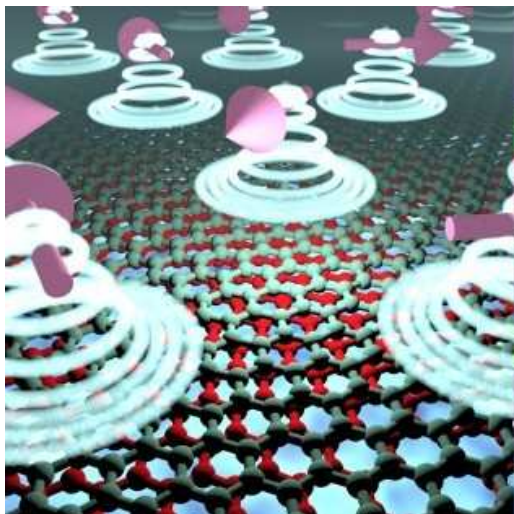


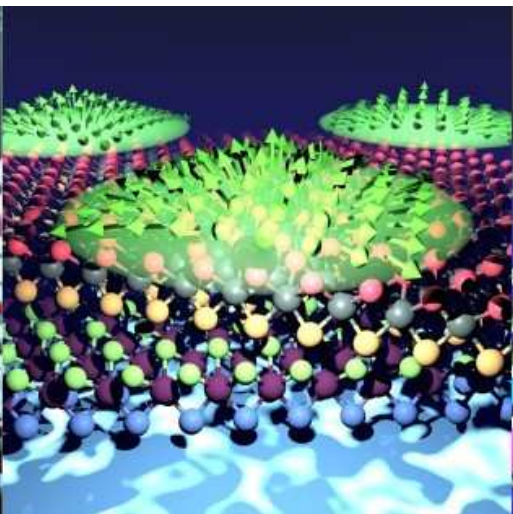
Designing correlated quantum matter with magnetic twisted van der Waals heterostructures

Jose Lado

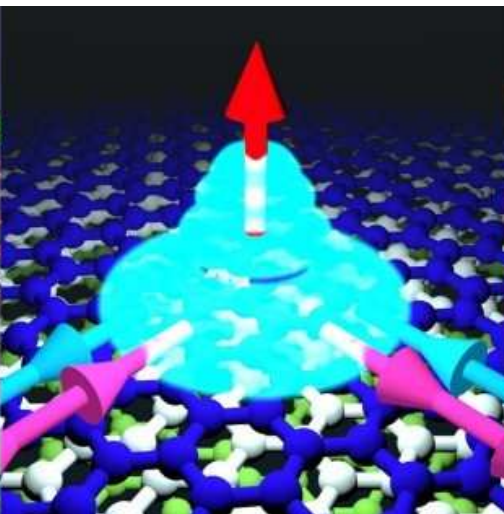
Department of Applied Physics, Aalto University, Finland



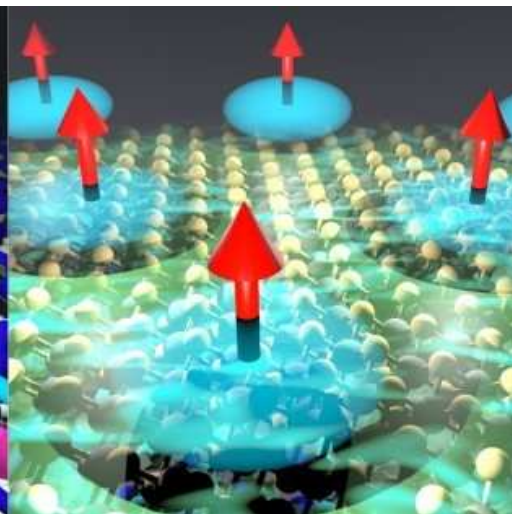
Phys. Rev. Lett. 126, 056803 (2021)



arXiv:2105.04502 (2021)



arXiv:2102.03312 (2021)



arXiv:2103.11989 (2021)

CNR Nano, Italy, June 24th 2021

About me



Ph.D. 2013-2016, INL Braga (Portugal)
Prof. Joaquin Fernandez-Rossier



ETH Fellow 2017-2019, ETH Zurich (Switzerland)
Prof. Manfred Sigrist *Prof. Oded Zilberberg*



Assistant Professor, Aalto University (Sep. 2019)

Exotic physics in quantum materials

Quantum spin liquids



Unconventional superconductivity



Topological matter



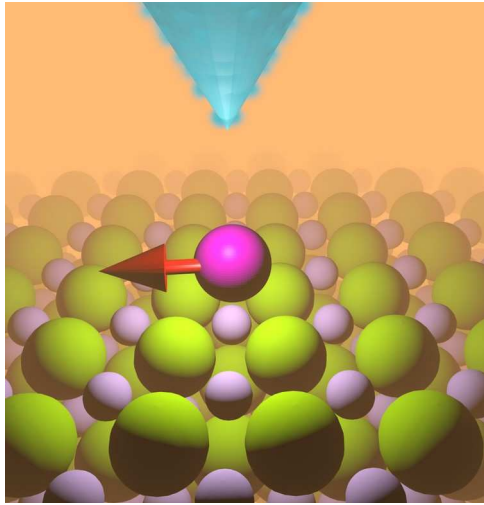
Topological quantum computing

Low consumption electronics

New physics not yet realized in nature (fractional quantum particles)

Building quantum matter with artificial lattices

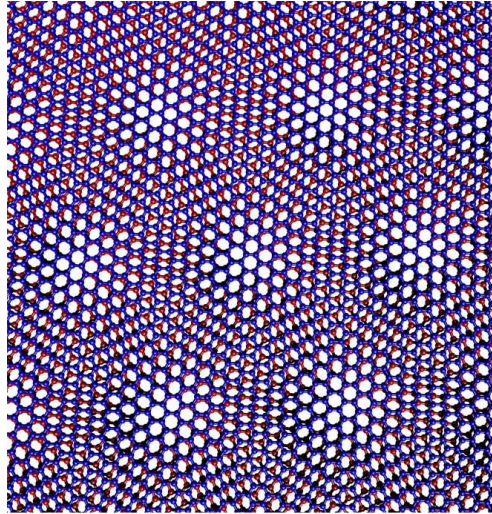
Atomic lattices



$a = 0.5 \text{ nm}$

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

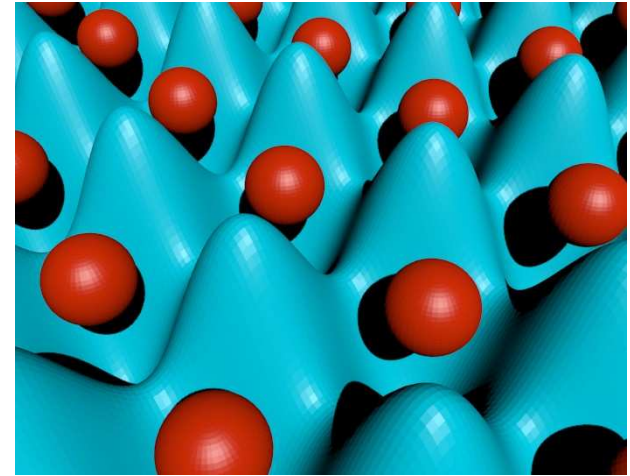
Twisted 2D moire materials



$a = 30 \text{ nm}$

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

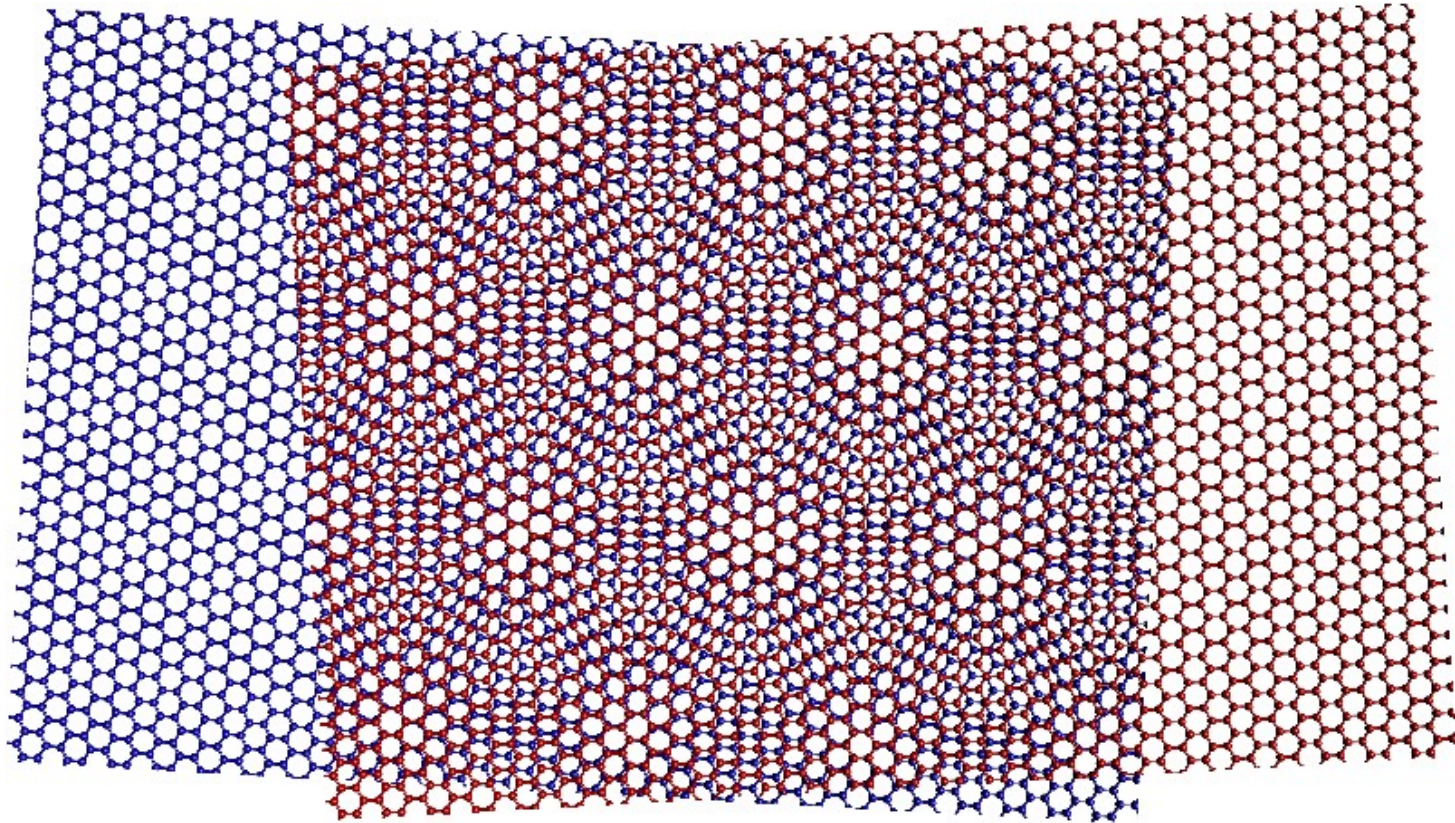
Cold atoms



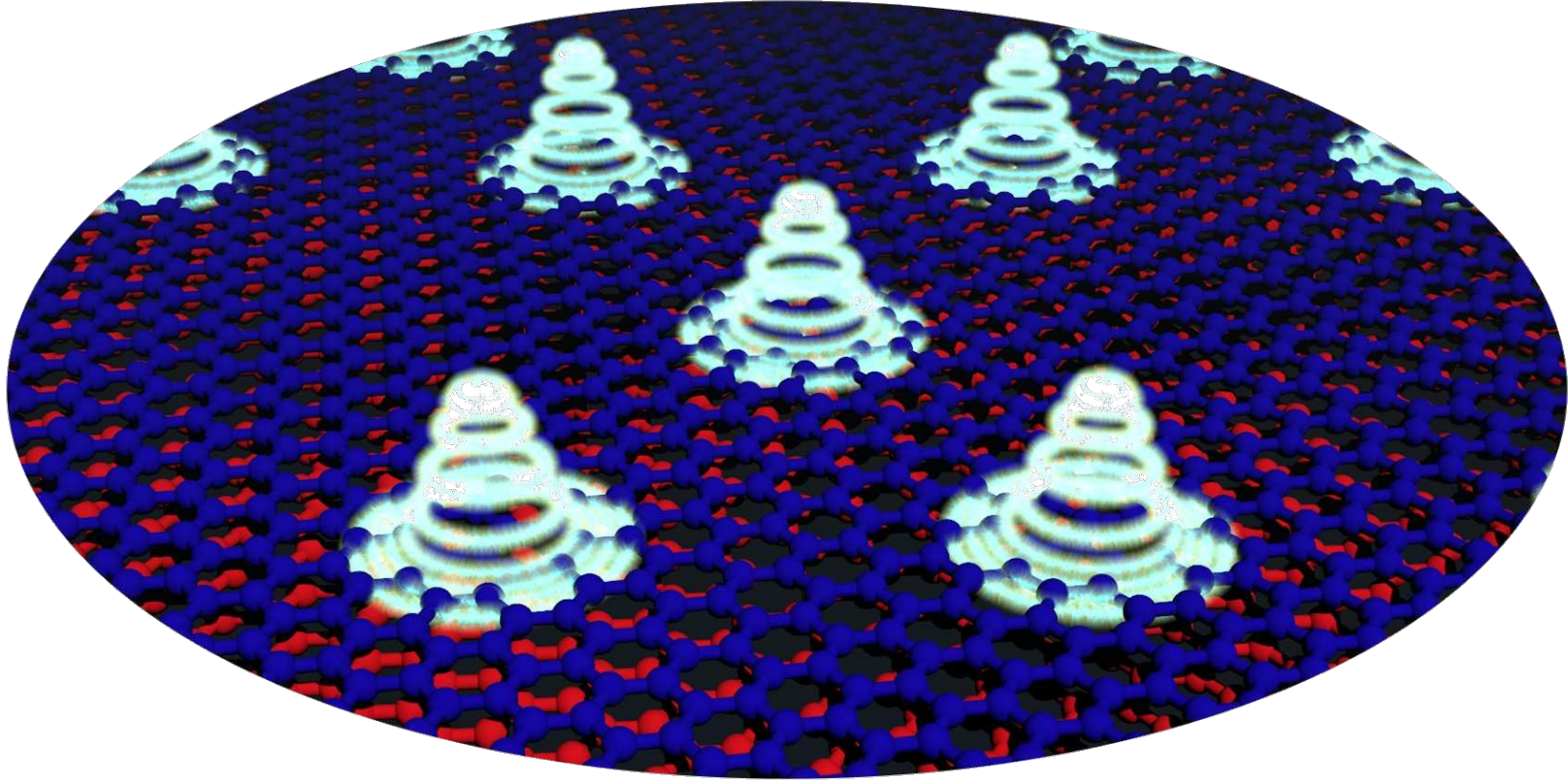
$a = 1000 \text{ nm}$

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

Twisted 2D materials as a platform for artificial quantum matter



A new universe in each new twisted material

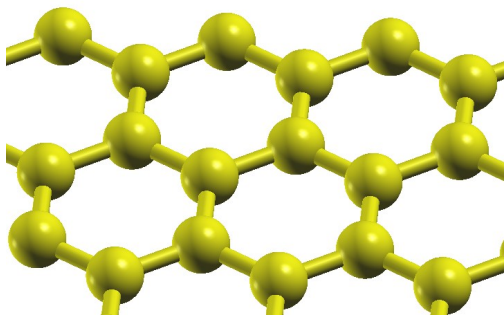


Each twisted material is a new universe for electrons, with laws that change from twist to twist

The two-dimensional materials world

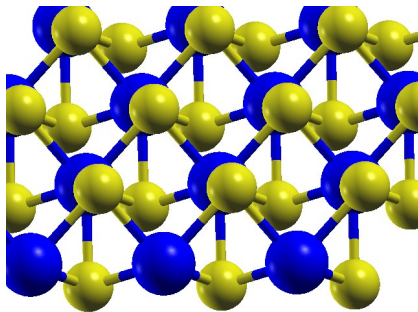
Semimetal

Graphene



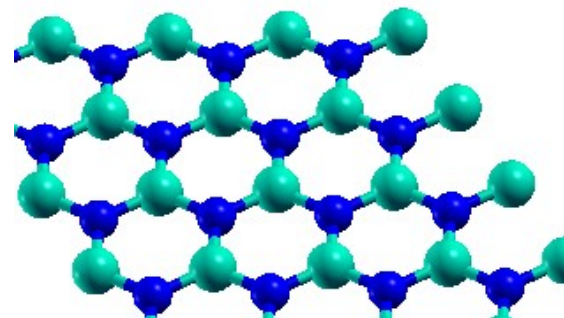
Superconductor

NbSe_2



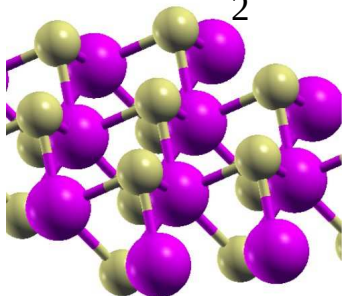
Insulator

BN



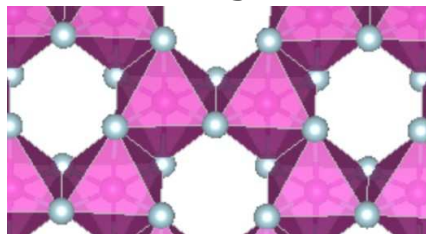
Semiconductor

WSe_2



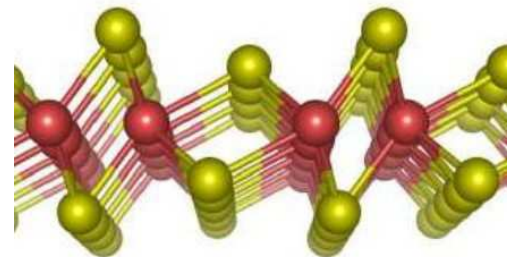
Ferromagnet

CrI_3



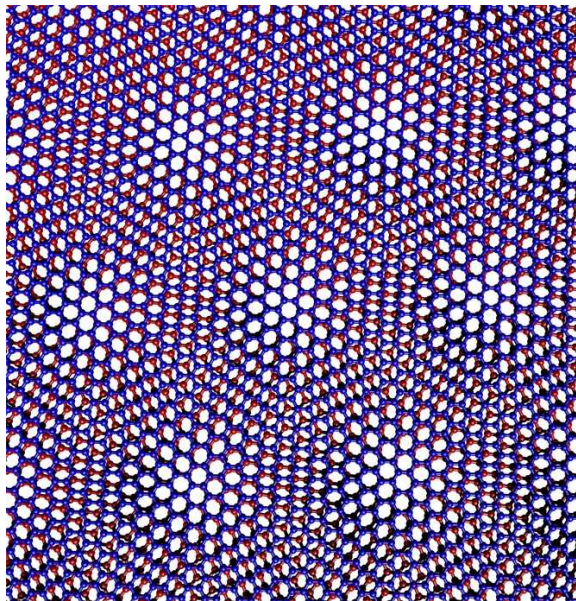
Quantum spin Hall insulator

WTe_2

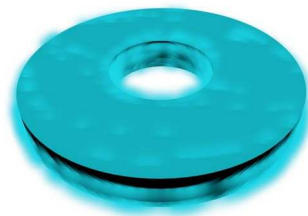


One material, a zoo of electronic phases

Twisted bilayer graphene

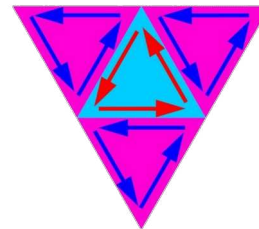


Superconductivity



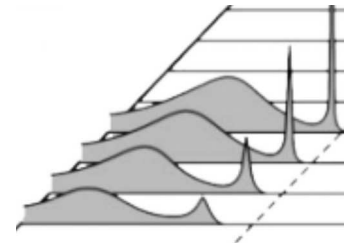
Nature 556, 43–50 (2018)

Topological networks



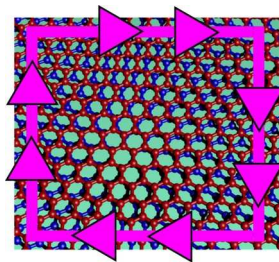
Nano Lett. 18, 11,
6725-6730 (2018)

Strange metals



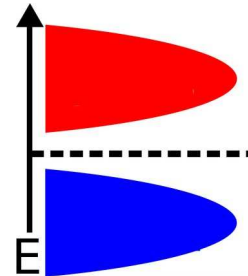
Phys. Rev. Lett. 124, 076801 (2020)

Chern insulators



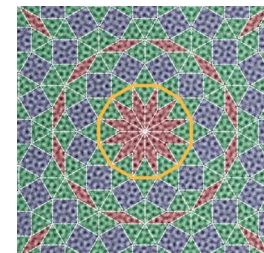
Science 365, 605-608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

Quasicrystalline physics



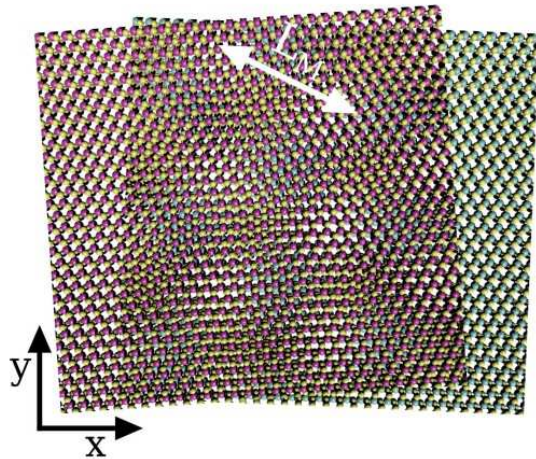
Science 361 782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

The generality of correlated physics in twisted 2D materials

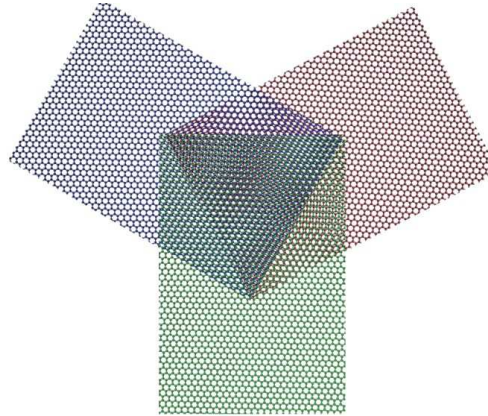
Superconductivity & correlated behavior found also in

Twisted dichalcogenides



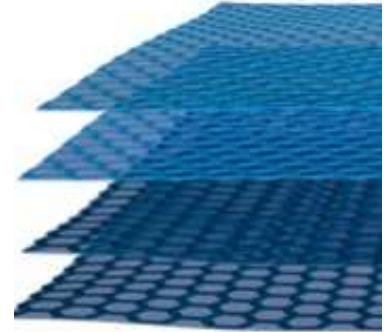
Nature 579, 359–363 (2020)

Twisted graphene trilayers



Nature 590, 249–255 (2021)

Twisted graphene tetralayers

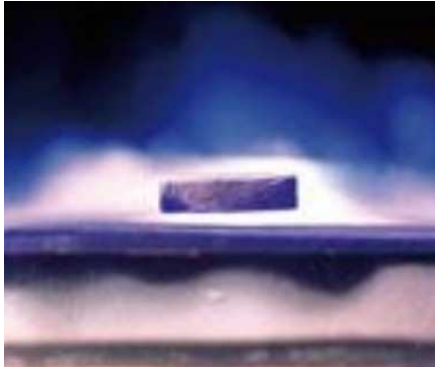


Nature 583, 221–225 (2020)

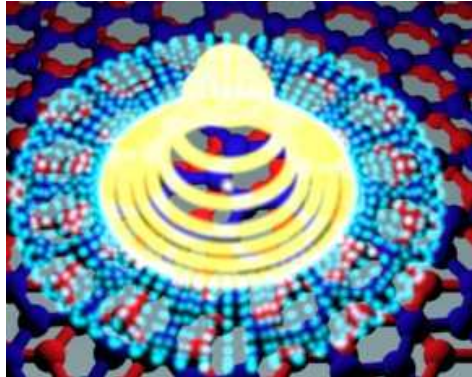
Some of new physics observed were only realized before in rare, heavy or even toxic compounds

The opportunities of twisted van der Waals materials

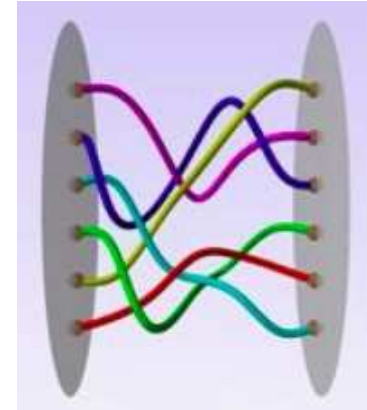
“Unveil” the nature of high T_c superconductivity (?)



