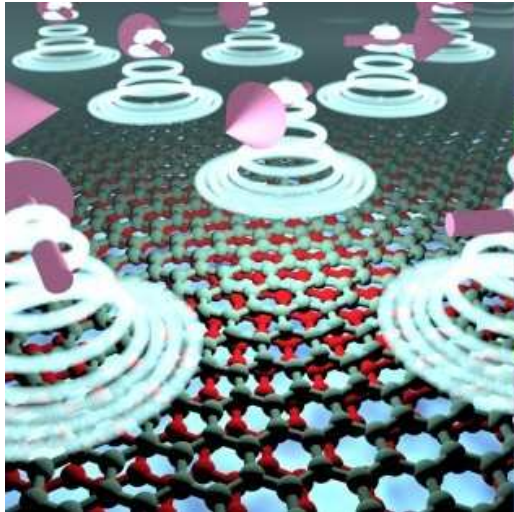


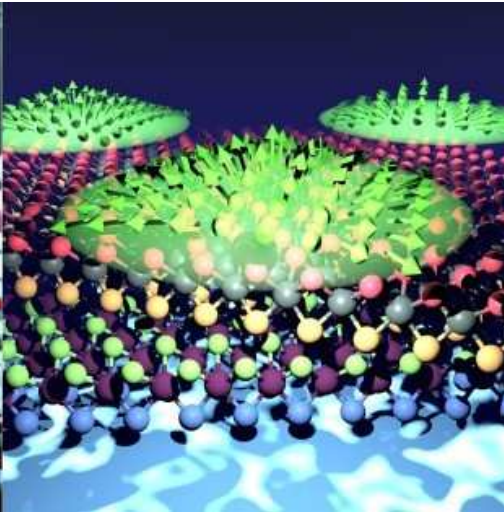
Designing correlated quantum matter with magnetic twisted van der Waals heterostructures

Jose Lado

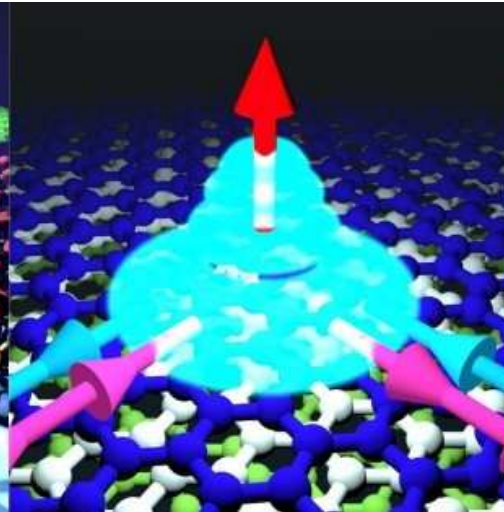
Department of Applied Physics, Aalto University, Finland



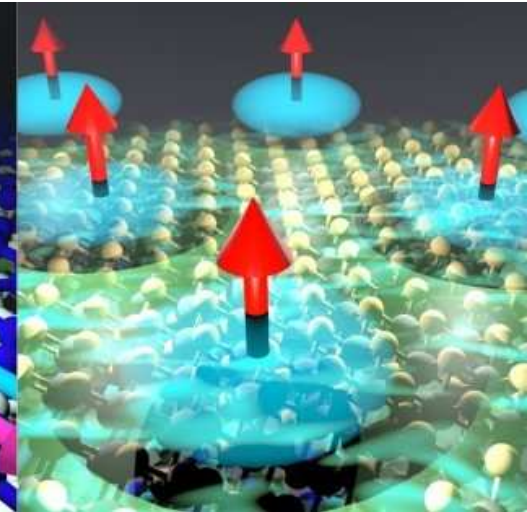
Phys. Rev. Lett. 126, 056803 (2021)



arXiv:2105.04502 (2021)



Phys. Rev. Lett. 127, 026401 (2021)

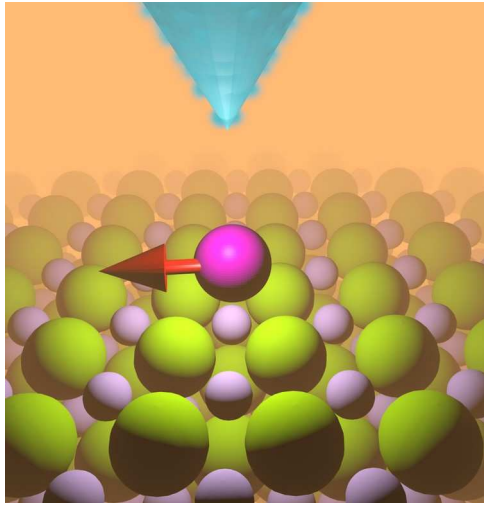


arXiv:2103.11989 (2021)

ICN+T 2021, July 13th 2021

Building quantum matter with artificial lattices

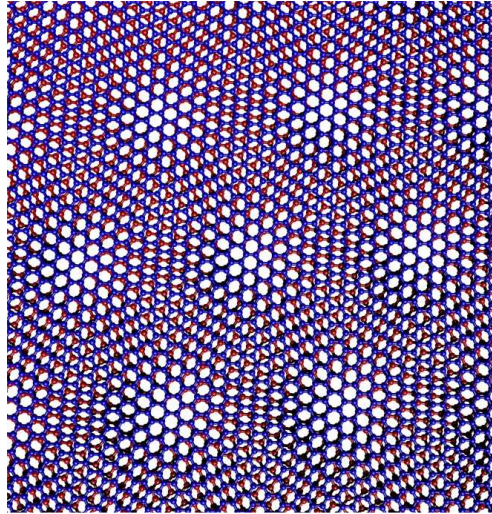
Atomic lattices



$a = 0.5 \text{ nm}$

Nature Physics 12 (7), 656 (2016)
Nature Physics 13 (7) 668 (2017)
Science 335 (6065), 196-199 (2012)

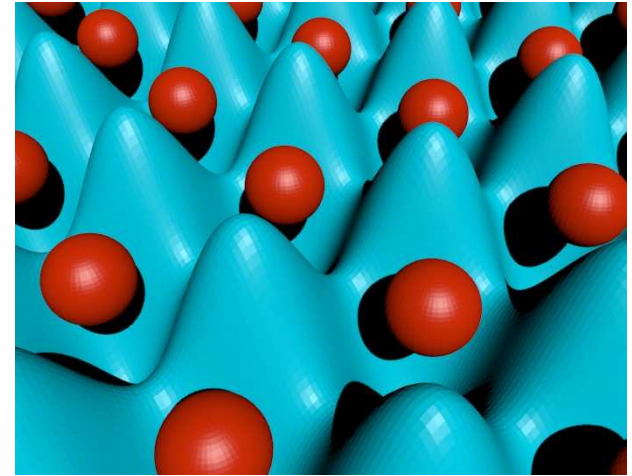
Twisted 2D moire materials



$a = 30 \text{ nm}$

Nature 556, 80–84 (2018)
Science 363 (6431) 1059-1064. (2019)

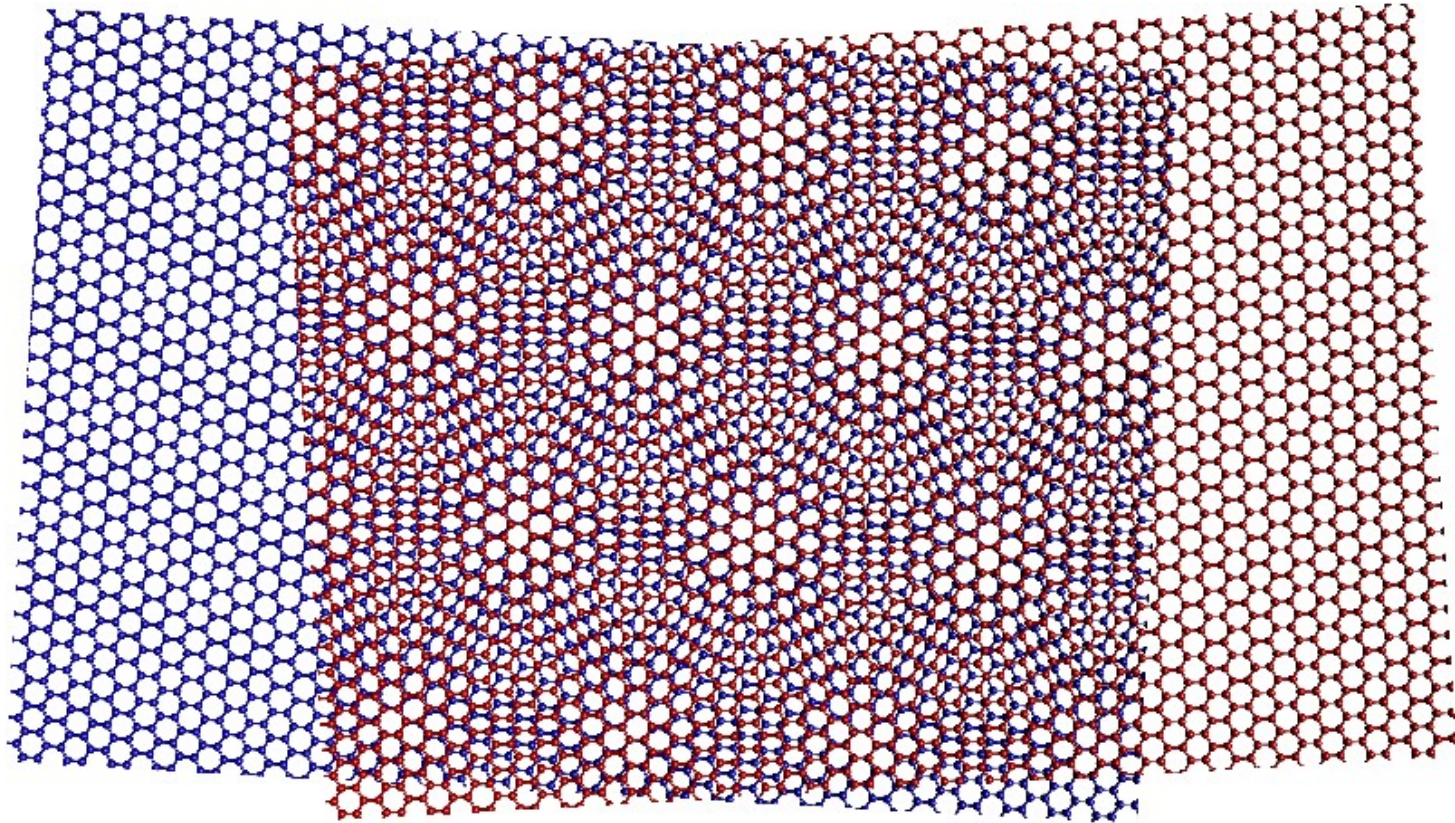
Cold atoms



$a = 1000 \text{ nm}$

Nature 545.7655 (2017)
Nature 455.7210 (2008)
Phys. Rev. Lett. 111, 185307 (2013)

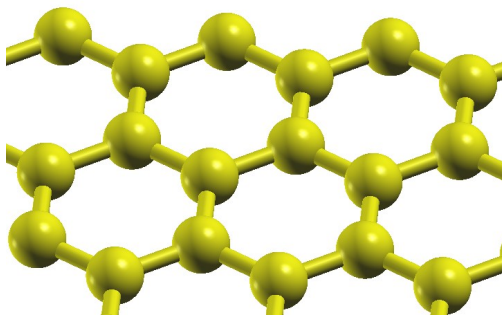
Twisted 2D materials as a platform for artificial quantum matter



The two-dimensional materials world

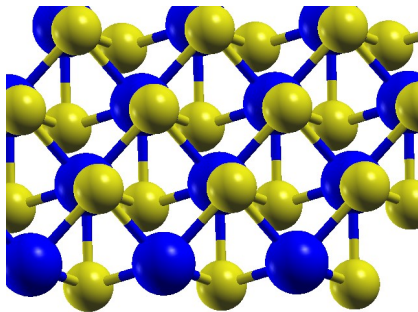
Semimetal

Graphene



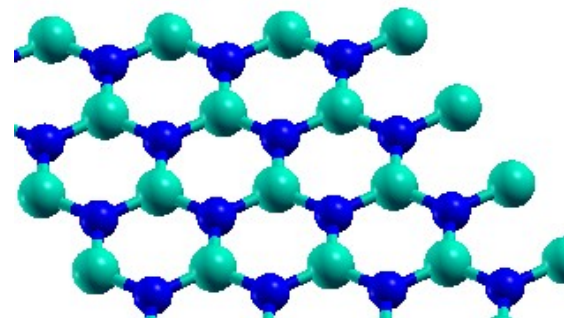
Superconductor

NbSe_2



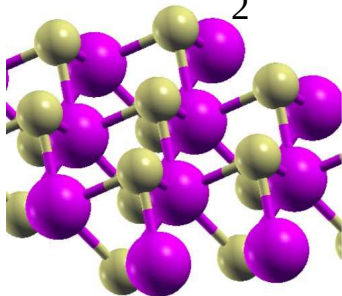
Insulator

BN



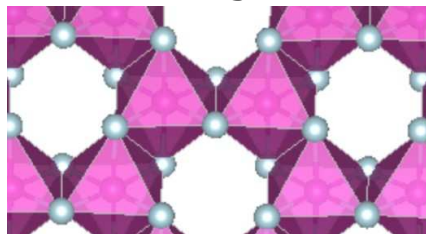
Semiconductor

WSe_2



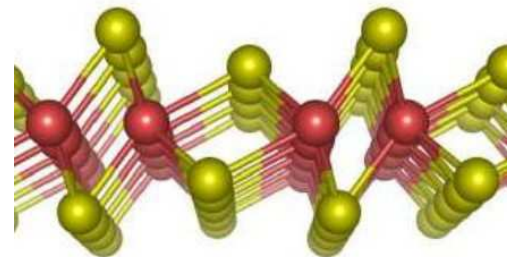
Ferromagnet

CrI_3



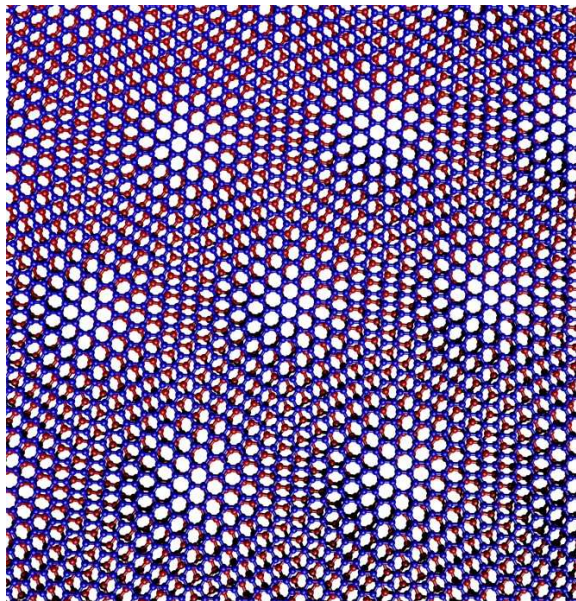
Quantum spin Hall insulator

WTe_2

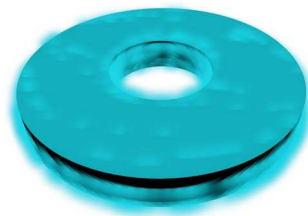


One material, a zoo of electronic phases

Twisted bilayer graphene

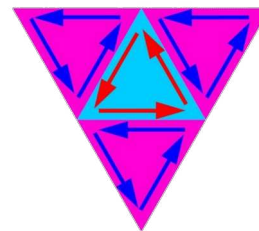


Superconductivity



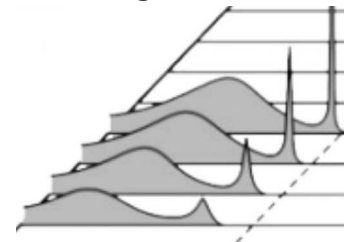
Nature 556, 43–50 (2018)

