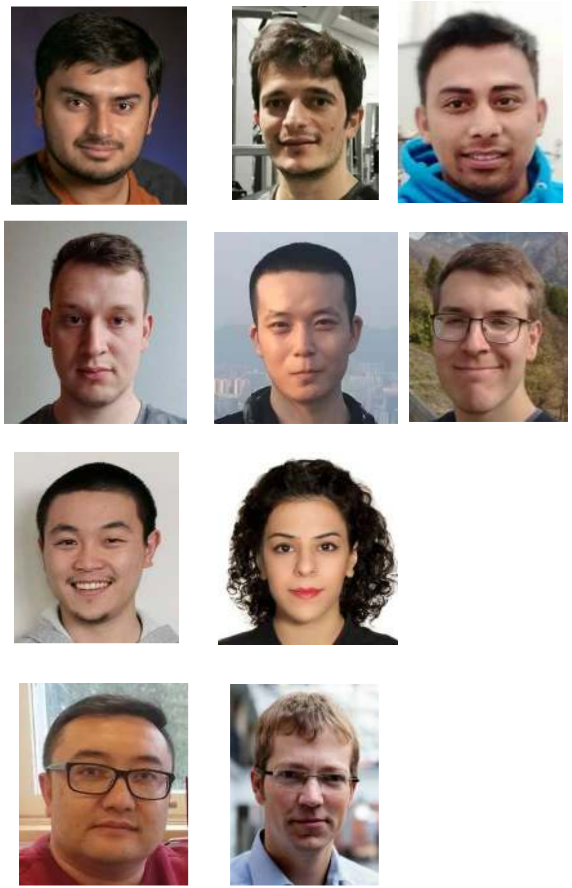
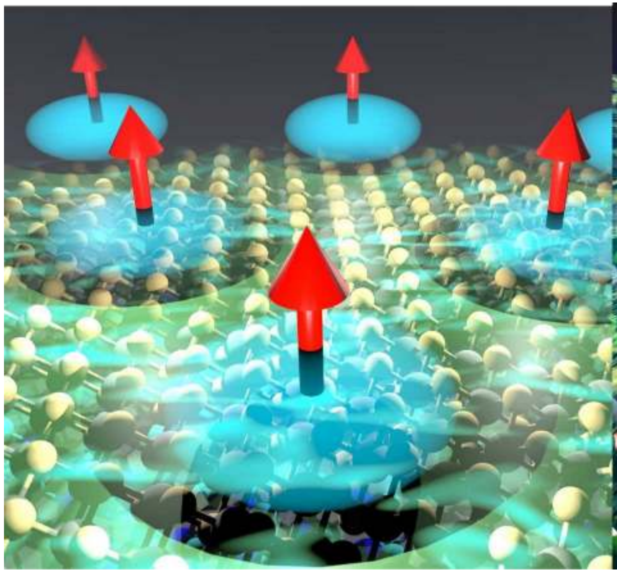
Deconstructing 4Hb-TaS_2: heavy-fermion Kondo insulators and nodal superconductivity

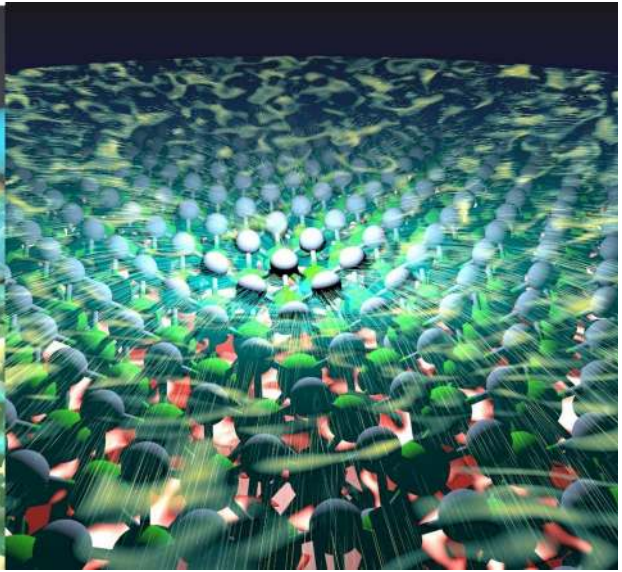


Jose Lado

Department of Applied Physics, Aalto University, Finland



Nature 599, 582–586 (2021)

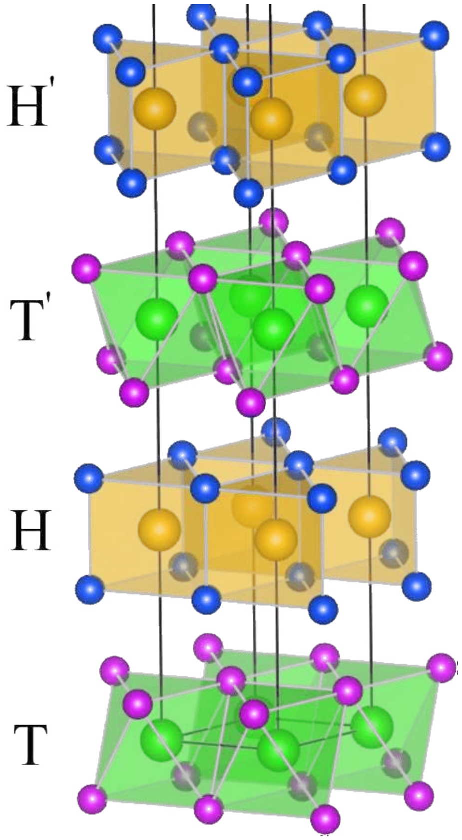


arXiv:2112.07316 (2021)

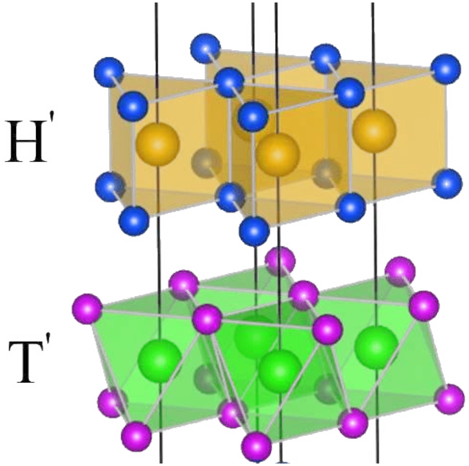
Hacking 4Hb

September 5th 2022, Weizmann Institute, Israel

Deconstructing 4Hb-TaS_2

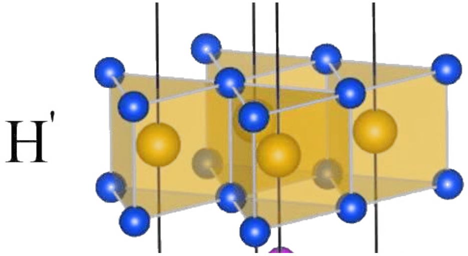


We will explore the physics of a deconstructed version



Heavy fermion
Kondo insulators

1H-1T bilayer



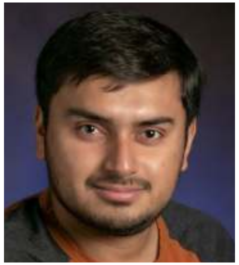
Nodal superconductivity

Ultraclean 1H monolayer

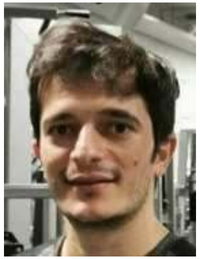
Behind the scenes

Experiment

S. Ganguli



M. Amini



M. Aapro

L. Yan

V. Vaňo

S. Kezilebieke

Md. Huda

P. Liljeroth

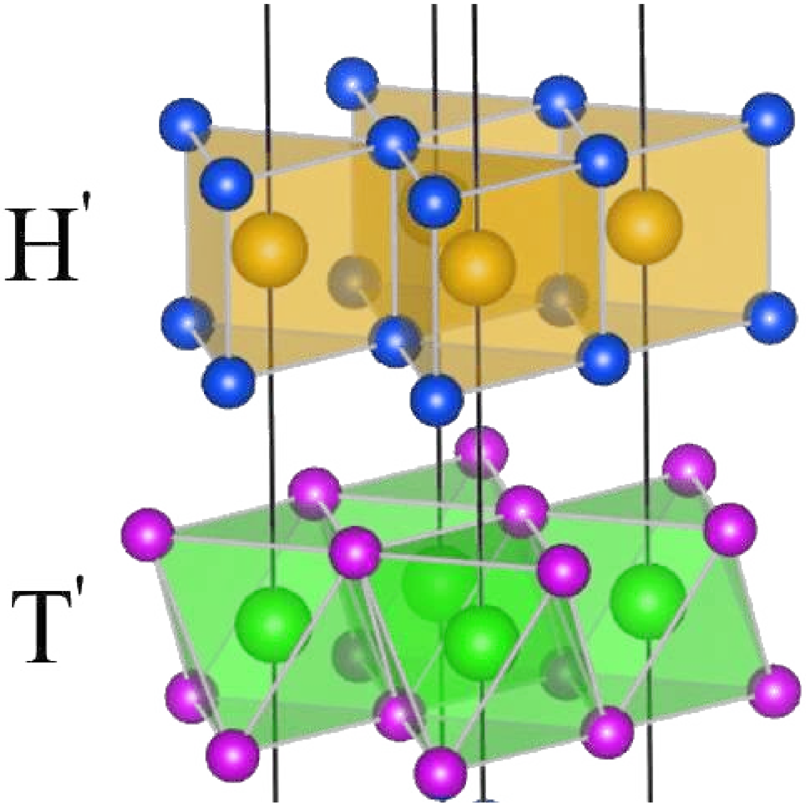
Theory

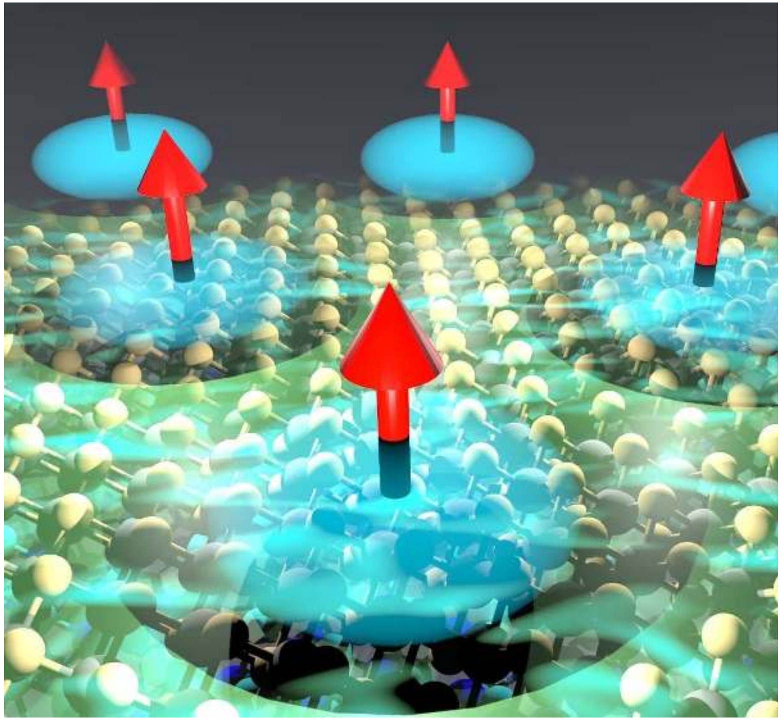
G. Chen

M. Khosravian

Aalto University

Heavy-fermion Kondo insulators in 1H-1T bilayer





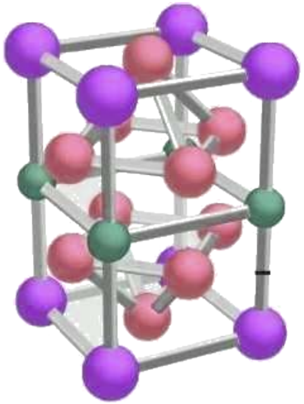
Nature 599, 582–586 (2021)

