Giant elastoresistance in magic-angle twisted bilayer graphene

Matthew Yankowitz
Physics, MSE
University of Washington

Organizing principles for condensed matter physics

Symmetry

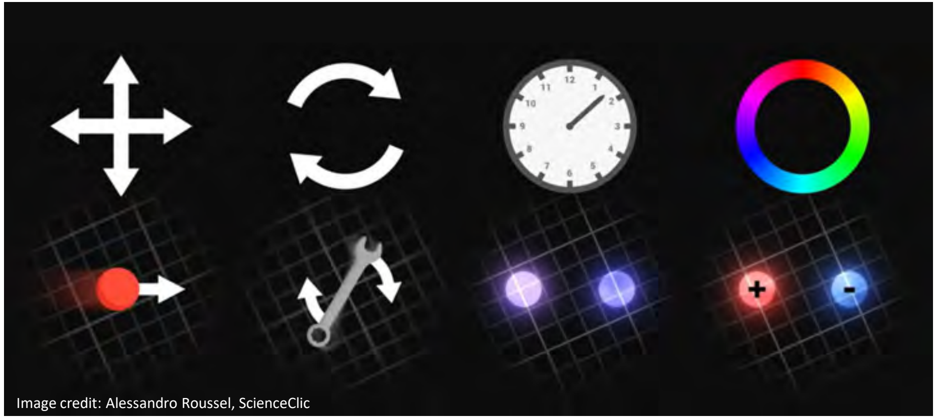


Image credit: Alessandro Roussel, ScienceClic

Topology

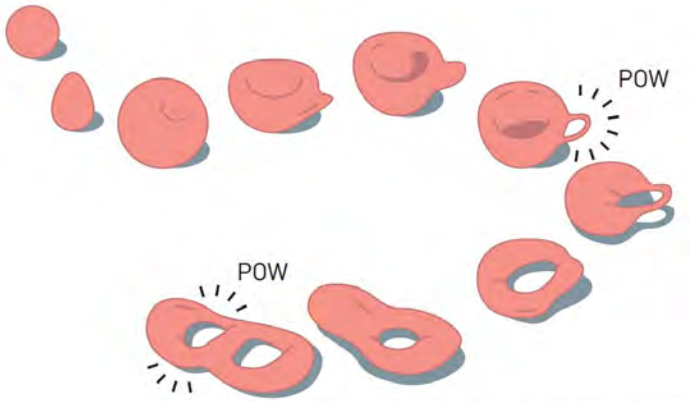


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

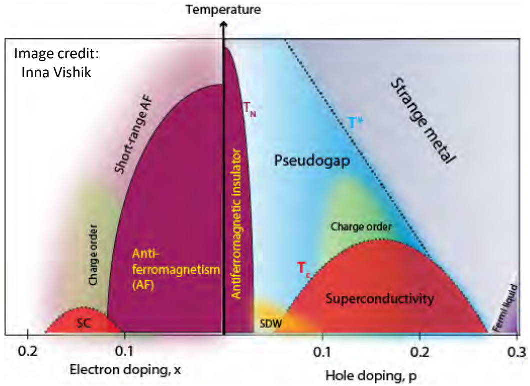
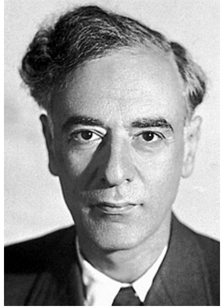


Image credit: Inna Vishik

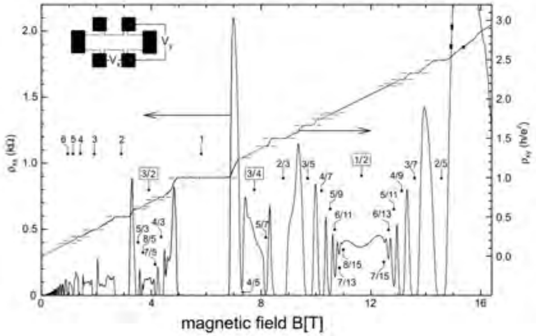
Lev Landau


phases described by their broken symmetries

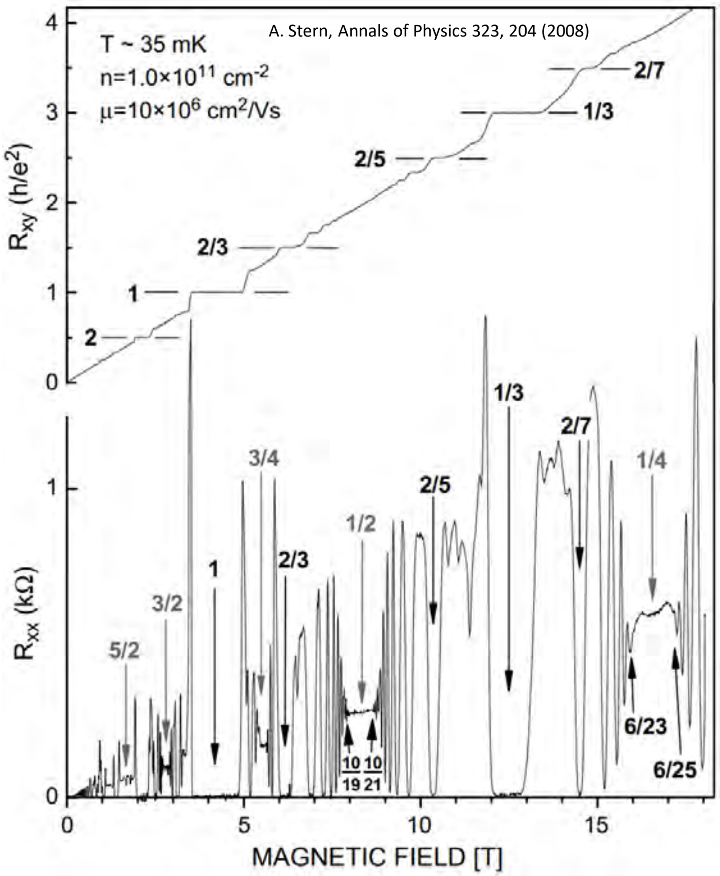
David Thouless


phases described by their topological invariants

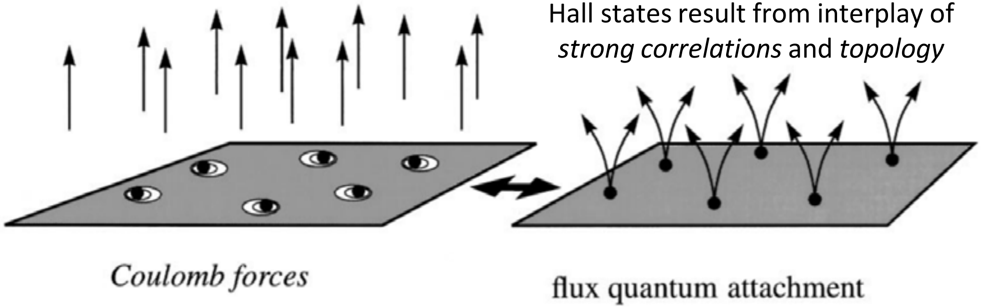
M. Goerbig, arXiv: 0909.1998 (2009)

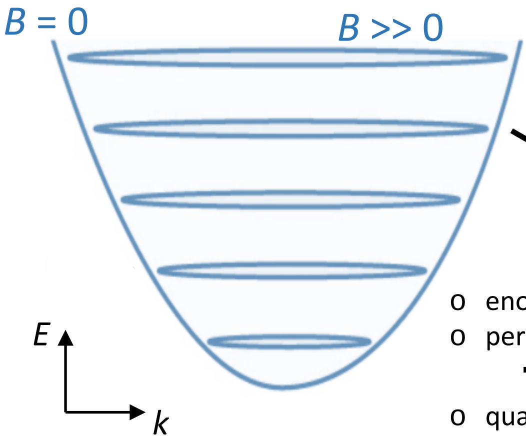


Intertwining of strong correlations and topology



rich sequence of fractional quantum Hall states result from interplay of *strong correlations* and *topology*





Landau level

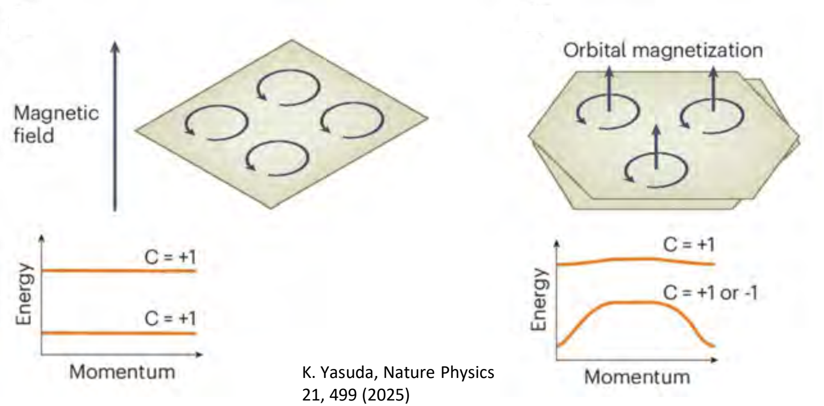
- enormous degeneracy (large density of states)
- perfectly flat (quenched kinetic energy)
  ➔ *strong Coulomb interactions*
- quantized integrated Berry curvature
  ➔ *topology*

Where the Topological Flat Bands Are

Need to have:

- flat electronic dispersion
  (*large ratio of Coulomb-to-kinetic energy*)

- Berry curvature
  (*effective magnetic field from atomic arrangement*)



K. Yasuda, Nature Physics 21, 499 (2025)

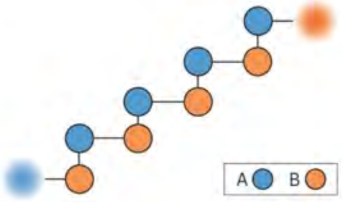
Options:

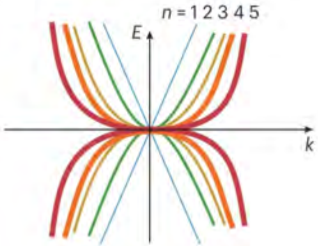
- *discover* a new material (…a "gift from nature")
- *engineer* a new material (…do it ourselves!)

Graphite: all we need

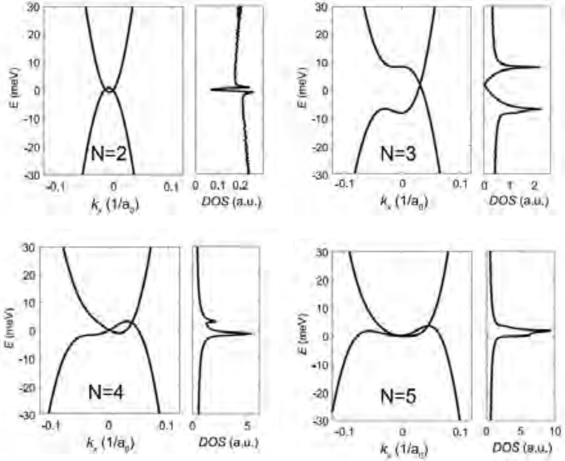
Designing topological flat bands in 2D materials

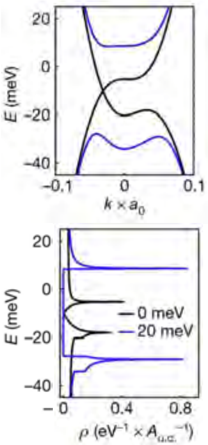
crystalline multilayers





Y. Cao, Nat. Nano. 19, 139 (2024)

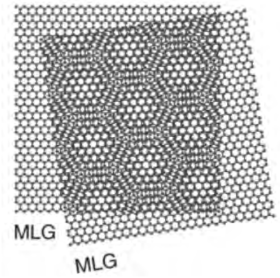




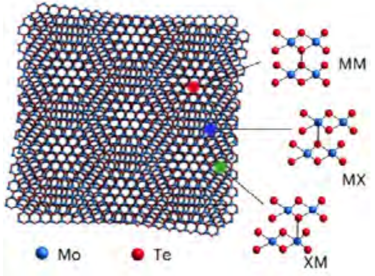
T. Han et al., Nat. Nano. 19, 181 (2024)

H. Zhou et al., Nature 598, 429 (2021)

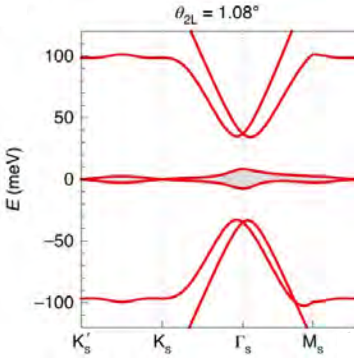
moiré multilayers



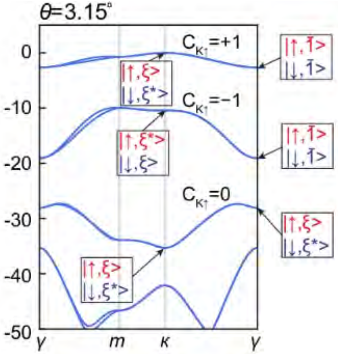
L. Balents et al., Nat. Phys. (2020)



E. Thompson et al., Nat. Phys. (2025)

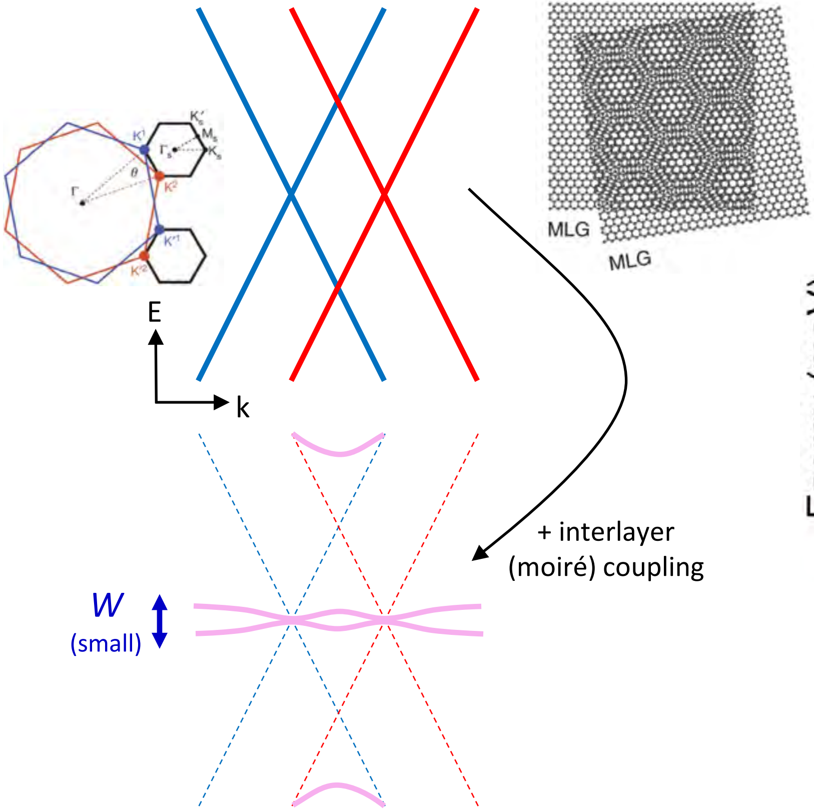


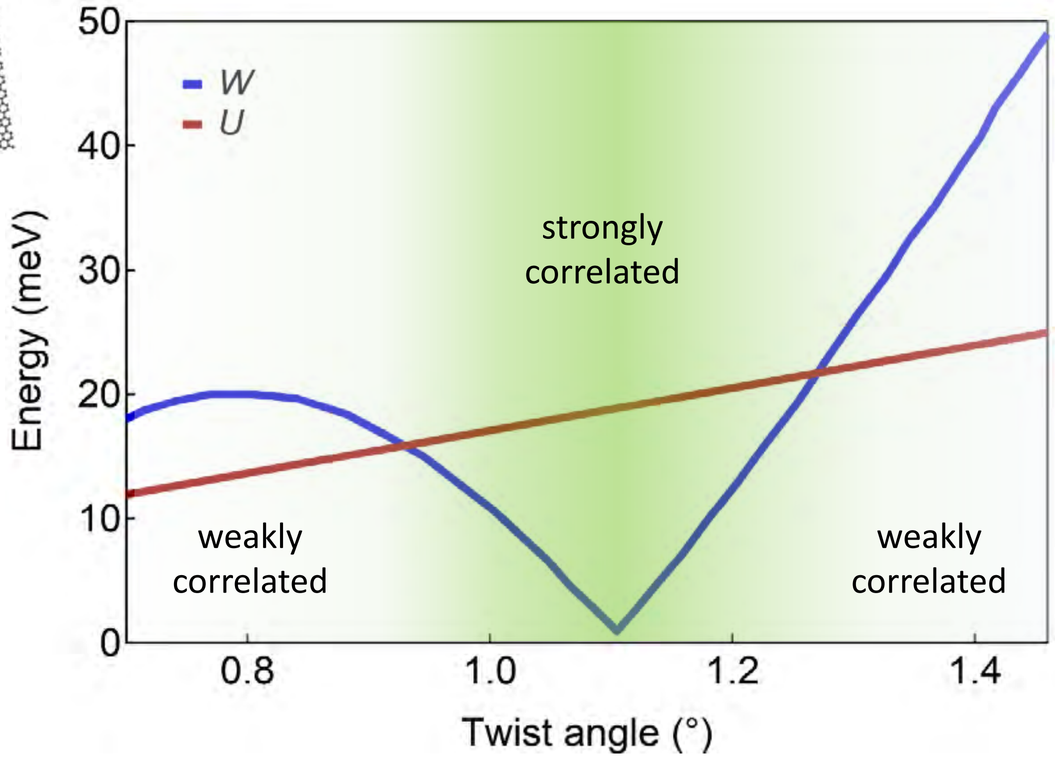
J. M. Park et al., Nat. Materials 21, 877 (2022)



X.-W. Zhang et al., Nat. Comms. 15, 4223 (2024)

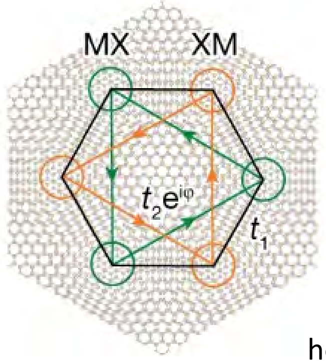
Band flattening in twisted bilayer graphene

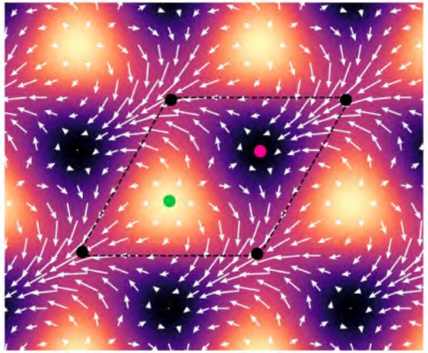


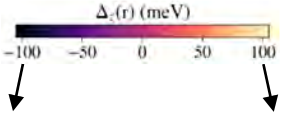


Topology from Berry curvature in moiré materials

Kane-Mele model







wavefunction on bottom layer

wavefunction on top layer

X. Zhang, arXiv:2311.12776 (2024)
See also: F. Wu, PRL 122, 086402 (2019)

how does moiré superlattice set band topology?

