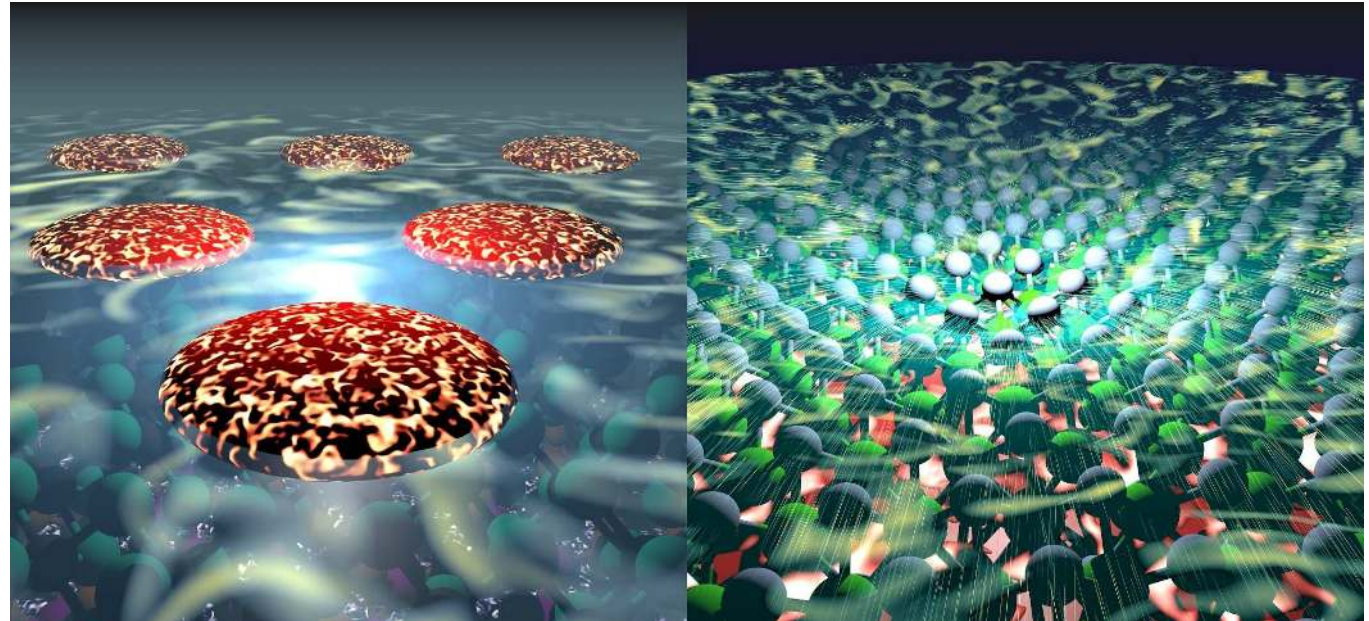


Engineering topological and nodal superconductivity in van der Waals materials



Jose Lado

Department of Applied Physics, Aalto University, Finland



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

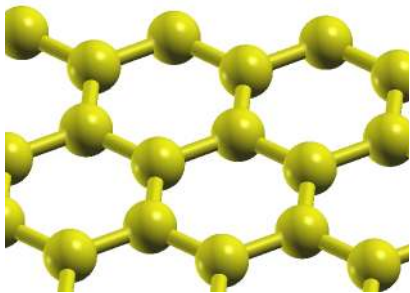
arXiv:2112.07316 (2021)

**4th International Workshop on Quantum Matter – Quantum Many-body Dynamics,
August 26th 2022, Tsung-Dao Lee Institute, China**

The two-dimensional materials world

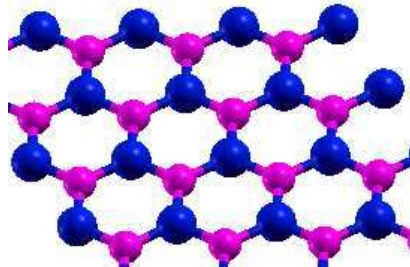
Semimetal

Graphene



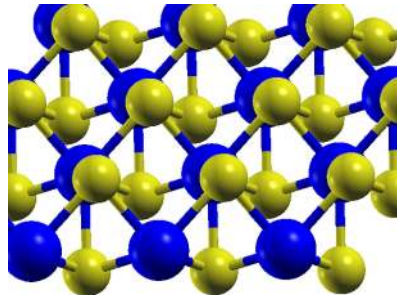
Insulator

BN



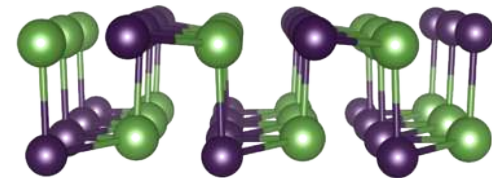
Superconductor

NbSe₂



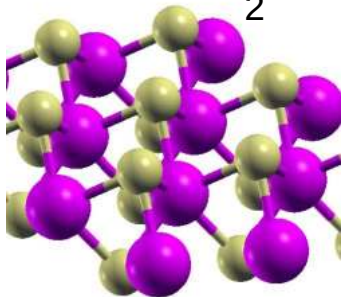
Ferroelectric

SnTe



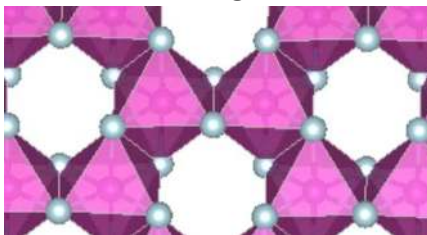
Semiconductor

WSe₂



Ferromagnet

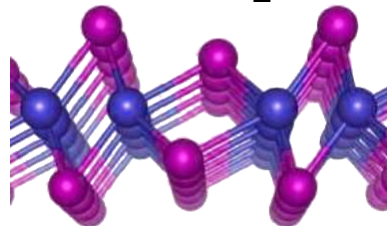
CrI₃



Quantum spin

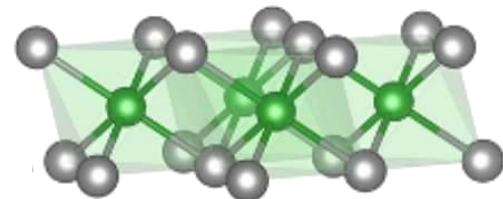
Hall insulator

WTe₂



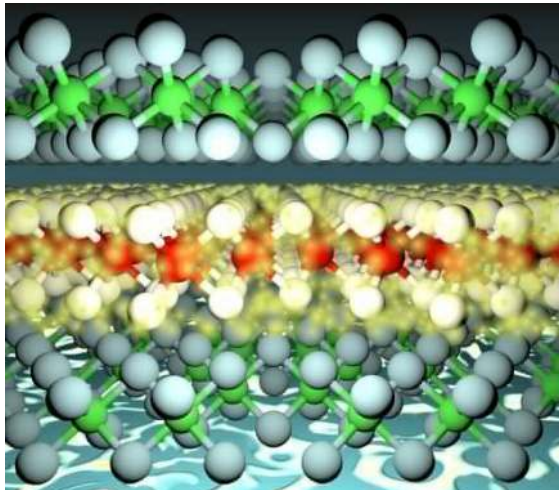
Multiferroic

NiI₂



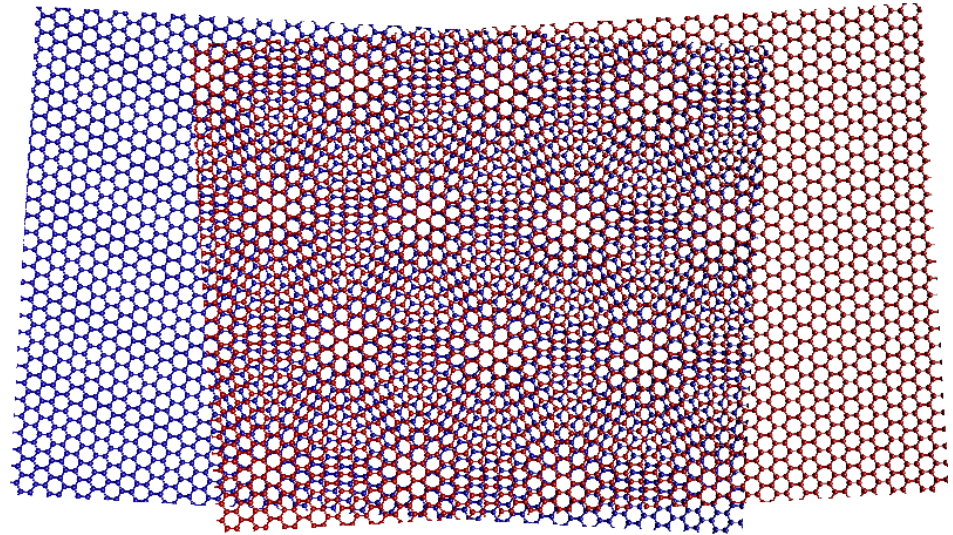
The flexibility of two-dimensional materials

They can be stacked



Nature 499.7459 419. (2013)

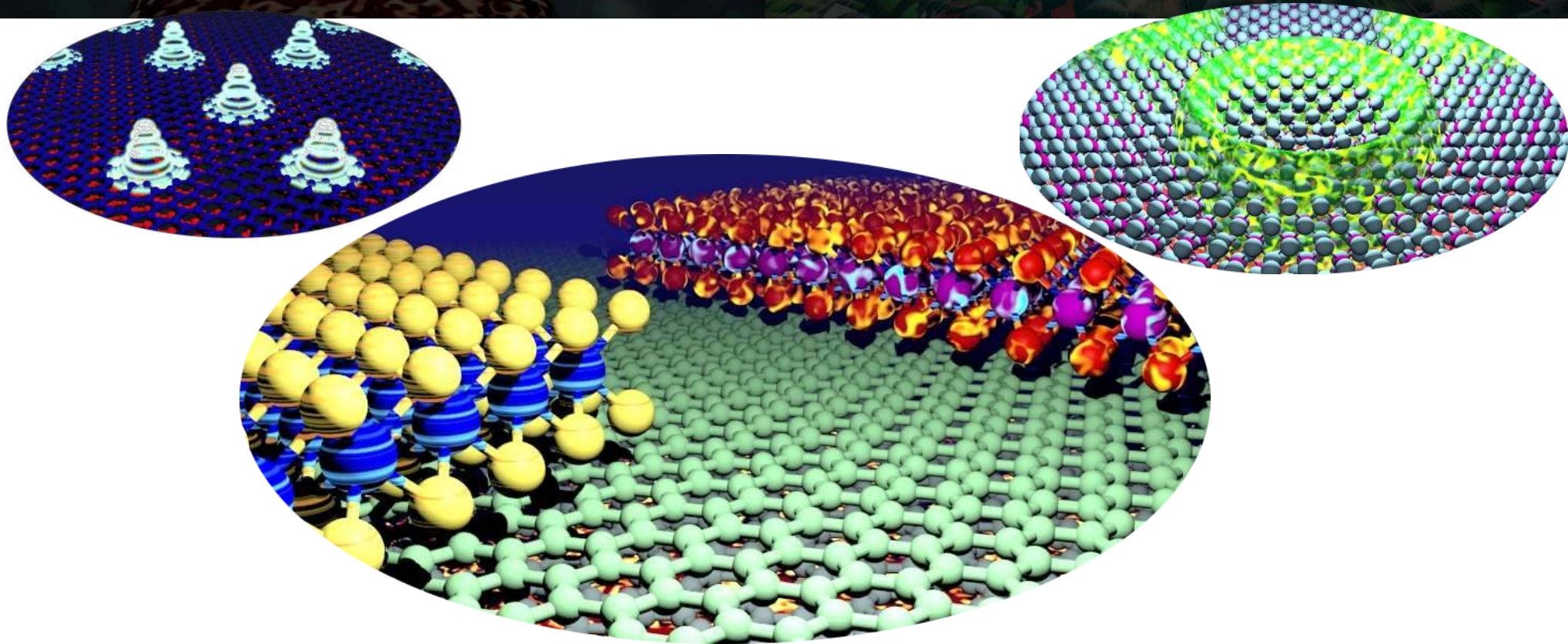
They can be rotated



Science 361.6403 690-693. (2018)

These are unique features of two-dimensional materials

A new universe in each van der Waals heterostructure



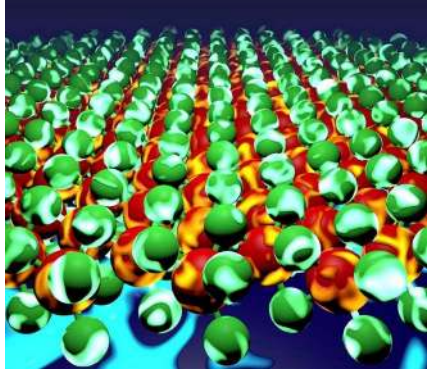
Each van der Waals heterostructure allows creating a whole new universe for electrons

Controlling 2D superconductors

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

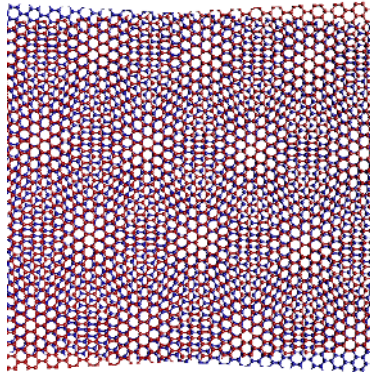
Most importantly, we can exploit the full tunability of van der Waals materials

Gating



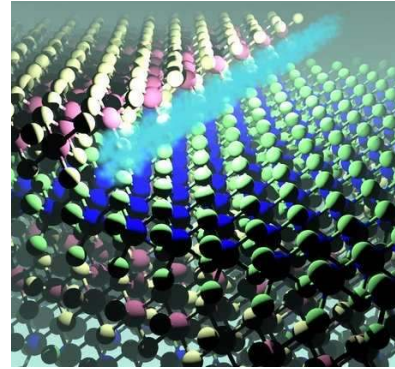
Science 306, 5696, 666-669 (2004)

Twist engineering



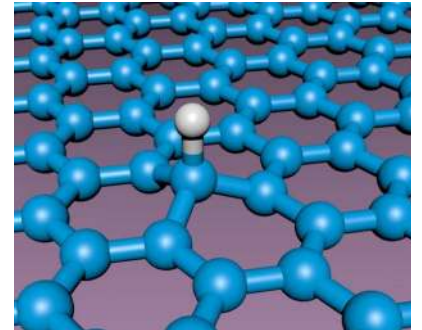
Nat, Rev, Mat, 6, 201–206 (2021)

Materials engineering



Nature 499, 419–425 (2013)

