Moiré-enabled topological superconductivity

Jose Lado

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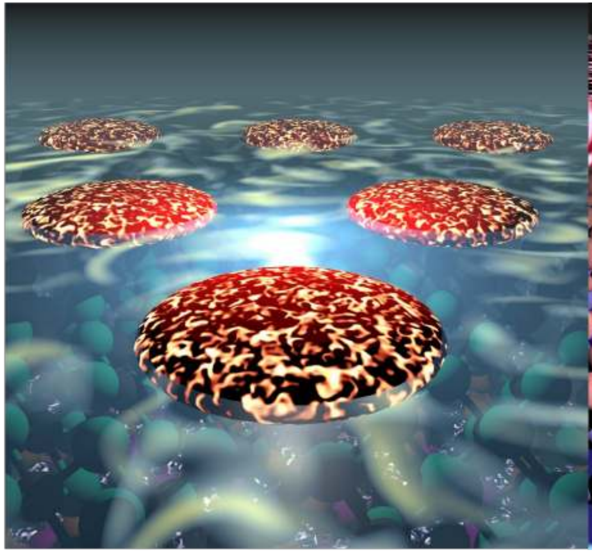
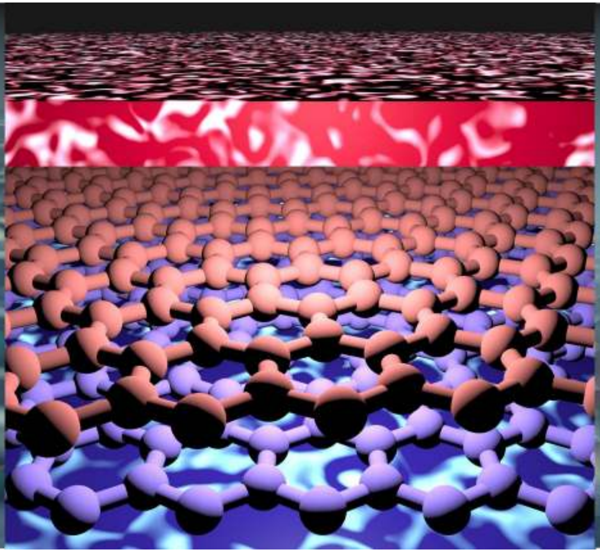
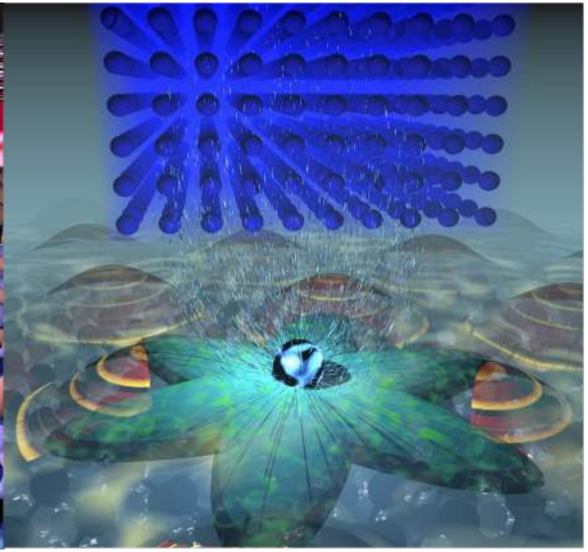


Nano Lett. 2022, 22, 1, 328–333 (2022)



arXiv:2307.04605 (2023)

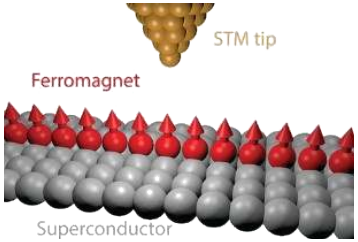


Journal of Physics: Materials 7 (1), 015012 (2024)

APS March Meeting, March 7th 2024
Minneapolis, US

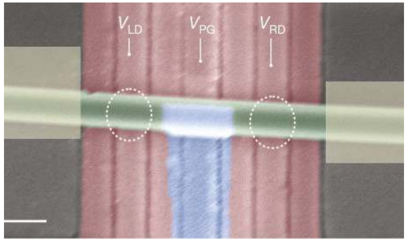
The world of topological superconductors

Magnetic atomic chains



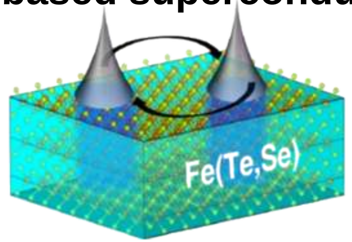
Nature Nano 17, 384–389 (2022)

Semiconductor-based



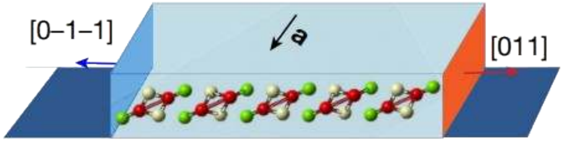
Nature 614, 445–450 (2023)

Fe-based superconductors



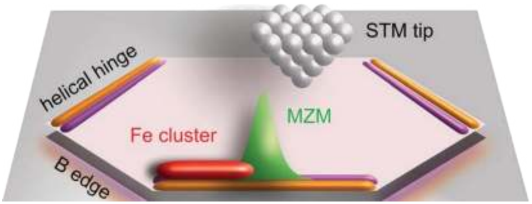
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



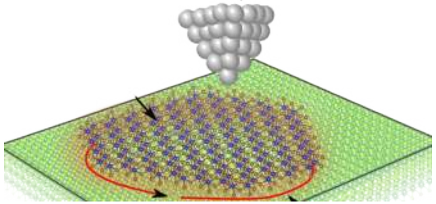
Nature 579, 523–527 (2020)

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

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

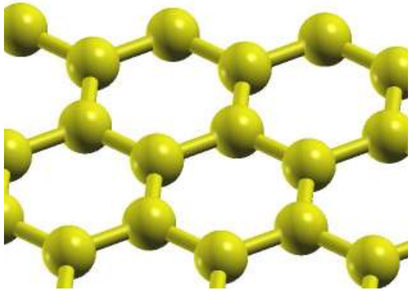
Nature Reviews Physics 2, 575–594 (2020)

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

The two-dimensional materials world

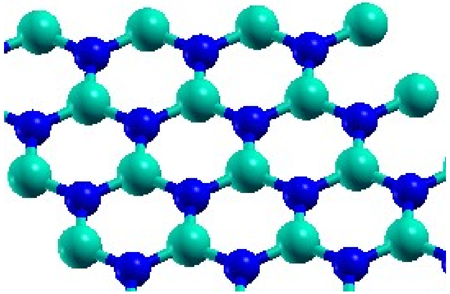
Semimetal

Graphene



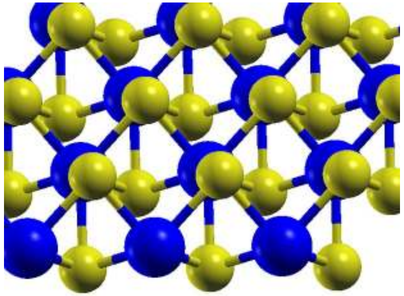
Insulator

BN



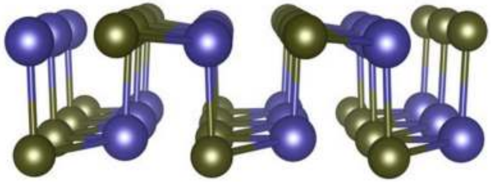
Superconductor

$NbSe_2$



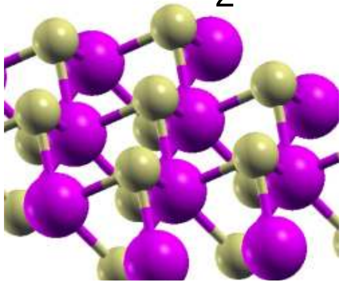
Ferroelectric

SnTe



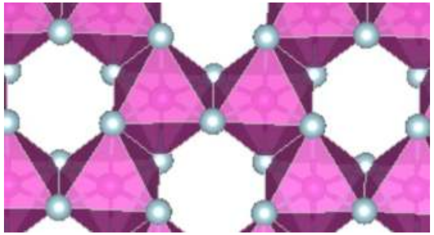
Semiconductor

WS_2



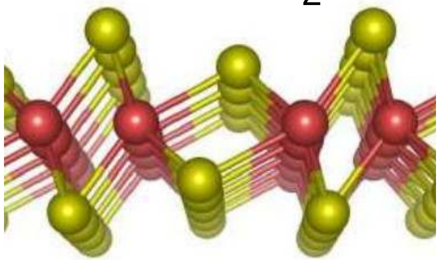
Ferromagnet

CrI_3



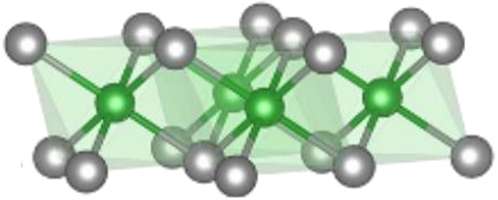
Quantum spin Hall insulator

WTe_2



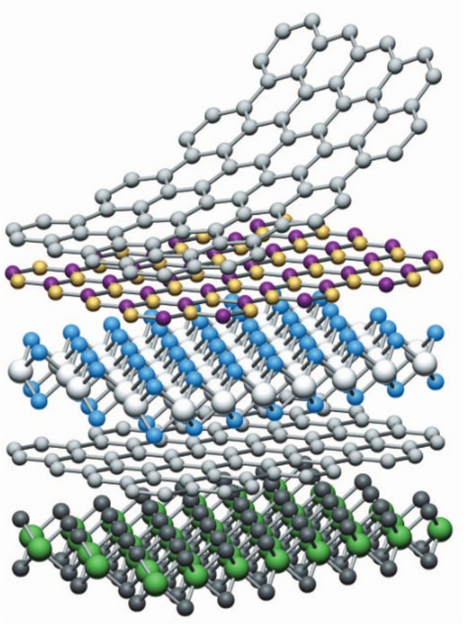
Multiferroic

NiI_2



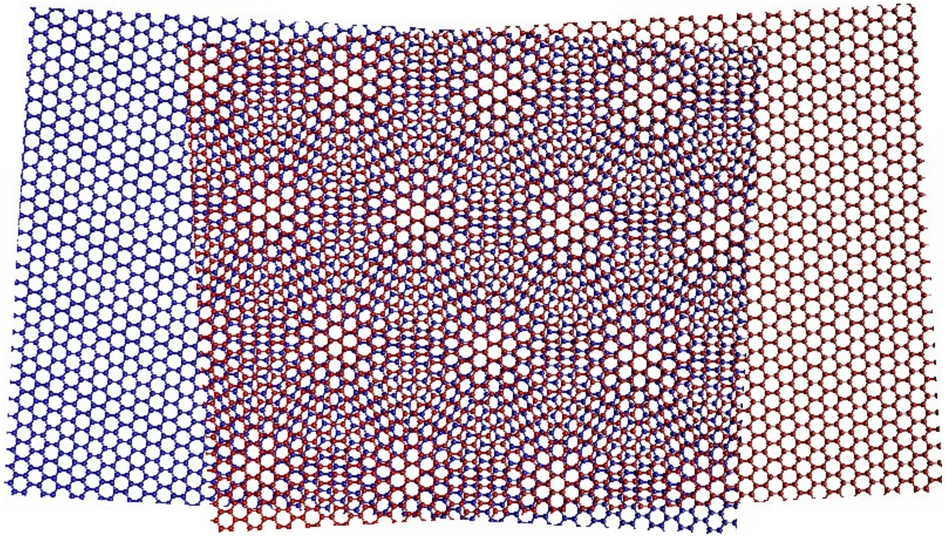
The flexibility of two-dimensional materials

They can be stacked



Nature 499, 419–425 (2013)

They can be rotated

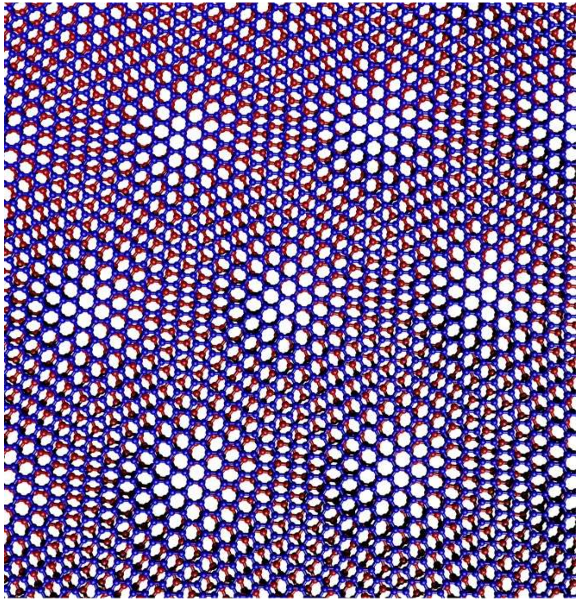


Science 361, 6403, 690-693 (2018)

These are unique features of two-dimensional materials

The tunability of twisted van der Waals materials

Twisted bilayer graphene



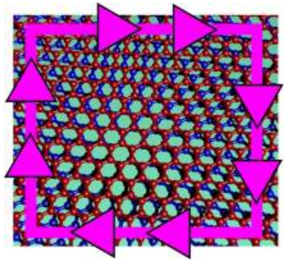
Superconductivity

Nature 556, 43–50 (2018)

Topological networks

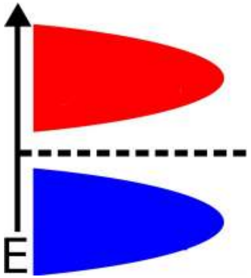
Nano Lett. 18, 11, 6725-6730 (2018)

Chern insulators



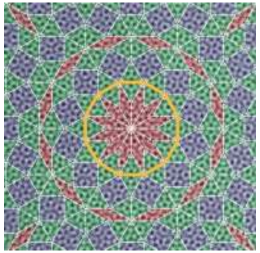
Science 365, 605-608 (2019)

Correlated insulators



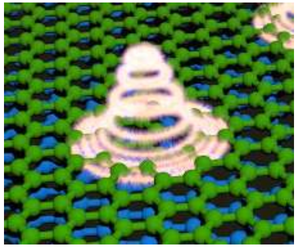
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

