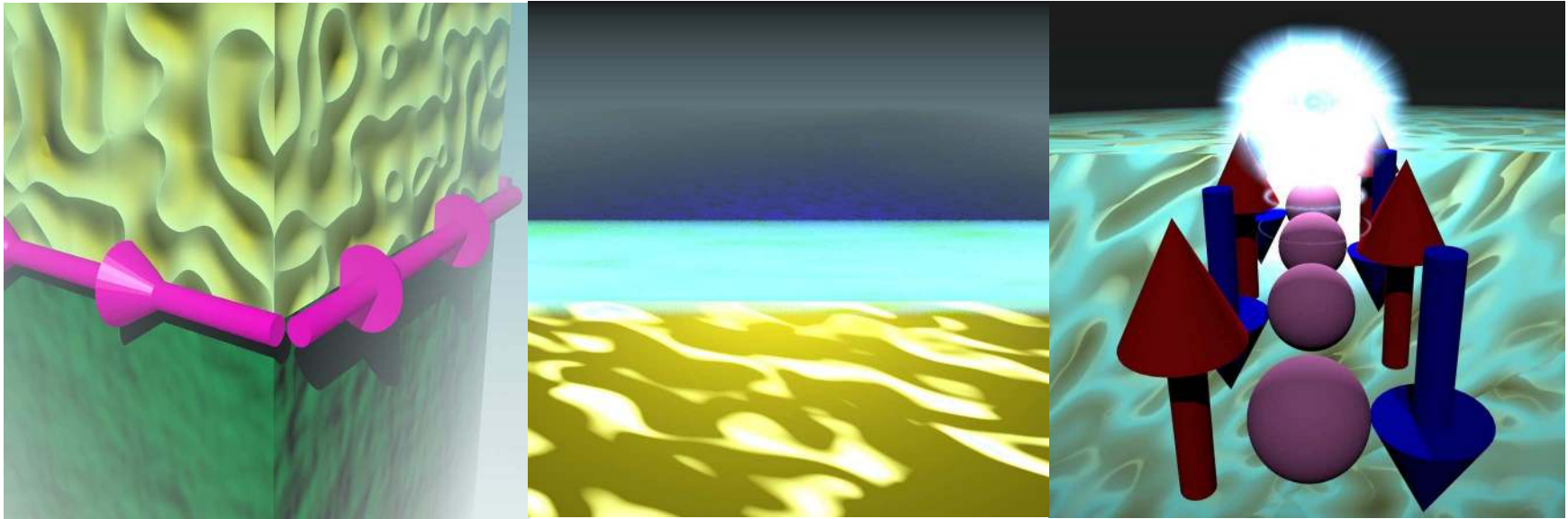


Solitons and topological superconductivity in antiferromagnet-superconductor interfaces

Jose Lado

Department of Applied Physics, Aalto University, Finland



Niels Bohr Institute, Denmark, Condensed Matter Seminar Series, February 5th 2021

Complexity, universality and emergence

Medicine

Biology

Biochemistry

Chemistry

Physics

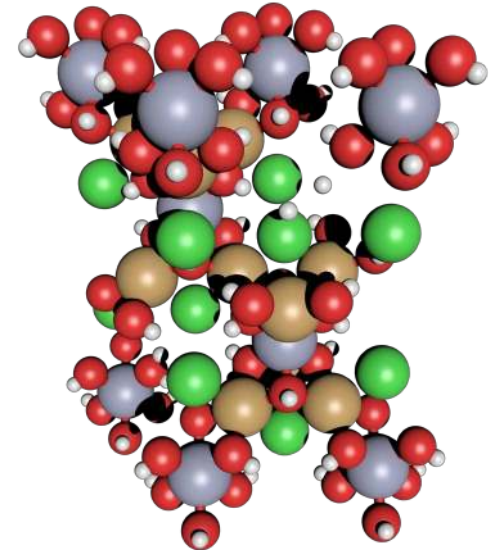
Complexity

Fish schools



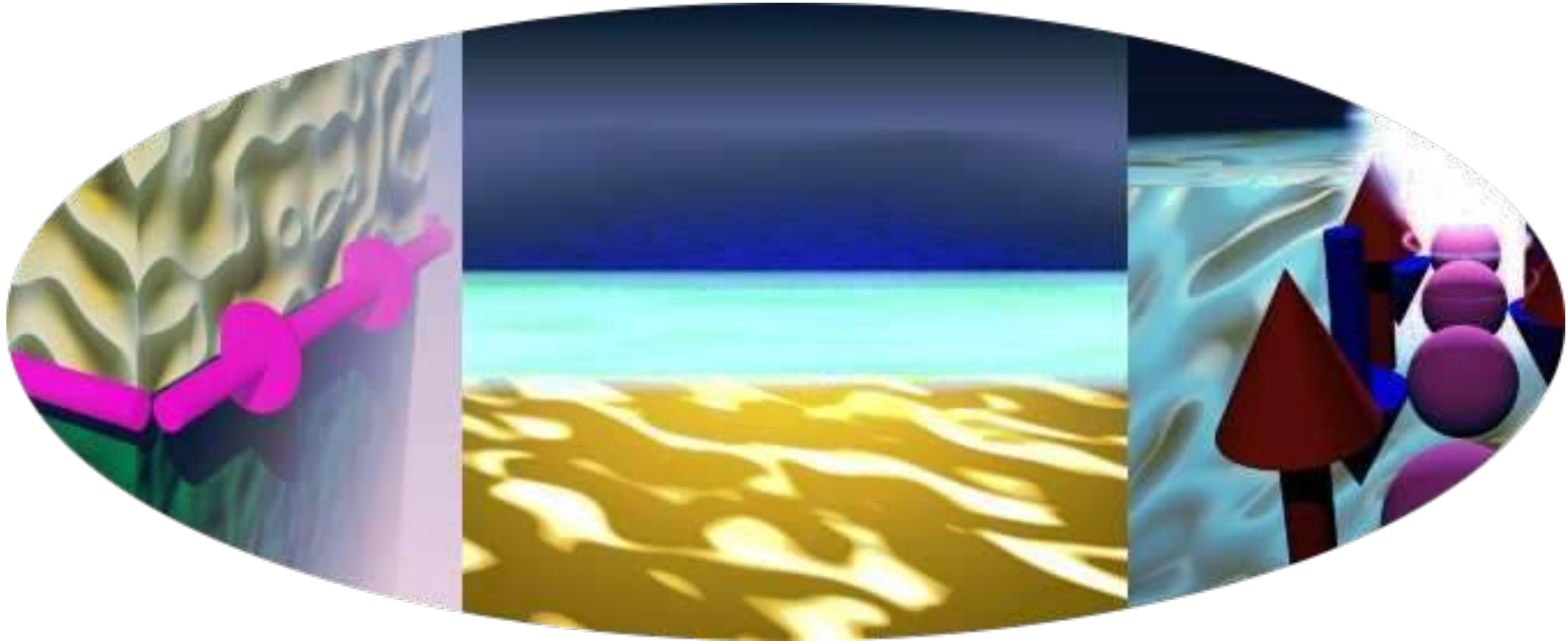
Phys. Rev. Lett. 120, 198101 (2018)

Complex compounds



Complex systems allow to have new phenomena that did not exist before 2

A new universe in each new material

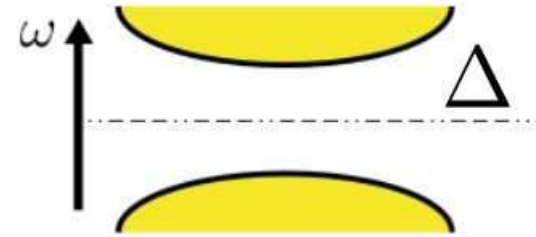


Each material is a new universe for electrons, with laws changing from compound to compound

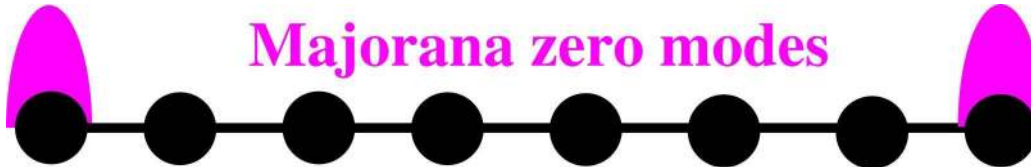
Topological superconductors and topological quantum computing

Topological superconductors with broken time reversal symmetry

Gapped bulk excitations

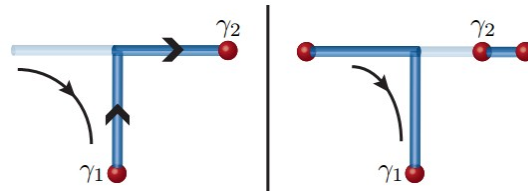


Gapless surface modes, single Majorana mode per edge



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

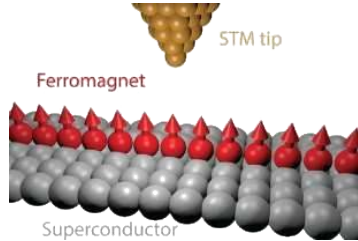
Anyonic statistics, suitable for quantum computing



Nature Physics 7, 412-417 (2011)

Platforms for Majorana physics

Ferromagnetic atomic chains



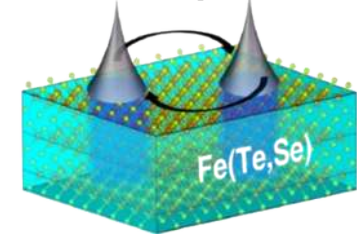
Science 346.6209 (2014): 602-607

Semiconductors



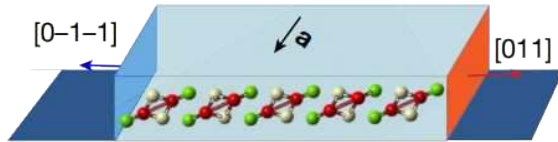
Science 354.6319 (2016): 1557-1562

Fe-based superconductors



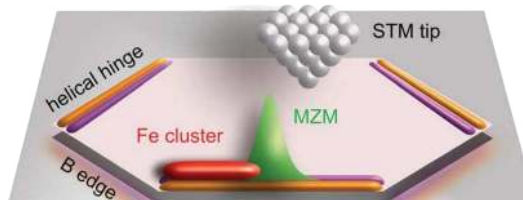
Science 362.6412 (2018): 333-335

Heavy-fermion compounds



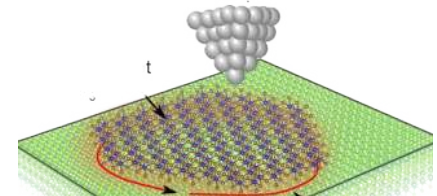
Nature 579, 523–527 (2020)

