Topological Superconductors, Majorana Fermions and Topological Quantum Computation

1. Bogoliubov de Gennes Theory
2. Majorana bound states, Kitaev model
3. Topological superconductor
4. Periodic Table of topological insulators and superconductors
5. Topological quantum computation
6. Proximity effect devices

BCS Theory of Superconductivity

mean field theory : $\Psi^\dagger \Psi \Psi^\dagger \Psi \quad \Rightarrow \quad \langle \Psi^\dagger \Psi^\dagger \rangle \Psi \Psi = \Delta^* \Psi \Psi$

$$H = \sum_{\mathbf{k}} \begin{pmatrix} \Psi^\dagger & \Psi \end{pmatrix} H_{BdG} \begin{pmatrix} \Psi \\ \Psi^\dagger \end{pmatrix}$$

Bogoliubov de Gennes Hamiltonian

$$H_{BdG} = \begin{pmatrix} H_0 & \Delta \\ \Delta^* & -H_0 \end{pmatrix}$$

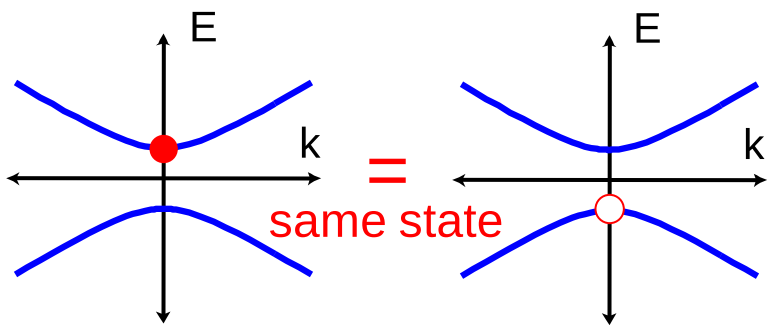
Intrinsic anti-unitary particle – hole symmetry

$$\Xi H_{BdG} \Xi^{-1} = -H_{BdG} \qquad \Xi \varphi = \tau_x \varphi^* \qquad \tau_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\Xi^2 = +1$$

Particle – hole redundancy

$$\varphi_{-E} = \Xi \varphi_E \quad \Rightarrow \quad \gamma_E^\dagger = \gamma_{-E}$$



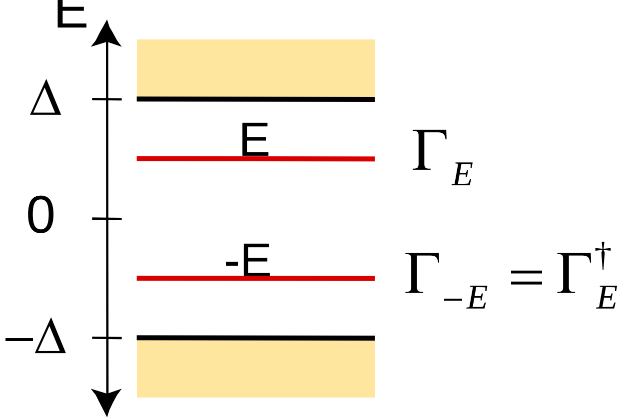
Bloch - BdG Hamiltonians satisfy $\Xi H_{BdG}(\mathbf{k}) \Xi^{-1} = -H_{BdG}(-\mathbf{k})$

Topological classification problem similar to time reversal symmetry

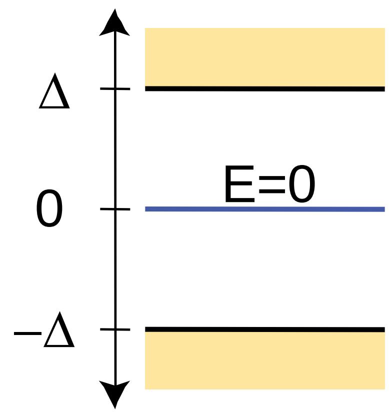
1D Z_2 Topological Superconductor : $\nu = 0,1$ (Kitaev, 2000)

Bulk-Boundary correspondence : Discrete end state spectrum

ν=0 "trivial"



ν=1 "topological"



Zero mode

$$\Gamma_{E=0}^\dagger = \Gamma_{E=0} \equiv \gamma$$

Majorana fermion bound state

Majorana Fermion : Particle = Antiparticle $\quad \gamma = \gamma^\dagger$

Real part of a Dirac fermion :

$$\begin{cases} \gamma_1 = \Psi + \Psi^\dagger & ; \quad \Psi = \gamma_1 + i\gamma_2 \\ \gamma_2 = -i(\Psi - \Psi^\dagger) & ; \quad \Psi^\dagger = \gamma_1 - i\gamma_2 \end{cases}$$

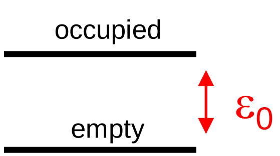
$$\gamma_i^2 = 1$$

$$\{\gamma_i, \gamma_j\} = 2\delta_{ij}$$

"Half a state"

Two Majorana fermions define a single two level system

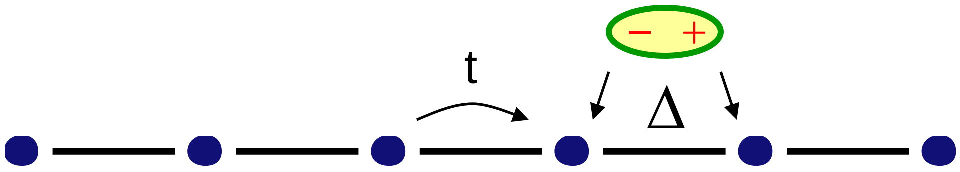
$$H = 2i\varepsilon_0 \gamma_1 \gamma_2 = \varepsilon_0 \Psi^\dagger \Psi$$



