Artificial heavy fermions in a dichalcogenide van der Waals heterostructure

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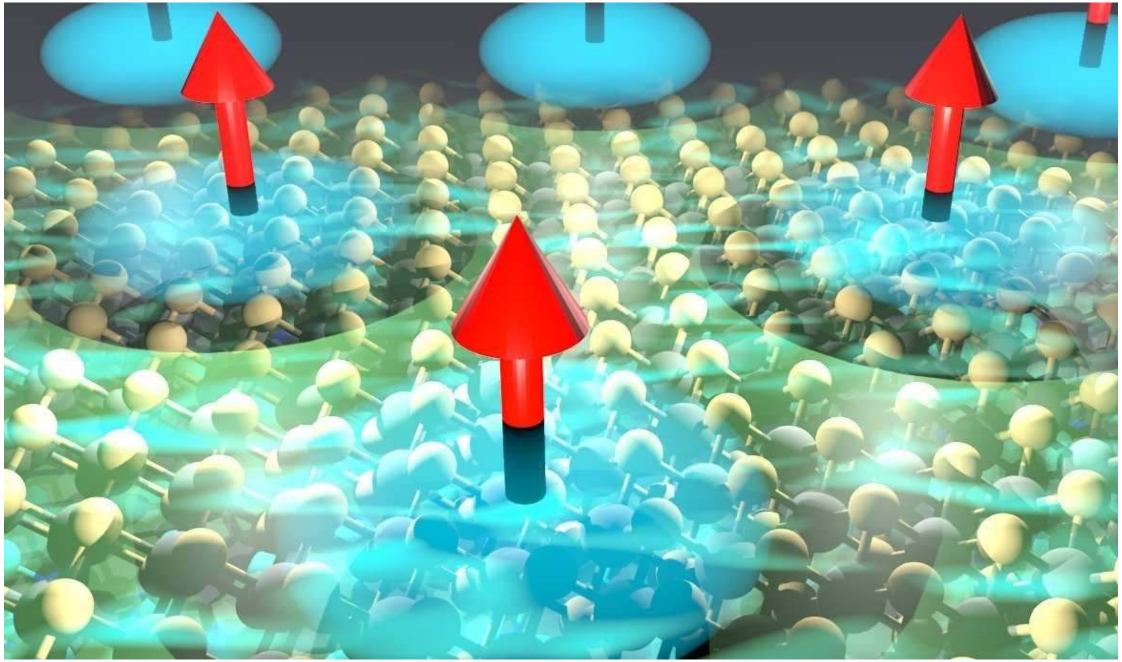


January 19th 2022

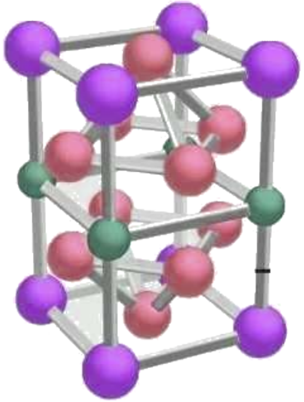
Nature 599, 582–586 (2021)

Young investigators online workshop on unconventional superconductivity in heavy fermions

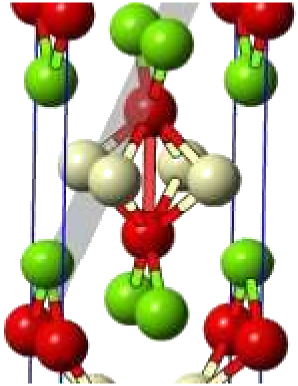
Searching for new heavy fermion compounds

We have a rich family of bulk heavy-fermion compounds

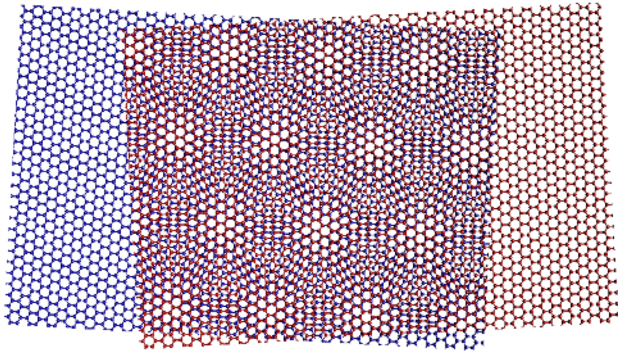
$CeCoIn_5$
Science 375, 6576, 76-81 (2021)

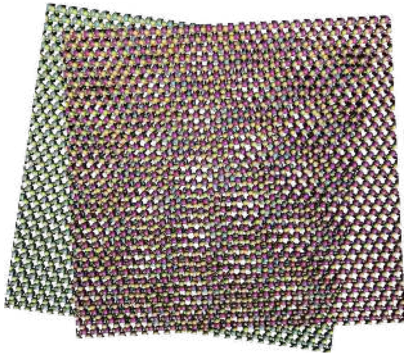


UTe_2
Nature 579, 523–527 (2020)



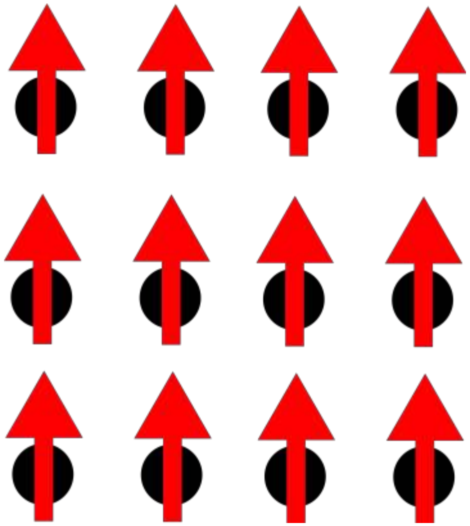
Can we realize heavy-fermion physics with two-dimensional materials?





Building an artifcicial heavy fermion state

Lattice of Kondo impurities



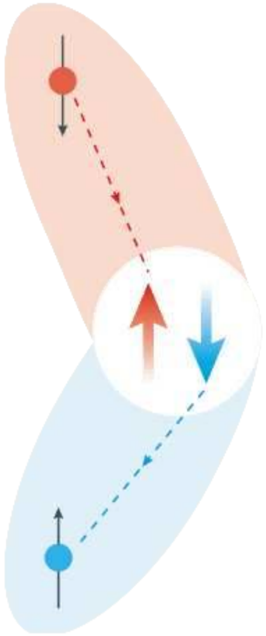
f-electrons in
rare-earth compounds

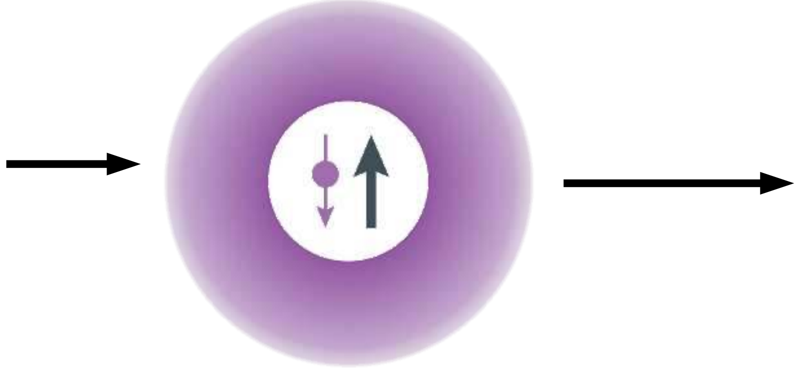
Dispersive electron gas

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

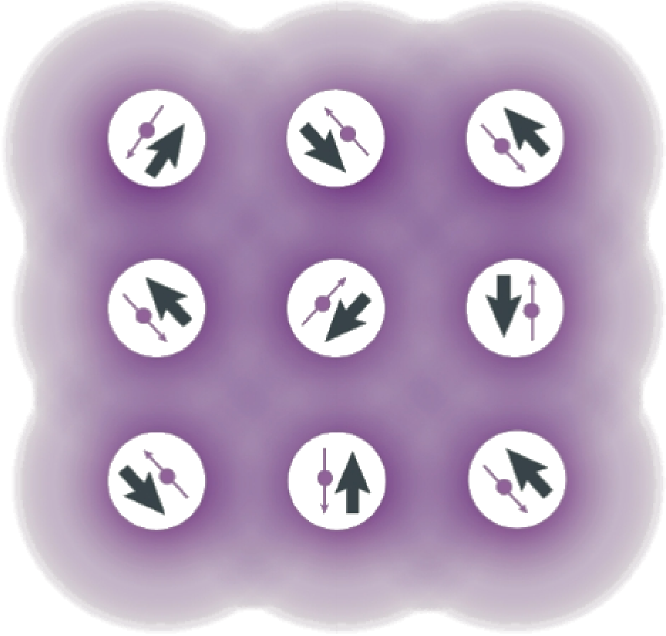
Building an artifcicial heavy fermion state