Controllable exotic quantum matter (?)



A platform for topological quantum computing (?)



Explore exotic physics with a degree of control unprecedented in any other material

- *Control of single particle and many-body interactions*
- *Explore physics that only appear in rare or toxic compounds*

Designing quantum matter in twisted materials

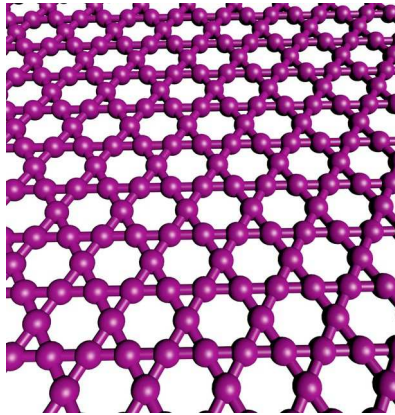
*The strength of
electronic correlations*

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



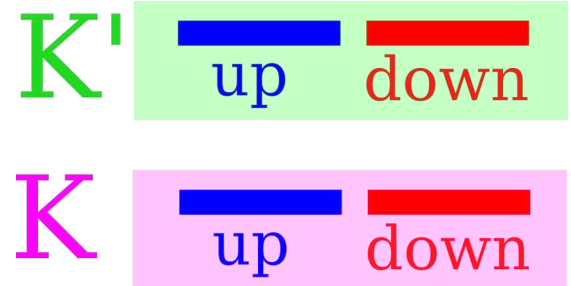
Twist angle control

*The details of the
electronic dispersion*



Interlayer bias

*The local quantum
degrees of freedom*

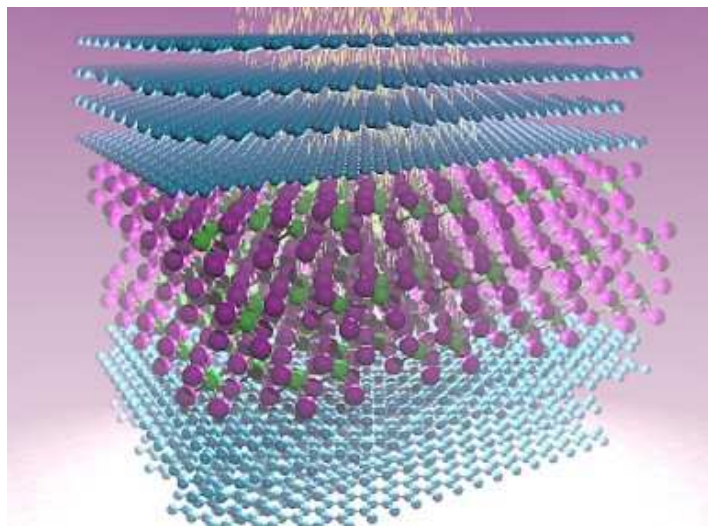


Magnetic encapsulation

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

Van der Waals spinorbitronics

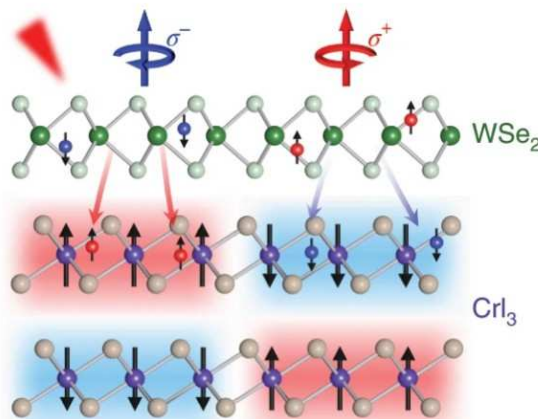
*Graphene/CrI₃
heterostructures*



Giant magnetoresistance

Science 360 (6394), 1218-1222 (2018)

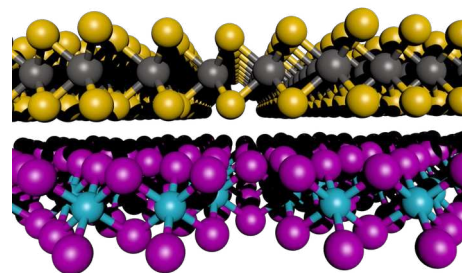
*MoSe₂/CrI₃
heterostructures*



*Exchange proximity
from magneto-optics*

*Nature Nanotechnology 15,
187–191 (2020)*

*NbSe₂/CrBr₃
heterostructures*



Topological superconductivity

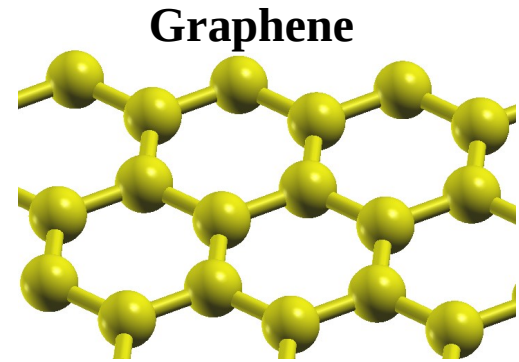
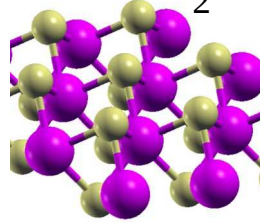
Nature 588 (7838), 424-428 (2020)

Designing quantum matter with twisted magnetic van der Waals materials



Semiconductor

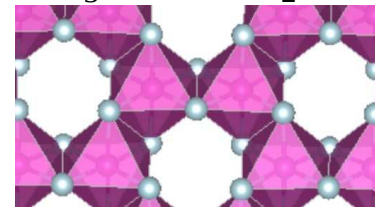
WSe_2



Graphene

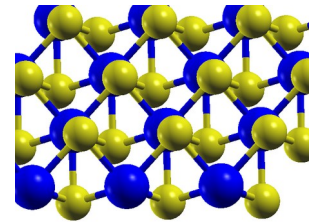
Magnet

CrBr_3 , 1T-TaS₂, CrI_3



Metal

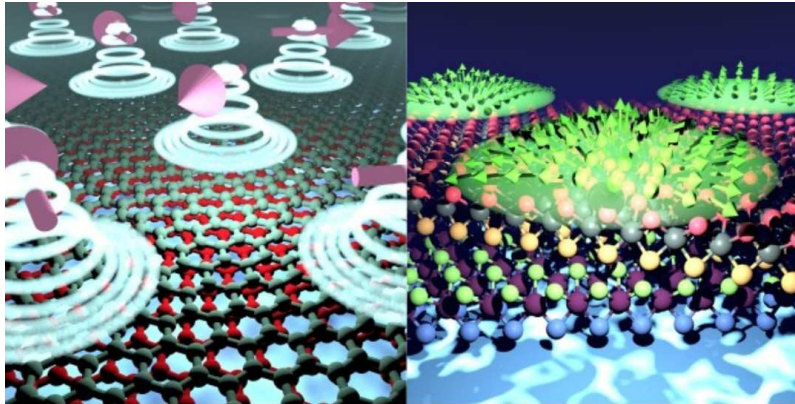
1H-TaS₂



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

Today's plan

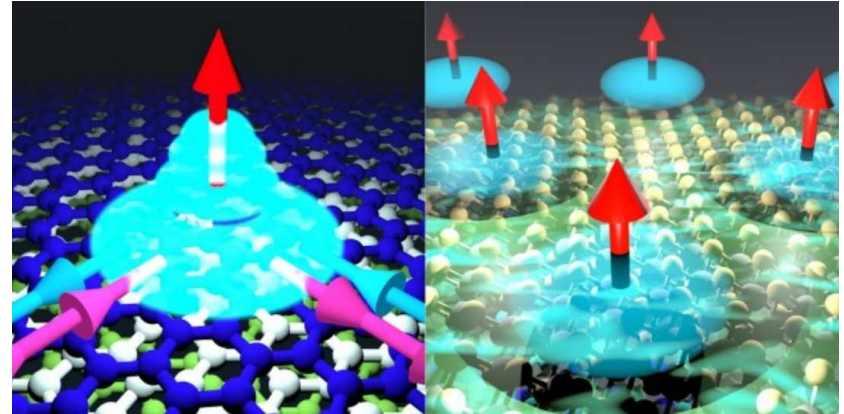
**Design of new correlated states
by magnetic encapsulation in
twisted materials**



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**

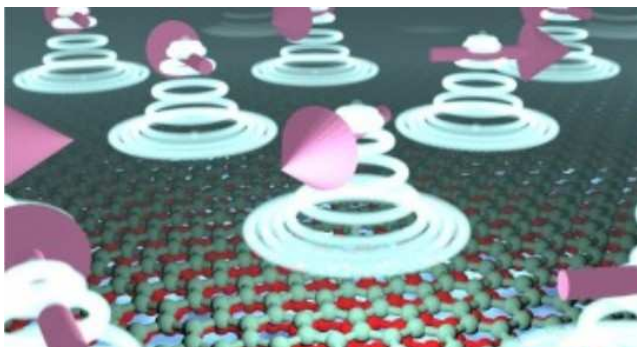


theory & experiment

arXiv:2102.03312 (2021)
arXiv:2103.11989 (2021)

Behind the scenes

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



Tobias
Wolf



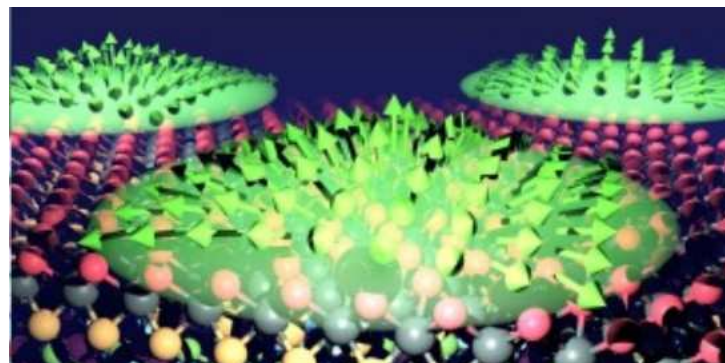
Gianni
Blatter



Oded
Zilberberg

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

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

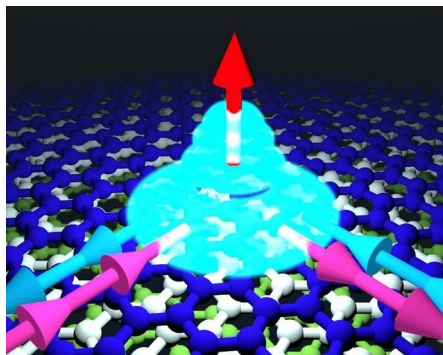


David
Soriano

arXiv:2105.04502 (2021)

Behind the scenes

Heavy fermions in twisted graphene trilayers

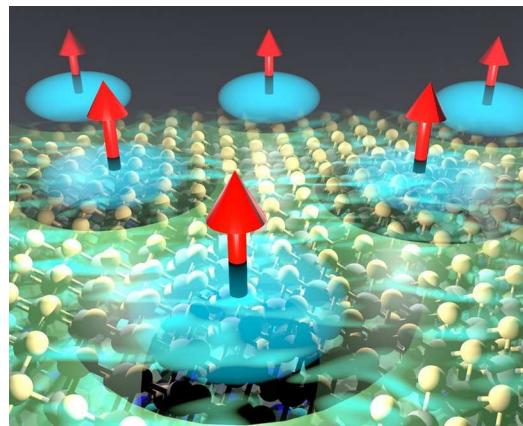


arXiv:2102.03312 (2021)
(accepted in Physical Review Letters)

A. Ramires



Heavy fermions in twisted dichalcogenide bilayers



arXiv:2103.11989 (2021)

V. Vaňo



S. Kezilebieke



P. Liljeroth



S. Ganguli



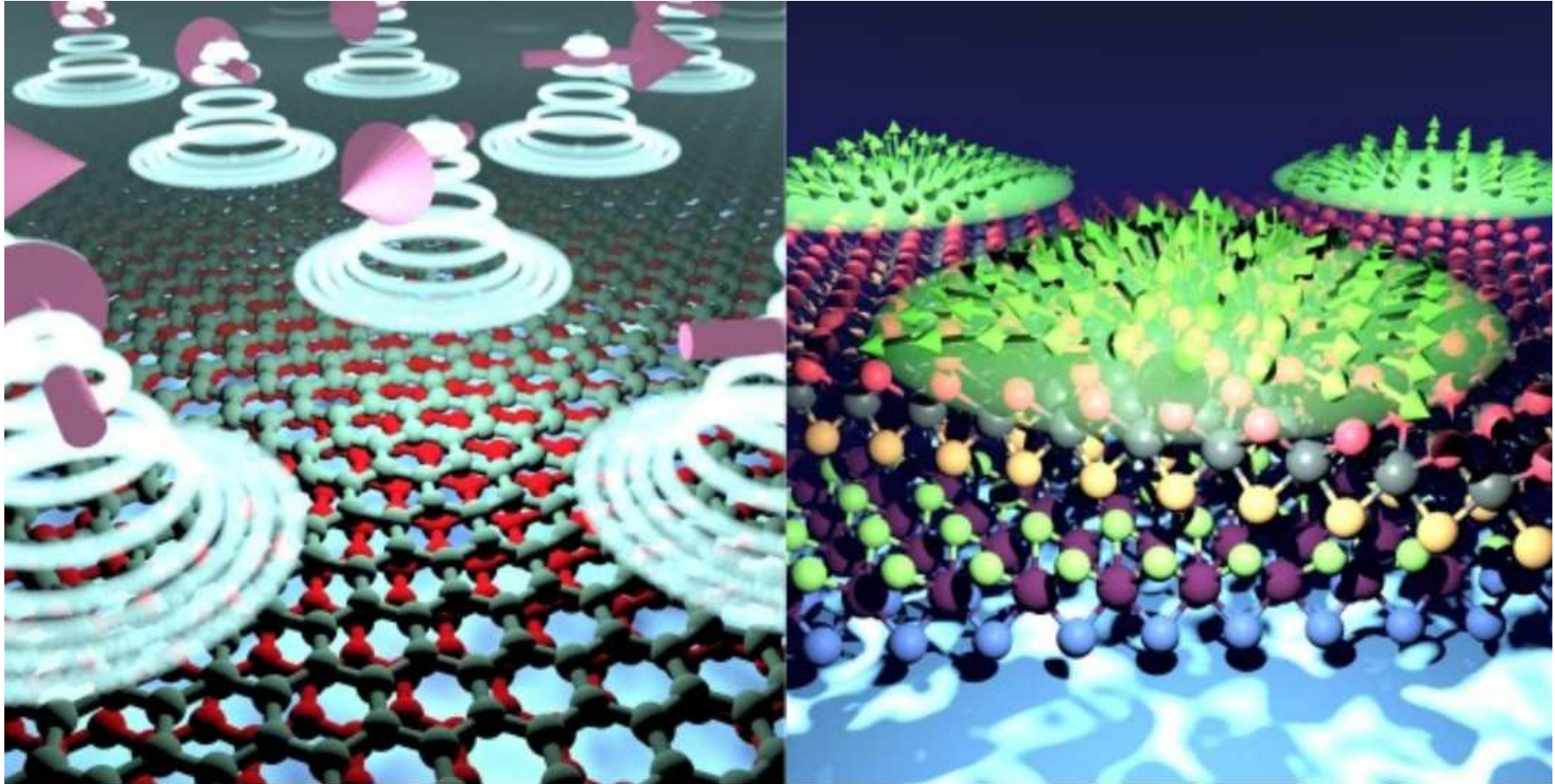
M. Amini



G. Chen



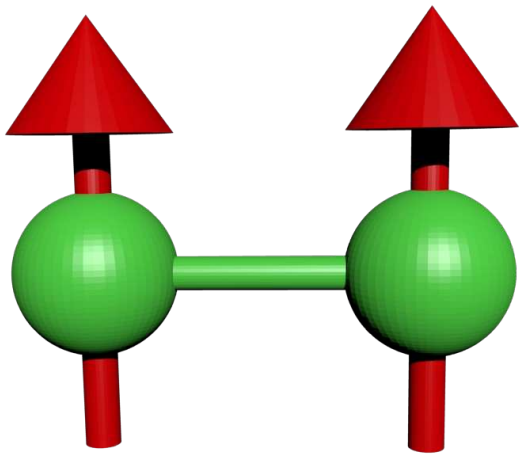
Design of new correlated states by magnetic encapsulation in twisted materials



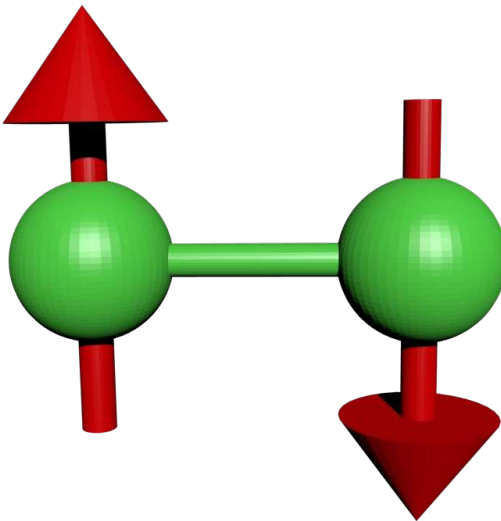
Frustration

A bird's eye view on magnetism

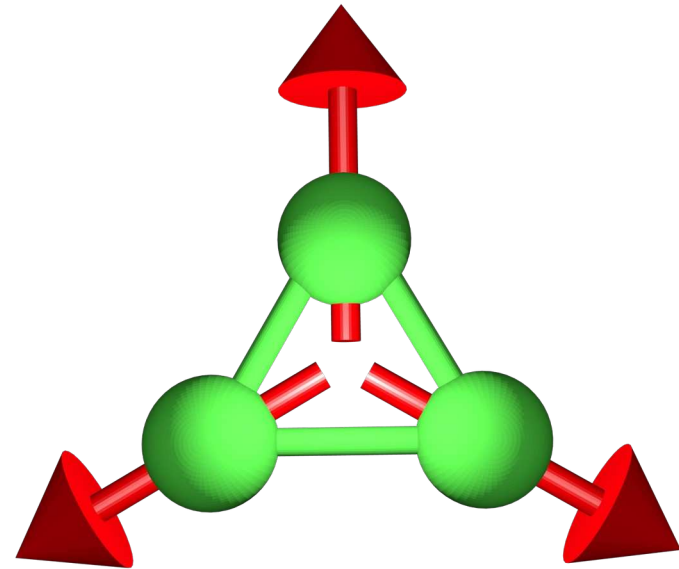
Ferromagnetism



Antiferromagnetism



Frustrated magnetism



Can we control the microscopic properties of a magnet?

What is the best that can happen?

