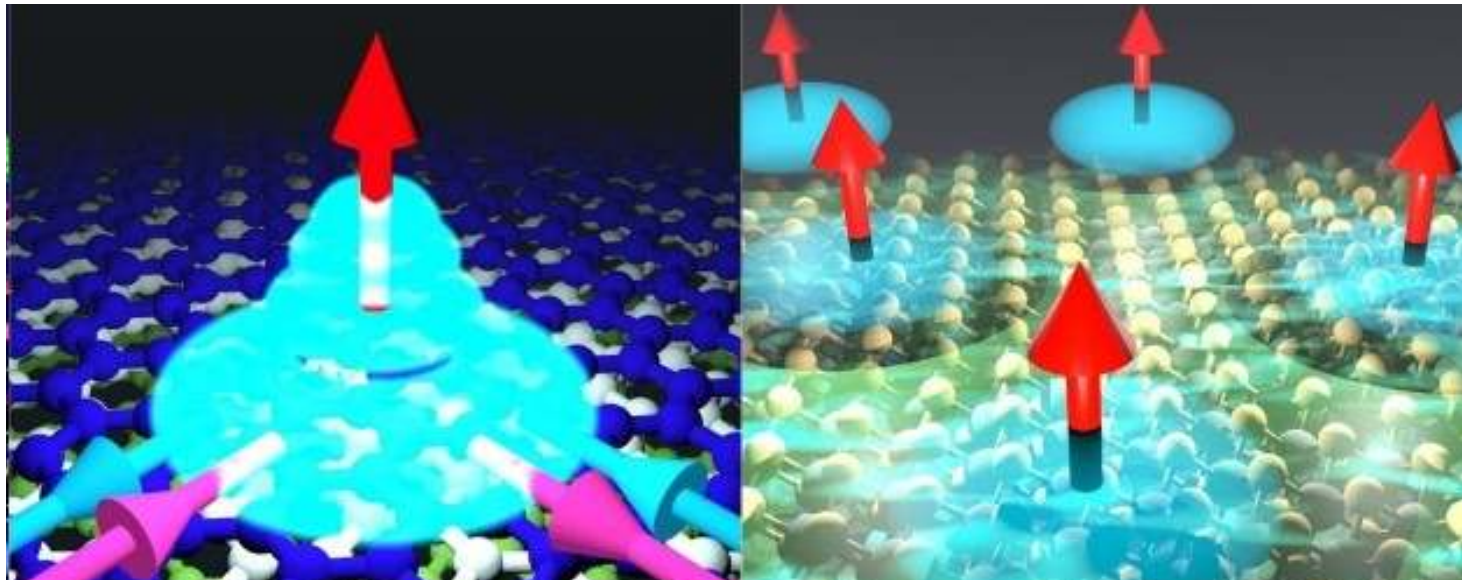


Engineering and probing two-dimensional van der Waals heavy-fermion Kondo quantum matter

Jose Lado

Department of Applied Physics, Aalto University, Finland



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

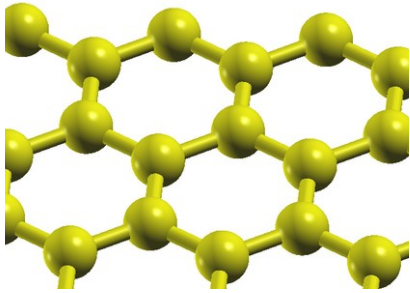
Nature 599, 582–586 (2021)

A quantum leap: unraveling the mysteries of correlated electronic states in quantum materials through atomic-scale imaging and spectroscopy, CMD31, Portugal September 4th 2024

Families of two-dimensional materials

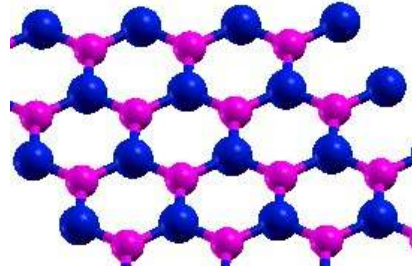
Semimetal

Graphene



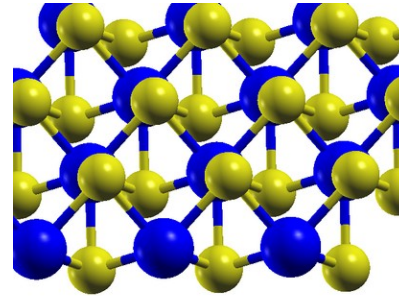
Insulator

BN



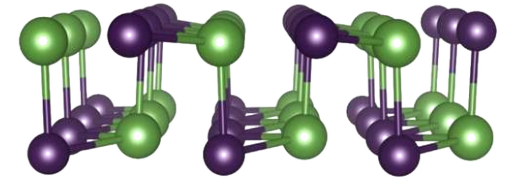
Superconductor

NbSe₂



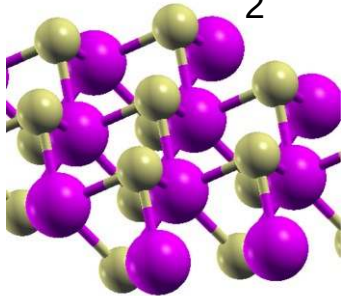
Ferroelectric

SnTe



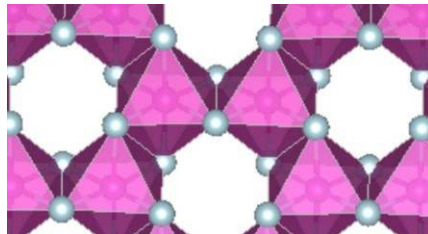
Semiconductor

WSe₂



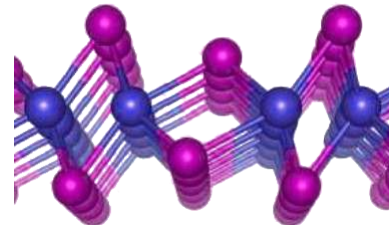
Ferromagnet

CrI₃



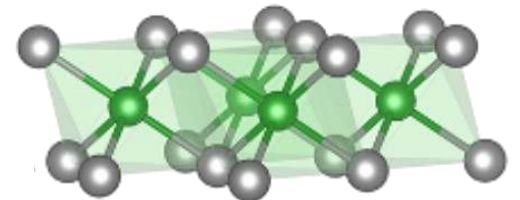
**Quantum spin
Hall insulator**

WTe₂



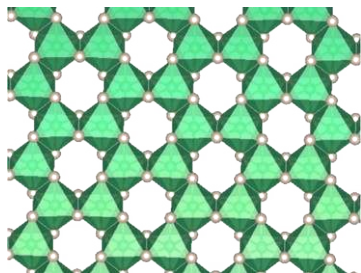
Multiferroic

NiI₂



Van der Waals magnetic materials

**Ferromagnet,
antiferromagnets**

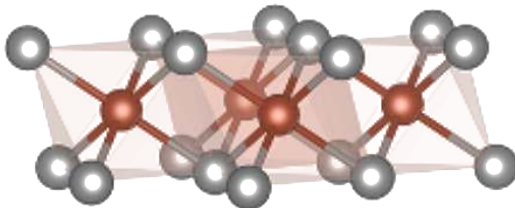


CrI_3 , CrCl_3 , CrBr_3

Nature 546, 270–273 (2017)

Break time-reversal

Multiferroics

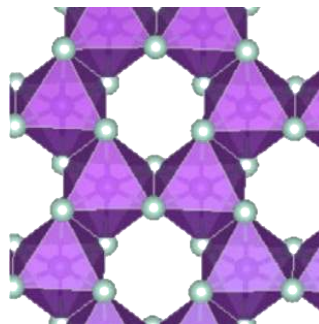


NiI_2

Nature 602, 601–605 (2022)

Break time-reversal
and inversion symmetry

**(proximal)
Quantum
spin-liquids**

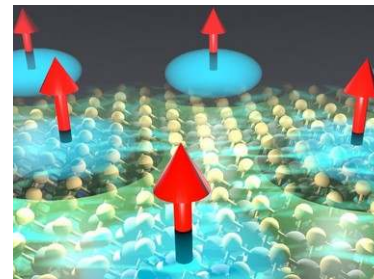


RuCl_3 , 1T-TaS_2

Nature Physics 17, 1154–1161 (2021)

Do not break time-reversal

**Heavy-fermion
Kondo insulators**

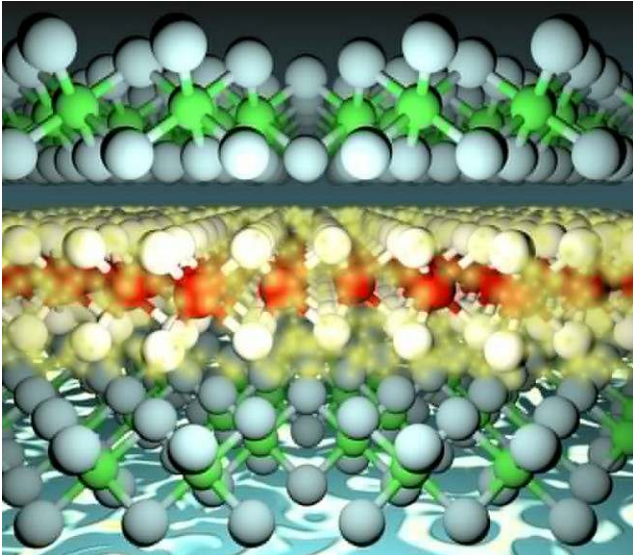


$1\text{T-TaS}_2/1\text{H-TaS}_2$

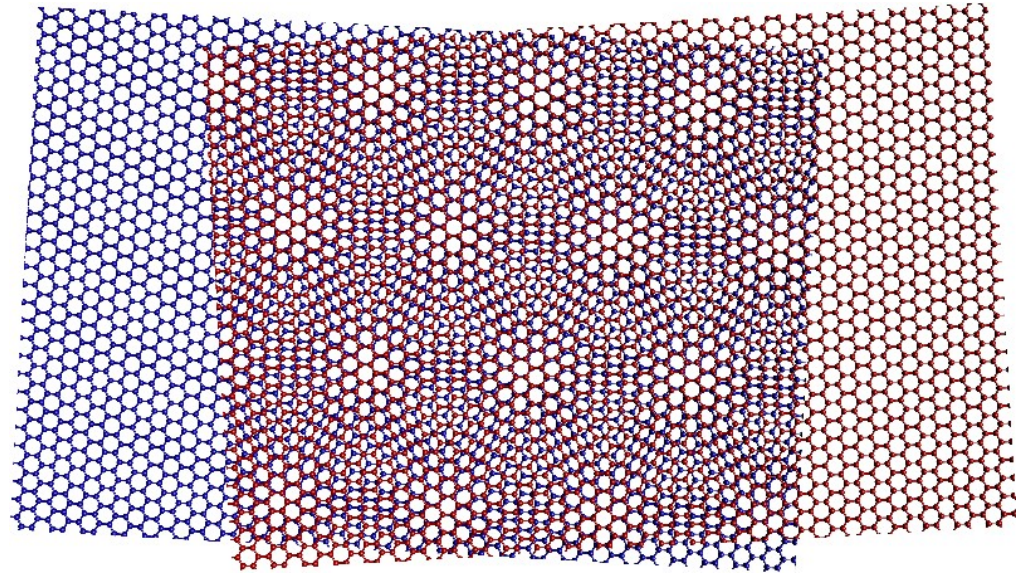
Nature 599, 582–586 (2021)

The flexibility of two-dimensional materials

They can be stacked



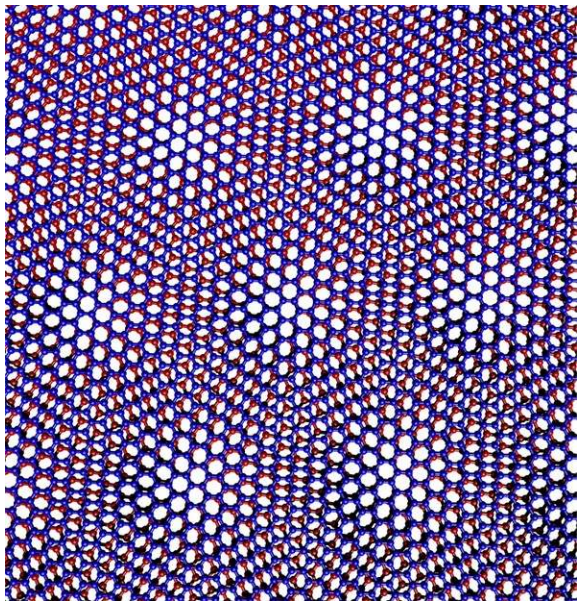
They can be rotated



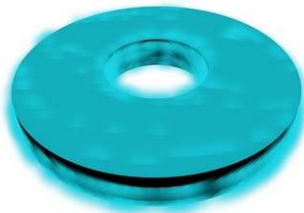
These are unique features of two-dimensional materials

One material, a zoo of electronic phases

Twisted bilayer graphene

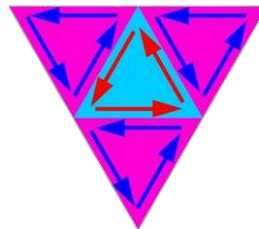


Superconductivity



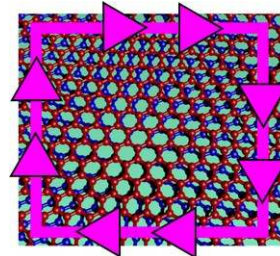
Nature 556, 43–50 (2018)
Nature 600, 240–245 (2021)

Topological networks



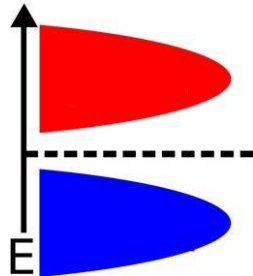
Nano Lett. 18, 11,
6725–6730 (2018)

Chern insulators



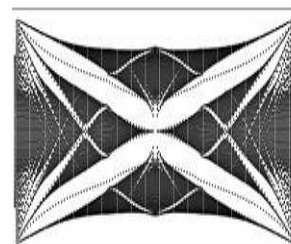
Science 365, 605–608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782–786 (2018)

Fractional Chern insulators

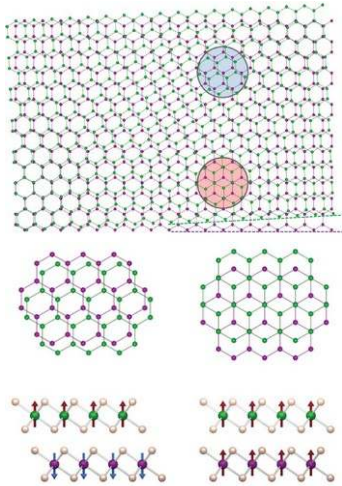


Nature 600, 439–443 (2021)

A bilayer of a van der Waals material realizes a variety of widely different electronic states

Artificial quantum matter in moire van der Waals heterostructures

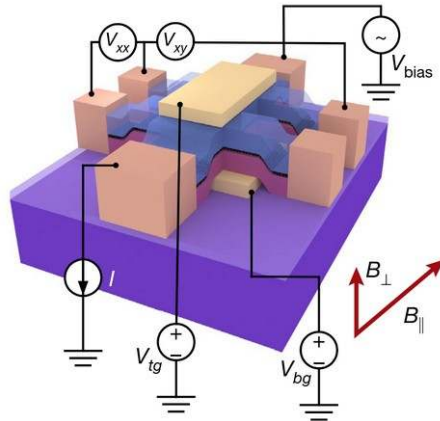
Unconventional magnets



Twisted CrBr_3

Science, 374(6571),
1140-1144 (2021)

