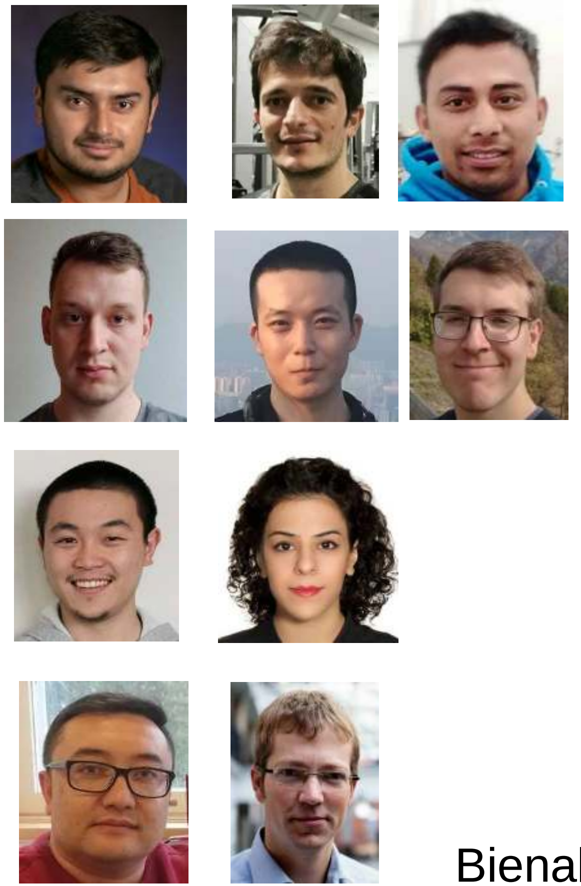
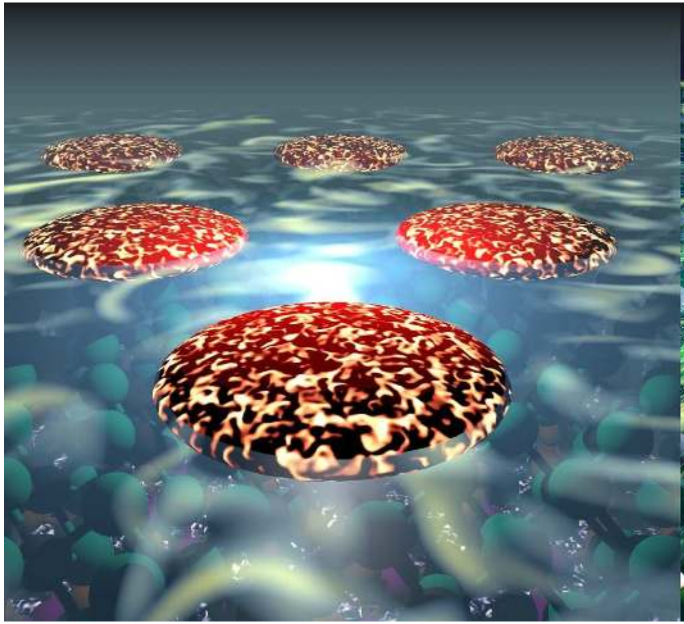
Topological and nodal superconductivity in artificial van der Waals materials

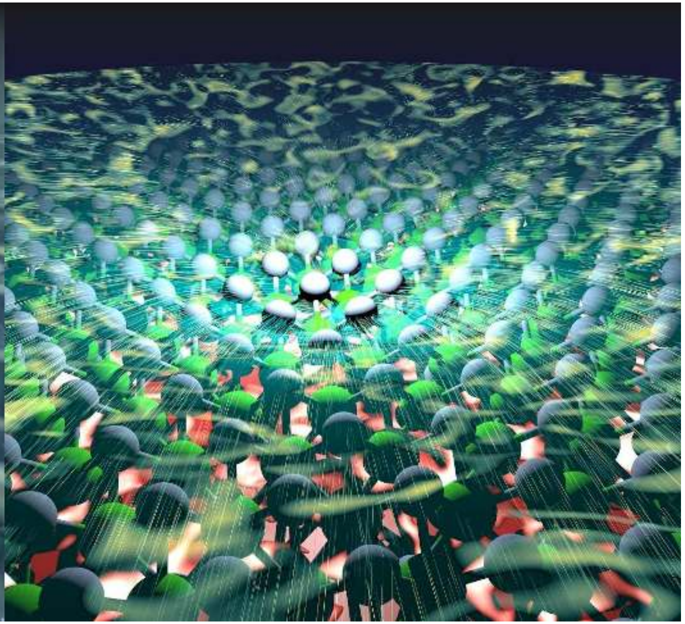


Jose Lado

Department of Applied Physics, Aalto University, Finland



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



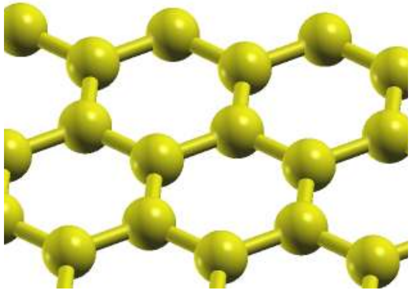
arXiv:2112.07316 (2021)

Bienal RSEF, New trends in superconductivity, July 11th 2022, Murcia, Spain

The two-dimensional materials world

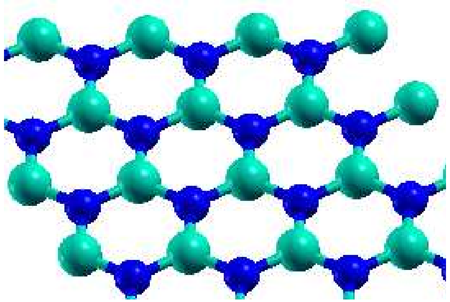
Semimetal

Graphene



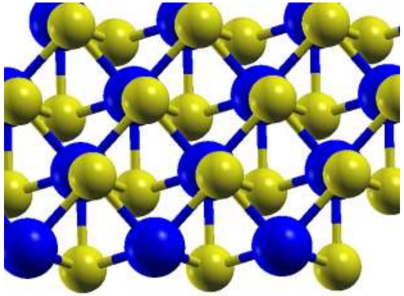
Insulator

BN



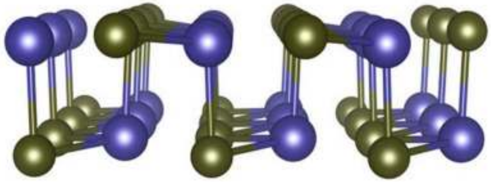
Superconductor

$NbSe_2$



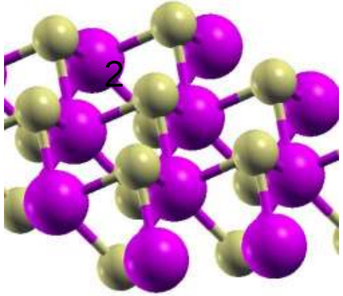
Ferroelectric

SnTe



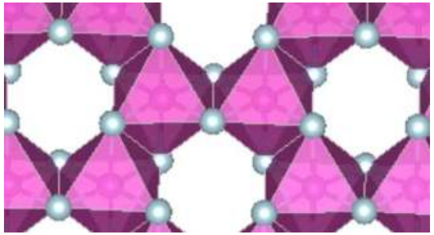
Semiconductor

WSe_2



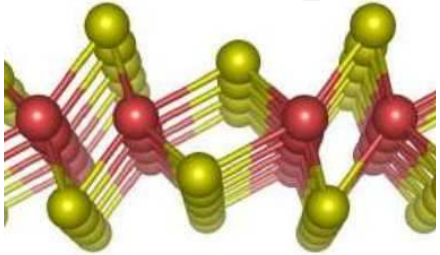
Ferromagnet

CrI_3



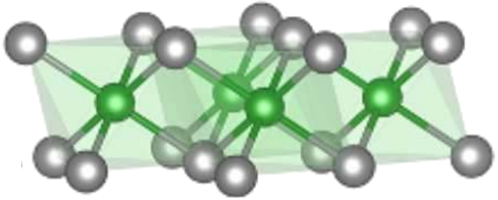
Quantum spin Hall insulator

WTe_2



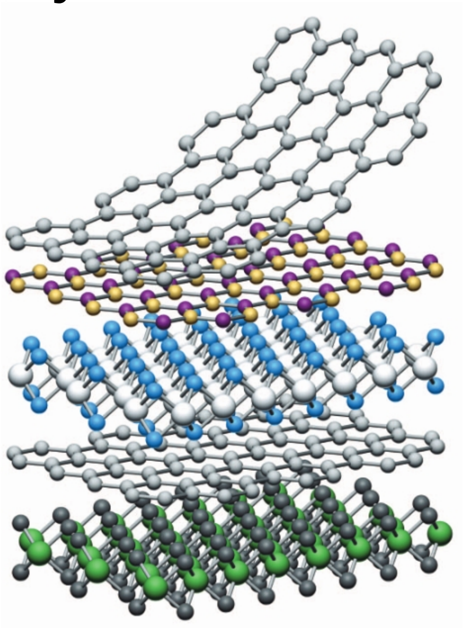
Multiferroic

NiI_2



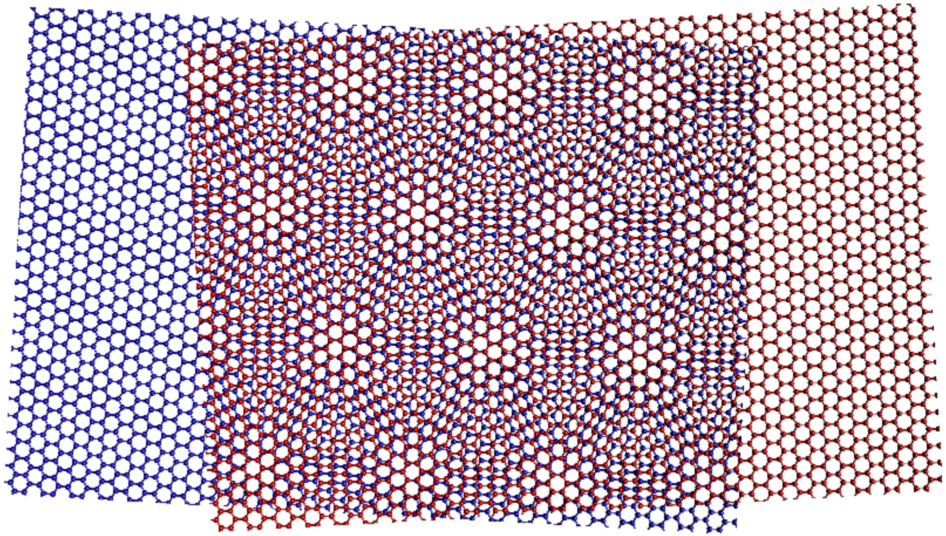
The flexibility of two-dimensional materials

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

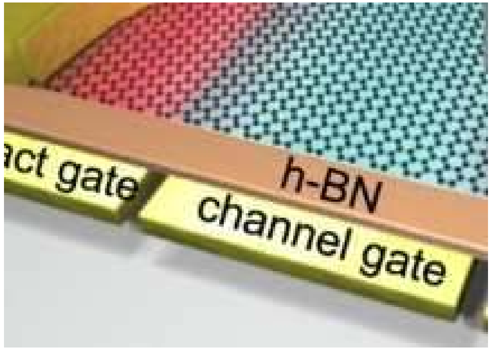
Controlling 2D superconductors

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

(pressure, chemical doping, etc)

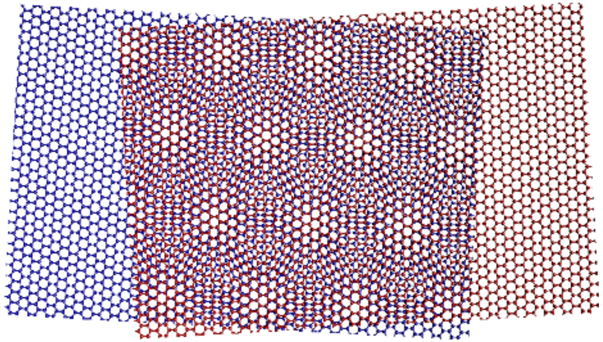
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



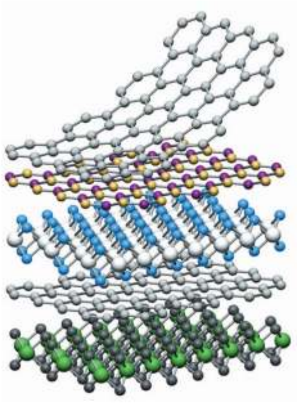
Science 306, 5696, 666-669 (2004)

Twist engineering



Nature Reviews Materials 6, 201–206 (2021)

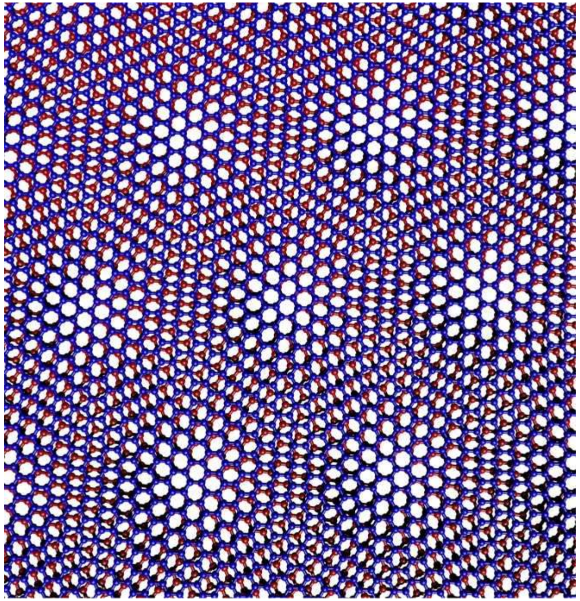
Materials engineering



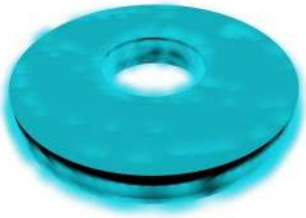
Nature 499, 419–425 (2013)

One material, a zoo of electronic phases

Twisted bilayer graphene



Superconductivity

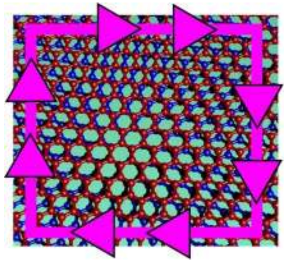


Nature 556, 43–50 (2018)

Topological networks

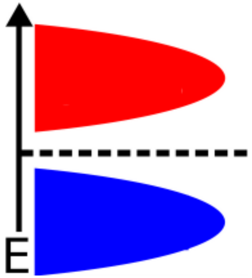
Nano Lett. 18, 11, 6725-6730 (2018)