Kitaev Model for 1D p wave superconductor

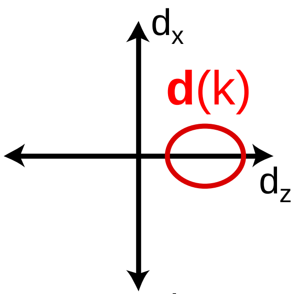
$$H-\mu N=\sum_i t(c_i^\dagger c_{i+1}+c_{i+1}^\dagger c_i)-\mu c_i^\dagger c_i+\Delta(c_i c_{i+1}+c_{i+1}^\dagger c_i^\dagger)$$

$$=\sum_k \begin{pmatrix} c_k^\dagger & c_{-k}\end{pmatrix} H_{BdG}(k)\begin{pmatrix} c_k \\ c_{-k}^\dagger\end{pmatrix}$$

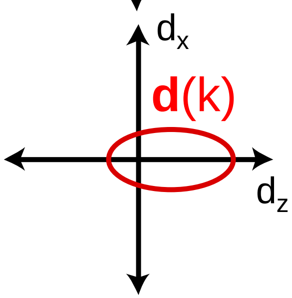


$$H_{BdG}(k)=\tau_z(2t\cos k-\mu)+\tau_x\Delta\sin k=\mathbf{d}(k)\cdot\vec{\tau}$$

$|\mu|>2t$: Strong pairing phase
trivial superconductor



$|\mu|<2t$: Weak pairing phase
topological superconductor



Similar to SSH model, except different symmetry : $(d_x,d_y,d_z)\big|_k=(-d_x,-d_y,d_z)\big|_{-k}$

Majorana Chain

$$c_i \to \gamma_{1i} + i\gamma_{2i}$$

$$\mu c_i^\dagger c_i \to 2i\mu\gamma_{1i}\gamma_{2i}$$

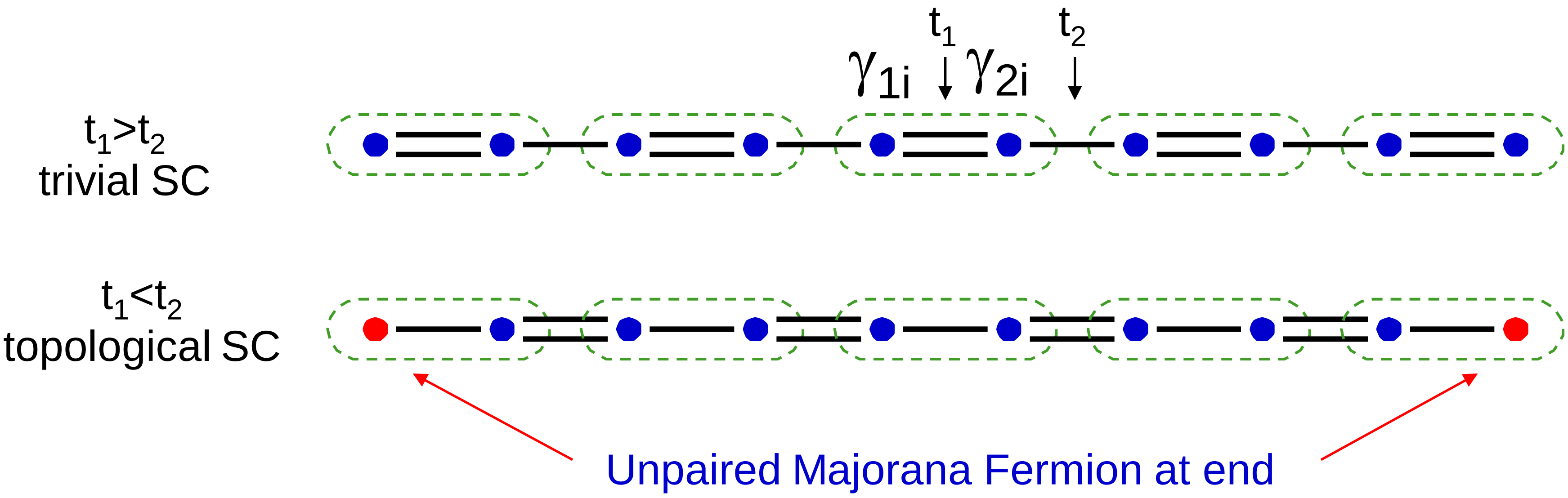
$$t\left(c_i^\dagger c_{i+1} + c_{i+1}^\dagger c_i\right) \to 2it\left(\gamma_{1i}\gamma_{2i+1} - \gamma_{2i}\gamma_{1i+1}\right)$$

$$\Delta\left(c_i c_{i+1} + c_{i+1}^\dagger c_i^\dagger\right) \to 2i\Delta\left(\gamma_{1i}\gamma_{2i+1} + \gamma_{2i}\gamma_{1i+1}\right)$$

$$H = 2i\sum_i t_1\gamma_{1i}\gamma_{2i} + t_2\gamma_{2i}\gamma_{1i+1}$$

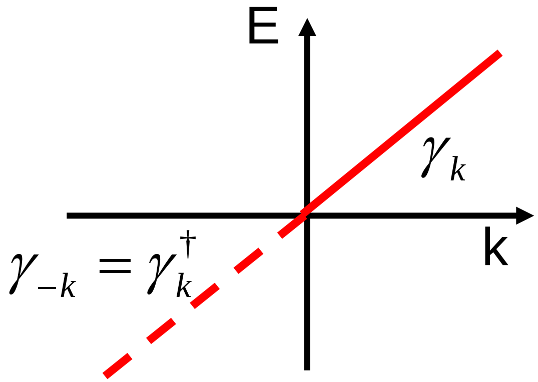
For Δ=t : nearest neighbor Majorana chain