Topological networks



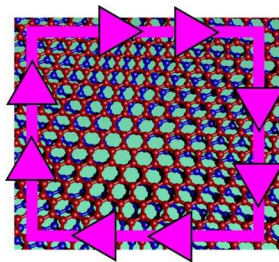
Nano Lett. 18, 11, 6725-6730 (2018)

Strange metals



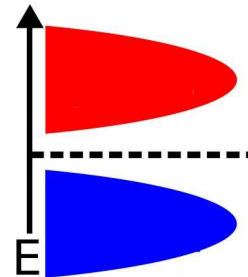
Phys. Rev. Lett. 124, 076801 (2020)

Chern insulators



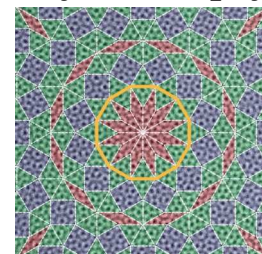
Science 365, 605-608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

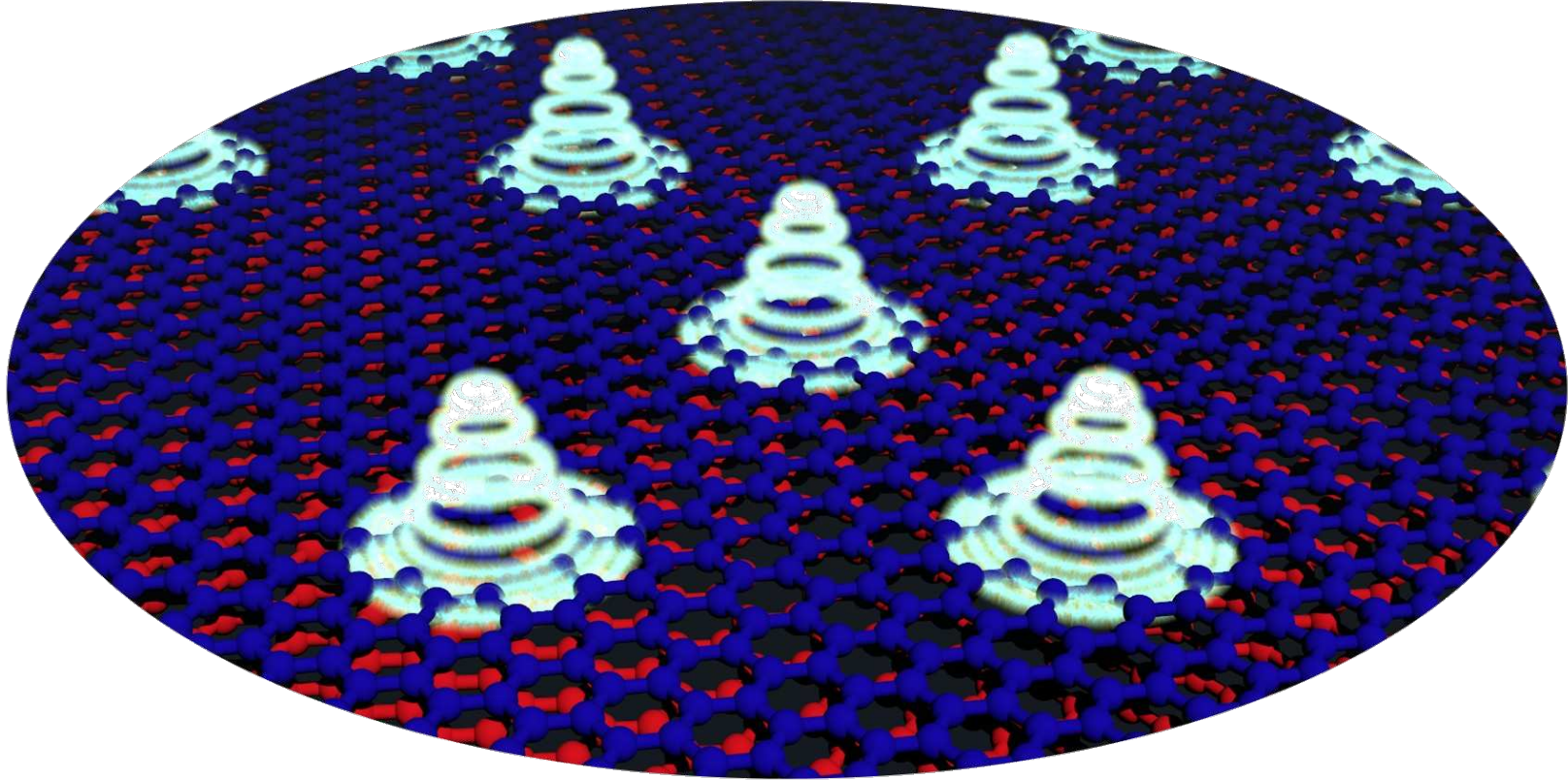
Quasicrystalline physics



Science 361 782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

A new universe in each new twisted material



Each twisted material is a new universe for electrons, with laws that change from twist to twist

Designing quantum matter in twisted materials

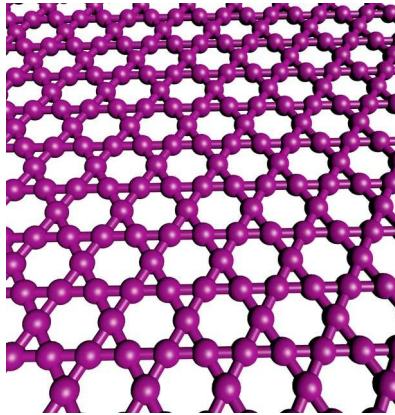
*The strength of
electronic correlations*

$$V_{ijkl}c_i^\dagger c_j c_k^\dagger c_l$$



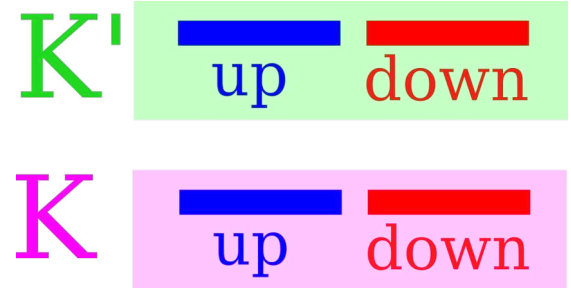
Twist angle control

*The details of the
electronic dispersion*



Interlayer bias

*The local quantum
degrees of freedom*



Magnetic encapsulation

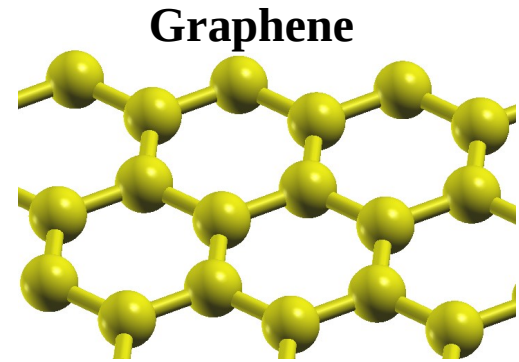
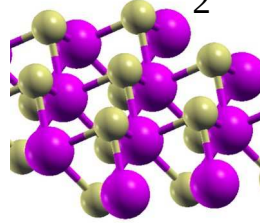
Goal: control local degrees of freedom via magnetic encapsulation a twisted material

Designing quantum matter with twisted magnetic van der Waals materials



Semiconductor

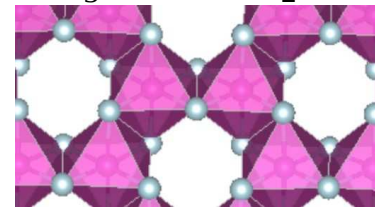
WSe_2



Graphene

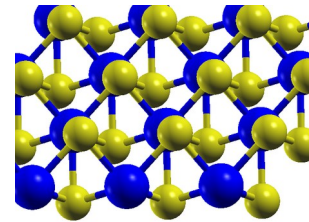
Magnet

CrBr_3 , 1T-TaS₂, CrI_3



Metal

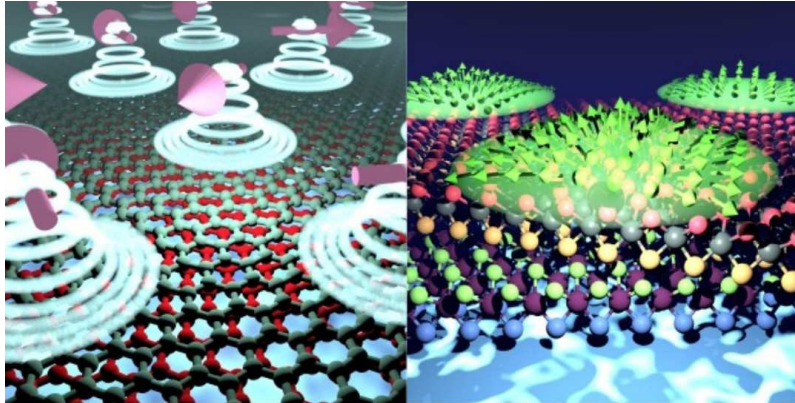
1H-TaS₂



Ingredients: Twist + exchange proximity + spin-orbit coupling + interactions

Today's plan

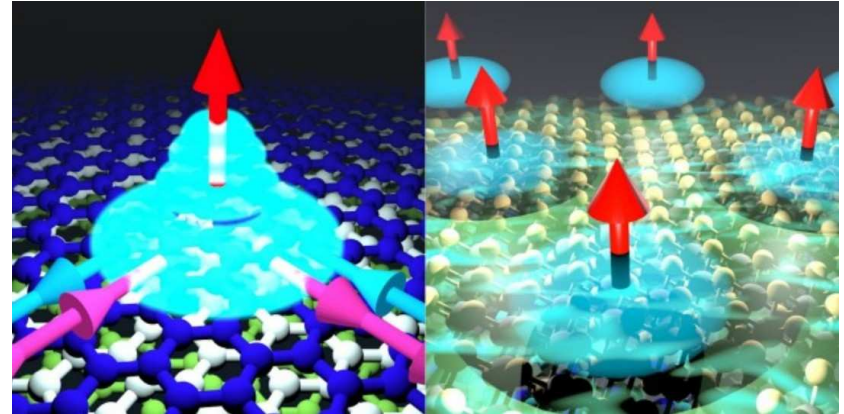
**Design of new correlated states
by magnetic encapsulation in
twisted materials**



theory

Phys. Rev. Lett. 126, 056803 (2021)
arXiv:2105.04502 (2021)

**A new family of correlated states
based on quantum magnetism:
heavy fermions in twisted materials**

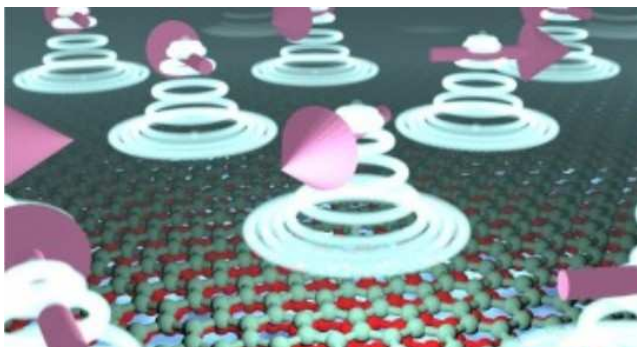


theory & experiment

Phys. Rev. Lett. 127, 026401 (2021)
arXiv:2103.11989 (2021)

Behind the scenes

**Valley-mixing correlations
in CrI_3 /twisted BG/ CrI_3**



Tobias
Wolf



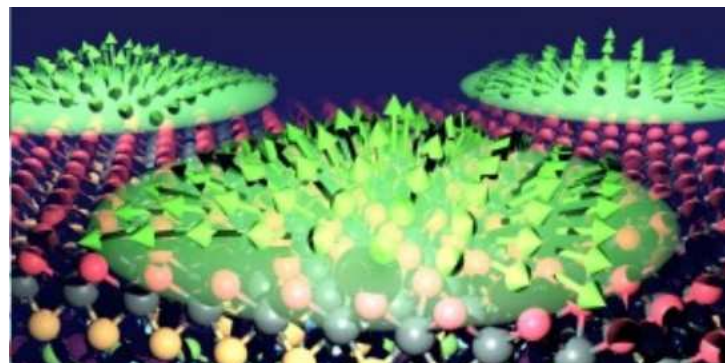
Gianni
Blatter



Oded
Zilberberg

Phys. Rev. Lett. 126, 056803 (2021)

**Correlated states dominated by spin-orbit coupling
in twisted Janus dichalcogenide bilayers**

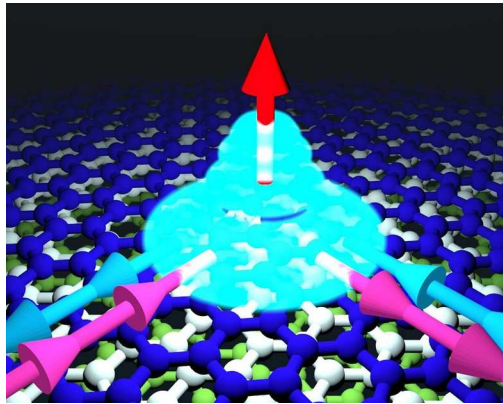


David
Soriano

arXiv:2105.04502 (2021)

Behind the scenes

Heavy fermions in twisted graphene trilayers

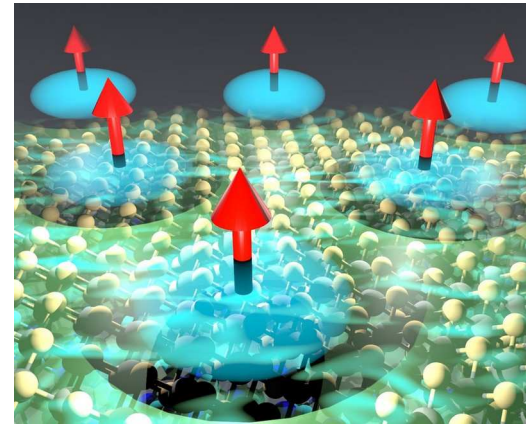


Aline Ramires



Phys. Rev. Lett. 127, 026401 (2021)

Heavy fermions in twisted dichalcogenide bilayers



V. Vaňo



S. Kezilebieke



P. Liljeroth



arXiv:2103.11989 (2021)

