Chair of Experimental Solid State Physics, LMU Munich

Transport properties of Magic Angle Twisted Bilayer Graphene

Dmitri K. Efetov

Capri 11/5/2022

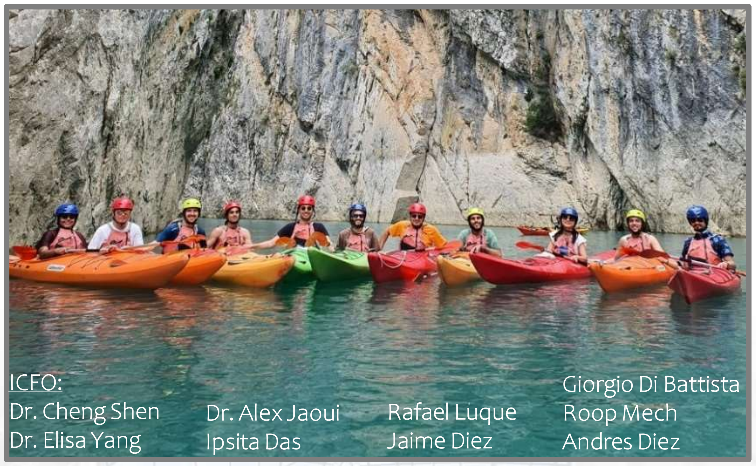
Chair of Solid State Physics

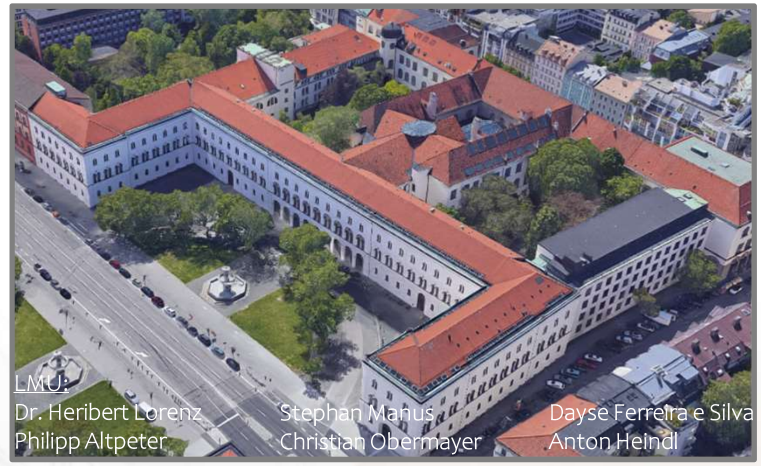
Outline

1. Introduction to 2D materials and vdW heterostructures
2. Low temperature transport measurements and twist-angle extraction
3. Correlated insulators and SU(4) symmetry breaking
4. Chern insulators
5. Orbital magnetism
6. Superconductivity
7. Screening
8. Gate induced Josephson junctions
9. Strange metal phase
10. Reentrant correlated insulators at one magnetic flux quantum
11. Thermal conductivity in the superconducting state

Chair of Experimental Solid State Physics @ LMU

ICFO Barcelona → LMU Munich





Collaborations

UT Austin
A. MacDonald

MIT
L. Levitov

Princeton
A. Bernevig

Harvard
A. Vishnawanth

HKUST
K. T. Law

Regensburg
S. Ganichev

Weizmann
E. Zeldov

Geneva
F. Baumberger

Funding

erc European Research Council

QUANTUM FLAGSHIP

European Commission

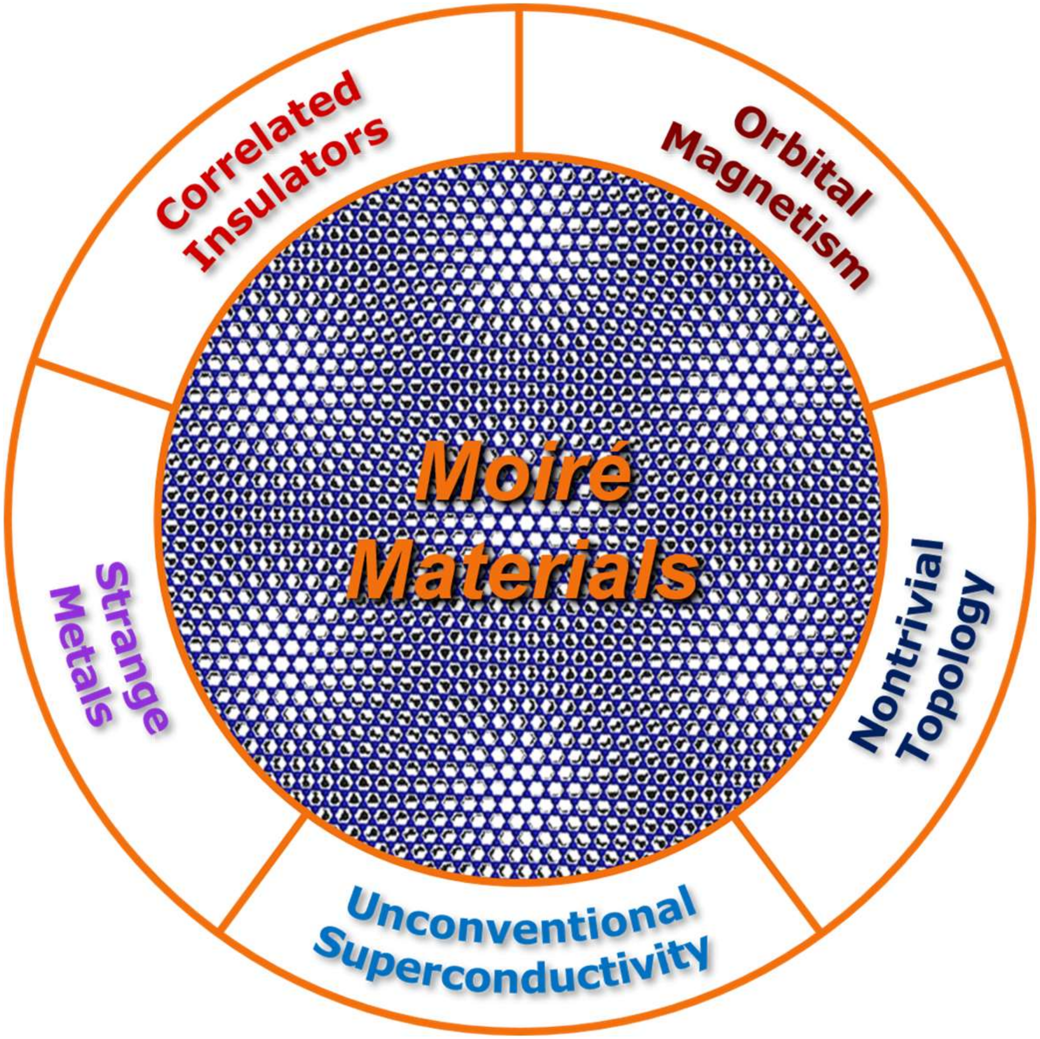
DFG

Munich Quantum Valley

MCQST

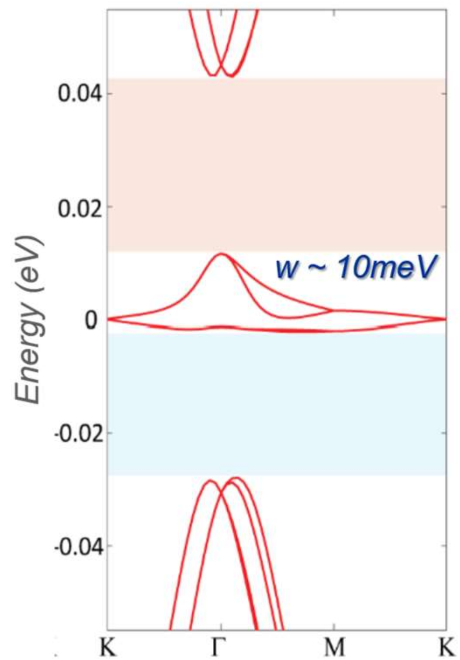
MUNICH QUANTUM CENTER

New platform for strongly correlated physics



Flat-bands in tBLG

Spin/valley degenerate flat bands:

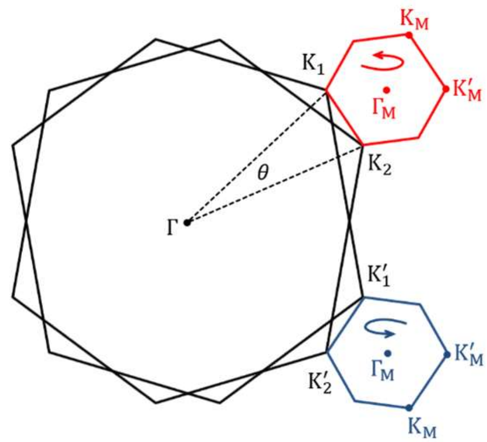


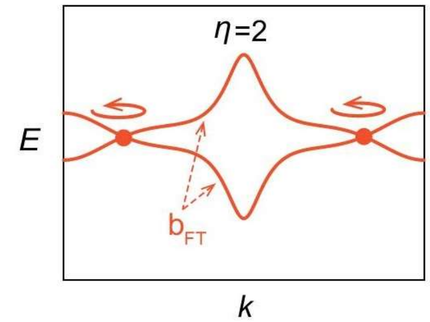
Continuum model calculations
(Bistritzer/MacDonald) + corrugations/strain

H. Yoo, … , E. Kaxiras, P. Kim, **Nature Materials 18, 448 (2019).**

and many many others.

Non-zero helicity η = 2:



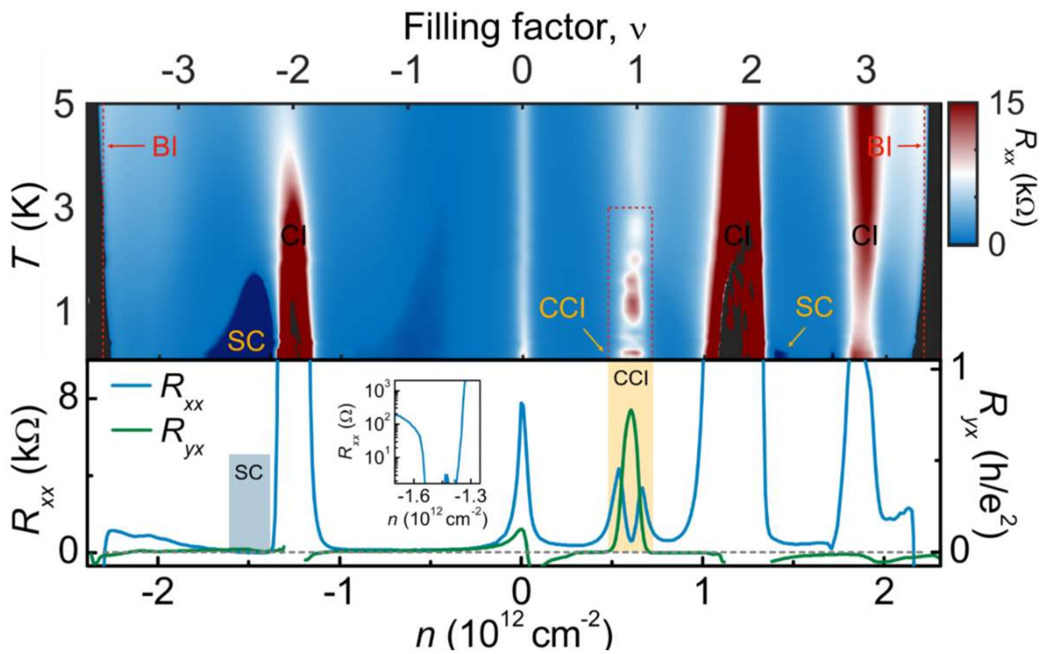


- *Spin/valley degeneracy 4e/uc*
- *Mini-BZs decoupled*
- *No localized Wannier functions → Chern bands*
- *Interactions can break C_2T symmetries*

Bernevig group **(2018).**
MacDonald group **(2019).**
Fu group **(2018).**
Vishnawanth group **(2018).**
Zaletel group **(2018).**
Todadri group **(2019).**

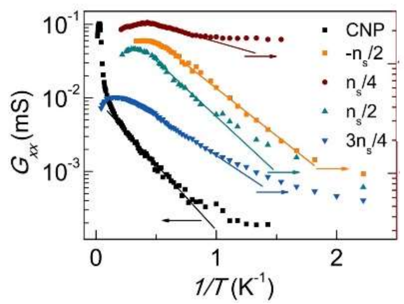
- ***quenched kinetic energy – t***
- ***dominant interaction energy – U***
- ***topological Chern bands***

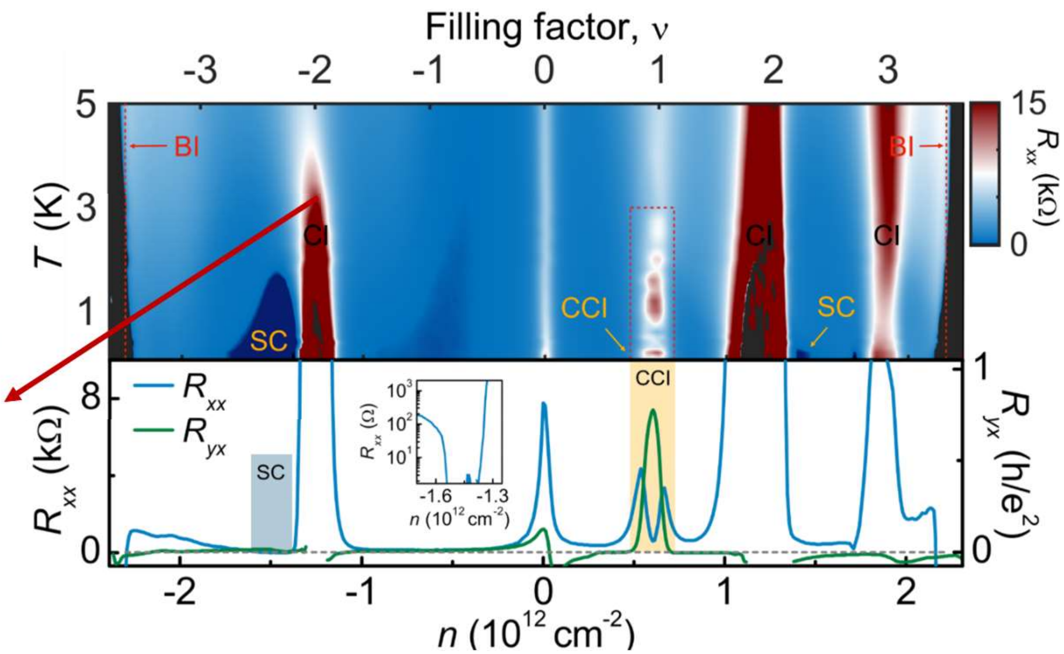
Magic angle twisted bilayer graphene - Phase diagram



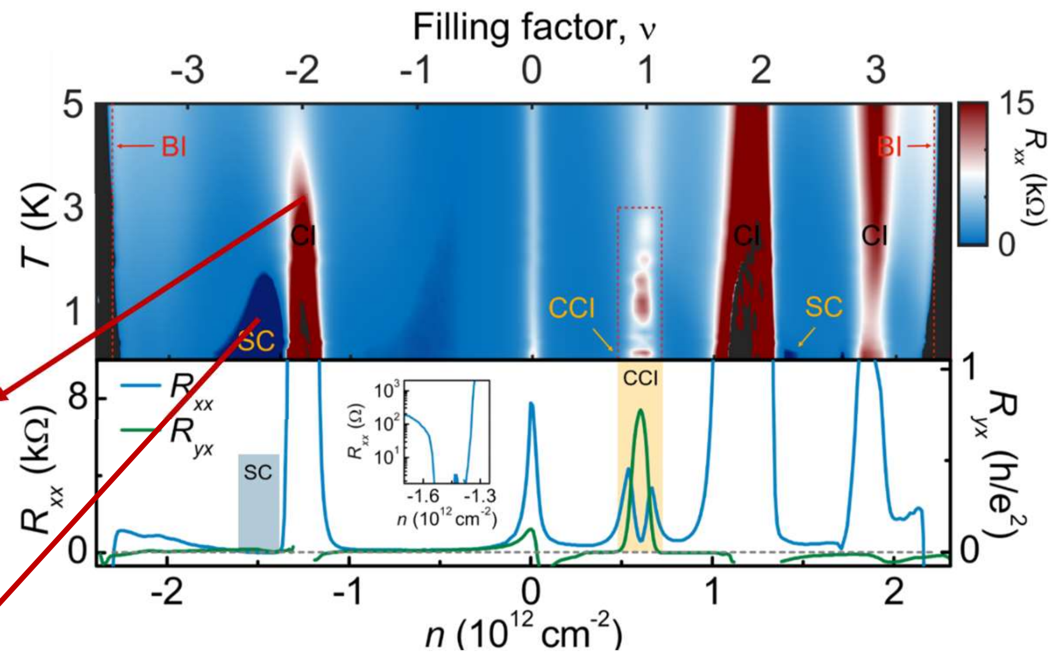
Magic angle twisted bilayer graphene - Phase diagram

Correlated Insulators:

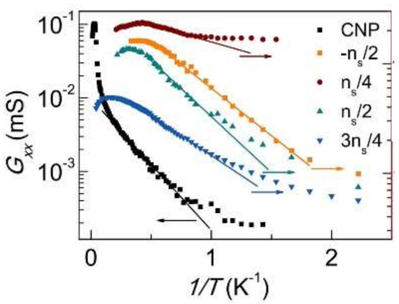




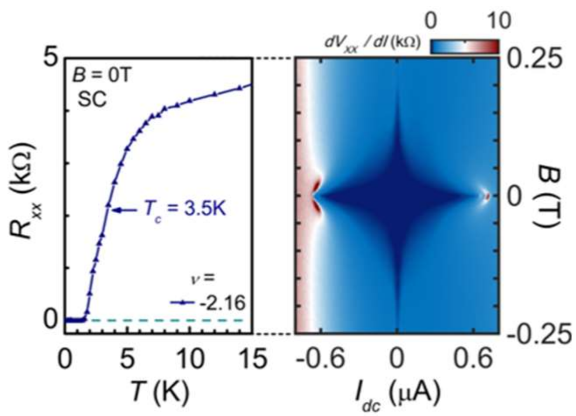
Magic angle twisted bilayer graphene - Phase diagram



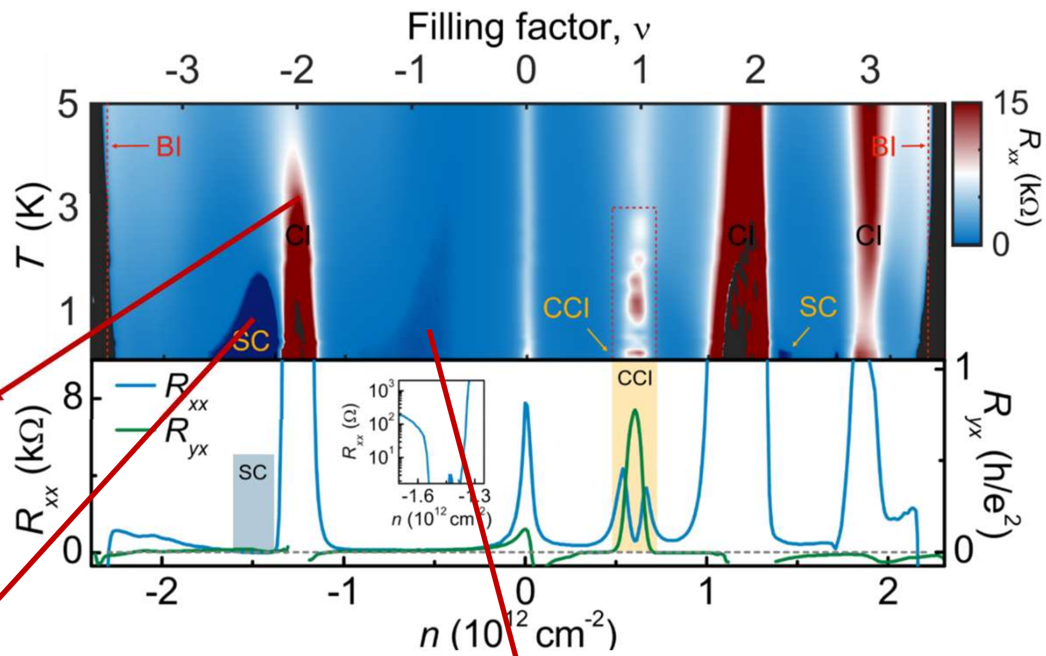
Correlated Insulators:



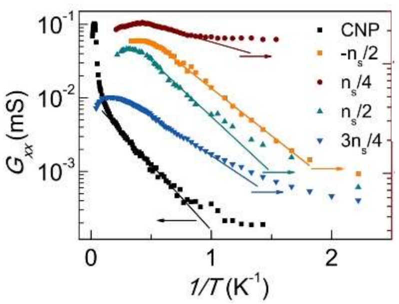
Superconductivity:



Magic angle twisted bilayer graphene - Phase diagram



Correlated Insulators:



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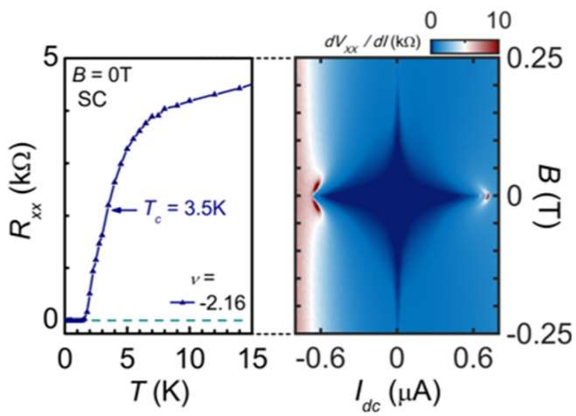
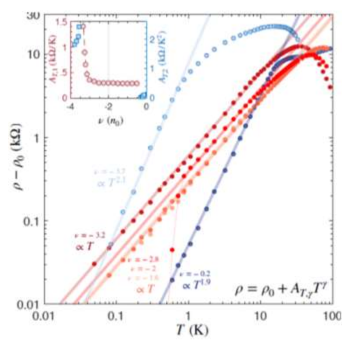


Strange metal:



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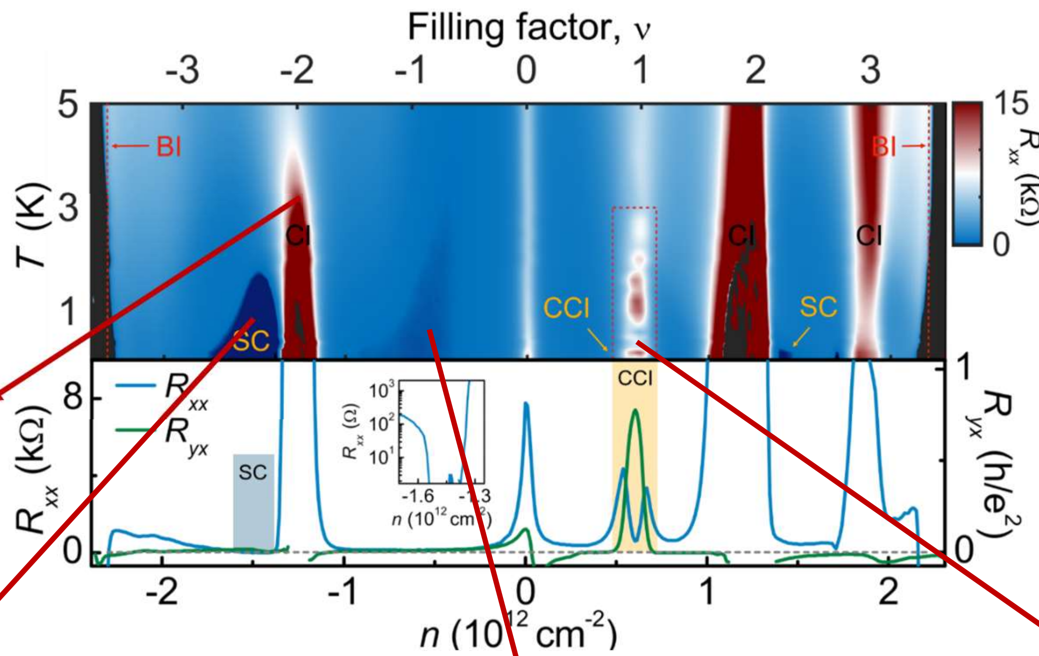
LMU Chair of Solid State Physics

Magic angle twisted bilayer graphene - Phase diagram



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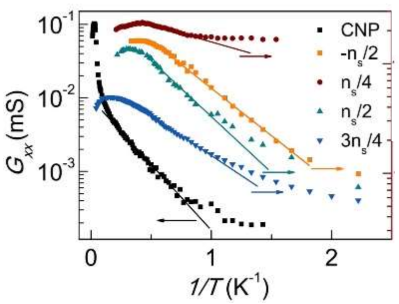
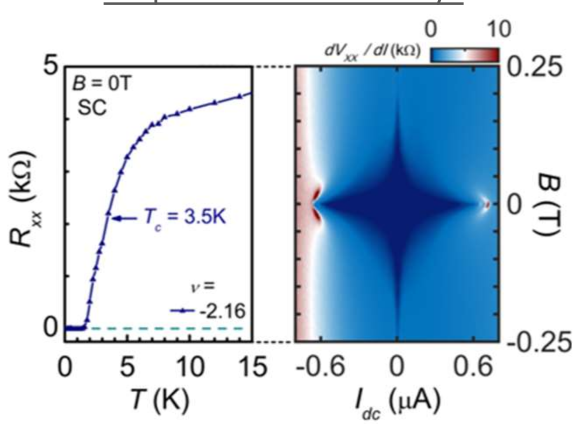


Superconductivity:



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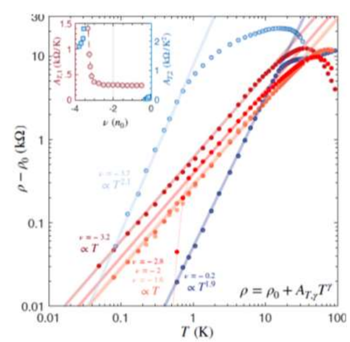
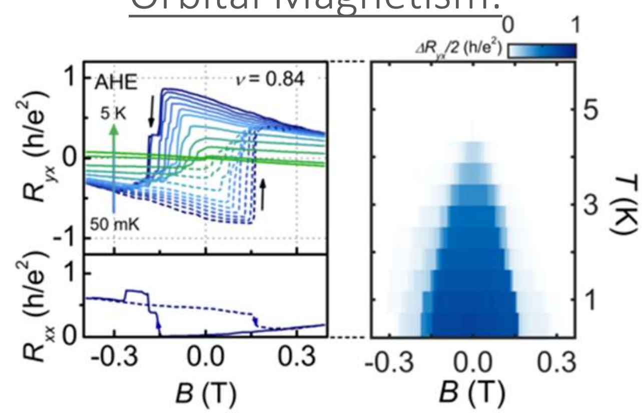


Orbital Magnetism:



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Magic angle twisted bilayer graphene - Phase diagram

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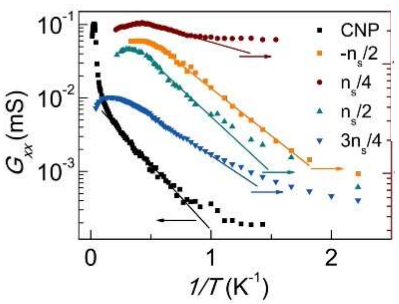
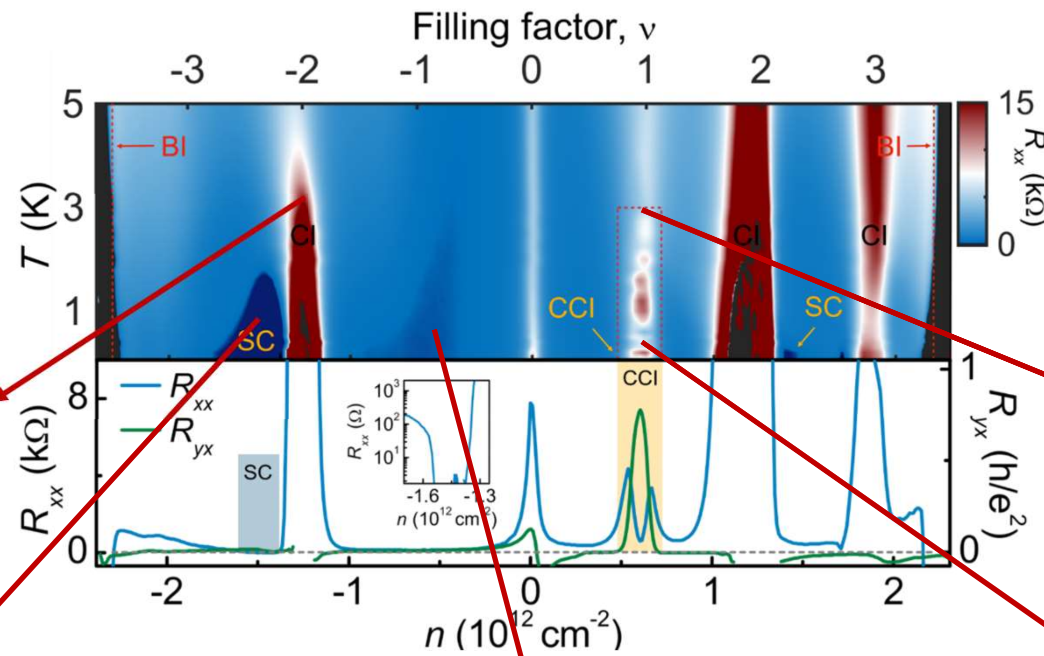
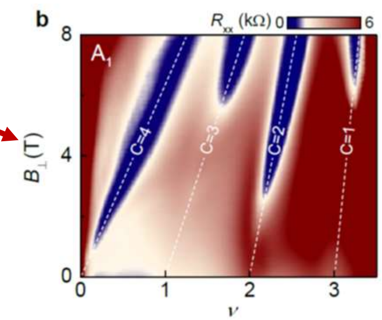
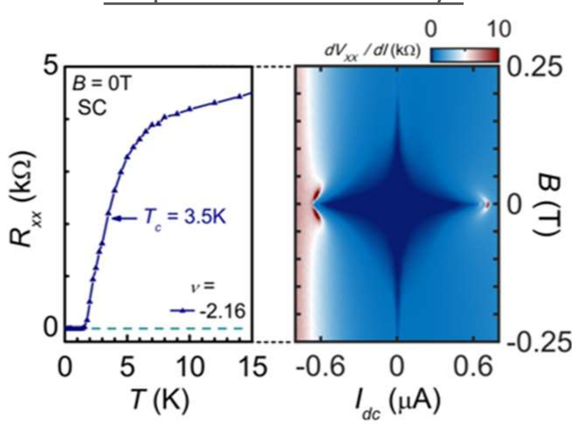




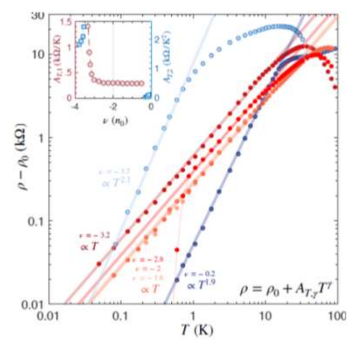
Chern Insulators:



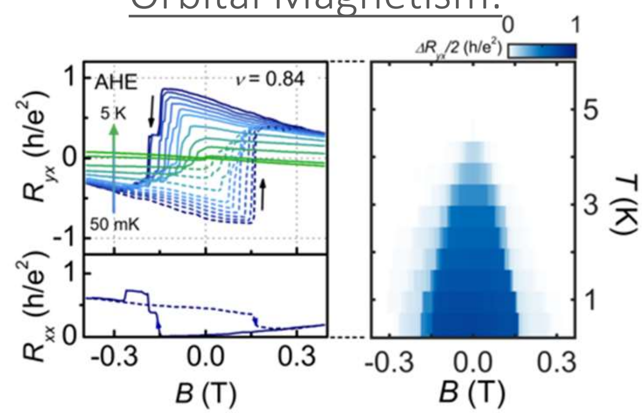
Superconductivity:



Strange metal:



Orbital Magnetism:



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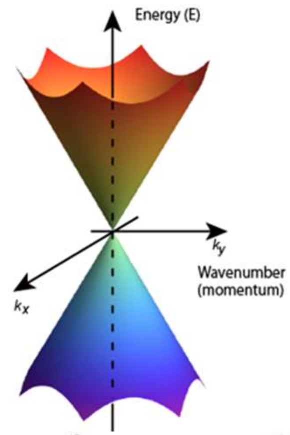
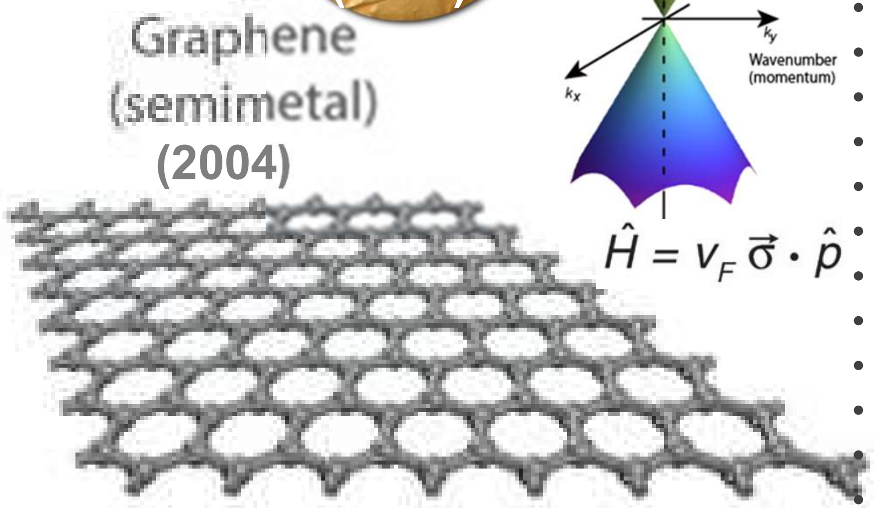
Advent of graphene and 2D van der Waals materials

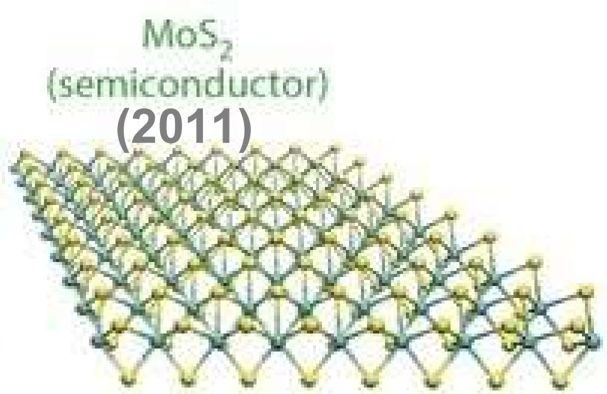


$$\hat{H} = v_F \vec{\sigma} \cdot \hat{p}$$



<u>*Record properties of graphene :*</u>

- *Thinnest imaginable material → **one atom thick***
- *Highest surface area → **2630 m^2/g***
- *Transparent to light → **97.7 %***
- *Ultra-broadband absorbtion → **uV - THz***
- *Stiffest material → **1 TPa***
- *Strongest material → **130GPa***
- *Most stretchable material → **20%***
- *Record thermal conductivity → **6000 W/mK***
- *Highest current density at RT → **10^6 > copper***
- *Highest intrinsic mobility → **100 > Si***
- *Lightest charge carrier → **massless Dirac fermions***
- *Longest mean free path at room temp → **microns***
- *Easily functionalised and process able*
- *Impervious to even He*



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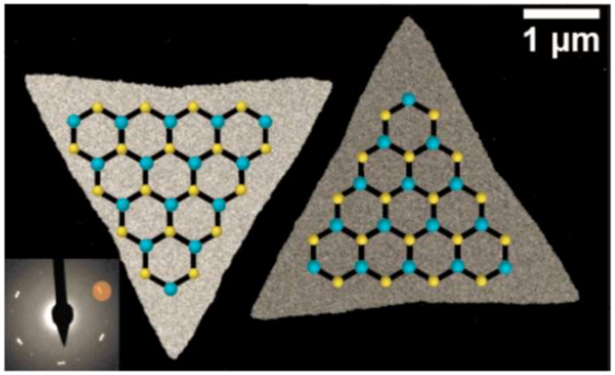
ICFO Research Group Low Dimensional Quantum Materials

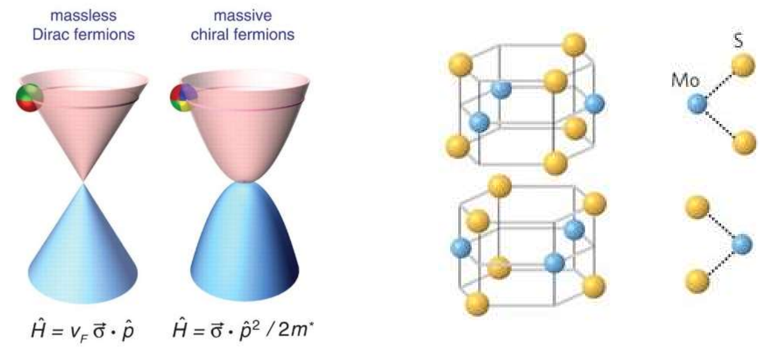
Single layer vdW materials

High quality single crystals - 2D physics in the clean limit



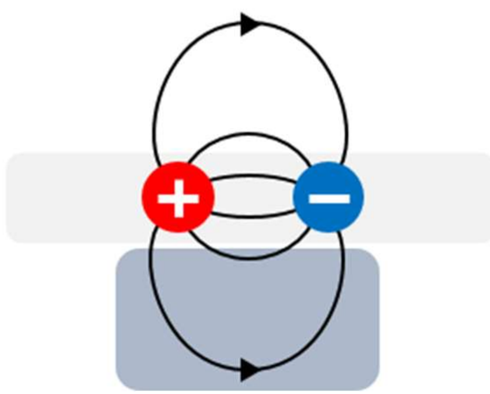
- True 2D high quality single crystals
- Quantum confinement in the z direction

Layer number control – new physical systems



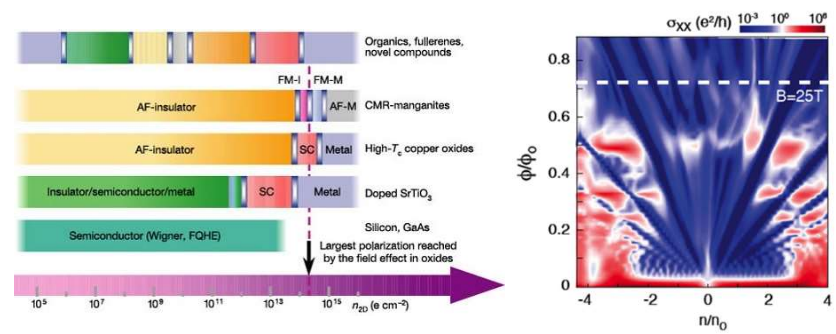
- Altered unit cells → changed degeneracies and broken inversion symmetries
- Altered band-structures below 8 layers
- Changed phonon spectrum

Enhanced electronic interactions



- Reduced environmental screening enhances electronic interactions

E- and B-field control



- Electric field control across phase-transitions
- Novel quantum phases in high B-fields

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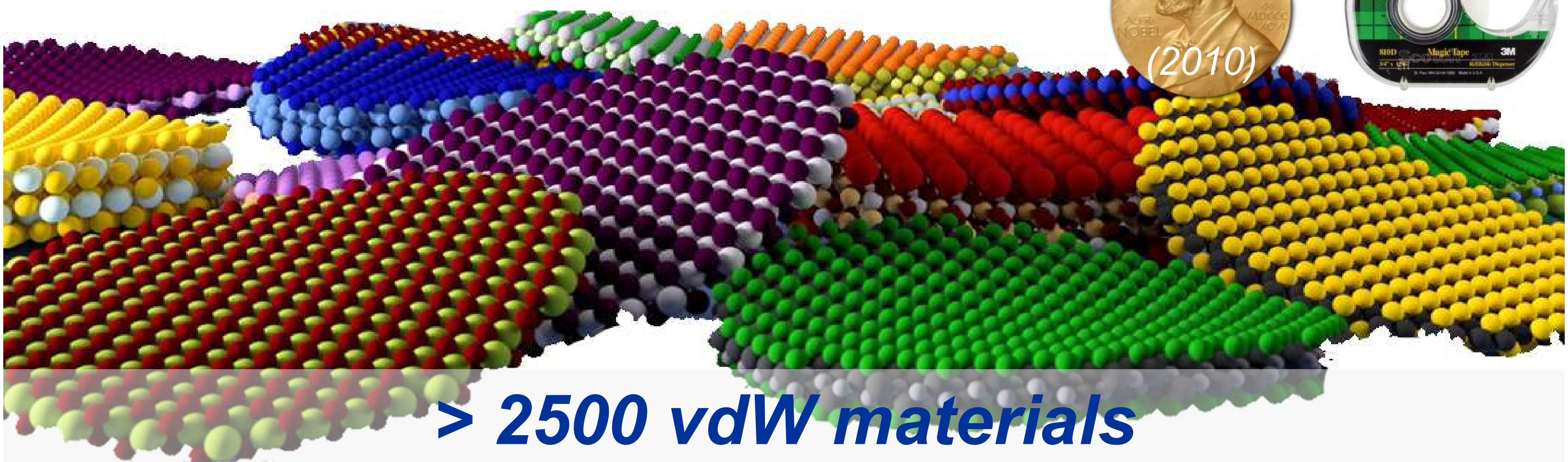
Graphene and 2D van der Waals materials

Graphene family	Graphene	hBN 'white graphene'	BCN	Fluorographene	Graphene oxide	
2D chalcogenides	MoS_2, WS_2, $MoSe_2$, WSe_2	Semiconducting dichalcogenides: $MoTe_2$, WTe_2, ZrS_2, $ZrSe_2$ and so on	Metallic dichalcogenides: $NbSe_2$, NbS_2, TaS_2, TiS_2, $NiSe_2$ and so on	Layered semiconductors: GaSe, GaTe, InSe, Bi_2Se_3 and so on		
2D oxides	Micas, BSCCO	MoO_3, WO_3	Perovskite-type: $LaNb_2O_7$, $(Ca,Sr)_2Nb_3O_{10}$, $Bi_4Ti_3O_{12}$, $Ca_2Ta_2TiO_{10}$ and so on	Hydroxides: $Ni(OH)_2$, $Eu(OH)_2$ and so on		
	Layered Cu oxides	TiO_2, MnO_2, V_2O_5, TaO_3, RuO_2 and so on		Others		