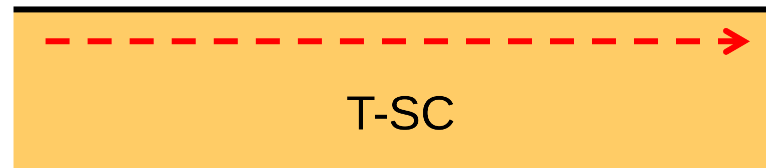
$$t_1 = \mu,\ \ t_2 = 2t$$



2D Z topological superconductor (broken T symmetry)

Bulk-Boundary correspondence: n = # Chiral Majorana Fermion edge states





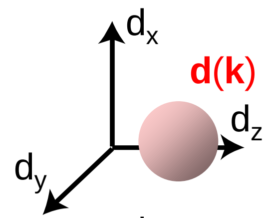
Examples

- Spinless p_x+ip_y superconductor (n=1)
- Chiral triplet p wave superconductor (eg Sr_2RuO_4) (n=2)

Read Green model :
$$H = \sum_{\mathbf{k}} \left(\frac{\mathbf{k}^2}{2m} - \mu \right) c_{\mathbf{k}}^\dagger c_{\mathbf{k}} + \left(\Delta(\mathbf{k}) c_{\mathbf{k}} c_{-\mathbf{k}} + c.c. \right) \qquad \Delta(\mathbf{k}) = \Delta_0 \left(k_x + i k_y \right)$$

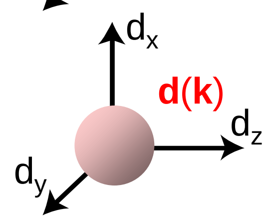
Lattice BdG model :
$$H_{BdG}(\mathbf{k}) = \tau_z \left(2t \left[\cos k_x + \cos k_y \right] - \mu \right) + \Delta \left(\tau_x \sin k_x + \tau_y \sin k_y \right) = \mathbf{d}(k) \cdot \vec{\tau}$$

$|\mu| > 4t$: Strong pairing phase
trivial superconductor



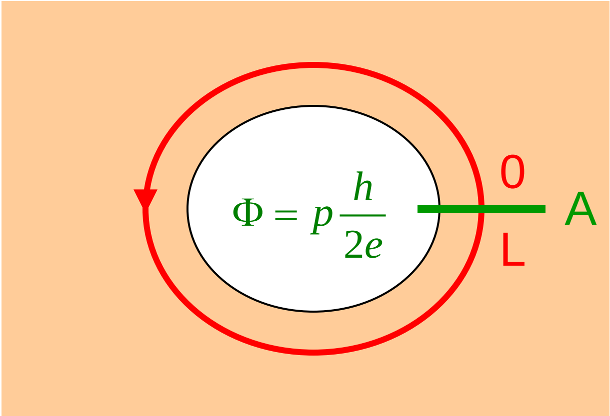
Chern number 0

$|\mu| < 4t$: Weak pairing phase
topological superconductor



Chern number 1

Majorana zero mode at a vortex

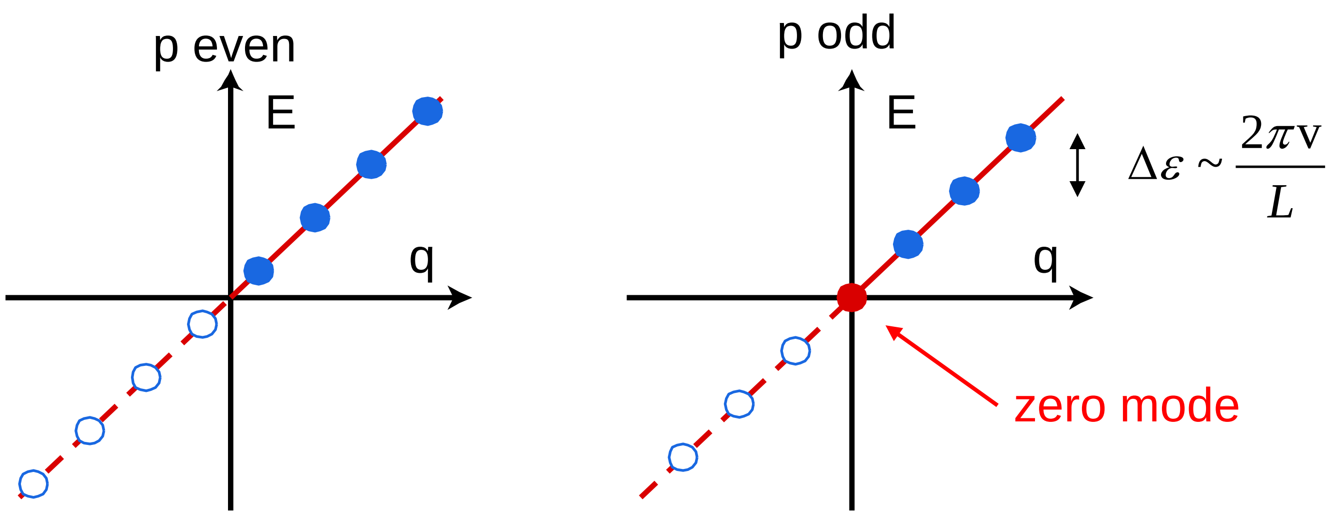


Hole in a topological superconductor threaded by flux

Boundary condition on fermion wavefunction

$$\psi(L) = (-1)^{p+1}\psi(0)$$

$$\psi(x) \propto e^{iq_m x} \quad ; \quad q_m = \frac{\pi}{L}(2m+1+p)$$



Without the hole : Caroli, de Gennes, Matricon theory ('64) $\Delta\varepsilon \sim \frac{\Delta^2}{E_F}$

