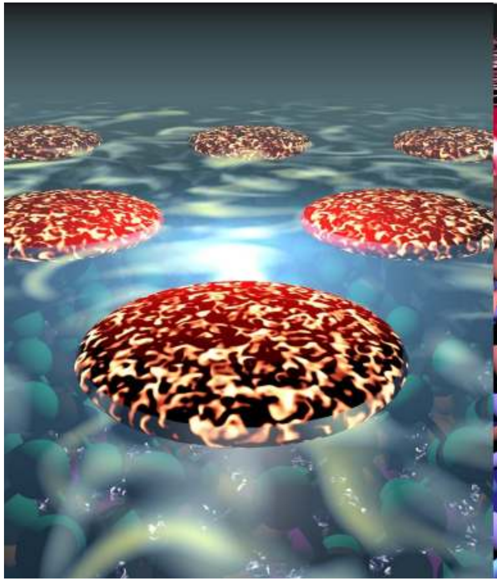
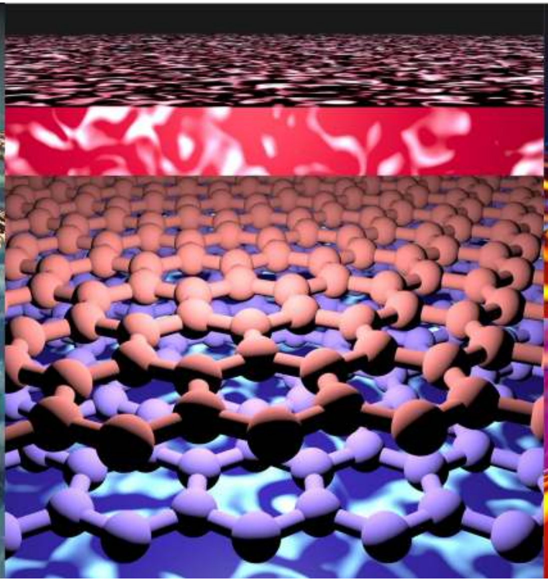
Moire-enabled topological superconductors and impurity spectroscopy in twisted van der Waals heterostructures

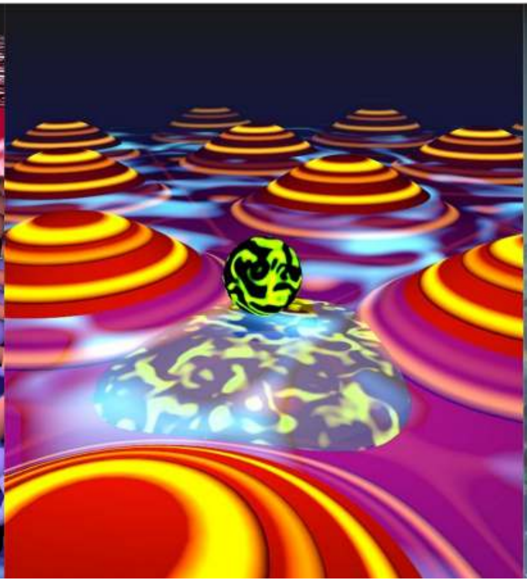
Jose Lado
Department of Applied Physics, Aalto University, Finland



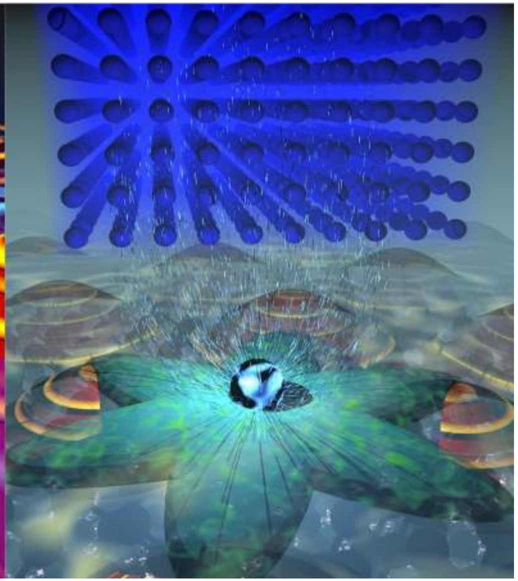
Nano Lett. 2022, 22, 1, 328–333 (2022)



arXiv:2307.04605 (2023)



Phys. Rev. Mat. 6, 094010 (2022)



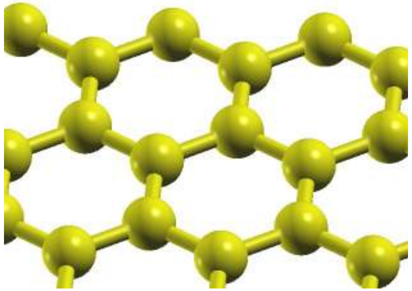
arXiv:2308.11400 (2023)

International Workshop on Superconductivity and Magnetism in Two Dimensional Films and Heterostructures
September 1st 2023, Bath, UK

The two-dimensional materials world

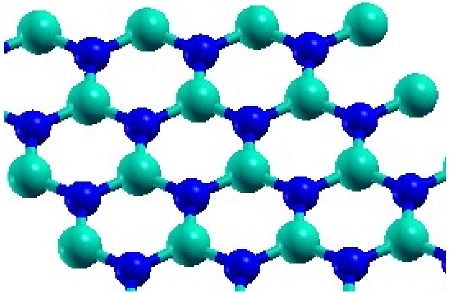
Semimetal

Graphene



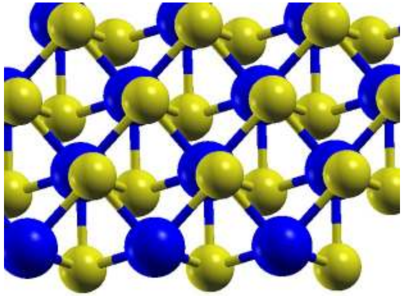
Insulator

BN



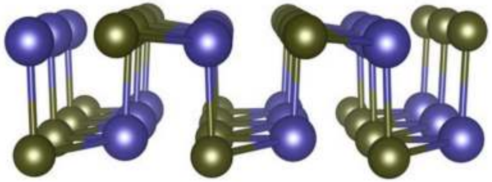
Superconductor

$NbSe_2$



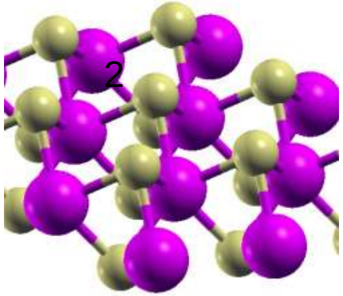
Ferroelectric

SnTe



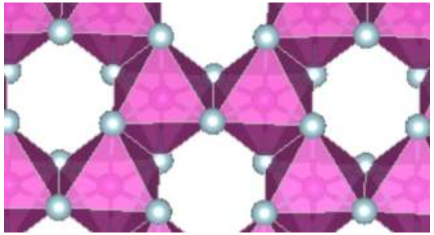
Semiconductor

WSe_2



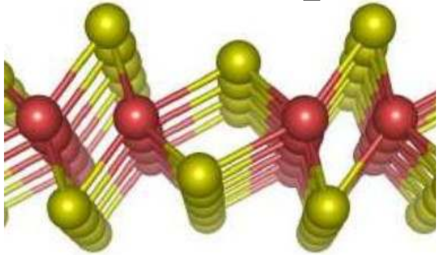
Ferromagnet

CrI_3



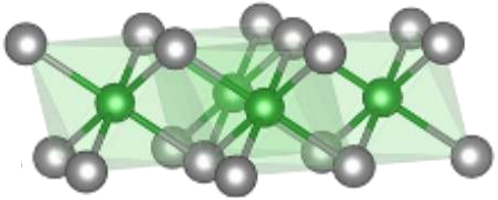
Quantum spin Hall insulator

WTe_2



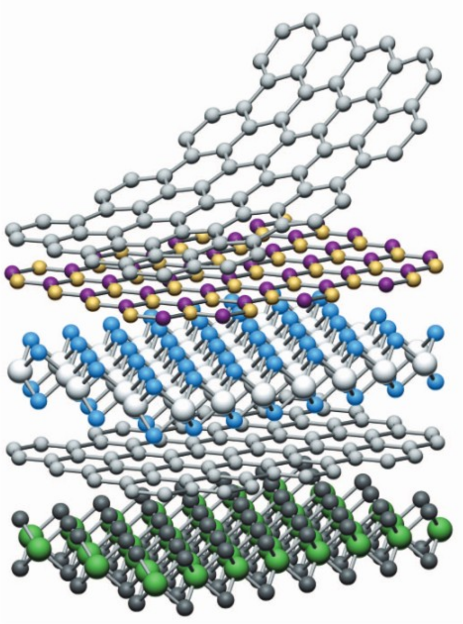
Multiferroic

NiI_2



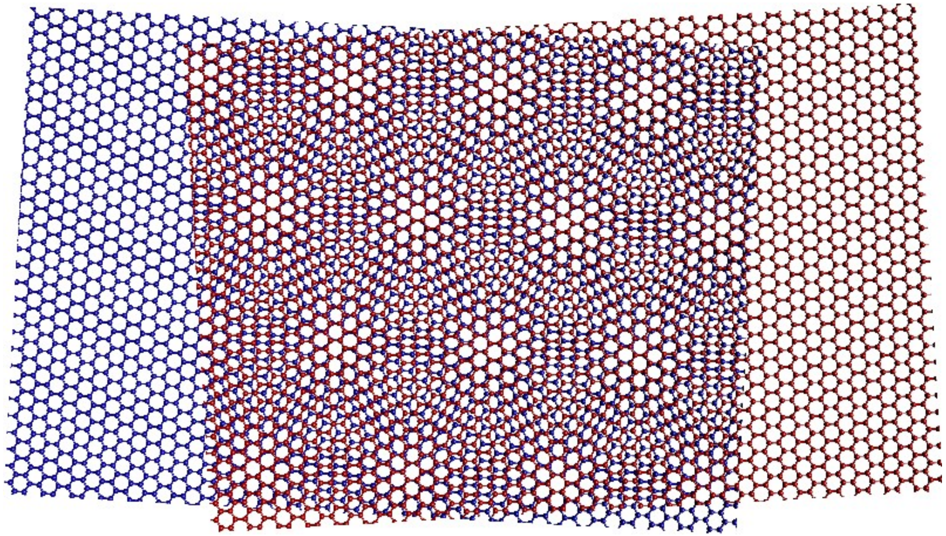
The flexibility of two-dimensional materials

They can be stacked



Nature 499, 419–425 (2013)

They can be rotated

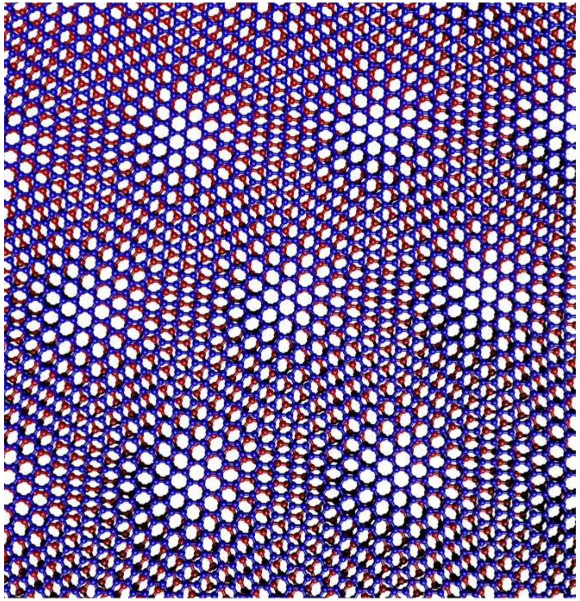


Science 361, 6403, 690-693 (2018)

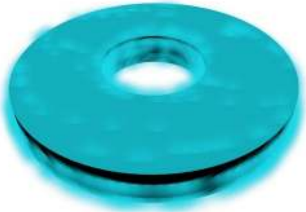
These are unique features of two-dimensional materials

One material, a zoo of electronic phases

Twisted bilayer graphene



Superconductivity

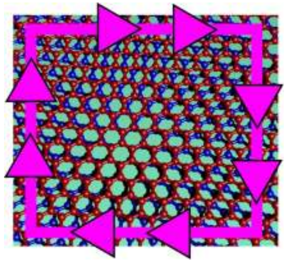


Nature 556, 43–50 (2018)

Topological networks

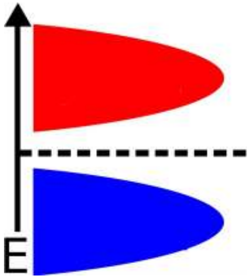
Nano Lett. 18, 11, 6725-6730 (2018)

Chern insulators



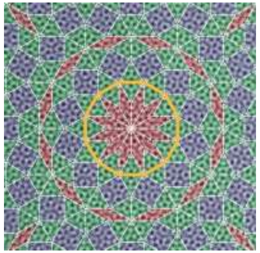
Science 365, 605-608 (2019)

Correlated insulators



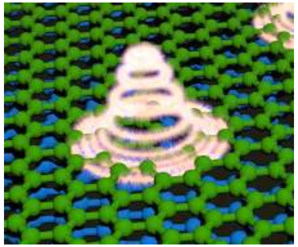
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

Fractional Chern insulators

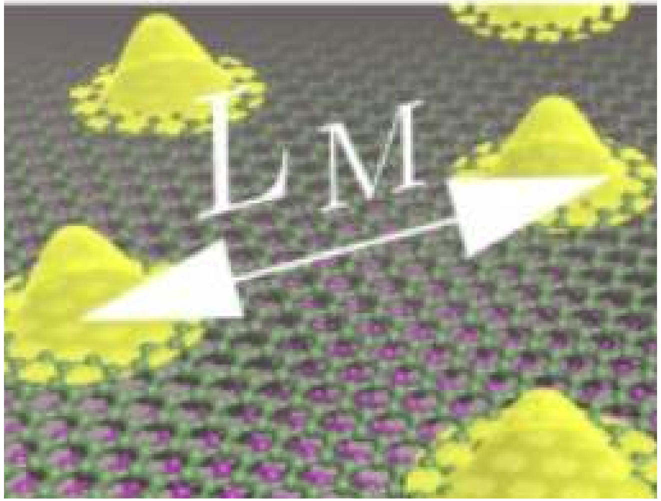


Nature 600, 439–443 (2021)

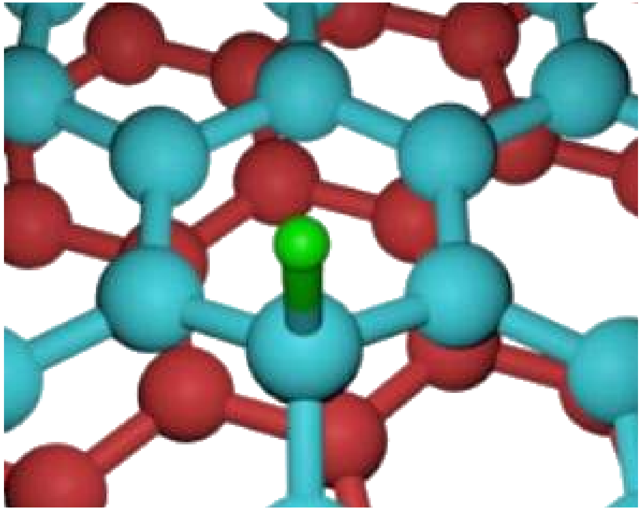
Twisted graphene multilayers provide a powerful platform for emergent phenomena

Two length scales in twisted van der Waals materials

The emergent moire scale



The original atomic scale

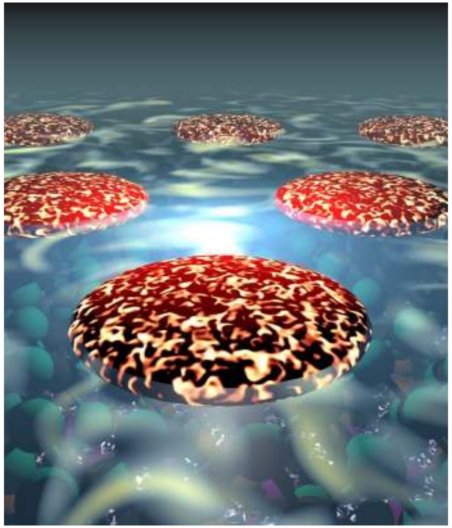


The coexistence of these two different scales is unique to moire systems

How do atomic impurities impact the physics emerging from much bigger length scales?

