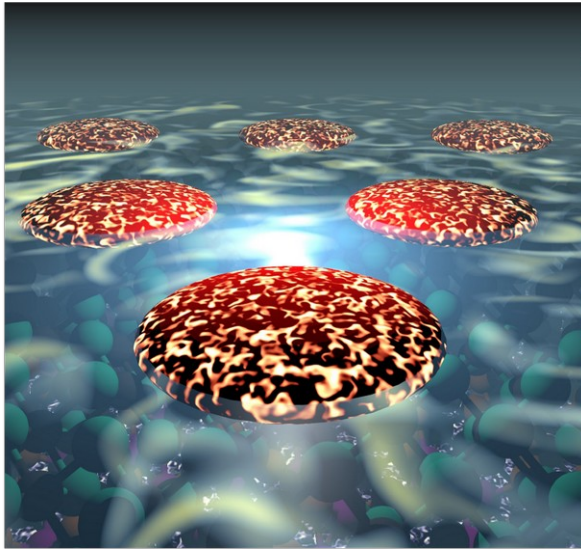


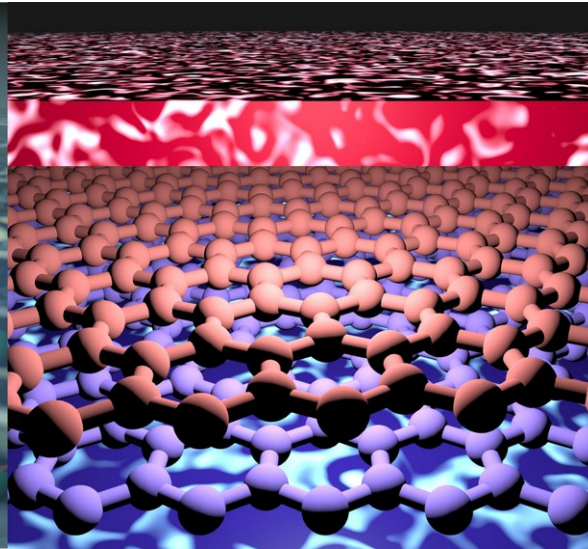
Moiré-enabled topological superconductivity

Jose Lado

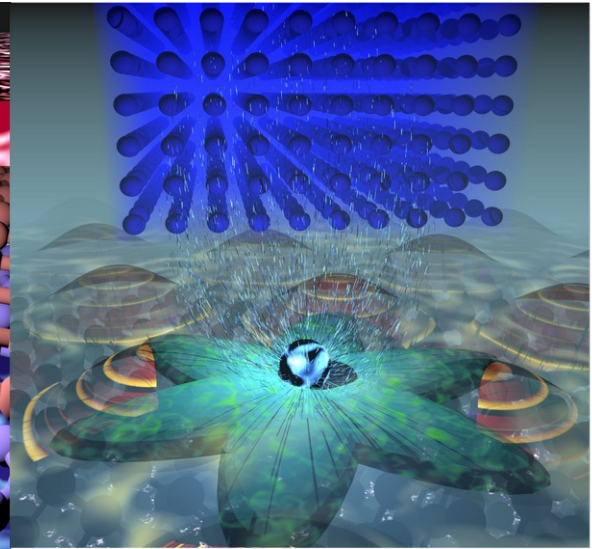
Department of Applied Physics, Aalto University, Finland



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



2D Materials
11 035012 (2024)



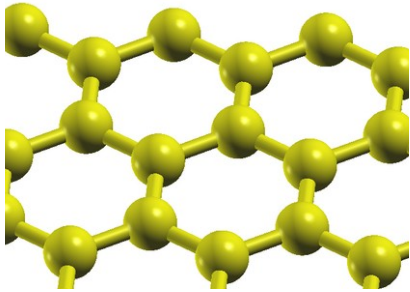
Journal of Physics: Materials
7 (1), 015012 (2024)

International Conference “Quantum sensing”, June 5th 2024, Paris

The two-dimensional materials world

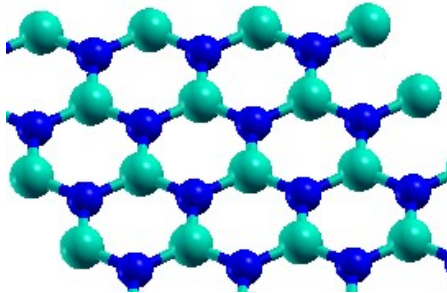
Semimetal

Graphene



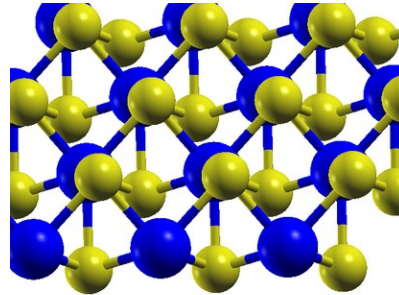
Insulator

BN



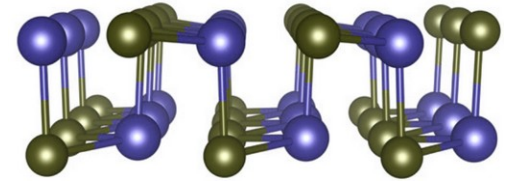
Superconductor

NbSe₂



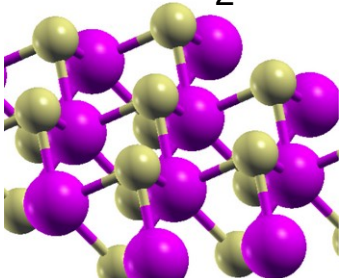
Ferroelectric

SnTe



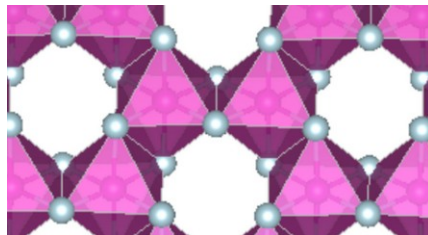
Semiconductor

WS₂



Ferromagnet

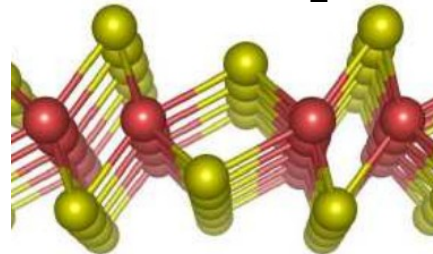
CrI₃



Quantum spin

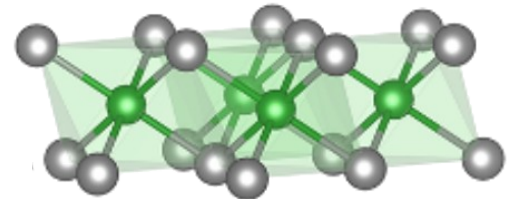
Hall insulator

WTe₂



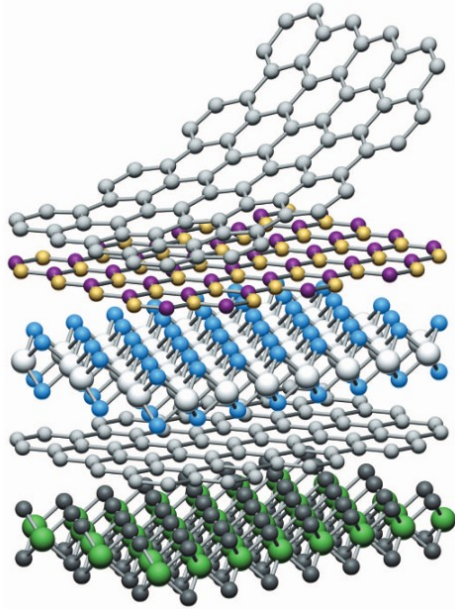
Multiferroic

NiI₂



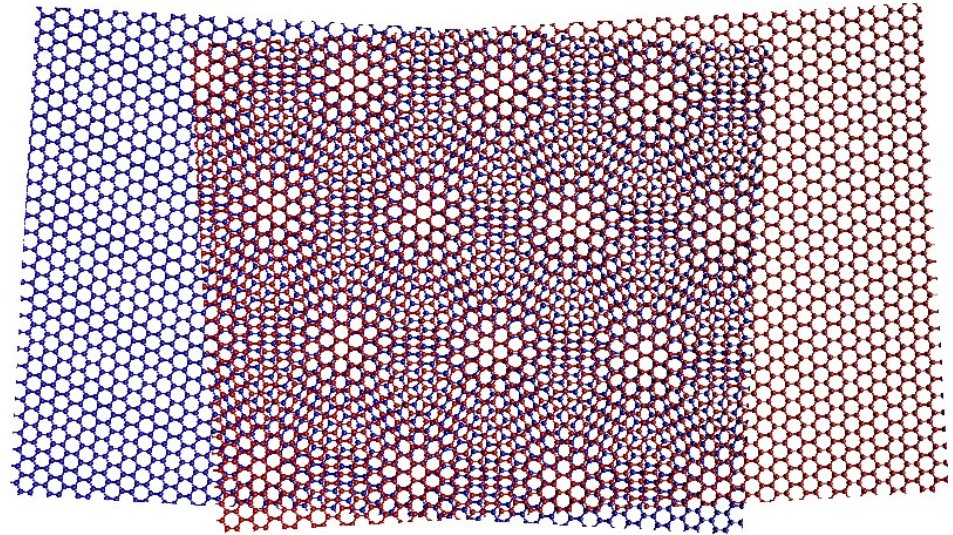
The flexibility of two-dimensional materials

They can be stacked



Nature 499, 419–425 (2013)

They can be rotated

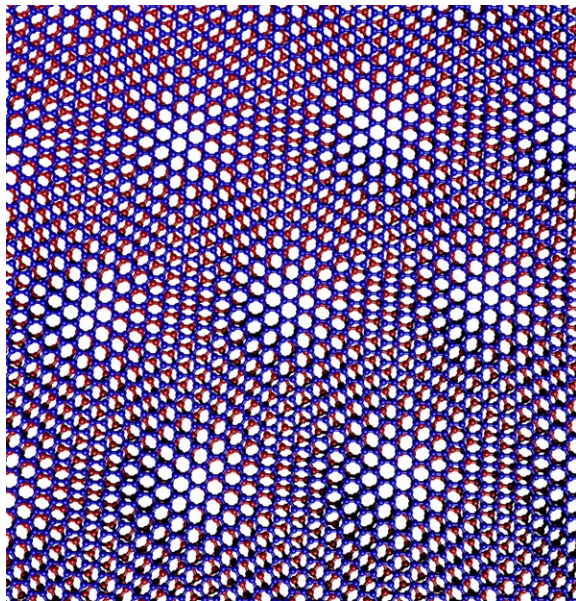


Science 361, 6403, 690–693 (2018)

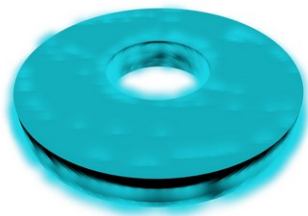
These are unique features of two-dimensional materials

The tunability of twisted van der Waals materials

Twisted bilayer graphene

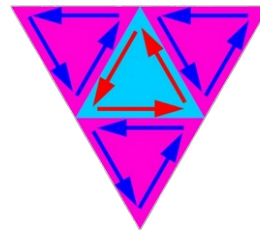


Superconductivity



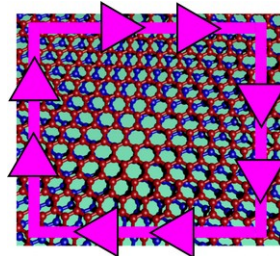
Nature 556, 43–50 (2018)

Topological networks



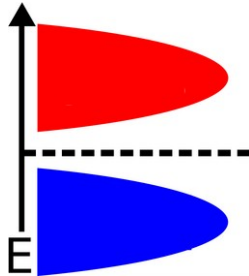
Nano Lett. 18, 11,
6725-6730 (2018)

Chern insulators



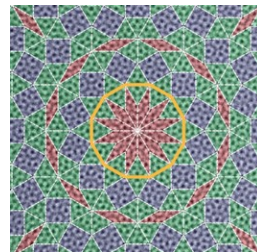
Science 365, 605-608 (2019)

Correlated insulators



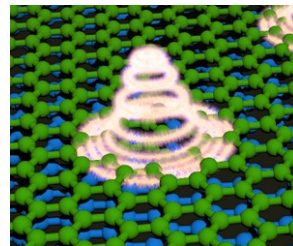
Nature 556, 80–84 (2018)

Quasicrystalline physics



Science 361, 782-786 (2018)

*Proximal fractional
Chern insulators*

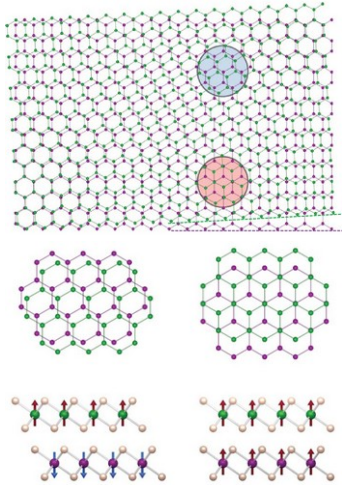


Nature 600, 439–443 (2021)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

Artificial quantum matter in moire van der Waals heterostructures

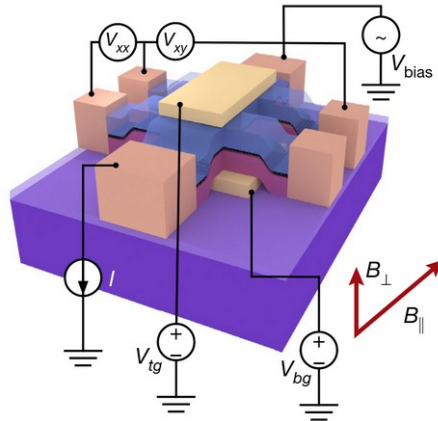
Unconventional magnets



Twisted CrBr_3

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

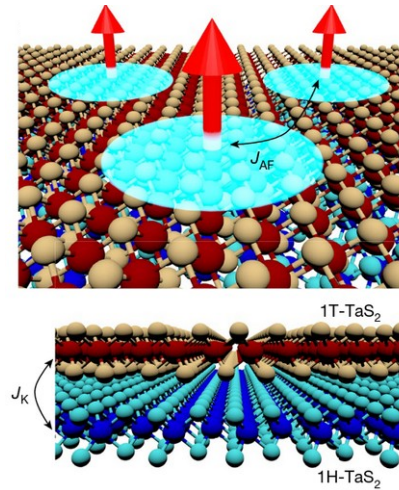
Unconventional superconductors



Twisted trilayer
graphene

Nature 595,
526–531 (2021)

