The wonders of moiré graphene materials

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Outline

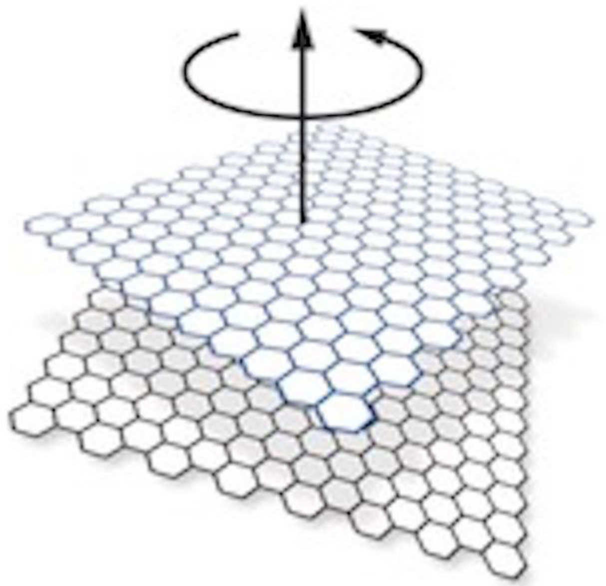
I. Twisted bilayer graphene: superconductivity, correlations and topology

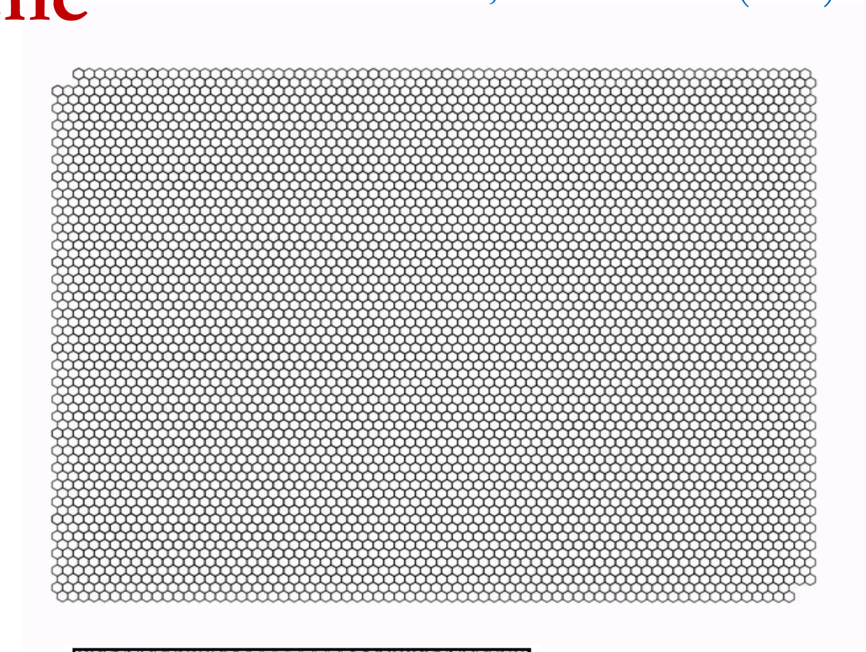
II. Chern mosaic in a trilayer geometry

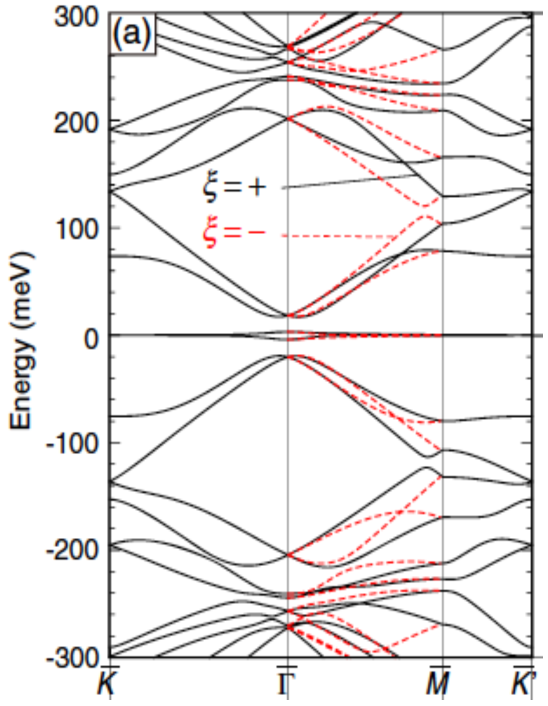
Twisted bilayer graphene: superconductivity, correlation and topology

Twisted bilayer graphene

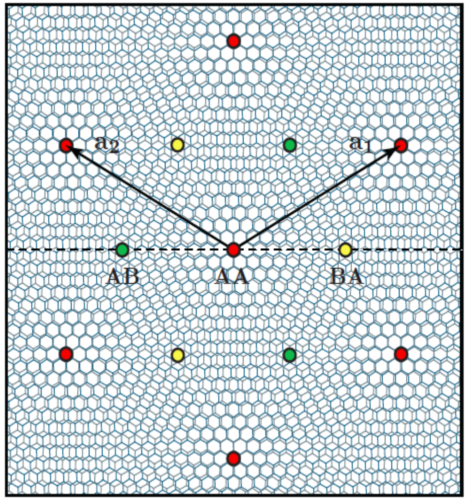
Cao et al., Nature 2018 (MIT)







$\theta = 1.05^o$



Moiré pattern

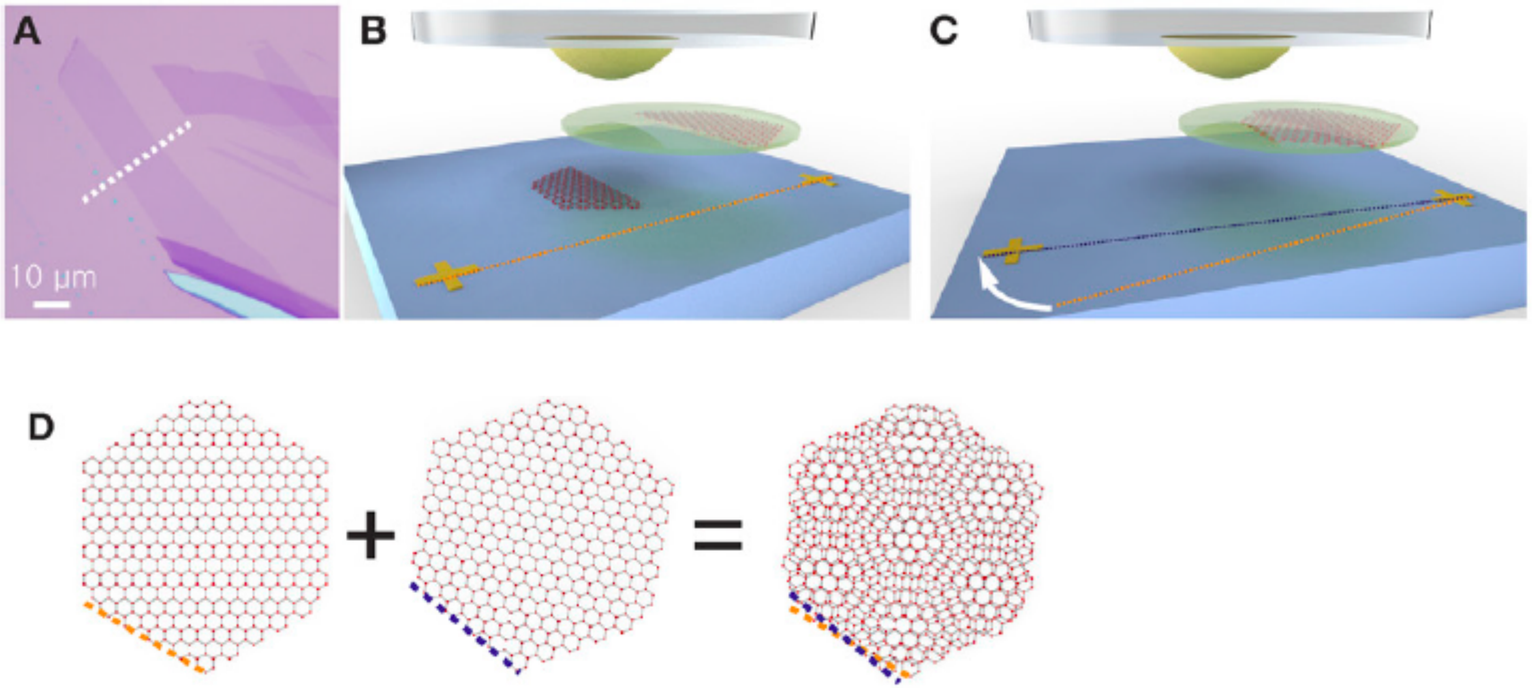
Band folding: electrons are slowed down

Electronic interactions (correlations) prevail

Lu, Efetov, Nature 2019

Yankowitz, Science 2019 (Colombia)

Fabrication - rotation

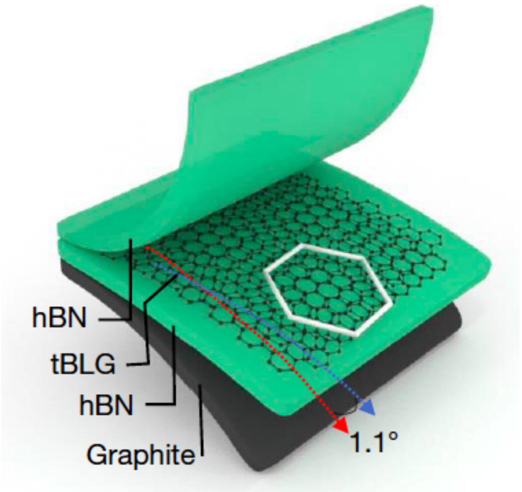


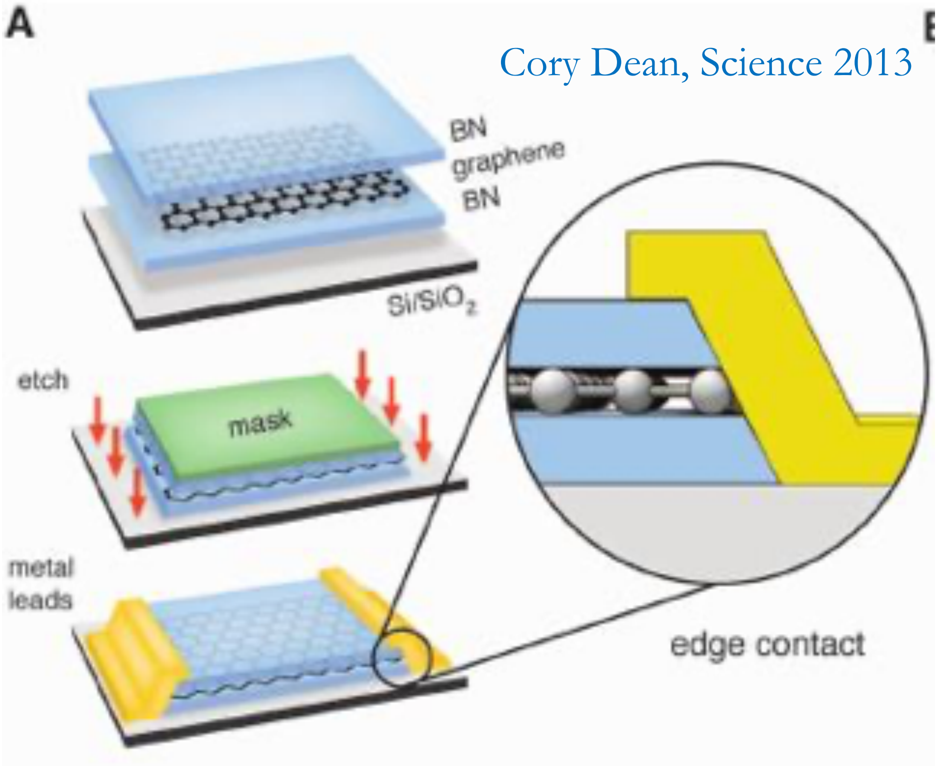
Hemispherical handle (polymer) picks up sequentially hBN substrate and graphene layers

Rotation between two graphene layer pick-up steps

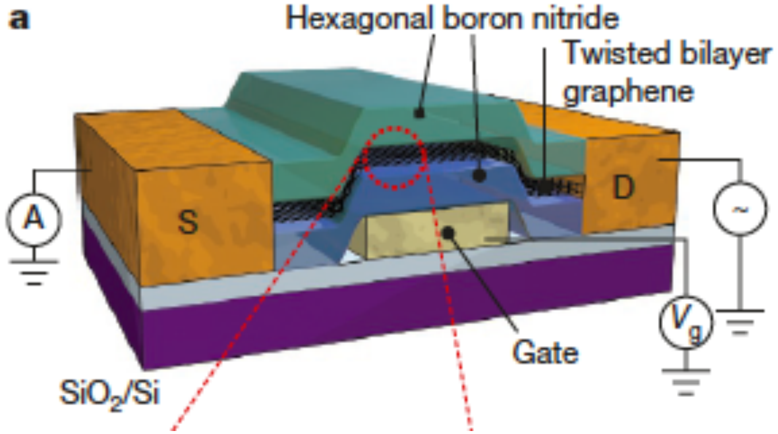
Kim, Tutuc, PNAS 2017, Nano Lett. 2016

Fabrication - encapsulation





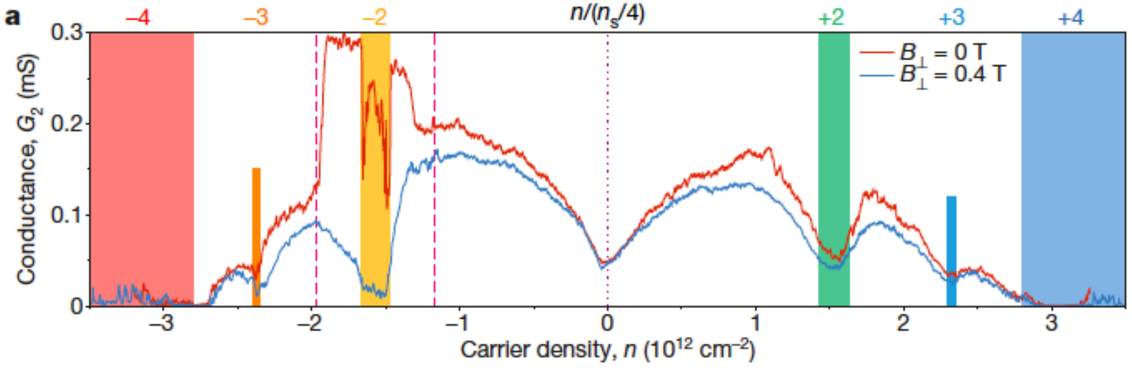
Cory Dean, Science 2013



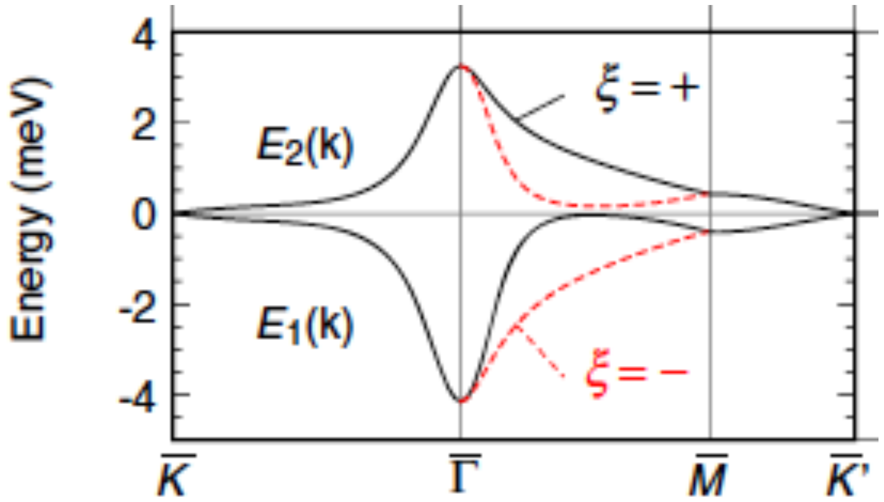
Cao et al., Nature 2018 (MIT)

Flat bands

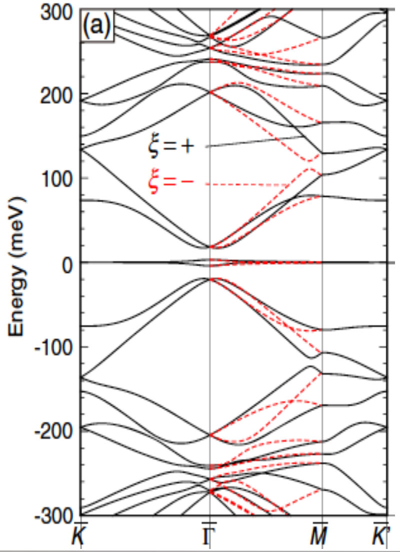
Cao et al., Nature 2018 (MIT)



2 valleys (K and K')