A. Geim, et. al. **Nature (2013).**

- *High quality single crystals – 2D physics in the clean limit*
- *Layer number control – multitude of new systems*
- *Enhanced electronic interactions*
- *E- and B-field control*



> 2500 vdW materials

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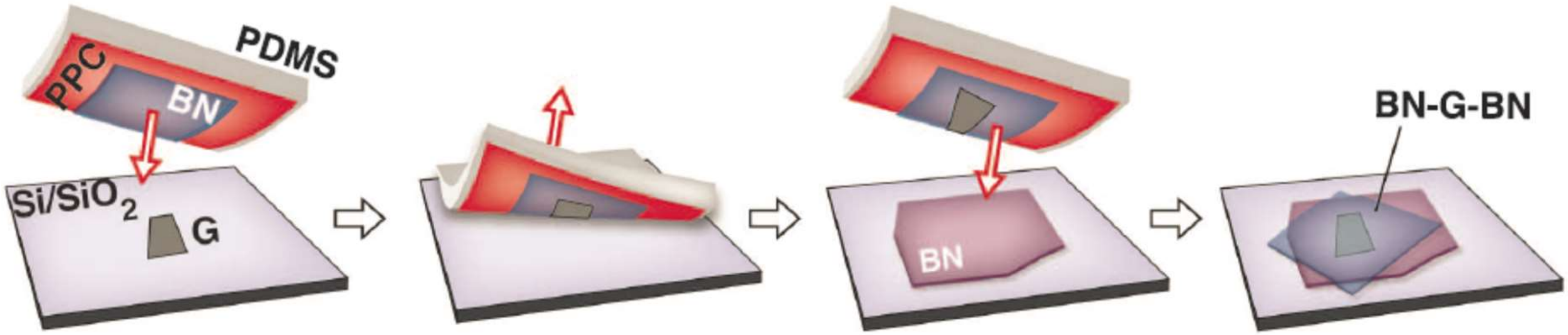
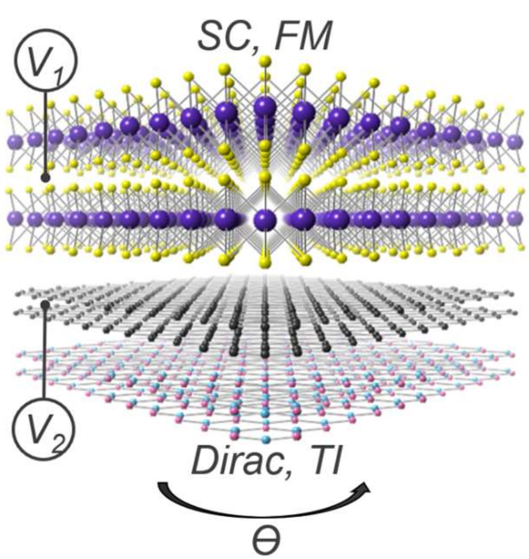
VdW heterostructures – clean coupling over <1nm

vdW co-lamination transfer technique:

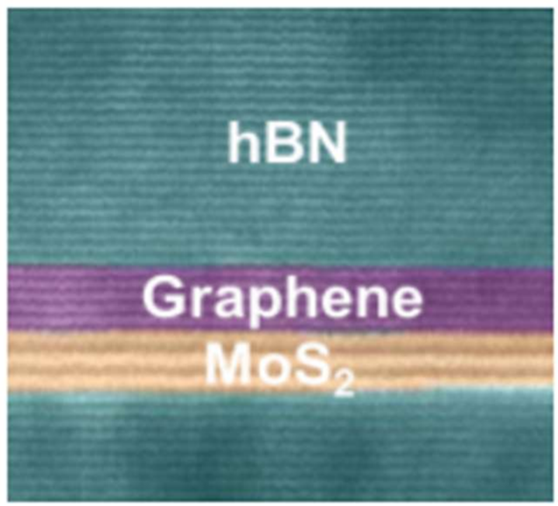


A. Geim, et. al. **Nature (2013).** C.Dean, P. Kim, J. Hone, et. al. **Science (2013).**

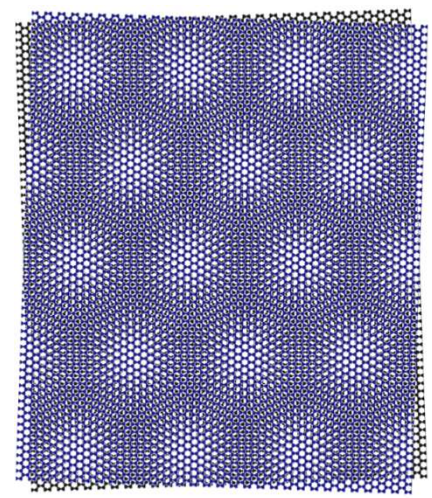
Designer vdW stack:



TEM cross-section:

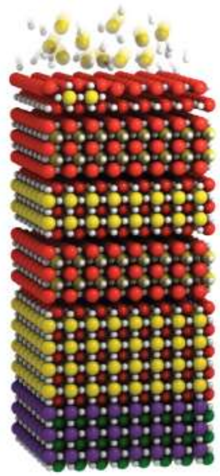


Moiré superlattice:

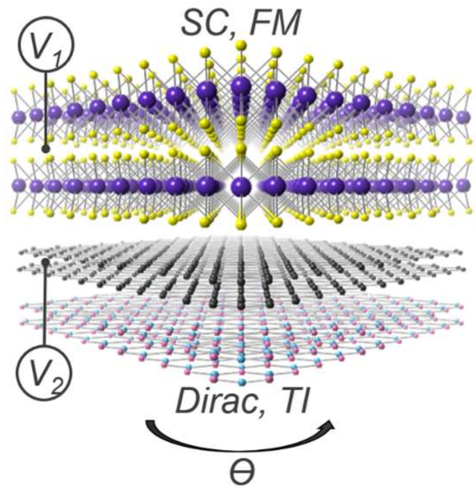


MBE (LEGO) vs. vdW (CARDS)

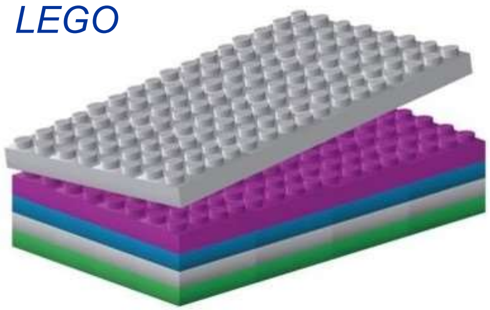
Molecular beam epitaxy:

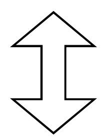


Van der Waals assembly:

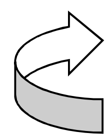


LEGO





Crystallographic orientation locked

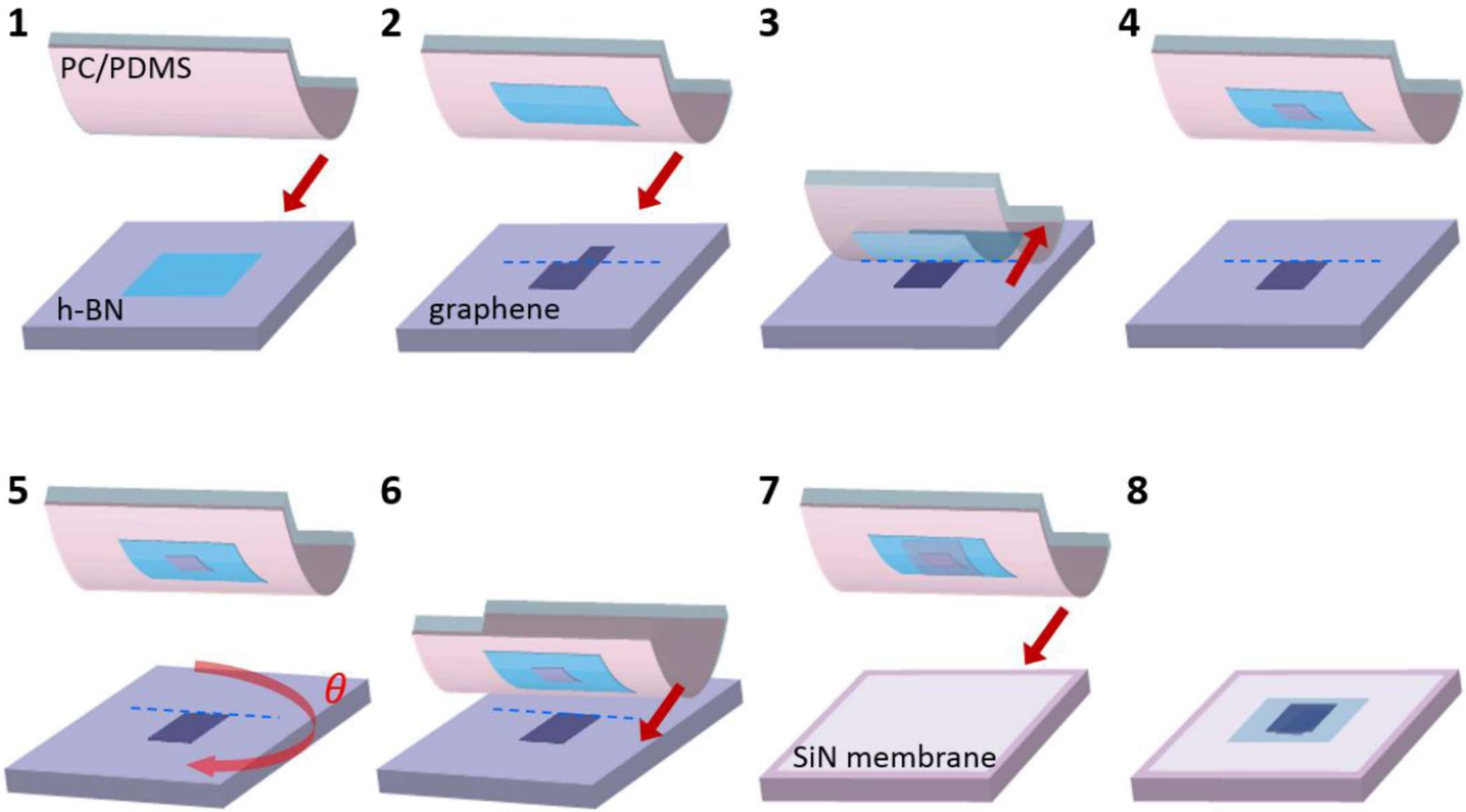


CARDS

Crystallographic orientation free

New → Free crystallographic orientation

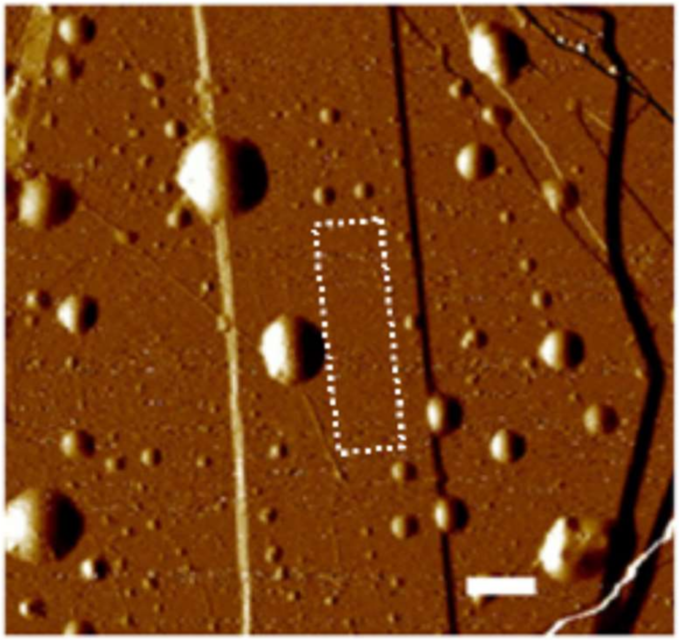
Device assembly → tear and stack



P. Kim, ***Nature Materials (2019);***

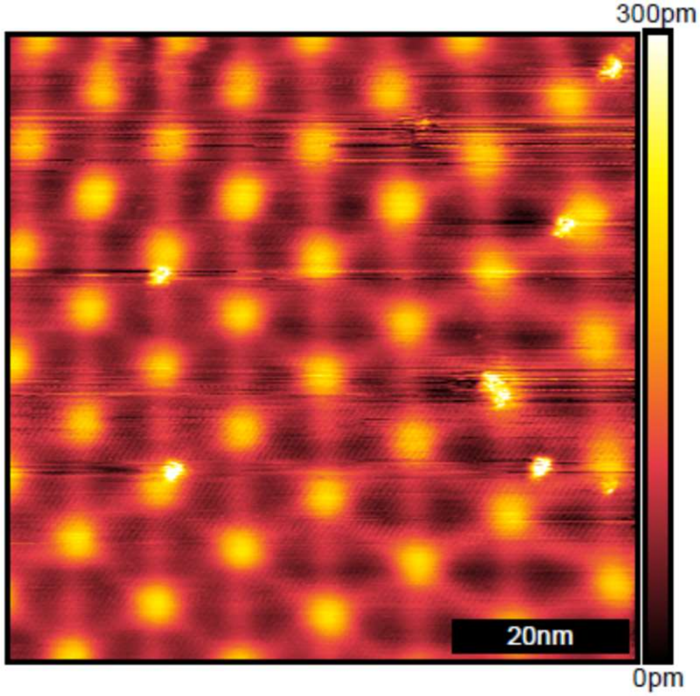
Large twist-angle inhomogeneity

AFM image of device:



M. Yankowitz, et. al. ***Science (2019)****;*

STM image of device:



A. Kerelsky, et. al. ***arXiv:1812.08776 (2018)****;*

Biggest source of disorder is twist-angle inhomogeneity – smearing of small interaction gaps in transport measurements

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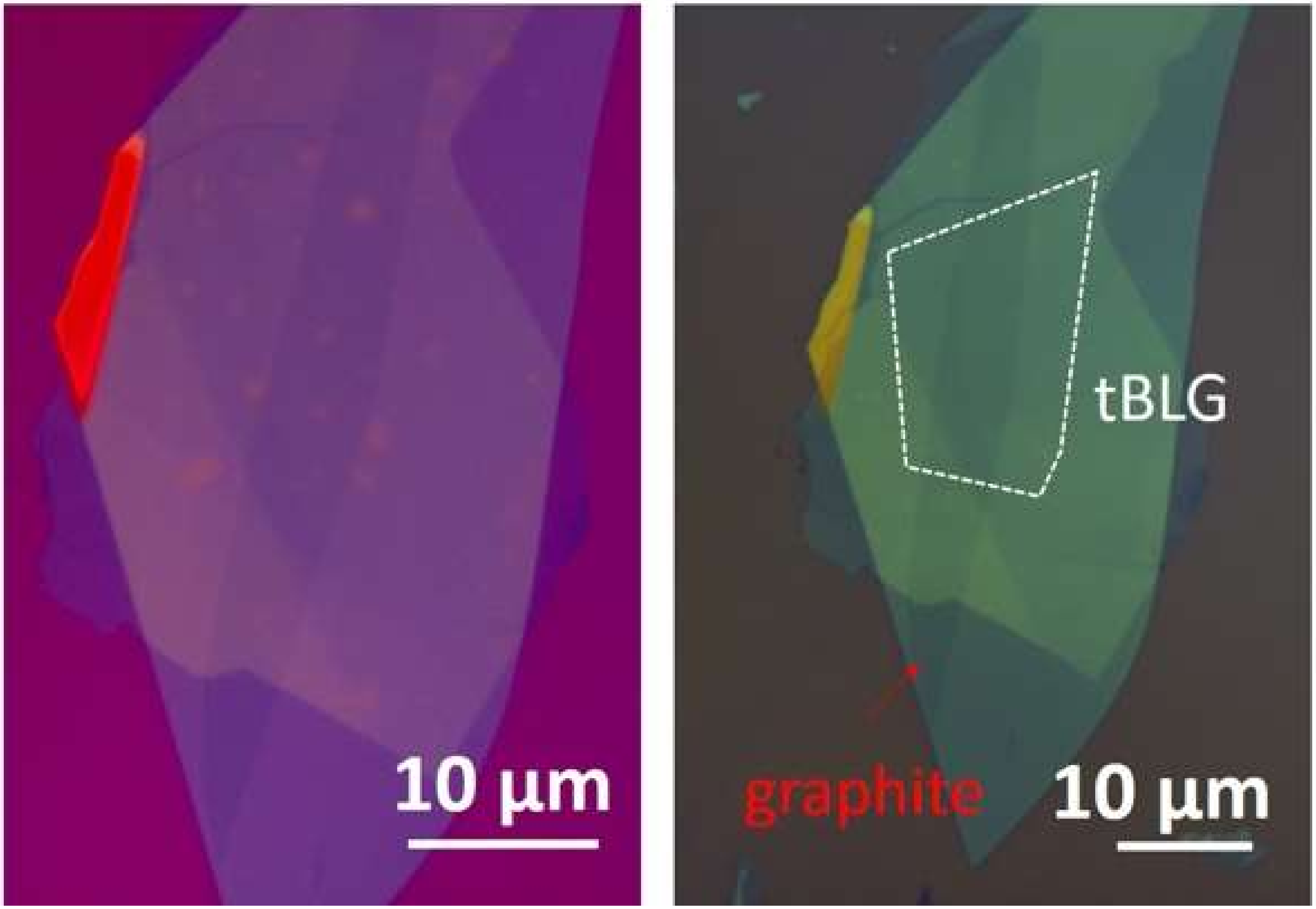
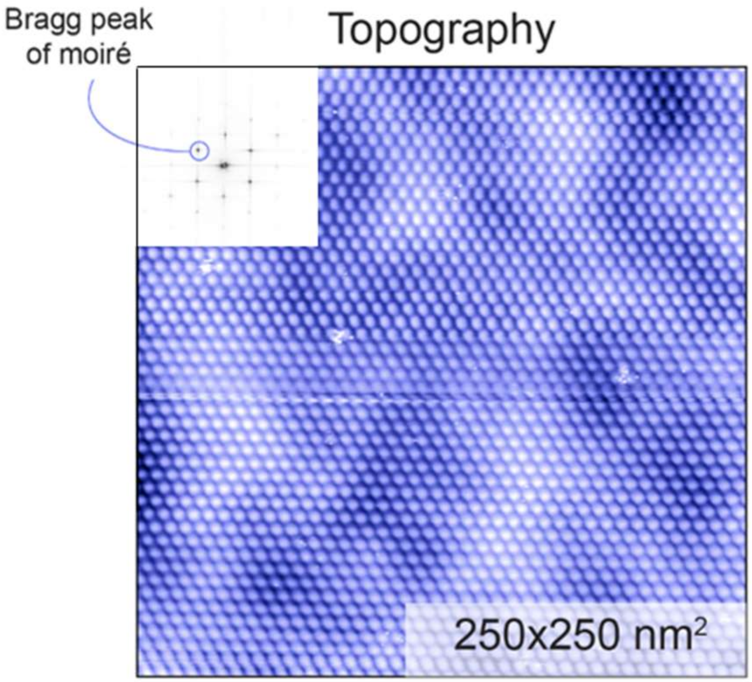
As prepared vdW heterostructures

<u>Before squeezing:</u> <u>After squeezing:</u>

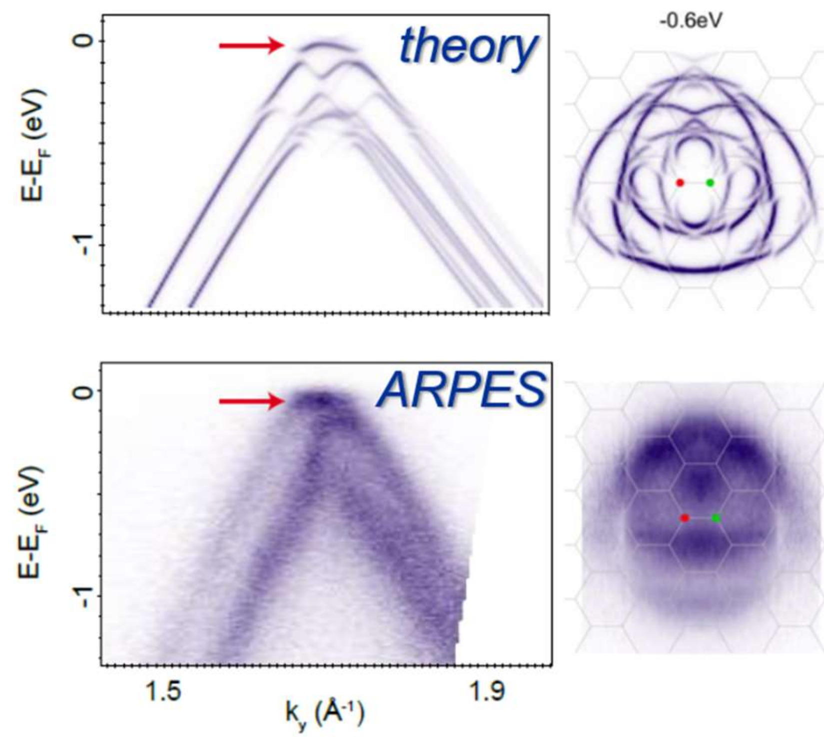


Moiré super-lattice and flat bands in tBLG

STM - Moiré topography:



Nano-ARPES for θ ~ 1.3°:



*T. Benshop, … , DKE, M. Allan, **in arXiv:2008.13766 (2020).***

Also:

*Nadj-Perge group, **Nature Physics (2019).***
*Yazdani group, **Nature (2019).***
*Pasupathy group, **Nature (2019).***
*Andrei group, **Nature (2019).***

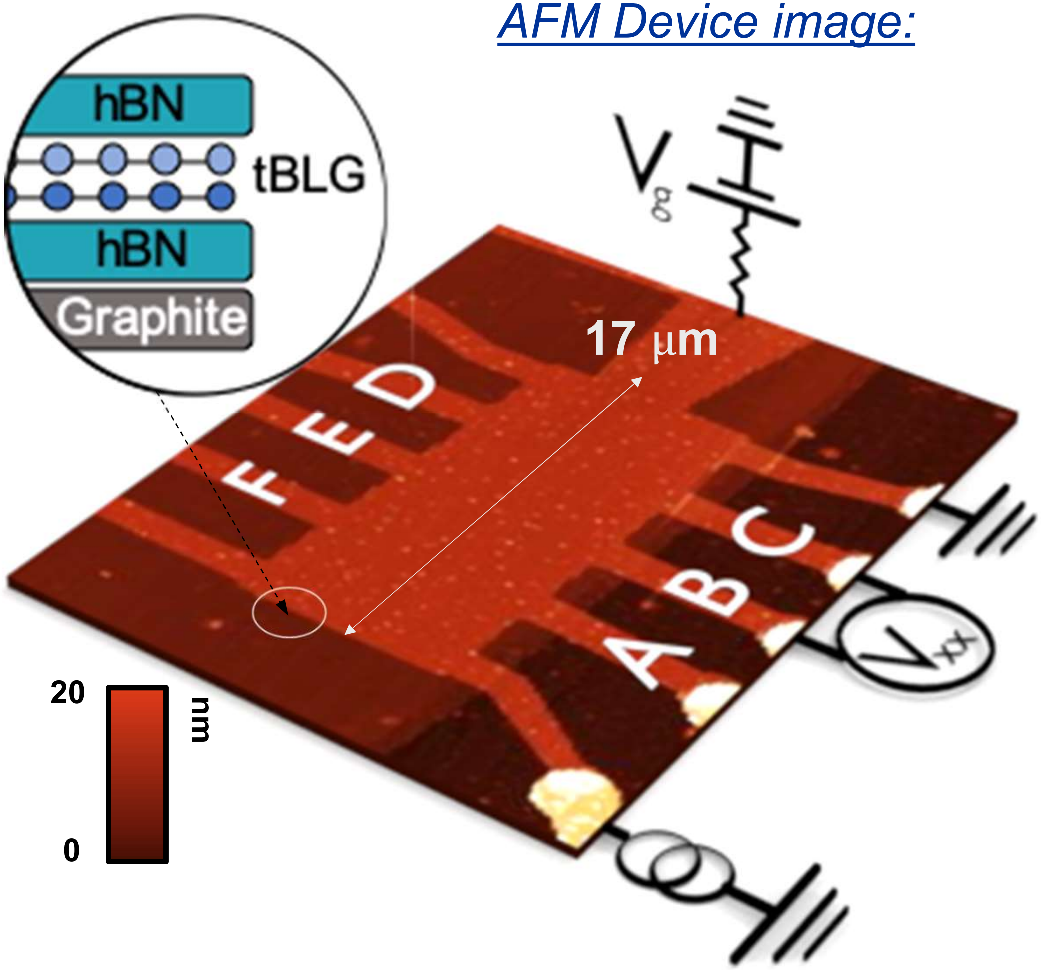
*S. Lisi, … , DKE, F. Baumberger, **Nature Physics (2020).***

Also:

*M. Utama, ... , F. Wang, **Nature Physics (2020).***

Transport Devices

AFM Device image:



X. Lu, … , DKE, ***Nature 574, 653 (2019).***
P. Stepanov, … , DKE, ***Nature 583, 375 (2020).***

Also:

K. Kim, et. al. ***PNAS (2017).***
Y. Cao, et. al. ***Nature (2018).***
M. Yankowitz, et. al. ***Science (2019).***
etc.

Ultra-low twist-angle inhomogeneity of $\Delta\theta < 0.01^\circ$ over 10μm

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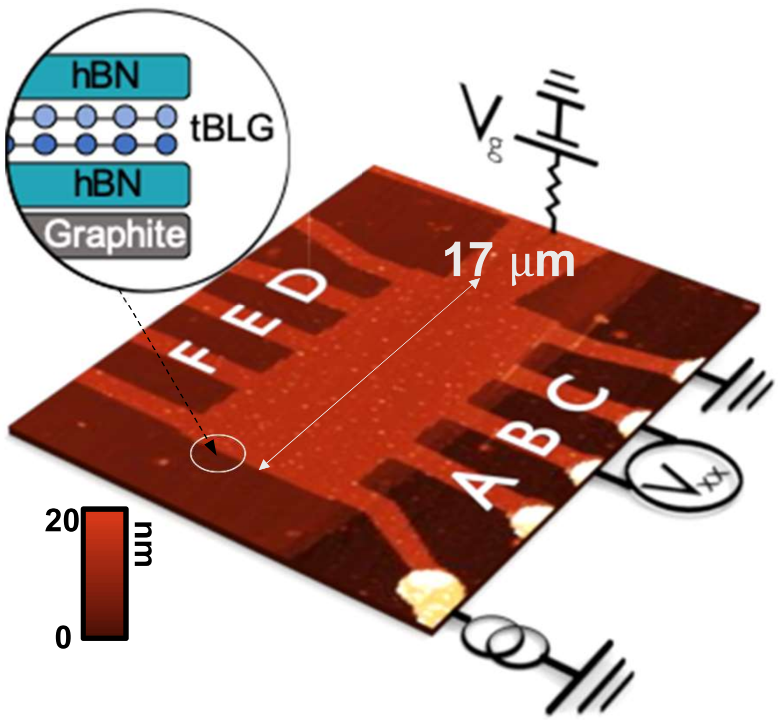
Transport Measurements



Longitudinal resistance: $R_{xx} = V_{xx}/I$

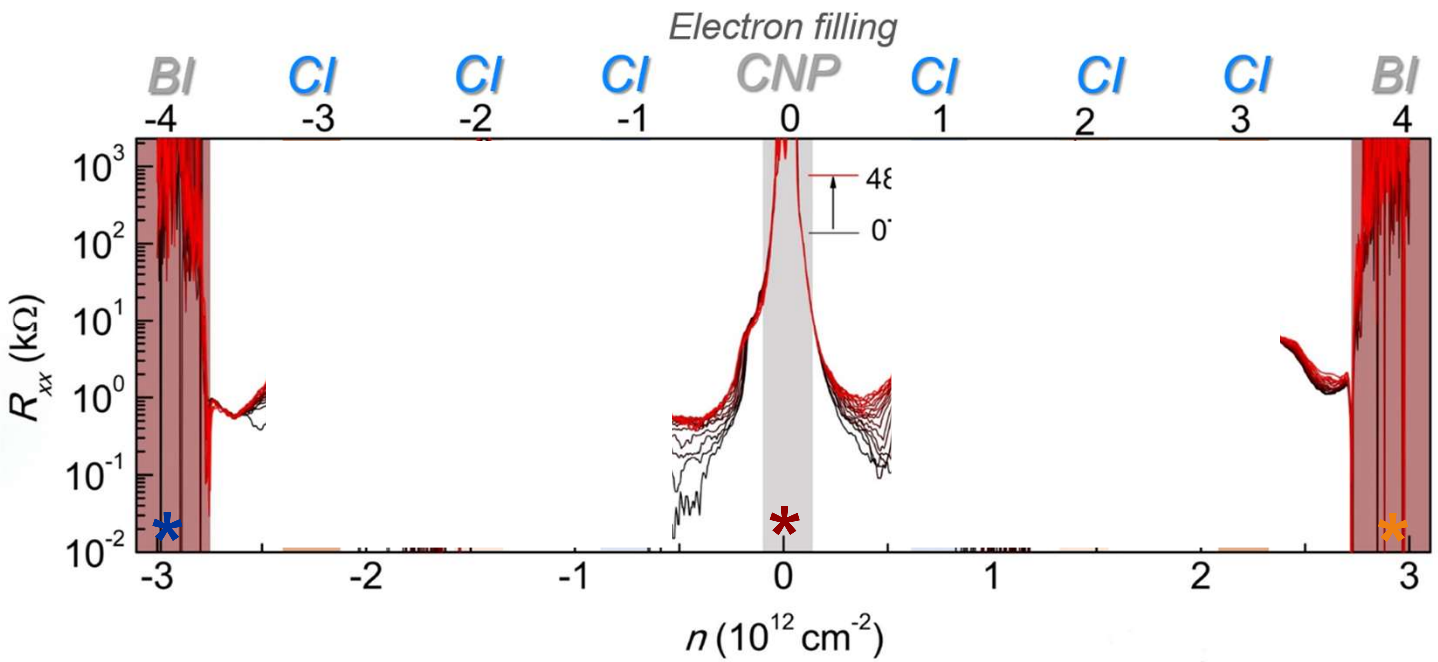
Hall resistance: $R_{xy} = V_{xy}/I$

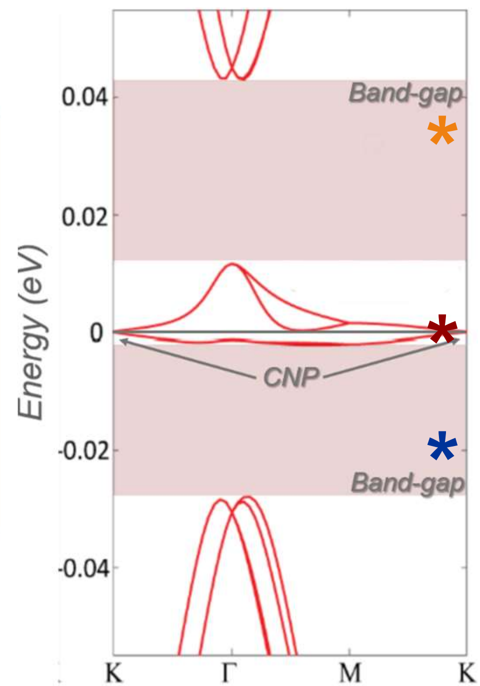
Carrier density: $n = C_g * V_g$

Hall density: $n = n_H = -B/eR_{xy}$

Capaciatance of graphite gate:
C_g ~ 260 nF/cm^2 ~ 10^{12} e/Vcm^2

Carrier density (filling) dependent resistivity





Single particle band-gaps and CNP

X. Lu, … , DKE, ***Nature 574, 653 (2019).***

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Devices made @ICFO

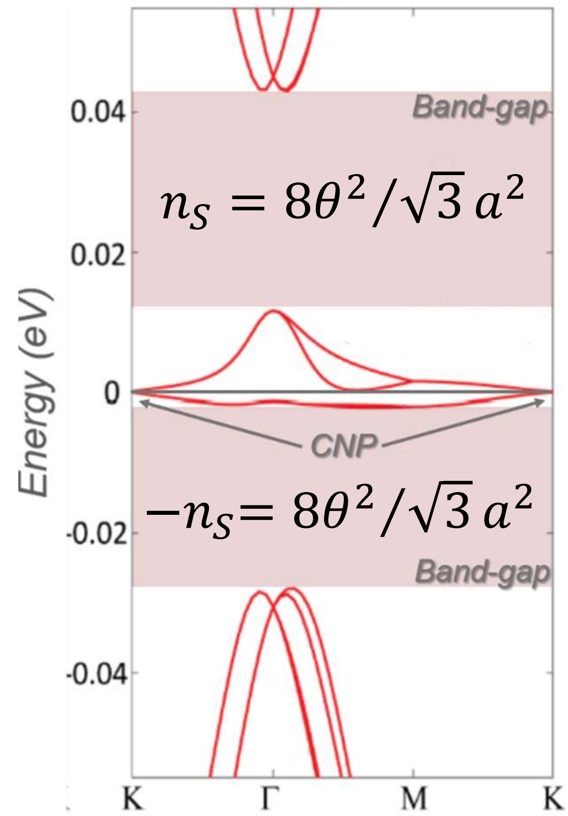
Graphene lattice constant: a = 0.246 nm

Size of moiré unit cell: $A_0 = \sqrt{3}a^2/\mathbf{2}\theta^2$ ~ 15nm*15nm

Density of 1 electron/hole per moiré unit cell:
$n_0 = A_0^{-1} = \mathbf{2}\theta^2/\sqrt{3}\,a^2$ ~ 10^{12} e/Vcm^2 or filling factor $v = n/n_0 = 1$

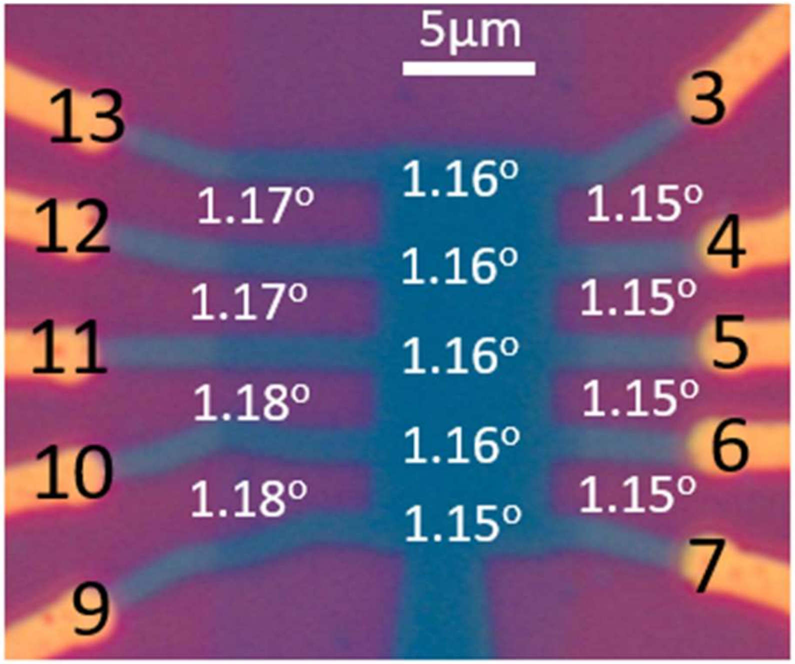
Fully filled moiré bands of 4 spin/valley degenerate electrons/holes per moiré unit cell:
$n_s = 4A_0^{-1} = \mathbf{8}\theta^2/\sqrt{3}\,a^2$ ~ $4*10^{12}$ e/Vcm^2 or filling factor $v = n/n_0 = 4$

Band structure:



Typical Devices

Optical device image:



X. Lu, … , DKE, **Nature 574, 653 (2019).**
P. Stepanov, … , DKE, **arXiv:1911.09198.**

Ultra-low twist-angle inhomogeneity of $\Delta\theta < 0.01^{\circ}$ over 10µm

Outline

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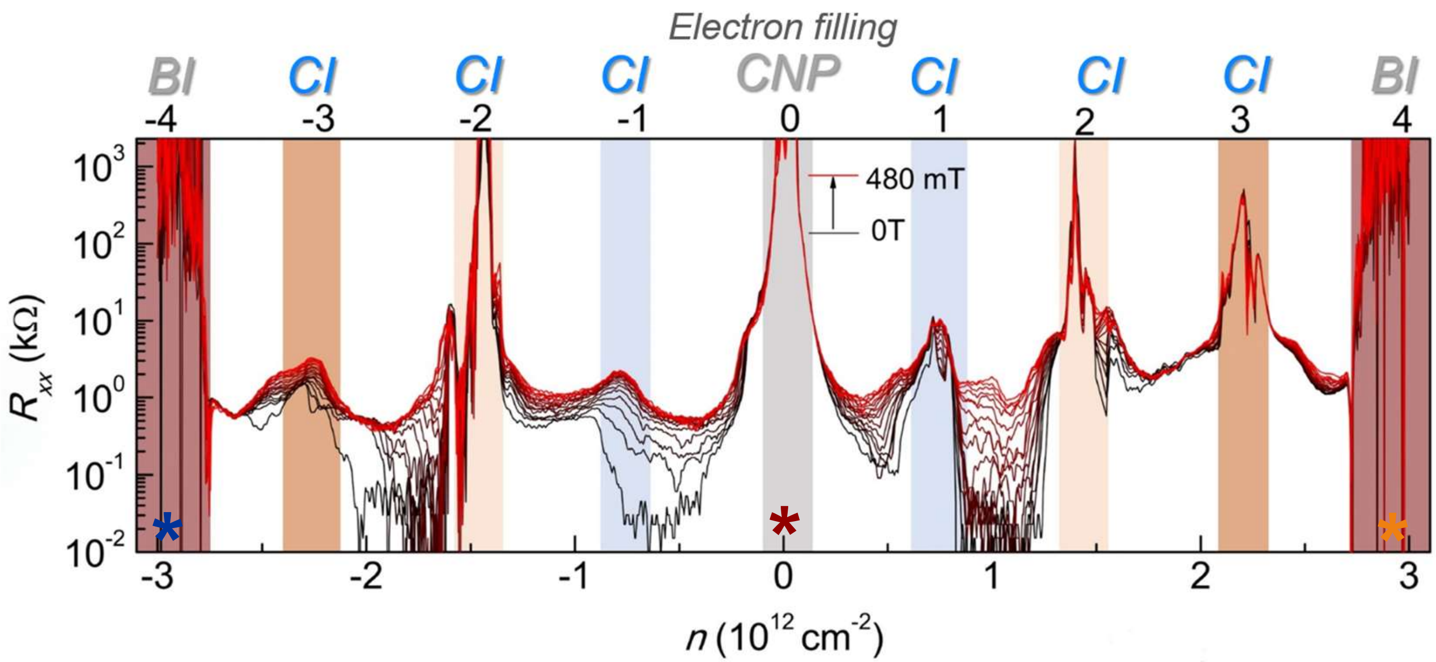

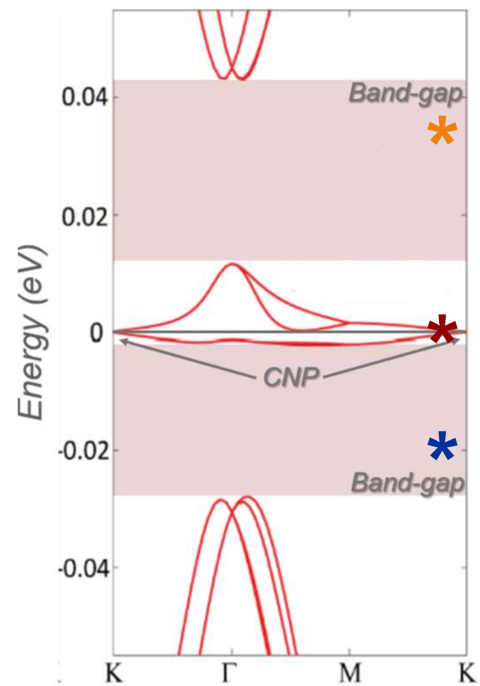

Correlated insulators at all integer fillings
v = 0,±1,±2,±3 e/uc

X. Lu, … , DKE, **Nature 574, 653 (2019).**

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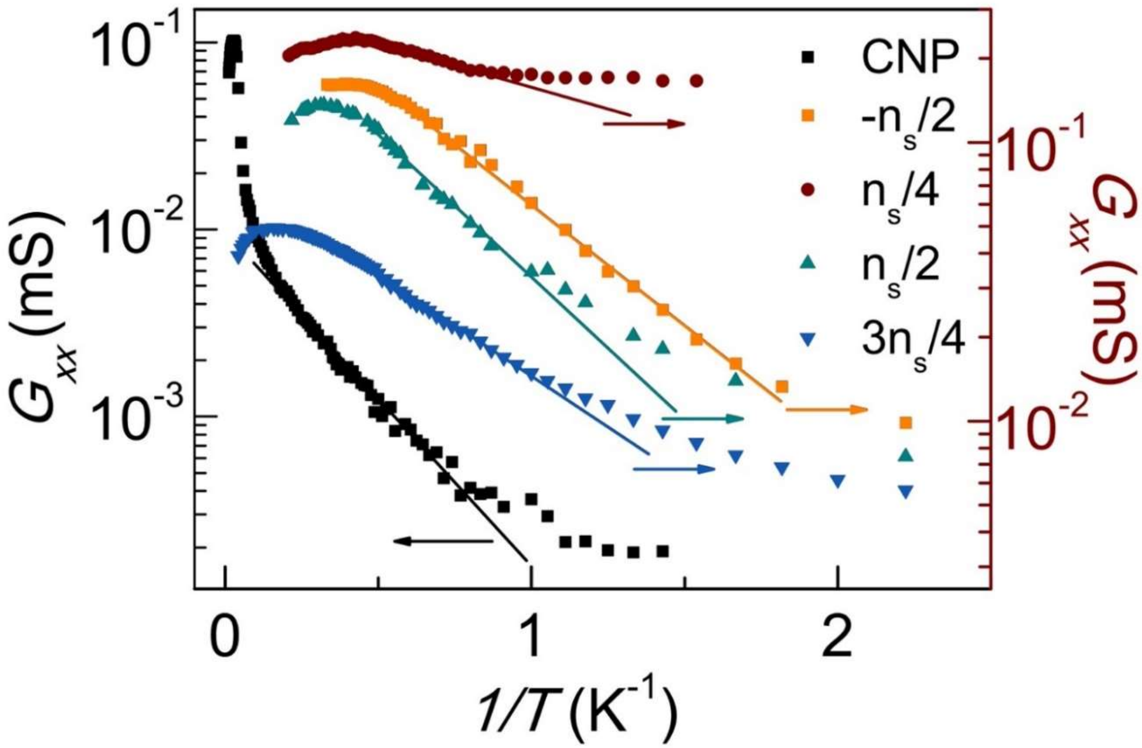
Temperature activated transport

