Condensed Matter Search for (elusive?) Majorana Modes

- Sau, Lutchyn, Tewari, Stanescu, Lobos, Liu, Lin, Hui
- Halperin, Flensberg
- Alicea, Refael, von Oppen, Fisher, Stern, Brouwer, Loss, Beenakker, Fu, Kane, ... and many more (now a huge subject)
- Kouwenhoven, Marcus, Yacoby,... and others (experiment)
- 5/2 FQHE, SrRuO$_4$, TI, He-3, Cold Atoms,.....
- Semiconductor/Superconductor Sandwich Structures (2D, 1D, 0D)
- s-SC+ proximity in SM + SO coupling + spin splitting
- Strong SO-coupling + Low Disorder + Good Interface
Majorana Returns!

- Majorana/Fermi (1937): "Real version" of Dirac Theory
- Majorana disappears (1938)
- Neutrino as Majorana (??): Double beta decay (lepton number!)
- Neutralino of SUSY is a Majorana fermion
- Read and Green (2000): $5/2$ FQHE = Chiral $p+ip$ SC
- Kitaev (2001): Majorana 1D chain
- Das Sarma, Freedman, Nayak (2005): $5/2$ FQH ‘Majorana’ Qubit
- Das Sarma, Nayak, Tewari (2006): $\text{SrRuO}_4$ Majorana (half-vortex)
- Fu, Kane (2008): Topological Insulator + SC
- Sau, Lutchyn, Tewari, Das Sarma (2010): $\text{SO/SM} + \text{SC} + \text{FMI}$
- Alicea (2010): $\text{SO/SM} + \text{SC}$
- Lutchyn, Sau, Das Sarma (2010): Majorana Nanowire
- Sau, Lin, Hui, Das Sarma (2012): $QD + SC$; ‘periodic structure’
Alternation and interchange of \( e/4 \) and \( e/2 \) period interference oscillations as evidence for filling factor 5/2 non-Abelian quasiparticles

Braiding of Abelian and Non-Abelian Anyons in the Fractional Quantum Hall Effect

Both the Majorana and the half-vortex have apparently already been seen

Observation of Half Quantum Vortices in an Exciton-Polariton

Condensate

Observation of half-height magnetization steps in \( \text{Sr}_2\text{RuO}_4 \)

New Anomaly in the Transverse Acoustic Impedance of Superfluid \(^3\text{He-B} \) with a Wall Coated by Several Layers of \(^4\text{He} \)

Topological Superconductivity in \( \text{Cu}_x\text{Bi}_2\text{Se}_3 \)

Both the Majorana and the half-vortex have apparently already been seen
Vortices in 2D spinless \((p_x + ip_y)\) Superconductor

**CHIRAL, p-WAVE, SPINLESS; ZERO ENERGY MODE AT THE CORE**

Order parameter phase rotates by \(2\pi n\) around the core

Order parameter amplitude suppressed at the core

**2D Majorana is an anyon**
Not a regular fermion because it is zero-energy! *Emergent Mode at low energy*

Low energy normal bound states in the core

**Bound states in vortex cores are e-h symmetric**

**ZERO-ENERGY CORE STATE IS MAJORANA**
**PROTECTED BY INDEX THEOREM (e-h symmetry)**
Qubit decoherence due to Majorana tunneling: The limit to topological protection

Splitting of Majorana-Fermion Modes due to Intervortex Tunneling in a $p_x + i p_y$ Superconductor

Meng Cheng, Roman M. Lutchyn, Victor Galitski, and S. Das Sarma
Condensed Matter Theory Center and Joint Quantum Institute, Department of Physics, University of Maryland,

New results:

- Tunneling energy splitting calculated:

  $$E_+ - E_- \approx \frac{\Delta_0}{\pi^2} \frac{\cos(k_FR + \frac{\pi}{4})}{\sqrt{k_FR}} e^{-\frac{R}{\xi}}$$

- New discovery is that the sign of the energy splitting oscillates! A behavior never seen before. It indicates that the additional effect of fluctuations is important for dephasing.
Topological Protection of Majorana Qubits

Meng Cheng, Roman M. Lutchyn, and S. Das Sarma

Fermion parity is the key here

As long as $T$ is much less than the superconducting (proximity) gap, the topological protection applies even if the Majorana minigap is much smaller than $T$, i.e. even when the non-zero BdG subgap levels are occupied in the ‘defect’: Not an obvious result at all. Visibility may be affected, but not protection

$$\Delta_M \propto \Delta^2/E_F \ll \Delta$$
**Question:** Are equations for spin-1/2 particles necessarily complex?

