Engineering and detecting unconventional superconductivity with disguised Dirac points

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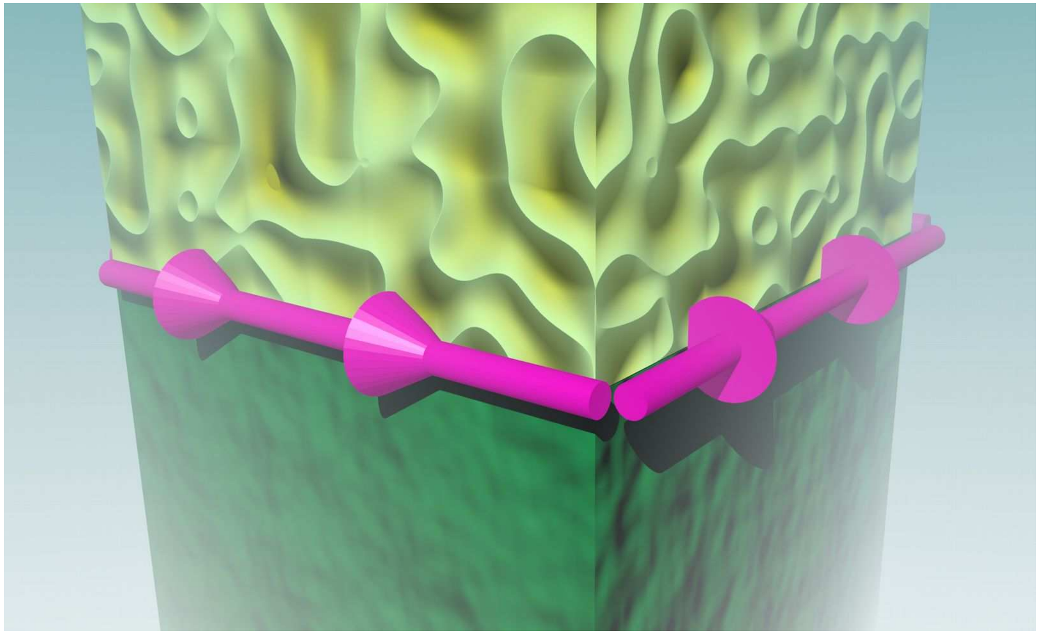
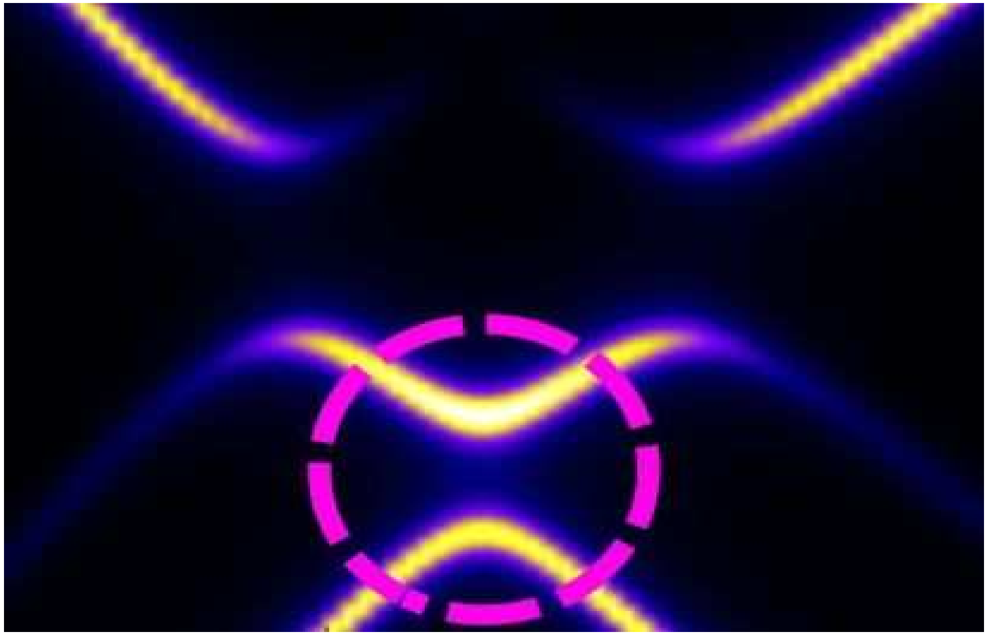


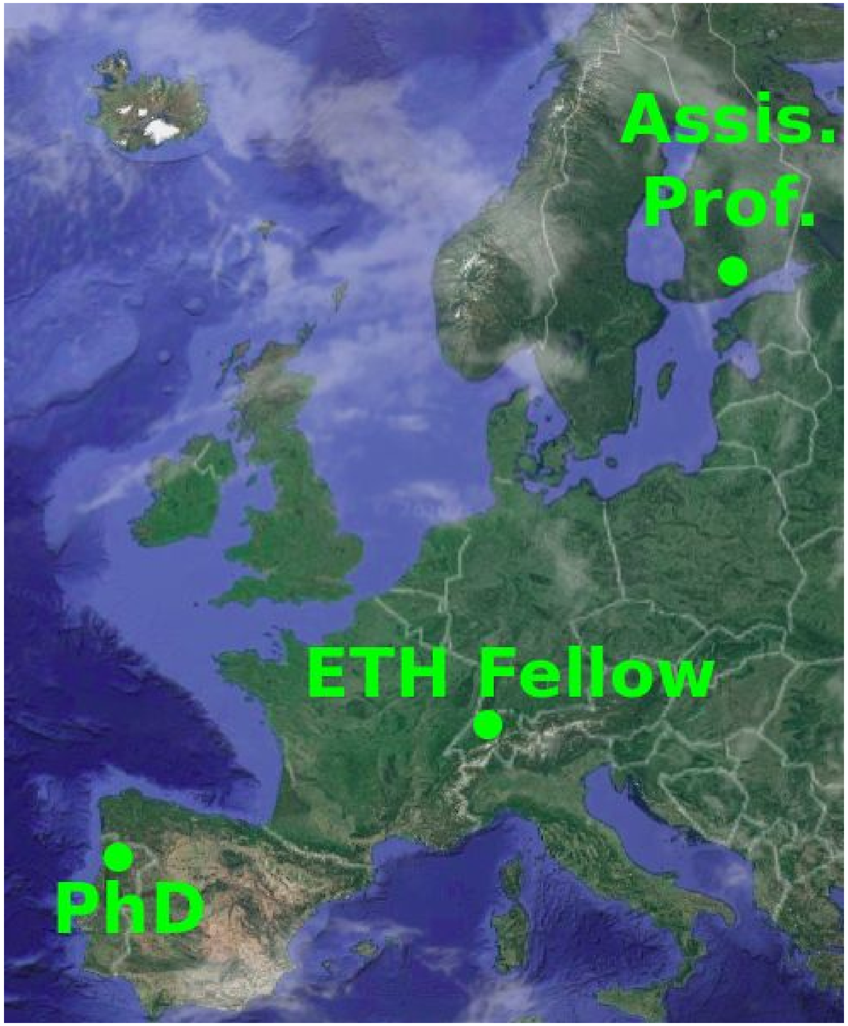
Phys. Rev. Lett. 121, 037002 (2018)



Phys. Rev. Research 1, 033107 (2019)

Radboud University, November 21st 2019

About me

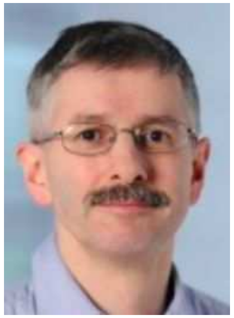


Ph.D. 2013-2016, INL Braga (Portugal)

Prof. Joaquin Fernandez-Rossier

ETH Fellow 2017-2019, ETH Zurich (Switzerland)

Prof. Manfred Sigrist



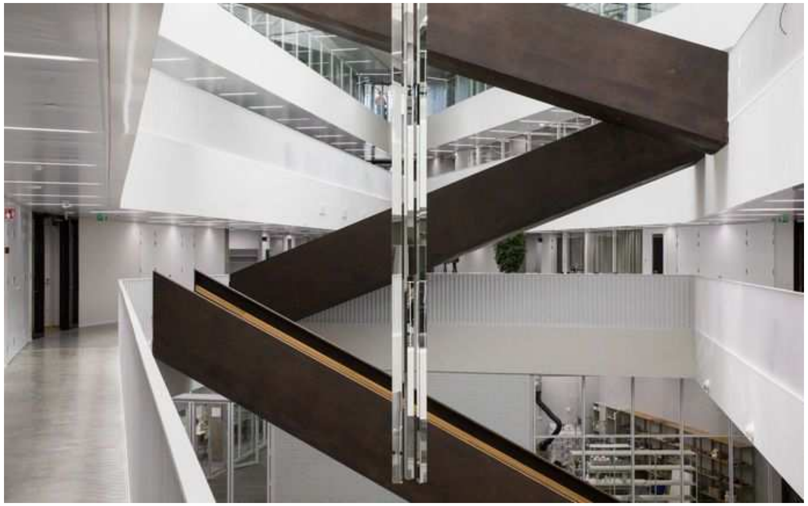
Prof. Oded Zilberberg

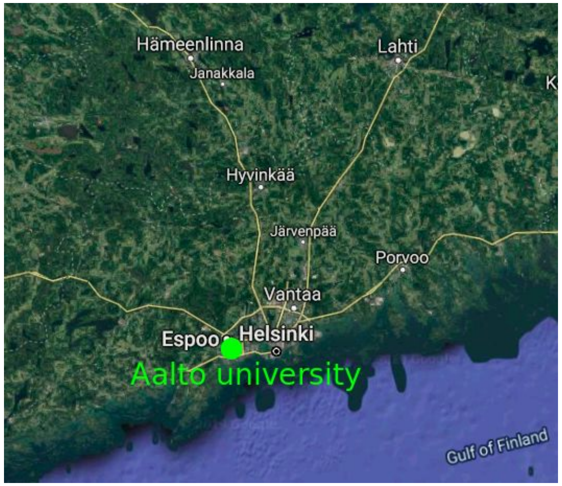
Assistant Professor, Aalto University (Sep. 2019)

Aalto University

About Aalto University, Finland

- Located in Espoo, 10km from Helsinki
- Established in 2010
- Science, business and arts
- Second largest University in Finland
- Around 17000 students and 4000 staff
- Around 20 research groups in the Department of Applied Physics





