Heavy fermion quantum matter and topological superconductivity in artificial van der Waals heterostructures

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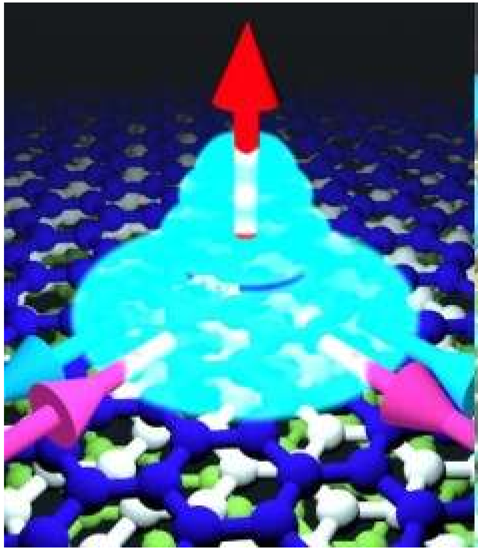
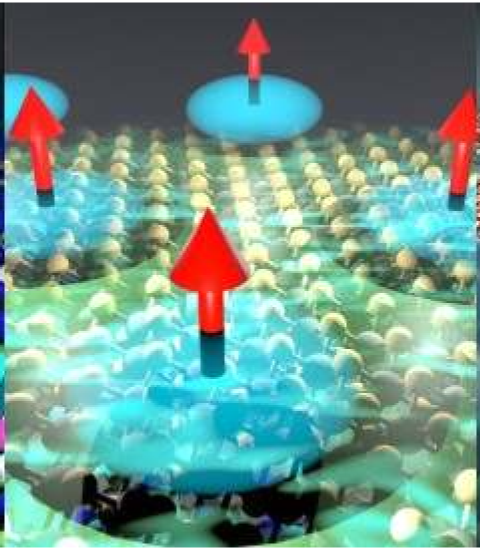
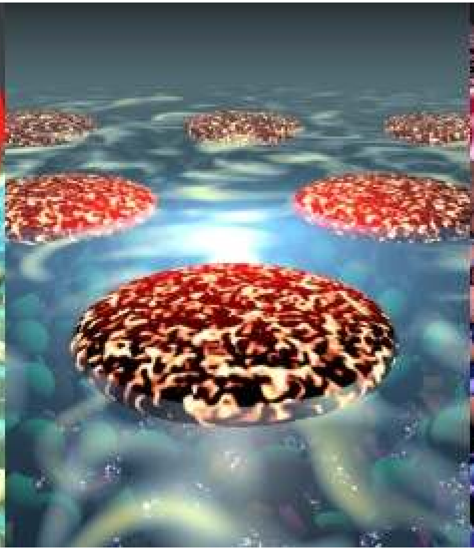


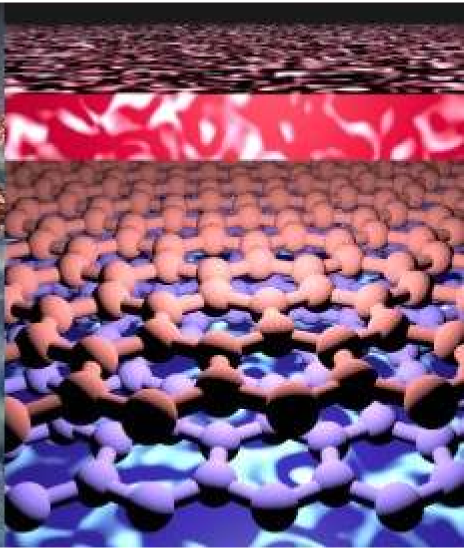
Phys. Rev. Lett. 127, 026401 (2021)



Nature 599, 582–586 (2021)



Nano Lett. 2022, 22, 1, 328–333 (2022)



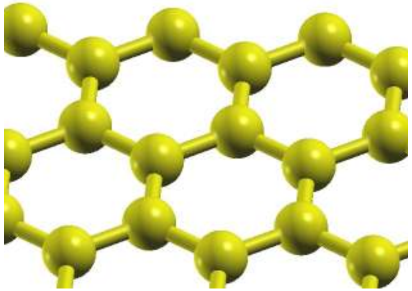
arXiv:2307.04605 (2023)

DPG meeting, Proximity Effects in Epitaxial Graphene, Berlin, Germany
March 22nd 2024

The two-dimensional materials world

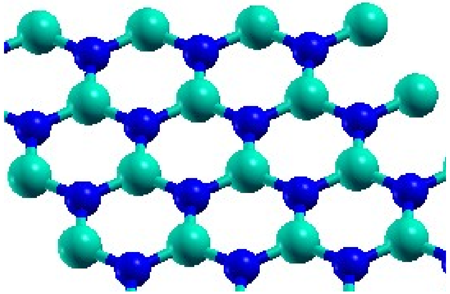
Semimetal

Graphene



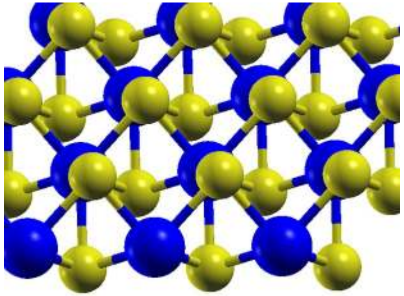
Insulator

BN



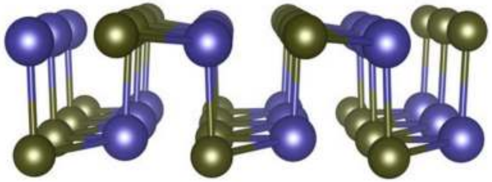
Superconductor

$NbSe_2$



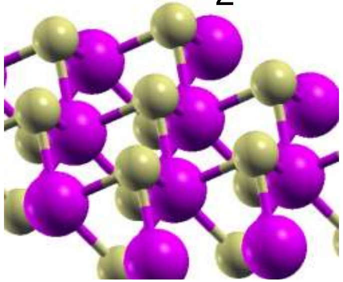
Ferroelectric

SnTe



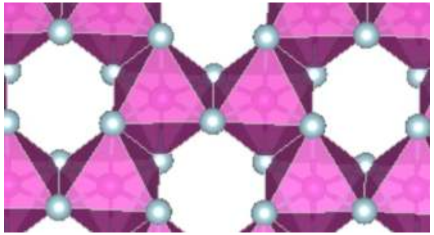
Semiconductor

WS_2



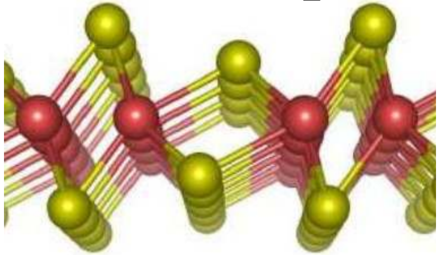
Ferromagnet

CrI_3



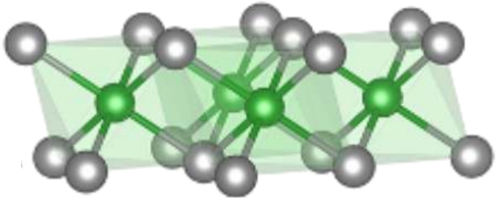
Quantum spin Hall insulator

WTe_2



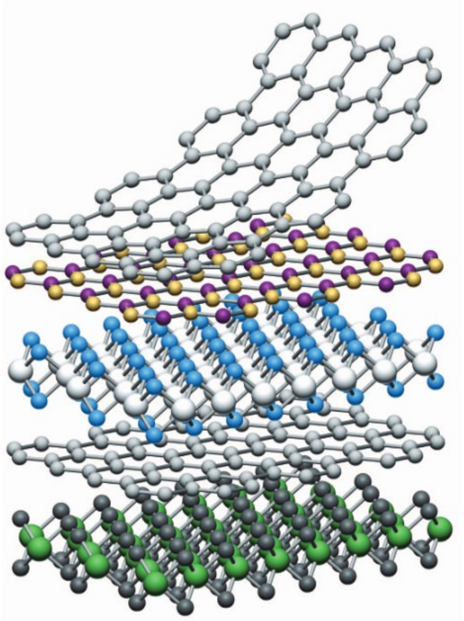
Multiferroic

NiI_2



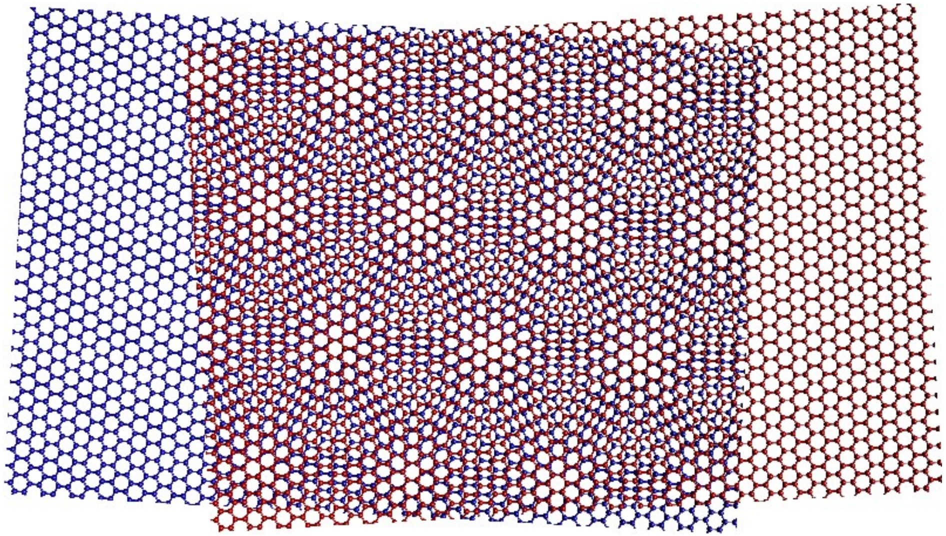
The flexibility of two-dimensional materials

They can be stacked



Nature 499, 419–425 (2013)

They can be rotated

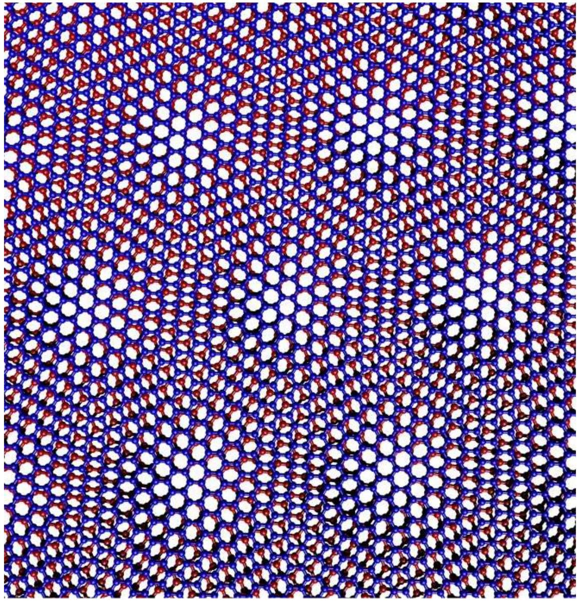


Science 361, 6403, 690-693 (2018)

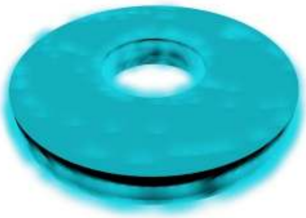
These are unique features of two-dimensional materials

The tunability of twisted van der Waals materials

Twisted bilayer graphene



Superconductivity

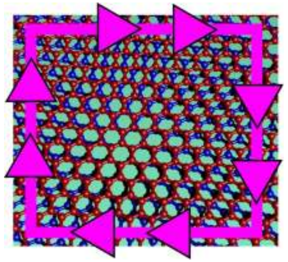


Nature 556, 43–50 (2018)

Topological networks

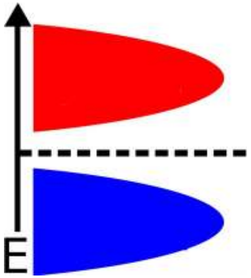
Nano Lett. 18, 11, 6725-6730 (2018)

Chern insulators



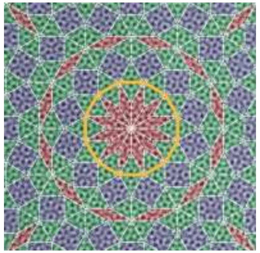
Science 365, 605-608 (2019)

Correlated insulators



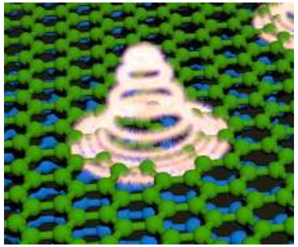
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

Proximal fractional Chern insulators

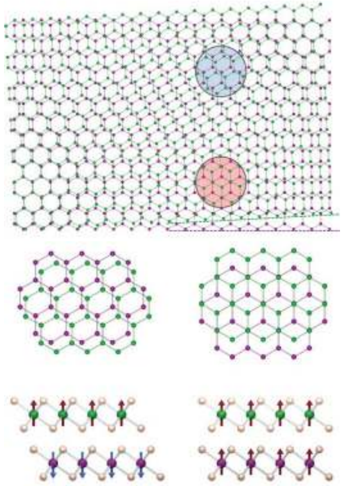


Nature 600, 439–443 (2021)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

Artificial quantum matter in moire van der Waals heterostructures

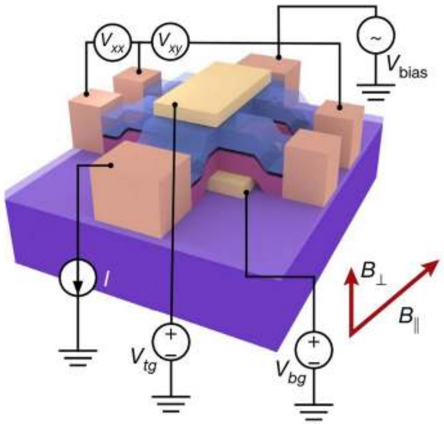
Unconventional magnets



Twisted $CrBr_3$

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

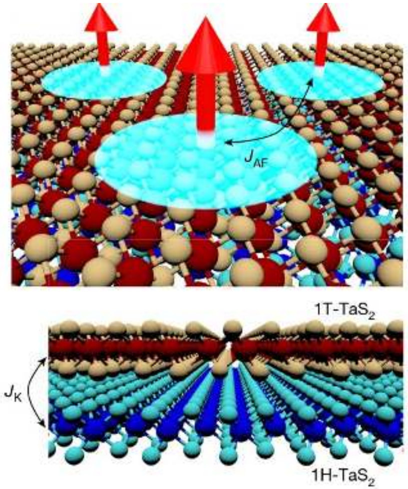
Unconventional superconductors



Twisted trilayer graphene

Nature 595, 526–531 (2021)

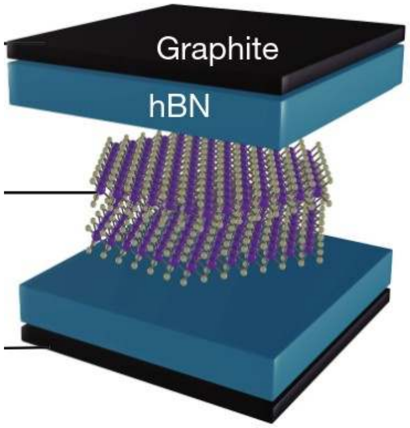
Heavy-fermion quantum materials



1H-1T TaS_2

Nature 599, 582–586 (2021)

Fractional topological matter

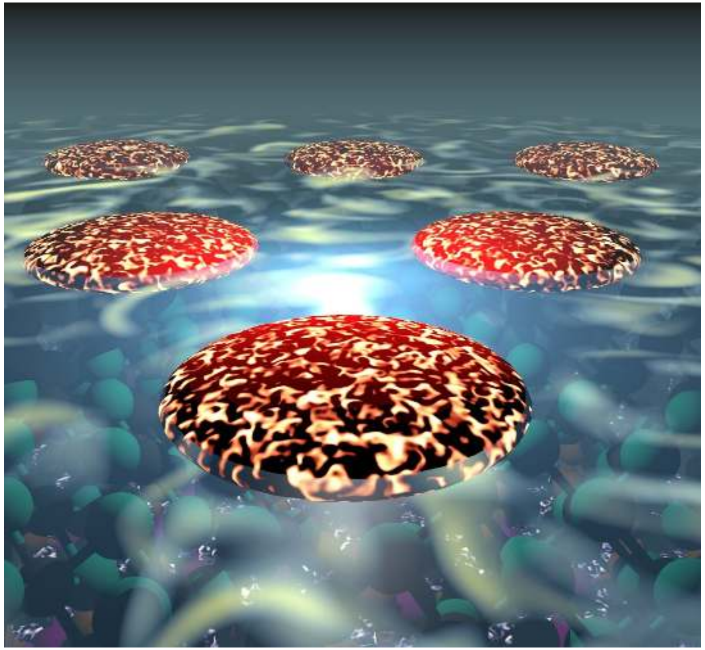


Twisted $MoTe_2$

Nature 622, 63–68 (2023)

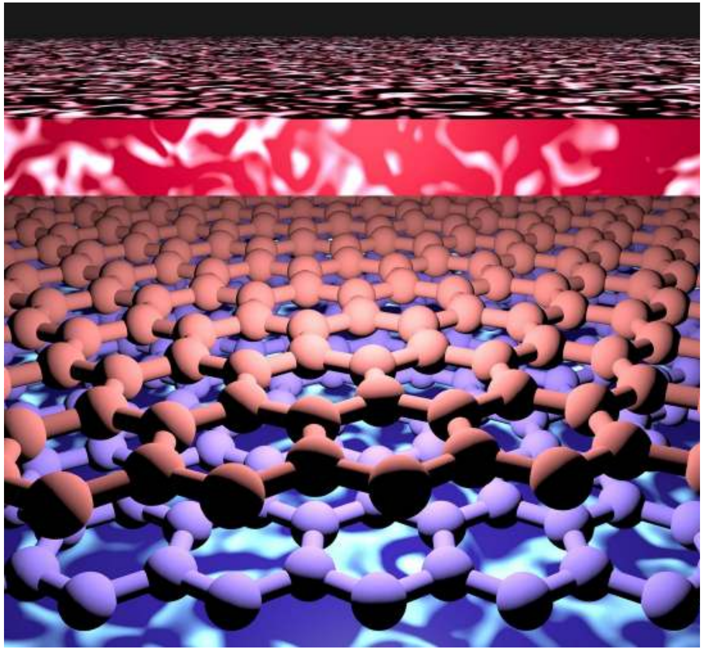
Today's plan: proximity-induced topological superconductivity

Moire-enabled topological superconductivity in $CrBr_3/NbSe_2$



Nano Lett. 2022, 22, 1, 328–333 (2022)

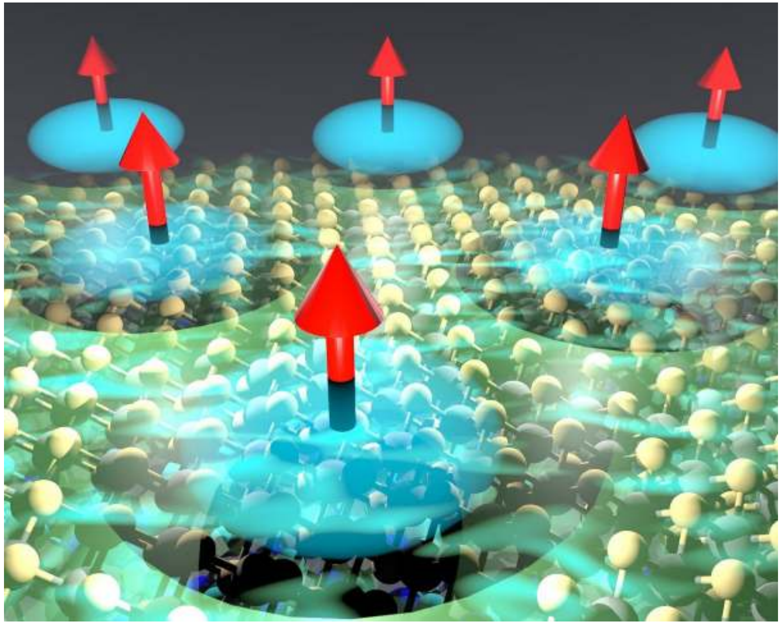
Moire-enabled topological superconductivity in twisted biilayer graphene



arXiv:2307.04605

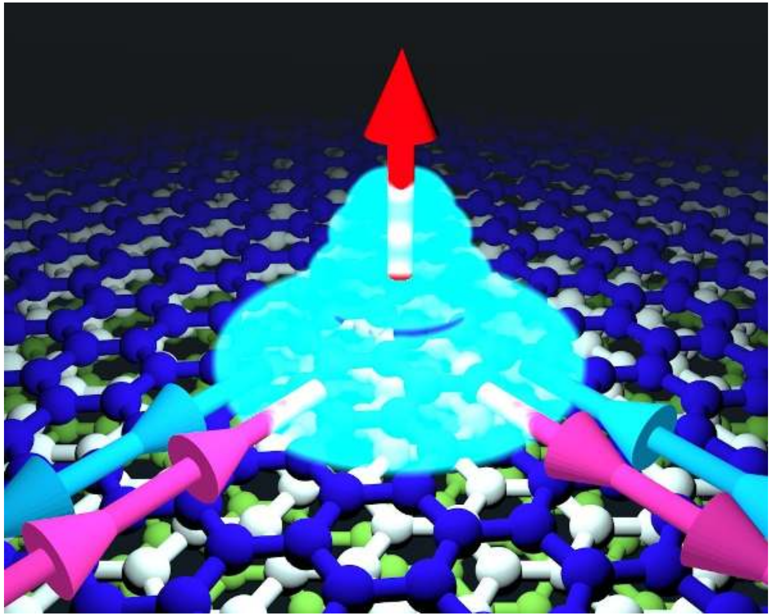
Today’s plan: proximity-induced heavy fermion Kondo matter

Heavy-fermion Kondo matter in proximitized dichalcogenide bilayer

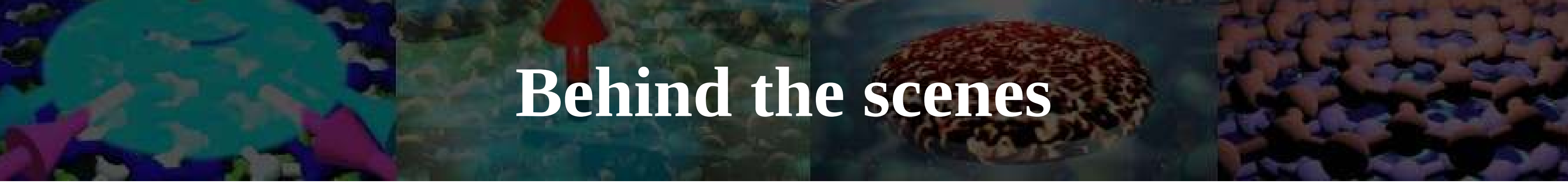


Nature 599, 582–586 (2021)

Heavy-fermion Kondo matter in twisted graphene trilayers



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



Behind the scenes

Experiment

S. Ganguli

M. Aapro

S. Kezilebieke

M. Amini

V. Vaňo

Md. Huda

P. Liljeroth

Nano Lett. 22, 1, 328-333 (2022)
Nature 599, 582–586 (2021)

Theory

E. Bascones

M. Khosravian

Aline Ramires

Guangze. Chen

arXiv:2307.04605
Phys. Rev. Lett. 127, 026401 (2021)

Topological superconductivity

The quest for topological superconductors

The prize

A potential strategy for noise-resilient quantum computing

Nature Physics 7, 412-417 (2011)
Phys. Rev. X 6, 031016 (2016)

The challenge

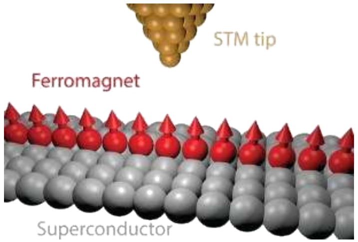
Incredibly rare in nature and hard to reliably identify
Practical applications require highly tunable materials

Nature Reviews Physics 2, 575–594 (2020)

How can we find new platform to engineer tunable topological superconducting states?