$\theta = 1.05^o$

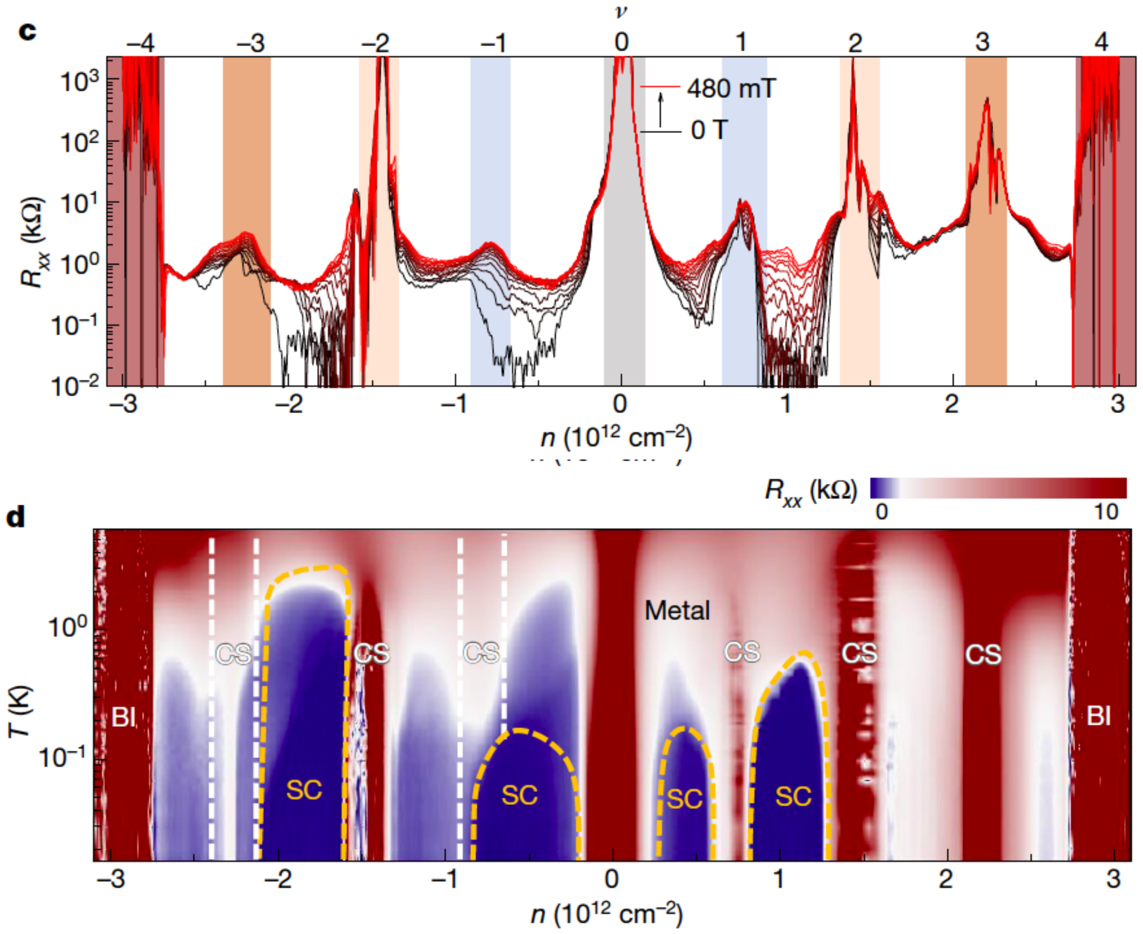


Magic angle where band is relatively non-dispersive

Gate voltage fills the Moiré band with four electrons (spin + valley)

Conductance dip (resistance peak) at each integer filling

Phase diagram

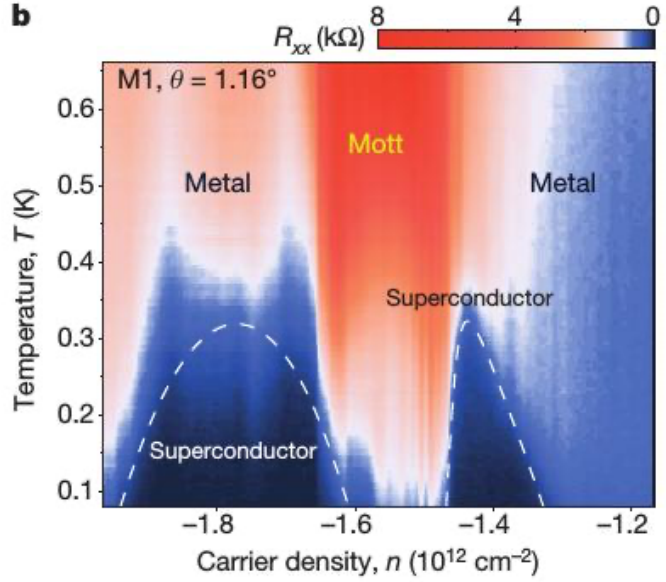


Lu, Efetov, Nature 2019

More complete phase diagram, contains

1) insulating phases - driven by interactions

2) superconducting regions

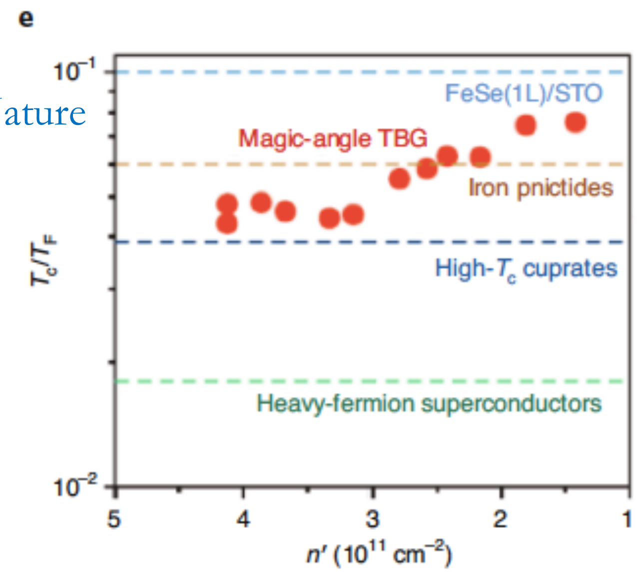


Cao et al., Nature 2018 (MIT)

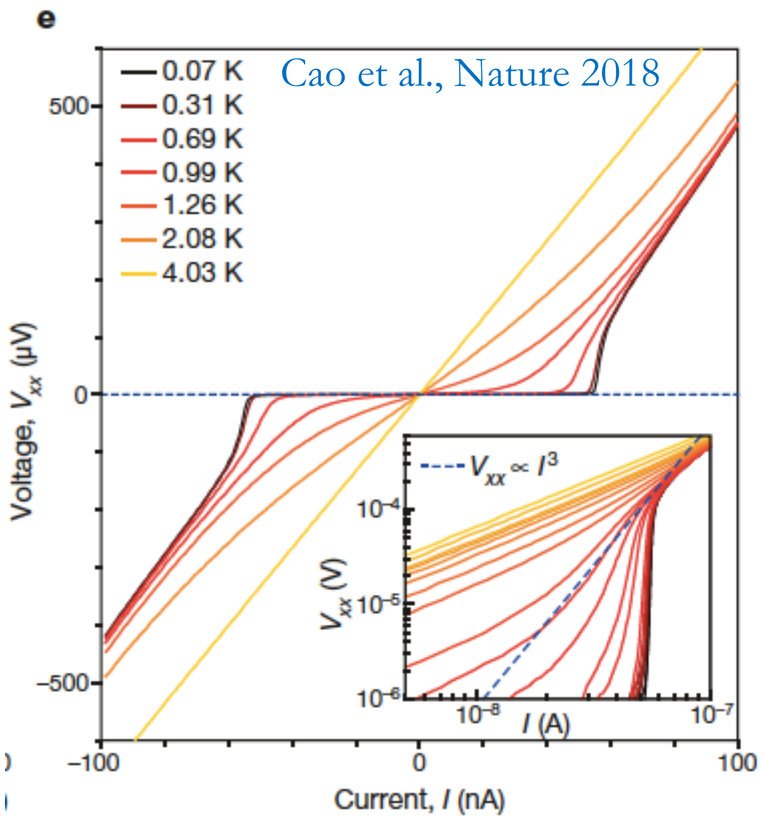
Yankowitz, Science 2019 (Colombia)

(unconventional) superconductivity

Andrei, MacDonald, Nature Mat. 2020

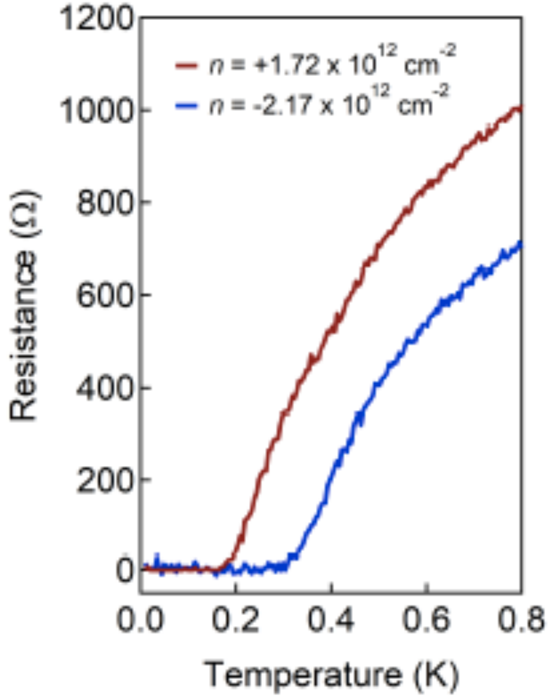


Cao et al., Nature 2018



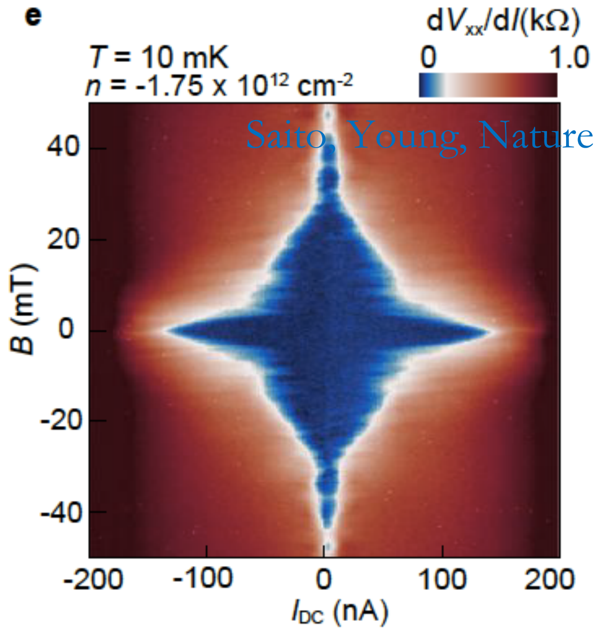
Non-linear BKT resistance

Yankowitz, Dean, Science 2019



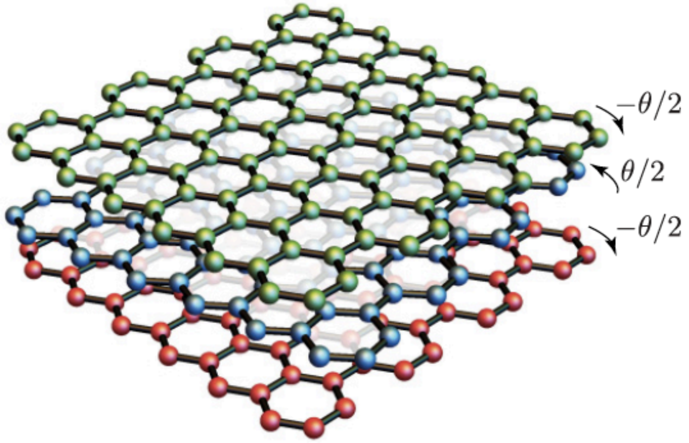
Vanishing resistance

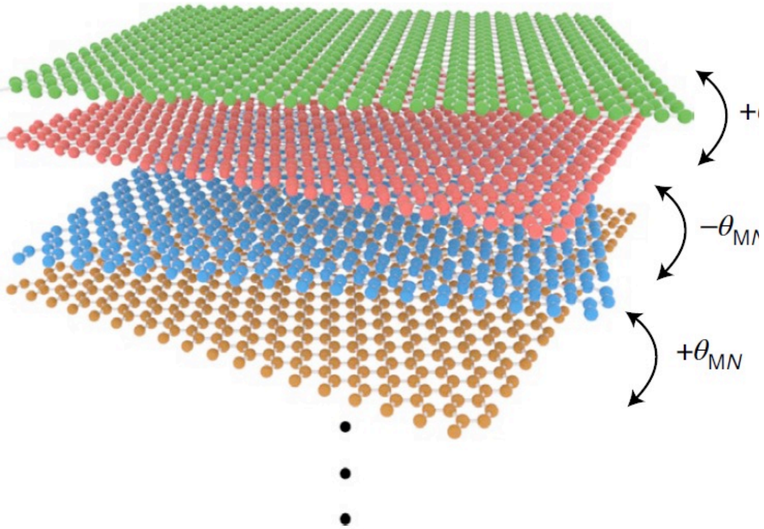
Saito, Young, Nature Phys. 2020

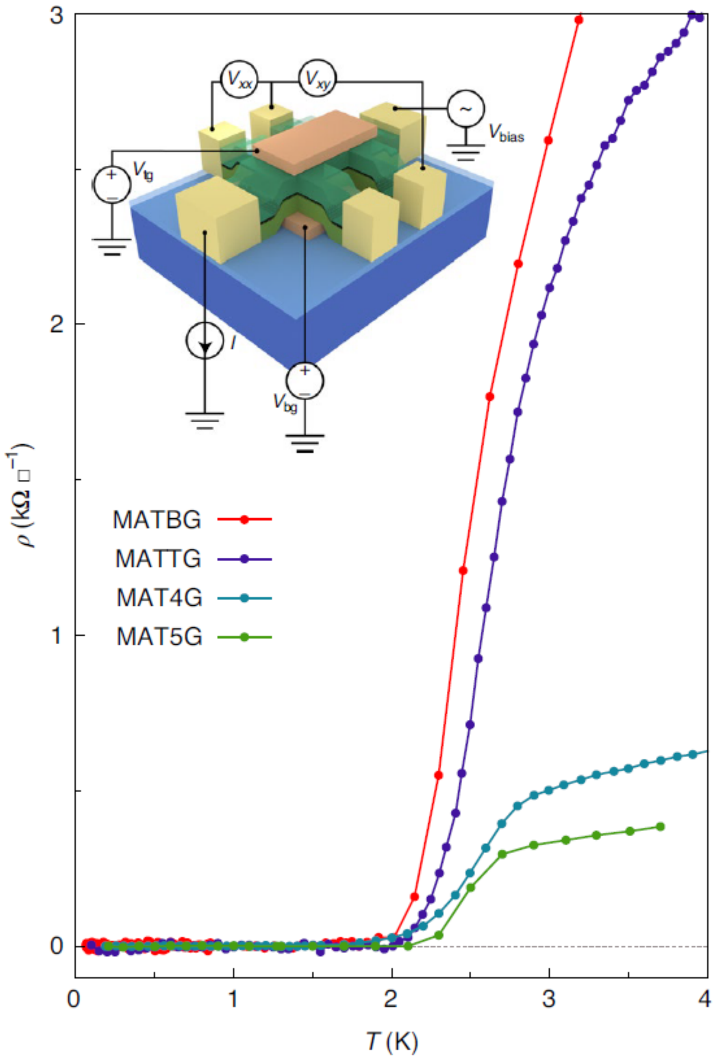


Fraunhofer oscillations

Multi-layer twisted graphene







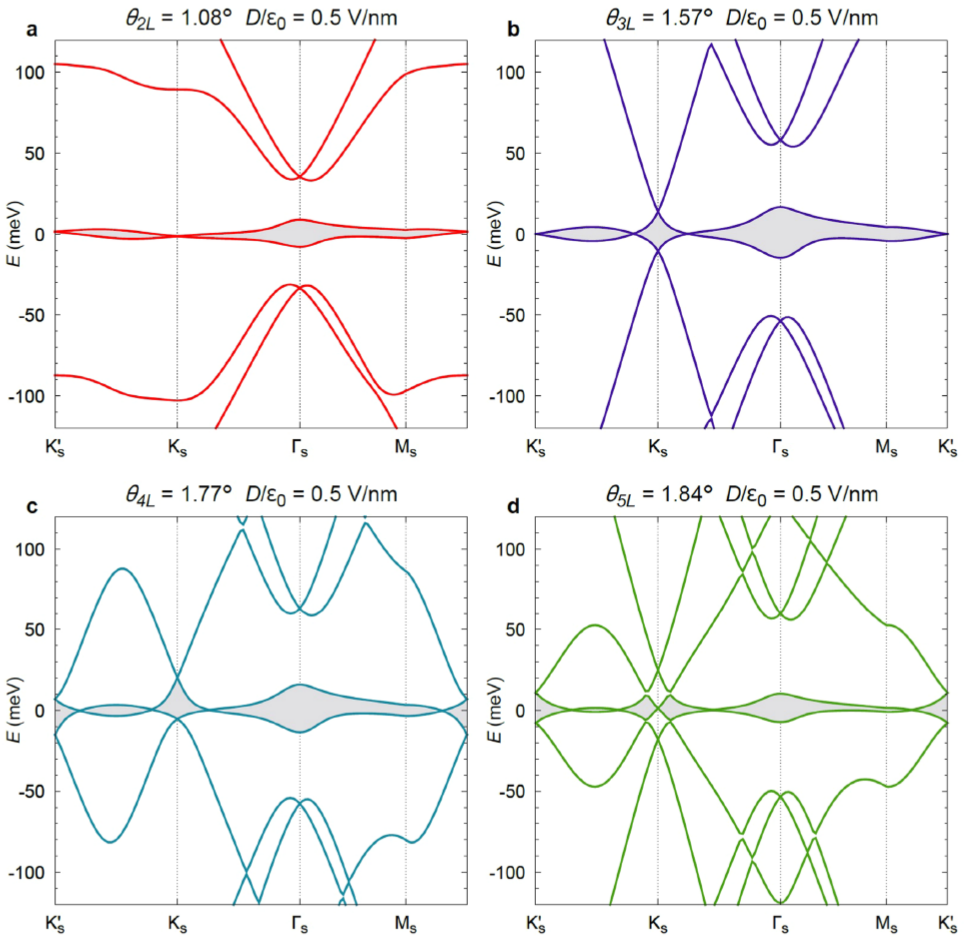
Stacking of 3, 4, 5 rotated graphene monolayers