The quantum materials age

Electronics

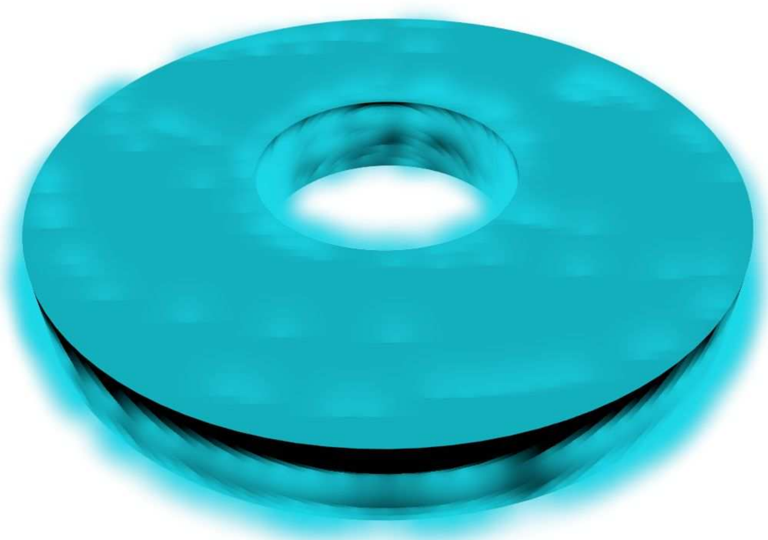
Imaging techniques in medicine

Renewable energy

Materials with exotic properties allow to tackle key technological challenges

Macroscopic materials, emergence and fundamental physics

Superconductivity

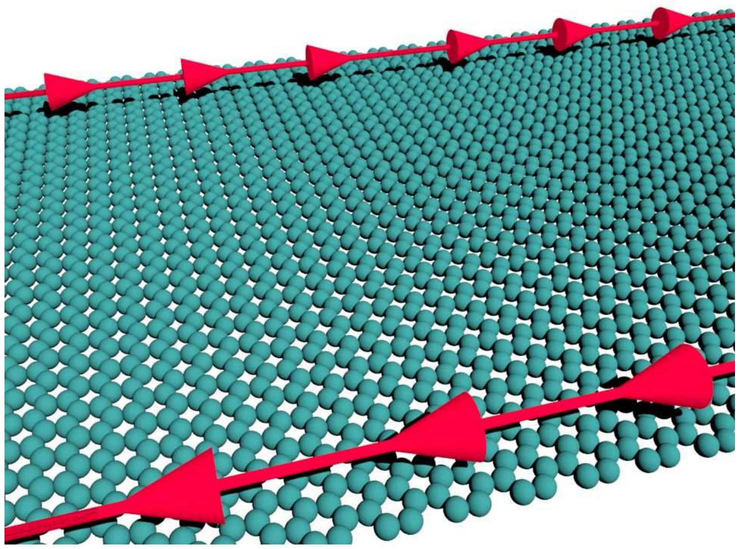


$$\Phi = \frac{h}{2e}$$

Many-body state

<u>Quantization</u> of flux

Quantum Hall effect



$$\sigma_{xy} = \nu \frac{e^2}{h}$$

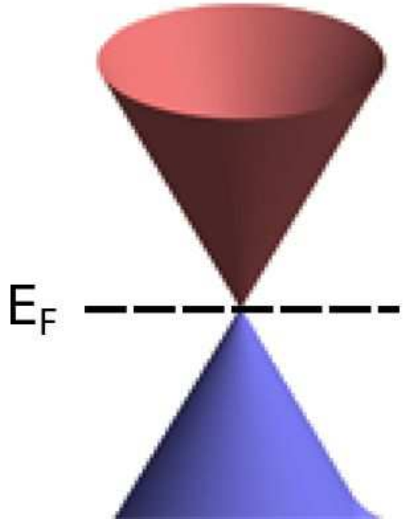
Single-particle state

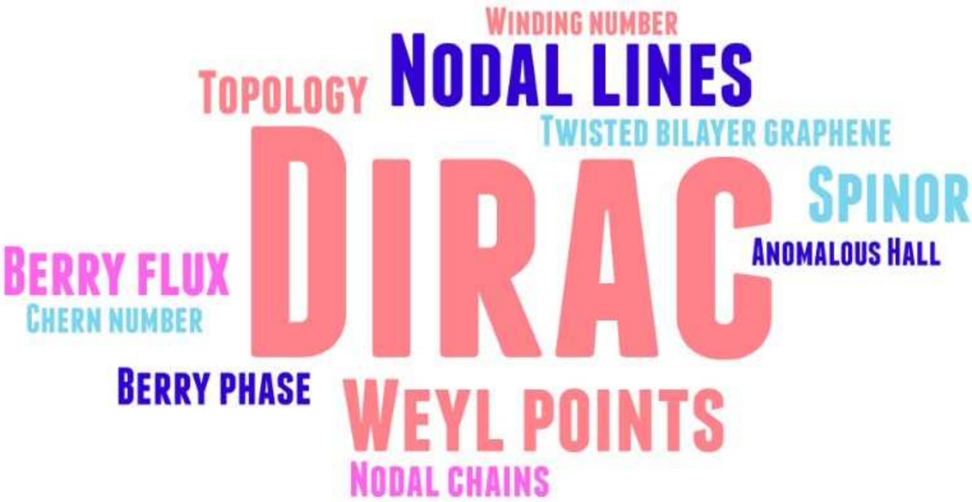
<u>Quantization</u> of conductance

Macroscopic quantum phenomena determine fundamental constants with the highest precision

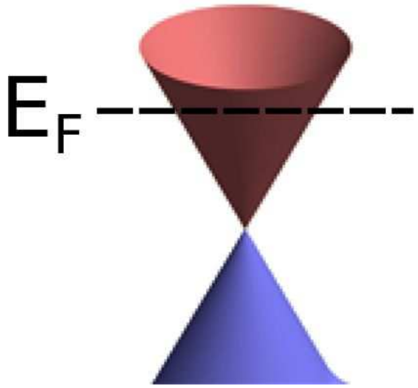
On Dirac crossings

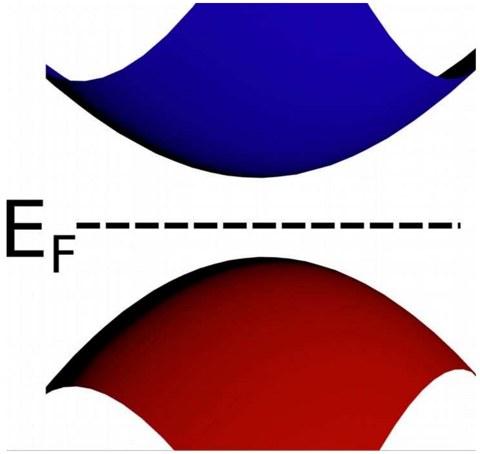
A platform to engineer exotic physics in solid state materials





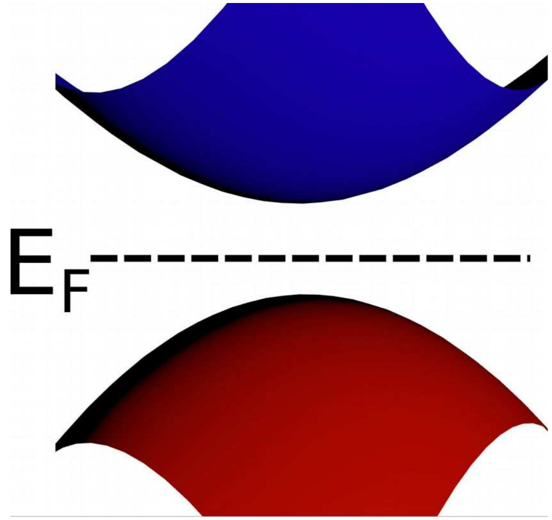
But what if the Dirac points are not observable at the chemical potential?





Exploiting disguised Dirac points

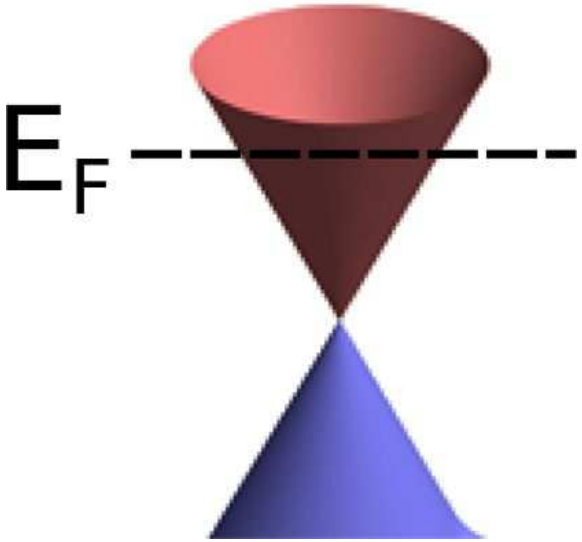
Platform for an artificial topological superconductor



Gaped out by antiferromagnetism

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

Platform to detect non-unitary superconductivity



Away from the Fermi energy

Phys. Rev. Research 1, 033107 (2019)

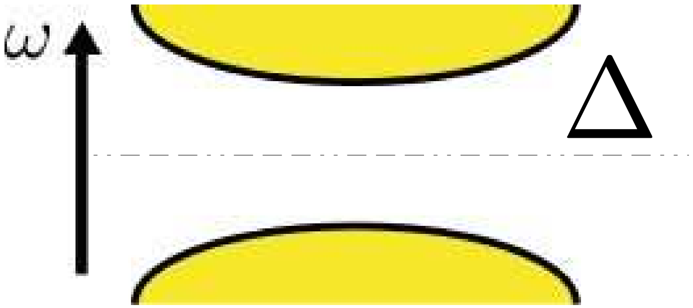
Manfred
Sigrist

Creating a topological superconductor with antiferromagnetically gaped Dirac points

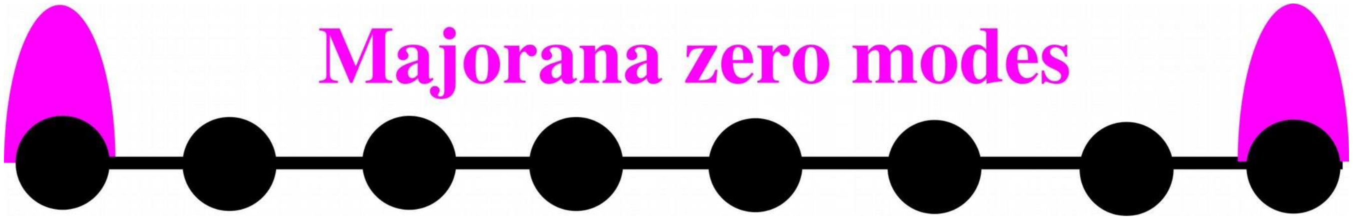
Topological superconductors

Topological superconductors with broken time reversal symmetry

Gapped bulk excitations

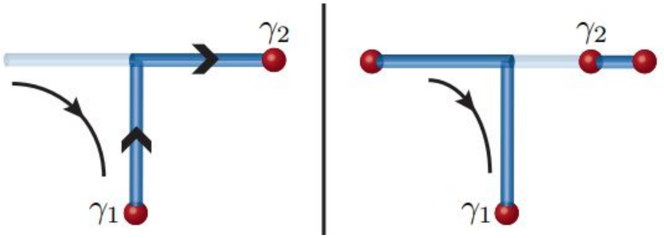


Gapless surface modes, single Majorana mode per edge



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

Anyonic statistics, suitable for quantum computing



Nature Physics 7, 412-417 (2011)

Our objective

Build a 2D topological superconductor with

- A conventional (s-wave) 3D superconductor
- **A 3D antiferromagnetic insulator**

The prize

Bringing a new solid state platform to realize artificial topological superconductors

The system for TS in an AF insulator

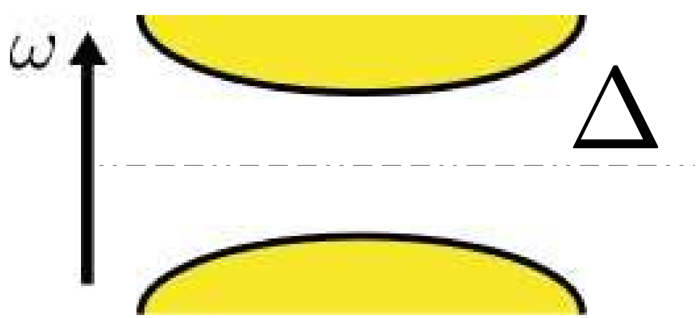
2d topological superconductor at the interface

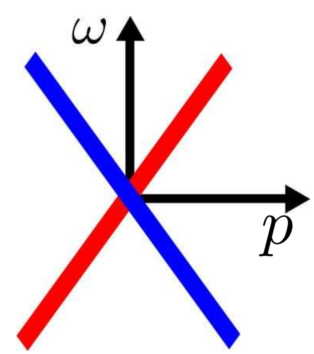
How to do your own topological superconductor

Ingredients

- s-wave pairing
- Helical states

Science 346.6209 (2014)
Science 354.6319 (2016)
Phys. Rev. Lett. 100, 096407 (2008)





Objective: realize a spin-less 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?

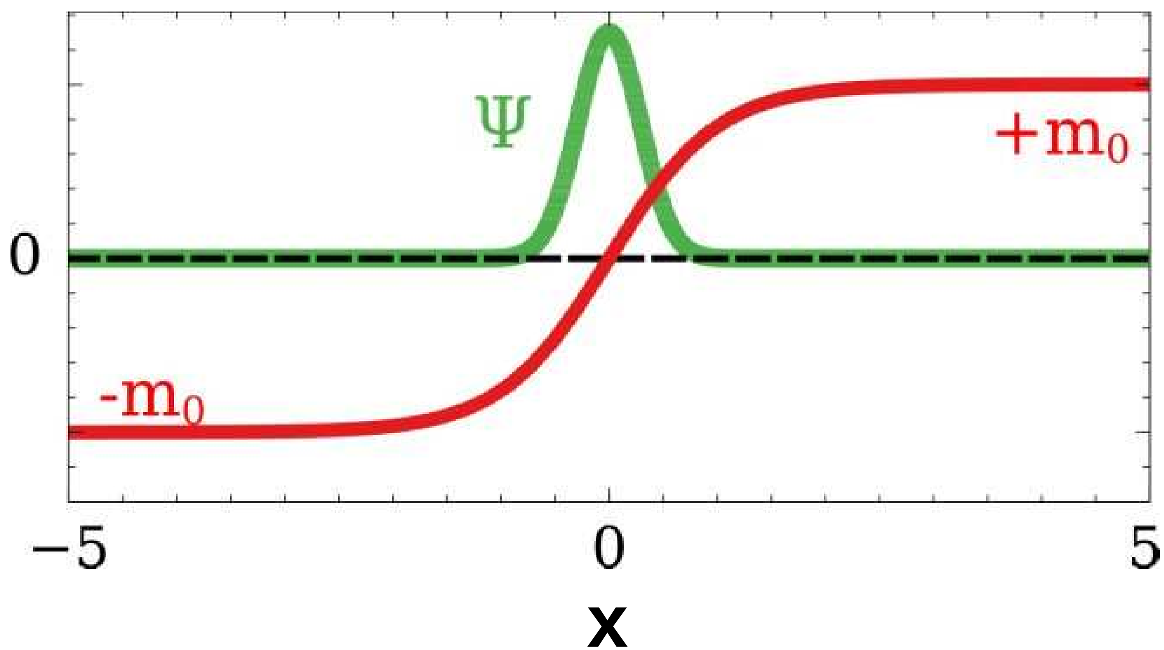
We need to create a “spinless” gapless state out of an insulator

Building an interface gas between two insulators

Lets take a 1d Dirac equation with spatially dependent mass

$$H = \begin{pmatrix} m(x) & p \\ p & -m(x) \end{pmatrix} = \sigma_x p + m(x)\sigma_z$$

$$m(\infty) = -m(-\infty) = m_0$$



Zero energy solution bound to the interface

$$\Psi = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix} e^{-\int_0^x m(\lambda) d\lambda}$$

$$H\Psi = 0$$

R. Jackiw and C. Rebbi
Phys. Rev. D 13, 3398 (1976)

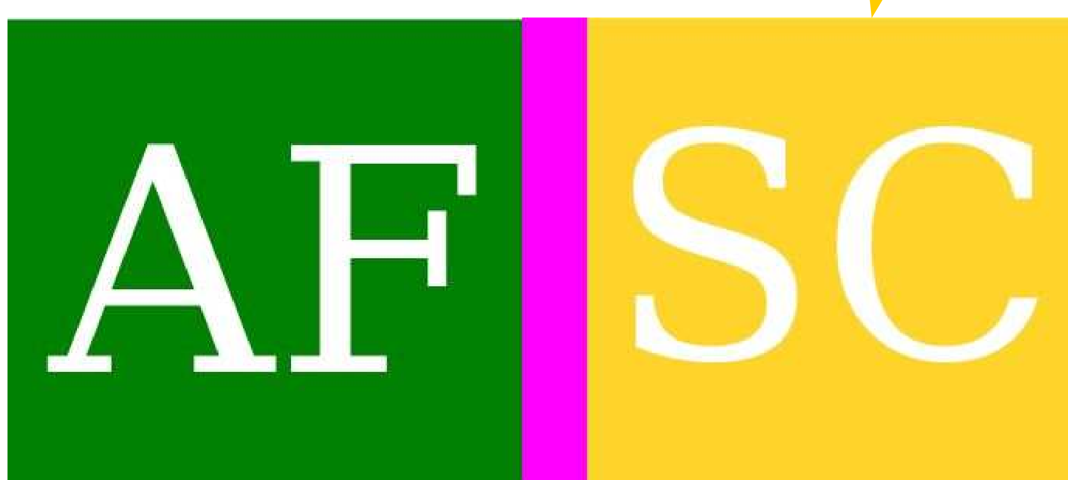
Interface modes between a 1D AF and a 1D SC

