Quantum Electronic Phases in Twisted Trilayer Graphene

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UCSD

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arXiv: 2509.07977
arXiv: 2509.03583

Slides available @ aaronsharpe.science

When interactions meet topology

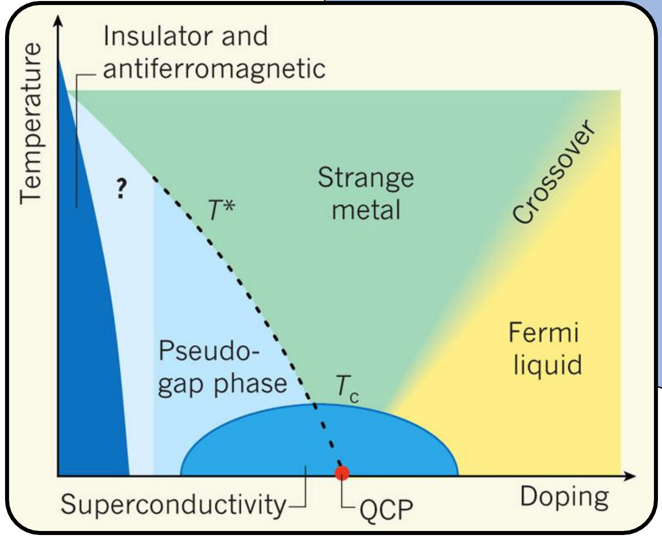
Electronic interactions

Mott insulators
Superconductivity
Magnetism
…

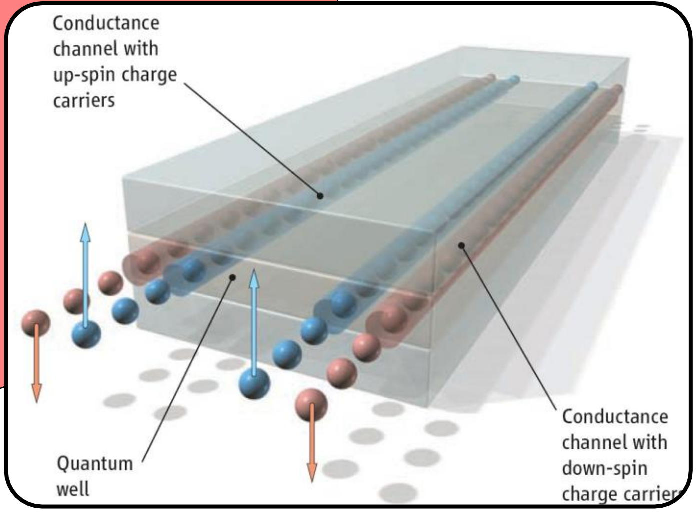
FQHE
FCI
…

Nontrivial topology

Quantum Hall states
Topological materials
…



Varma, Nature (2010)



König, et al., Science (2007)

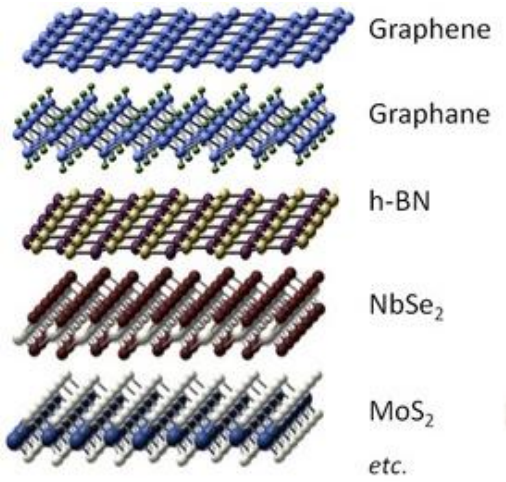
Van der Waals materials with a twist

(semimetal)

insulator

superconductor

semiconductor



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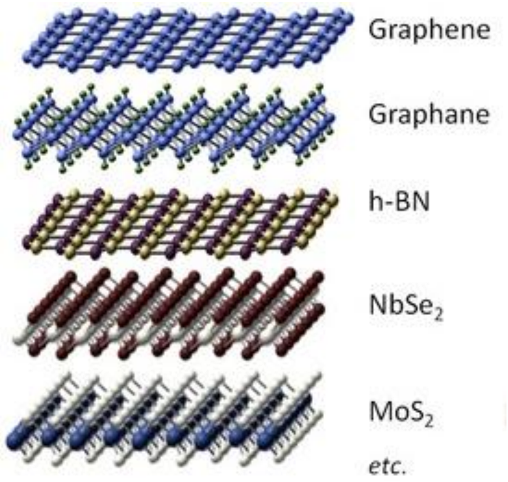

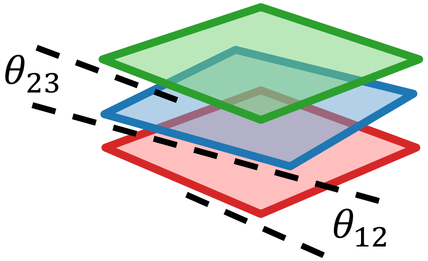

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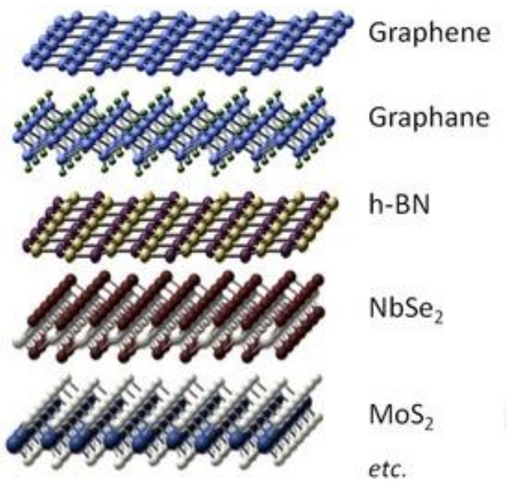

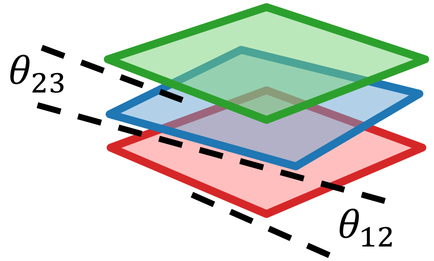

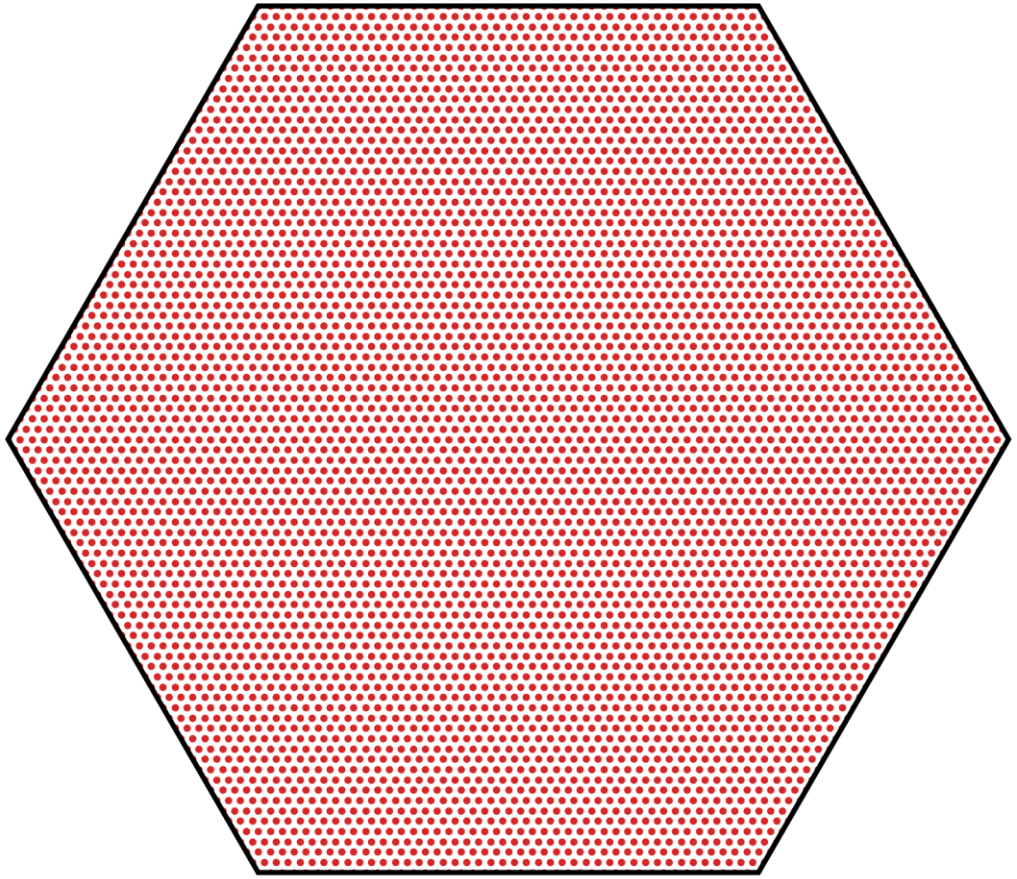

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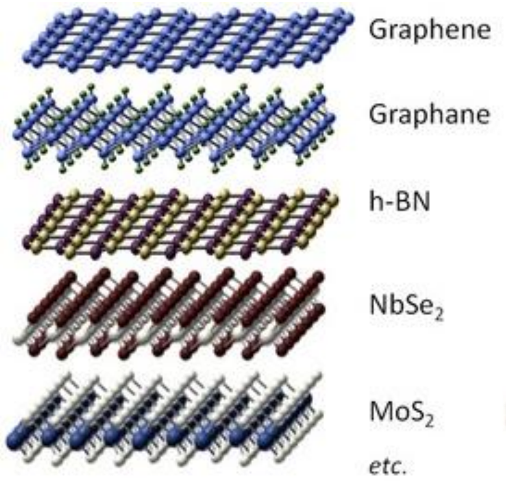

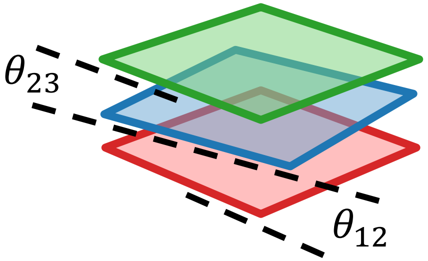

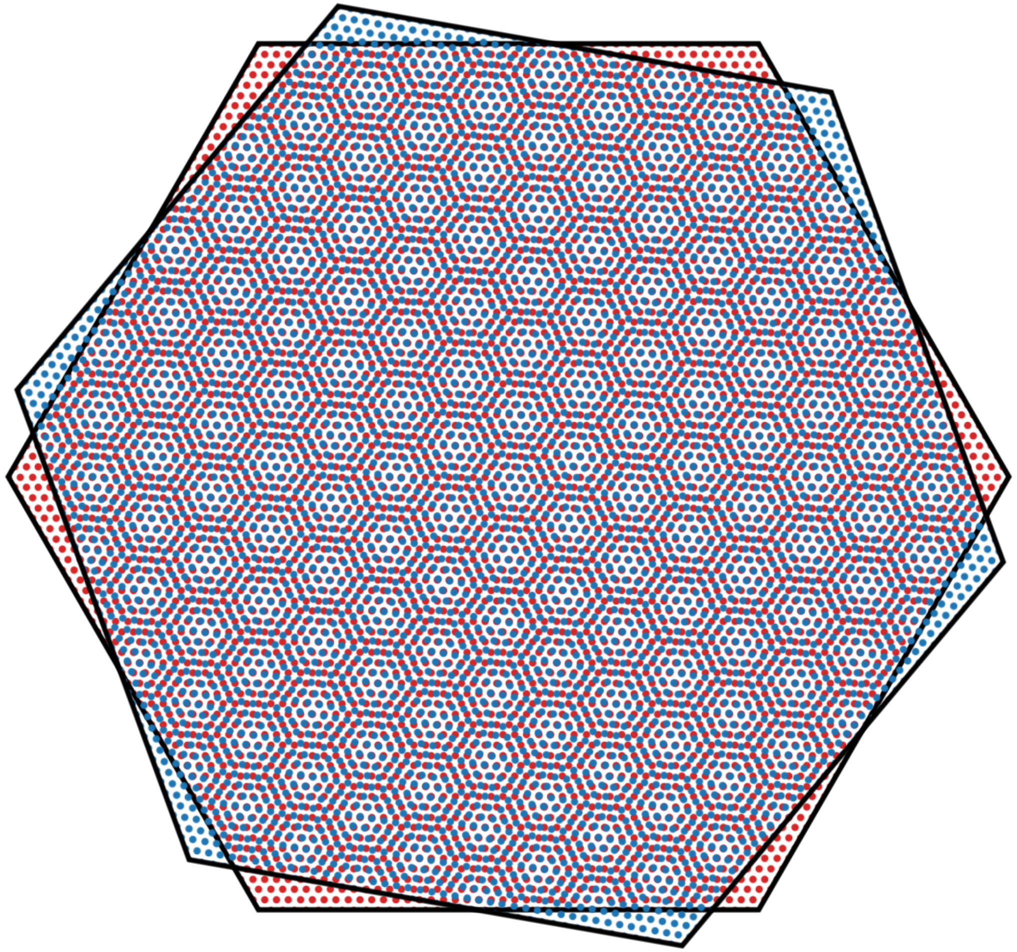

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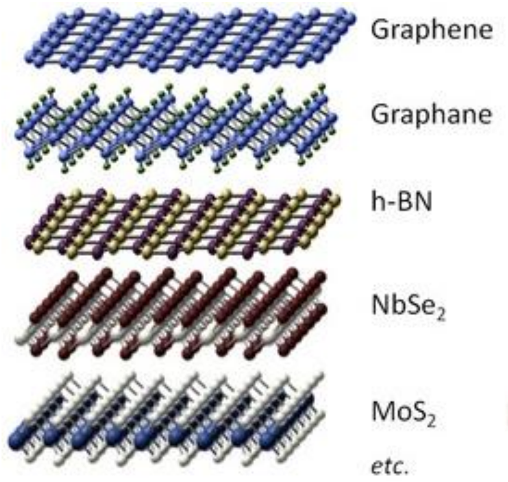

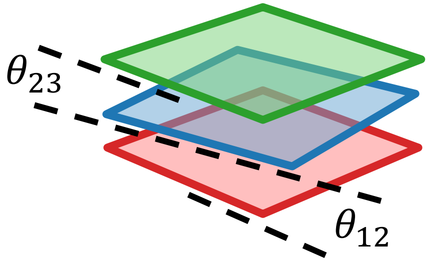

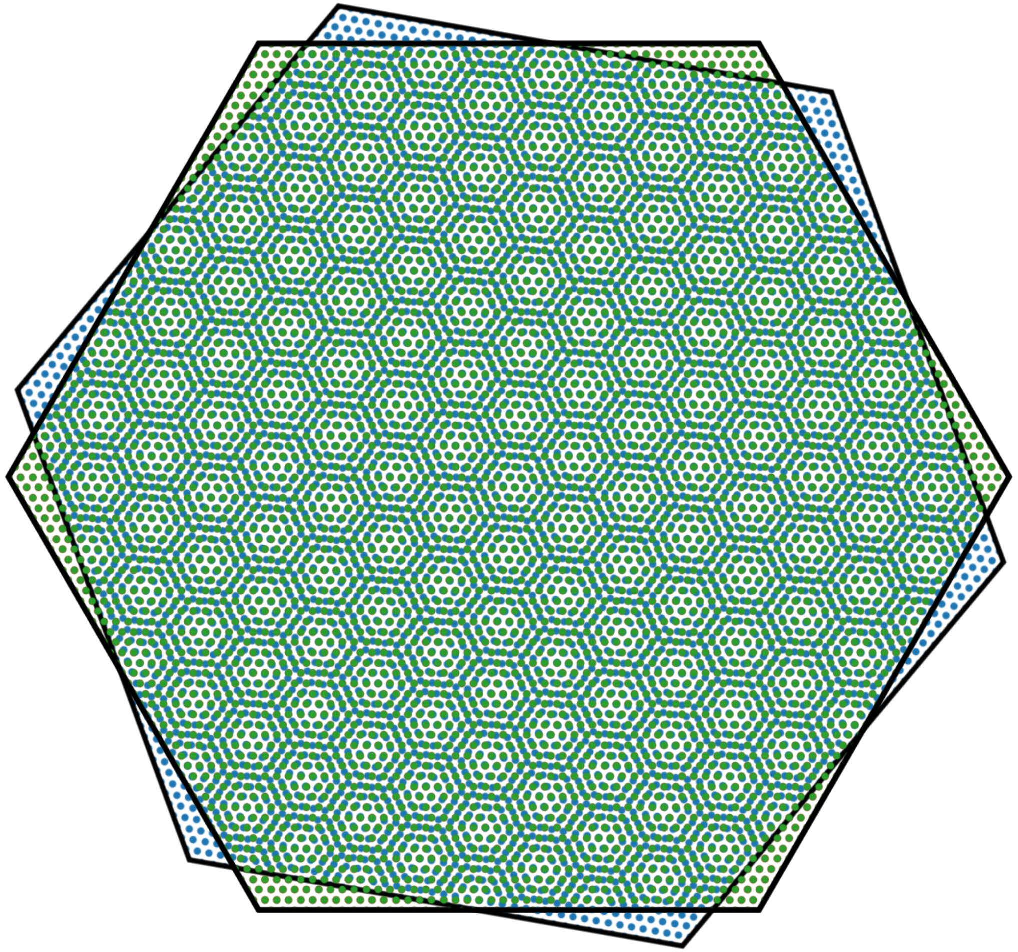

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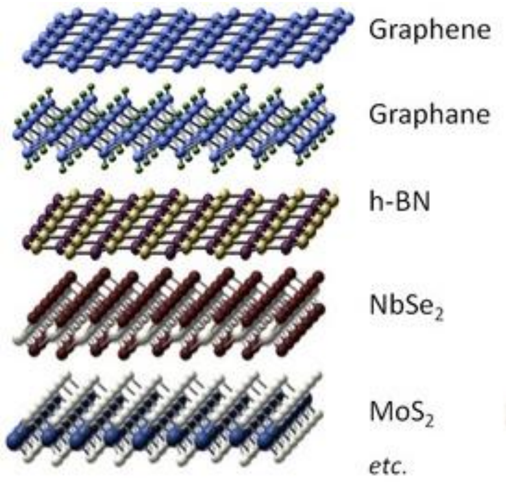

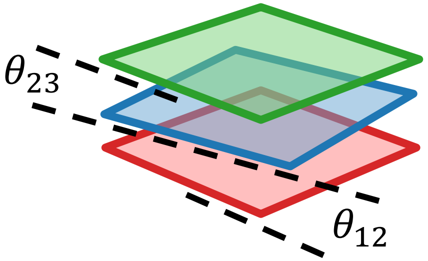

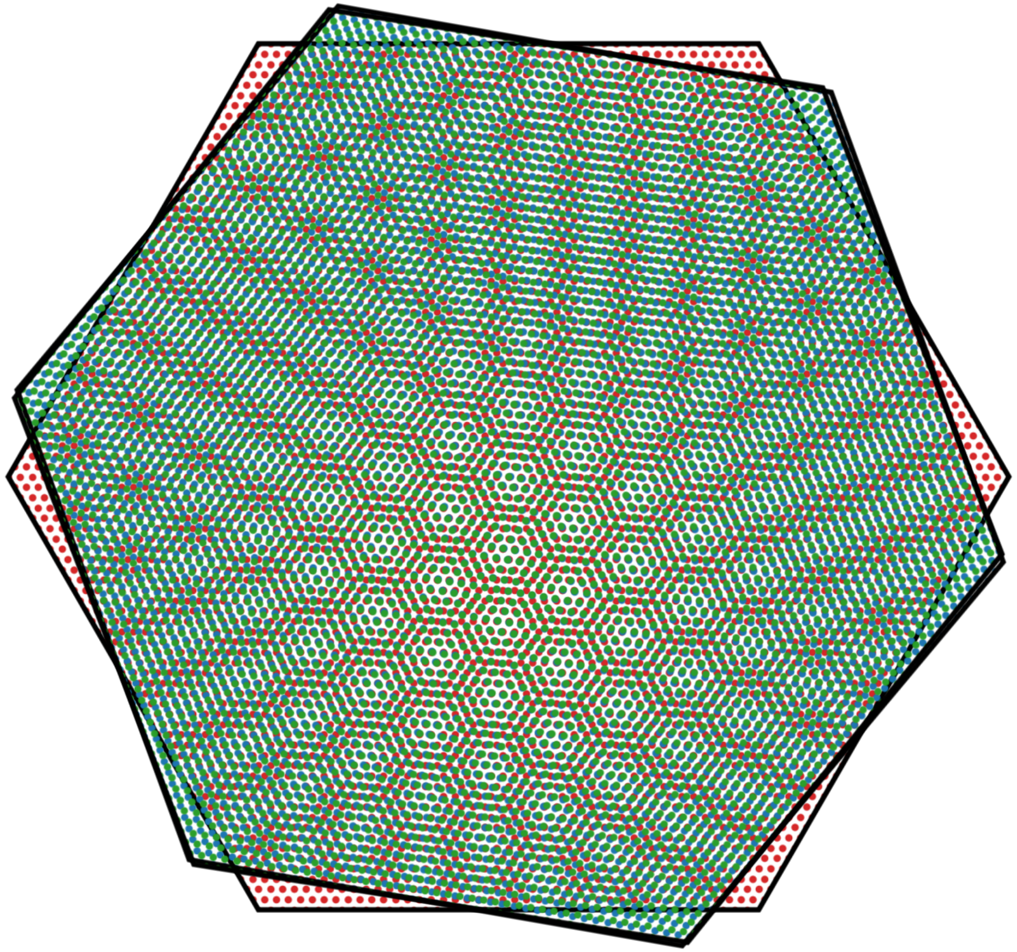

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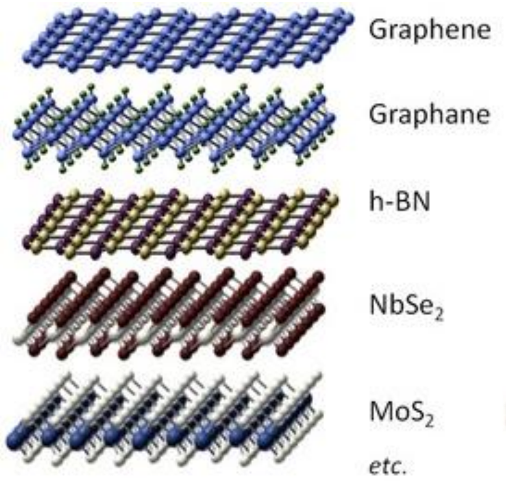
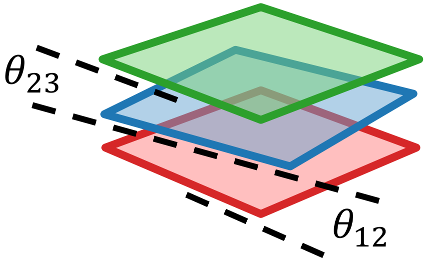
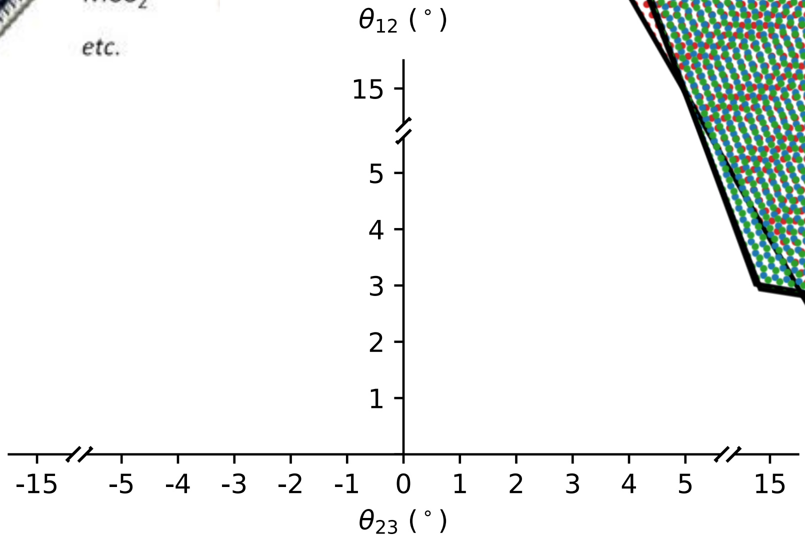
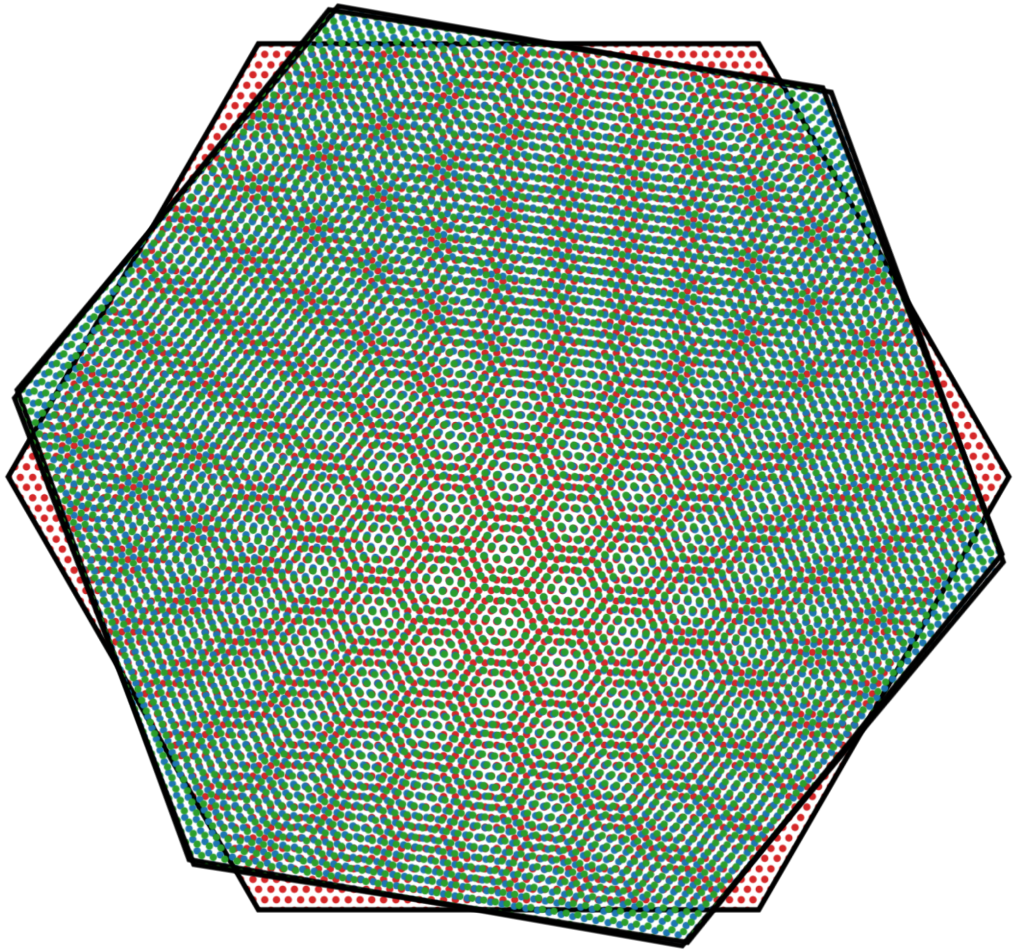






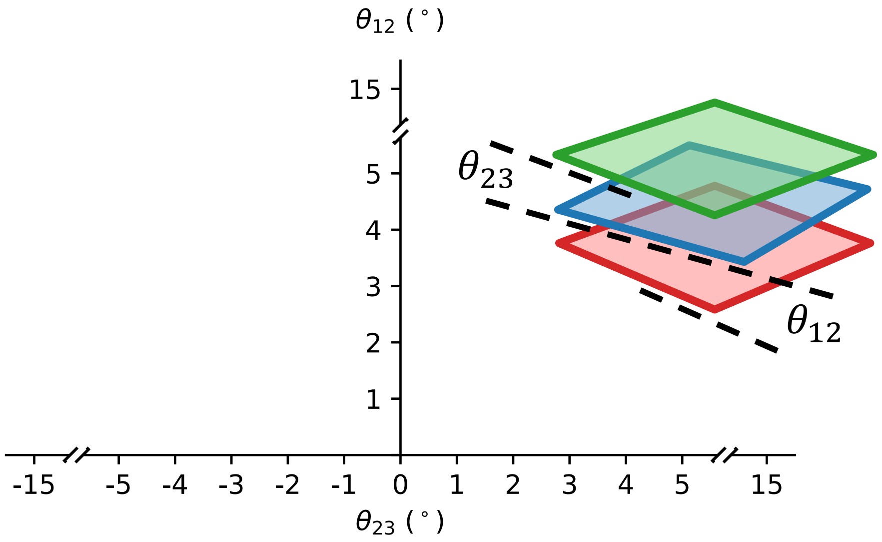


Outline

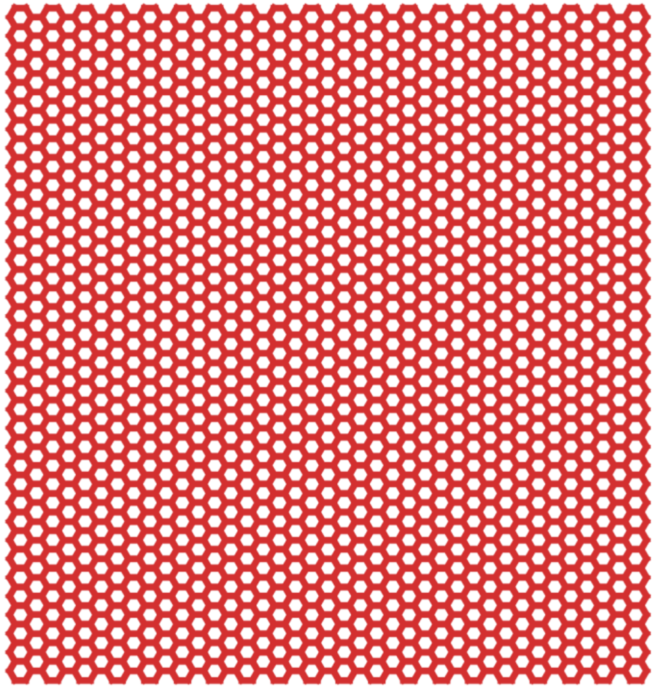
Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation

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



Bandstructure engineering with moirés



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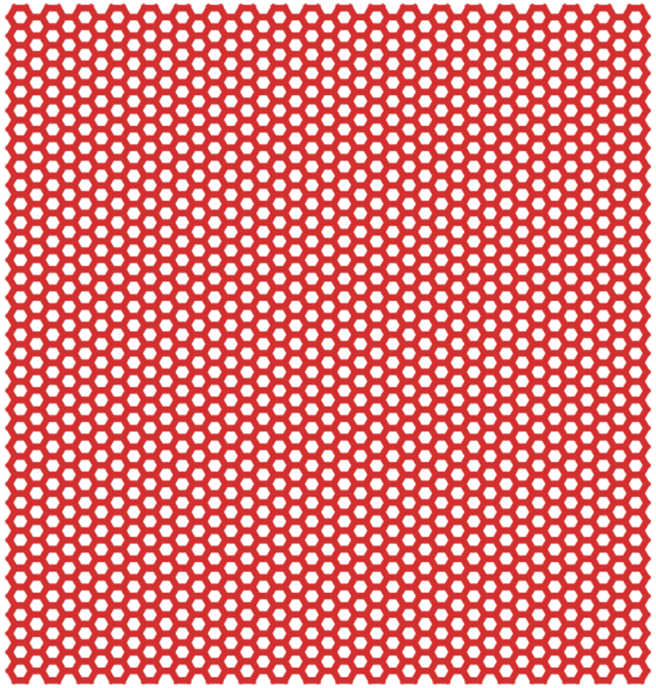

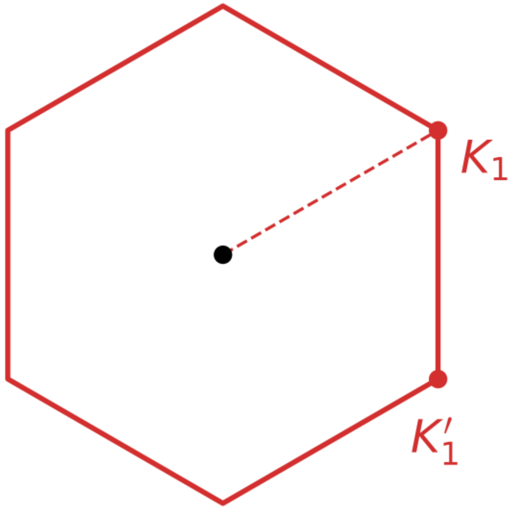

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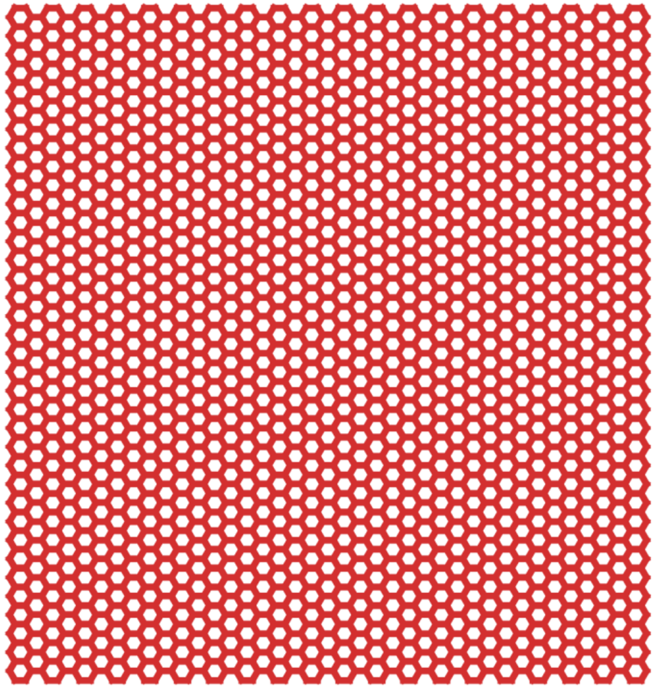

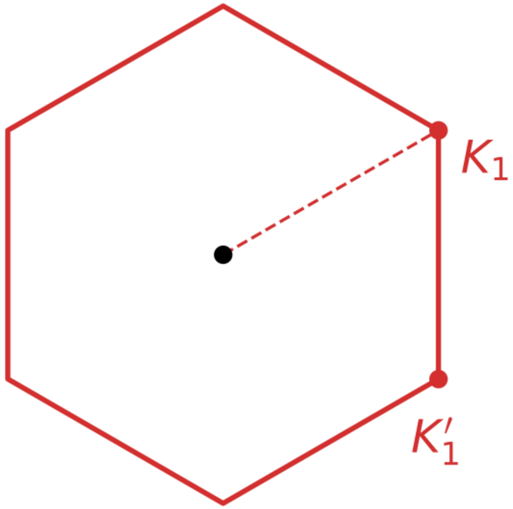

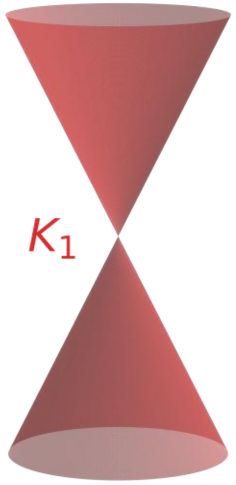

4-fold degenerate
spin x valley

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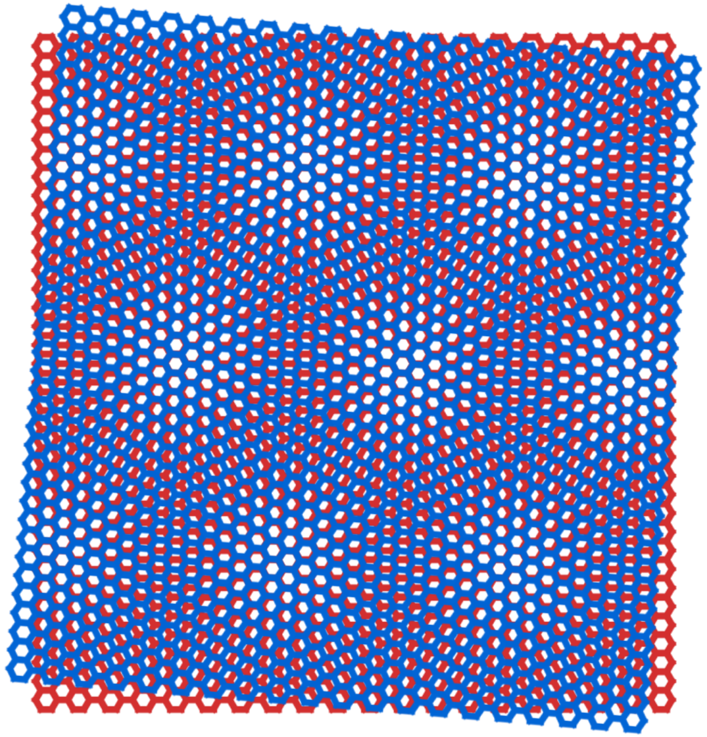

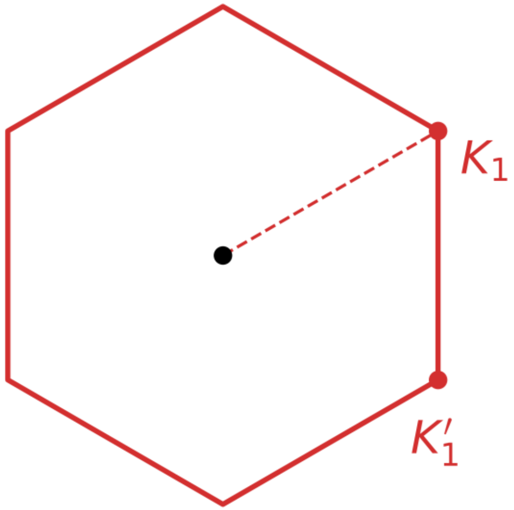

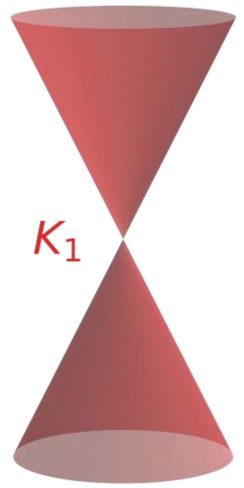

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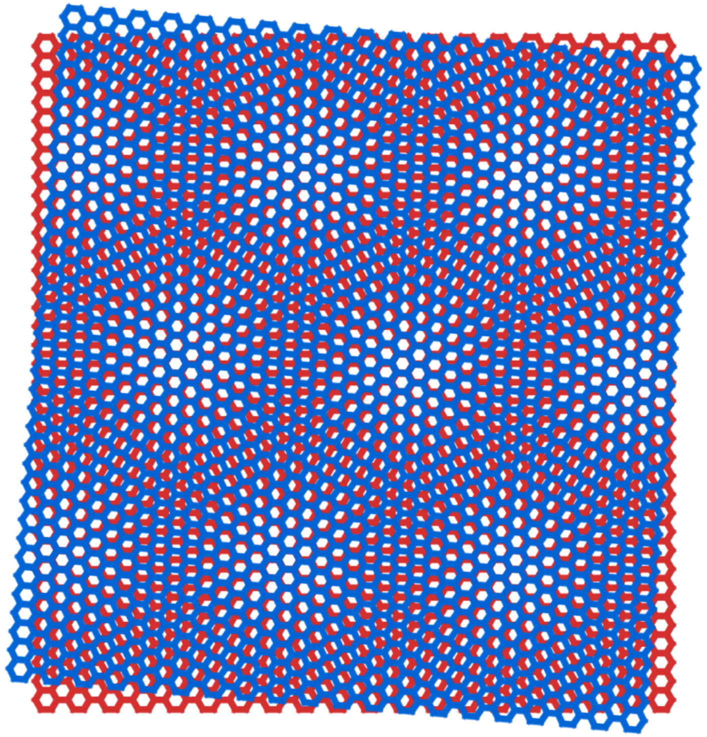

