Solitons and topological superconductivity in antiferromagnet-superconductor interfaces

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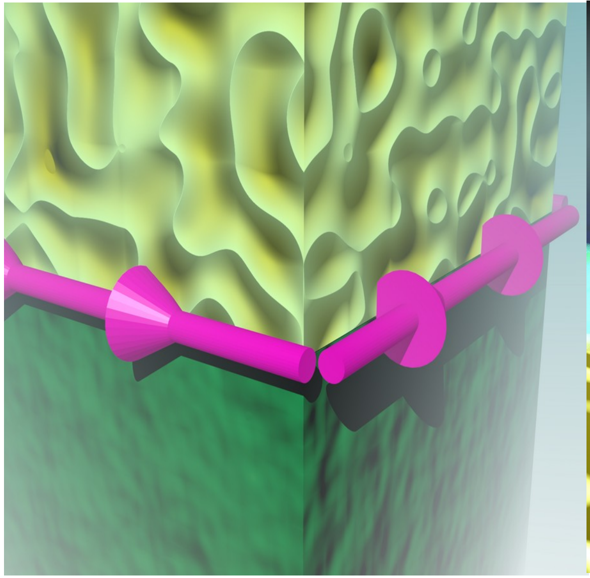
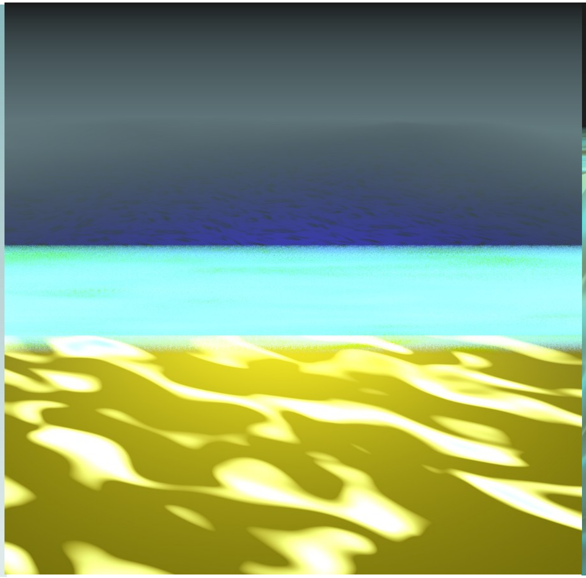
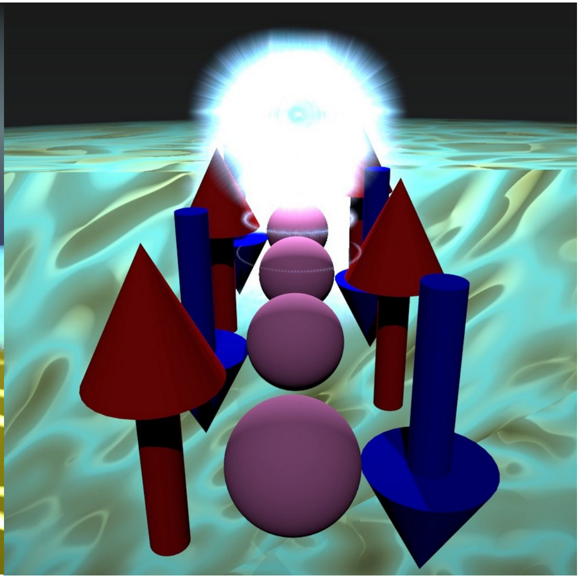


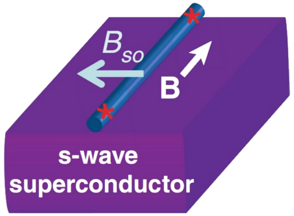




Coherent order and transport in spin-active systems: Interplay between magnetism and superconductivity, SPICE, November 17th 2020

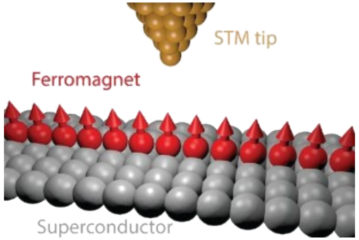
Platforms for Majorana physics

Semiconductors



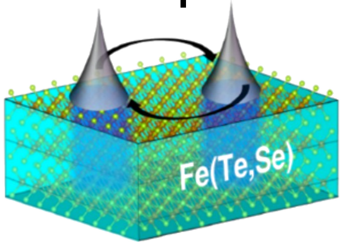
Science 336.6084 (2012): 1003-1007

Ferromagnetic atomic chains



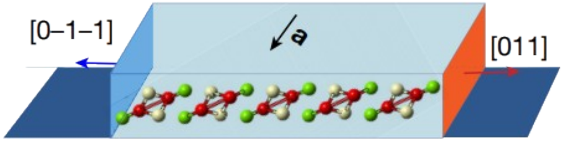
Science 346.6209 (2014): 602-607

Fe-based superconductors



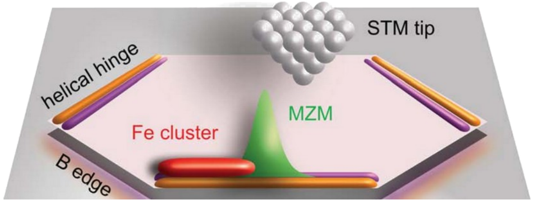
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



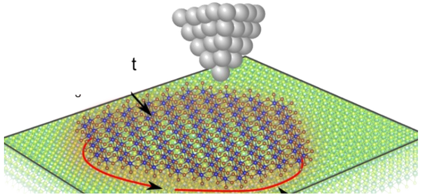
Nature 579, 523–527 (2020)

Topological insulators



Science 364.6447 (2019): 1255-1259

Two-dimensional materials



arXiv:2002.02141 (2020)

New materials open new venues for engineering and controlling Majorana physics

Topological superconductivity with antiferromagnetic insulators

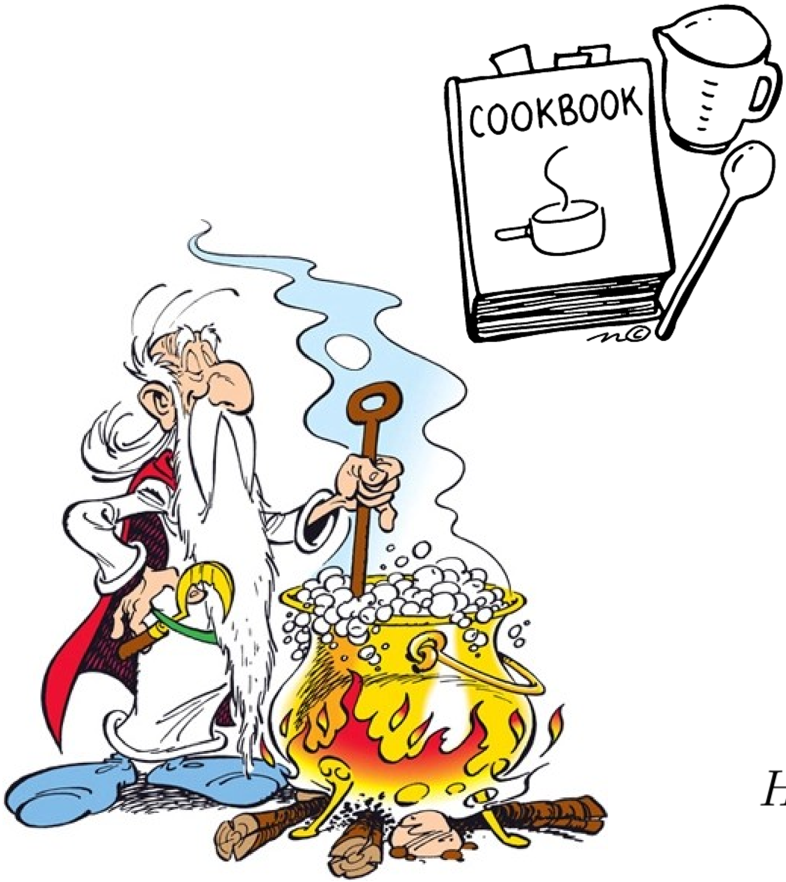
Build a topological superconductor with

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

The prize

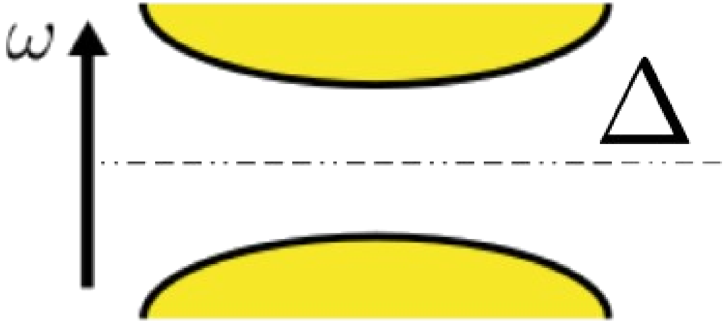
<u>Bringing a new solid state platform to realize artificial topological superconductors</u>

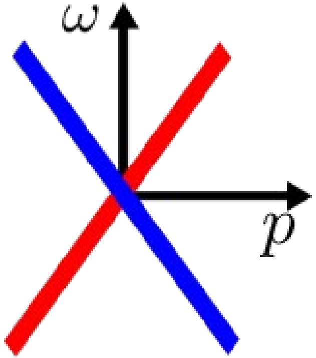
How to build your own topological superconductor