Chern insulators



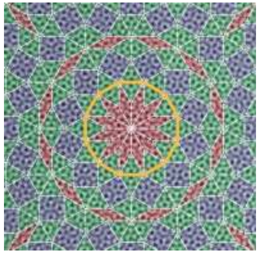
Science 365, 605-608 (2019)

Correlated insulators



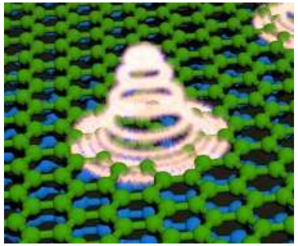
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

Fractional Chern insulators

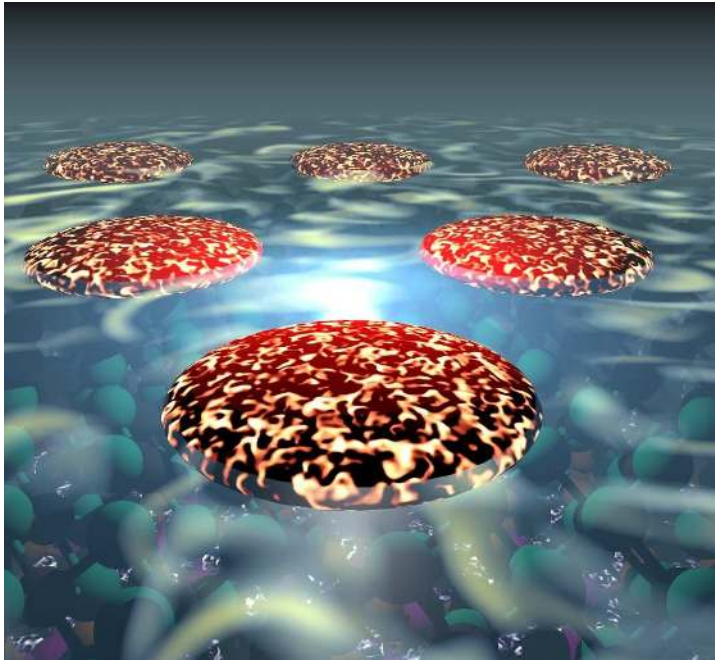


Nature 600, 439–443 (2021)

Twisted van der Waals multilayers provide a powerful platform for emergent phenomena

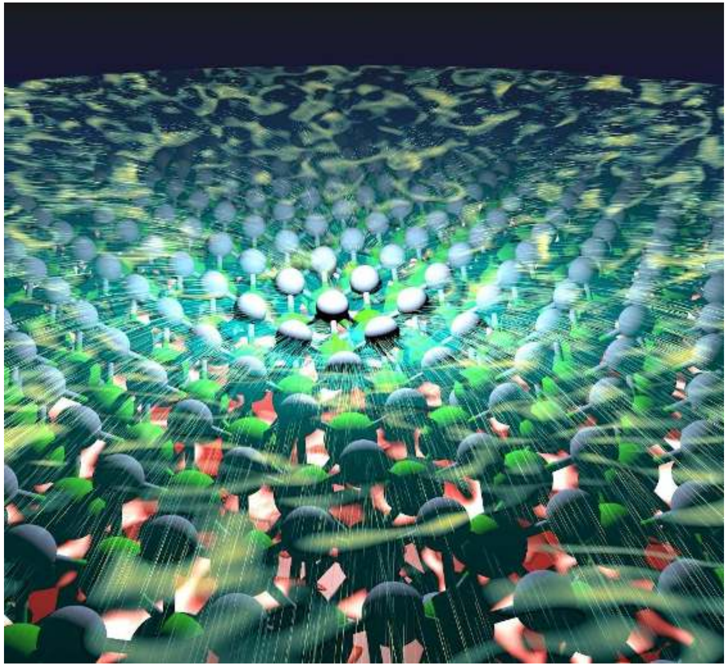
Today’s plan

Artificial topological moire superconductivity in $CrBr_3/NbSe_2$



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

Nodal superconductivity in ultraclean TaS_2 monolayer

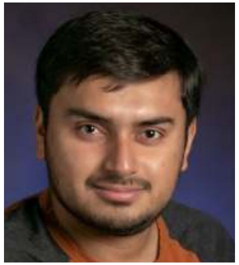


arXiv:2112.07316 (2021)

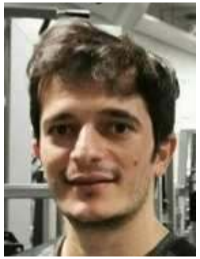
Behind the scenes

Experiment

S. Ganguli



M. Amini



M. Aapro

L. Yan

V. Vaňo

S. Kezilebieke

Md. Huda

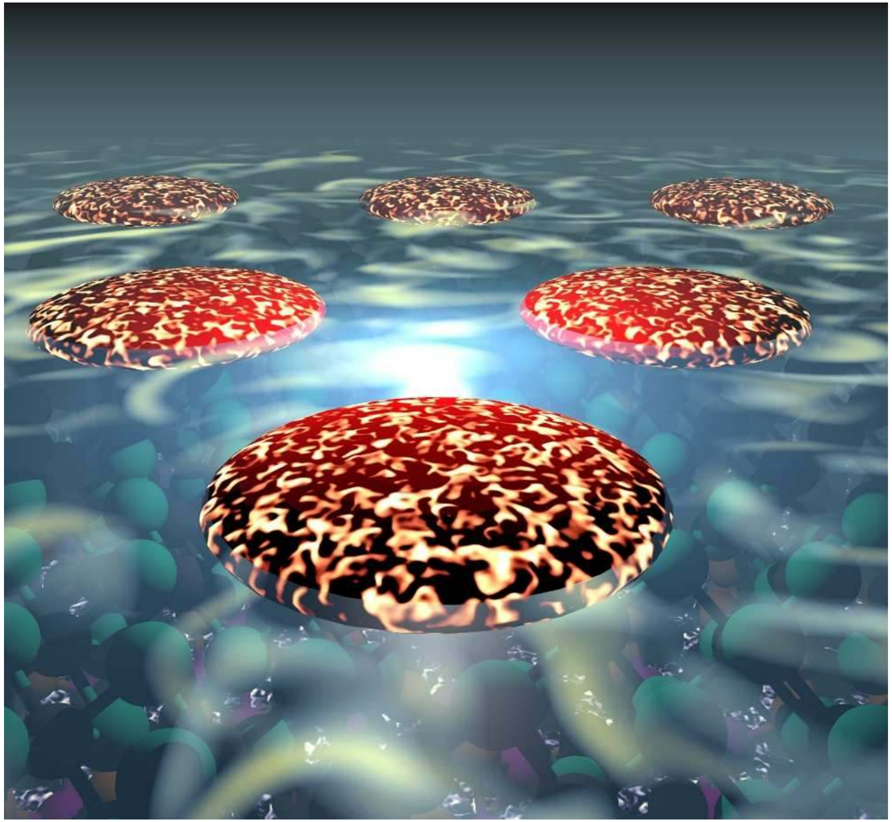
P. Liljeroth

Theory

G. Chen

M. Khosravian

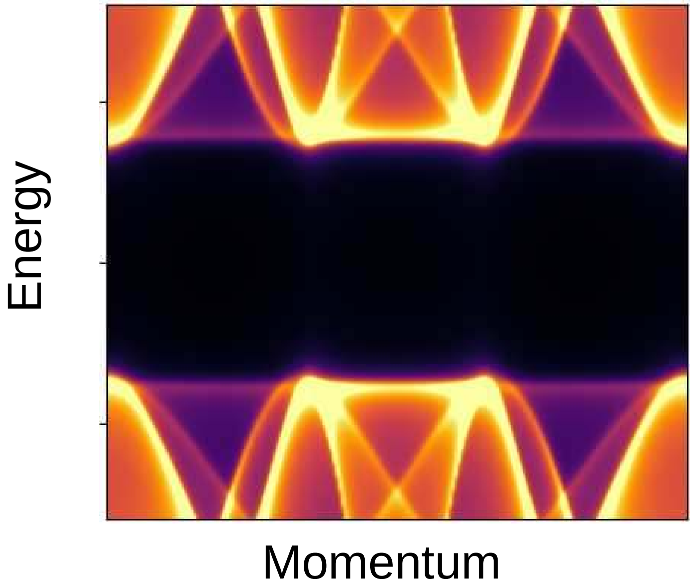
Artificial topological moire superconductivity in $NbSe_2/CrBr_3$



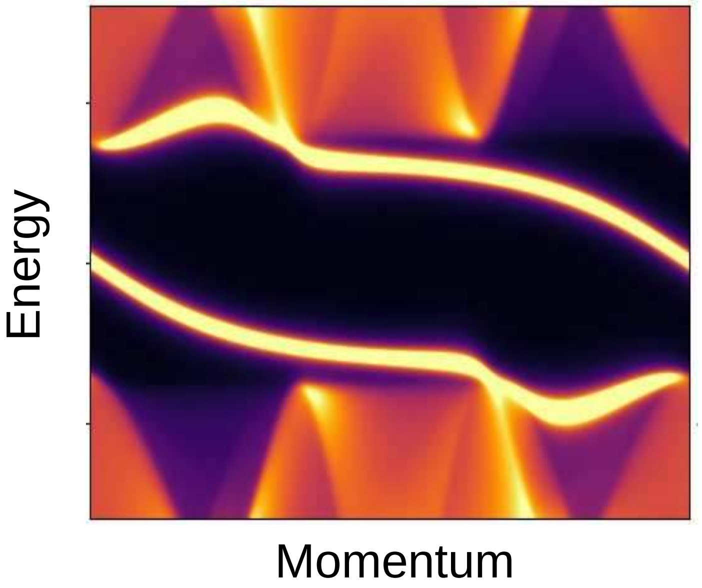
Nano Lett. 2022, 22, 1, 328–333 (2022)

Topological superconductors

Full gap in the bulk



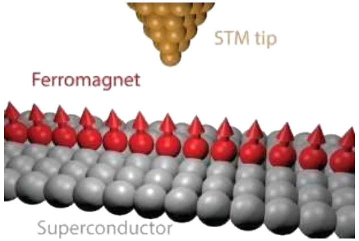
Gapless (Majorana) mode at the edge



Topological superconductors are rare in nature, and thus have to be artificially engineered

Platforms for topological superconductivity

Ferromagnetic atomic chains

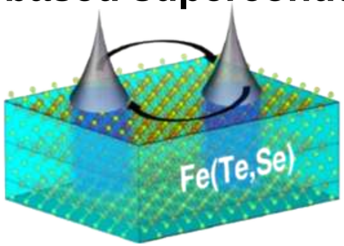


Science 346.6209 (2014): 602-607

Semiconductors

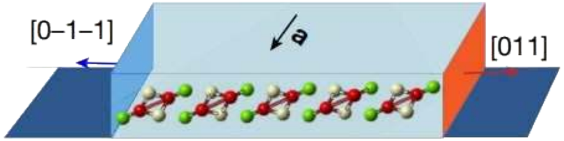
Science 354.6319 (2016): 1557-1562

Fe-based superconductors



Science 362.6412 (2018): 333-335

Heavy-fermion compounds

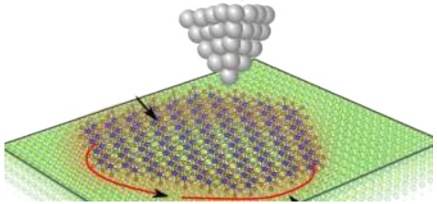


Nature 579, 523–527 (2020)

Topological insulators

Science 364.6447 (2019): 1255-1259

Two-dimensional materials



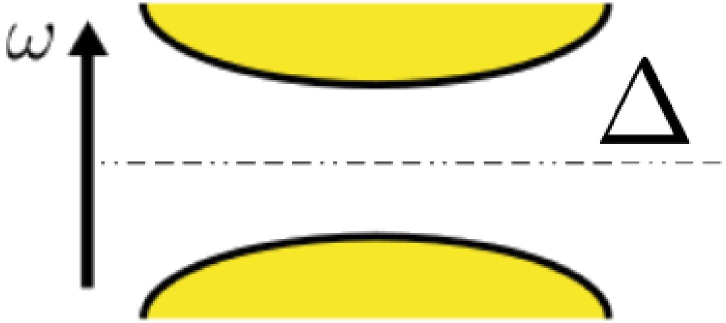
Nature 588, 424–428 (2020)

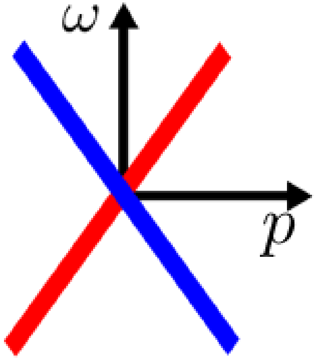
New materials open new venues for engineering and controlling Majorana physics

How to build your own topological superconductor

Ingredients

- s-wave pairing
- Helical states





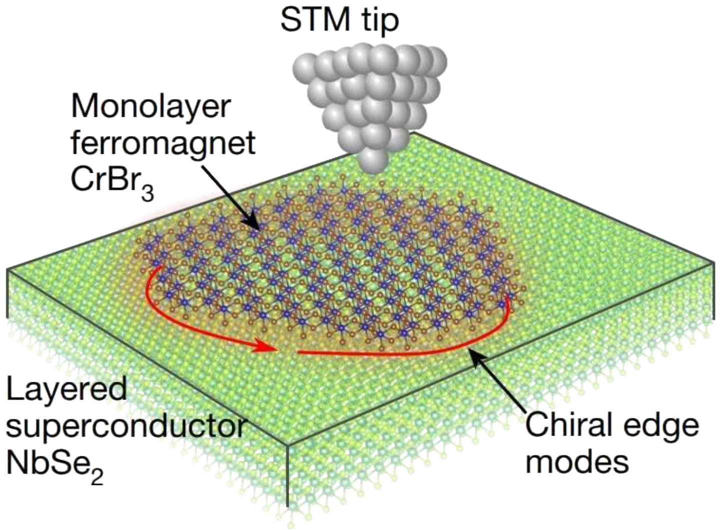
Objective: to realize a spinless superconductor