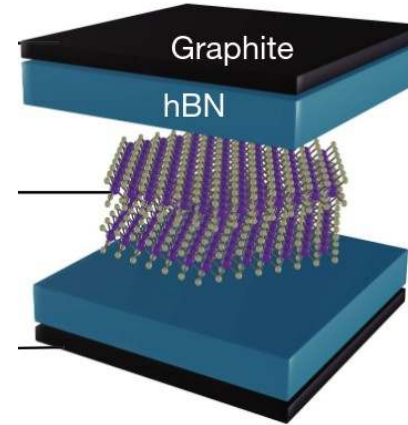
Unconventional superconductors



Twisted trilayer
graphene

Nature 595,
526–531 (2021)

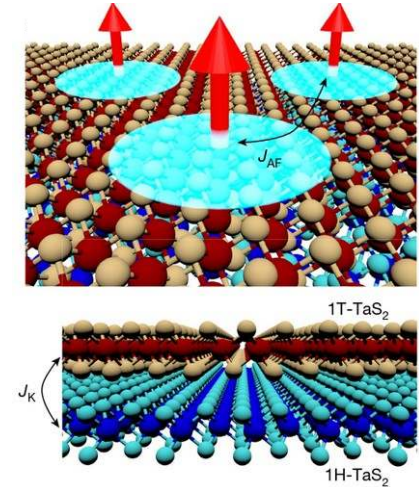
Fractional topological matter



Twisted MoTe_2

Nature 622,
63–68 (2023)

Heavy-fermion quantum materials



1H-1T TaS_2

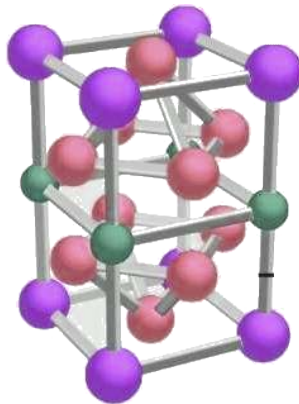
Nature 599,
582–586 (2021)

Searching for new heavy fermion compounds

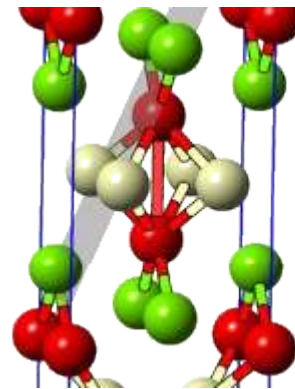
We have a rich family of bulk heavy-fermion compounds



Science 375, 6576, 76-81 (2021)



Nature 579, 523–527 (2020)



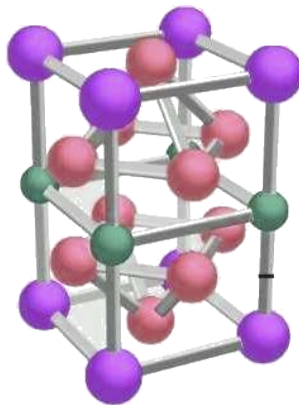
- Strongly correlated matter, dominated by Kondo lattice physics
- Unique system to realize quantum criticality and unconventional superconductivity
- Found in rare-earth compounds, such as UTe_2 or UPt_3

Searching for new heavy fermion compounds

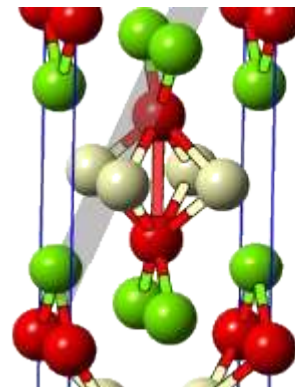
We have a rich family of bulk heavy-fermion compounds



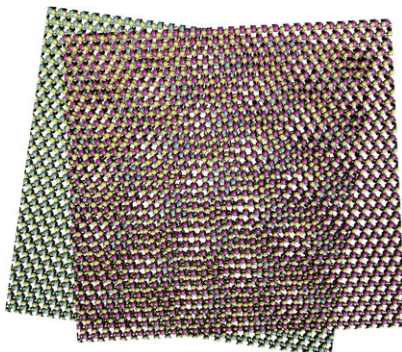
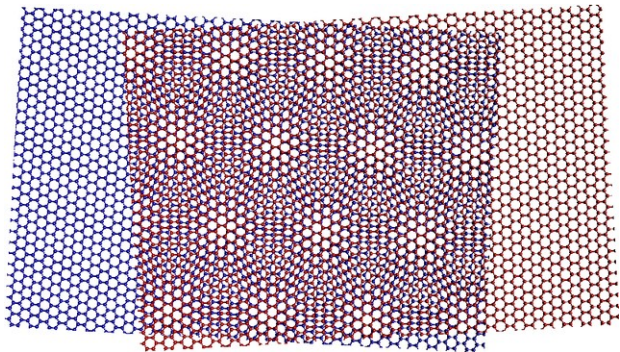
Science 375, 6576, 76-81 (2021)



Nature 579, 523–527 (2020)



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



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

Nature 599, 582–586 (2021)

Phys. Rev. Research 3, 043173 (2021)

Phys. Rev. B 106, L041116 (2022)

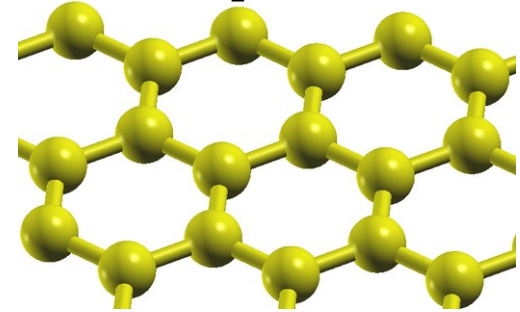
Phys. Rev. Lett. 129, 047601 (2022)

Nature 616, 61–65 (2023)

Designing heavy-fermion quantum matter with twisted magnetic van der Waals materials

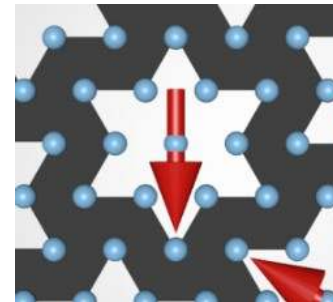


Graphene



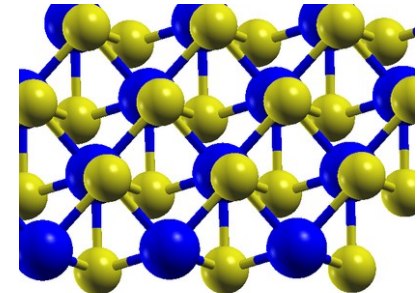
Magnet

1T-TaS₂



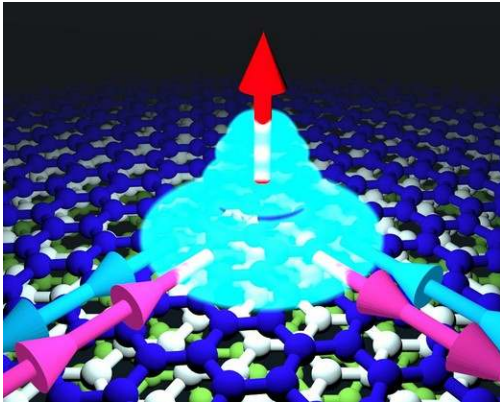
Metal

1H-TaS₂



Behind the scenes

Heavy fermions in twisted graphene trilayers

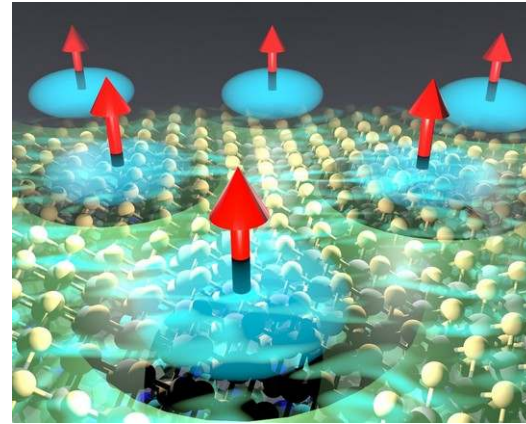


Aline Ramires



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

Heavy fermions in twisted dichalcogenide bilayers



V. Vaňo



S. Kezilebieke



P. Liljeroth



Nature 599, 582–586 (2021)

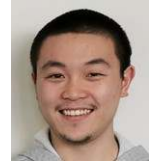
S. Ganguli



M. Amini



G. Chen

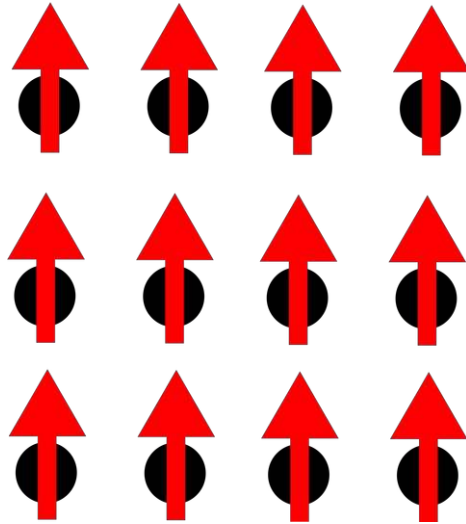


The Kondo lattice problem

Building an artificial heavy fermion state



Lattice of Kondo impurities



f-electrons in
rare-earth compounds

Dispersive electron gas

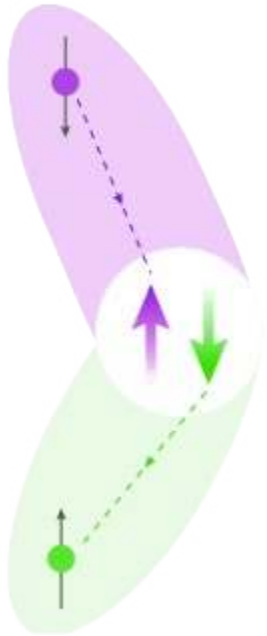


s/p/d-electrons in
rare-earth compounds

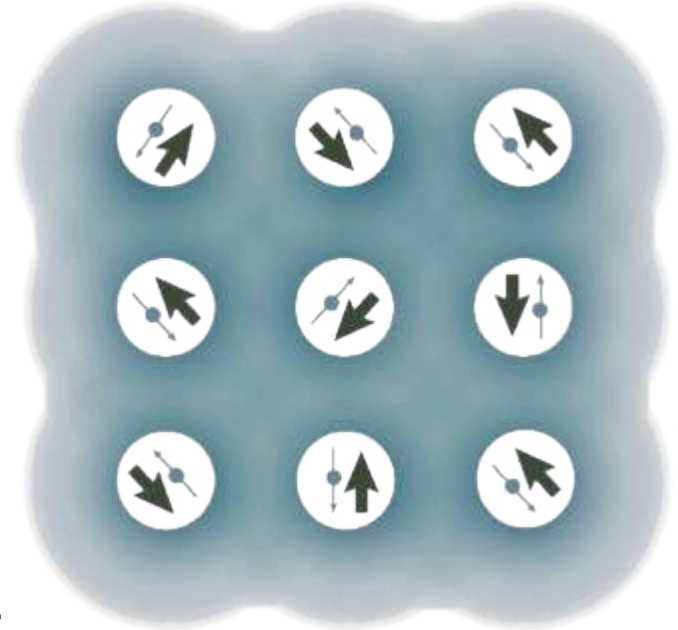


Building an artificial heavy fermion state

Conduction electrons form
Kondo singlets with the impurities



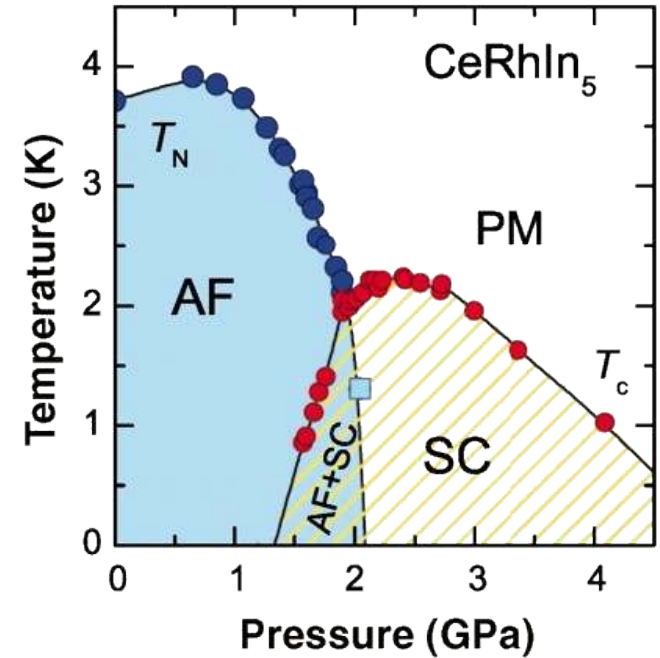
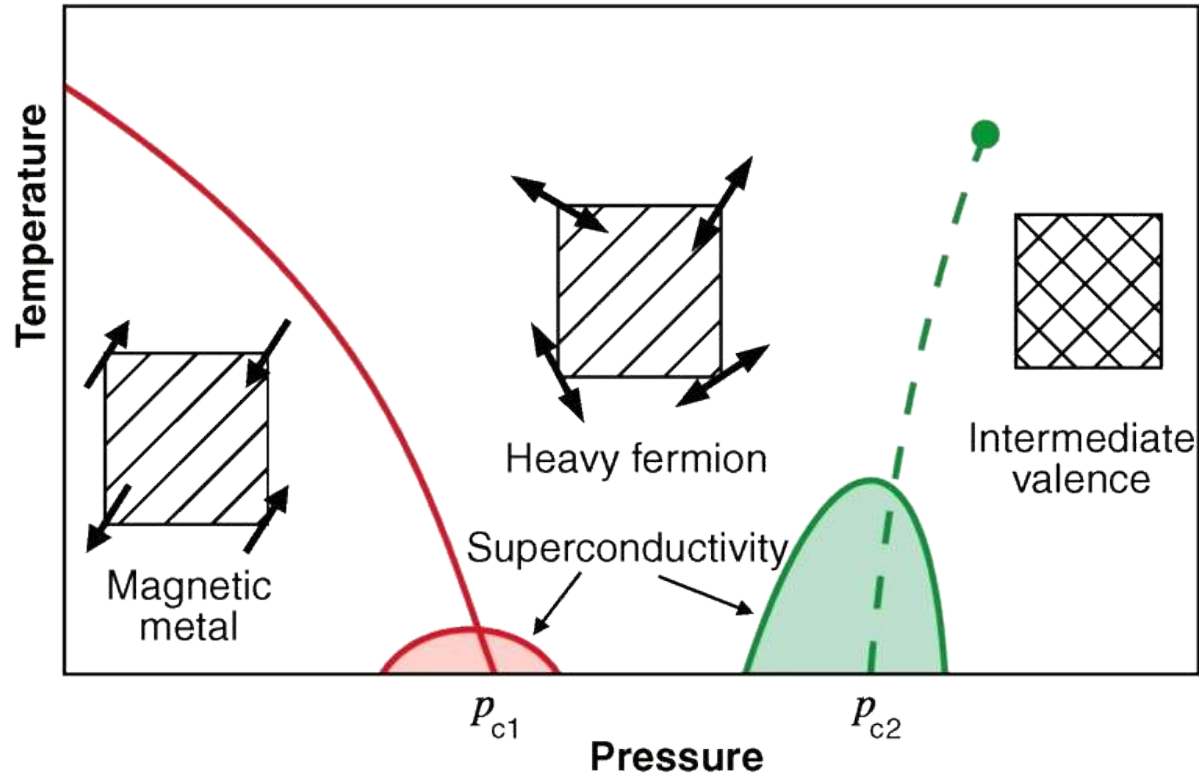
Kondo-lattice model