Kinetic part

Antiferromagnetic order

Superconducting order

$$H = H_{kin} + H_{AF} + H_{SC}$$



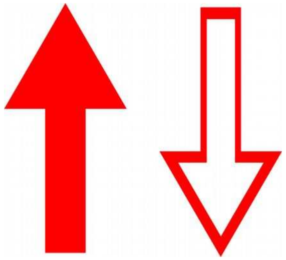
Solitonic modes between Dirac AF and SC

Total Hamiltonian

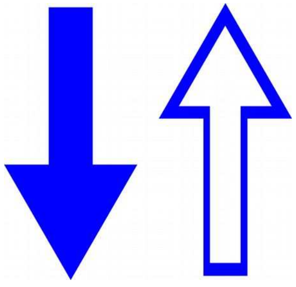
$$H = H_{kin} + H_{AF} + H_{SC}$$

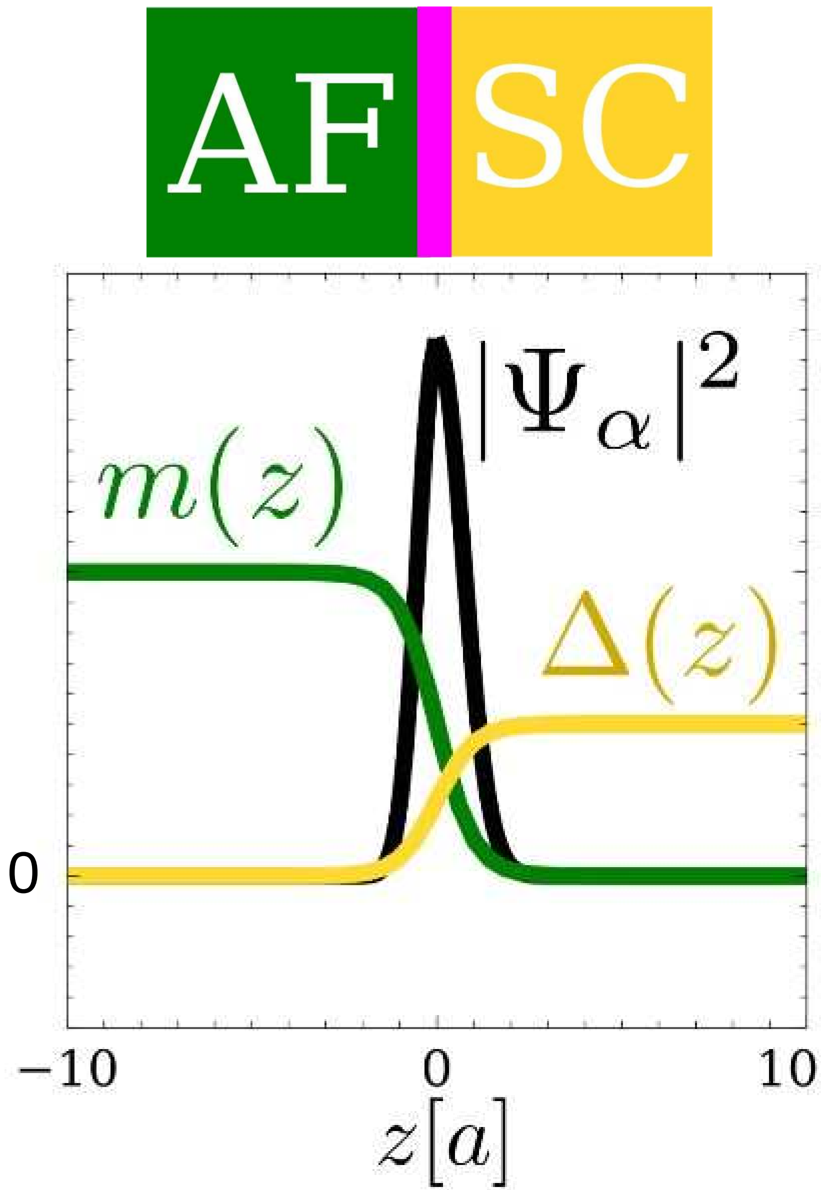
There will be two zero solutions

Sector #1
Up electron, down hole



Sector #2
Down electron, up hole

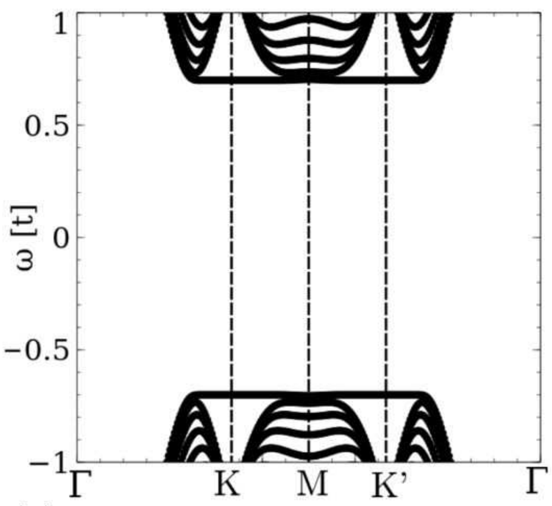




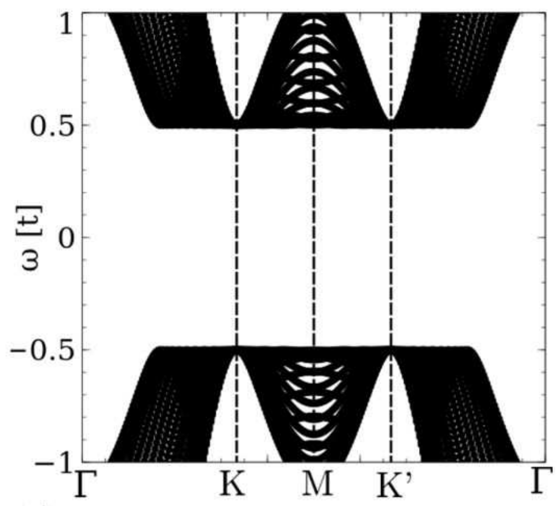
Phys. Rev. X 5, 041042 (2015)

Emergence of interfacial modes, no spin-orbit coupling

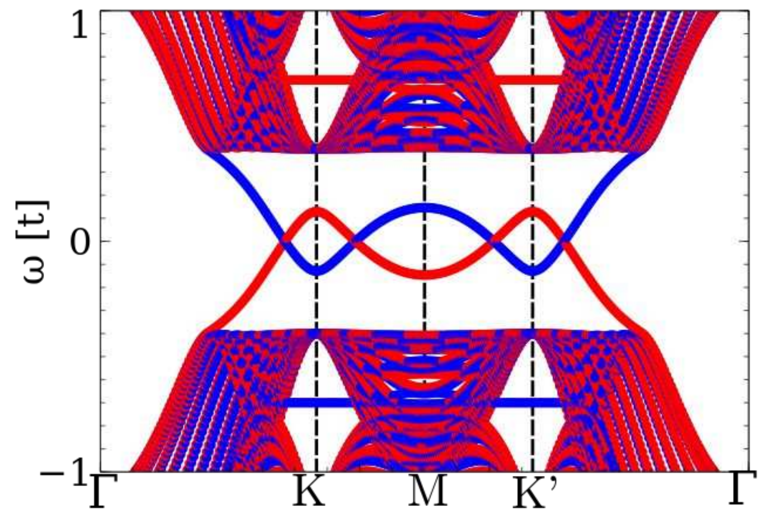
Antiferromagnet



Superconductor



AF/SC heterostructure

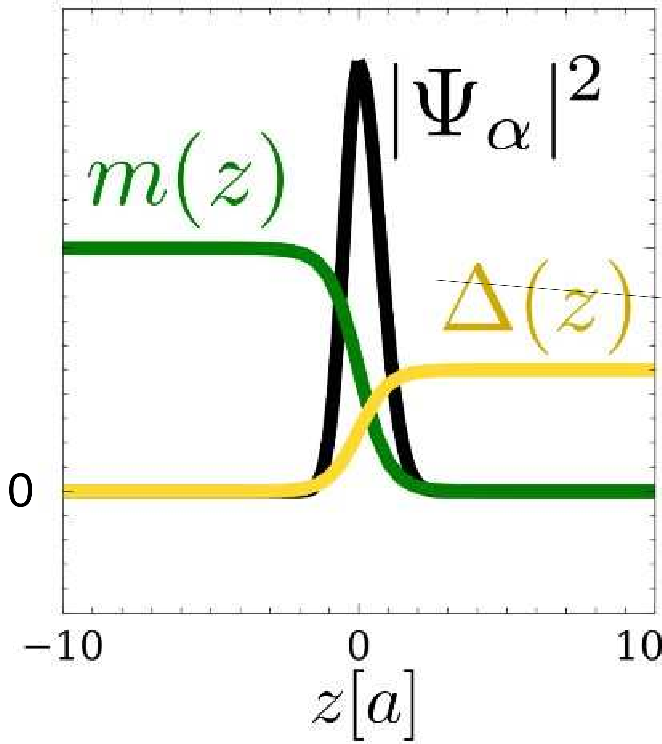


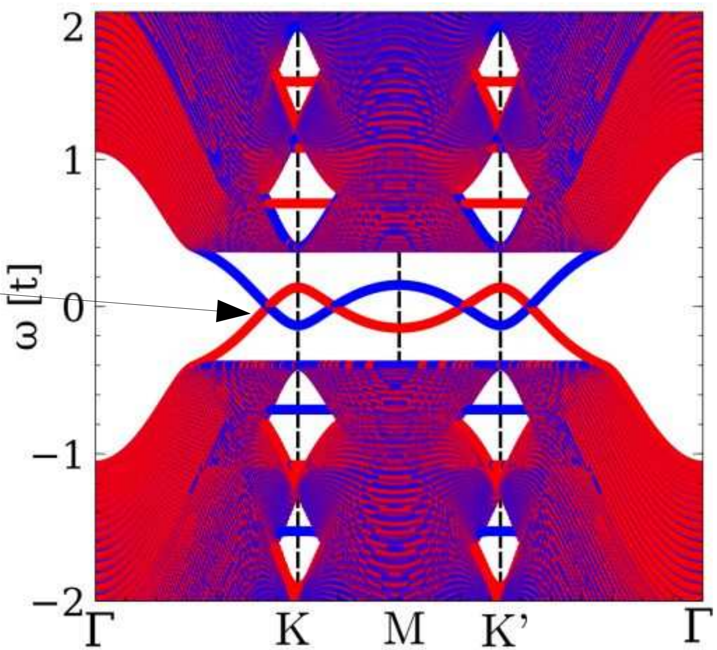
Interface states between AF and SC

Superconducting solitonic excitations

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

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

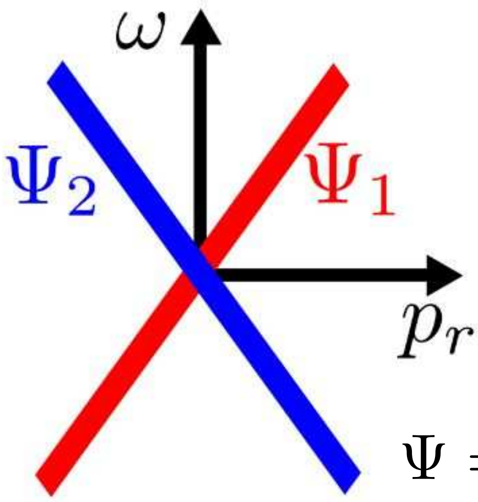




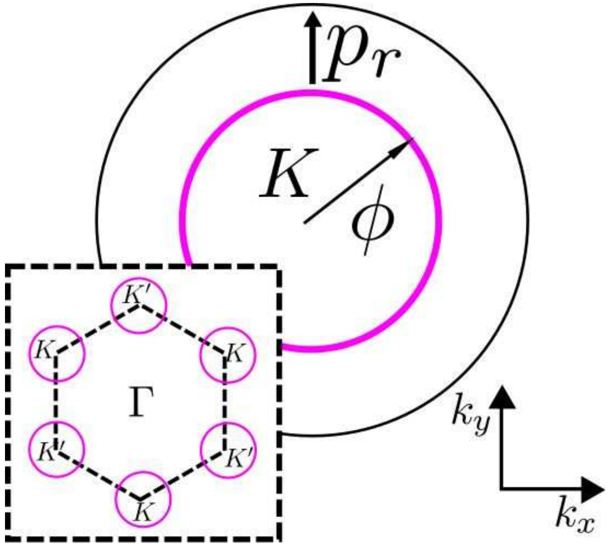
Effective model without spin-orbit coupling

