Quantum Electronic Phases in Twisted Trilayer Graphene

Aaron Sharpe
University of Washington
February 23th, 2026

arXiv: 2509.07977
arXiv: 2509.03583

Slides available @ aaronsharpe.science

When interactions meet topology

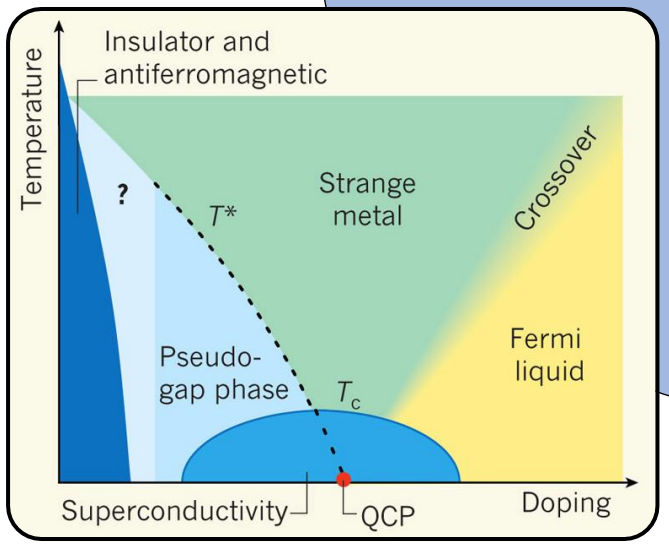
Electronic interactions

Mott insulators
Superconductivity
Magnetism
…

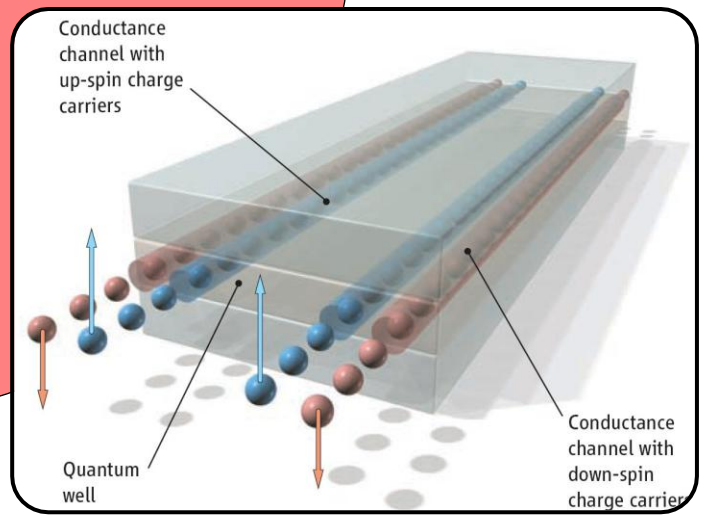
FQHE
FCI
…

Nontrivial topology

Quantum Hall states
Topological materials
…



Varma, Nature (2010)



König, et al., Science (2007)

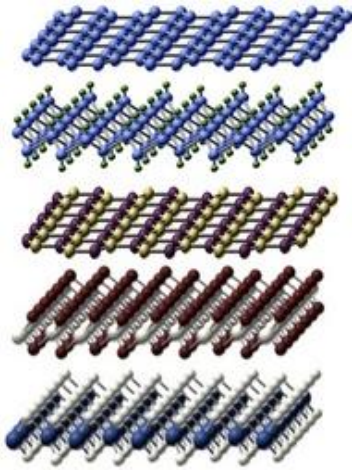
Our materials toolkit

(semimetal)

insulator

superconductor

semiconductor



Graphene

Graphane

hBN

NbSe2

TMDs

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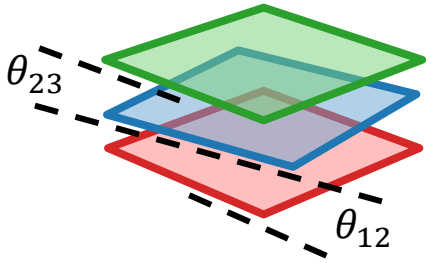

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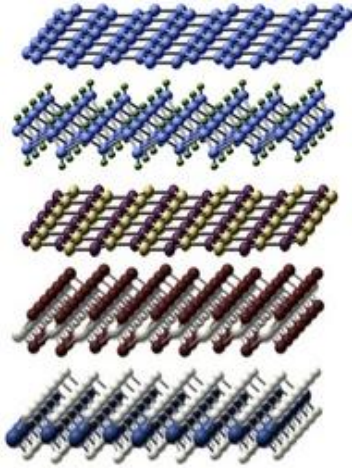

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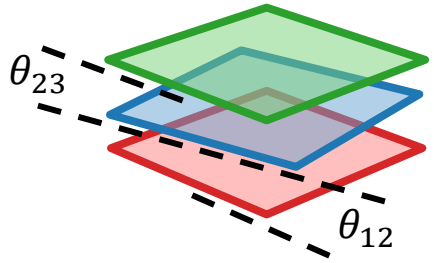

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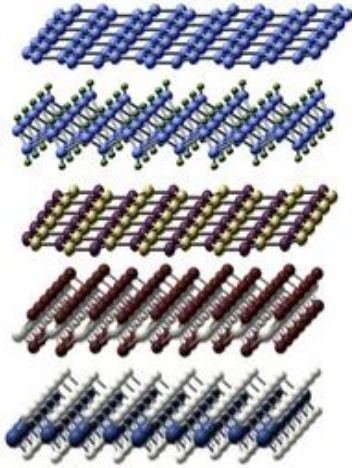

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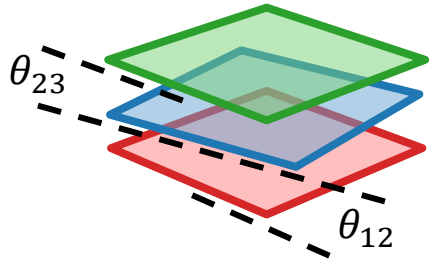

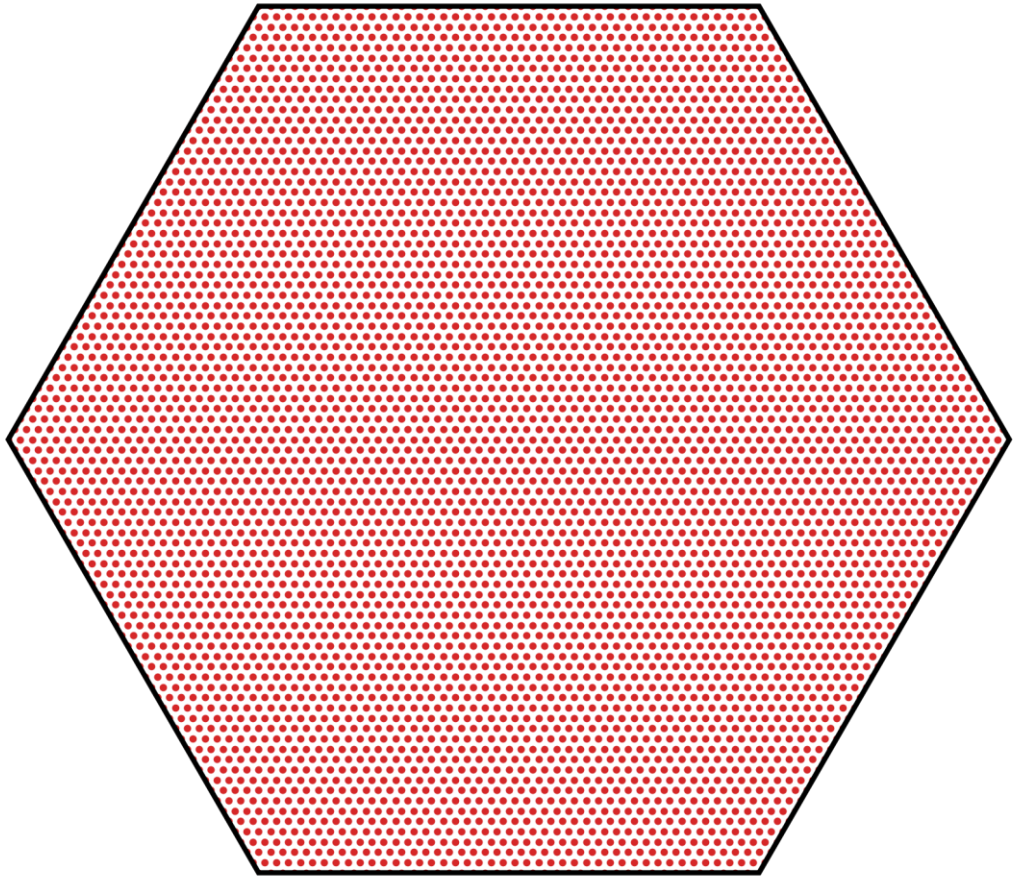

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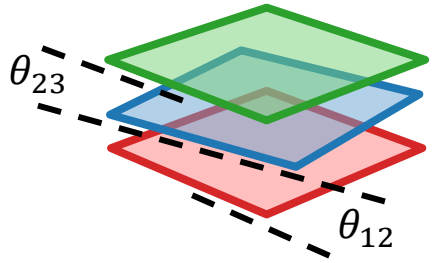

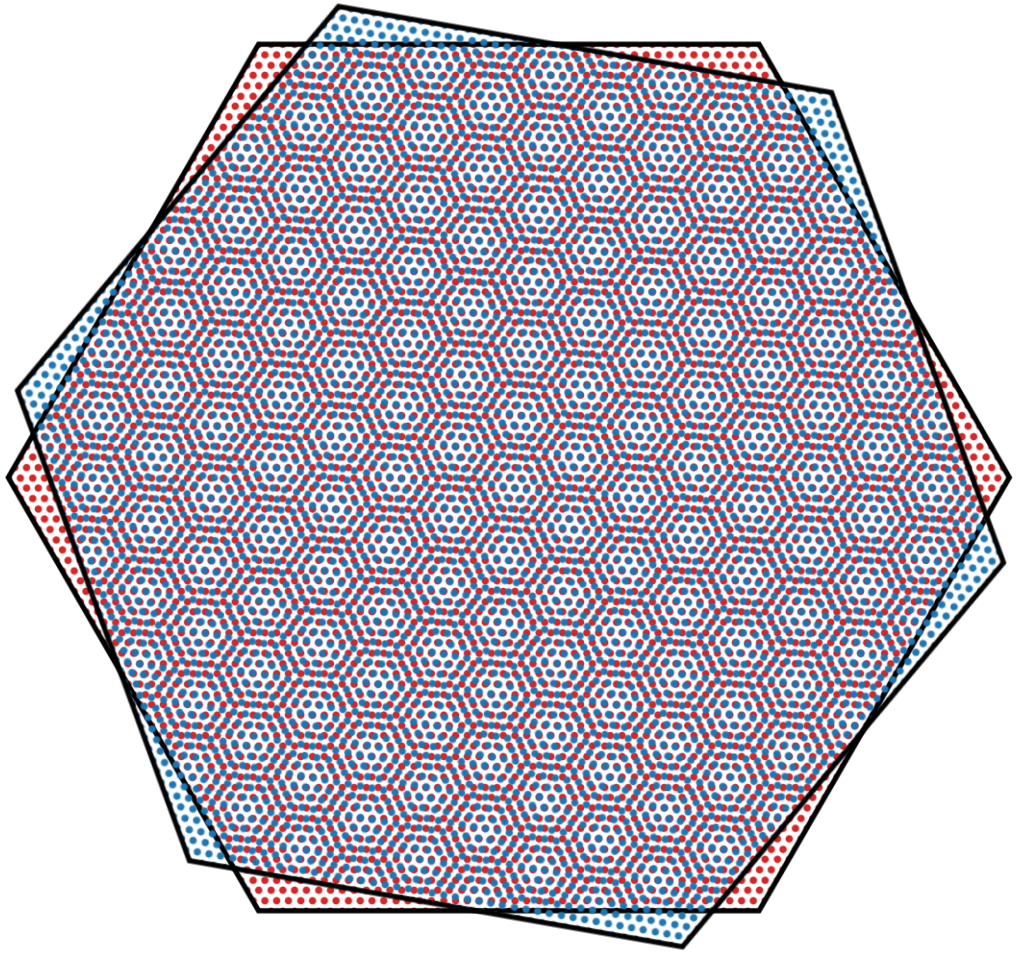

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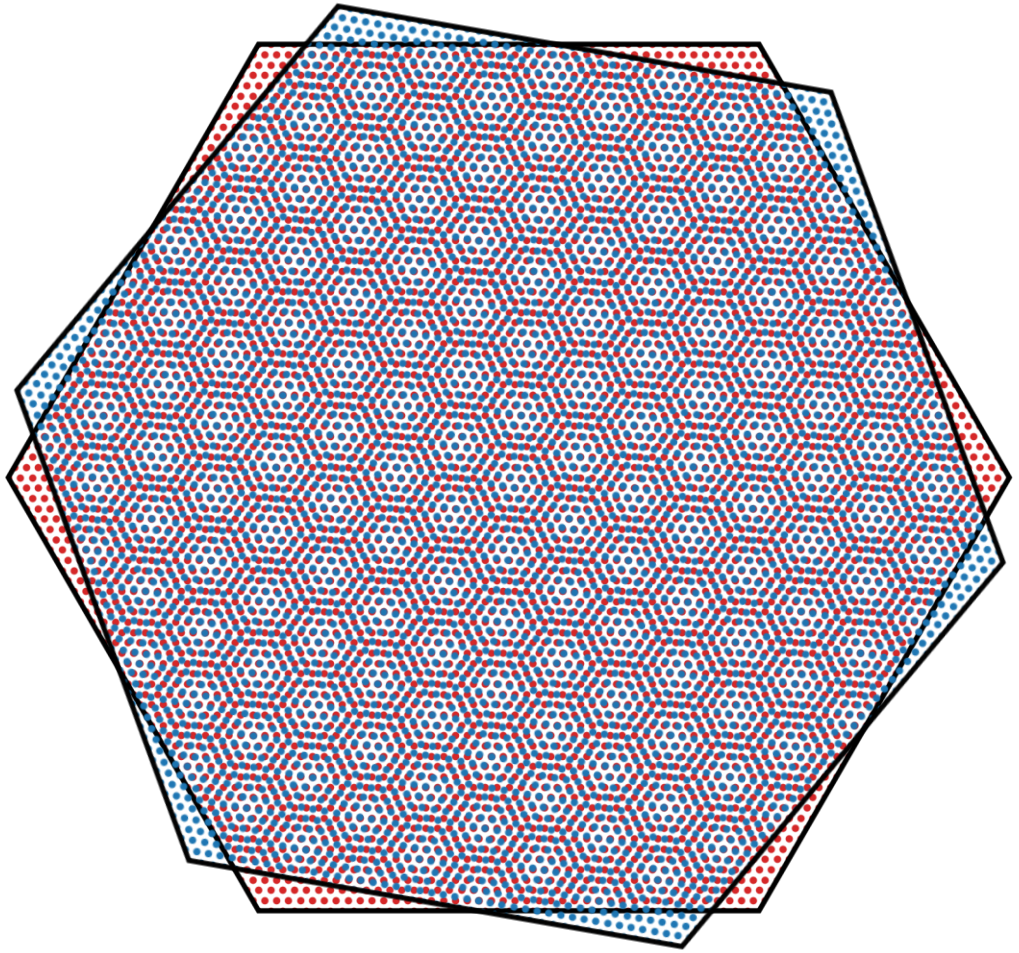
1. Add **third twisted layer.** Introduces ***supermoiré*** length scale. What is the role of this length scale?



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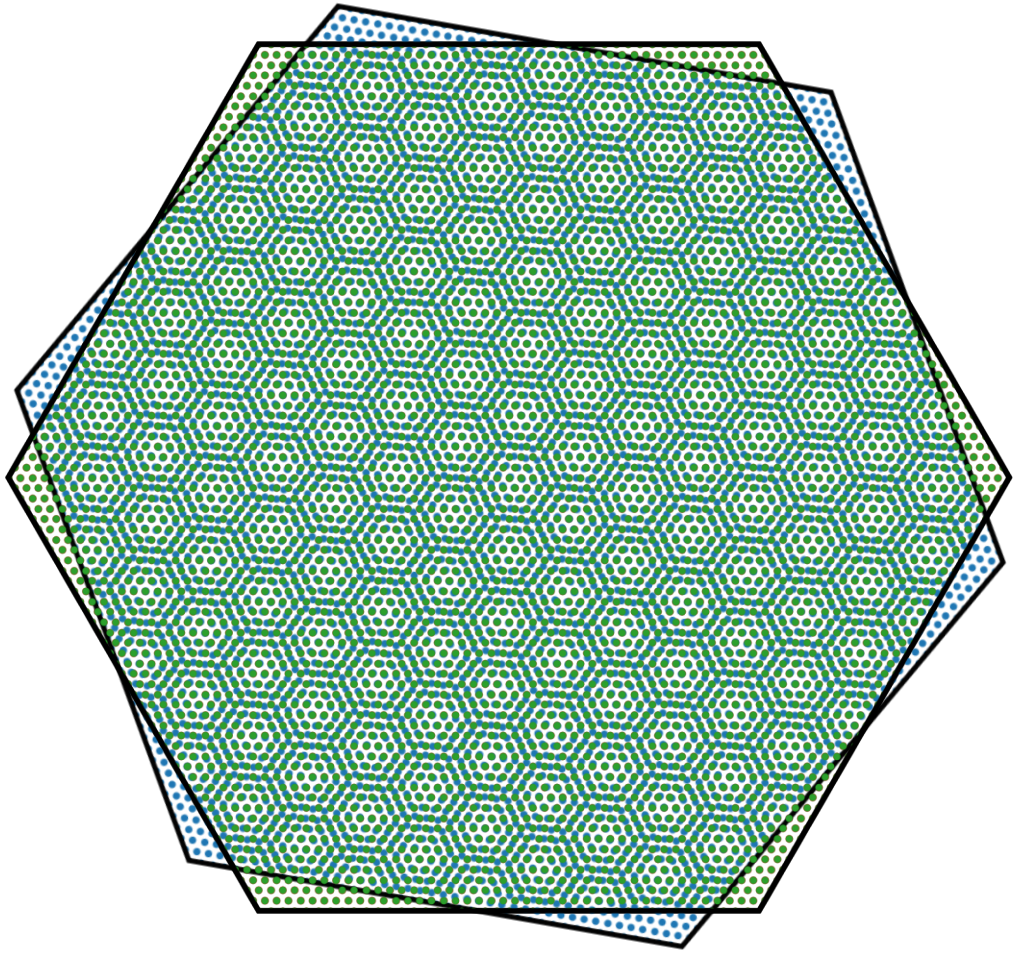

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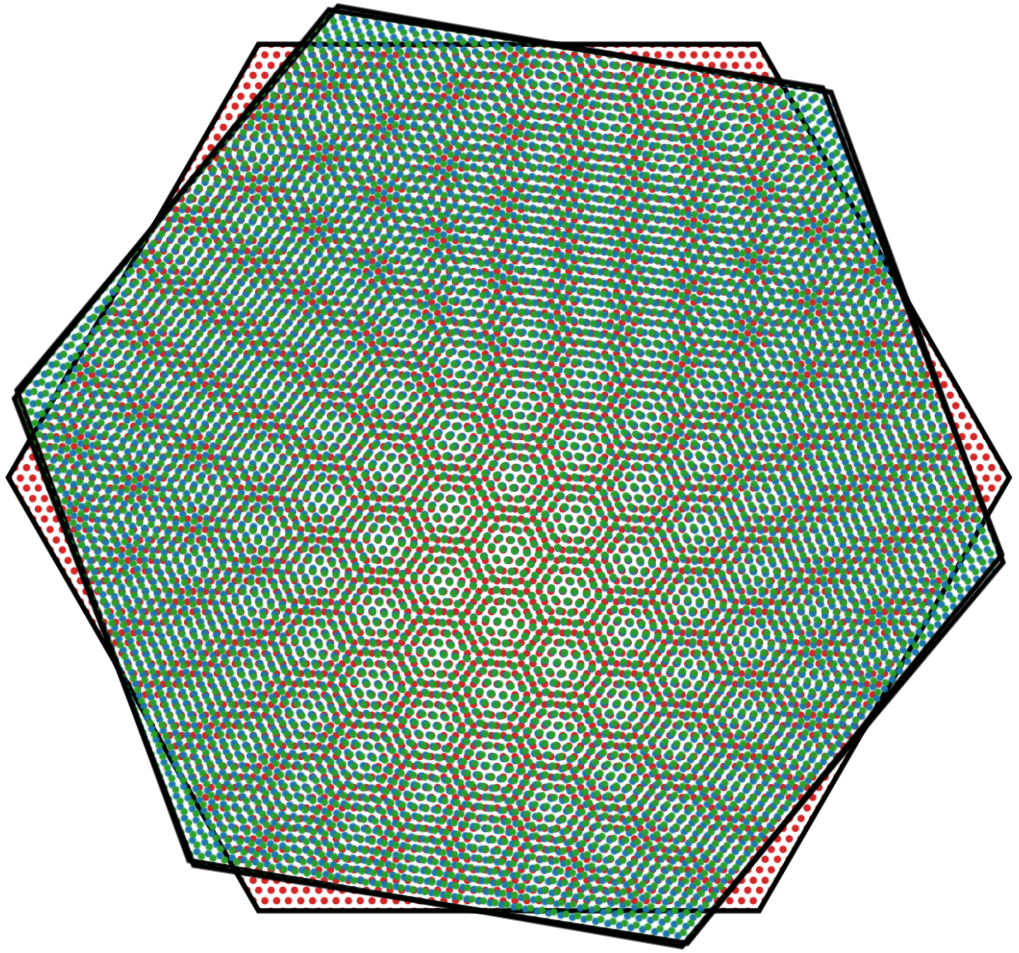

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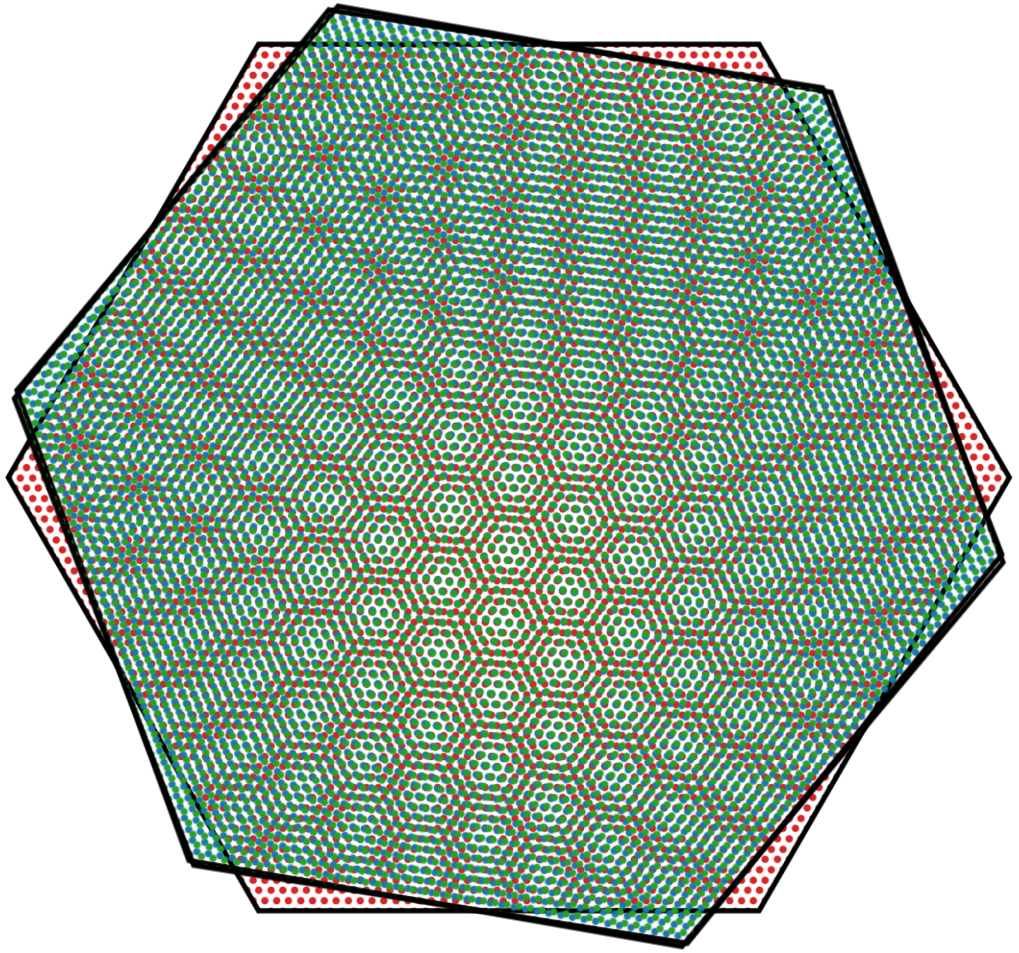

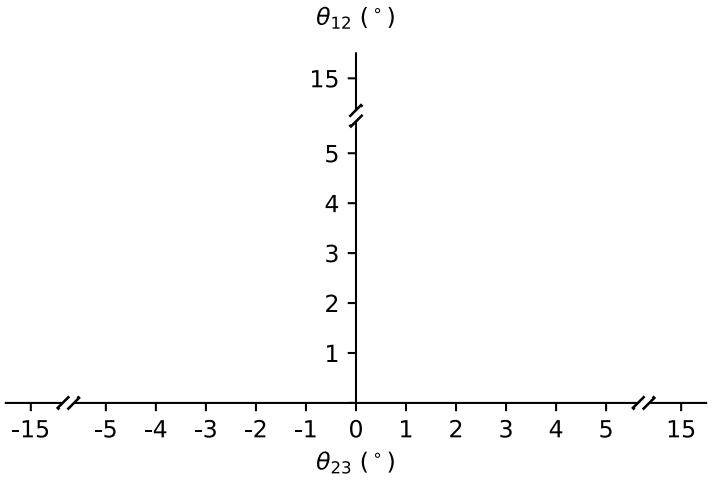

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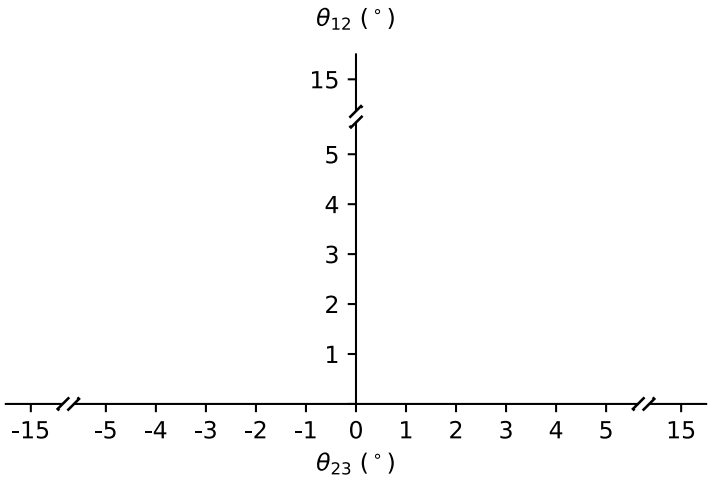
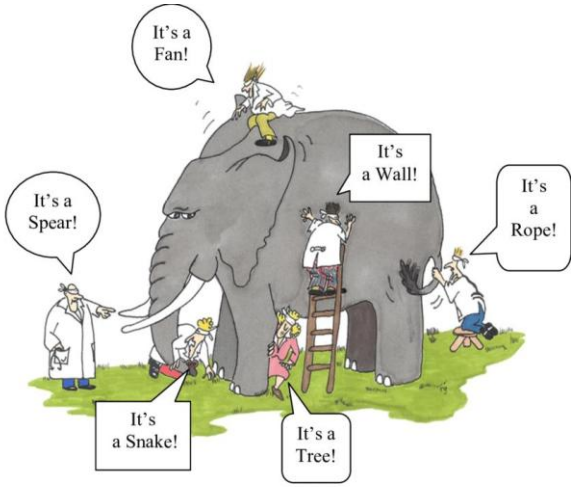
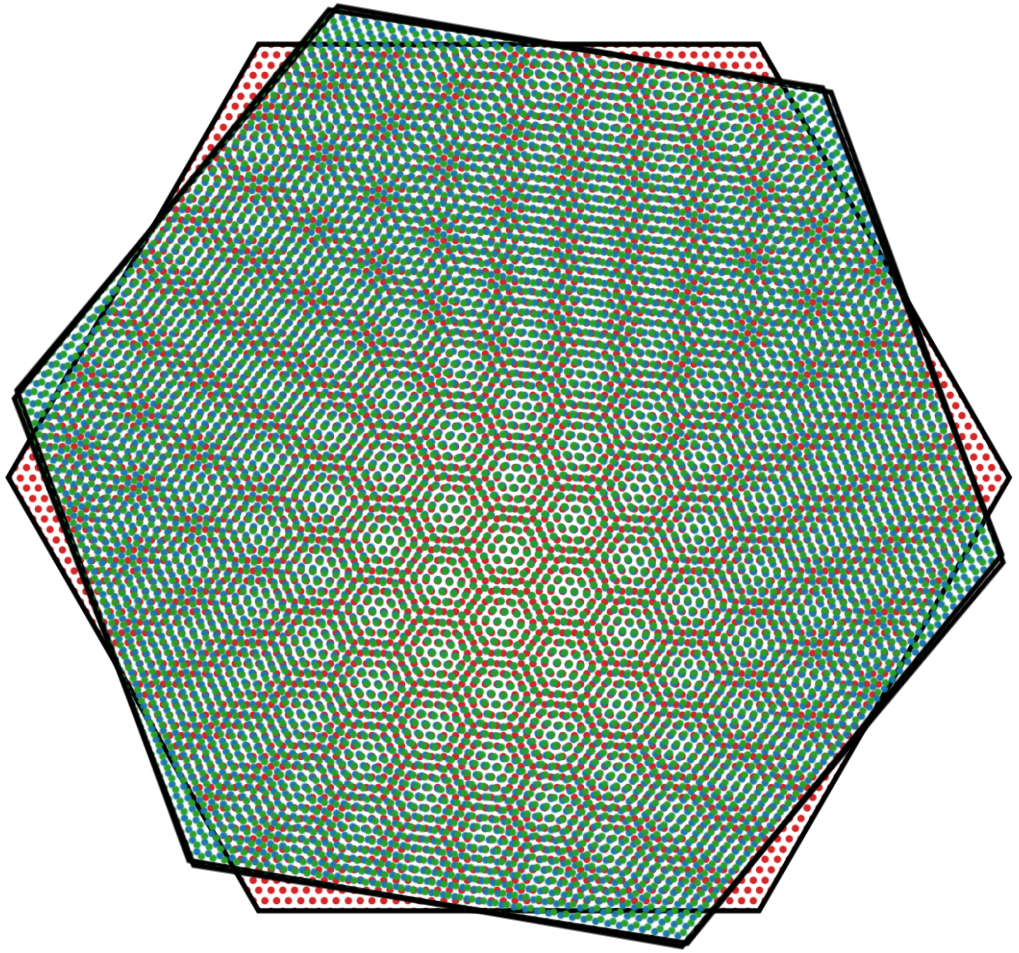
3. Comparing **different devices** is challenging. How will we systematically explore this space?





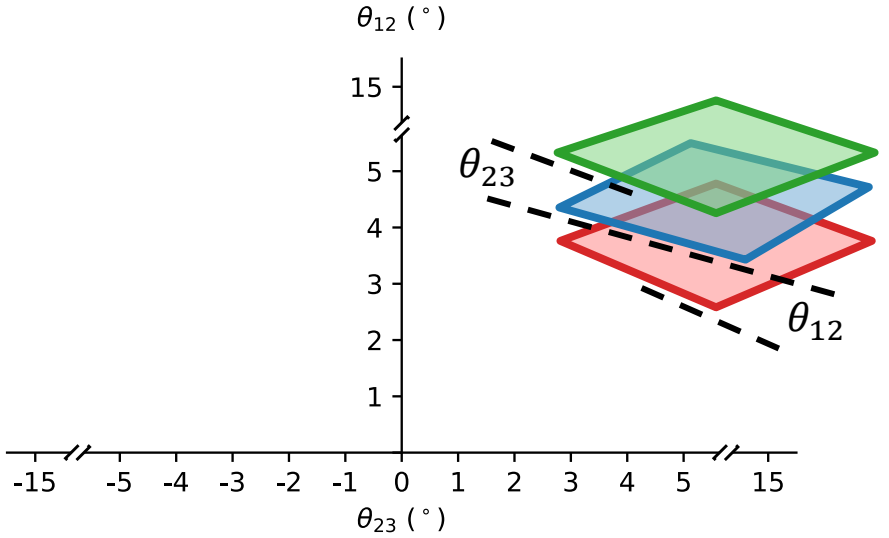


Outline

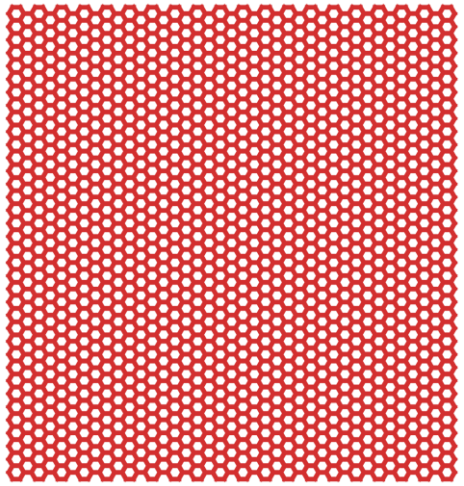
Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation teaser

Linking thermodynamic probes and transport:
- Fine-grained evolution of correlations
- Cross comparison of distinct experimental probes

Exploring the "magic continuum":
- Broad comparison across many devices in angle-angle space



Bandstructure engineering with moirés



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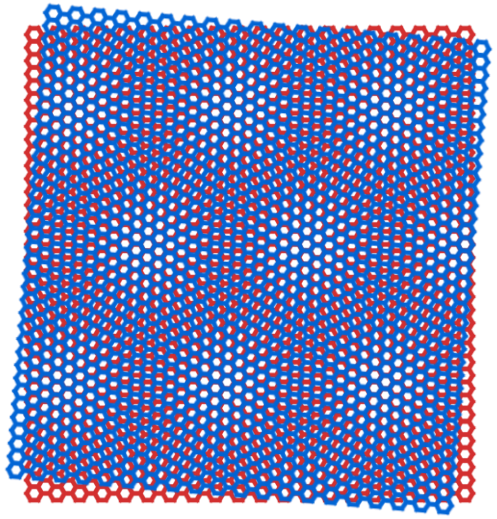

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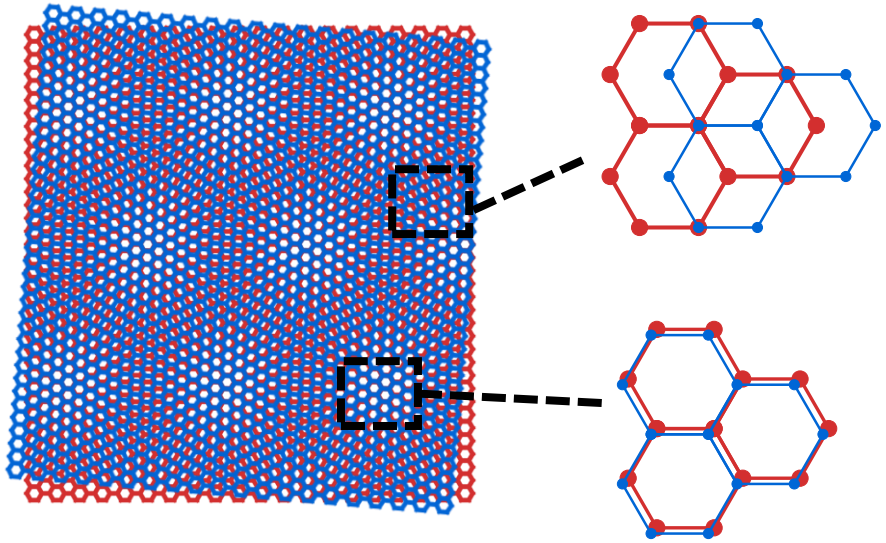

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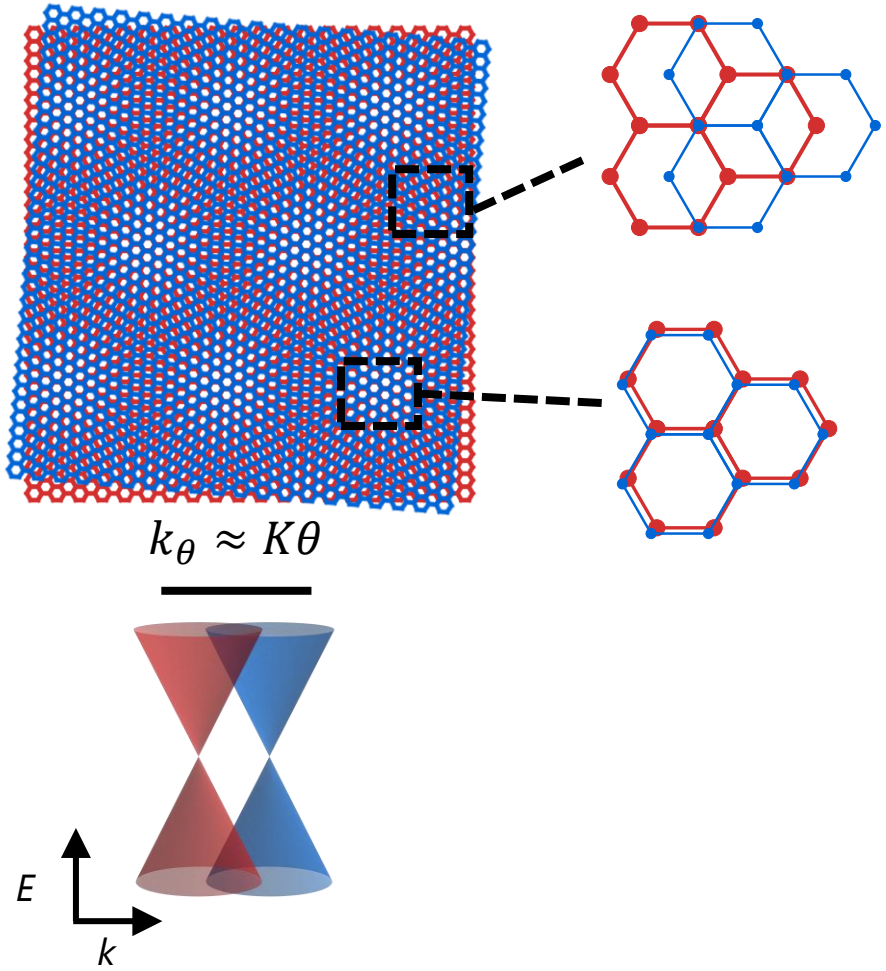

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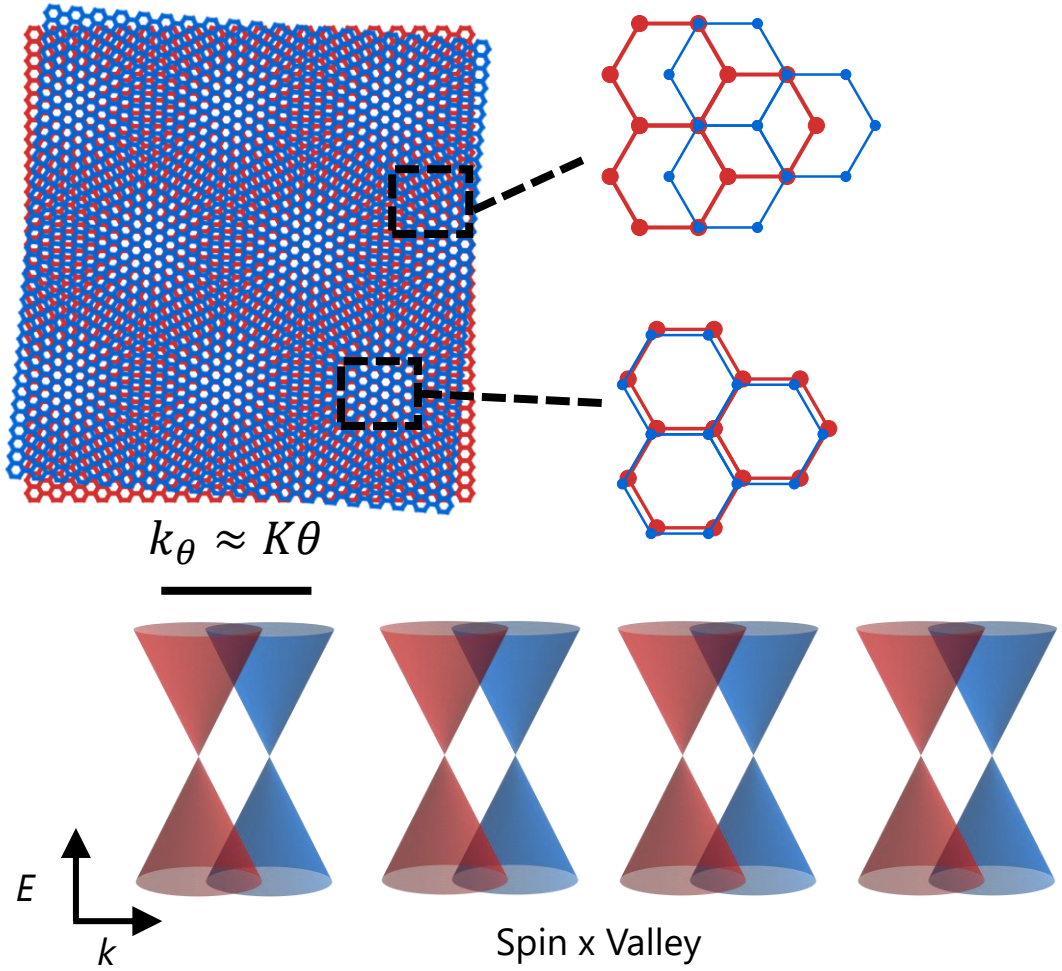