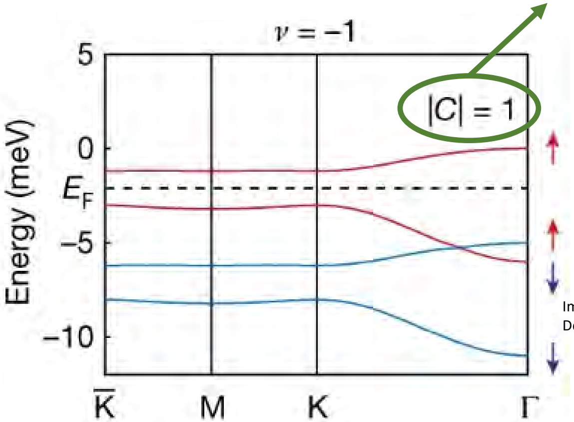
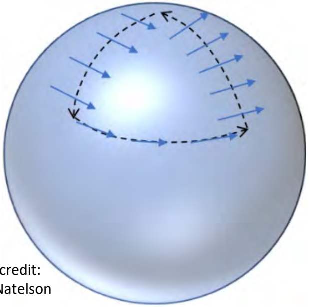


Image credit:
Doug Natelson



…through its Berry phases

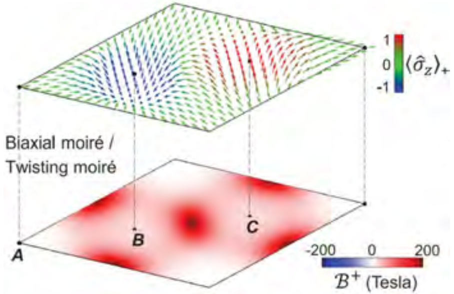
H. Park, Nature 622, 74 (2023)

<u>real-space Berry curvature analog:</u>

$$\dot{\mathbf{k}} = -\frac{\partial E}{\partial \mathbf{R}} + \dot{\mathbf{R}} \times \boldsymbol{\Omega}^R$$

$$\boldsymbol{\Omega}^R \equiv i \left\langle \frac{\partial u}{\partial \mathbf{R}} \right| \times \left| \frac{\partial u}{\partial \mathbf{R}} \right\rangle$$

superlattice-generated effective magnetic field



H. Yu, National Science Review 7, 12 (2020)

<u>"Brute force" calculation:</u>

$$\dot{\mathbf{R}} = \frac{\partial E}{\partial \mathbf{k}} - \dot{\mathbf{k}} \times \boldsymbol{\Omega}^k$$

(anomalous velocity)

$$\boldsymbol{\Omega}^k \equiv i \left\langle \frac{\partial u}{\partial \mathbf{k}} \right| \times \left| \frac{\partial u}{\partial \mathbf{k}} \right\rangle$$

(Berry curvature)

$$\mathcal{C} = \frac{1}{2\pi} \mathbf{e}_z \cdot \int_{\mathrm{mBZ}} \boldsymbol{\Omega}^k \, d\mathbf{k}$$

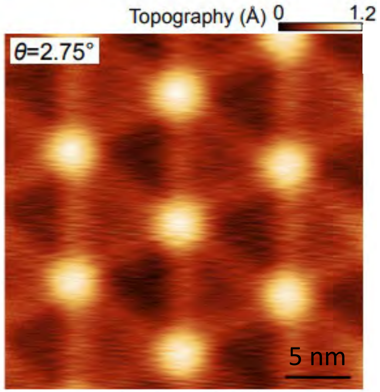
Microscopic fingerprints of topology

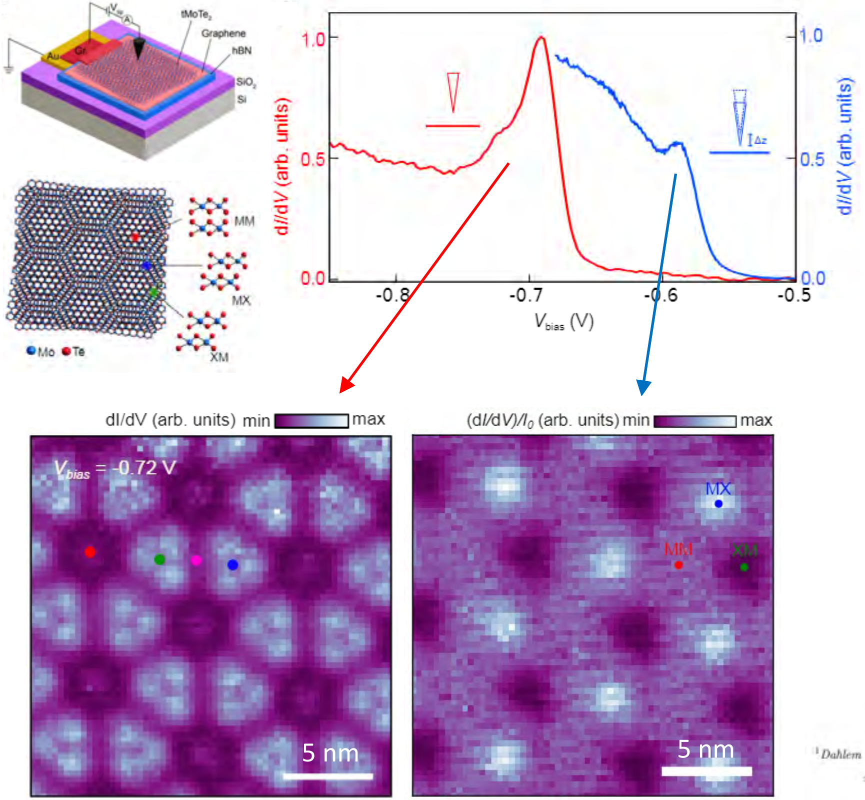

Ellis Thompson


Toby Chu

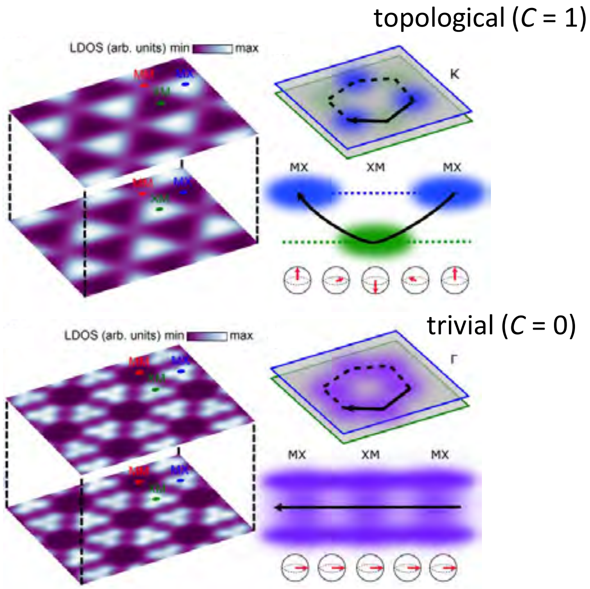

Dr. Florie Mesple

Prof. Xiaodong Xu
Prof. Ting Cao
Prof. Di Xiao
Dr. Xiao-Wei Zhang





DFT calculation



Robustness of real-space topology in moiré systems

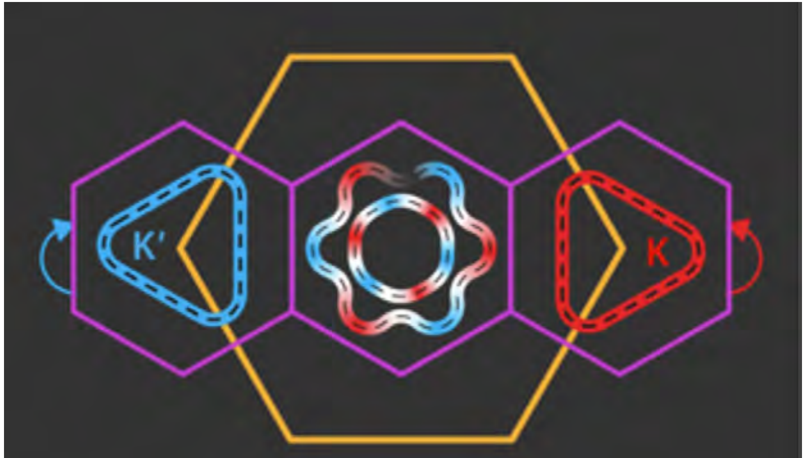
Kryštof Kolář,[1,2] Kang Yang,[1] Felix von Oppen,[1] and Christophe Mora[3]
[1] Dahlem Center for Complex Quantum Systems and Fachbereich Physik, Freie Universität Berlin, 14195 Berlin, Germany
[2] Department of Applied Physics, Aalto University School of Science, FI-00076 Aalto, Finland
[3] Université Paris Cité, CNRS, Laboratoire Matériaux et Phénomènes Quantiques, 75013 Paris, France
(Dated: July 2, 2025)

E. Thompson, K. T. Chu, F. Mesple, M. Yankowitz, Nature Physics 21, 1224 (2025)

-> theoretically extends concept to MATBG

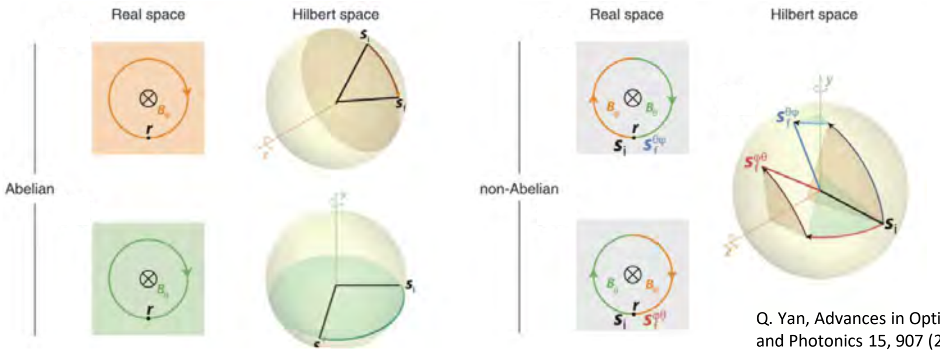
Graphene platforms for new quantum effects

flat bands
→ *strong correlations and symmetry breaking*



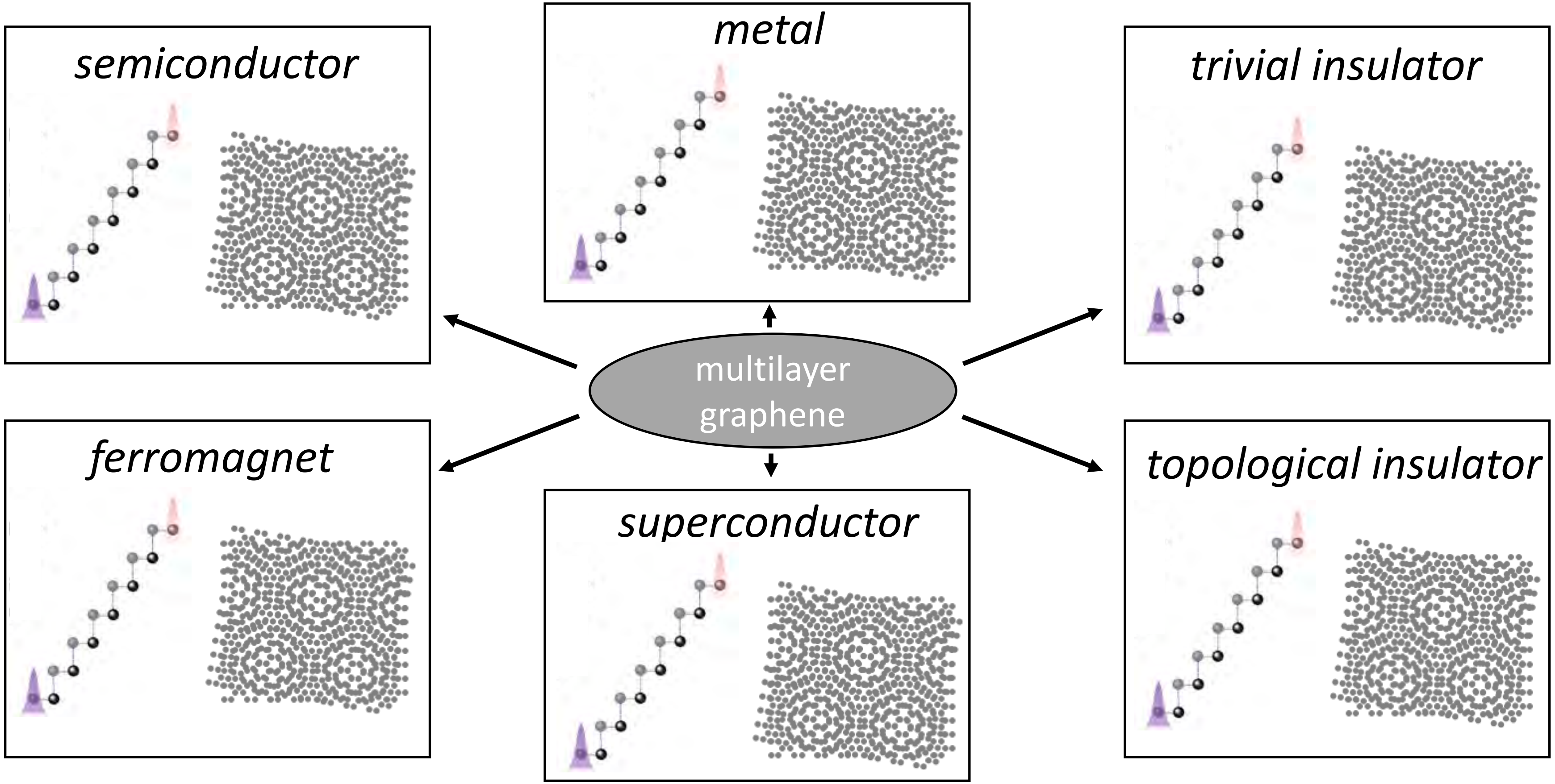
C. Gutiérrez, Physics 14, 76 (2021)

atomic stacking (and moiré)
→ *Berry-curved bands and topology*

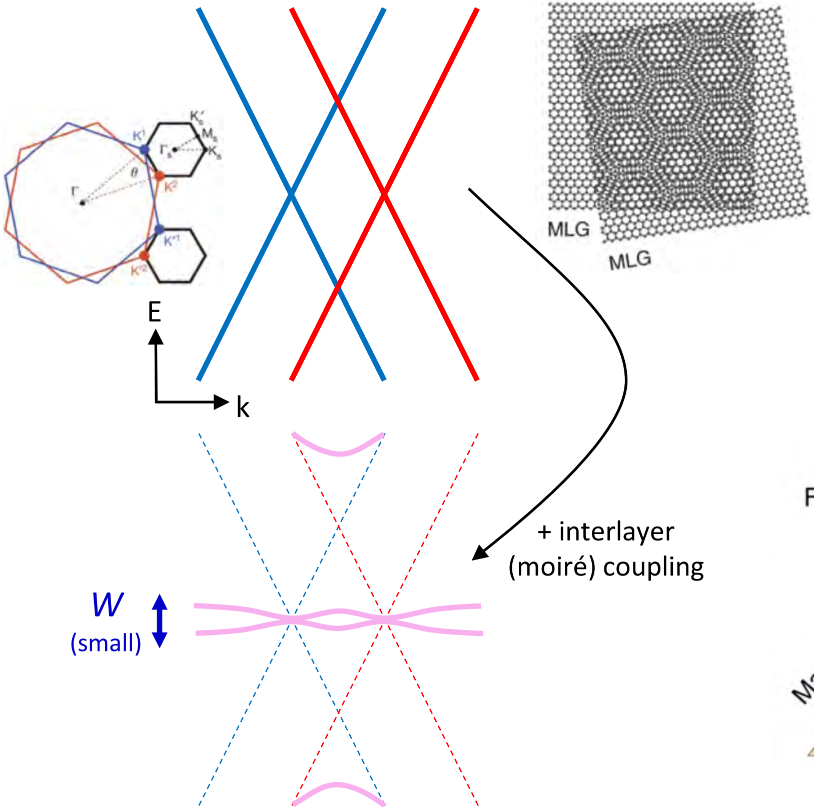


Q. Yan, Advances in Optics and Photonics 15, 907 (2023)

Platforms for intermixed correlations and topology



Summary of a "typical" MATBG phase diagram



rich phase diagram when $U >> W$

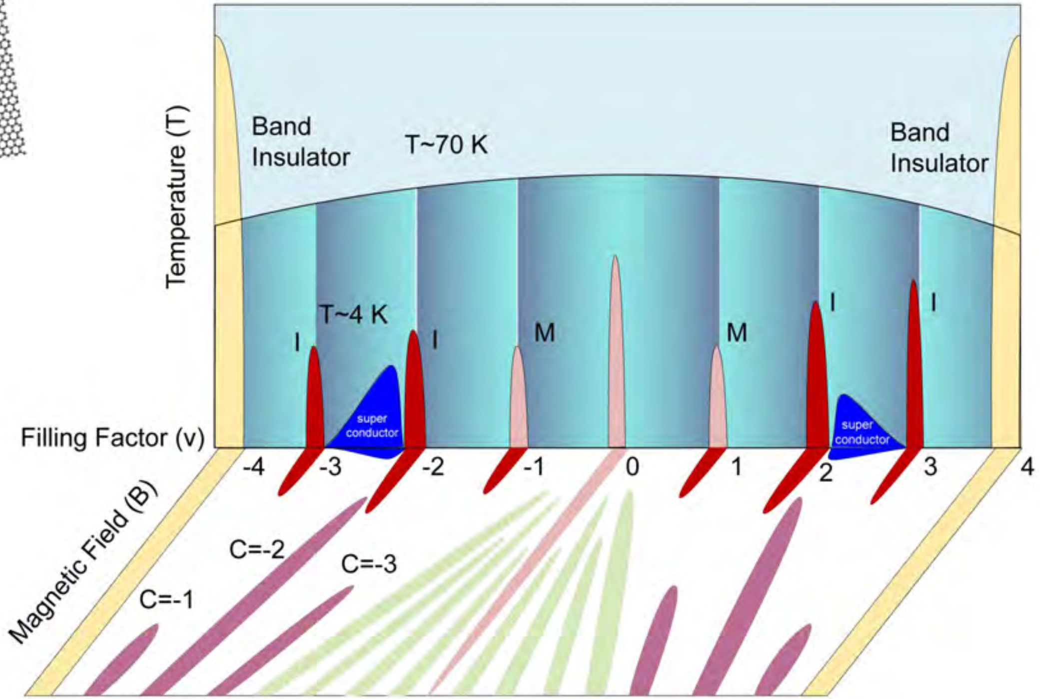
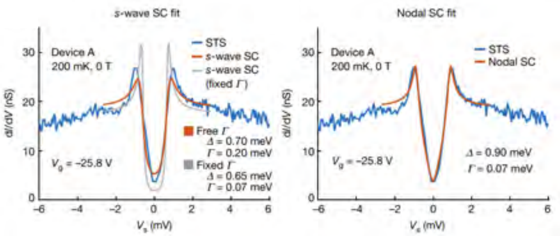


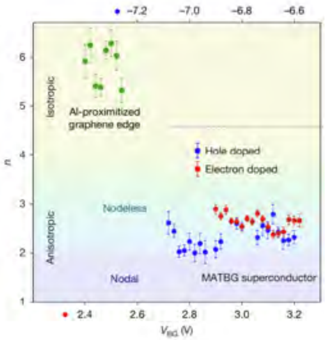
Image credit: Jane Park

Big open questions

superconductivity

What sets the pairing mechanism and gap symmetry?



