Designing topological superconductivity from solitons in antiferromagnet-superconductor interfaces

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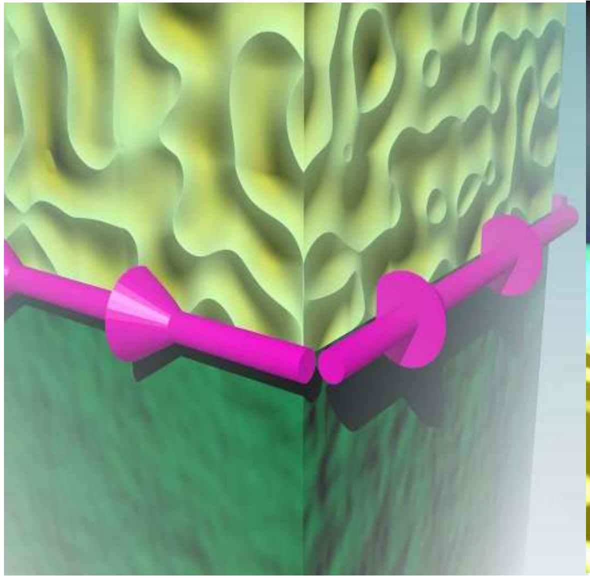
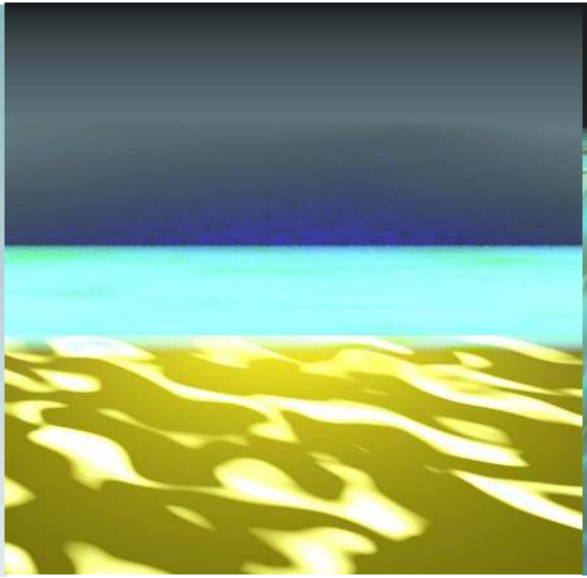
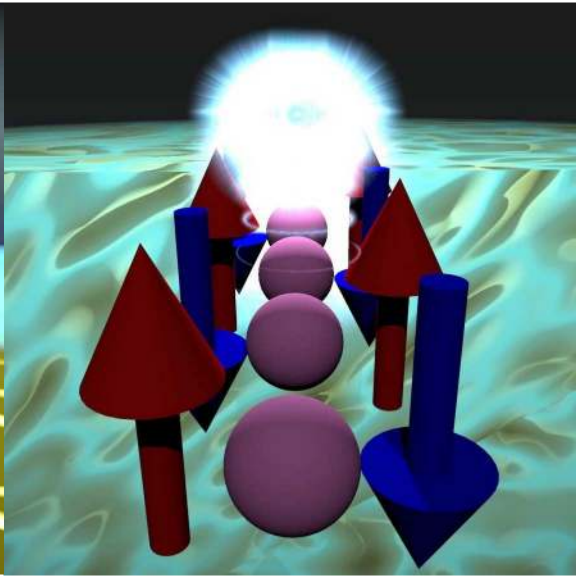


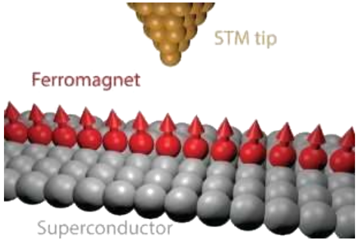




TopoSuper2021, Aalto University (online), June 8th 2021

Topological superconductivity in quantum materials

Ferromagnetic atomic chains

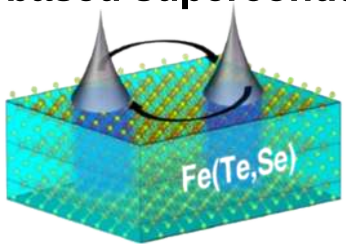


Science 346.6209 (2014): 602-607

Semiconductors

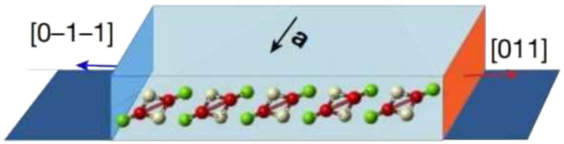
Science 354.6319 (2016): 1557-1562

Fe-based superconductors



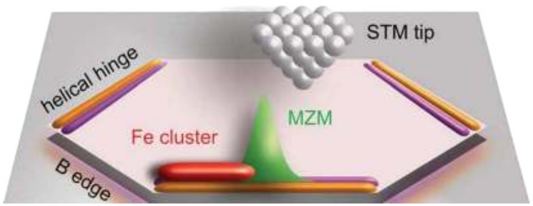
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



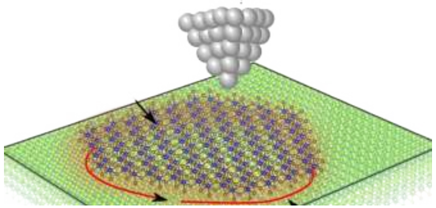
Nature 579, 523–527 (2020)

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

Topological superconductivity with antiferromagnetic insulators

Goal: to build a topological superconductor with

- A conventional (s-wave) superconductor
- **<u>An antiferromagnetic insulator</u>**

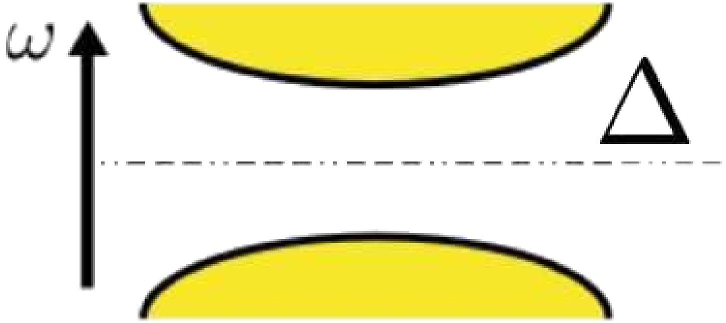
The prize

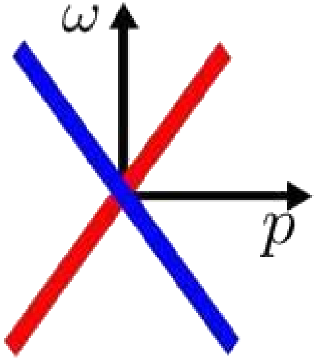
<u>Bringing a new solid state platform to realize artificial topological superconductors</u>

How to build your own topological superconductor

Ingredients

- s-wave pairing
- Helical states





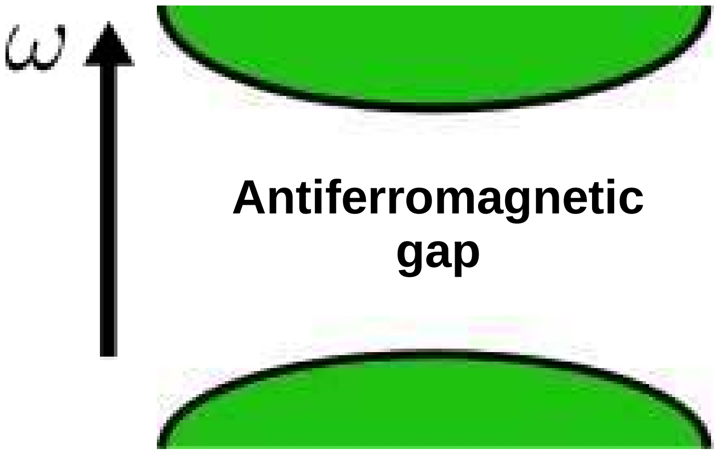
Objective: to realize a spinless superconductor

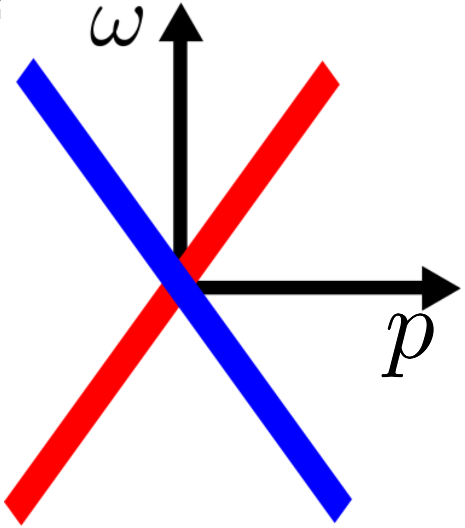
$$H = \sum_n t c^\dagger_{n+1} c_n + \Delta c_n c_{n+1} + c.c.$$

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

The initial problem

How can we get a topological phase starting from a trivial insulator?

