Title: The magic of moirÃ© quantum matter

Speakers: Pablo Jarillo-Herrero

Series: Colloquium

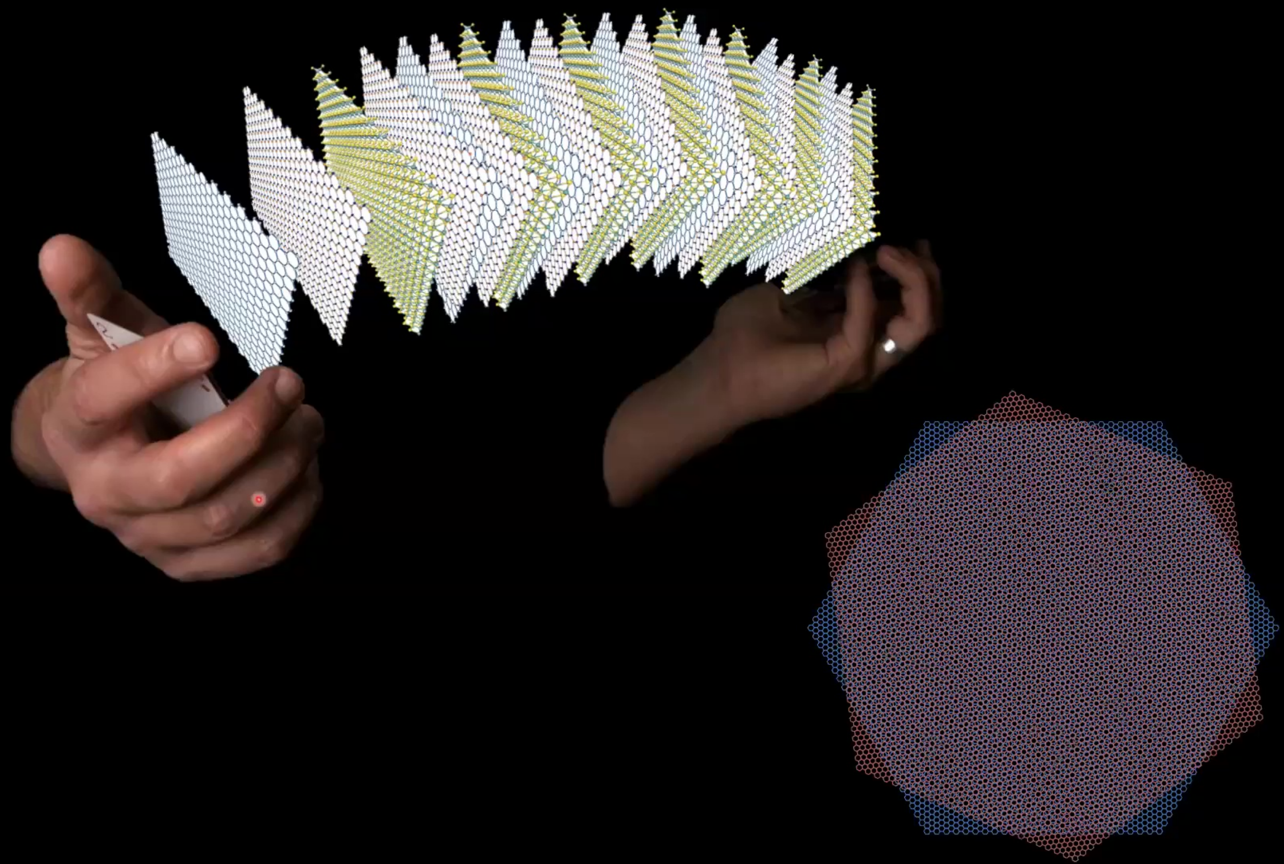
Date: March 10, 2021 - 2:00 PM

URL: http://pirsa.org/21030004

Abstract: The understanding of strongly-correlated quantum matter has challenged physicists for decades. The discovery three years ago of correlated phases and superconductivity in magic angle twisted bilayer graphene led to the emergence of a new materials platform to investigate strongly correlated physics, namely moirÃ© quantum matter. These systems exhibit a plethora of quantum phases, such as correlated insulators, superconductivity, magnetism, Chern insulators, and more. In this talk I will review some of the recent advances in the field, focusing on the newest generation of moirÃ© quantum systems, where correlated physics, superconductivity, and other fascinating phases can be studied with unprecedented tunability. I will end the talk with an outlook of some exciting directions in this emerging field.

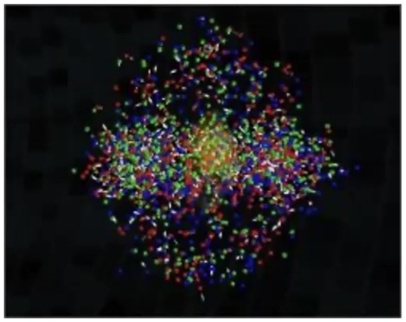
The Magic of Moiré Quantum Matter

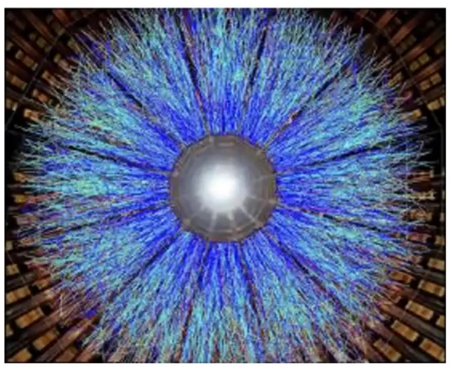
Pablo Jarillo-Herrero – MIT



Strongly Correlated States of Matter

Quark-Gluon Plasma

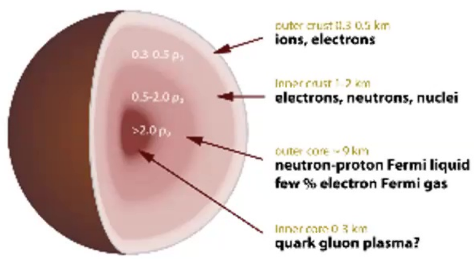




Brookhaven National Laboratory

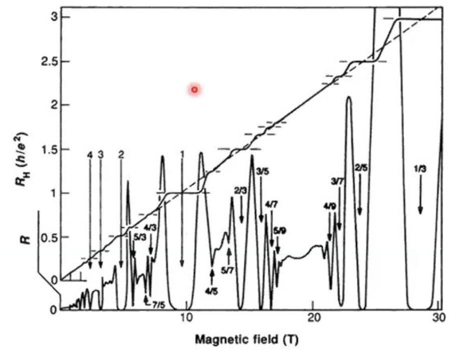
Nuclear Matter in Neutron Stars

Chandra X-Ray Observatory

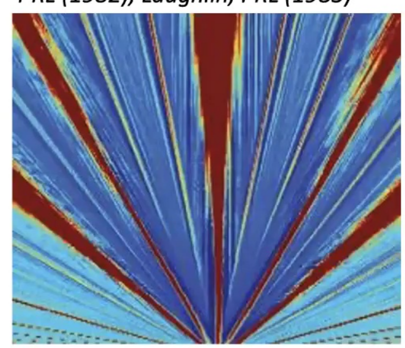


Wikipedia: nuclear pasta

Topological States of Matter



Stormer et al. PRL (1992)
Von Klitzing et al. PRL(1980), Tsui et al. PRL (1982), Laughlin, PRL (1983)



Yacoby Lab

Strongly Correlated Quantum Materials

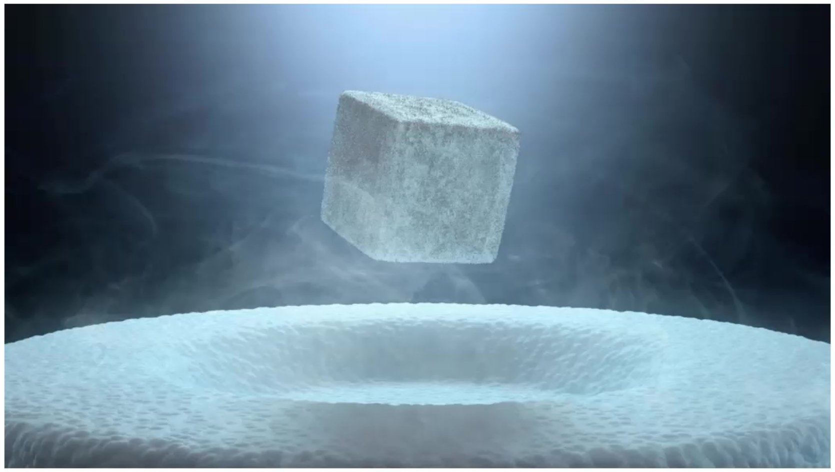


Image Credit: ktsdesign / Shutterstock.com

High-T_C Superconductors

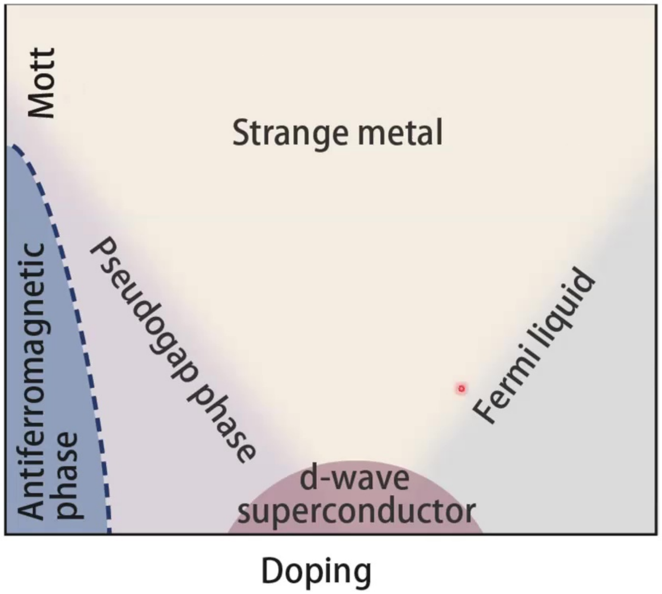
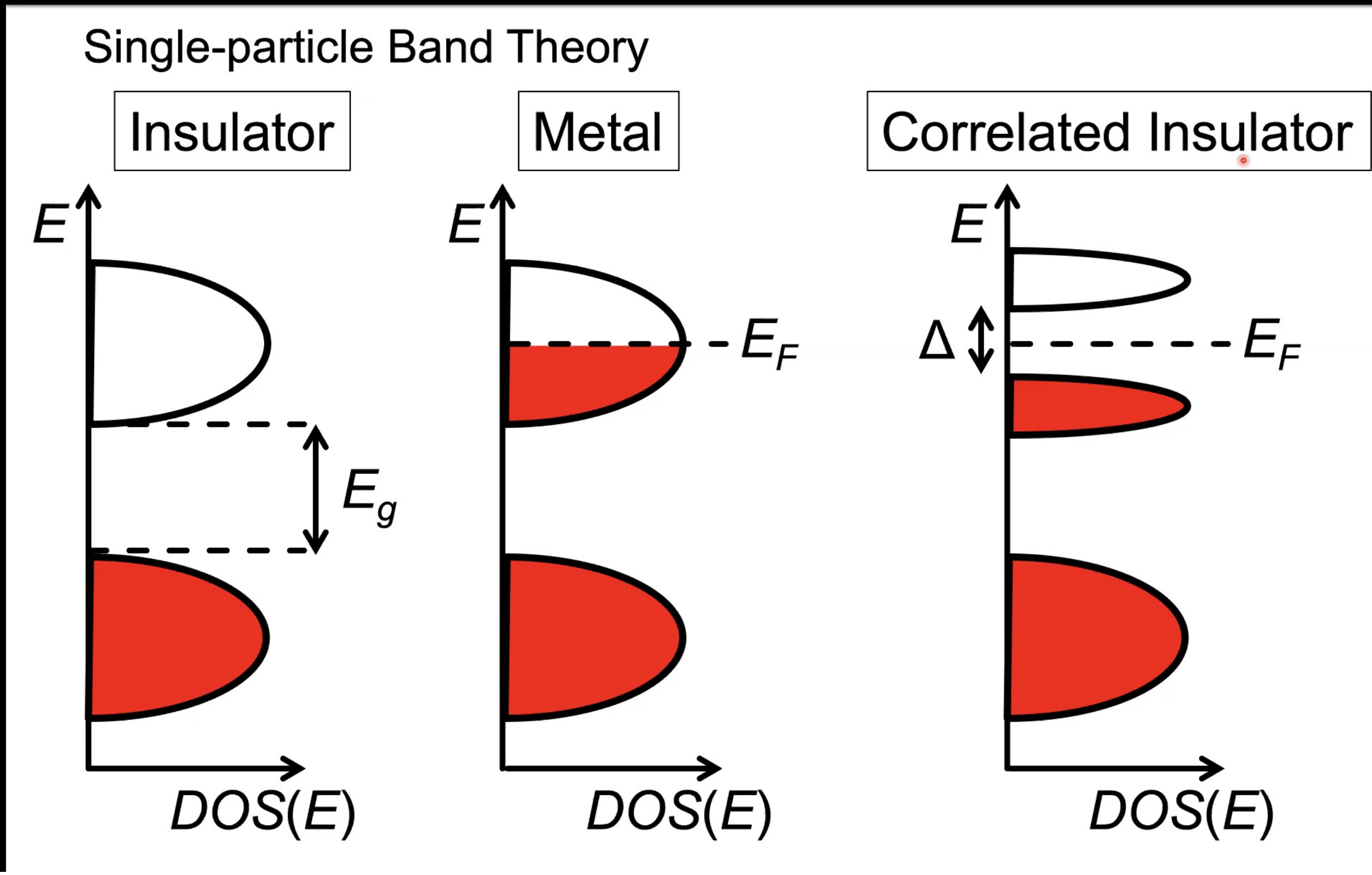
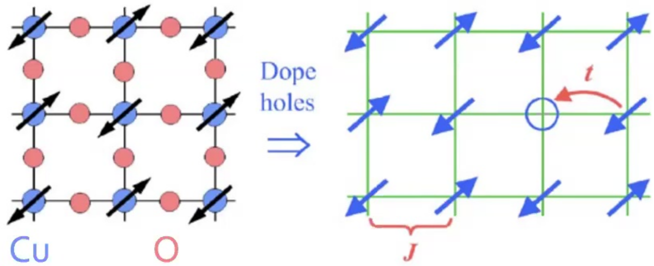


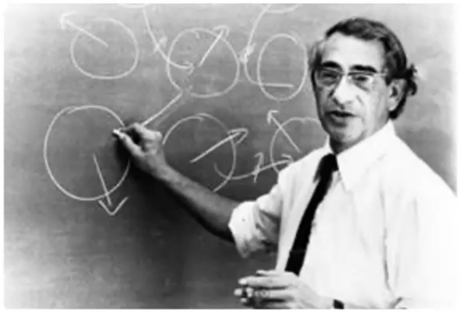
Image: Mazurenko et al. Nature (2017)

Metals, Insulators…and Correlated Insulators



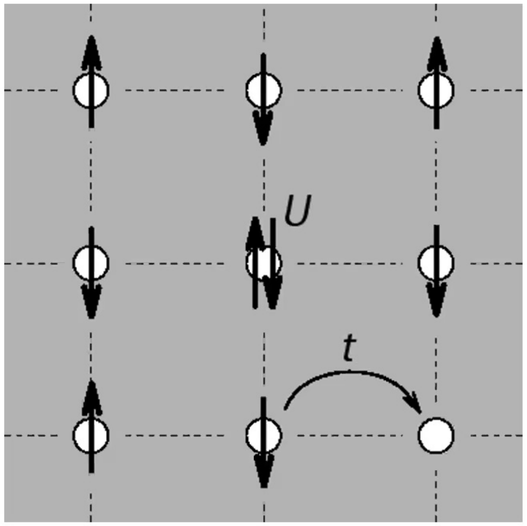
Example correlated insulator: Mott Insulator, parent compound High-T_C Cuprate Superconductors

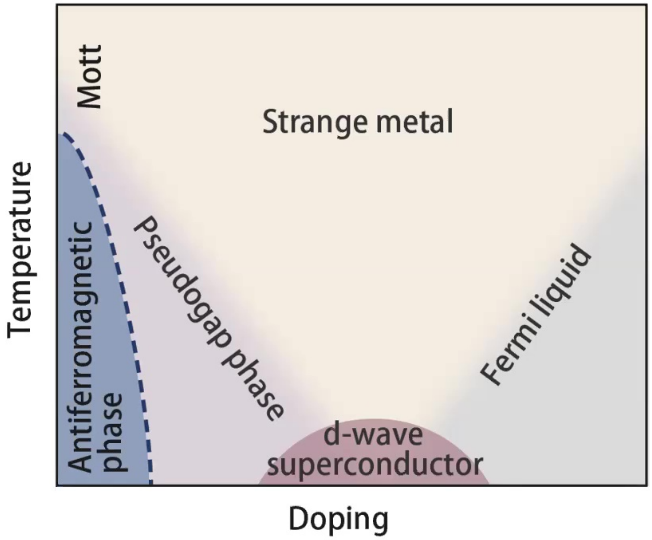




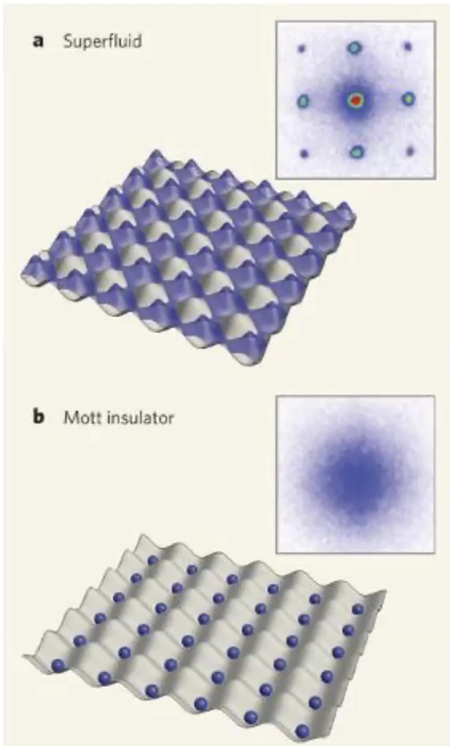
John Hubbard (1931-1980)

Hubbard Model (1963)

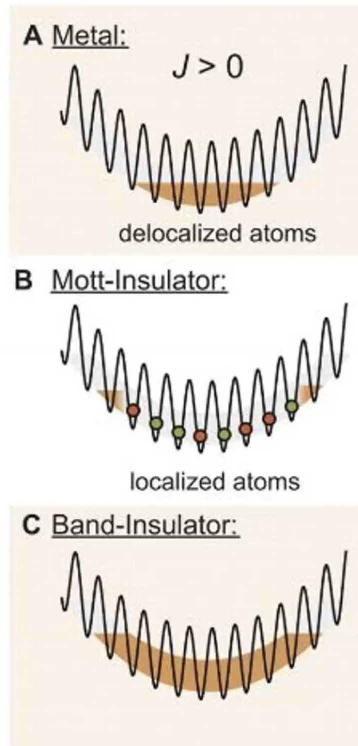




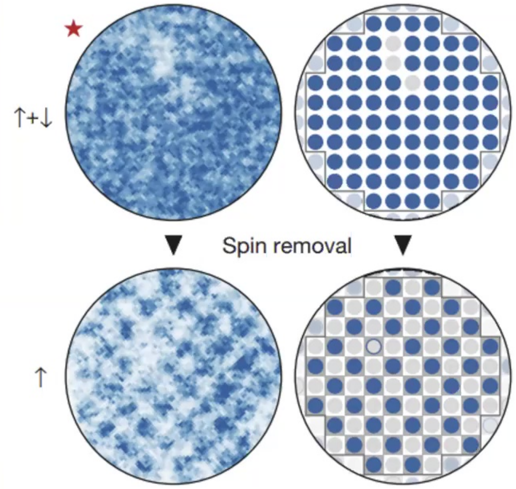
Novel Approaches to Investigate Strongly Correlated Quantum Materials: ultra-cold atom lattices