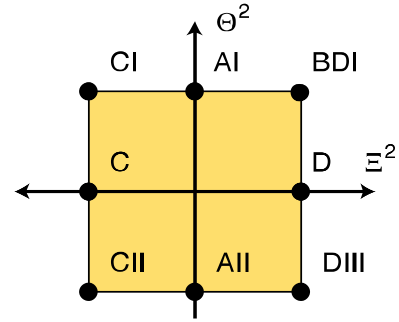
Periodic Table of Topological Insulators and Superconductors

Anti-Unitary Symmetries :

- Time Reversal : $\Theta H(\mathbf{k})\Theta^{-1} = +H(-\mathbf{k})\ ; \quad \Theta^2 = \pm 1$

- Particle - Hole : $\Xi H(\mathbf{k})\Xi^{-1} = -H(-\mathbf{k})\ ; \quad \Xi^2 = \pm 1$

Unitary (chiral) symmetry : $\Pi H(\mathbf{k})\Pi^{-1} = -H(\mathbf{k})\ ; \quad \Pi \propto \Theta\Xi$



8 antiunitary symmetry classes

Symmetry				d							
AZ	Θ	Ξ	Π	1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	-1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	-1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	-1	-1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	-1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	-1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Complex K-theory (A, AIII)

Real K-theory (AI – CI)

Altland-Zirnbauer Random Matrix Classes

Bott Periodicity $d \rightarrow d+8$

Kitaev, 2008
Schnyder, Ryu, Furusaki, Ludwig 2008

Majorana Fermions and Topological Quantum Computing

(Kitaev '03)

The degenerate states associated with Majorana zero modes define a topologically protected quantum memory

- 2 Majorana separated bound states = 1 fermion $\Psi = \gamma_1 + i\gamma_2$
  - 2 degenerate states (full/empty) = 1 qubit
- 2N separated Majoranas = N qubits
- Quantum Information is stored non locally
  - Immune from local decoherence

Braiding performs unitary operations

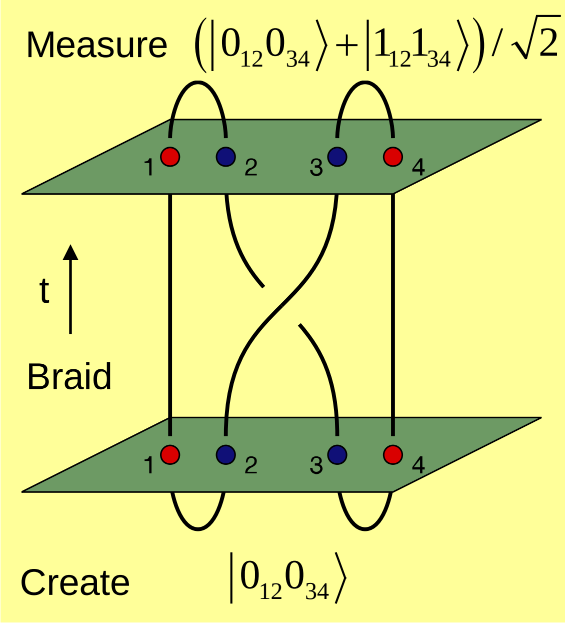
Non-Abelian statistics

Interchange rule (Ivanov 03)

$$\gamma_i \to \gamma_j$$

$$\gamma_j \to -\gamma_i$$

These operations, however, are not sufficient to make a universal quantum computer



Potential condensed matter hosts for Majorana bound states

- Quasiparticles in fractional Quantum Hall effect at $\nu=5/2$ Moore Read '91
- Unconventional superconductors
  - Sr_2RuO_4 Das Sarma, Nayak, Tewari '06
  - Fermionic atoms near feshbach resonance Gurarie '05
- Proximity Effect Devices using ordinary s wave superconductors
  - Topological Insulator devices Fu, Kane '08
  - Semiconductor/Magnet devices Sau, Lutchyn, Tewari, Das Sarma '09, Lee '09, ...
- .... among others

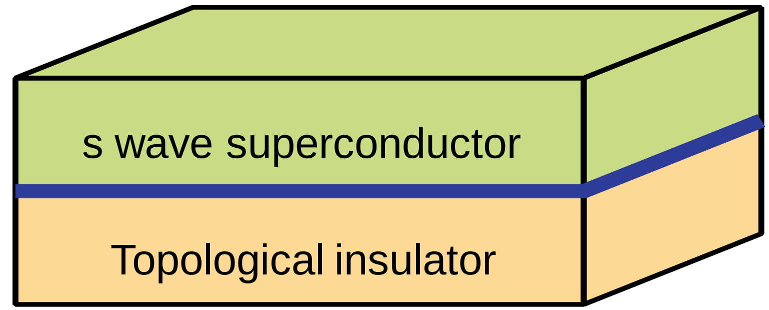
Current Status : Not Observed

Superconducting Proximity Effect

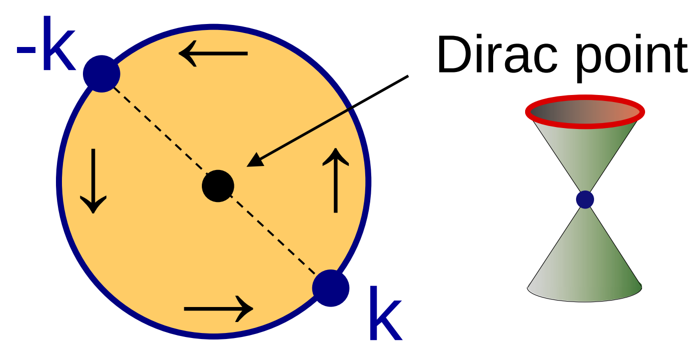
$$H = \psi^\dagger(-iv\vec{\sigma}\cdot\vec{\nabla} - \mu)\psi$$