Searching for new heavy fermion compounds

We have a rich family of bulk heavy-fermion compounds

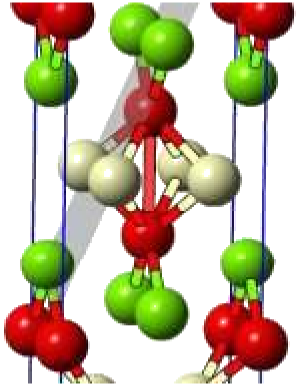
$CeCoIn_5$

Science 375, 6576, 76-81 (2021)



UTe_2

Nature 579, 523–527 (2020)



- 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

Building an artifcicial heavy fermion state

Triangular lattice of local magnetic moments

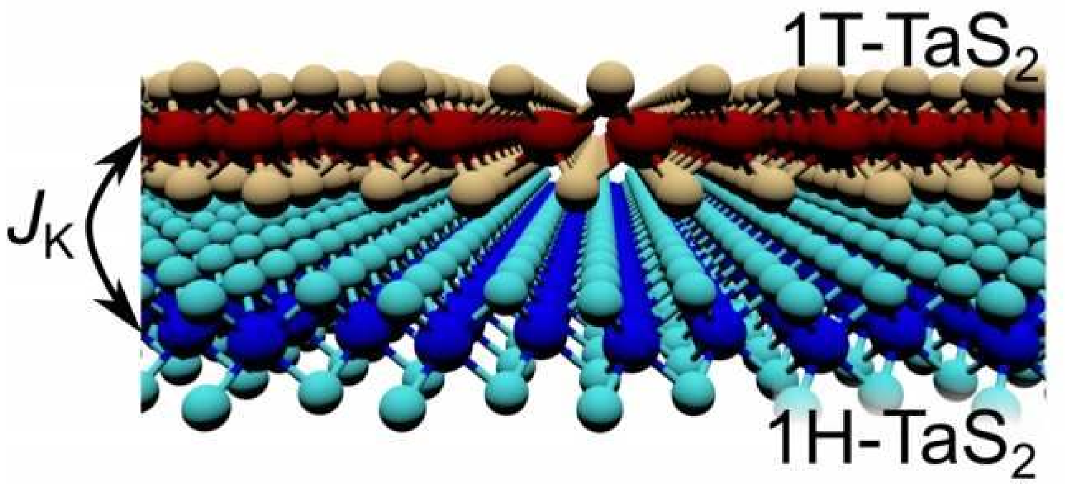
$1T\text{-}TaS_2$

Two-dimensional electron gas

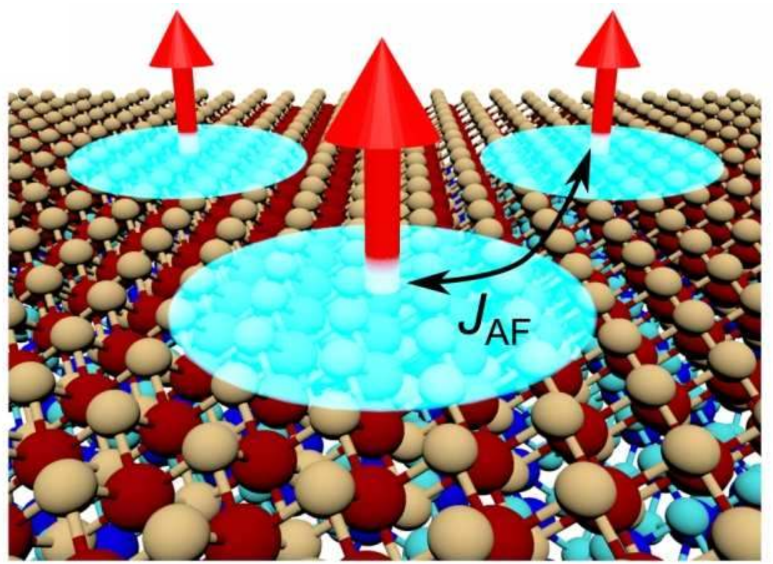
$1H\text{-}TaS_2$

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling create the Kondo coupling

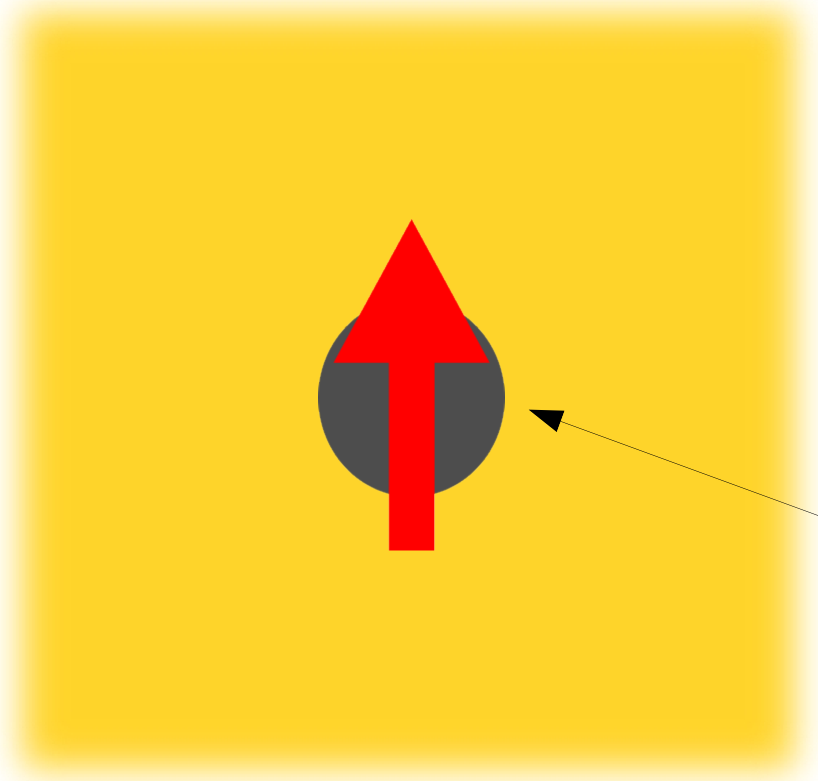


Intralayer exchange between local moments



The bilayer realizes all the ingredients for heavy-fermion physics

The Kondo problem



Conduction electrons

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

Kondo coupling

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

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

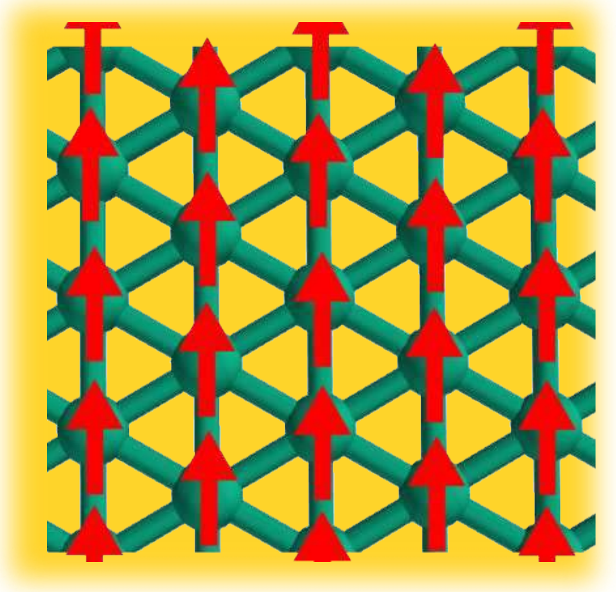
The Kondo lattice problem

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

Kondo sites

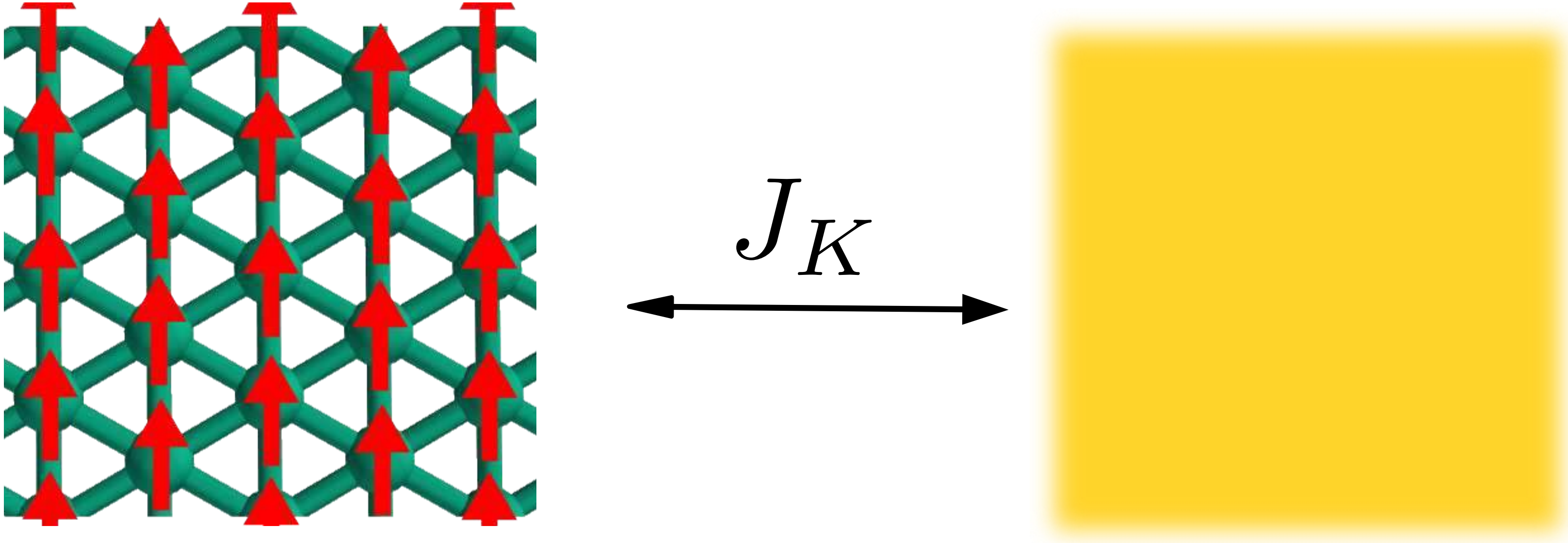
Kondo coupling

Conduction electrons



Building an artificial heavy fermion state

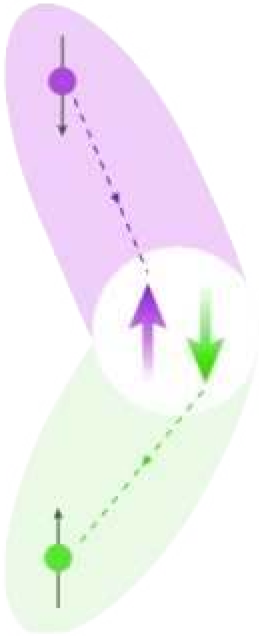
Lattice of Kondo impurities **Dispersive electron gas**

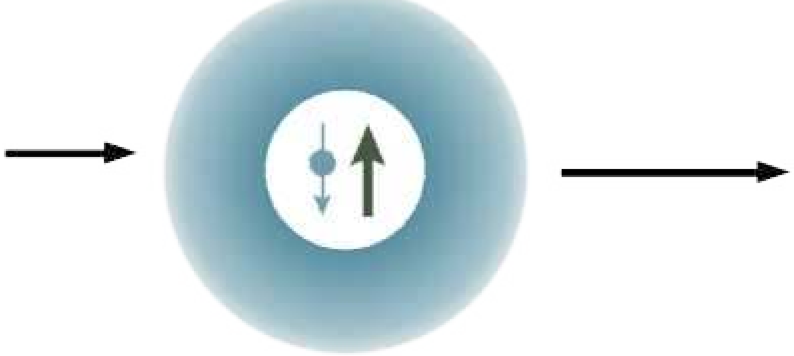


Both ingredients coupled through Kondo coupling

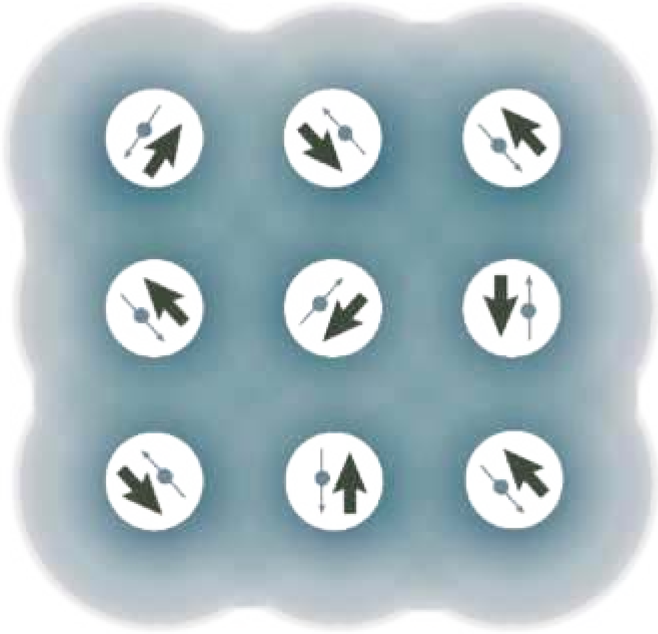
Building an artificial heavy fermion state