Bose-Hubbard Model
Greiner *et. al., Nature* (2002)

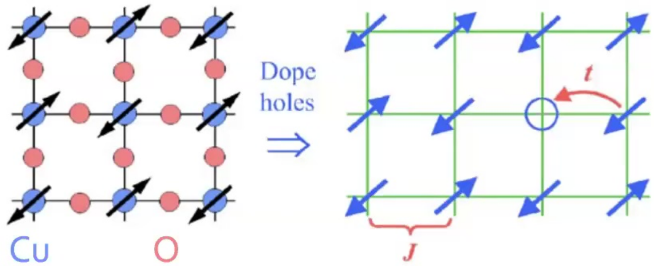


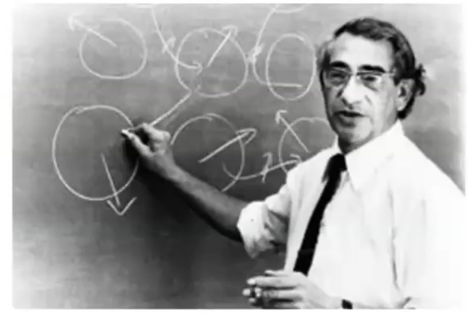
Fermi-Hubbard Model
J. Jördens *et.al., Nature* (2008)
U. Schneider *et.al, Science* (2008)



Antiferromagnetism in F-H Model
Mazurenko e*t. al., Nature* (2017)
Cheuk *et al. Science* (2016)
Parsons *et al. Science* (2016)
Boll *et al. Science* (2016)

Example correlated insulator: Mott Insulator, parent compound High-T_C Cuprate Superconductors





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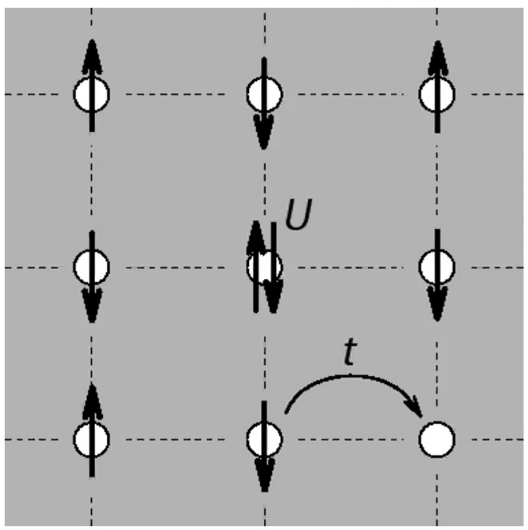
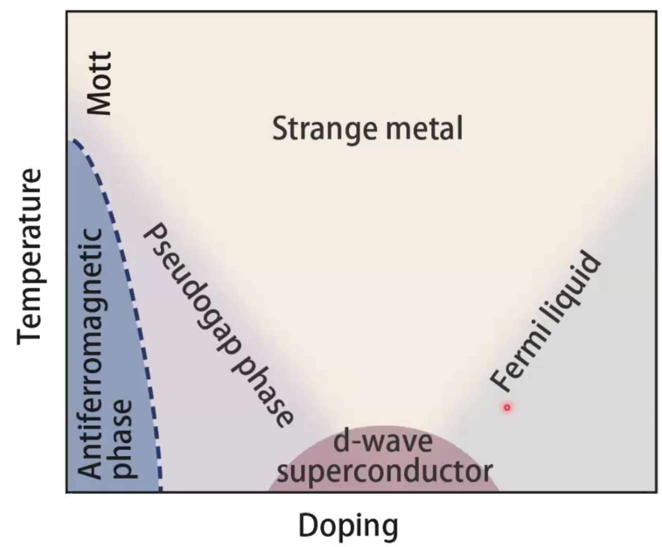
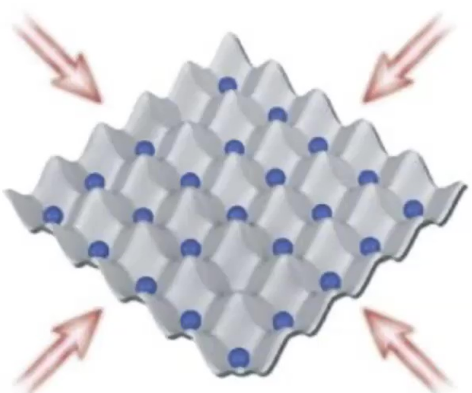
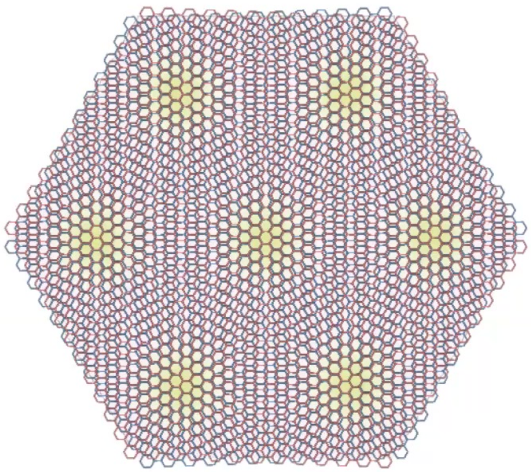


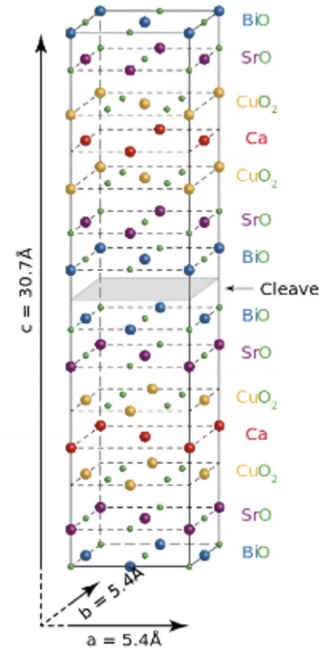


Moiré Quantum Matter: a New Platform for Strongly Correlated Physics

Cold Atoms Optical Lattices	Moiré Quantum Matter	Quantum Materials
Length scale ~ **1 micron**	Moiré length **~ 10nm**	Lattice scale **~ few Å**
Temperature scale	Temperature scale	Temperature scale
~ **0.1-1 nanoKelvin**	~ **1-10 Kelvin**	~ **100-1,000 Kelvin**

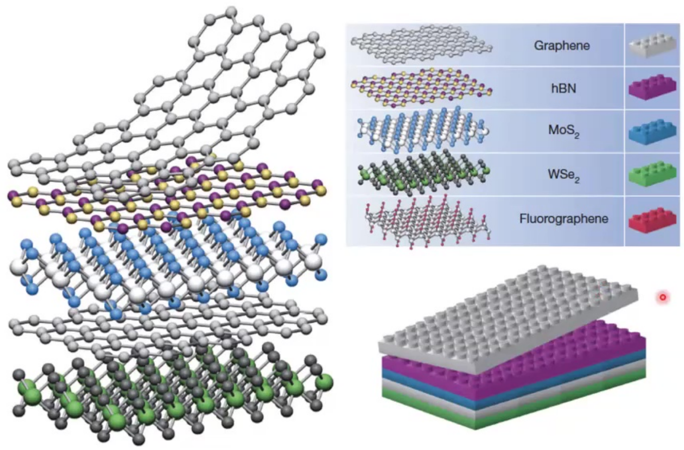






$Bi_2Sr_2Ca_nCu_{n+1}O_{2n+6-d}$

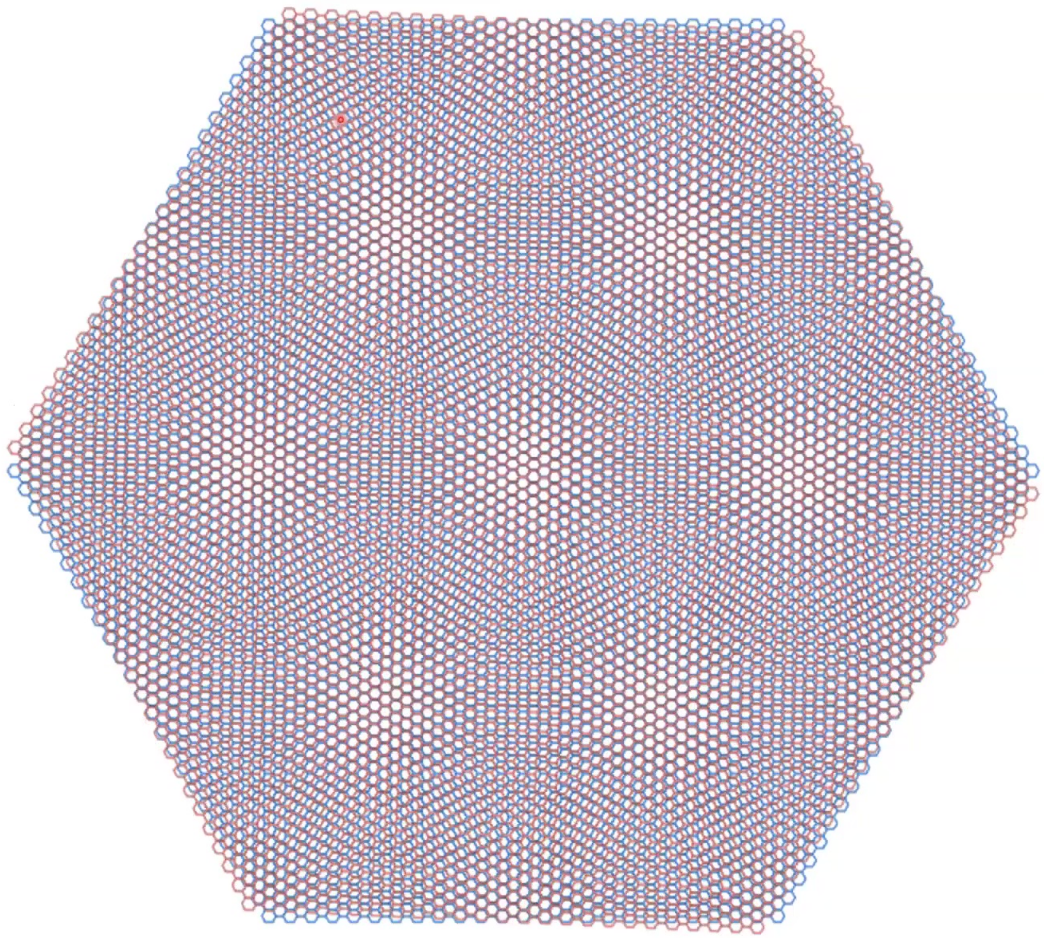
Welcome to 2D Materials Legoland



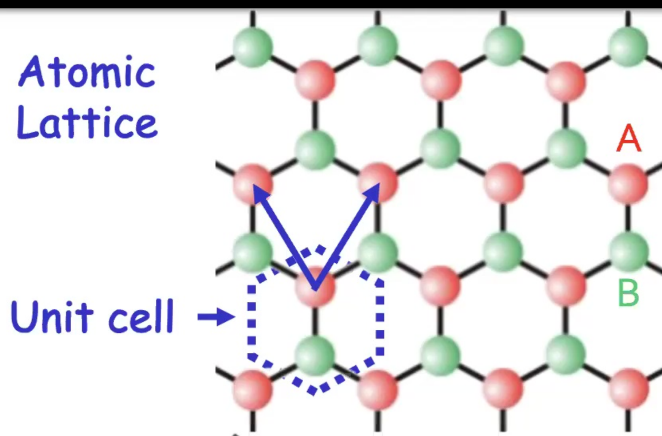
Geim & Grigorieva, Nature (2013)

Ajayan, Kim & Banerjee, Physics Today (2016)

Twistronics: 2D materials beyond Legoland

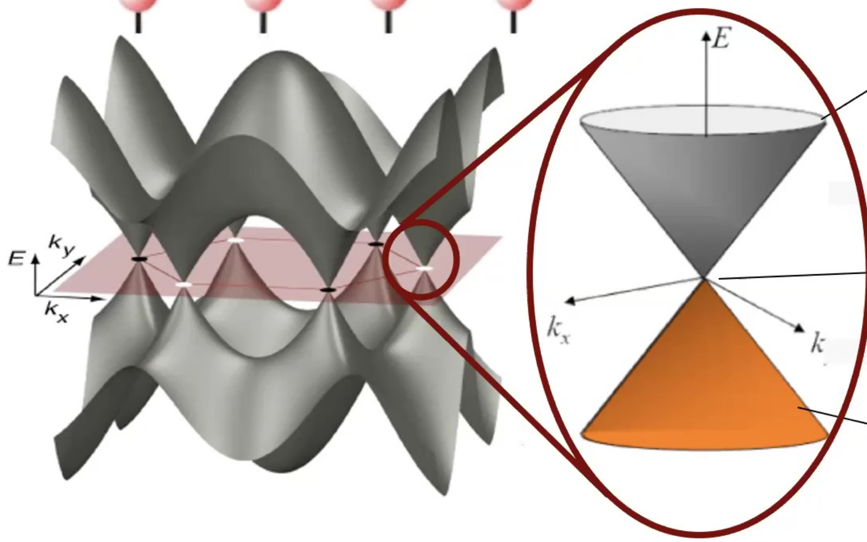


Masless Dirac Fermions in Graphene



Dirac equation in 2D for massless particles

$$\hbar v_F \vec{k}\vec{\sigma}\begin{pmatrix}\alpha_k \\ \beta_k\end{pmatrix} = E(\vec{k})\begin{pmatrix}\alpha_k \\ \beta_k\end{pmatrix}$$