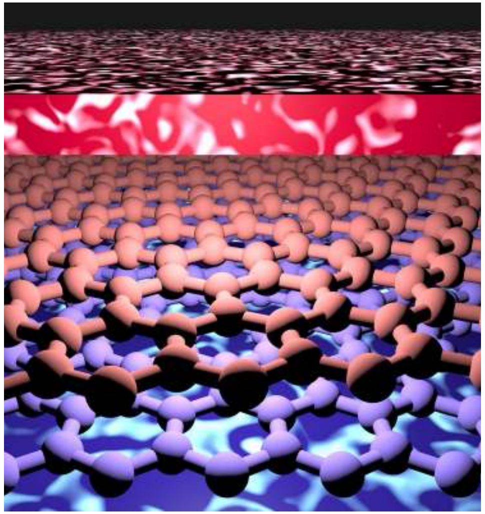
Today’s plan

Moire-enabled topological superconductivity in $CrBr_3/NbSe_2$



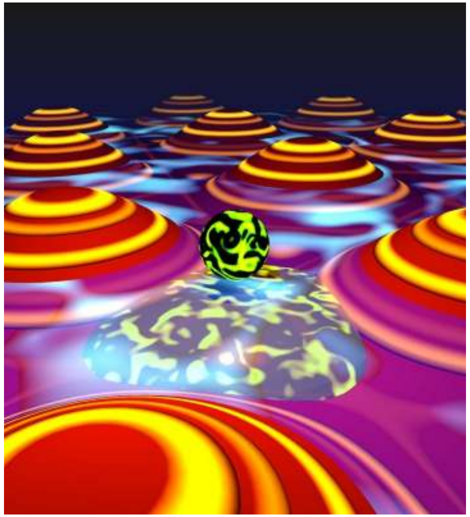
Nano Lett. 2022, 22, 1, 328–333 (2022)

Moire-enabled topological superconductivity in twisted graphene



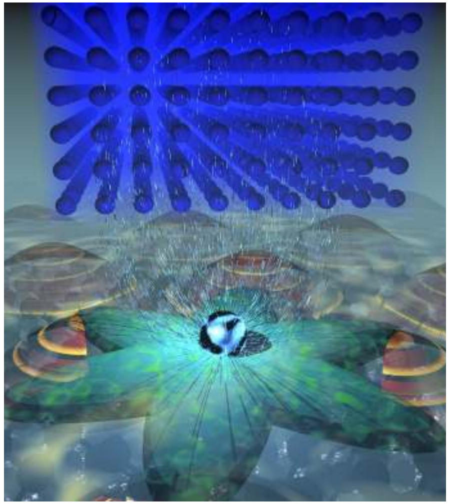
arXiv:2307.04605

Impurities in twisted moire topological superconductors

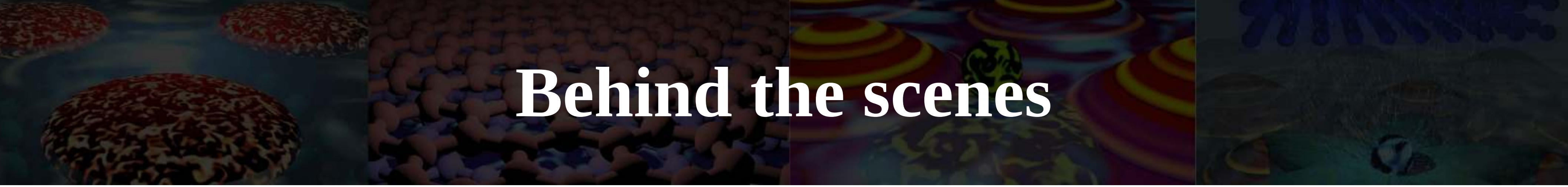


Phys. Rev. Mat. 6, 094010 (2022)

Hamiltonian learning from moire impurity tomography



arXiv:2308.11400



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

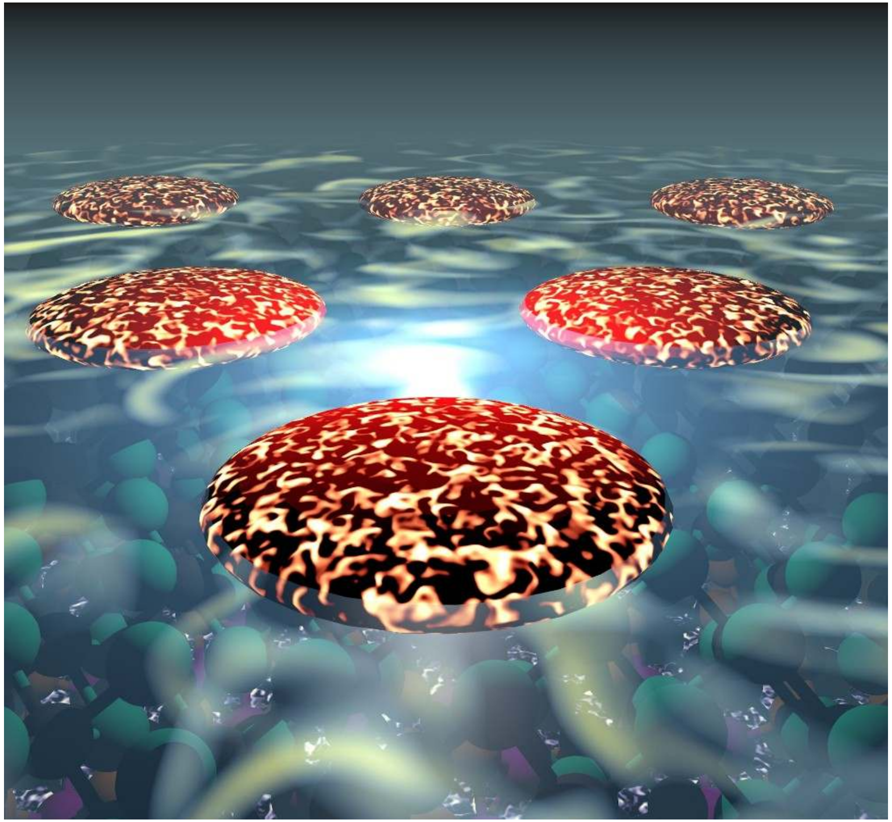
R. Koch

arXiv:2307.04605

arXiv:2308.11400

Phys. Rev. Materials 6, 094010 (2022)

Artificial topological moire superconductivity in $NbSe_2/CrBr_3$



S. Ganguli

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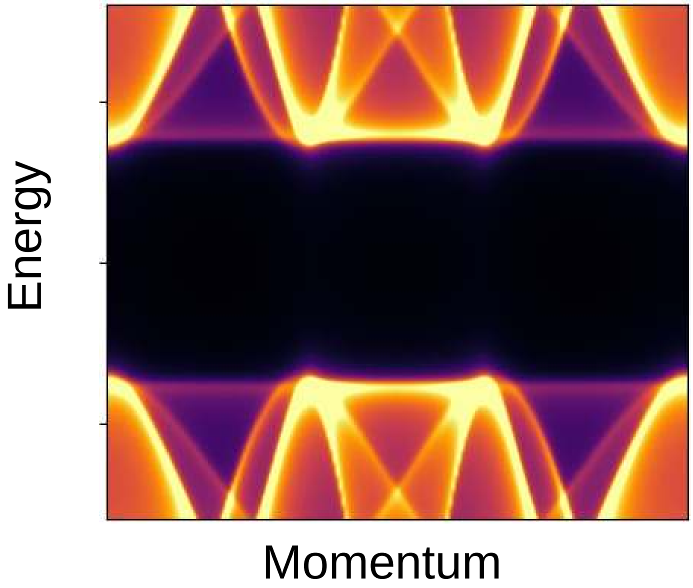
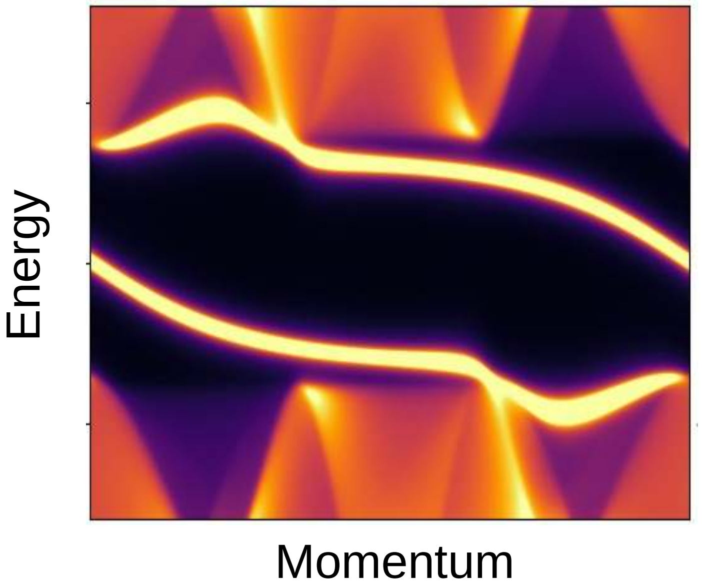
Nano Lett. 22, 1, 328-333 (2022)