Temperature activated Arrhenius plots:



$$R_{xx} = 1/G_{xx} \sim exp(\Delta/2\,kT)$$

Insulating states:

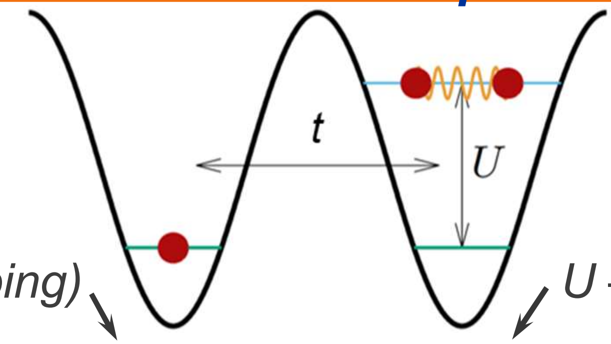
- v = 0, Δ ~ 0.86 meV
- v = -2, Δ ~ 0.34 meV
- v = 1, Δ ~ 0.14 meV
- v = 2, Δ ~ 0.37 meV
- v = 3, Δ ~ 0.25 meV

Semi-metallic states?:

- v = -3, no gap
- v = -1, no gap

Insulating (v = 0,±2,+3) and semi-metallic correlated states (v = ±1,-3)

Mott insulator picture



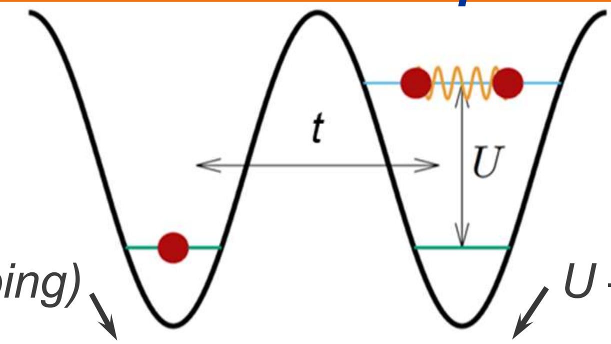
t – kinetic energy (hopping)

U – onsite energy (Coulomb)

$U = e^2\theta/(4\pi\varepsilon_0\kappa a)$

$$H = -t \sum_{i,j,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Mott insulator picture



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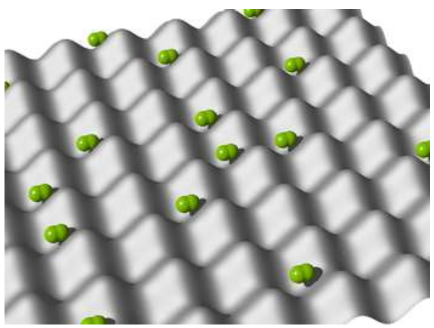
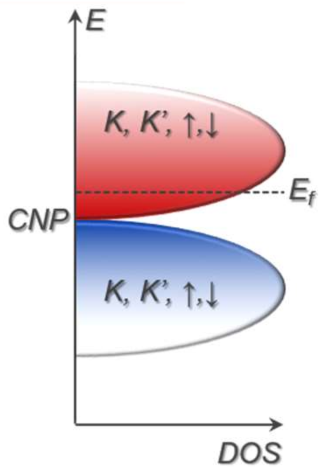
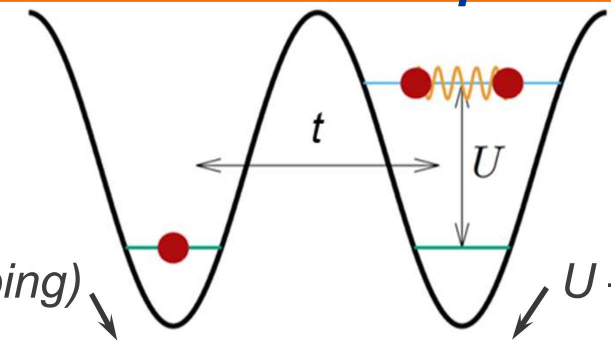
partial filling - correlated metal:





Mott insulator picture



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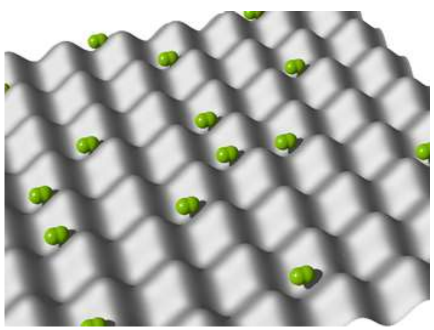
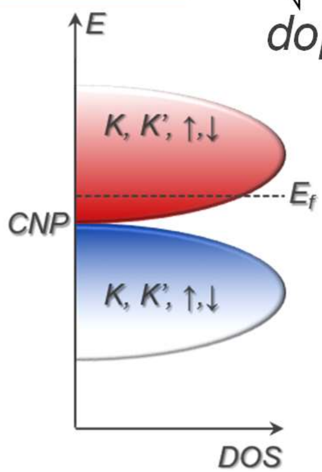
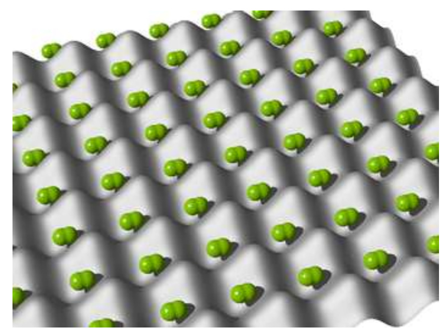
partial filling - correlated metal:

doping

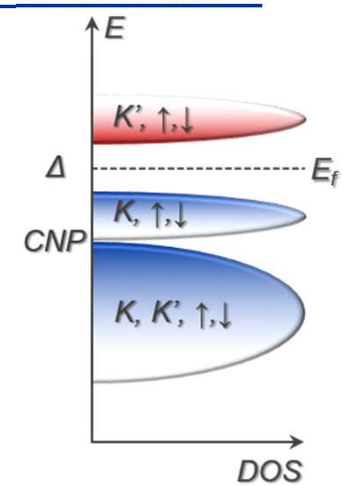
integer filling – Mott insulator:



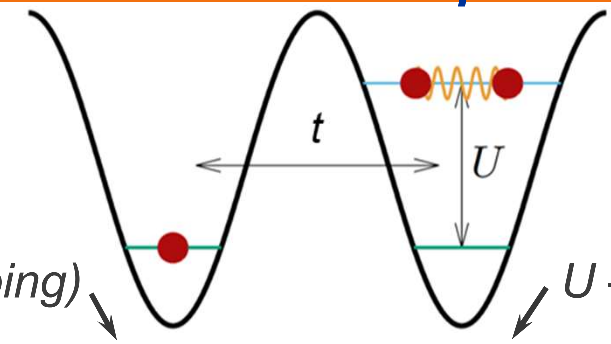




U/t >> 1



Mott insulator picture



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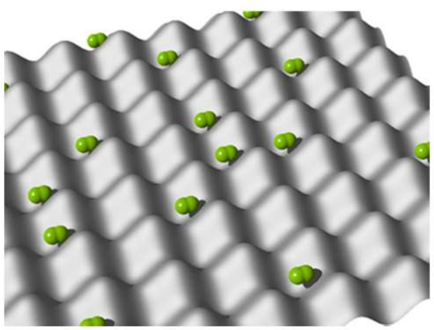
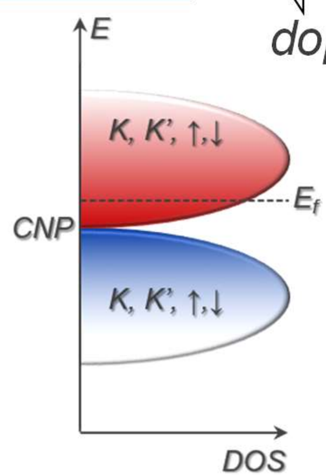
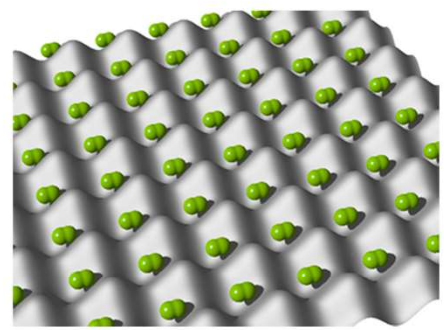
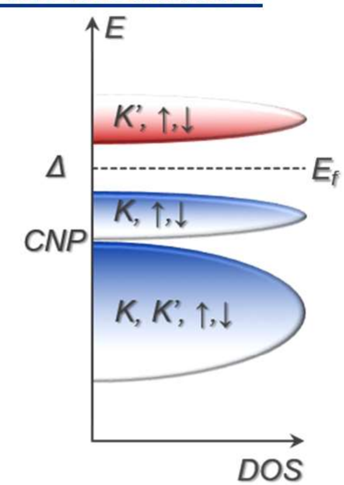
partial filling - correlated metal: ⟺ doping ⟺ integer filling – Mott insulator:







U/t >> 1



Breaking of SU(4) spin/valley symmetry → correlated gaps at ± 0,1,2,3 e/uc

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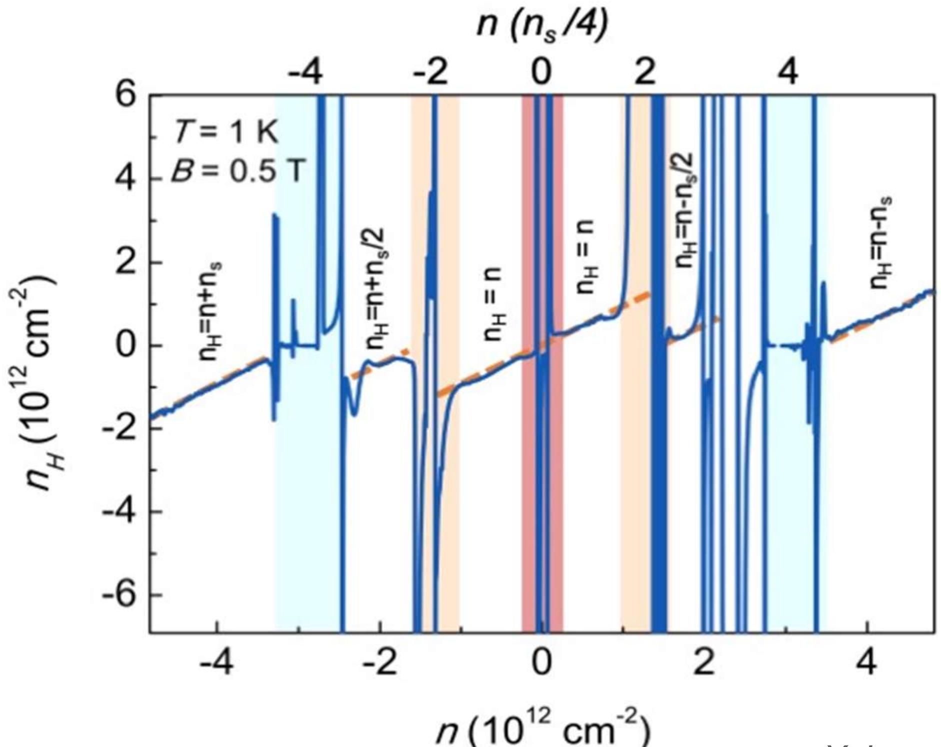
Carrier density (filling) dependent Hall density

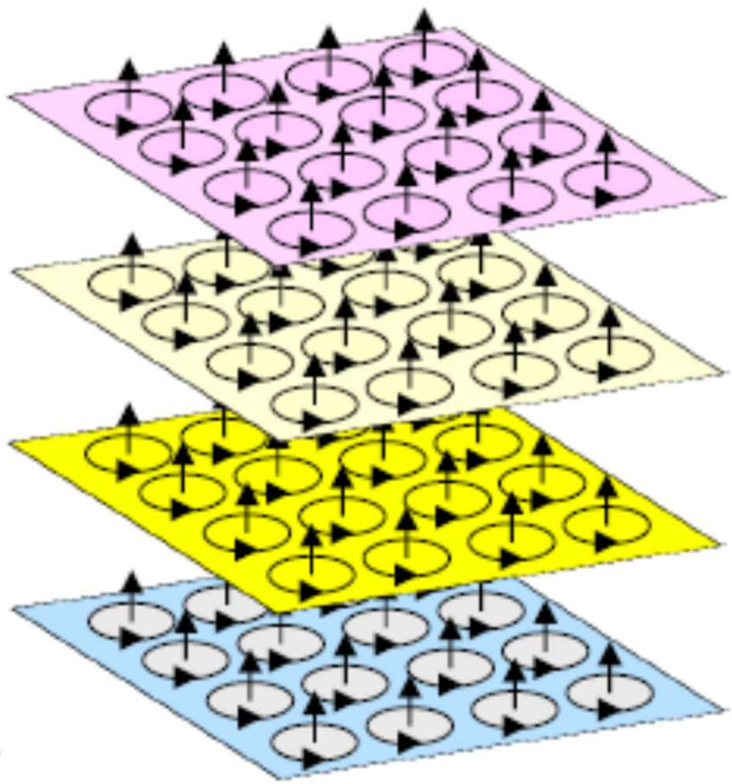
Hall density: $n = n_H = -B/eR_{xy}$

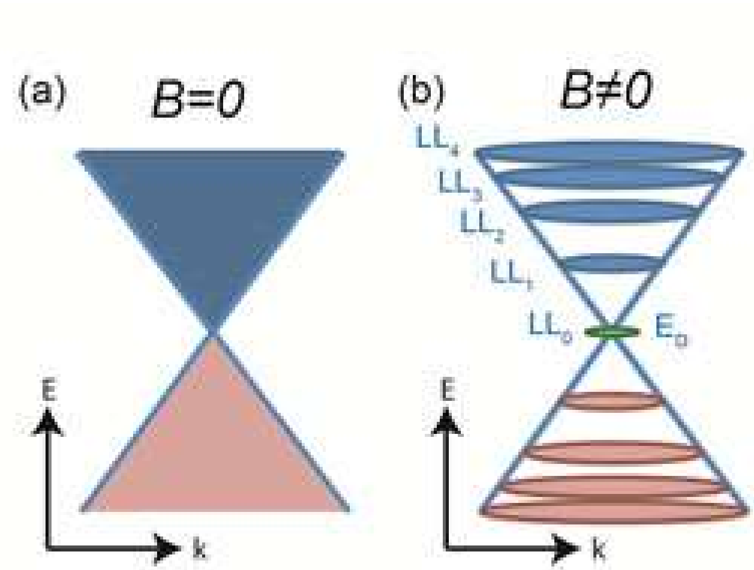


X. Lu, … , DKE, ***Nature 574, 653 (2019).***

Carrier density (Fermi level) resets at all integer fillings ν = 0,±1,±2,±3 e/uc

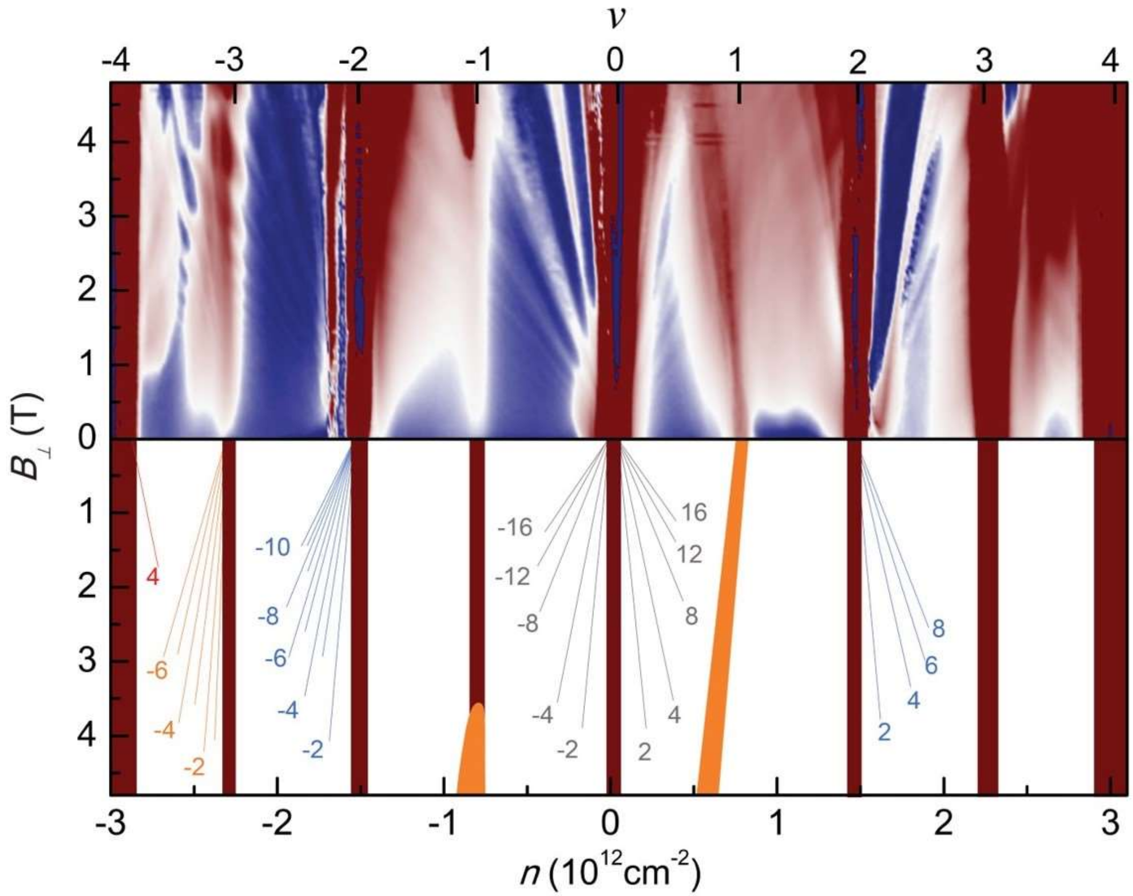
Quantum oscillations - Landau Fan diagram





$$\nu = 2\pi \ell_B^2 n \quad \Rightarrow \quad B = \frac{\phi_0}{\nu} n$$

Quantum oscillations - Landau Fan diagram



Landau levels:

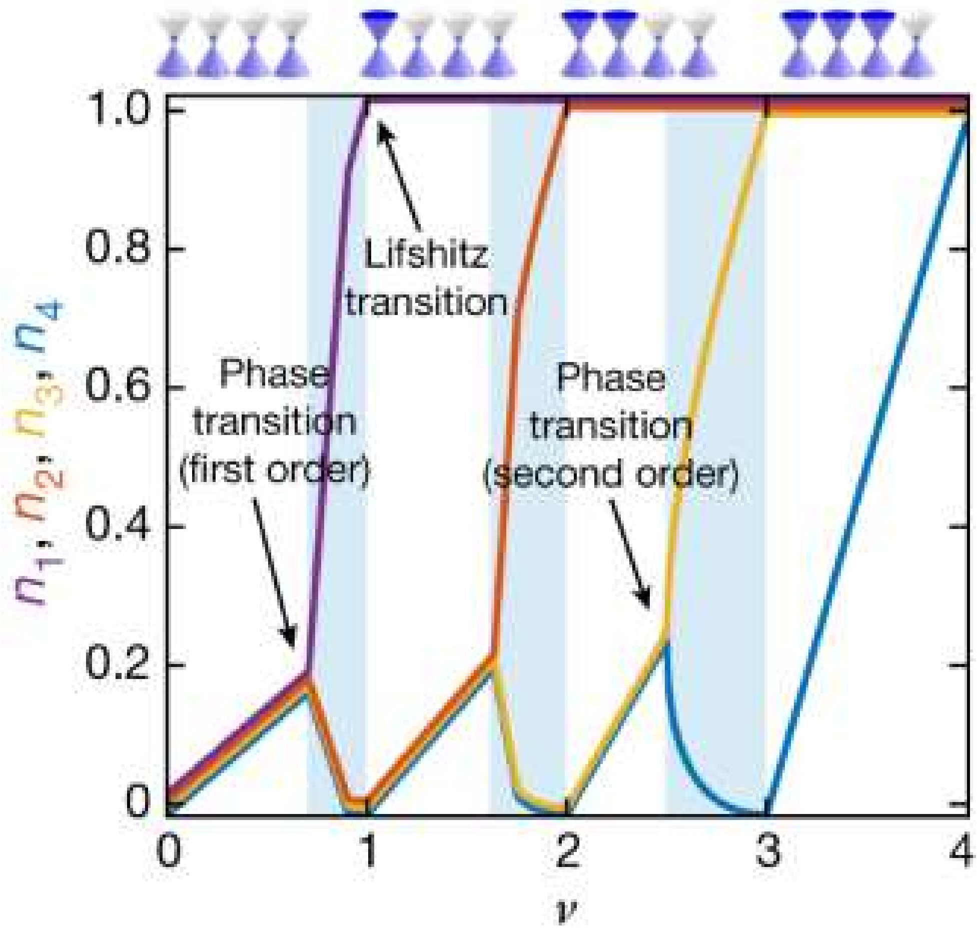
- v = 0, 4-fold
- v = ±1, no LLs
- v = ±2, 2-fold
- v = ±3, 1-fold

Chern insulators?:

- v = -1, C = 1
- v = 1, C = 2

Breaking of SU(4) spin/valley symmetry → different degeneracy of LLs from different v

Carrier density (filling) dependent Hall density



*S. Ilani, **Nature (2020).***

Carrier density (Fermi level) resets at all integer fillings v = 0,±1,±2,±3 e/uc

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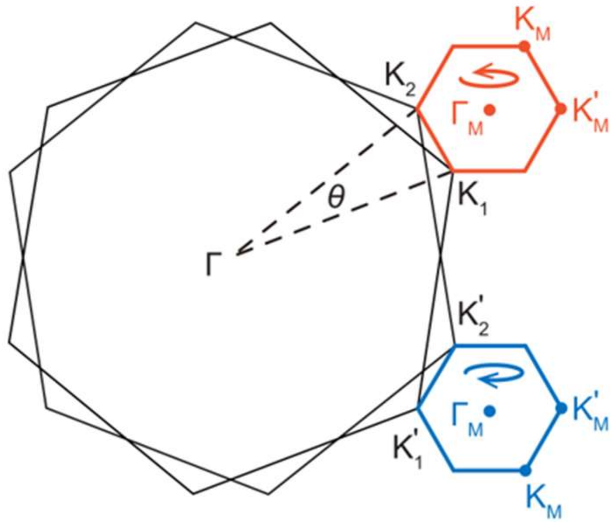
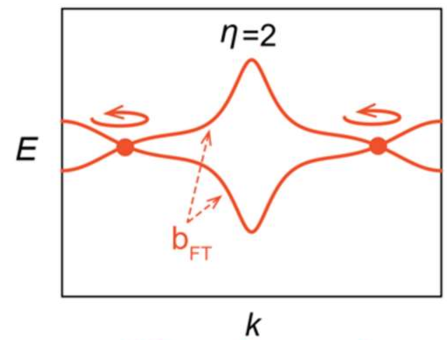
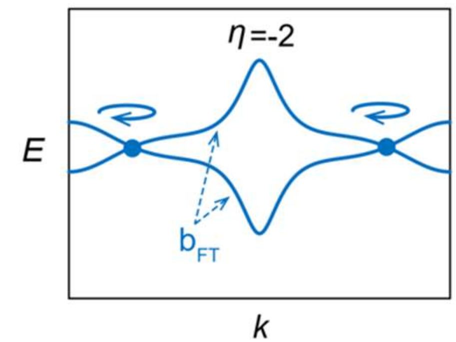
Topological flat-bands in tBLG

Mini-BZ with helicity $\eta = \pm 2$:





$H_K \sim h v_F \boldsymbol{\sigma} \boldsymbol{k}$



$H_{K'} \sim -h v_F \boldsymbol{\sigma}^* \boldsymbol{k}$

- *Mini-BZs decoupled*
- *No localized Wannier functions → Chern bands*
- *C_2T - symmetry*

→

Spin ↑,↓; Valley K, K'; Sublattice A, B;

- *4 Chern bands with C = -1*
- *4 Chern bands with C = 1*

*Vafek group **(2018).***
*Bernevig group **(2018).***
*MacDonald group **(2019).***
*Fu group **(2018).***

C = -1:	|↑, K', A>, |↓, K', A>, |↑, K, B>, |↓, K, B>;
C = 1:	|↑, K, A>, |↓, K, A>, |↑, K', B>, |↓, K', B>;

*Vishnawanth group **(2018).***
*Zaletel group **(2018).***
*Todadri group **(2019).***
*Dai group **(2019).***
*Balents **(2019).***

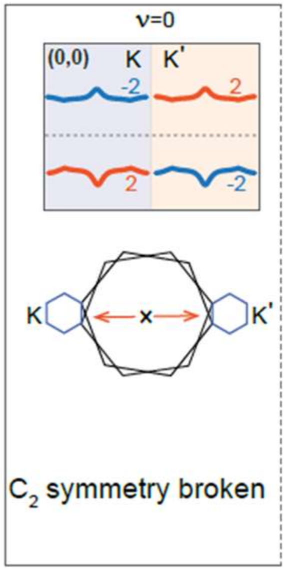
B-field induced Chern insulators

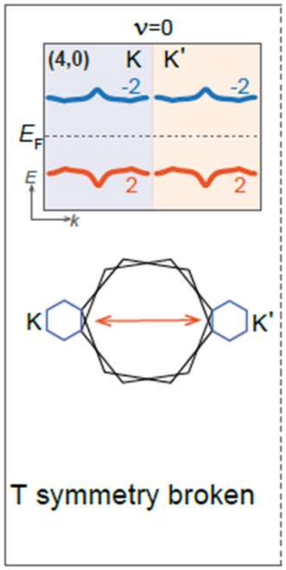
Gap out degeneracy of the bands → break one or both C_2T symmetries

Break single particle
C_2 - symmetry
→ align to hBN

Valley asymmetric C

A. Sharpe, et. al. **Science (2019)**;
B. M. Serlin, et. al. **Science (2019)**;





Break single particle
T - symmetry
→ apply B-field

Valley symmetric C

P. Stepanov, I. Das, … ,
DKE, et. al. **Nature (2020)**;

Interactions directly break C_2T symmetries?

B. Lian, Z.-D. Song, … , B. A. Bernevig, **arXiv:2009.13530 (2020).**
K. Nuckolls, … , B. A. Bernevig, A. Yazdani, **arXiv:2007.03810 (2020).**
I. Das, X. Lu, … , B. A. Bernevig, DKE, **arXiv:2007.13390 (2020).**

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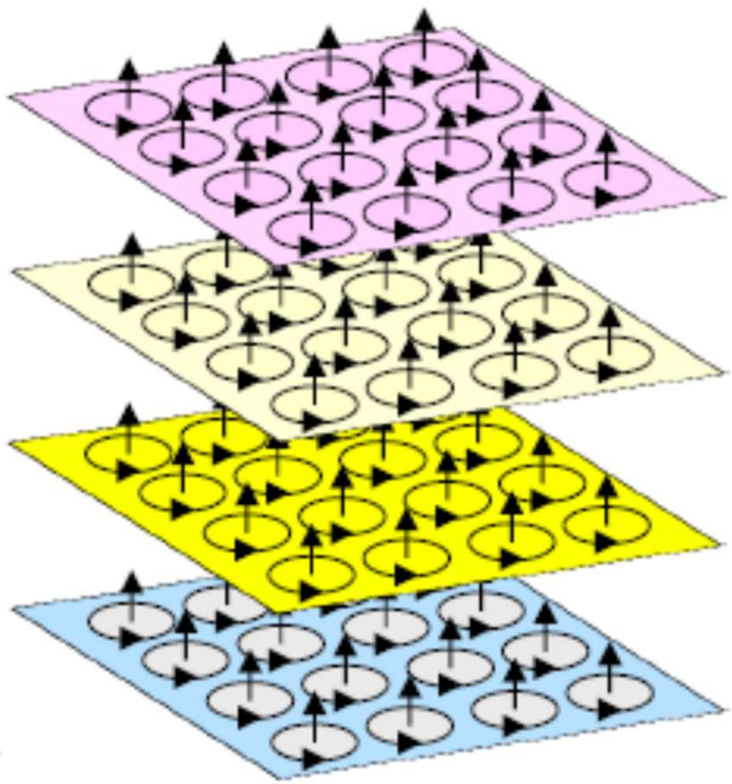
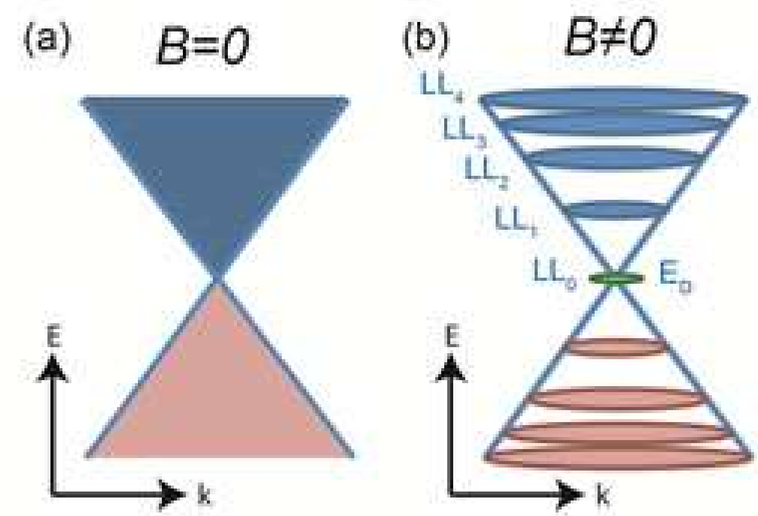
Quantum oscillations - Landau Fan diagram





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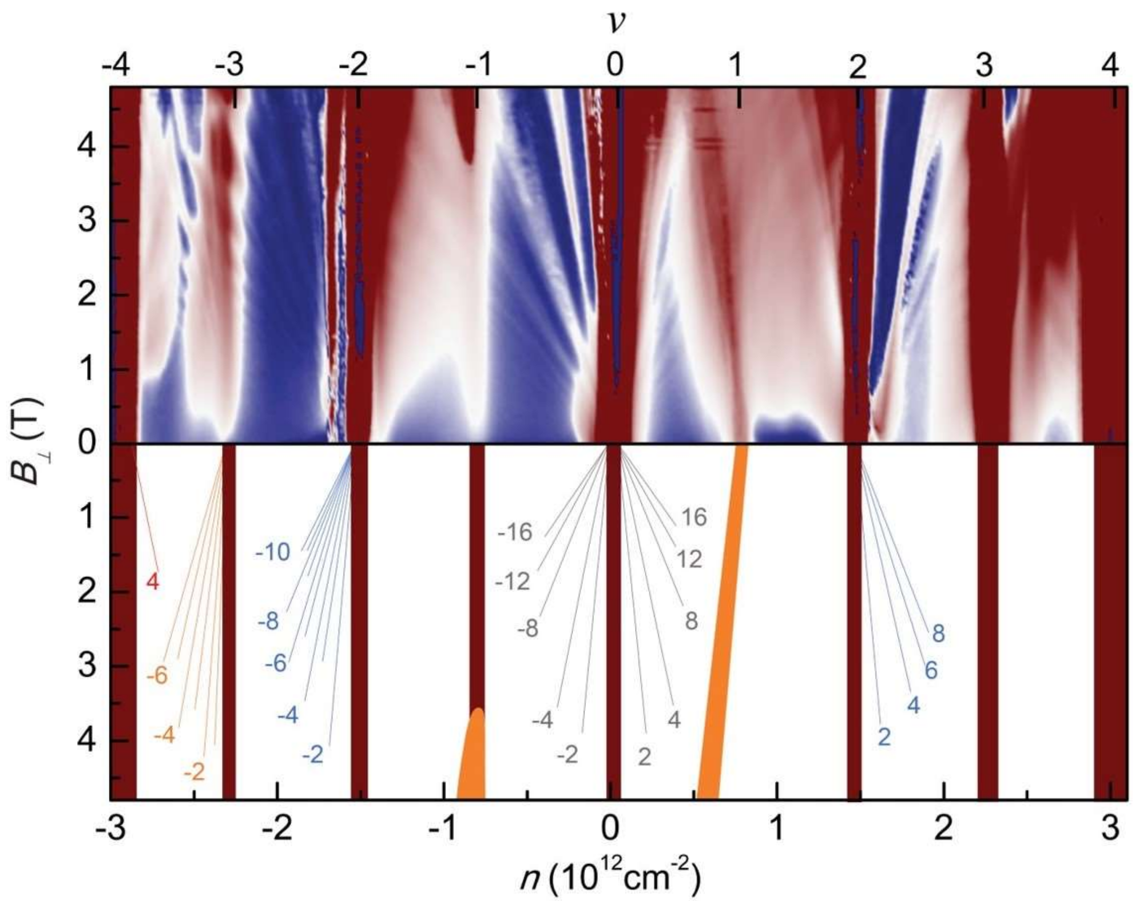

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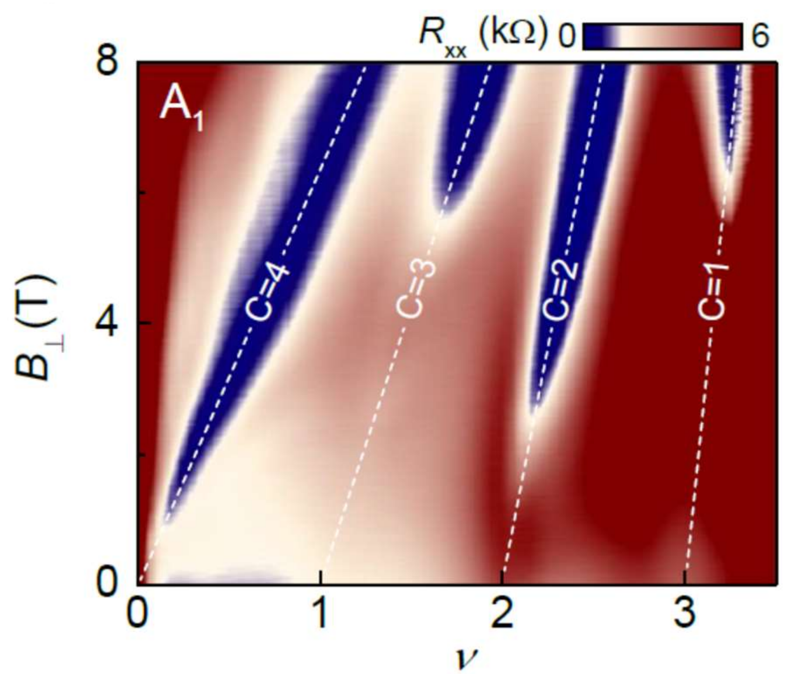
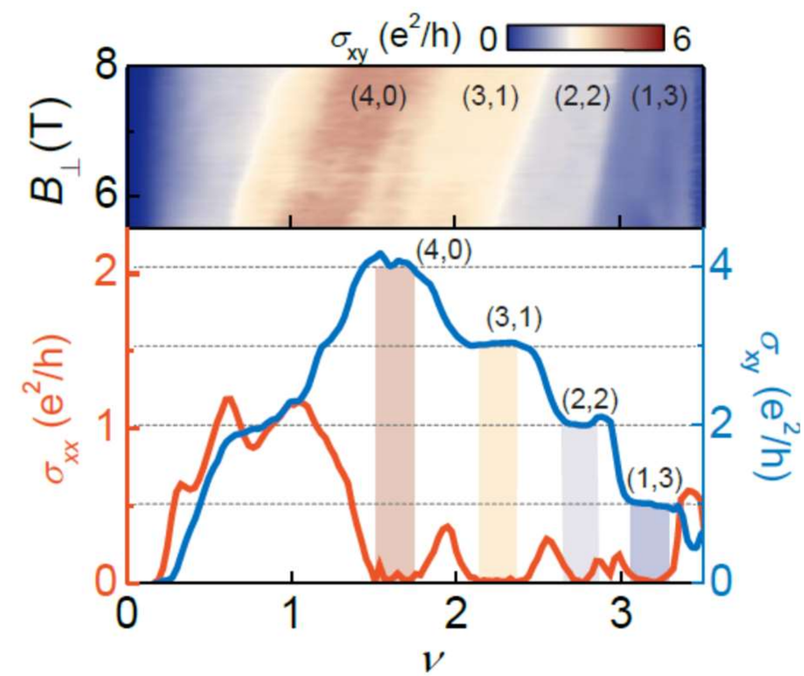
Correlated Chern insulators in B-field





Chern insulators in B-field - Streda Formula:

$$dn/dB_\perp = Ce/h$$

I. Das, X. Lu, … , DKE, **Nature Physics (2021).**

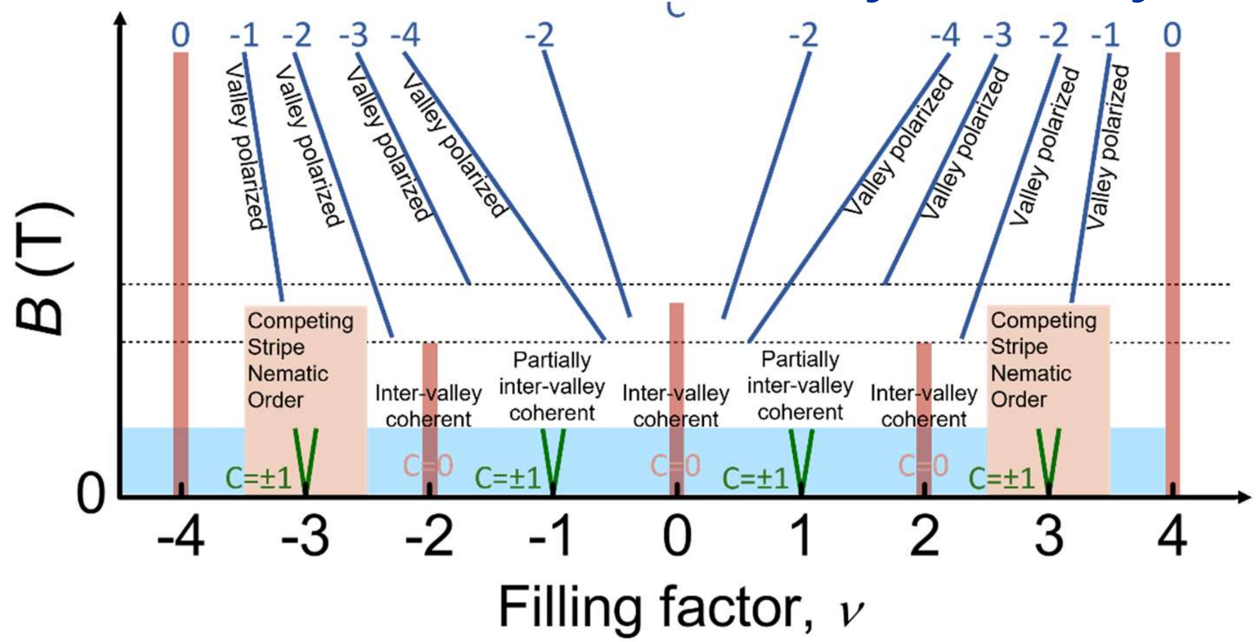
Quantized Hall conductance:

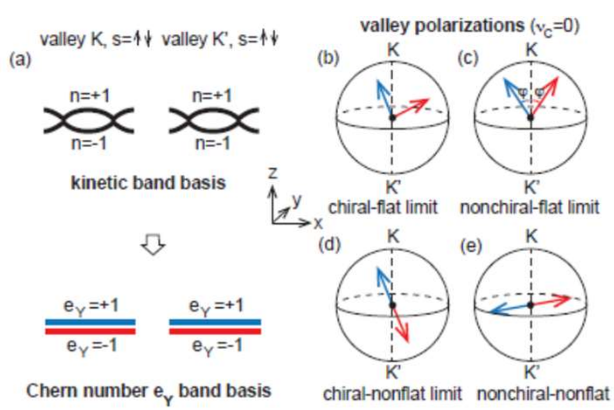
$$\sigma_{xy} \sim Ce^2/h$$

*Yazdani group, **(2020)**; Young group, **(2020)**.*
*Nadj-Perge group, **(2020)**; Andrei group, **(2020)**.*
*Jarillo-Herrero group, **(2020)**.*

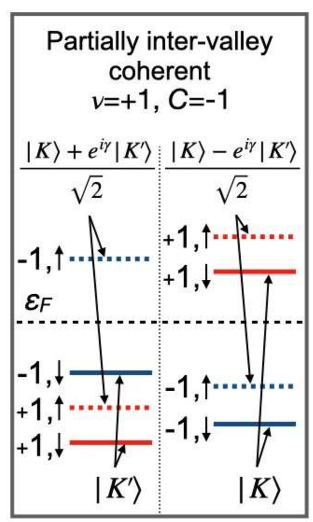
***Energy gaps:* CCI (1meV) >> LL (0.1meV)**
***Quantization field:* CCI (0.3T) << LL (3T)**
***STM:* interaction induced gaps show spectral broadening**

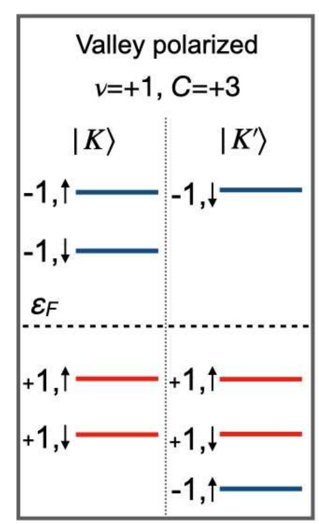
TBGIV → Interaction induced symmetry breaking





