Topological superconductivity with antiferromagnetic insulators

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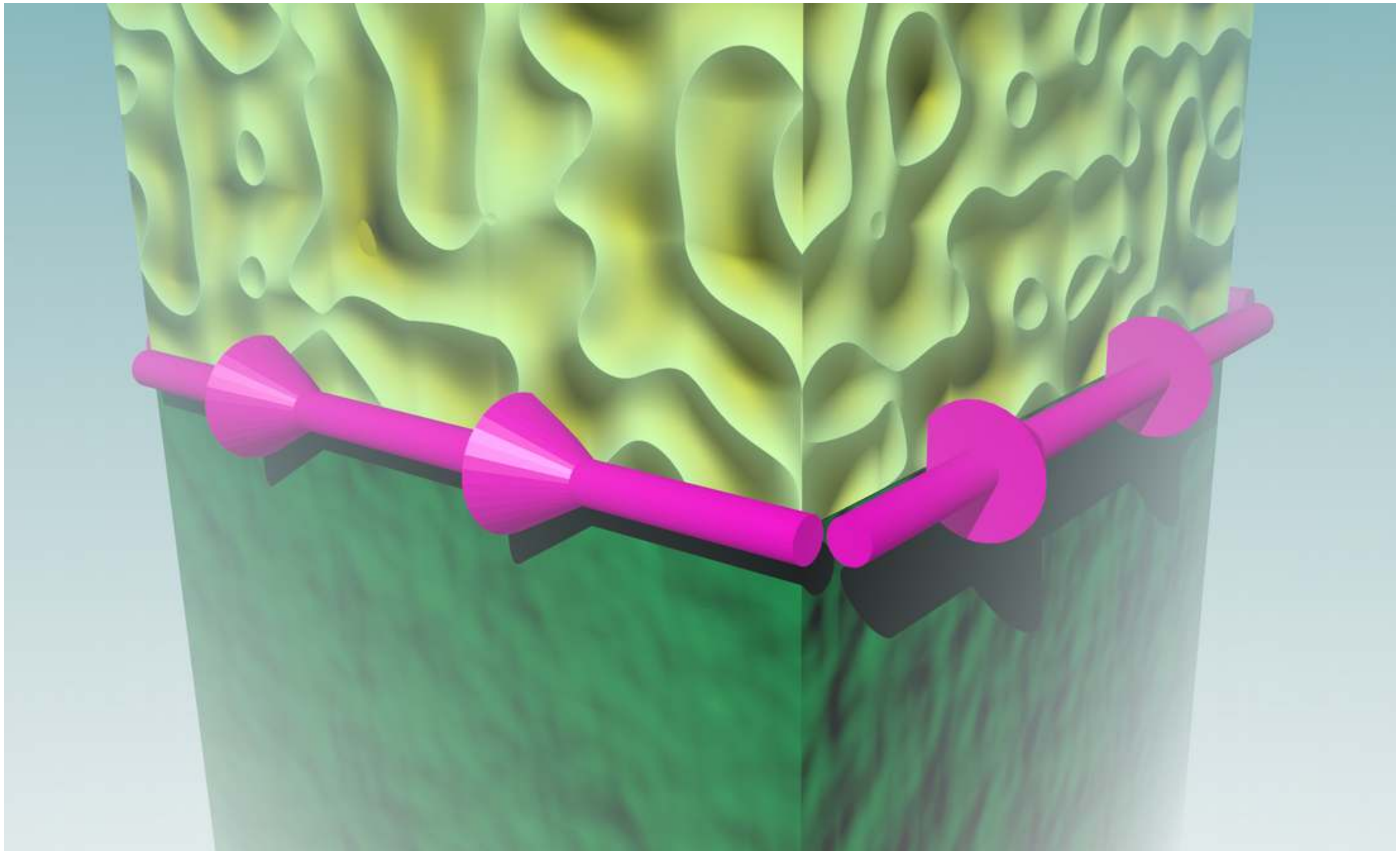


arXiv:1803.01781

OSS2018, April 11th 2018

About

ETH Zurich, Switzerland

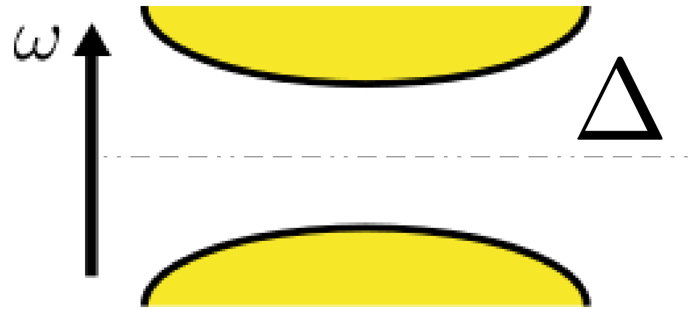
Institute for Theoretical Physics

Prof. Manfred Sigrist's group

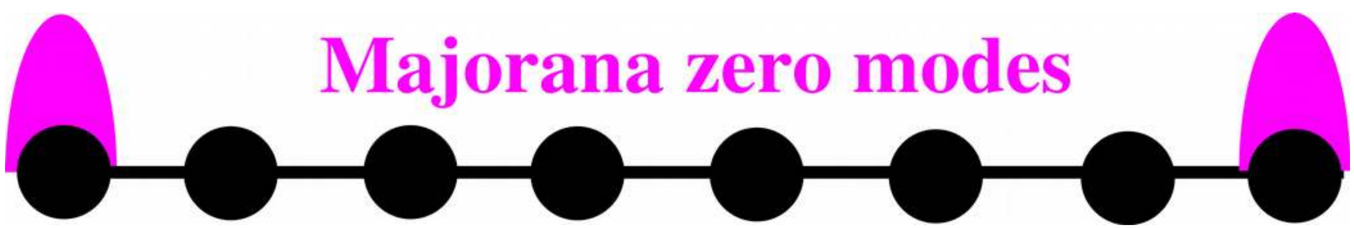
Topological superconductors

Topological superconductors with broken time reversal symmetry

Gapped bulk excitations

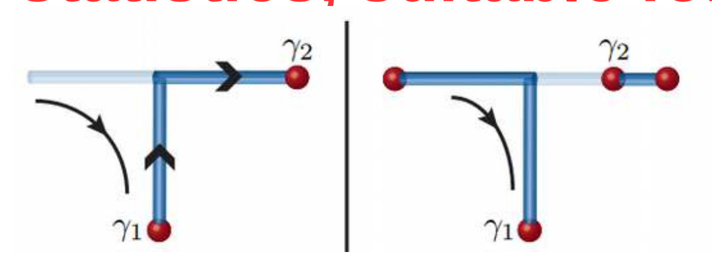


Gapless surface modes, single Majorana mode per edge



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

Anyonic statistics, suitable for quantum computing



Nature Physics 7, 412-417 (2011)

Engineering topological phases of matter

Topological superconductors are extremely rare in nature

Can we create an artificial topological superconductor using conventional materials?