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 5

Topological superconductivity with antiferromagnetic insulators

Build a topological superconductor with

- A conventional (s-wave) superconductor
- An antiferromagnetic insulator

The prize

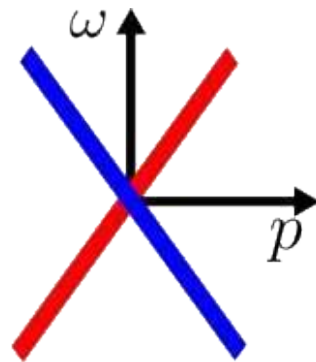
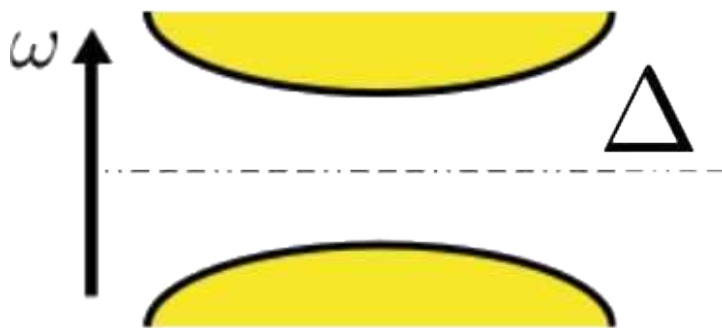


Bringing a new solid state platform to realize artificial topological superconductors

How to build your own topological superconductor

Ingredients

- s-wave pairing
- Helical states



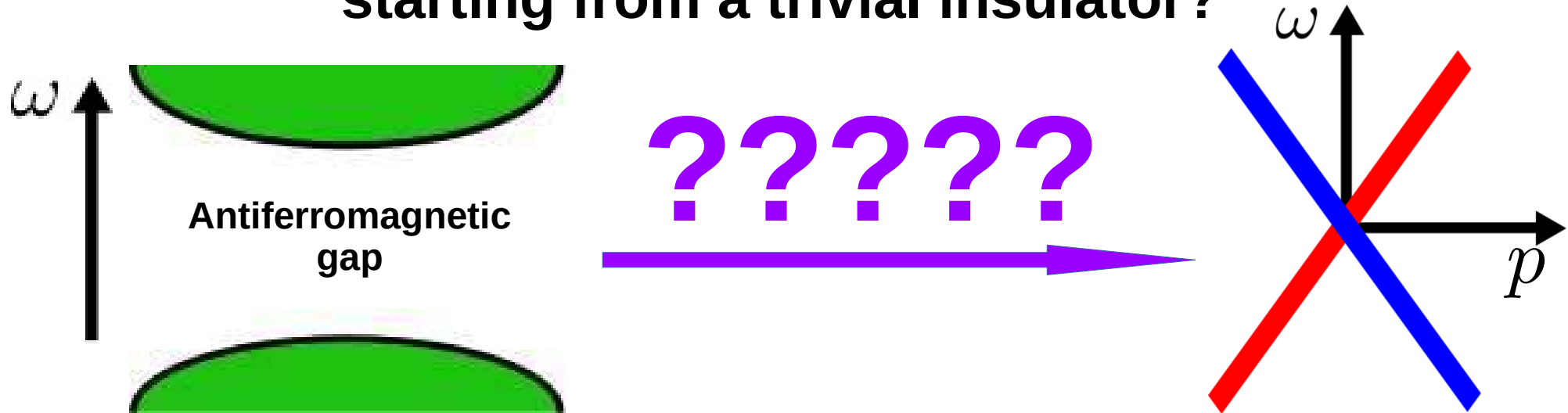
Objective: to realize a spinless superconductor

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



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



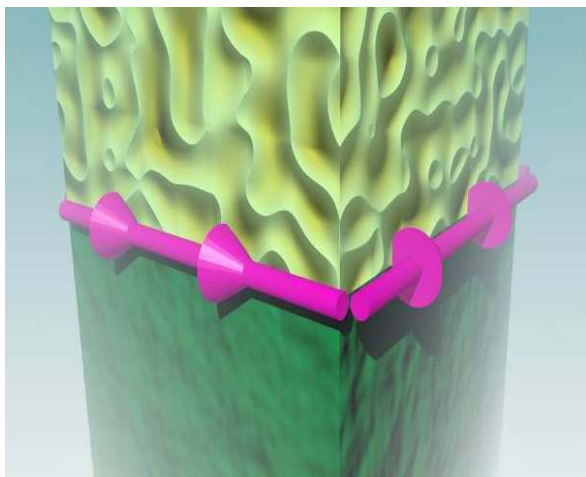
Päivi Törmä



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

arXiv:2011.06990 (2020)

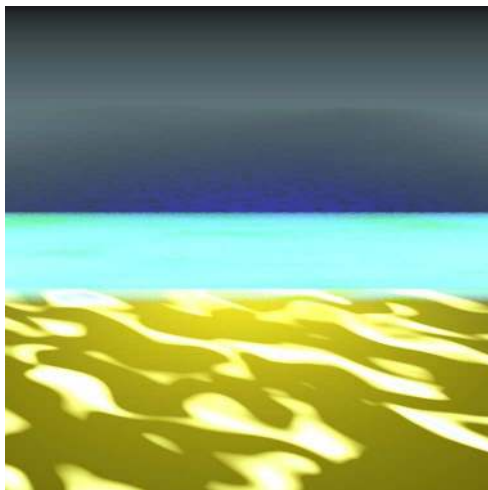
Today's story



Topological superconductivity (TS)
in 3D AF insulators

No interactions

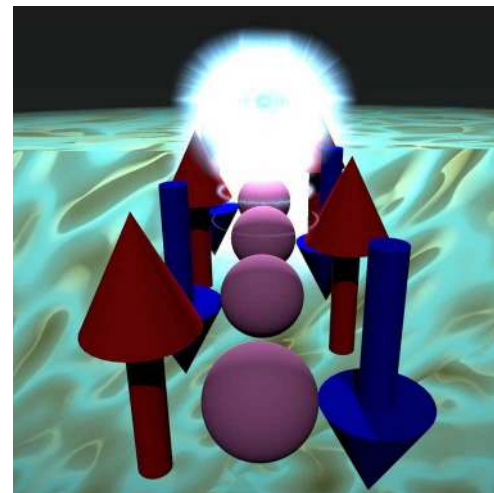
Phys. Rev. Lett. 121, 037002 (2018)



Interaction-induced
TS in 2D AF insulators

Mean-field interactions

arXiv:2011.06990 (2020)



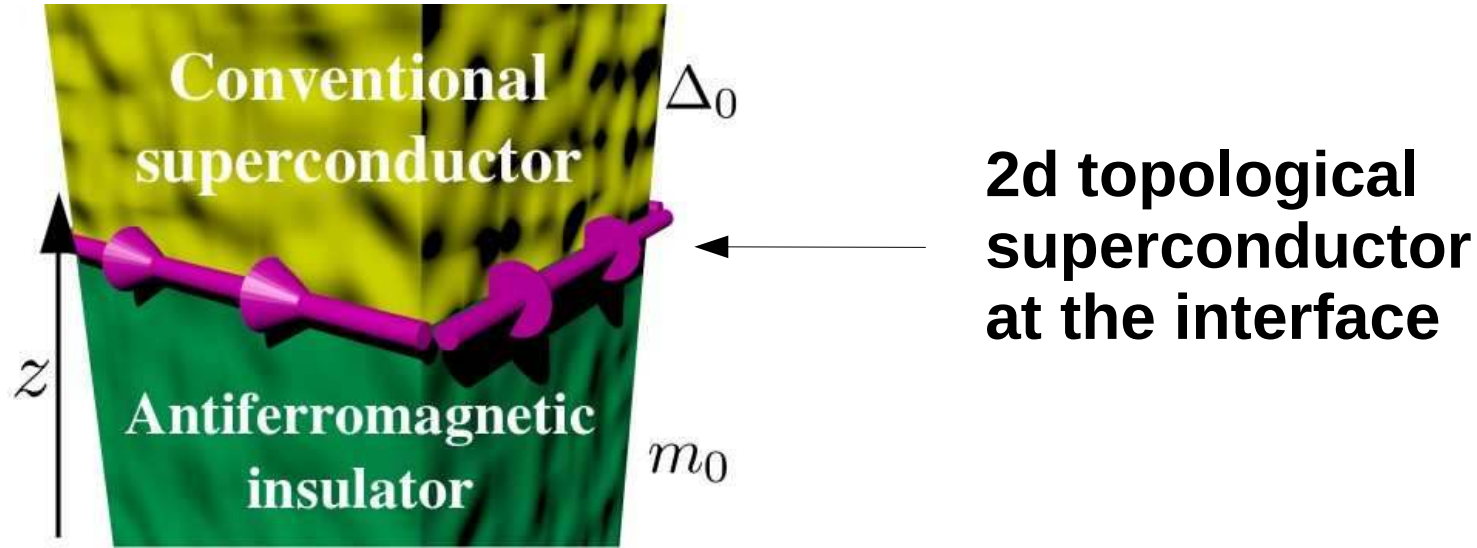
The quantum many-body
1D limit

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



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

Kinetic
energy

Antiferromagnetism

Superconductivity

Spin-orbit coupling

Solitonic modes between Dirac AF and SC

Total Hamiltonian, for an antiferromagnet with gaped Dirac points

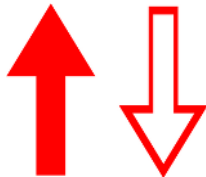
$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{AF}} + \mathcal{H}_{\text{SC}}$$

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

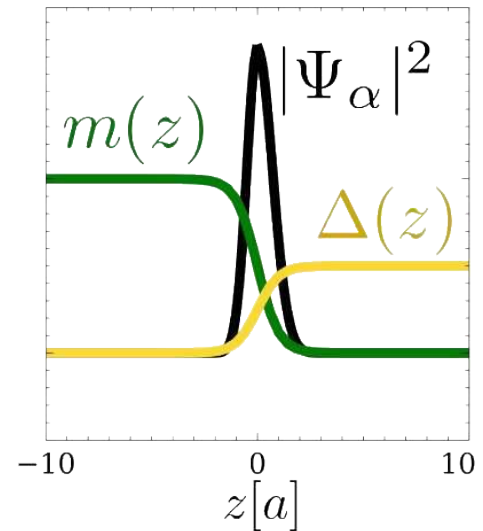
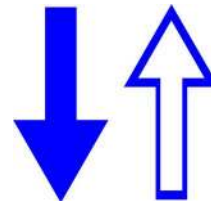
Phys. Rev. X 5, 041042 (2015)