Ingredients

- s-wave pairing
- Helical states





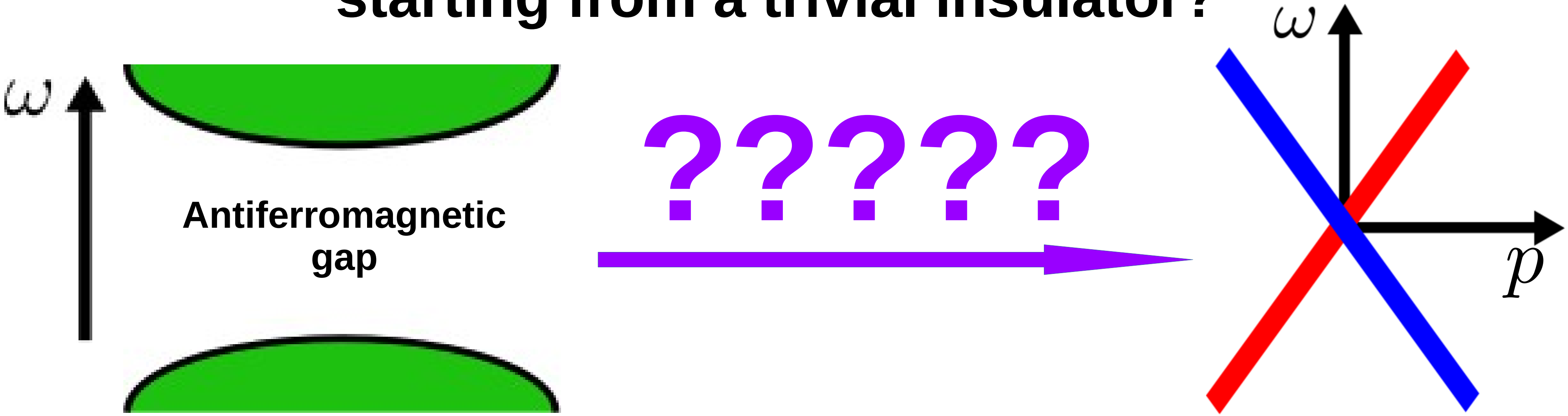
Objective: to realize a spinless superconductor

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

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

The initial problem

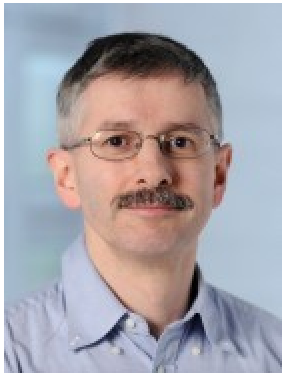
How can we get a topological phase starting from a trivial insulator?



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

Behind the scenes

Manfred Sigrist



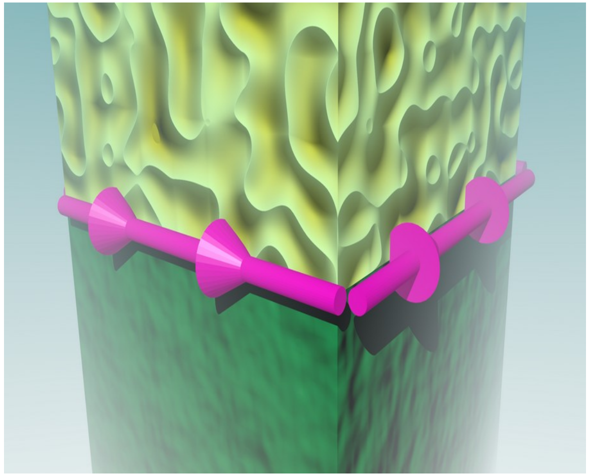
Senna Luntama

Päivi Törmä

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

arXiv:2011.06990 (2020)

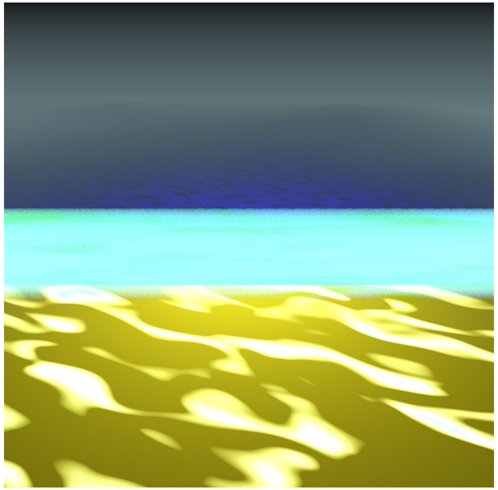
Today's story



Topological superconductivity (TS) in 3D AF insulators

No interactions

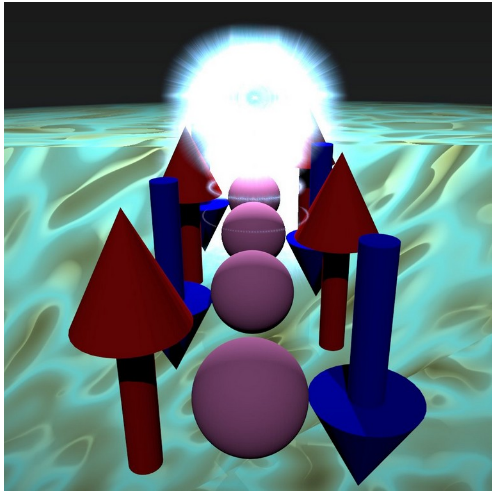
Phys. Rev. Lett. 121, 037002 (2018)



Interaction-induced TS in 2D AF insulators

Mean-field interactions

arXiv:2011.06990 (2020)



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

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

Kinetic energy

Antiferromagnetism

Superconductivity

Spin-orbit coupling

Solitonic modes between Dirac AF and SC

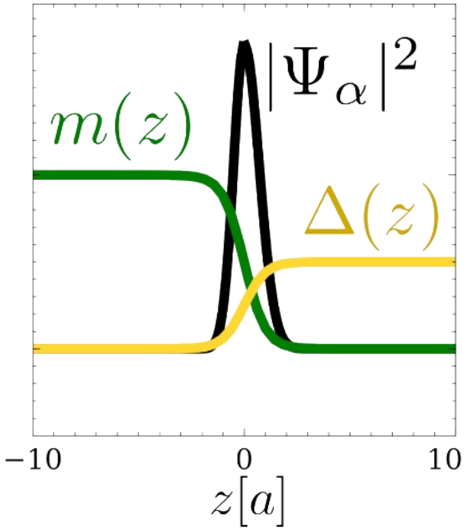
Total Hamiltonia, <u>for an antiferromagnet with gaped Dirac points</u>

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

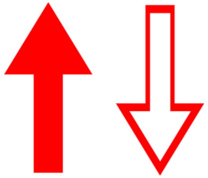
There will be two zero solutions $\mathcal{H}|\Psi_\alpha\rangle = 0$

Phys. Rev. X 5, 041042 (2015)

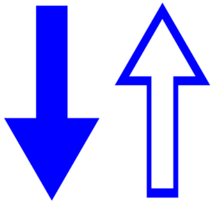
similar to a Jackiw-Rebbi soliton
Phys. Rev. D 13, 3398 (1976)