Topological superconductors

Full gap in the bulk

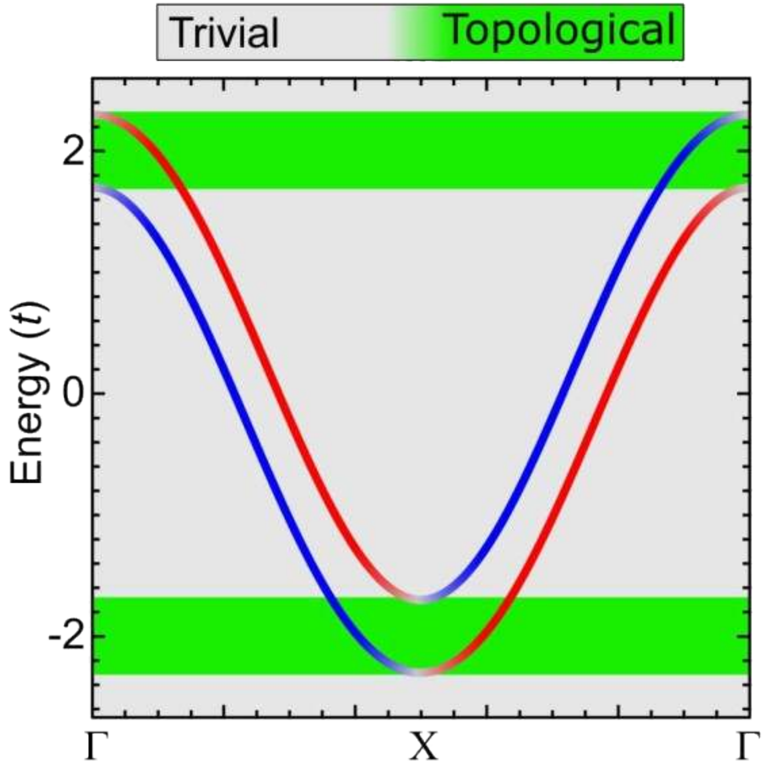


Gapless (Majorana) mode at the edge



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

Warm up: 1D topological superconductor



$$H = H_0 + H_J + H_R$$

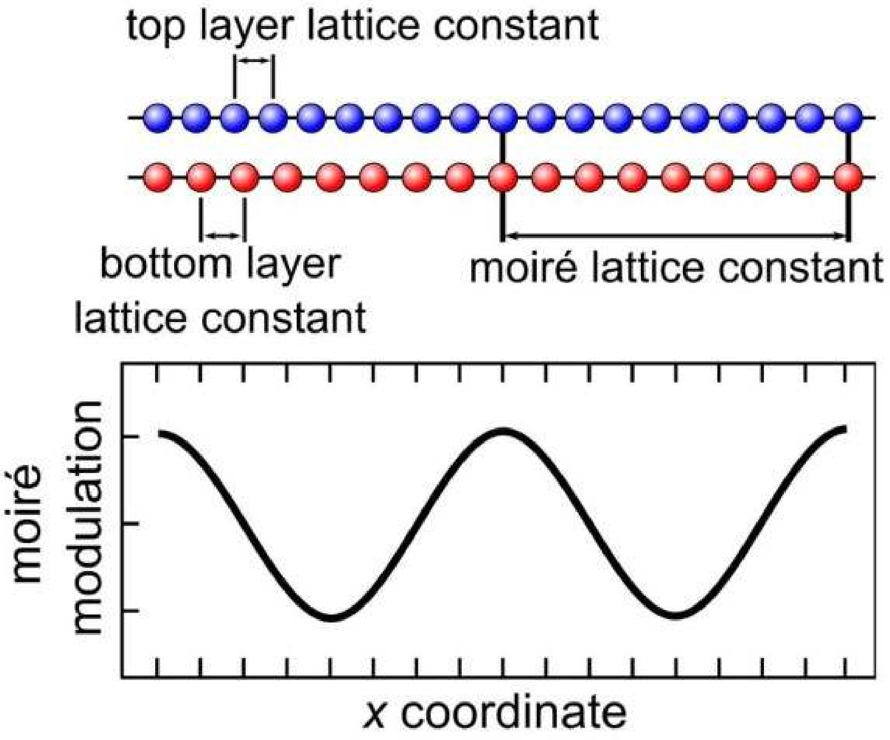
Kinetic energy

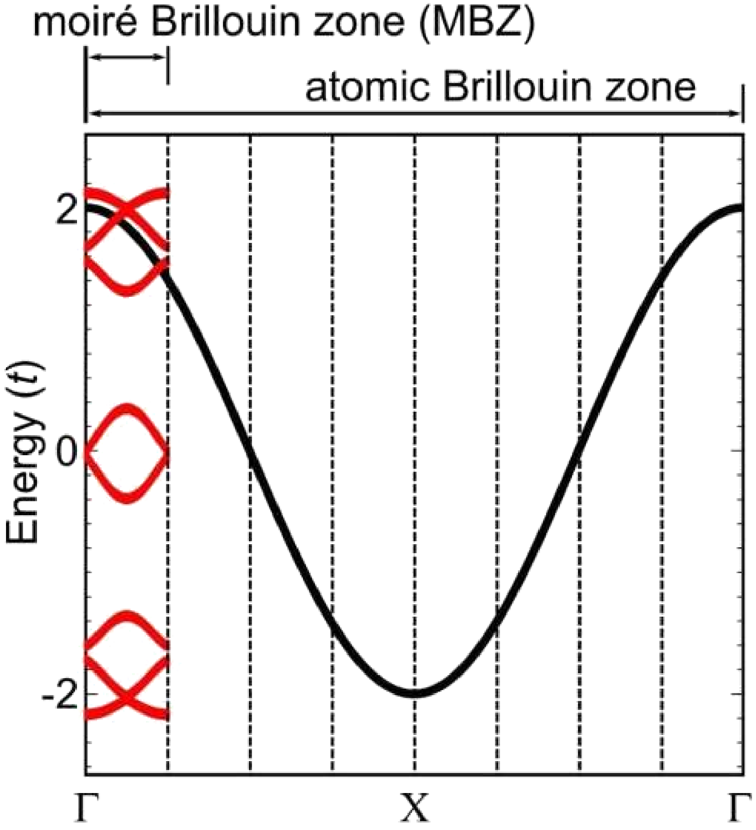
Exchange field

Rashba spin-orbit coupling

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

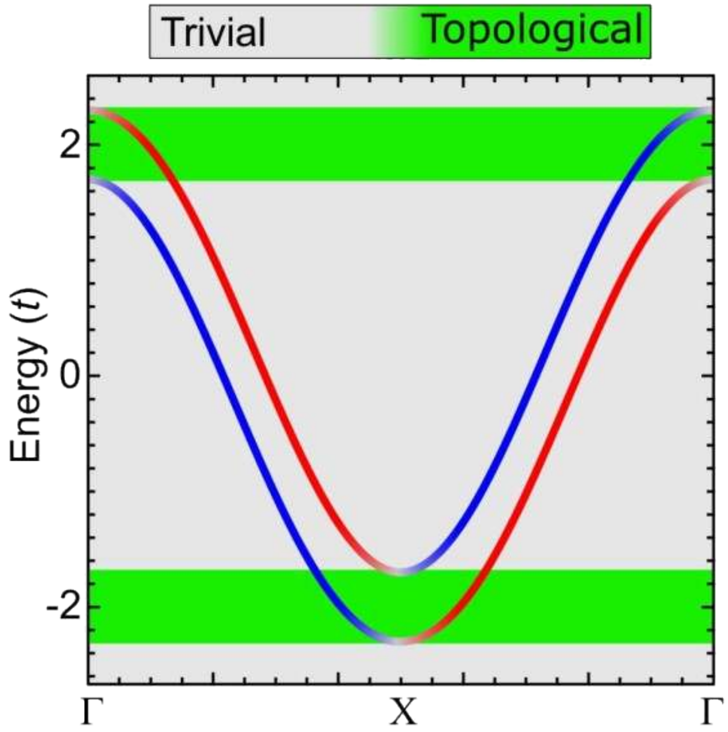
Warm up: 1D moire superconductor



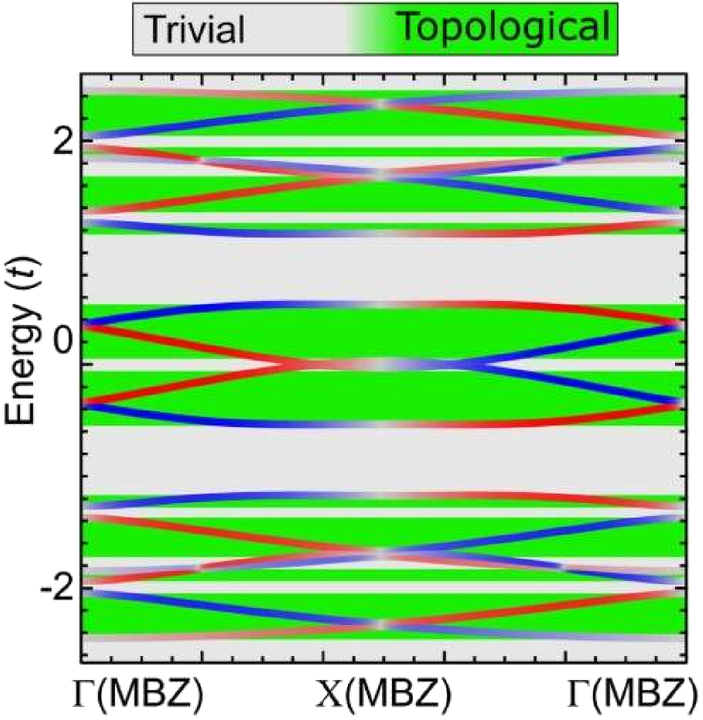


Warm up: 1D moire superconductor

Without moire



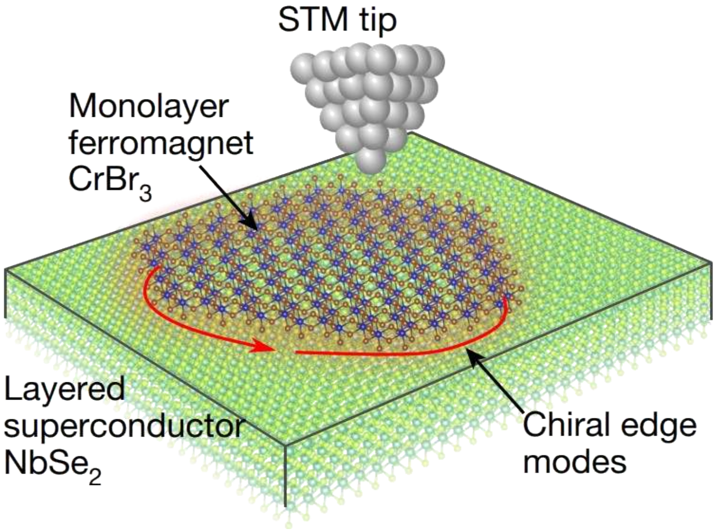
With moire



Moire pattern allow to realize topological superconductivity in otherwise forbidden energies

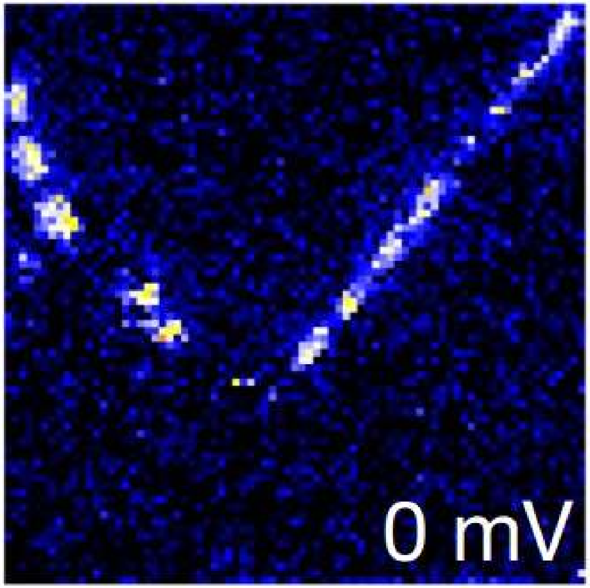
Topological superconductivity in a van der Waals heterostructure

$CrBr_3/NbSe_2$ heterostructure



Nature 588, 424–428 (2020)