Simple clever modification of the Dirac equation that involves **ONLY REAL** numbers

**Majorana fermion** - electrically neutral particle which is its own antiparticle  \( \gamma = \gamma^\dagger \)

**E. Majorana (1937)**

**Relevance:**
- particle physics (neutrinos)
- (neutralinos)

**Experimental status:**
- NOT observed

**Emergent Majorana?**

**Majorana returns**

F. Wilczek, Nature Physics’09
Non-abelian statistics and topological qubits increasing simplicity

Fractional Quantum Hall

Chiral p-wave superconductors

Topological insulator/ S-wave superconductor

Spin-orbit coupled Semiconductor/ S-wave superconductor

1D Kitaev chain

Majorana Fermions

Spin-orbit coupled Nanowire/ S-wave superconductor
Quantum Hall Effect: Which QH states might be non-Abelian?

The fragile 5/2 plateau is a strong candidate to be a non-Abelian quantum Hall state (Pfaffian). First seen (1987) by Willett et al.

To determine if it is, we would have to measure the effect of quasiparticle braiding.

There is sound theoretical reason to believe that the even-denominator 5/2 FQHE is a chiral p-wave SC with Majoranas as quasiparticles.

Very small gap ~ 10-100 mK! Fragile!
Superconducting Order Parameter for the Even-denominator Fractional Quantum Hall Effect

Hantao Lu,¹ S. Das Sarma,² and Kwon Park¹

Odd-even effect as in SC grains (in 5/2, but not 1/2, FQHE)
Direct numerical demonstration of superconductivity in 5/2 FQHE

F(r) ~ SC gap parameter: finite!
Presence of SC order
5/2 FQHE: No Quantum Phase Transition as a function of $x$: Adiabatic continuity $x=0$ to $1$

$V = (1-x)V_{2b} + xV_{3b}$

1/2 FQHE: Quantum Phase Transition as a function of $x$: No Adiabatic continuity $x=0$ to $1$
Finite-Layer Thickness Stabilizes the Pfaffian State for the 5/2 Fractional Quantum Hall Effect: Wave Function Overlap and Topological Degeneracy

Michael. R. Peterson, Th. Jolicoeur, and S. Das Sarma


Unity wavefunction overlap and the correct degeneracy show up for d/l~4
PROPOSED TOPOLOGICAL QC ARCHITECTURES

- **OPTICAL LATTICES** (analog simulation of Kitaev model, extended Hubbard model, etc.)
- **COLD ATOMS** (rotating BEC, p+ip fermionic superfluid, artificial B-field)
- **‘SUITABLE’ MAGNETIC LATTICES**
- **SUPERCONDUCTOR sandwiches**
- **p+ip SUPERCONDUCTORS** (ruthenates)
- **TOPOLOGICAL INSULATORS + s-SC**
- **NONABELIAN FQHE STATES**

**KEY IDEA:** Non-Abelian modes in p-SC (‘Majorana’)

Sufficient for TQC up to some regular noisy gates (~ 20% error)

All involve Majorana modes as the basic qubit element: \((SU_2)^2\) conformal field theory
Generic New Platform for Topological Quantum Computation Using Semiconductor Heterostructures
Jay D. Sau, Roman M. Lutchyn, Sumanta Tewari, and S. Das Sarma

Majorana Fermions and a Topological Phase Transition in Semiconductor-Superconductor Heterostructures
Roman M. Lutchyn, Jay D. Sau, and S. Das Sarma

Search for Majorana Fermions in Multiband Semiconducting Nanowires
Roman M. Lutchyn, Tudor D. Stanescu, and S. Das Sarma

Topological periodic superconductor-nanowire structures
Jay D. Sau, Chien Hung Lin, Hoi-Yin Hui, and S. Das Sarma

How to realize a robust practical Majorana chain in a quantum dot-superconductor linear array
Jay D. Sau and S. Das Sarma
FIG. 2: Spectrum of a disordered 1D Kitaev chain of length $N = 20$ sites. The hopping amplitudes $t$ and pairing amplitudes $\Delta$ are distributed randomly and uniformly in the interval [0.5, 1.5] K. The spectrum shows a near-zero-mode separated by a gap $\sim 1$ K in a range of on-site QD chemical potential $|\mu| < 0.15\text{meV}$. Thus the TS state shows a robust gap in this regime despite the large fluctuations in the hopping.