Associated with Kondo lattice physics:

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

Basics of heavy fermion physics



The Kondo problem

Conduction electrons

$$H = -t \sum_{(i,j)\sigma} \left(c_{i\sigma}^\dagger c_{j\sigma} + \text{H.c} \right)$$

Kondo coupling

$$H_K = J_K \sum_{\alpha\beta} \left(c_{0\beta}^\dagger \vec{\sigma}_{\beta\alpha} c_{0\alpha} \right) \cdot \vec{S}$$

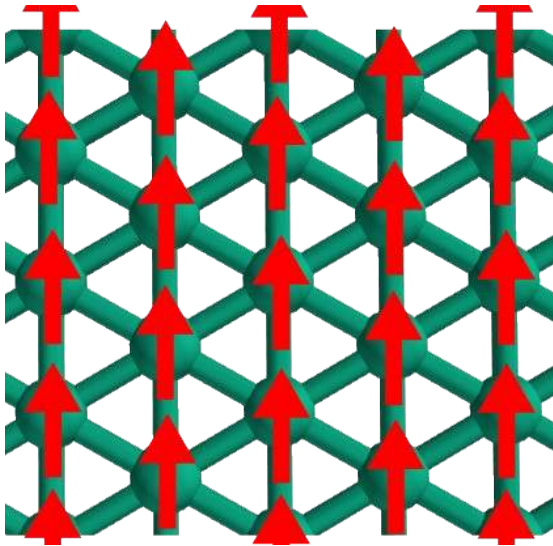
We now take a quantum spin $S=1/2$

$$|GS\rangle \sim \frac{1}{\sqrt{2}} [|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]$$



The Kondo lattice problem

Lattice of Kondo impurities



Dispersive electron gas



$$J_K$$

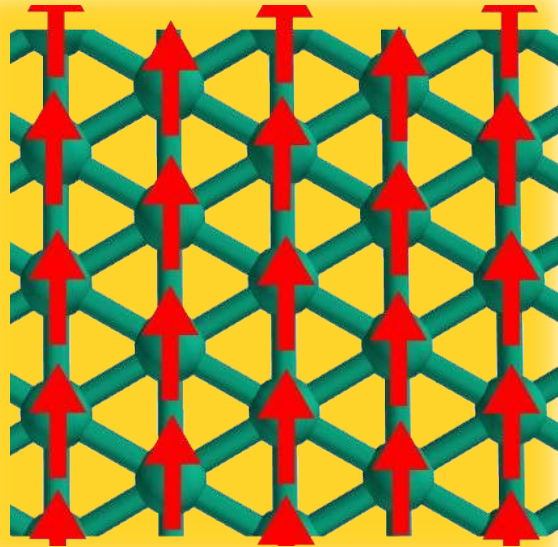

Both ingredients coupled through Kondo coupling

The Kondo lattice problem

The Kondo lattice problem

$$H = -t \sum_{(i,j)\sigma} \left(c_{i\sigma}^\dagger c_{j\sigma} + \text{H.c} \right) + J_K \sum_{j,\alpha\beta} \left(c_{j\beta}^\dagger \vec{\sigma}_{\beta\alpha} c_{j\alpha} \right) \cdot \vec{S}_j$$

Conduction electrons



Kondo coupling

Kondo sites

Solving the Kondo lattice problem

$$H = -t \sum_{(i,j)\sigma} \left(c_{i\sigma}^\dagger c_{j\sigma} + \text{H.c} \right) + J_K \sum_{j,\alpha\beta} \left(c_{j\beta}^\dagger \vec{\sigma}_{\beta\alpha} c_{j\alpha} \right) .$$

Replace the spin sites by auxiliary fermions

$$S_{\alpha\beta}(j) \sim f_{j\alpha}^\dagger f_{j\beta} - \frac{n_f(j)}{N} \delta_{\alpha\beta}$$

This makes the effective Hamiltonian an “interacting” fermionic Hamiltonian

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^\dagger c_{\mathbf{k}\alpha} - J_K \sum_{j,\alpha\beta} \left(c_{j\beta}^\dagger f_{j\beta} \right) \left(f_{j\alpha}^\dagger c_{j\alpha} \right)$$

Solving the Kondo lattice problem

Now we decouple the fermions with a mean-field approximation

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} - J_K \sum_{j,\alpha\beta} \left(c_{j\beta}^{\dagger} f_{j\beta} \right) \left(f_{j\alpha}^{\dagger} c_{j\alpha} \right)$$

Obtaining a quadratic Hamiltonian

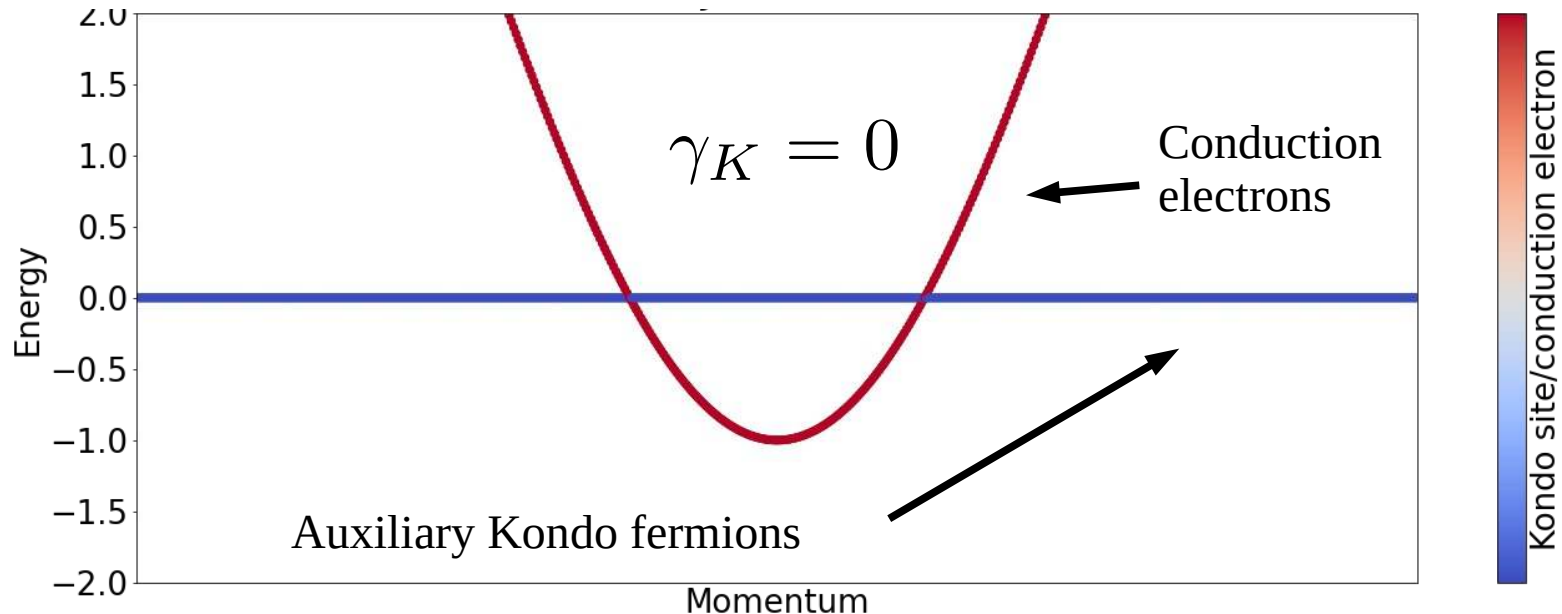
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha} f_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} + h.c.$$

Conduction band dispersion

Kondo hybridization

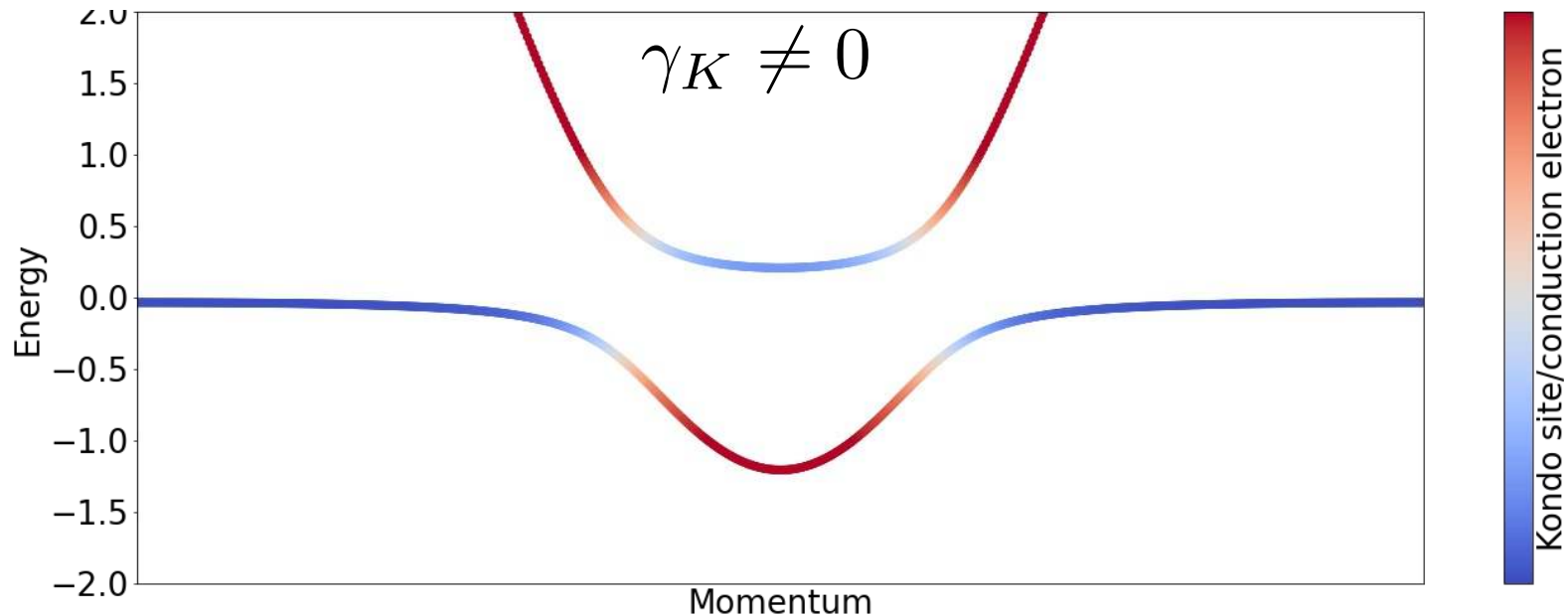
Electronic structure of the Kondo lattice problem

$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k}, \alpha\beta} f_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} + h.c.$$



Electronic structure of the Kondo lattice problem

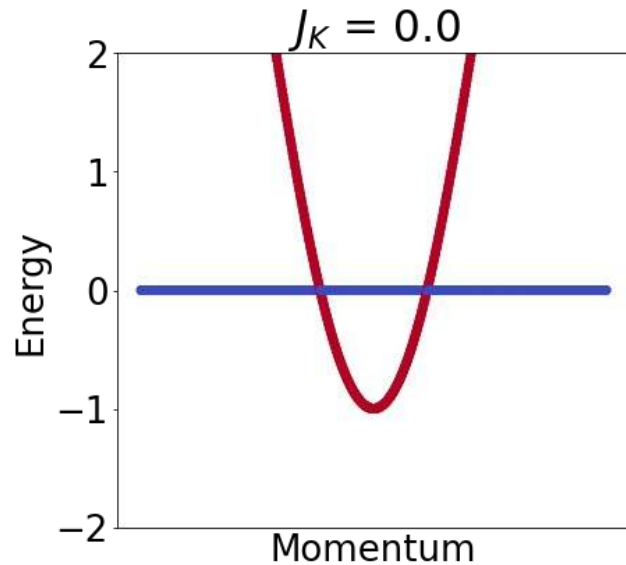
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k}, \alpha\beta} f_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha} + h.c.$$



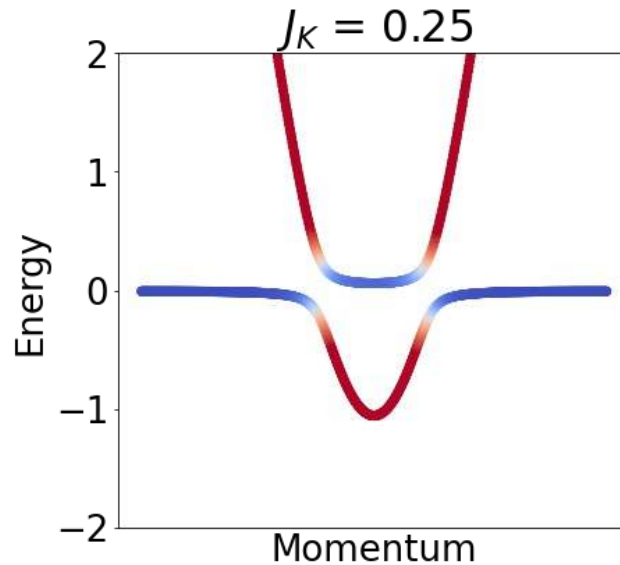
The Kondo coupling opens up a gap in the electronic structure

Dependence on the Kondo coupling

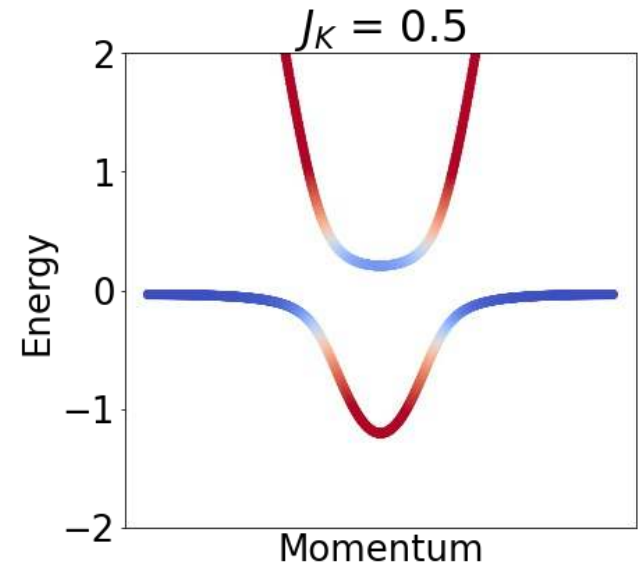
The heavy-fermion gap becomes bigger as the Kondo coupling increases