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

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

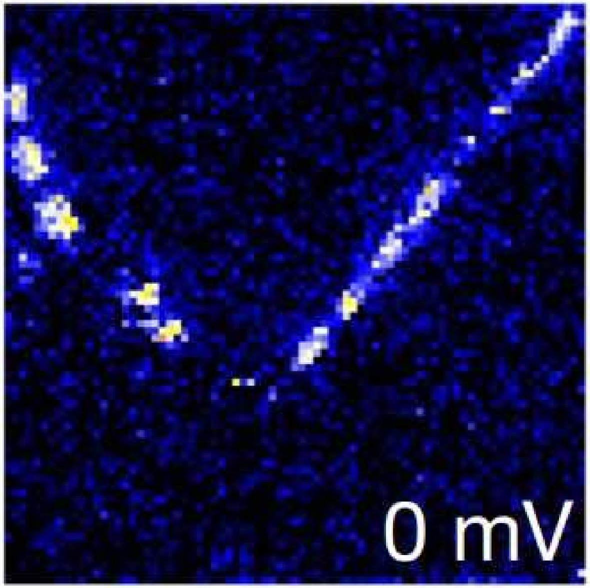
Topological superconductivity in a van der Waals heterostructure

$CrBr_3/NbSe_2$ heterostructure



Nature 588, 424–428 (2020)

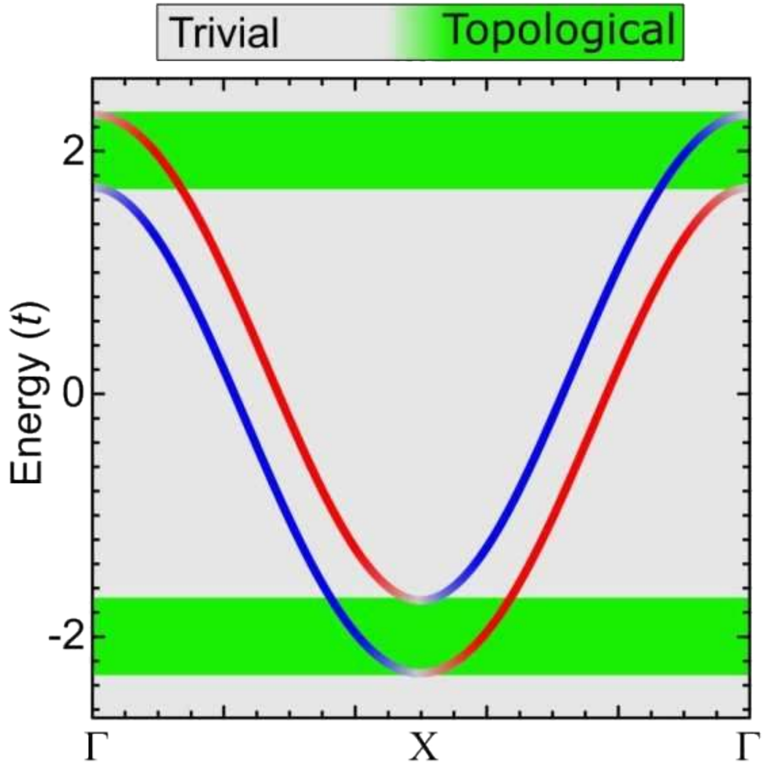
Zero bias dIdV



A topological superconducting state appears in $CrBr_3/NbSe_2$

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

Warm up: 1D topological superconductor



$$H = H_0 + H_J + H_R$$

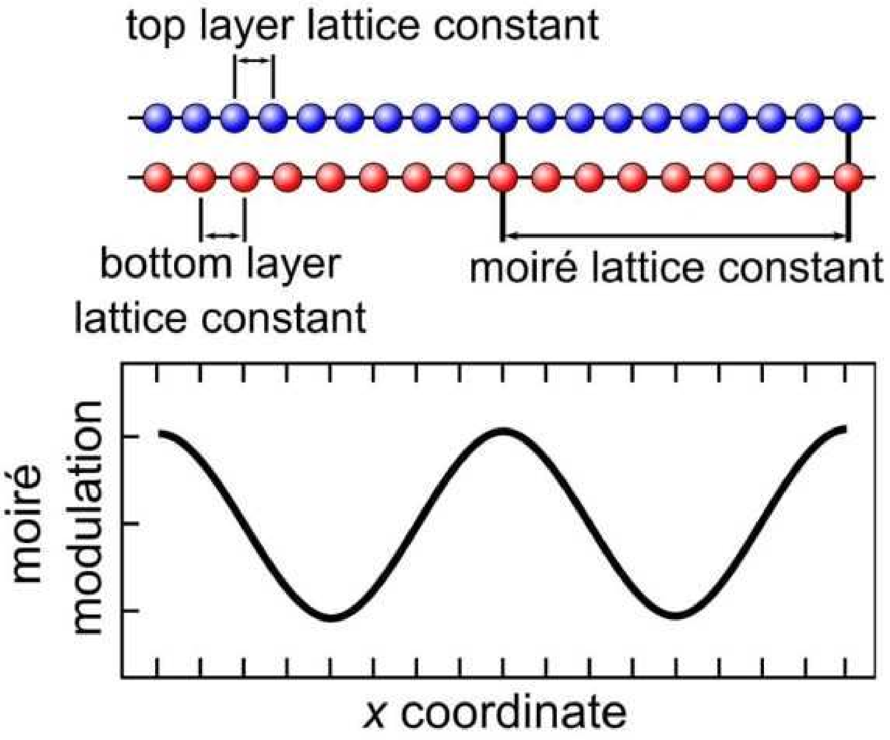
Kinetic energy

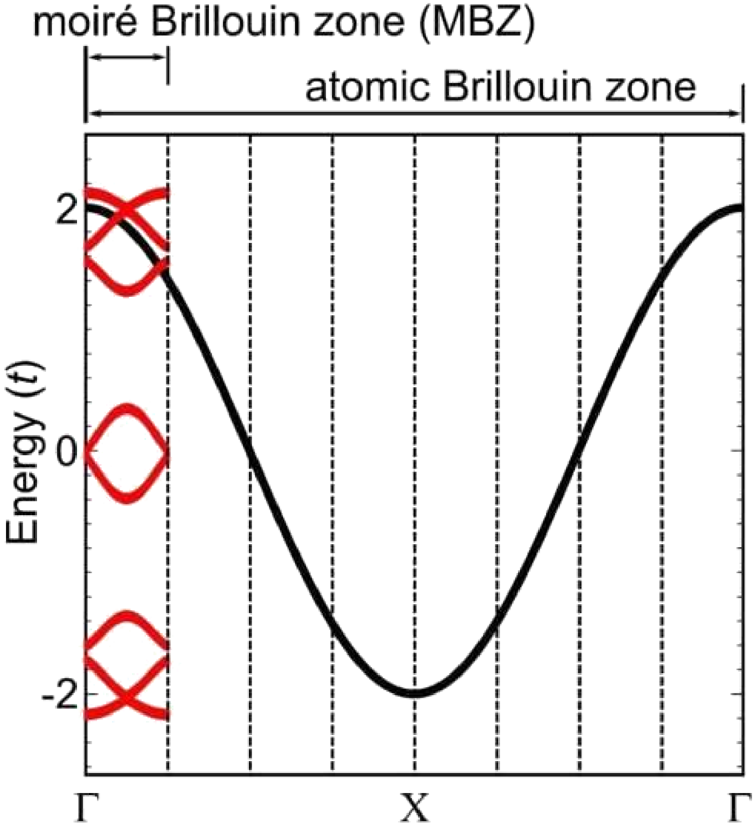
Exchange field

Rashba spin-orbit coupling

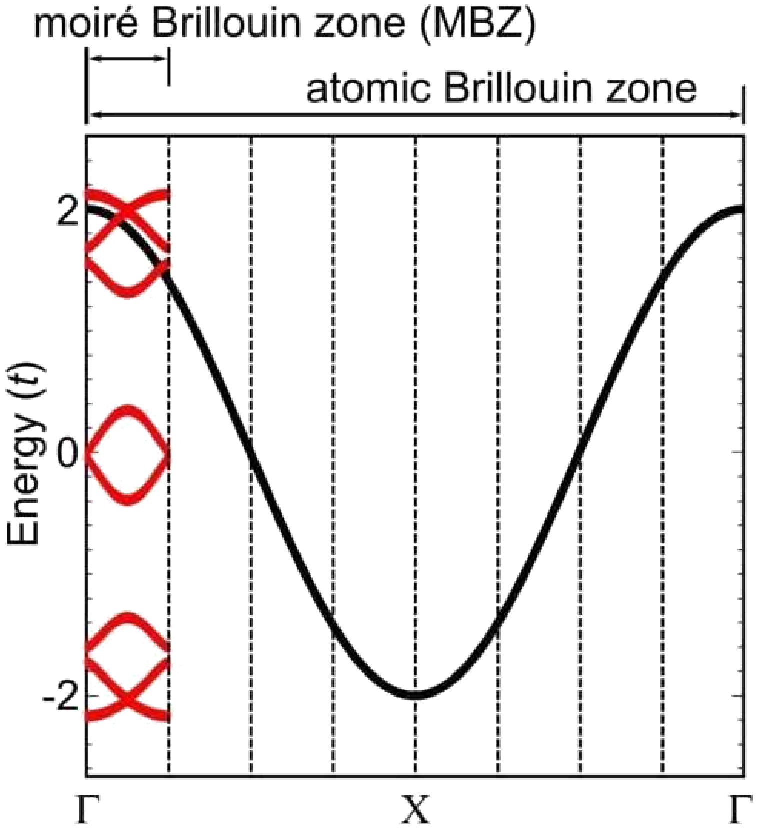
When switching on an s-wave pairing, green regions lead to topological superconductivity