Atomic engineering

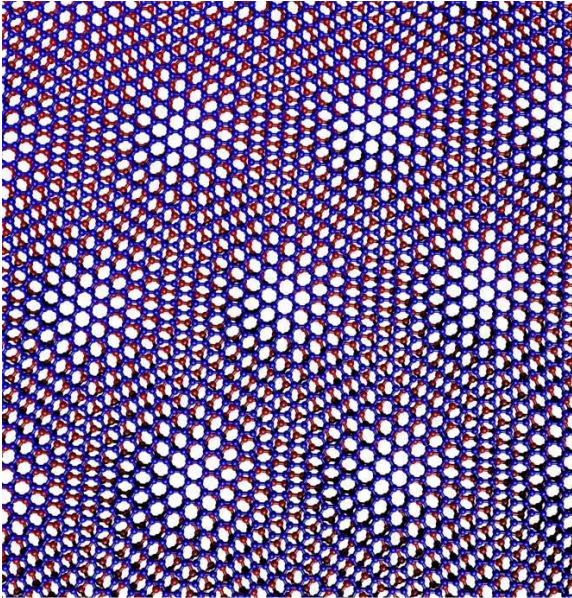


Science, 352(6284), 437-441 (2016)

Allowing to independently control different features of the electronic structure

One material, a zoo of electronic phases

Twisted bilayer graphene

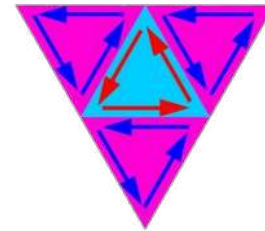


Superconductivity



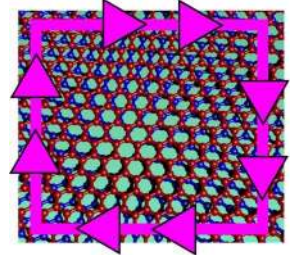
Nature 556, 43–50 (2018)

Topological networks



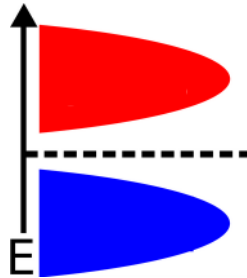
Nano Lett. 18, 11, 6725-6730 (2018)

Chern insulators



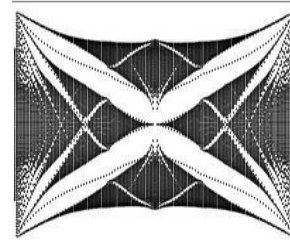
Science 365, 605-608 (2019)

Correlated insulators



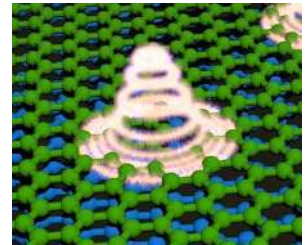
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

Fractional Chern insulators

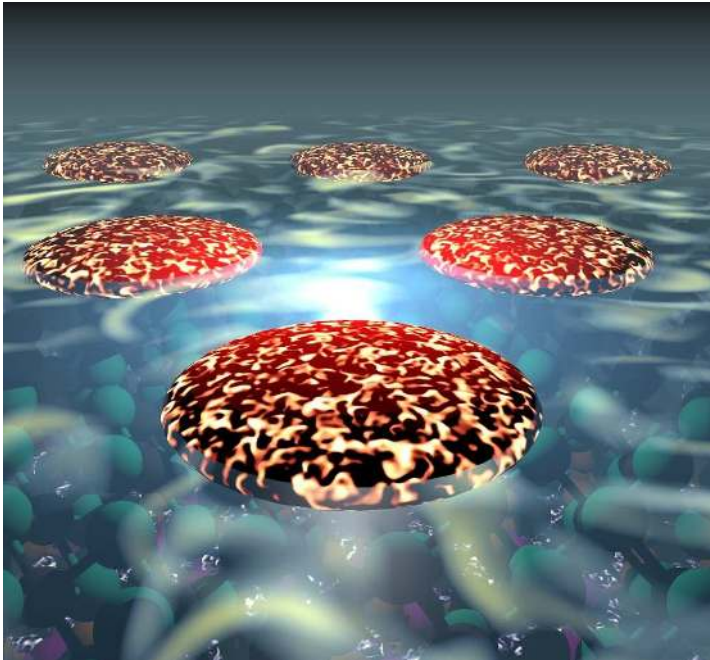


Nature 600, 439–443 (2021)

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

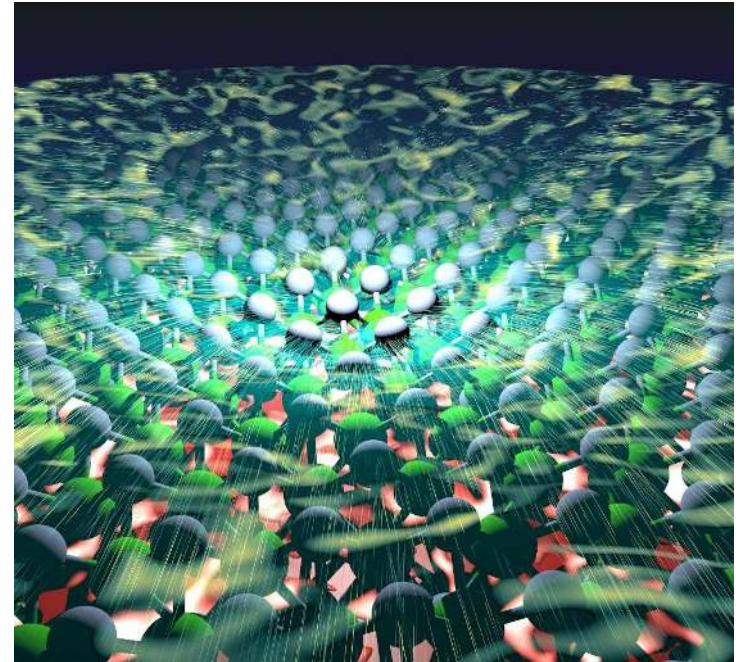
Today's plan

Artificial topological moiré
superconductivity in $\text{CrBr}_3/\text{NbSe}_2$



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

Nodal superconductivity in
ultraclean TaS_2 monolayer



arXiv:2112.07316 (2021)

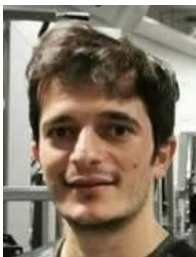
Behind the scenes

Experiment

S. Ganguli



M. Amini



M. Aapro



L. Yan



V. Vaňo



S. Kezilebieke



Md. Huda



P. Liljeroth



Theory

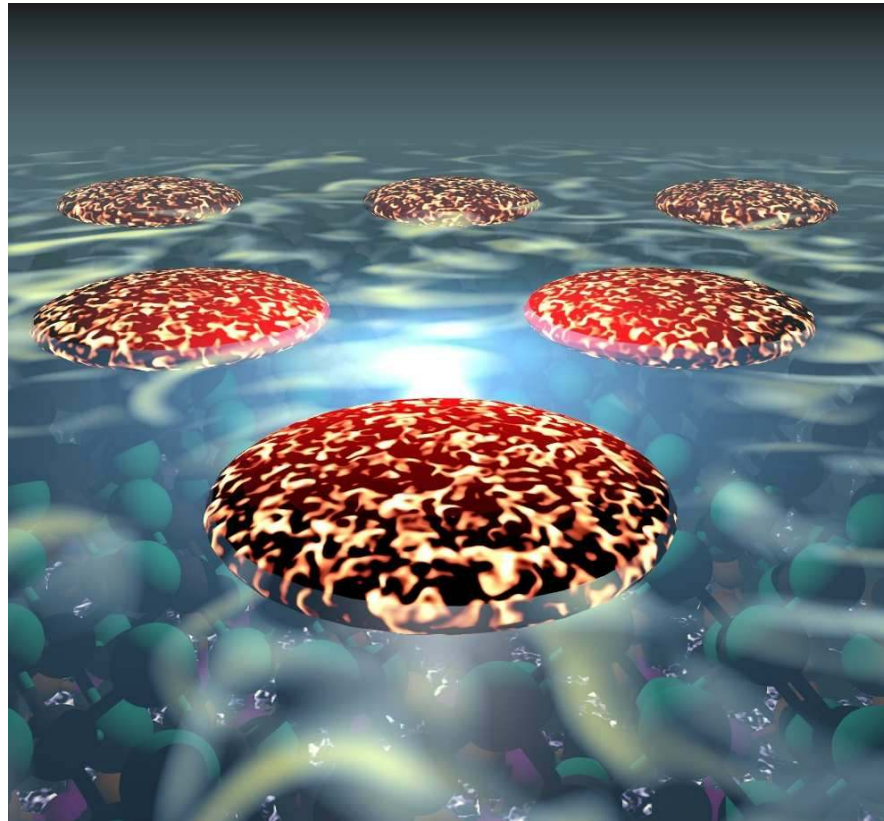
G. Chen



M. Khosravian



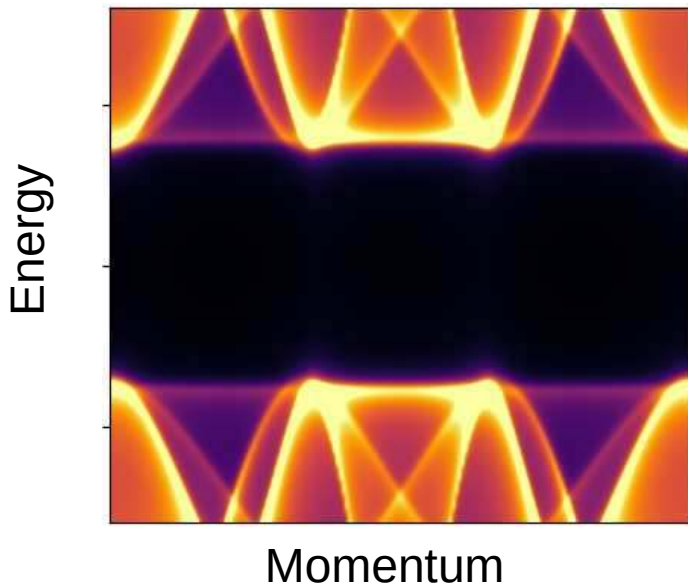
Artificial topological moire superconductivity in $\text{NbSe}_2/\text{CrBr}_3$



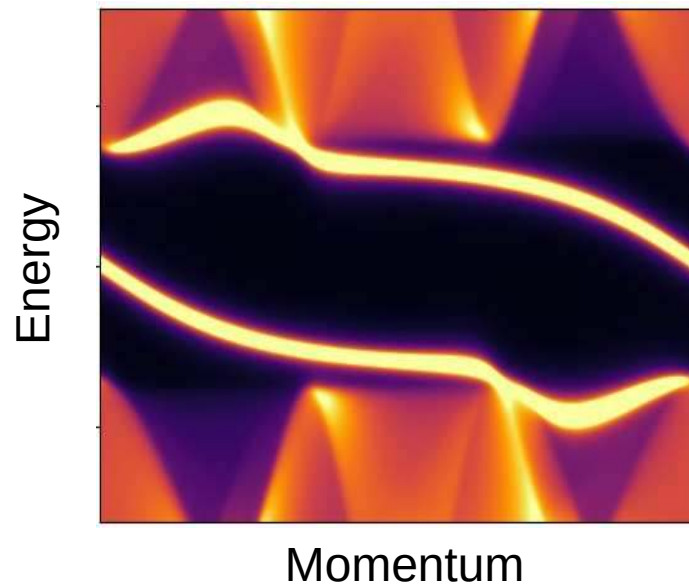
Nano Lett. 2022, 22, 1, 328–333 (2022)

Topological superconductors

Full gap in the bulk



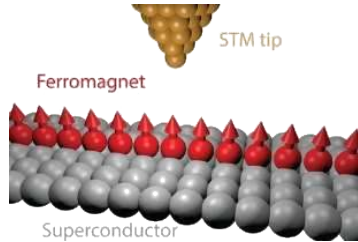
Gapless (Majorana) mode at the edge



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

Platforms for topological superconductivity

Ferromagnetic atomic chains



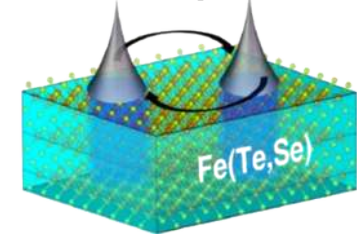
Science 346.6209 (2014): 602-607

Semiconductors



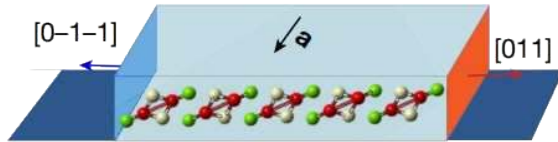
Science 354.6319 (2016): 1557-1562

Fe-based superconductors



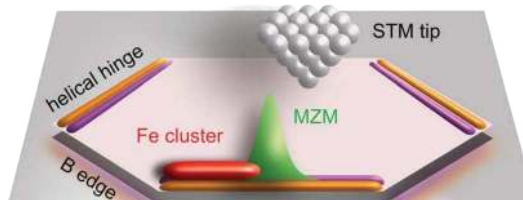
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



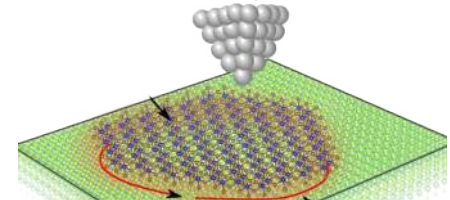
Nature 579, 523-527 (2020)

Topological insulators



Science 364.6447 (2019): 1255-1259

Two-dimensional materials



Nature 588, 424-428 (2020)

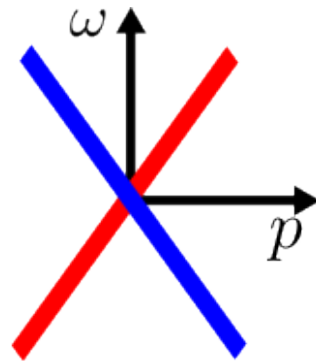
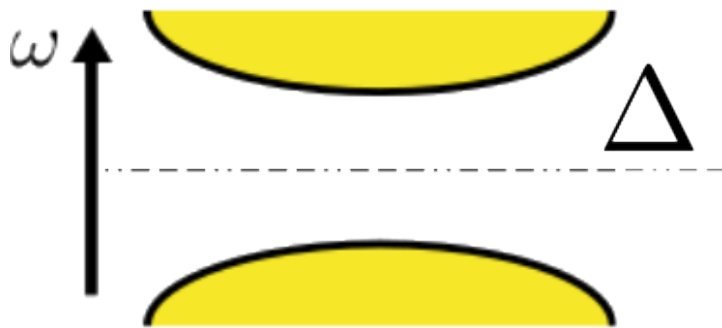
New materials open new venues for engineering and controlling Majorana physics