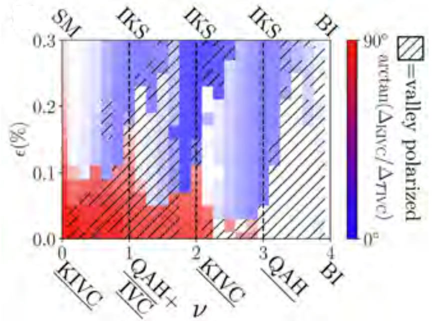


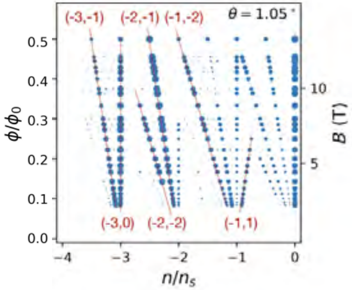
Evidence suggests unconventional superconductivity, but a definitive mechanism and pairing state remain unsettled.

Too big a question for today!

correlated ground states

What order and topology arise across the flat bands?



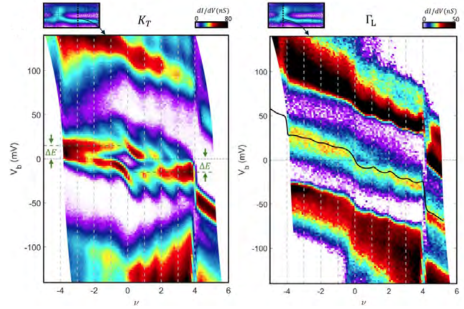


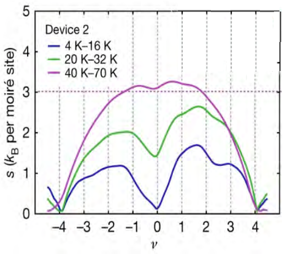
A broad picture is emerging, and many calculations and experiments agree on the main features.

Still, there are surprises.

normal state

What is the organizing principle of the high-temperature normal state (~100 K)?





We lack a fully quantitative theory for the high-temperature transport and thermodynamics.

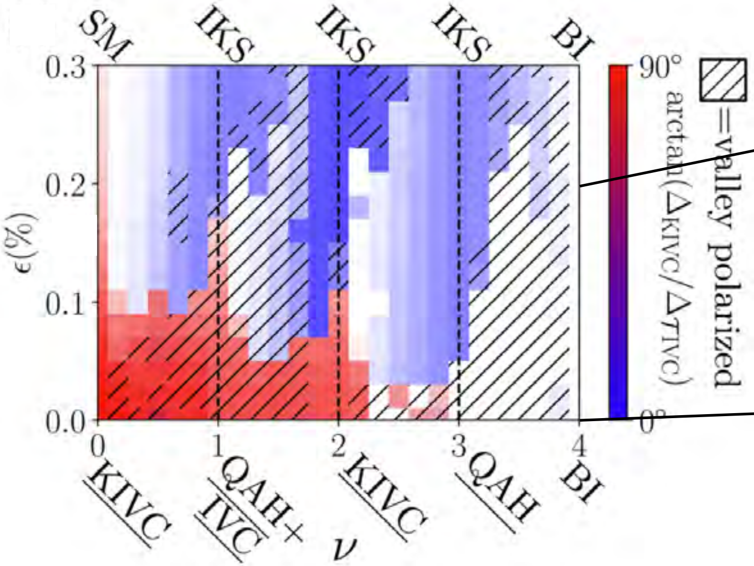
There are suggestive links to heavy-fermion phenomenology with nontrivial topology, but we have more to learn.

Hartree-Fock predictions for MATBG ground states

PHYSICAL REVIEW LETTERS **128,** 156401 (2022)

Global Phase Diagram of the Normal State of Twisted Bilayer Graphene

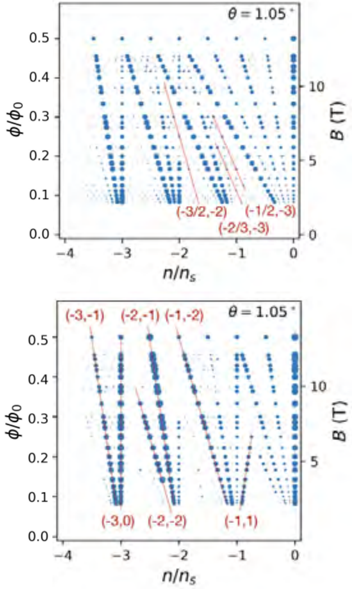
Glenn Wagner,[1,2] Yves H. Kwan,[1] Nick Bultinck,[1,3] Steven H. Simon,[1] and S. A. Parameswaran[1]
[1]*Rudolf Peierls Centre for Theoretical Physics, Parks Road, Oxford OX1 3PU, United Kingdom*
[2]*Department of Physics, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[3]*Department of Physics, Ghent University, Krijgslaan 281, 9000 Gent, Belgium*



PHYSICAL REVIEW X **14,** 021042 (2024)

Theory of Correlated Chern Insulators in Twisted Bilayer Graphene

Xiaoyu Wang[1,*] and Oskar Vafek[1,2,†]
[1]*National High Magnetic Field Lab, Tallahassee, Florida 32310, USA*
[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*



- many closely competing ground states with varying spin, valley, and sublattice ordering
- symmetry-broken states evolve into a cascade of Chern insulators upon formation of Hofstadter subbands in a magnetic field
- ground state ordering is very sensitive to heterostrain between the two graphene sheets!

Chern insulator states tunable by doping


nature physics

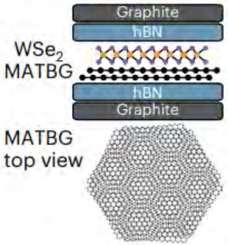
Article

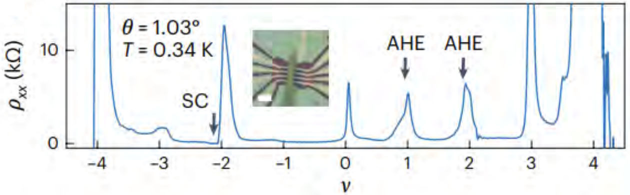
https://doi.org/10.1038/s41567-025-02997-4

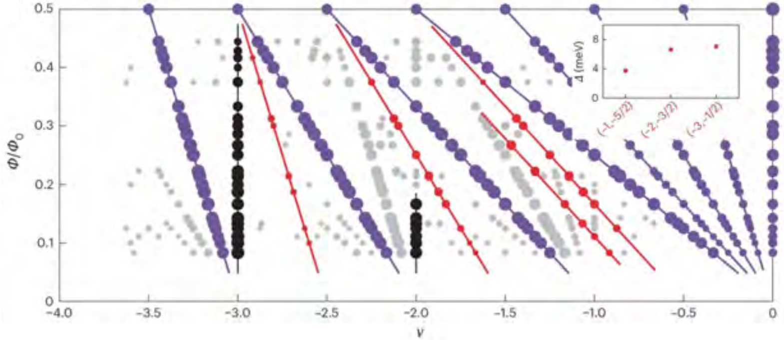
Strongly interacting Hofstadter states in magic-angle twisted bilayer graphene

Received: 1 August 2024
Accepted: 14 July 2025
Published online: 11 August 2025

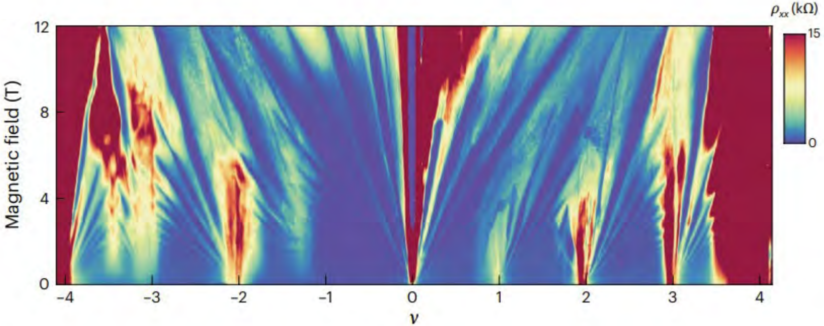
Minhao He, Xiaoyu Wang, Jiaqi Cai, Jonah Herzog-Arbeitman, Ran Peng, Takashi Taniguchi, Kenji Watanabe, Ady Stern, B. Andrei Bernevig, Matthew Yankowitz, Oskar Vafek & Xiaodong Xu

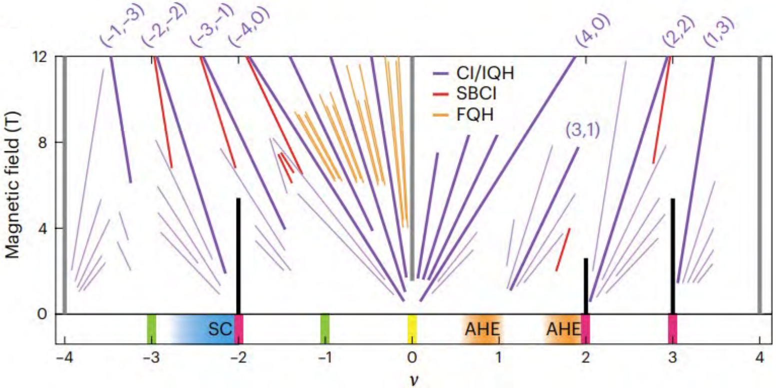






- cascades of Chern states appear in a magnetic field
- some states break the moiré translational symmetry
- sequences broadly captured by Hartree-Fock calculations



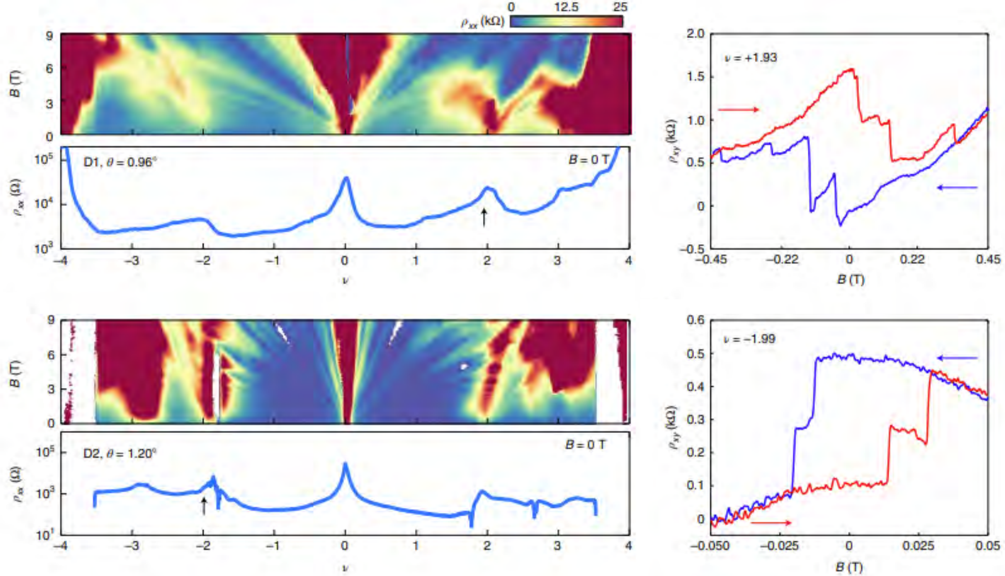


Still a few surprises to understand

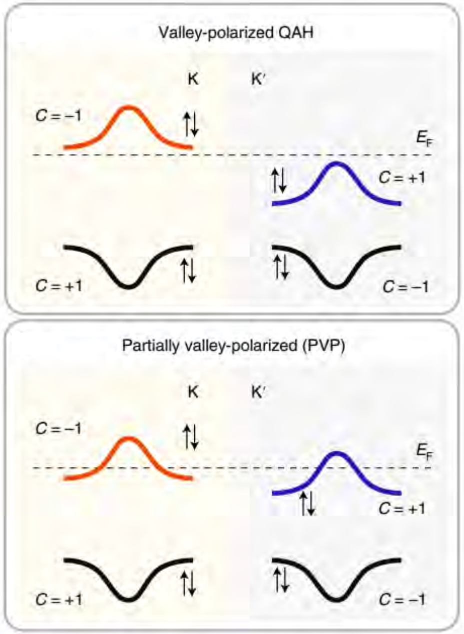
LETTERS
https://doi.org/10.1038/s41567-022-01697-7
nature physics
Check for updates

Anomalous Hall effect at half filling in twisted bilayer graphene

Chun-Chih Tseng[1,5], Xuetao Ma[2,5], Zhaoyu Liu[1,5], Kenji Watanabe[3], Takashi Taniguchi[4], Jiun-Haw Chu[1] and Matthew Yankowitz[1,2]



- intervalley Hund's coupling disfavors valley polarized states at ν = ±2…
- …so why do they appear here?



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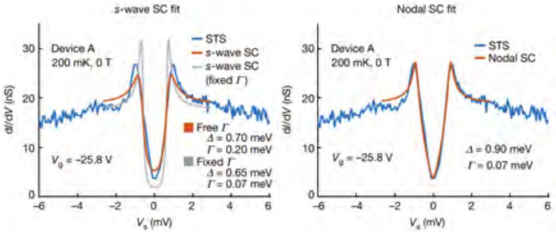

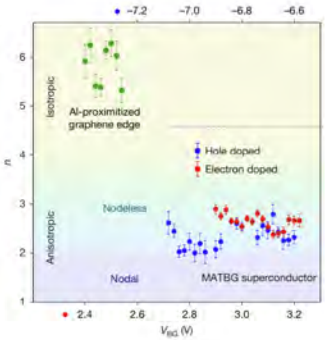

Evidence suggests unconventional superconductivity, but a definitive mechanism and pairing state remain unsettled.

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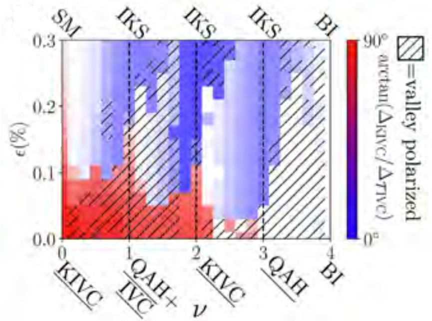

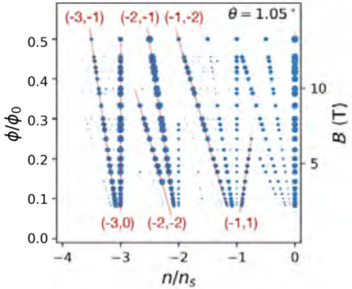

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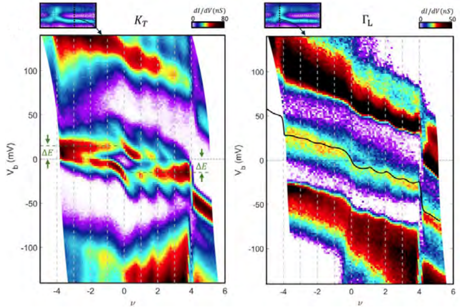
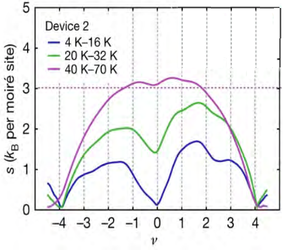


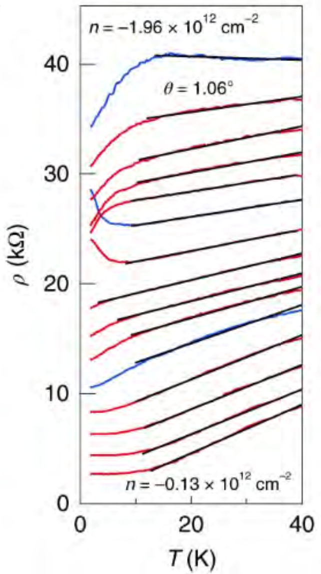


We lack a fully quantitative theory for the high-temperature transport and thermodynamics.

There are suggestive links to heavy-fermion phenomenology with nontrivial topology, but we have more to learn.

Unusual transport in the normal state of MATBG

H. Polshyn, M. Yankowitz et al., Nature Physics 15, 1011 (2019)



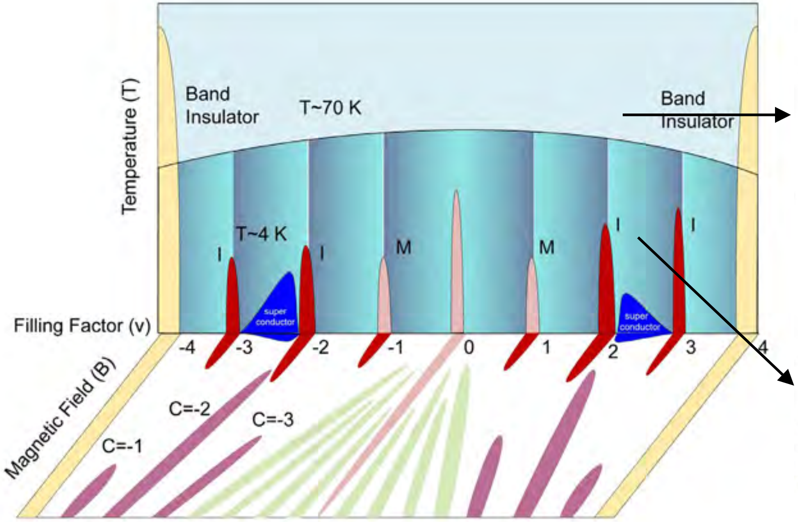
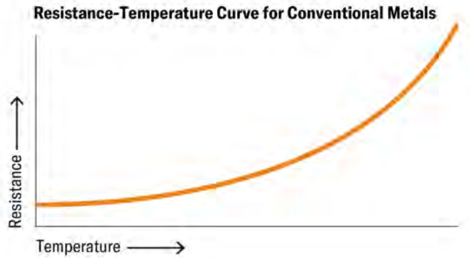
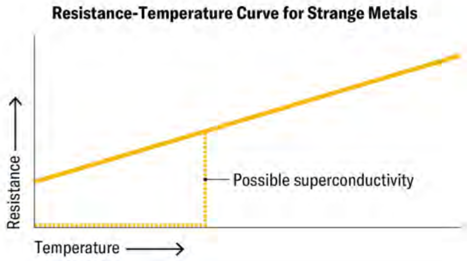
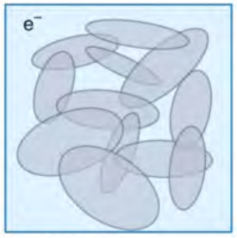


Image credit: Jane Park



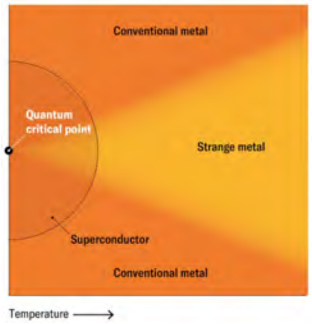
Normal Metal





Strange Metal

See also: Y. Cao et al., PRL 124, 076801 (2020)
A. Jaoui et al., Nature Physics 18, 633 (2022)



related strange metals and superconductivity in:

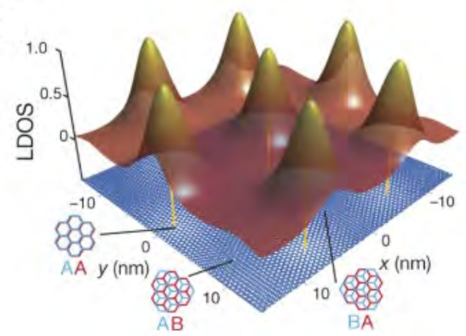
cuprates, iron-based superconductors, nickelates, ruthenates, Kagome metals, heavy-fermion Kondo lattices, organic charge-transfer salts, etc.