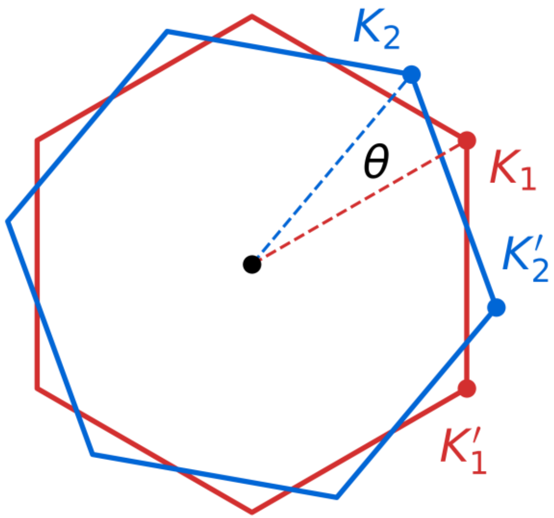

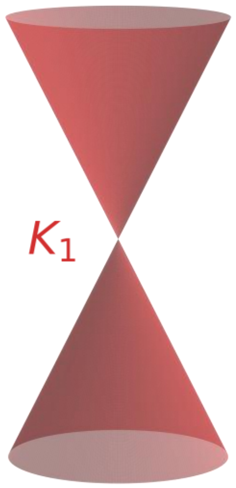

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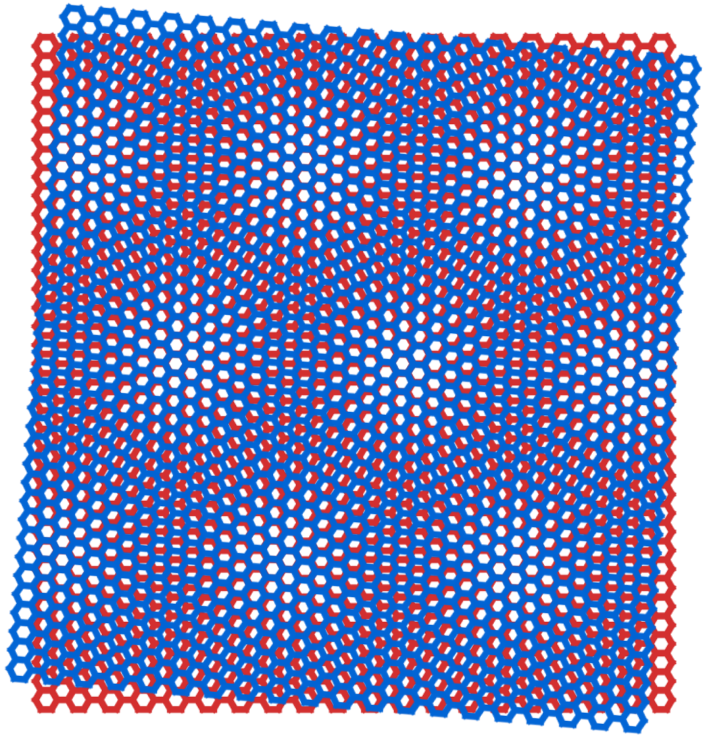
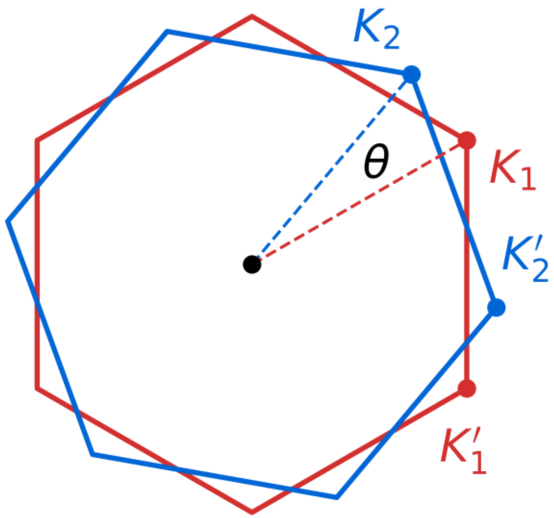
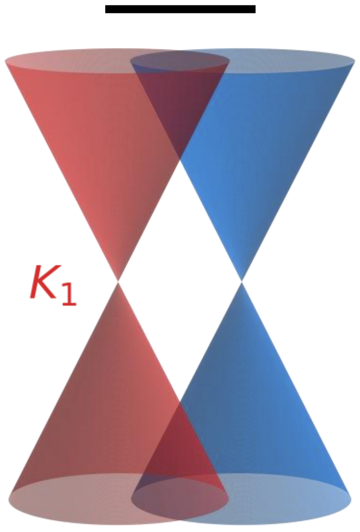




$k_\theta \approx K\theta$



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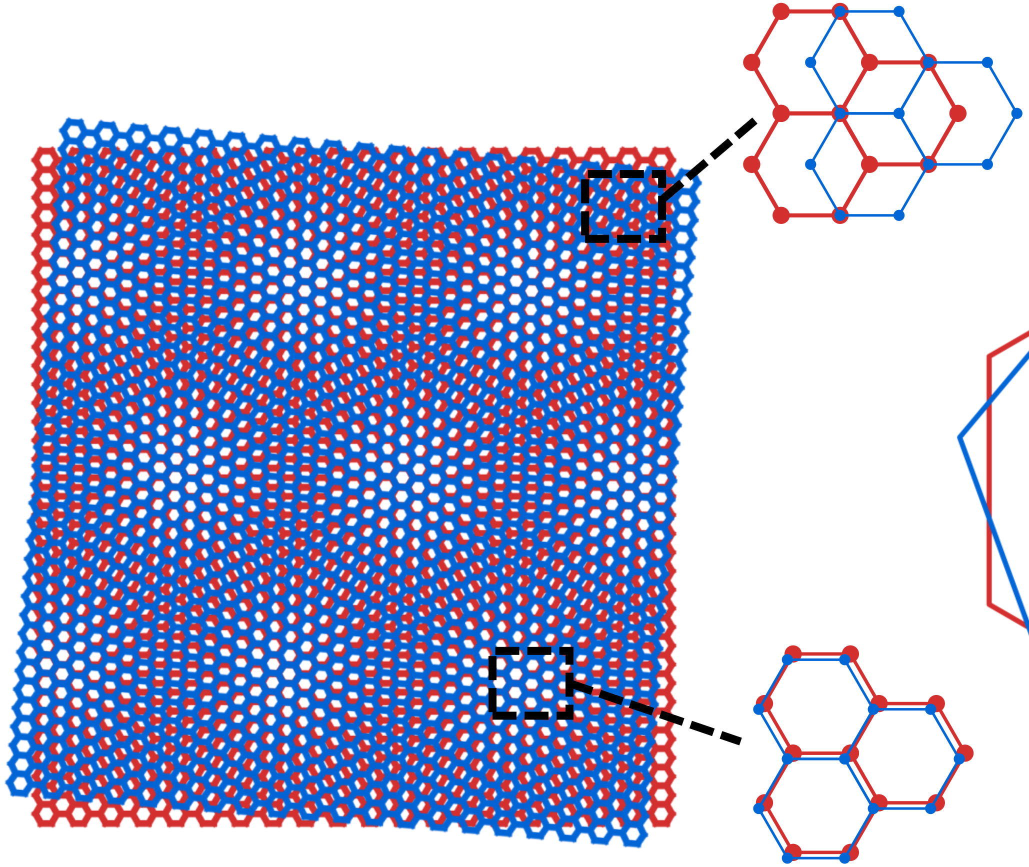

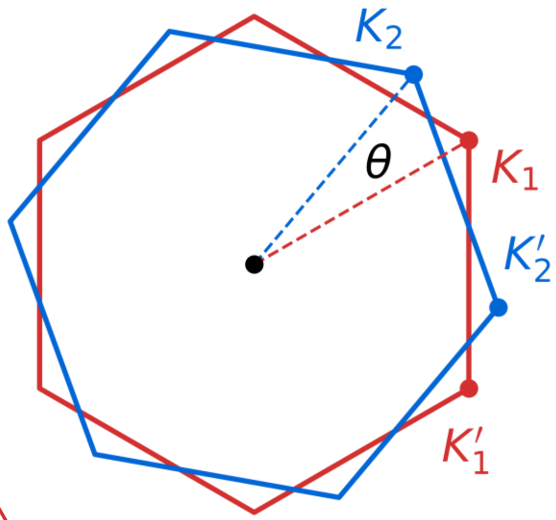

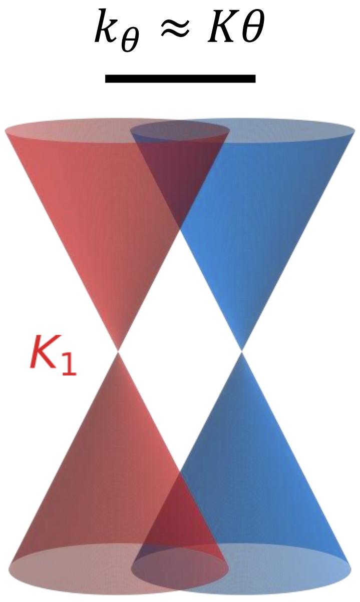

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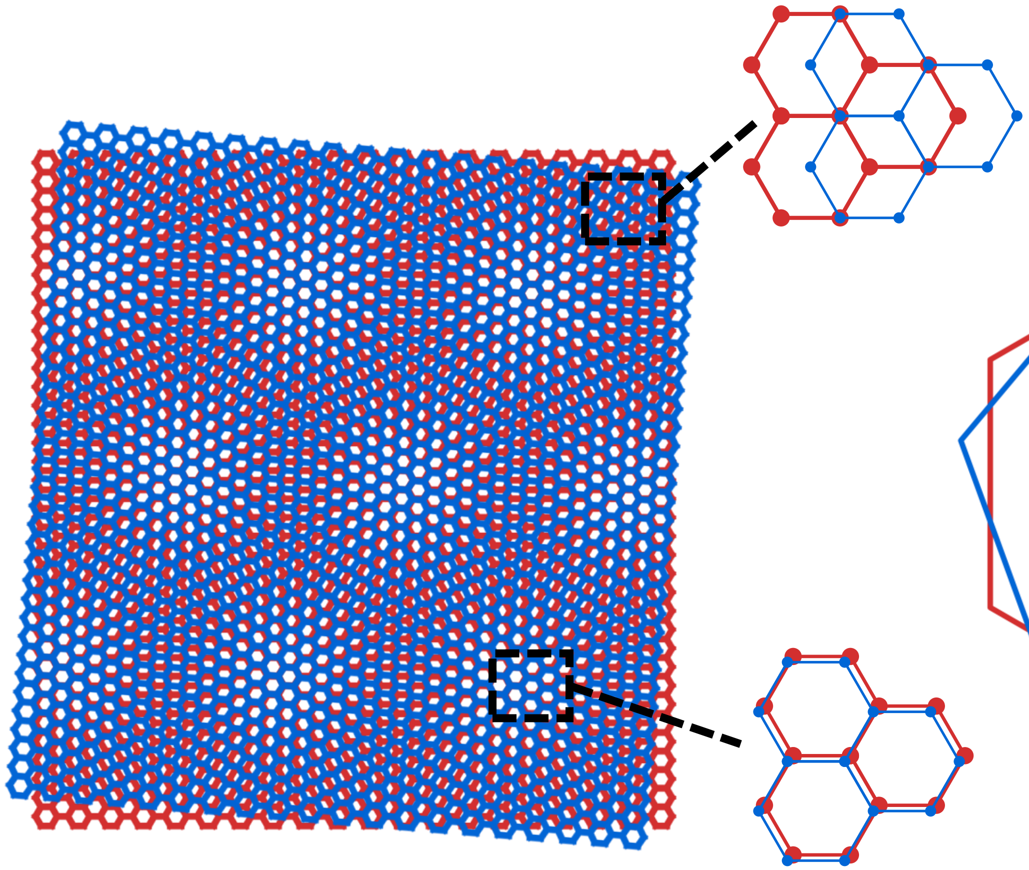

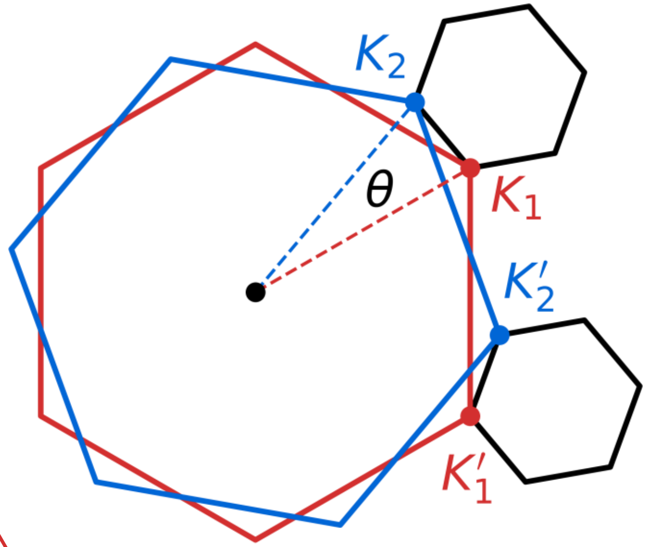

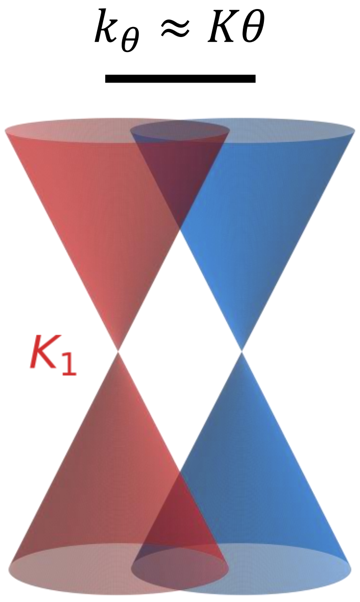

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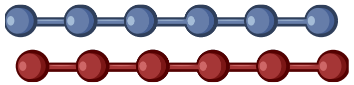
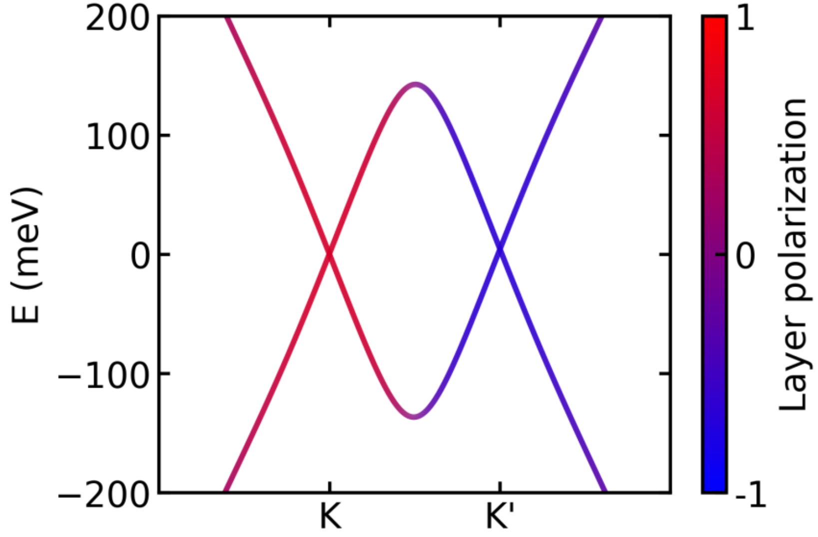


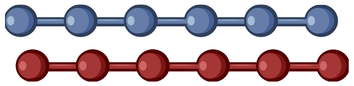
3.0°



~Electronically decoupled
from momentum mismatch

git.sr.ht/~spxtr/bm_model + Julian May-Mann
Bistritzer and MacDonald, PNAS (2011)

Bandstructure engineering with moirés



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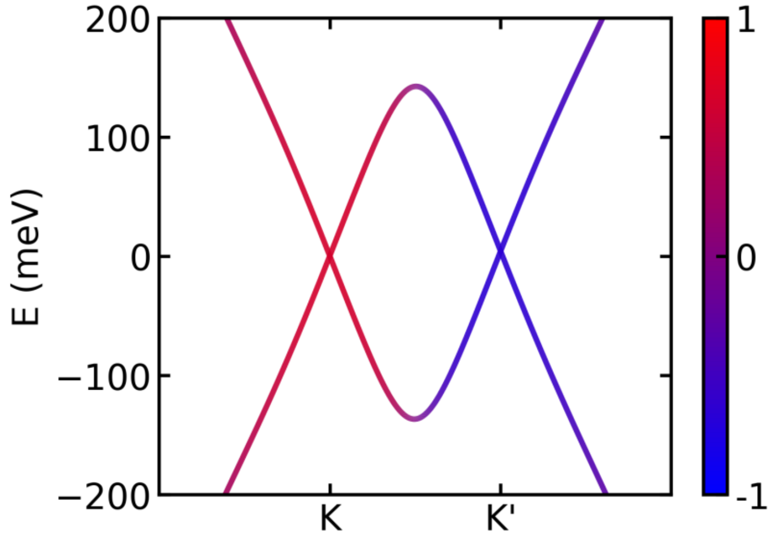

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Decreasing twist angle

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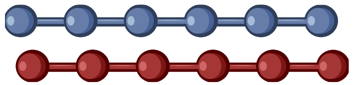

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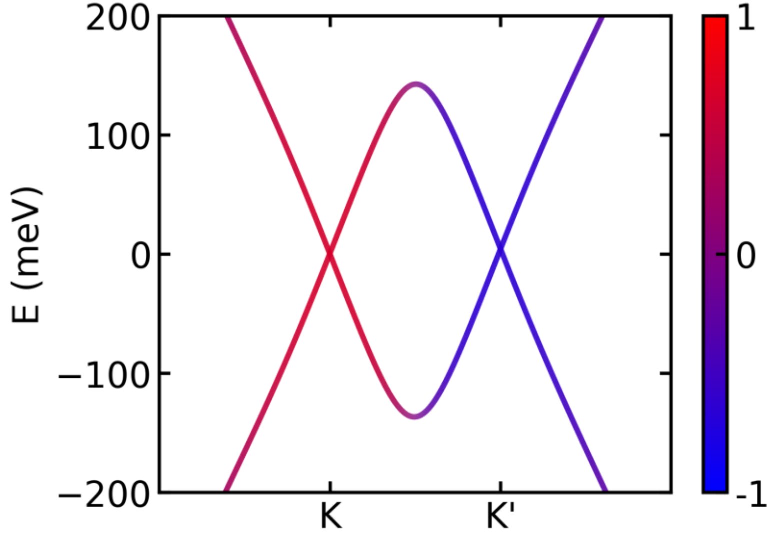

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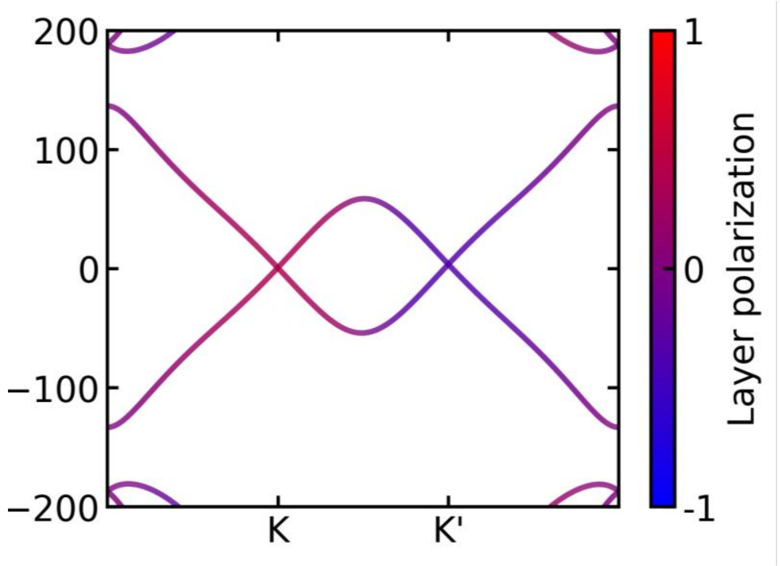
2.0°



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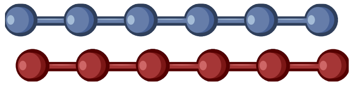
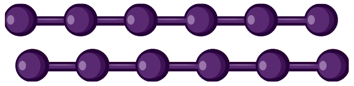
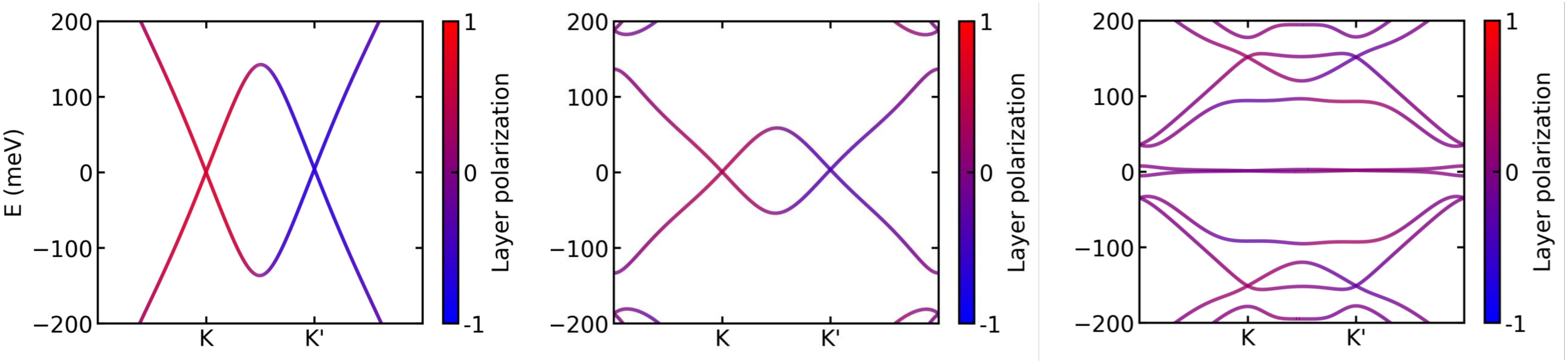




3.0° | 2.0° | 1.1°



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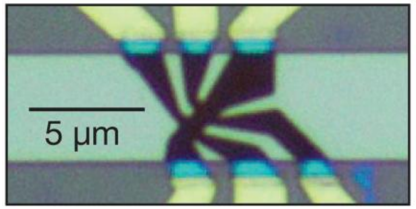
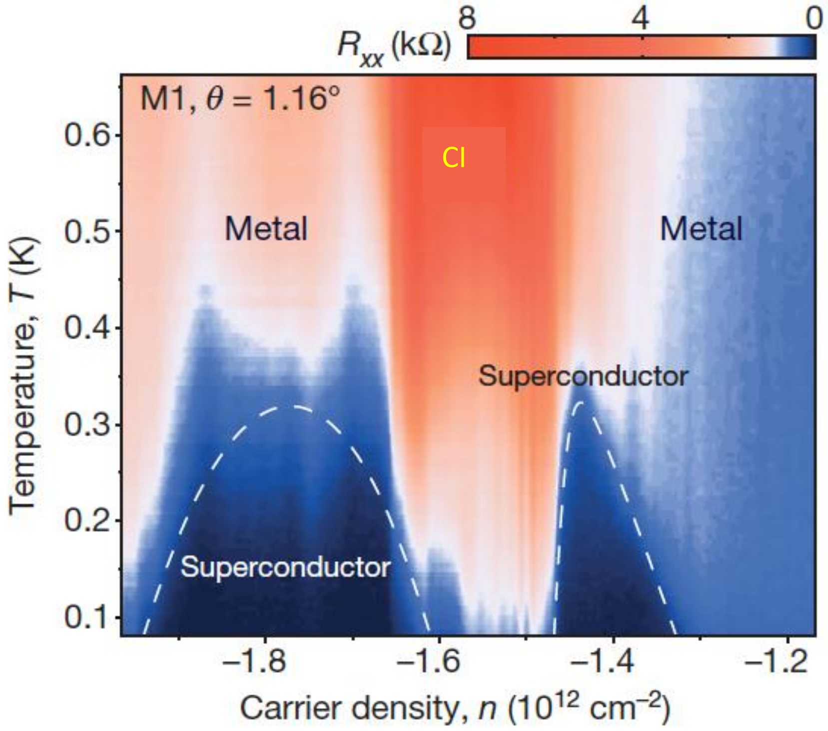
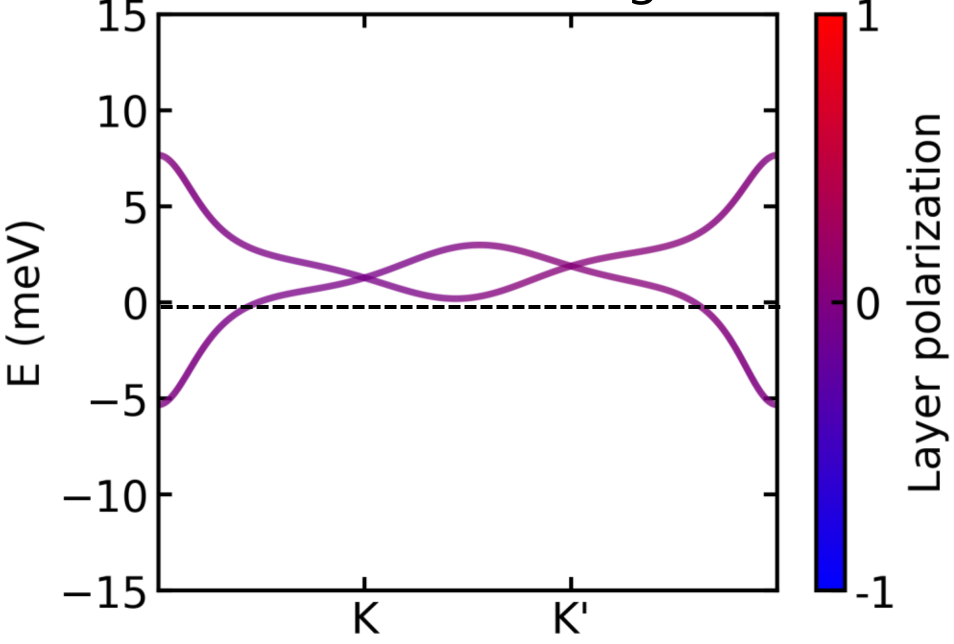
Magic angle twisted bilayer graphene (MATBG)





Remember 4-fold degenerate!



Cao, et al. Nature (2018)
Yoo et al. Nat. Nano. (2019)
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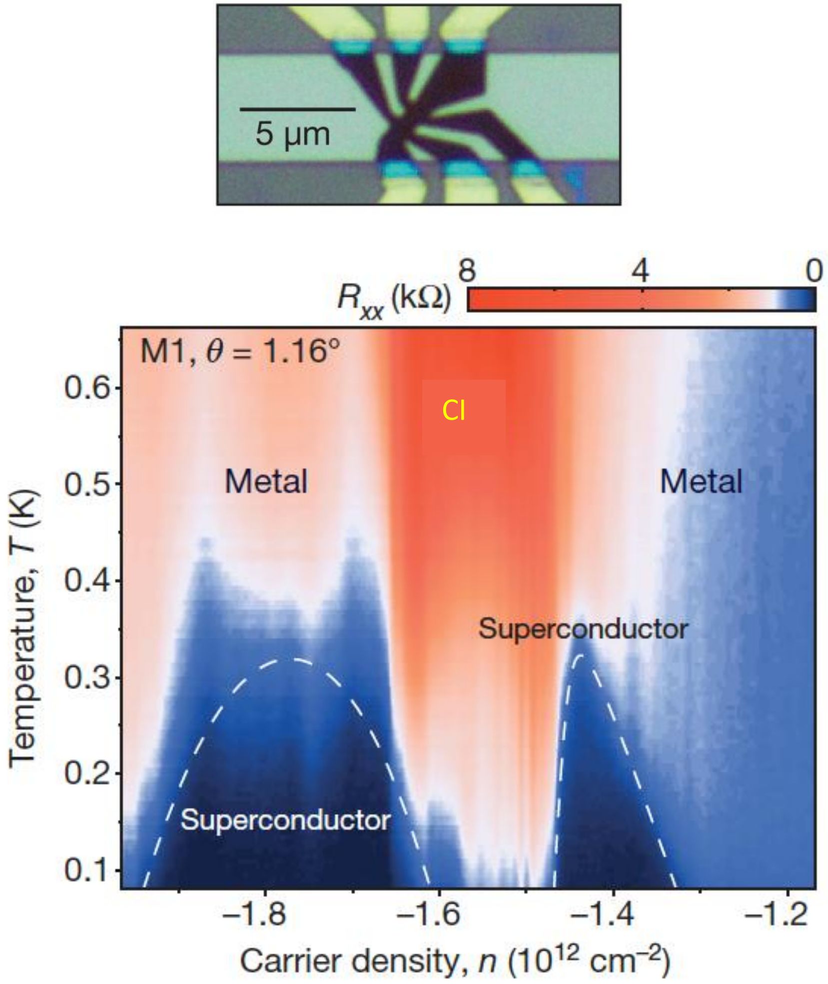

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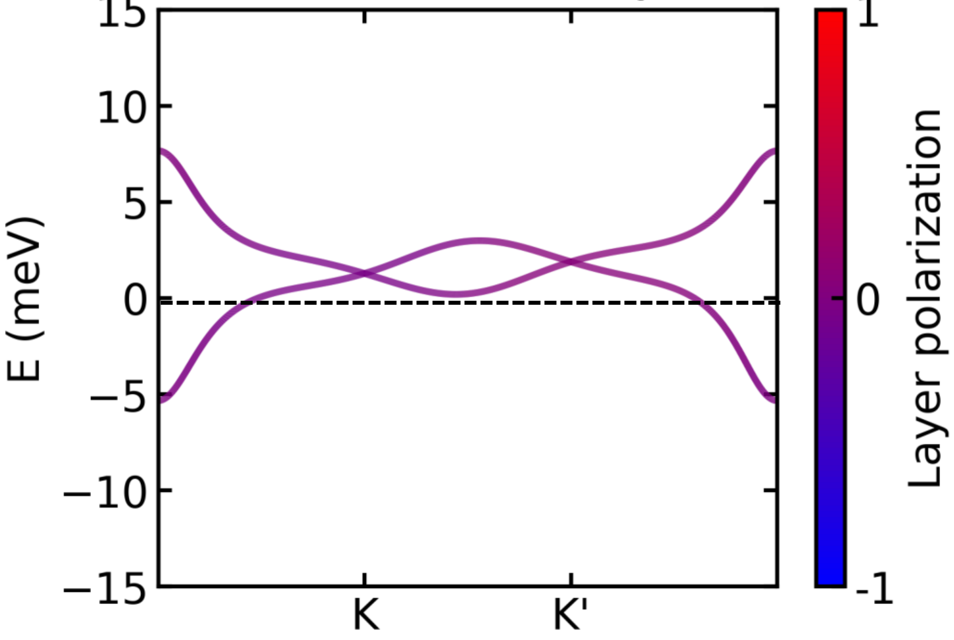
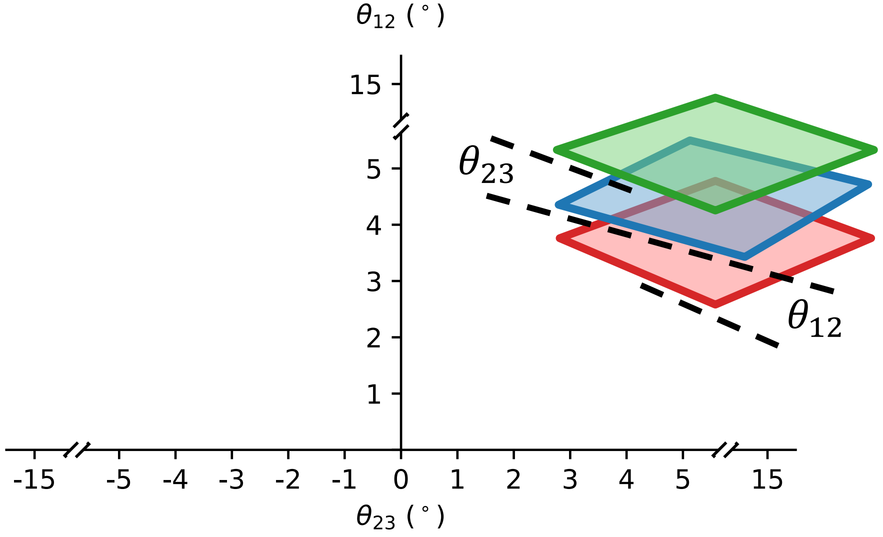


Let's add a third layer of graphene!

Cao, et al. Nature (2018)
Yoo et al. Nat. Nano. (2019)
Bistritzer and MacDonald, PNAS (2011)

Problem statement:



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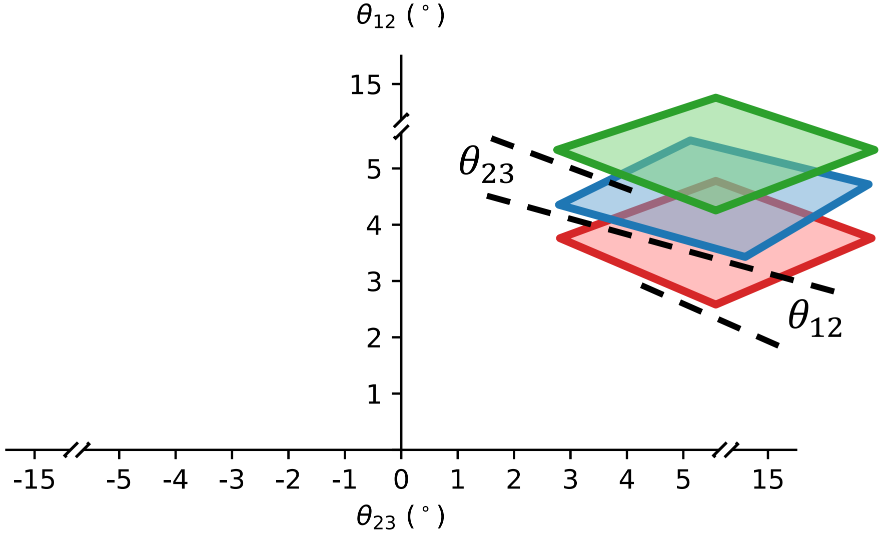
2. Do we also find **strong electronic correlations** in trilayer structures? How do correlations **evolution with twist**? Distinct regions in angle-angle space? What **drives** the resultant phenomenology?



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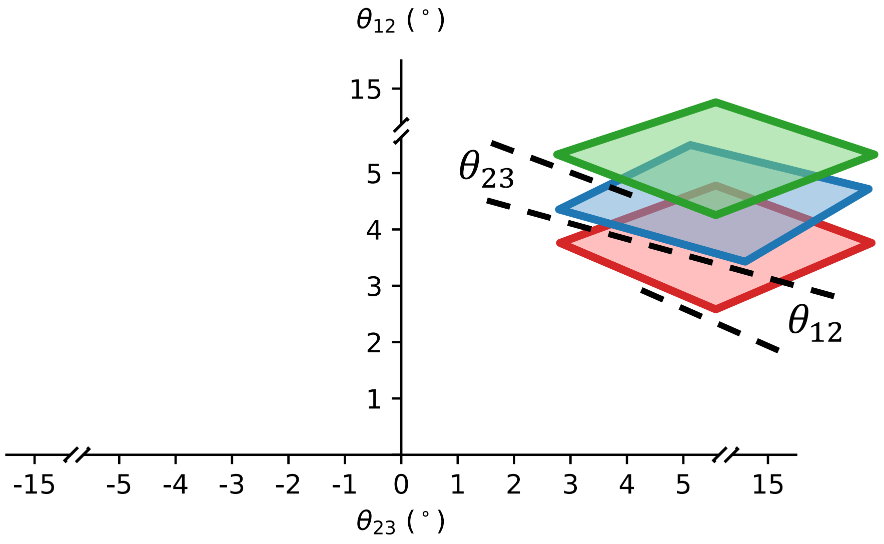
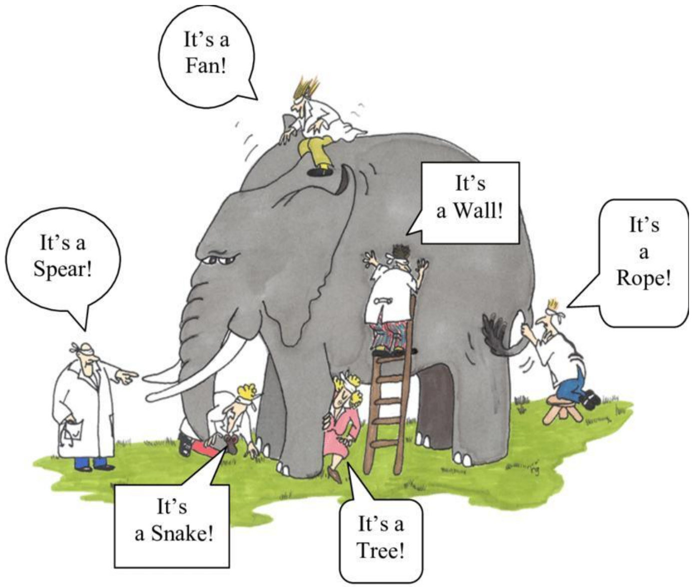
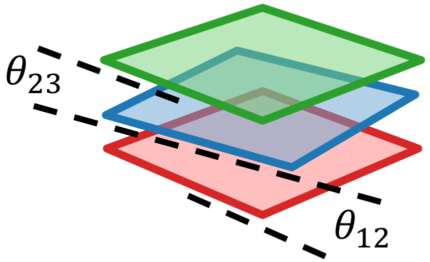
3. Comparing **different** devices is challenging. How will we systematically explore this space?





