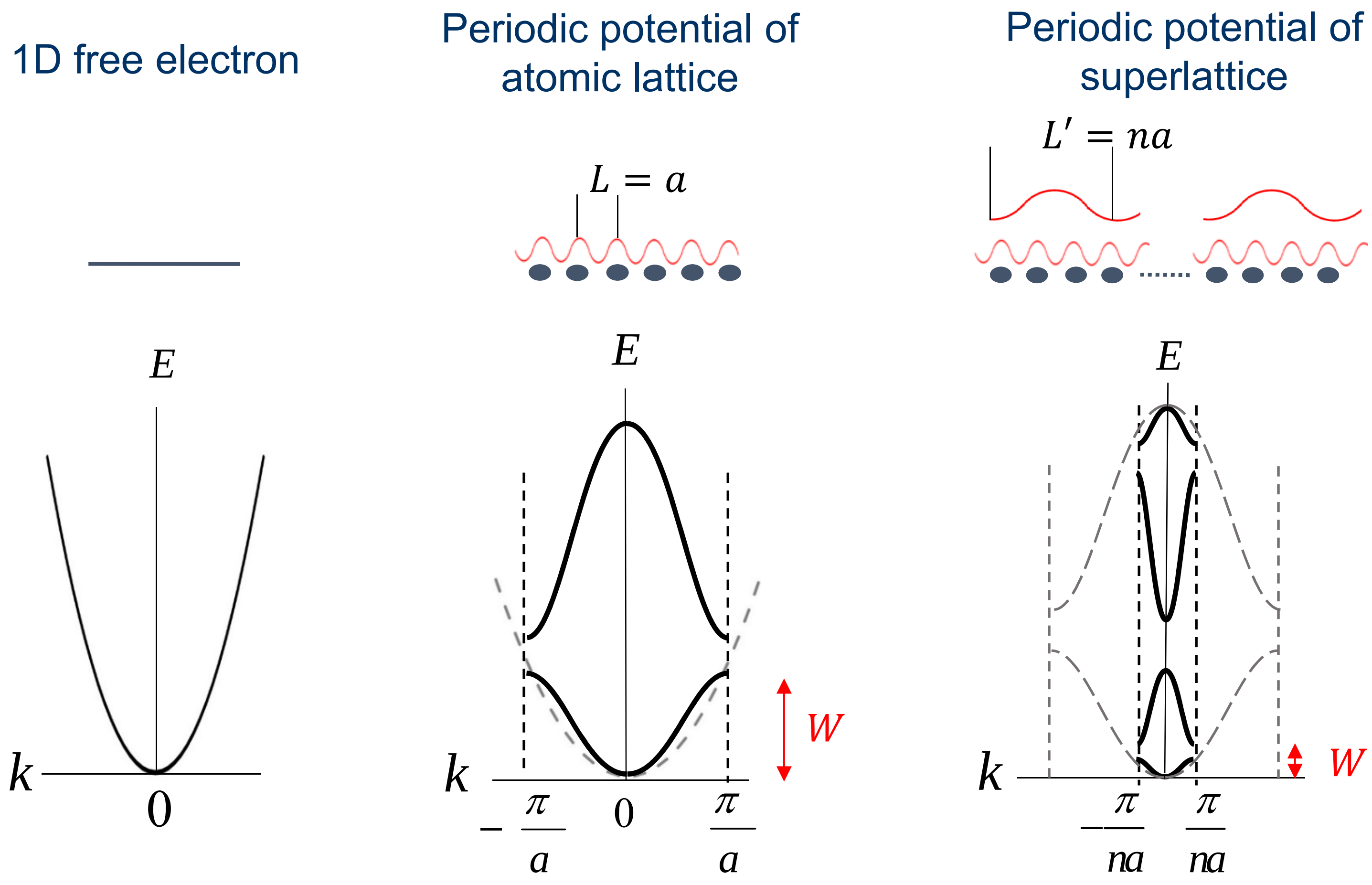




L ~ 15nm at zero twisting angle

Band folding in periodic potential

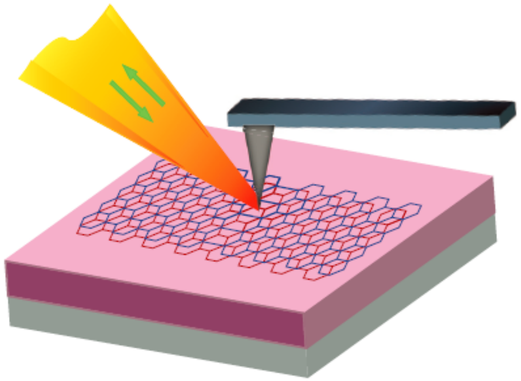
$U > W$



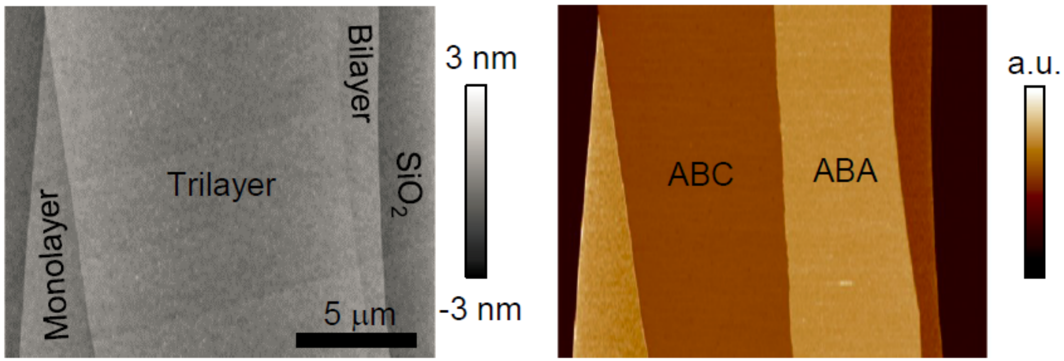
$$W' \sim \frac{1}{m_e} \cdot \frac{1}{(nL)^2} = \frac{1}{n^2} W$$

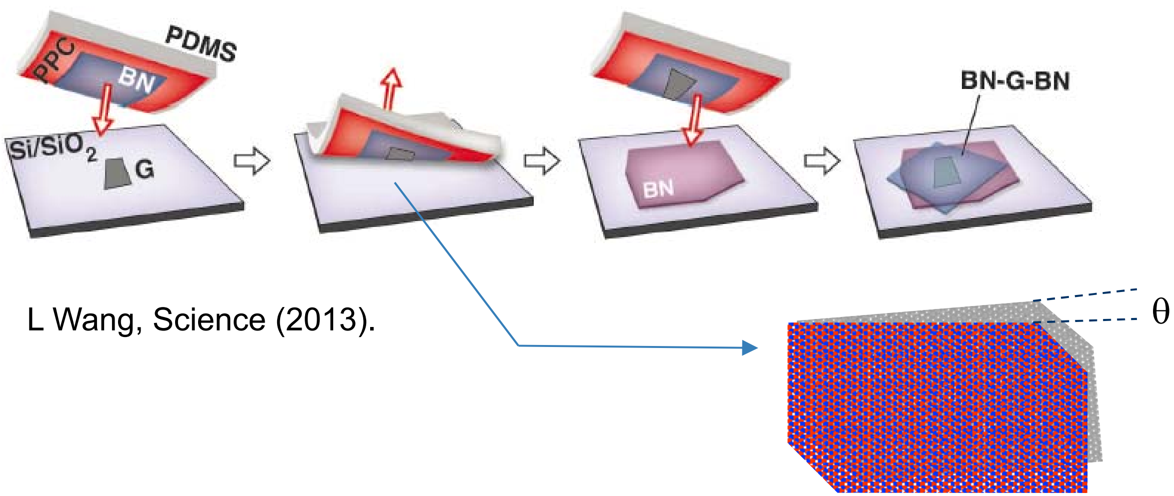
Bandwidth *W* is much reduced by band folding of superlattice.