Sector #1
Up electron, down hole

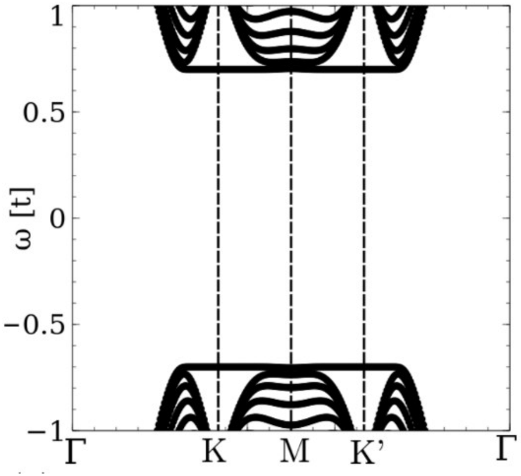


Sector #2
Down electron, up hole

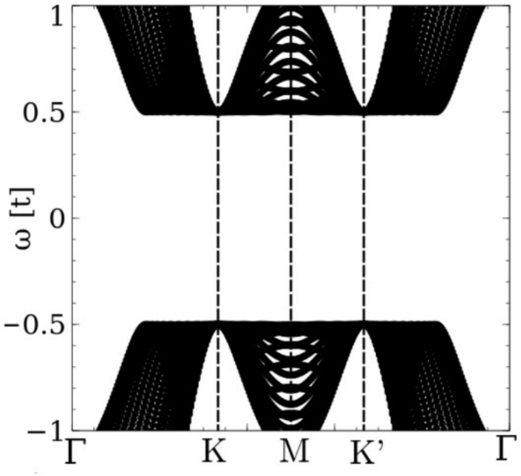


Emergence of interfacial modes, no spin-orbit coupling

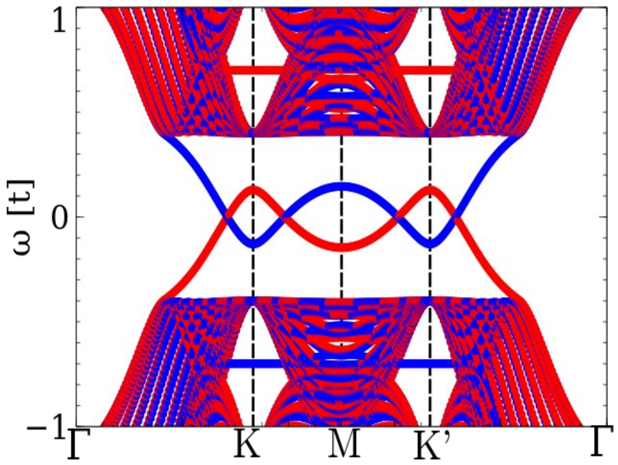
Antiferromagnet



Superconductor



AF/SC heterostructure



AF

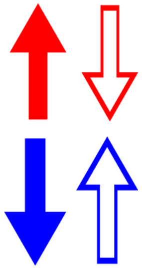
SC

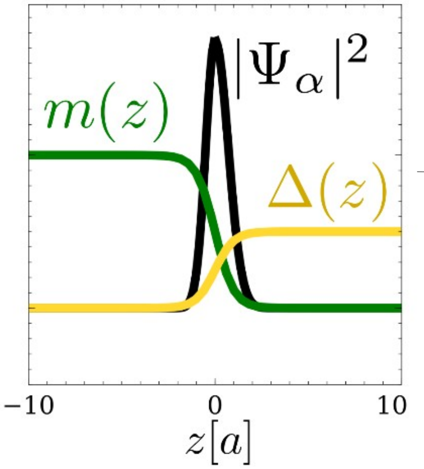
AF SC

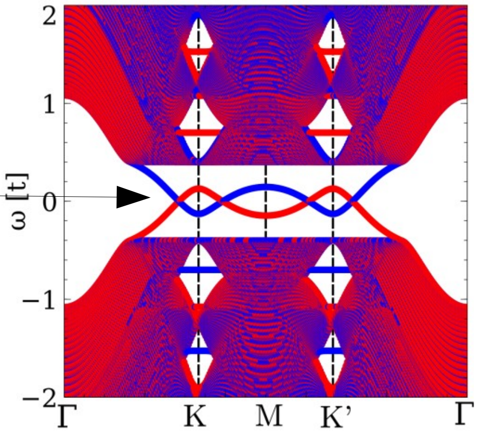
Interface states between AF and SC

Superconducting solitonic excitations

$$\Psi_1(z) = g(z)[c_{A,\vec{k}_\parallel,\uparrow} - ic_{B,\vec{k}_\parallel,\uparrow} - c^\dagger_{A,-\vec{k}_\parallel,\downarrow} - ic^\dagger_{B,-\vec{k}_\parallel,\downarrow}]$$
$$\Psi_2(z) = g(z)[c_{A,\vec{k}_\parallel,\downarrow} + ic_{B,\vec{k}_\parallel,\downarrow} - c^\dagger_{A,-\vec{k}_\parallel,\uparrow} + ic^\dagger_{B,-\vec{k}_\parallel,\uparrow}]$$

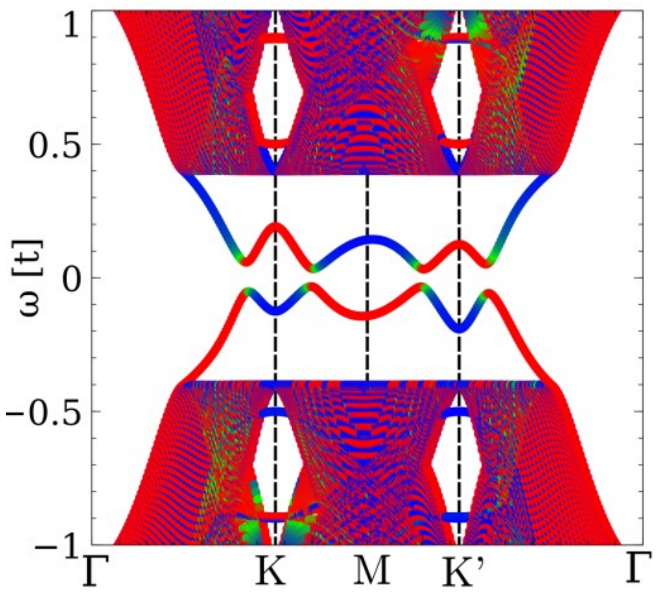




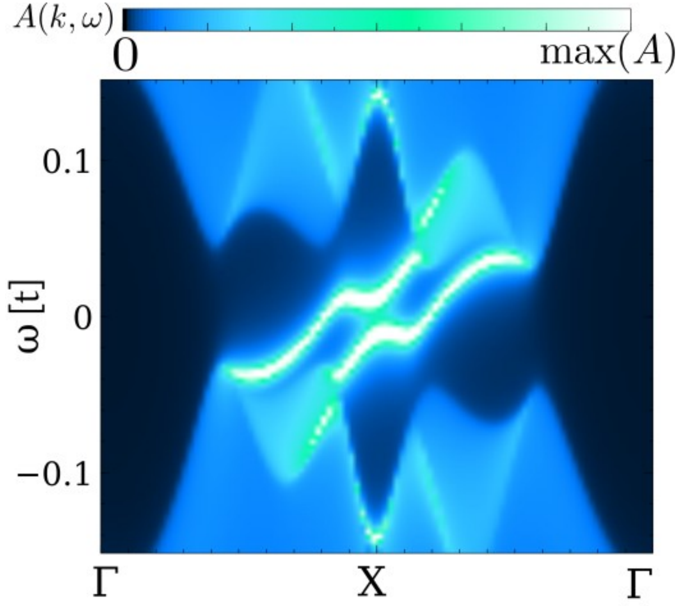


Topological superconductivity with spin-orbit coupling

Band structure

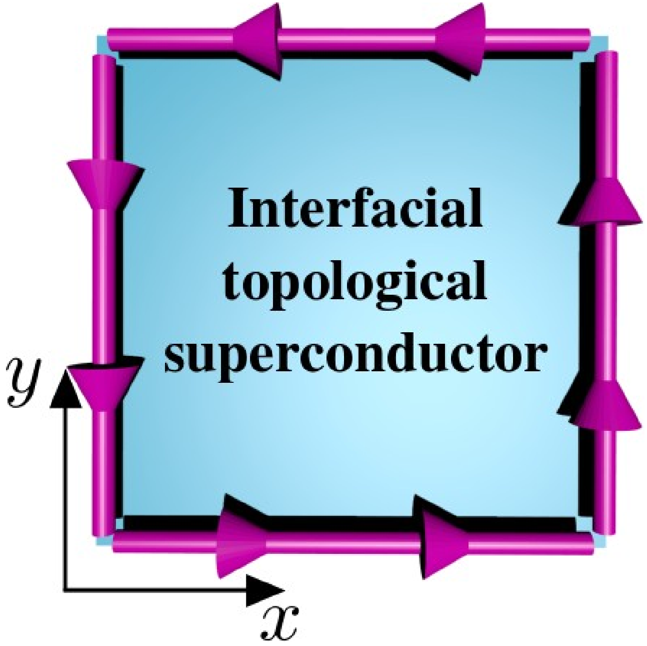


Edge spectral function

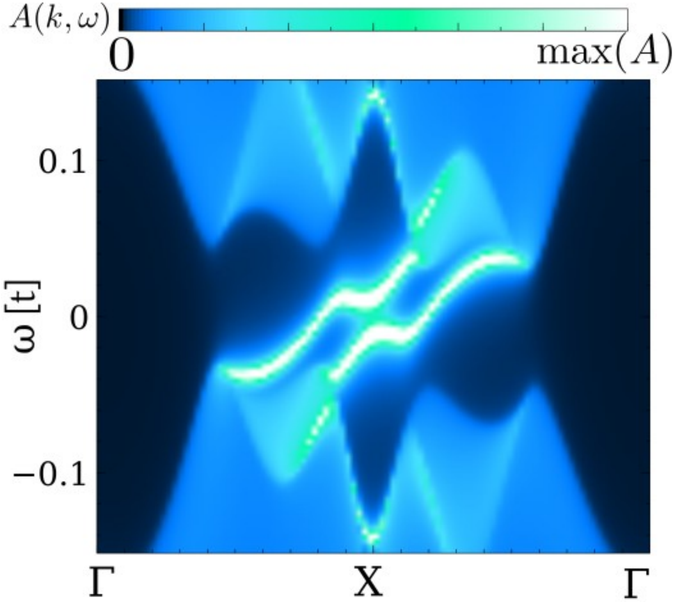


Topological superconductivity showing gapless Majorana modes

Adding spin-orbit coupling



Edge spectral function



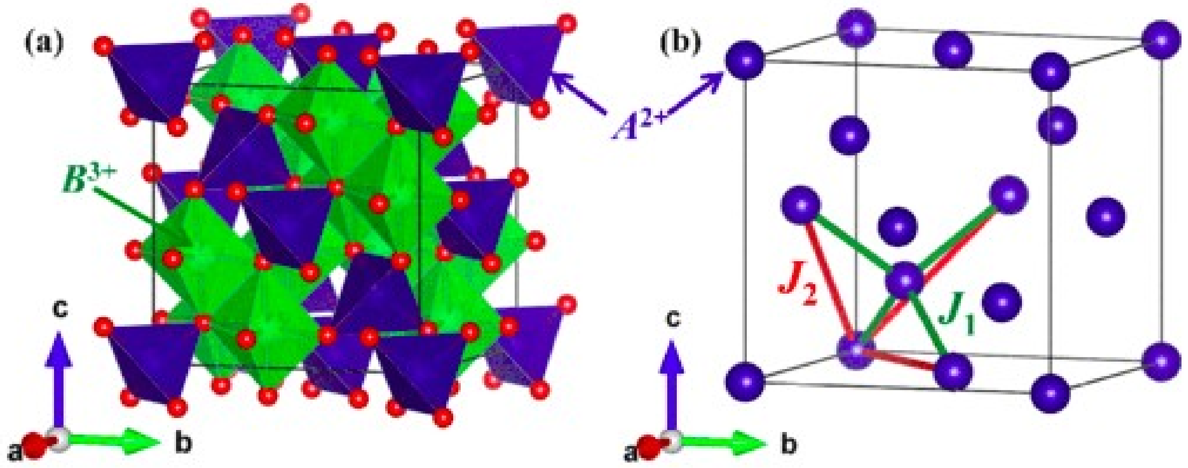
The interface realizes a topological superconductor