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

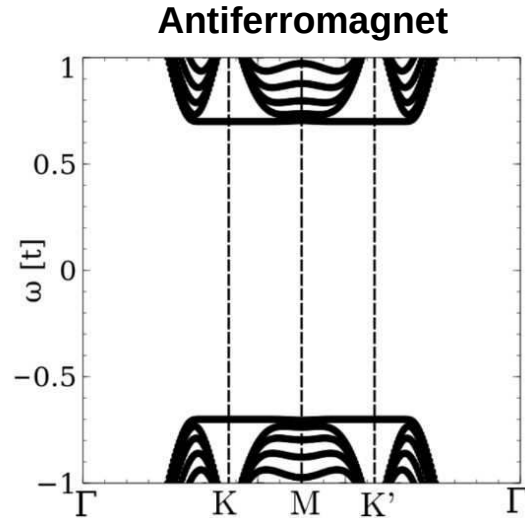
Sector #1
Up electron, down hole



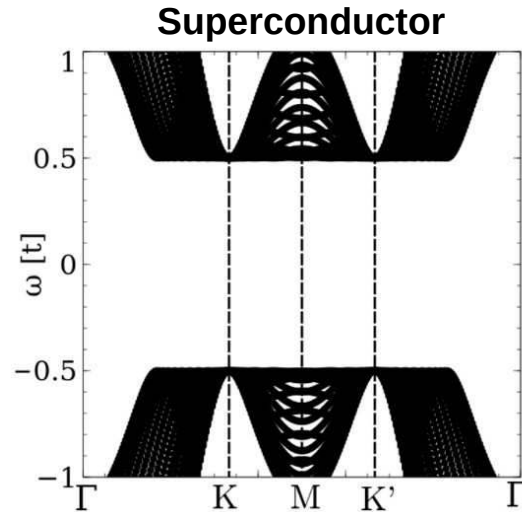
Sector #2
Down electron, up hole



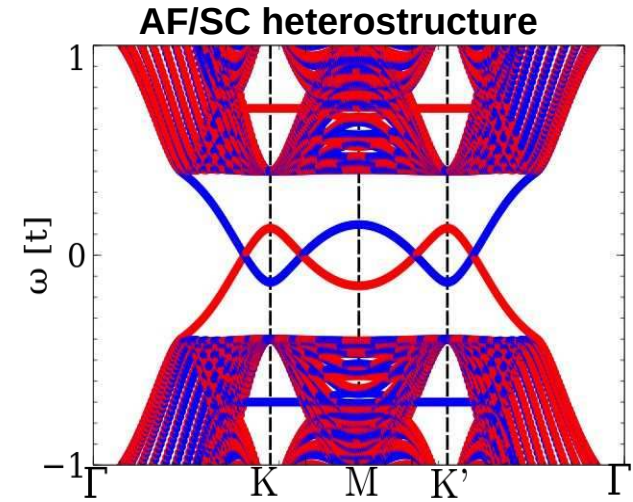
Emergence of interfacial modes, no spin-orbit coupling



AF

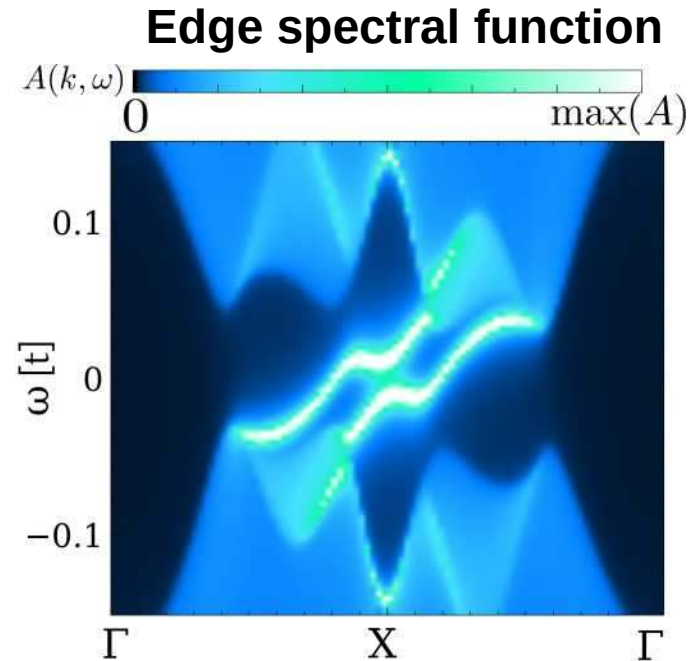
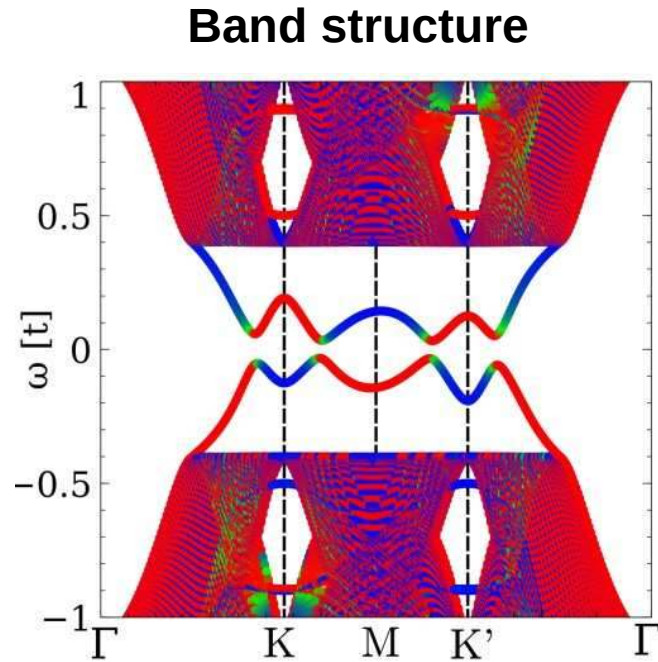


SC



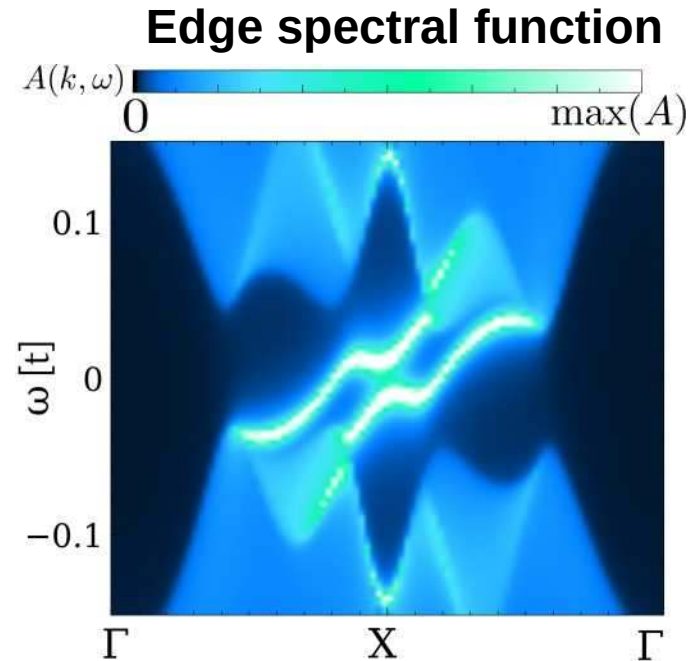
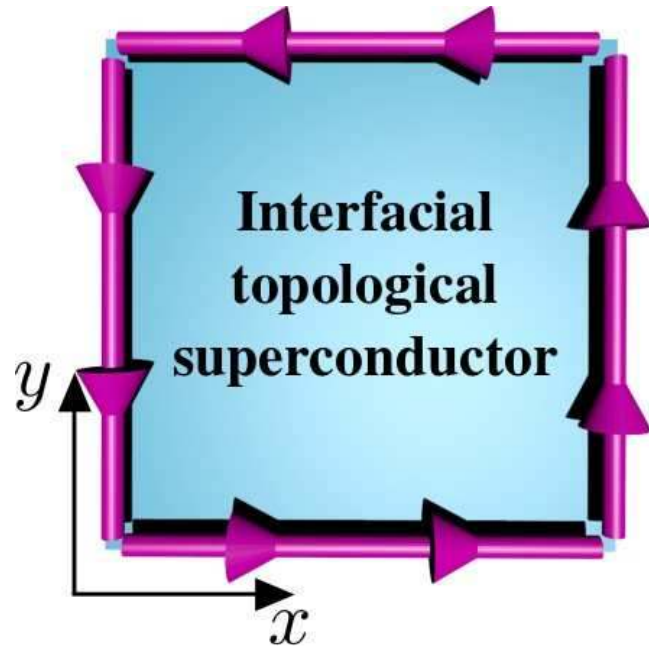
AF SC

Topological superconductivity with spin-orbit coupling



Topological superconductivity showing gapless Majorana modes

Adding spin-orbit coupling

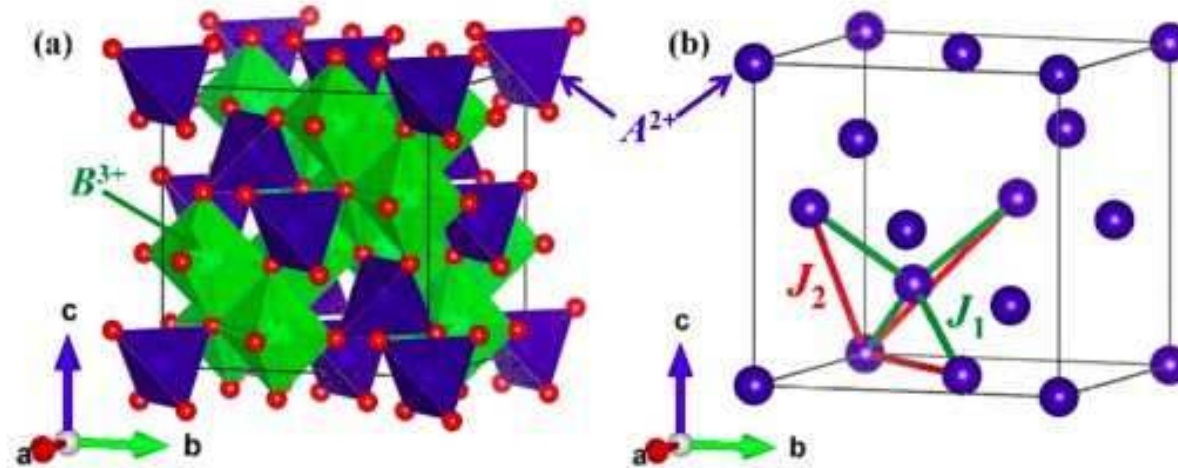


The interface realizes a topological superconductor

3D AF material candidates, spinels

Antiferromagnet forming a diamond lattice

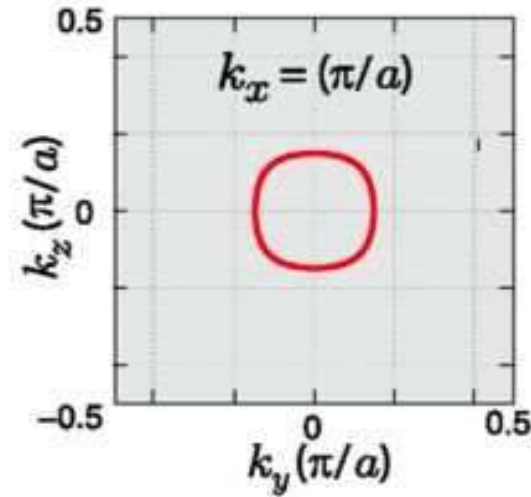
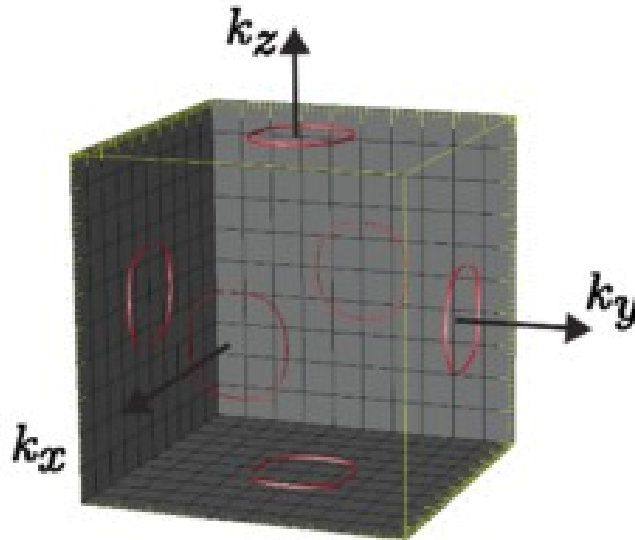
Antiferromagnetic spinels