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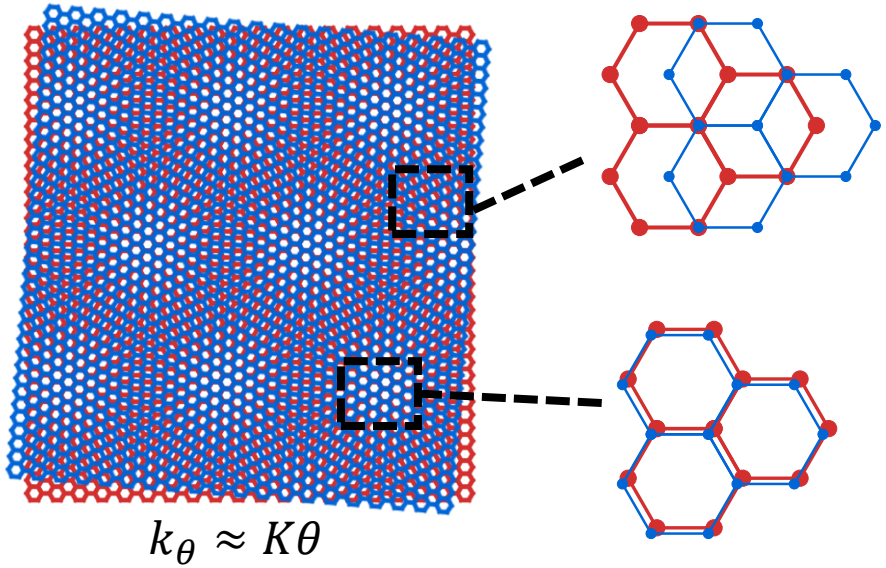
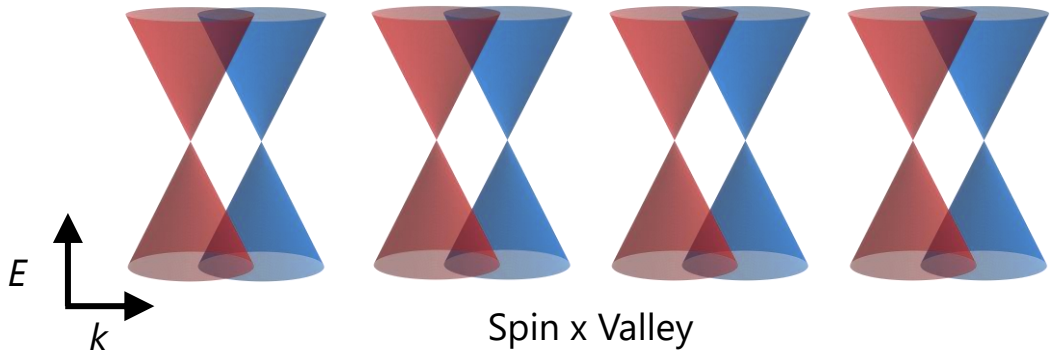
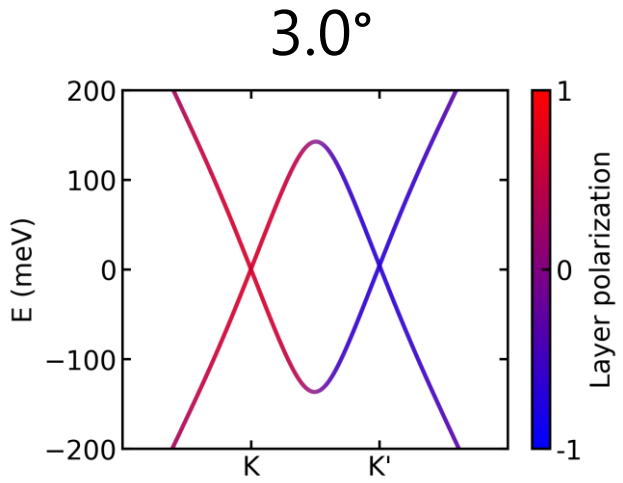


$k_\theta \approx K\theta$



Spin x Valley



~Electronically decoupled from momentum mismatch

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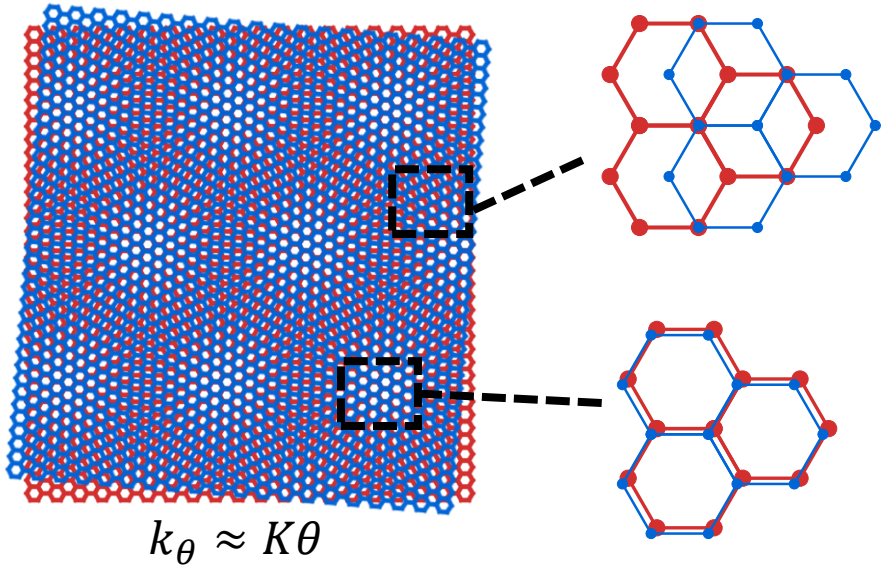

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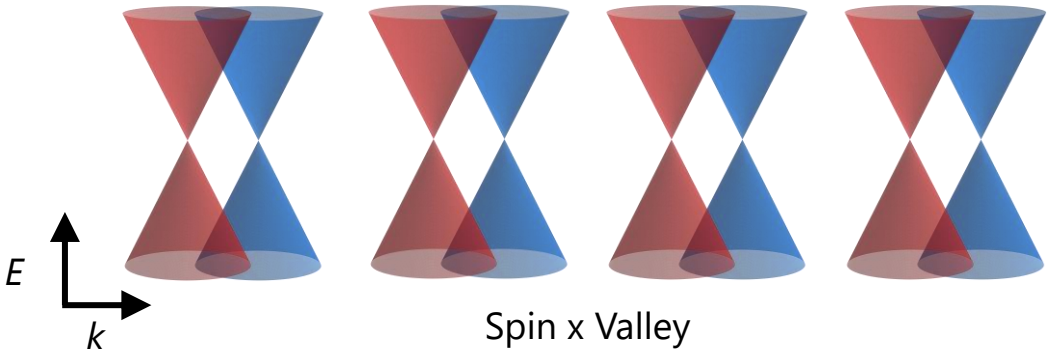
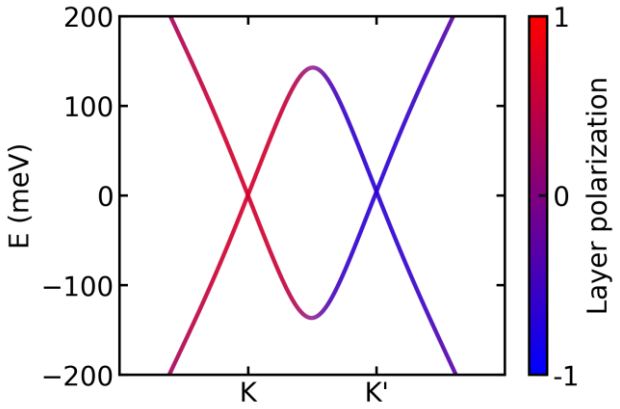


Spin x Valley

3.0°

Decrease twist angle



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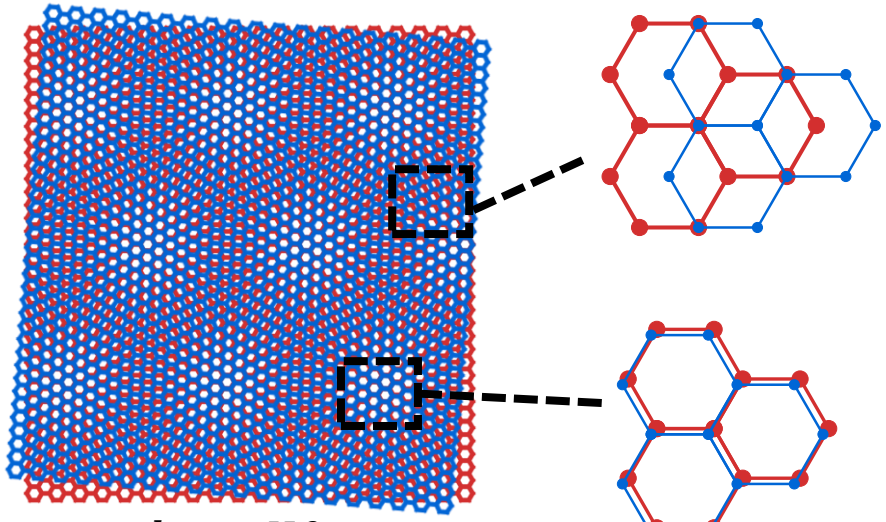

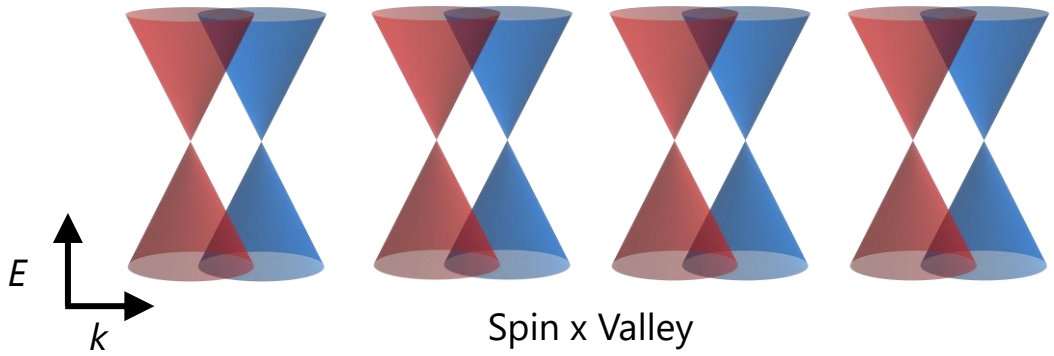

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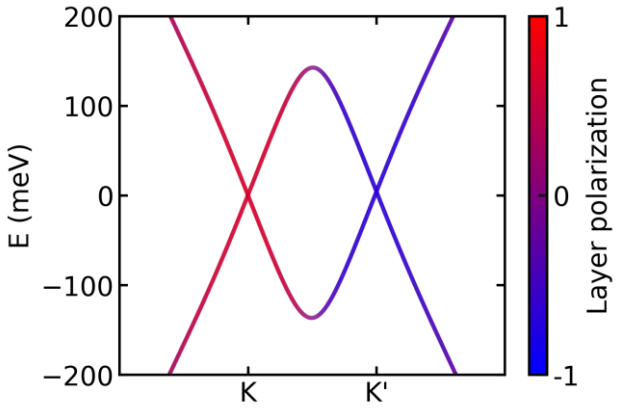
3.0° → Decrease twist angle → 1.1°



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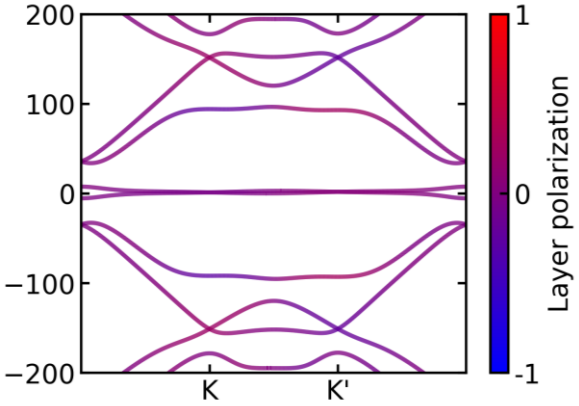

Strong coupling between layers

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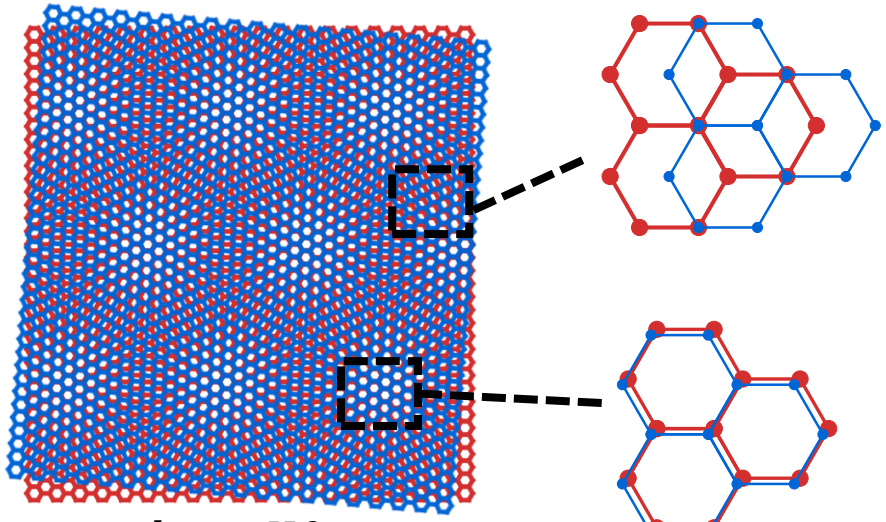

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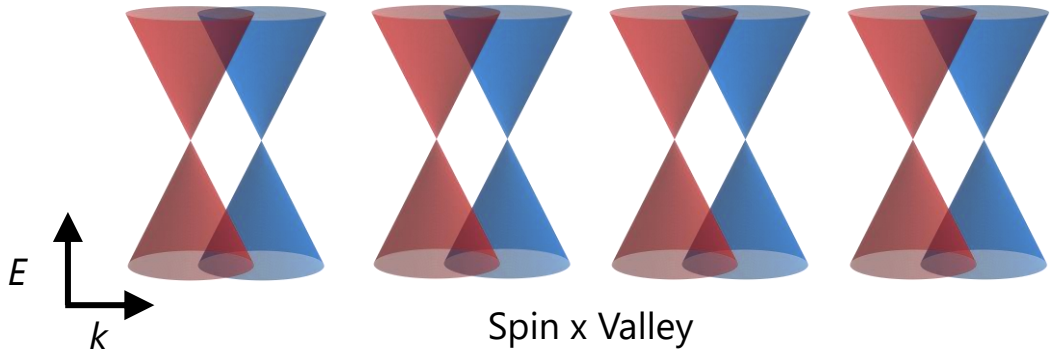

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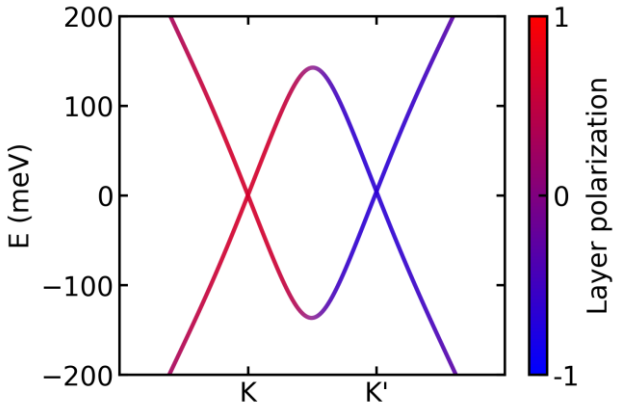

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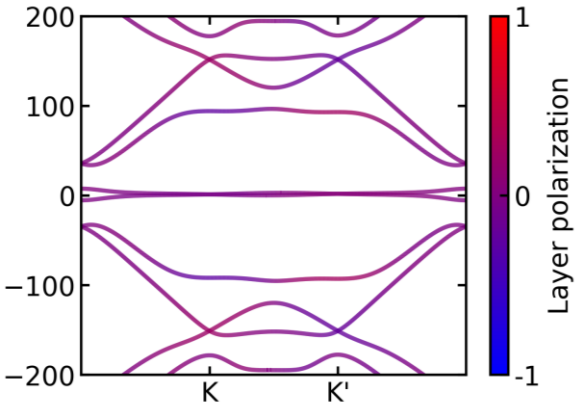

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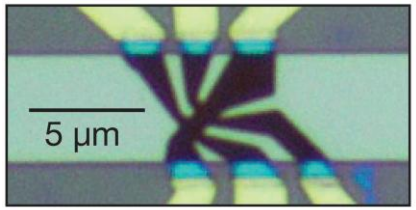
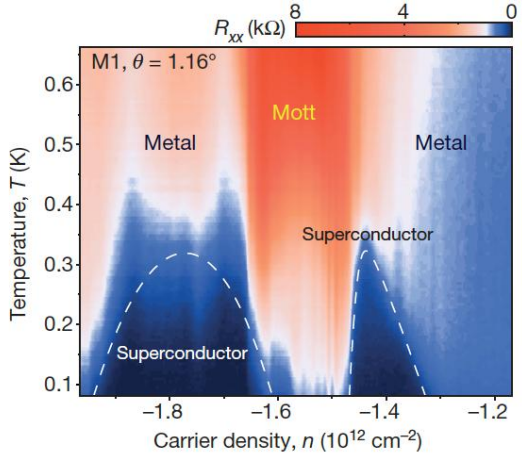
Experimental realization





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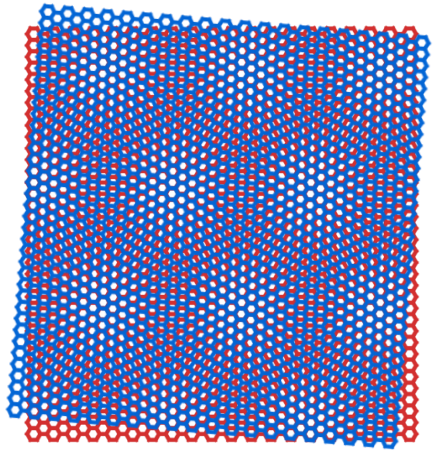
Where to begin? “Magic Angle Twisted Trilayer”



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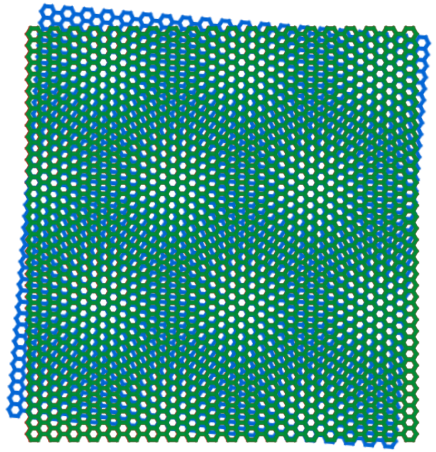

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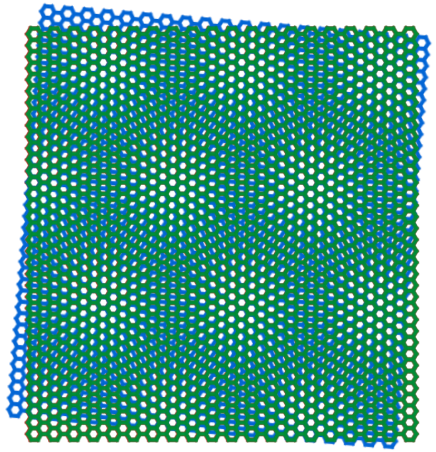

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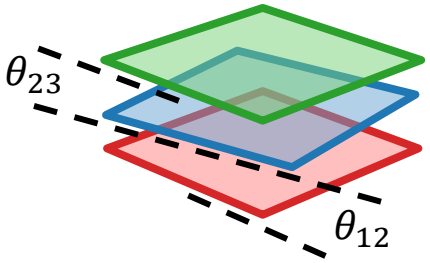

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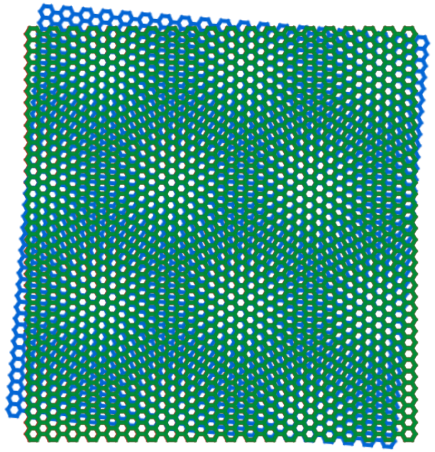

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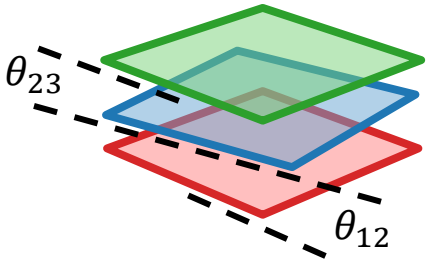

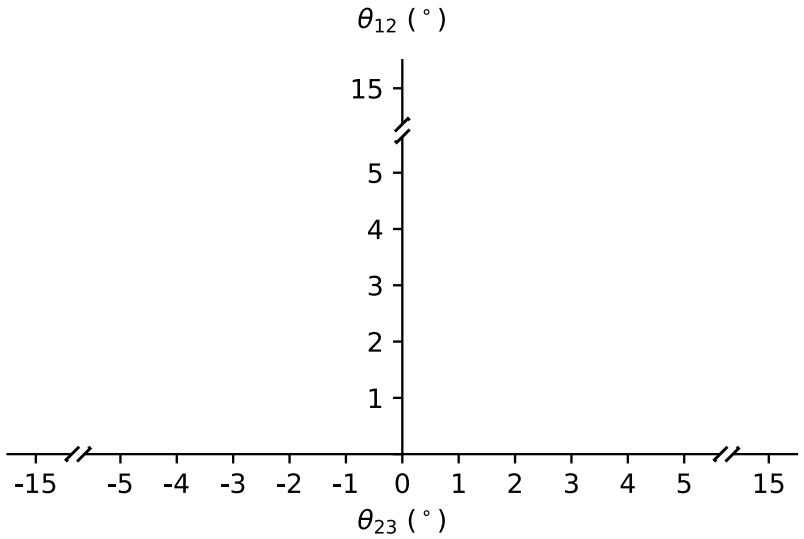

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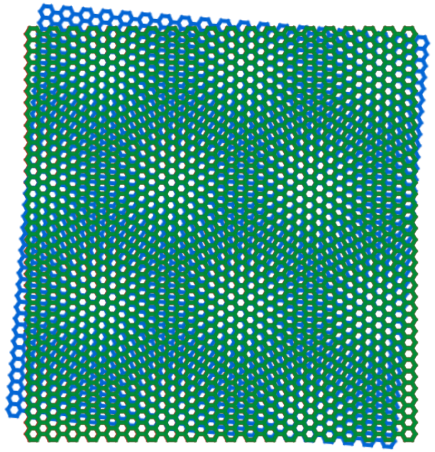

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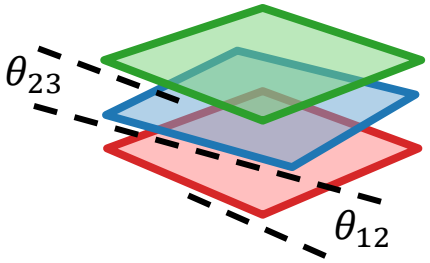

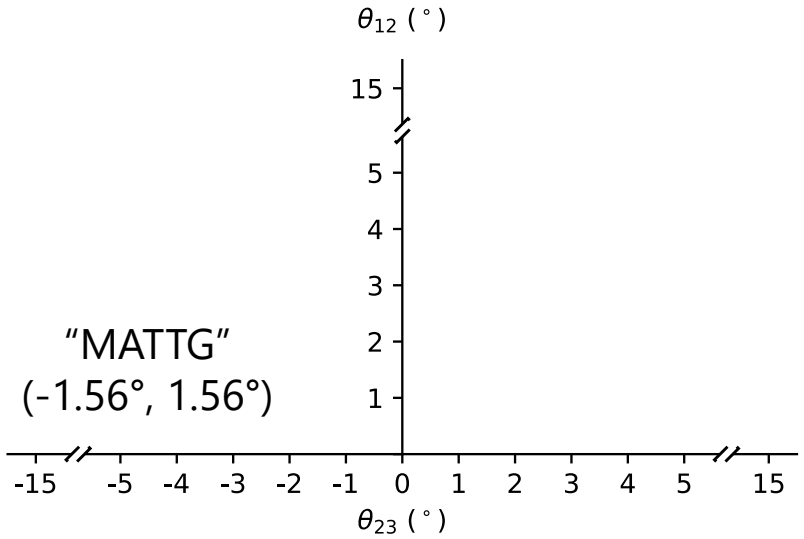

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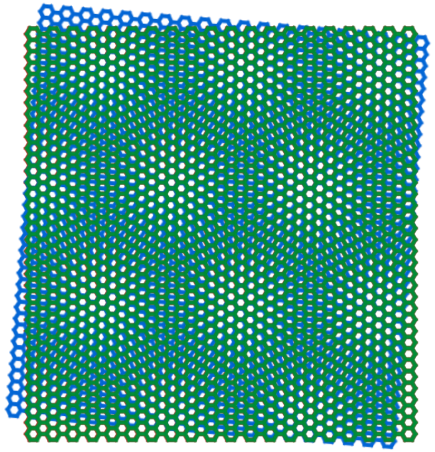
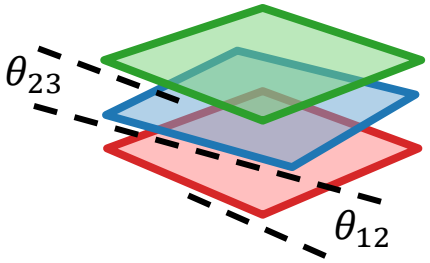
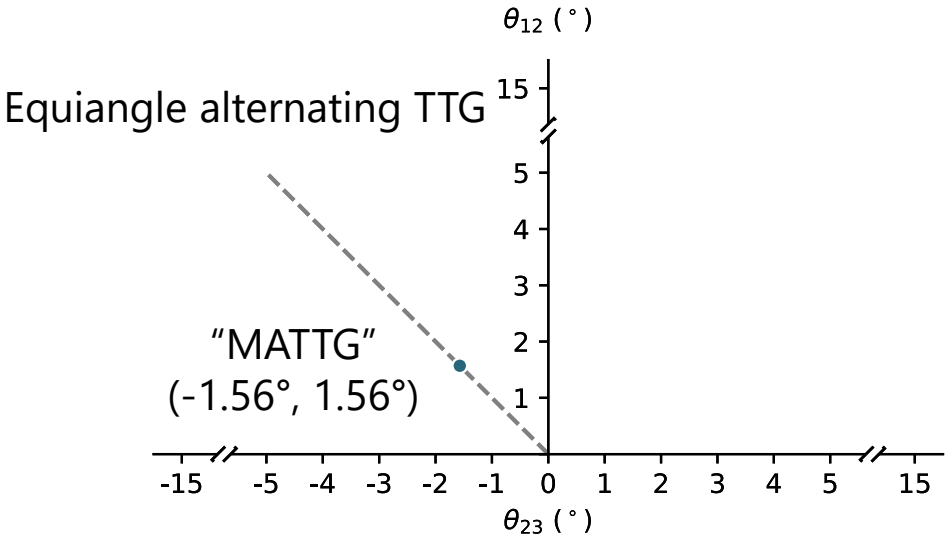
Where to begin? “Magic Angle Twisted Trilayer”



Morally equivalent*
to MATBG





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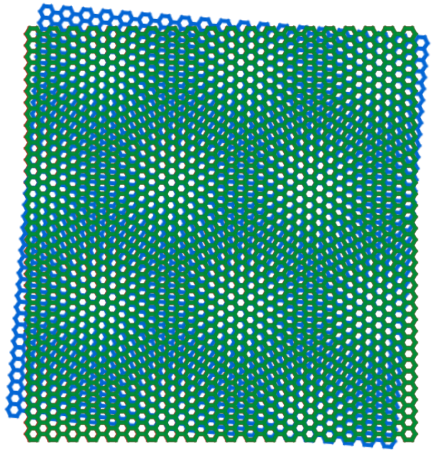

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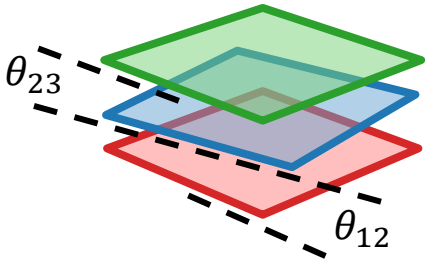
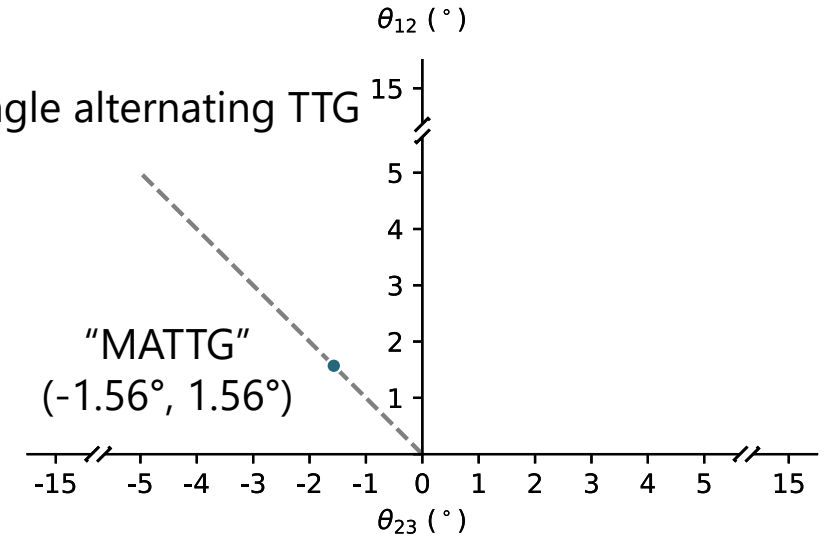
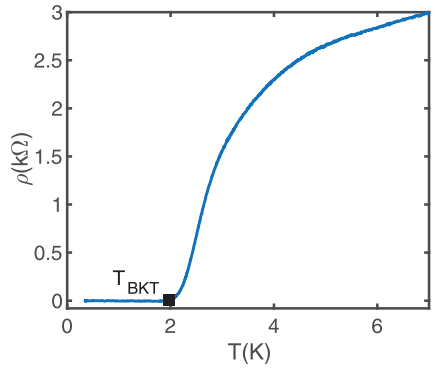
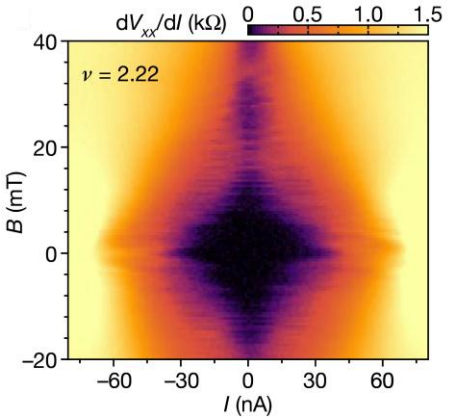


Equiangle alternating TTG



Superconductivity!





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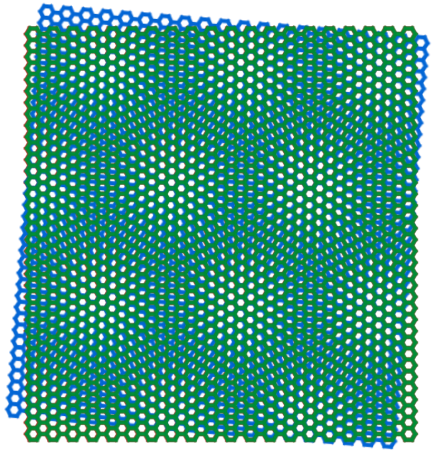

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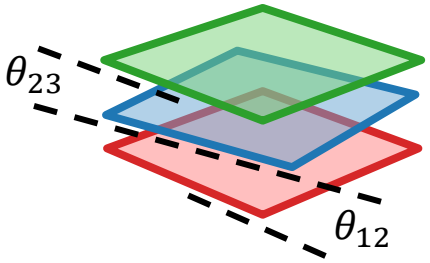

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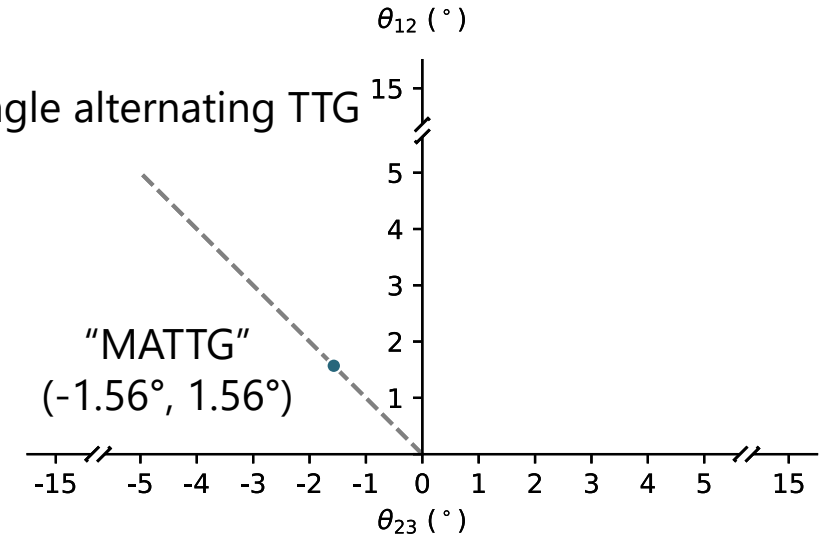

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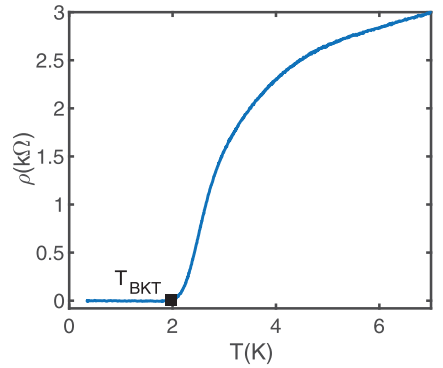

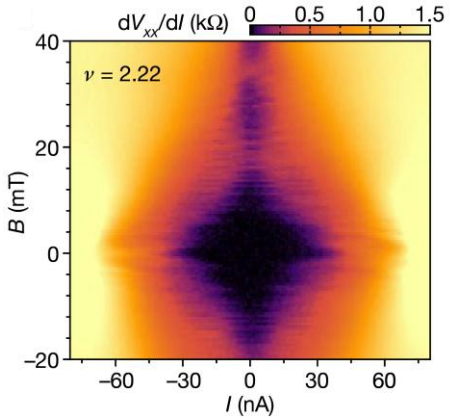

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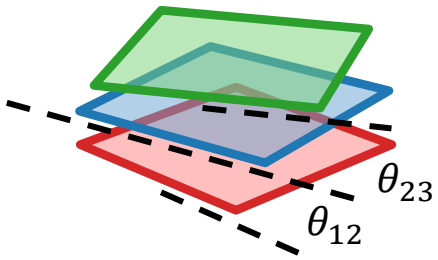
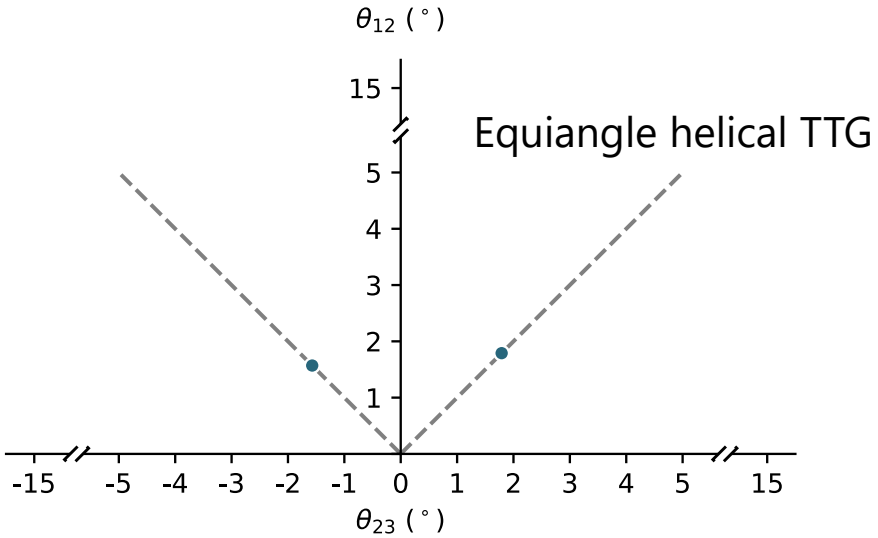
For equiangle alternating TTG
moirés patterns are *exactly* commensurate

Equiangle Helical Trilayer





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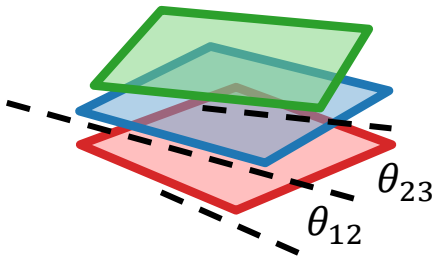

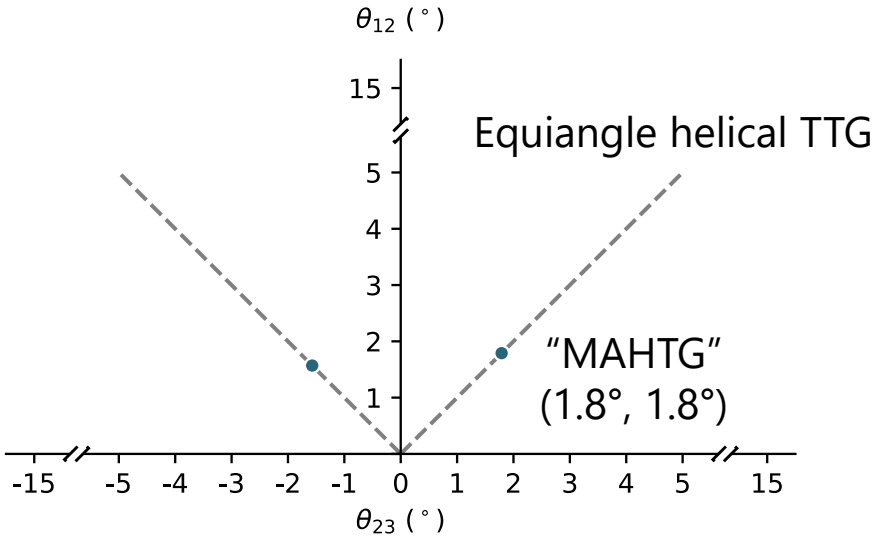

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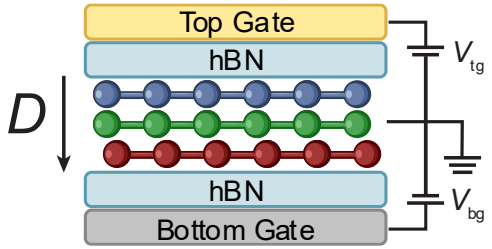