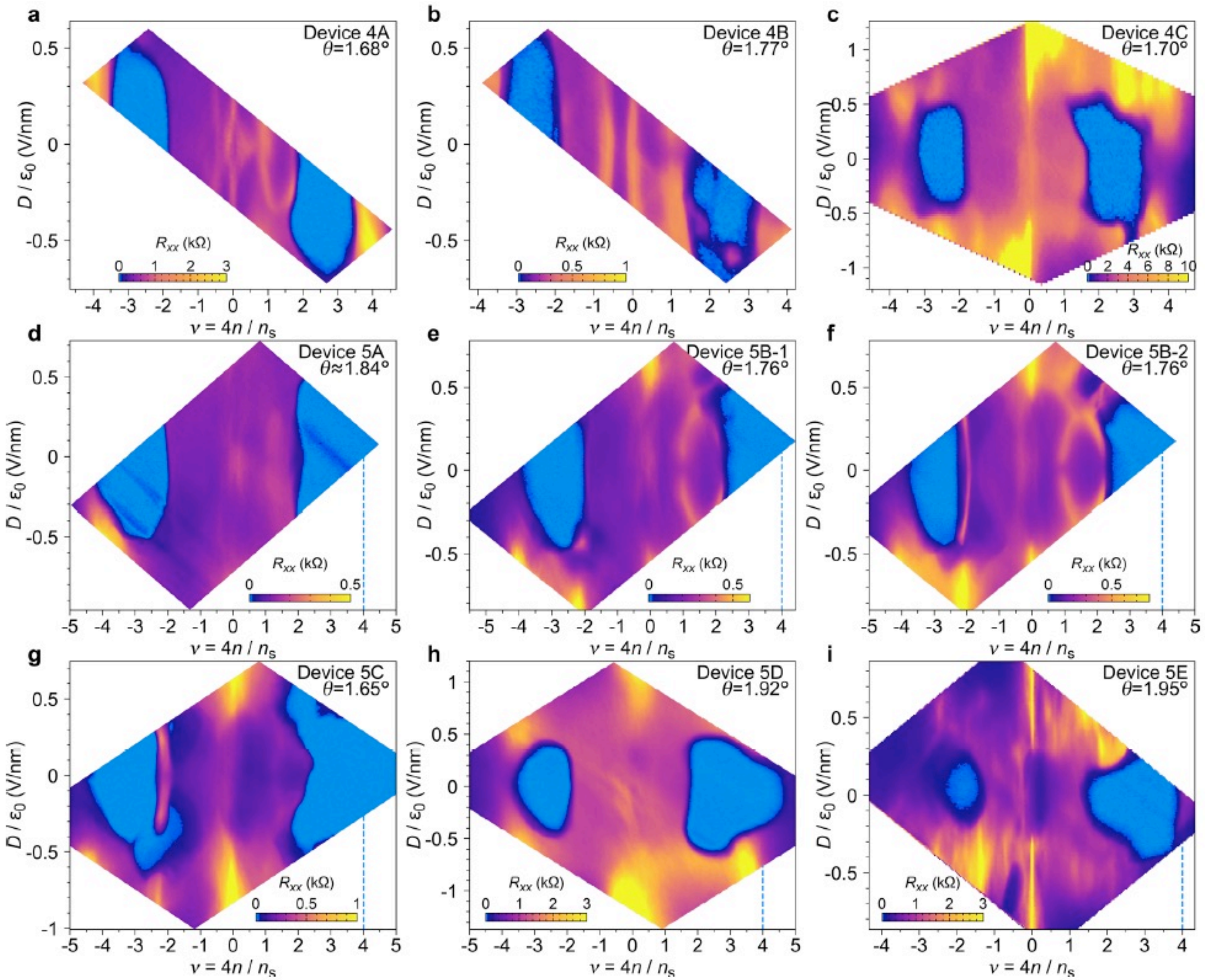
All exhibit robust signatures of superconductivity

Pauli limited is exceeded for N>2

Park, Jarillo-Herrero et al., Nature Mat 2023

Multi-layer twisted graphene

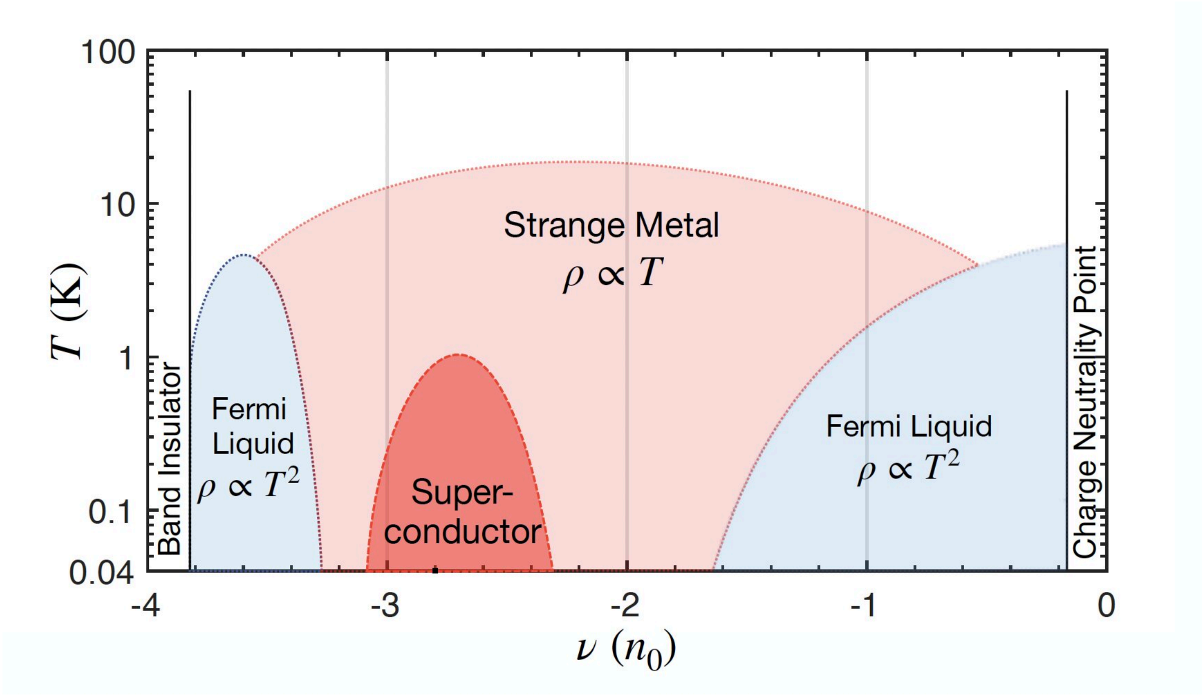


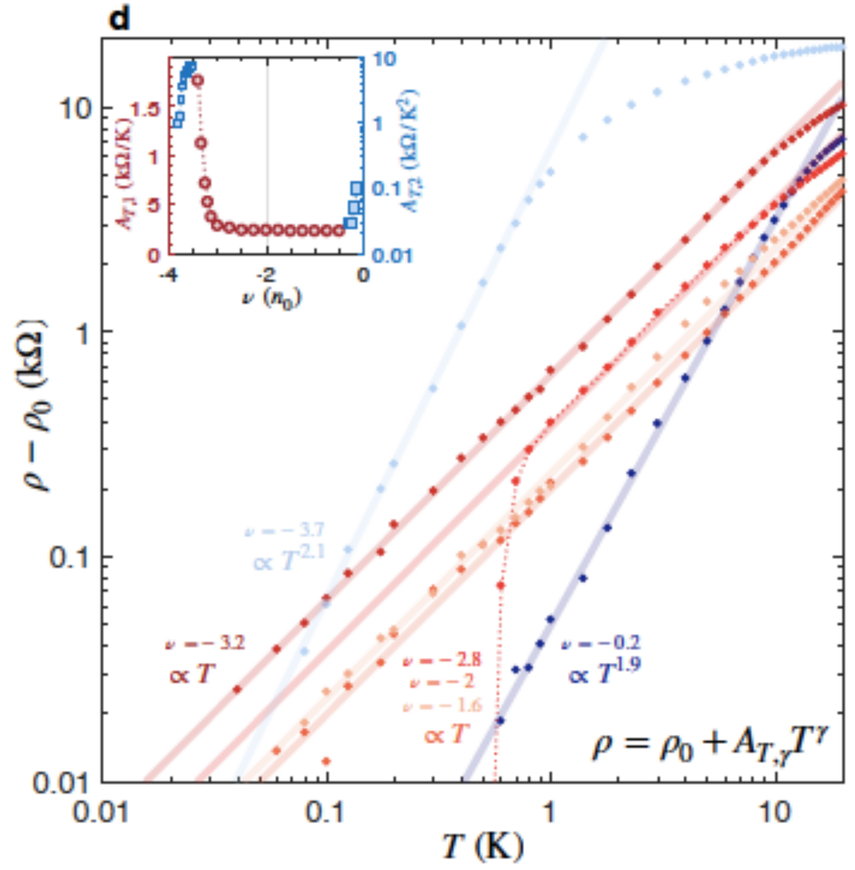


Park, Jarillo-Herrero et al., Nature Mat 2023

Strange metal behavior

A. Jaoui, D. Efetov Nature Phys 2022 (ICFO)

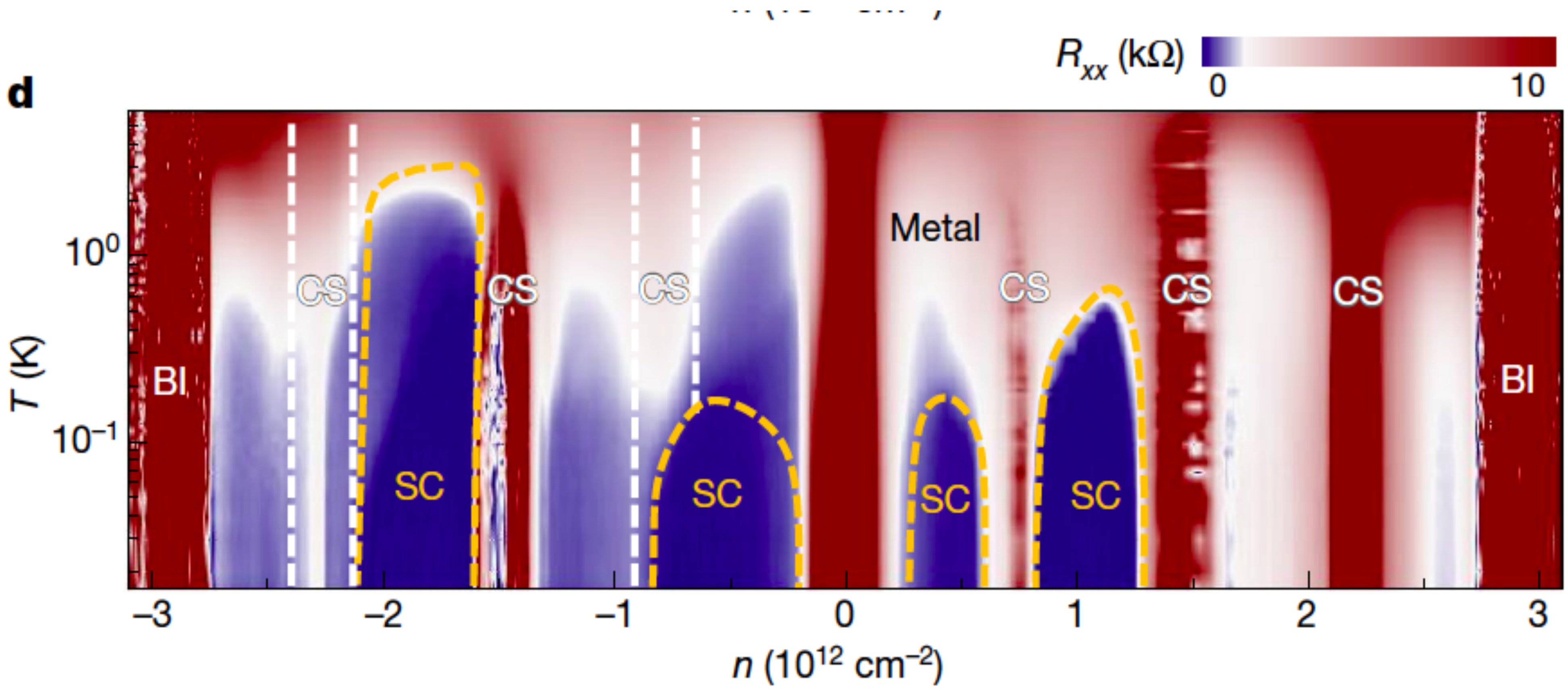




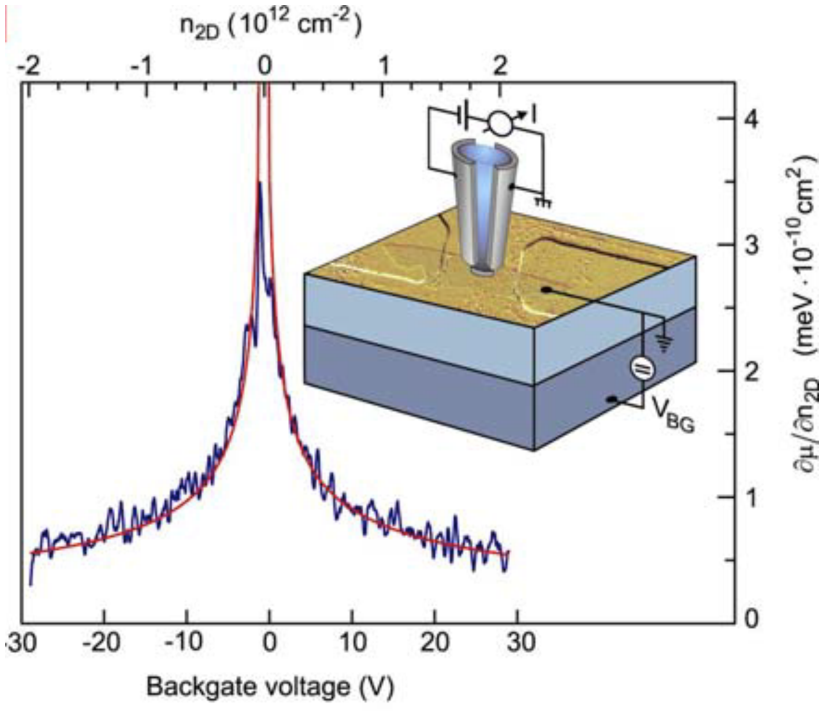
Linear in T resistivity: quantum critical fluctuations (origin is not known)

Similarity with many correlated materials (cuprates, ruthenates, pnictides, heavy fermions)

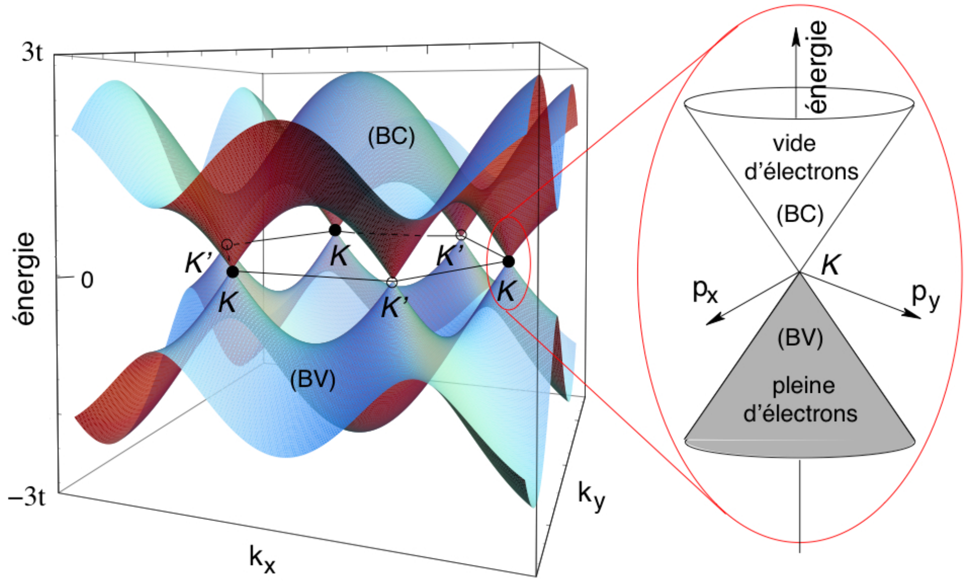
Correlated states and symmetry breaking



Compressibility in monolayer graphene

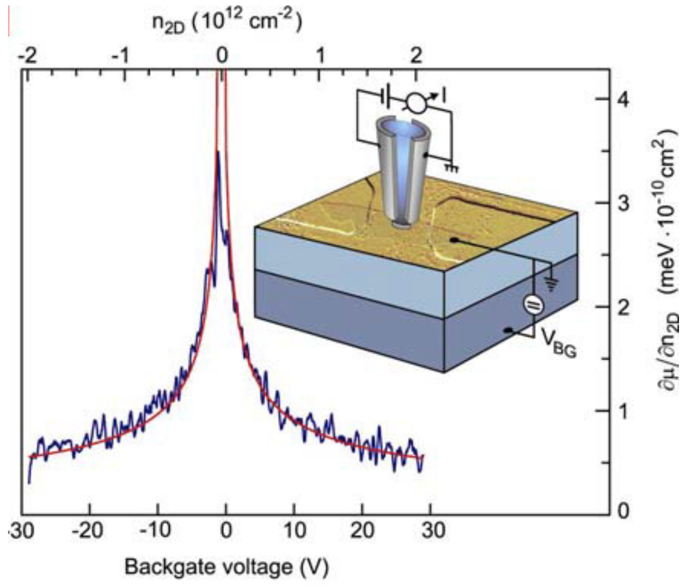


Martin, Yacoby, Nat. Phys. 2008

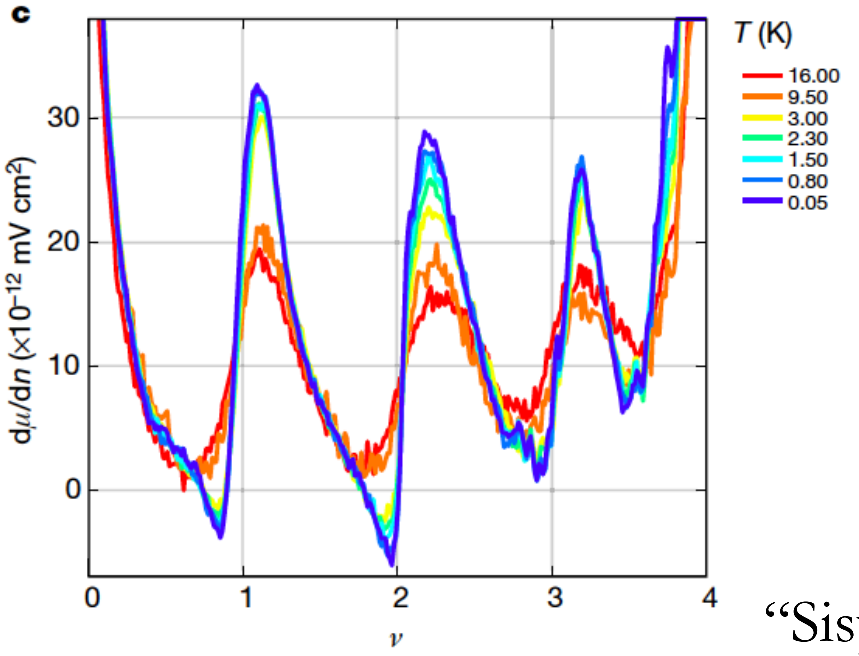


Compressibility shows a peak at charge neutrality in graphene (vanishing density of states)