Co atoms form a diamond lattice

3D AF material candidates, Dirac materials

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

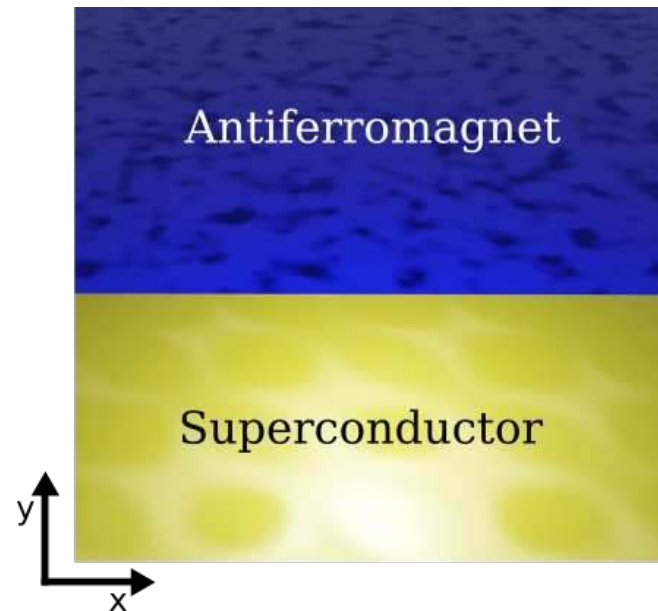


Phys. Rev. Lett. 115, 036806 (2015)

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

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

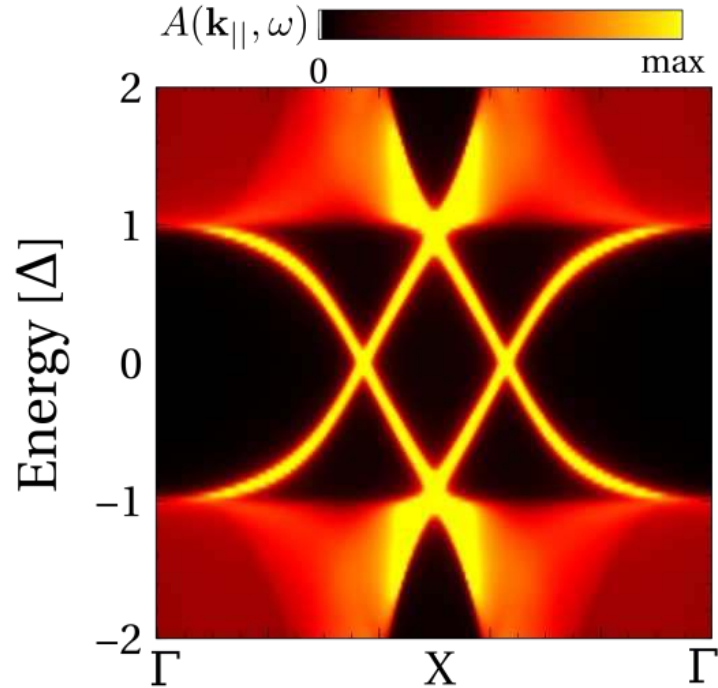
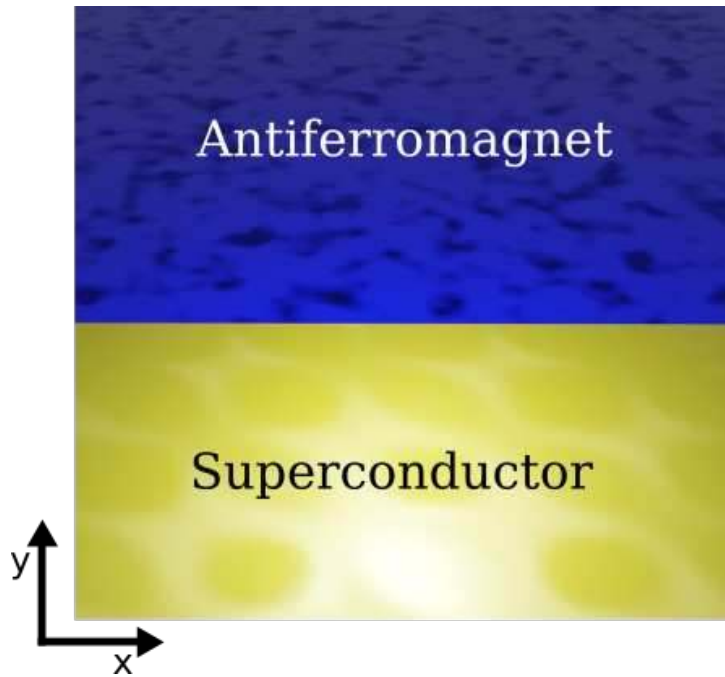
Kinetic energy Antiferromagnetism Repulsive interactions

Superconductivity

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

Interface AF-SC modes

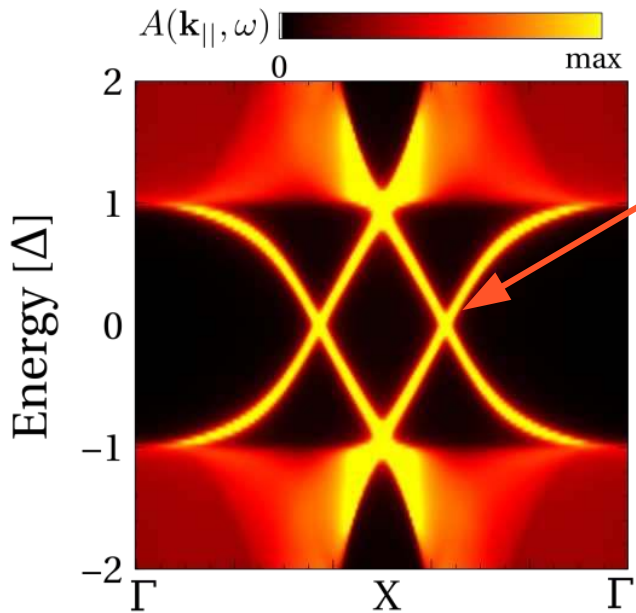
$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{AF}} + \mathcal{H}_{\text{SC}}$$



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

Interactions in the model

What happens when we now include interactions in whole system?

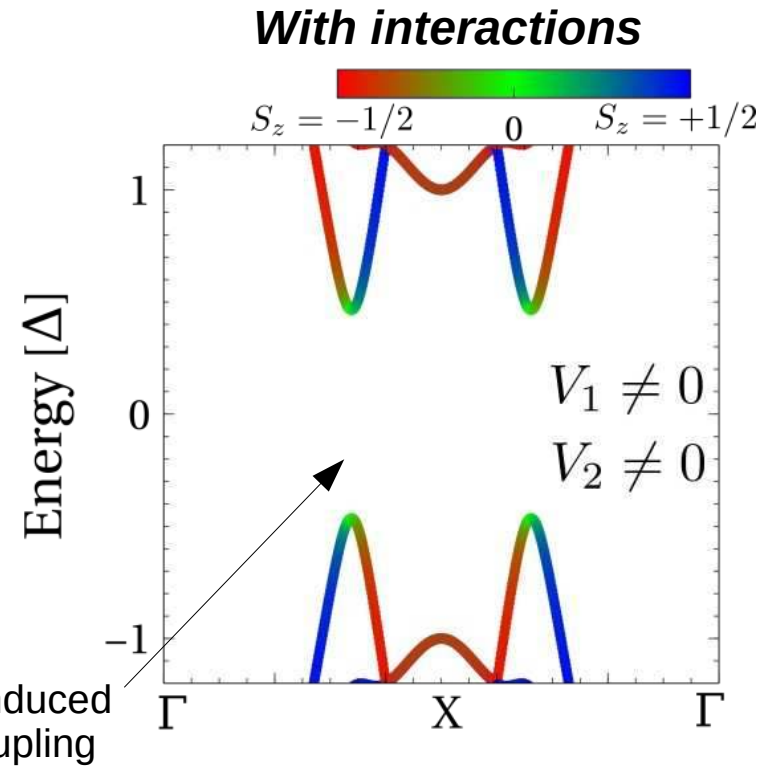
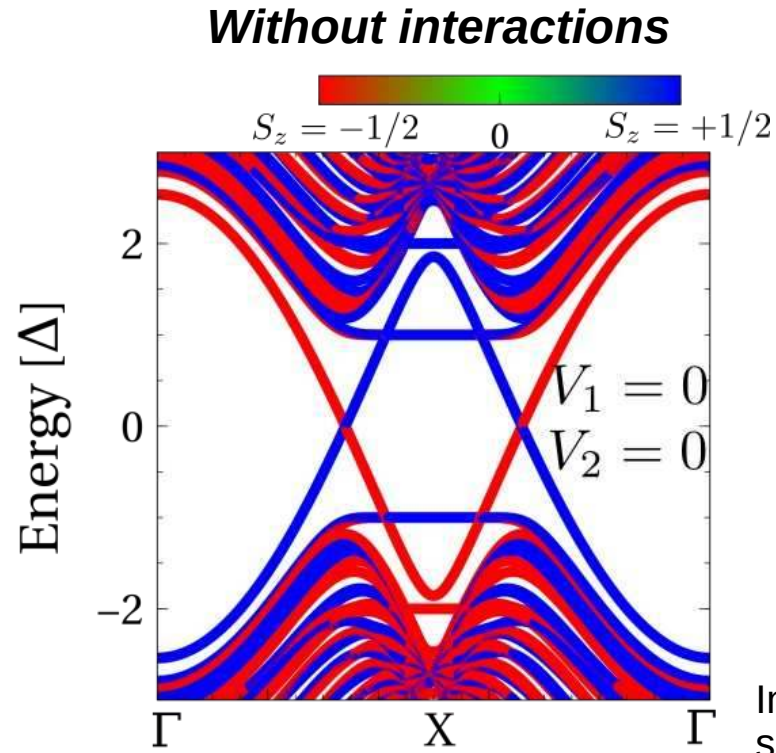


Could there be an interaction-induced gap opening of the interface modes?