3D AF material candidates, spinels

Antiferromagnet forming a diamond lattice

Antiferromagnetic spinels

$CoAl_2O_4$

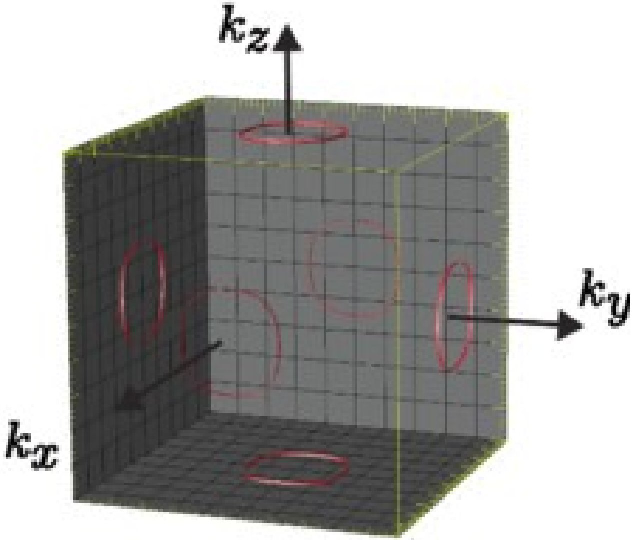


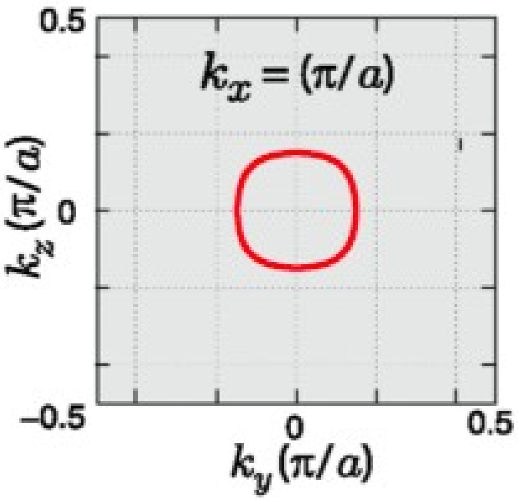
Co atoms form a diamond lattice

Phys. Rev. B 95, 094404 (2017)

3D AF material candidates, Dirac materials

Dirac lines in the absence of spin-orbit coupling and magnetism



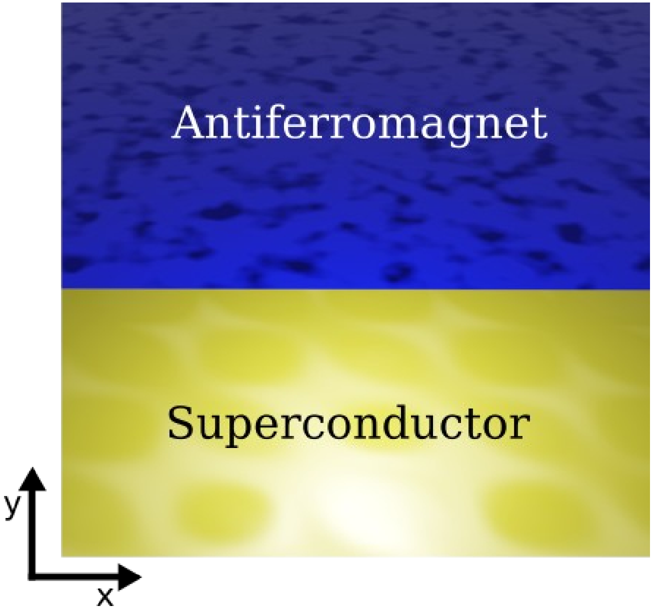


Phys. Rev. Lett. 115, 036806 (2015)

Antiferromagnets whose paramagnetic state hosts Dirac lines

Interaction-induced 1D topological superconductivity in 2D antiferromagnets

Topological superconductivity driven by interactions



We will focus on a heterostructure between a 2D superconductor and a 2D superconductor

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

Kinetic energy

Antiferromagnetism

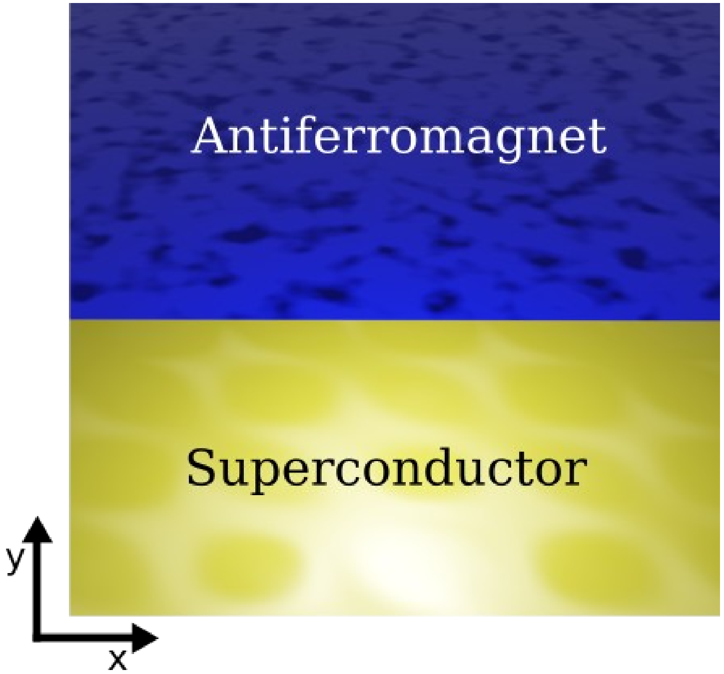
Superconductivity

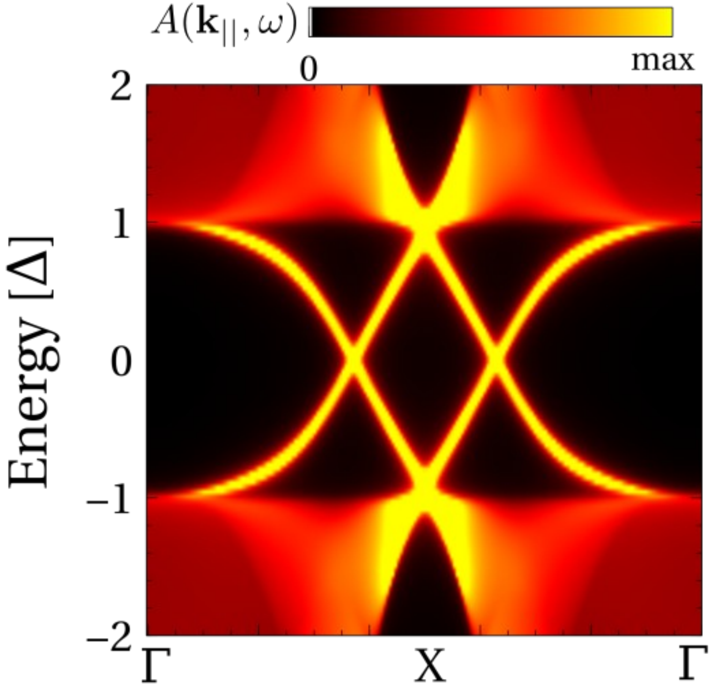
Repulsive interactions

Can we get topological superconductivity just driven by repulsive electronic interactions?

Interface AF-SC modes

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

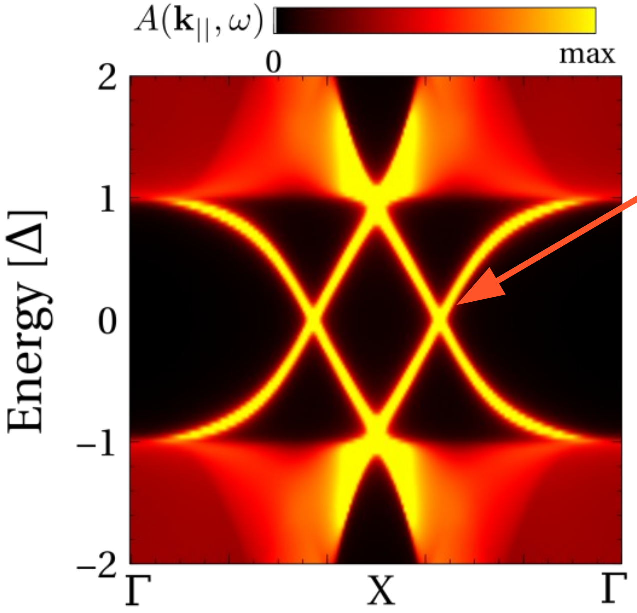




Gapless zero modes appear at the one-dimensional AF-SC interface

Interactions in the model

What happens when we now include interactions in whole system?



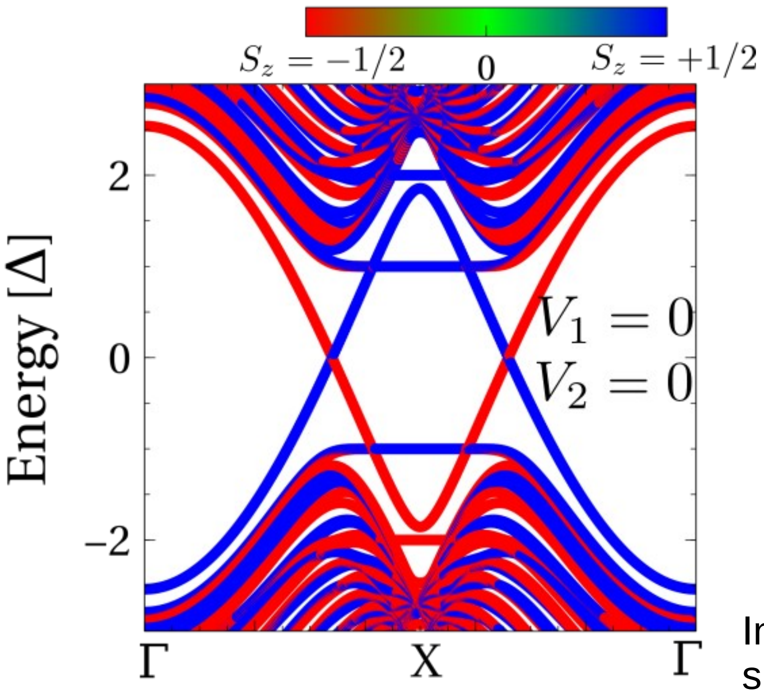
Could there be an interaction-induced gap opening of the interface modes?