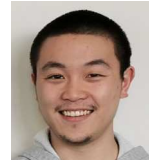
S. Ganguli



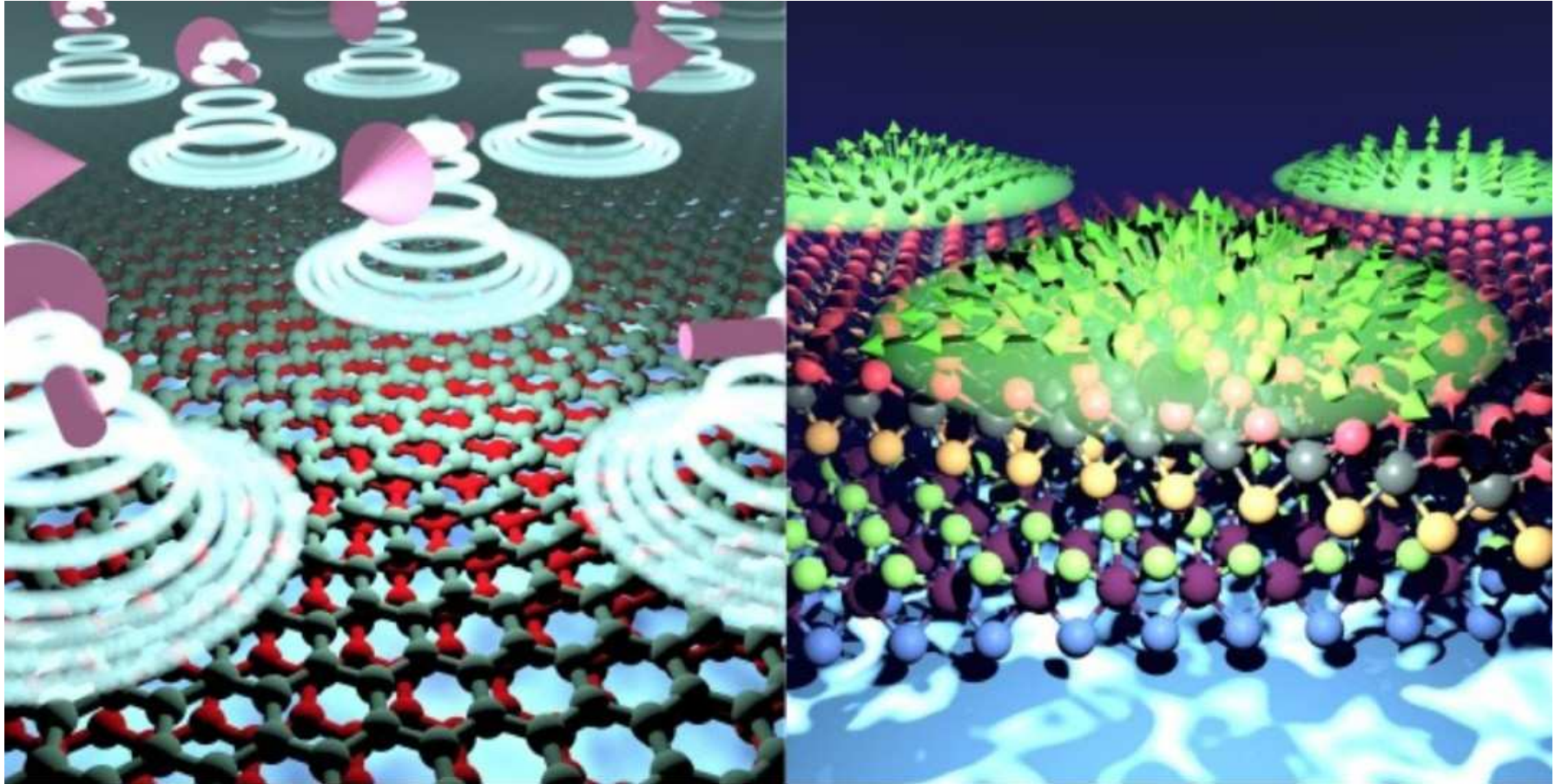
M. Amini



G. Chen



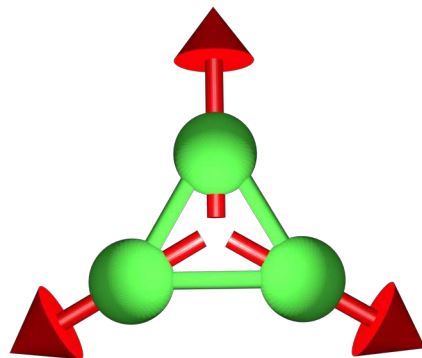
Design of new correlated states by magnetic encapsulation in twisted materials



Frustration

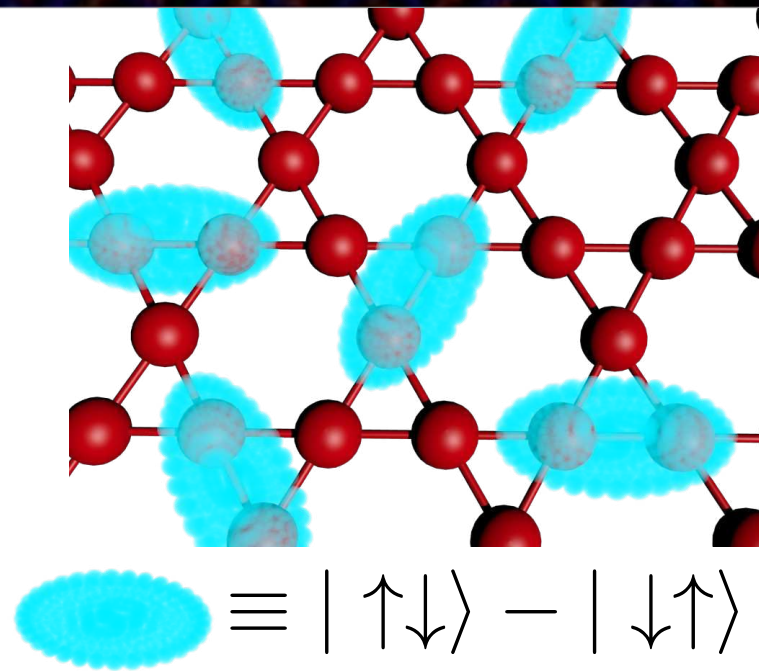
What is the best that frustration can bring?

Frustrated magnetism



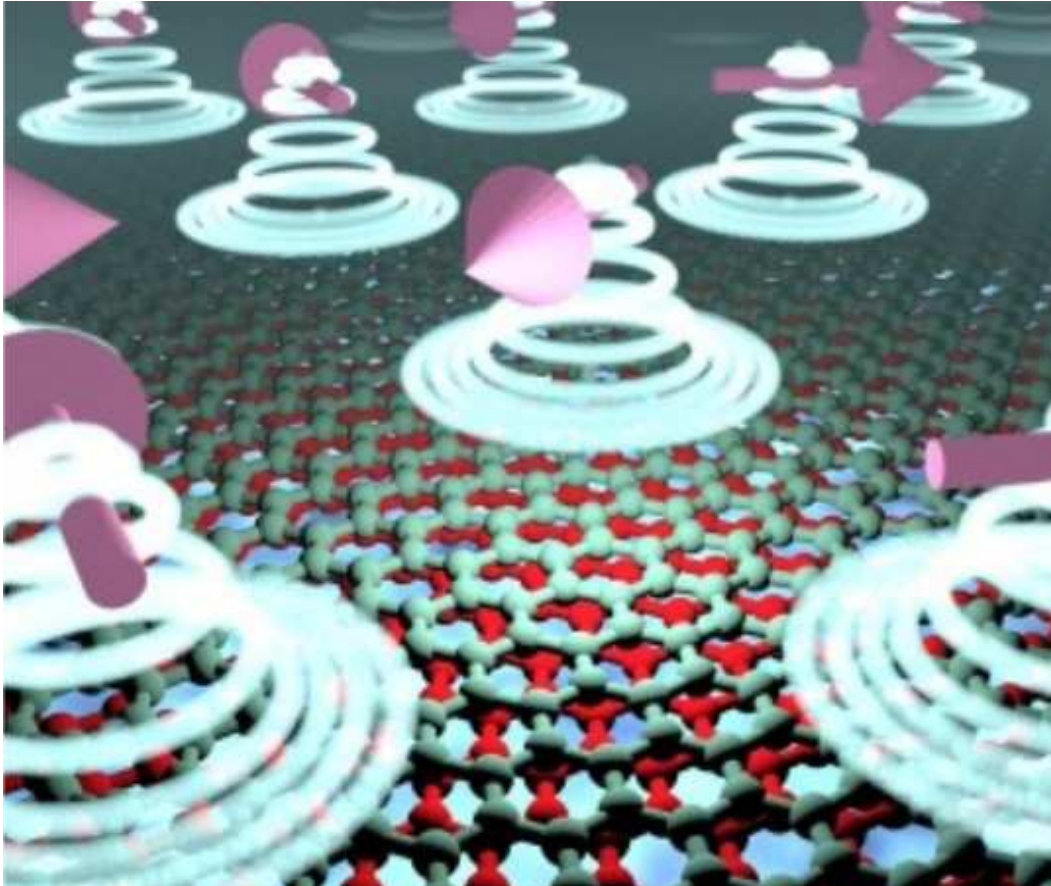
Quantum spin liquids

Non-trivial topological properties
Fractional excitations
Macroscopic quantum state
“Ultra-quantum” matter



**Can we create a controllable frustrated magnet, not in the spin
but in the “valley” degree of freedom?**

Valley-mixing correlations in magnetically encapsulated tBG



Tobias
Wolf



Gianni
Blatter

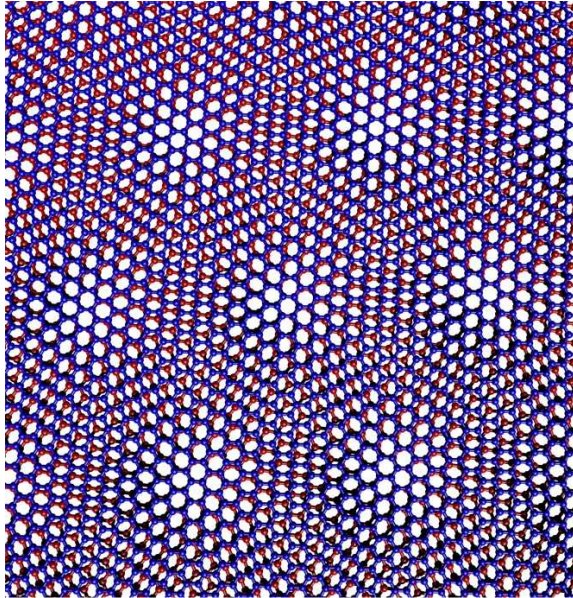


Oded
Zilberberg

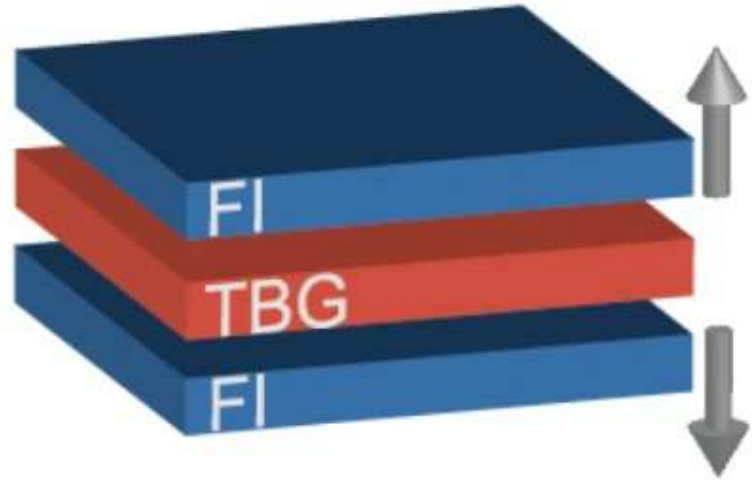
Phys. Rev. Lett. 126, 056803 (2021)

Magnetically encapsulated twisted graphene bilayer

Moire structure



Magnetic encapsulation



CrI_3 /twisted bilayer graphene/ CrI_3

Let us focus on the antiferromagnetic configuration of the encapsulation

Magnetically encapsulated twisted graphene bilayer

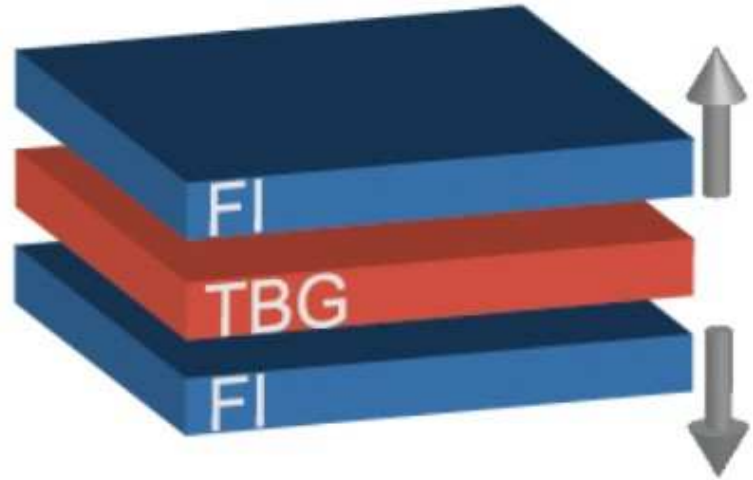
$$H = H_0 + H_J + H_R$$

Kinetic
energy

Exchange
proximity
effect

Rashba
spin-orbit
coupling

Magnetic encapsulation



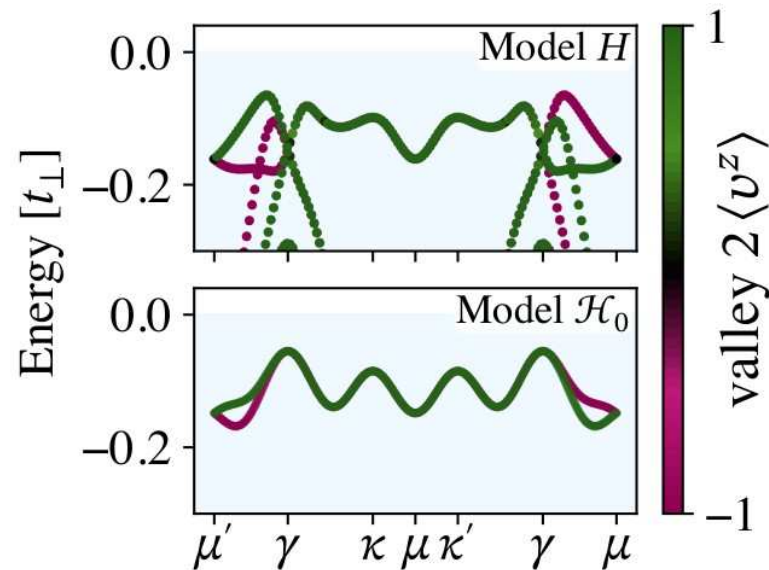
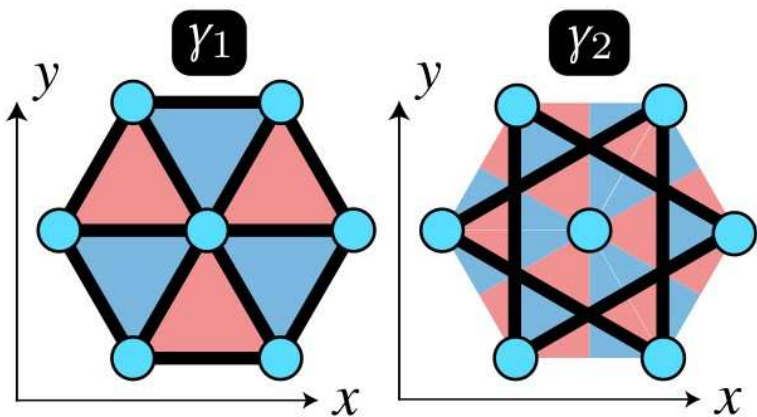
Valley frustration from combined twist engineering, exchange proximity and spin-orbit coupling.

