Designing correlated quantum matter with magnetic twisted van der Waals heterostructures

Jose Lado
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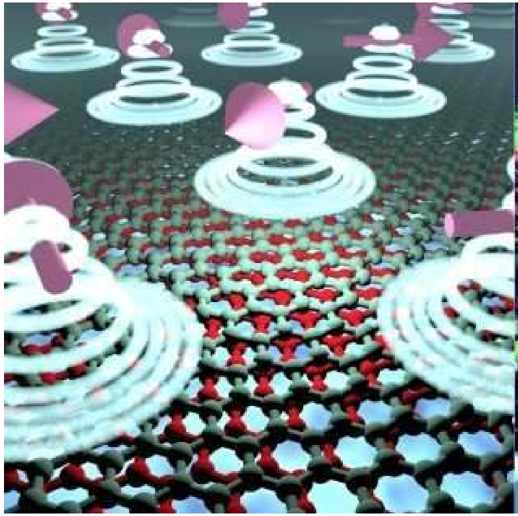
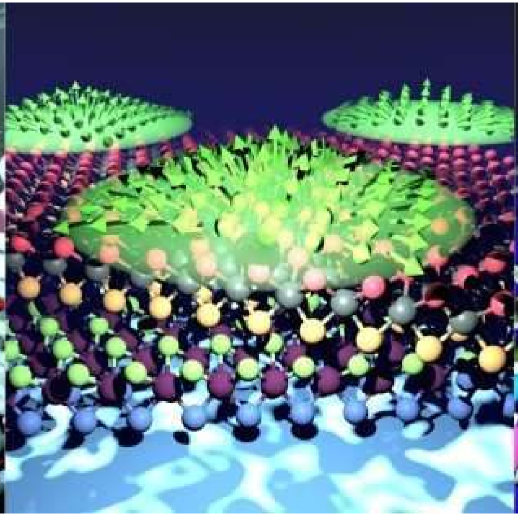
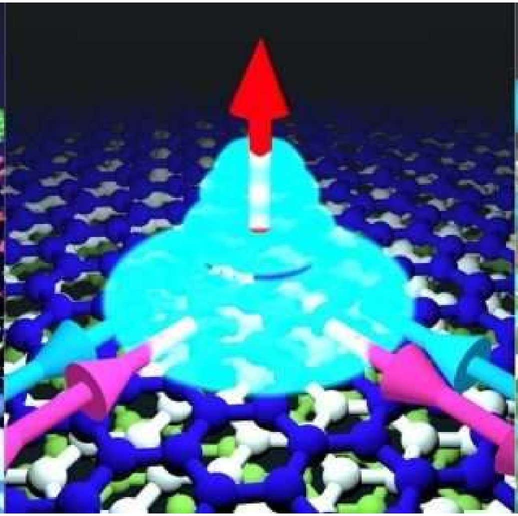


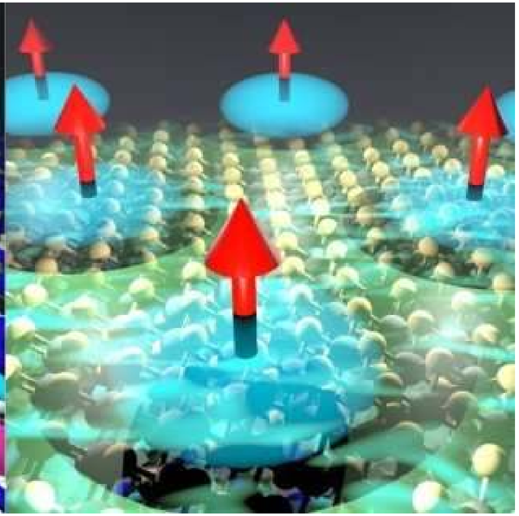
Phys. Rev. Lett. 126, 056803 (2021)



New J. Phys. 23 073038 (2021)



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

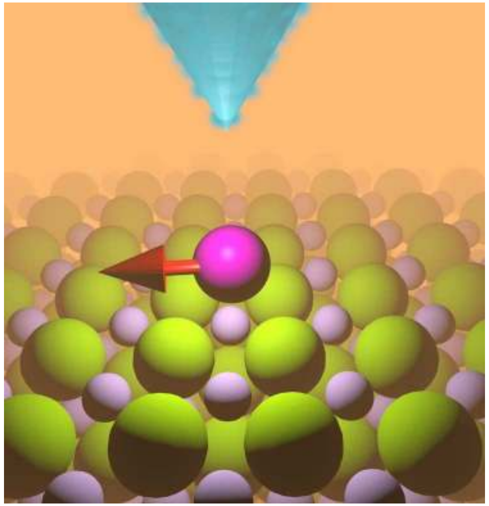


arXiv:2103.11989 (2021)

Moiré-Twistronics workshop, UK, August 13th 2021

Building quantum matter with artificial lattices

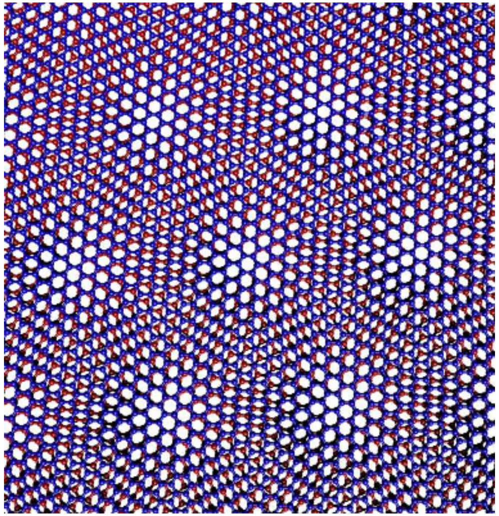
Atomic lattices



a = 0.5 nm

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

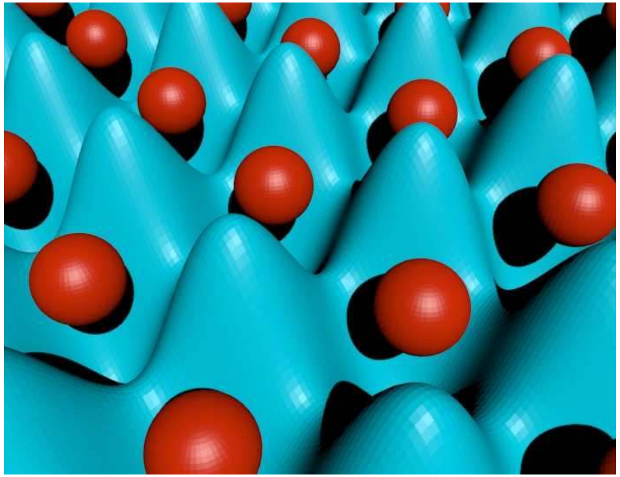
Twisted 2D moire materials



a = 30 nm

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

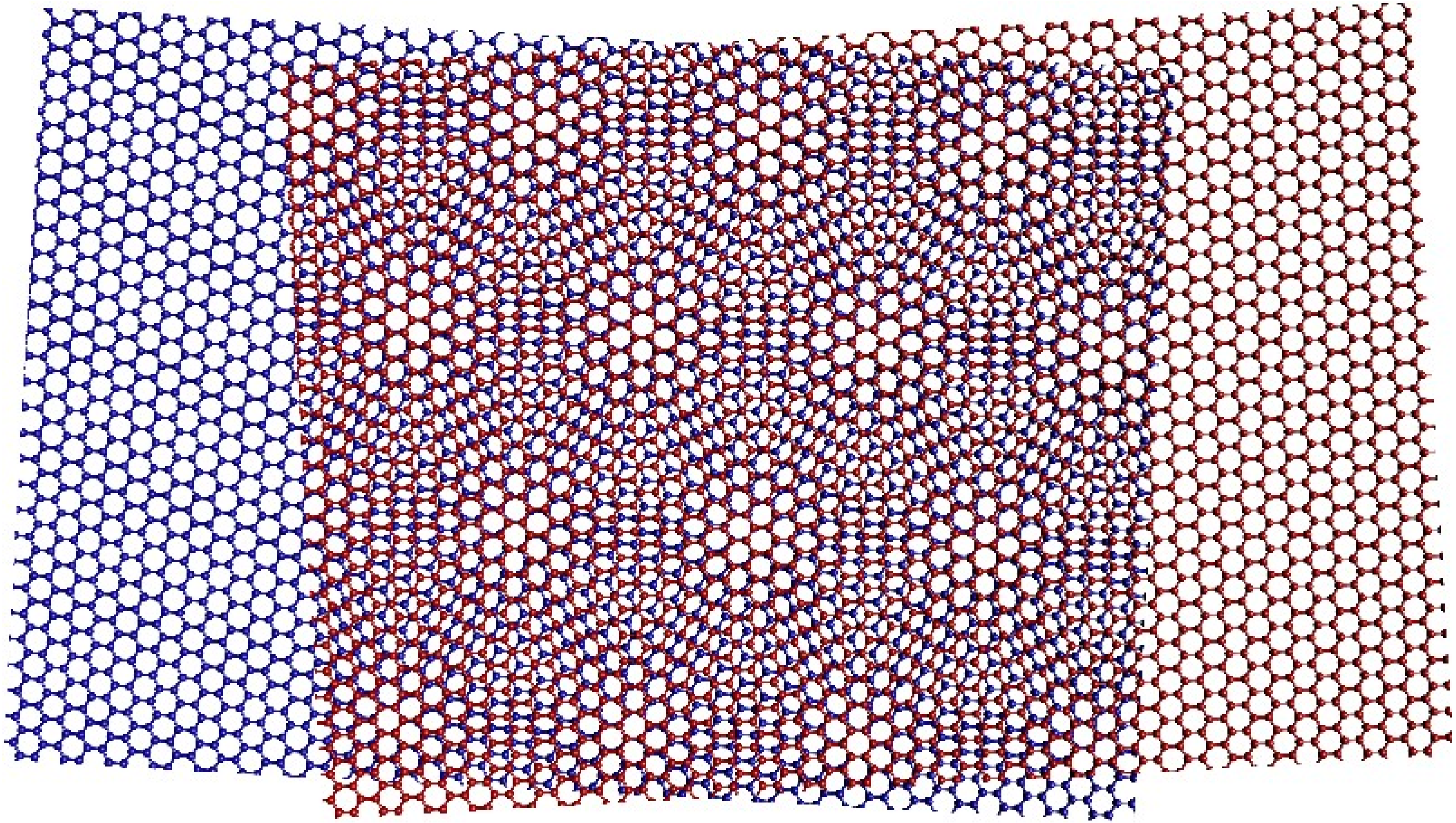
Cold atoms



a = 1000 nm

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

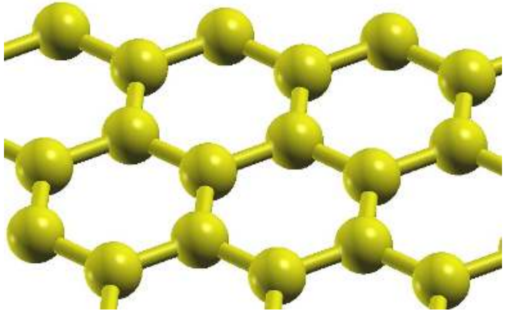
Twisted 2D materials as a platform for artificial quantum matter



The two-dimensional materials world

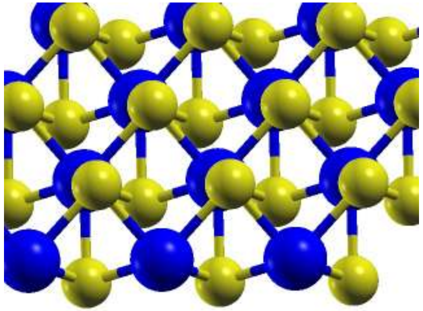
Semimetal

Graphene



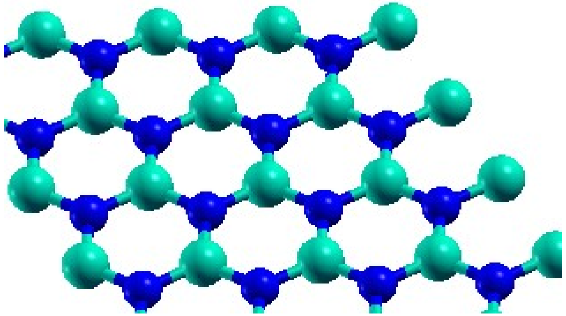
Superconductor

$NbSe_2$



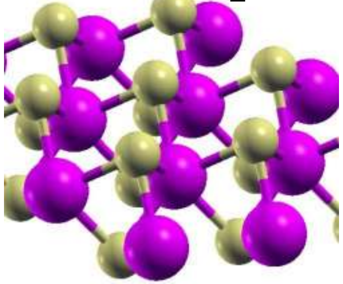
Insulator

BN



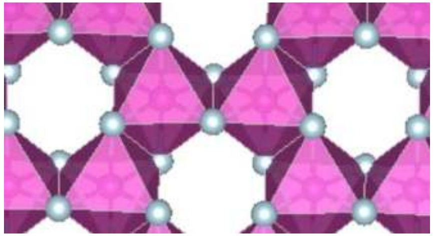
Semiconductor

WSe_2



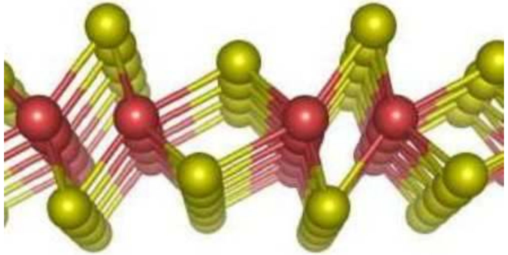
Ferromagnet

CrI_3



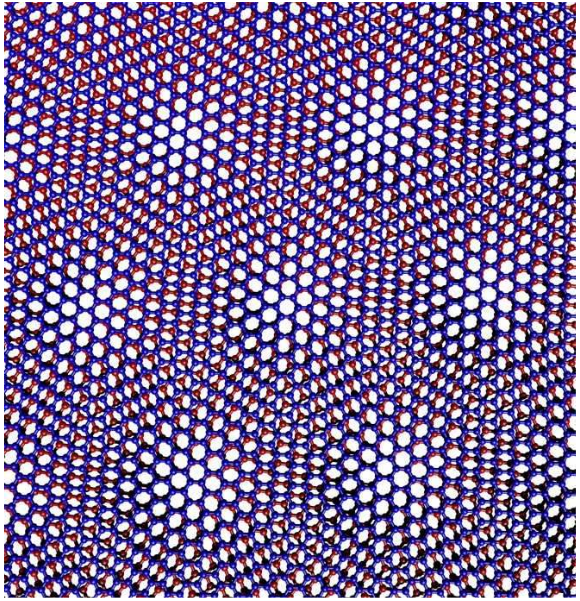
Quantum spin Hall insulator

WTe_2

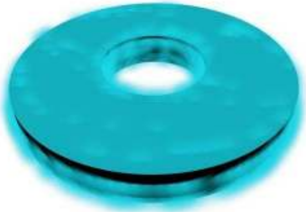


One material, a zoo of electronic phases

Twisted bilayer graphene



Superconductivity

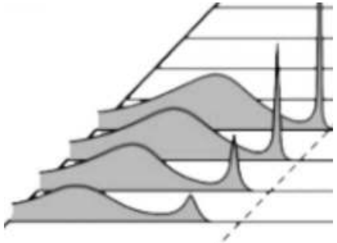


Nature 556, 43–50 (2018)

Topological networks

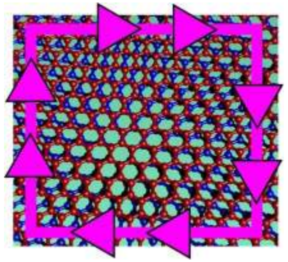
Nano Lett. 18, 11, 6725-6730 (2018)

Strange metals



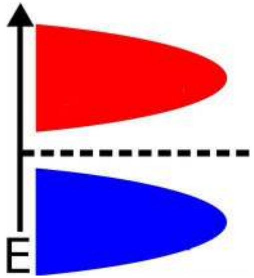
Phys. Rev. Lett. 124, 076801 (2020)

Chern insulators



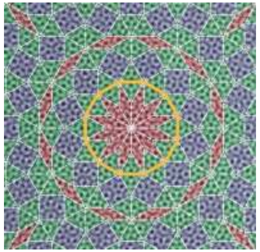
Science 365, 605-608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