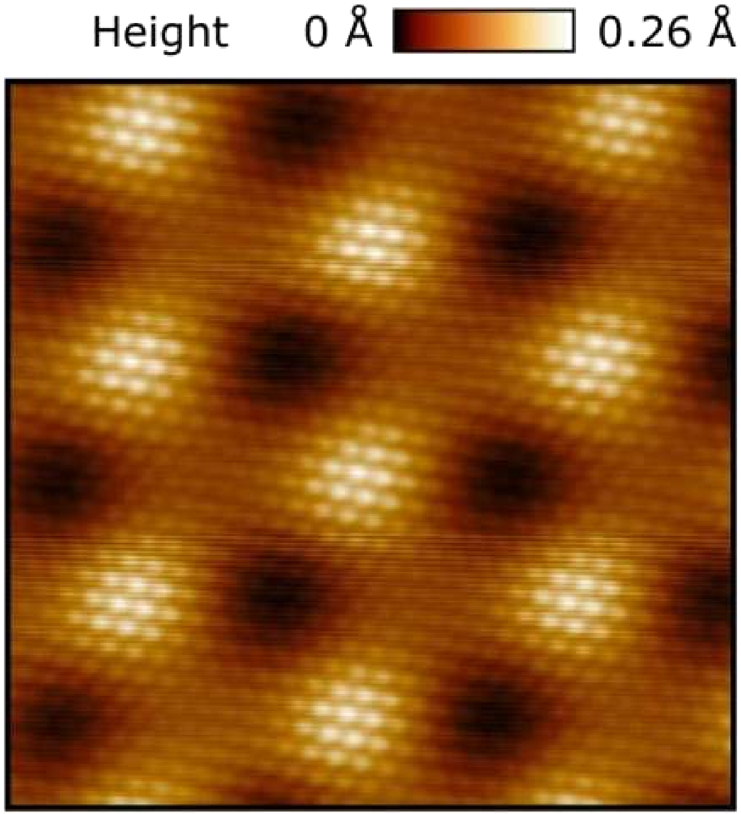
Zero bias dIdV

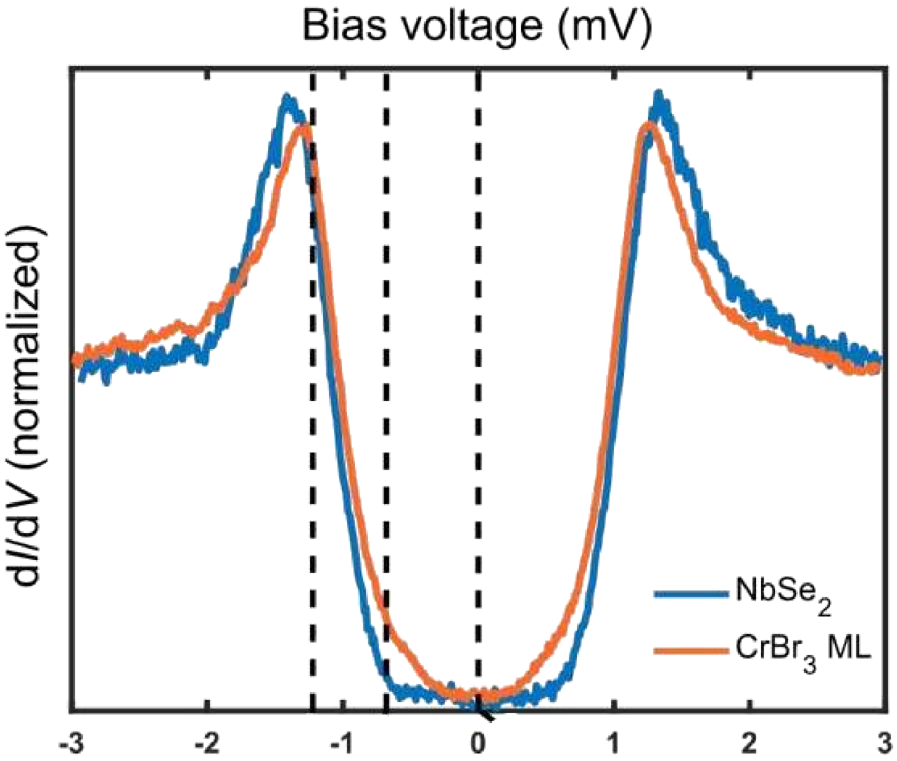


A topological superconducting state appears in $CrBr_3/NbSe_2$

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

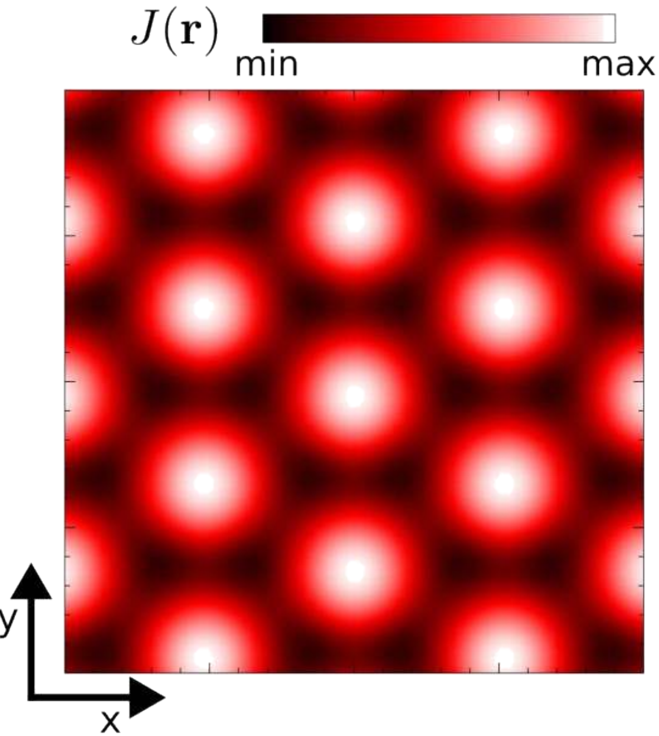
$CrBr_3/NbSe_2$ heterostructure



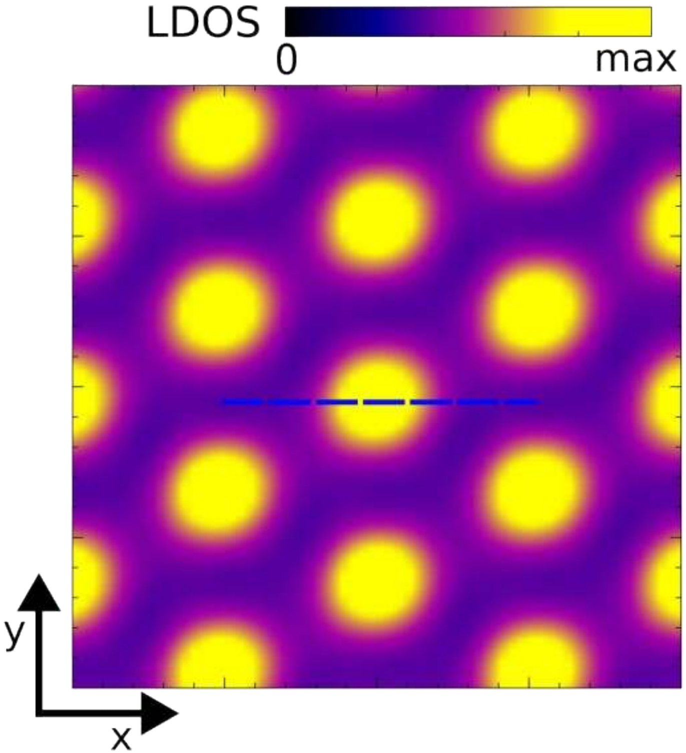


Bulk Yu-Shiba-Rusinov states

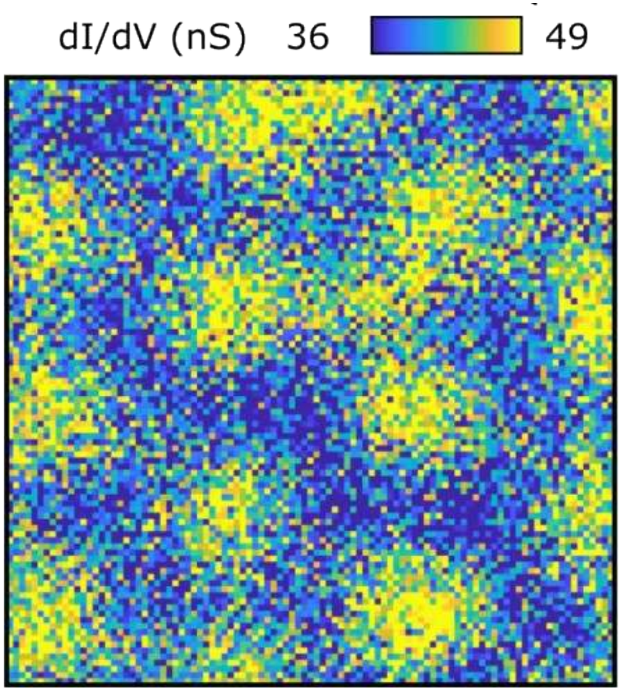
Exchange profile



Theoretical LDOS



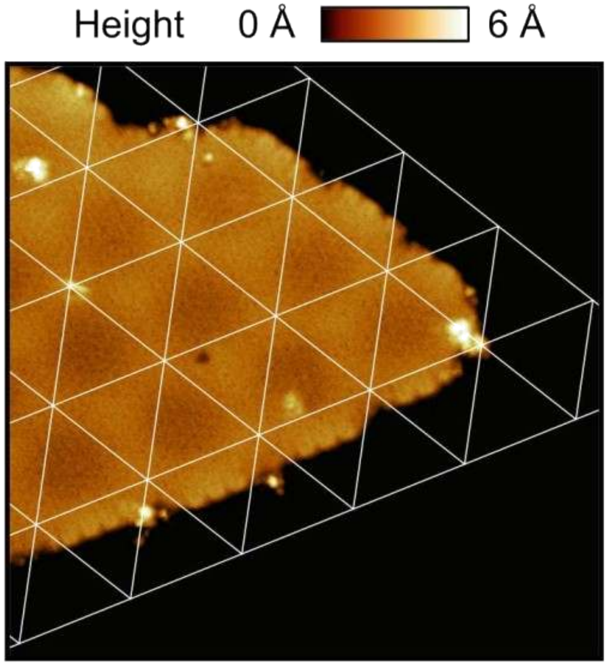
Experimental dIdV



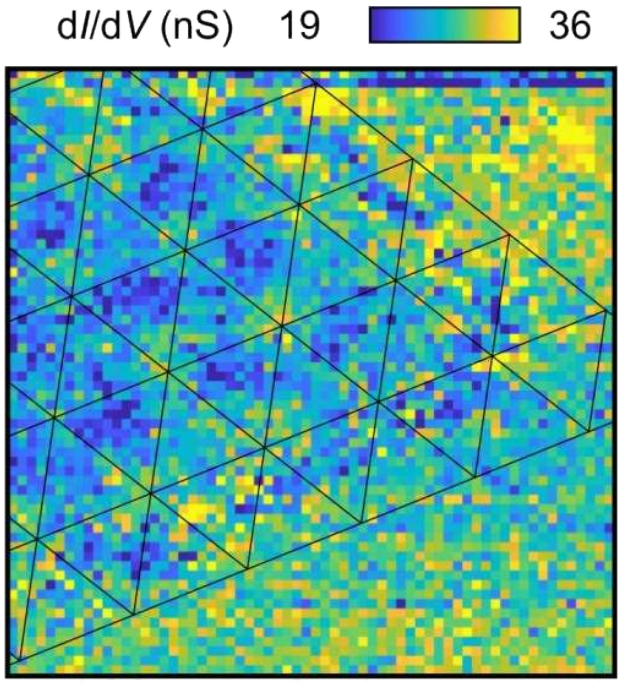
Bulk Yu-Shibe-Rusinov states are imprinted by the modulated exchange profile

Bulk Yu-Shiba-Rusinov states

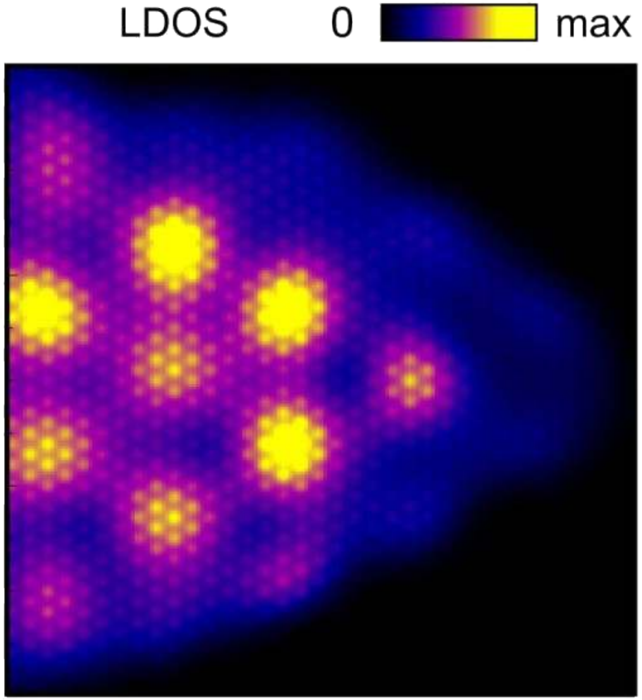
Topography



Experimental dIdV



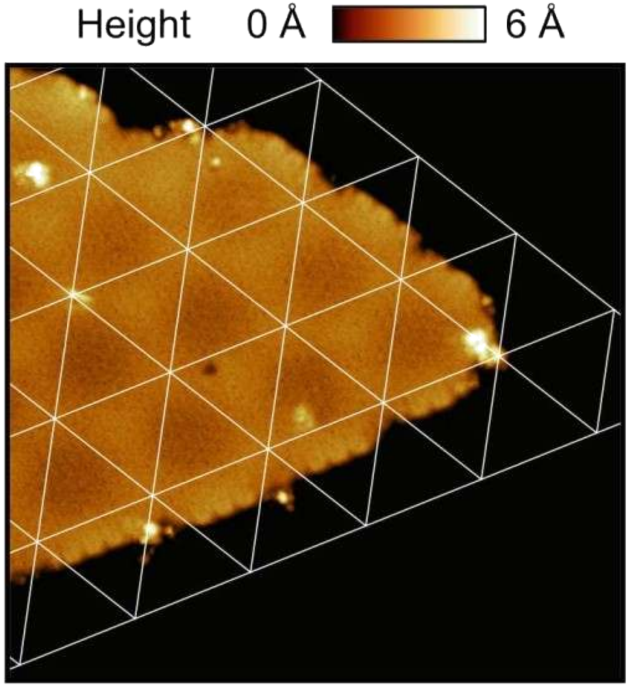
Theoretical dIdV



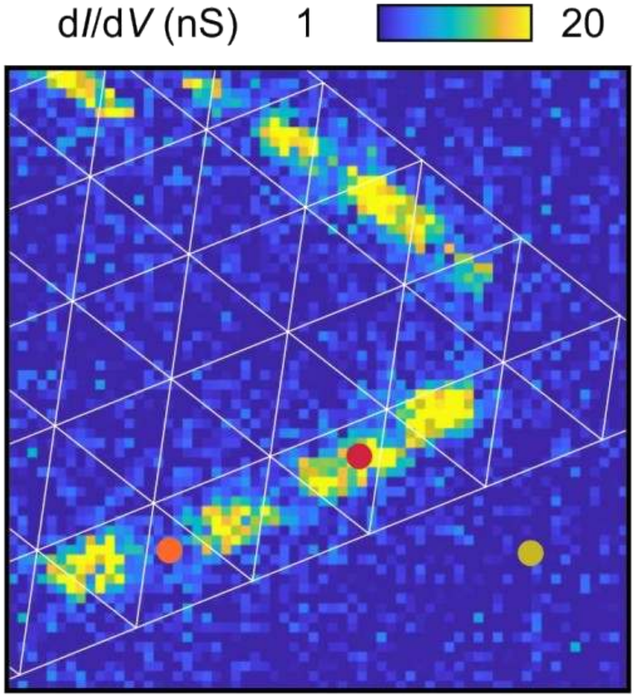
Bulk Yu-Shibe-Rusinov states are imprinted by the modulated exchange profile