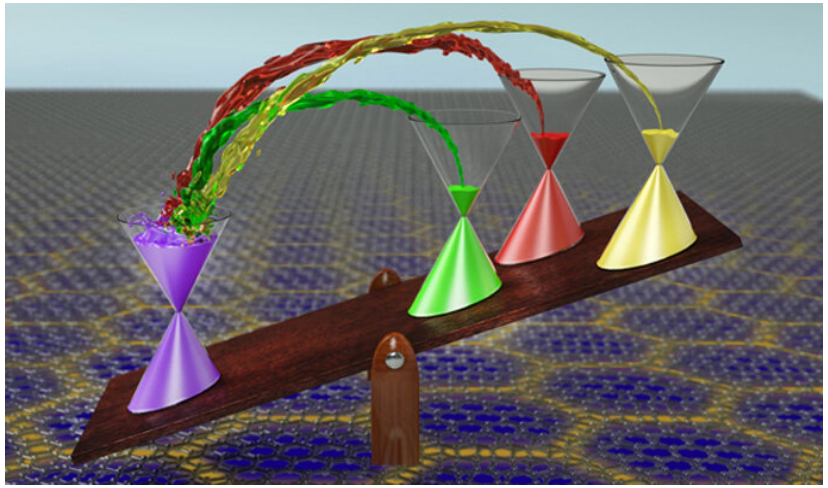
Symmetry-breaking phases



Monolayer graphene



Twisted bilayer graphene



“Sisyphus” resetting to the Dirac point

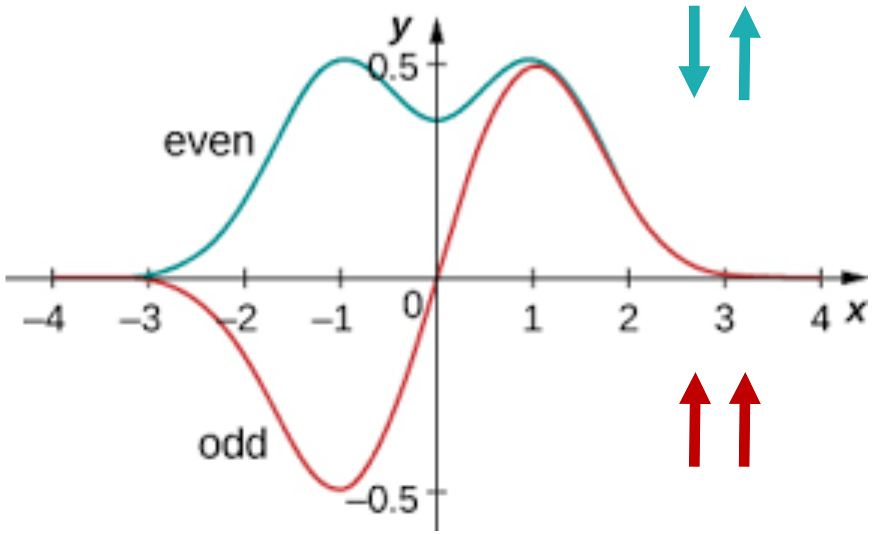
At (relatively) higher temperature/magnetic field

Measure of compressibility reveals a cascade of Stoner-like ferromagnetic transitions

Zondiner, Ilani, Nature 2020 ; Wong, Yazdani, Nature 2020 ; Saito, Young, Nature Physics 2021

Exchange energy

Gregarious tendancy of interacting electrons

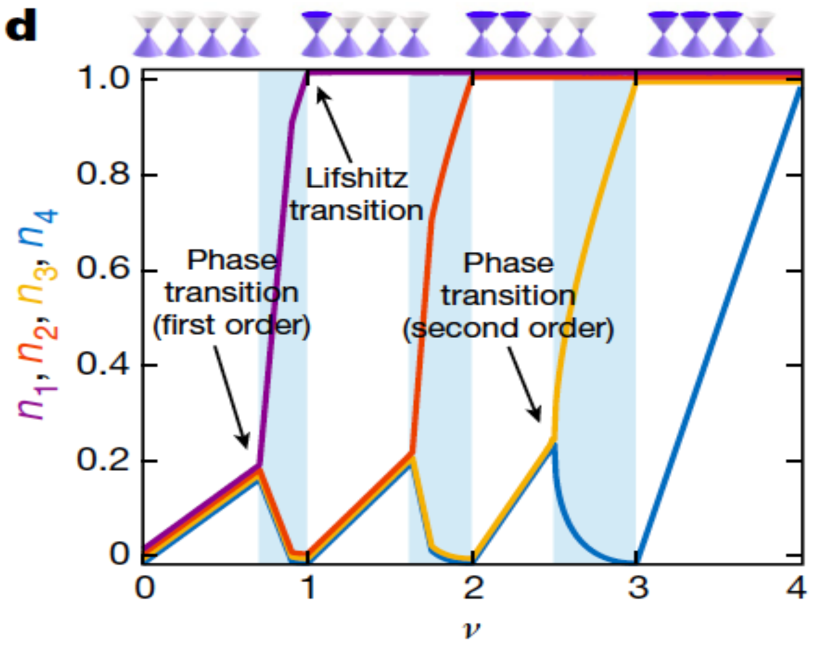


$$\int dr \frac{e^2}{\varepsilon_0 \, r} \, |\psi_{\mathrm{odd}}(r)|^2 < \int dr \frac{e^2}{\varepsilon_0 \, r} \, |\psi_{\mathrm{even}}(r)|^2$$

Odd two-electron wavefunction (singlet spin state) is less energetic than even (triplet spin)

$\Longrightarrow$ Favors symmetric spin configuration (ferromagnetic)

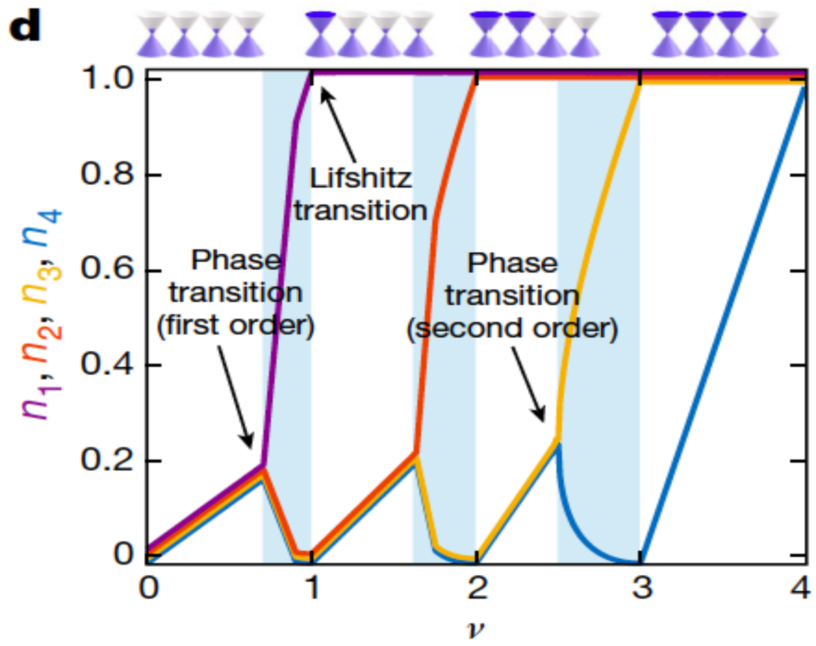
Stoner mechanism and ferromagnetism

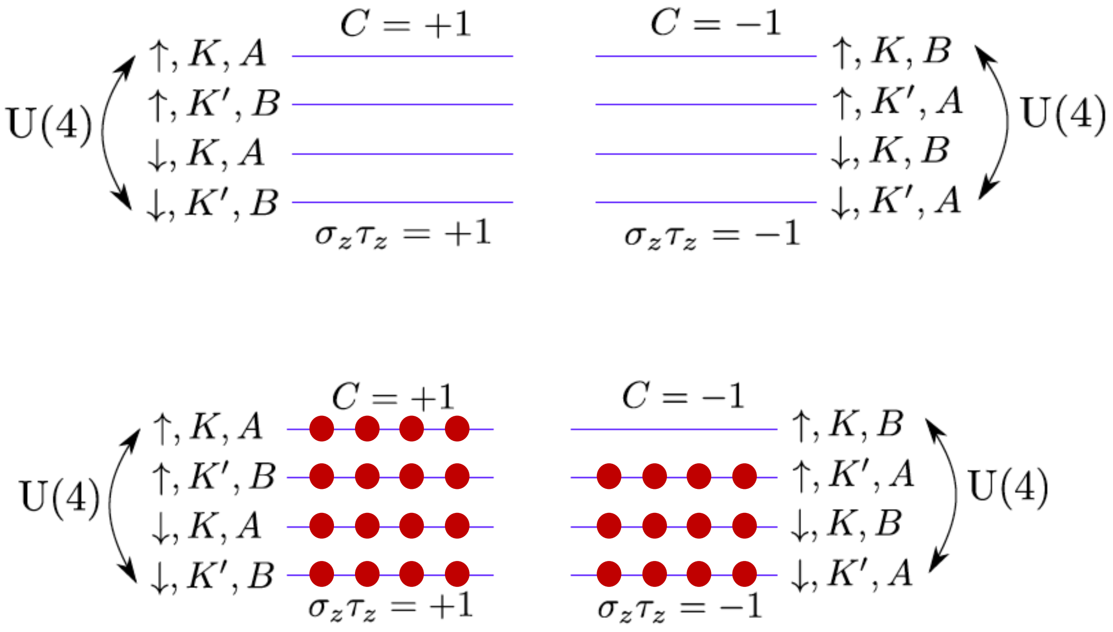


Stoner transition to an isospin (valley+spin) magnet to maximize exchange energy

Zondiner, Ilani, Nature 2021

Stoner mechanism and ferromagnetism



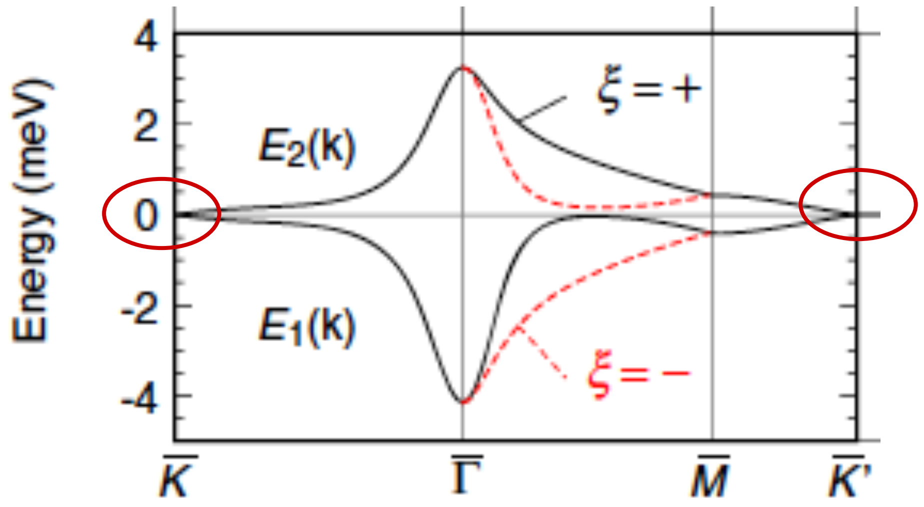


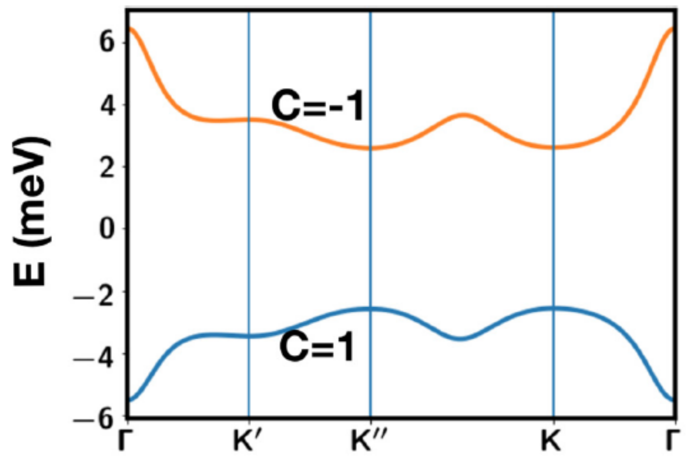
Stoner transition to an isospin (valley+spin) magnet to maximize exchange energy

Zondiner, Ilani, Nature 2021

Topology and Chern bands

hBN substrate - aligned with TBG - opens a gap at the two Dirac points





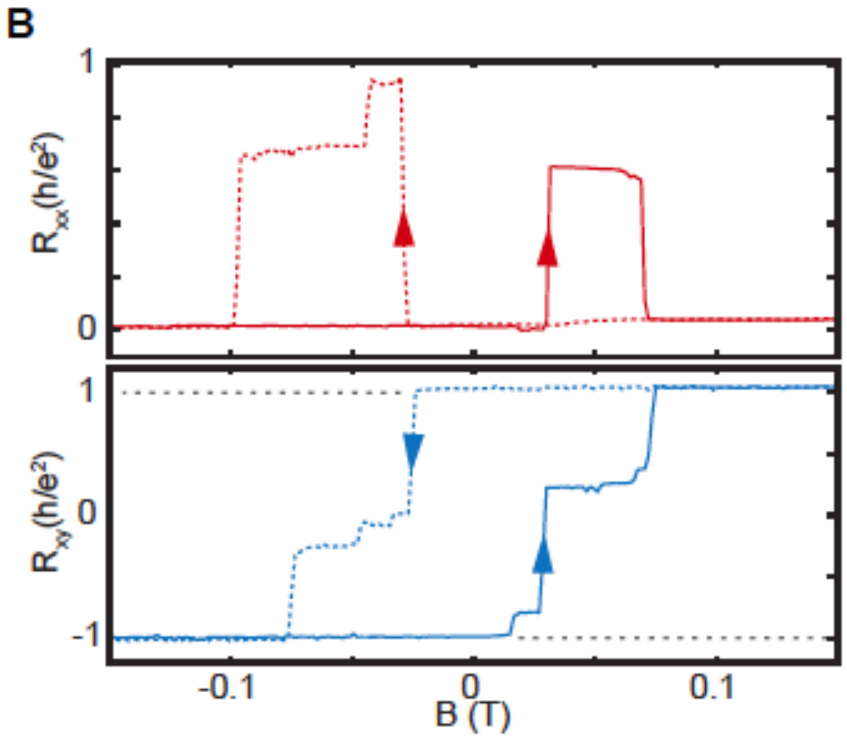
Non-zero Chern numbers

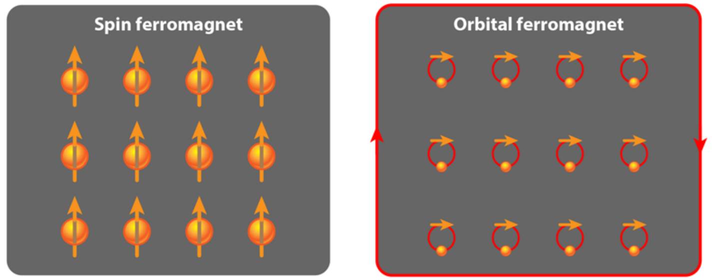
Resulting bands are topological because the two Dirac points have the same helicity (Berry phase)

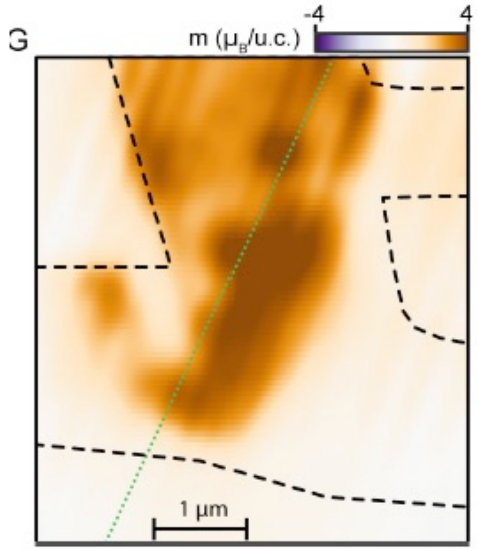
Anomalous quantum Hall effect

(anomalous) quantum Hall effect without magnetic field

Filling of bands with isospin symmetry breaking







Quantized transverse resistance with no magnetic field !