How to build your own topological superconductor



Ingredients

- s-wave pairing
- Helical states

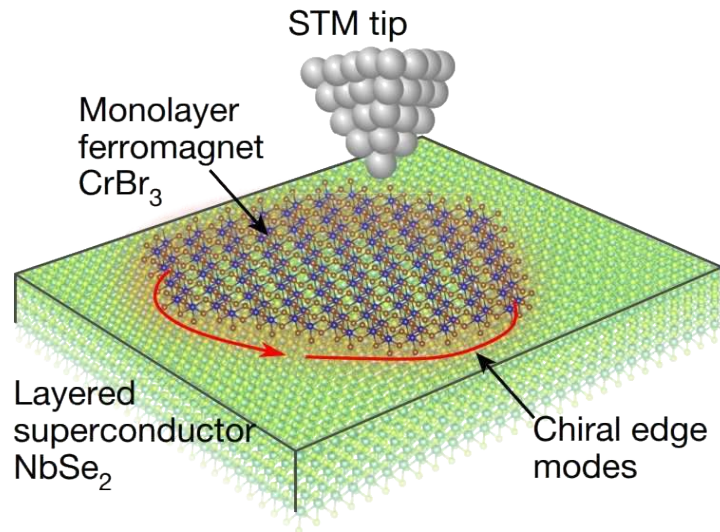


Objective: to realize a spinless superconductor

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

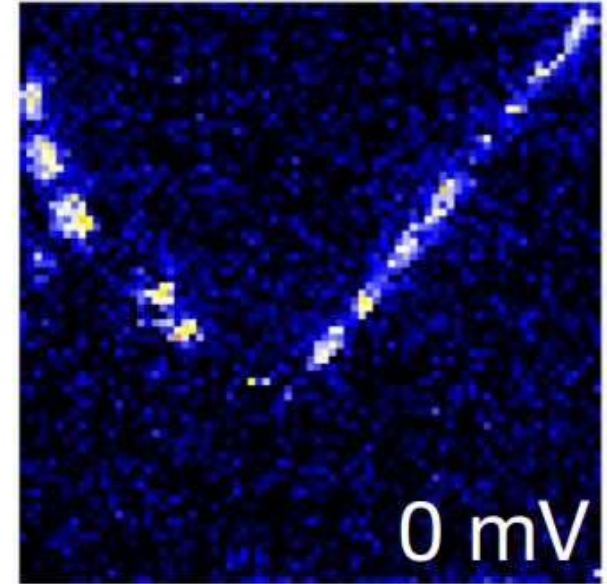
Topological superconductivity in a van der Waals heterostructure

CrBr₃/NbSe₂ heterostructure



Nature 588, 424–428 (2020)

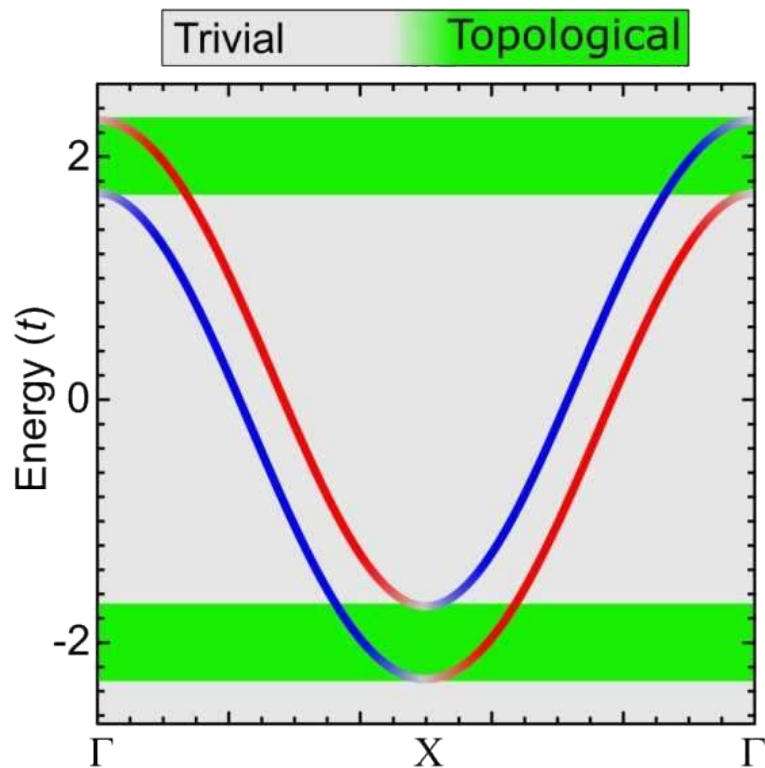
Zero bias dI/dV



A topological superconducting state appears in CrBr₃/NbSe₂

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

Warm up: 1D topological superconductor



$$H = H_0 + H_J + H_R$$

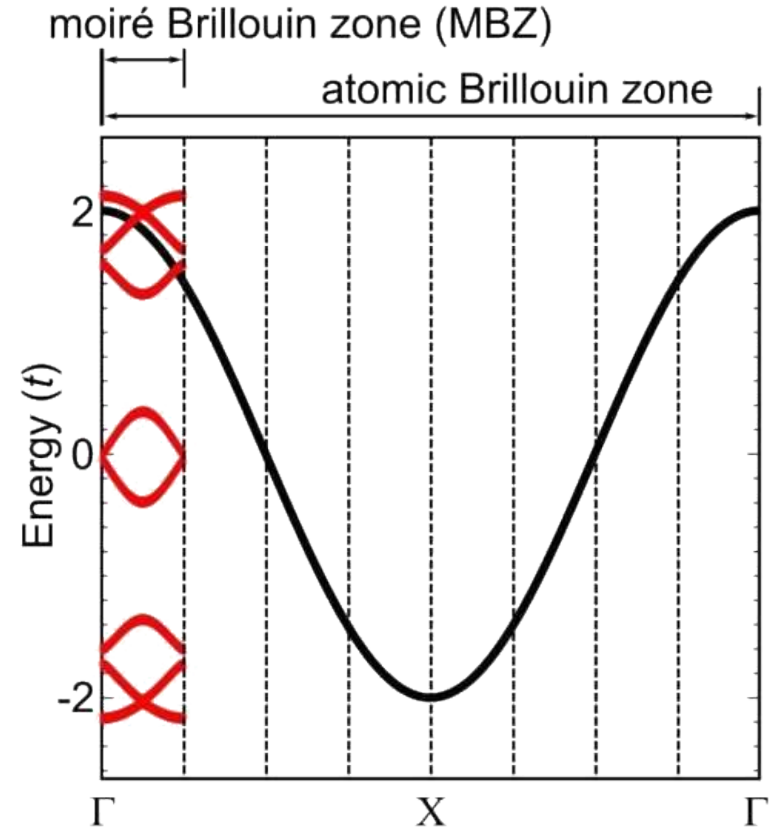
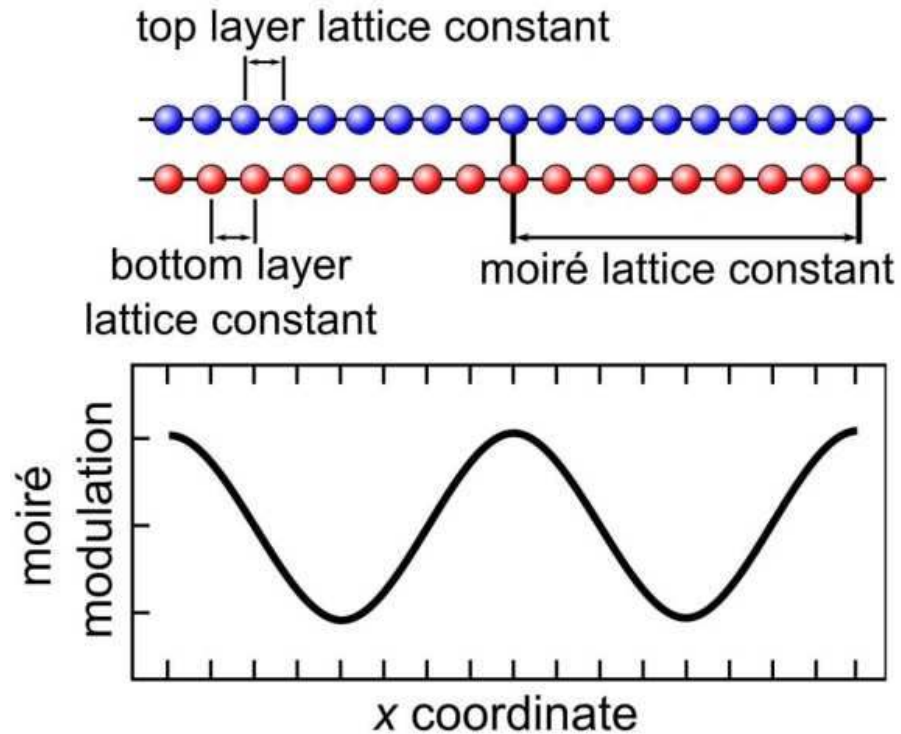
Kinetic energy

Exchange field

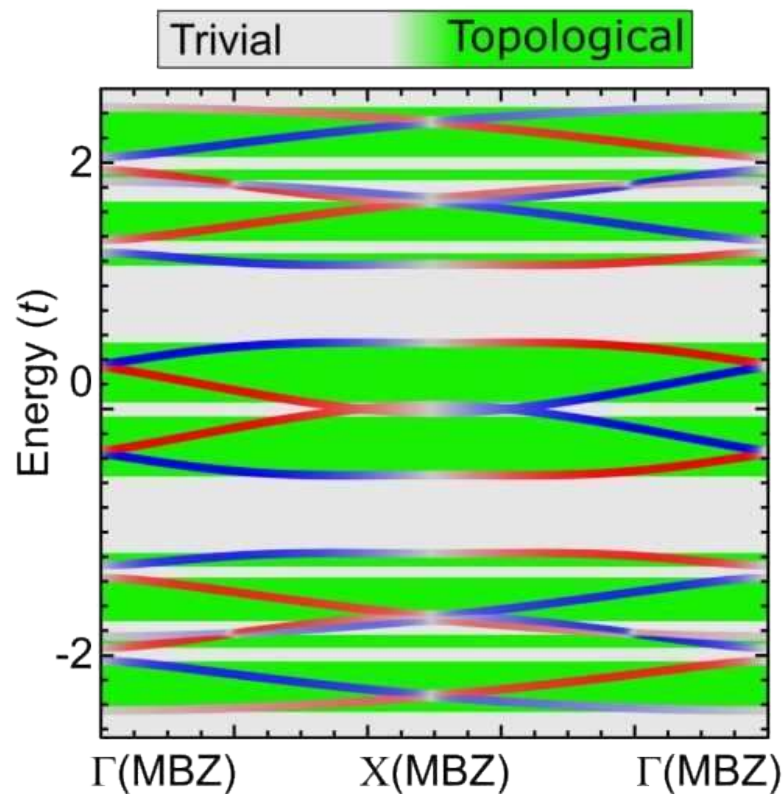
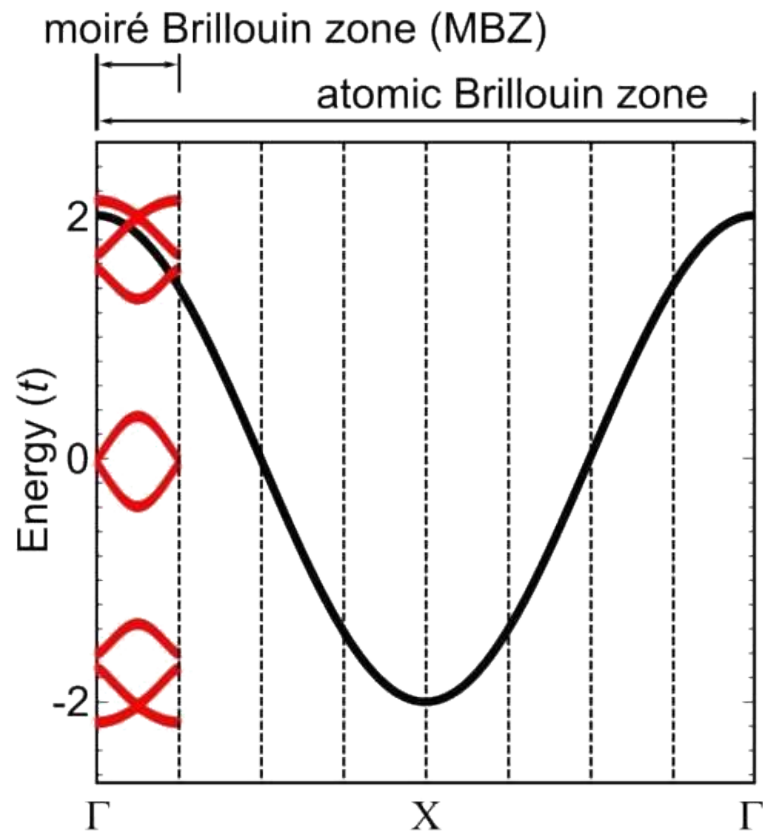
Rashba spin-orbit coupling