Proximal fractional Chern insulators

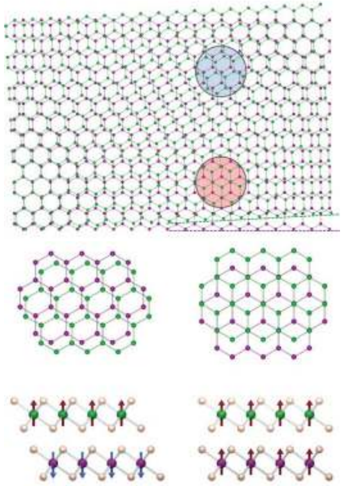


Nature 600, 439–443 (2021)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

Artificial quantum matter in moire van der Waals heterostructures

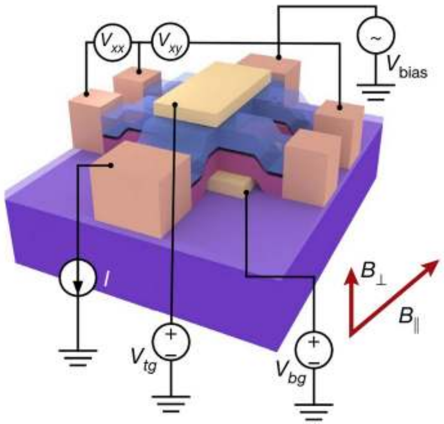
Unconventional magnets



Twisted $CrBr_3$

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

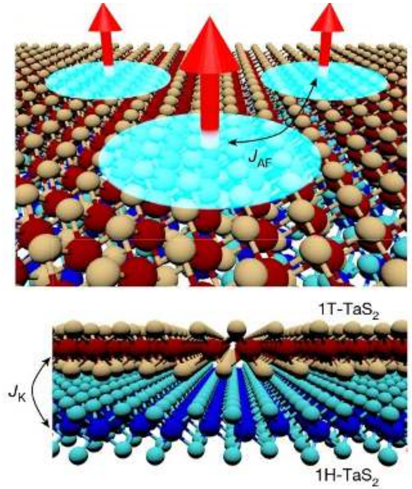
Unconventional superconductors



Twisted trilayer graphene

Nature 595, 526–531 (2021)

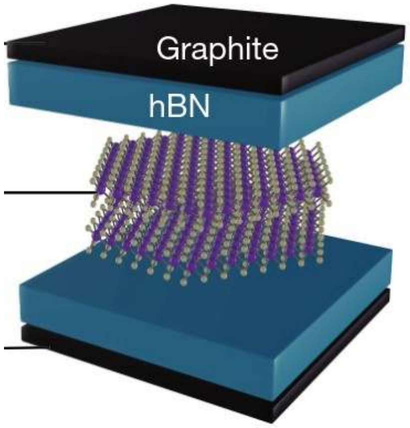
Heavy-fermion quantum materials



1H-1T TaS_2

Nature 599, 582–586 (2021)

Fractional topological matter

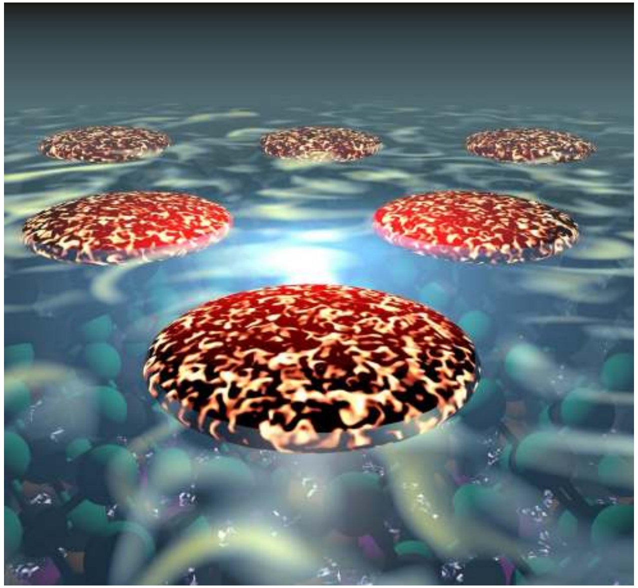


Twisted $MoTe_2$

Nature 622, 63–68 (2023)

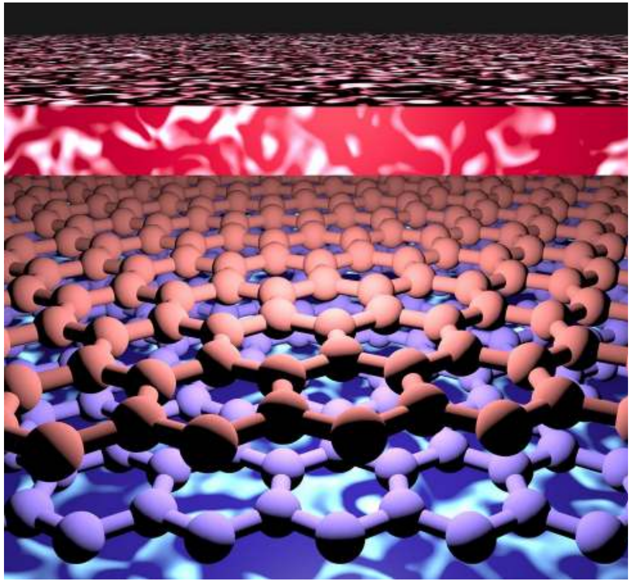
Today's plan

Moire-enabled topological superconductivity in $CrBr_3/NbSe_2$



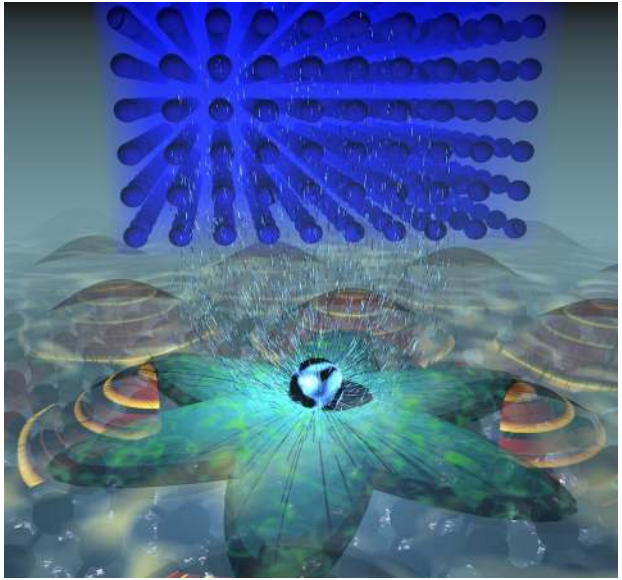
Nano Lett. 2022, 22, 1, 328–333 (2022)

Moire-enabled topological superconductivity in twisted biilayer graphene



arXiv:2307.04605

Hamiltonian learning from moire impurity tomography



Journal of Physics: Materials 7 (1), 015012 (2024)

Behind the scenes

Experiment

S. Ganguli

M. Aapro

S. Kezilebieke

V. Vaňo

Md. Huda

P. Liljeroth

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

Theory

E. Bascones

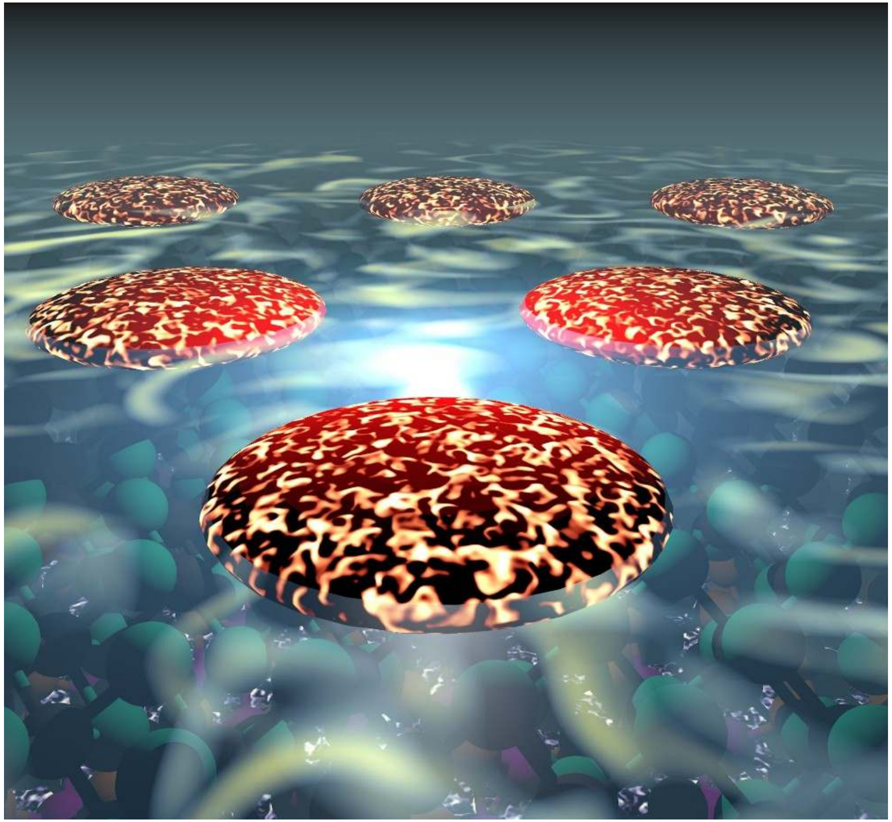
M. Khosravian

R. Koch

arXiv:2307.04605

Journal of Physics: Materials
7 (1), 015012 (2024)

Artificial topological moiré superconductivity in $NbSe_2/CrBr_3$



S. Ganguli

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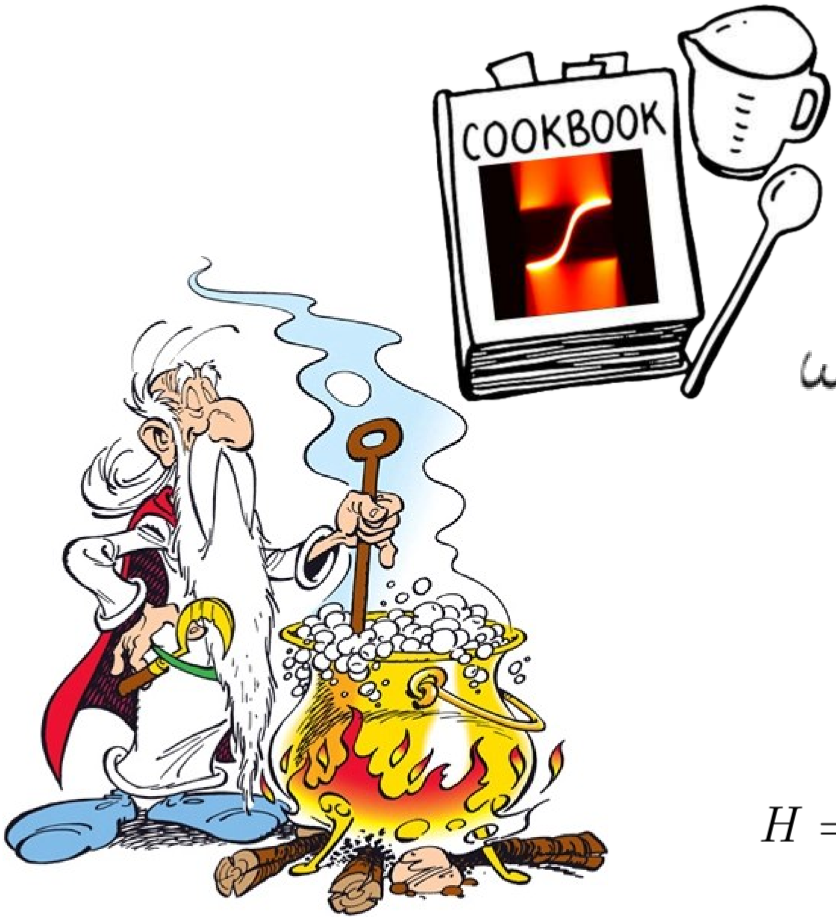
Md. Huda

P. Liljeroth

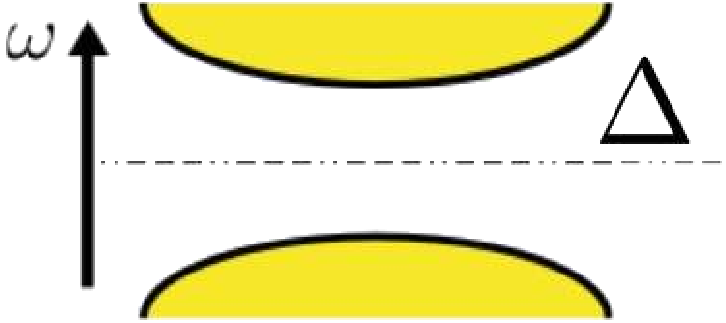
Nano Lett. 22, 1, 328-333 (2022)

How to build your own topological superconductor

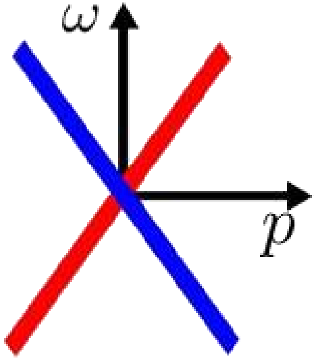


Ingredients

s-wave pairing



Helical channels



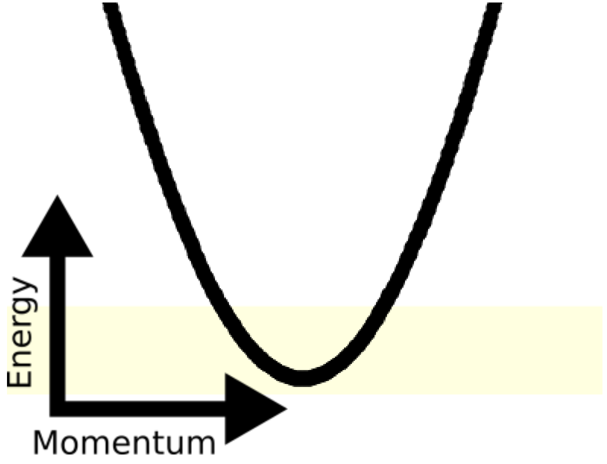
Objective: to realize a spinless superconductor

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

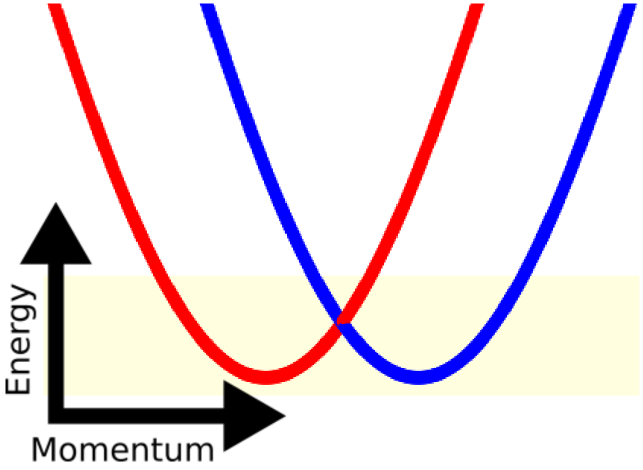
A. Y. Kitaev. Physics-Uspekhi, 44:131, 2001