Where to begin? “Magic Angle Twisted Trilayer”



Khalaf, et al. PRB (2019)
Park, et al. Nature (2021)
Hao, et al. Science (2021)
Kim, et al. Nature (2022)

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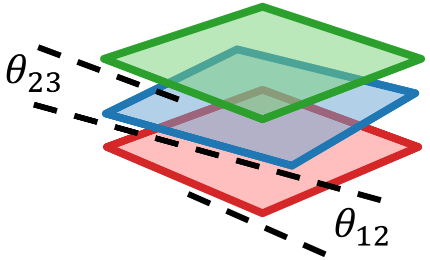

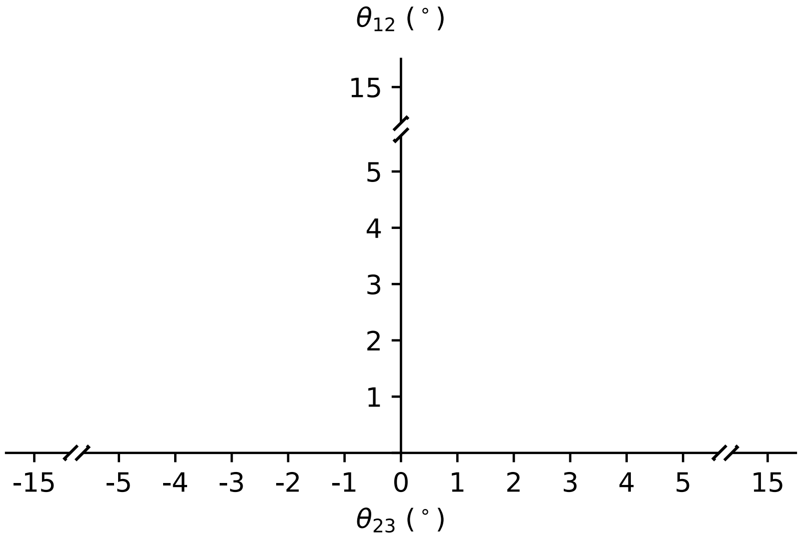

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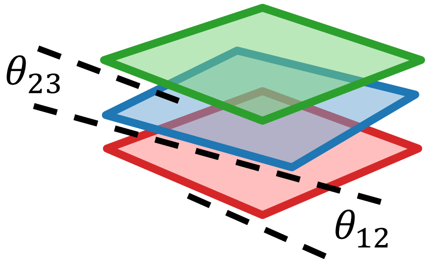
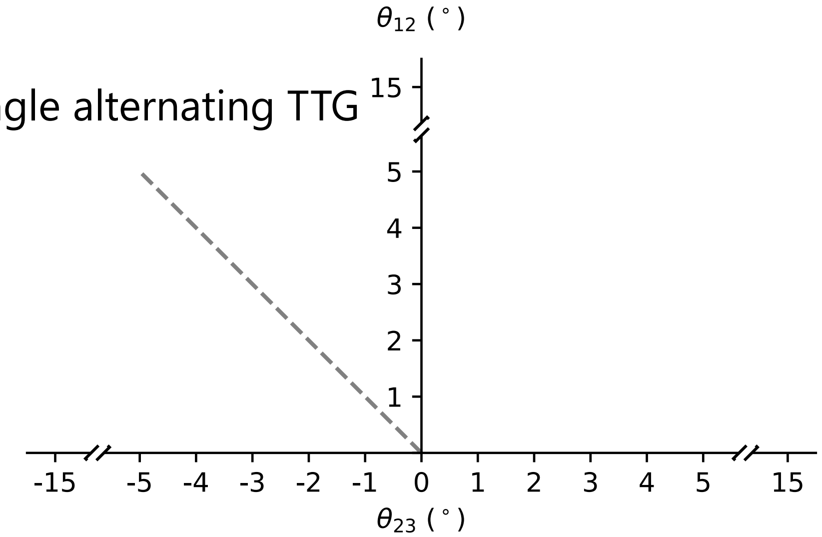
Where to begin? “Magic Angle Twisted Trilayer”



Equiangle alternating TTG



Khalaf, et al. PRB (2019)
Park, et al. Nature (2021)
Hao, et al. Science (2021)
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For equiangle alternating TTG
moirés patterns are *exactly* commensurate

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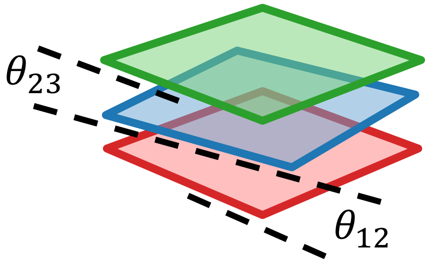

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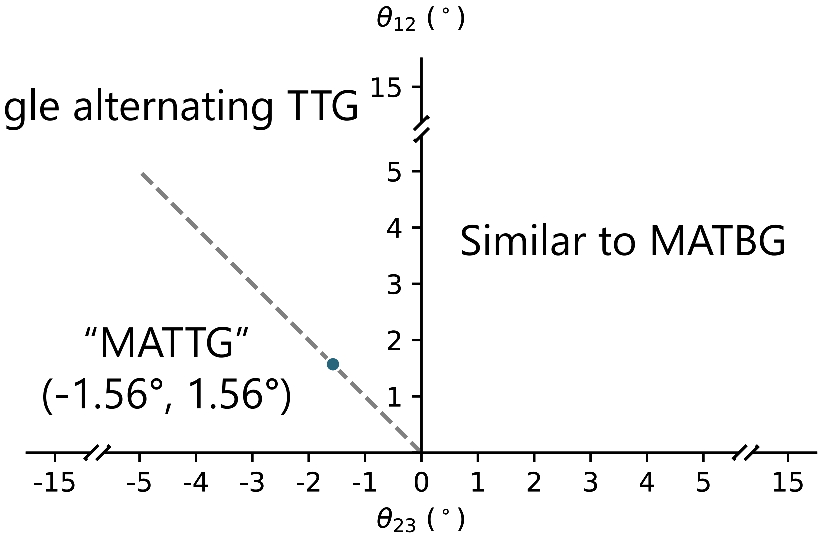

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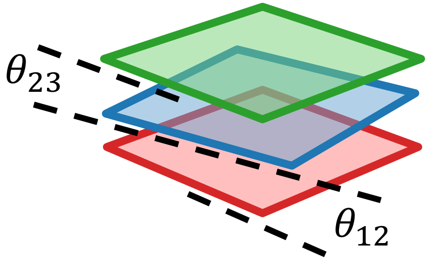
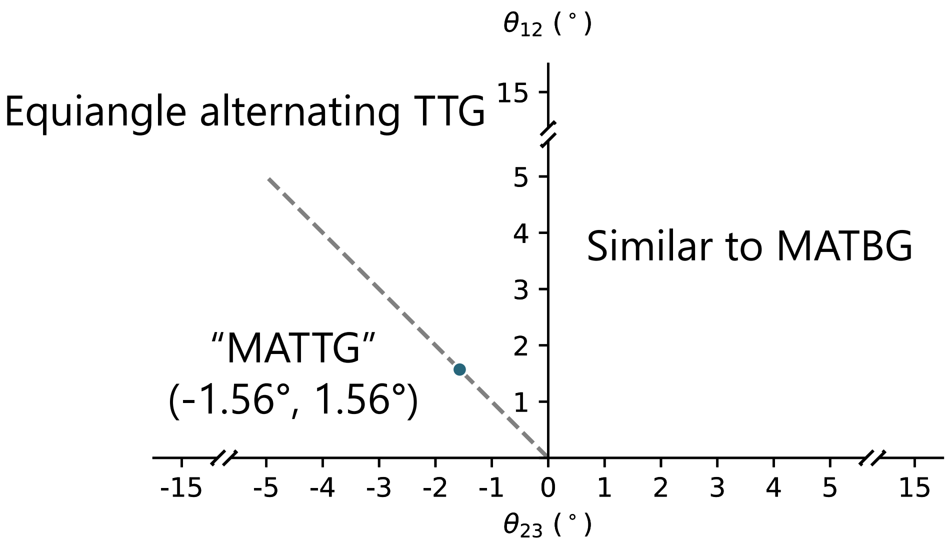
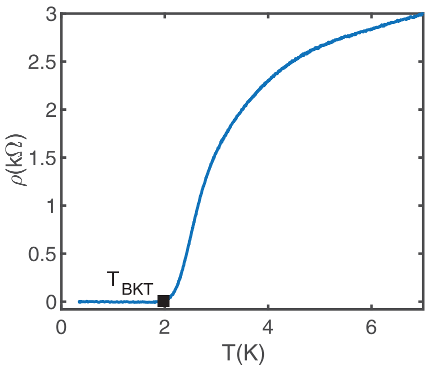
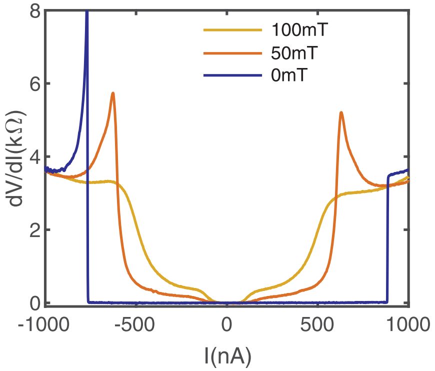




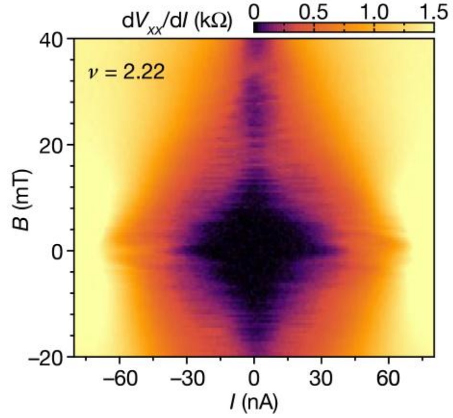
Dissipationless



Non-linear



Phase coherent



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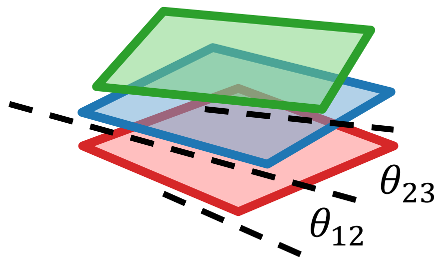
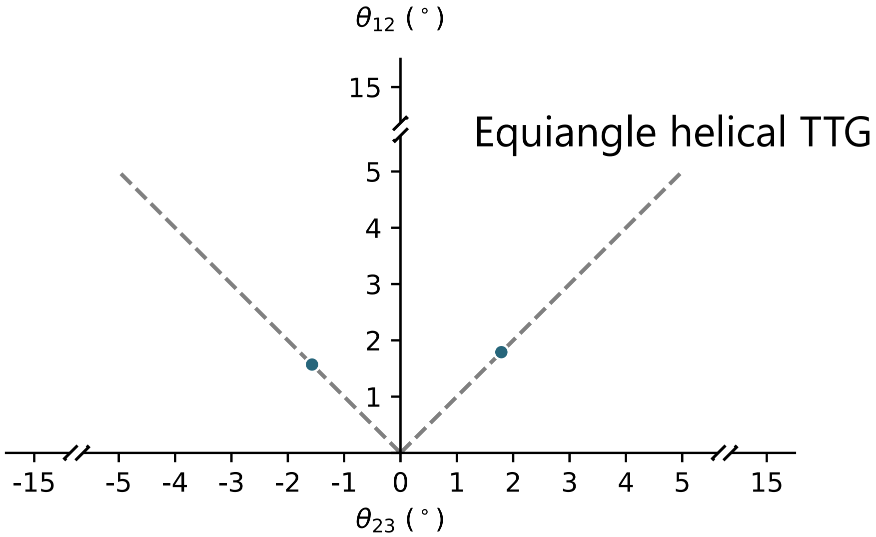
Equiangle Helical Trilayer





Devakul, et al. Sci. Adv. (2023)
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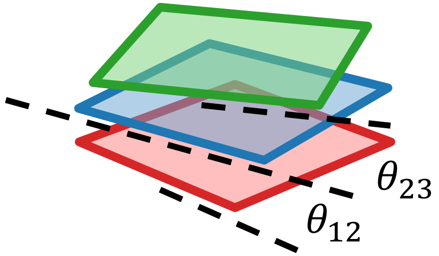

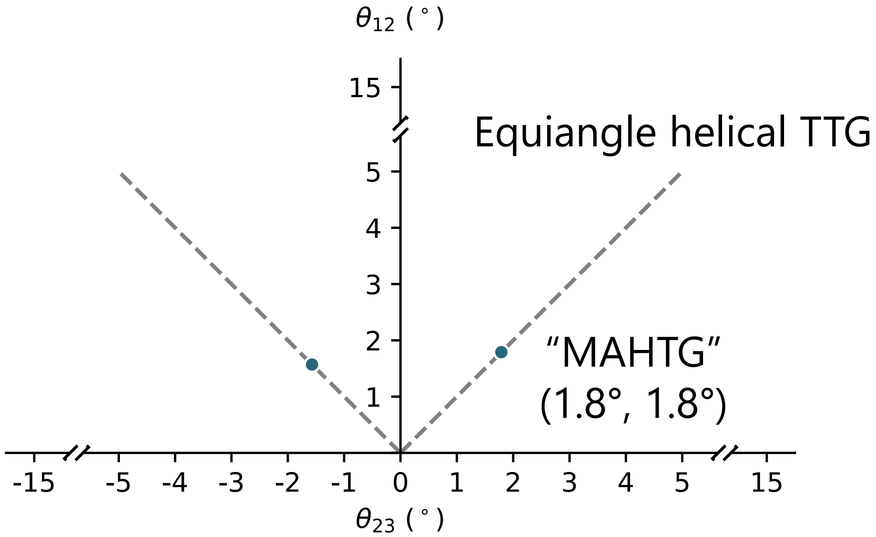

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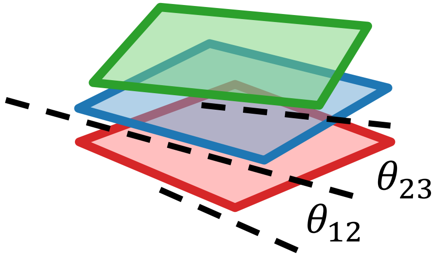

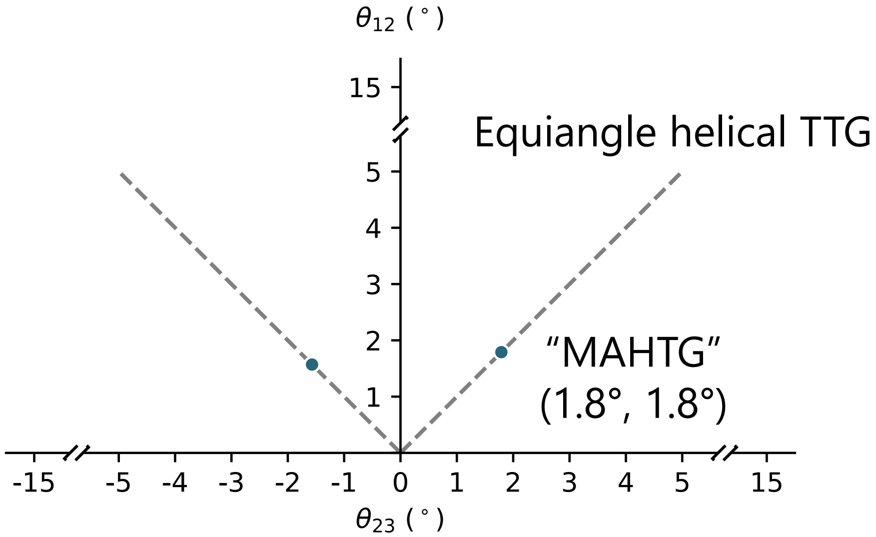

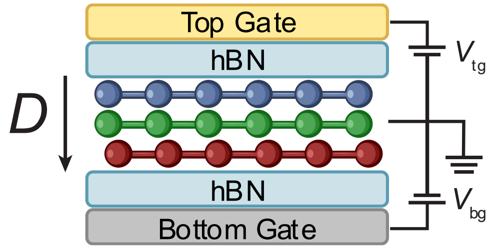

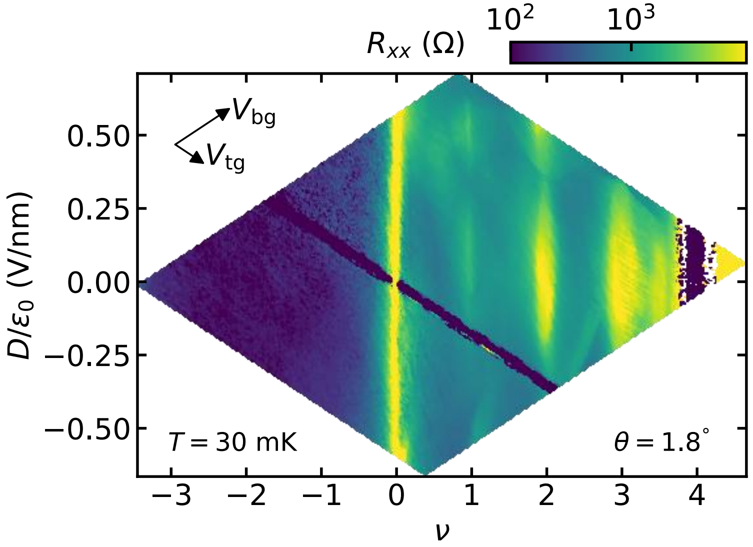

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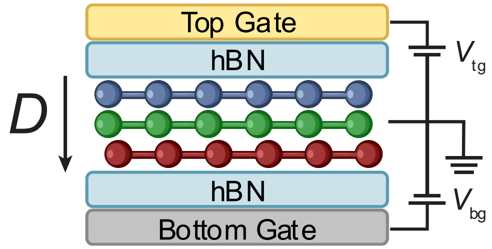
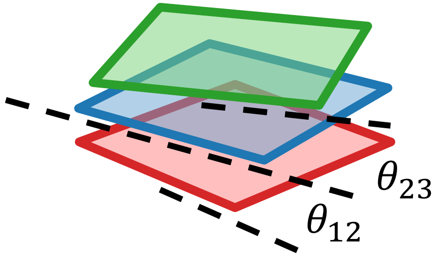
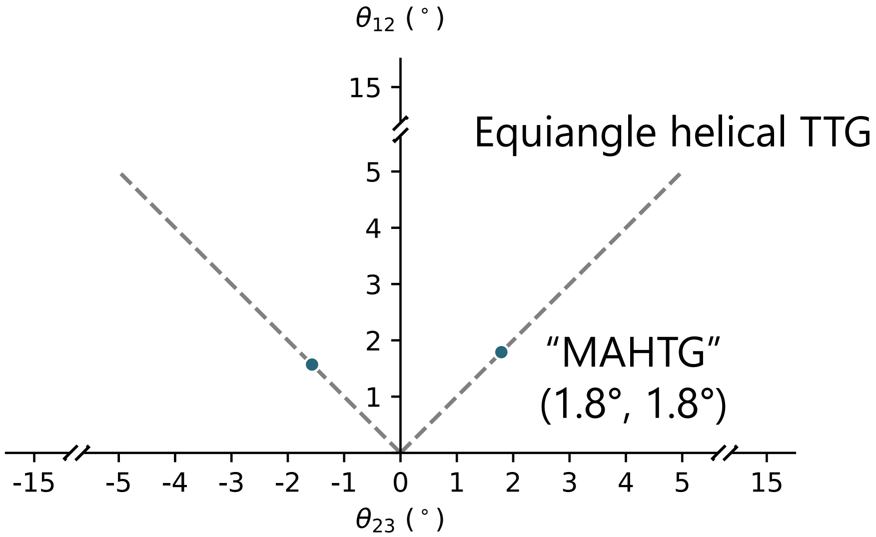
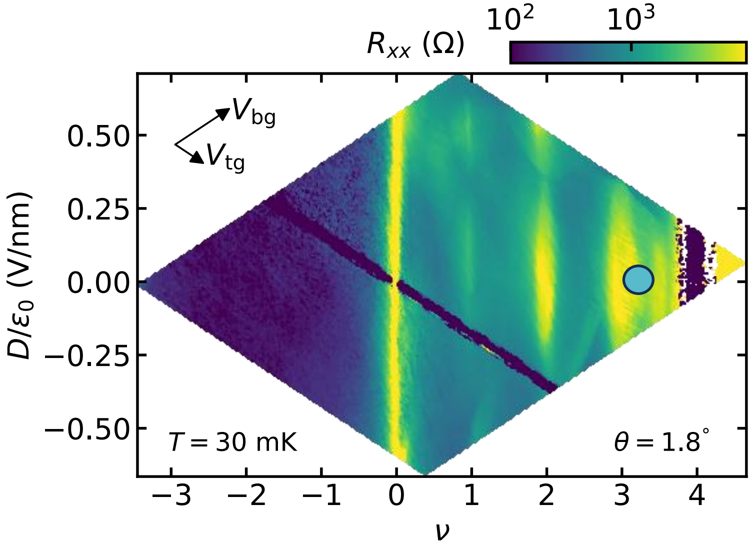
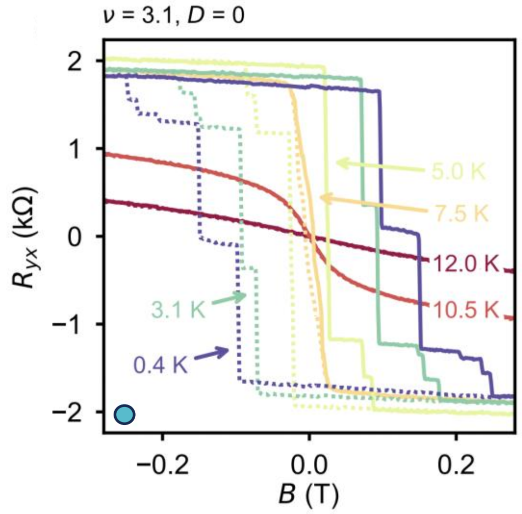






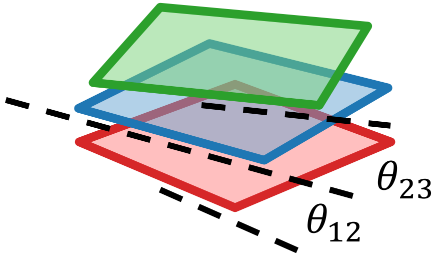


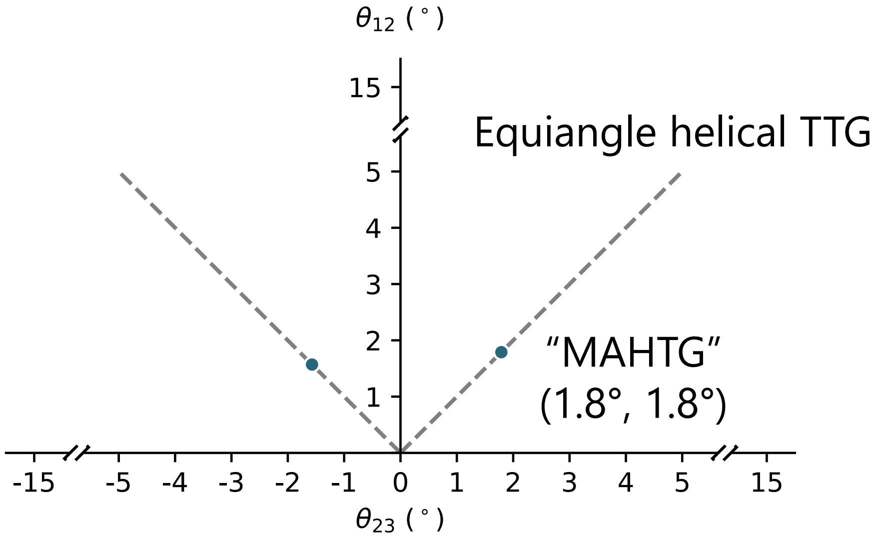


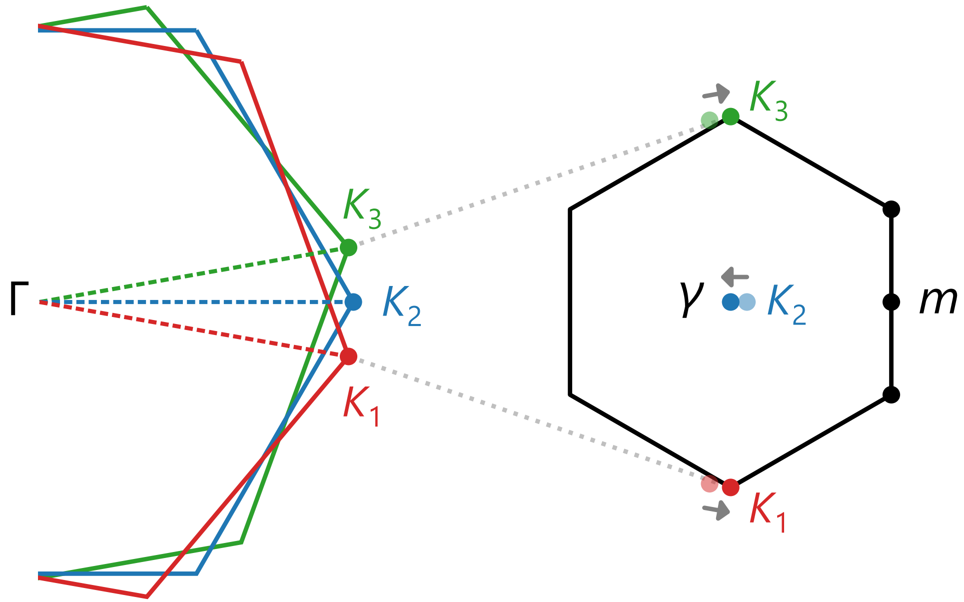
No signs of superconductivity so far.
Unquantized anomalous Hall. Domain physics?
What is driving this change in the resulting physics?

Devakul, et al. Sci. Adv. (2023)
Xia,..., Sharpe, et al. Nat. Phys (2025)

Generically have incommensurate moirés





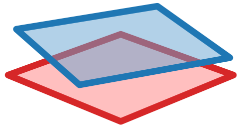


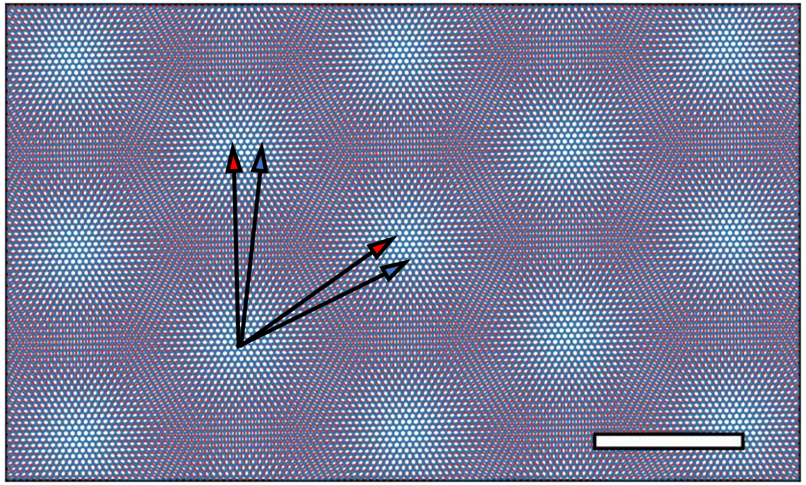
In HTG, the two moirés are rotated!
We have a moiré of moiré

Devakul, et al. Sci. Adv. (2023)

From moiré to multimoiré

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





Scale bars: 5 nm

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

Atomic lattices that make up moirés generally incommensurate → continuum approximation

From moiré to multimoiré

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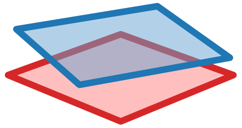

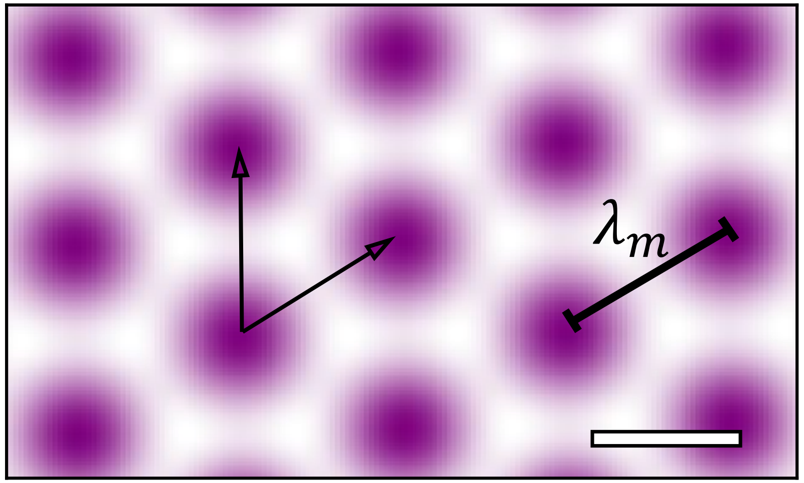

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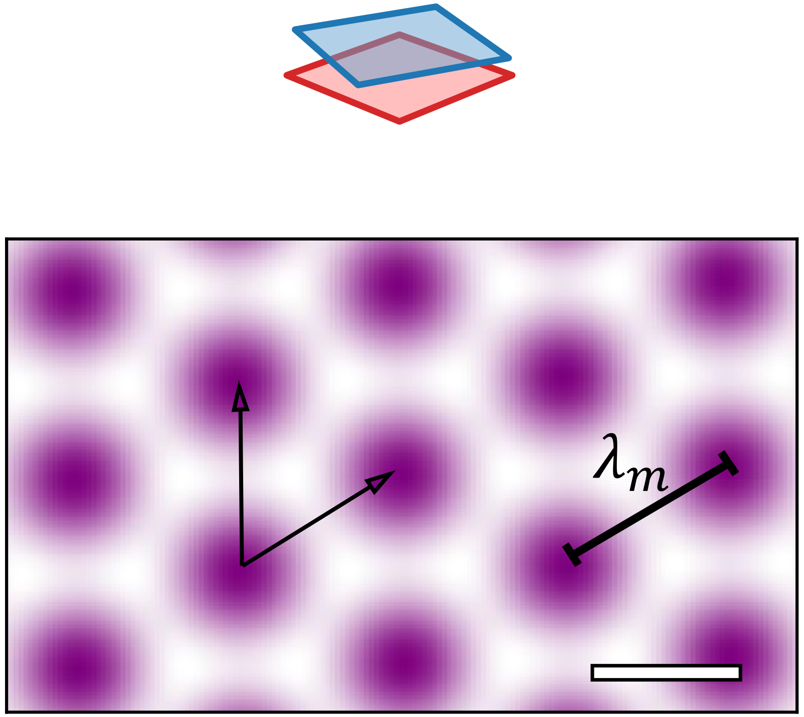
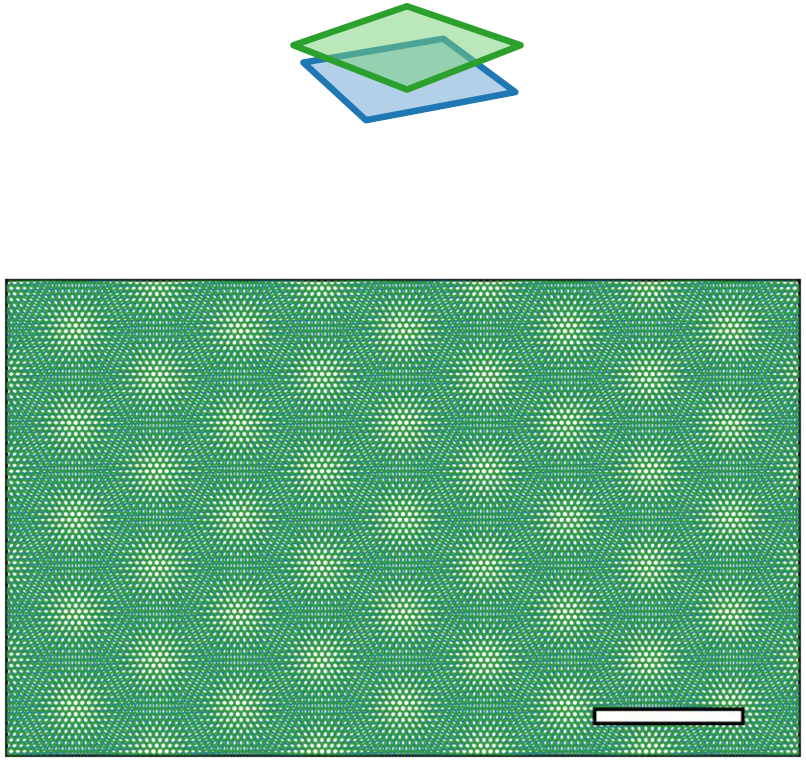


Layers **2** and **3**



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Atomic lattices that make up moirés generally incommensurate → continuum approximation

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From moiré to multimoiré

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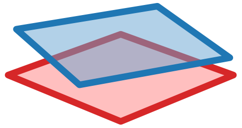
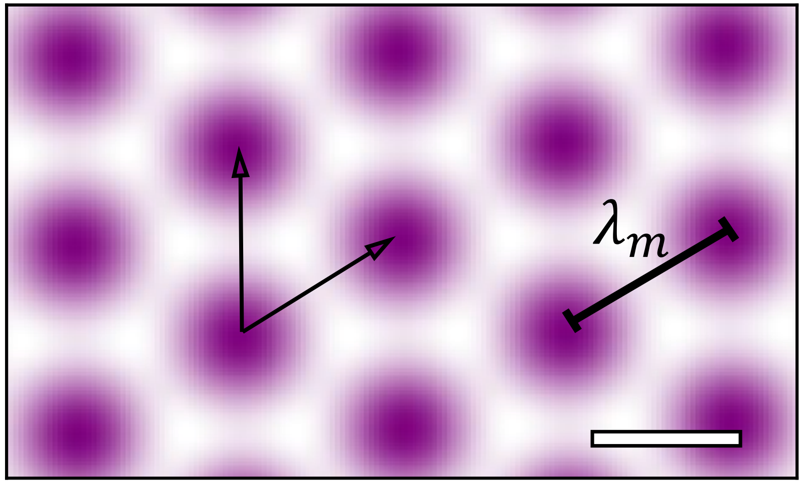
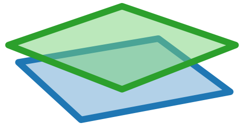
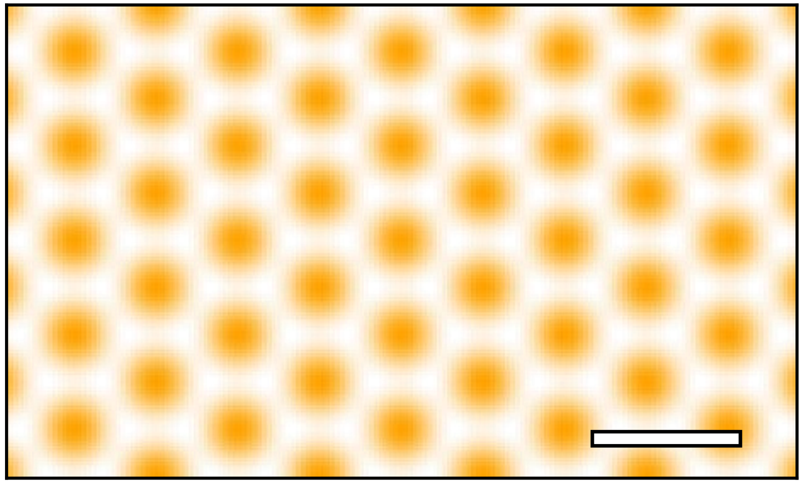




Layers 2 and 3





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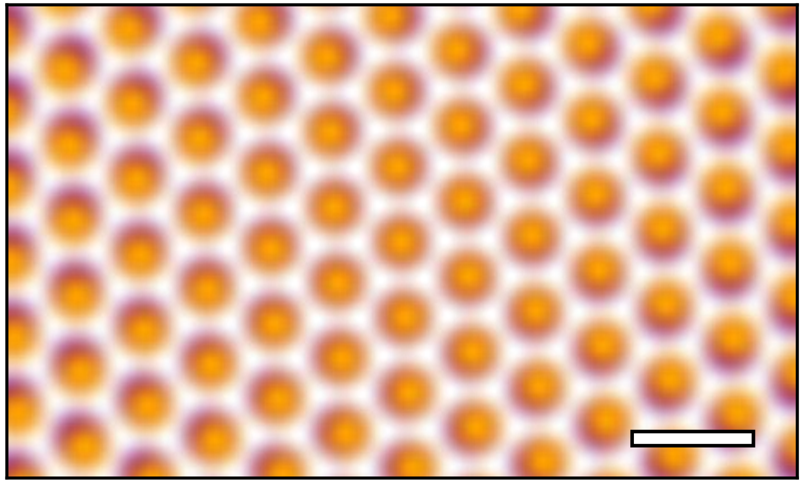
Incommensurability and the supermoiré length scale

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



● AA_{12} ● AA_{23}

Scale bars: 10 nm

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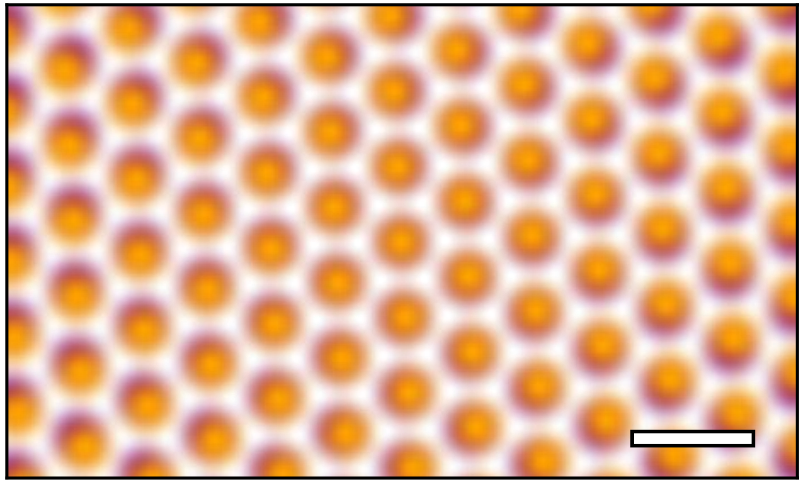

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Scale bars: 10 nm

Translate window →

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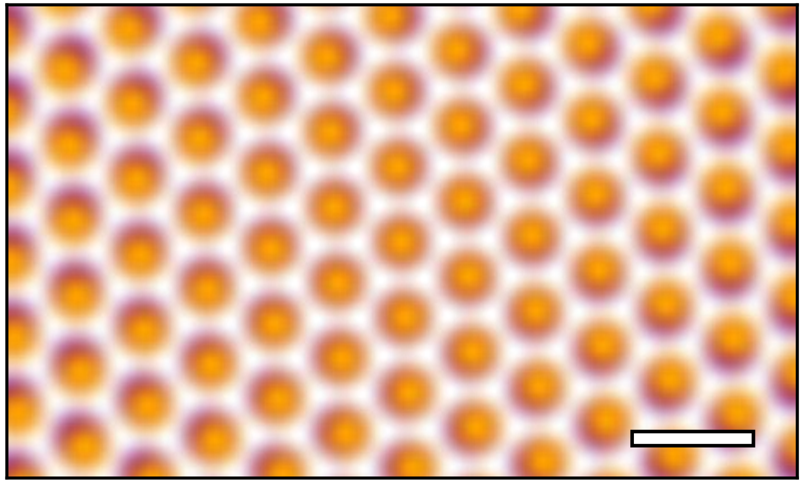