Measurement of orbital magnetization

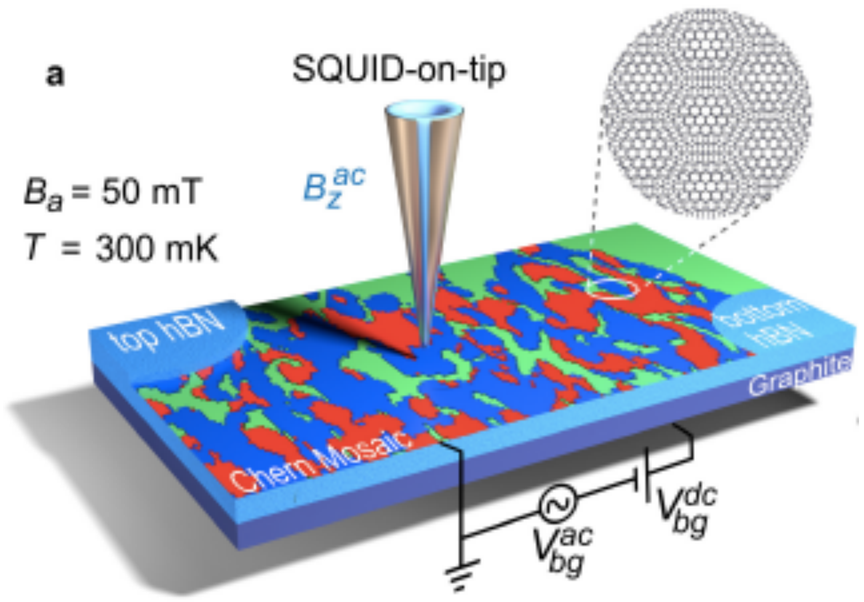
Tschirhart, Young, et al. Science 2021

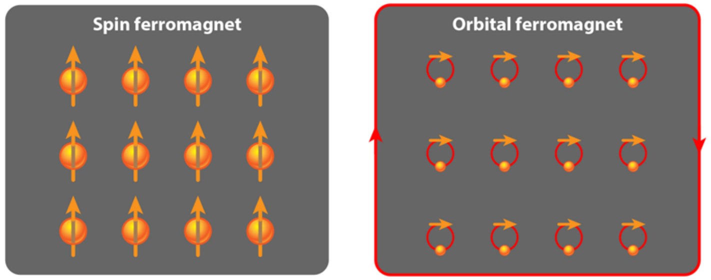
Chern mosaic

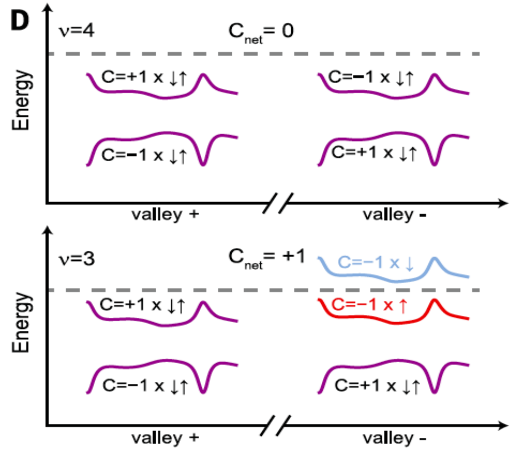
Grover, Efetov, Zeldov, Nature Phys 2022

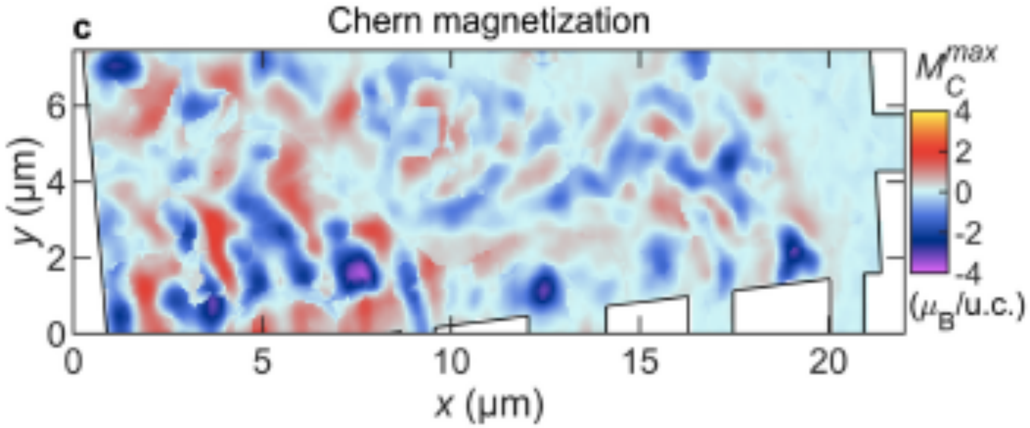
Chern bands in the moiré minibands

Spontaneous isospin (valley) symmetry breaking







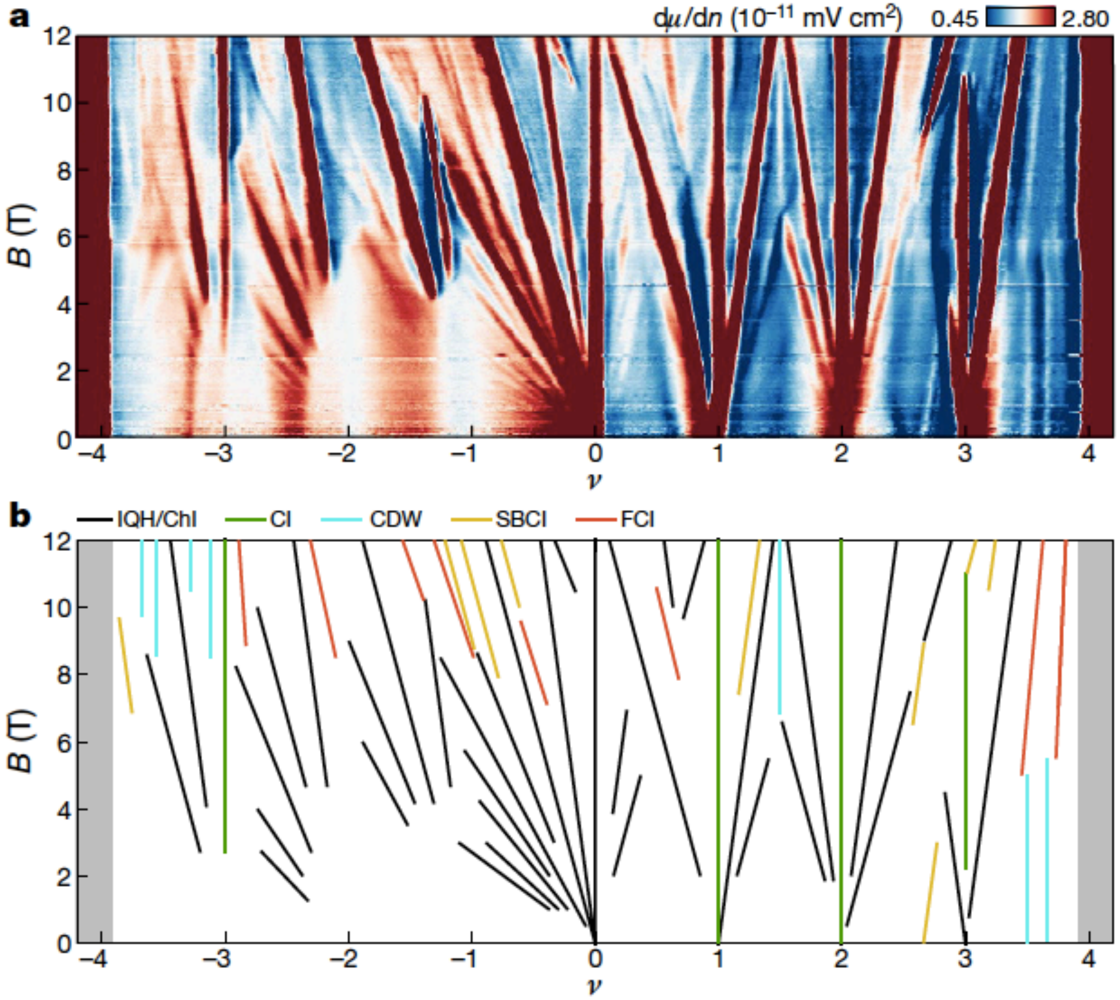


Fractional Chern insulators ?

Xie, Jarillo-Herrero, Yacoby, Nature 2021

Fractional Chern insulators identified in Fan diagrams

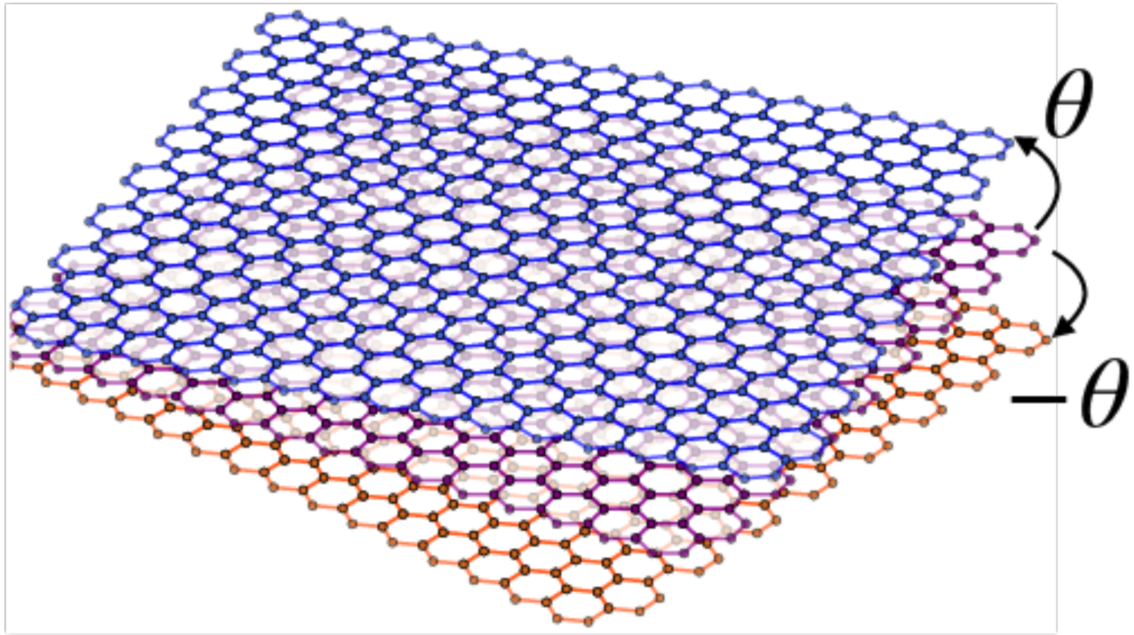
But they appear (are stabilized ?) above 5T

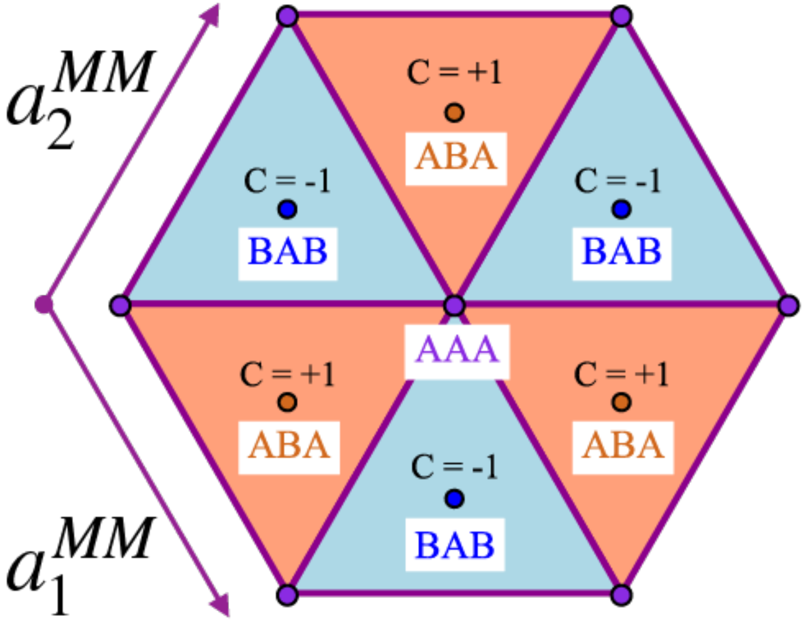


Chern mosaic in twisted trilayer graphene

Helical twisted trilayer graphene

Stacking develops two incommensurate moiré patterns: there is a supermoiré modulation on top of the moiré pattern



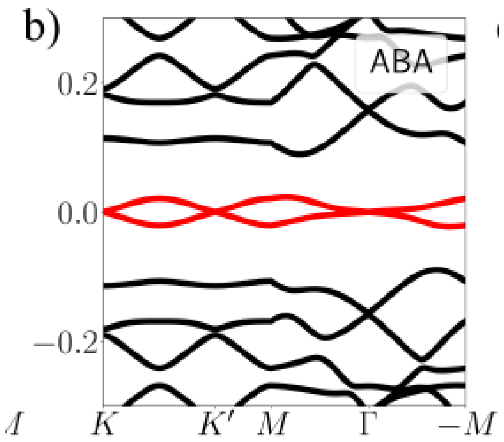


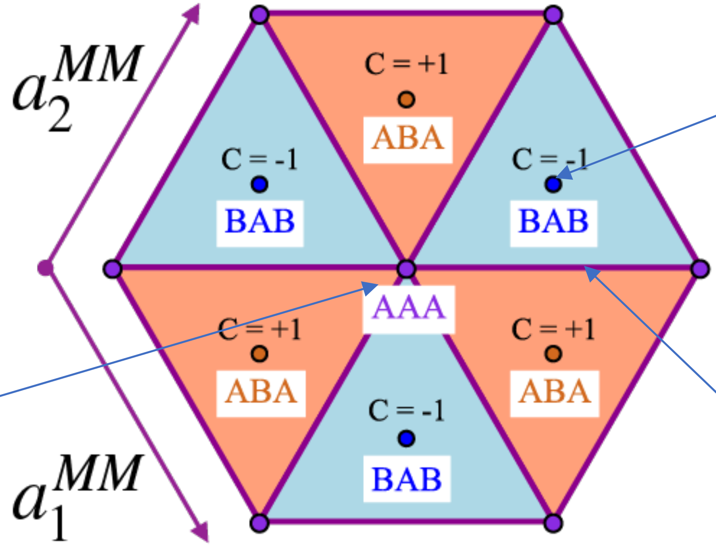
At the supermoiré scale, we find a triangular lattice of topological Chern bands separated by chiral edge channels

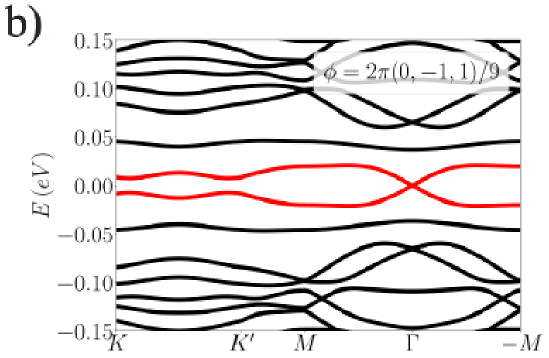
Chern mosaic of topological bands

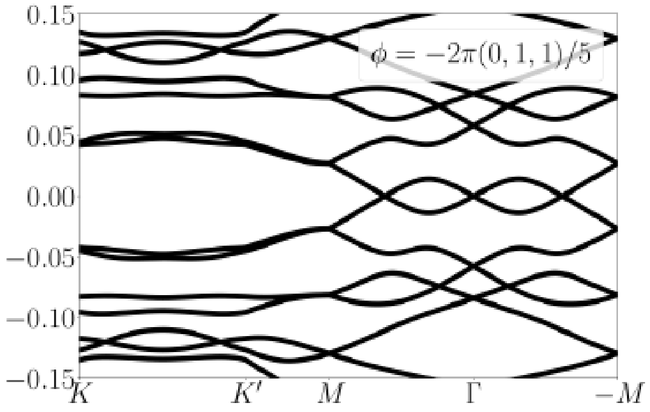
The two central bands carry a non-vanishing Chern value

$$\theta = 1.69^\circ$$

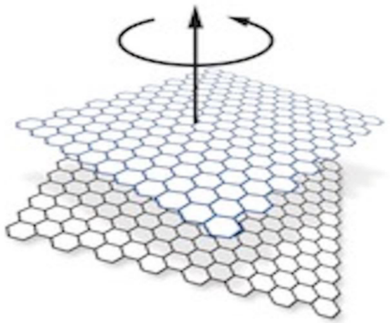


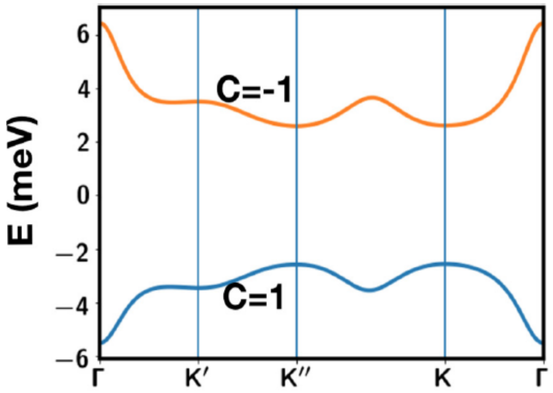






Difference with TBG

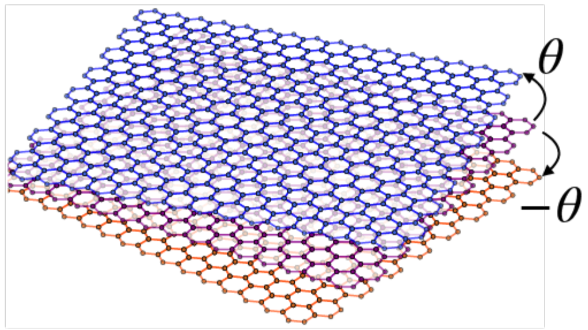


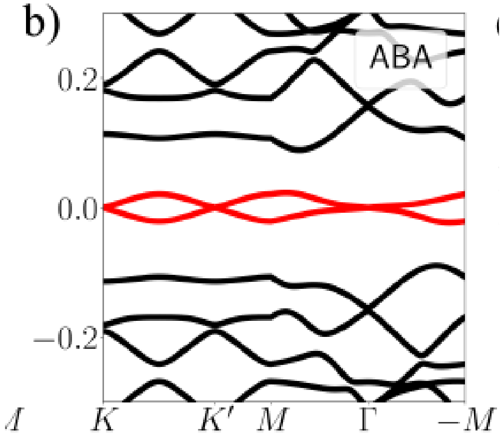


The two central bands carry opposite Chern values

Need of a mechanism to split them (with HBN)