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

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

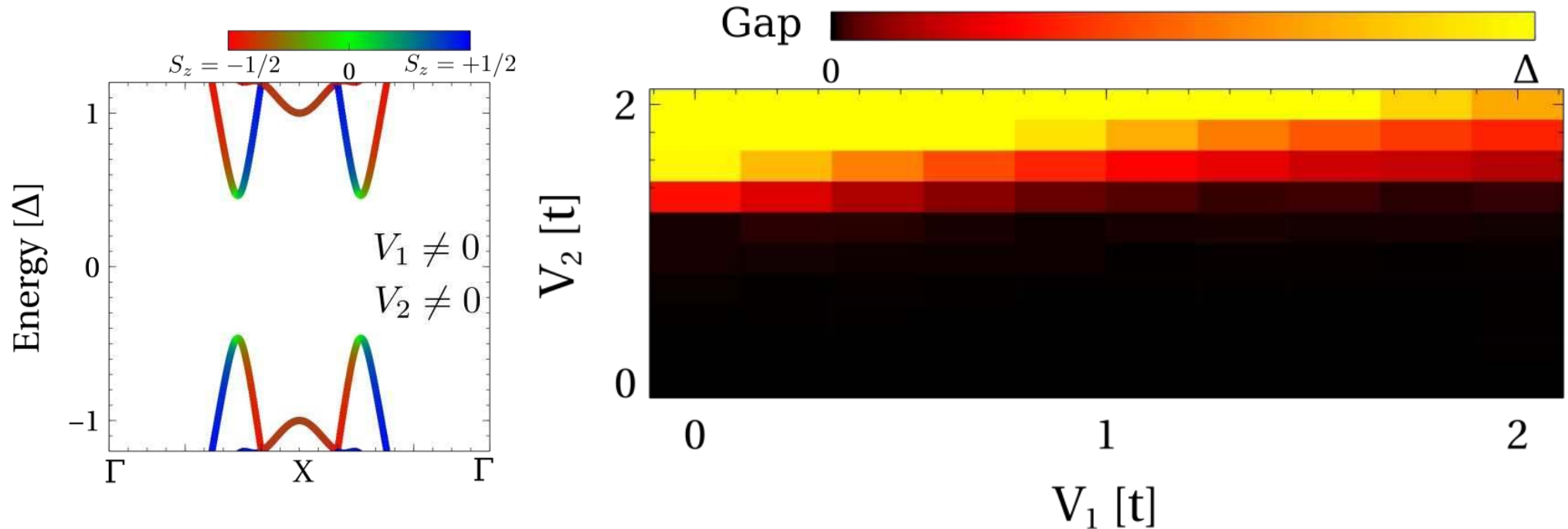
Impact of interactions



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

Interaction-induced gap VS interaction strength

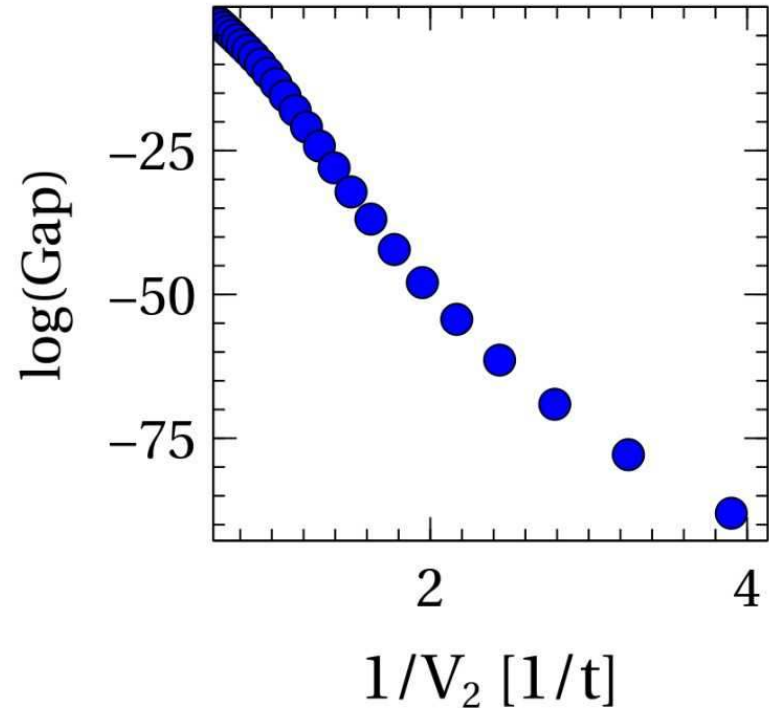
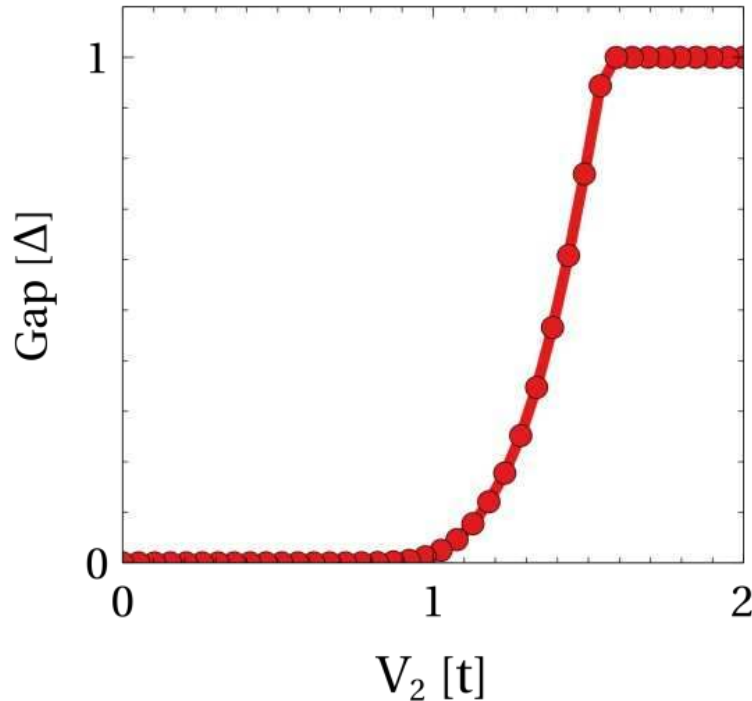
Dependence of the topological gap with respect to first and second neighbor interactions



The interaction-induced gap saturates to Δ , the gap of the s-wave superconductor₂₄

Topological superconductivity without a critical interaction

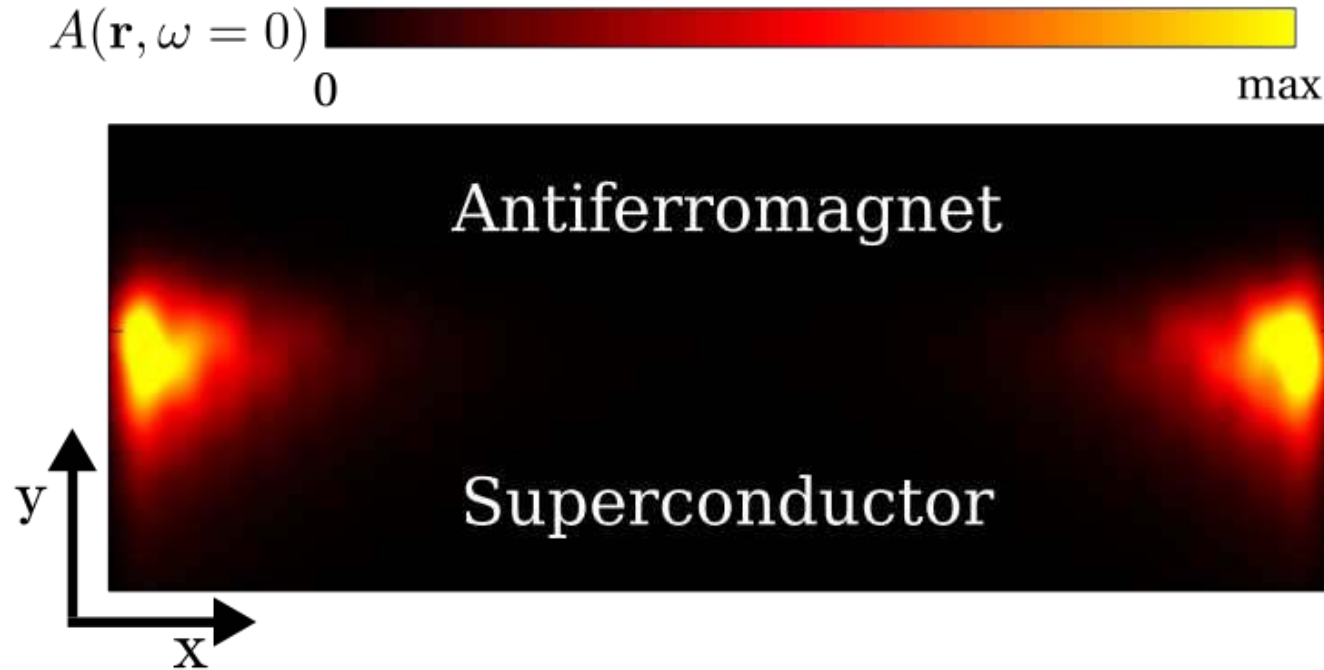
Topological gap VS interaction strength



A topological gap opens up for arbitrarily small interactions

Majorana zero modes

Spectral function at zero energy, featuring Majorana edge modes



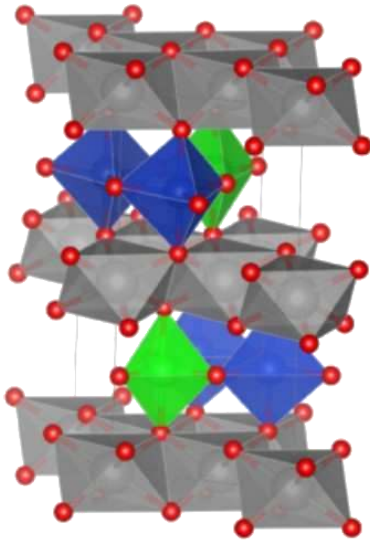
Majorana zero modes emerge at the edge due to electronic interactions

AF material candidates

Antiferromagnetic honeycomb oxides

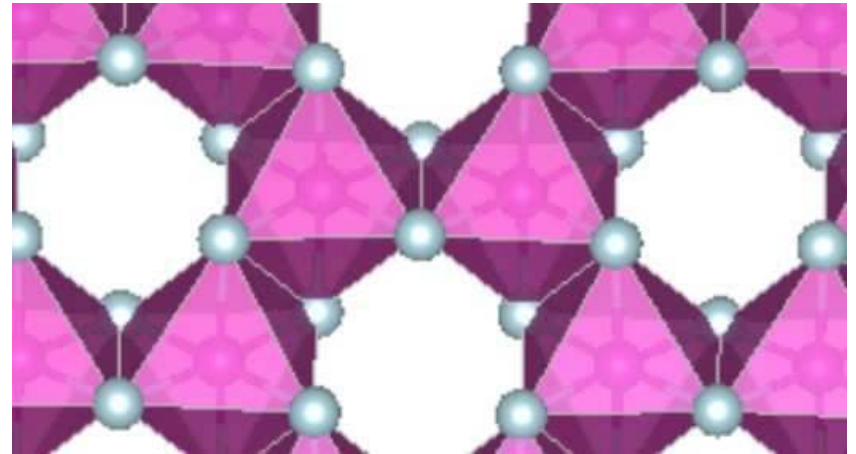
$\text{InCu}_{2/3}\text{V}_{1/3}\text{O}_3$ *Phys. Rev. B* 78, 024420 (2008)

$\beta\text{-Cu}_2\text{V}_2\text{O}_7$ *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)