Trilayer graphene/hBN heterostructure

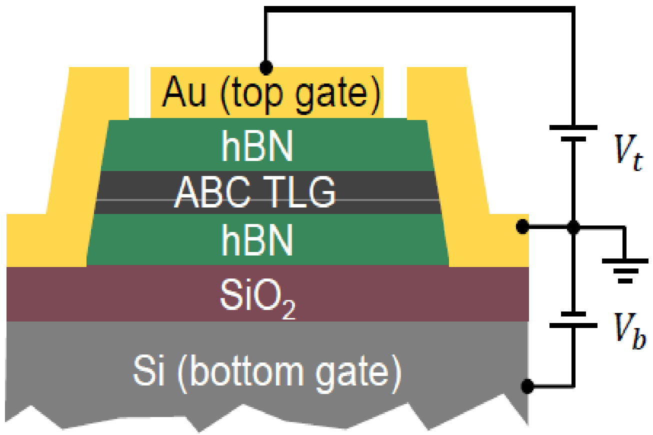


Scanning near-field infrared nanoscopy.
Long Ju *et al*, Nature (2015).



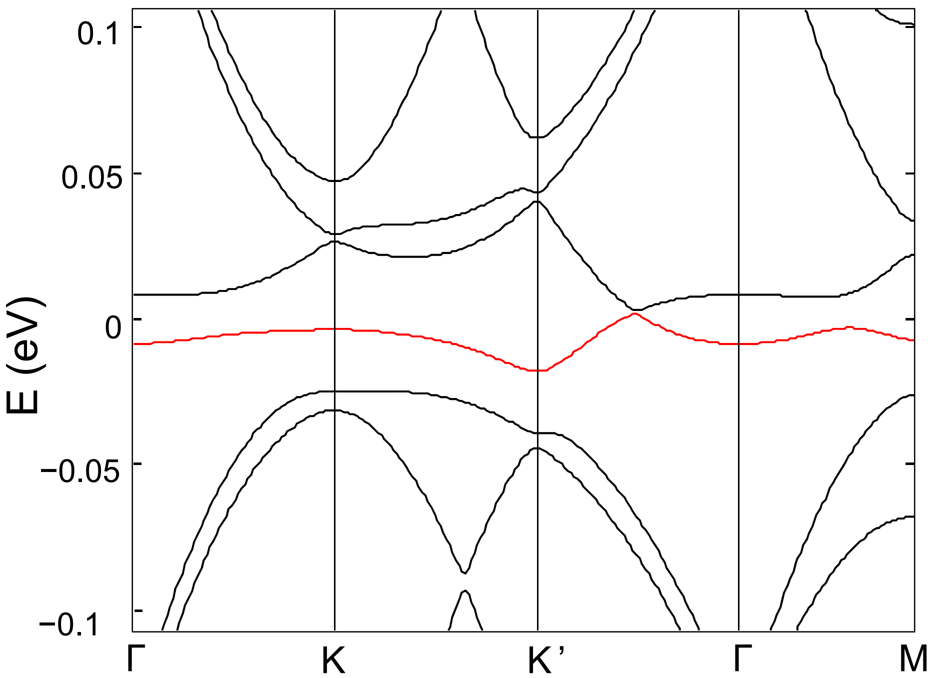


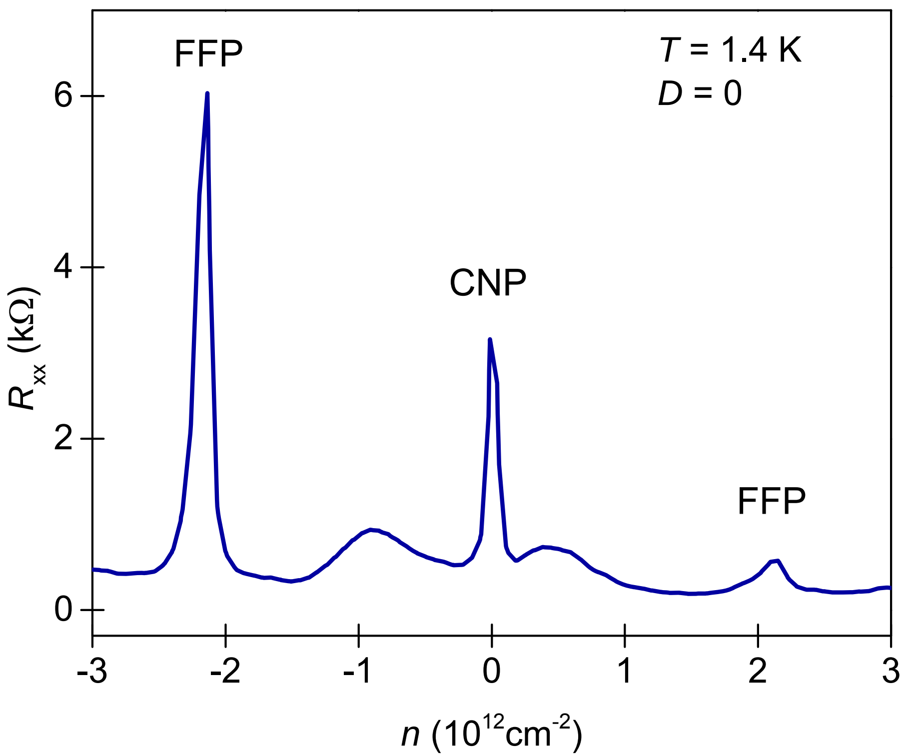
L Wang, Science (2013).