T. Stauber et al., Nature Physics 18, 619 (2022)

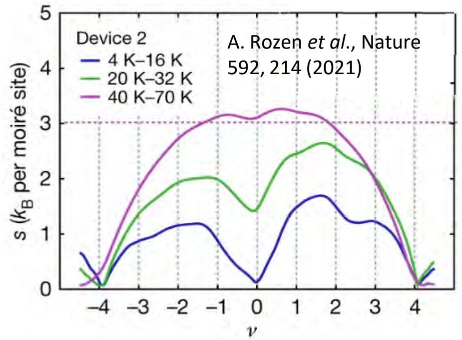
D. Natelson, Scientific American 330, 42 (2024)

Local or nonlocal physics in MATBG?

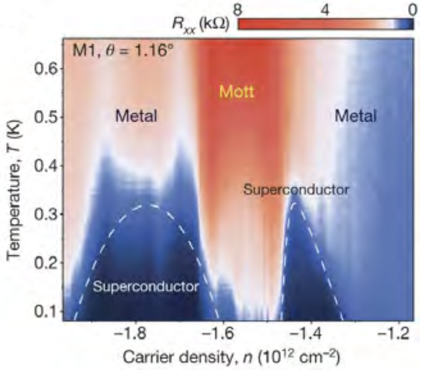
local description:
Mott insulators on a triangular lattice of AA-stacked sites

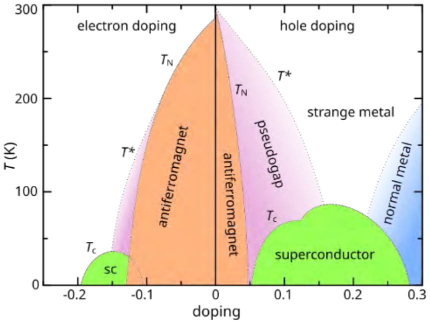


Y. Cao *et al.*, Nature 556, 43 (2018)



A. Rozen *et al.*, Nature 592, 214 (2021)

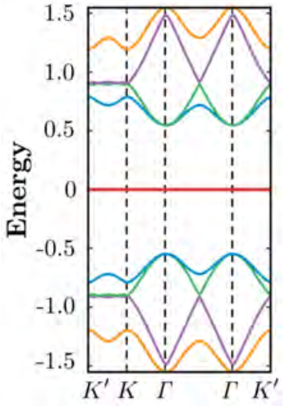


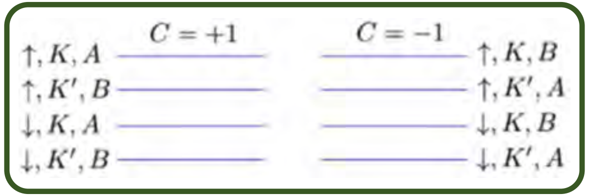


reminiscent of superconductivity from doped Mott insulators

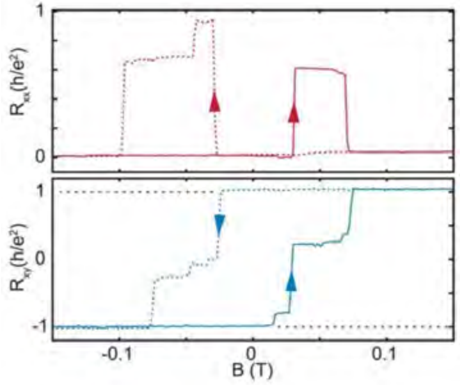
nonlocal description:
analog of quantum Hall ferromagnets

G. Tarnopolsky *et al.*, PRL 122, 106405 (2019)





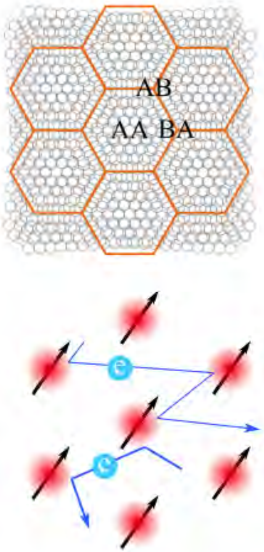
Serlin et al., Science 367, 900 (2020)
see also: Sharpe *et al.*, Science 365, 605 (2019)

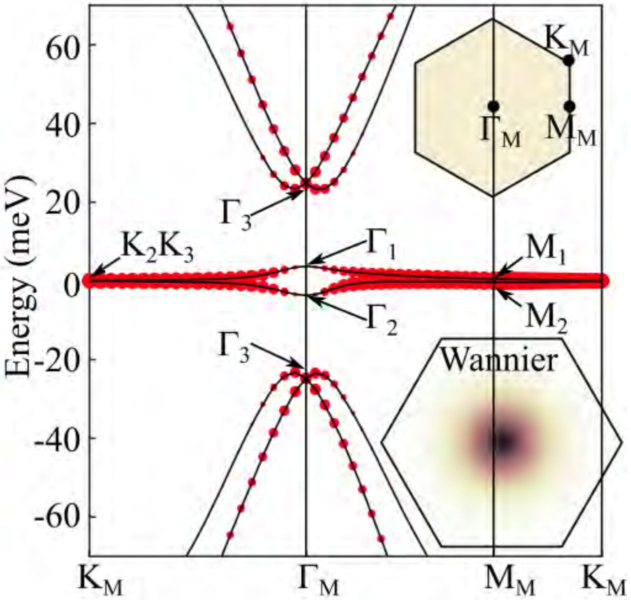


topological states require delocalized electrons

Topological heavy fermion model

Z.-D. Song and B. A. Bernevig, PRL 129, 047601 (2022)

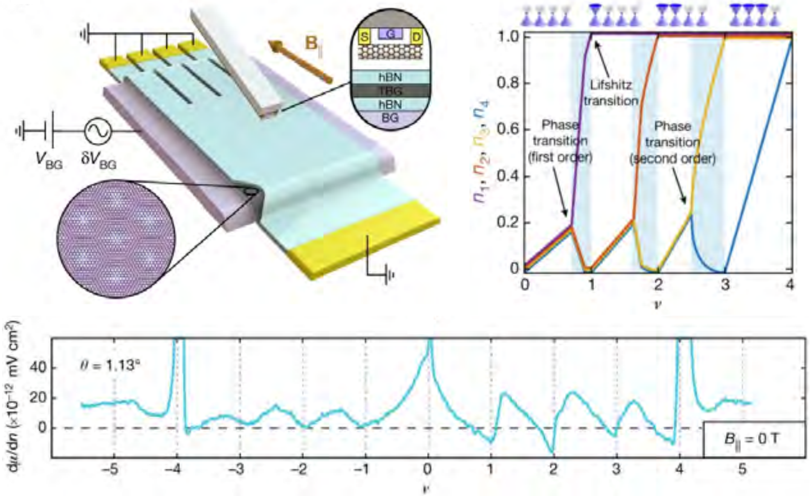




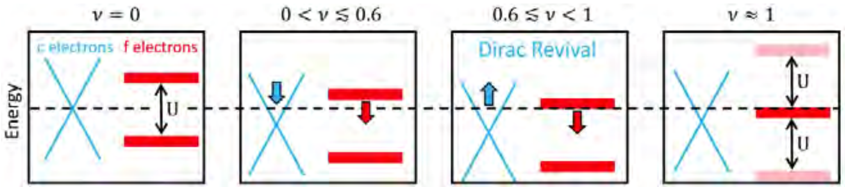
- topology/symmetry of the moiré lattice obstructs the formation of exponentially localized Wannier orbitals
- construct bands by hybridizing localized moments on the AA-stacking sites with dispersive bands from AB/BA-sites

low-temperature:
symmetry breaking

U. Zondiner *et al.*, Nature 582, 203 (2020)



high temperature: *heavy fermion physics*

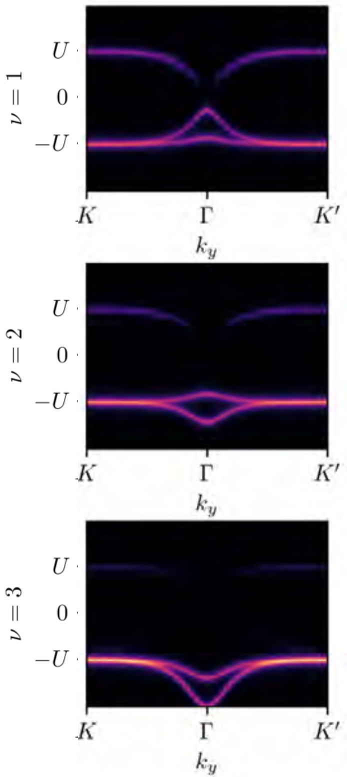


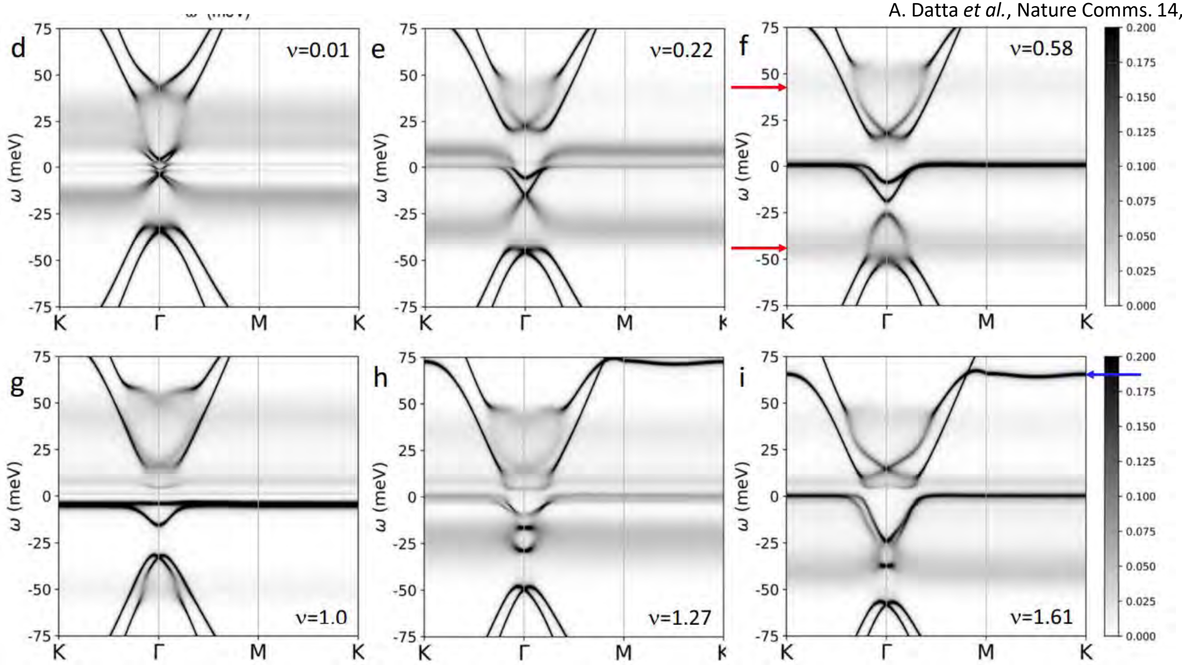
J. Xiao *et al.*, arXiv:2506.20738 (2025)

No matter the exact model, do many-body calculations

Hartree-Fock + dynamical mean-field theory (DMFT) -> spectral function

A. Datta *et al.*, Nature Comms. 14, 5036 (2023)



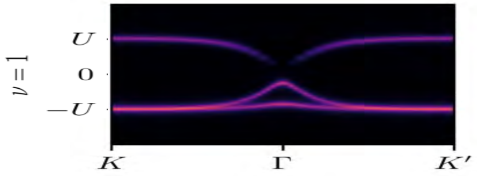


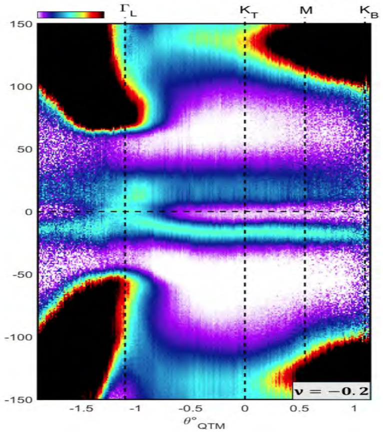
calculations generally agree on flat, spectrally-incoherent "Hubbard bands" broadened by ~2*U* almost everywhere across the moiré Brillouin zone, along with dispersive, sharply defined quasiparticles near Γ

P. Ledwith *et al.*, PRX 15, 021087 (2025)

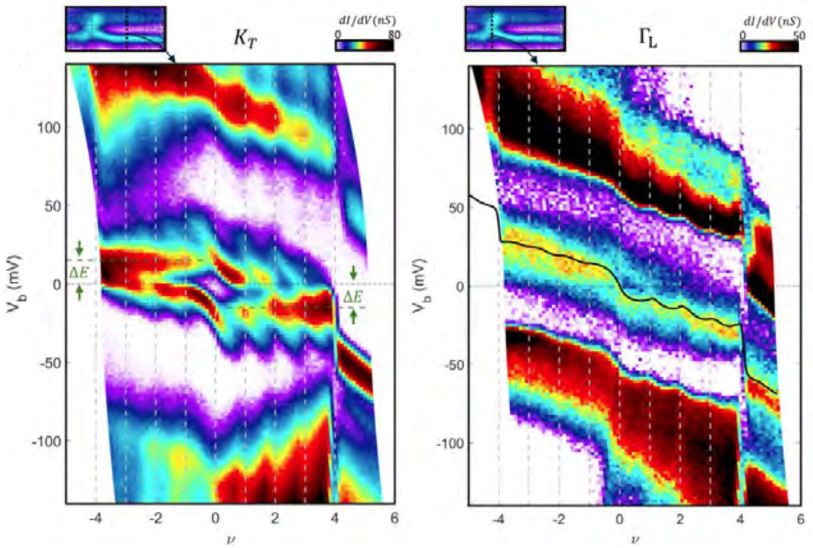
Key recent findings from tunneling measurements

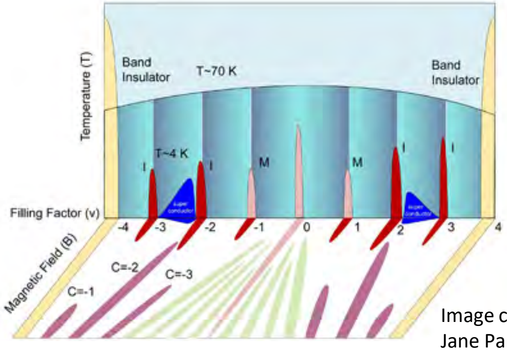
interactions profoundly reshape
the bands at the magic angle





quantum twisting microscope measurements may help
to unite the localized and extended electronic behavior
with a topological heavy fermion framework





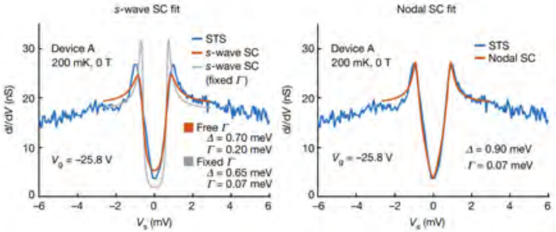
what happens <4 K once isospin
symmetries break, and correlated
and superconducting gaps open?

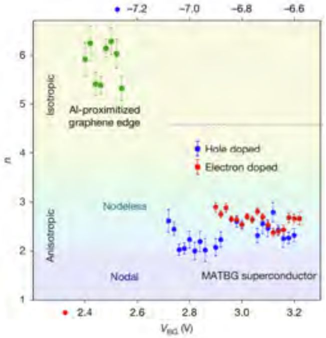
Image credit:
Jane Park

Big open questions

superconductivity

What sets the pairing mechanism and gap symmetry?



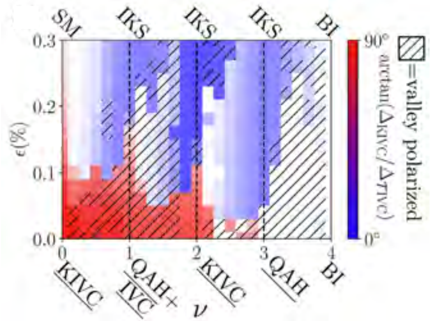


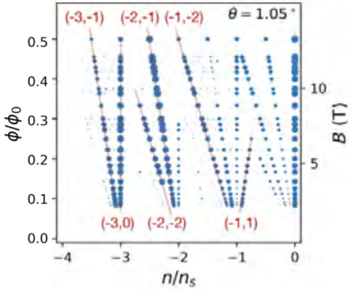
Evidence suggests unconventional superconductivity, but a definitive mechanism and pairing state remain unsettled.

Too big a question for today!

correlated ground states

What order and topology arise across the flat bands?



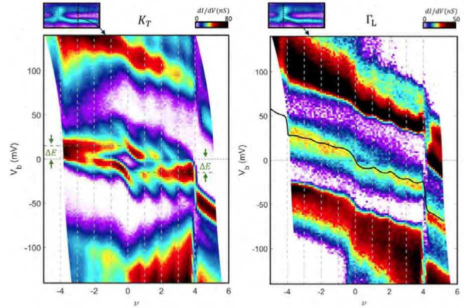


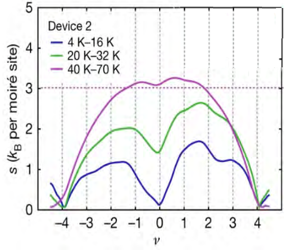
A broad picture is emerging, and many calculations and experiments agree on the main features.

Still, there are surprises.

normal state

What is the organizing principle of the high-temperature normal state (~100 K)?