Effective Hamiltonian without spin-orbit coupling

$$\mathcal{H}(p_r,\phi) = \Psi^\dagger \begin{pmatrix} v_r p_r & 0 \\ 0 & -v_r p_r \end{pmatrix} \Psi$$



$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

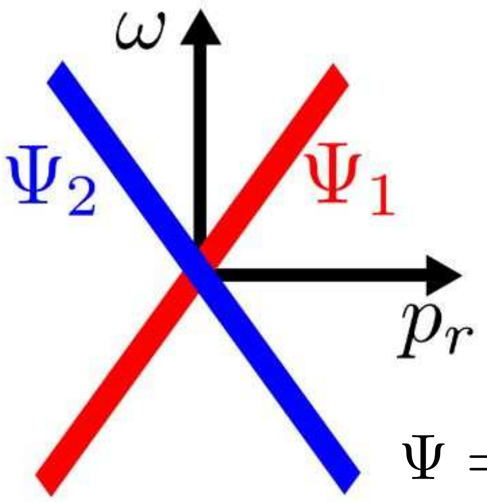


Every point of the Dirac line creates a zero mode

Effective model with spin-orbit coupling

Effective Hamiltonian with spin-orbit coupling

$$\mathcal{H}(p_r, \phi) = \Psi^\dagger \begin{pmatrix} v_r p_r & -i\lambda e^{i\phi} \\ i\lambda e^{-i\phi} & -v_r p_r \end{pmatrix} \Psi$$



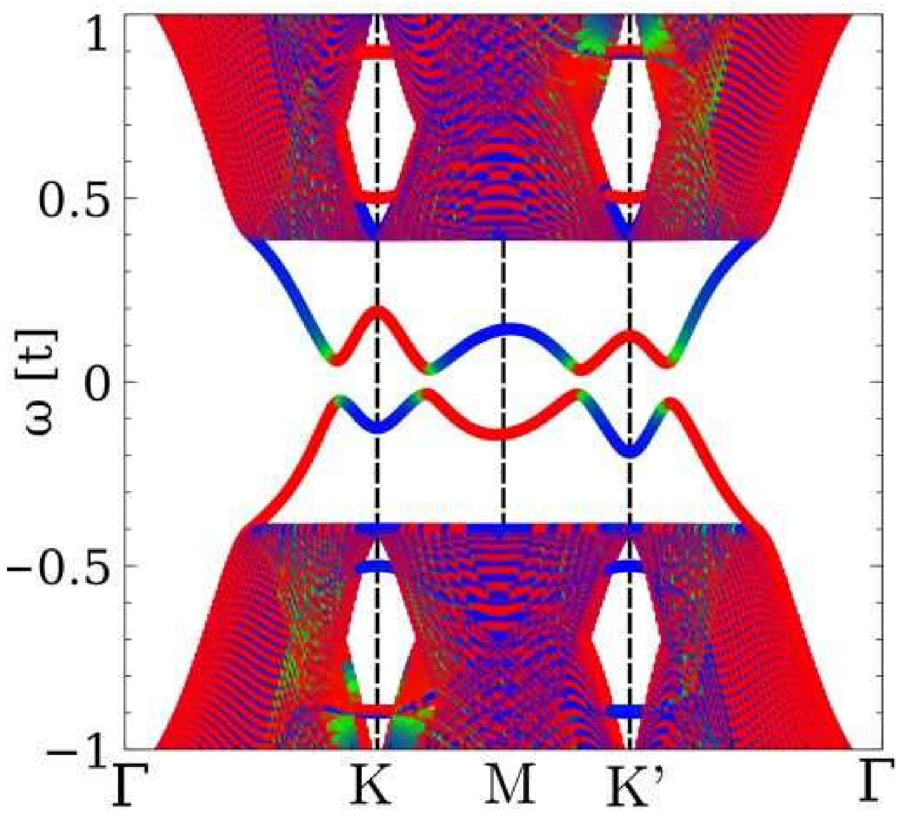
$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

Spin-orbit coupling takes the form of a chiral pairing

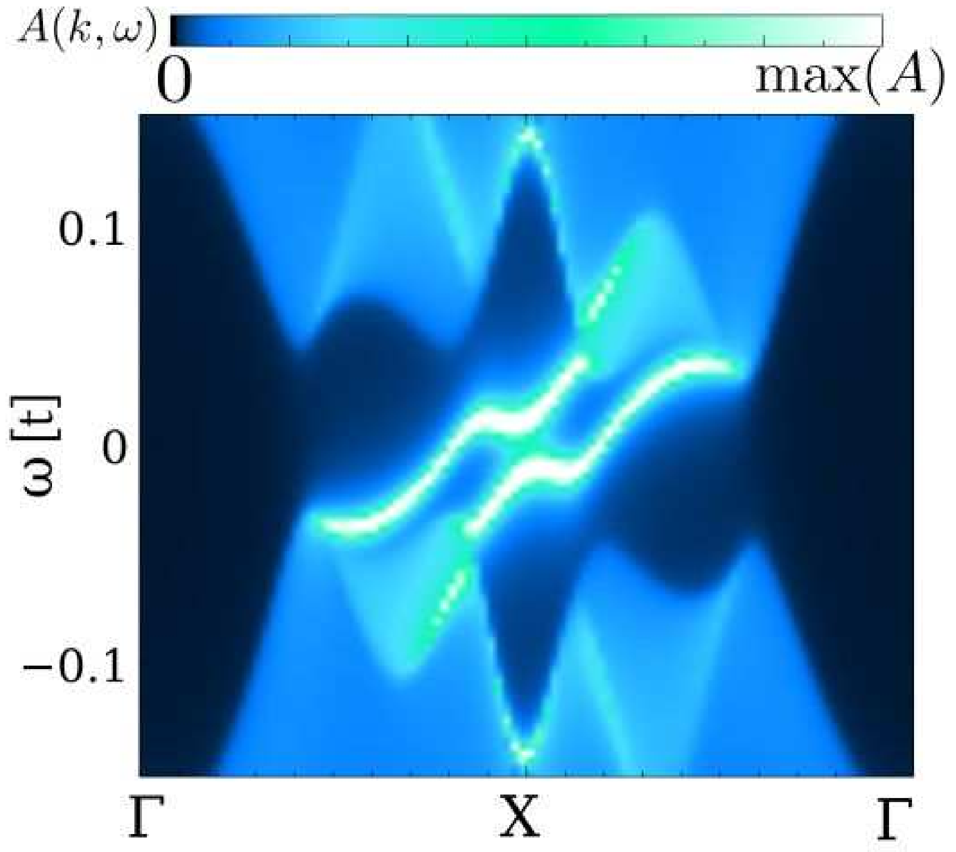
Chern number $\mathcal{C} = \pm 1$ **per Dirac line**

Adding spin-orbit coupling

Band structure

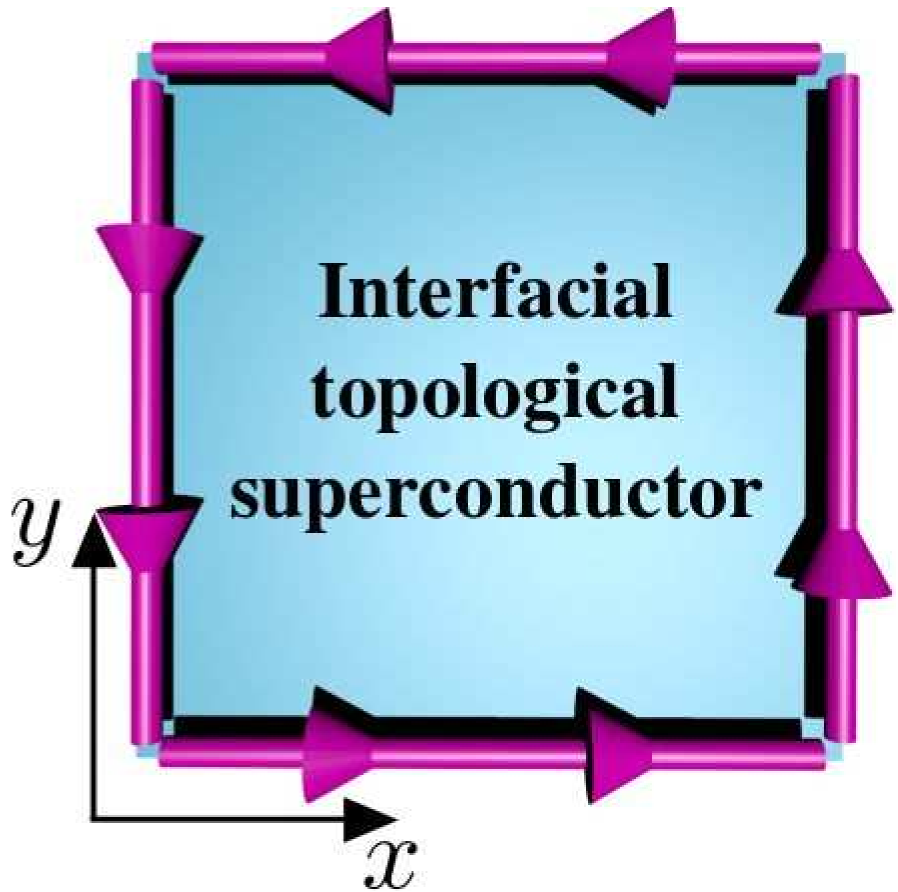


Edge spectral function

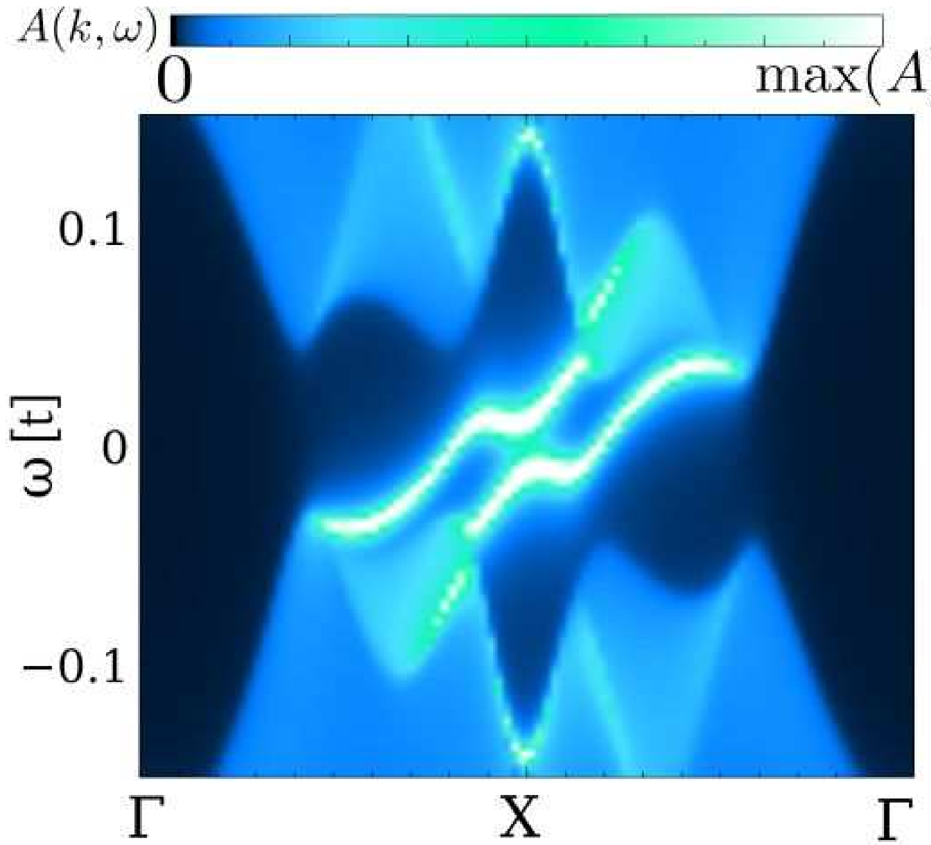


Two co-propagating edge modes

An interfacial topological superconductor



Edge spectral function



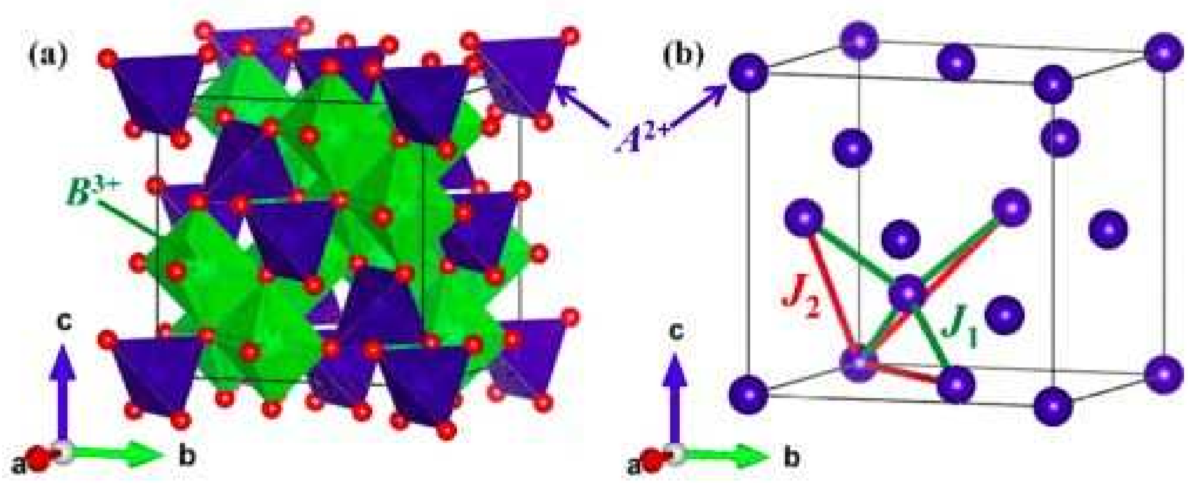
The interface realizes a topological superconductor