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

Warm up: 1D moiré superconductor

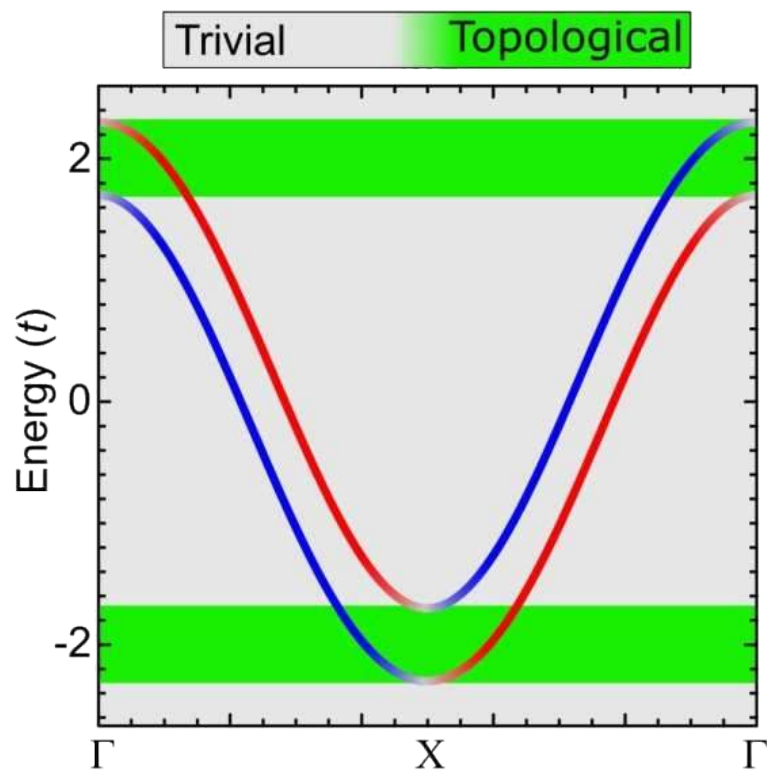


Warm up: 1D moiré superconductor

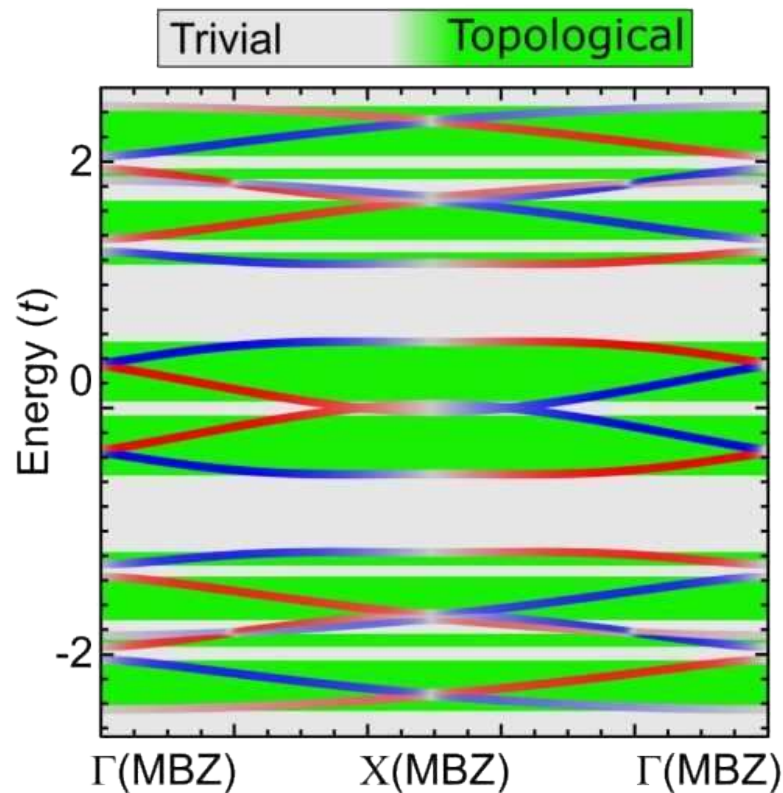


Warm up: 1D moire superconductor

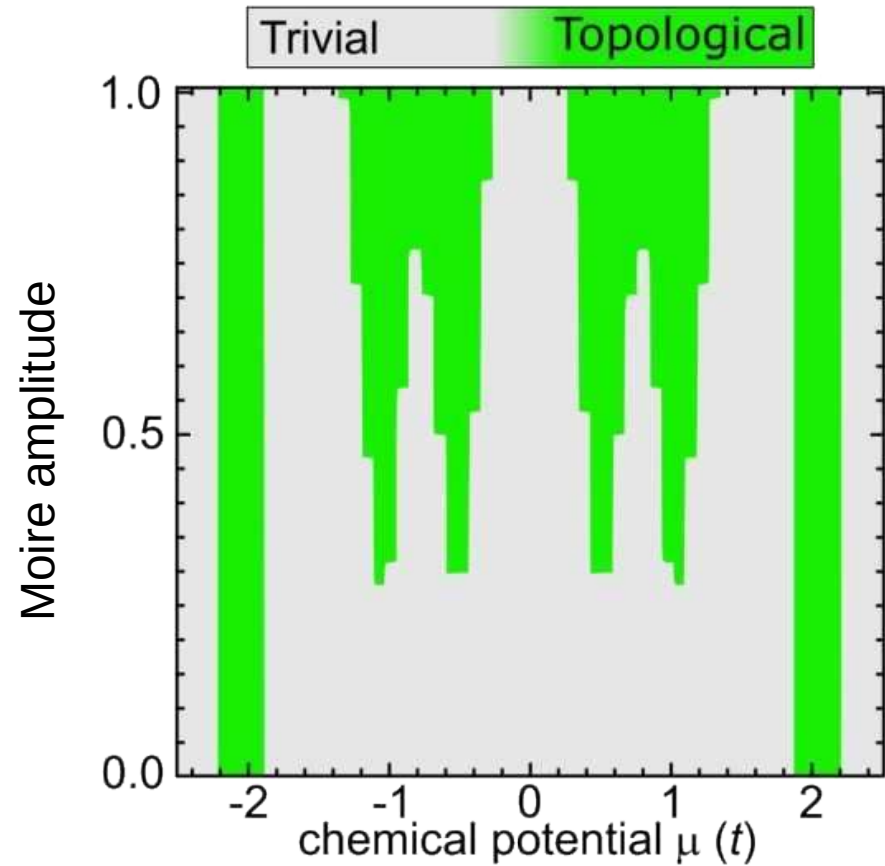
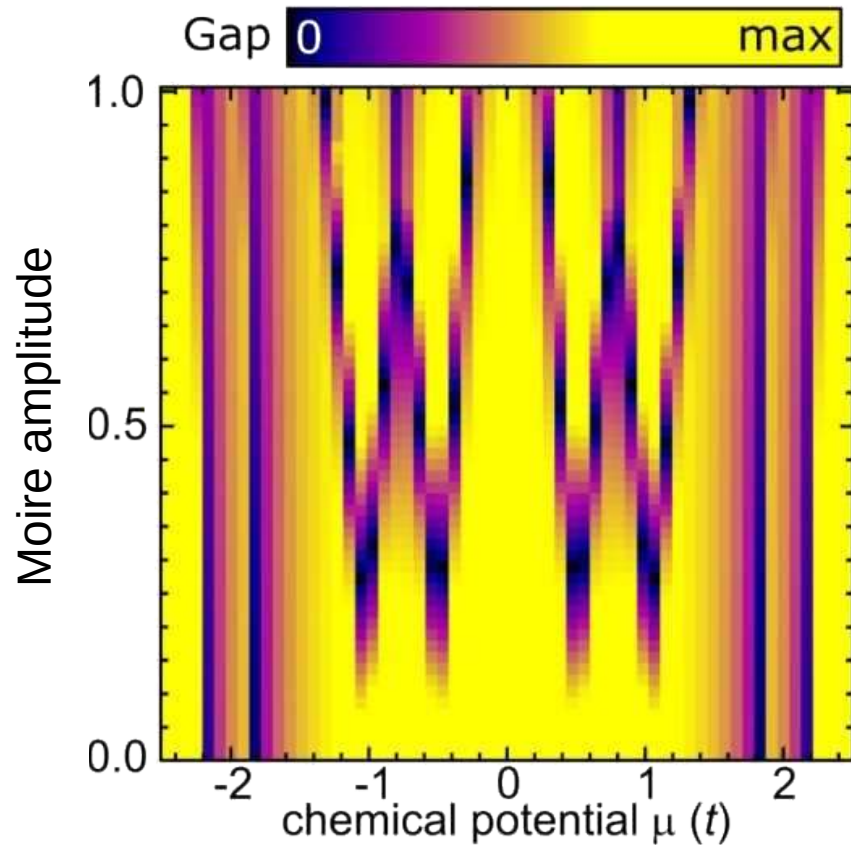
Without moire



With moire

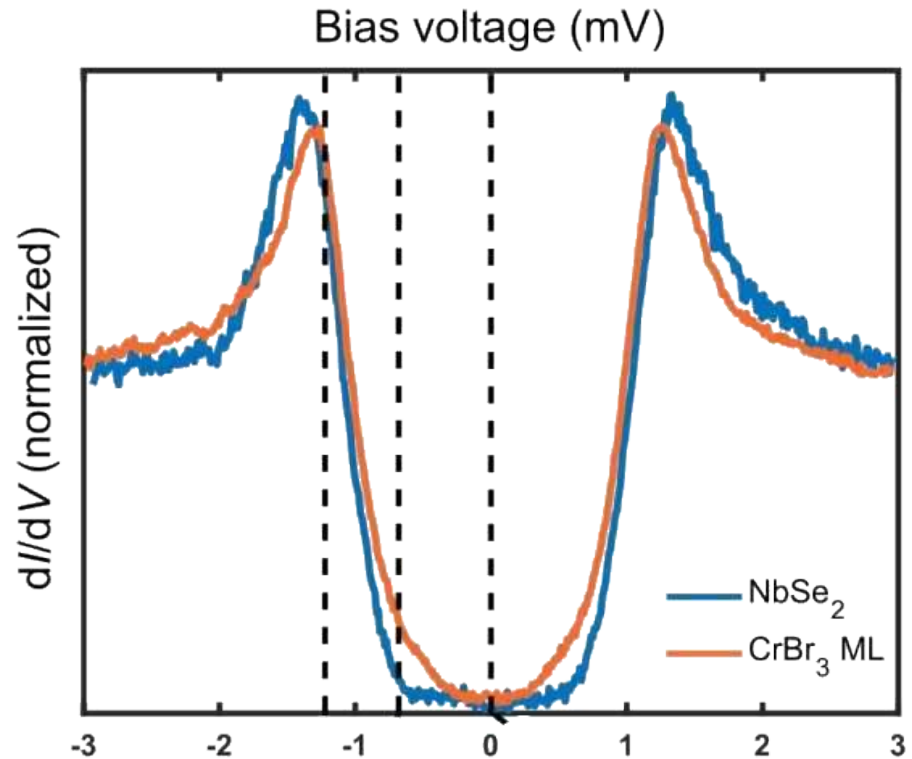
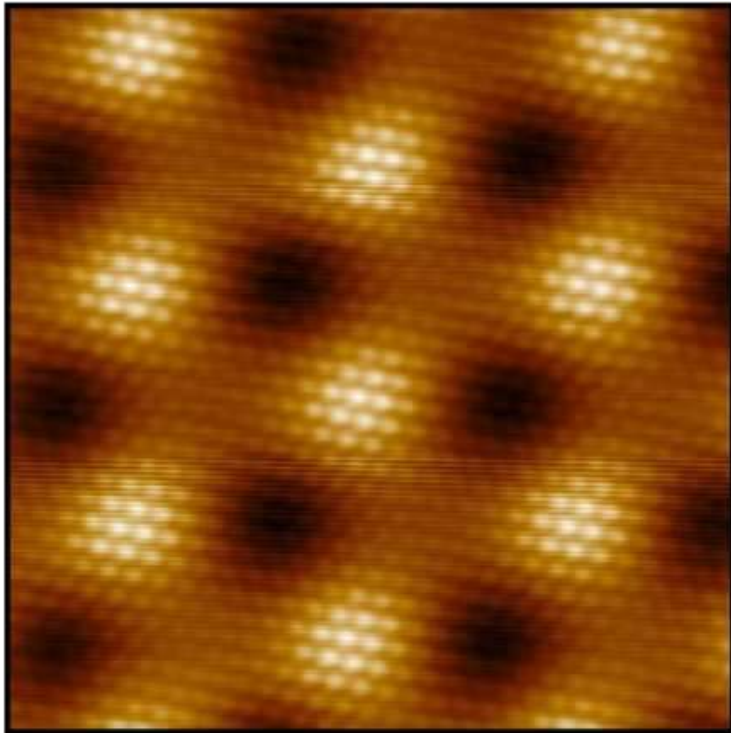


Warm up: 1D moire superconductor



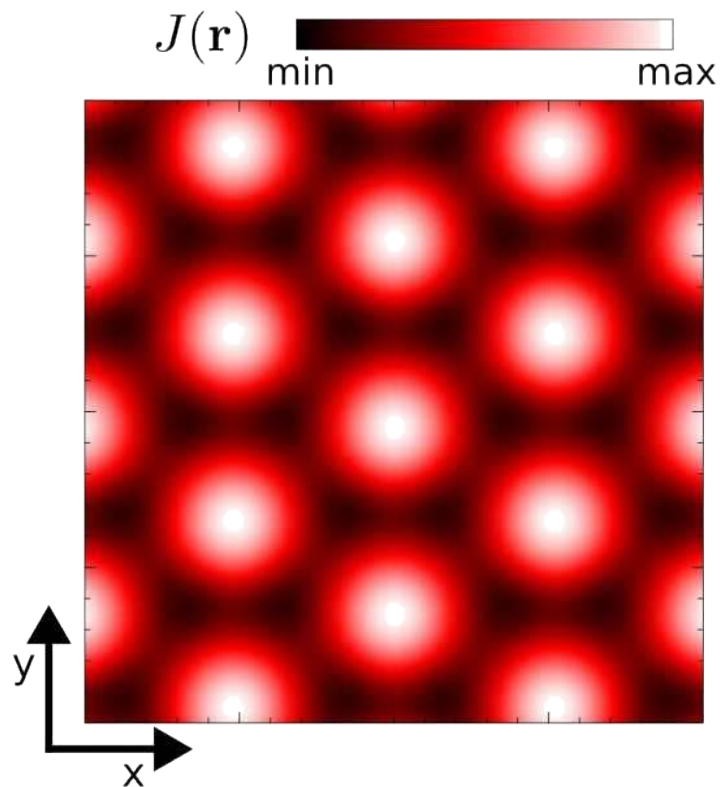
$\text{CrBr}_3/\text{NbSe}_2$ heterostructure

Height 0 Å  0.26 Å



Bulk Yu-Shiba Rusinov bands

Exchange profile



Full Hamiltonian of the moire system

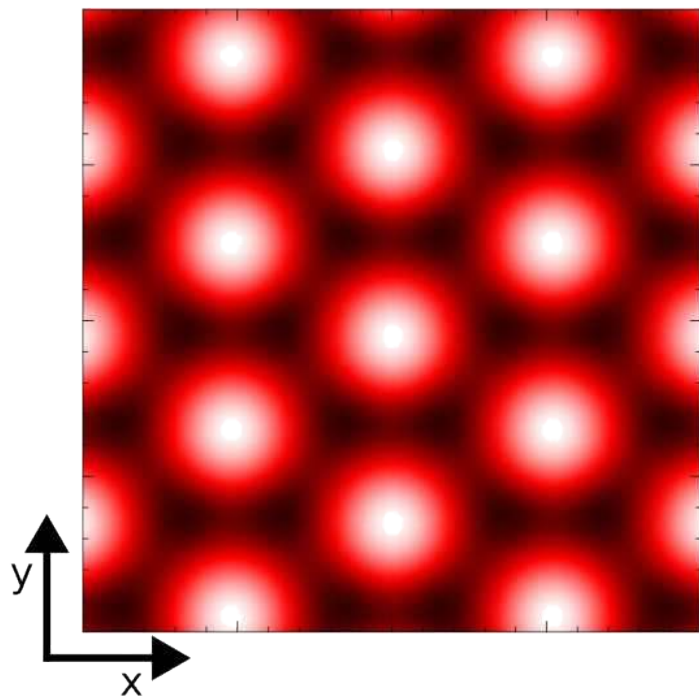
$$\begin{aligned}
 H = & \sum_{\langle ij \rangle, s} t \left(\frac{\mathbf{r}_i + \mathbf{r}_j}{2} \right) c_{i,s}^\dagger c_{j,s} + \sum_{i,s} \mu(\mathbf{r}) c_{i,s}^\dagger c_{i,s} + \\
 & i \sum_{\langle ij \rangle, s, s'} \lambda \left(\frac{\mathbf{r}_i + \mathbf{r}_j}{2} \right) \mathbf{d}_{ij}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