Topological moire edge states

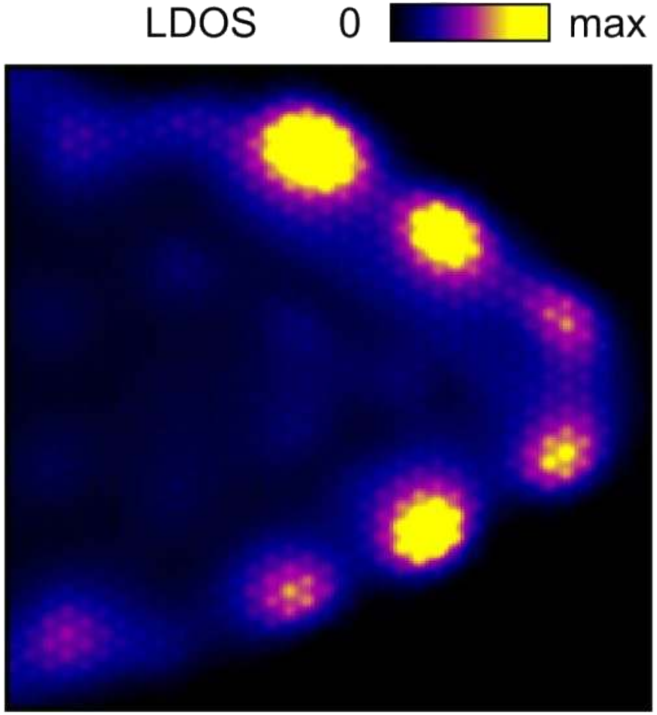
Topography



Experimental dIdV

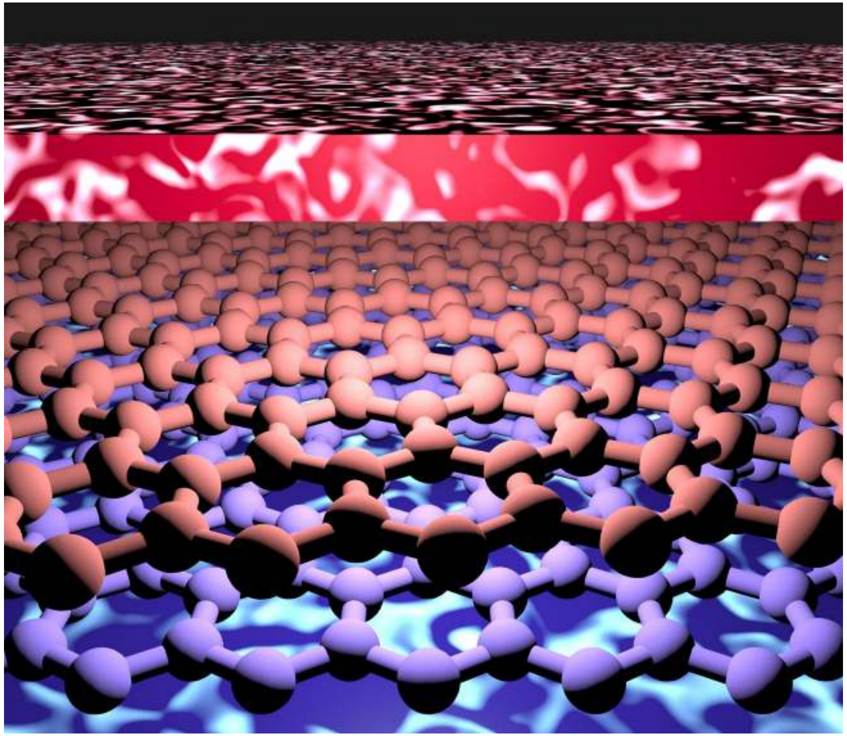


Theoretical dIdV



Topological edge modes are imprinted by the modulated exchange profile

Moire-enabled artificial superconductors in twisted bilayer graphene

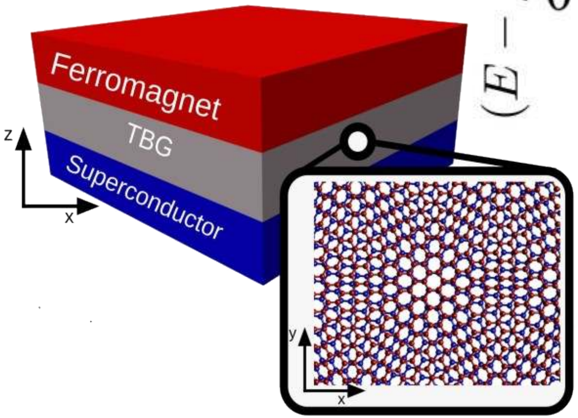


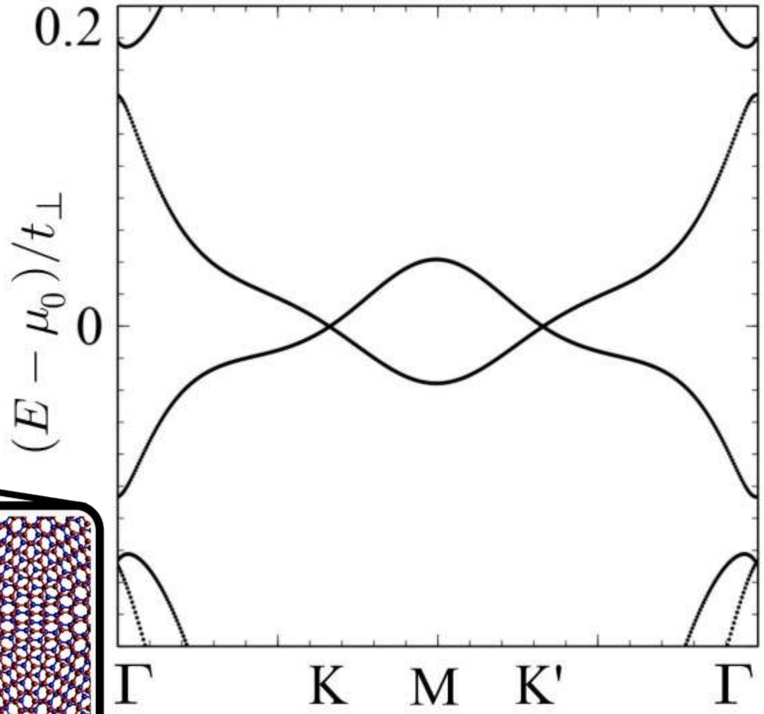
Maryam Khosravian

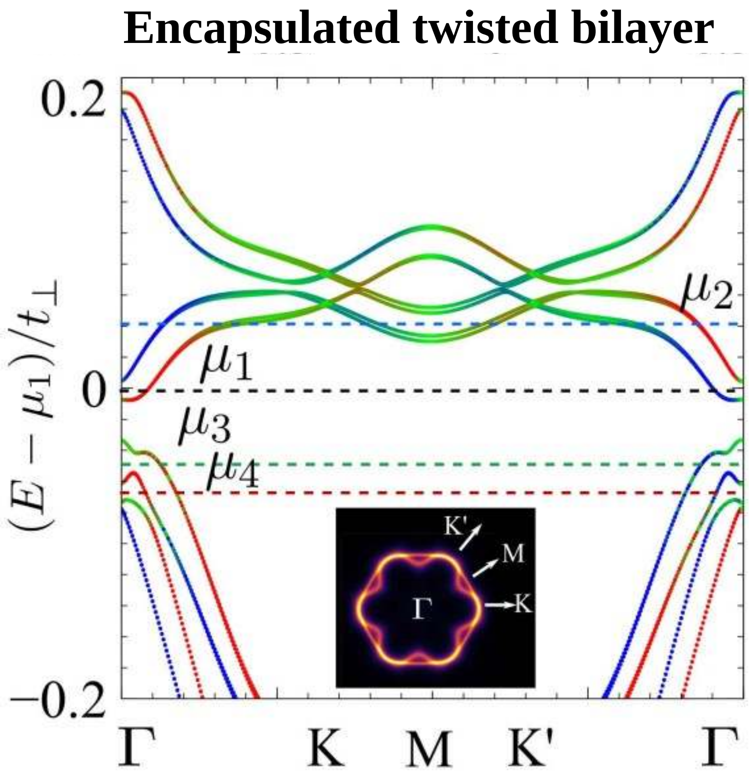
Elena Bascones

arXiv:2307.04605

Moire-enabled artificial superconductors in twisted bilayer graphene



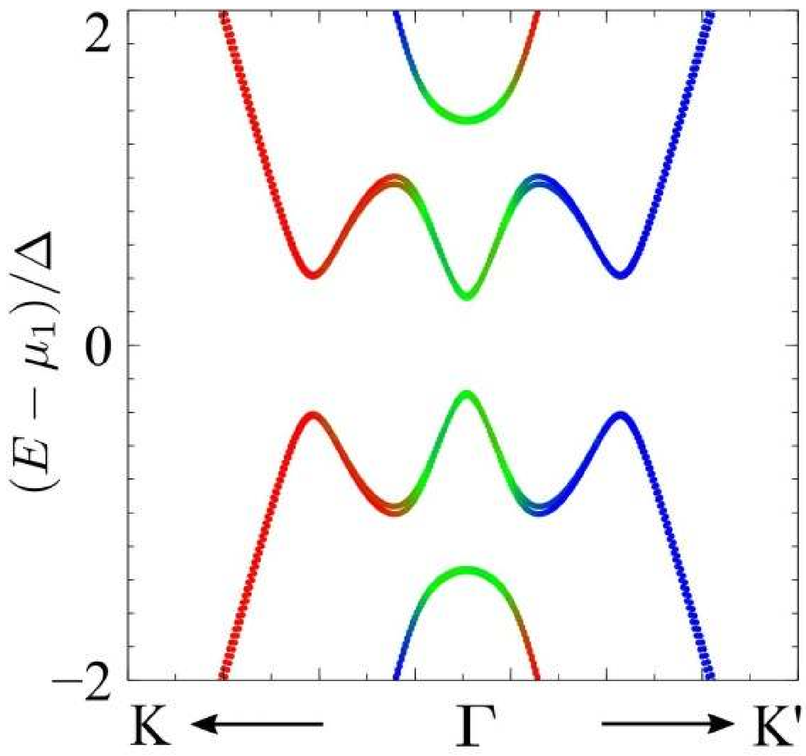




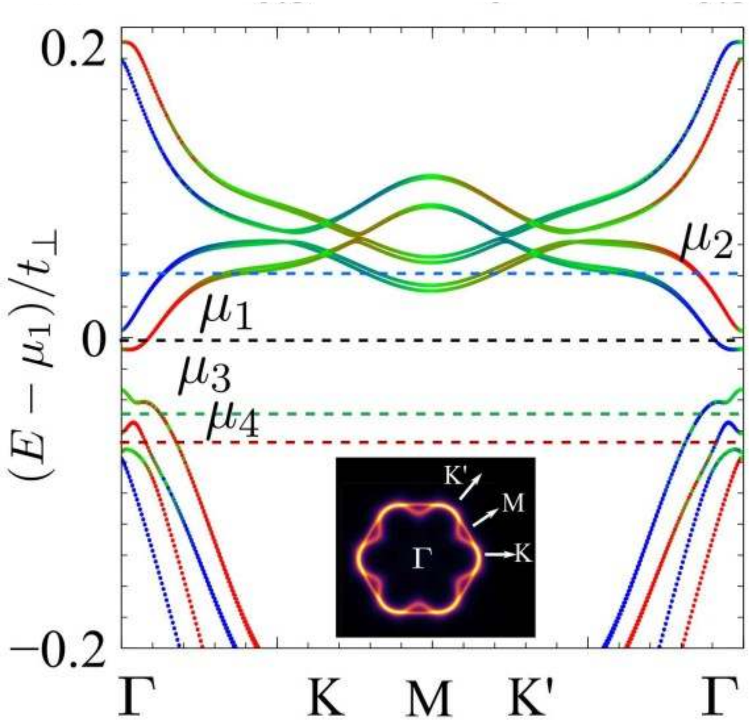
Moire effect gives rise to minigaps featuring helical states with encapsulation

Moire-enabled artificial superconductors in twisted bilayer graphene

With superconductivity



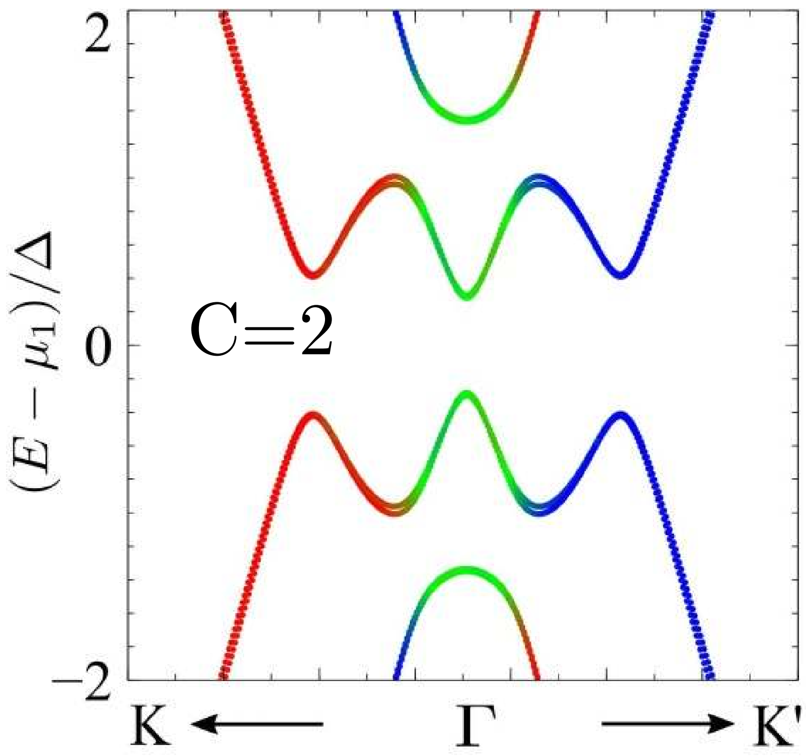
Without superconductivity



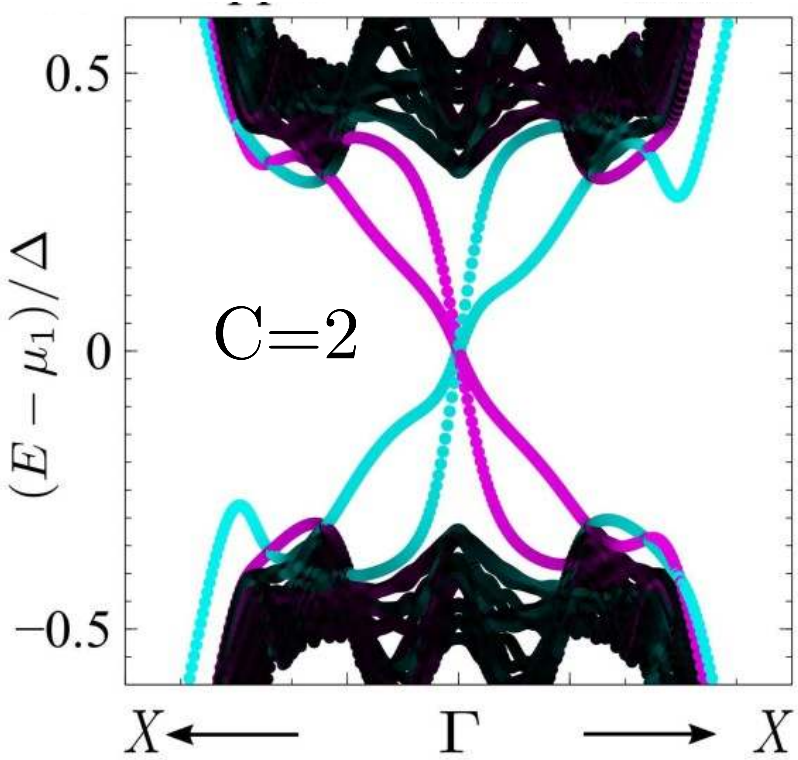
Switching on superconductivity gives rise to a topological superconducting state

Moire-enabled artificial superconductors in twisted bilayer graphene

Bulk band structure



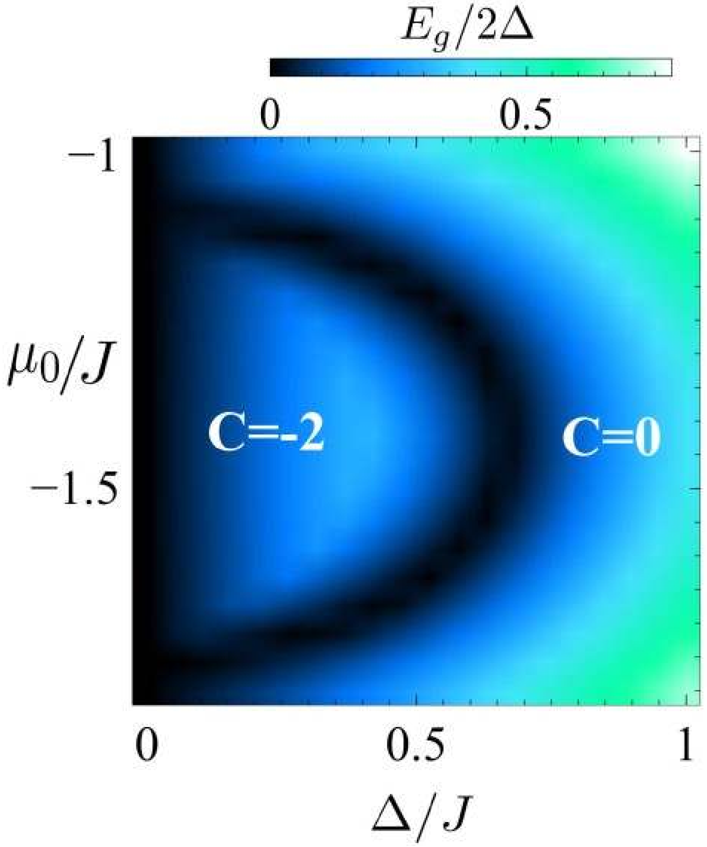
Ribbon band structure



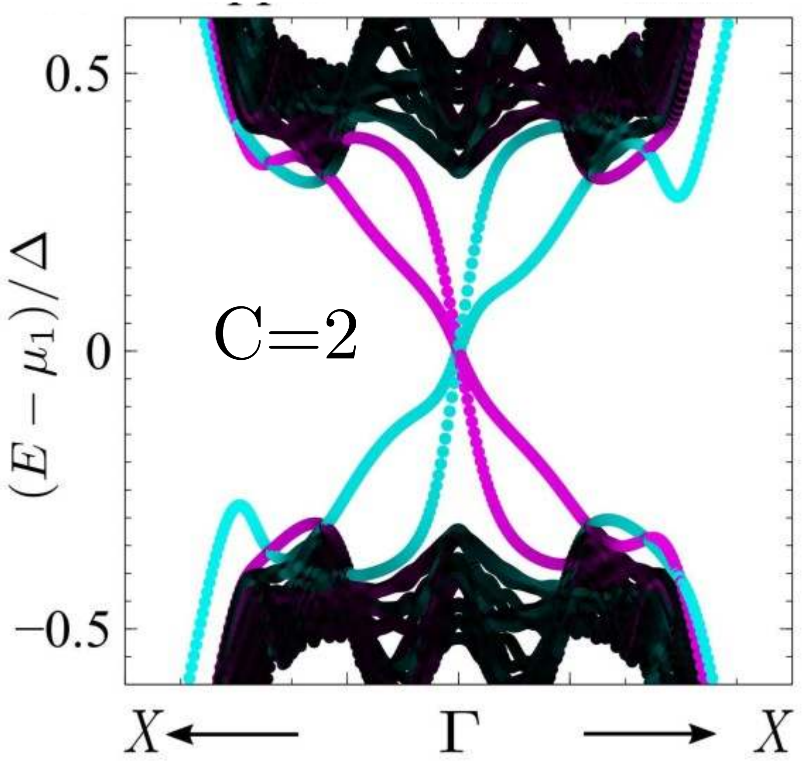
The topological state features chiral Majorana modes in a ribbon geometry