Possible materials, spinels

- Antiferromagnet forming a diamond lattice

Antiferromagnetic spinels

$CoAl_2O_4$



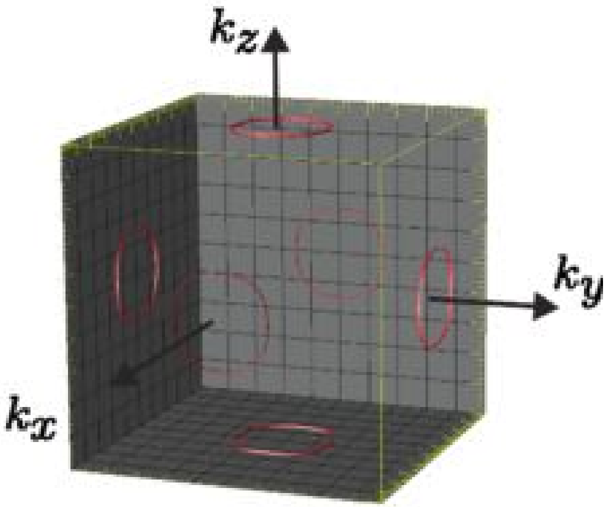
Co atoms form a diamond lattice

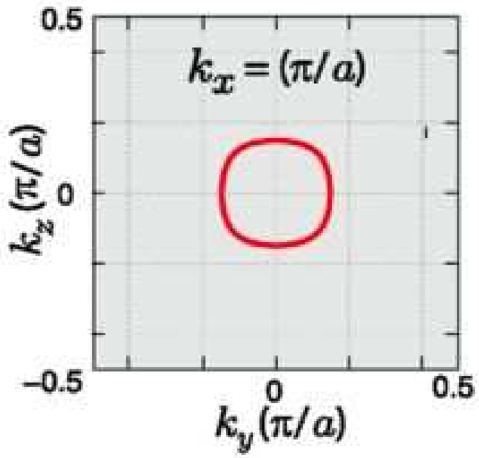
Phys. Rev. B 95, 094404 (2017)

Possible materials, Dirac materials in the AF phase

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

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



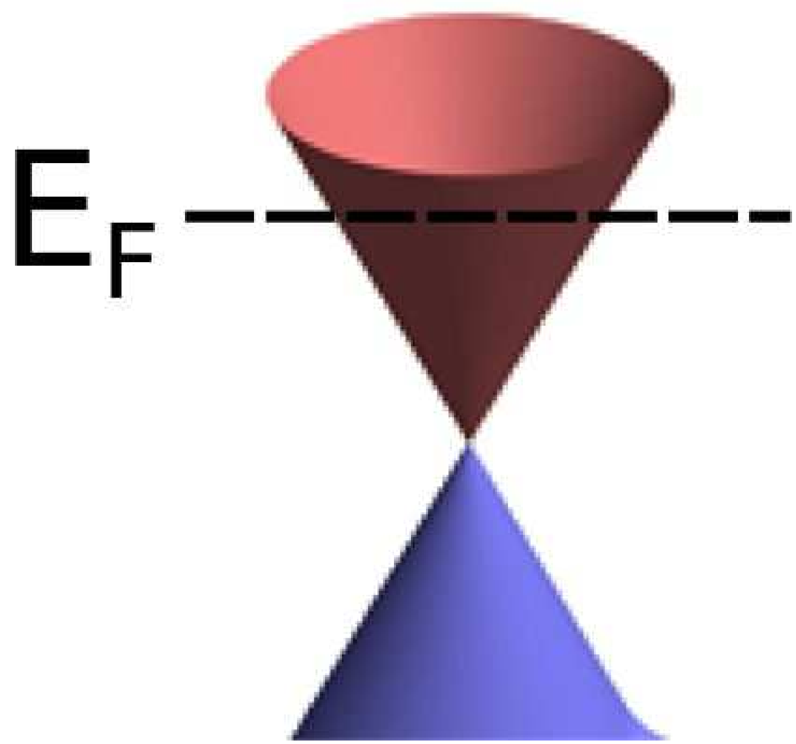


Antiferromagnets whose paramagnetic state hosts Dirac lines

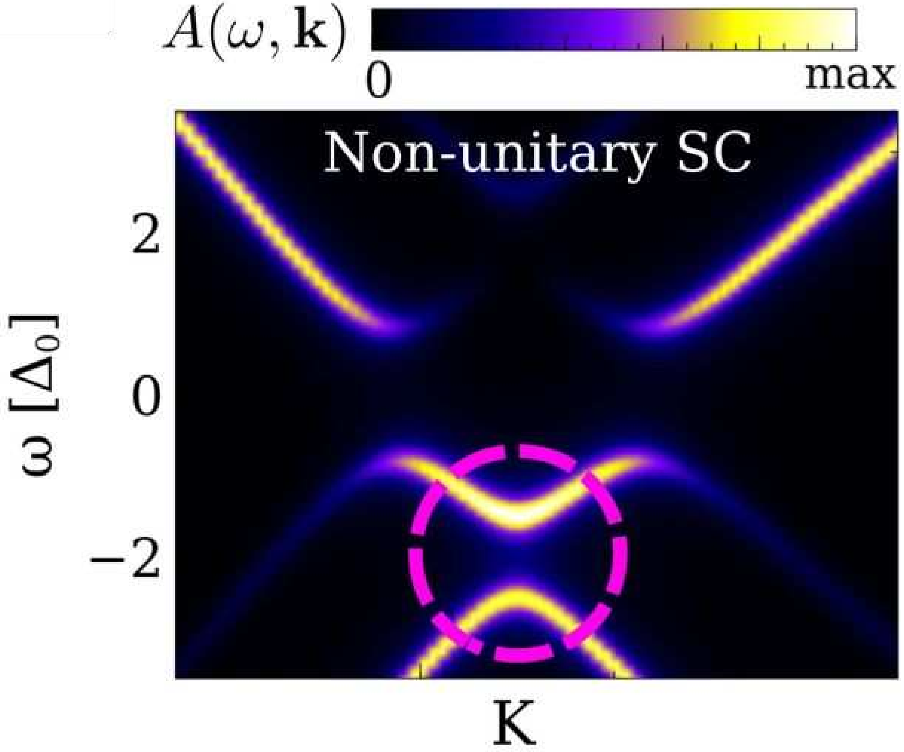
Detecting non-unitary superconductivity through deep Dirac points

Superconducting symmetry from ARPES experiments

Normal state band structure



ARPES in superconducting state



Can we detect non-unitary superconductivity from an ARPES experiment?

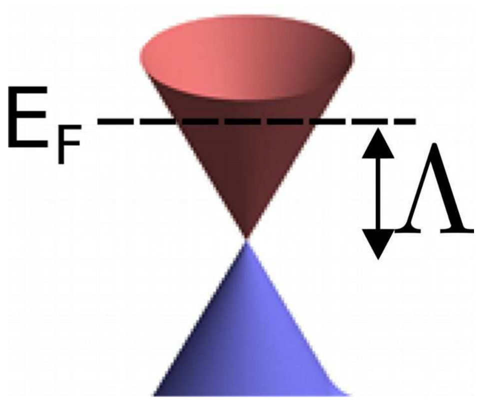
Gap opening by singlet multiorbital superconductivity

Two orbital band structure with a Dirac crossing, singlet pairing

Hamiltonian in normal state

$$\psi^\dagger_{\mathbf{k}} = (c^\dagger_{\alpha,\mathbf{k}}, c^\dagger_{\beta,\mathbf{k}}),$$

$$H_0^{DP}(\mathbf{k}) = -\Lambda\tau_0 + \tau_x k_x + \tau_y k_y$$



Hamiltonian in SC state

$$\Psi^\dagger_{\mathbf{k}} = (c^\dagger_{\alpha_0,\uparrow,\mathbf{k}}, c^\dagger_{\beta_0,\uparrow,\mathbf{k}}, c_{\alpha_0,\downarrow,-\mathbf{k}}, c_{\beta_0,\downarrow,-\mathbf{k}}),$$

$$H_{BdG}(\mathbf{k}) = \begin{pmatrix} H_0^{DP}(\mathbf{k}) & \Delta(\mathbf{k}) \\ \Delta(\mathbf{k}) & -H_0^{DP}(-\mathbf{k}) \end{pmatrix}$$

Effective Hamiltonian after Schrieffer-Wolff transformation

$$H^{DP} = H_0^{DP} + \frac{\Delta\Delta^\dagger}{2\Lambda}$$

SC gap opening at the Dirac point if $\Upsilon = \mathrm{Tr}[\tau_z \Delta\Delta^\dagger] \neq 0$

Topological invariant of the gap opening

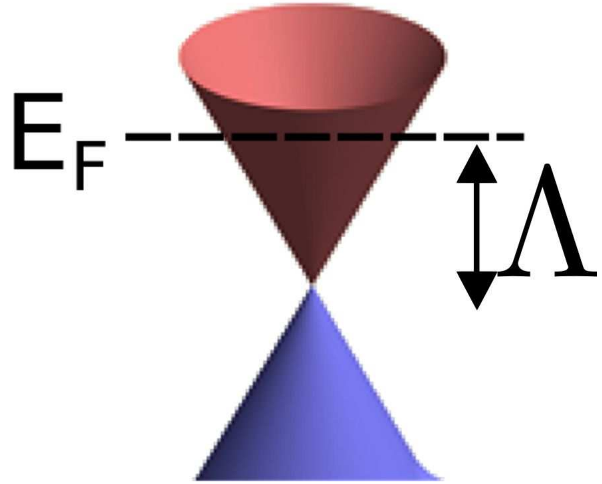
Full Hamiltonian

$$H_{BdG}(\mathbf{k}) = \begin{pmatrix} H_0^{DP}(\mathbf{k}) & \Delta(\mathbf{k}) \\ \Delta(\mathbf{k}) & -H_0^{DP}(-\mathbf{k}) \end{pmatrix}$$

Effective Hamiltonian

$$H^{DP} = -\bar{\Lambda}\tau_0 + \bar{p}_x\tau_x + \bar{p}_y\tau_y + \gamma_z\tau_z$$

$$\gamma_z = \Upsilon/4\Lambda$$



SC gap opening at the Dirac point if $\Upsilon = \mathrm{Tr}[\tau_z \Delta\Delta^\dagger] \neq 0$