Transport in trilayer graphene/hBN heterostructure

$\Delta = 0$

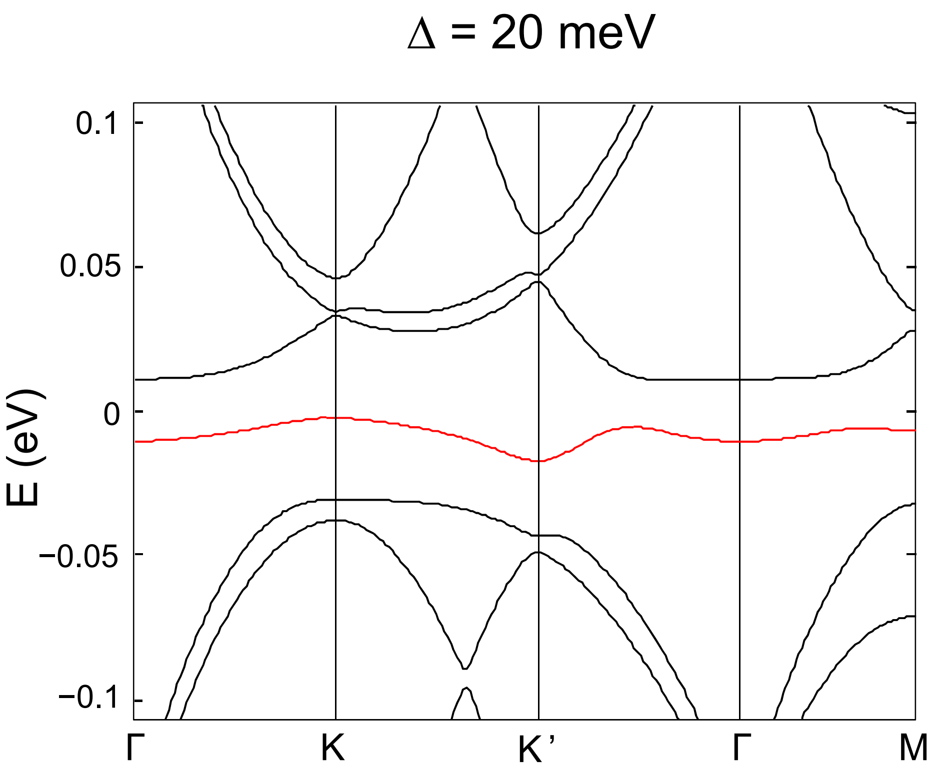


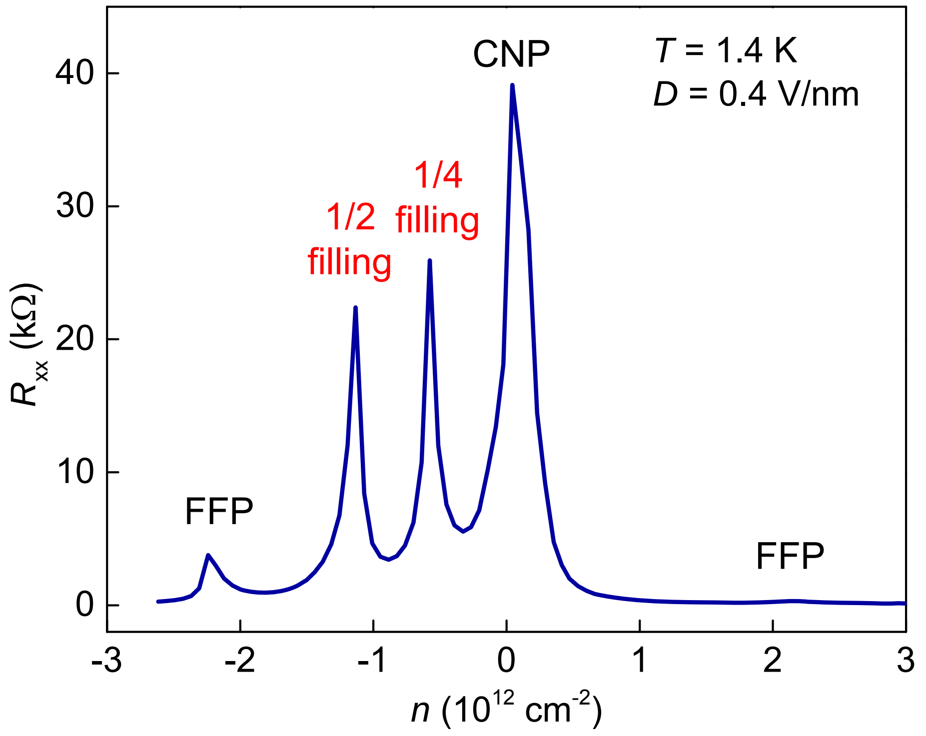


Significant electron and hole asymmetry

Hole band: W ~ 20 meV
U ~ 20 meV

Electrical control of the bandwidth



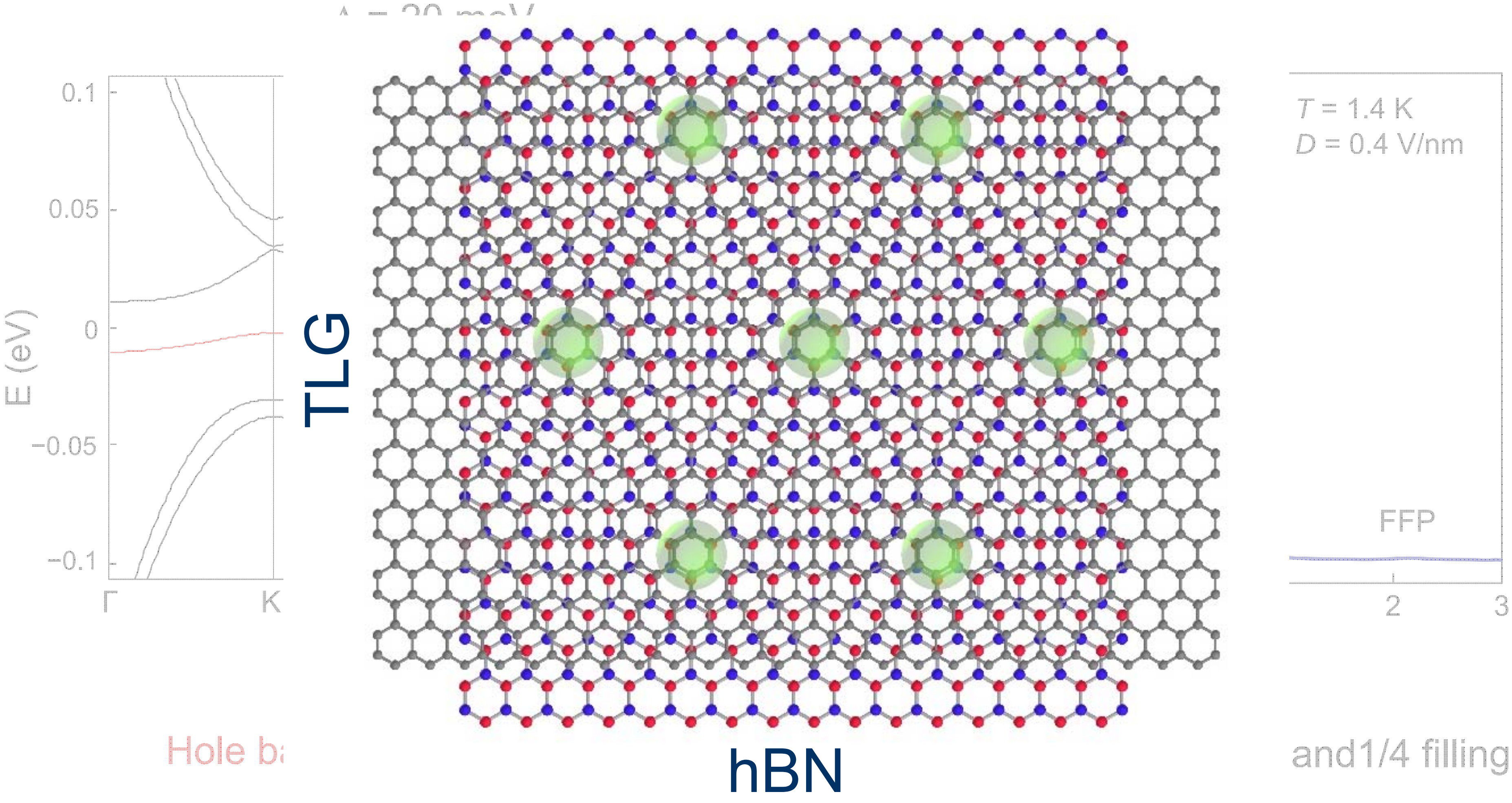


Hole band: W ~ 13 meV
U ~ 20 meV

U > *W* : Mott insulator at 1/2 and1/4 filling

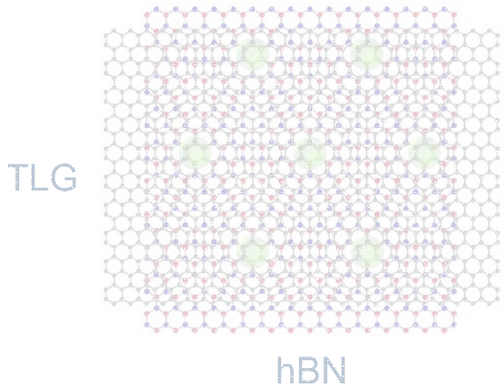
It’s a Mott insulator!