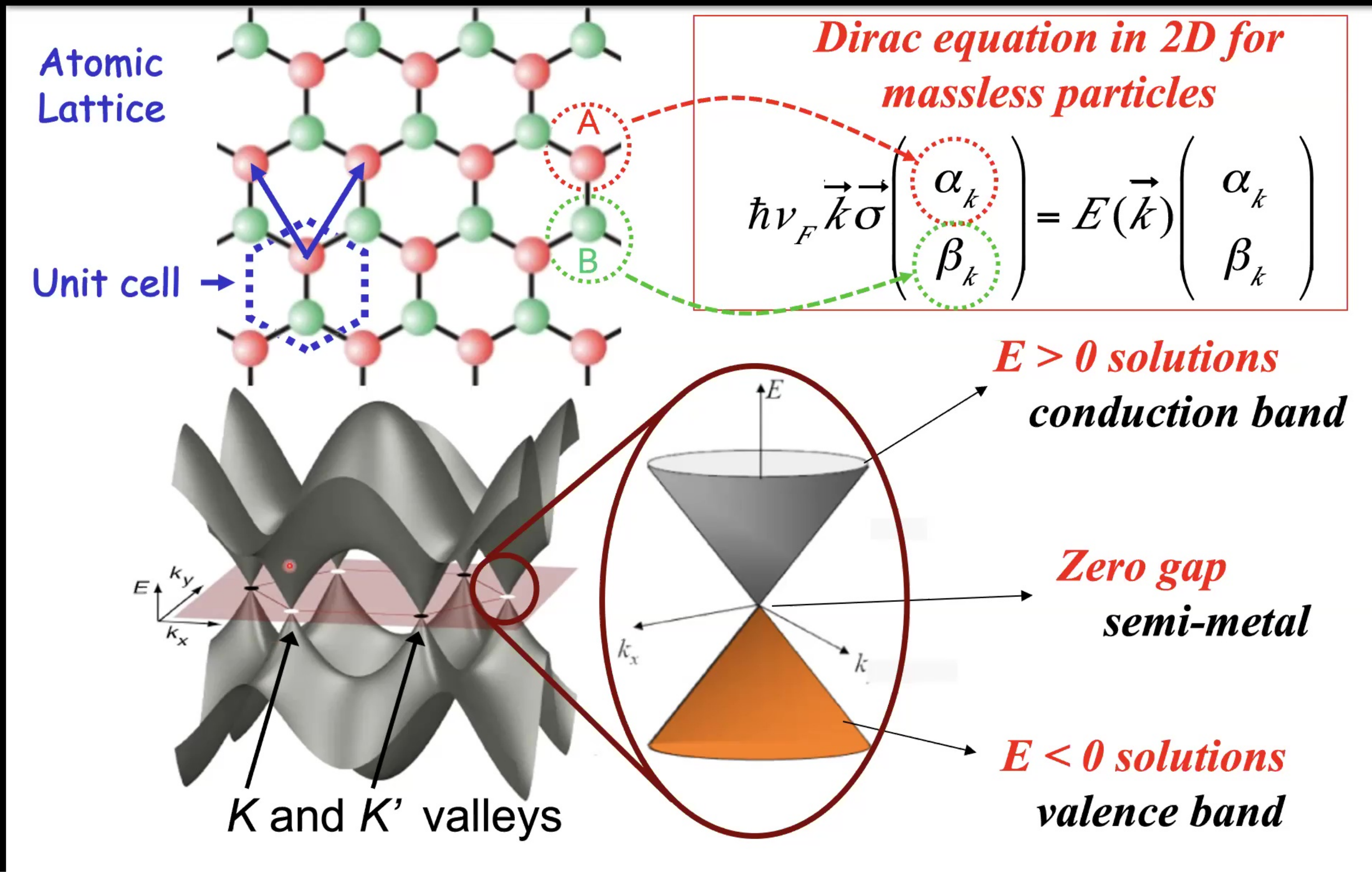


E > 0 solutions
conduction band

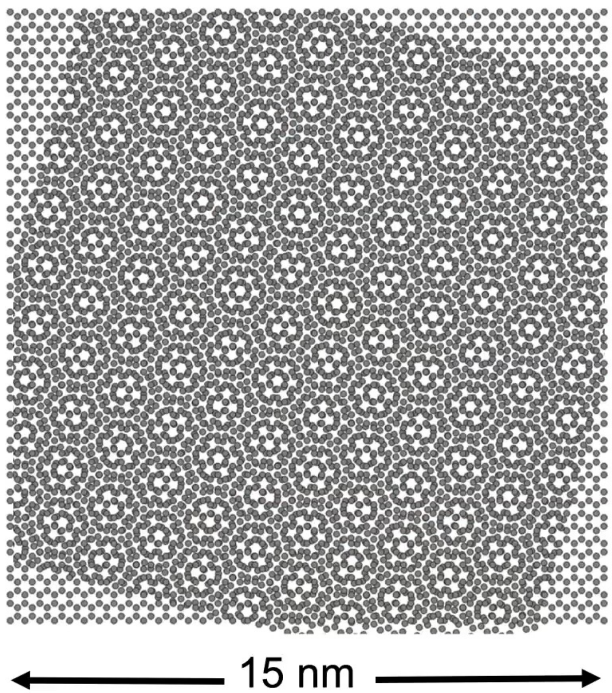
Zero gap
semi-metal

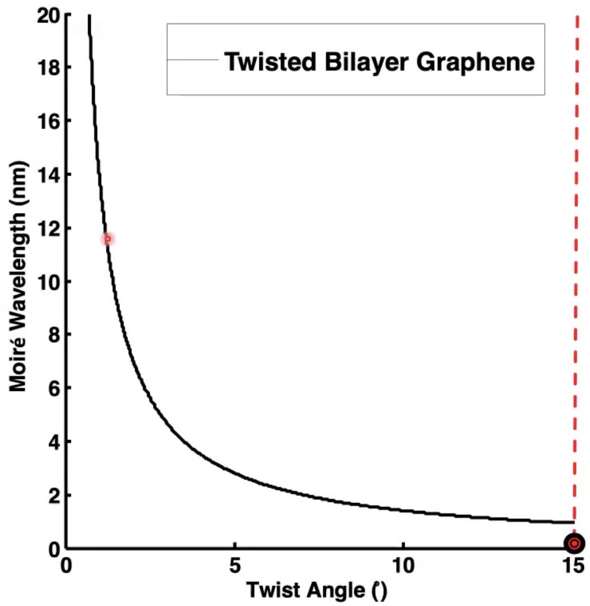
E < 0 solutions
valence band

Masless Dirac Fermions in Graphene

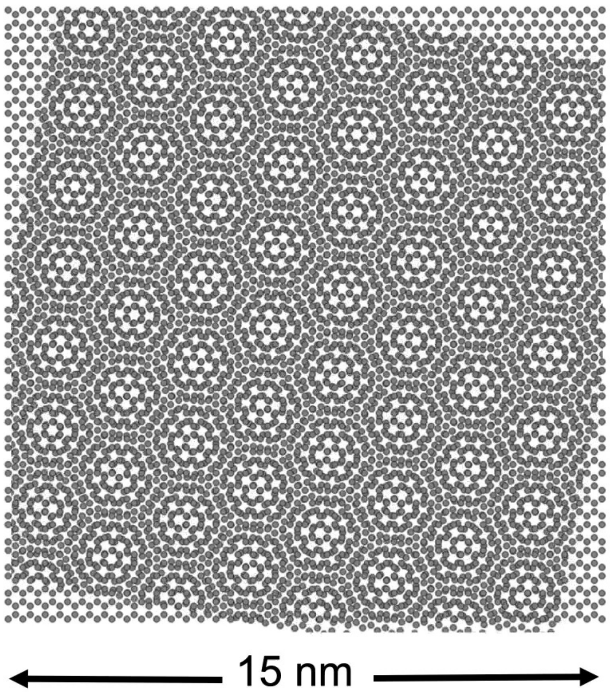


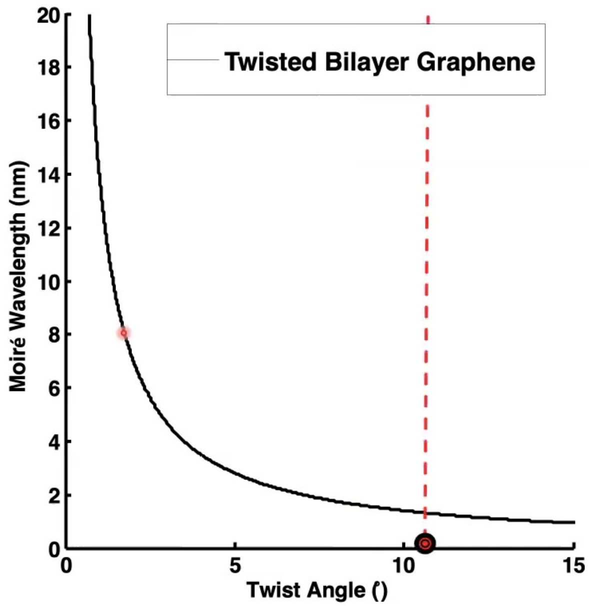
Graphene/Graphene moiré heterostructures





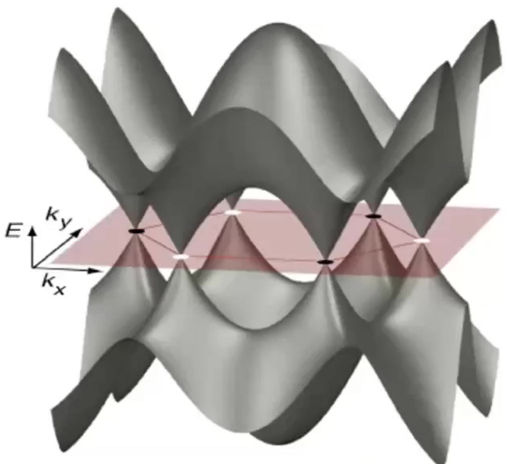
Graphene/Graphene moiré heterostructures

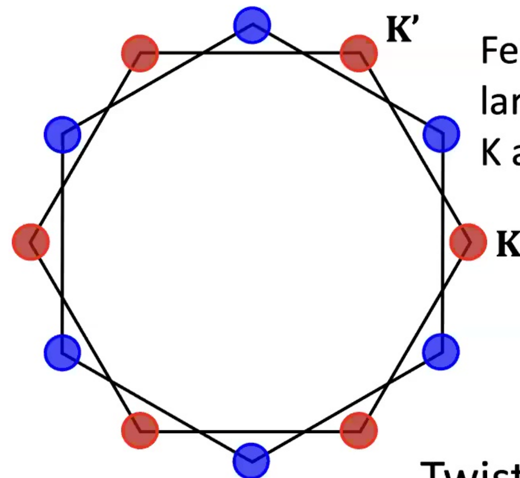




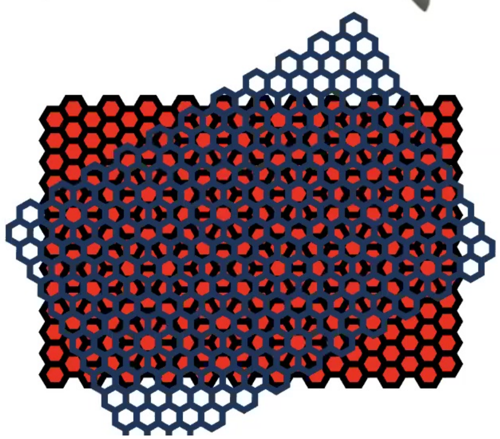
Twisted bilayer graphene: twist angle dependence

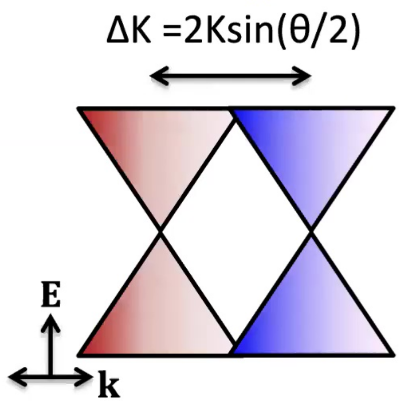
Graphene band structure





Fermi surfaces at large momentum: K and K'

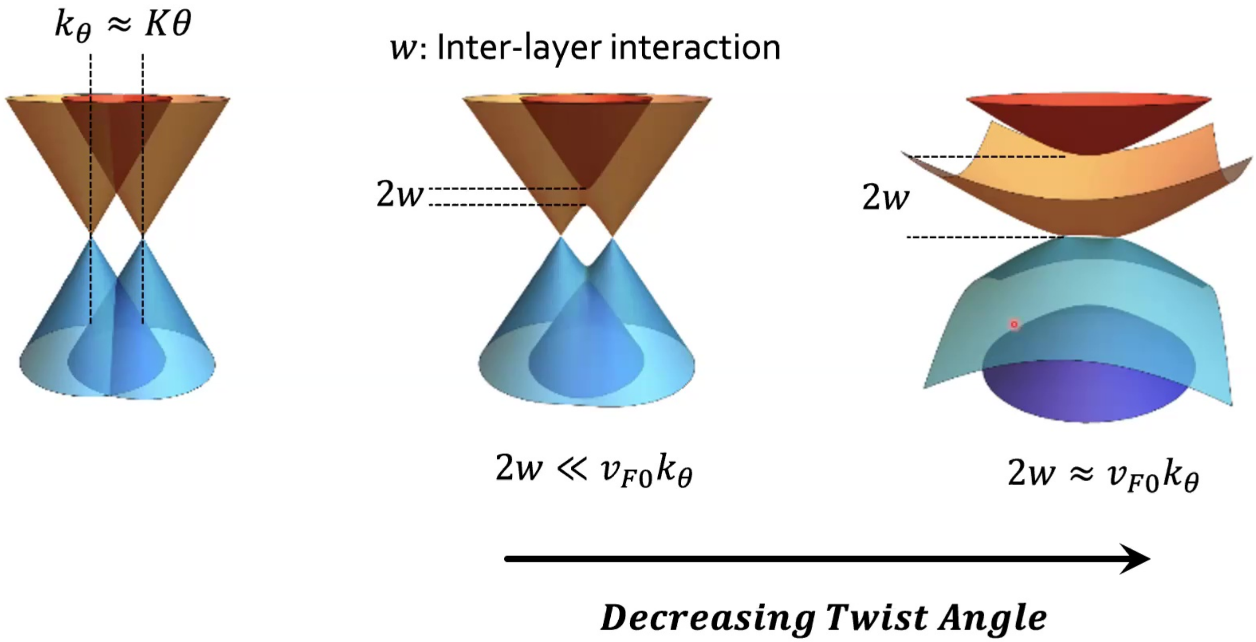




Twisting leads to layer Dirac cones separating in momentum space!

Lopes dos Santos *et al*. *PRL* (2007)
Li *et al. Nature Phys* (2010)
Shallcross *et al. PRB* (2010)
Suarez-Morell *et al. PRB* (2010)
Mele, *PRB* (2010) & (2011)
Bistritzer & MacDonald, *PNAS* (2011)

Magic-Angle Twisted Bilayer Graphene (MA-TBG)

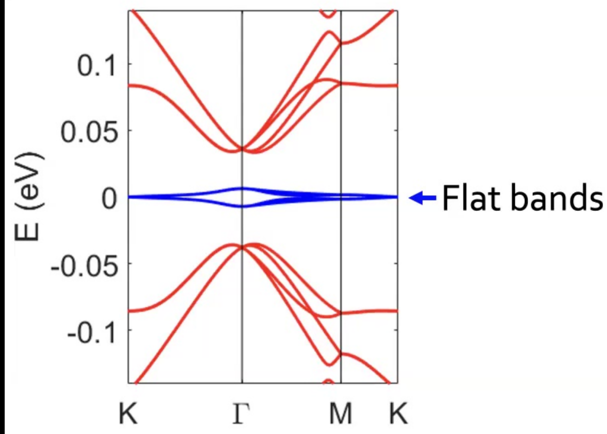


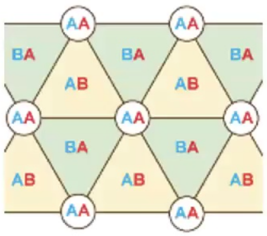
"Flat Band" condition is reached at the "Magic Angle"

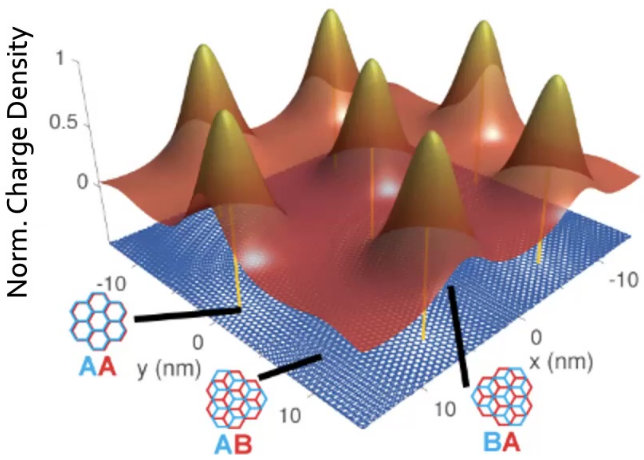
$$\theta_M \approx 1.1°$$

Bistritzer & MacDonald, *PNAS* (2011)
Also: Li *et al. Nature. Phys.* (2010)
Suarez-Morell *et al. PRB* (2010)

Flat Bands in *k*-space -> Localization in real space







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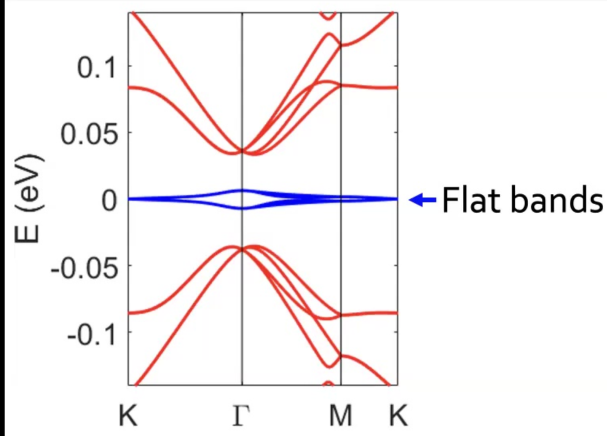
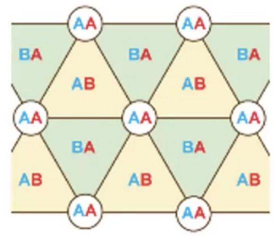
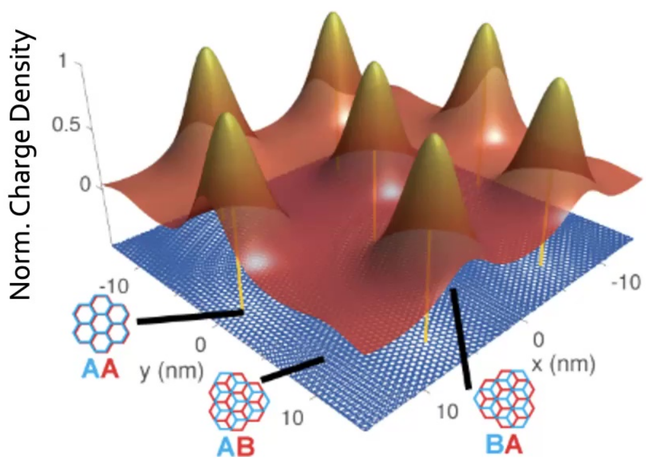
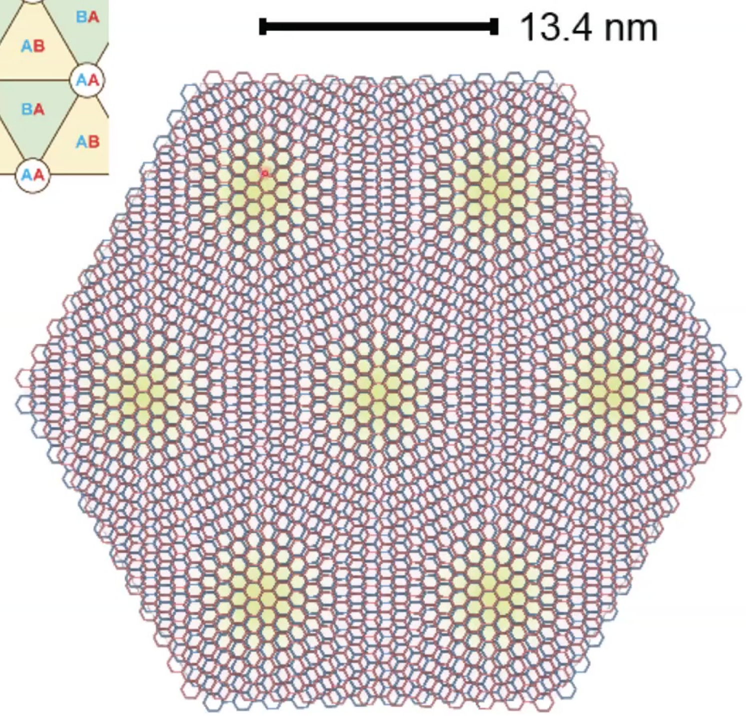




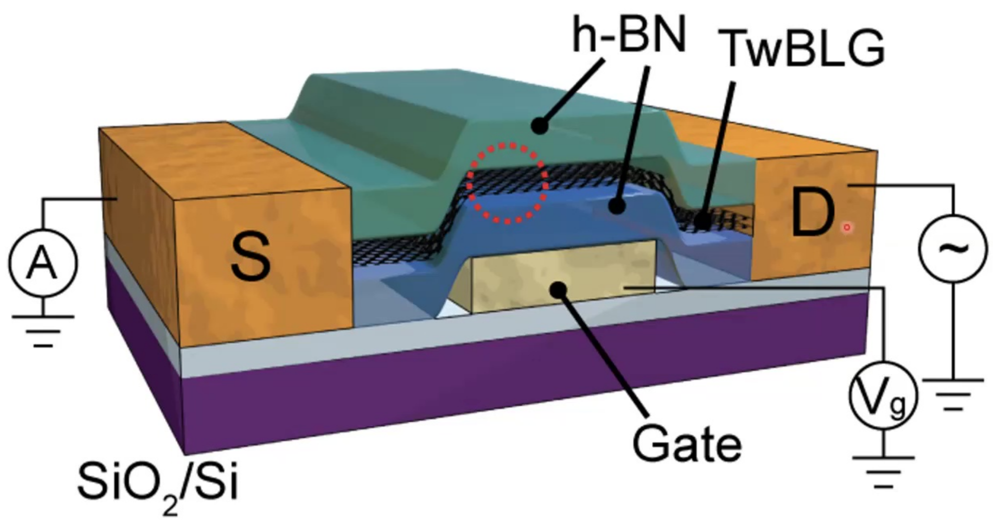




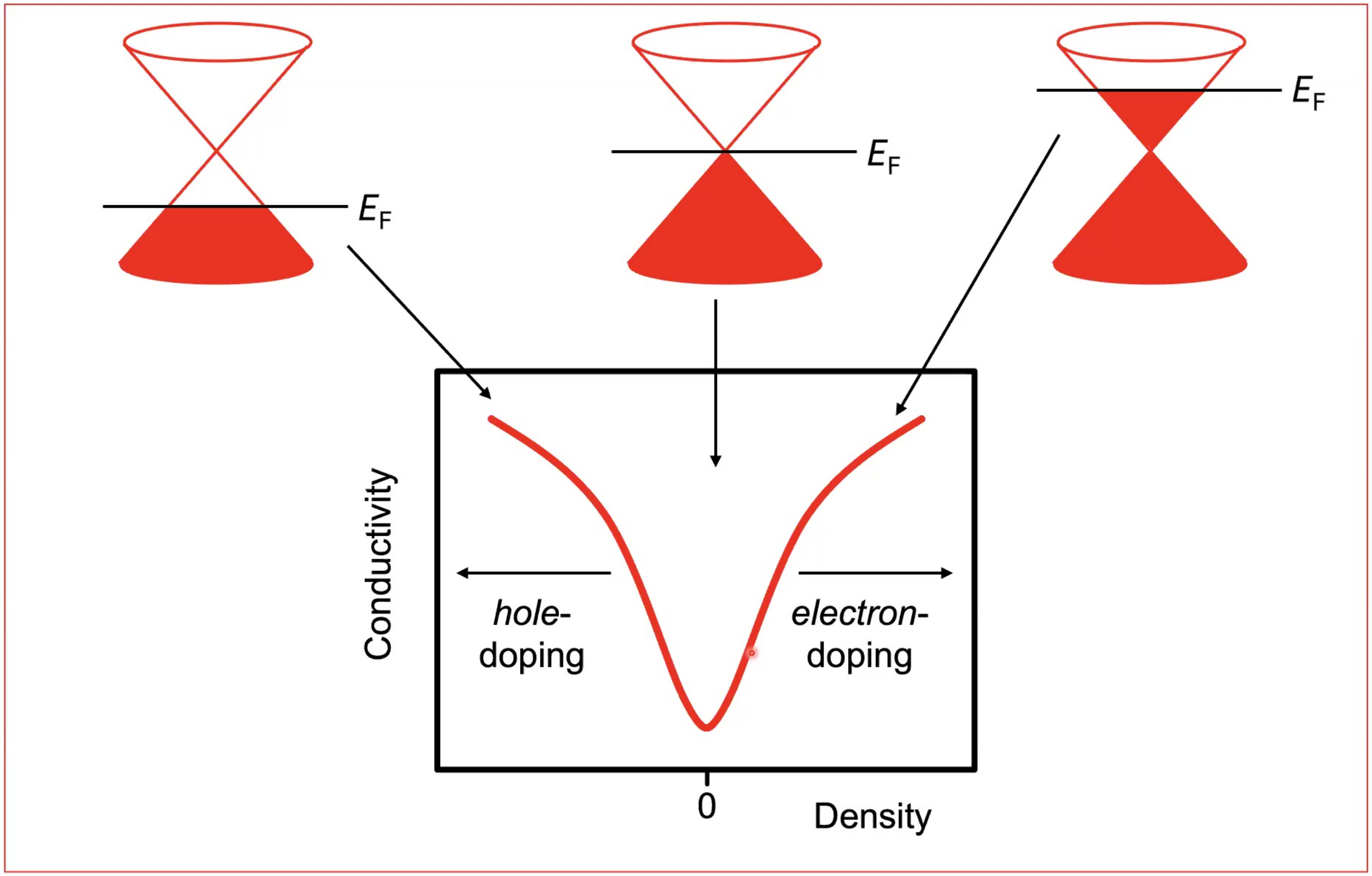
“Triangular” Fermi-Hubbard Lattice

Cao, PJH *et al. Nature* **556**, 80 (2018)