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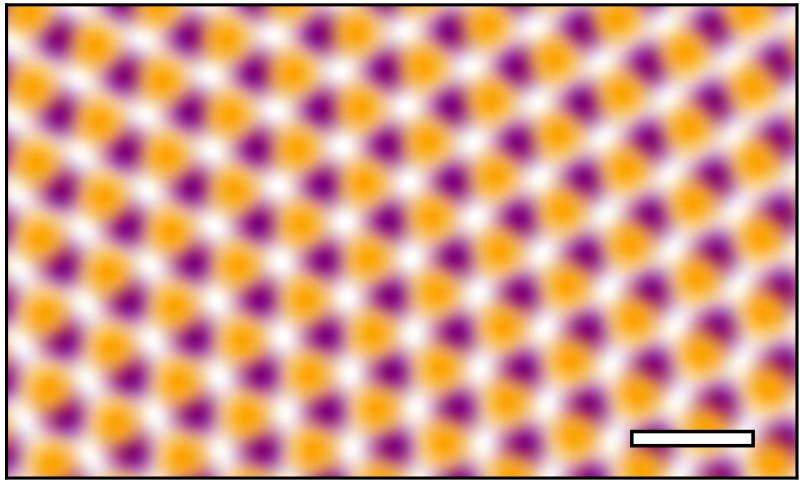

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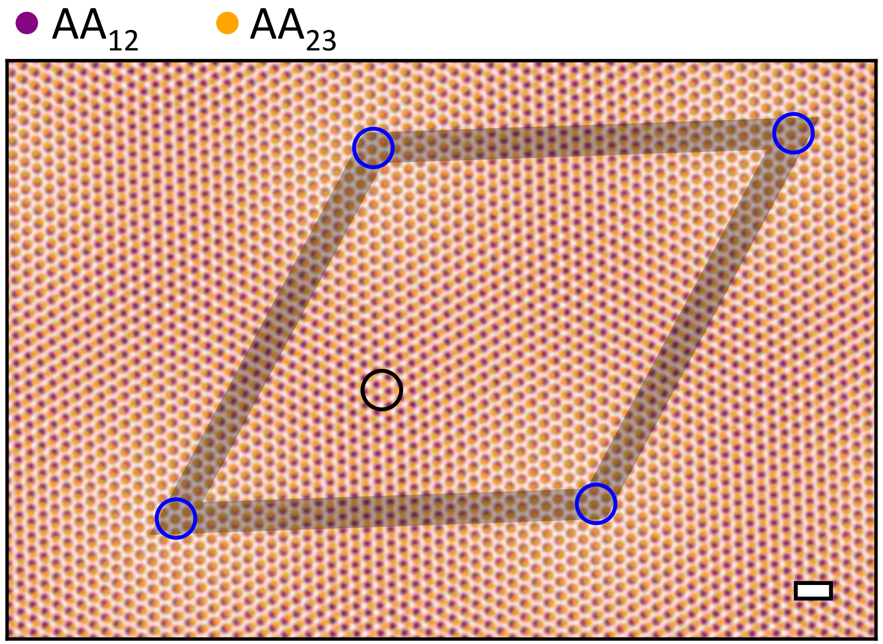
Shift dependent electronic bands



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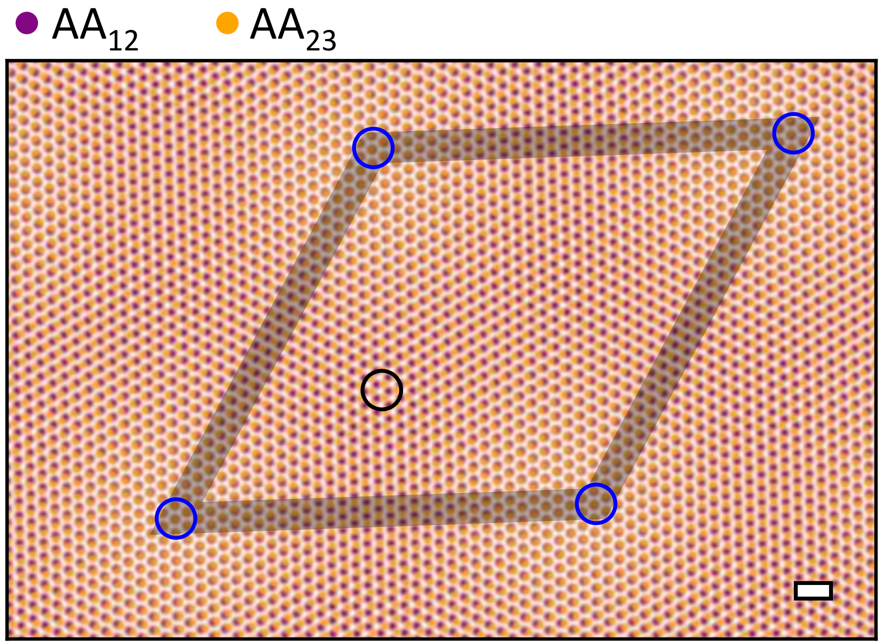

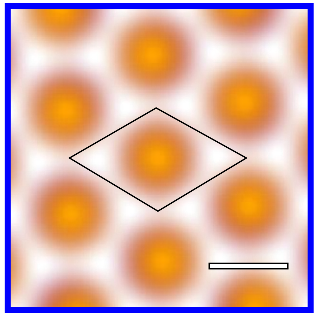

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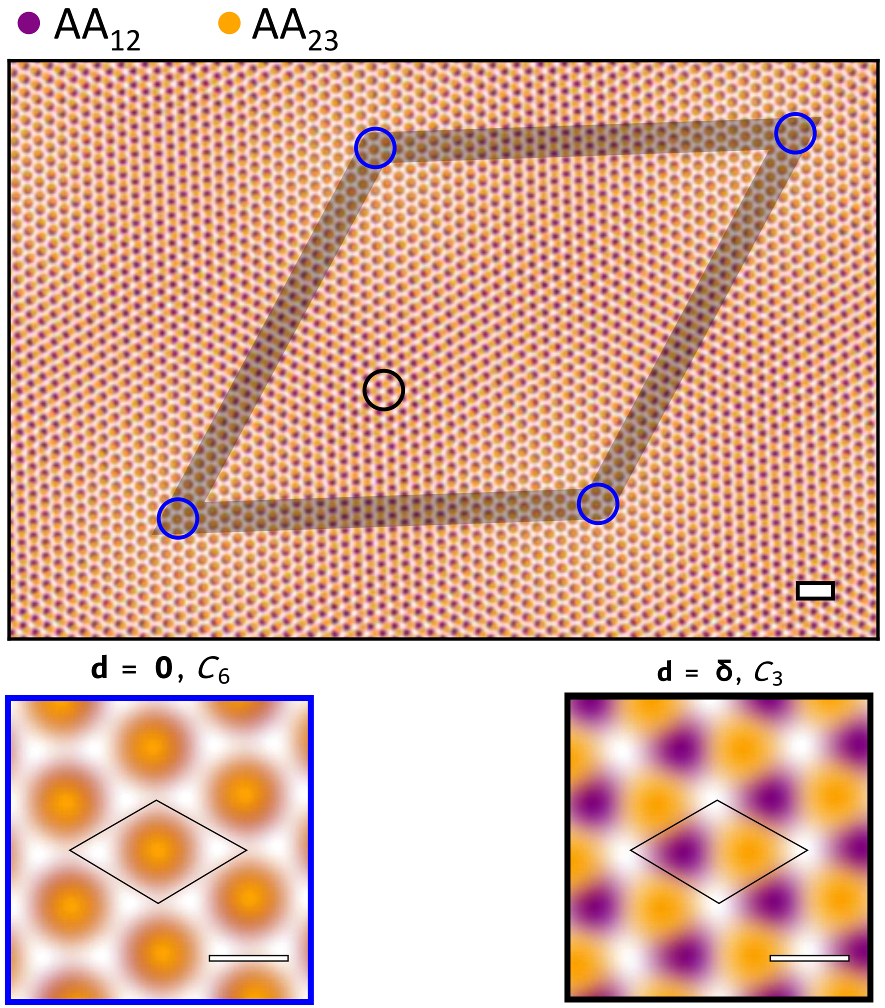

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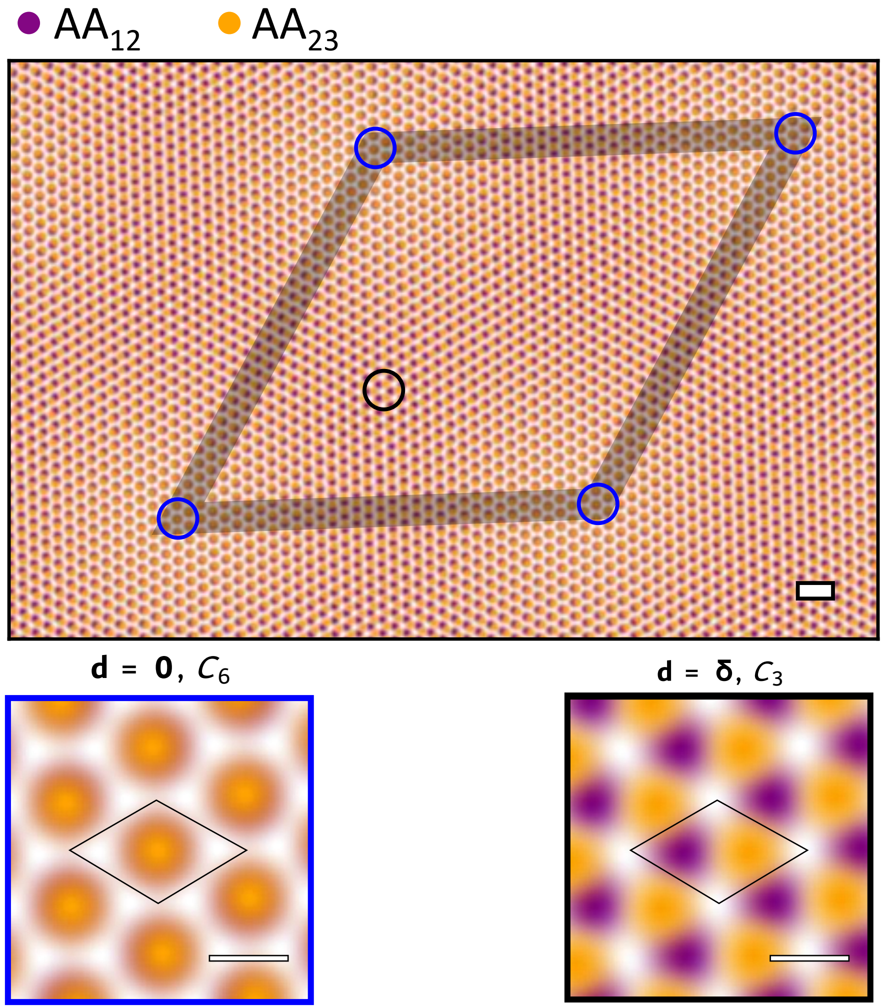

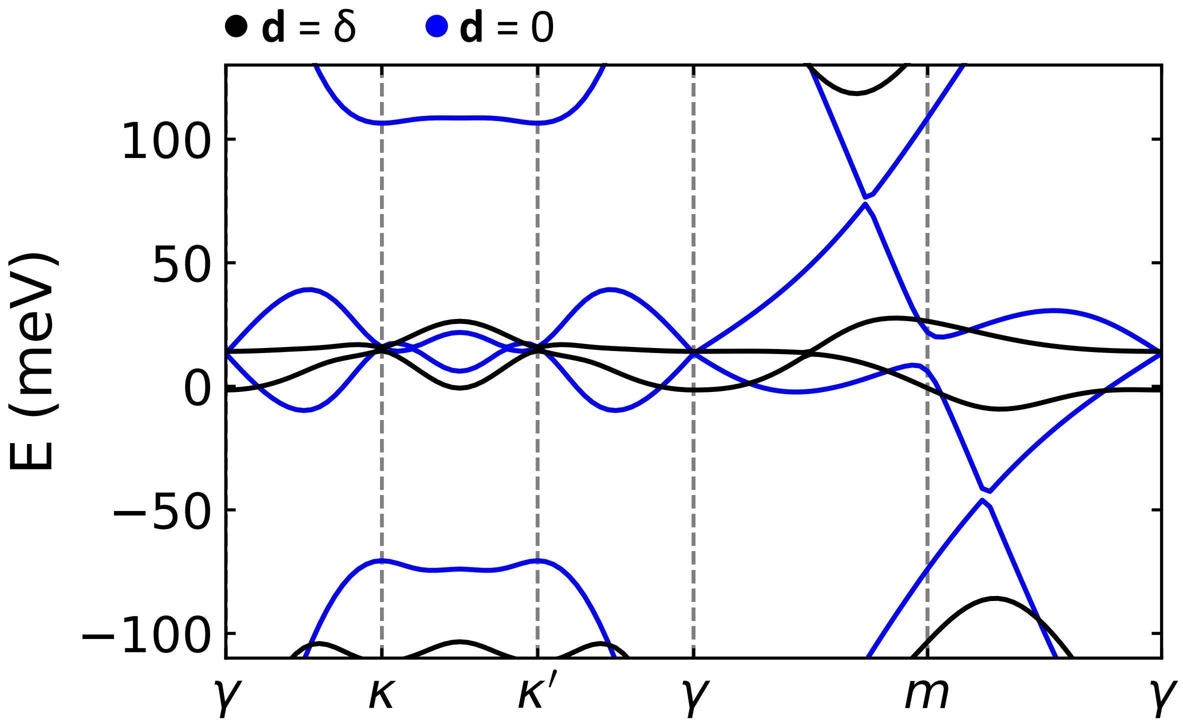

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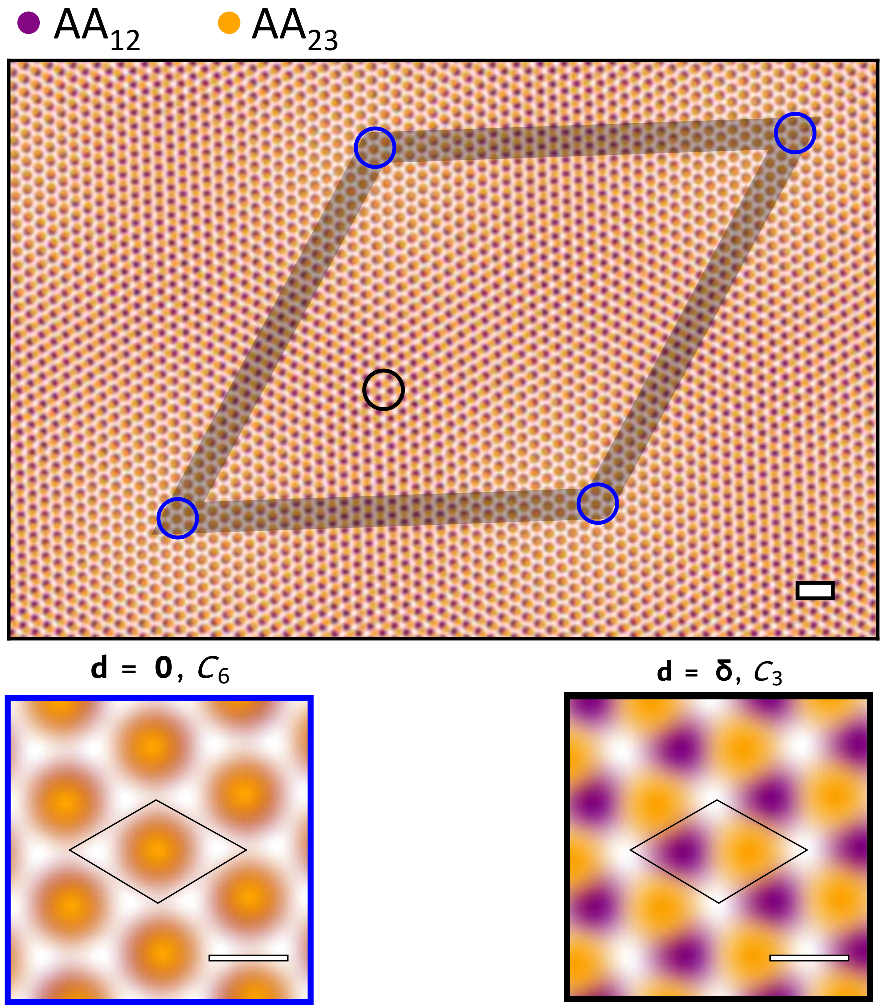

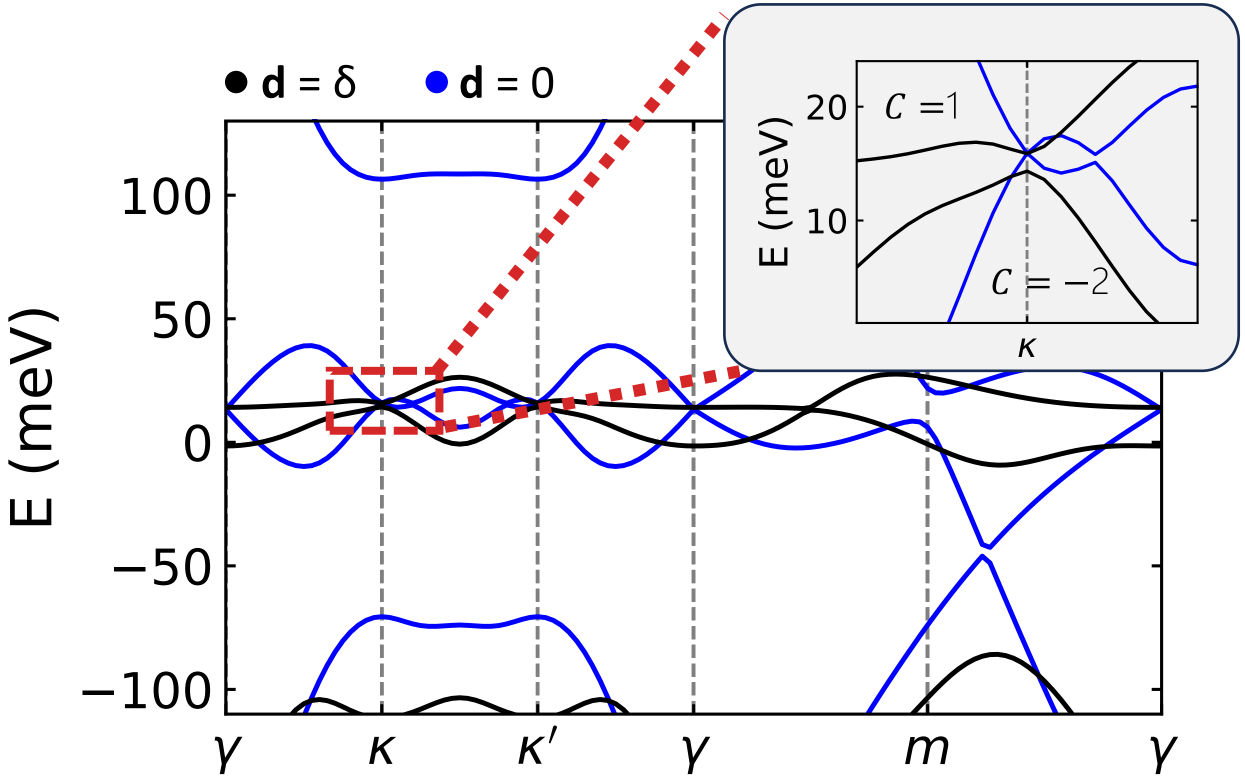

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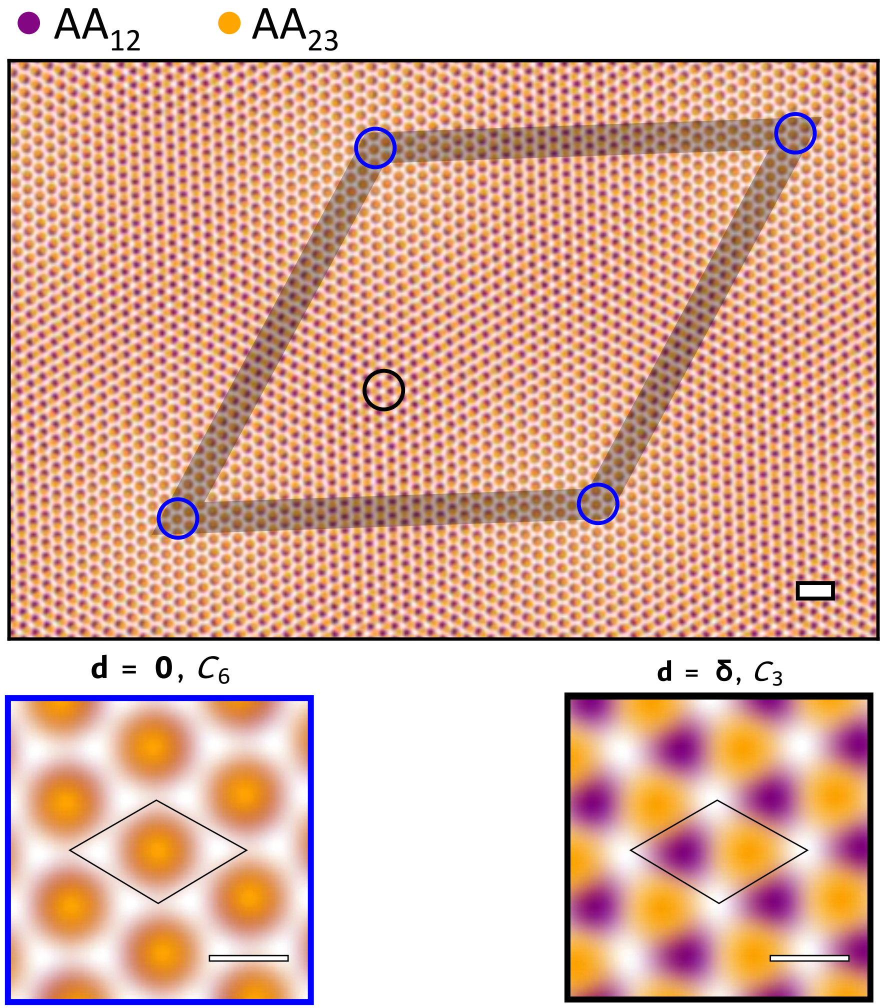

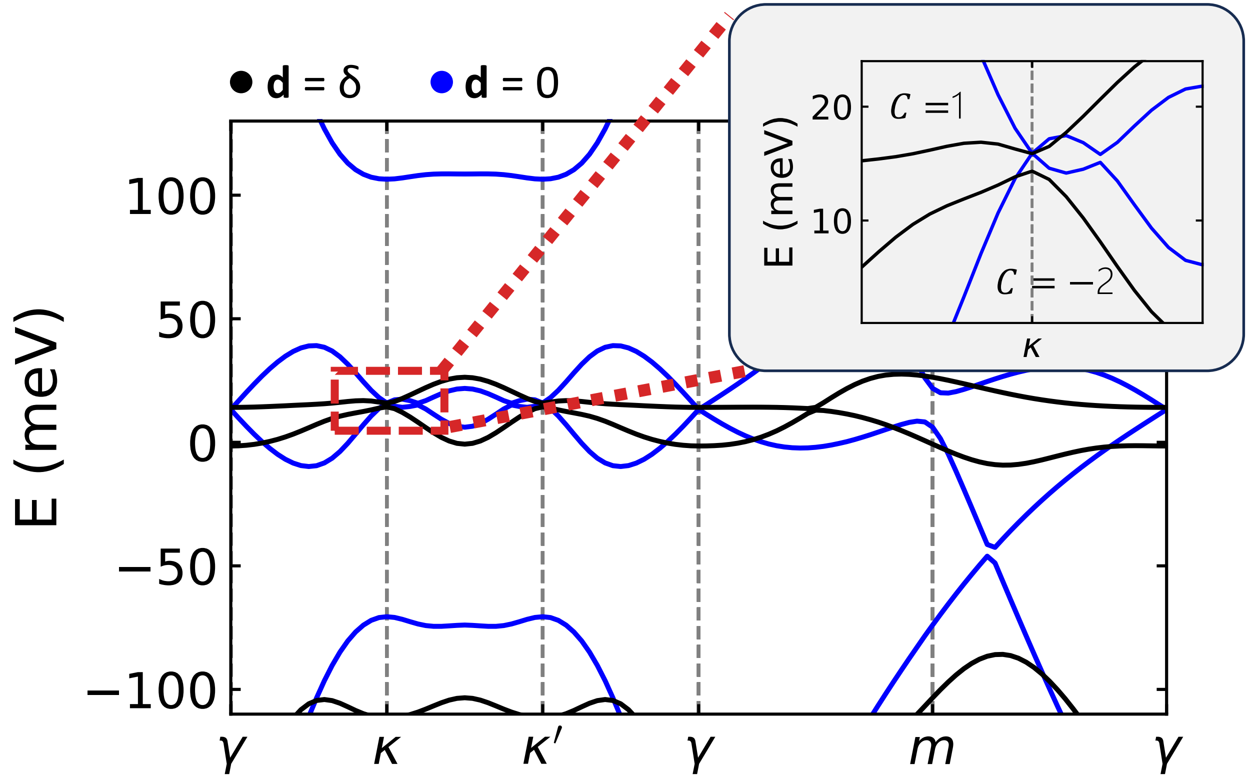

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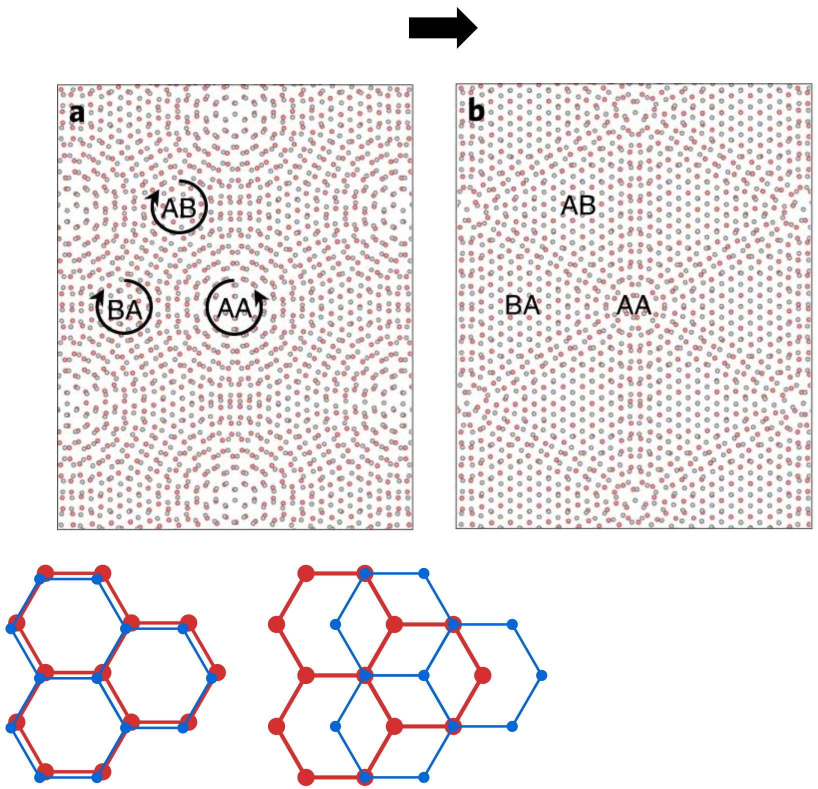
How do we weight intermoiré shifts?

Lattice relaxation on the supermoiré scale

Relaxation at the moiré scale



Yoo et al. Nat. Nano. (2019)
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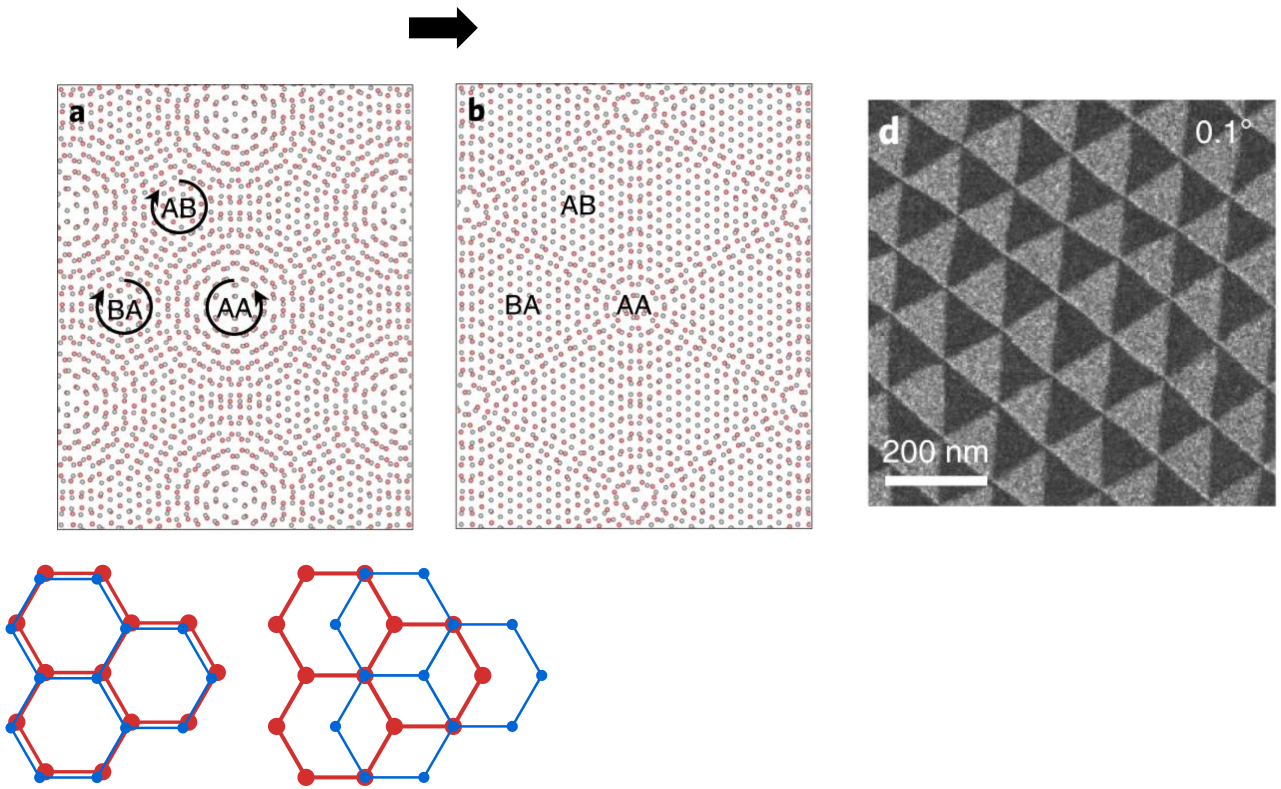

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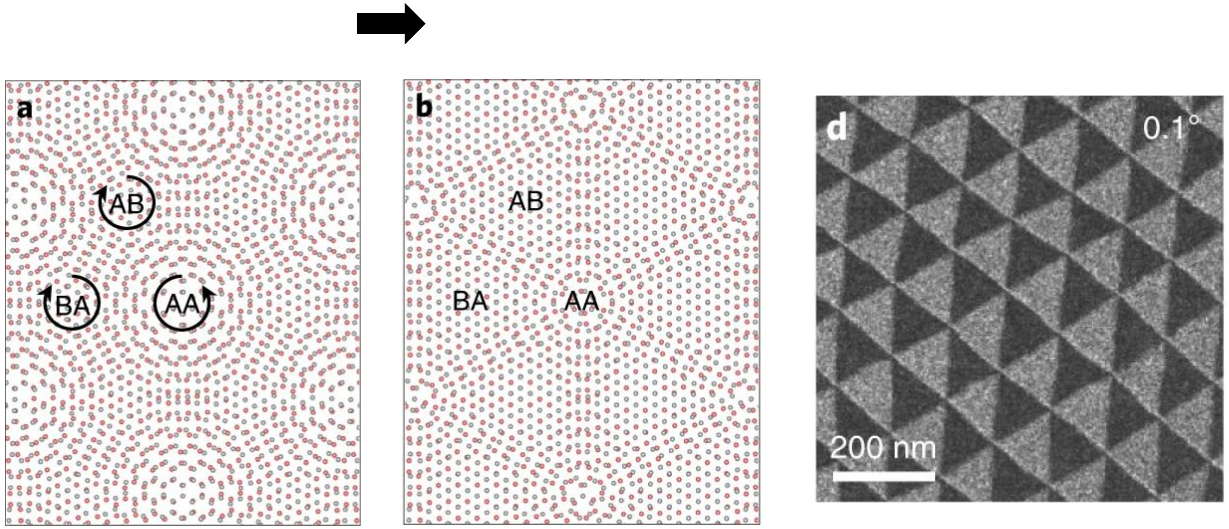

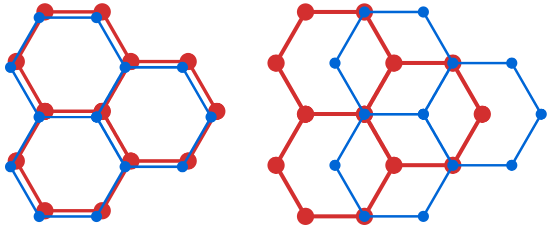

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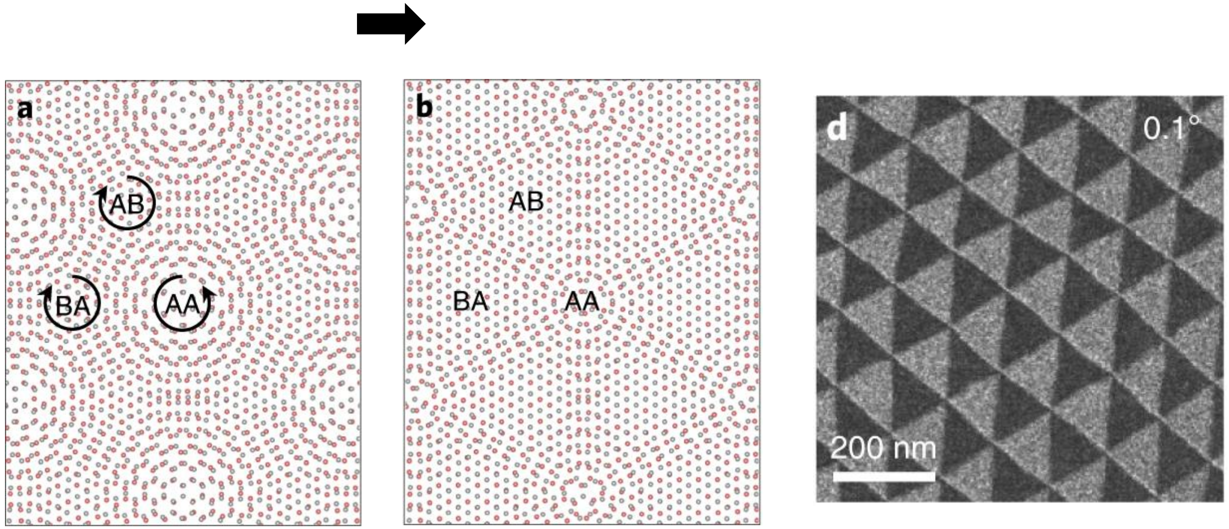
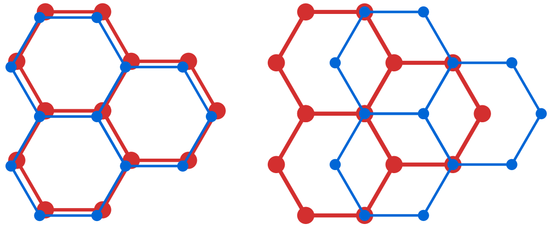
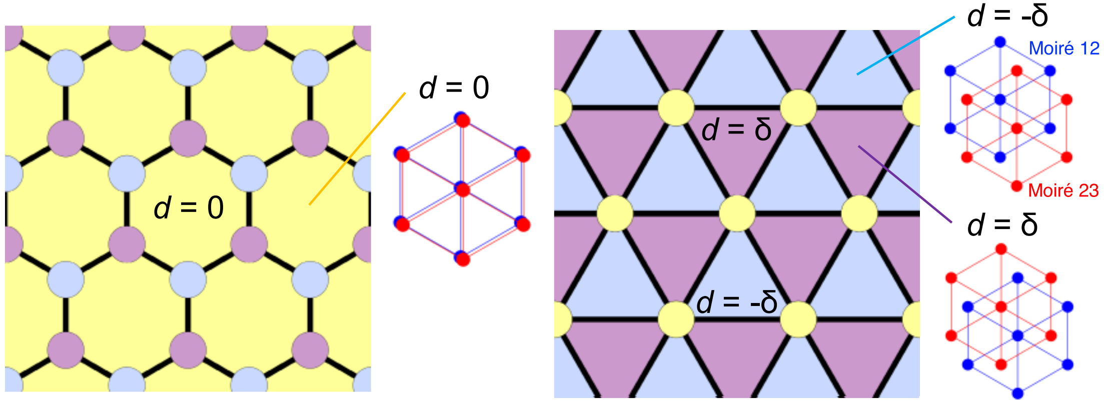




Relaxation at the supermoiré scale

Alternating

Helical



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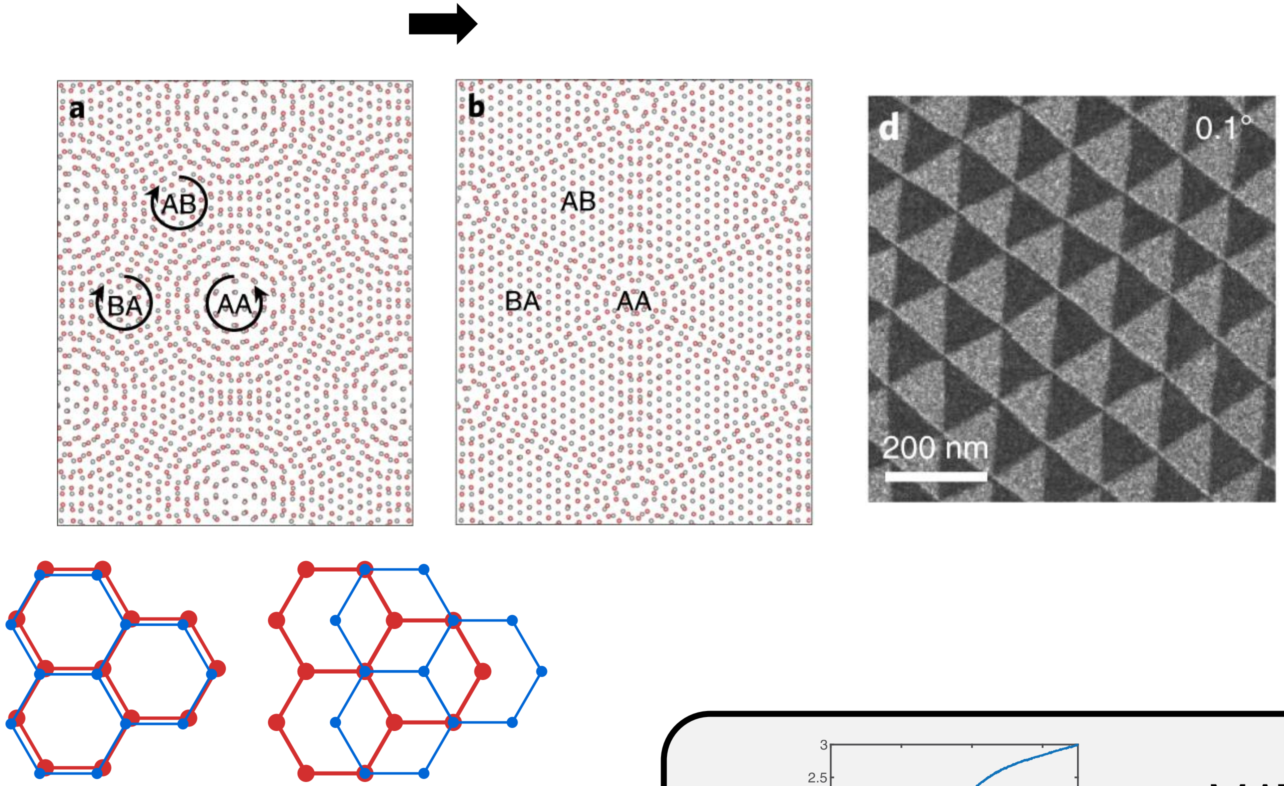