Common material # 1 + **Common material # 2** = **Topological material**

C.W.J. Beenakker, Ann. Rev. Condens. Matter Phys. 4, 113-136 (2013)

J. Alicea, Rep. Prog. Phys. 75, 076501 (2012)

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

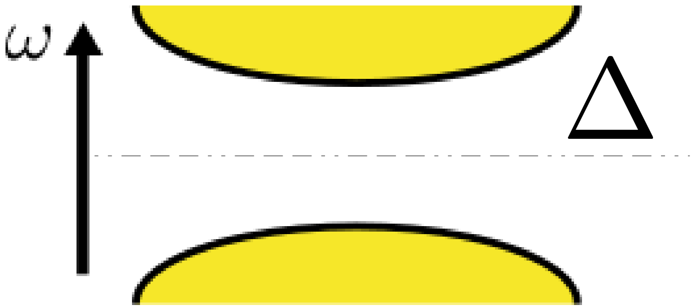
2d topological superconductor at the interface

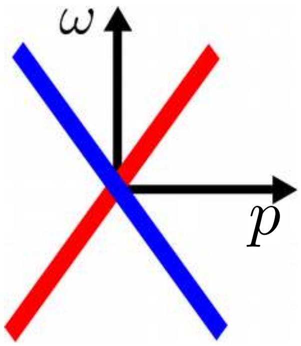
How to do your own topological superconductor

Ingredients

- s-wave pairing
- Helical states

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





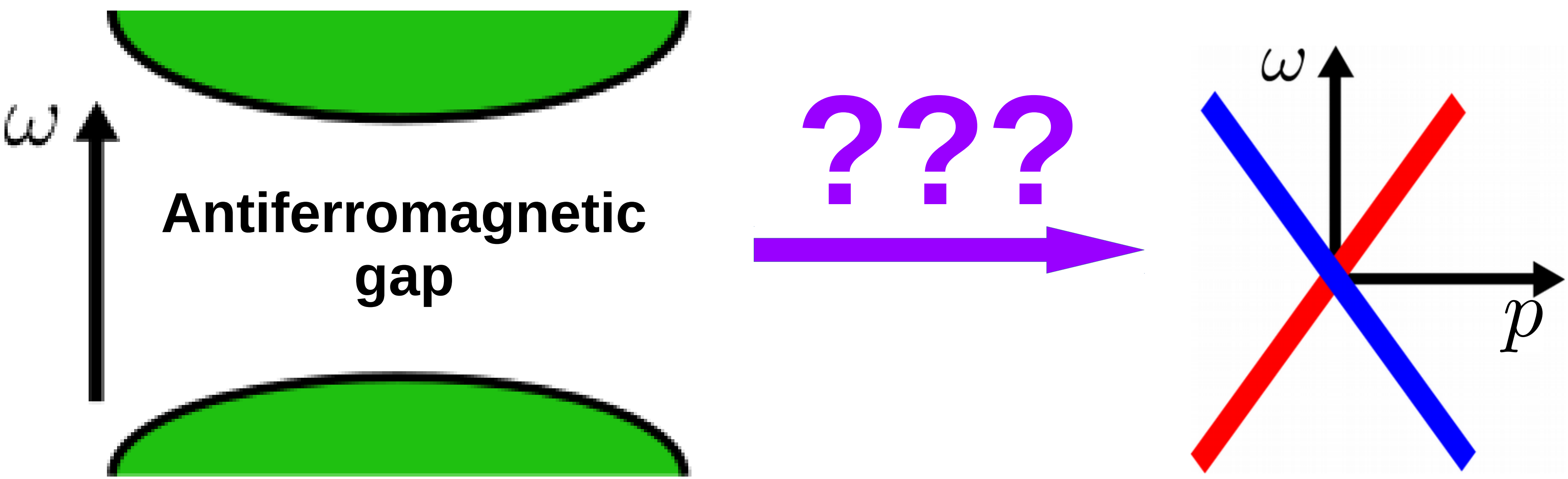
Objective: realize a spin-less superconductor

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

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

The initial problem

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



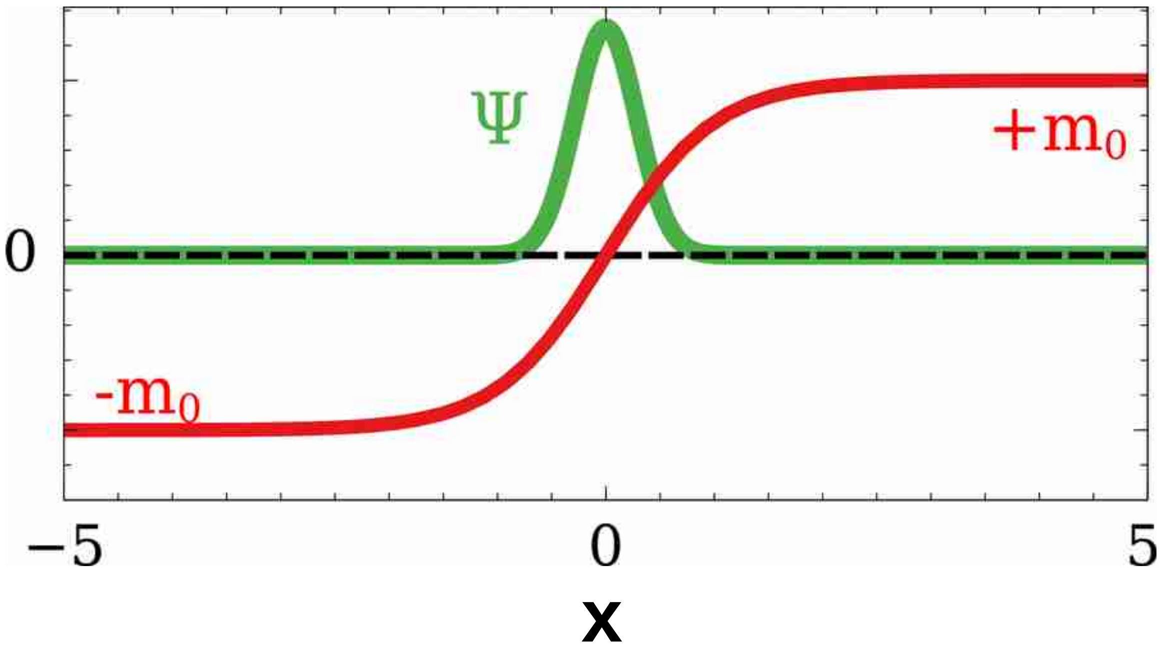
We need to create a “spinless” gapless state out of an insulator

Solitonic modes in a massive Dirac equation

Take a 1d Dirac equation with spatially dependent mass

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

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



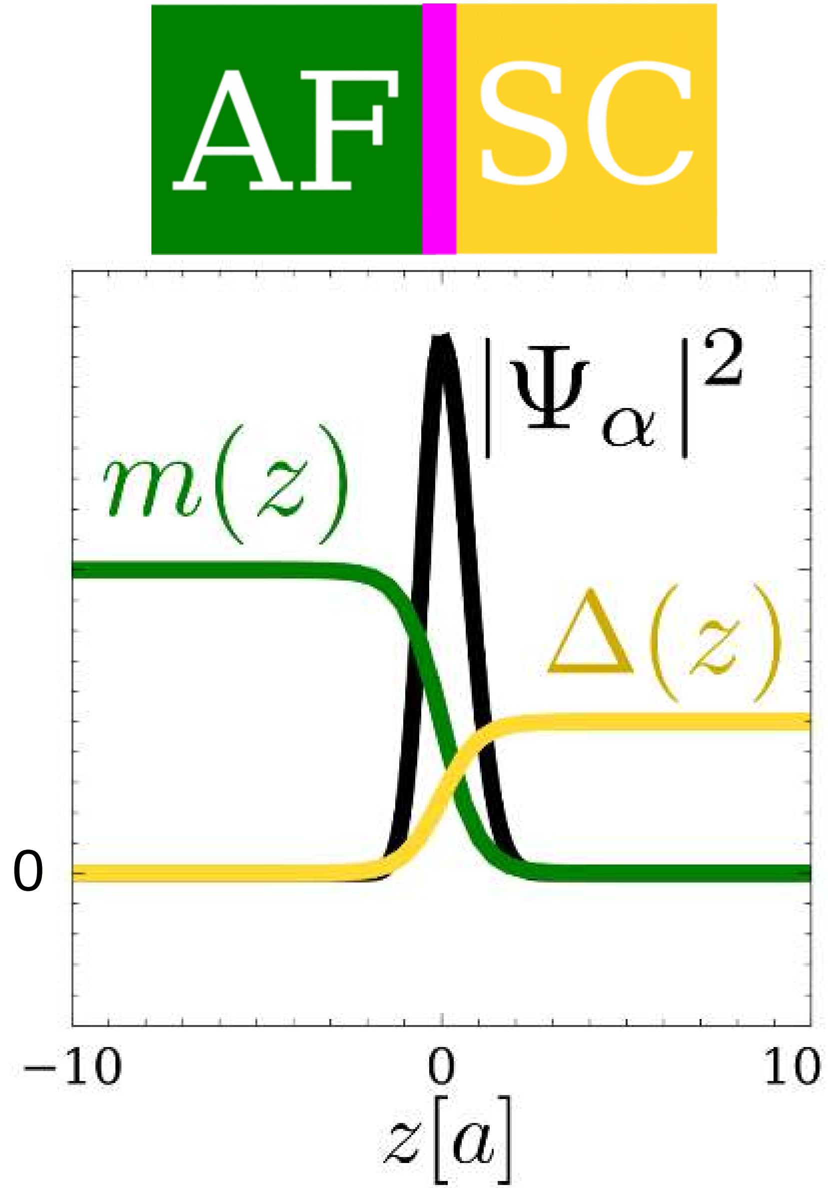
Zero energy solution appears at the interface