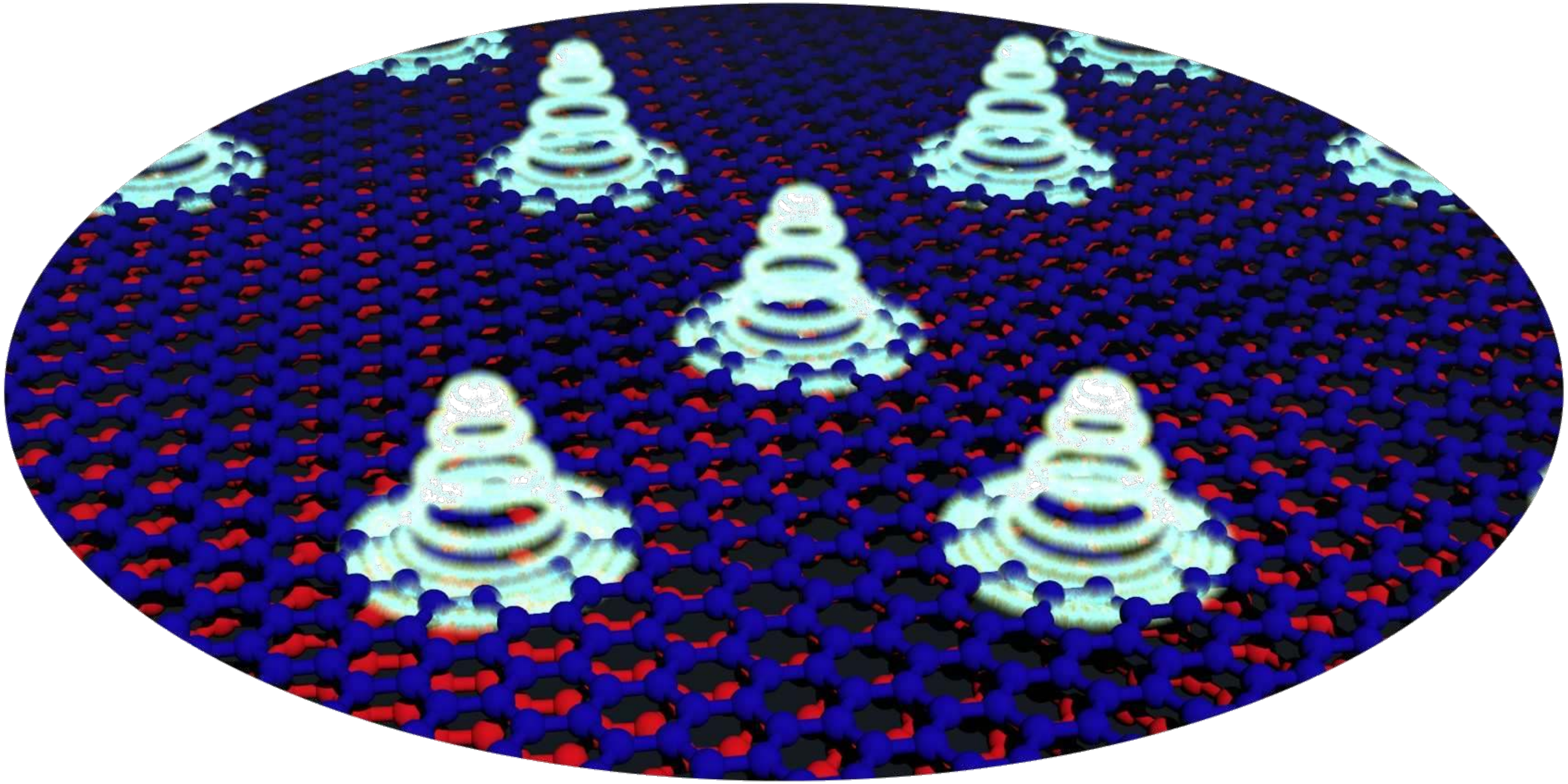
Quasicrystalline physics



Science 361 782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

A new universe in each new twisted material



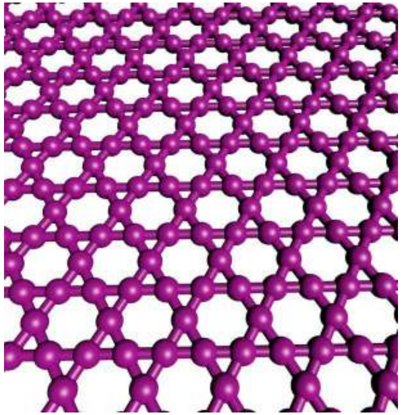
Each twisted material is a new universe for electrons, with laws that change from twist to twist

Designing quantum matter in twisted materials

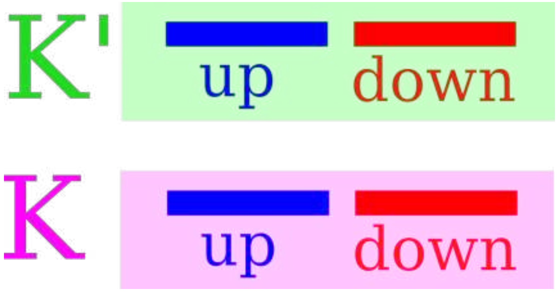
The strength of electronic correlations

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

The details of the electronic dispersion



The local quantum degrees of freedom



Twist angle control

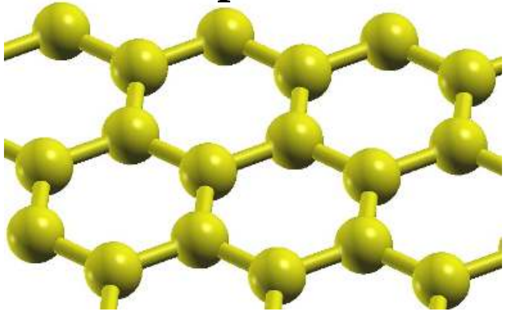
Interlayer bias

<u>Magnetic encapsulation</u>

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

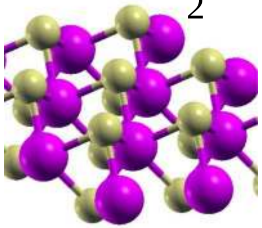
Designing quantum matter with twisted magnetic van der Waals materials

Graphene



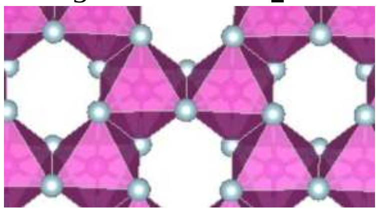
Semiconductor

WSe_2



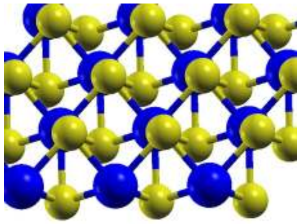
Magnet

$CrBr_3$, 1T-TaS_2, CrI_3



Metal

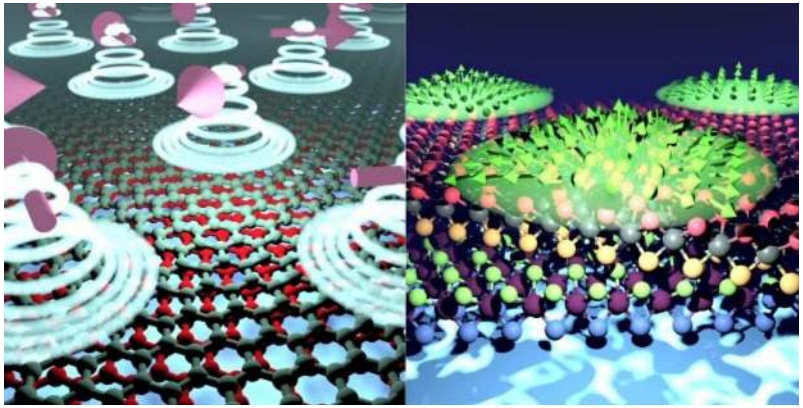
1H-TaS_2



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

Today's plan

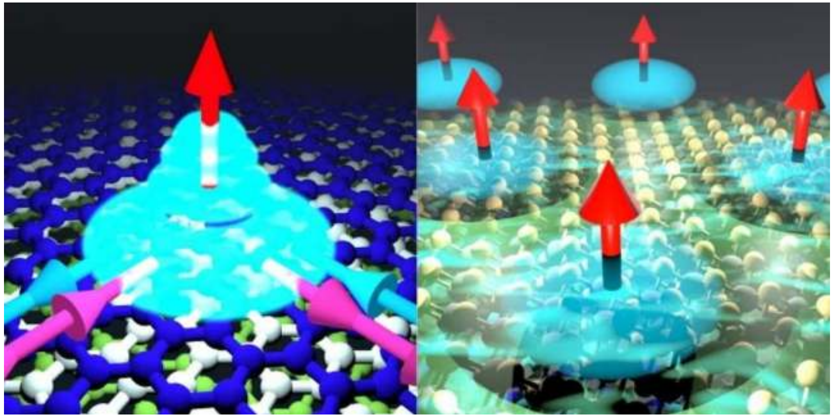
Design of new correlated states by magnetic encapsulation in twisted materials



theory

Phys. Rev. Lett. 126, 056803 (2021)
New J. Phys. 23 073038 (2021)

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

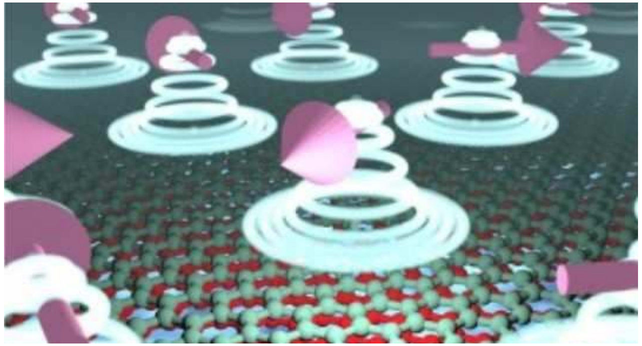


theory & experiment

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

Behind the scenes

Valley-mixing correlations in CrI_3/twisted BG/CrI_3



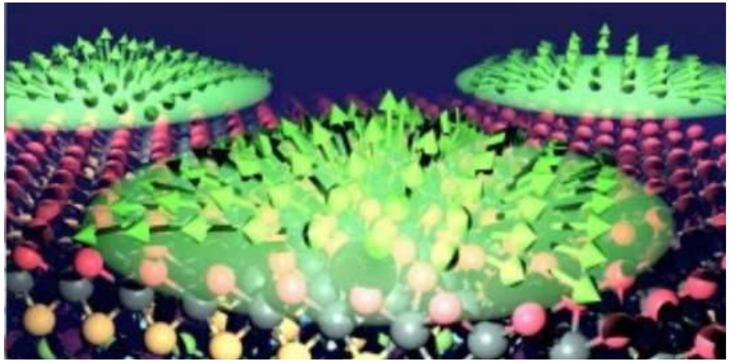
Tobias Wolf

Gianni Blatter

Oded Zilberberg

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

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

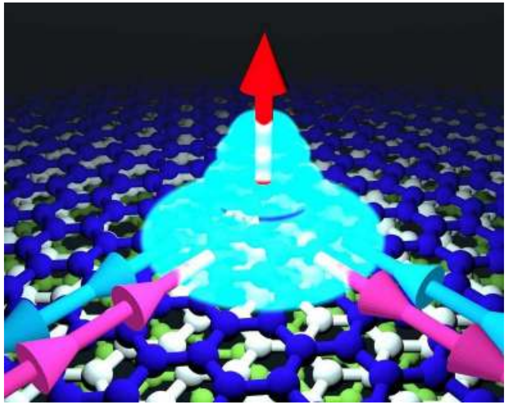


David Soriano

New J. Phys. 23 073038 (2021)

Behind the scenes

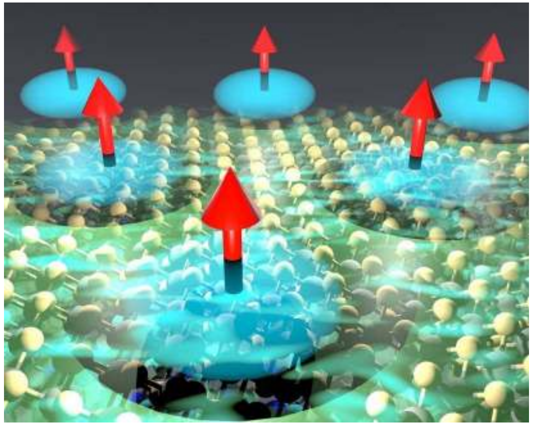
Heavy fermions in twisted graphene trilayers



Aline Ramires

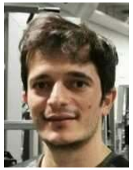
Phys. Rev. Lett. 127, 026401 (2021)

Heavy fermions in twisted dichalcogenide bilayers



S. Ganguli

M. Amini



G. Chen

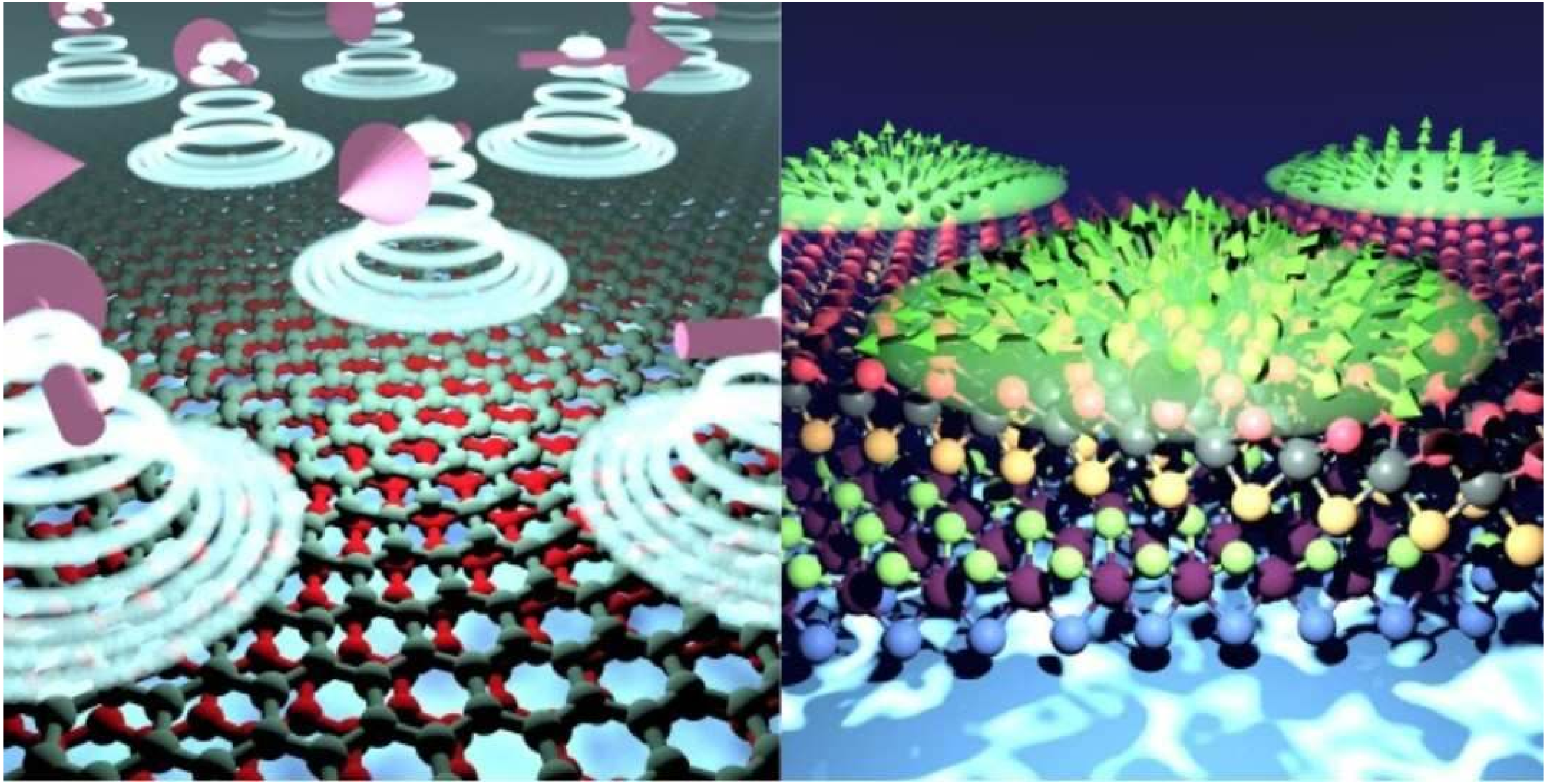
V. Vaňo

S. Kezilebieke

P. Liljeroth

arXiv:2103.11989 (2021)

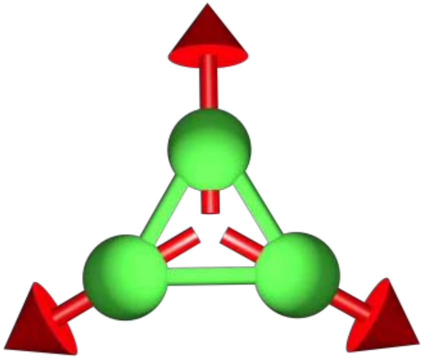
Design of new correlated states by magnetic encapsulation in twisted materials

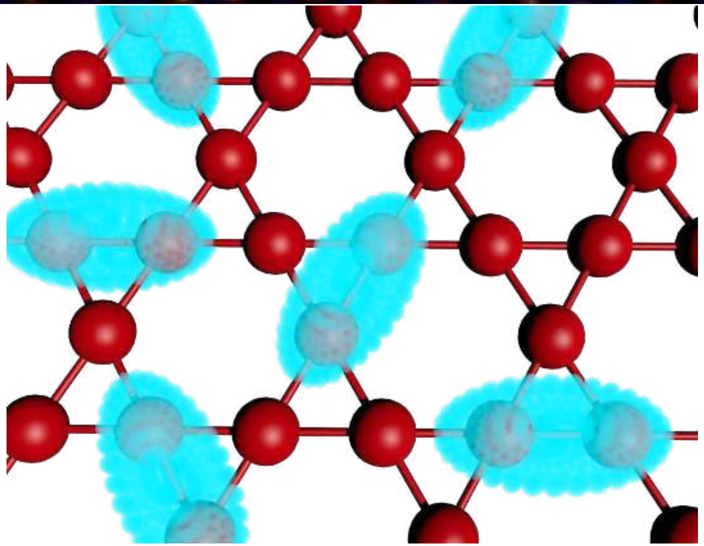


Frustration

What is the best that frustration can bring?