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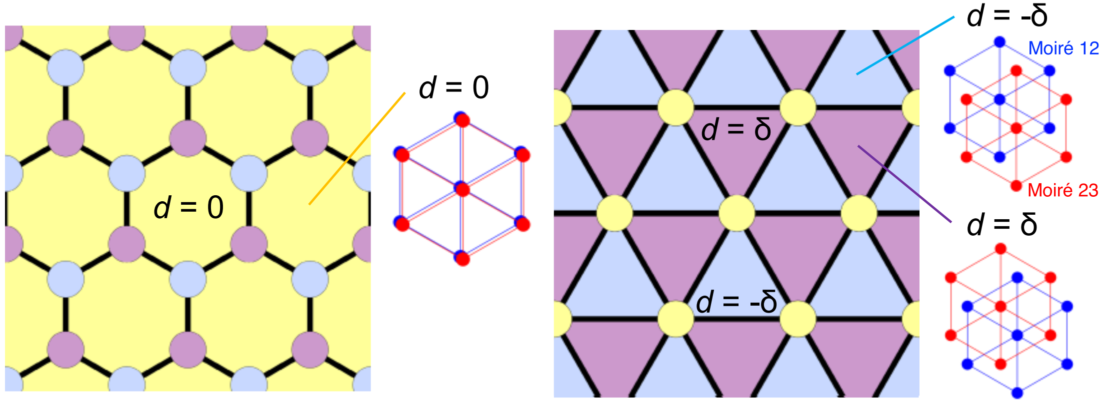
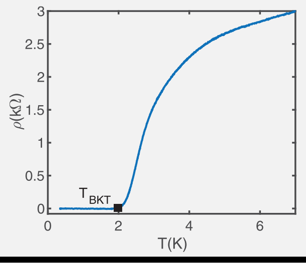
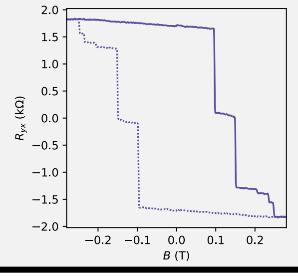


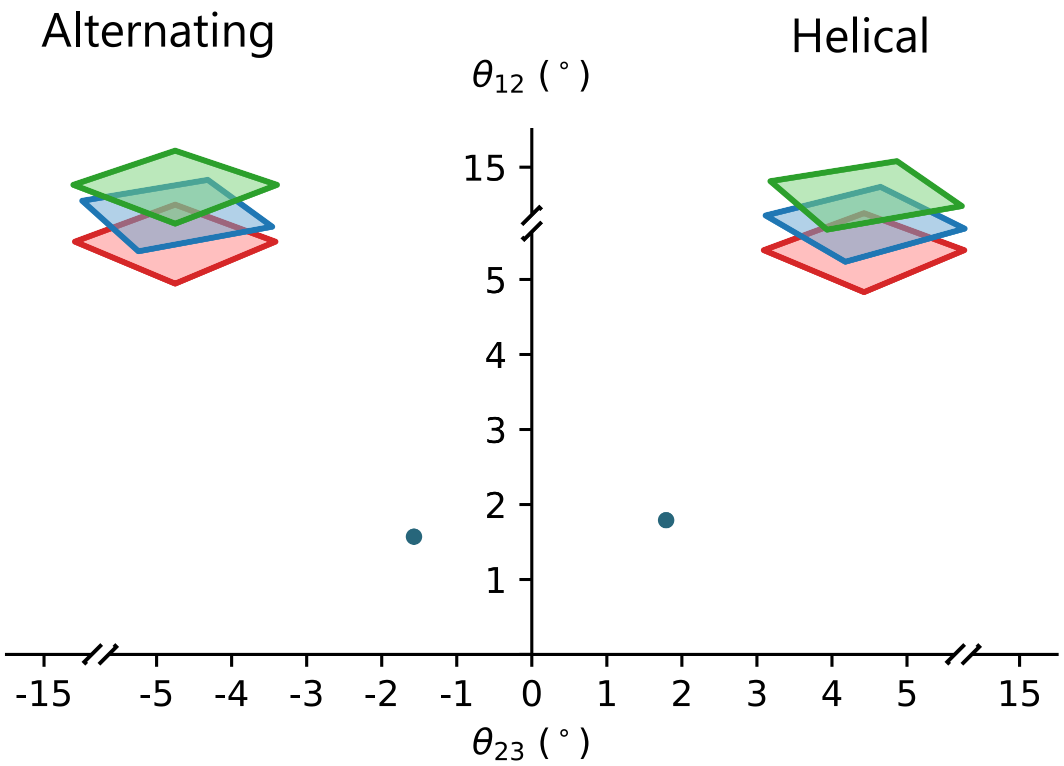


MATTG: *d*=0 domains
MAHTG: *xy*-inversion broken domains!



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

Expectations for the angle-angle phase diagram



1. Start with a TTG structure that is nearly commensurate => $(\theta_{12}, \theta_{23}) = (p\theta, q\theta)$

2. Calculate bandstructure for all intermoiré shifts

3. Expectation for correlations: θ that maximizes single particle density of states

4. Strongly reconstruct?
   Yes for $(\theta, \pm\theta)$ and $(\theta, 2\theta)$

Uri, et al. Nature (2023)
Hoke, et al. Nat. Comms. (2024)
Xia, et al. Nat. Phys. (2025)
Yang, et al. arXiv:2310.12961

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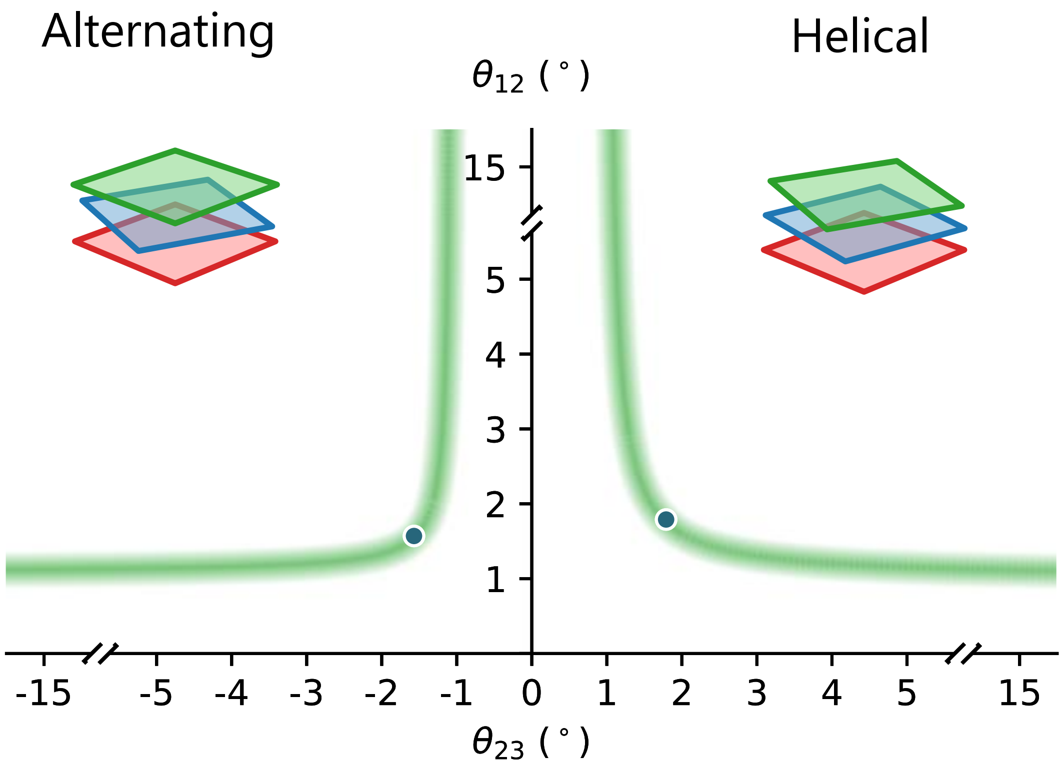

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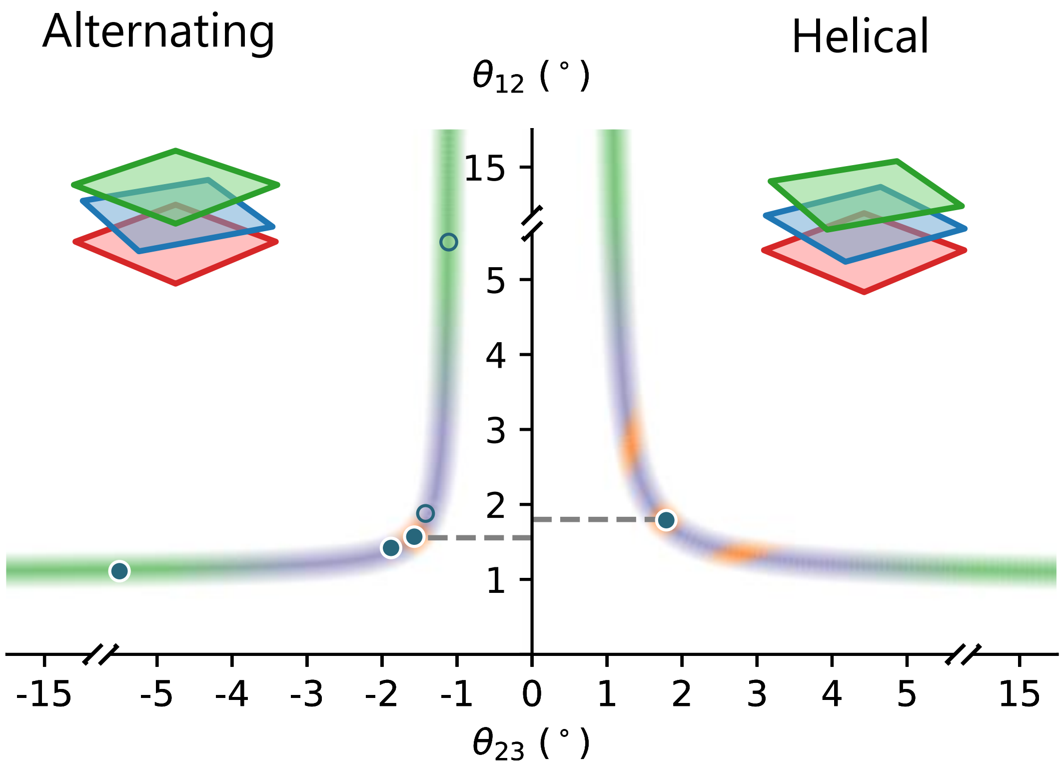

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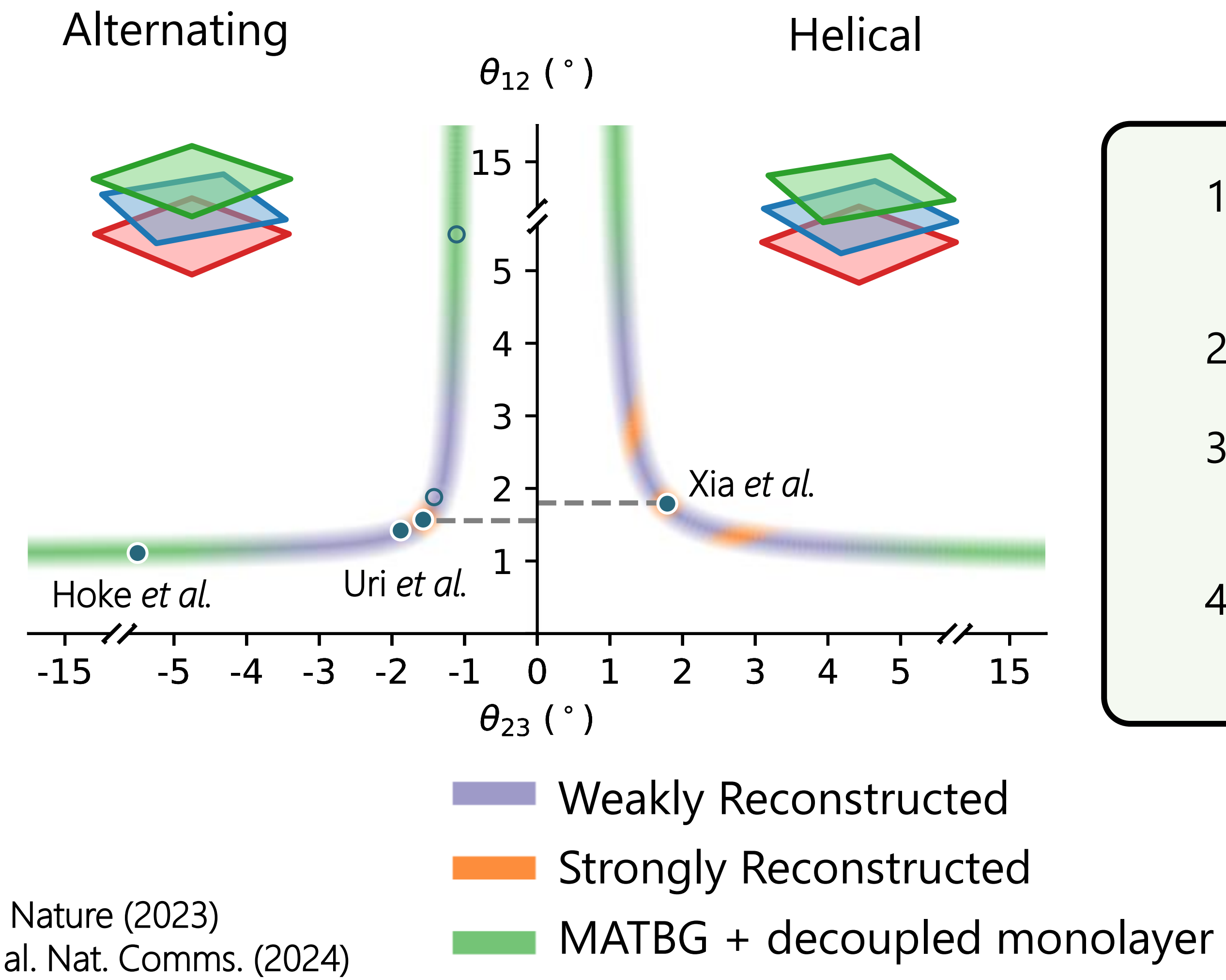

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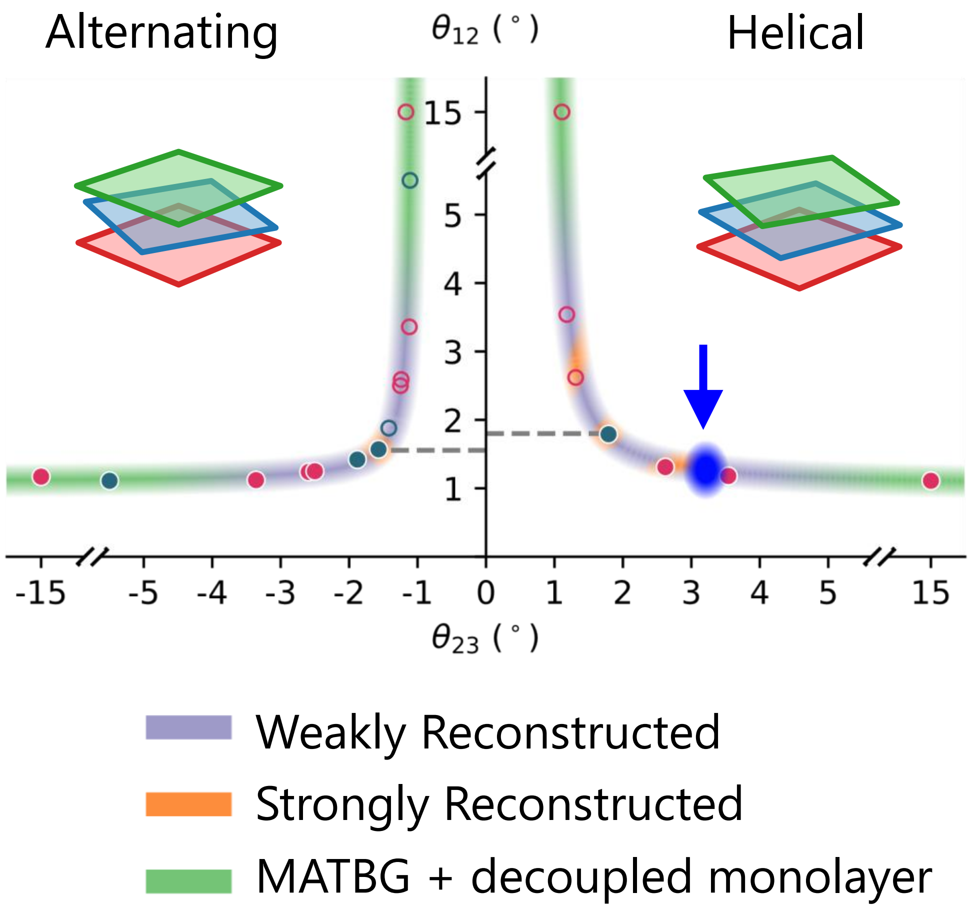
Outline

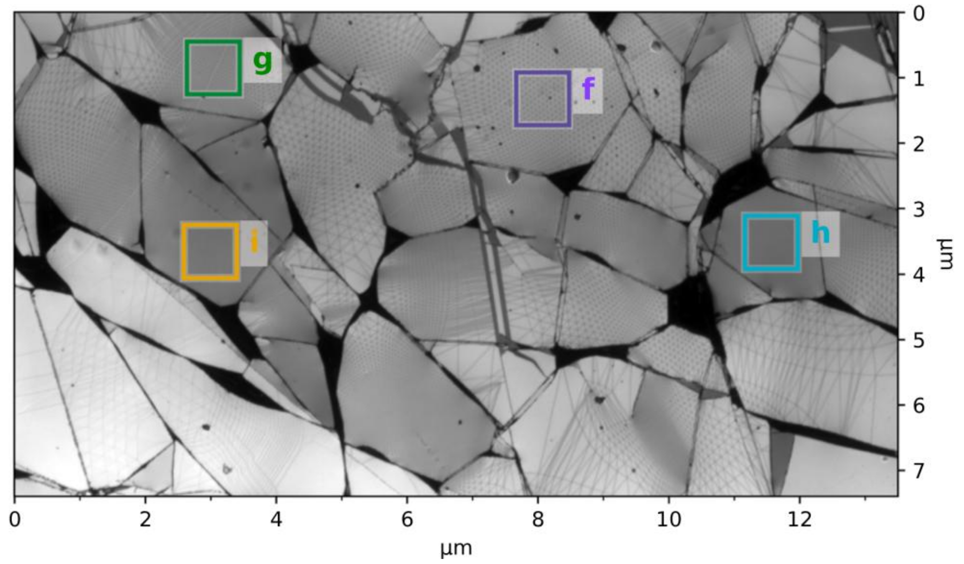
Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation

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



de Jong, et al. Nat. Comms. (2022)
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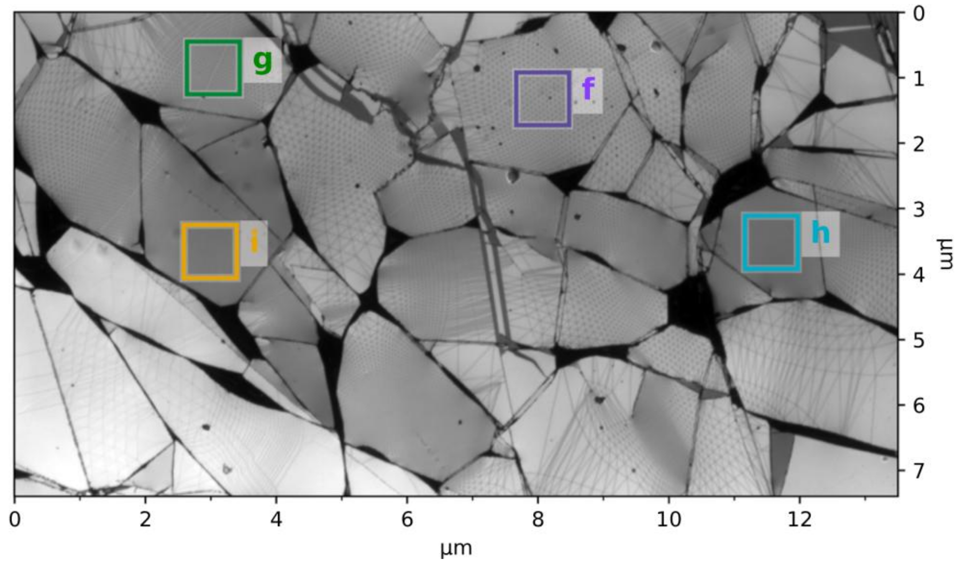

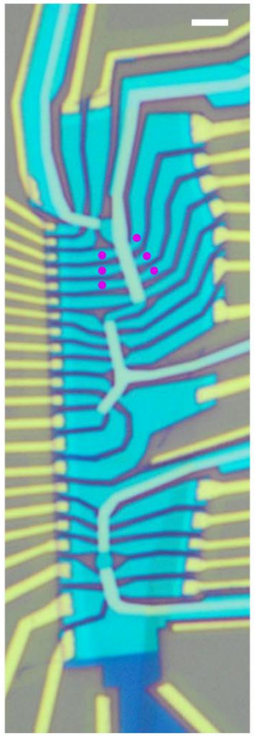

Usual approach: probe as much of the heterostructure as possible

Can we take a better approach?

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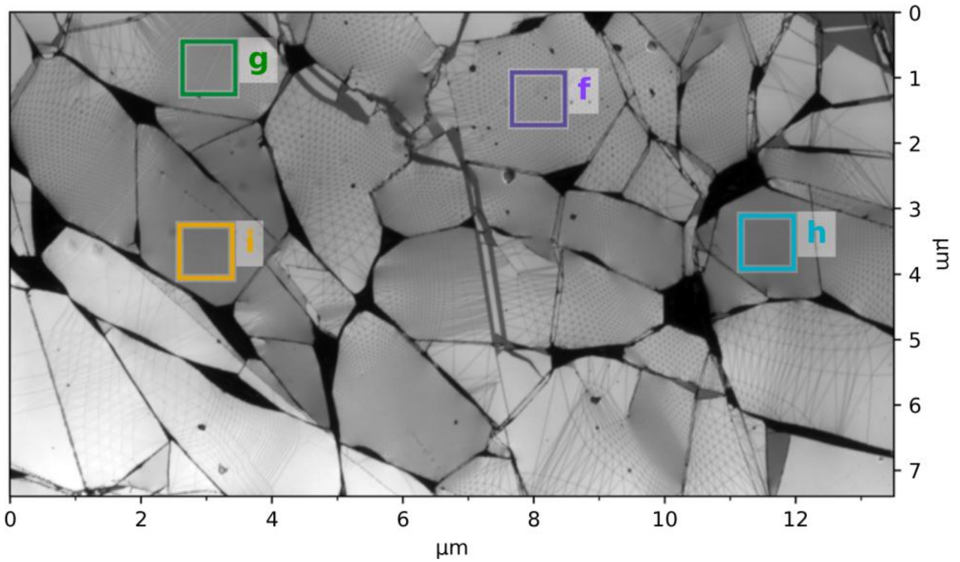
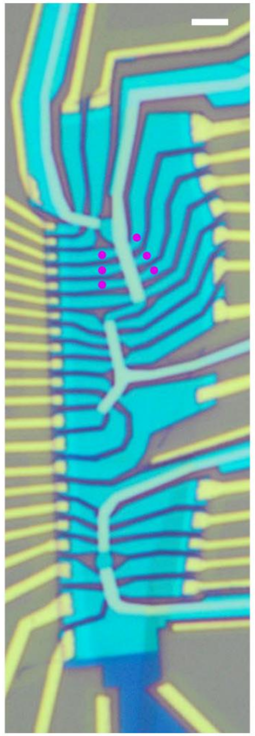
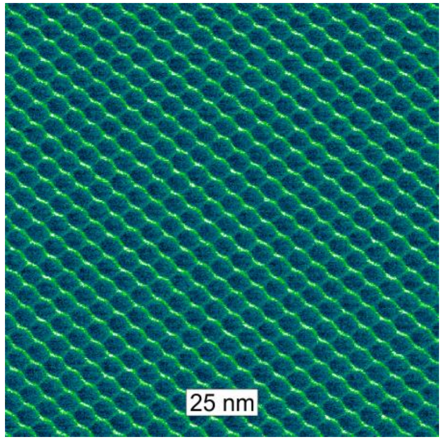




TFM



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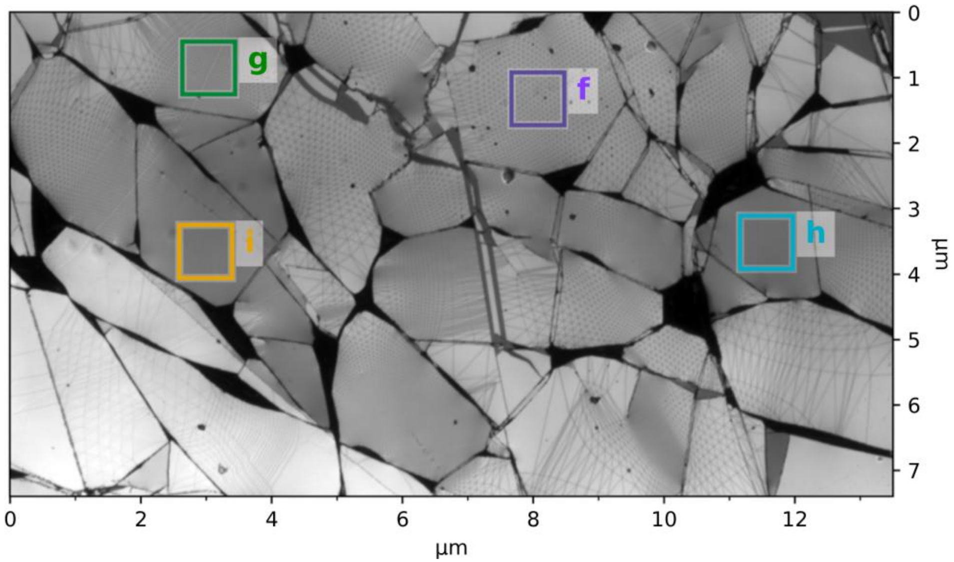

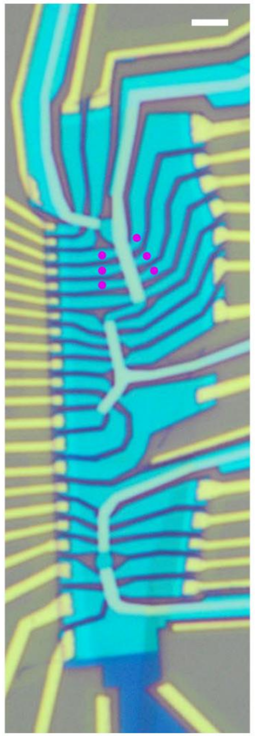

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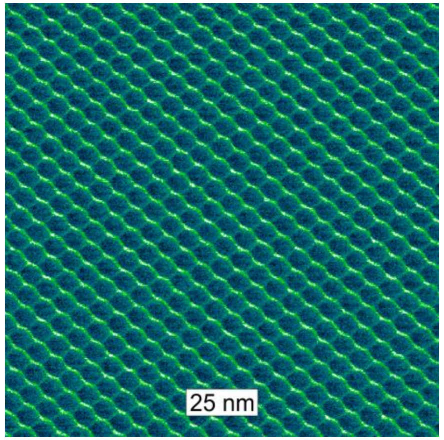
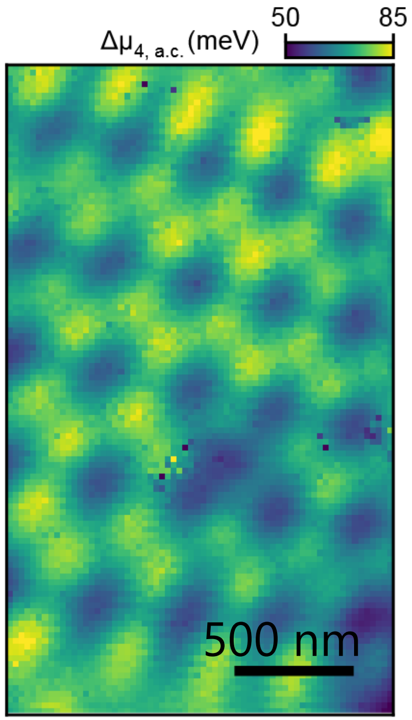


SET



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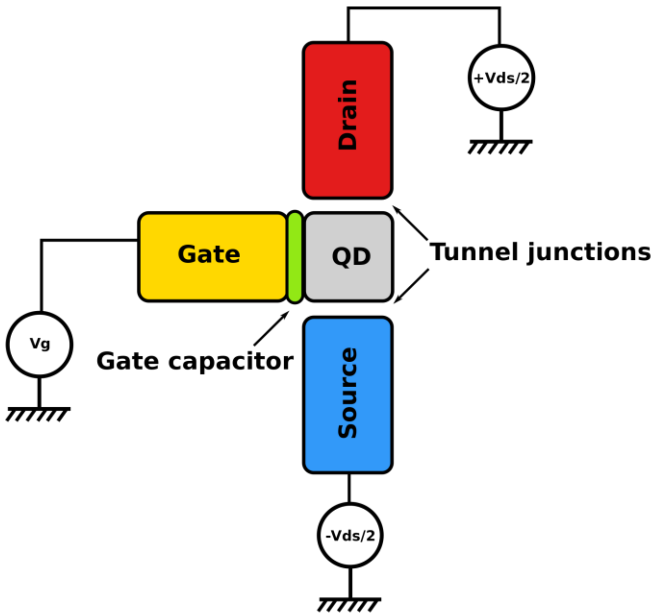
Scanning single-electron transistor



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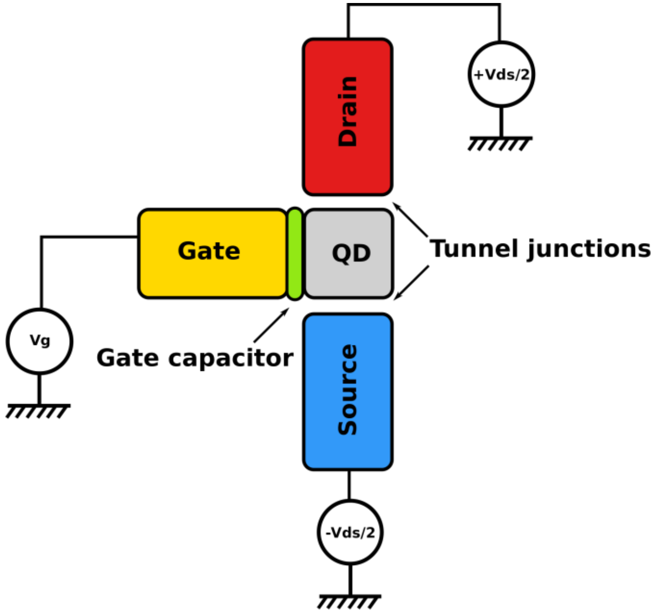

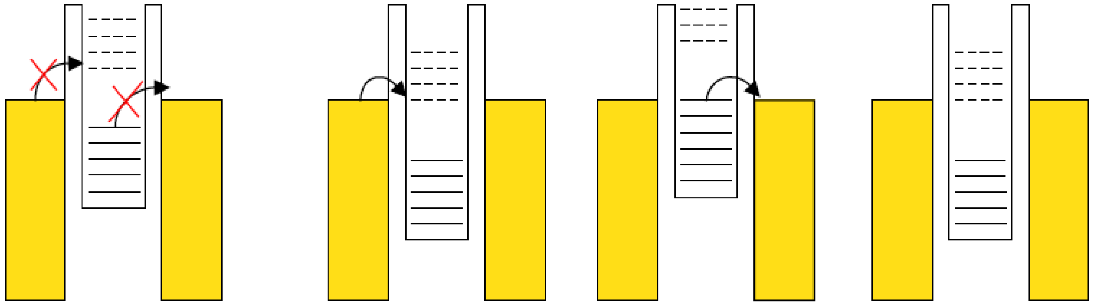

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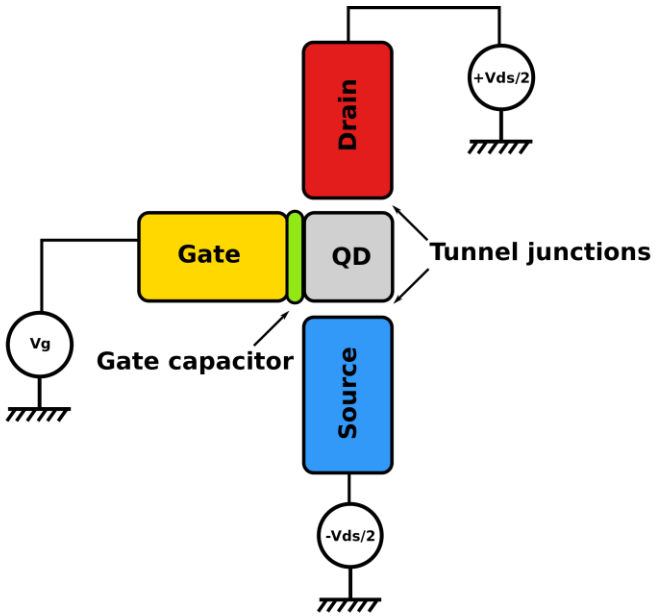

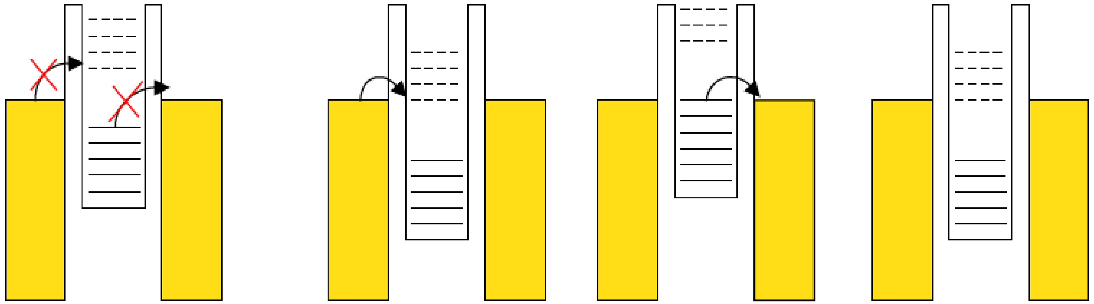

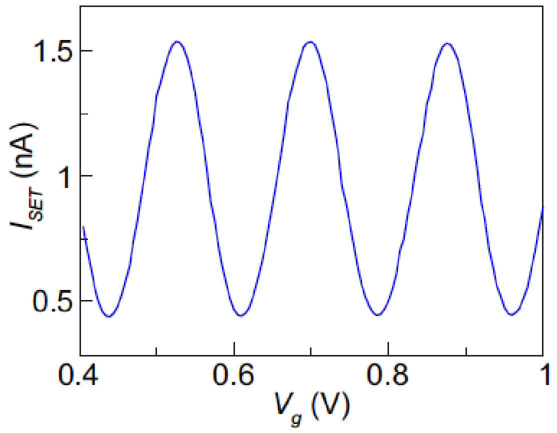

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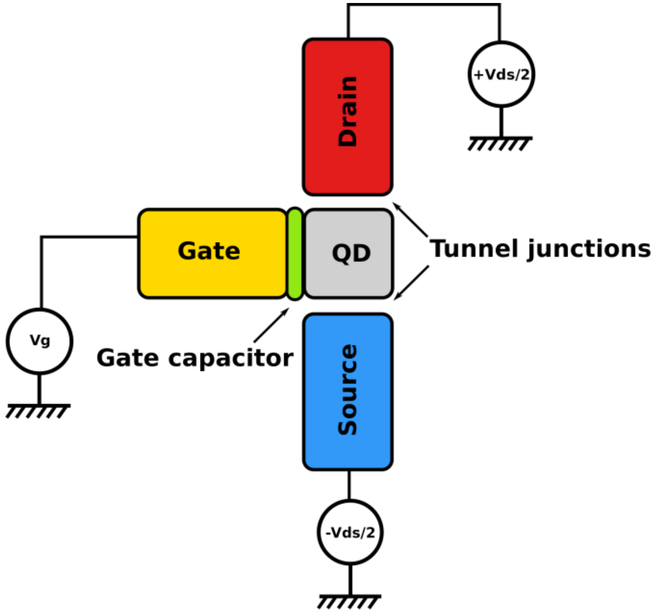
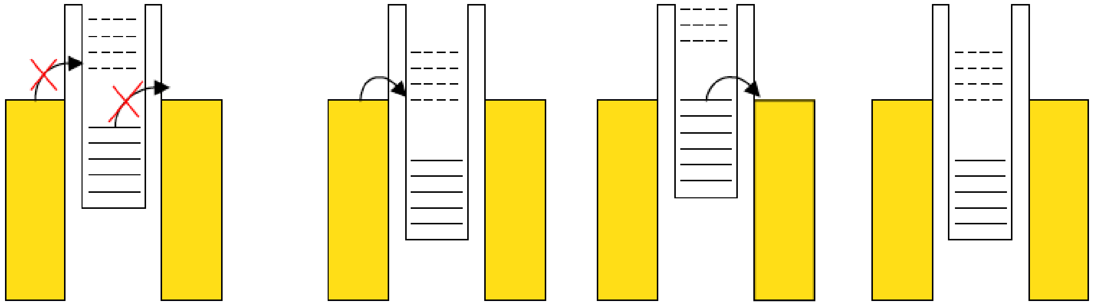
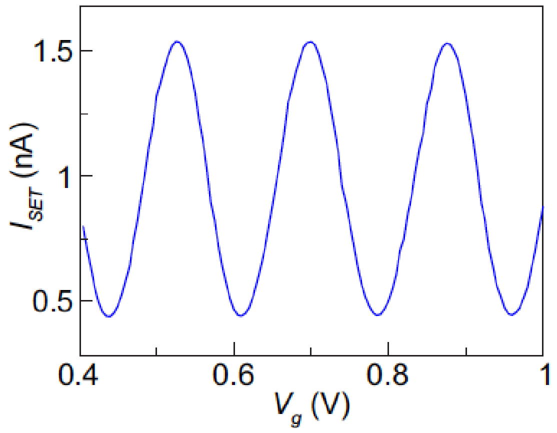
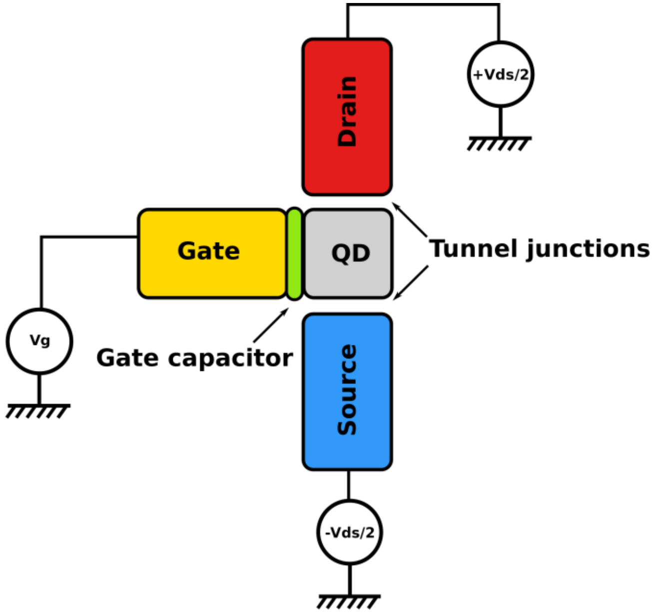