How to build your own helical gas

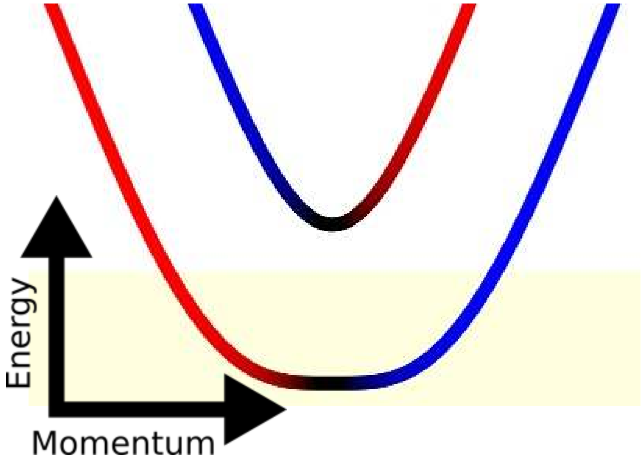
Take a parabolic band



Create spin-momentum locking with Rashba spin-orbit coupling



Split the Gamma point with an exchange field

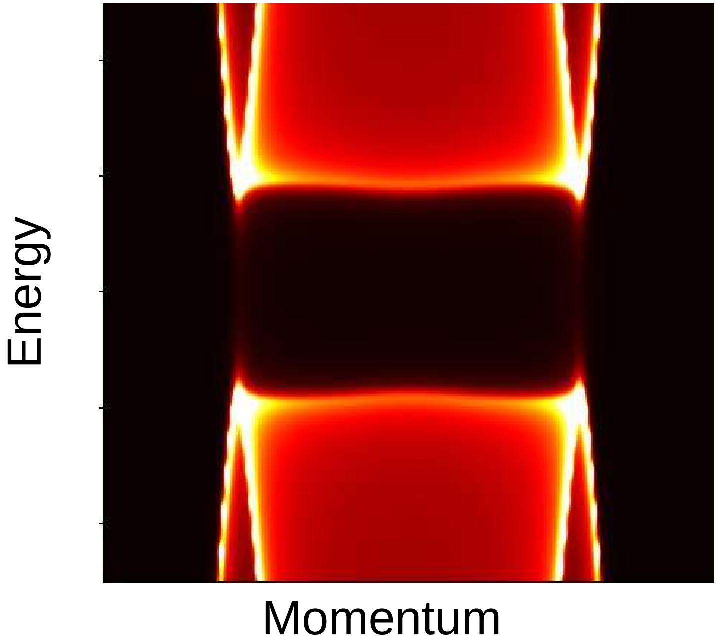


For a chemical potential inside the split gap, we have helical states

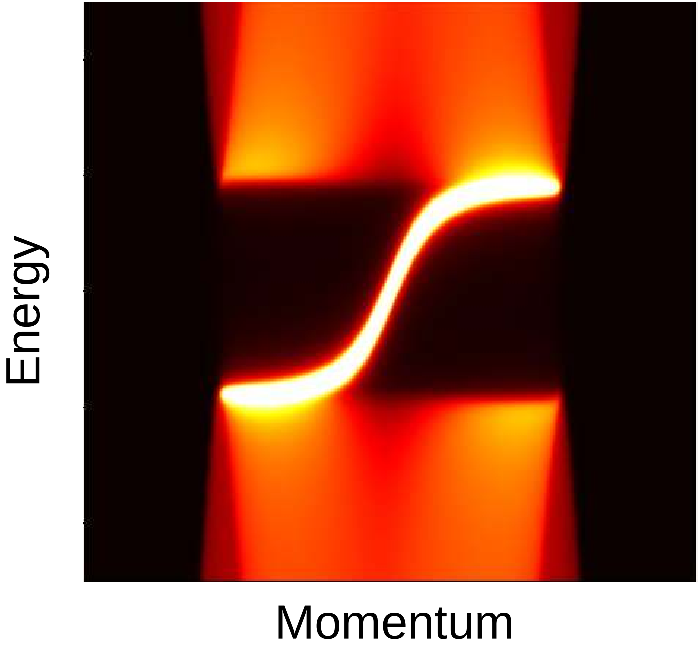
Having a topological superconductor requires having a tunable material

The spectra of a topological superconductor

Full gap in the bulk

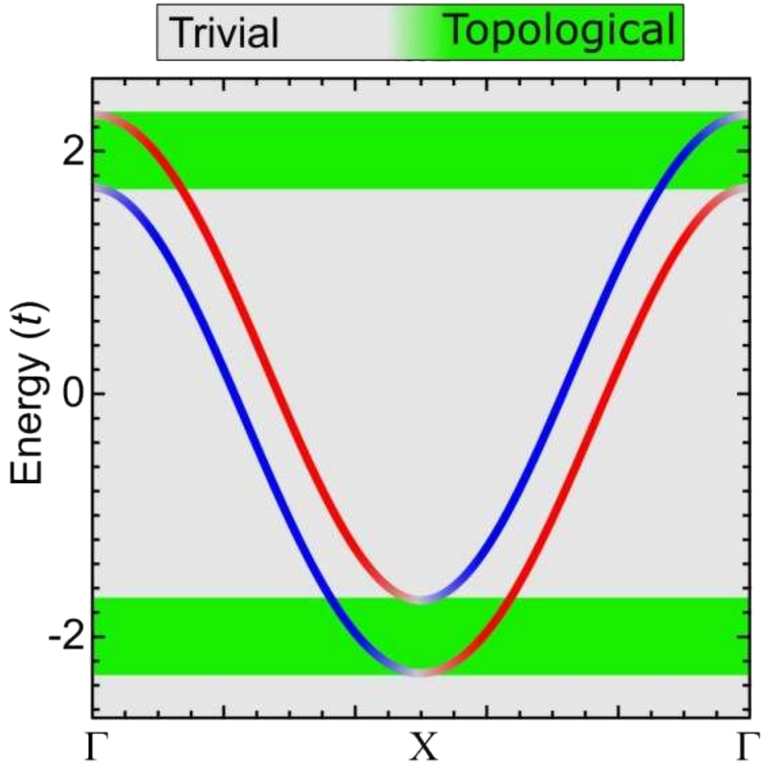


Gapless (Majorana) mode at the edge



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

1D topological superconductor, without moire



$$H = H_0 + H_J + H_R$$

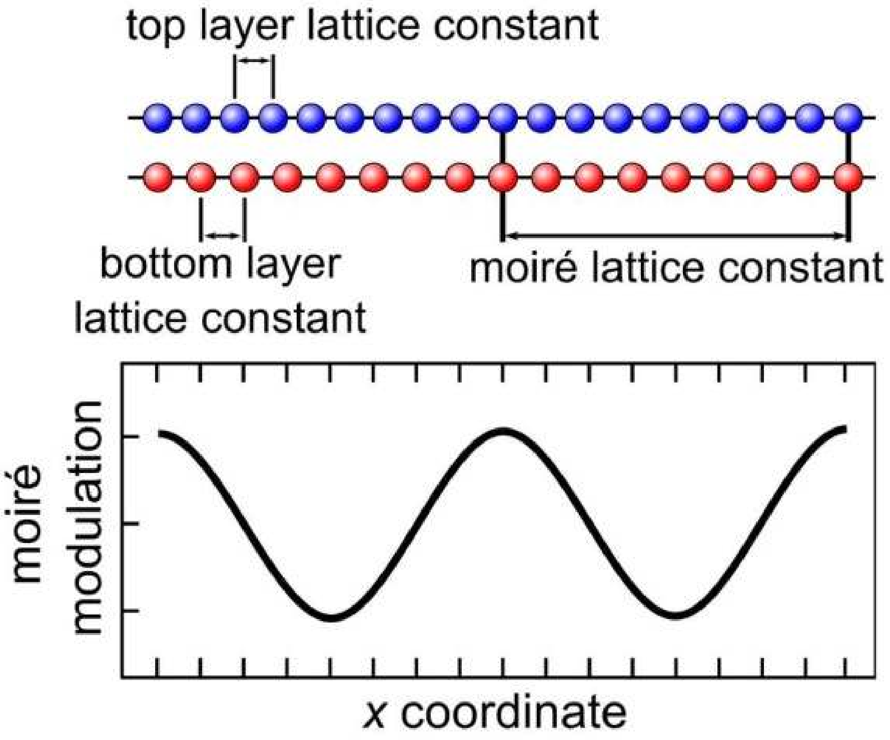
Kinetic energy

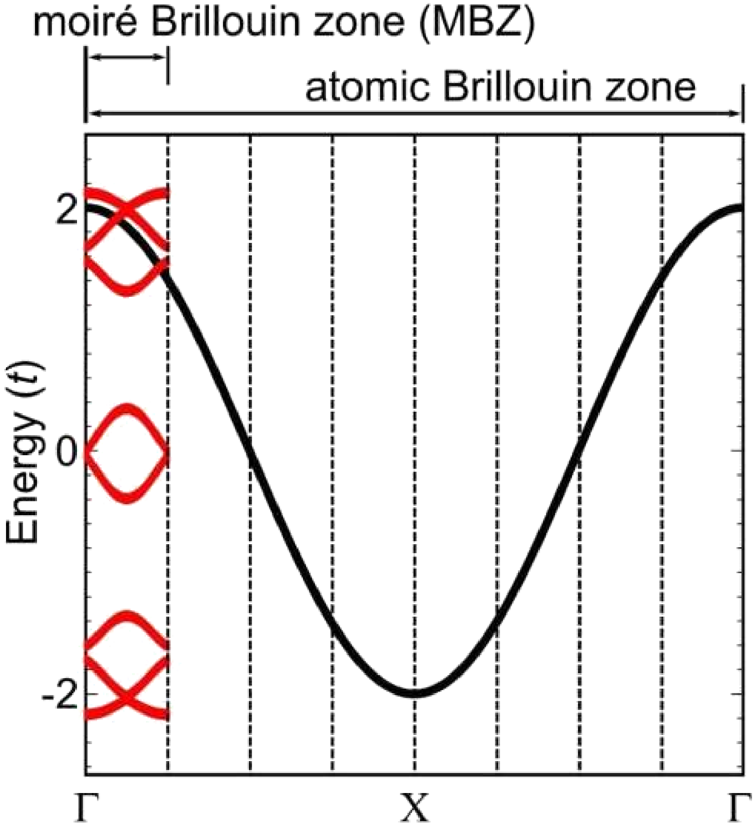
Exchange field

Rashba spin-orbit coupling

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

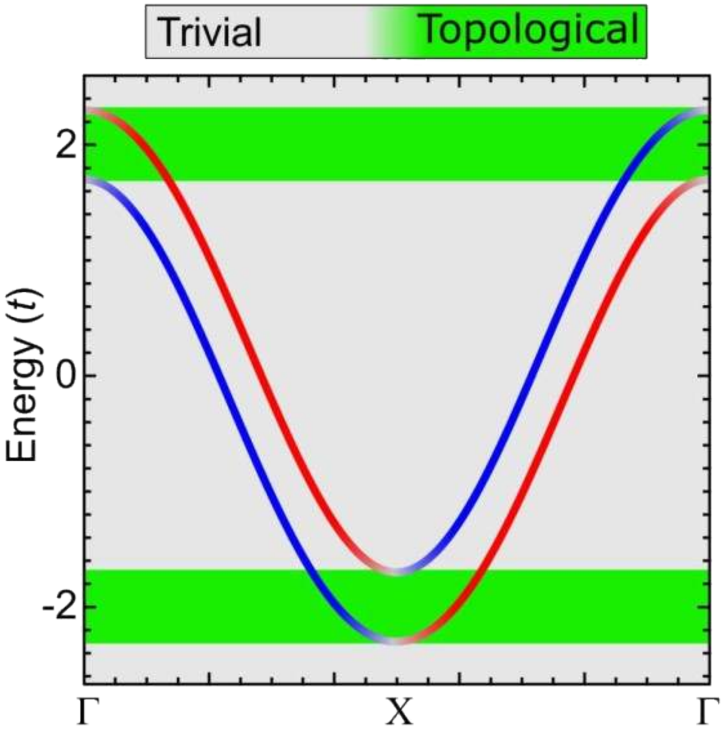
1D topological superconductor, with moire



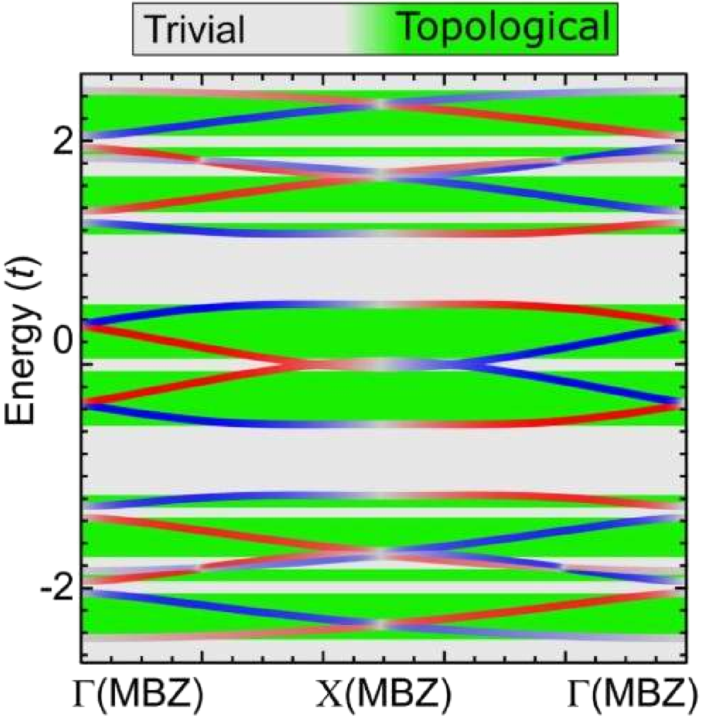


1D topological superconductor, with moire

Without moire



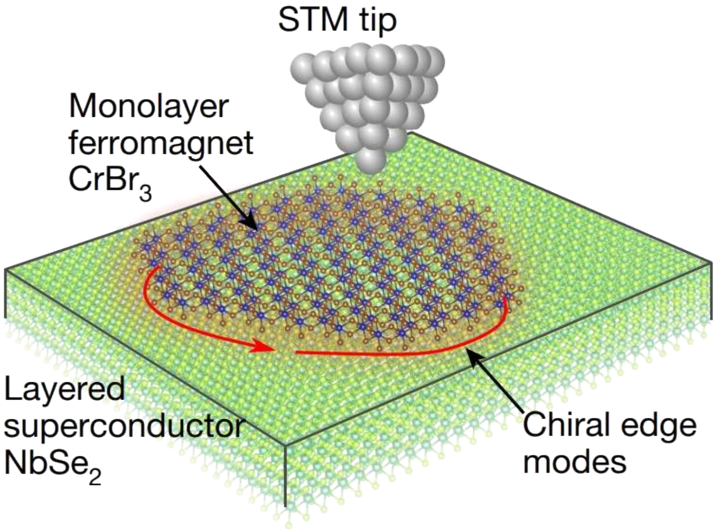
With moire



Moire pattern allow to realize topological superconductivity in otherwise forbidden energies

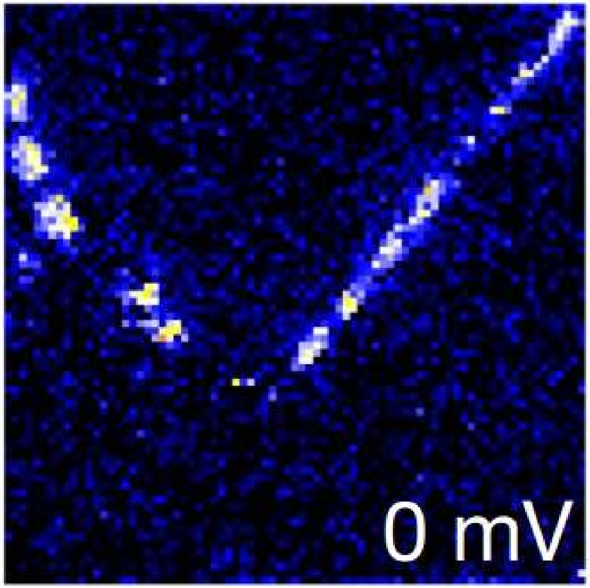
Topological superconductivity in a van der Waals heterostructure