Quantum spin liquids

No magnetic ordering at $T=0$

Non-trivial topological properties

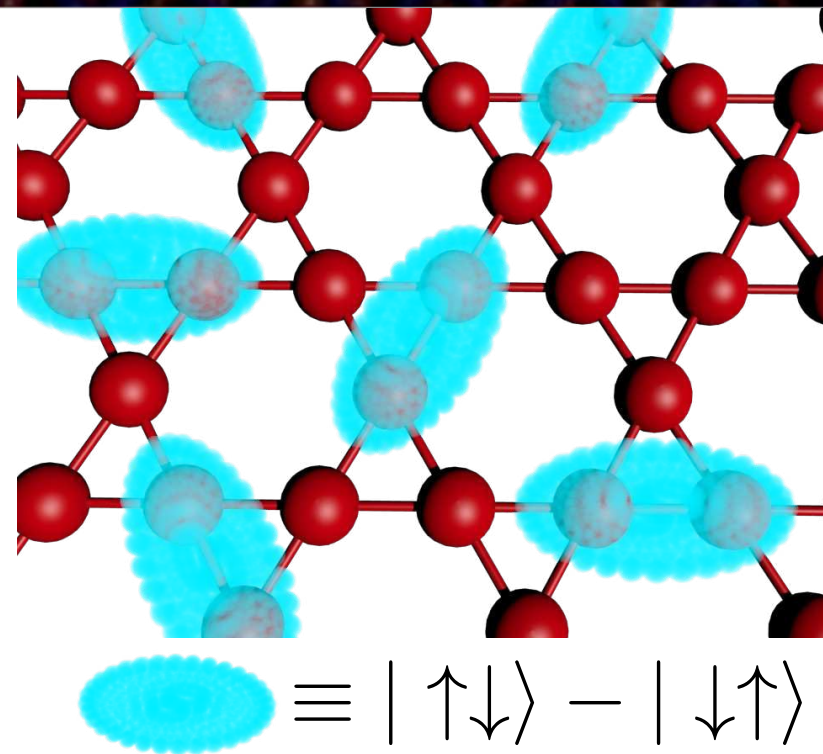
Fractional excitations

Macroscopic quantum state

“Ultra-quantum” matter

$$\mathcal{H} = \sum_{ij} \vec{S}_i \hat{J}_{ij} \vec{S}_j$$

Rep. Prog. Phys. 80, 016502 (2017)



Kitaev's honeycomb

Annals of Physics 321.1 (2006)

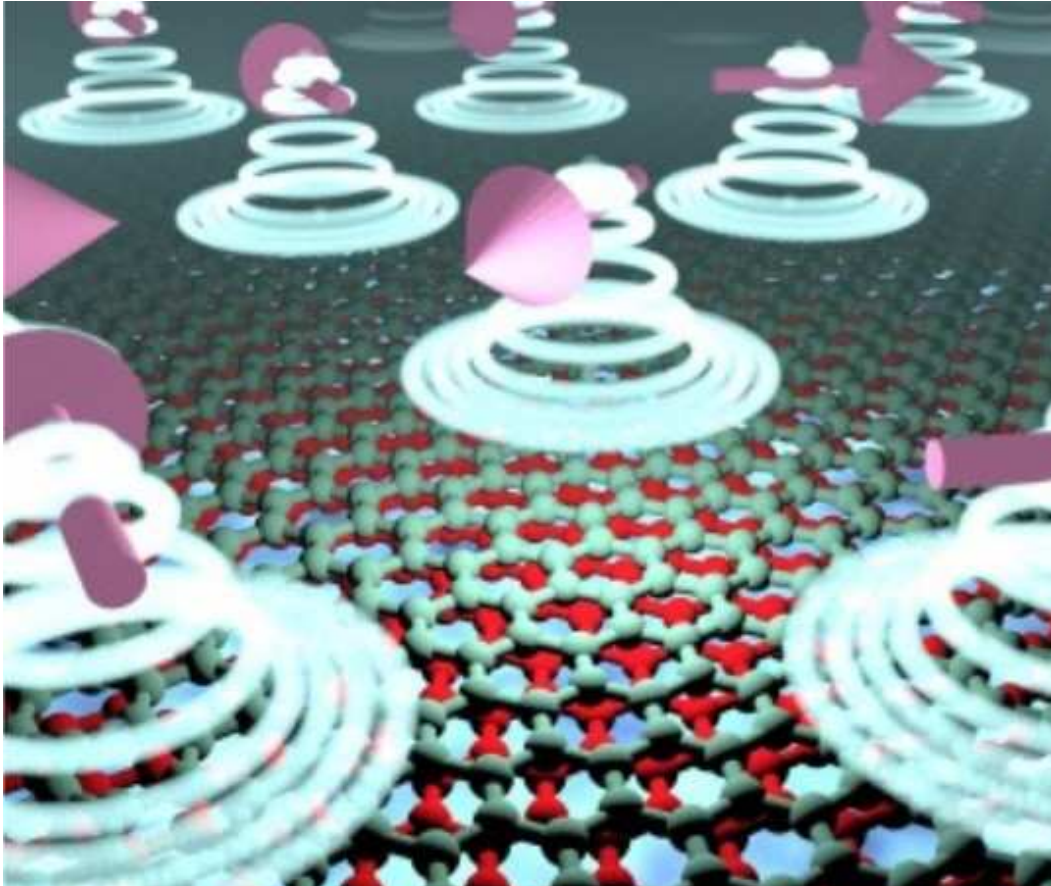
Kagome Heisenberg

Science 332, 1173-1176 (2011)

Extended triangular Heisenberg

J. Phys. Soc. Jpn 83, 093707 (2014)

Valley-mixing correlations in magnetically encapsulated tBG



Tobias
Wolf



Gianni
Blatter

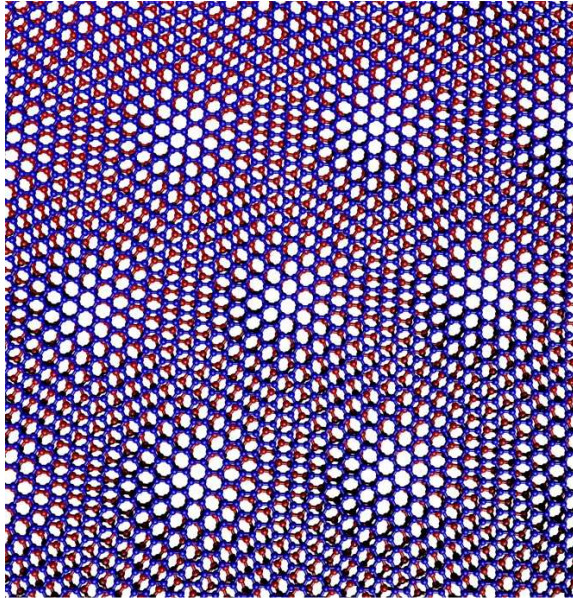


Oded
Zilberberg

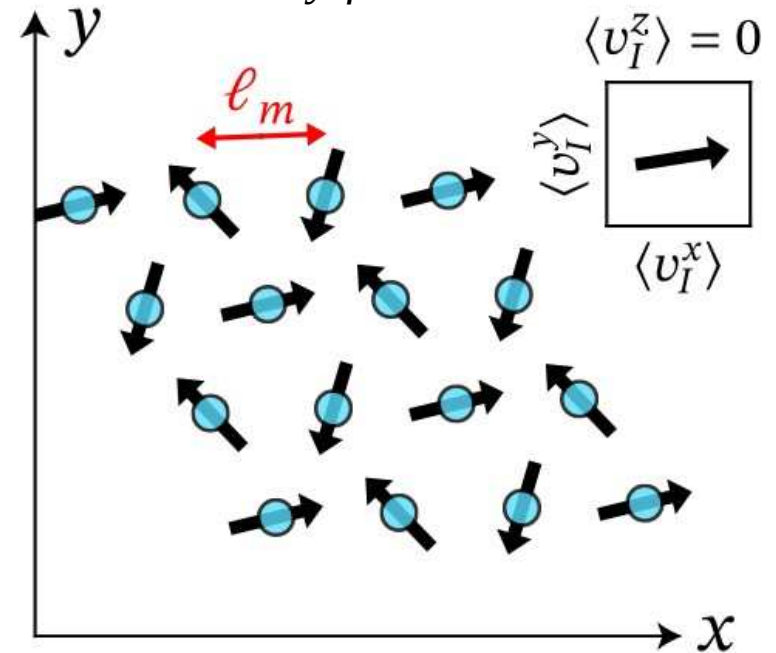
Phys. Rev. Lett. 126, 056803 (2021)

Frustrated valley magnetism

Moire structure



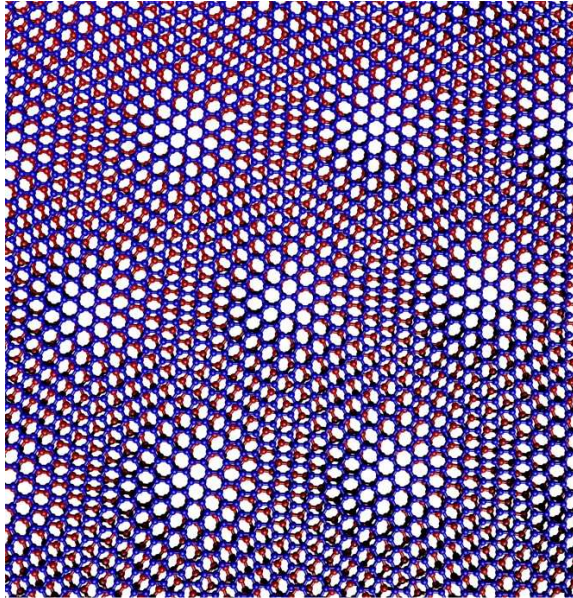
Valley-frustrated state



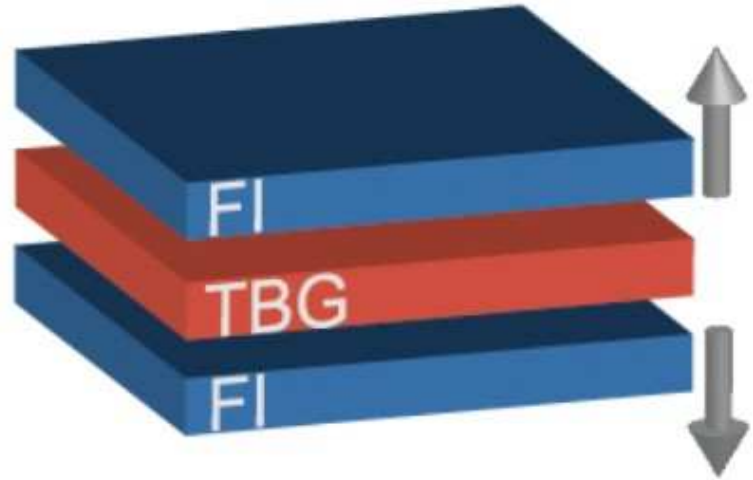
Can we create a controllable valley-only frustrated magnet?

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

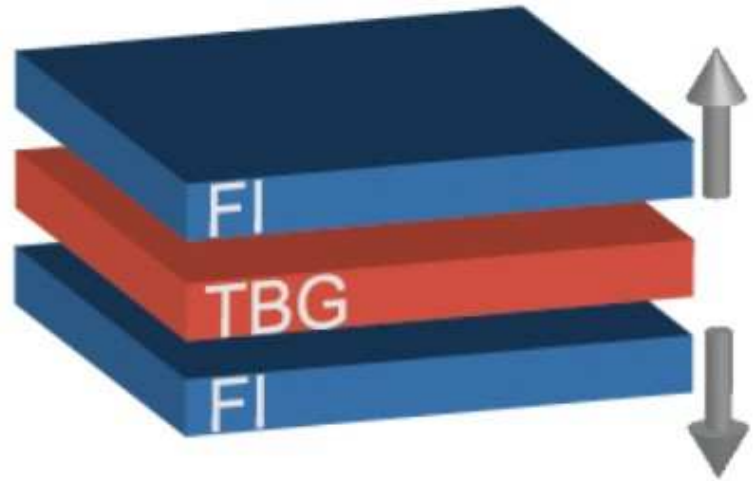
$$H = H_0 + H_J + H_R$$

Kinetic
energy

Exchange
proximity
effect

Rashba
spin-orbit
coupling

Magnetic encapsulation

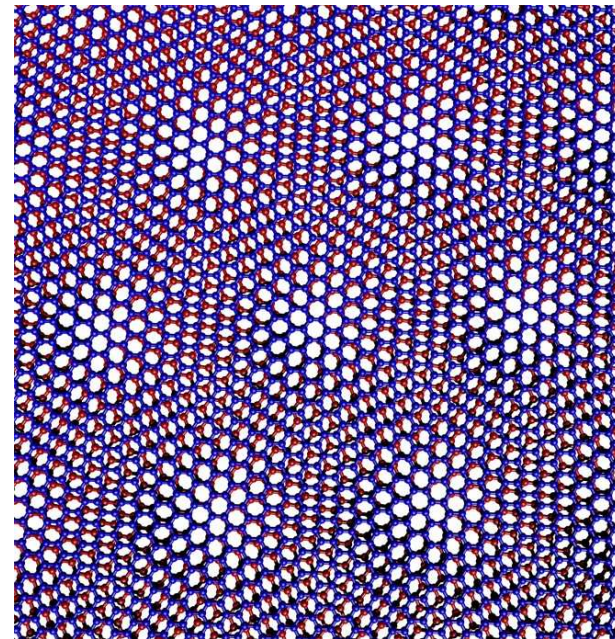
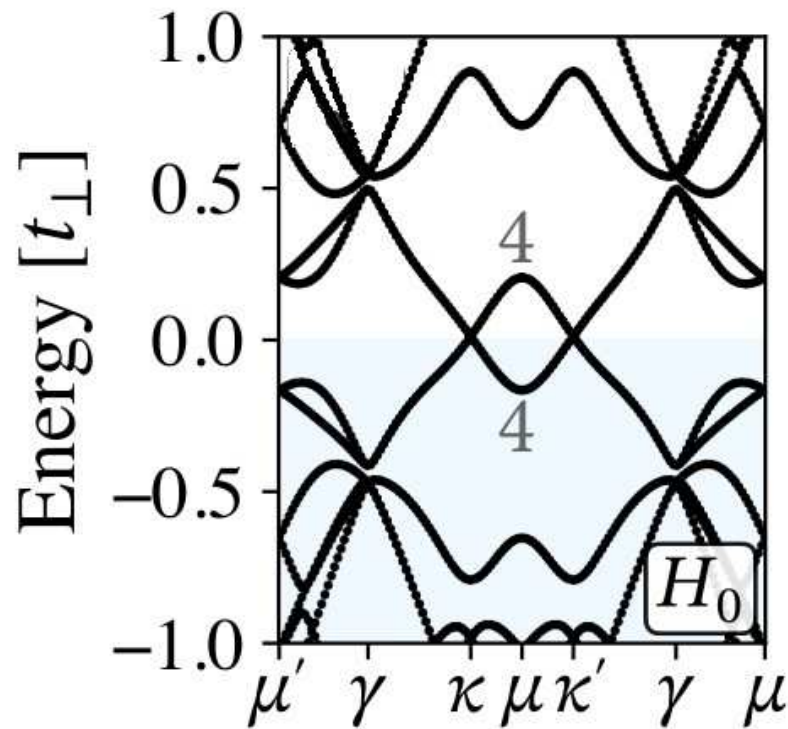


Valley frustration from combined twist engineering, exchange proximity and spin-orbit coupling.

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

Twisted graphene bilayer at 2 degrees

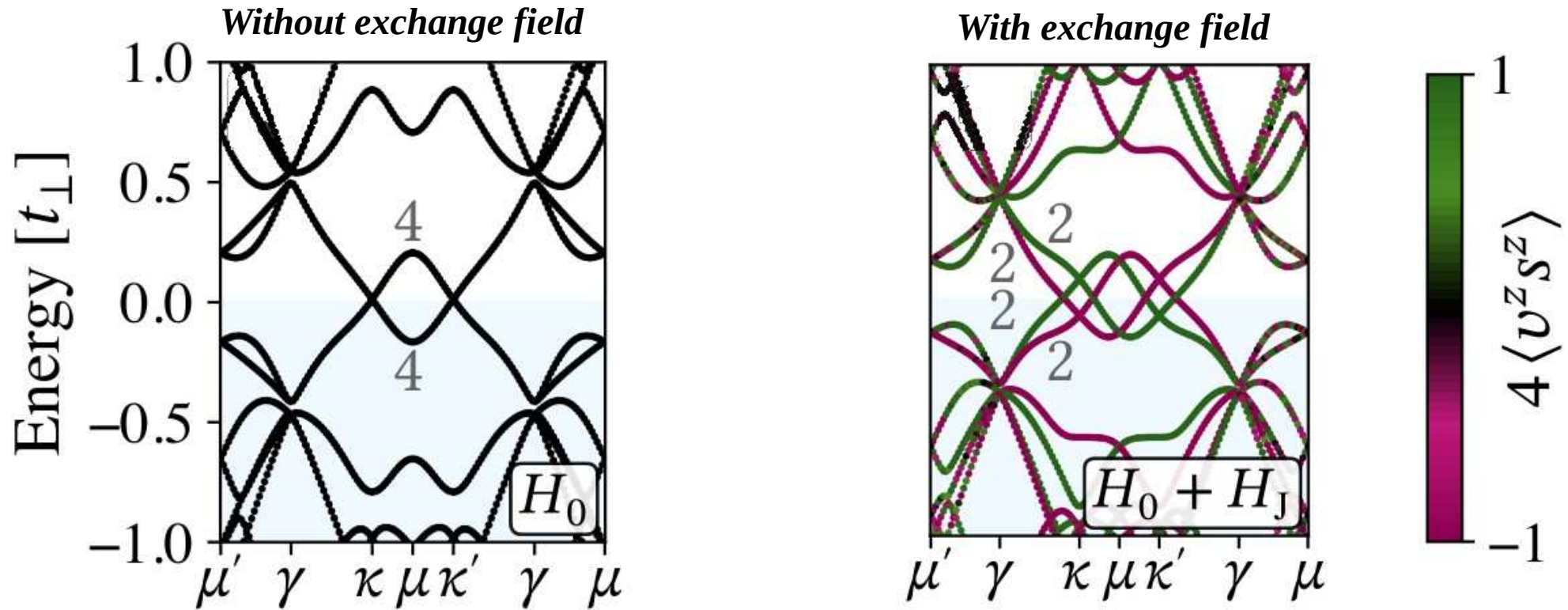
Without exchange field nor spin-orbit coupling



Renormalized Dirac cones

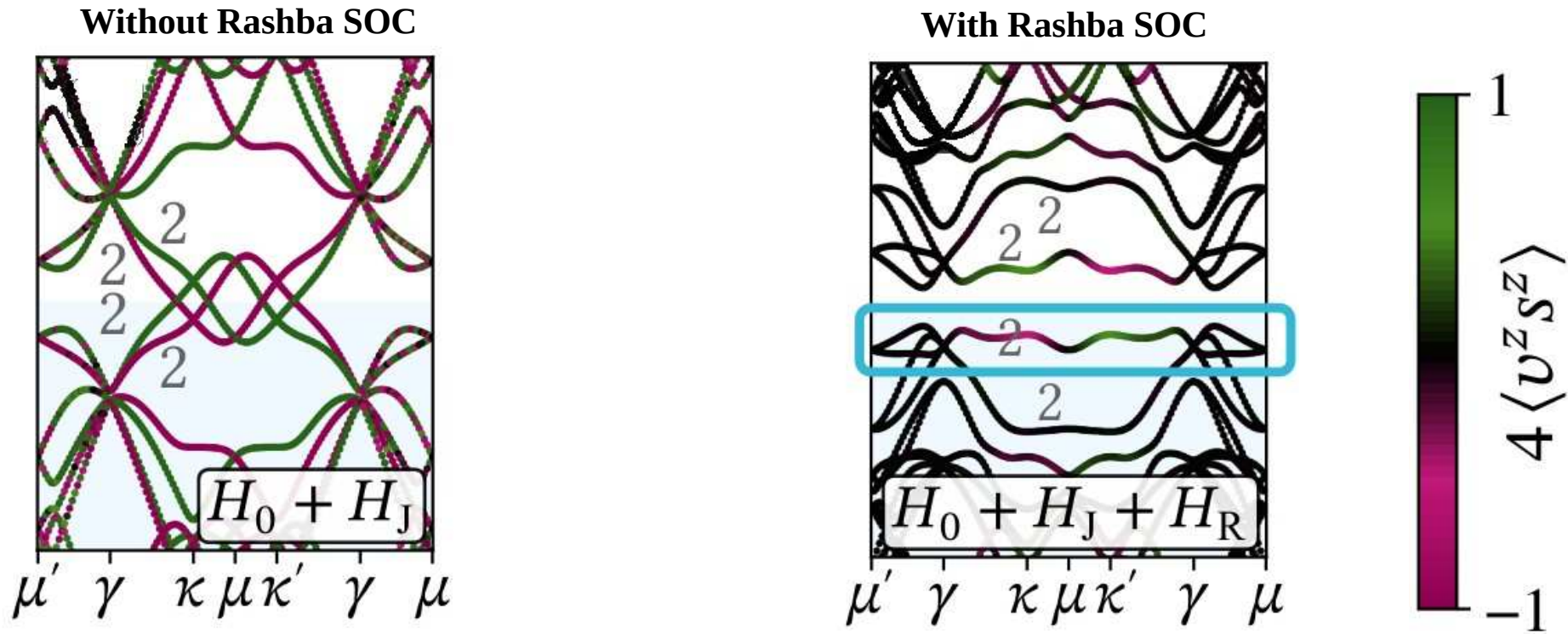
Phys. Rev Lett. 99 256802 (2007)
Phys. Rev. B 82, 121407(R) (2010)
PNAS 108 30 12233-12237 (2011)