Kondo site/conduction electron

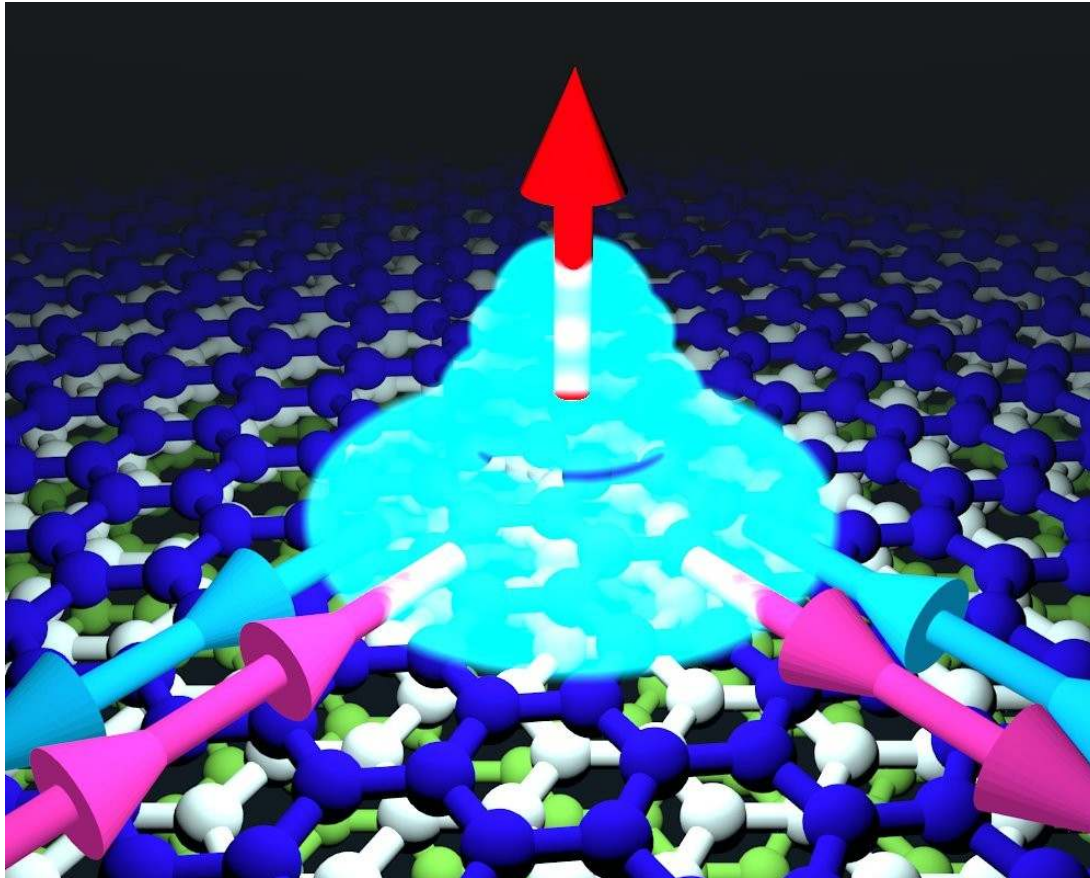


Kondo site/conduction electron



Kondo site/conduction electron

Heavy-fermions in twisted graphene trilayers



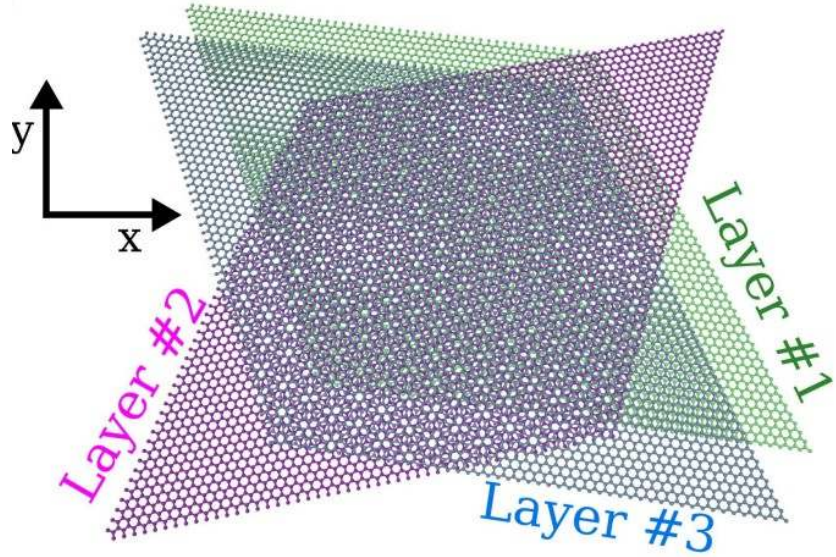
Aline Ramires



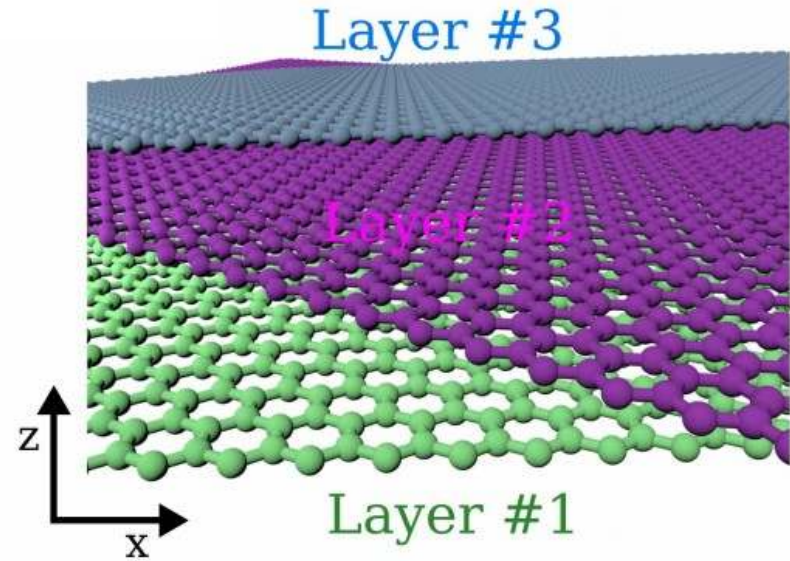
Phys. Rev. Lett. 127, 026401 (2021)

Heavy-fermions in twisted graphene trilayers

Top view

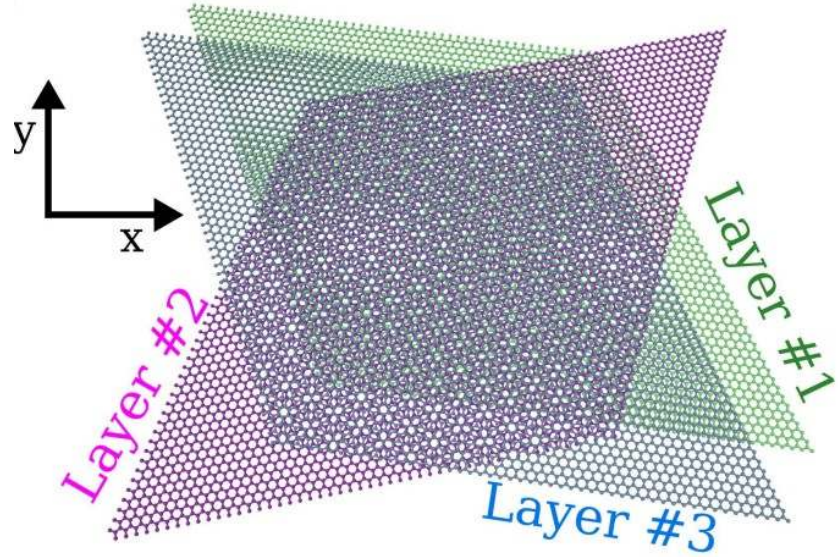


Lateral view

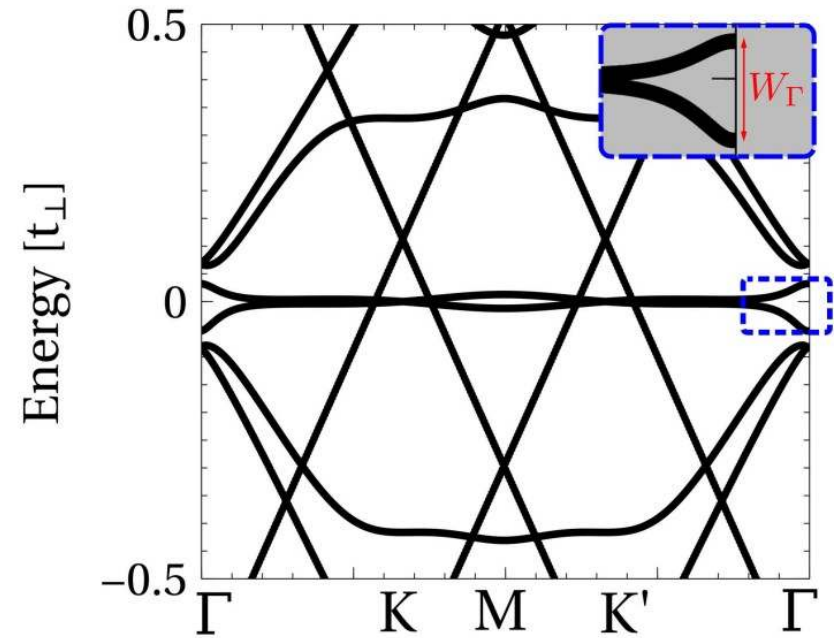


Heavy-fermions in twisted graphene trilayers

Top view

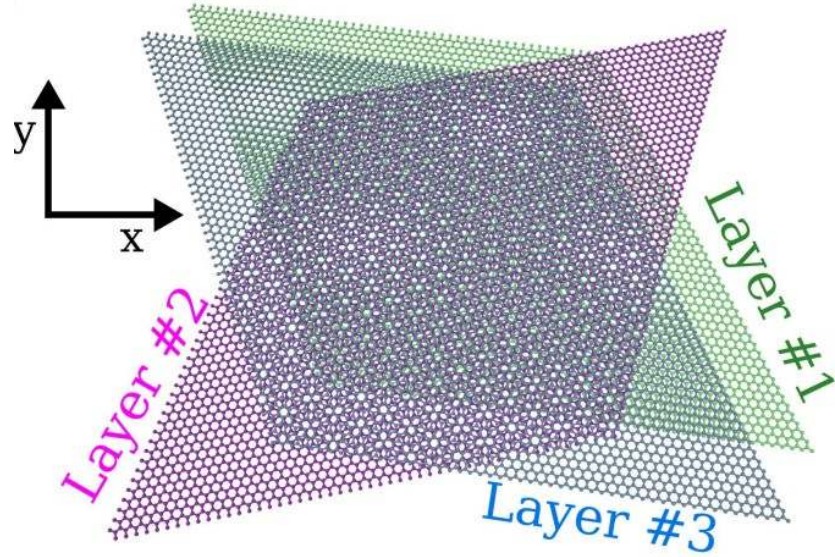


Band structure

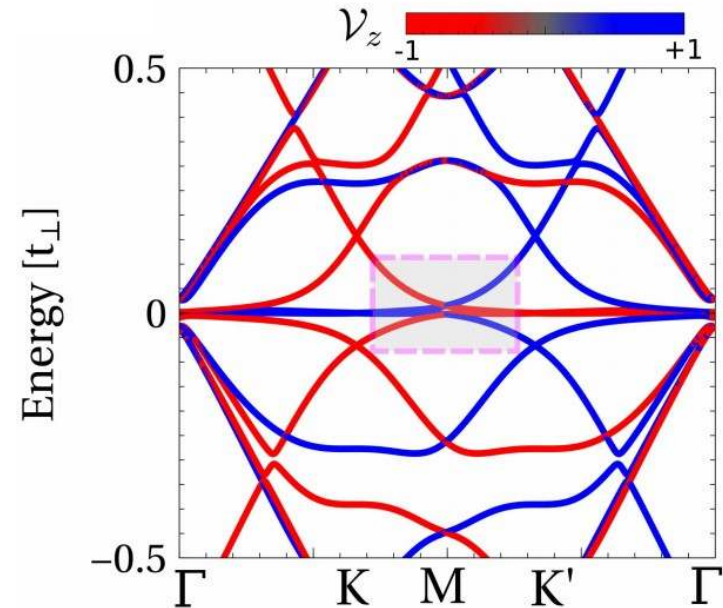


Heavy-fermions in twisted graphene trilayers

Top view

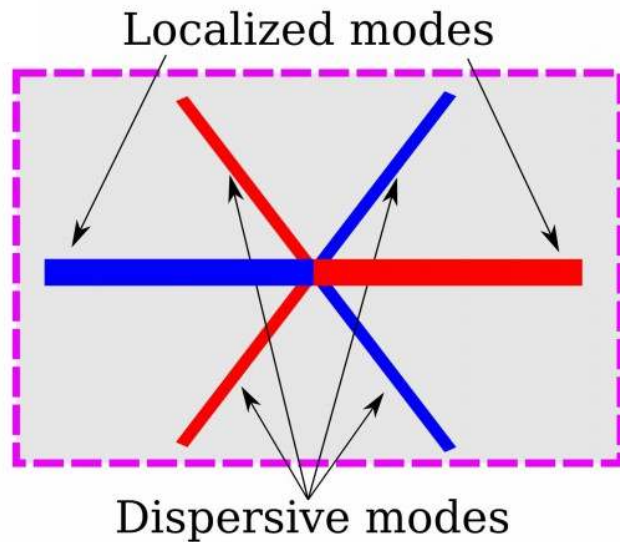


Electronic structure in the presence of an electric bias

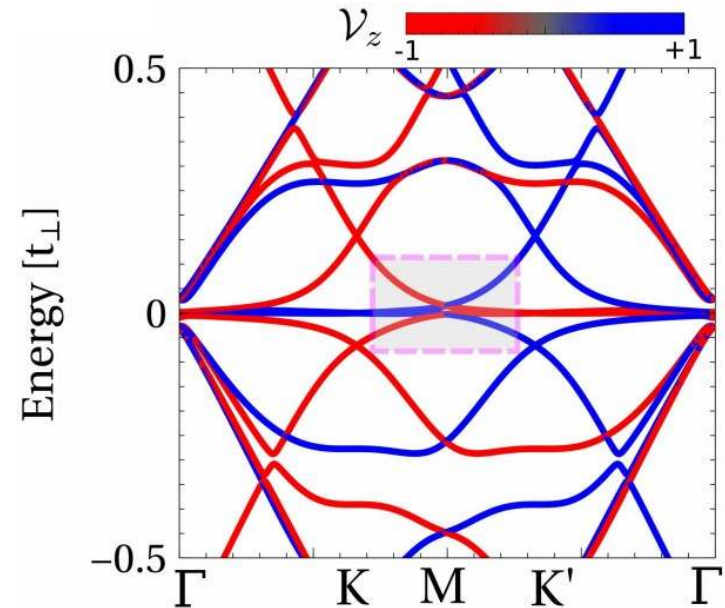


Heavy-fermions in twisted graphene trilayers

Low energy model

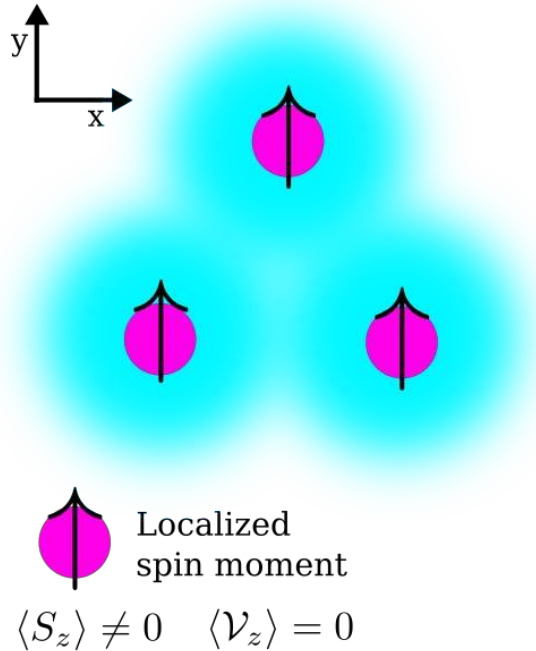


Electronic structure in the presence of an electric bias

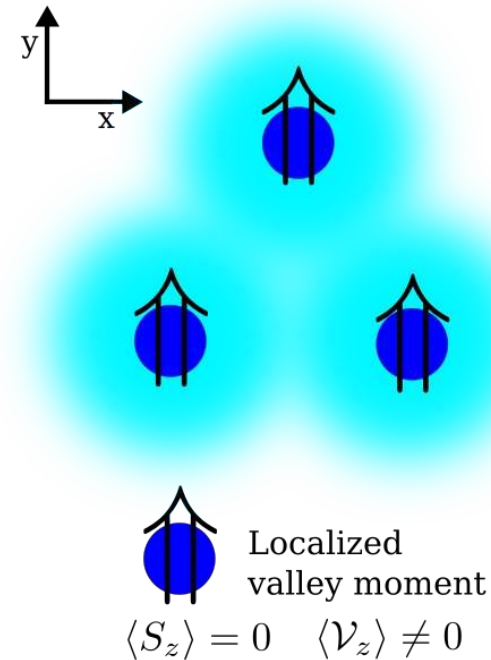


Mean-field electronic structure at half filling

Promoting spin moment formation



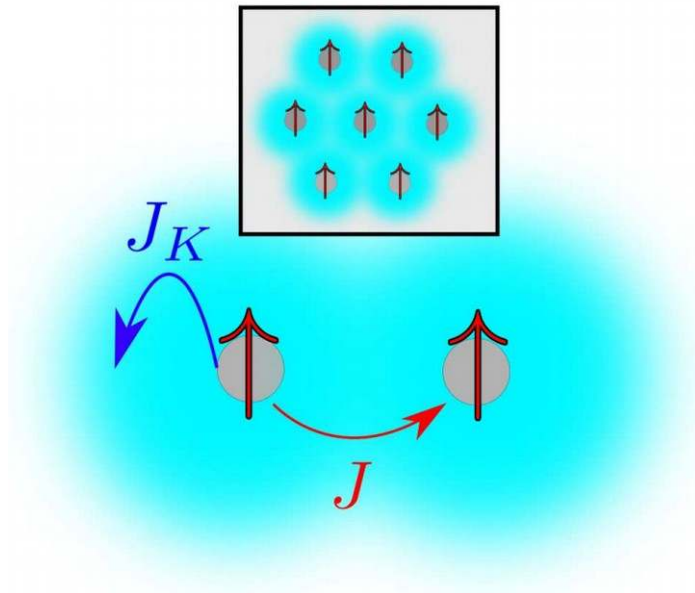
Promoting valley moment formation



Local spin and valley moments appear when including electronic interactions at the mean-field level

Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Kondo coupling Exchange coupling

$$H = H_{\text{dispersive}} + J_K \sum_{\langle i\alpha \rangle} \mathbf{S}_i \cdot \mathbf{s}_\alpha + J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

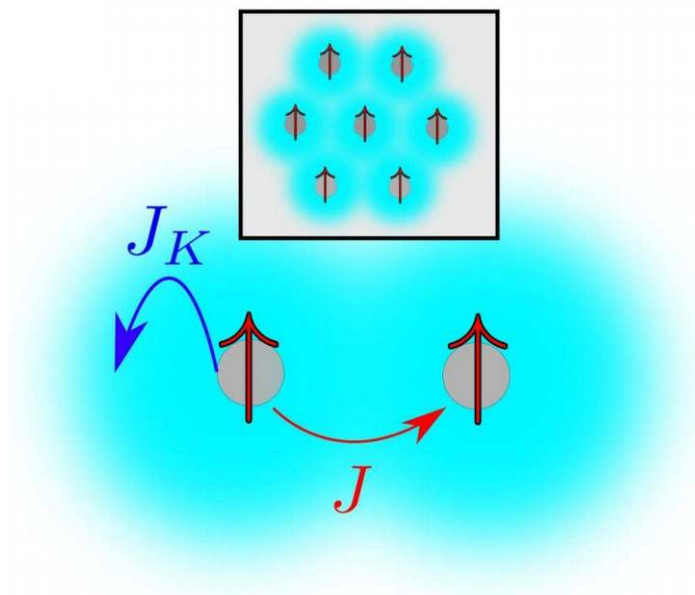
Promotes Kondo screening Promotes magnetic order

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

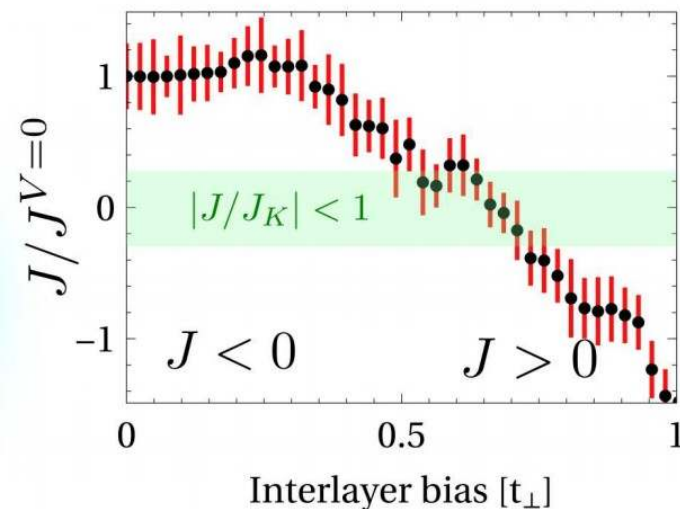
$$|J/J_K| < 1$$

Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Electric control of the Kondo regime

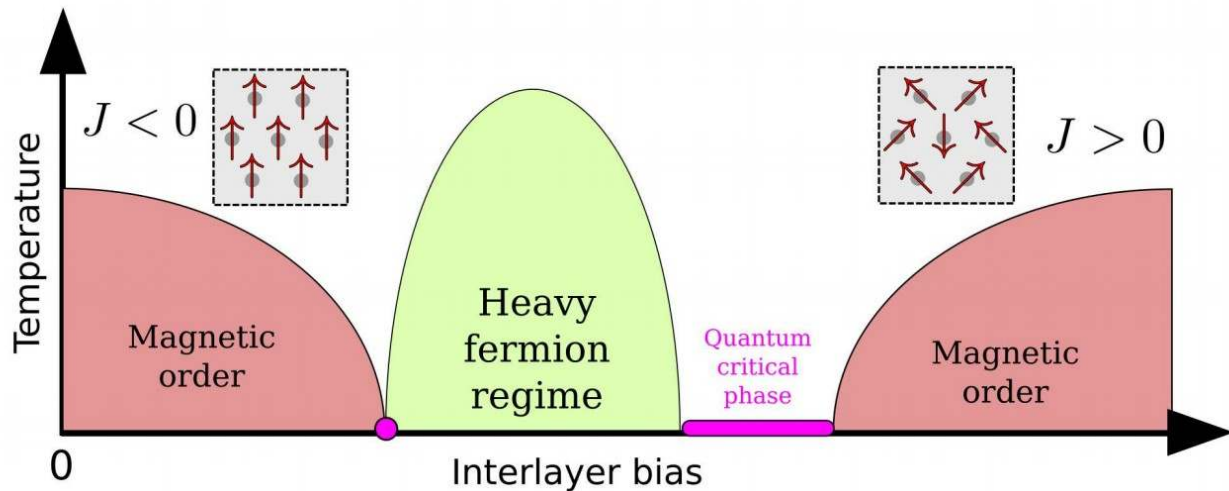


A heavy fermion regime appears when the Kondo coupling dominates over the exchange coupling

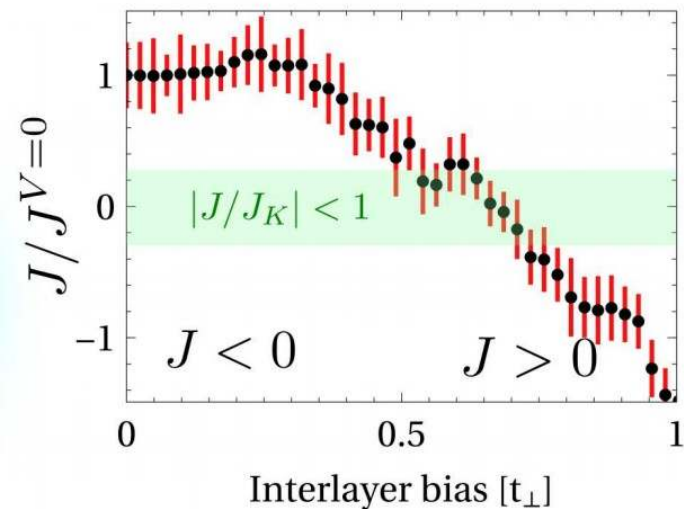
$$|J/J_K| < 1$$

Heavy-fermions in twisted graphene trilayers

Heavy-fermion (Doniach) phase diagram



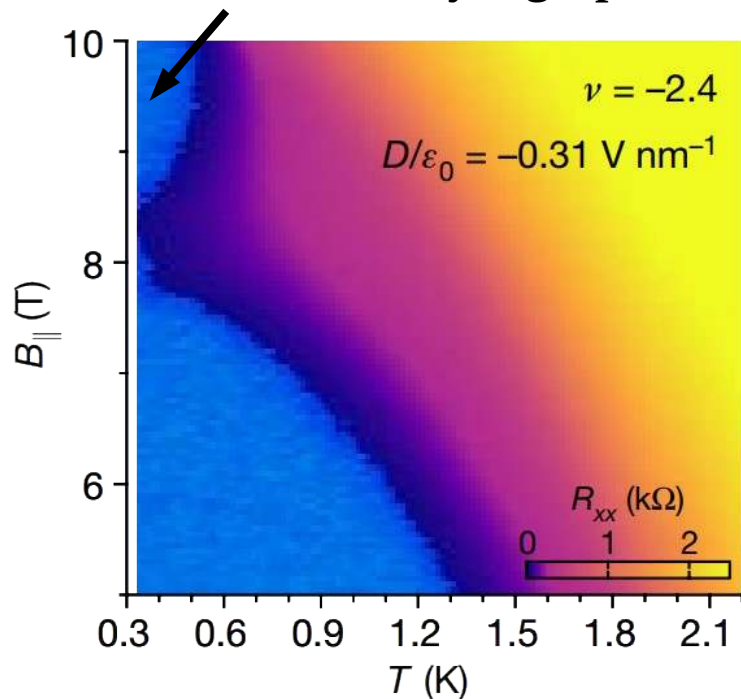
Electric control of the Kondo regime



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

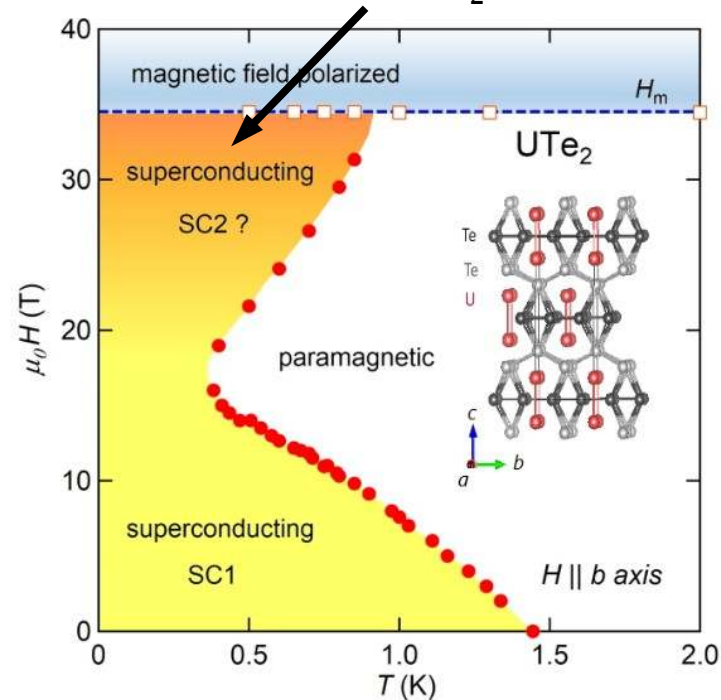
An experimental signature of heavy-fermion physics: spin-triplet superconductivity

Reentrant superconductivity
in twisted trilayer graphene



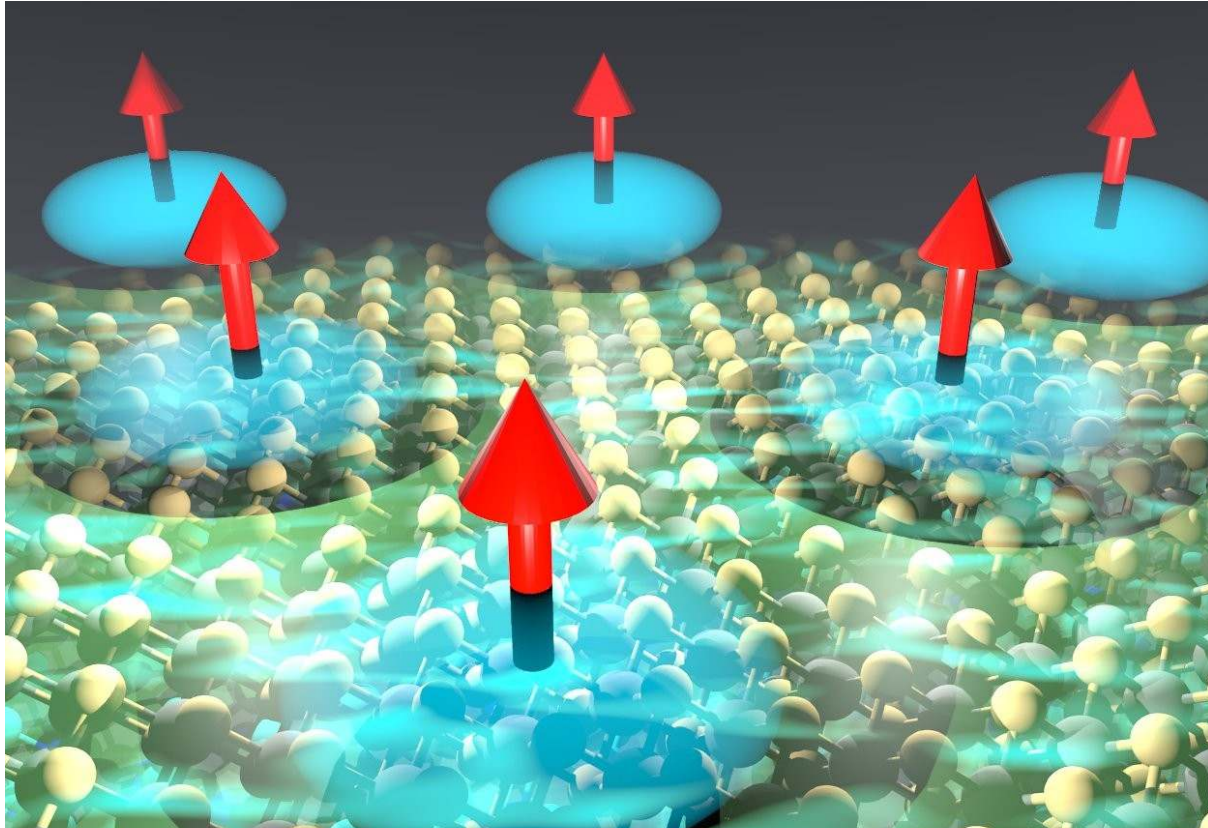
Nature 595, 526–531 (2021)

Reentrant superconductivity
in UTe_2



Nat. Phys. 15, 1250 (2019)
Science 365, 684 (2019)

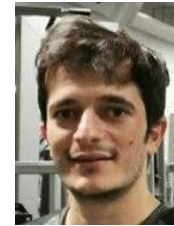
Heavy-fermions in a van der Waals dichalcogenide heterostructure



V. Vaňo



M. Amini



G. Chen



S. Ganguli



S. Kezilebieke



P. Liljeroth



Nature 599, 582–586 (2021)