$CrBr_3/NbSe_2$ heterostructure



Nature 588, 424–428 (2020)

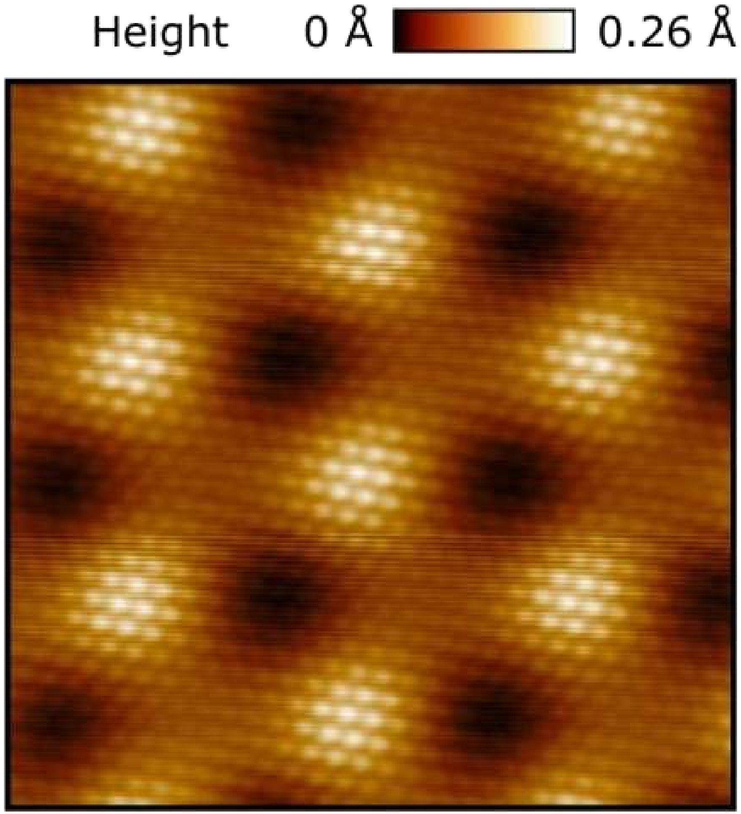
Zero bias dIdV

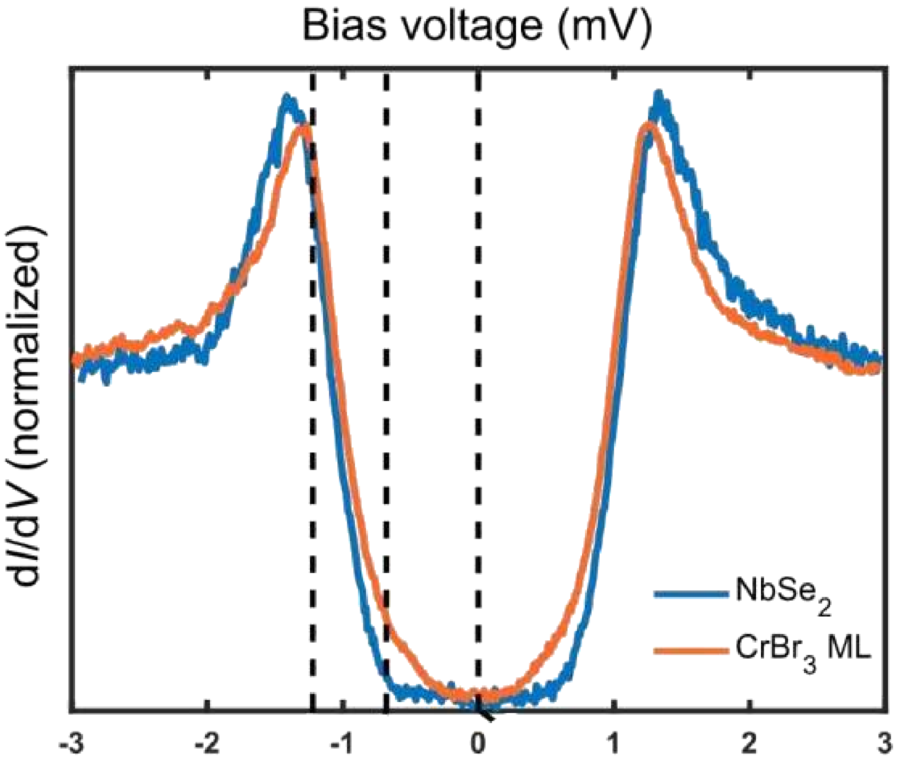


A topological superconducting state appears in $CrBr_3/NbSe_2$

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

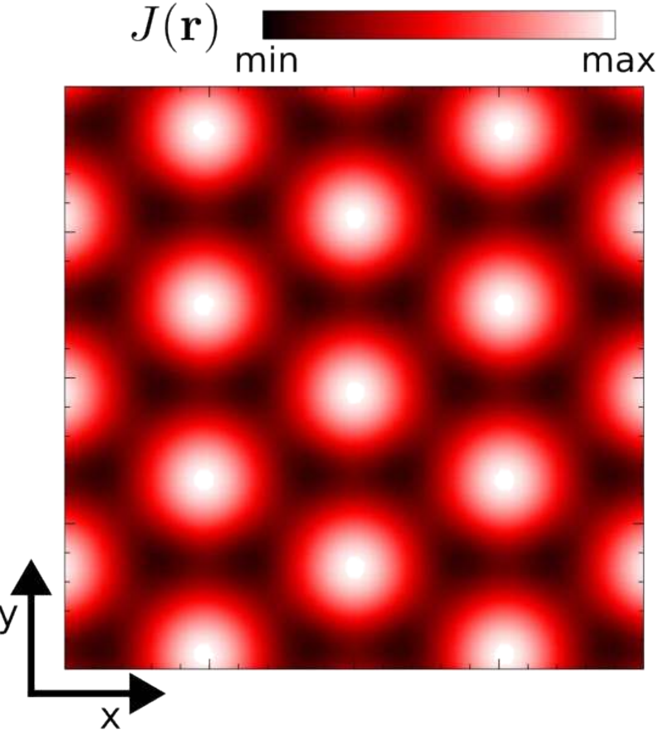
$CrBr_3/NbSe_2$ heterostructure



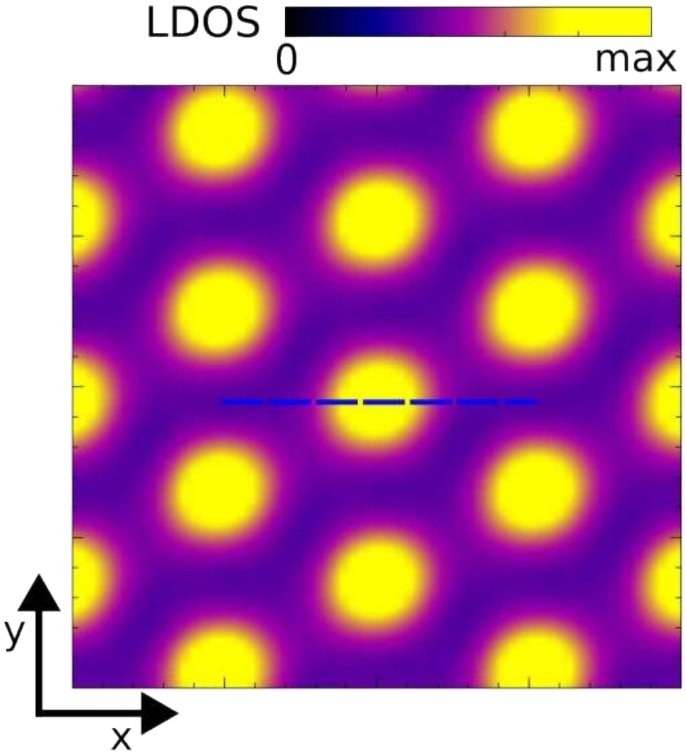


Bulk Yu-Shiba-Rusinov states

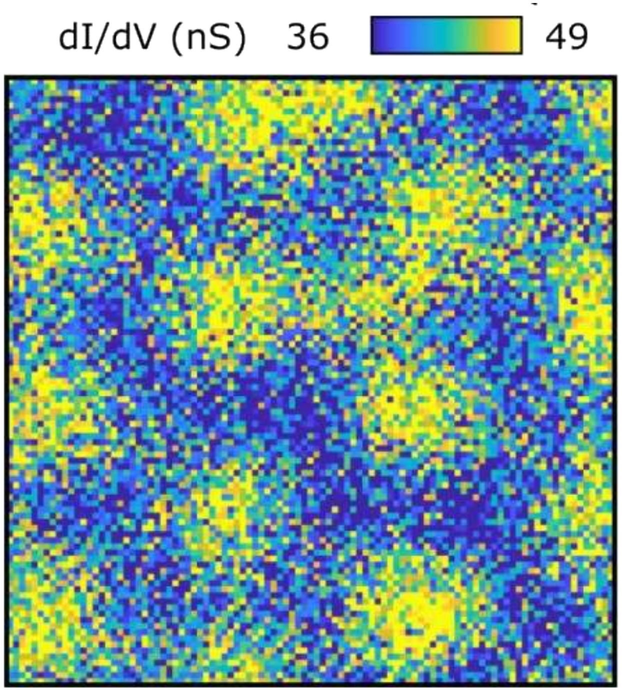
Exchange profile



Theoretical LDOS



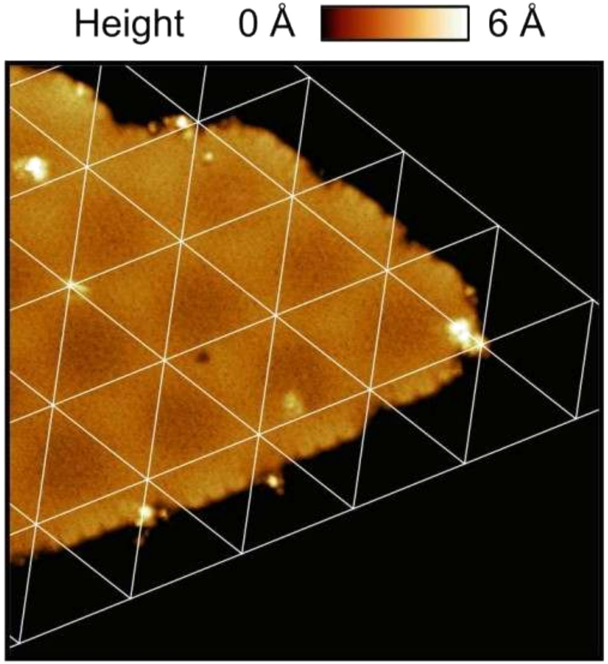
Experimental dIdV



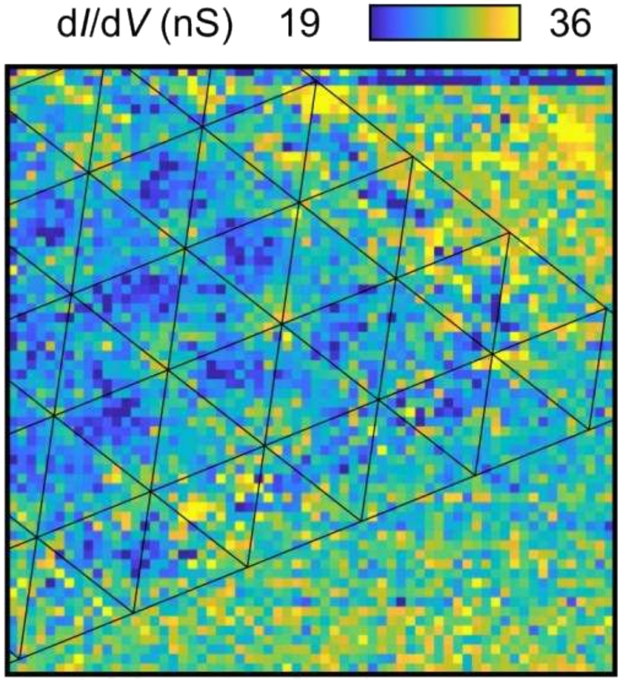
Bulk Yu-Shibe-Rusinov states are imprinted by the modulated exchange profile

