Majorana fermions in He-3 Superfluid

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Grand Challenges in QFS
August 8, 2015

Majorana Fermion concept (1)

(Wilczek, Nat Phys '09)

E Majorana (1906 - 1938?)

TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

Nota di ETTORE MAJORANA

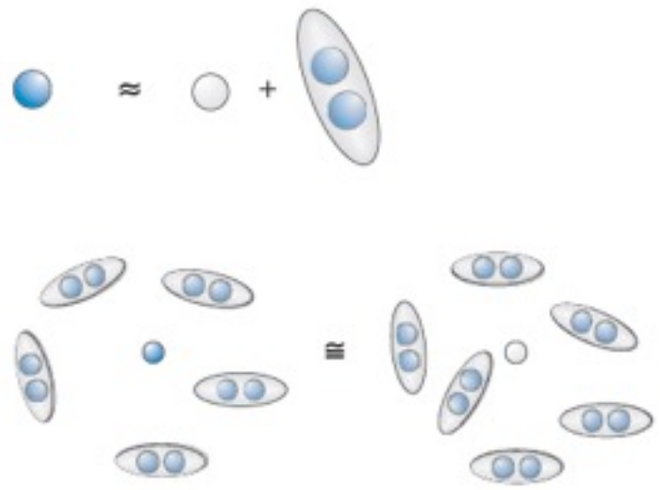
Il Nuovo Cimento **14** 171 (1937)

- Fermion identical to its own anti-particle
  (a *real* fermion, 1/2 of an electron)

- Proposed as a theory for elementary particle,
  i.e. neutrino, but NO experimental confirmation

Majorana Fermion concept (2)

- Can *emerge* as quasi-particles of superconductors



(Wilczek, Nat Phys ’09)

▶ hole can considered as anti-particle:
real fermion ≈
particle-hole conjugation invariant
e.g. $\psi + \psi^\dagger$, $\psi - \psi^\dagger$

- Requires de-pairing equal-spin pairs

- Fermions (e.g. electron, He3 atom) fractionalized into localized $\psi + \psi^\dagger$ and $\psi - \psi^\dagger$ separated from each other

Outline

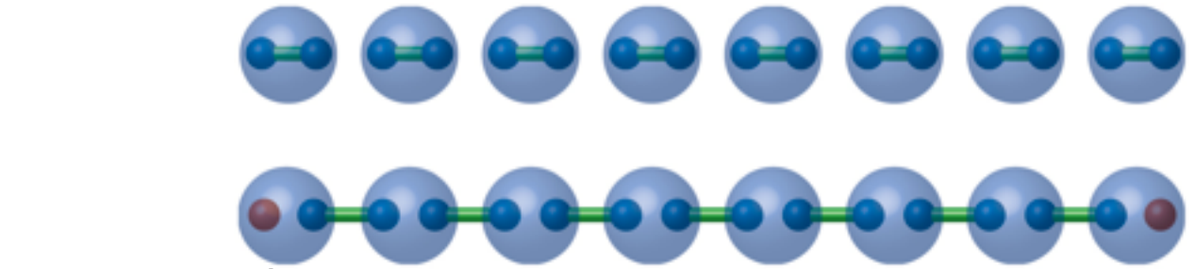
- Current status of Majorana fermions in 3He-B

- Grand Challenge: Qualitative detection of 3He-B Majorana fermions
  - ▶ Surface ion nano-bubble
  - ▶ Possibility in thin slab

- Further challenge: interaction effect in Majorana surface

Majorana in condensed matter systems

- Best publicized in 1D topological superconductor (TSC)



$a = c_1 + c_1^\dagger$ $\qquad$ $b = -i(c_N - c_N^\dagger)$

(Kitaev, Physics Uspekhi '01)

$\longrightarrow$ Majorana zero modes topologically protected by the bulk energy gap