Twisted graphene bilayer at 2 degrees



Valley-spin splitting degeneracy lifting

Valley-only correlated states in twisted graphene bilayers

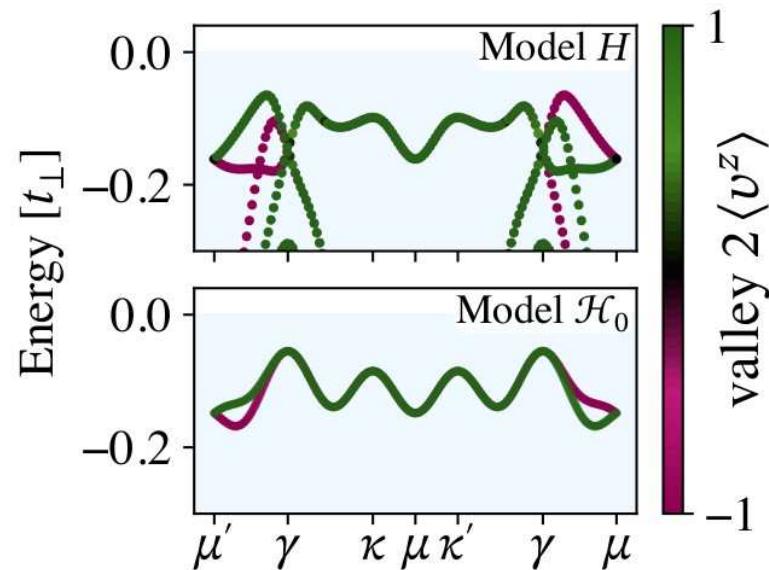
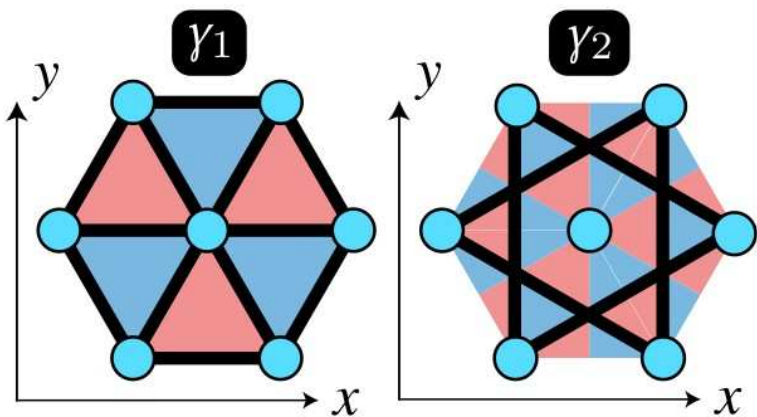


Nearly flat bands created from twist + exchange + spin-orbit coupling

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

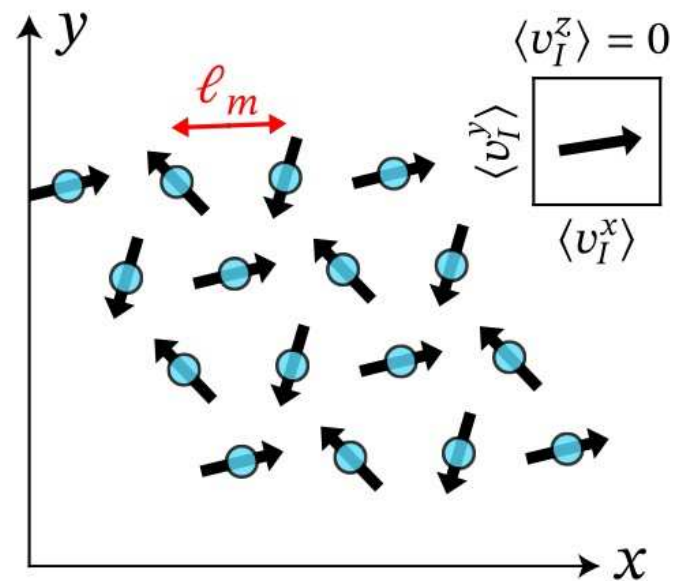
Impact of interactions

Lets add electronic interactions

Free
Hamiltonian

Electronic
interactions

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

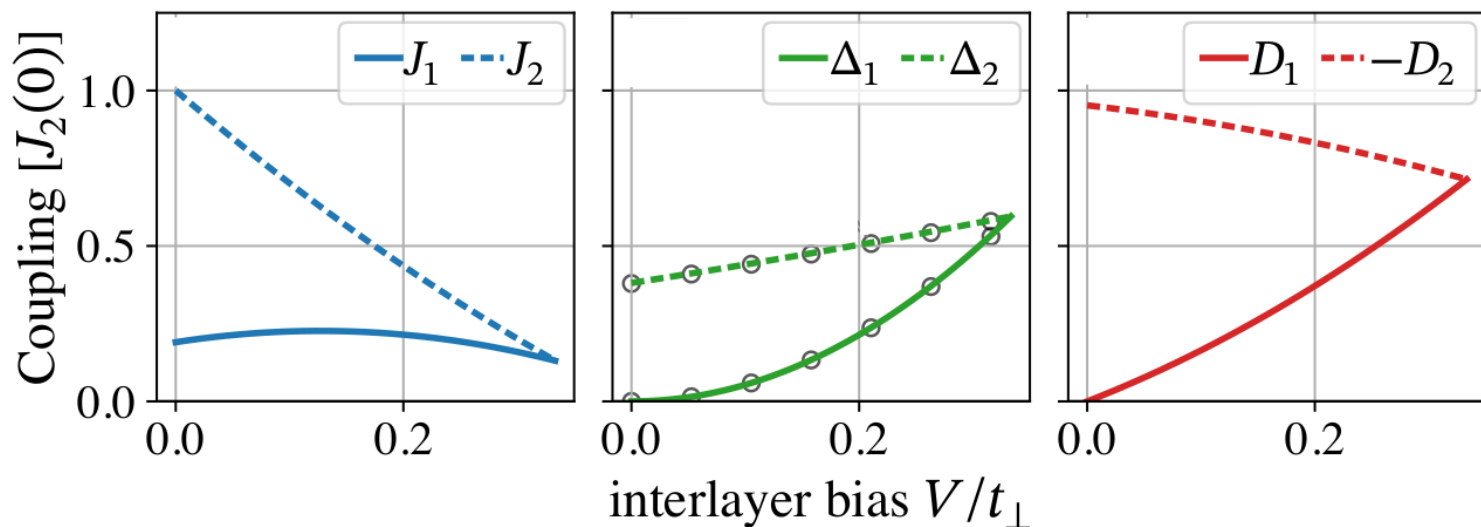


And compute the effective valley-Heisenberg Hamiltonian in the strong coupling limit

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

Controlling a valley-Heisenberg model electrically

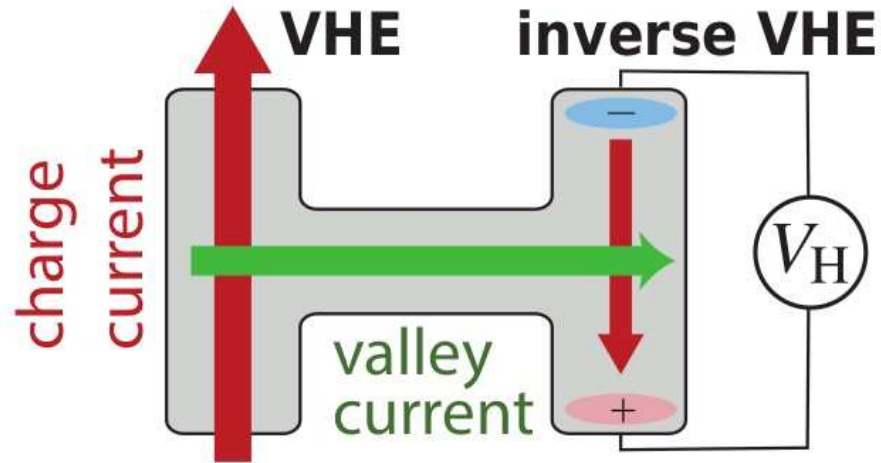
$$\mathcal{H}_v = \sum_{IJ} J_{IJ} \mathbf{v}_I \cdot \mathbf{v}_J + \Delta_{IJ} v_I^z v_J^z + v_{IJ} D_{IJ} (\mathbf{v}_I \times \mathbf{v}_J)_z$$



An interlayer bias provides a tunable anisotropic valley-Heisenberg model

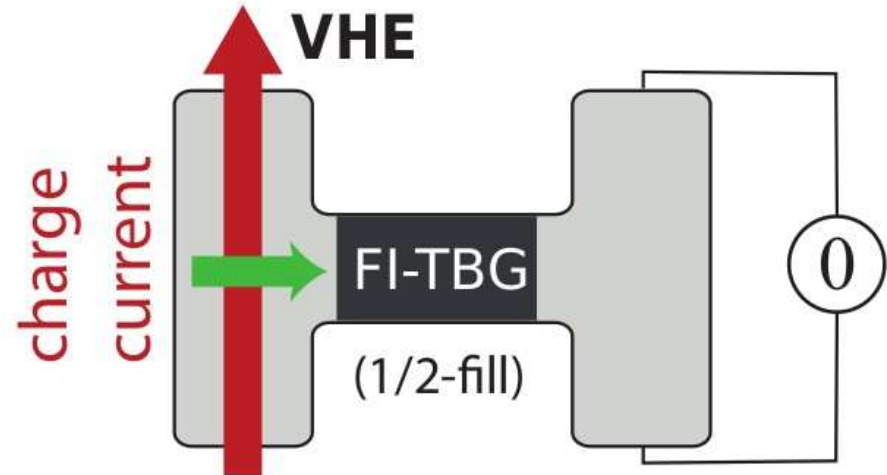
Detecting the valley spiral

No valley mixing



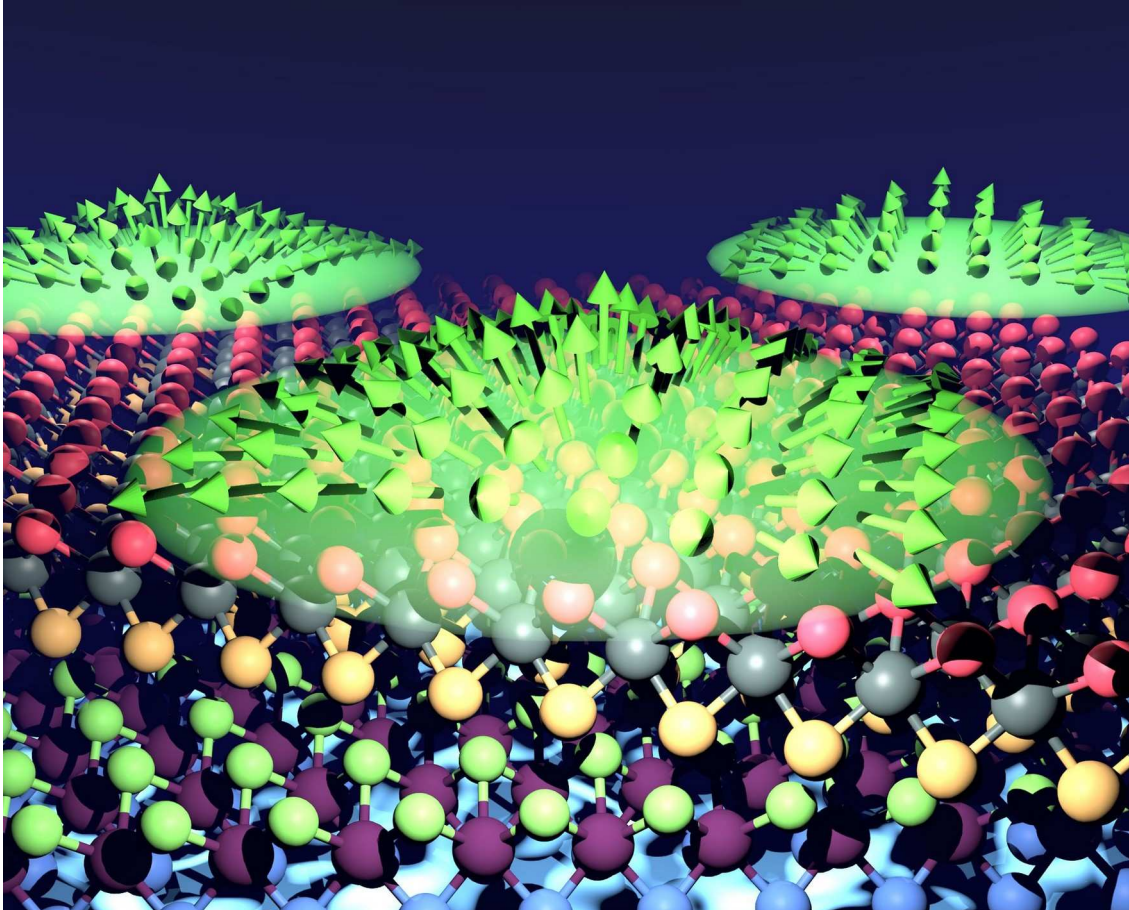
Finite non-local conductance

Finite valley mixing



Zero non-local conductance

Correlated states dominated by spin-orbit coupling in Janus dichalcogenides

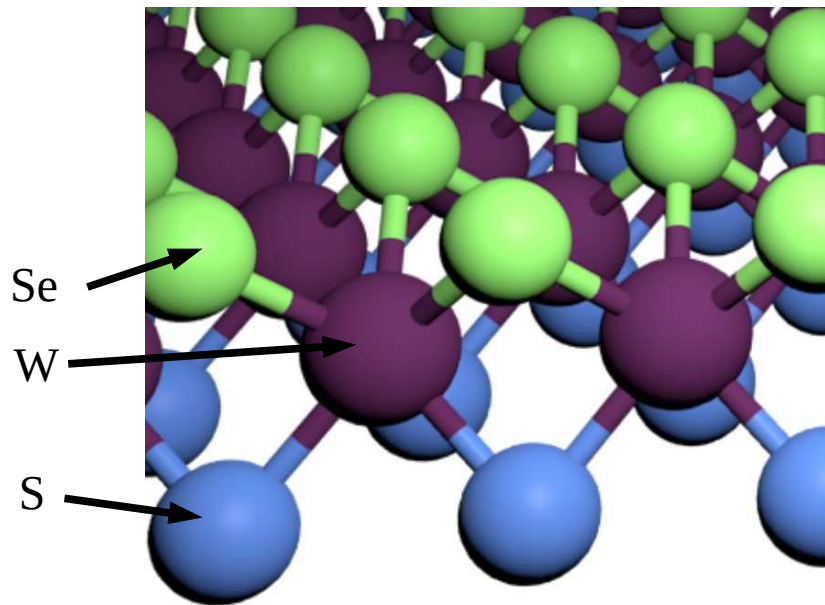


David Soriano

arXiv:2105.04502 (2021)

Janus dichalcogenide monolayers

WSe structure



Intrinsic mirror symmetry breaking

Colossal Rashba SOC effects

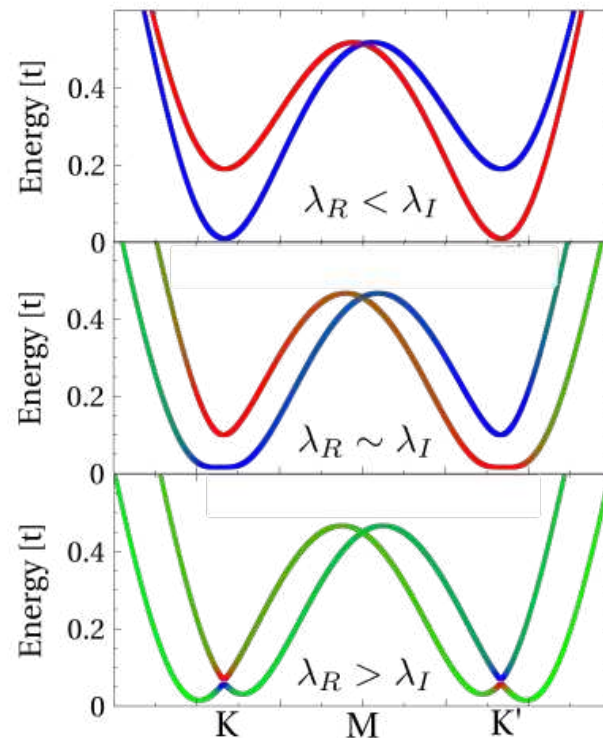
Rashba SOC

$$\lambda_R$$

Ising SOC

$$\lambda_I$$

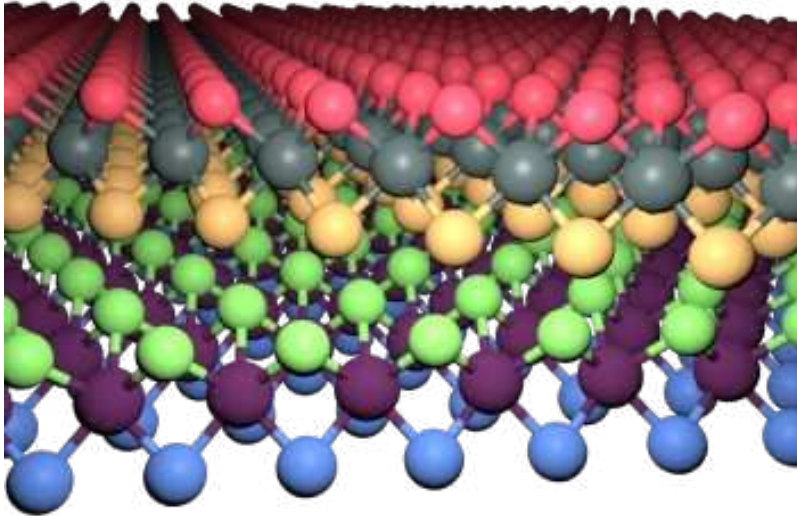
Band structure



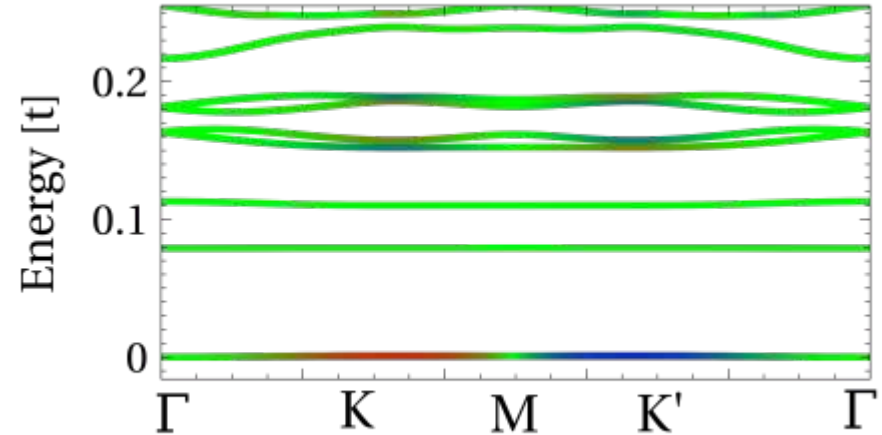
Rashba SOC strongly impact the low energy dispersion

Twisted Janus bilayers

Twisted Janus bilayer

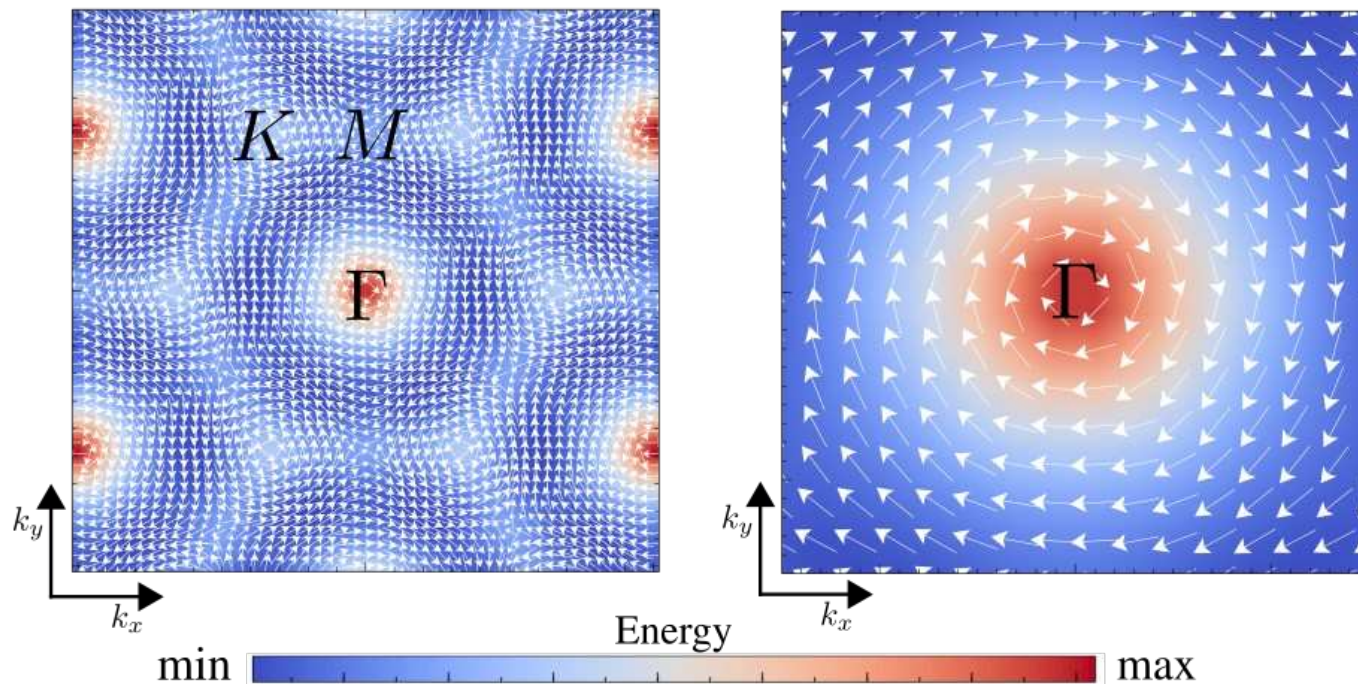


Band structure



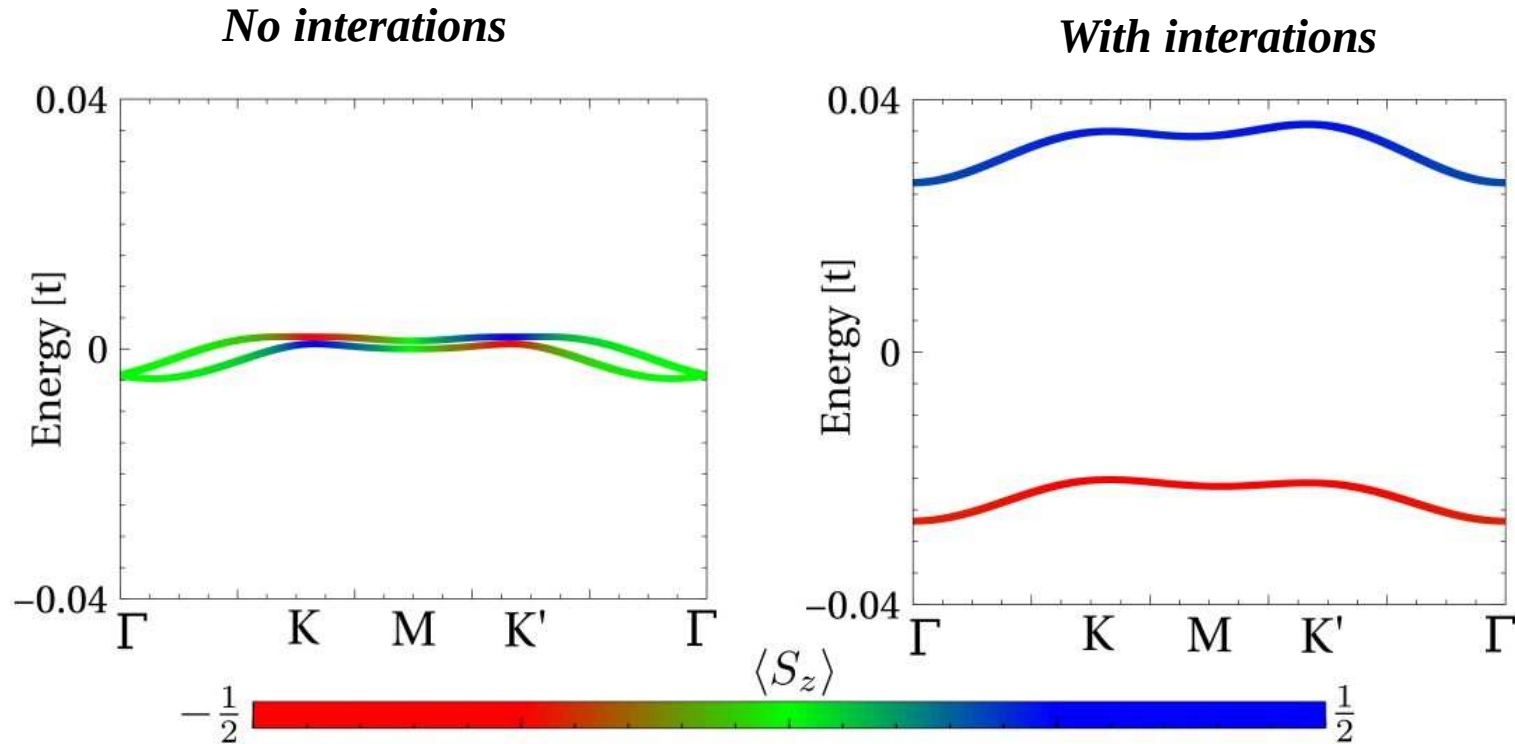
Flat bands emerge in a twisted Janus bilayer, inheriting the colossal Rashba SOC effects