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

$$H\Psi = 0$$

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

Solitonic modes between Dirac AF and SC

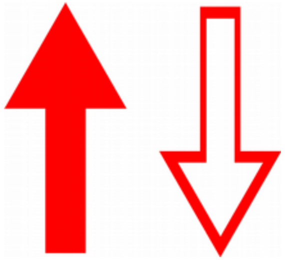


Total Hamiltonian

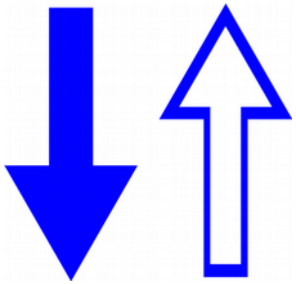
$$H = H_{kin} + H_{AF} + H_{SC}$$

There will be two zero solutions

Sector #1
Up electron, down hole

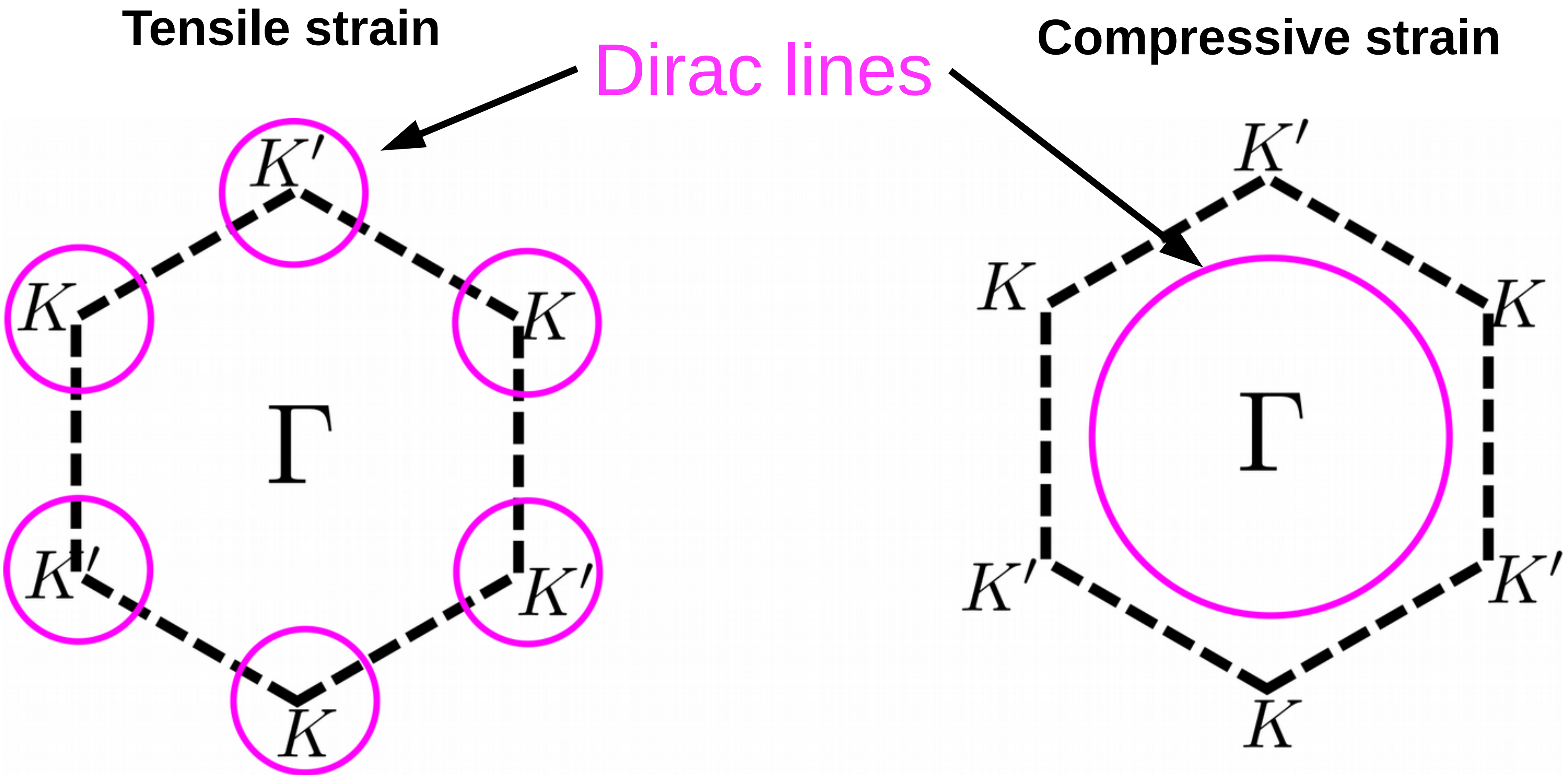


Sector #2
Down electron, up hole



Phys. Rev. X 5, 041042 (2015)

Dirac lines in the diamond lattice



Effective Hamiltonian in each point of the line

$$H = \begin{pmatrix} 0 & p_z \\ p_z & 0 \end{pmatrix}$$

The full Hamiltonian

Tight binding model in a diamond lattice

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

Kinetic energy $\hat{H}_{kin} = \sum_{\langle ij\rangle,s} t_{ij} c^{\dagger}_{i,s} c_{j,s} - \sum_{i,s} \mu(z_i) c^{\dagger}_{i,s} c_{i,s}$

Antiferromagnetic order $\hat{H}_{AF} = \sum_{i,s,s'} m(z_i) \tau_z^{i,i} \sigma_z^{s,s'} c^{\dagger}_{i,s} c_{i,s'}$

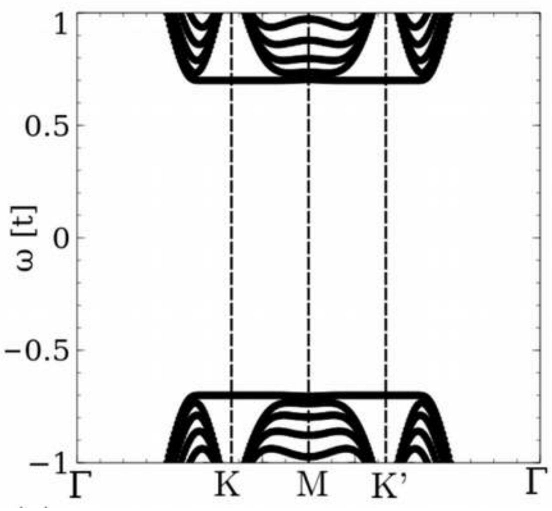
Superconducting order $\hat{H}_{SC} = \sum_{i} \Delta(z_i) [c_{i,\downarrow} c_{i,\uparrow} + c^{\dagger}_{i,\uparrow} c^{\dagger}_{i,\downarrow}]$