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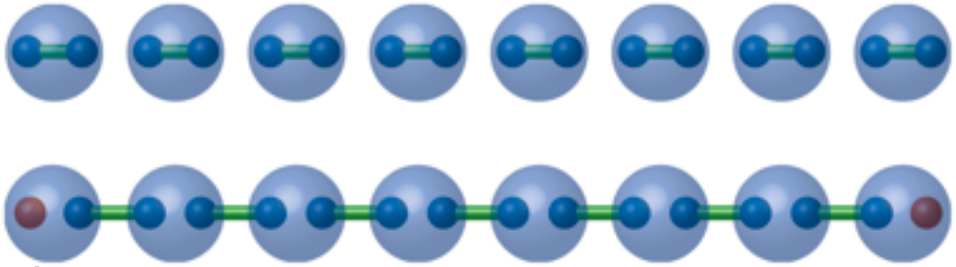

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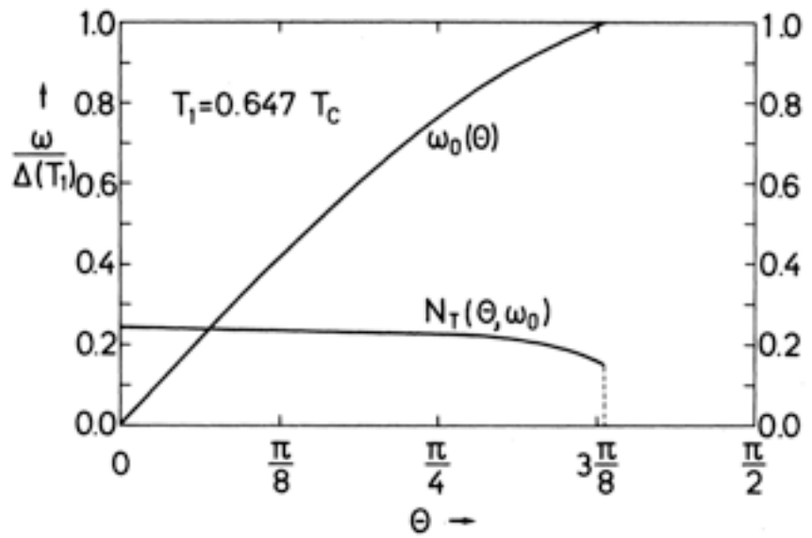
- 3He superfluid: FIRST condensed matter system identified!

(1) 3He-B surface state



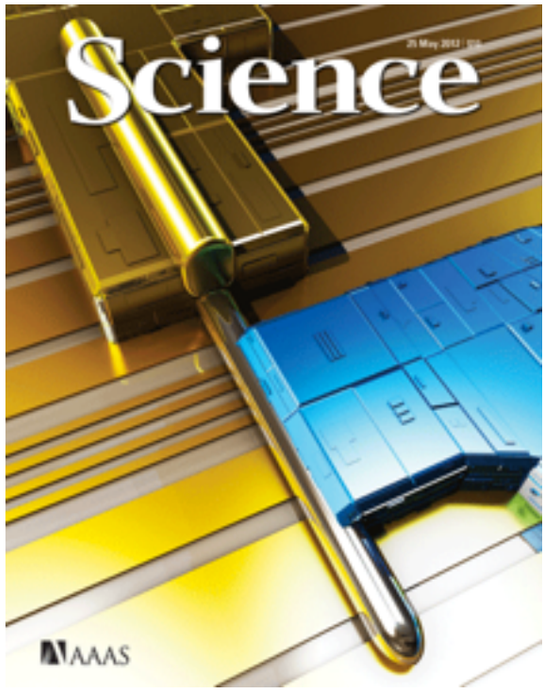
(Buchholtz and Zwicknagl, PRB 1981)