Conduction electrons form Kondo singlets with the impurities





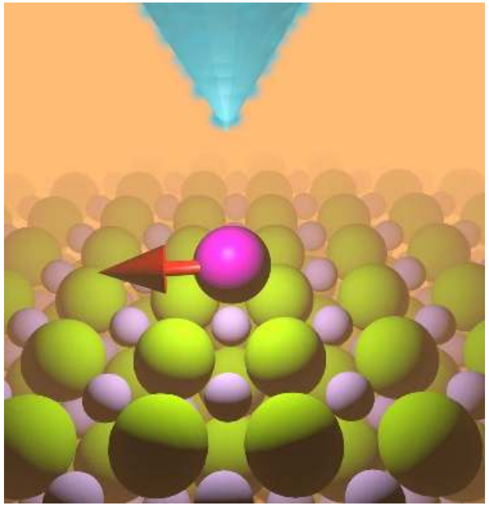
Kondo-lattice model



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

Building heavy-fermions with artificial lattices

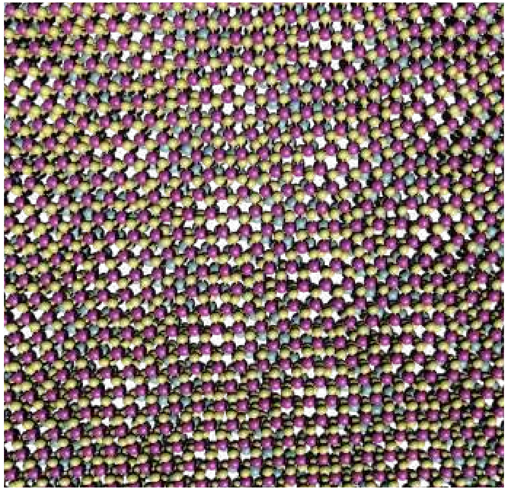
Atomic lattices



a = 0.5 nm

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

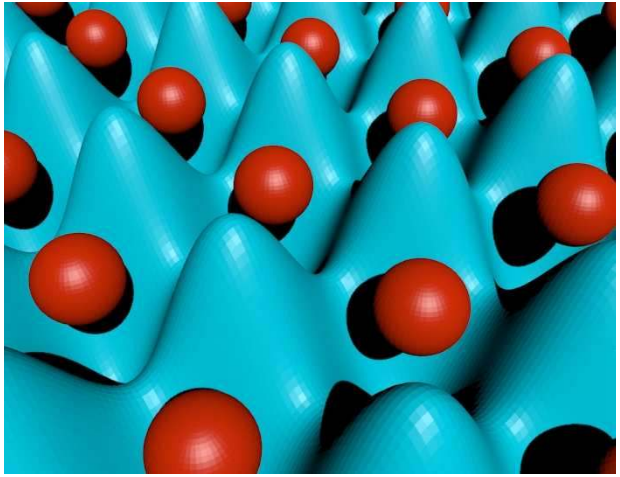
Twisted 2D moire materials



a = 10 nm

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

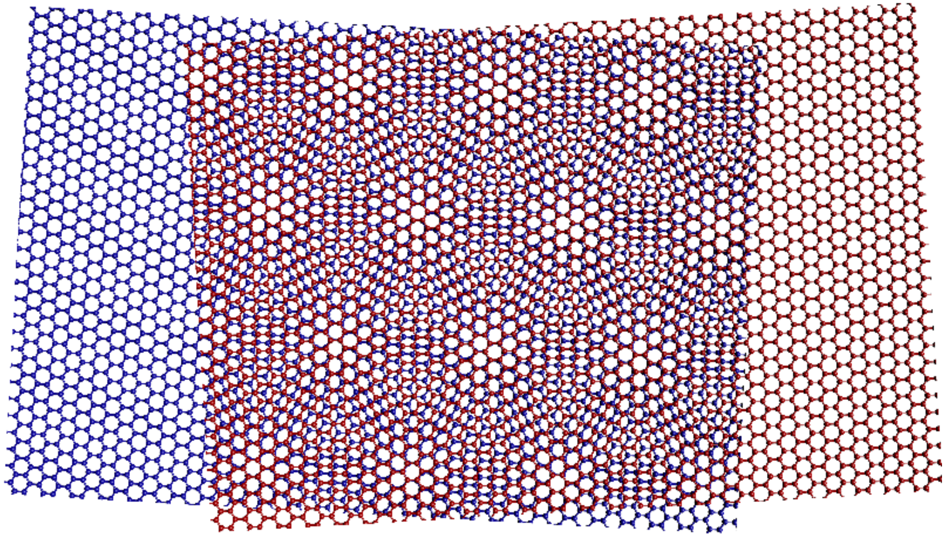
Cold atoms

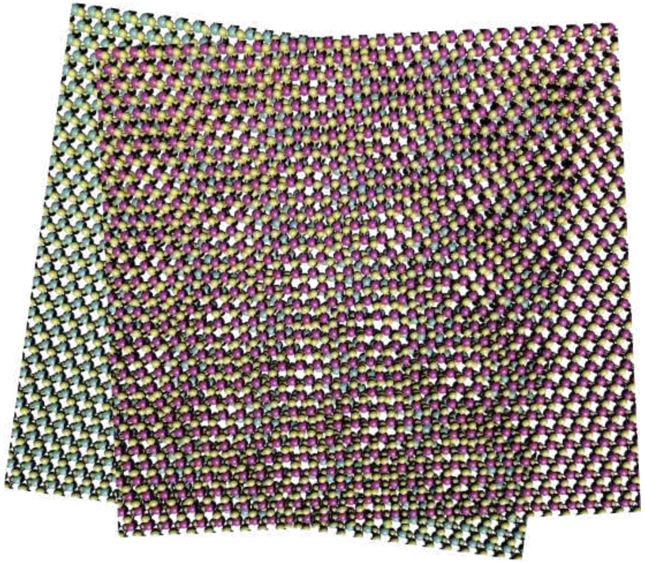


a = 1000 nm

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

Van der Waals materials as a platform for artificial heavy-fermions

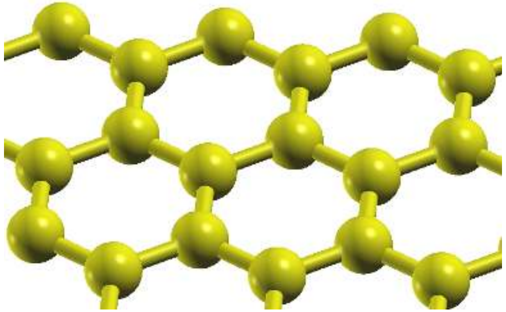




The two-dimensional materials world

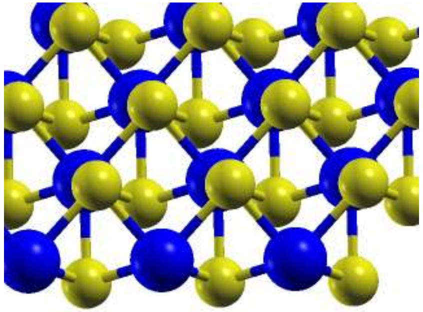
Semimetal

Graphene



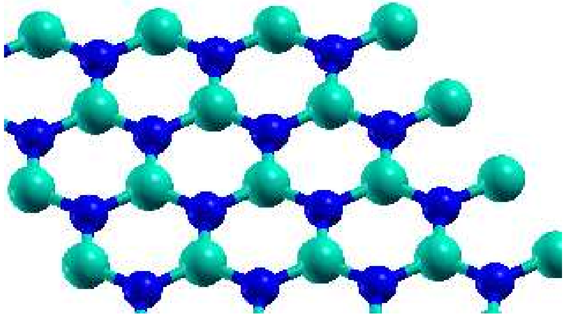
Superconductor

$NbSe_2$



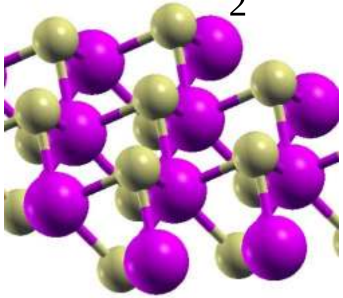
Insulator

BN



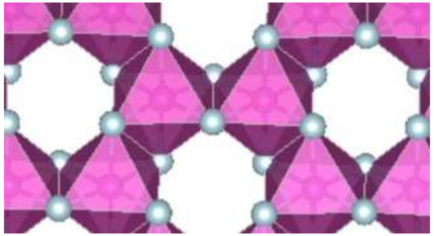
Semiconductor

WSe_2



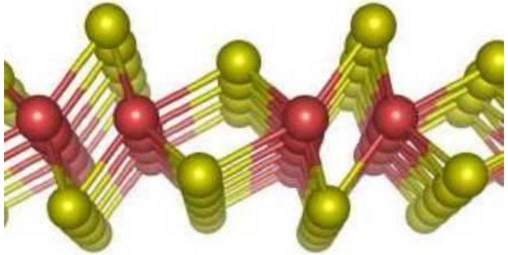
Ferromagnet

CrI_3



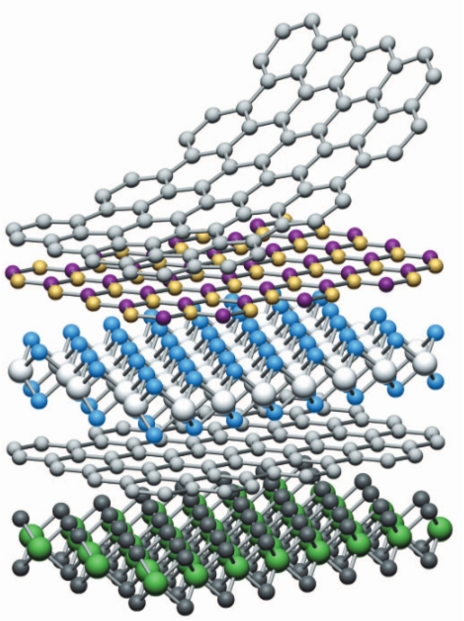
Quantum spin Hall insulator

WTe_2



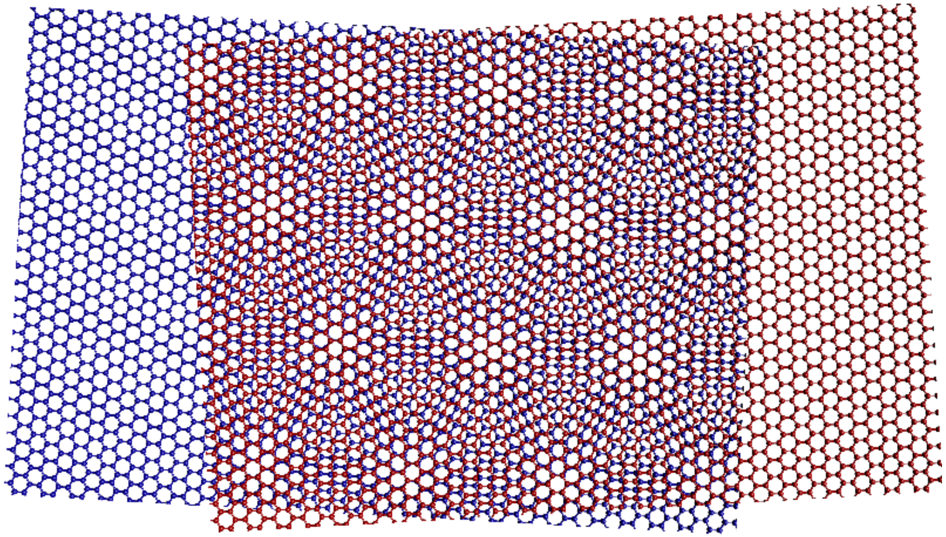
The flexibility of two-dimensional materials