FIG. 1: (a) Geometry to observe zero-bias tunneling signature associated with MFs in gated semiconductor nanowire (thick black line) in the topological regime ($\mu < \mu_c$). Superconductivity is induced from the side of the gated nanowire region by the superconducting (blue box) layer on the left. (b) Tunneling density of state of nanowire system shows broadened zero-bias tunneling peak at the interface for large Zeeman potential ($V_Z = 0.75\text{meV} > \Delta_0 = 0.5\text{meV}$) and gate chemical potential $\mu_g = 0\text{meV}$. The chemical potential $\mu_g$ directly next to the superconductor is taken to be large ($\mu_g = 3\text{meV} \gg \mu_c \approx 0.5\text{meV}$). (c) Zero-bias tunneling density of states shows quasilocalized states at interface that decays in superconductor and propagates in the gated region.
Majorana bound states in SM/SC heterostructure

Bogoliubov-de-Gennes equations

$$H_{\text{BdG}} \Psi = E \Psi$$

$$\Psi = (\psi_\uparrow, \psi_\downarrow, \psi_\downarrow^\dagger, -\psi_\uparrow^\dagger)^T$$

$$H_{\text{BdG}} = \left(-\frac{\nabla^2}{2m} - \mu - i\alpha(\vec{\sigma} \times \vec{v}) \cdot \hat{\mathbf{z}} + V_z \sigma_z\right) \tau_z + \Delta_0(r)(\tau_x \cos \theta + \tau_y \sin \theta)$$

Non-degenerate zero-energy solution exists when

$$\sqrt{\mu^2 + \Delta_0^2} < |V_z|$$

Majorana number $\mathcal{M}$

$$\mathcal{M} = e^{i\pi C_1} = \pm 1$$

Topo condition does not involve SO coupling.

Sau, Lutchyn, Tewari, Das Sarma, PRL’10
Majorana at spin-orbit coupled semiconductor (Sm)-SC interfaces

Need single non-degenerate Fermi-surface

\[ H_{Sm} = k^2 + V_z \sigma_z \]

Fermion doubling avoided: Majorana!

Rashba + Zeeman break inversion and time-reversal for chiral edge mode

Sau, Lutchyn, Tewari, Das Sarma  PRL(2010)
Engineering spinless $p + ip$ superconductor

Rather than looking for $p_x + ip_y$ SC in nature, we could try to engineer suitable Hamiltonians via proximity effect.

Chirality has to come from the bandstructure

Strong spin-orbit interaction is necessary to avoid fermion doubling

Ordinary S-wave SC + 2D (or 1D) Semiconductor with Strong SO Coupling

Superconducting heterostructures

2D: Majoranas “live” in vortices

1D: Majoranas “live” at the ends of wires

Sau, Lutchyn, Tewari, Das Sarma, PRL’10

Sau et al. PRB (2010)

Sau, Tewari, Das Sarma Ann Phys’10

1D Lutchyn, Sau, Das Sarma, PRL(2010)

Q1D Lutchyn, Stanescu, Das Sarma, PRL’11
Superconductors are natural hosts for Majorana fermions.

Bogoliubov quasiparticle:

\[ \gamma = u\psi + v\psi^\dagger \]

where

\[ u = v^* \]

The equal superposition of a particle and a hole:

Majorana fermion:

\[ \gamma = \gamma^\dagger \]

Look for ZERO energy states!

Energy levels:

- Empty state at \( E = 0 \)
- Occupied state at \( E = 2\Delta_0 \)

Bound states in vortices

Midgap states at the interfaces
Topological protection of zero-energy mode

Bogoliubov-de-Gennes equations

\[
\begin{pmatrix}
 h_0 & \Delta \\
 \Delta^\dagger & -h_0^T
\end{pmatrix}
\begin{pmatrix}
 u \\
v
\end{pmatrix}
= E
\begin{pmatrix}
 u \\
v
\end{pmatrix}
\]

Particle-hole symmetry:

If \( \begin{pmatrix}
 u \\
v
\end{pmatrix} \) is a solution with \( E \) then \( \begin{pmatrix}
 v^* \\
u^*
\end{pmatrix} \) is a solution with \( -E \)