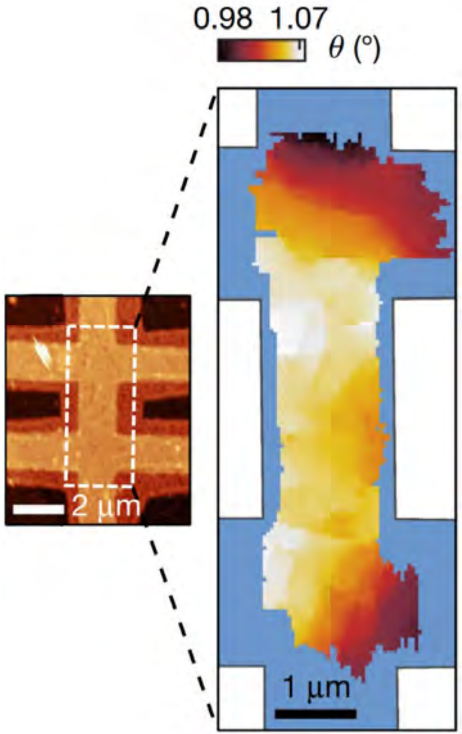


We lack a fully quantitative theory for the high-temperature transport and thermodynamics.

There are suggestive links to heavy-fermion phenomenology with nontrivial topology, but we have more to learn.

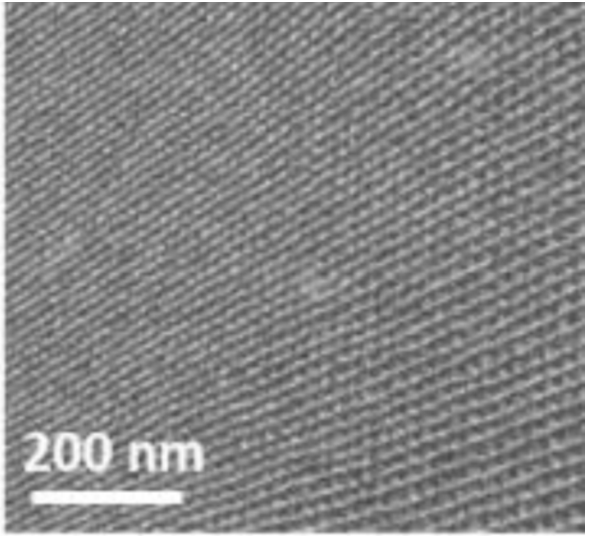
A challenge: prevalence of unintended strain

scanning SQUID



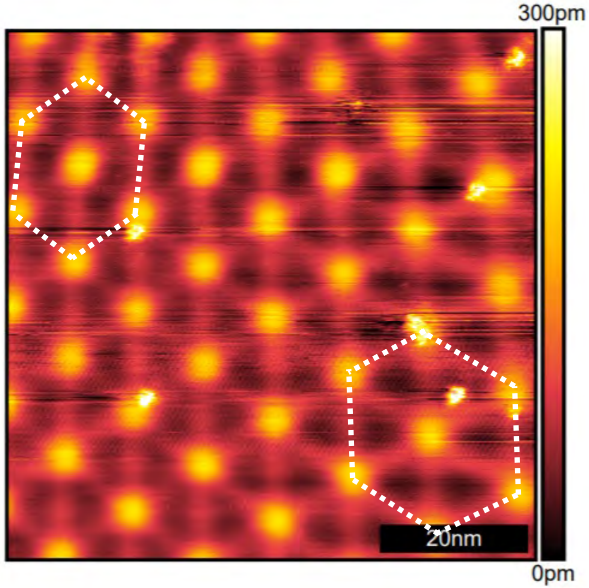
Zeldov group, Nature (2020)

TEM



Kim group, Nature Materials (2019)

STM



Pasupathy group, Nature (2019)

Unintended strain complicates device behavior

Review

Reproducibility in the fabrication and physics of moiré materials

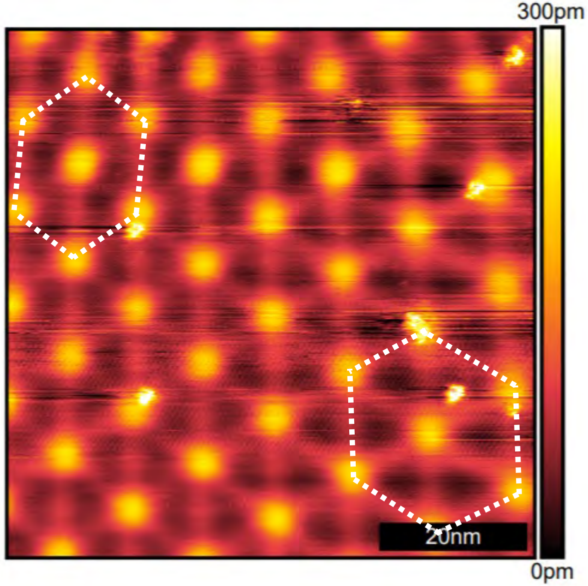
https://doi.org/10.1038/s41586-021-04173-z

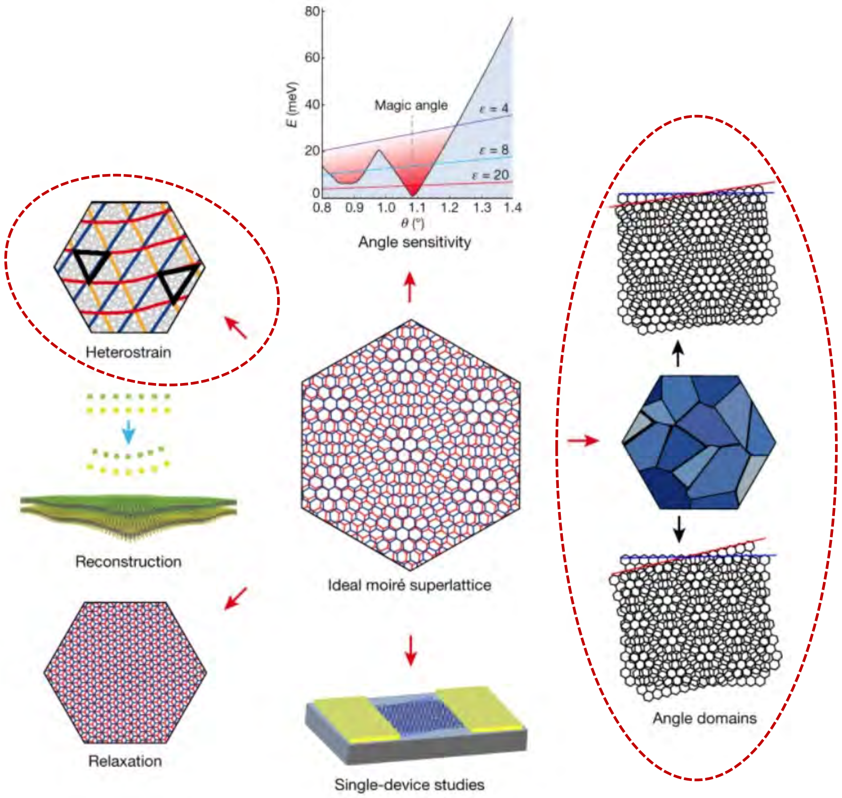
Chun Ning Lau[1]✉, Marc W. Bockrath[1], Kin Fai Mak[2] & Fan Zhang[3]

Received: 16 March 2021

Accepted: 21 October 2021

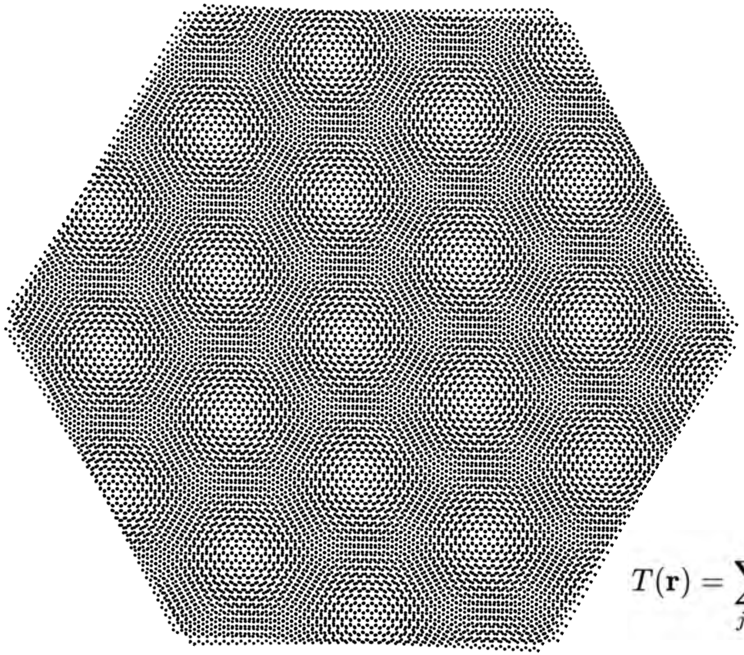
Published online: 2 February 2022





Strain modifies the moiré Hamiltonian

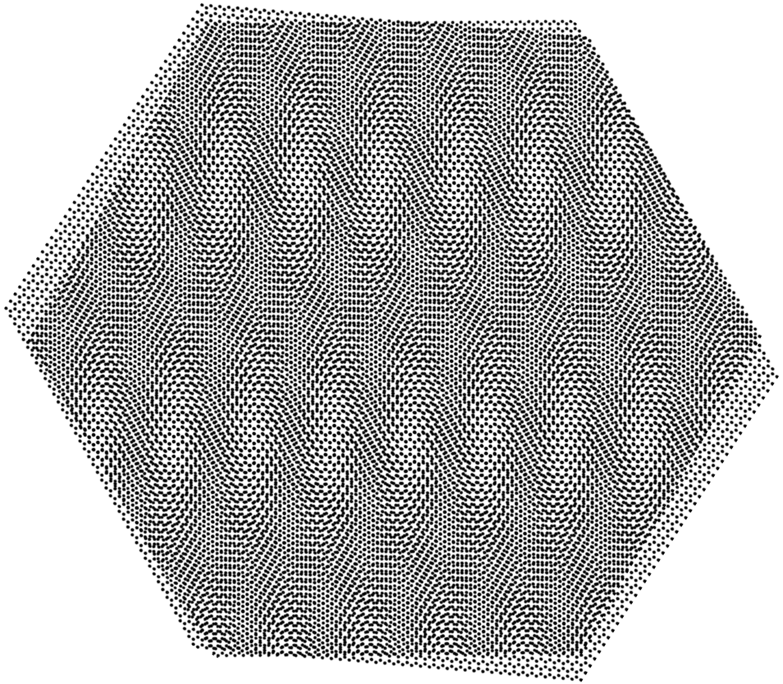
unstrained



$$T(\mathbf{r}) = \sum_{j=1}^{3} T_j \, e^{i\mathbf{q}_j \cdot \mathbf{r}}$$

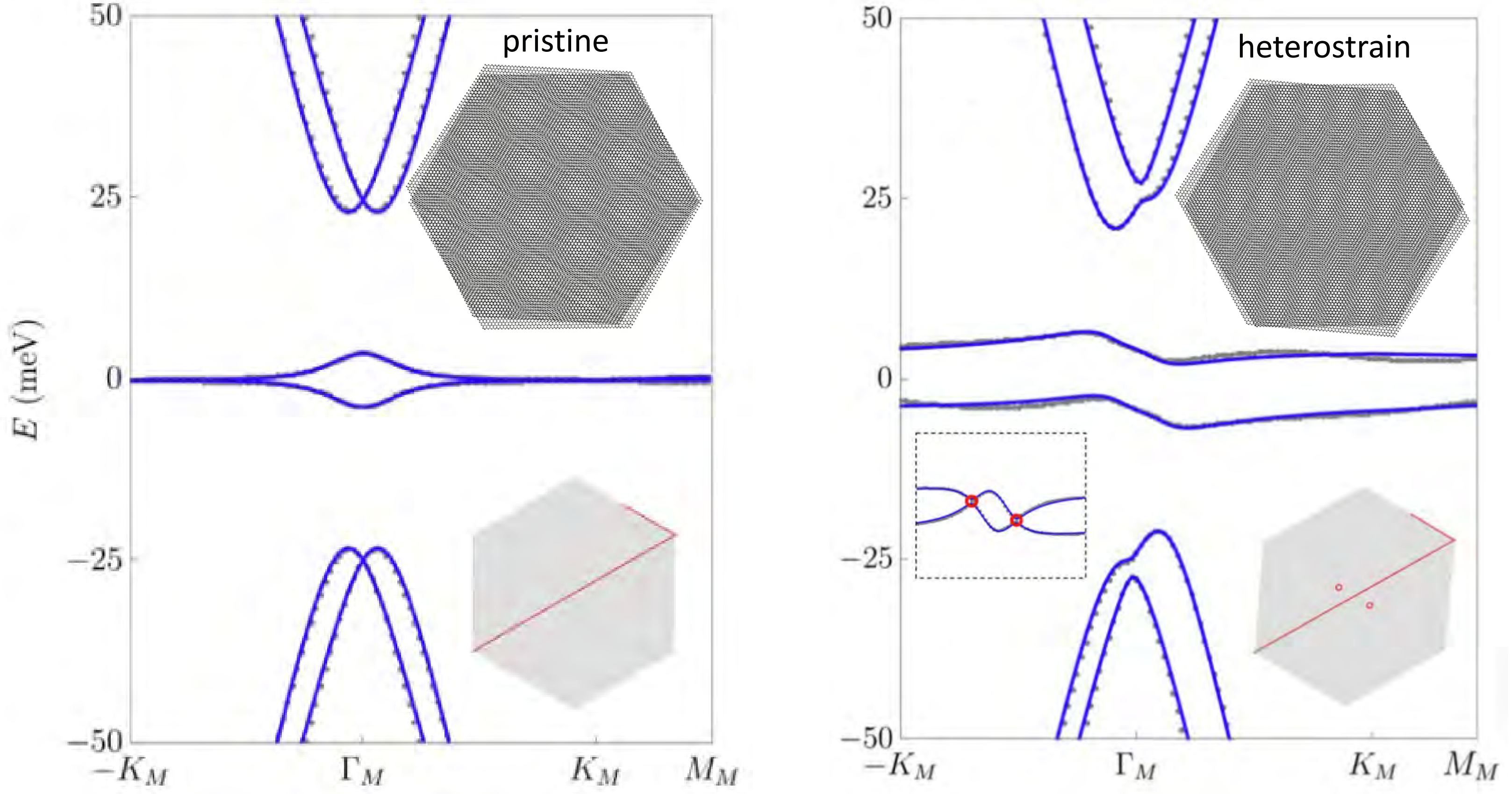
$$h_{\mathrm{BM}}^{K}(\mathbf{r}) = \begin{pmatrix} -iv_F \, \nabla \cdot \boldsymbol{\sigma} & T(\mathbf{r}) \\ T^{\dagger}(\mathbf{r}) & -iv_F \, \nabla \cdot \boldsymbol{\sigma} \end{pmatrix}$$

heterostrain



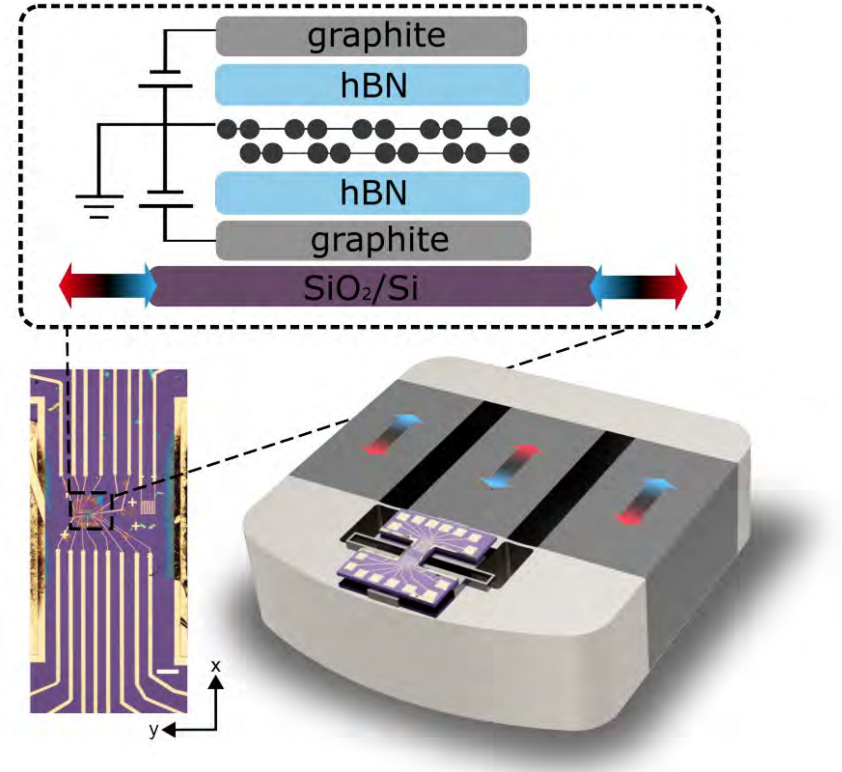
$$\mathbf{q}_j \;\rightarrow\; \mathbf{q}_j(\varepsilon) = \mathbf{q}_j^{(0)} + \delta\mathbf{q}_j(\varepsilon)$$

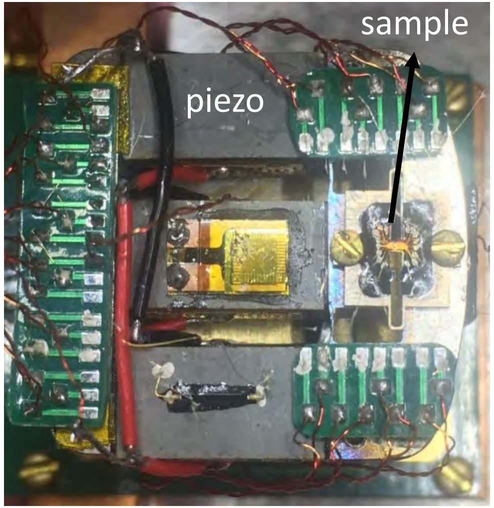
Effect of heterostrain on the moiré bands

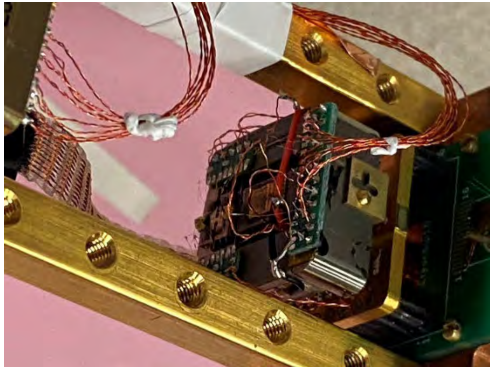


J. Herzog-Arbeitman *et al.*, PRB 112, 125128 (2025)

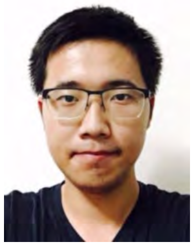
Directly controlling strain in vdW devices