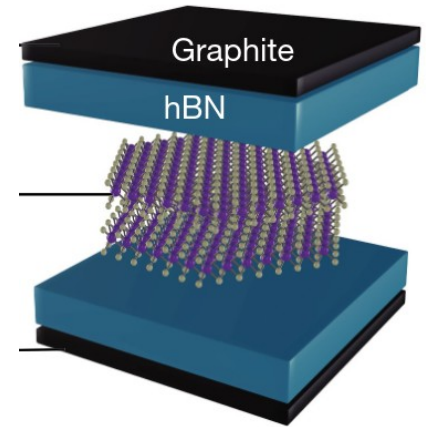
Heavy-fermion quantum materials



1H-1T TaS_2

Nature 599,
582–586 (2021)

Fractional topological matter

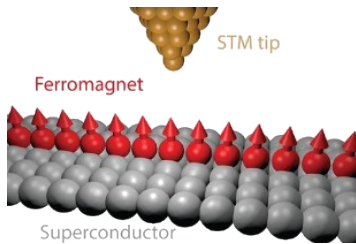


Twisted MoTe_2

Nature 622,
63–68 (2023)

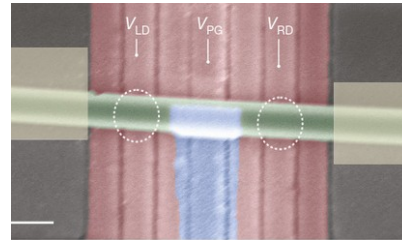
The world of topological superconductors

Magnetic atomic chains



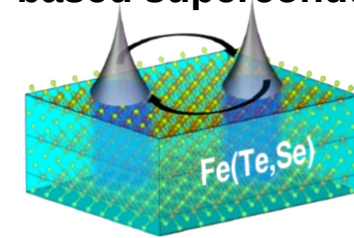
Nature Nano 17, 384–389 (2022)

Semiconductor-based



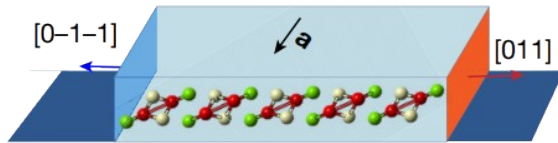
Nature 614, 445–450 (2023)

Fe-based superconductors



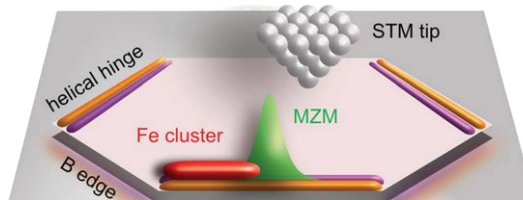
Science 362.6412 (2018): 333–335

Heavy-fermion compounds



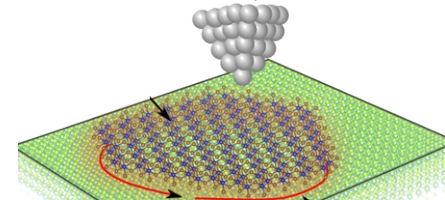
Nature 579, 523–527 (2020)

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)

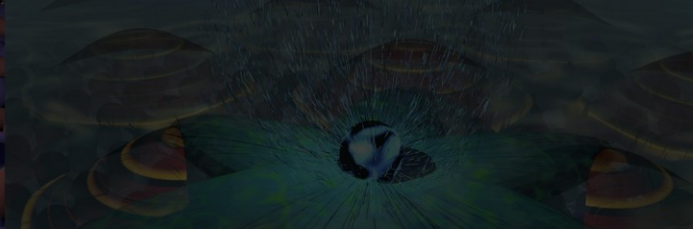
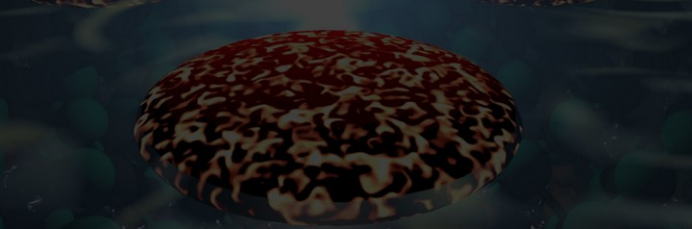
The challenge



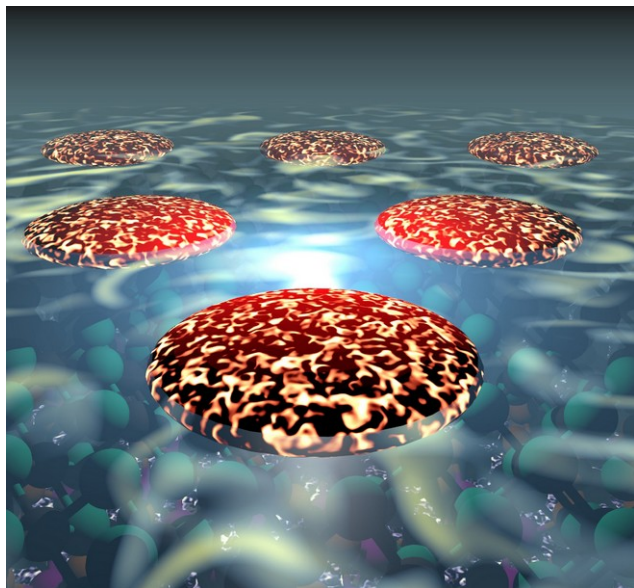
Incredibly rare in nature and hard to reliably identify
Practical applications require highly tunable materials

Nature Reviews Physics 2, 575–594 (2020)

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

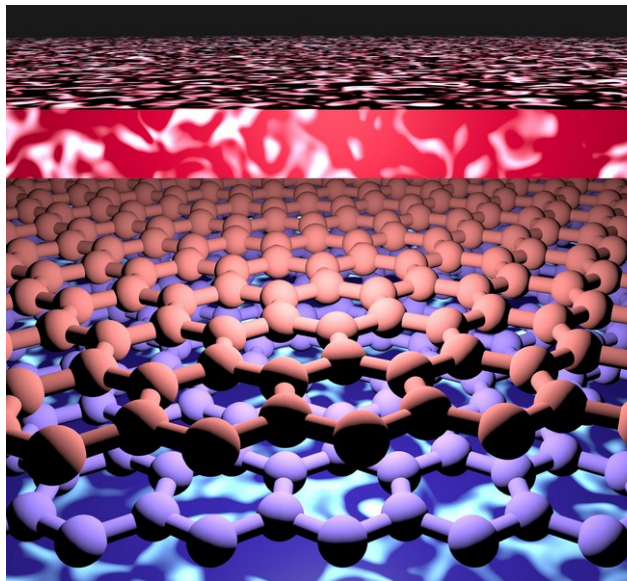


*Moiré-enabled topological
superconductivity
in $\text{CrBr}_3/\text{NbSe}_2$*



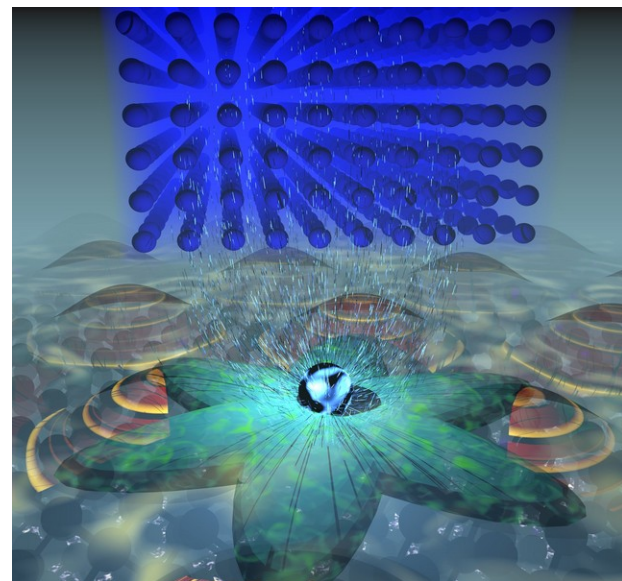
Nano Lett. 2022, 22, 1,
328–333 (2022)

*Moiré-enabled topological
superconductivity in
twisted bilayer graphene*



2D Materials
11 035012 (2024)

*Hamiltonian learning
from moiré 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

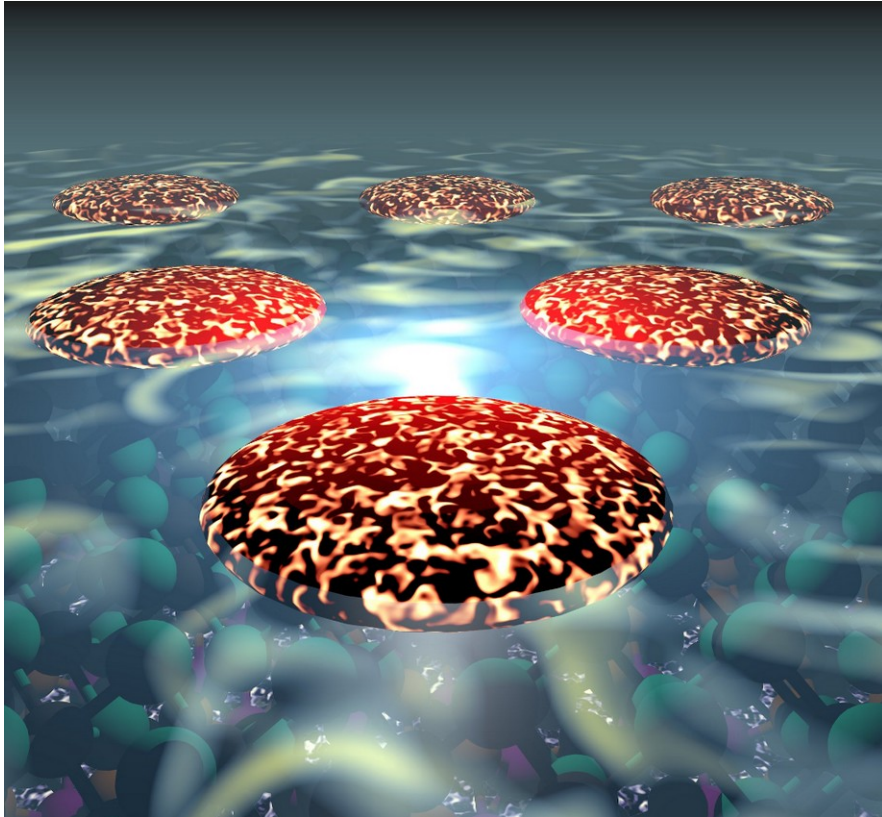


R. Koch



2D Materials Journal of Physics: Materials
11 035012 (2024) 7 (1), 015012 (2024)

Artificial topological moiré superconductivity in NbSe₂/CrBr₃



S. Ganguli



M. Aapro



S. Kezilebieke



V. Vaňo



Md. Huda



P. Liljeroth



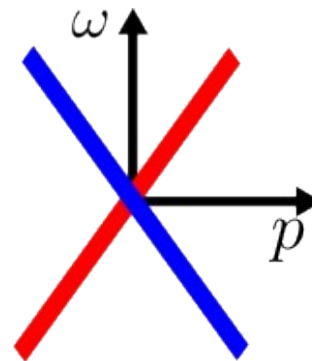
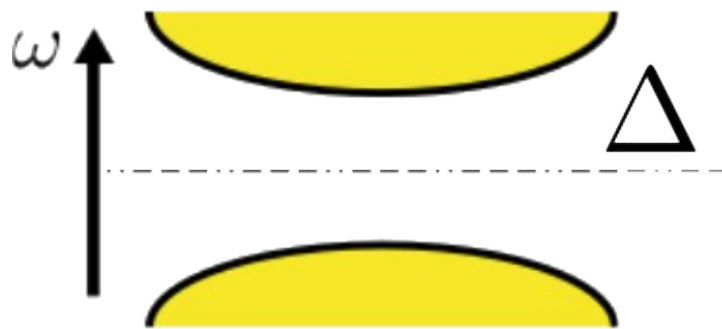
Nano Lett. 22, 1, 328-333 (2022)

How to build your own topological superconductor

Ingredients

s-wave pairing

Helical channels



Objective: to realize a spinless superconductor

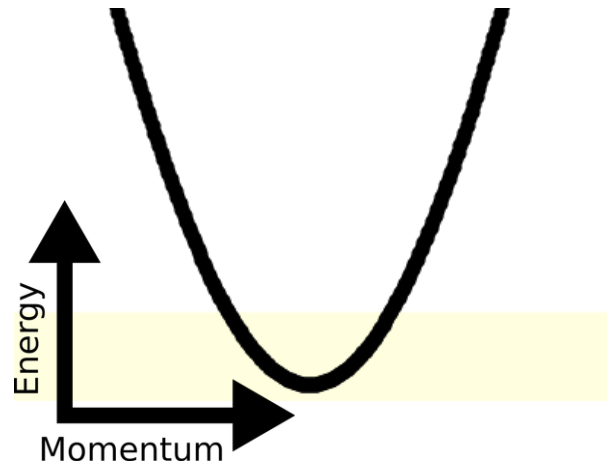
$$H = \sum_n t c_{n+1}^\dagger c_n + \Delta c_n c_{n+1} + c.c.$$