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

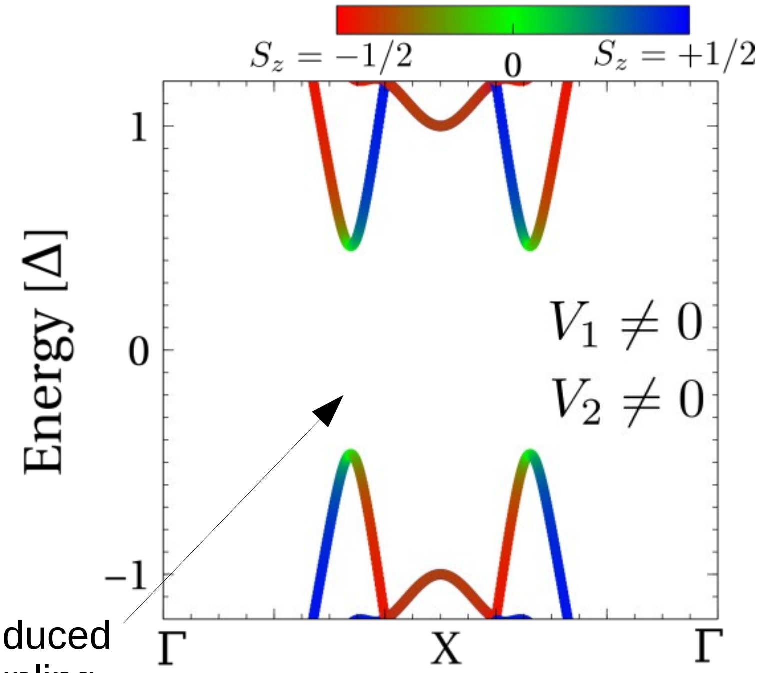
We will solve a model with repulsive long-range interactions at the mean-field level