Dr. Xuetao Ma



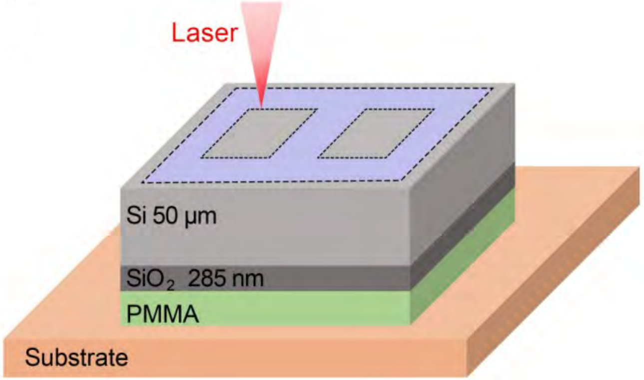
Dr. Zhaoyu Liu

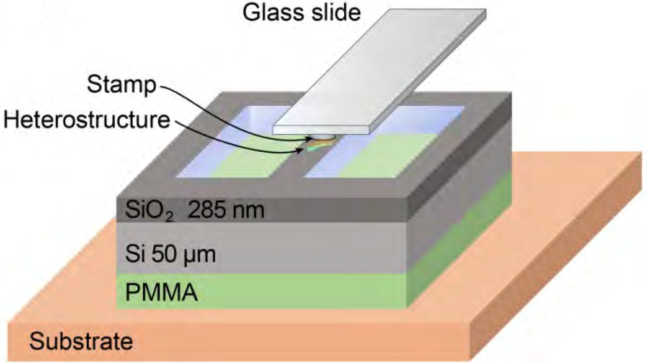
Prof. Jiun-Haw Chu

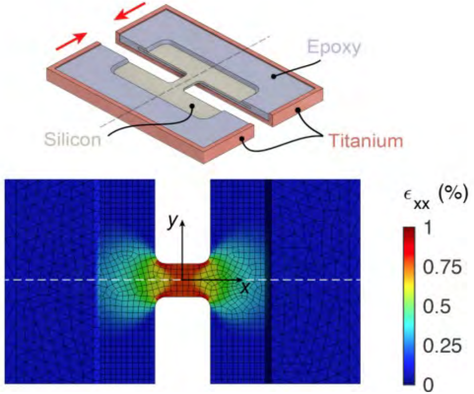
X. Ma, M. Yankowitz *et al.*, arXiv:2505.10506 (2025)

Z. Liu, M. Yankowitz, J.-H. Chu *et al.*,
J. Appl. Phys. 135, 204306 (2024)

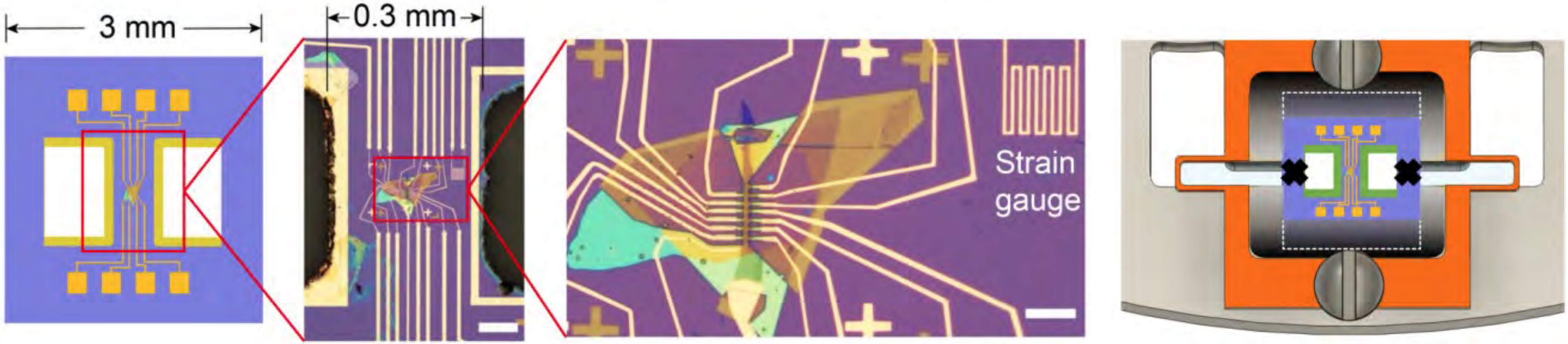
Achieving uniaxial strain in complex vdW devices





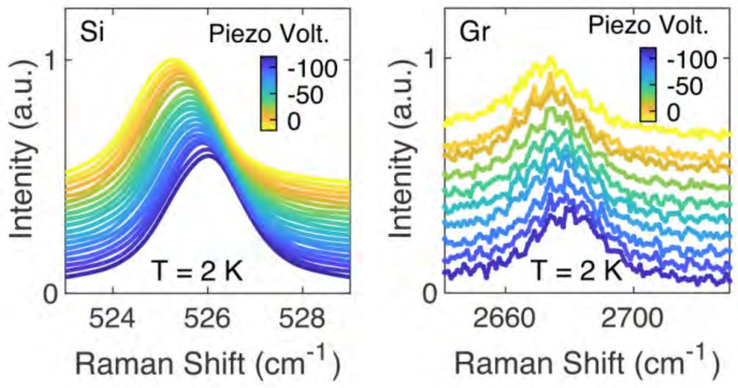


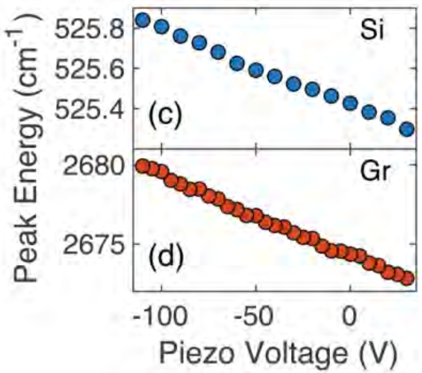
Z. Liu, M. Yankowitz, J.-H. Chu *et al.*, J. Appl. Phys. 135, 204306 (2024)



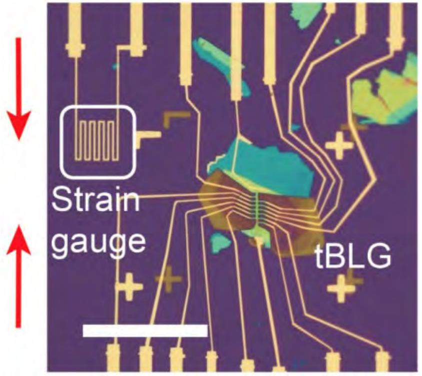
Measuring the induced strain

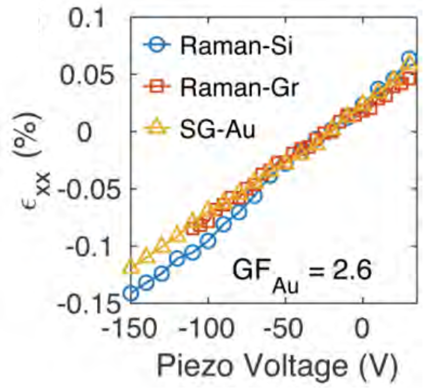
optically:



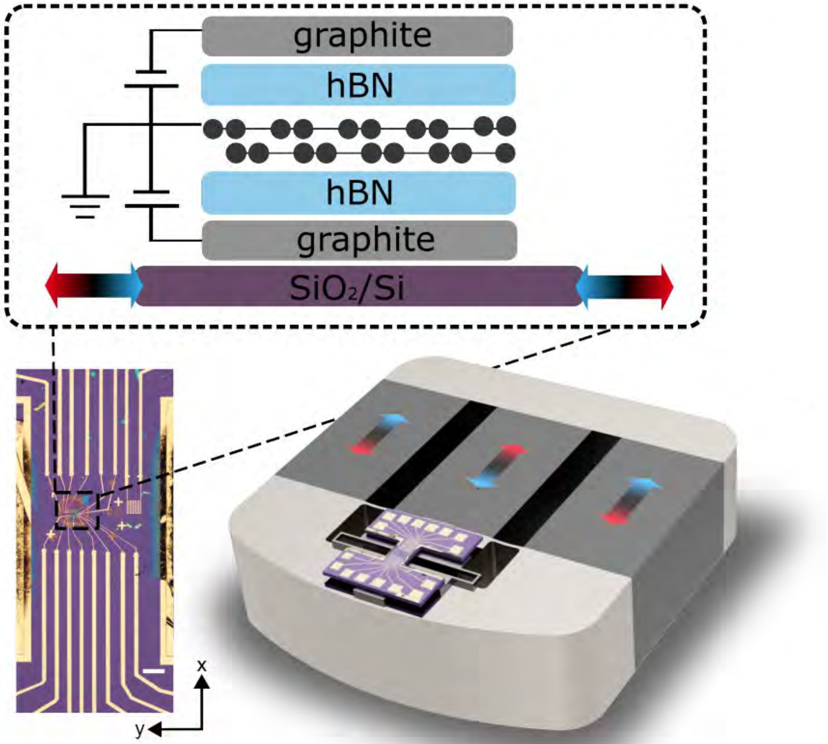


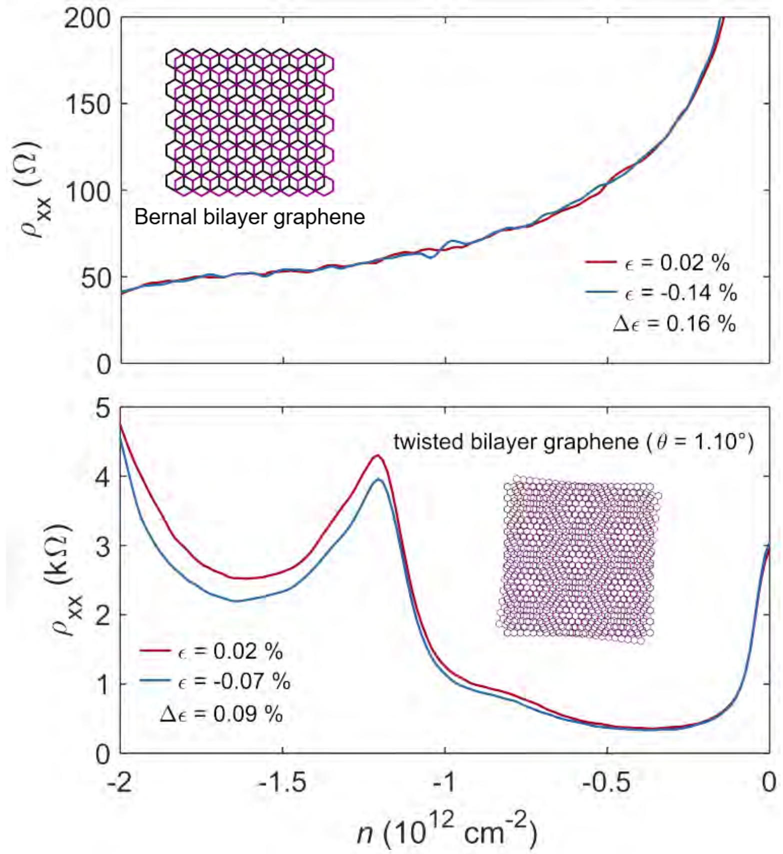
electrically:





Giant elastoresistance in magic-angle twisted graphene

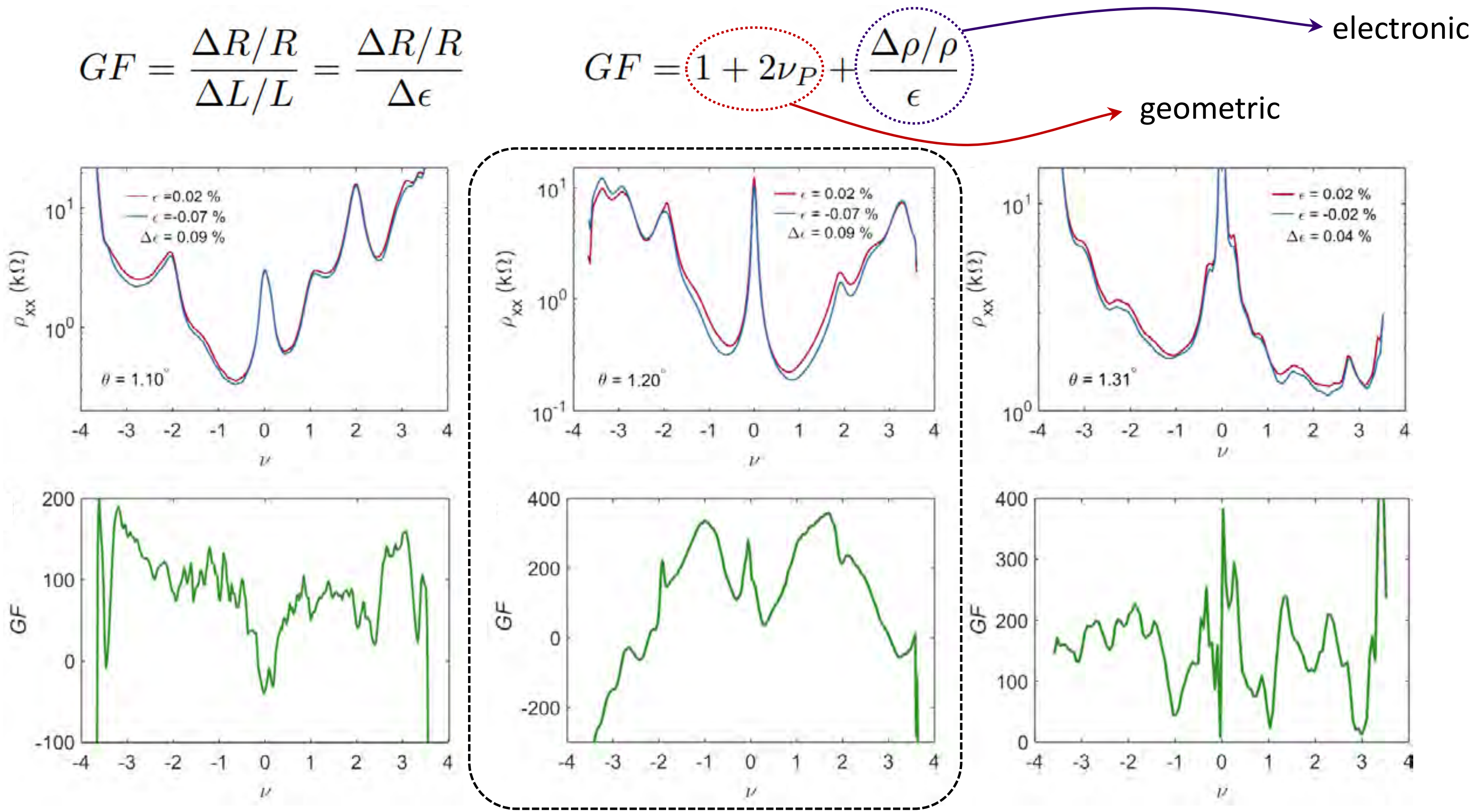




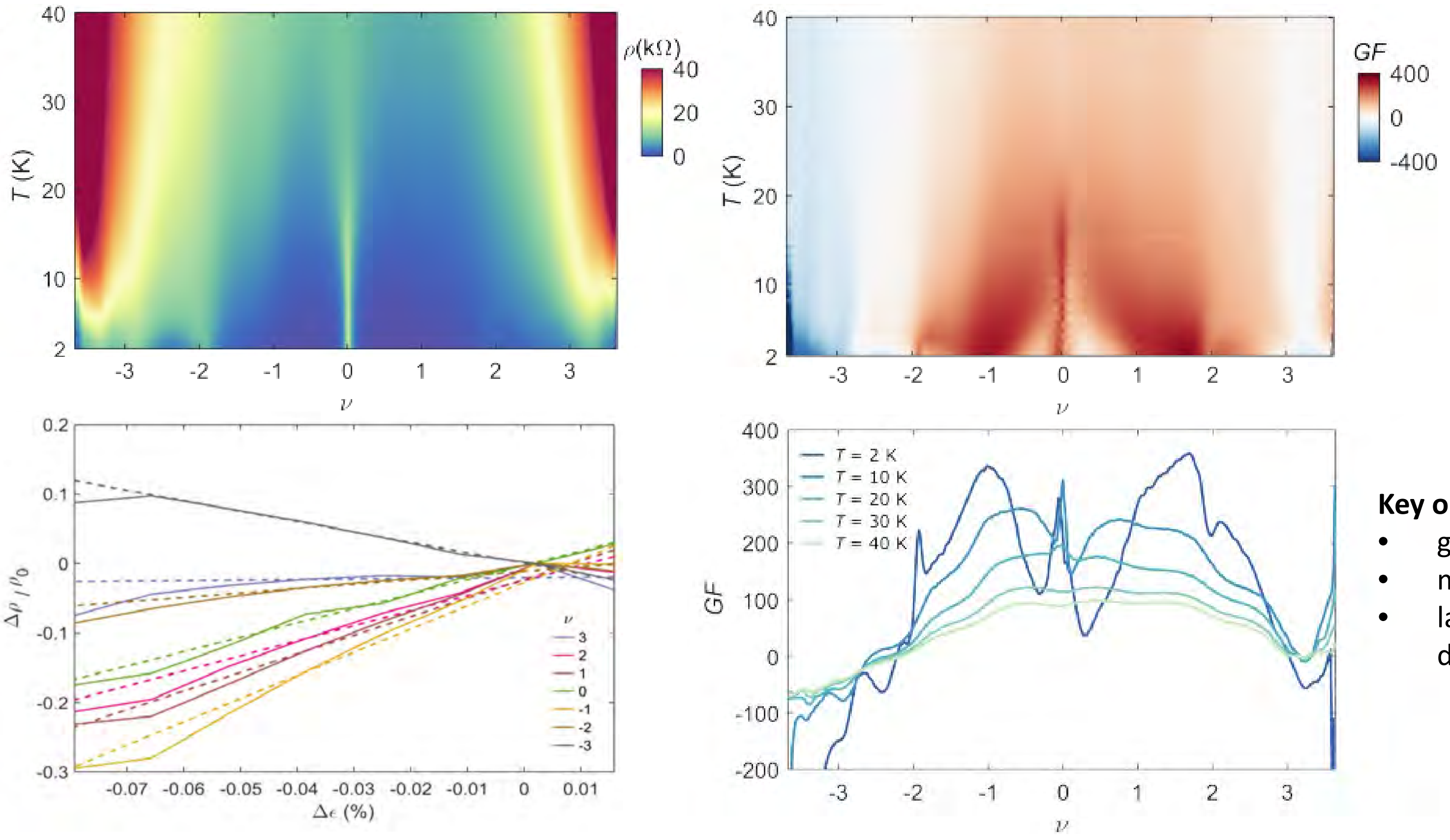
X. Ma, M. Yankowitz *et al.*, arXiv:2505.10506 (2025)

Figure of merit: gauge factor

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\Delta \epsilon} \qquad GF = 1 + 2\nu_P + \frac{\Delta \rho/\rho}{\epsilon}$$



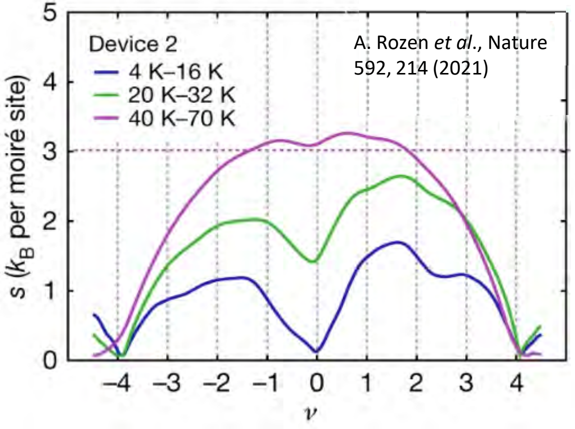
Temperature dependence of the elastoresistance