1/4 filling : 1e / unit cell

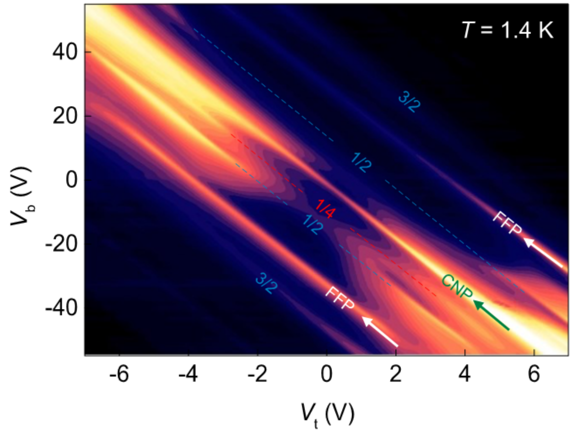


Outline

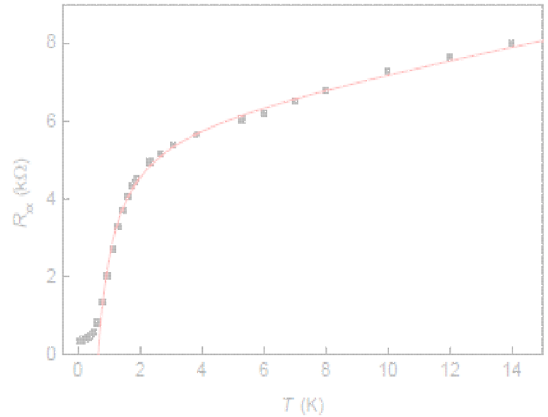
- Tunable Mott insulator in TLG/hBN



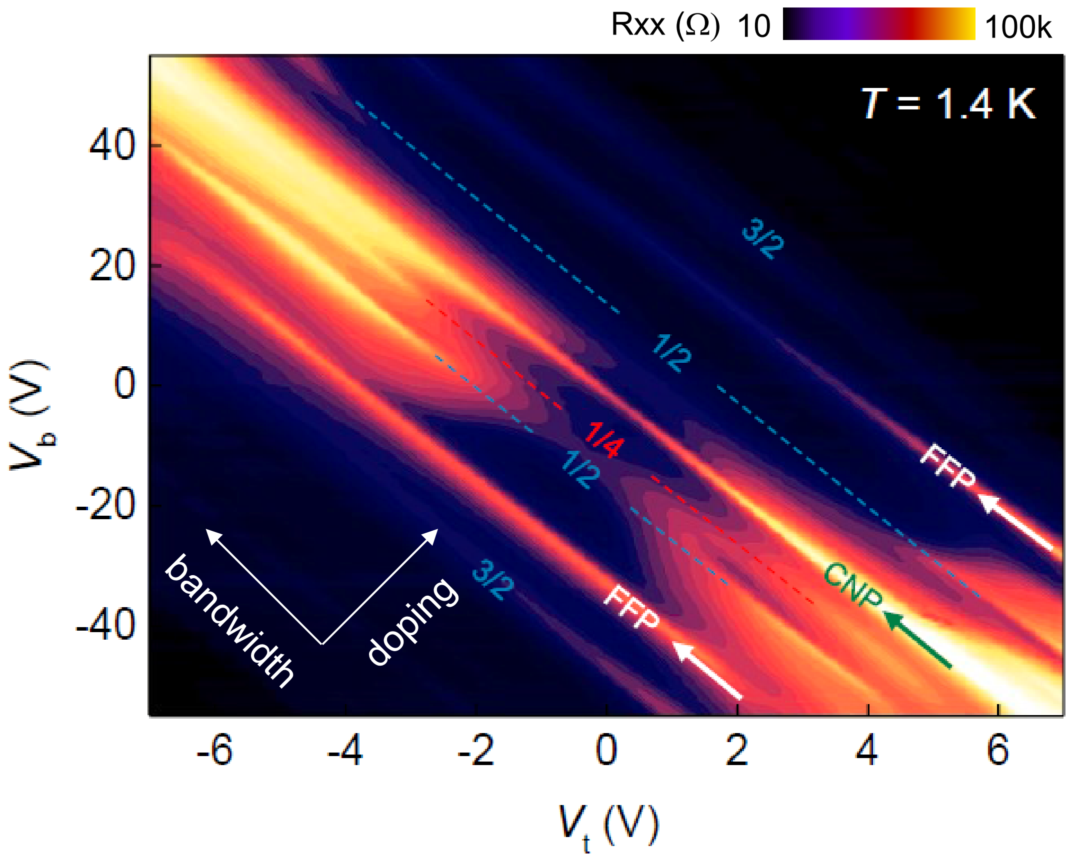
- **Correlated quantum transport**

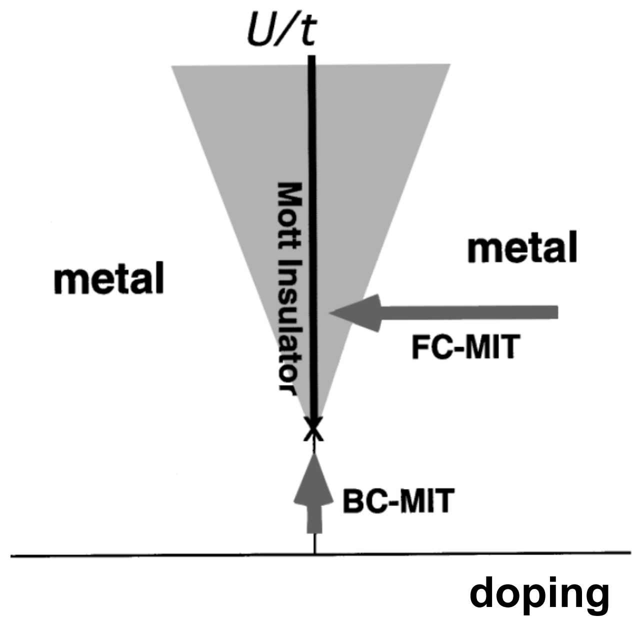


- Signatures of superconductivity



Amazing tunable Mott insulator

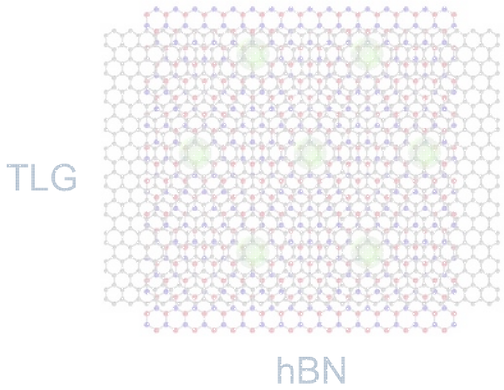




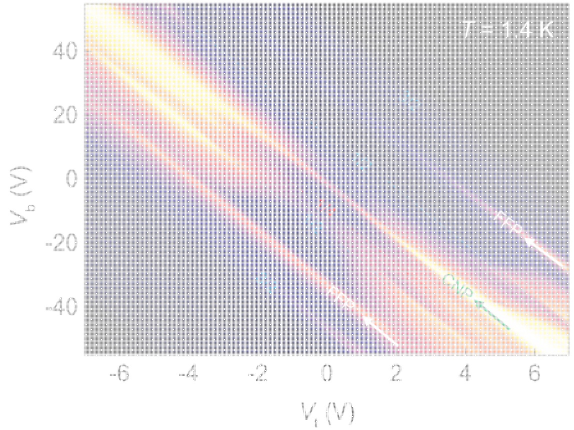
An ideal model system: excellent control of both doping and bandwidth