For spinless fermions particle-hole symmetry guarantees Majorana mode at \( E = 0 \)

Two topological classes of BdG Hamiltonians

- **2N + 1 solutions**
  - Topological reconstruction of the spectrum requires closing of the bulk gap
  - Bound states in the vortex core

- **2N solutions**

Read and Green, PRB'00
Semiconductor with spin-orbit interaction

Semiconductor with Rashba interaction

\[ H_0 = \begin{pmatrix}
\frac{p^2}{2m} - \mu & \alpha i (p_x - i p_y) \\
-\alpha i (p_x + i p_y) & \frac{p^2}{2m} - \mu
\end{pmatrix} \]

Fermi sea

spin orientation changes around Fermi surface

Sau, Lutchyn, Tewari, Das Sarma, PRL’10;
1D wires with spin-orbit: helical state

\[ H_0 = \int_{-L}^{L} dx \psi^\dagger_\sigma(x) \left( -\frac{\partial^2}{2m^*} - \mu + i\alpha\sigma_y \partial_x + V_x\sigma_x \right) \psi_{\sigma'}(x) \]

- **Single channel nanowire**
- **Spin-orbit coupling**
- **Zeeman splitting**

\[ \varepsilon(p_x) \]

Magnetic field \( B_x \) opens up gap in the spectrum at \( p_x = 0 \)

**InAs, InSb nanowires**

- Large spin-orbit (\( \alpha \sim 0.1 eV \AA \))
- Large \( g \)-factor (\( g \sim 10 - 50 \))
- Good contacts with metals
**Majorana quantum wires**

\[ H_{MW} = \int_{-L}^{L} dx \left[ \psi_\sigma^\dagger \left( -\frac{\partial_x^2}{2m^*} - \mu + i\alpha \sigma_y \partial_x + V_x \sigma_x \right) \psi_{\sigma'} + \Delta_0^* \psi_\uparrow \psi_\downarrow + \Delta_0 \psi_\downarrow^\dagger \psi_\uparrow^\dagger \right] \]

Rashba spin-orbit + in-plane field

Proximity-induced superconductivity

Diagonalize \( H_0 \)

\[ \Psi_+(p) \quad \mu = 0 \]

\[ \Psi_-(p) \]

**Lutchyn, Sau, Das Sarma PRL 2010**

Drive topological phase transition by changing \( V_x \) or \( \mu \)
What are the roles of various parameters?

SC gap, SC-SM tunneling, SO coupling, Zeeman splitting, chemical potential, SC disorder, SM disorder, system configuration, environment........

Large SC gap
Weak SC-SM tunneling
Large SO coupling
Not too large Zeeman splitting
Cleanest possible SM ballistic
Little chemical pot. Fluctuations
SC disorder (short-range) okay
Multiband better
But not too many bands
FIG. 2: (Color online) Dependence of the minimum quasiparticle excitation gap in the BdG spectrum given by Eq. (16) on the Zeeman field $\Gamma$ for different SM–SC couplings. The chemical potential is $\mu = 0$ and the Rashba coefficient is $\alpha_r = 0.15$ eV $\cdot$ Å for the curve represented by small (green) circles and $\alpha_r = 0.1$ eV $\cdot$ Å for the other three curves. The system becomes gapless at $\Gamma_c = \sqrt{\gamma^2 + \mu^2}$. The superconducting state with $\Gamma < \Gamma_c$ is topologically trivial, while for $\Gamma > \Gamma_c$ one has a topological superconductor that supports Majorana bound states. Note that the optimal quasiparticle gap for the topological SC has a weak dependence on the SM–SC coupling but varies strongly with the strength of the spin–orbit coupling.
The goal is to have the largest possible SC proximity induced gap in the SM with also the largest possible minigap or BdG quasiparticle gap for the Majorana mode staying within the topological regime. This requires careful tuning of all the system parameters!
Experimental and materials considerations for the topological superconducting state in electron and hole doped semiconductors: searching for non-Abelian Majorana modes in 1D nanowires and 2D heterostructures