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

Solving the Kondo lattice problem

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

Replace the spin sites by auxiliary fermions

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

This makes the effective Hamiltonian an “interacting” fermionic Hamiltonian

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

Solving the Kondo lattice problem

Now we decouple the fermions with a mean-field approximation

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

Obtaining a quadratic Hamiltonian

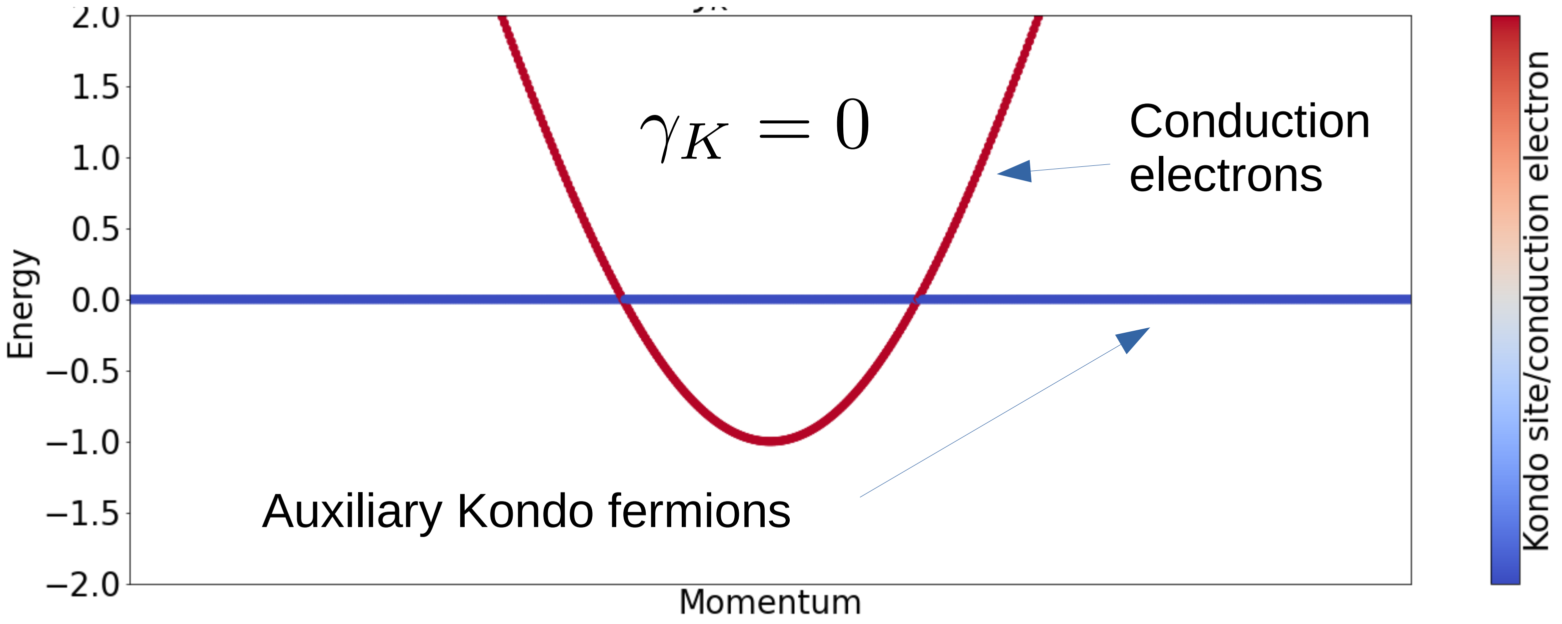
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha\beta} f^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + h.c.$$

Conduction band dispersion

Kondo hybridization

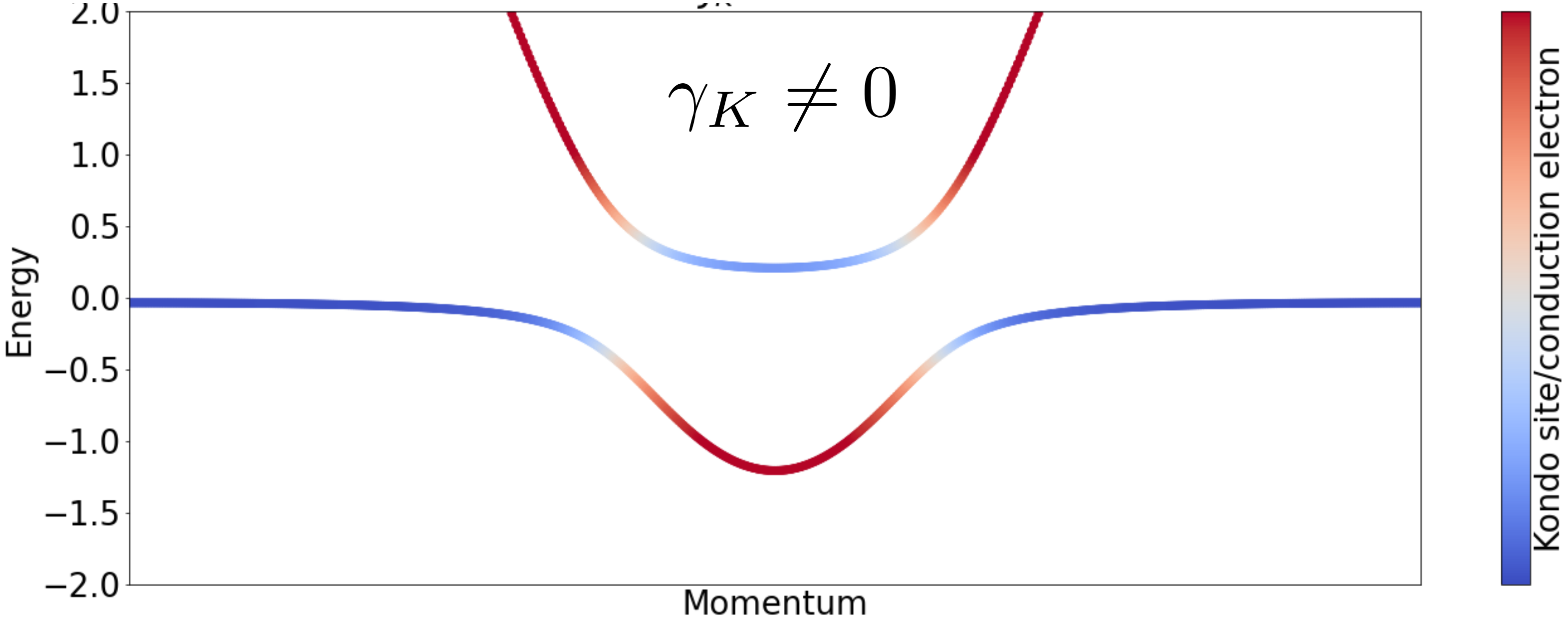
Electronic structure of the Kondo lattice problem

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



Electronic structure of the Kondo lattice problem

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

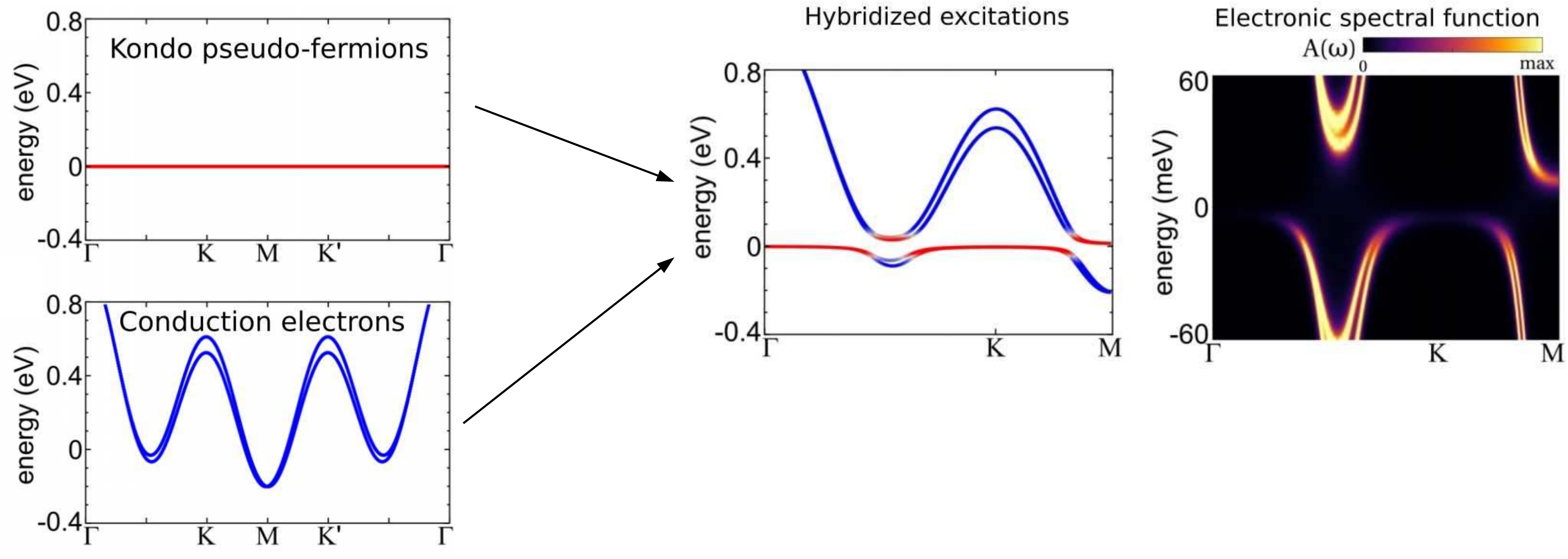


The Kondo coupling opens up a gap in the electronic structure

Brief theory of heavy-fermions

Kondo physics introduces resonant pseudo-fermions at the chemical potential

Leading to the opening of a heavy-fermion gap

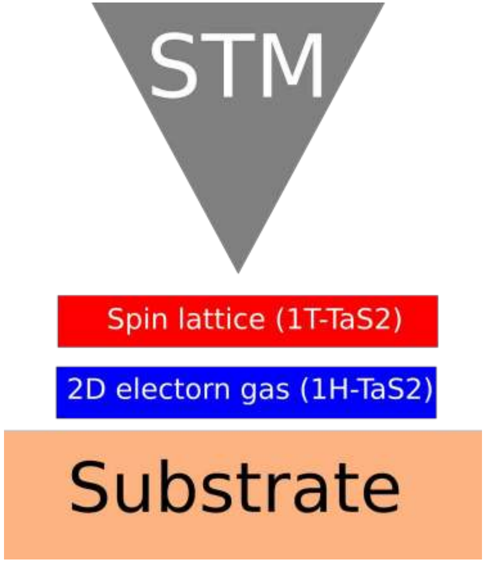


Experimental signatures of heavy-fermion physics

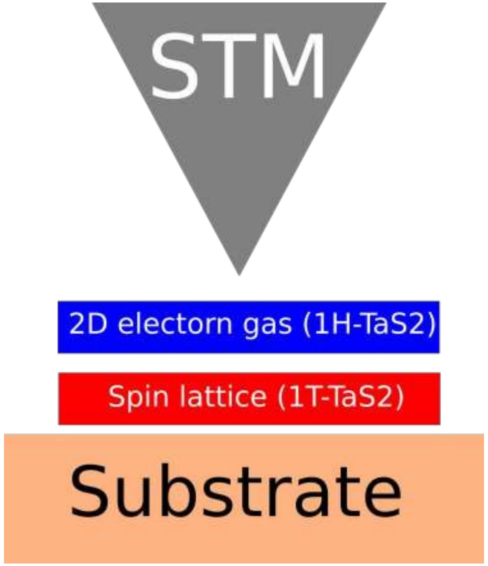
- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