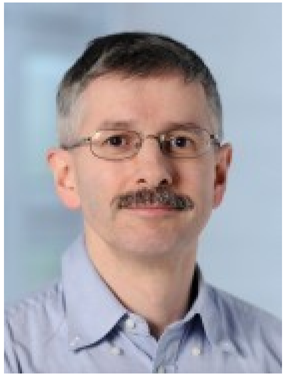




We need to create a “spinless” gapless state out of an insulator

Behind the scenes

Manfred Sigrist



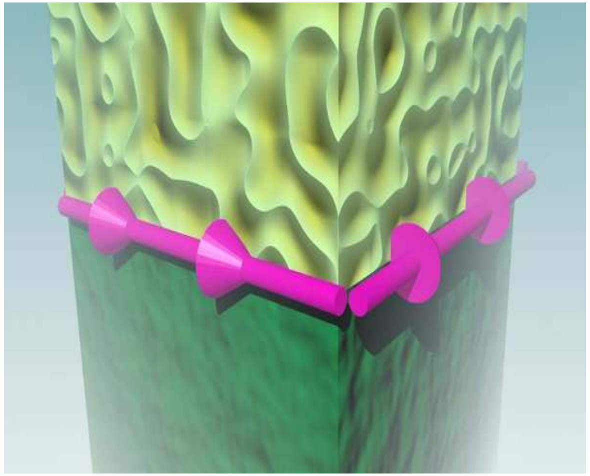
Senna Luntama

Päivi Törmä

Phys. Rev. Lett. 121, 037002 (2018)
Phys. Rev. Research 2, 023347 (2020)

Phys. Rev. Research 3, L012021 (2021)

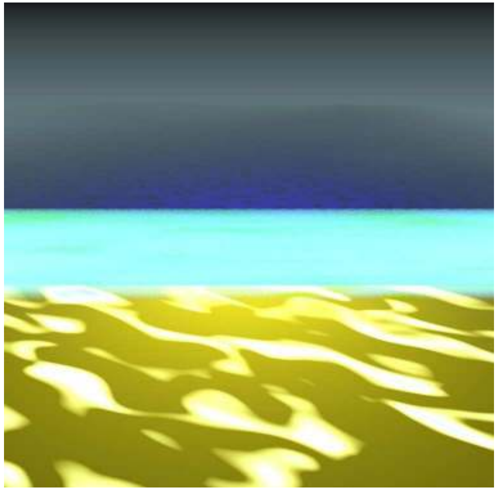
Today's story



Topological superconductivity (TS) in 3D AF insulators

No interactions

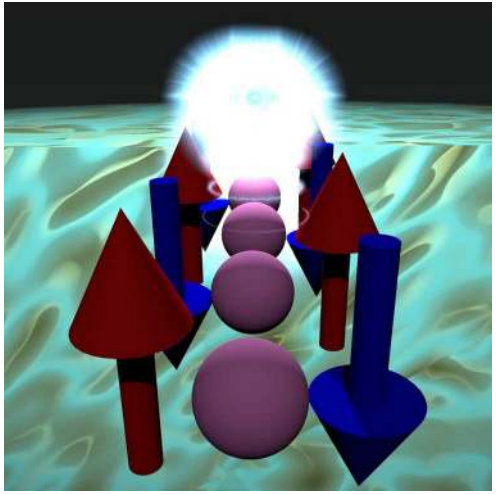
Phys. Rev. Lett. 121, 037002 (2018)



Interaction-induced TS in 2D AF insulators

Mean-field interactions

Phys. Rev. Research 3, L012021 (2021)



The quantum many-body 1D limit

Purely quantum many-body

Phys. Rev. Research 2, 023347 (2020)

Creating a 2D topological superconductor with a 3D antiferromagnetic insulator

Heterostructure for 2D TS in a 3D AF insulator

2d topological superconductor at the interface

$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{AF}} + \mathcal{H}_{\text{SC}} + \mathcal{H}_{\text{SOC}}$$

Kinetic energy

Antiferromagnetism

Superconductivity

Spin-orbit coupling

Solitonic modes between Dirac AF and SC

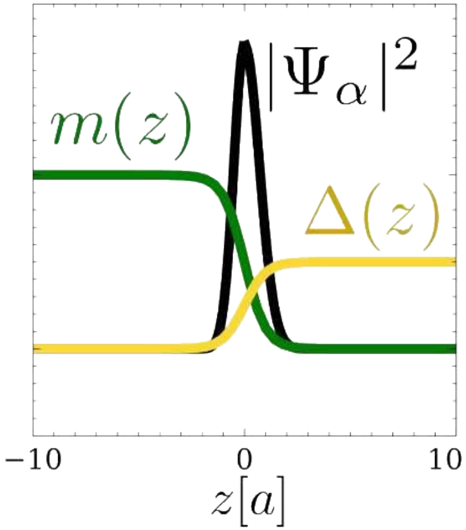
Total Hamiltonian, <u>for an antiferromagnet with gaped Dirac points</u>

$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{AF}} + \mathcal{H}_{\mathrm{SC}}$$

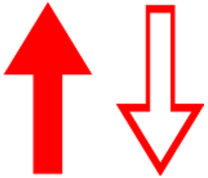
There will be two zero solutions $\mathcal{H}|\Psi_\alpha\rangle = 0$

Phys. Rev. X 5, 041042 (2015)

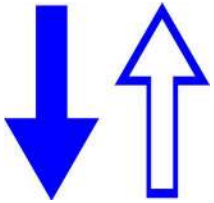
similar to a Jackiw-Rebbi soliton
Phys. Rev. D 13, 3398 (1976)