$$+\Delta_S\psi_\uparrow^\dagger\psi_\downarrow^\dagger + \Delta_S^*\psi_\downarrow\psi_\uparrow$$

proximity induced superconductivity at surface

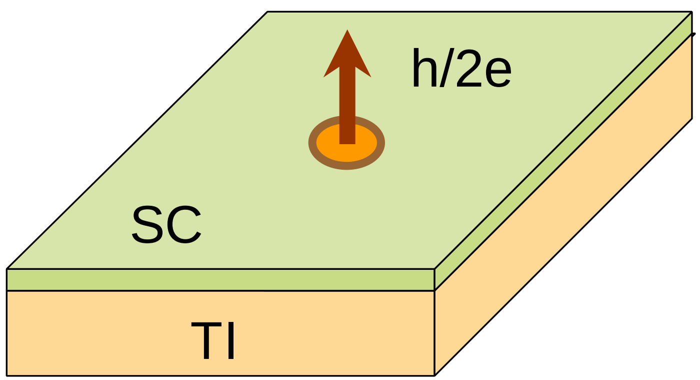


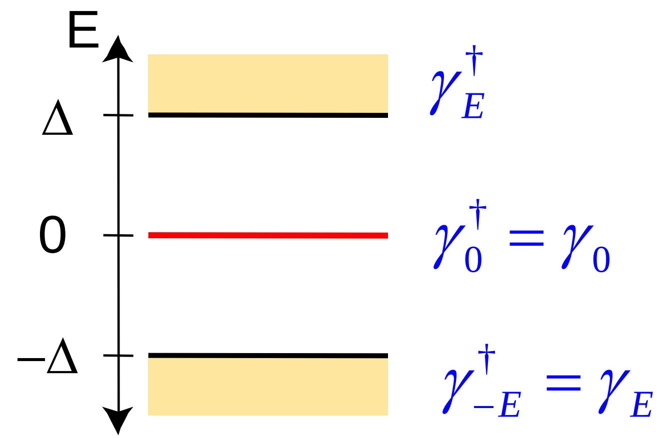
- Half an ordinary superconductor
- Similar to spinless p_x+ip_y superconductor, except :
  - Does not violate time reversal symmetry
  - s-wave singlet superconductivity
  - Required minus sign is provided by π Berry's phase due to Dirac Point
- Nontrivial ground state supports Majorana fermion bound states at vortices



Majorana Bound States on Topological Insulators

1. h/2e vortex in 2D superconducting state

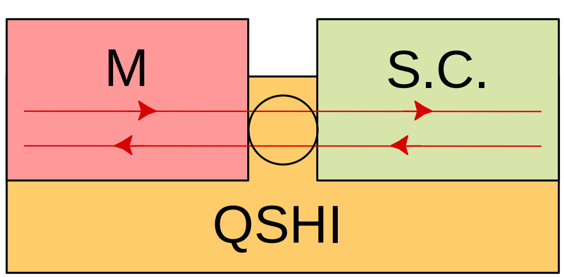




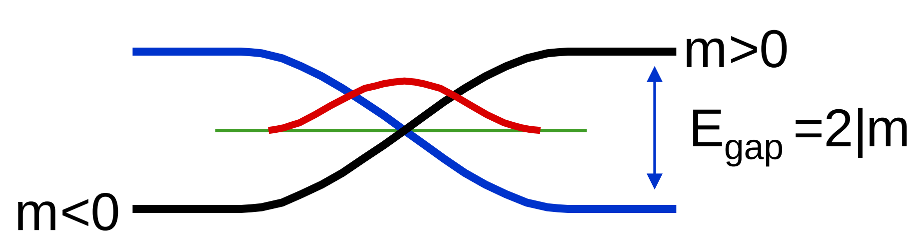
Quasiparticle Bound state at E=0

Majorana Fermion γ_0 "Half a State"

