

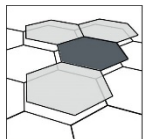
# Moiré heterostructures: a condensed matter quantum simulator

**Dante M. Kennes**

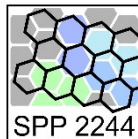
RWTH Aachen University  
and

Max Planck Institute for the Structure and Dynamics of Matter

ICTS, July 18<sup>th</sup> 2024



Aachen  
Graphene &  
2D Materials  
Center



SPP 2244

**DFG** Deutsche  
Forschungsgemeinschaft  
German Research Foundation

**m-ps-d**  
Max-Planck-Institut für  
Struktur und Dynamik der Materie

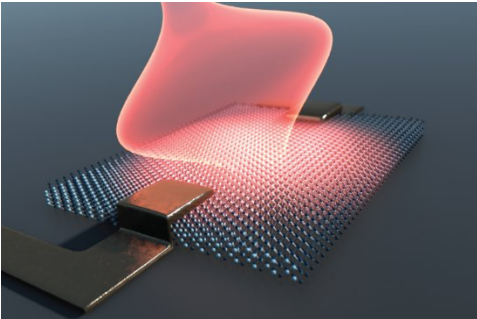
**e-βH**

**RWTH AACHEN**  
UNIVERSITY

# Pathways of Design

1)

## Ultrafast Materials Science

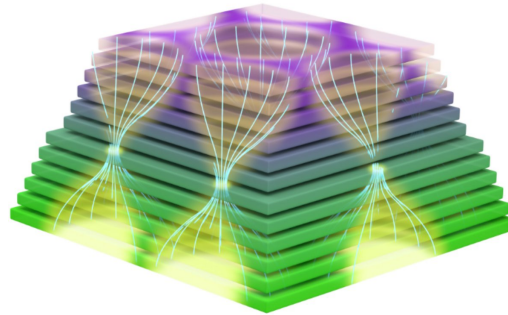


- Floquet Engineering
- hidden states of matter
- nonlinear phononics

A. de la Torre, **DMK**, *et al.*  
Rev. Mod. Phys. **93**, 041002 (2021)

2)

## Van der Waals heterostructuring

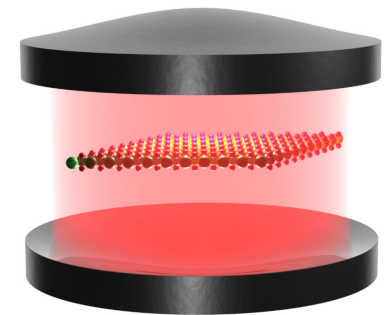


- moiré engineering
- substrate design:
  - environment
  - doping

**DMK**, *et al.*  
Nature Physics **17**, 155 (2021)

3)

## Cavitronics



- quantum Floquet engineering
- light-matter hybrids
- stationary to flying qubits

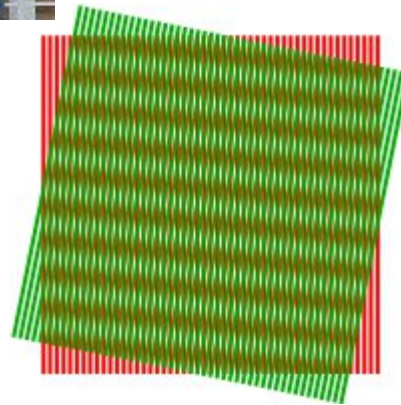
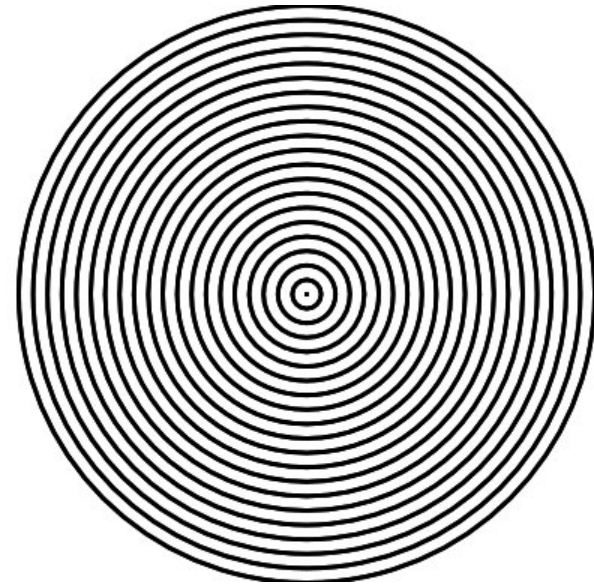
F. Schlawin, **DMK**, M. A. Sentef  
App. Phys. Rev. **9**, 011312 (2022)

**Dante M. Kennes**

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Theoretische Physik der kondensierten Materie | RWTH Aachen



# Moiré-Effect



[https://en.wikipedia.org/wiki/Moir%C3%A9\\_pattern](https://en.wikipedia.org/wiki/Moir%C3%A9_pattern)

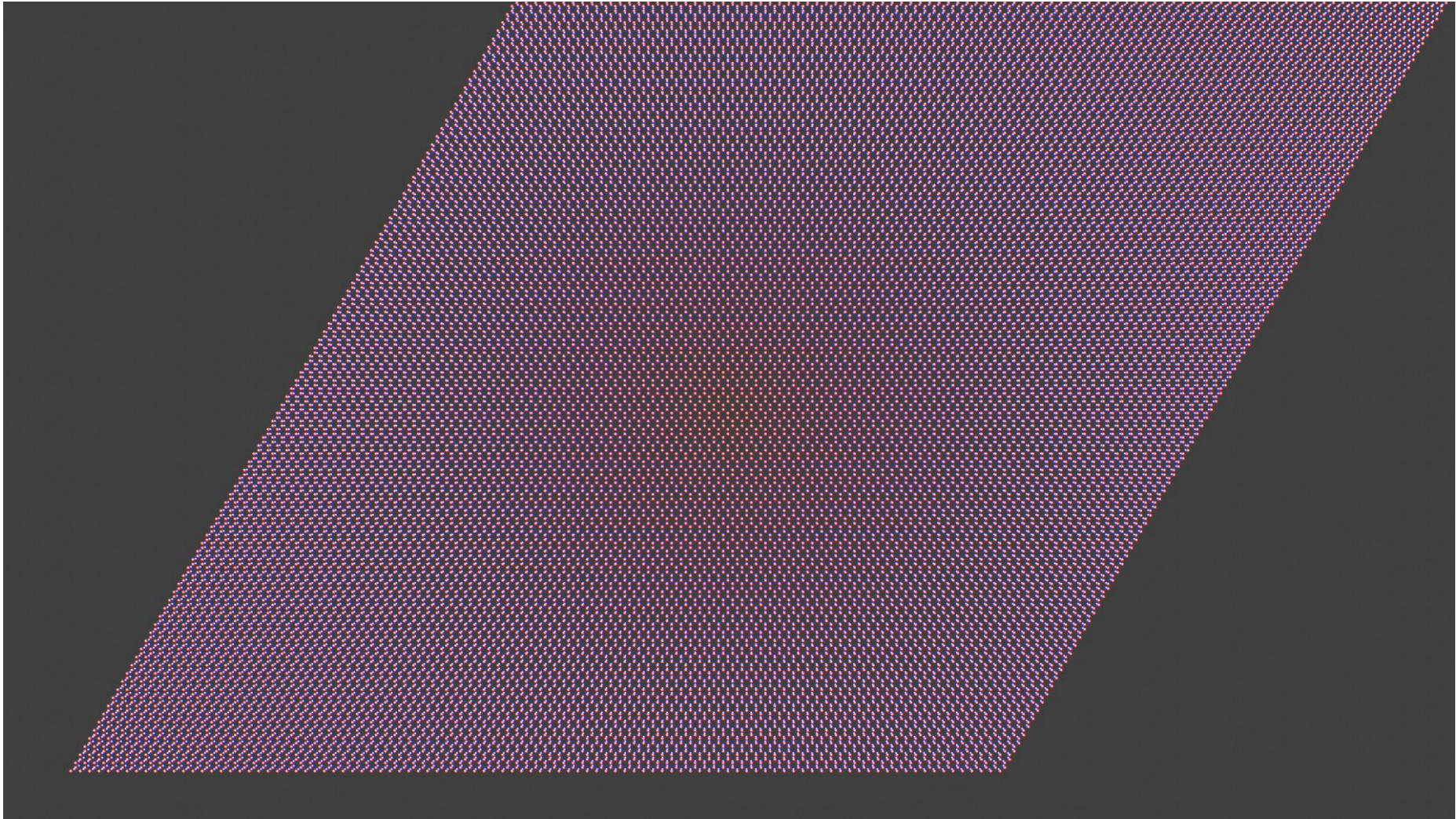
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# Honeycomb Lattice? (Graphene)

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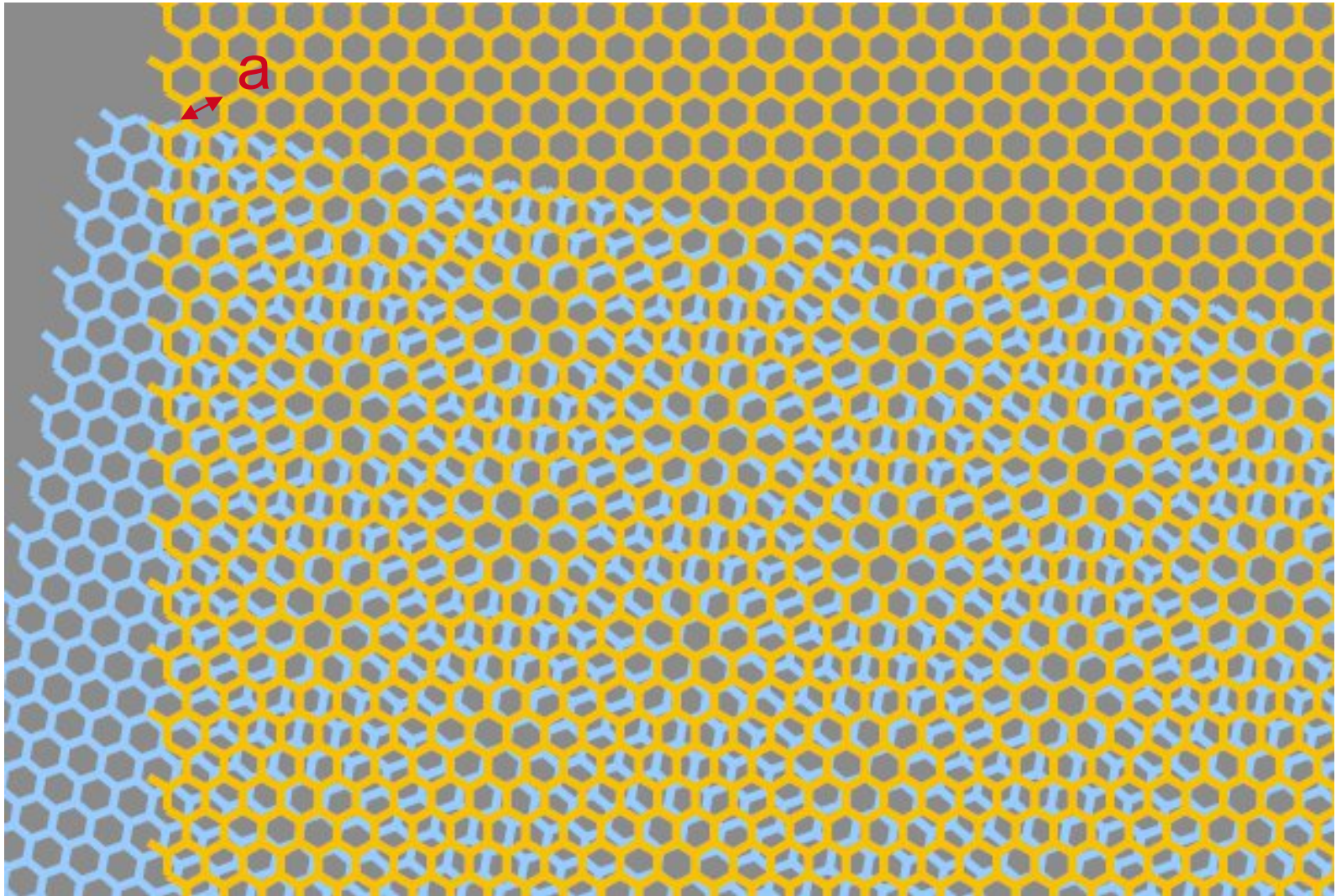