Sector #1
Up electron, down hole

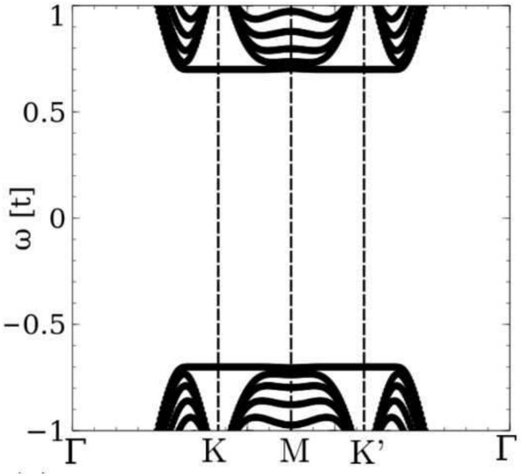


Sector #2
Down electron, up hole

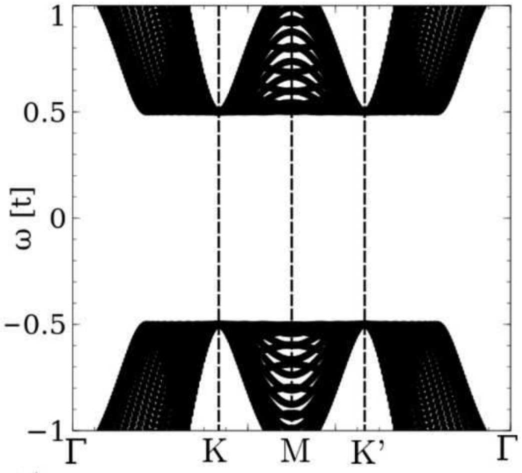


Emergence of interfacial modes, no spin-orbit coupling

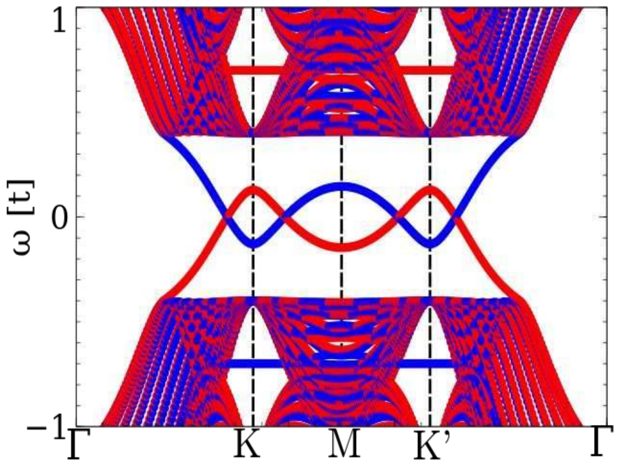
Antiferromagnet



Superconductor

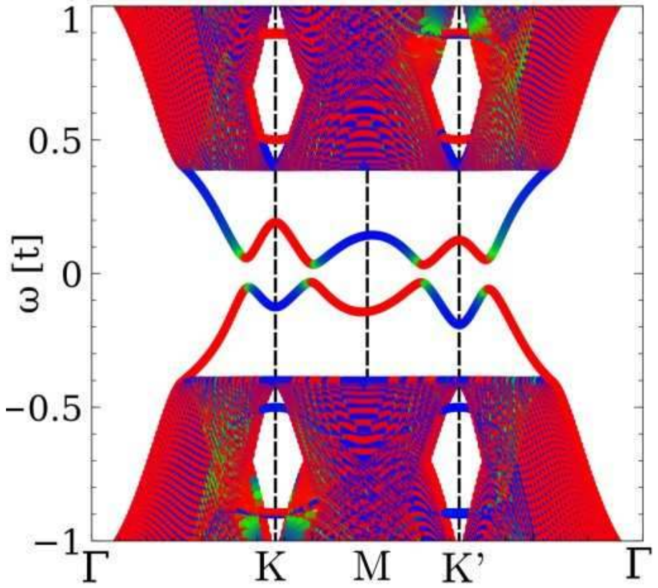


AF/SC heterostructure

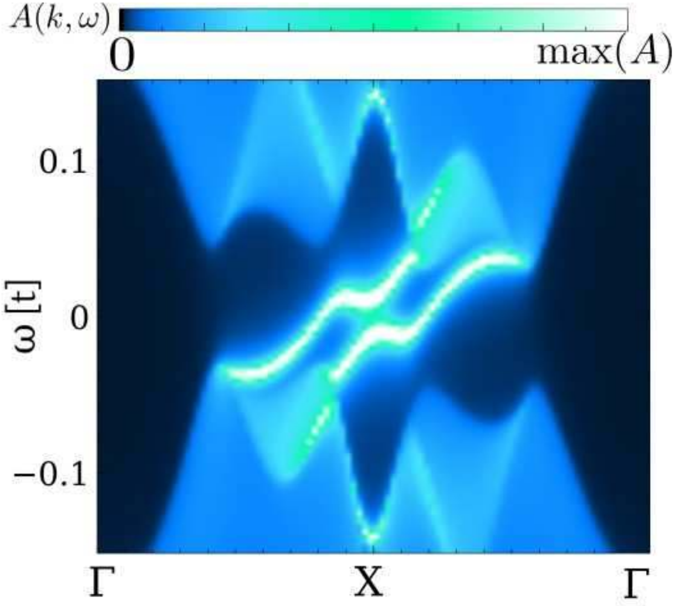


Topological superconductivity with spin-orbit coupling

Band structure

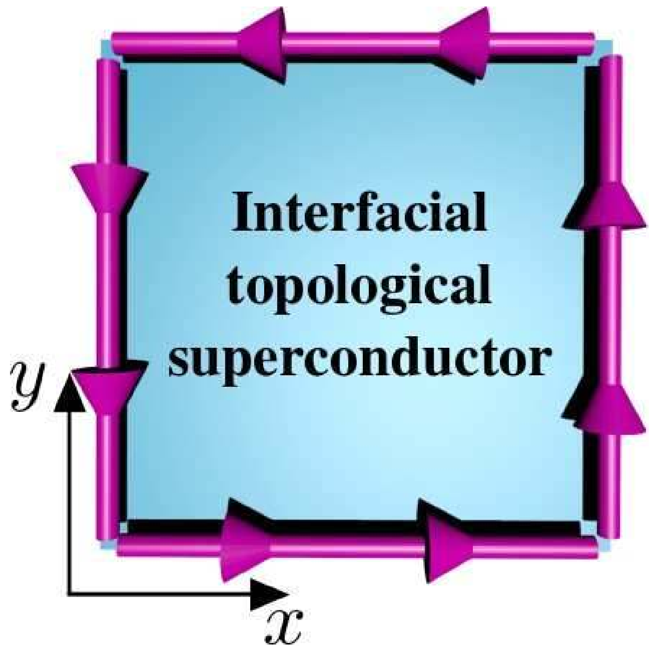


Edge spectral function

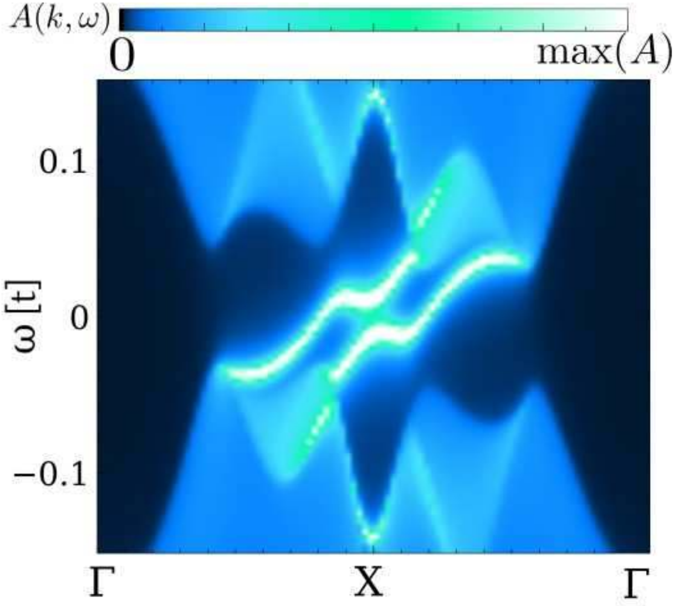


Topological superconductivity showing gapless Majorana modes

Topological superconductivity with spin-orbit coupling



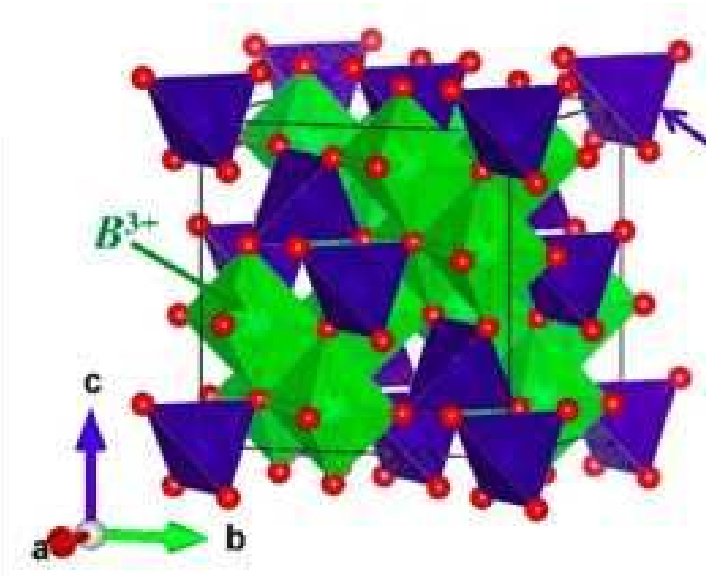
Edge spectral function



The interface realizes a topological superconductor

Material candidates

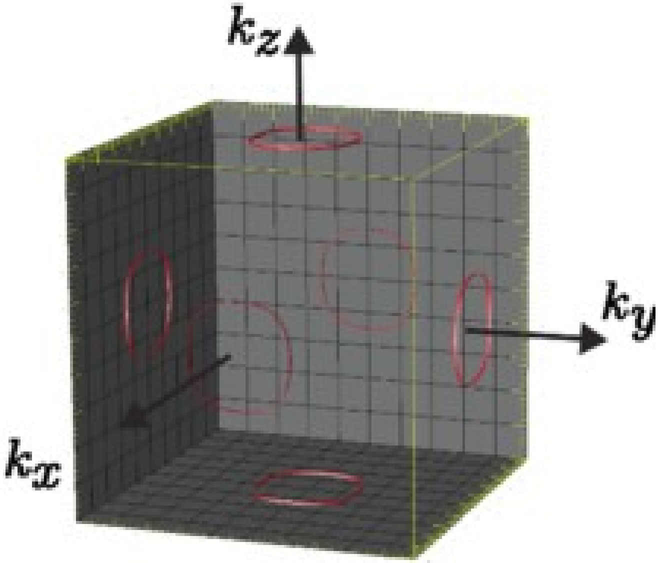
Antiferromagnetic spinels



$CoAl_2O_4$

Phys. Rev. B 95, 094404 (2017)

Antiferromagnets arising from a Dirac material

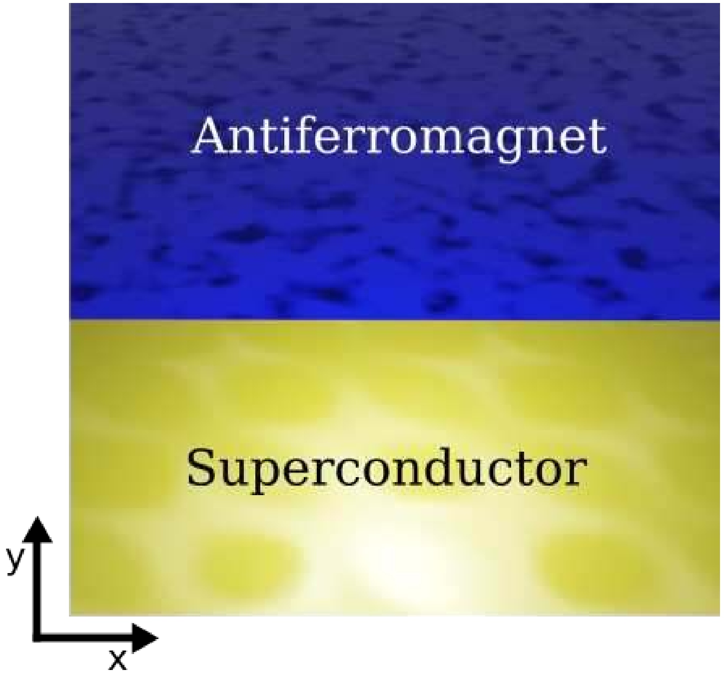


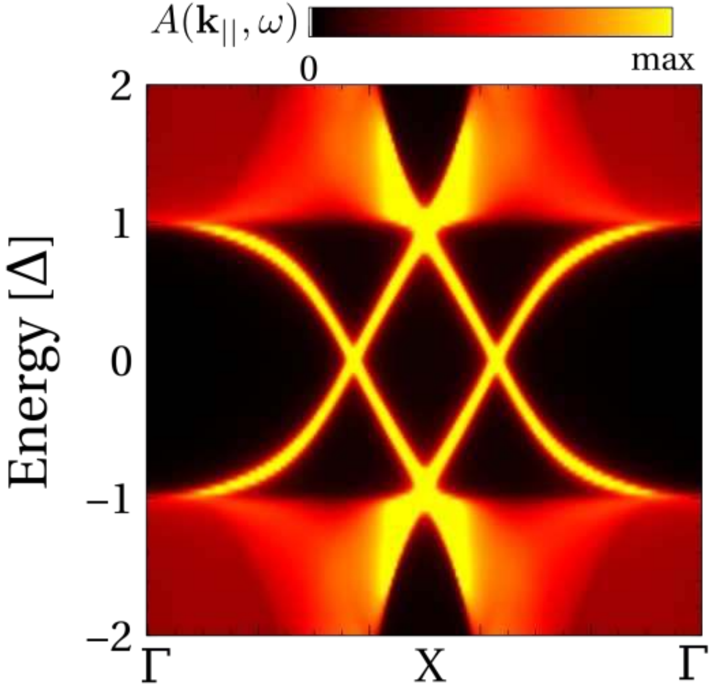
Phys. Rev. Lett. 115, 036806 (2015)

Interaction-induced
1D topological superconductivity in
2D antiferromagnets

Interface AF-SC modes

$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{AF}} + \mathcal{H}_{\text{SC}}$$

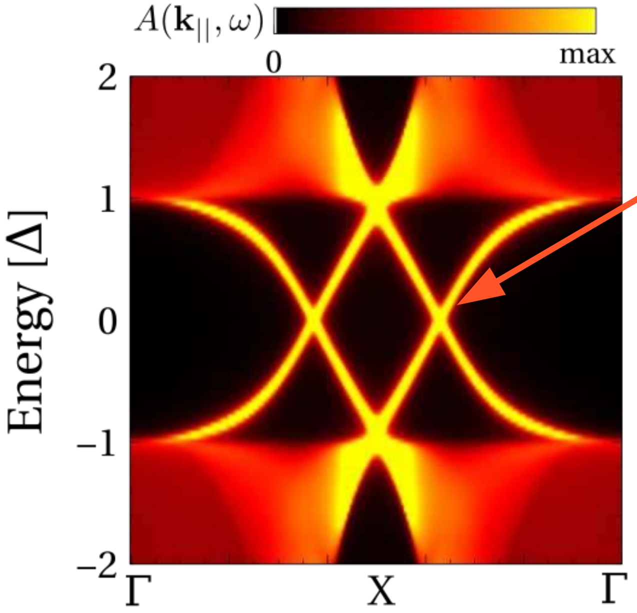




Gapless zero modes appear at the one-dimensional AF-SC interface

Topological superconductivity from interactions

Can we get topological superconductivity without SOC, just driven by repulsive electronic interactions?