2. Superconductor-magnet interface at edge of 2D QSHI



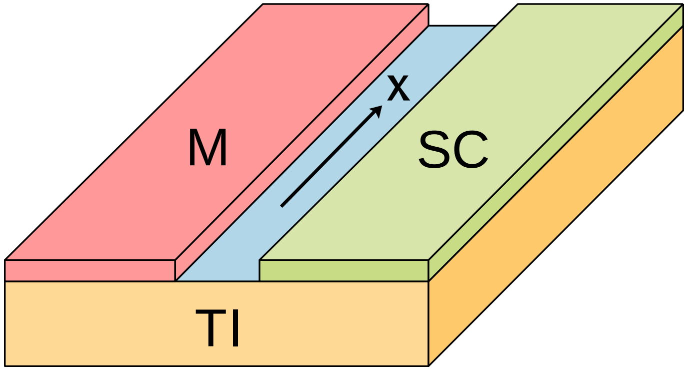
$$m = |\Delta_S| - |\Delta_M|$$

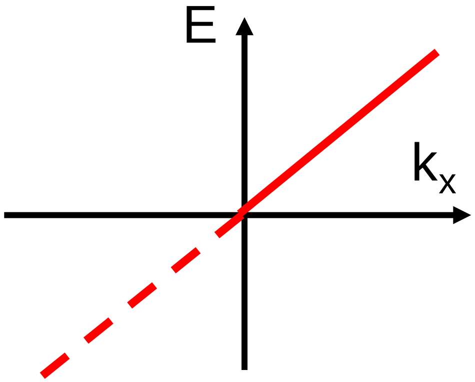


Domain wall bound state γ_0

1D Majorana Fermions on Topological Insulators

1. 1D Chiral Majorana mode at superconductor-magnet interface

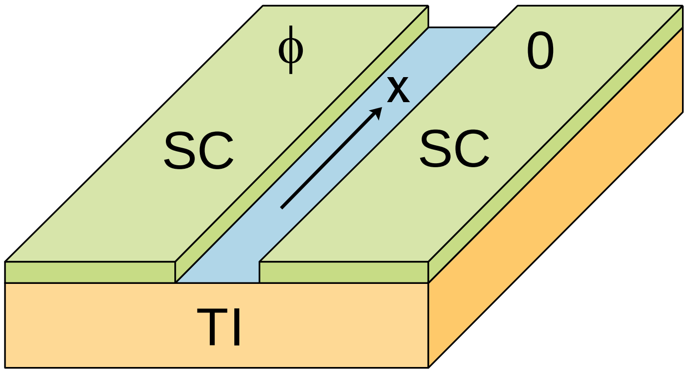


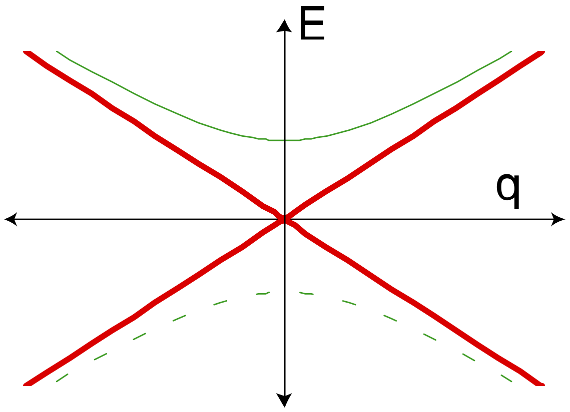


$\gamma_k = \gamma_{-k}^\dagger$: "Half" a 1D chiral Dirac fermion

$$H = -i\hbar v_F \ \gamma \partial_x \gamma$$

2. S-TI-S Josephson Junction



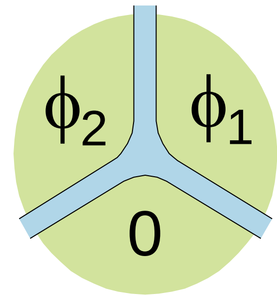


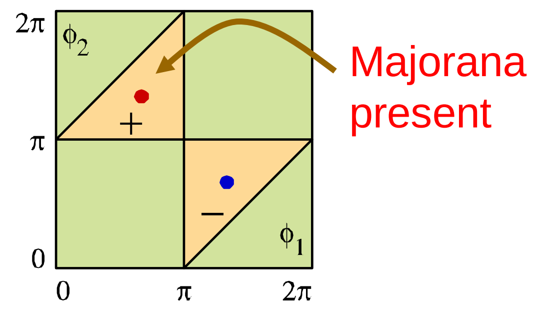
Gapless non-chiral Majorana fermion for phase difference $\phi = \pi$

$$H = -i\hbar v_F \ \left(\gamma_L \partial_x \gamma_L - \gamma_R \partial_x \gamma_R\right) + i\Delta \cos(\phi/2)\gamma_L \gamma_R$$

Manipulation of Majorana Fermions

Control phases of S-TI-S Junctions



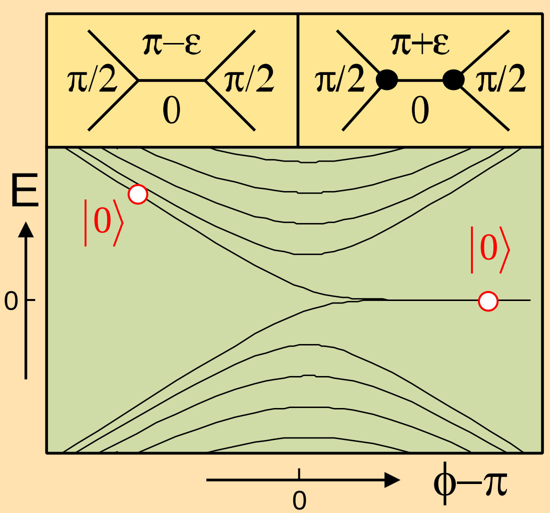


Tri-Junction :

A storage register for Majoranas

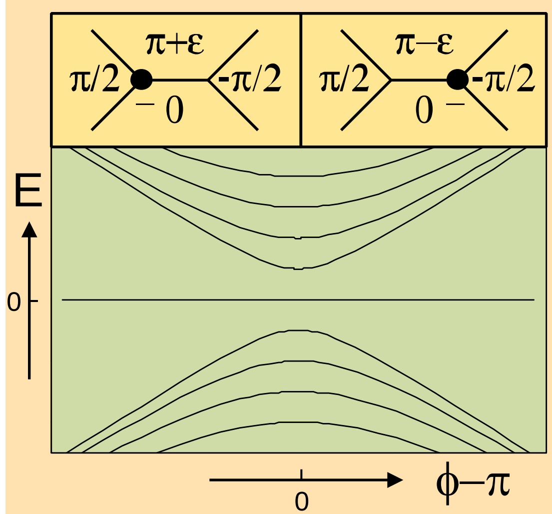
Create

A pair of Majorana bound states can be created from the vacuum in a well defined state |0>.