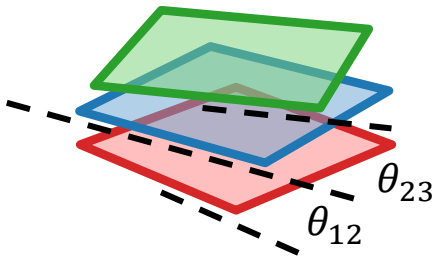

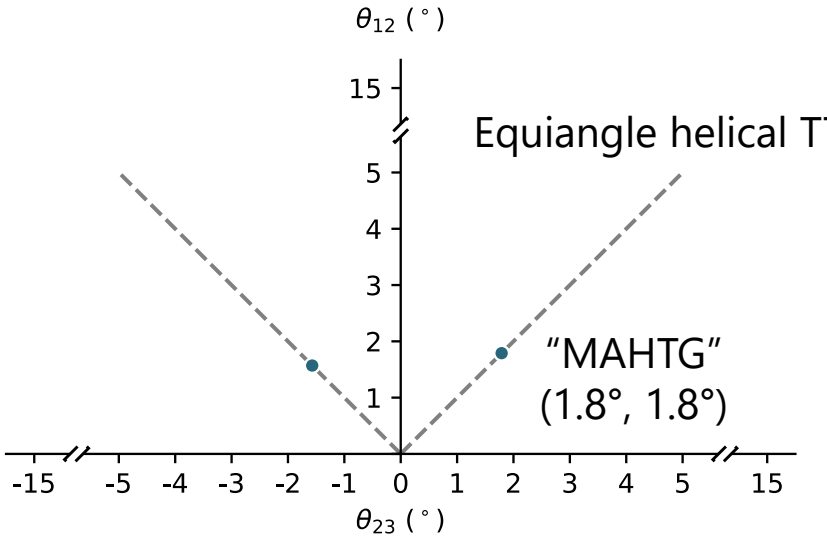

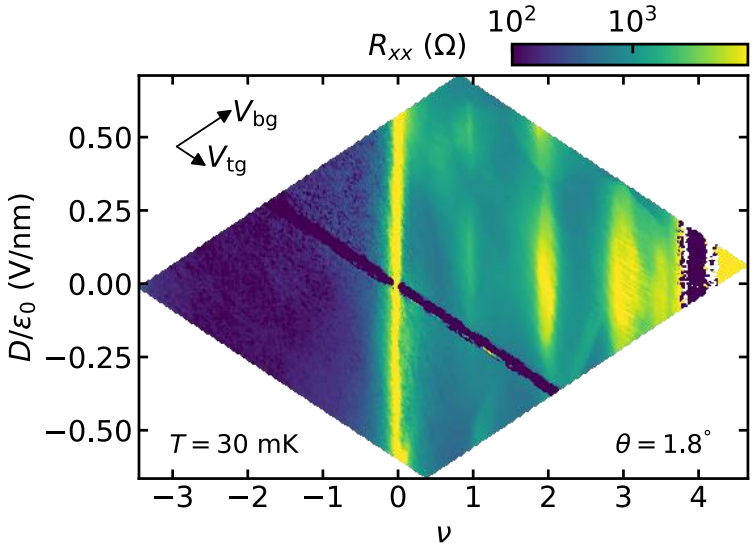

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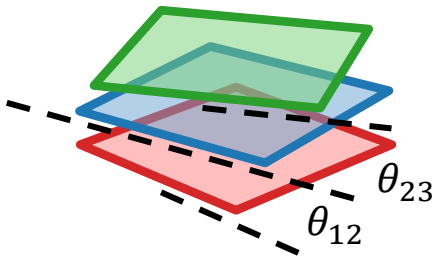

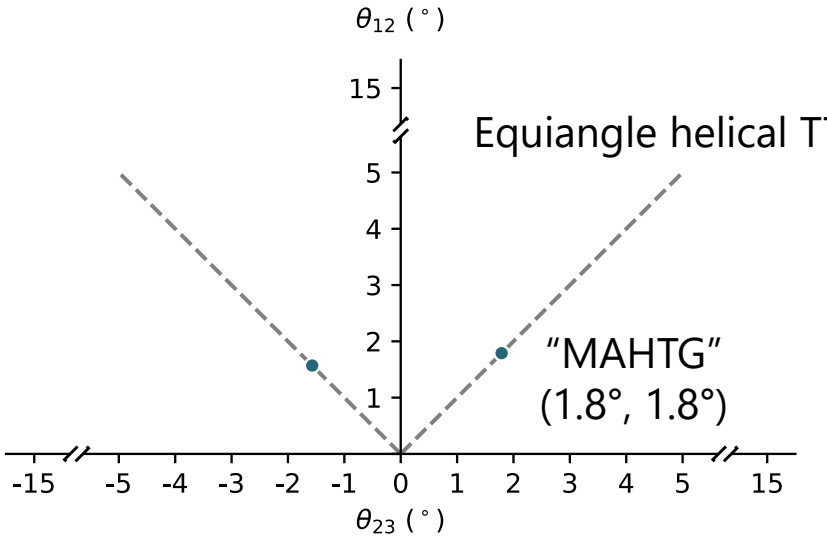

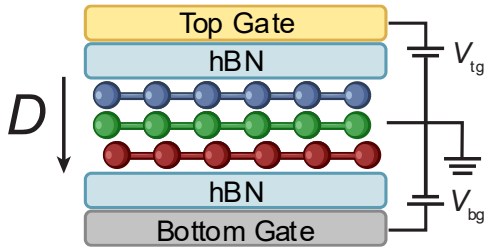

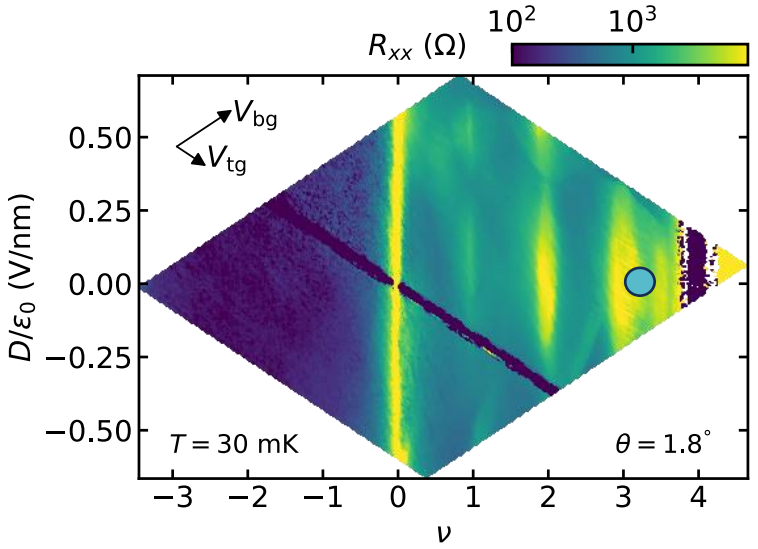

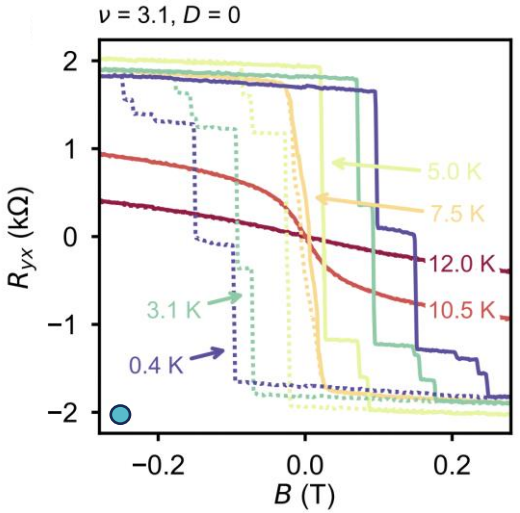

No signs of superconductivity so far.
Unquantized anomalous Hall. Domain physics?
What is driving this change in the resulting physics?

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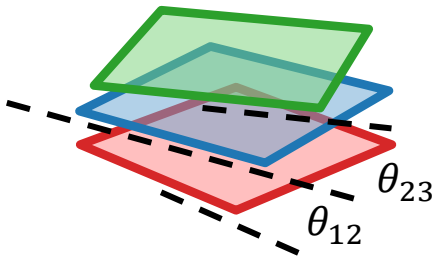

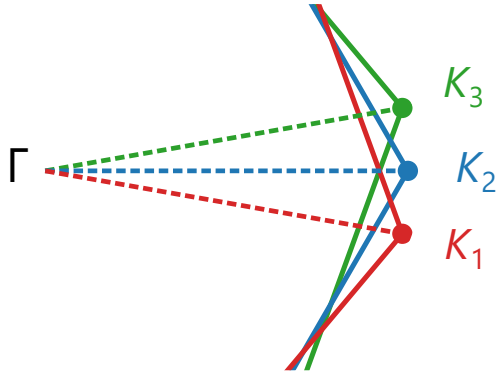

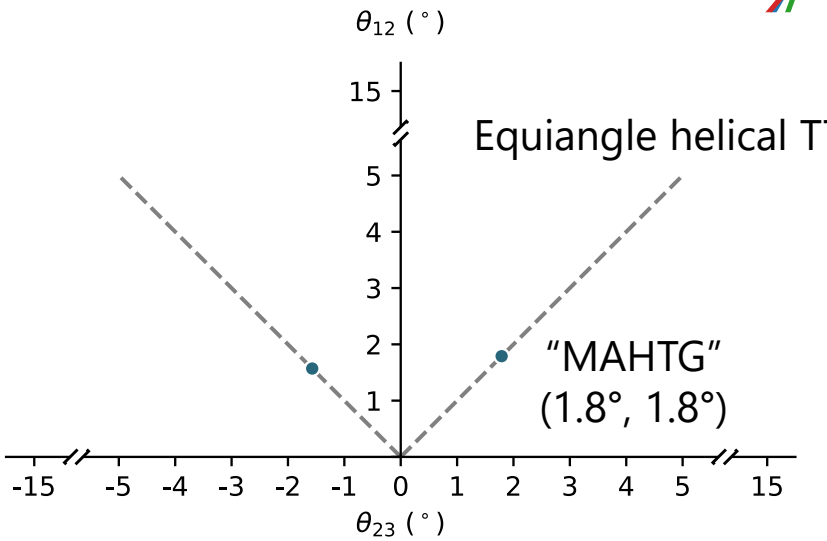

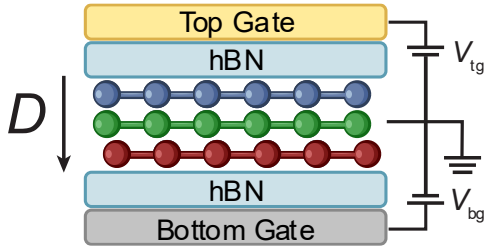

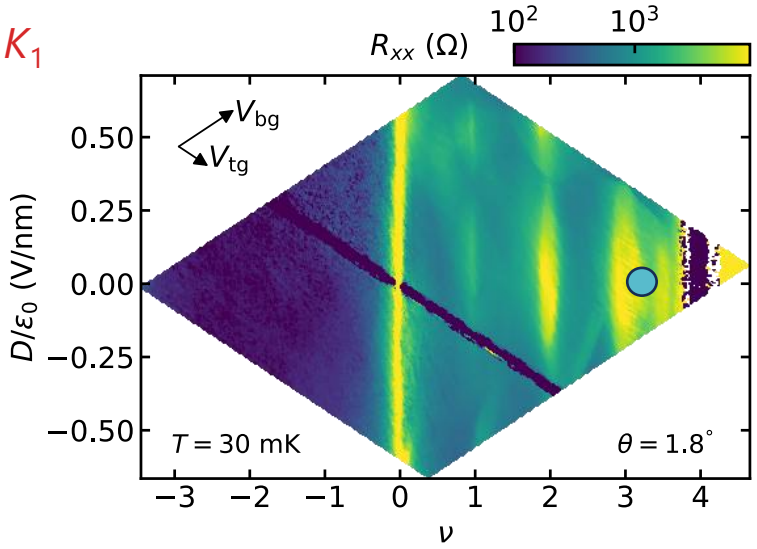

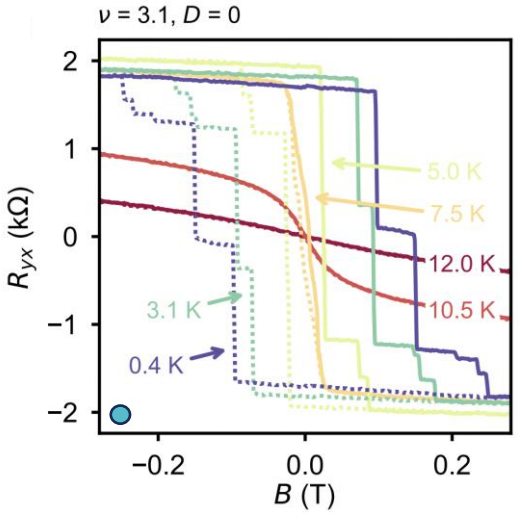

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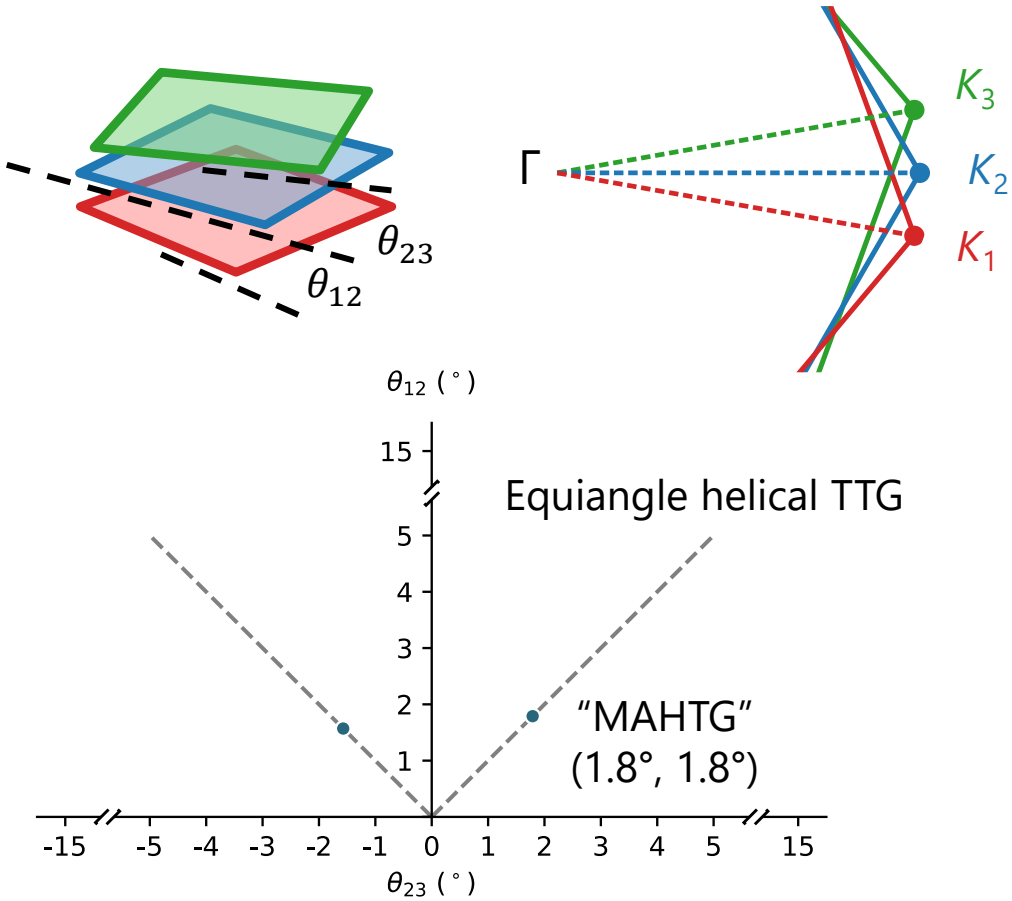

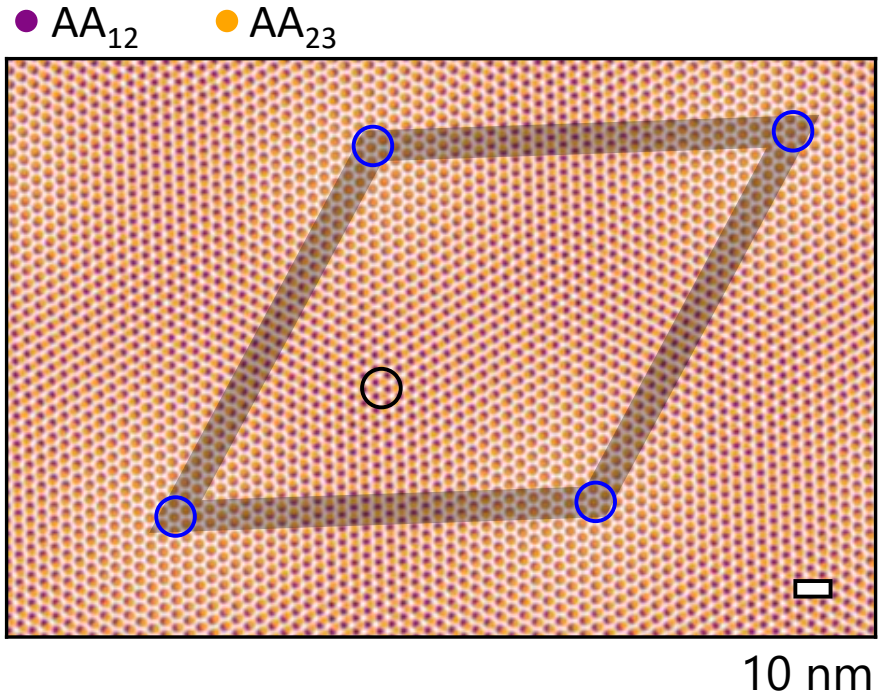

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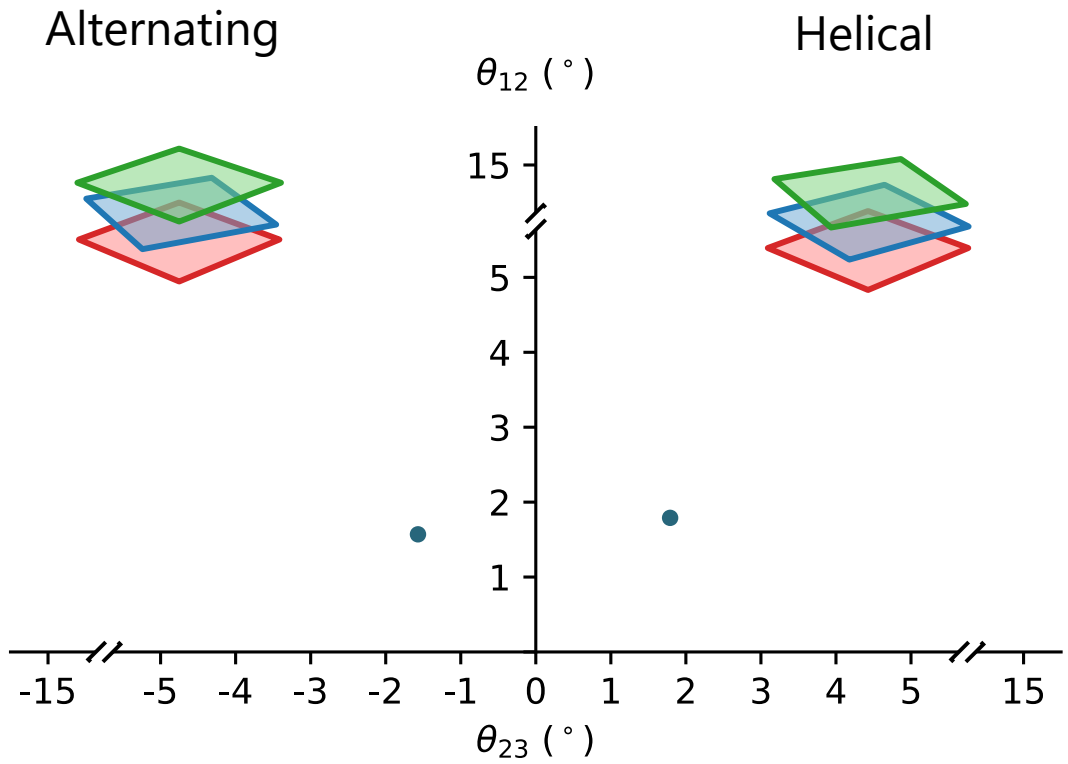
Expectations for the angle-angle phase diagram



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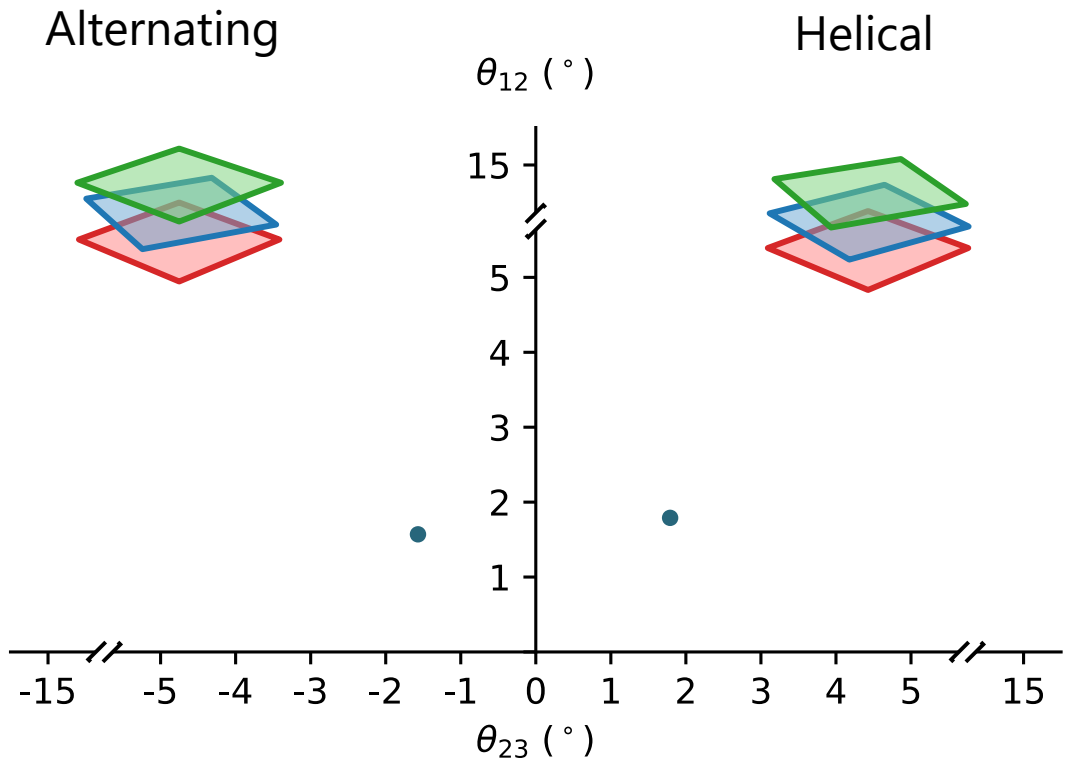

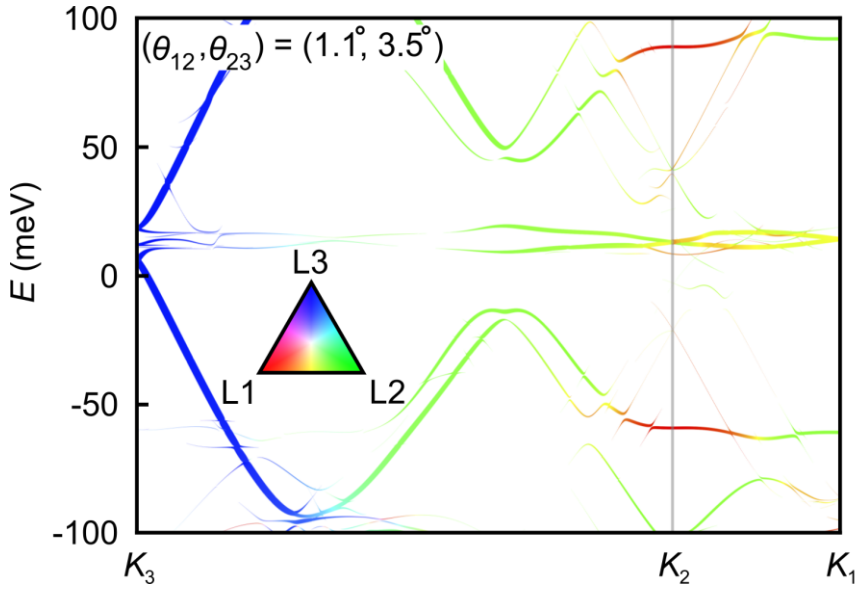

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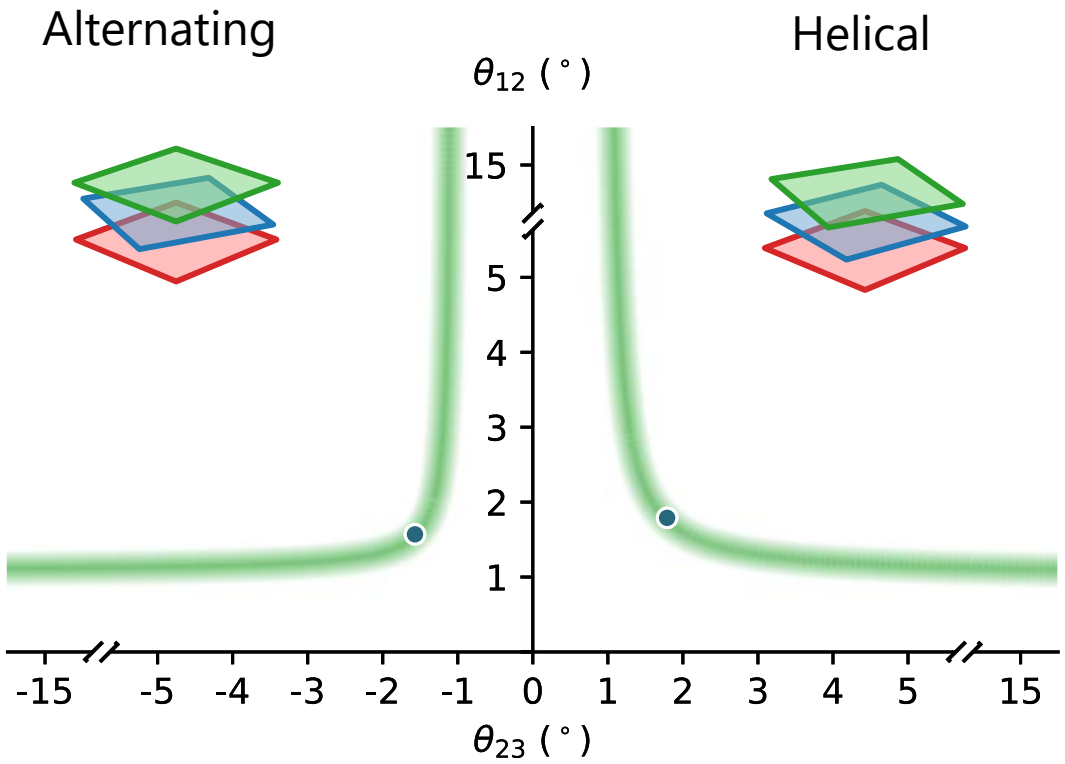

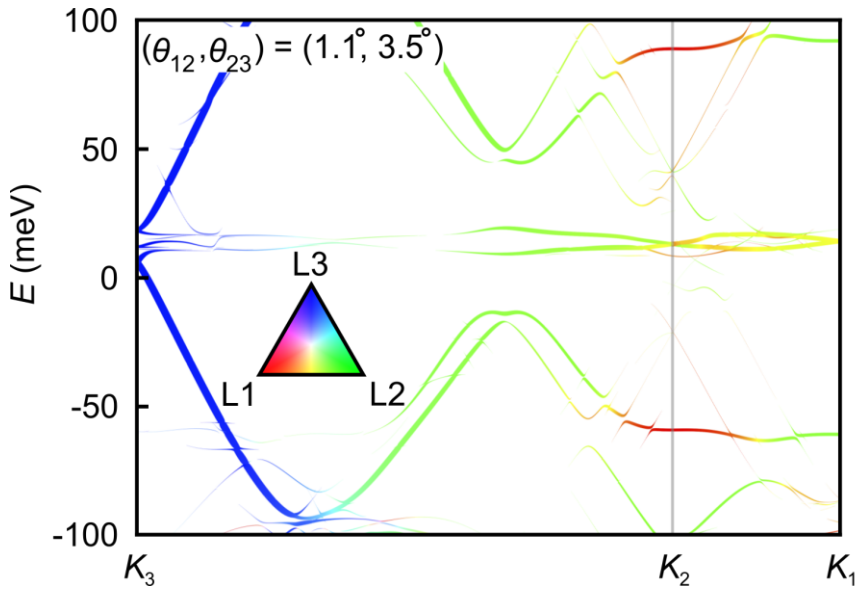

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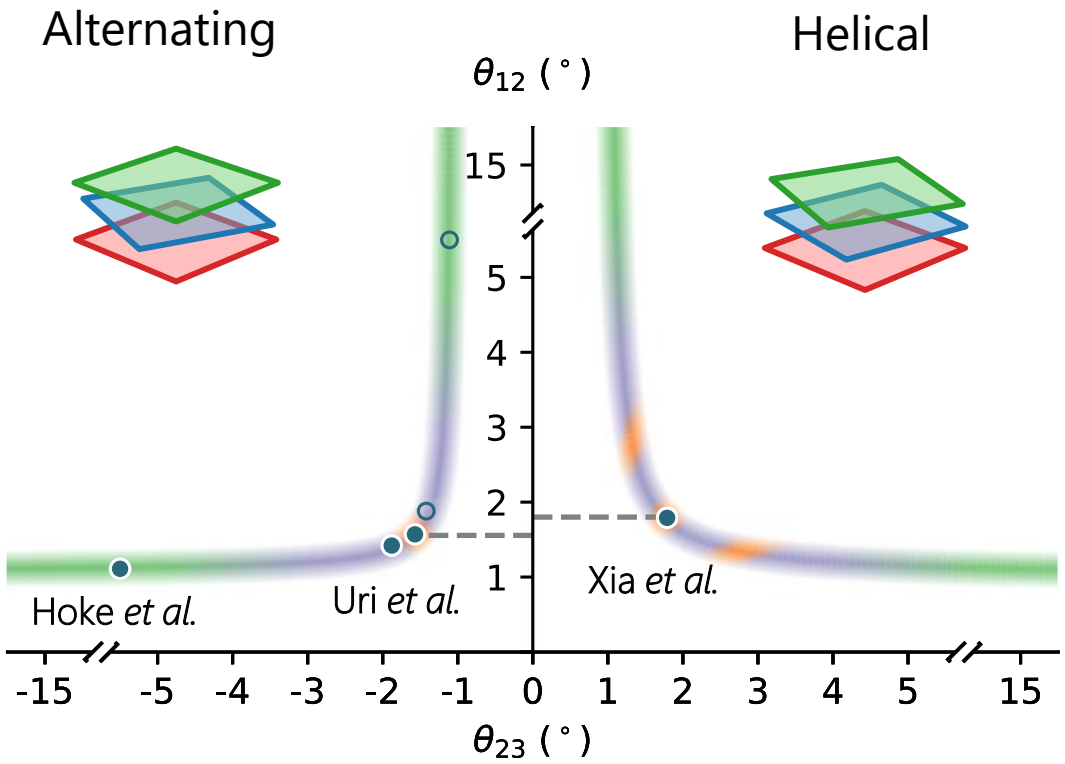
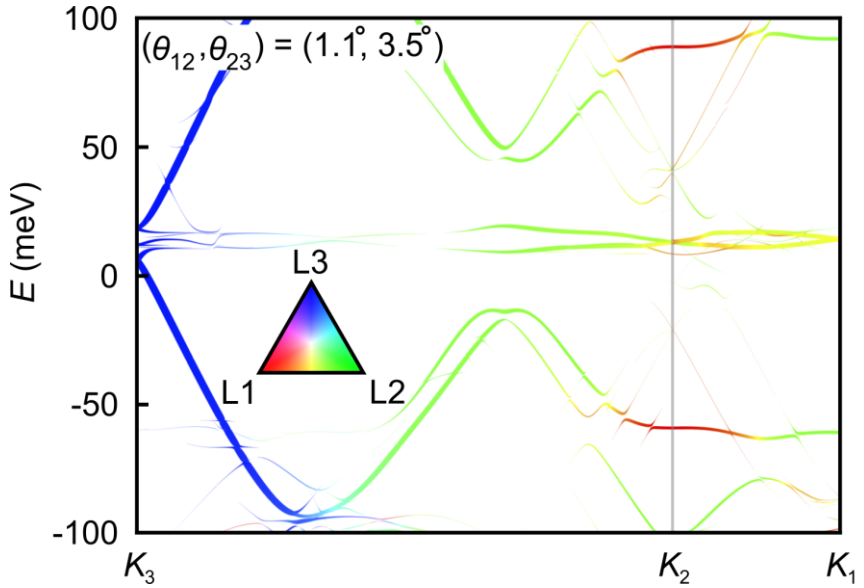


Weakly Reconstructed

Strongly Reconstructed

MATBG + decoupled monolayer



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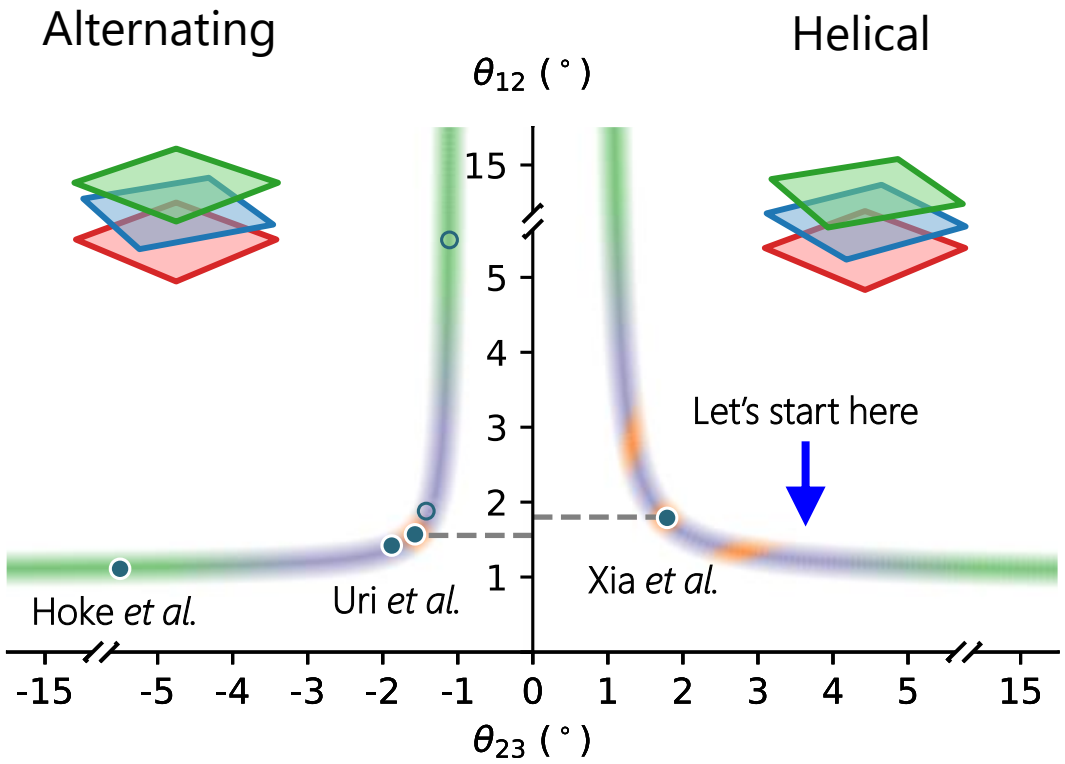

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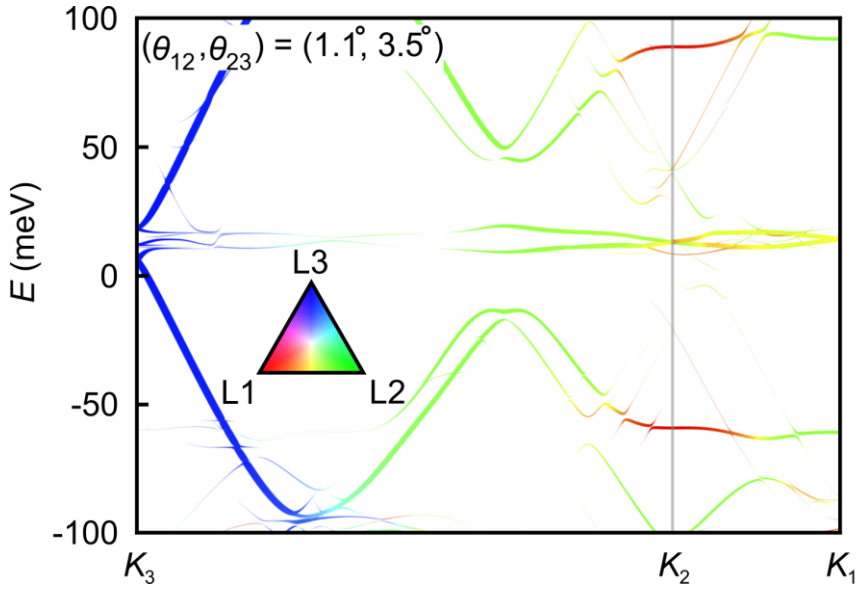

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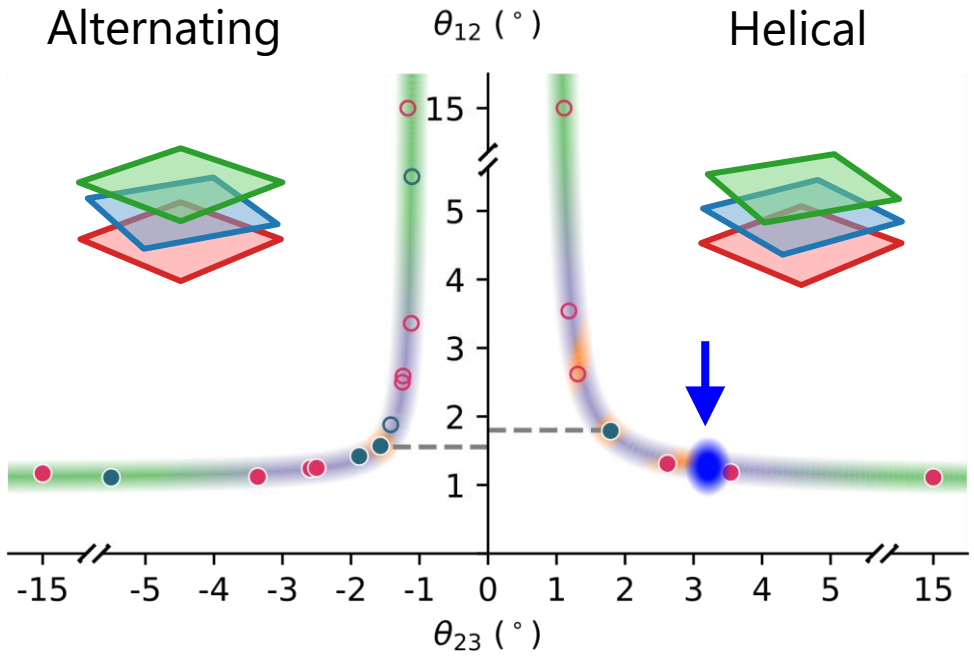
Outline

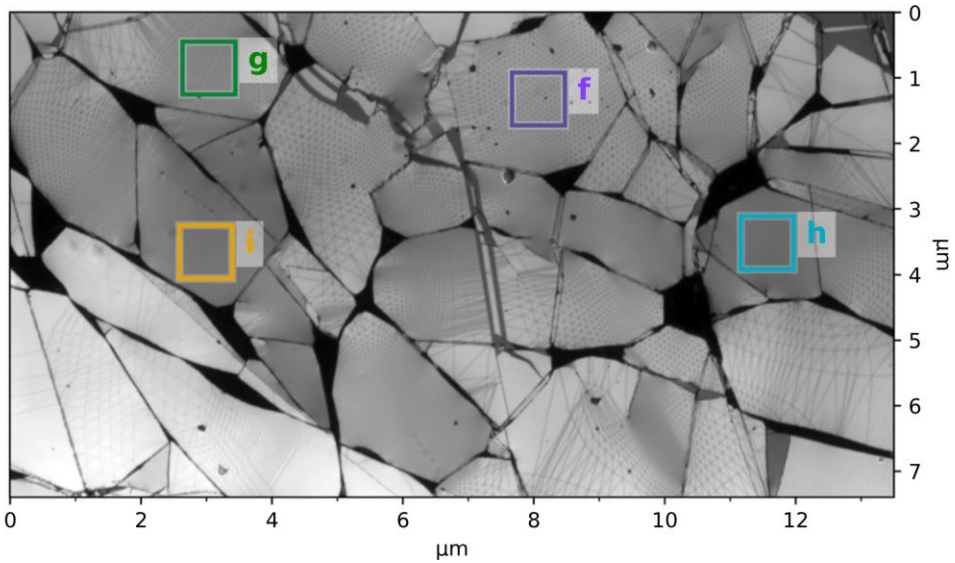
Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation

Linking thermodynamic probes and transport:
- Fine-grained evolution of correlations
- Cross comparison of distinct experimental probes

Exploring the "magic continuum":
- Broad comparison across many devices in angle-angle space



These samples vary wildly



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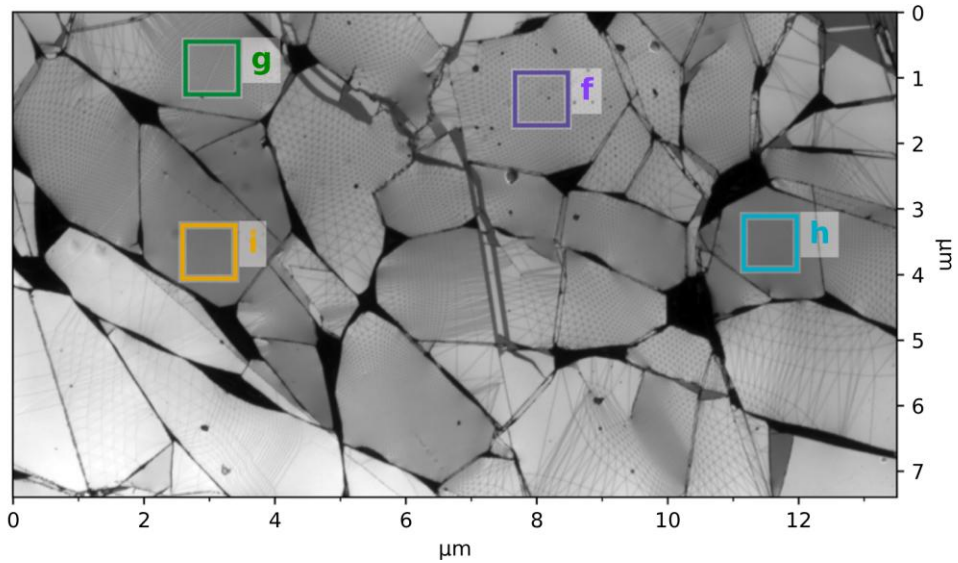

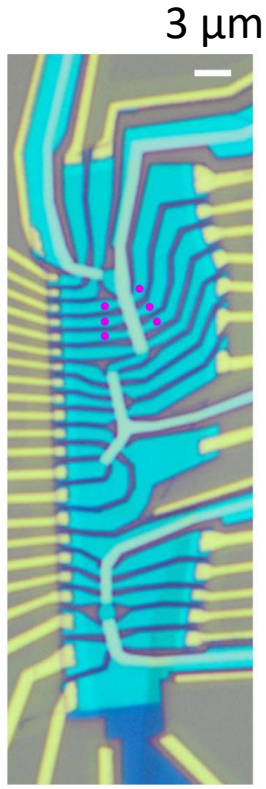

Usual approach: probe as much of the heterostructure as possible

Can we take a better approach?