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

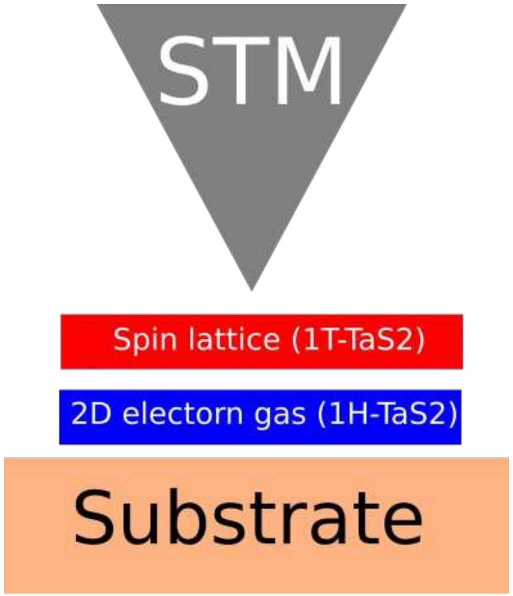
Probing the Kondo peak



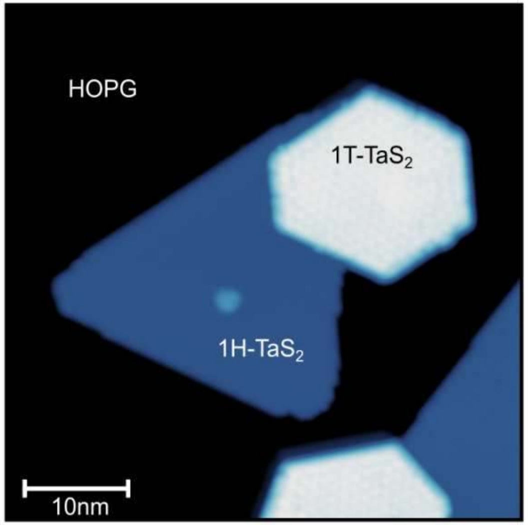
Probing the heavy-fermion gap



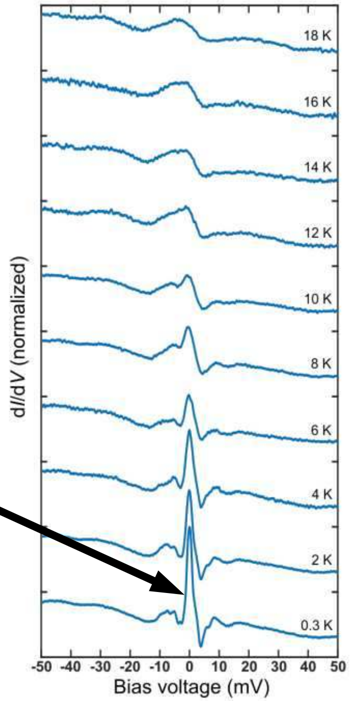
Kondo physics in the magnetic lattice



Sample



Differential conductance

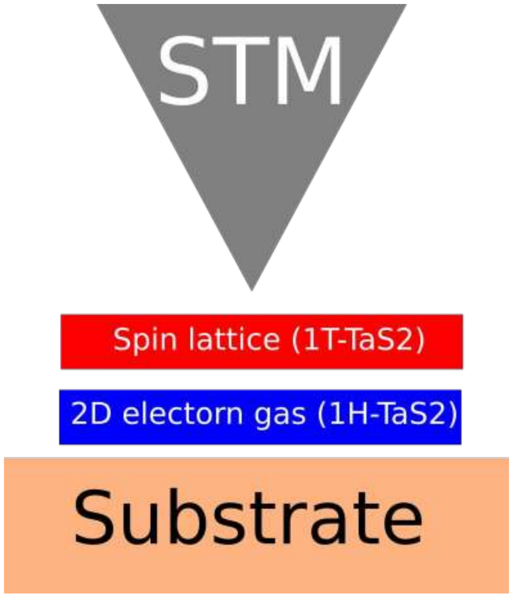


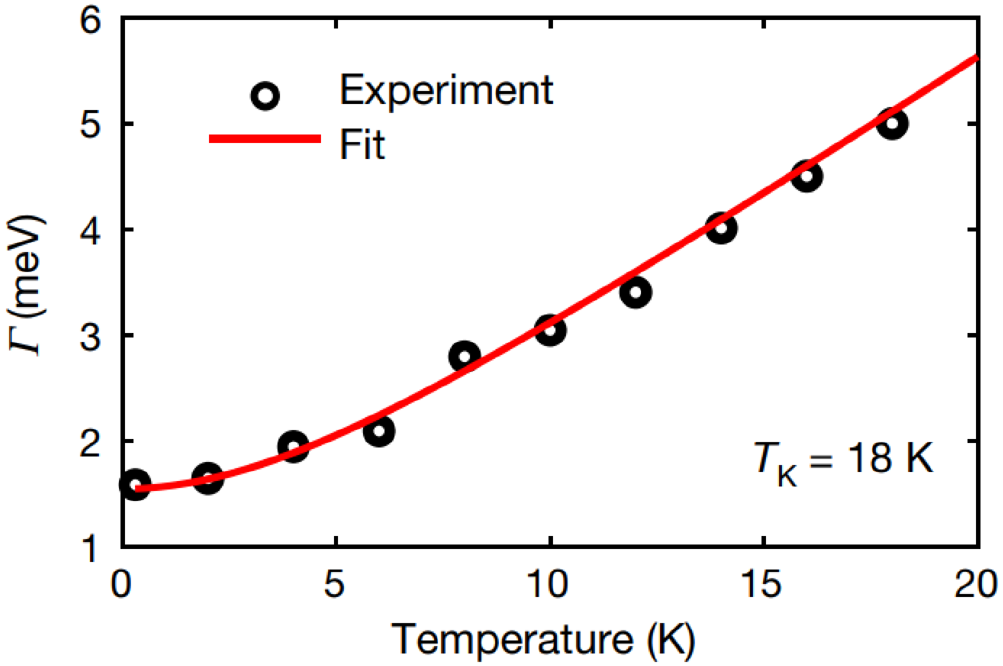
Kondo peak

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

Temperature and field dependence consistent with Kondo

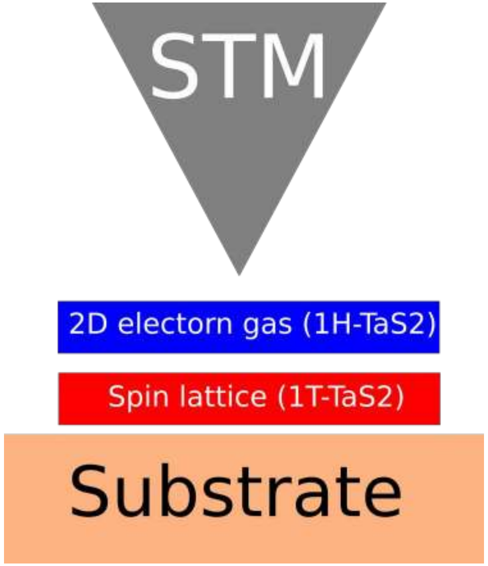
Kondo physics in the magnetic lattice



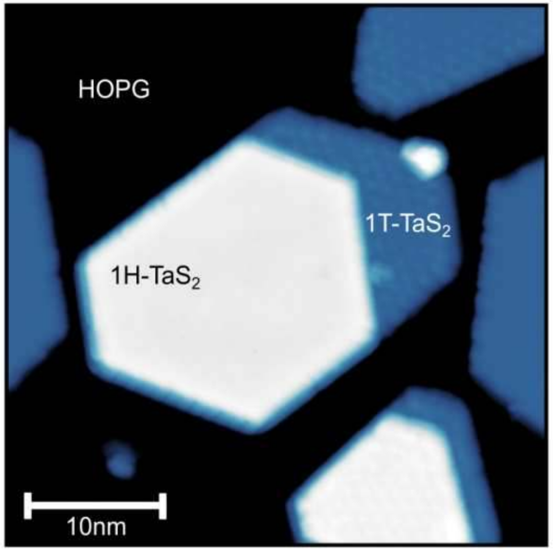


The Kondo peak follows the expected temperature dependence

Heavy-fermion gap in the 2D electron gas

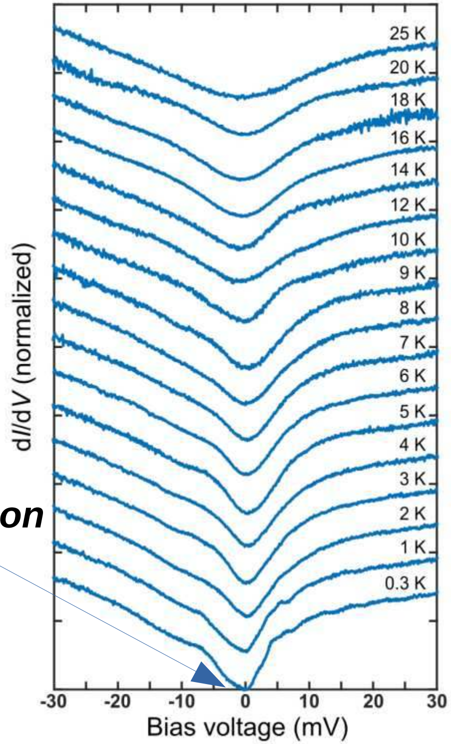


Sample



Differential conductance

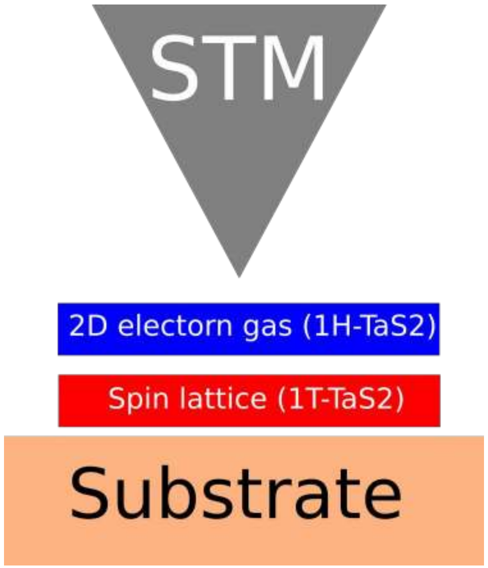
Heavy-fermion gap

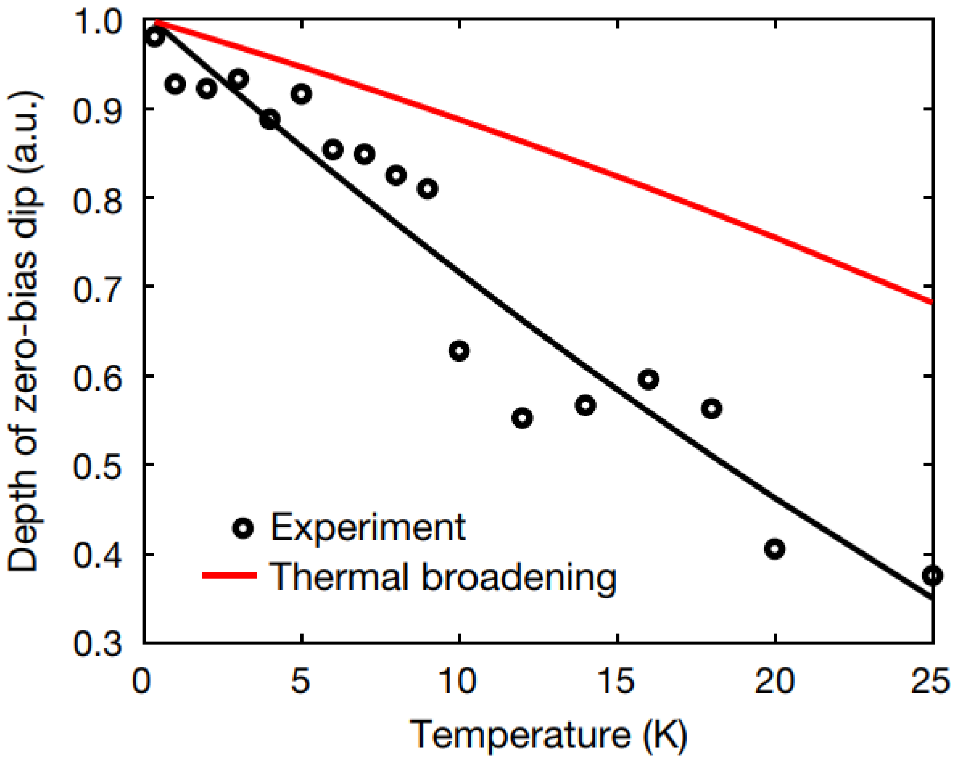


A heavy-fermion gap appears on the metal side