B. Lian, Z.-D. Song, … , B. A. Bernevig,
arXiv:2009.13530 (2020).





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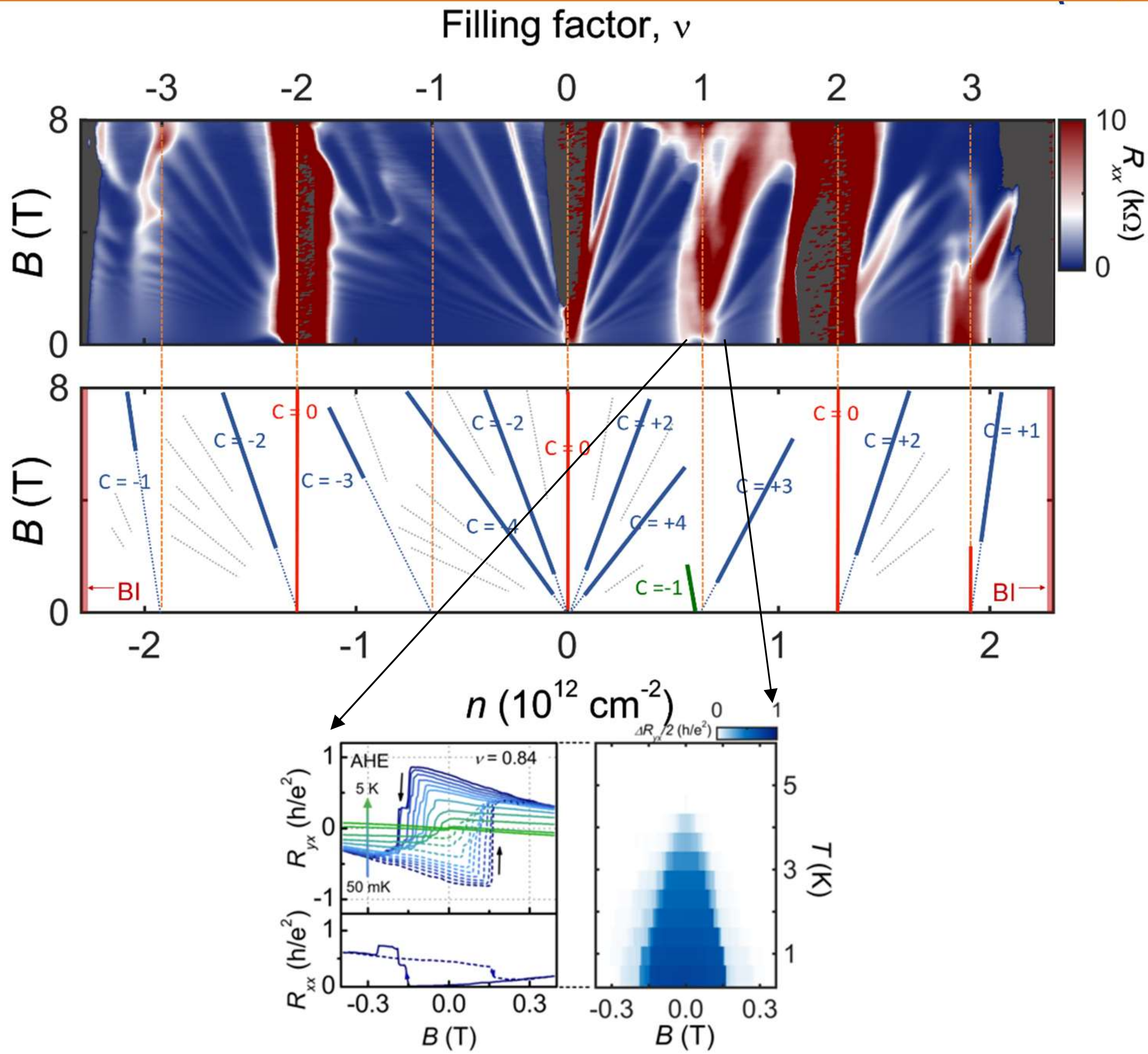
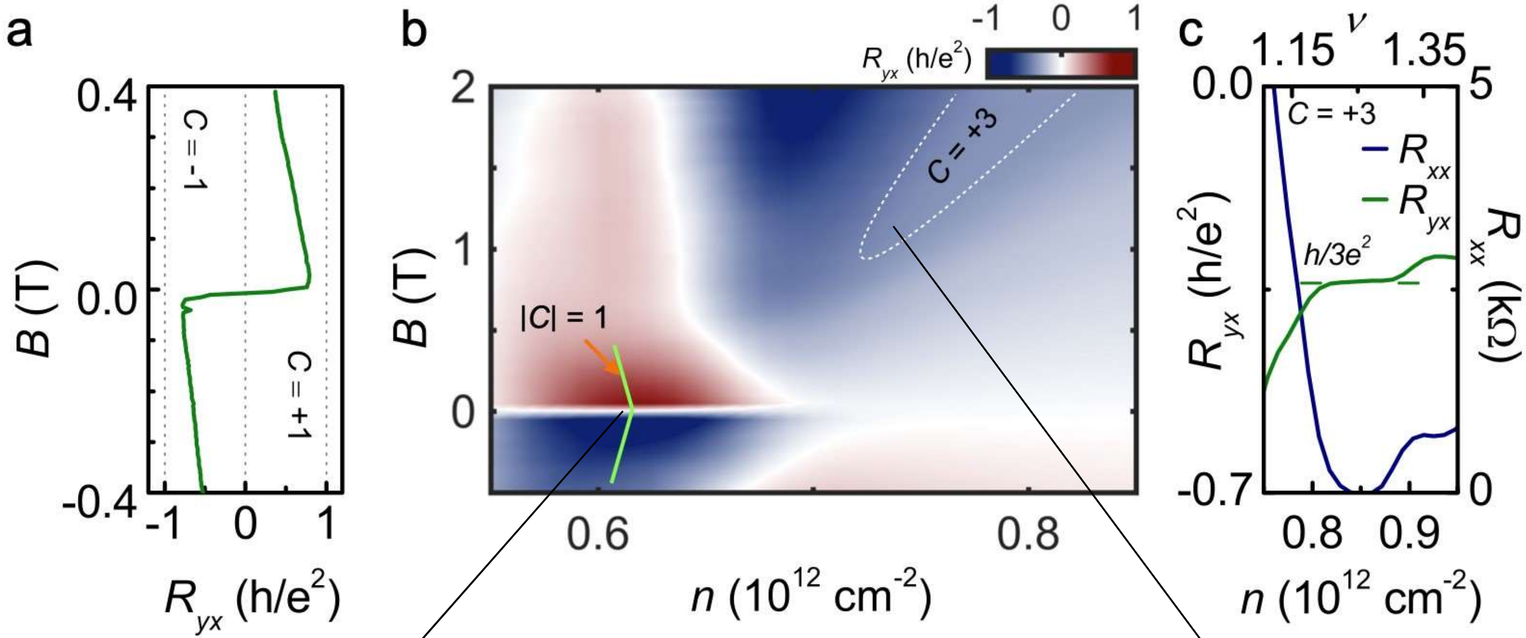
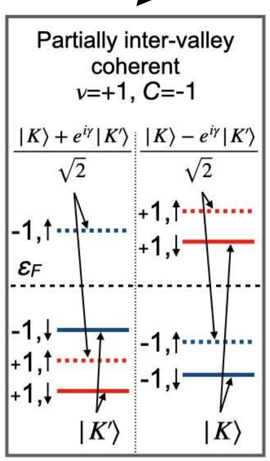
Observation of a zero-field CCI with (1,1)



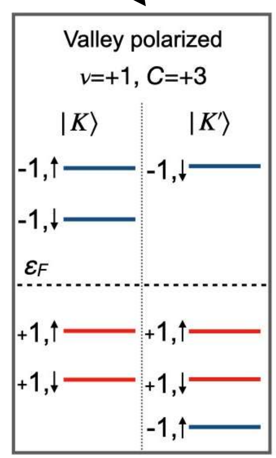
P. Stepanov, M. Xie, … , A. MacDonald, B. A. Bernevig, DKE, **in preparation (2020).**

Competition of (1,1) and (3,1) in B-field

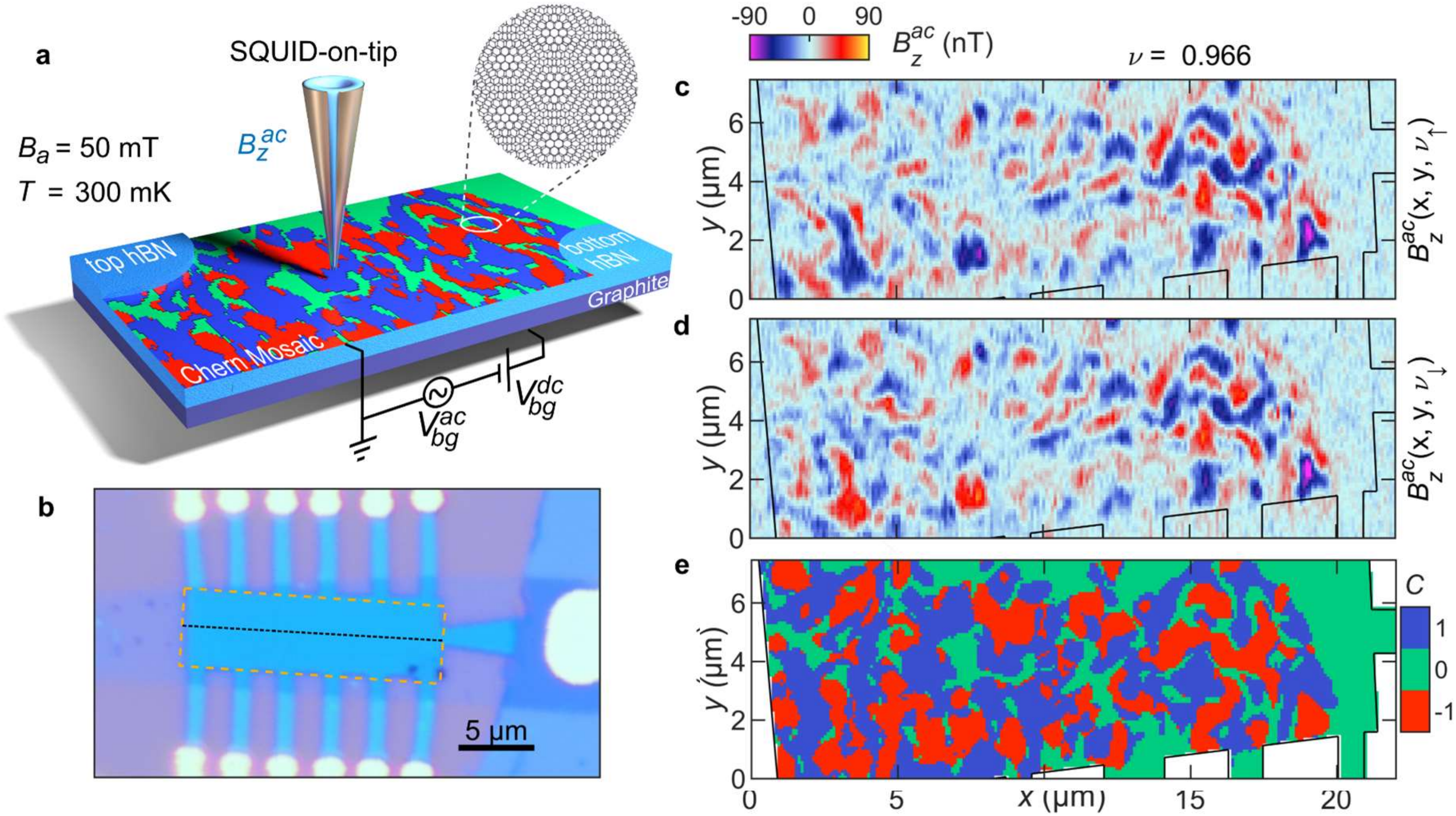




B-field induced transition from (1,1) and (3,1)



Disordered domain structure and Chern mosaic



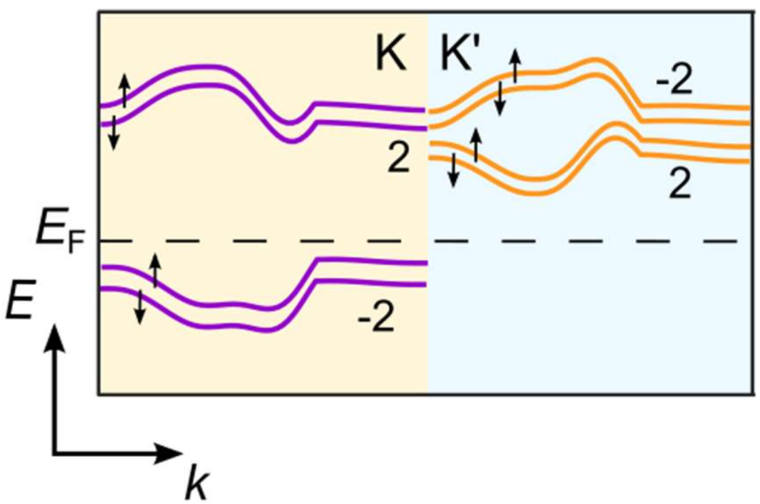
→ Rich and disordered domain wall structure for different ν

→ Variety of orbital states with different Chern numbers

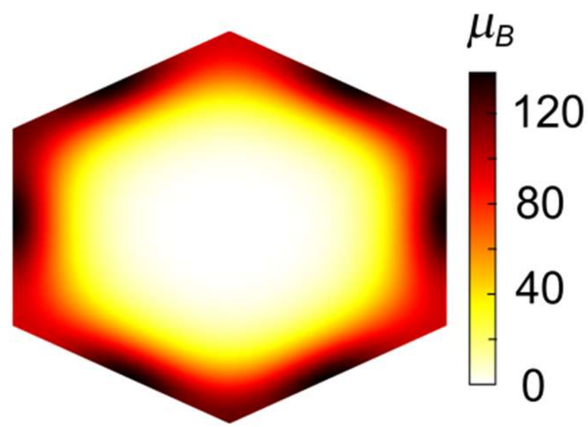
S. Grover, M. Bocarsly, … , A. Stern, E. Berg, DKE, E. Zeldov Nature Physics – in press (2022).

Possible ground state of the ν=-2 state

Valley polarized state with C=-2:



Orbital magnetization ~ 10μ_B :



Outline

Magic angle graphene - MAG

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]

Correlated insulator behaviour at half-filling in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Ahmet Demir[1], Shiang Fang[2], Spencer L. Tomarken[1], Jason Y. Luo[1], Javier D. Sanchez-Yamagishi[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4], Ray C. Ashoori[1] & Pablo Jarillo-Herrero[1]

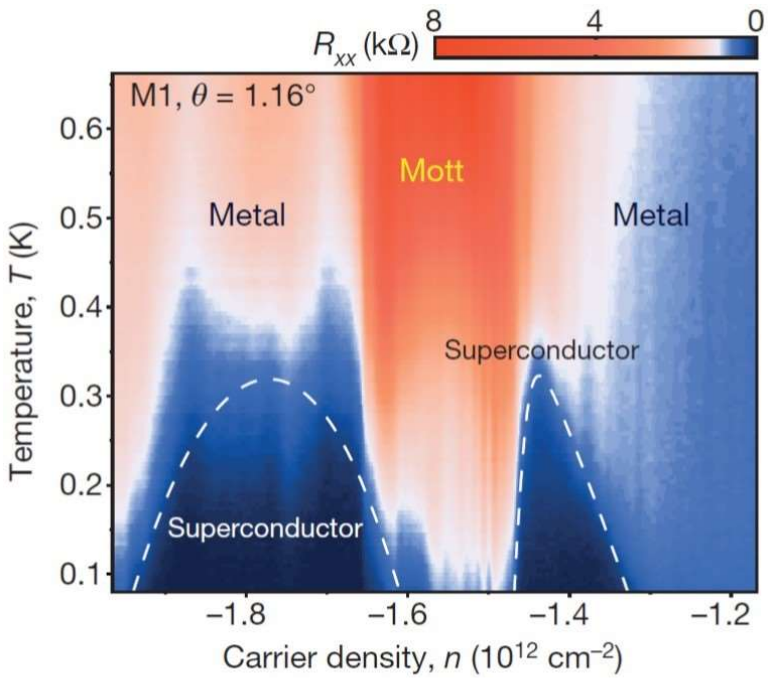
physicsworld

MATERIALS NEWS

Discovery of 'magic-angle graphene' that behaves like a high-temperature superconductor is *Physics World* 2018 Breakthrough of the Year

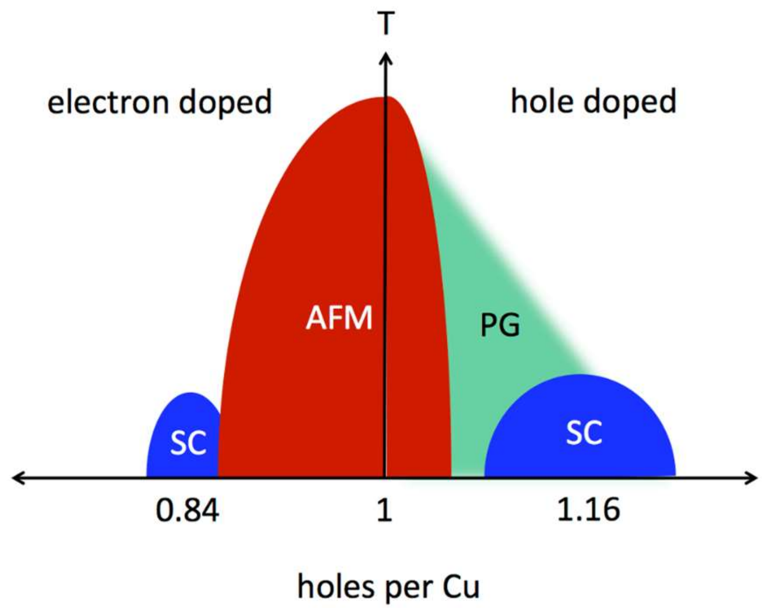
13 Dec 2018 Hamish Johnston

Phase-diagram MAG:



Y. Cao, et. al. ***Nature (2018)**;*

Phase-diagram cuprates:

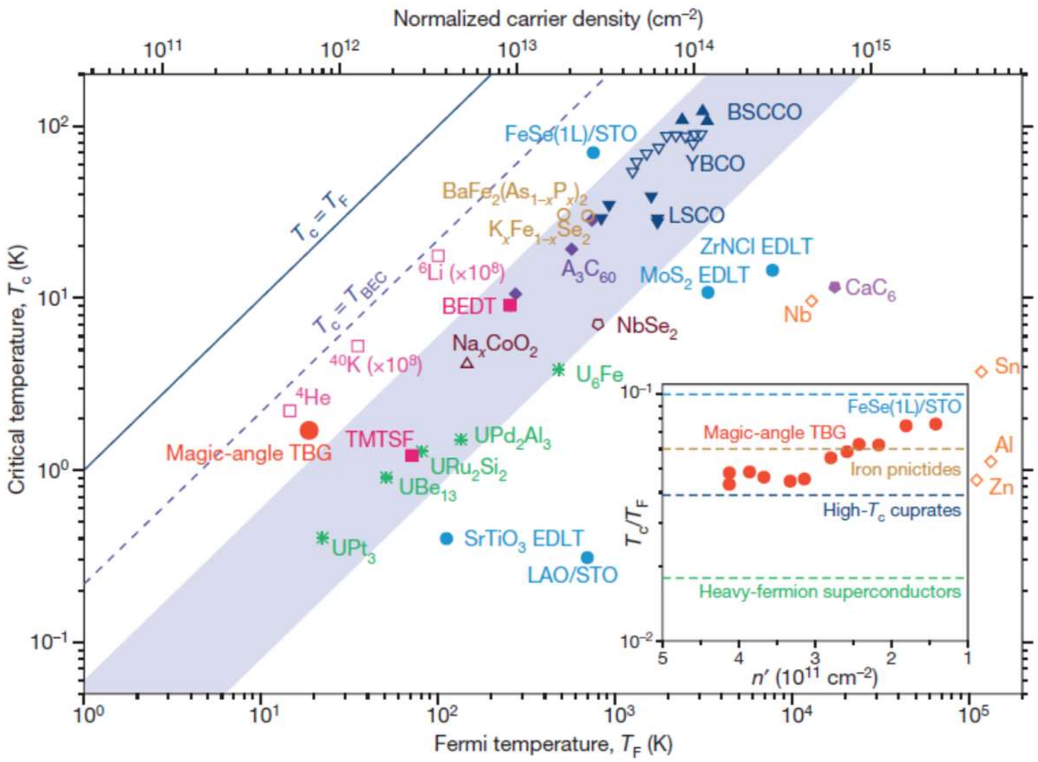


Dmitri K. Efetov

ICFO Research Group Low Dimensional Quantum Materials

Unconventional superconductivity in MAG?

Uemura plot:

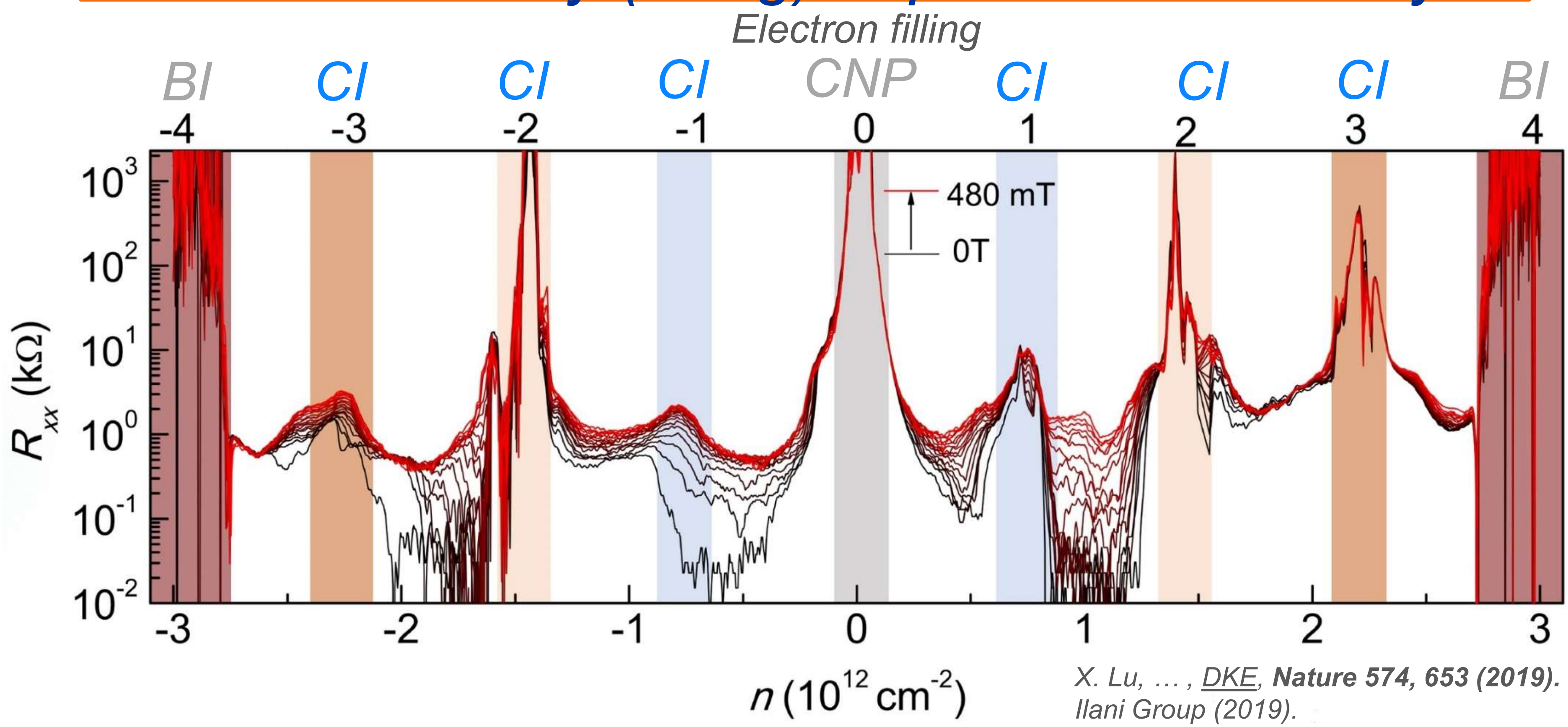


Superconductivity in MAG:

- *Record low carrier density of any superconductor*
- *T_c ~ 1.7K*
- *Record strong coupling – defined by T_c/T_f ~ 0.1*
- *Proximity to integer filling Mott states – non e-ph mechanism?*

2x - Y. Cao, et. al. ***Nature (2018)****;*

Carrier density (filling) dependent resistivity

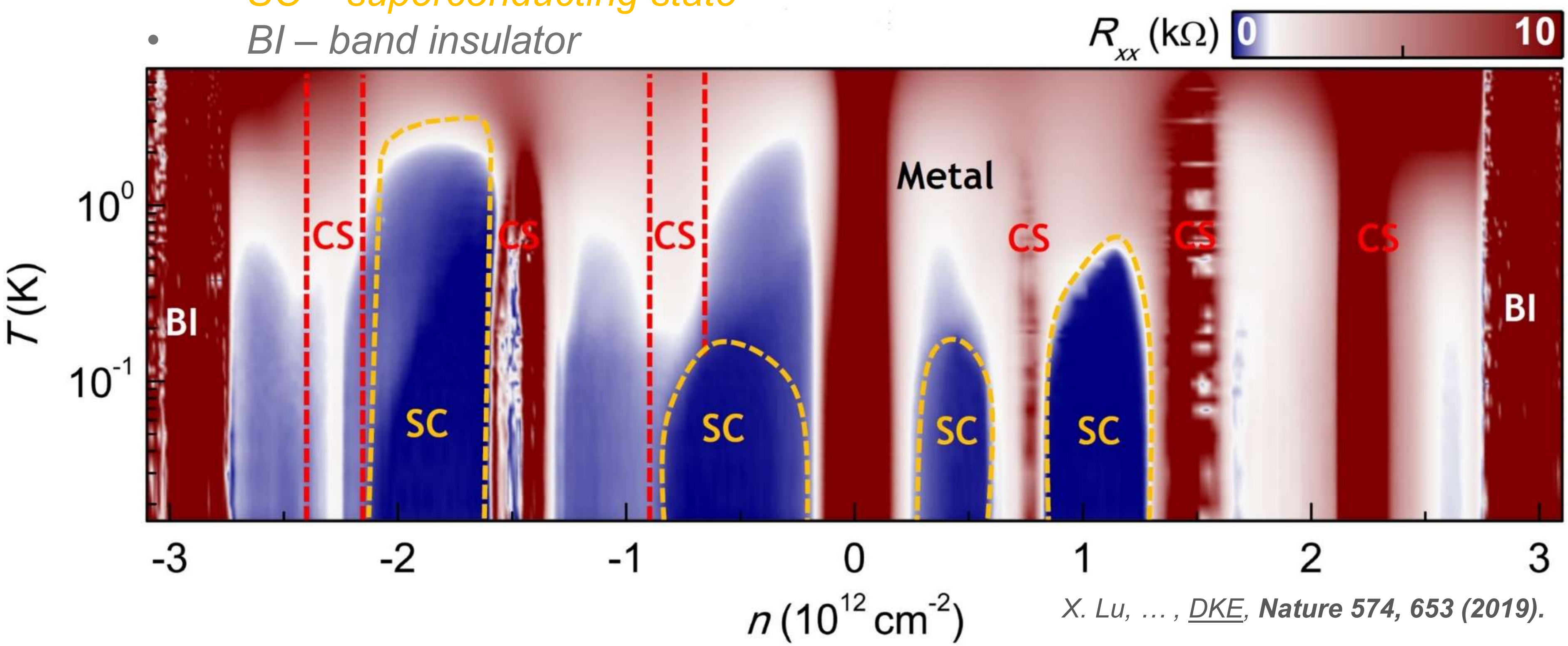


X. Lu, … , DKE, ***Nature 574, 653 (2019).***
Ilani Group (2019).
Yazdani Group (2019).

Correlated insulators at all integer fillings
v = 0,±1,±2,±3

Phase diagram

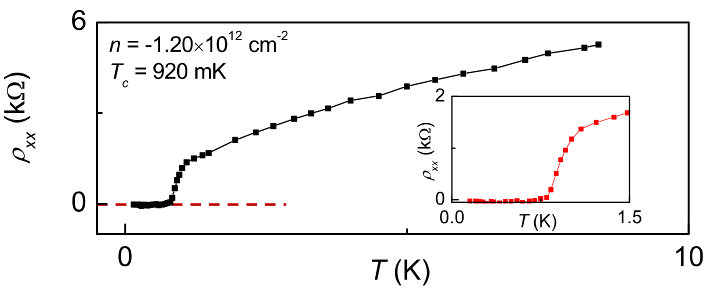
- CS – correlated state
- SC – superconducting state
- BI – band insulator



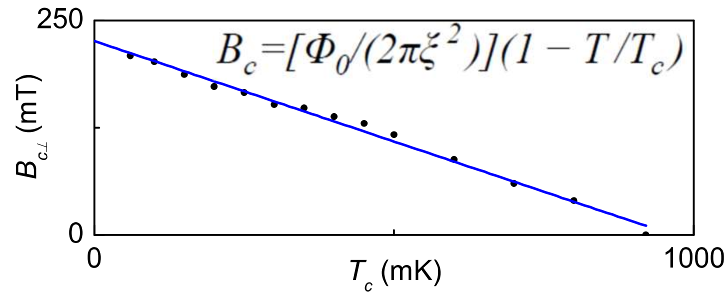
X. Lu, … , DKE, **Nature 574, 653 (2019).**

Signatures of Superconductivity

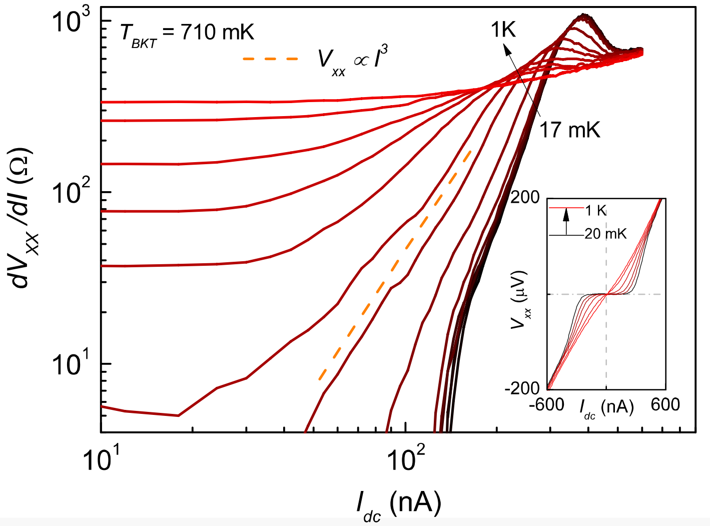
Critical temperature T_C:



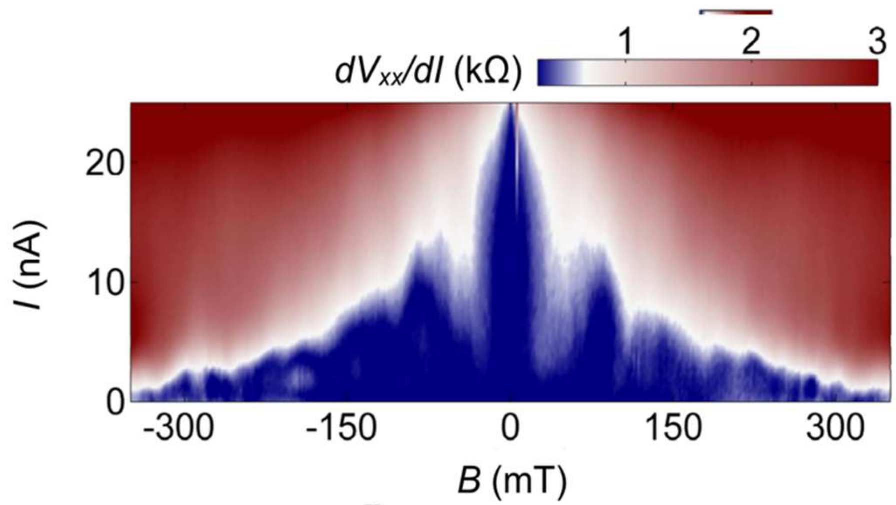
Critical B-field B_C:



Critical current I_C:



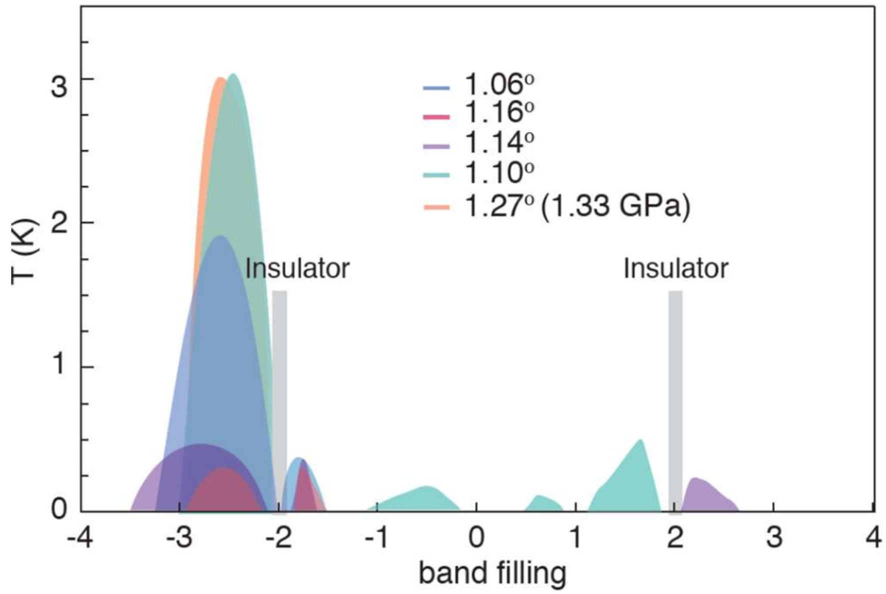
Frauenhofer interference (disorder):

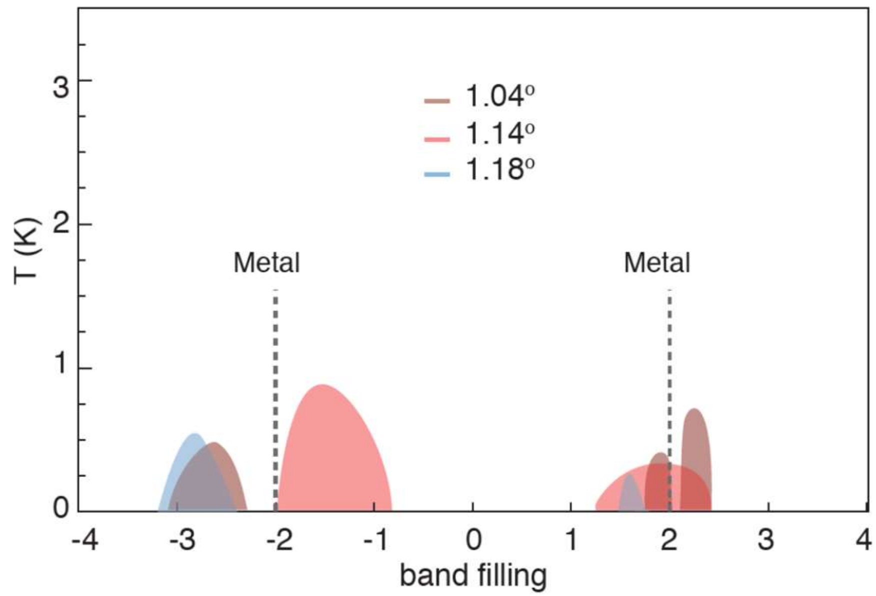


Consistent with GL and BKT theories with:

T_c ~ 1K, H_c ~ 100mT, I_c ~ 10nA, ξ ~ 50nm

Evolving phase diagram 2020





L. Balents, C. Dean, DKE, A. Young, **Nature Physics (2020)**.

Open questions:

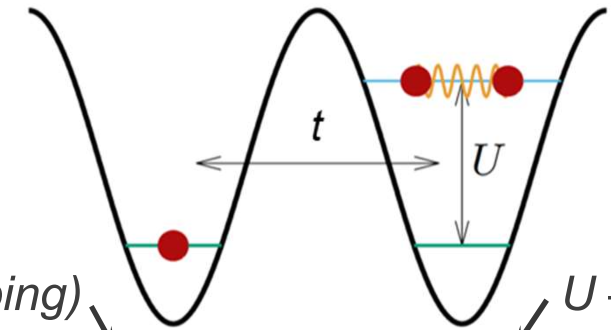
- *Nature of SC and CI?*
- *Competition of SC and CI, or mother-child-relationship?*
- *Similarity to cuprates - or interesting in its own right?*

Key challenges:

- *Twist-angle control and homogeneity*
- *Strain control and homogeneity*
- *Dielectric environment*
- *Statistics*

Outline

Novel control knobs for Mott systems



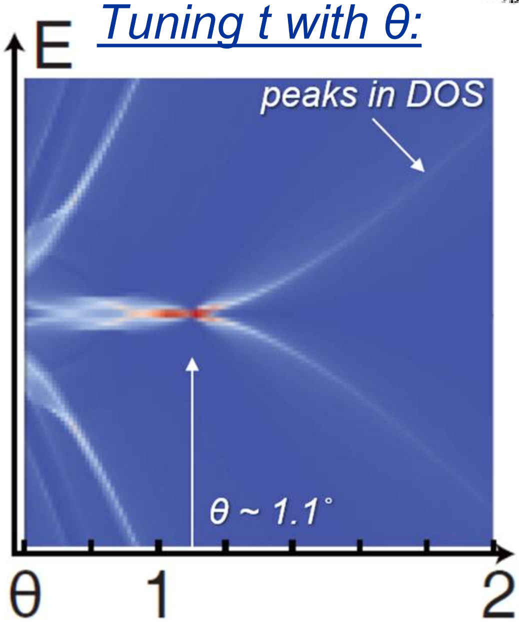
t – kinetic energy (hopping)

U – onsite energy (Coulomb)

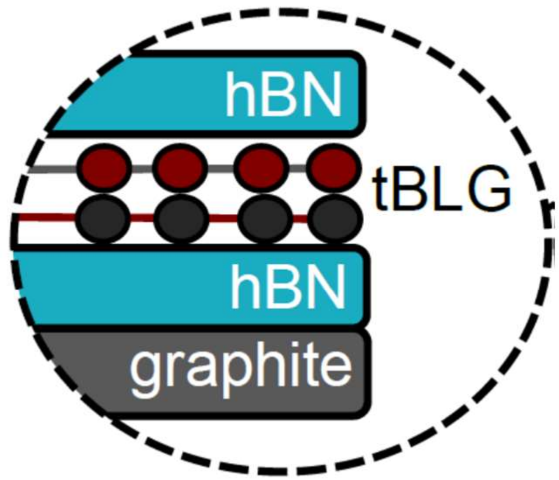
$U = e^2\theta/(4\pi\varepsilon_0\kappa a)$

$$H = -t \sum_{i,j,\sigma} c^{\dagger}_{i,\sigma} c_{j,\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Tuning t with θ:

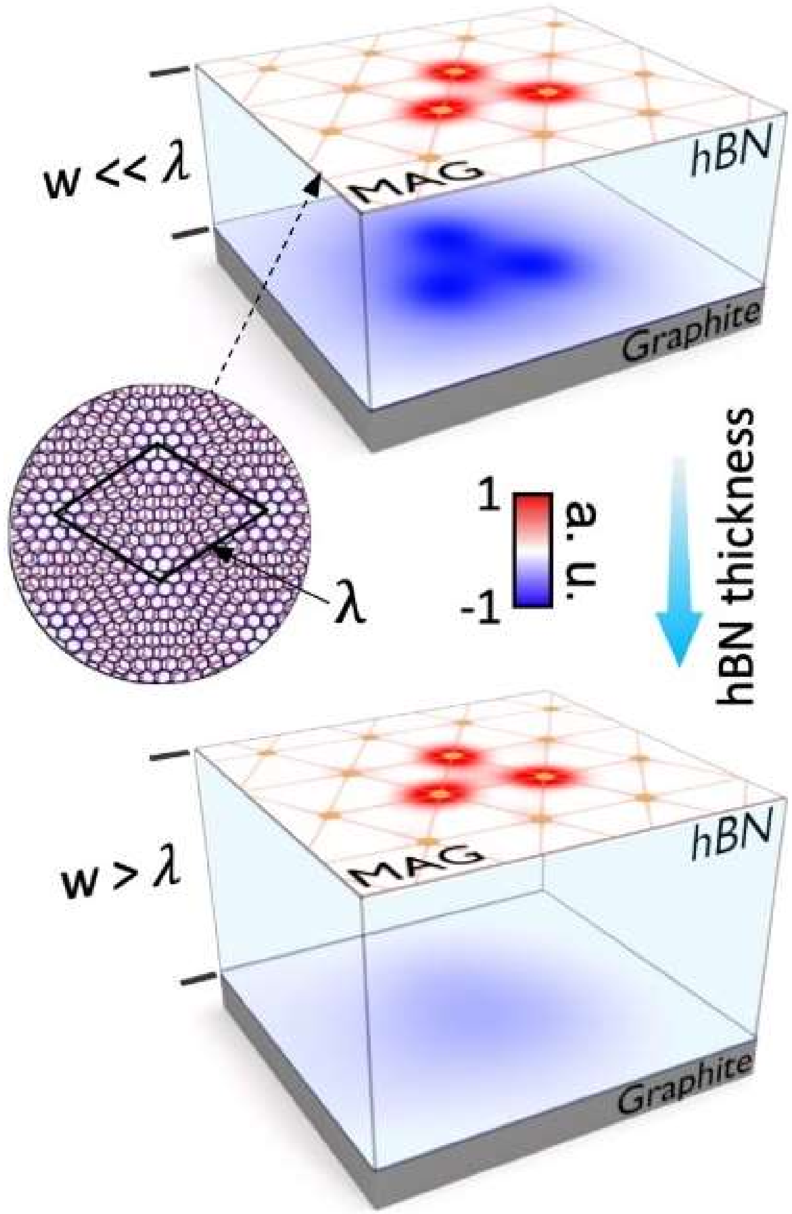


Tuning U with screening:

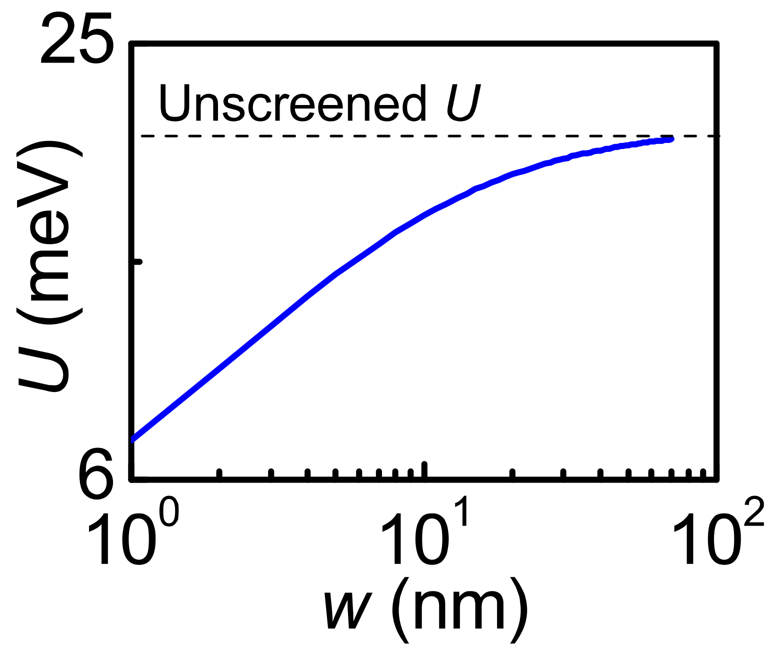


→ control of U/t ratio

Screening with proximal metal layers



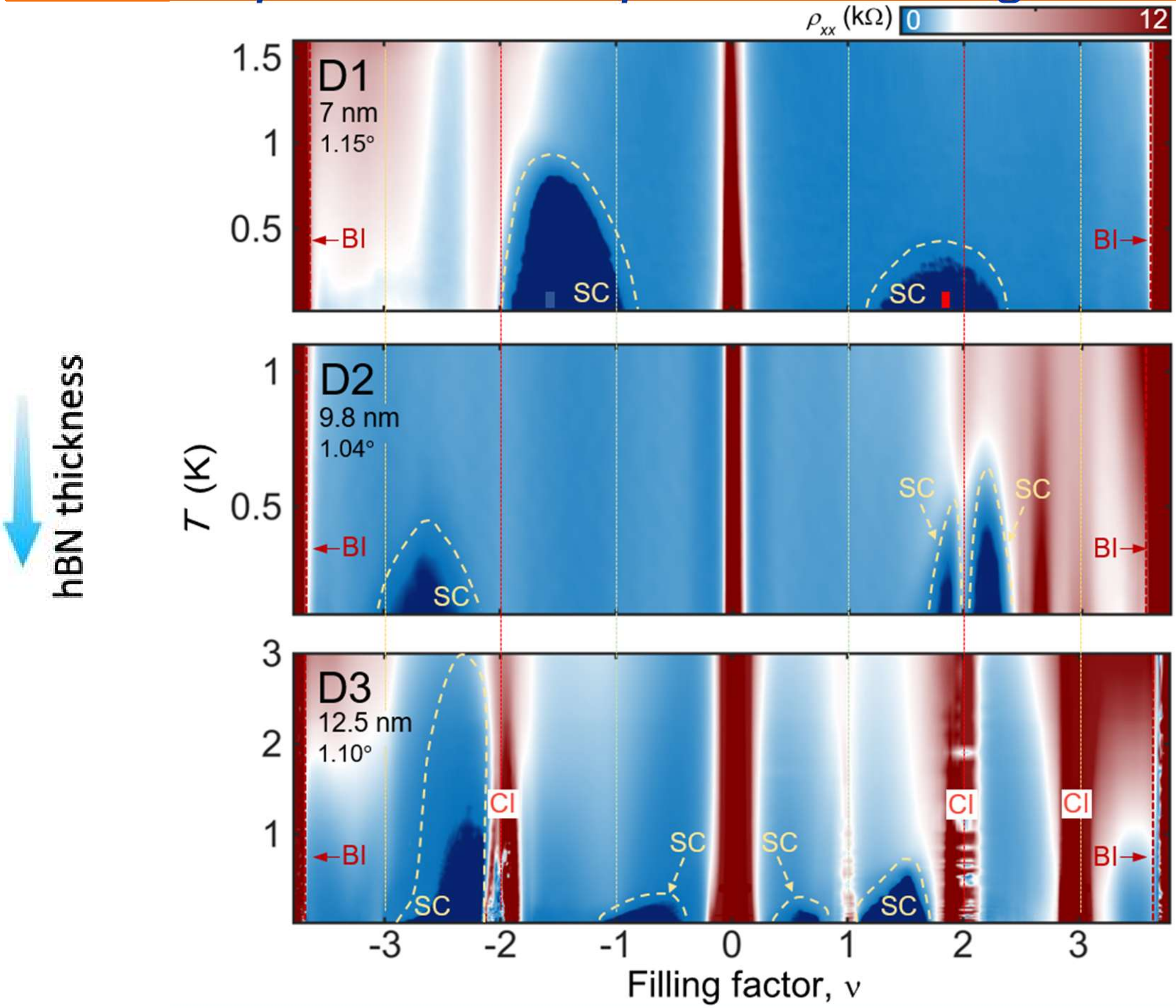
Screened onsite energy U:



$$U = \int_0^\infty d^2\boldsymbol{x}\, d^2\boldsymbol{x}' |W(\boldsymbol{x})|^2 |W(\boldsymbol{x}')|^2 V(|\boldsymbol{x} - \boldsymbol{x}'|)$$

P. Stepanov, I. Das, … , DKE, **Nature 583, 375 (2020).**

Unperturbed superconducting domes



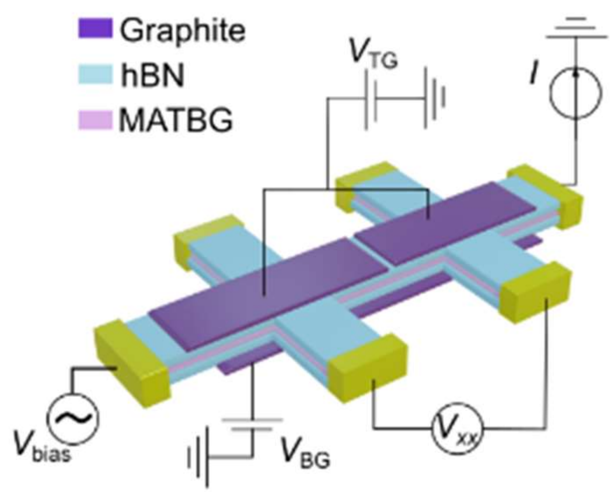
Outline

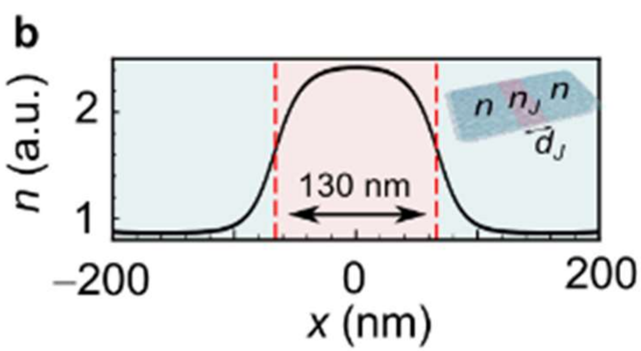
1. Introduction to 2D materials and vdW heterostructures
2. Low temperature transport measurements and twist-angle extraction
3. Correlated insulators, Fermi surface resets and SU(4) symmetry breaking
4. Chern insulators
5. Orbital magnetism
6. Superconductivity
7. Screening
8. Gate induced Josephson junctions
9. Strange metal phase
10. Reentrant correlated insulators at one magnetic flux quantum
11. Thermal conductivity in the superconducting state

Double gated θ~1.08 device

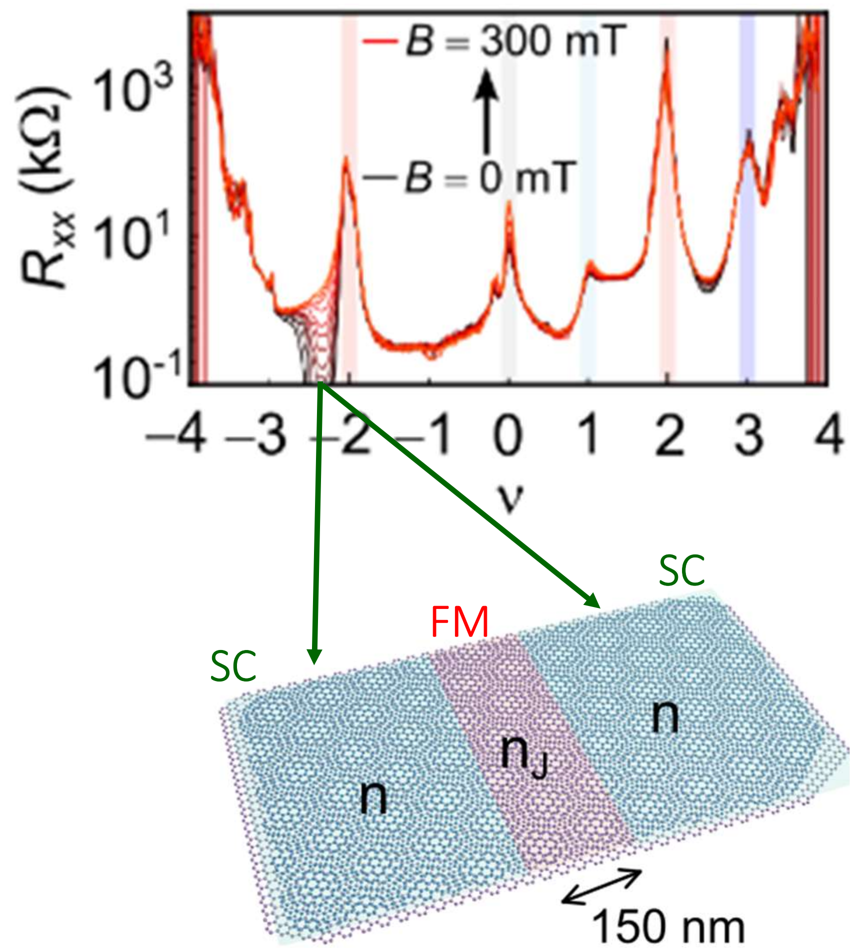
Device schematics:

Previous work by Jarrillo-Herrero and Ensslin groups, Nature Nano (2021).



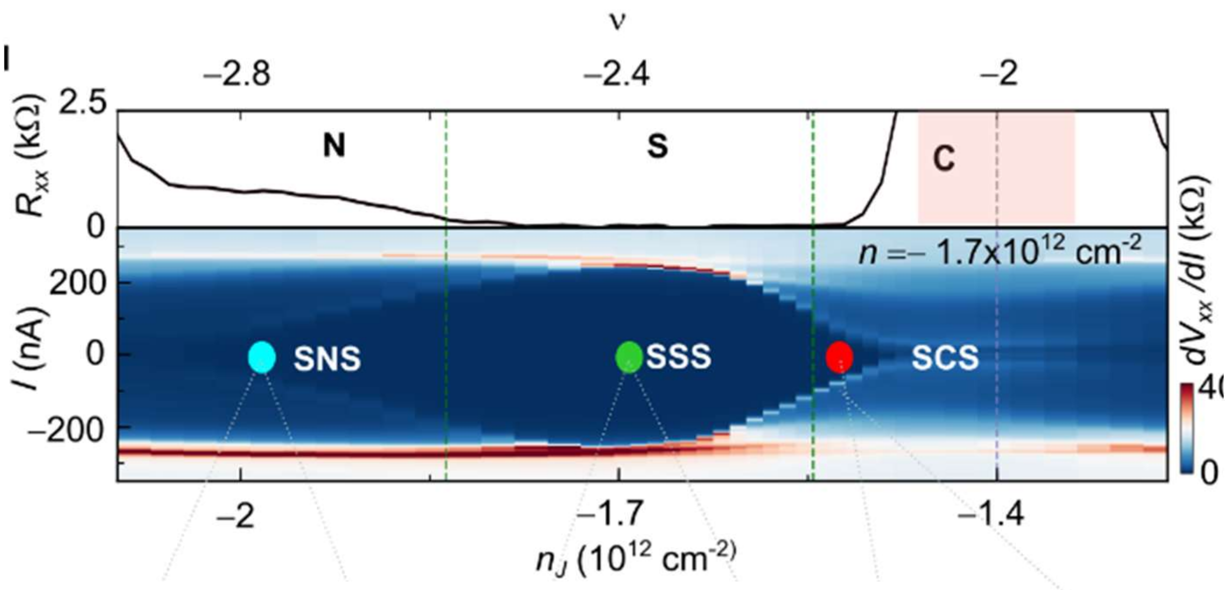


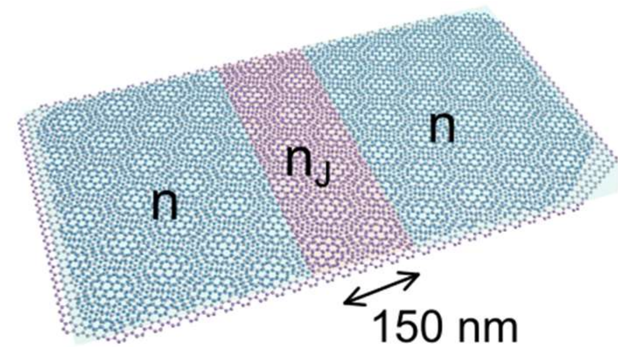
R_{xx} vs. filling ν:



J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

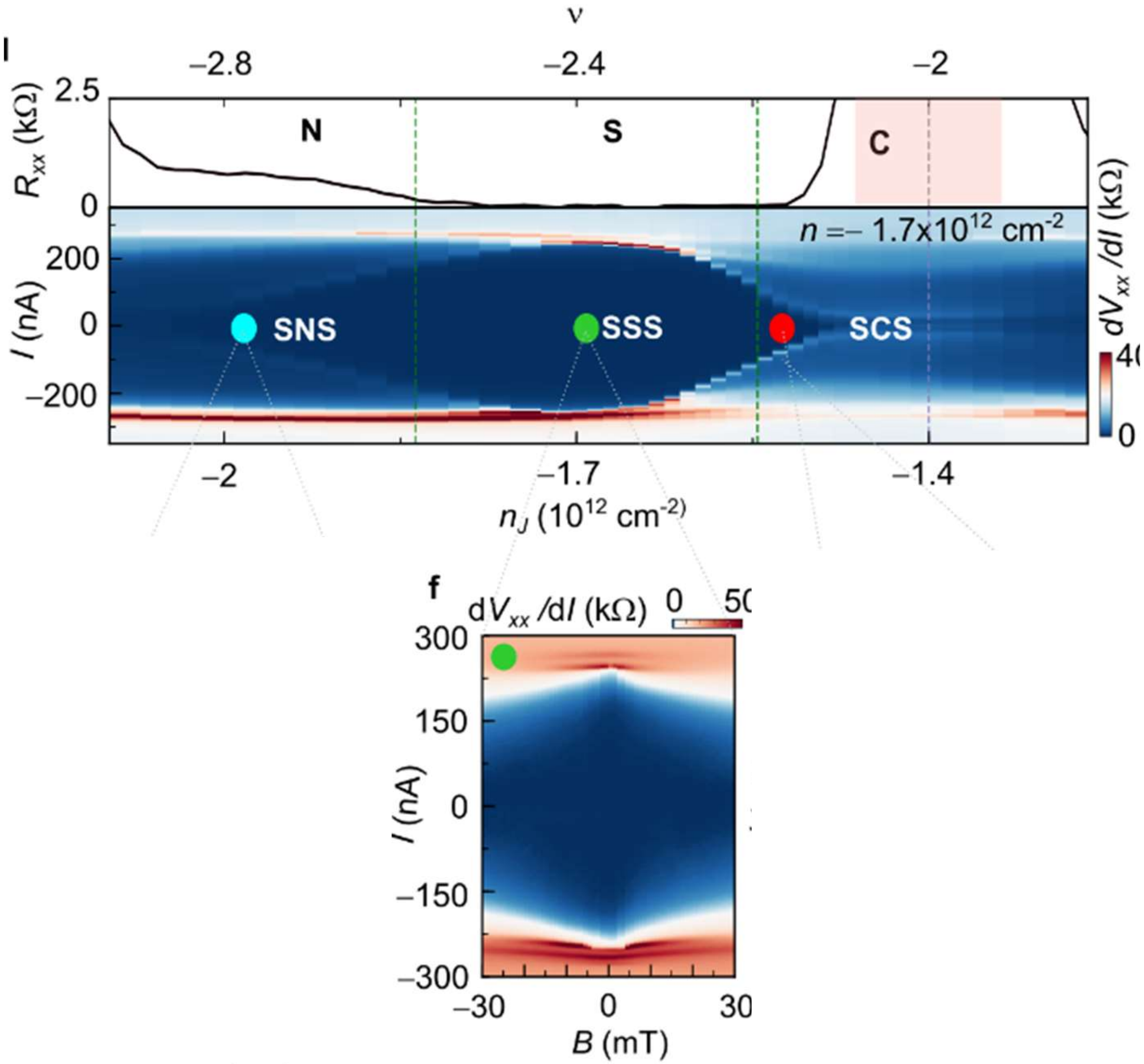
MATBG Josephson Junctions

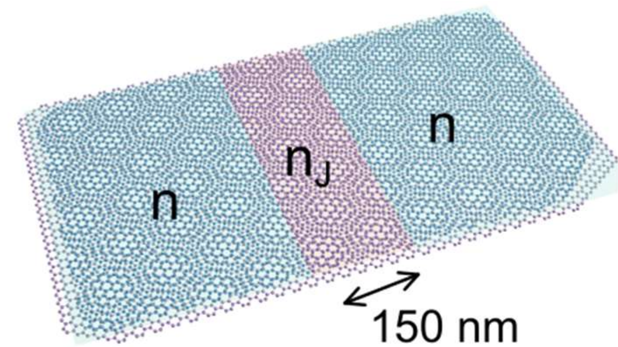




J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

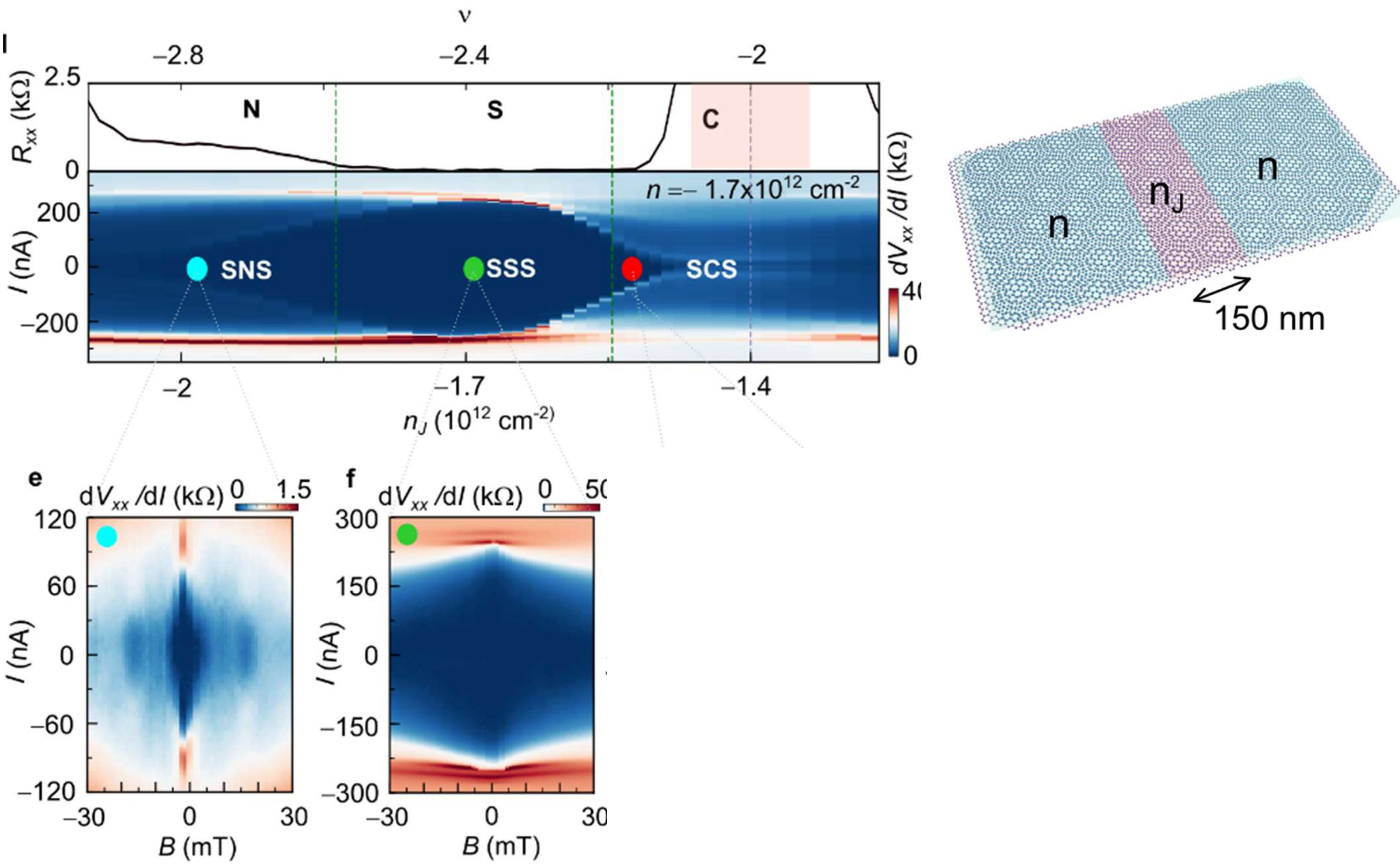
MATBG Josephson Junctions





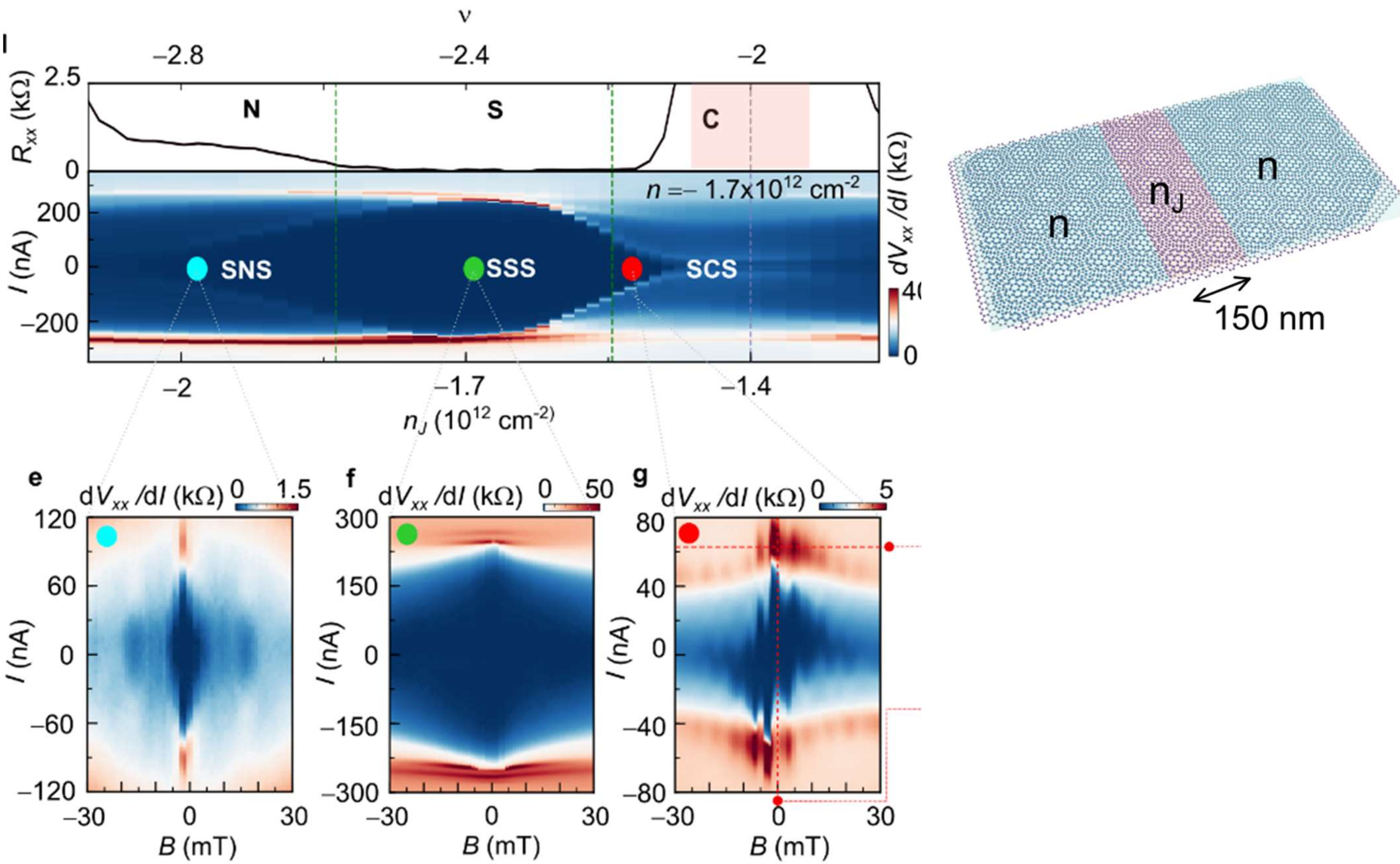
J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

MATBG Josephson Junctions



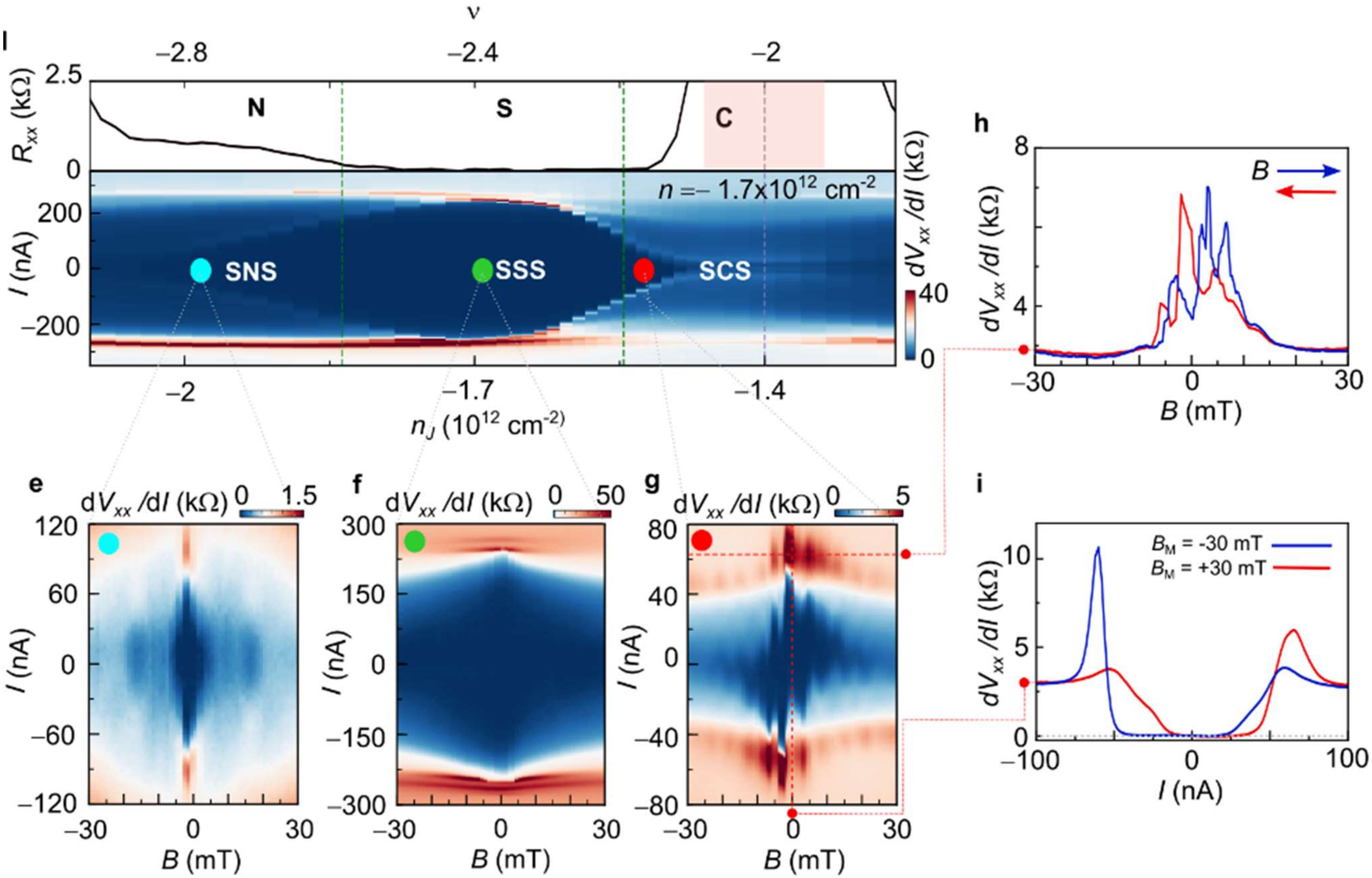
J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

MATBG Josephson Junctions



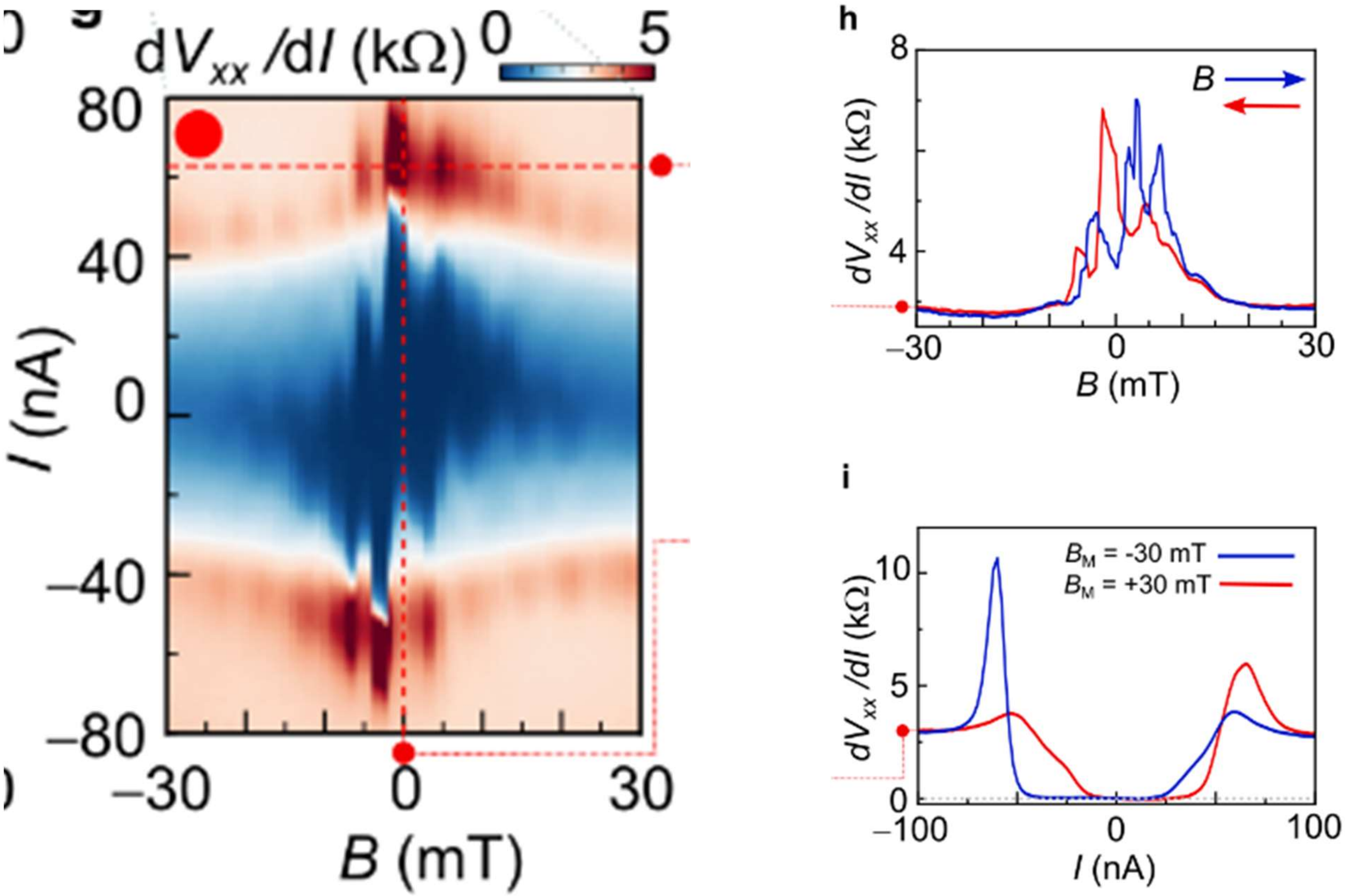
J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

MATBG Josephson Junctions



J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

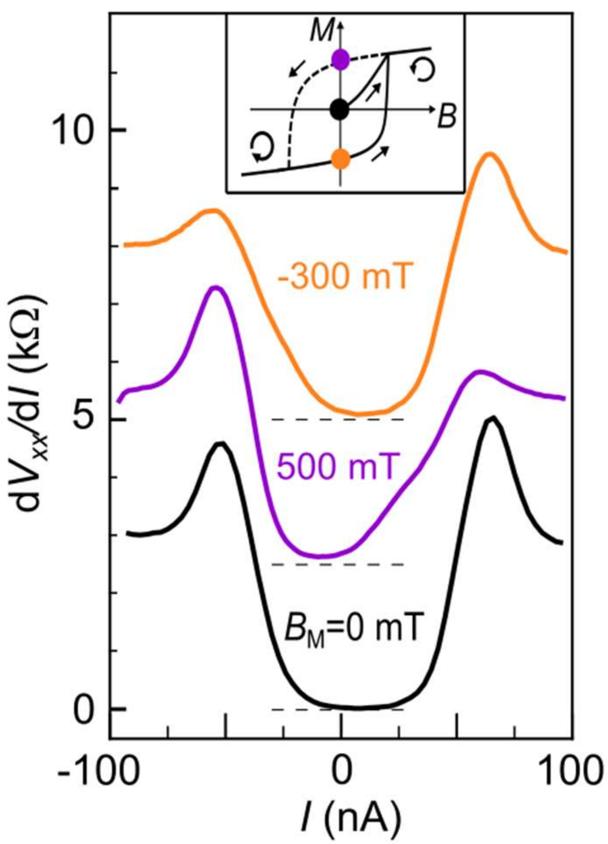
MATBG Josephson Junctions



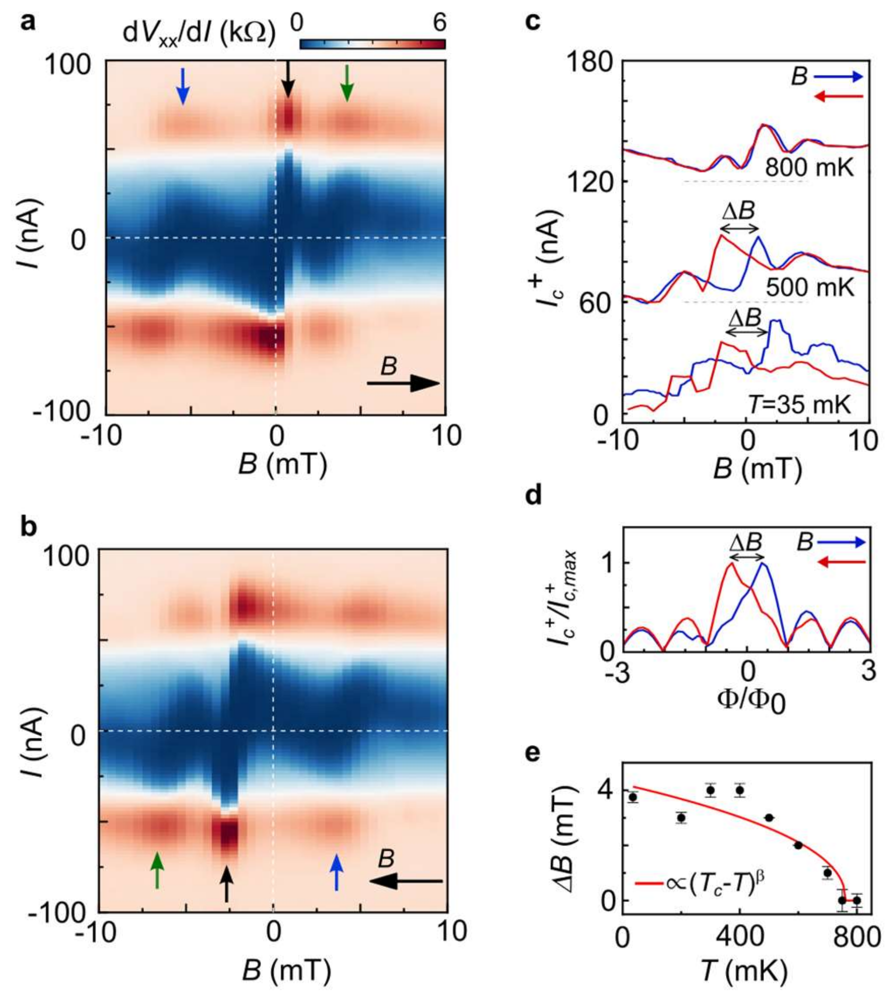
J. Diez-Merida, A. Díez-Carlón, S. Y. Yang, … , K.T. Law, DKE, arXiv:2110.01067 (2021).