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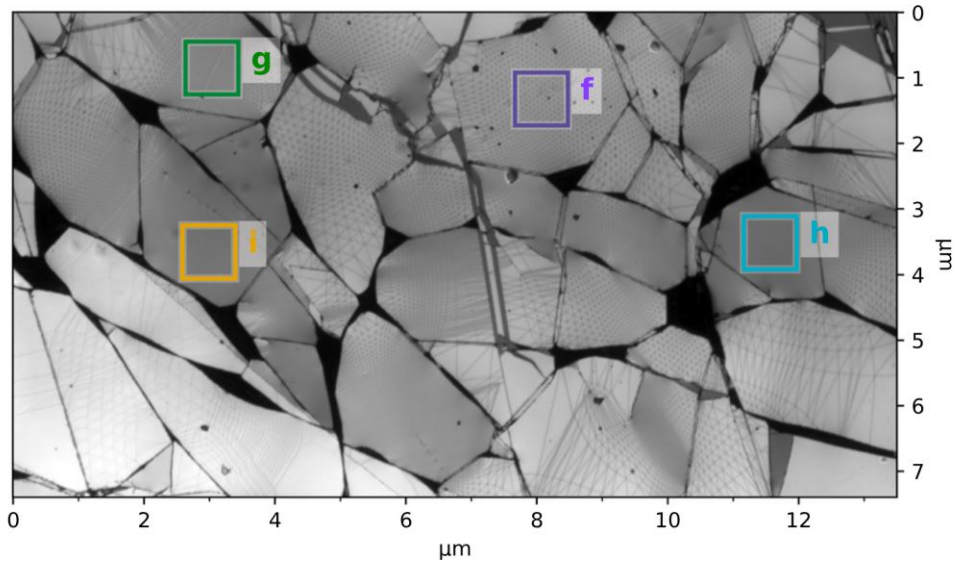

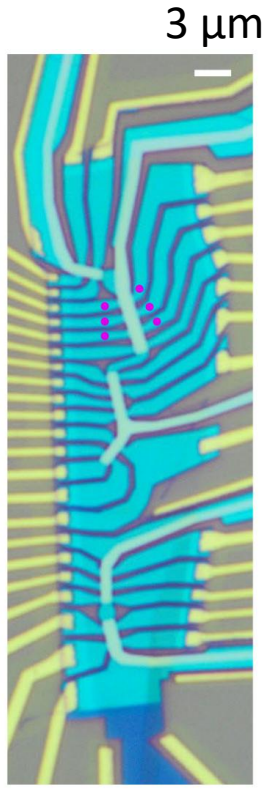

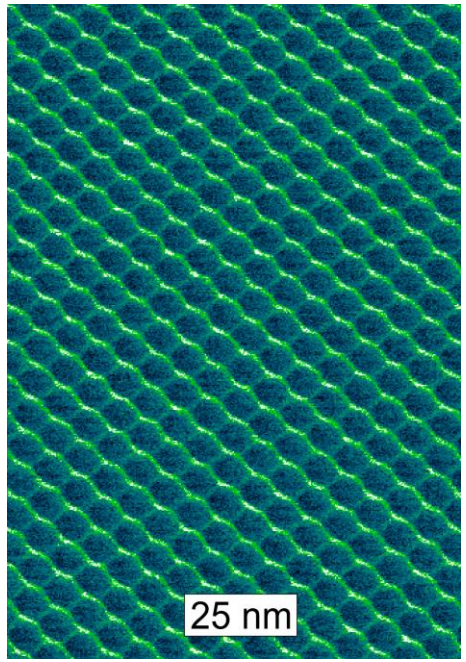

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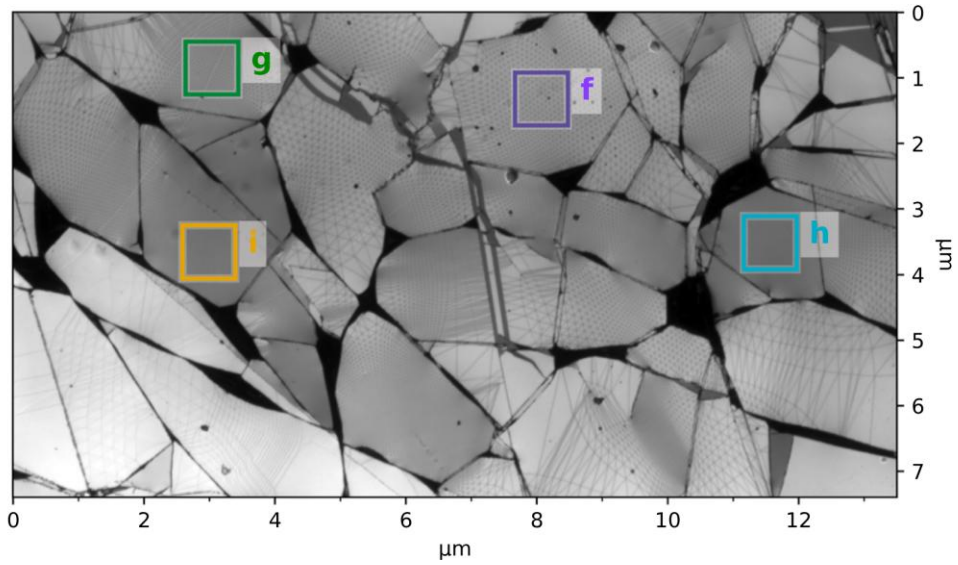
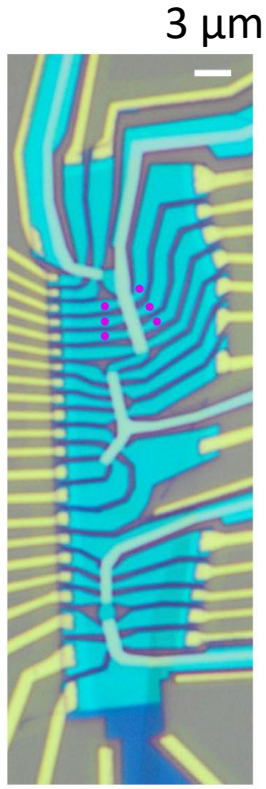
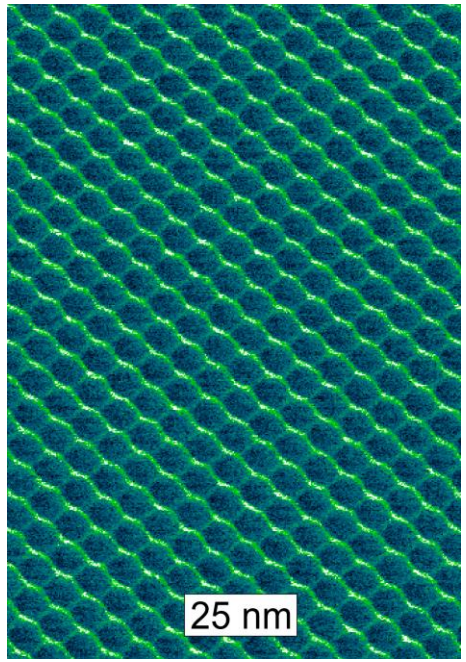
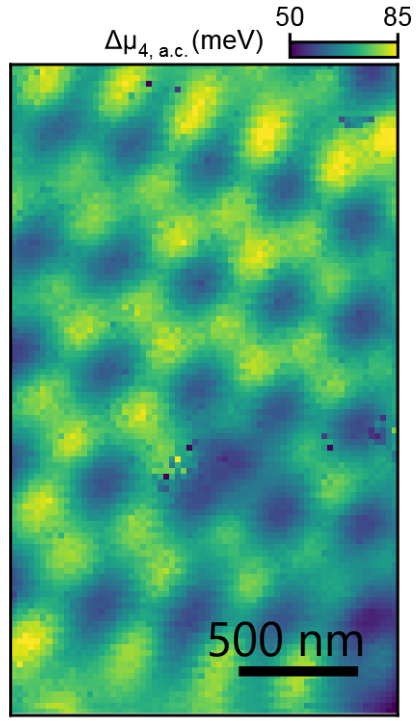




TFM



SET

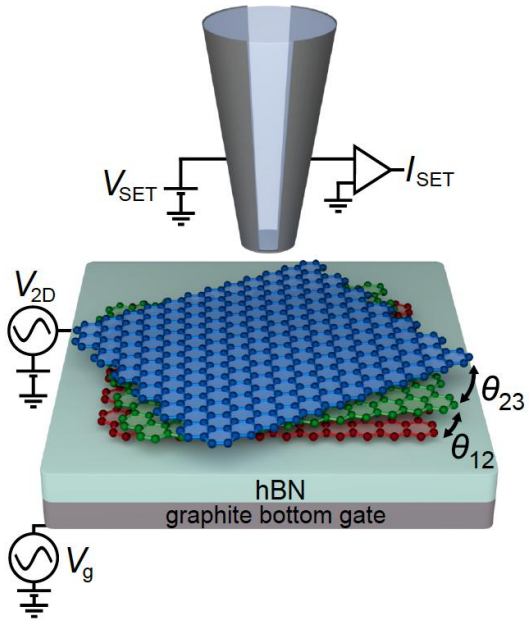


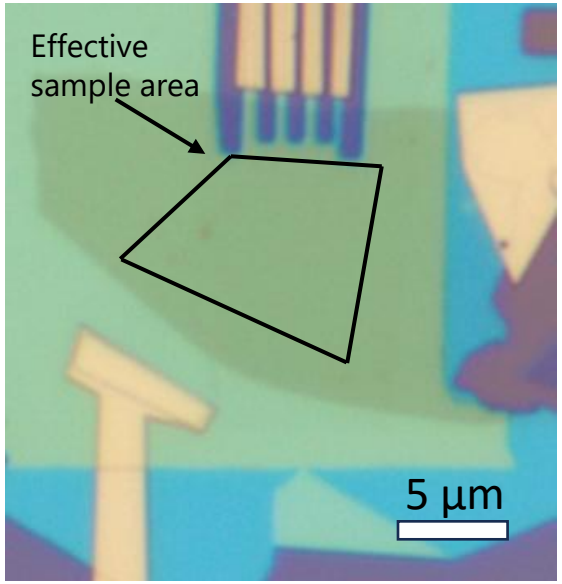
Usual approach: probe as much of the heterostructure as possible

Can we take a better approach?

de Jong, et al. Nat. Comms. (2022)
Pendarkar, …, Sharpe, et al. PNAS (2024)
Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583
Hoke, et al. Nat. Mat. (2026)

Scanning single-electron transistor





Sample held at fixed electrochemical potential
$eV = \mu + e\phi$

Spatial resolution: ~100 nm
Sensitivity: ~10 µV/√Hz
$T_{\text{base}} = 330$ mK

Hoke,..., Sharpe, Feldman arXiv:2509.07977

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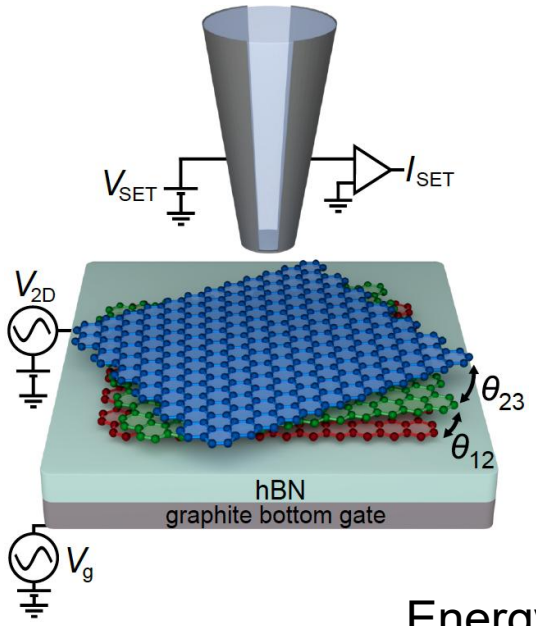

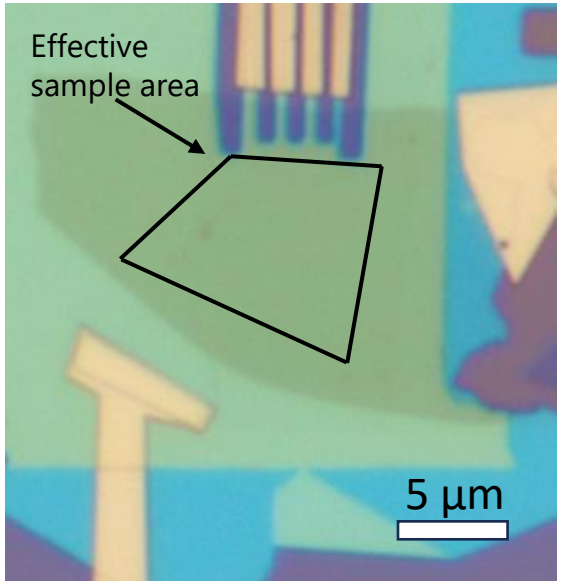

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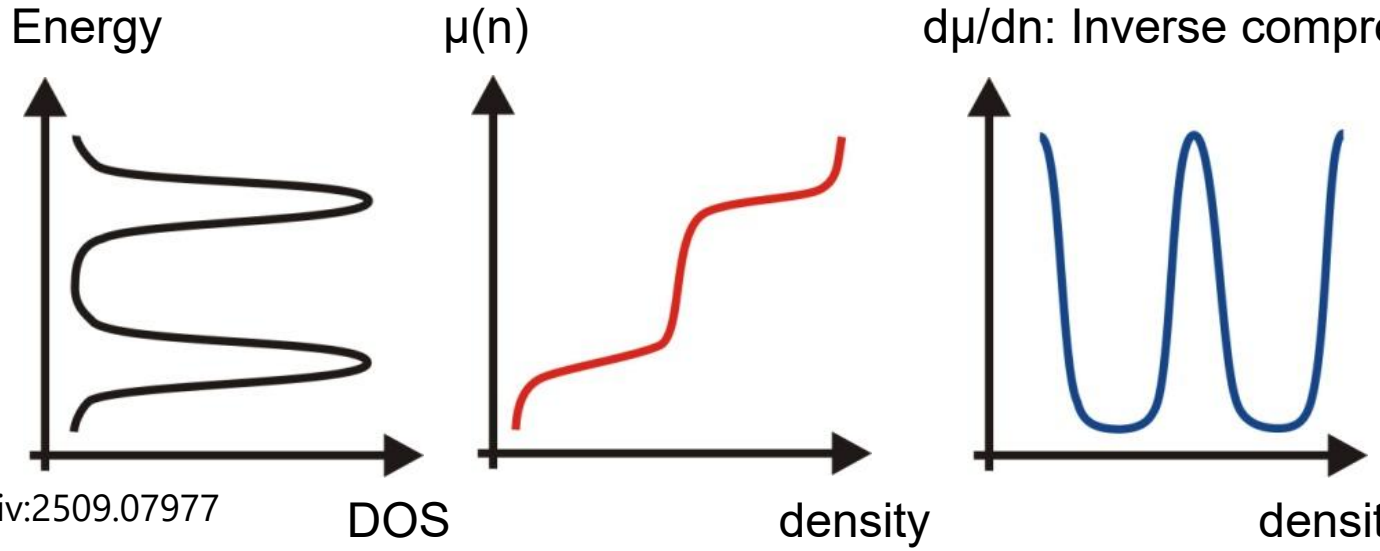
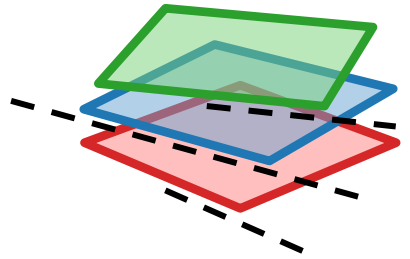
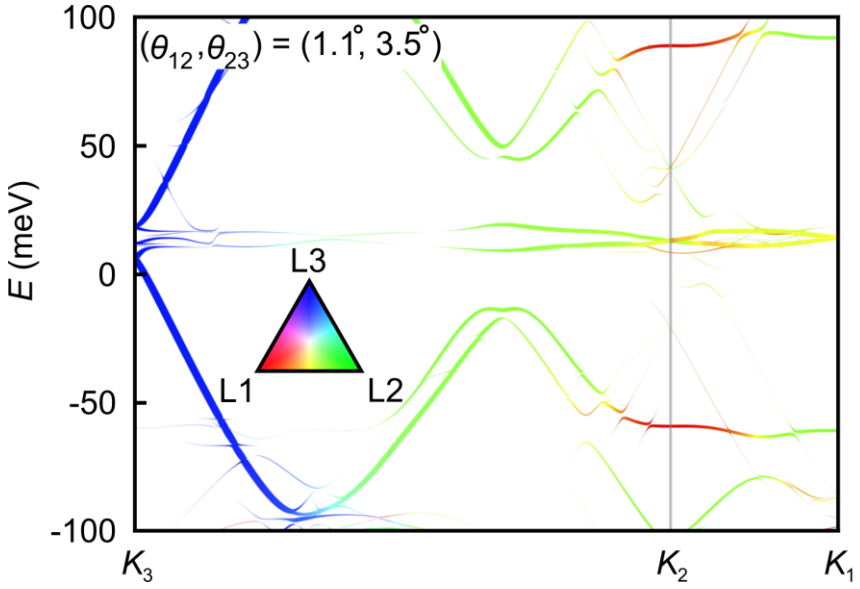


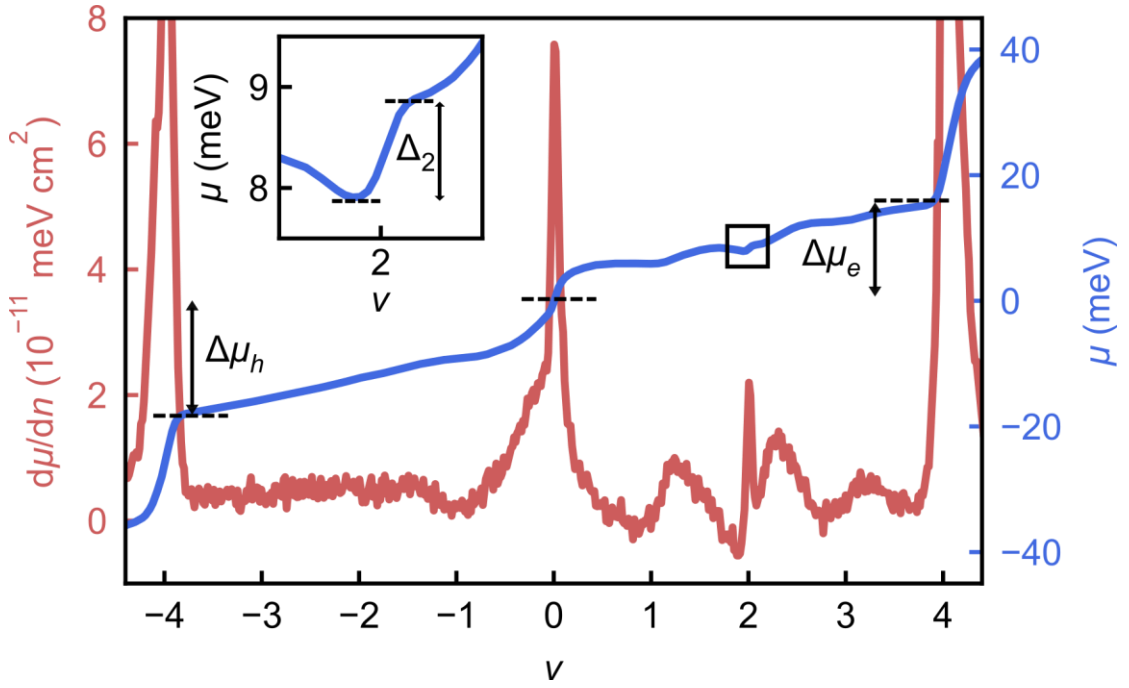
Hoke,..., Sharpe, Feldman arXiv:2509.07977

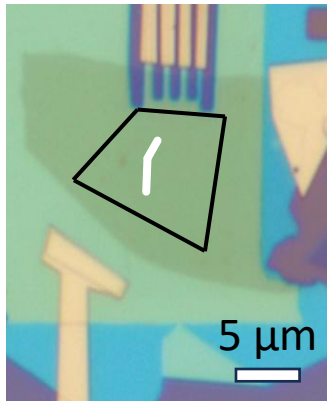
Imaging twisted trilayer compressibility[-1]



$\theta_{23} \approx 3 - 3.5°$
$\theta_{12} \approx 1 - 1.4°$







Zondiner, et al. Nature (2020)
Wong, et al. Nature (2020)
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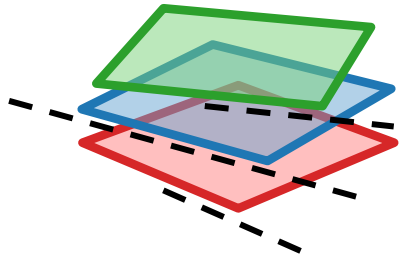

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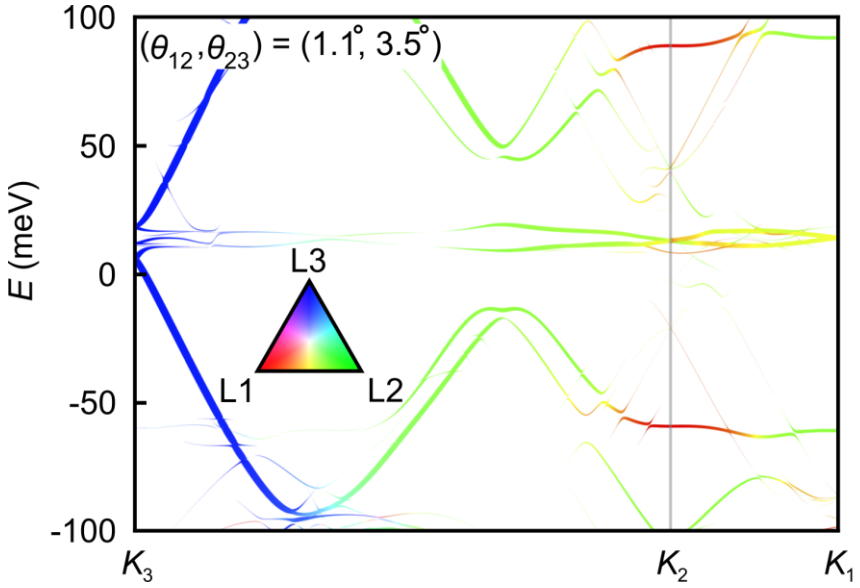

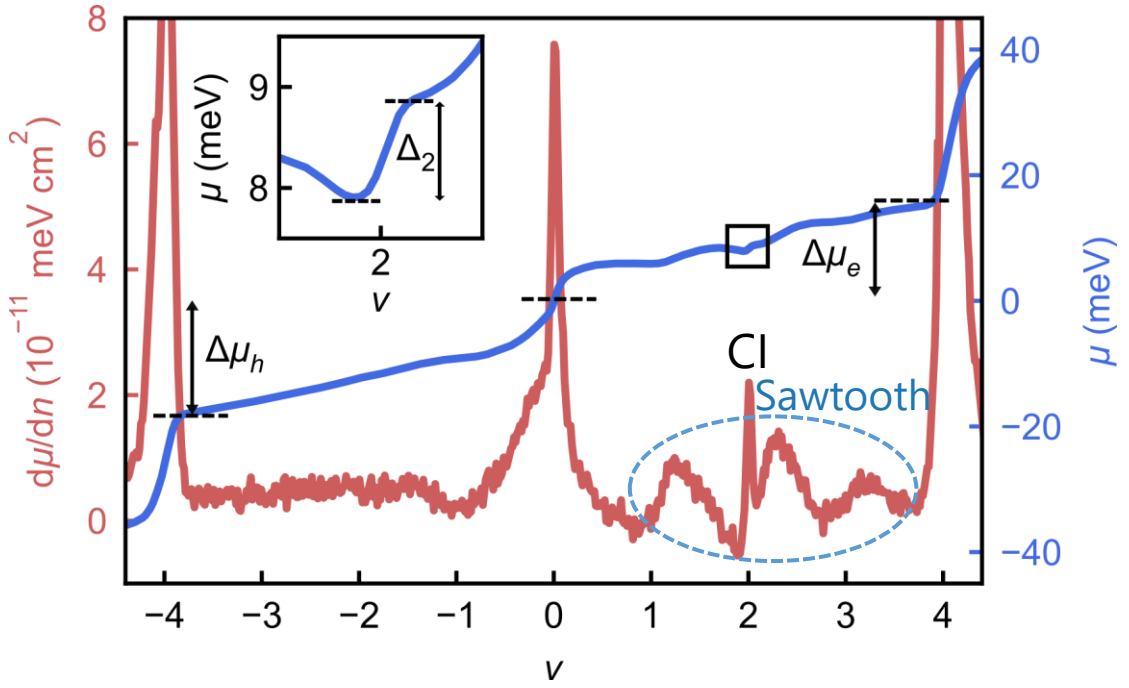

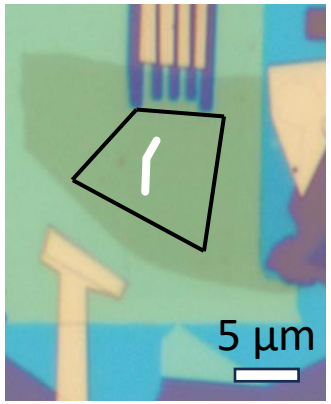

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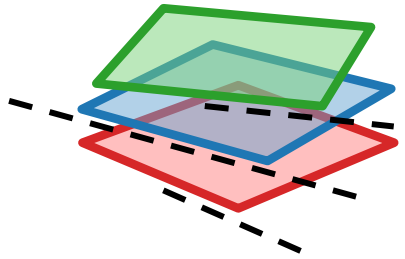

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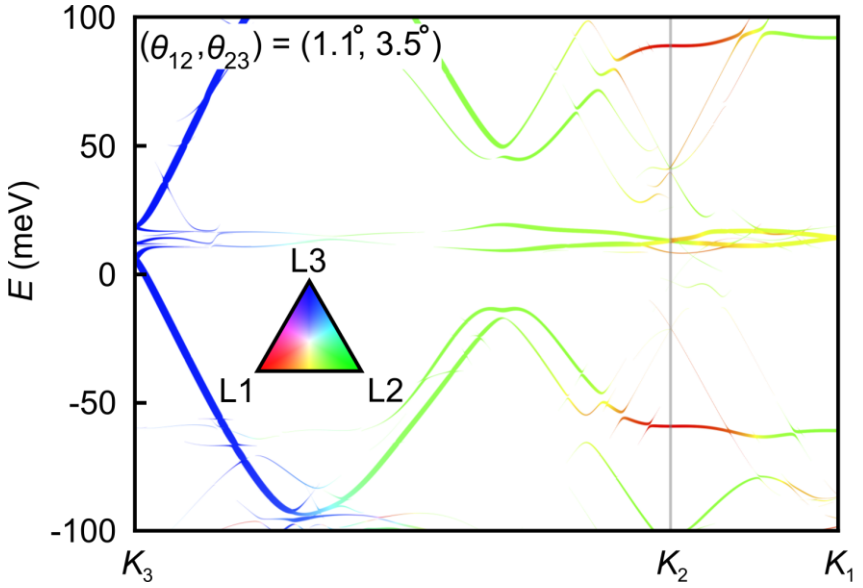
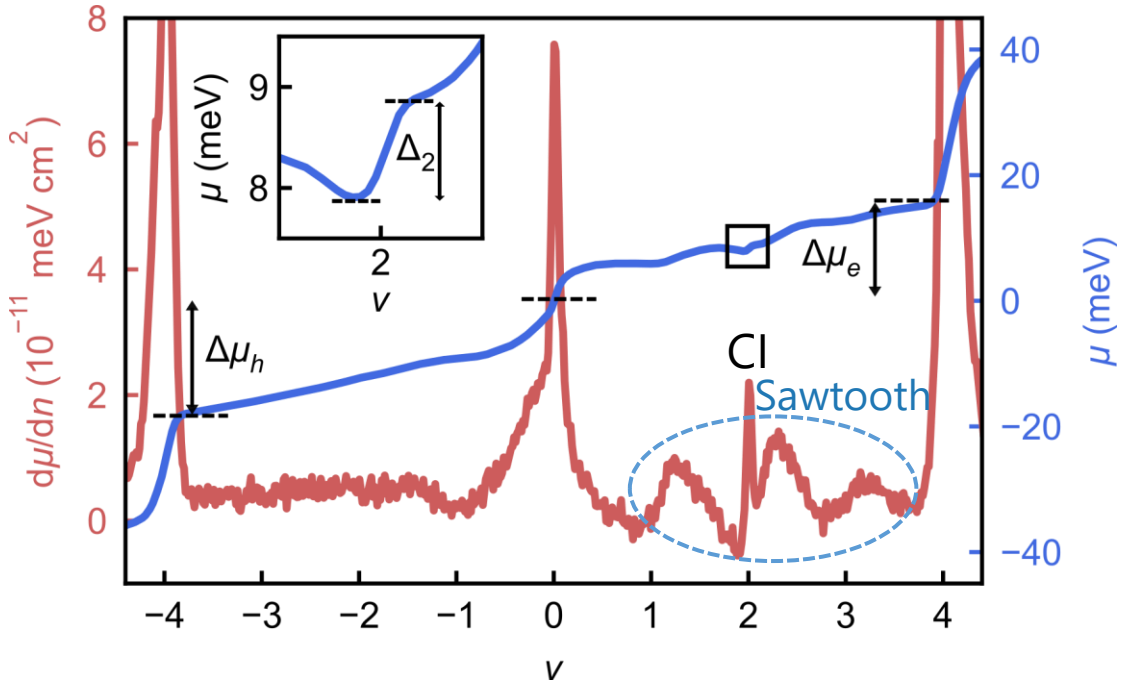
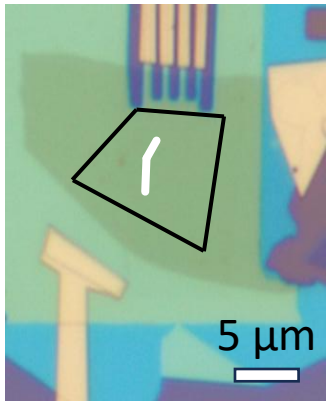
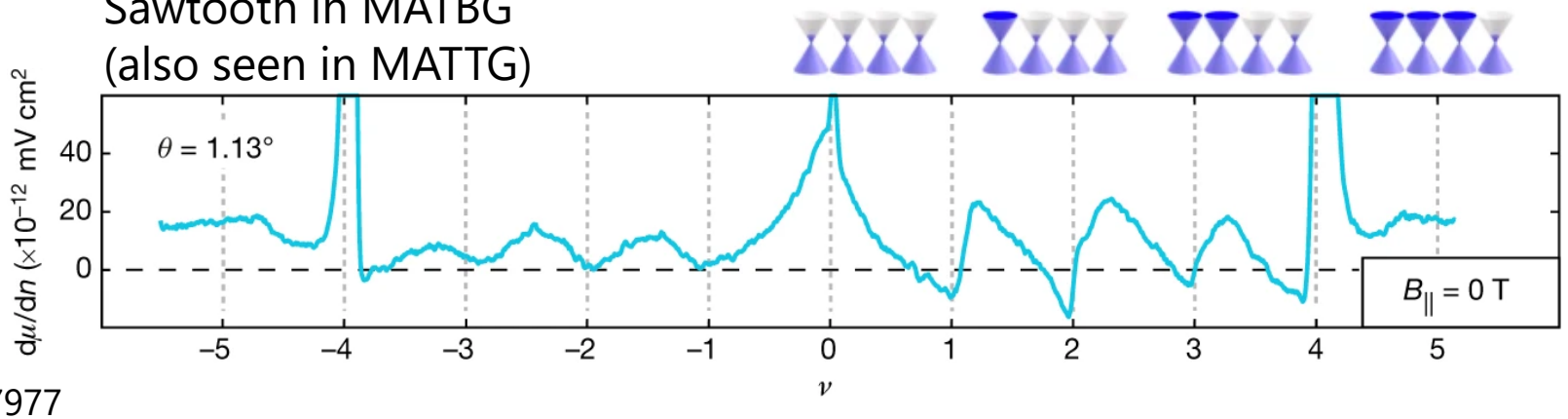






Sawtooth in MATBG
(also seen in MATTG)



Zondiner, et al. Nature (2020)
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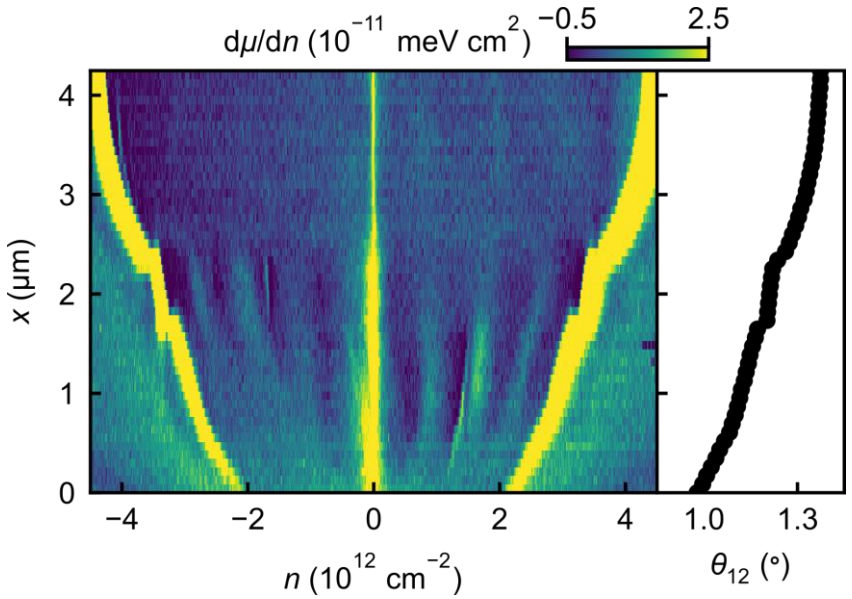
Turkel et al. Science (2022)
Hoke,..., Sharpe, Feldman arXiv:2509.07977

Twist angle dependent correlations



Hoke,..., Sharpe, Feldman arXiv:2509.07977

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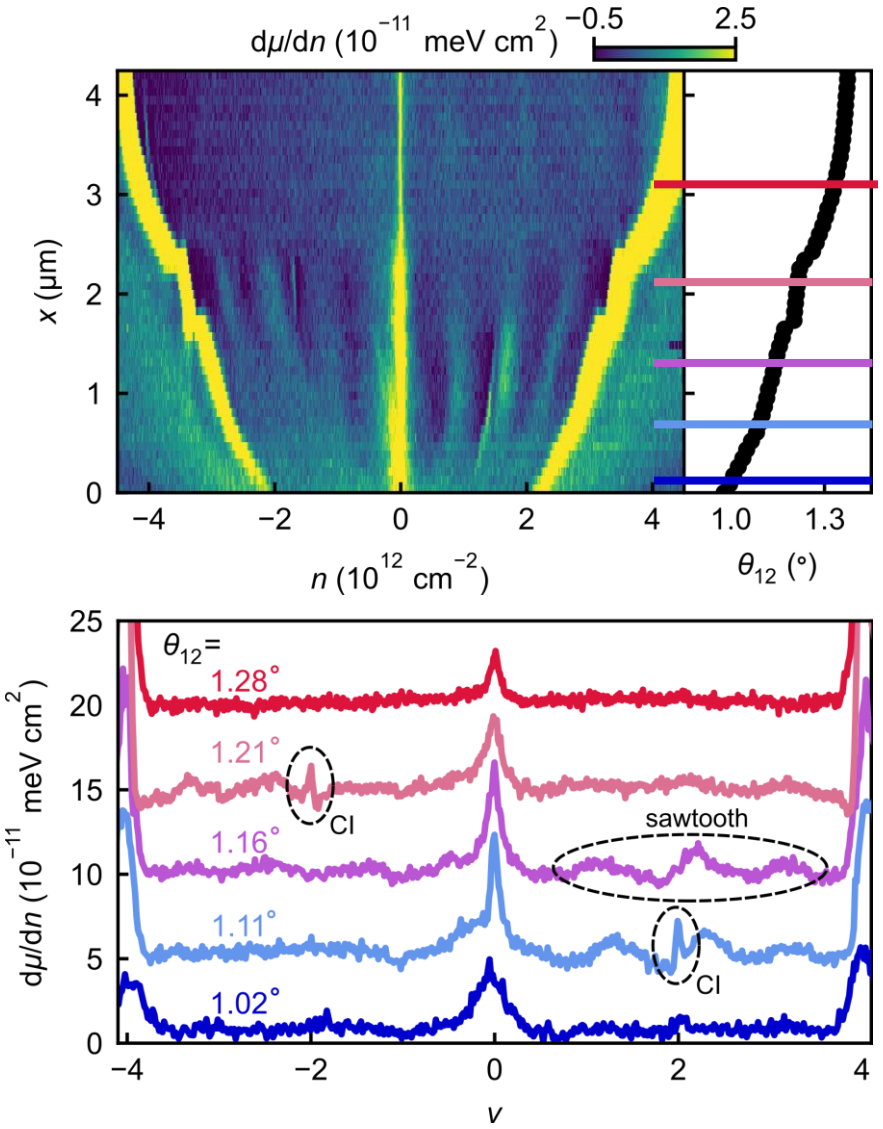