Bulk Yu-Shiba-Rusinov states

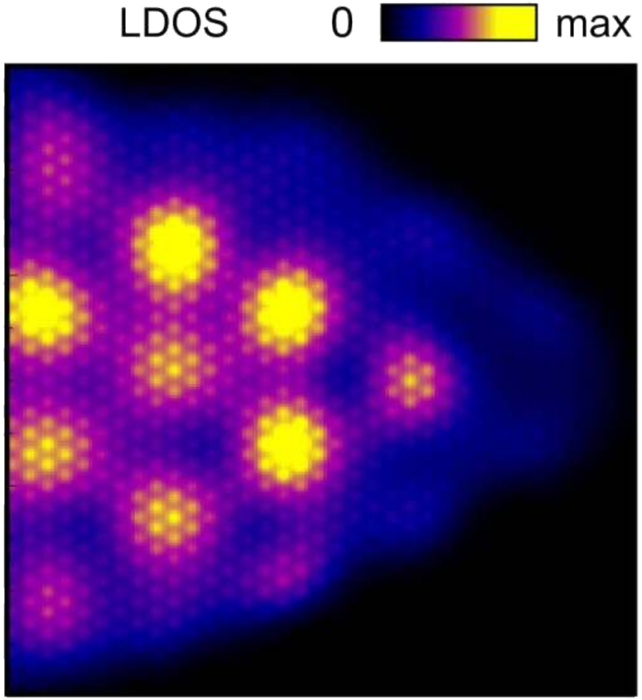
Topography



Experimental dIdV

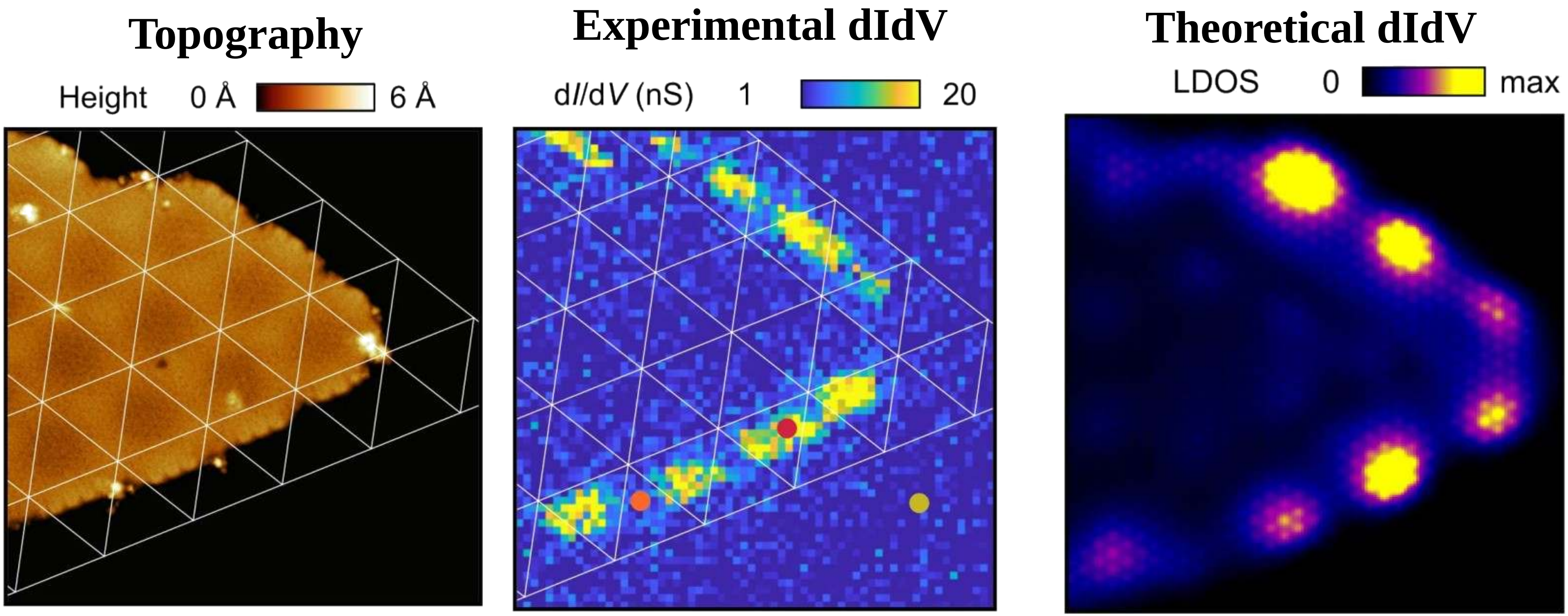


Theoretical dIdV



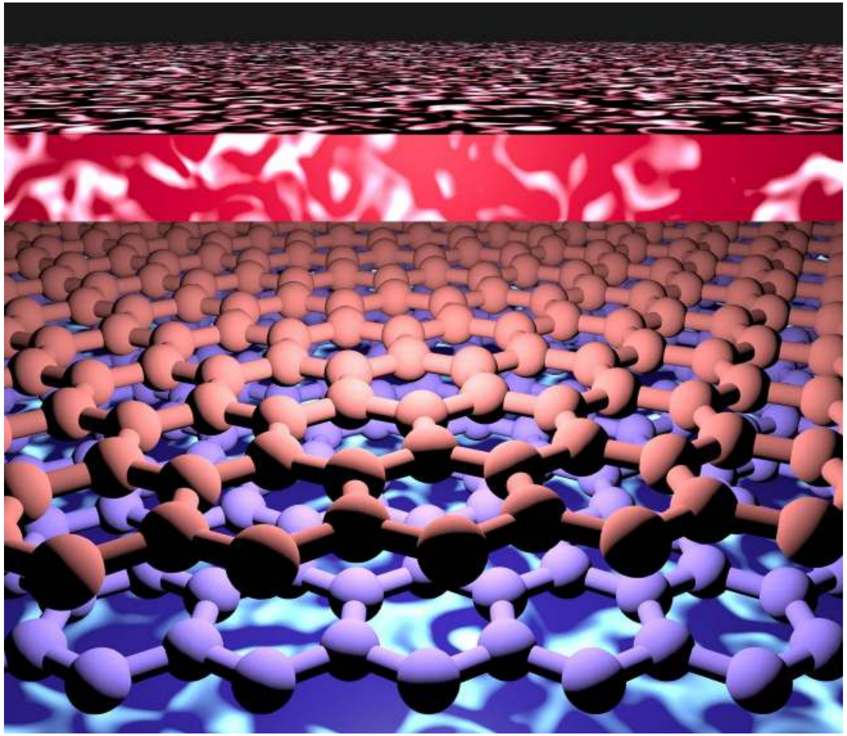
Bulk Yu-Shiba-Rusinov states are imprinted by the modulated exchange profile

Topological moire edge states



Topological edge modes are imprinted by the modulated exchange profile

Moire-enabled artificial superconductors in twisted bilayer graphene



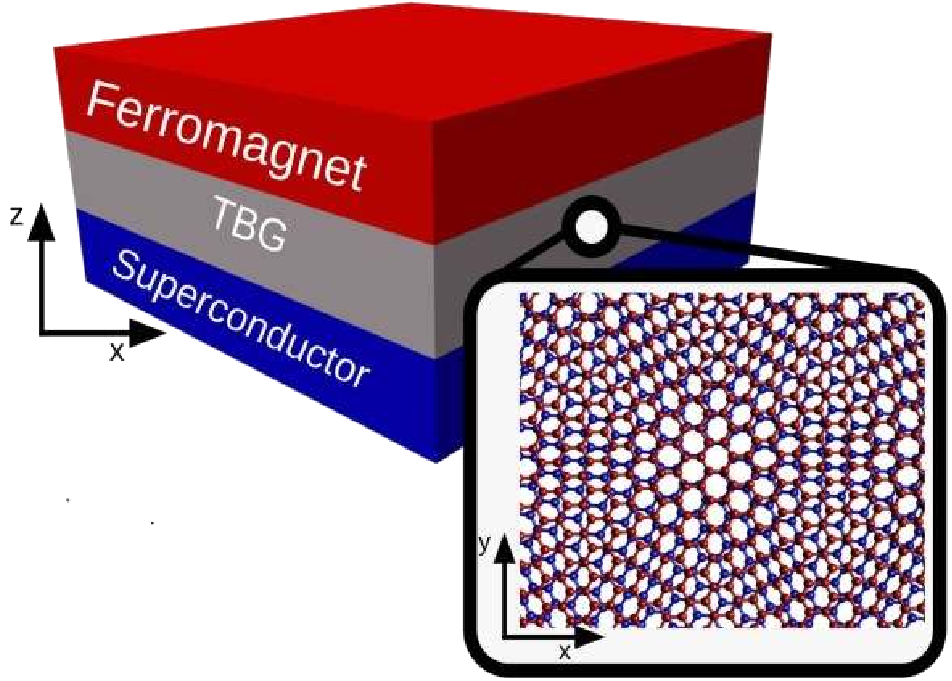
Maryam Khosravian

Elena Bascones

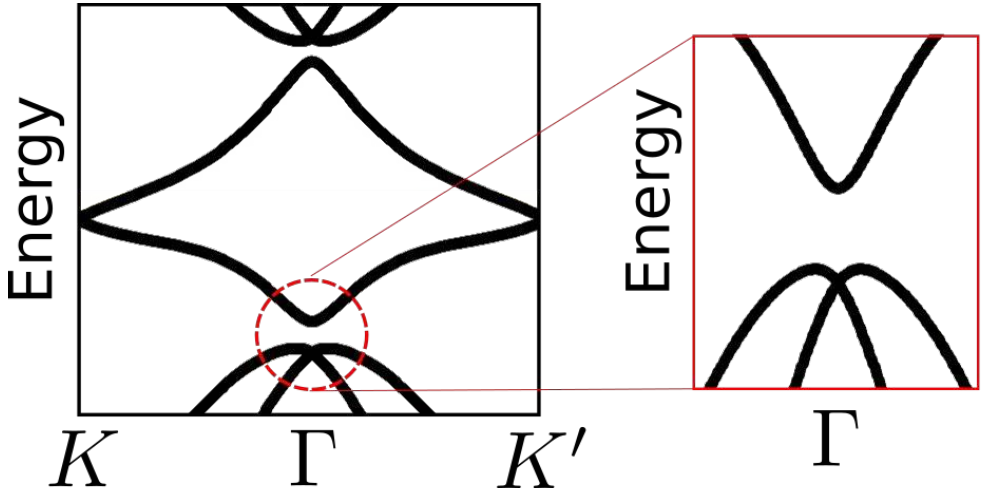
arXiv:2307.04605

Encapsulated twisted graphene bilayers

Twisted bilayer graphene encapsulated between a ferromagnet and superconductor



Twisted bilayer band structure



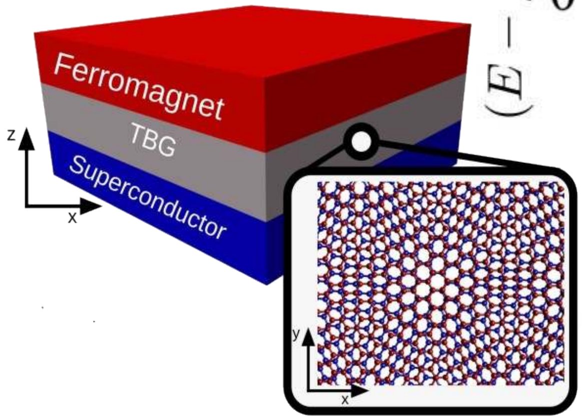
Parabolic bands at the Γ point

$$1.5 - 3^{\circ}$$

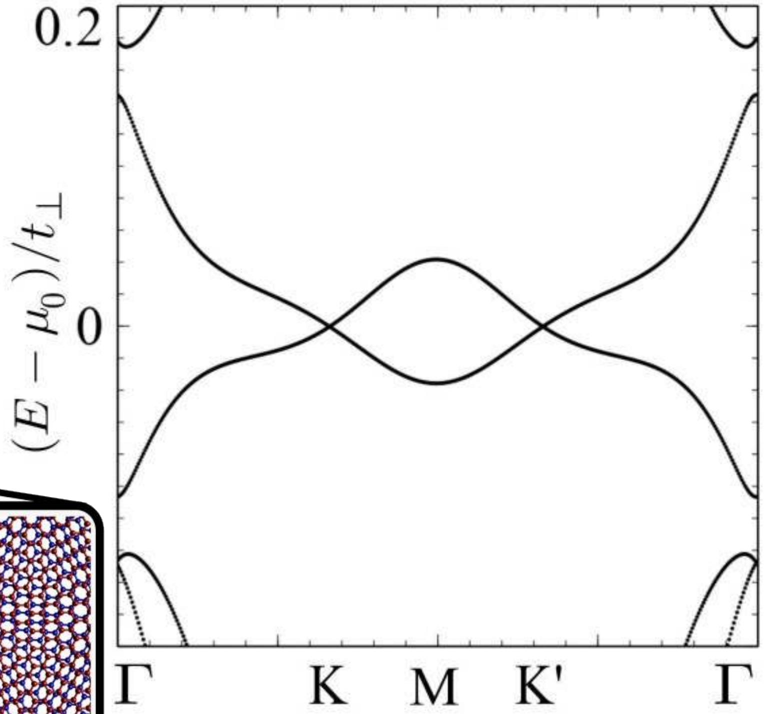
Moire-enabled artificial superconductors in twisted bilayer graphene

Twisting angles

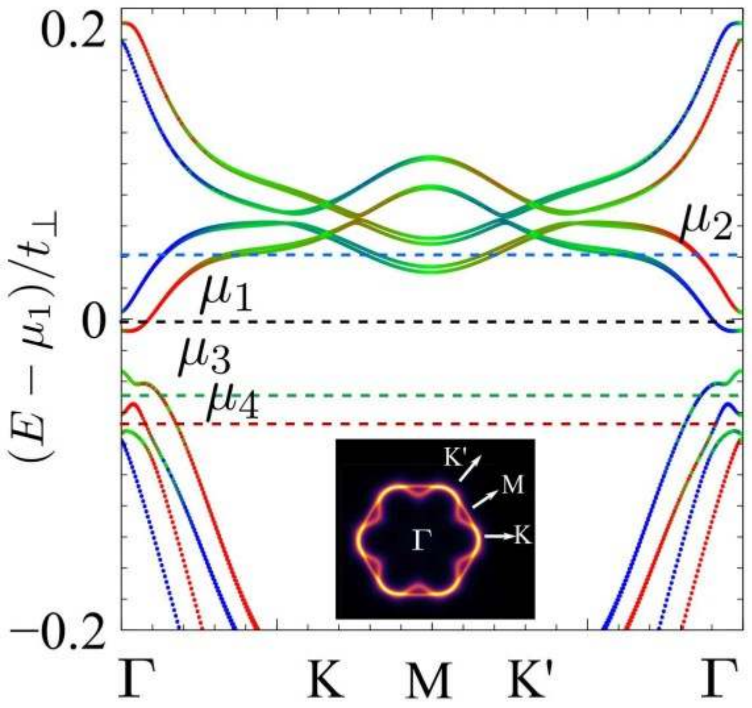
$$1.5 - 3^\circ$$



Pristine twisted bilayer



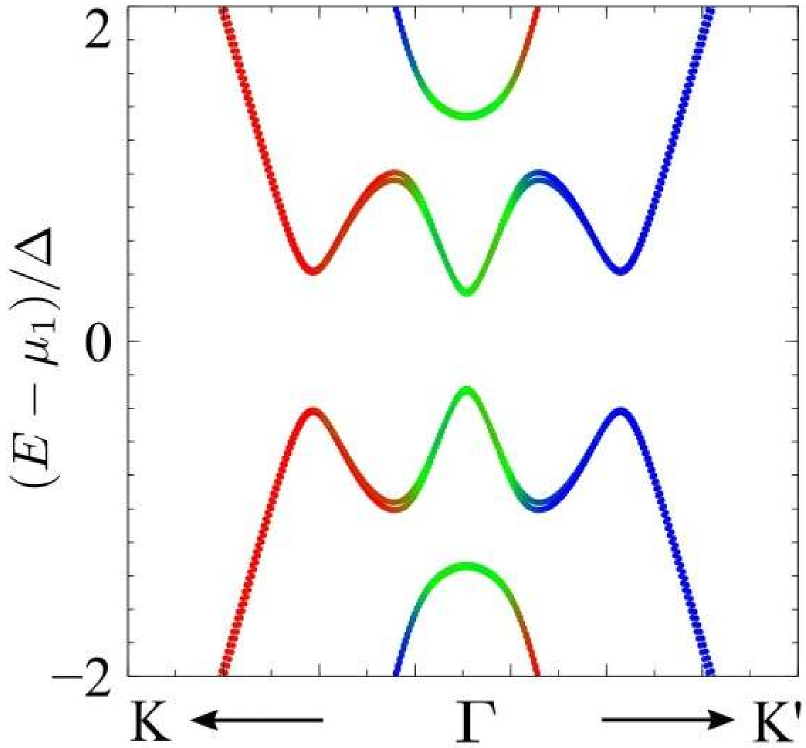
Encapsulated twisted bilayer



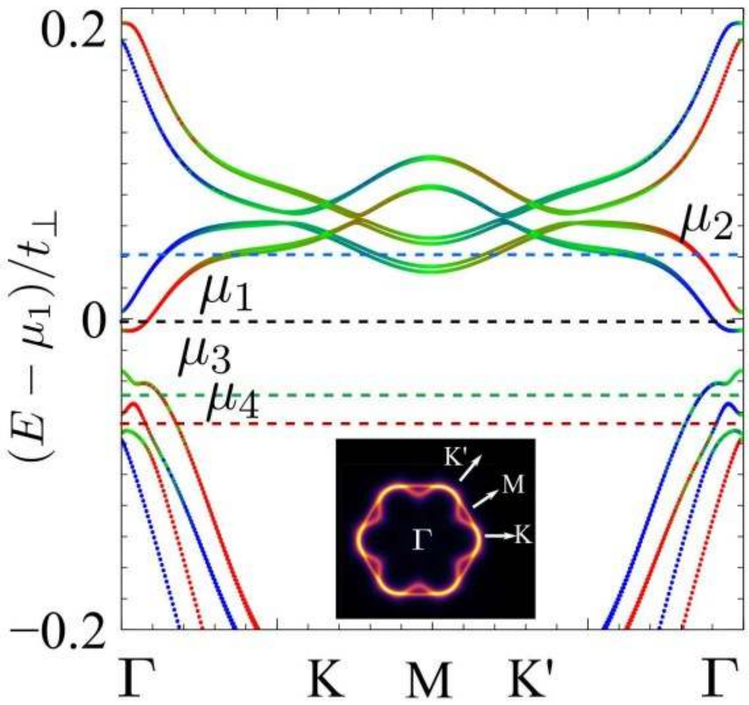
The moire effect gives rise to minigaps featuring helical states with encapsulation