They can be stacked



Nature 499, 419–425 (2013)

They can be rotated

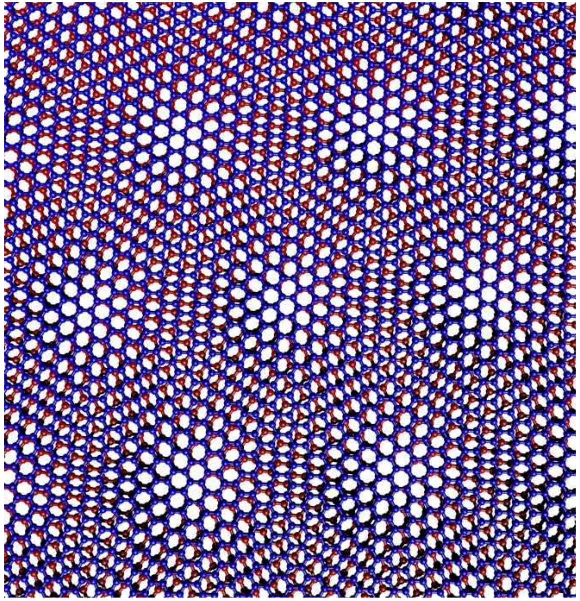


Science 361, 6403, 690-693 (2018)

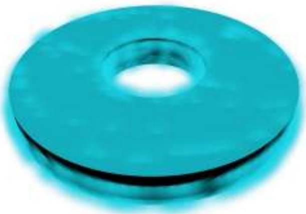
These are unique features of two-dimensional materials

One material, a zoo of electronic phases

Twisted bilayer graphene



Superconductivity

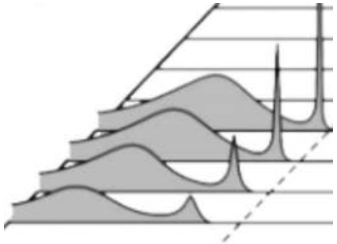


Nature 556, 43–50 (2018)

Topological networks

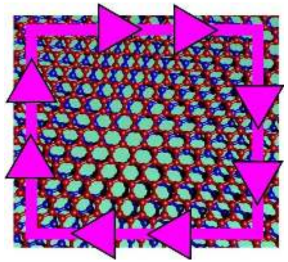
Nano Lett. 18, 11, 6725-6730 (2018)

Strange metals



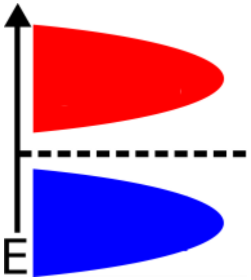
Phys. Rev. Lett. 124, 076801 (2020)

Chern insulators



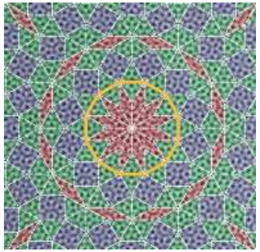
Science 365, 605-608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

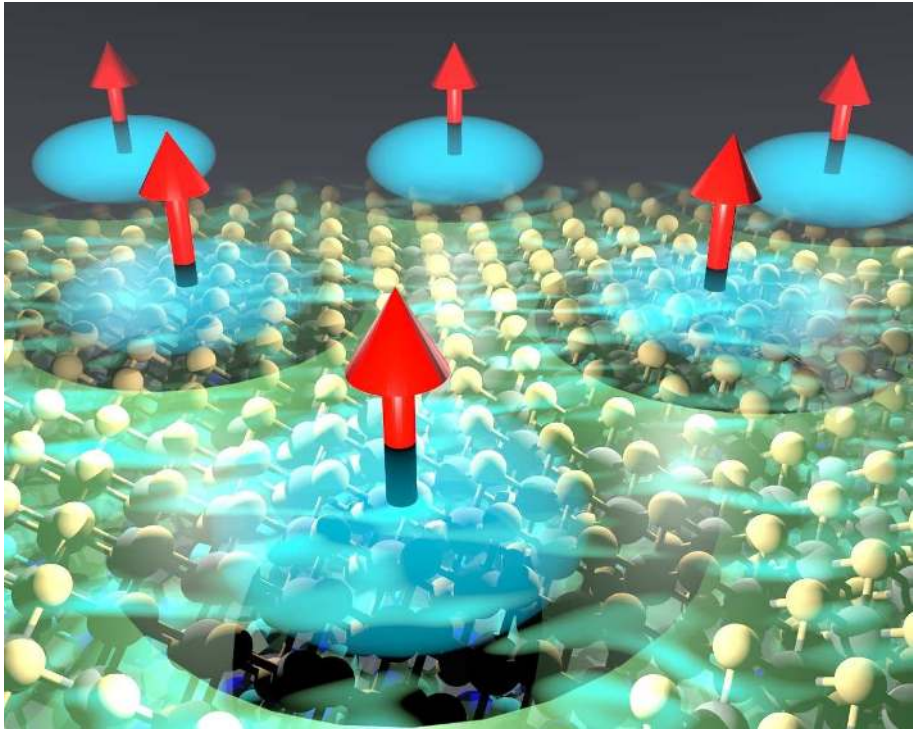
Quasicrystalline physics



Science 361 782-786 (2018)

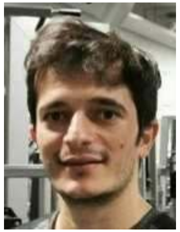
Twisted van der Waals provide a highly flexible platform for quantum phenomena

Behind the scenes

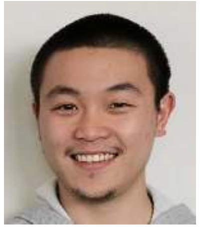


S. Ganguli

M. Amini



G. Chen



V. Vaňo

S. Kezilebieke

P. Liljeroth

Nature 599, 582–586 (2021)

Aalto university

Heavy-fermions in dichalcogenide bilayers

Triangular lattice of local magnetic moments

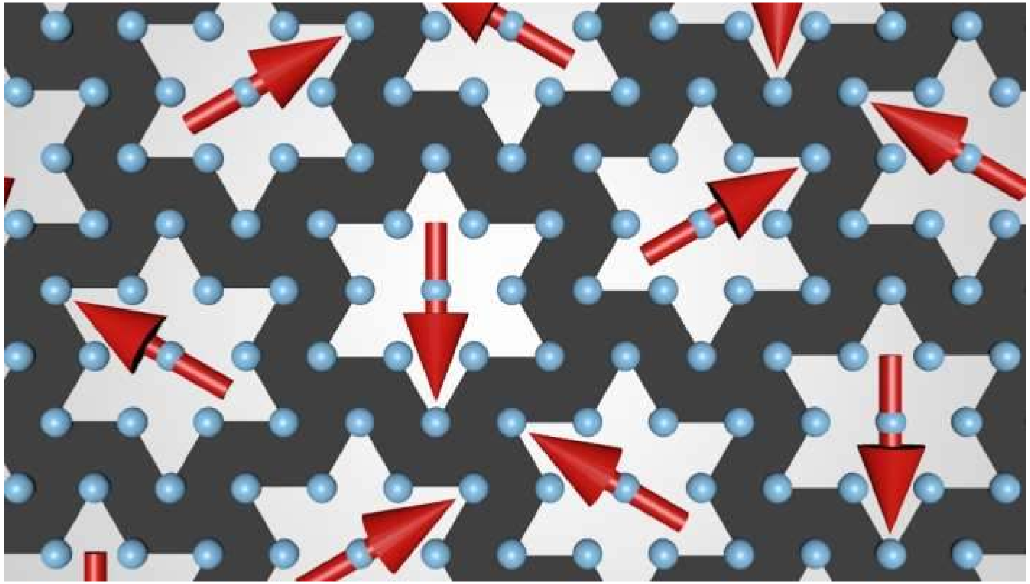
$1T\text{-}TaS_2$

Two-dimensional electron gas

$1H\text{-}TaS_2$

Moment formation in 1T-TaS_2

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



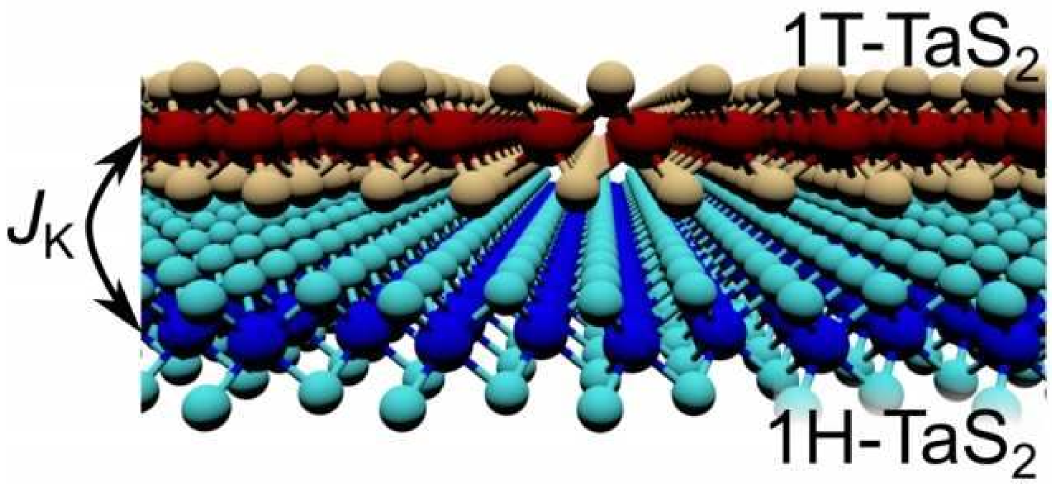
Strong interactions give rise to local moment formation