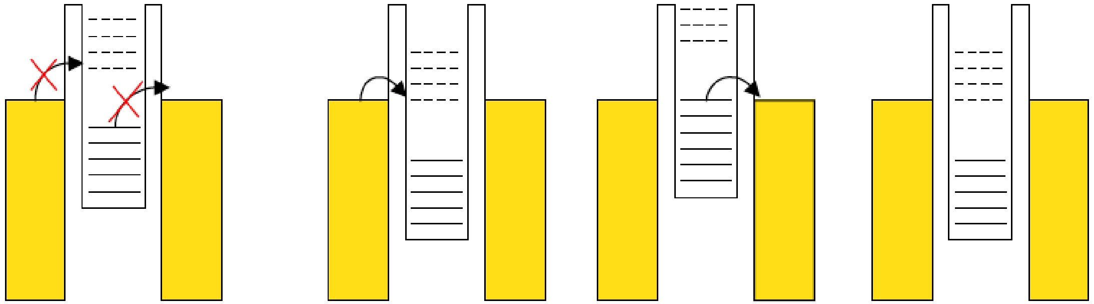


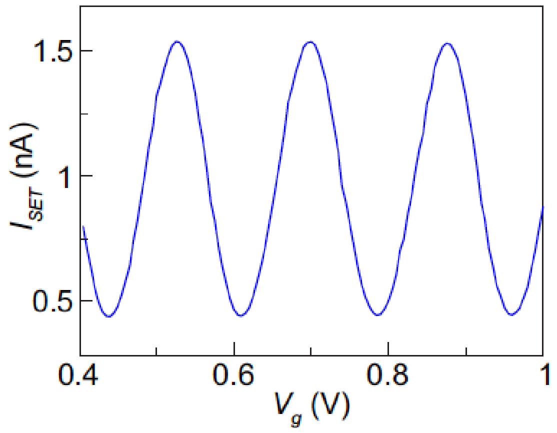


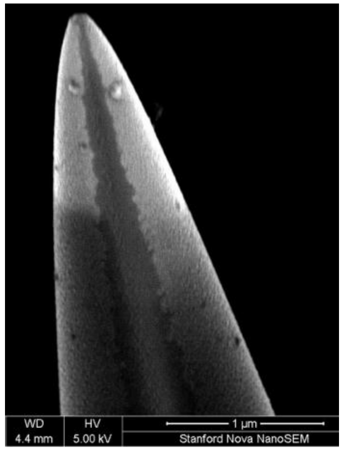
Coulomb blockade: makes SET exquisitely sensitive to electrostatic potential

Scanning single-electron transistor









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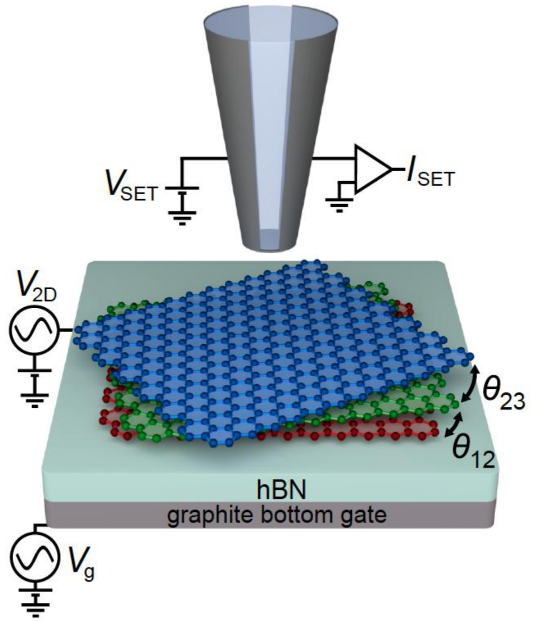

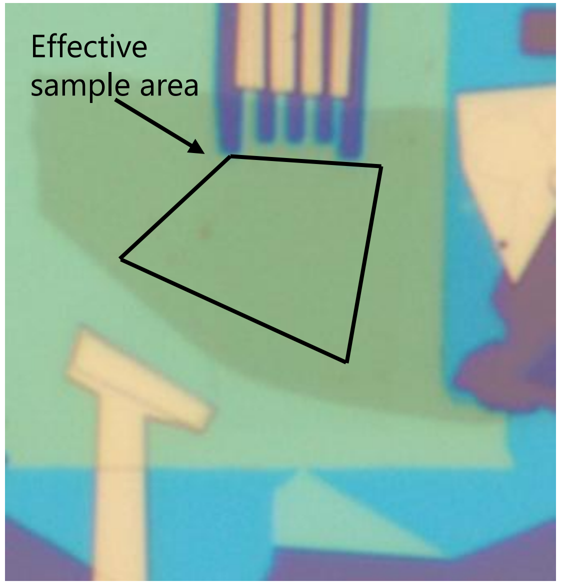

Sample held at fixed electrochemical potential
$eV = \mu + e\phi$

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

Hoke,…, Sharpe, Feldman arXiv:2509.07977

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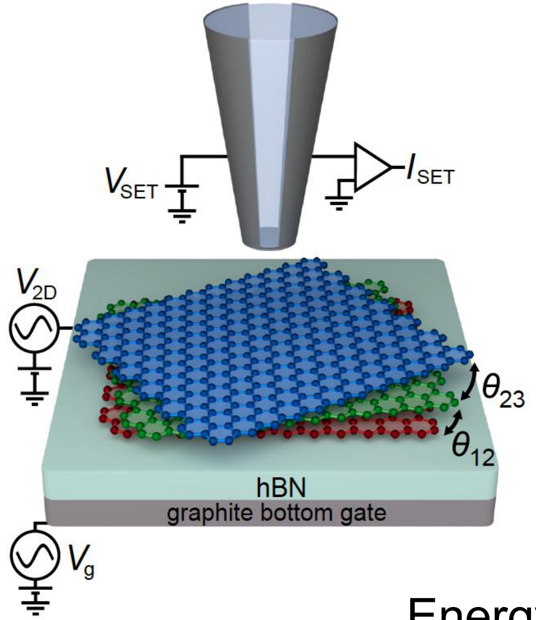

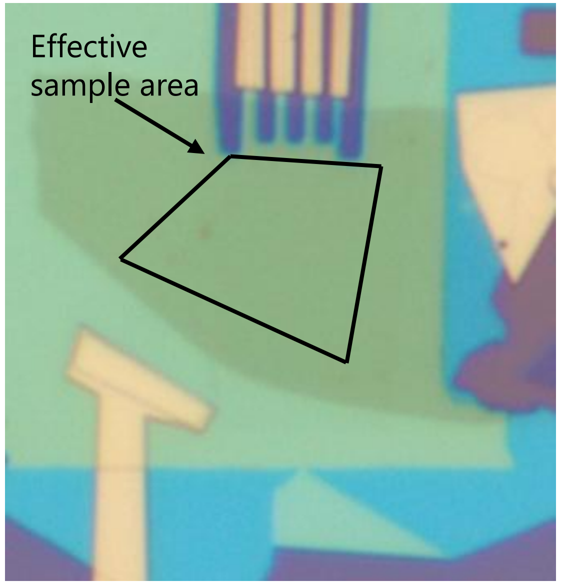

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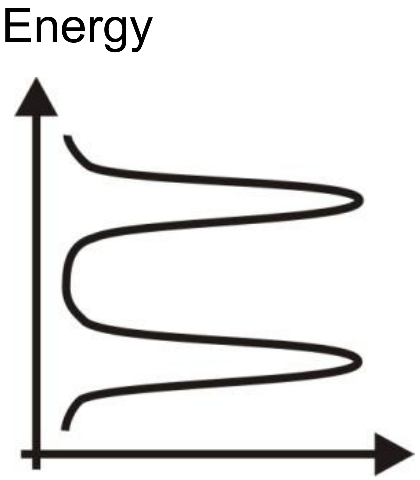
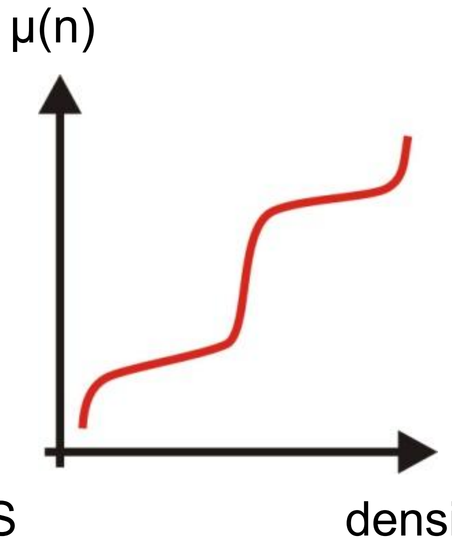
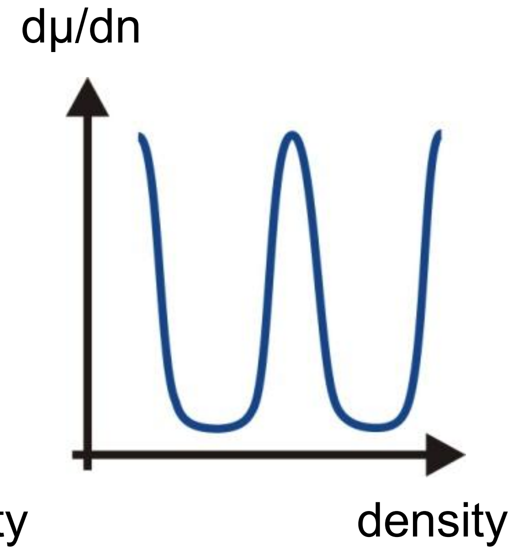


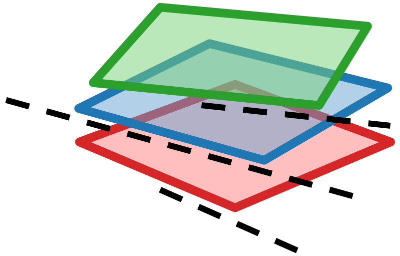
DOS

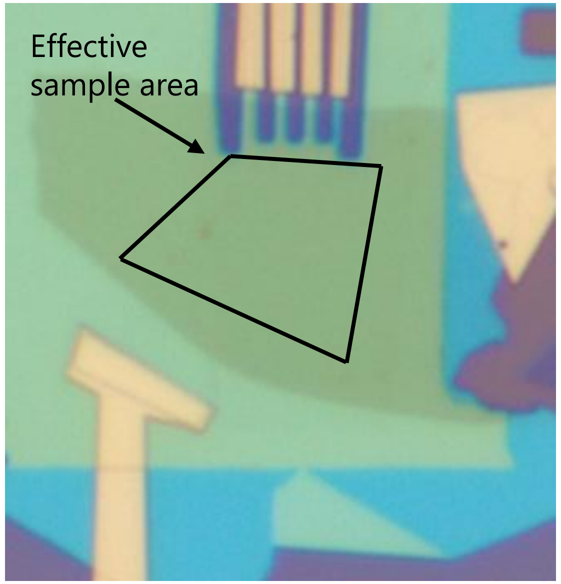


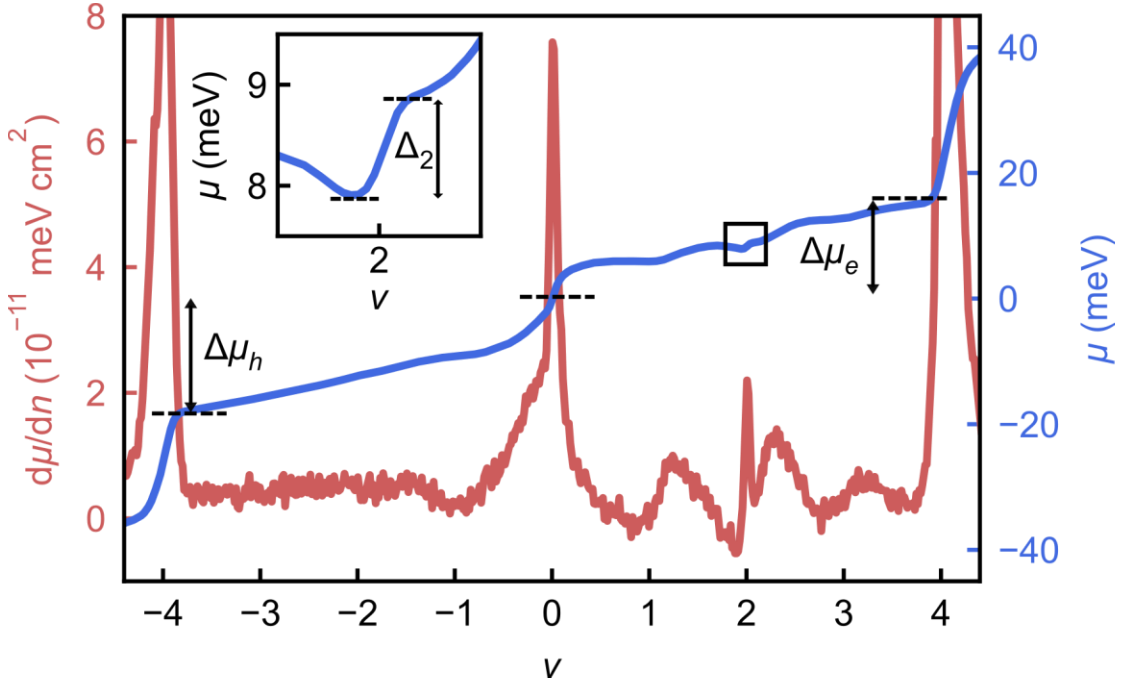


Hoke,..., Sharpe, Feldman arXiv:2509.07977

Imaging twisted trilayer compressibility^{-1}







Zondiner, et al. Nature (2020)
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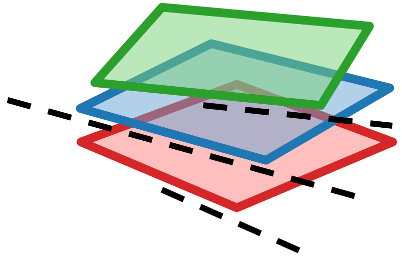
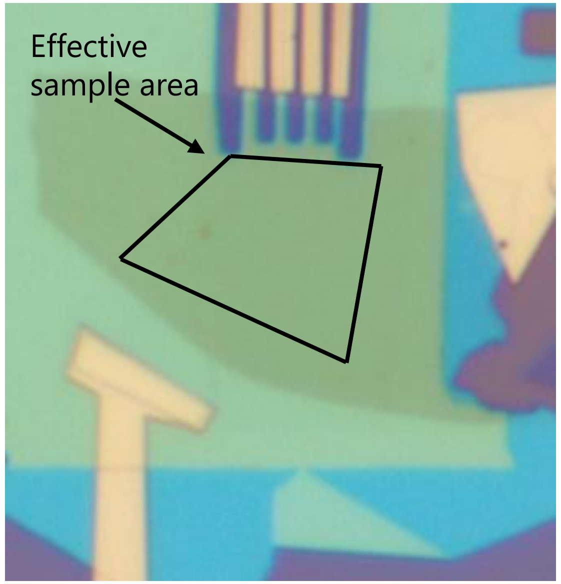
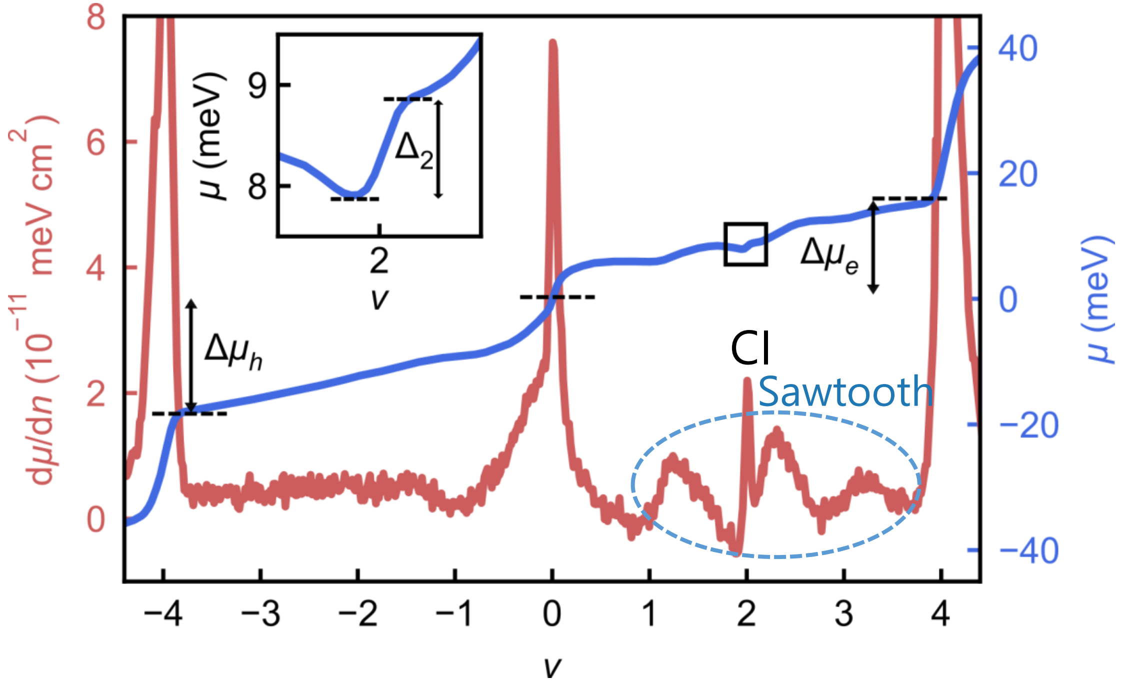
Imaging twisted trilayer compressibility[-1]







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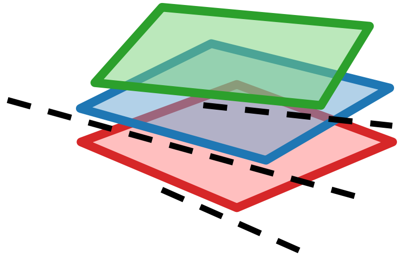
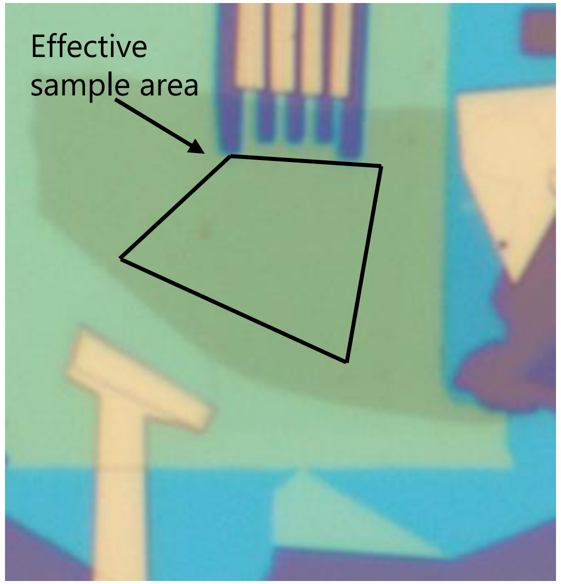
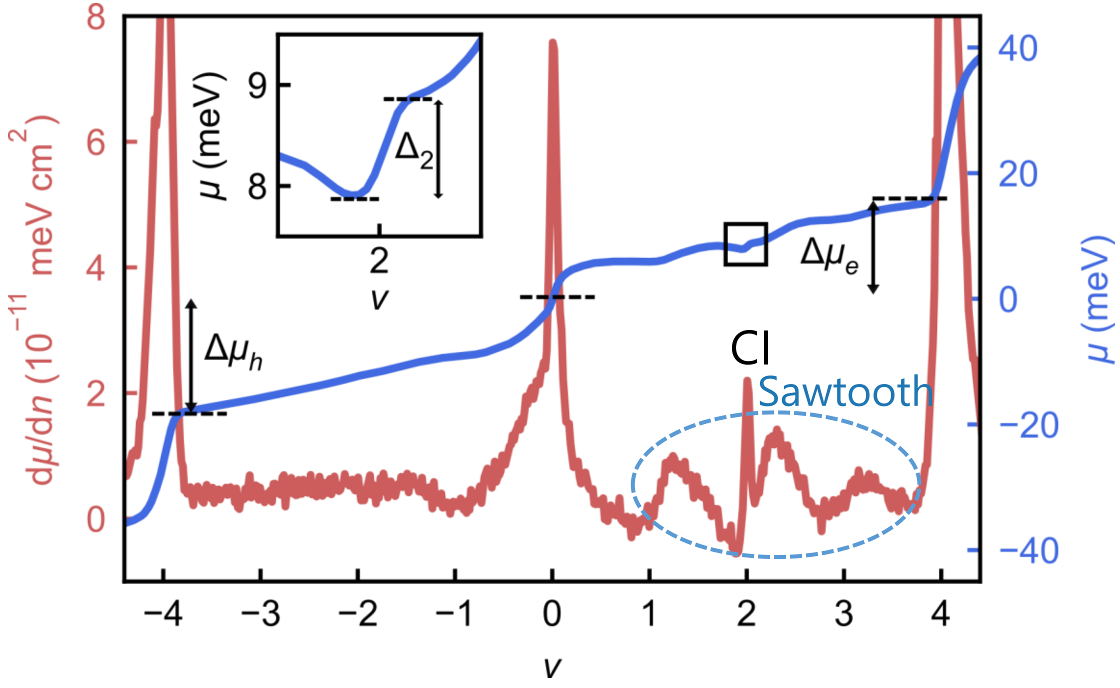
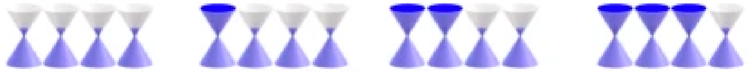


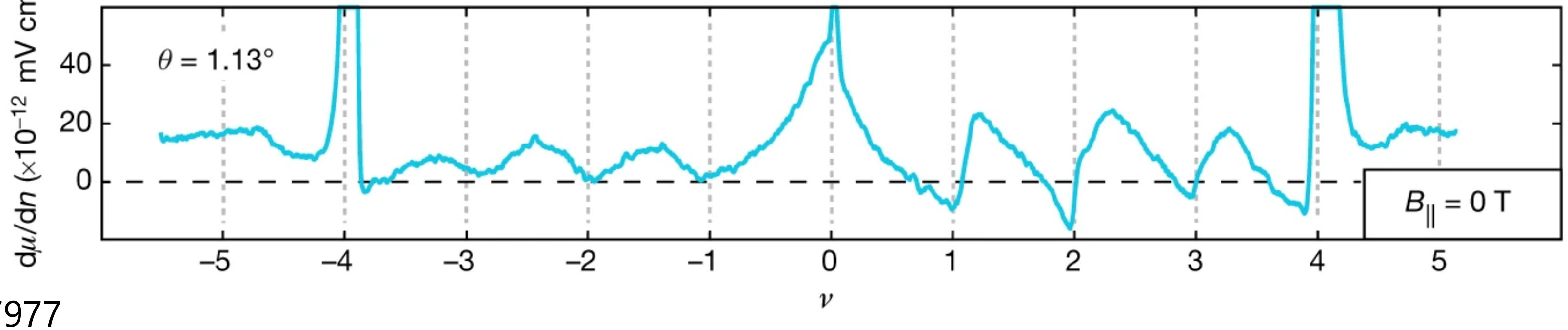
$\theta_{23} \approx 3 - 3.5°$
$\theta_{12} \approx 1 - 1.4°$





Sawtooth in MATBG
(also seen in MATTG)





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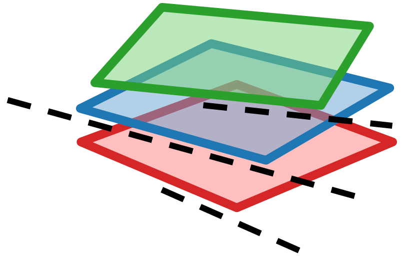
Imaging twisted trilayer compressibility[-1]



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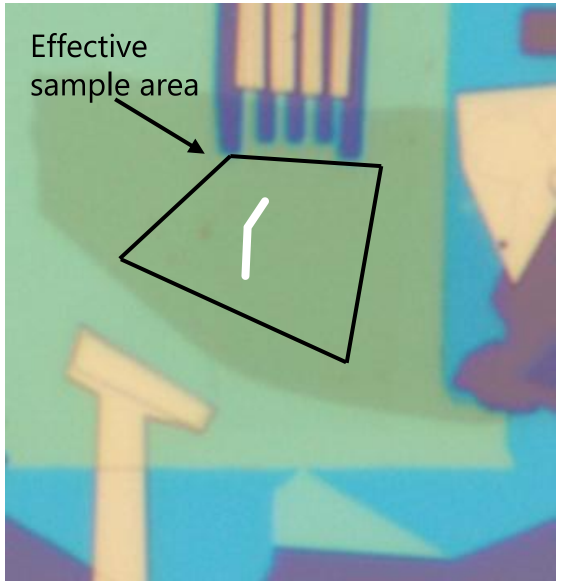
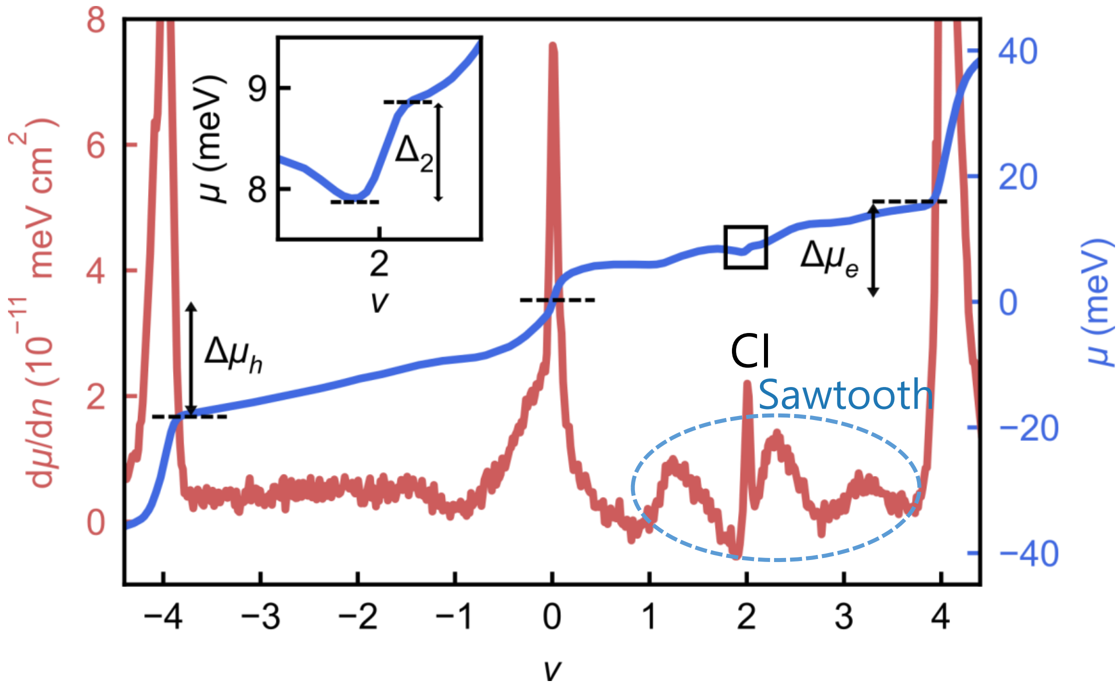
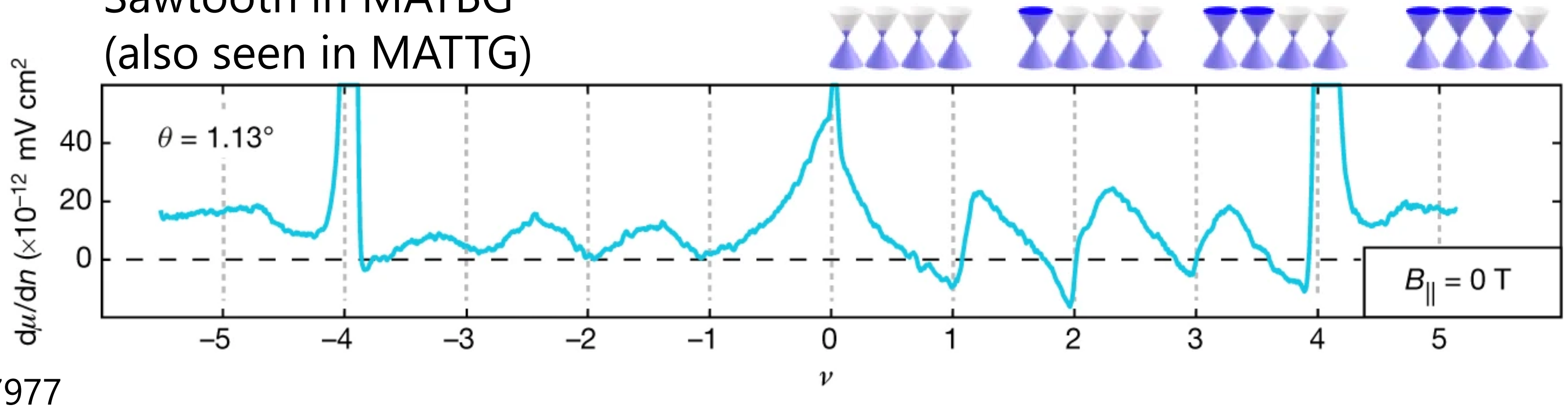




Sawtooth in MATBG
(also seen in MATTG)



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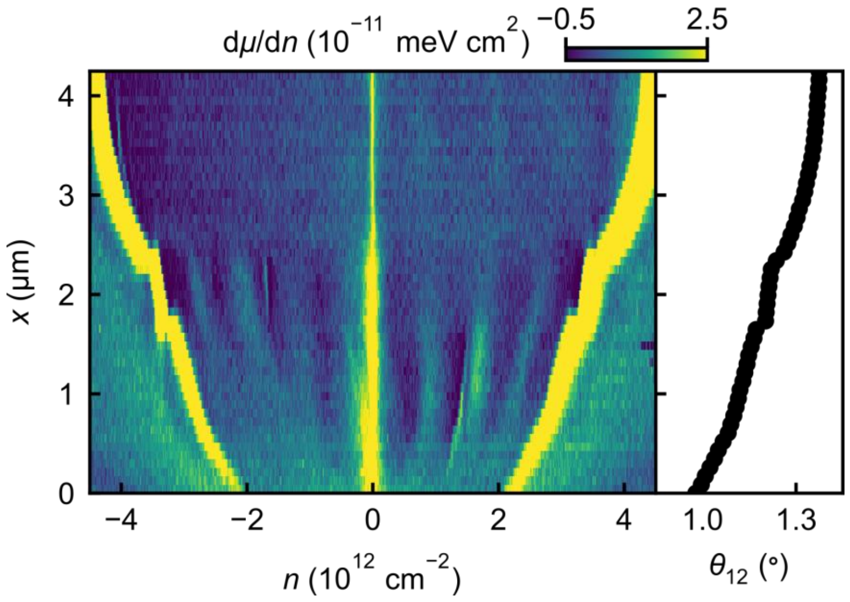
Twist angle dependent correlations



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

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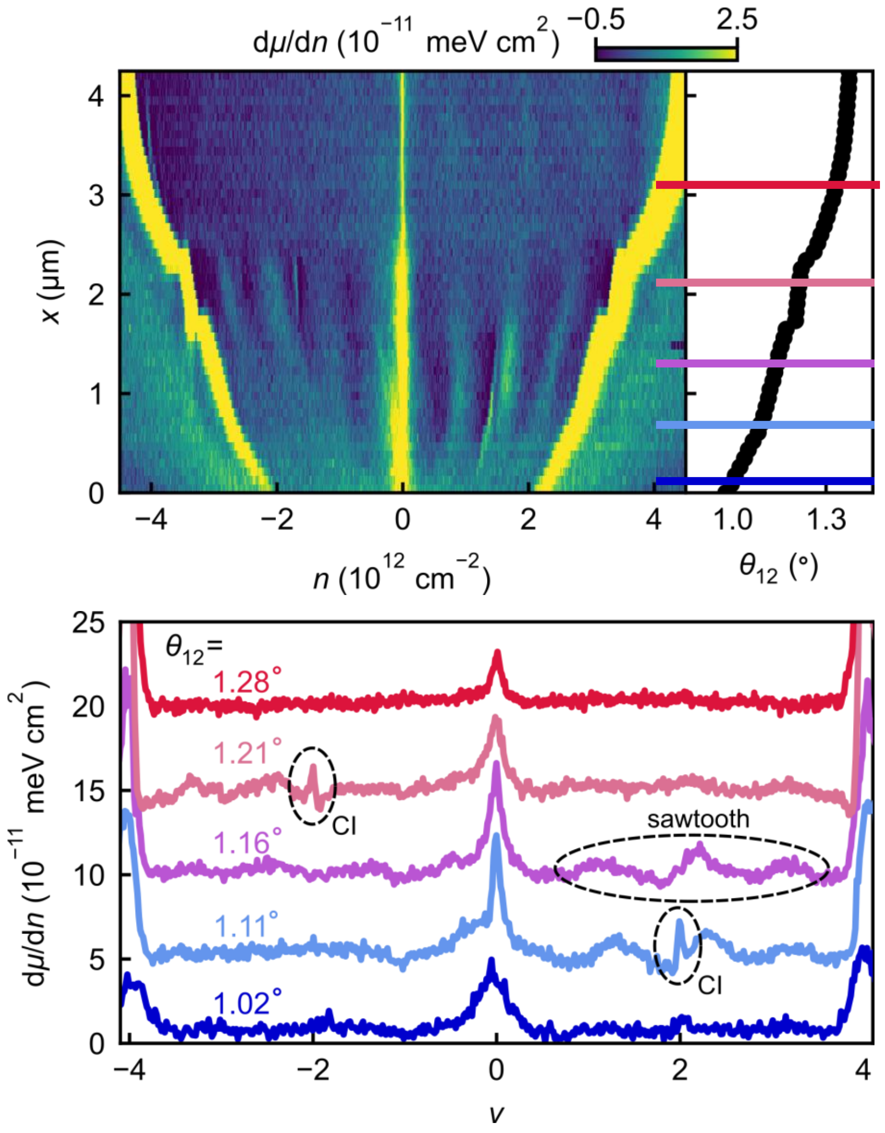

Hoke,…, Sharpe, Feldman arXiv:2509.07977

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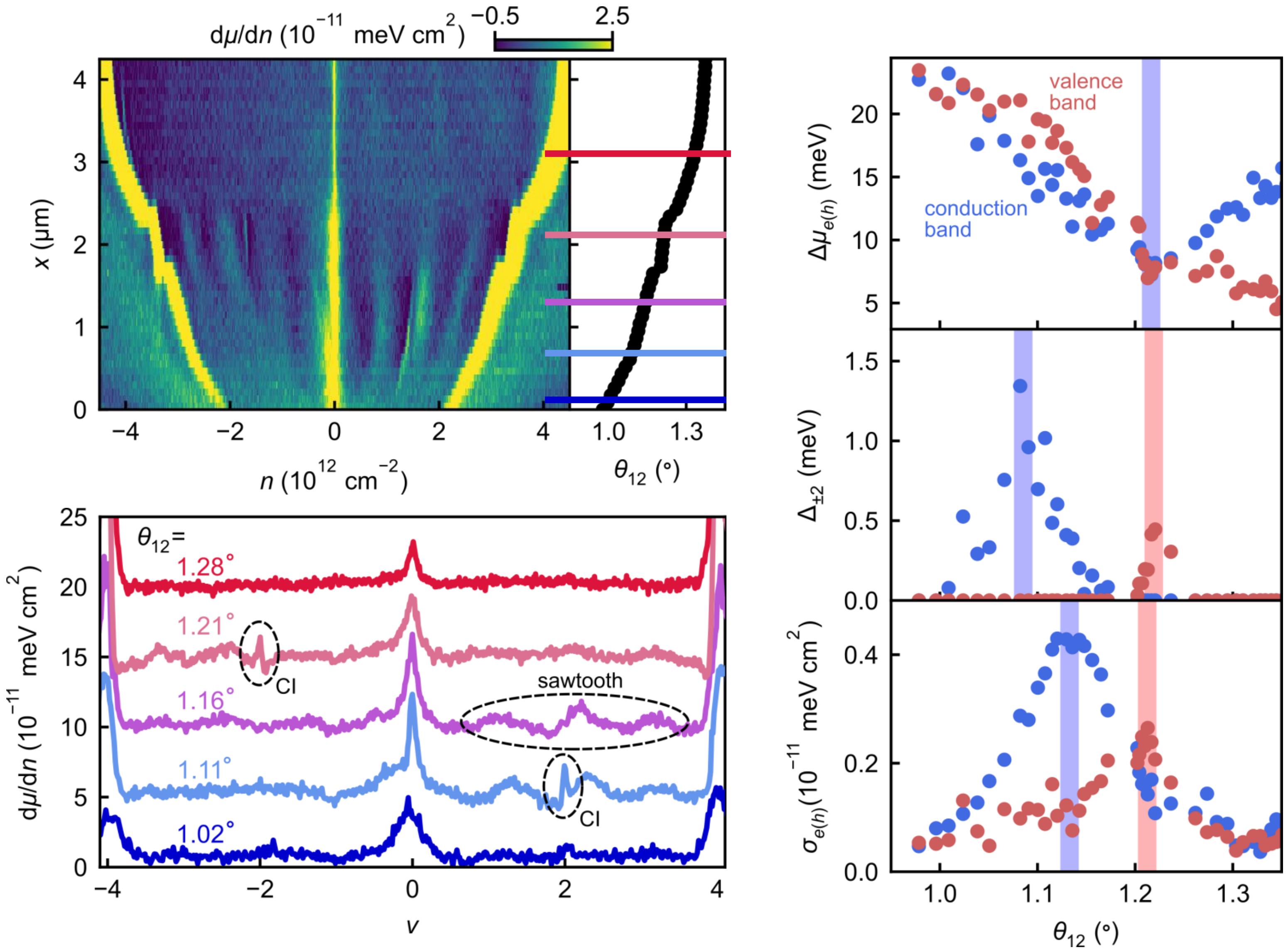
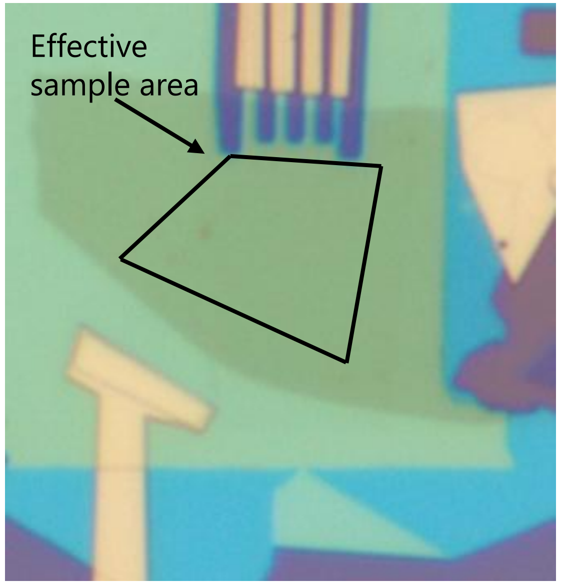