Intrinsic spin-orbit coupling $\hat{H}_{SOC} = \sum_{\langle\langle ij\rangle\rangle} i\Lambda \vec{\sigma}^{s,s'} \cdot (\vec{r}_{il} \times \vec{r}_{lj}) c^{\dagger}_{i,s} c_{j,s'}$

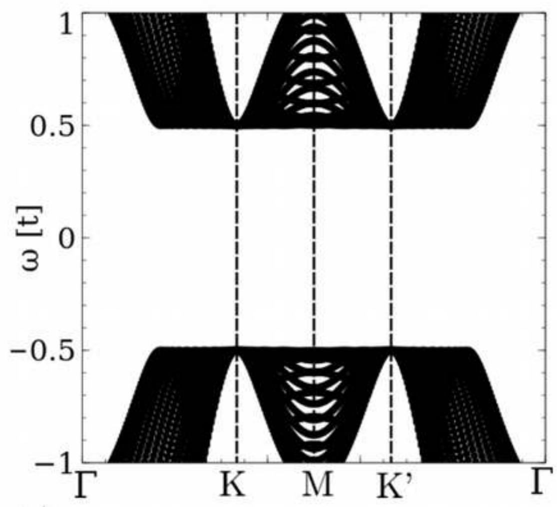
In this geometry

Emergence of interfacial modes, no spin-orbit coupling

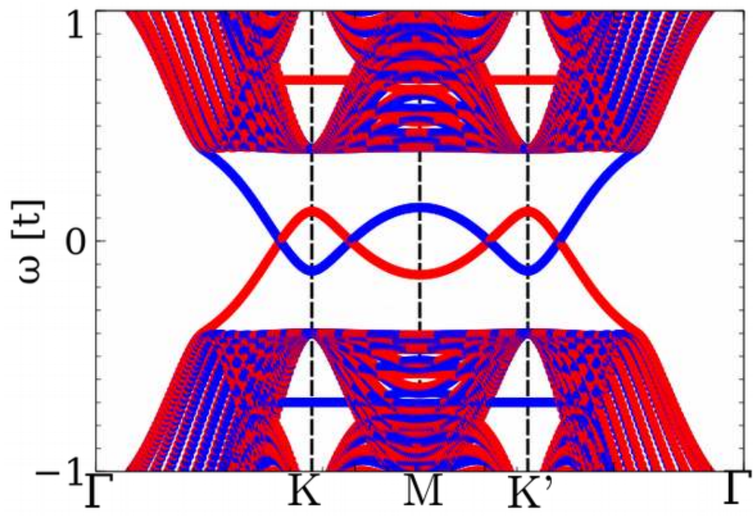
Antiferromagnet



Superconductor



AF/SC heterostructure

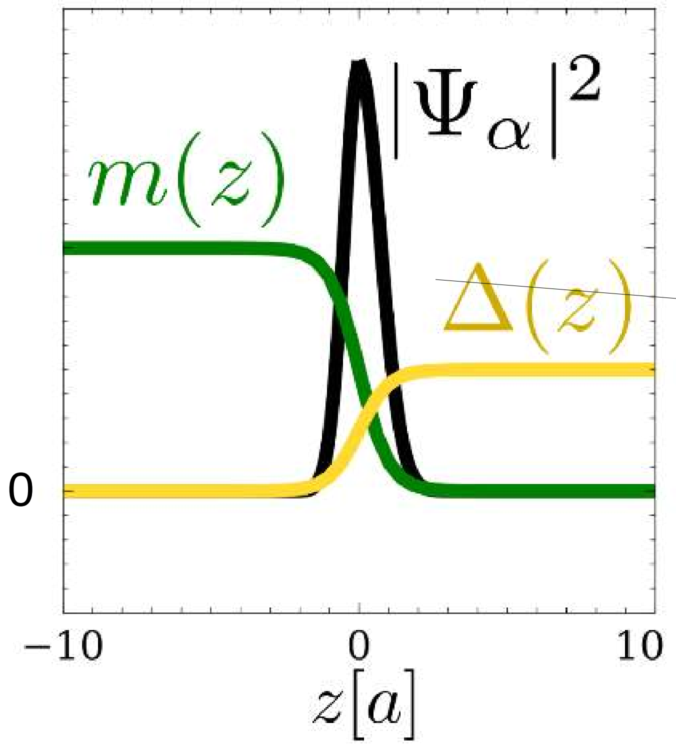


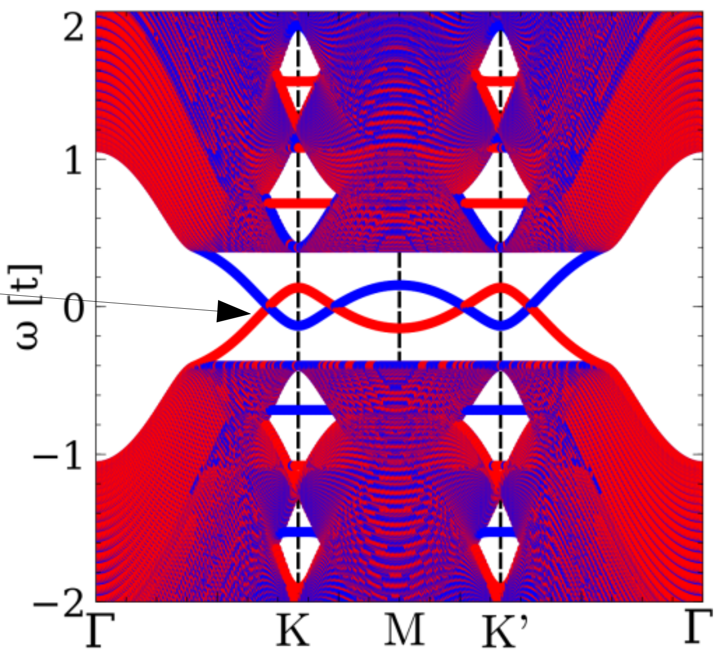
Interface states between AF and SC

Superconducting solitonic excitations

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

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

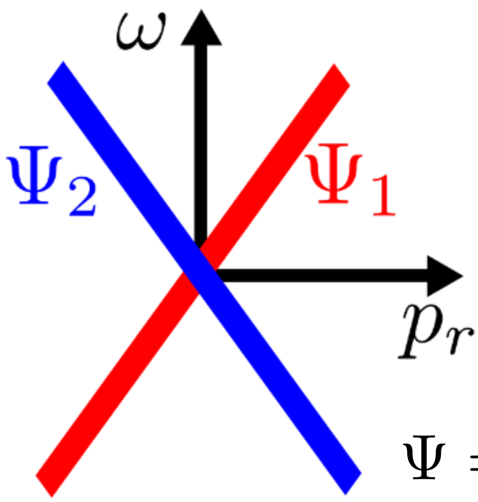




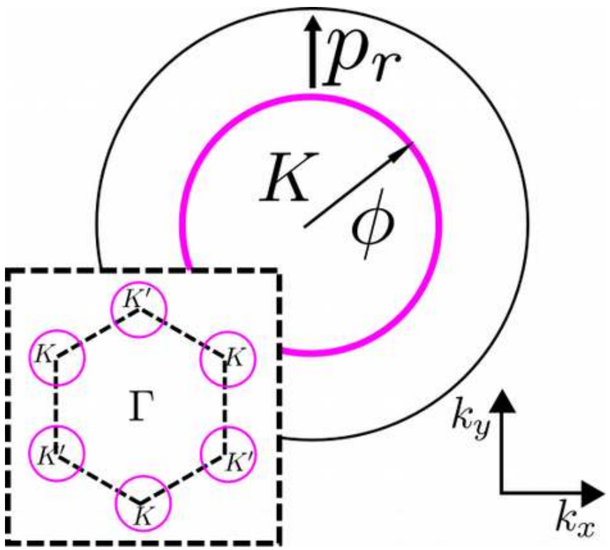
Effective model for the interface states