Berry flux (non-integer Chern number) associated to the Dirac crossing

$$C = \frac{1}{2}\mathrm{sign}(\Upsilon)\mathrm{sign}(\Lambda)$$

Conditions for a Dirac gap opening

$$\Upsilon = \mathrm{Tr}(\tau_z \Delta \Delta^\dagger)$$

No gap opening $\Upsilon = 0$

Unitary states

Intraorbital

$$\Delta \sim \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Interorbital

$$\Delta \sim \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

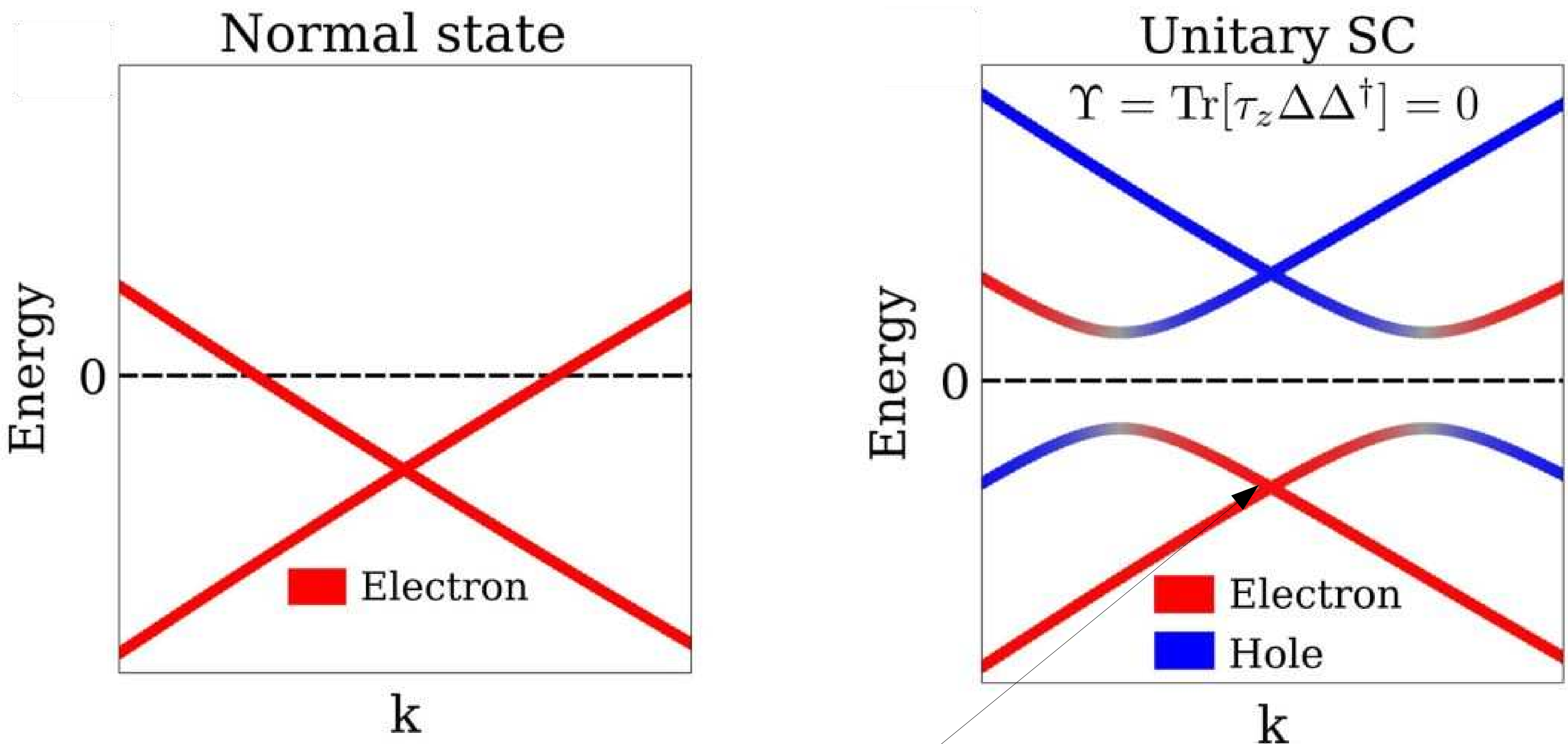
Gap opening $\Upsilon \neq 0$

Non-unitary states

Non-unitary intraorbital

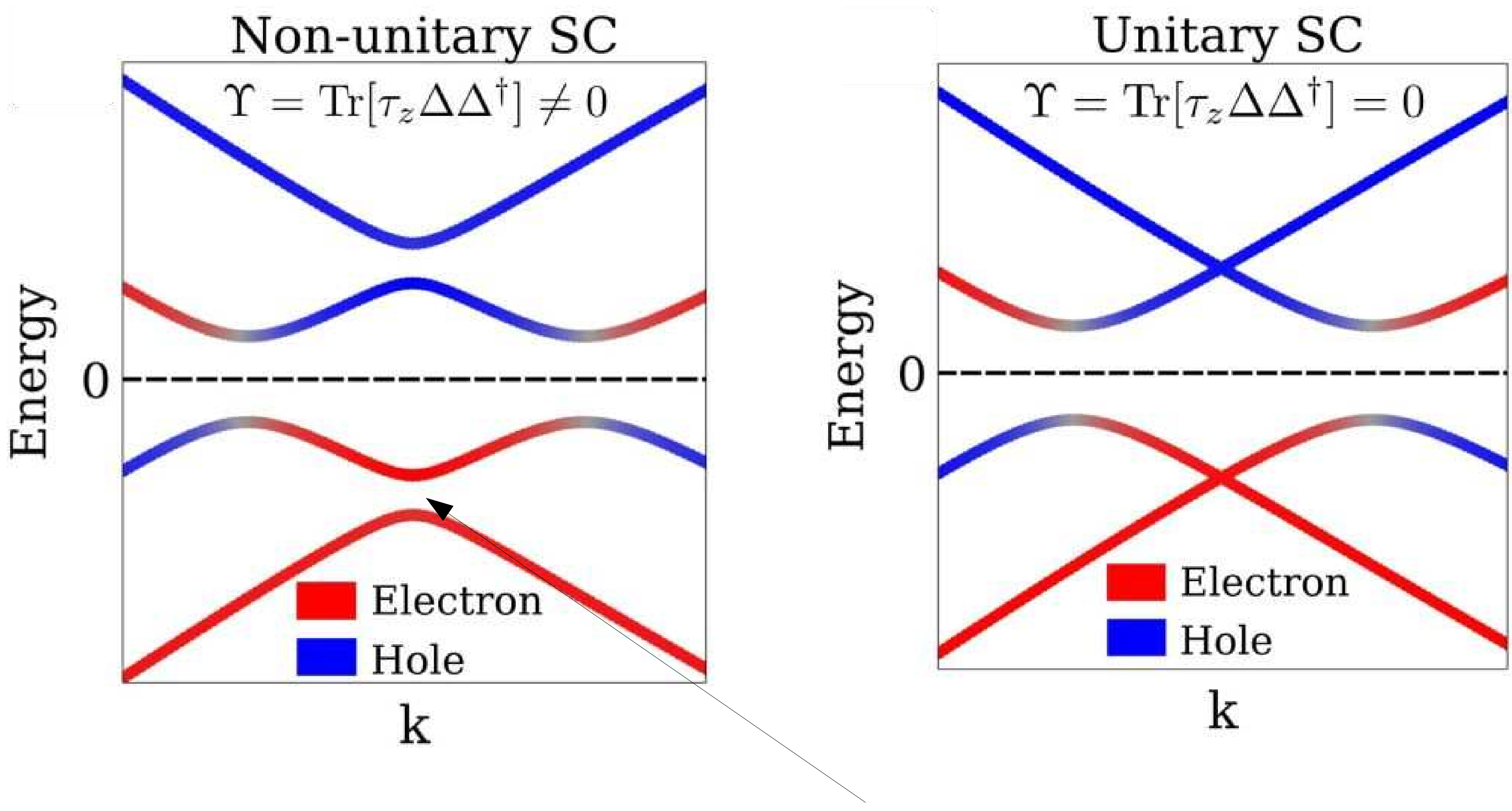
$$\Delta \sim \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Dirac crossing in the superconducting state



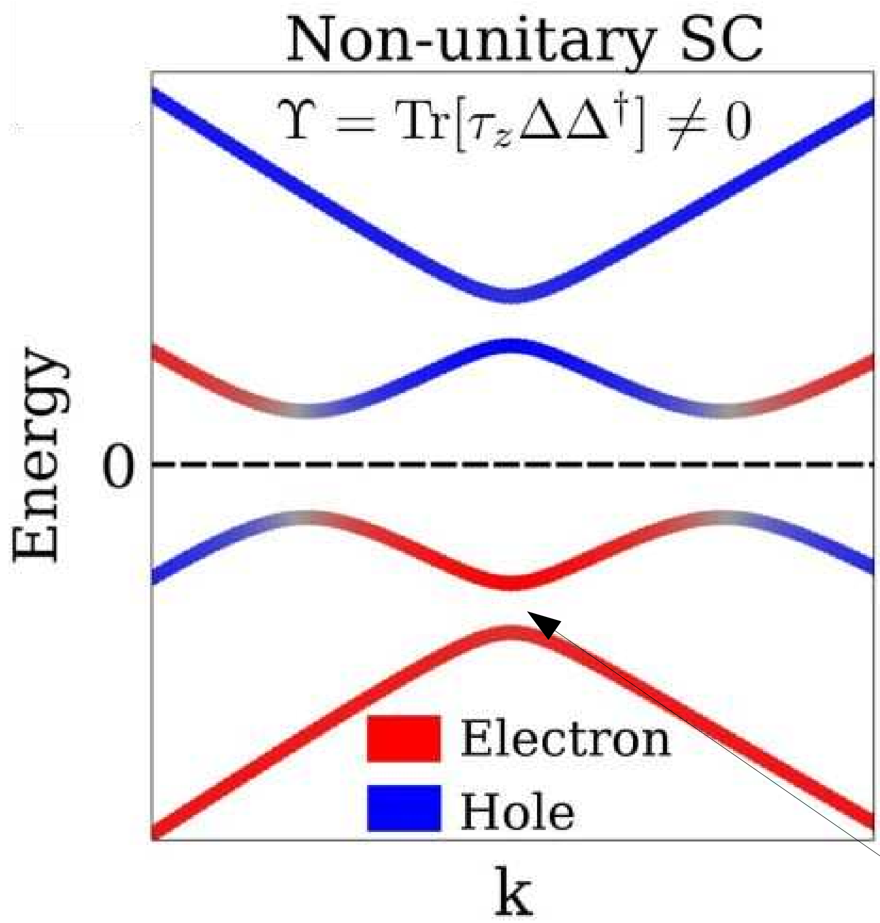
Conventional superconducting state: Dirac point remains closed

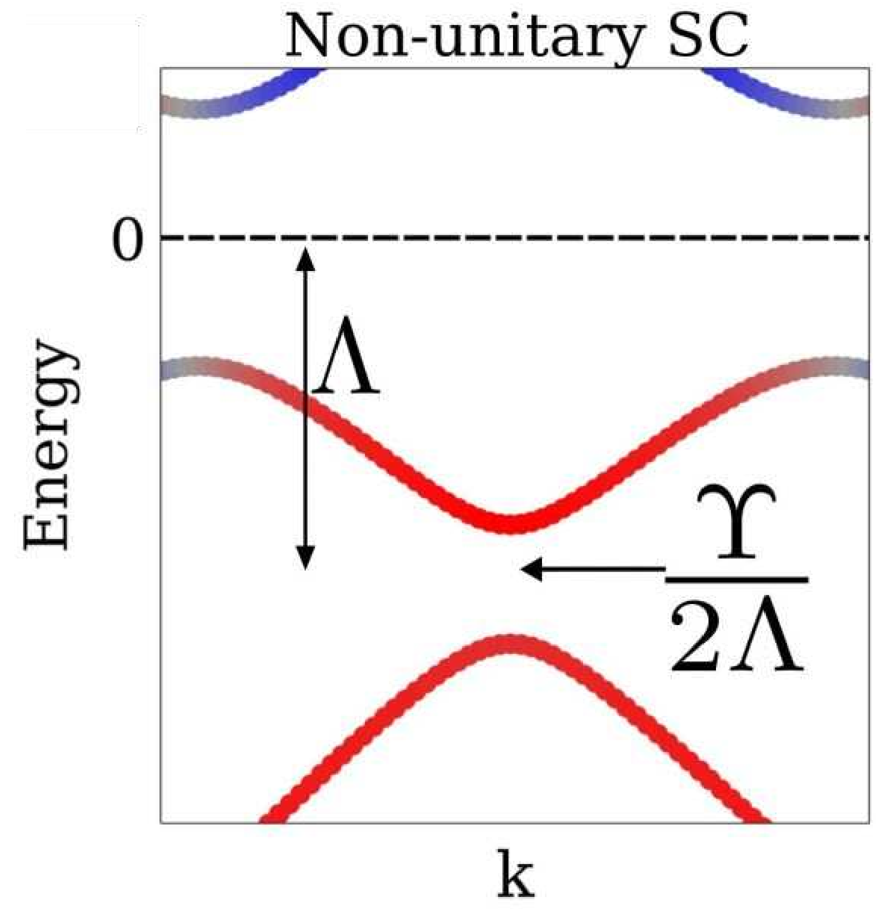
Dirac crossing in the superconducting state



Dirac gap generation is a hallmark of non-unitary superconductivity

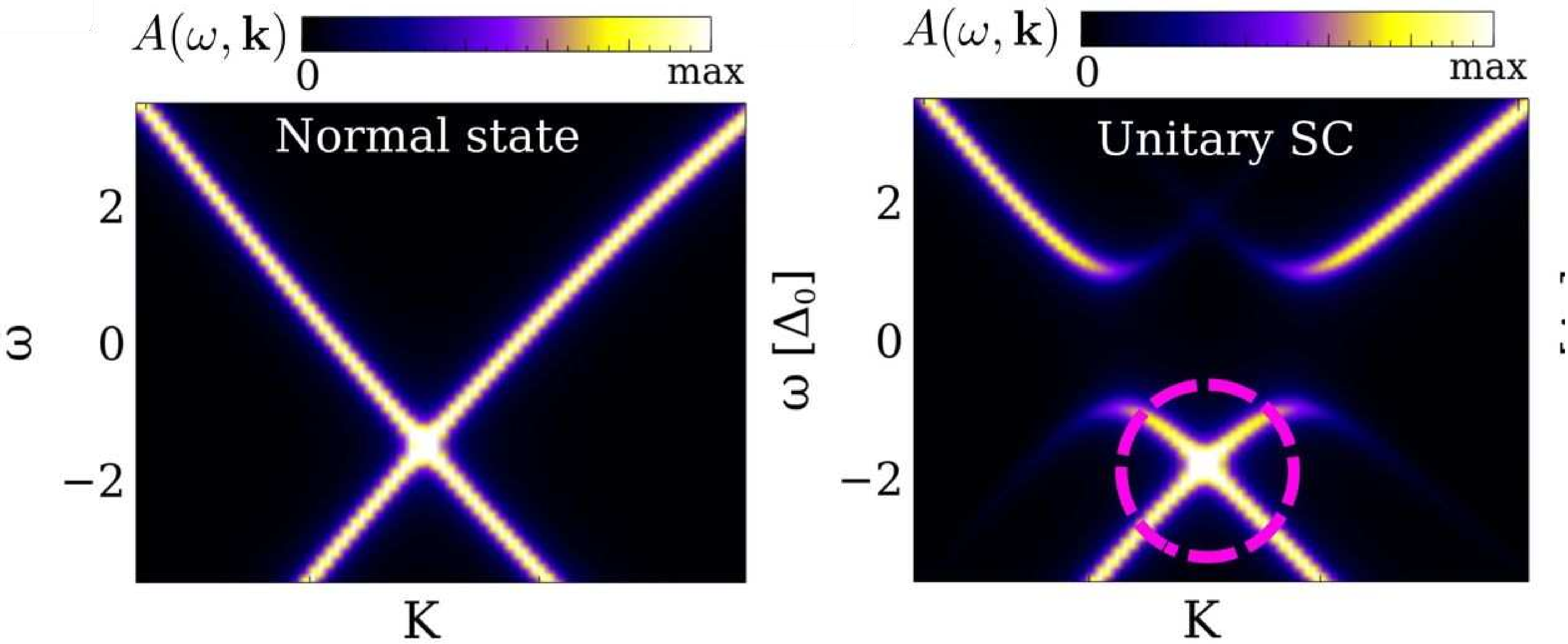
Dirac crossing in the superconducting state