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

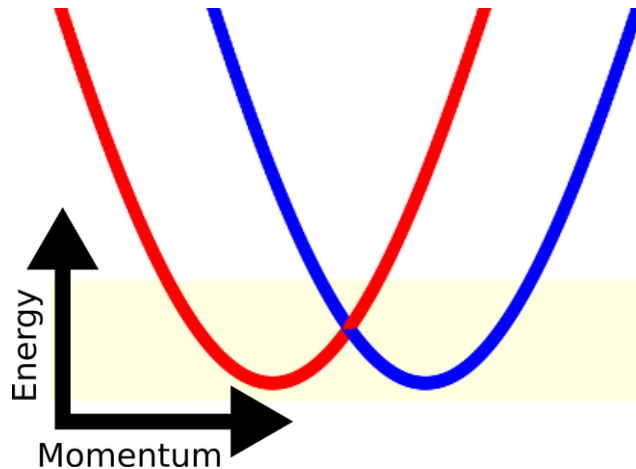


How to build your own helical gas

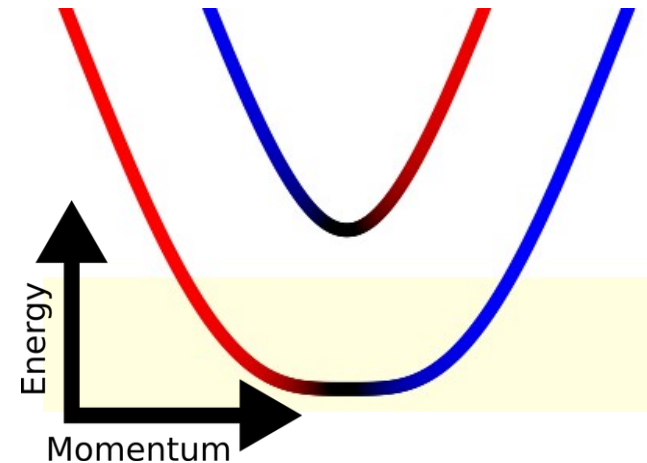
Take a parabolic band



Create spin-momentum locking with Rashba spin-orbit coupling



Split the Gamma point with an exchange field

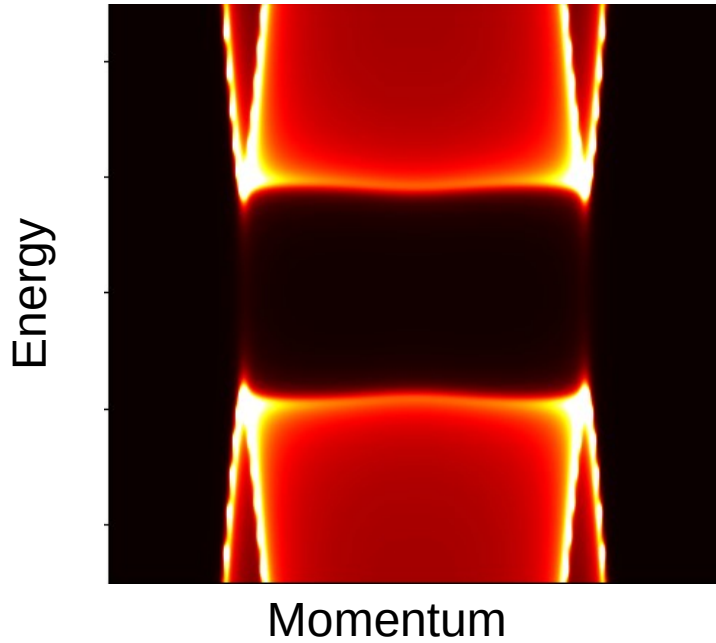


For a chemical potential inside the split gap, we have helical states

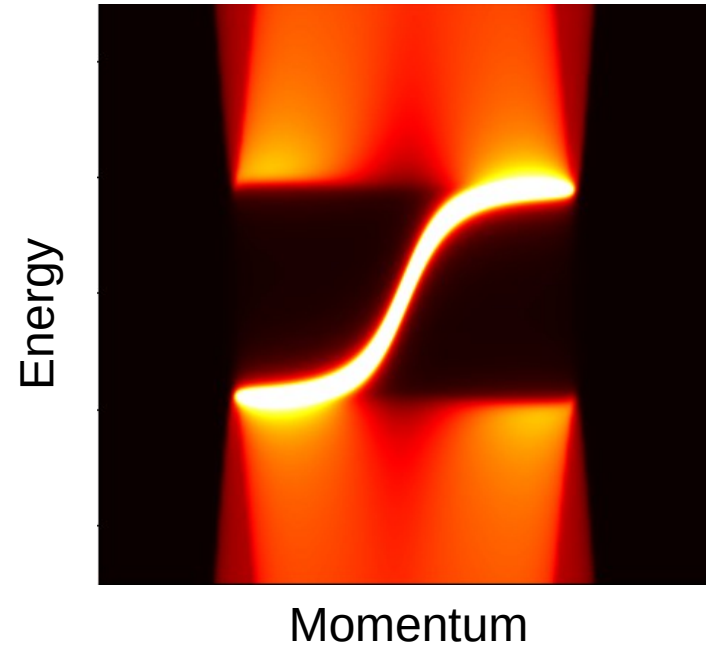
Having a topological superconductor requires having a tunable material

The spectra of a topological superconductor

Full gap in the bulk

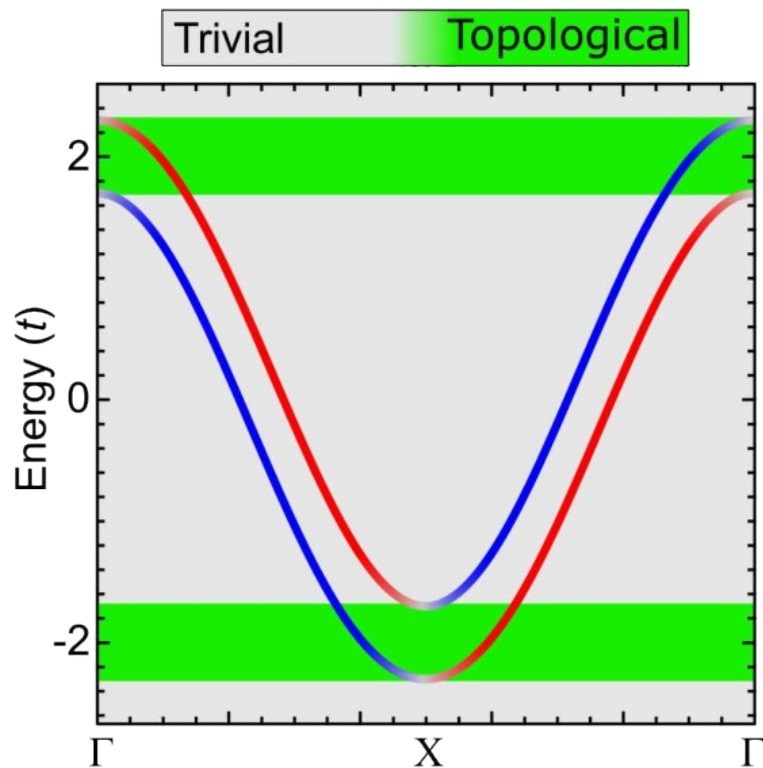


Gapless (Majorana) mode at the edge



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

1D topological superconductor, without moire



$$H = H_0 + H_J + H_R$$

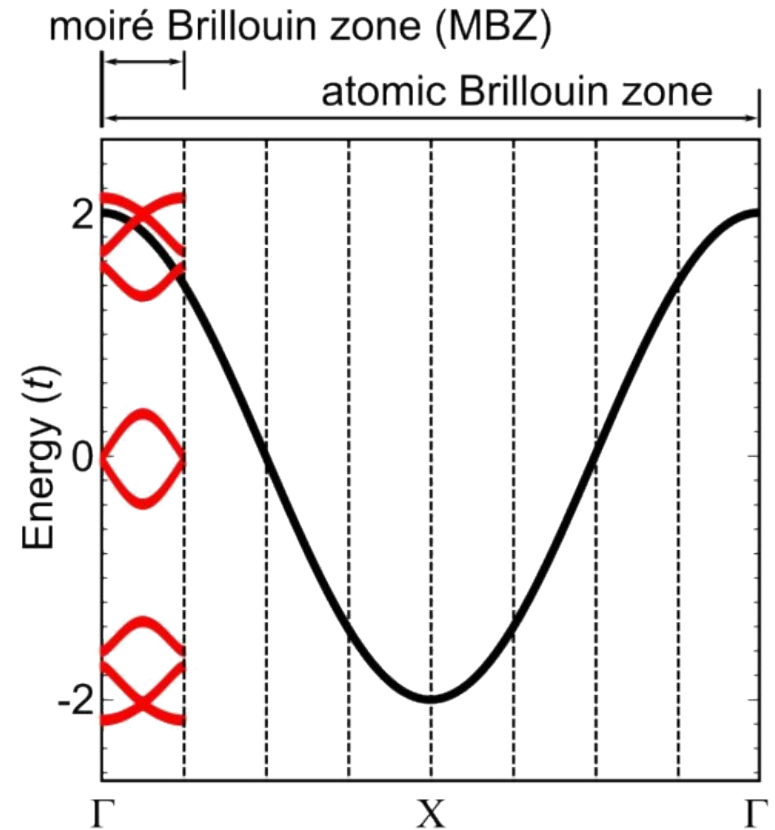
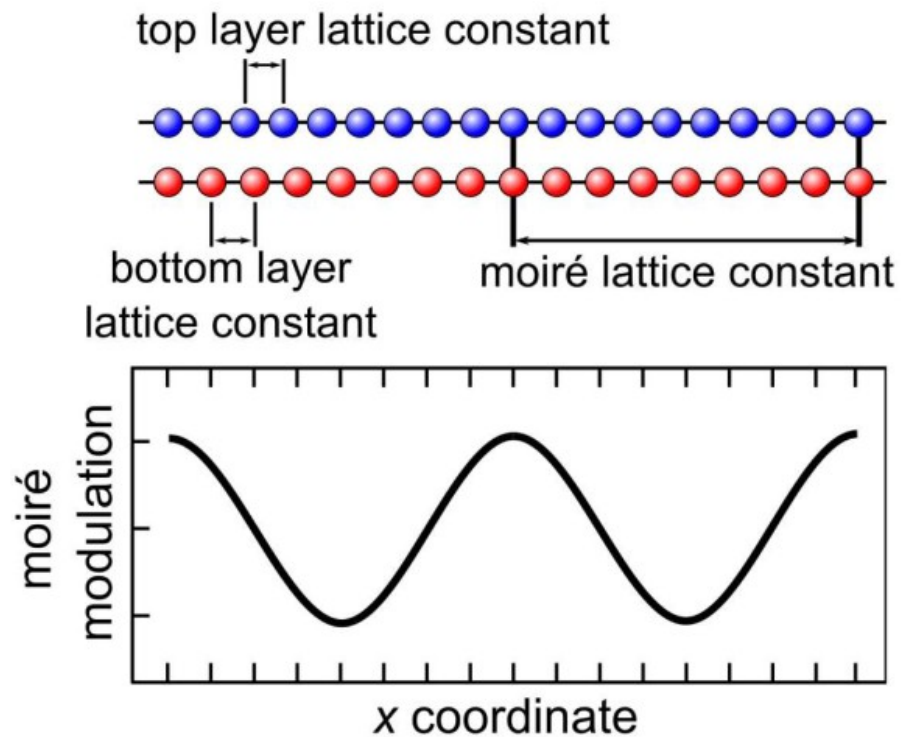
Kinetic energy

Exchange field

Rashba spin-orbit
coupling

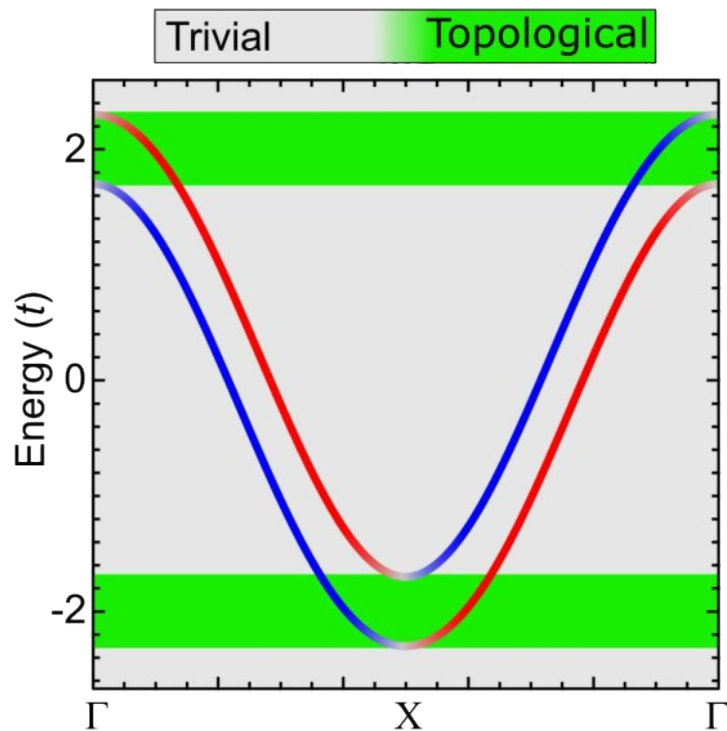
When switching on an s-wave pairing,
green regions lead to topological superconductivity

1D topological superconductor, with moire

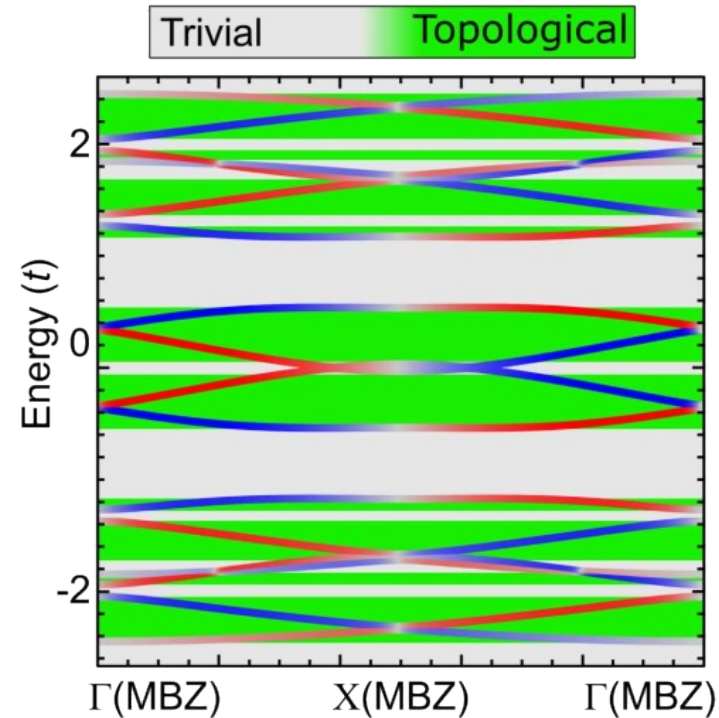


1D topological superconductor, with moire

Without moire

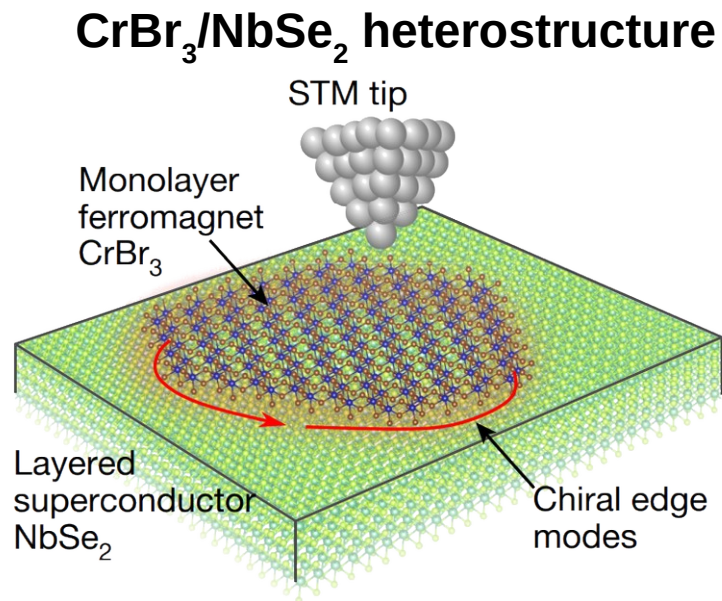


With moire



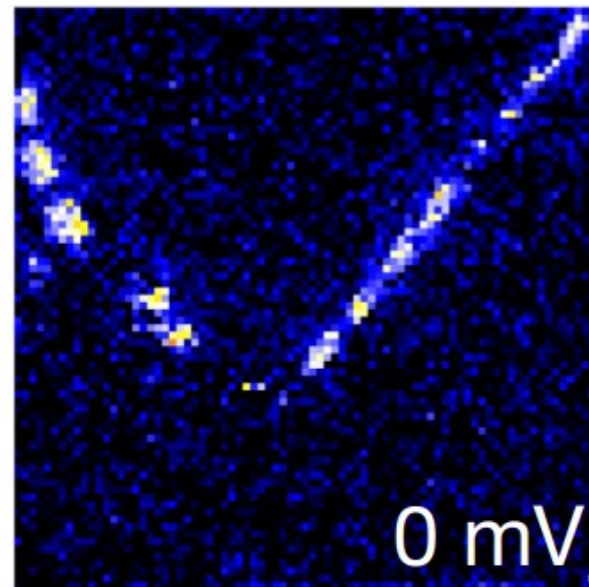
Moire pattern allow to realize topological superconductivity in otherwise forbidden energies