Heavy-fermions in dichalcogenide bilayers

**Triangular lattice of
local magnetic moments**



1T-TaS₂

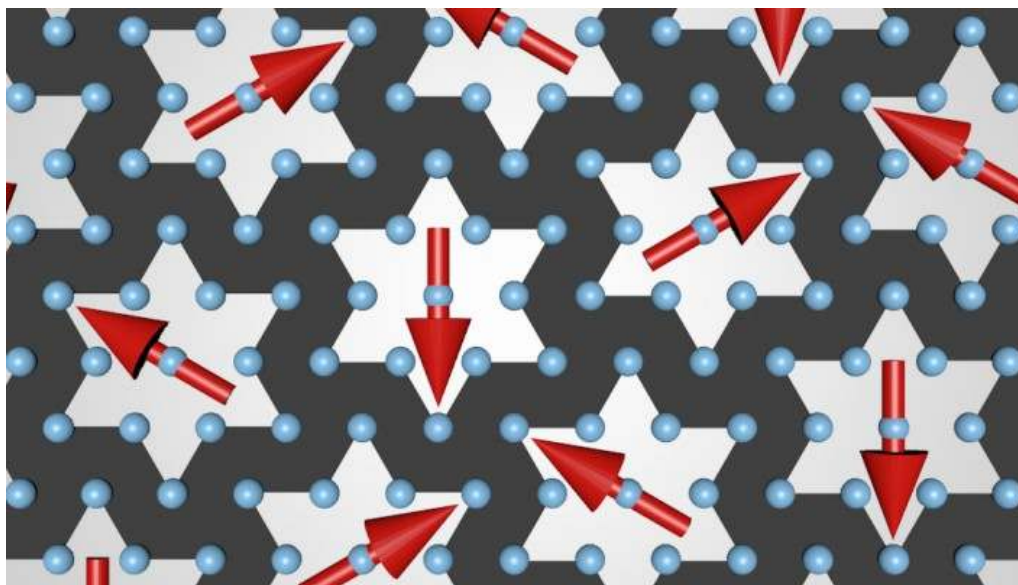
Two-dimensional electron gas



1H-TaS₂

Moment formation in 1T-TaS₂

Charge-density wave reconstruction, leading to a localized orbital in a $\sqrt{13} \times \sqrt{13}$ unit cell



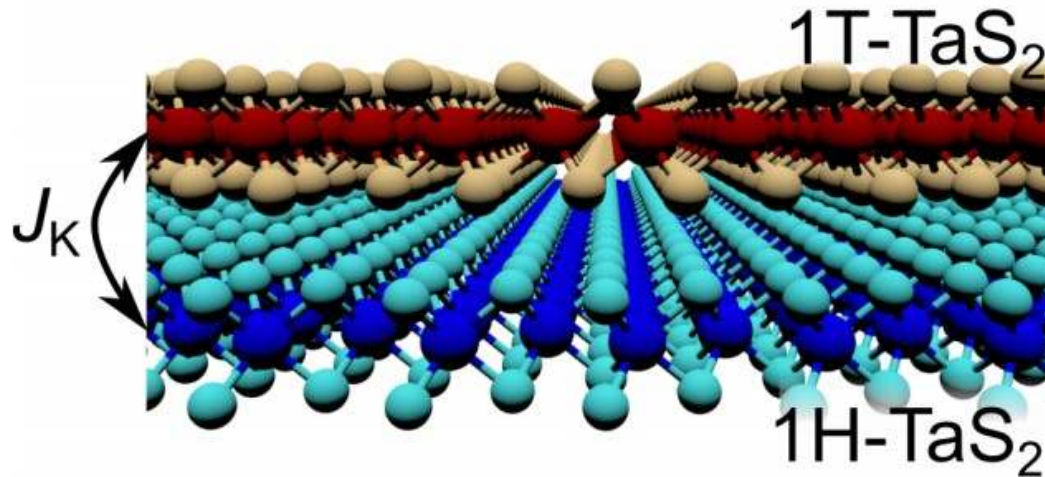
Strong interactions give rise to local moment formation

Effectively described by an S=1/2 Heisenberg model in a triangular lattice

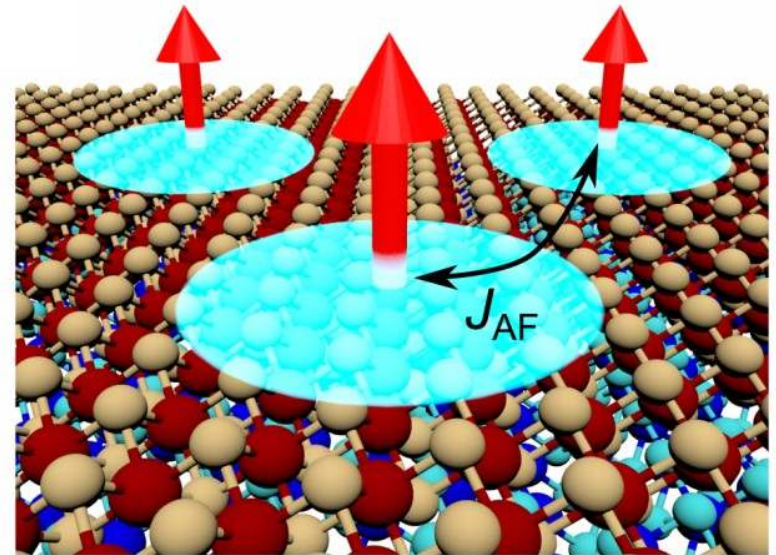
PNAS 114.27 (2017)
Phys. Rev. X 7, 041054 (2017)
Phys. Rev. B 96, 195131 (2017)

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling creates
the Kondo coupling



Intralayer exchange between
local moments

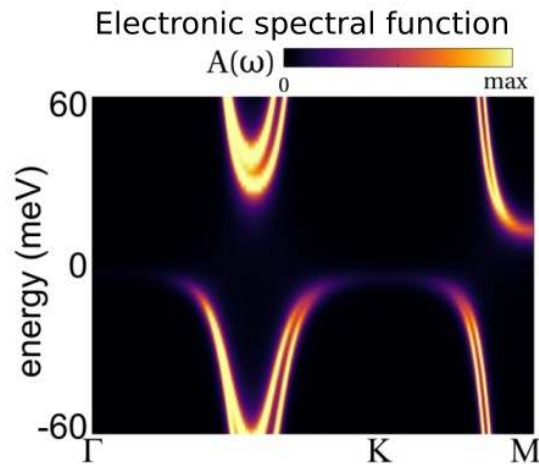
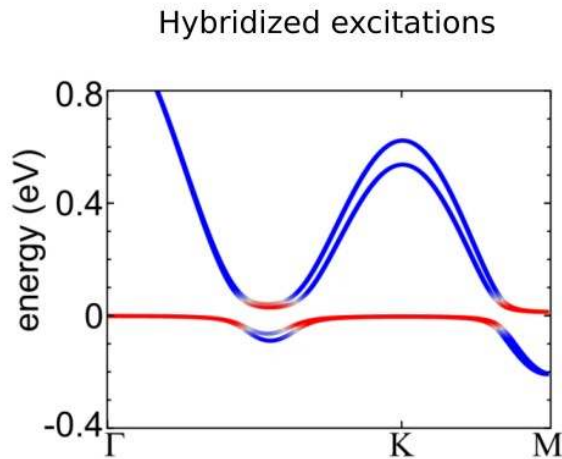
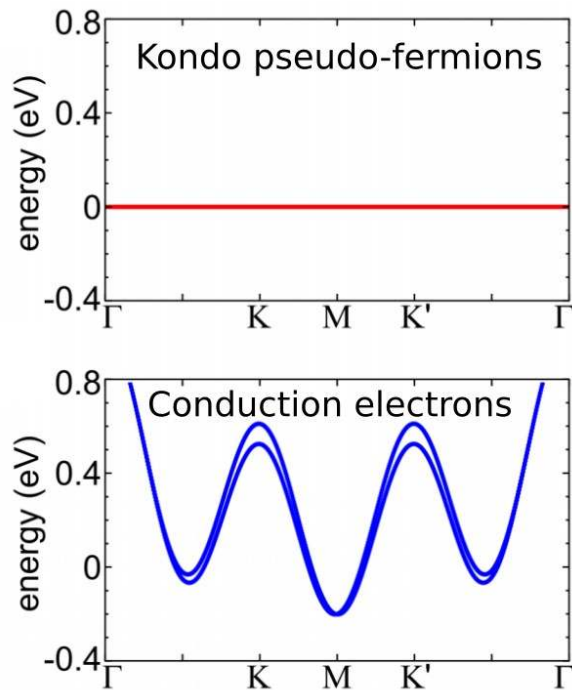


The bilayer realizes all the ingredients for heavy-fermion physics

Heavy-fermion hybridization gap

Kondo physics introduces resonant pseudo-fermions at the chemical potential

Leading to the opening of a heavy-fermion gap

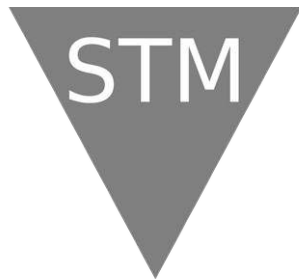


Experimental signatures of heavy-fermion physics

- 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

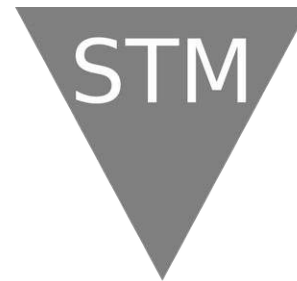


Spin lattice (1T-TaS2)

2D electron gas (1H-TaS2)

Substrate

Probing the heavy-fermion gap

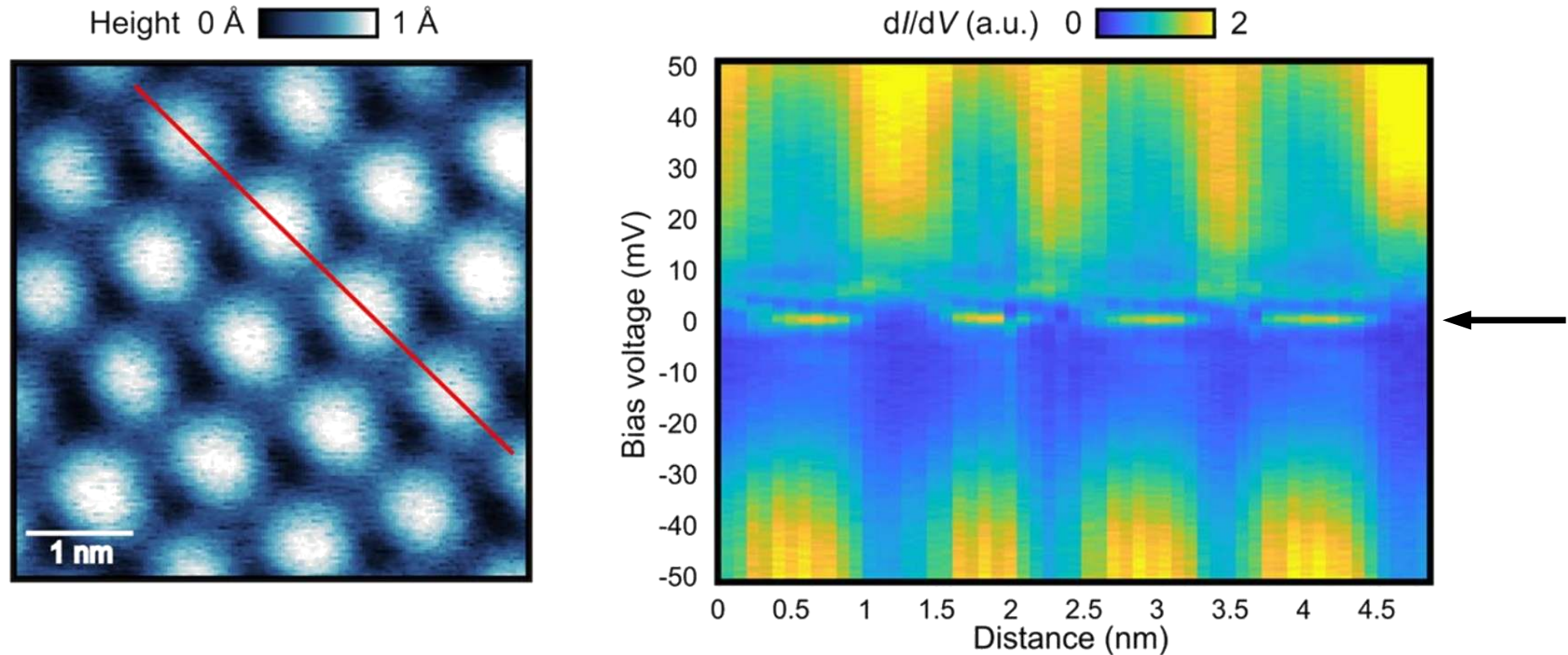


2D electron gas (1H-TaS2)

Spin lattice (1T-TaS2)