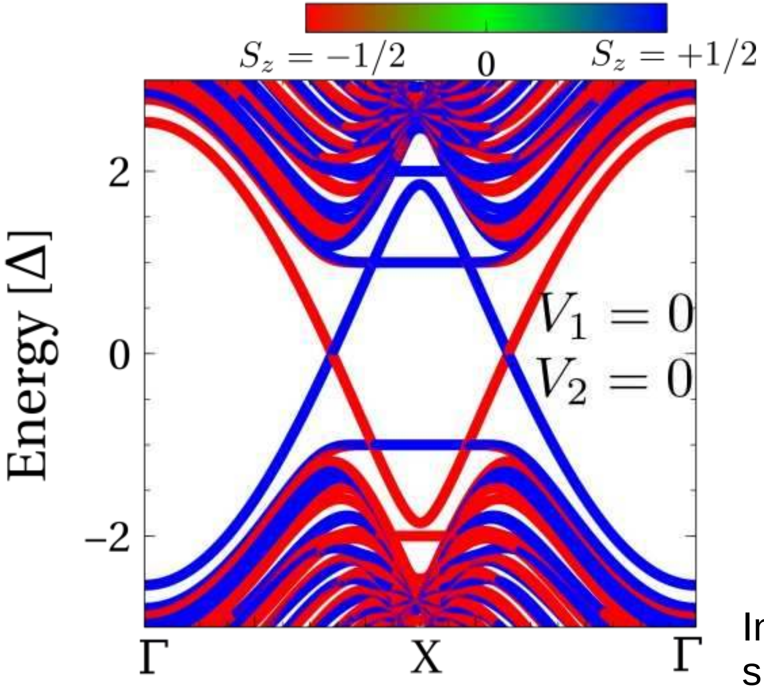
Could there be an interaction-induced gap opening of the interface modes?

$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{AF}} + \mathcal{H}_{\mathrm{SC}} + \mathcal{H}_{\mathrm{int}}$$

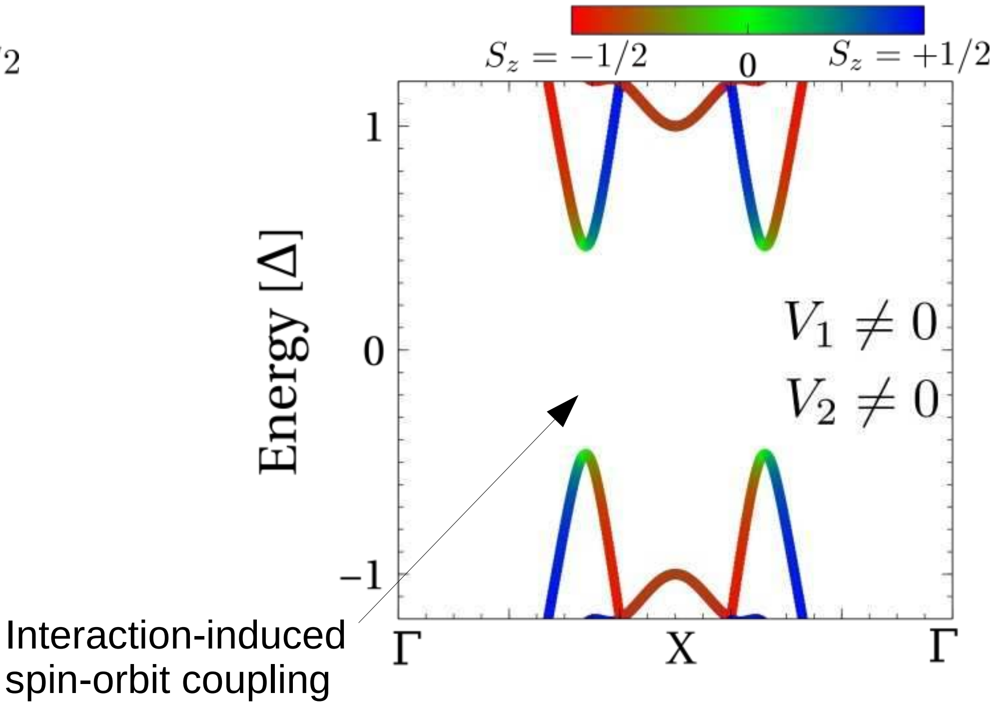
We will solve a model with repulsive long-range interactions at the mean-field level

Impact of interactions

Without interactions



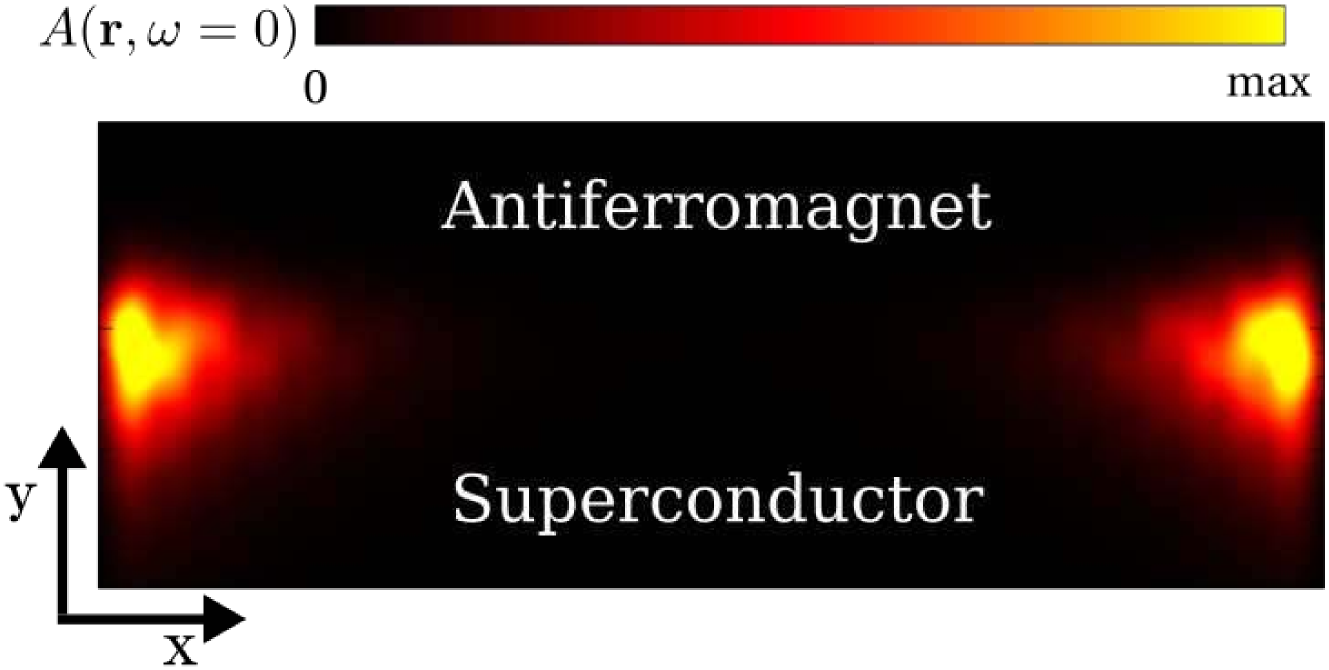
With interactions



Including repulsive interactions opens up a topological gap in the solitonic modes

Majorana zero modes

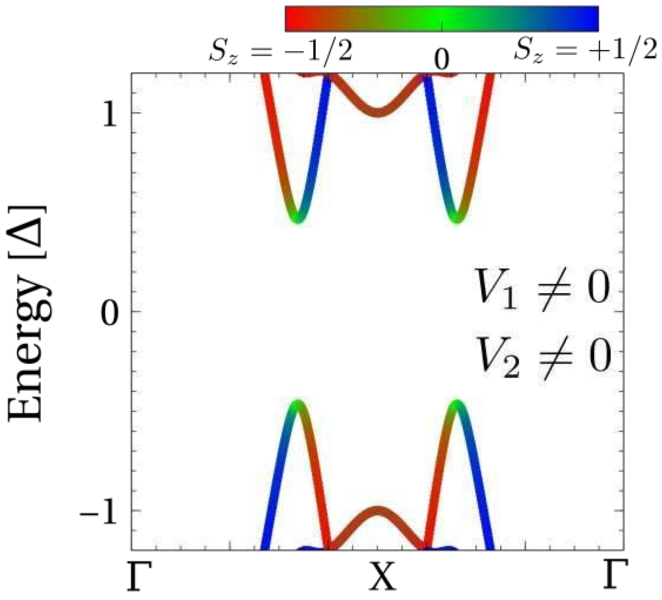
Spectral function at zero energy, featuring Majorana edge modes

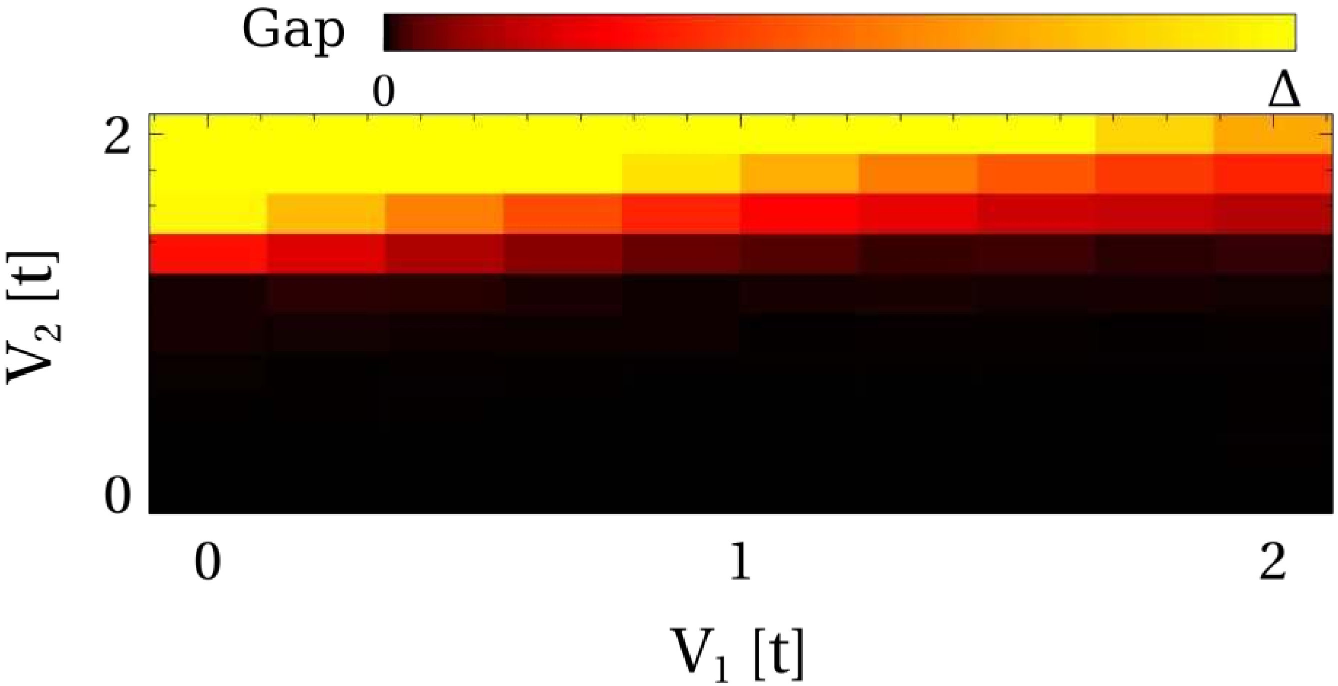


Majorana zero modes emerge at the edge due to electronic interactions

Interaction-induced gap VS interaction strength

Dependence of the topological gap with respect to first and second neighbor interactions