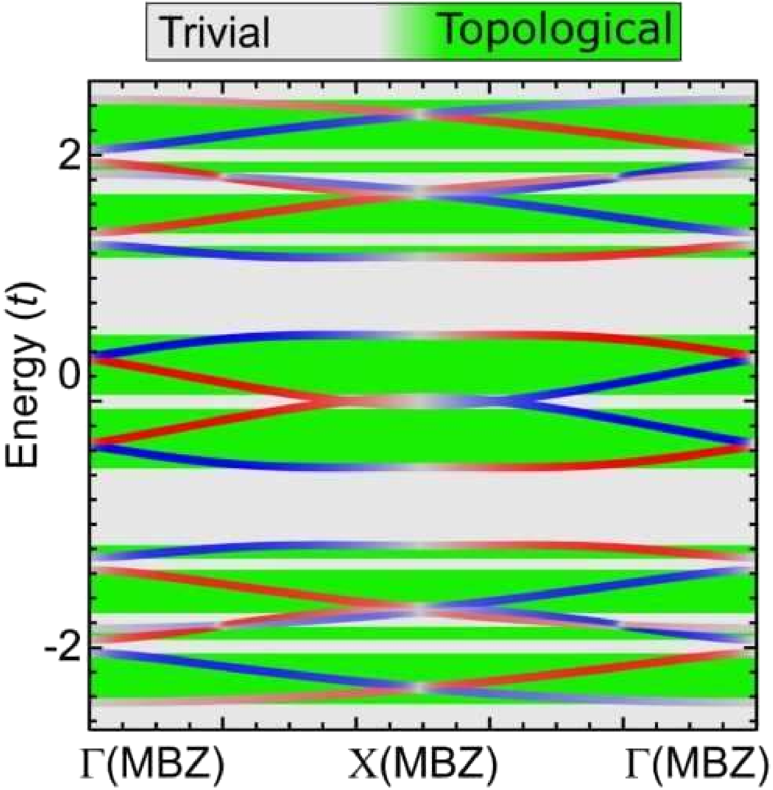
Warm up: 1D moire superconductor





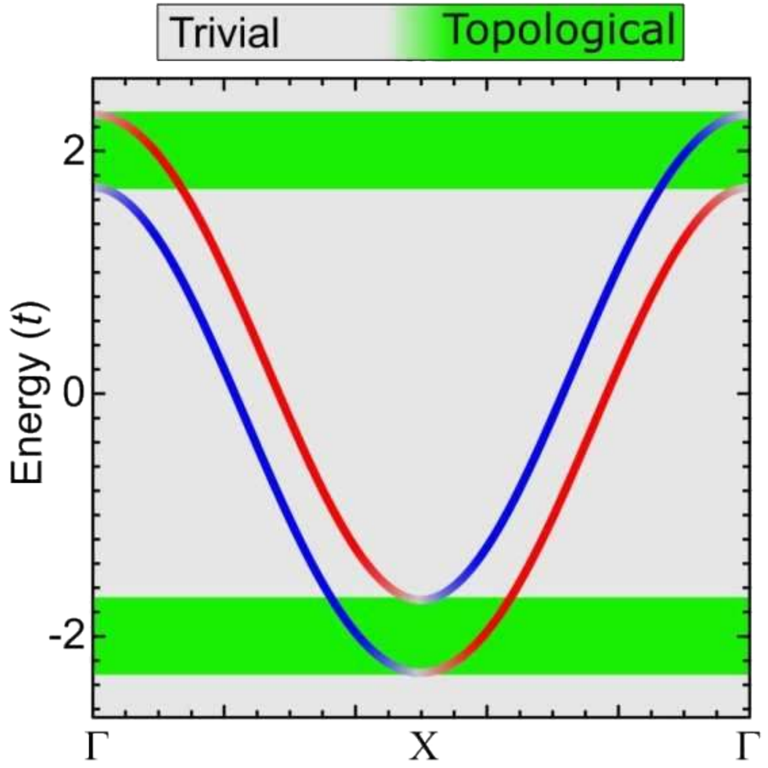
Warm up: 1D moire superconductor



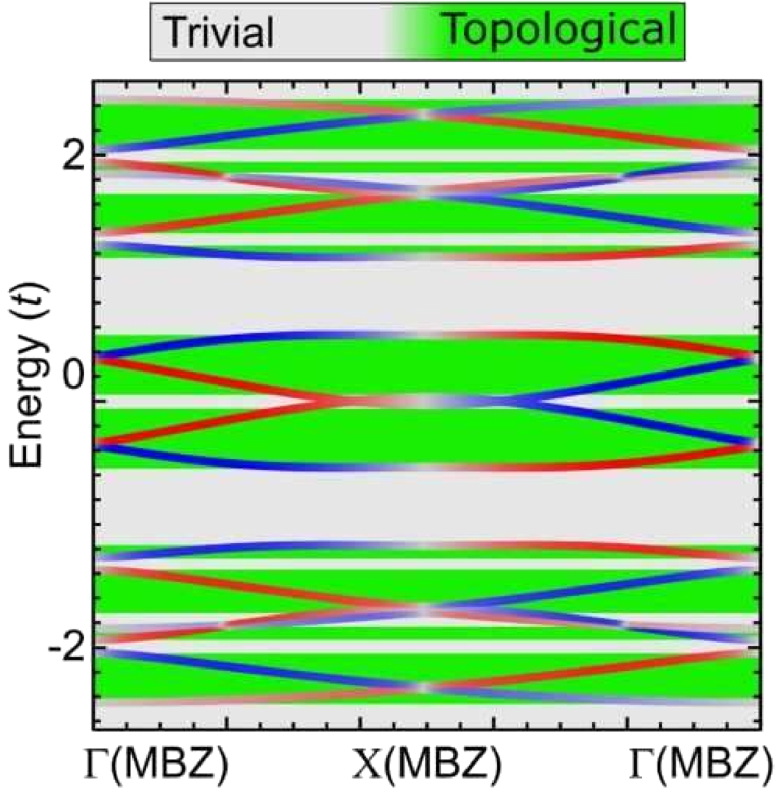


Warm up: 1D moire superconductor

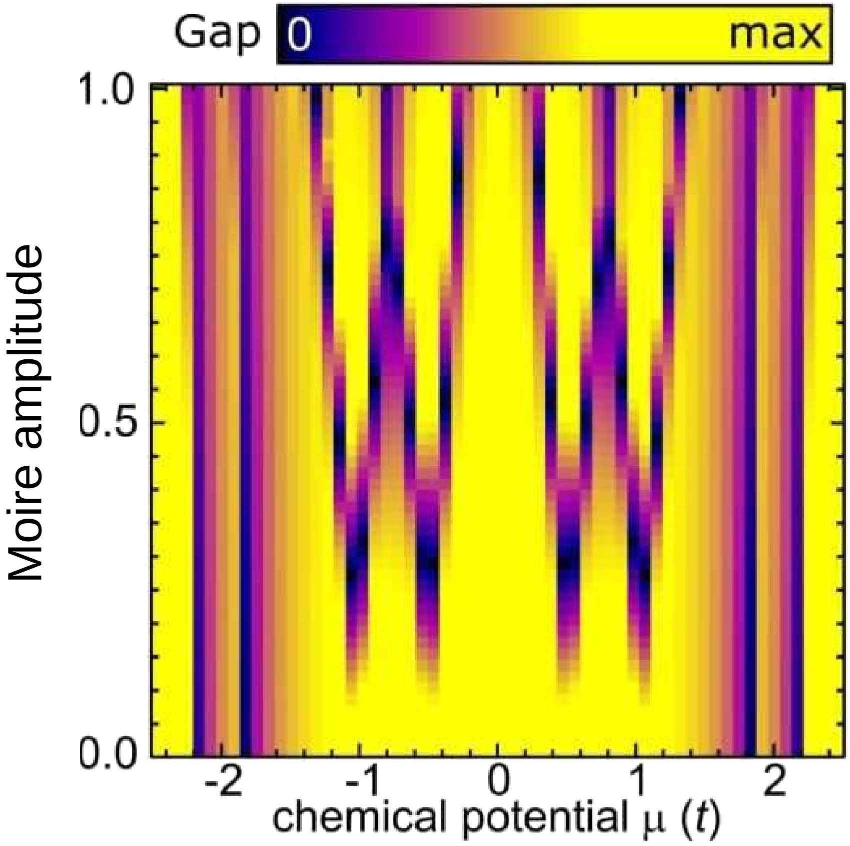
Without moire

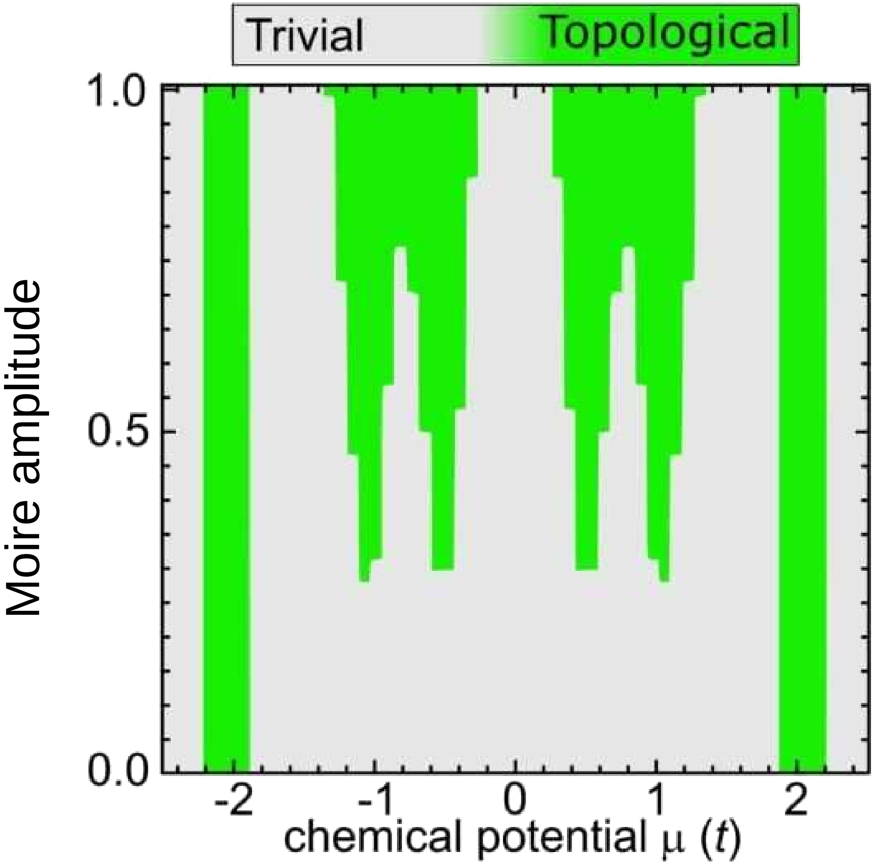


With moire

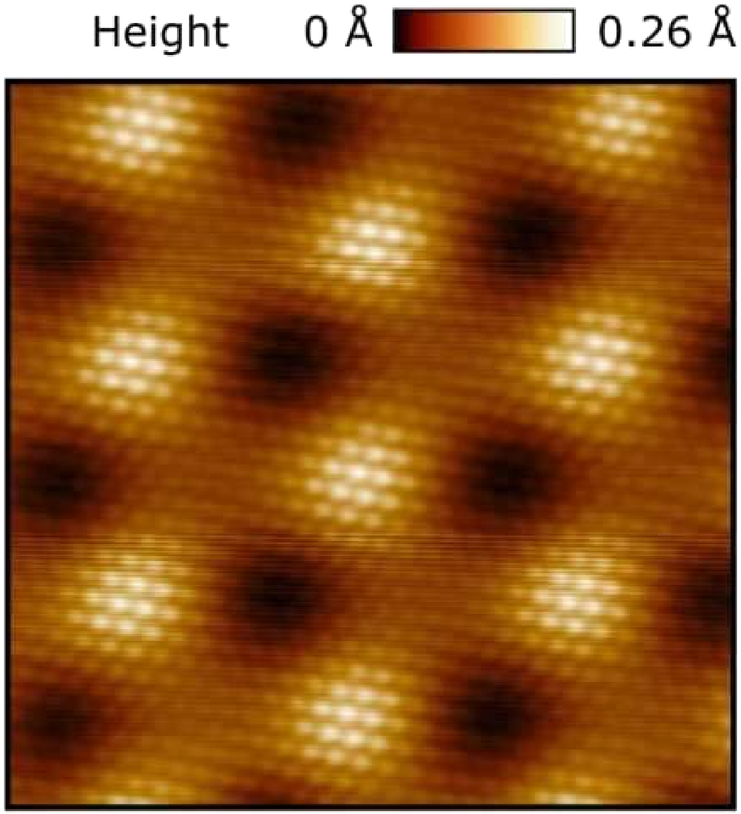


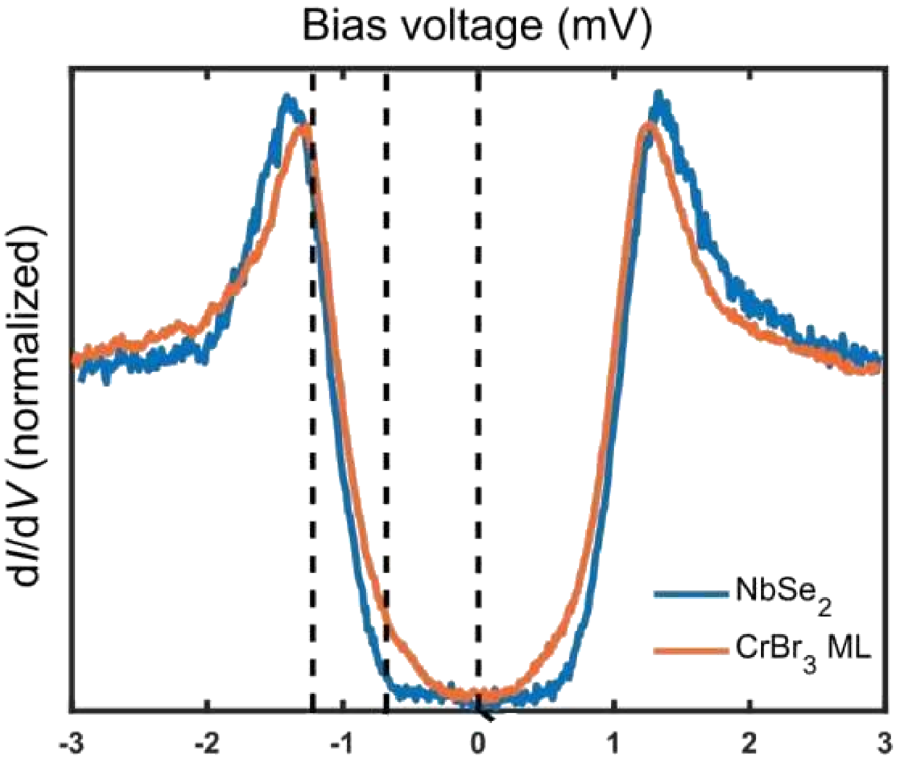
Warm up: 1D moire superconductor





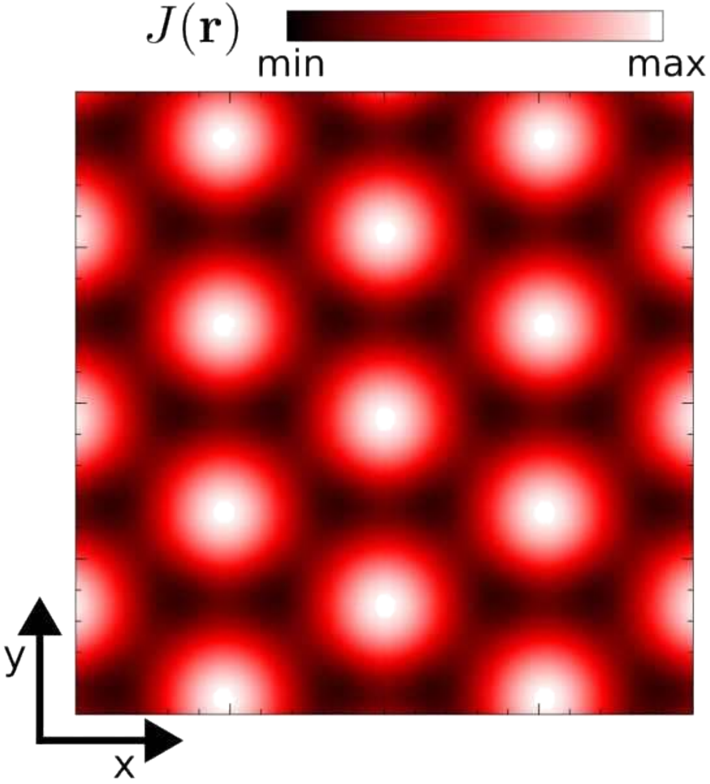
$CrBr_3/NbSe_2$ heterostructure





Bulk Yu-Shiba Rusinov bands

Exchange profile



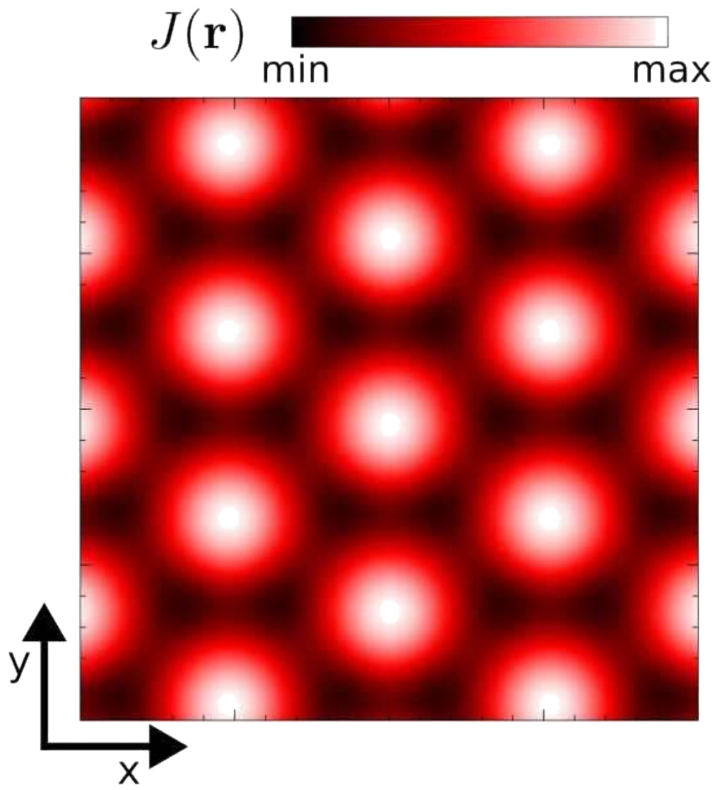
Full Hamiltonian of the moire system

$$
\begin{aligned}
H = &\sum_{\langle ij\rangle,s} t\left(\frac{\mathbf{r}_i+\mathbf{r}_j}{2}\right) c^\dagger_{i,s}c_{j,s} + \sum_{i,s}\mu(\mathbf{r})c^\dagger_{i,s}c_{i,s} + \\
& i\sum_{\langle ij\rangle,s,s'} \lambda\left(\frac{\mathbf{r}_i+\mathbf{r}_j}{2}\right)\mathbf{d}_{ij}\cdot\sigma^{s,s'}c^\dagger_{i,s}c_{j,s'} + \\
& \sum_{i,s,s'} J(\mathbf{r}_i)\sigma_z^{s,s'}c^\dagger_{i,s}c_{i,s'} + \sum_i \Delta(\mathbf{r}_i)c^\dagger_{i,\uparrow}c^\dagger_{i,\downarrow} + \mathrm{h.c.}
\end{aligned}
$$