Jay D. Sau¹, * Sumanta Tewari², and S. Das Sarma¹

\[ E_{SO} > V_Z > 2\lambda > 2\Delta > 2E_g > 0 \quad \Delta = \frac{\lambda\Delta_s}{\lambda + \Delta_s \sqrt{V_Z^2 + \alpha^2k_F^2}} \quad E_g = \Delta \left[ 1 - \frac{1}{2^{1/3}} (\pi\tau_{sm}\Delta)^{-2/3} |\langle k_F | - k_F^s \rangle|^{4/3} \right]. \]

\[ \Delta \sim \frac{\alpha k_F}{\sqrt{V_Z^2 + \alpha^2k_F^2}} \Delta_0. \]

\[ \Delta_0 = \frac{\lambda}{\lambda + \Delta_s} \quad \langle k_F | - k_F^s \rangle = \frac{V_Z}{\sqrt{V_Z^2 + \alpha^2k_F^2}} \quad V_Z > \lambda^2 + \epsilon_{F,sm}^2 \]

**Gap as large as possible**

**SO coupling as large as possible**

**Disorder as small as possible**

**TS phase arises after the s-SC is killed by the Zeeman field**

Fig. 1: (a) Calculated disordered TS state quasiparticle gap \( E_g \) as a function of semiconductor mobility \( \mu_{sem} \) for electron-doped wires with \( E_{SO} = 2m^*\alpha^2 = 2K, 4K \). (b) The values of \( V_Z = 2\lambda \) realizing \( E_g \) in panel (a) plotted with \( \mu_{sem} \). The gaps in the adjacent bulk superconductor are taken to be \( \Delta_s = 2K \) corresponding to Al and \( \Delta_s = 4K \) corresponding to Nb.

Fig. 2: (a) Calculated disordered TS state quasiparticle gap \( E_g \) as a function of semiconductor mobility \( \mu_{sem} \) for hole-doped wires with \( E_{SO} = 300K \). (b) The values of \( V_Z = 2\lambda \) realizing \( E_g \) in panel (a) plotted with \( \mu_{sem} \). The gaps in the adjacent bulk superconductor are taken to be \( \Delta_s = 2K \) corresponding to Al and \( \Delta_s = 4K \) corresponding to Nb.
Density of states across phase transition

Finite-size numerical studies $L_x = 10\,\mu m$

DoS in topologically non-trivial phase

$$|V_x| > \sqrt{\mu^2 + \Delta_0^2}$$

DoS in topologically trivial phase

$$|V_x| < \sqrt{\mu^2 + \Delta_0^2}$$

$s$-wave superconductor (Al or Nb)

$2L \gg \xi$
Experimental considerations

Tunable Supercurrent Through Semiconductor Nanowires

Yong-Joo Doh, Jorden A. van Dam, Aarnoud L. Roest, Erik P. A. M. Bakkers, Leo P. Kouwenhoven, Silvano De Franceschi

Science 309, 272 (2005)

Supercurrent reversal in quantum dots

Jorden A. van Dam, Yuli V. Nazarov, Erik P. A. M. Bakkers, Silvano De Franceschi & Leo P. Kouwenhoven


Al/InAs/Al heterostructure

Experimental efforts: Delft, Harvard, McGill, UCSB, Weizmann ...
Tunneling experiments

- probing Majorana bound states using tunneling experiments

Resonant Andreev reflection

\[ \frac{dI}{dV} \left[ \frac{2e^2}{h} \right] \]

**topological**

**non-topological**

\[ G = \frac{2e^2}{h} \quad |V_x| > \sqrt{\mu^2 + \Delta^2_0} \]

\[ T = 0 \]

\[ G = 0 \quad |V_x| < \sqrt{\mu^2 + \Delta^2_0} \]

Sau, Tewari, Lutchyn, Satansecu, Das Sarma, PRB’10
Majorana Fermions in Semiconductor Nanowires

Tudor Stanescu,1 Roman M. Lutchyn,2 and S. Das Sarma3

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(Dated: June 1

Calculated spectrum wavefunction and experimental tunneling results for multiband nanowire in the presence of realistic disorder
Weak coupling analysis $\Delta \to 0$

$\mathcal{M} = (-1)^{\nu(0) - \nu(\Lambda)}$  Kitaev, arXiv’00

Topological phase exists when

Second band  $|V_x| > \sqrt{(\mu - E_{sb})^2 + \Delta_0^2}$

First band  $|V_x| > \sqrt{\mu^2 + \Delta_0^2}$

Lutchyn, Stanescu, Das Sarma, arXiv’10
Fractional ac Josephson effect

Andreev bound states

\[ E \]

\[ \Delta_L = \Delta e^{i\varphi} \]

\[ \Delta_R = \Delta_0 \]