Outline

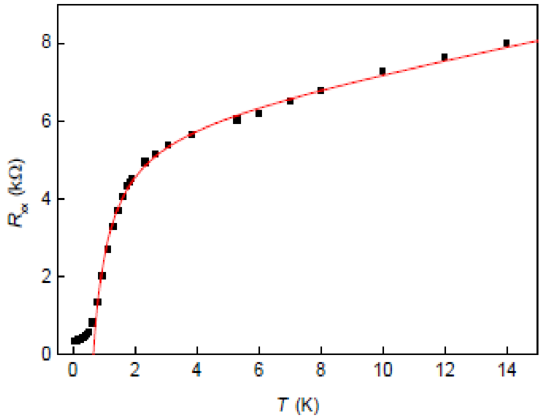
- Tunable Mott insulator in TLG/hBN



- Correlated quantum transport

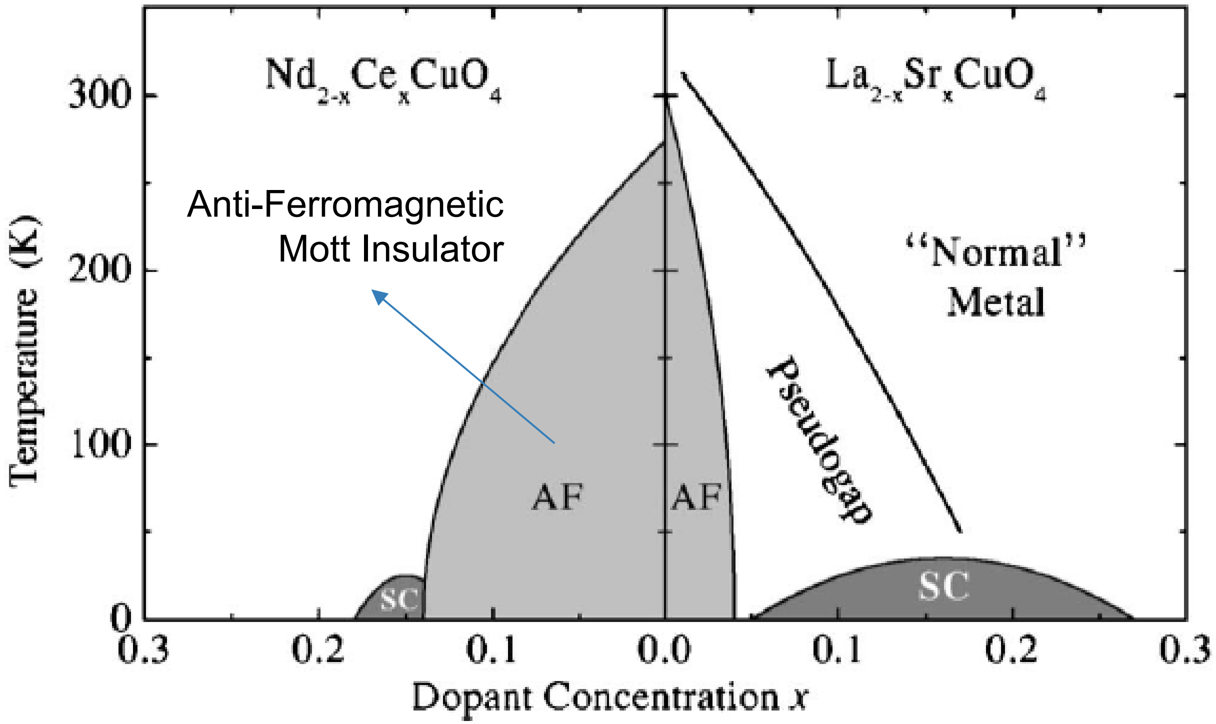


- Signatures of superconductivity

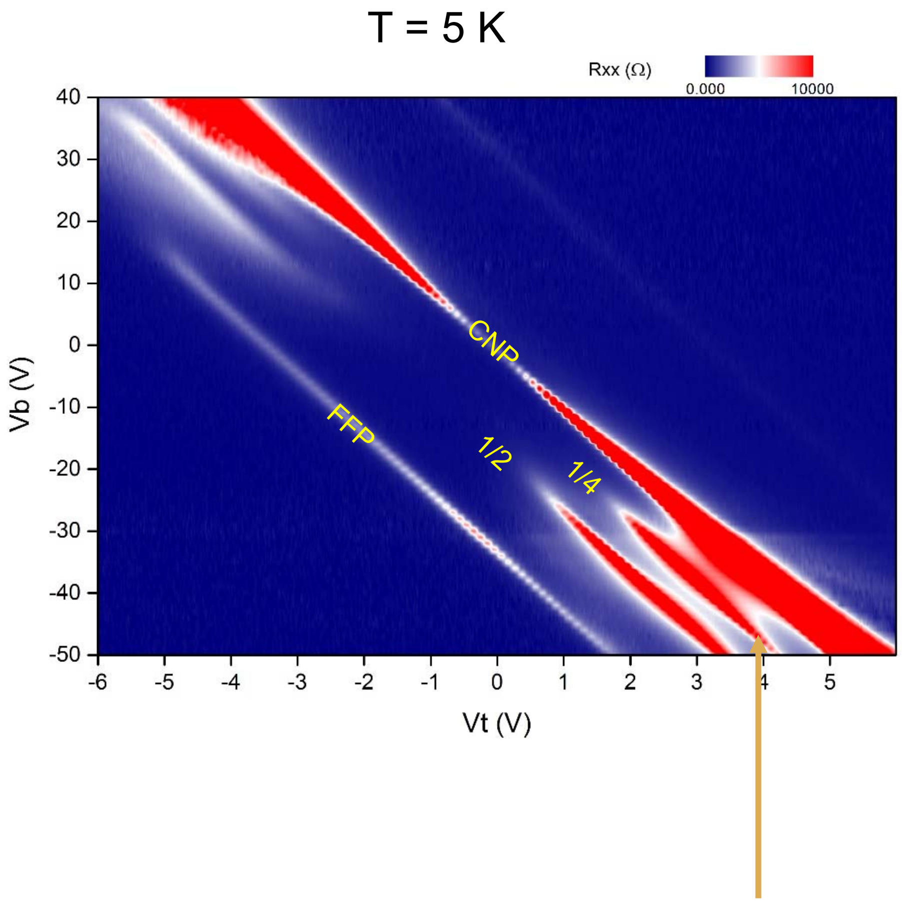


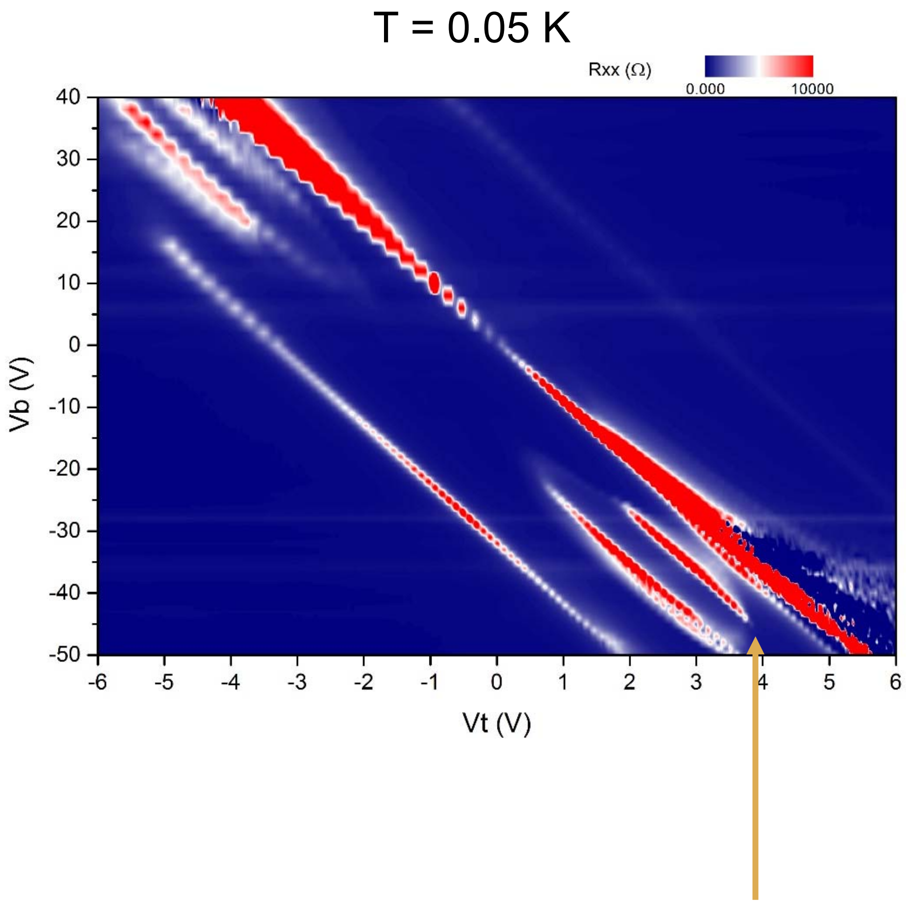
Doped Mott insulators - high T_c superconductor