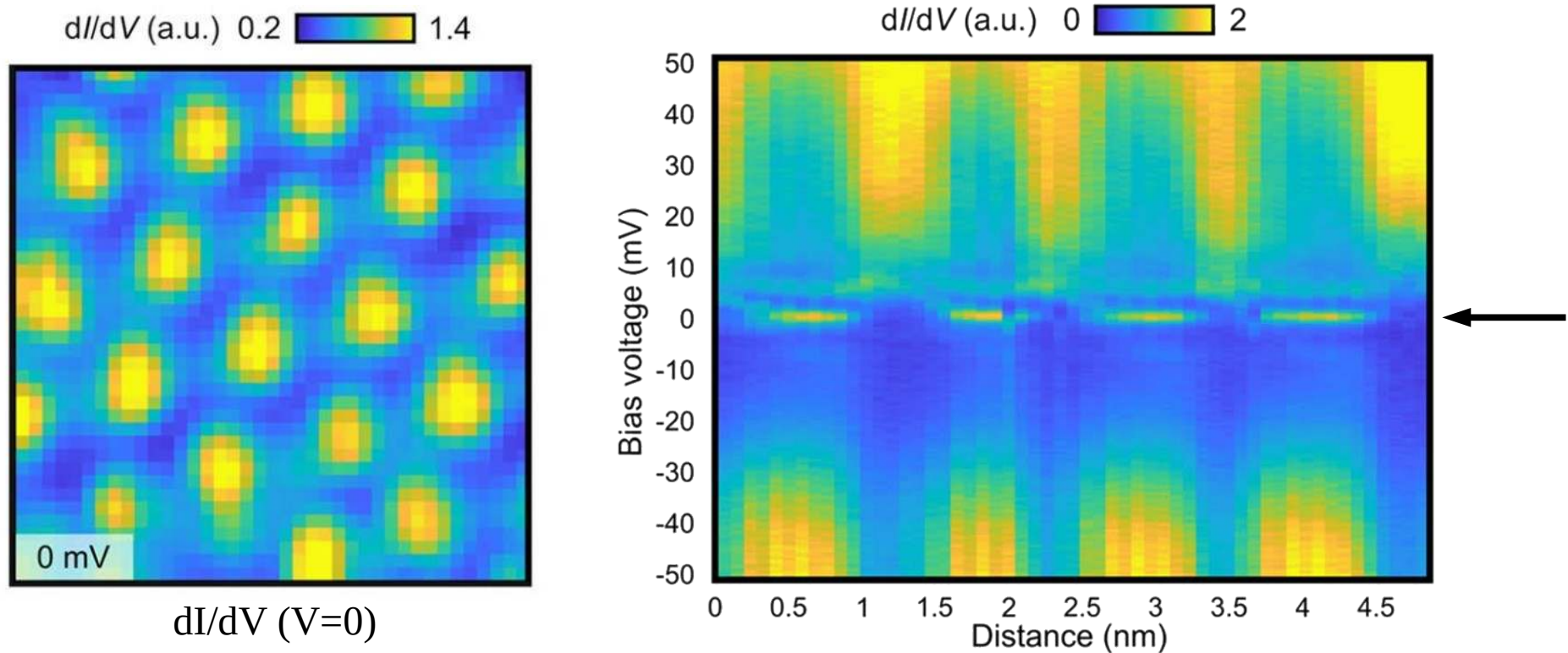
Substrate

Grid spectroscopy of 1T-1H



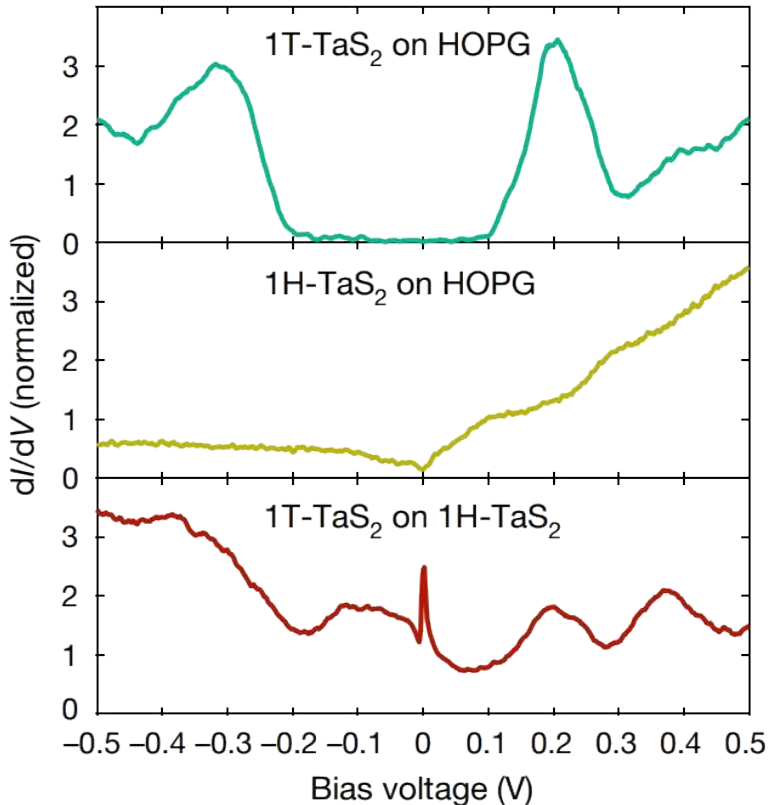
Zero bias (Kondo) peak appearing with the CDW periodicity

Grid spectroscopy of 1T-1H



Zero bias (Kondo) peak appearing with the CDW periodicity

Zero bias Kondo peak

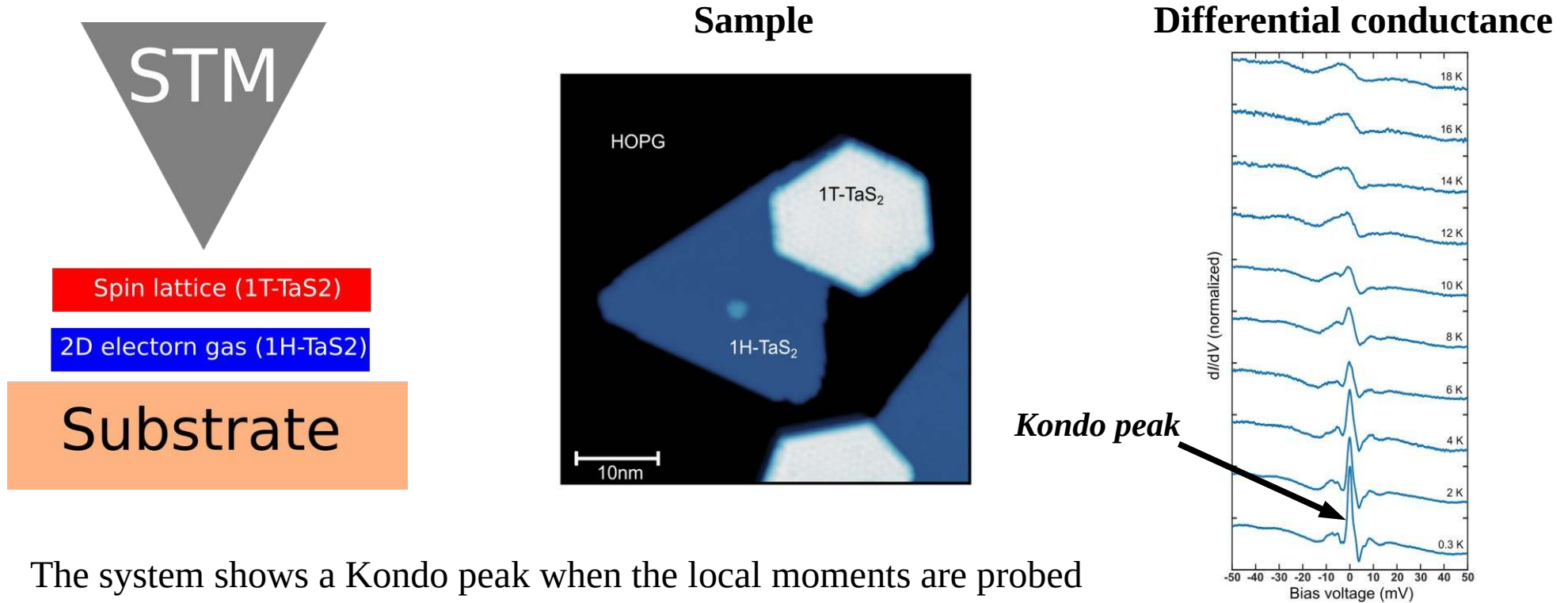


1T @ HOPG: Mott insulator

1H @ HOPG: Metal
(with a SC state at very low T)

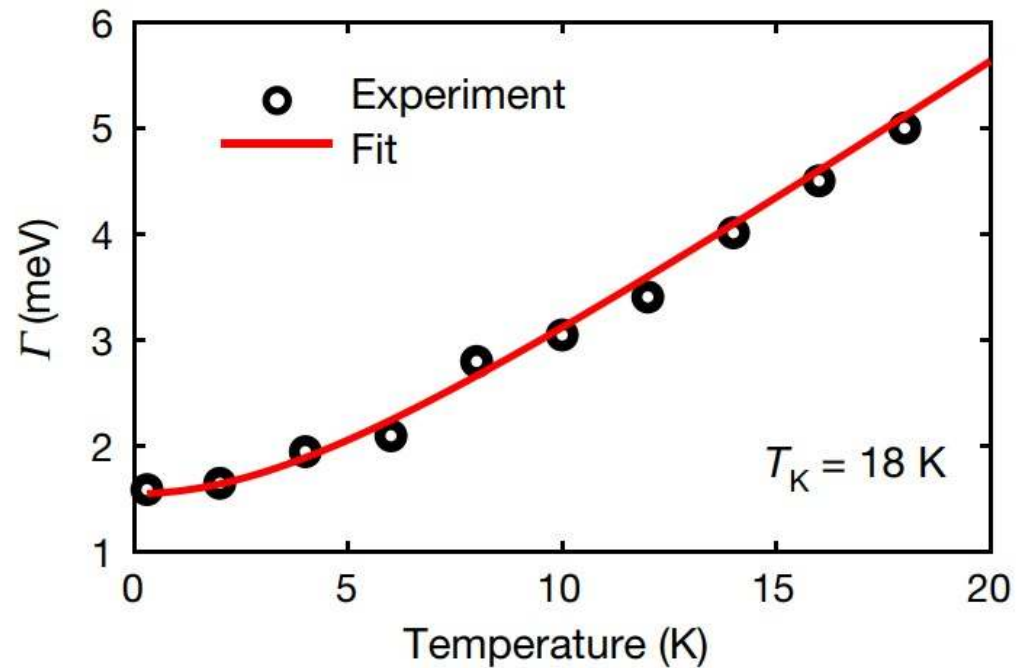
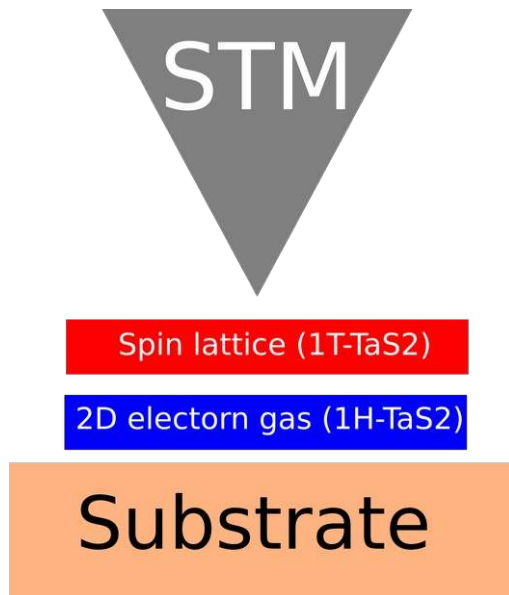
1T @ 1H: Kondo peak

Kondo physics in the magnetic lattice



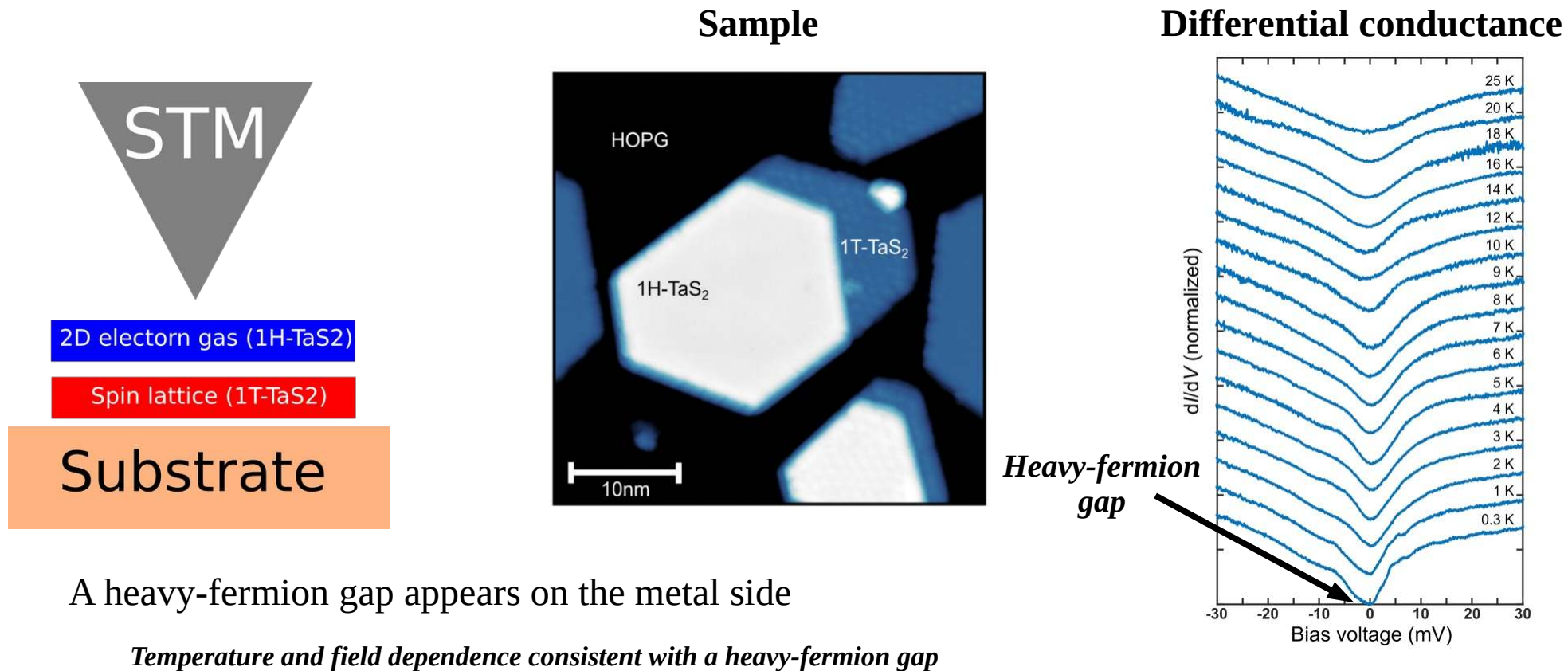
Temperature and field dependence consistent with Kondo

Kondo physics in the magnetic lattice



The Kondo peak follows the expected temperature dependence

Heavy-fermion gap in the 2D electron gas



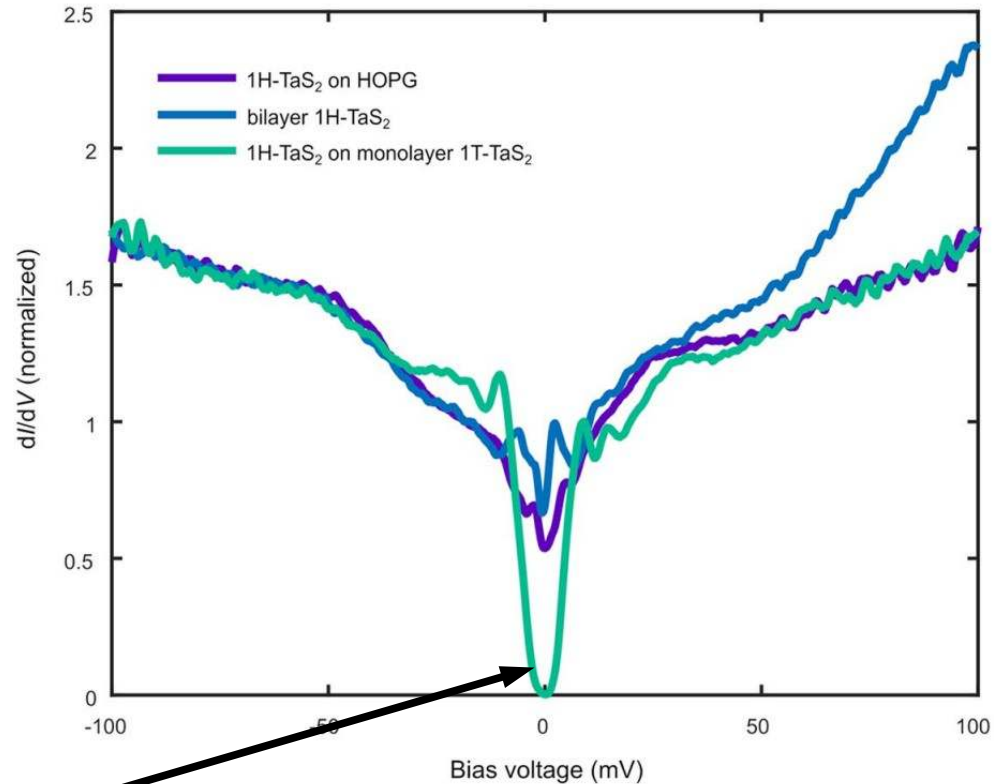
Heavy-fermion gap in the 2D electron gas

STM

2D electron gas (1H-TaS₂)