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

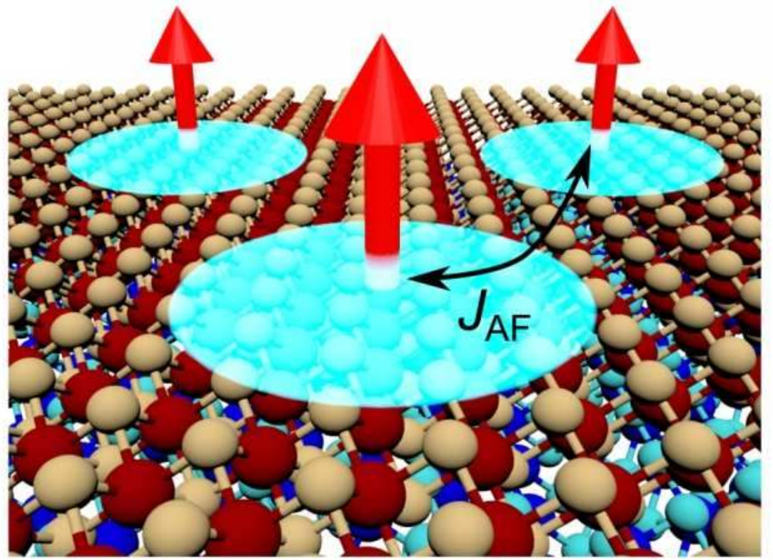
PNAS 114.27 (2017)
Phys. Rev. X 7, 041054 (2017)
Phys. Rev. B 96, 195131 (2017)

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling create the Kondo coupling



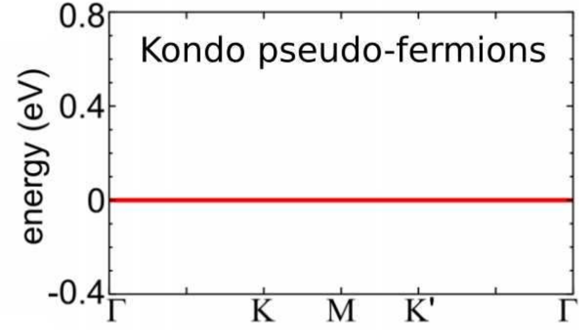
Intralayer exchange between local moments

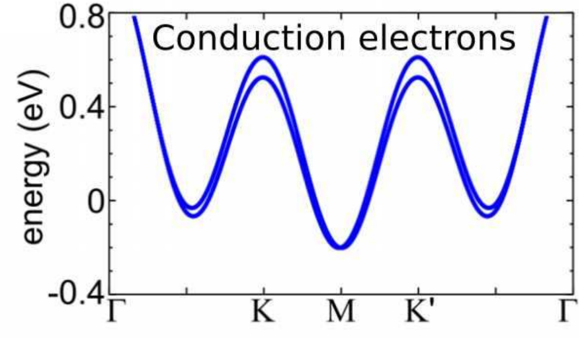


The bilayer realizes all the ingredients for heavy-fermion physics

Pseudofermion treatment at half filling

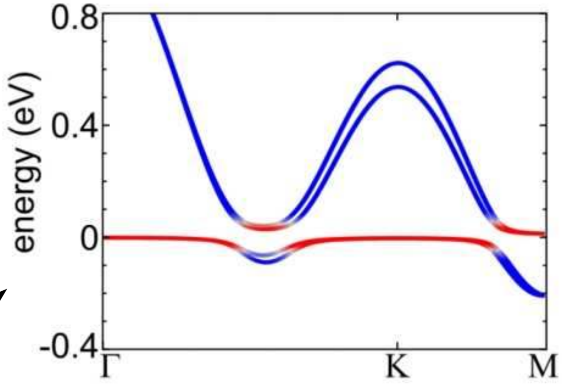
Kondo physics introduces resonant pseudo-fermions at the chemical potential



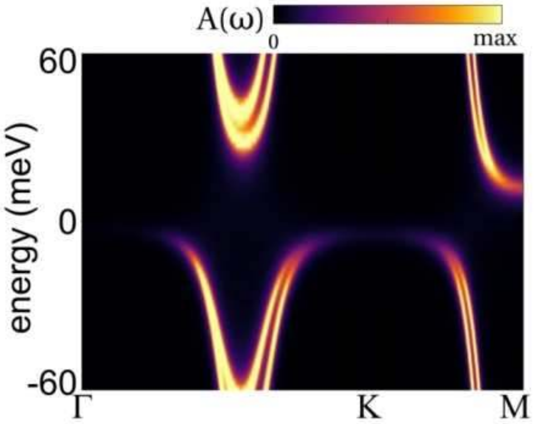


Leading to the opening of a heavy-fermion gap

Hybridized excitations



Electronic spectral function

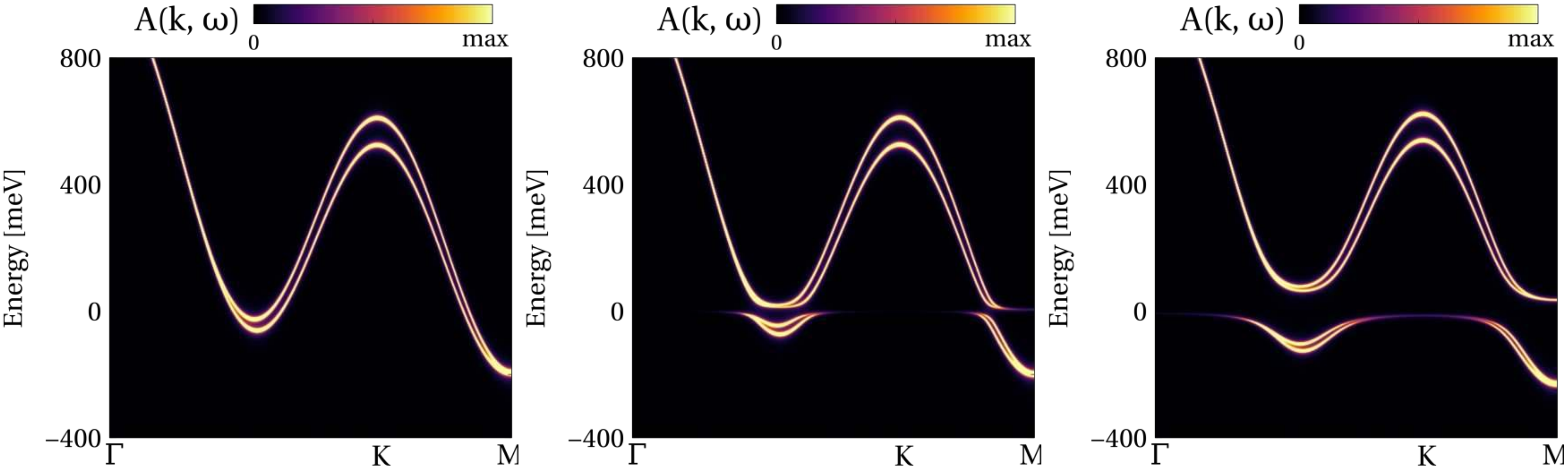


$$H = \sum_{ijss'} t_{ij}^{ss'} c^{\dagger}_{i,s} c_{j,s'} + J_K \sum_{\langle i\mu\rangle ss'} \vec{\sigma}_{s,s'} \cdot \vec{S}_{\mu} c^{\dagger}_{i,s} c_{i,s'} + J \sum_{\langle \mu\nu\rangle} \vec{S}_{\mu} \cdot \vec{S}_{\nu}$$

$$H^{\mathrm{eff}} = \sum_{ijss'} t_{ij}^{ss'} c^{\dagger}_{i,s} c_{j,s'} + \gamma_K \sum_{\langle i\mu\rangle s} c^{\dagger}_{i,s} f_{\mu,s} + \gamma_J \sum_{\langle \mu\nu\rangle s} f^{\dagger}_{\mu,s} f_{\nu,s} + \mu_J \sum_{\mu s} f^{\dagger}_{\mu,s} f_{\mu,s} + \mathrm{h.c.}$$