Doped Mott insulator: superconductor



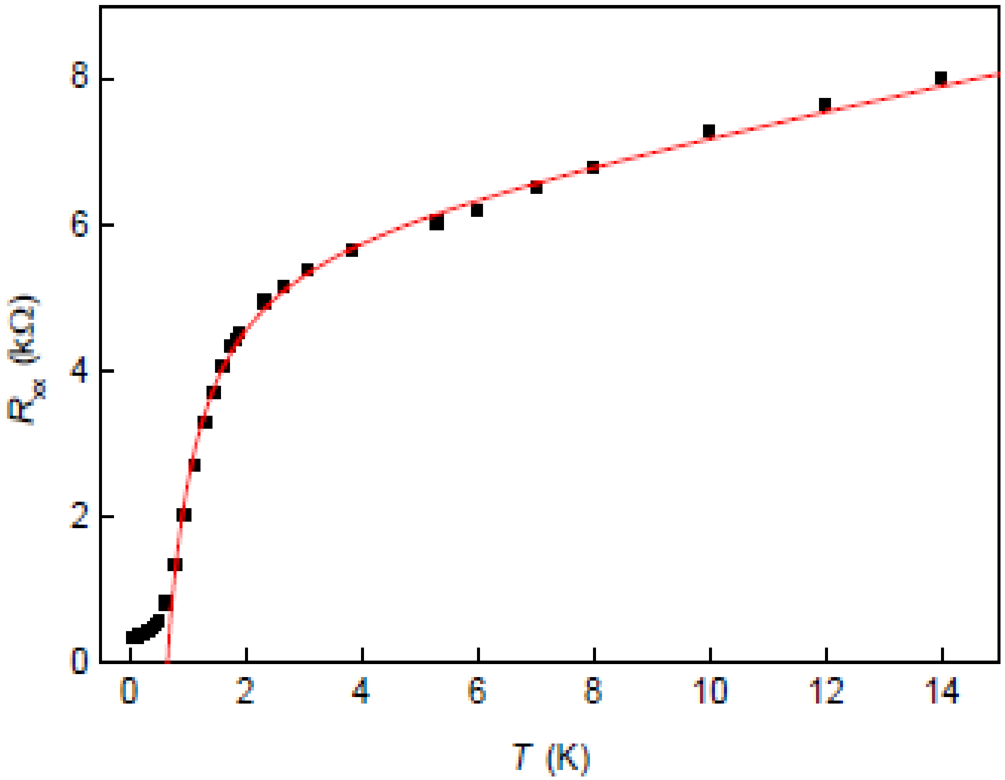
Where is superconductivity in TLG/hBN?





Emerging superconductivity

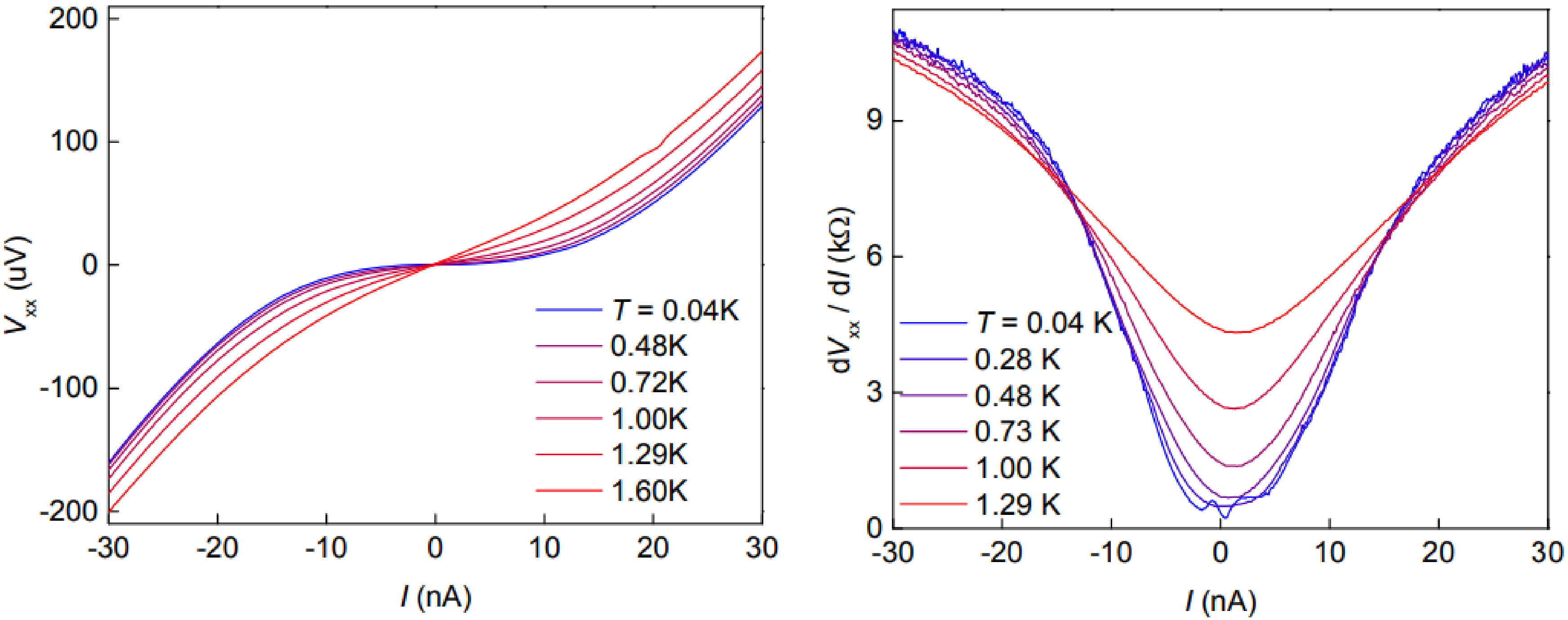
Close to 1/4 filling, at D = 0.5 V/nm



Residue resistance may be due to non-ideal contact.