Frustrated magnetism





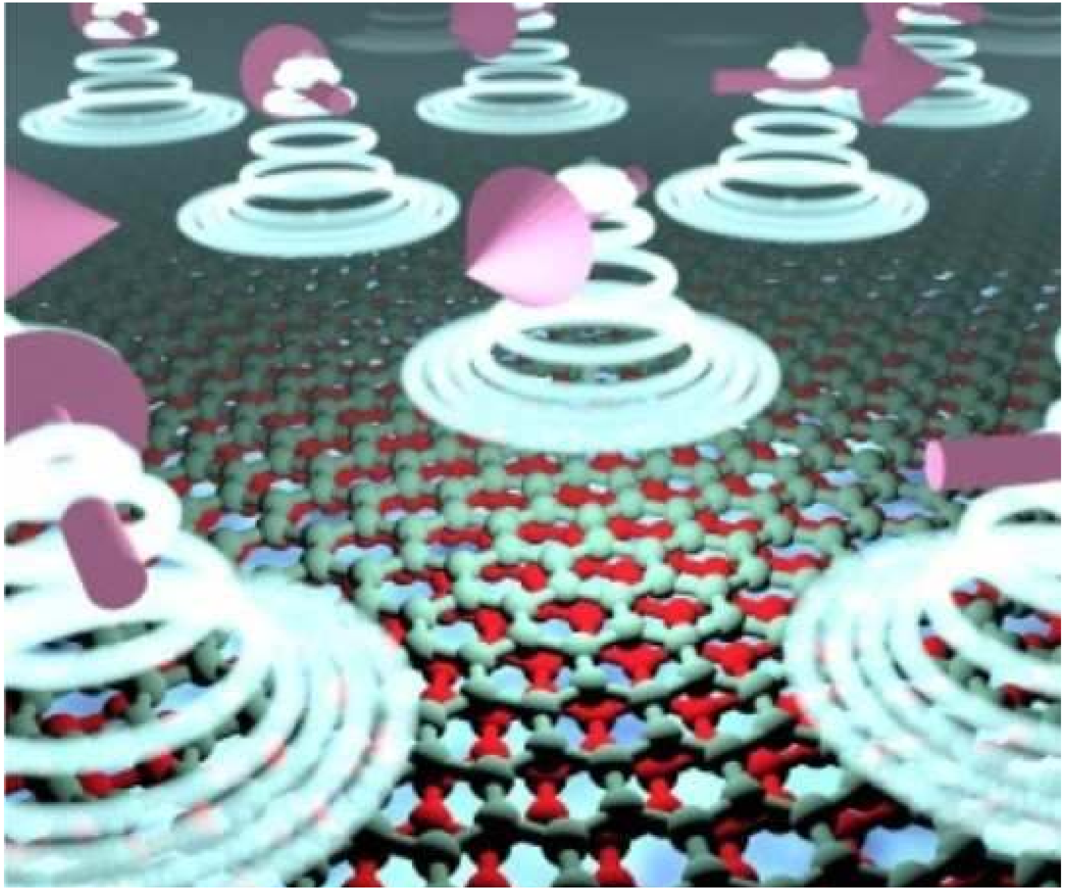
 $\equiv |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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

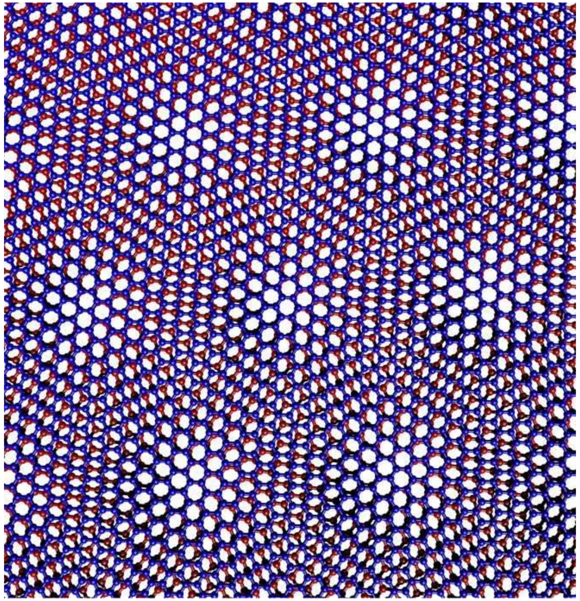
Gianni
Blatter

Oded
Zilberberg

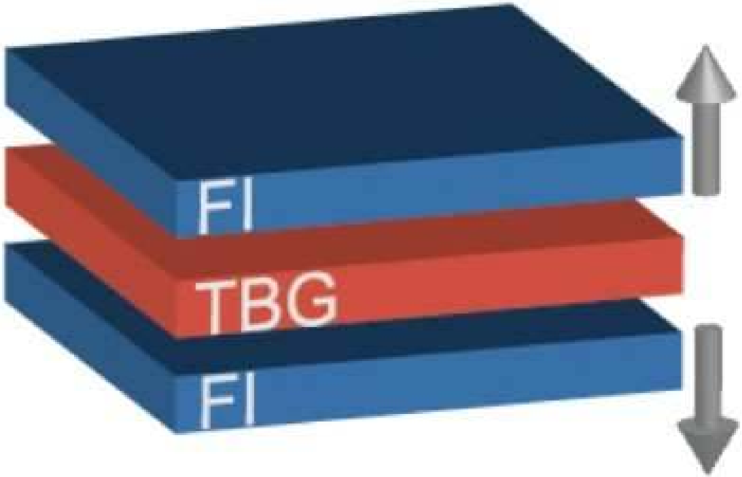
Phys. Rev. Lett. 126, 056803 (2021)

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

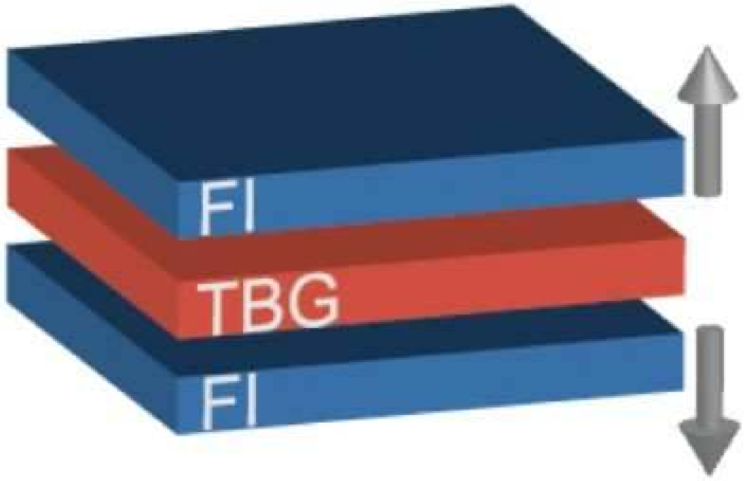
Magnetic encapsulation

$$H = H_0 + H_\mathrm{J} + H_\mathrm{R}$$

Kinetic energy

Exchange proximity effect

Rashba spin-orbit coupling



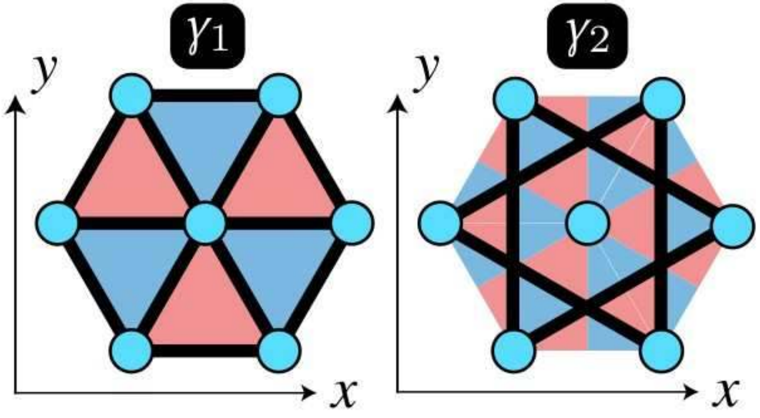
Valley frustration from combined twist engineering, exchange proximity and spin-orbit coupling.

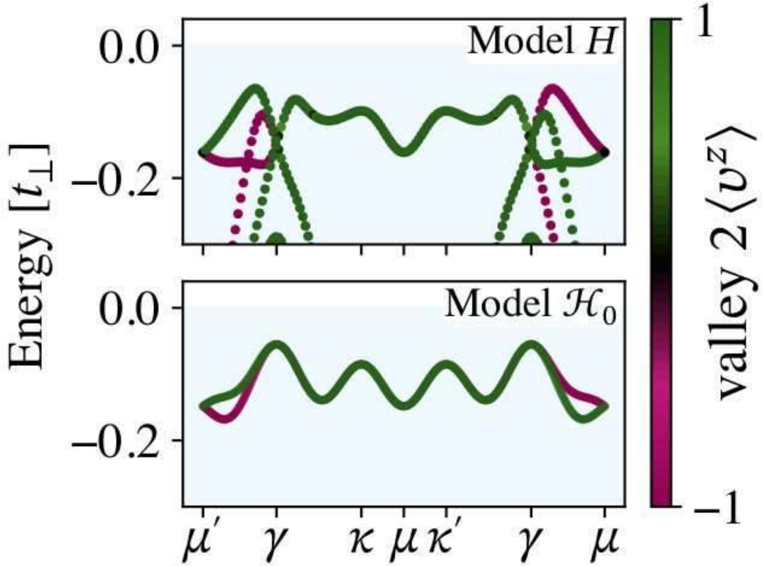
Lets focus on the regime $\alpha = 1.3^\circ - 2^\circ$

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

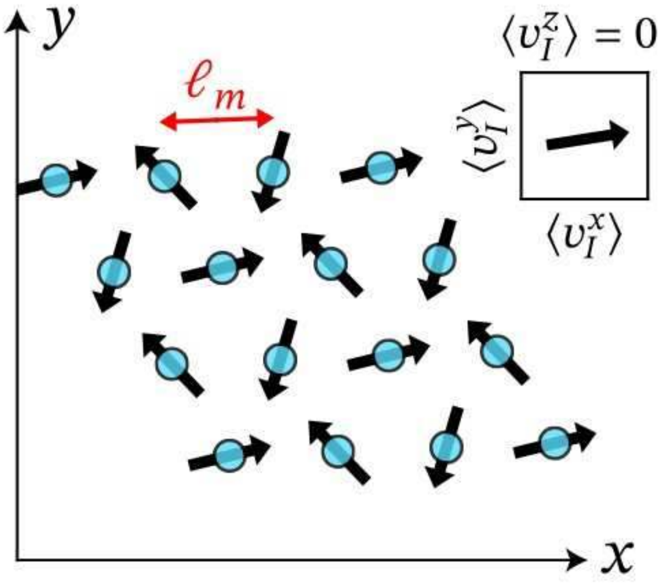
Impact of interactions

Lets add electronic interactions

Free Hamiltonian

Electronic interactions

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

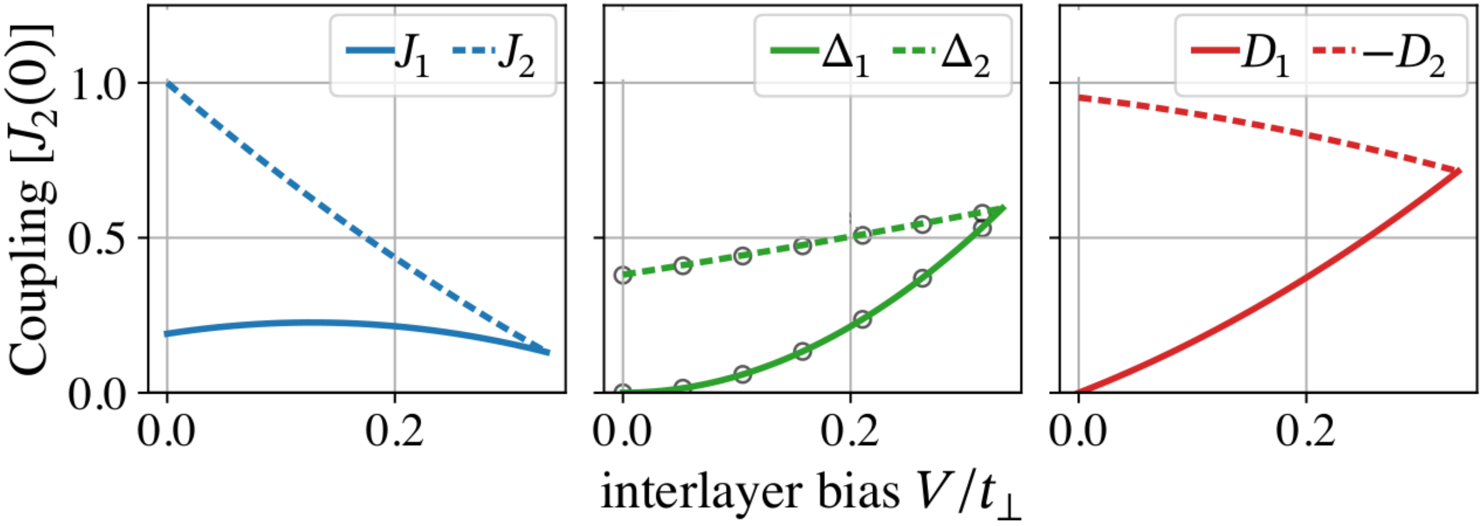


And compute the effective valley-Heisenberg Hamiltonian in the strong coupling limit

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

Controlling a valley-Heisenberg model electrically

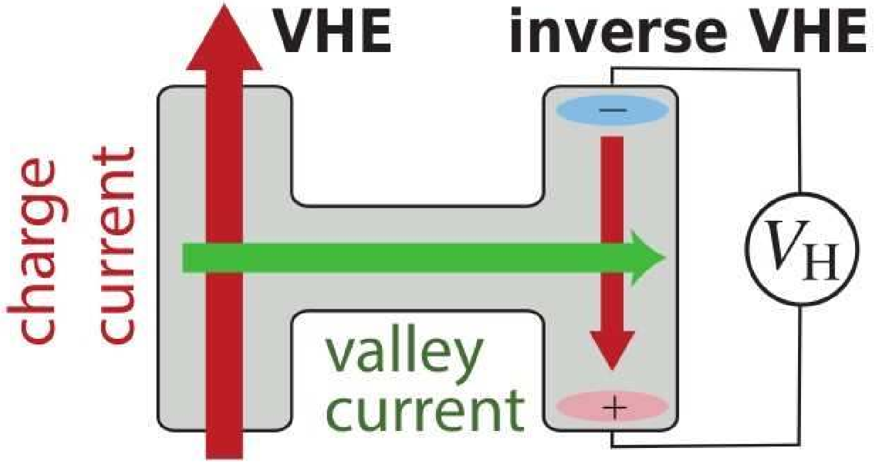
$$\mathcal{H}_v = \sum_{IJ} J_{IJ}\, \boldsymbol{v}_I \cdot \boldsymbol{v}_J + \Delta_{IJ}\, v_I^z v_J^z + \nu_{IJ}\, D_{IJ}\, (\boldsymbol{v}_I \times \boldsymbol{v}_J)_z$$