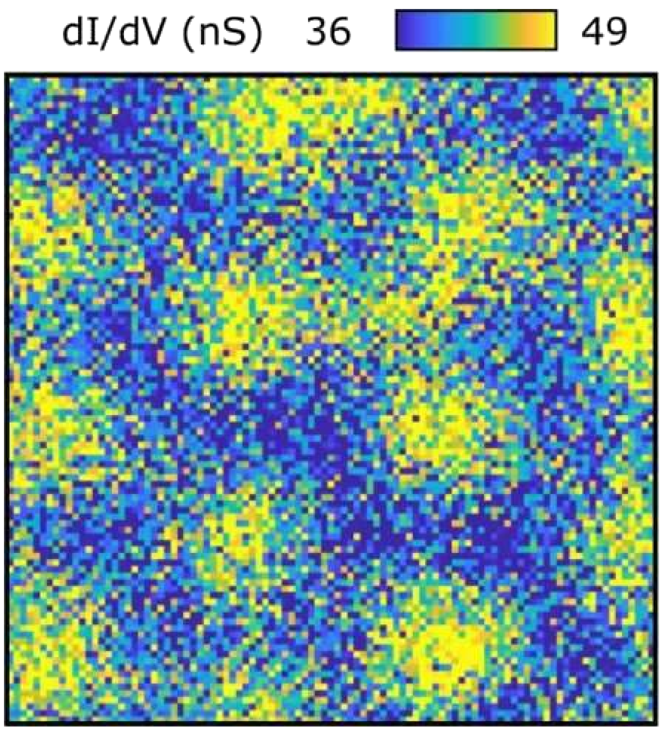
Exchange profile following the moire

Bulk Yu-Shiba Rusinov bands

Exchange profile

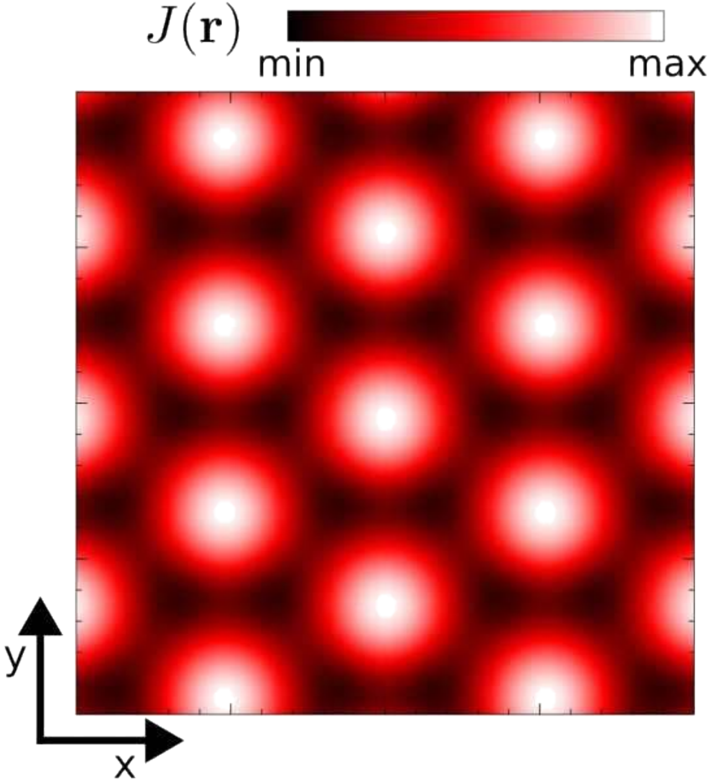


Experimental dIdV

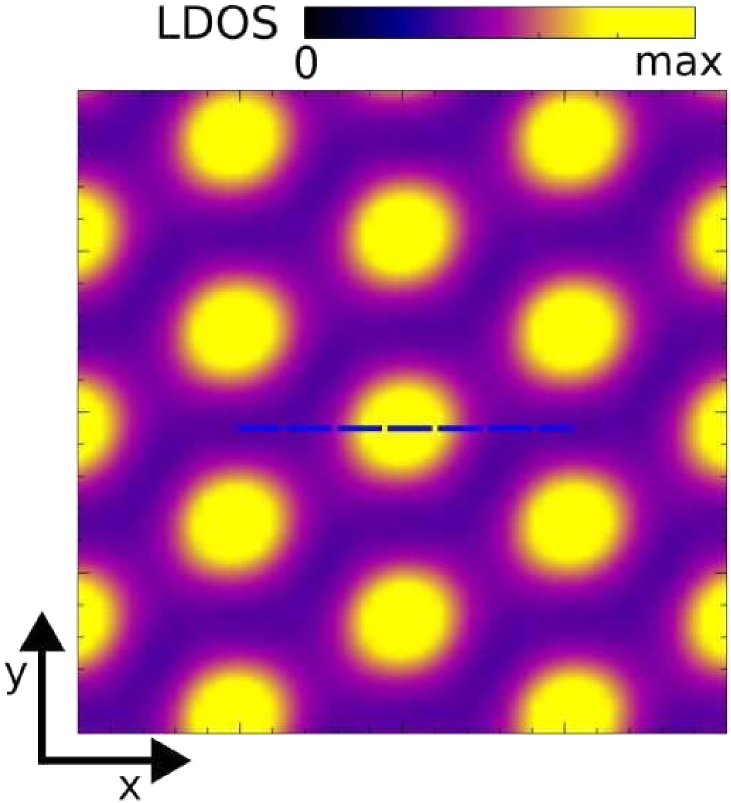


Bulk Yu-Shiba Rusinov bands

Exchange profile

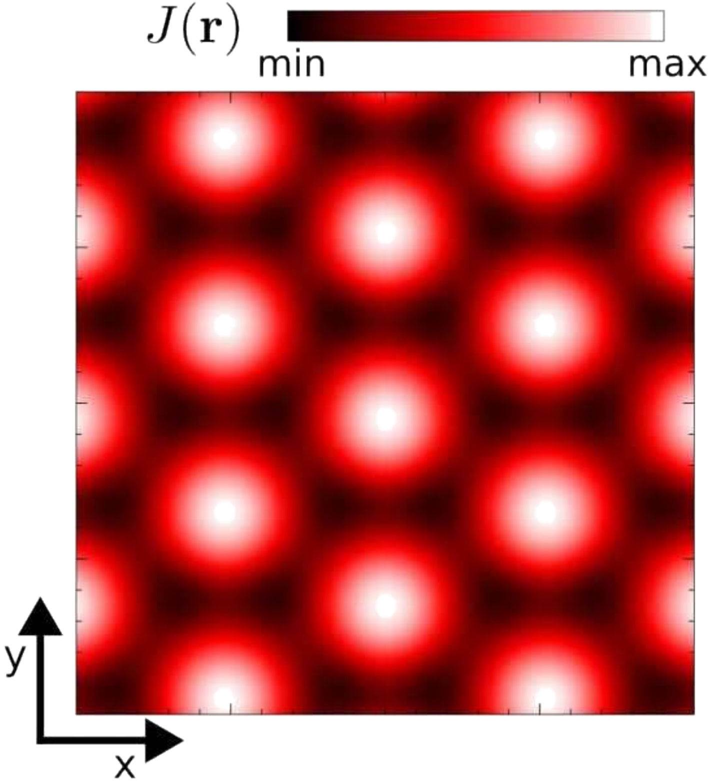


Theoretical LDOS

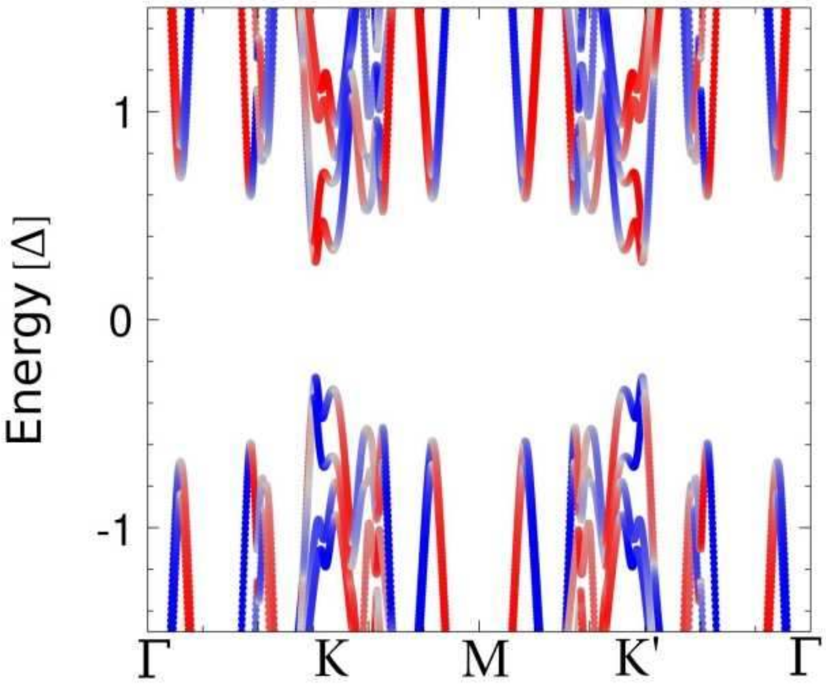


Bulk Yu-Shiba Rusinov bands

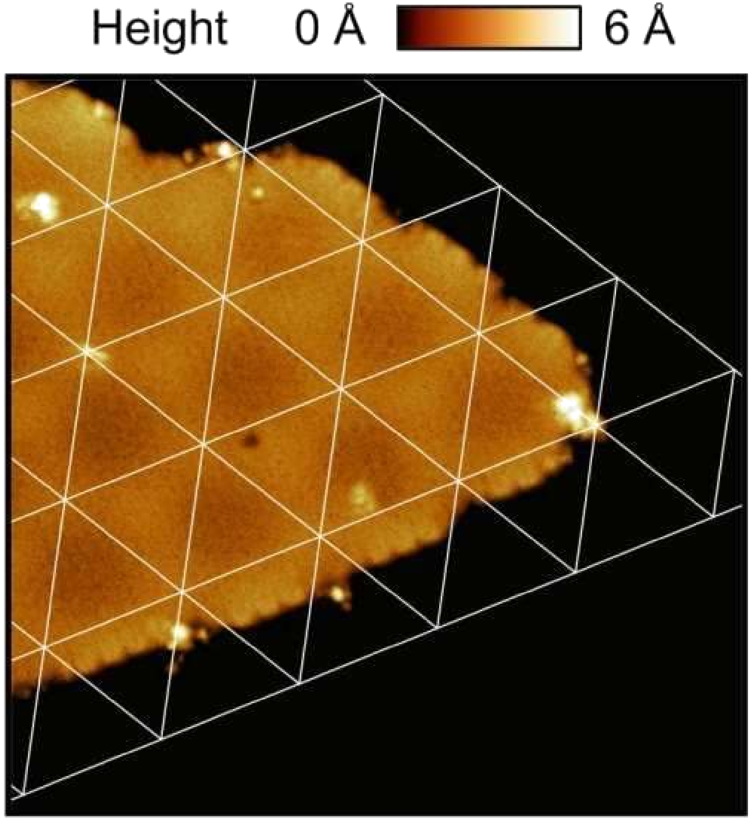
Exchange profile



Moire electronic structure

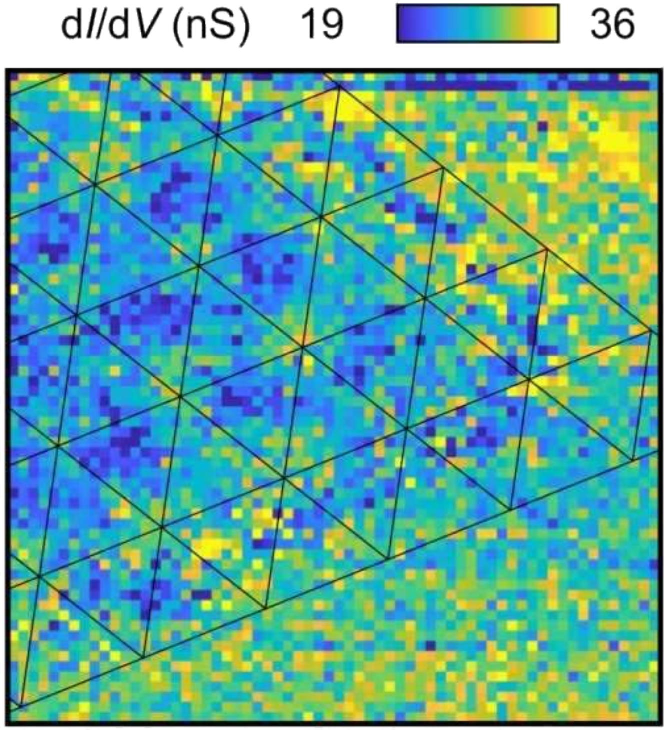


Spectral properties close to boundaries

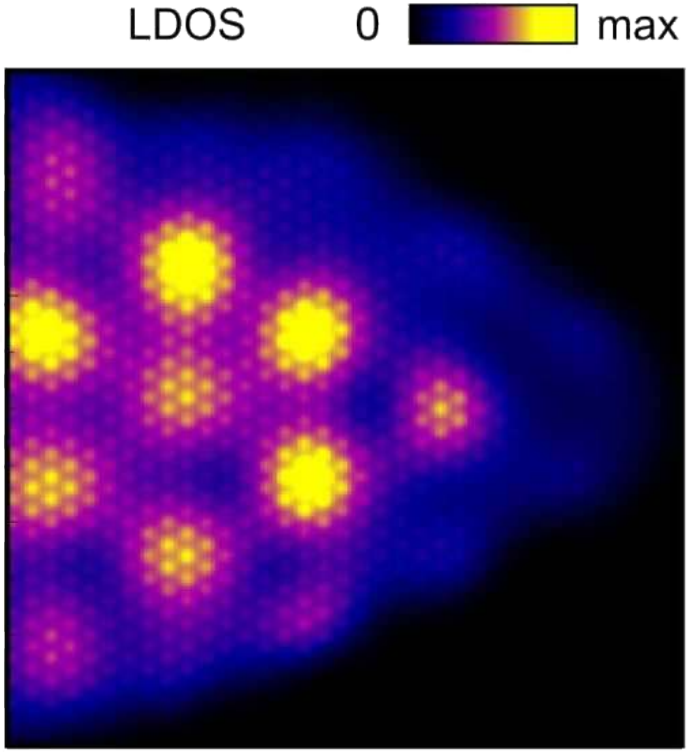


Bulk Yu-Shiba-Rusinov states

Experiment

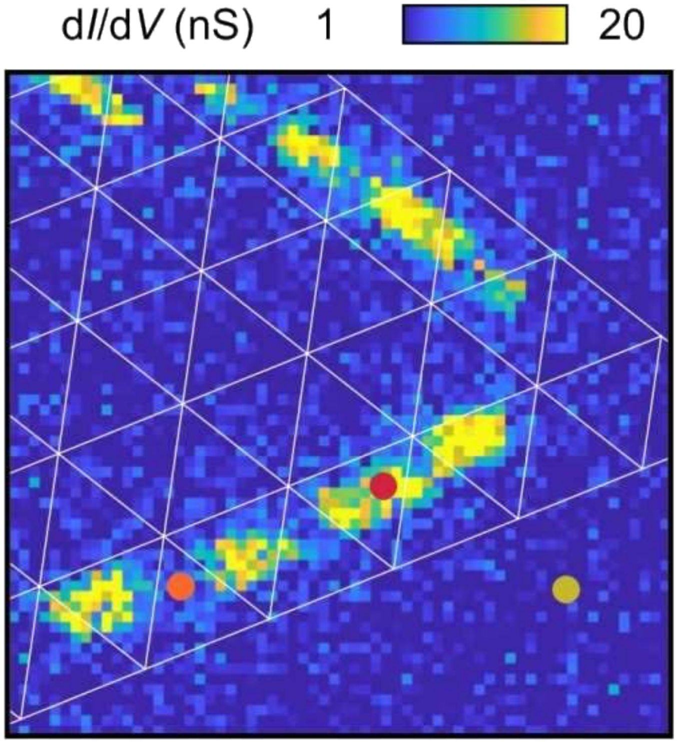


Theory

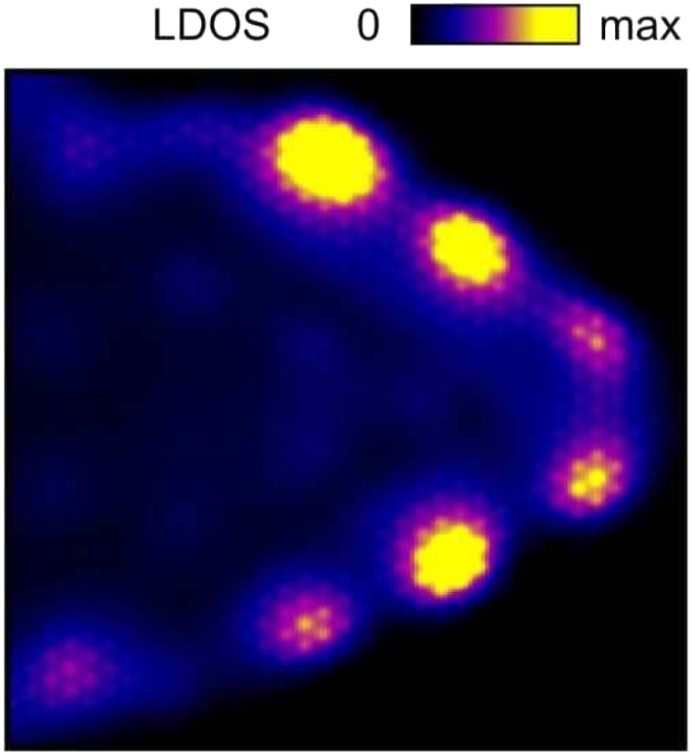


Topological moire edge states

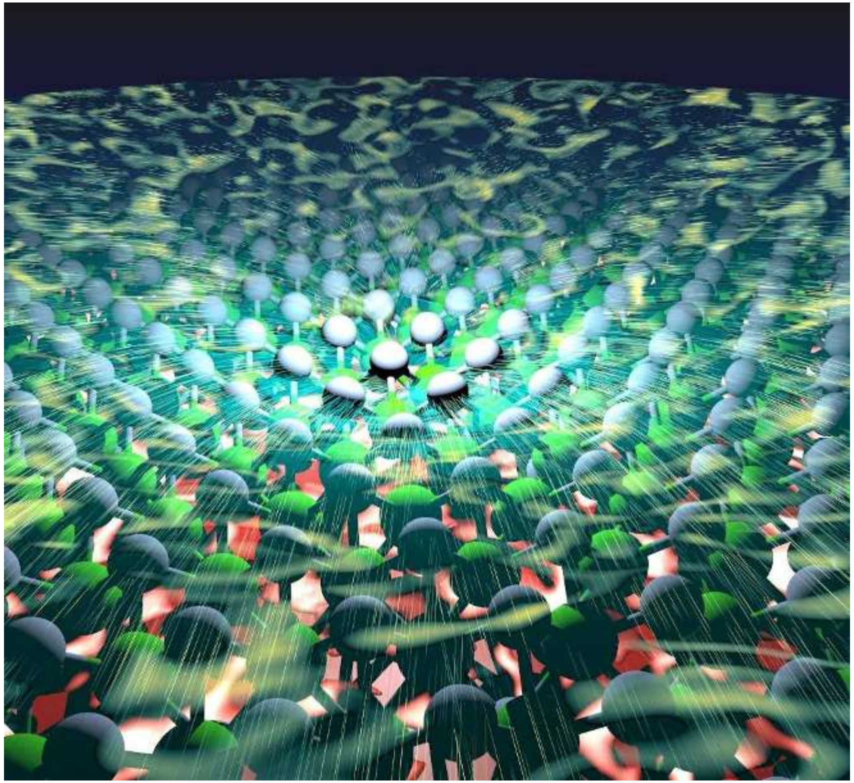
Experiment



Theory



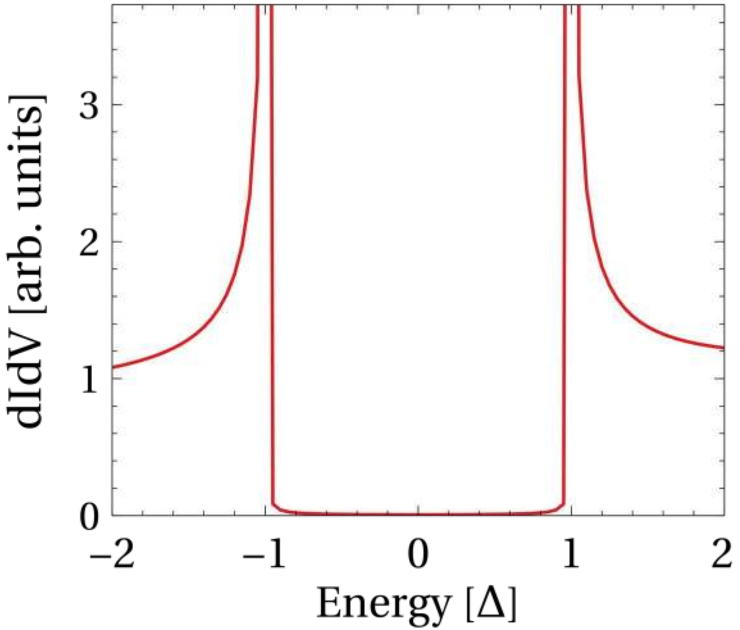