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

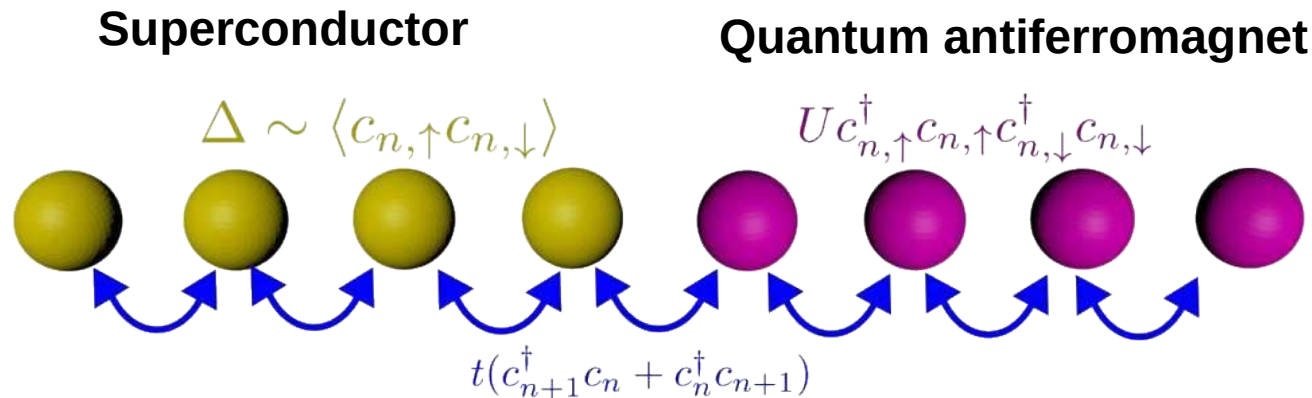
Quantum antiferromagnet (many-body solution)

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

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

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

Superconductor-quantum antiferromagnet junction



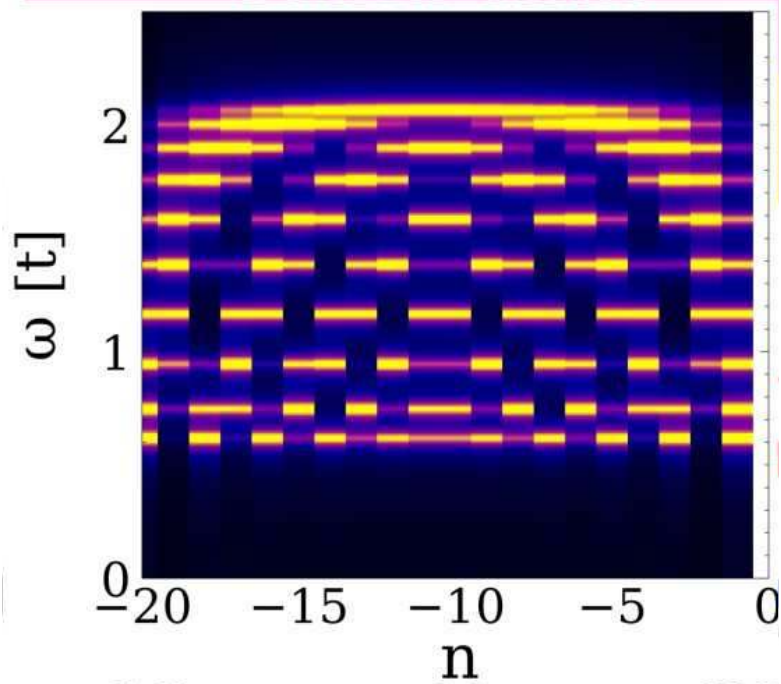
$$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{SC}} + \mathcal{H}_{\text{int}}$$

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

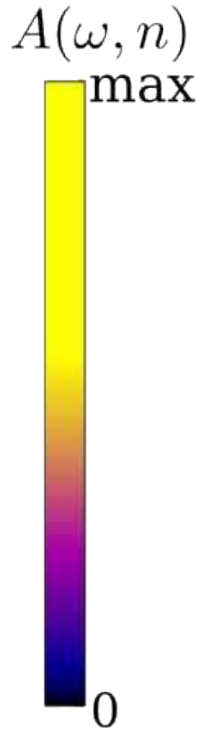
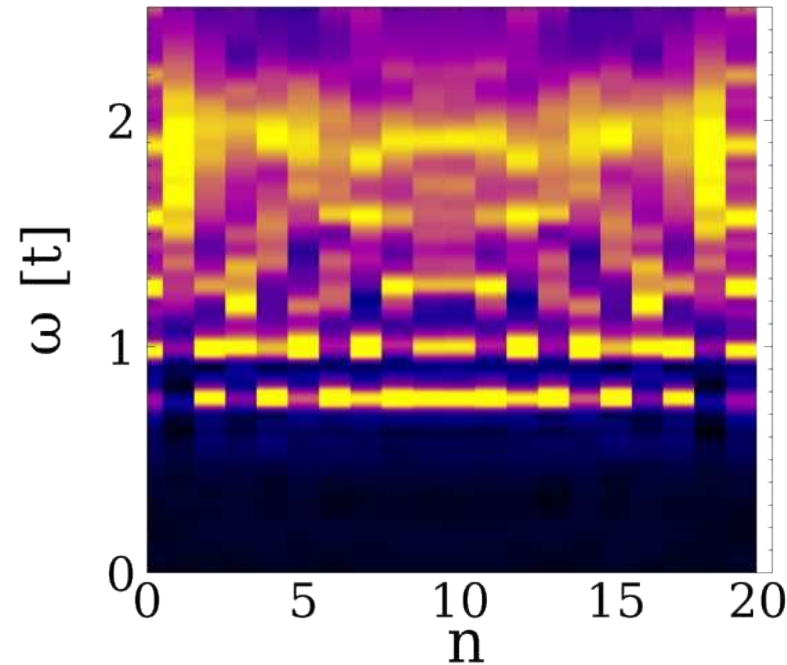
The ground state does not break time-reversal symmetry

Many-body spectral function

DOS in the superconductor



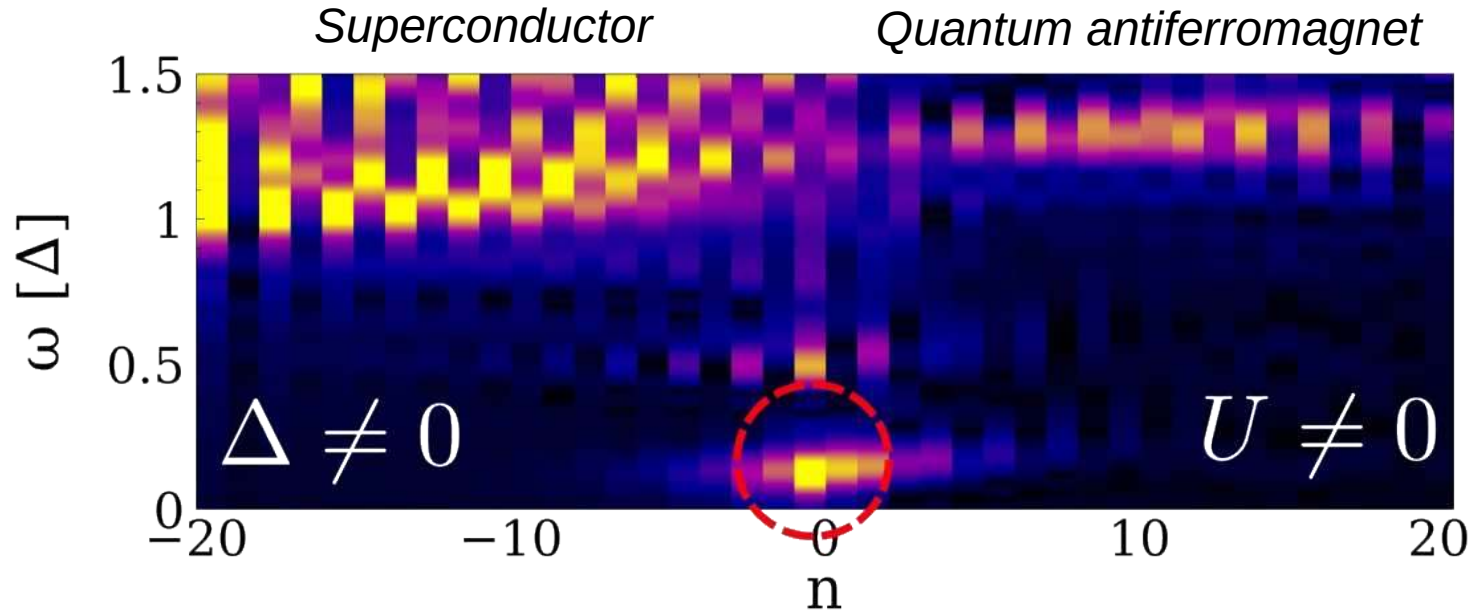
DOS in the quantum antiferromagnet



Both systems show an electronic gap when decoupled

In-gap modes at the SC-quantum AF interface

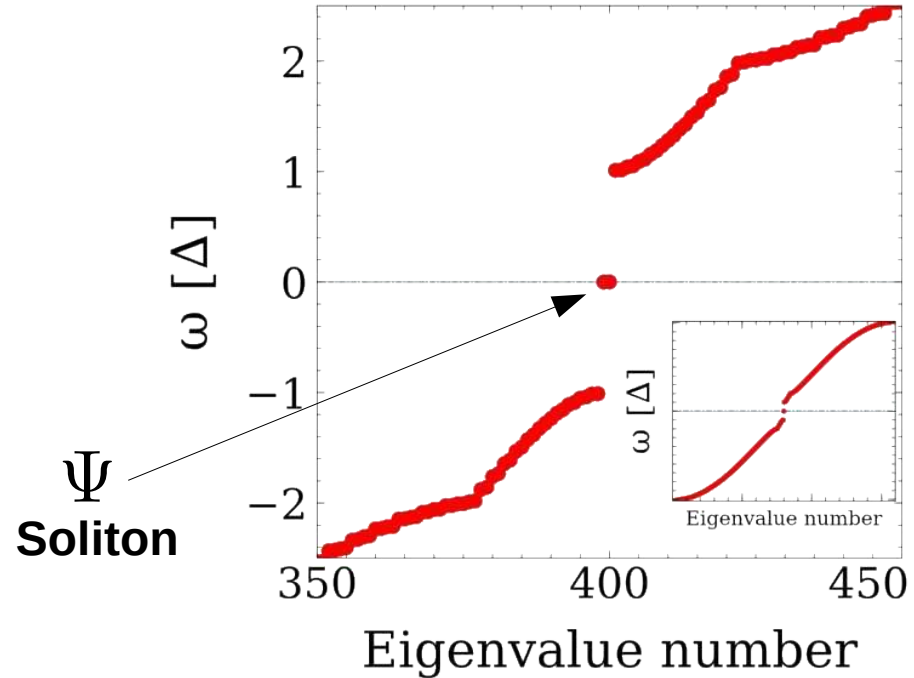
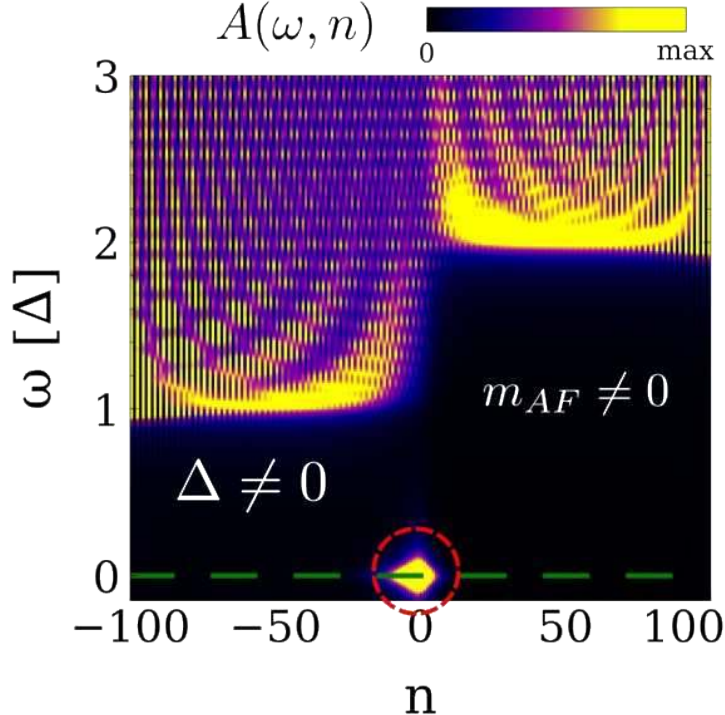
Superconductor-quantum antiferromagnet junction