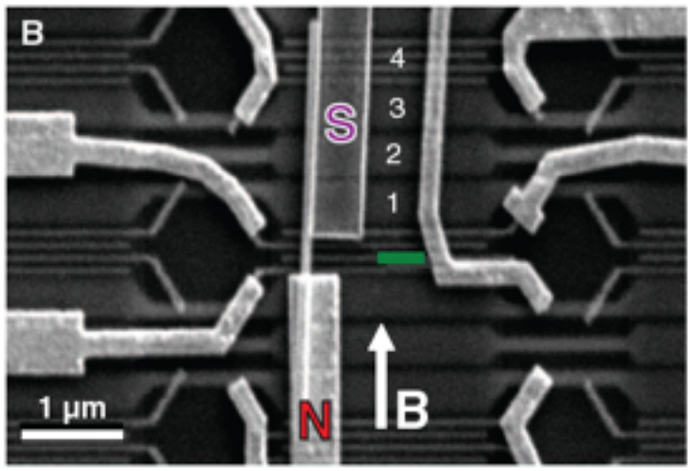
(2) 3He-B topology

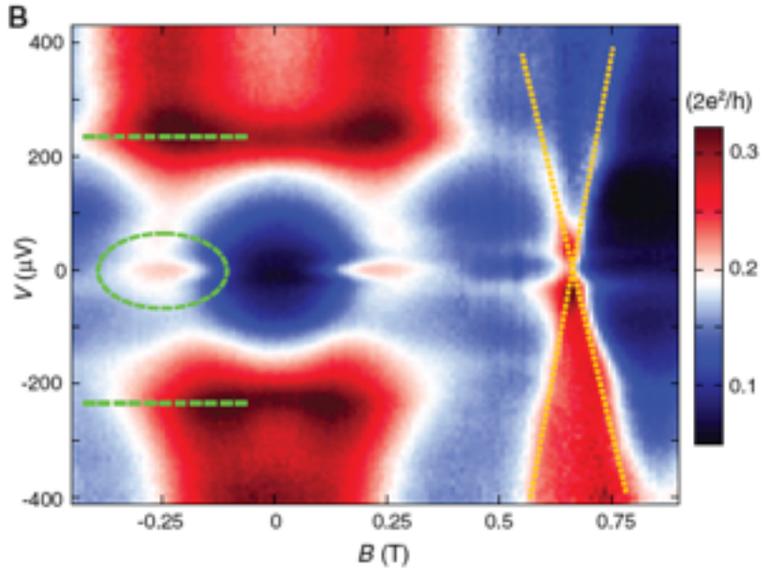
$$N = \frac{1}{48\pi^2} \int_{S^3 \text{ around instanton}} dS_\mu \varepsilon^{\mu\nu\alpha\beta} \mathrm{Tr}(U^\dagger \partial_\nu U)(U^\dagger \partial_\alpha U)(U^\dagger \partial_\beta U)$$

(Salomaa and Volovik, PRB 1988)

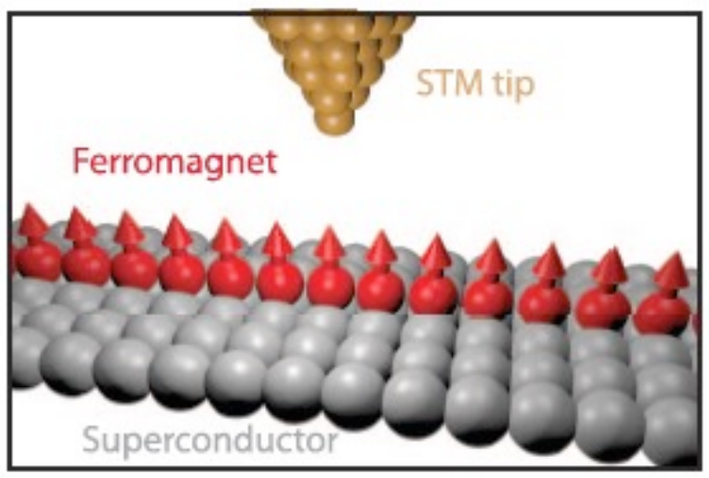
Recent solid state experiments:

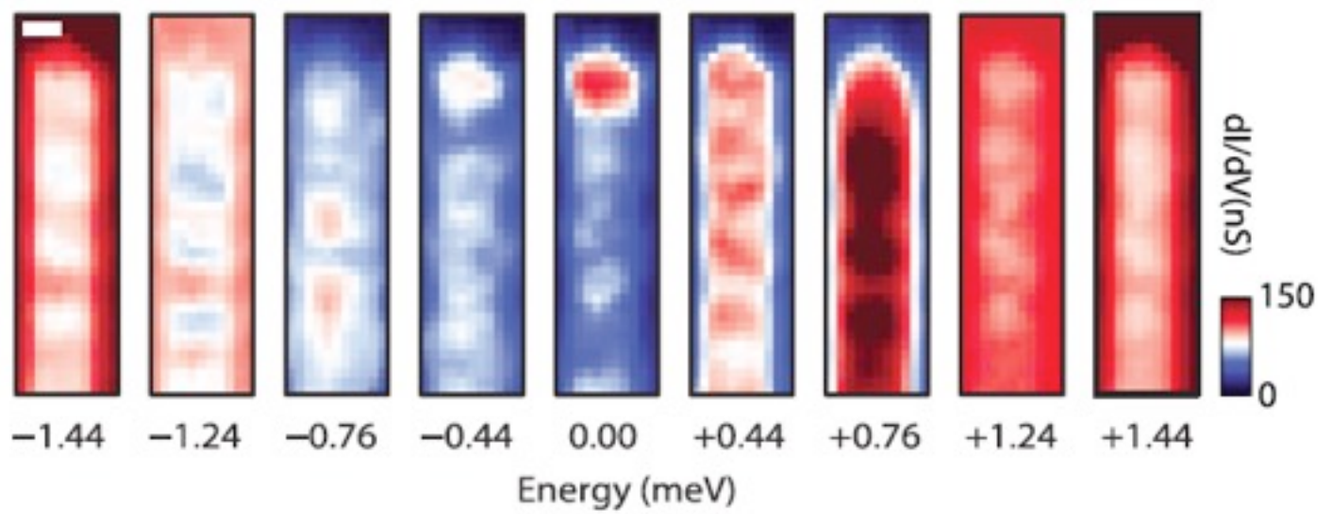






(Mourik, Kouwenhoven et al Science ’12)