Reciprocal space texture of the flat bands



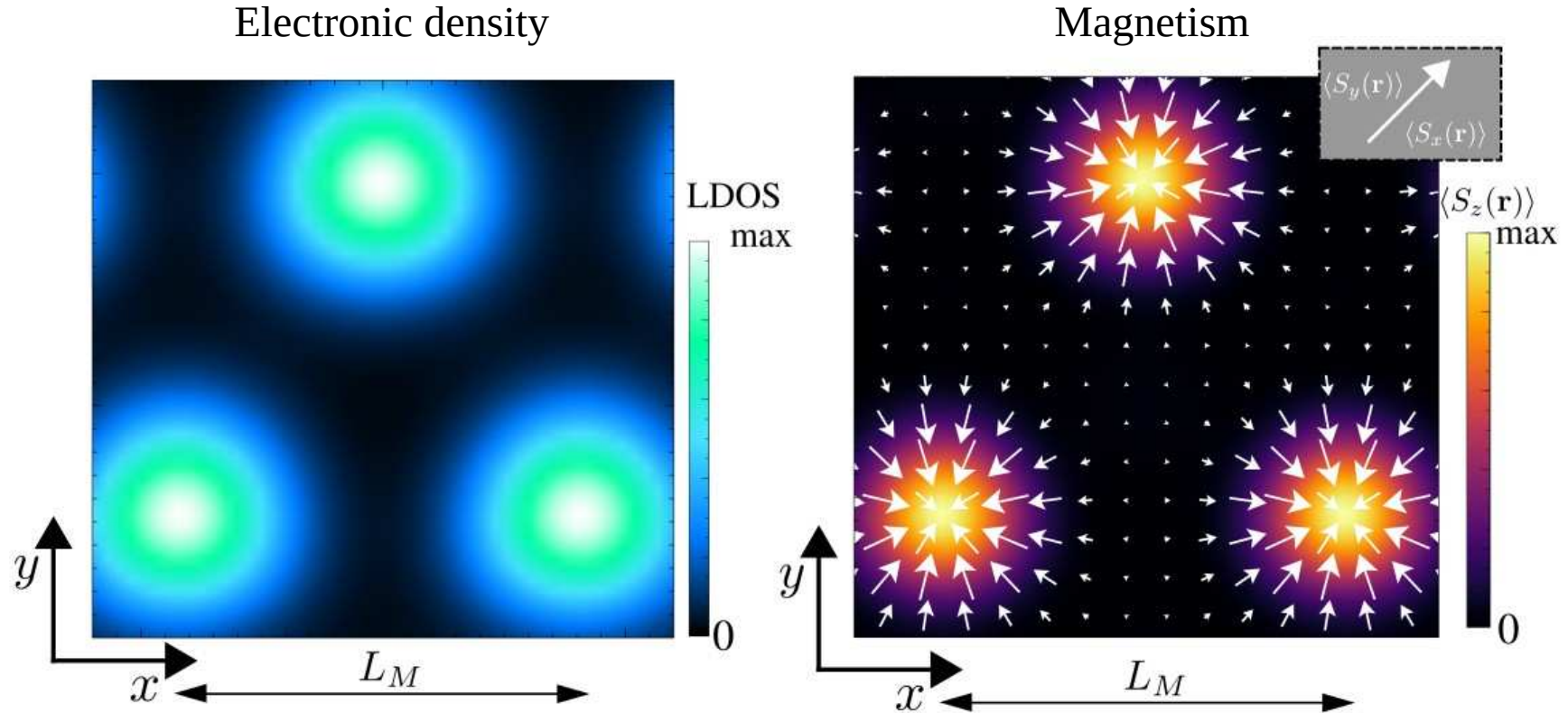
Flat bands are dominated by a strong spin-momentum texture, stemming from the Janus structure

Impact of interactions at low energies



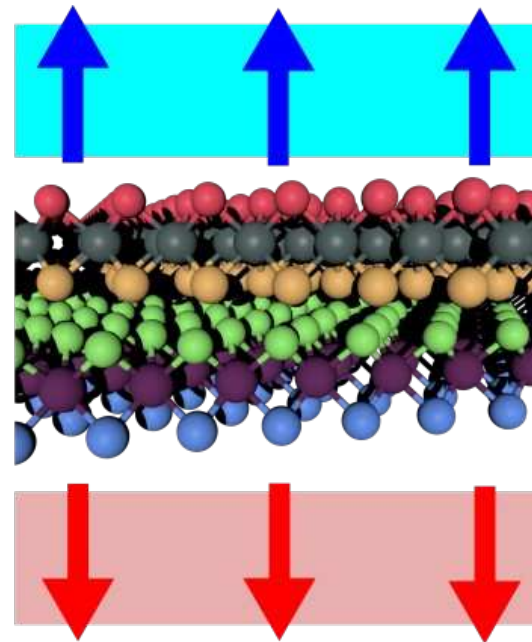
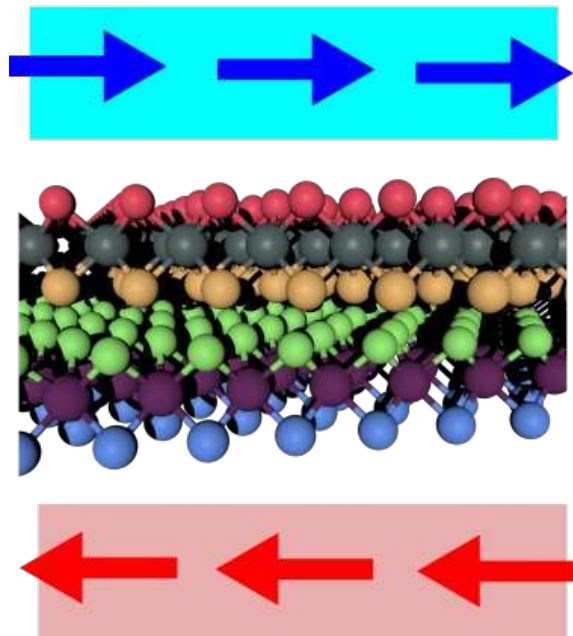
When including interactions in the full lattice model, a symmetry broken state arises

Real space profile when including interactions



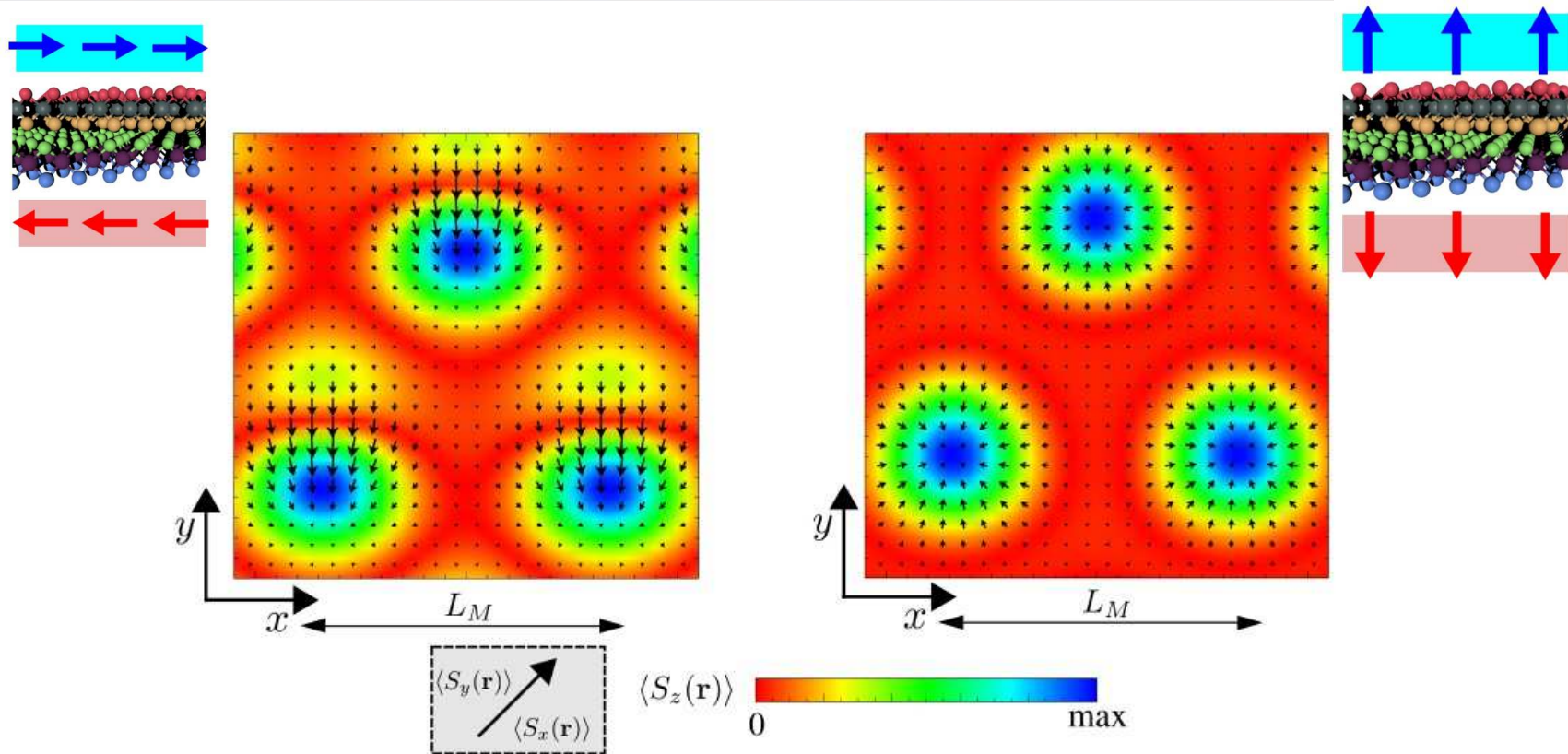
A moire meron magnetic structure appears due to the presence of interactions

Control by magnetic encapsulation



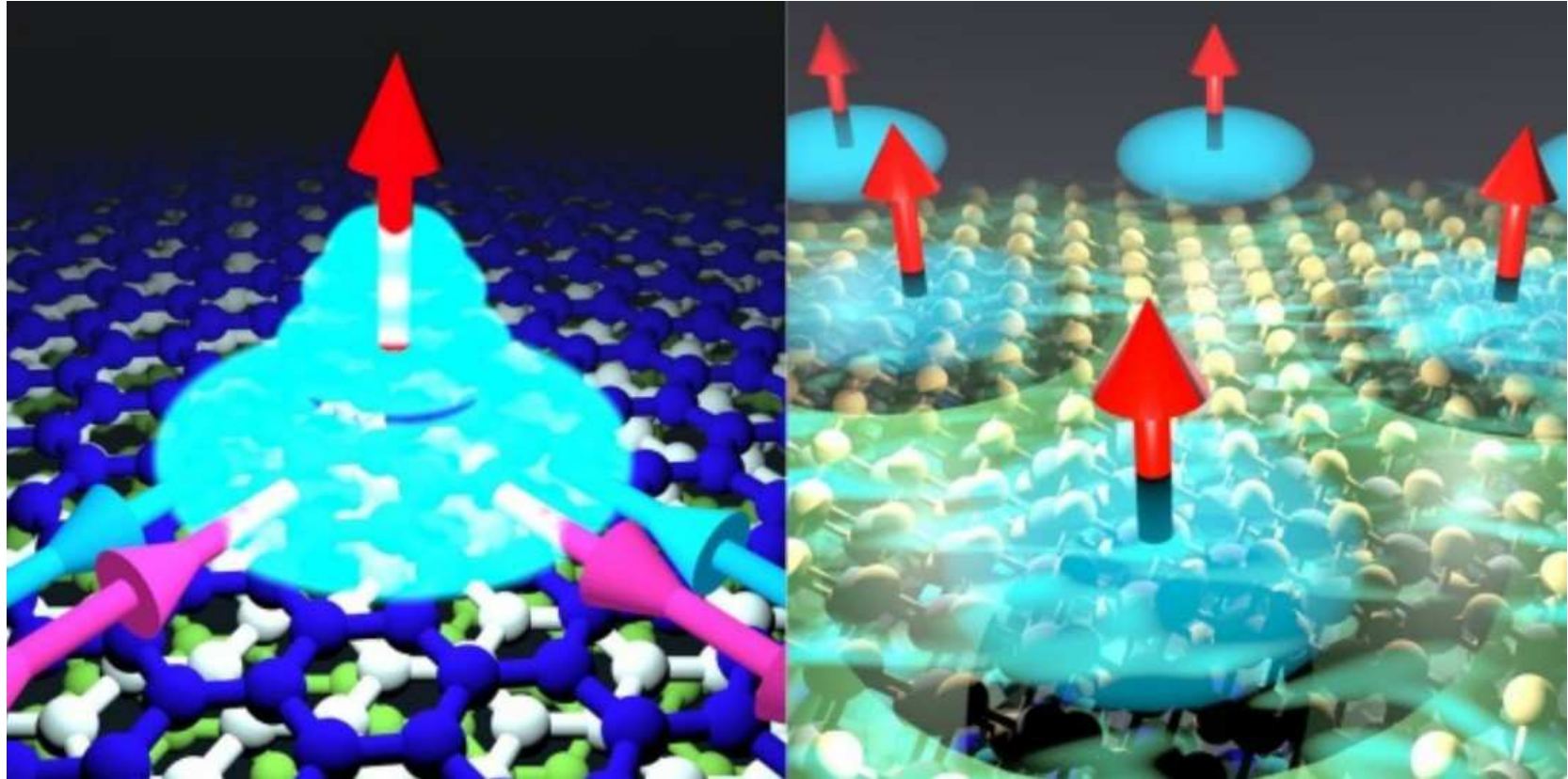
Let us explore the impact of a magnetic encapsulation in the correlated Janus bilayer

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



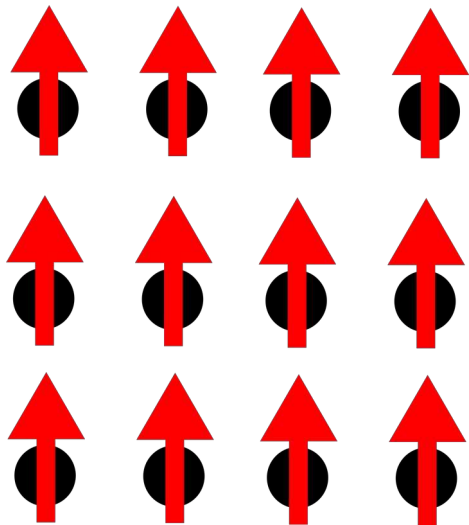
Basics of heavy fermion physics

- 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

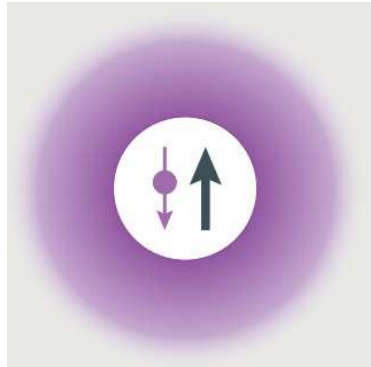
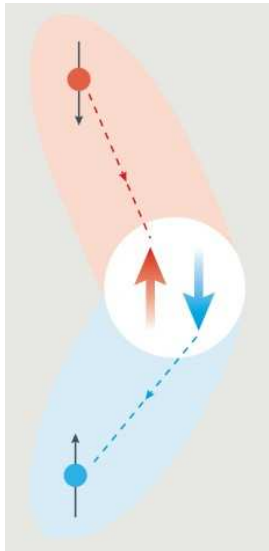
Dispersive electron gas



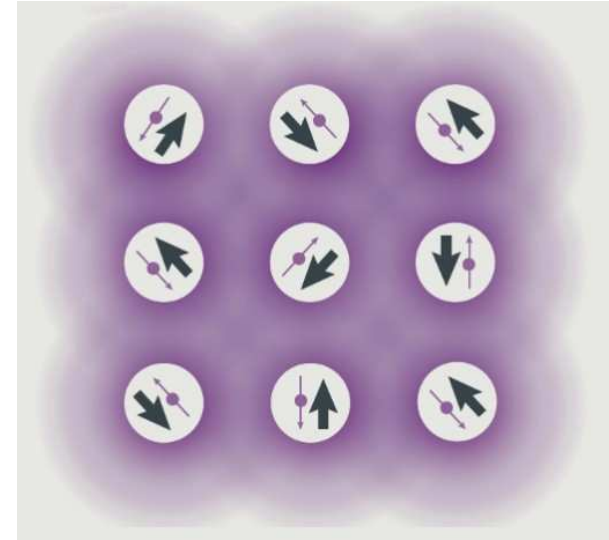
s/p/d-electrons in
rare-earth compounds

Basics of heavy fermion physics

Conduction electrons form
Kondo singlets with the impurities



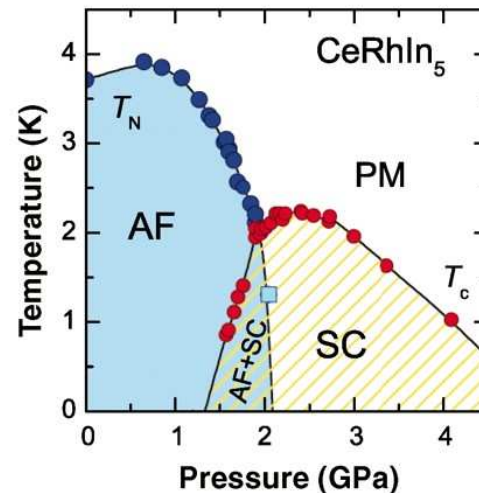
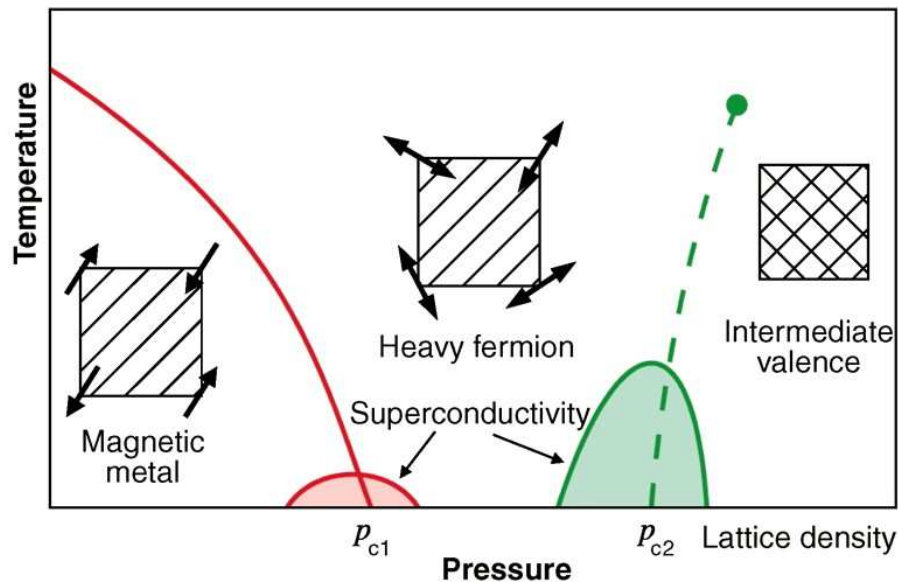
Kondo-lattice model



Associated with Kondo lattice physics:

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

Basics of heavy fermion physics

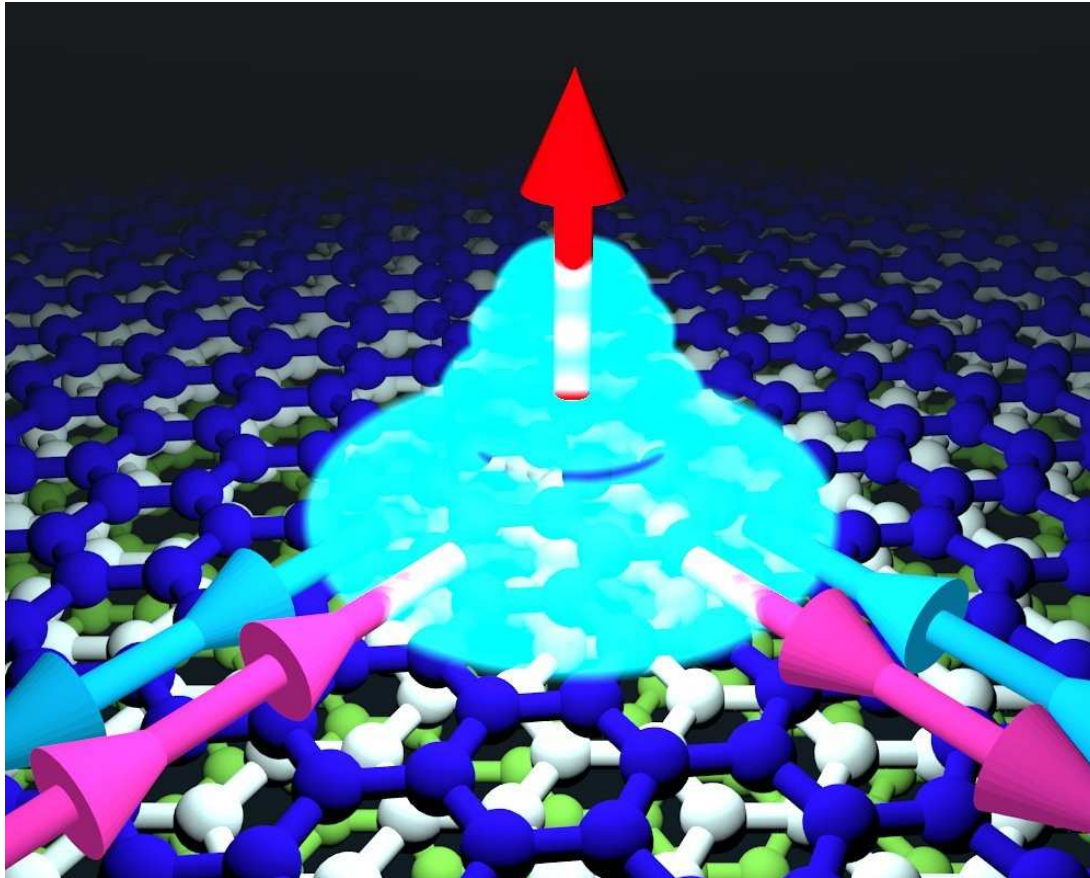


Science 332.6026, 196-200 (2011)

Associated with Kondo lattice physics:

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

Heavy-fermions in twisted graphene trilayers



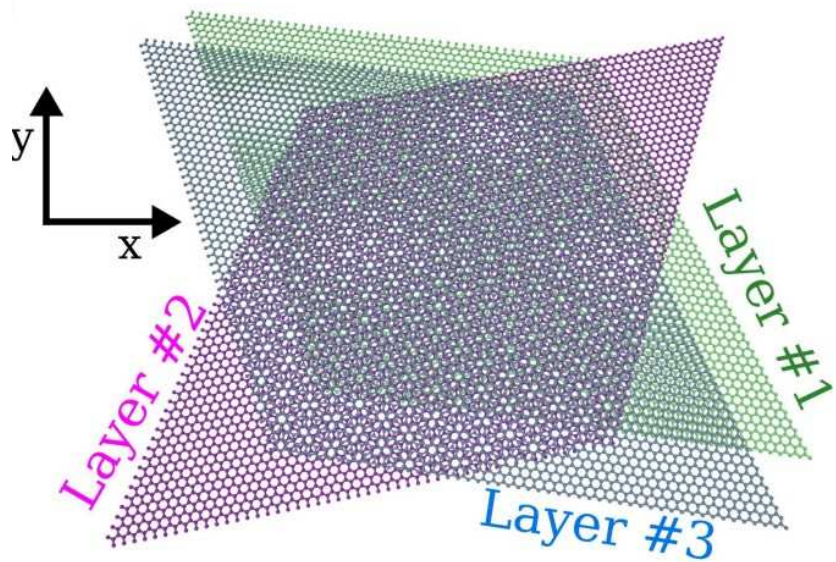
A. Ramires



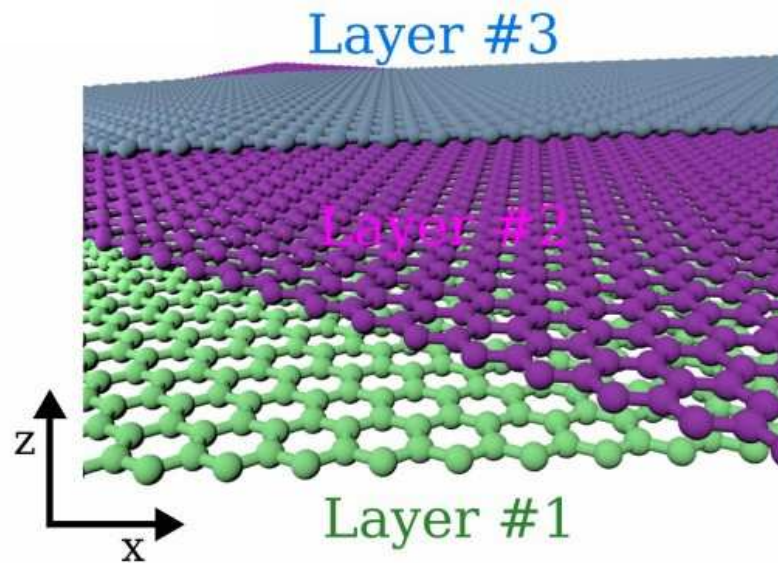
arXiv:2102.03312 (2021)
(accepted in Physical Review Letters)

Heavy-fermions in twisted graphene trilayers

Top view

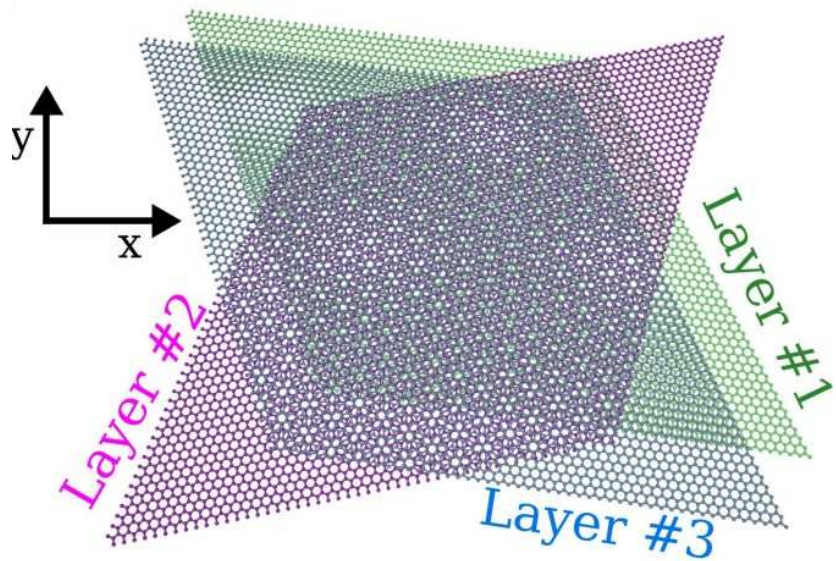


Lateral view

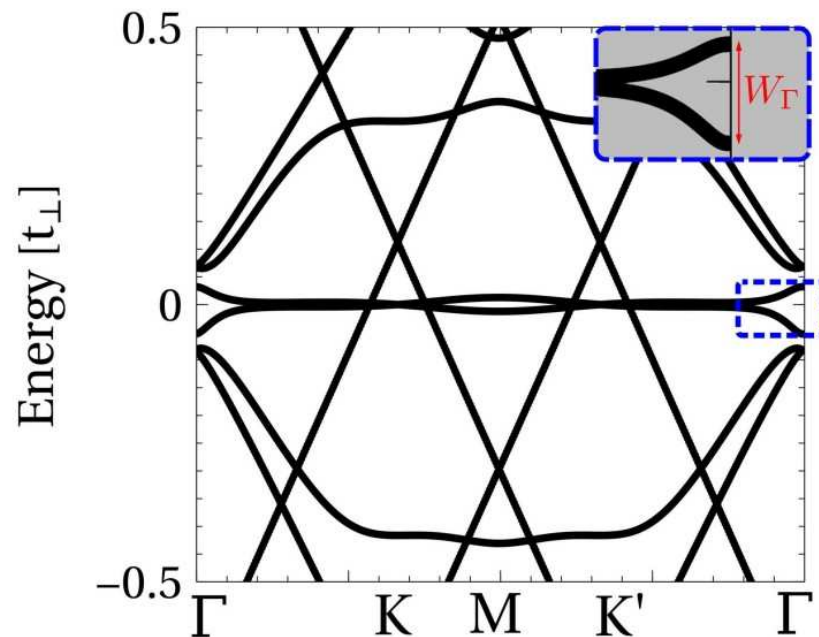


Heavy-fermions in twisted graphene trilayers

Top view

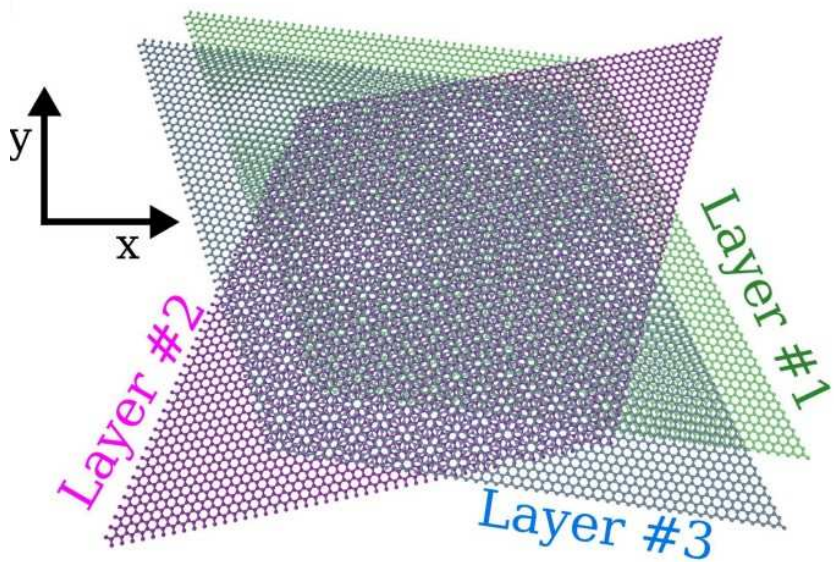


Band structure

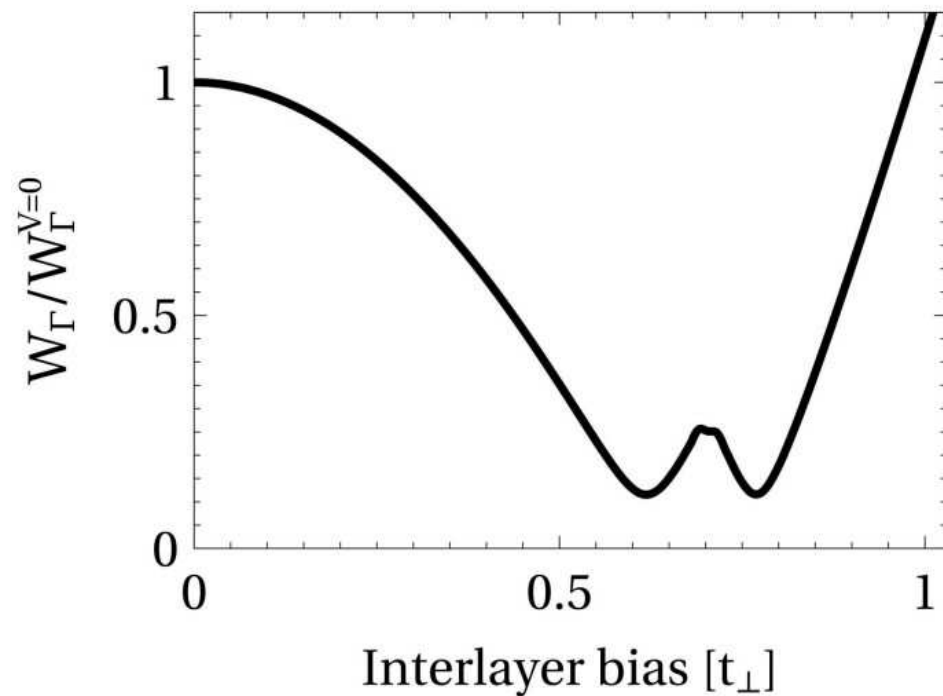


Heavy-fermions in twisted graphene trilayers

Top view



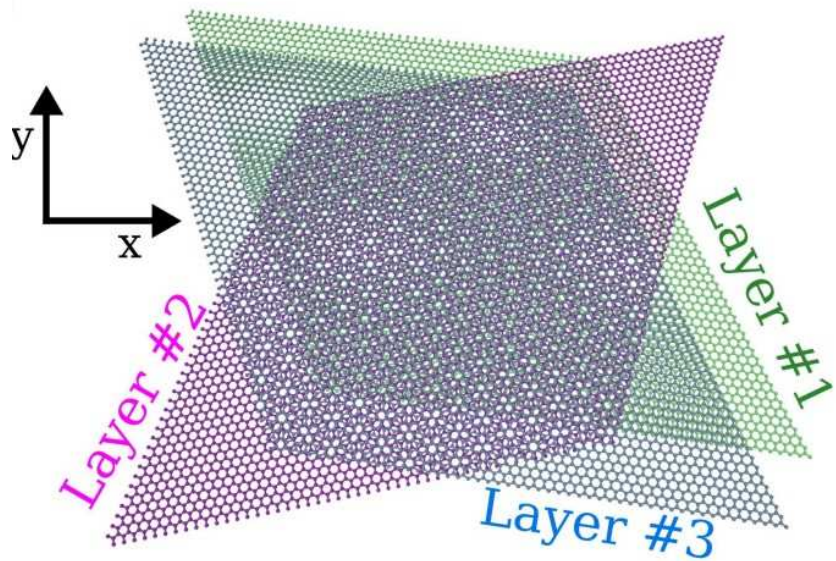
Bandwidth of nearly flat bands



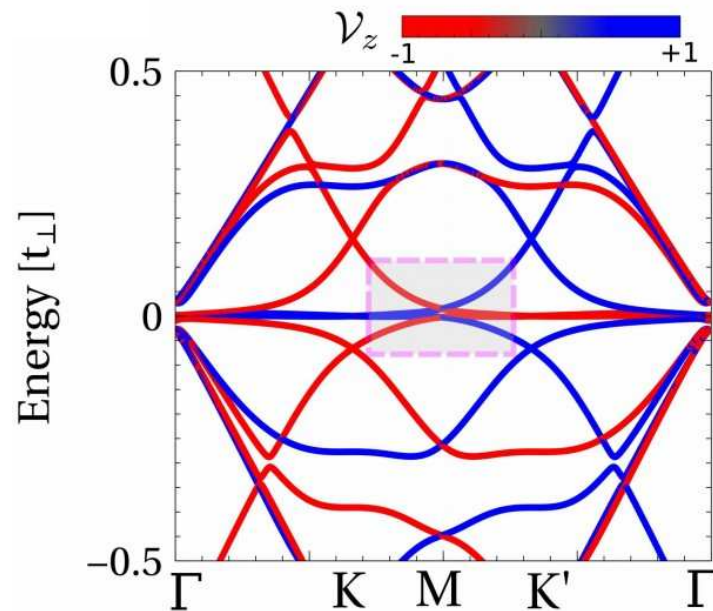
Band flattening as an interlayer bias is applied

Heavy-fermions in twisted graphene trilayers

Top view

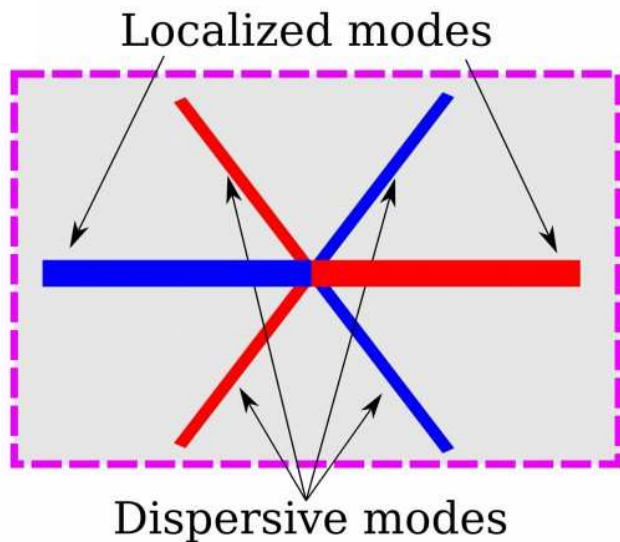


Electronic structure in the presence of an electric bias

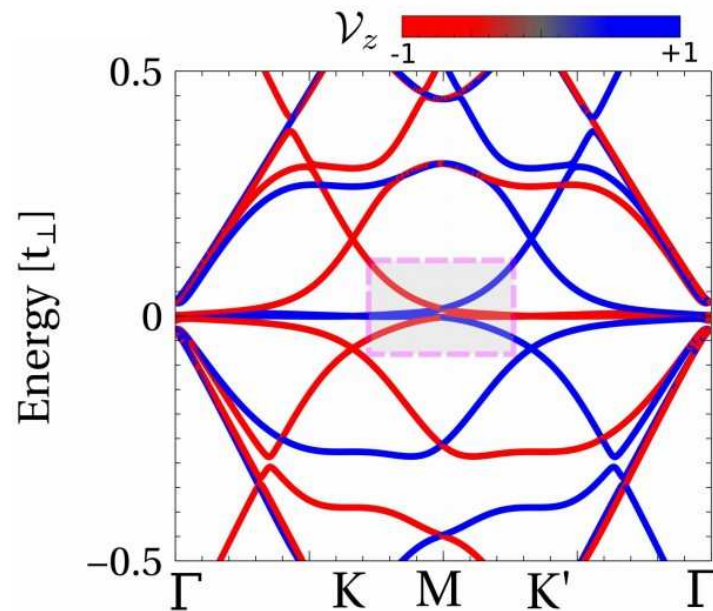


Heavy-fermions in twisted graphene trilayers

Low energy model

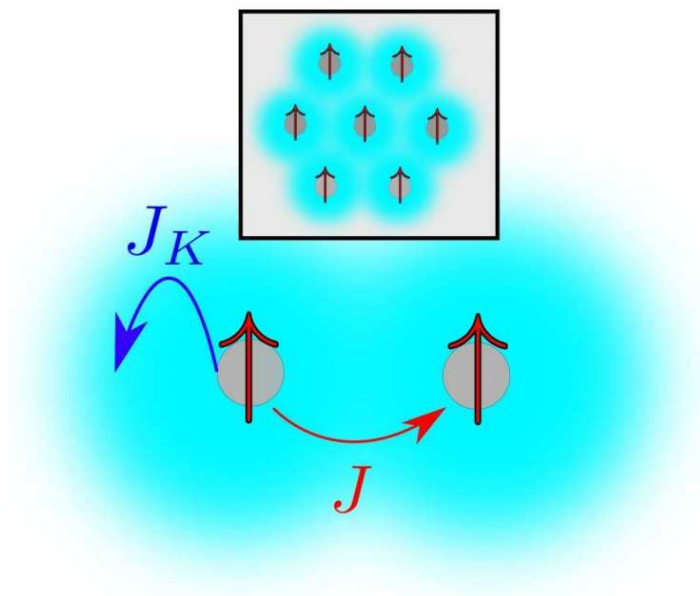


Electronic structure in the presence of an electric bias

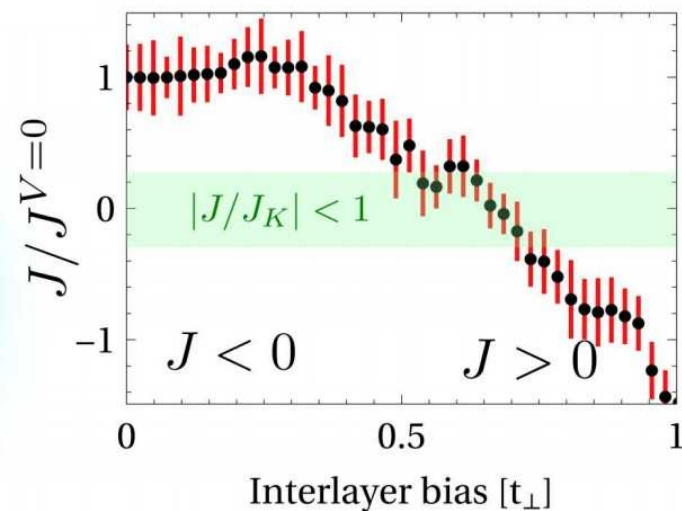


Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Electric control of the Kondo regime