Also symmetry breaking is required





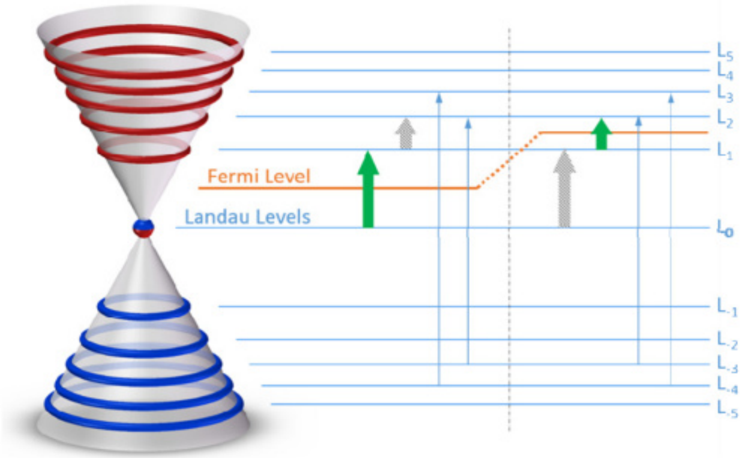
The two central bands have directly C=1

The magic twist angle is larger than for TBG

Why flat bands in TBG ?

$$H_{\rm Dirac} = (\mathbf{k} - e\mathbf{A})\cdot\boldsymbol{\sigma} = \mathbf{k}\cdot\boldsymbol{\sigma} - e\begin{pmatrix} 0 & A_x - iA_y \\ A_x + iA_y & 0 \end{pmatrix}$$

Any nonuniform coupling between the two sublattices act as an effective magnetic field



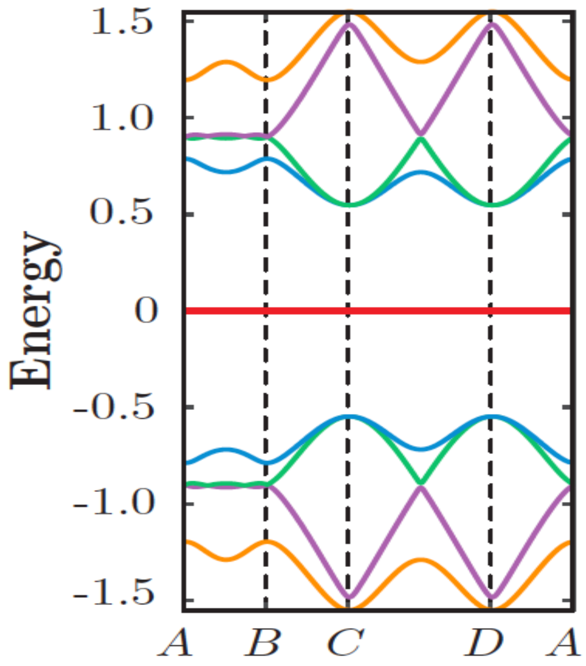
Continuum model for TBG

$$H = \begin{pmatrix} \mathbf{k}\cdot\boldsymbol{\sigma} & T(\mathbf{r}) \\ T^\dagger(\mathbf{r}) & \mathbf{k}\cdot\boldsymbol{\sigma} \end{pmatrix}$$

$$T(\mathbf{r}) = \begin{pmatrix} w(r) & f_1(\mathbf{r}) \\ f_2(\mathbf{r}) & w(r) \end{pmatrix}$$

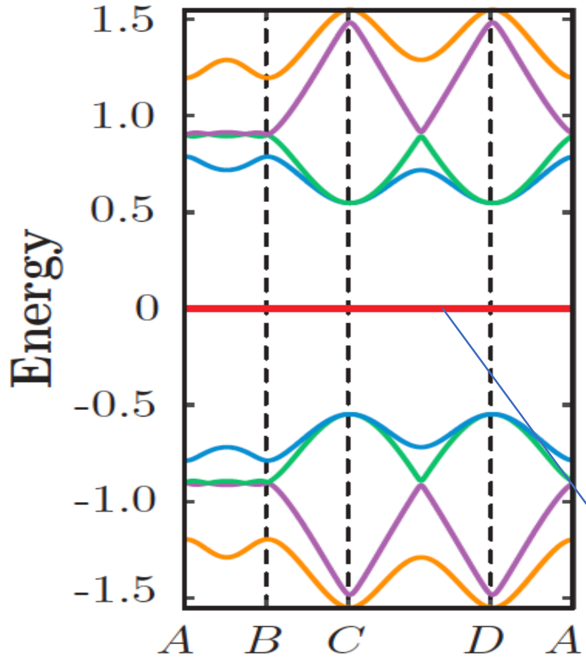
Chiral limit

w=0: exactly flat band at magic angle !



Tarnopolsky et al, PRL 2019

Ideal flat bands in the chiral limit (TBG)



The quantum geometric tensor $Q_{ab}(k) = \langle D_{k_a} u_k | D_{k_b} u_k \rangle$

Involves a covariant derivative $D_{k_a} = \partial_{k_a} + i\mathcal{A}_a(k)$

with the Berry connection $\mathcal{A}_a(k) = i\langle u_k | \partial_a u_k \rangle$

Quantum metric

$$g_{ab}(k) = \frac{Q_{ab}(k) + Q_{ba}(k)}{2}$$

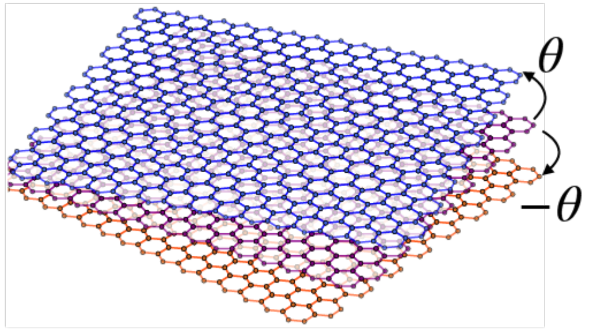
Berry curvature

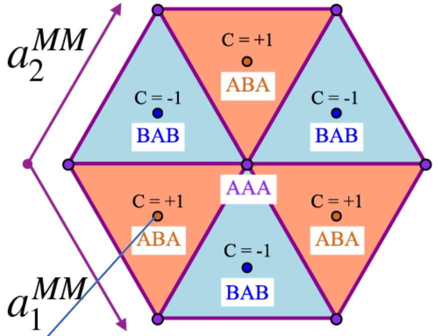
$$\Omega(k) = i\varepsilon_{ab} Q_{ab}(k)$$

When the trace condition is met $\mathrm{Tr}\, g(k) = |\Omega(k)|$ ⇒ Fractional Hall states emerge as solutions of interacting electrons

Ledwith, Vishwanath et al, PRR 2020

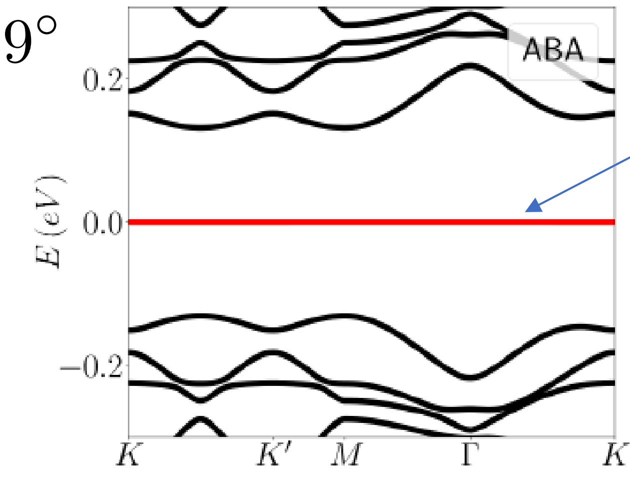
Exactly flat bands in the chiral limit of helical trilayer





Bands are also ideal in the sense that the trace condition is satisfied $\mathrm{Tr}g(k) = |\Omega(k)|$

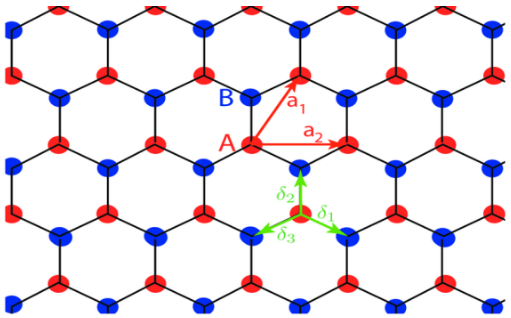
$\theta = 1.69°$



Chiral limit

Two bands with Chern number +2 and -1

(sublattice-polarized)



Exactly flat bands in the chiral limit of helical trilayer

We find an analytical expression for the color-entangled exact wavefunction with Chern C=+2

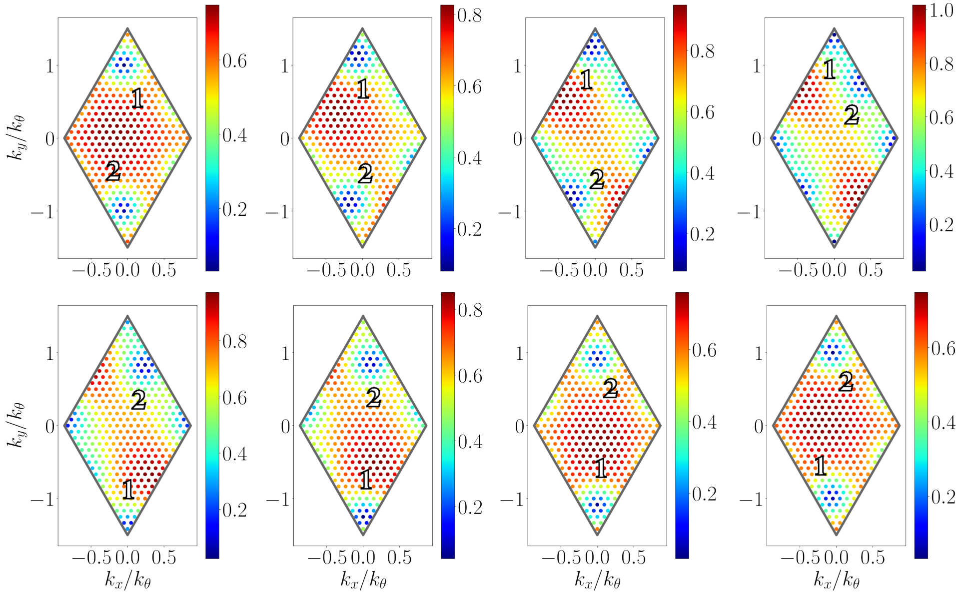
$$a_k = \vartheta_1[(k-K)/b_2, \omega]$$

$$\omega = e^{2i\pi/3}$$

$$\psi_k(r) = a_k \eta_{k-K}(z)\psi_K(r) + a_{-k}\eta_{k-K'}(z)\psi_{K'}(r)$$

$$\eta_k(z) = e^{ik_1 z/a_1} \frac{\vartheta_1[z/a_1 - k/b_2, \omega]}{\vartheta_1[z/a_1, \omega]}$$

Lowest landau level wavefunction on the torus



Guerci, Mao and Mora, Arxiv 2023

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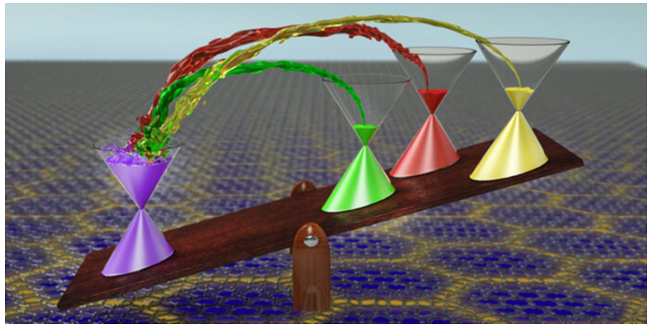
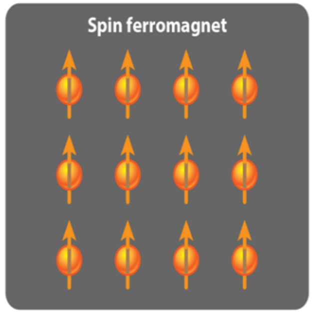
Weizmann

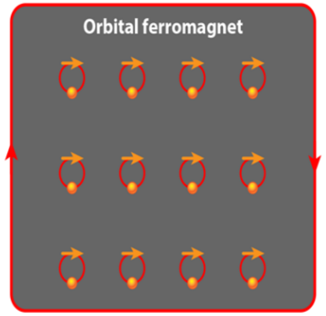
Yuval Oreg
Gal Shavit

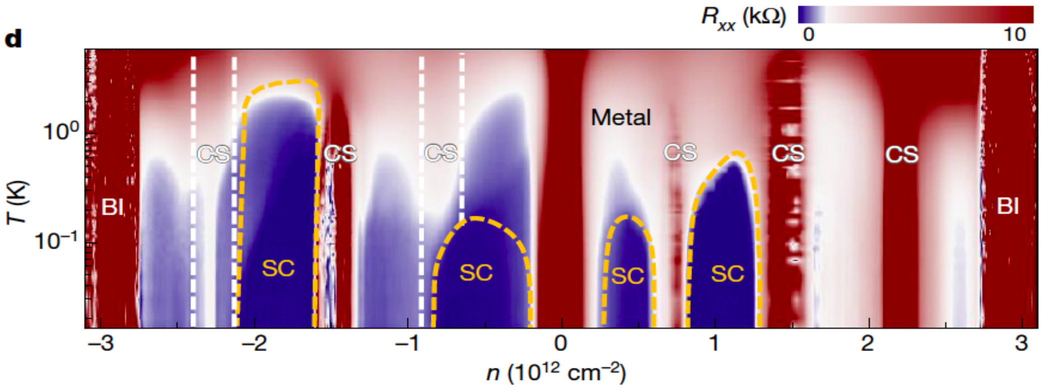
Conclusion

Twisted bilayer graphene: fantastic plateform to explore novel correlated states, topological phases, superconductivity…





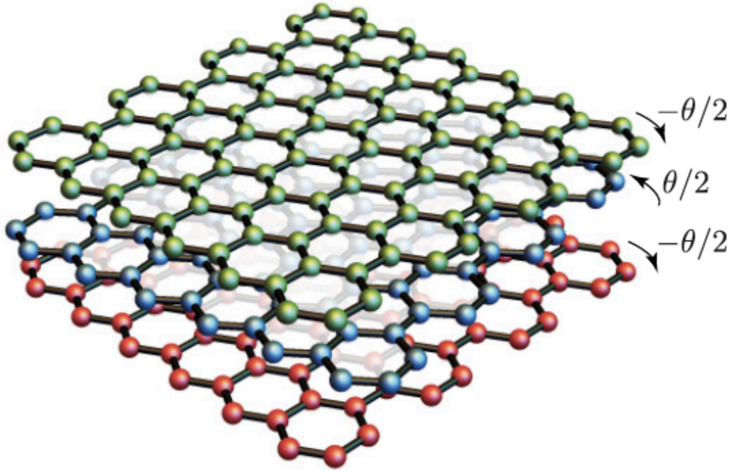




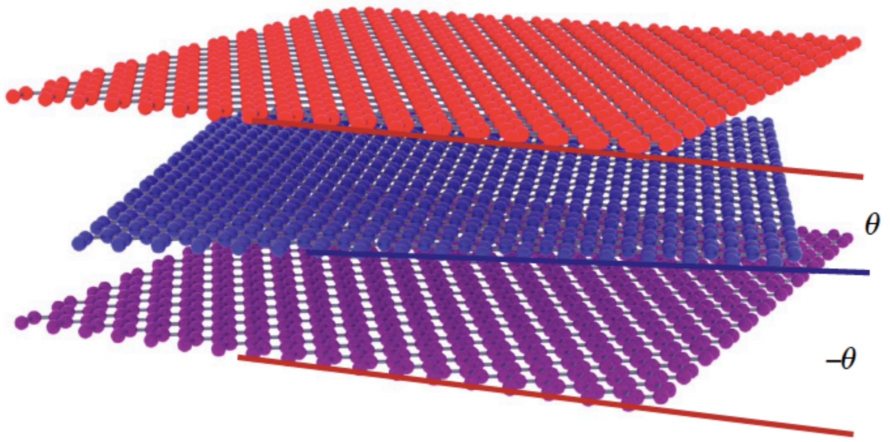
Other interesting effects: nematicity, broken translation invariance, fractional Chern insulators, unconventional superconductivity, anomalous Josephson junctions, strange metal…