Superconductivity critical current

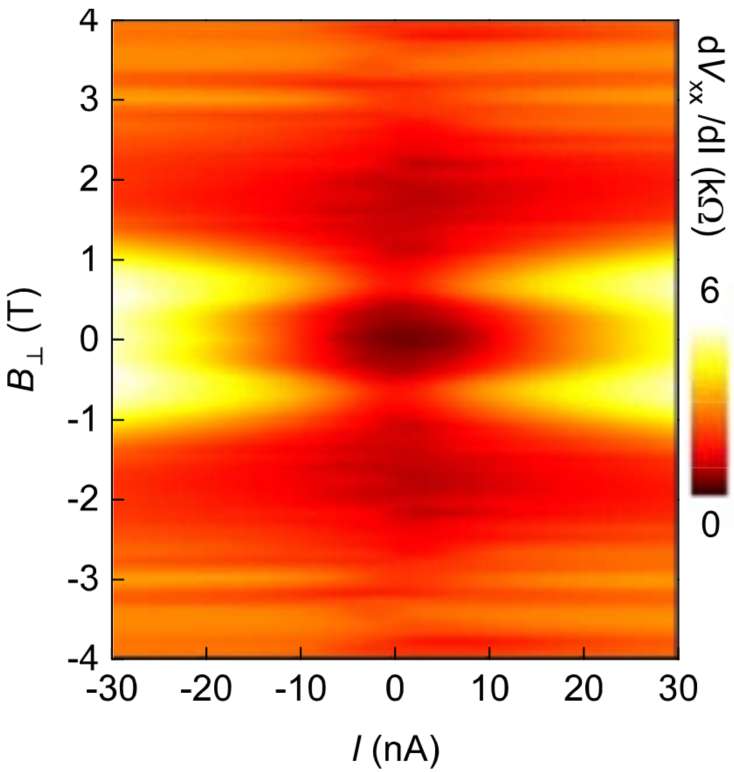
Close to 1/4 filling, at D = 0.5 V/nm

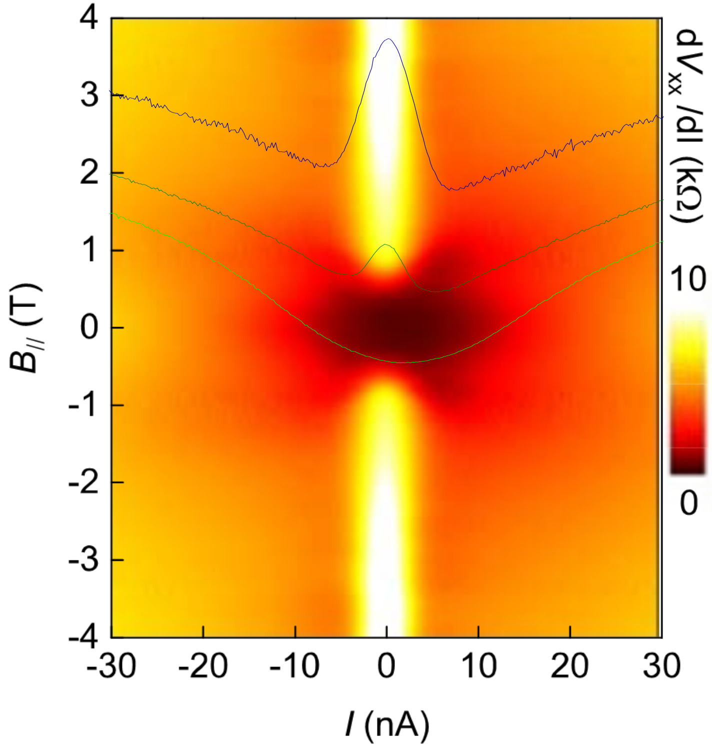


Nonlinear IV curve

Superconductivity suppression in magnetic field

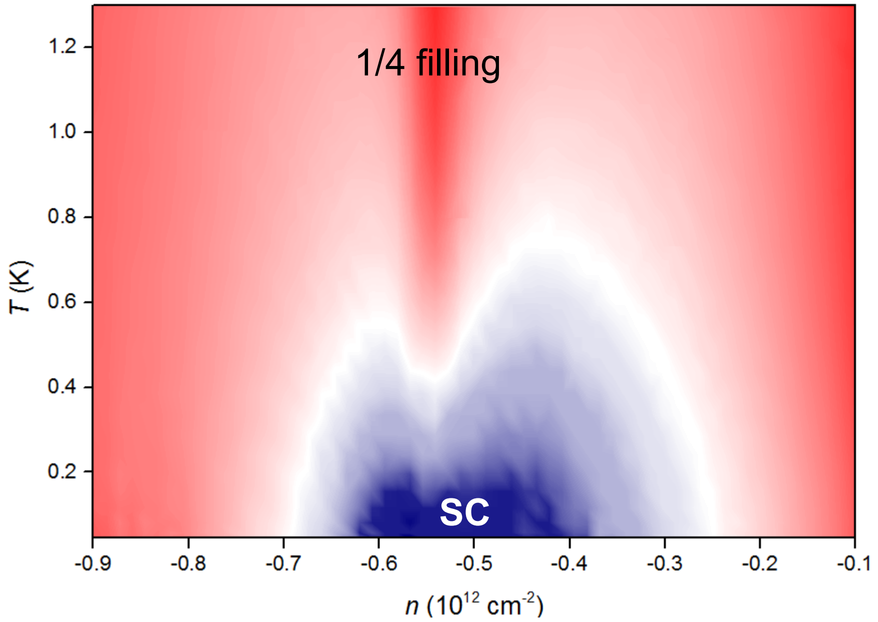
Close to 1/4 filling, at D = 0.5 V/nm

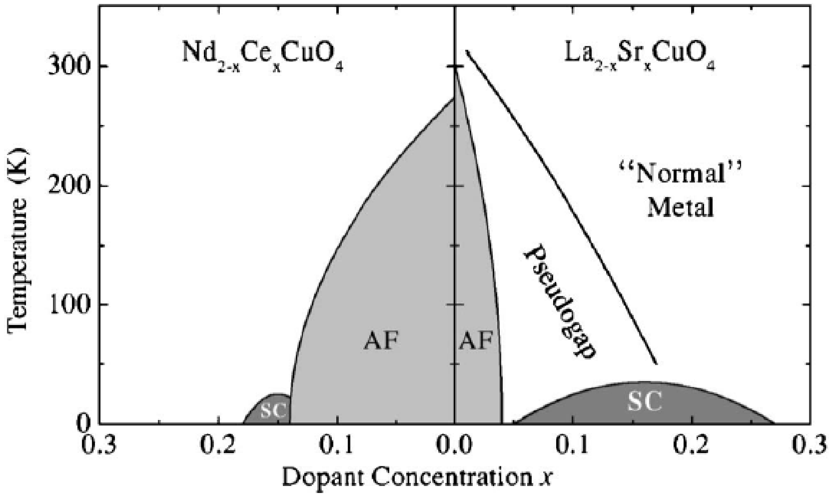




Anomalous resistance peak at zero bias in in-plane magnetic field

Phase diagram of TLG superconductivity



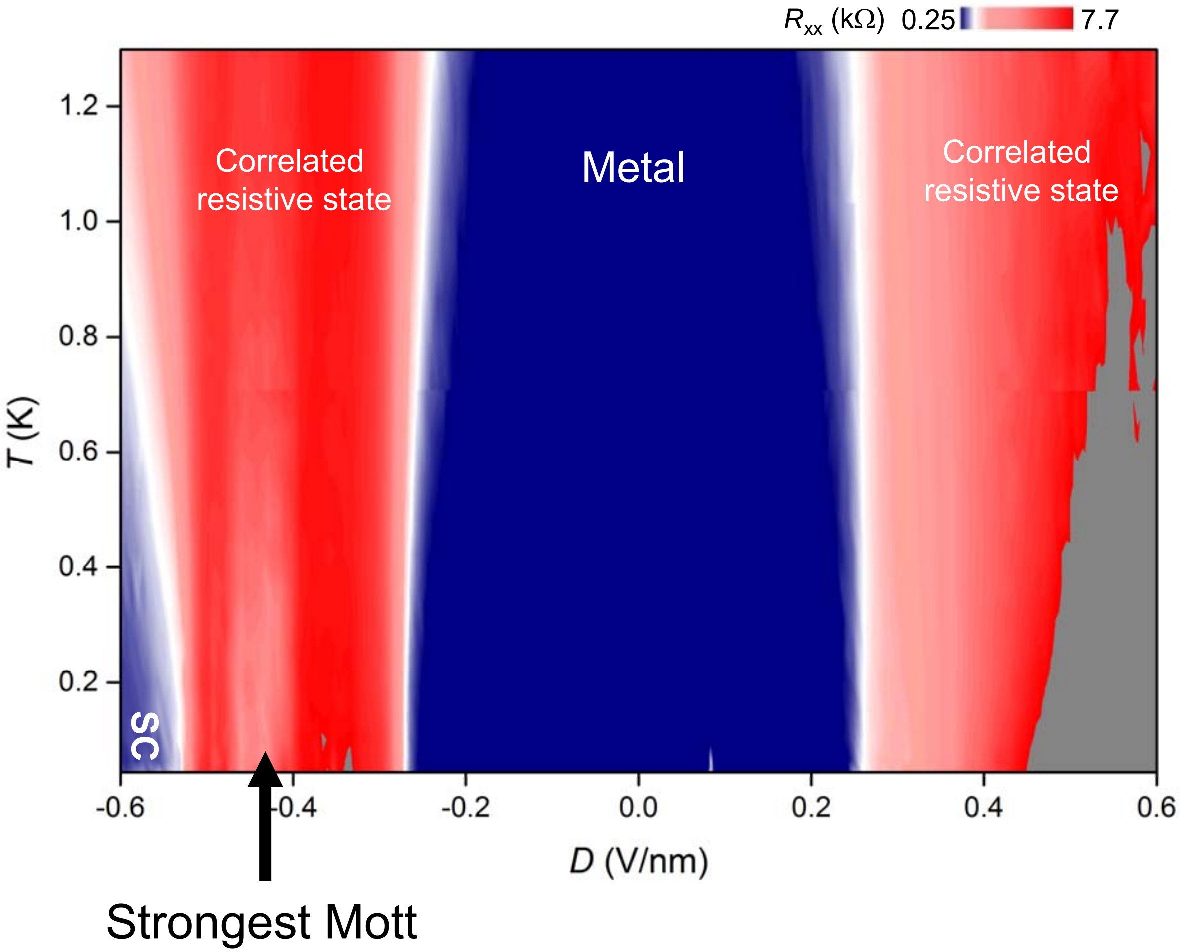


1. Two superconducting domes near 1/4 filling.

2. Phase diagram can be obtained in one TLG/hBN sample.

Berkeley
UNIVERSITY OF CALIFORNIA

D dependent phase diagram in TLG/hBN



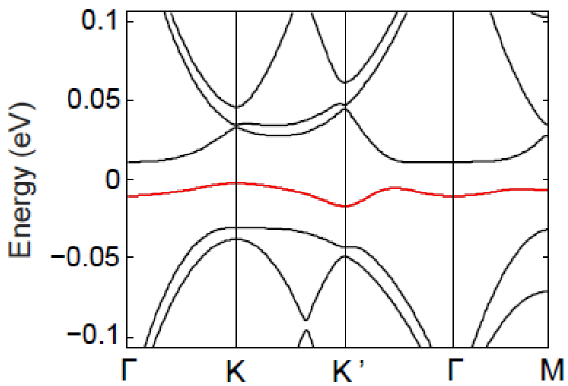
Engineering correlation in 2D heterostructures

Large m_e materials
+
Moiré

Correlated 2D system

A general route to strong correlation in 2D materials.

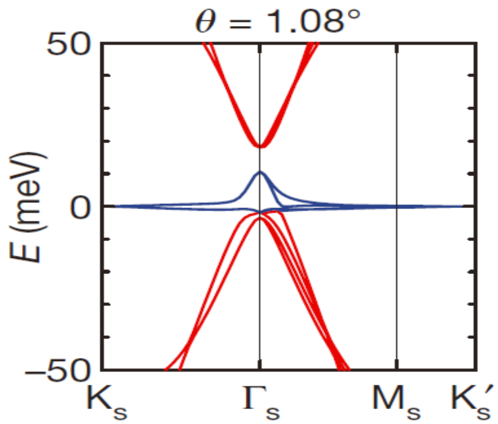
Trilayer graphene



L ~ 15 nm
$m_e \sim 0.1 m_0$

G Chen et al. Nature Physics (2019)
G Chen et al. arXiv:1901.04621 (2019)

Magic angle twisted bilayer

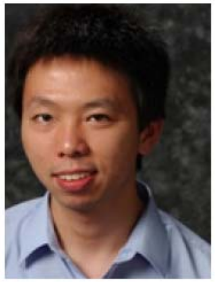


Strong hybridization
+
large disperse