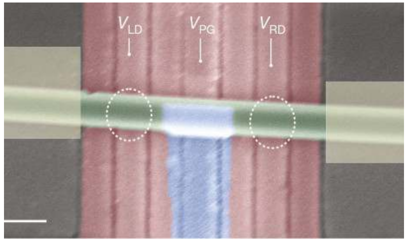
Engineering topological superconductors

Magnetic atomic chains



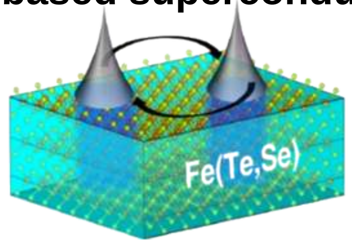
Nature Nano 17, 384–389 (2022)

Semiconductor-based



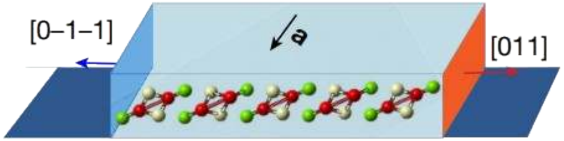
Nature 614, 445–450 (2023)

Fe-based superconductors



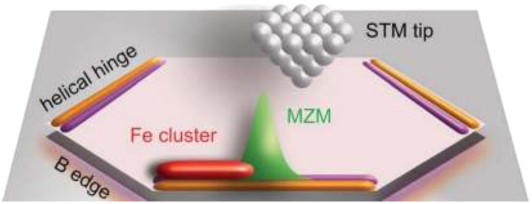
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



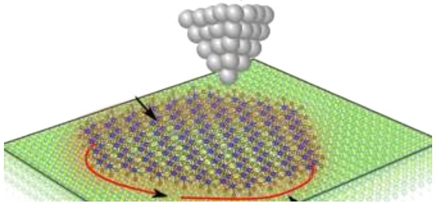
Nature 579, 523–527 (2020)

Topological insulators



Science 364.6447 (2019): 1255-1259

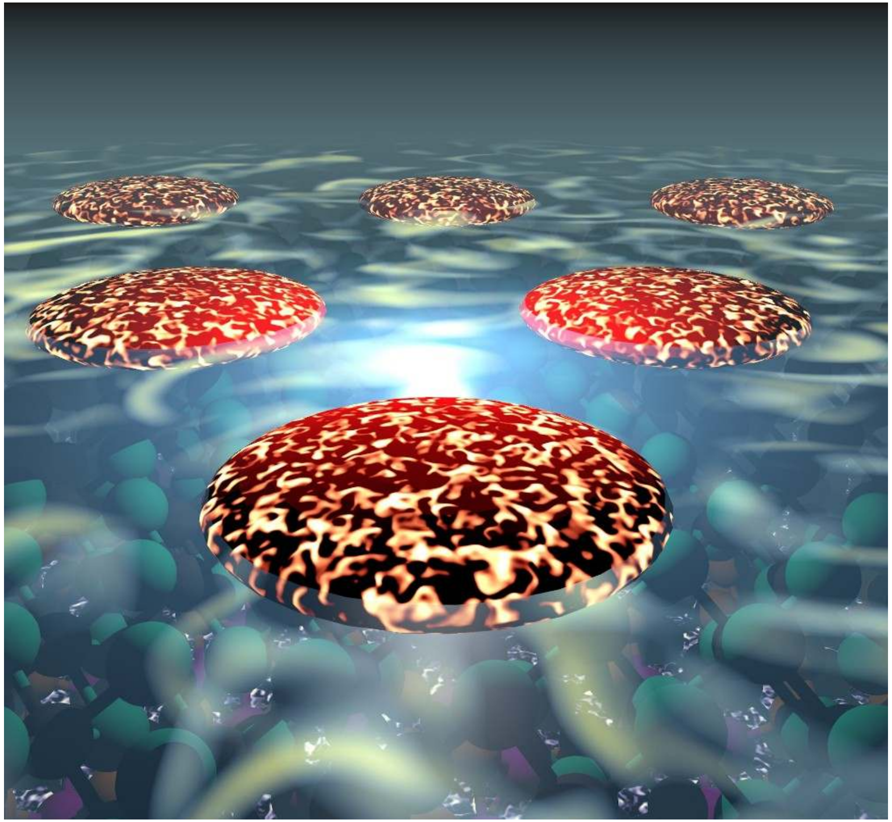
Two-dimensional materials



Nature 588, 424–428 (2020)

New materials open new venues for engineering and controlling Majorana physics

Artificial topological moiré superconductivity in $NbSe_2/CrBr_3$



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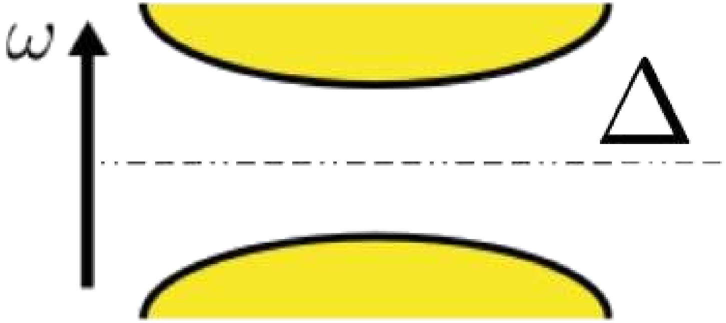
Nano Lett. 22, 1, 328-333 (2022)

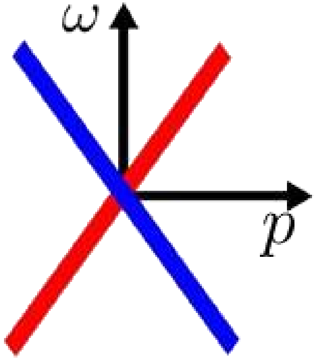
How to build your own topological superconductor

Ingredients

s-wave pairing



Helical channels



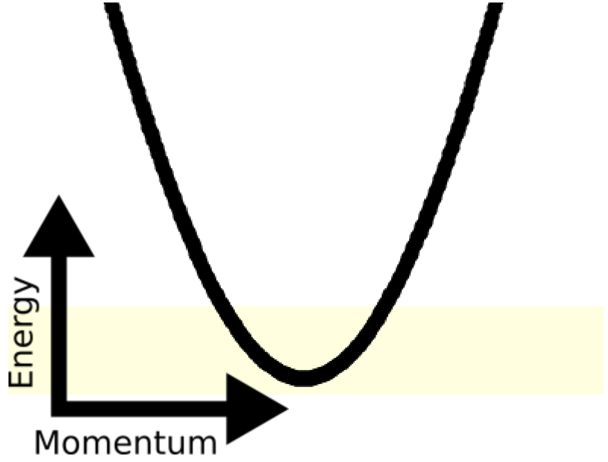
Objective: to realize a spinless superconductor

$$H = \sum_n t c^\dagger_{n+1} c_n + \Delta c_n c_{n+1} + c.c.$$

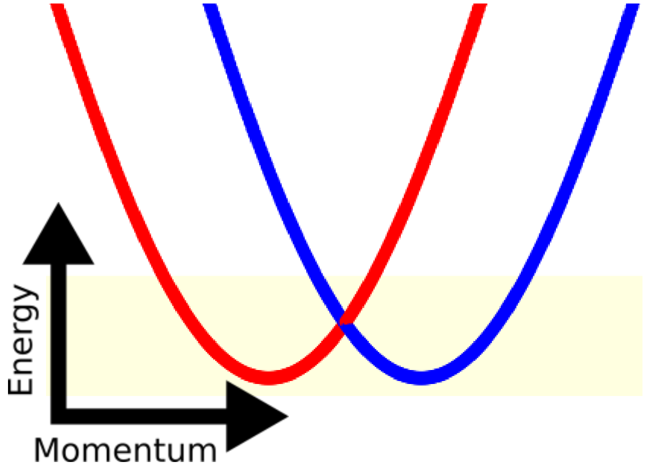
A. Y. Kitaev. Physics-Uspekhi, 44:131, 2001

How to build your own helical gas

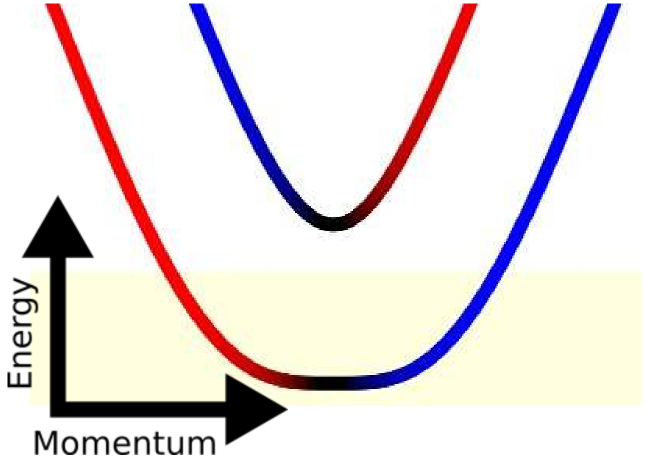
Take a parabolic band



Create spin-momentum locking with Rashba spin-orbit coupling



Split the Gamma point with an exchange field

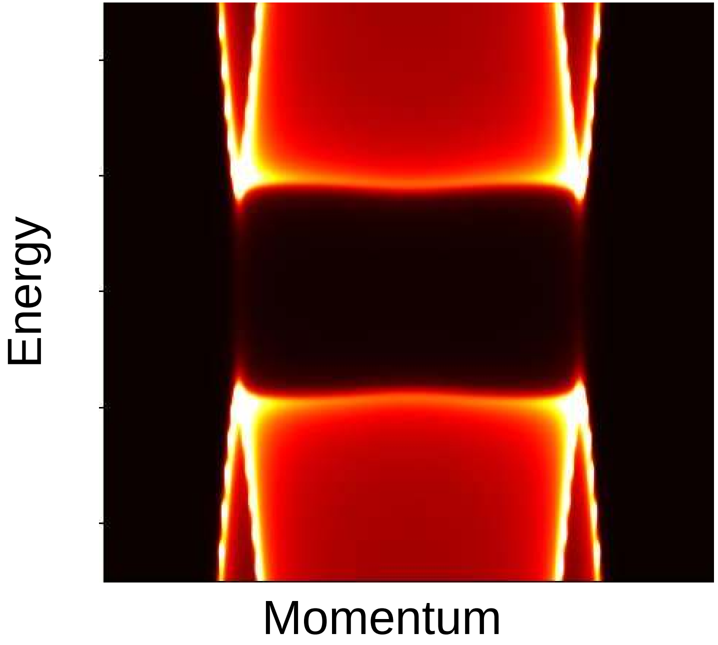


For a chemical potential inside the split gap, we have helical states

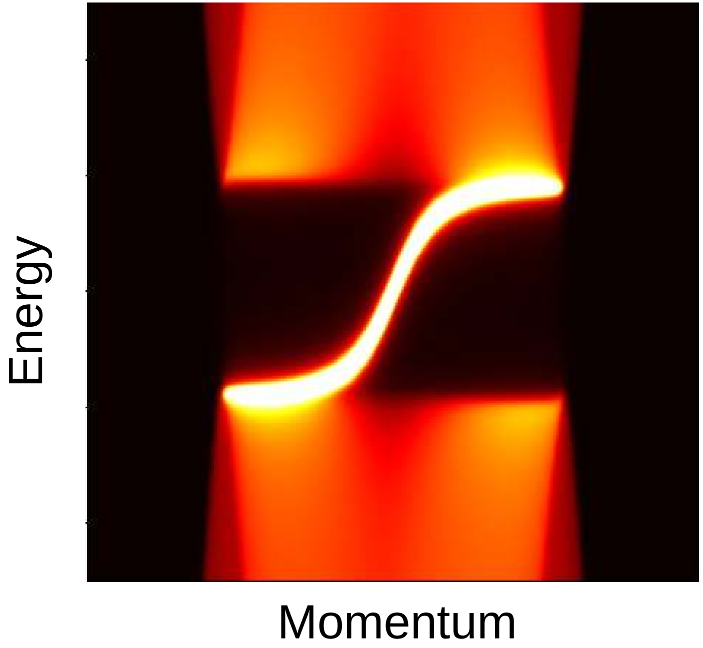
Having a topological superconductor requires having a tunable material

The spectra of a topological superconductor

Full gap in the bulk

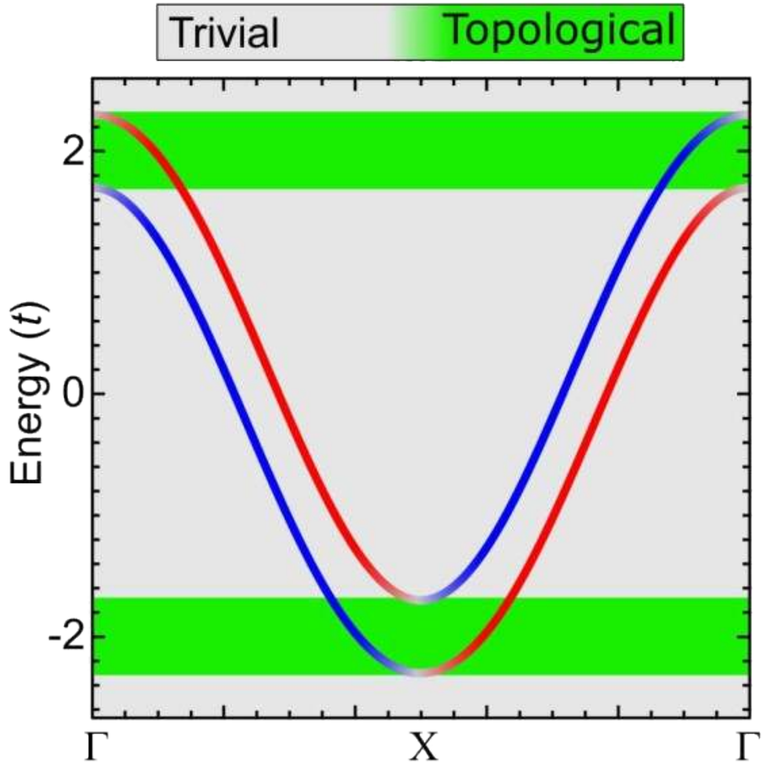


Gapless (Majorana) mode at the edge



Topological superconductors feature a gap on the bulk, and gapless modes at the edges

1D topological superconductor, without moire



$$H = H_0 + H_J + H_R$$

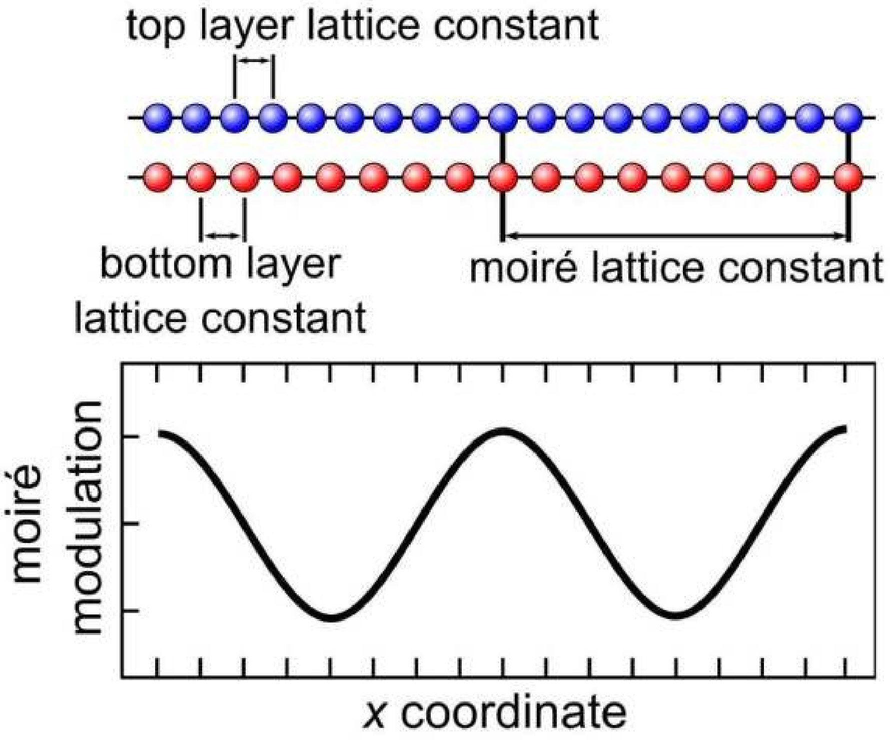
Kinetic energy

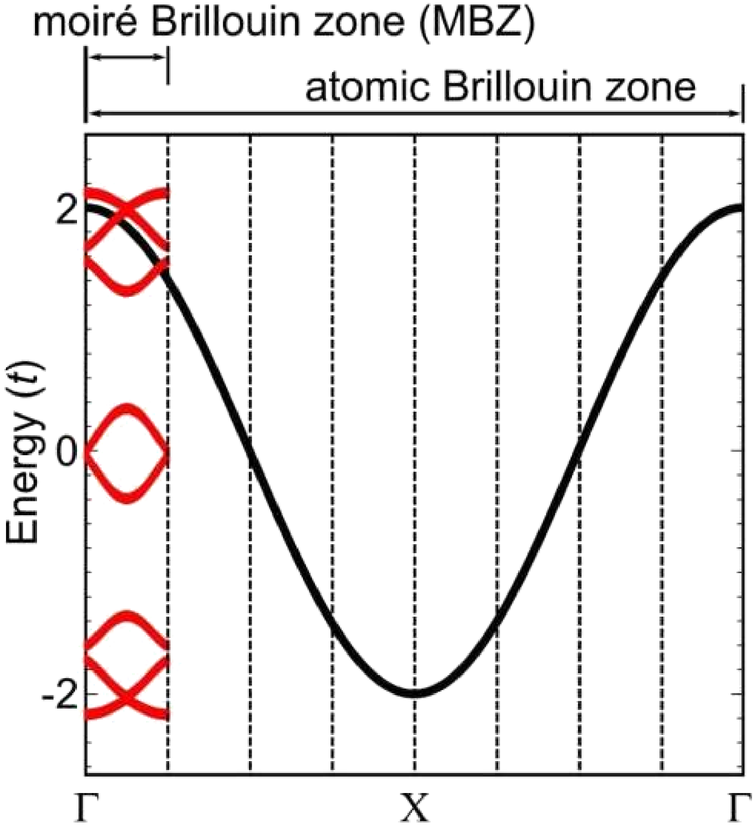
Exchange field

Rashba spin-orbit coupling

When switching on an s-wave pairing, green regions lead to topological superconductivity