Effective Hamiltonian

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



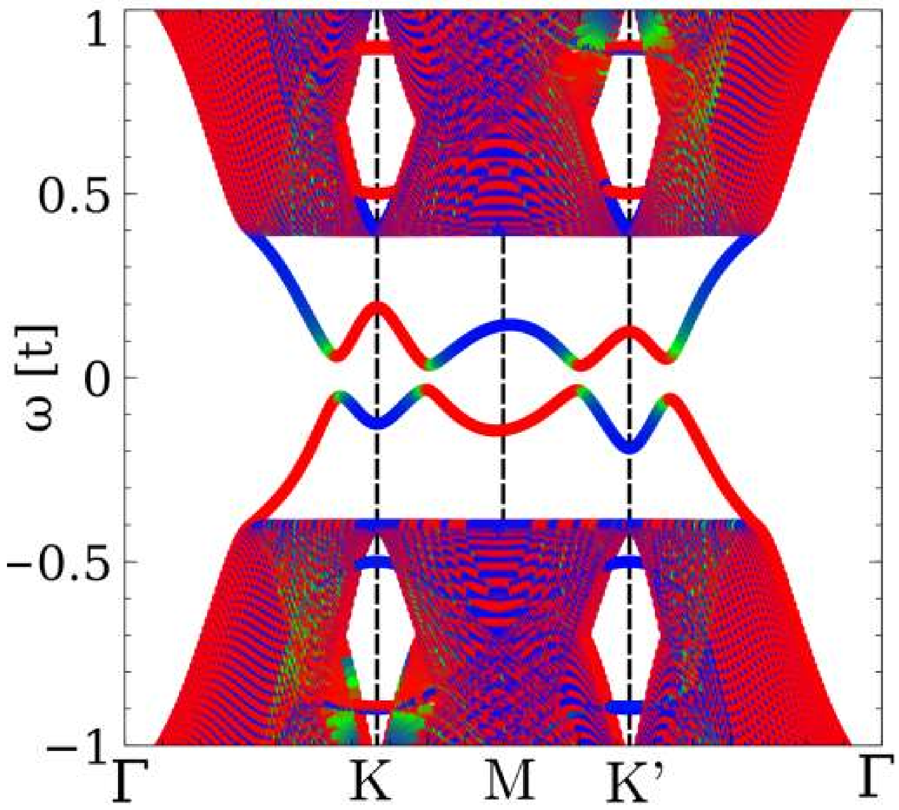
$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$



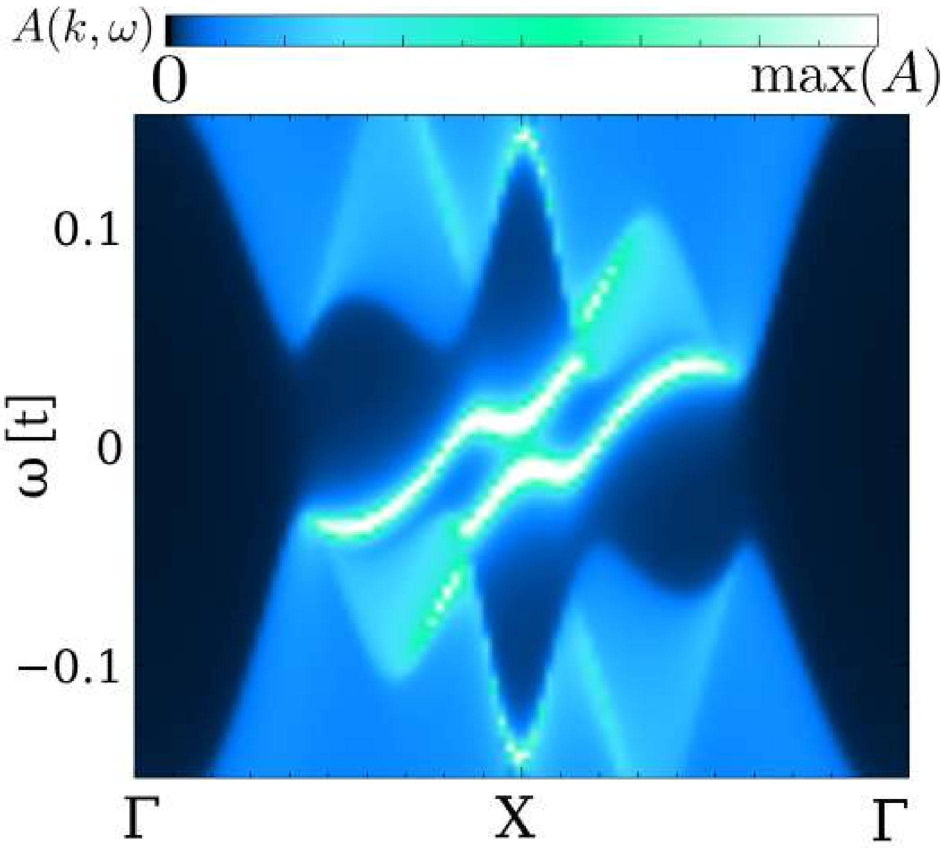
Every point of the Dirac line creates a zero mode