Exchange profile following the moire

Bulk Yu-Shiba Rusinov bands

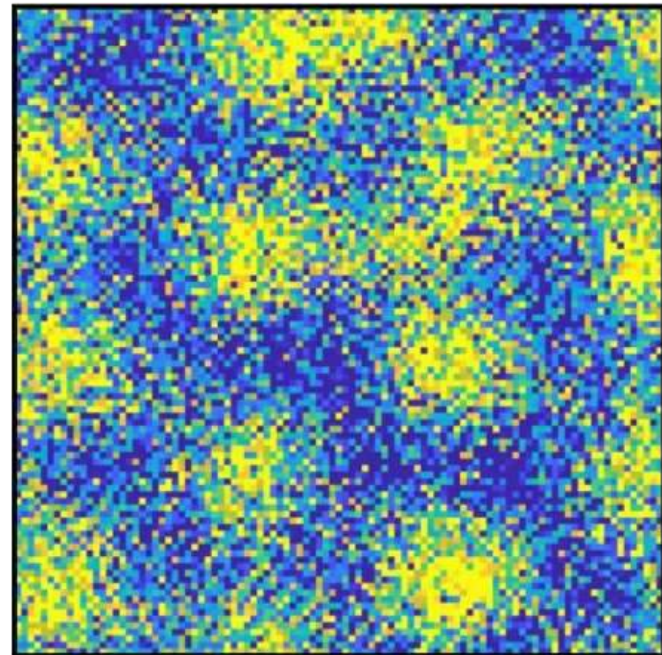
Exchange profile

$J(\mathbf{r})$  min max



Experimental dIdV

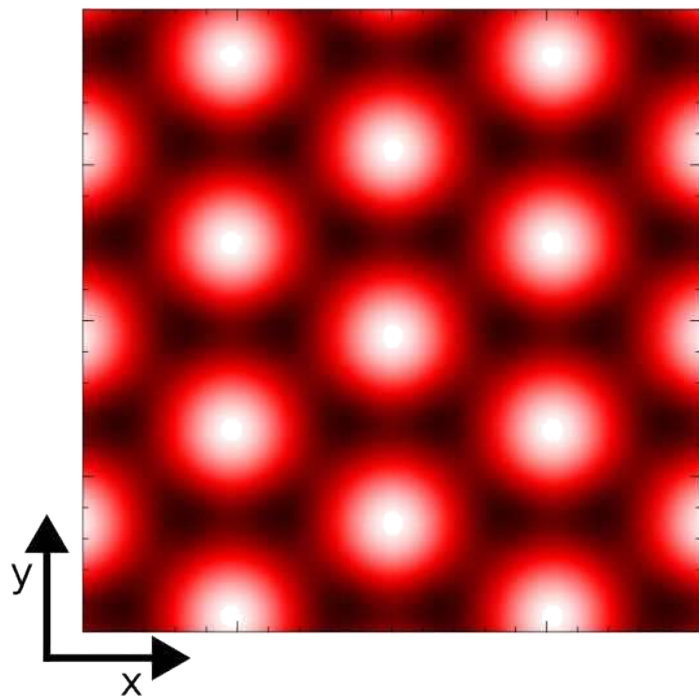
dI/dV (nS) 36  49



Bulk Yu-Shiba Rusinov bands

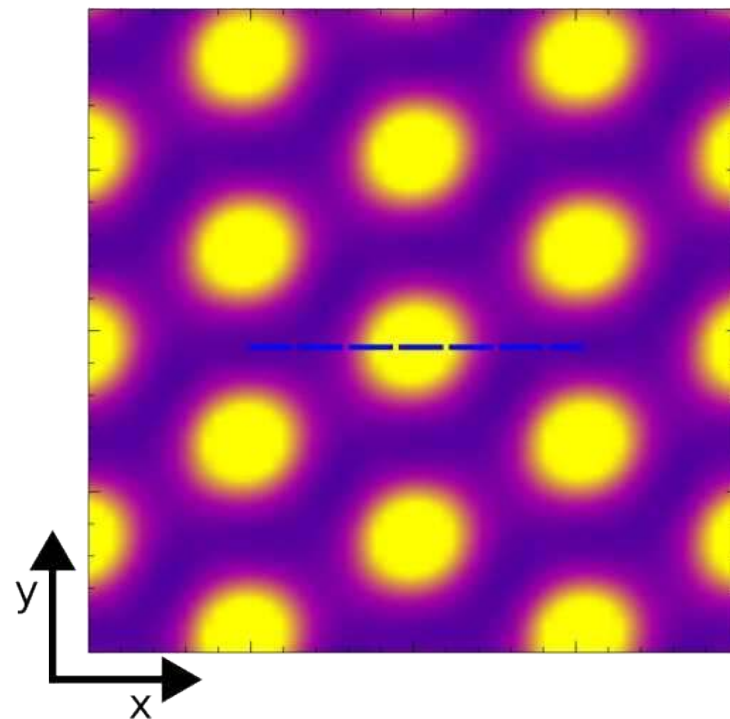
Exchange profile

$J(\mathbf{r})$  min max



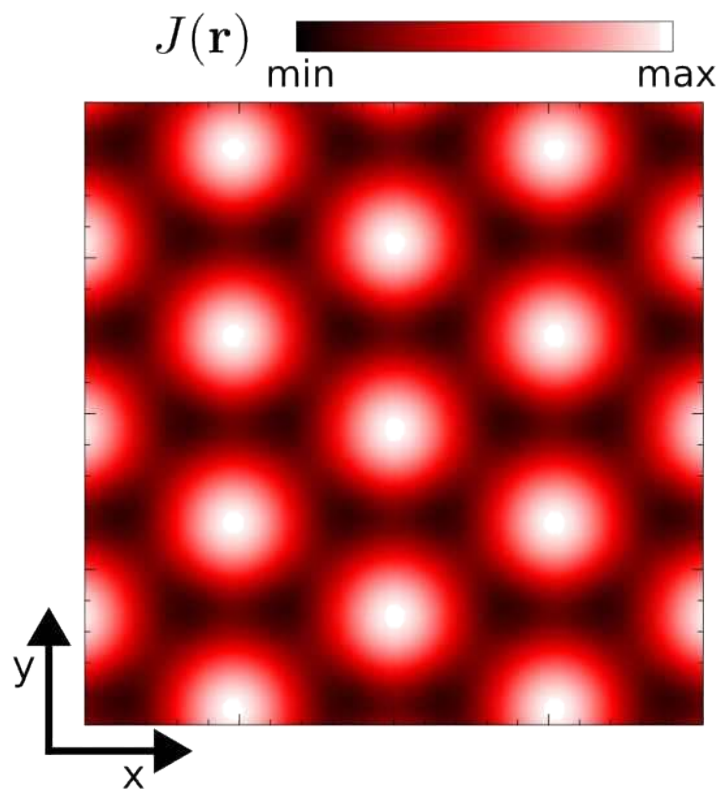
Theoretical LDOS

LDOS  0 max

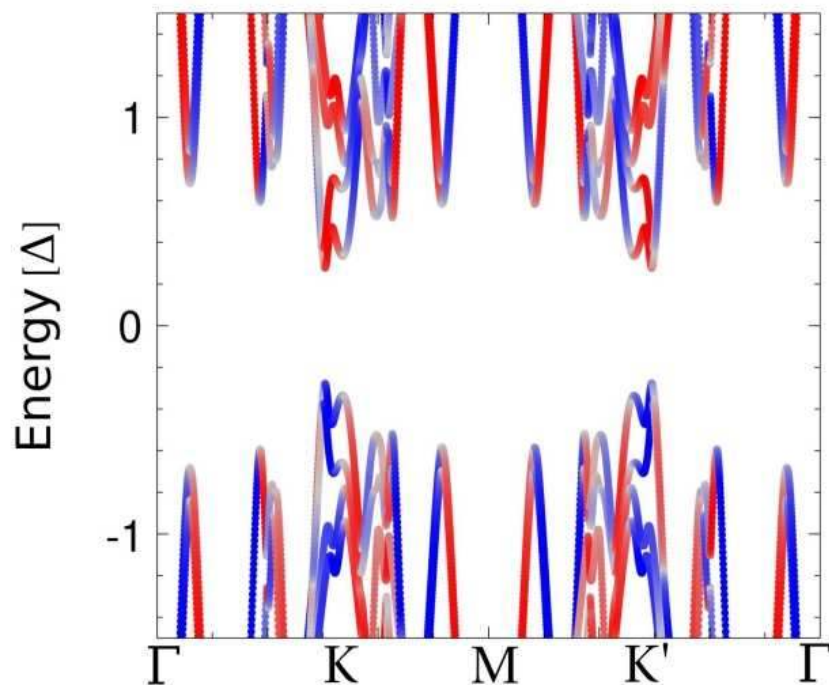


Bulk Yu-Shiba Rusinov bands

Exchange profile

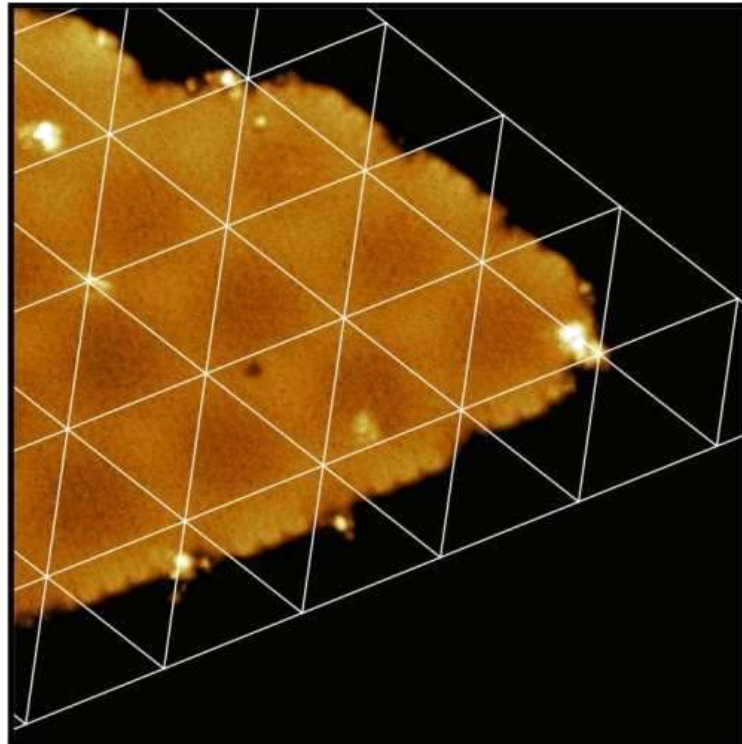


Moire electronic structure



Spectral properties close to boundaries

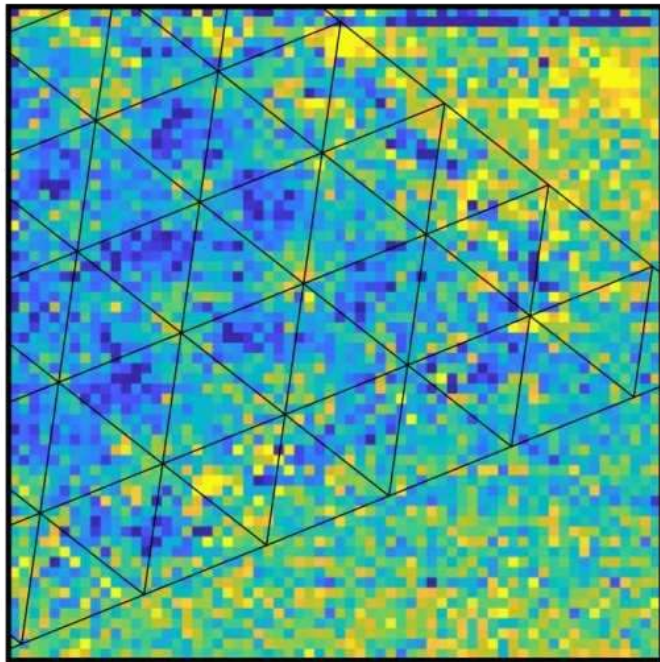
Height 0 Å 6 Å



Bulk Yu-Shiba-Rusinov states

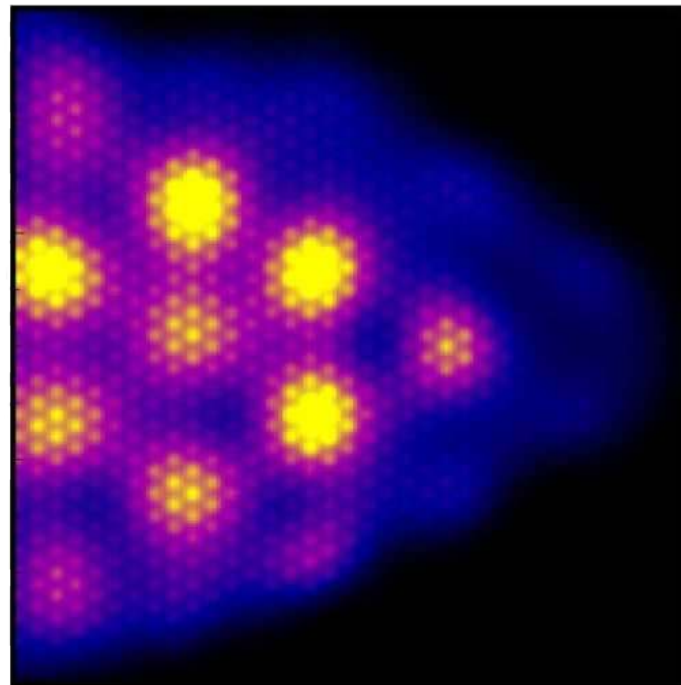
Experiment

dI/dV (nS) 19 36



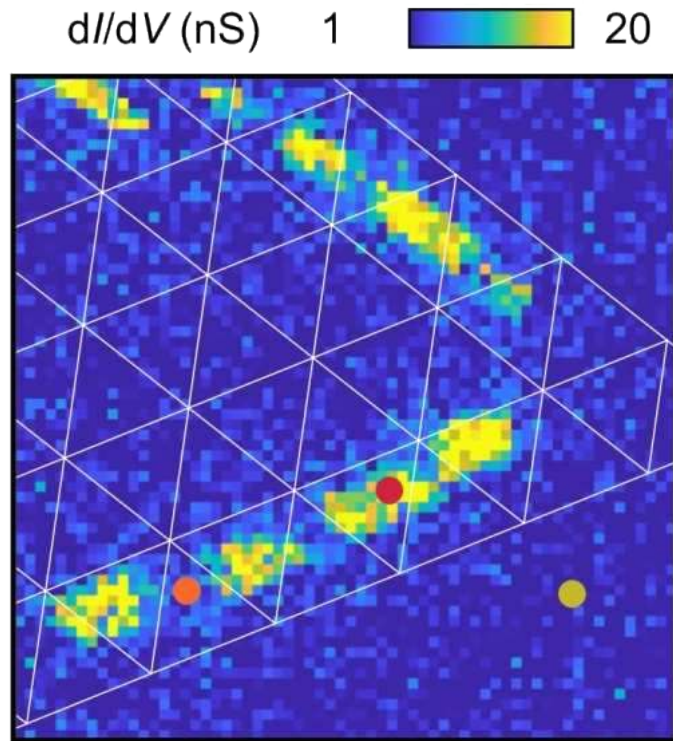
Theory

LDOS 0 max

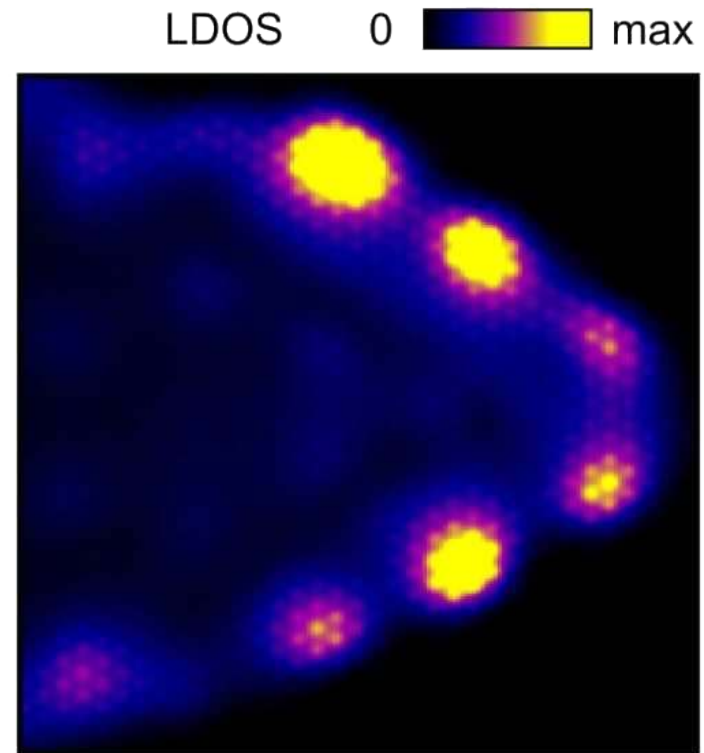


Topological moire edge states

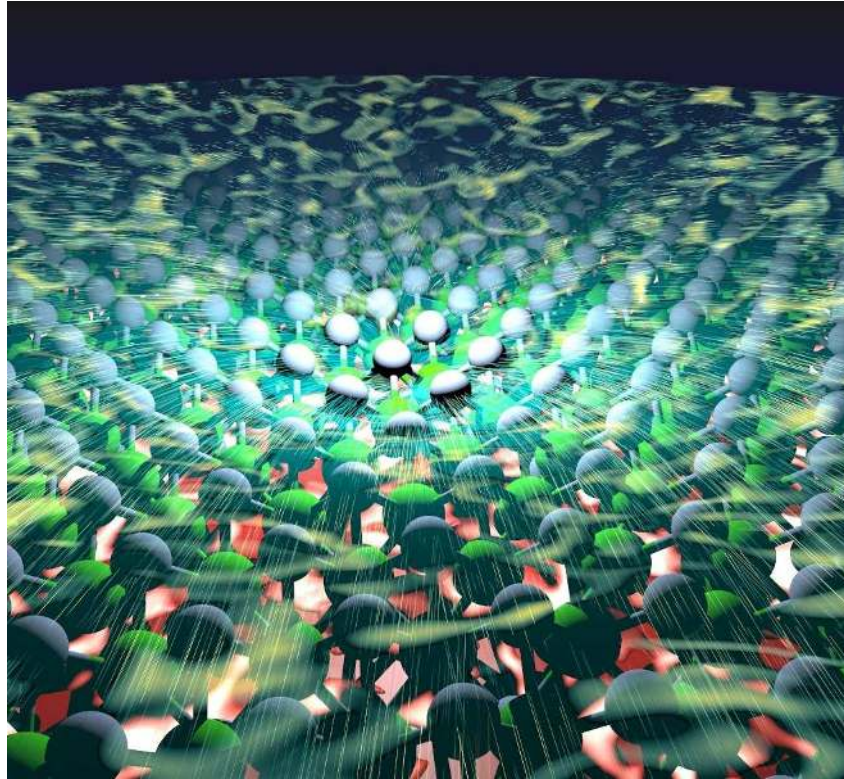
Experiment



Theory