An interlayer bias provides a tunable anisotropic valley-Heisenberg model

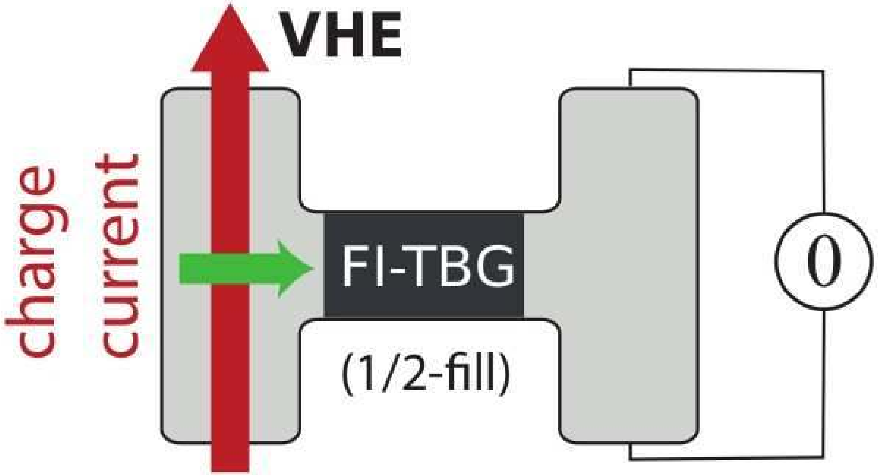
Detecting the valley spiral

No valley mixing



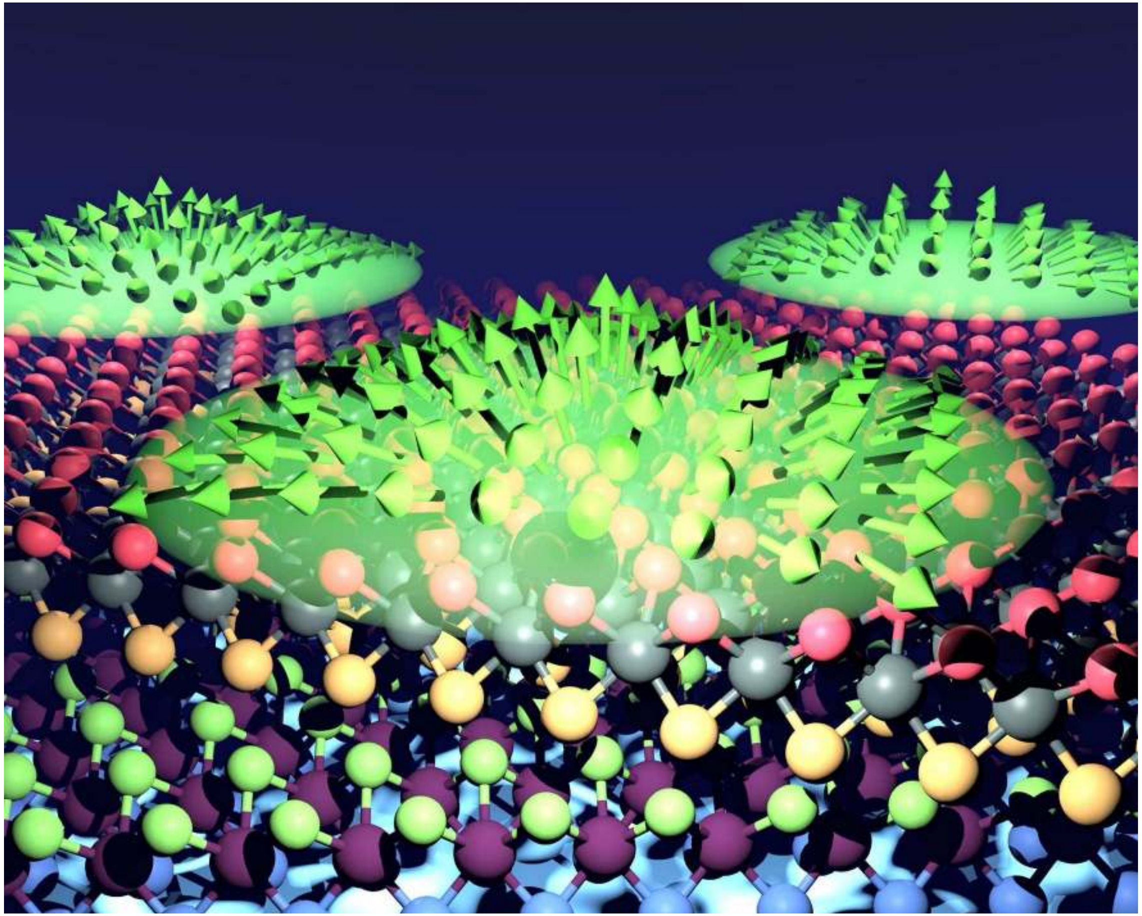
Finite non-local conductance

Finite valley mixing



Zero non-local conductance

Correlated states dominated by spin-orbit coupling in Janus dichalcogenides

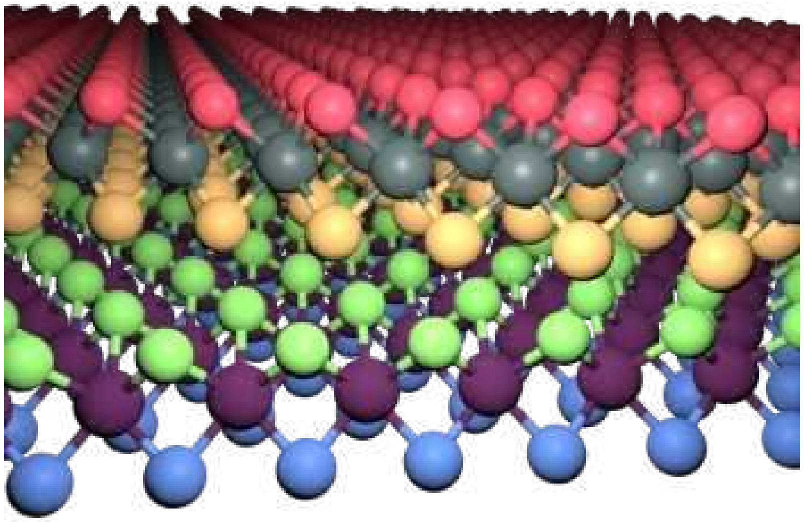


David Soriano

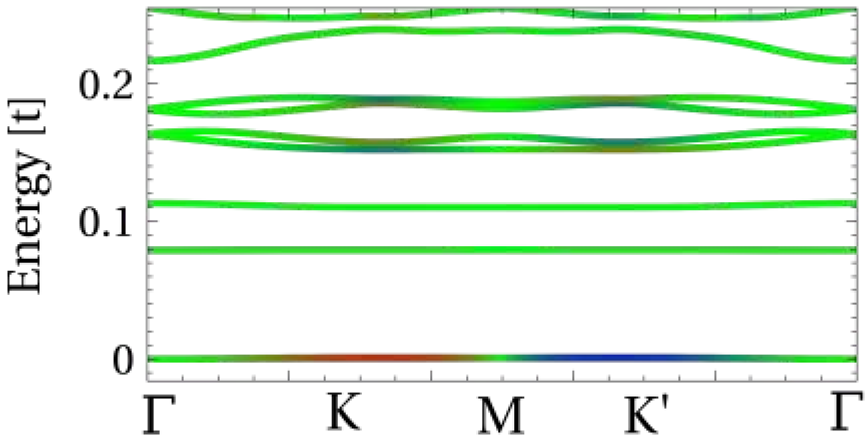
New J. Phys. 23 073038 (2021)

Twisted Janus bilayers

Twisted Janus bilayer

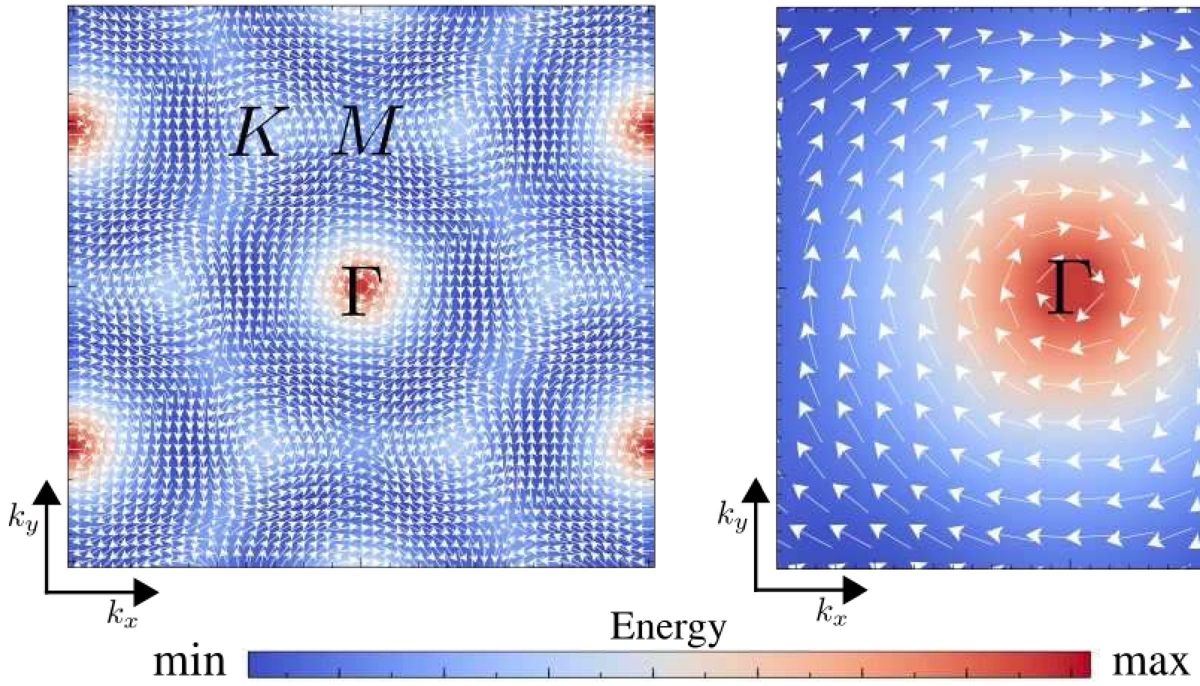


Band structure



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

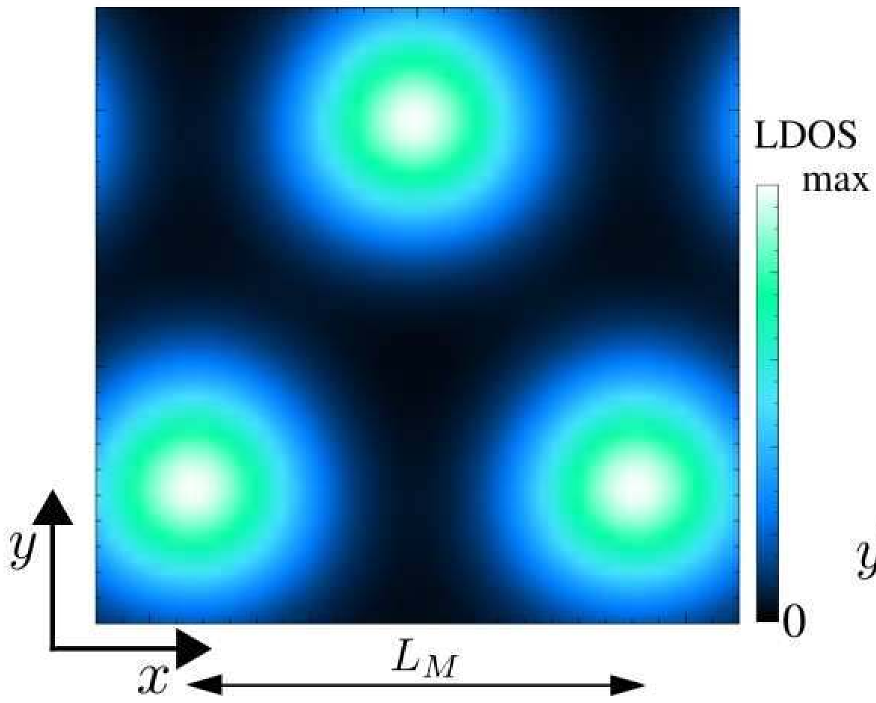
Reciprocal space texture of the flat bands



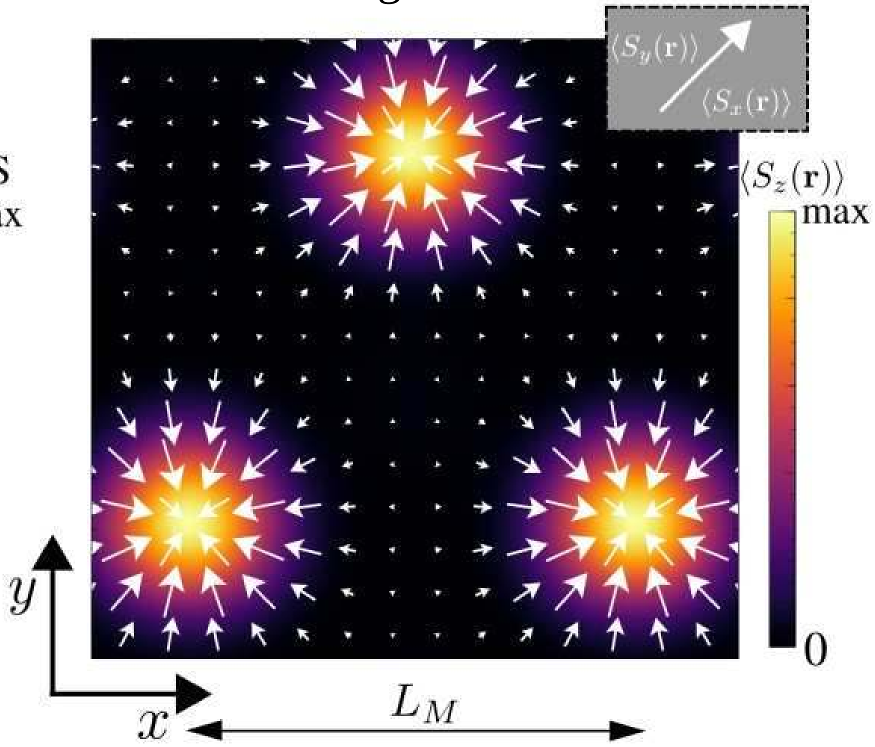
Flat bands are dominated by a strong spin-momentum texture, stemming form the Janus structure