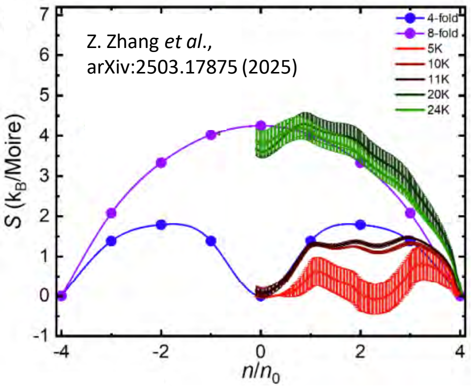


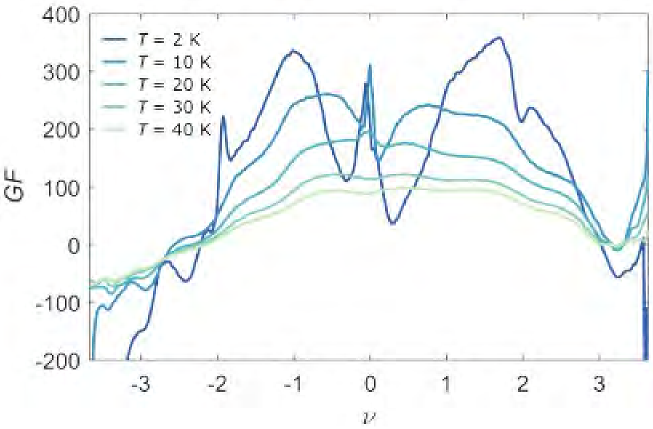
Key observations:

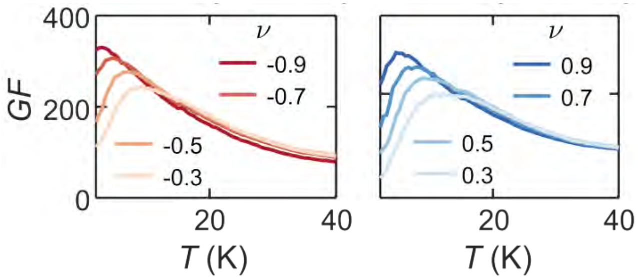
- giant gauge factor
- modulated by doping
- large temperature dependence

Large electronic entropy in MATBG









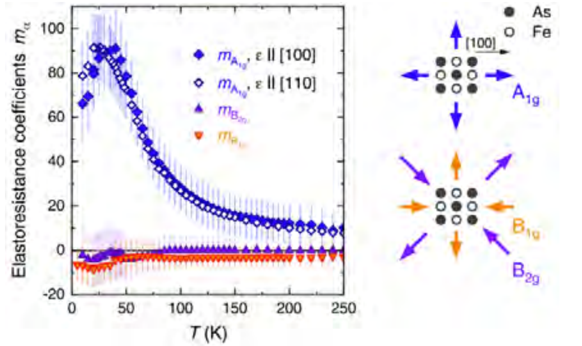
weakly diverging elastoresistance near the charge neutrality point

Dominant In-Plane Symmetric Elastoresistance in $CsFe_2As_2$

P. Wiecki, A.-A. Haghighirad, F. Weber, M. Merz, R. Heid, and A. E. Böhmer
Karlsruhe Institute of Technology, Institute for Quantum Materials and Technologies, 76021 Karlsruhe, Germany

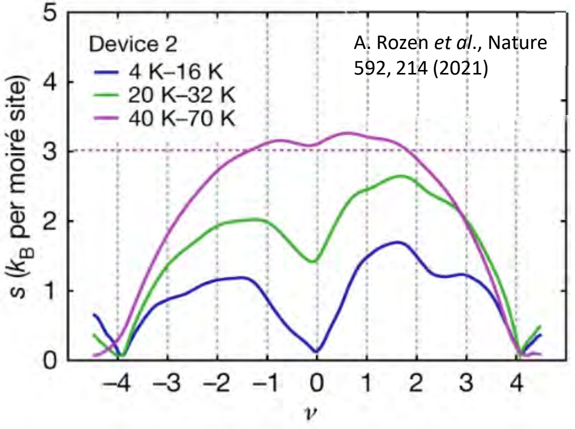
(Received 20 May 2020; revised 15 July 2020; accepted 24 September 2020; published 28 October 2020)

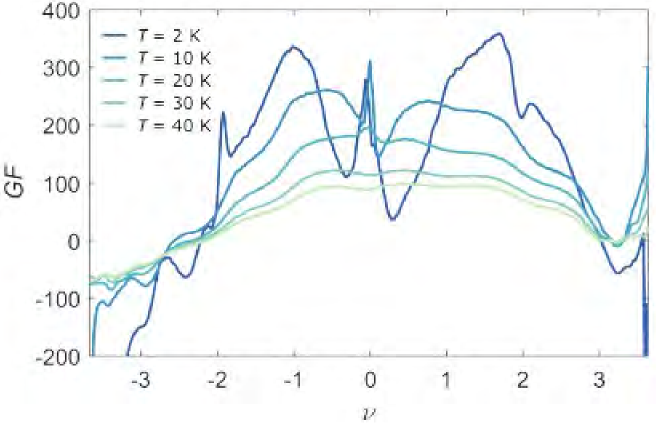
We study the elastoresistance of the highly correlated material $CsFe_2As_2$ in all symmetry channels. Neutralizing its thermal expansion by means of a piezoelectric-based strain cell is demonstrated to be essential. The elastoresistance response in the in-plane symmetric channel is found to be large, while the response in the symmetry-breaking channels is weaker and provides no evidence for a divergent nematic susceptibility. Rather, our results can be interpreted naturally within the framework of a coherence-incoherence crossover, where the low-temperature coherent state is sensitively tuned by the in-plane atomic distances.

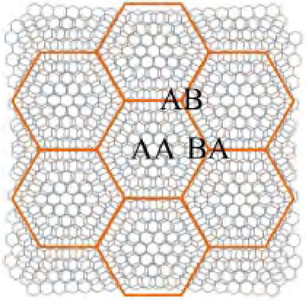


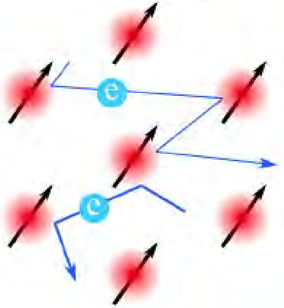
related observations in iron-based superconductors with weak nematicity

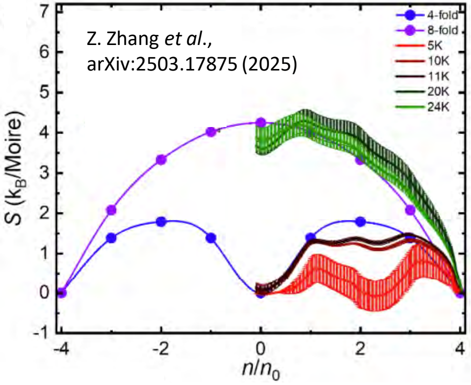
Large electronic entropy in MATBG

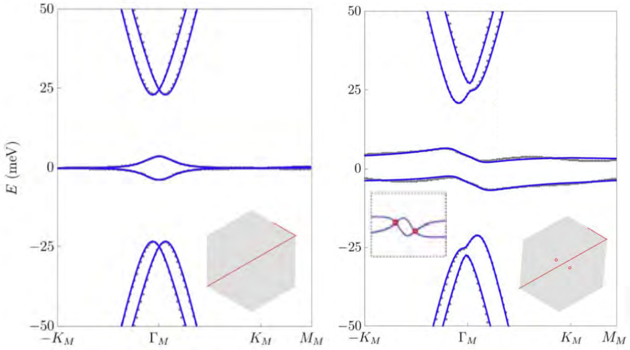






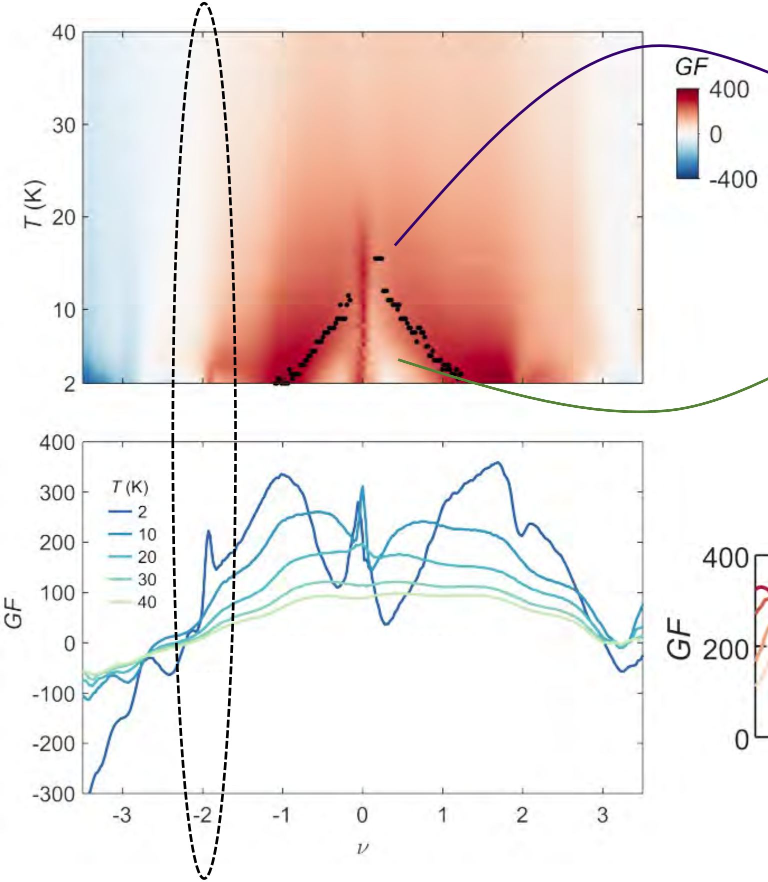


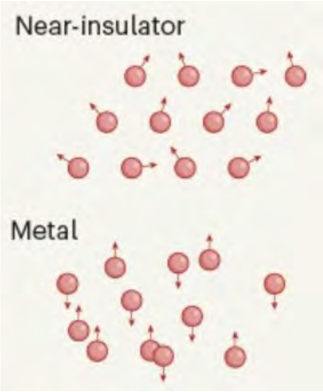


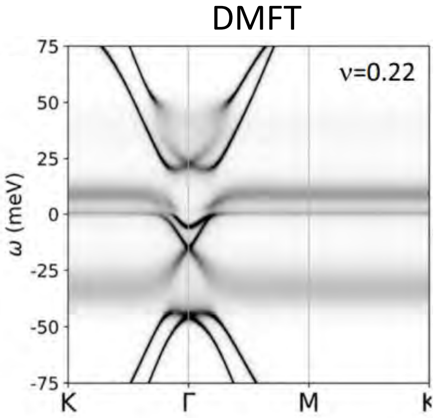


strain-induced band structure deformations may modify hybridization between light and heavy sectors

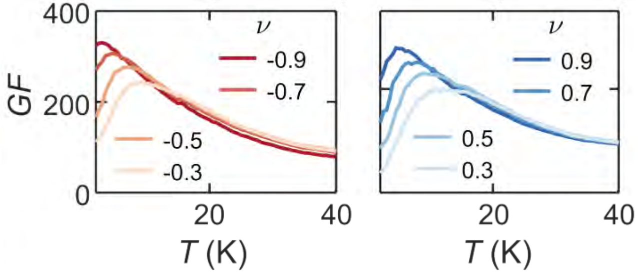
Possible signature of coherence-incoherence crossover

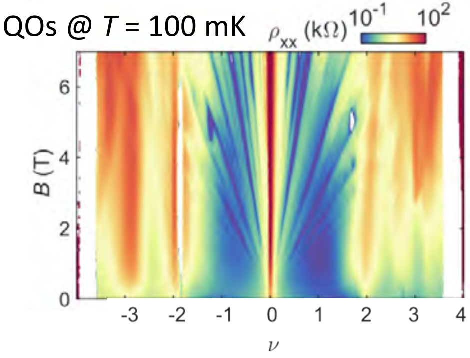






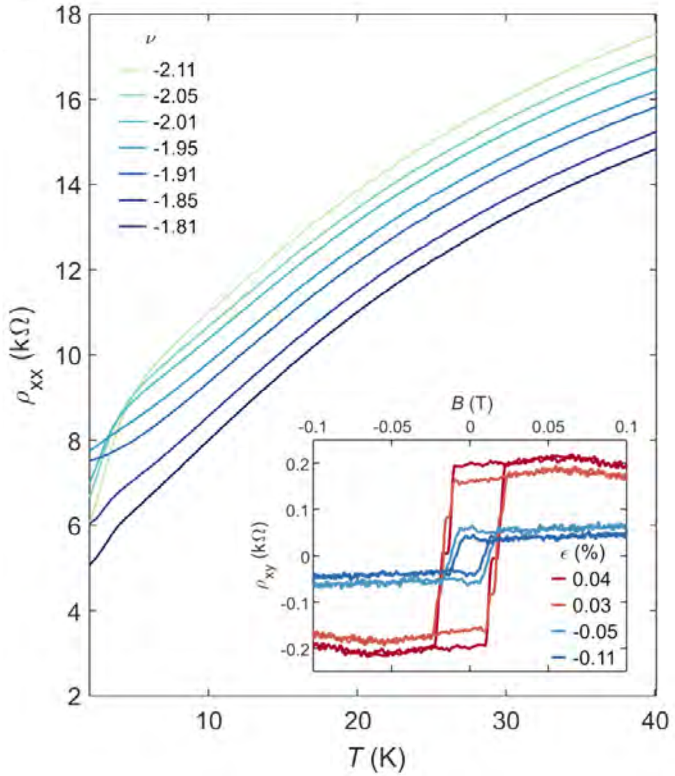
A. Datta *et al.*, Nature Comms. 14, 5036 (2023)

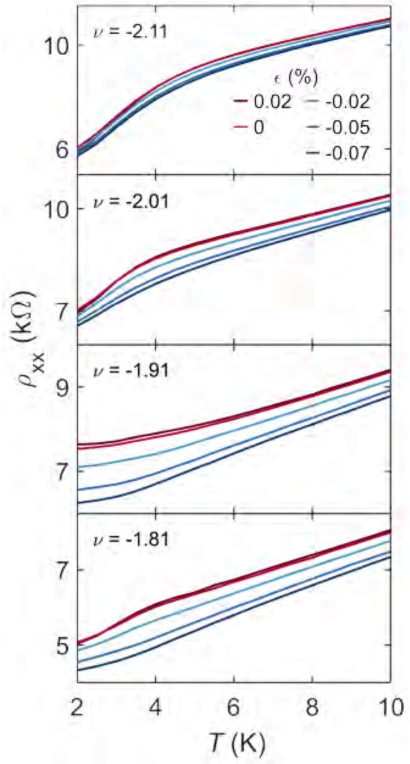


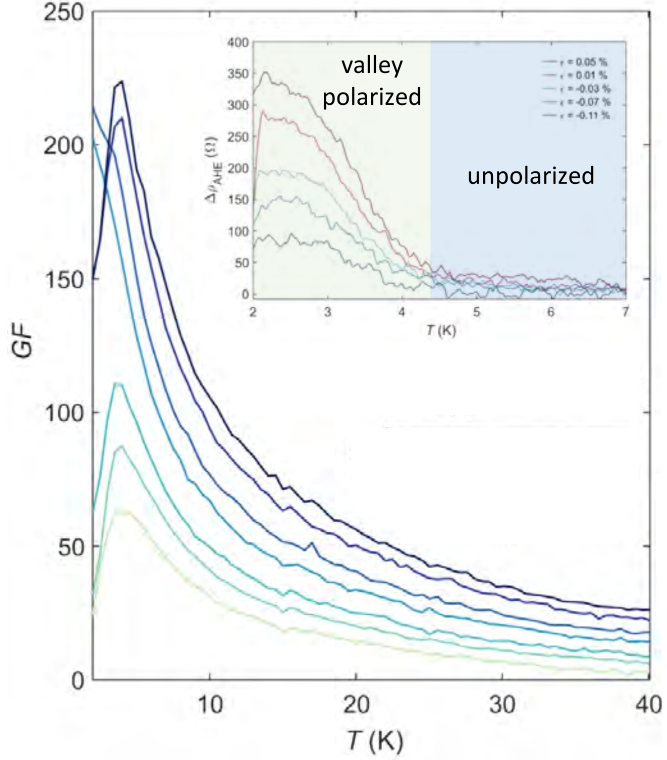


Diverging elastoresistance and ordered state formation

cutoff of the diverging elastoresistance associated
with the formation of an isopin-ordered phase