Magnetization reversal and hysteresis

Magnetization reversal:

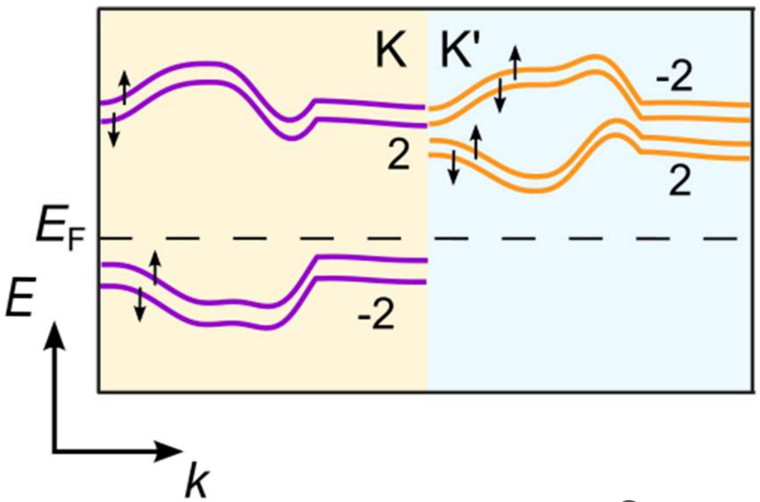


Hysteresis and symmetry switching:

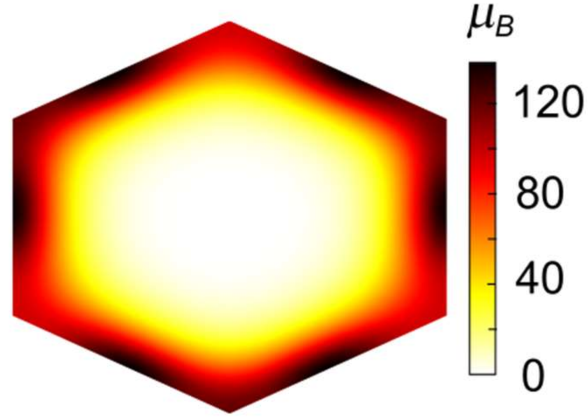


Possible ground state of the ν=-2 state

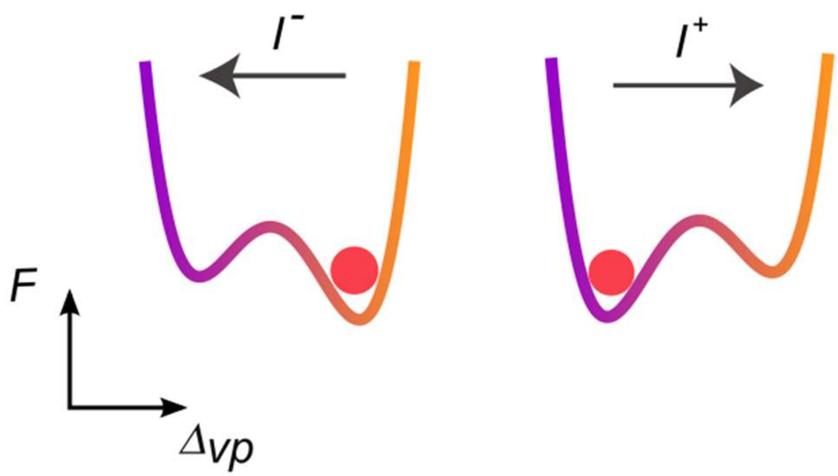
Valley polarized state with C=-2:



Orbital magnetization ~ 10μ_B :

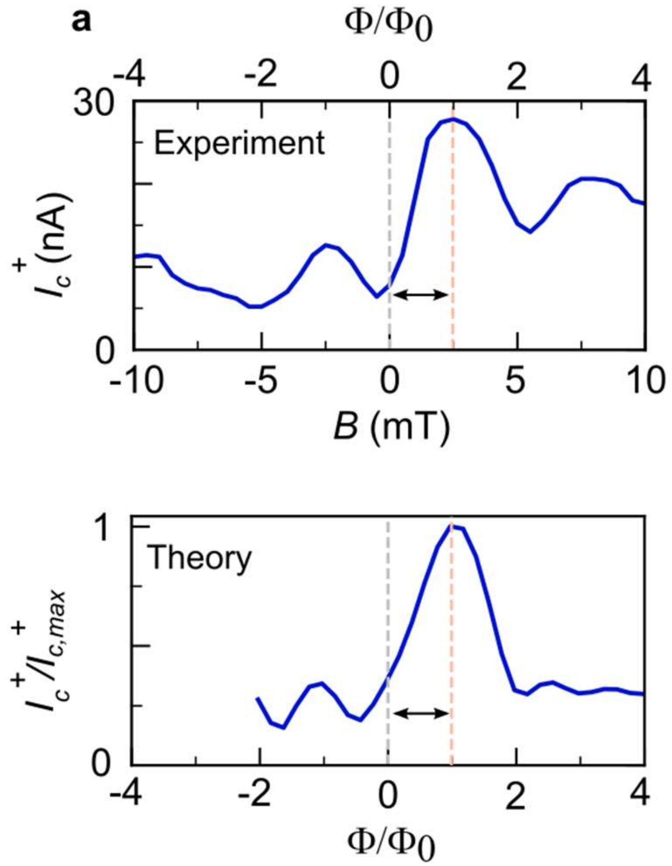


Current induced switching:

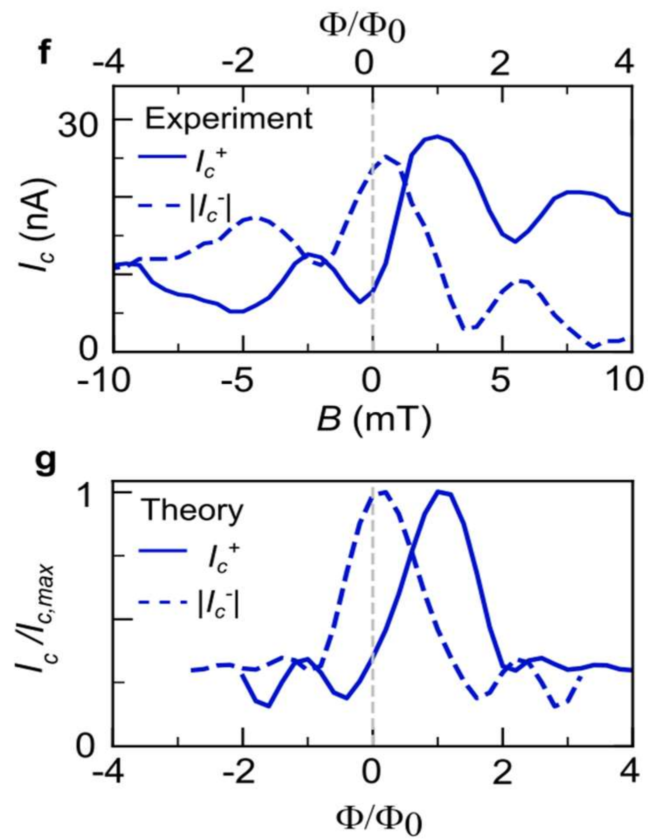


Phase shift and current switching Frauenhofer

Phase shifted Frauenhofer:



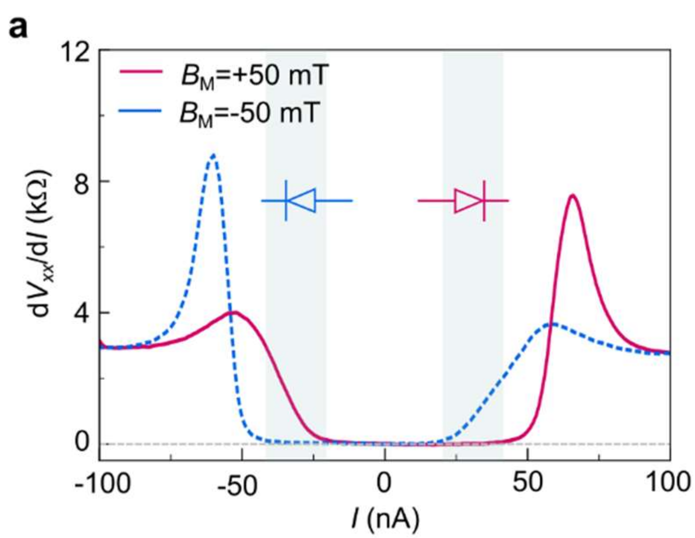
Current switching of Frauenhofer:



→ Phase shift of ~ 3-4μ_B

→ Clear current induced symmetry switching

Superconducting Diode behavior



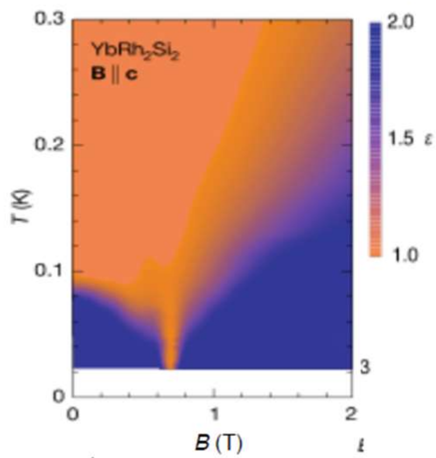
Outline

Strange metals and quantum criticality

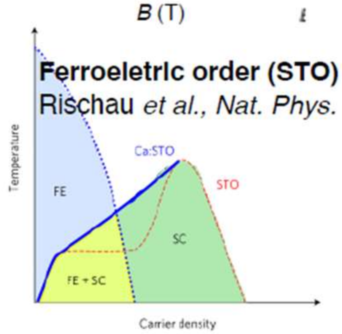
Electrical transport

Quantum criticality

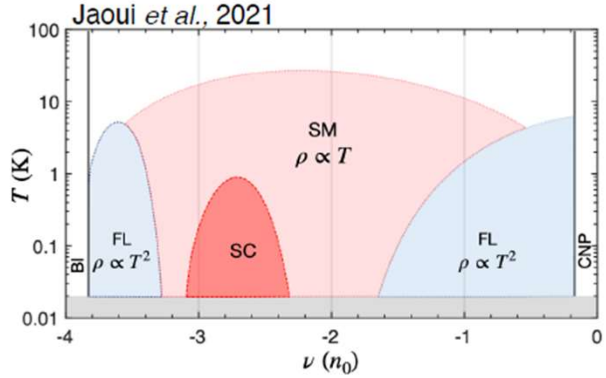
Antiferromagnet (HF)
J. Custers *et al.*, *Nature* **424** (2003)



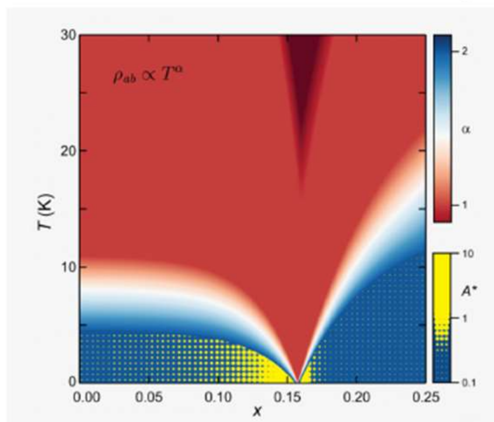
Ferroeletric order (STO)
Rischau *et al.*, *Nat. Phys.* **424** (2017)



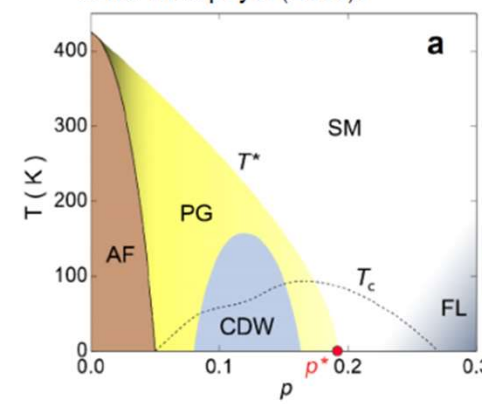
MATBG
Jaoui *et al.*, 2021



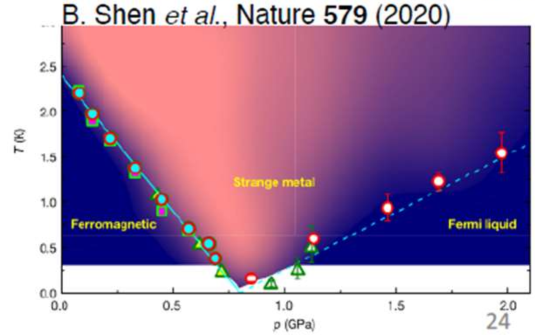
Iron chalcogenides (nematic order)
S. Licciardello *et al.*, *Nature* **567** (2019)



Cuprates
Proust & Taillefer, Annual Reviews of cond. Mat. phys. (2019).



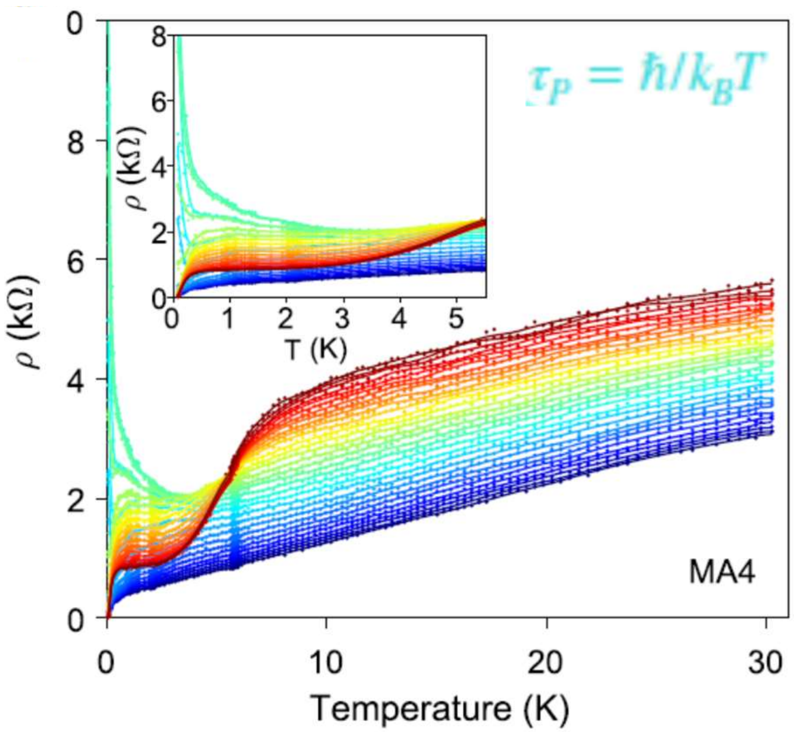
Pure ferromagnetic Kondo lattice (HF)
B. Shen *et al.*, Nature **579** (2020)



→ Linear R vs. T and B close to magnetic phase transitions
→ Planckian scattering rates

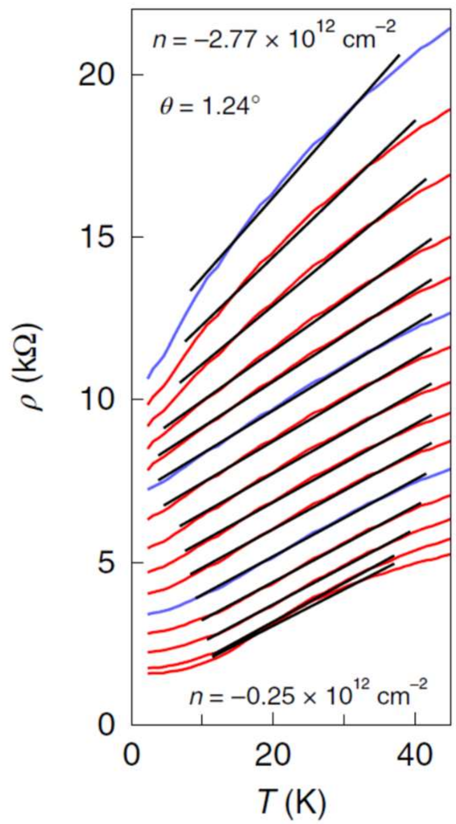
Linear T-dependence - strange metal or e-ph?

Strange metal in MATBG?:



Y. Cao, … , Pablo Jarillo-Herrero, PRL (2020).

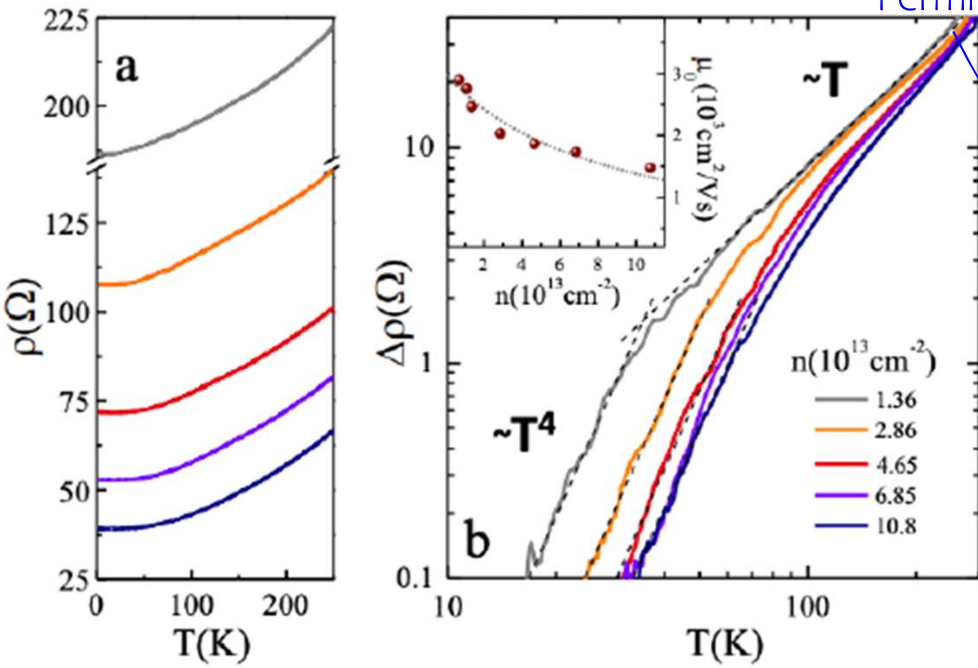
E-ph interaction in MATBG?:



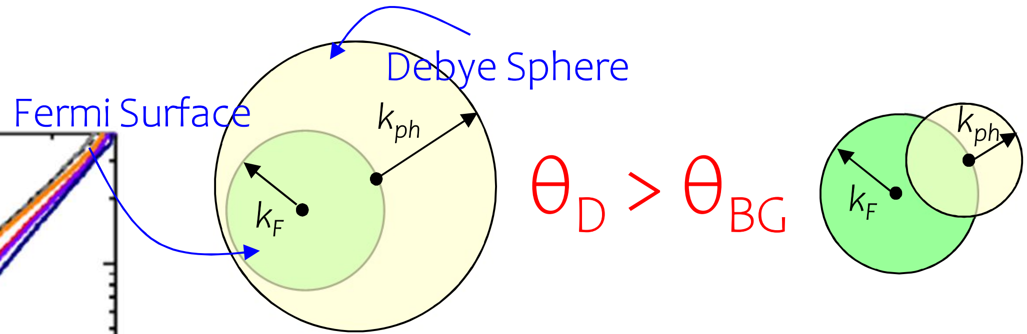
H. Polshyn, … , Andrea Young, Nature Physics (2019).

→ Linear T-dependence with ultra-steep slope T = 1 – 30K
→ Planckian scattering rates

Bloch-Grueneisen e-ph scattering in graphene



D.K.Efetov and P. Kim, PRL (2010).

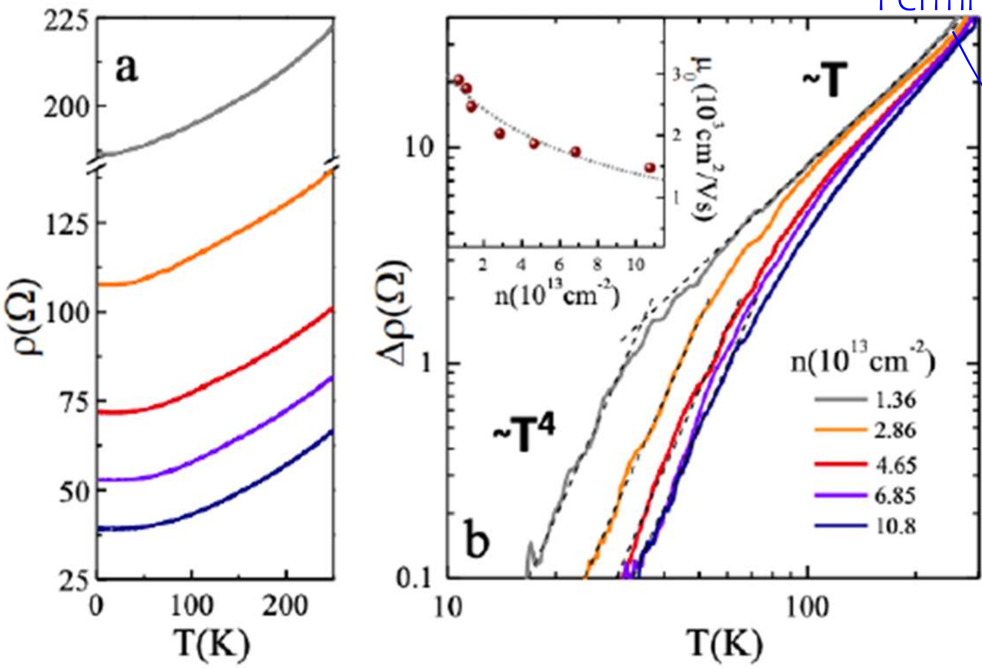


Quasi-elastic electron-acoustic phonon scattering
→ restricted by momentum transfer on Fermi surface

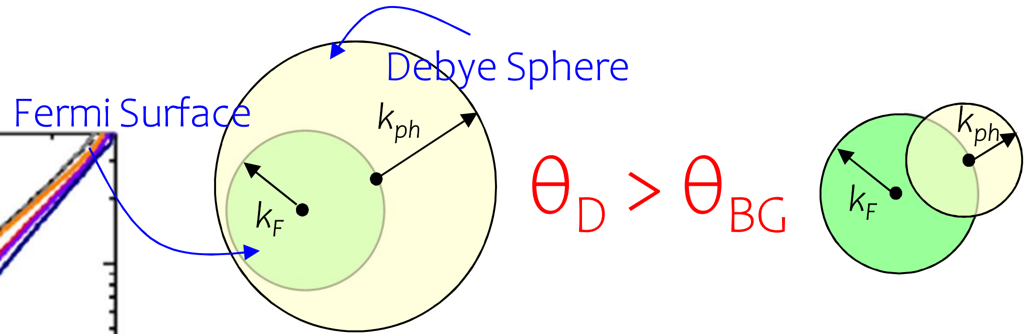
$$k_B \Theta_{BG} = 2hk_F v_s \sim \sqrt{n}$$

$$\rho_A(T) = \alpha(n) T^4 = \frac{\pi D^2 k_B}{2e^2\hbar \;\; v_F^2 v_{ph}^2 \rho_m} T$$

Bloch-Grueneisen e-ph scattering in graphene



D.K.Efetov and P. Kim, PRL (2010).



$\Theta_D > \Theta_{BG}$

Quasi-elastic electron-acoustic phonon scattering
→ restricted by momentum transfer on Fermi surface

Very small at ν = 2

$$k_B \Theta_{BG} = 2hk_F v_s \sim \sqrt{n}$$

$$\rho_A(T) = \alpha(n) T^4 = \frac{\pi D^2 k_B}{2e^2 \hbar\, v_F^2 v_{ph}^2 \rho_m} T$$

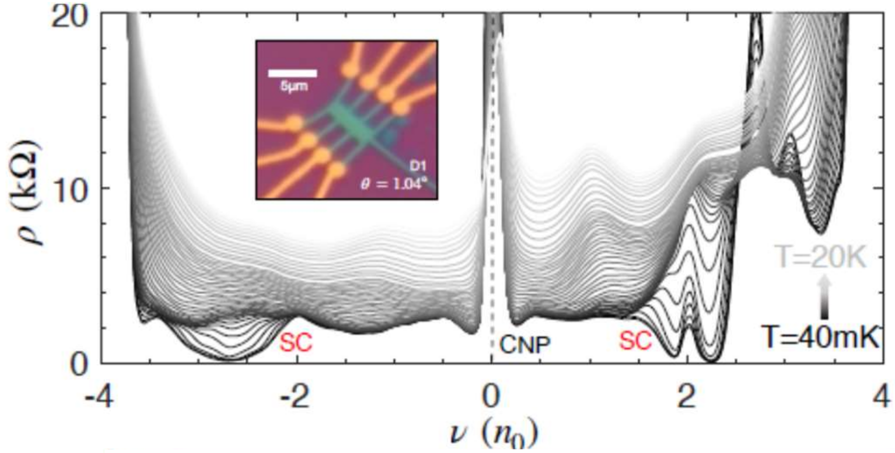
Very small

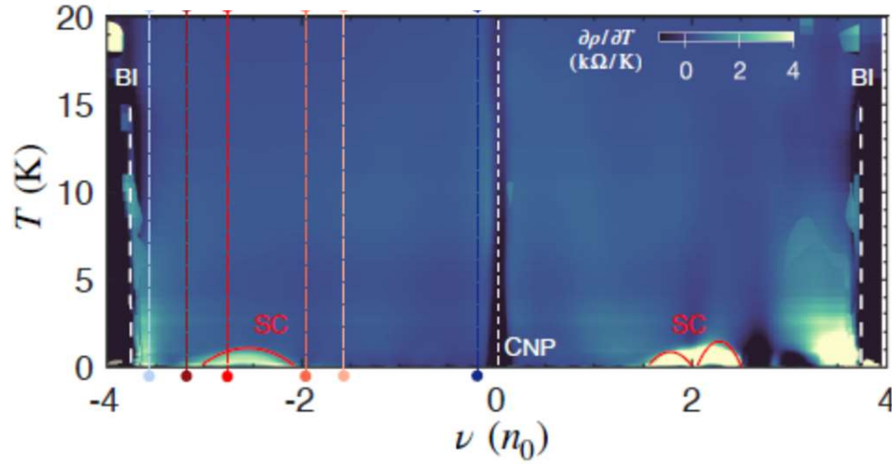
For MATGB:

→ Linear T-dependence above $\Theta_{BG} > 1K$

→ Ultra-steep slope due to reduced Fermi velocity

Exploring the T →0 limit in a screened device



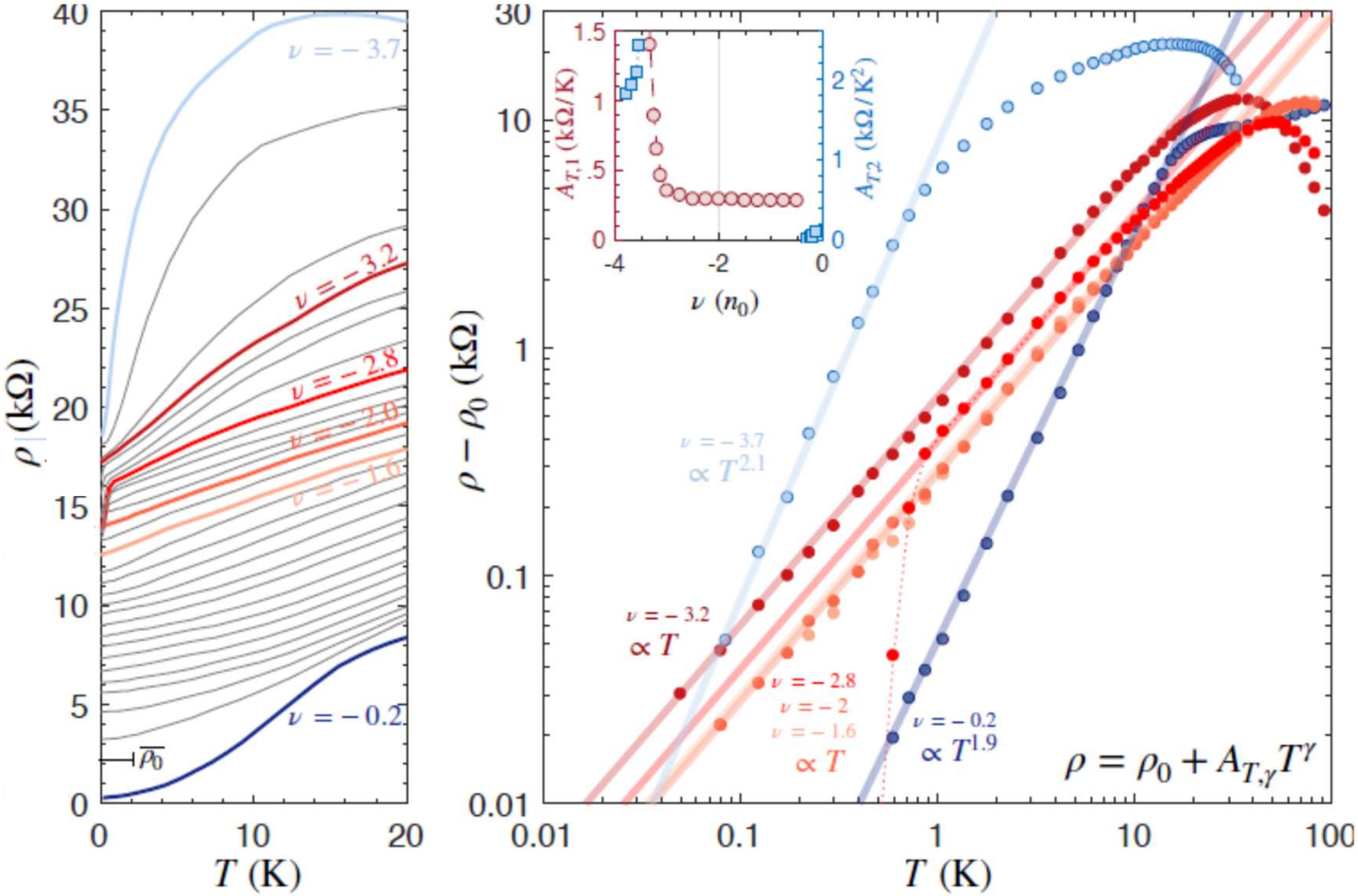


A. Jaoui, … , L. Levitov, DKE, Nature Physics (2022).

→ Screened devices

→ Measurements in the ultra-low T regime T < 1K

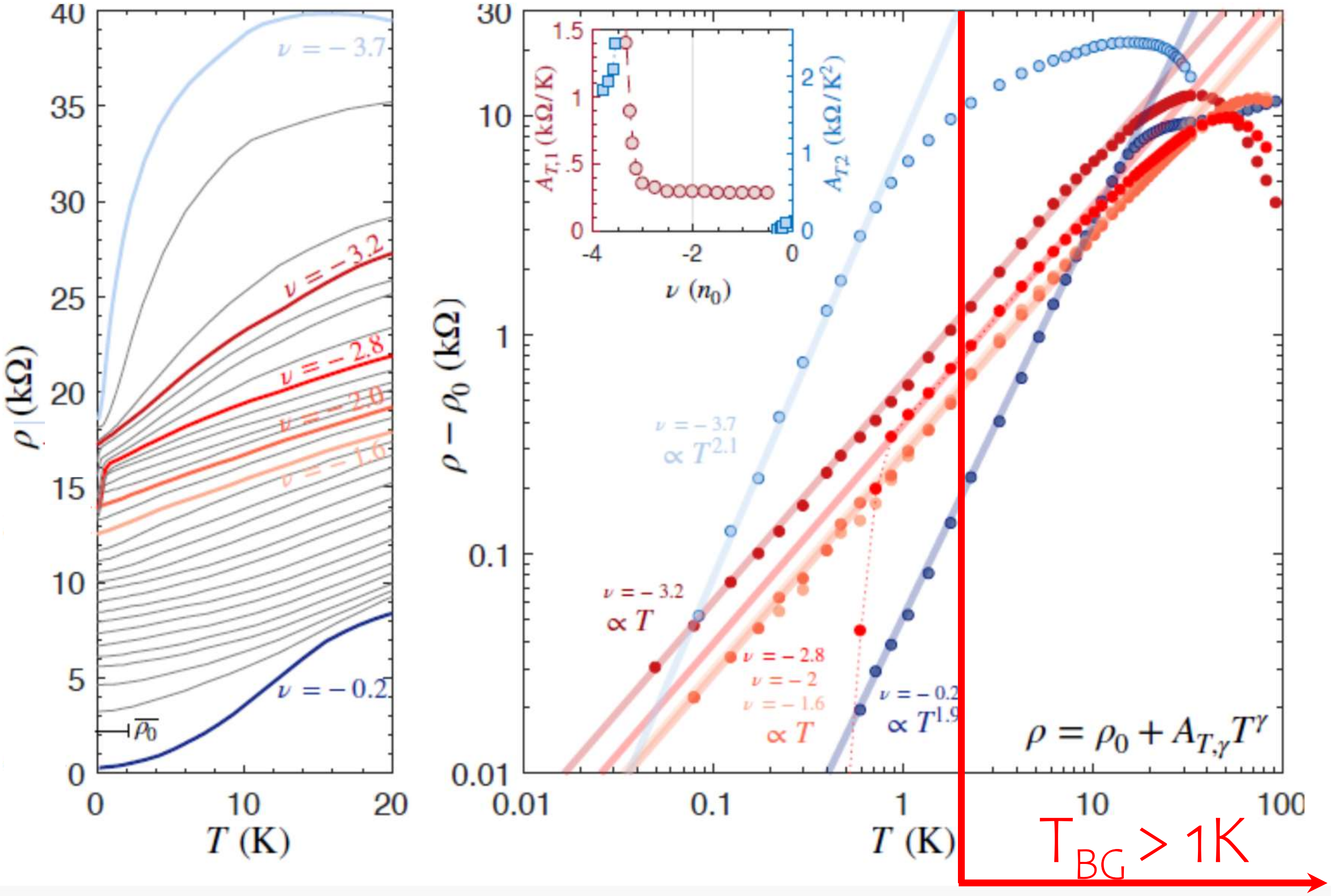
Linear T-dependence down to T=40mK



→ Linear R vs. T over 3 orders and down to T=40mK

A. Jaoui, … , L. Levitov, DKE, Nature Physics (2022).

Linear T-dependence down to T=40mK

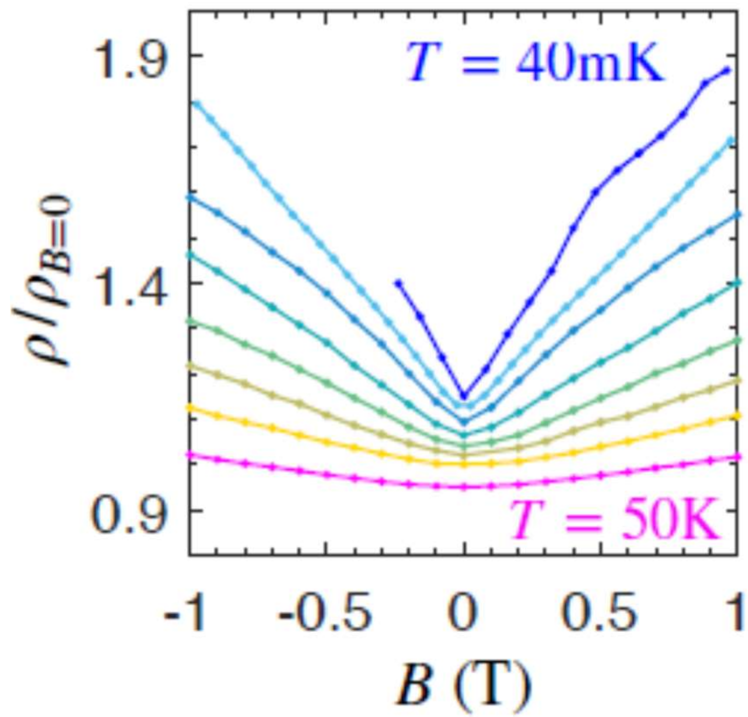


→ Linear R vs. T over 3 orders and down to T=40mK

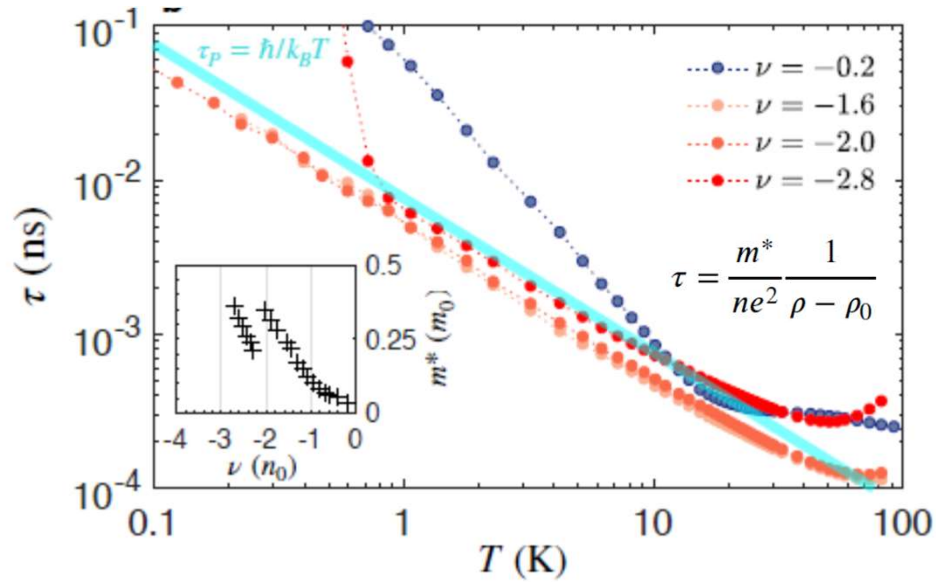
A. Jaoui, … , L. Levitov, DKE, Nature Physics (2022).

Linear B-dependence and Planckian scattering rate

R vs. B-dependence:



Planckian scattering rates:

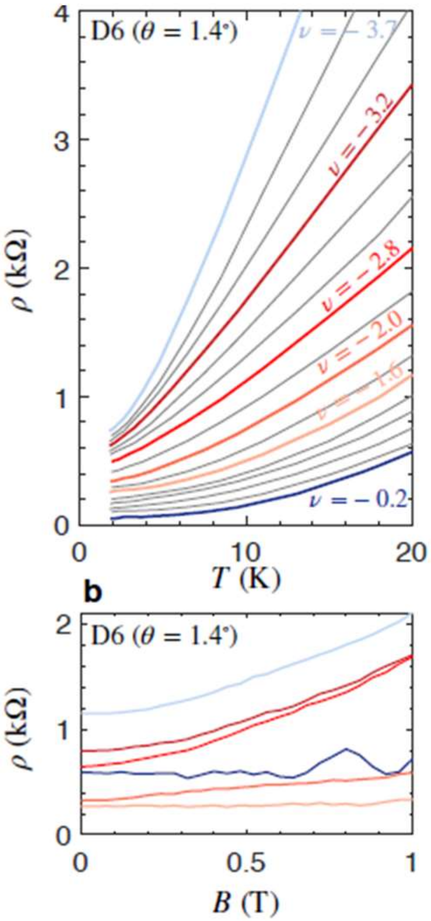


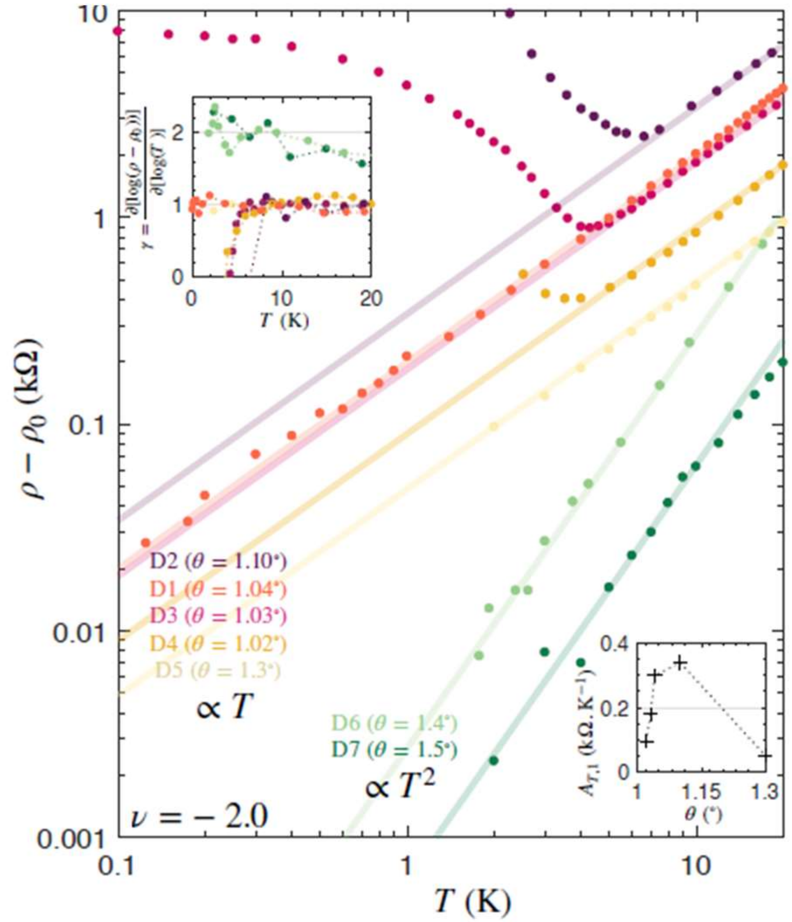
$$\tau \sim \tau_P = \hbar / k_B T$$

→ Density ranges of linear T- and B-dependence and Planckian scattering rate coincide

Suppression of strange metal away from magic angle

Device	Twist angle (°)	Width x Length (μm²)
D1	1.04	3x2
D2	1.10	2.5x3
D3	1.03	2.9x3.6
D4	1.02	-
D5	1.3	3x3.5
D6	1.4	1.8x2.8
D7	1.5	1.4x7.4
D8	1.05	1.8x10.4



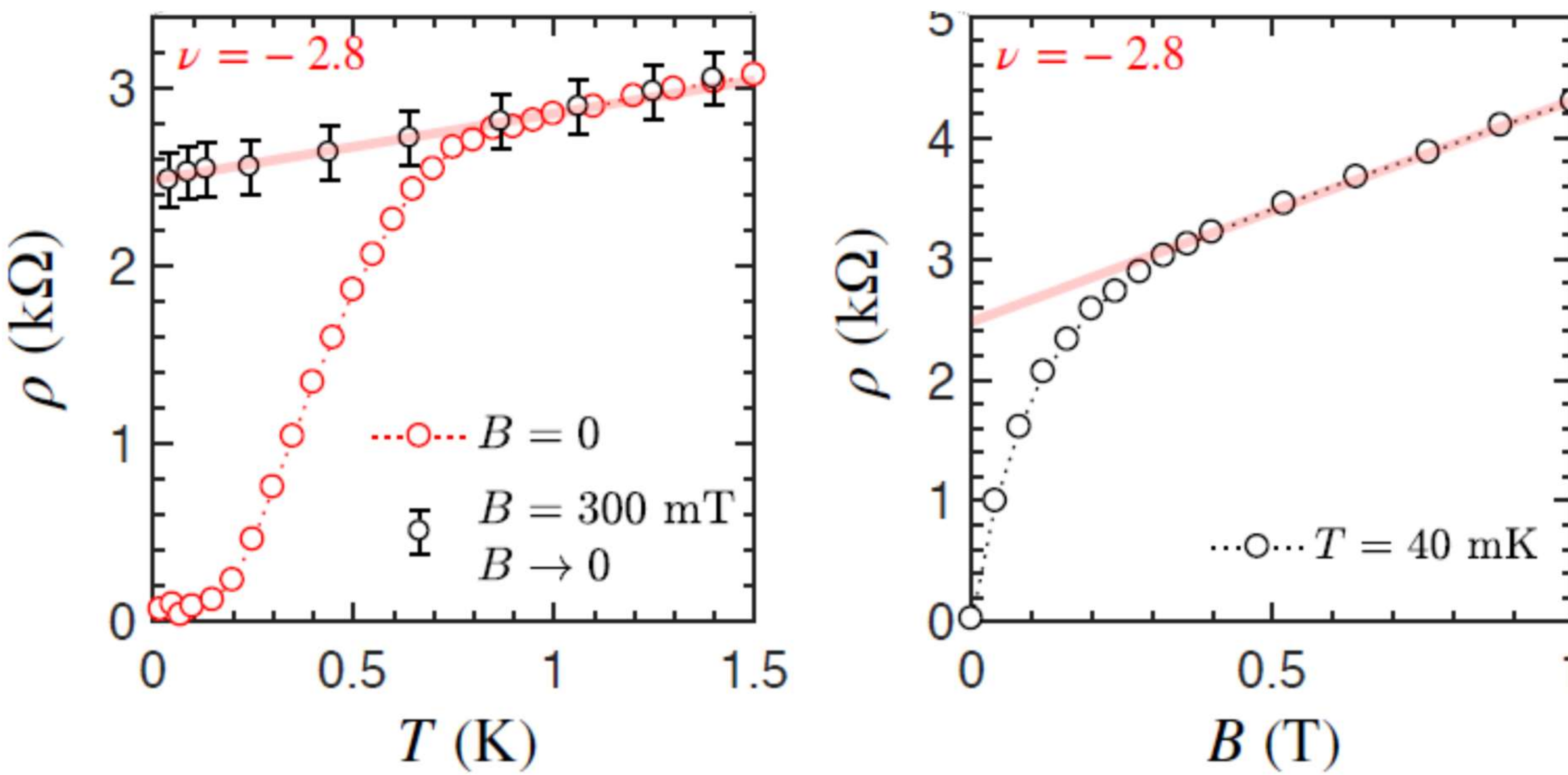


Away from the magic angle:

→ Suppression of strange metal

→ Recovery of Fermi liquid

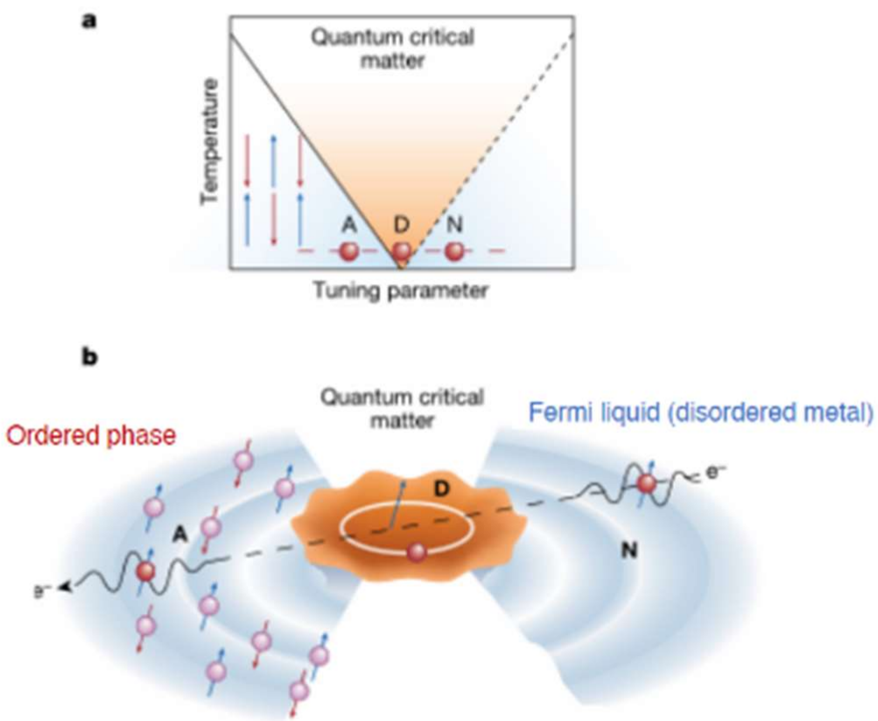
Strange metal - parent state of the SC state



→ Density ranges of linear T- and B-dependence coincide
→ Energy scales of linear behavior in T and B coincide

Magnetic fluctuations in MATBG

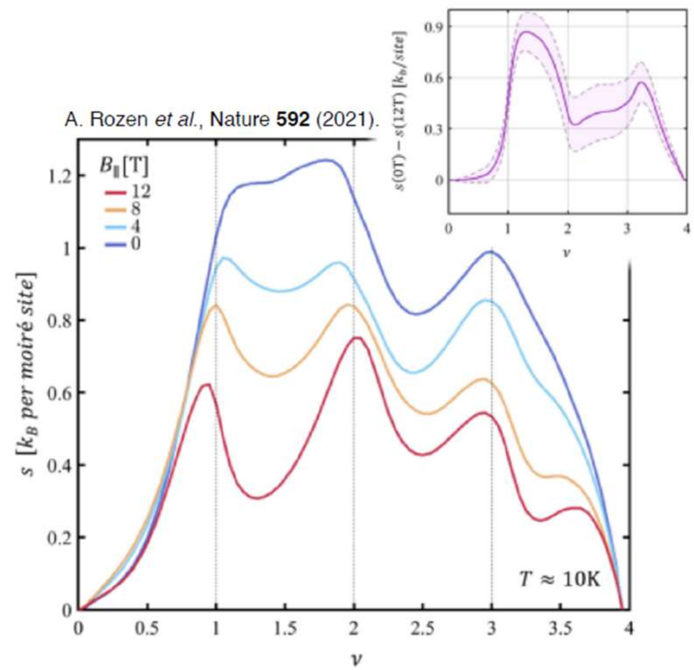
Magnetic fluctuations in quantum matter:



Adapted from Coleman et al, Nature **433** (2005)

Pomeranchuk effect in MATBG
→ Magnetically ordered phases:

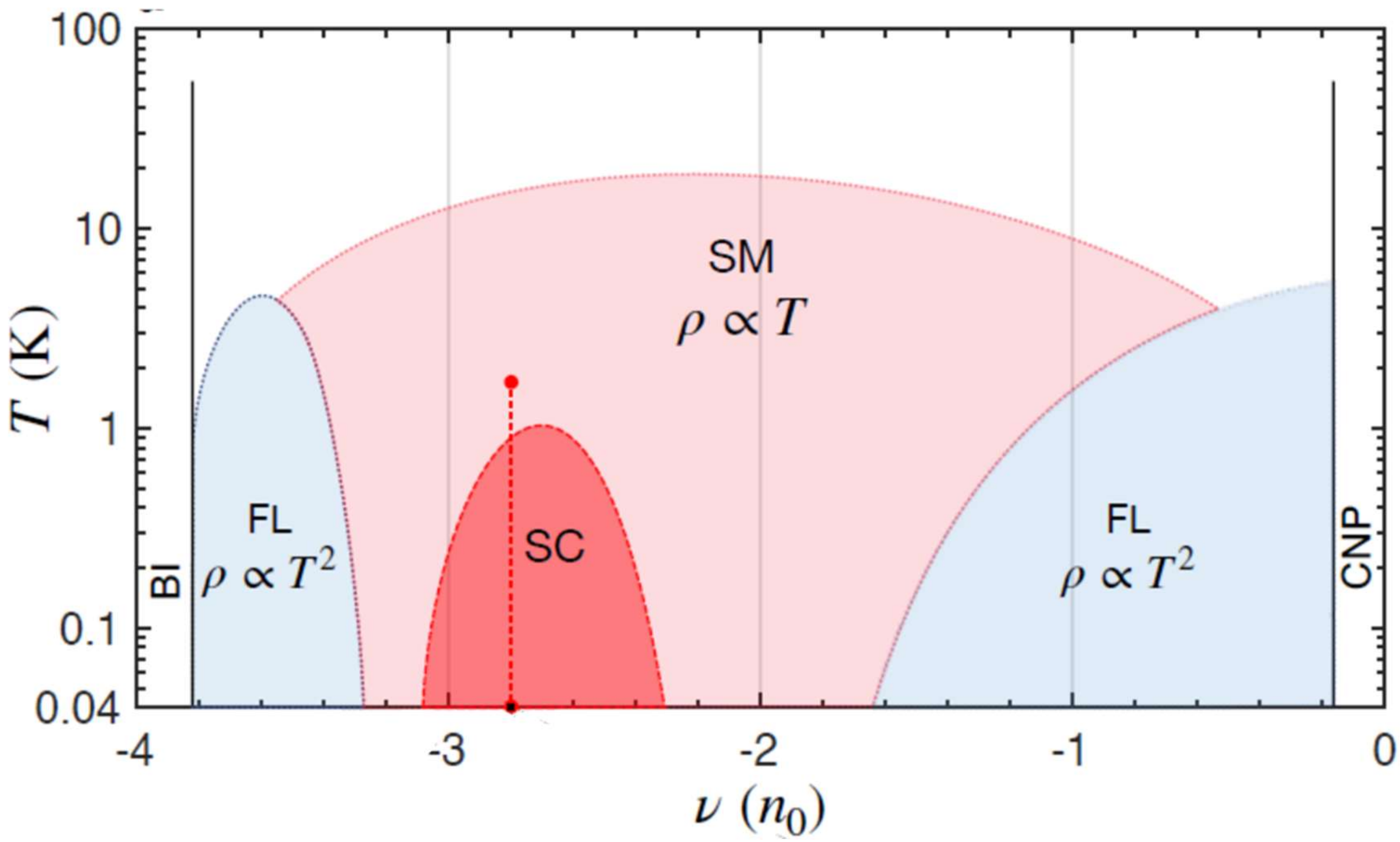
A. Rozen *et al.*, Nature **592** (2021).