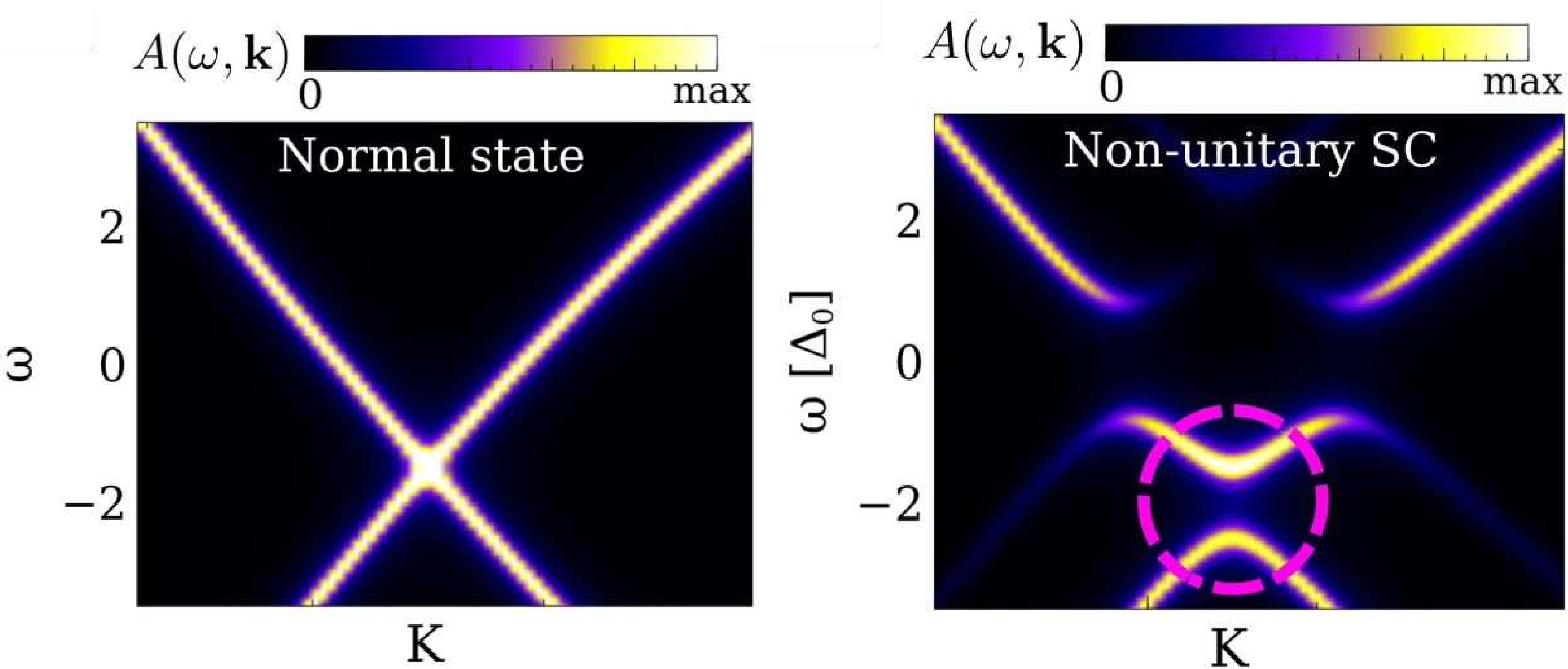
Dirac gap generation is a hallmark of non-unitary superconductivity

ARPES of a unitary SC



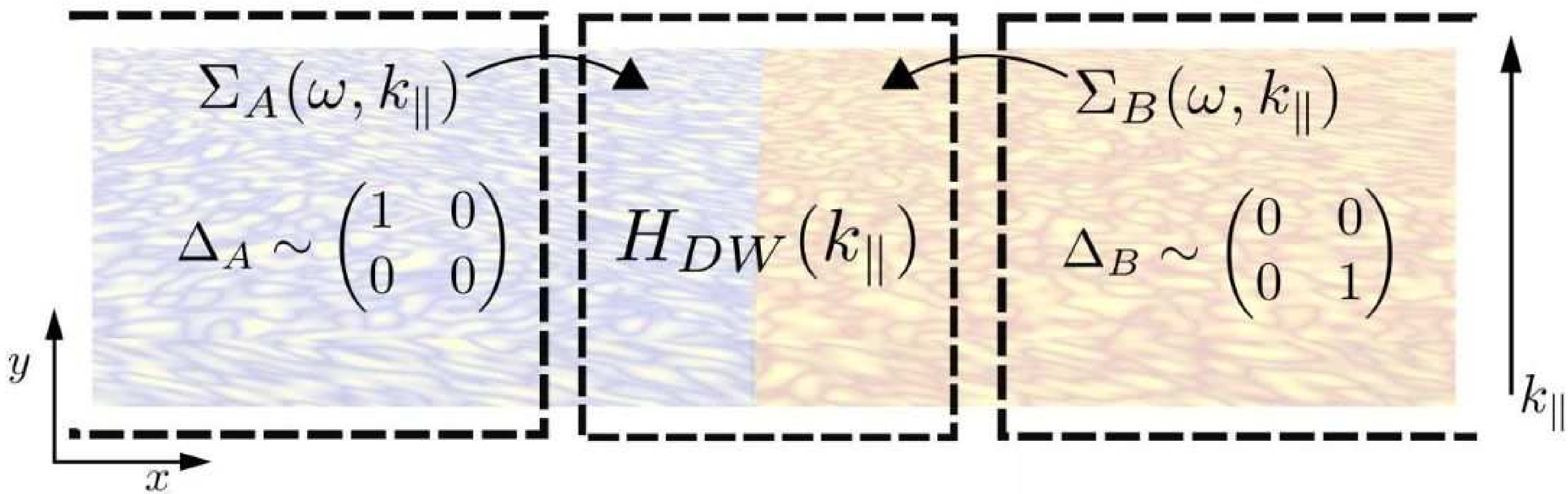
No gap generated at the Dirac point for a unitary state

ARPES of a non-unitary SC



Finite gap generated at the Dirac point for a non-unitary state

Superconducting orbital domain wall

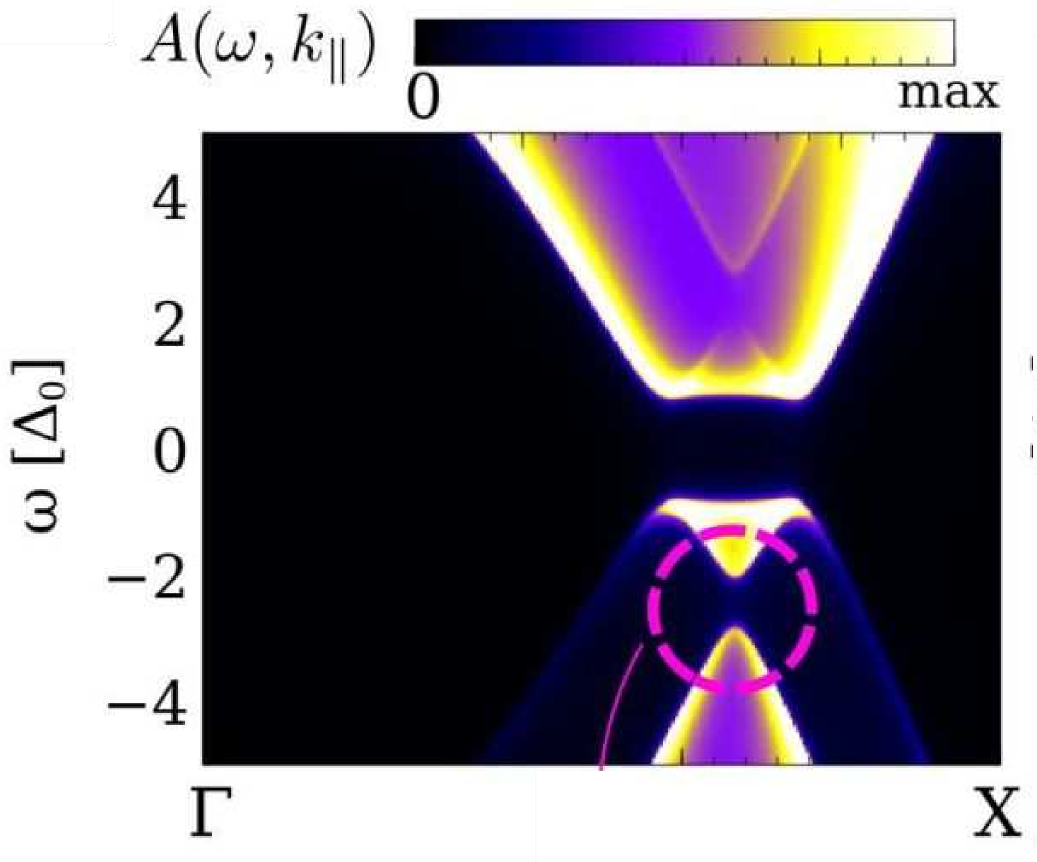


Is a superconducting domain wall visible in a spectral function?

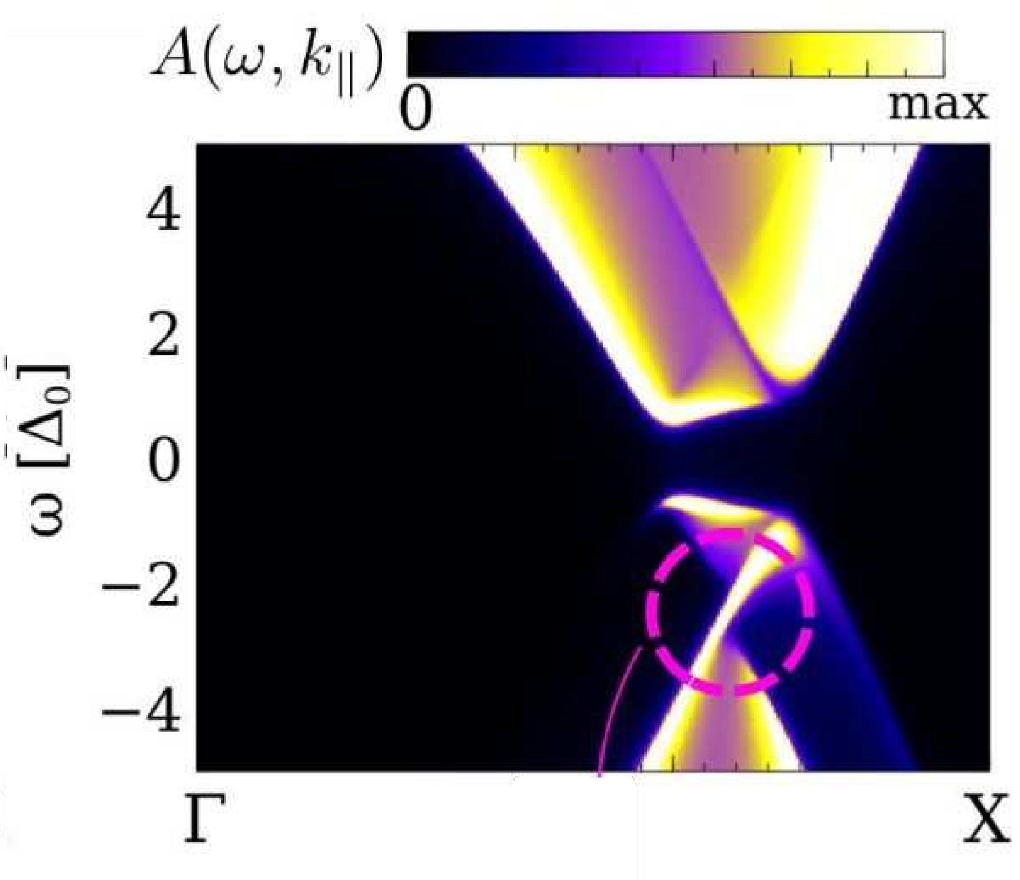
$$A(\omega, \mathbf{k}) = -\frac{1}{\pi}\mathrm{Im}(\mathrm{Tr}\{P_e[\omega - H(\mathbf{k}) + i0^+]^{-1}\})$$