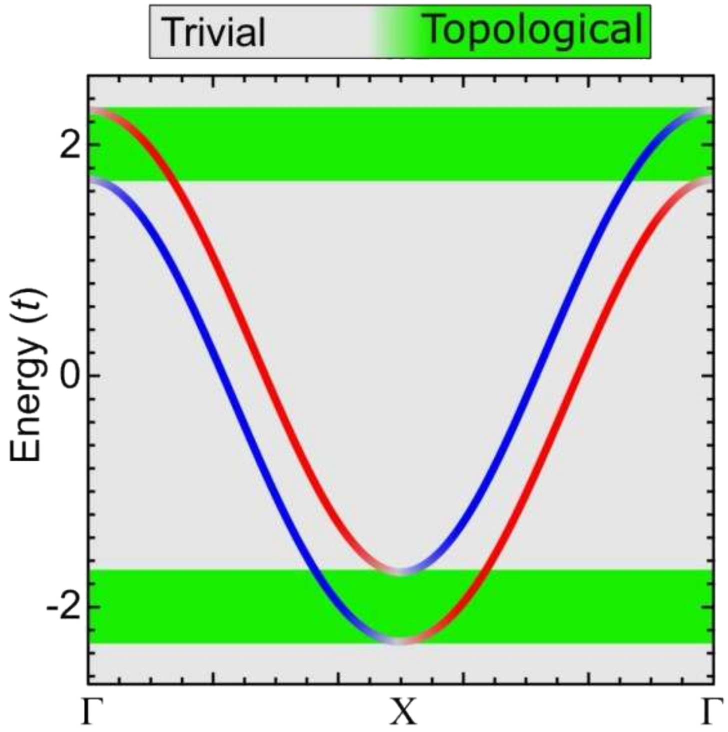
1D topological superconductor, with moire



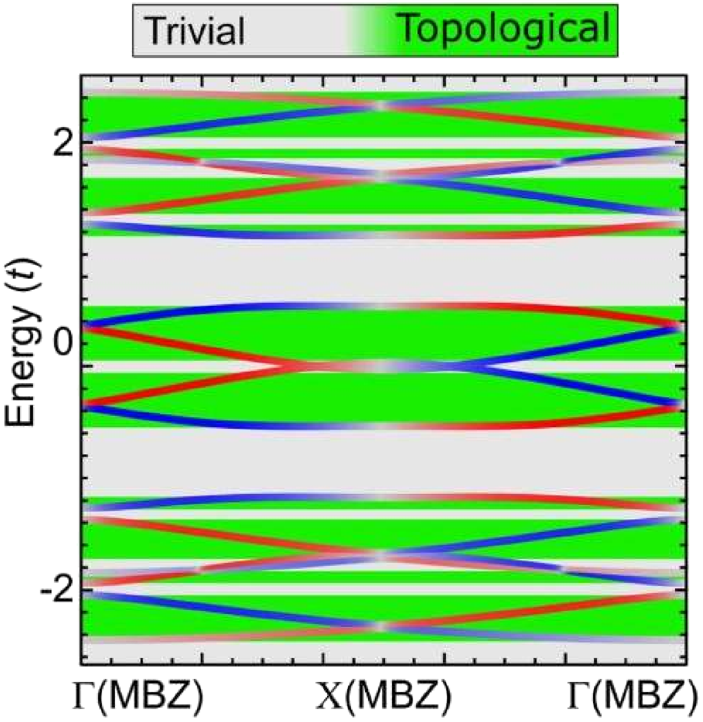


1D topological superconductor, with moire

Without moire



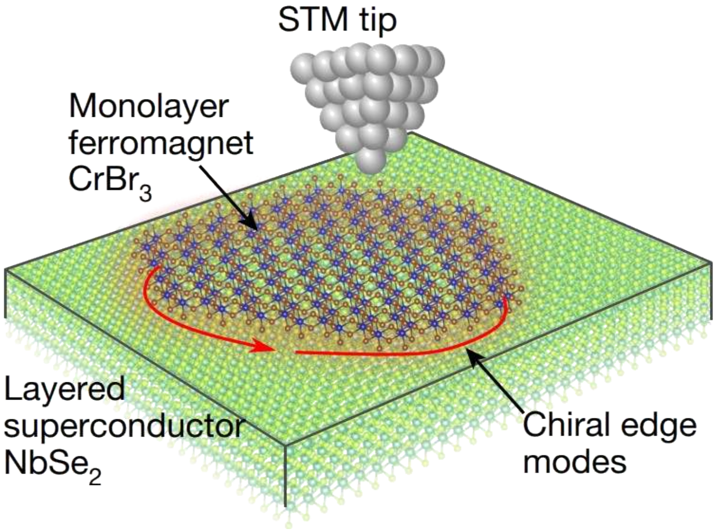
With moire



Moire pattern allow to realize topological superconductivity in otherwise forbidden energies

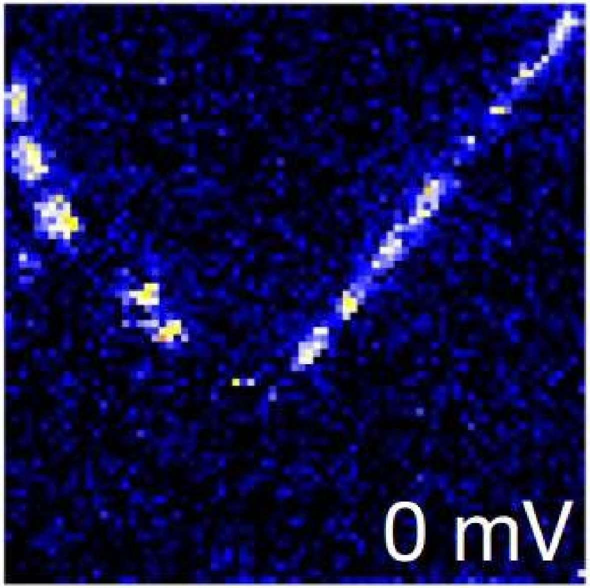
Topological superconductivity in a van der Waals heterostructure

$CrBr_3/NbSe_2$ heterostructure



Nature 588, 424–428 (2020)

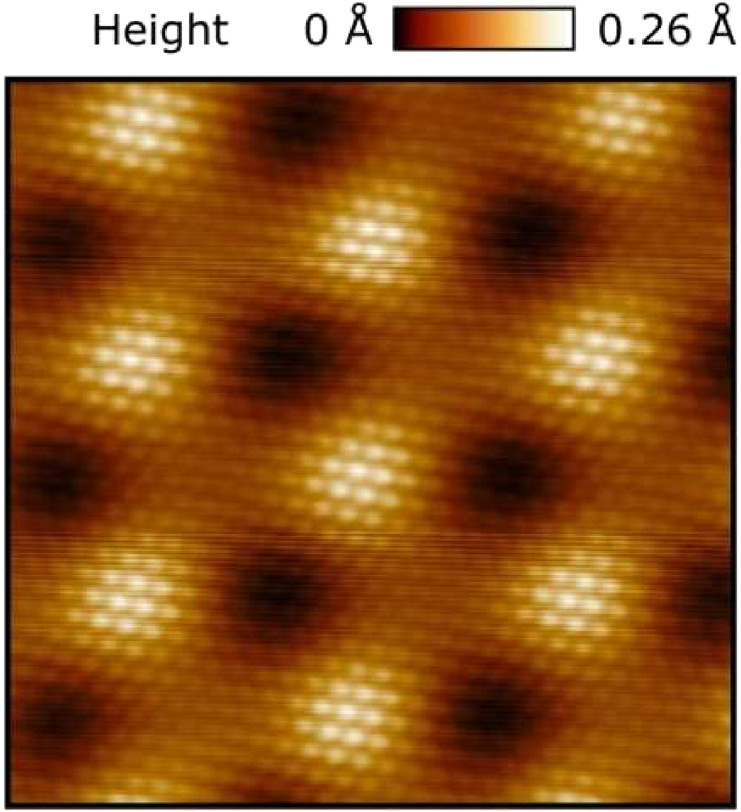
Zero bias dIdV

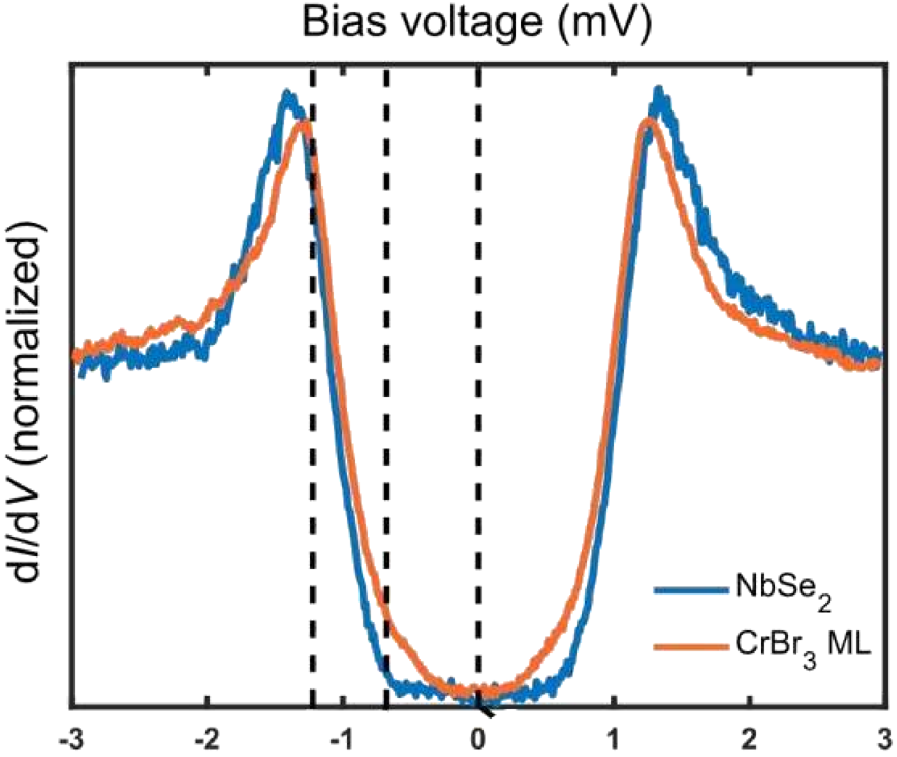


A topological superconducting state appears in $CrBr_3/NbSe_2$

What is the role of the twist between the two van der Waals materials?

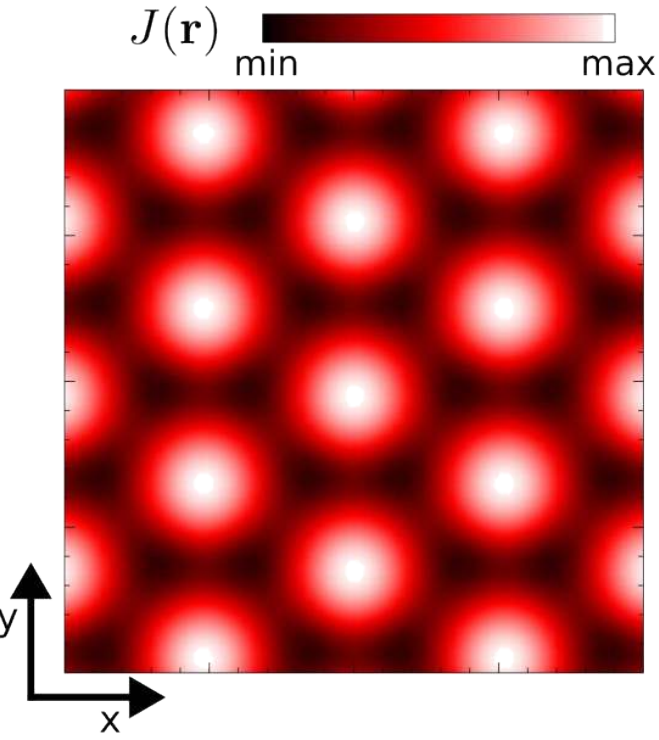
$CrBr_3/NbSe_2$ heterostructure



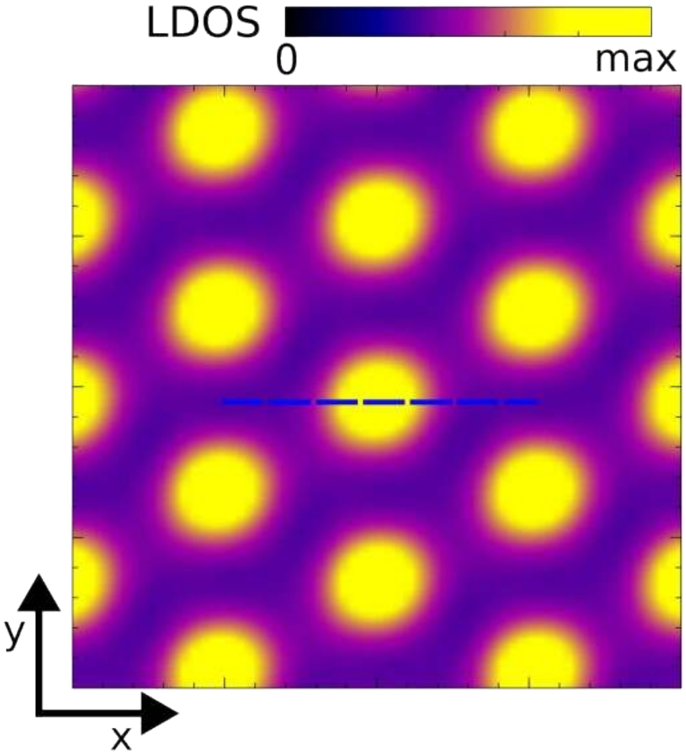


Bulk Yu-Shiba-Rusinov states

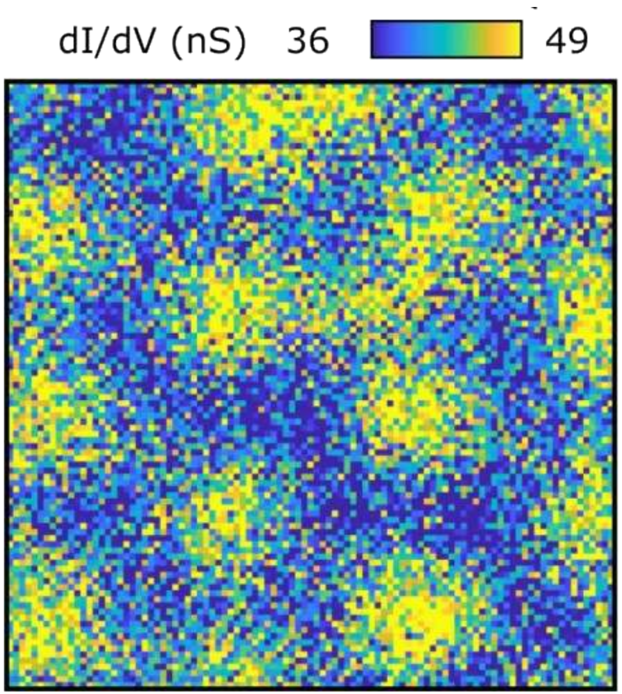
Exchange profile



Theoretical LDOS



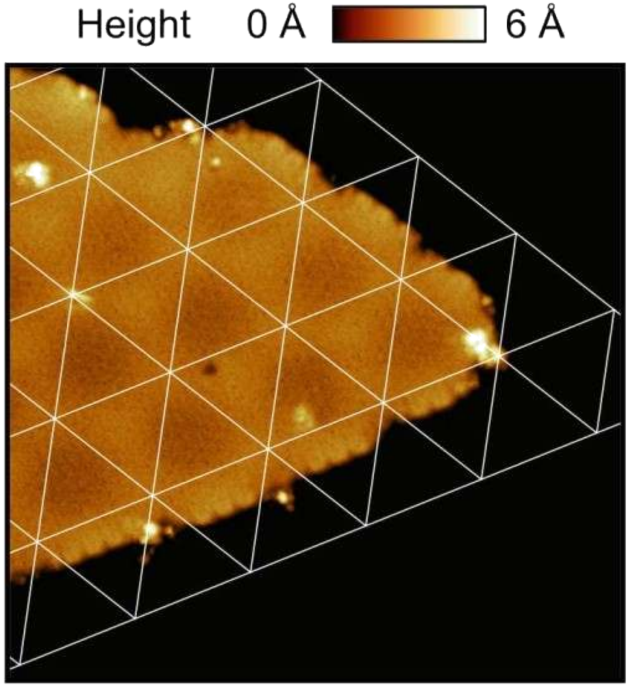
Experimental dIdV



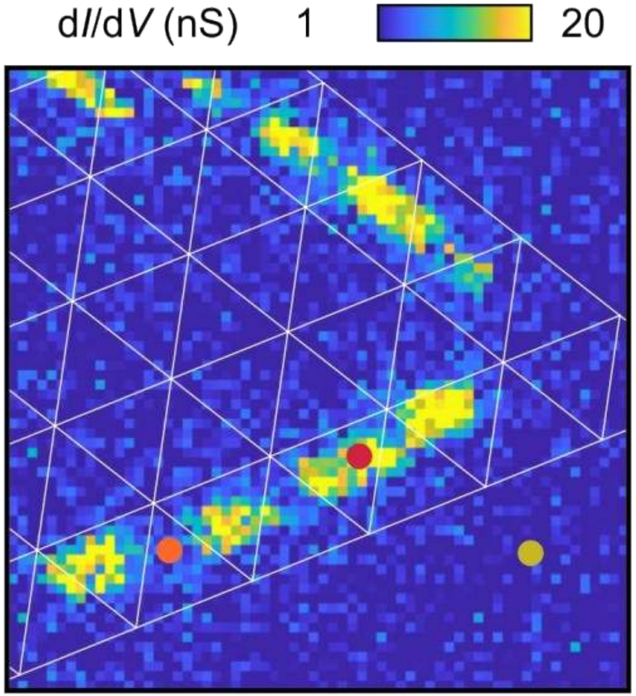
Bulk Yu-Shibe-Rusinov states are imprinted by the modulated exchange profile