Moire-enabled artificial superconductors in twisted bilayer graphene

With superconductivity



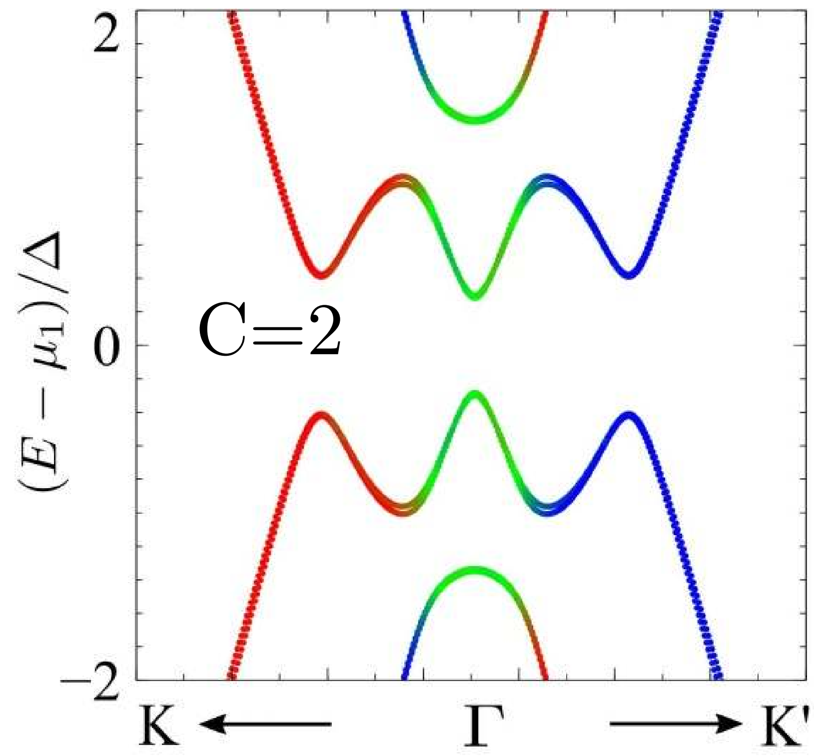
Without superconductivity



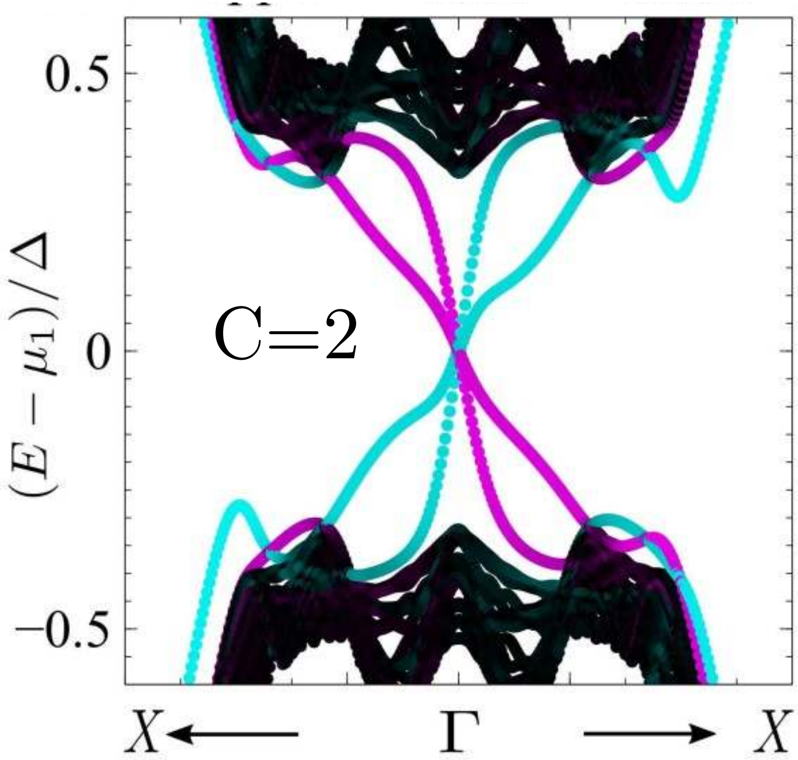
Switching on superconductivity gives rise to a topological superconducting state

Moire-enabled artificial superconductors in twisted bilayer graphene

Bulk band structure



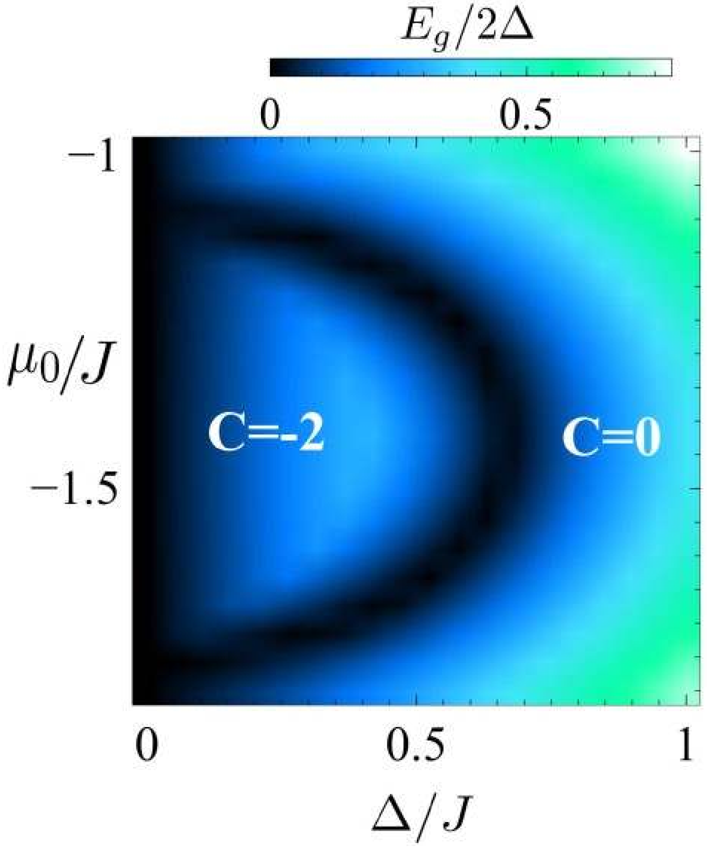
Ribbon band structure



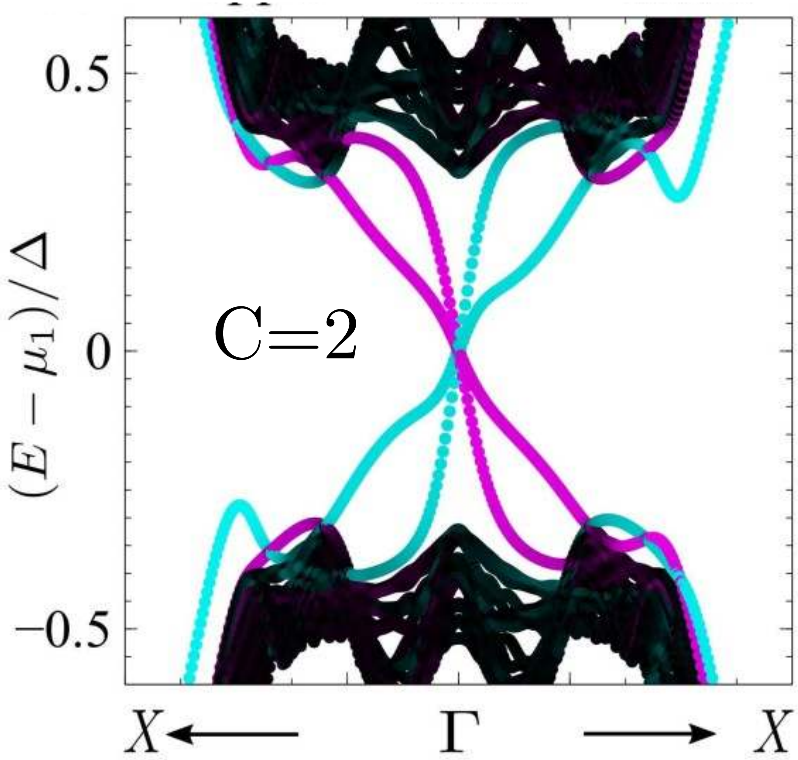
The topological state features chiral Majorana modes in a ribbon geometry

Moire-enabled artificial superconductors in twisted bilayer graphene

Gap VS chemical potential



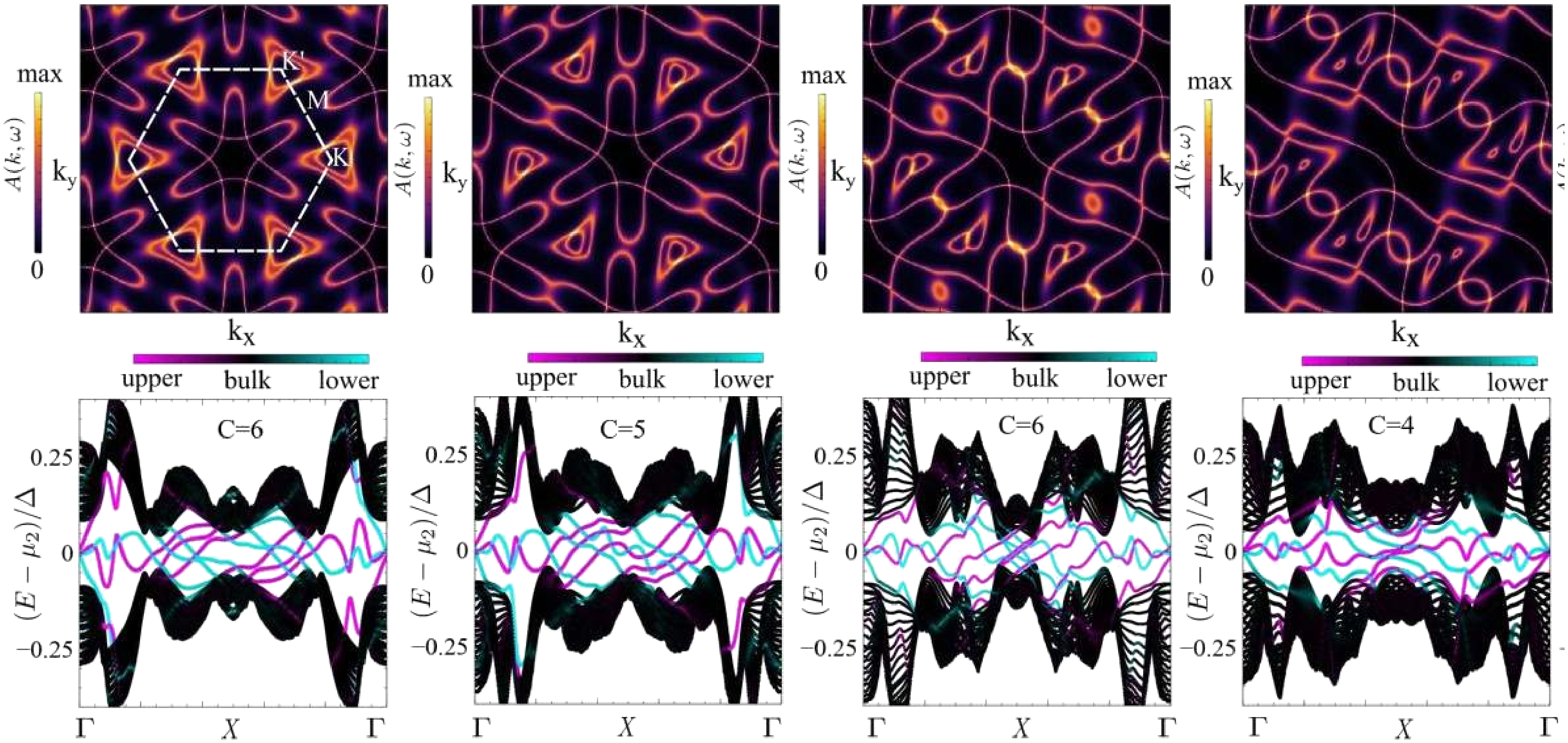
Ribbon band structure



Multiple topological phases tunable by strain

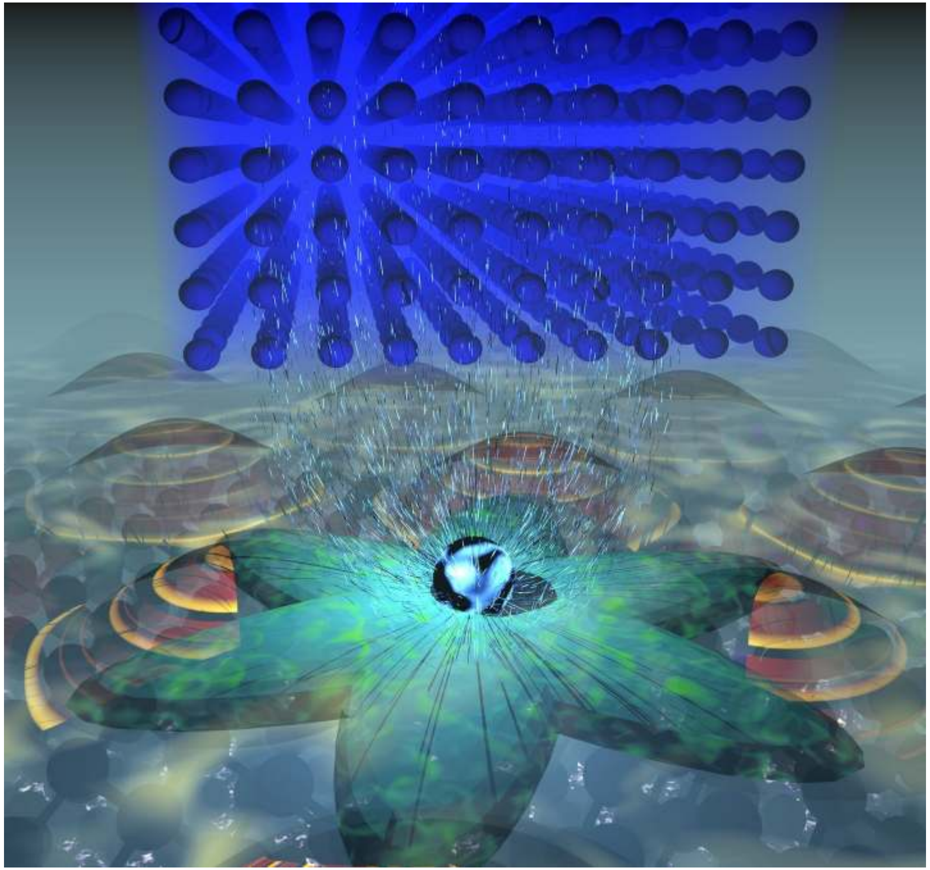
Fermi surface

Ribbon bands



Strain allows to realize topological states with different Chern numbers

Hamiltonian learning from impurity tomography in moire superconductors



Maryam Khosravian

Rouven Koch

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The challenge of identifying topological superconductors

How do we know that we have a topological superconductor, and not a superconductor that happens to have edge modes?