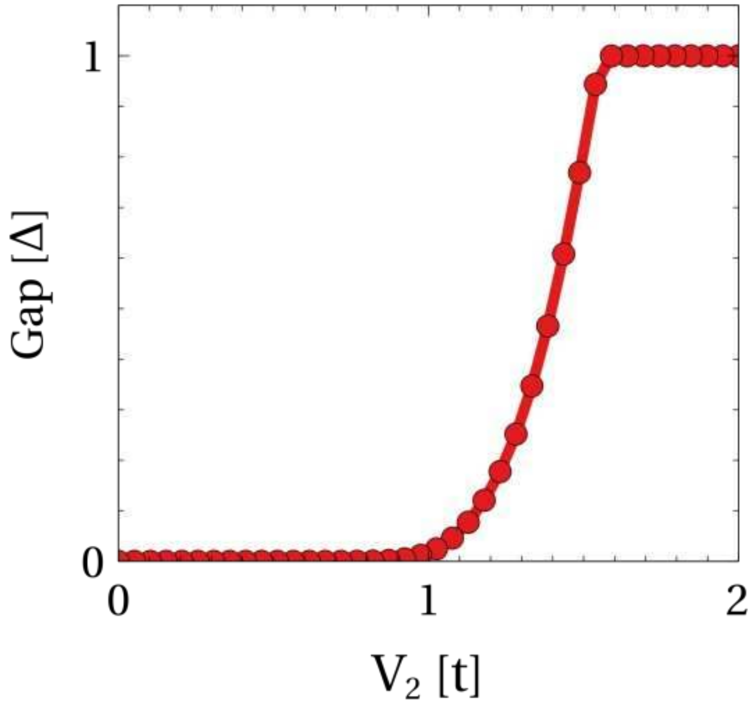


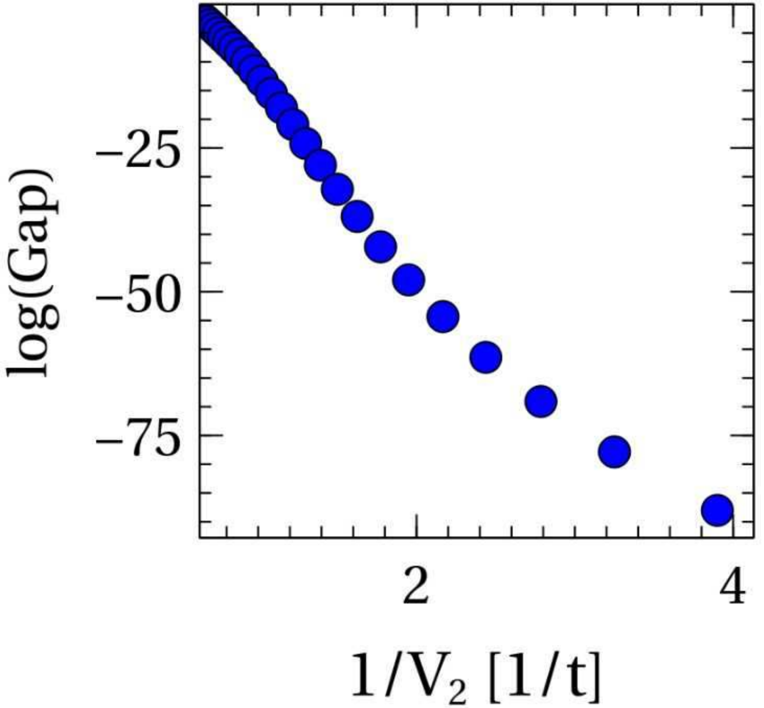


The interaction-induced gap saturates to Δ, the gap of the s-wave superconductor

Topological superconductivity without a critical interaction

Topological gap VS interaction strength





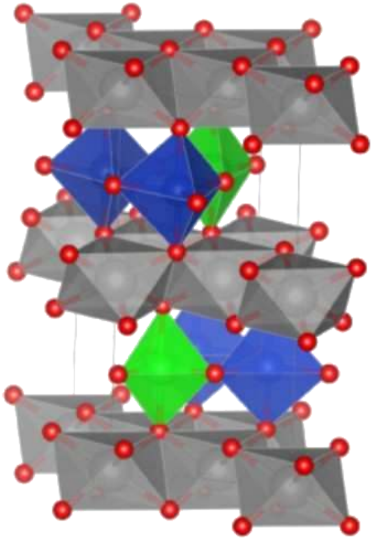
A topological gap opens up for arbitrarily small interactions

AF material candidates

Antiferromagnetic honeycomb oxides

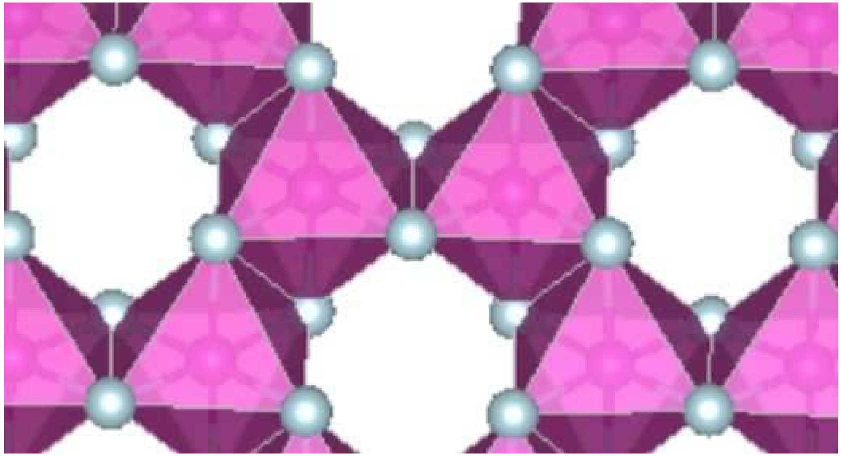
$InCu_{2/3}V_{1/3}O_3$ *Phys. Rev. B 78, 024420 (2008)*

β-$Cu2V_2O_7$ *Phys. Rev. B 82, 144416 (2010)*



2D van der Waals materials (strained)

Phys. Rev. B 98, 144411 (2018)



Many-body excitations in quantum antiferromagnet-superconductor junctions

Diving into the quantum many-body regime

Stagger antiferromagnet (mean-field solution)

$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{AF}} \qquad |GS\rangle = |\uparrow\downarrow\rangle$$

Quantum antiferromagnet (many-body solution)

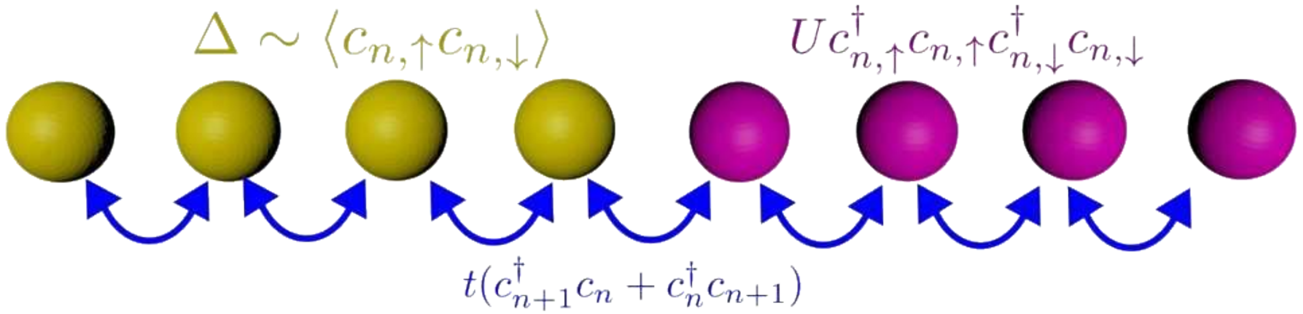
$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{U}} \qquad |GS\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Hubbard interaction $\mathcal{H}_{\mathrm{U}} = \sum_n U c^{\dagger}_{n,\uparrow} c_{n,\uparrow} c^{\dagger}_{n,\downarrow} c_{n,\downarrow}$

What happens at interfaces between a quantum many-body 1D antiferromagnet and a superconductor?