Topological superconductivity in a van der Waals heterostructure



Nature 588, 424–428 (2020)

Zero bias dI/dV

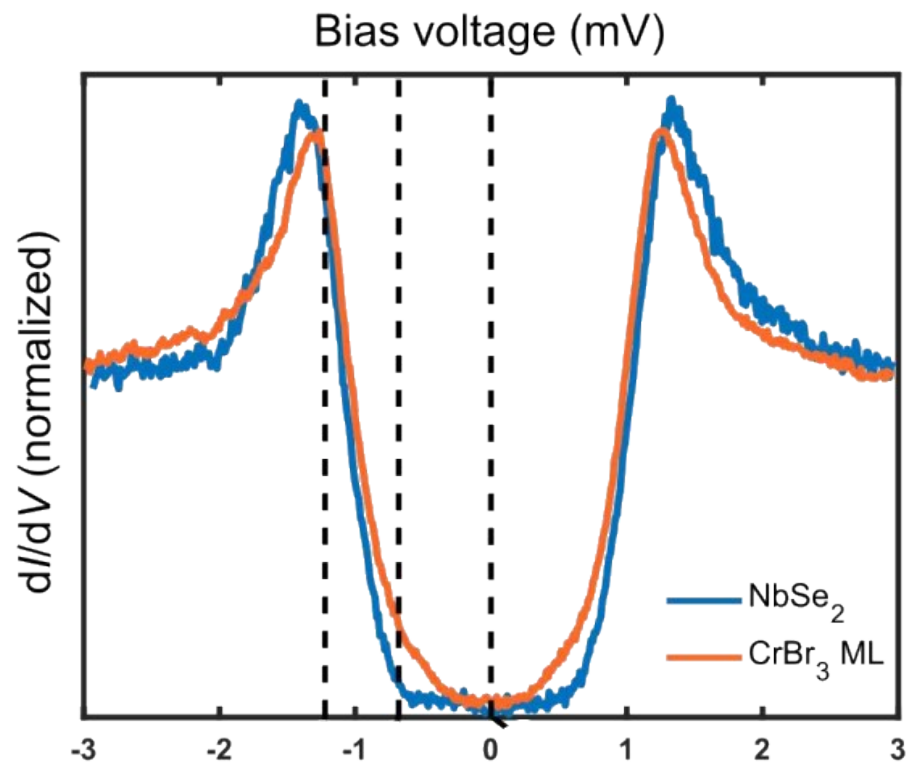
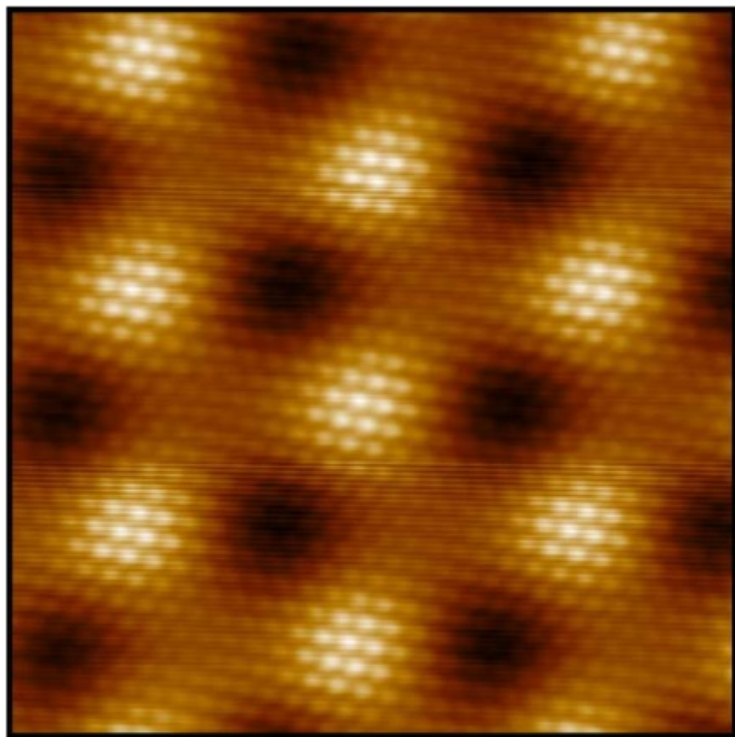


A topological superconducting state appears in CrBr₃/NbSe₂

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

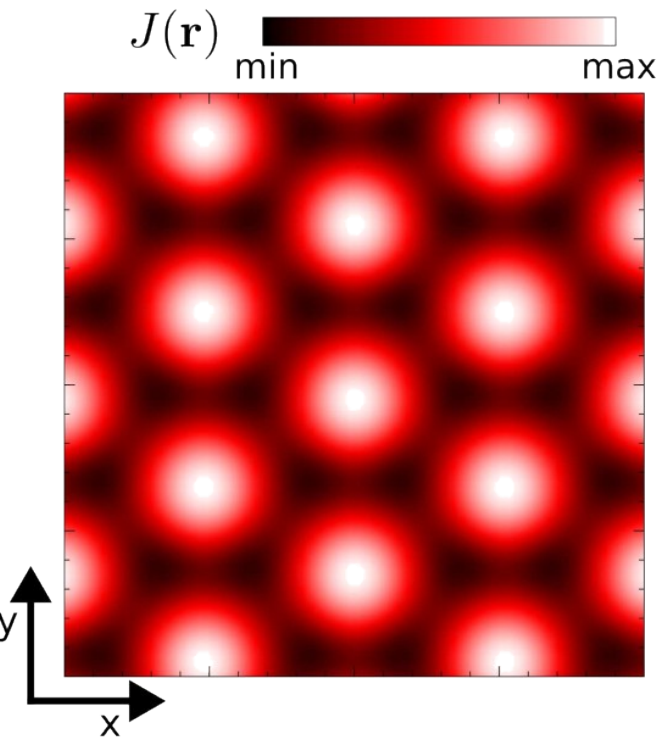
$\text{CrBr}_3/\text{NbSe}_2$ heterostructure