Heavy-fermion hybridization gap

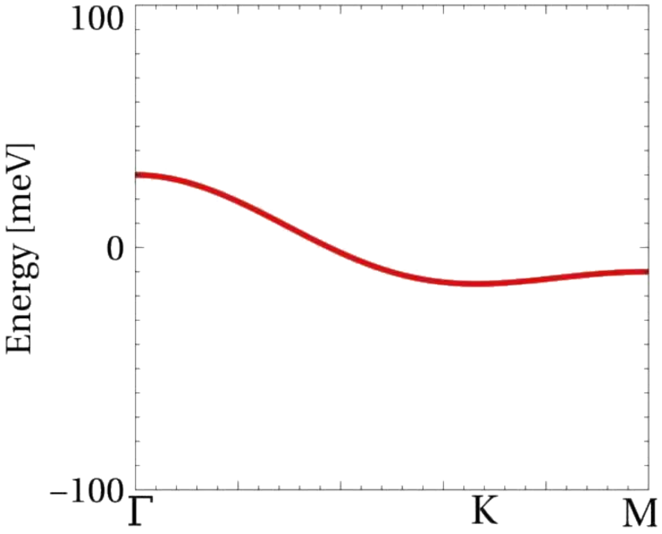
Increasing Kondo coupling



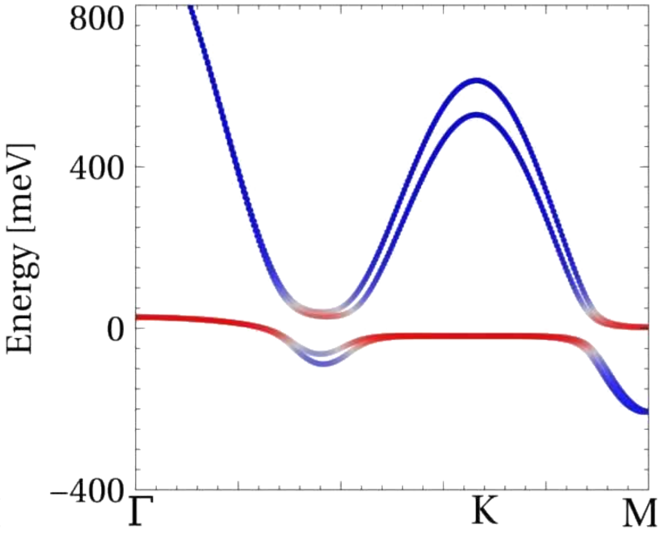
The Kondo coupling leads to a heavy-fermion gap opening in the metal

Heavy-fermion hybridization gap

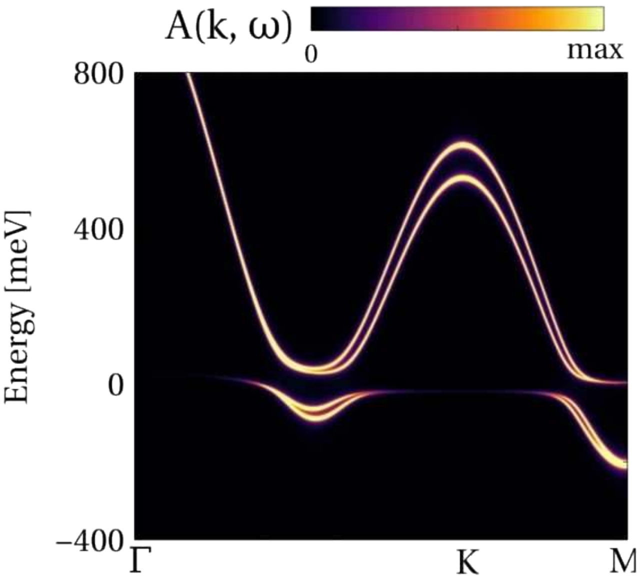
Kondo pseudofermions



Hybridized excitations



Conduction spectral function



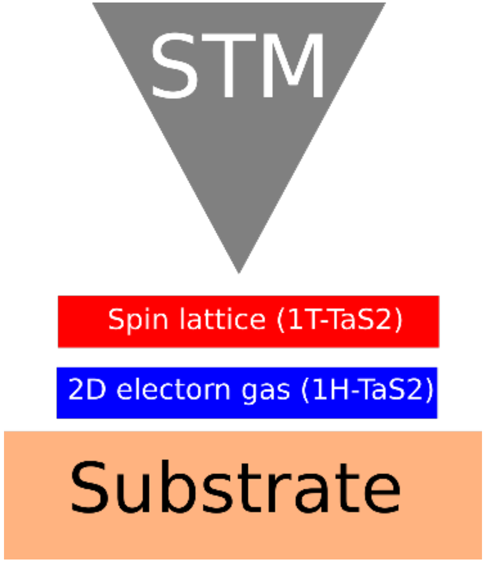
The gap remains open when including a small psedofermion dispersion

Two signatures of heavy-fermion physics

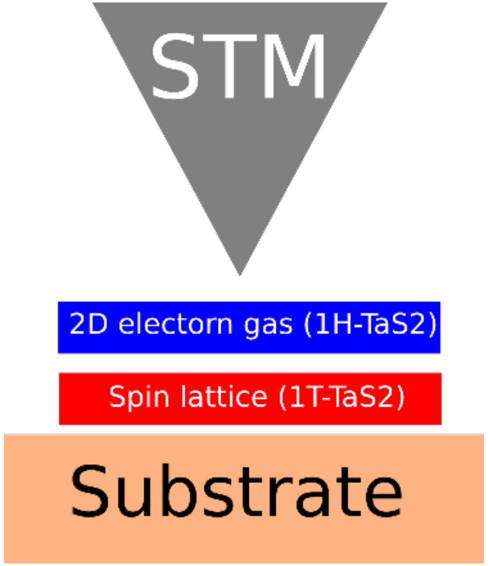
- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