Adding spin-orbit coupling

Band structure

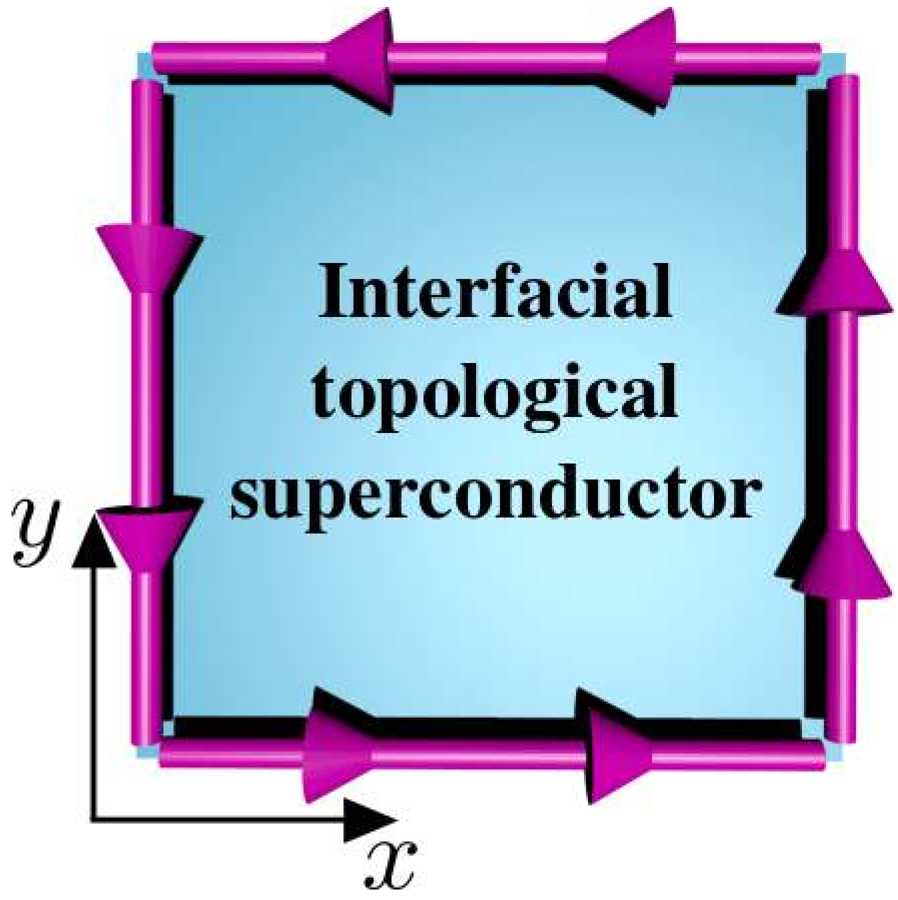


Edge spectral function

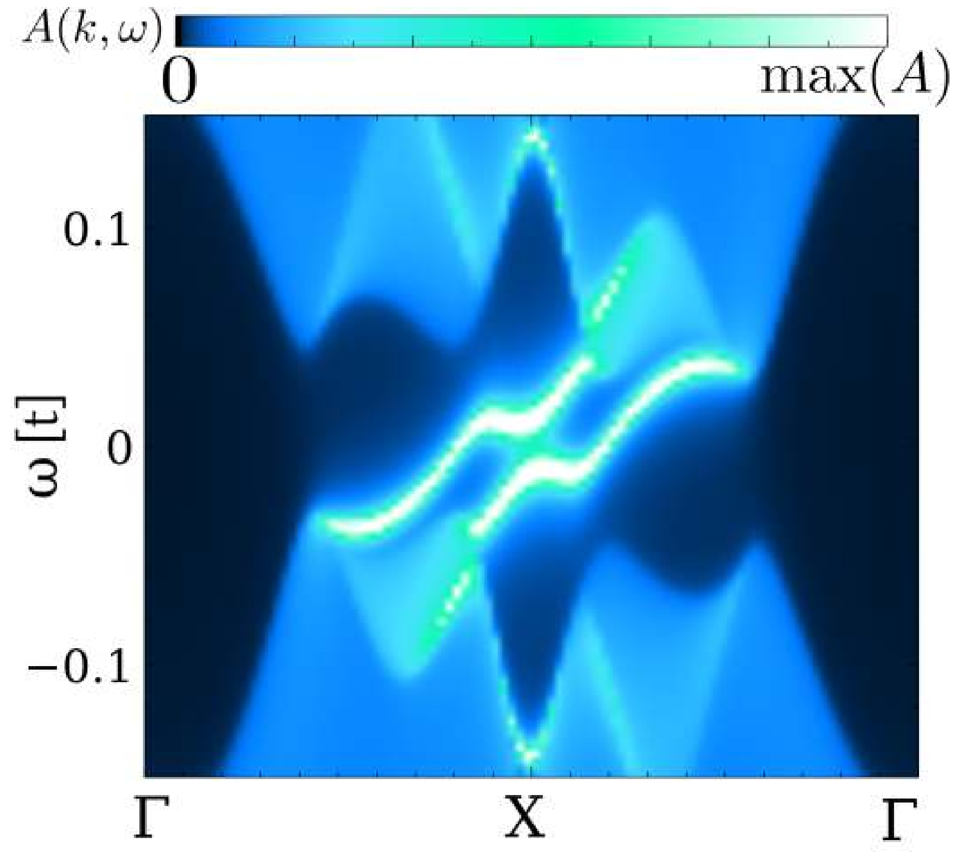


Two co-propagating edge modes

An interfacial topological superconductor



Edge spectral function



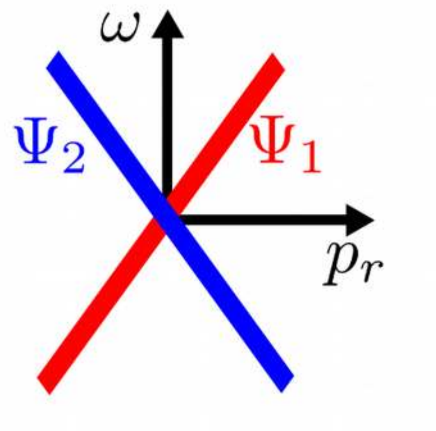
The interface realizes a topological superconductor