Nodal superconductivity in ultraclean TaS_2



arXiv:2112.07316 (2021)

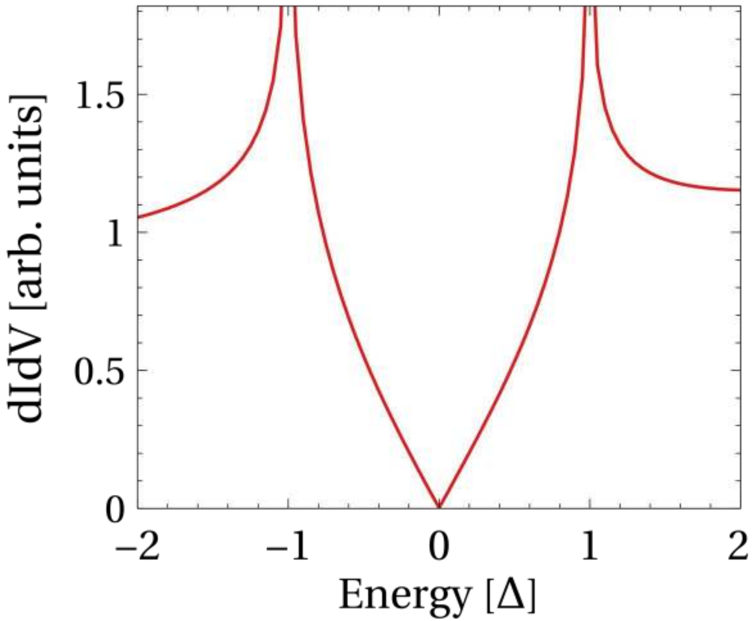
Gaped and nodal superconductivity

Conventional s-wave



Driven by electron-phonon

Unconventional nodal f-wave



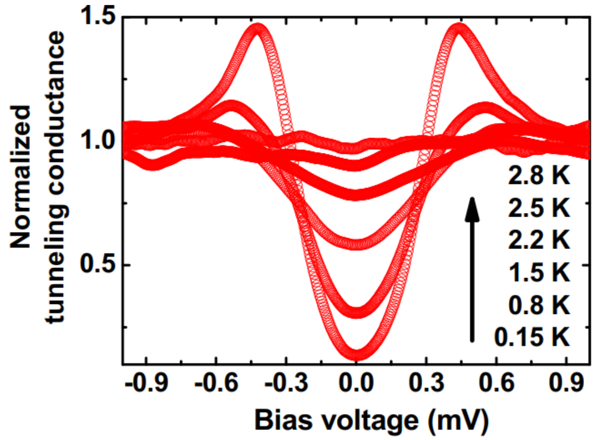
Driven by unconventional mechanism
(magnons, valence fluctuations)

The nature of superconductivity in dichalcogenide monolayers

$NbSe_2$, TaS_2 monolayers are (believed to be) weakly correlated s-wave superconductors

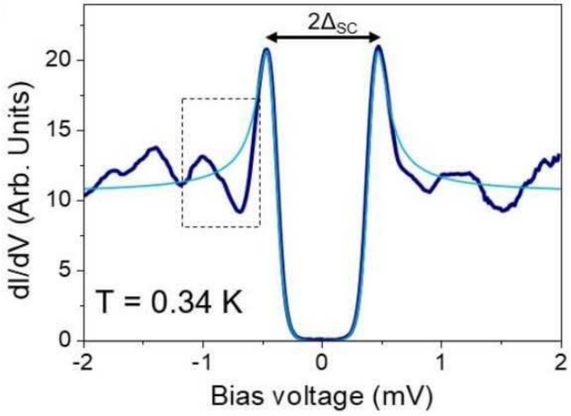
However, there are signatures hinting that they may be close to a phase transition

Signatures of f-wave in TaS_2



Phys. Rev. B 89, 224512 (2014)

Legget modes in $NbSe_2$

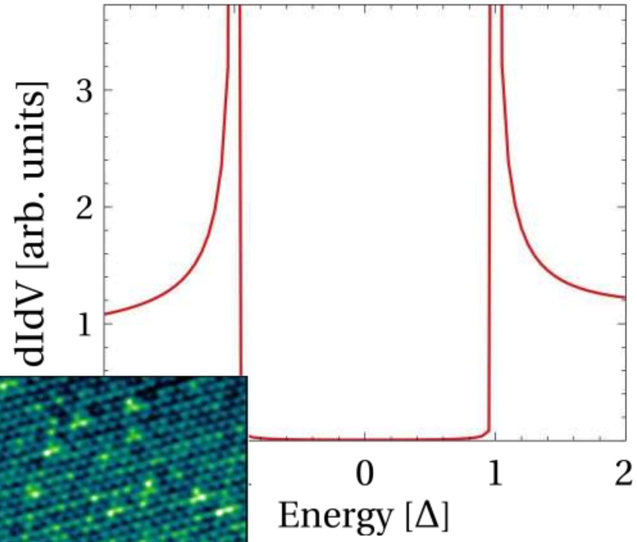


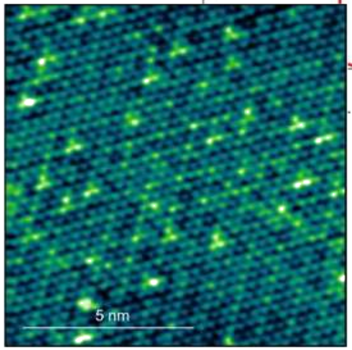
arXiv:2101.04050 (2021)

Miguel M. Ugeda's talk at 16:00

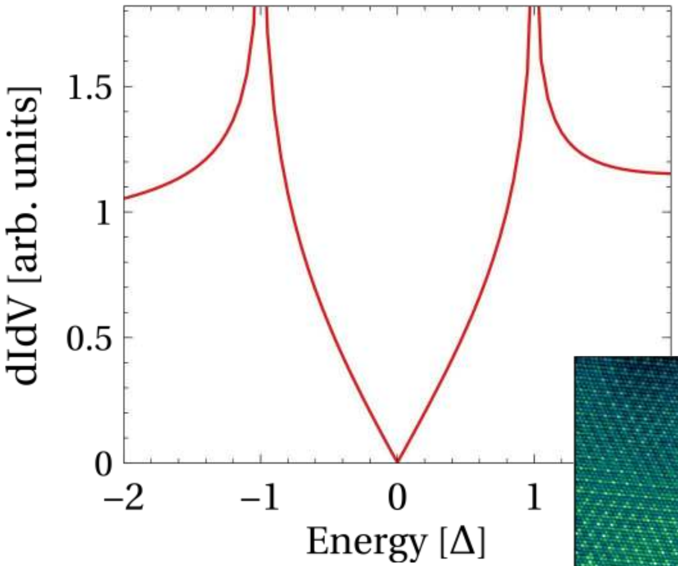
Two superconducting states in TaS_2 monolayer