Real space profile when including interactions

Electronic density

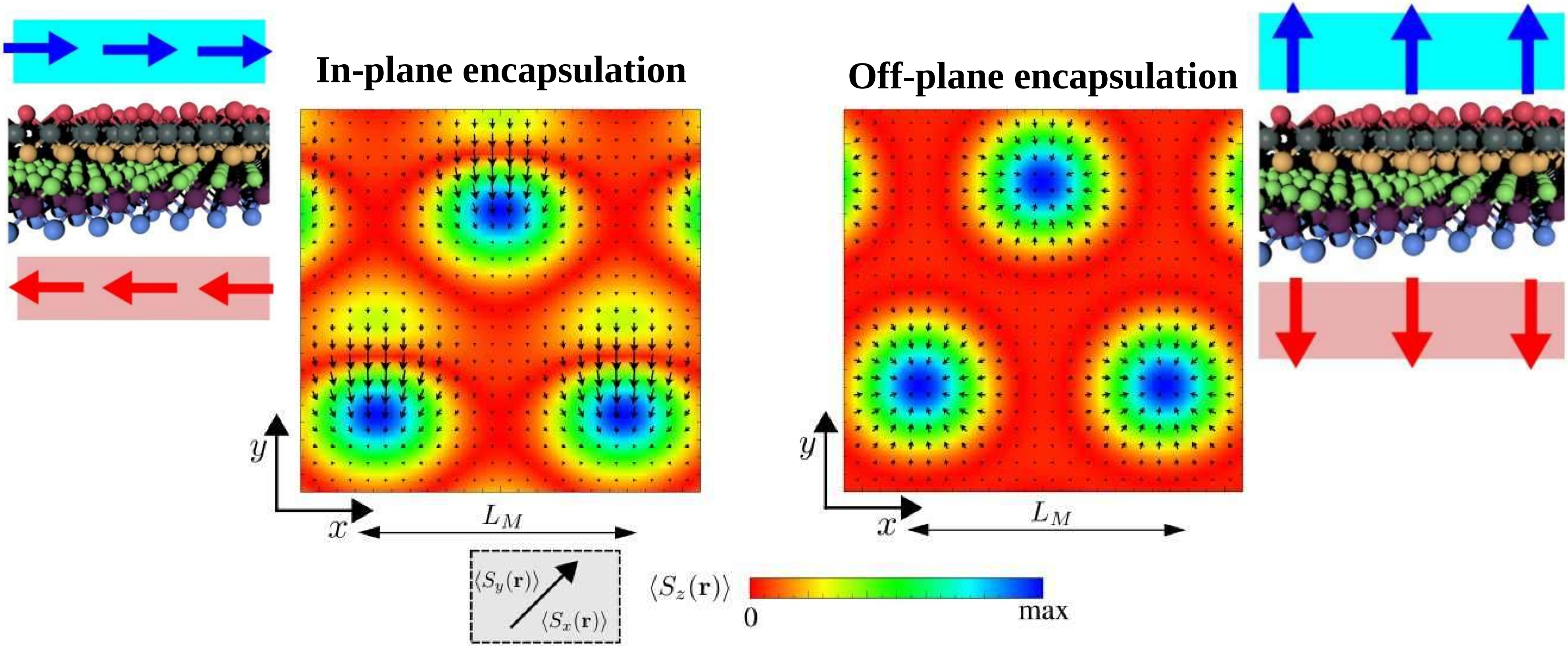


Magnetism



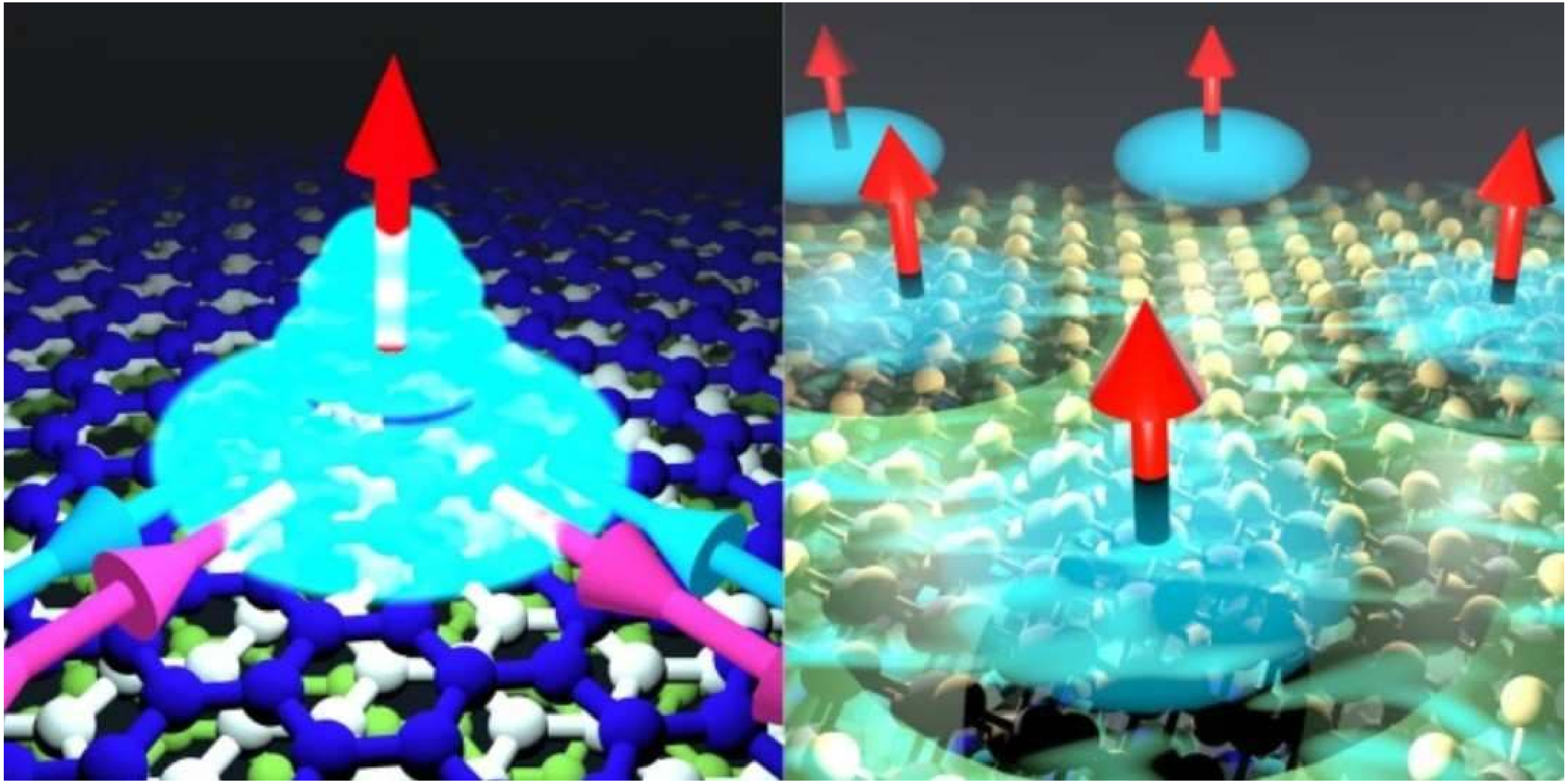
A moire meron magnetic structure appears due to the presence of interactions

Control by magnetic encapsulation



Magnetic moire merons controlled by the magnetic encapsulation

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



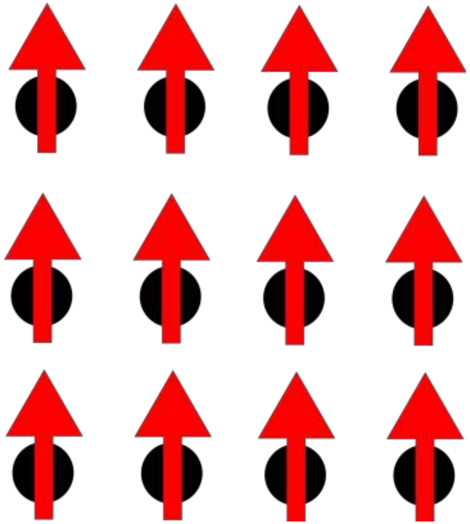
Basics of heavy fermion physics

- 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



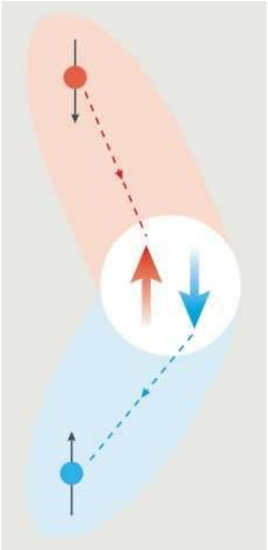
f-electrons in
rare-earth compounds

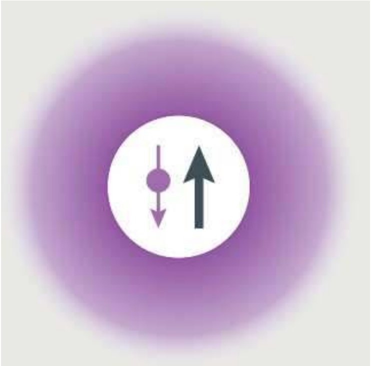
Dispersive electron gas

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

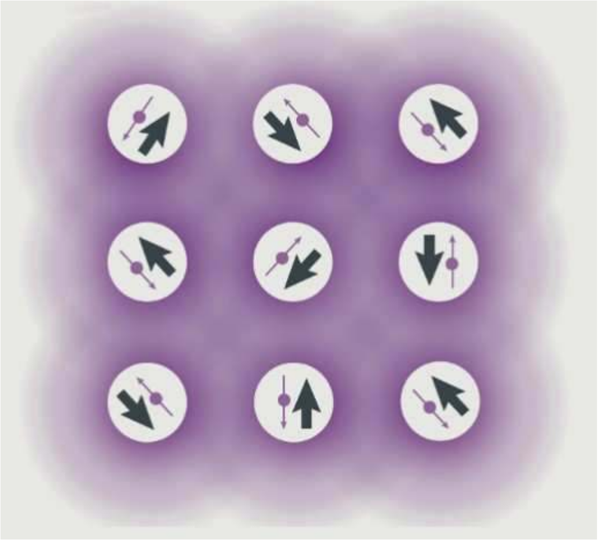
Basics of heavy fermion physics

Conduction electrons form Kondo singlets with the impurities



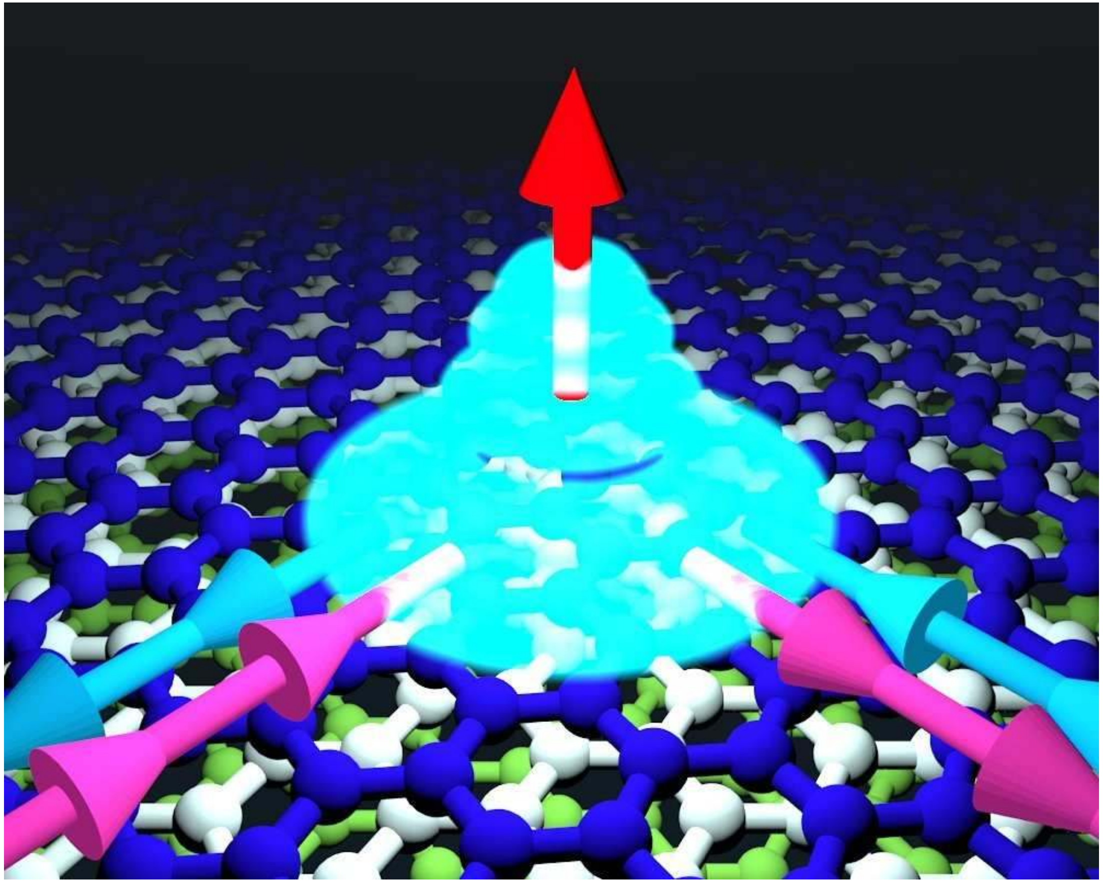


Kondo-lattice model



Associated with Kondo lattice physics:
- Colossal mass enhancement of electrons
- Quantum criticality
- Unconventional (topological) superconductivity

Heavy-fermions in twisted graphene trilayers

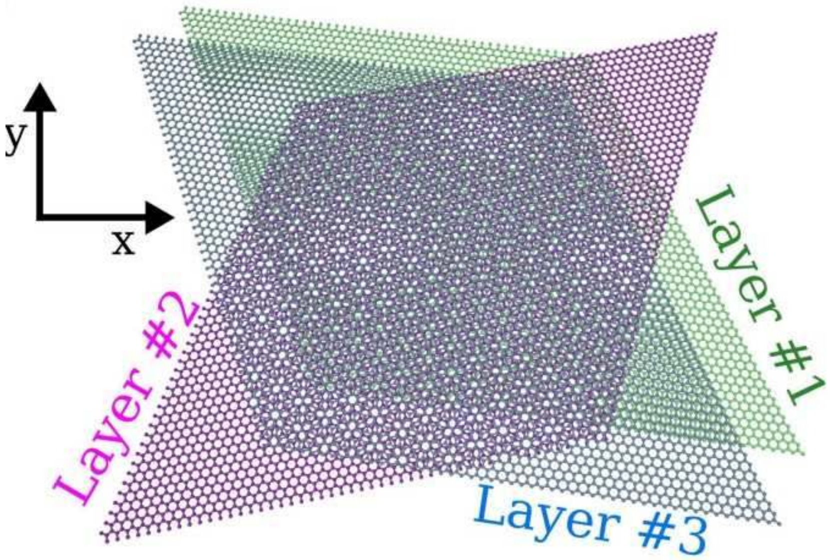


Aline Ramires

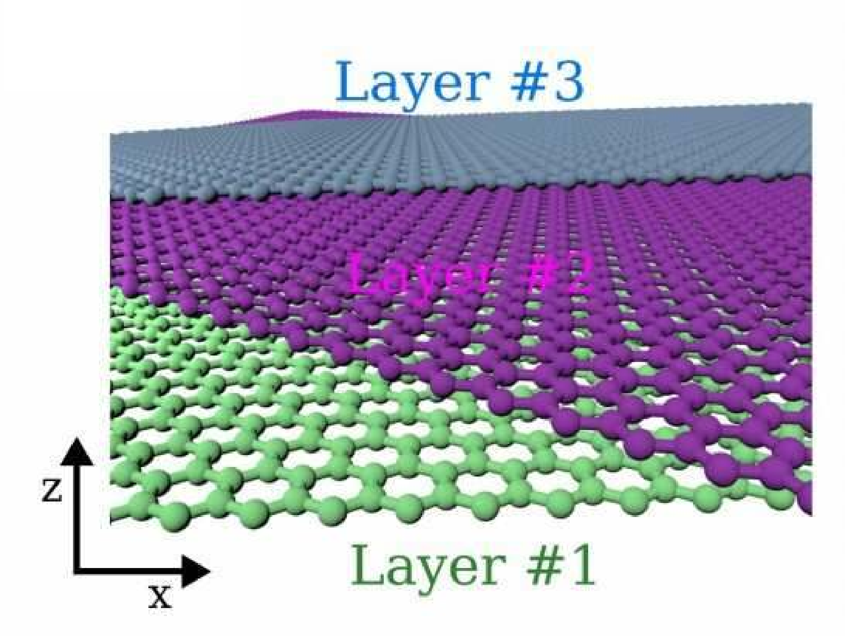
Phys. Rev. Lett. 127, 026401 (2021)