ARPES of the SC with and without SC domain wall

Without domain wall



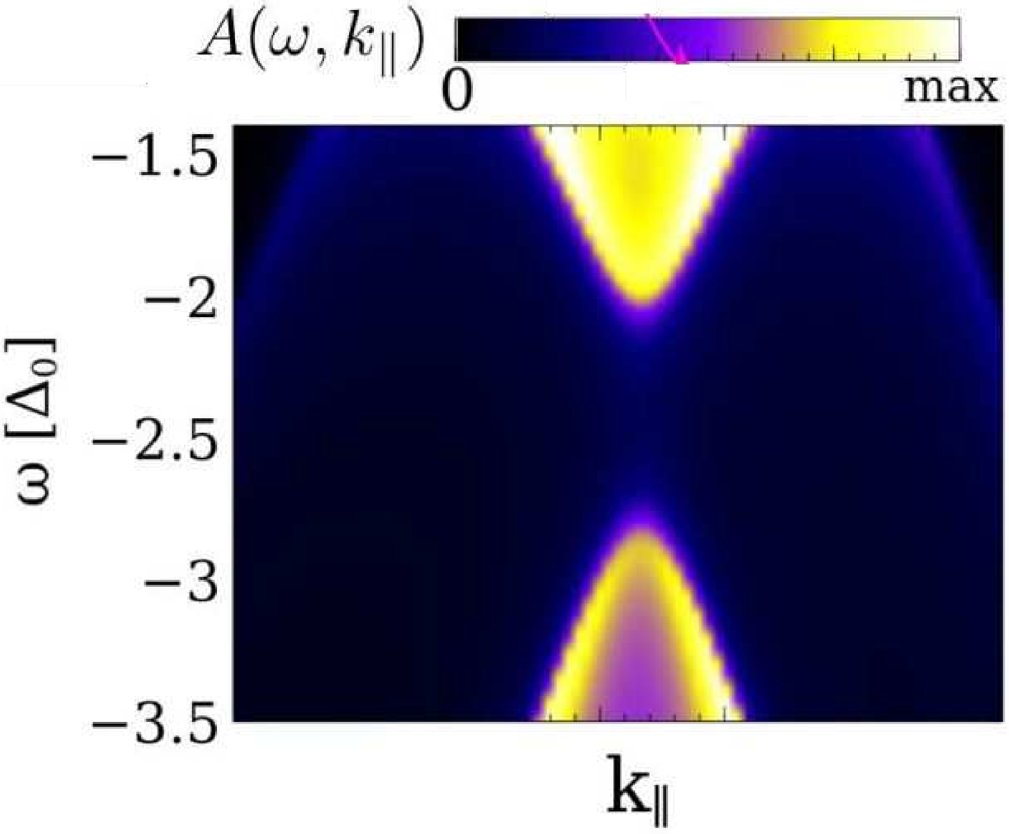
With domain wall



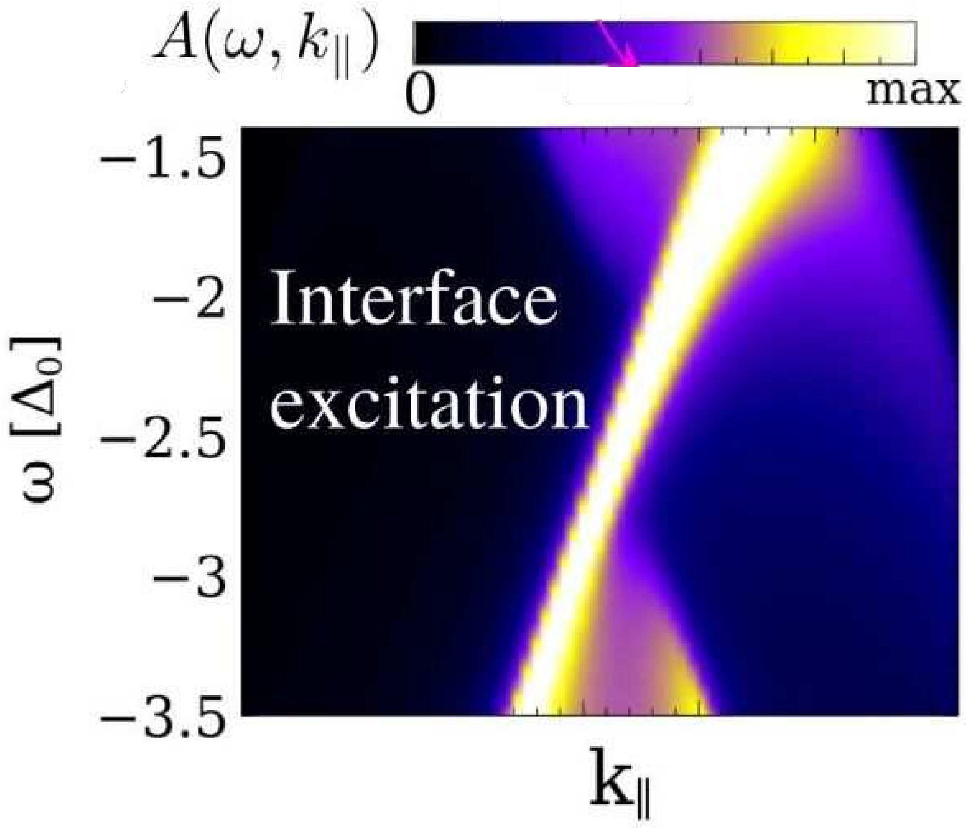
Superconducting domains generate states inside the Dirac gap

ARPES of the SC with and without SC domain wall

Without domain wall



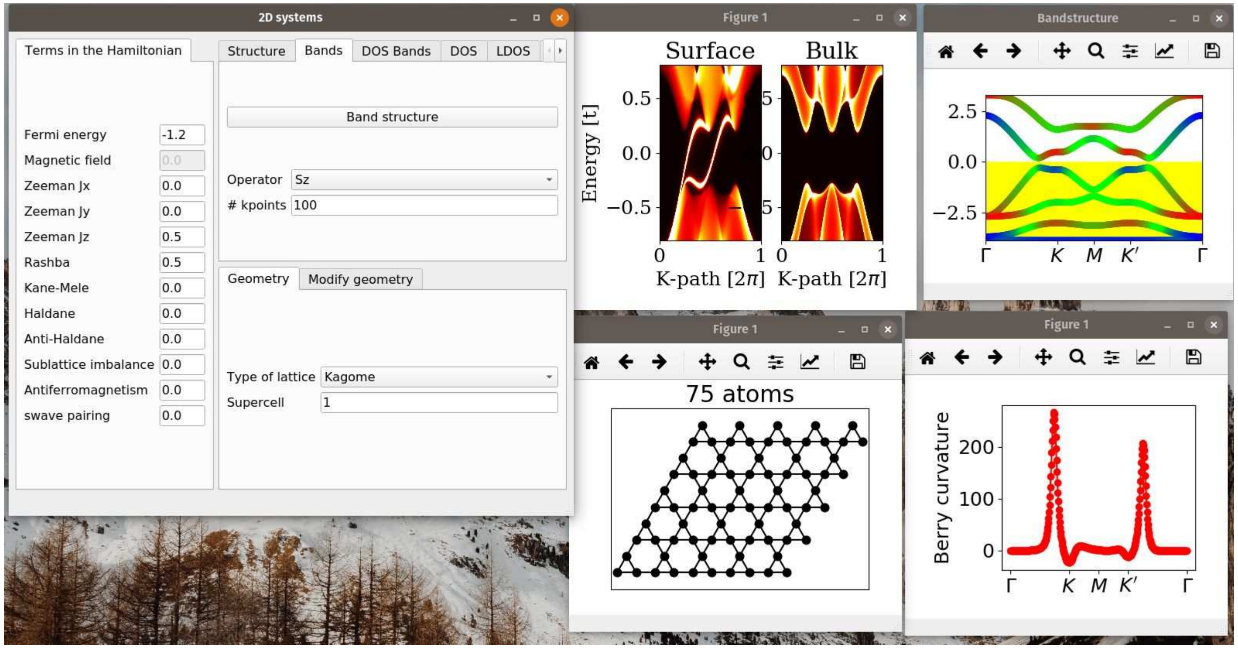
With domain wall



Superconducting domains generate states inside the Dirac gap

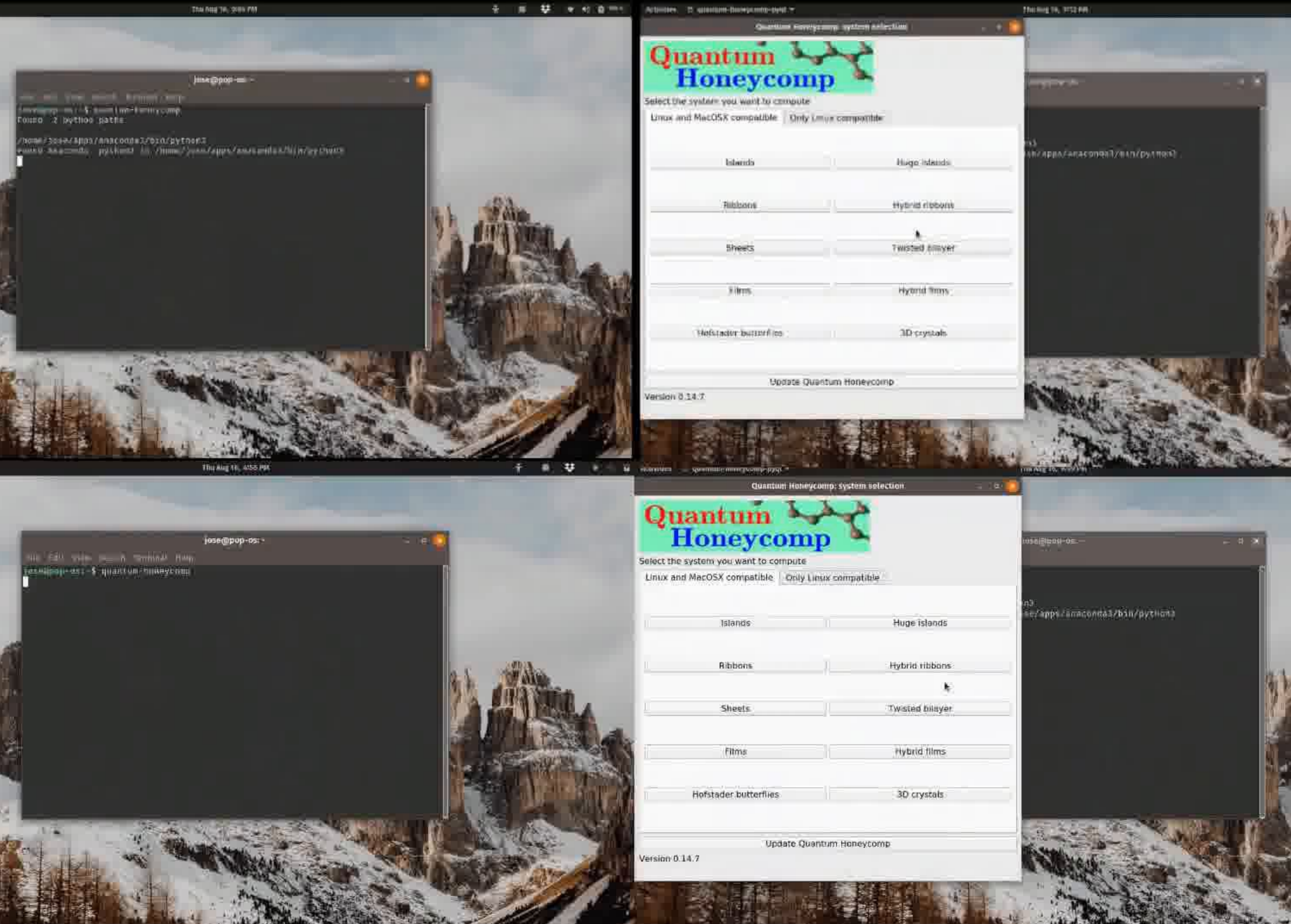
Computing electronic properties

A user interface to compute electronic properties



Quantum Honeycomp: open source interactive interface for tight binding modeling

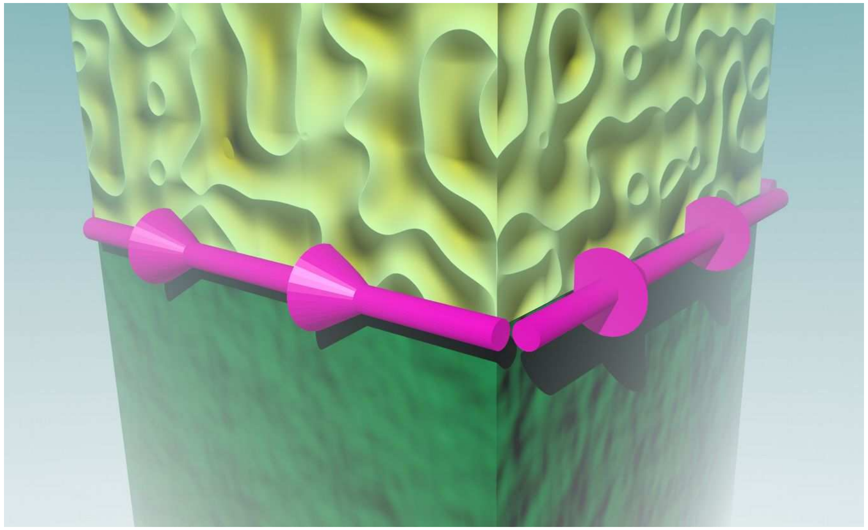
https://github.com/joselado/quantum-honeycomp



jose@pop-os: ~
Found 2 python paths
/home/jose/apps/anaconda3/bin/python3
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
jose@pop-os:~$ quantum-honeycomp

Take home

- **Antiferromagnetically gaped Dirac points allow to generate topological superconductors**
- **ARPES can detect non-unitary multiorbital superconductivity in doped Dirac materials**



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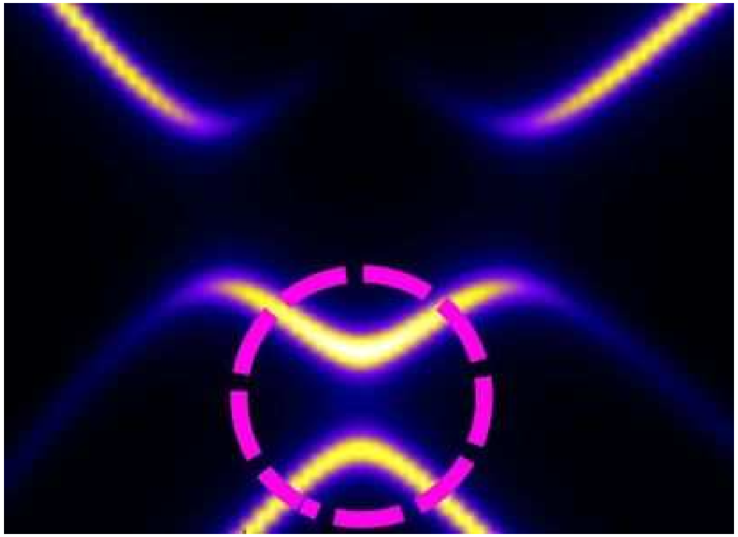

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