Superconductor-quantum antiferromagnet junction

Superconductor **Quantum antiferromagnet**



$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{SC}} + \mathcal{H}_{\mathrm{int}}$$

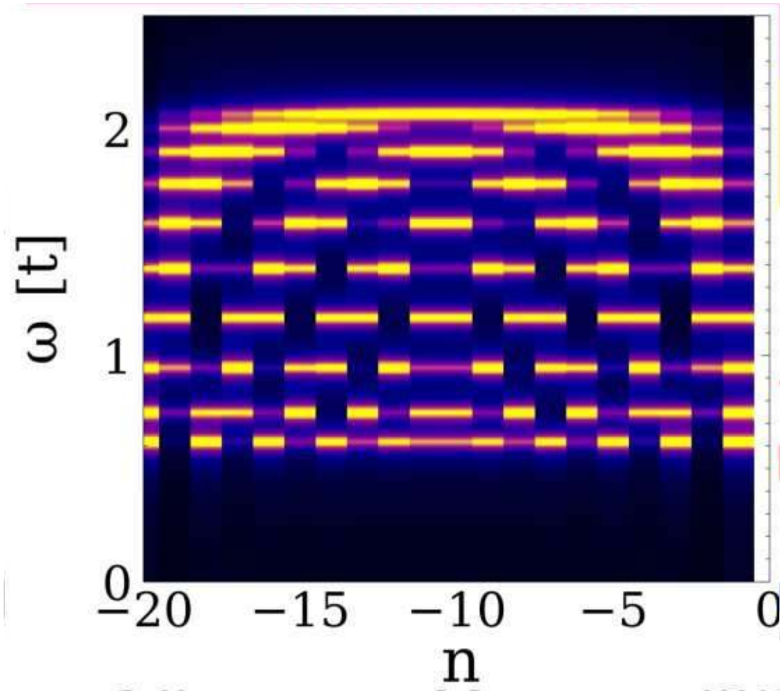
We will solve the interacting model exactly using the tensor network formalism

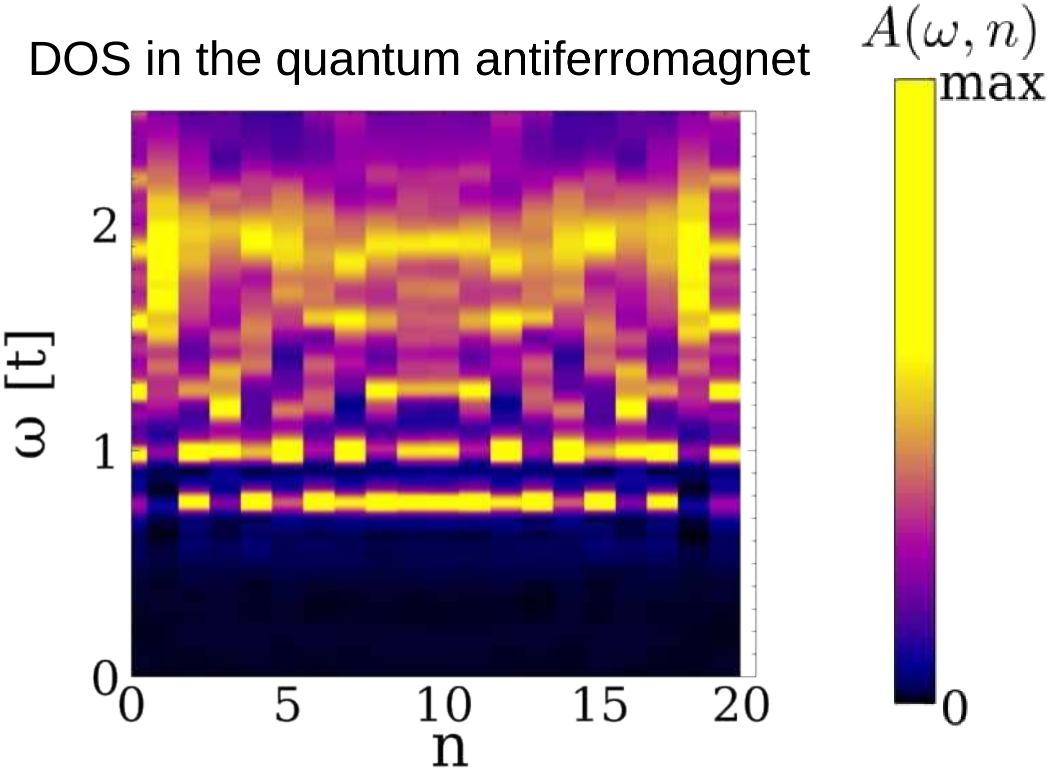
<u>The ground state does not break time-reversal symmetry</u>

Many-body spectral function

DOS in the superconductor

DOS in the quantum antiferromagnet

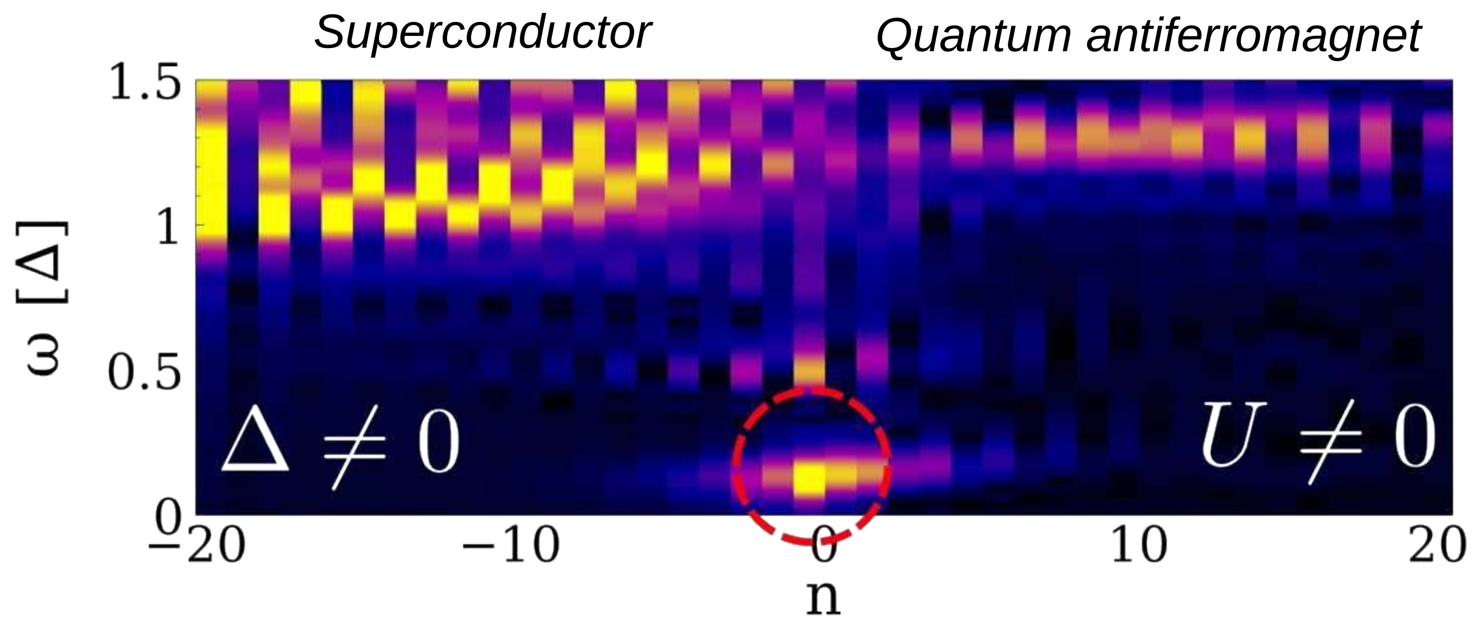




Both systems show an electronic gap when decoupled

In-gap modes at the SC-quantum AF interface

Superconductor-quantum antiferromagnet junction

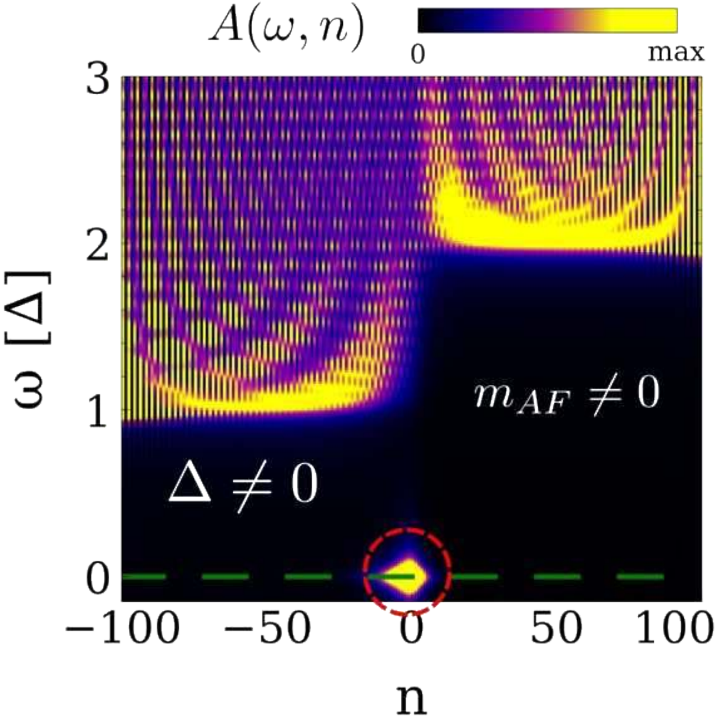


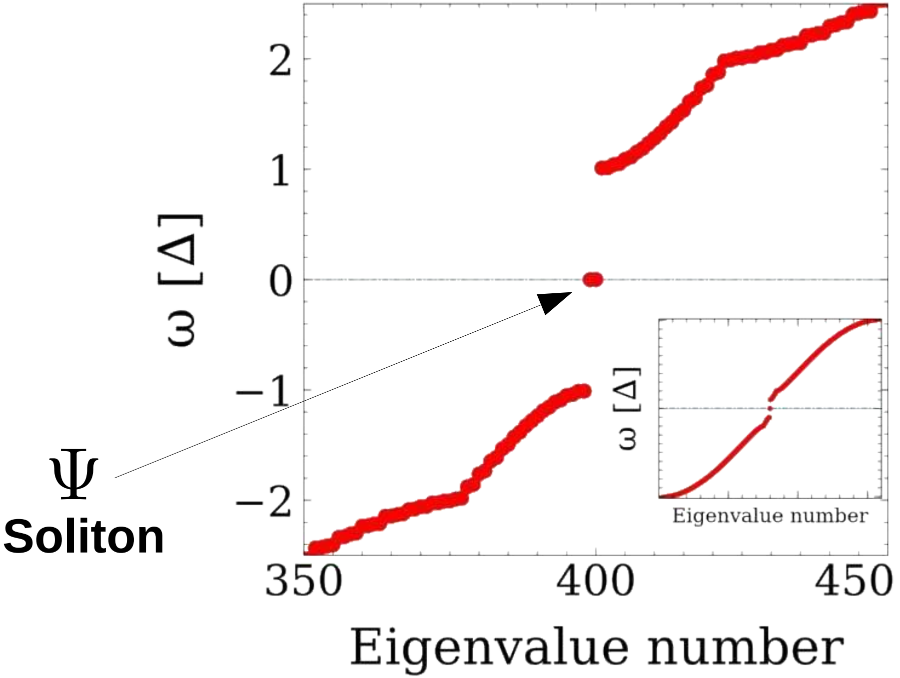
Solitonic in-gap modes appear between the superconductor and the quantum antiferromagnet