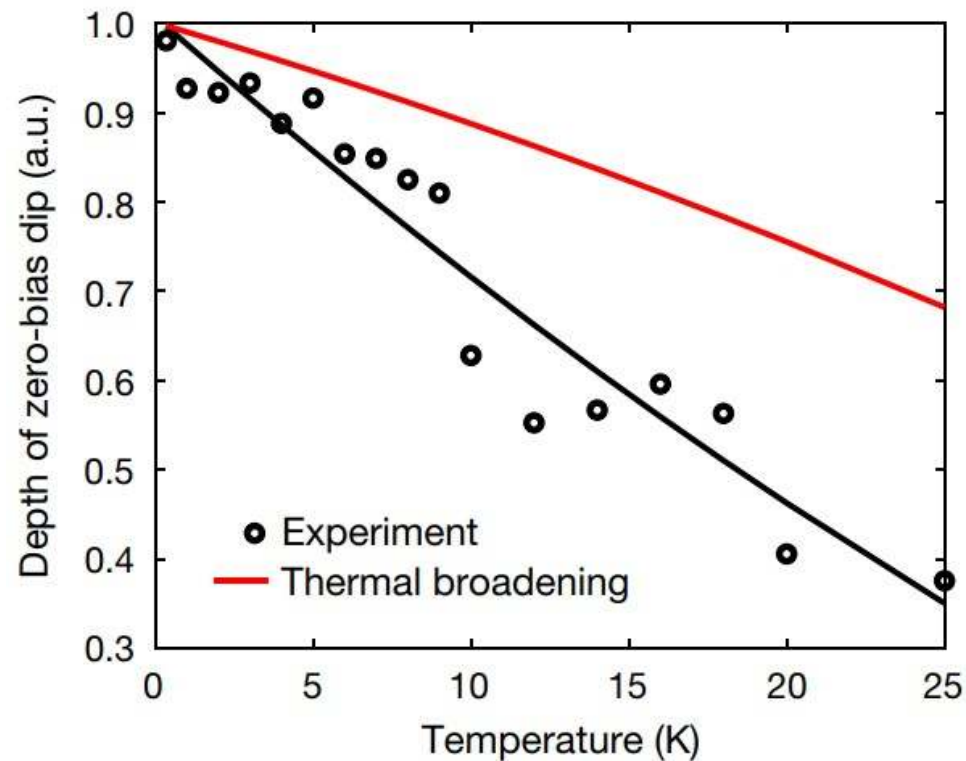
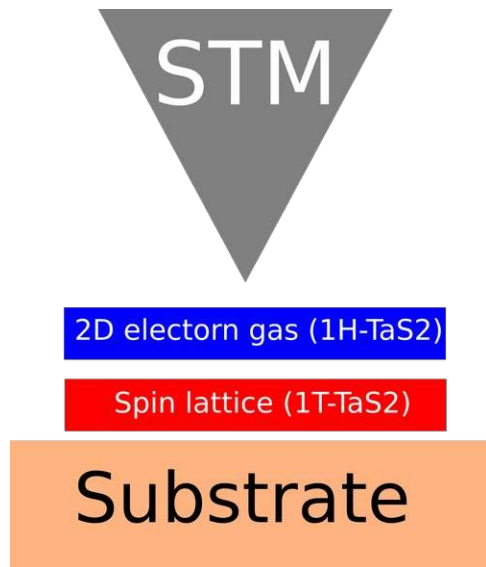
Spin lattice (1T-TaS₂)

Substrate



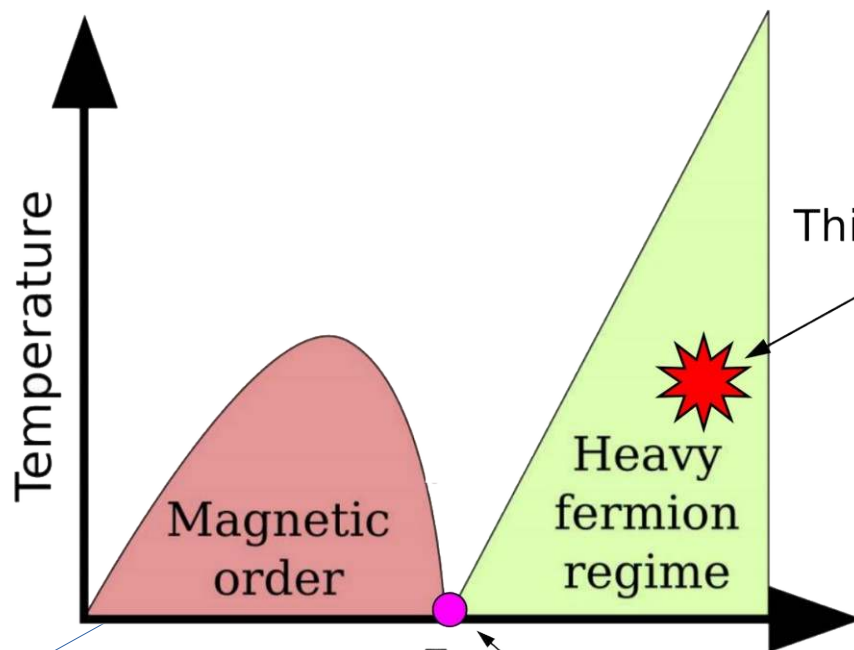
Heavy-fermion gap

Heavy-fermion gap in the 2D electron gas



The gap shows a temperature dependence beyond thermal broadening, expected from a heavy-fermion gap

Next steps in van der Waals heavy-fermions



This experiment

Nature 599, 582–586 (2021)

Nature Comm. 14, 7005 (2023)

J_K

Critical point

Can we push this system to critical and different unconventional superconducting regime

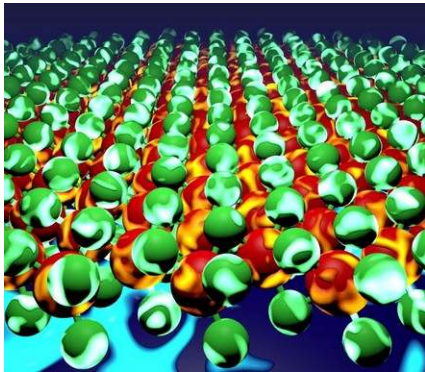
Doped Mott and charge order arXiv:2401.08296

Controlling the heavy-fermion state

*Of course, we can use the typical knobs of bulk heavy fermion compounds
(pressure, chemical doping, etc)*

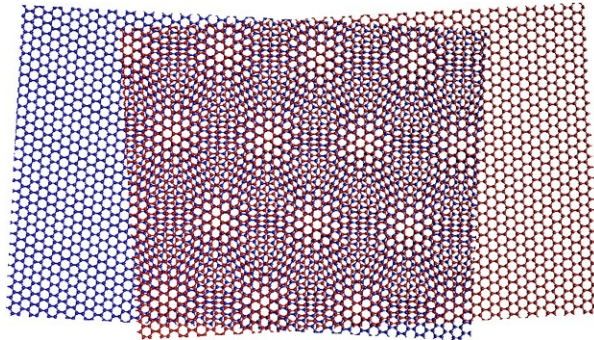
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



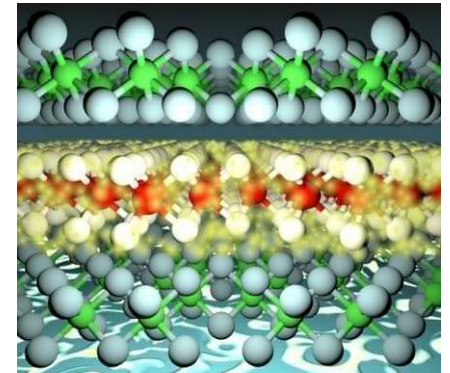
Science 306, 5696, 666-669 (2004)

Twist engineering



Nature Reviews Materials 6, 201–206 (2021)

Materials engineering

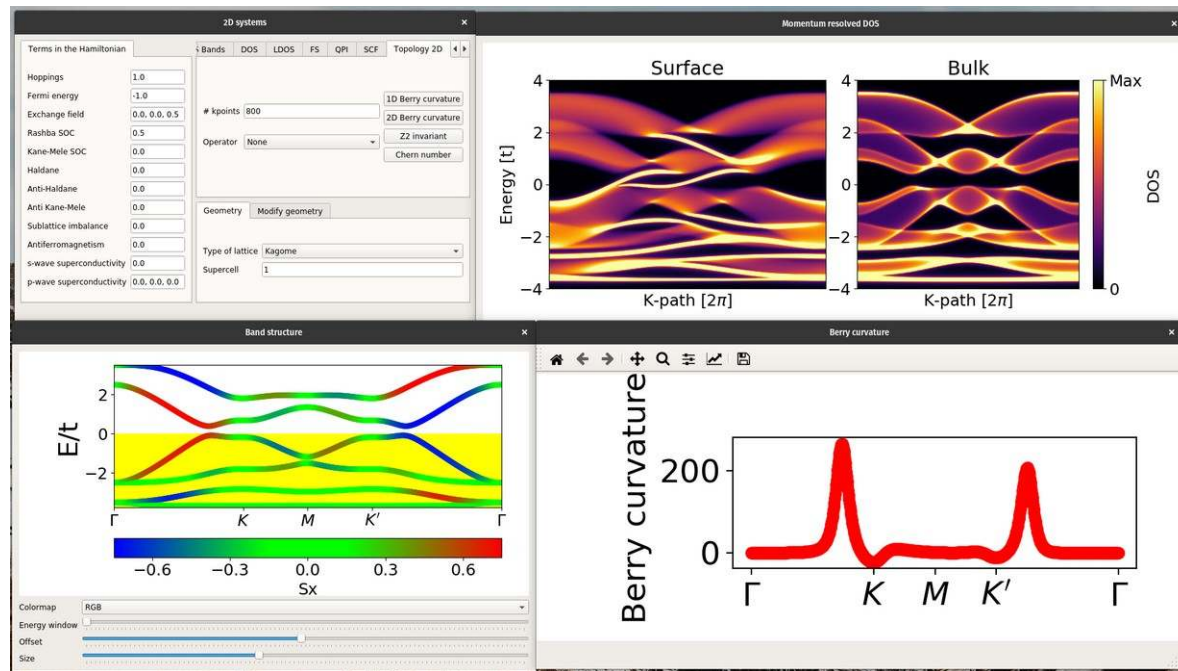
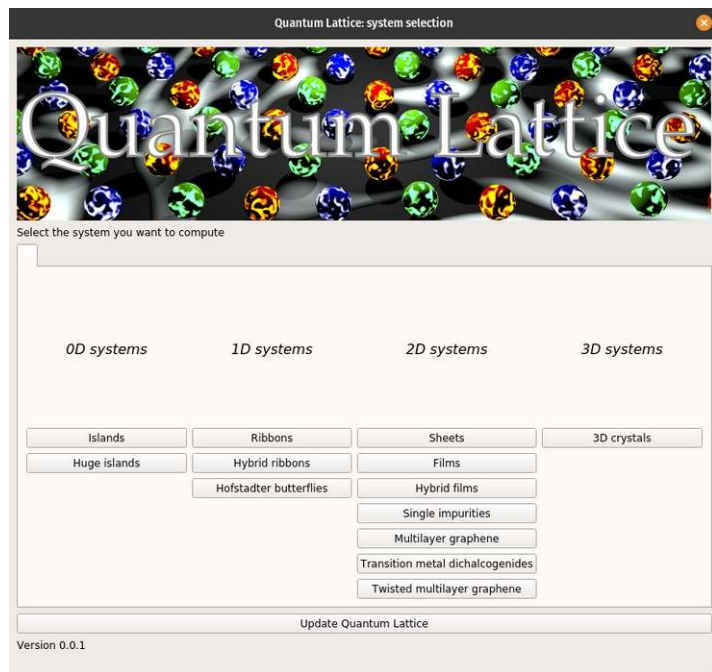


Nature 499, 419–425 (2013)

Allowing to independently control Kondo coupling, exchange coupling, doping and electronic dispersion

Computing electronic
properties

Quantum Lattice: A user interface to compute electronic properties

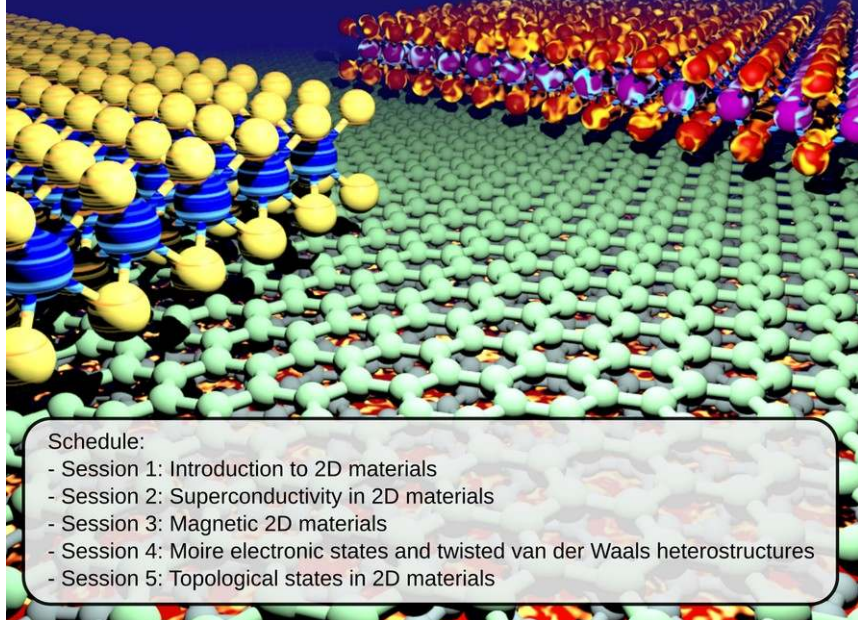


Quantum Lattice: open source interactive interface for tight binding modeling

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

Quantum matter in van der Waals materials school

University of Jyväskylä 31st Jyväskylä Summer School
Emergent quantum matter in
artificial two-dimensional materials
August 8th-12th 2022



Schedule:

- Session 1: Introduction to 2D materials
- Session 2: Superconductivity in 2D materials
- Session 3: Magnetic 2D materials
- Session 4: Moire electronic states and twisted van der Waals heterostructures
- Session 5: Topological states in 2D materials

Recordings available at

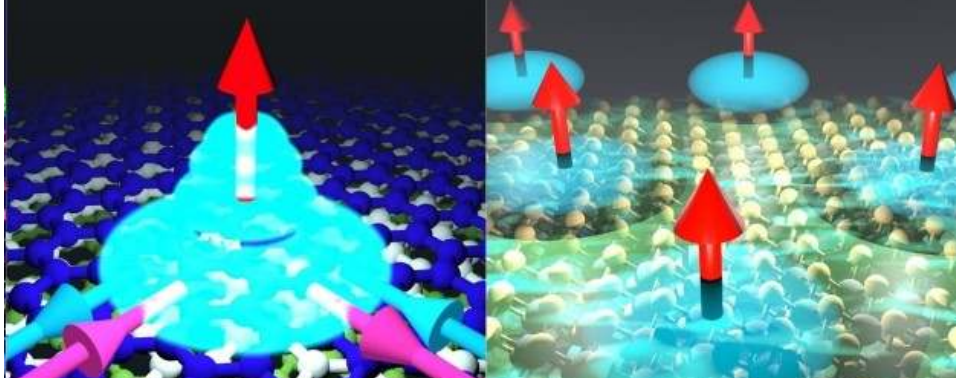


<https://www.youtube.com/channel/UCgnB-4CcqRQnvTi7P0cUakQ>

- Session 1: Introduction to 2D materials
- Session 2: Superconductivity in 2D materials
- Session 3: Magnetic 2D materials
- Session 4: Moire electronic states and twisted van der Waals heterostructures
- Session 5: Topological states in 2D materials

Take home

Van der Waals heterostructures provide a platform to engineer heavy-fermion physics, opening a pathway to a whole new family of emergent quantum states



Phys. Rev. Lett. 127, 026401 (2021)
Nature 599, 582–586 (2021)

Thank you!

Funding from