Heavy-fermions in twisted graphene trilayers

Top view

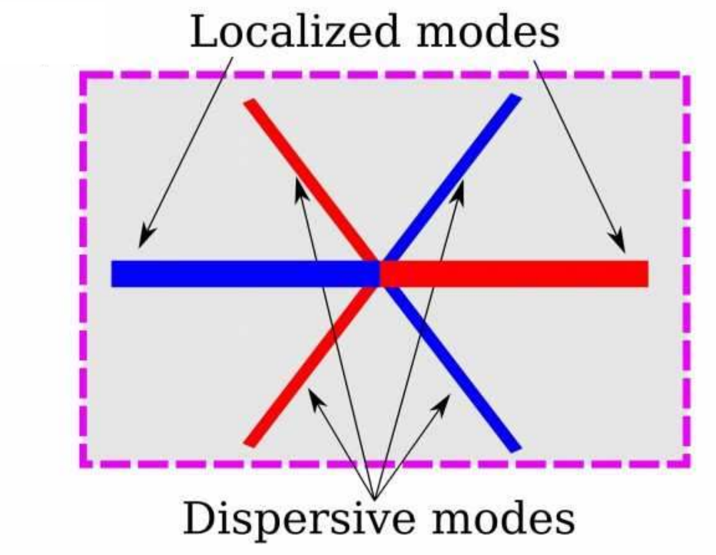


Lateral view

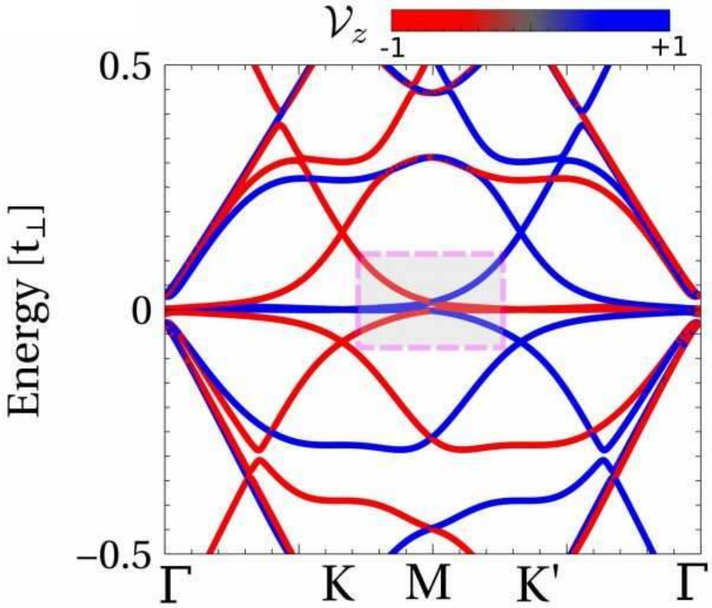


Heavy-fermions in twisted graphene trilayers

Low energy model

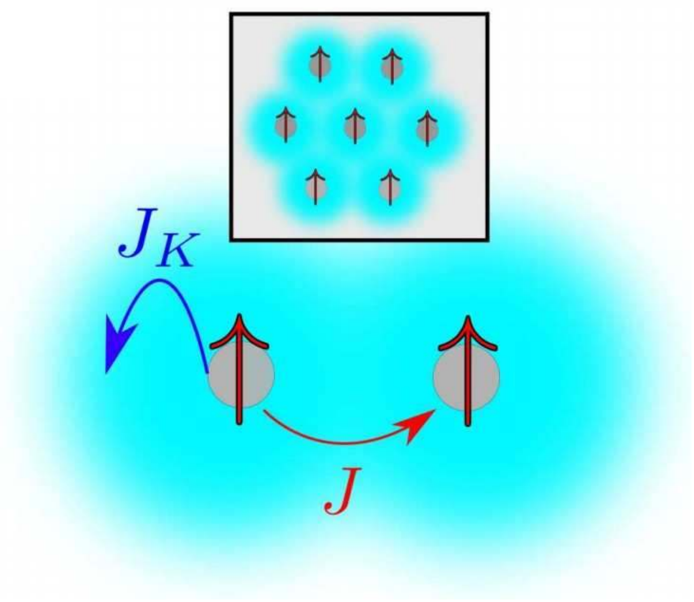


Electronic structure in the presence of an electric bias

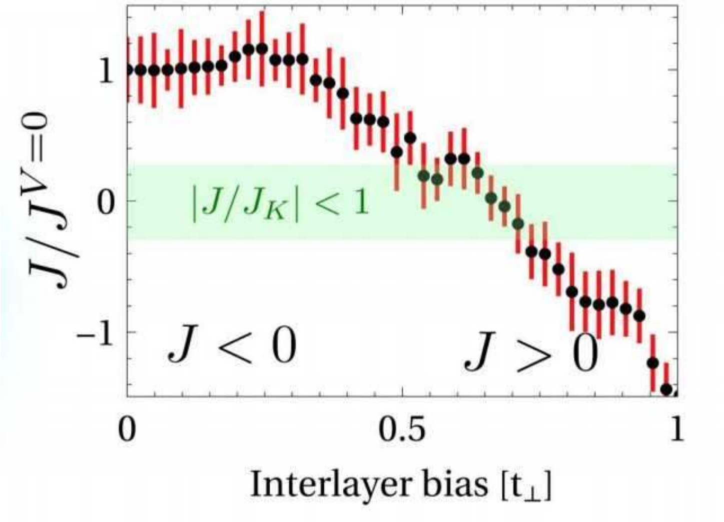


Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Electric control of the Kondo regime

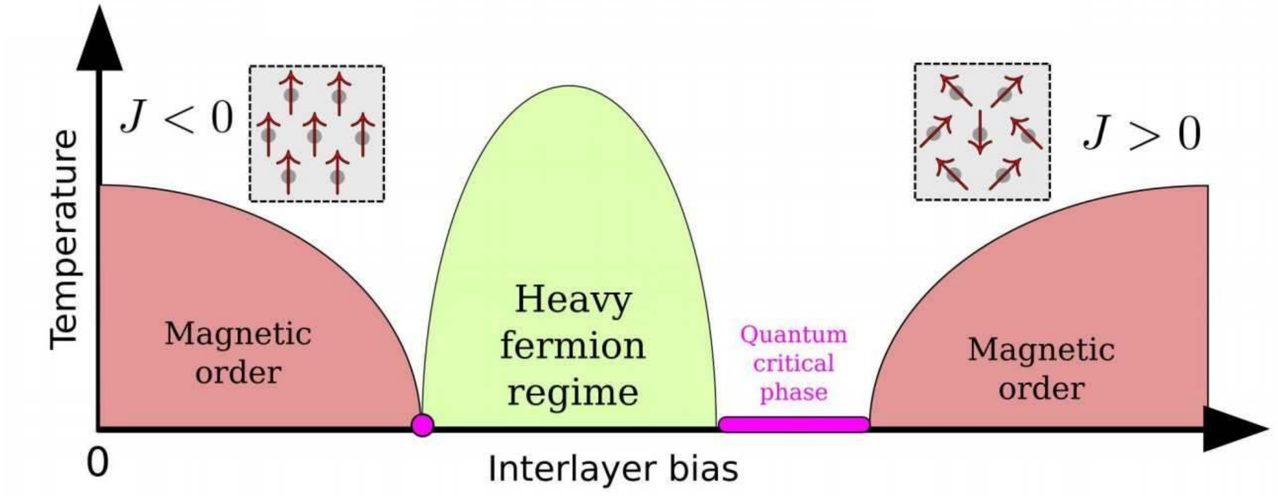


A heavy fermion regime appears when the Kondo coupling dominates over the exchange coupling

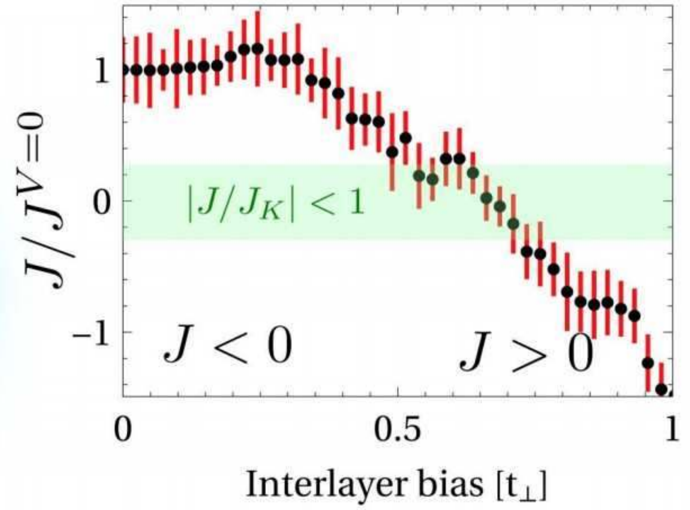
$$|J/J_K| < 1$$

Heavy-fermions in twisted graphene trilayers

Heavy-fermion (Doniach) phase diagram

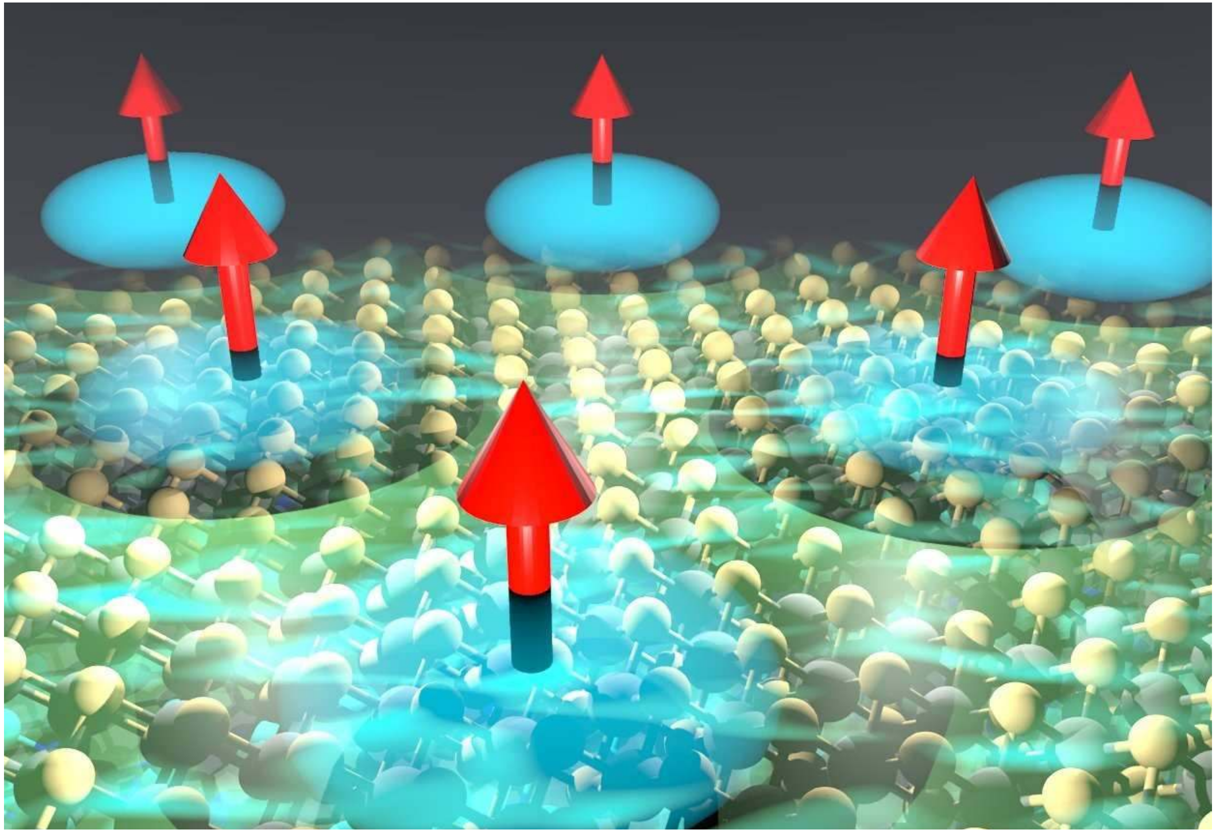


Electric control of the Kondo regime



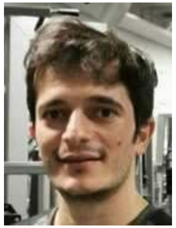
The full phase diagram of the heavy fermion system can be explored in a single twisted graphene, by tuning the system with an electric bias

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

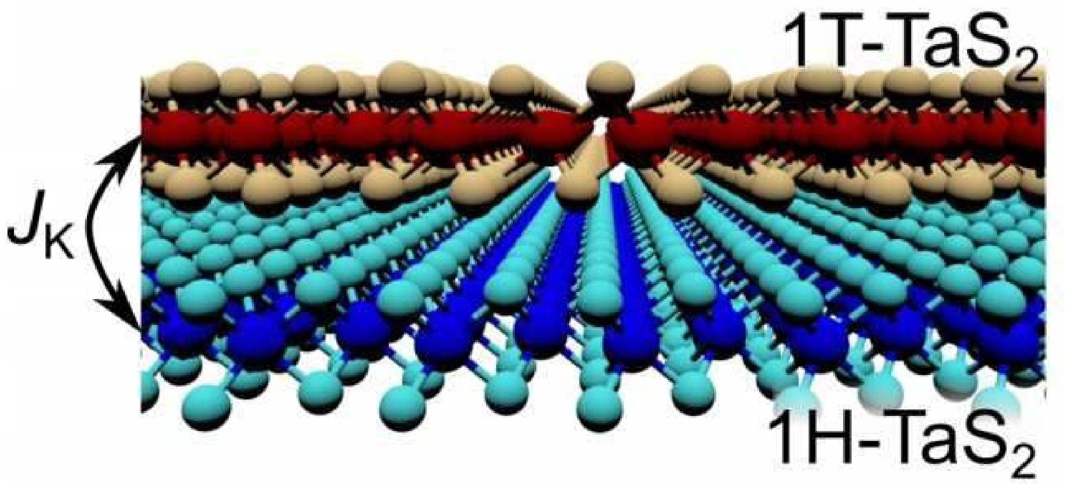
$1T\text{-}TaS_2$

Two-dimensional electron gas

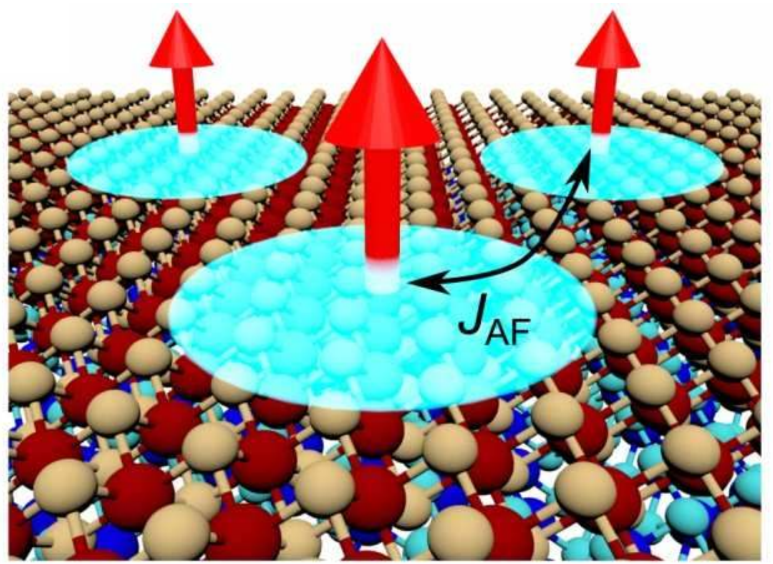
$1H\text{-}TaS_2$

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling create the Kondo coupling



Intralayer exchange between local moments

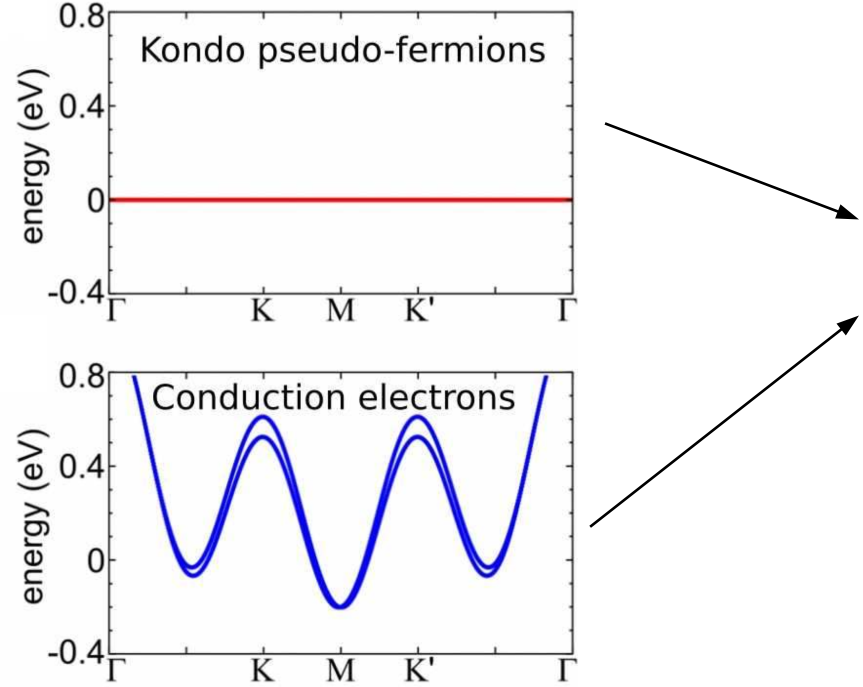


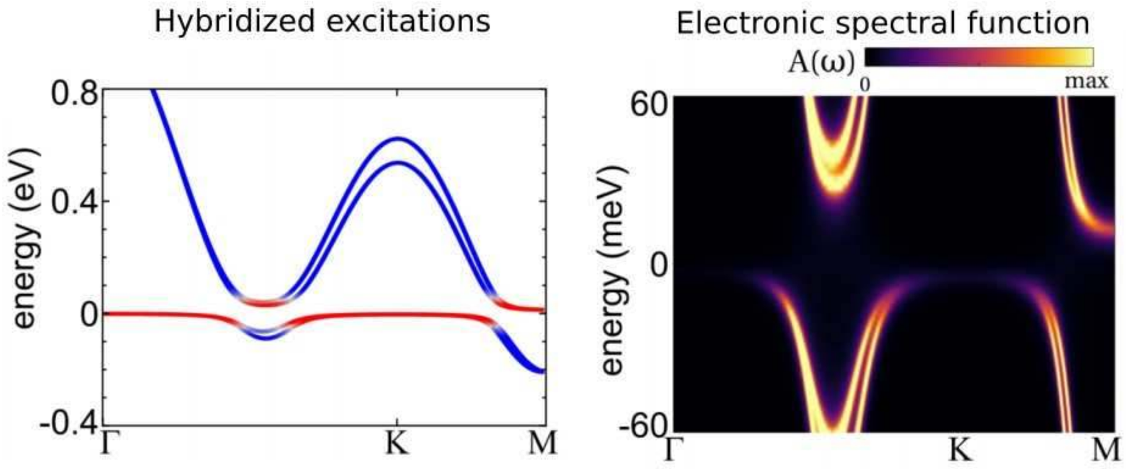
The bilayer realizes all the ingredients for heavy-fermion physics