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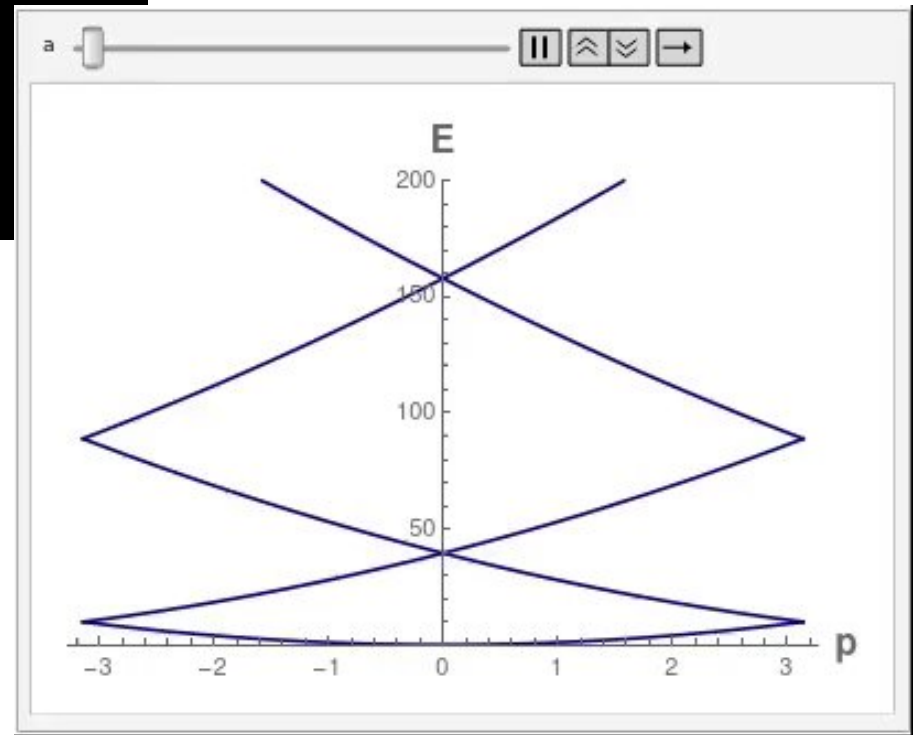
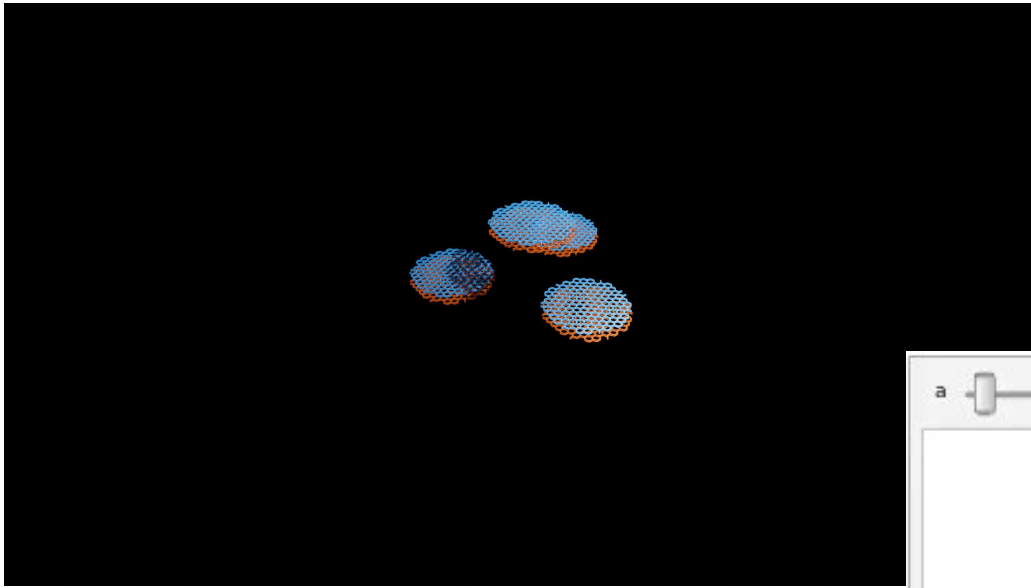
# Honeycomb Lattice? (Graphene)



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# Band Narrowing by the Moiré-Effect

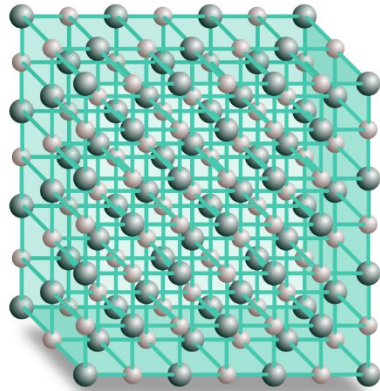


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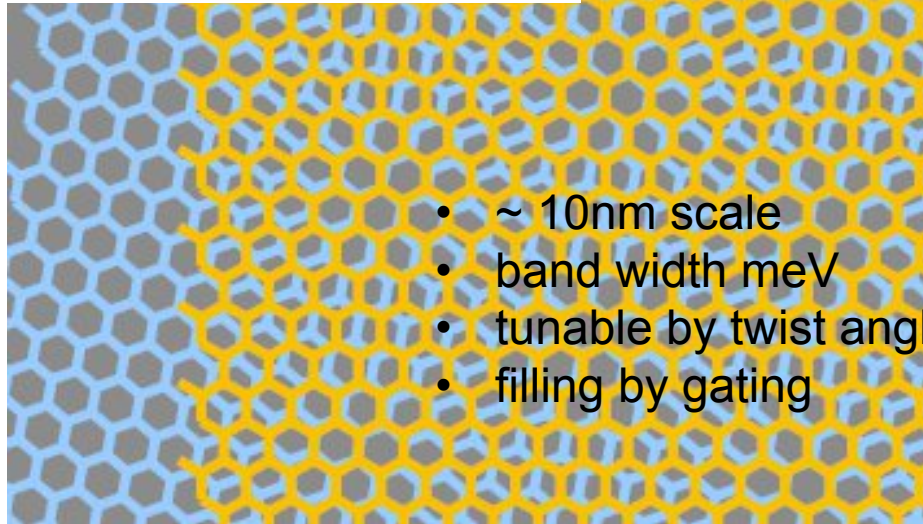
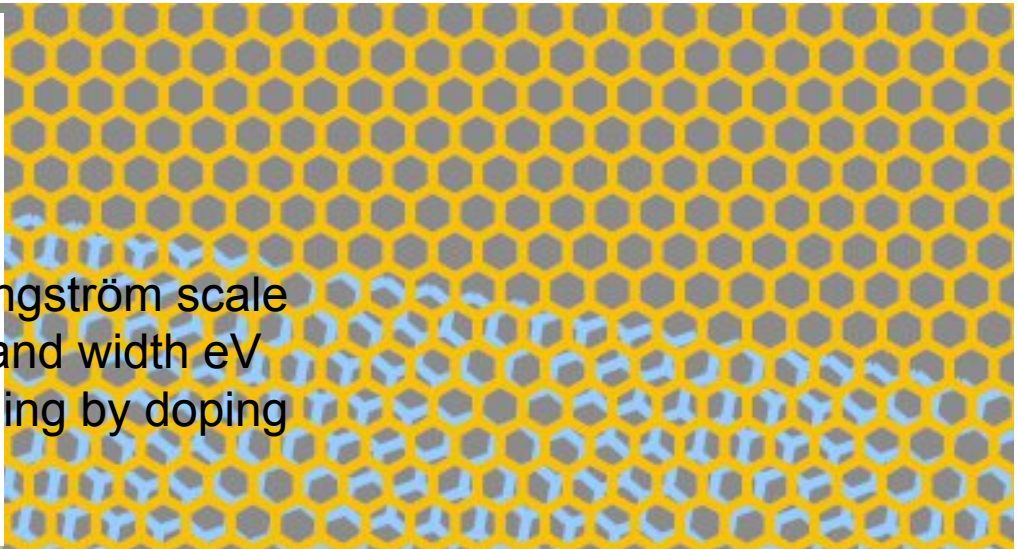
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## conventional solids

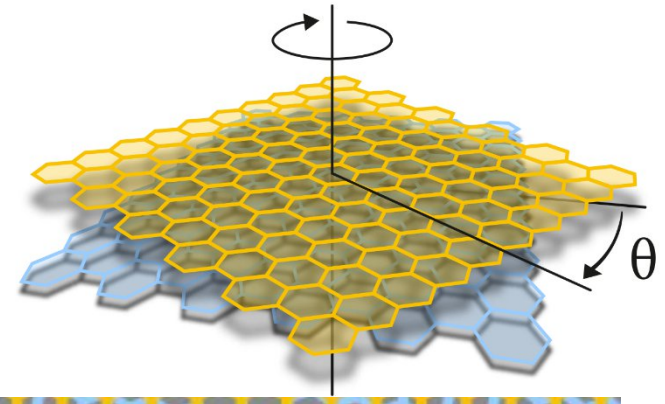


- Angström scale
- band width eV
- filling by doping



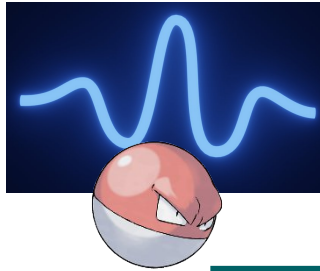
- ~ 10nm scale
- band width meV
- tunable by twist angle
- filling by gating

## twisted vdW materials



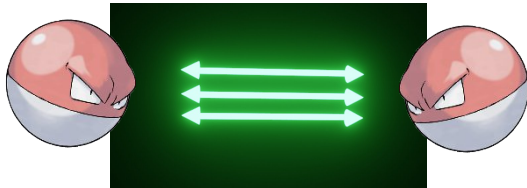
# Twistronics!

kinetic energy:

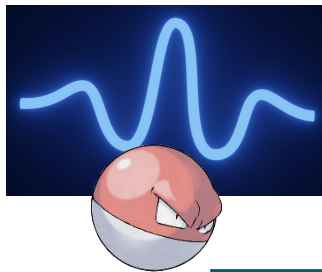


- How easily do electrons move through crystal
- determined by bandwidth

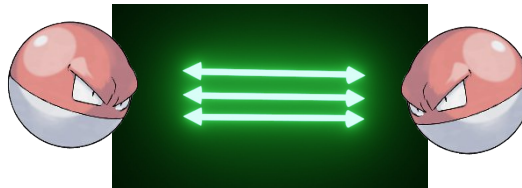
potential energy:



- how strongly do electrons interact
- determined by charge, localization, ...



vs.