Temperature and field dependence consistent with a heavy-fermion gap

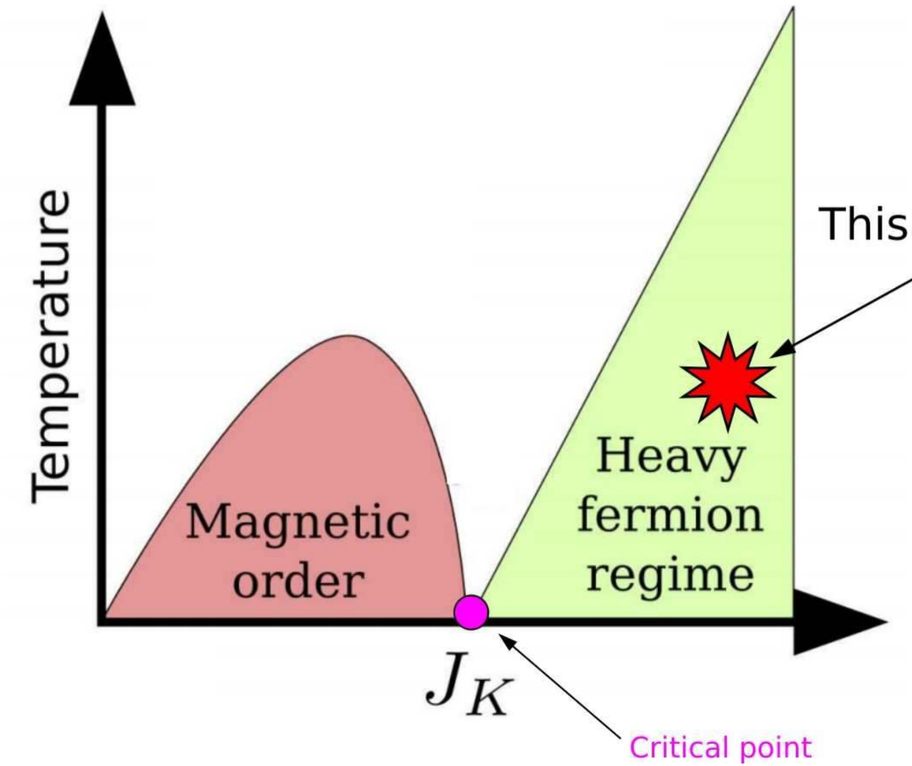
Heavy-fermion gap in the 2D electron gas





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 regim

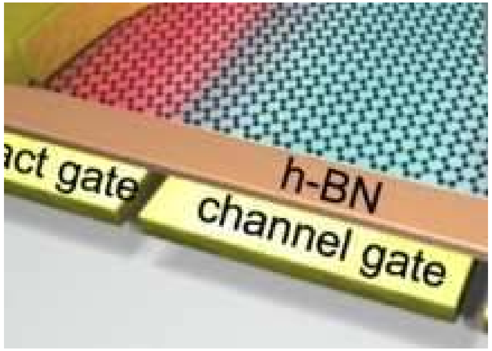
Controlling the heavy-fermion state

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

(pressure, chemical doping, etc)

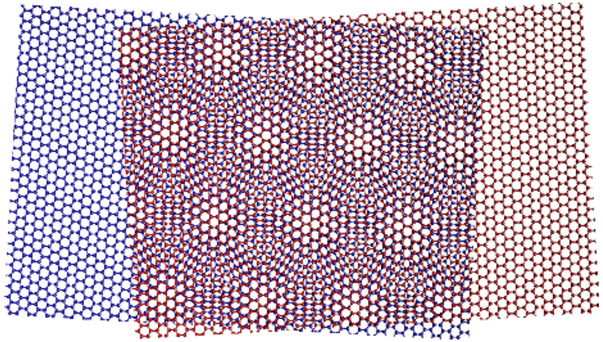
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



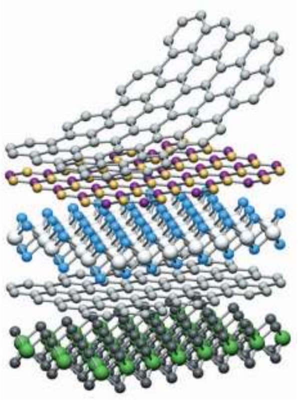
Science 306, 5696, 666-669 (2004)

Twist engineering



Nature Reviews Materials 6, 201–206 (2021)

Materials engineering

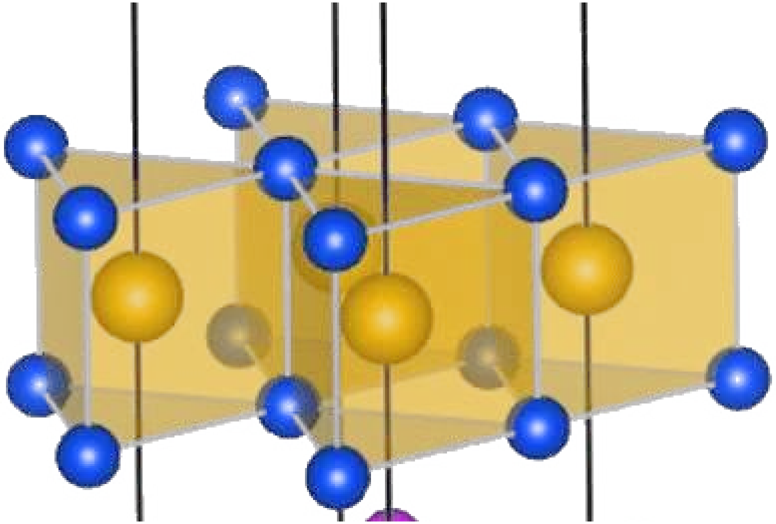


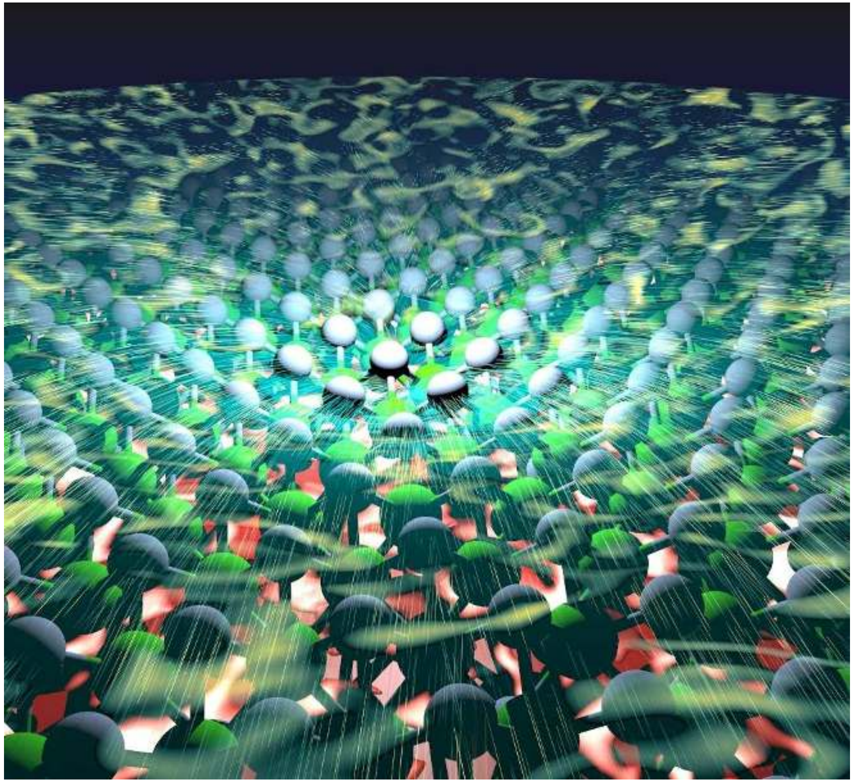
Nature 499, 419–425 (2013)

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

Nodal superconductivity in ultraclean TaS_2

H'

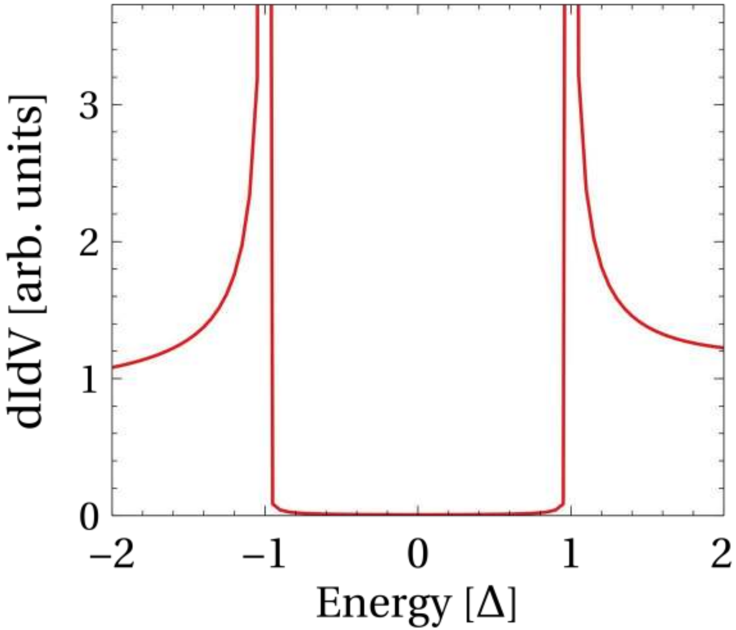




arXiv:2112.07316 (2021)