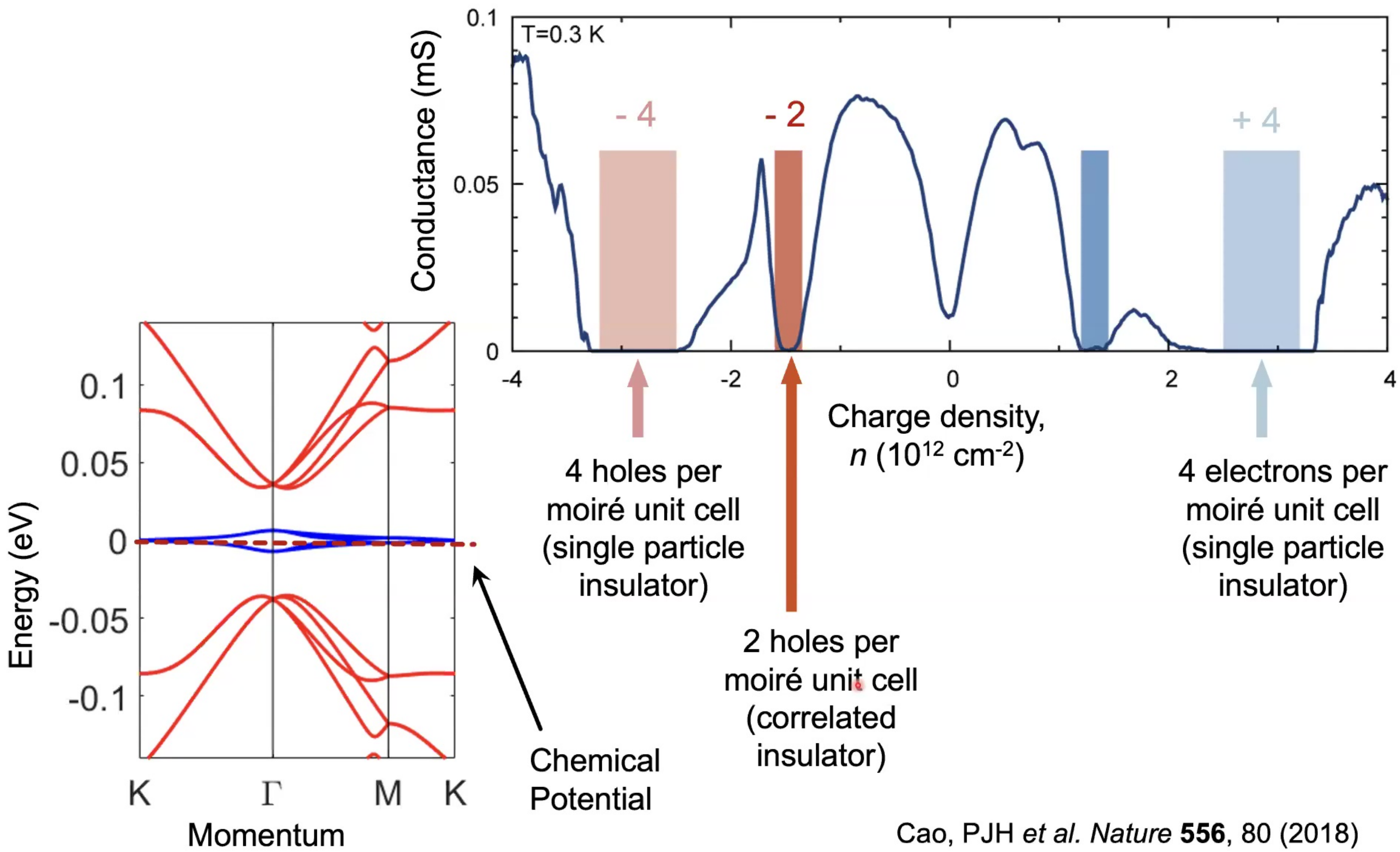
Device Geometry & Measurement Scheme



Reminder: conduction through regular graphene

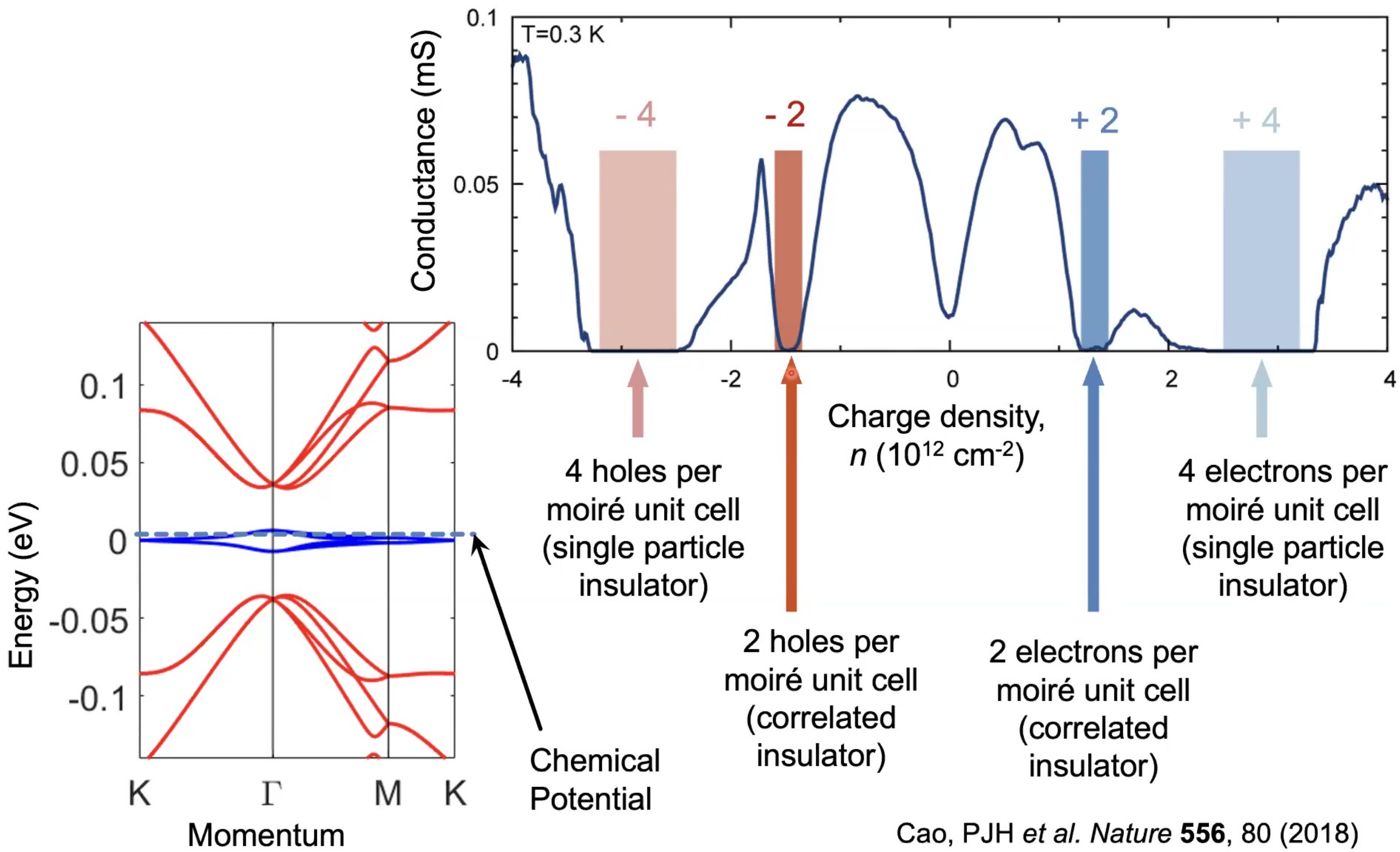


Correlated Insulator Behavior at Half-Filling



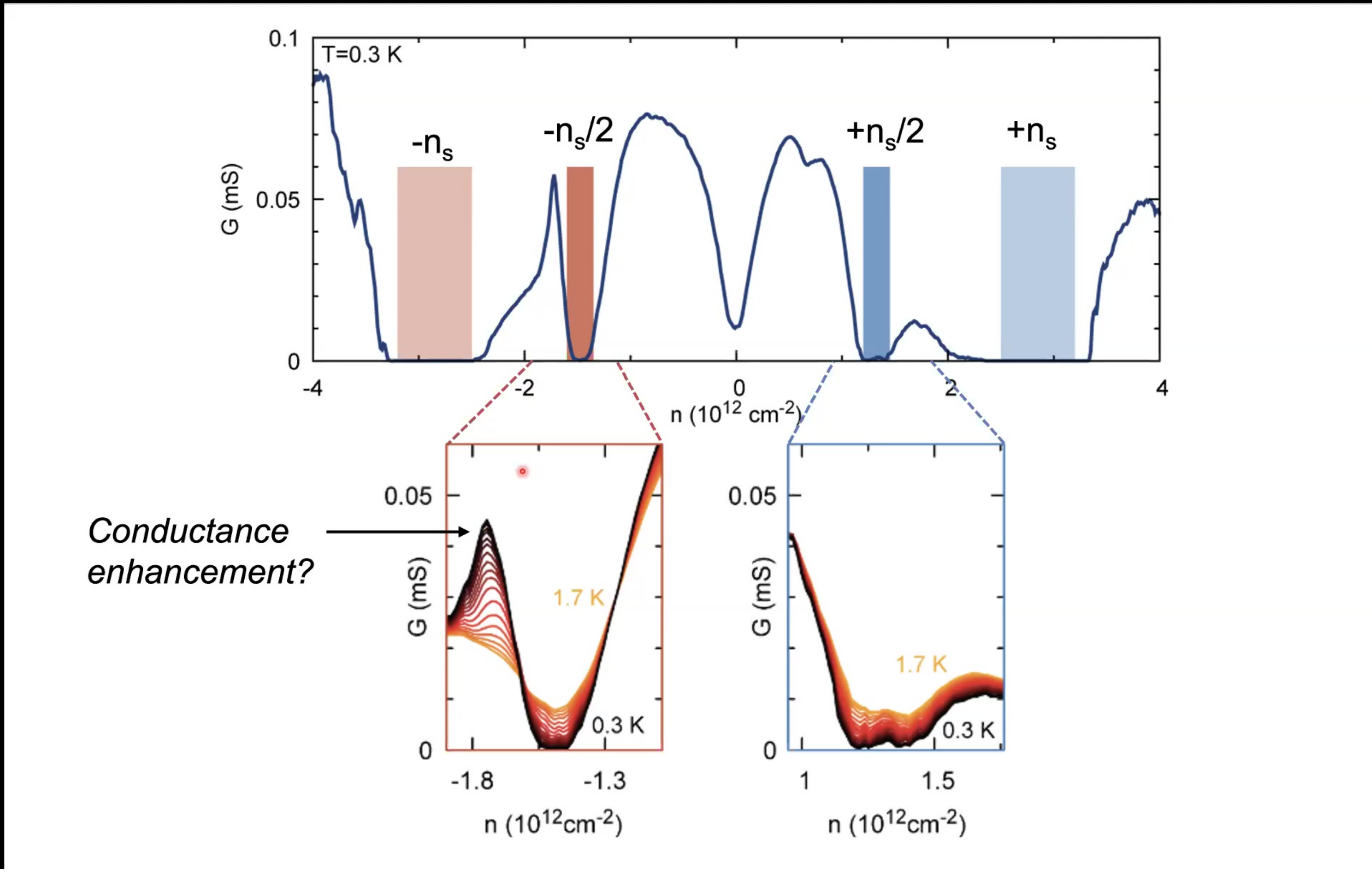
Cao, PJH *et al.* *Nature* **556**, 80 (2018)

Correlated Insulator Behavior at Half-Filling

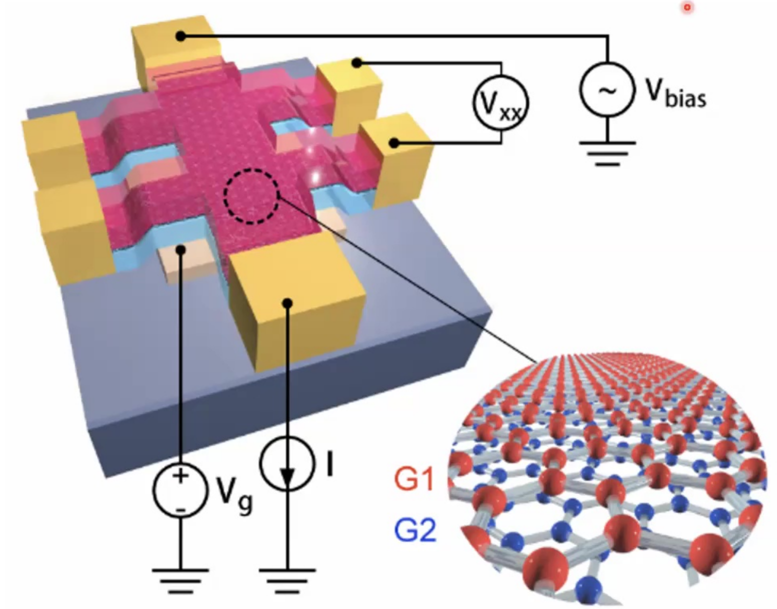


Cao, PJH *et al.* *Nature* **556**, 80 (2018)

Let's explore more carefully what happens as we electrostatically dope away from correlated insulator state…

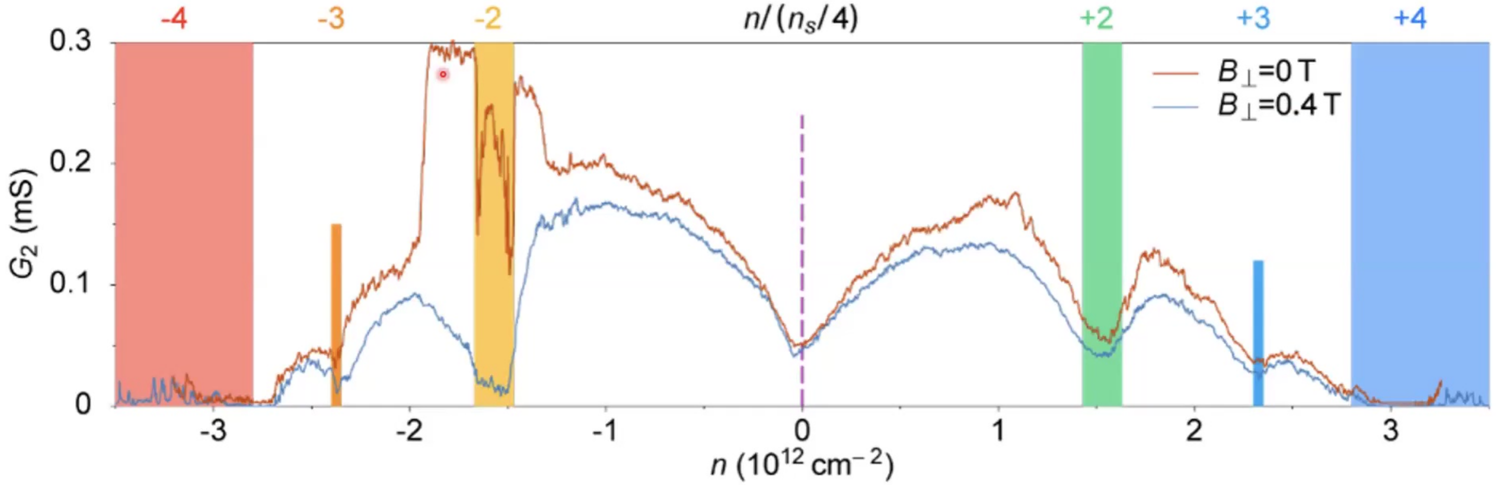


Four-Probe Device Geometry & Measurement Scheme



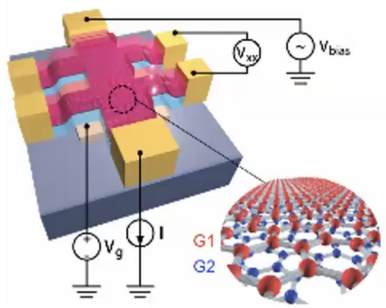
MA-TBLG: new devices, initial 2-probe characterization

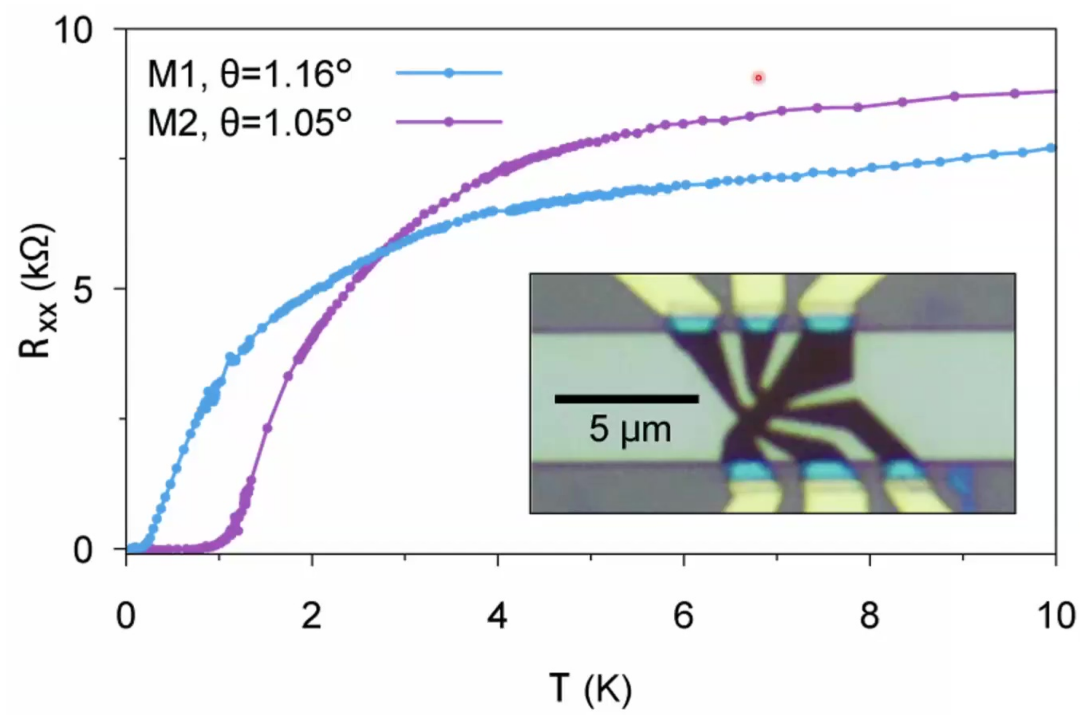
New device: M1, θ =1.16°



Cao, PJH *et al. Nature* **556**, 43 (2018)

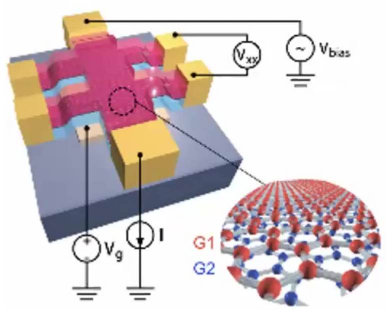
MA-TBLG Superconducts!!!