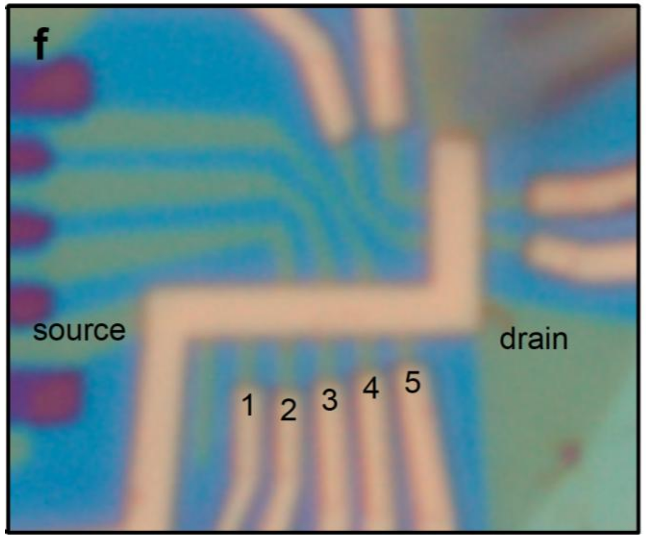
1. Distinct "magic angles" for electrons and holes
2. Correlated insulators like MATBG and TTG
3. "Sawtooth" in compressibility[-1] also like MATBG/MATTG

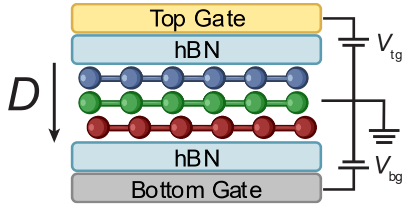
Hoke,…, Sharpe, Feldman arXiv:2509.07977

Compare to Transport



→ Fab



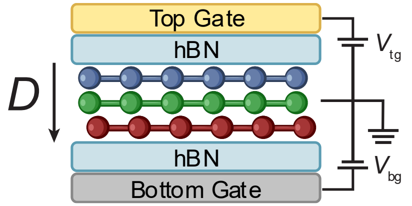


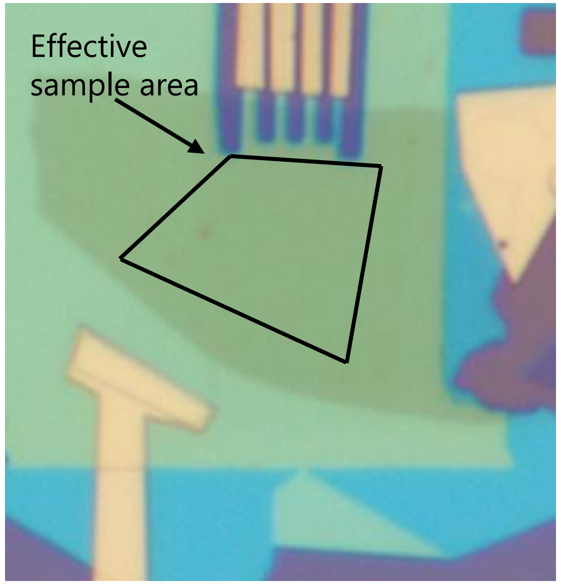
Etched a 'magic' region of the device and added a top gate

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

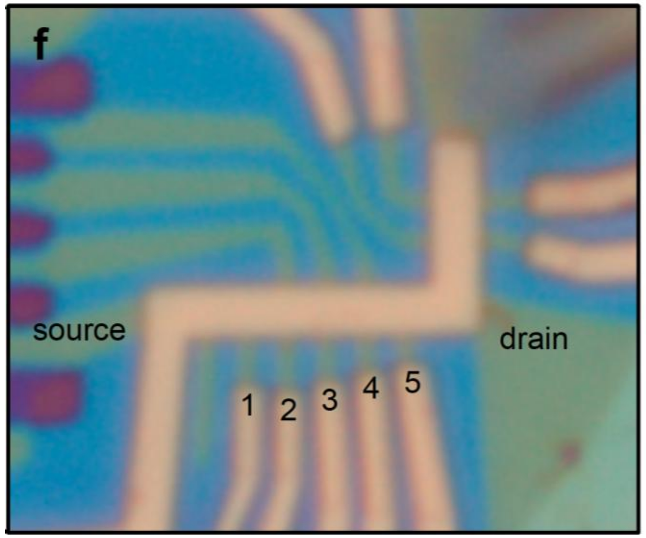
Hoke,..., Sharpe, Feldman arXiv:2509.07977

Compare to Transport



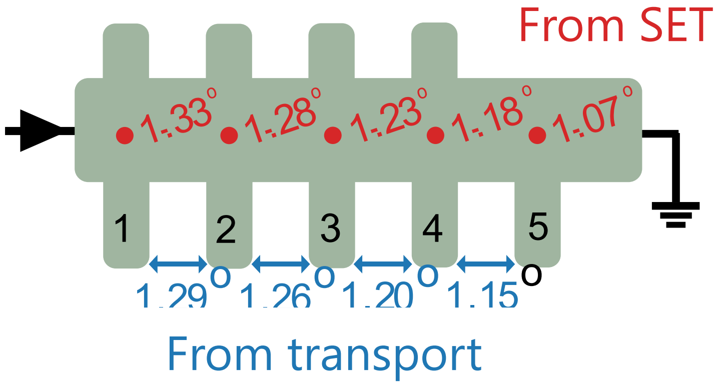


→ Fab



Etched a ‘magic’ region of the device and added a top gate

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



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

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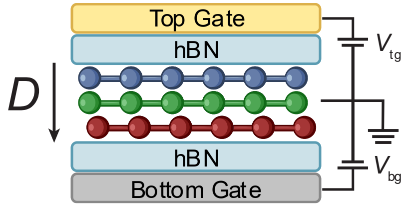

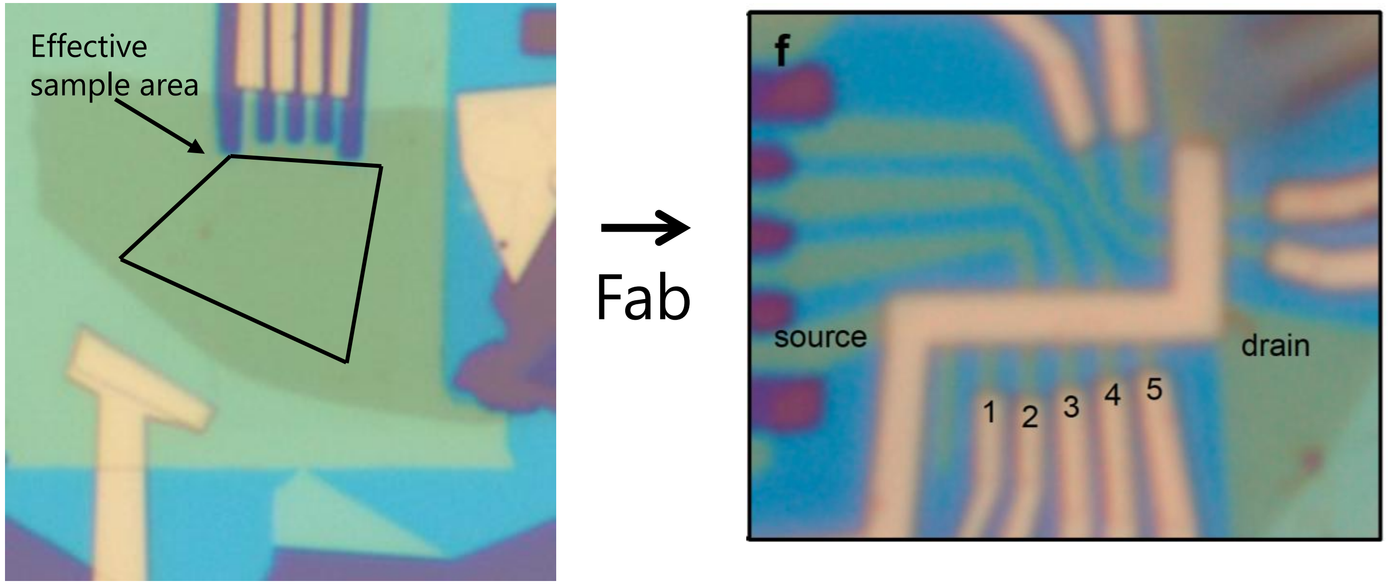

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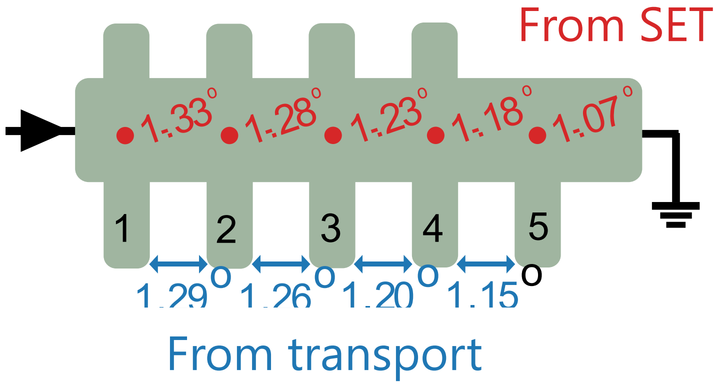
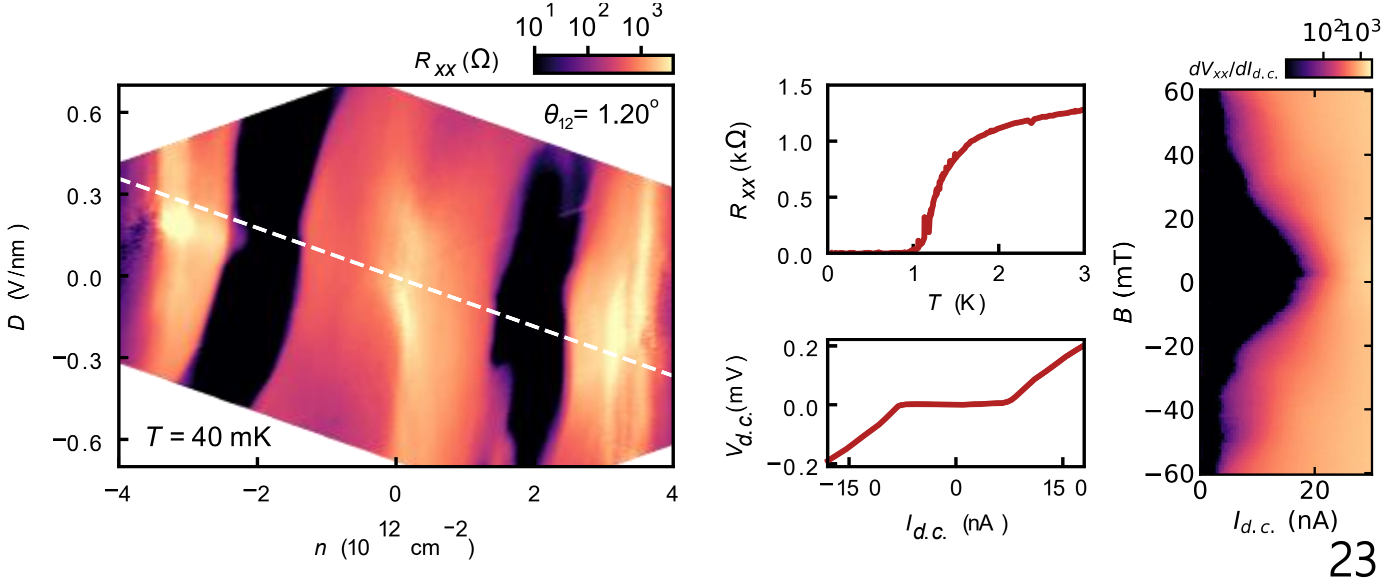
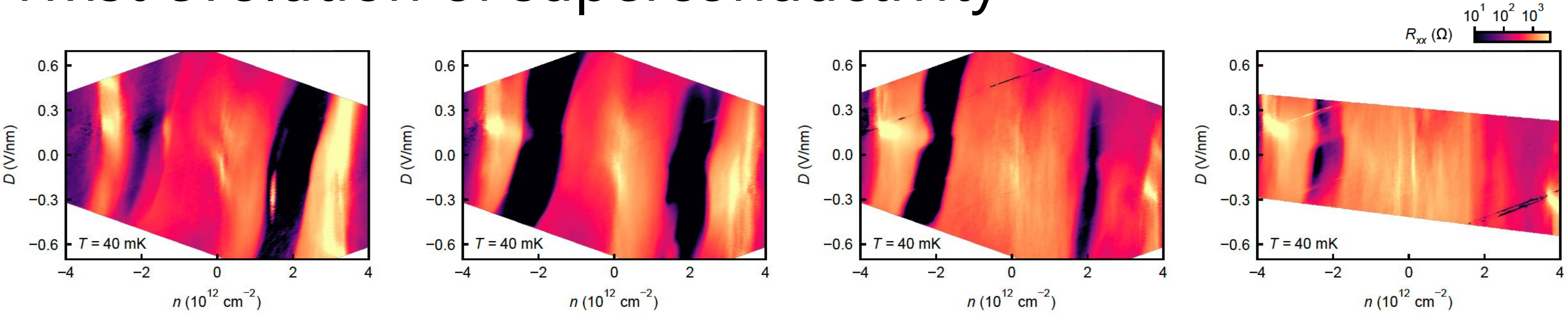




Hoke,..., Sharpe, Feldman arXiv:2509.07977

Twist evolution of superconductivity



1.15°   Increasing angle   1.29°

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

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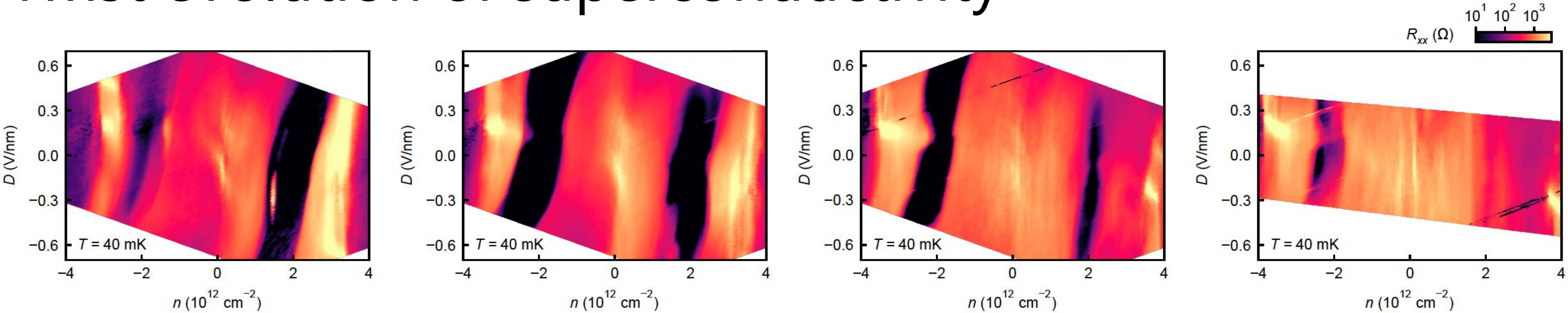

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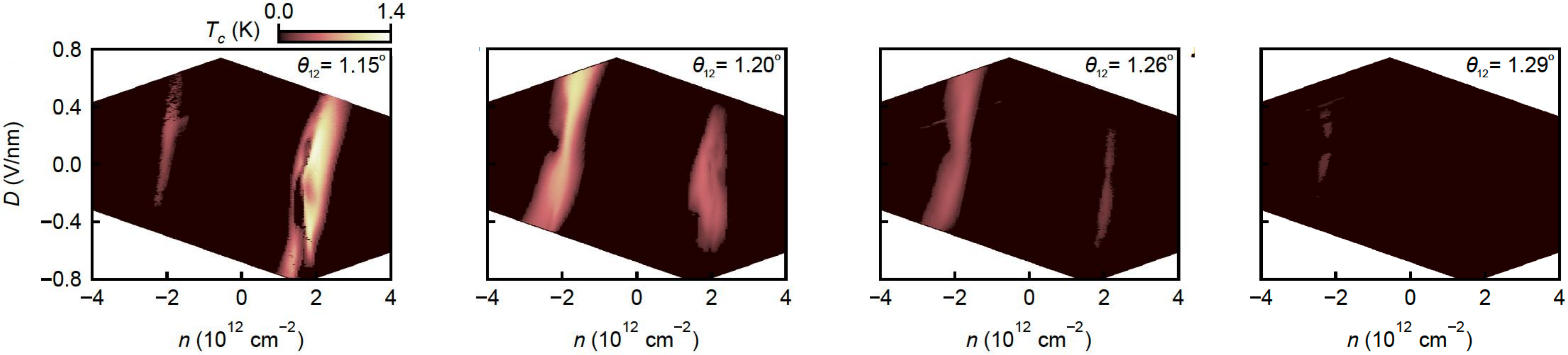
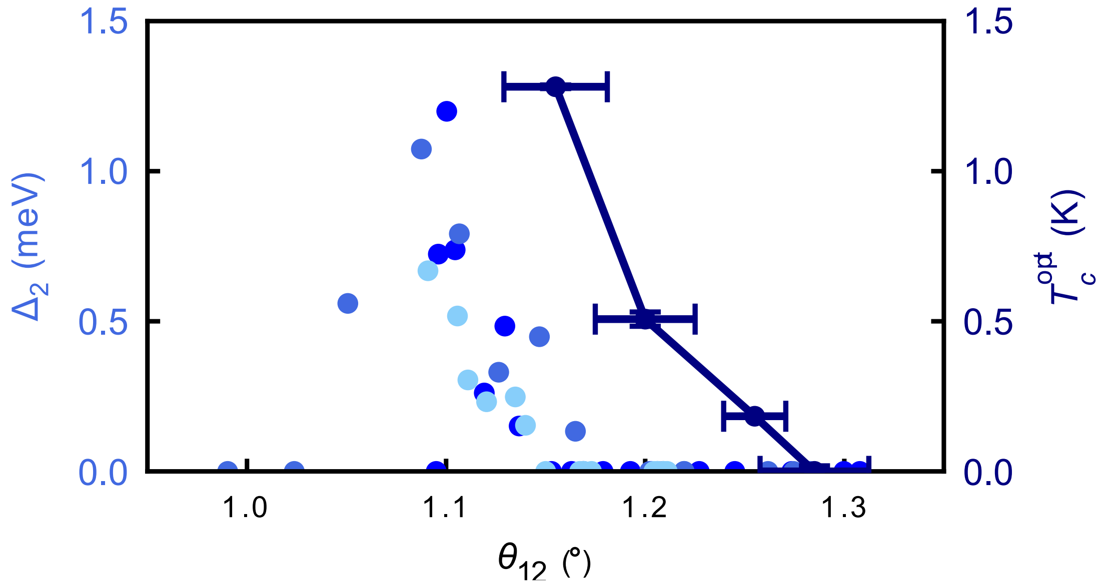


Hoke,..., Sharpe, Feldman arXiv:2509.07977

Comparing superconductivity and sawtooth strength



Hoke,…, Sharpe, Feldman arXiv:2509.07977

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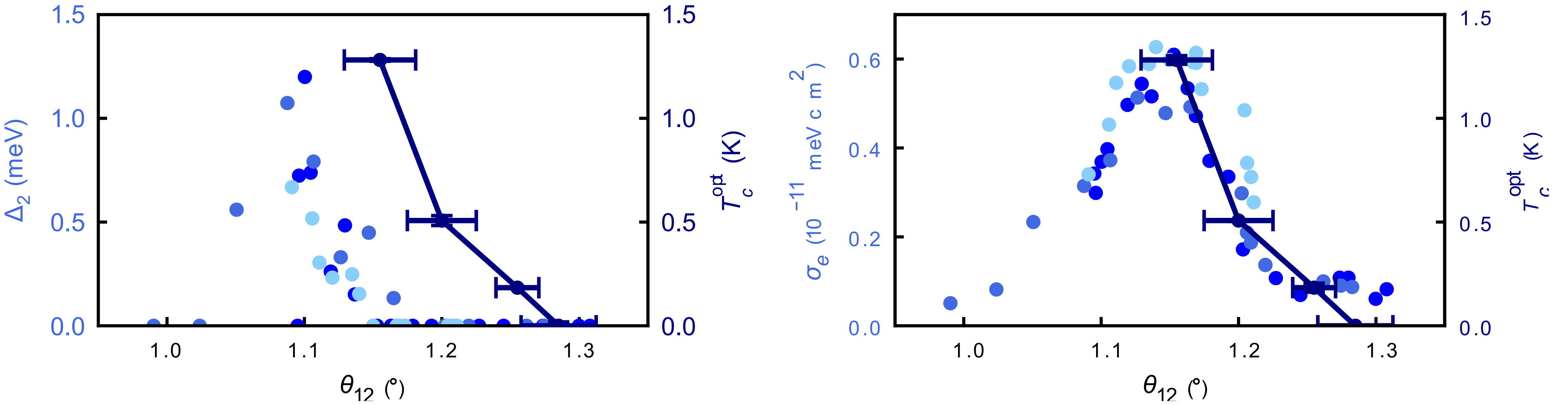
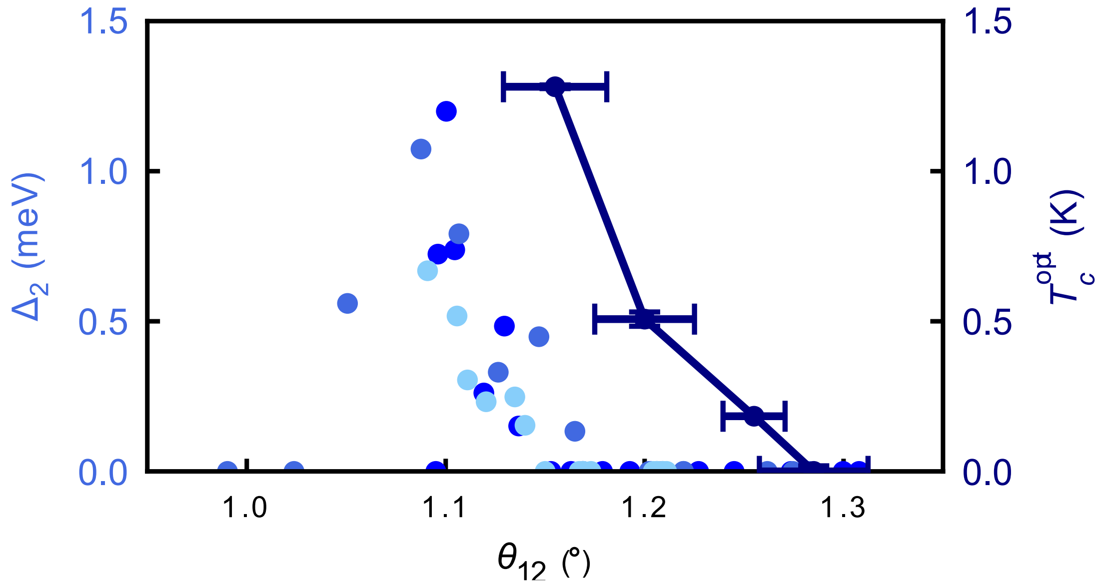
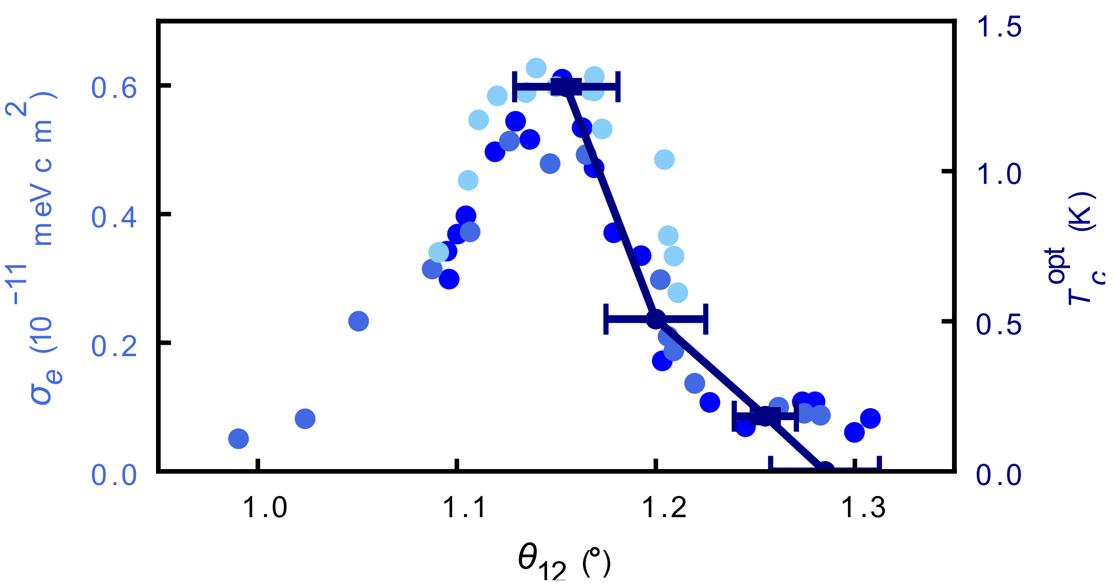


Hoke,..., Sharpe, Feldman arXiv:2509.07977

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

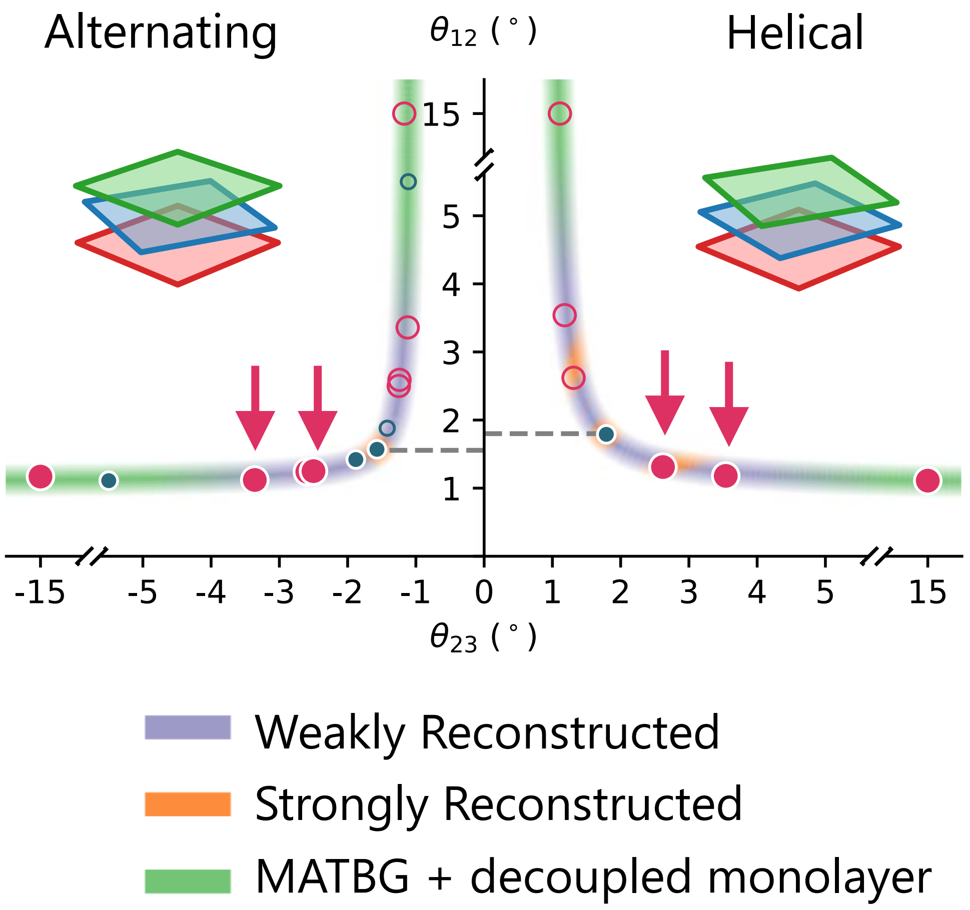
Hoke,..., Sharpe, Feldman arXiv:2509.07977

Outline

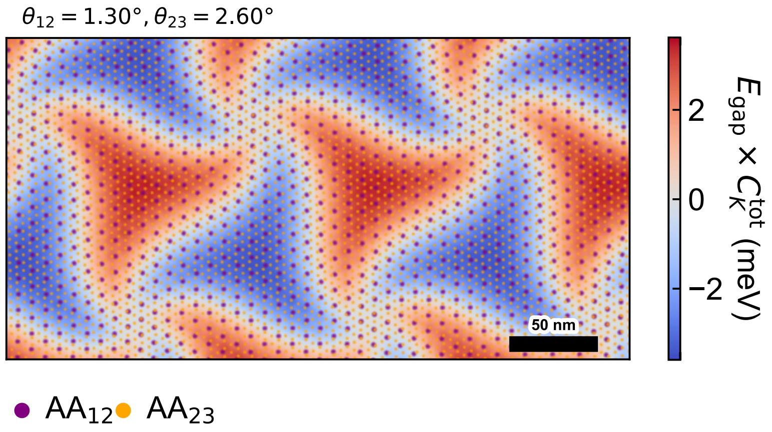
Introduction:
- From moiré to supermoiré
- Helical vs. alternating stacking
- Lattice relaxation

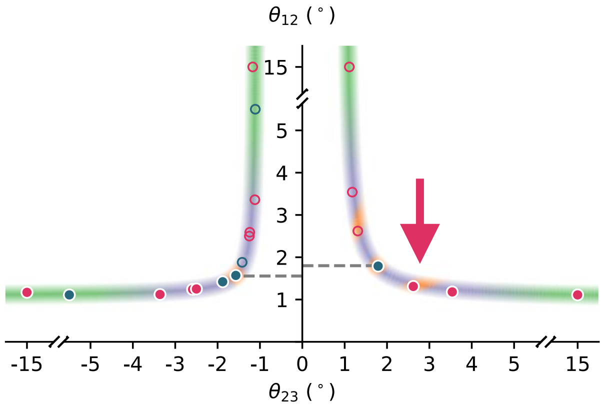
Linking thermodynamic probes and transport:
- Fine-grained evolution of correlations
- Cross comparison of distinct experimental probes

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



(2θ, θ) – Helical Trilayer Graphene





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

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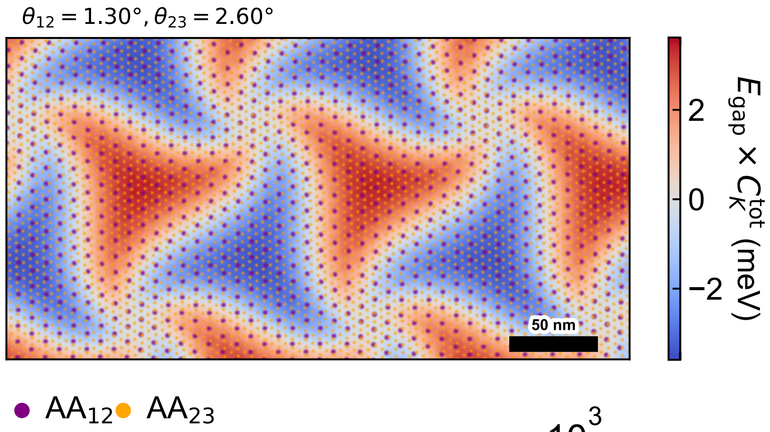

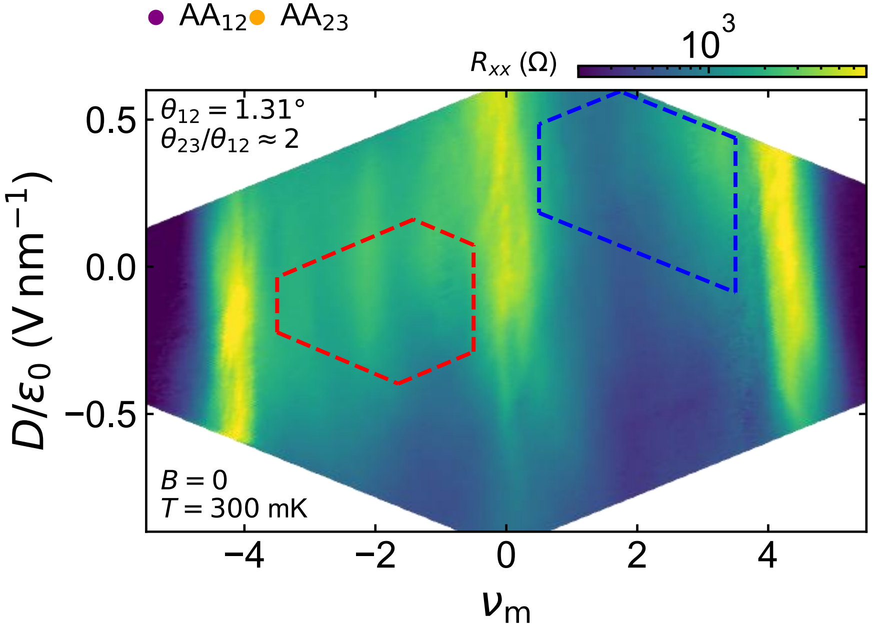

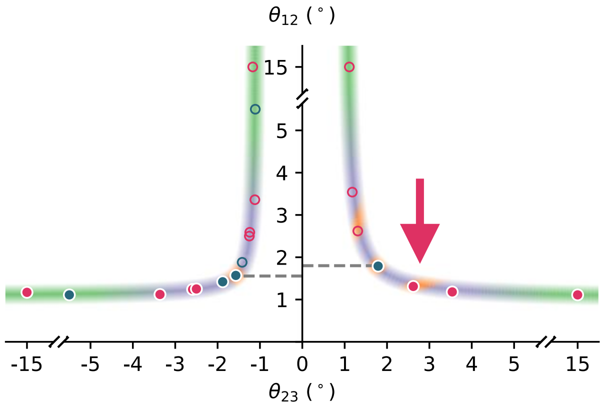

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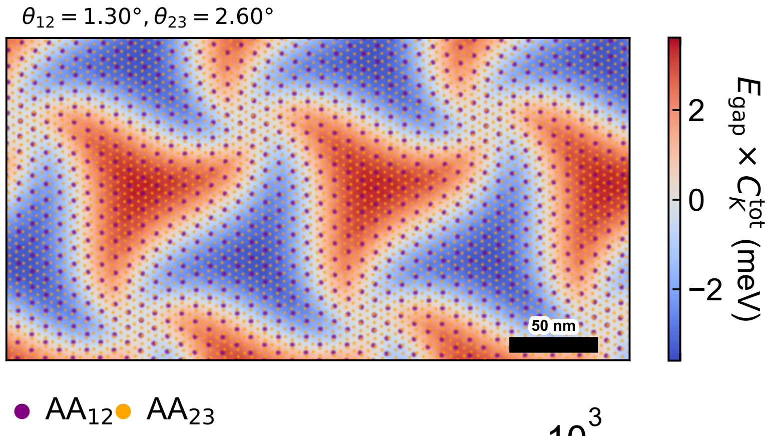
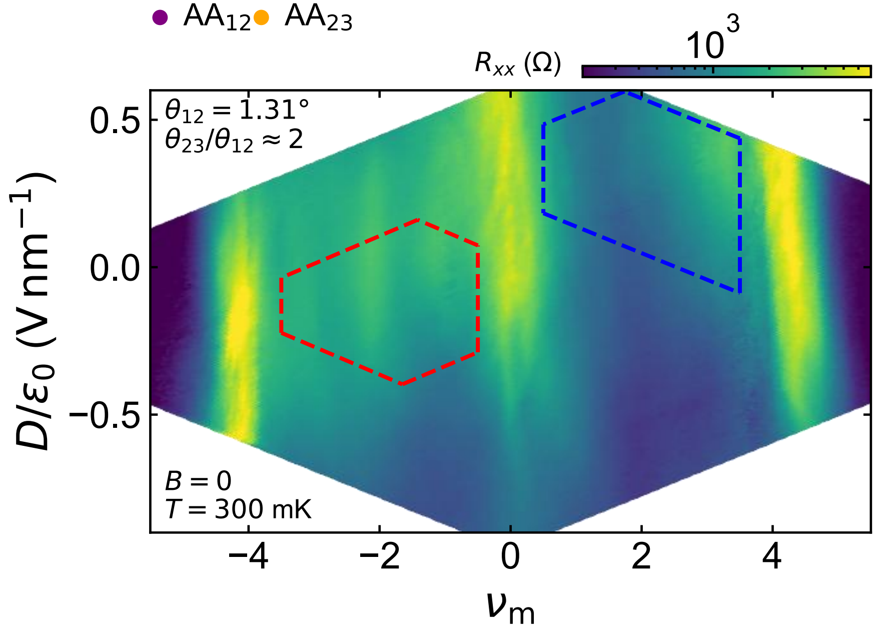
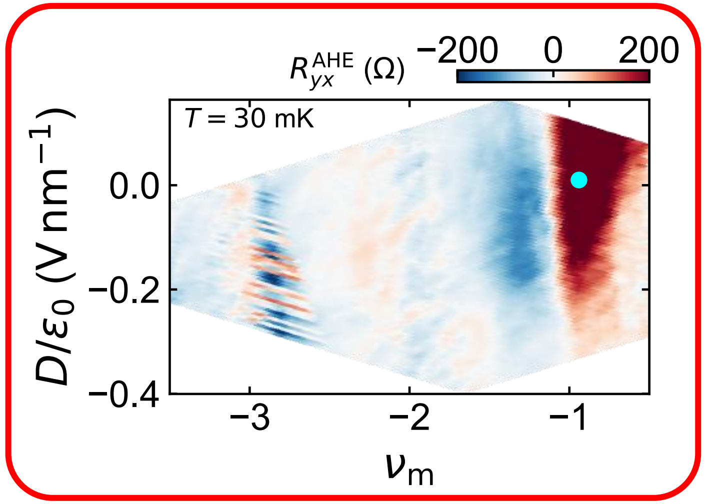
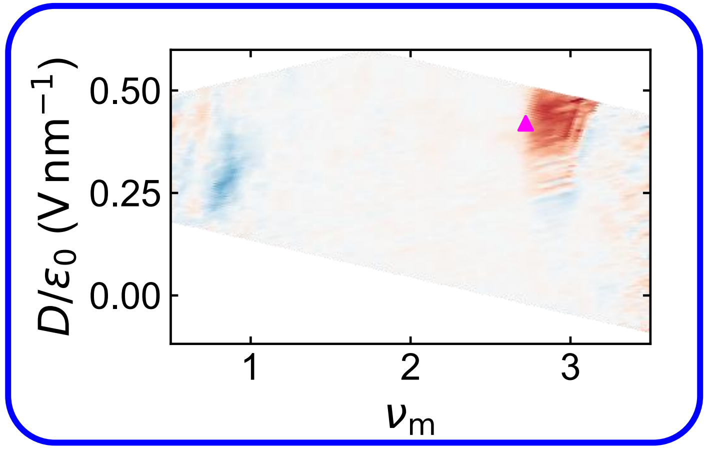
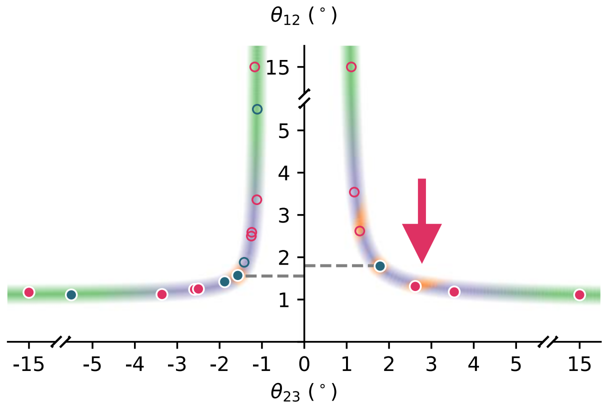
$(2\theta, \theta)$ – Helical Trilayer Graphene