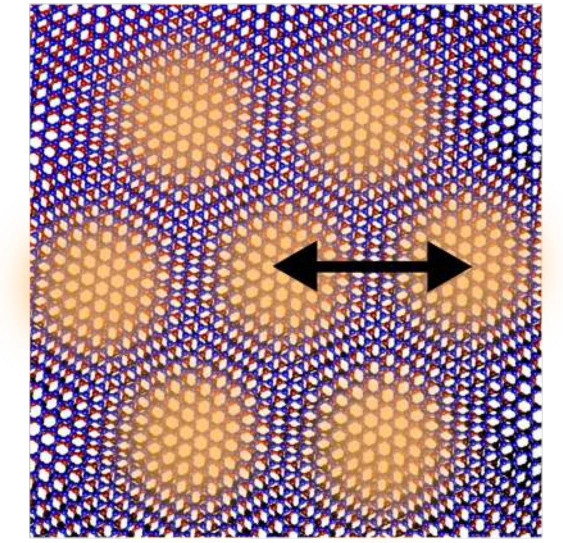
Solution #1: Do experimentally vortex braiding (long term)

Solution #2: Get the exact experimental Hamiltonian, and asses its nature

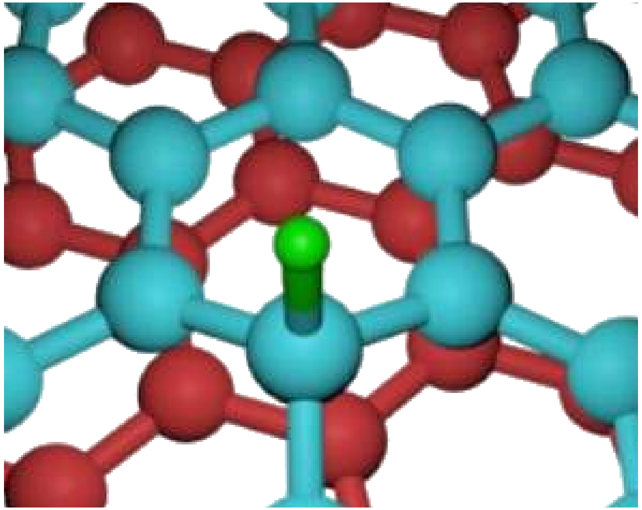
How can we extract the Hamiltonian of a complex moire quantum material?

Two length scales in twisted van der Waals materials

The emergent moire scale



The original atomic scale

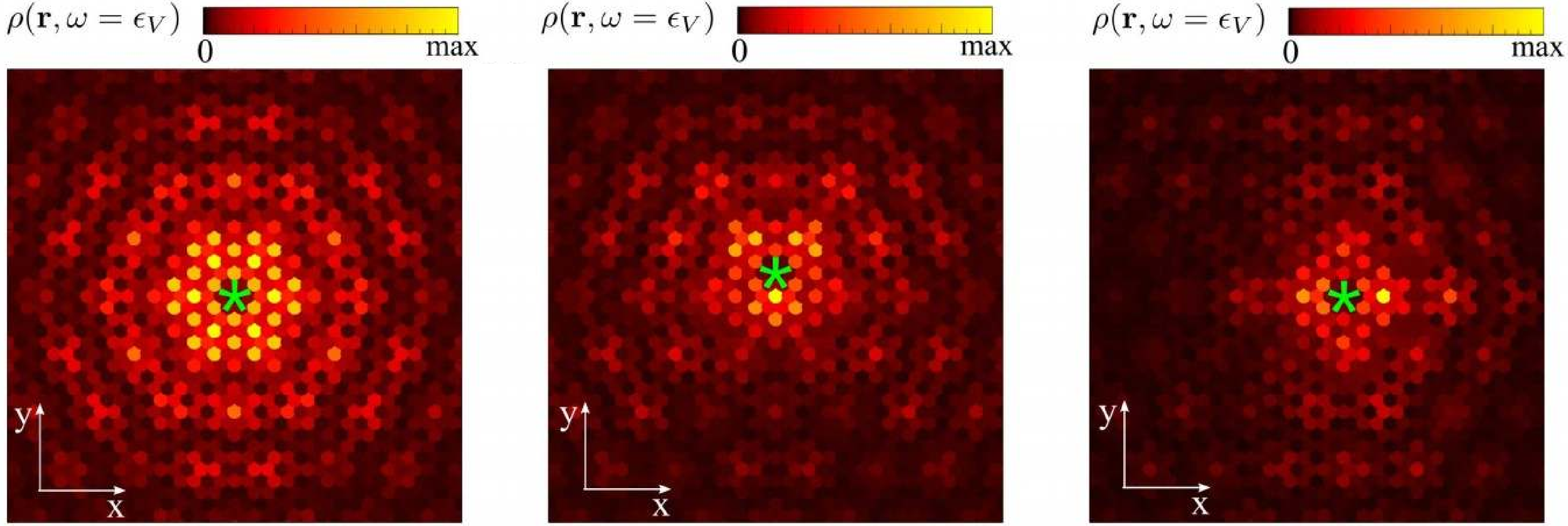


The coexistence of these two different scales is unique to moire systems

How can we use impurities to extract information of a moire system?

Single impurity in a topological moire superconductor

Wavefunction of an in-gap Yu-Shiba-Rusinov state for different impurity locations

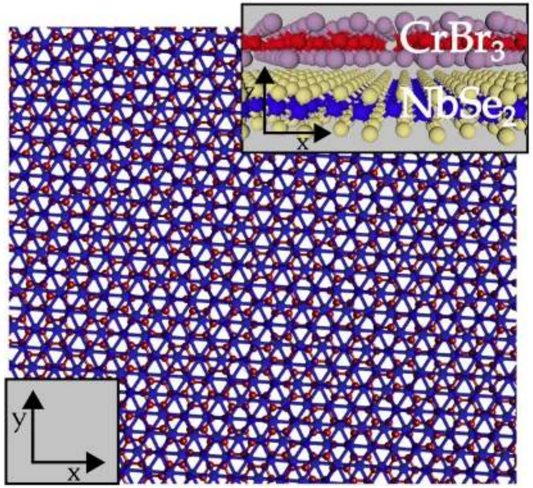


The YSR state wavefunction and the moire give rise to interference effects

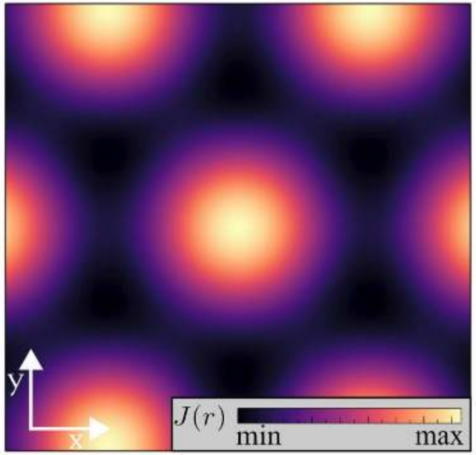
Could we learn physics of the system by exploiting these interference effects?

Hamiltonian for the pristine moire topological superconductor

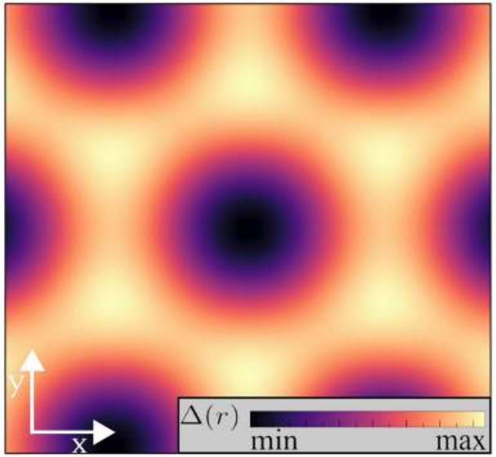
Structure



Exchange profile



Superconducting profile



$$\mathcal{H}_0 = \mathcal{H}_{\text{kin}} + \mathcal{H}_J + \mathcal{H}_R + \mathcal{H}_{\text{SC}}$$

Kinetic energy

Exchange coupling profile

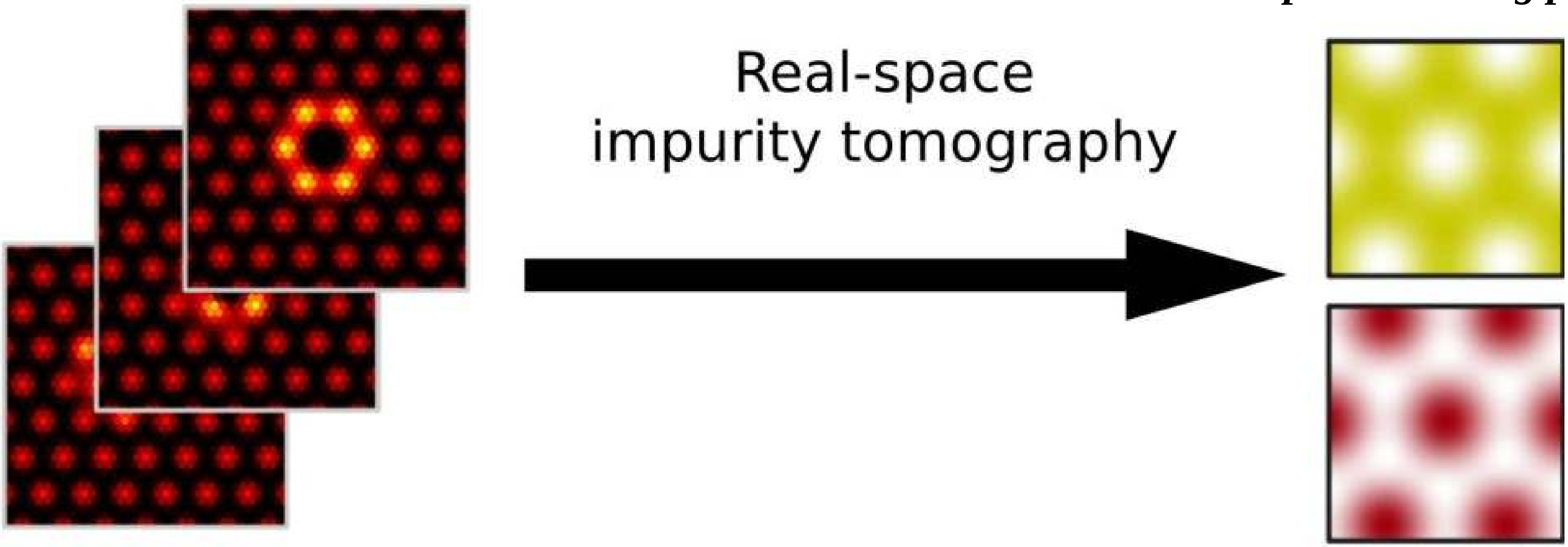
Rashba SOC

S-wave superconducting profile

Real-space impurity tomography

YSR for different impurity locations

Superconducting profile

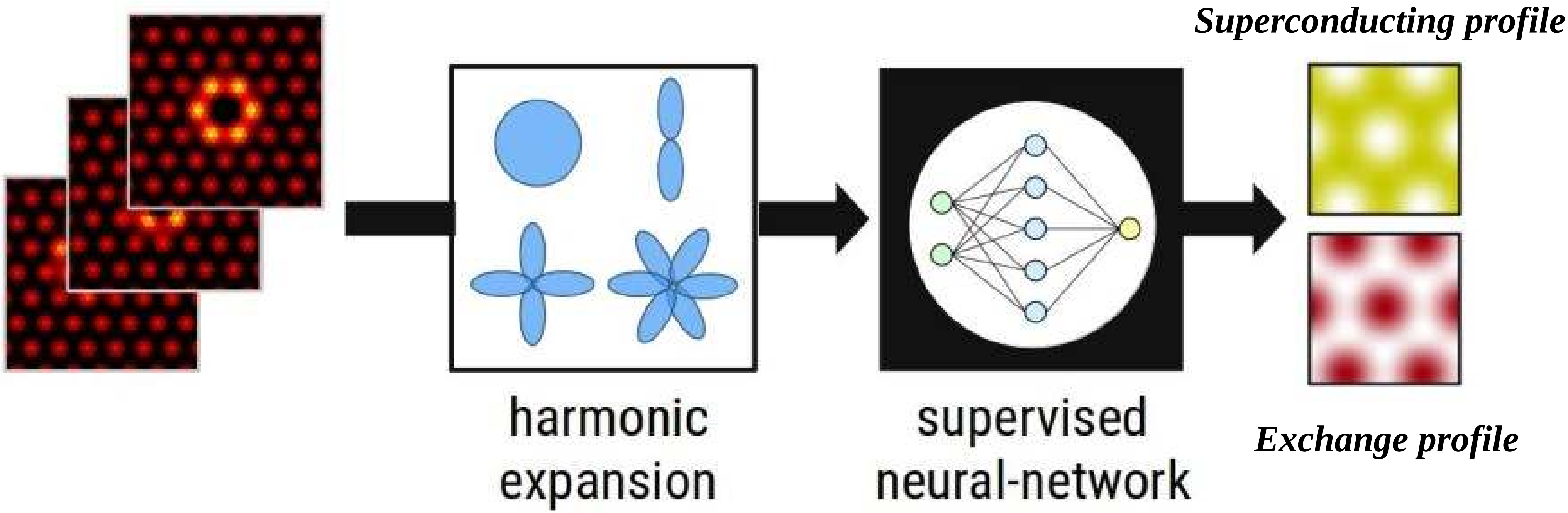


Exchange profile

Can we learn the real space moire Hamiltonian directly from impurity spectroscopy?