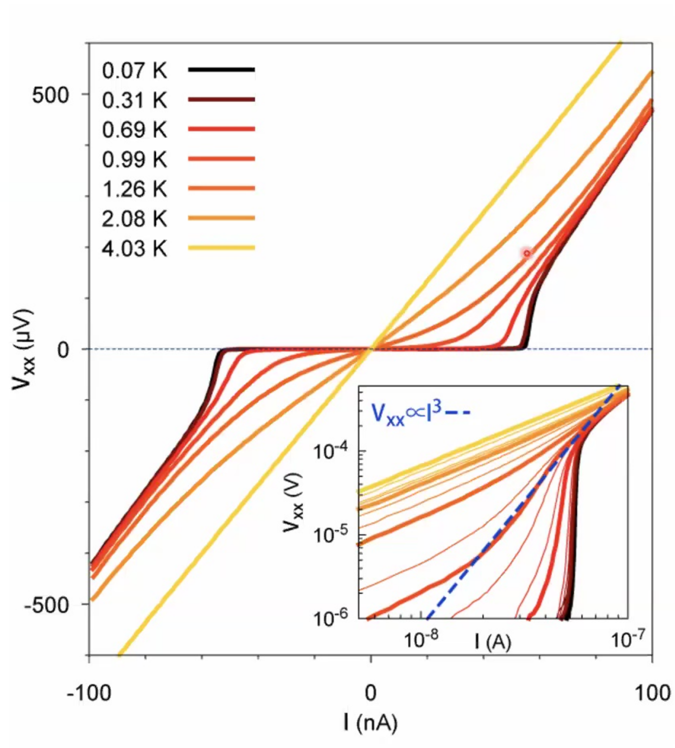




Cao, PJH *et al. Nature* **556**, 43 (2018)

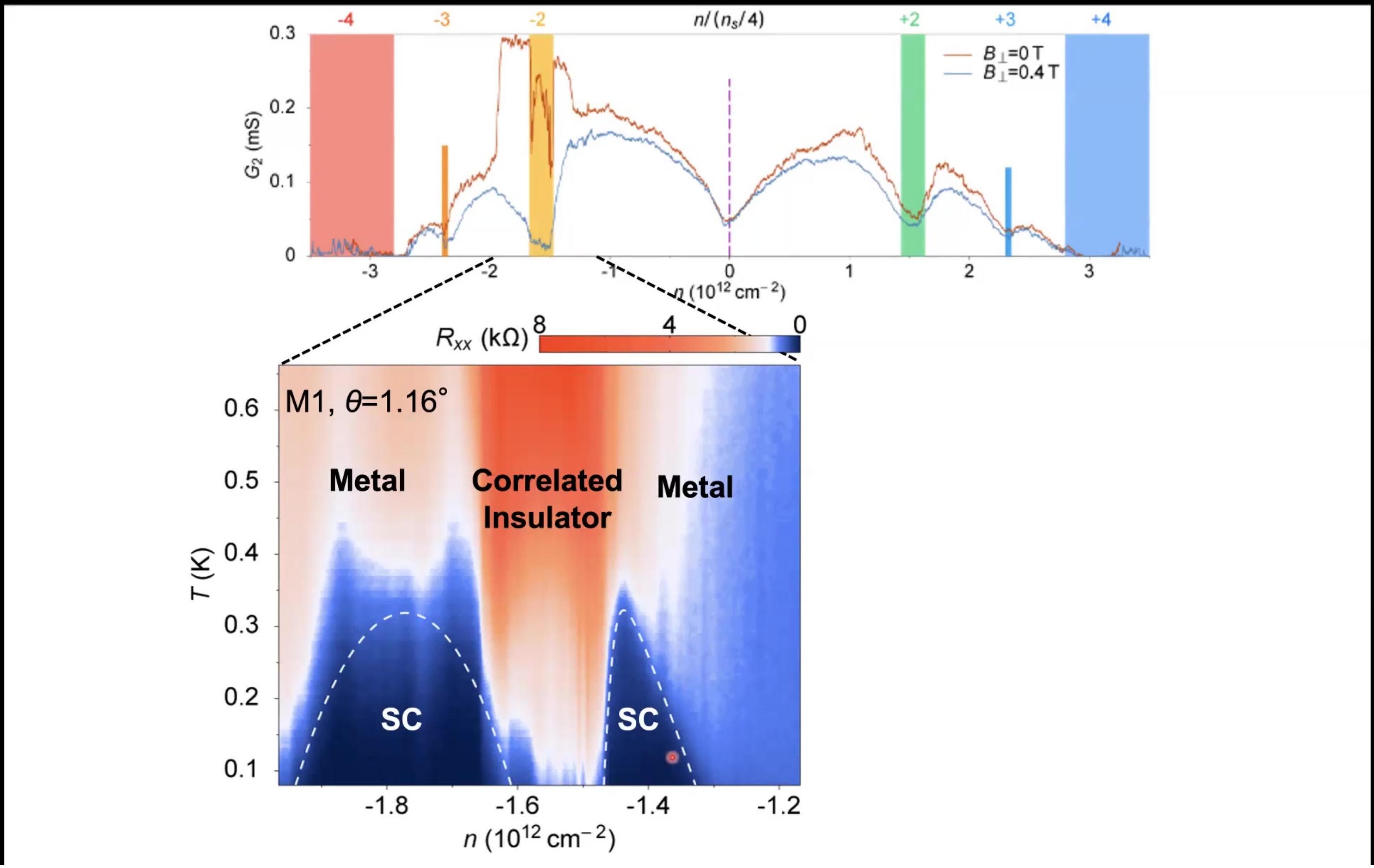
MA-TBLG Superconducts!!!



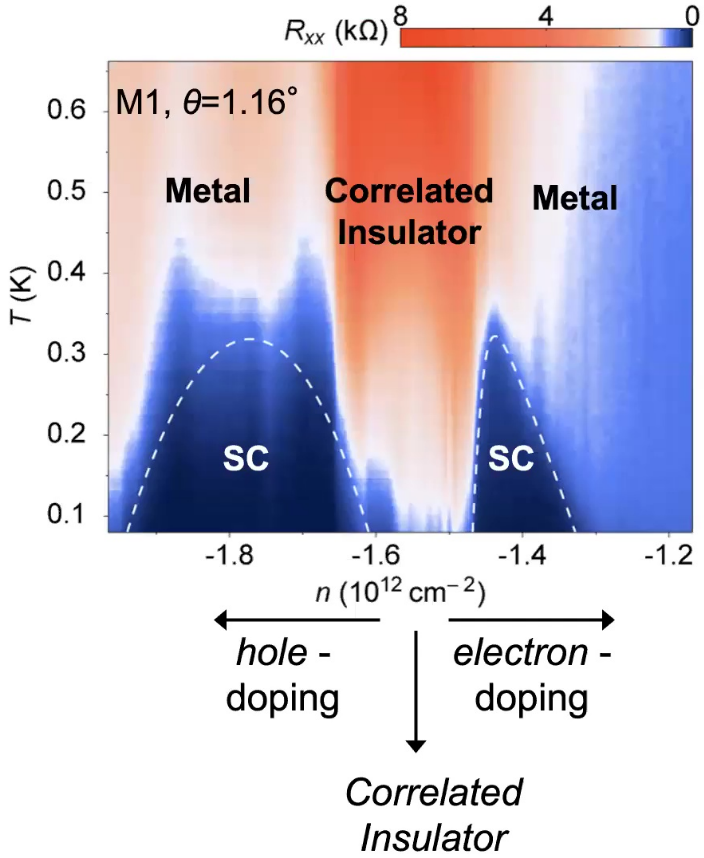


Cao, PJH *et al. Nature* **556**, 43 (2018)

MA-TBLG: an electrically tunable superconductor

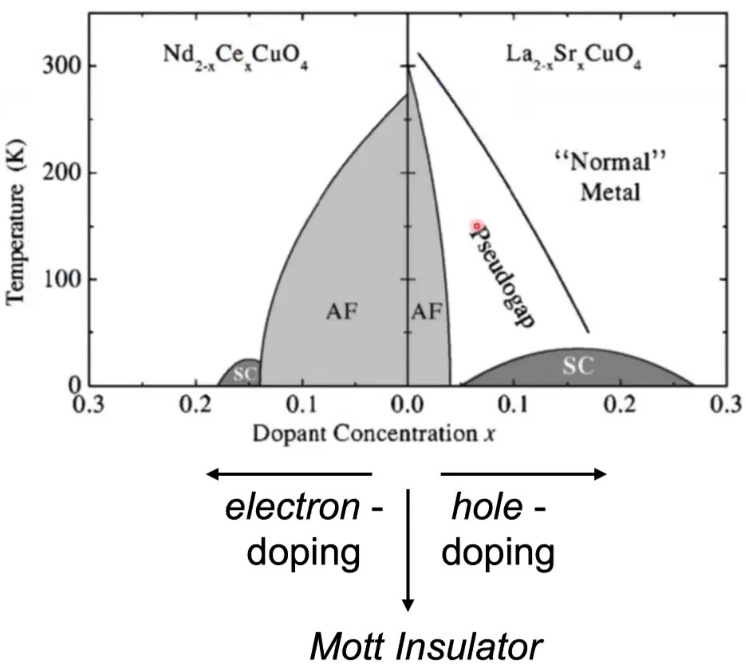


Similarity MA-TBLG vs Cuprates

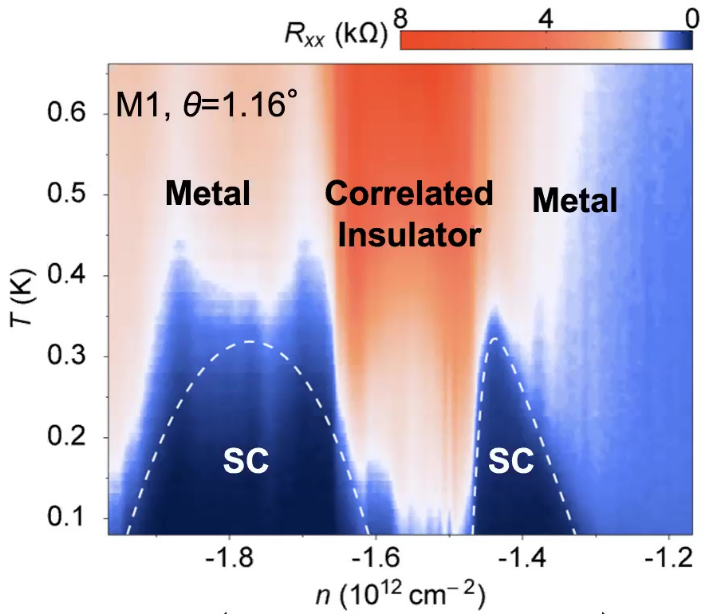


Cao, PJH *et al. Nature* **556**, 43 (2018)

Damascelli, Hussain & Shen, *Rev. Mod. Phys.* (2003)



Similarity MA-TBLG vs Cuprates

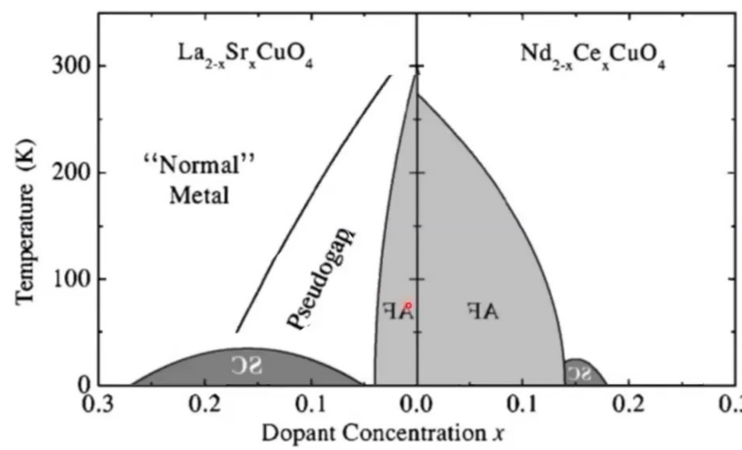


hole - doping

electron - doping

Correlated Insulator

Damascelli, Hussain & Shen, *Rev. Mod. Phys.* (2003)



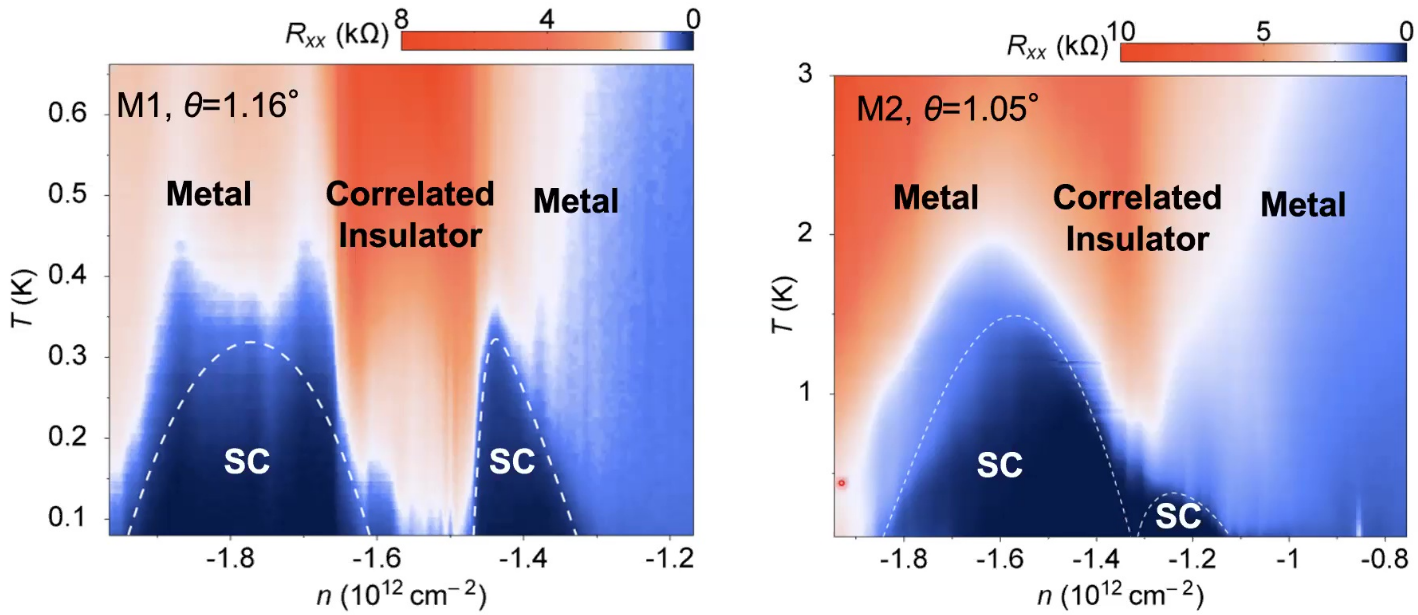
hole - doping

electron - doping

Mott Insulator

Cao, PJH *et al. Nature* **556**, 43 (2018)

MA-TBLG: great sensitivity to twist angle

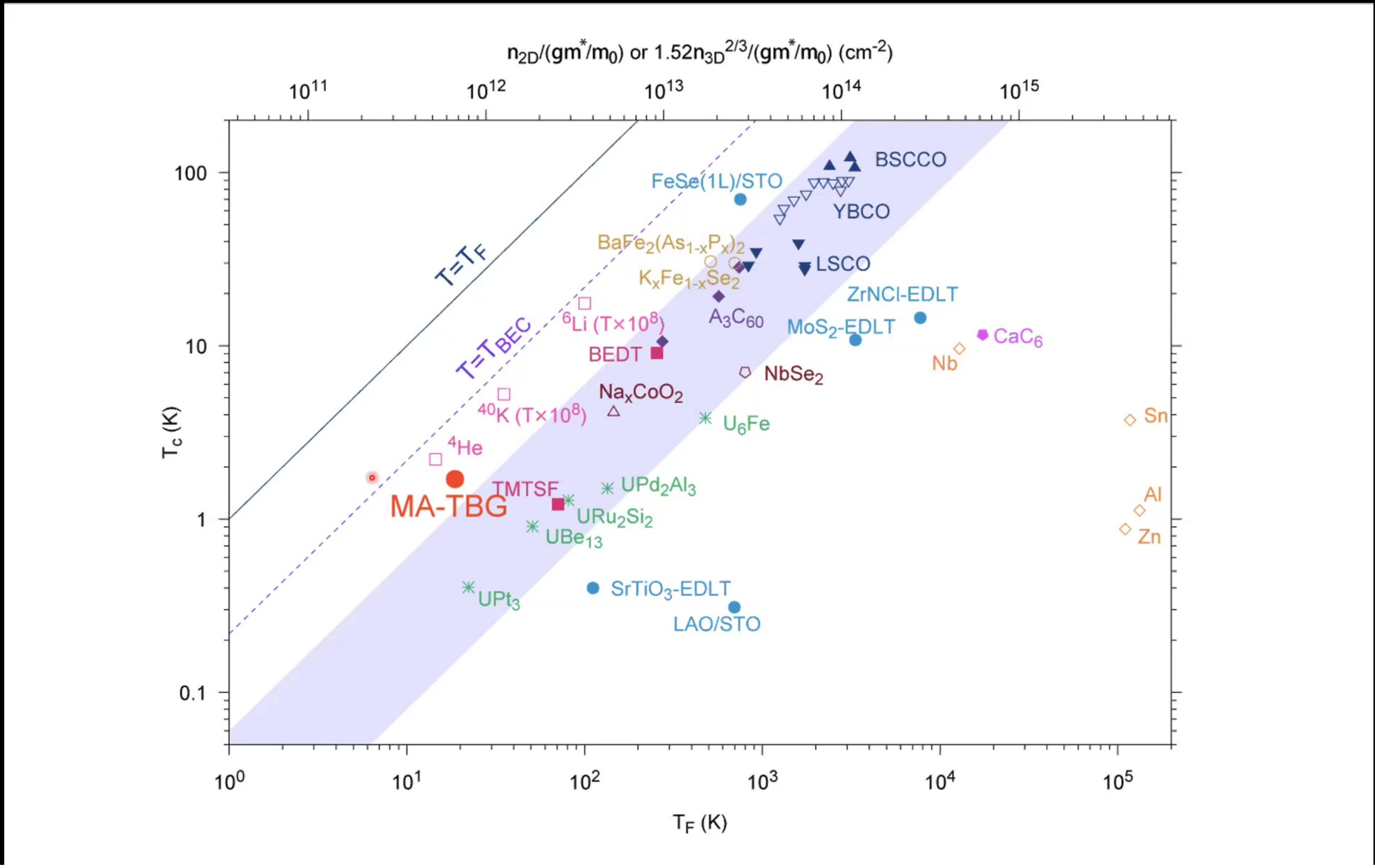


M1, θ = 1.16°
Max. T_C ~ 0.5 K

M2, θ = 1.05°
Max. T_C ~ 1.7 K !