Impact of interactions

Without interactions



With interactions

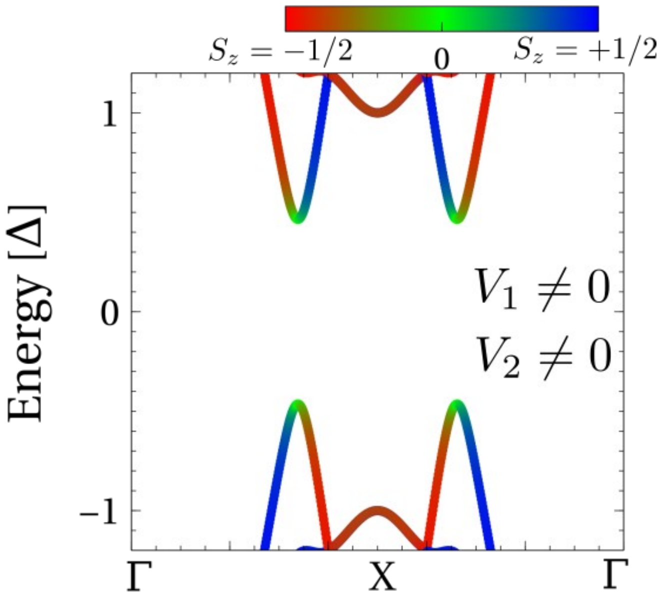


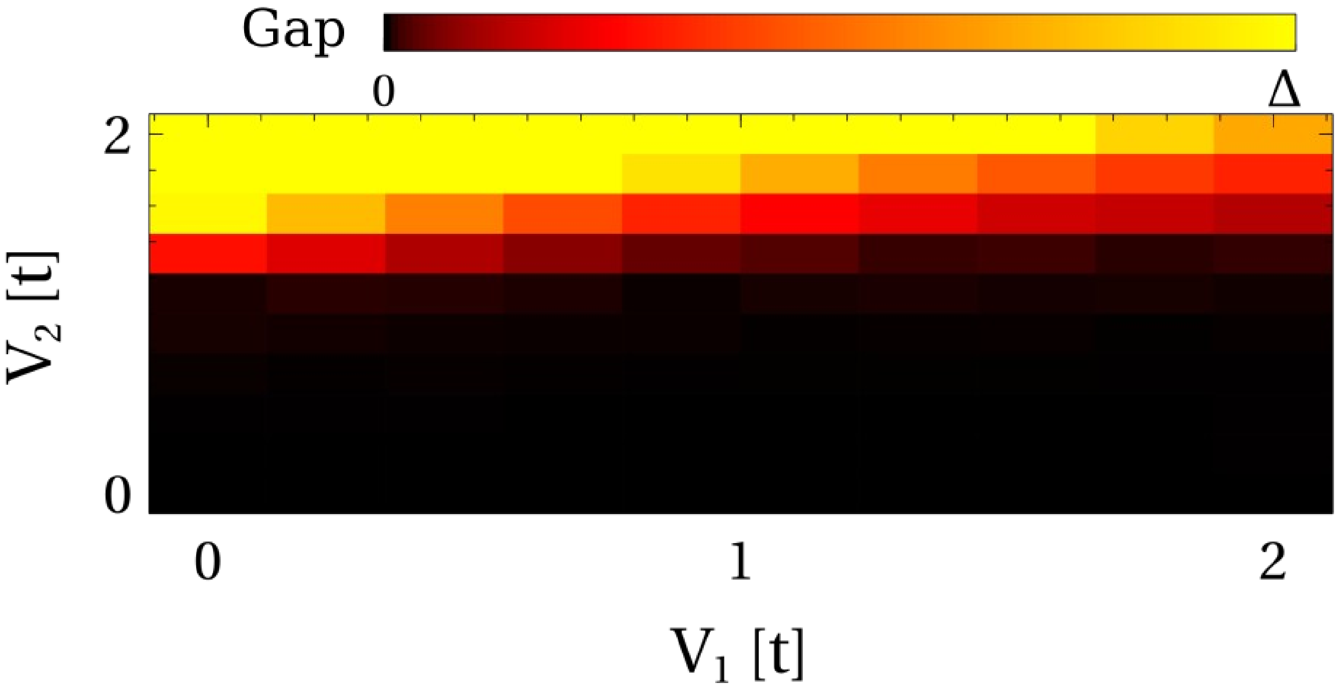
Interaction-induced
spin-orbit coupling

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

Interaction-induced gap VS interaction strength

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

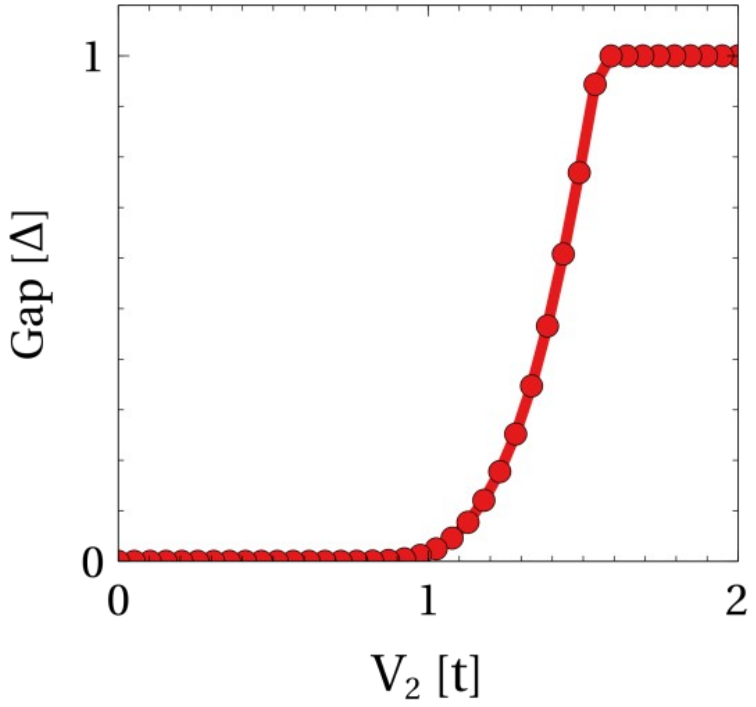


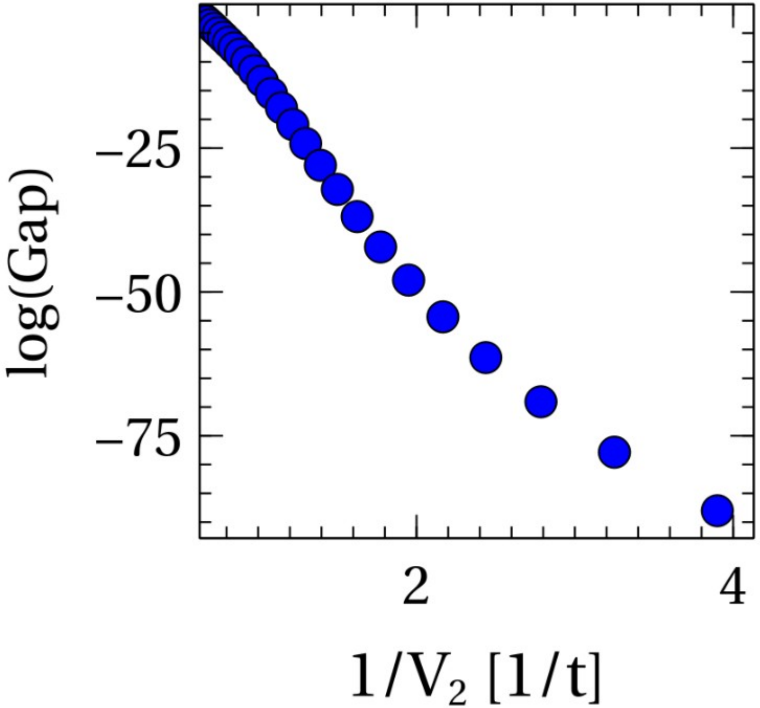


The interaction-induced gap saturates to Δ, the gap of the s-wave superconductor

Topological superconductivity without a critical interaction

Topological gap VS interaction strength

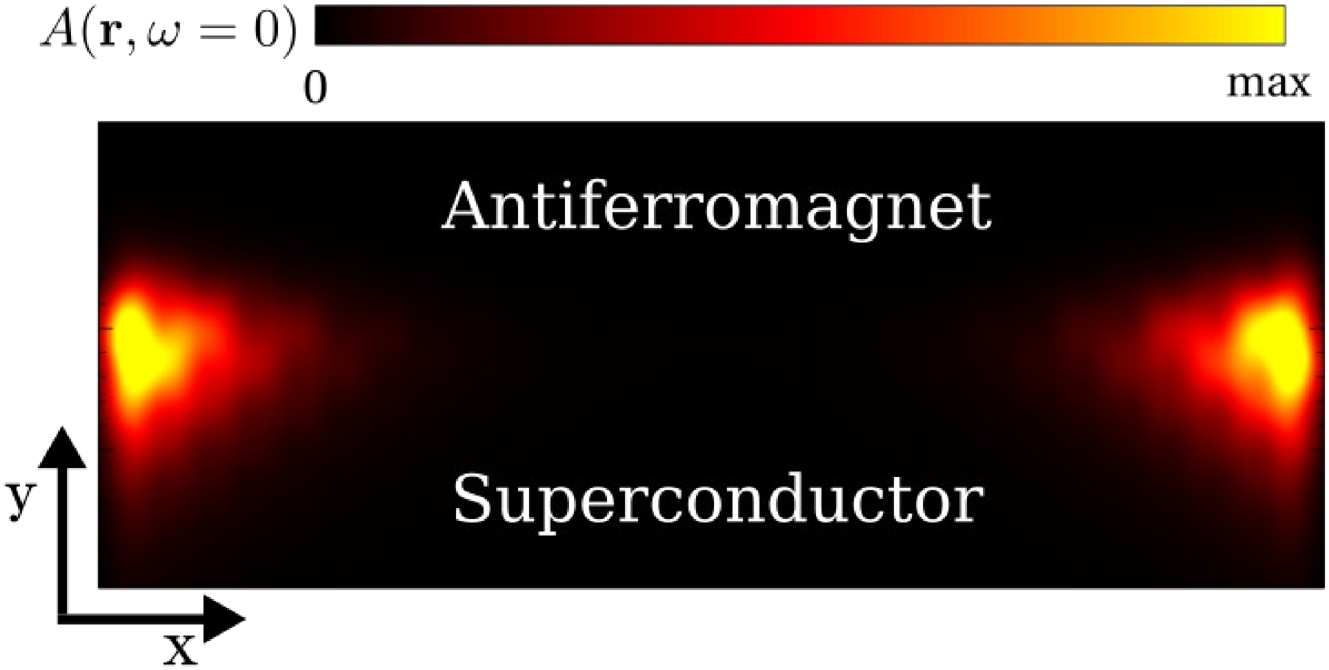




A topological gap opens up for arbitrarily small interactions

Majorana zero modes

Spectral function at zero energy, featuring Majorana edge modes



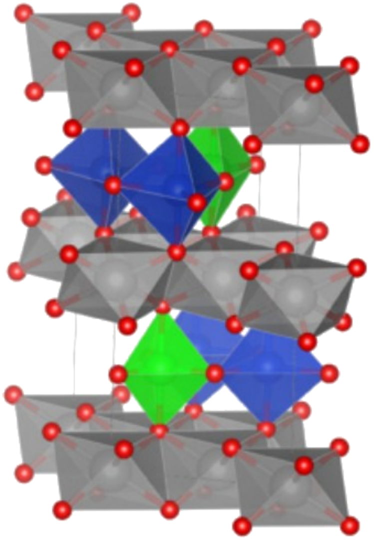
Majorana zero modes emerge at the edge due to electronic interactions

AF material candidates

Antiferromagnetic honeycomb oxides

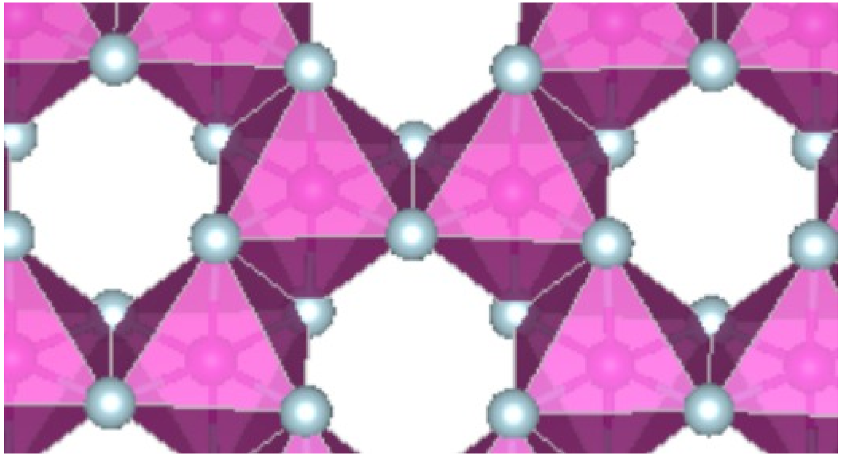
$InCu_{2/3}V_{1/3}O_3$ *Phys. Rev. B 78, 024420 (2008)*

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)

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

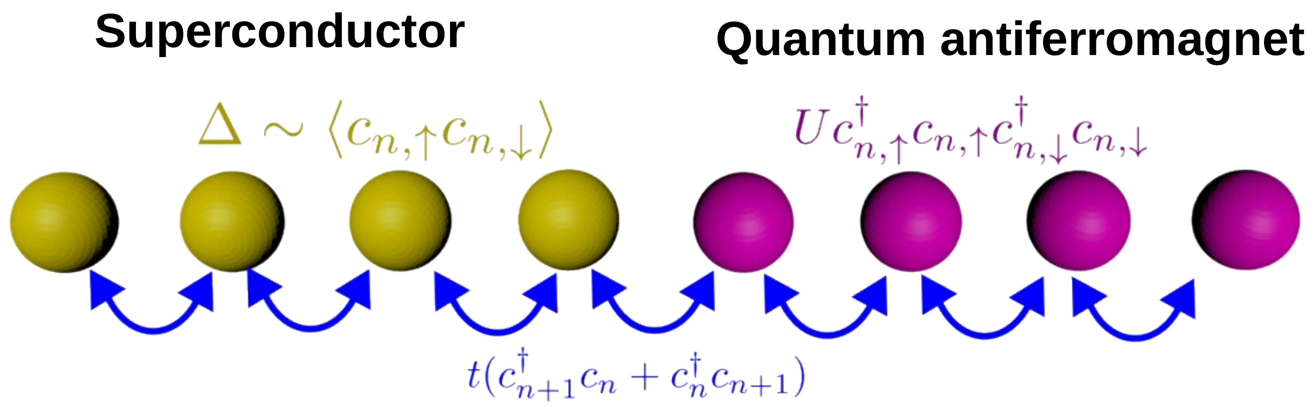
Quantum antiferromagnet (many-body solution)

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

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

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

Superconductor-quantum antiferromagnet junction



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

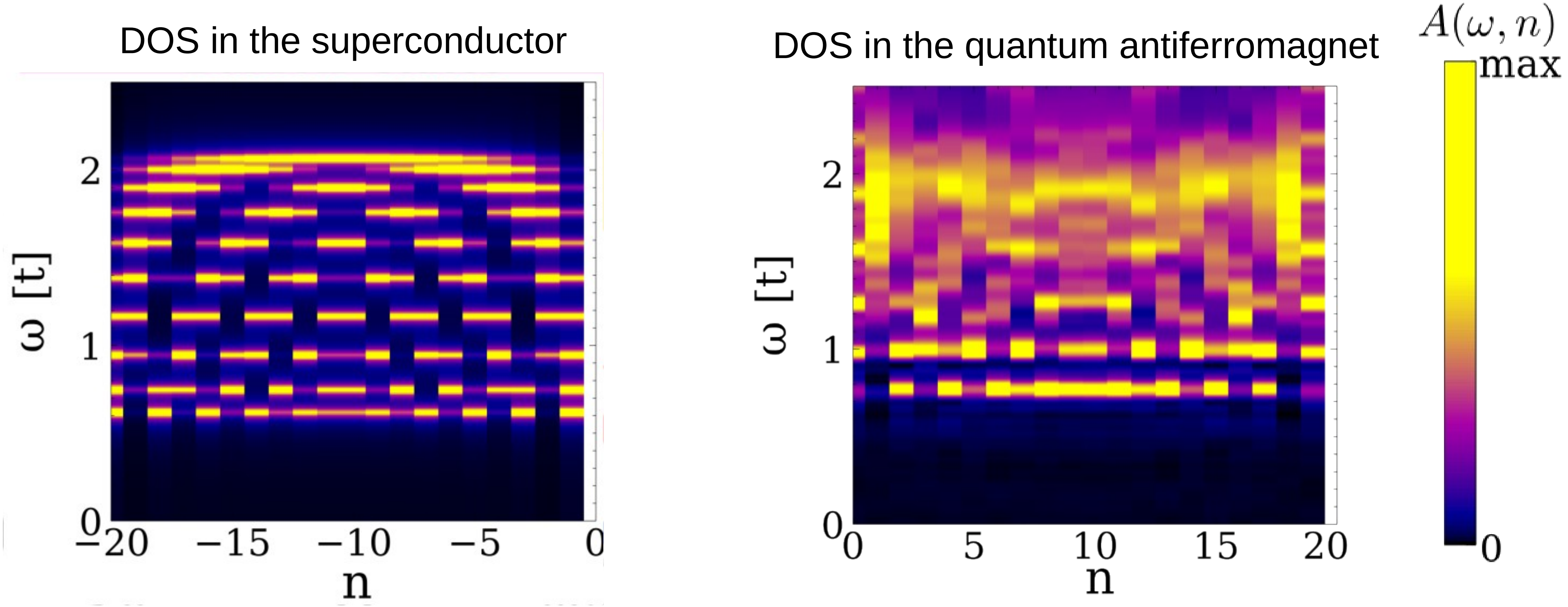
We will solve the interacting model exactly using the tensor network formalism