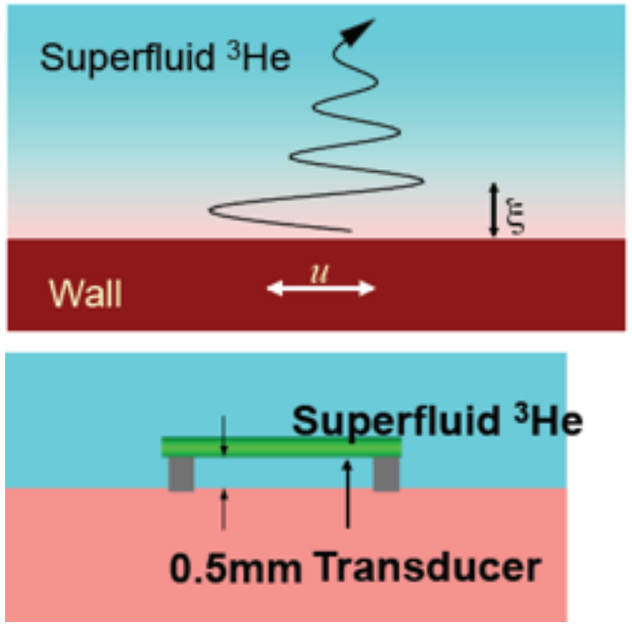


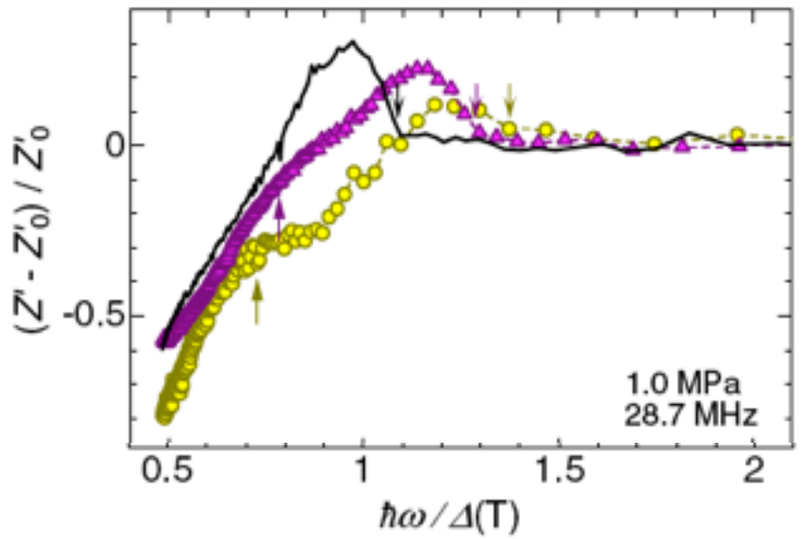


(Nadj-Perge, Yazdani et al Science ’14)

Analogous earlier experiments 3He-B!

- Surface acoustic impedance below pair breaking frequency





(Aoki, Nomura *et al.* PRL ’05; Murakawa, Nomura *et al.* JPSJ ’10)

⇒ indicates subgap quasiparticles at the surface
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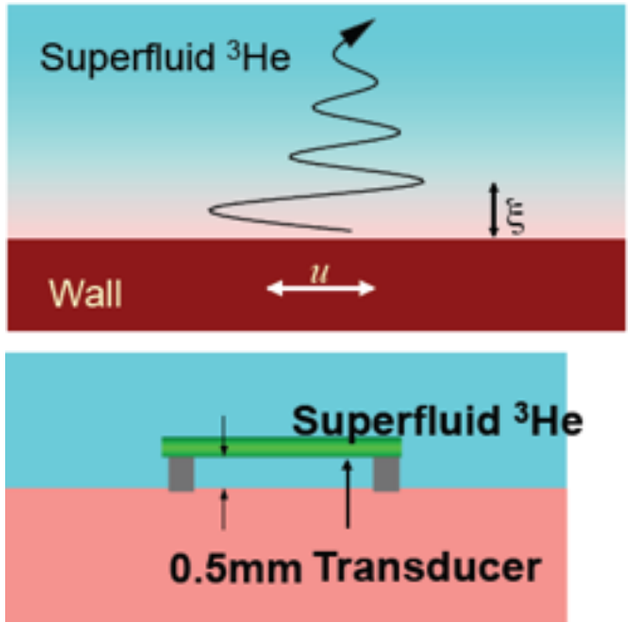