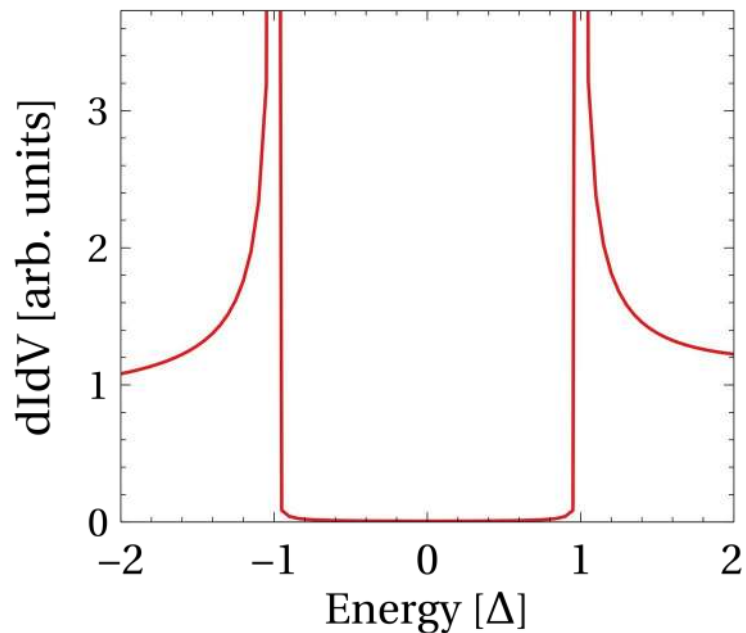
Nodal superconductivity in ultraclean TaS_2



arXiv:2112.07316 (2021)

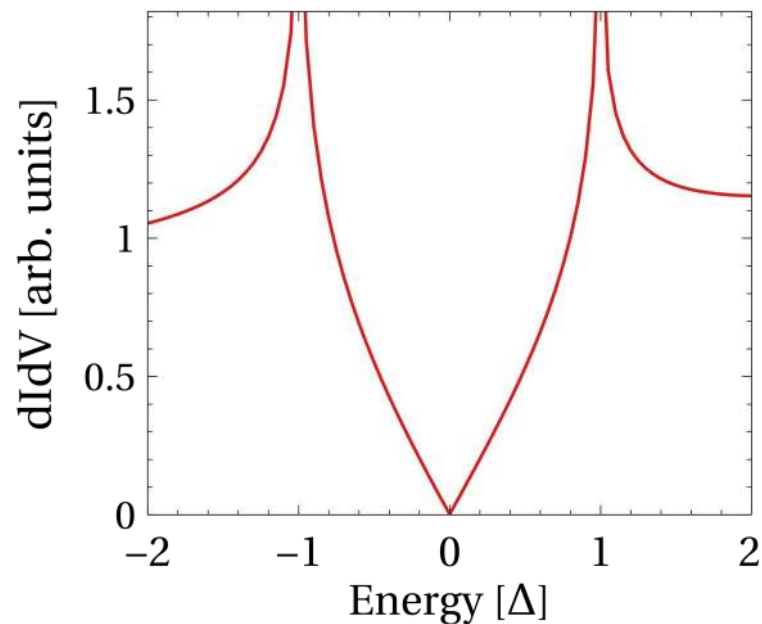
Gapped and nodal superconductivity

Conventional s-wave



Driven by electron-phonon

Unconventional nodal f-wave



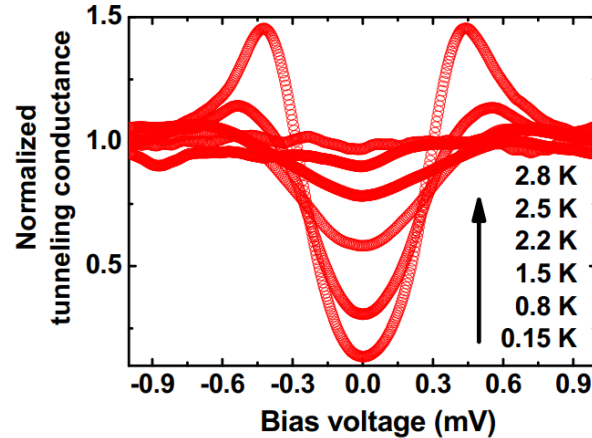
Driven by unconventional mechanism
(magnons, valence fluctuations)

The nature of superconductivity in dichalcogenide monolayers

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

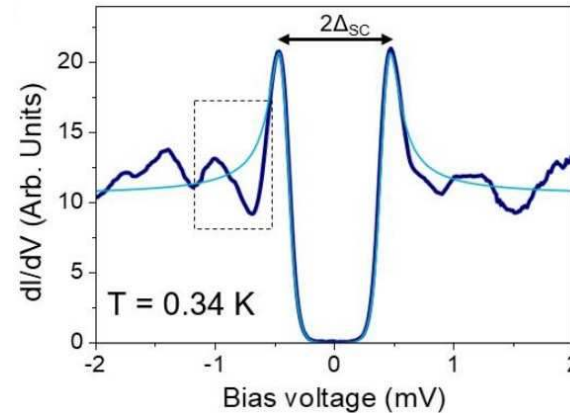
However, there are signatures hinting that they may be close to a phase transition

Signatures of f-wave in TaS_2



Phys. Rev. B 89, 224512 (2014)

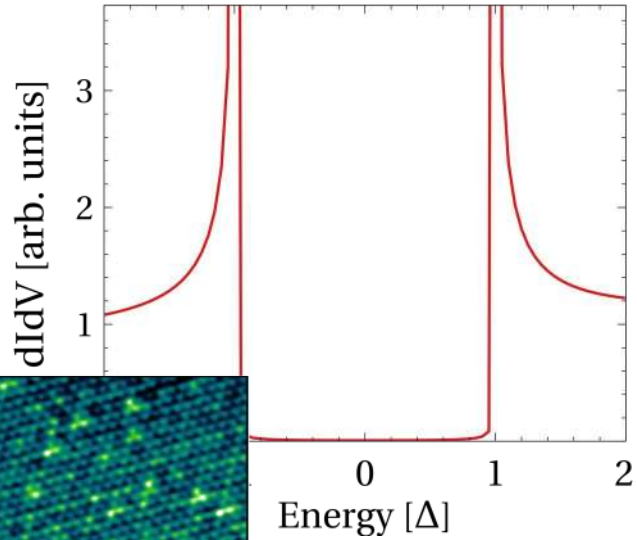
Leggett modes in NbSe_2



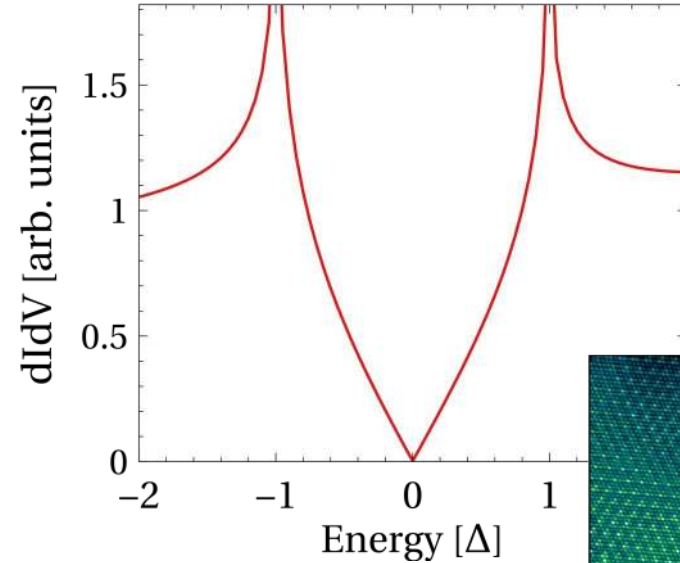
arXiv:2101.04050 (2021)

Two superconducting states in TaS₂ monolayer

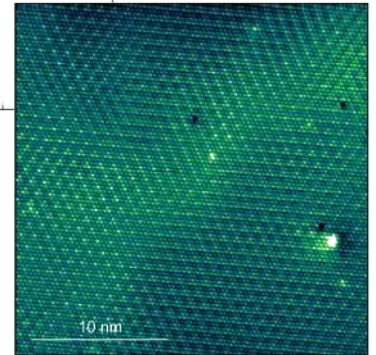
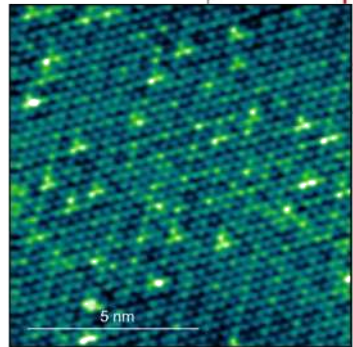
Strong disorder
Fully-gaped s-wave