Brief theory of heavy-fermions

Kondo physics introduces resonant pseudo-fermions at the chemical potential

Leading to the opening of a heavy-fermion gap



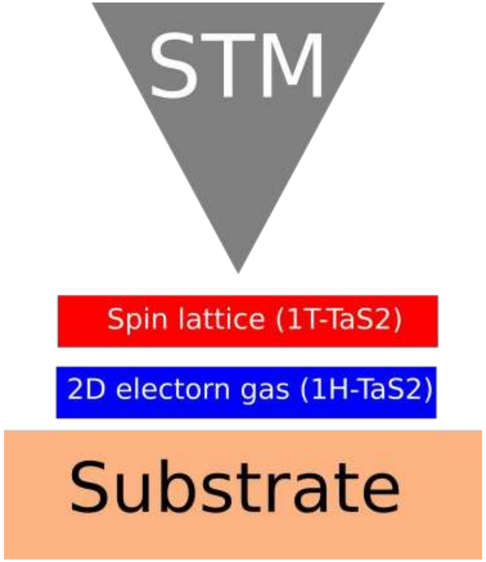


Experimental signatures of heavy-fermion physics

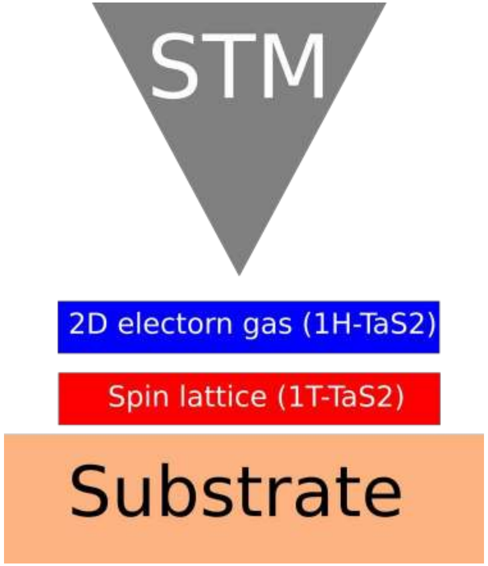
- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

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

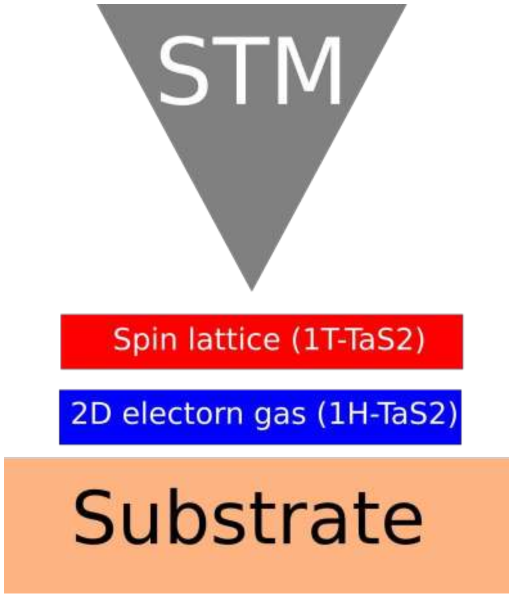
Probing the Kondo peak



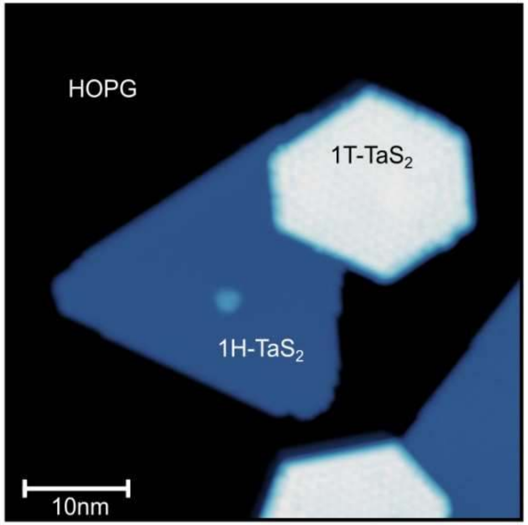
Probing the heavy-fermion gap



Kondo physics in the magnetic lattice

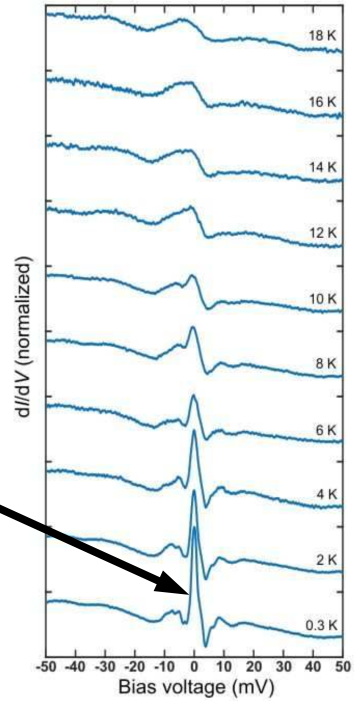


Sample



Differential conductance

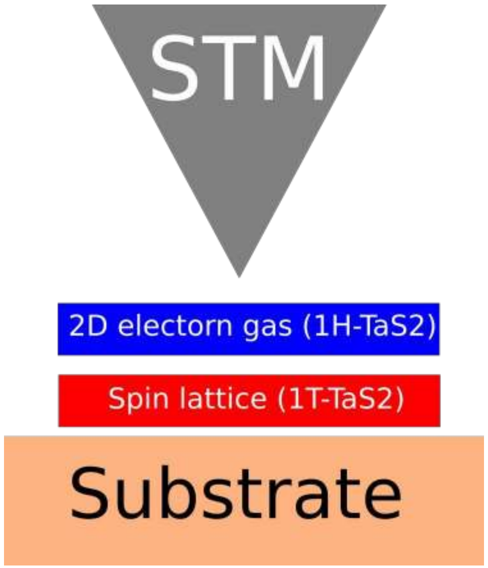
Kondo peak



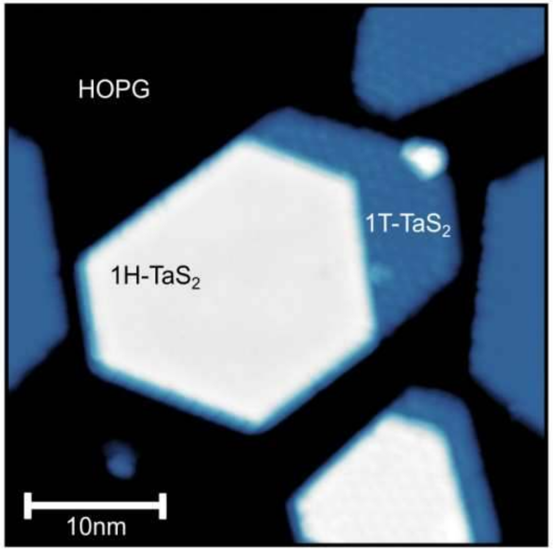
The system shows a Kondo peak when the local moments are probed

Temperature and field dependence consistent with Kondo

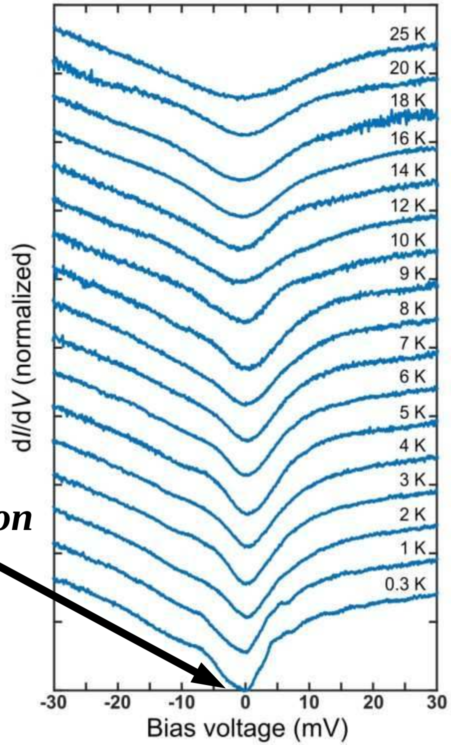
Heavy-fermion gap in the 2D electron gas



Sample



Differential conductance



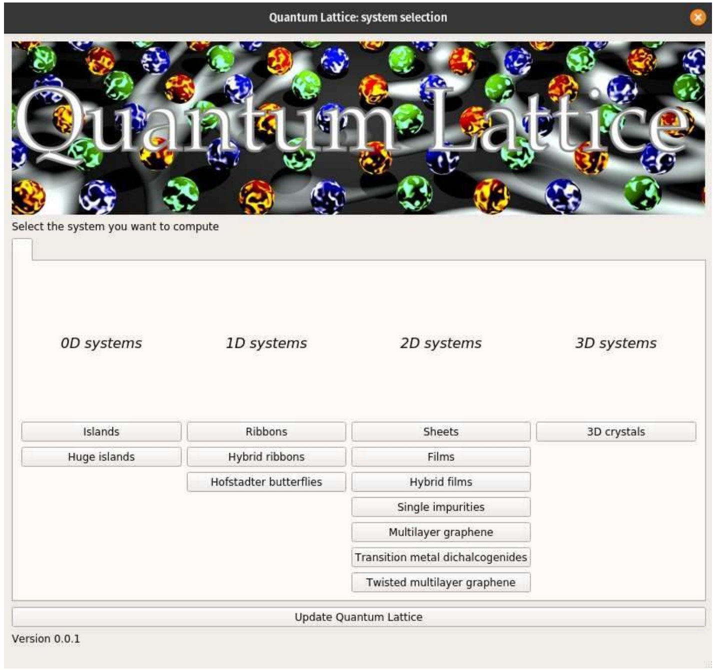
Heavy-fermion gap

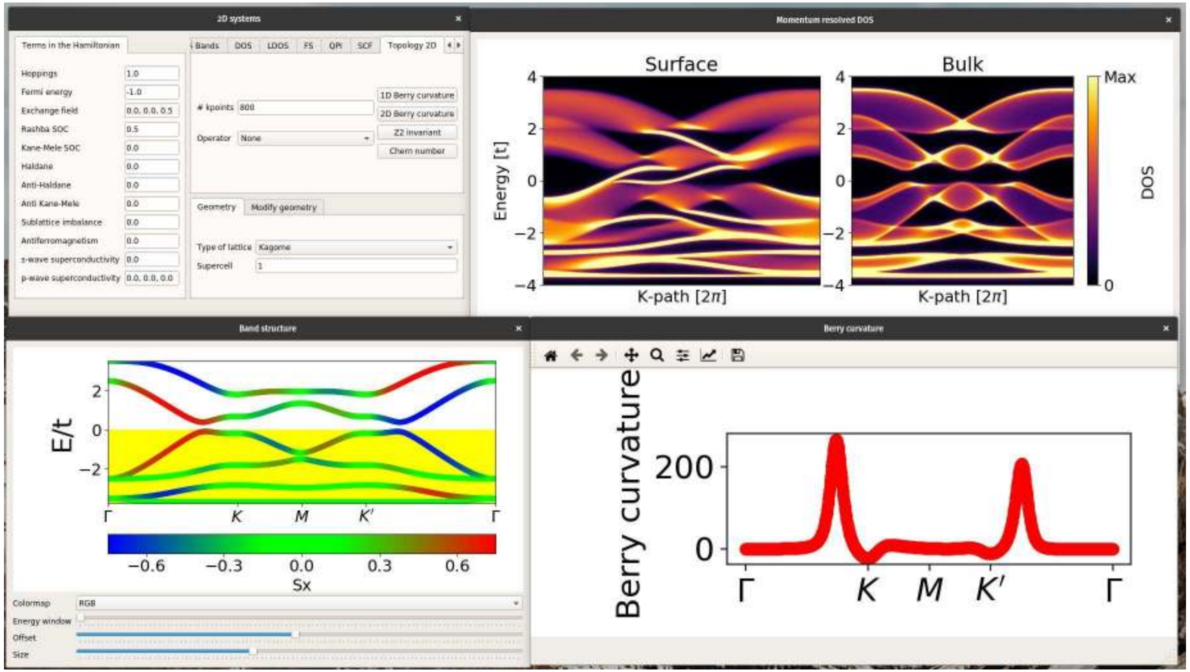
A heavy-fermion gap appears on the metal side

Temperature and field dependence consistent with a heavy-fermion gap

Computing electronic properties

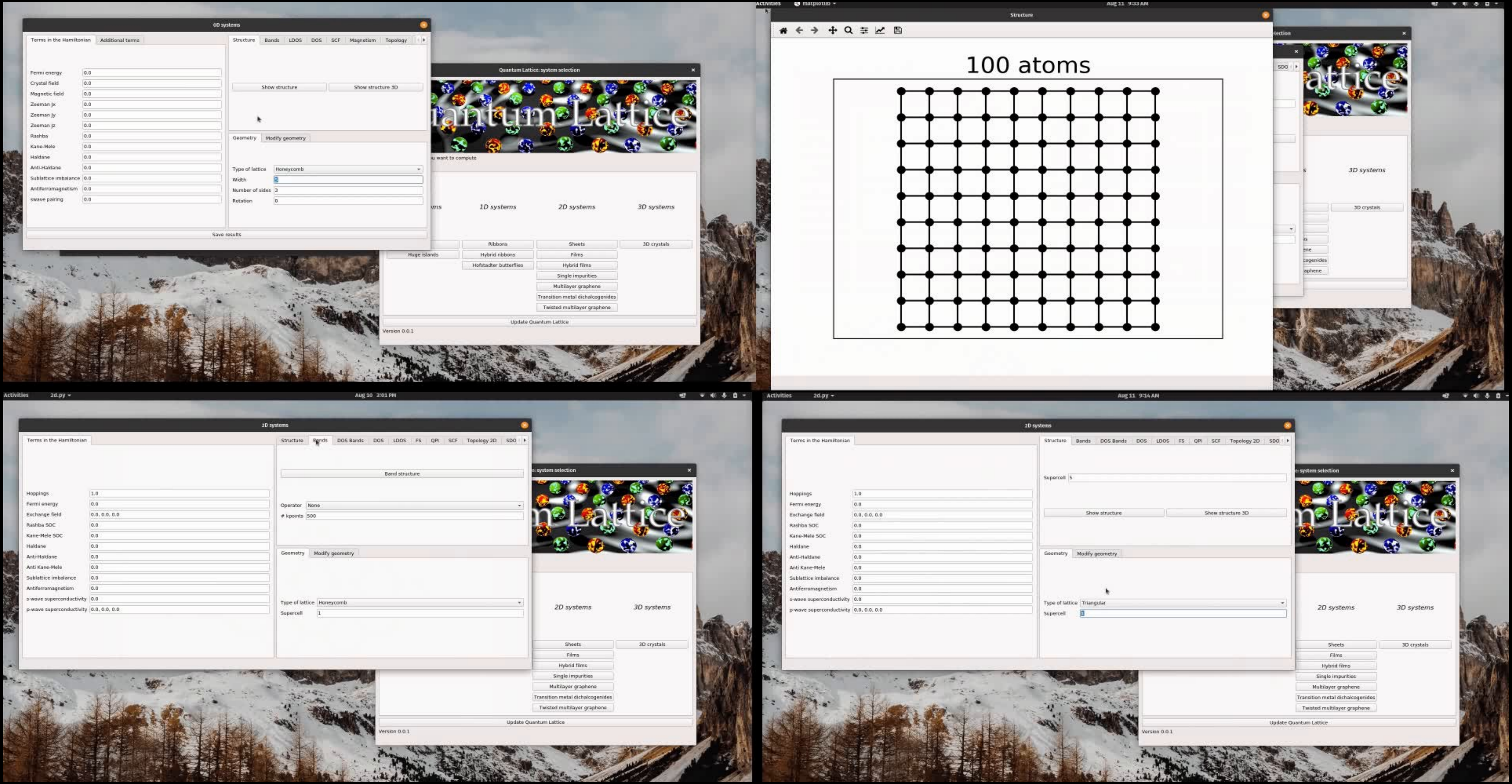
Quantum Lattice: A user interface to compute electronic properties