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

Back to single-particle solitonic zero modes

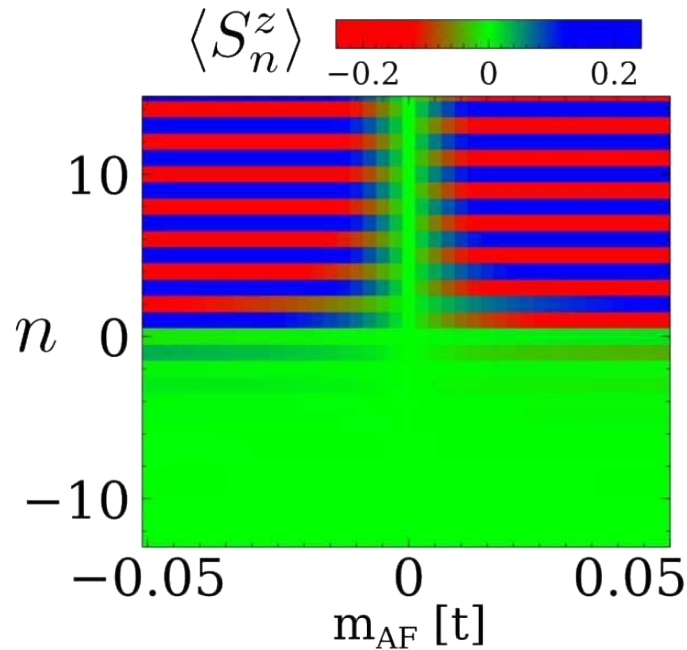
$\mathcal{H} = \mathcal{H}_{\text{kin}} + \mathcal{H}_{\text{SC}} + \mathcal{H}_{\text{AF}}$ Single particle limit (stagger magnetization and no interactions)



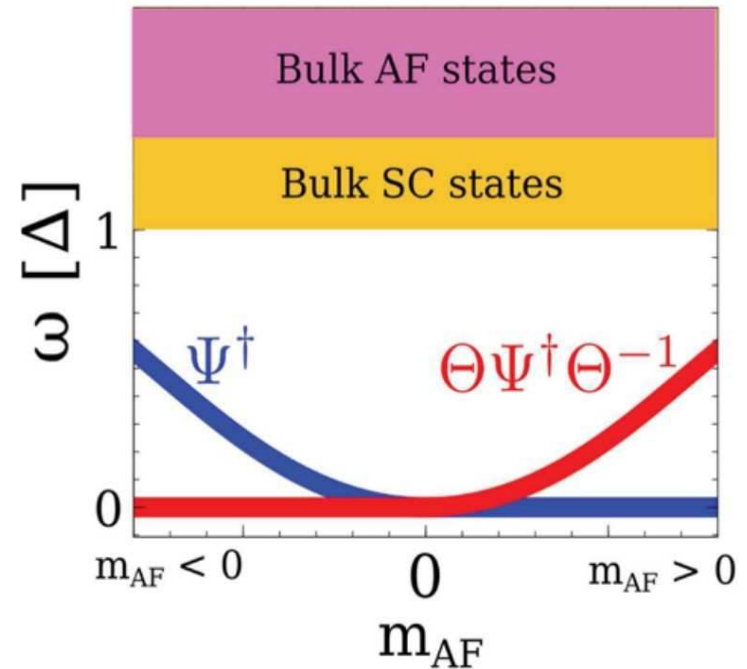
How are these modes connected to the many-body in-gap mode from before?

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

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

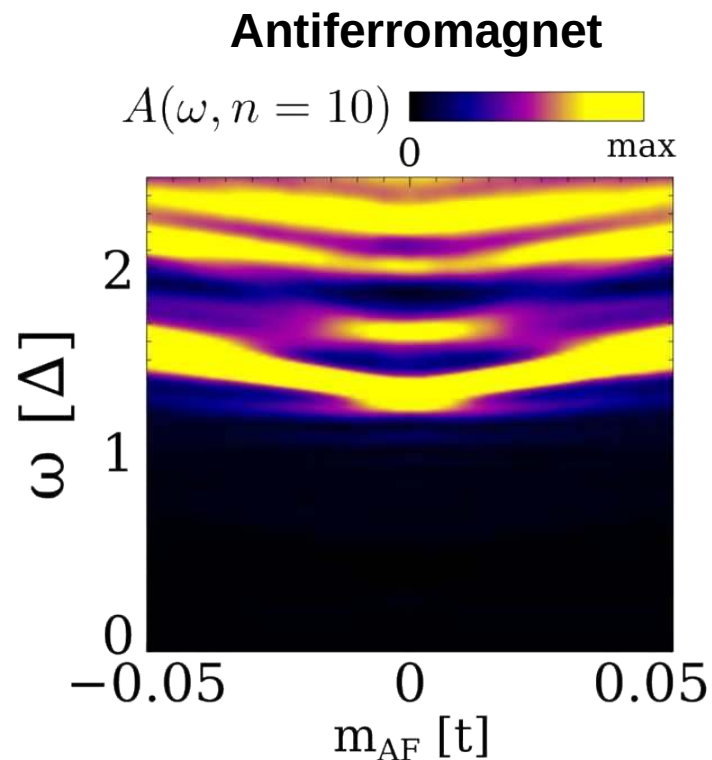
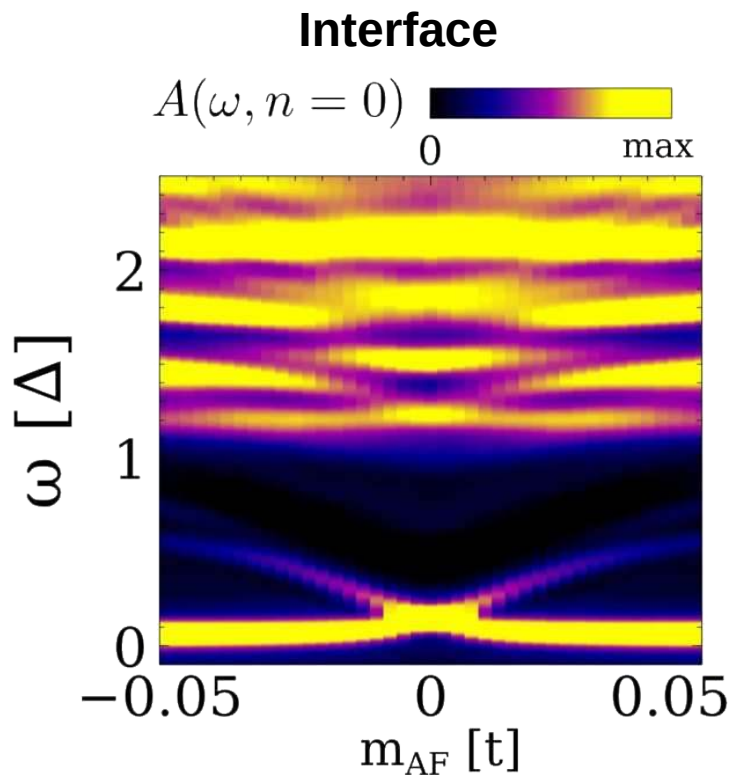


Sketch of the charge excitations



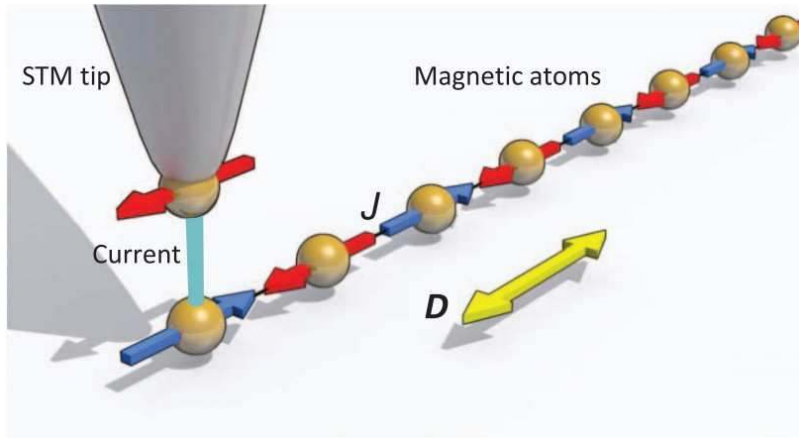
Switching on a magnetization pushes the interacting model to the symmetry broken state 34