Hoke,..., Sharpe, Feldman arXiv:2509.07977

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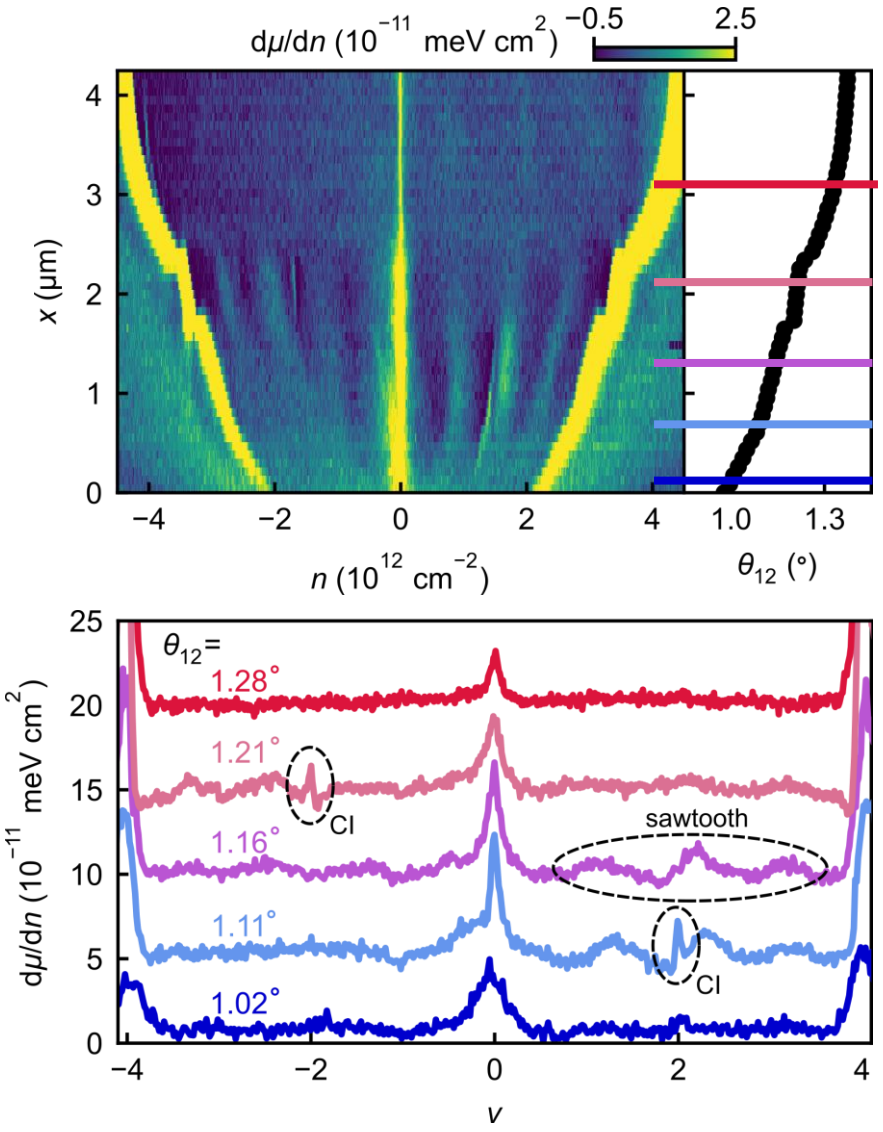
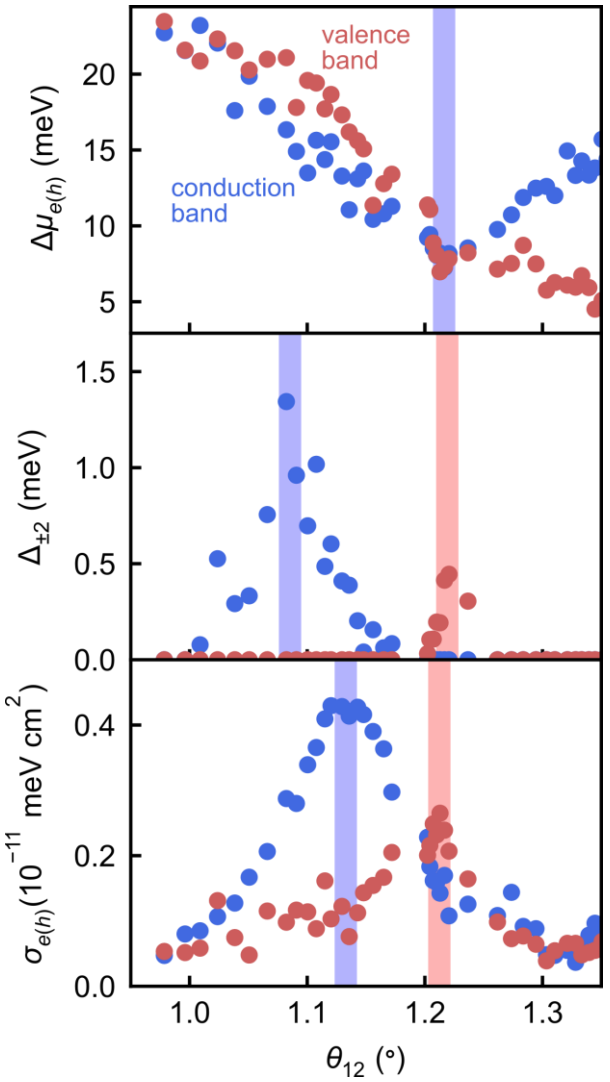
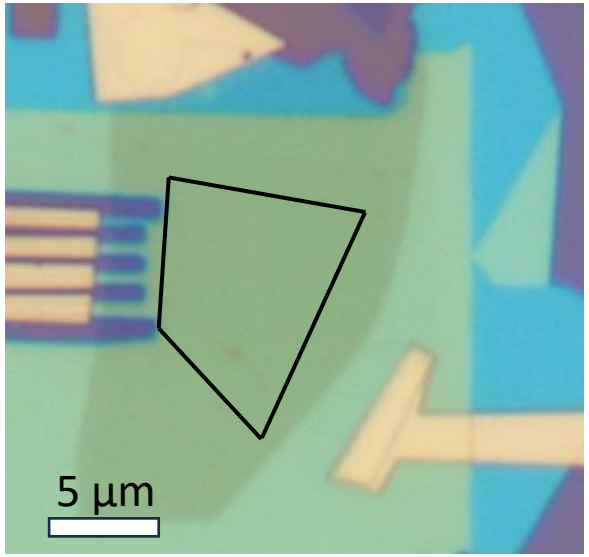




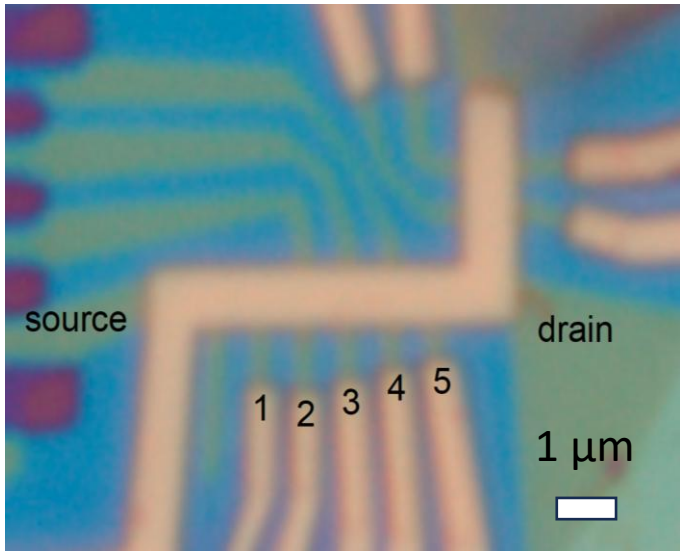
1. Distinct “magic angles” for electrons and holes
2. Correlated insulators like MATBG and TTG
3. “Sawtooth” in compressibility^{-1} also like MATBG/MATTG

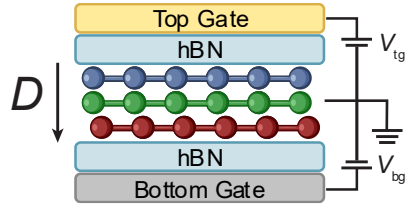
Hoke,…, Sharpe, Feldman arXiv:2509.07977

Compare to Transport



Fab





Etched a 'magic' region of the device and added a top gate

Direct comparison of compressibility^{-1} and transport in the same device!

Hoke, et al. Nat. Comms (2024)
Hoke,…, Sharpe, Feldman arXiv:2509.07977

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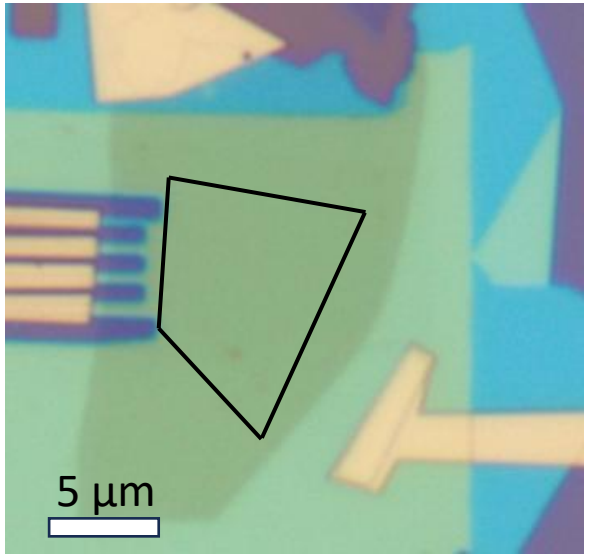

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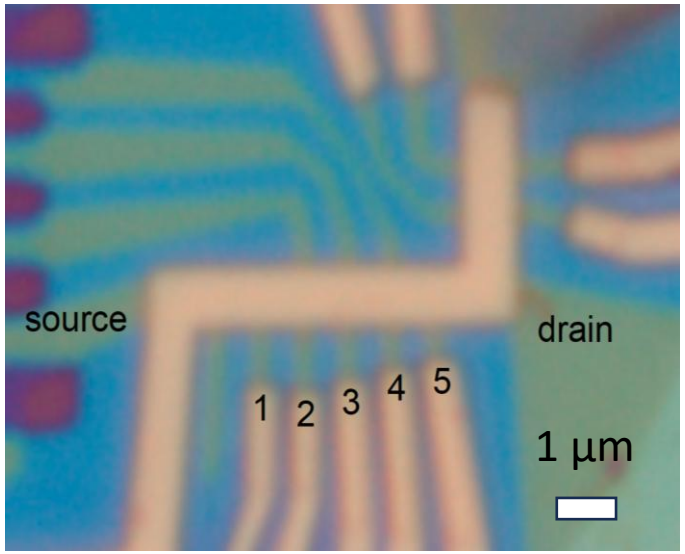

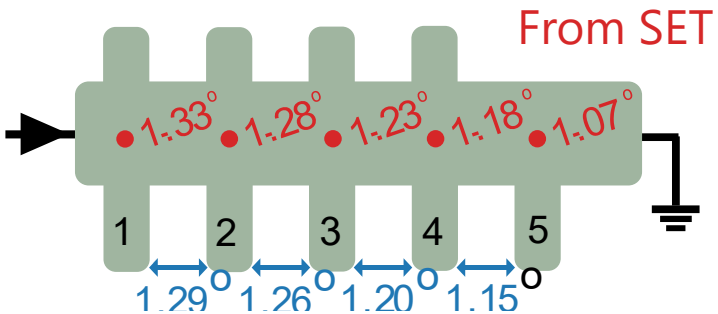

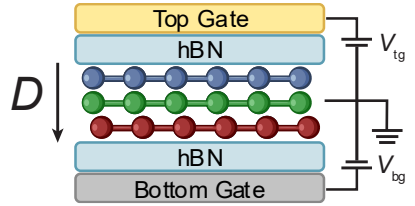

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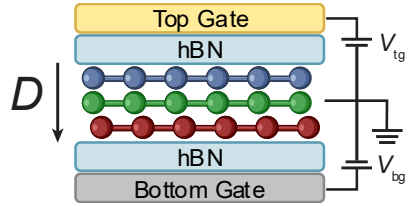

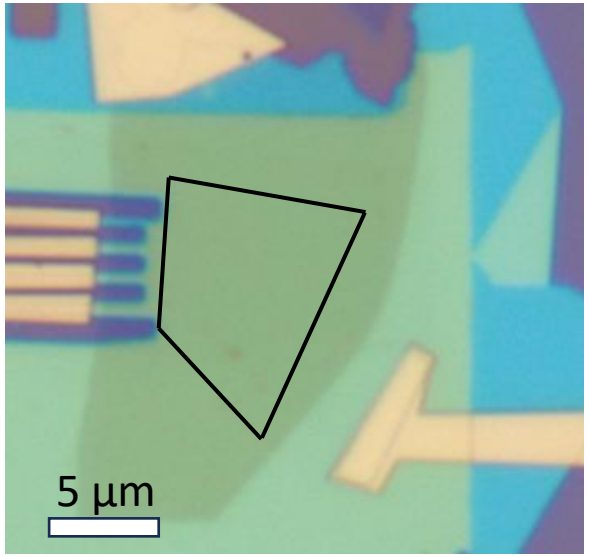

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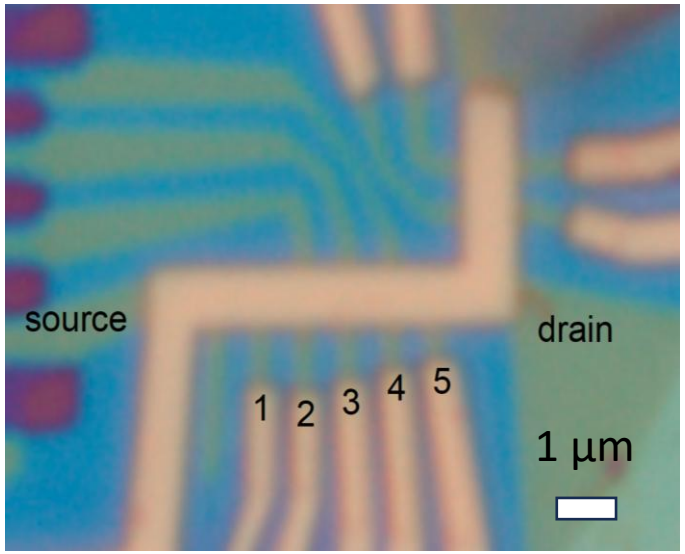

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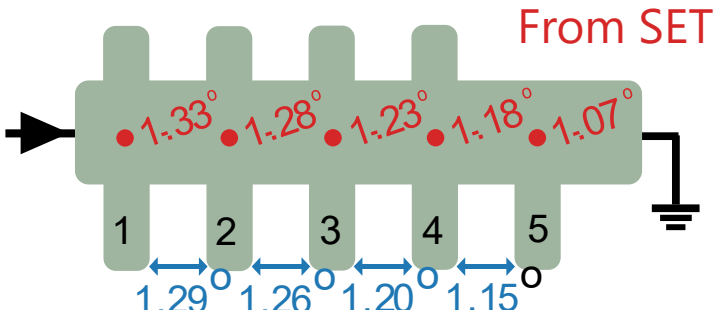

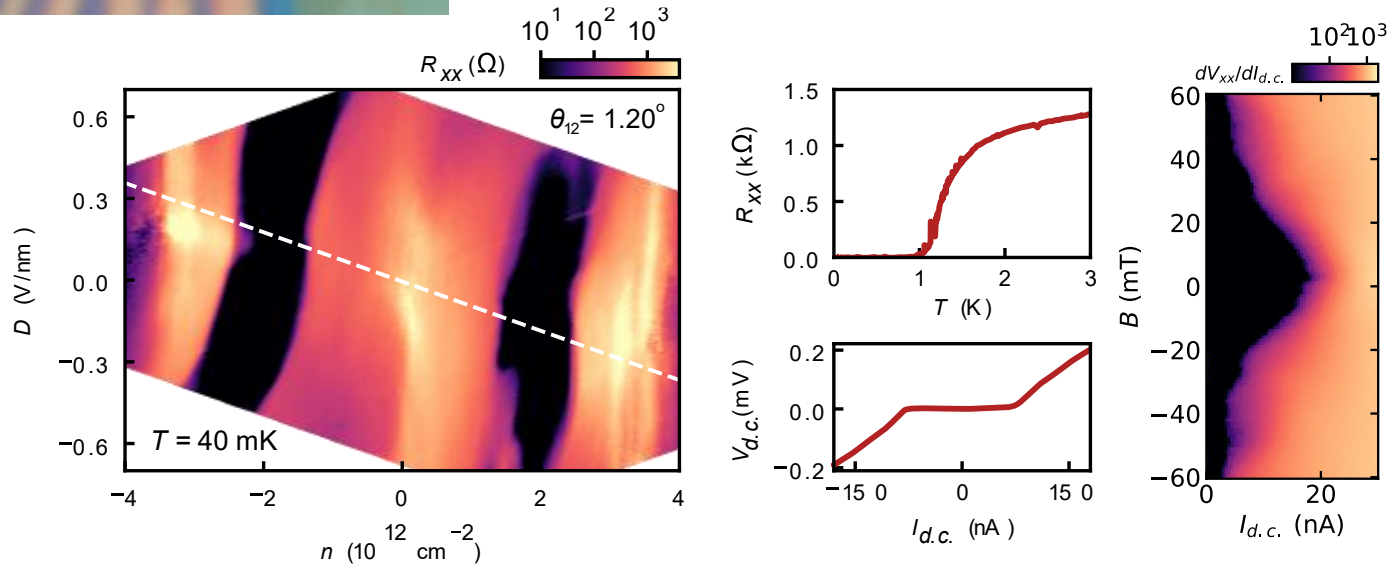

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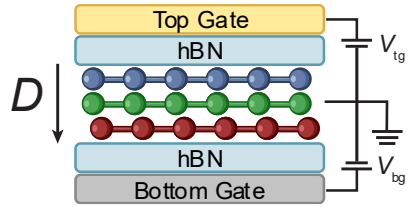

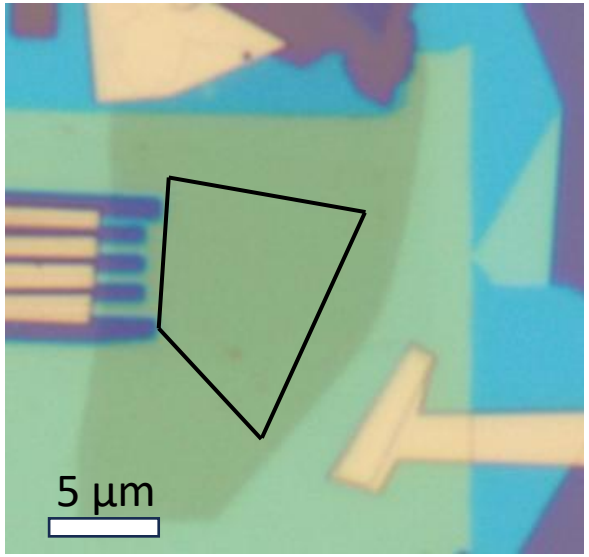

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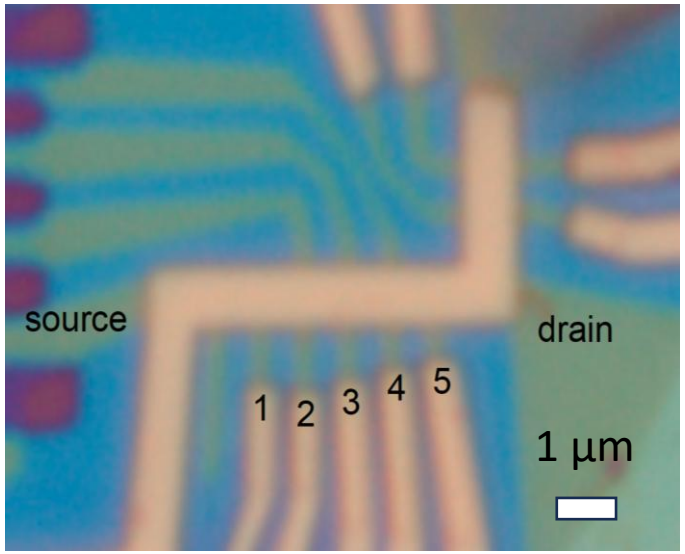

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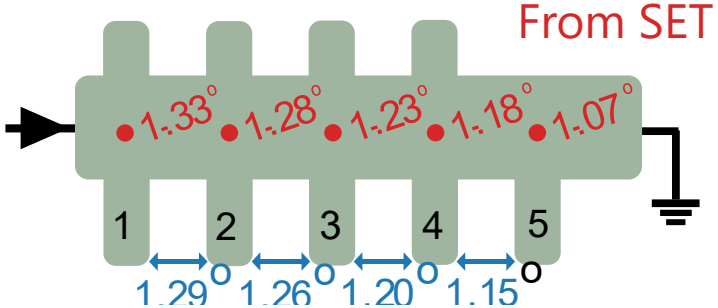
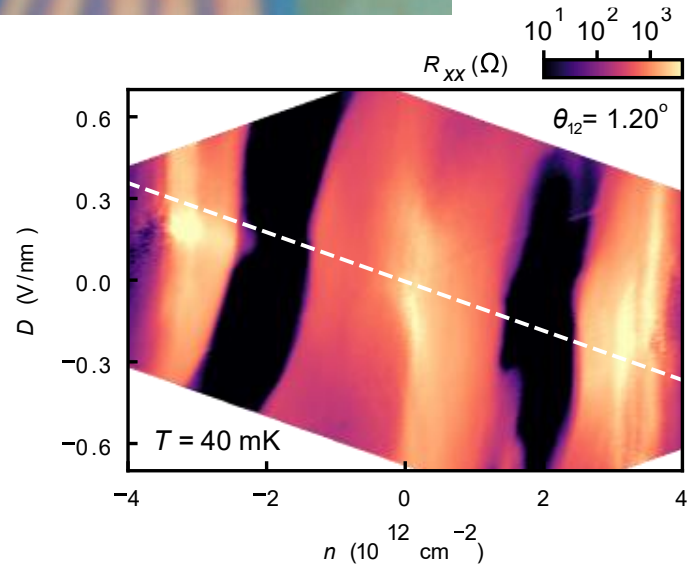
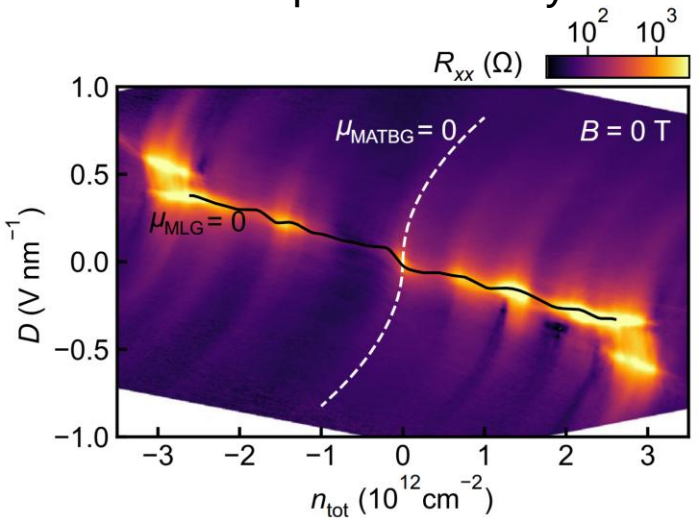


From transport

Decoupled third layer





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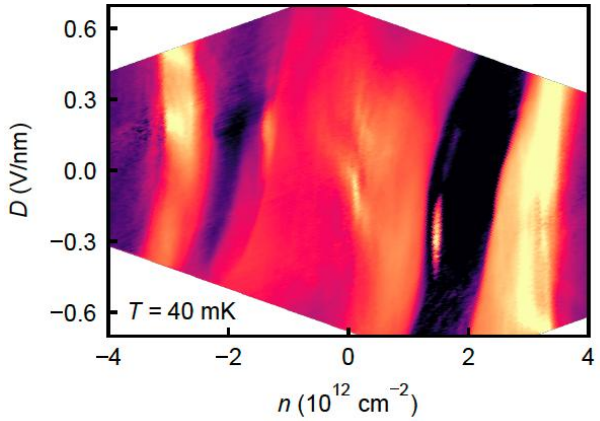
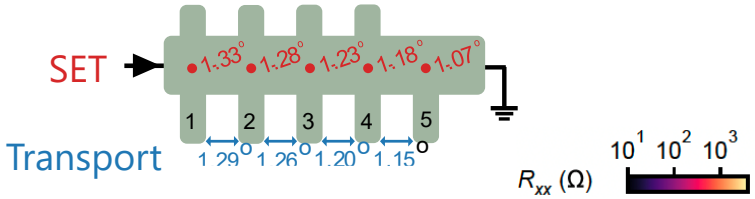
Hoke,..., Sharpe, Feldman arXiv:2509.07977

Twist evolution of superconductivity



1.15°



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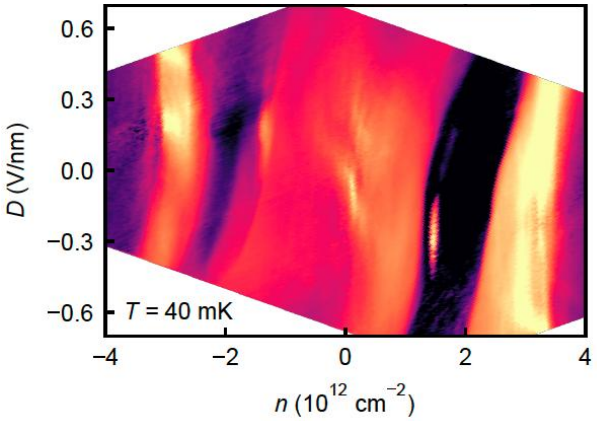

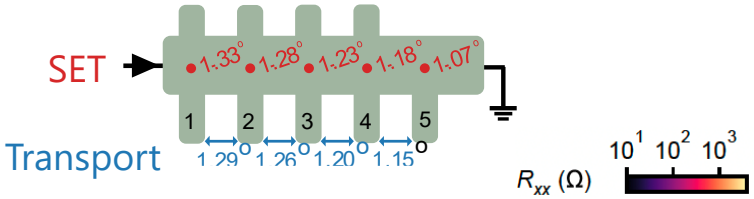

1.15° Increasing angle 1.29°

Hoke,..., Sharpe, Feldman arXiv:2509.07977

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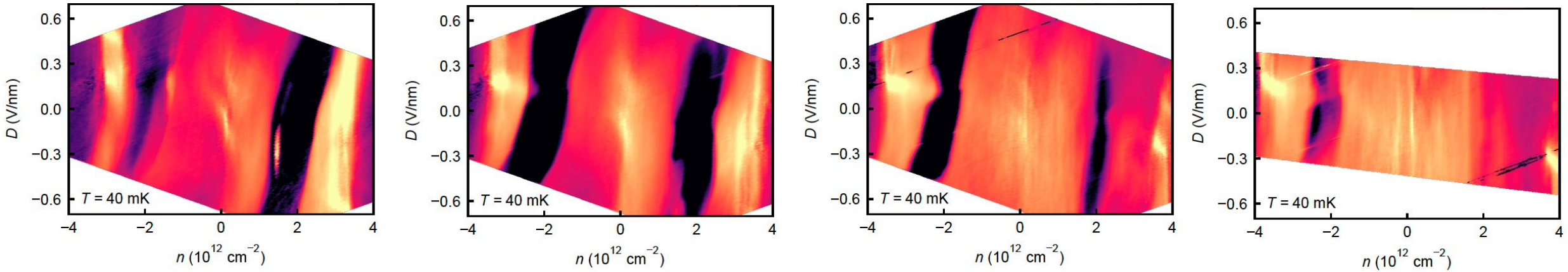

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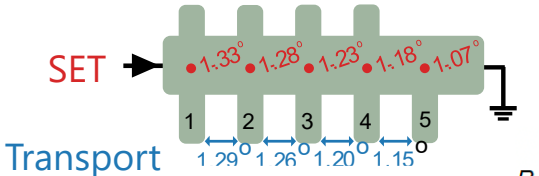

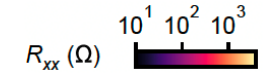

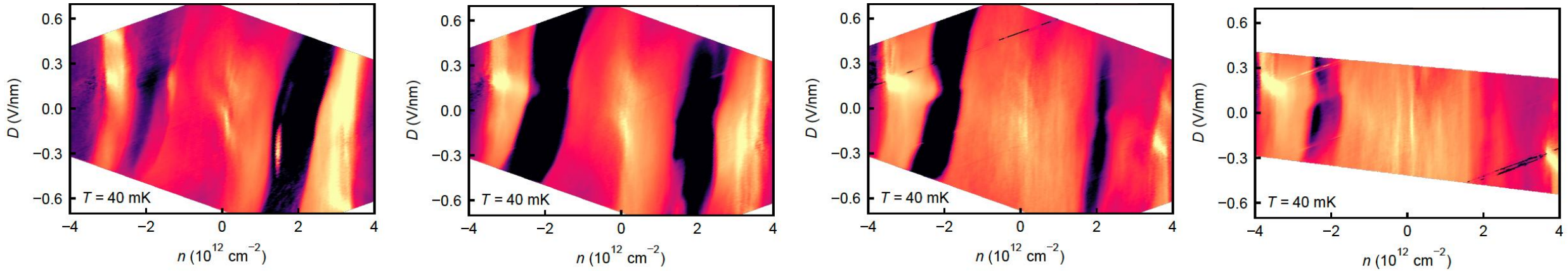

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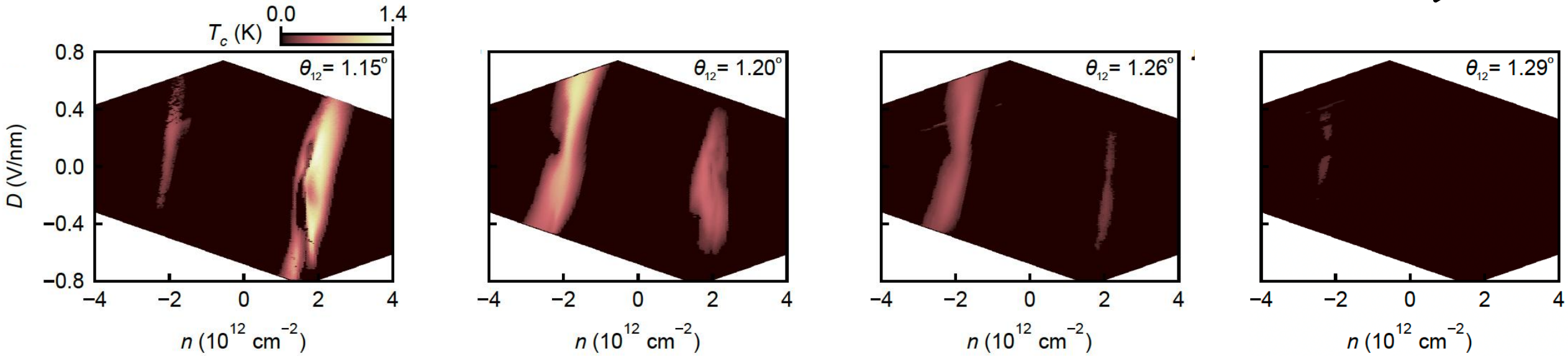
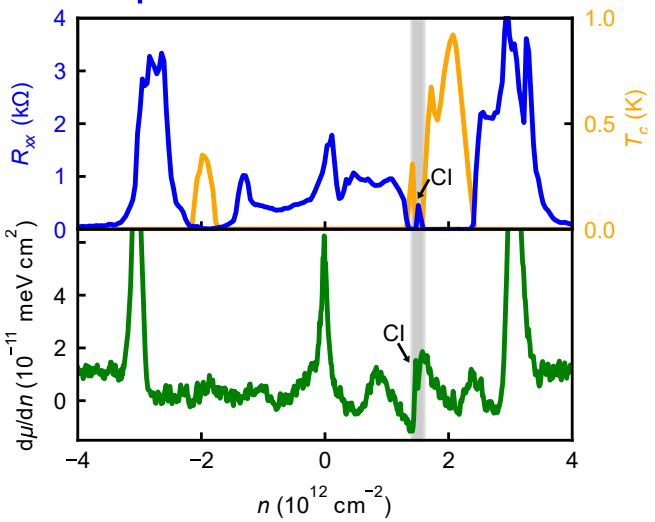


Hoke,..., Sharpe, Feldman arXiv:2509.07977

Comparing superconductivity and sawtooth strength

Transport: 1.15°



SET: 1.15°

Hoke,..., Sharpe, Feldman arXiv:2509.07977

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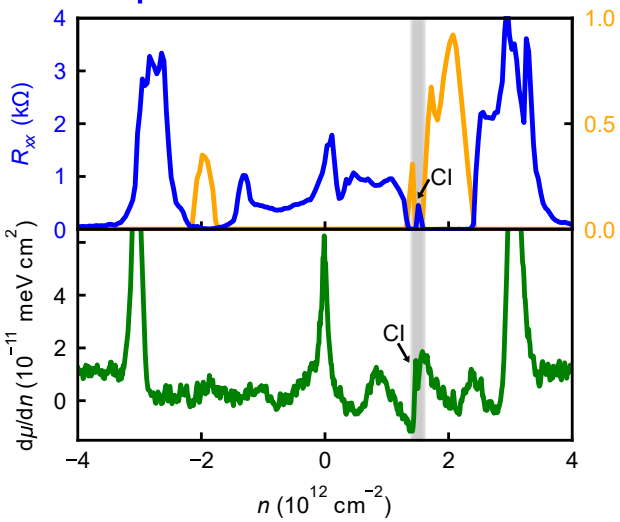
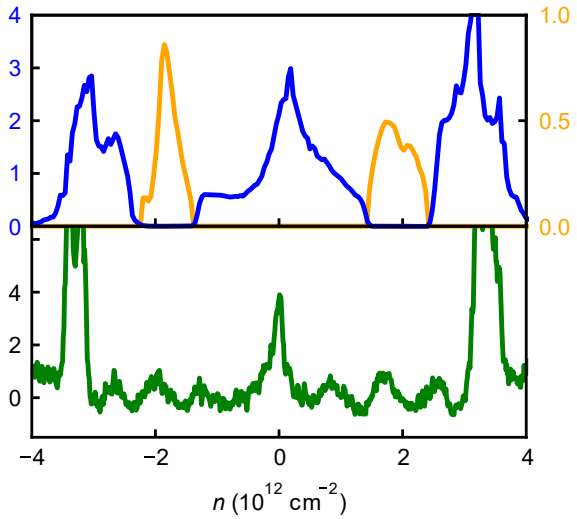


1.20°



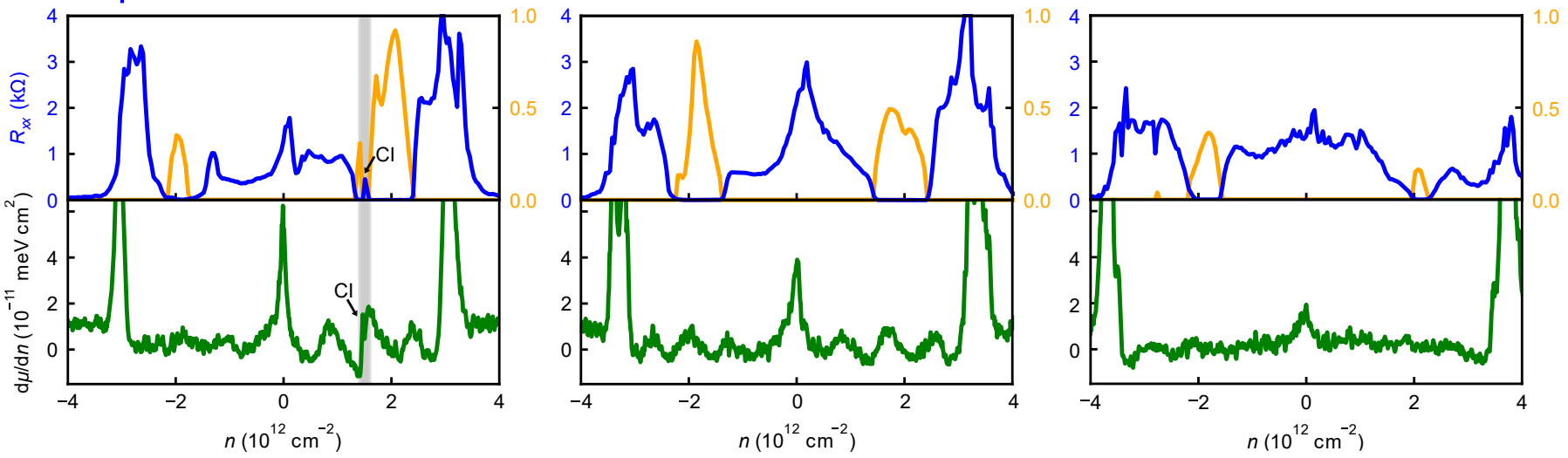
SET: 1.15°

1.20°

Hoke,..., Sharpe, Feldman arXiv:2509.07977

Comparing superconductivity and sawtooth strength

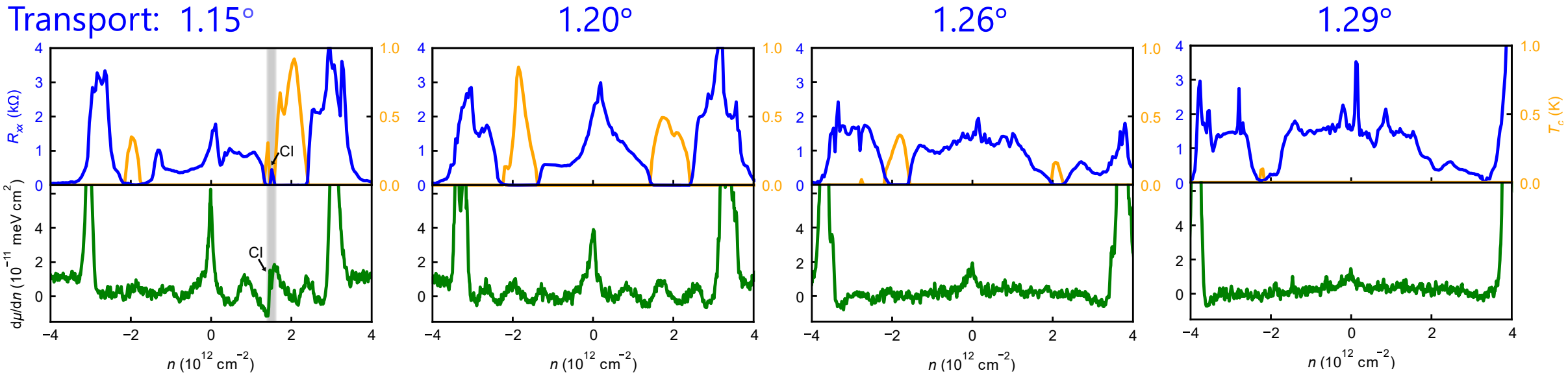
Transport: 1.15° 1.20° 1.26°



SET: 1.15° 1.20° 1.26°

Hoke,..., Sharpe, Feldman arXiv:2509.07977

Comparing superconductivity and sawtooth strength



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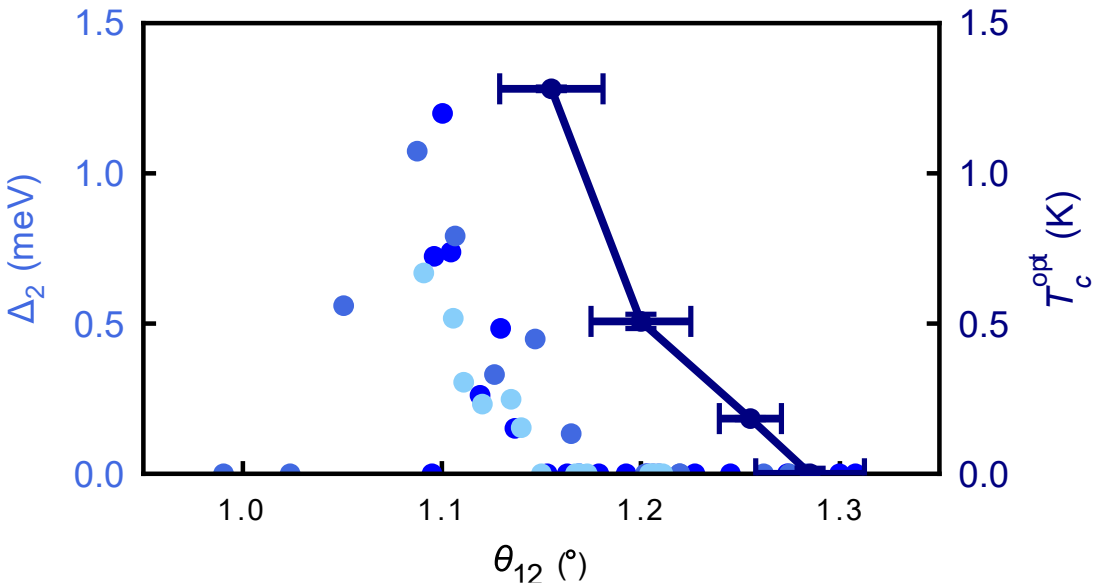