Effective model with spin-orbit coupling

Effective model with spin-orbit coupling

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

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

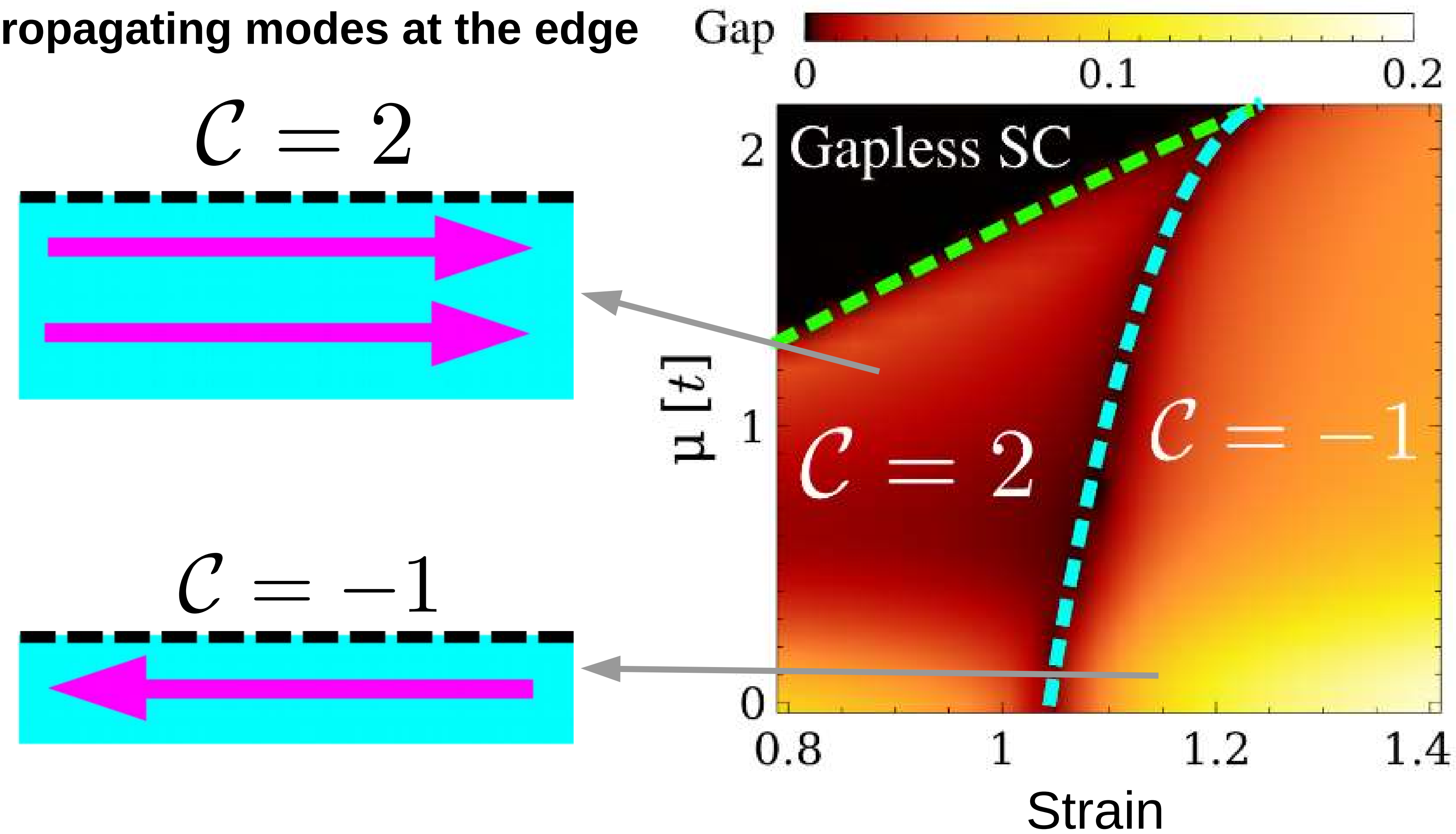


Spin-orbit coupling takes the form of a chiral pairing

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

Phase diagram with strain and doping

Propagating modes at the edge

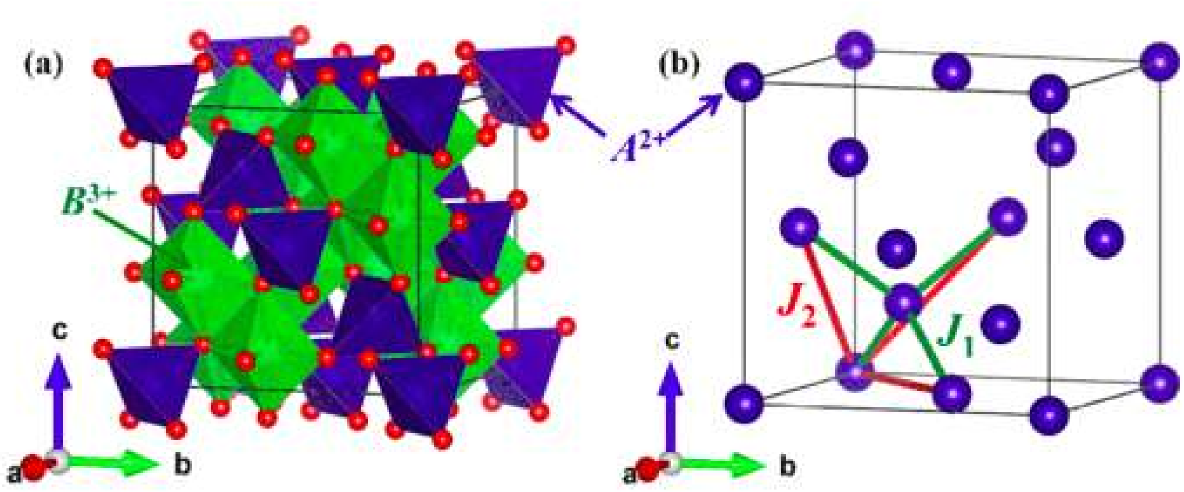


Possible materials, spinels

- Antiferromagnet forming a diamond lattice

Antiferromagnetic spinels

$CoAl_2O_4$



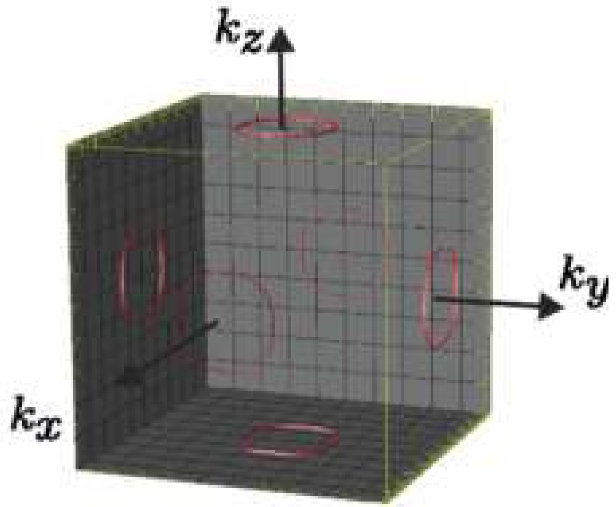
Co atoms form a diamond lattice

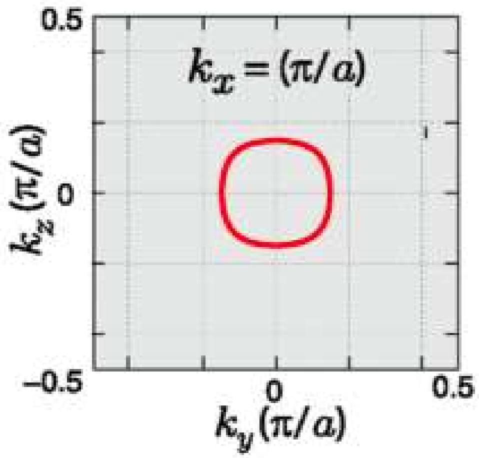
Phys. Rev. B 95, 094404 (2017)

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)

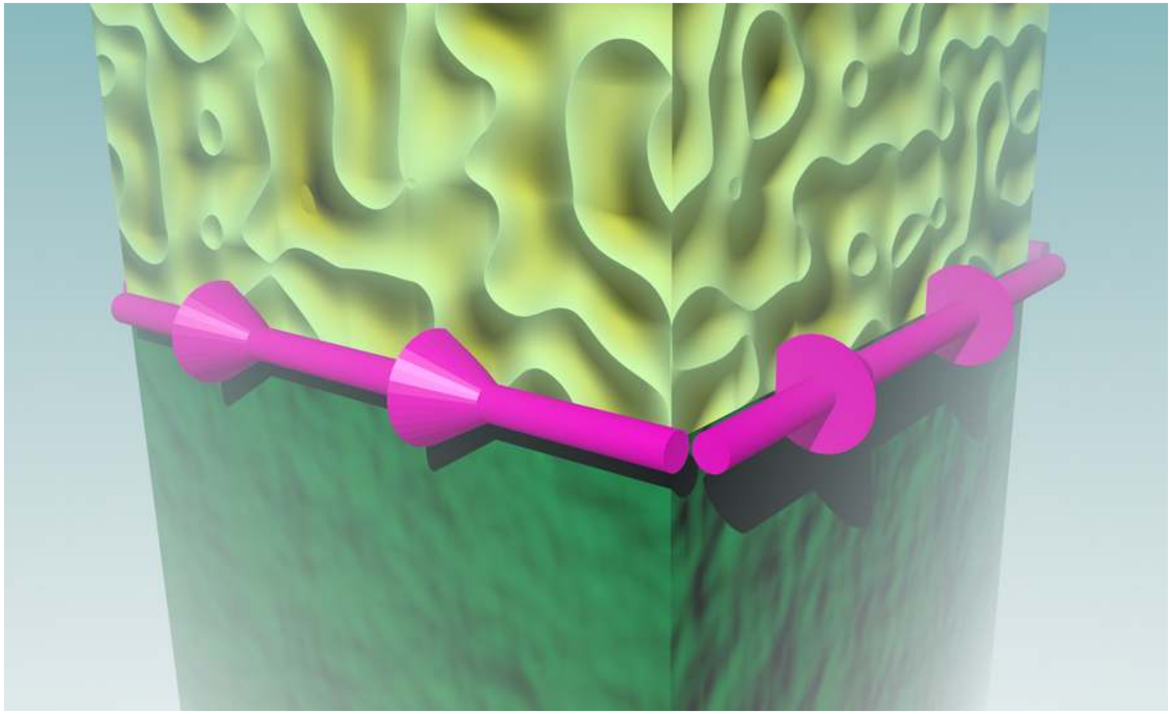




Antiferromagnets whose paramagnetic state hosts Dirac lines

Take home

Antiferromagnetic insulators can yield a robust platform to engineer two dimensional topological superconductors



arXiv:1803.01781

Thank you!