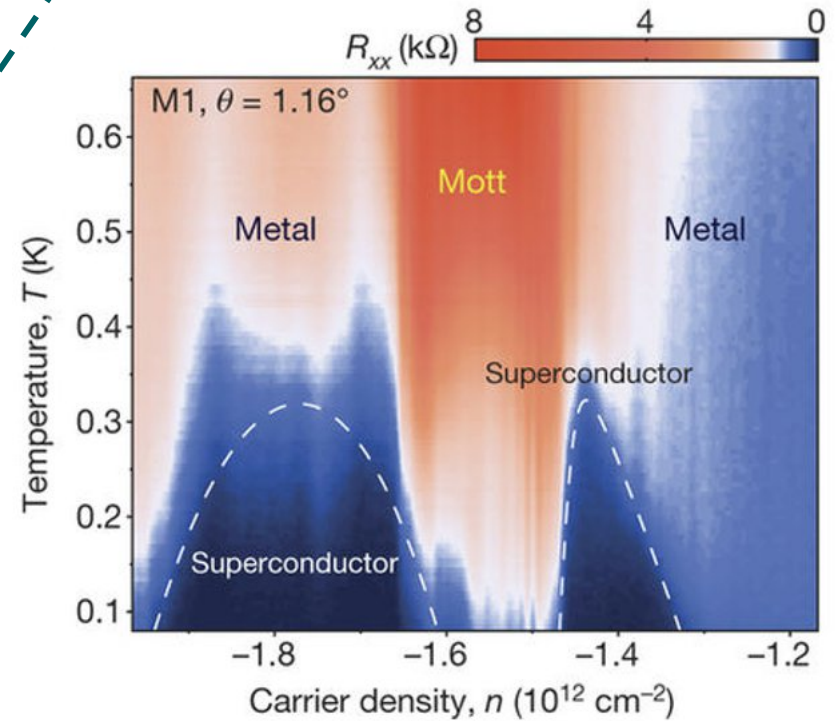
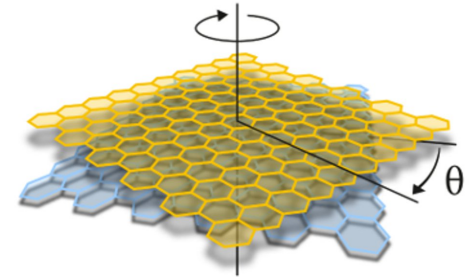
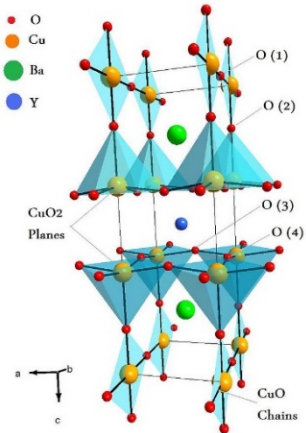
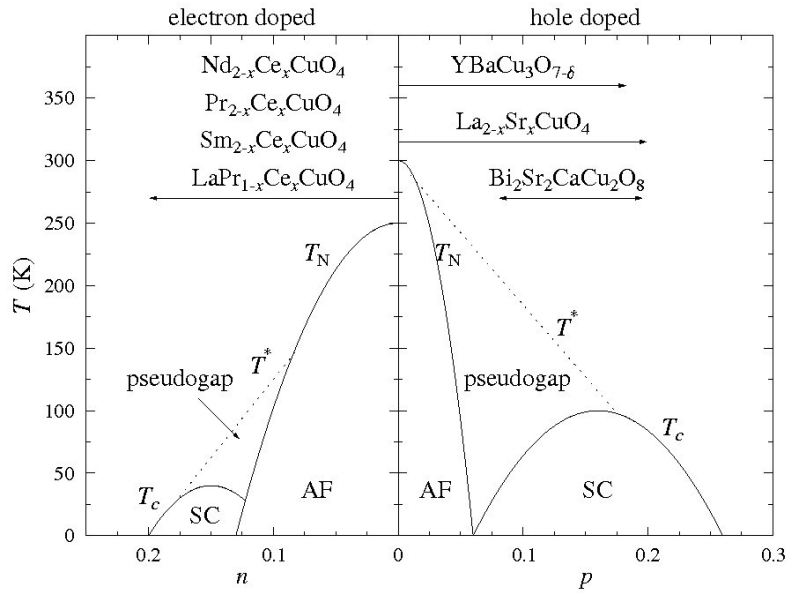
- determined by „twist“

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# Twistronics!

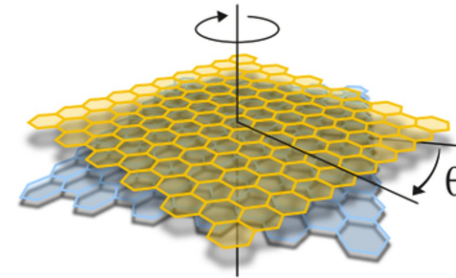
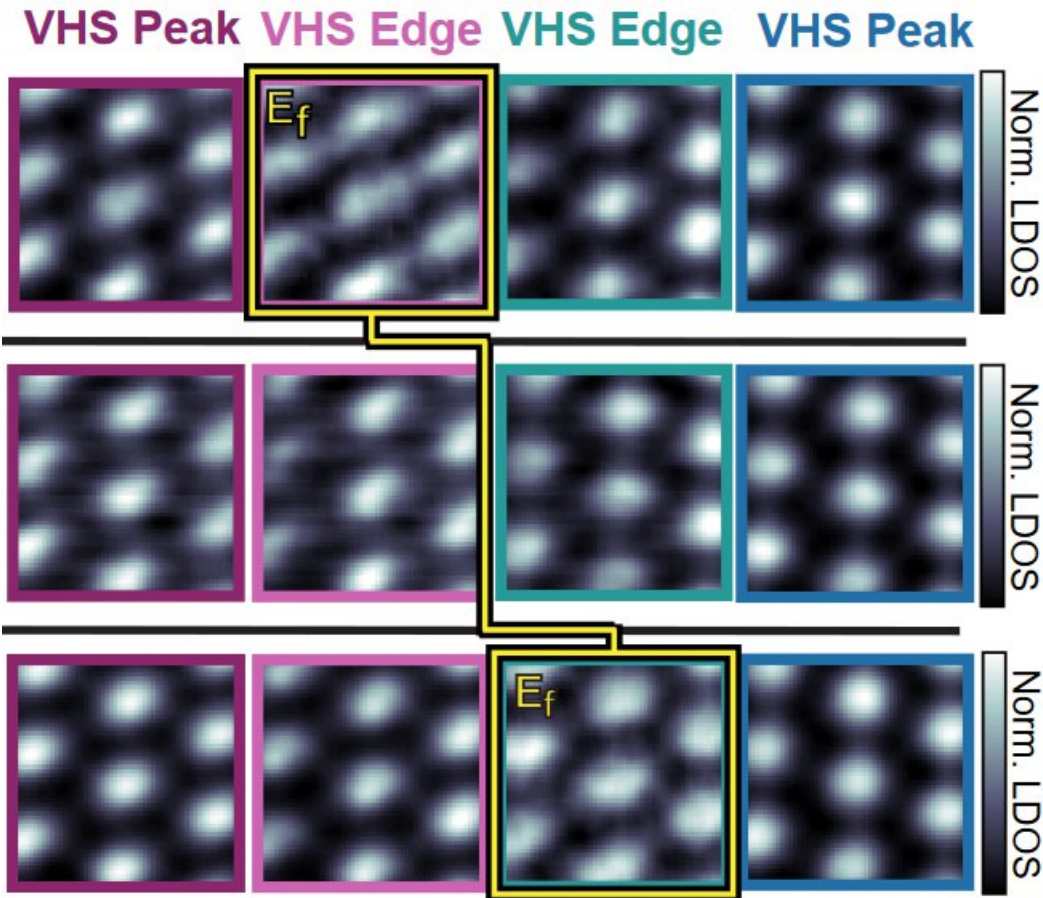


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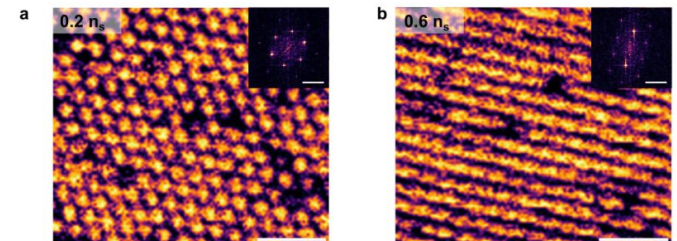
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# Twistronics!

- One more signature often seen in unconventional SC: Nematic order



- Also in twisted double bilayer





Lecture Notes in Physics 1000

Roberta Citro · Maciej Lewenstein · Angel Rubio  
Wolfgang P. Schleich · James D. Wells · Gary P. Zank *Editors***Sketches of Physics**

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This book takes us on a journey through the wonders of physics, the special thousandth volume of the renowned Lecture Notes in Physics book series. From quantum physics to solar physics, this volume showcases the beauty of physics in various fields. Written by series editors and colleagues, these essays are accessible to non-specialists and graduate-level students alike, making for an intriguing read for anyone interested in learning about physics beyond their own field of study. Explore the historical development of the series with two insightful forewords.