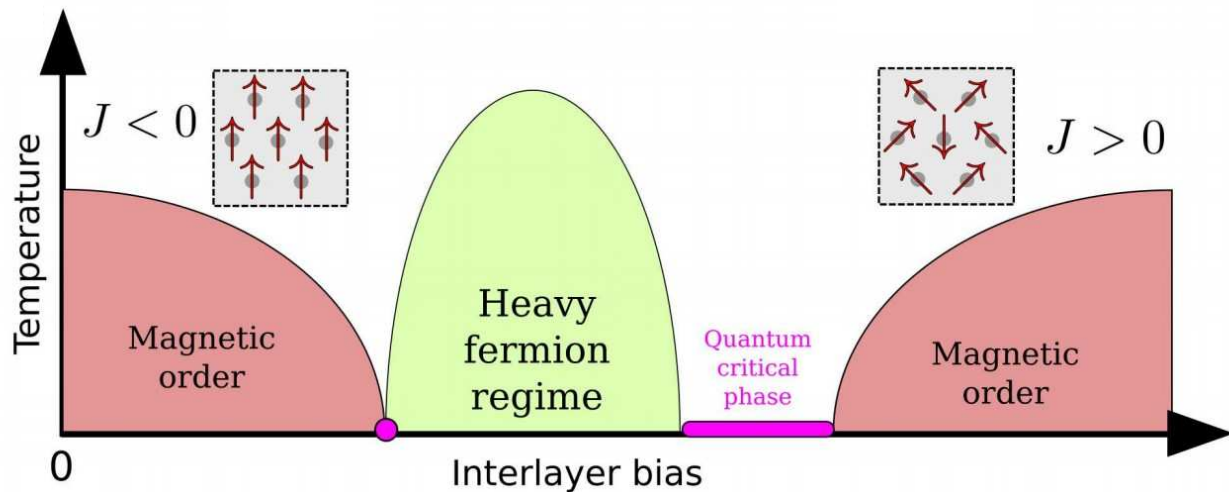


A heavy fermion regime appears when the Kondo coupling dominates over the exchange coupling

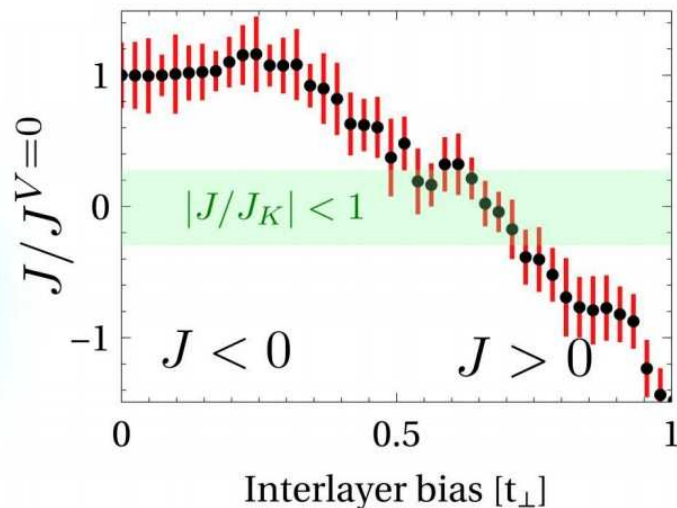
$$|J/J_K| < 1$$

Heavy-fermions in twisted graphene trilayers

Heavy-fermion (Doniach) phase diagram

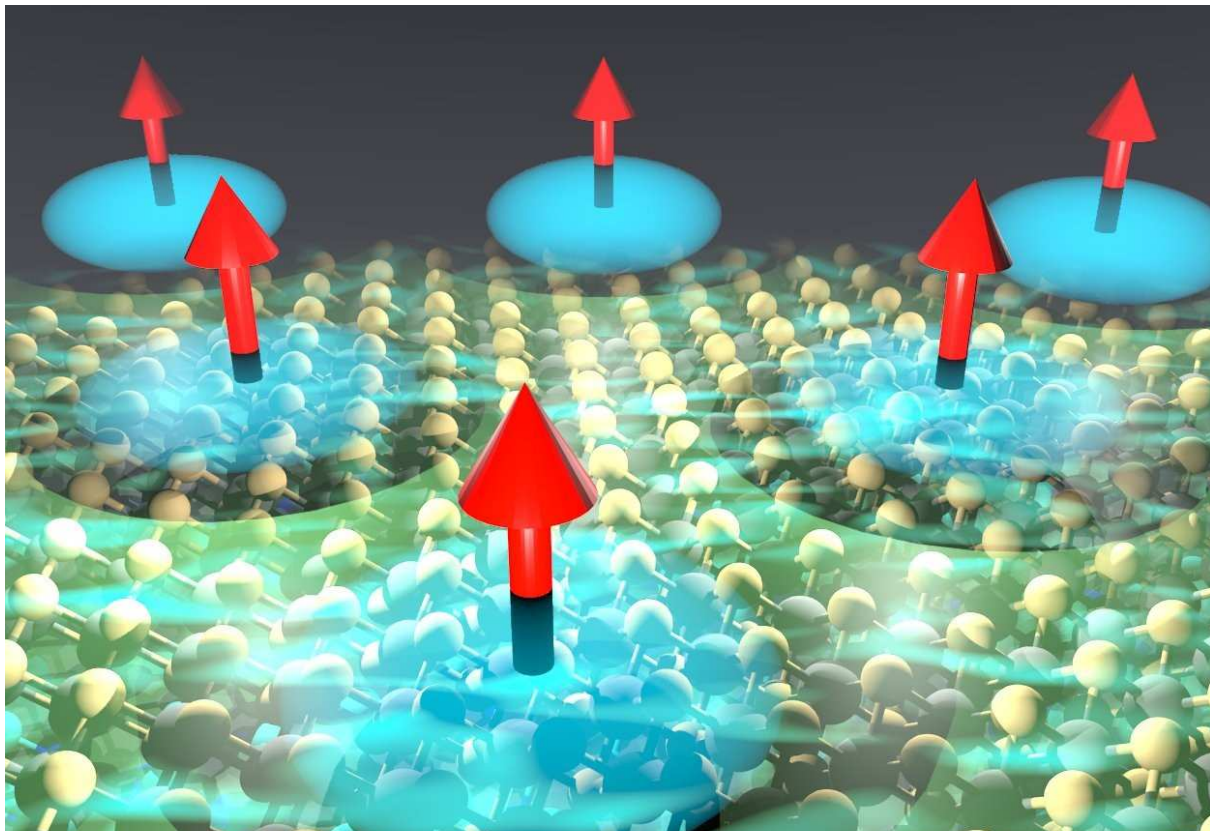


Electric control of the Kondo regime



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

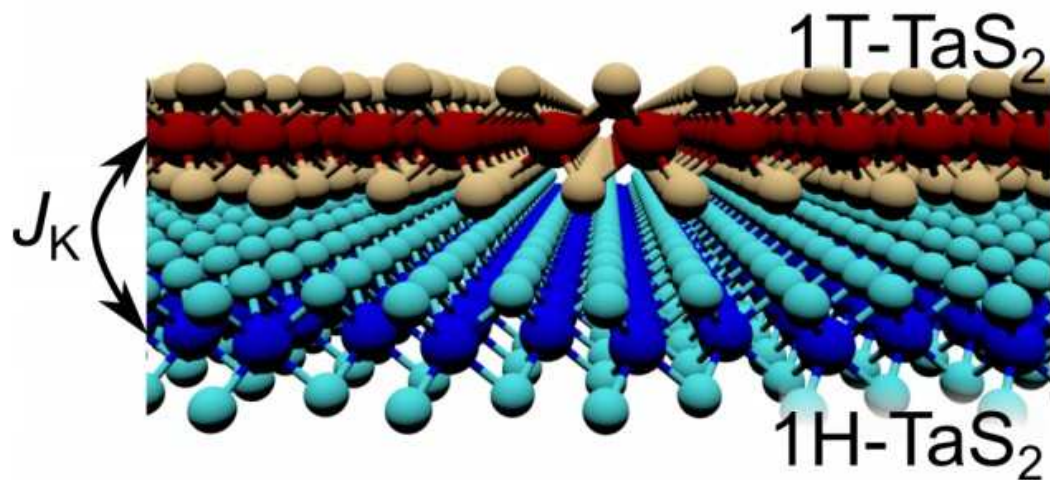
Two-dimensional electron gas



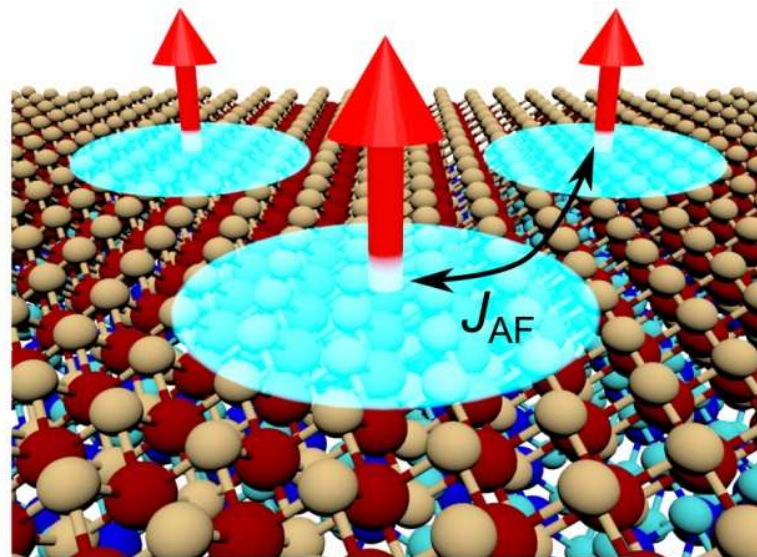
1H-TaS₂

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling create
the Kondo coupling



Intralayer exchange between
local moments

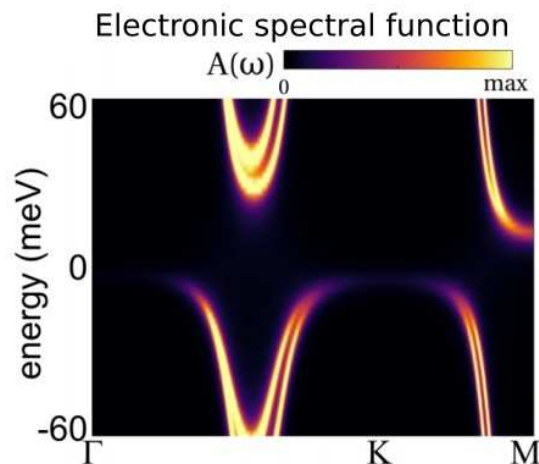
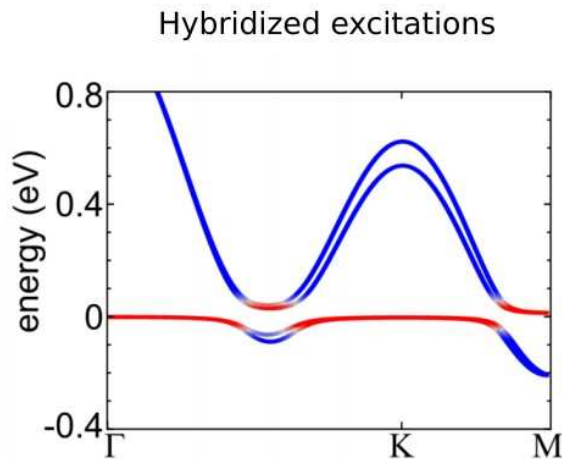
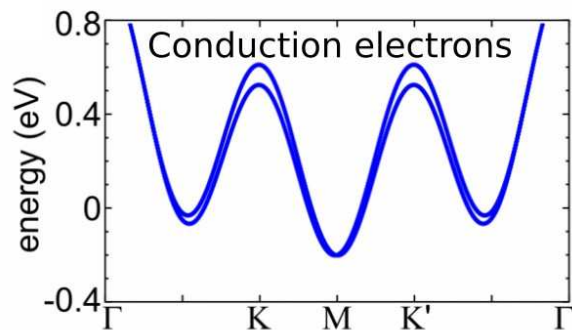
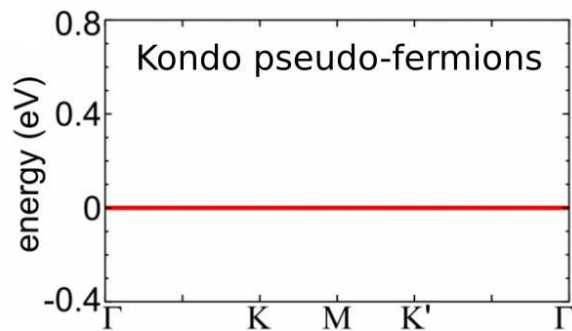


The bilayer realizes all the ingredients for heavy-fermion physics

Brief theory of heavy-fermions

Kondo physics introduces resonant pseudo-fermions at the chemical potential

Leading to the opening of a heavy-fermion gap

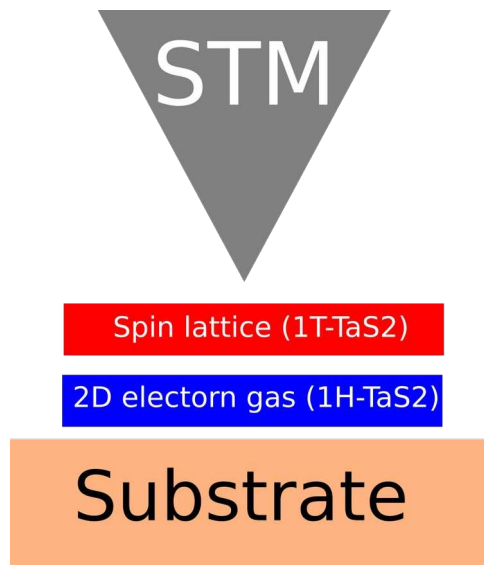


Experimental signatures of heavy-fermion physics

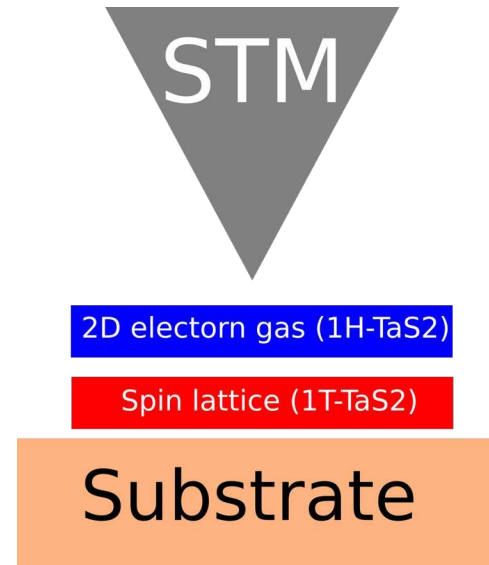
- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

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

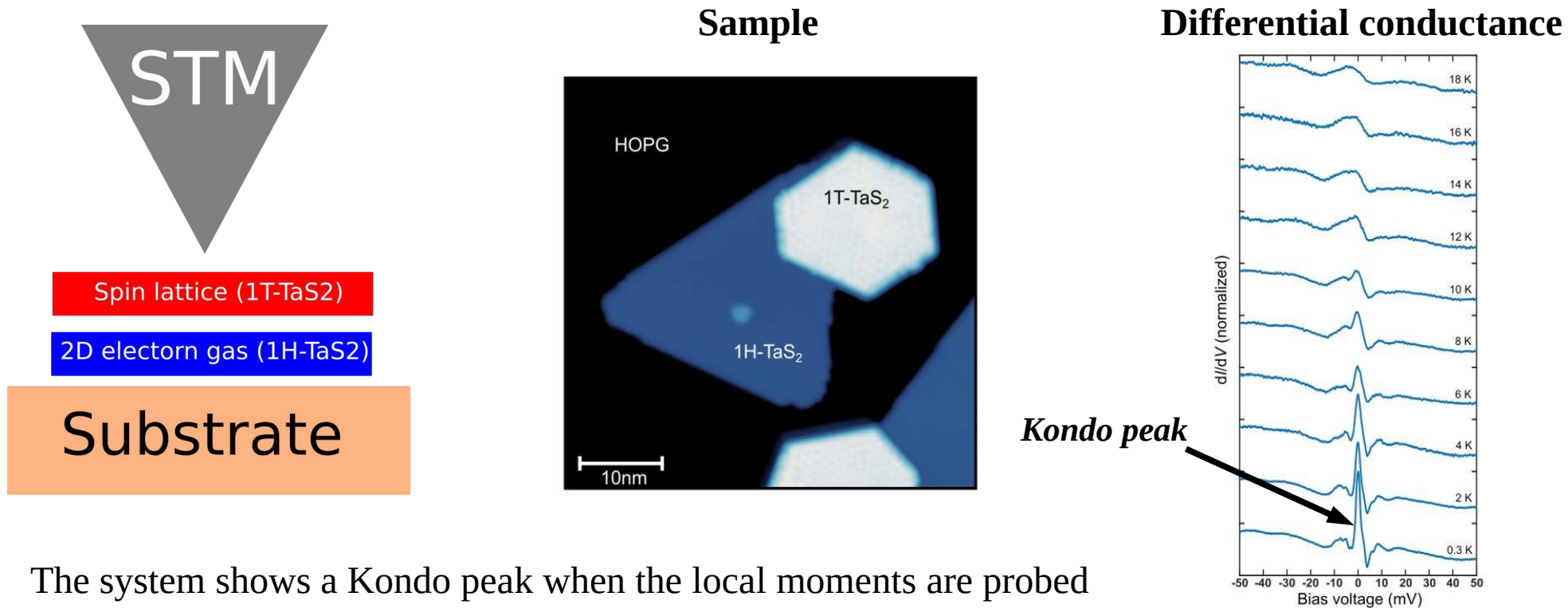
Probing the Kondo peak



Probing the heavy-fermion gap



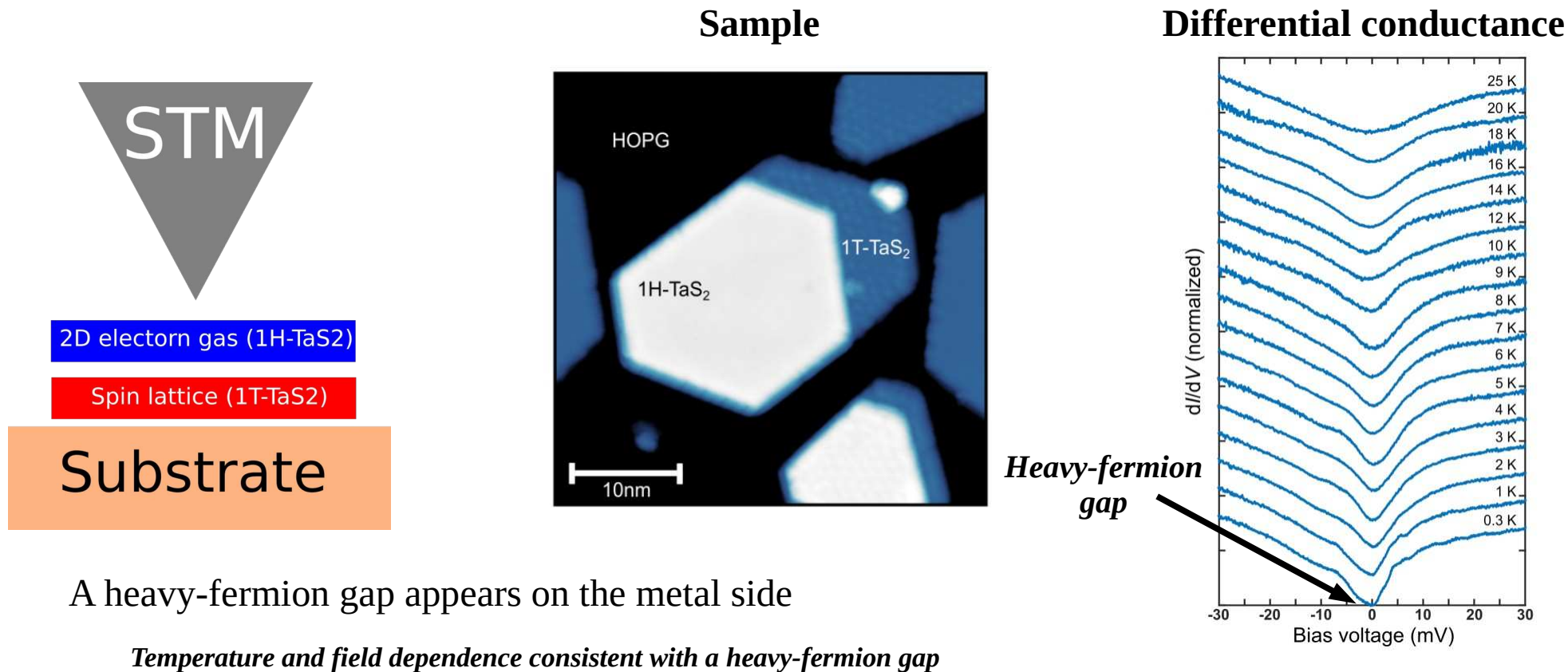
Kondo physics in the magnetic lattice



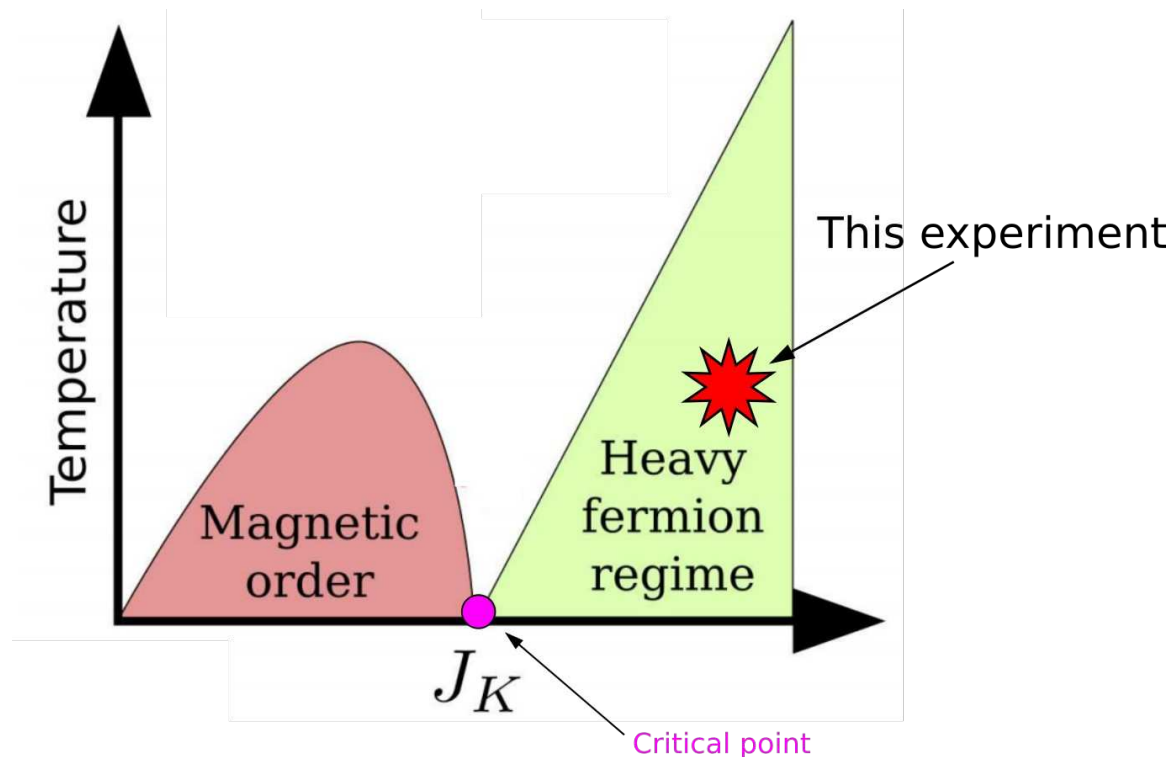
The system shows a Kondo peak when the local moments are probed