Height 0 Å  0.26 Å

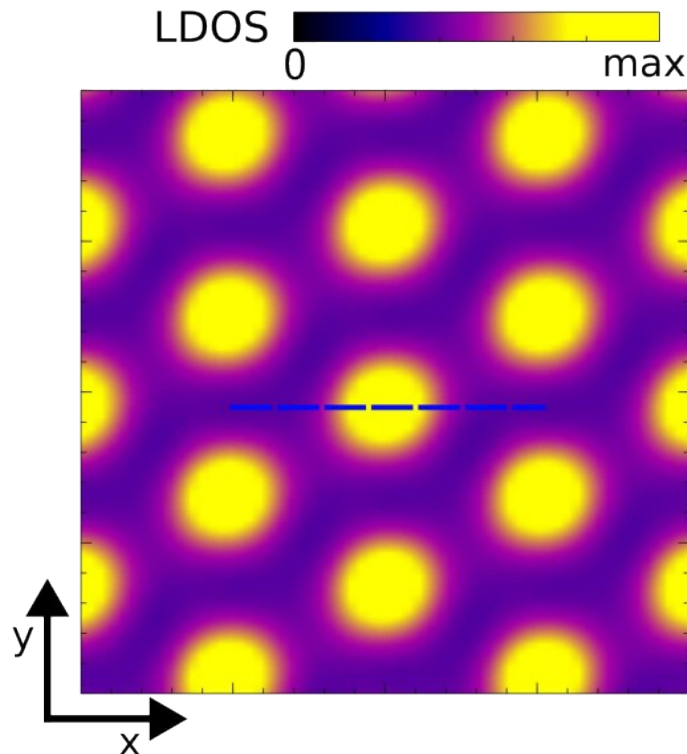


Bulk Yu-Shiba-Rusinov states

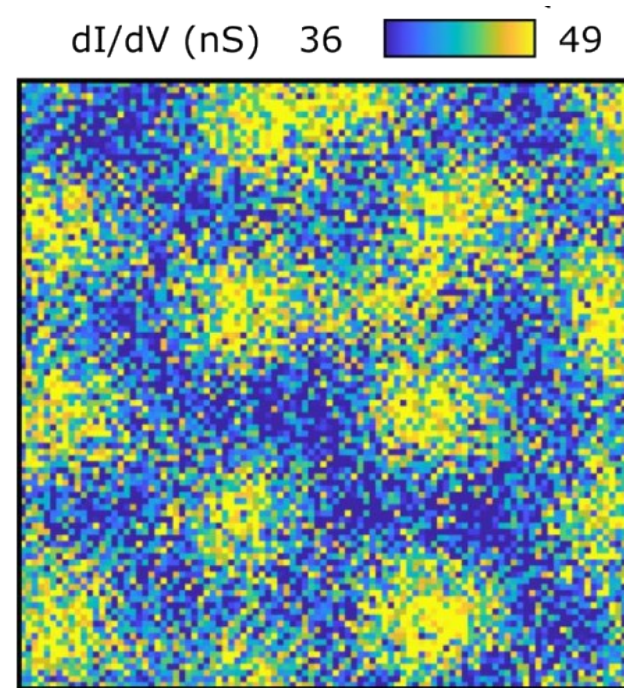
Exchange profile



Theoretical LDOS



Experimental dI/dV

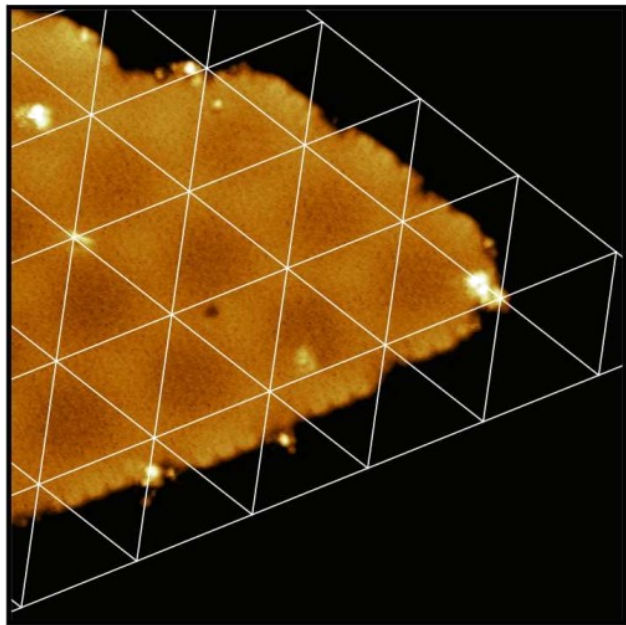


Bulk Yu-Shiba-Rusinov states are imprinted by the modulated exchange profile

Topological moire edge states

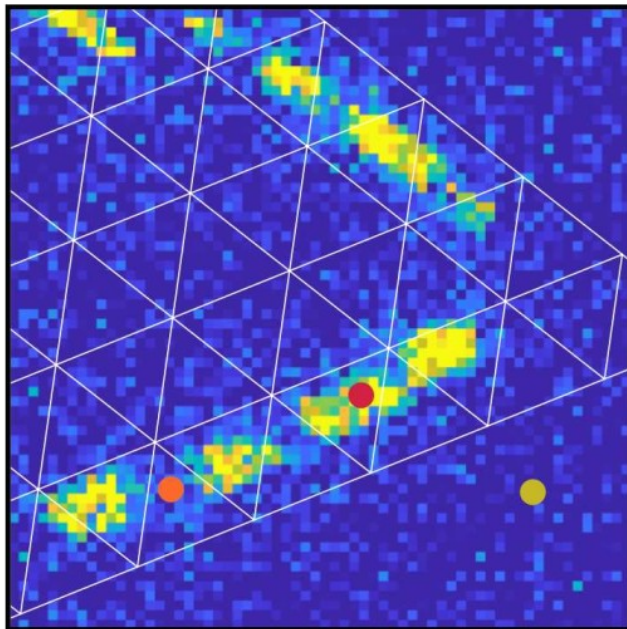
Topography

Height 0 Å  6 Å



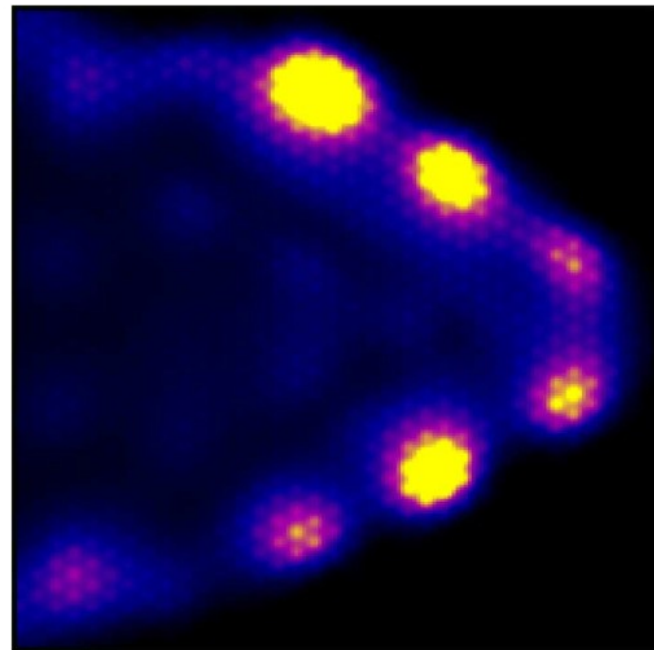
Experimental dIdV

dI/dV (nS) 1  20



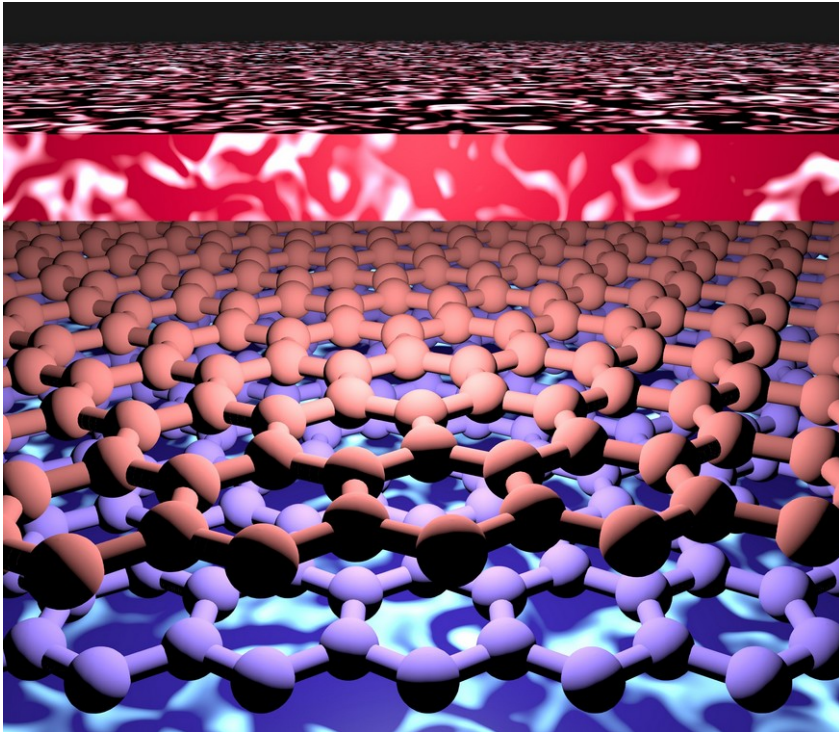
Theoretical dIdV

LDOS 0  max



Topological edge modes are imprinted by the modulated exchange profile

Moire-enabled artificial superconductors in twisted bilayer graphene



Maryam Khosravian



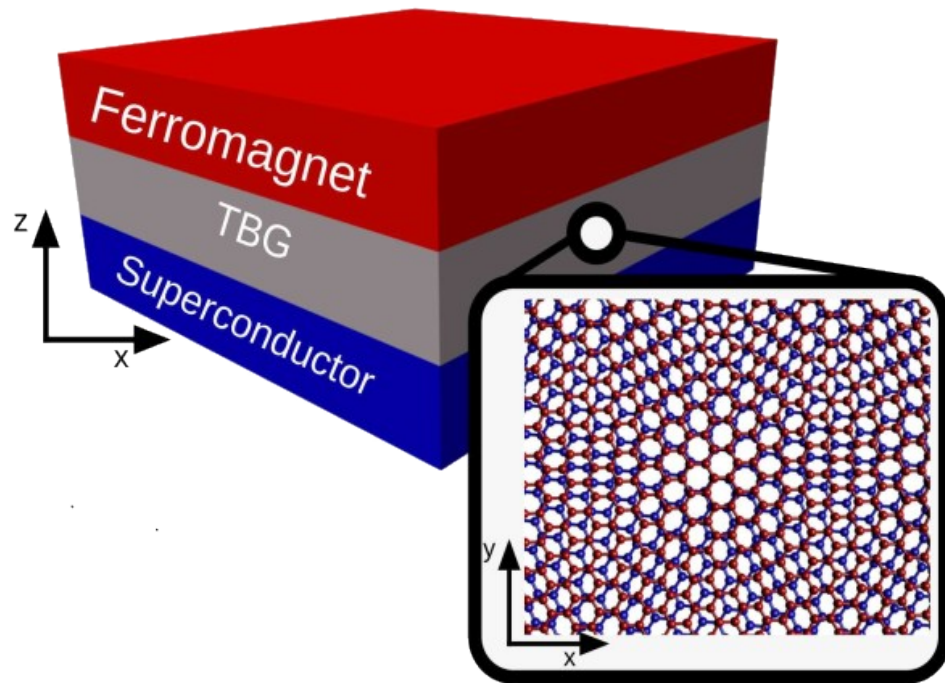
Elena Bascones



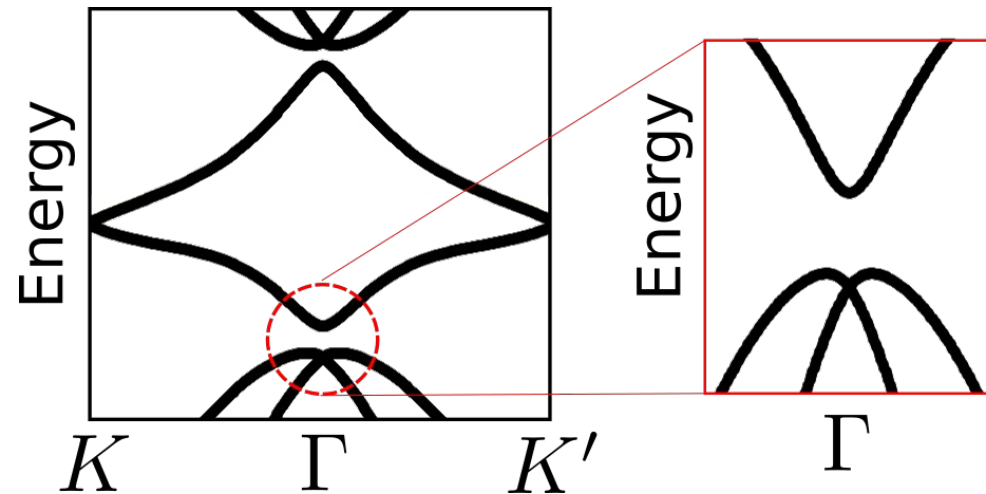
2D Materials 11 035012 (2024)

Encapsulated twisted graphene bilayers

Twisted bilayer graphene encapsulated between a ferromagnet and superconductor



Twisted bilayer band structure

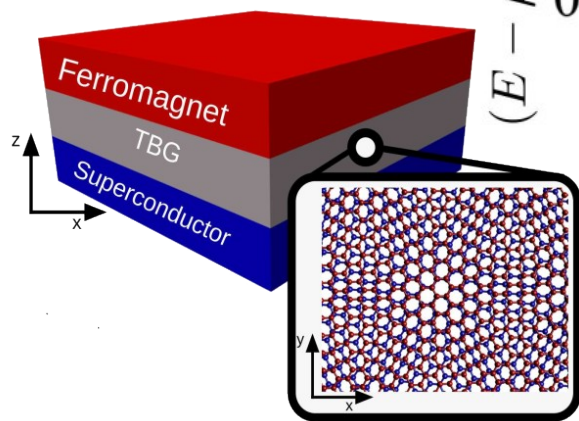


Parabolic bands at the Γ point
 $1.5 - 3^\circ$

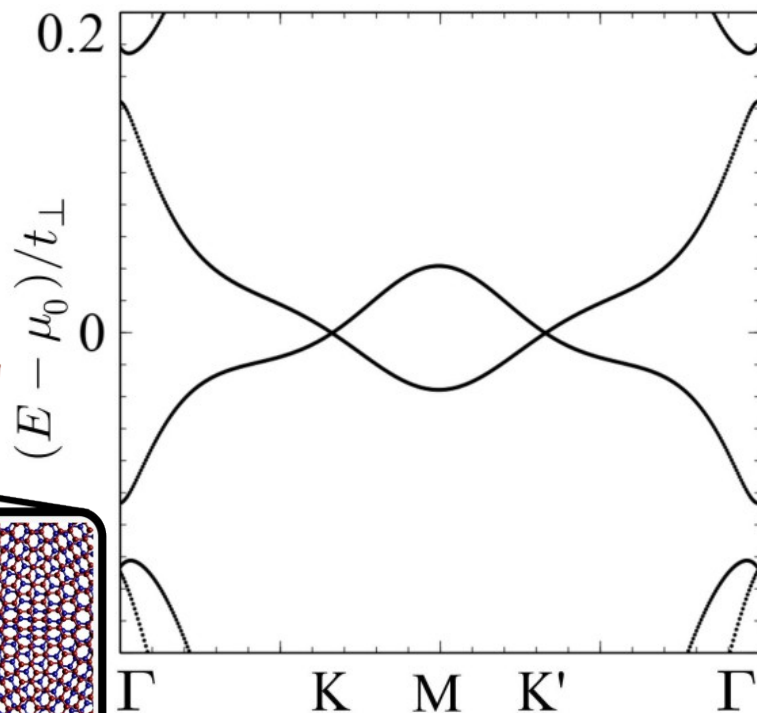
Moire-enabled artificial superconductors in twisted bilayer graphene

Twisting angles

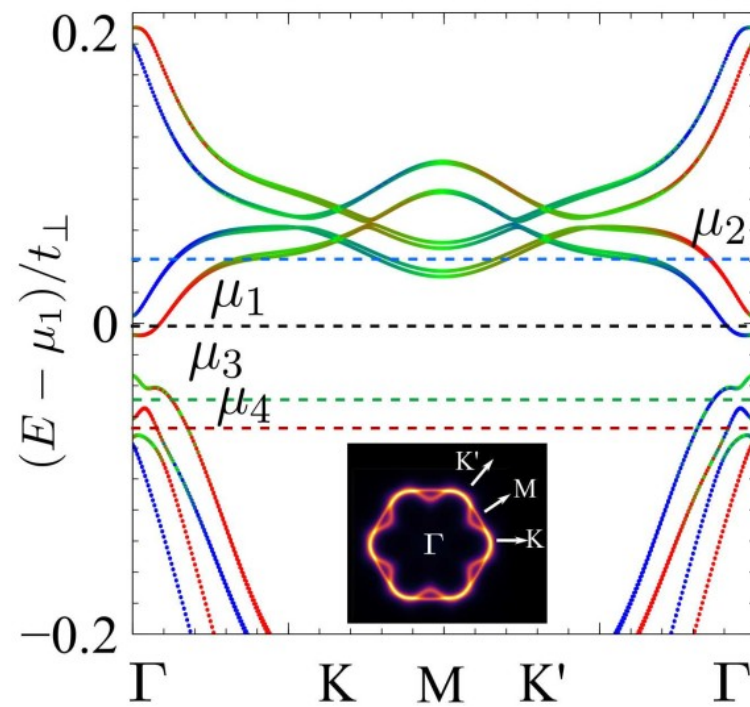
$$1.5 - 3^\circ$$



Pristine twisted bilayer



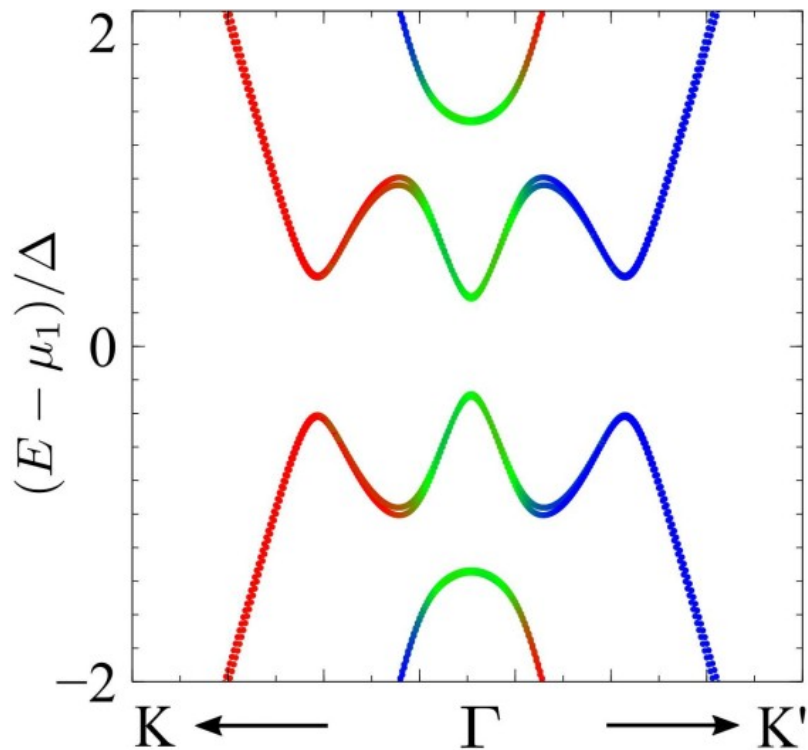
Encapsulated twisted bilayer



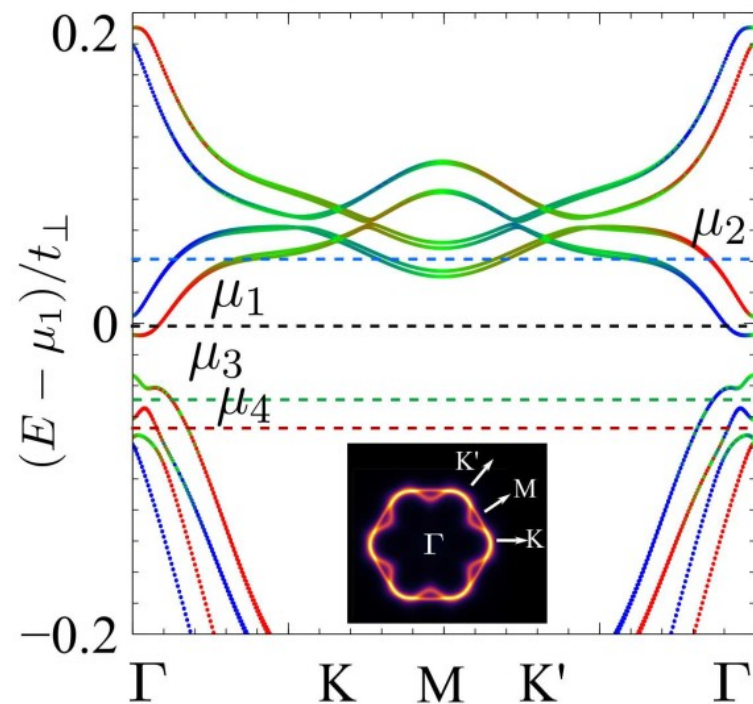
The moire effect gives rise to minigaps featuring helical states with encapsulation