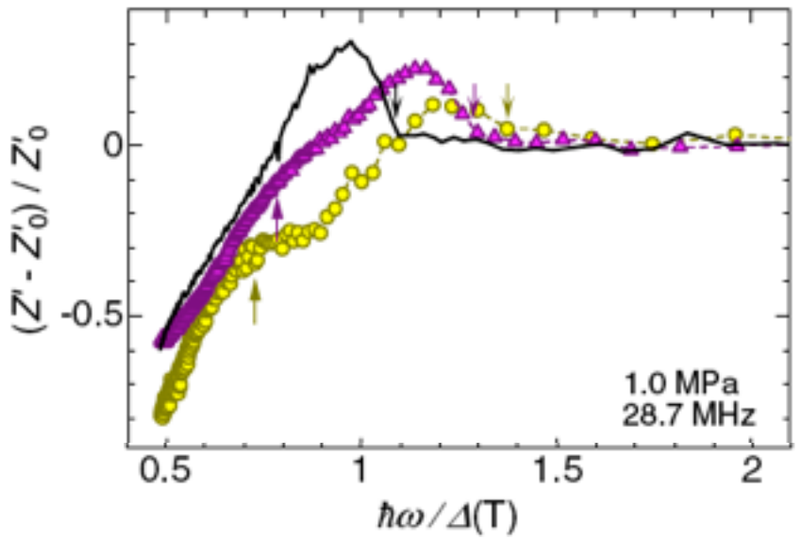

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⇒ indicates subgap quasiparticles at the surface
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- No qualitative (e.g. *more* than zero bias anomaly) Majorana detection in either 3He superfluid or any solid state systems

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  - ▶ Surface ion nano-bubble
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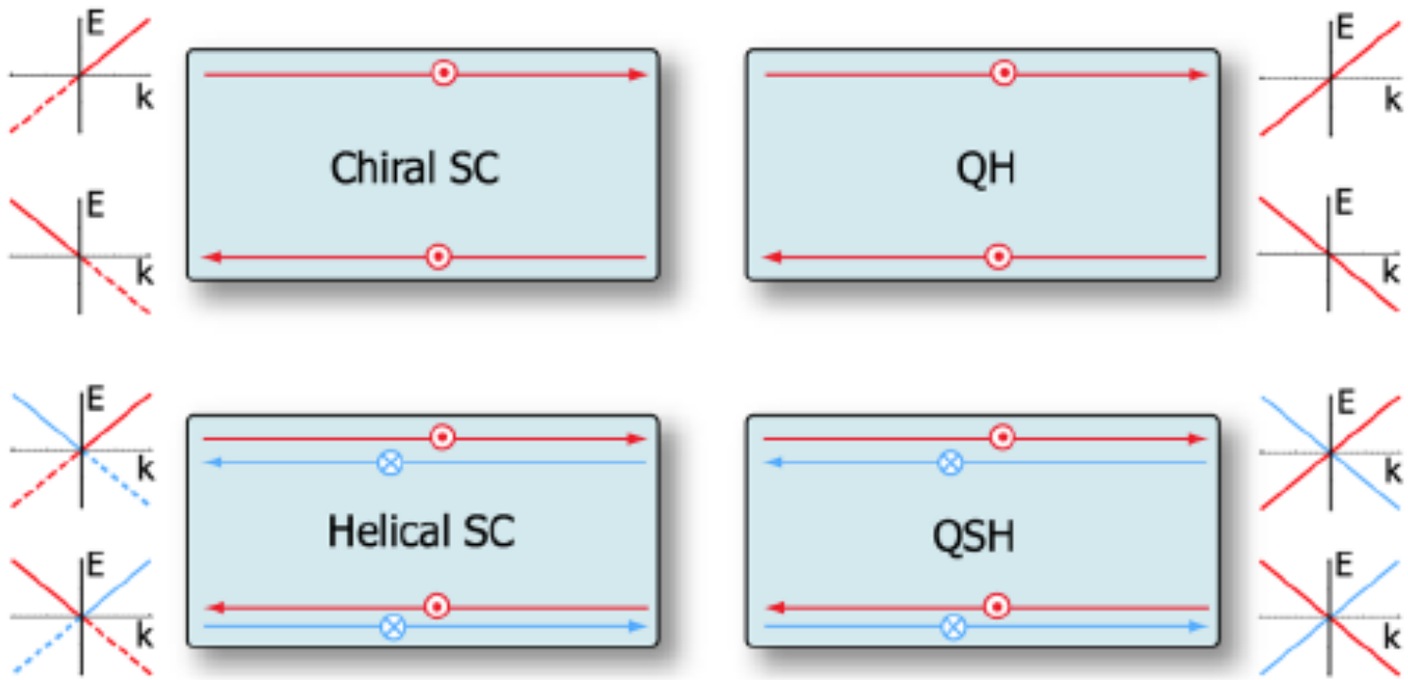
TI surface and TSC Majorana surface analogy