Lets focus on the regime $\alpha = 1.3^\circ - 2^\circ$

Effective low energy valley model

Flux model in the triangular lattice

$$\mathcal{H}_0 = \sum_{\langle IJ \rangle} \gamma_1 \psi_I^\dagger e^{i\sigma^z \nu_{IJ} \phi_1} \psi_J + \sum_{\langle\langle IJ \rangle\rangle} \gamma_2 \psi_I^\dagger e^{i\sigma^z \nu_{IJ} \phi_2} \psi_J$$



Two-band valley-only model in the triangular lattice

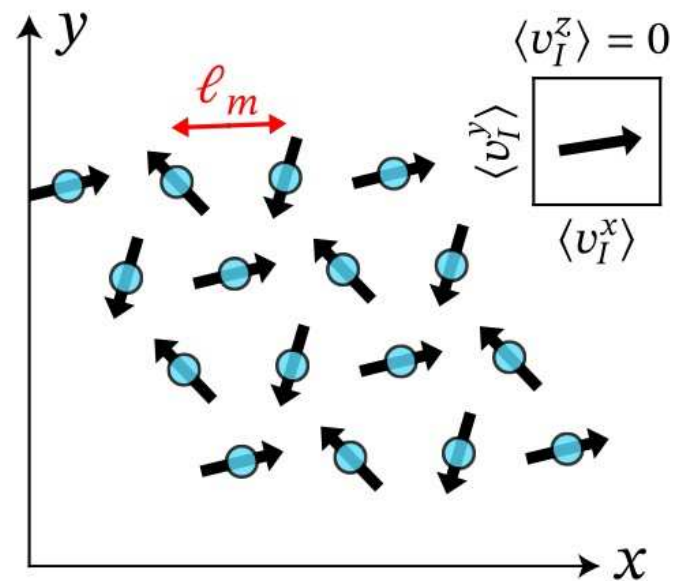
Impact of interactions

Lets add electronic interactions

Free
Hamiltonian

Electronic
interactions

$$\bar{H} = H + H_{int}$$

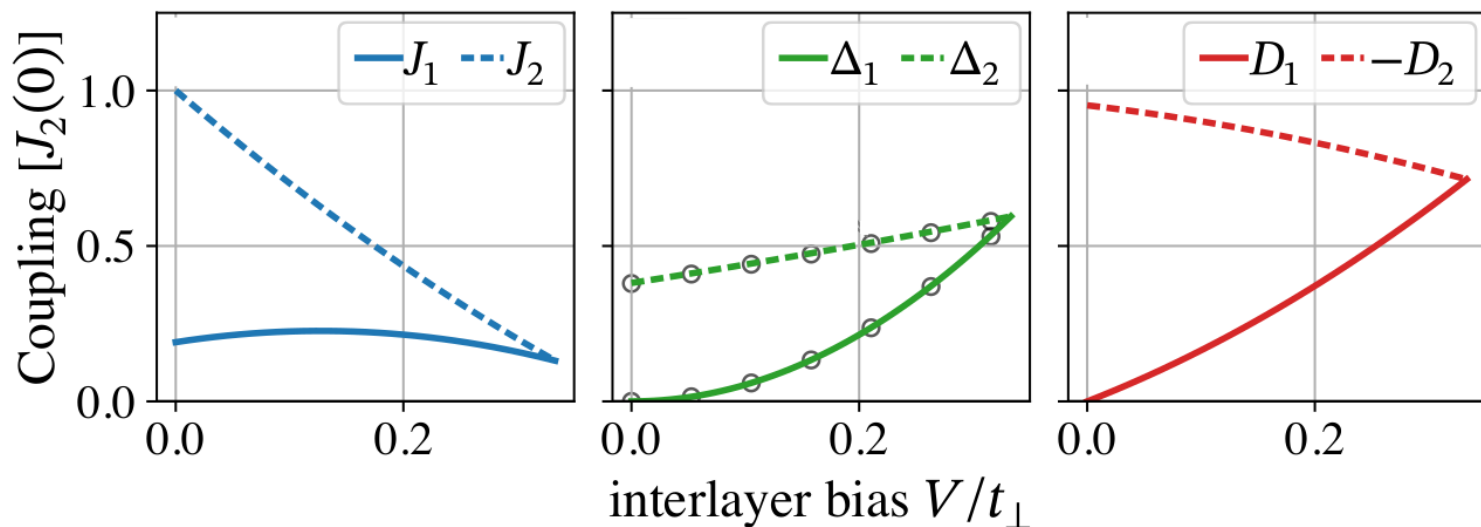


And compute the effective valley-Heisenberg Hamiltonian in the strong coupling limit

$$\mathcal{H}_v = \sum_{IJ} J_{IJ} \mathbf{v}_I \cdot \mathbf{v}_J + \Delta_{IJ} v_I^z v_J^z + \nu_{IJ} D_{IJ} (\mathbf{v}_I \times \mathbf{v}_J)_z$$

Controlling a valley-Heisenberg model electrically

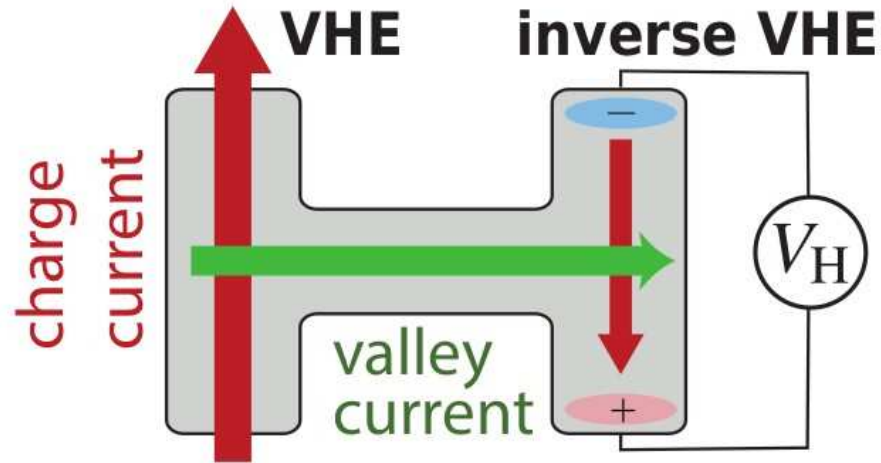
$$\mathcal{H}_v = \sum_{IJ} J_{IJ} \mathbf{v}_I \cdot \mathbf{v}_J + \Delta_{IJ} v_I^z v_J^z + v_{IJ} D_{IJ} (\mathbf{v}_I \times \mathbf{v}_J)_z$$



An interlayer bias provides a tunable anisotropic valley-Heisenberg model

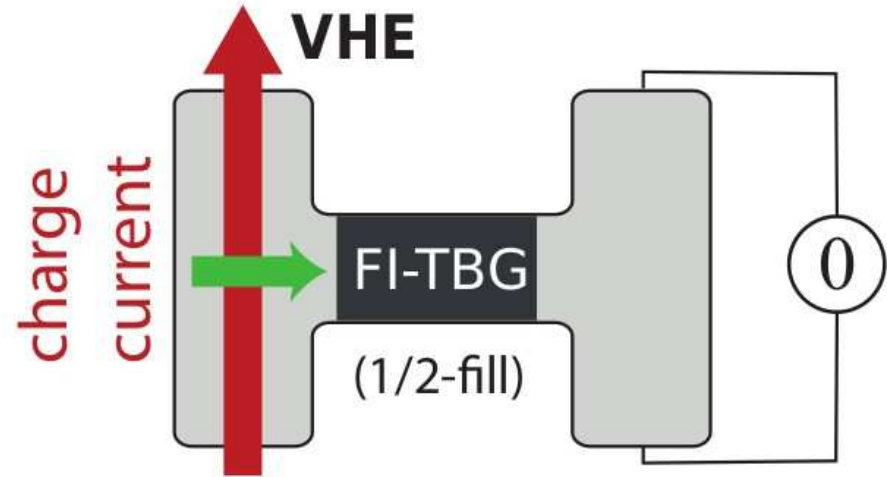
Detecting the valley spiral

No valley mixing



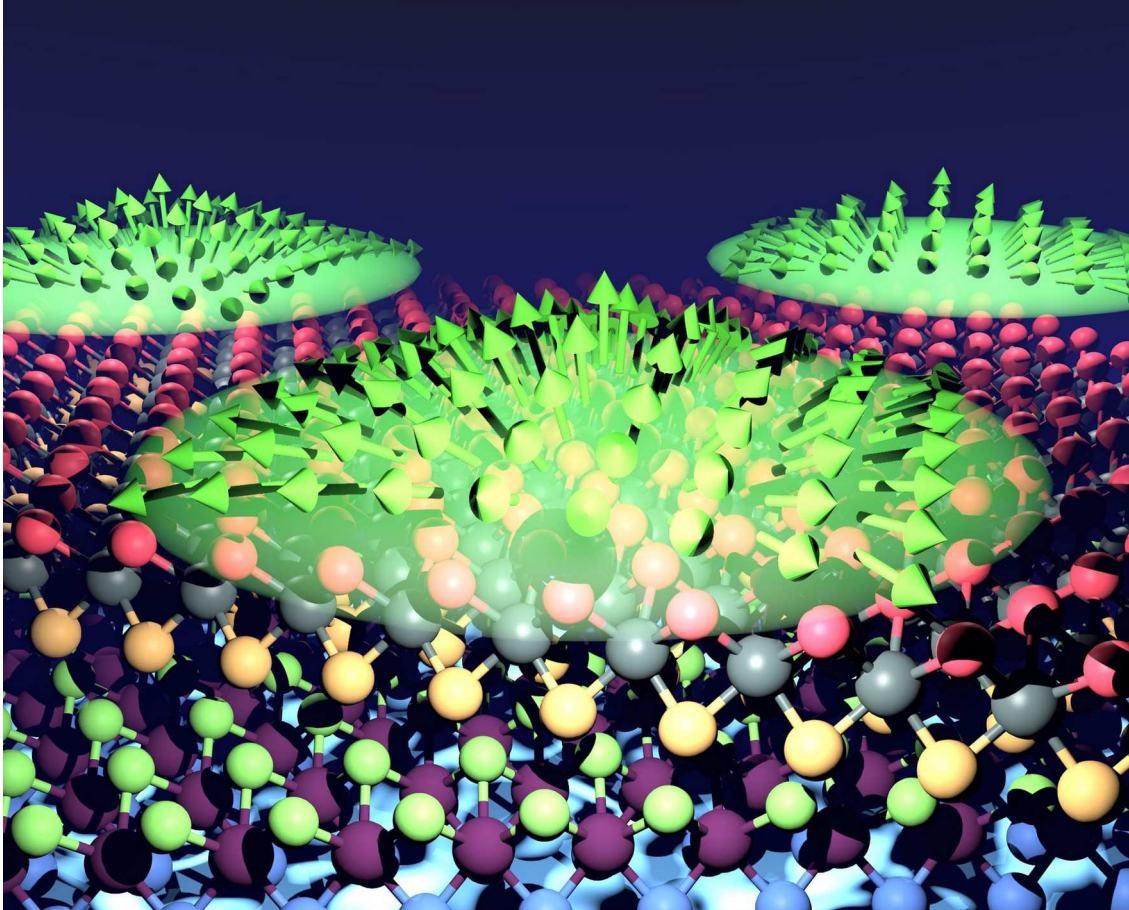
Finite non-local conductance

Finite valley mixing



Zero non-local conductance

Correlated states dominated by spin-orbit coupling in Janus dichalcogenides

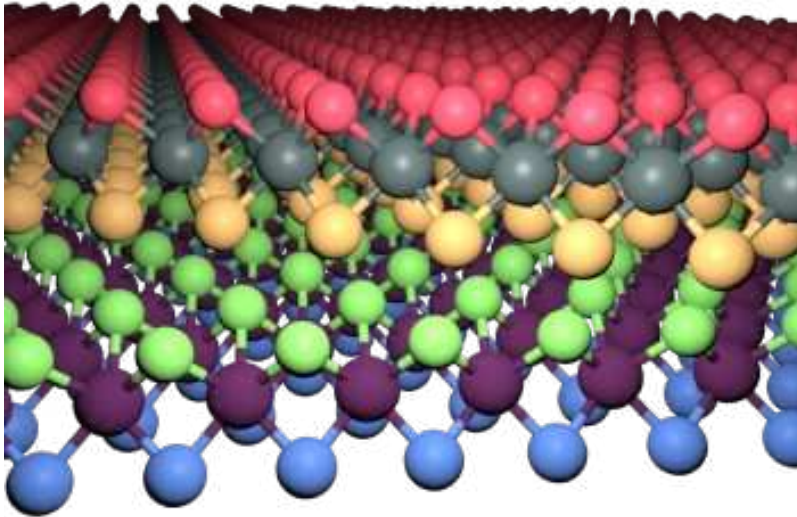


David Soriano

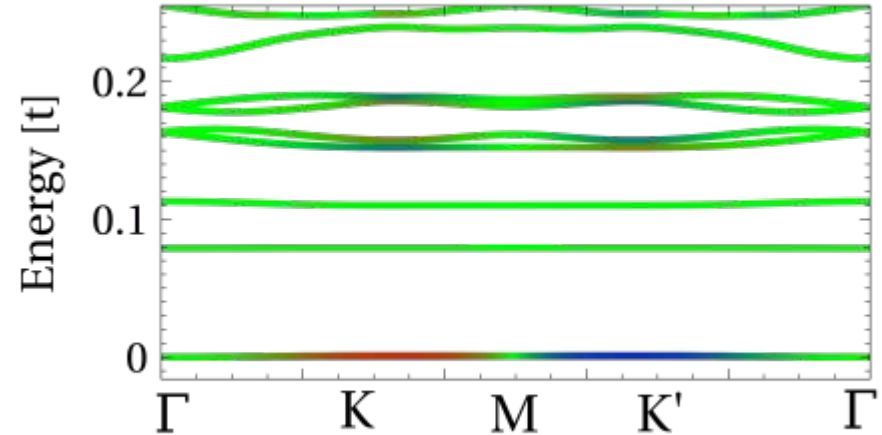
arXiv:2105.04502 (2021)