It seems, in both cases, more “robust” dome is for hole doping (from correlated insulator state)

Strong Coupling Superconductivity



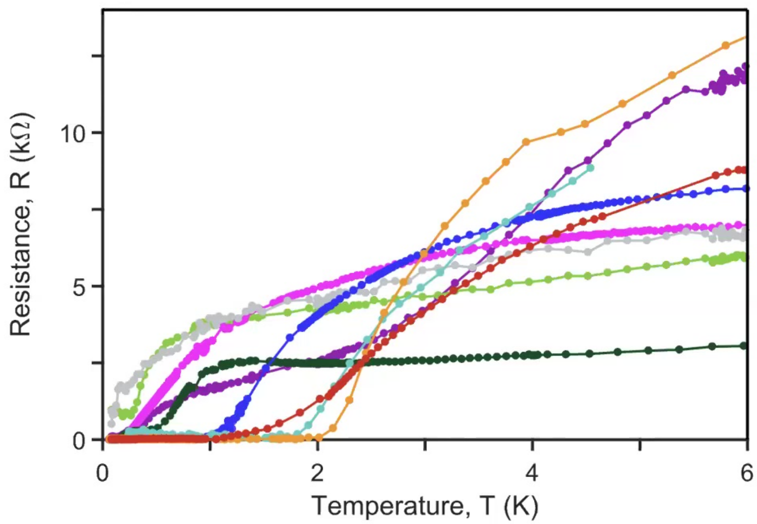
Some of the key questions…

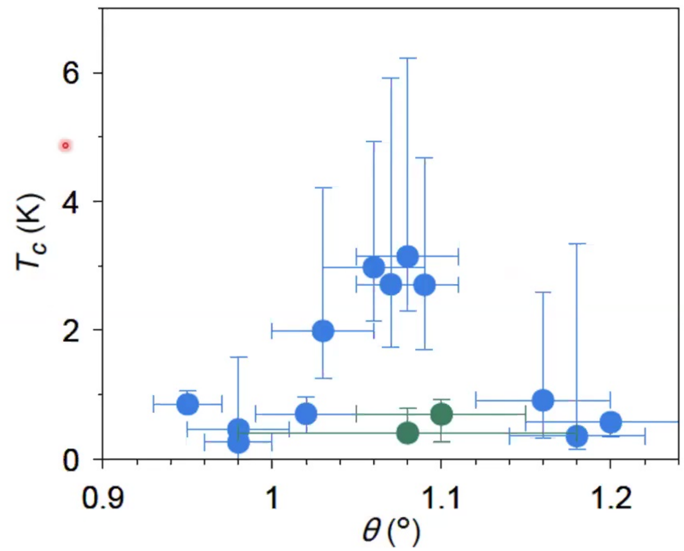
- What is the origin of correlated insulator state and what is SC order parameter?
  - Xu *et al.*, arXiv:1803.08057 -> triangular lattice, d+id chiral topological SC
  - Volovik, arXiv:1803.08799 -> route to room temp. SC
  - Yuan et al. arXiv:1803.09699 -> honeycomb lattice, special Mott state
  - Po et al. arXiv:1803.09742 -> honeycomb lattice, intervalley coherence SC
  - Roy et al. arXiv:1803.11190 -> p+ip (charge neutrality)
  - Guo et al. arXiv:1804.00159 -> triangular lattice, d+id topological SC
  - Baskaran, arXiv:1804.00627 -> Josephson moiré lattice
  - Padhi et al. arXiv:1804.01101 -> Wigner crystal melting SC
  - Irkhin et al. arXiv:1804.02236 -> Spin liquid
  - Dodaro et al. arXiv:1804.03162 -> Nematic phases
  - Huang et al. arXiv:1804.06096 -> AFM Mott and d+id chital top. SC
  - Liu et. al, arXiv: 1804.10009 -> SDW and d+id' SC
  - Xu et. al, arXiv: 1805.00478 -> Kekulé valance bond solid
  - Fidrysiak et. al., arXiv: 1805.01179 -> d+id topological SC
  - Peltonen et. al., arXiv: 1805.01039 -> unconventional BCS theory
  - Rademaker et. al., arXiv: 1805.05294 -> hole (p+ip) vs. electron (d+id)
  - Kennes et. al., arXiv: 1805.06310 -> d+id SC in competition with Mott
  - Isobe *et al.* arXiv:1805.06449 -> CDW and spin singlet SC
  - Koshino *et al.* arXiv:1805.06819 -> peculiar Wannier orbitals
  - You *et al.* arXiv:1805.06867 -> SC mediated by valley fluctuations, d+id mixed with p-ip
  - Wu et al. arXiv:1805.06906 -> weak Mott insulator / SDW order
  - Pizarro *et al.* arXiv:1805.07303 -> non-local AFM correlations
  - Wu *et al.* arXiv:1805.08735 -> phonon mediated d-wave
  - Ochi et al. arXiv:1805.09606 -> spin and valley FM insulators or Dirac semimetal states
  - Thomson et al. arXiv:1806.02837 -> triangular AFM in honeycomb lattice
  - Guinea et al. arXiv:1806.05990 -> band distortions, long range Coulomb and SC
  - Zou et al. arXiv:1806.07873 -> Emergent symmetries and Wannier obstructions
  - Gonzalez et al. arXiv:1807.01275 -> Kohn-Luttinger SC
  - Su et al. arXiv:1807.02196 -> spontaneous vortex-antivortex lattice, mixed d+id + p+ip; s+p+d
  - Lian et al. arXiv:1807.04382 -> phonon-mediated SC
  - Shekunov et al. arXiv:1807.05524 -> uniform charge instability, s+- and s++ SC

Experimental Developments since Apr 2018…

- We have reproduced our own results! (a lot more devices…)

MA-TBLG Superconducts! (New Data)





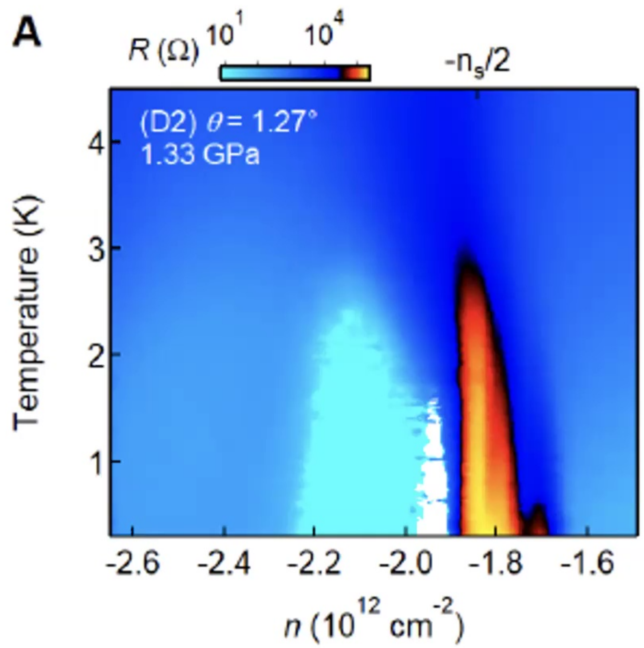
Cao, et al…PJH, arxiv.2004.04148 (2020)

See also: Yankowitz *et al.* Science (2019), and Lu *et al.* Nature (2019)

Experimental Developments since Apr 2018…

Tuning superconductivity in twisted bilayer graphene

Matthew Yankowitz[1*], Shaowen Chen[1,2*], Hryhoriy Polshyn[3*], K. Watanabe[4], T. Taniguchi[4], David Graf[5], Andrea F. Young[3†], and Cory R. Dean[1†]

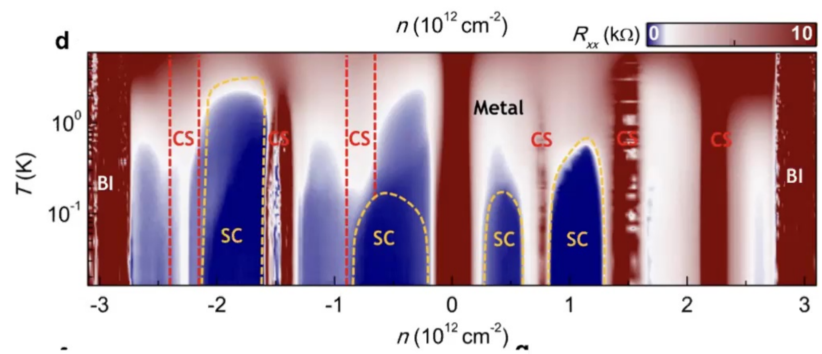


Yankowitz *et al. Science* (2019)

arXiv:1903.06513 [pdf] cond-mat.str-el cond-mat.mes-hall

Superconductors, Orbital Magnets, and Correlated States in Magic Angle Bilayer Graphene

Authors: 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



Lu *et al. Nature* (2019)

Experimental Developments since Apr 2018…

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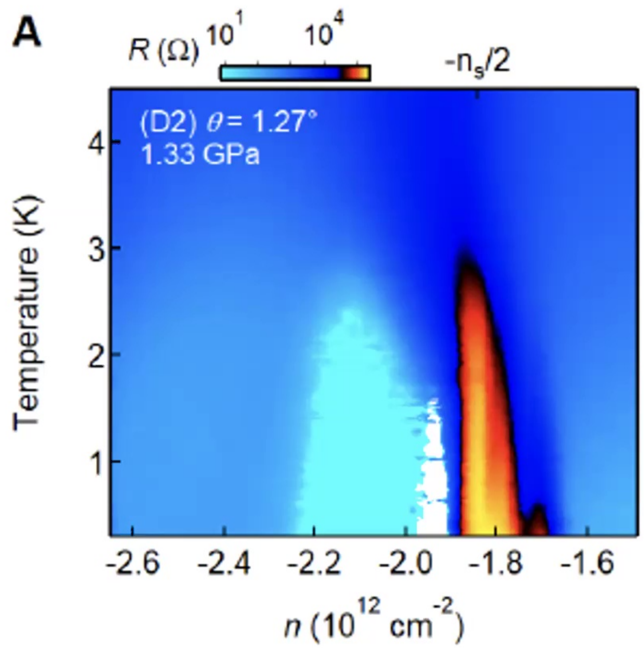

Yankowitz *et al. Science* (2019)

arXiv:1903.06513 [pdf] cond-mat.str-el cond-mat.mes-hall

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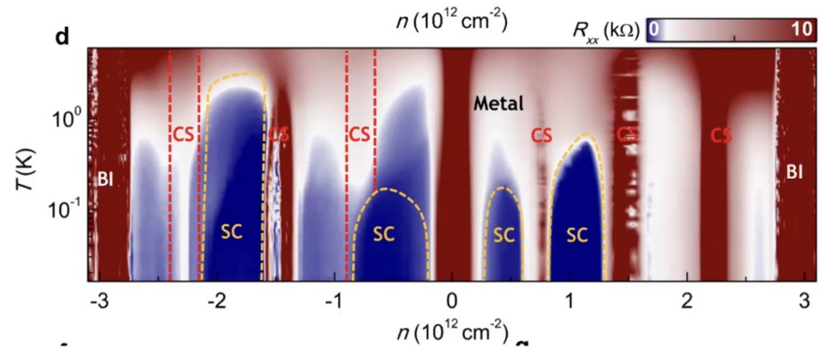


Lu *et al. Nature* (2019)

Robust superconductivity reproduced and extended by many groups (Columbia, UCSB, ICFO, Caltech, Princeton, Ohio State, Brown, ETH, Stanford, etc)

Experimental Developments since Apr 2018…

- We have reproduced our own results! (a lot more devices…)
- Many groups have independently reproduced our results… and even extended them to other systems (stay tuned!)
- Linear resistivity behavior… strange metal/Planckian physics
- Anisotropies in Hc// & Ic vs B//… nematicity in the SC state…
- Magic-Angle Twisted Bilayer-Bilayer Graphene
- Scanning probe microscopy studies
- Ferromagnetism, Anomalous Hall and Quantum Anomalous Hall physics -> Topology!

Topology & Flat Bands in Moiré Heterostructures

PHYSICAL REVIEW B **99**, 075127 (2019)

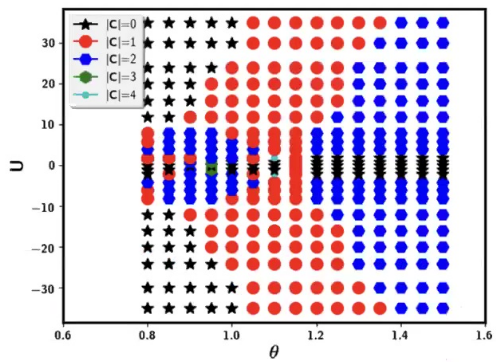
Nearly flat Chern bands in moiré superlattices

Ya-Hui Zhang, Dan Mao, Yuan Cao, Pablo Jarillo-Herrero, and T. Senthil*
artment of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

TABLE I. Chern number $|C|$ of conduction/valence bands for twisting graphene/h-BN ($\Delta_0 = 0$) and graphene/graphene systems ($\Delta_0 \lesssim 2$ meV).

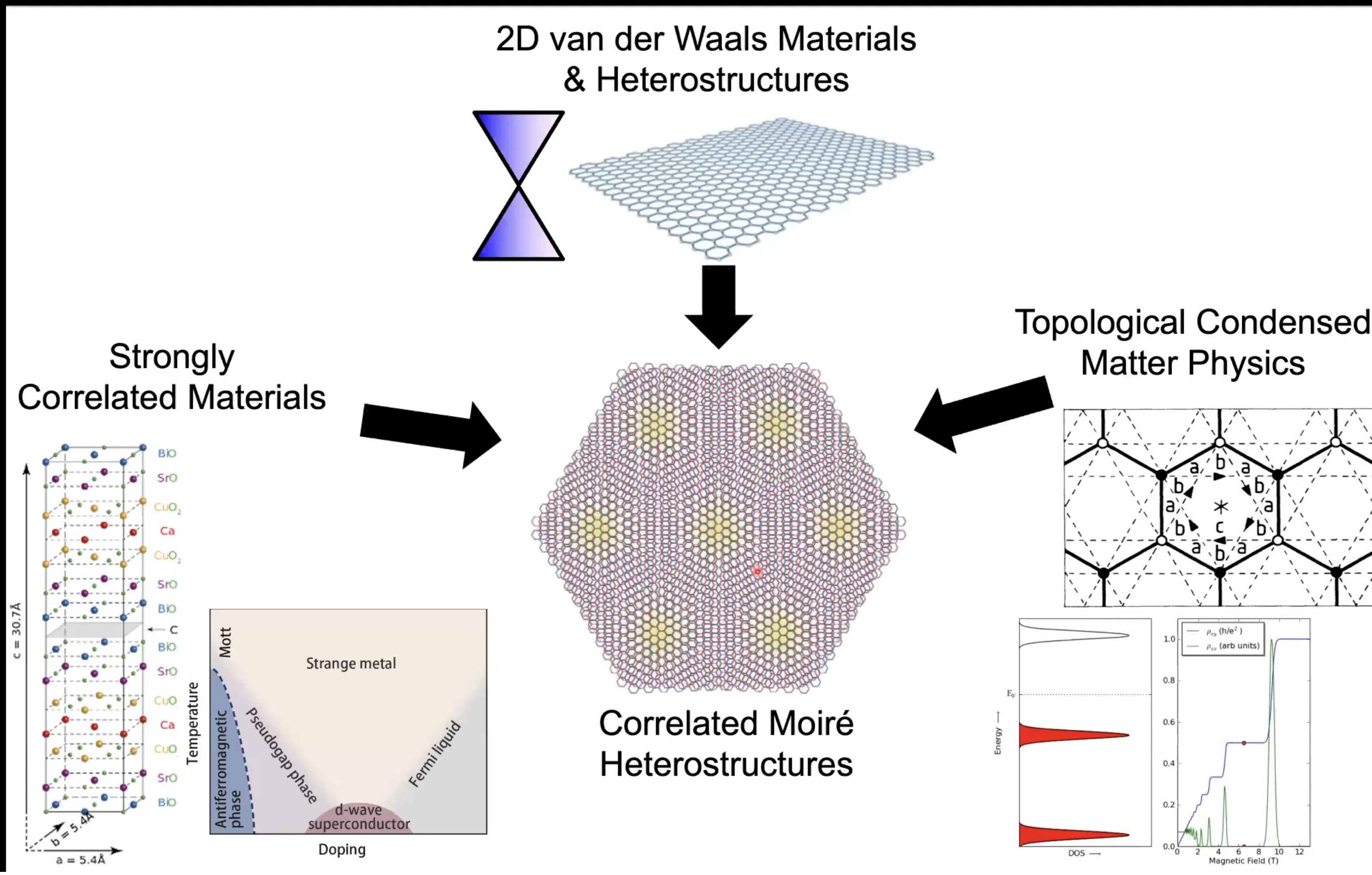
Systems	$U < -\Delta_0$	$U > \Delta_0$
BG/h-BN, valence	0	2
TG/h-BN, valence	0	3
BG/h-BN, conduction	2	0
TG/h-BN, conduction	3	0
BG/BG	2	2
TG/TG	3	3
TG/BG, conduction	2	3
TG/BG, valence	3	2

by 1. The phase diagram for the BG/BG system is shown



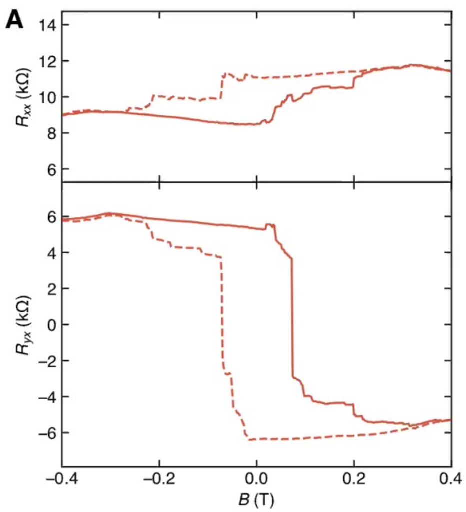
Related theory work:
- Po et al. PRX 8, 031089 (2018).
- Lian et al. arXiv:1811.11786 (2018)
- Bultinck et al., arXiv:1901.08110 (2019)
- Ya-Hui Zhang, arXiv:1901.08209 (2019)

Correlated Moiré Heterostructures -> merging of modern condensed matter communities



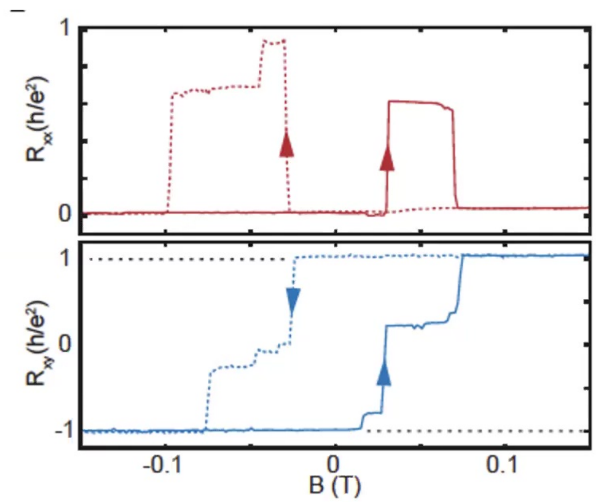
Ferromagnetism, (quantum) anomalous Hall effect: magic-angle graphene aligned to hBN

Large Anomalous Hall Effect



Sharpe et al. *Science* (2019)

Quantized Anomalous Hall Effect



Serlin et al. Science (2020)

See also experiment in ABC/hBN: Chen et al. *et al. Nature* (2020)*;*

Theory:
- Ya-Hui Zhang et al. Phys. Rev. B 99, 075127 (2019)
- Bultinck et al., arXiv:1901.08110 (2019)
- Ya-Hui Zhang, arXiv:1901.08209 (2019)

Experimental Developments since Apr 2018…

- We have reproduced our own results! (a lot more devices…)
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- Anisotropies in Hc// & Ic vs B//… nematicity in the SC state…
- Magic-Angle Twisted Bilayer-Bilayer Graphene
- Scanning probe microscopy studies
- Ferromagnetism, Anomalous Hall and Quantum Anomalous Hall physics -> Topology!
- Second robust "Moiré Superconductor"… Magic Angle Twisted Trilayer Graphene (lots more surprises to come!)