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- The Geometric Phase: Consequences in Classical and Quantum Physics
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- Exploring the Hottest Atmosphere with the Parker Solar Probe
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LNP  
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Sketches of Physics

Lecture Notes in Physics 1000

Roberta Citro · Maciej Lewenstein  
Angel Rubio · Wolfgang P. Schleich  
James D. Wells · Gary P. Zank *Editors*

# Sketches of Physics

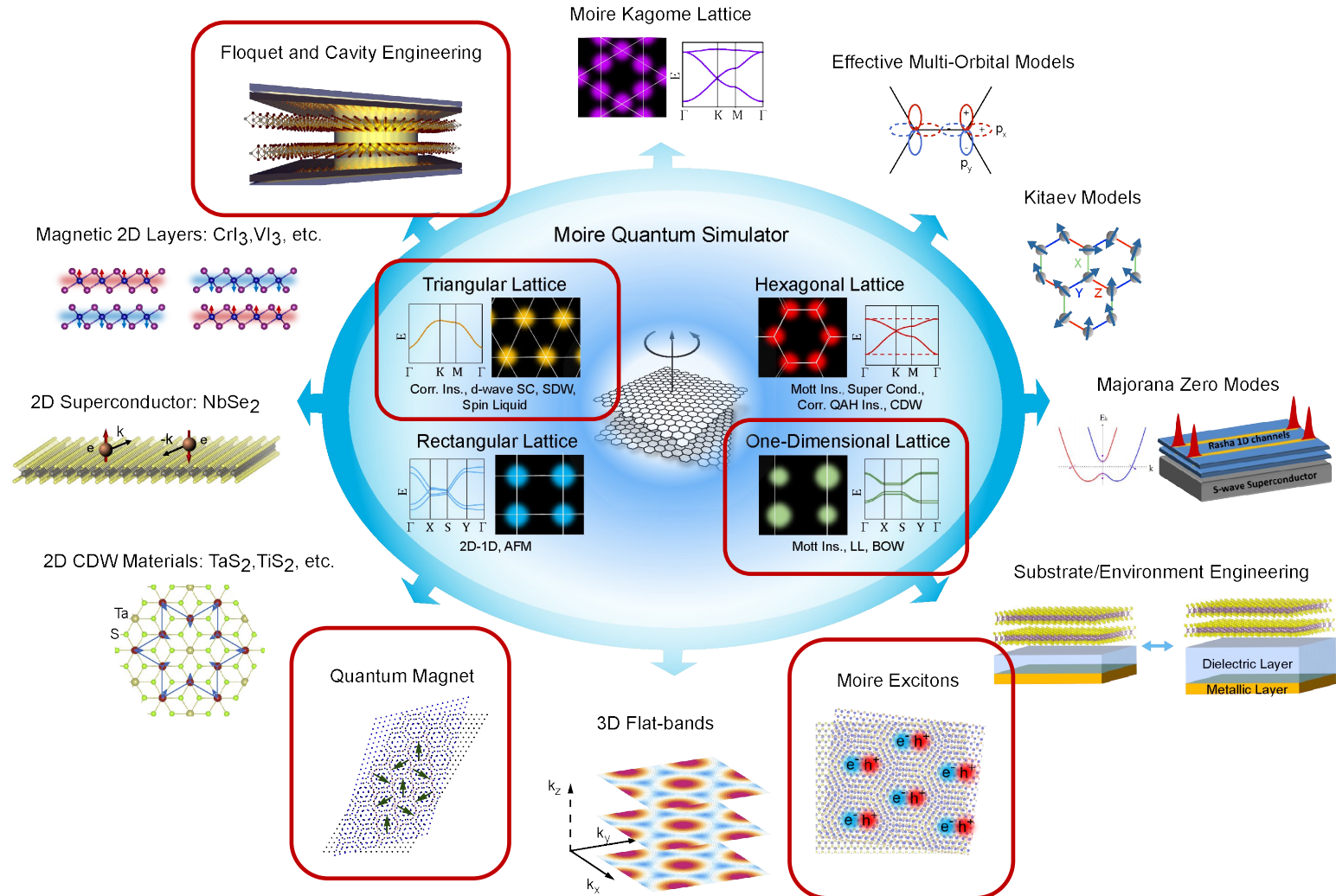
The Celebration Collection

Springer

ISBN 978-3-031-32468-0

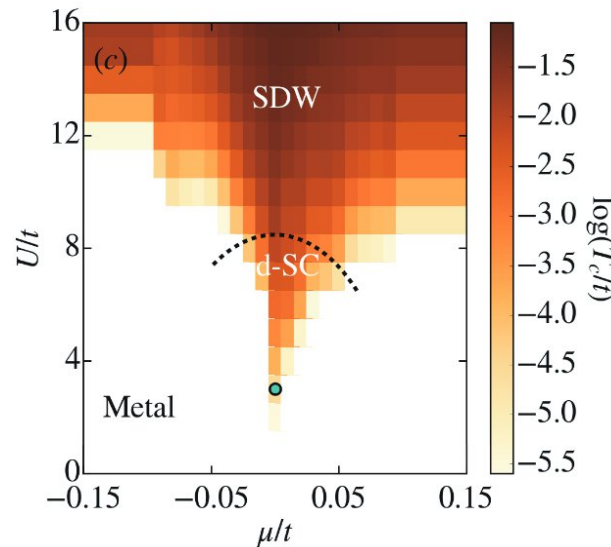
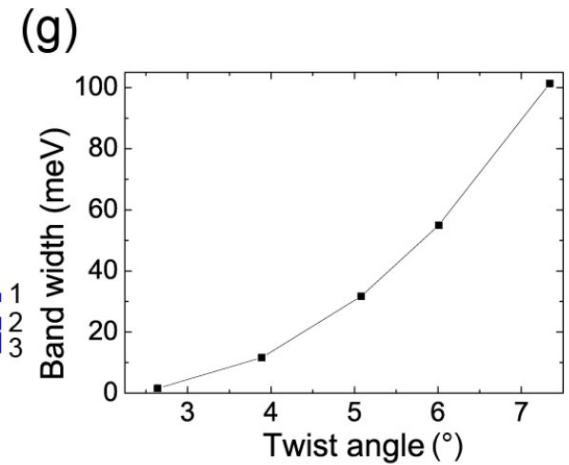
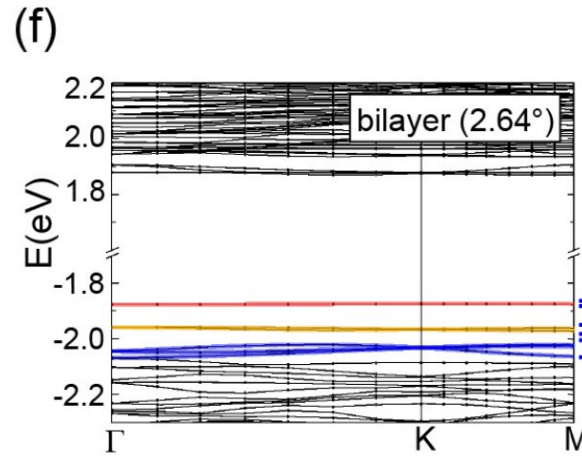
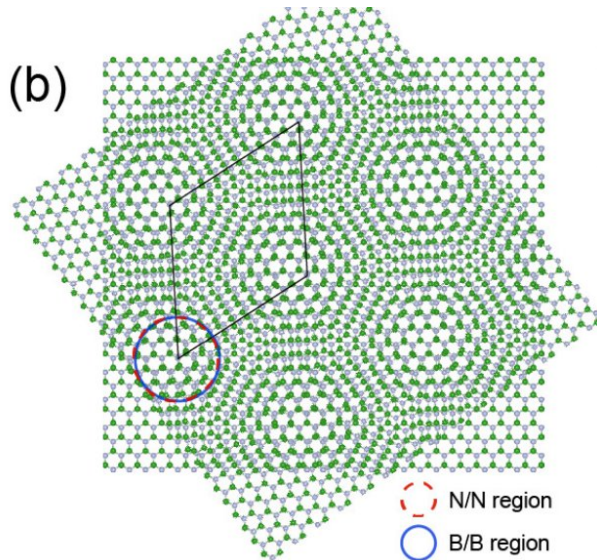
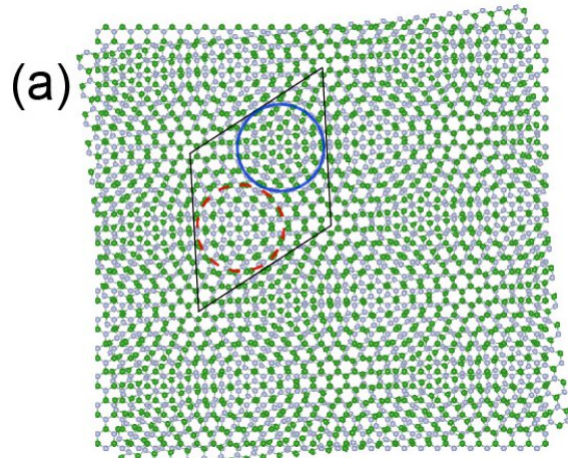
▶ [springer.com](http://springer.com)

# Moiré heterostructures hold many promises for flexible control





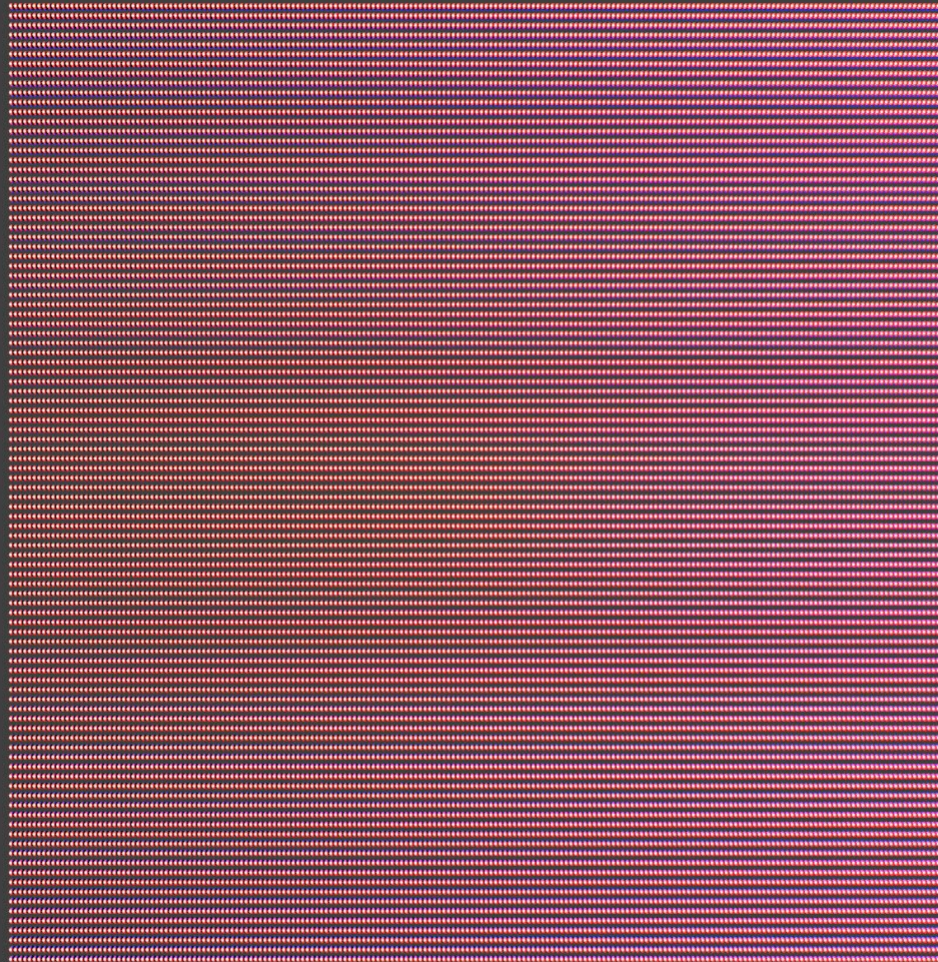
# Multi-flat bands and strong correlations in Twisted Bilayer Boron Nitride