Moire-enabled artificial superconductors in twisted bilayer graphene

With superconductivity



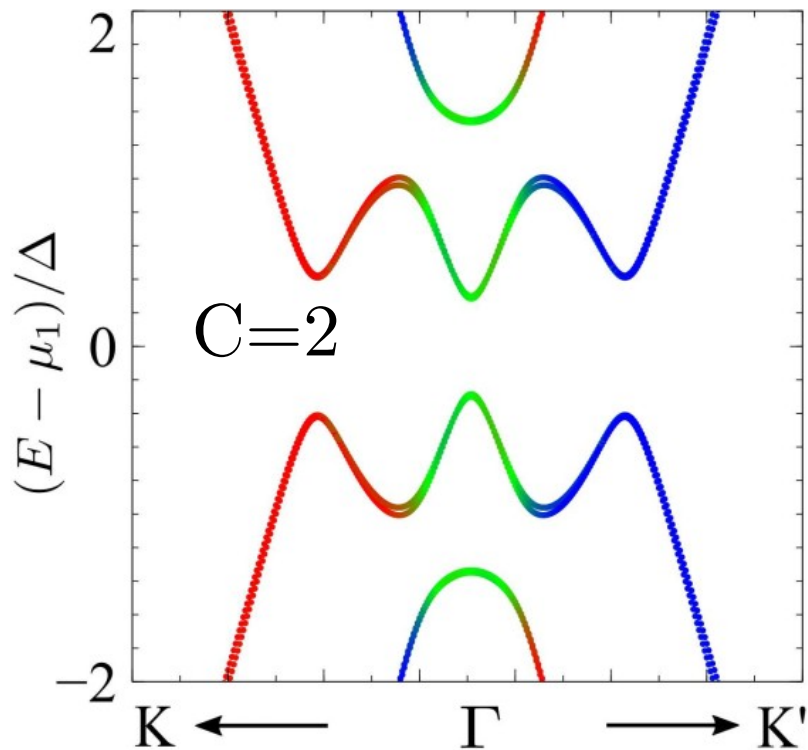
Without superconductivity



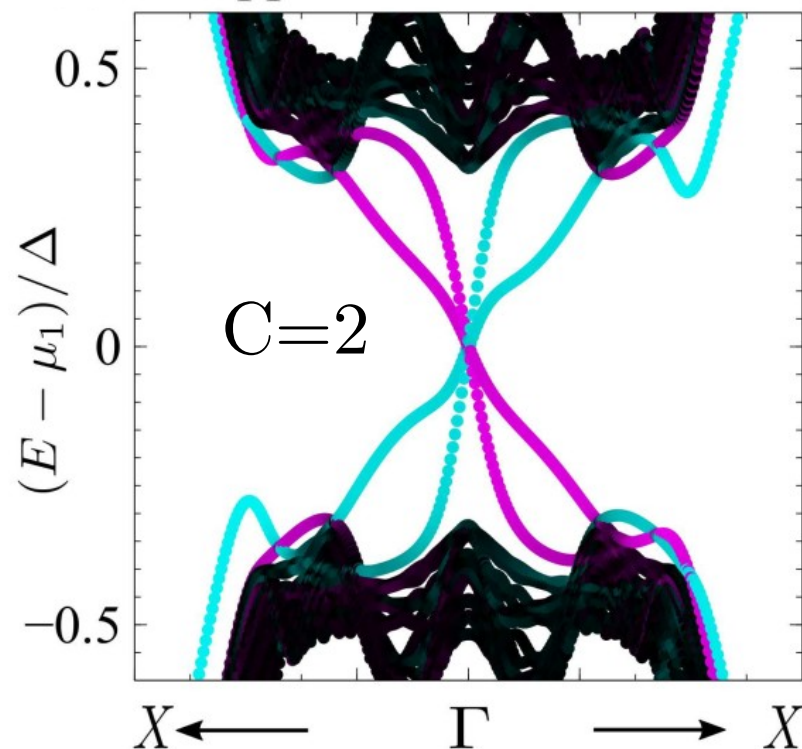
Switching on superconductivity gives rise to a topological superconducting state

Moire-enabled artificial superconductors in twisted bilayer graphene

Bulk band structure

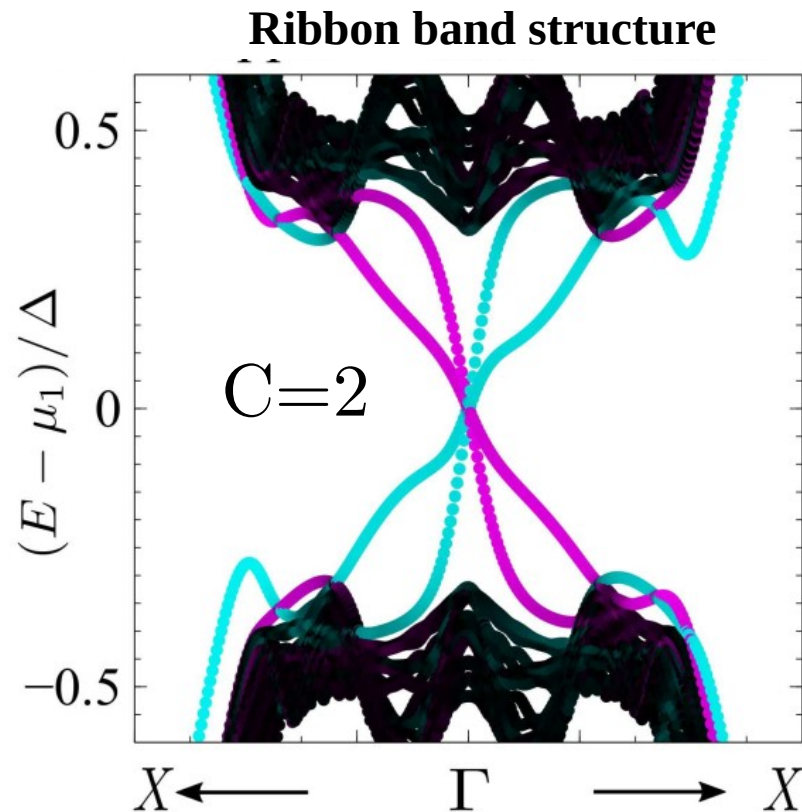
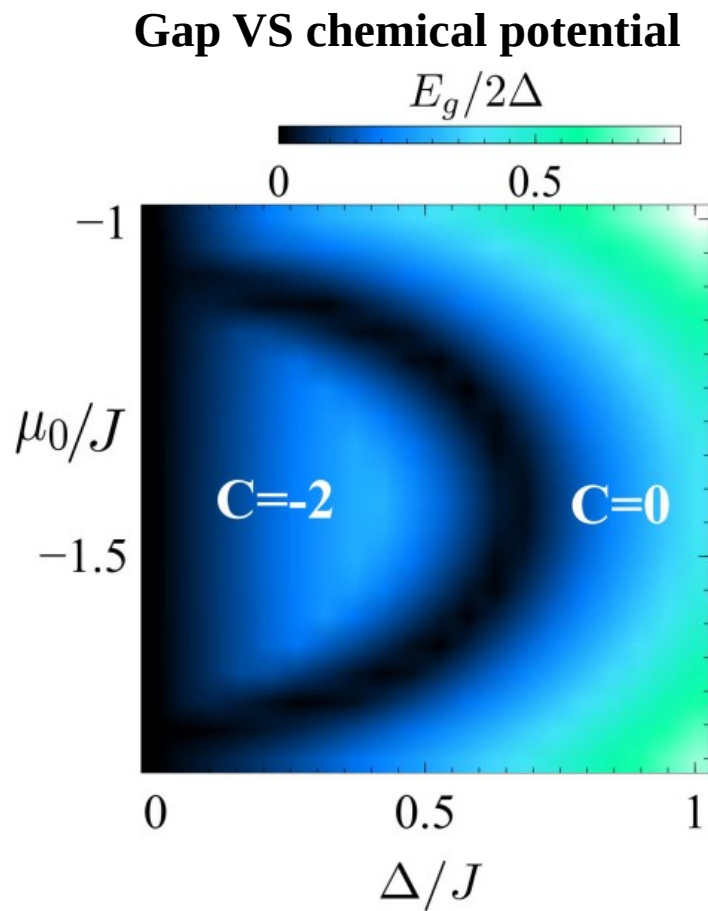


Ribbon band structure



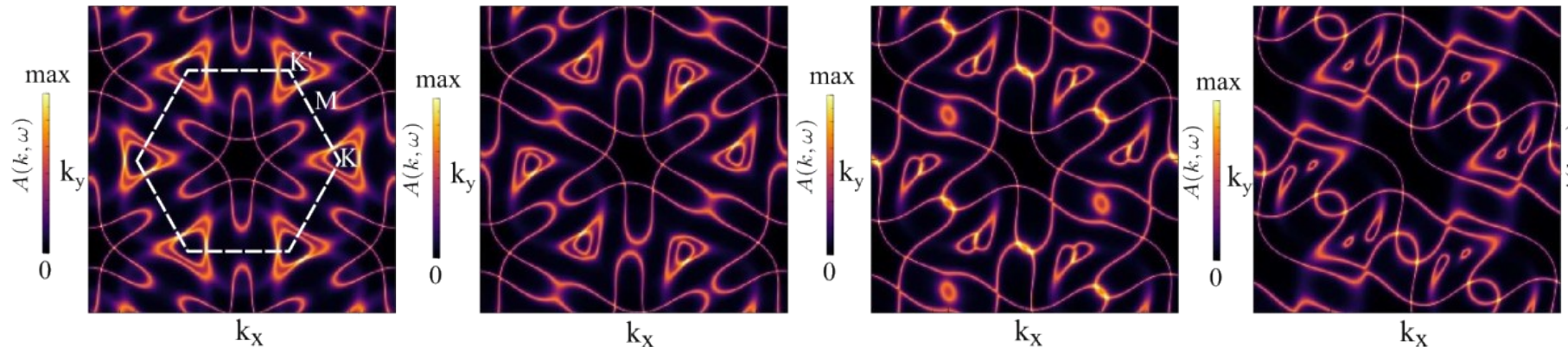
The topological state features chiral Majorana modes in a ribbon geometry

Moire-enabled artificial superconductors in twisted bilayer graphene

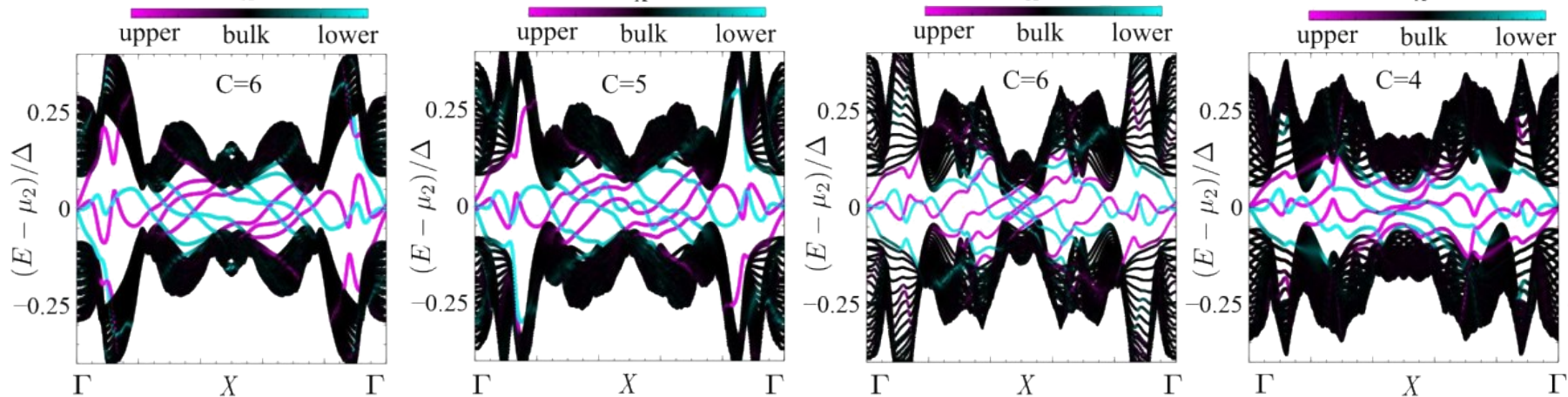


Multiple topological phases tunable by strain

Fermi surface

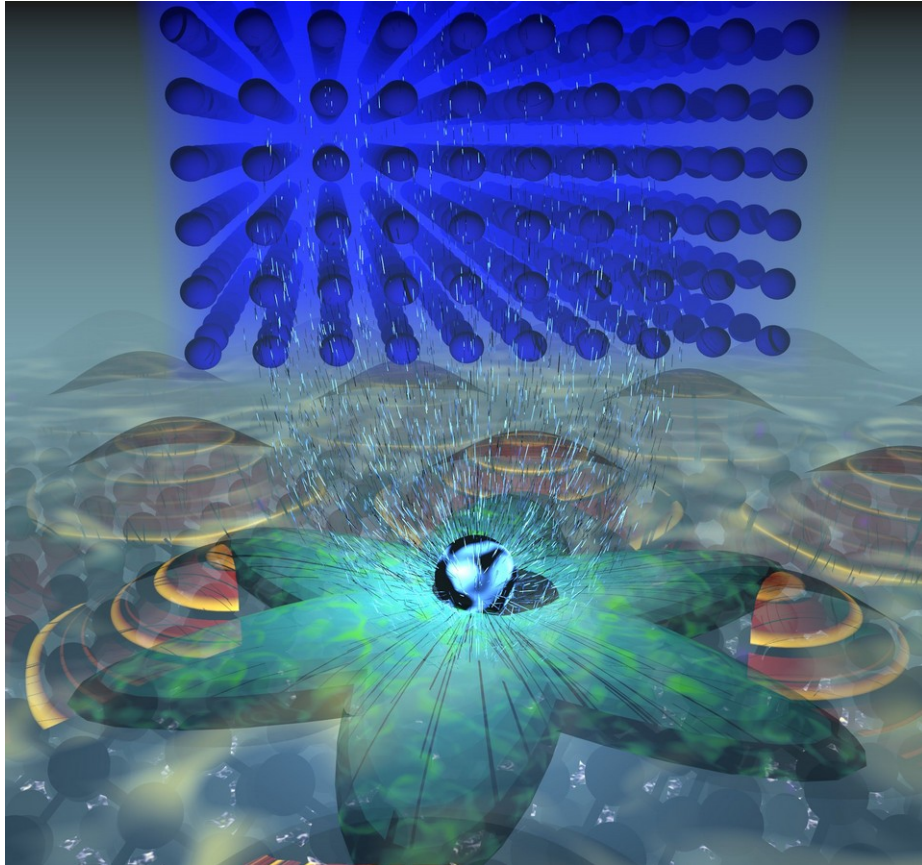


Ribbon bands



Strain allows to realize topological states with different Chern numbers

Hamiltonian learning from impurity tomography in moire superconductors



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The challenge of identifying topological superconductors