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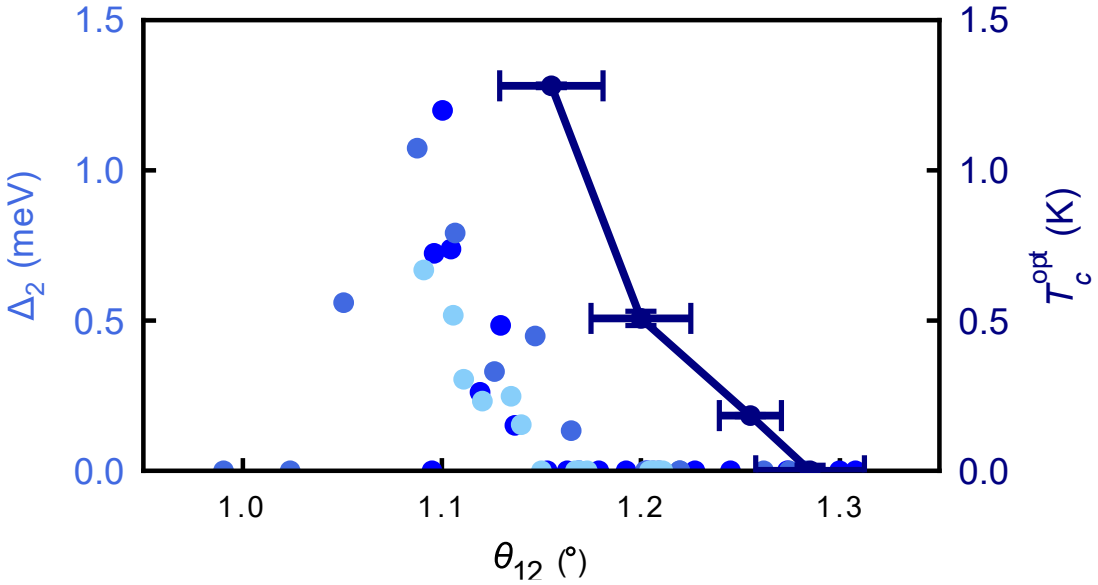
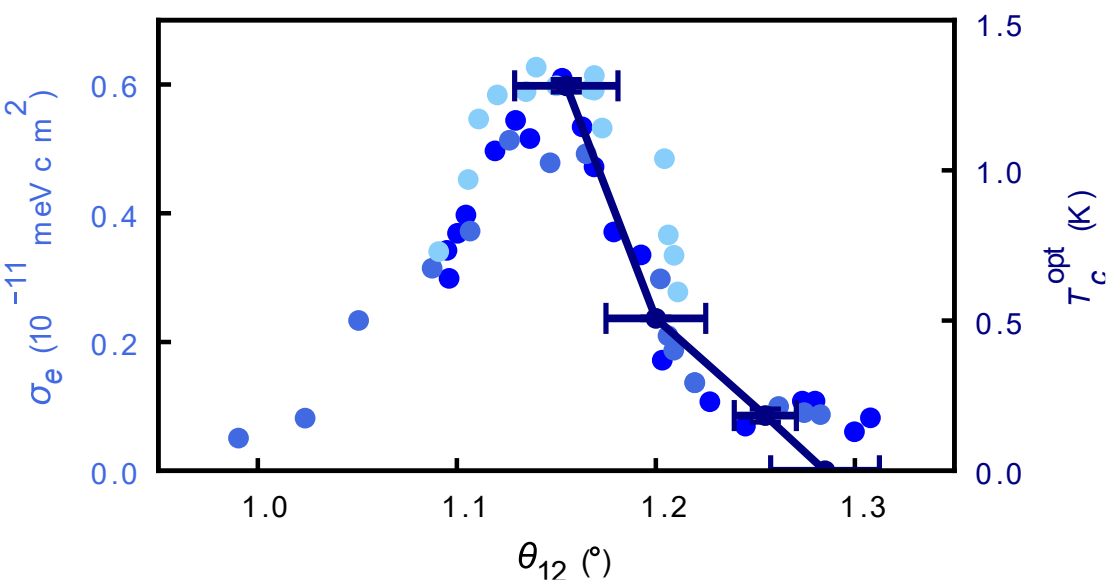
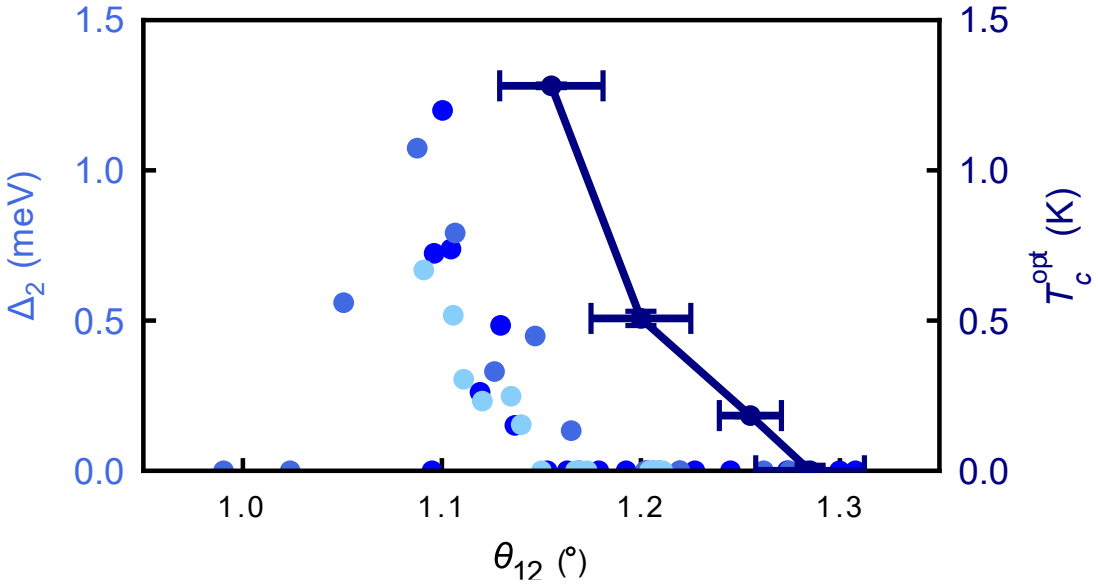
Comparing superconductivity and sawtooth strength

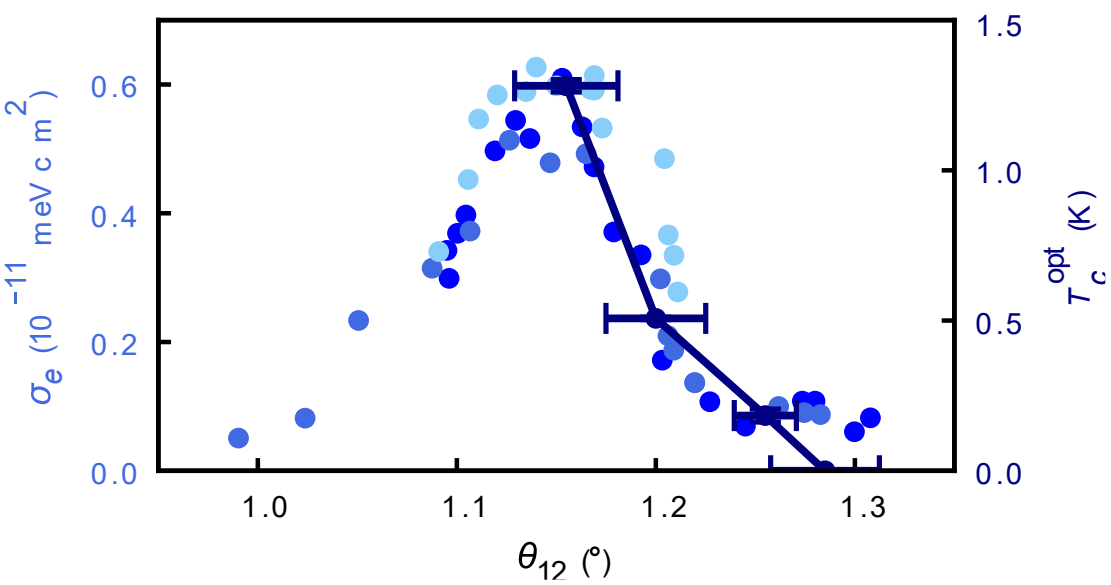




Hoke,..., Sharpe, Feldman arXiv:2509.07977

Comparing superconductivity and sawtooth strength



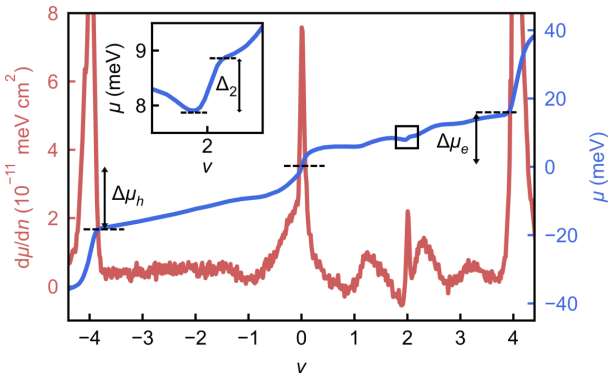


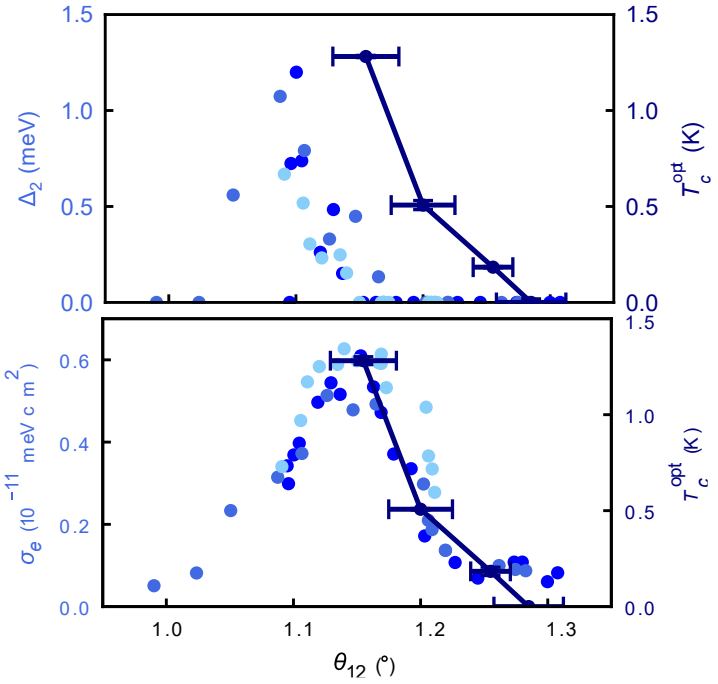
- Strength (T_c) of superconductivity scales similarly with sawtooth
- No clear correspondence to correlated insulators
- For now: just an observation (there is correlation), but no crisp conclusion about origin of superconductivity

Hoke,..., Sharpe, Feldman arXiv:2509.07977

Takeaways

Superconductivity tied to Sawtooth Strength





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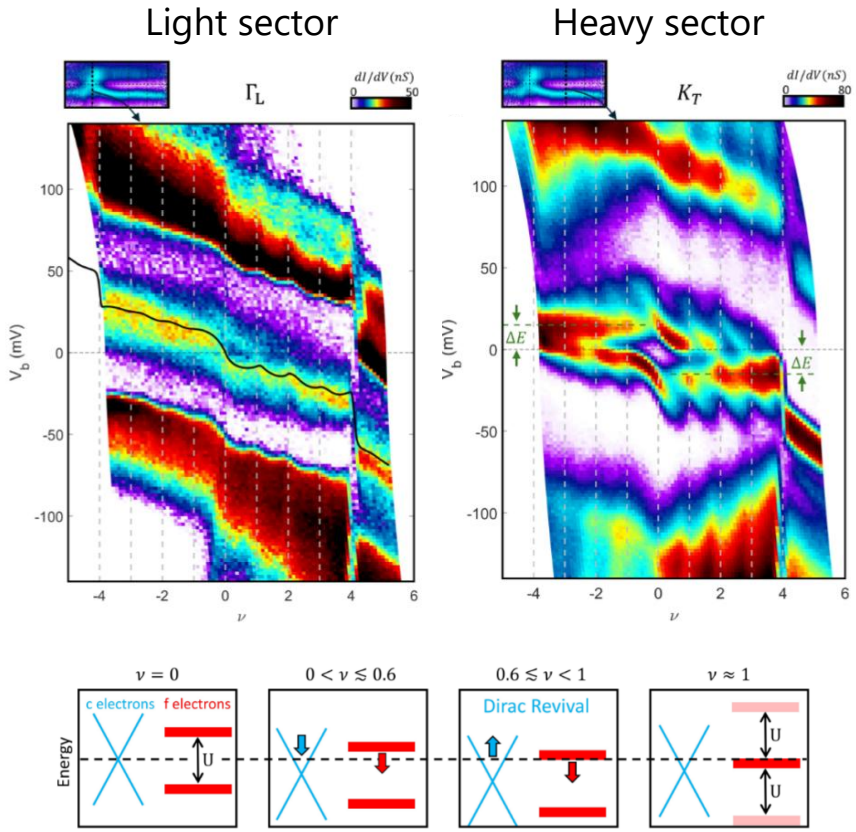
Sawtooth – Reshuffling of charge



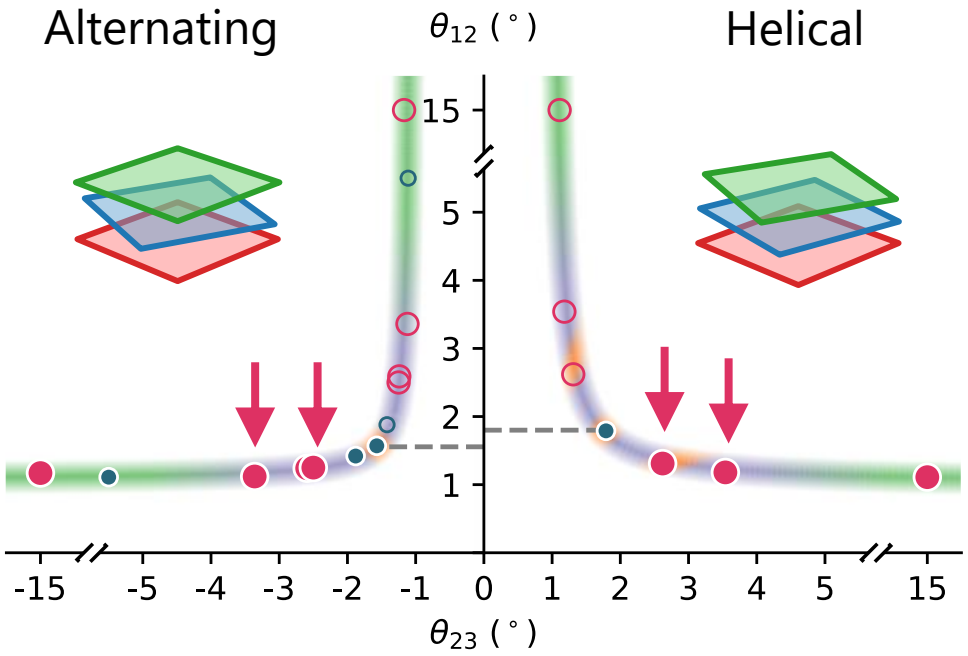
Xiao, et al. arXiv:2506.20738
Hoke,..., Sharpe, Feldman arXiv:2509.07977

Outline

Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation

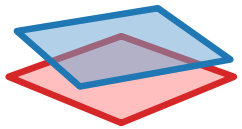
Linking thermodynamic probes and transport:
- Fine-grained evolution of correlations
- Cross comparison of distinct experimental probes

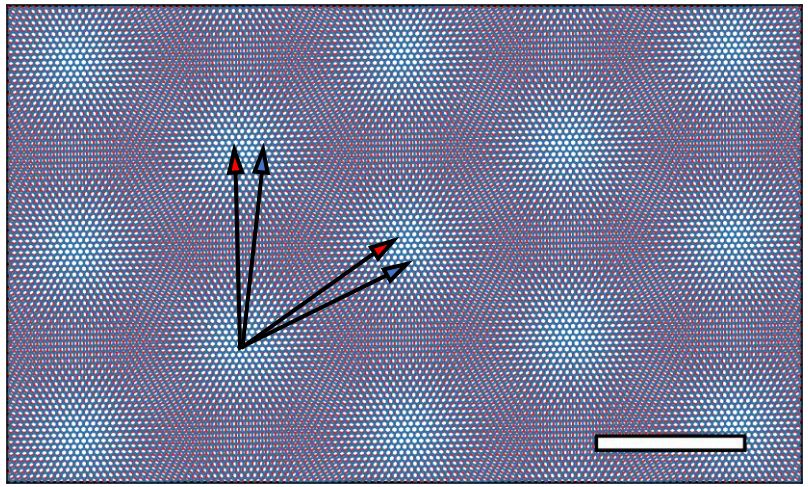
Exploring the "magic continuum":
- Broad comparison across many devices in angle-angle space



From moiré to multimoiré

Layers **1** and **2**





Scale bars: 5 nm

Yang, et al. PRB (2024)
Nakatsuji, et al. PRX (2023)
Foo, et al. PRR (2024)
Bistritzer and MacDonald, PNAS (2011)

Atomic lattices that make up moirés generally incommensurate → continuum approximation

From moiré to multimoiré

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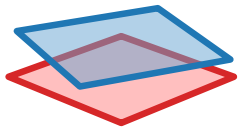

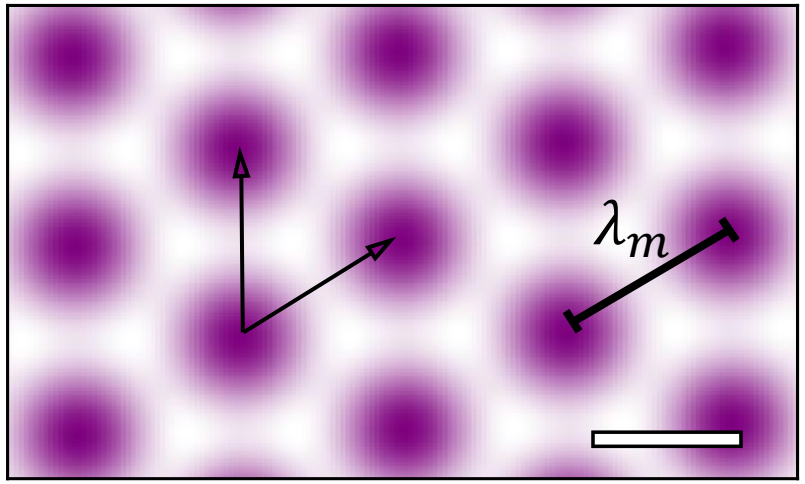

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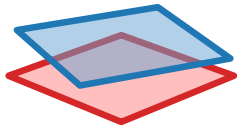
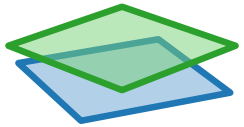
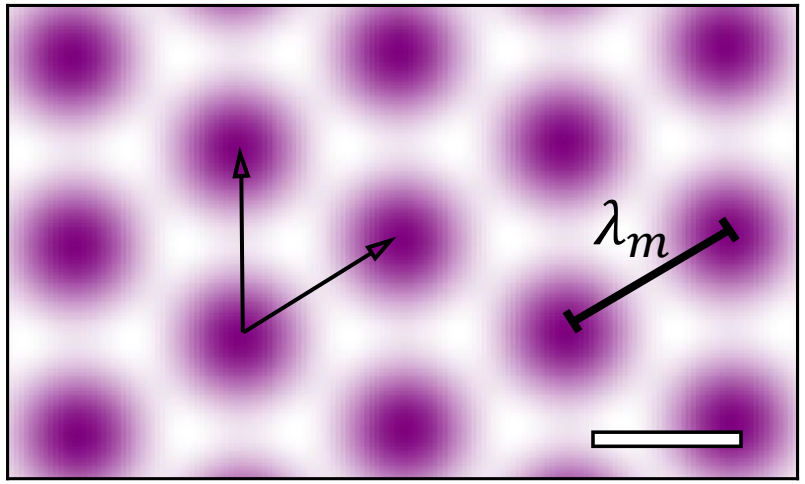
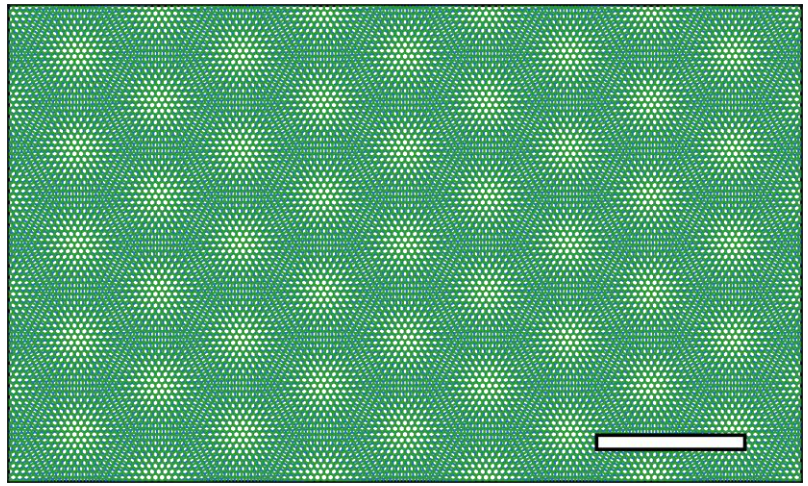


Layers **2** and **3**







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Atomic lattices that make up moirés generally incommensurate → continuum approximation

From moiré to multimoiré

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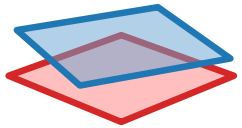

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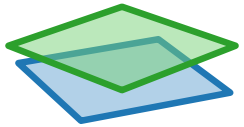

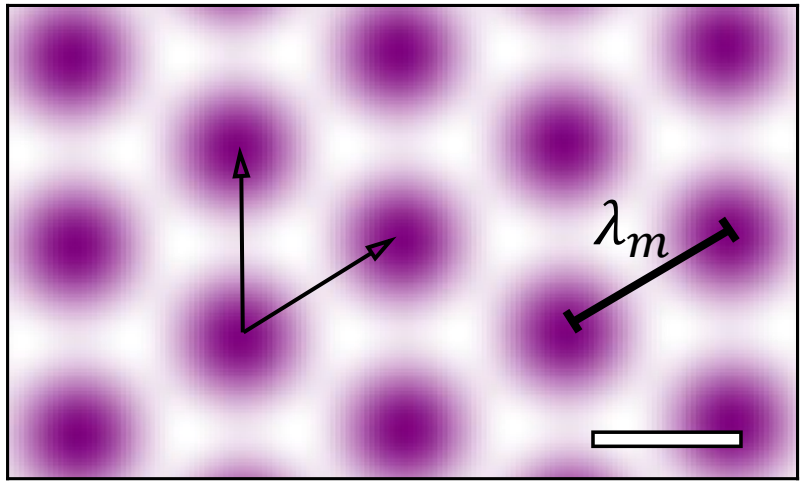

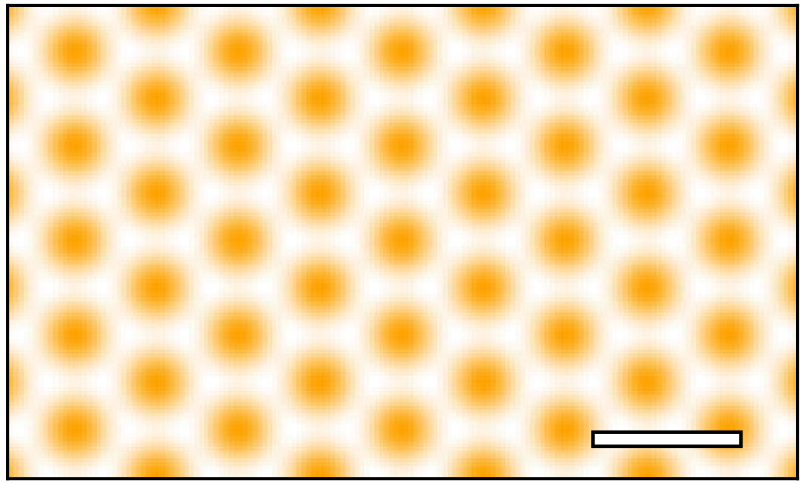

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Atomic lattices that make up moirés generally incommensurate → continuum approximation

Yang, et al. PRB (2024)
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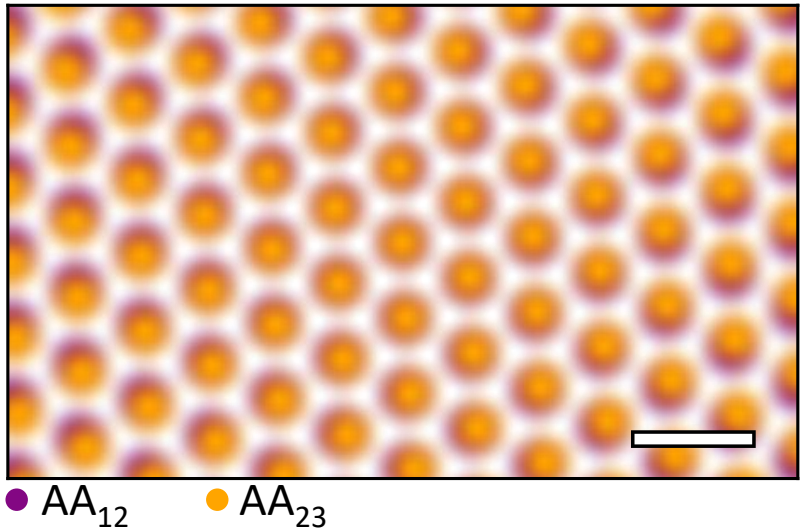
Bistritzer and MacDonald, PNAS (2011)

Incommensurability and the supermoiré length scale

$(\theta_{12}, \theta_{23}) = (2°, 2°)$



Scale bars: 10 nm

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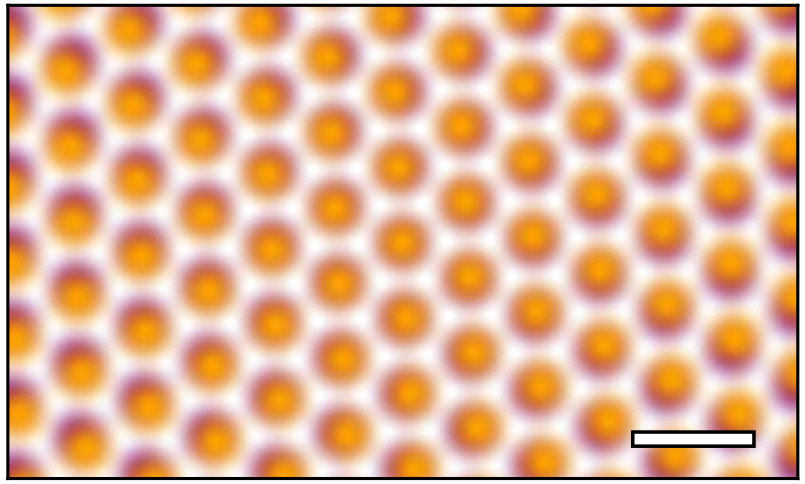

● AA_{12} ● AA_{23}

Scale bars: 10 nm

Translate window

Yang, et al. PRB (2024)
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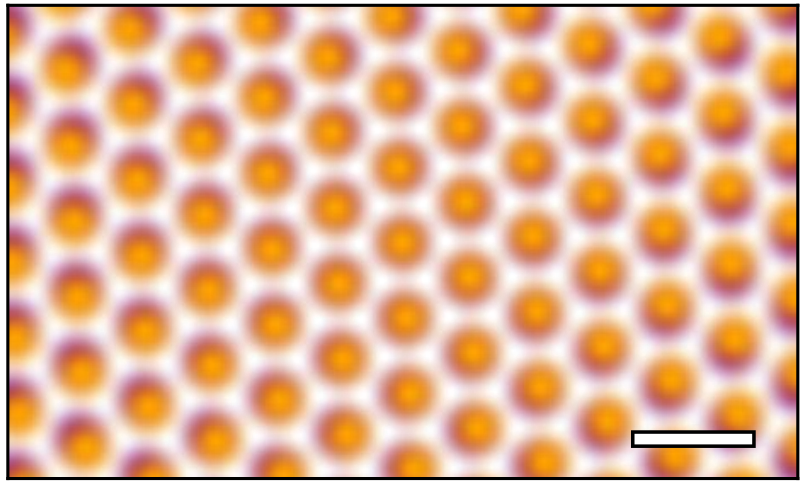

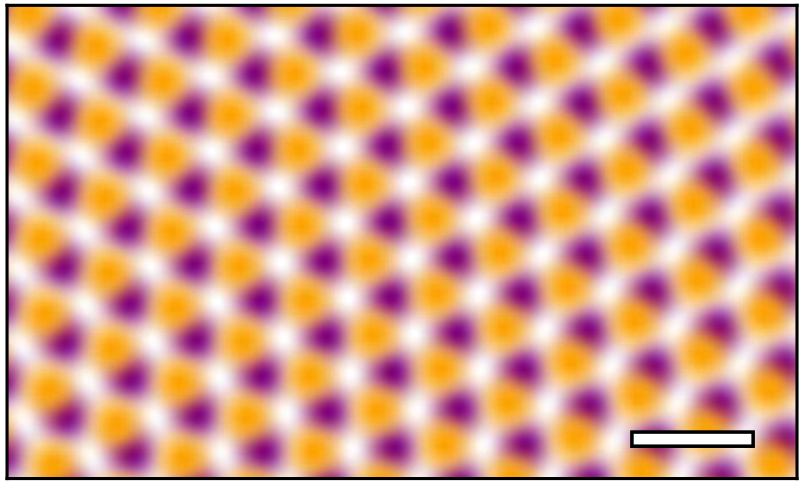

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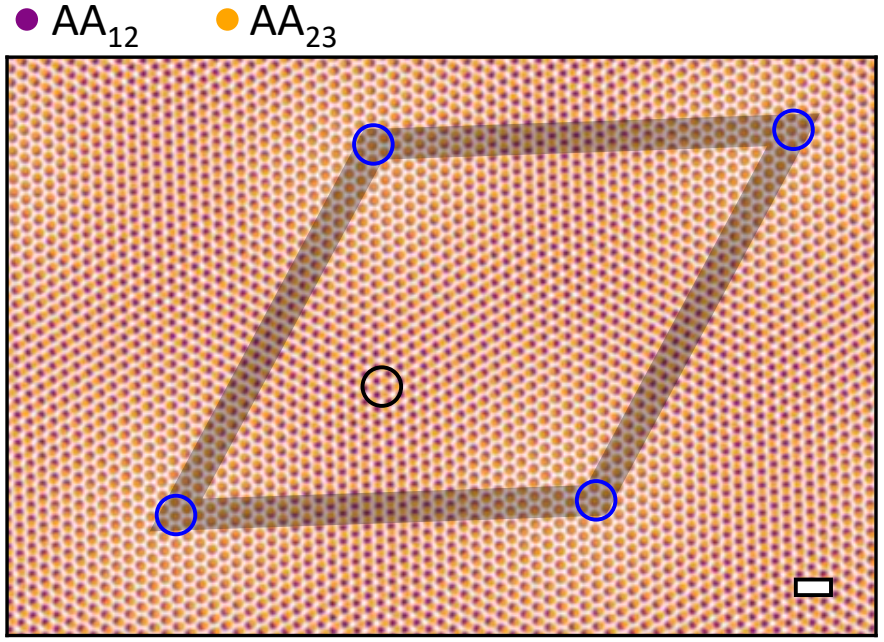
Shift dependent electronic bands



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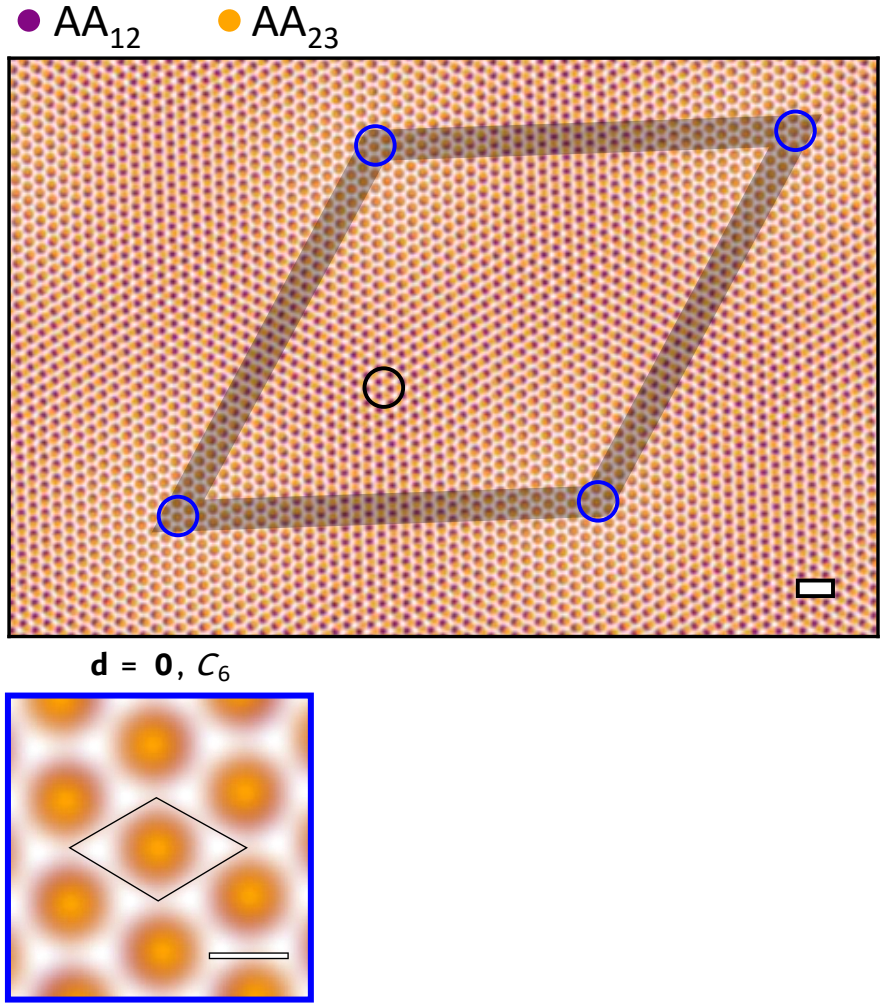

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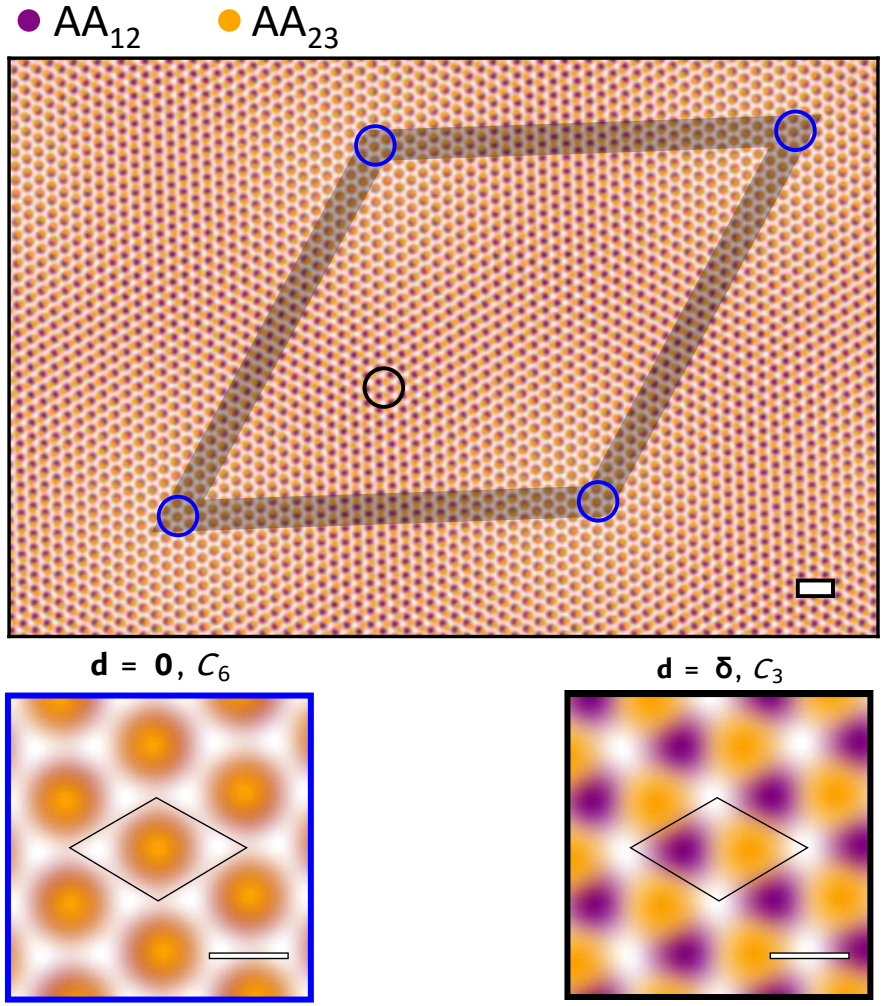

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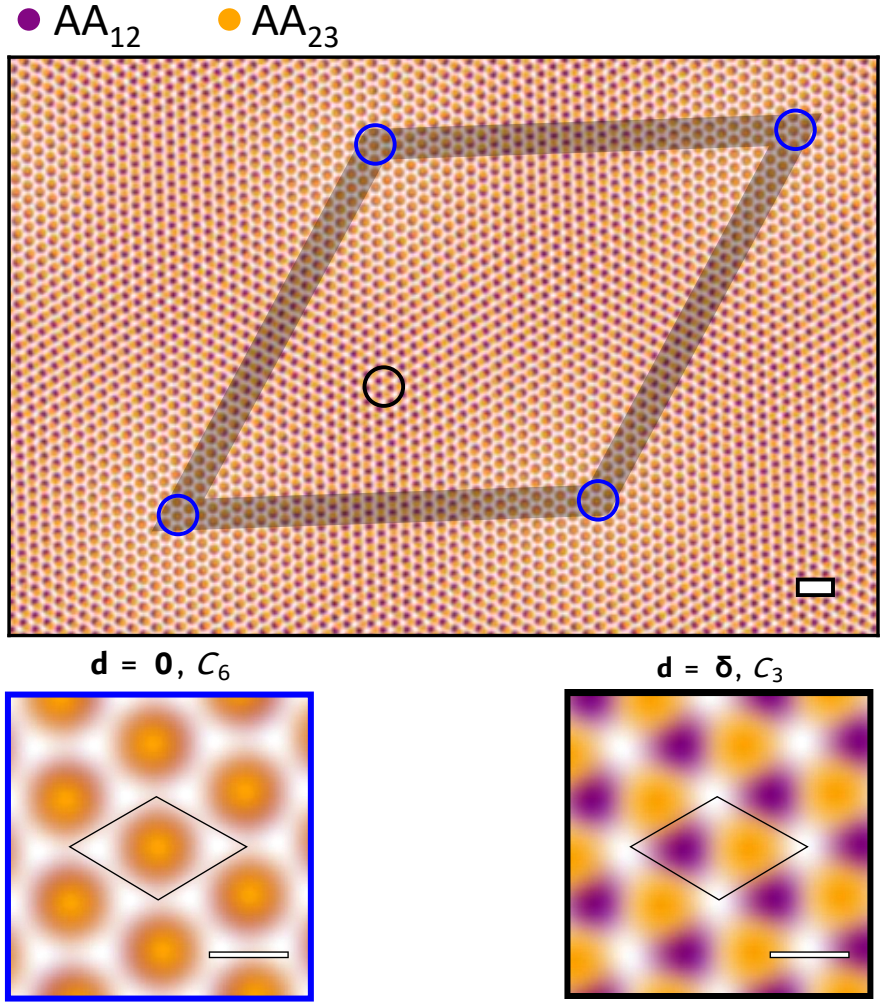