Moire-enabled artificial superconductors in twisted bilayer graphene

Gap VS chemical potential



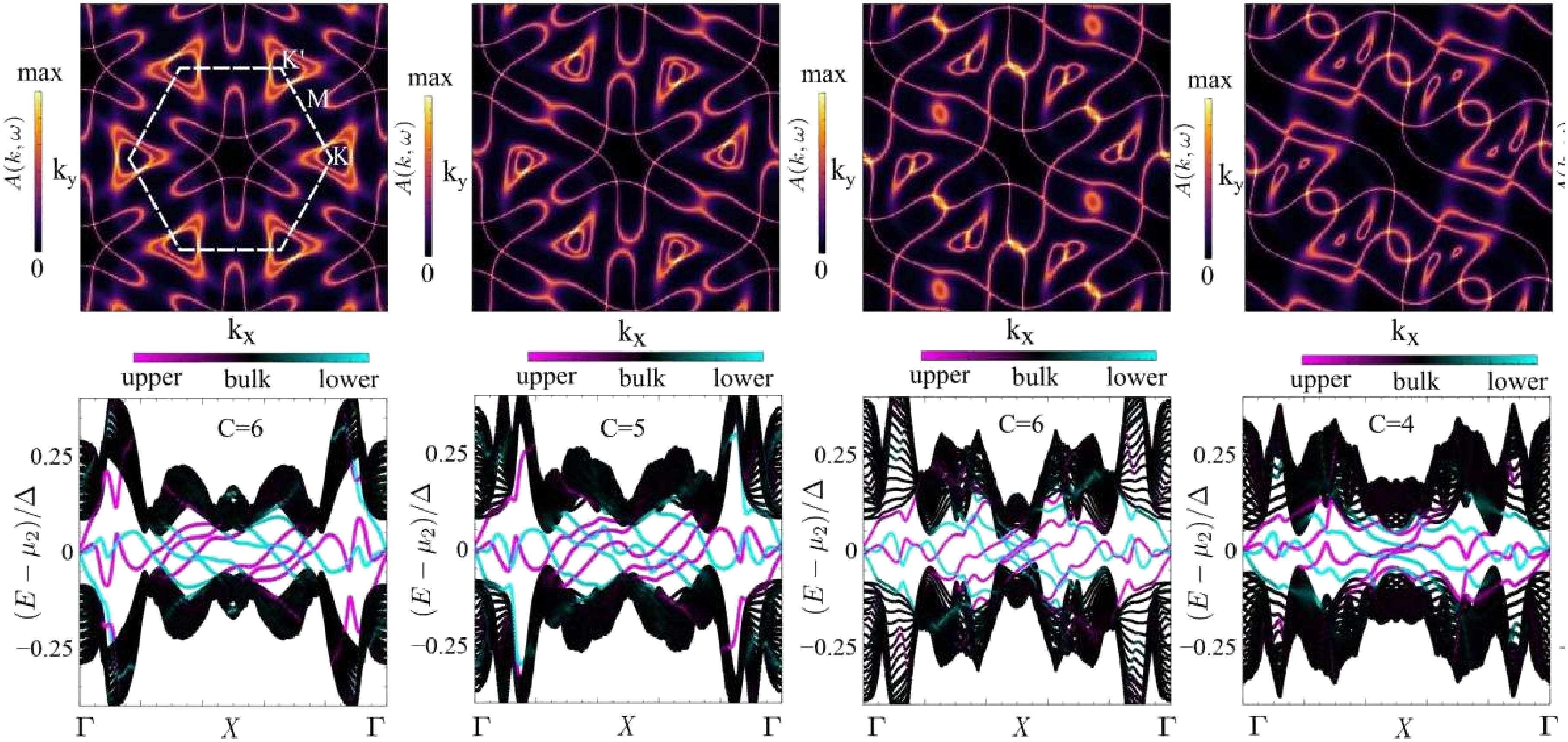
Ribbon band structure



Multiple topological phases tunable by strain

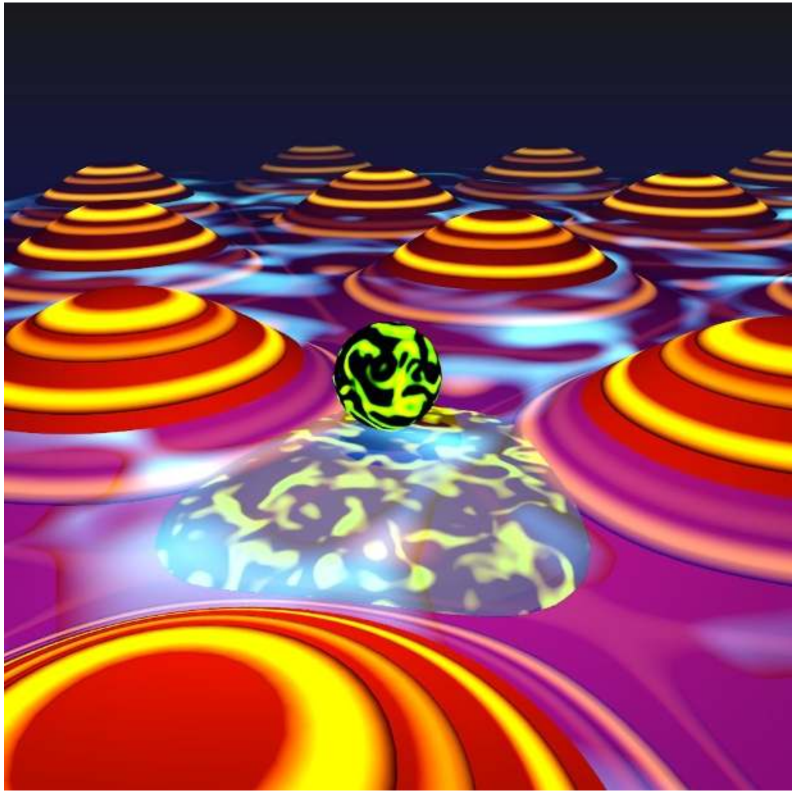
Fermi surface

Ribbon bands



Strain allows to realize topological states with different Chern numbers

Impurities in twisted moire topological superconductors

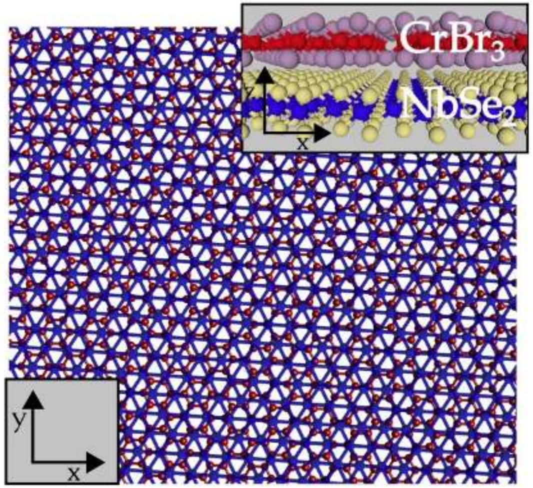


Maryam Khosravian

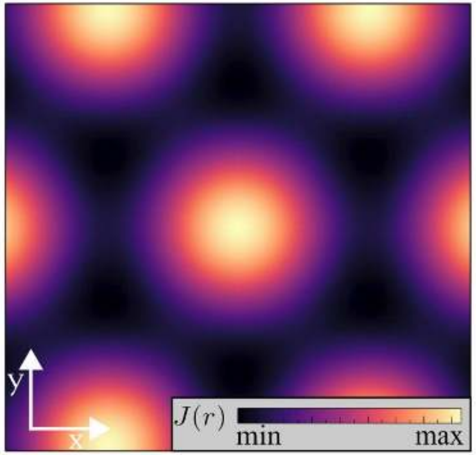
Phys. Rev. Materials 6, 094010 (2022)

Hamiltonian for the pristine moire topological superconductor

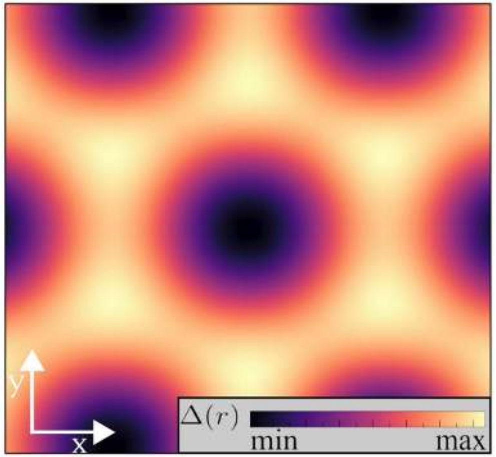
Structure



Exchange profile



Superconducting profile



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

Kinetic energy

Exchange coupling

Rashba SOC

s-wave superconductivity

Hamiltonian for the defective moire topological superconductor

Full Hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\text{imp}}$$

Local impurity in the moire system

$$\mathcal{H}_{\text{imp}} = w \sum_s c^\dagger_{n,s} c_{n,s}$$

Weak impurity

$$w \to 0$$

Strong impurity

$$w \to \infty$$

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

Kinetic energy

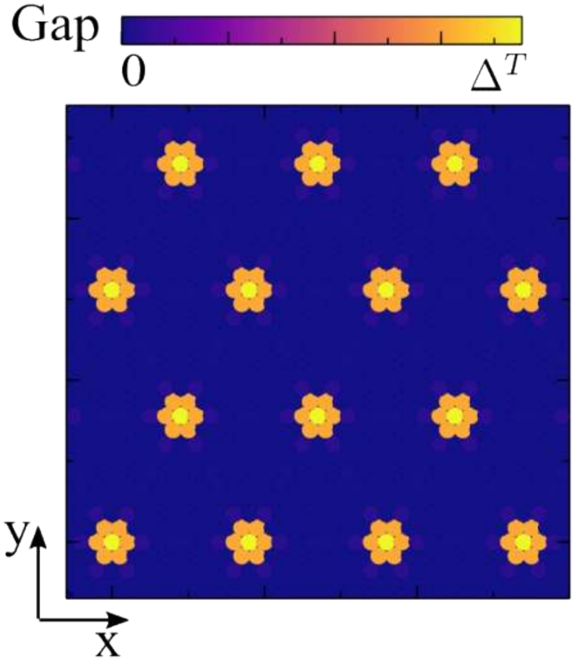
Exchange coupling

Rashba SOC

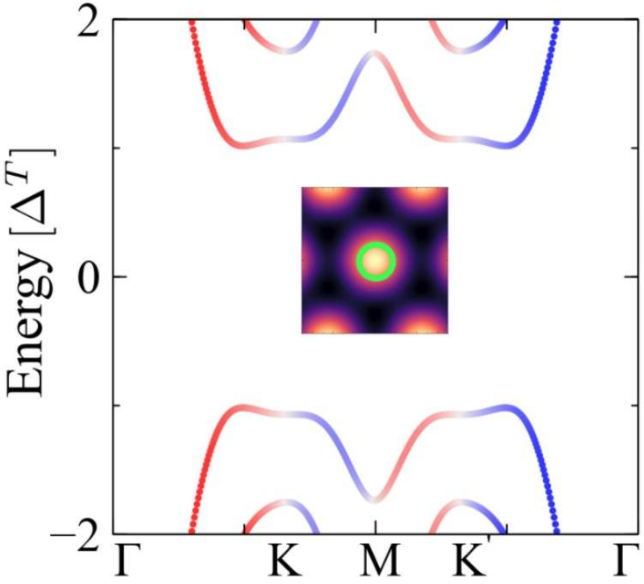
s-wave superconductivity

Gap as a function of the location of a strong impurity

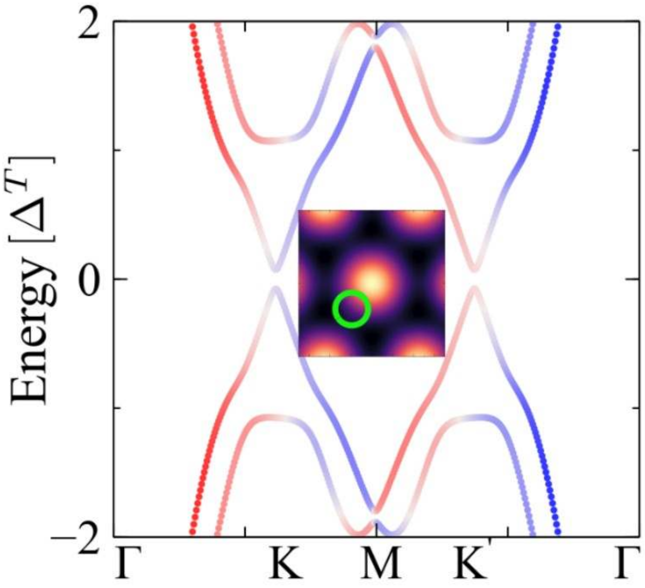
Gap as function of the location of the impurity



Band structure for impurity at the center



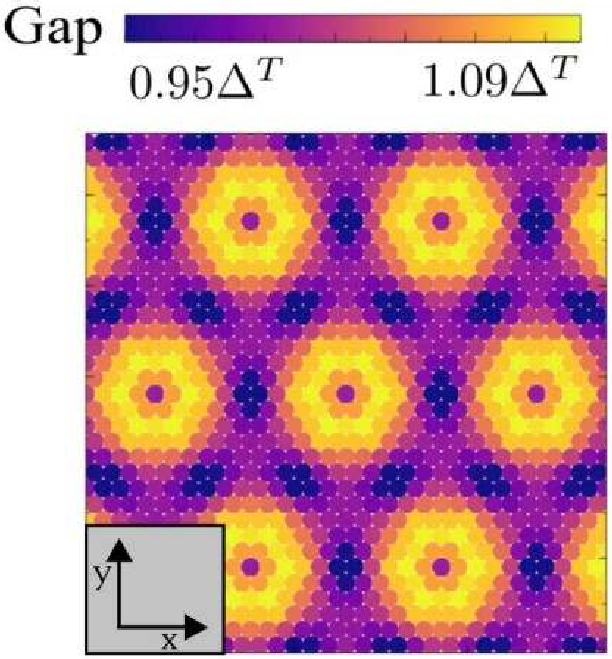
Band structure for impurity away from the center



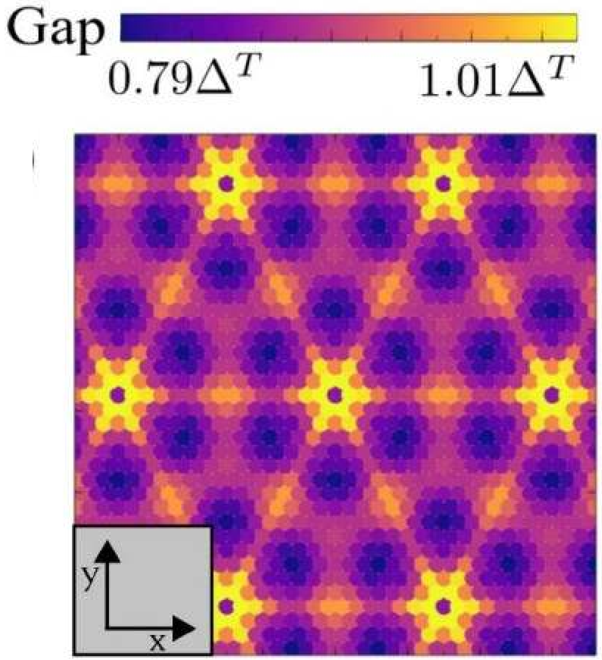
The location of the impurity strongly affects the resulting gap