Topological moire edge states

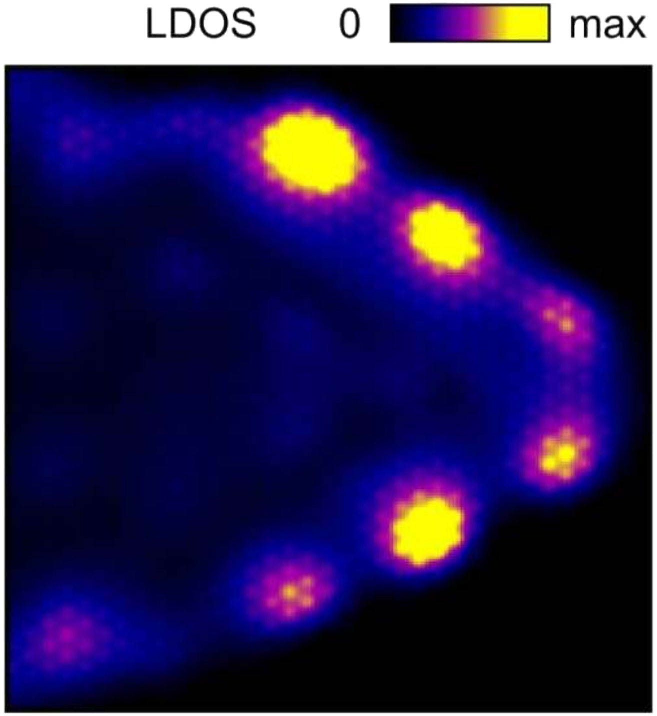
Topography



Experimental dIdV

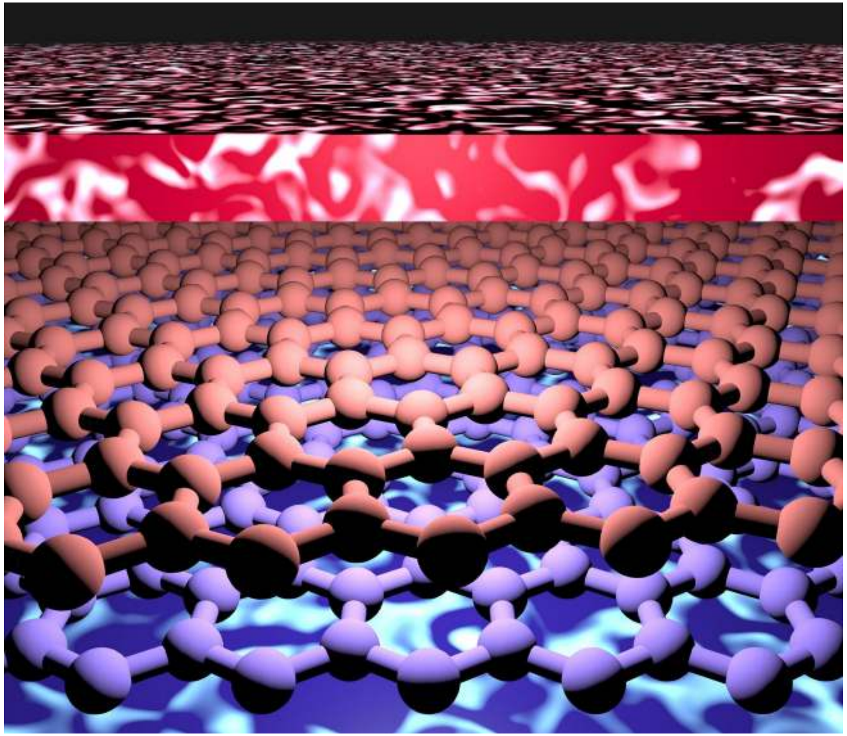


Theoretical dIdV



Topological edge modes are imprinted by the modulated exchange profile

Moire-enabled artificial superconductors in twisted bilayer graphene



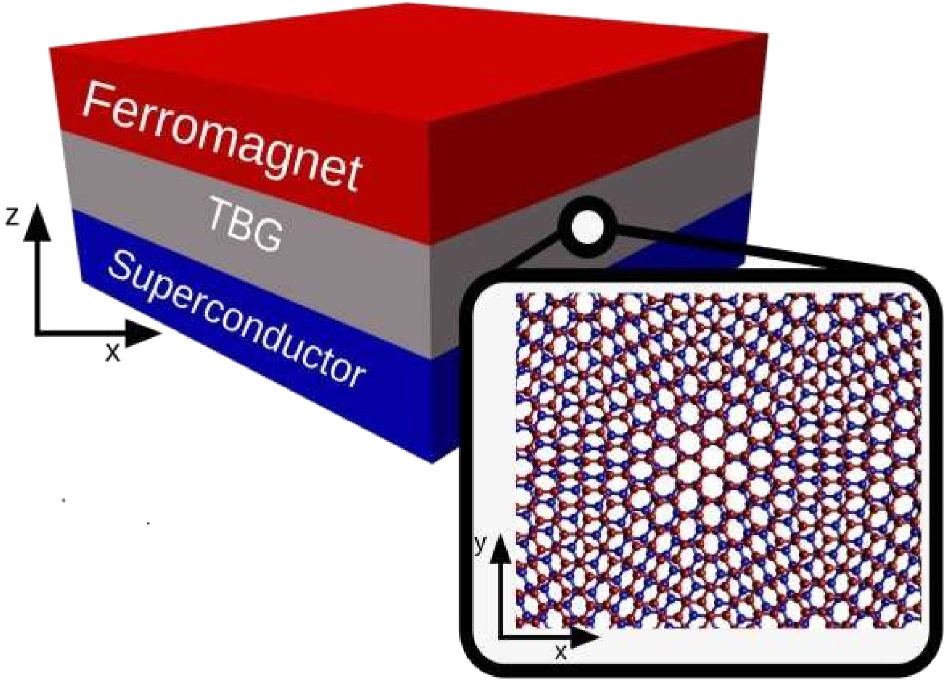
Maryam Khosravian

Elena Bascones

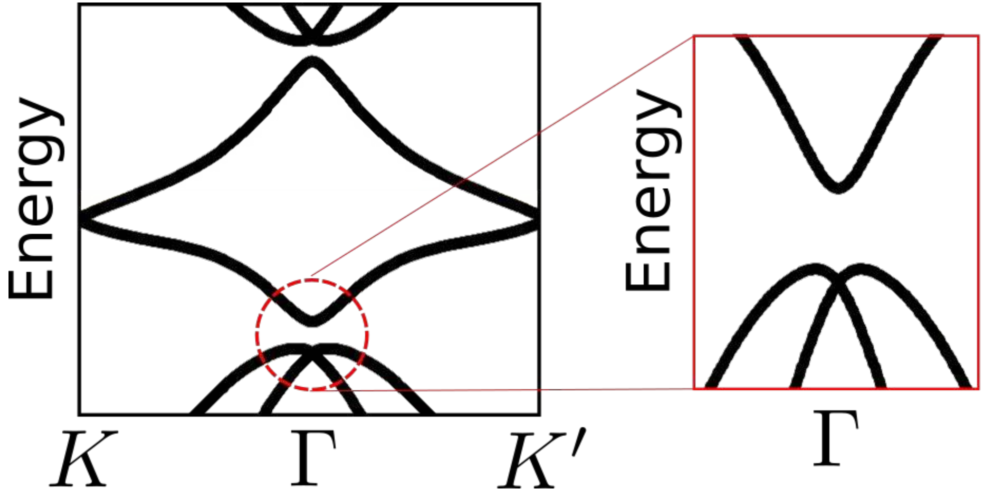
arXiv:2307.04605

Encapsulated twisted graphene bilayers

Twisted bilayer graphene encapsulated between a ferromagnet and superconductor



Twisted bilayer band structure



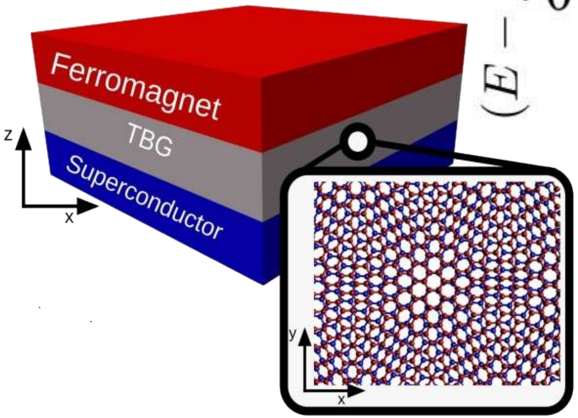
Parabolic bands at the Γ point

$$1.5 - 3^\circ$$

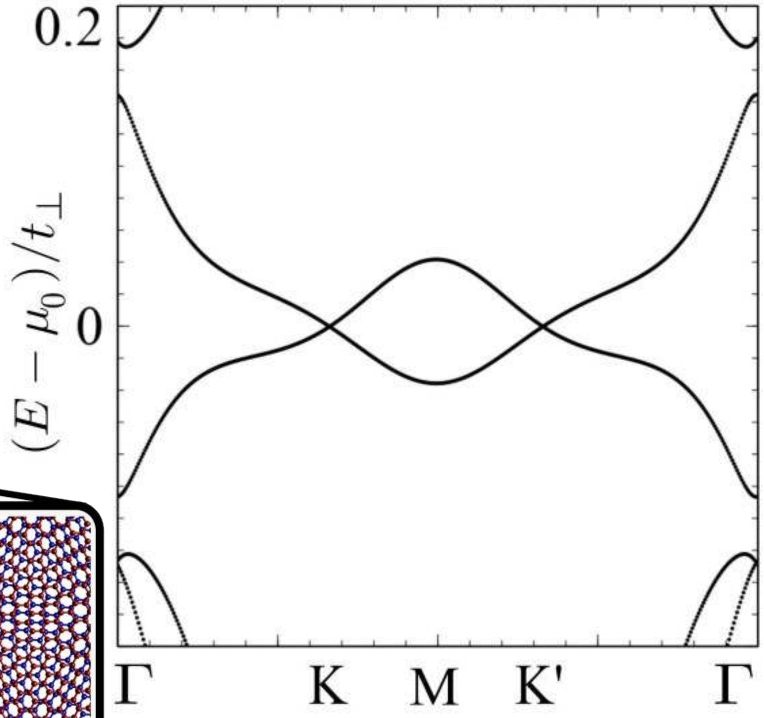
Moire-enabled artificial superconductors in twisted bilayer graphene

Twisting angles

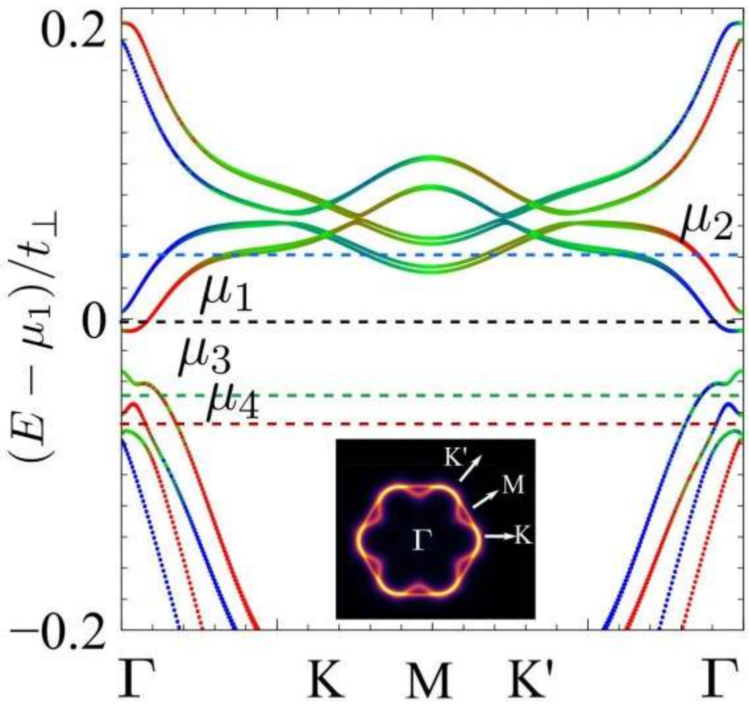
$$1.5 - 3^\circ$$



Pristine twisted bilayer



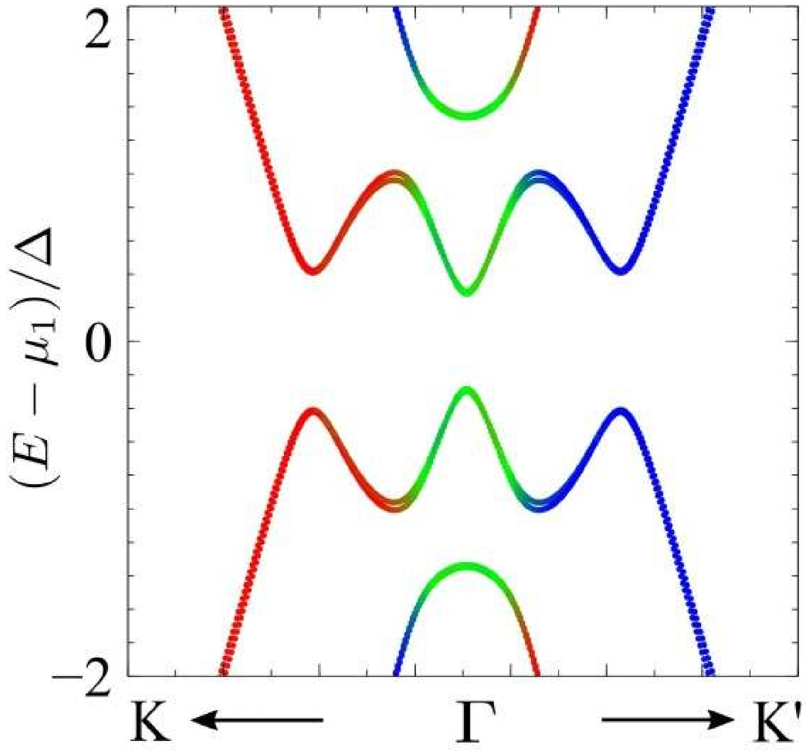
Encapsulated twisted bilayer



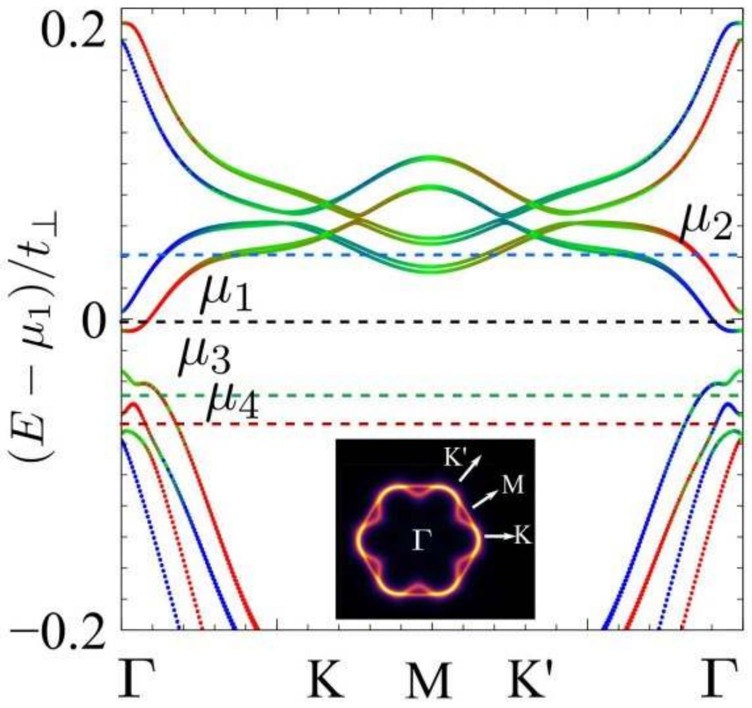
The moire effect gives rise to minigaps featuring helical states with encapsulation

Moire-enabled artificial superconductors in twisted bilayer graphene

With superconductivity



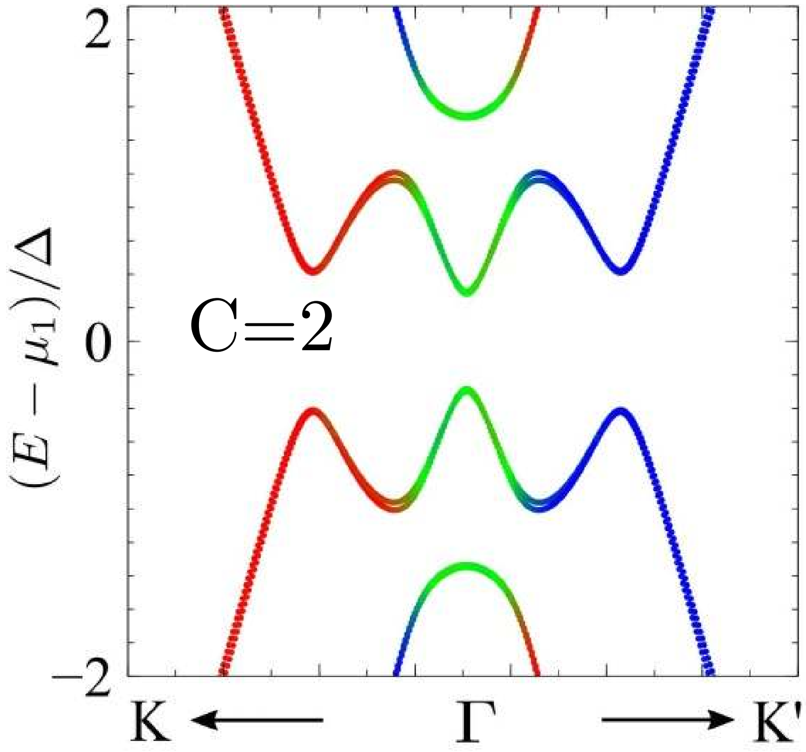
Without superconductivity



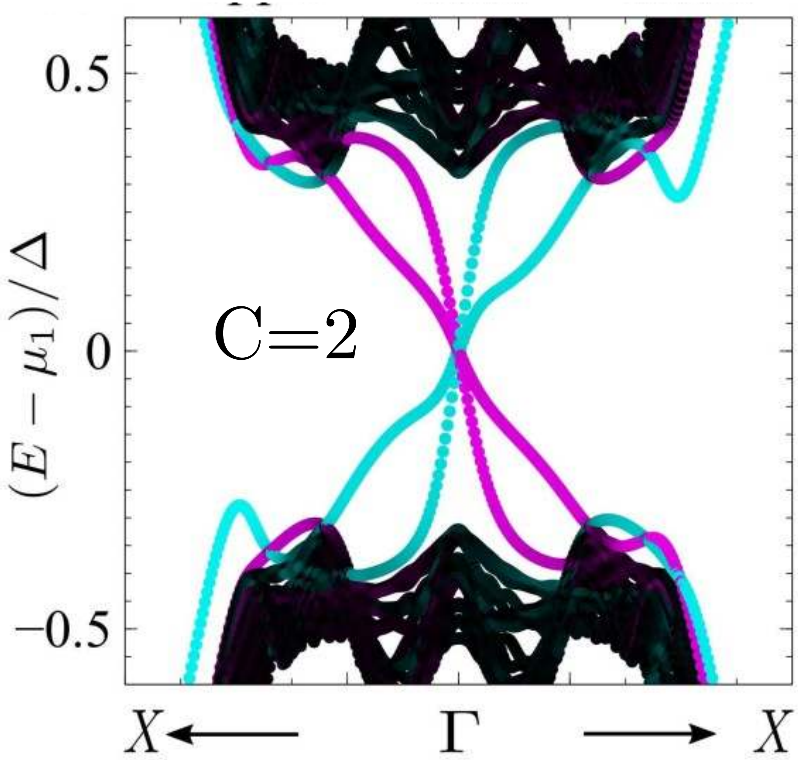
Switching on superconductivity gives rise to a topological superconducting state

Moire-enabled artificial superconductors in twisted bilayer graphene

Bulk band structure



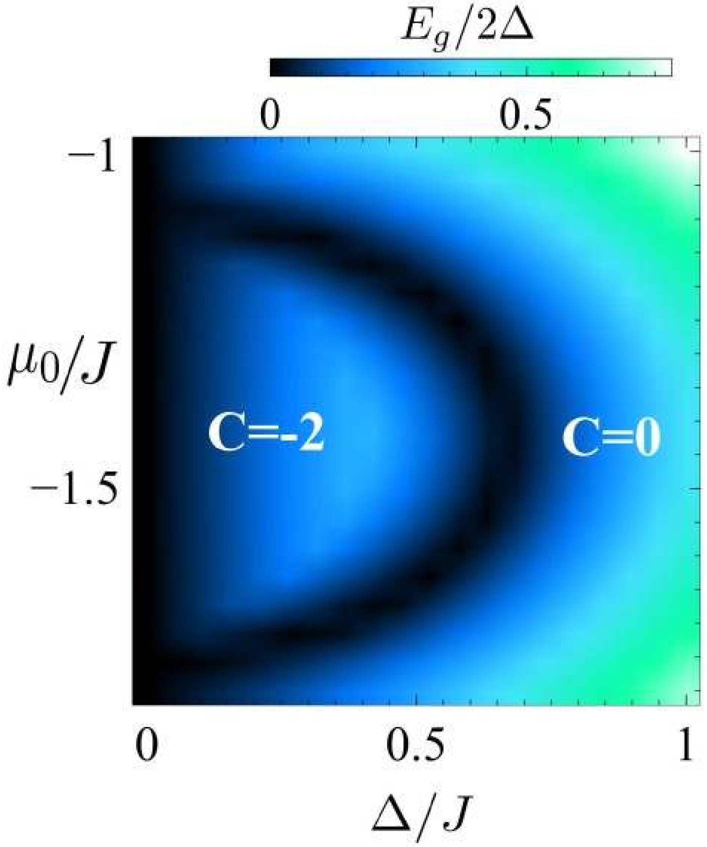
Ribbon band structure



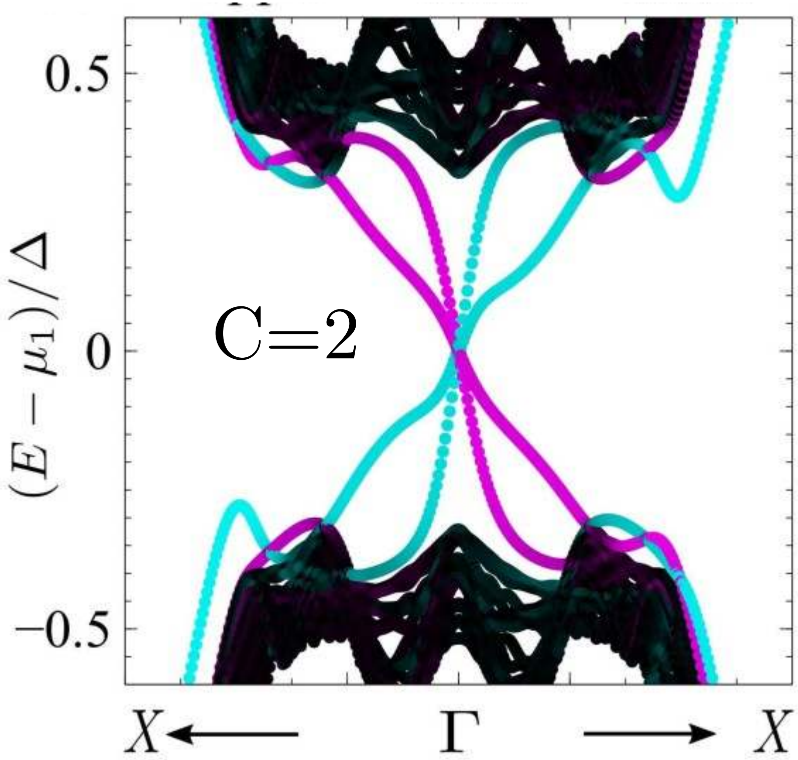
The topological state features chiral Majorana modes in a ribbon geometry