Financial support from ETH Fellowship program

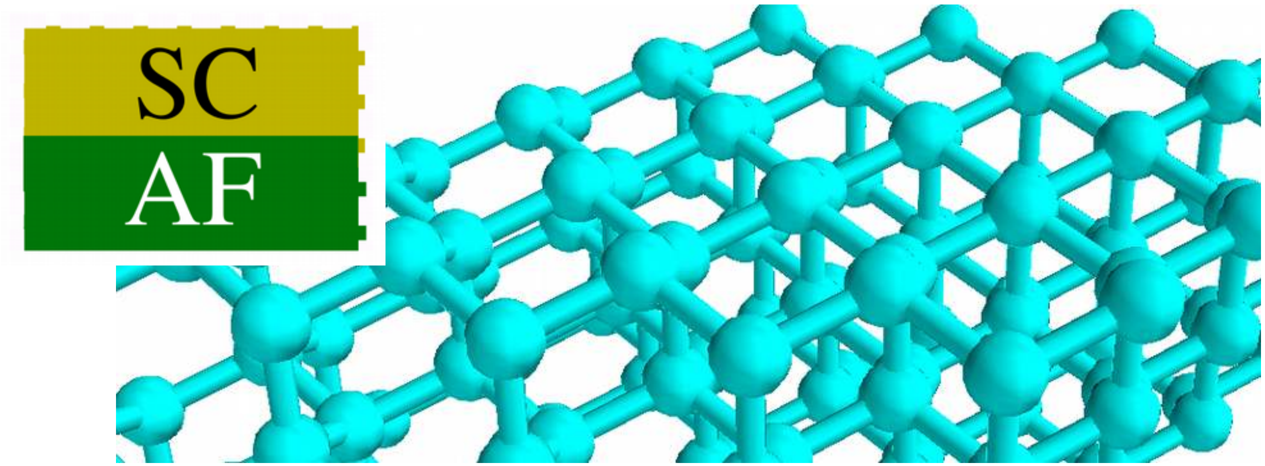
European Commission

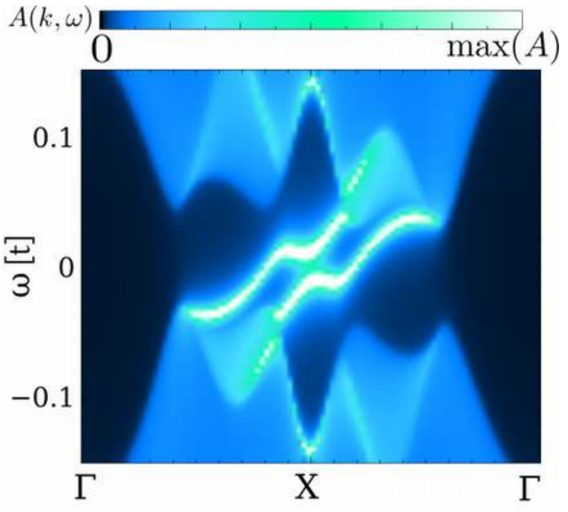
Program supported under FP7

ETH zürich

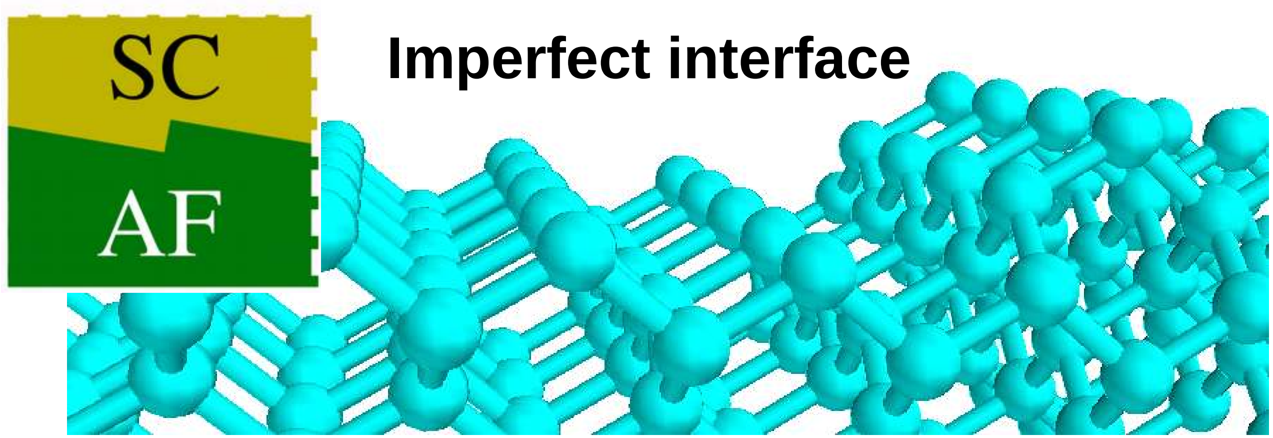
Influence of the interface

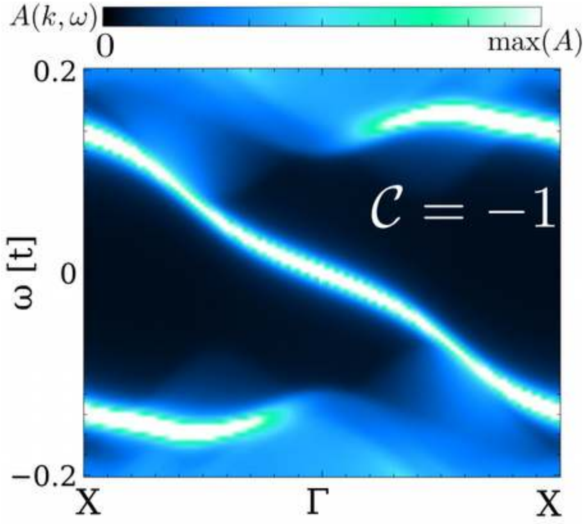
Perfect interface





Imperfect interface





The topological phase survives in imperfect interfaces

The mathematical structure of the interface modes

Nambu spinor $\varphi_1^\dagger = \begin{pmatrix} c^\dagger_{A,\vec{k}_\parallel,\uparrow} & c^\dagger_{B,\vec{k}_\parallel,\uparrow} & c_{A,-\vec{k}_\parallel,\downarrow} & c_{B,-\vec{k}_\parallel,\downarrow} \end{pmatrix}$

Hamiltonian $h_1 = \begin{pmatrix} m & p_z & \Delta & 0 \\ p_z & -m & 0 & \Delta \\ \Delta & 0 & m & -p_z \\ 0 & \Delta & -p_z & -m \end{pmatrix}$

$\mathcal{H}_1 = \varphi_1^\dagger h_1 \varphi_1$

$\Delta = \Delta(z)$

$m = m(z)$

Zero energy solution
$h_1 u_1 = 0$

$$u_1(z) = \frac{1}{2}\begin{pmatrix} 1 \\ -i \\ -1 \\ -i \end{pmatrix} e^{\int_0^z [m(z') - \Delta(z')]dz'}$$

Asymptotic conditions

$m(-\infty) = m_0 \quad m(+\infty) = 0 \quad \Delta(+\infty) = \Delta_0 \quad \Delta(-\infty) = 0$

Assuming $m_0 > 0 \quad \Delta_0 > 0$

Looking for a minimal lattice model hosting Dirac equations

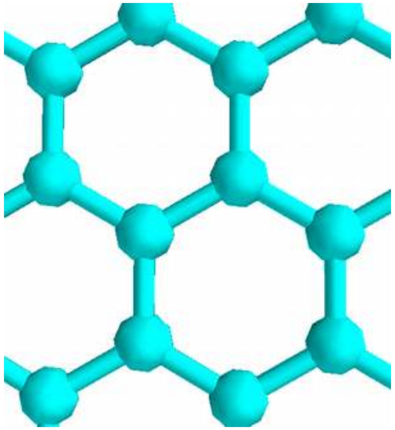
Bloch Hamiltonian

k.p Hamiltonian

$$H_k = \begin{pmatrix} 0 & f(\vec{k}) \\ f^*(\vec{k}) & 0 \end{pmatrix} = \begin{pmatrix} 0 & k_x + ik_y \\ k_x - ik_y & 0 \end{pmatrix}$$

In 2D lattice

Honeycomb lattice (graphene)



In a 3D lattice

Diamond lattice