Gap as function of location for different moire unit cells

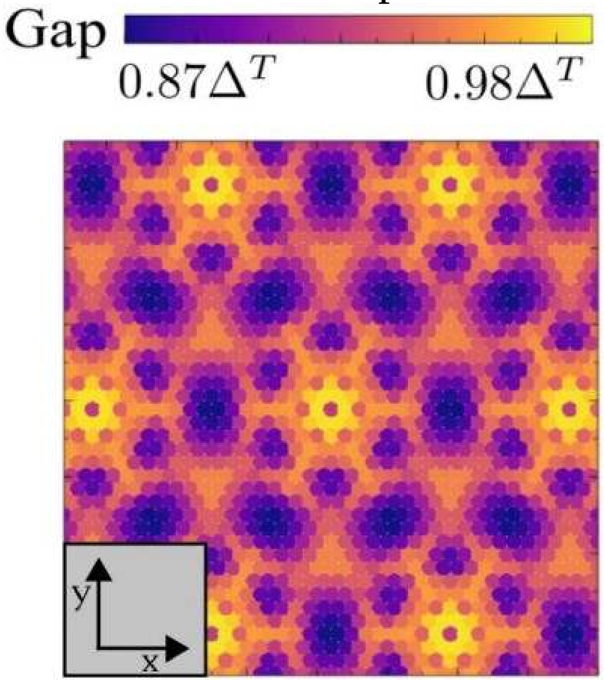
11x11 supercell



15x15 supercell



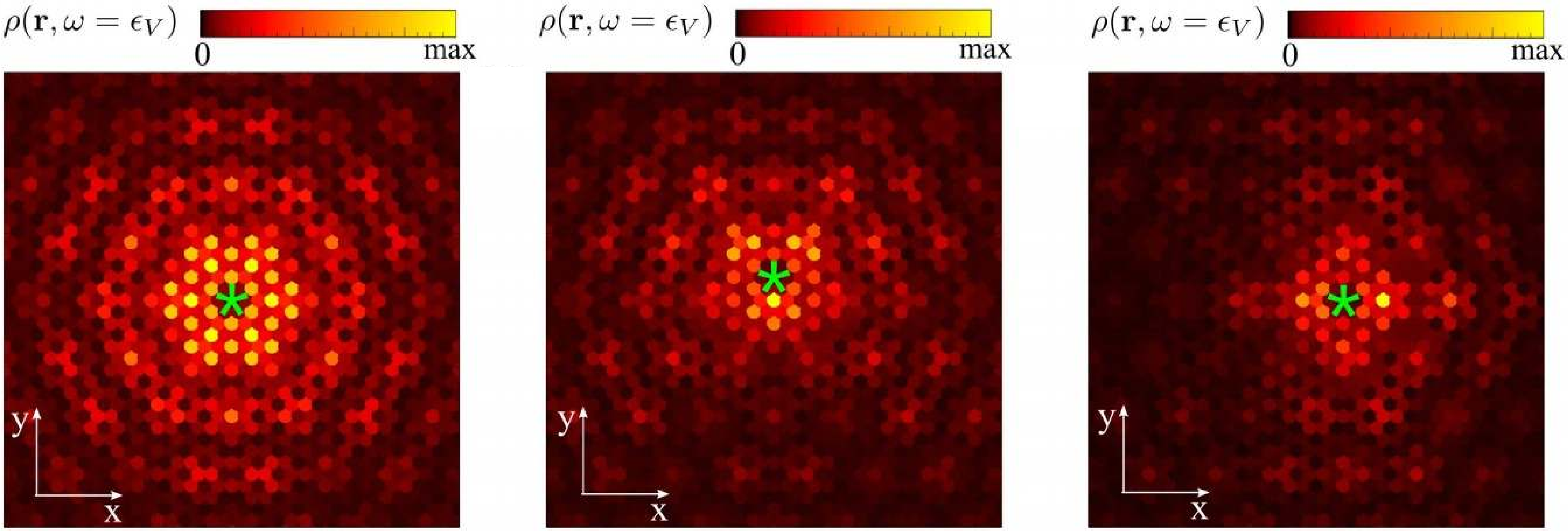
17x17 supercell



Detrimental locations for impurities depend on the specific moire supercell

Single impurity in a topological moire superconductor

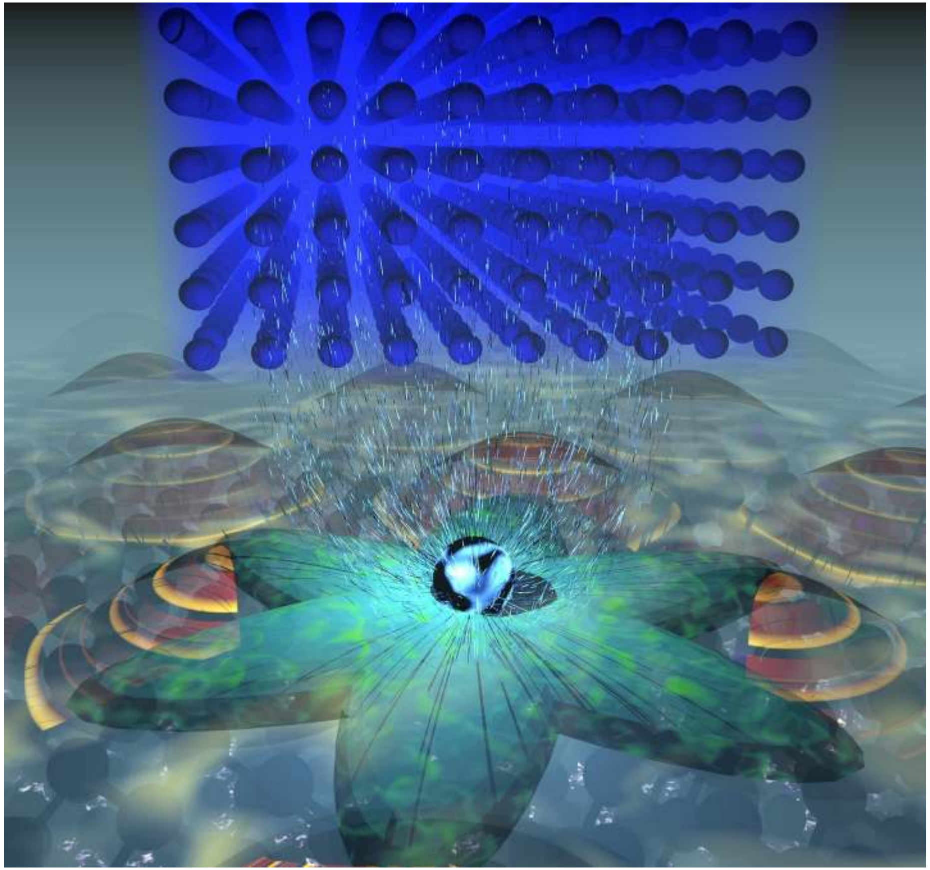
Wavefunction of the YSR state for different impurity locations



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 learning from impurity tomography in moire superconductors

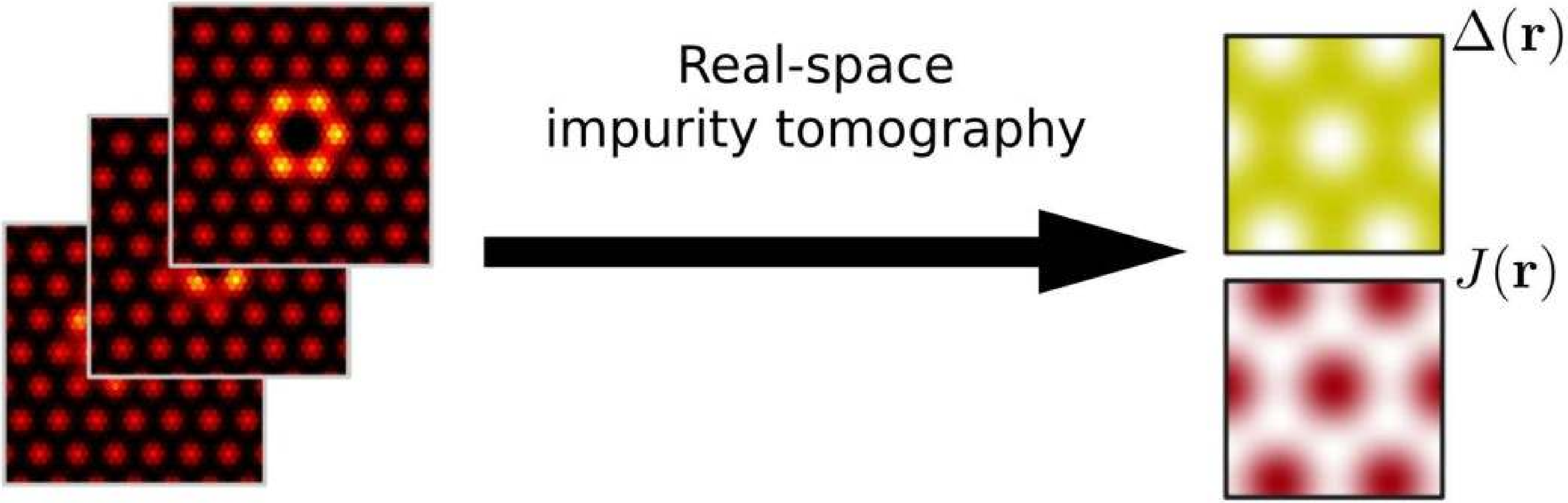


Maryam Khosravian

Rouven Koch

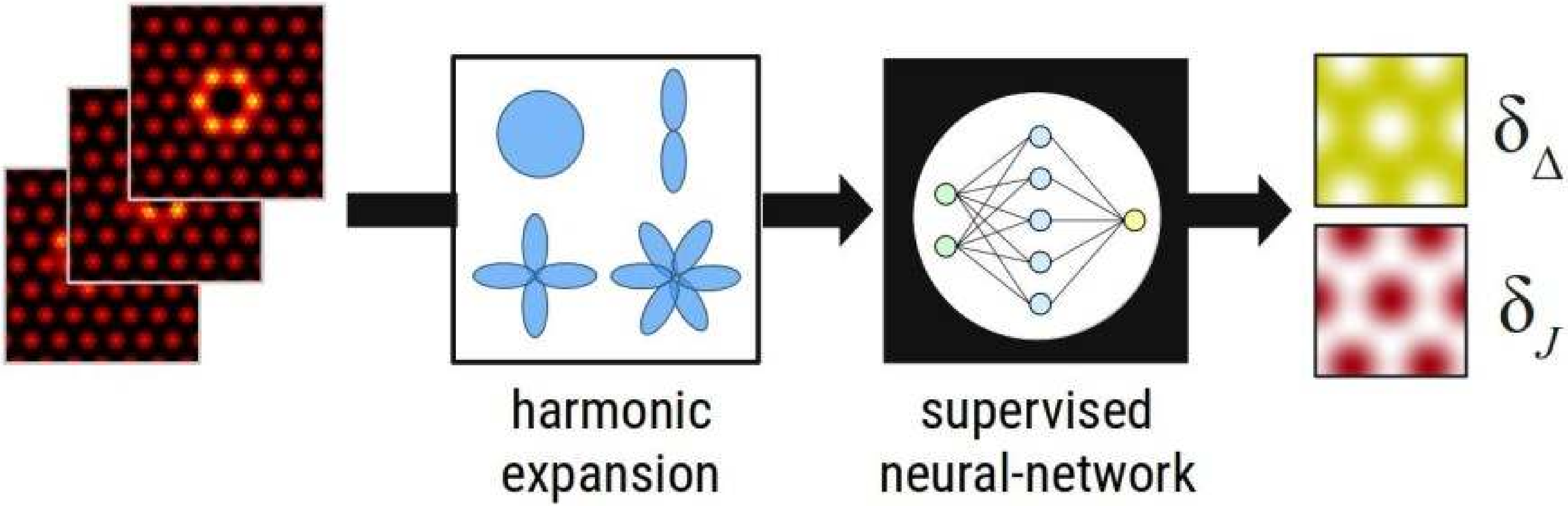
arXiv:2308.11400

Real-space impurity tomography



Can we learn real-space superconducting and exchange profiles directly from spectroscopy?

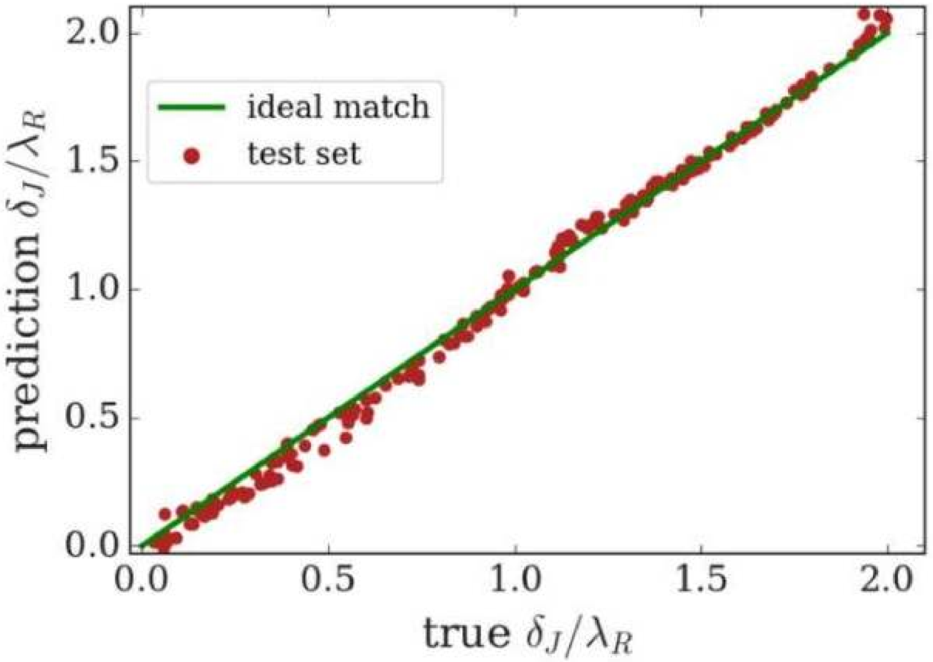
Real-space impurity tomography



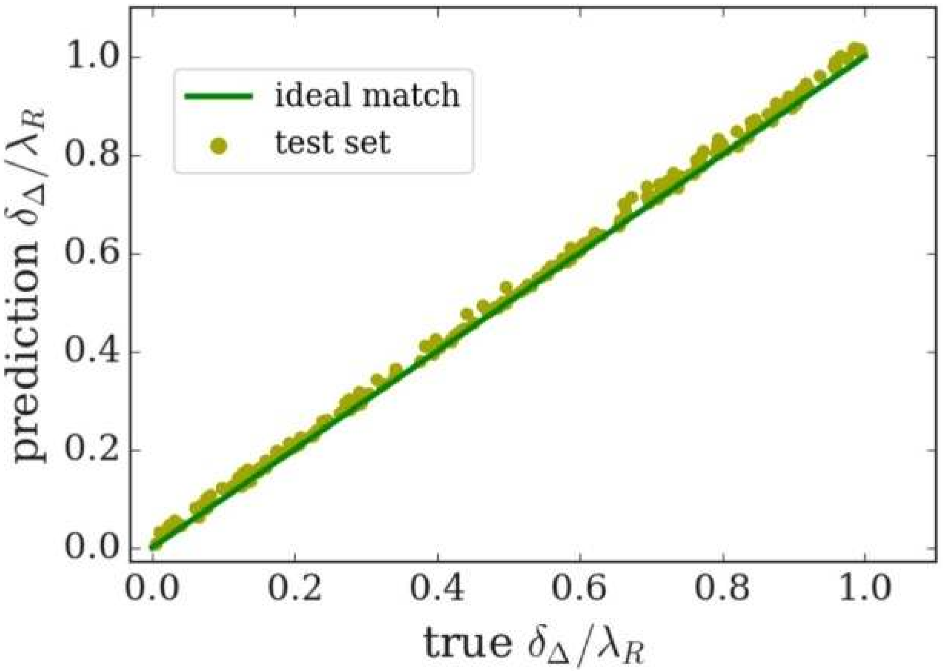
$$c_{ln} = \sum_{\alpha} \rho(\mathbf{r}_\alpha) e^{il\phi_\alpha} r_\alpha^n e^{-r_\alpha/\lambda}$$