Moire-enabled artificial superconductors in twisted bilayer graphene

Gap VS chemical potential



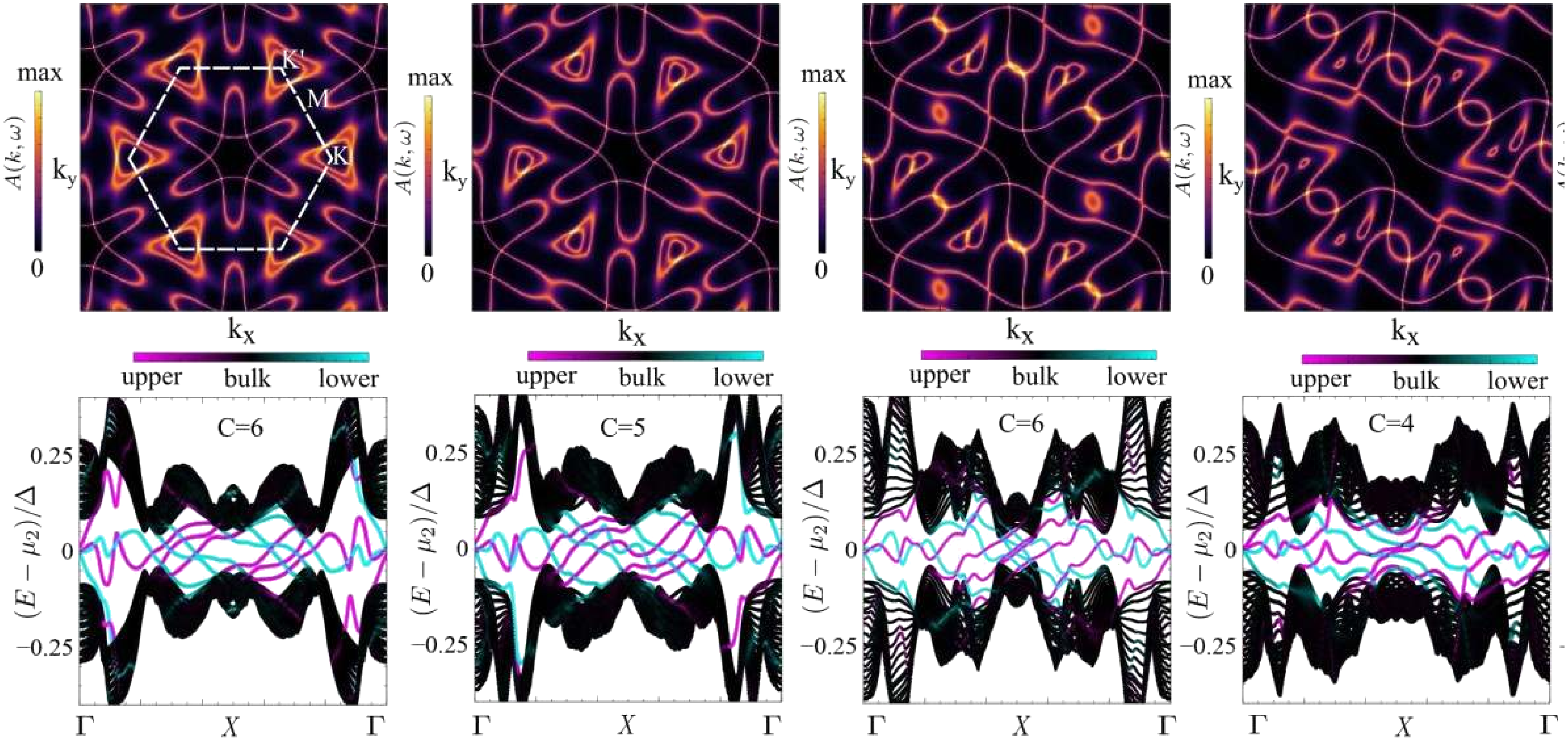
Ribbon band structure



Multiple topological phases tunable by strain

Fermi surface

Ribbon bands



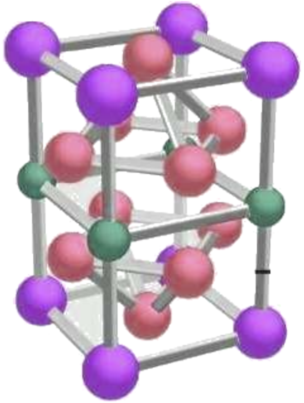
Strain allows to realize topological states with different Chern numbers

Heavy fermion quantum matter

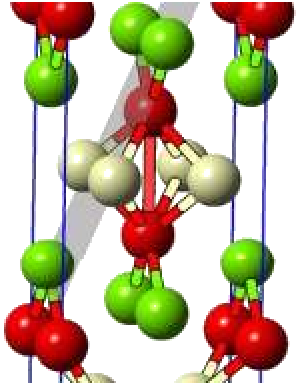
Searching for new heavy fermion compounds

We have a rich family of bulk heavy-fermion compounds

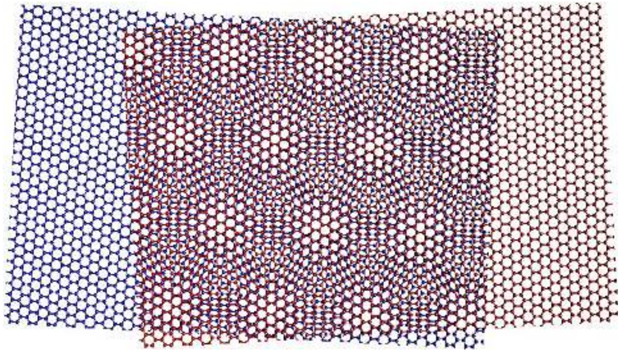
$CeCoIn_5$
Science 375, 6576, 76-81 (2021)

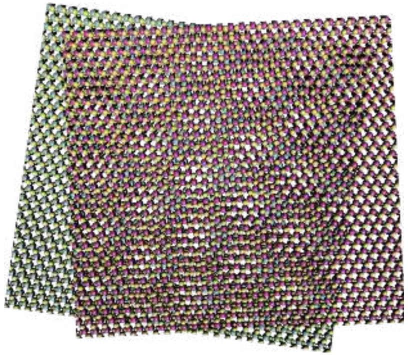


UTe_2
Nature 579, 523–527 (2020)

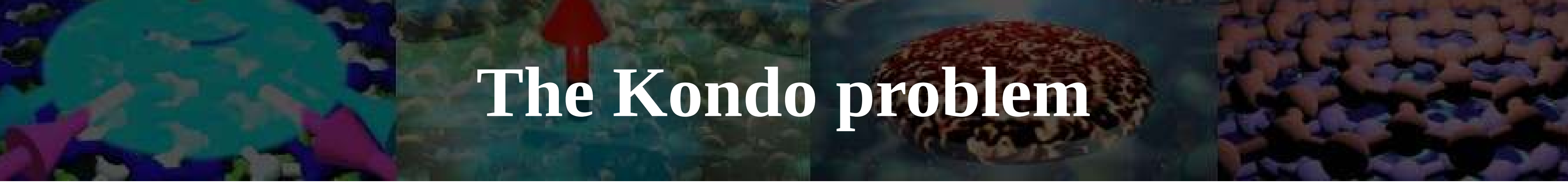


Can we realize heavy-fermion physics with two-dimensional materials?

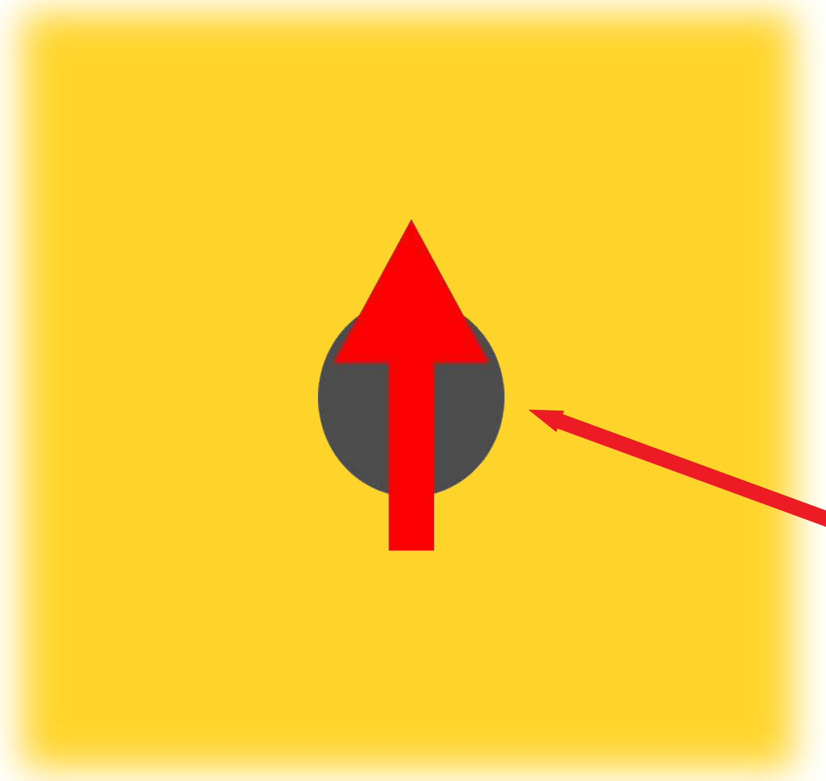




Phys. Rev. Lett. 127, 026401 (2021)
Nature 599, 582–586 (2021)
Phys. Rev. Research 3, 043173 (2021)
Phys. Rev. B 106, L041116 (2022)
Phys. Rev. Lett. 129, 047601 (2022)
Nature 616, 61–65 (2023)



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

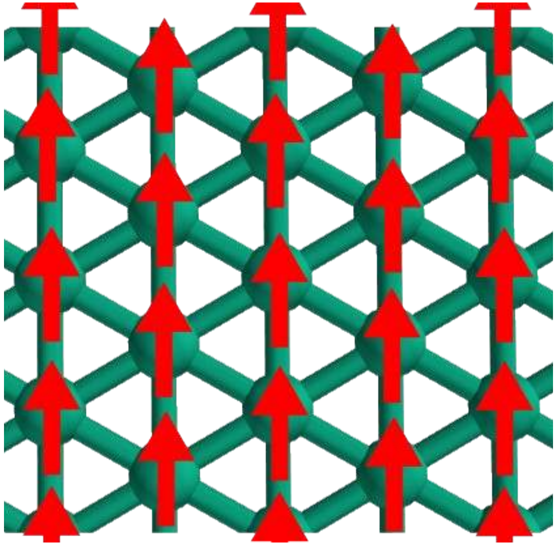
$$H_K = J_K \sum_{\alpha\beta} \left(c^\dagger_{0\beta} \vec{\sigma}_{\beta\alpha} c_{0\alpha} \right) \cdot \vec{S}$$

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

Lattice of Kondo impurities



$$J_K$$

Dispersive electron gas

Both ingredients coupled through Kondo coupling

The Kondo lattice problem

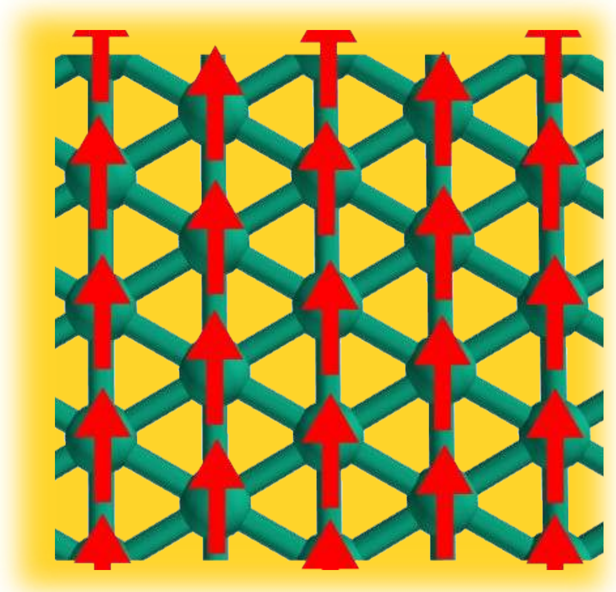
The Kondo lattice problem

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

Kondo sites

Kondo coupling

Conduction electrons



Solving the Kondo lattice problem

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

In the screened regime

Replace the spin sites by auxiliary pseudofermions

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

This makes the effective Hamiltonian an “interacting” fermionic Hamiltonian

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

Solving the Kondo lattice problem

Now we decouple the fermions with a mean-field approximation

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

Obtaining a quadratic Hamiltonian

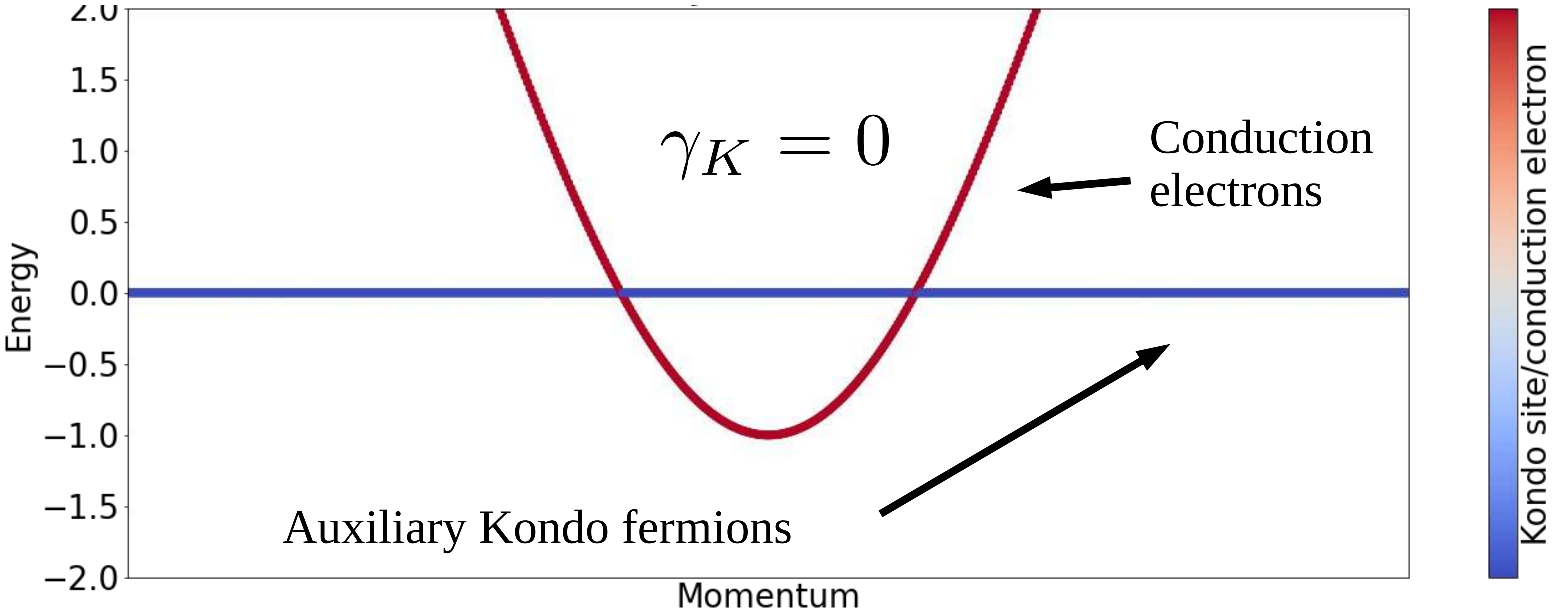
$$H \sim \sum_{\mathbf{k}\alpha} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} - \gamma_K \sum_{\mathbf{k},\alpha} f^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha} + h.c.$$

Conduction band dispersion

Kondo hybridization

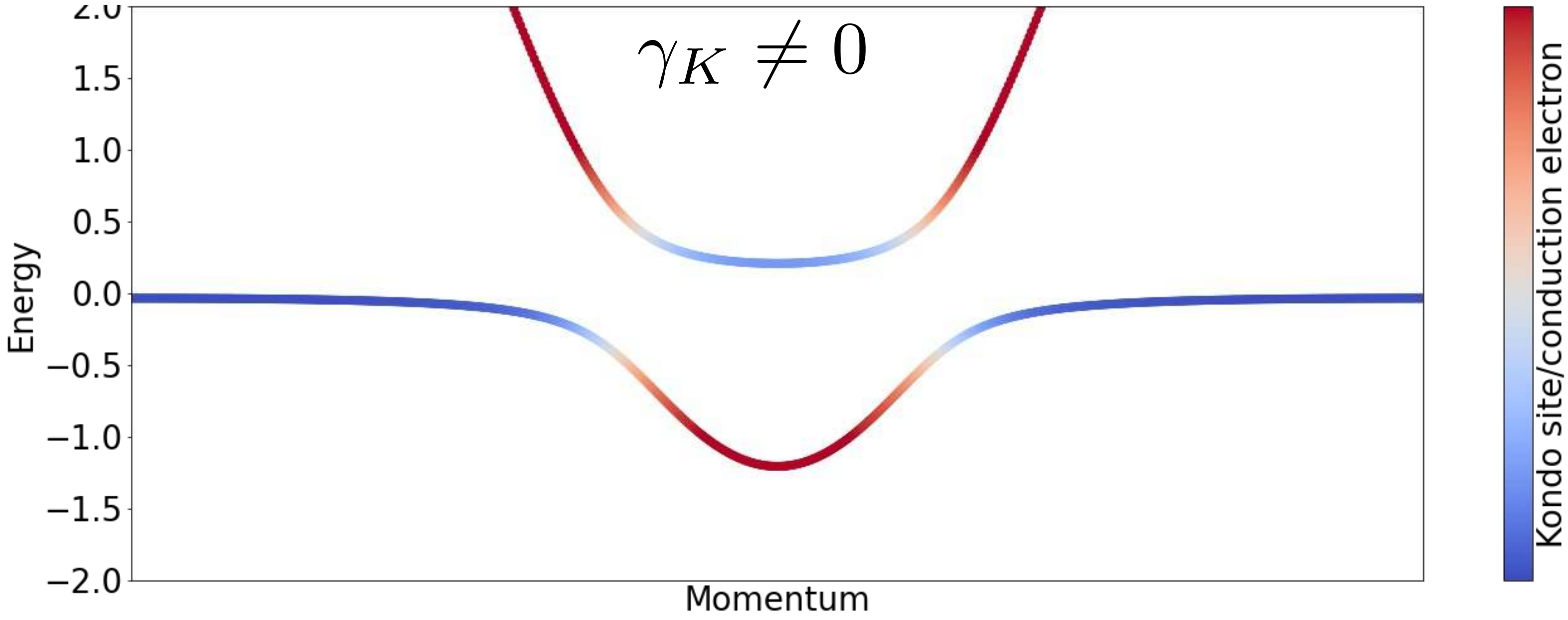
Electronic structure of the Kondo lattice problem

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



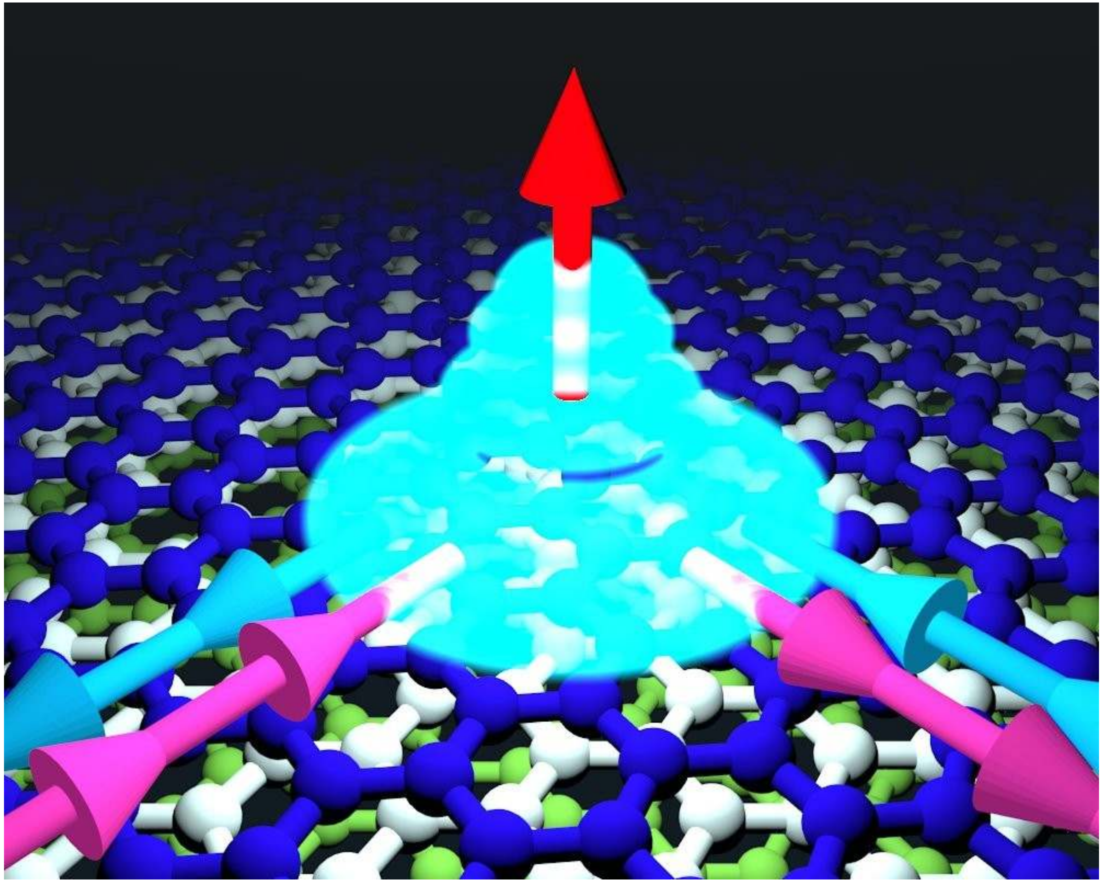
Electronic structure of the Kondo lattice problem