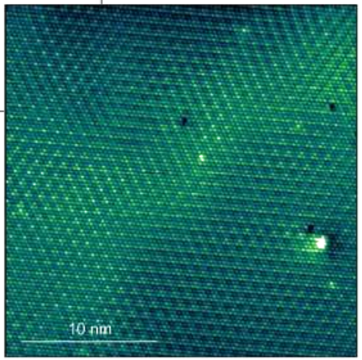
Strong disorder
Fully-gaped s-wave





Weak disorder
Gapless nodal f-wave

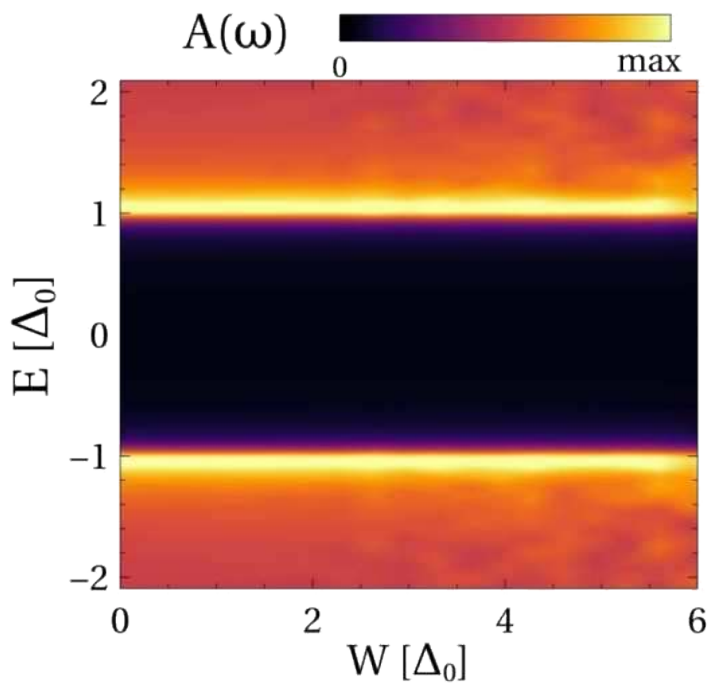




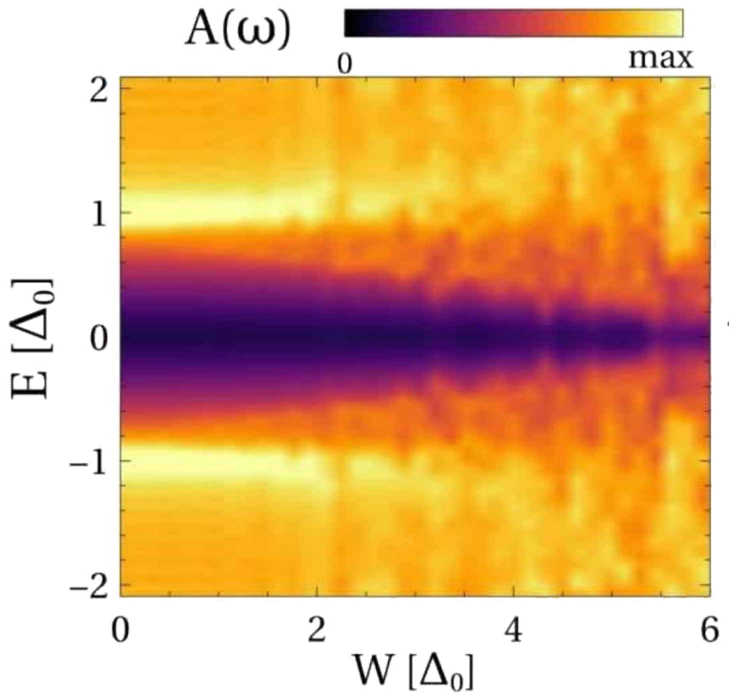
Superconducting phase transition associated with disorder

Impact of disorder for f-wave and s-wave

Disorder on s-wave

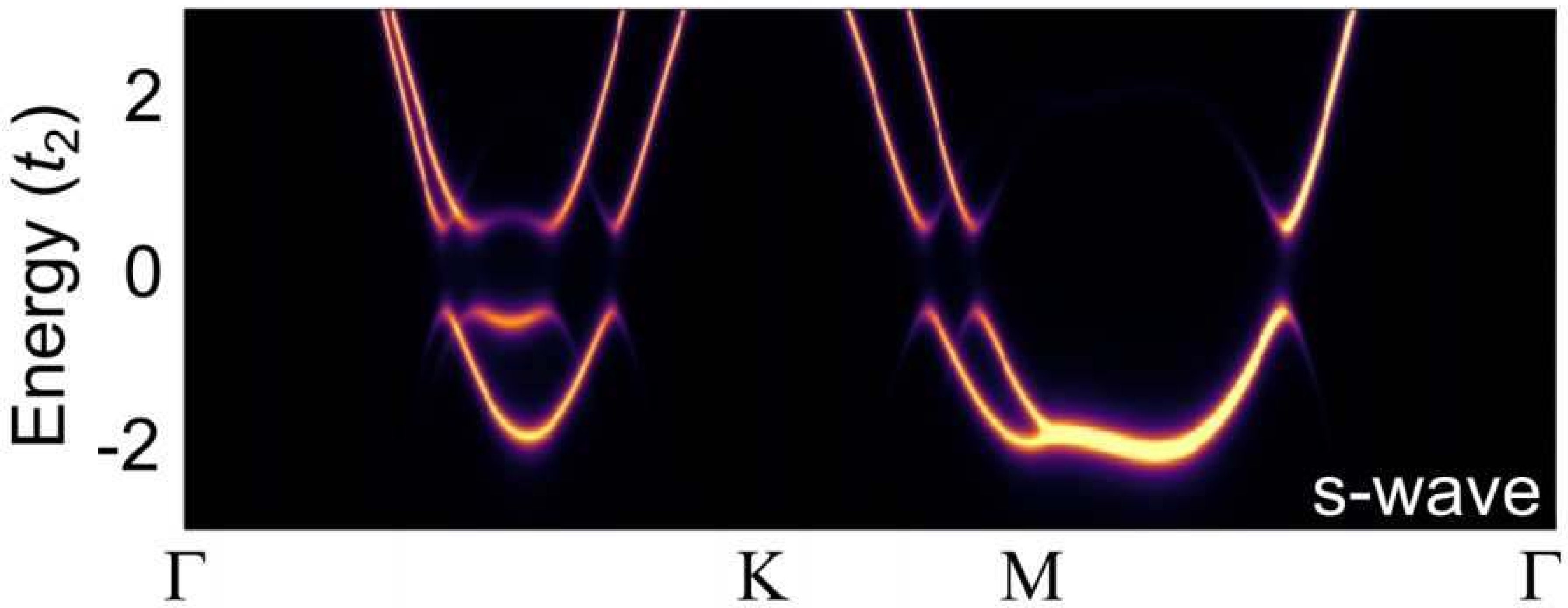


Disorder on f-wave



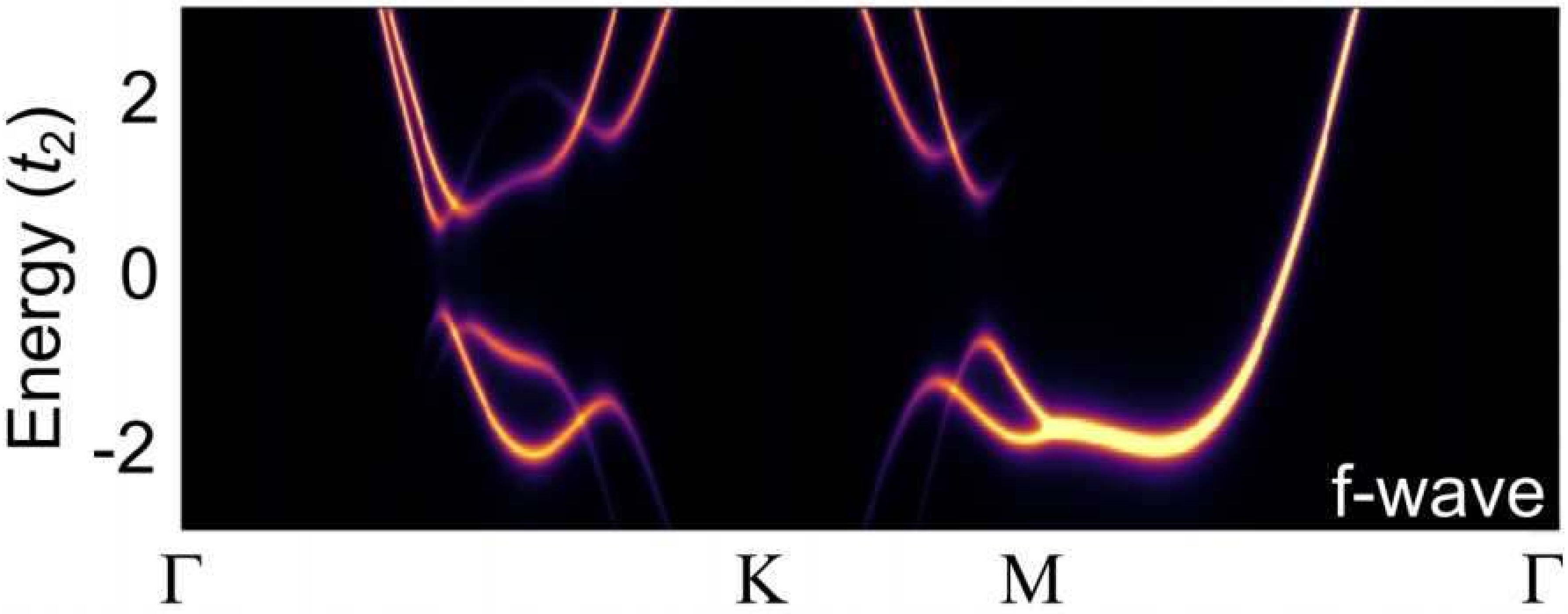
$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{SC} + \sum_{n,s} W_n c^\dagger_{n,s} c_{n,s}$$

Electronic structure with an s-wave gap



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

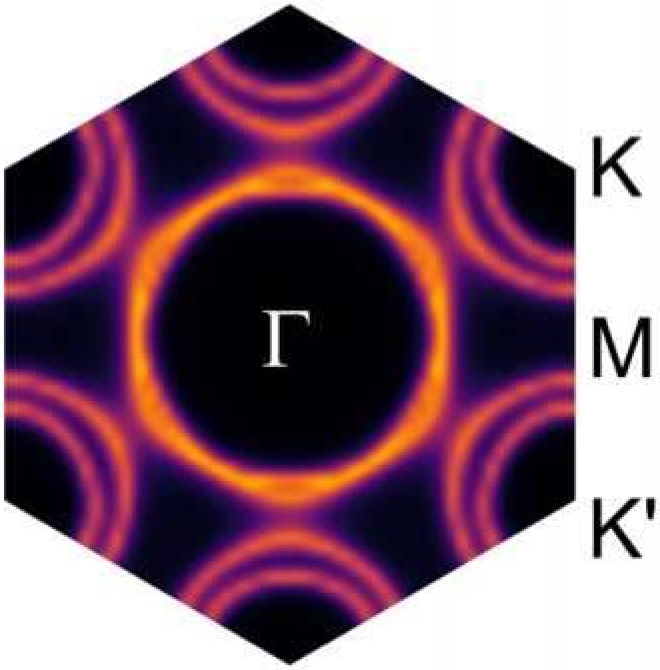
Electronic structure with an f-wave gap



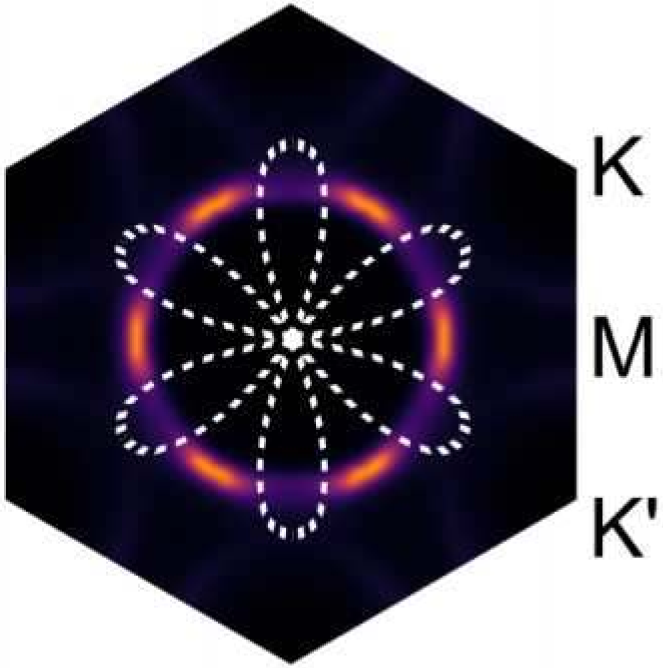
Part of the band structure remains gapless in the presence of superconductivity