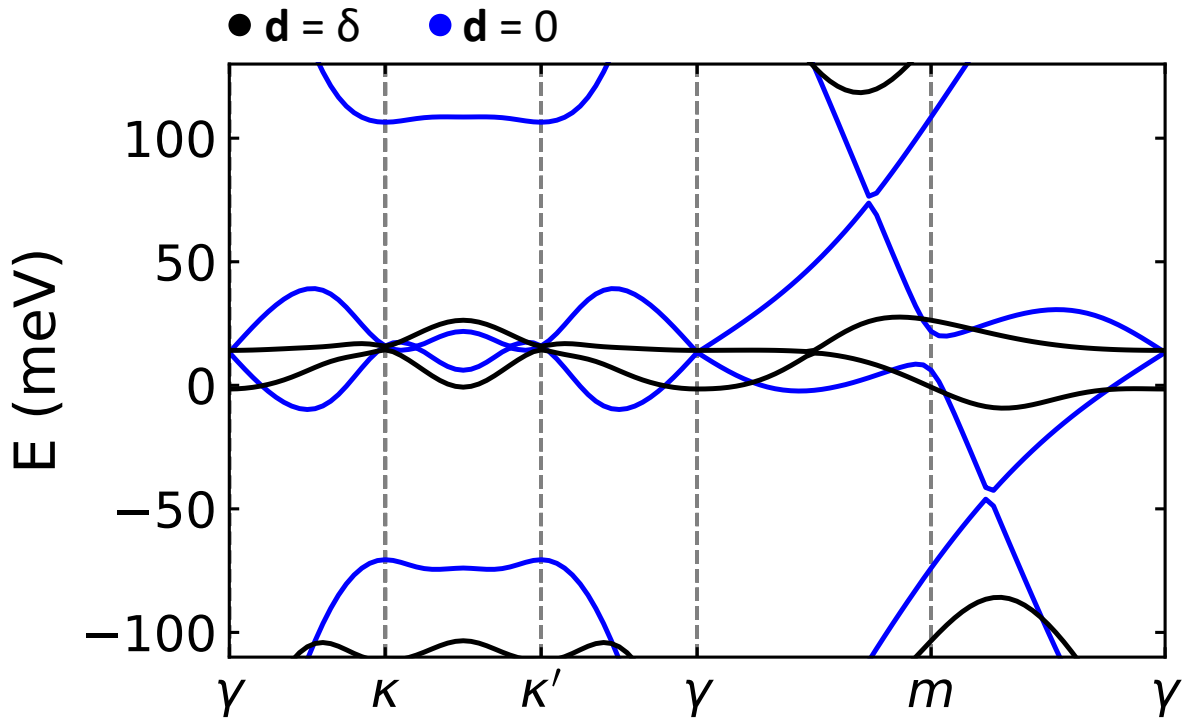

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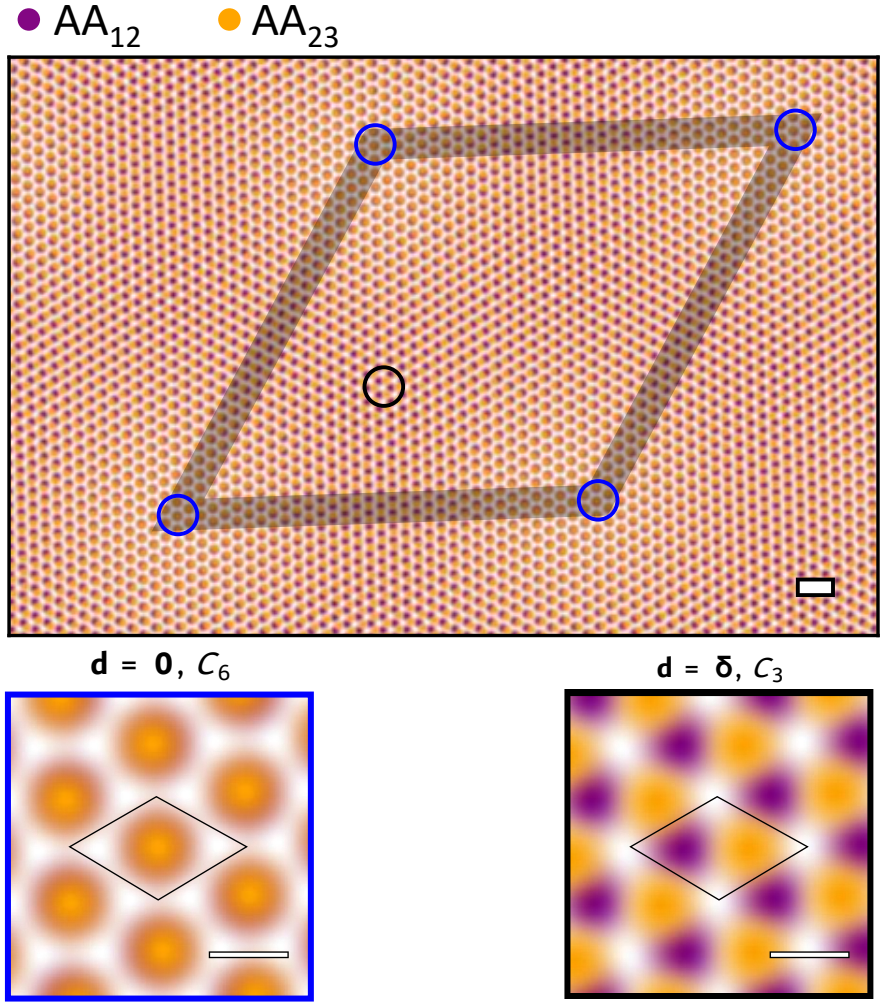

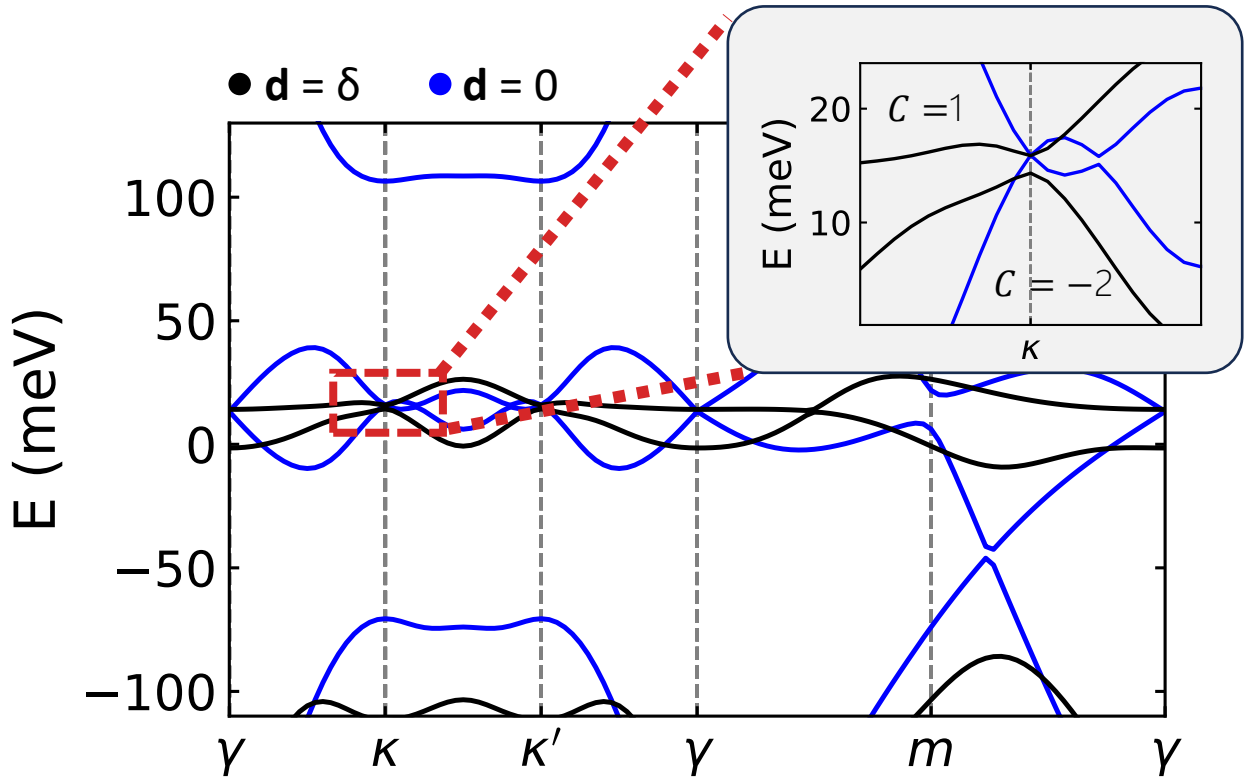

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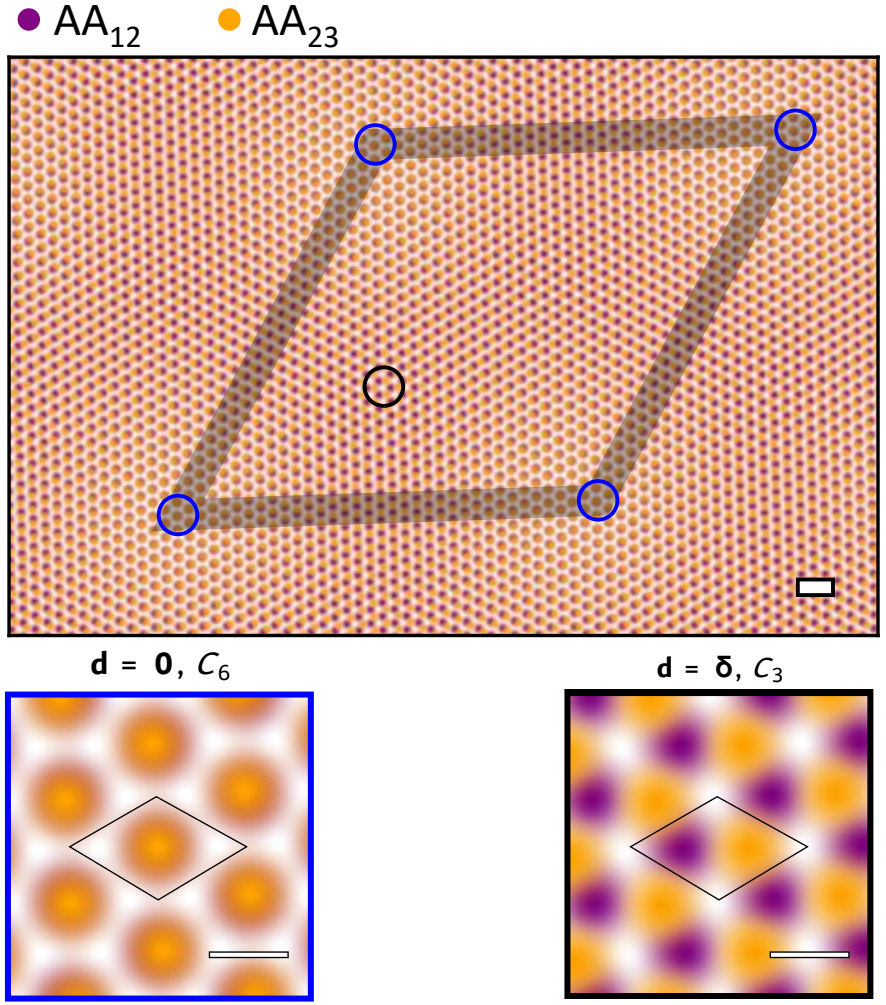
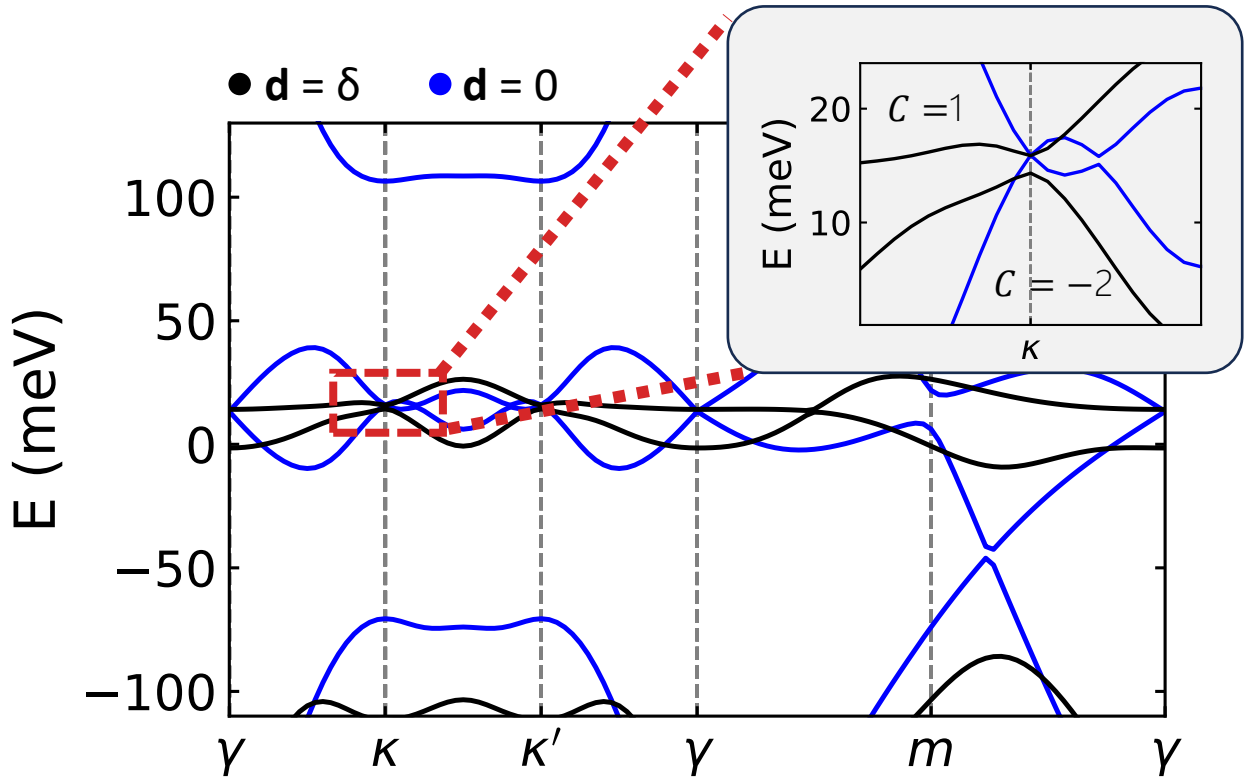


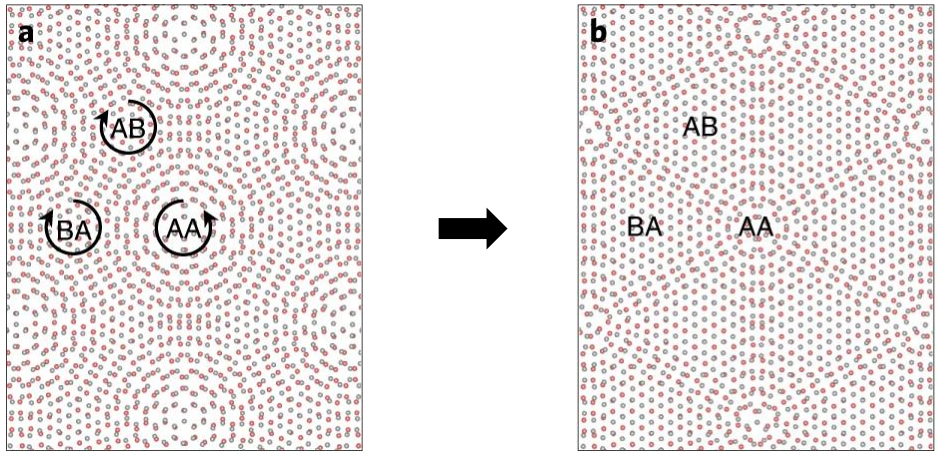


How do we weight intermoiré shifts?

Yang, et al. PRB (2024)
Nakatsuji, et al. PRX (2023)
Foo, et al. PRR (2024)
Bistritzer and MacDonald, PNAS (2011)

Lattice relaxation on the supermoiré scale

Relaxation at the moiré scale



Yoo et al. Nat. Nano. (2019)
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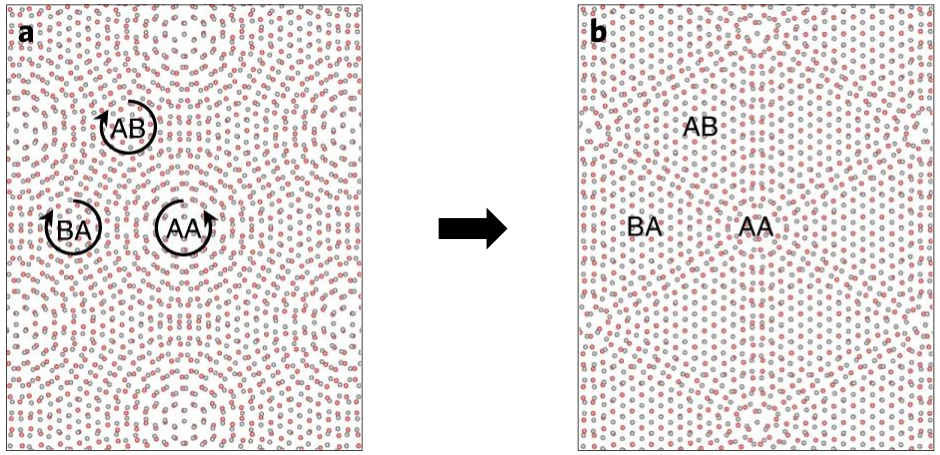

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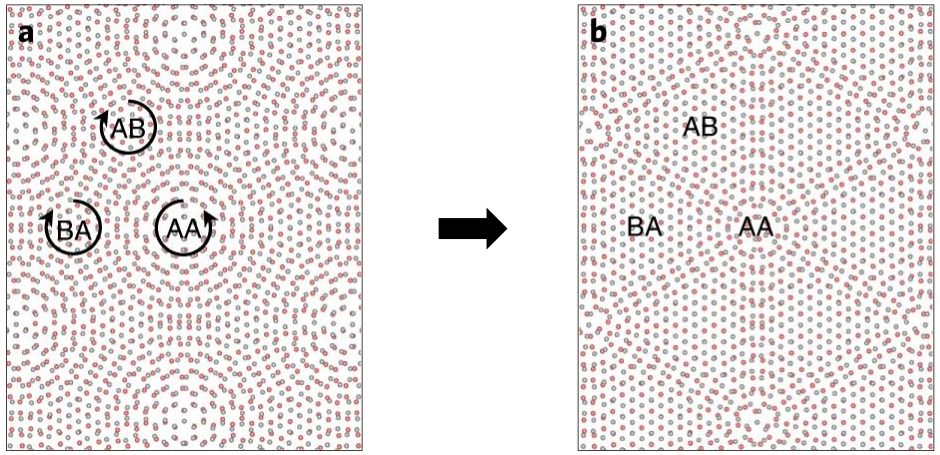
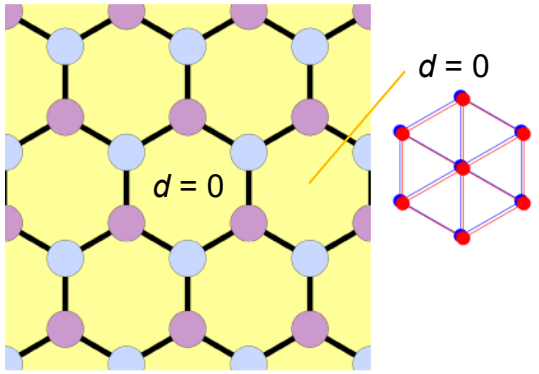
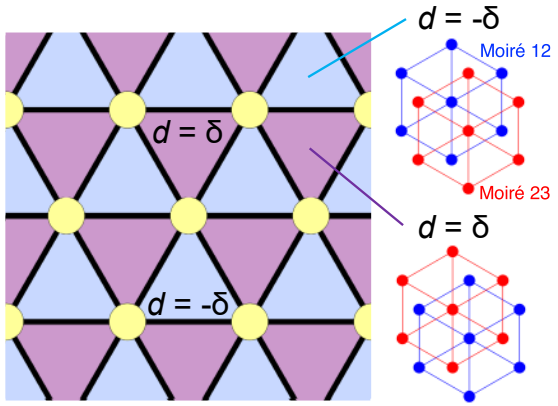


Relaxation at the supermoiré scale

Alternating



Helical



Yoo et al. Nat. Nano. (2019)
Nakatsuji, et al. PRX (2023)

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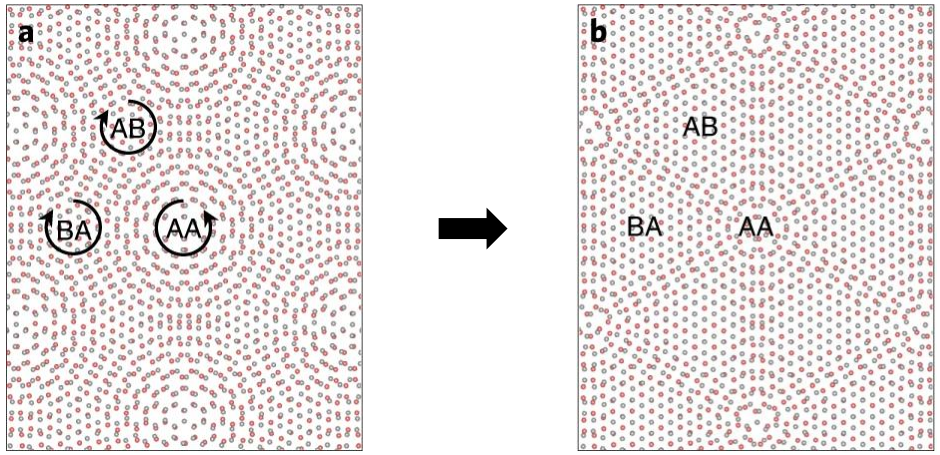
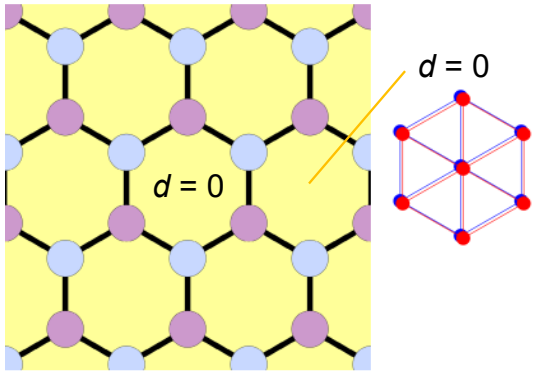
Relaxation at the moiré scale



Relaxation at the supermoiré scale

Alternating



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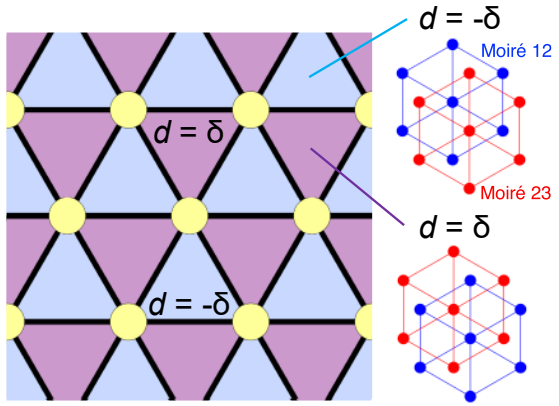
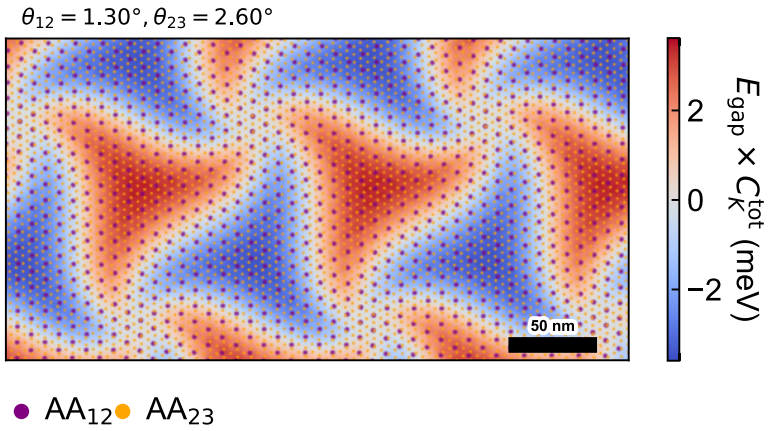
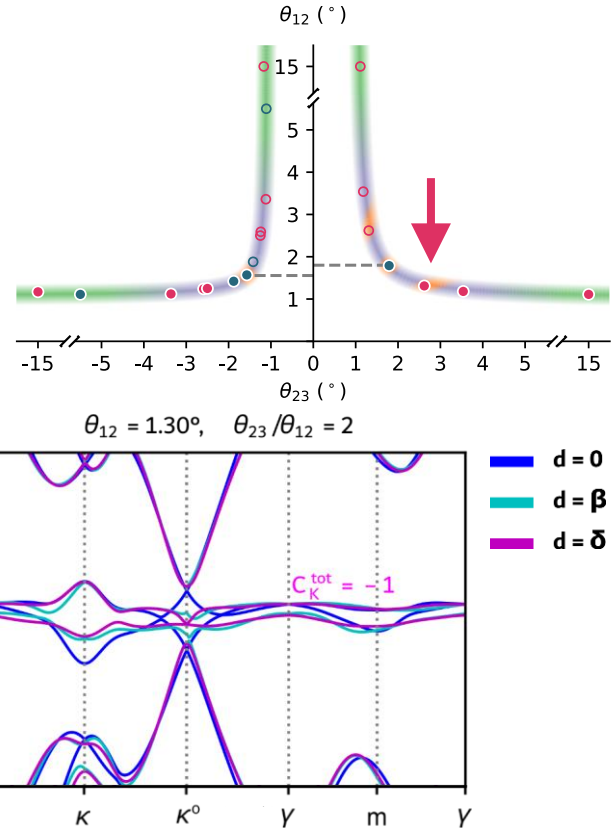


MATTG: *d*=0 domains ~ superconductivity
MAHTG: *xy*-inversion broken domains! ~ AH

Yoo et al. Nat. Nano. (2019)
Nakatsuji, et al. PRX (2023)

(2θ, θ) – Helical Trilayer Graphene





Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583

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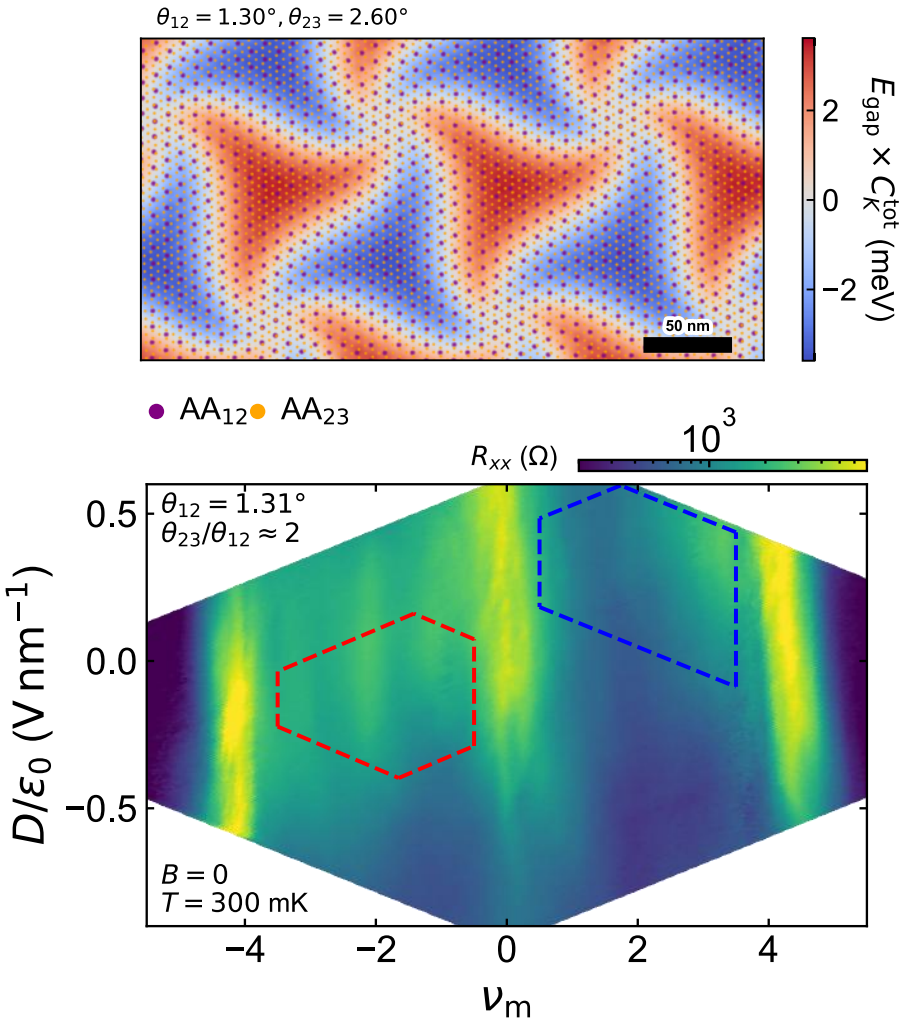

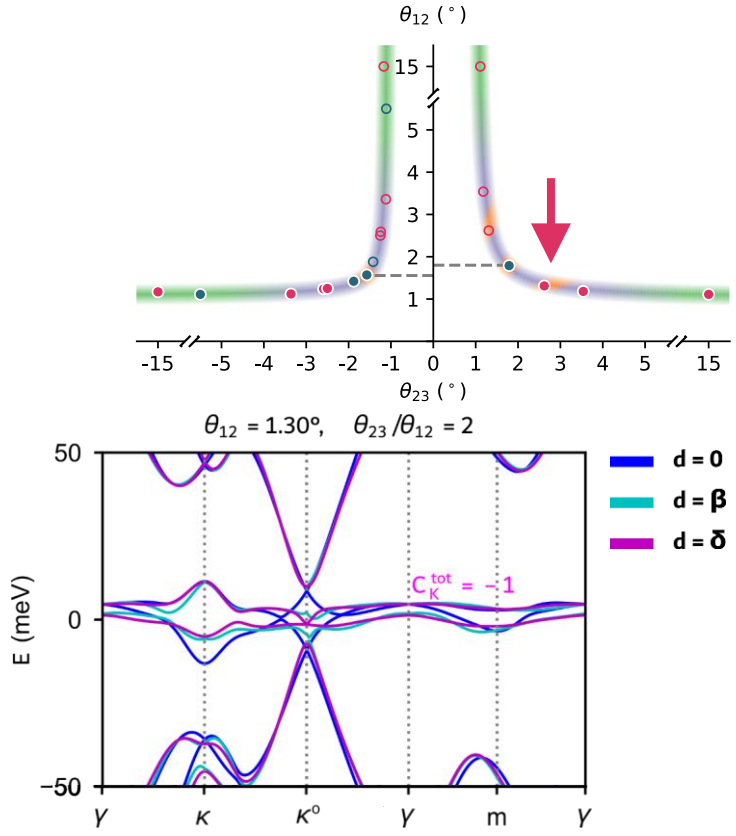

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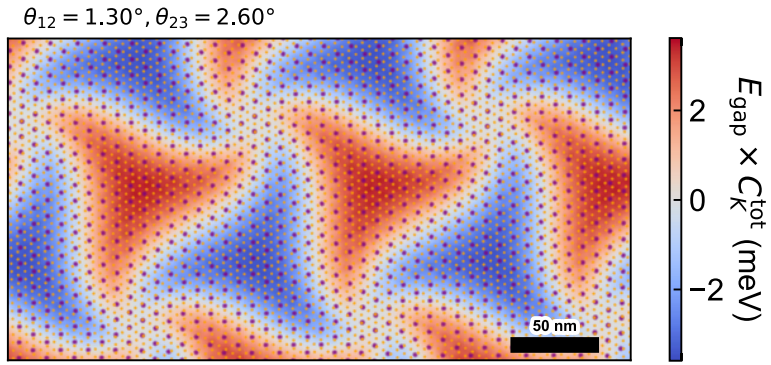
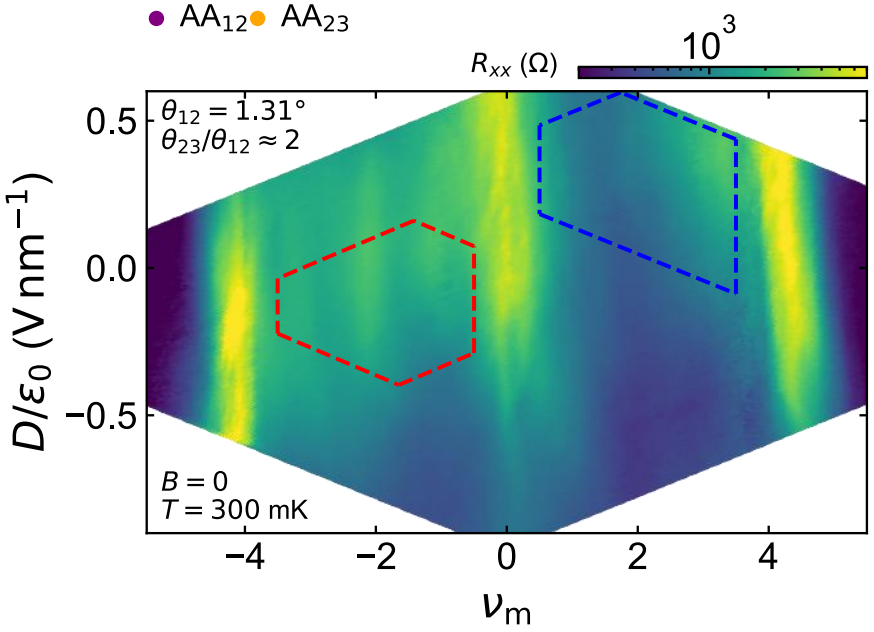
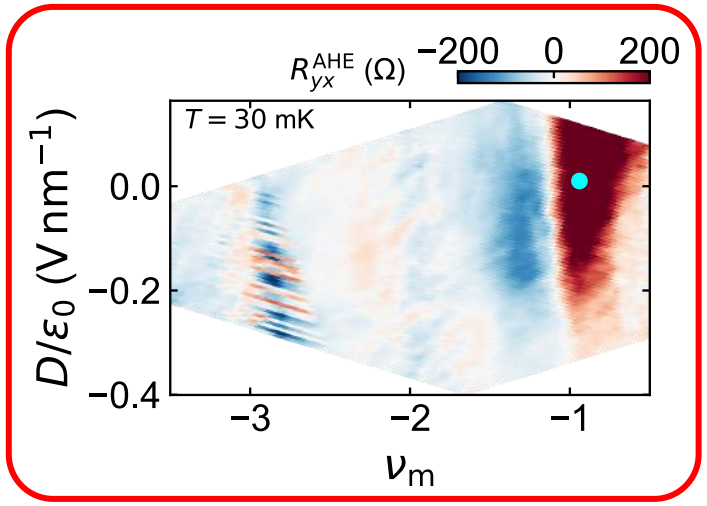
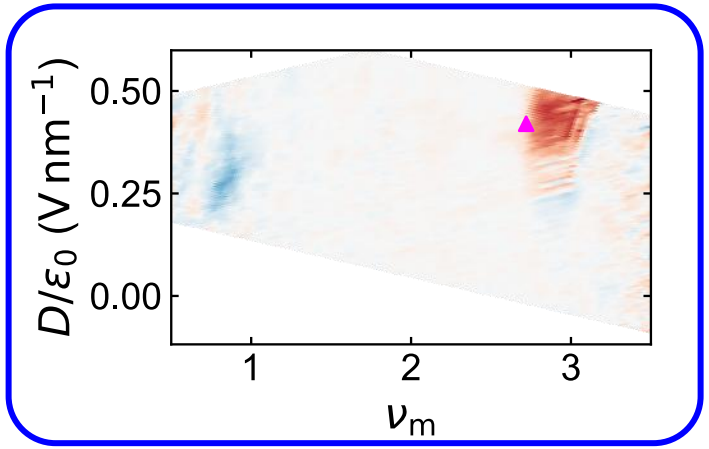
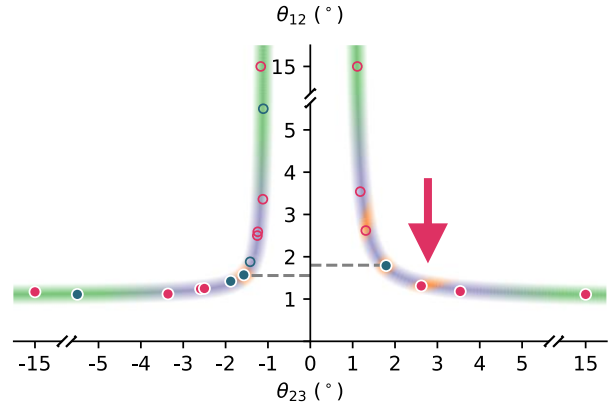
(2θ, θ) – Helical Trilayer Graphene