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



The Kondo coupling opens up a gap in the electronic structure

Heavy-fermions in twisted graphene trilayers

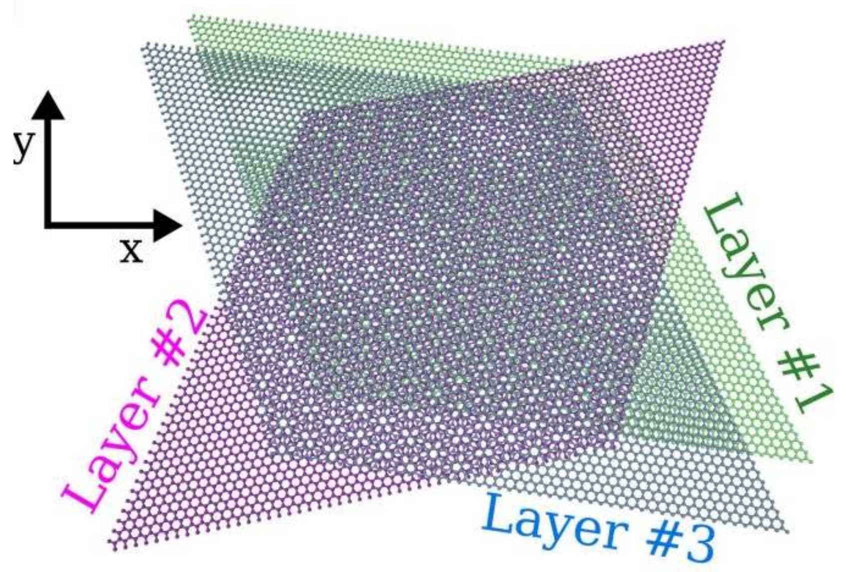


Aline Ramires

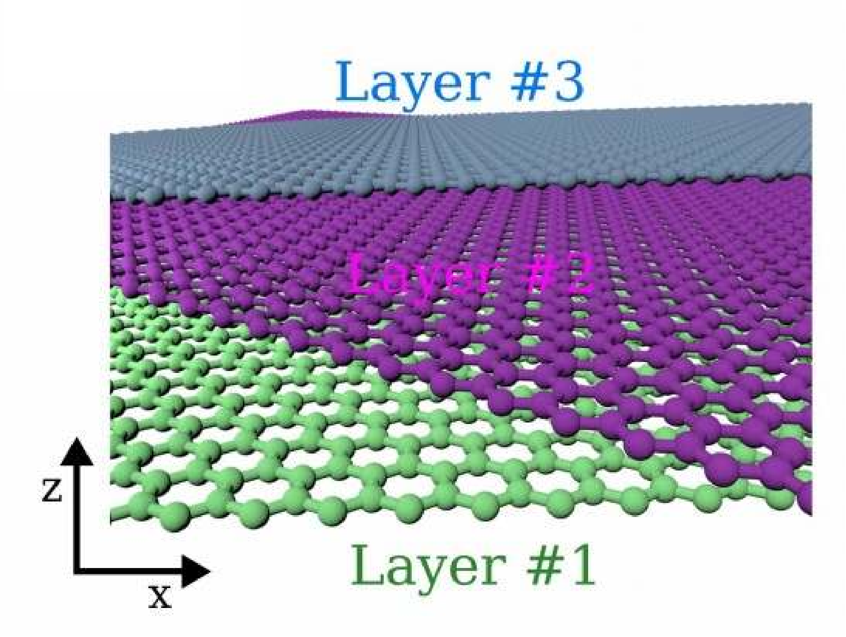
Phys. Rev. Lett. 127, 026401 (2021)

Heavy-fermions in twisted graphene trilayers

Top view

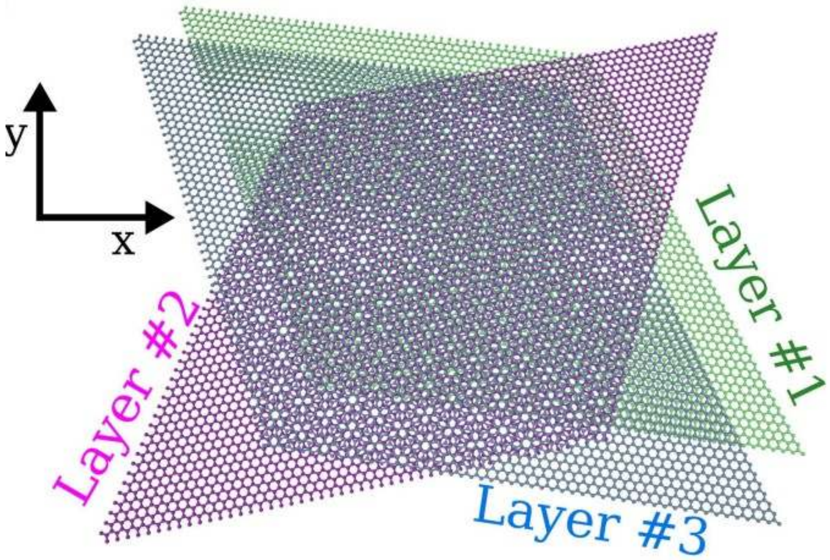


Lateral view

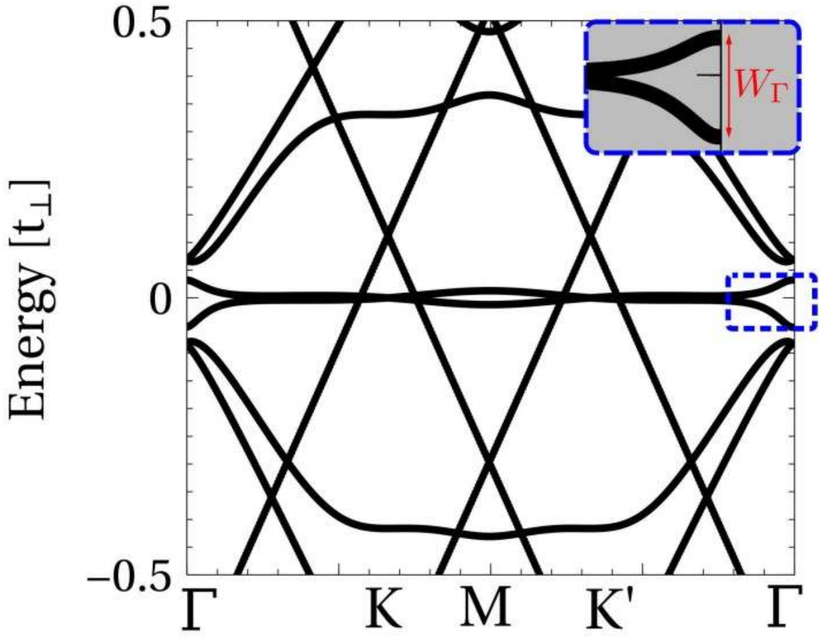


Heavy-fermions in twisted graphene trilayers

Top view

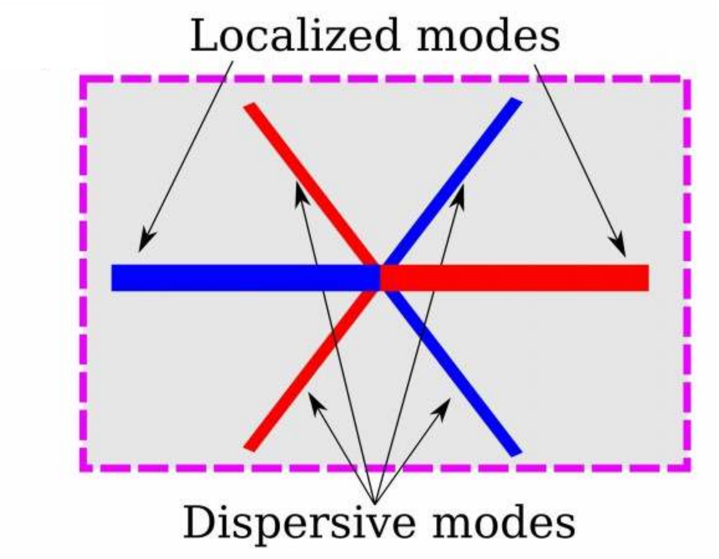


Band structure

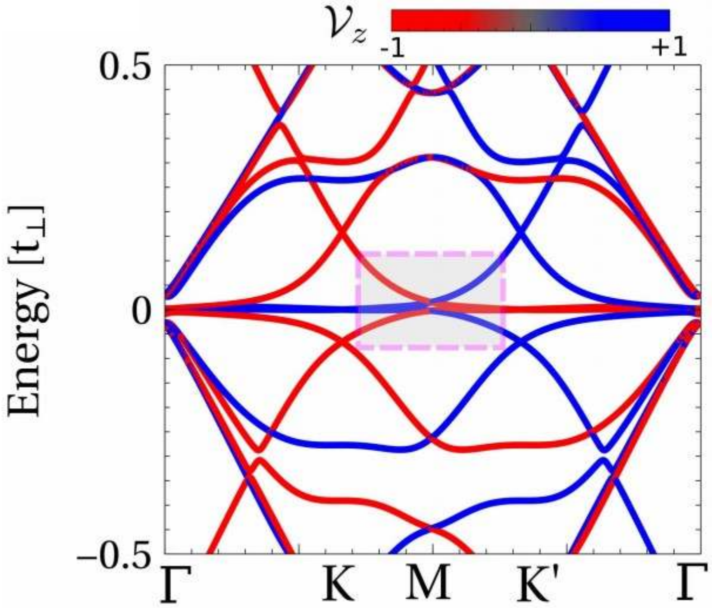


Heavy-fermions in twisted graphene trilayers

Low energy model

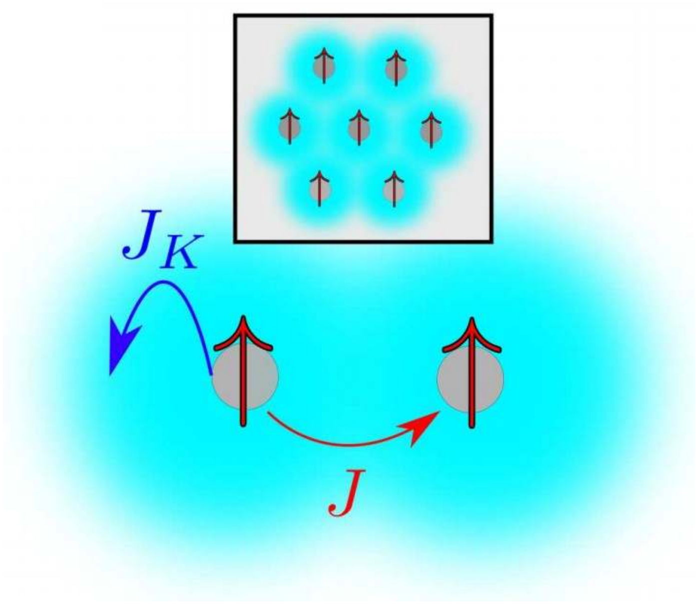


Electronic structure in the presence of an electric bias



Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



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

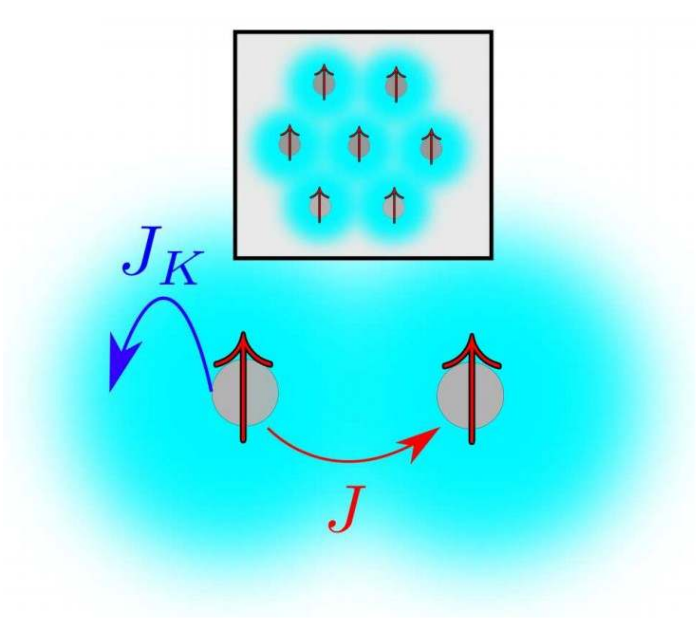
Promotes
magnetic order

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

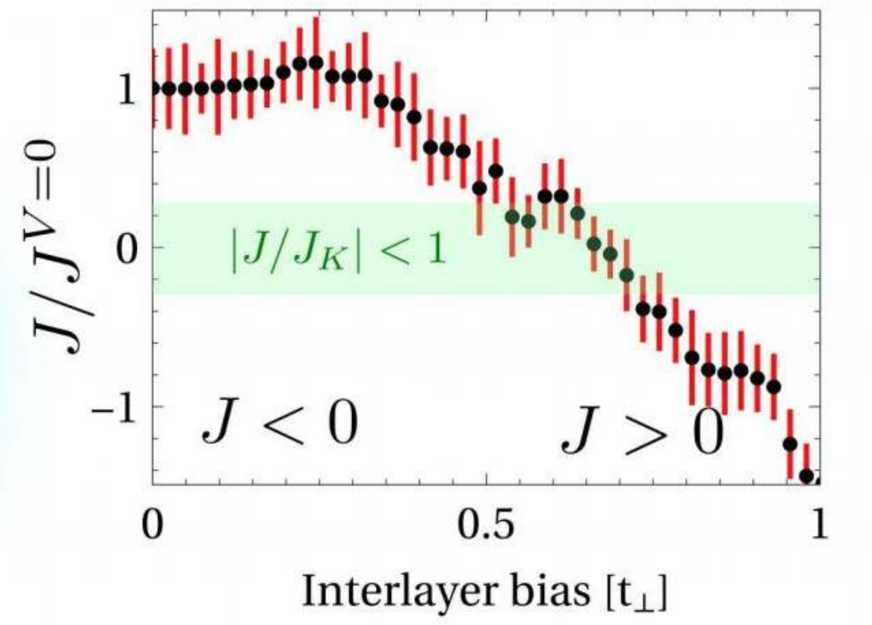
$$|J/J_K| < 1$$

Kondo lattice model in the presence of interactions

Interactions of the Kondo lattice model



Electric control of the Kondo regime

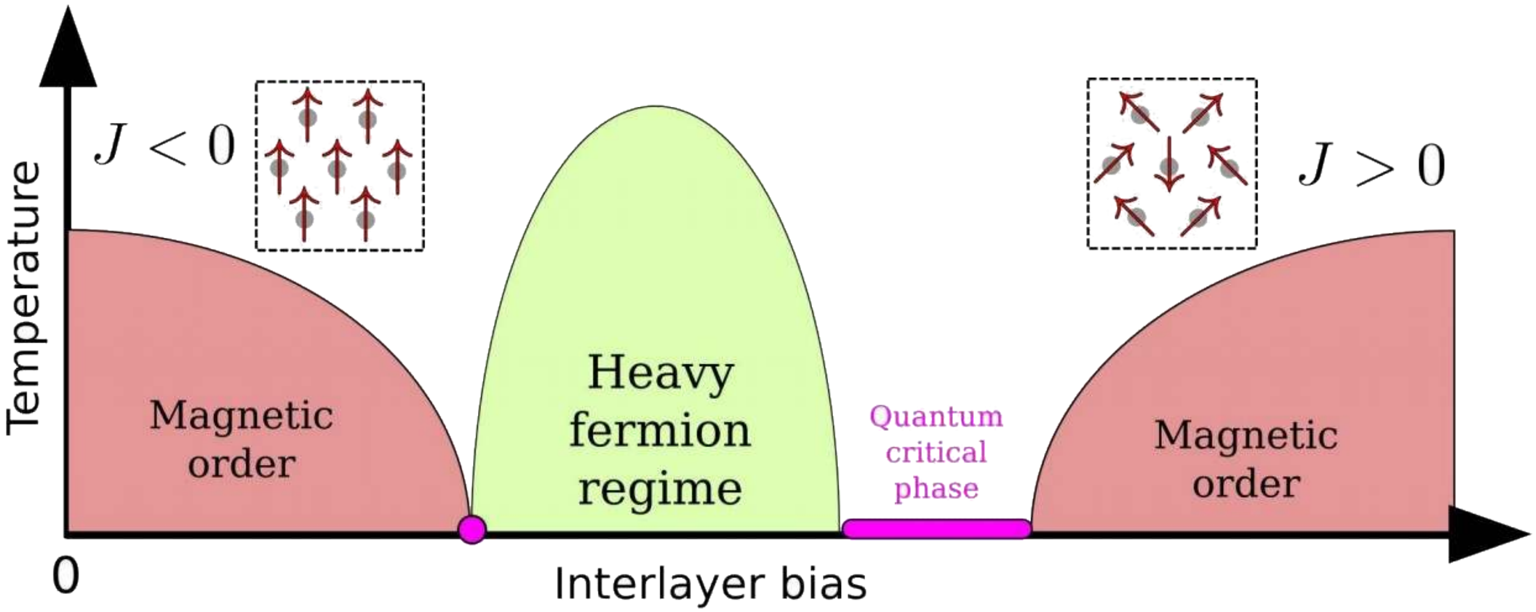


A heavy fermion regime appears when the Kondo coupling dominates over the exchange coupling

$$|J/J_K| < 1$$

Heavy-fermions in twisted graphene trilayers

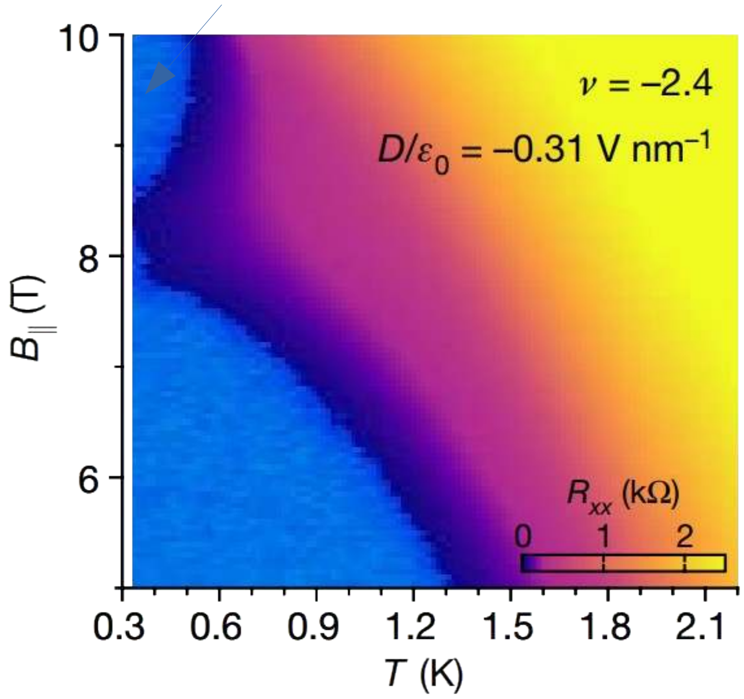
Heavy-fermion (Doniach) phase diagram



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

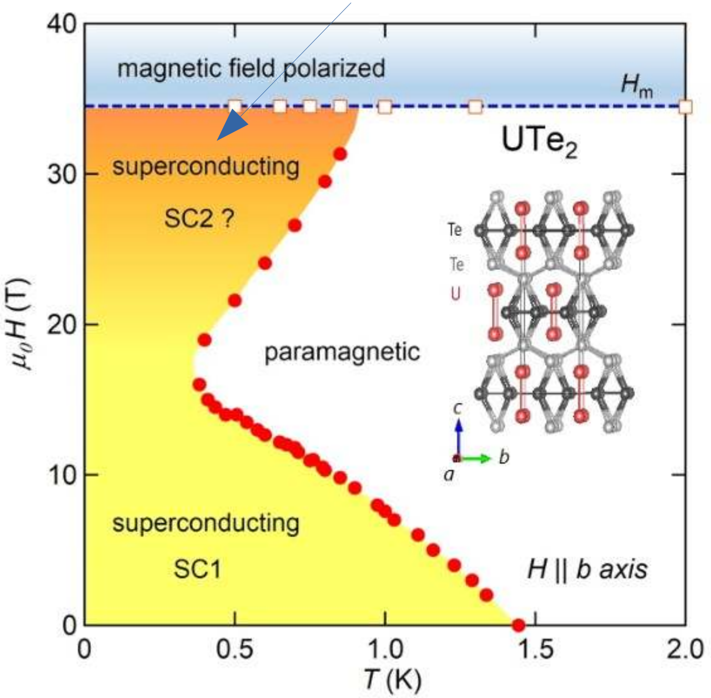
An experimental signature of heavy-fermion physics: spin-triplet superconductivity

Reentrant superconductivity in twisted trilayer graphene



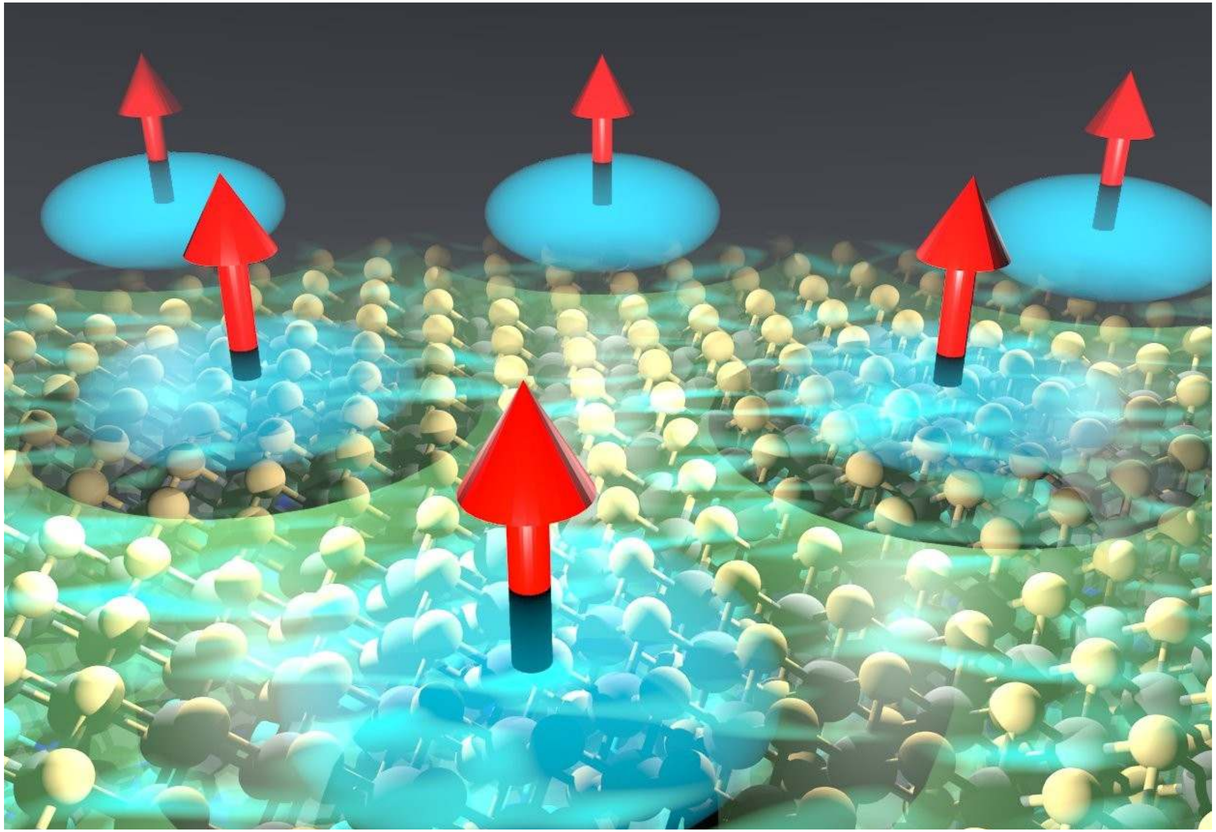
Nature 595, 526–531 (2021)