Temperature and field dependence consistent with Kondo

Heavy-fermion gap in the 2D electron gas



Next steps in van der Waals heavy-fermions

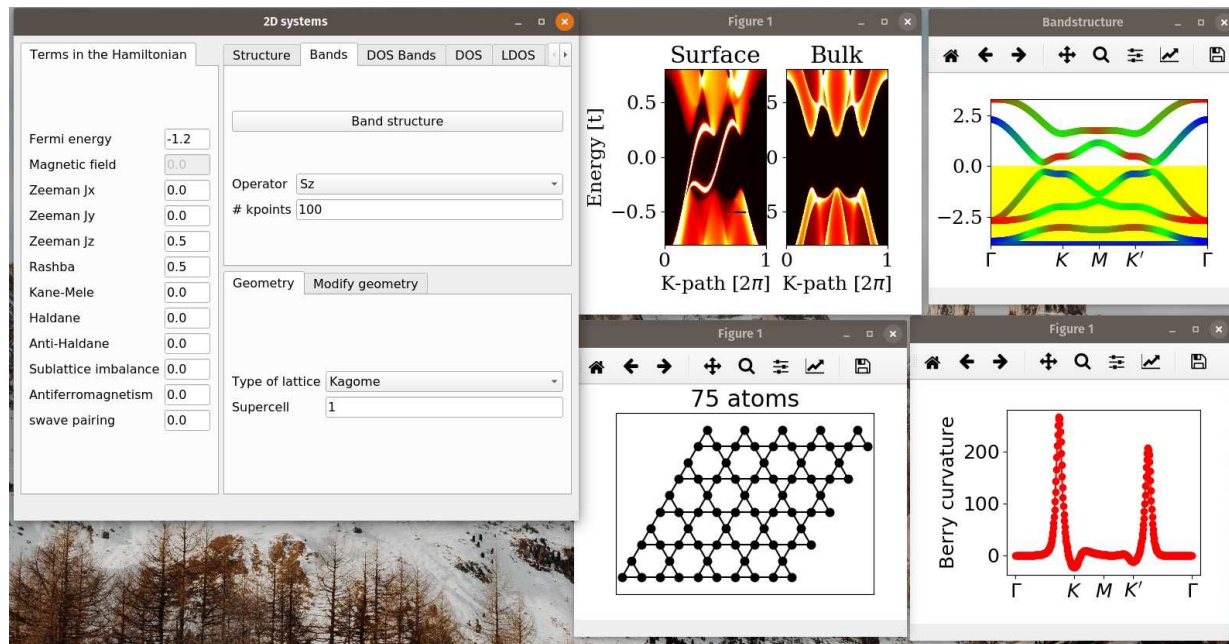


Can we push this system to the critical and ultimately topological superconducting regimes?

(twist, material engineering, gating, etc...)

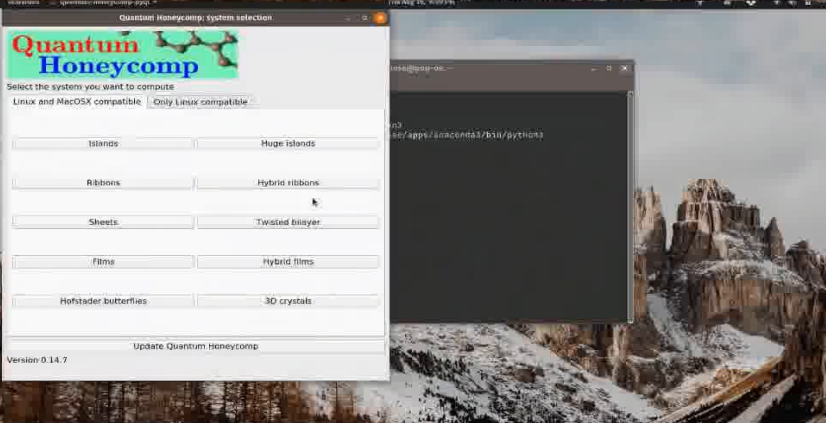
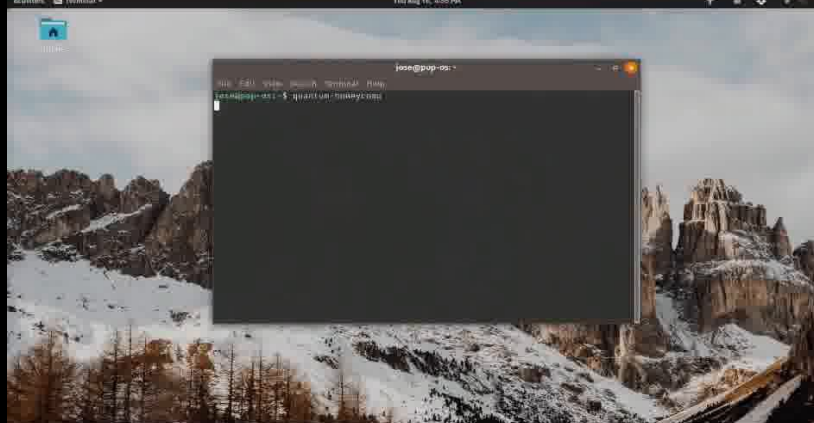
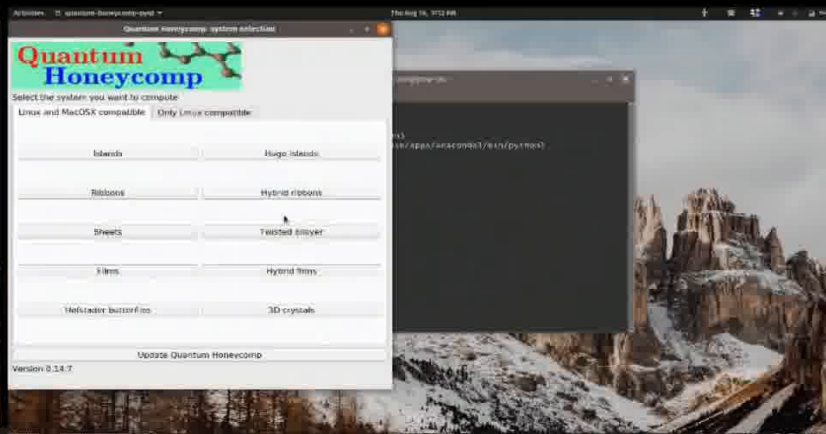
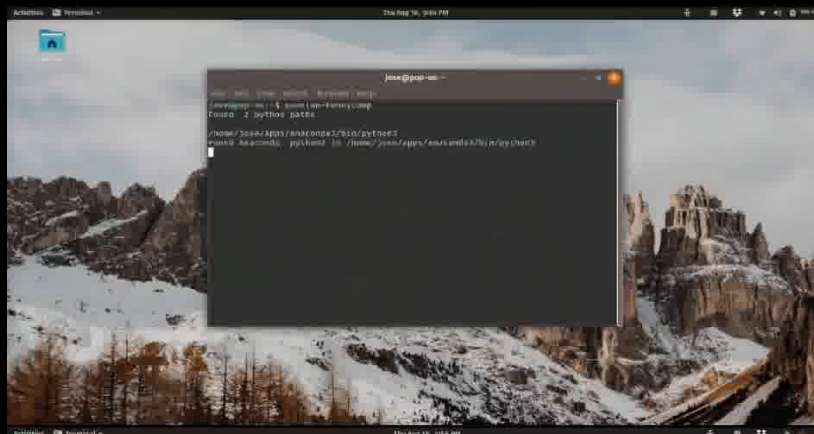
Computing electronic properties

A user interface to compute electronic properties

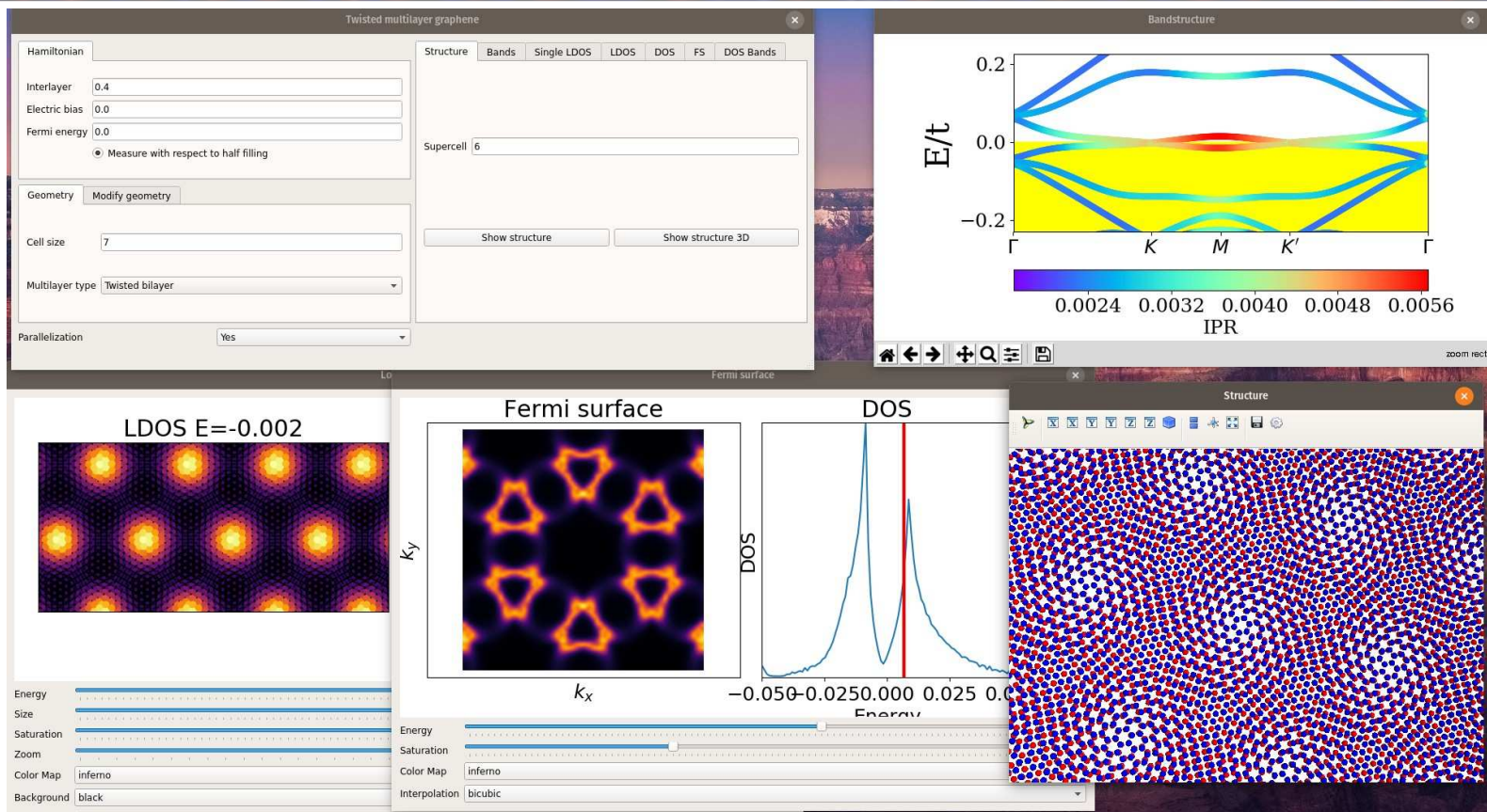


Quantum Honeycomp: open source interactive interface for tight binding modeling

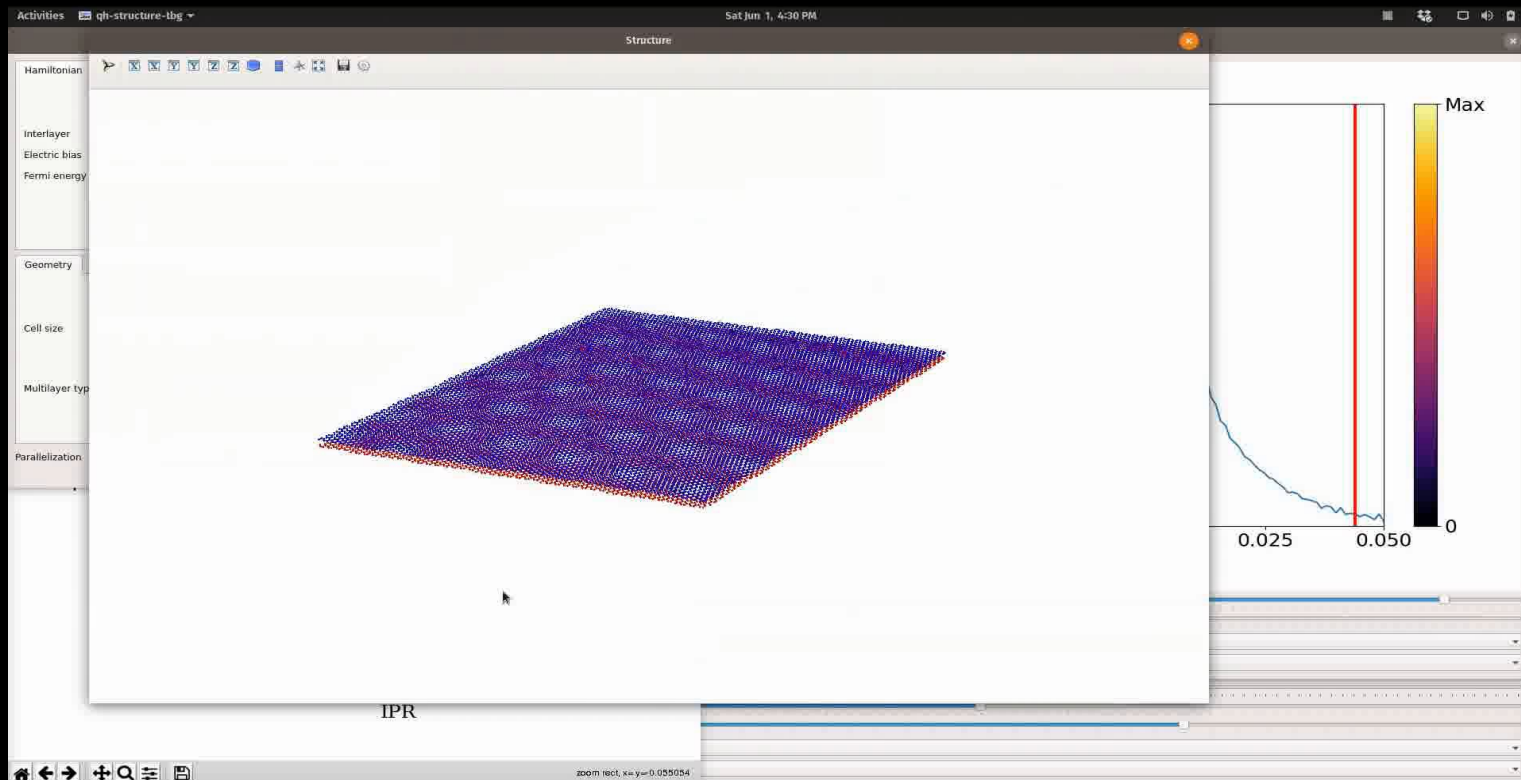
<https://github.com/joselado/quantum-honeycomp>



Twisted bilayer with the user interface

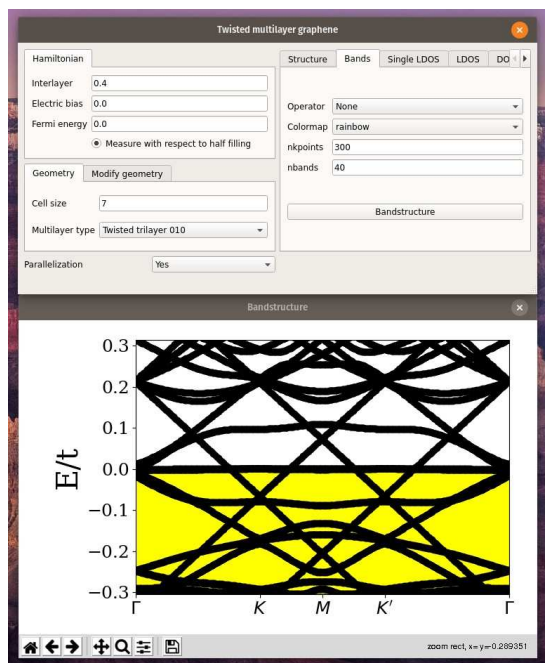


<https://github.com/joselado/quantum-honeycomp>

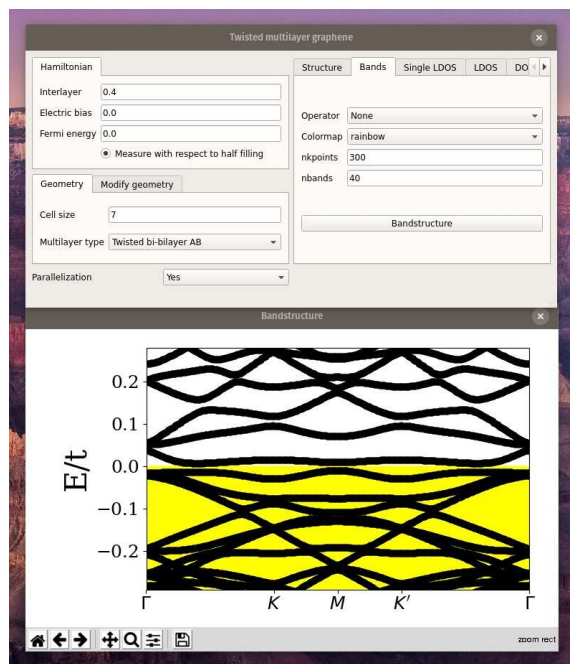


Twisted multilayers

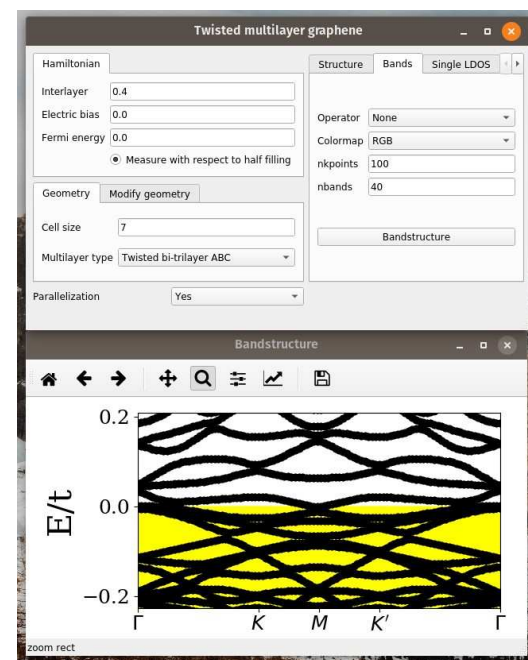
Twisted trilayer graphene



Twisted bi-bilayer graphene

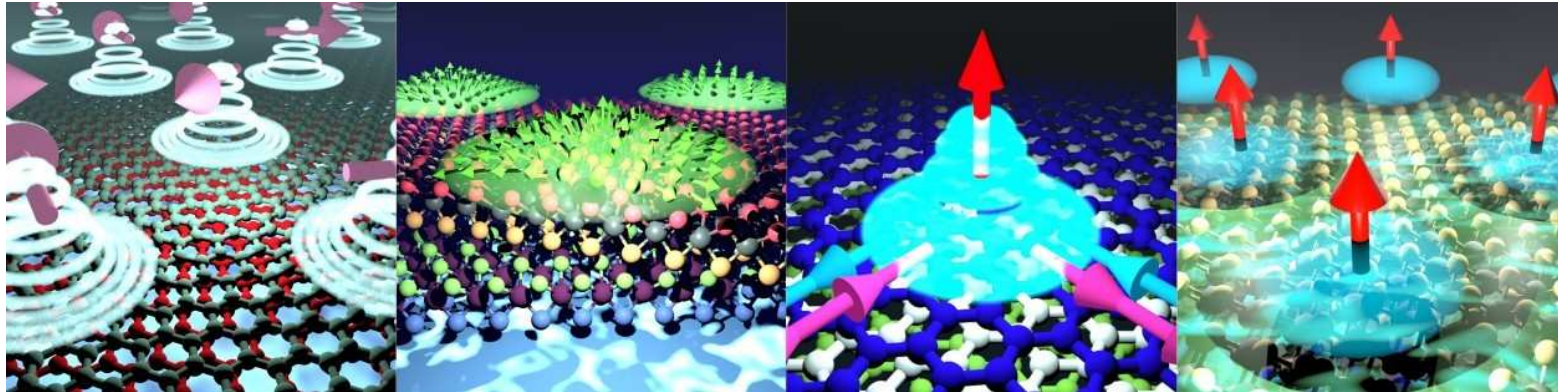


Twisted bi-trilayer graphene



Take home

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



Phys. Rev. Lett. 126, 056803 (2021)
arXiv:2105.04502 (2021)
arXiv:2102.03312 (2021)
arXiv:2103.11989 (2021)

Thank you!

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SUOMEN
AKATEMIA