The ground state does not break time-reversal symmetry

Many-body spectral function

DOS in the superconductor

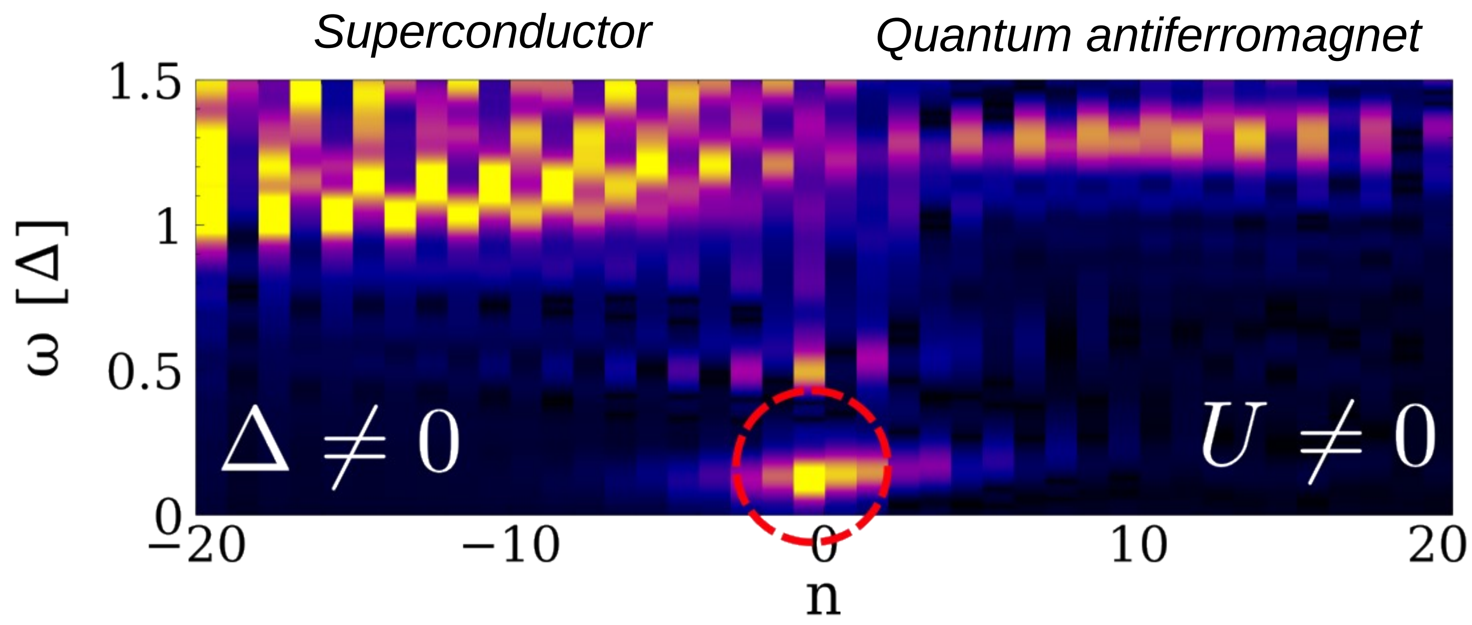
DOS in the quantum antiferromagnet



Both systems show an electronic gap when decoupled

In-gap modes at the SC-quantum AF interface

Superconductor-quantum antiferromagnet junction

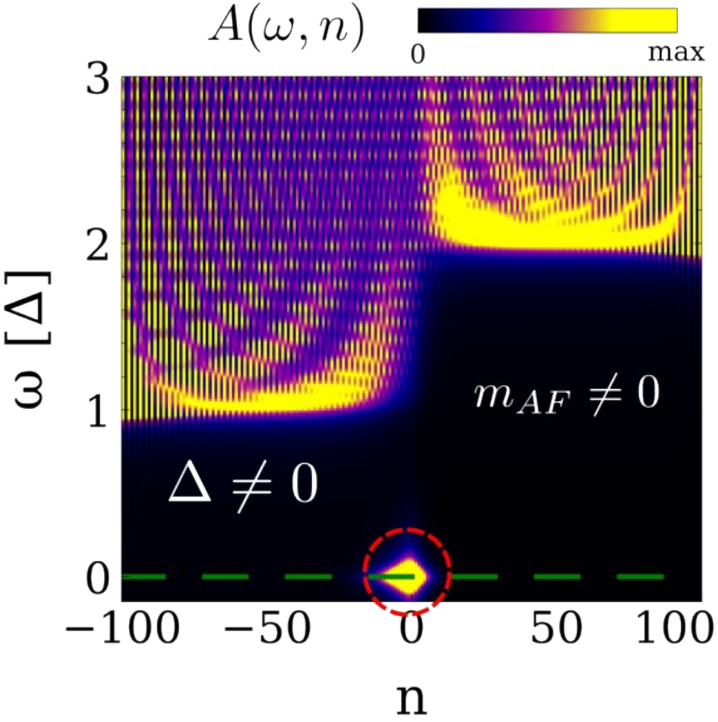


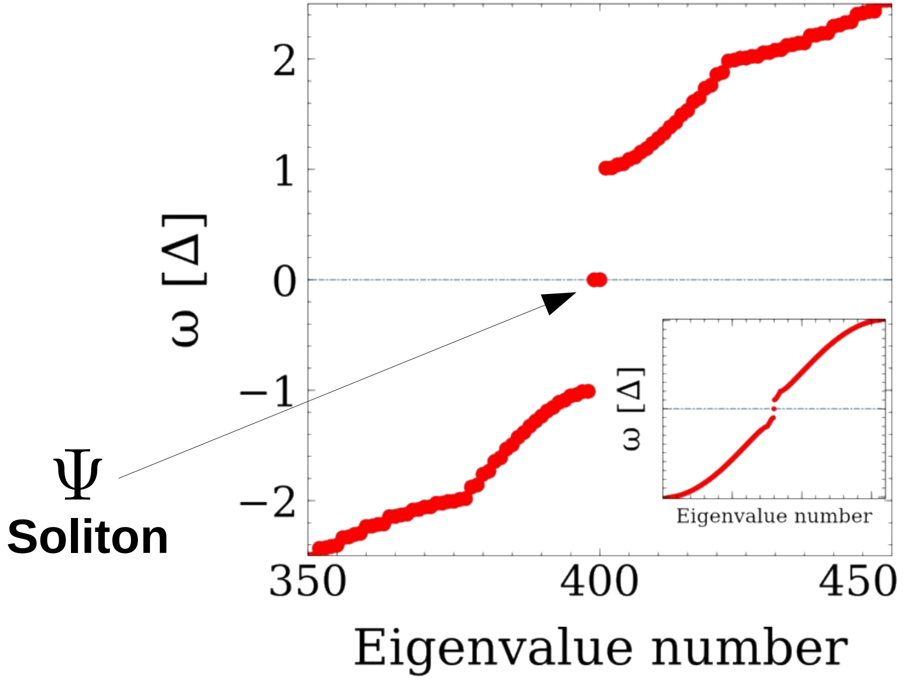
Solitonic in-gap modes appear between the superconductor and the quantum antiferromagnet

Back to single-particle solitonic zero modes

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

Single particle limit (stagger magnetization and no interactions)

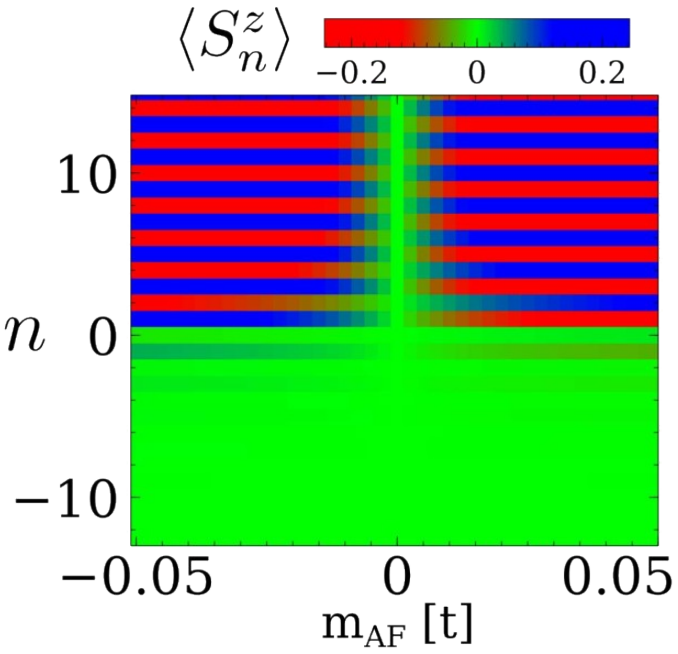




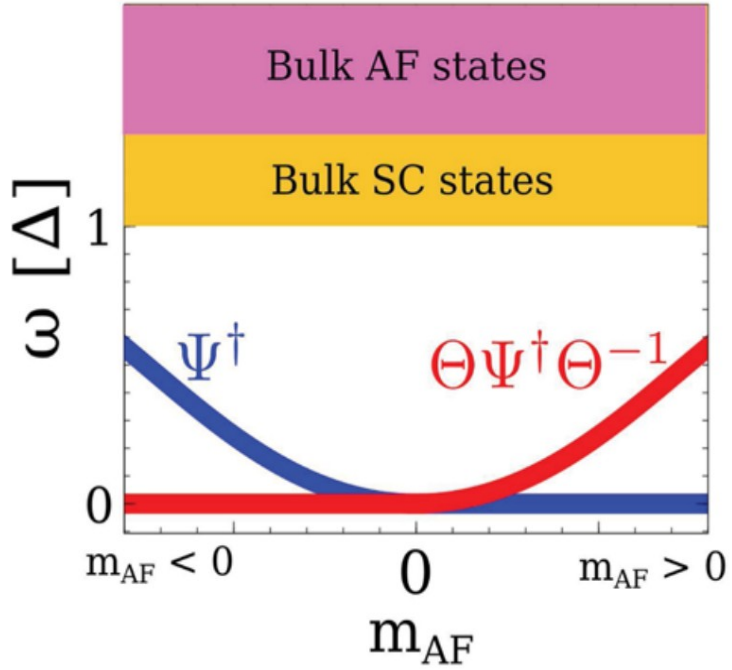
How are these modes connected to the many-body in-gap mode from before?