- A. L. Sharpe *et al*, Science
- A. Rozen *et al.*, Nature **592** (2021).
- Y. Saito *et al.*, Nature **592** (2021).

→ Quantum critical point and strong magnetic fluctuations in MATBG?

Phase diagram



→ Quantum criticality in the center of the flat-bands

→ Fermi liquid behavior at the band edges

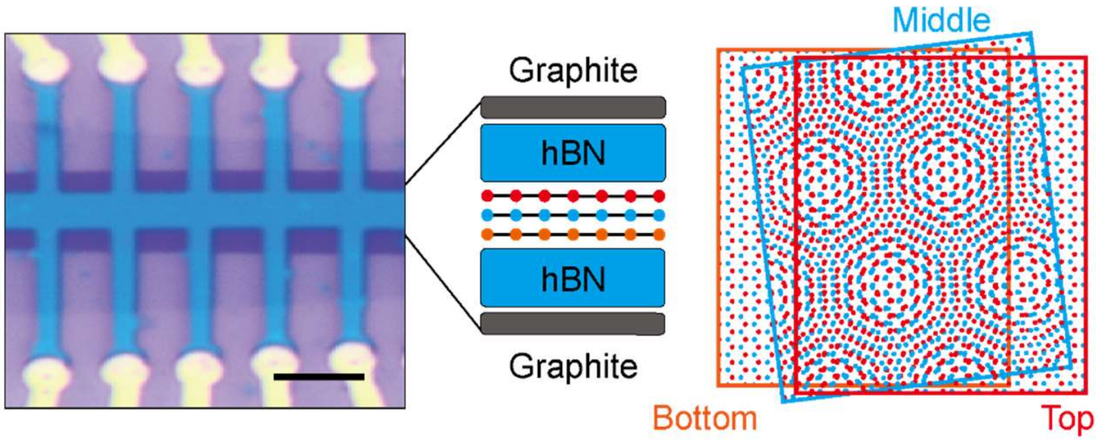
→ Superconductivity in presence of magnetic fluctuations?

Outline

1. Introduction to 2D materials and vdW heterostructures
2. Low temperature transport measurements and twist-angle extraction
3. Correlated insulators, Fermi surface resets and SU(4) symmetry breaking
4. Chern insulators
5. Orbital magnetism
6. Superconductivity
7. Screening
8. Gate induced Josephson junctions
9. Strange metal phase
10. Reentrant correlated insulators at one magnetic flux quantum
11. Thermal conductivity in the superconducting state

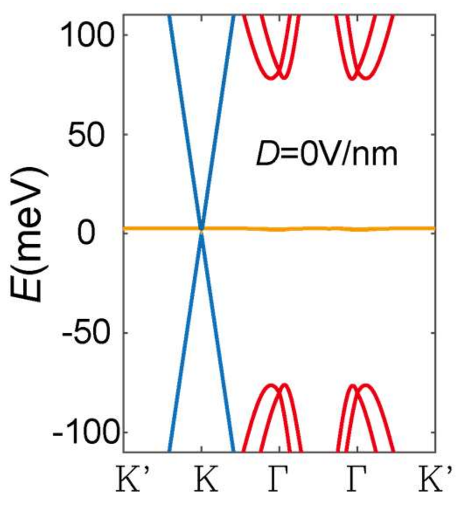
Magic angle mirror symmetric trilayer graphene

Device structure:

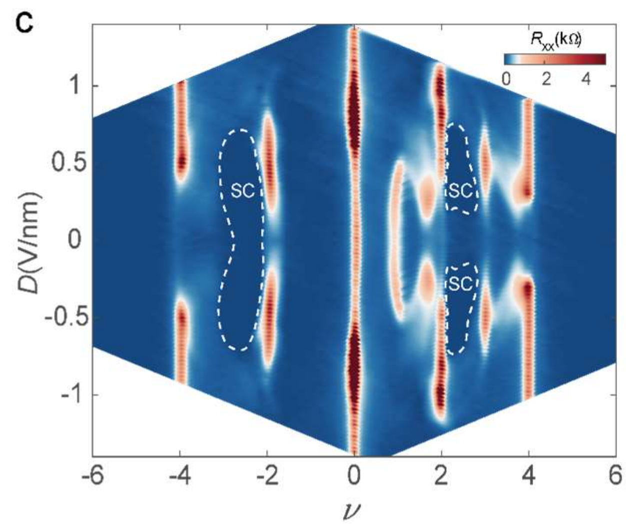


2x Jarillo-Herrero Group, Nature (2021).
Kim Group, Science (2021).

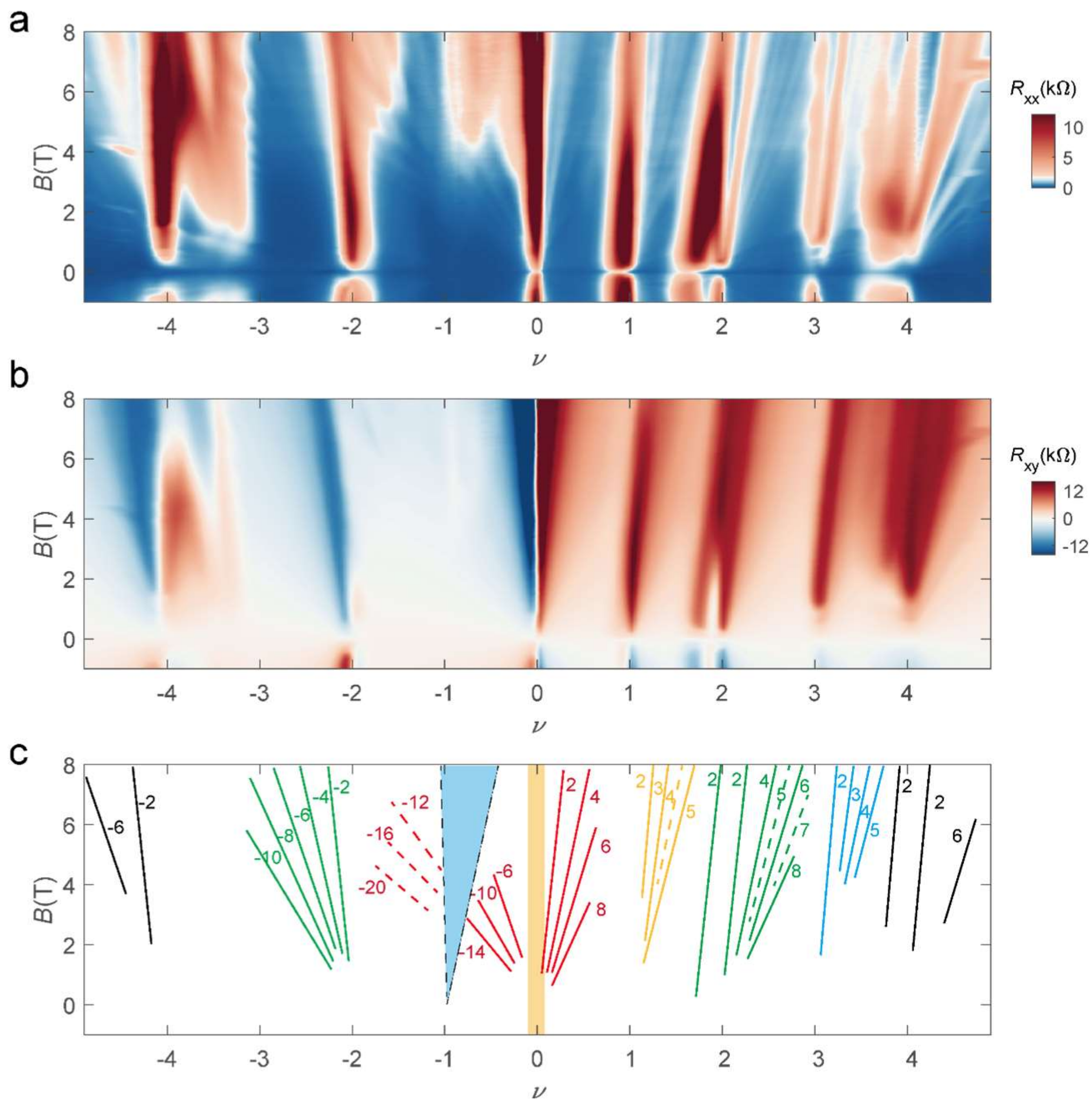
Bandstructure – flat-band+Dirac cone:



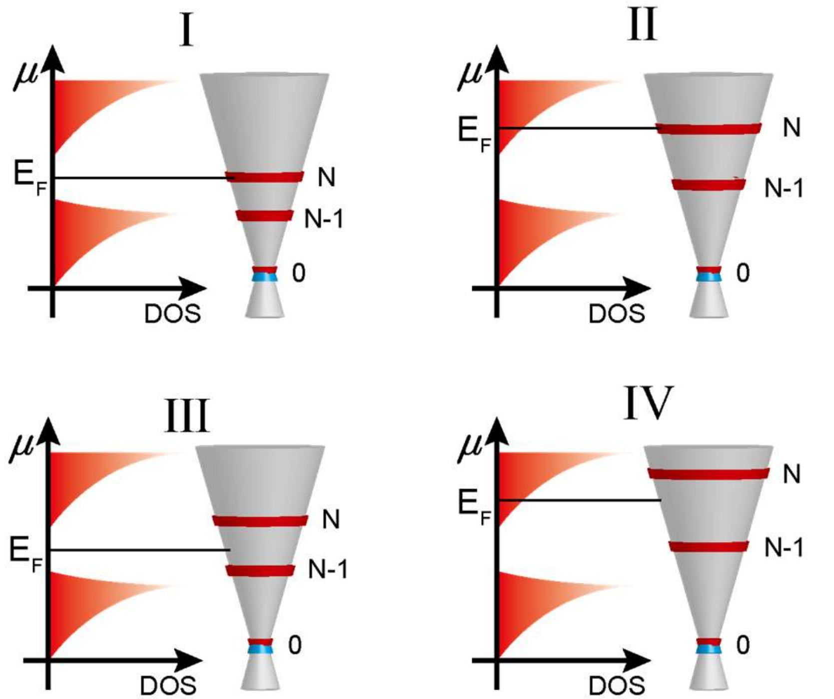
Phase diagram in displacement field:

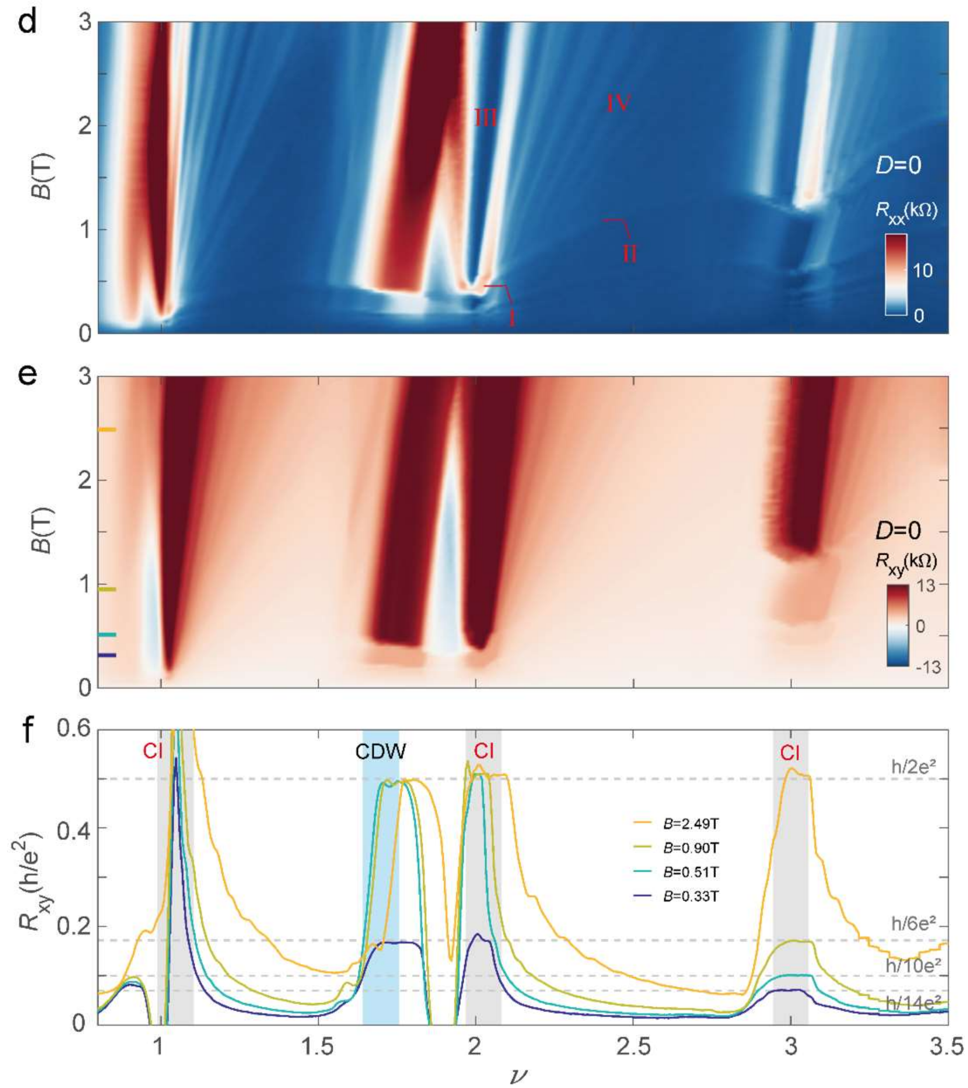


Landau Fan - Chern insulators obscured by Dirac LLs



Dirac cone spectroscopy

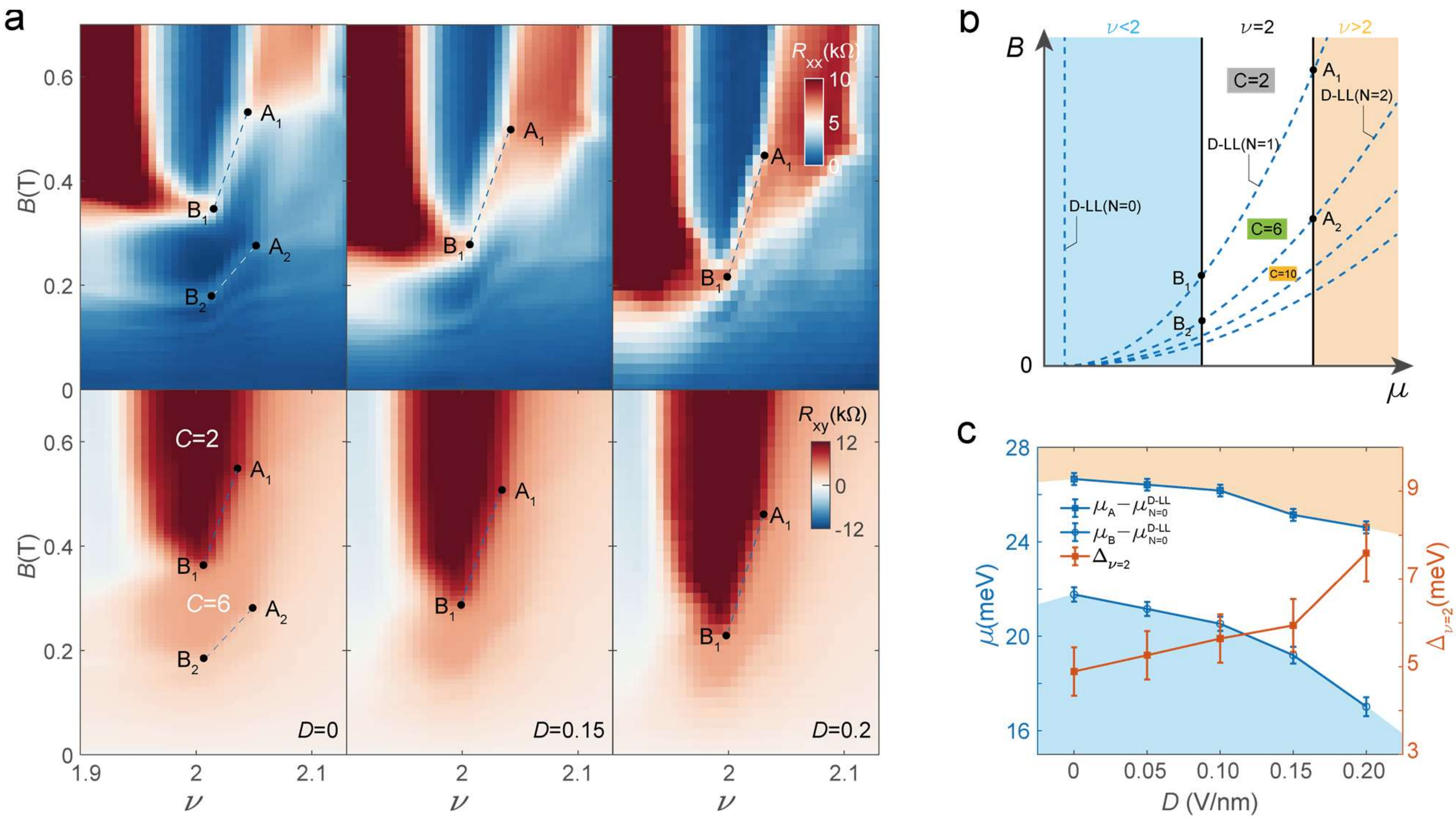




$$C^f = C - (4N+2) = 2,6,10$$

$$\mu_N^{D-LL} = \mu_{N=0}^{D-LL} + v_F\sqrt{2e\hbar N sgn(N) B}$$

Extraction of gaps and Chern numbers

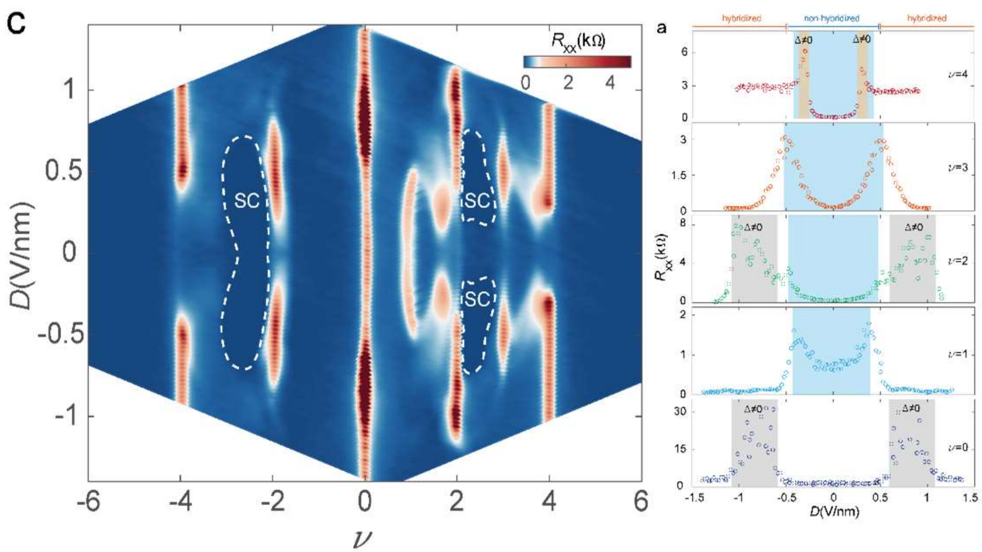


→ Extraction of Chern numbers ang correlated gaps

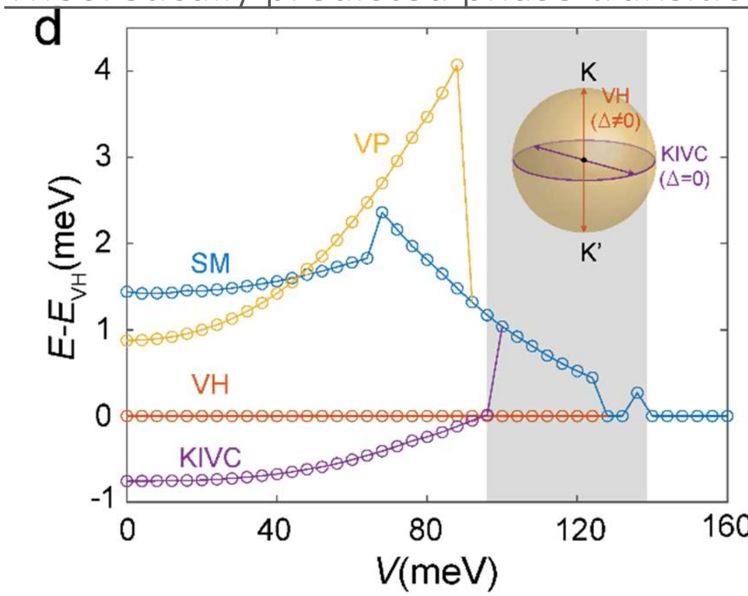
→ Interactions become stronger with displacement field

Displacement field driven phase transitions

Displacement driven resistivity:



Theoretically predicted phase transitions:

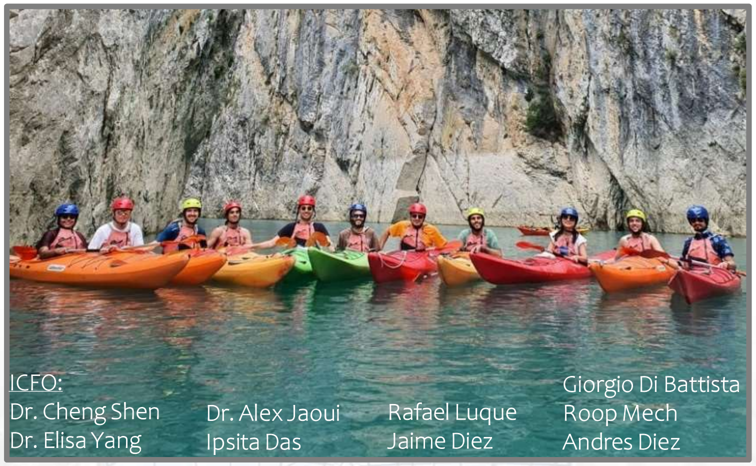


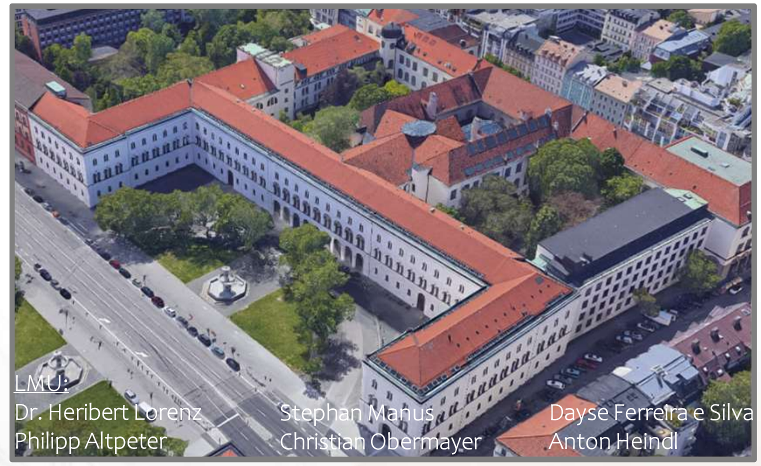
→ Displacement field induced hybridization of the bands

→ Displacement field induced phase transitions

Chair of Experimental Solid State Physics @ LMU

ICFO Barcelona → LMU Munich





Collaborations

UT Austin
A. MacDonald

MIT
L. Levitov

Princeton
A. Bernevig

Harvard
A. Vishnawanth

HKUST
K. T. Law

Regensburg
S. Ganichev

Weizmann
E. Zeldov

Geneva
F. Baumberger

Funding

erc European Research Council

QUANTUM FLAGSHIP

European Commission

DFG

Munich Quantum Valley

MCQST

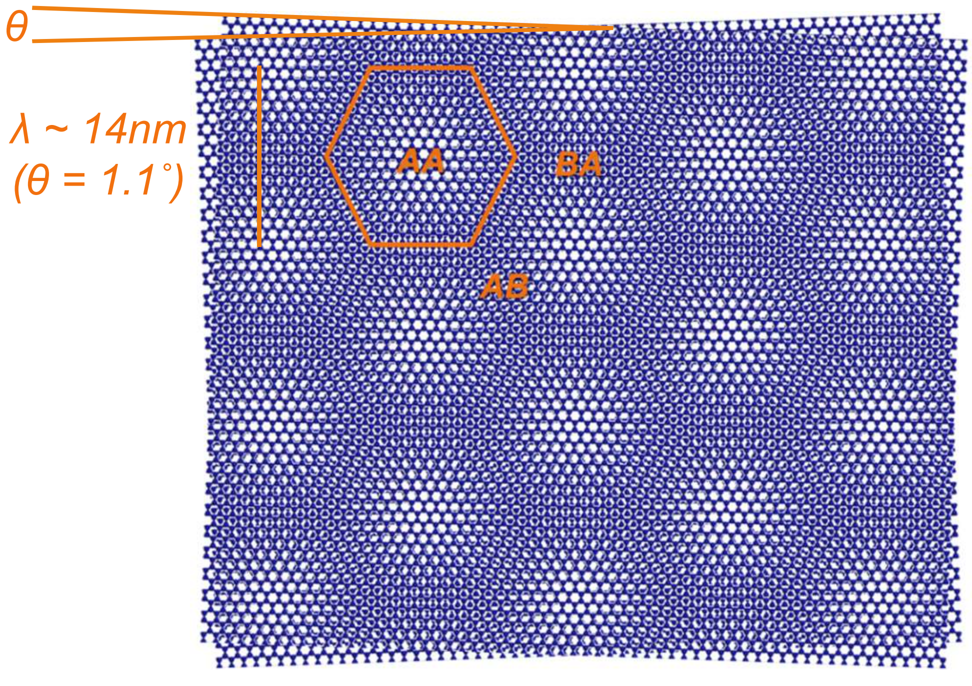
MUNICH QUANTUM CENTER

Dmitri K. Efetov

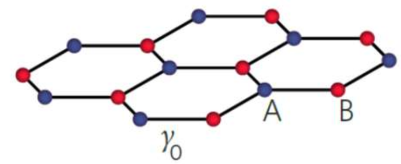
LMU Ludwig-Maximilians-Universität München — Chair of Solid State Physics

Moiré super-potential in twisted bilayer graphene

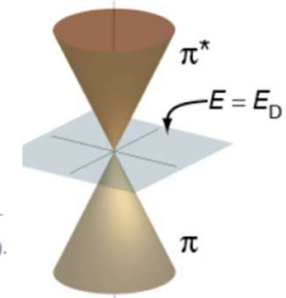
Twisted bilayer graphene:



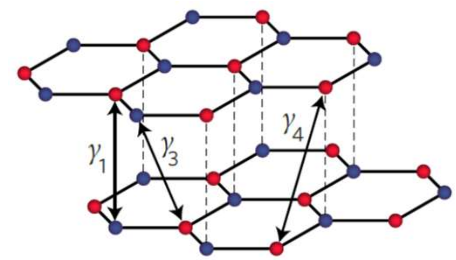
Single layer graphene:

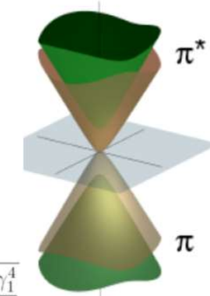


$$\varepsilon_\pm(\vec{k}) = \pm\gamma_0\sqrt{3+4\cos\left(\frac{\sqrt{3}ak_x}{2}\right)\cos\left(\frac{ak_y}{2}\right)+2\cos\left(ak_y\right)}.$$



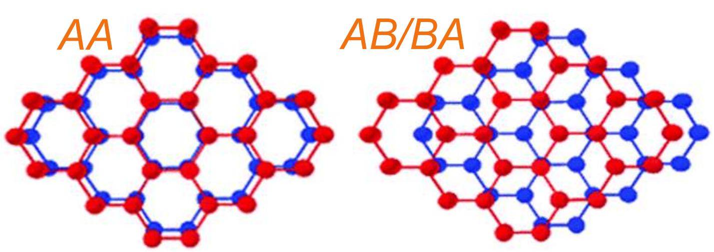
AB bilayer graphene:



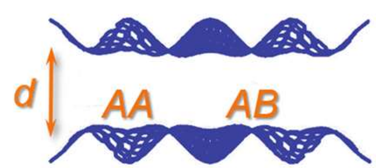


$$\varepsilon(p)^2 = (v_f p)^2 + \frac{\gamma_1^2}{2} + \frac{\Delta^2}{4} \pm \sqrt{(v_f p)^2\left(\gamma_1^2+\Delta^2\right)+\frac{\gamma_1^4}{4}}$$

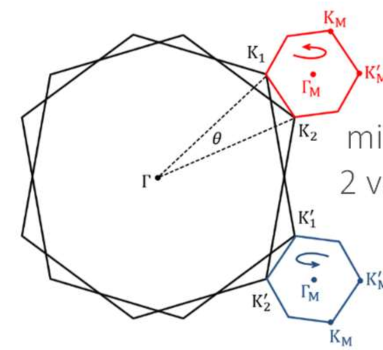
Atomic arrangement:



Height profile:



Brillouin zone:



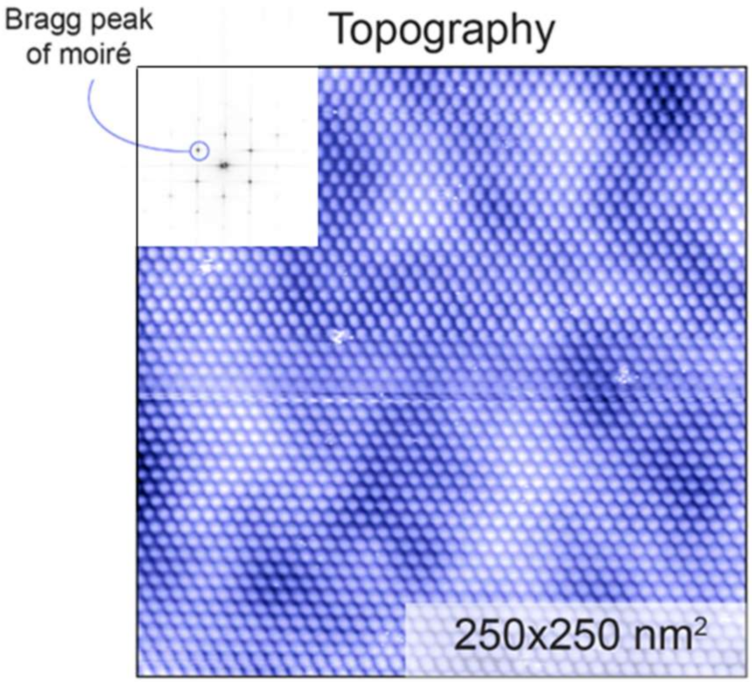
mini-BZ
2 valleys

Dmitri K. Efetov

LMU Ludwig-Maximilians-Universität München
Chair of Solid State Physics

Moiré super-lattice and flat bands in tBLG

STM - Moiré topography:

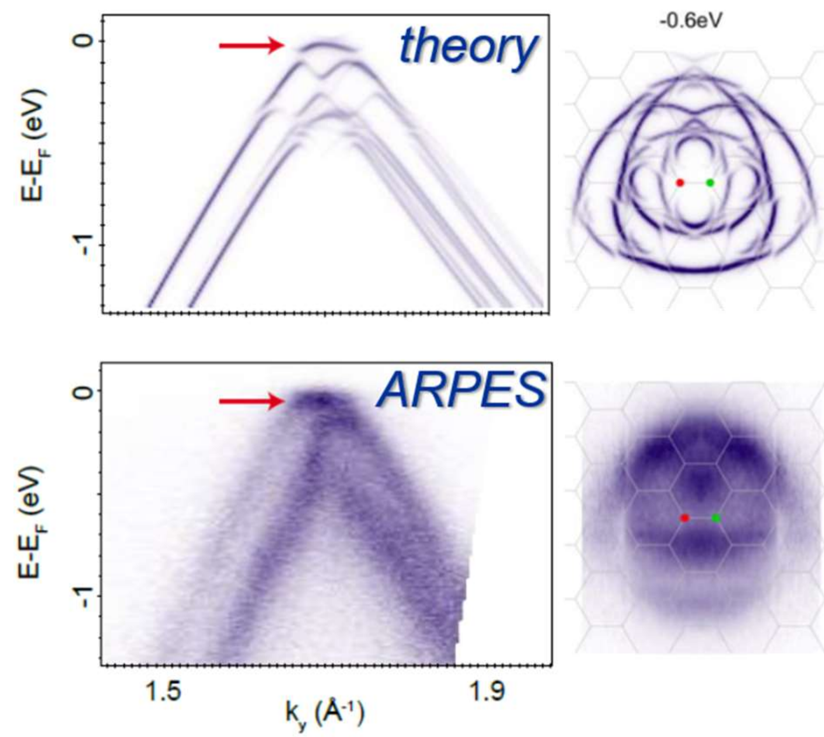


T. Benshop, ... , DKE, M. Allan, Physical Review Research (2020).

Also:

Nadj-Perge group, Nature Physics (2019).
Yazdani group, Nature (2019).
Pasupathy group, Nature (2019).
Andrei group, Nature (2019).