YSR

Majorana

Majorana

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

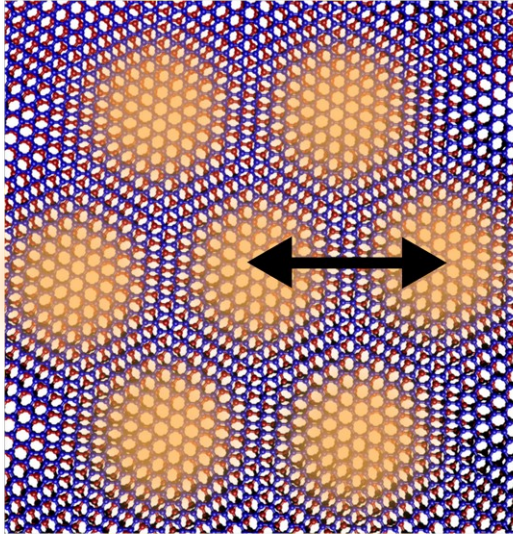
Solution #1: Do experimentally vortex braiding (long term)

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

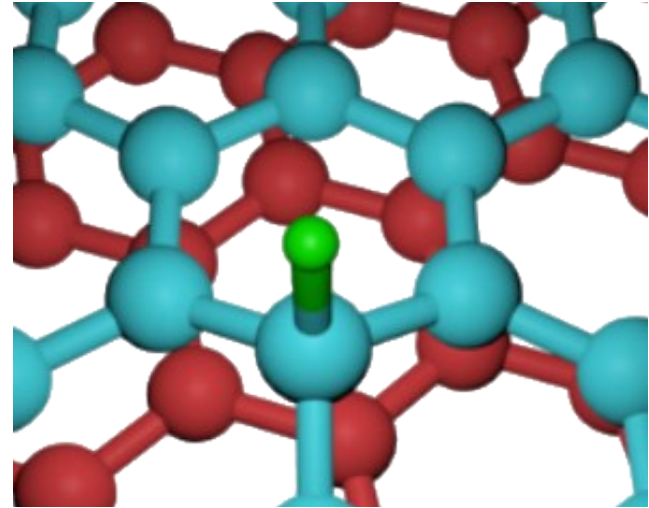
How can we extract the Hamiltonian of a complex moire quantum material?

Two length scales in twisted van der Waals materials

The emergent moire scale



The original atomic scale



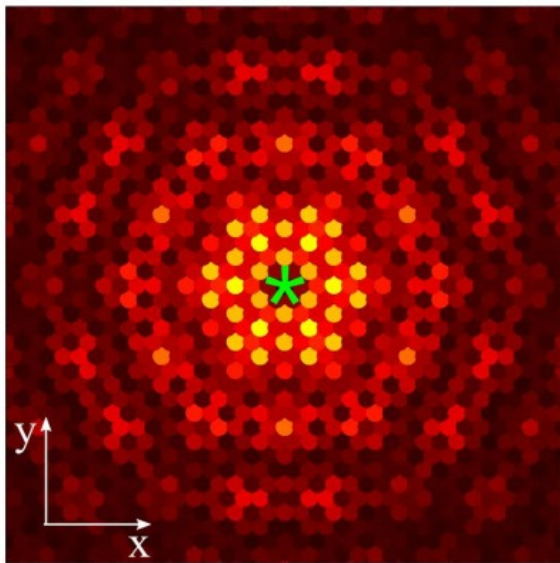
The coexistence of these two different scales is unique to moire systems

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

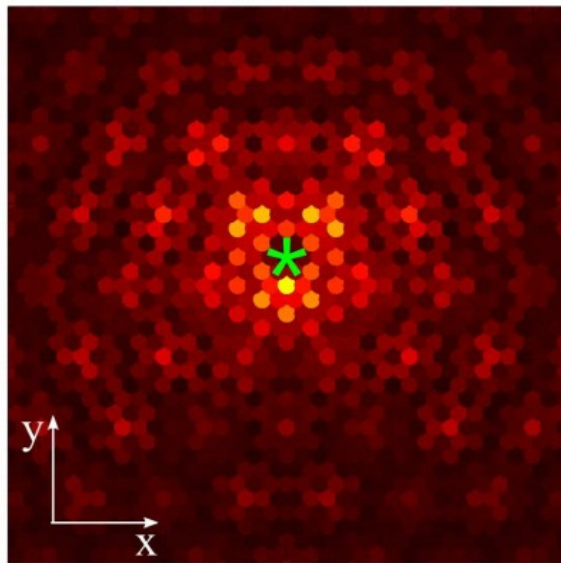
Single impurity in a topological moire superconductor

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

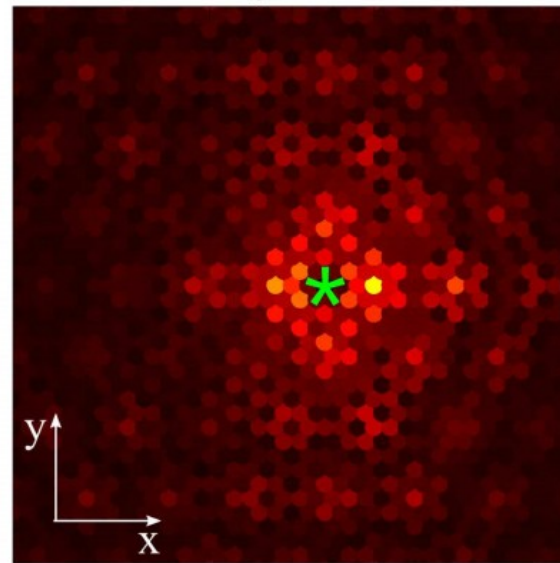
$\rho(\mathbf{r}, \omega = \epsilon_V)$ 0 max



$\rho(\mathbf{r}, \omega = \epsilon_V)$ 0 max



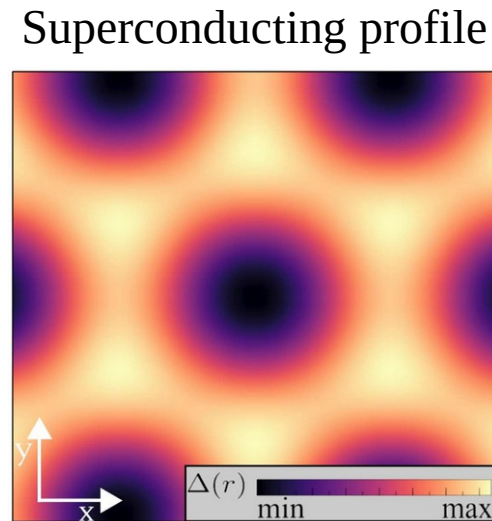
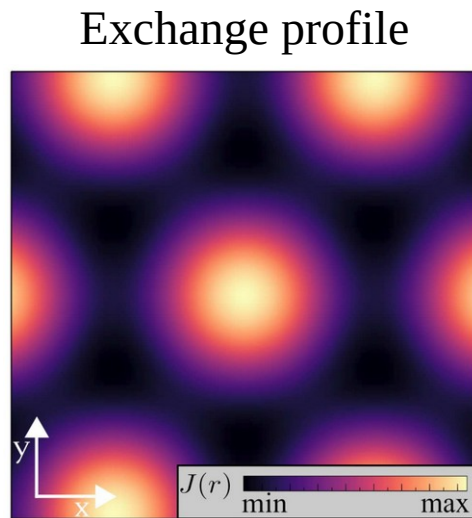
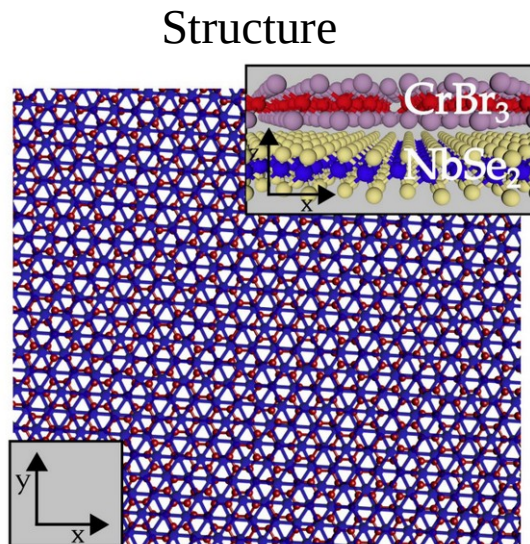
$\rho(\mathbf{r}, \omega = \epsilon_V)$ 0 max



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



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

Kinetic
energy

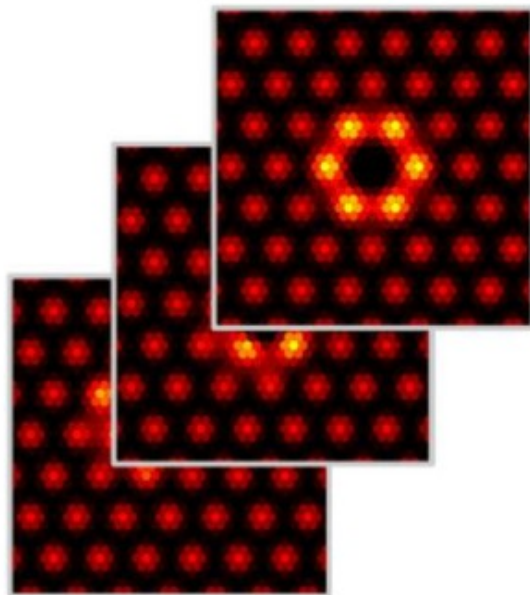
Exchange
coupling
profile

Rashba
SOC

S-wave superconducting
profile

Real-space impurity tomography

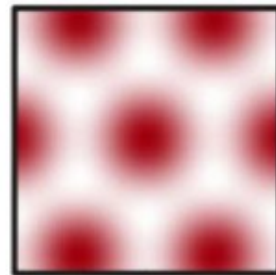
YSR for different impurity locations



Real-space
impurity tomography



Superconducting profile

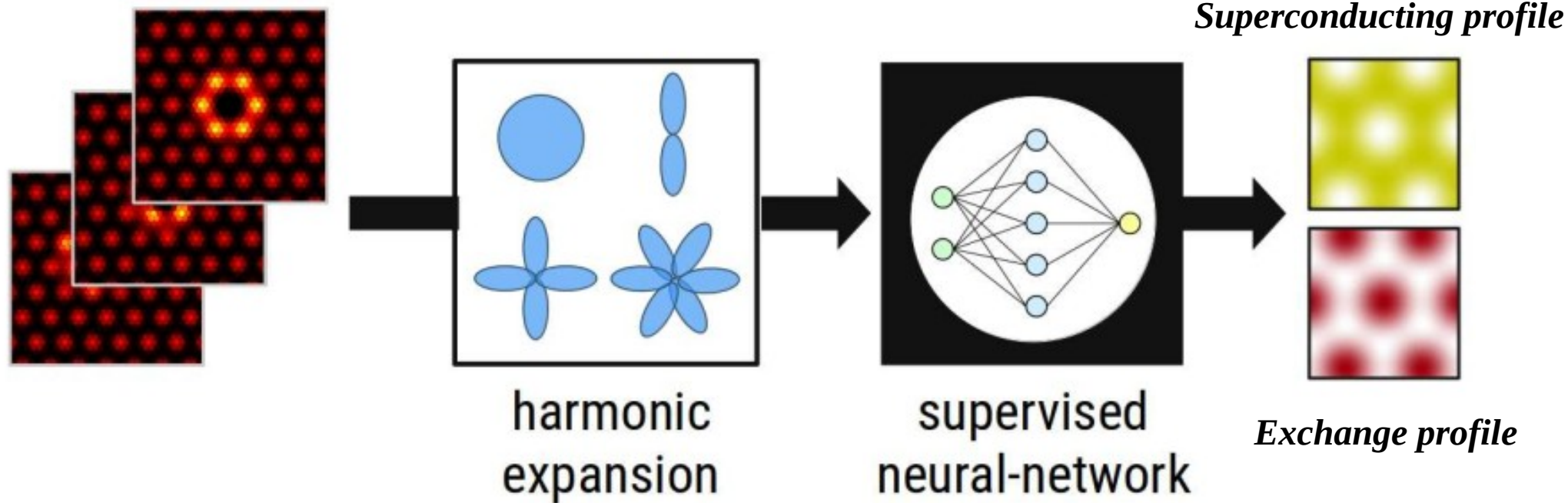


Exchange profile

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

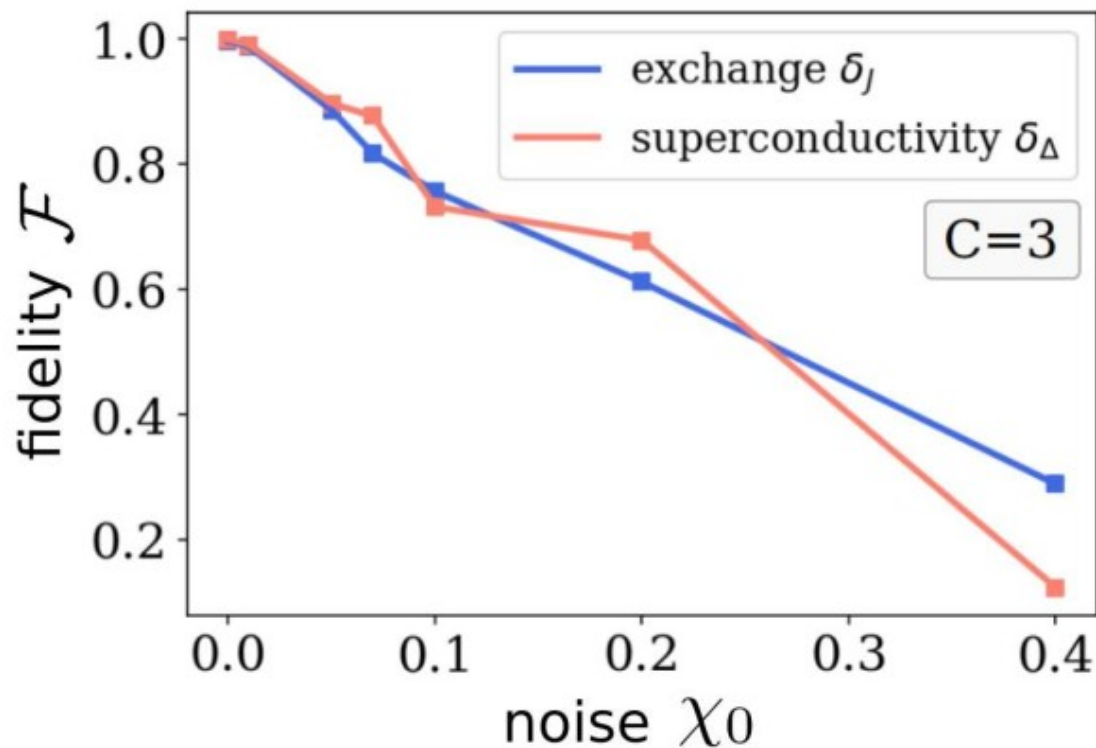
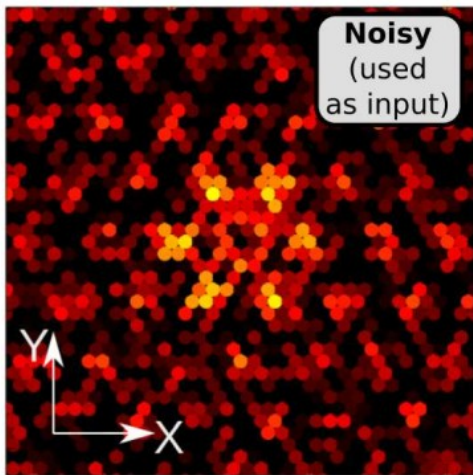
Hamiltonian learning with noisy spectroscopy