Back to single-particle solitonic zero modes

$$\mathcal{H} = \mathcal{H}_{\mathrm{kin}} + \mathcal{H}_{\mathrm{SC}} + \mathcal{H}_{\mathrm{AF}}$$

Single particle limit (stagger magnetization and no interactions)

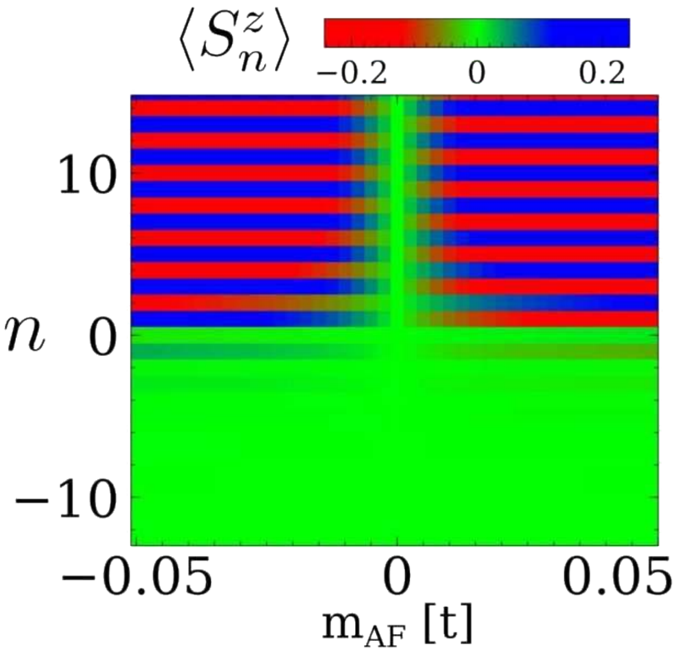




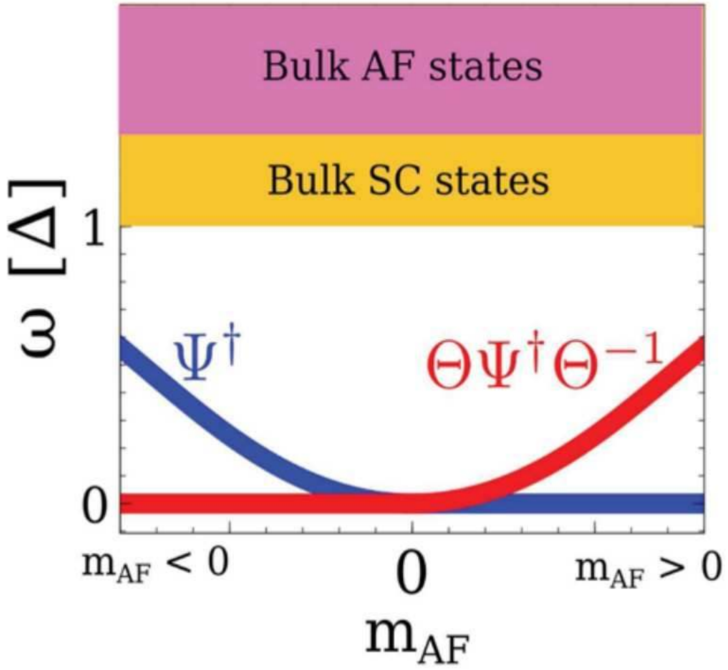
How are these modes connected to the many-body in-gap mode from before?

From many-body to the single-particle symmetry broken state

$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{SC}} + \mathcal{H}_{\text{AF}} + \mathcal{H}_{\text{int}}$$



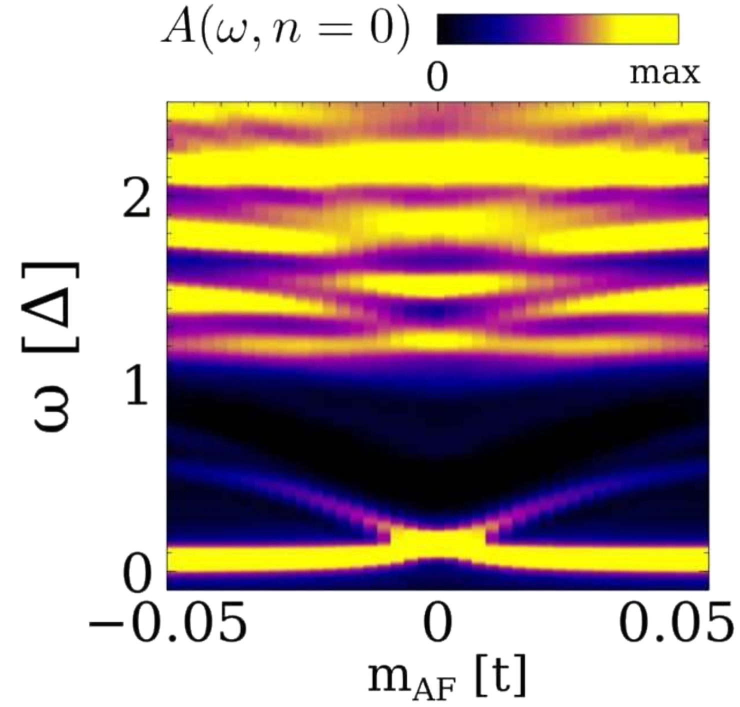
Sketch of the charge excitations



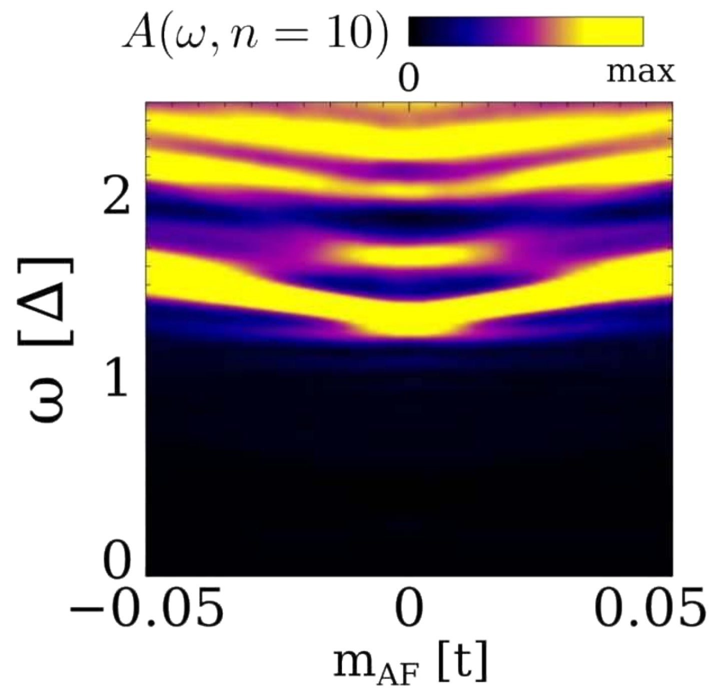
Switching on a magnetization pushes the interacting model to the symmetry broken state