- DFT characterization
- Two inequivalent twists
- Multiple families of flatbands
- Band width continuous function of twist angle
- Low energy: effective triangular lattice (TB + U)

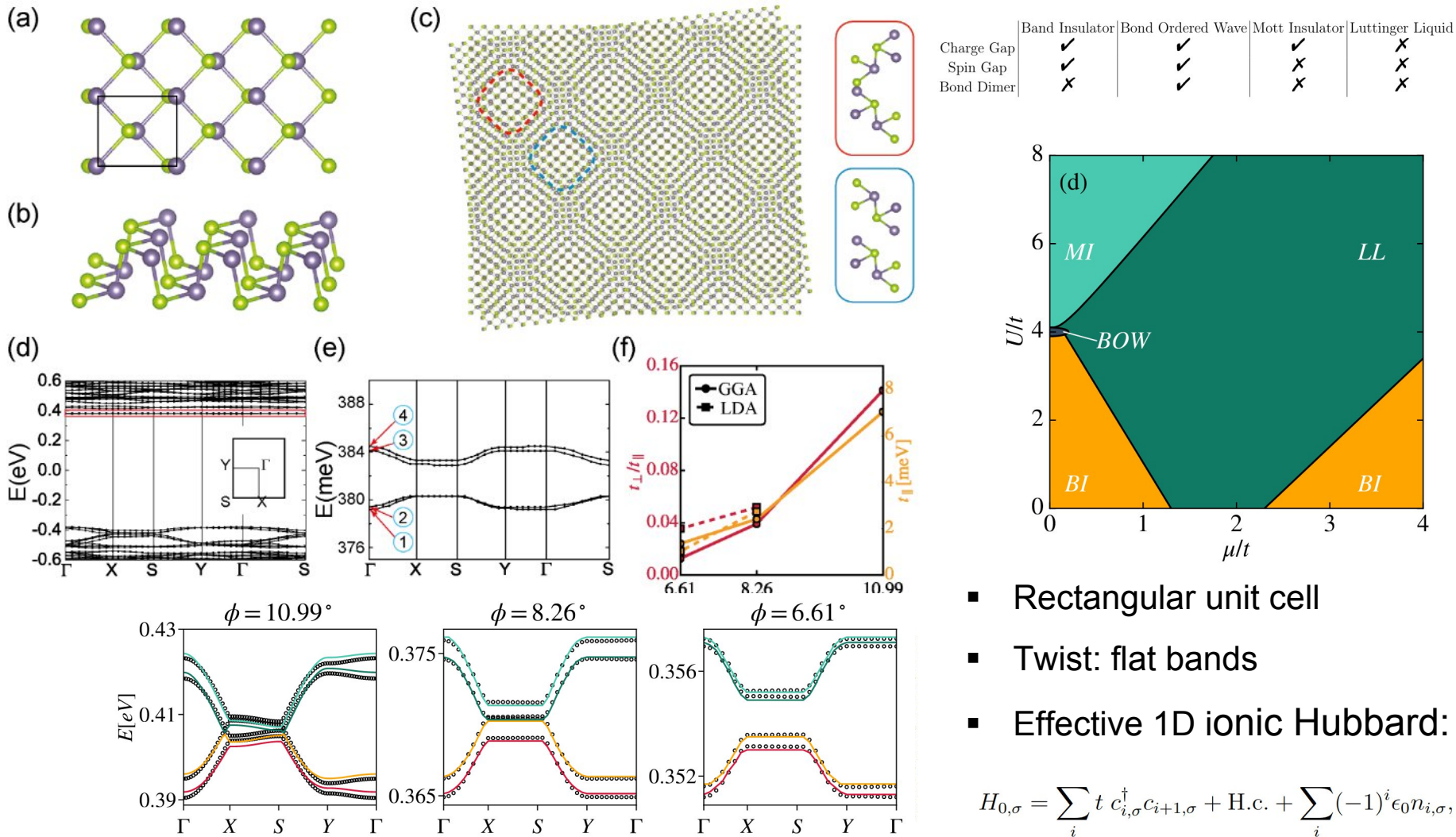


# One-dimensional flat bands in twisted bilayer germanium selenide





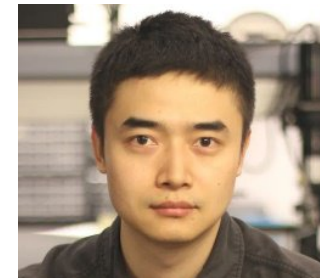
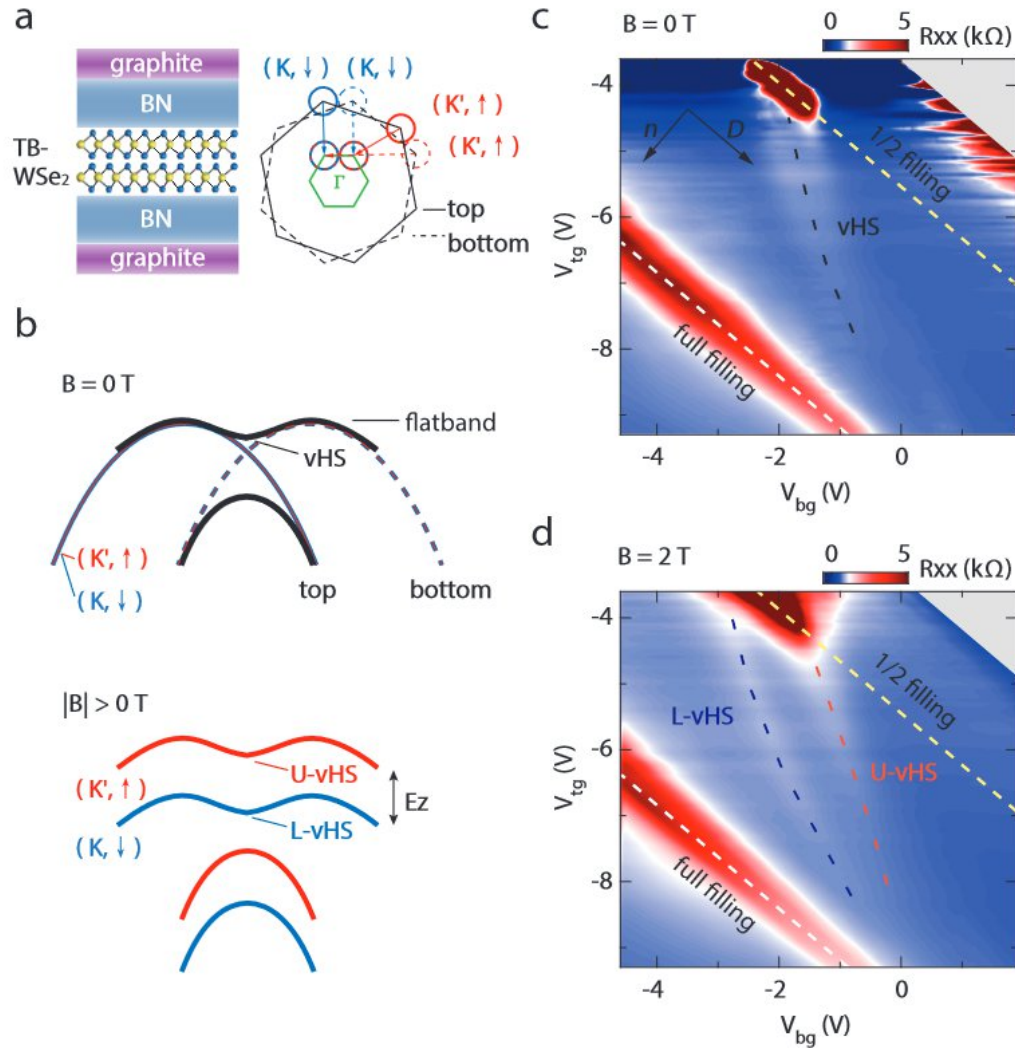
# One-dimensional flat bands in twisted bilayer germanium selenide



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# Mapping the Mottness under Magnetic Field