Published a few weeks ago!… *Moiré Magic 3.0*

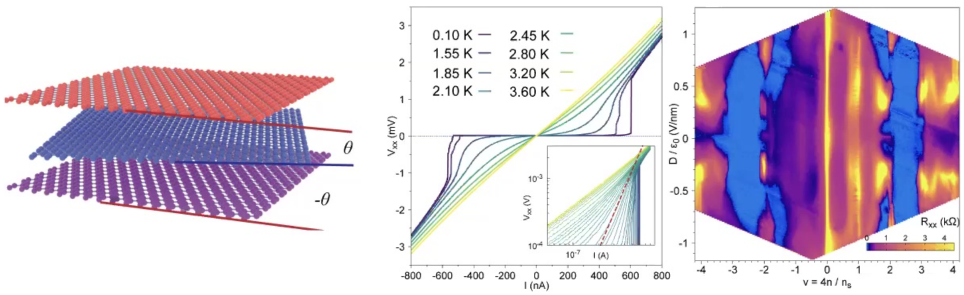
nature

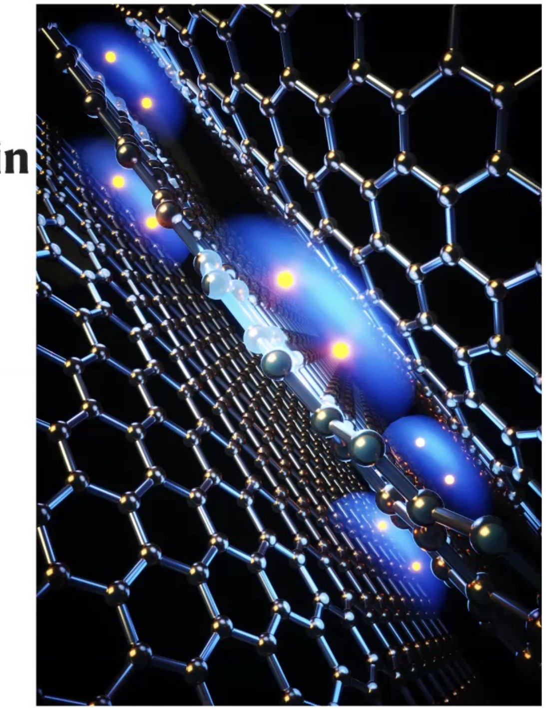
Article | Published: 01 February 2021

DOI
https://doi.org/10.1038/s41586-021-03192-0

Tunable strongly coupled superconductivity in magic-angle twisted trilayer graphene

Jeong Min Park, Yuan Cao, Kenji Watanabe, Takashi Taniguchi & Pablo Jarillo-Herrero





Science

Science 04 Feb 2021:
eabg0399
DOI: 10.1126/science.abg0399

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REPORT

Electric field tunable superconductivity in alternating twist magic-angle trilayer graphene

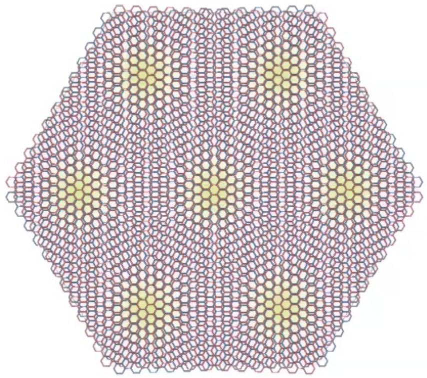
Zeyu Hao[1,*], A. M. Zimmerman[1,*], Patrick Ledwith[1], Eslam Khalaf[1], Danial Haie Najafabadi[1], Kenji Watanabe[2], Takashi Taniguchi[3], Ashvin Vishwanath[1], Philip Kim[1,†]

The Magic of Moiré Quantum Matter

Correlated Insulators
(MATBG, ABC/hBN, Twisted Bi-Bi,
TMD moiré heterostructures, etc)

Superconductivity
(MATBG, MATTG,
possibly others)

Topological Phases
(MATBG, MATBG/hBN,
ABC/hBN, Twisted Bi-Bi,
Twisted Mono-Bi, etc))



Magnetism
(MATBG/hBN, ABC/hBN,
Twisted Mono-Bi)

Nematicity
(MATBG)

Moiré Ferroelectricity?

Fresh from a couple months ago: "Moiré" Ferroelectricity

arXiv:2010.05182 [pdf] cond-mat.mes-hall

Interfacial Ferroelectricity by van-der-Waals Sliding

Authors: Maayan Vizner Stern, Yuval Waschitz, Wei Cao, Iftach Nevo, Kenji Watanabe, Takashi Taniguchi, Eran Sela, Michael Urbakh, Oded Hod, Moshe Ben Shalom

arXiv:2010.06600 [pdf] cond-mat.mes-hall cond-mat.mtrl-sci

Stacking-engineered ferroelectricity in bilayer boron nitride

Authors: Kenji Yasuda, Xirui Wang, Kenji Watanabe, Takashi Taniguchi, Pablo Jarillo-Herrero

arXiv:2010.06914 [pdf] cond-mat.mes-hall

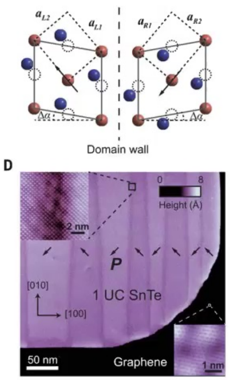
Charge-polarized interfacial superlattices in marginally twisted hexagonal boron nitride

Authors: C. R. Woods, P. Ares, H. Nevison-Andrews, M. J. Holwill, R. Fabregas, F. Guinea, A. K. Geim, K. S. Novoselov, N. R. Walet, L. Fumagalli

See also related work: McGilly et al. Nature Nanotechnology **15**, 580 (2020)

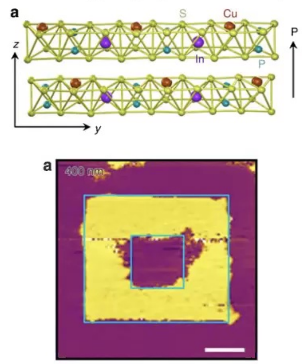
2D Ferroelectrics

SnTe, SnSe (in-plane)



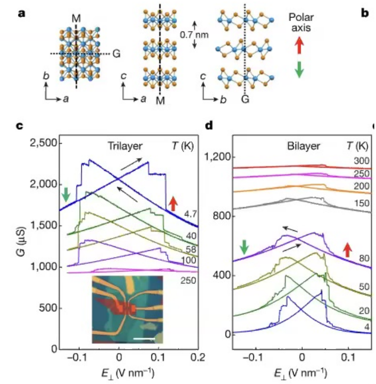
K. Chang *et al.*, *Science* **353**, 274 (2016).

$CuInP_2S_6$ (out-of-plane)



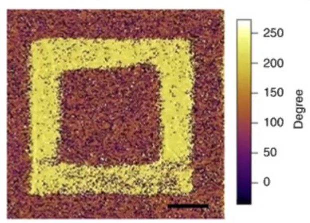
F. Liu *et al.*, *Nat. Commun.* **7**, 12357 (2016).

WTe_2 (out-of-plane)



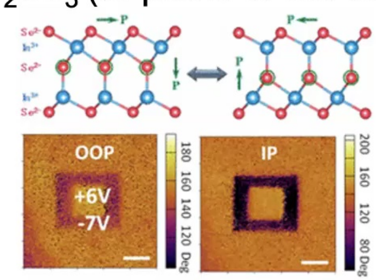
F. Liu *et al.*, *Nature*. **560**, 336 (2018).

$MoTe_2$ (out-of-plane)



F. Yuan *et al.*, *Nat. Commun.* **10**, 1775 (2019).

In_2Se_3 (in-plane & out-of-plane)

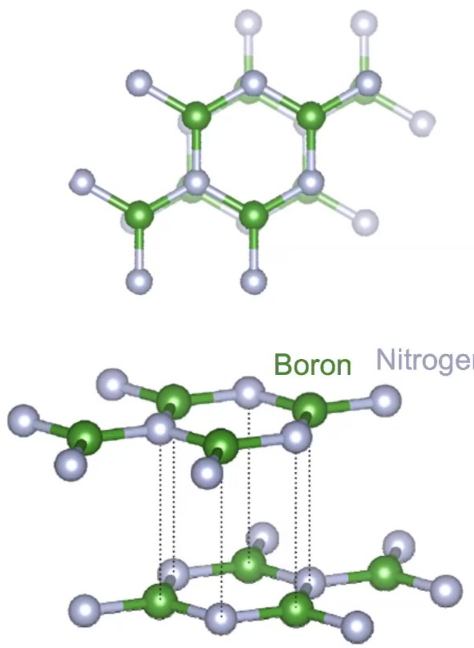


C. Cui *et al.*, *Nano Lett.* **18**, 1253 (2018).

Ferroelectric 2D materials obtained by exfoliating bulk polar materials

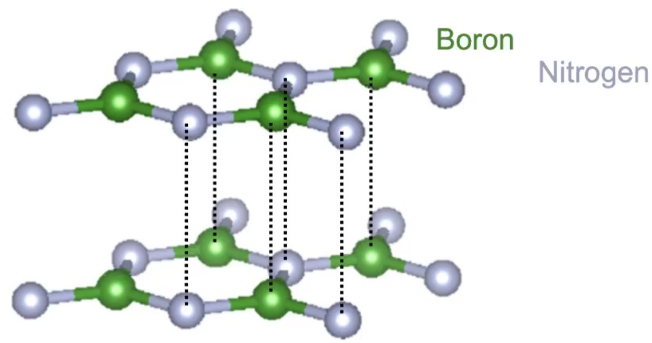
Bulk bilayer hBN versus “parallel stacked” bilayer hBN

AA’ stacking (bulk hBN)
Centrosymmetric



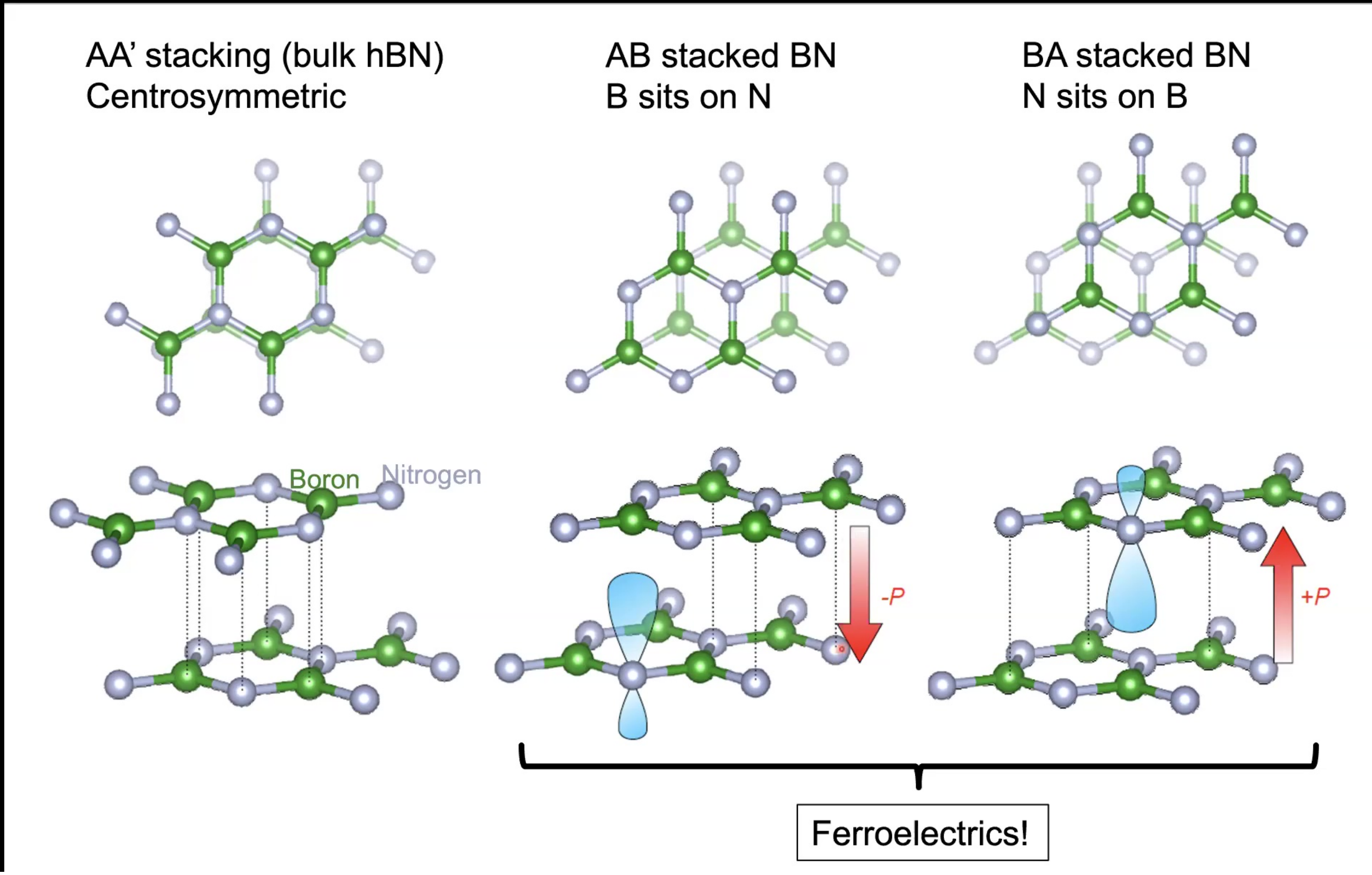
Natural stacking has hBN layer “2” rotated by 180º on top of Layer “1”

Parallel stacked bilayer hBN
Non-Centrosymmetric

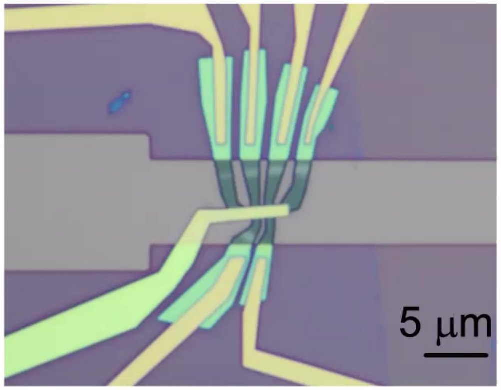


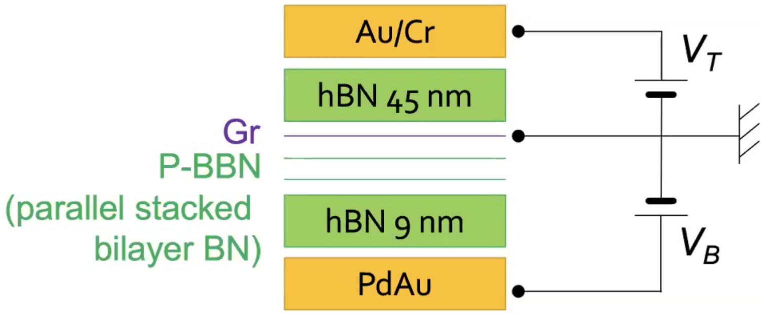
Parallel stacking has hBN layer “2” non-rotated (0º) on top of Layer “1”

Stacking engineered ferroelectricity in bilayer hBN

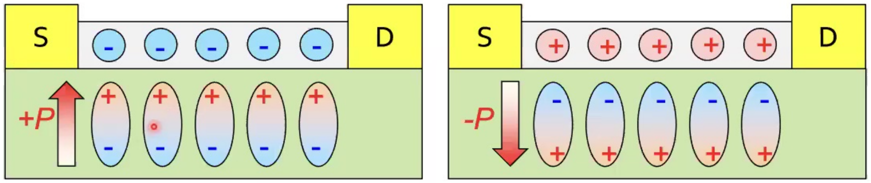


Bilayer hBN based Graphene Ferroelectric FET





Ferroelectric field effect transistor (FeFET)



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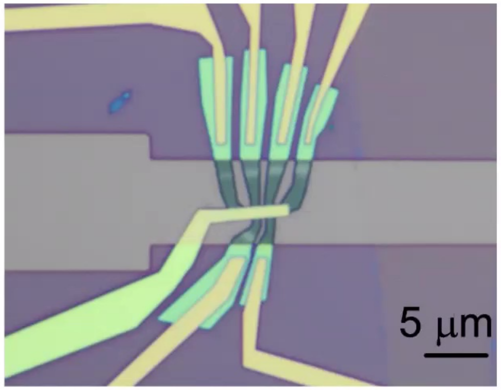

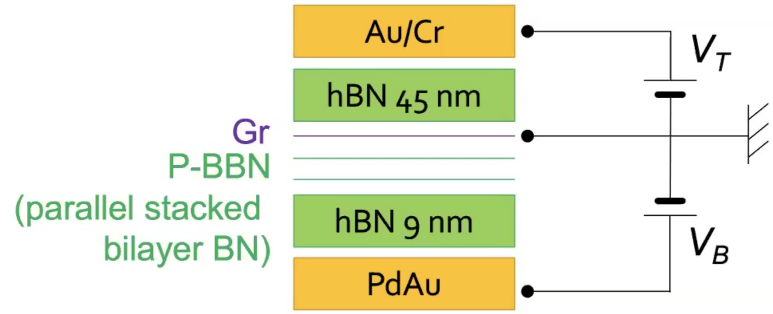

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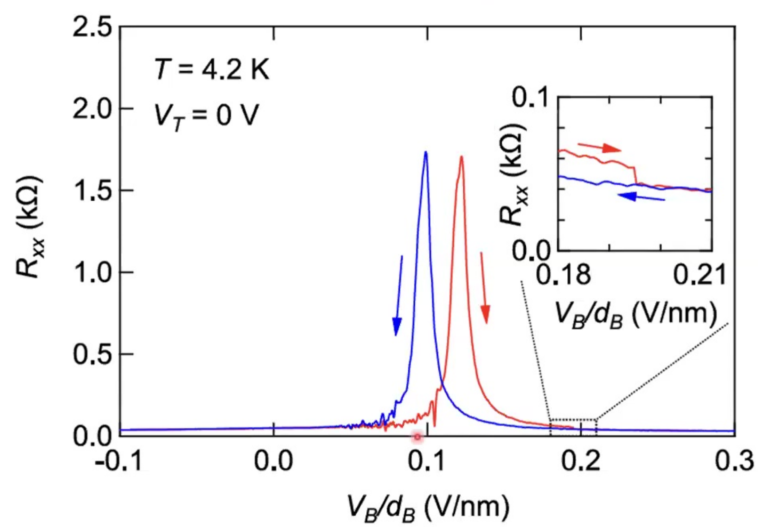
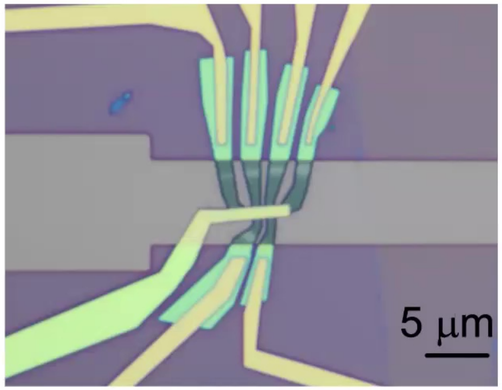
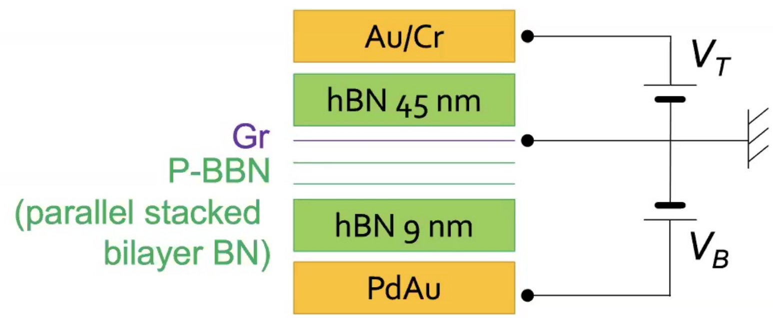