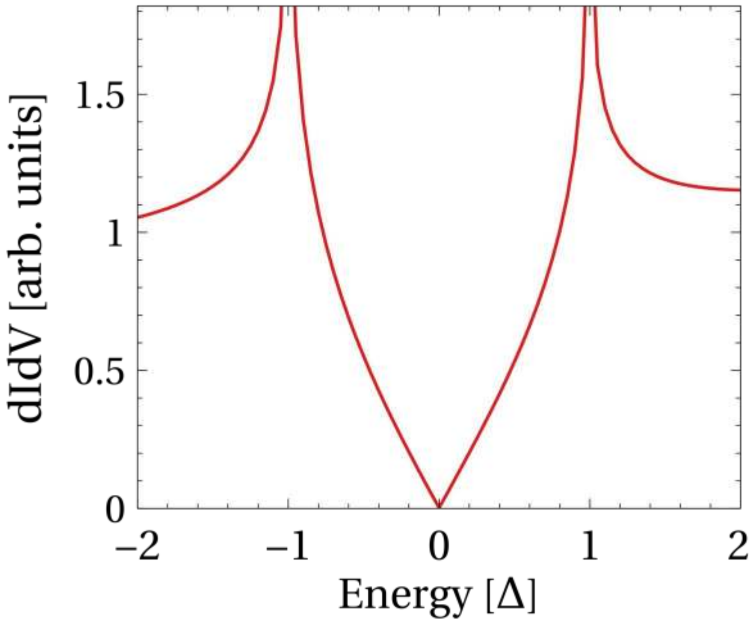
Gapped and nodal superconductivity

Conventional s-wave



Driven by electron-phonon

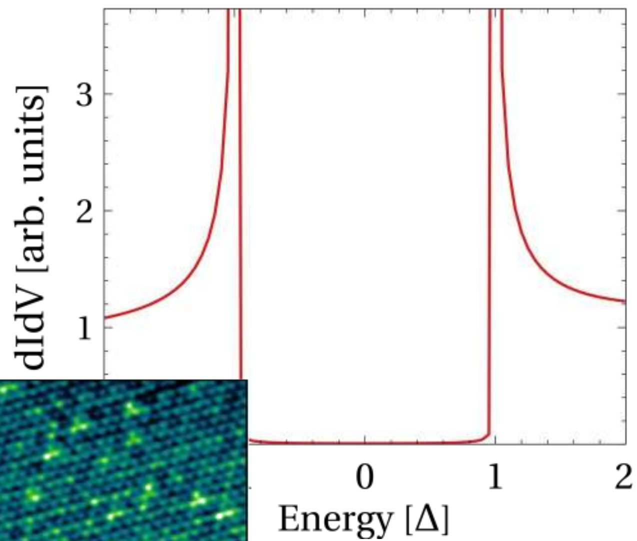
Unconventional nodal f-wave

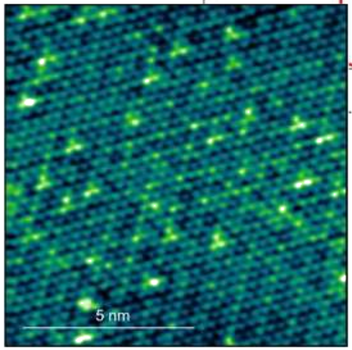


Driven by unconventional mechanism
(magnons, valence fluctuations)

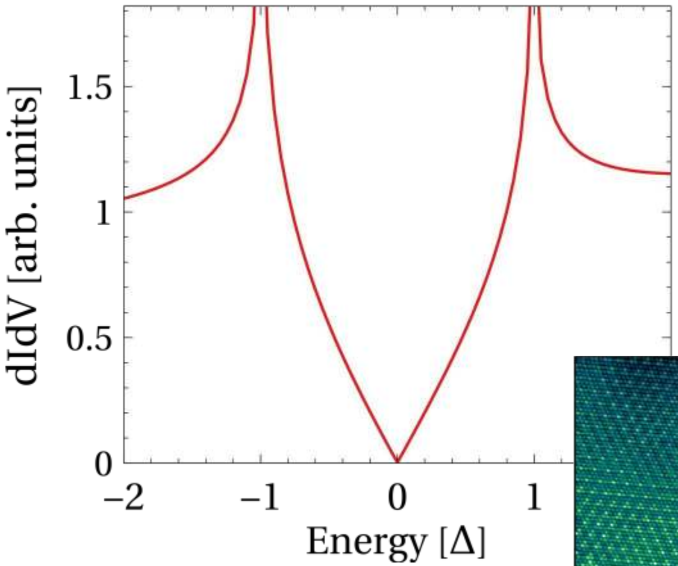
Two superconducting states in TaS_2 monolayer

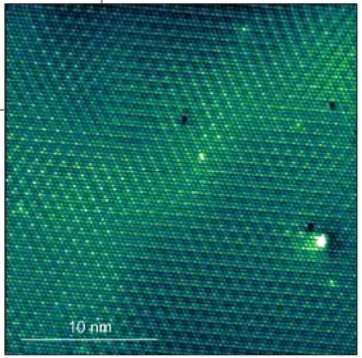
Strong disorder
Fully-gaped s-wave





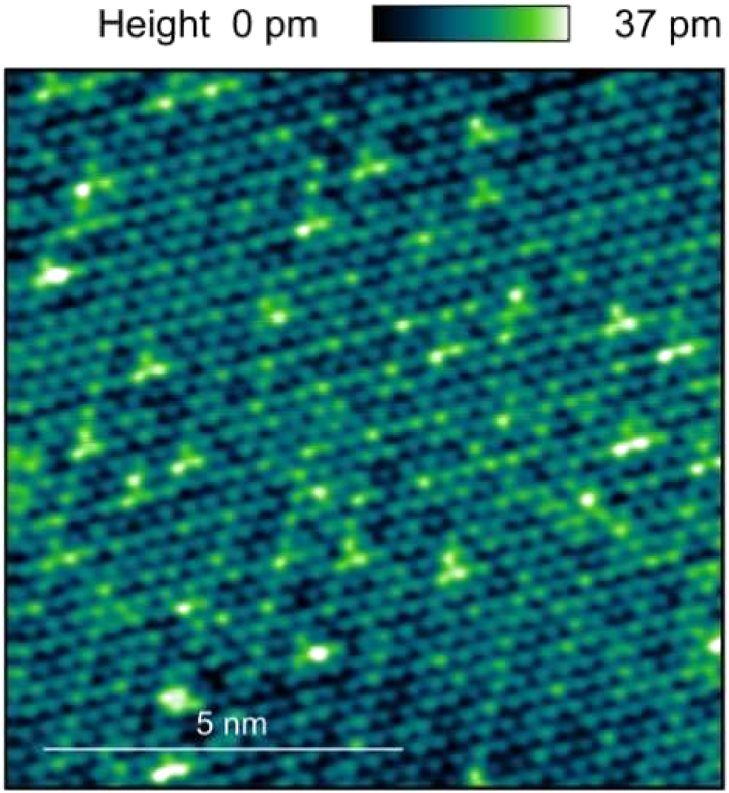
Weak disorder
Gapless nodal f-wave

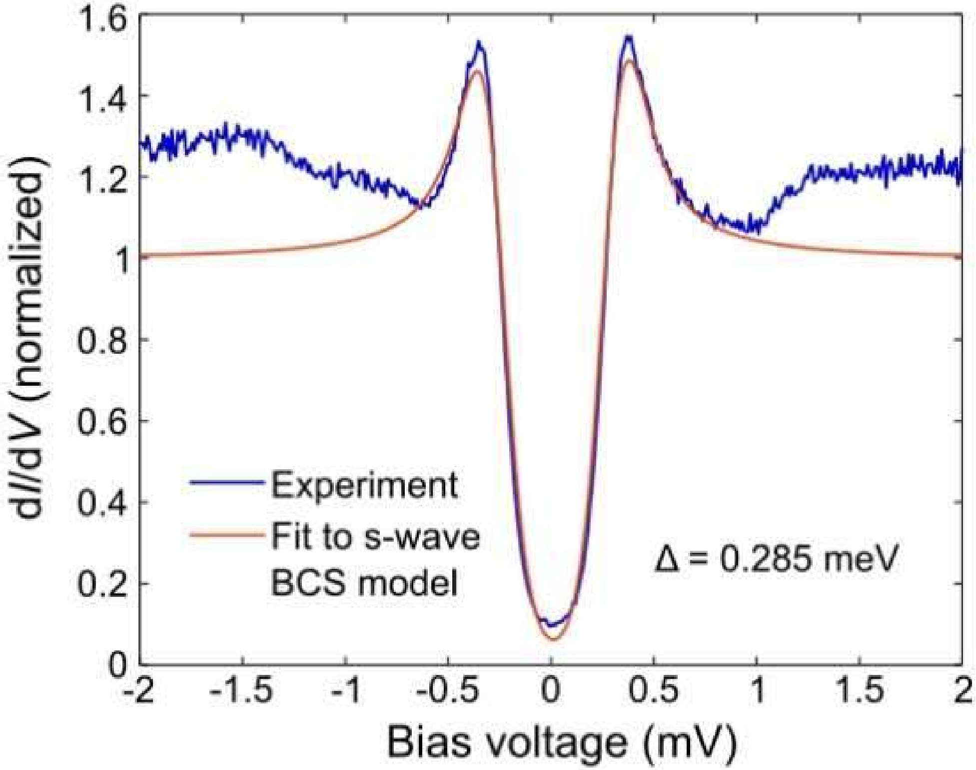




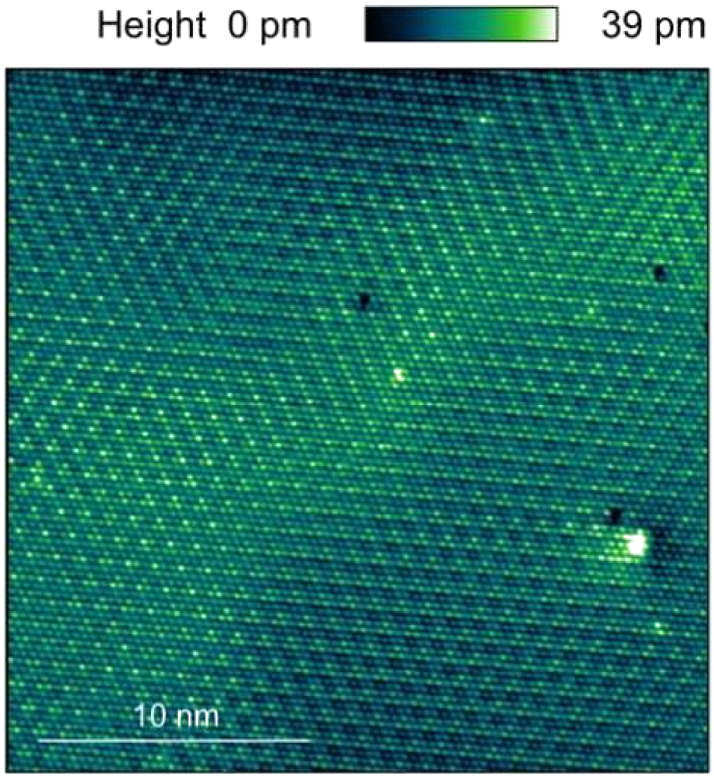
Superconducting phase transition associated with disorder