Twisted Janus bilayers

Twisted Janus bilayer

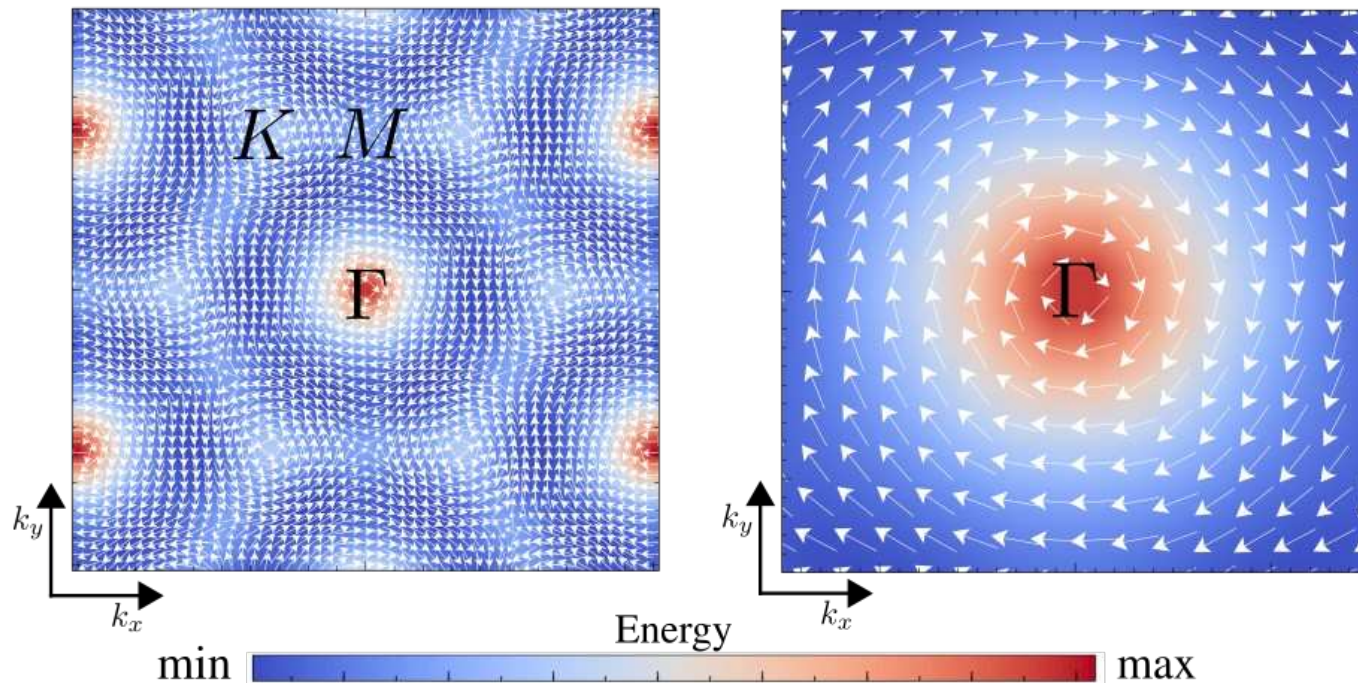


Band structure



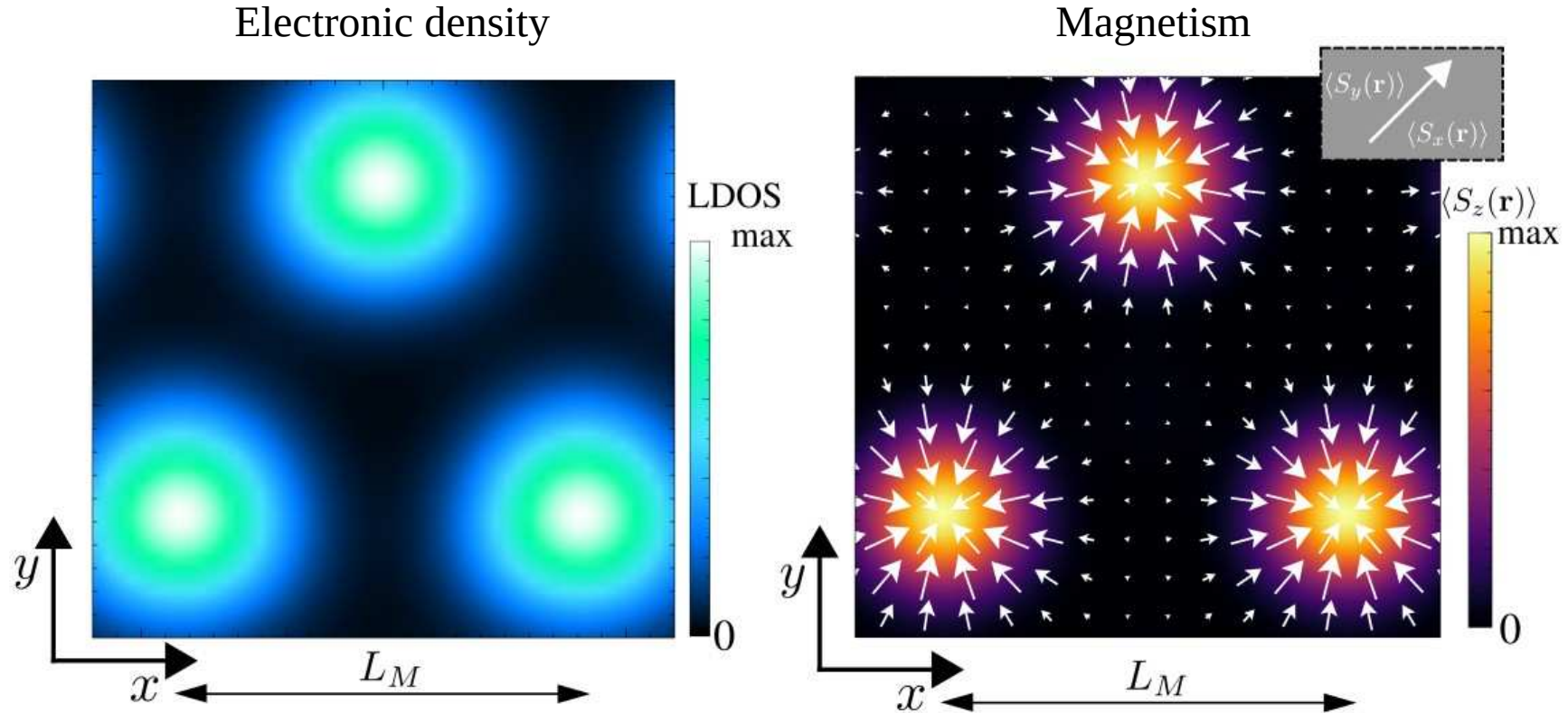
Flat bands emerge in a twisted Janus bilayer, inheriting the colossal Rashba SOC effects

Reciprocal space texture of the flat bands



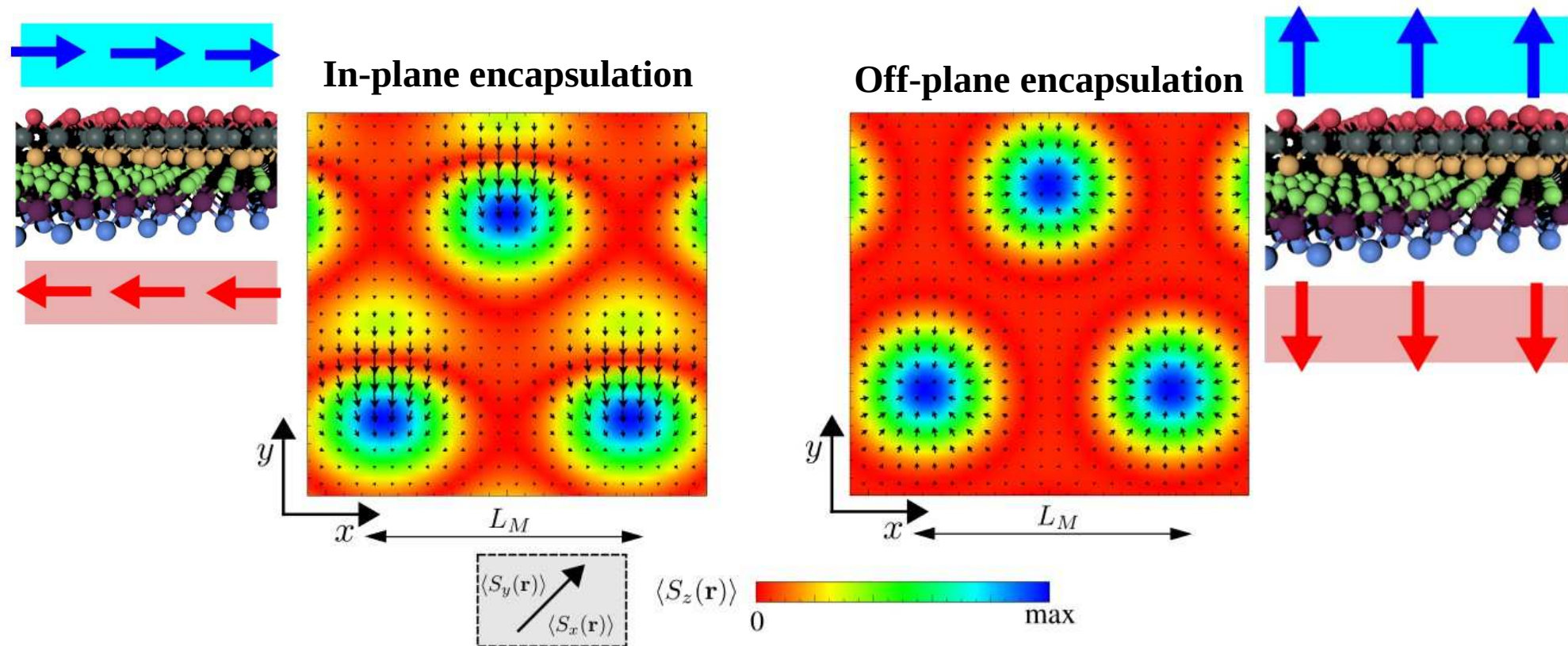
Flat bands are dominated by a strong spin-momentum texture, stemming from the Janus structure

Real space profile when including interactions



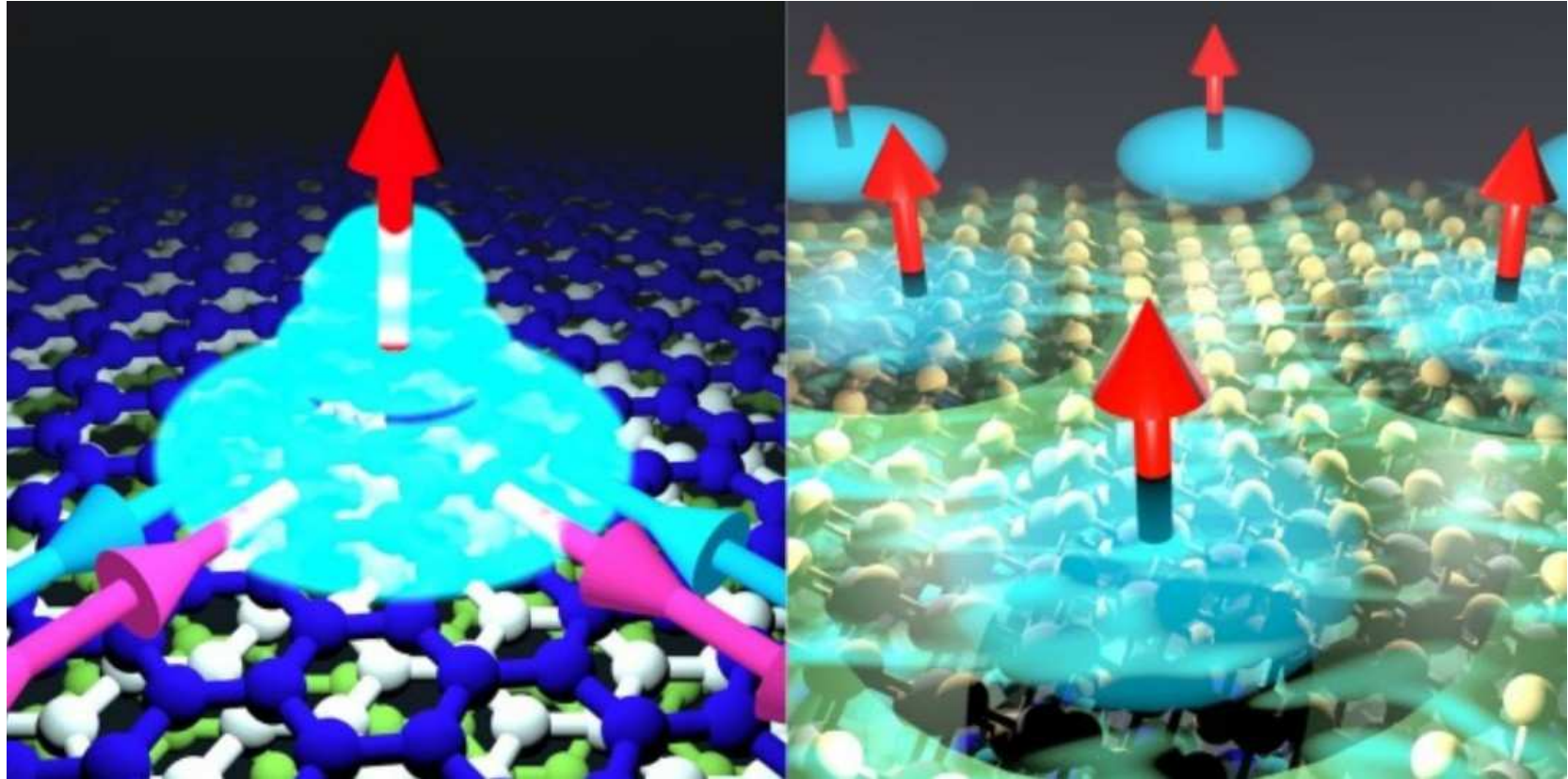
A moire meron magnetic structure appears due to the presence of interactions

Control by magnetic encapsulation



Magnetic moiré merons controlled by the magnetic encapsulation

A new family of correlated states based on quantum magnetism: heavy fermions in twisted materials



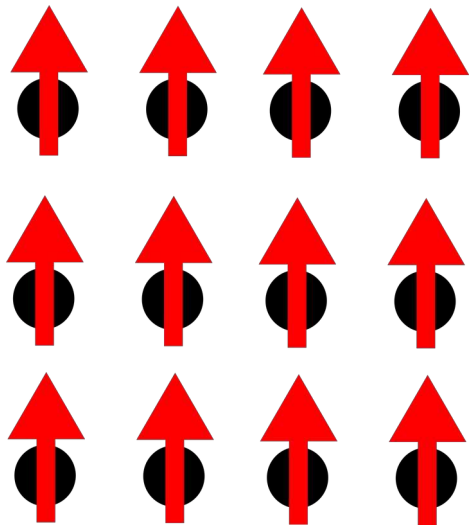
Basics of heavy fermion physics

- Strongly correlated matter, dominated by Kondo lattice physics
- Unique system to realize quantum criticality and unconventional superconductivity
- Found in rare-earth compounds, such as UTe_2 or UPt_3

**Can we realize heavy-fermion physics
with twisted two-dimensional materials?**

Basics of heavy fermion physics

Lattice of Kondo impurities



f-electrons in
rare-earth compounds

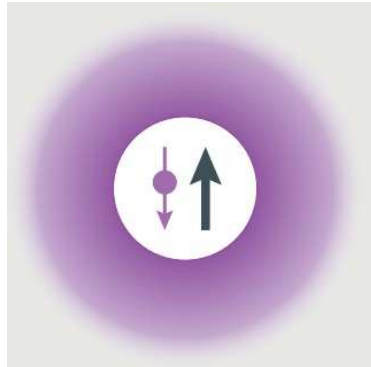
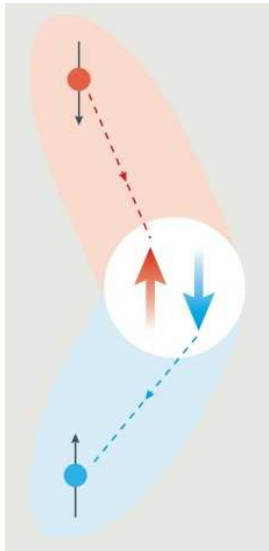
Dispersive electron gas



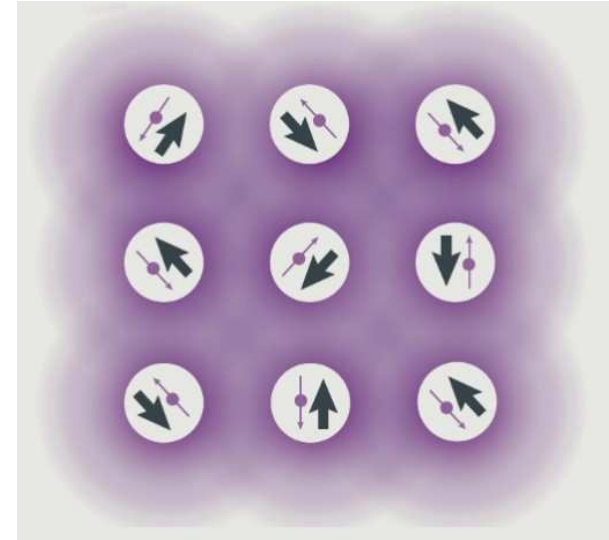
s/p/d-electrons in
rare-earth compounds

Basics of heavy fermion physics

Conduction electrons form
Kondo singlets with the impurities



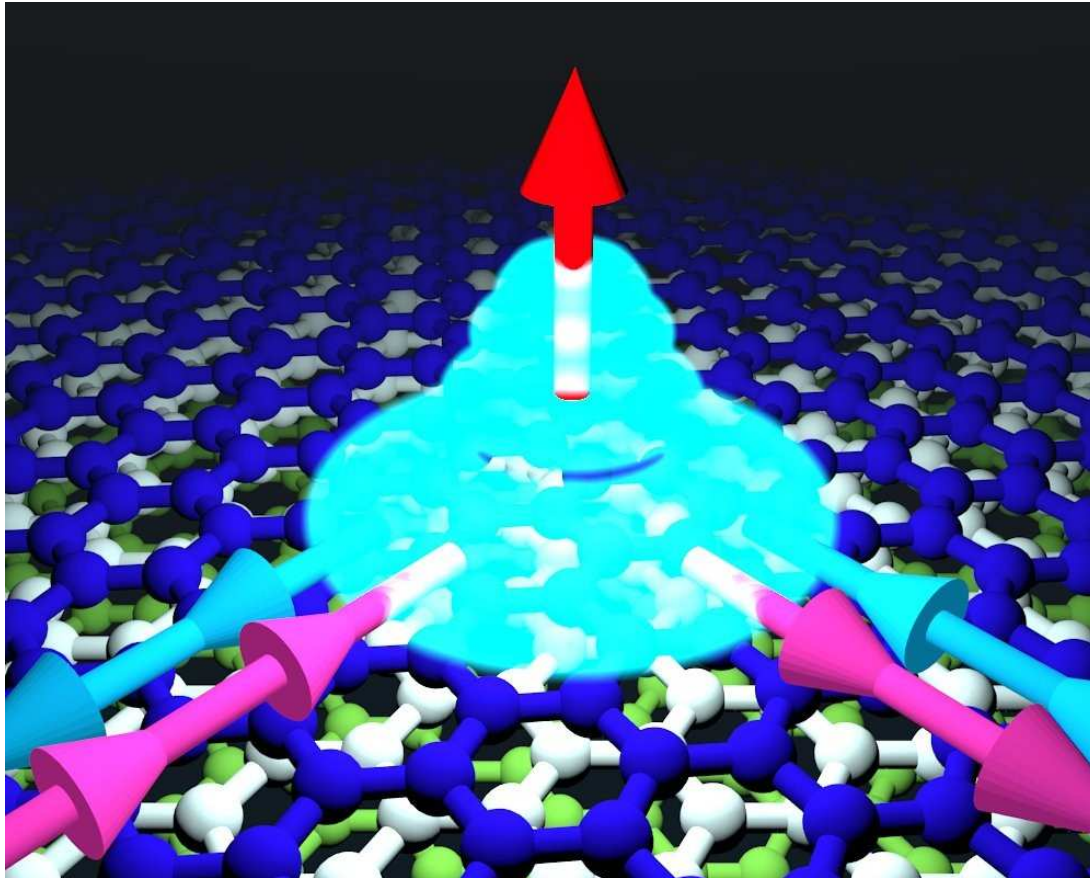
Kondo-lattice model



Associated with Kondo lattice physics:

- Colossal mass enhancement of electrons
- Quantum criticality
- Unconventional (topological) superconductivity

Heavy-fermions in twisted graphene trilayers



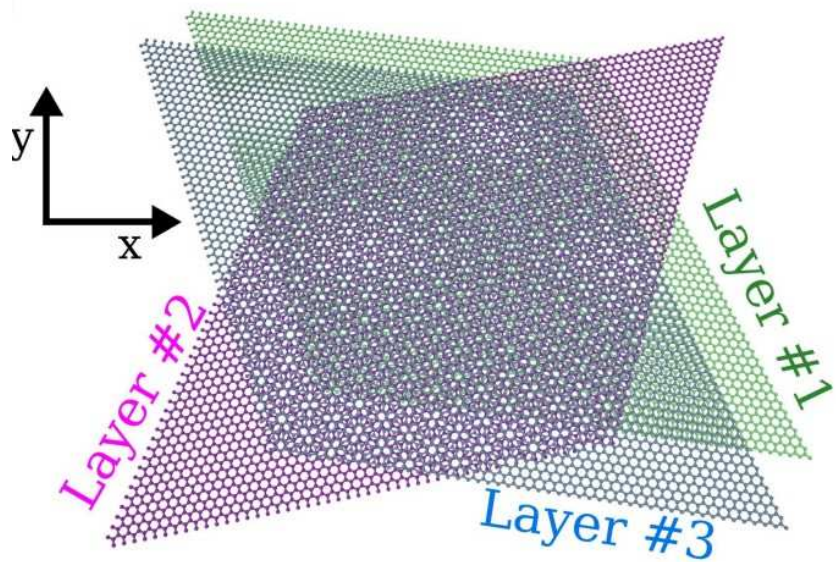
Aline Ramires



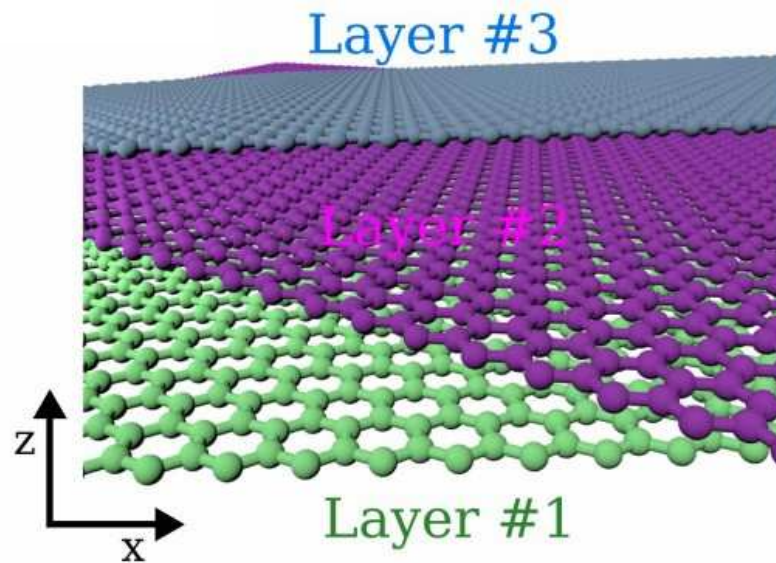
Phys. Rev. Lett. 127, 026401 (2021)

Heavy-fermions in twisted graphene trilayers

Top view

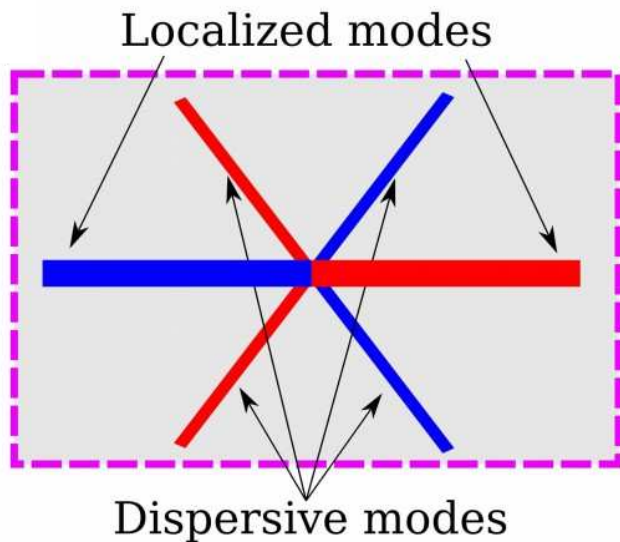


Lateral view

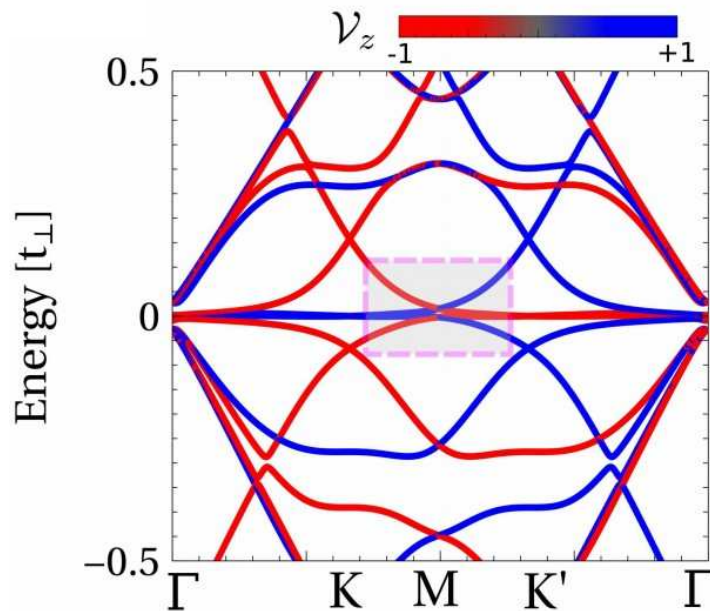


Heavy-fermions in twisted graphene trilayers

Low energy model

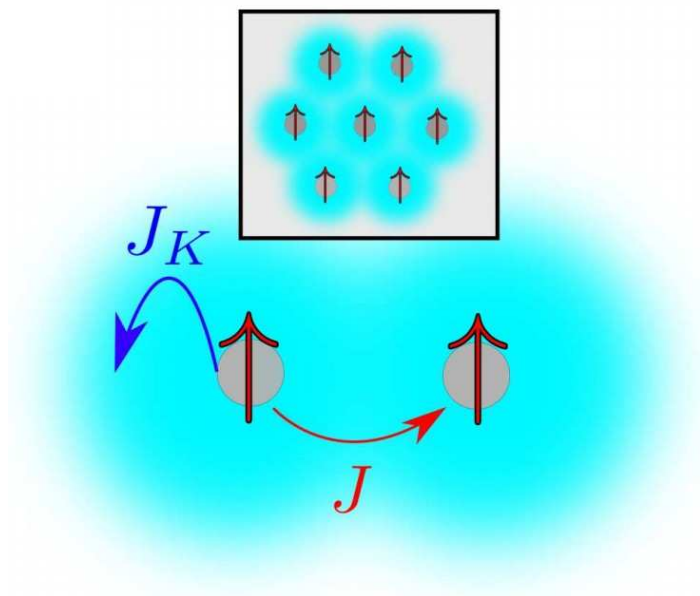


Electronic structure in the presence of an electric bias

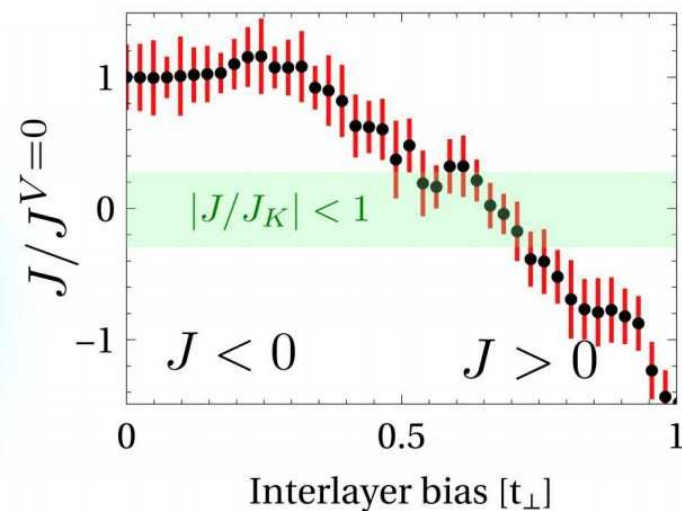


Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Electric control of the Kondo regime

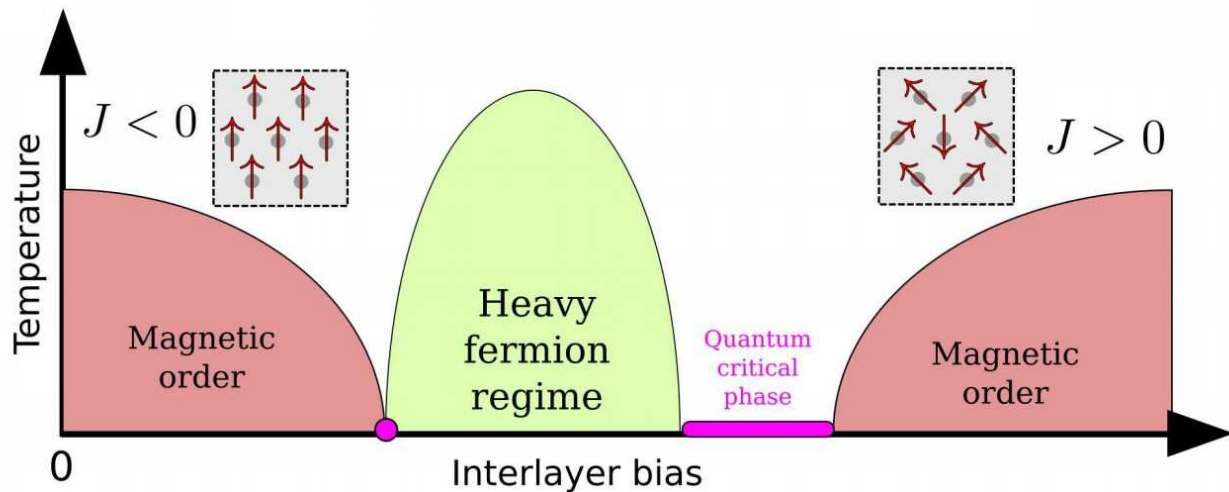


A heavy fermion regime appears when the Kondo coupling dominates over the exchange coupling

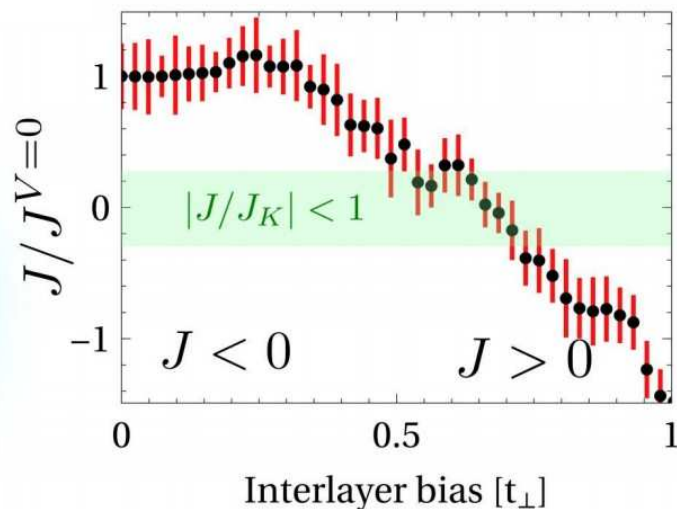
$$|J/J_K| < 1$$

Heavy-fermions in twisted graphene trilayers

Heavy-fermion (Doniach) phase diagram

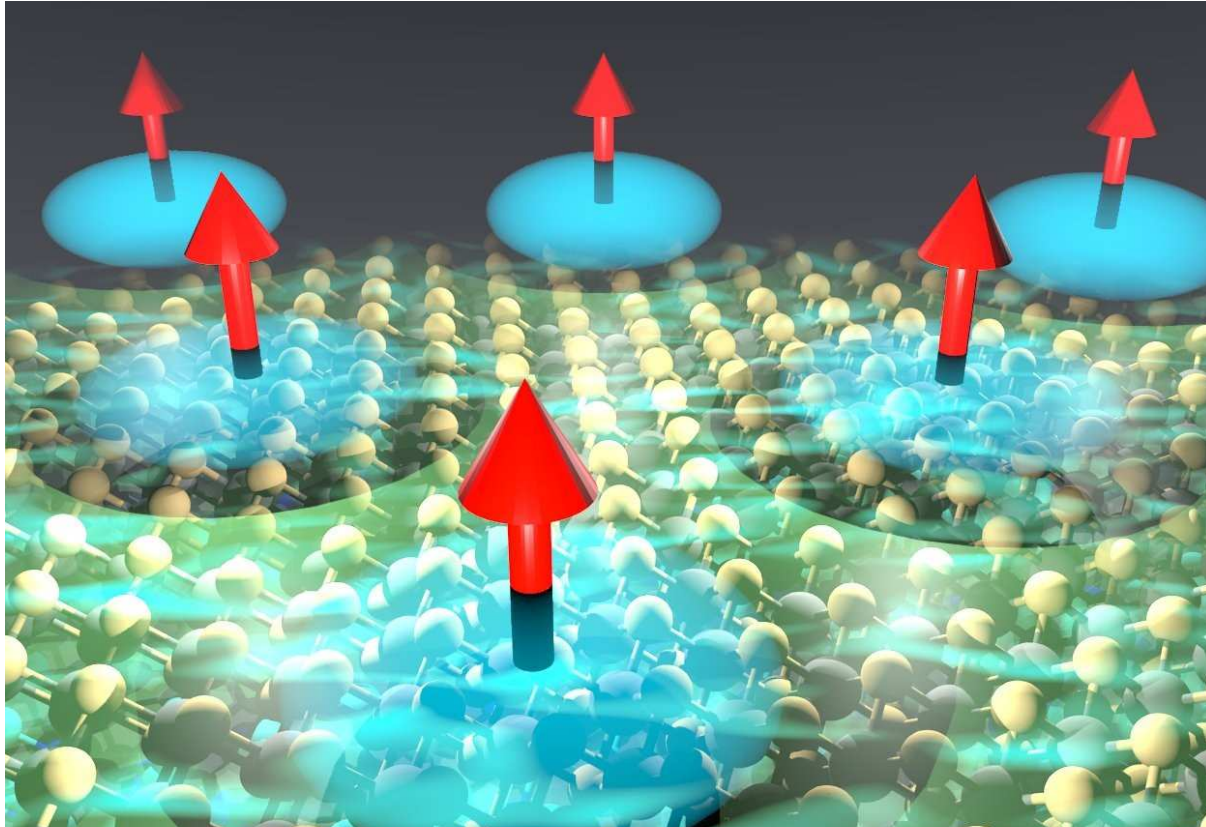


Electric control of the Kondo regime



The full phase diagram of the heavy fermion system can be explored in a single twisted graphene, by tuning the system with an electric bias