Reentrant superconductivity in UTe_2



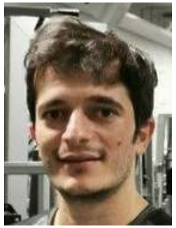
Nat. Phys. 15, 1250 (2019)
Science 365, 684 (2019)

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

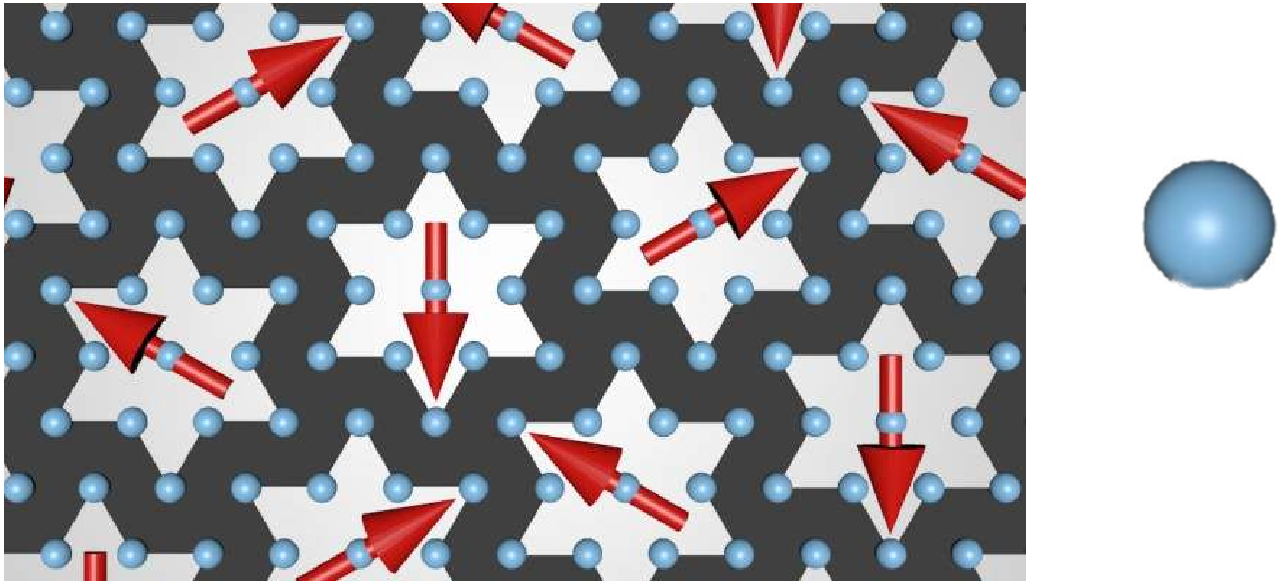
$1T\text{-}TaS_2$

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



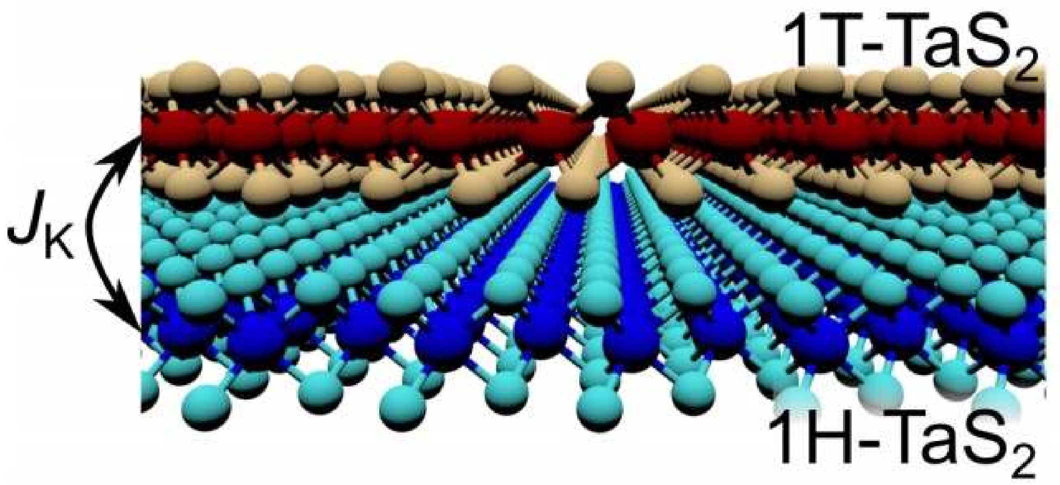
Strong interactions give rise to local moment formation

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

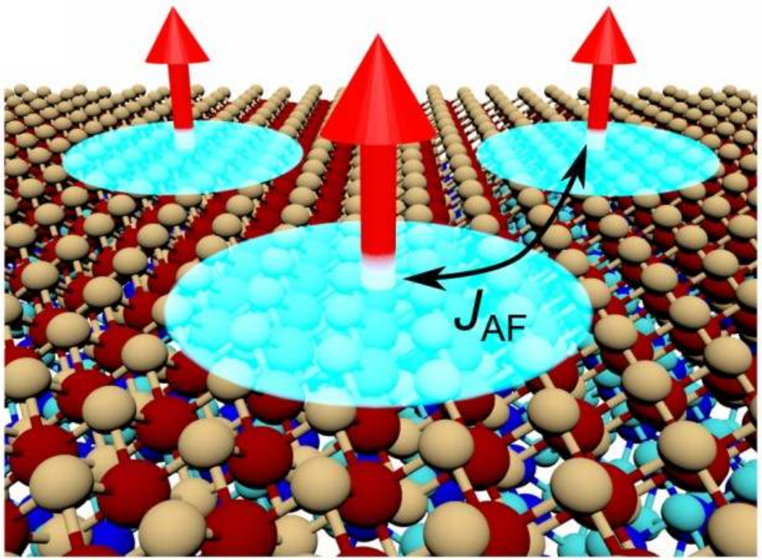
PNAS 114.27 (2017)
Phys. Rev. X 7, 041054 (2017)
Phys. Rev. B 96, 195131 (2017)

Heavy-fermions in dichalcogenide bilayers

Interlayer coupling creates the Kondo coupling



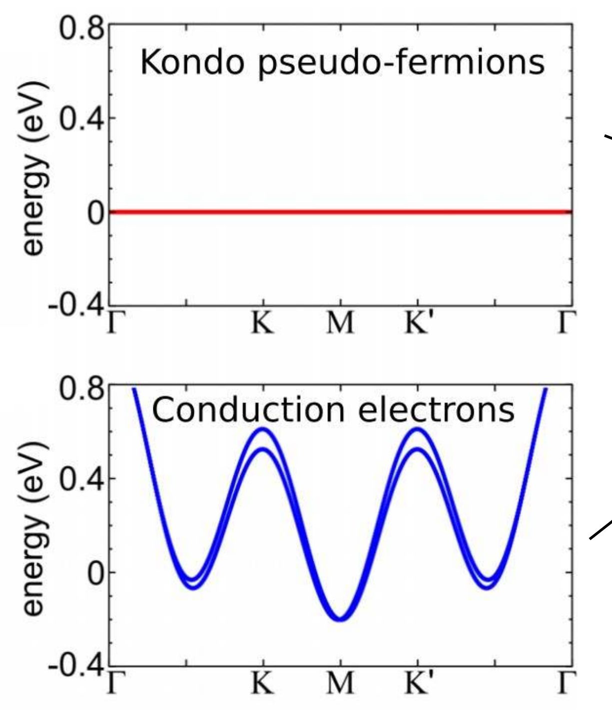
Intralayer exchange between local moments



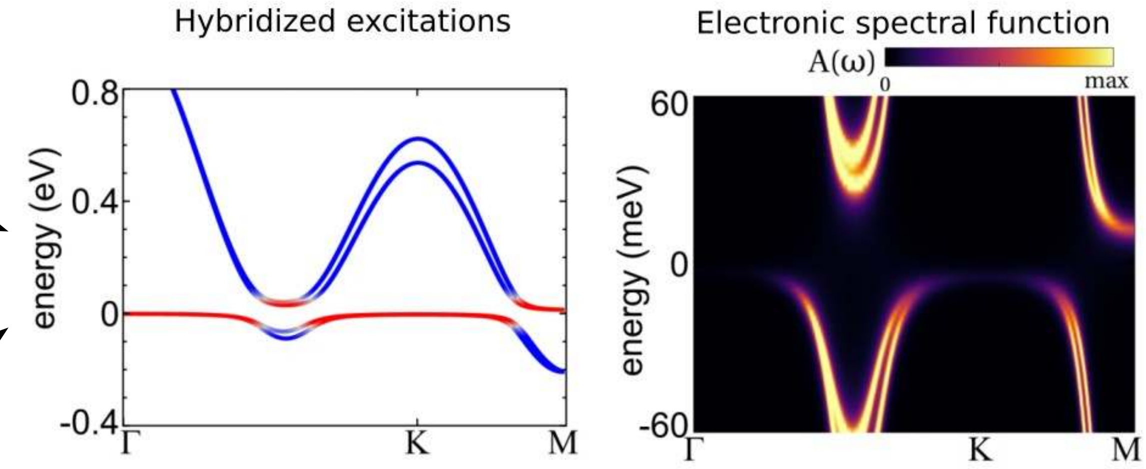
The bilayer realizes all the ingredients for heavy-fermion physics

Heavy-fermion hybridization gap

Kondo physics introduces resonant pseudo-fermions at the chemical potential



Leading to the opening of a heavy-fermion gap

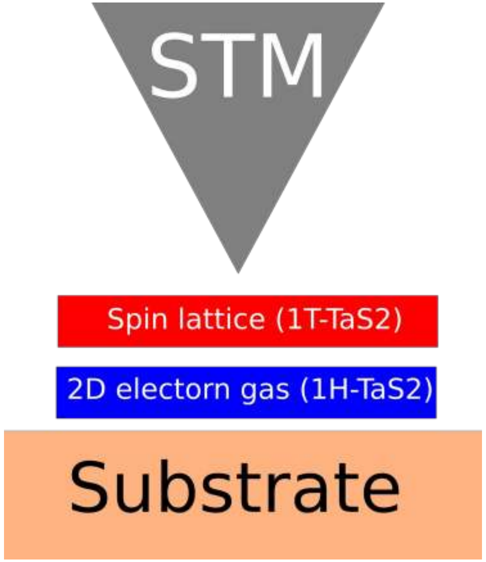


Experimental signatures of heavy-fermion physics

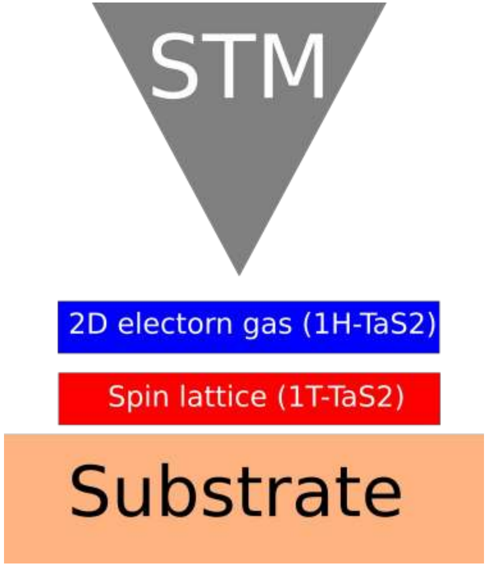
- Kondo physics in the magnetic lattice
- Gap opening in the metallic layer

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

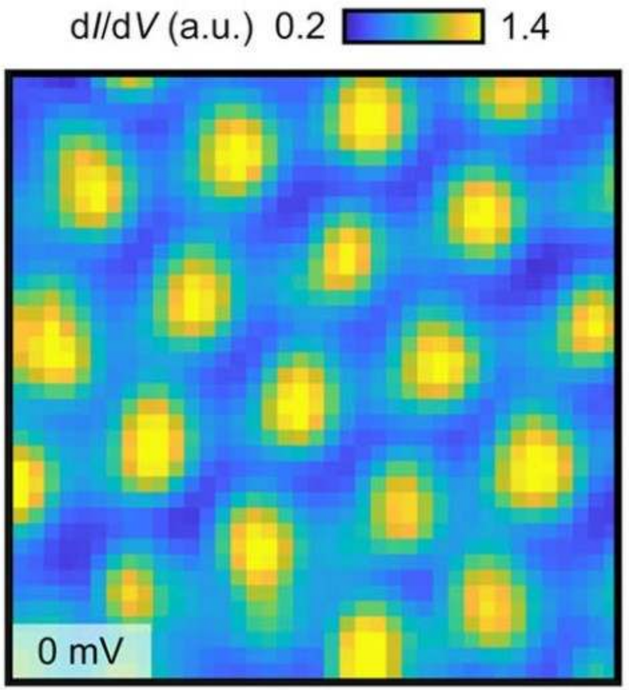
Probing the Kondo peak



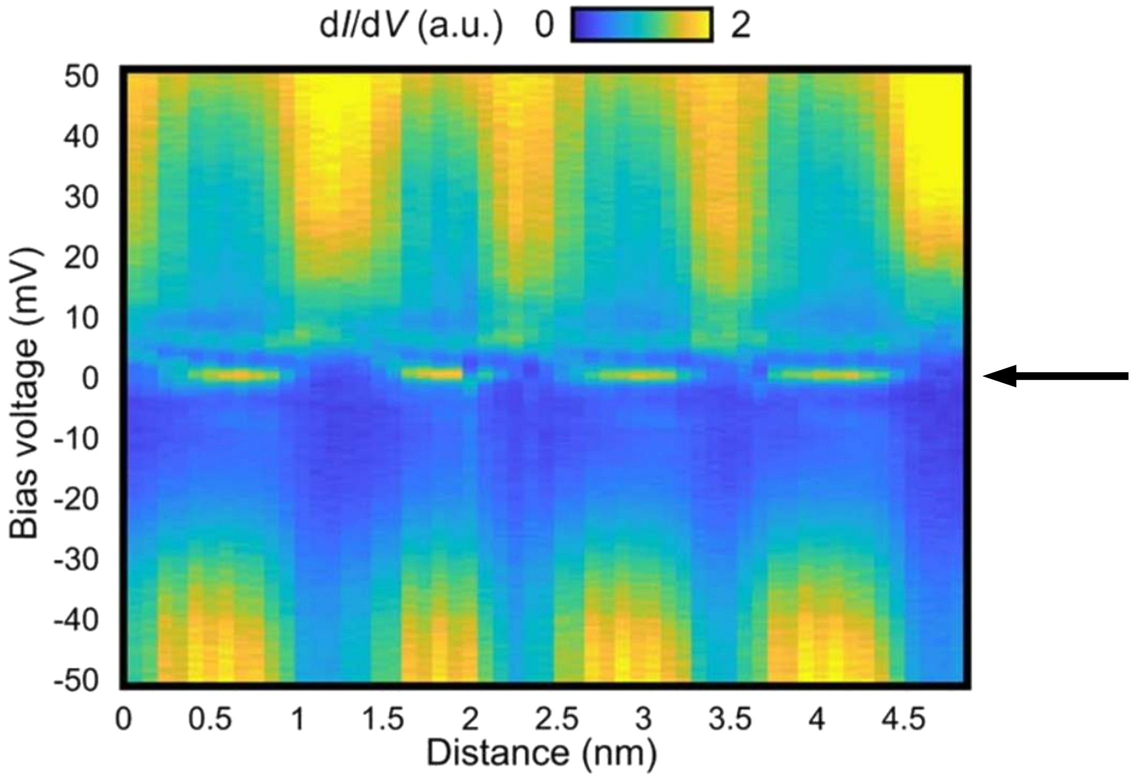
Probing the heavy-fermion gap



Grid spectroscopy of 1T-1H

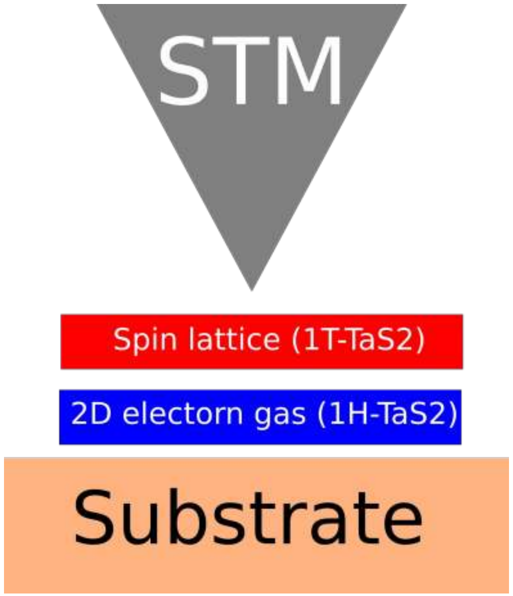


dI/dV (V=0)