Real-space impurity tomography

YSR for different impurity locations



Spectra around different impurity locations allows us to extract the exchange and superconducting profile in real-space

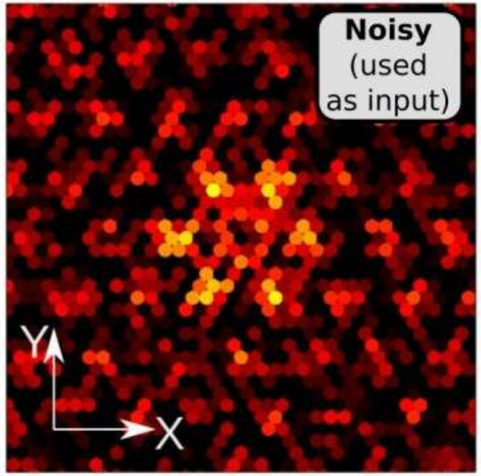
Hamiltonian learning with noisy spectroscopy

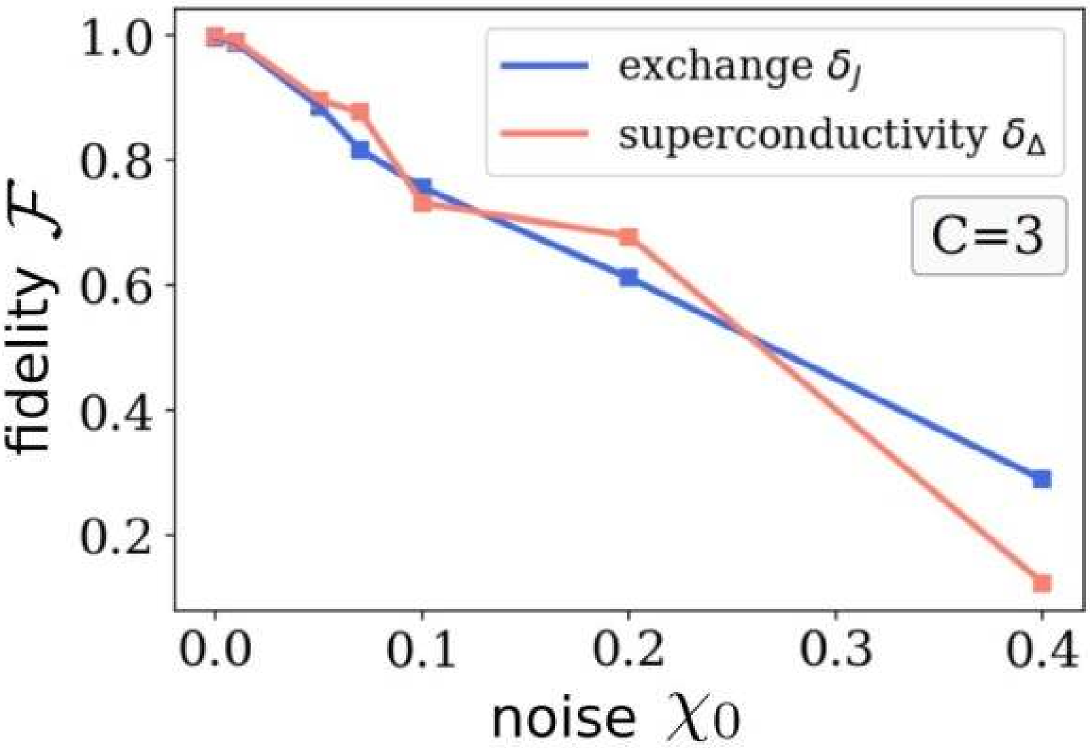
Prediction accuracy (fidelity)

$\mathcal{F} = 1$ Perfect prediction

$\mathcal{F} = 0$ No predictive power

Noise $\chi_0 = 0.2$

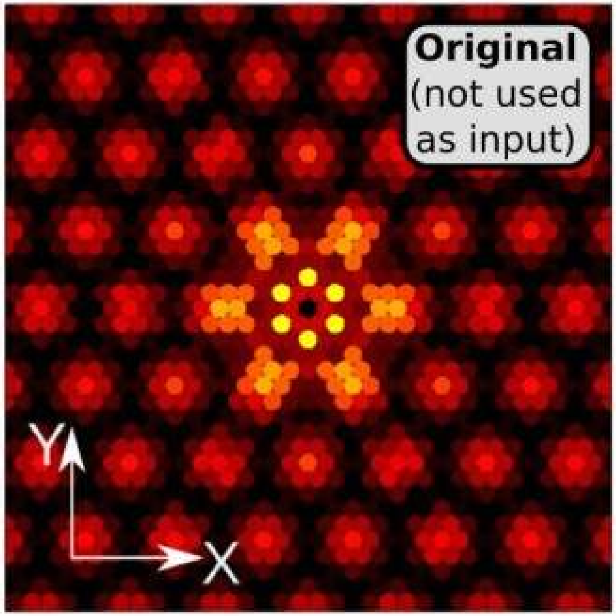




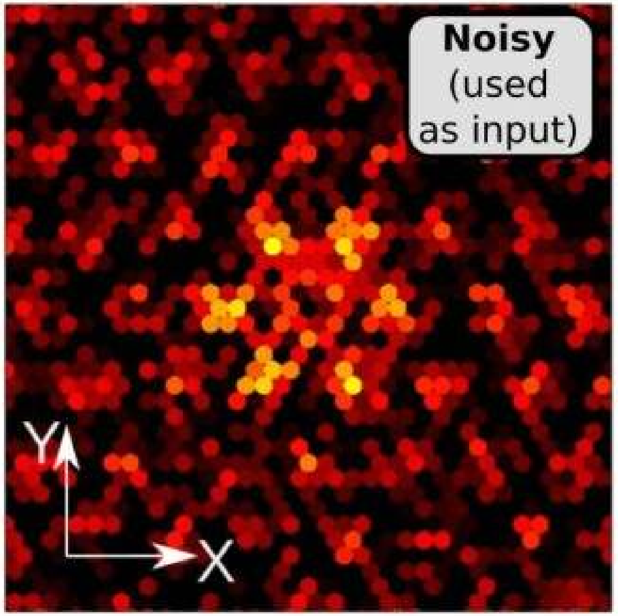
Hamiltonian learning is successful even with moderate noise

Noisy Hamiltonian reconstruction

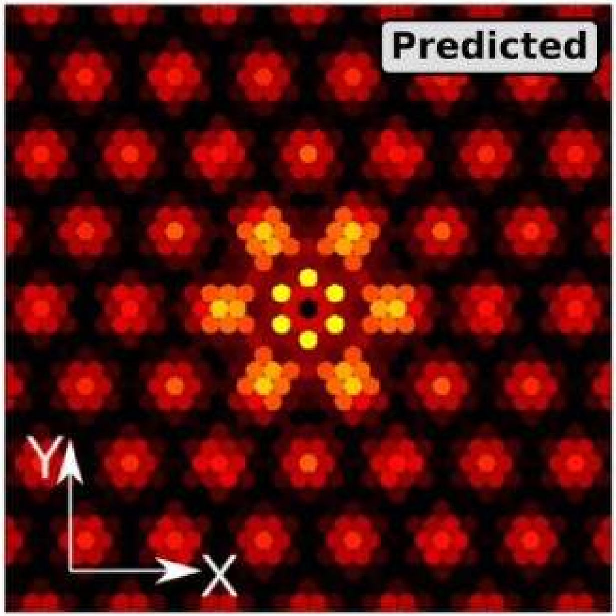
Original non-noisy profile



Noisy profile provided to the machine learning algorithm



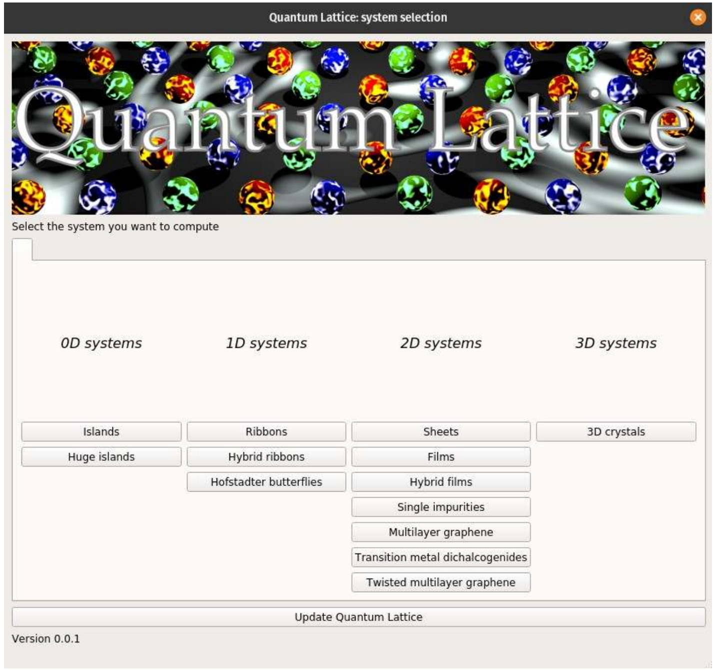
Predicted profile of the extracted Hamiltonian

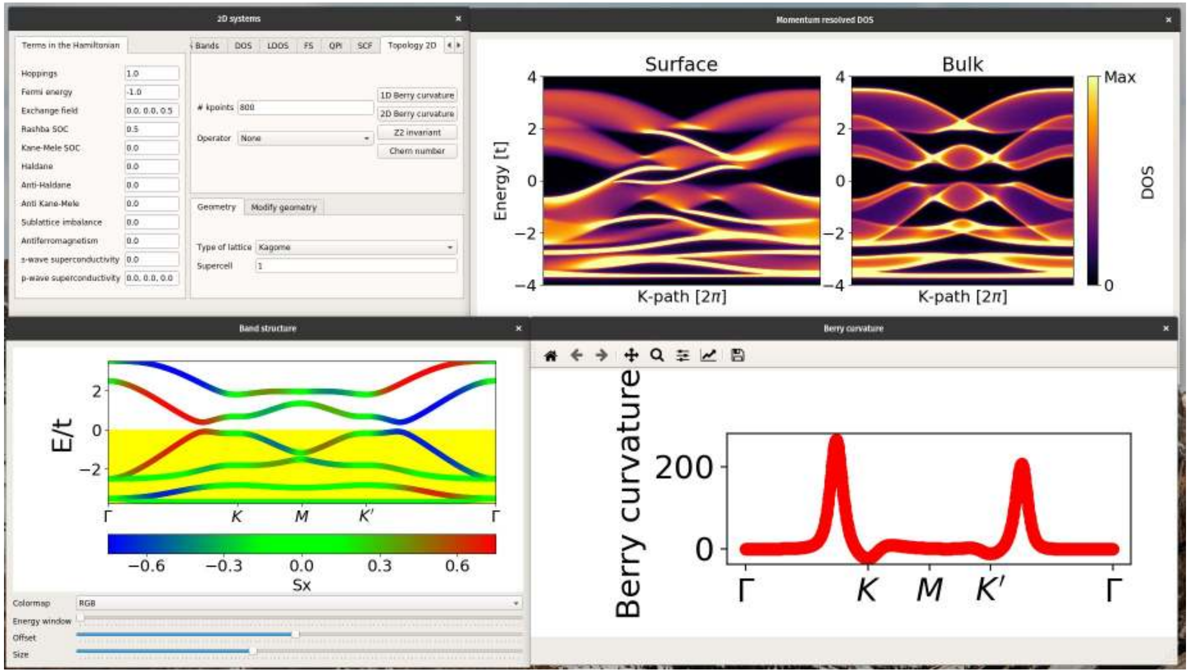


A reconstructed Hamiltonian from noisy data reproduced the original noiseless in-gap modes

Computing electronic properties

Quantum Lattice: A user interface to compute electronic properties

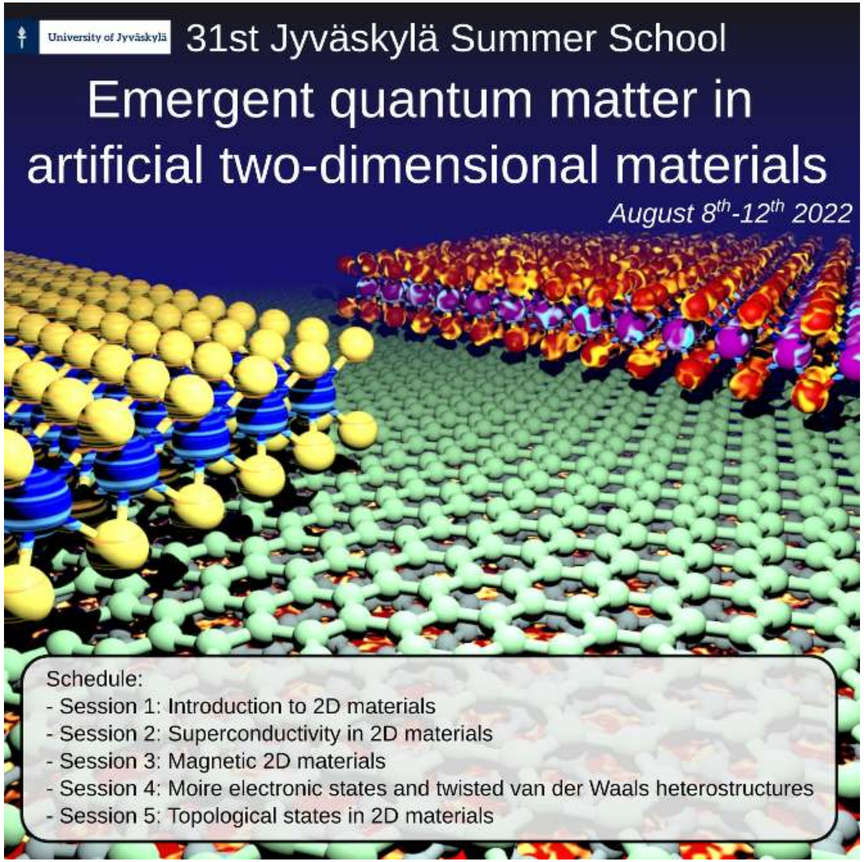




Quantum Lattice: open source interactive interface for tight binding modeling

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

Quantum matter in van der Waals materials school



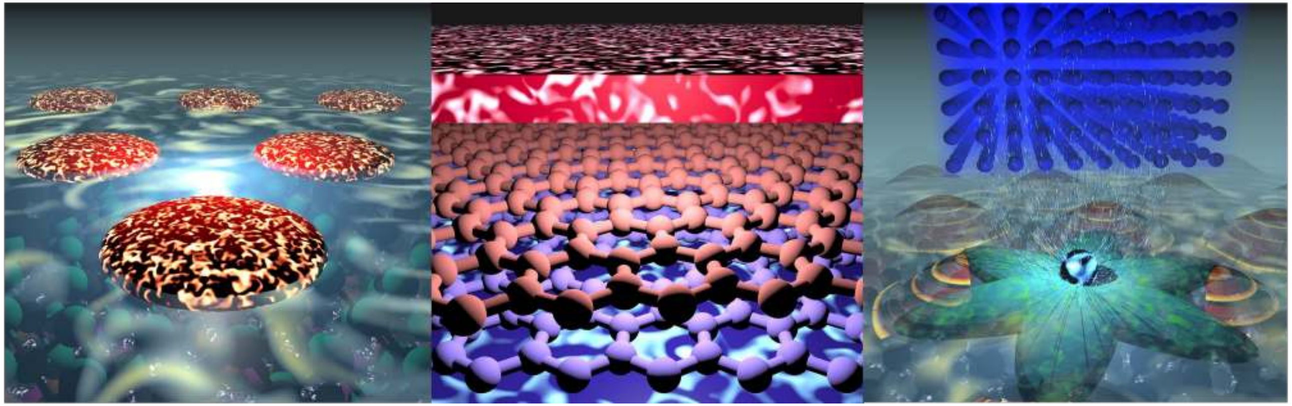
Recordings available at

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

Moiré physics provides a powerful strategy to engineer and probe controllable topological superconductivity



Thank you!

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