Heavy-fermions in a van der Waals dichalcogenide heterostructure



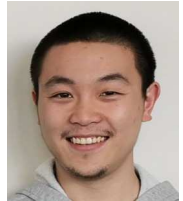
S. Ganguli



M. Amini



G. Chen



V. Vaňo



S. Kezilebieke



P. Liljeroth



arXiv:2103.11989 (2021)

Heavy-fermions in dichalcogenide bilayers

Triangular lattice of
local magnetic moments



1T-TaS₂

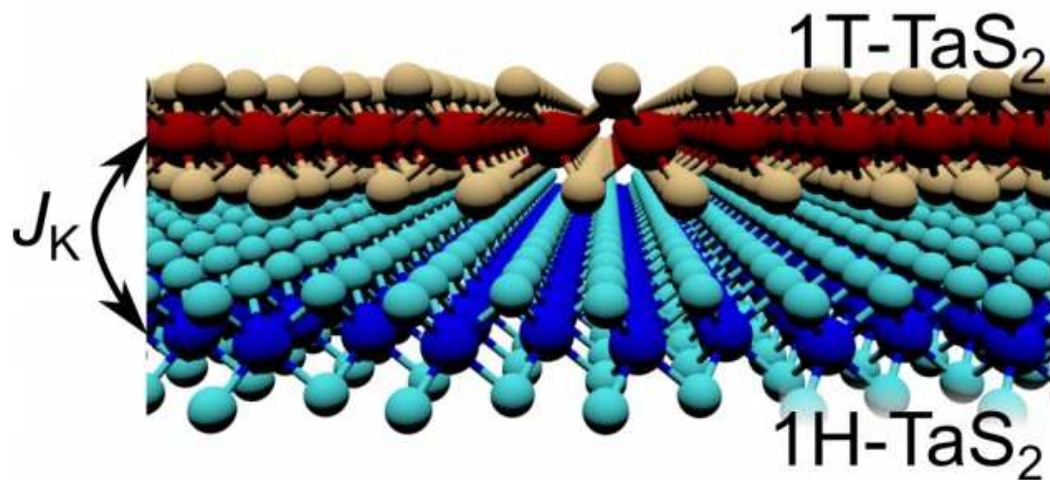
Two-dimensional electron gas



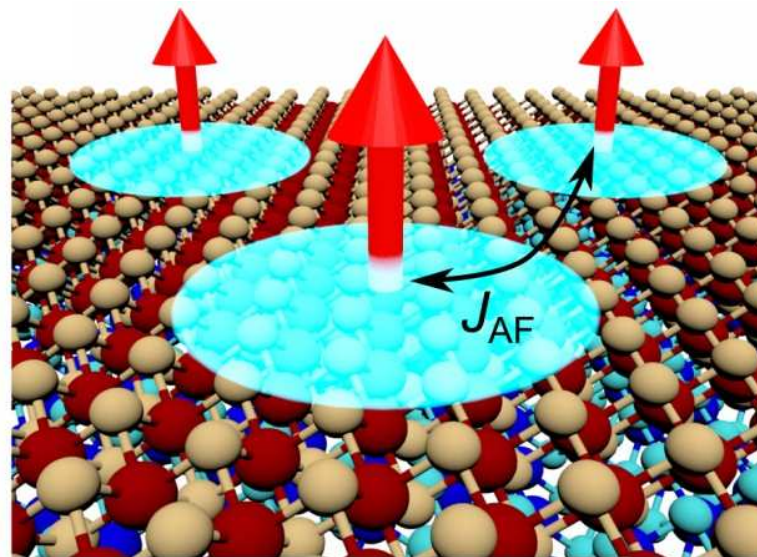
1H-TaS₂

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling create
the Kondo coupling



Intralayer exchange between
local moments

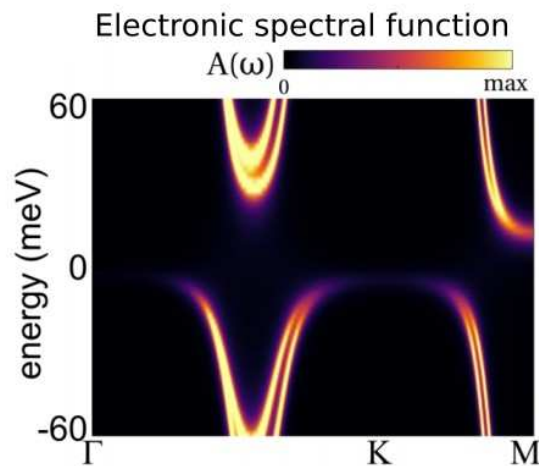
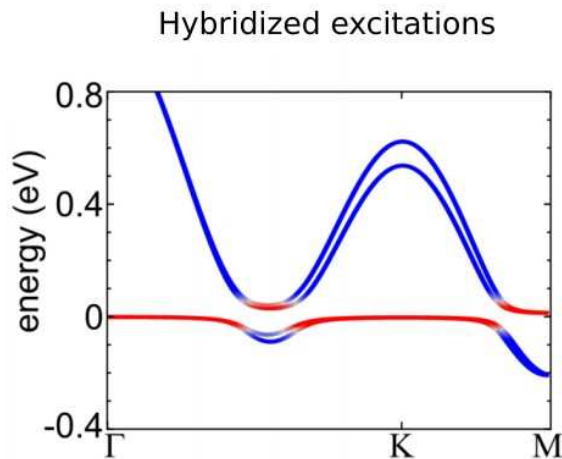
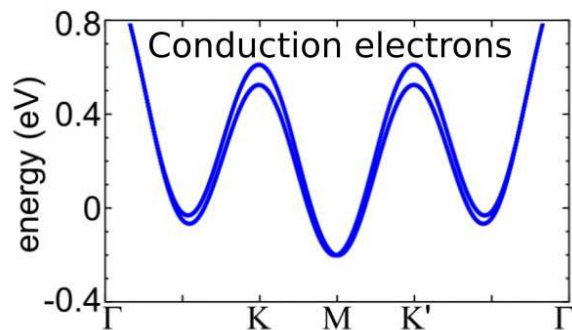
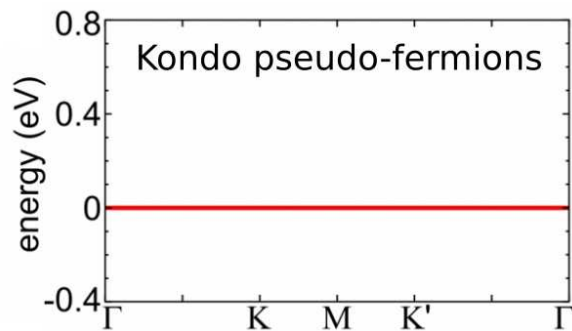


The bilayer realizes all the ingredients for heavy-fermion physics

Brief theory of heavy-fermions

Kondo physics introduces resonant pseudo-fermions at the chemical potential

Leading to the opening of a heavy-fermion gap

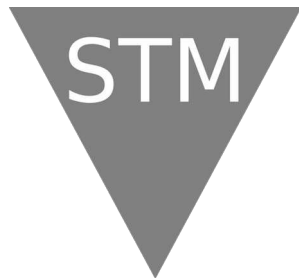


Experimental signatures of heavy-fermion physics

- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

Both signatures can be probed with scanning tunnel microscopy by growing two heterostructures

Probing the Kondo peak

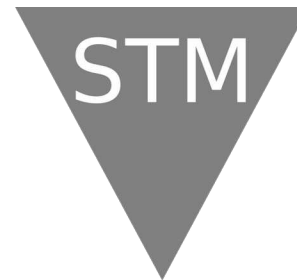


Spin lattice (1T-TaS2)

2D electorn gas (1H-TaS2)

Substrate

Probing the heavy-fermion gap

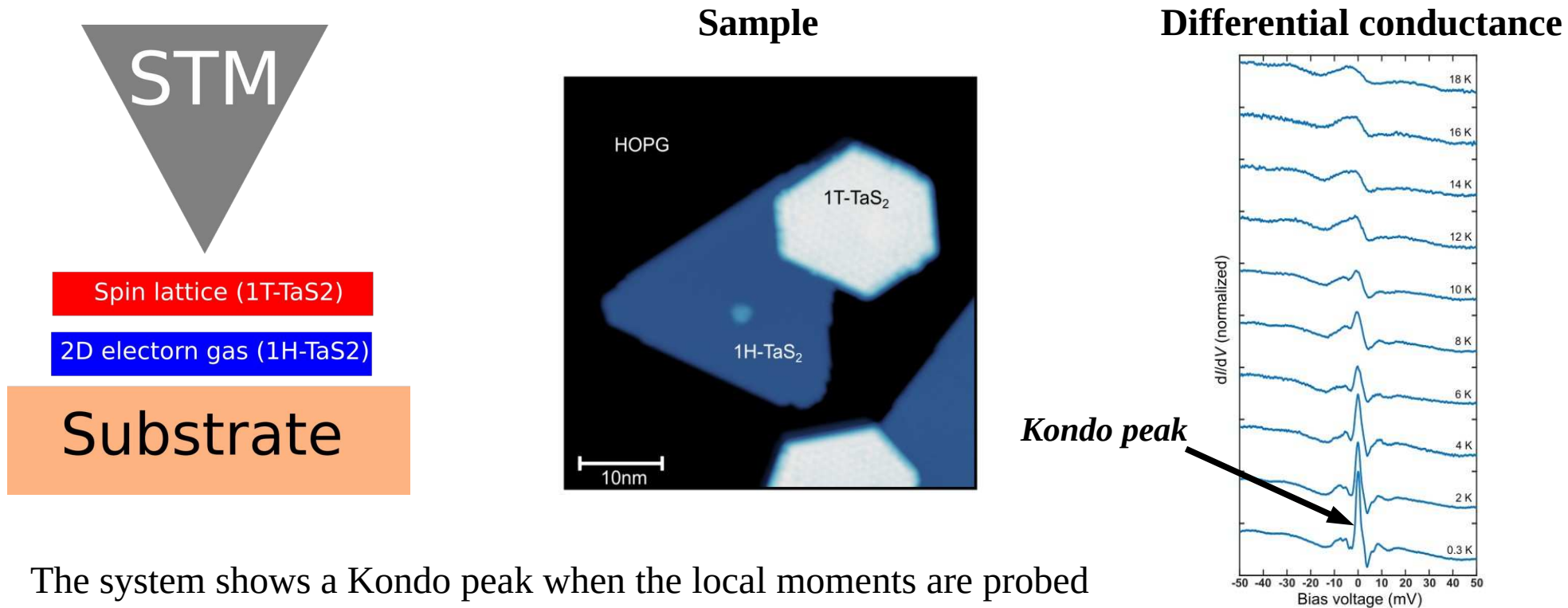


2D electorn gas (1H-TaS2)

Spin lattice (1T-TaS2)

Substrate

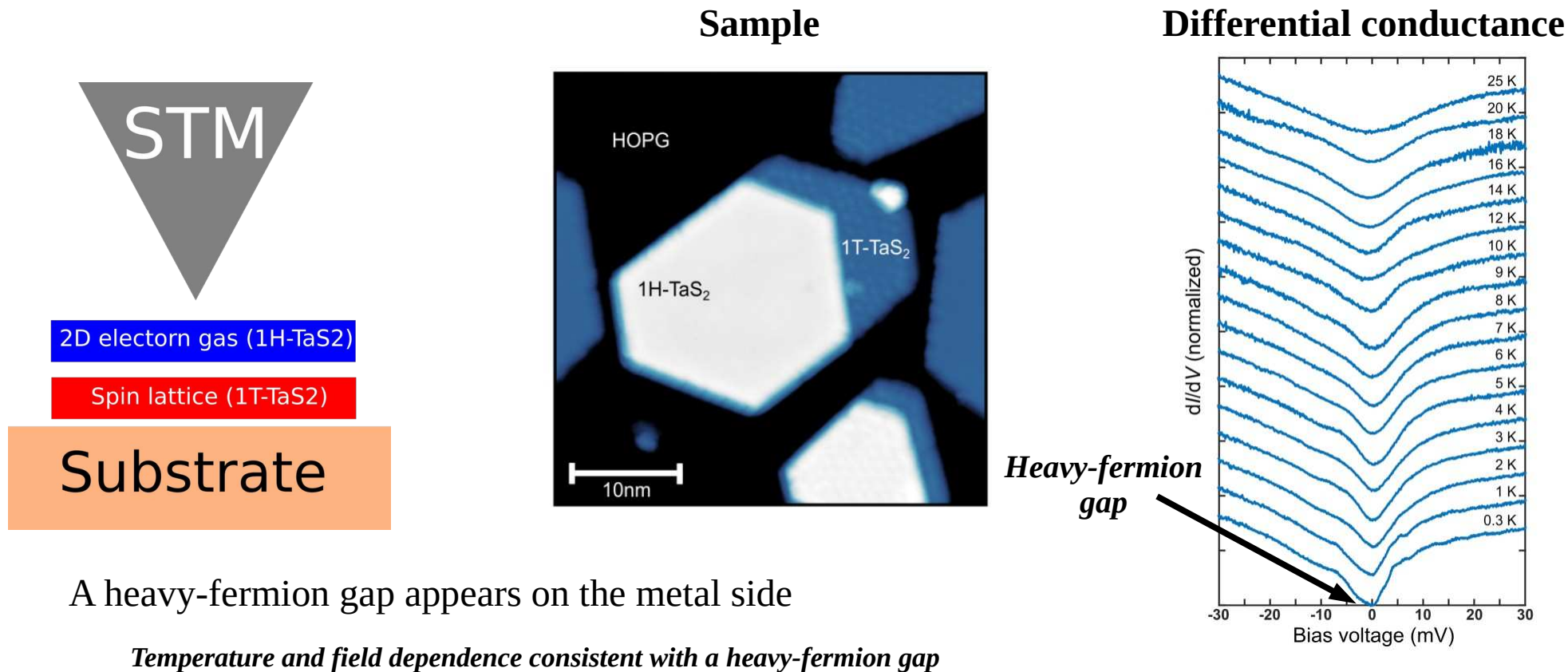
Kondo physics in the magnetic lattice



The system shows a Kondo peak when the local moments are probed

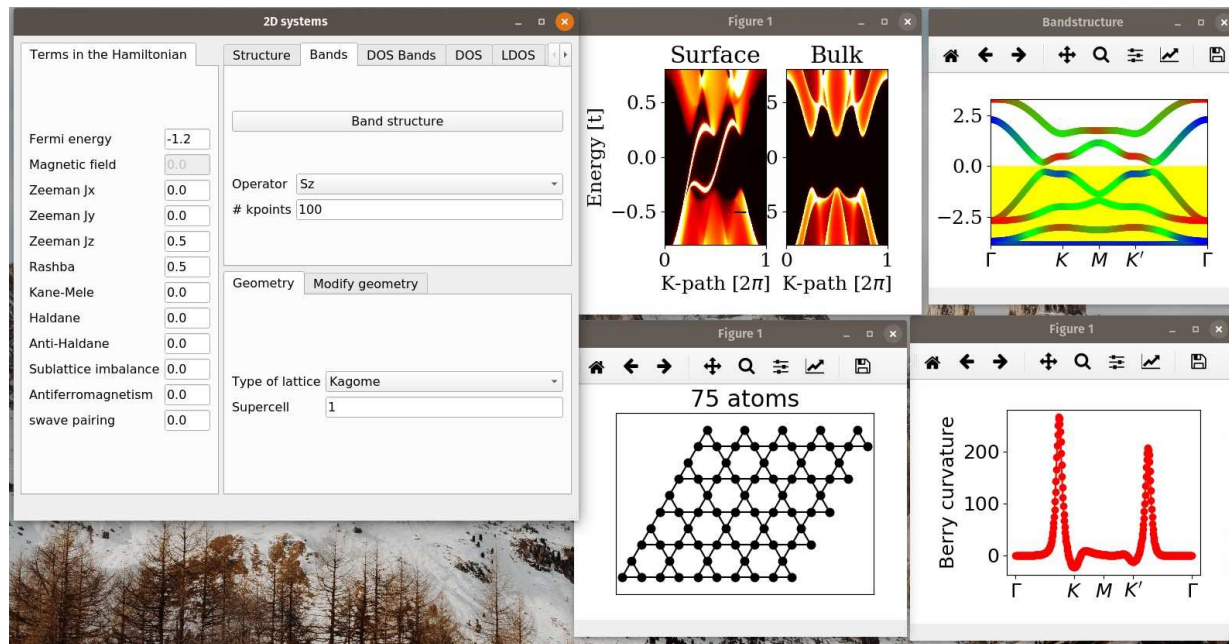
Temperature and field dependence consistent with Kondo