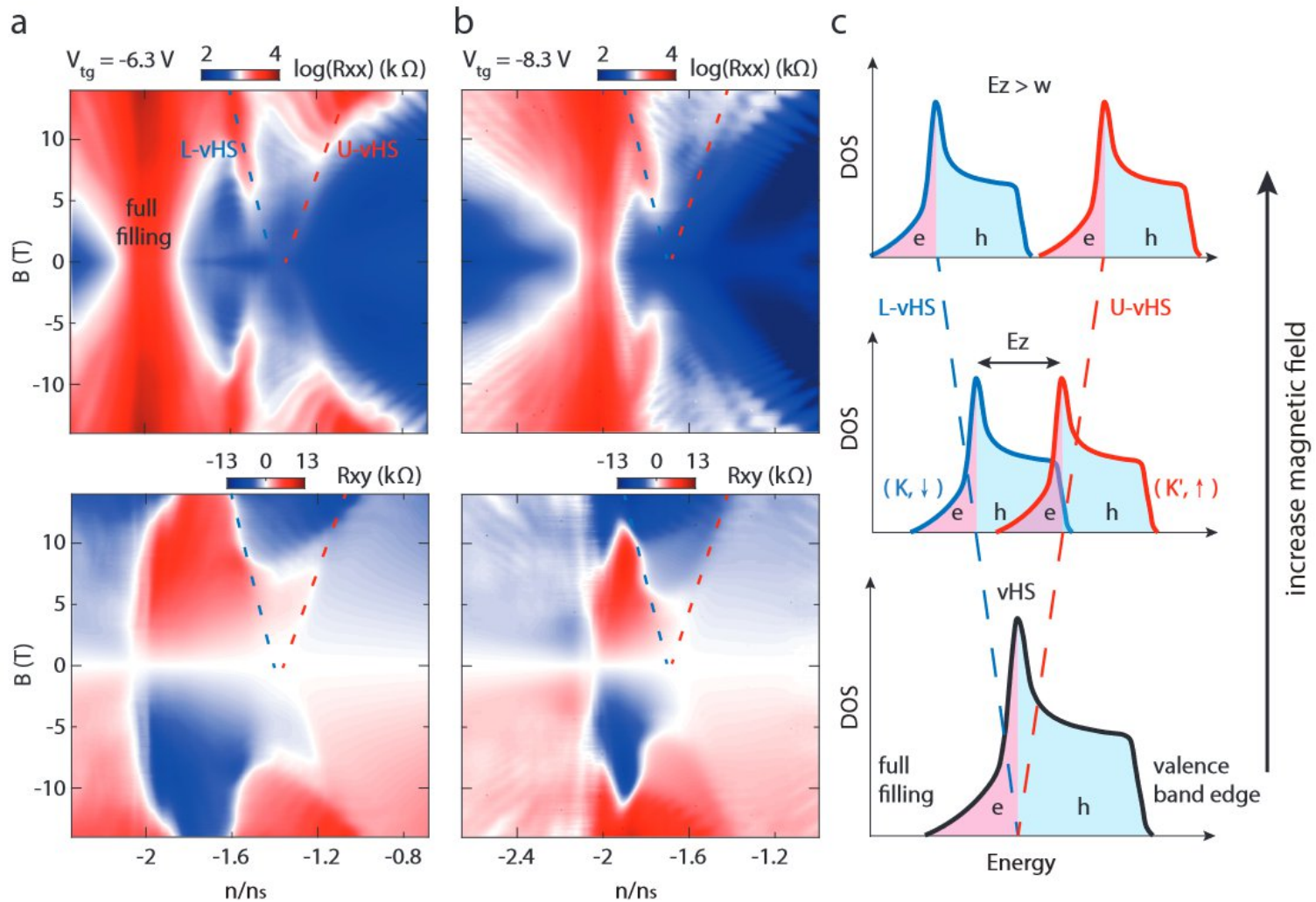


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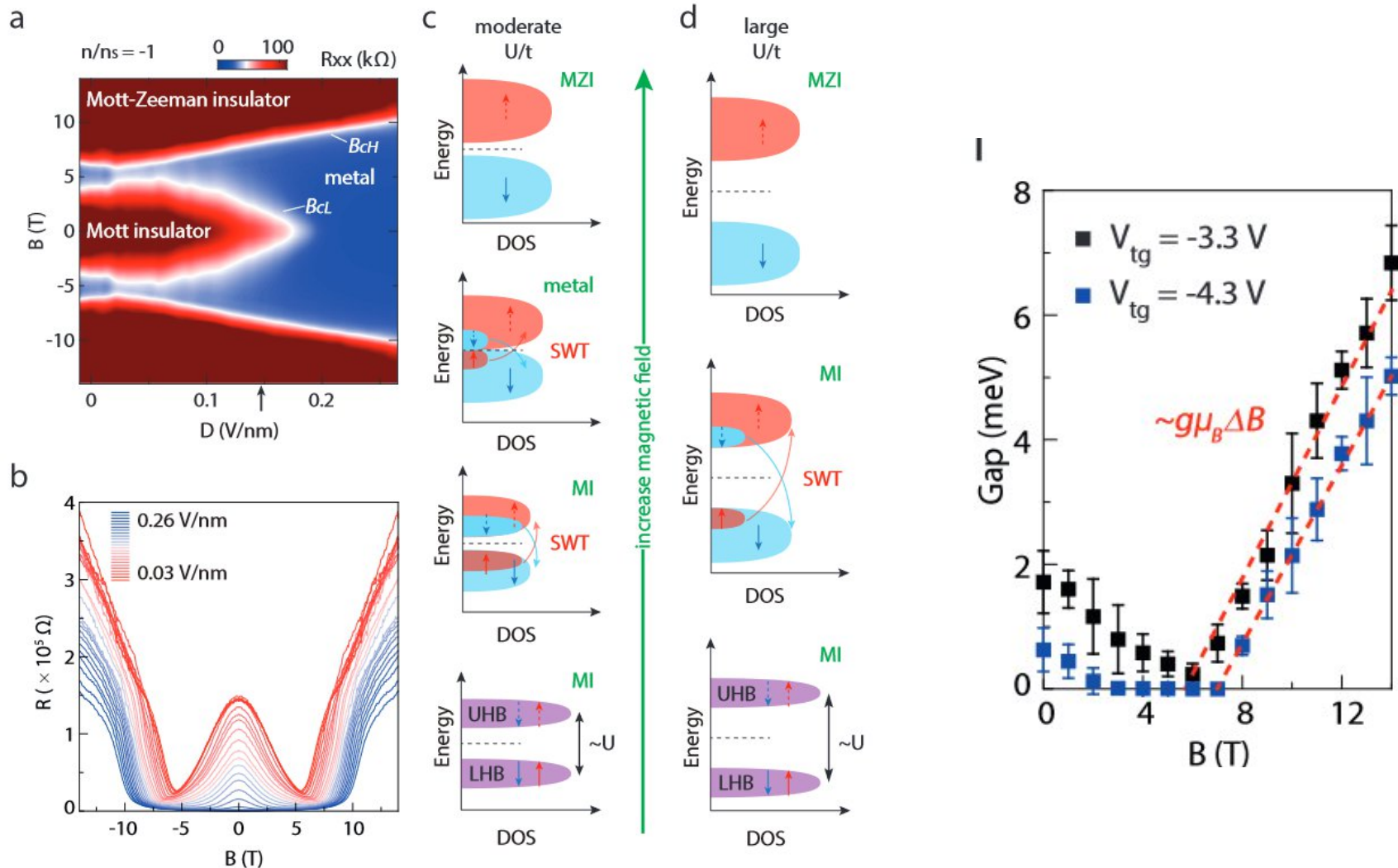
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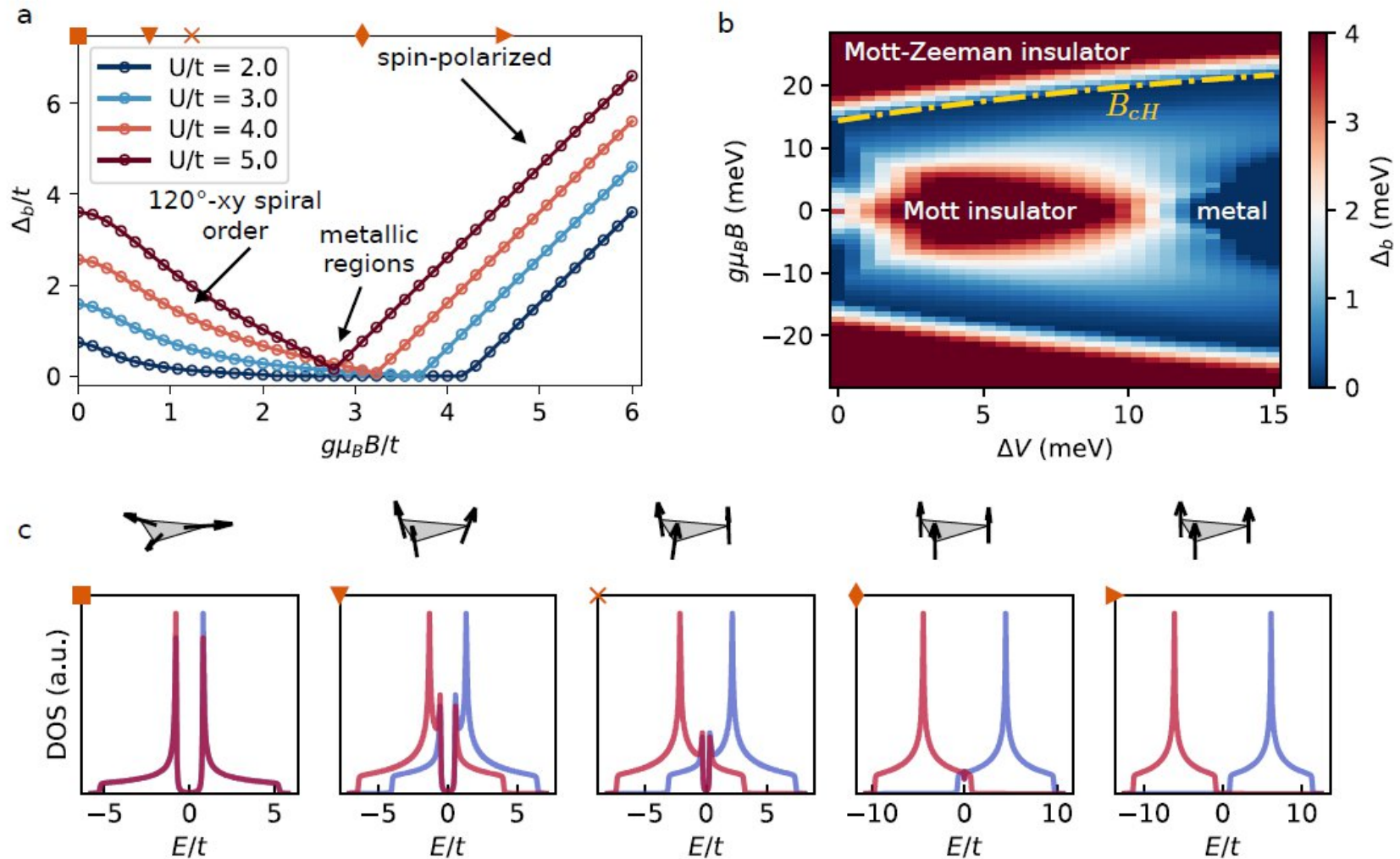