Nano-ARPES for θ ~ 1.3°:

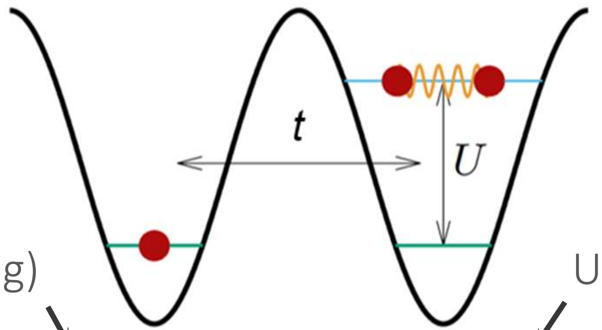


S. Lisi, ... , DKE, F. Baumberger, Nature Physics (2020).

Also:

M. Utama, ... , F. Wang, Nature Physics (2020).

Mott insulator picture



t – kinetic energy (hopping)

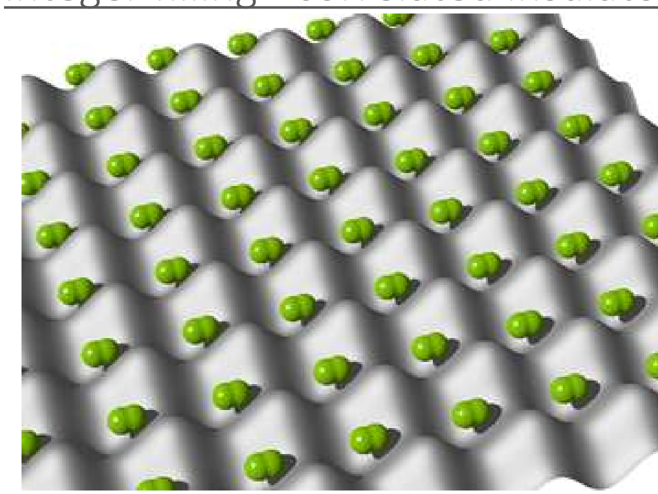
U – onsite energy (Coulomb)

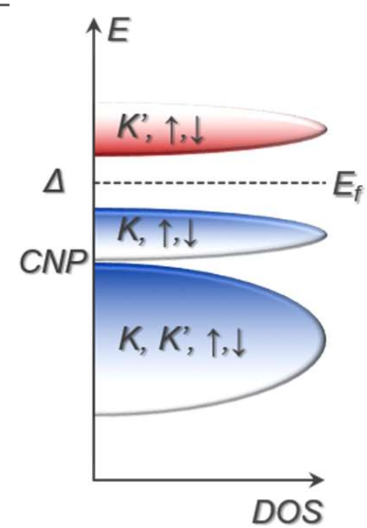
$U = e^2\theta/(4\pi\varepsilon_0\kappa a)$

$$H = -t\sum_{i,j,\sigma} c^{\dagger}_{i,\sigma}c_{j,\sigma} + U\sum_{i} n_{i,\uparrow}n_{i,\downarrow}$$

integer filling - correlated insulator:

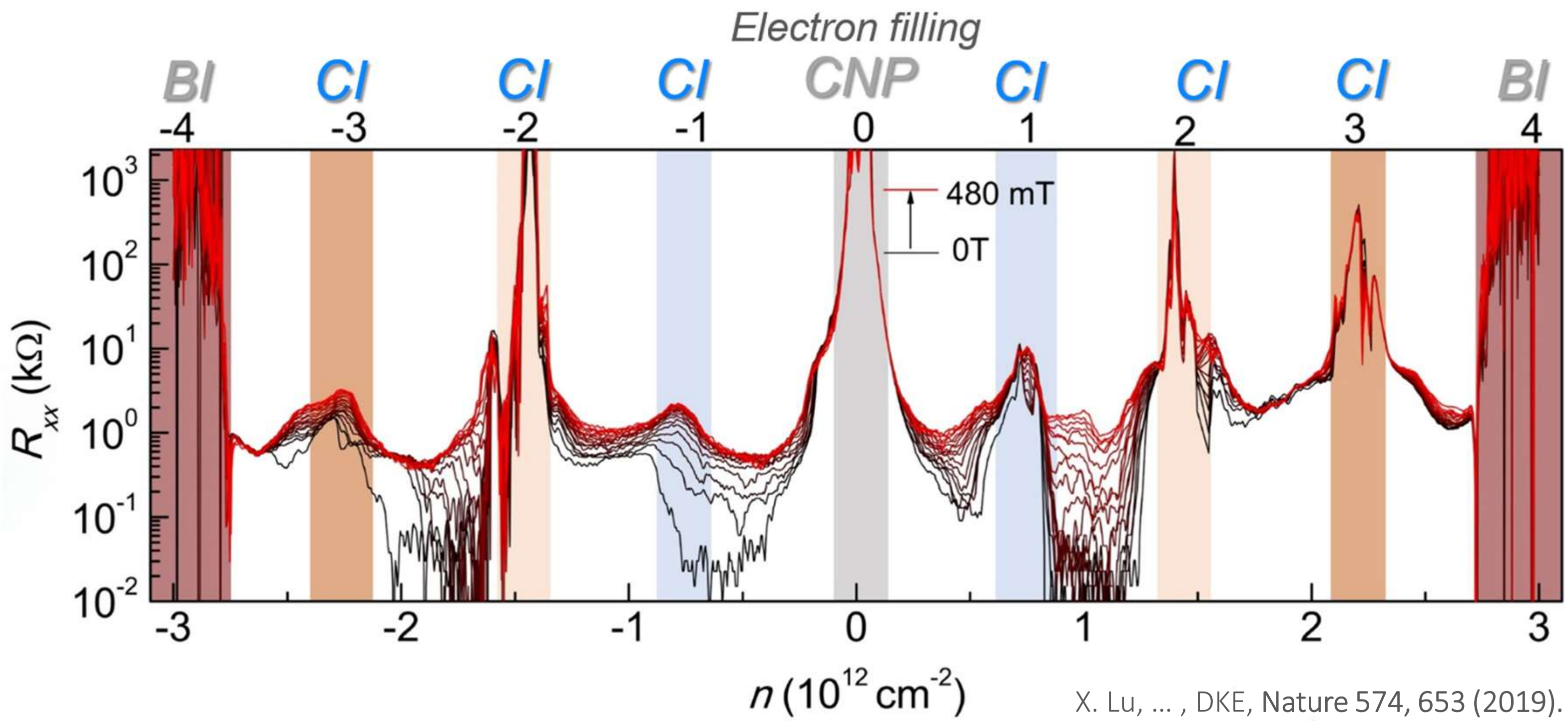
U/t >> 1
condition for Mott insulator





SU(4) spin/valley symmetry breaking

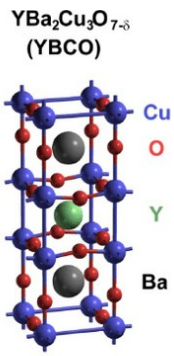
Transport measurements



X. Lu, … , DKE, Nature 574, 653 (2019).

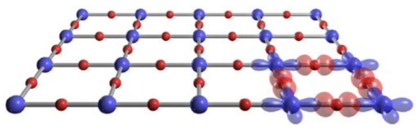
Symmetry broken correlated insulators at all integer fillings ν = 0,±1,±2,±3 e/uc

New platform for strongly correlated physics



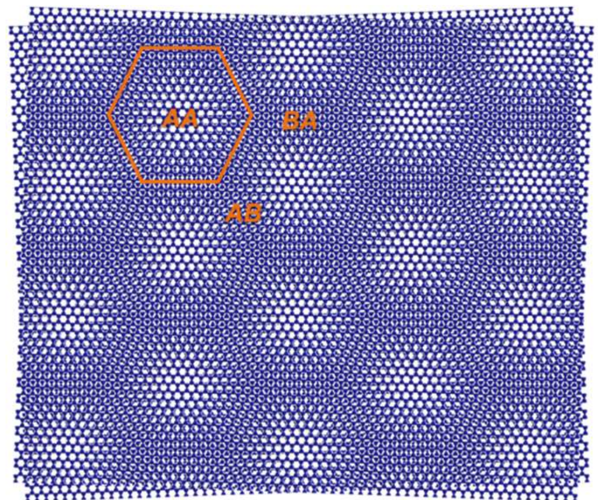
Crystals:

cuprates



λ ~ 1Å
U ~ eV

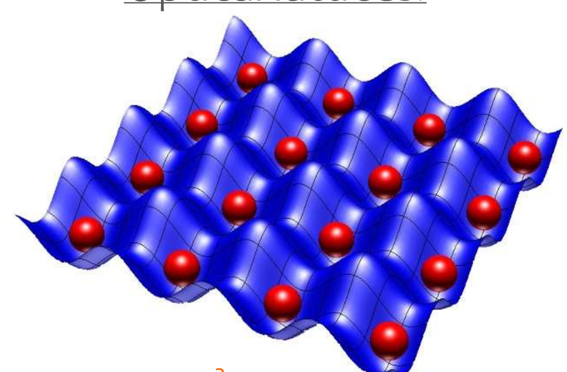
Magic-angle tBLG:



λ ~ 10nm
U ~ meV

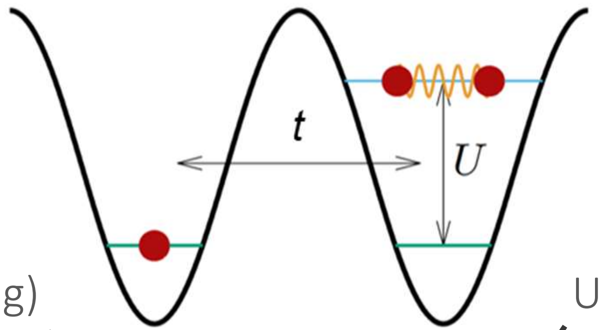
Lattice constant
Interaction strength

Optical lattices:



λ ~ 1µm
U ~ peV

New platform for strongly correlated physics



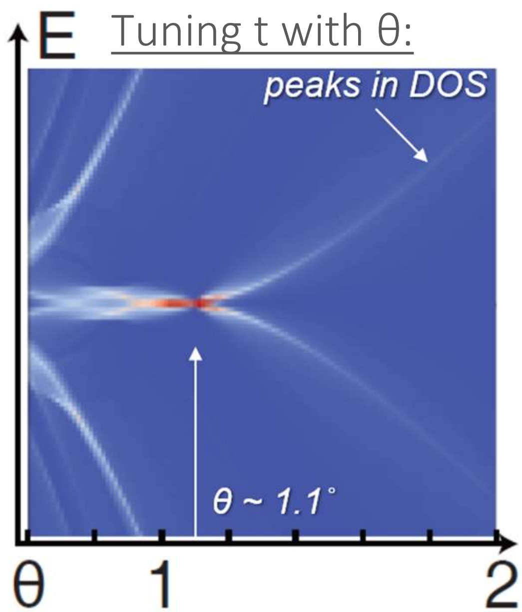
t – kinetic energy (hopping)

U – onsite energy (Coulomb)

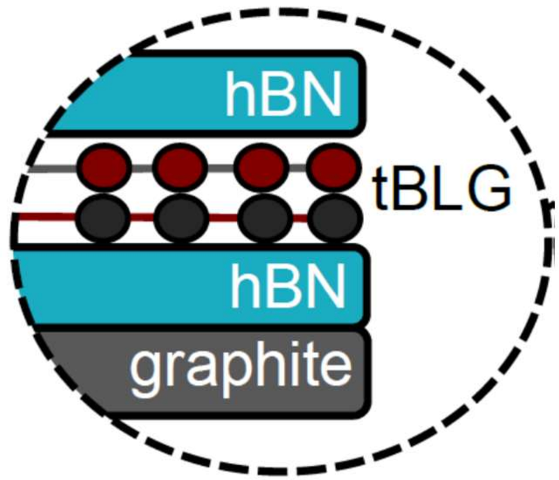
$U = e^2\theta/(4\pi\varepsilon_0\kappa a)$

$$H = -t \sum_{i,j,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

Tuning t with θ:



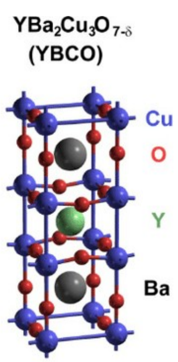
Tuning U with screening:



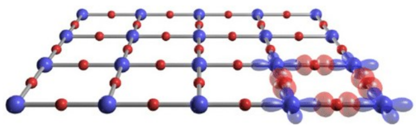
→ control of U/t ratio

New platform for strongly correlated physics

Crystals:

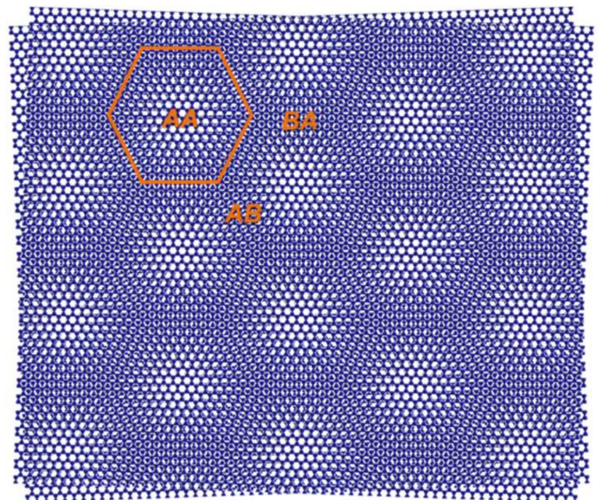


cuprates



λ ~ 1Å
U ~ eV

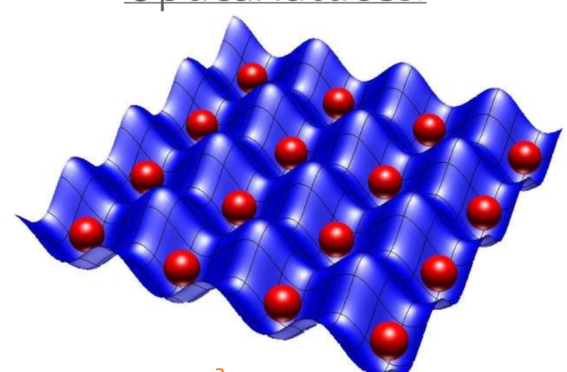
Magic-angle tBLG:



λ ~ 10nm
U ~ meV

Lattice constant
Interaction strength

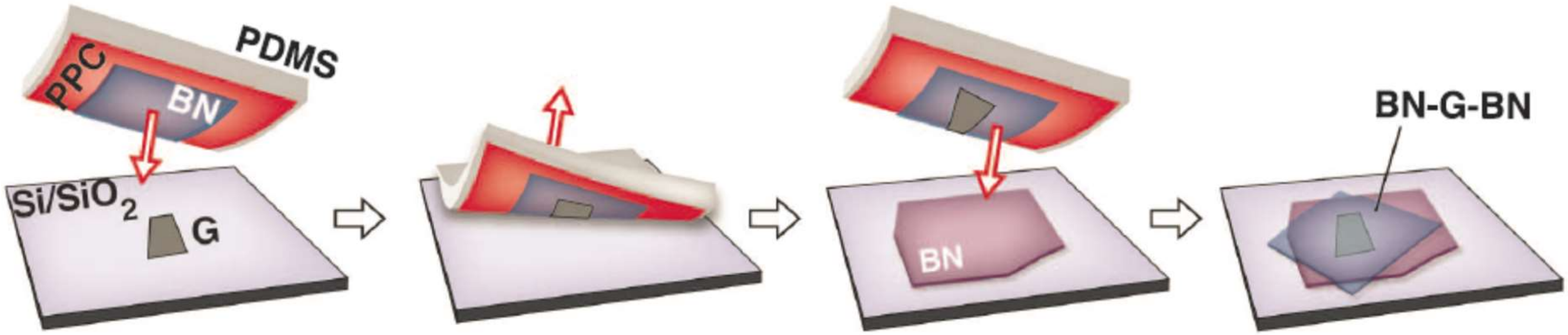
Optical lattices:



λ ~ 1µm
U ~ peV

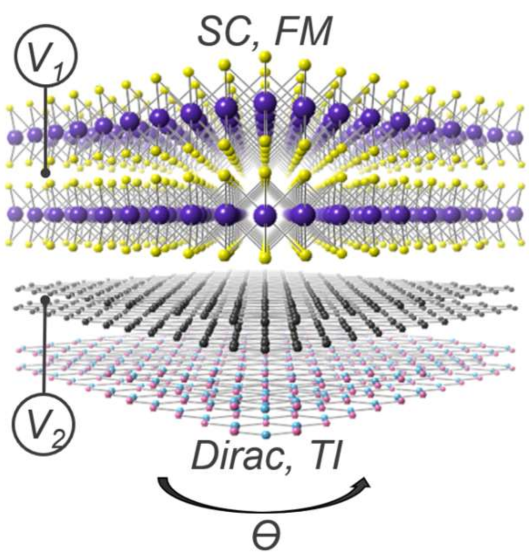
VdW heterostructures – clean coupling over < 1nm

vdW co-lamination transfer technique:

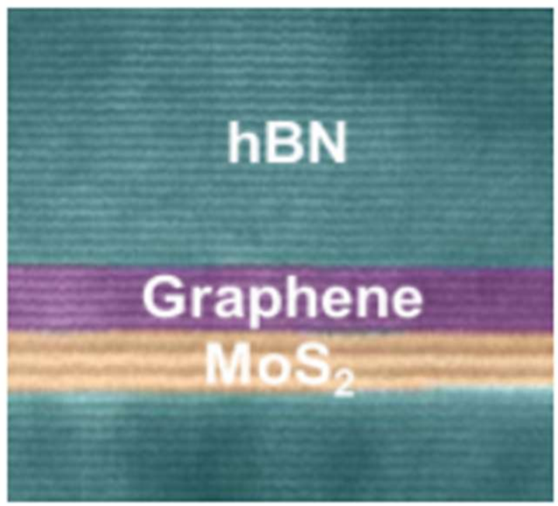


A. Geim, et. al. **Nature** (2013). C.Dean, P. Kim, J. Hone, et. al. **Science** (2013).

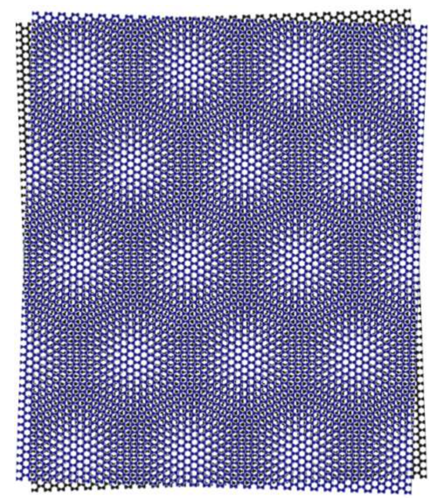
Designer vdW stack:



TEM cross-section:

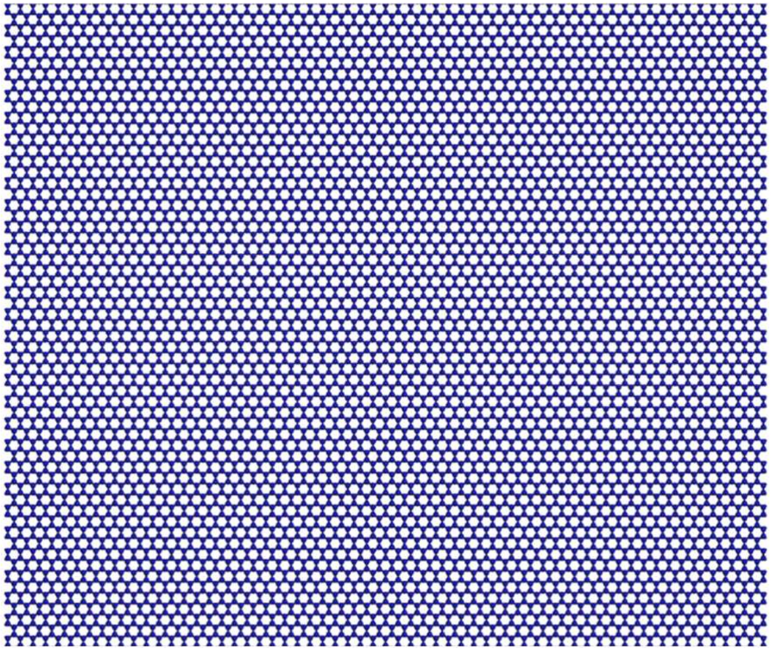


Moiré superlattice:

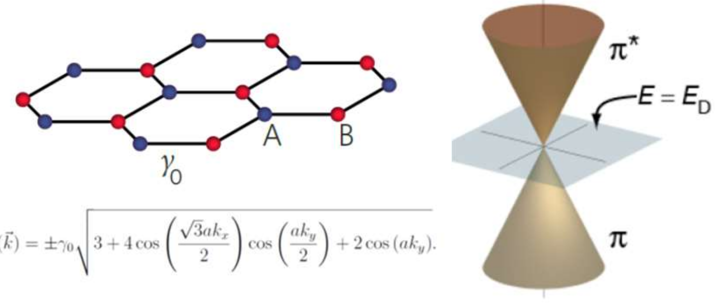


Moiré super-potential in twisted bilayer graphene

Twisted bilayer graphene:

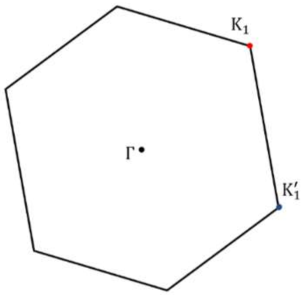


Single layer graphene:



$$\varepsilon_{\pm}(\vec{k}) = \pm\gamma_0\sqrt{3 + 4\cos\left(\frac{\sqrt{3}ak_x}{2}\right)\cos\left(\frac{ak_y}{2}\right) + 2\cos\left(ak_y\right)}.$$

Brillouin zone:



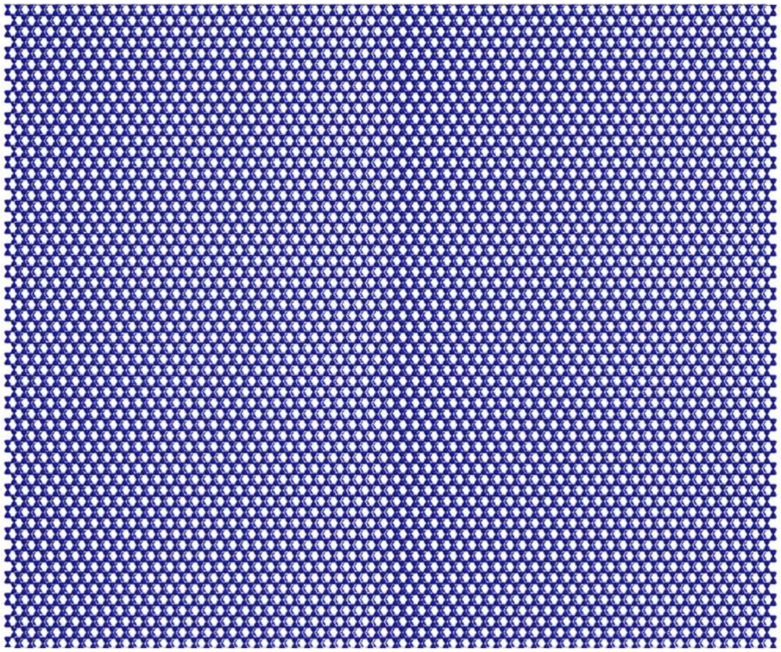
2 valleys

Dmitri K. Efetov

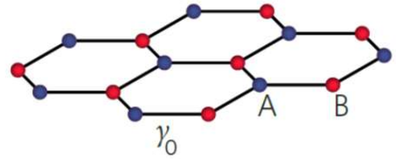
ICFO Research Group Low Dimensional Quantum Materials

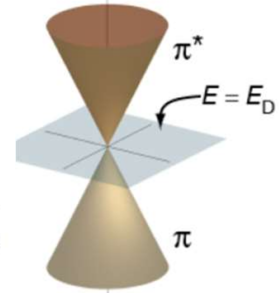
Moiré super-potential in twisted bilayer graphene

Twisted bilayer graphene:



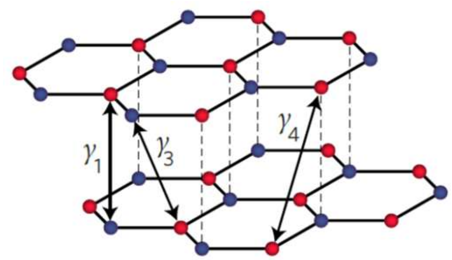
Single layer graphene:

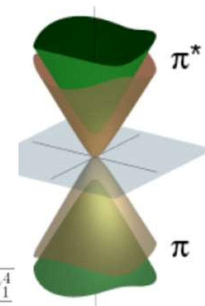




$$\varepsilon_{\pm}(\vec{k}) = \pm\gamma_0\sqrt{3 + 4\cos\left(\frac{\sqrt{3}ak_x}{2}\right)\cos\left(\frac{ak_y}{2}\right) + 2\cos(ak_y)}.$$

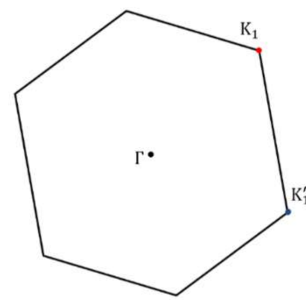
AB bilayer graphene:





$$\varepsilon(p)^2 = (v_f p)^2 + \frac{\gamma_1^2}{2} + \frac{\Delta^2}{4} \pm \sqrt{(v_f p)^2(\gamma_1^2 + \Delta^2) + \frac{\gamma_1^4}{4}}$$

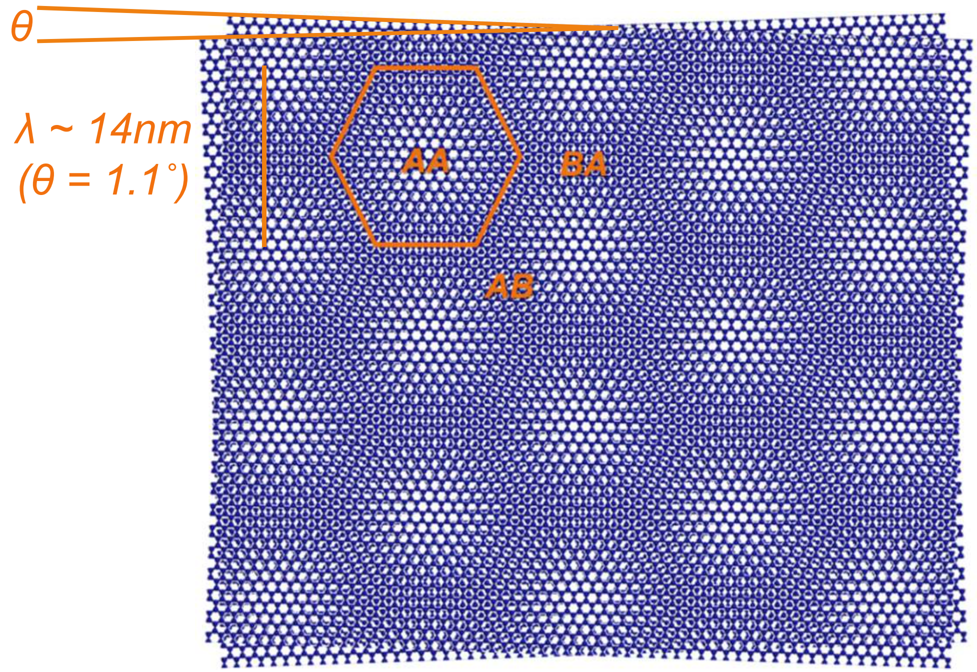
Brillouin zone:



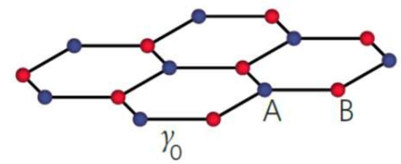
2 valleys

Moiré super-potential in twisted bilayer graphene

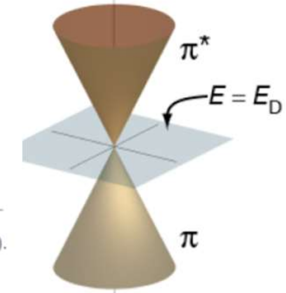
Twisted bilayer graphene:



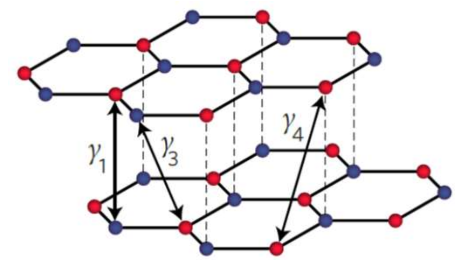
Single layer graphene:

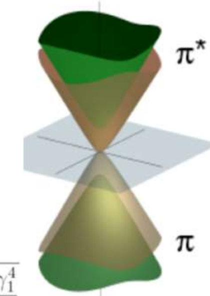


$$\varepsilon_{\pm}(\vec{k}) = \pm\gamma_0\sqrt{3 + 4\cos\left(\frac{\sqrt{3}ak_x}{2}\right)\cos\left(\frac{ak_y}{2}\right) + 2\cos(ak_y)}.$$



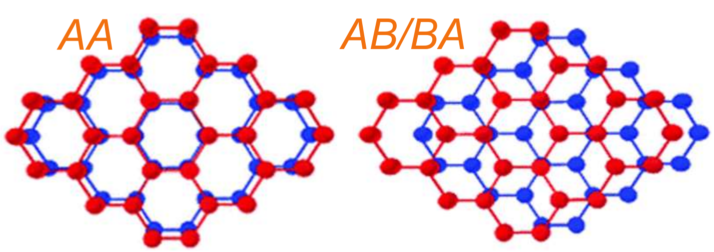
AB bilayer graphene:



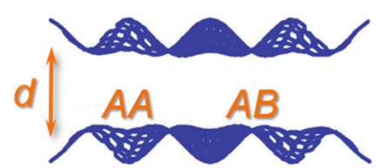


$$\varepsilon(p)^2 = (v_f p)^2 + \frac{\gamma_1^2}{2} + \frac{\Delta^2}{4} \pm \sqrt{(v_f p)^2(\gamma_1^2 + \Delta^2) + \frac{\gamma_1^4}{4}}$$

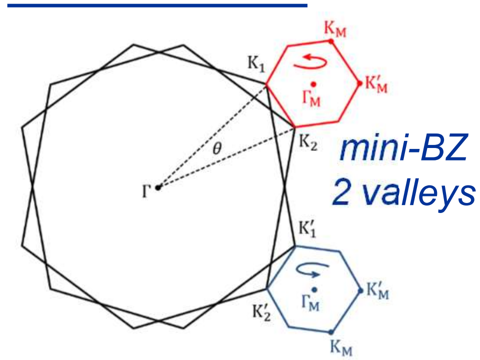
Atomic arrangement:



Height profile:



Brillouin zone:

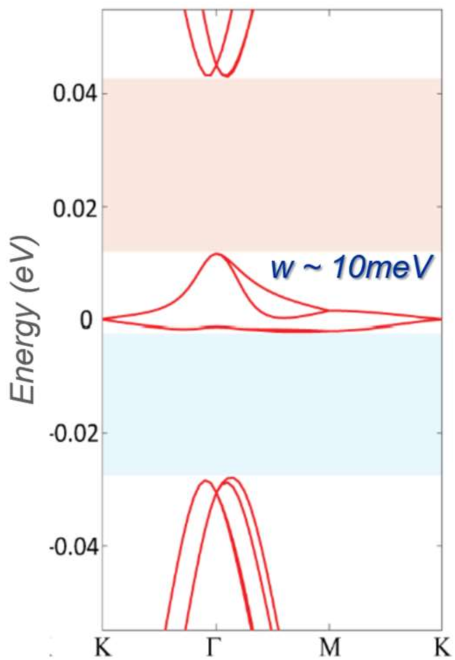


Dmitri K. Efetov

ICFO Research Group Low Dimensional Quantum Materials

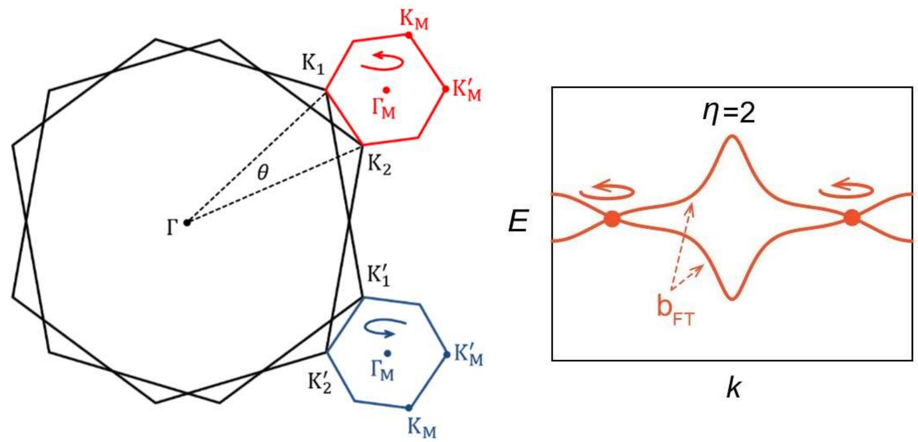
Flat-bands in tBLG

Spin/valley degenerate flat bands:



Continuum model calculations
(Bistritzer/MacDonald) + corrugations/strain

Non-zero helicity η = 2:



- Spin/valley degeneracy 4e/uc
- Mini-BZs decoupled
- No localized Wannier functions → Chern bands
- Interactions can break C_2T symmetries

H. Yoo, … , E. Kaxiras, P. Kim, **Nature Materials 18, 448 (2019).**

and many many others.

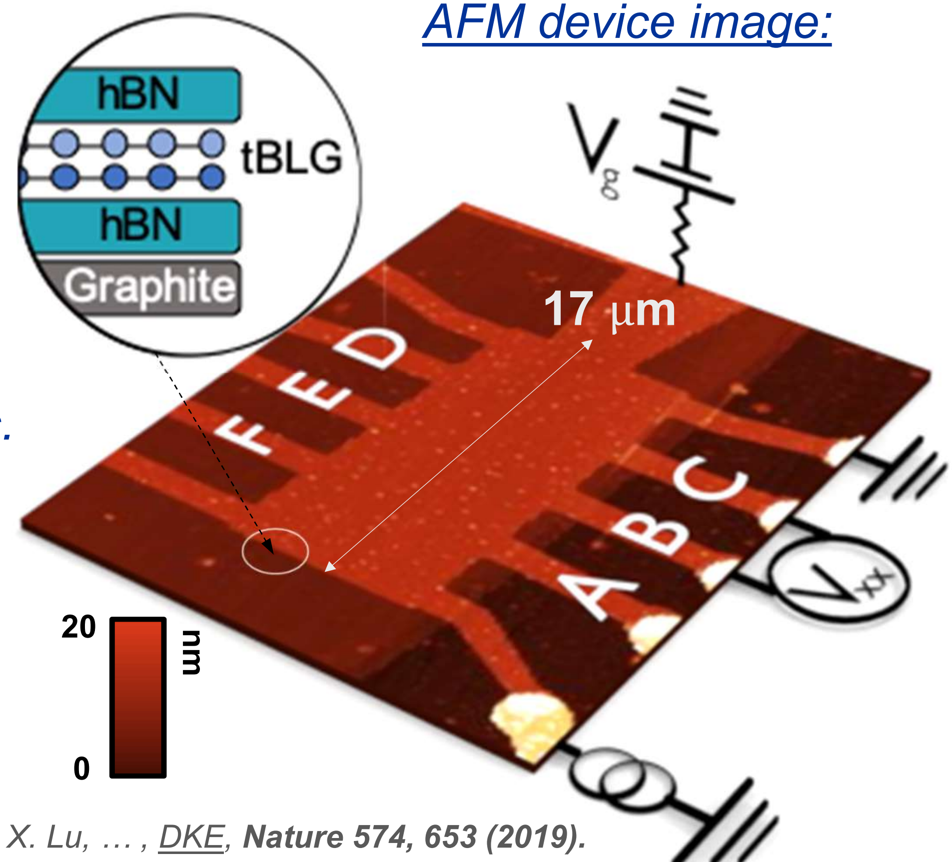
Bernevig group **(2018).**
MacDonald group **(2019).**
Fu group **(2018).**

Vishnawanth group **(2018).**
Zaletel group **(2018).**
Todadri group **(2019).**

- **quenched kinetic energy – t**
- **dominant interaction energy – U**

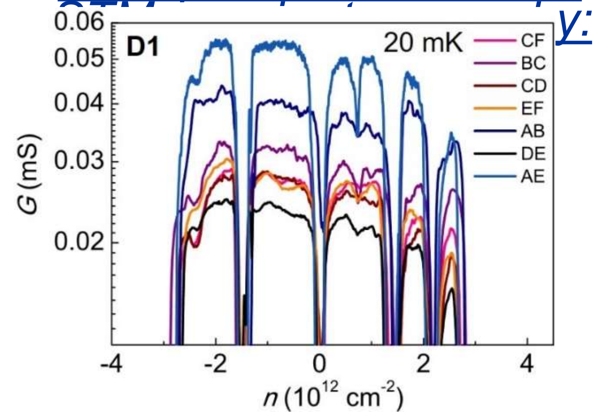
Devices made @ICFO

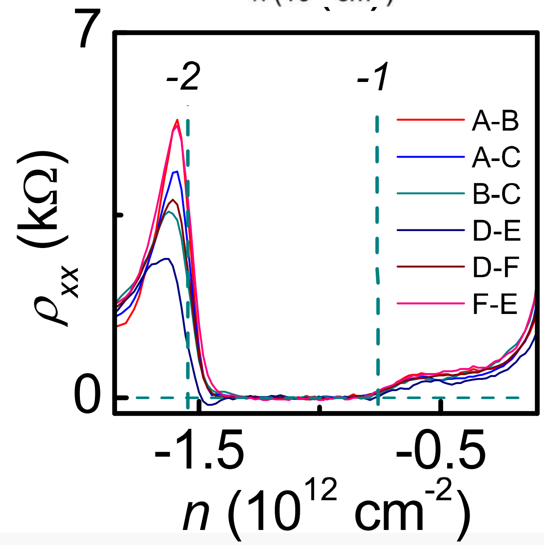
AFM device image:



X. Lu, … , DKE, **Nature 574, 653 (2019).**
P. Stepanov, … , DKE, **arXiv:1911.09198.**

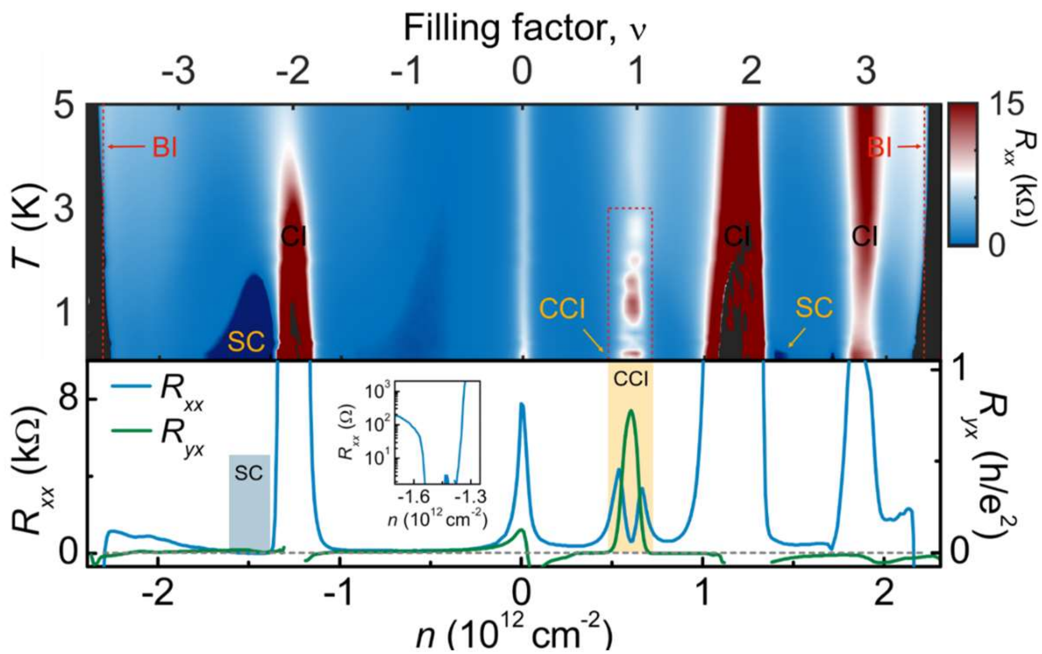
Transport meaurements:



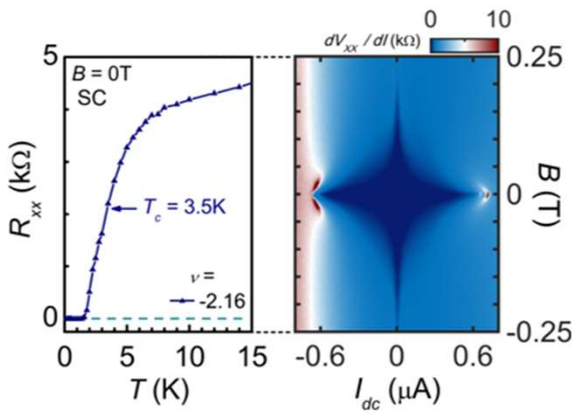


Ultra-low twist-angle inhomogeneity of $\Delta\theta < 0.01^o$ over 10µm

Gate tunability between SC to FM in MATBG

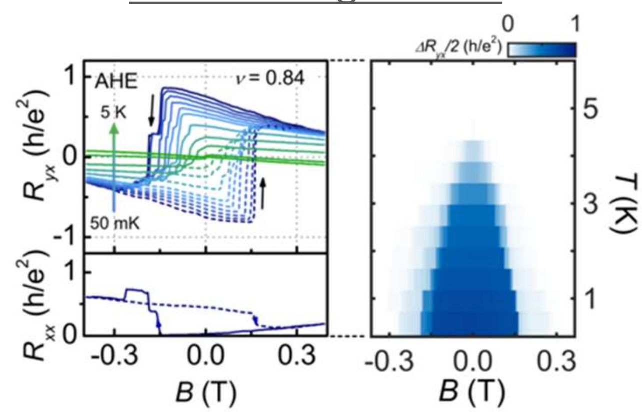


Superconductivity:



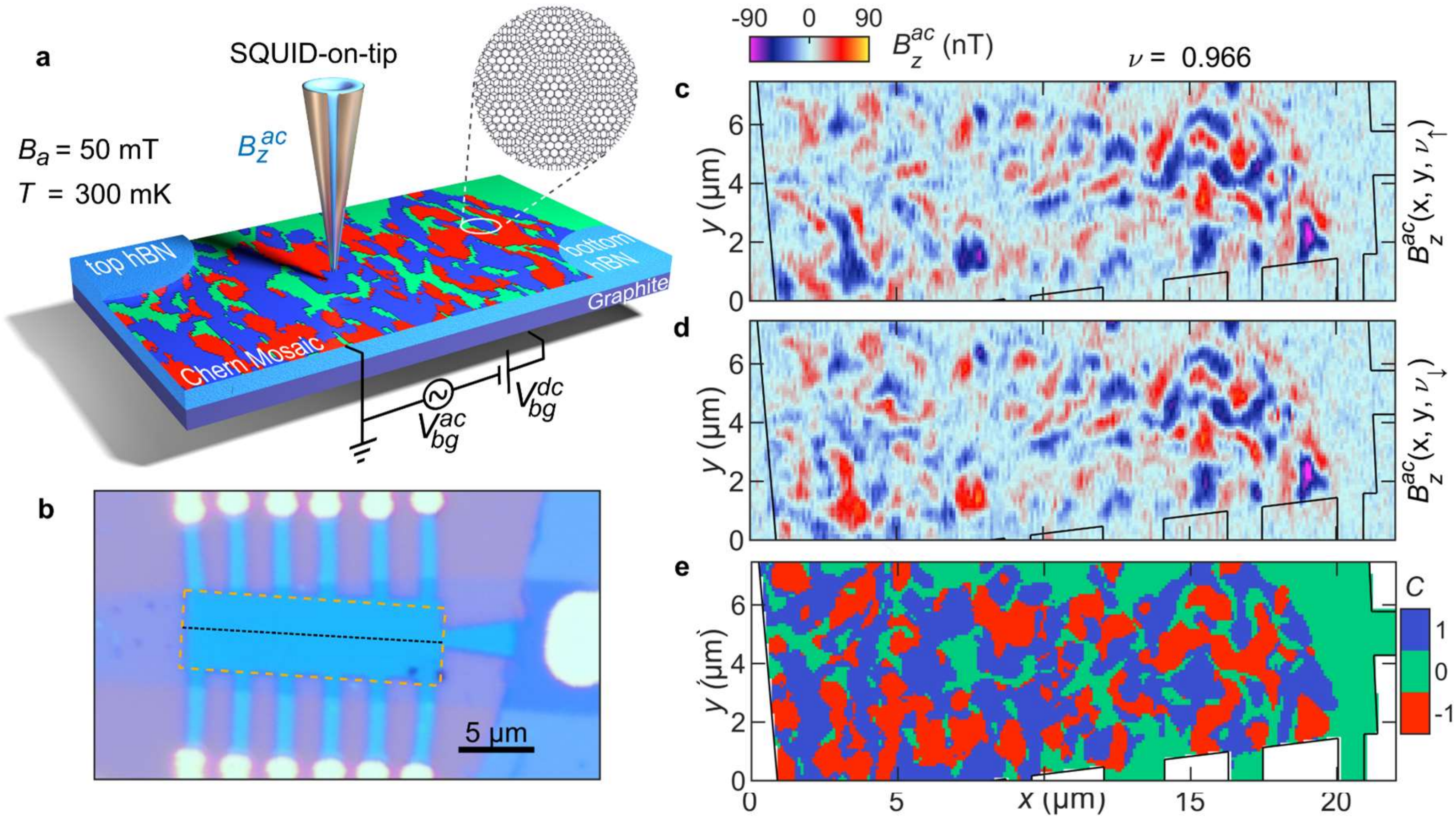
Zero-field gate induced transitions between ← SC and CCI →

Orbital Magnetism:



P. Stepanov, … , DKE, Physical Review Letters (2021).

Disordered domain structure and Chern mosaic



→ Rich and disordered domain wall structure for different ν

→ Variety of orbital states with different Chern numbers

S. Grover, M. Bocarsly, … , A. Stern, E. Berg, DKE, E. Zeldov Nature Physics – in press (2022).