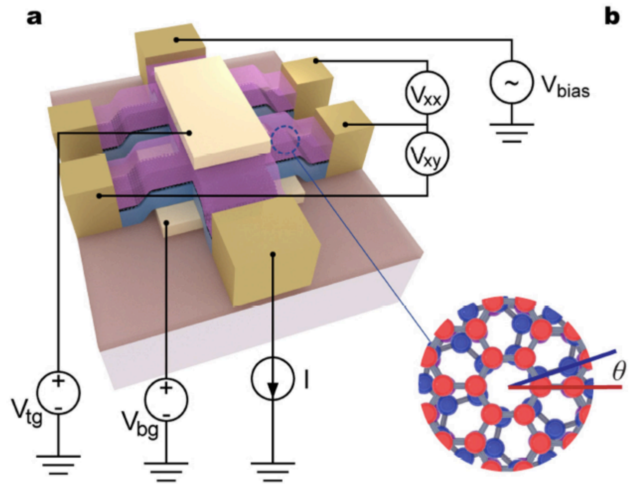
Helical trilayer graphene shows interesting topological features with a Chern mosaic and unconventional C=+2 Chern bands

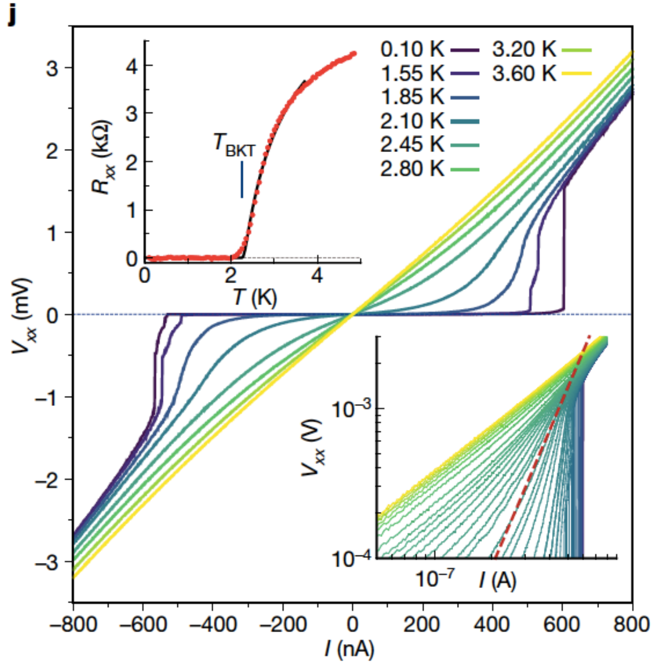
Twisted trilayer graphene



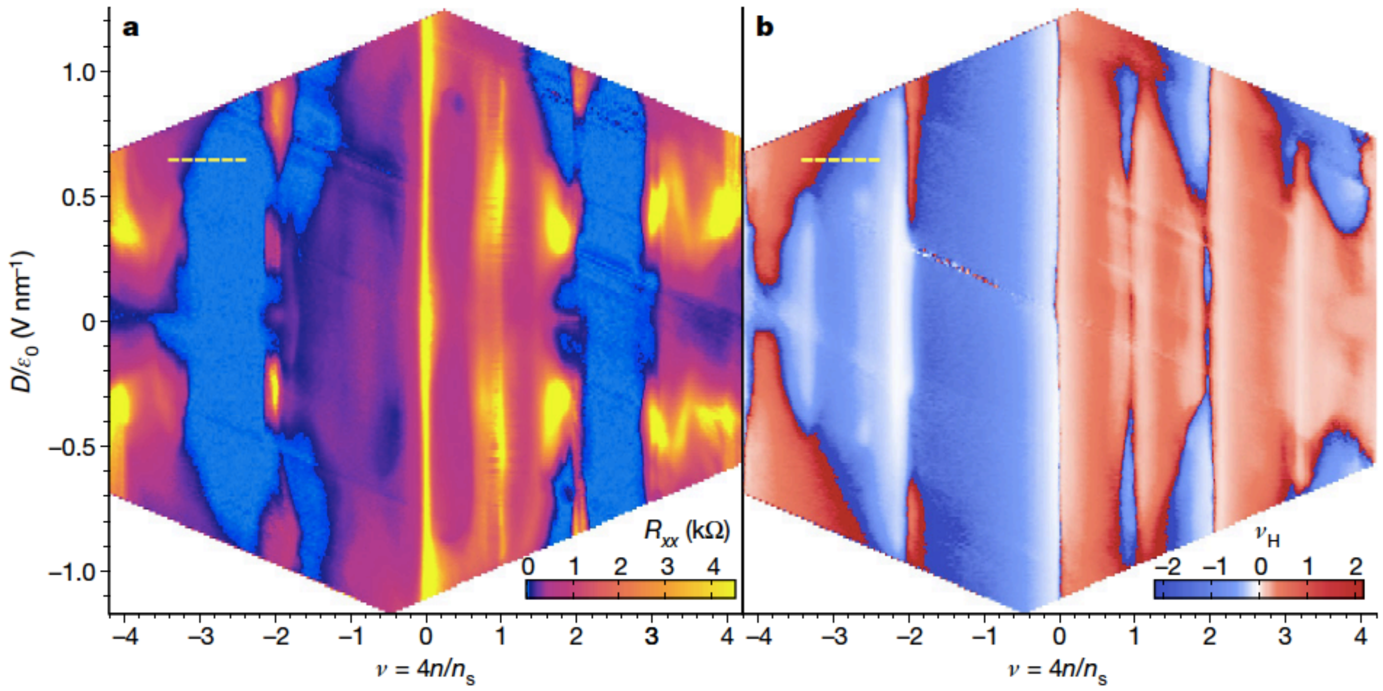
a

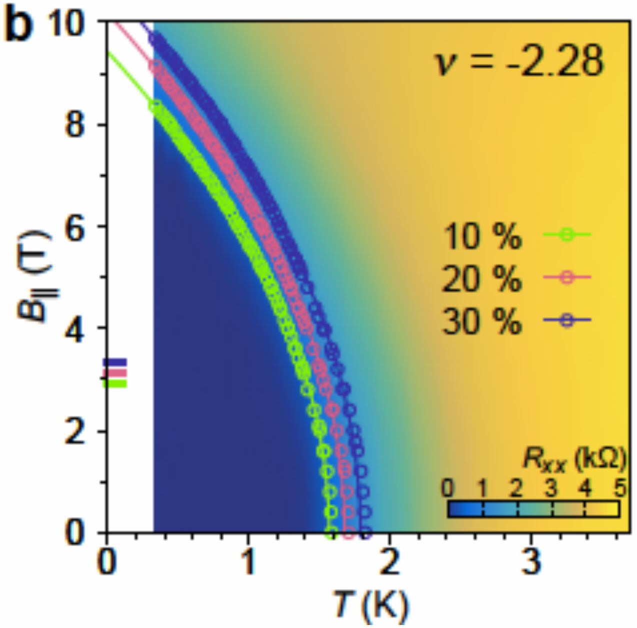


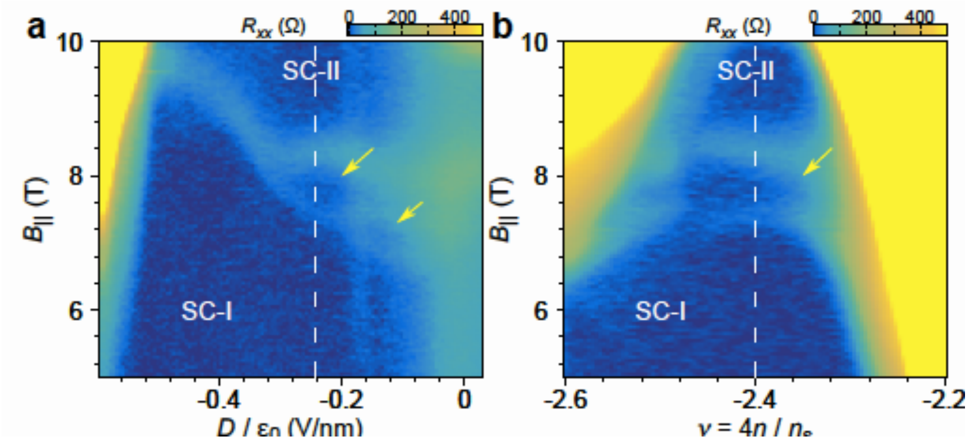




Twisted trilayer graphene





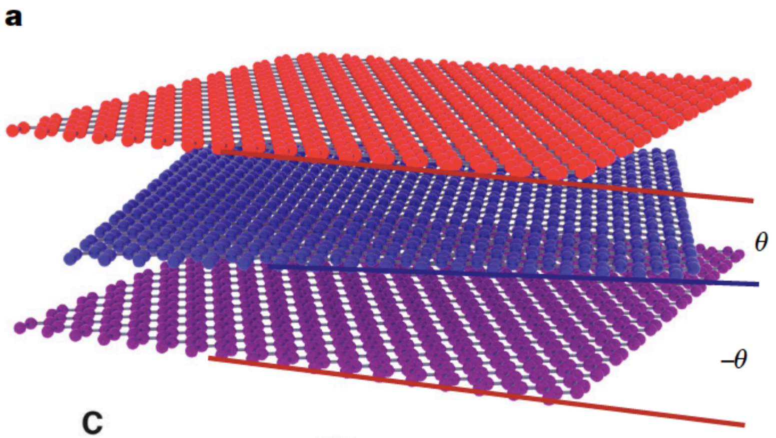


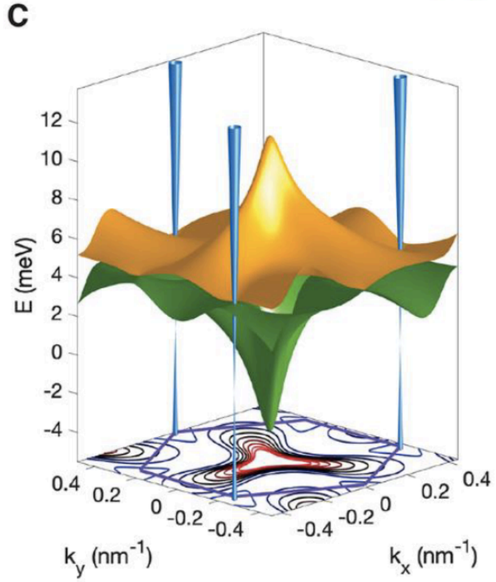
Insulating ferromagnetic phases

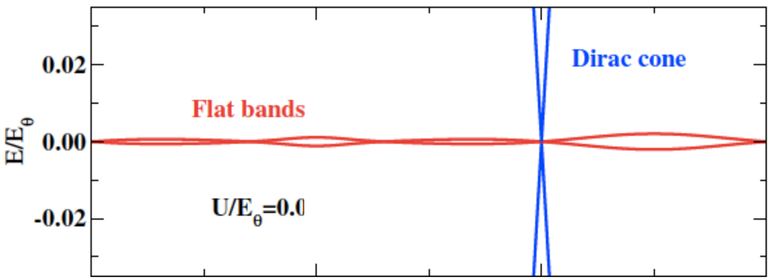
Superconducting states with high critical field (p-wave ?)

Superconducting regions bordered by van Hove singularity

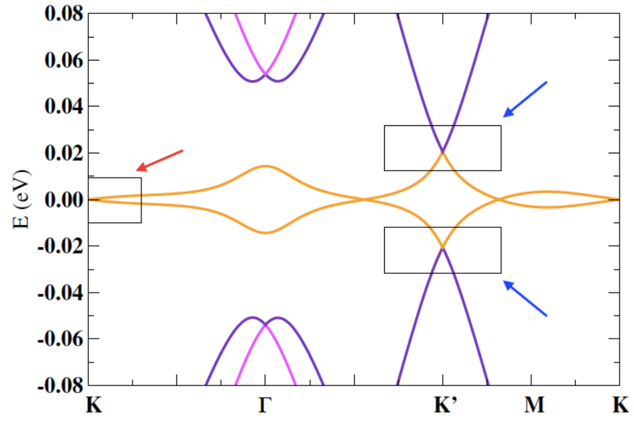
Twisted trilayer graphene







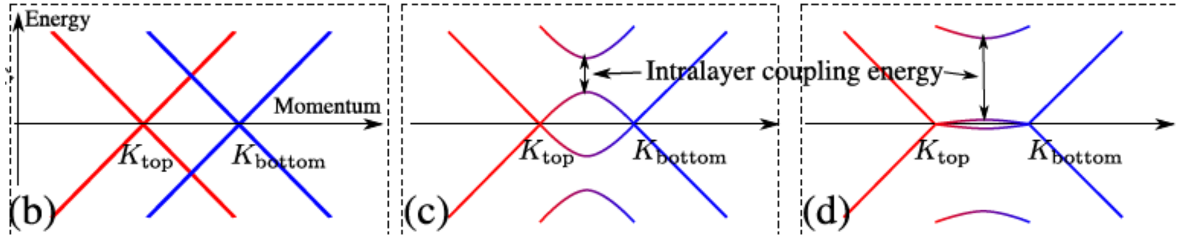
Zero electric field

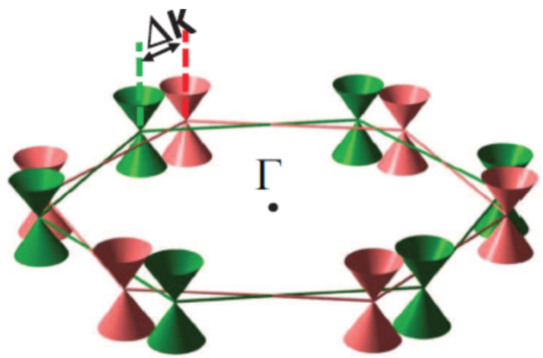


Finite electric field

Shifted Dirac cones

T. Heikkilä & T. Hyart 2019



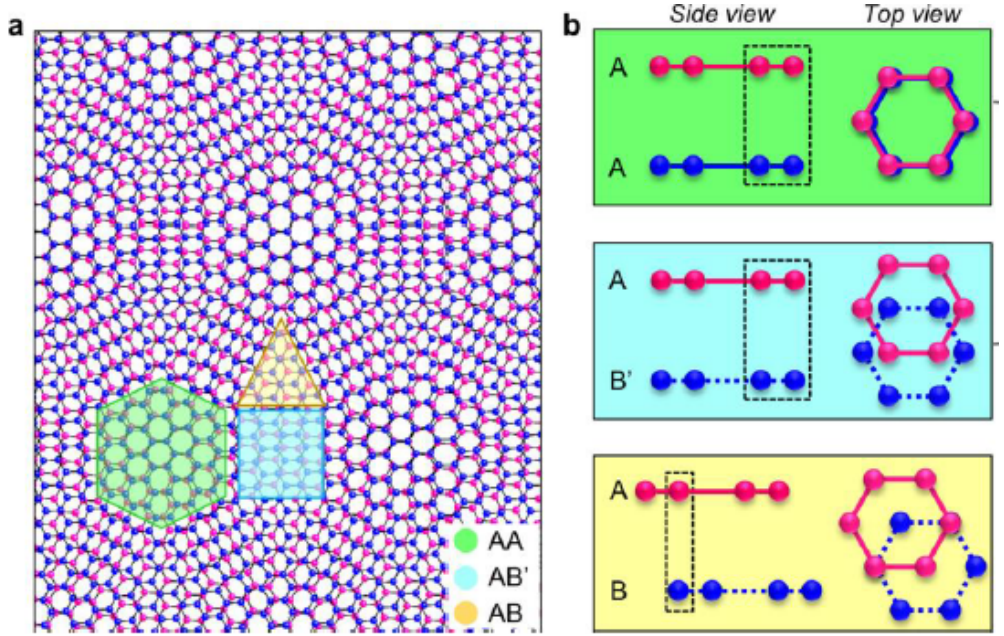


Mini-graphene spectrum with two Dirac cones

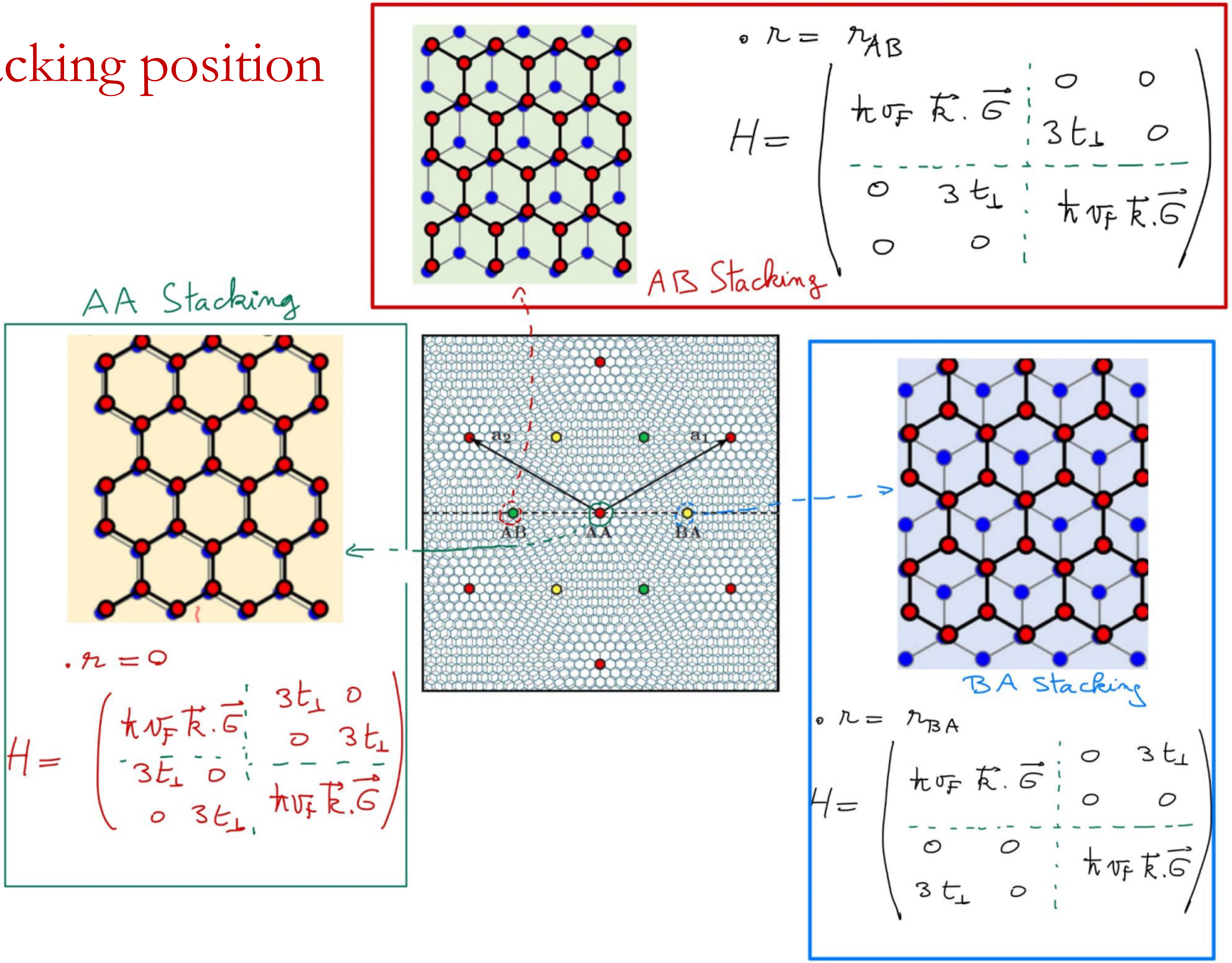
Interlayer coupling renormalizes down the Dirac velocity

$$H = \begin{pmatrix} \mathbf{k}\cdot\boldsymbol{\sigma} & T(\mathbf{r}) \\ T^\dagger(\mathbf{r}) & \mathbf{k}\cdot\boldsymbol{\sigma} \end{pmatrix} \qquad T(\mathbf{r}) = \begin{pmatrix} w(r) & f_1(\mathbf{r}) \\ f_2(\mathbf{r}) & w(r) \end{pmatrix}$$