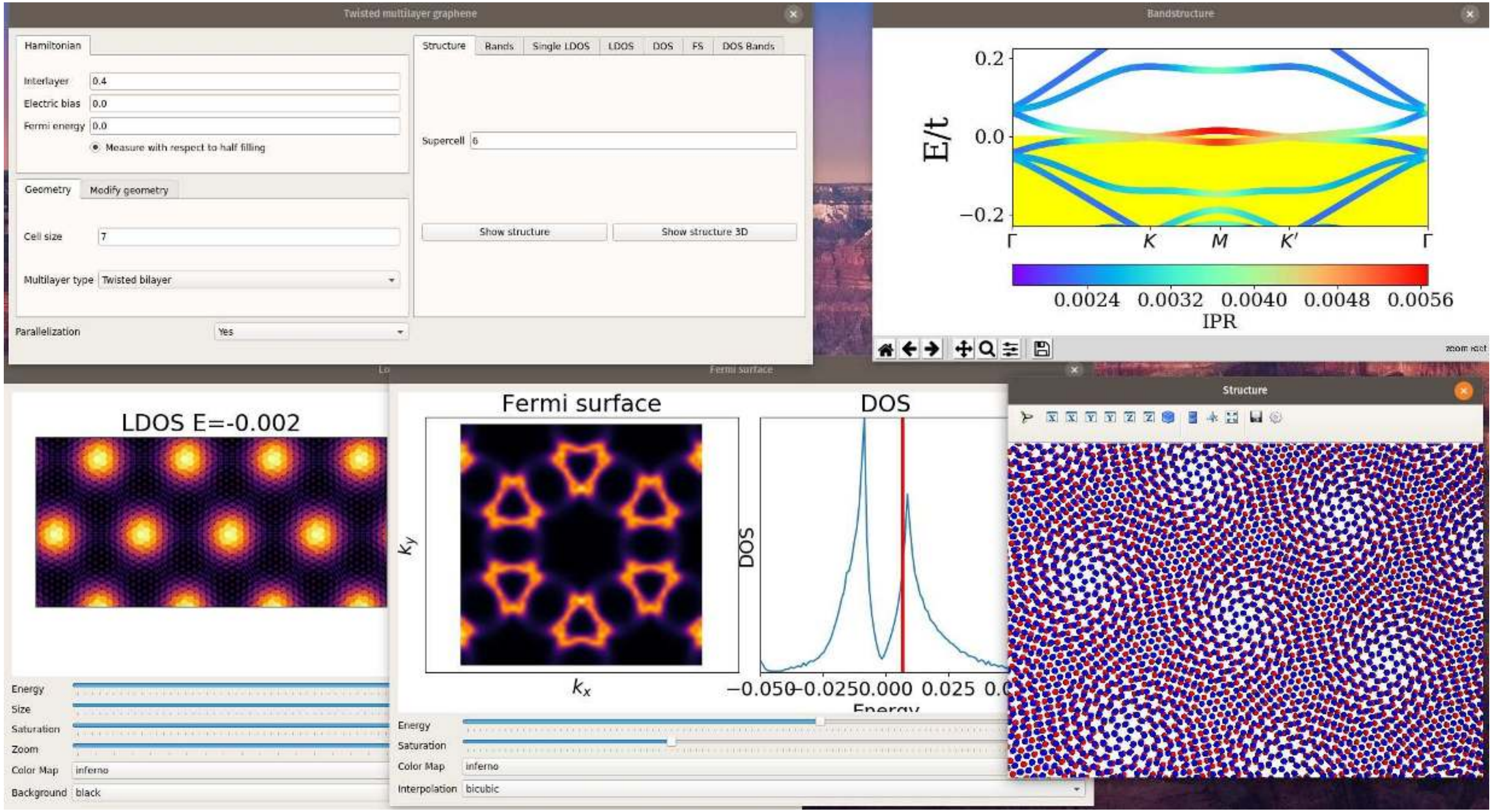


Quantum Lattice: open source interactive interface for tight binding modeling

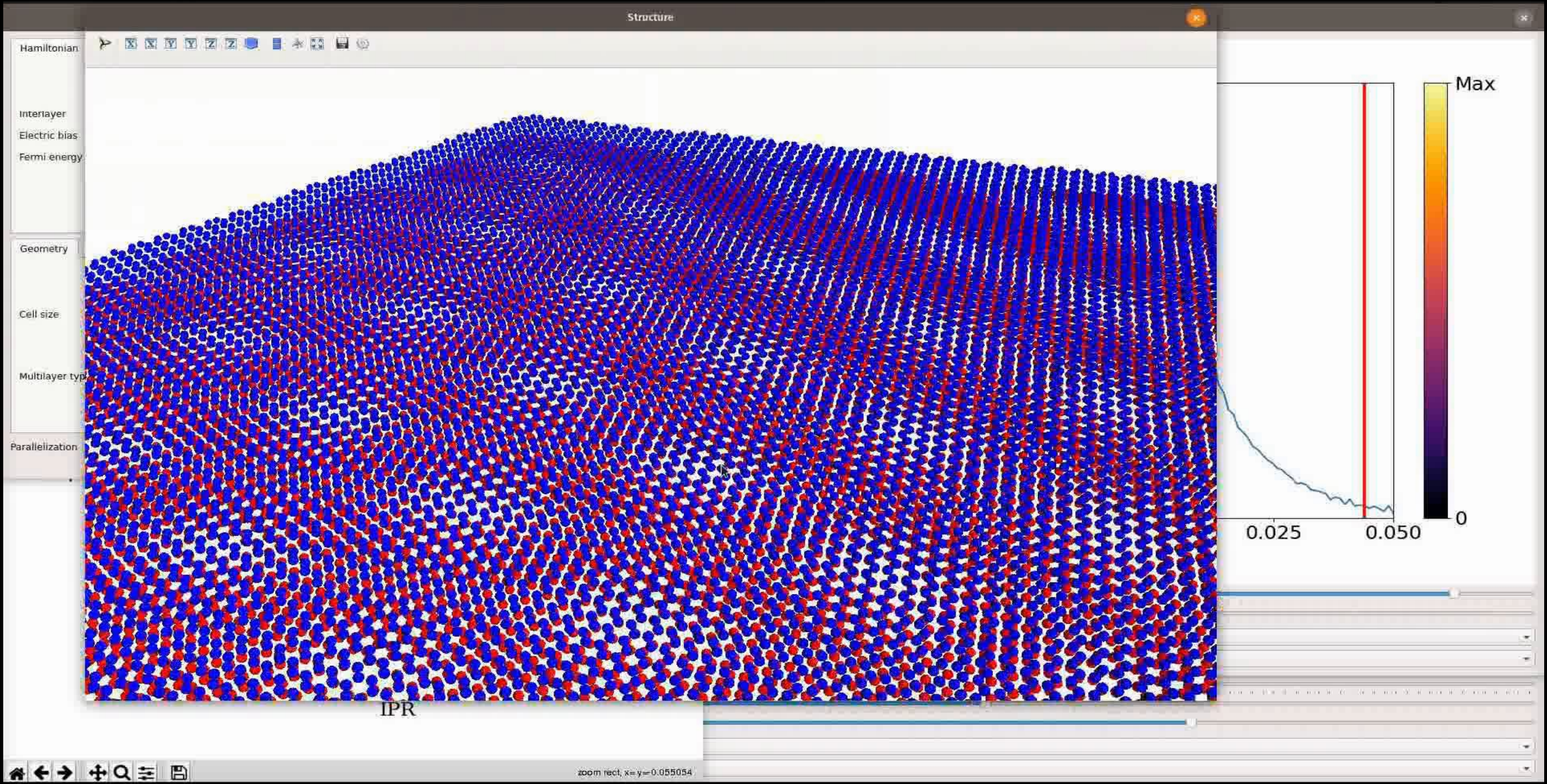
https://github.com/joselado/quantum-lattice


0D systems
Terms in the Hamiltonian
Additional terms
Structure
Bands
LDOS
DOS
SCF
Magnetism
Topology
Fermi energy
Crystal field
Magnetic field
Zeeman Jx
Zeeman Jy
Zeeman Jz
Rashba
Kane-Mele
Haldane
Anti-Haldane
Sublattice imbalance
Antiferromagnetism
swave pairing
Show structure
Show structure 3D
Geometry
Modify geometry
Type of lattice
Honeycomb
Width
Number of sides
Rotation
Save results
Quantum Lattice: system selection
1D systems
2D systems
3D systems
Ribbons
Sheets
3D crystals
Huge islands
Hybrid ribbons
Films
Hofstadter butterflies
Hybrid films
Single impurities
Multilayer graphene
Transition metal dichalcogenides
Twisted multilayer graphene
Update Quantum Lattice
Version 0.0.1
Structure
100 atoms
2D systems
Hoppings
Exchange field
Rashba SOC
Kane-Mele SOC
Anti Kane-Mele
s-wave superconductivity
p-wave superconductivity
DOS Bands
FS
QPI
Topology 2D
Band structure
Operator
None
kpoints
Supercell
Triangular

Twisted bilayer with the user interface

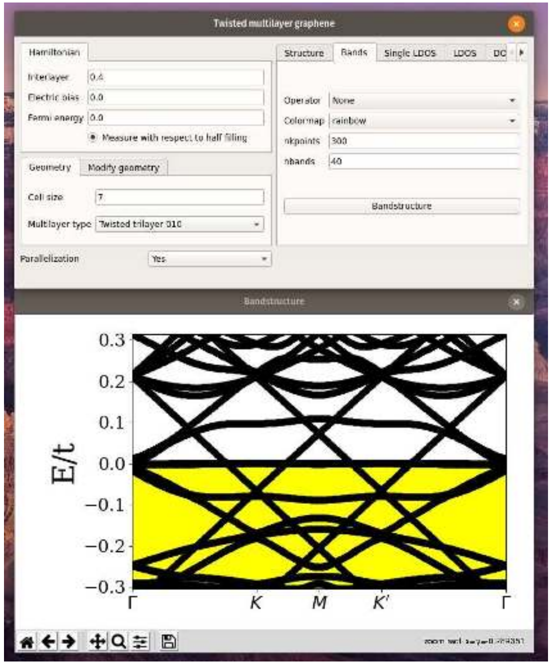


https://github.com/joselado/quantum-lattice

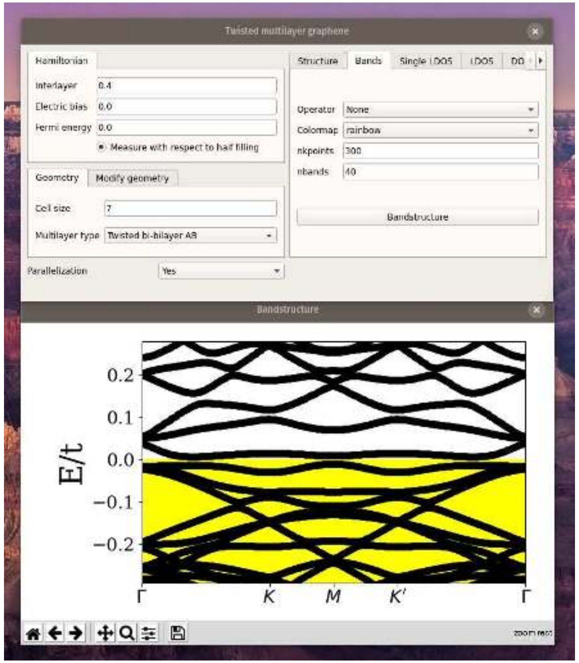

Structure
Hamiltonian
Interlayer
Electric bias
Fermi energy
Geometry
Cell size
Multilayer typ
Parallelization
Max
0
0.025
0.050
IPR
zoom rect, x=y=0.055054

Twisted multilayers

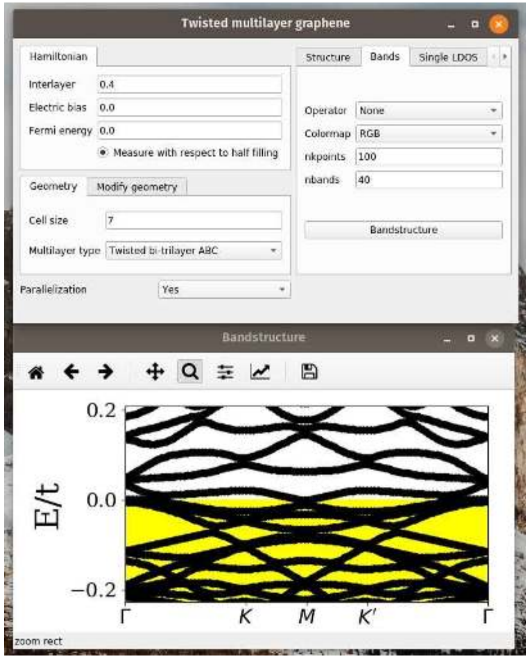
Twisted trilayer graphene



Twisted bi-bilayer graphene



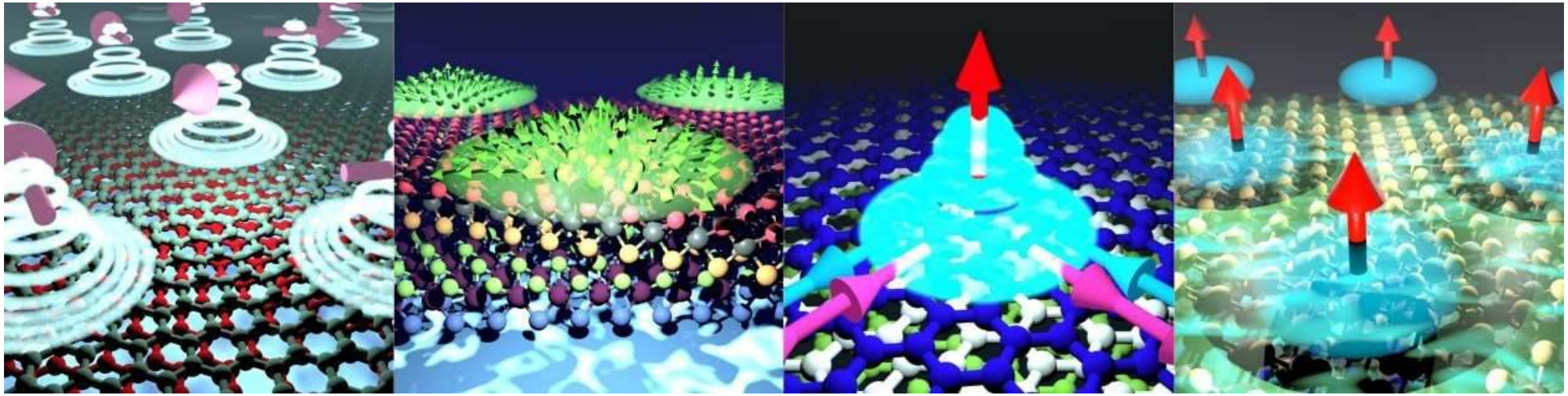
Twisted bi-trilayer graphene



https://github.com/joselado/quantum-lattice

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!

Funding from

J&AE JANE AND AATOS ERKKO FOUNDATION

SUOMEN AKATEMIA

Phys. Rev. Lett. 126, 056803 (2021)
New J. Phys. 23 073038 (2021)
Phys. Rev. Lett. 127, 026401 (2021)
arXiv:2103.11989 (2021)