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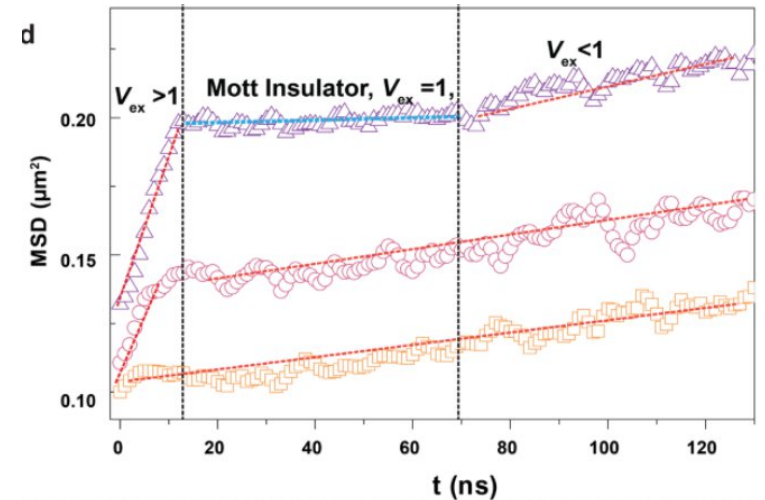
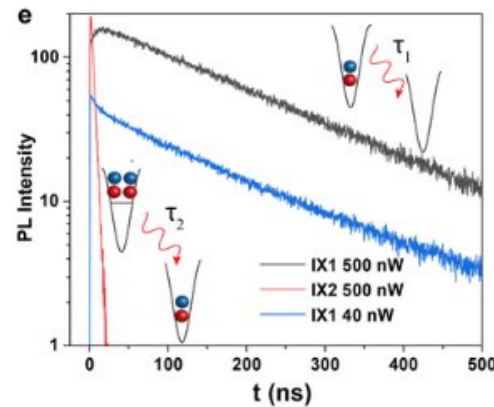
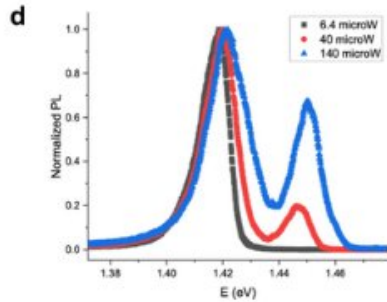
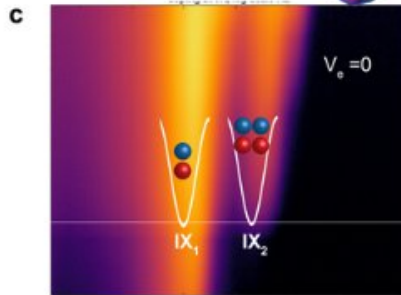
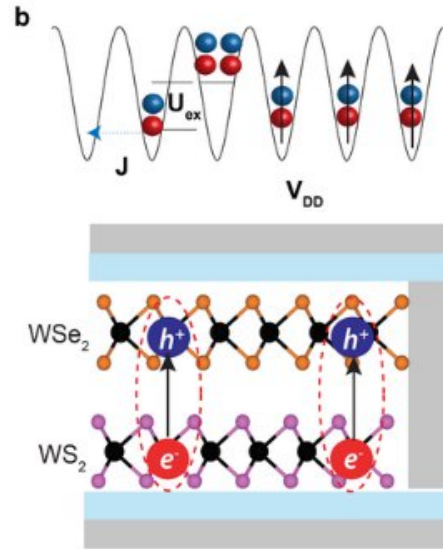
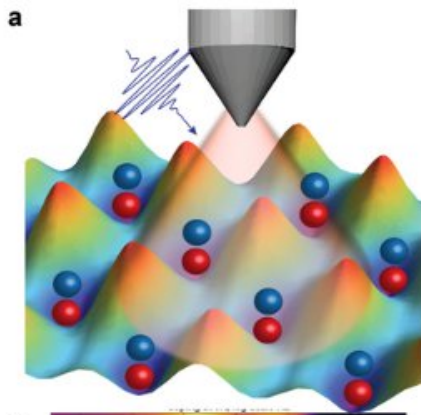


# Mapping the Mottness under Magnetic Field



# Long-Ranged Interactions Freeze the Dynamics of Dipolar Moiré Exciton Mott Insulators

S. Deng, J. Reimann,...DMK, L. Huang in review



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# Long-Ranged Interactions Freeze the Dynamics of Dipolar Moiré Exciton Mott Insulators

S. Deng, J. Reimann,...**DMK**, L. Huang in review

Letter | Published: 15 June 2006

## Repulsively bound atom pairs in an optical lattice

[K. Winkler](#), [G. Thalhammer](#), [F. Lang](#), [R. Grimm](#), [J. Hecker Denschlag](#) , [A. J. Daley](#), [A. Kantian](#), [H. P. Büchler](#)

& [P. Zoller](#)

[Nature](#) **441**, 853–856 (2006) | [Cite this article](#)

Article | Published: 15 January 2012

## Fermionic transport and out-of-equilibrium dynamics in a homogeneous Hubbard model with ultracold atoms

[Ulrich Schneider](#) , [Lucia Hackermüller](#), [Jens Philipp Ronzheimer](#), [Sebastian Will](#), [Simon Braun](#), [Thorsten Best](#), [Immanuel Bloch](#), [Eugene Demler](#), [Stephan Mandt](#), [David Rasch](#) & [Achim Rosch](#)

[Nature Physics](#) **8**, 213–218 (2012) | [Cite this article](#)

### Editors' Suggestion

## Expansion Dynamics of Interacting Bosons in Homogeneous Lattices in One and Two Dimensions

J. P. Ronzheimer, M. Schreiber, S. Braun, S. S. Hodgman, S. Langer, I. P. McCulloch, F. Heidrich-Meisner, I. Bloch, and U. Schneider

Phys. Rev. Lett. **110**, 205301 – Published 13 May 2013

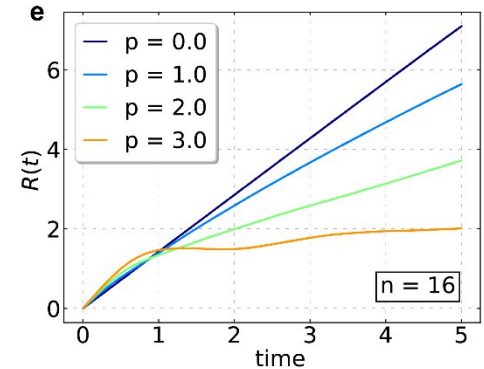
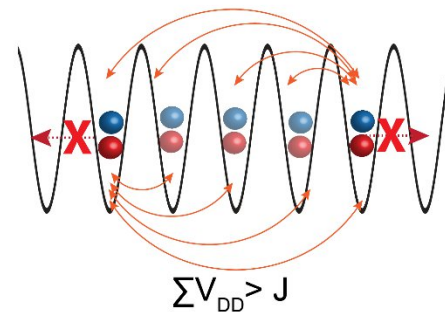
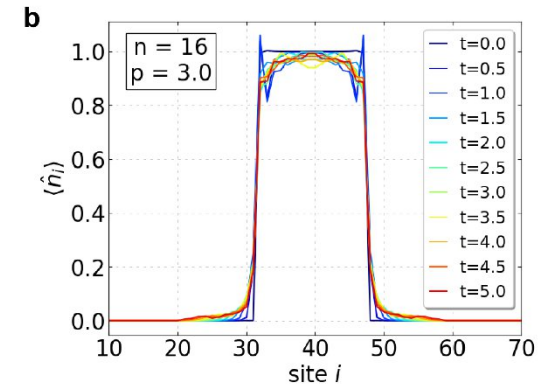
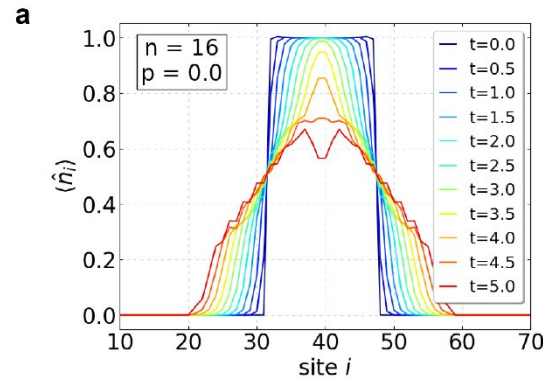
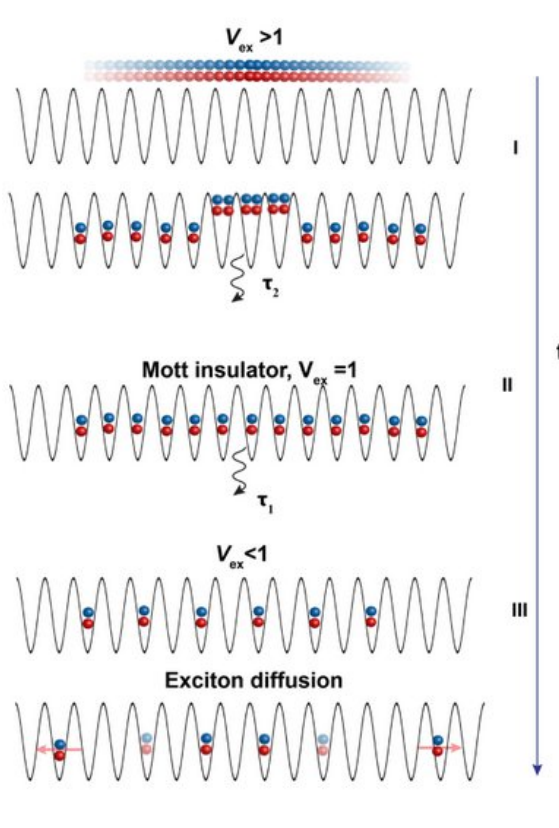
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# Long-Ranged Interactions Freeze the Dynamics of Dipolar Moiré Exciton Mott Insulators

S. Deng, J. Reimann,...**DMK**, L. Huang in prep.



## Moiré Exciton Review:

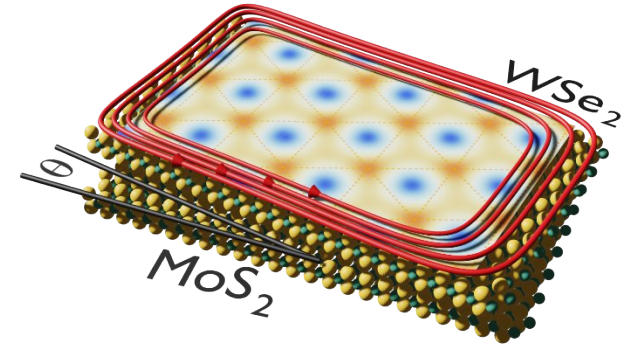
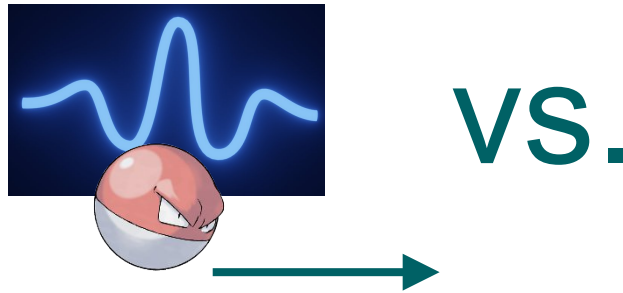
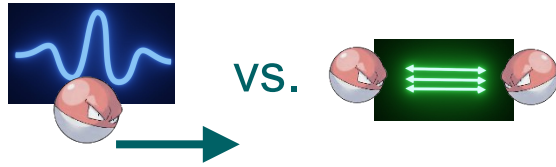
A. de la Torre, **DMK**, E. Malic, S. Kar  
arXiv:2402.19236