Heavy-fermion gap in the 2D electron gas



Computing electronic
properties

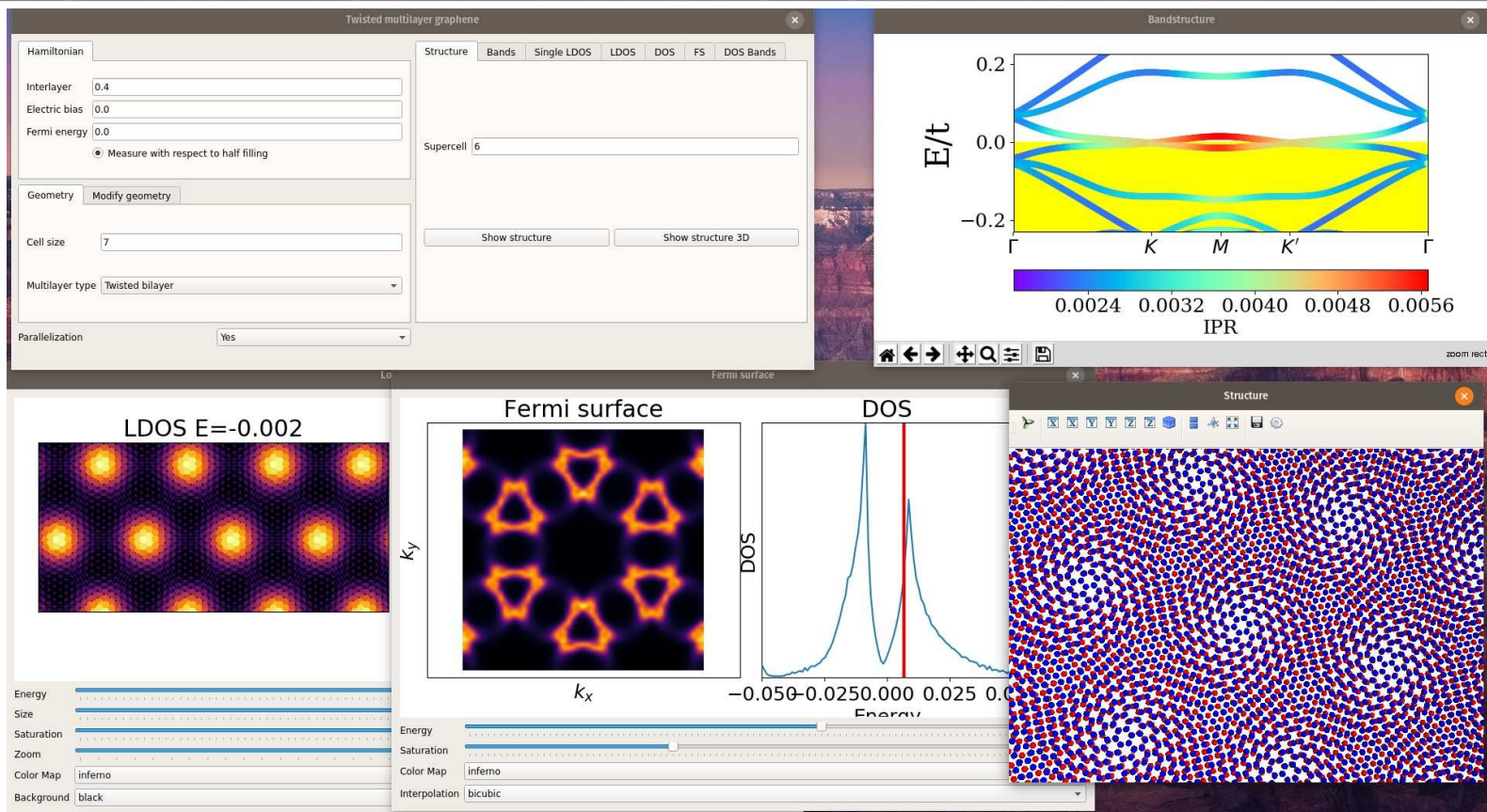
A user interface to compute electronic properties



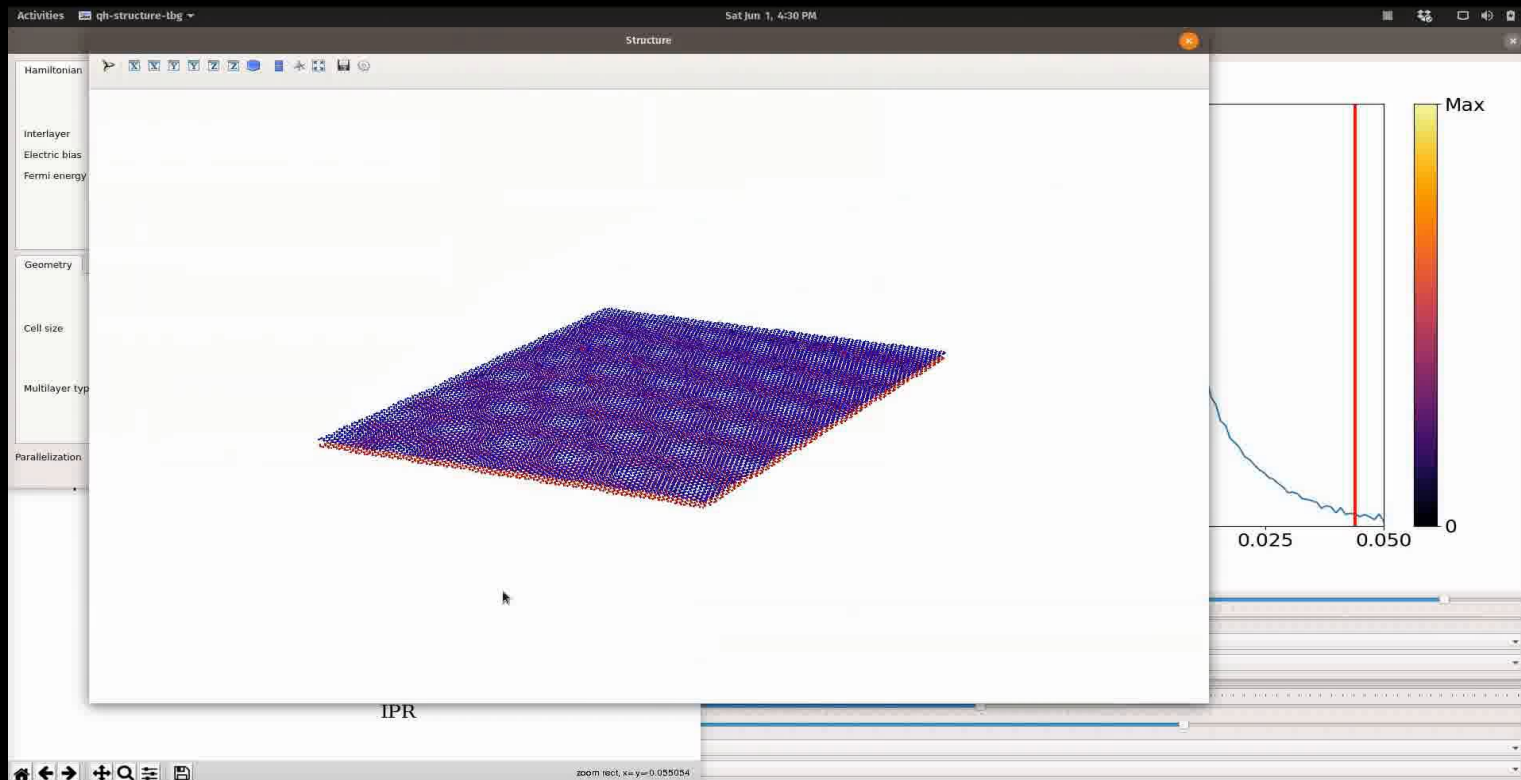
Quantum Honeycomp: open source interactive interface for tight binding modeling

<https://github.com/joselado/quantum-honeycomp>

Twisted bilayer with the user interface

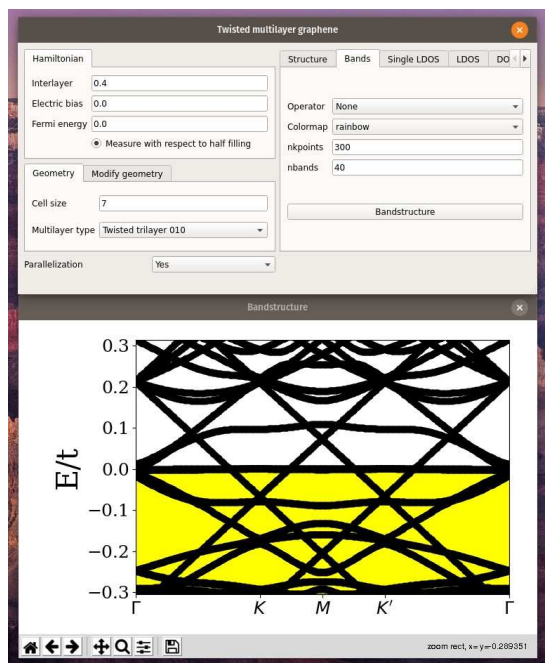


<https://github.com/joselado/quantum-honeycomp>

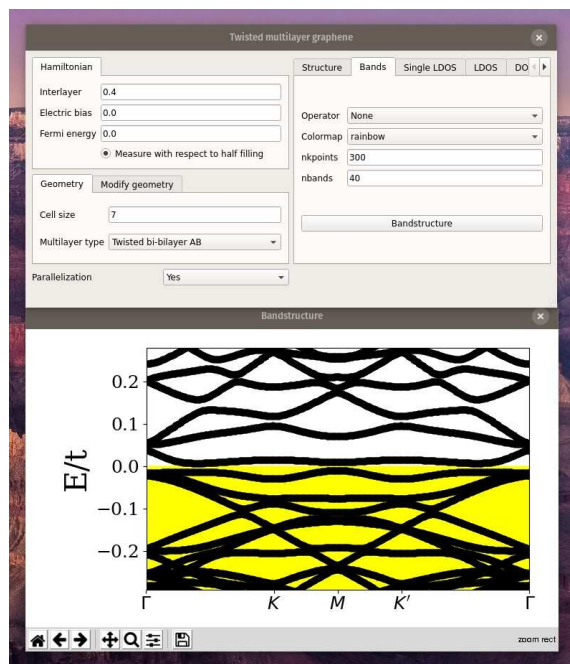


Twisted multilayers

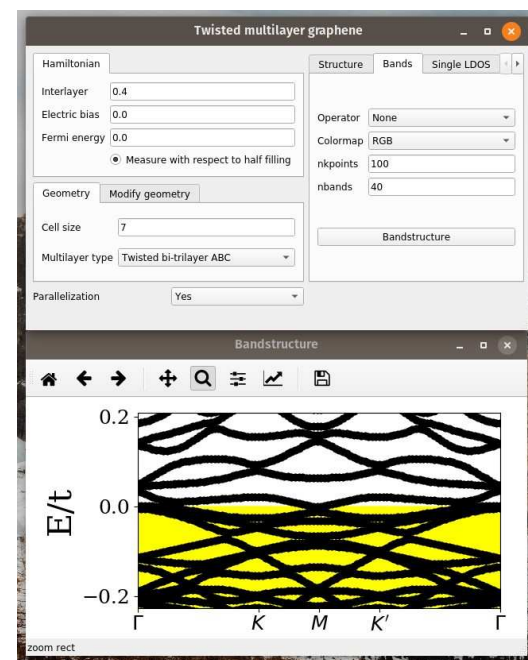
Twisted trilayer graphene



Twisted bi-bilayer graphene

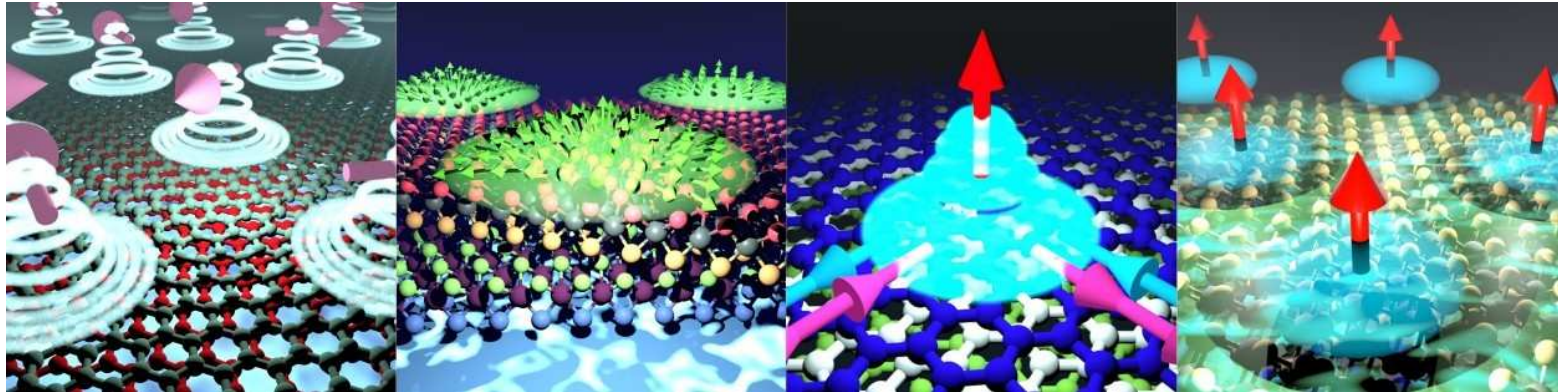


Twisted bi-trilayer graphene



Take home

Magnetic twisted van der Waals materials provide a platform to engineer a new family of correlated states, including exotic heavy-fermion physics



Thank you!

Phys. Rev. Lett. 126, 056803 (2021)
arXiv:2105.04502 (2021)
Phys. Rev. Lett. 127, 026401 (2021)
arXiv:2103.11989 (2021)

Funding from