From many-body to symmetry broken

Interface

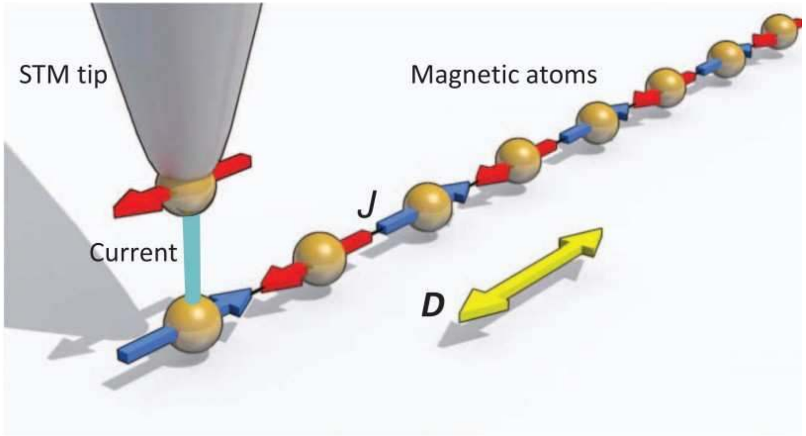


Antiferromagnet

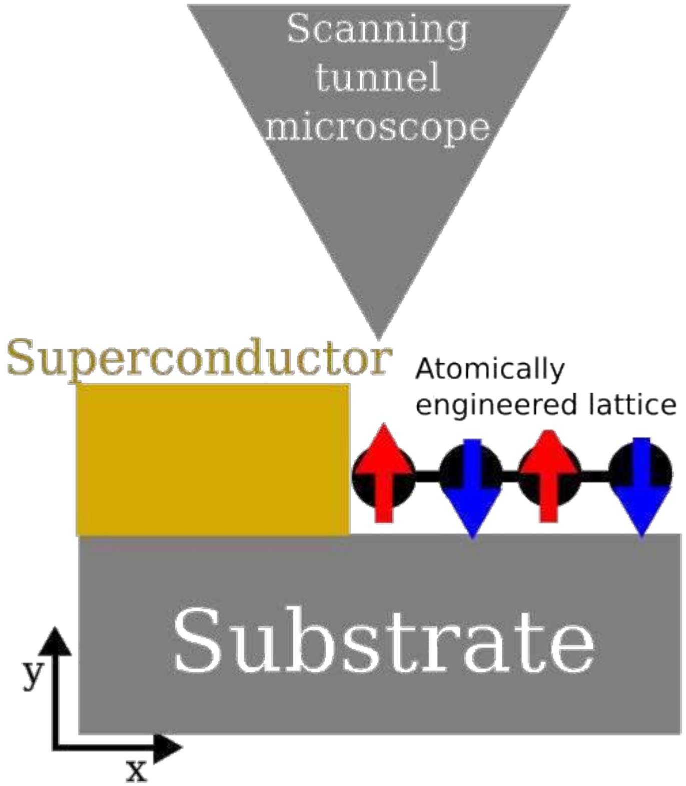


The solitonic single-particle mode transforms into the many-body in-gap mode

Experimental realization with atomically engineered lattices

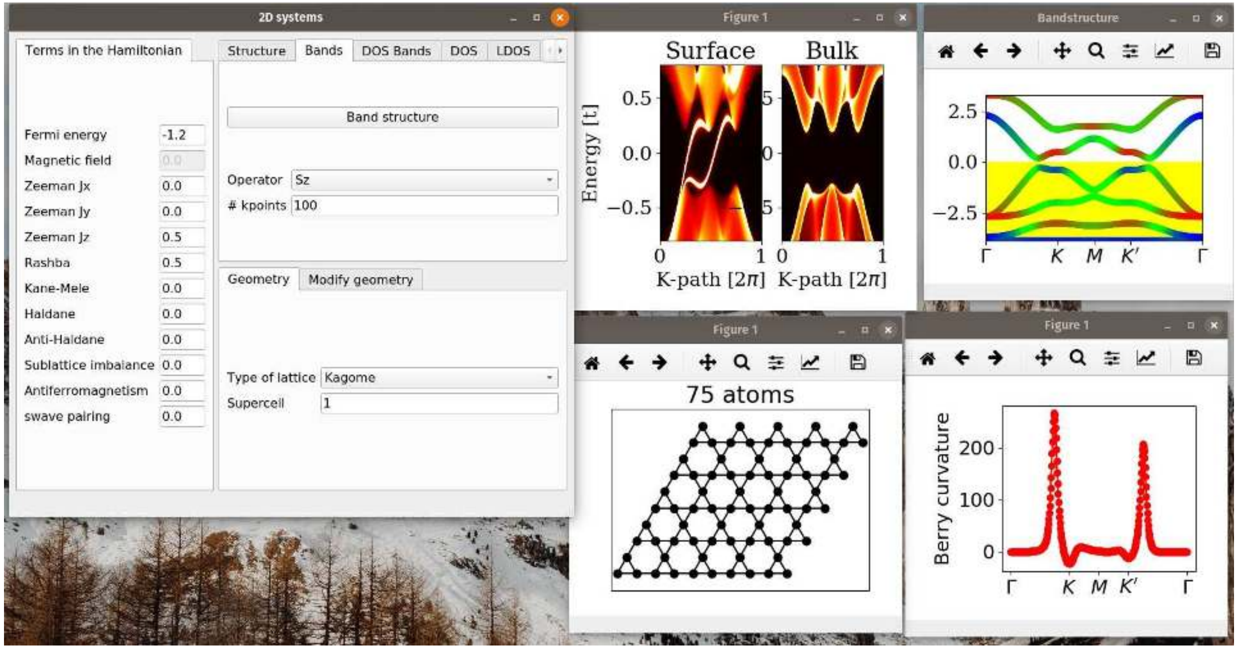


Science 335.6065 (2012): 196-199
Nature Physics 12, 656–660 (2016)
Rev. Mod. Phys. 91, 041001 (2019)



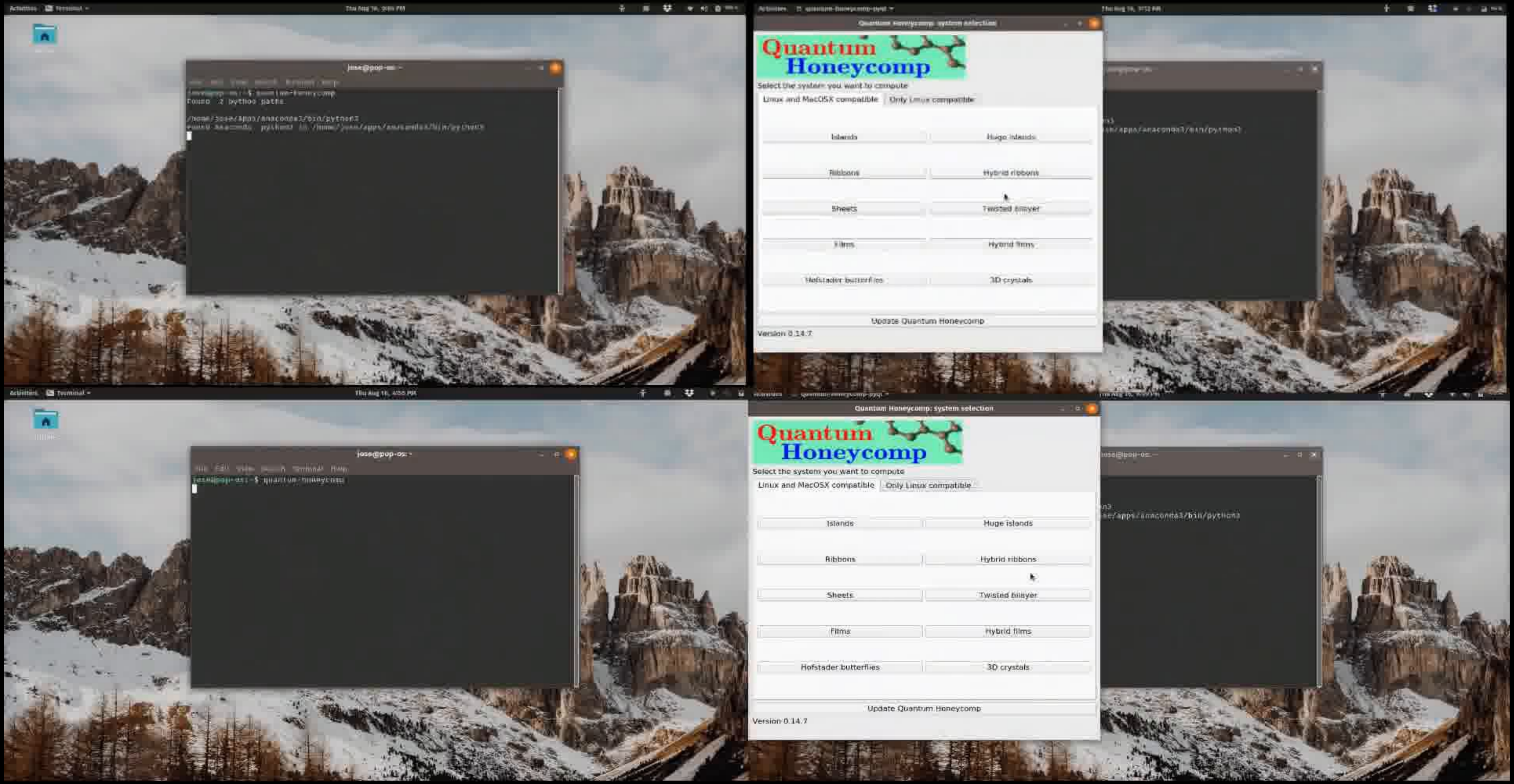
Computing electronic properties

A user interface to compute electronic properties



Quantum Honeycomp: open source interactive interface for tight binding modeling

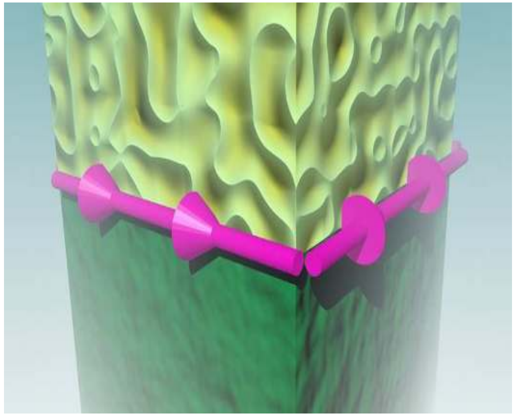
https://github.com/joselado/quantum-honeycomp



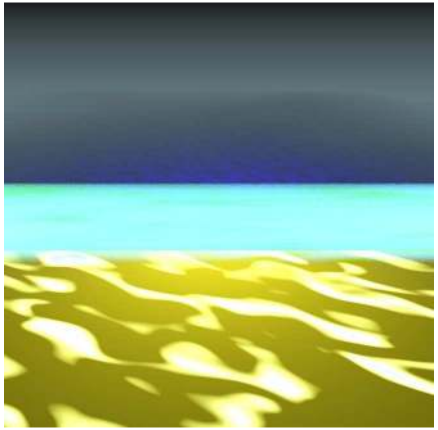
jose@pop-os: ~
jose@pop-os:~$ quantum-honeycomp
Quantum Honeycomp: system selection
Quantum
Honeycomp
Select the system you want to compute
Linux and MacOSX compatible
Only Linux compatible
Islands
Huge Islands
Ribbons
Hybrid ribbons
Sheets
Twisted bilayer
Films
Hybrid films
Hofstader butterflies
3D crystals
Update Quantum Honeycomp
Version 0.14.7

Take home

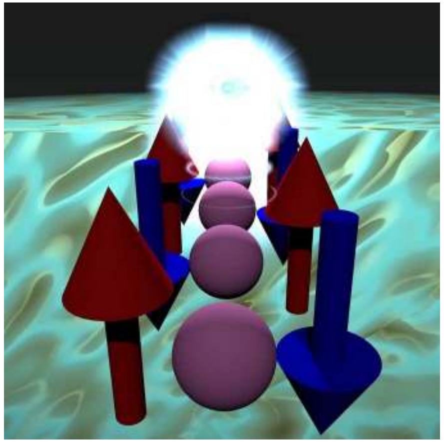
Antiferromagnet-superconductor junctions provide a powerful platform to engineer solitons, unconventional superconductors and robust many-body excitations.



Phys. Rev. Lett. 121, 037002 (2018)



Phys. Rev. Research 3, L012021 (2021)



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Thank you!