Dante M. Kennes

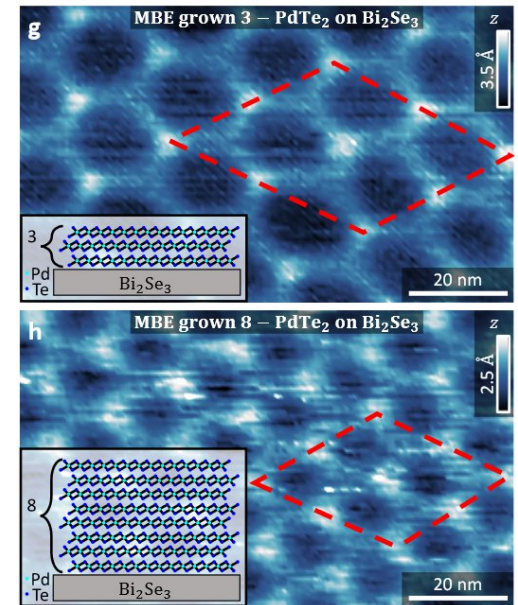
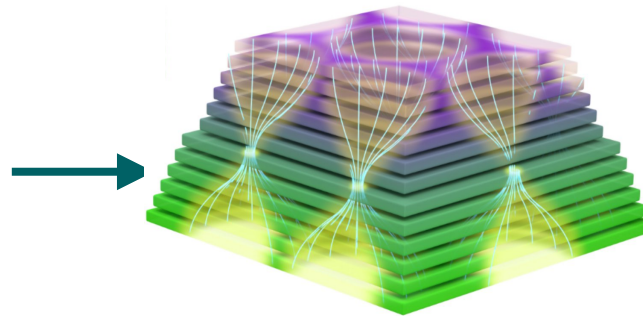
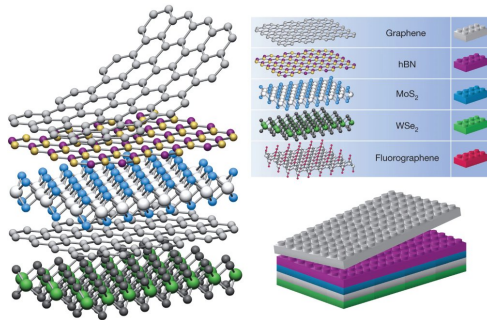
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# Outlook



## What about other 2D materials?

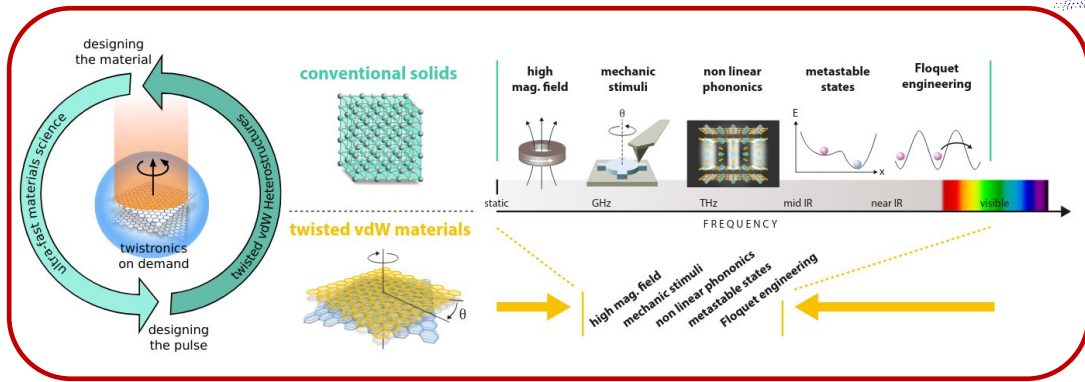
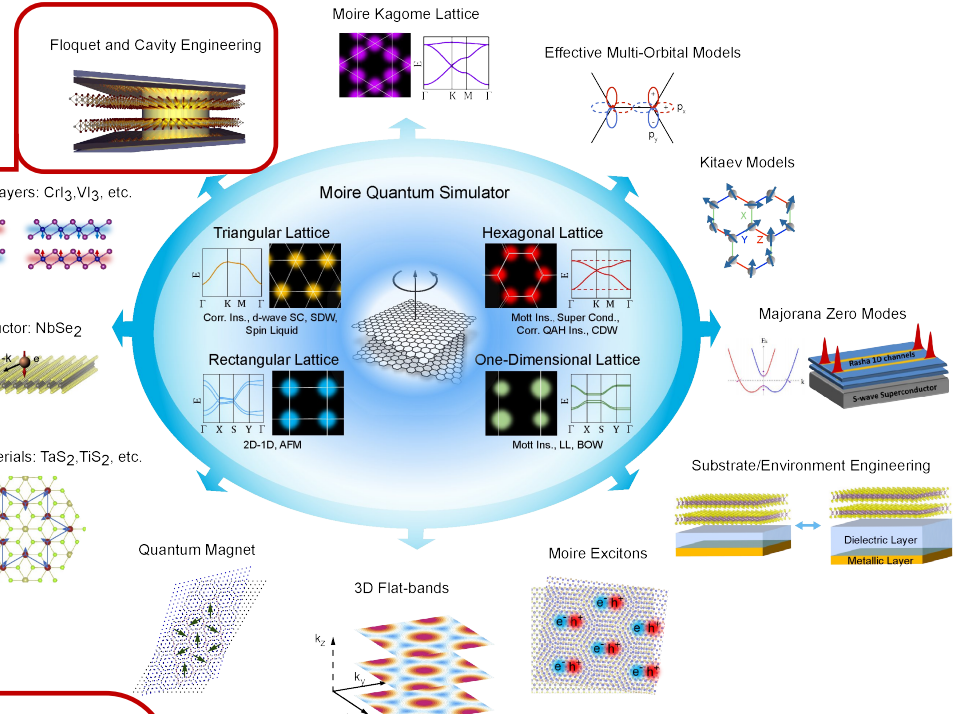
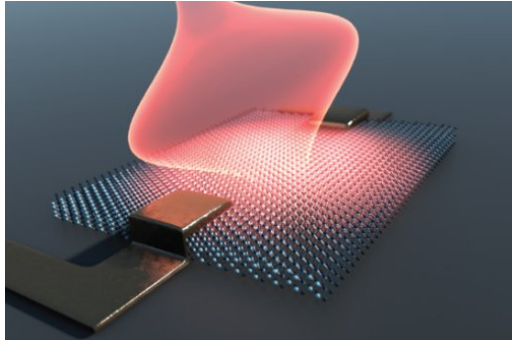


Geim, A., Grigorieva, I.  
Van der Waals heterostructures.  
*Nature* **499**, 419–425 (2013)

# Moiré heterostructures hold many promises for flexible control

*Colloquium: Nonthermal pathways to ultrafast control in quantum materials*

Alberto de la Torre, Dante M. Kennes, Martin Claassen, Simon Gerber, James W. McIver, and Michael A. Sentef  
 Rev. Mod. Phys. 93, 041002 – Published 14 October 2021



- Reduced energy scales meV: weak driving control, THz control?
- Light to tune to the magic angle?
- Cavity: outsized light-matter coupl.?



# Collaborations: Moiré-related works

---

## Columbia:

- Pasupathy group
- Dean group
- Basov group
- Hone group
- Millis group

## MPSD Hamburg:

- Rubio group
- Sentef group

## U. Penn:

- Claassen group

## Songshan Lake

### Materials Laboratory:

- Xian group

### Imperial College:

- Lischner group
- Mostofi group

## Univ. Collogne:

- Trebst group
- Scherer group

## Univ. of Minnesota:

- Fernandes group

## Beihang University:

- Tang group

## College de France:

- Georges group

## RWTH Aachen:

- Honerkamp group
- Stampfer group

## Nanjing University:

- Wang group

## Univ. of Trieste:

- V. Vitale

## Purdue University:

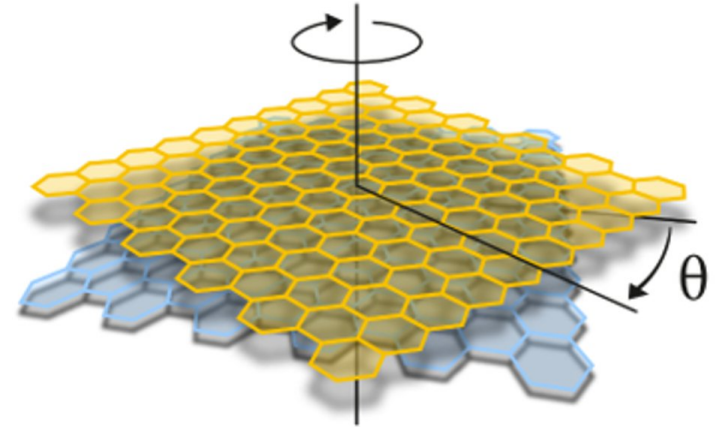
- Huang group

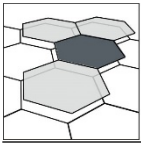
## Univ. of Hamburg:

- Wehling group

## Univ. of Münster:

- Wurstbauer group





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Graphene &  
2D Materials  
Center

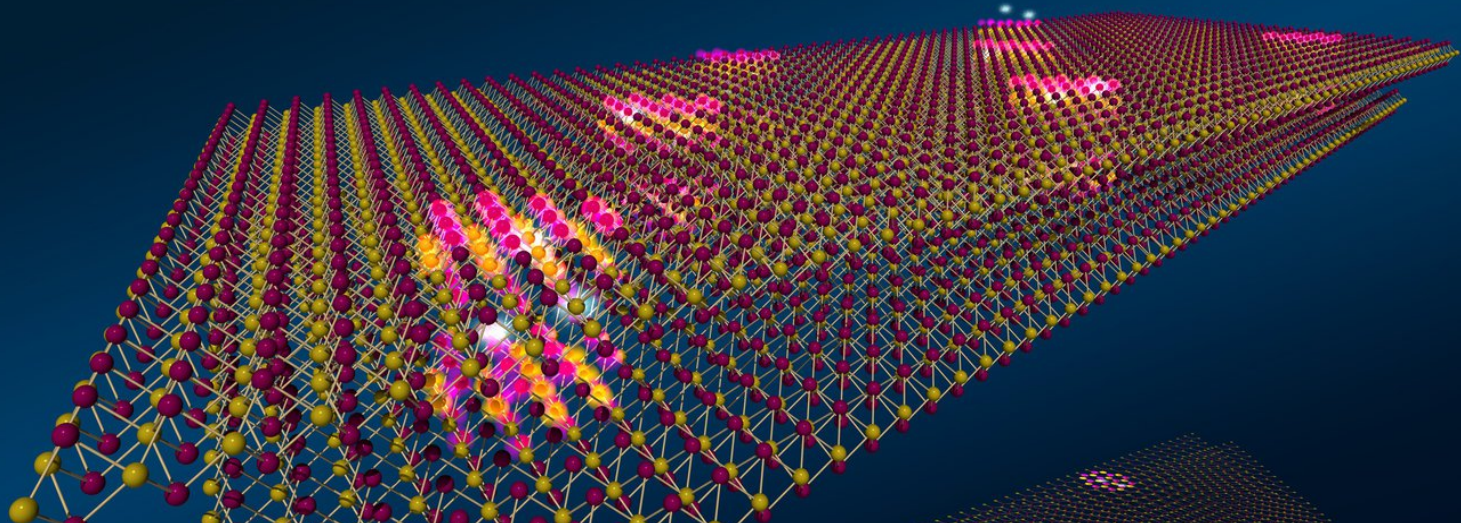


2D Materials  
Physics of  
van der Waals  
[hetero]structures

ML<sup>4</sup>Q

DFG Deutsche  
Forschungsgemeinschaft  
German Research Foundation

# Thank you for your attention



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Struktur und Dynamik der Materie

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