Moire Hamiltonian learning with real-space impurity tomography

Exchange profile prediction



Superconducting profile prediction



Impurity tomography allow to extract the superconducting and exchange profiles

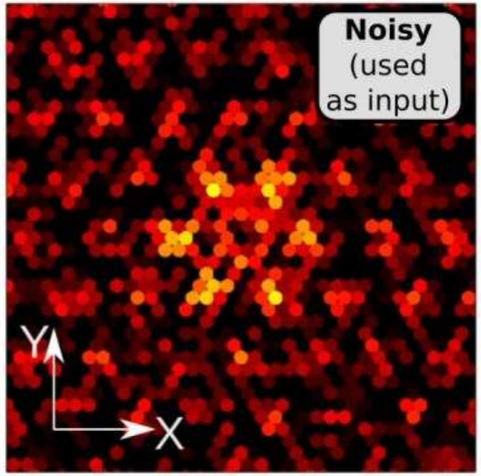
Hamiltonian learning with noisy spectroscopy

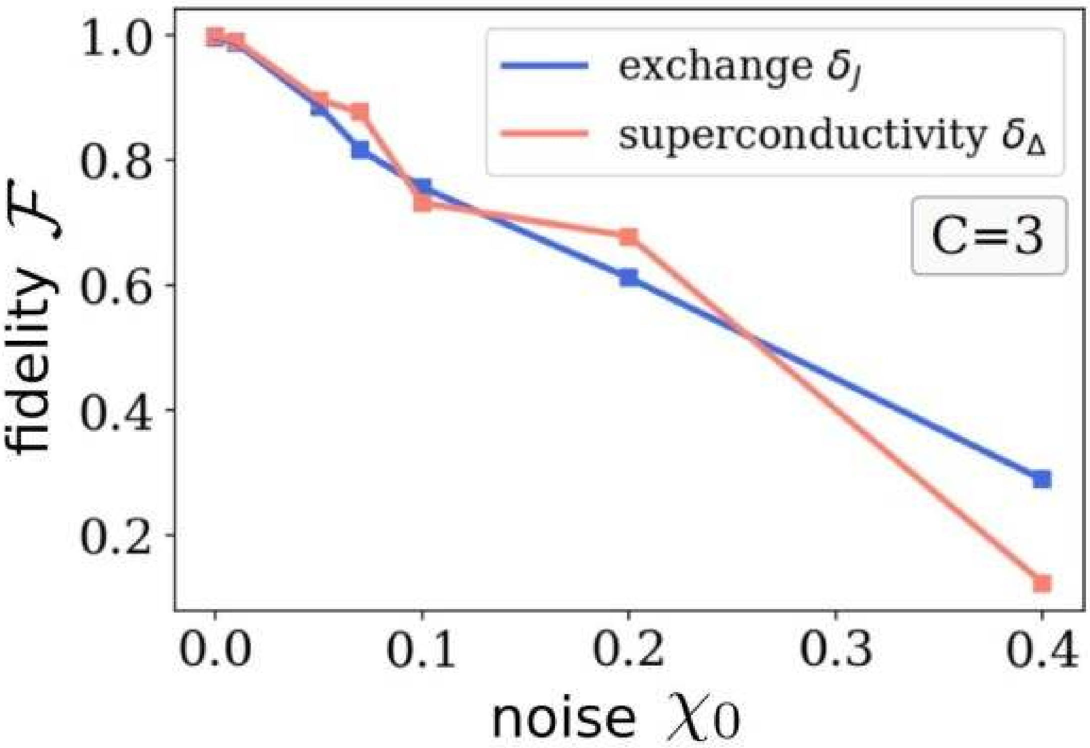
Prediction accuracy (fidelity)

$\mathrm{F} = 1$ Perfect prediction

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

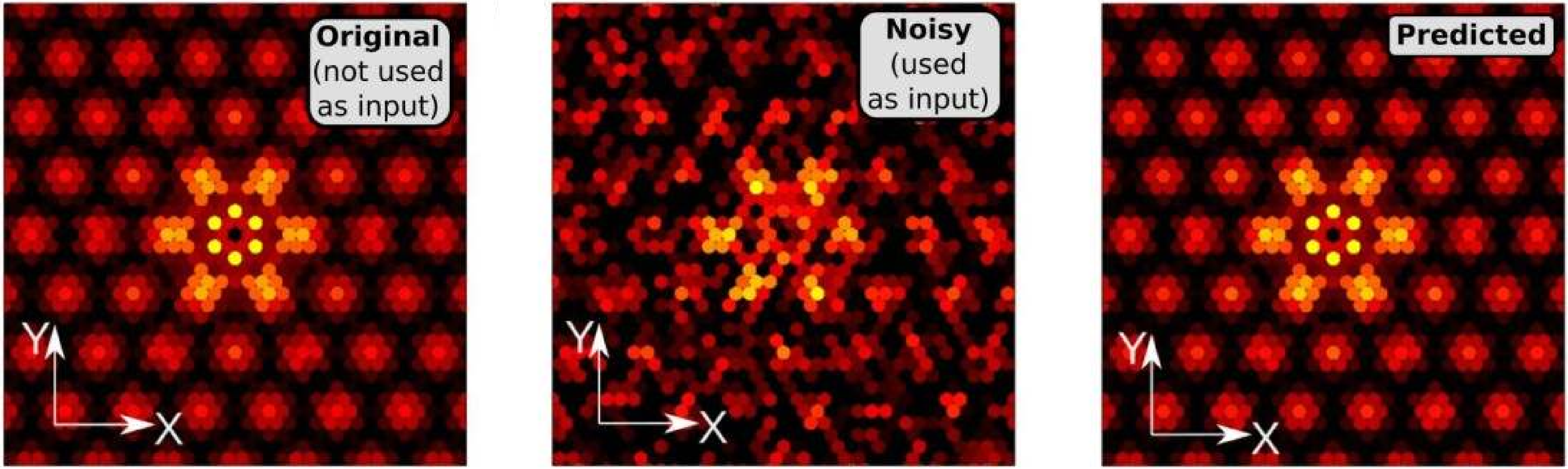
Noise $\chi_0 = 0.2$





Hamiltonian learning is partially successful even with strong noise

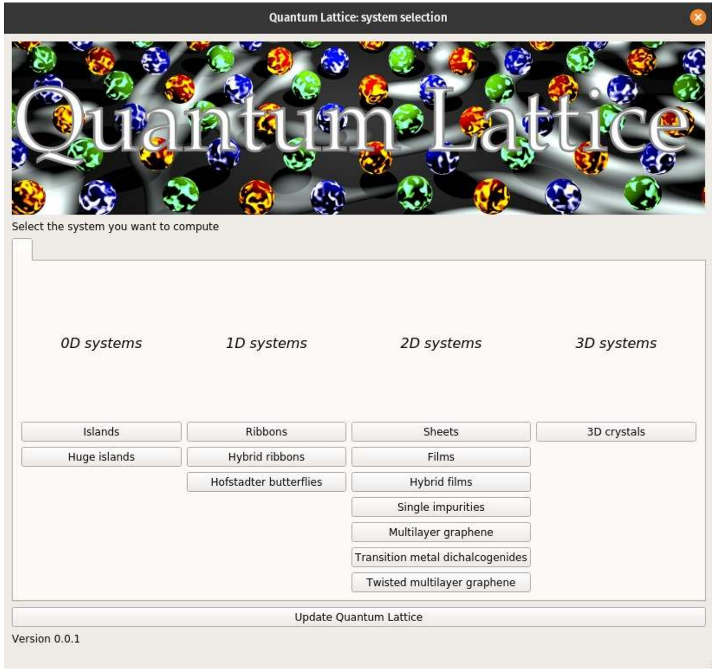
Noisy Hamiltonian reconstruction

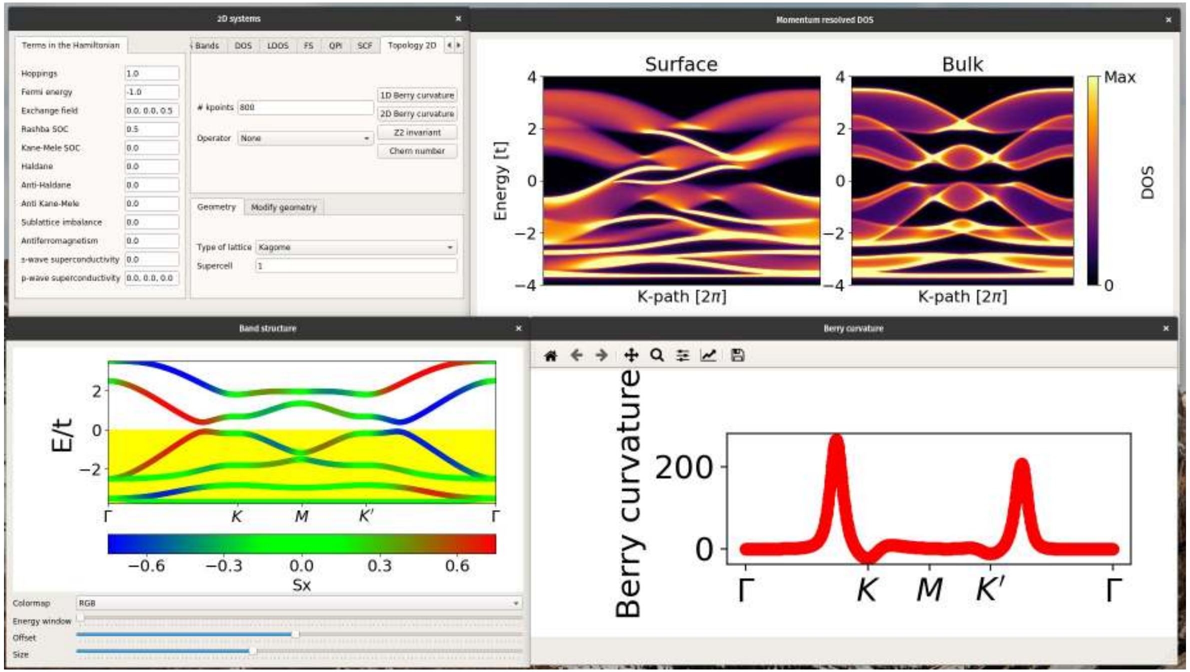


A reconstructed Hamiltonian from noisy data reproduced the original noiseless in-gap modes

Computing electronic properties

Quantum Lattice: A user interface to compute electronic properties

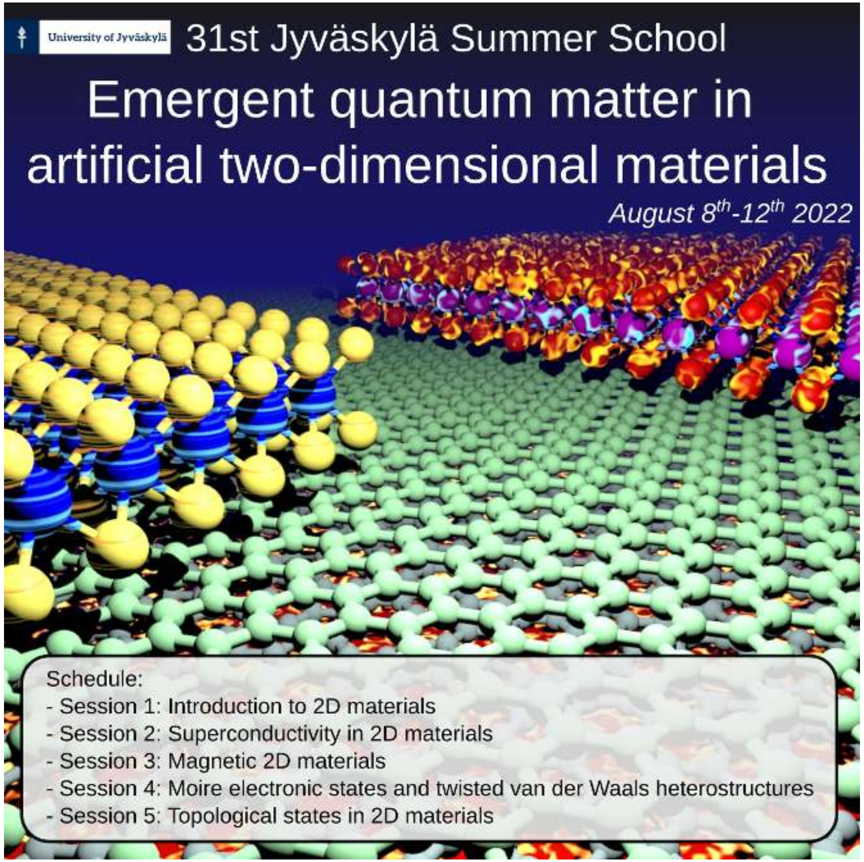




Quantum Lattice: open source interactive interface for tight binding modeling

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

Quantum matter in van der Waals materials school



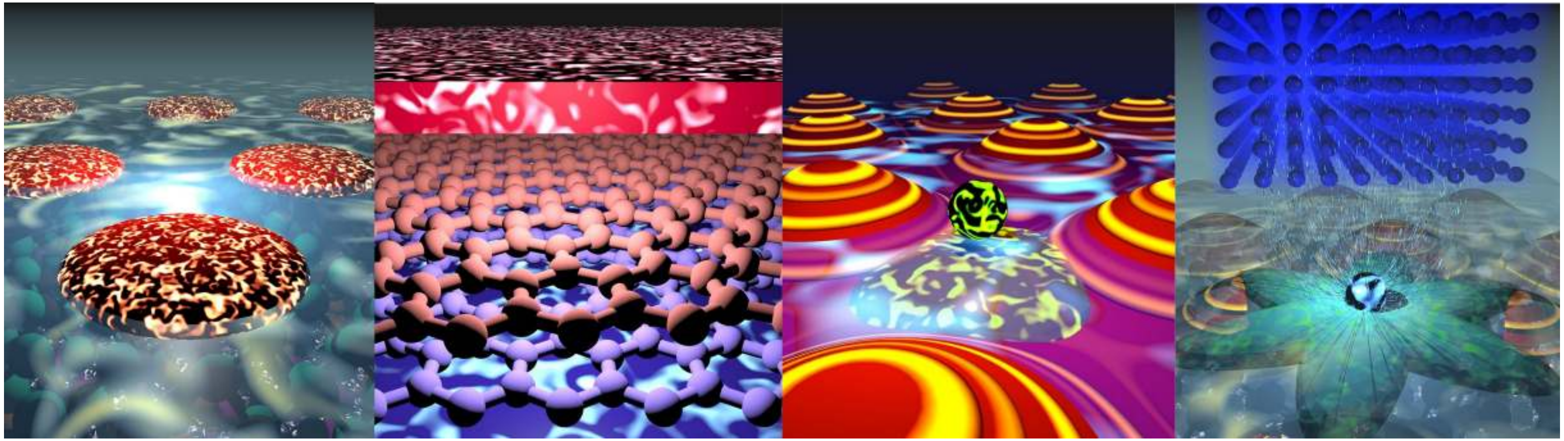
Recordings available at

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

The interplay of moire and atomic length scales offers new possibilities to engineer topological superconductors, with impurity effects allowing us to perform Hamiltonian extraction



Thank you!

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arXiv:2307.04605 (2023)
Phys. Rev. Mat. 6, 094010 (2022)
arXiv:2308.11400 (2023)

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