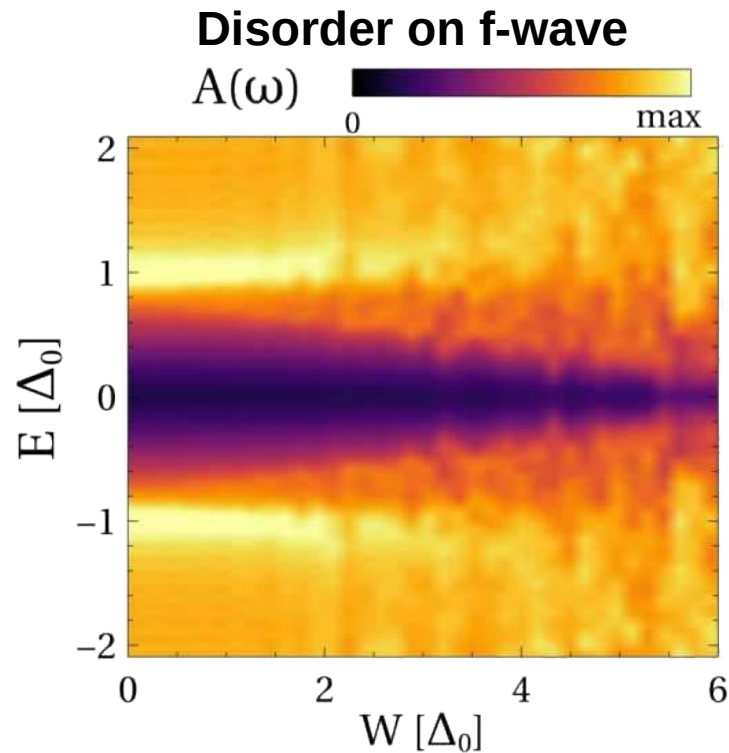
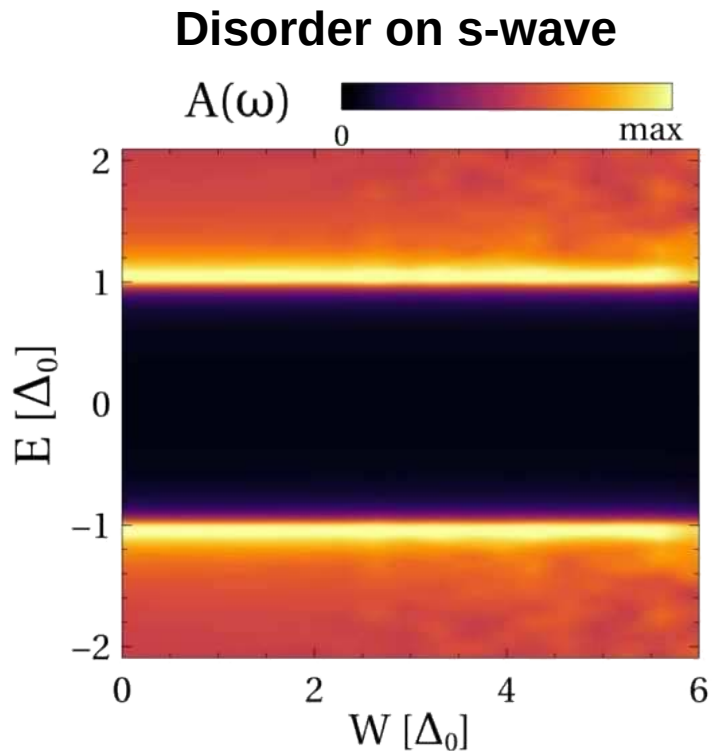
Weak disorder
Gapless nodal f-wave



Superconducting phase transition associated with disorder

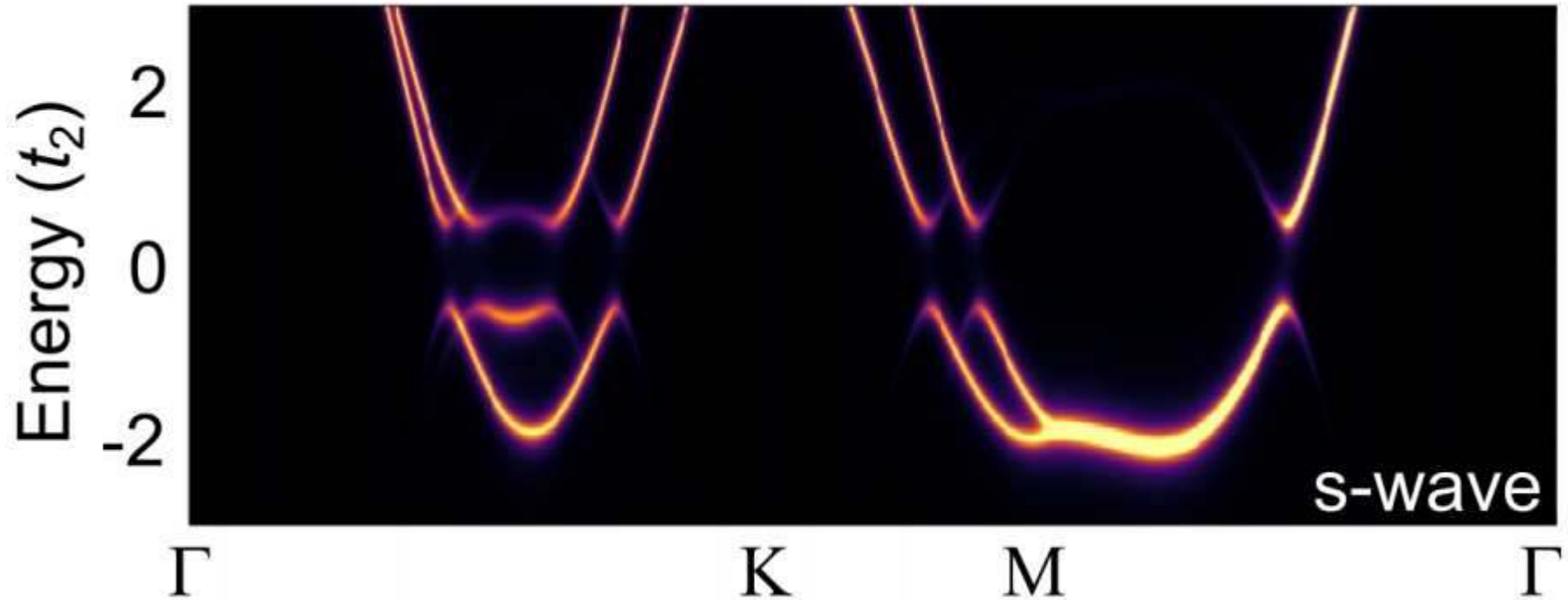


Impact of disorder for f-wave and s-wave



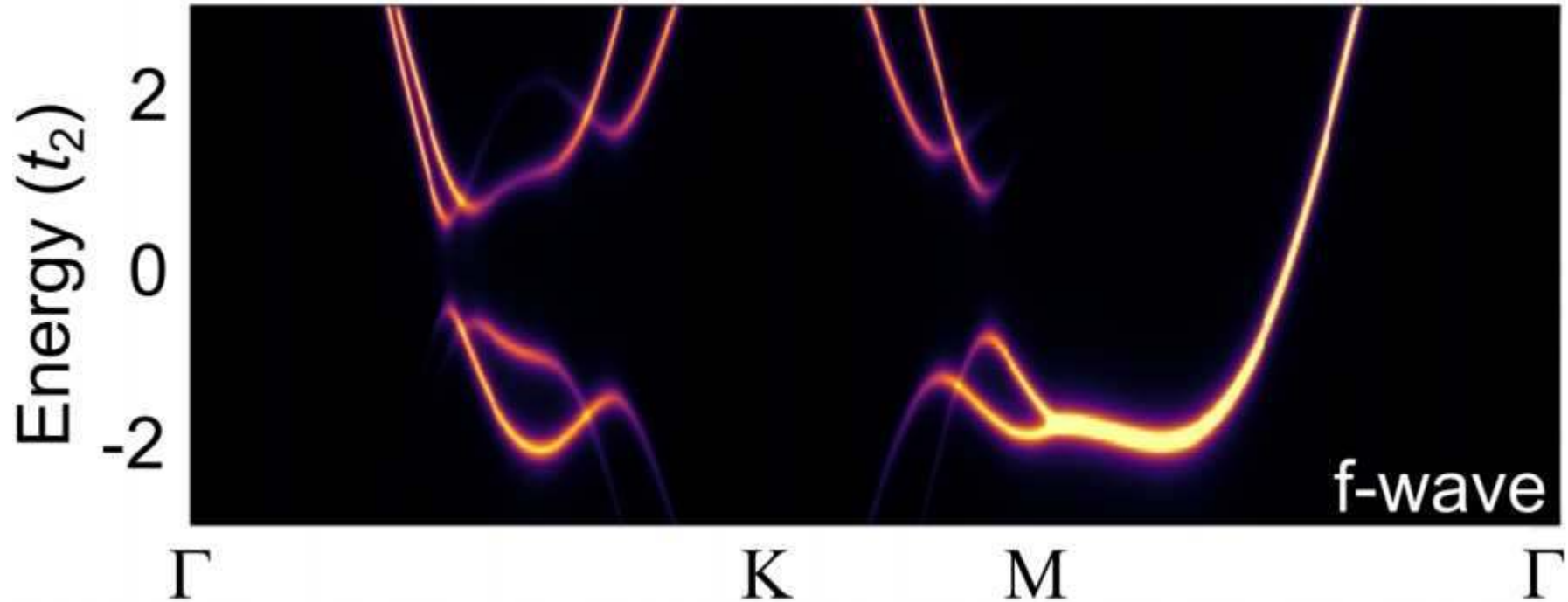
$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{SC} + \sum_{n,s} W_n c_{n,s}^\dagger c_{n,s}$$

Electronic structure with an s-wave gap



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

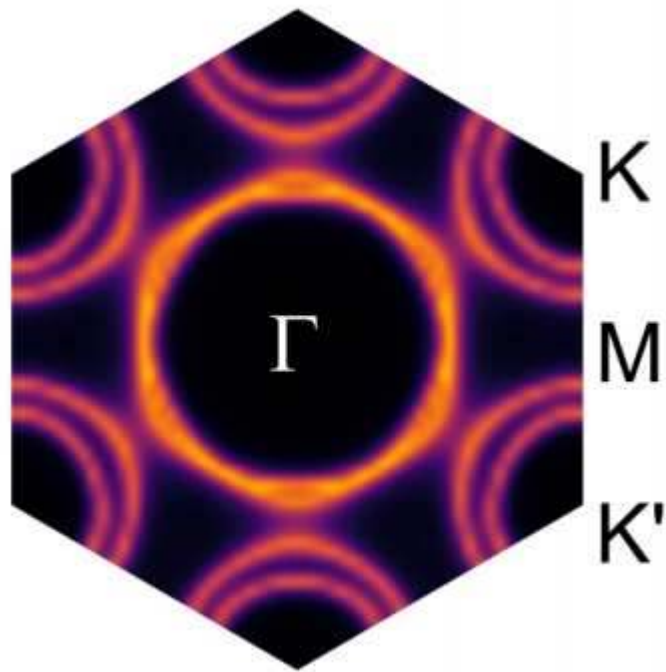
Electronic structure with an f-wave gap



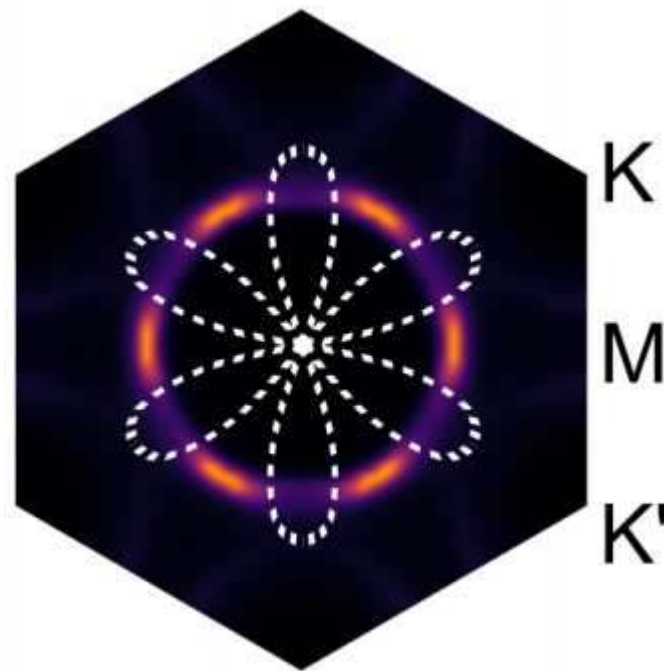
Part of the band structure remains gapless in the presence of superconductivity

Fermi surface of TaS_2

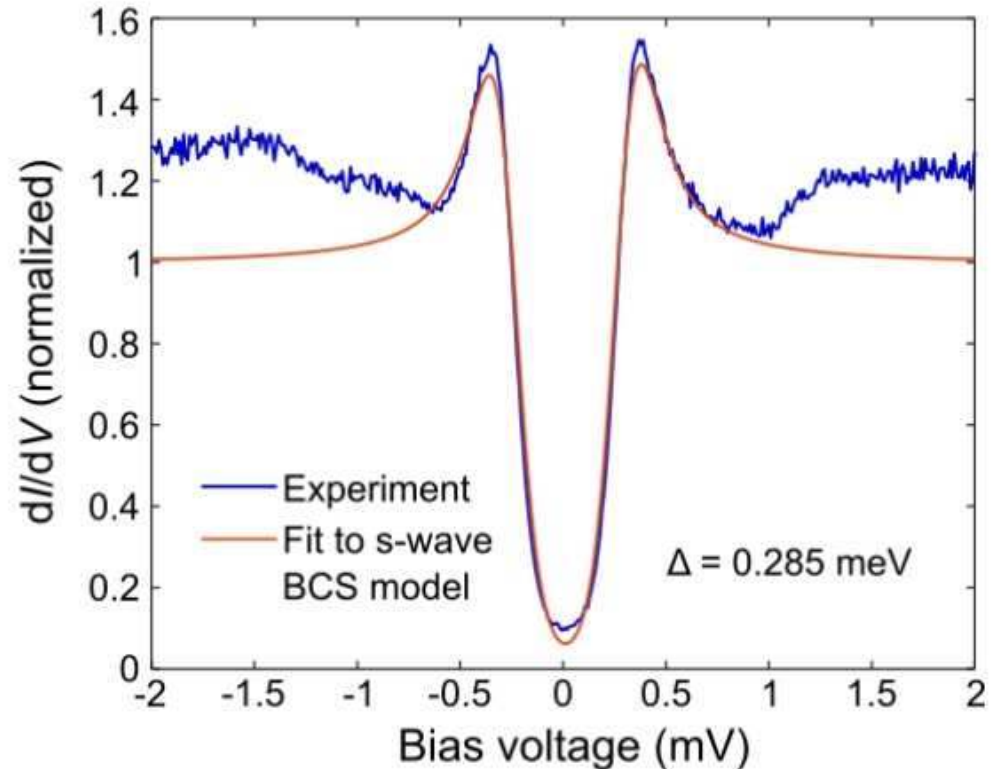
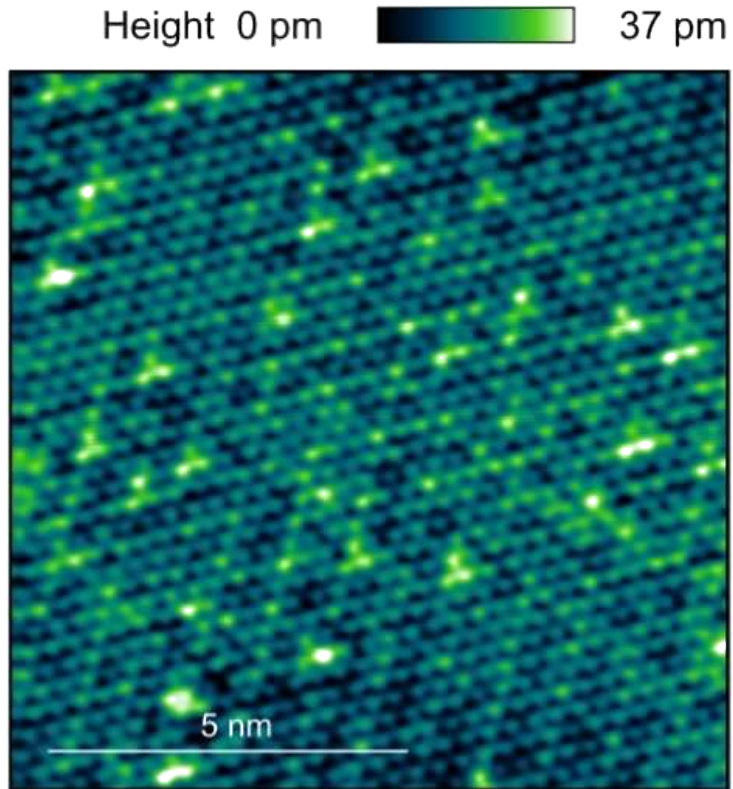
Normal State