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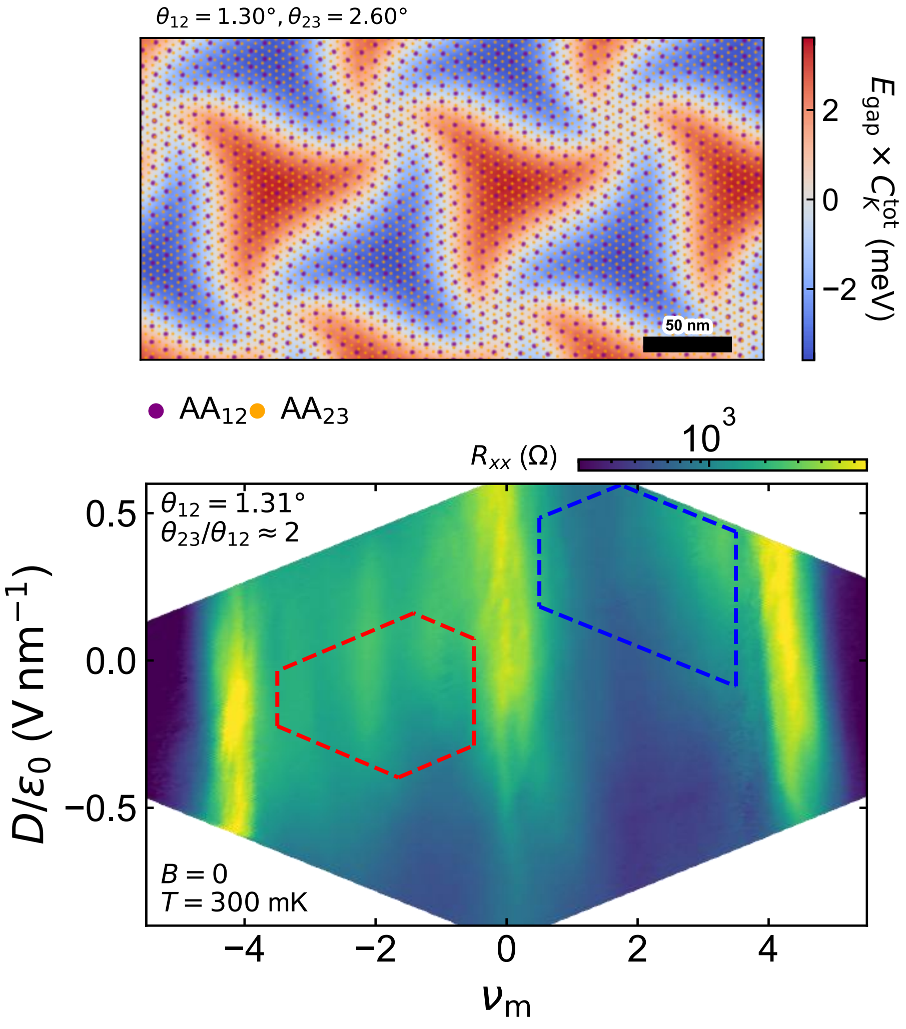

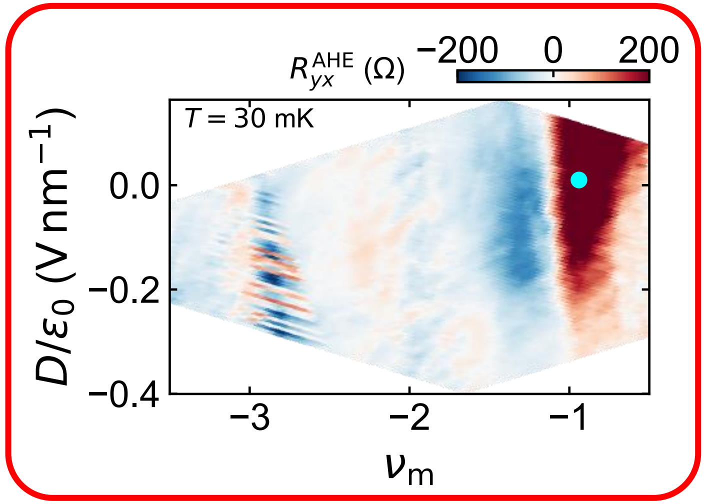

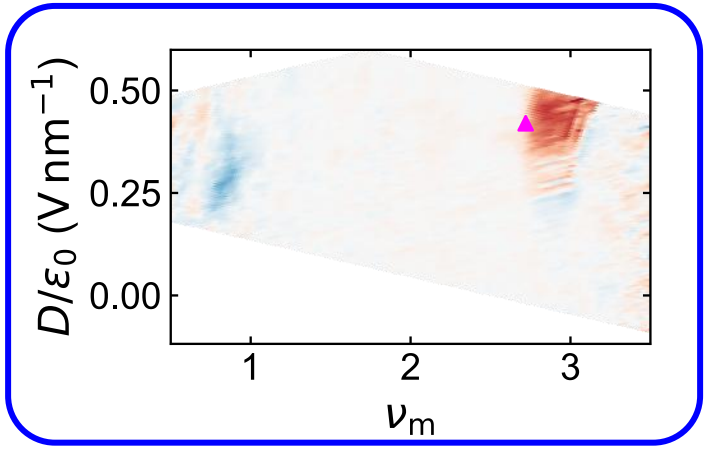

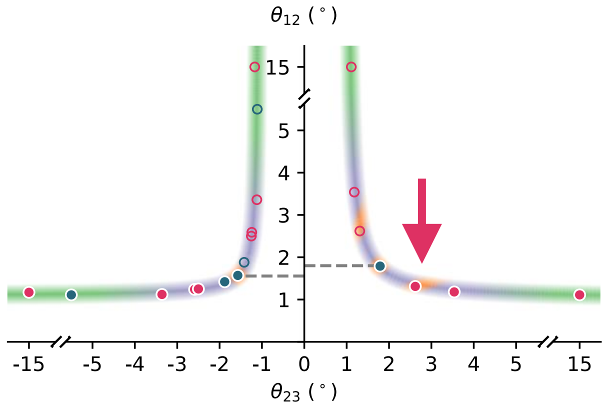

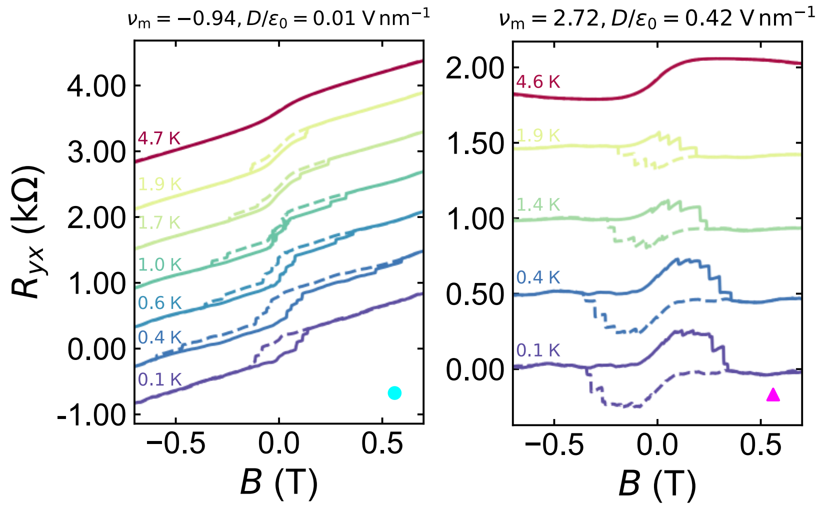

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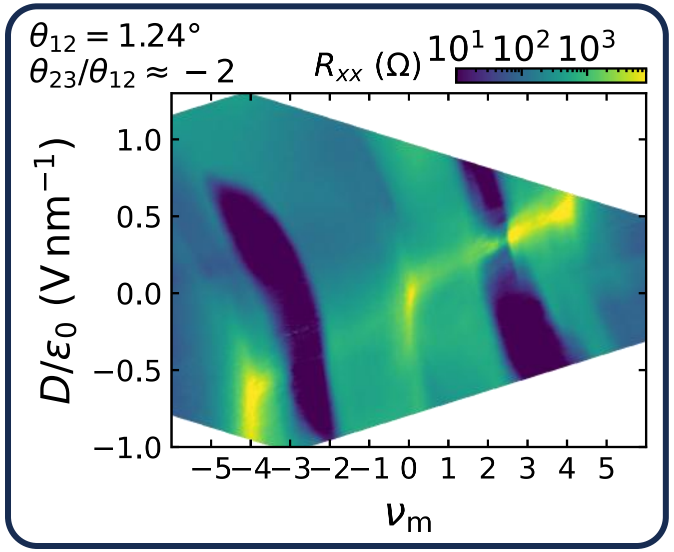
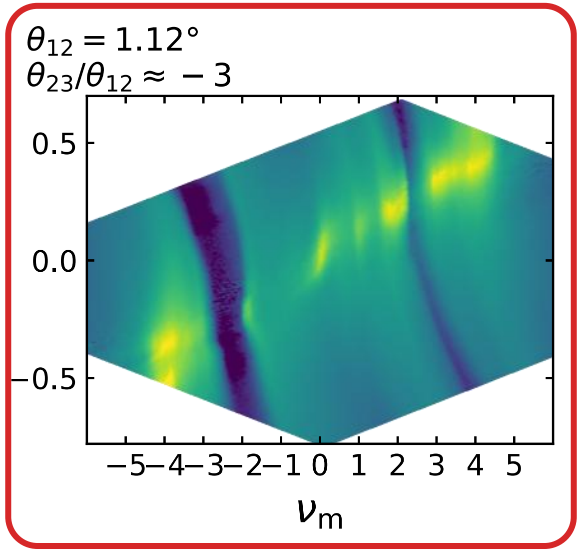
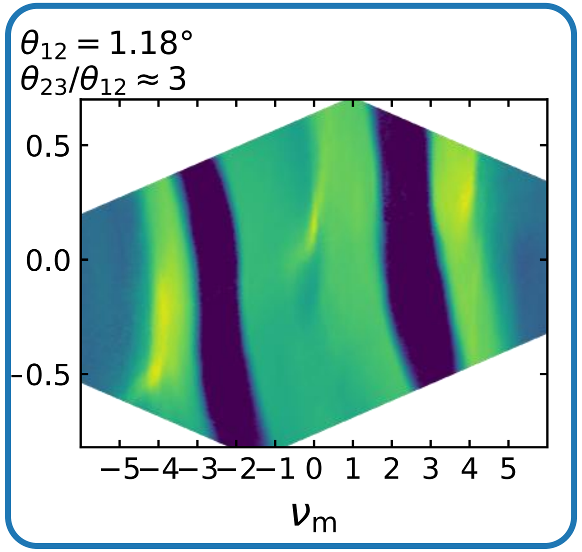
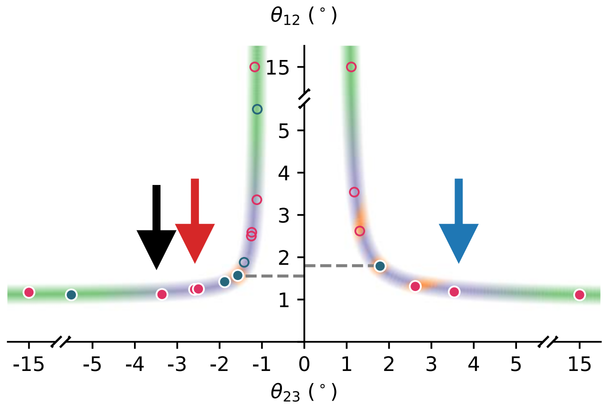
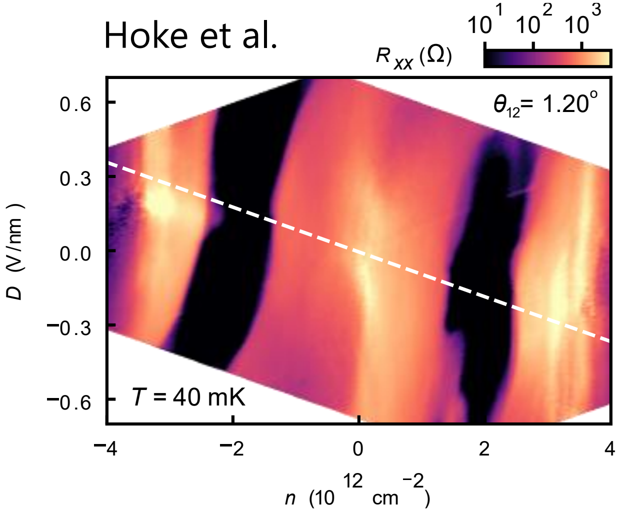
Weakly-Reconstructed TTG











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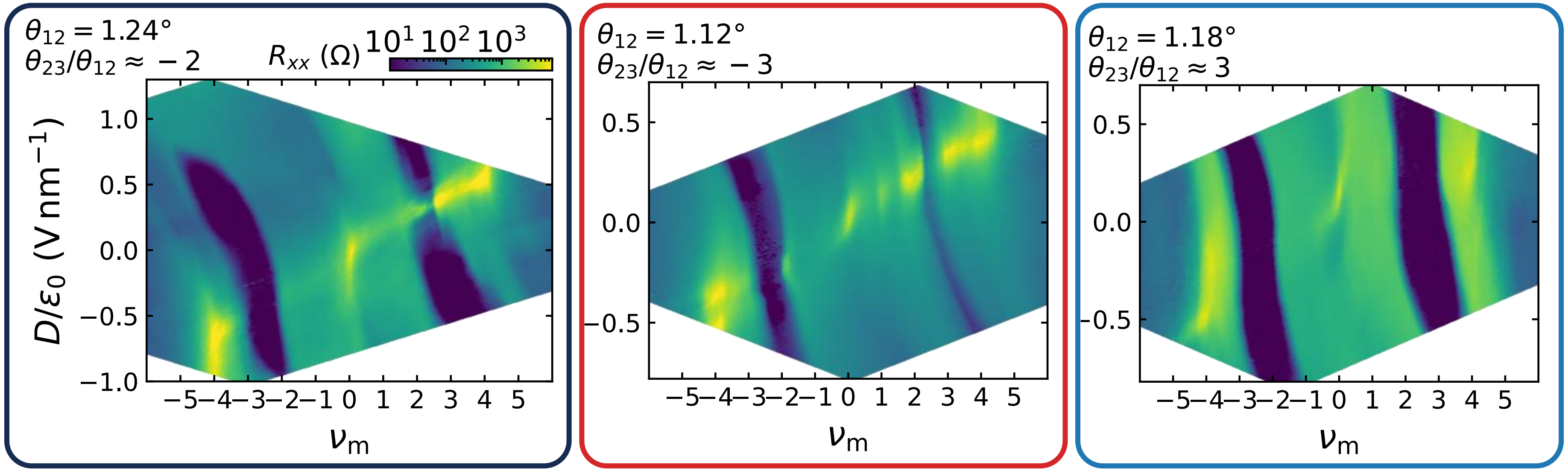
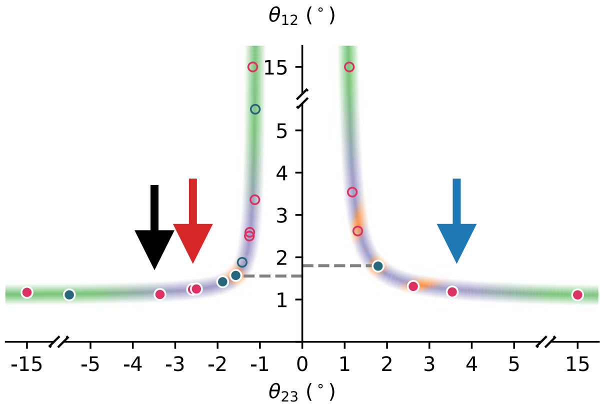
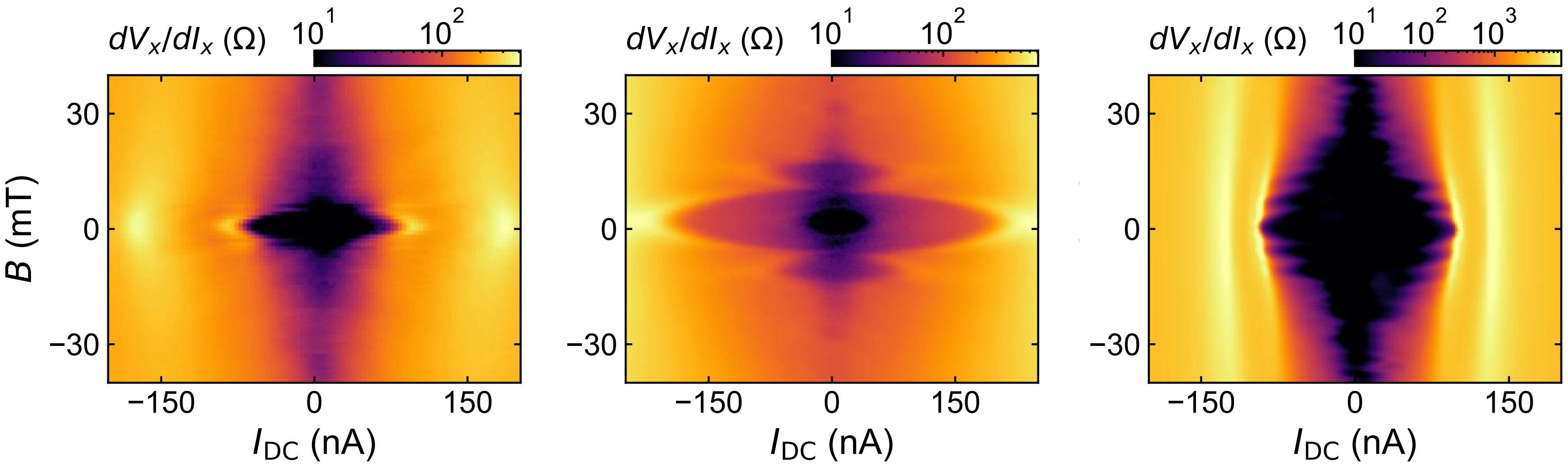
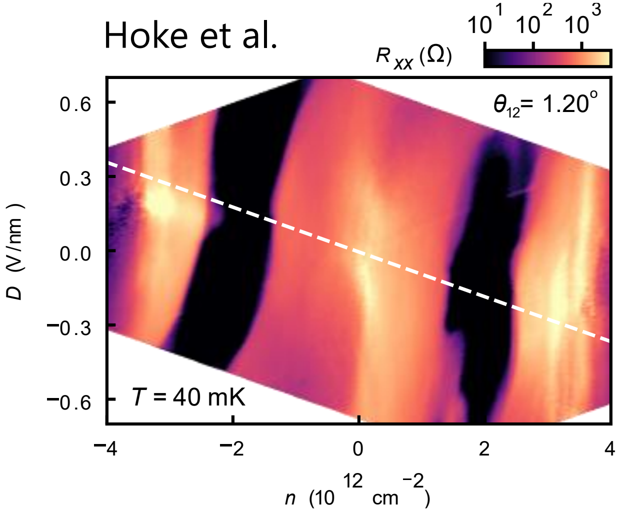


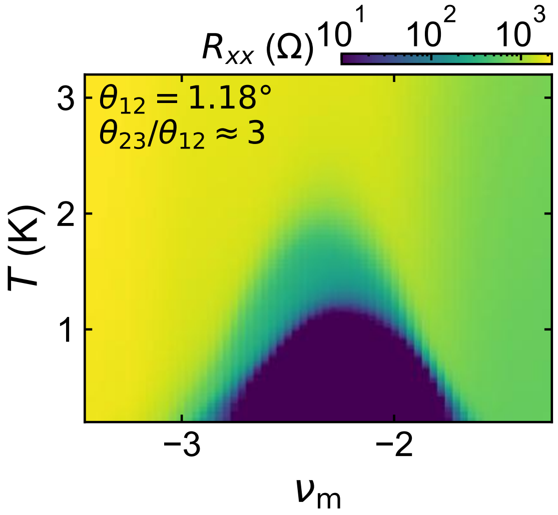






Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583

Supermoiré-modulation of superconductivity?



Eley, et al. Nat. Phys (2011)
Xia*, Uri*, Yan*, Sharpe* et al. arXiv:2509.03583

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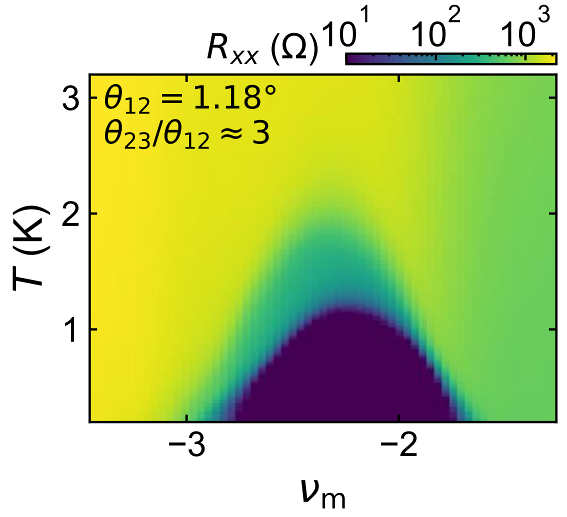

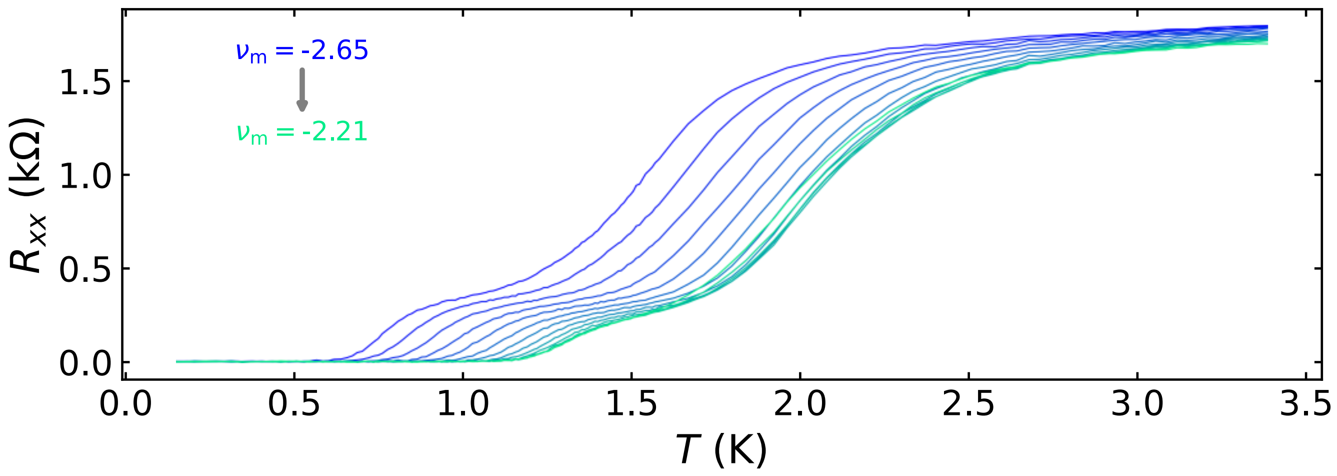

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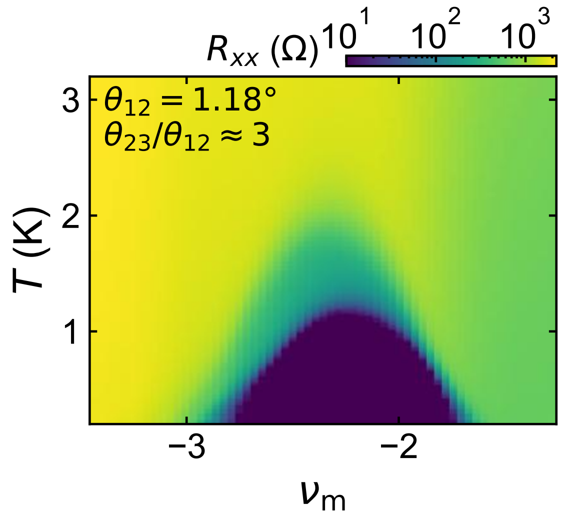
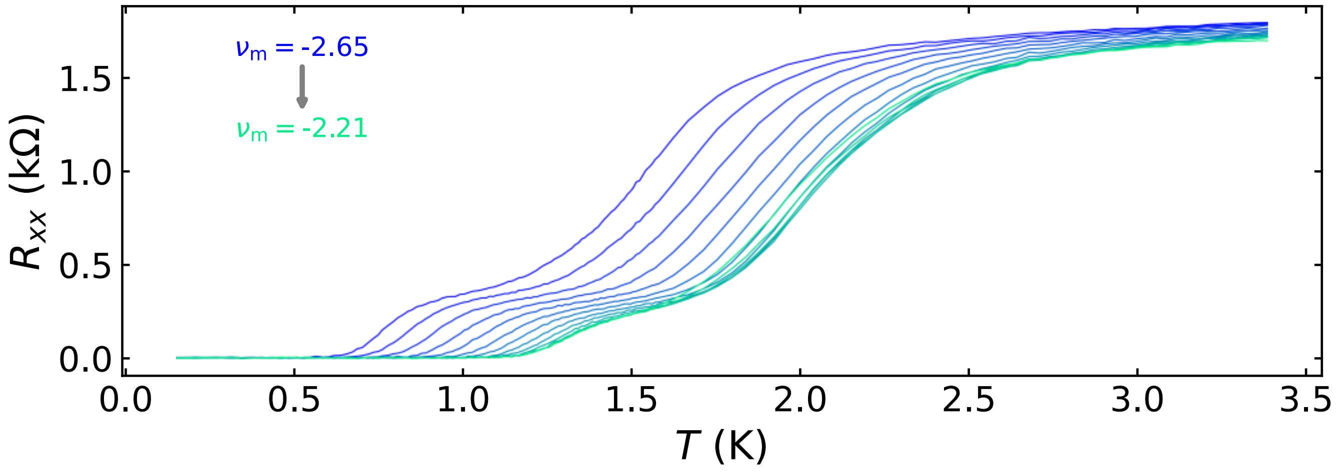
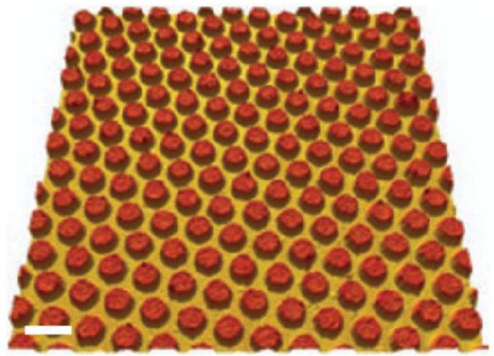
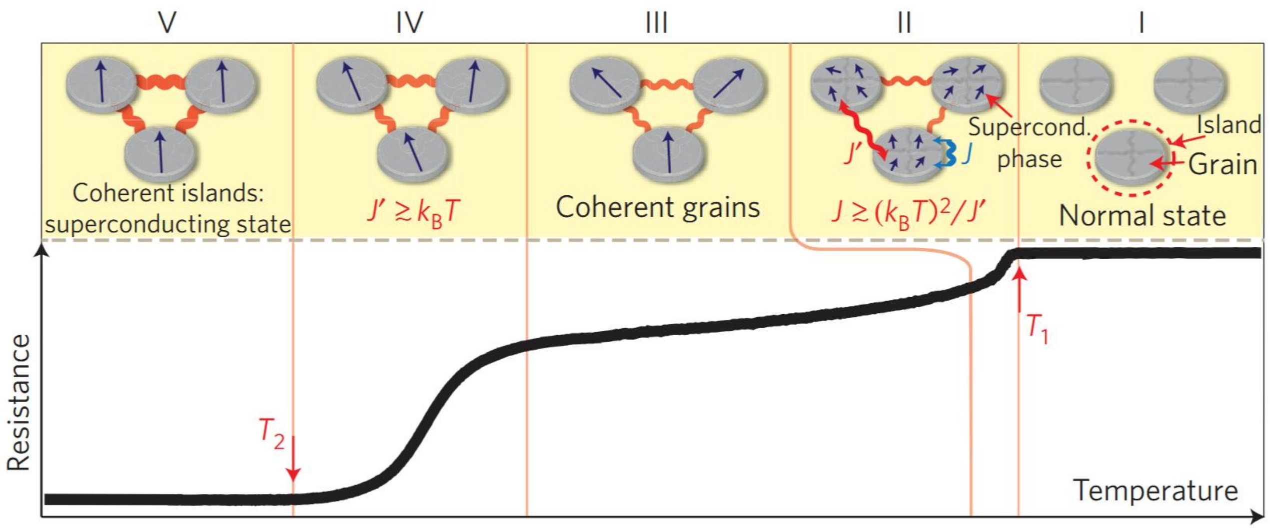




Nb islands on Cu





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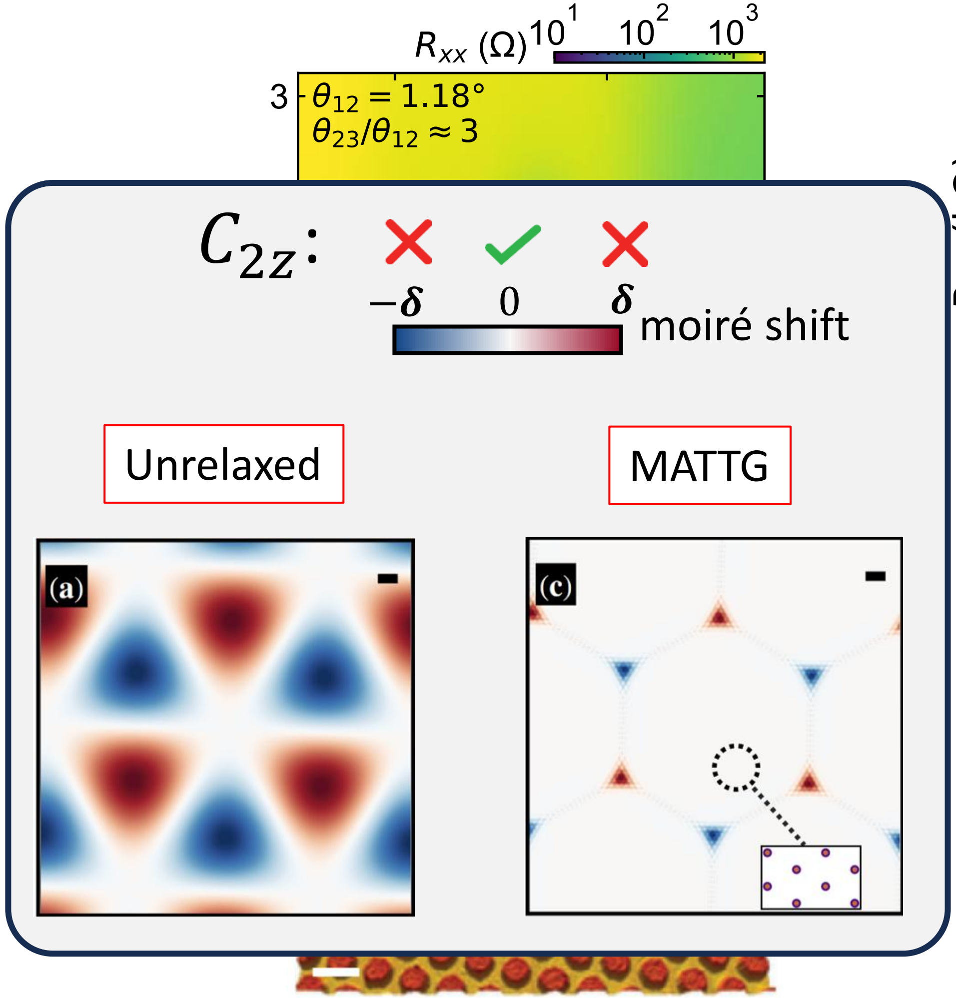

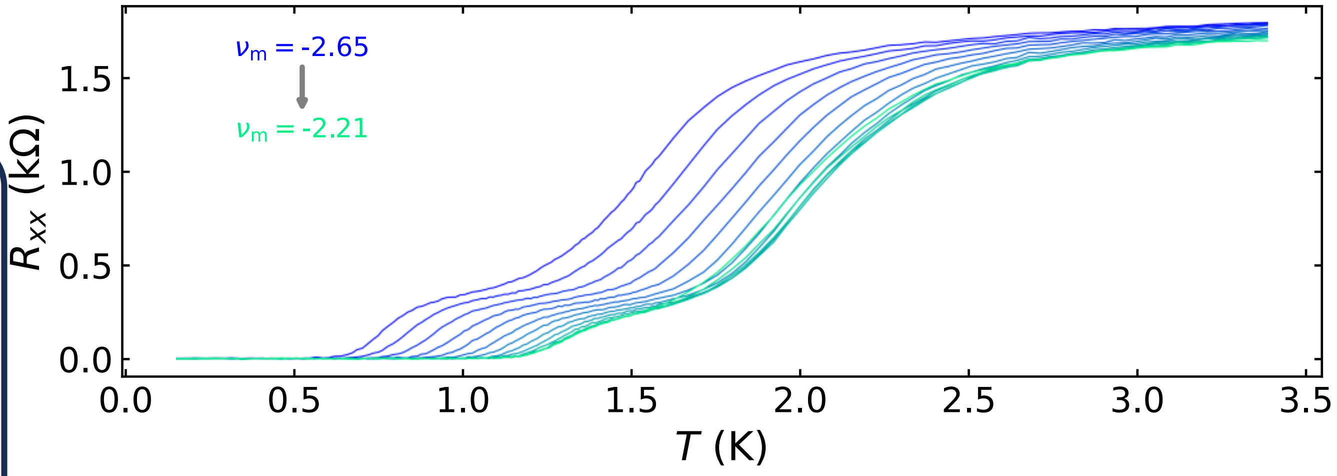

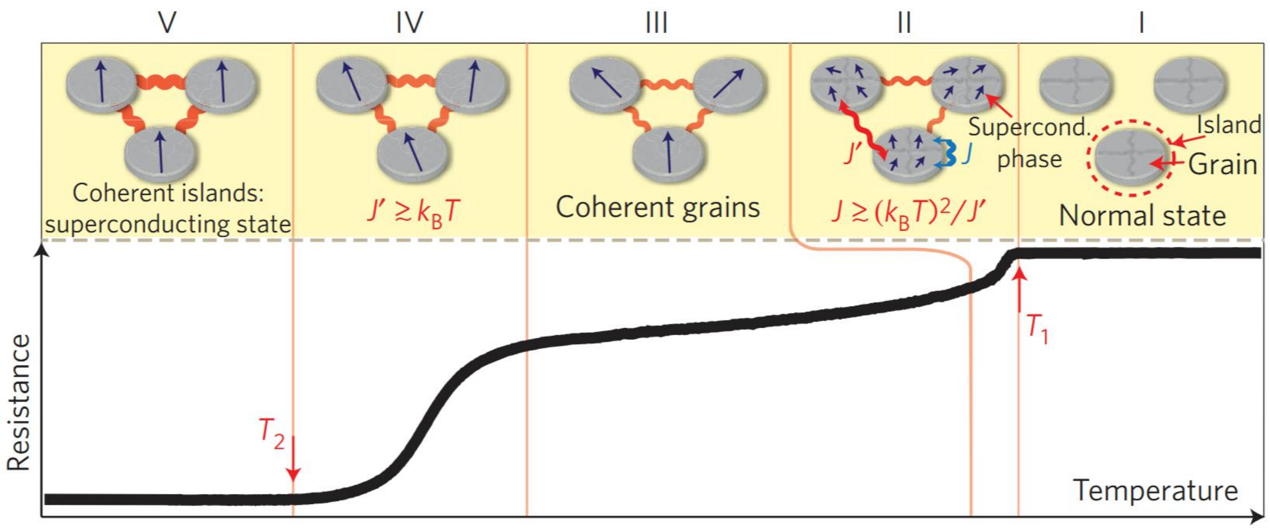

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Aviram Uri


Jiaoji Yan


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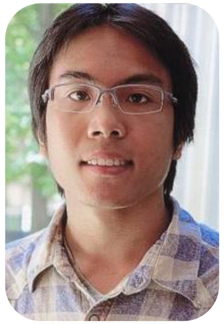
Ben Feldman


Trithep Devakul


Jarillo-Herrero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Jurgen Smet

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Takashi Taniguchi and Kenji Watanabe

Charles Yang, Yves Kwan, Zoe Zhu, B. Andrei Bernevig, Xi Dai, Patrick Ledwith, Marc A. Kastner

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.**