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

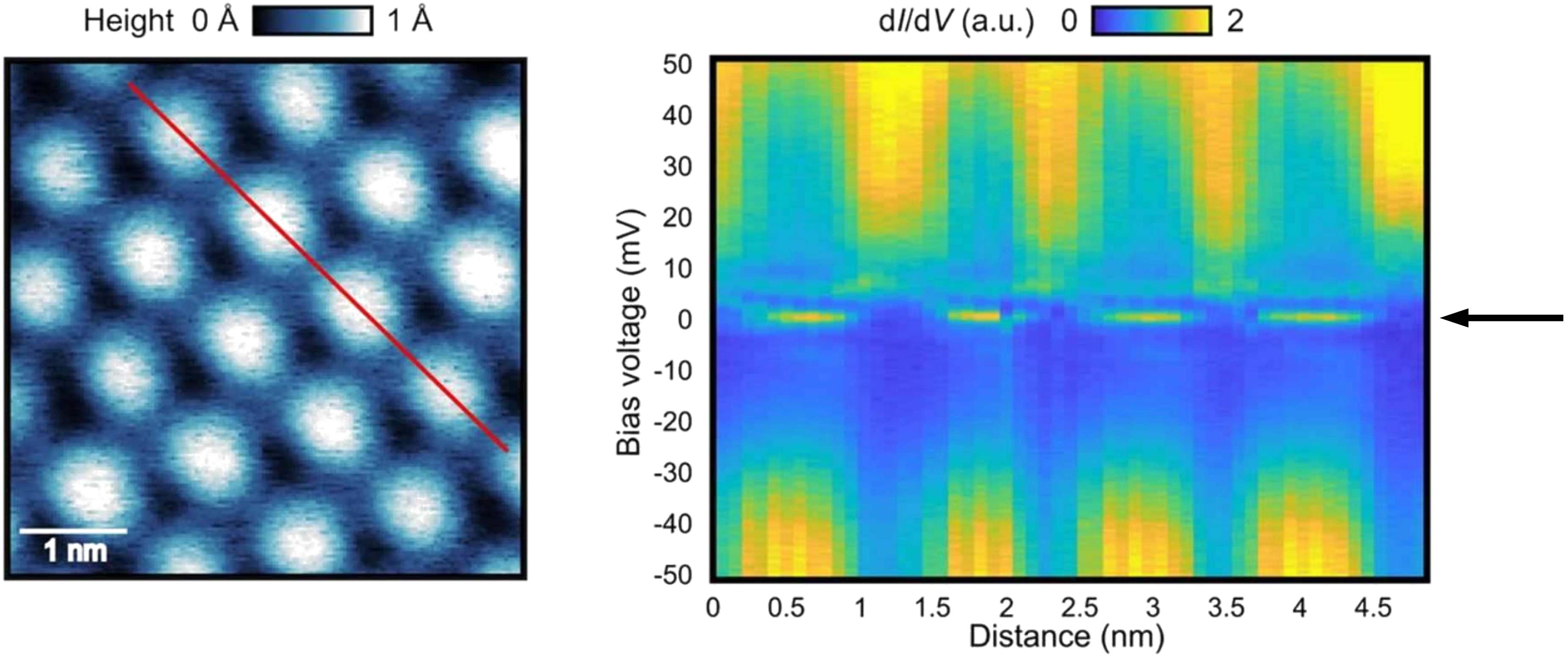
Probing the Kondo peak



Probing the heavy-fermion gap

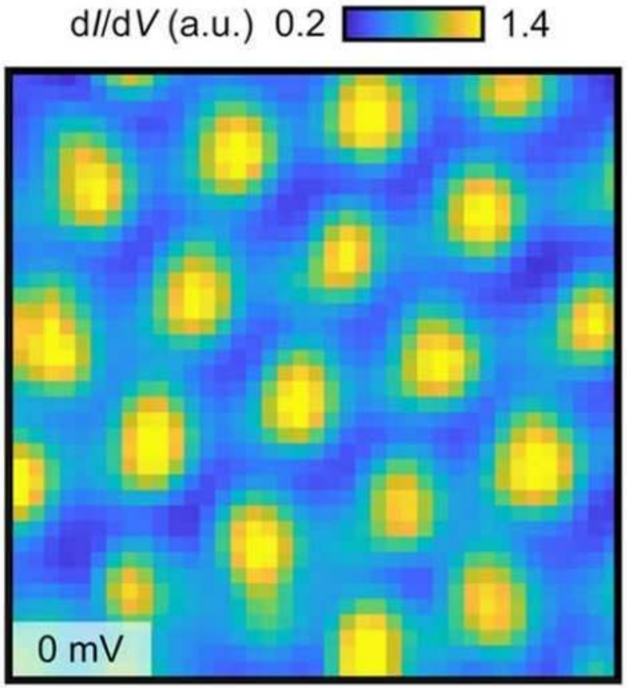


Grid spectroscopy of 1T-1H

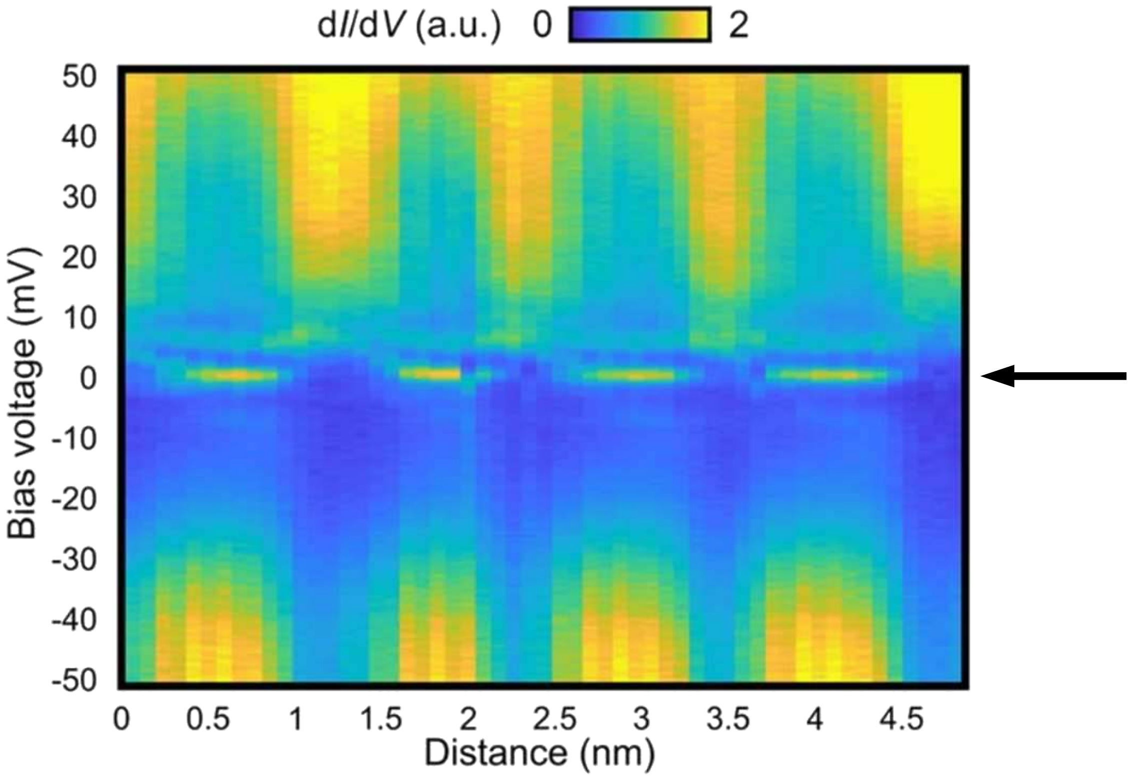


Zero bias (Kondo) peak appearing with the CDW periodicity

Grid spectroscopy of 1T-1H

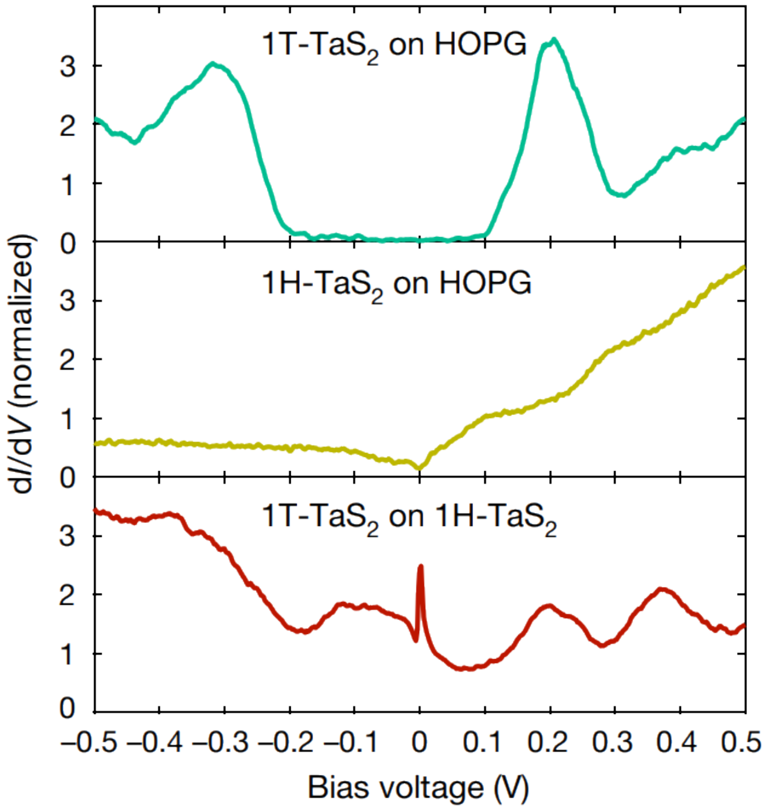


dI/dV (V=0)



Zero bias (Kondo) peak appearing with the CDW periodicity

Zero bias Kondo peak

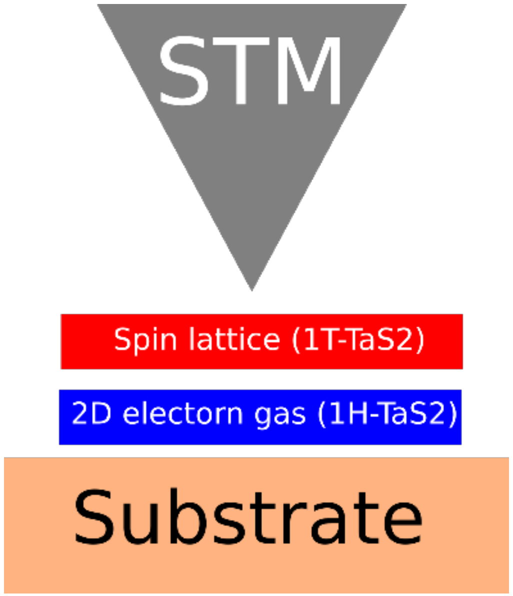


1T @ HOPG: Mott insulator

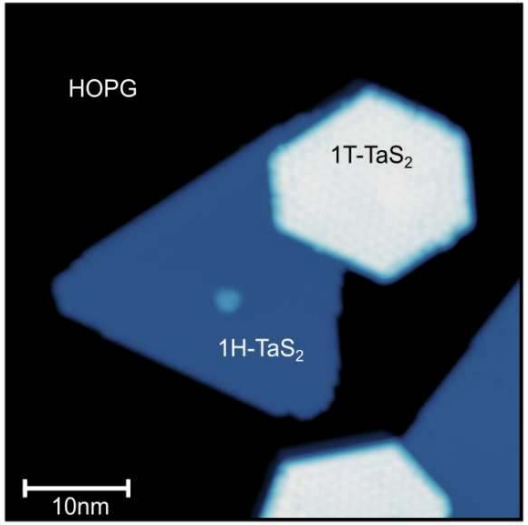
1H @ HOPG: Metal
(with a SC state at very low T)