Short junction limit  
(\( L \ll \xi \))

particle-hole symmetry protects  
true level crossing at \( \varphi = \pi \)

Lutchyn, Sau, Das Sarma, PRL’10

Topology non-trivial phase: \( V_x > \sqrt{\mu^2 + \Delta_0^2} \)
Josephson current through heterostructure

\[ I_{\pm}(\varphi) \propto \frac{\partial E_{\pm}(\varphi)}{\partial \varphi} \]

Fractional ac Josephson effect is a robust signature of topological SC
Experimental proposal: nanowire embedded into SQUID

Measurement of Josephson inductance

$Z(\omega)$ is a function of the inductance of the SQUID!

$\Phi$

Measure $V_{\text{out}}$ in time domain

$V_{\text{in}} \sim \ldots$ rf-driven tank circuit

$V_{\text{out}} \sim \ldots$

$M$

$Z(\omega)$

$L_c \sim 10\text{nA}$

$L_{J,\text{min}} \sim 10 - 100\text{nH}$

Lutchyn, Sau, Das Sarma, PRL’10
The search for the Majorana ‘fermion’ may finally be coming to an end. The Majorana mode may soon be observed in table-top experiments as an emergent zero-energy mode in solid state semiconductor-superconductor sandwich structures. ‘Majorana’ may return after a 75-year hiatus – thanks to topological quantum computation. Actually, we get more than the original Majorana particle, we get the realization of the 2D Majorana operator and non-abelian statistics.
Q. Marcus (slide 1): Why does topological phase (or Majorana) show up in so many different places theoretically?
A. Because the chiral spinless p-wave SC generically shows up in many places, and they all have Majorana modes in their ‘defects’

Q. Halperin (slide 3): Where is the Majorana claimed to be in the 3D TI system?
A. In the 2D topological surface layer

Q. Millis (slide 3): Why is the Majorana hard to observe in cold atoms in spite of many theoretical proposals?
A. Because the measurement techniques in cold atom systems are highly limited and there is little that could simulate transport or tunneling od solid state measurements

Q. Halperin (slide 10): What is the geometry for the numerical calculation?
A. It is the standard spherical geometry.
Q. Kouwenhoven, Marcus, Stern, Halperin, Fisher (slide 15): What about Coulomb blockade? What about interaction effects in the QD/SC structure? Does the SC need to be phase coherent?
A. Coulomb blockade is incorporated. Interaction effects are not particularly important here. The SC must be phase coherent, i.e. fingers coming in from the same SC block.

Q. Kouwenhoven (slide 20): How is the Majorana protected?
A. Majorana, being a zero energy mode which is neither electron nor hole, cannot decay into the electron or hole states.

Q. Marcus/Kouwenhoven (slide 24): Can nuclear spins be important here?
A. Yes, through its effect on the Overhauser field affecting the electrons.

Q. Freedman (slide 24): What is the intuitive reason for the magnetic field to suppress the topological gap?
A. If the electron spins are parallel, as would happen for a large magnetic field, the basic proximity effect would simply vanish since the SC is an s-wave SC

Q. Marcus (slide 27): How important is disorder and why?
A. Disorder scale in the semiconductor must be smaller than the SC gap, otherwise the p-wave gap will vanish since it is not immune to disorder
Q. Yacoby, Kouwenhoven, Stern (slide 31): What is the nature of the various subgap states? Do they move around with magnetic field and other parameters?
A. The subgap states arise from random impurities in the system (except for the zero-energy Majorana state in the topological phase above the critical magnetic field), and they all move around with system parameters such as the magnetic field, etc. The Majorana remains at zero energy in the topological phase, and does not exist in the non-topological phase. It is either there as a robust state or it is not there.

Q. Halperin/Aleiner/Glazman/Millis: How is the interaction included in the proximity calculation?
A. The interaction is included in the mean field level in the proximity 2D calculation and in the RG treatment in the 1D calculation. For the 2D mean field calculation, it is just like the “\(\mu^*\)” effect in the Eliashberg theory.

Q. Falko: Can one see the Majorana in a SC metal wire if it also has a strong SO coupling and an externally applied magnetic field?
A. No, because far too many subbands (“channels”) will be occupied in metals.

Q. Levitov: What are the experimental requirements?
A. Necessary condition is zero-bias anomaly, sufficient is fractional ac Josephson