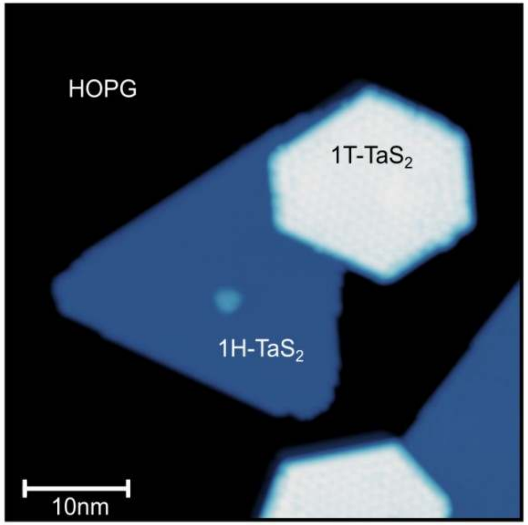


Zero bias (Kondo) peak appearing with the CDW periodicity

Kondo physics in the magnetic lattice

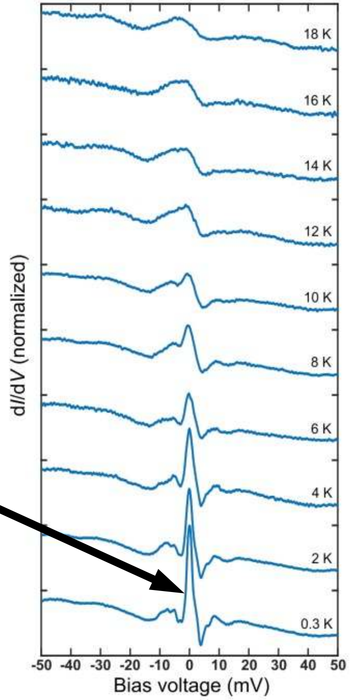


Sample



Differential conductance

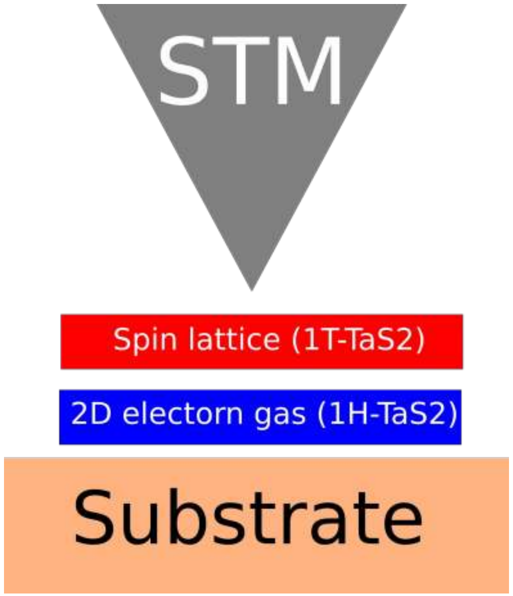
Kondo peak

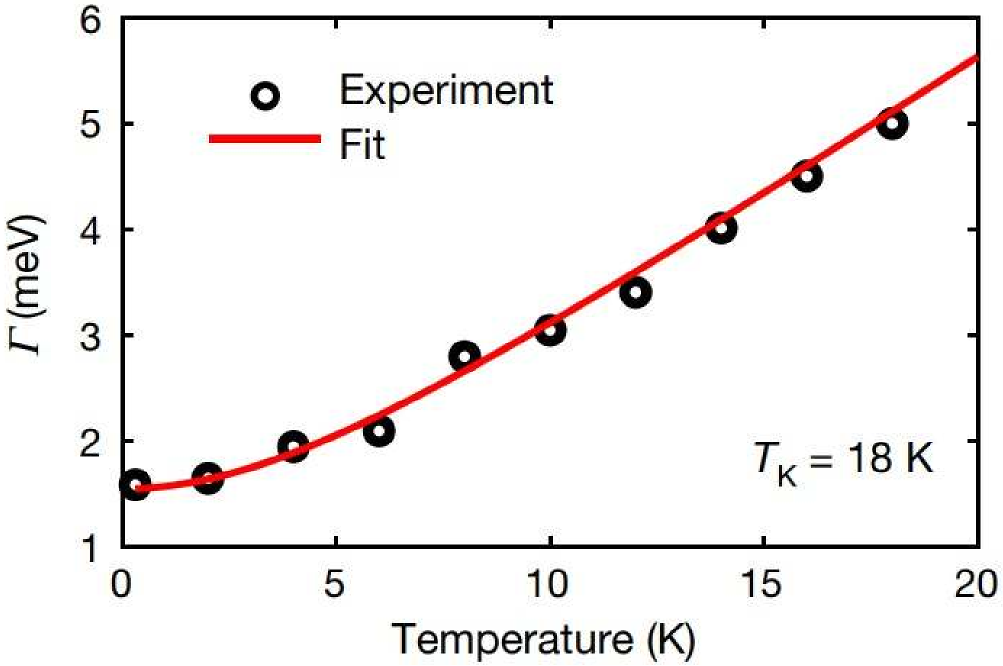


The system shows a Kondo peak when the local moments are probed

Temperature and field dependence consistent with Kondo

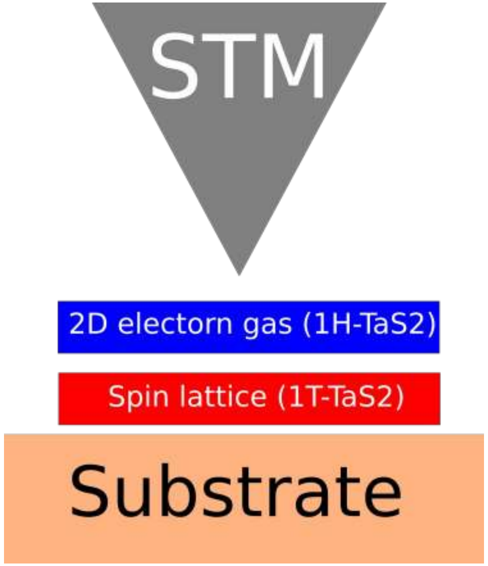
Kondo physics in the magnetic lattice



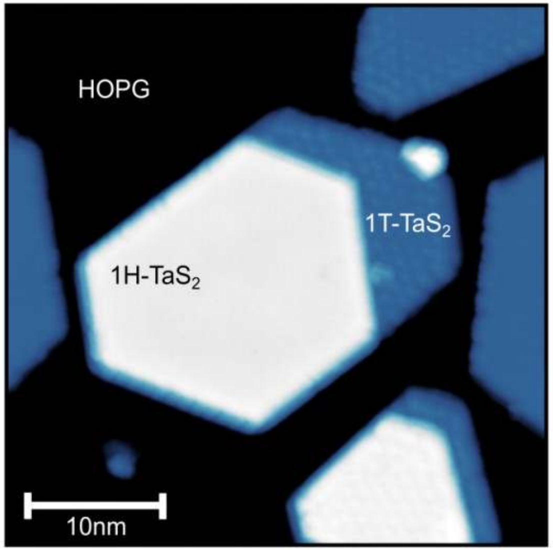


The Kondo peak follows the expected temperature dependence

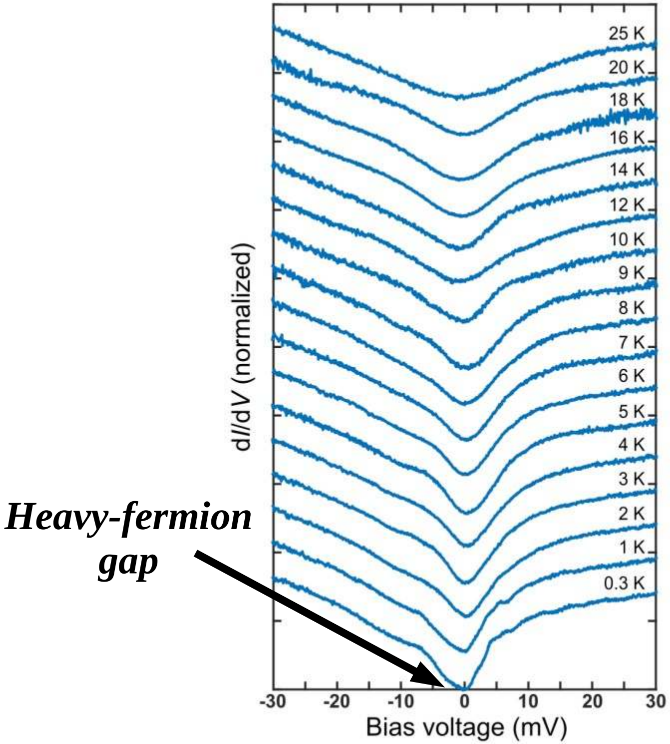
Heavy-fermion gap in the 2D electron gas



Sample



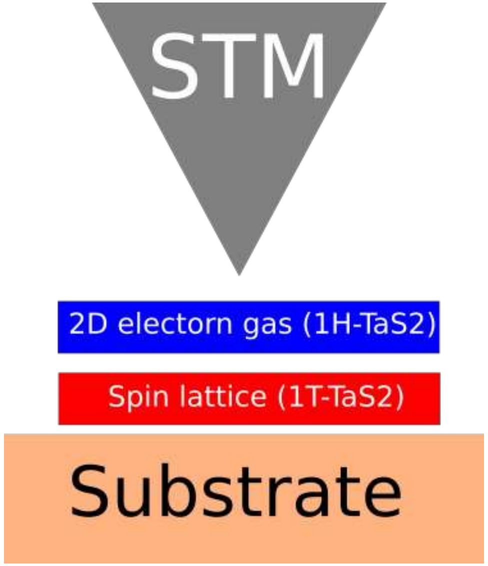
Differential conductance

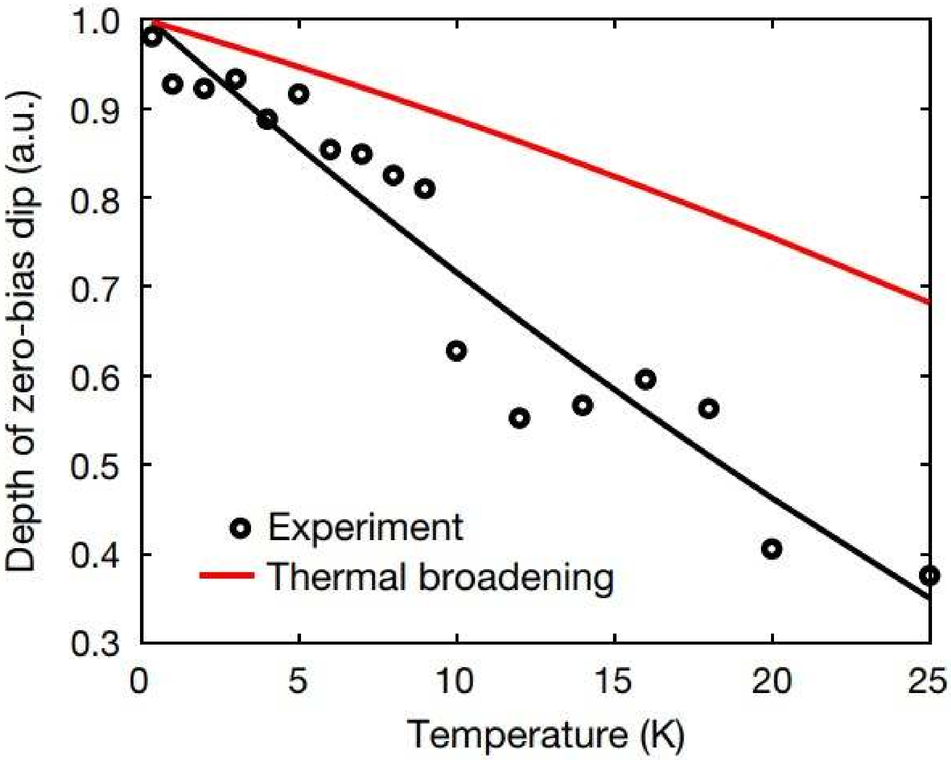


A heavy-fermion gap appears on the metal side

Temperature and field dependence consistent with a heavy-fermion gap

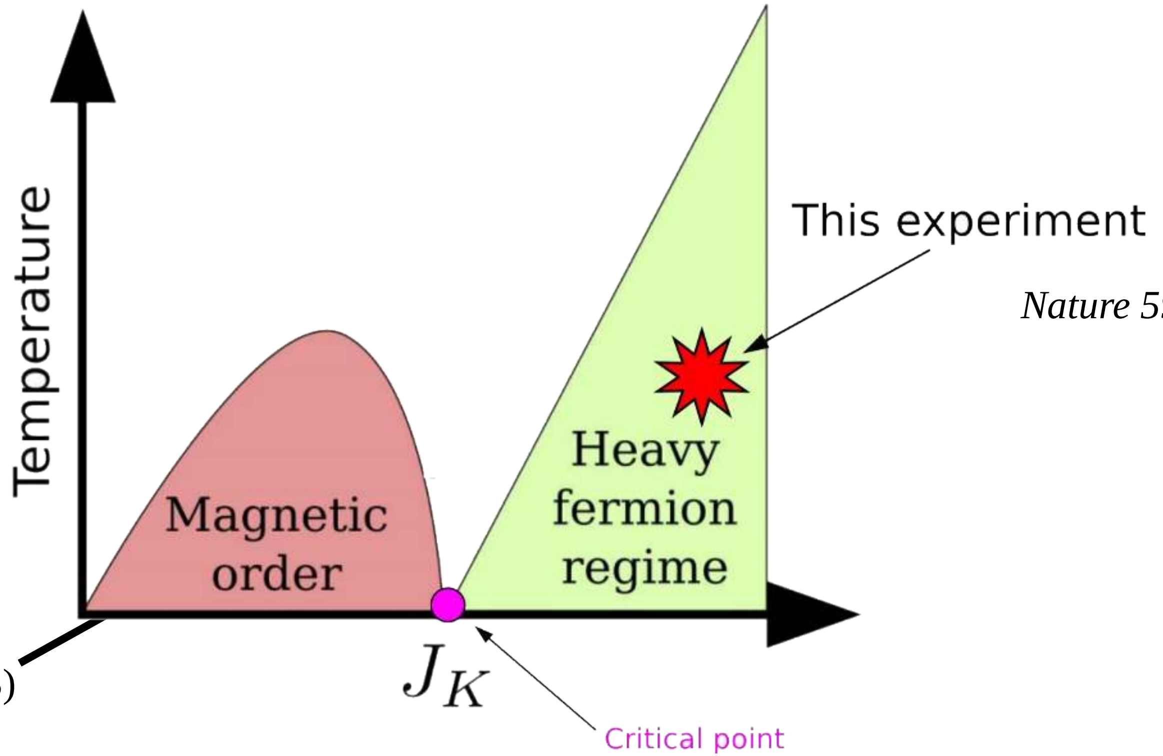
Heavy-fermion gap in the 2D electron gas





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

Next steps in van der Waals heavy-fermions



Nature 599, 582–586 (2021)

Nature Comm. 14, 7005 (2023)

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

Doped Mott and charge order arXiv:2401.08296

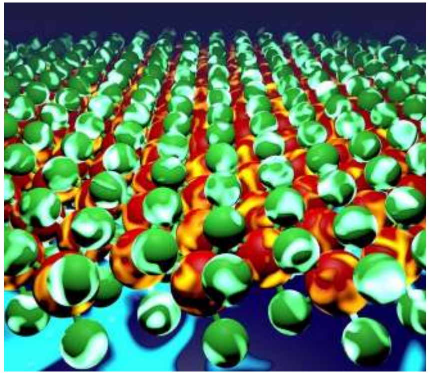
Controlling the heavy-fermion state

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

(pressure, chemical doping, etc)

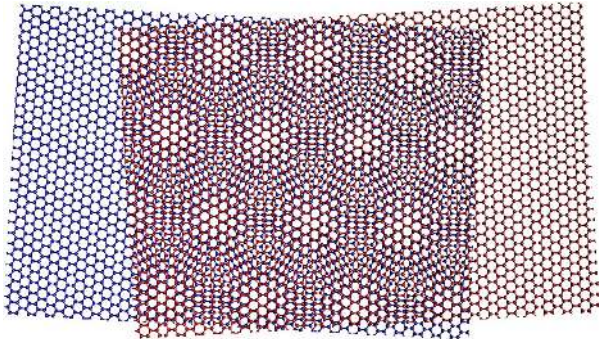
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



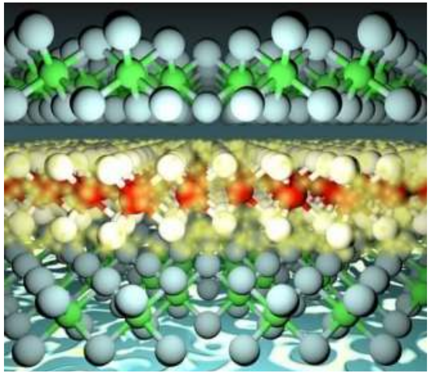
Science 306, 5696, 666-669 (2004)

Twist engineering



Nature Reviews Materials 6, 201–206 (2021)

Materials engineering

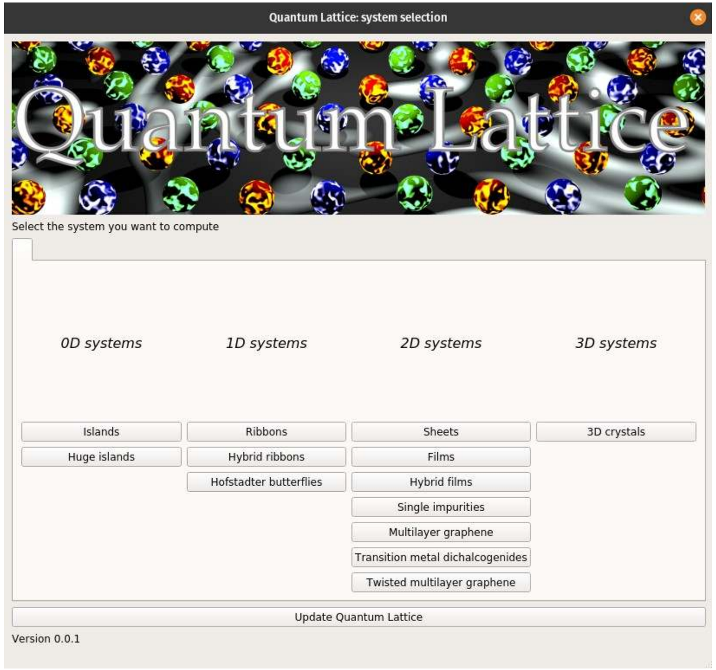


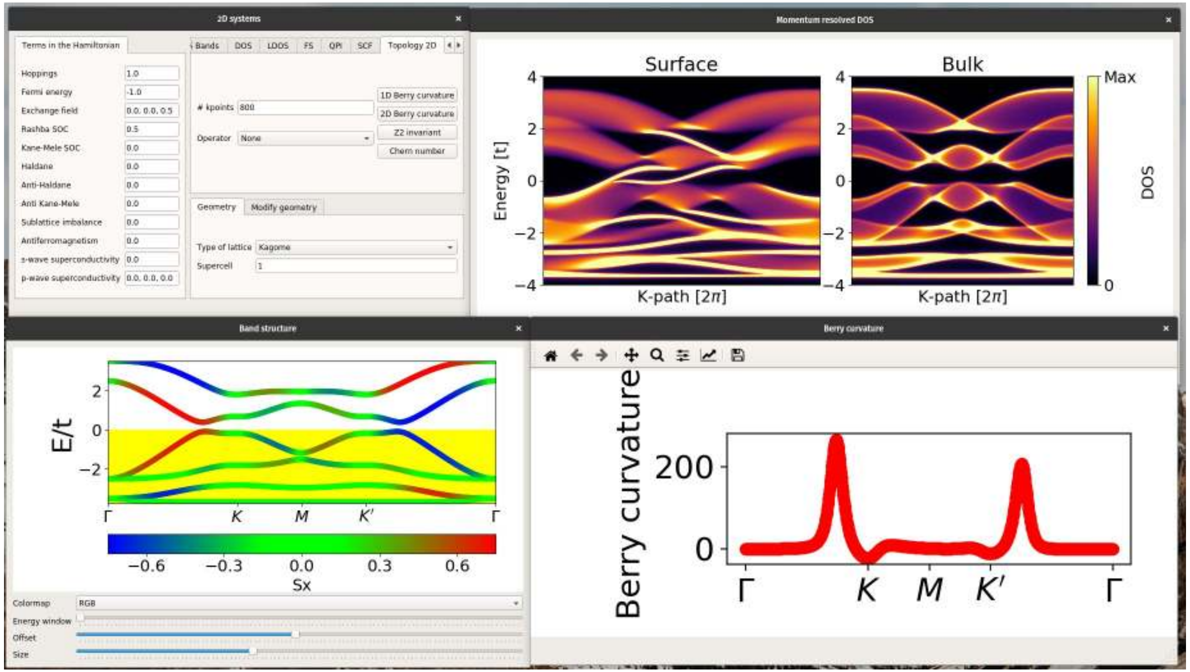
Nature 499, 419–425 (2013)

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

Computing electronic properties

Quantum Lattice: A user interface to compute electronic properties

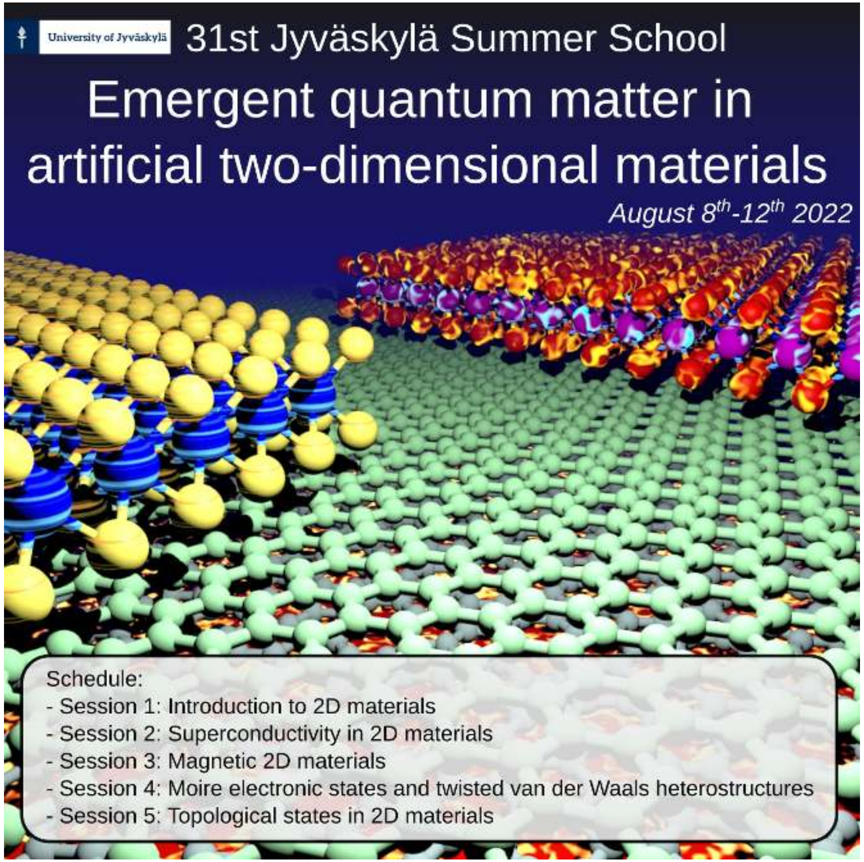




Quantum Lattice: open source interactive interface for tight binding modeling

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

Quantum matter in van der Waals materials school



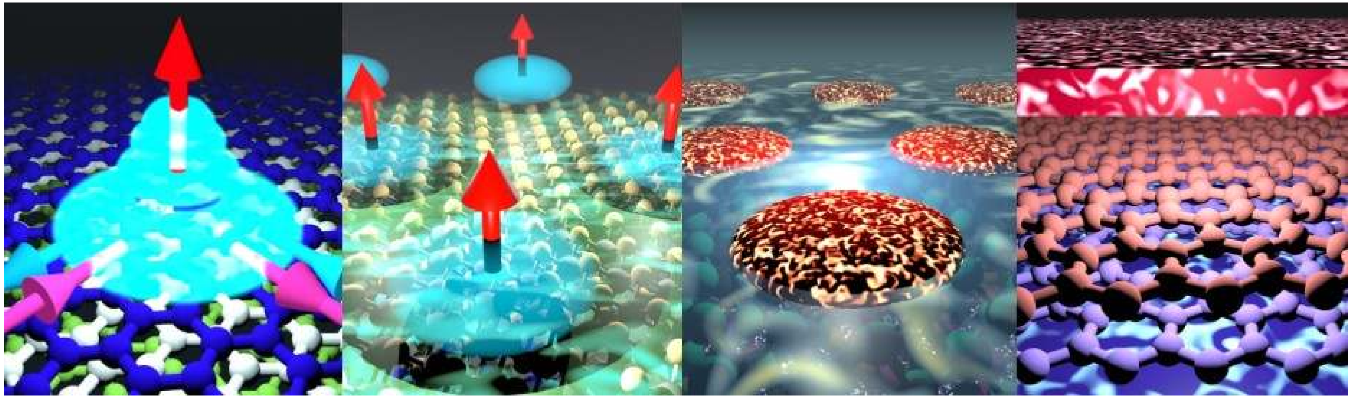
Recordings available at

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

Proximity effects in van der Waals materials provide a powerful strategy to engineer topological superconductivity and heavy fermion Kondo matter



Nature 599, 582–586 (2021)
Phys. Rev. Lett. 127, 026401 (2021)
Nano Lett. 2022, 22, 1, 328–333 (2022)
arXiv:2307.04605 (2023)

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SUOMEN AKATEMIA