1T @ 1H: Kondo peak

Kondo physics in the magnetic lattice

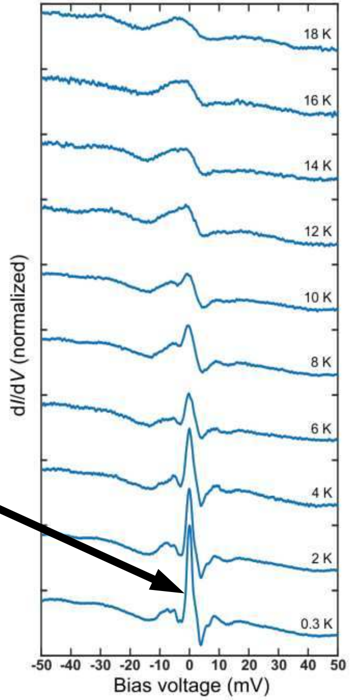


Sample



Differential conductance

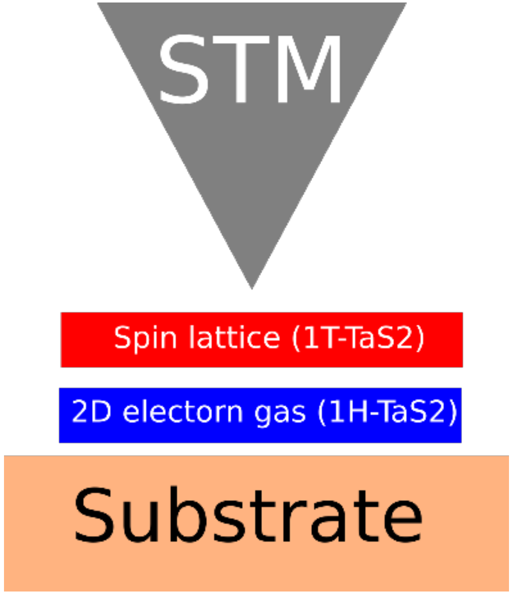
Kondo peak

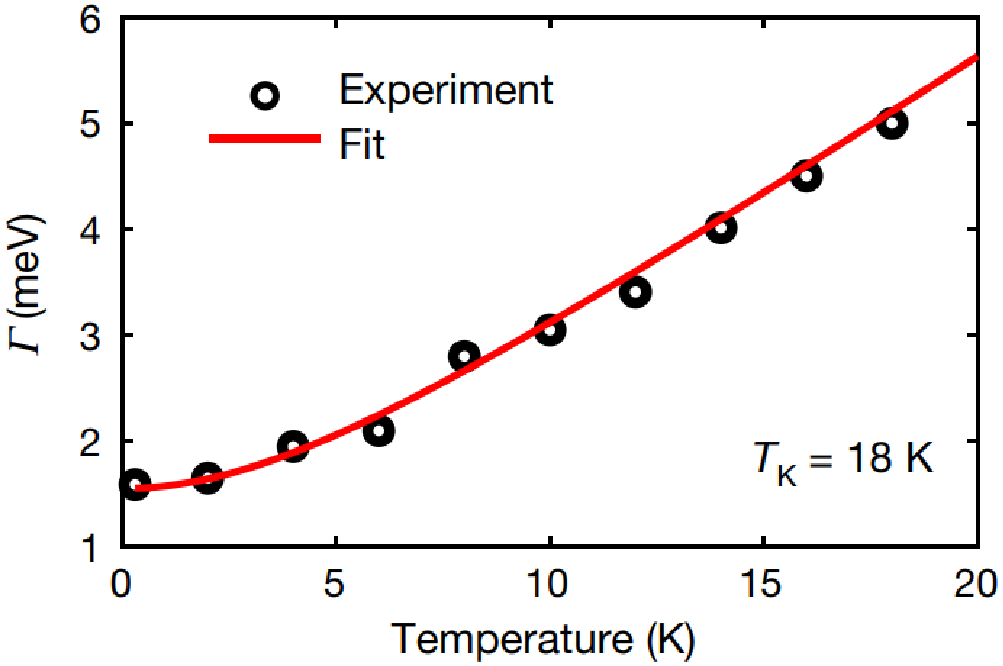


The system shows a Kondo peak when the local moments are probed

Temperature and field dependence consistent with Kondo

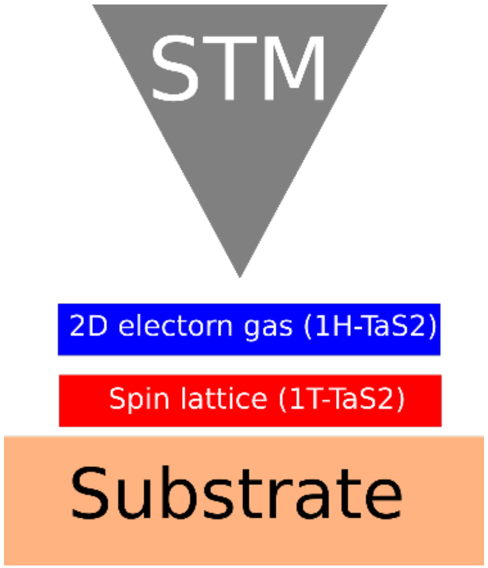
Kondo physics in the magnetic lattice



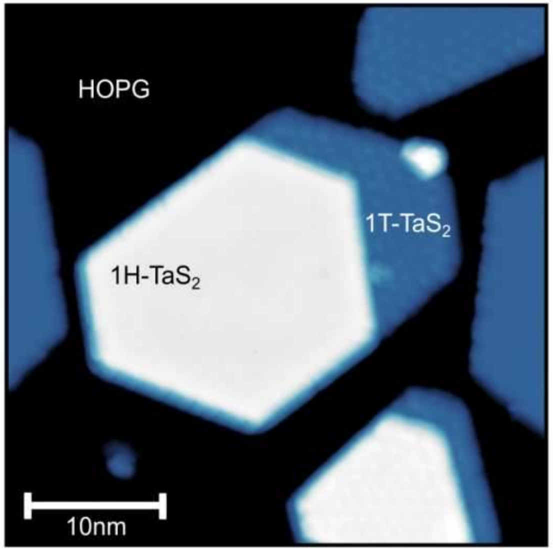


The Kondo peak follows the expected temperature dependence

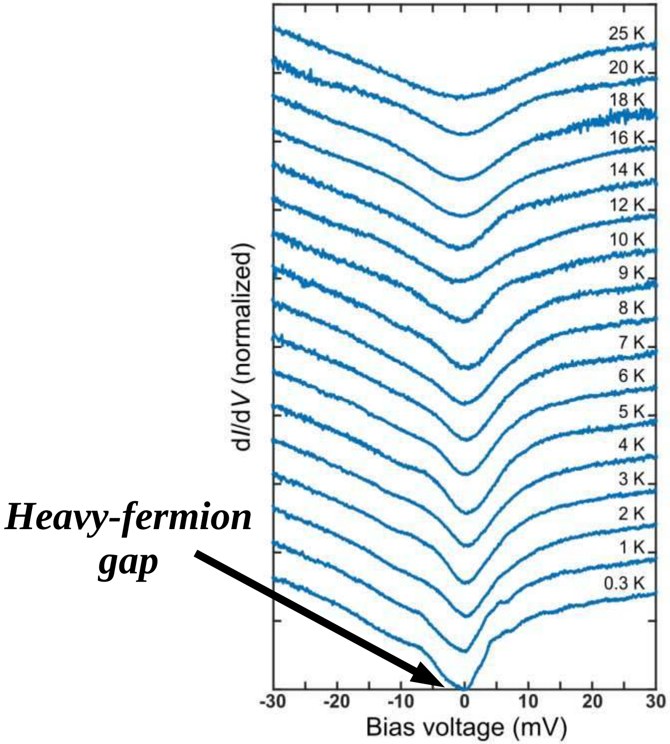
Heavy-fermion gap in the 2D electron gas



Sample



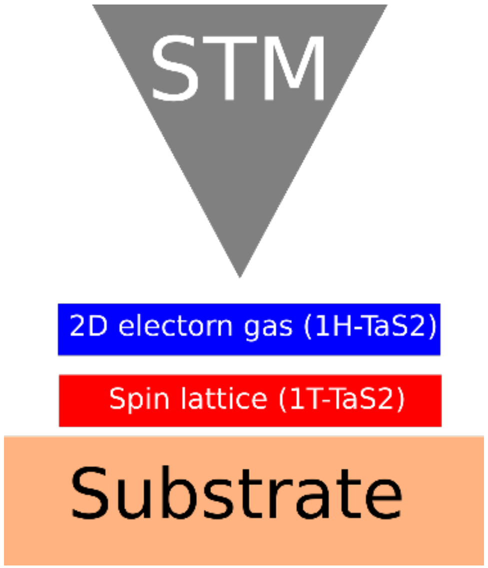
Differential conductance

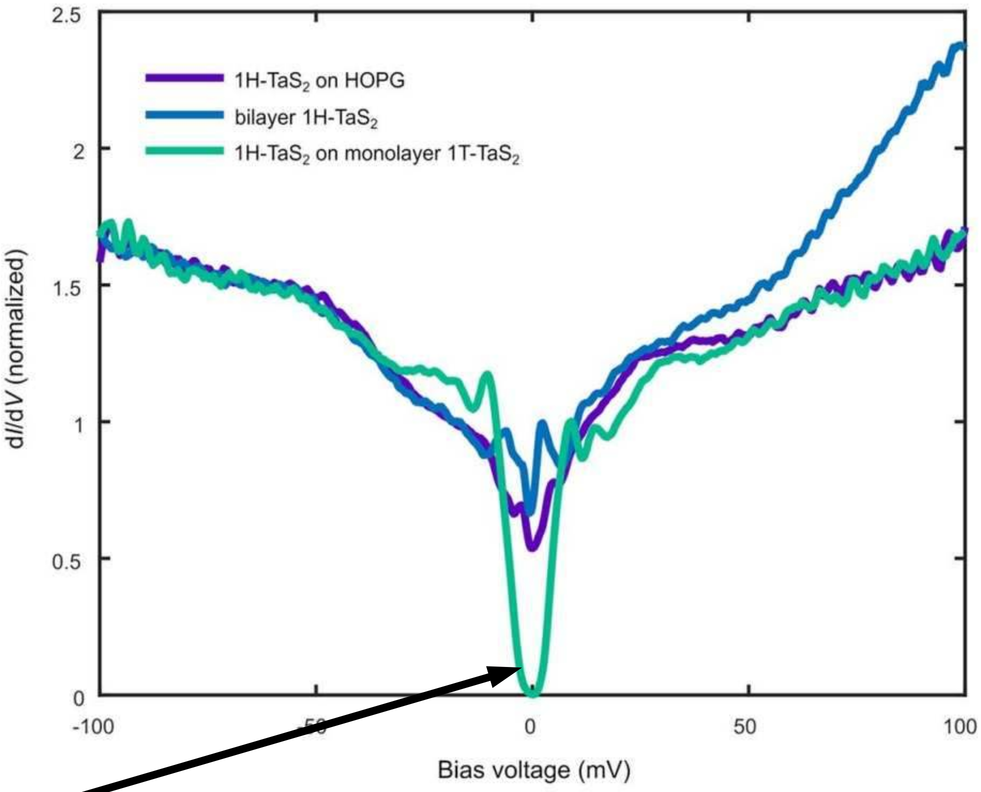


A heavy-fermion gap appears on the metal side

Temperature and field dependence consistent with a heavy-fermion gap

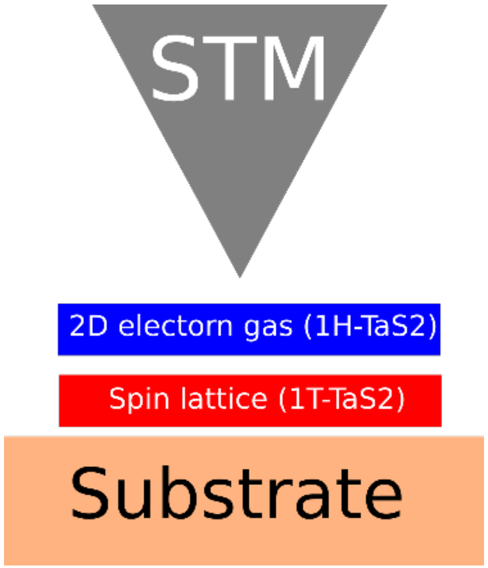
Heavy-fermion gap in the 2D electron gas