Braid

A single Majorana can be moved between junctions. Allows braiding of multiple Majoranas

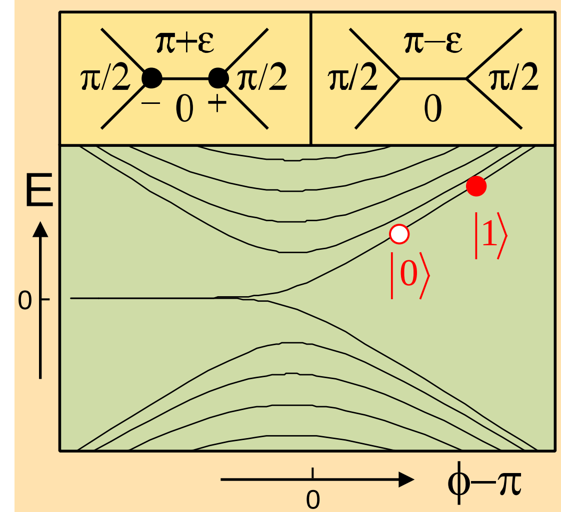


Measure

Fuse a pair of Majoranas.

States |0,1> distinguished by

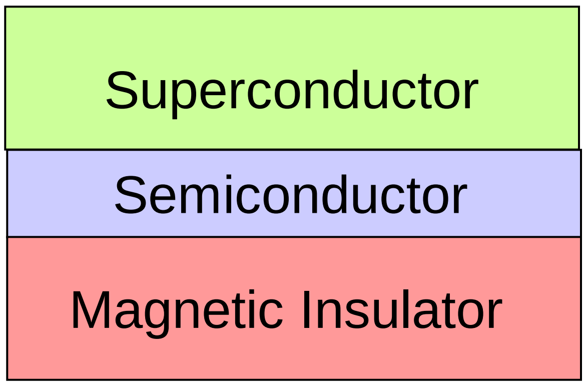
- presence of quasiparticle.
- supercurrent across line junction

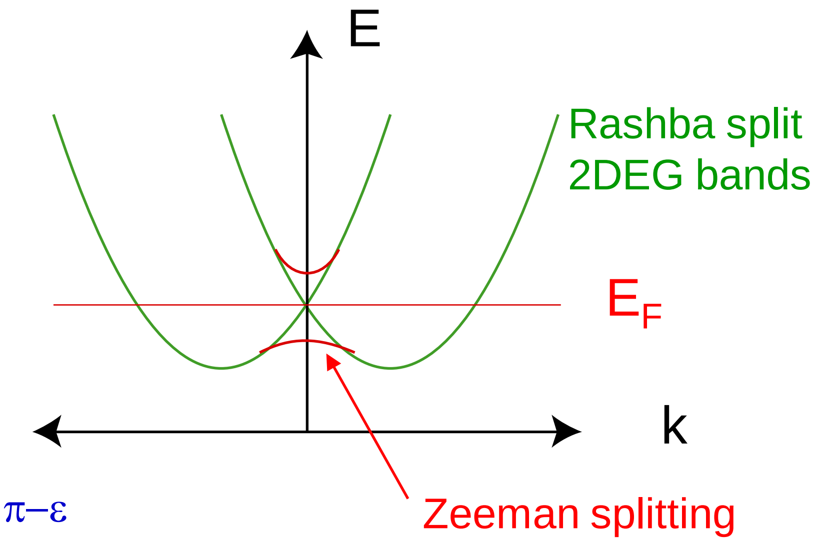


Another route to the 2D p+ip superconductor

Semiconductor - Magnet - Superconductor structure

Sau, Lutchyn, Tewari, Das Sarma ‘09

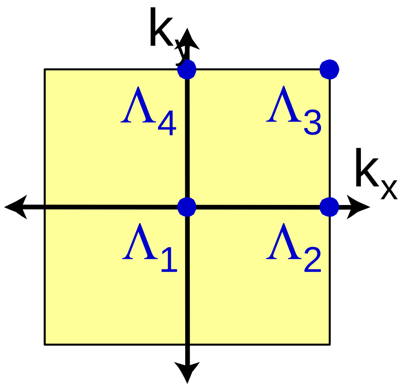




- Single Fermi circle with Berry phase $\pi-\varepsilon$
- Topological superconductor with Majorana edge states and Majorana bound states at vortices.
- Variants :
  - use applied magnetic field to lift Kramers degeneracy (Alicea ’10)
  - Use 1D quantum wire (eg InAs). A route to 1D p wave superconductor with Majorana end states. (Oreg, von Oppen, Alicea, Fisher ’10
- Challenge : requres very low electron density $\rightarrow$ high purity.

Formula for the Z_2 invariant

- Bloch wavefunctions : $|u_n(\mathbf{k})\rangle$ (N occupied bands)
- T - Reversal Matrix : $w_{mn}(\mathbf{k}) = \langle u_m(\mathbf{k})|\Theta|u_n(-\mathbf{k})\rangle \in U(\mathrm{N})$
- Antisymmetry property : $\Theta^2 = -1 \Rightarrow w(\mathbf{k}) = -w^T(-\mathbf{k})$
- T - invariant momenta : $\mathbf{k} = \Lambda_a = -\Lambda_a \Rightarrow w(\Lambda_a) = -w^T(\Lambda_a)$



Bulk 2D Brillouin Zone

- Pfaffian : $\det[w(\Lambda_a)] = \left(\mathrm{Pf}[w(\Lambda_a)]\right)^2$ e.g. $\det\begin{pmatrix} 0 & z \\ -z & 0 \end{pmatrix} = z^2$
- Fixed point parity : $\delta(\Lambda_a) = \dfrac{\mathrm{Pf}[w(\Lambda_a)]}{\sqrt{\det[w(\Lambda_a)]}} = \pm 1$
- Gauge dependent product : $\delta(\Lambda_a)\delta(\Lambda_b)$