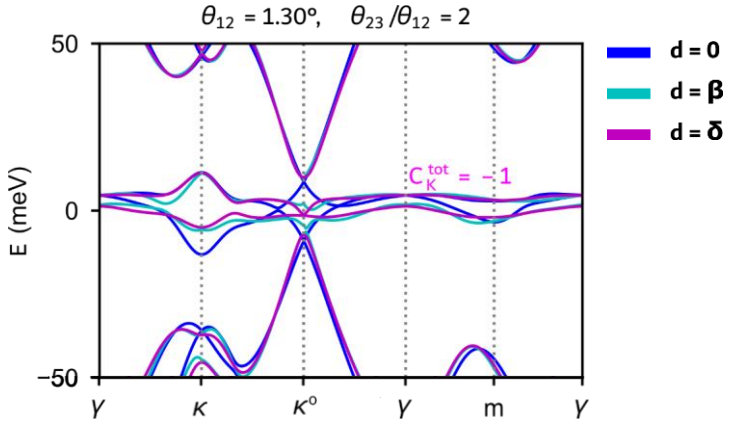












Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583

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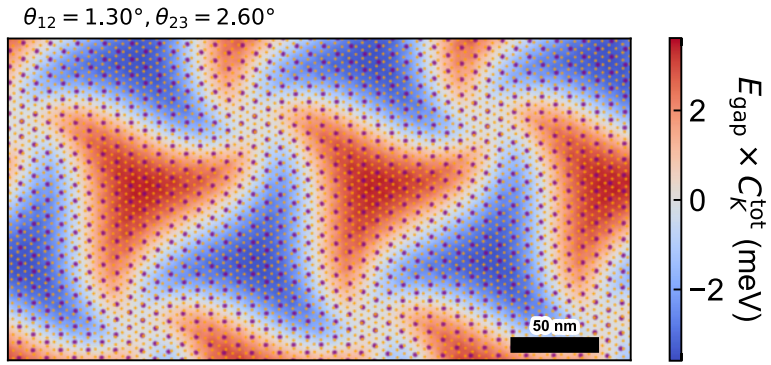
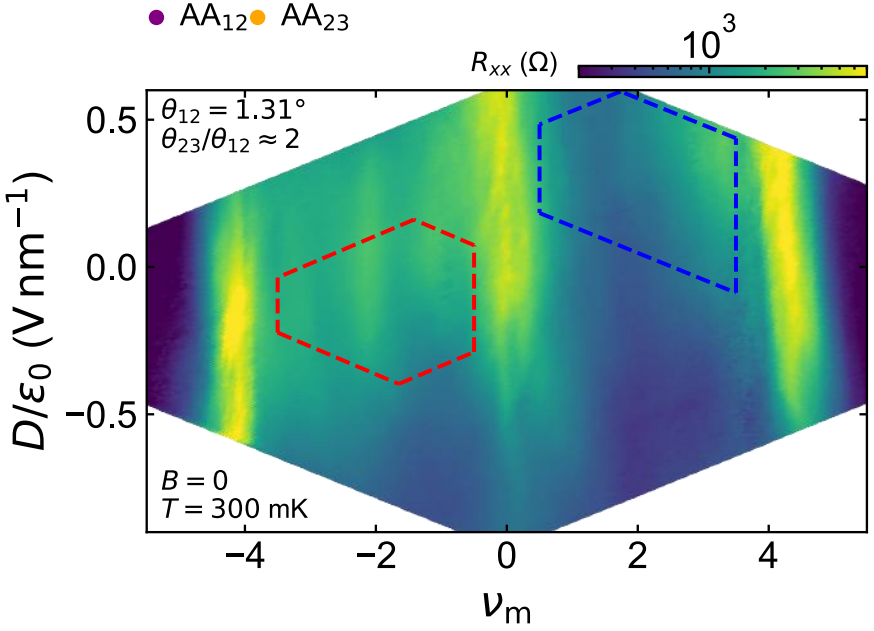
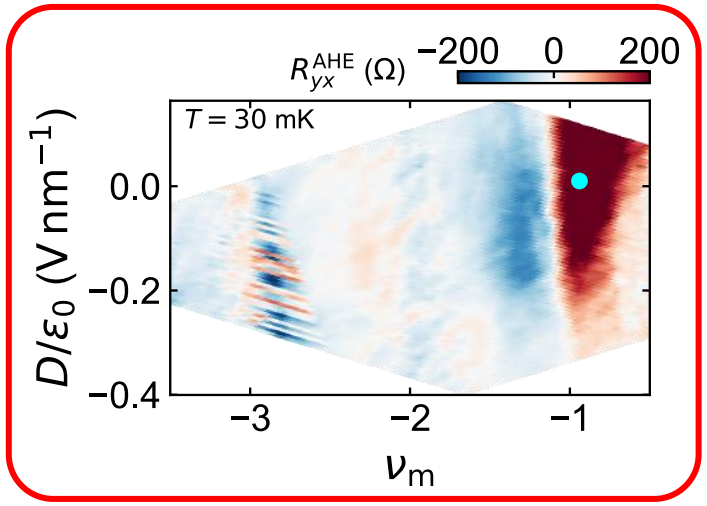
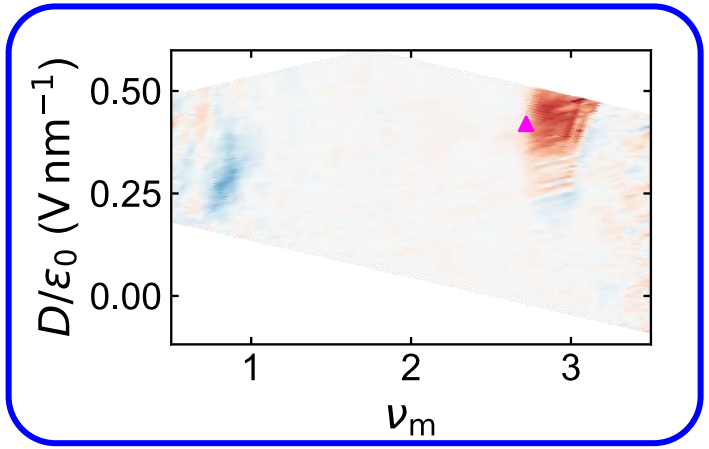
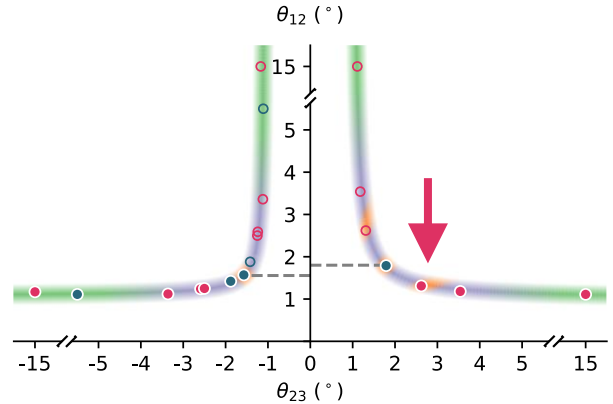
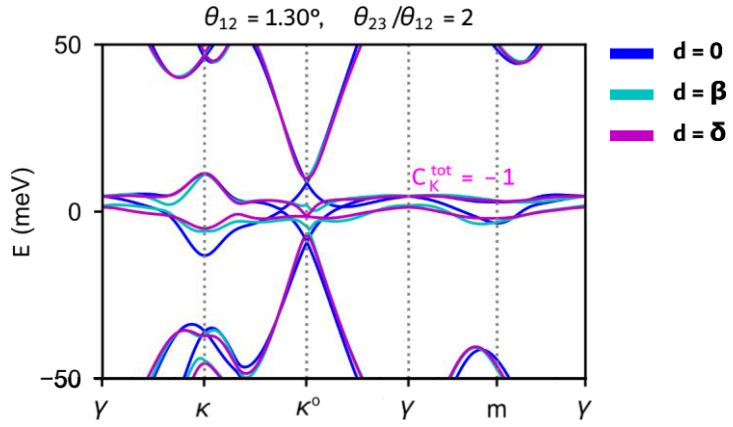


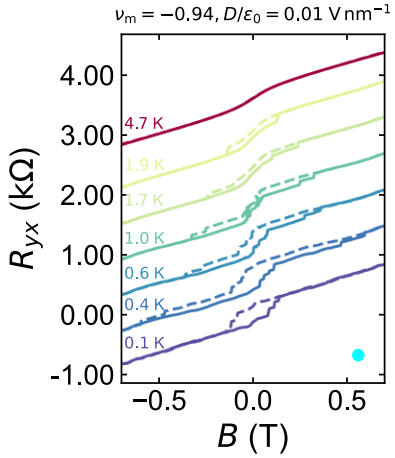


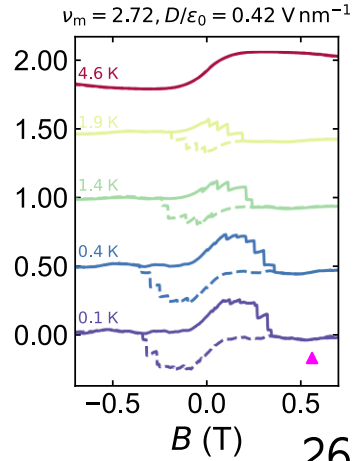






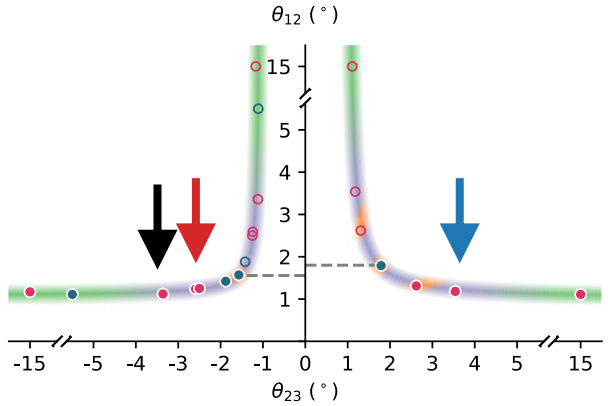


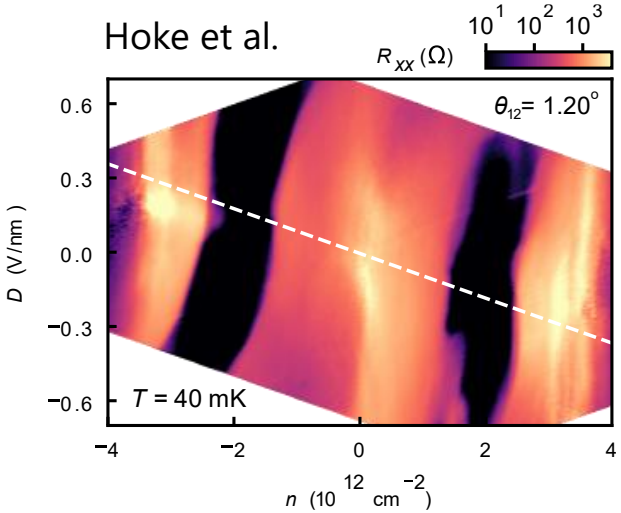




Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583

Weakly-Reconstructed TTG





$\theta_{12} \approx 1 - 1.4°$
$\theta_{23} \approx 3 - 3.5°$

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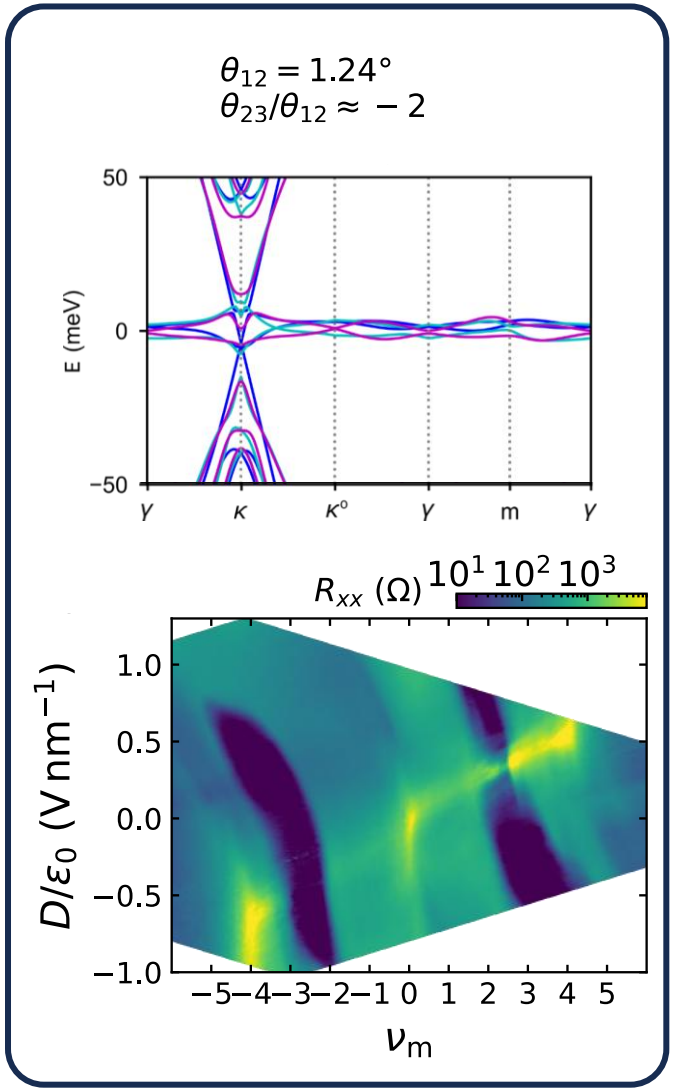

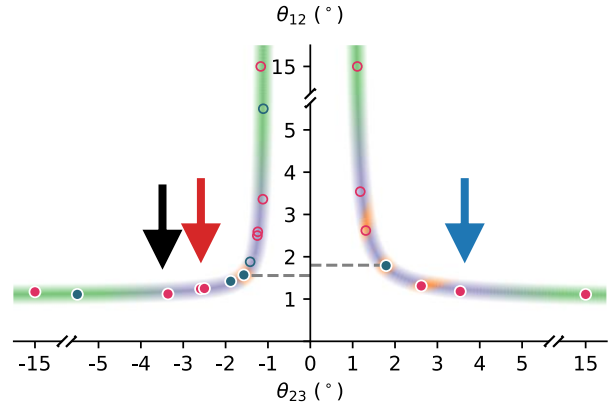

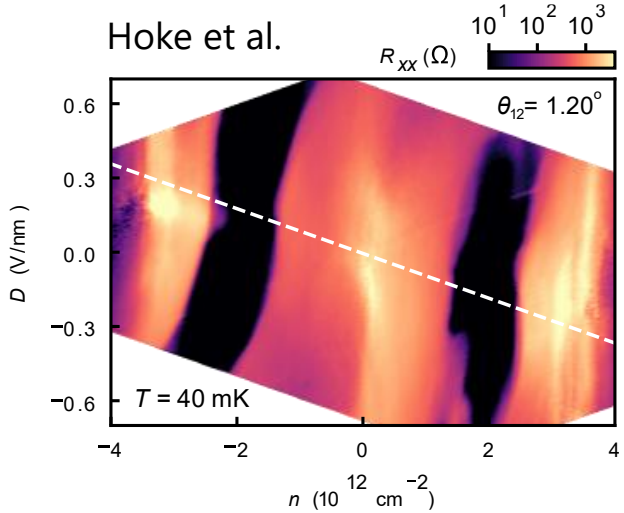

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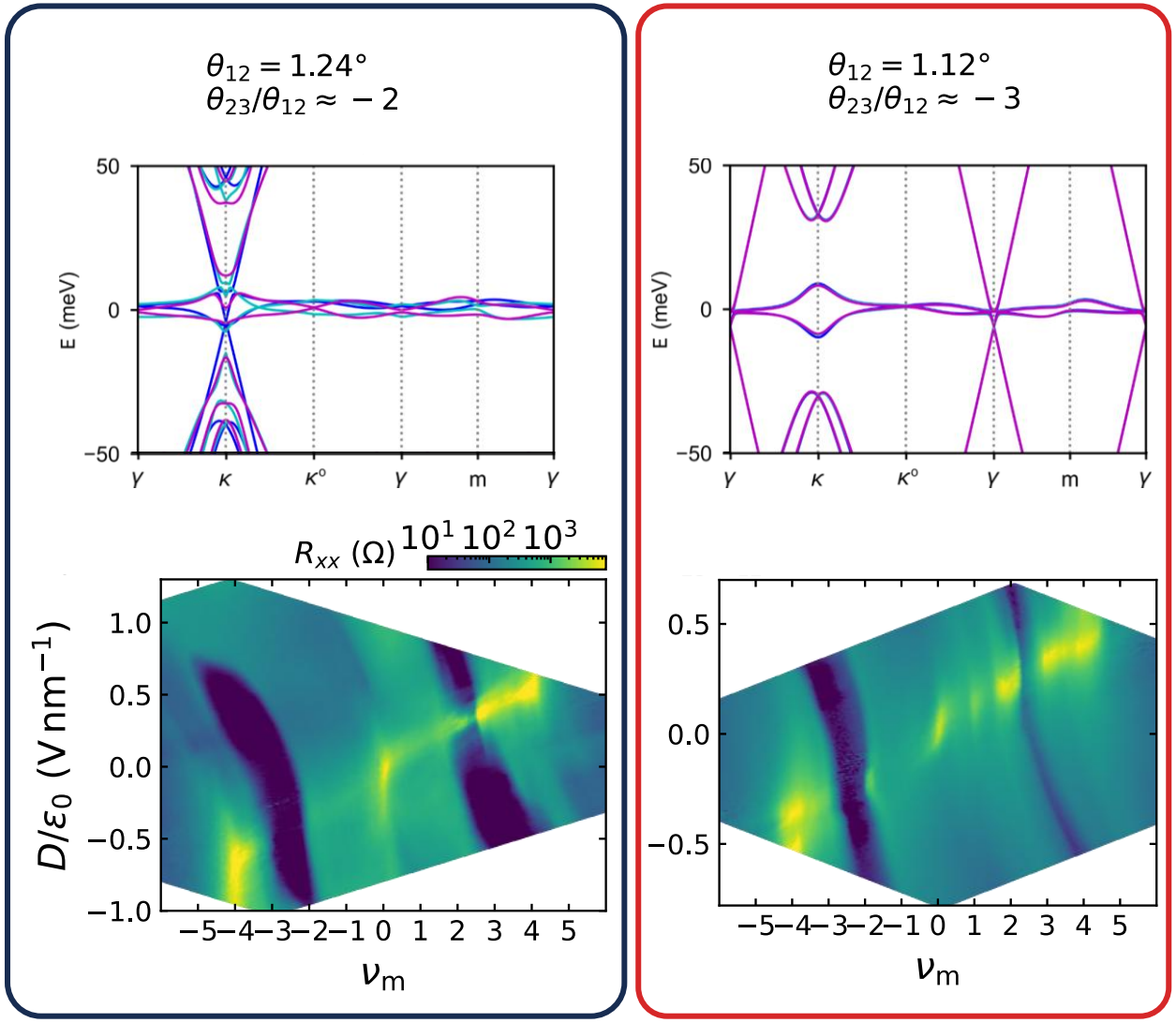

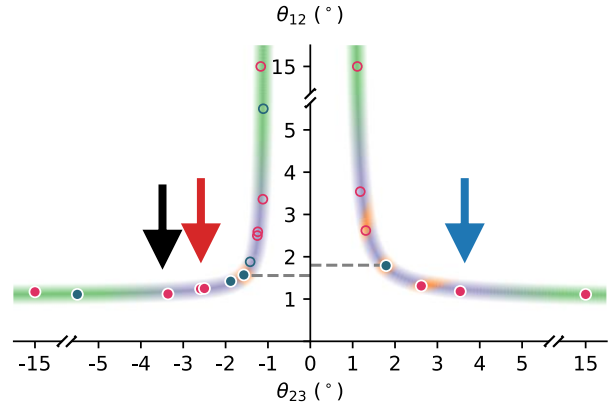

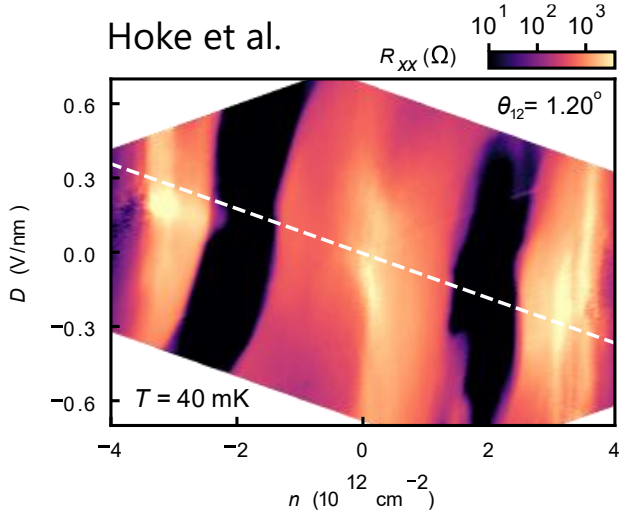

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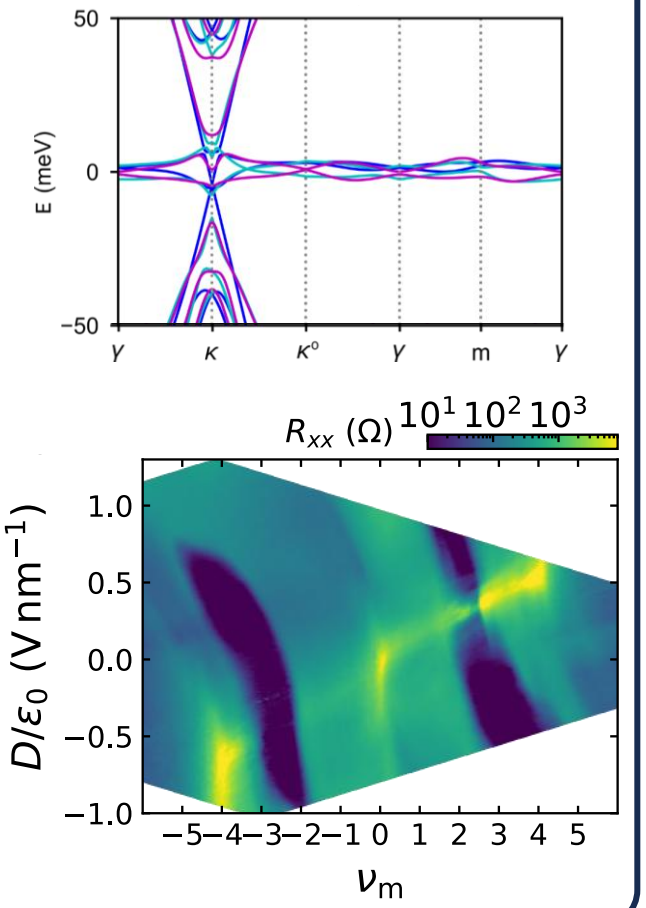
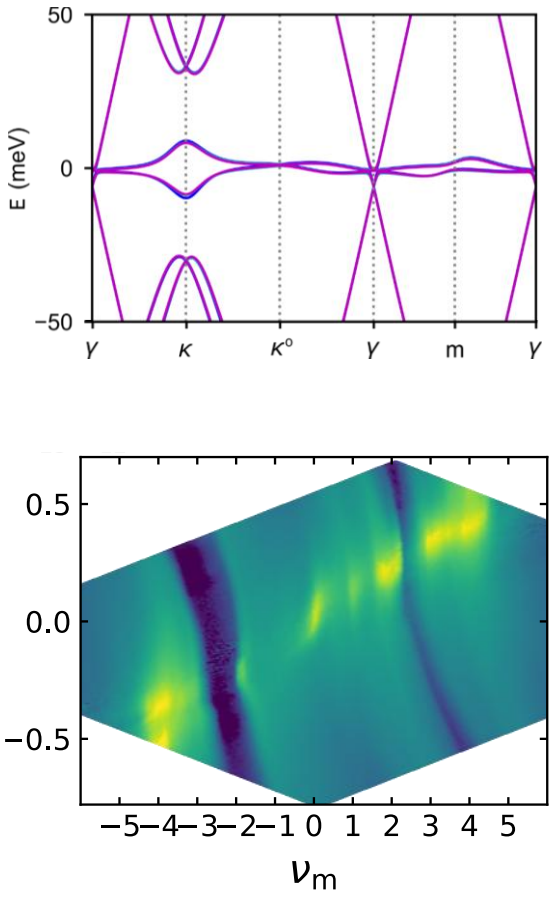
Weakly-Reconstructed TTG

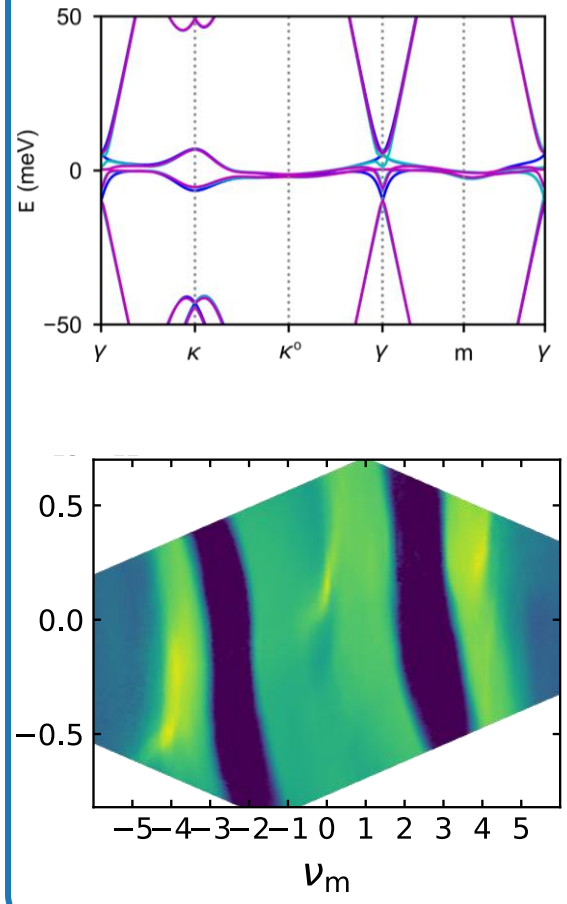
$\theta_{12} = 1.24°$
$\theta_{23}/\theta_{12} \approx -2$

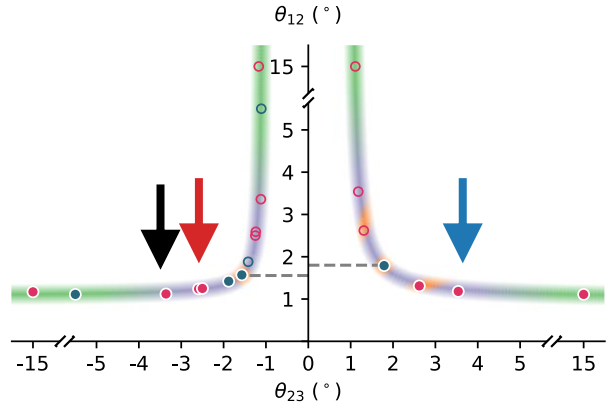


$\theta_{12} = 1.12°$
$\theta_{23}/\theta_{12} \approx -3$

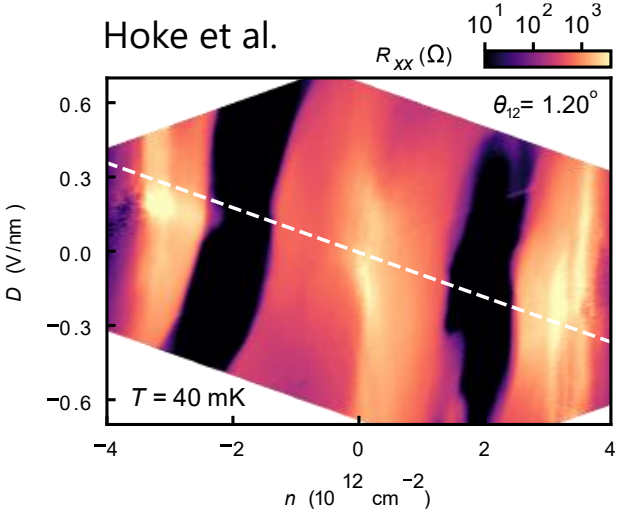


$\theta_{12} = 1.18°$
$\theta_{23}/\theta_{12} \approx 3$





Hoke et al.



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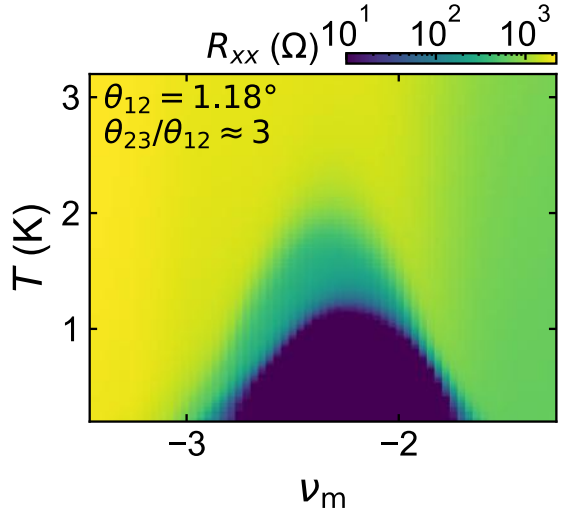
Supermoiré-modulation of superconductivity?



Eley, et al. Nat. Phys (2011)
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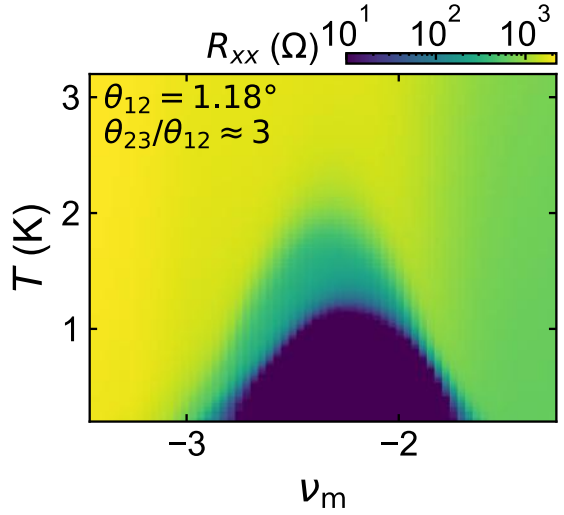
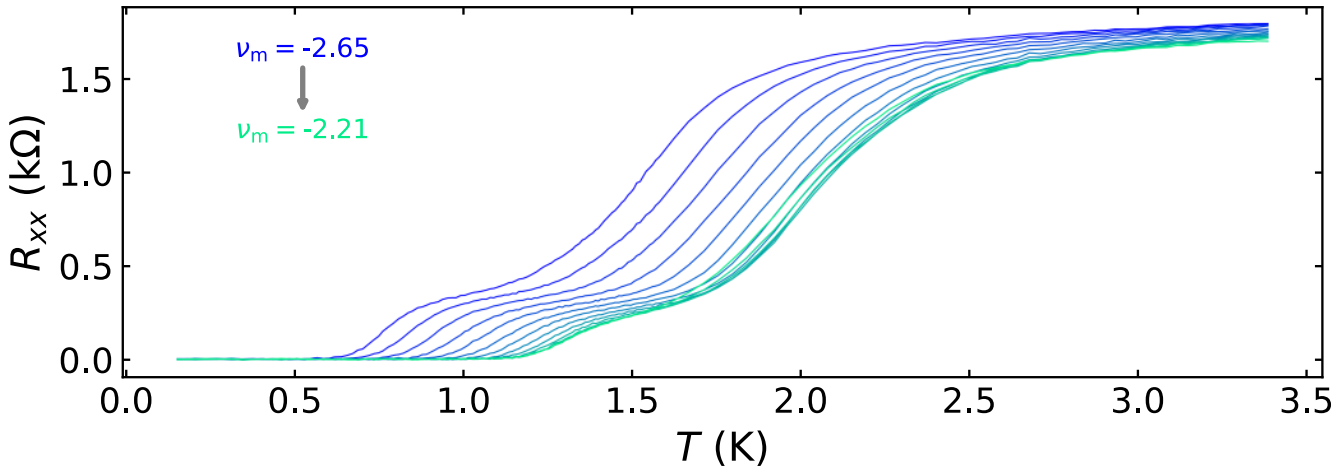
Supermoiré-modulation of superconductivity?





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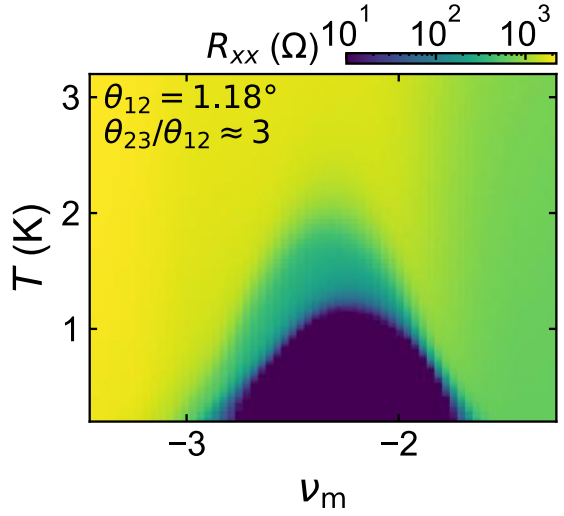
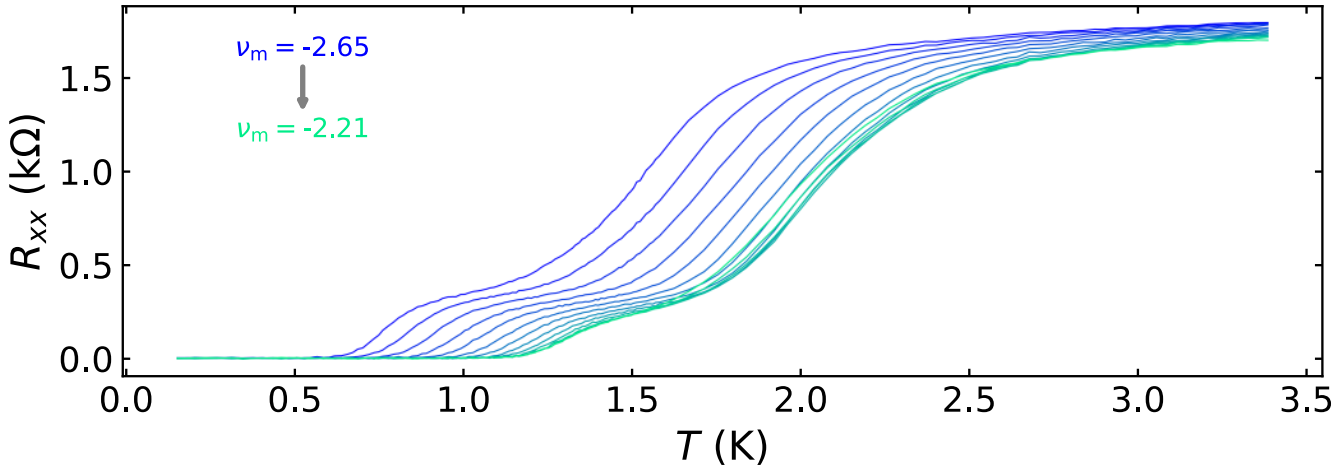
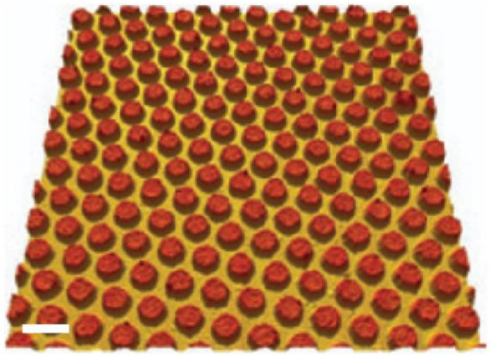
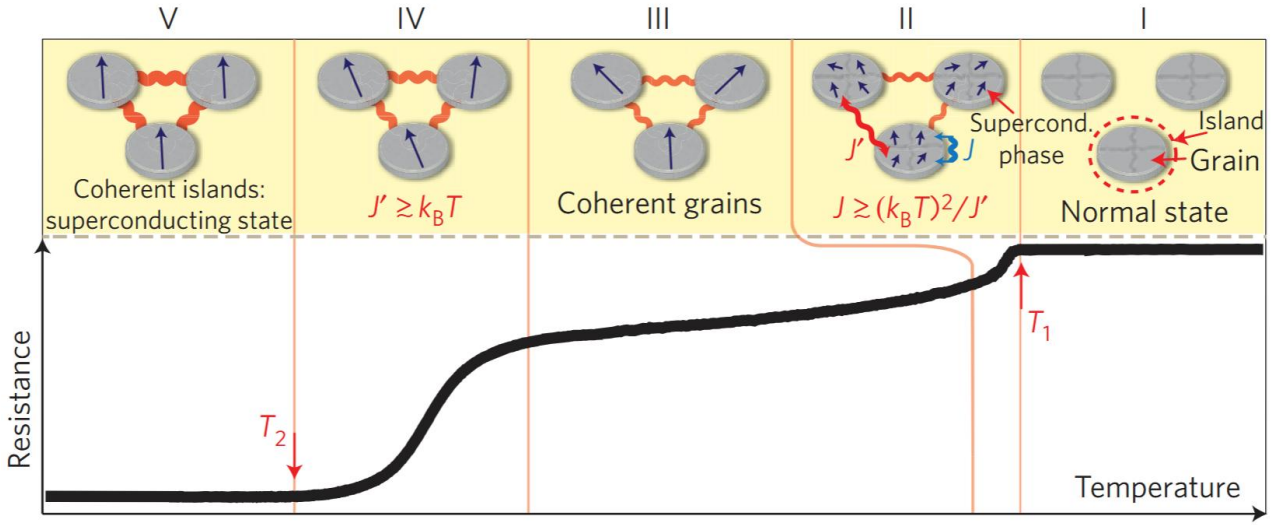




Nb islands on Au





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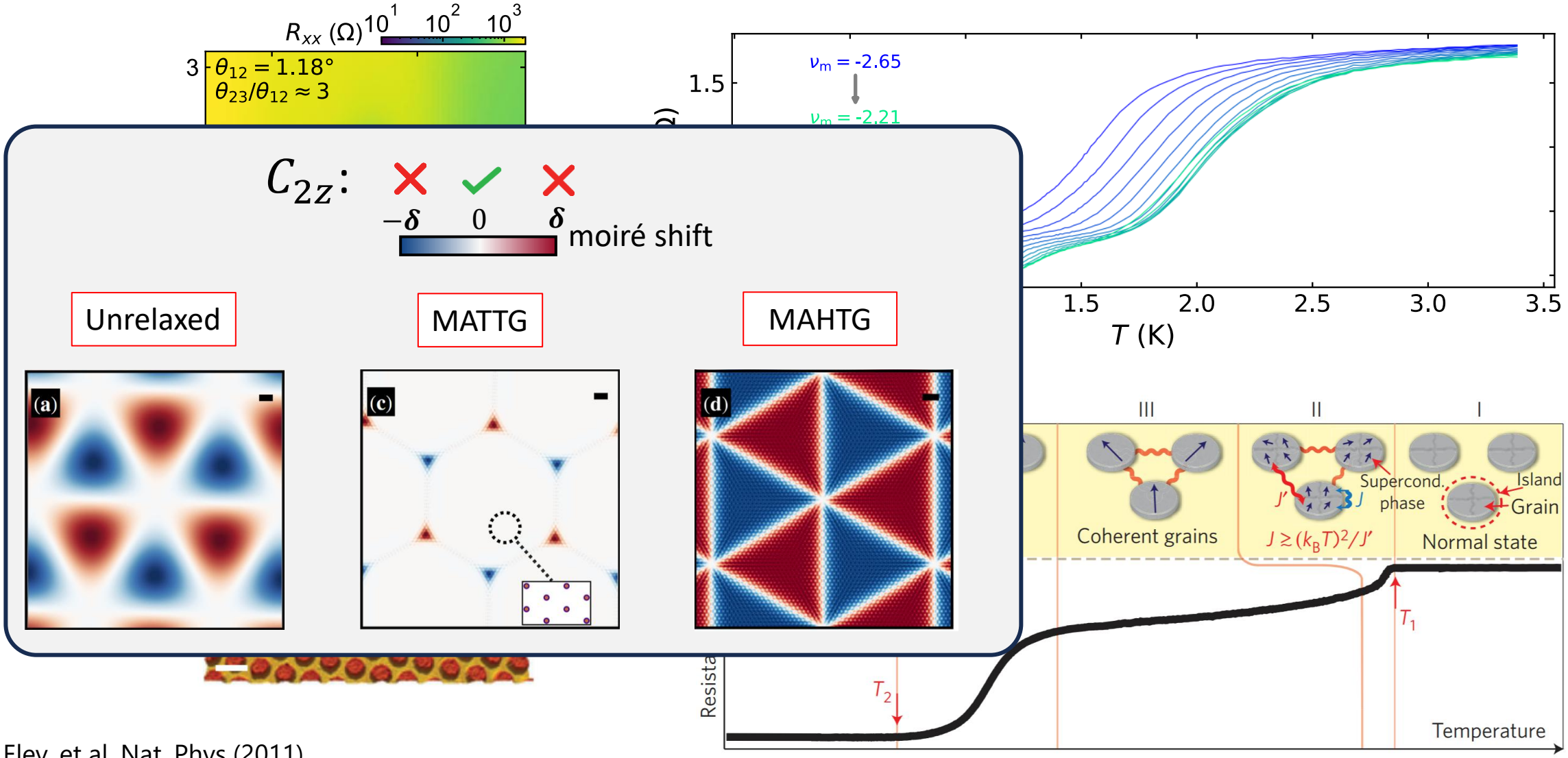

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Jesse Hoke


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Liqiao Xia


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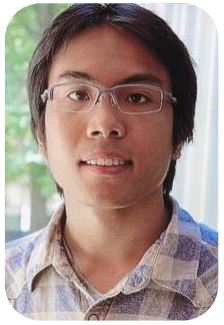
Jiaoji Yan


Ben Feldman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Jarillo-Herrero


Liang Fu


Jurgen Smet

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National High Magnetic Field Laboratory

Main takeaways:

1. VdW systems are an exciting platform for exploring the interplay between **electronic correlations** and **topology**
2. Experimentally, **distinct correlated phenomena** at different points in **angle-angle space**.
3. Driver of phenomenology is more subtle than **helical vs alternating stacking**. Our modeling suggests **lattice relaxations** are paramount.
4. Through **local thermodynamic probes and transport,** we study evolution of correlations in a narrow region of this space. We find a **link between compressibility and superconductivity.**