Fermi surface of TaS_2

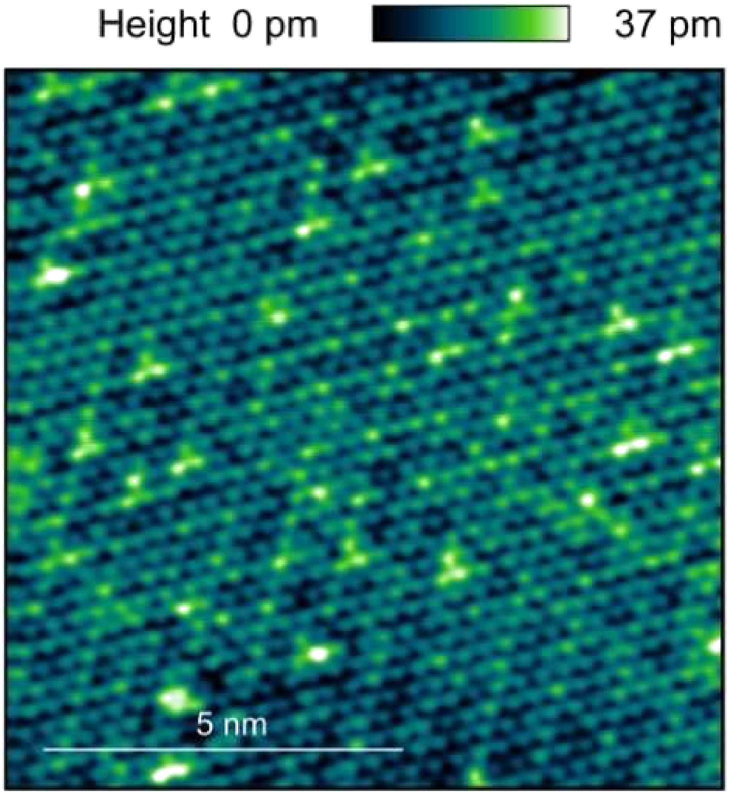
Normal State

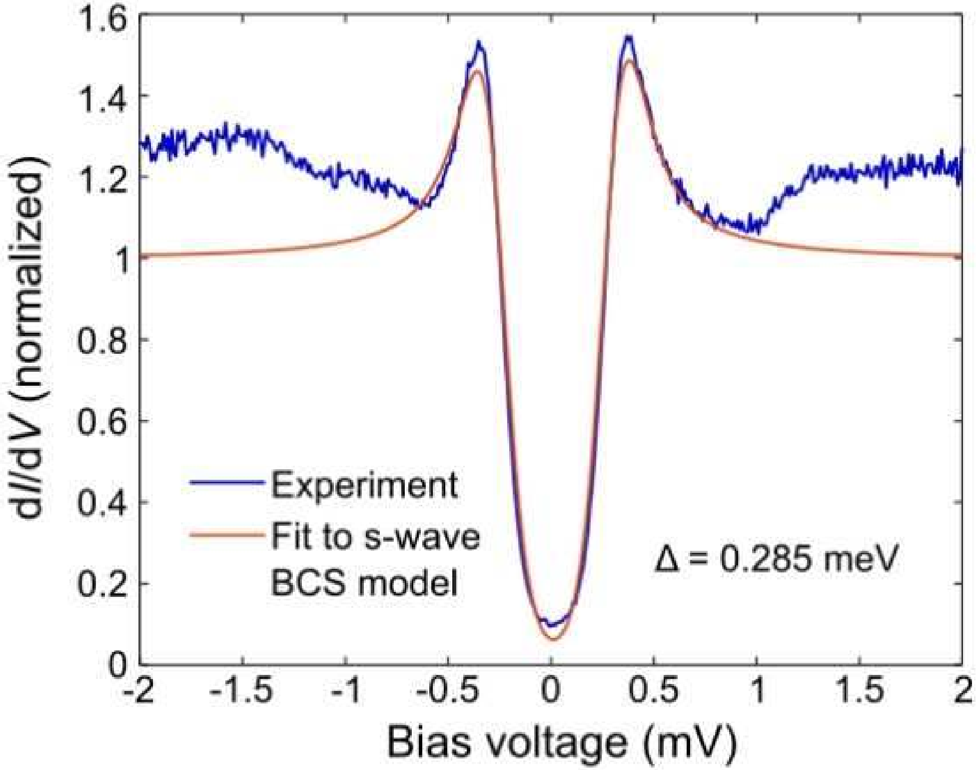


Nodal superconducting state

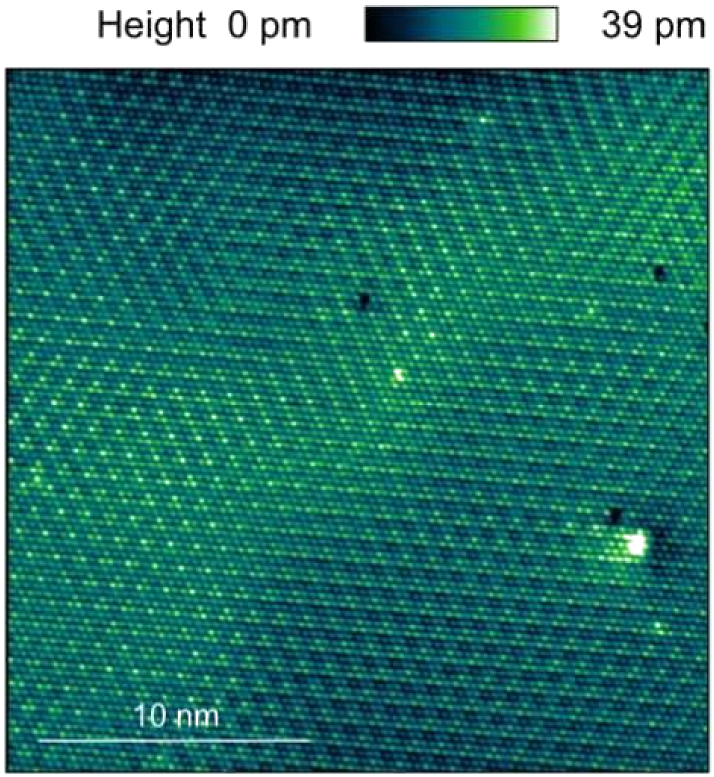


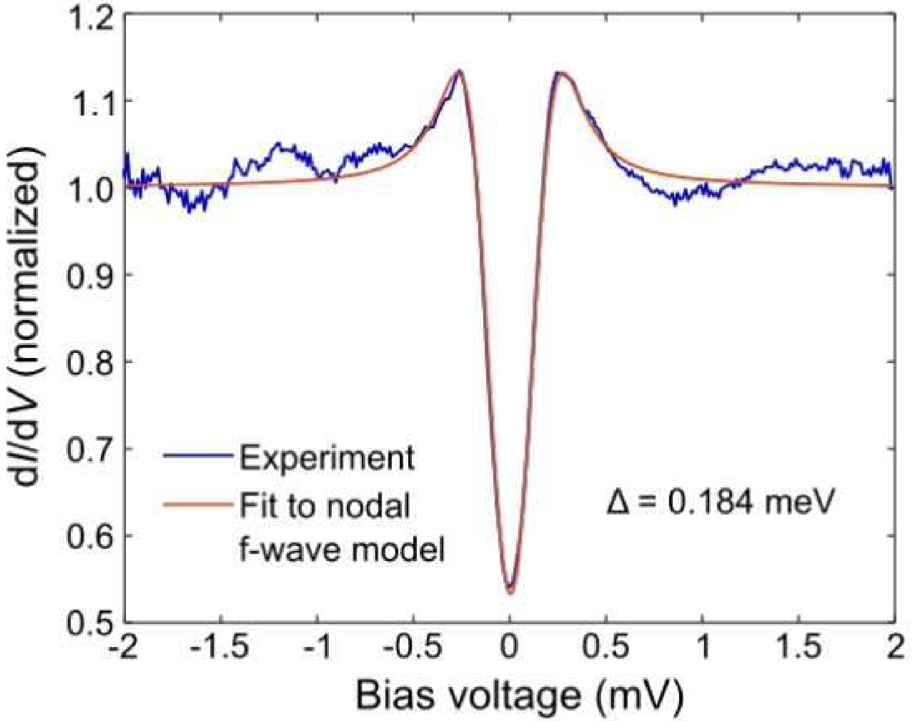
Dirty TaS_2 monolayer sample



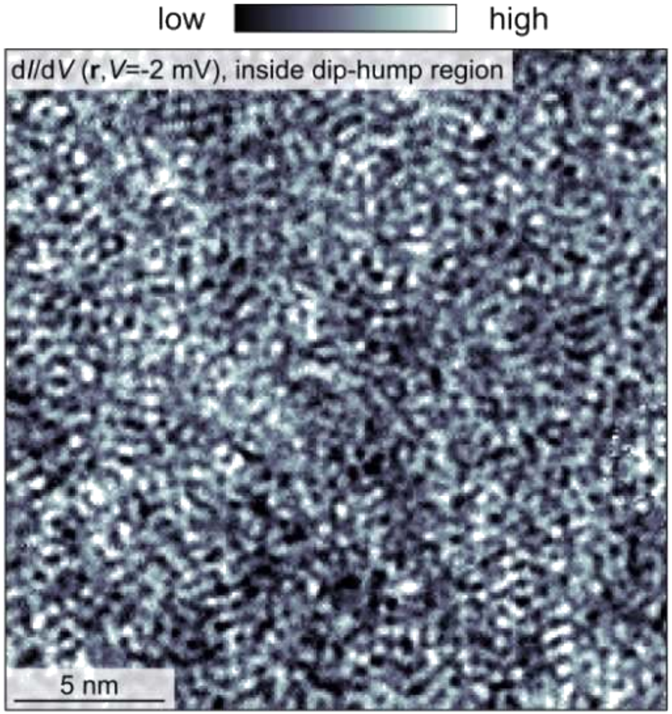


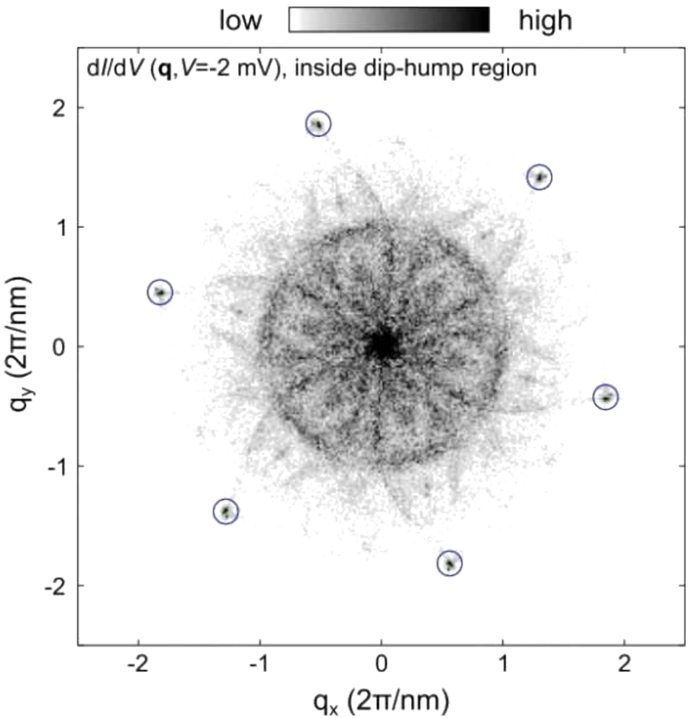
Ultra-clean TaS_2 monolayer sample





Hidden order many-body fluctuations

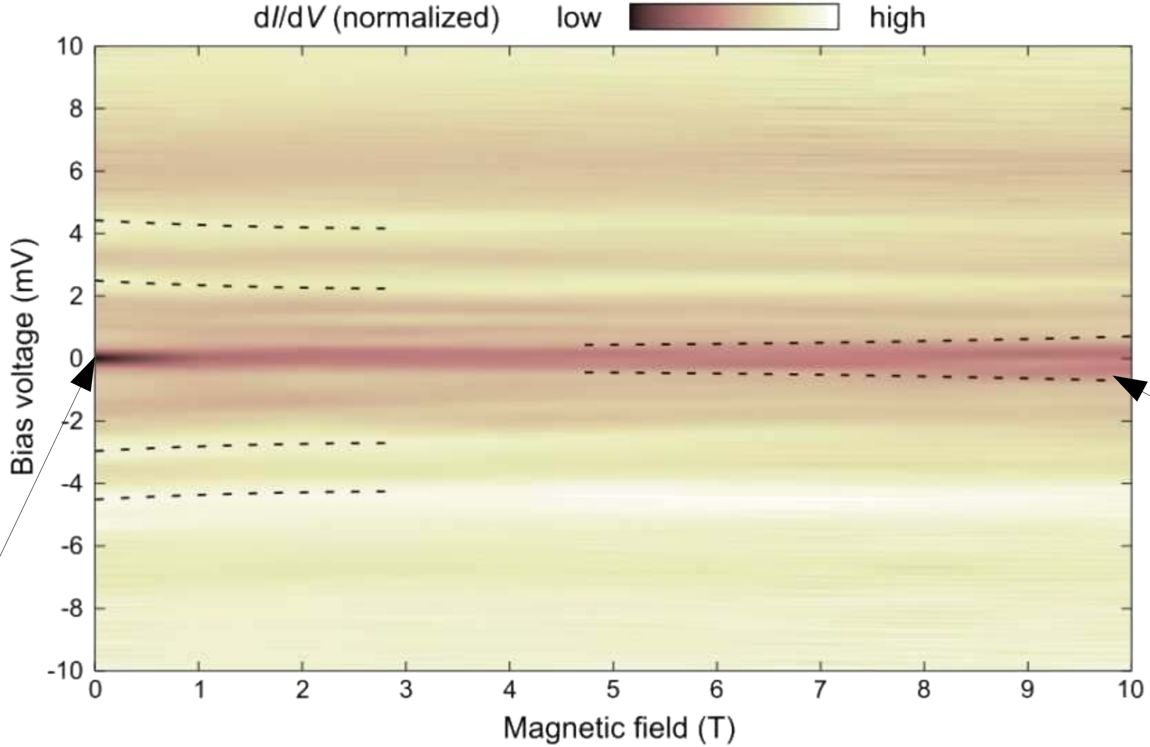


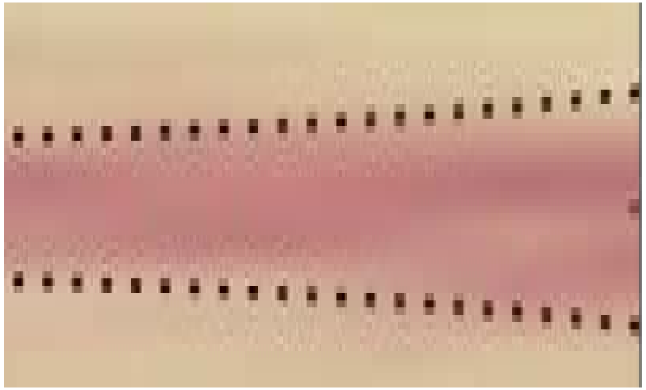


Inelastic excitations with a characteristic length scale emerge above the coherence peaks

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

Ultraclean sample versus magnetic field





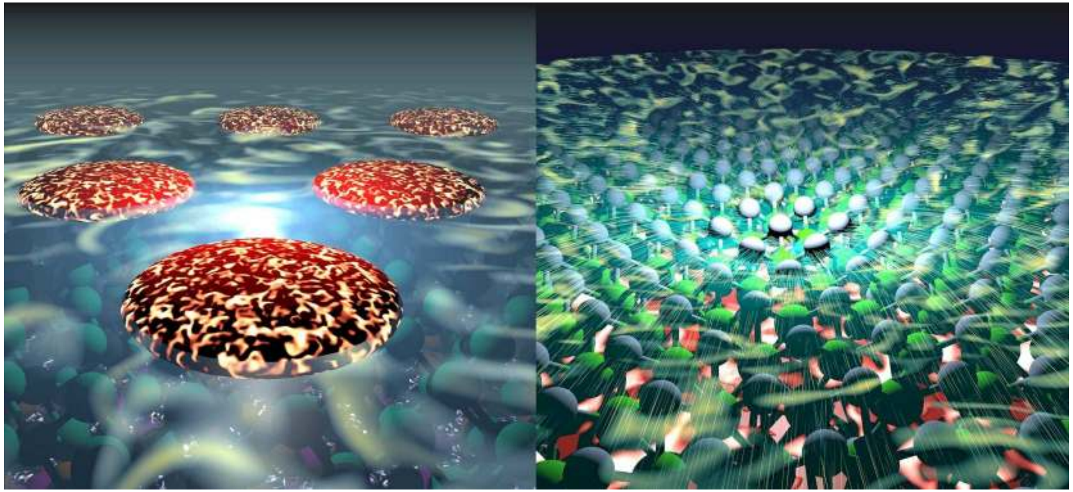
Pseudo-gap

Superconducting gap

A magnetic field increases a pseudo gap at the chemical potential

Take home

Van der Waals materials provide a platform to realize topological and nodal superconductivity



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Thank you

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J&AE JANE AND AATOS ERKKO FOUNDATION

SUOMEN AKATEMIA