  "time reversal polarization" analogous to $\frac{e}{2\pi}\oint A(k)dk$

- Z_2 invariant : $(-1)^\nu = \prod_{a=1}^{4} \delta(\Lambda_a) = \pm 1$

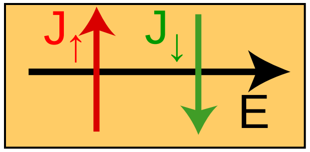
Gauge invariant, but requires continuous gauge

ν is easier to determine if there is extra symmetry:

1. S_z conserved : independent spin Chern integers :

$$n_\uparrow = -n_\downarrow \quad \text{(due to time reversal)}$$

Quantum spin Hall Effect :



$$\nu = n_{\uparrow,\downarrow} \mod 2$$

2. Inversion (P) Symmetry : determined by Parity of occupied 2D Bloch states

$$P\left|\psi_n(\Lambda_a)\right\rangle = \xi_n(\Lambda_a)\left|\psi_n(\Lambda_a)\right\rangle$$

$$\xi_n(\Lambda_a) = \pm 1$$

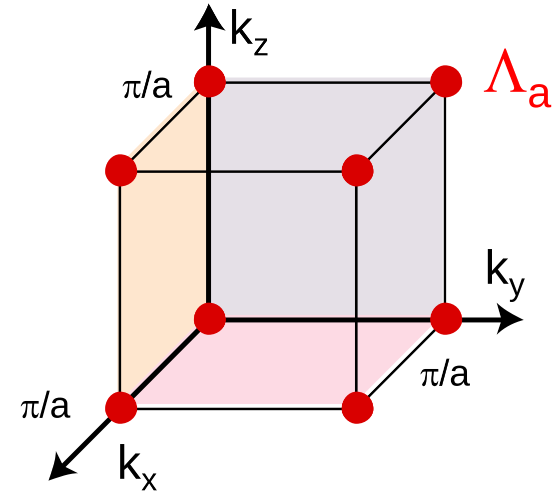
In a special gauge: $\delta(\Lambda_a) = \prod_n \xi_n(\Lambda_a)$

$$(-1)^\upsilon = \prod_{a=1}^{4}\prod_n \xi_{2n}(\Lambda_a)$$

Allows a straightforward determination of ν from band structure calculations.

Topological Invariants in 3D

1. 2D → 3D : Time reversal invariant planes

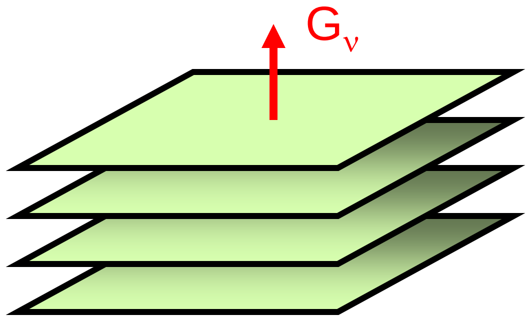


The 2D invariant

$$(-1)^{\nu} = \prod_{a=1}^{4} \delta(\Lambda_a) \qquad \delta(\Lambda_a) = \frac{\mathrm{Pf}[w(\Lambda_a)]}{\sqrt{\det[w(\Lambda_a)]}}$$

Each of the time reversal invariant planes in the 3D Brillouin zone is characterized by a 2D invariant.

Weak Topological Invariants (vector):



$$(-1)^{\nu_i} = \prod_{a=1}^{4} \delta(\Lambda_a) \Big|_{k_i=0 \text{ plane}} \qquad \mathbf{G}_\nu = \frac{2\pi}{a}(\nu_1, \nu_2, \nu_3)$$

"mod 2" reciprocal lattice vector indexes lattice planes for layered 2D QSHI

Strong Topological Invariant (scalar)

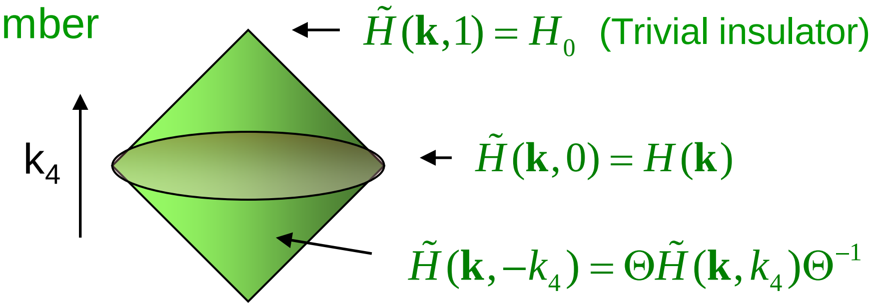
$$(-1)^{\nu_o} = \prod_{a=1}^{8} \delta(\Lambda_a)$$

Topological Invariants in 3D

2. 4D → 3D : Dimensional Reduction

Add an extra parameter, k_4, that smoothly connects the topological insulator to a trivial insulator (while breaking time reversal symmetry)

H(**k**,k_4) is characterized by its second Chern number



$$n = \frac{1}{8\pi^2}\int d^4k \,\mathrm{Tr}[\mathbf{F}\wedge\mathbf{F}]$$

n depends on how H(**k**) is connected to H_0, but due to time reversal, the difference must be even.

$$\nu_0 = n \bmod 2$$

Express in terms of Chern Simons 3-form : $\mathrm{Tr}[\mathbf{F}\wedge\mathbf{F}] = dQ_3$

$$\nu_0 = \frac{1}{4\pi^2}\int \mathrm{d}^3k\, Q_3(\mathbf{k}) \bmod 2$$

$$Q_3(\mathbf{k}) = \mathrm{Tr}[\mathbf{A}\wedge d\mathbf{A} + \frac{2}{3}\mathbf{A}\wedge\mathbf{A}\wedge\mathbf{A}]$$

Gauge invariant up to an even integer.