Valley decoupling at small angle

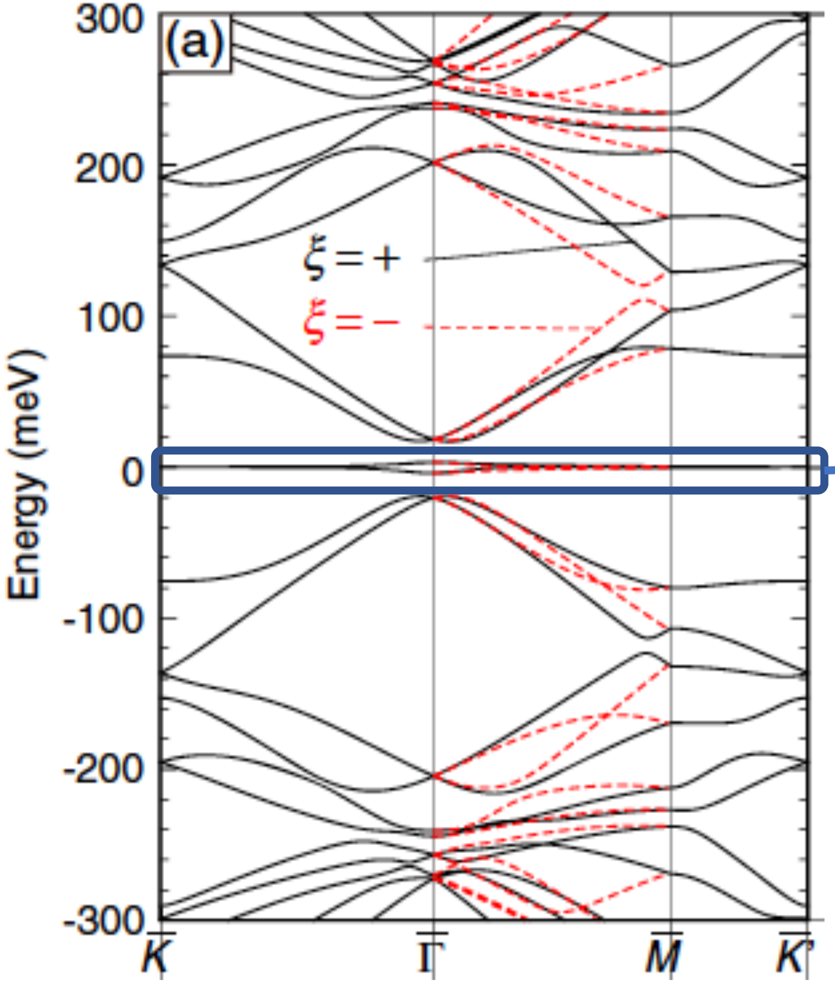


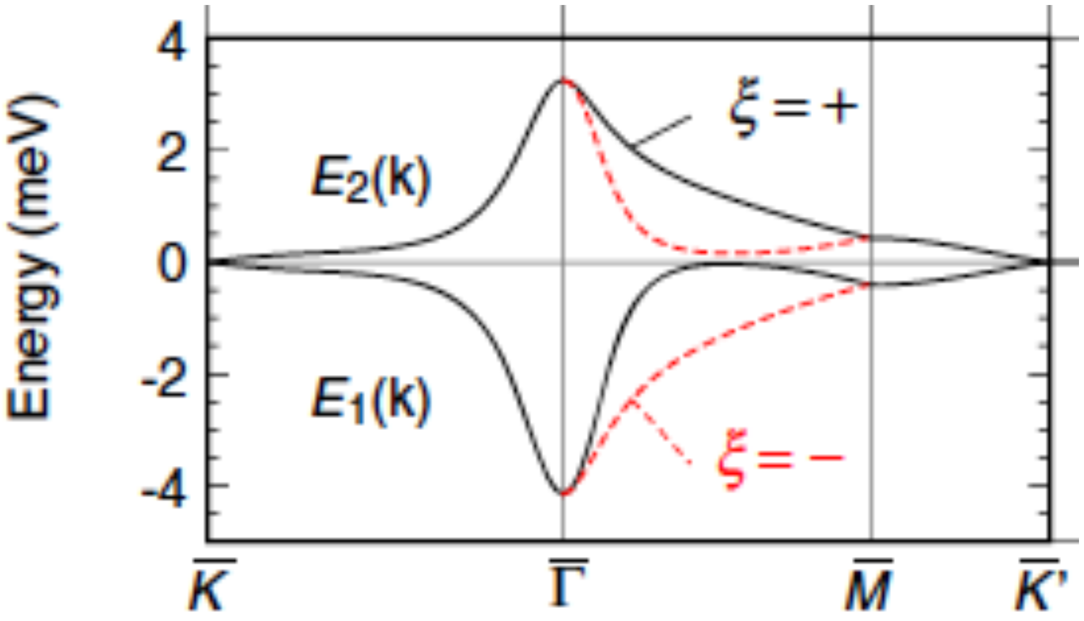
Bilayer with a shifting stacking position



Two narrow bands close to the Fermi energy

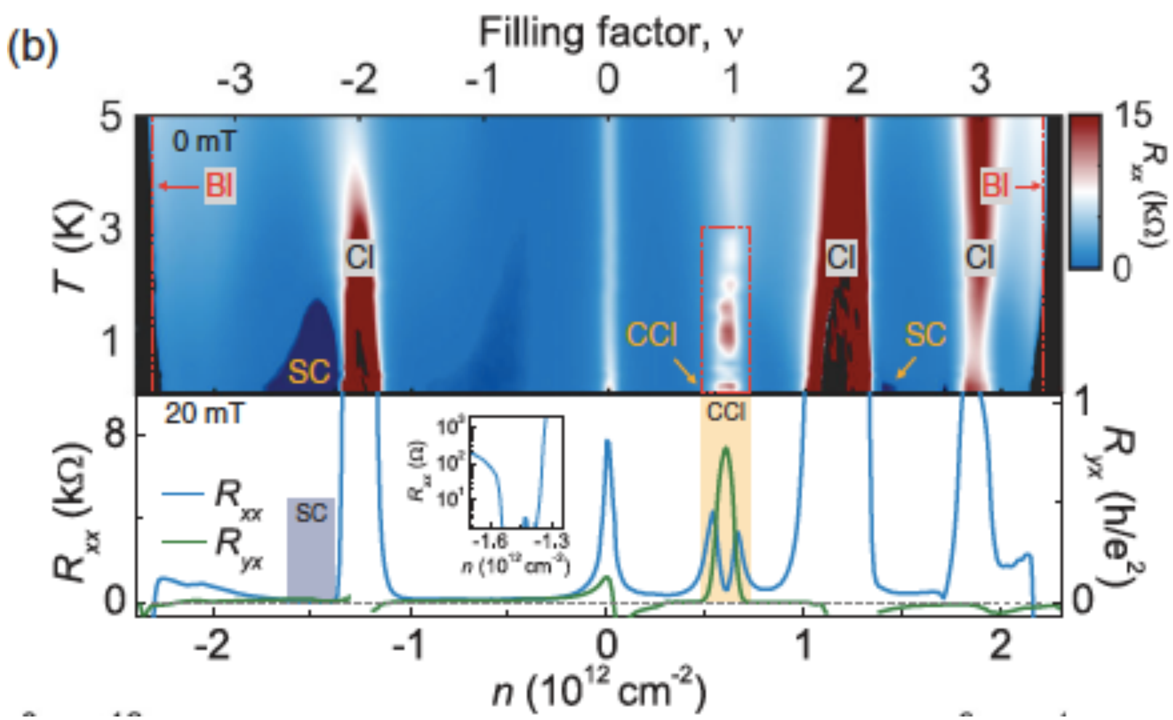
$\theta = 1.05^o$

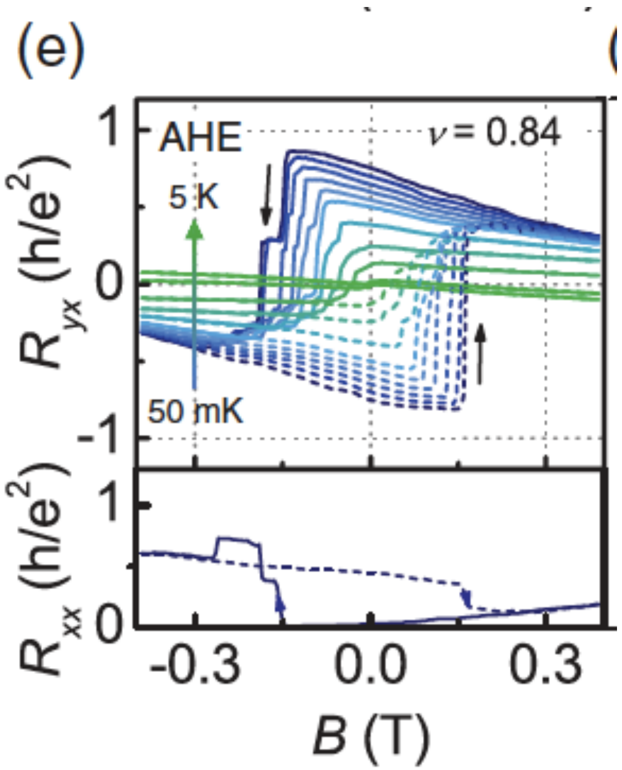




Koshino et al, PRX 2018

Zero-field Chern insulator (anomalous Hall effect)



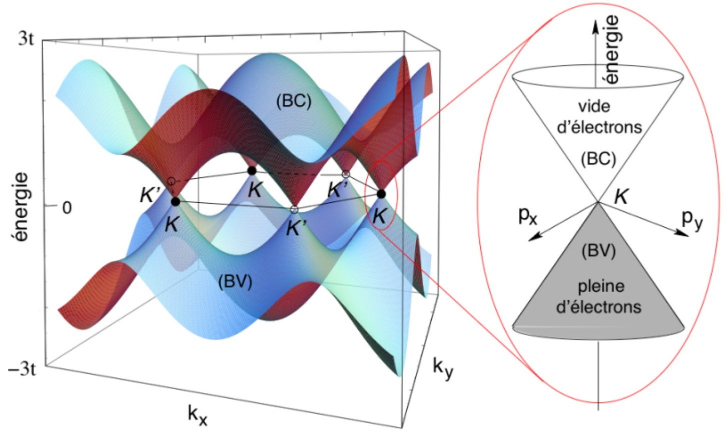


Intrinsic QAHE: no aligned hBN substrate

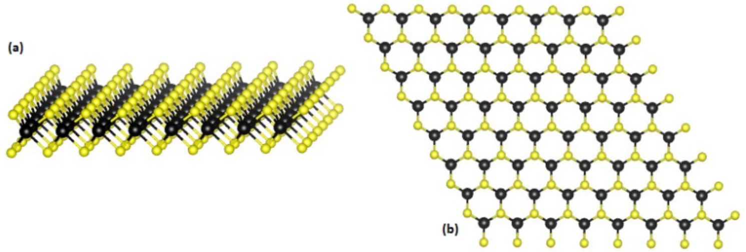
Stepanov, Efetov, PRL 2021

Versatile playground of 2D materials

Flourishing topic since 2004: 2D materials are accessible on the surface, tunable via gating, low densities. Stacking of layers provides infinite possibilities.



Graphene: monolayer and multilayer stacked structures + twistronics



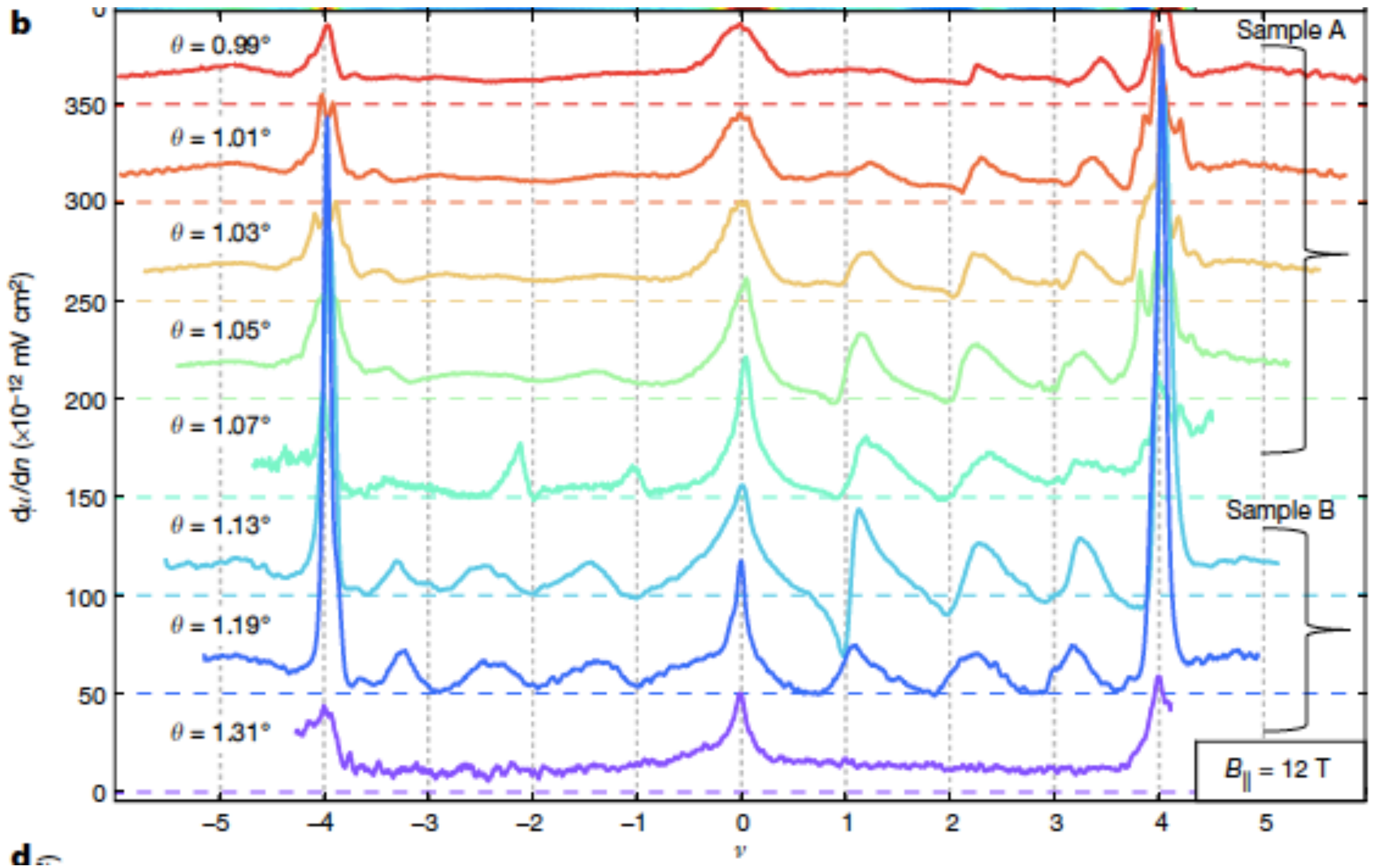
Transition metal dichalcogenide (MoS2, TeW2, …)

Strong spin-orbit: interplay between valley and spin

Strong interactions: Wigner crystal, correlated insulators, ferromagnetism, etc.

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	

Angle dependence of strong interactions



Zondiner, Ilani, Nature 2020