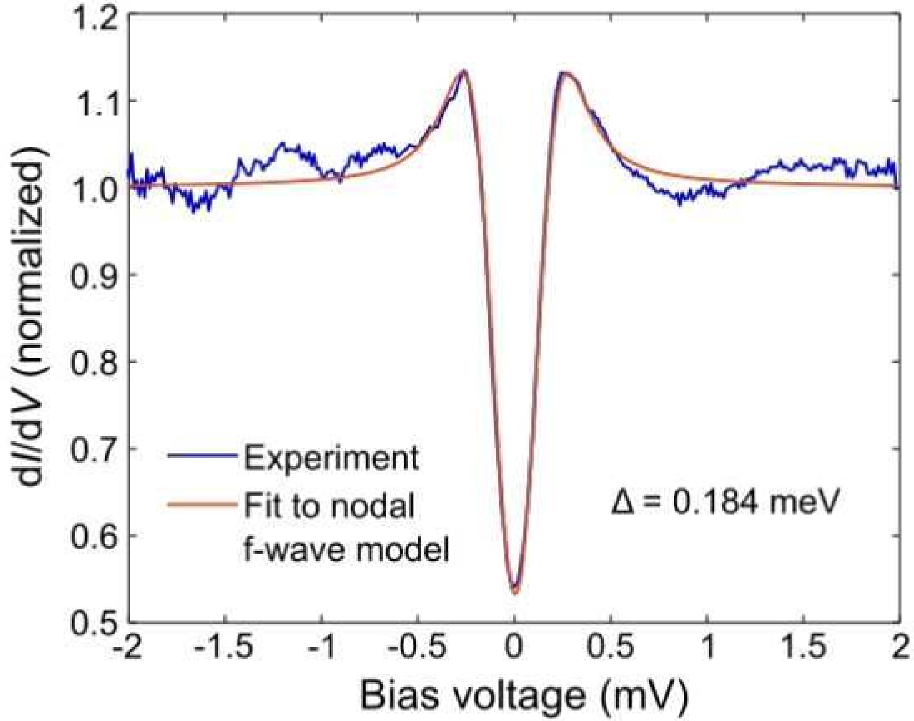
Dirty TaS_2 monolayer sample





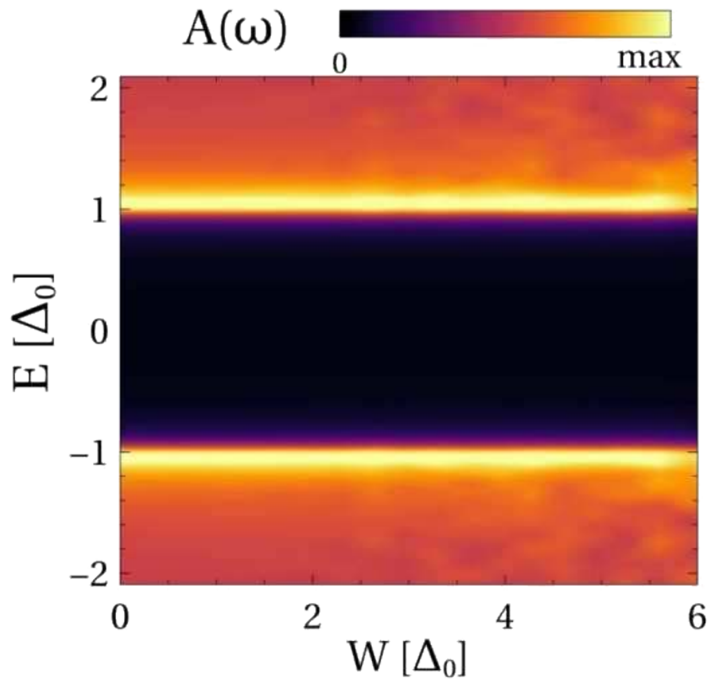
Ultra-clean TaS_2 monolayer sample



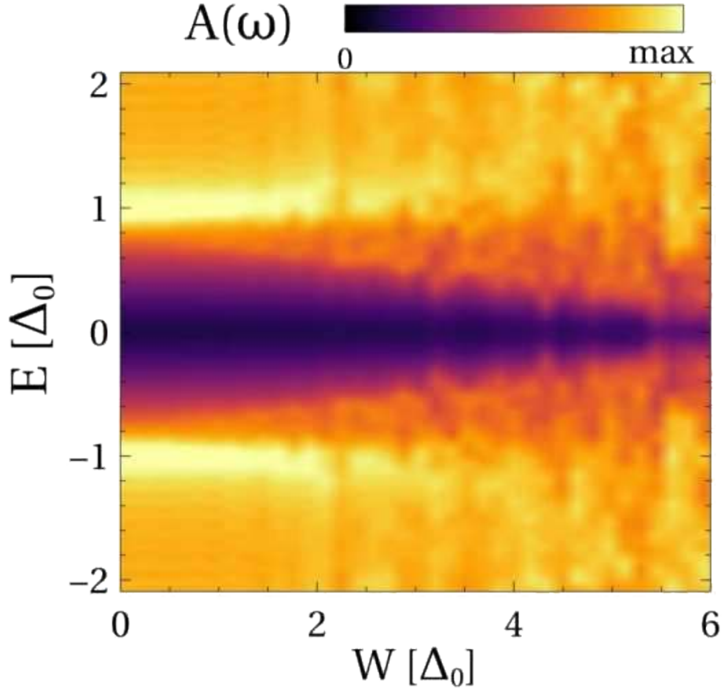


Impact of disorder for f-wave and s-wave

Disorder on s-wave

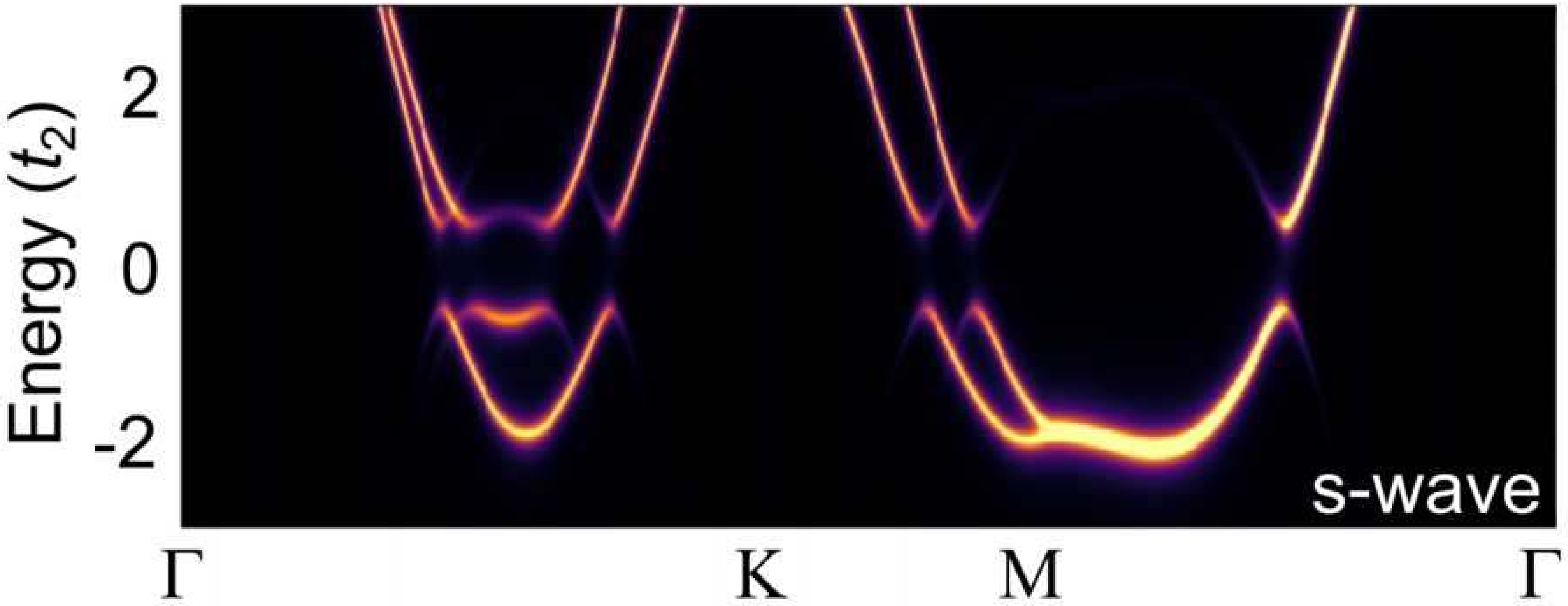


Disorder on f-wave



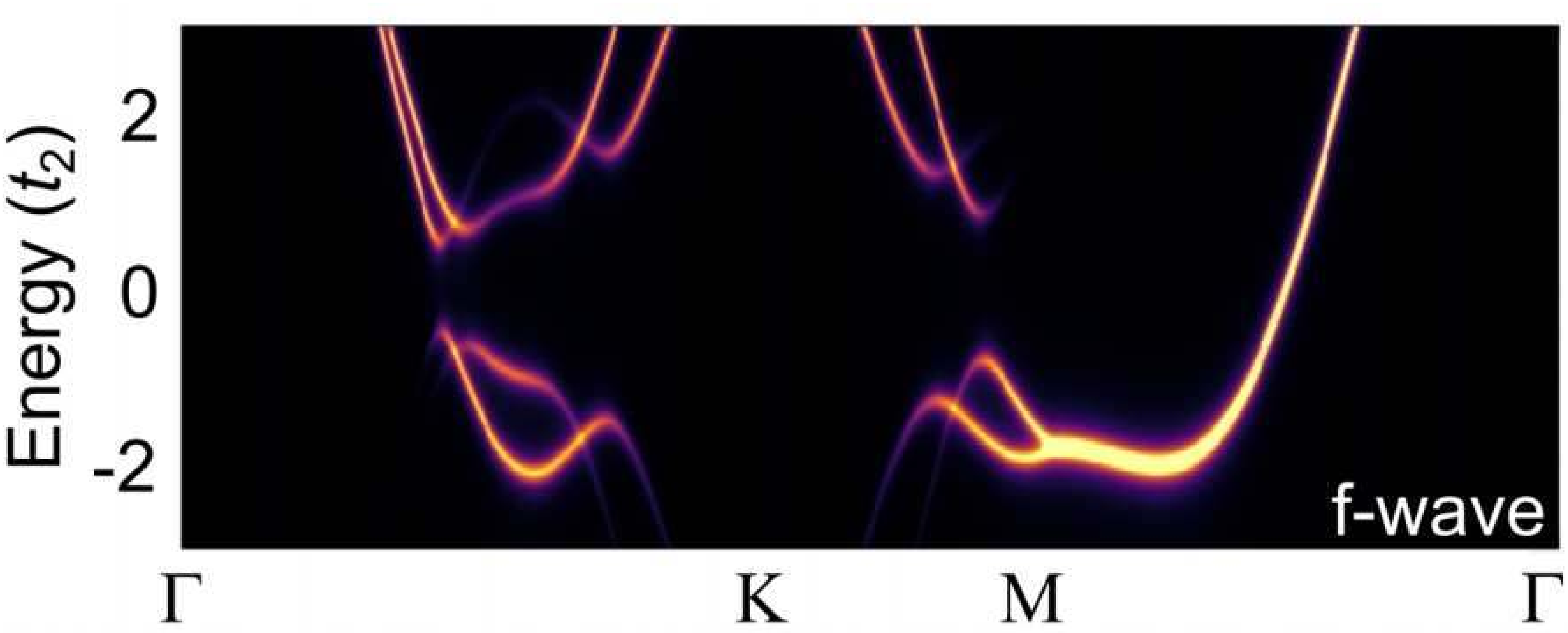
$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{SC} + \sum_{n,s} W_n c^\dagger_{n,s} c_{n,s}$$

Electronic structure with an s-wave gap



A full gap appear in the band structure in the presence of superconductivity

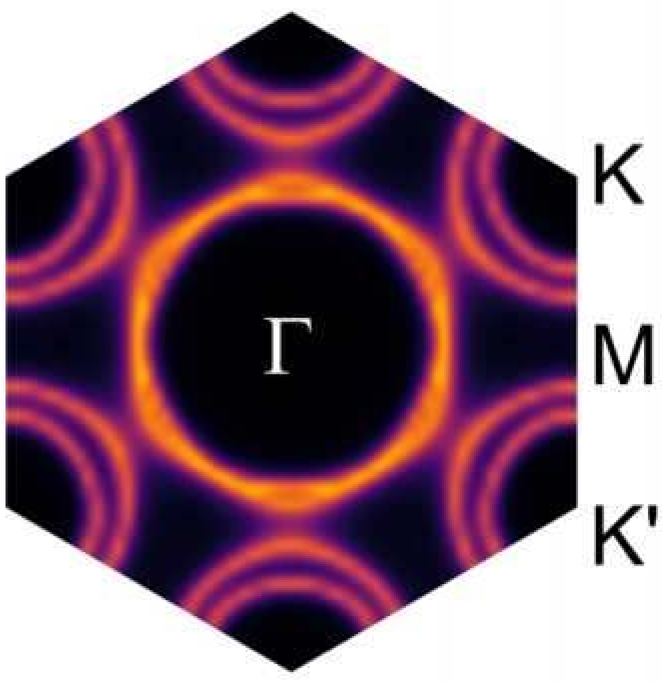
Electronic structure with an f-wave gap



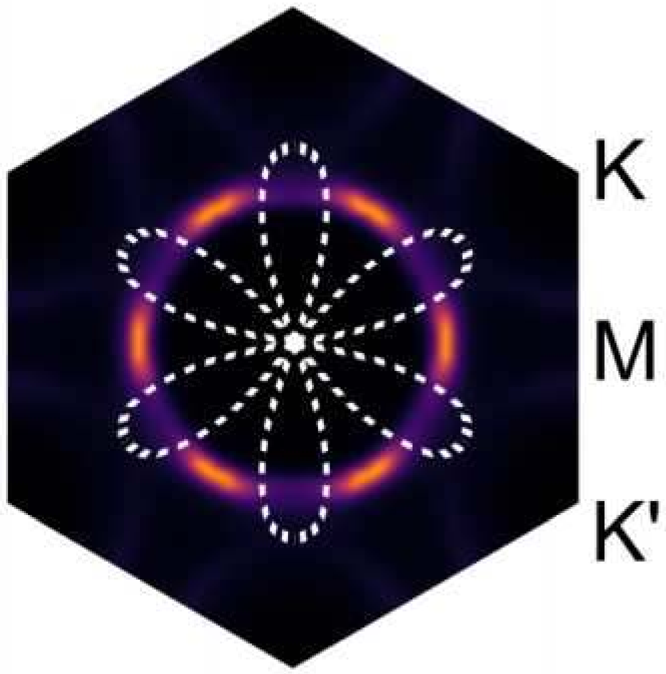
Part of the band structure remains gapless in the presence of superconductivity