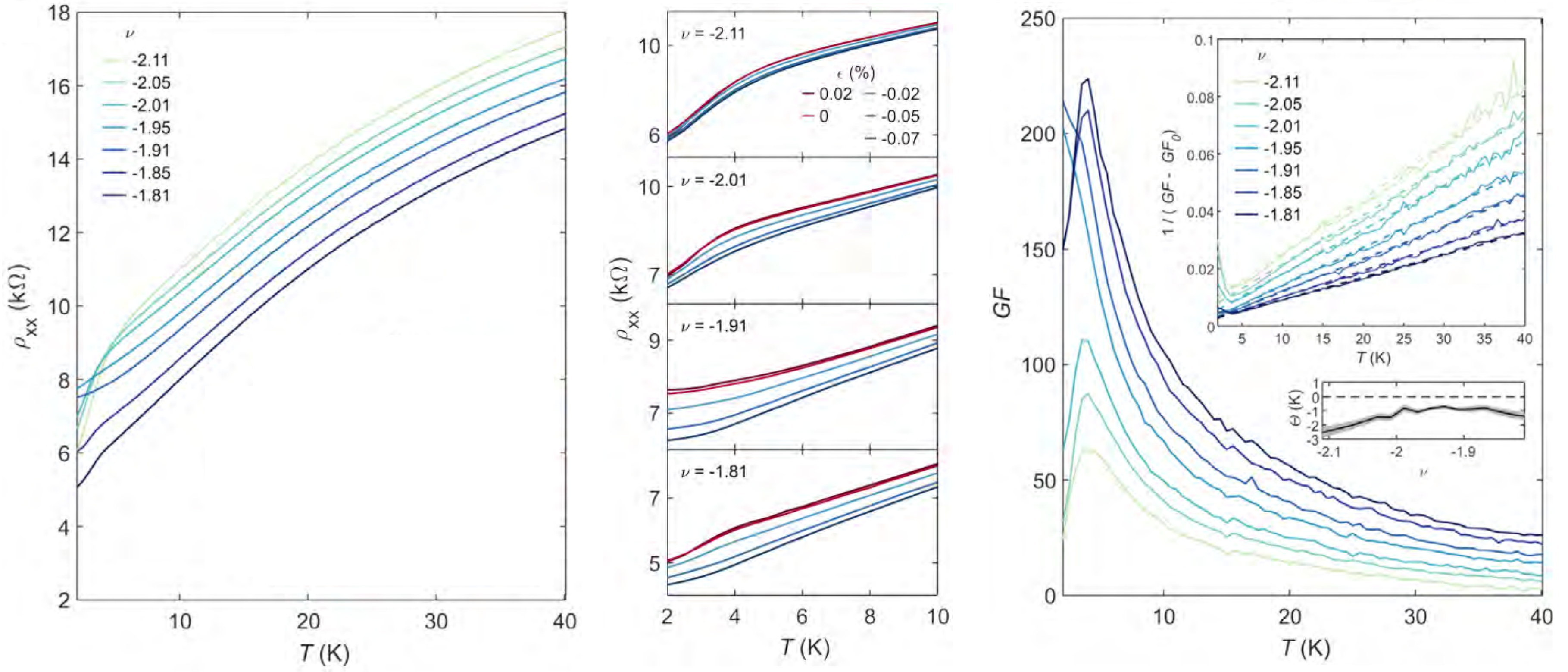




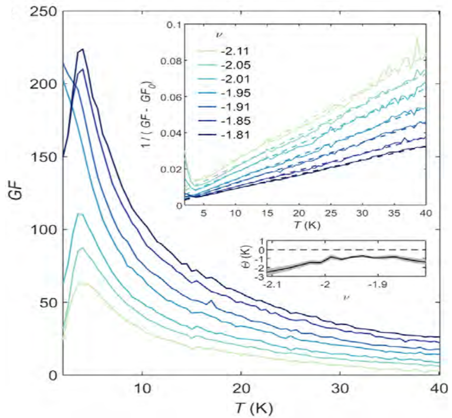


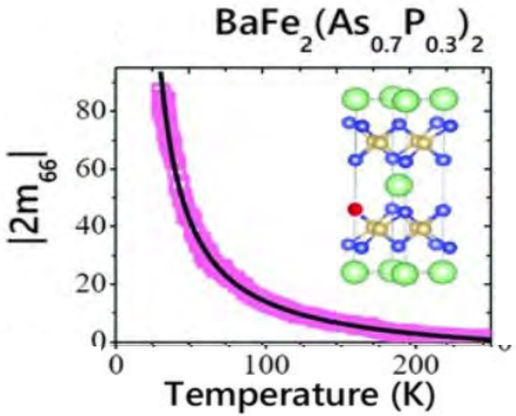
Curie-Weiss divergence of the elastoresistance

Curie-Weiss Law: $GF = \frac{C}{T - \Theta} + GF_0$



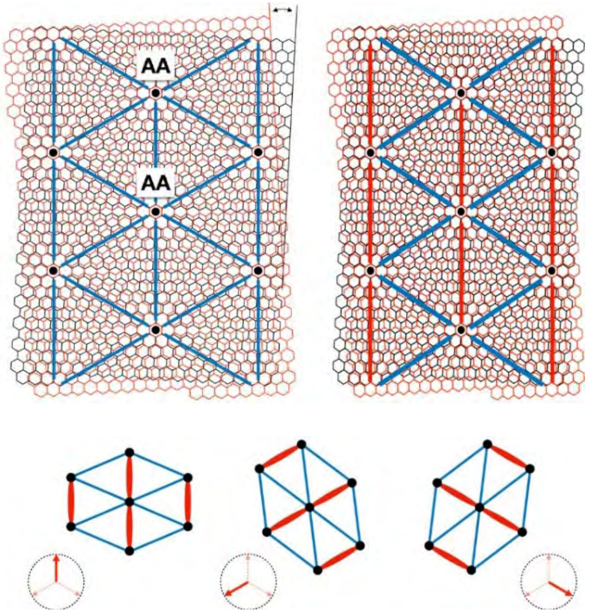
Possible role of nematic quantum critical fluctuations





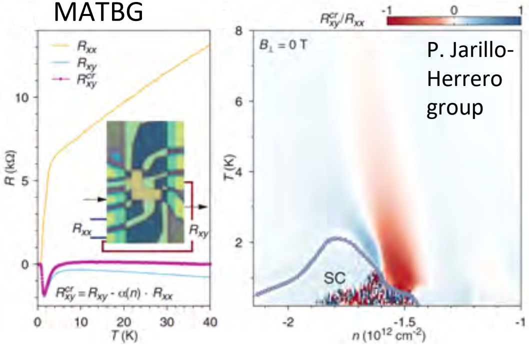
H.-H. Kuo *et al.*, Science 352, 958 (2016)

nematic fluctuations



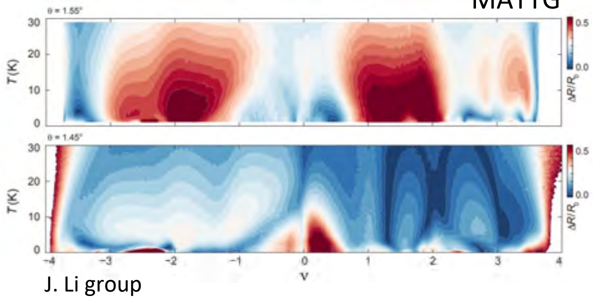
R. Fernandes & J. Venderbos, Science Advances 6, 8834 (2020)

MATBG



P. Jarillo-Herrero group

MATTG

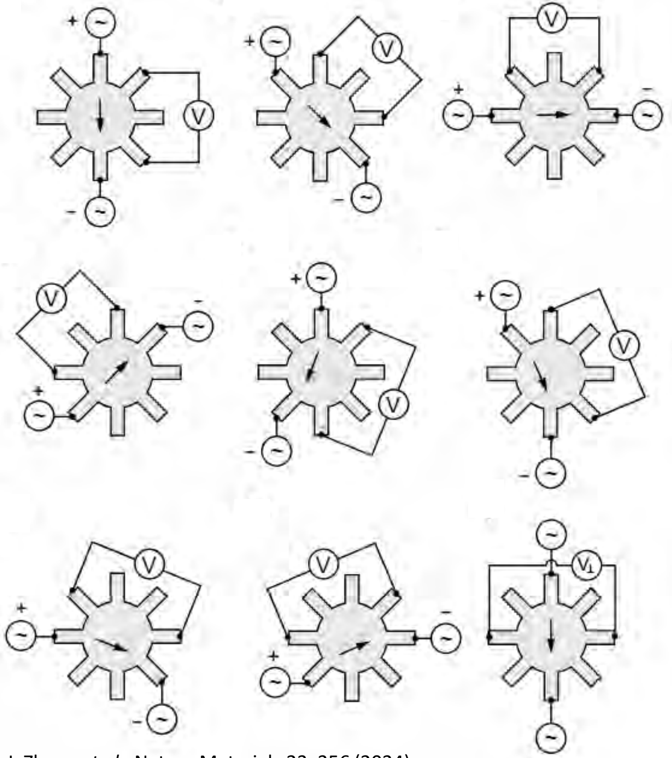


J. Li group

transport anisotropies hint at nematic ordering in MATBG (and MATTG)

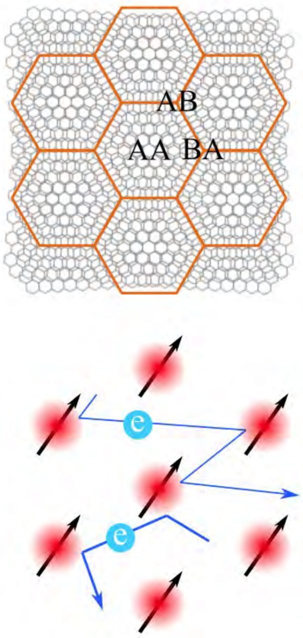
Future work: symmetry-decomposed elastoresistance

"sunflower" geometry for full resistivity tensor decomposition



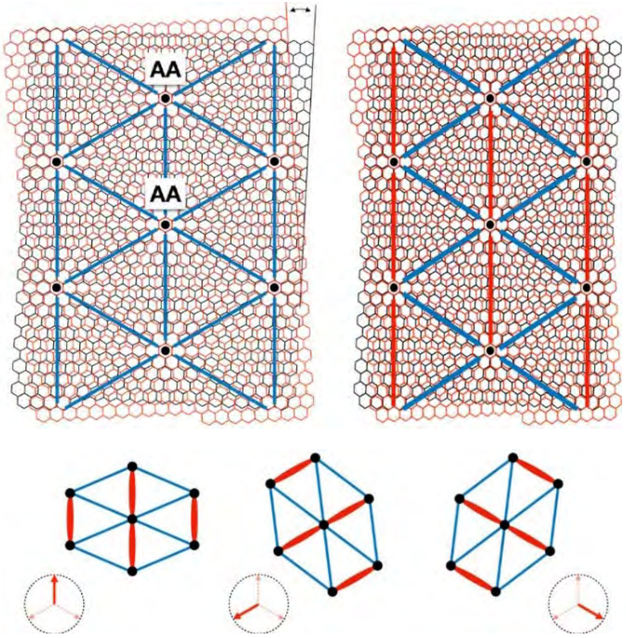
N. J. Zhang *et al.*, Nature Materials 23, 356 (2024)

isotropic



Z.-D. Song & B. A. Bernevig, PRL 129, 047601 (2022)

anisotropic

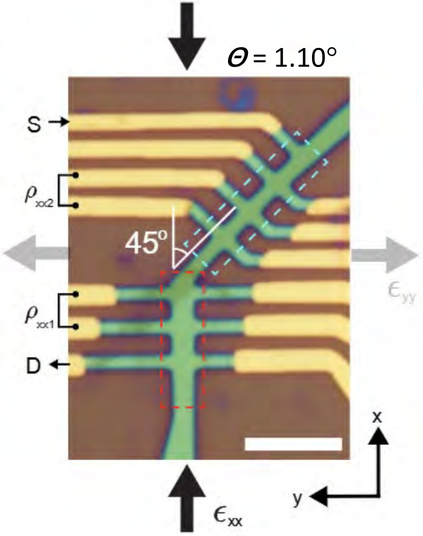


R. Fernandes & J. Venderbos, Science Advances 6, 8834 (2020)

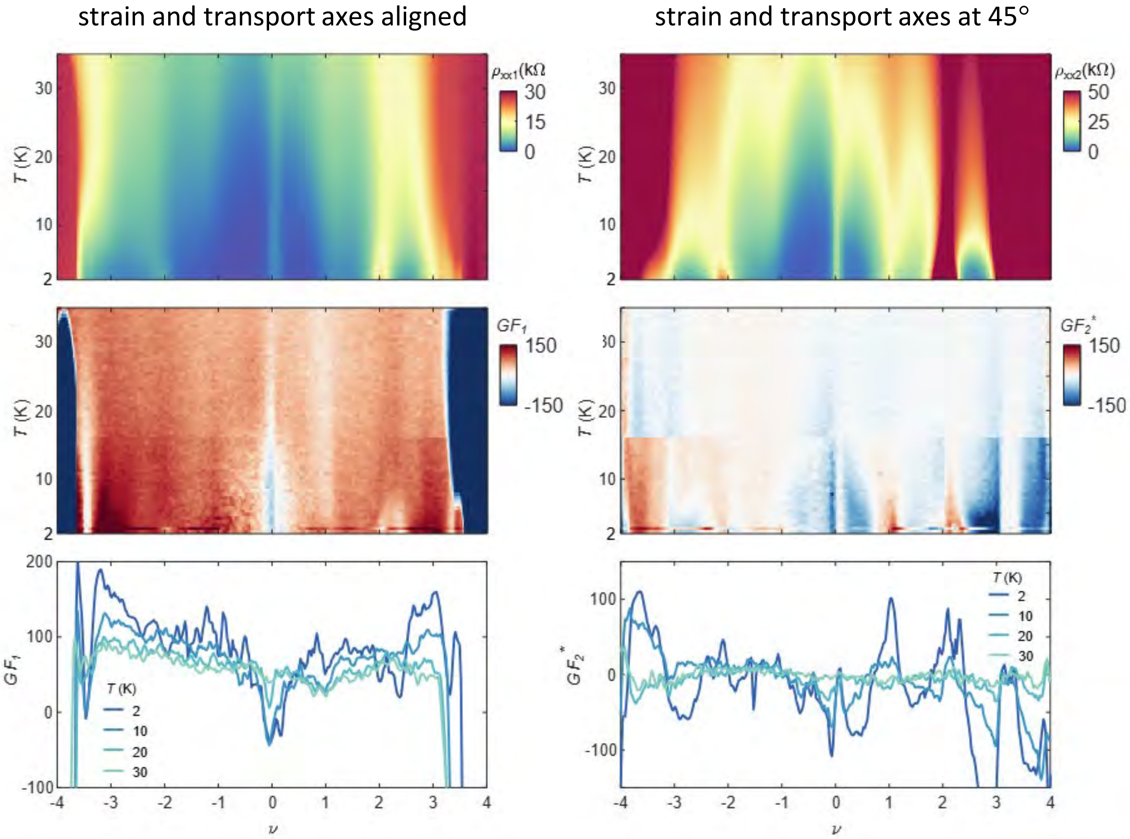
Preliminary attempt at symmetry resolution

$$\epsilon_{\text{iso}} = (\epsilon_{xx} + \epsilon_{yy})/2$$

$$\epsilon_{\text{aniso}} = (\epsilon_{xx} - \epsilon_{yy})/2$$

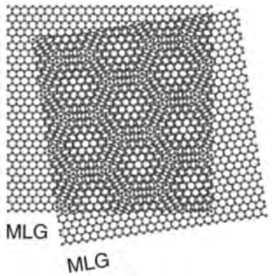


distinct strain response in two regions implies contributions from both symmetric and anisotropic channels

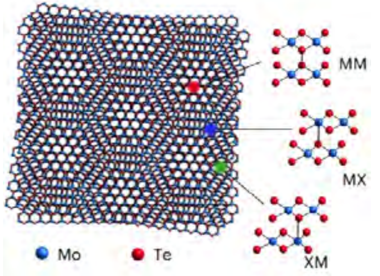


Strain for controlling van der Waals materials

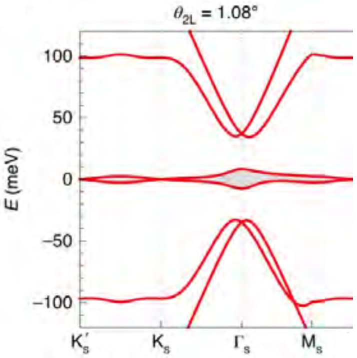
moiré multilayers



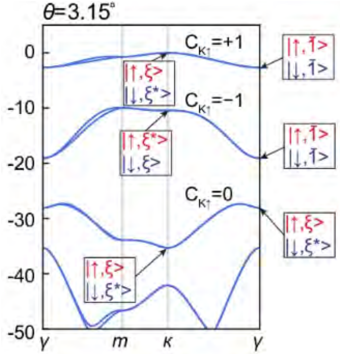
L. Balents et al., Nat. Phys. (2020)



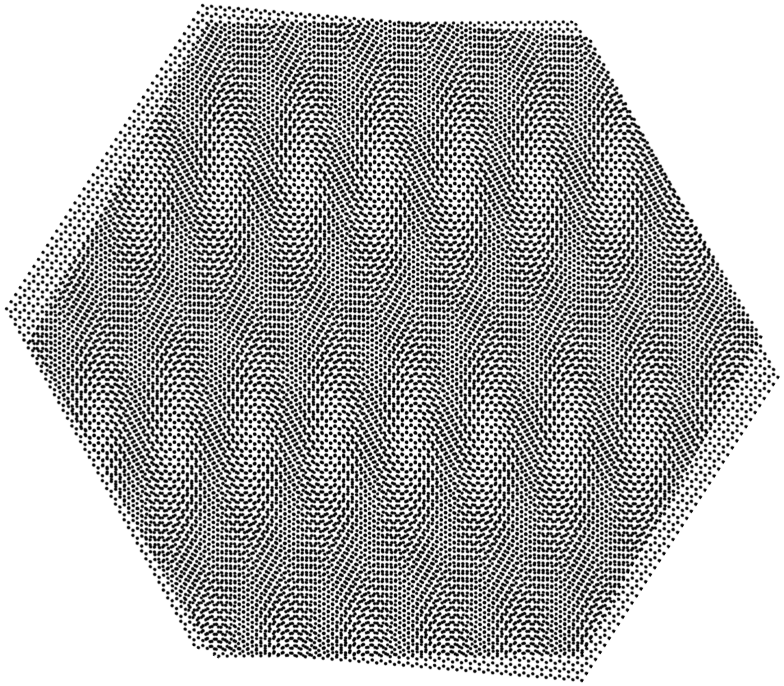
E. Thompson et al., Nat. Phys. (2025)



J. M. Park et al., Nat. Materials 21, 877 (2022)

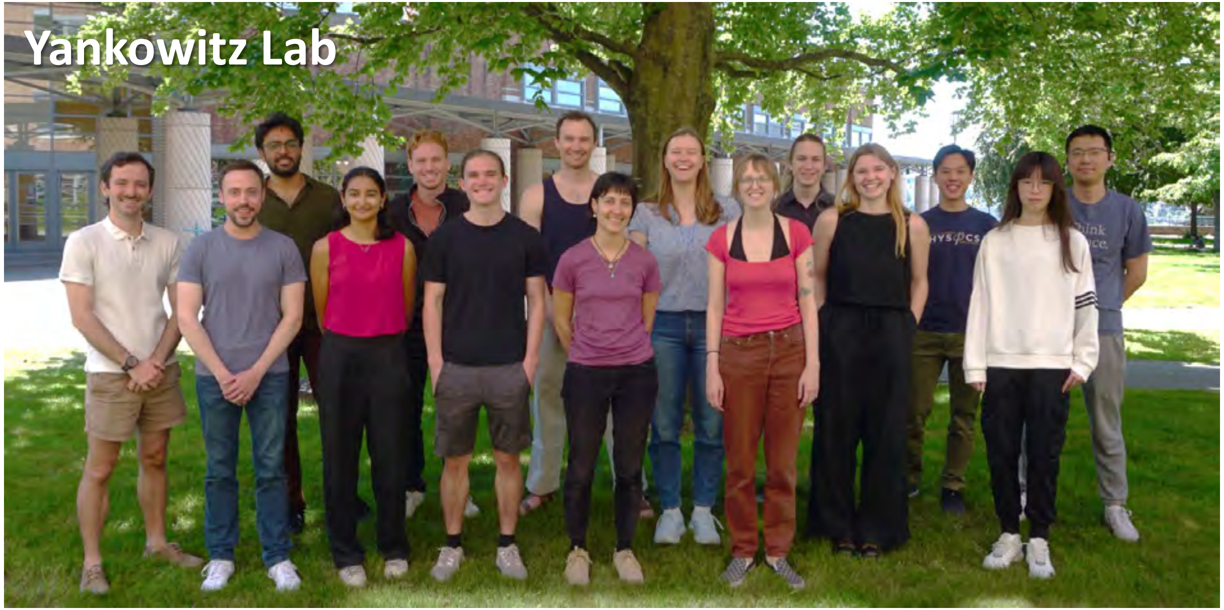


X.-W. Zhang et al., Nat. Comms. 15, 4223 (2024)



…toward new discoveries with designer Hamiltonians

Acknowledgements



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