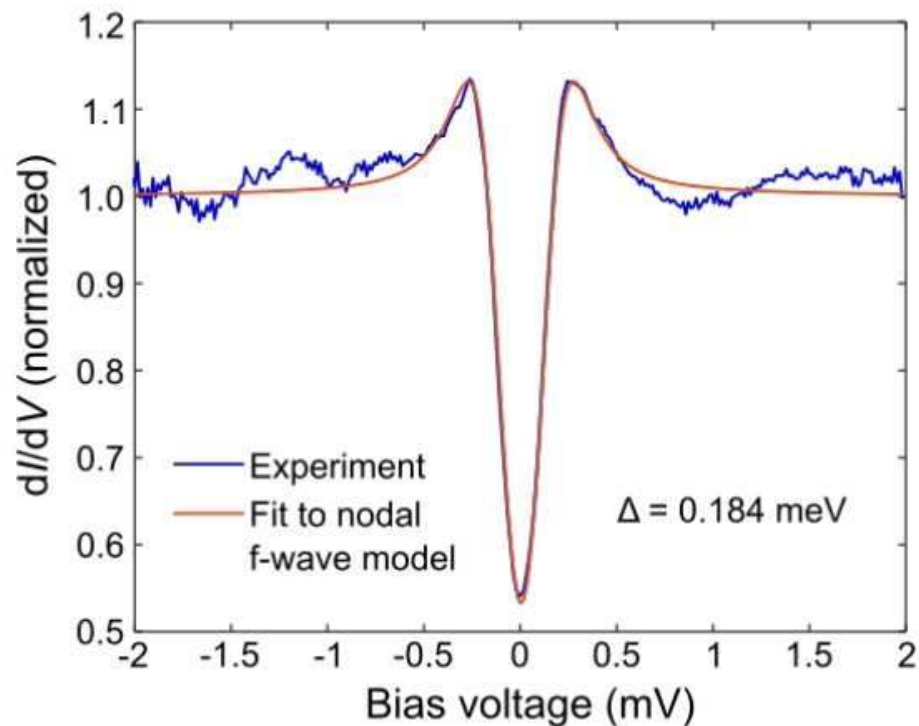
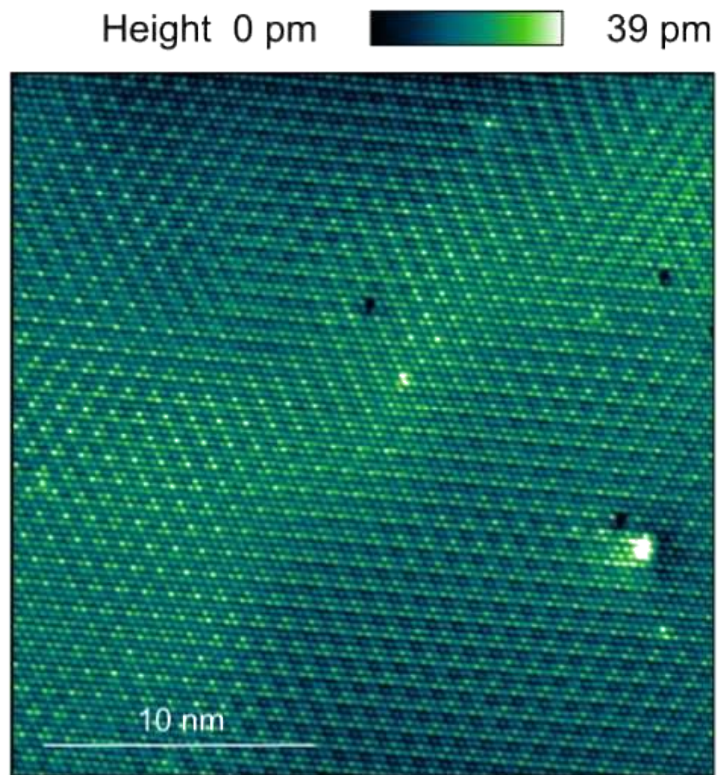
Nodal superconducting state



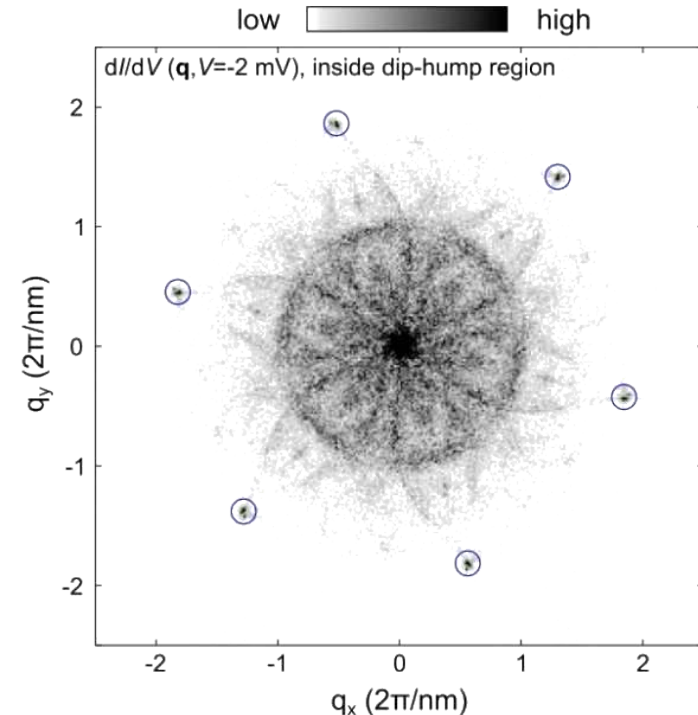
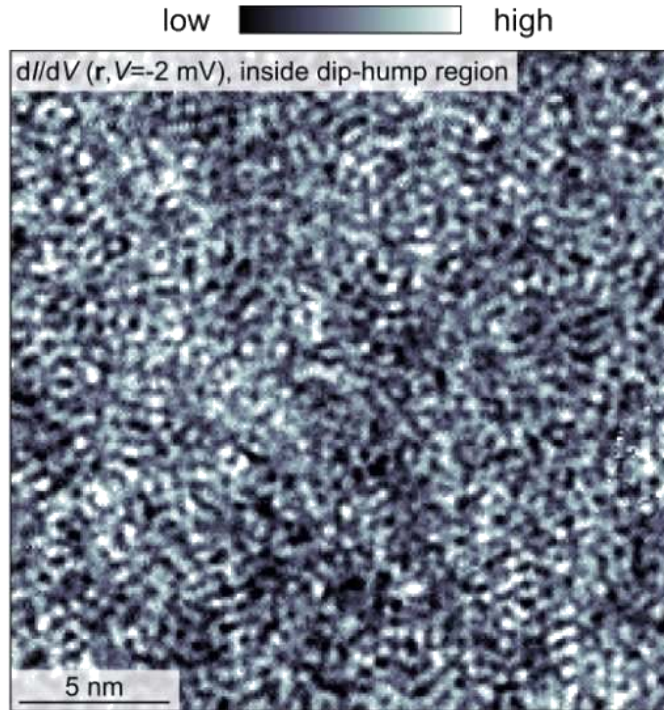
Dirty TaS₂ monolayer sample



Ultra-clean TaS₂ monolayer sample



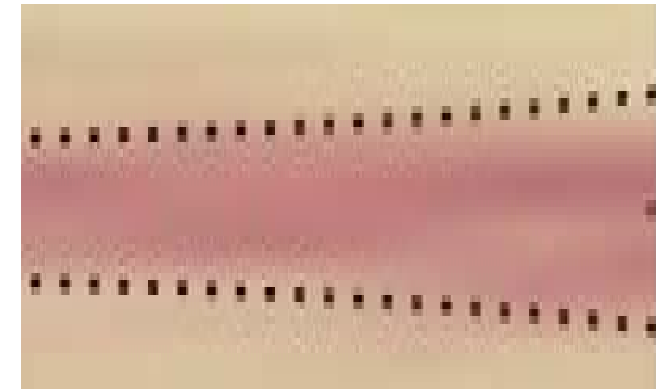
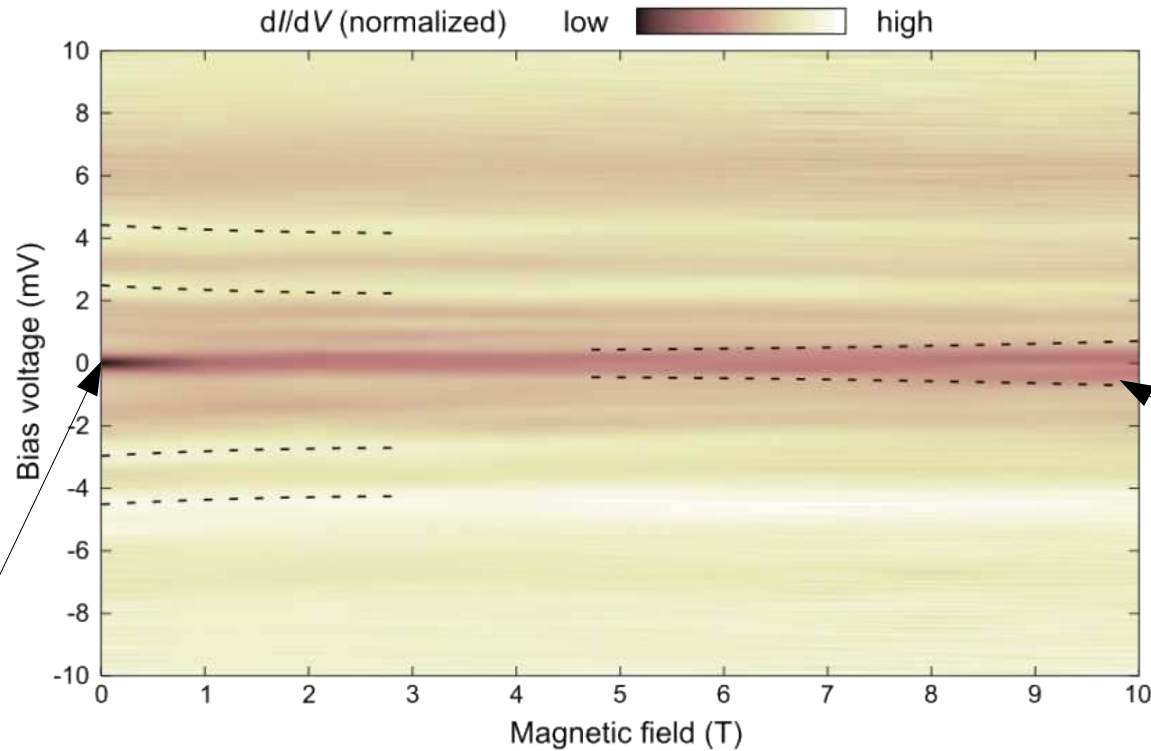
Hidden order many-body fluctuations



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



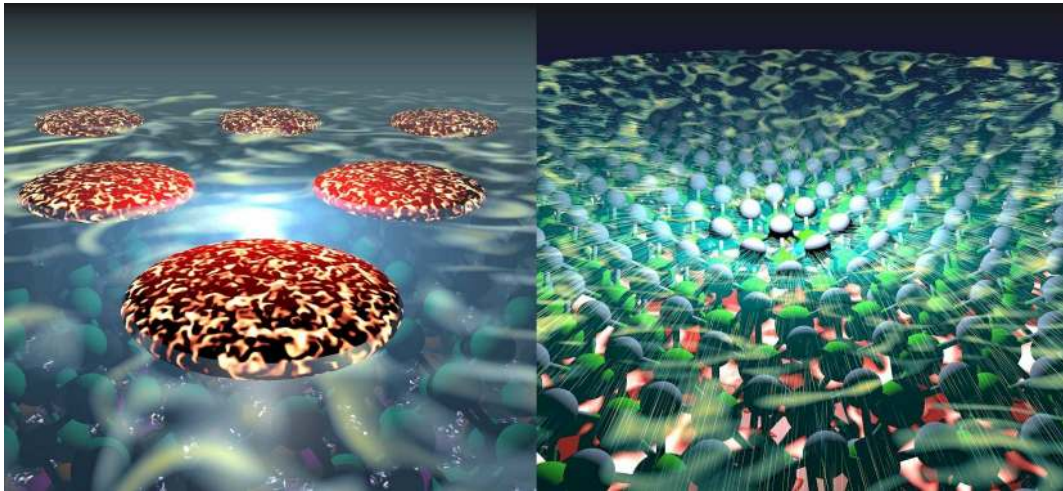
Pseudo-gap

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

Funding from