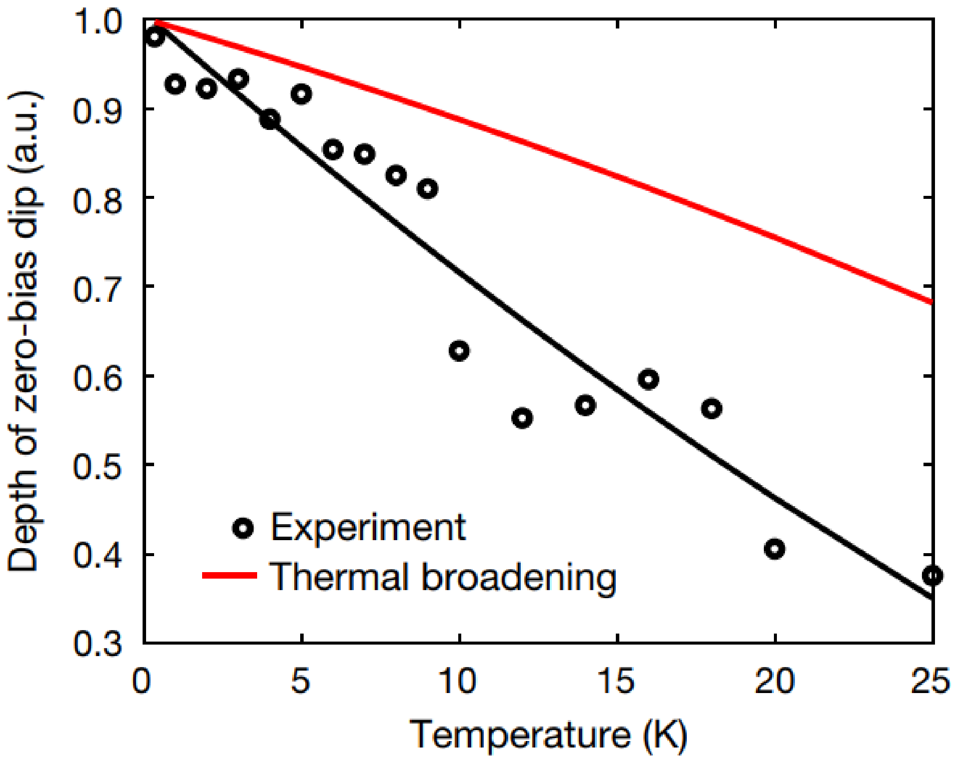




Heavy-fermion gap

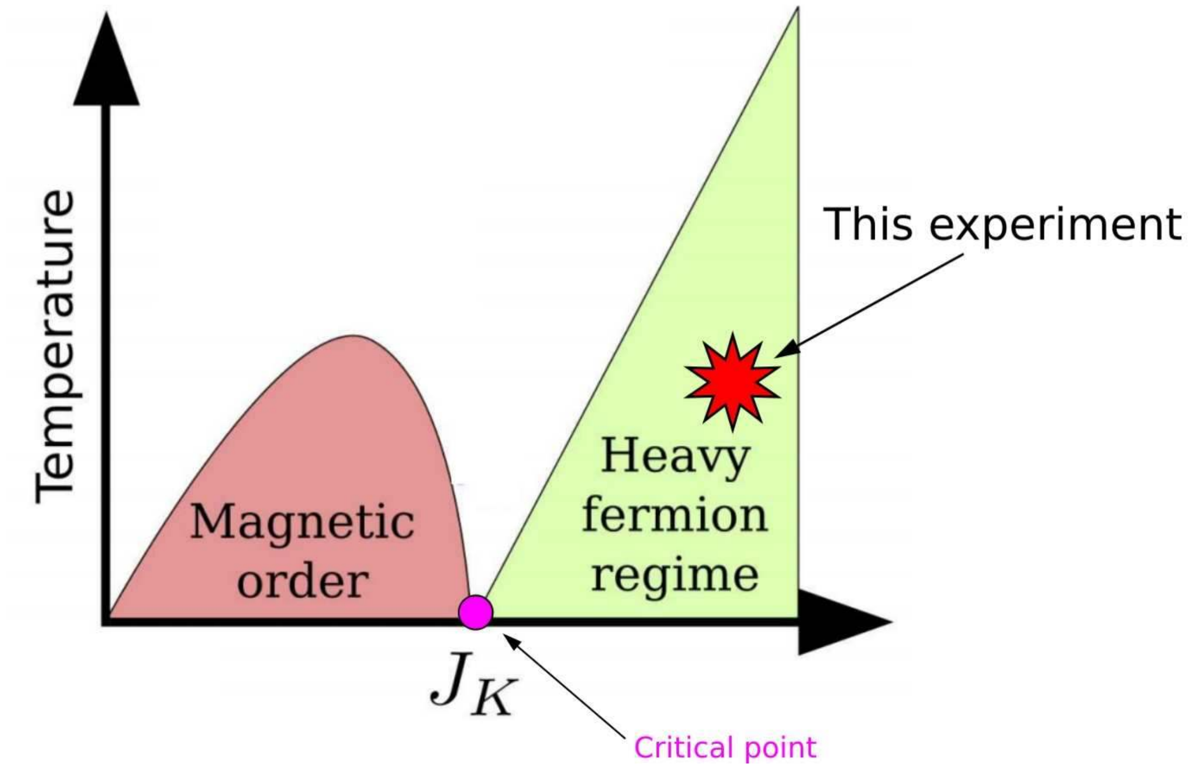
Heavy-fermion gap in the 2D electron gas





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

Next steps in van der Waals heavy-fermions



Can we push this system to critical and different unconventional superconducting regimes?

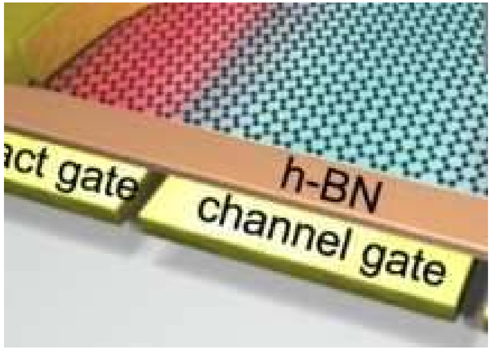
Controlling the heavy-fermion state

Of course, we can use the typical knobs of bulk heavy fermion compounds

(pressure, chemical doping, etc)

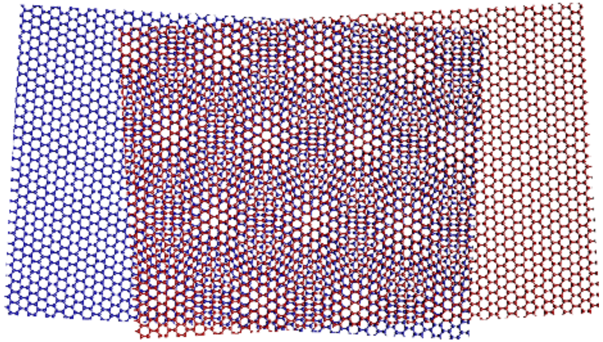
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



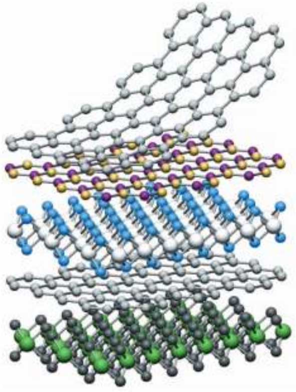
Science 306, 5696, 666-669 (2004)

Twist engineering



Nature Reviews Materials 6, 201–206 (2021)

Materials engineering

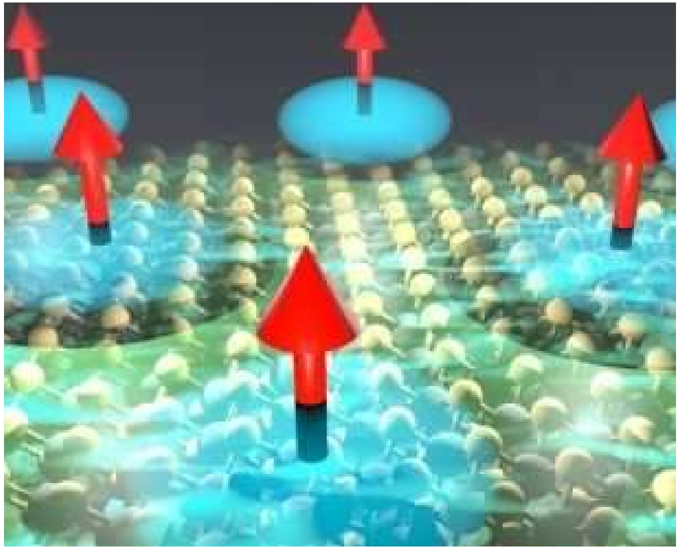


Nature 499, 419–425 (2013)

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

Take home

Van der Waals heterostructures provide a platform to engineer heavy-fermion physics, opening a pathway to explore heavy-fermion phenomena in a highly tunable platform



Nature 599, 582–586 (2021)

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