Correlated insulator and superconductivity

Y Cao et al. Nature (2018)

Acknowledgement



UC Berkeley
Lili Jiang
Shuang Wu
Patrick Gallagher
Prof. Feng Wang

Fudan University
Prof. Yuanbo Zhang

Stanford University
Aaron Sharpe
Eli Fox
Ilan Rosen
Prof. David Goldhaber-Gordon

Shanghai Jiao Tong University
Bosai Lyu
Hongyuan Li
Prof. Zhiwen Shi

University of Seoul
Bheema Lingam Chittari
Prof. Jeil Jung

National Institute for Materials Science
Kenji Watanabe
Takashi Taniguchi

Discussion with Mike Zaletal (Berkeley), Ehud Altman (Berkeley), Senthil (MIT) and Ashvin (Harvard).

ONR, ARO, DOE

Berkeley
UNIVERSITY OF CALIFORNIA

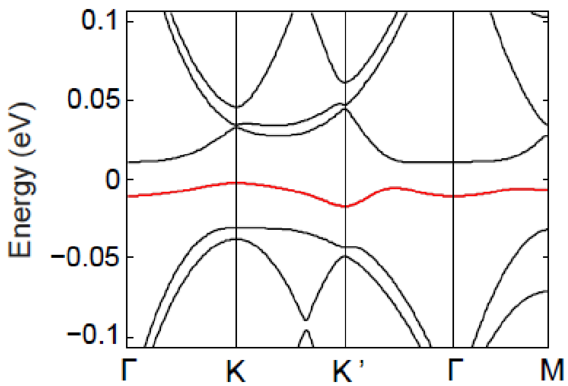
Engineering correlation in 2D heterostructures

Large m_e materials
+
Moiré

Correlated 2D system

A general route to strong correlation in 2D materials.

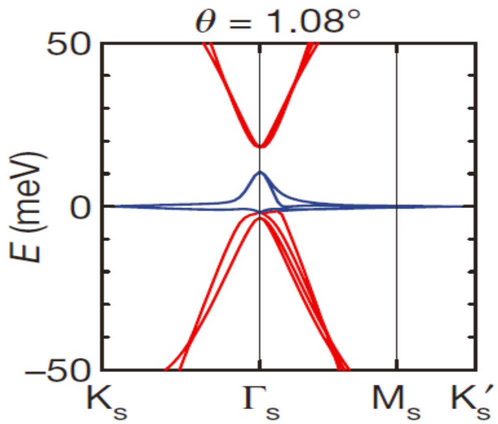
Trilayer graphene



L ~ 15 nm
$m_e \sim 0.1 m_0$

G Chen et al. Nature Physics (2019)
G Chen et al. arXiv:1901.04621 (2019)

Magic angle twisted bilayer



Strong hybridization
+
large disperse

Correlated insulator and superconductivity

Y Cao et al. Nature (2018)

Berkeley
UNIVERSITY OF CALIFORNIA