Prediction accuracy (fidelity)

$\mathcal{F} = 1$ Perfect prediction

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

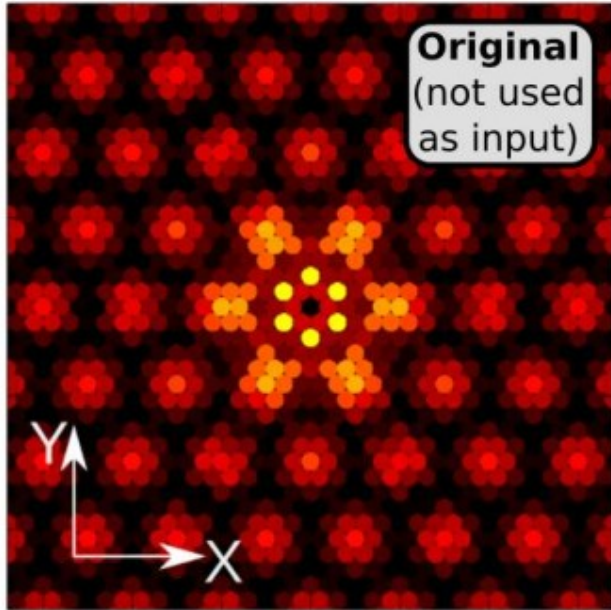
Noise $\chi_0 = 0.2$



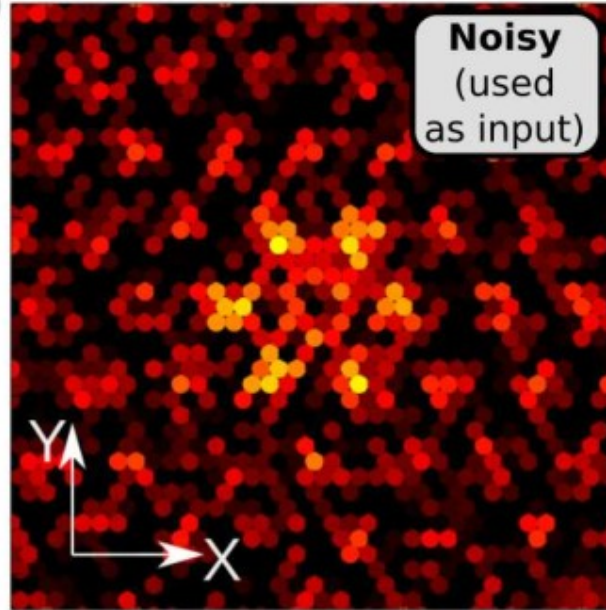
Hamiltonian learning is successful even with moderate noise

Noisy Hamiltonian reconstruction

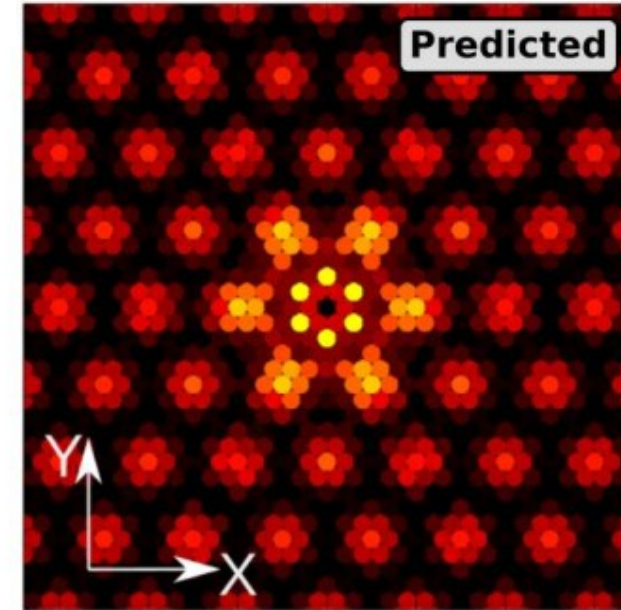
Original non-noisy profile



Noisy profile provided to the machine learning algorithm



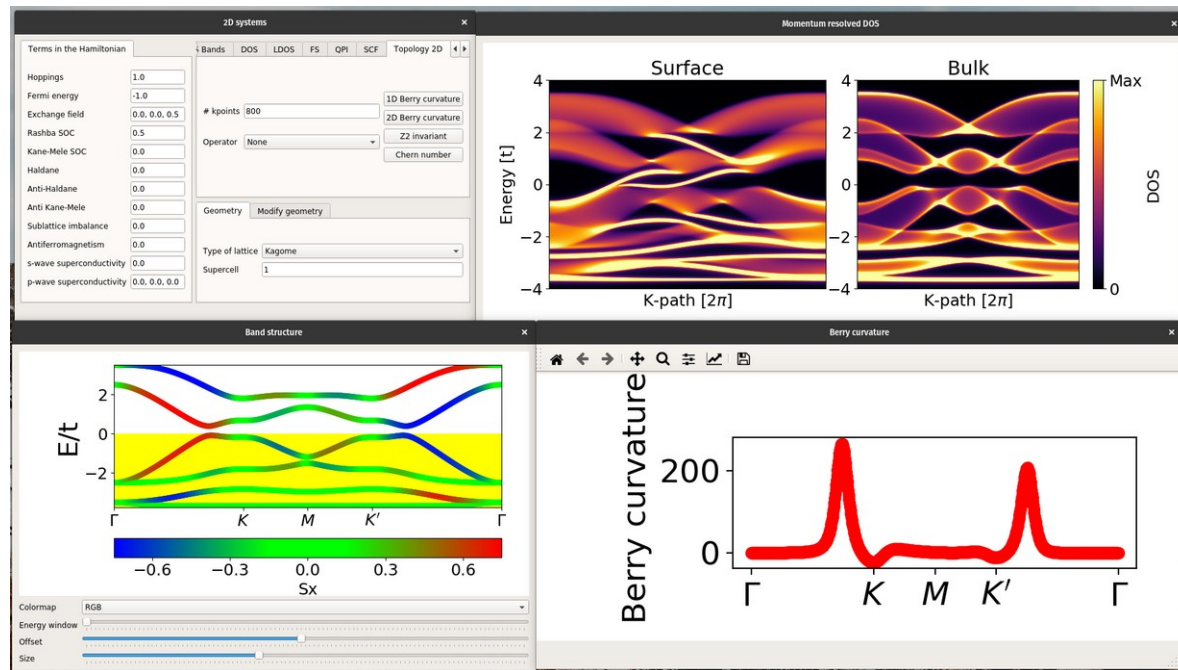
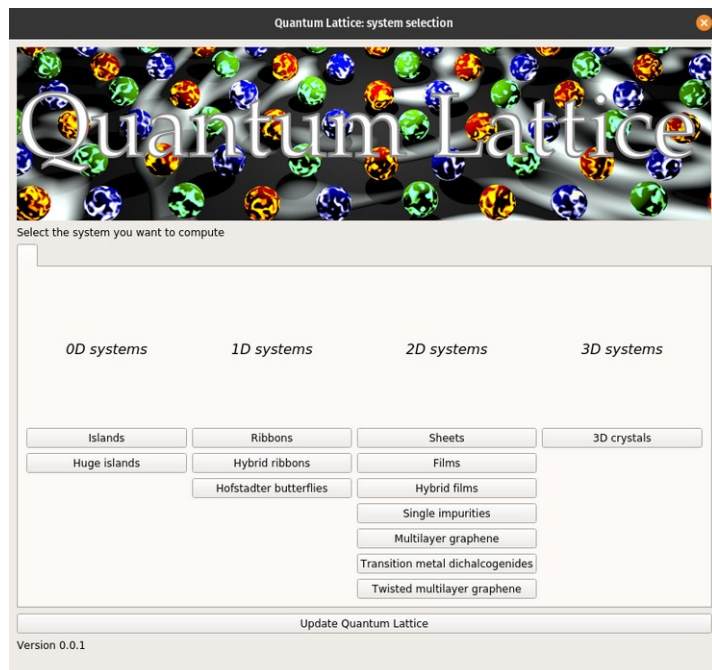
Predicted profile of the extracted Hamiltonian



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

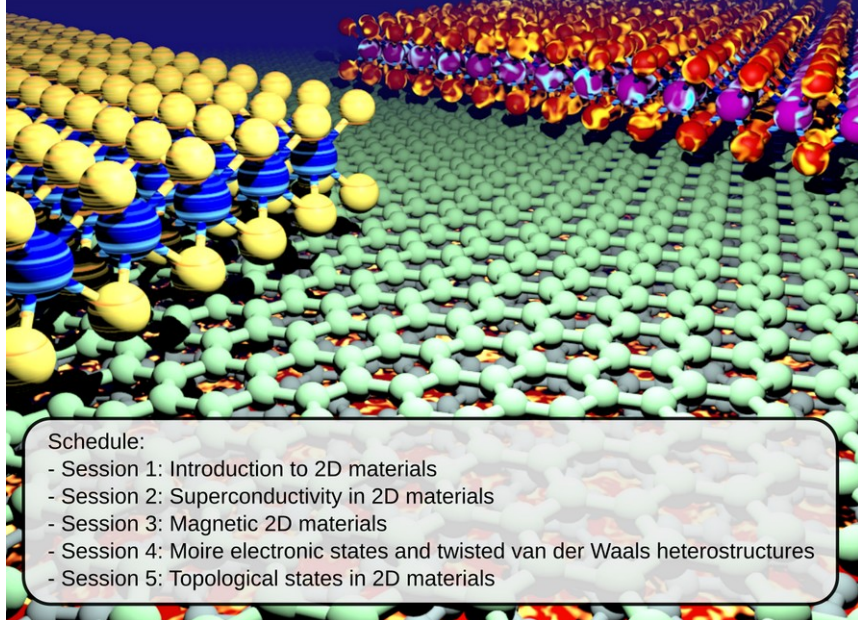


Quantum Lattice: open source interactive interface for tight binding modeling

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

Quantum matter in van der Waals materials school

University of Jyväskylä 31st Jyväskylä Summer School
Emergent quantum matter in
artificial two-dimensional materials
August 8th-12th 2022



Schedule:

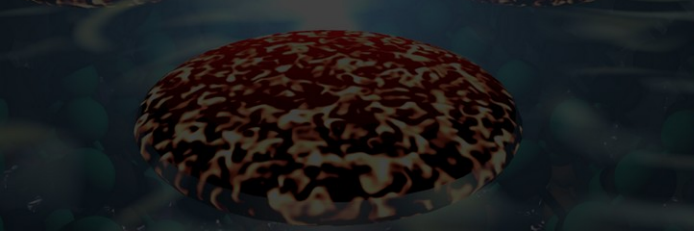
- Session 1: Introduction to 2D materials
- Session 2: Superconductivity in 2D materials
- Session 3: Magnetic 2D materials
- Session 4: Moire electronic states and twisted van der Waals heterostructures
- Session 5: Topological states in 2D materials

Recordings available at

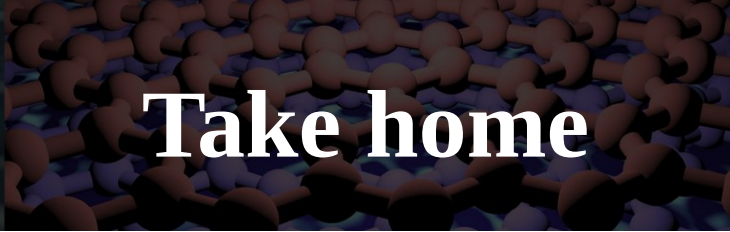


<https://www.youtube.com/channel/UCgnB-4CcqRQnvTi7P0cUakQ>

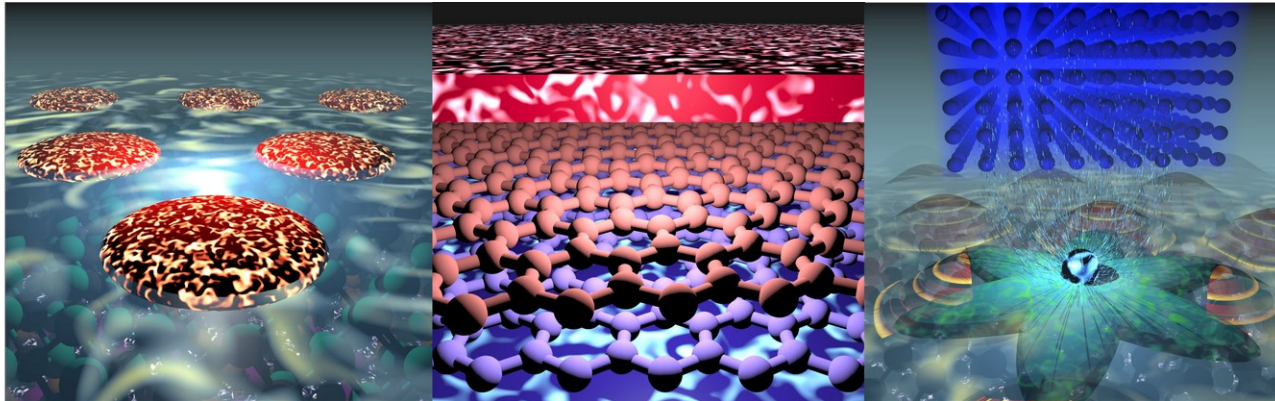
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Take home



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



Thank you!

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