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

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



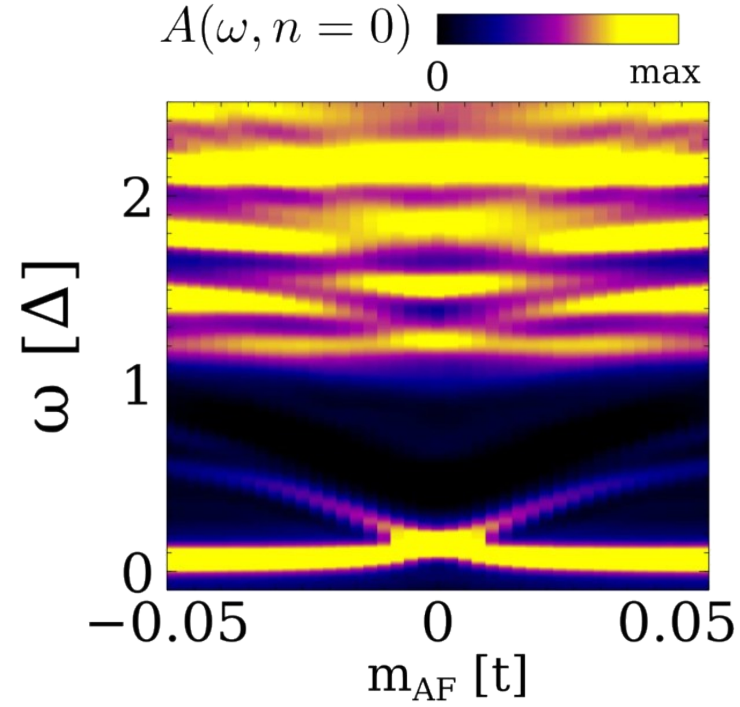
Sketch of the charge excitations



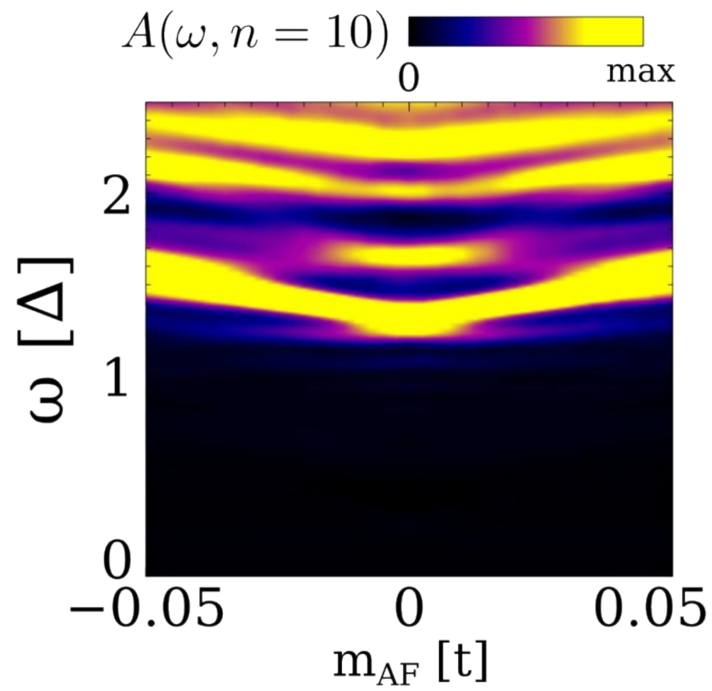
Switching on a magnetization pushes the interacting model to the symmetry broken state

From many-body to symmetry broken

Interface

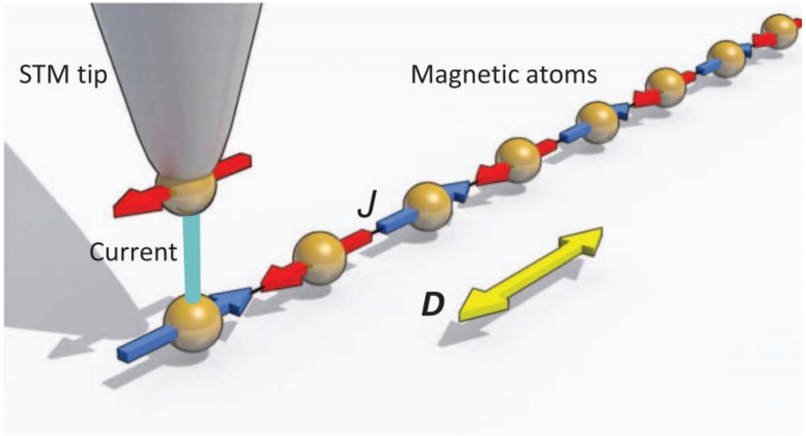


Antiferromagnet

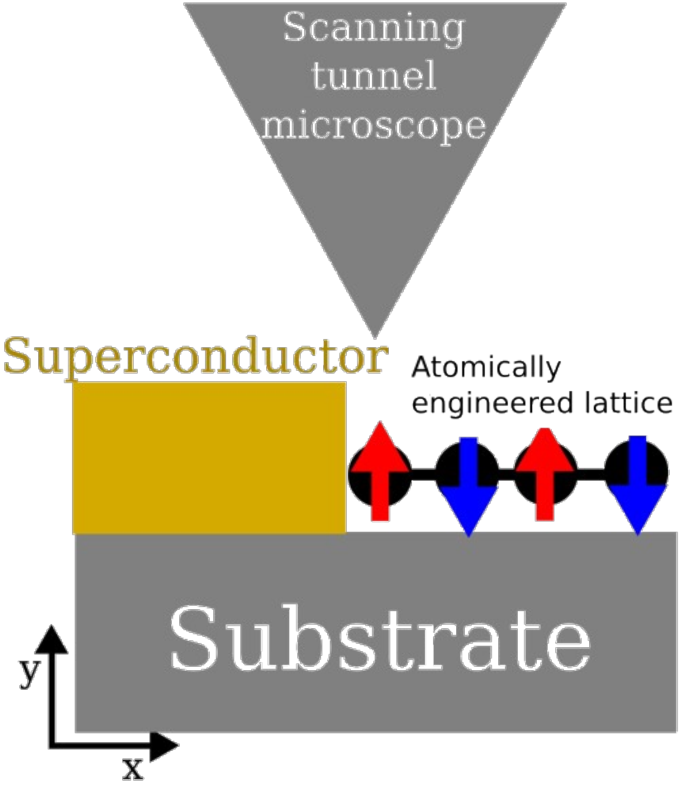


The solitonic single-particle mode transforms into the many-body in-gap mode

Experimental realization with atomically engineered lattices

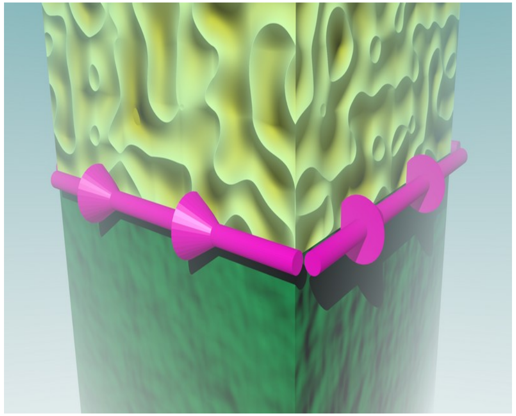


Science 335.6065 (2012): 196-199
Nature Physics 12, 656–660 (2016)
Rev. Mod. Phys. 91, 041001 (2019)

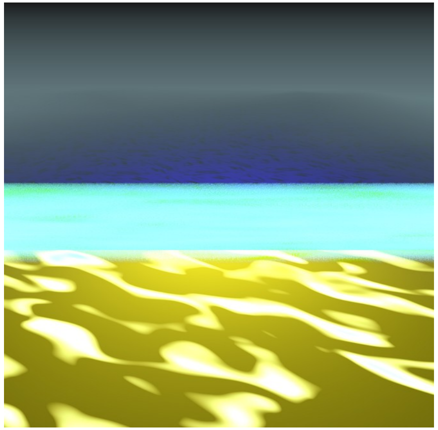


Take home

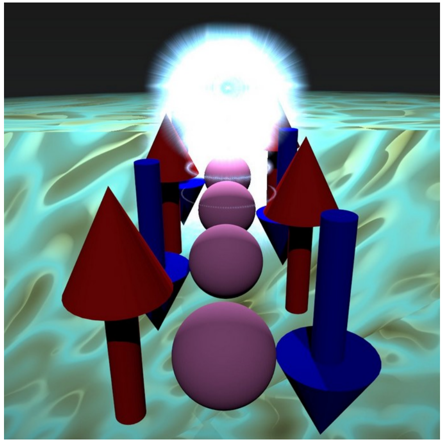
Antiferromagnet-superconductor junctions provide a powerful platform to engineer solitons, unconventional superconductors and robust many-body excitations.



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



arXiv:2011.06990 (2020)



Phys. Rev. Research 2, 023347 (2020)

Thank you!

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