From many-body to symmetry broken

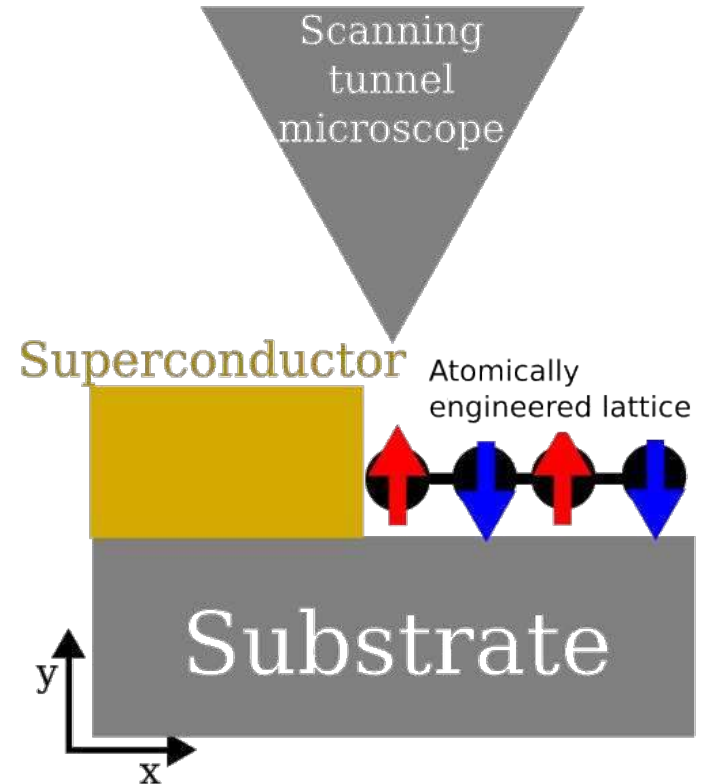


The solitonic single-particle mode transforms into the many-body in-gap mode 35

Experimental realization with atomically engineered lattices

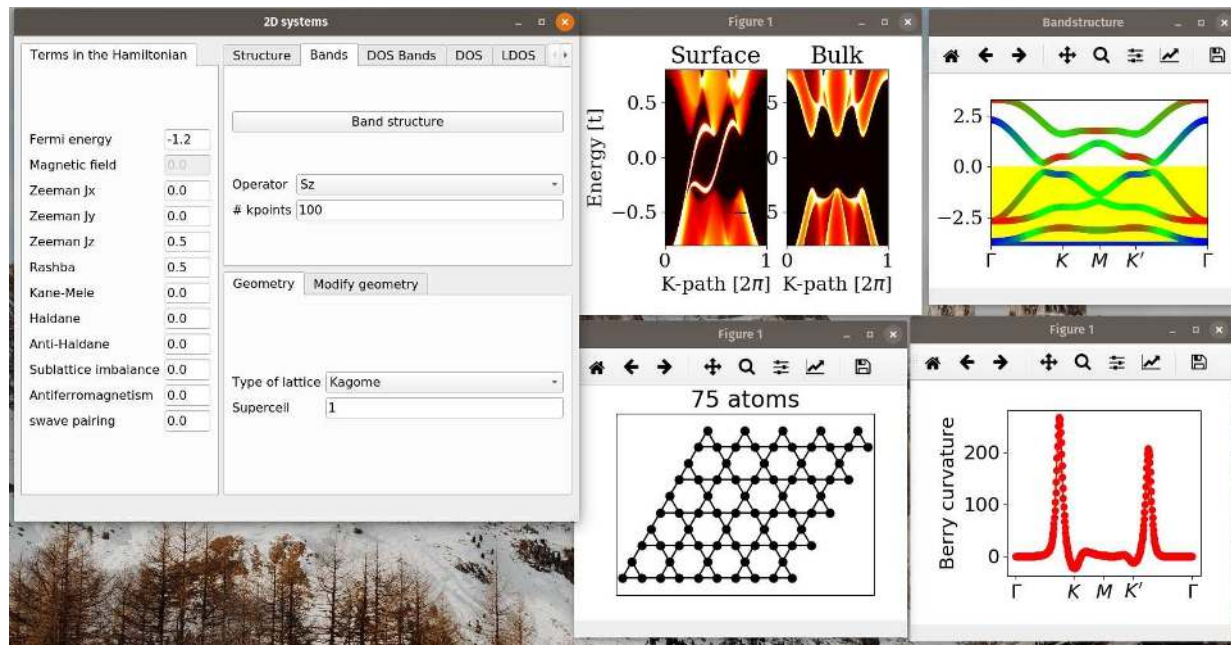


Science 335.6065 (2012): 196-199
Nature Physics 12, 656–660 (2016)
Rev. Mod. Phys. 91, 041001 (2019)



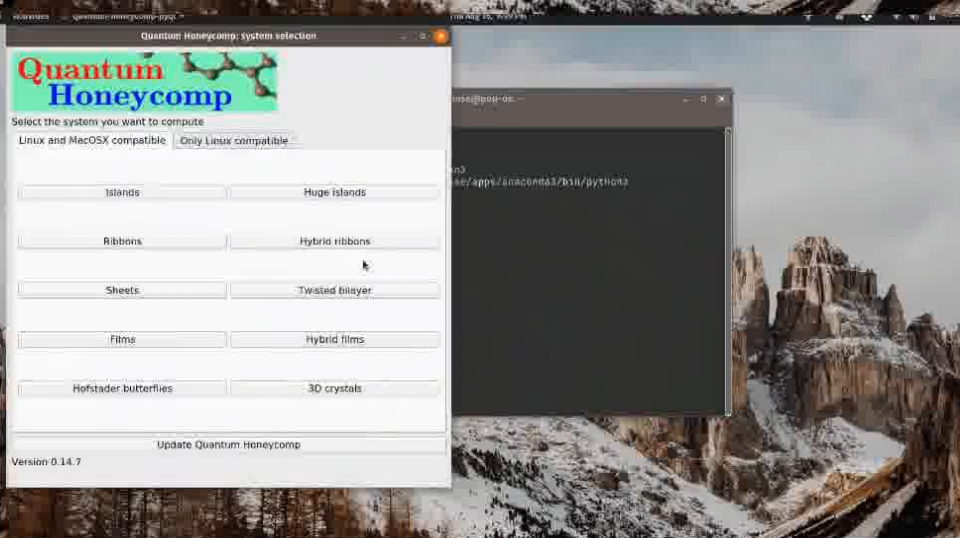
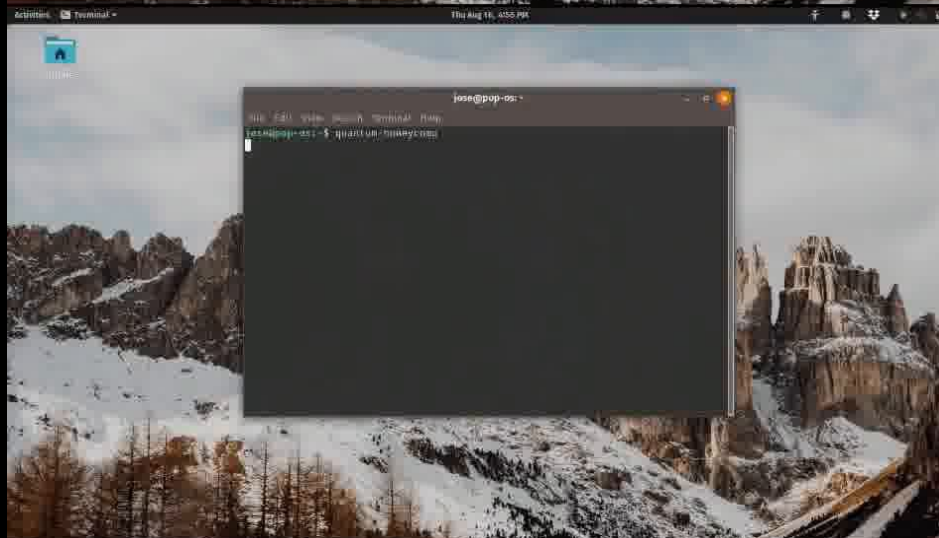
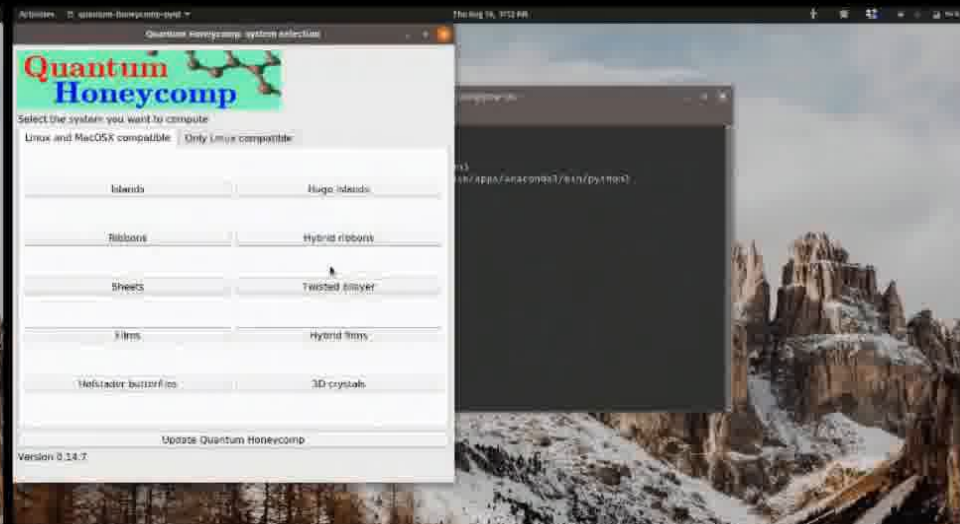
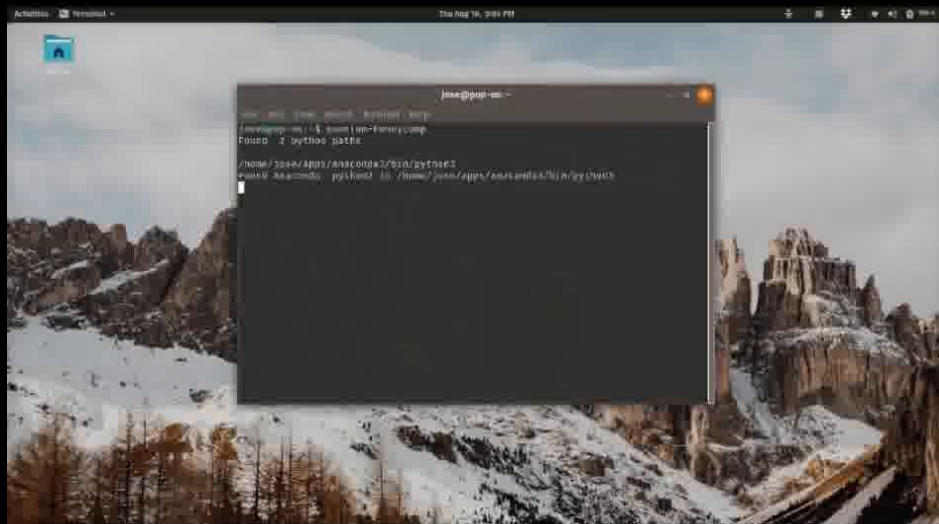
Computing electronic
properties

A user interface to compute electronic properties



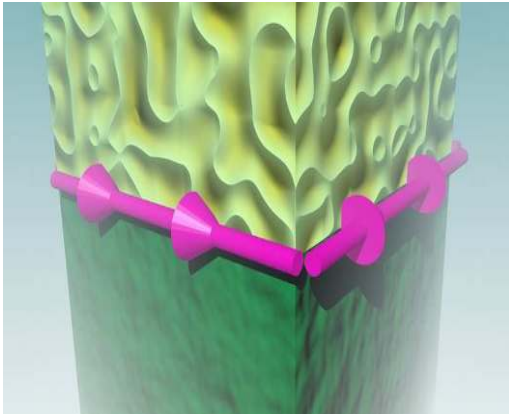
Quantum Honeycomp: open source interactive interface for tight binding modeling

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

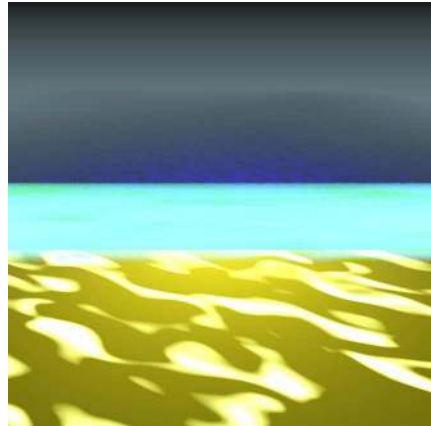


Take home

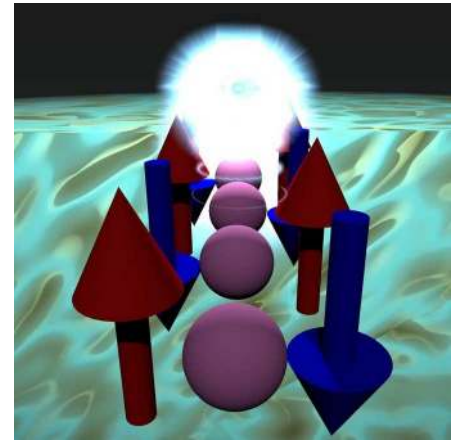
Antiferromagnet-superconductor junctions provide a powerful platform to engineer solitons, unconventional superconductors and robust many-body excitations.



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



arXiv:2011.06990 (2020)



Phys. Rev. Research 2, 023347 (2020)

Thank you!