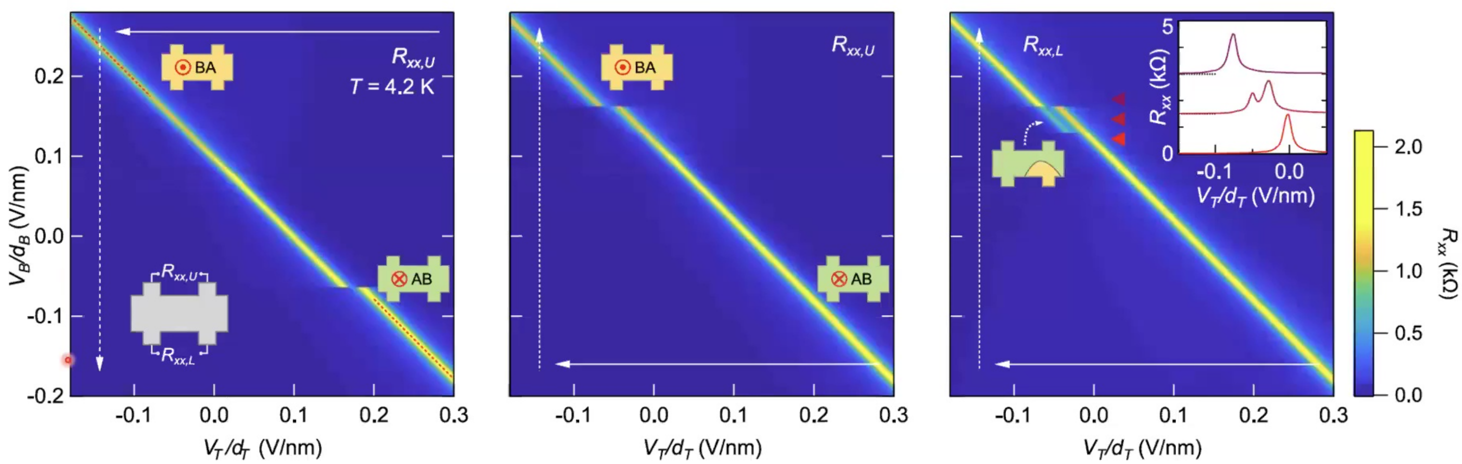
Yasuda, Wang, et al.,.., PJH, arXiv:2010.06600 (2020)

Bilayer hBN based Graphene Ferroelectric FET



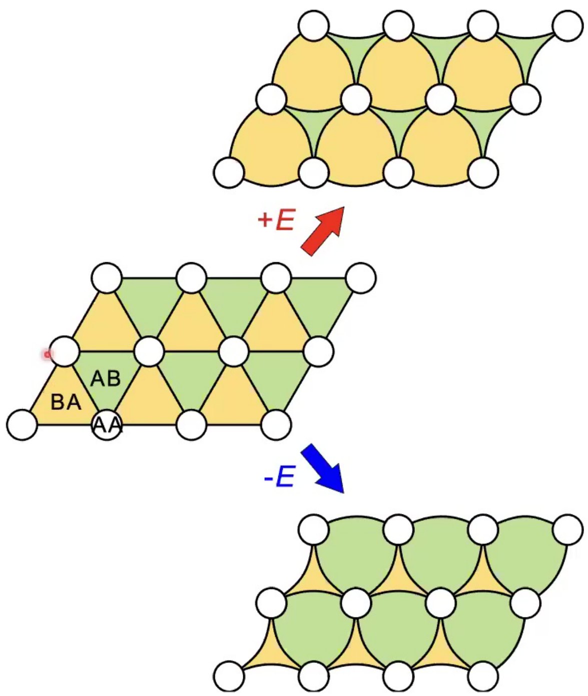


Ferroelectric field effect transistor (FeFET)

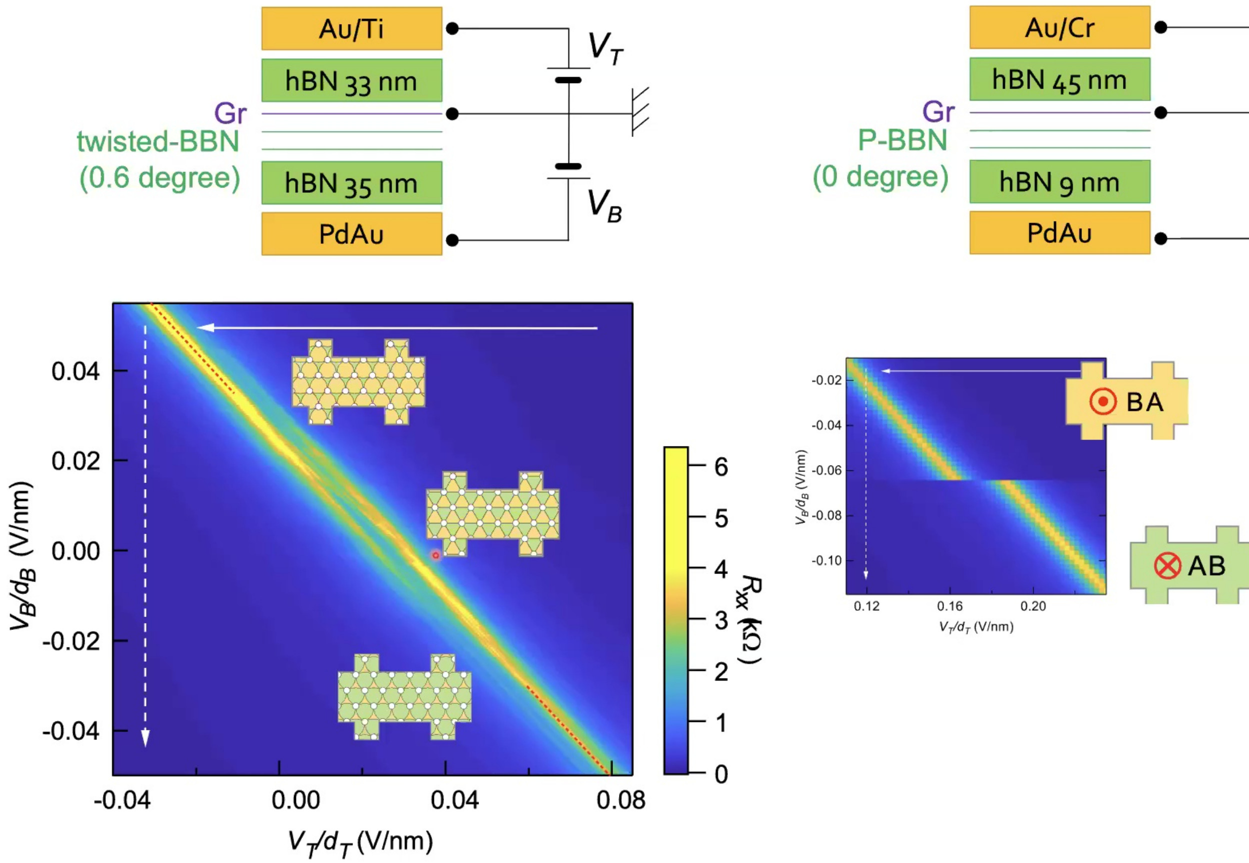


Moiré Ferroelectric switching in twisted bilayer hBN

Parallel stacking with a small twist angle generates a moiré pattern with AB/BA domains

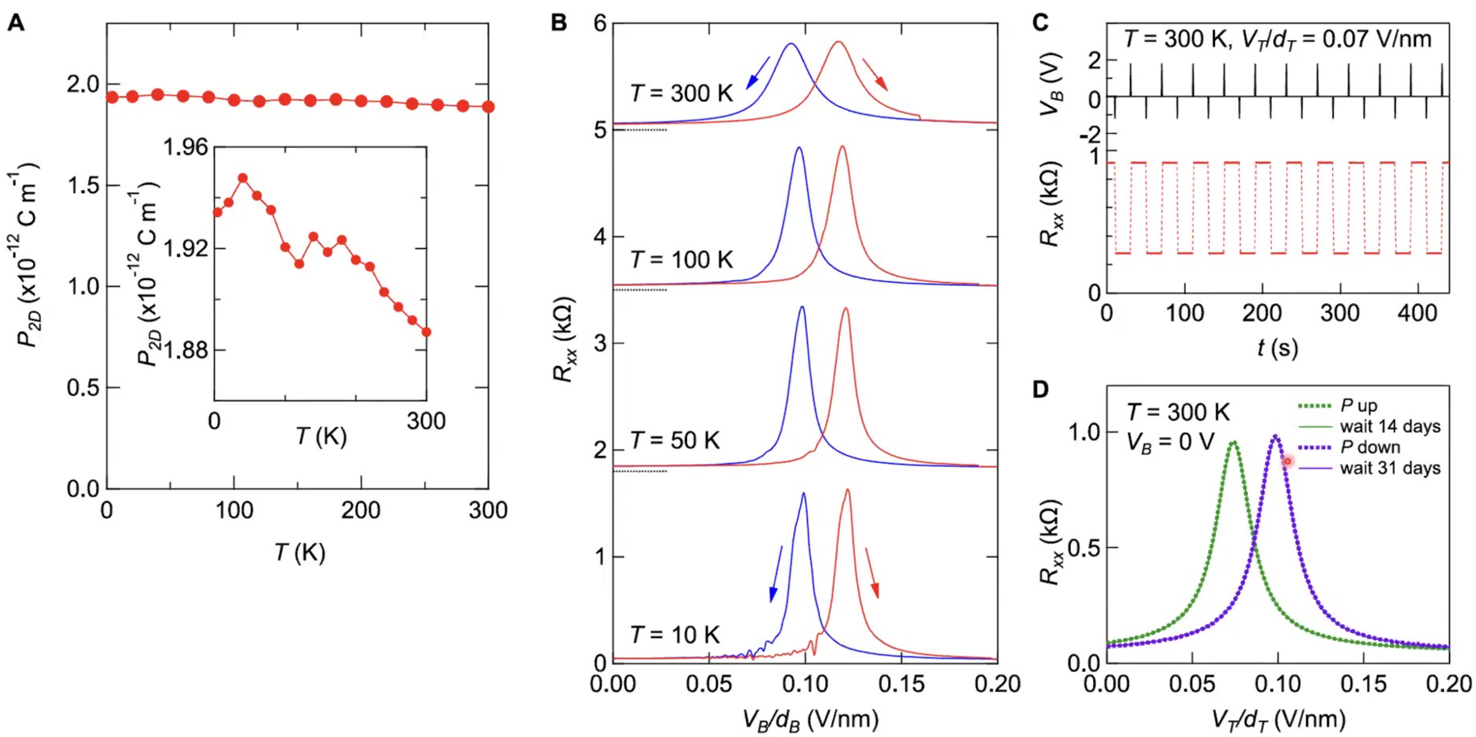


Ferroelectric switching in twisted bilayer hBN



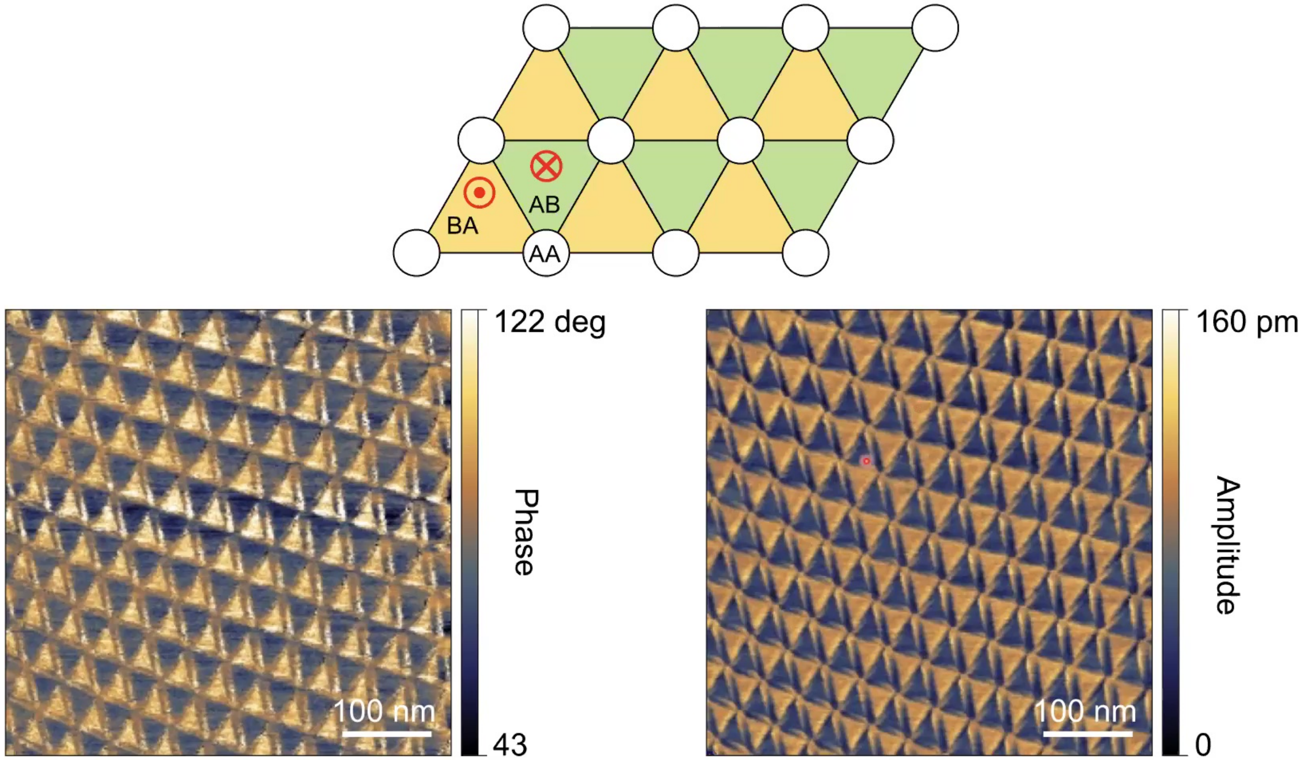
Much gradual switching in twisted bilayer BN

Robust Room Temperature Operation



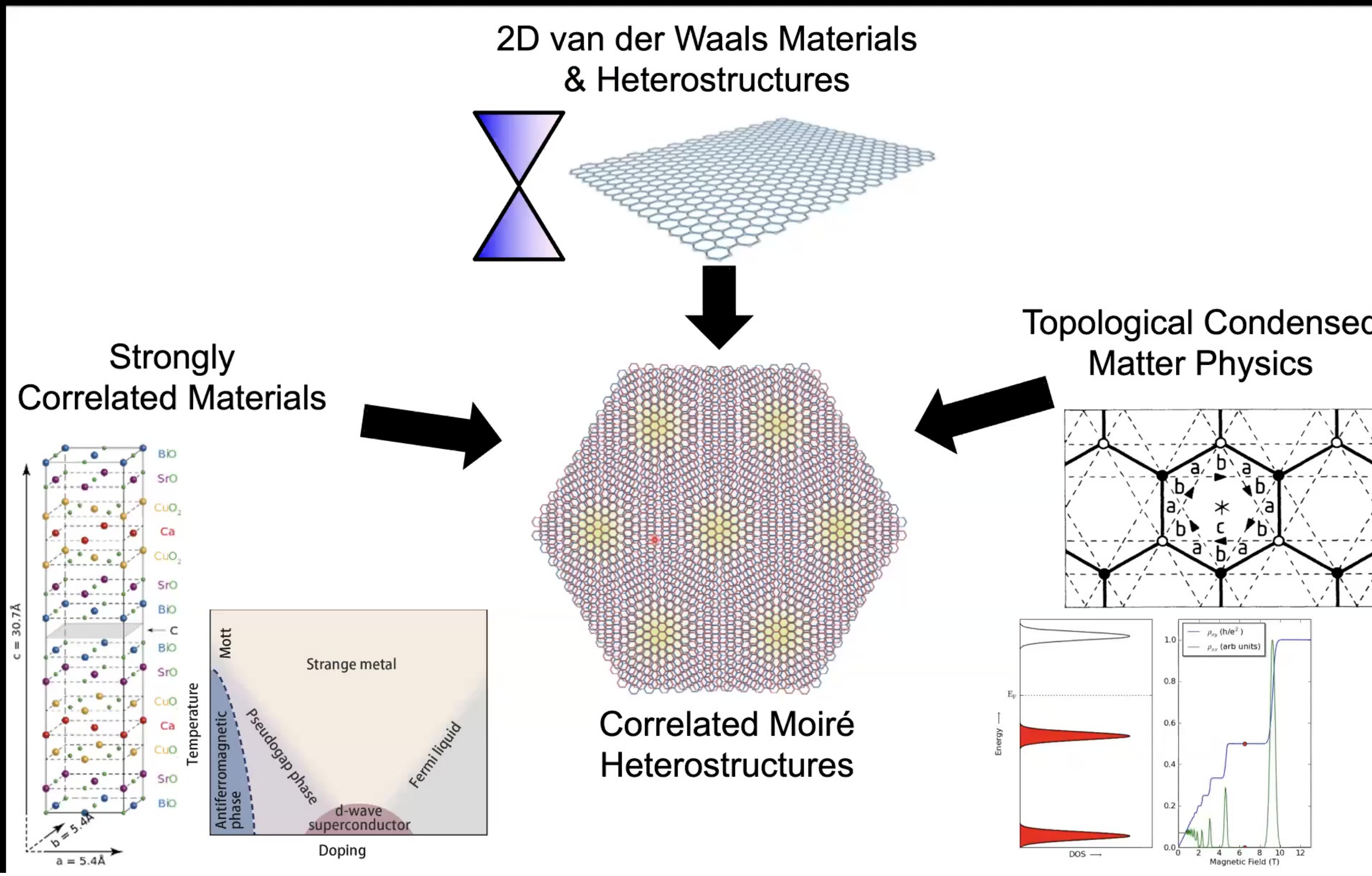
Yasuda, Wang, et al.,.., PJH,
arXiv:2010.06600 (2020)

Direct Imaging of Ferroelectricity: vertical Piezoelectric Force Microscopy



Similar images:: Stern et al. arxiv:2010.05182 (2020); Woods et al. arxiv:2010.06914(2020)
See also related work McGilly et al. Nature Nanotechnology **15**, 580 (2020)

Correlated Moiré Heterostructures -> merging of modern condensed matter communities



Acknowledgements

Yuan Cao | Daniel Rodan-Legrain | Jane Park | Kenji Yasuda | Xirui Wang

Jarillo-Herrero Extended Group (Paella Dinner!)

MIT: Valla Fatemi, Jason Luo, Javier Sanchez-Yamagishi, Oriol Rubies-Bigorda, Ahmet Demir, Spencer Tomarken, Ray Ashoori, Fanqi Noah Yuan, Liang Fu, Debanjan Chowdury, Senthil Todadri.

Harvard: Shiang Fang, Efthimios Kaxiras

Weizmann: Uri Zondiner, Asaf Rozen, Raquel Queiroz, Yuval Oreg, Ady Stern, Erez Berg, Shahal Ilani

NIMS (Japan): Kenji Watanabe, Takashi Taniguchi

Funding & Support

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NSF

CIQM NSF DMR-1231319

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