Fermi surface of 1H-TaS_2

Normal State

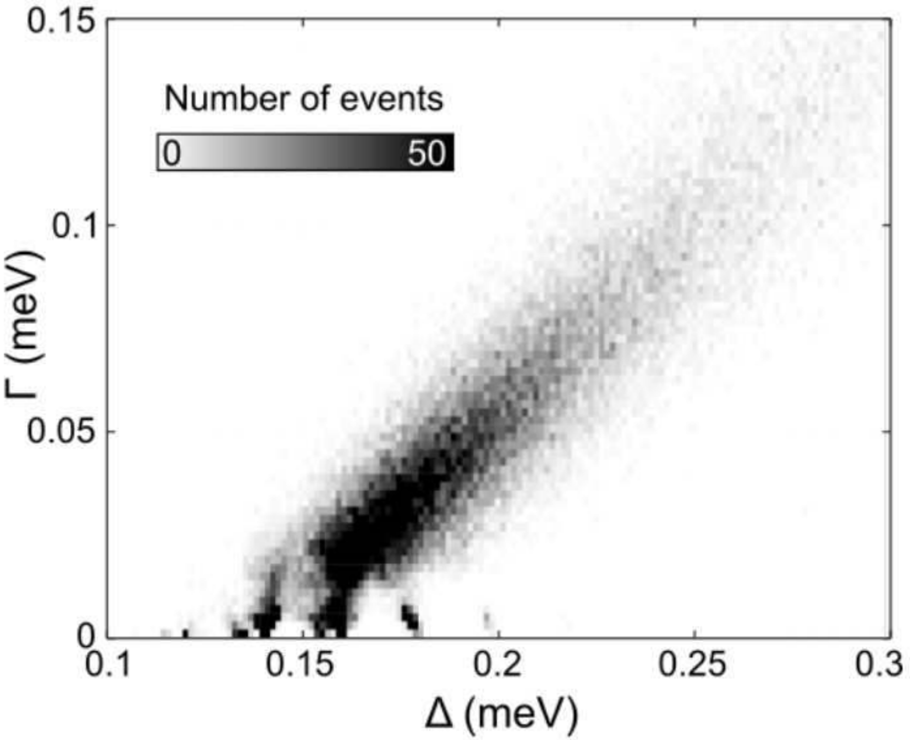


Nodal superconducting state



Nodal f-wave order

Gap versus pair breaking in ultraclean TaS_2



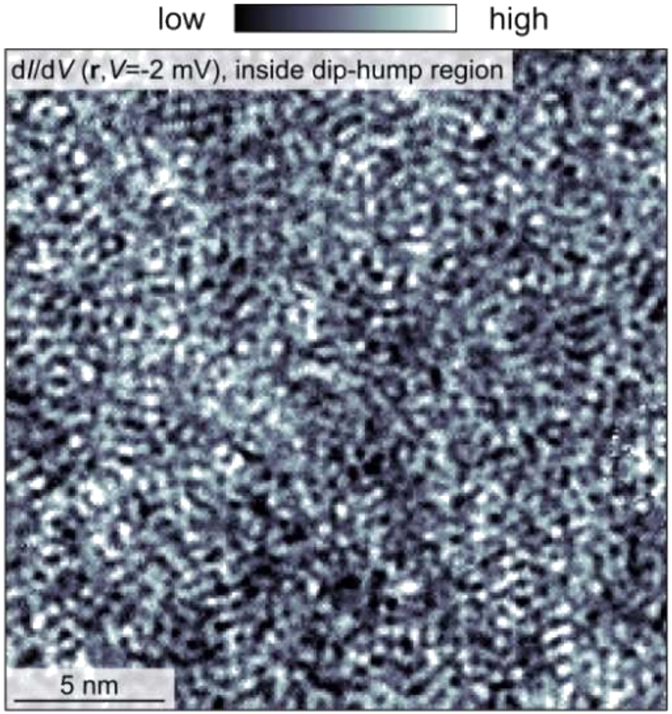
Let assume that the ultraclean sample is actually s-wave with pair breaking (Dynes)

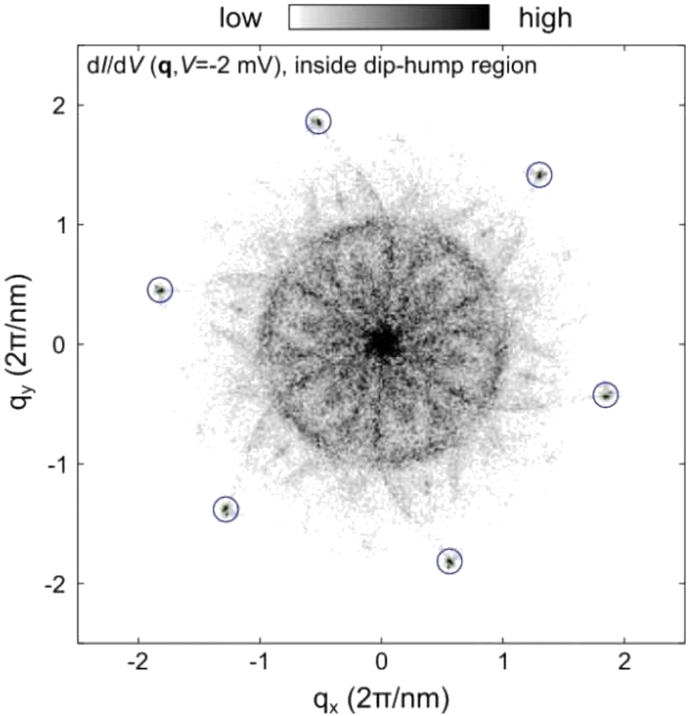
$$\rho(E) = \left| \Re \left[\frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}} \right] \right|$$

Physically, the gap must be anticorrelated with the pair-breaking

The ultraclean sample is incompatible with s-wave gap with pair breaking

Hidden order many-body fluctuations

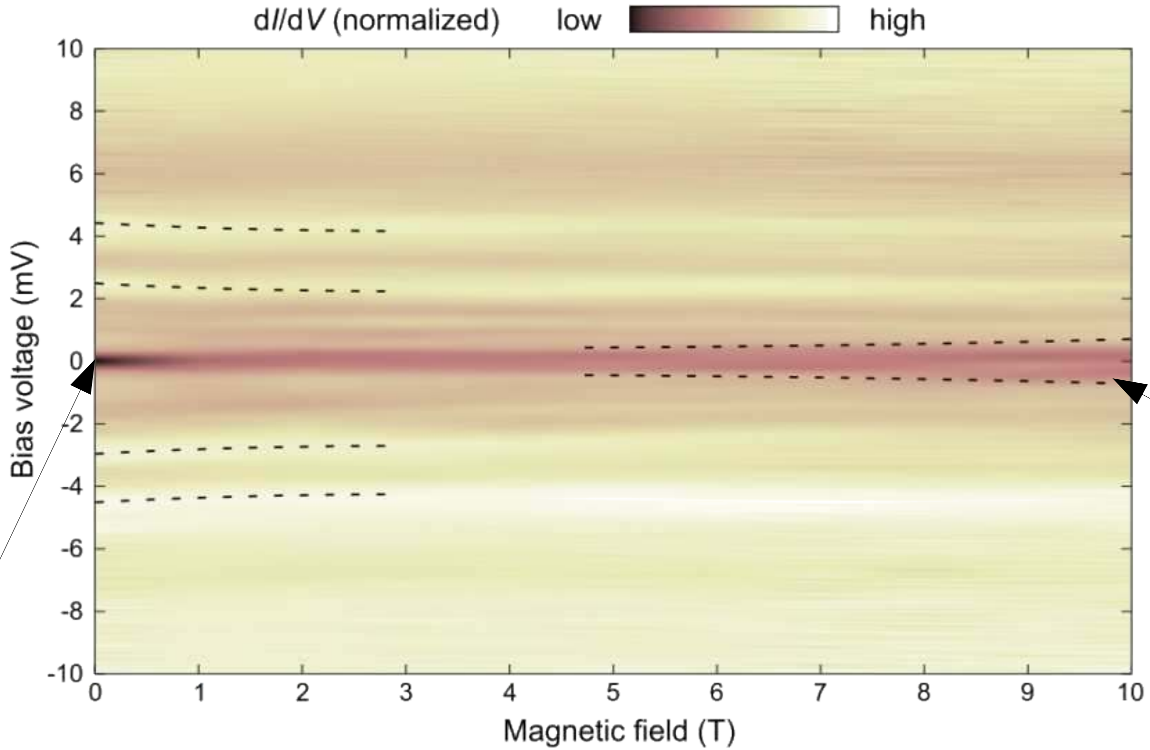


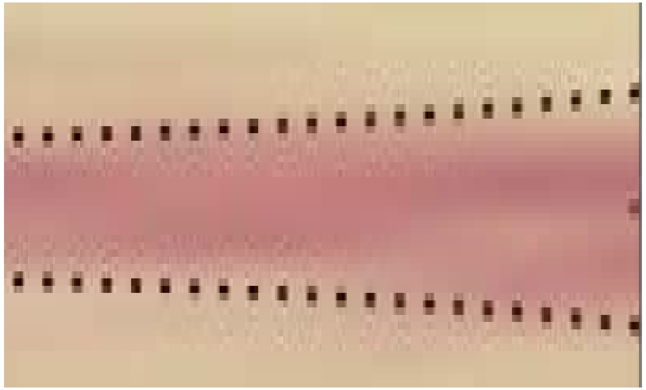


Inelastic excitations with a characteristic length scale emerge above the coherence peaks

Existence of collective many-body modes, potentially related with the superconducting state

Ultraclean sample versus magnetic field





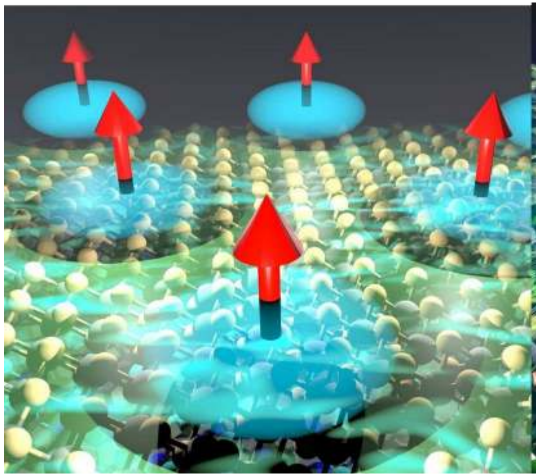
Pseudo-gap

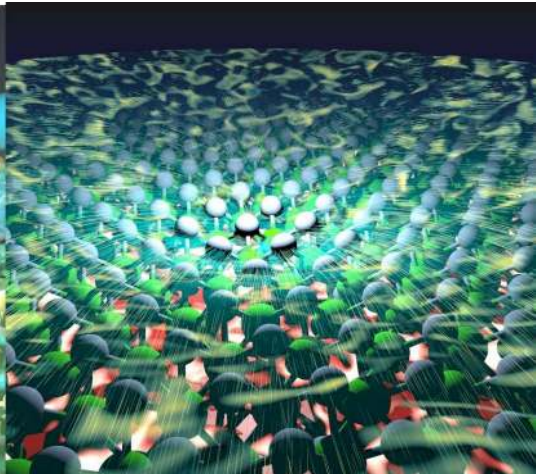
Superconducting gap

A magnetic field increases a pseudo gap at the chemical potential

Take home

- 1H-1T TaS_2 bilayer shows heavy-fermion Kondo insulator behavior
- Ultraclean 1H TaS_2 monolayer shows nodal superconductivity





Nature 599, 582–586 (2021)

arXiv:2112.07316 (2021)

Thank you

Funding from

J&AE JANE AND AATOS ERKKO FOUNDATION

SUOMEN AKATEMIA