(Qi, Hughes, Raghu and Zhang PRL '09)

- The Majorana edge state same dispersion as the TI edge state for both chiral and time-reversal invariant (TRI) TSC
  - ▶ e.g. p+ip (chiral) superconductor: E = vk (like ν=1 IQH)
    2D TRI TSC : E = σvk (like QSH)
    (requires both $|\uparrow\uparrow\rangle$ & $|\downarrow\downarrow\rangle$)

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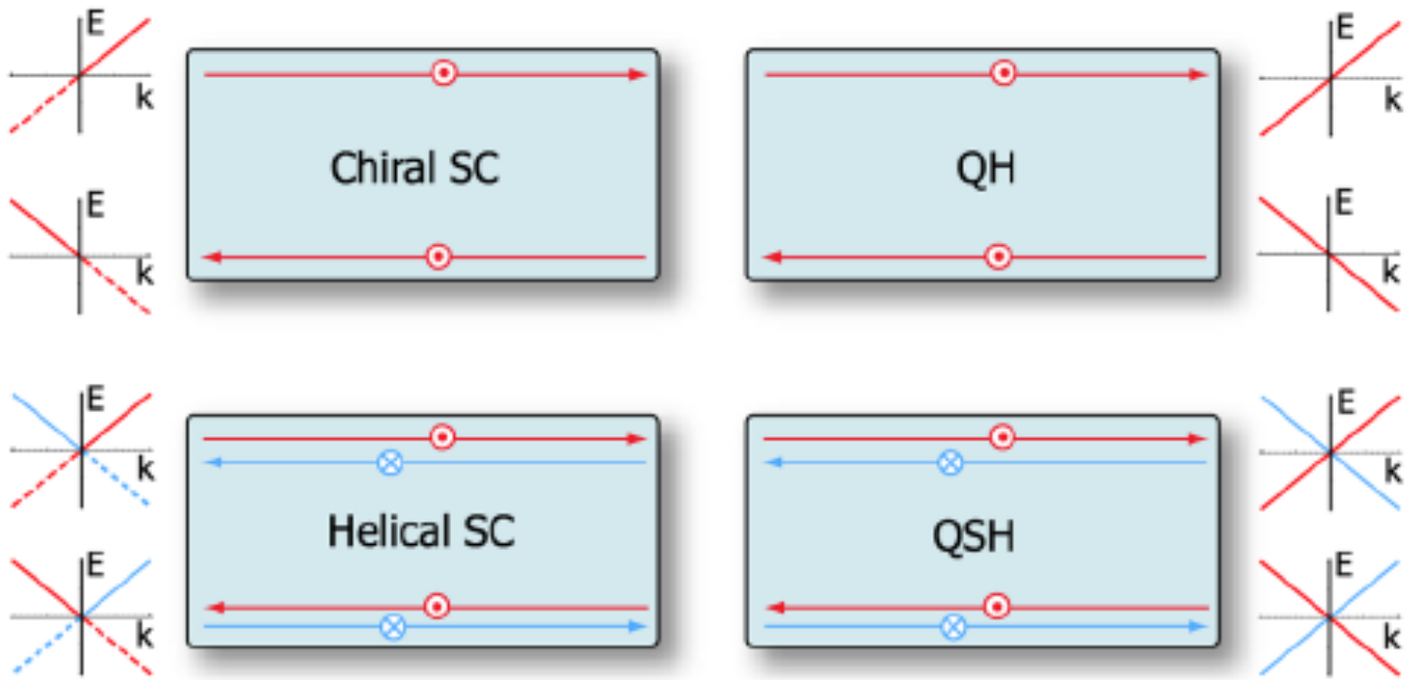

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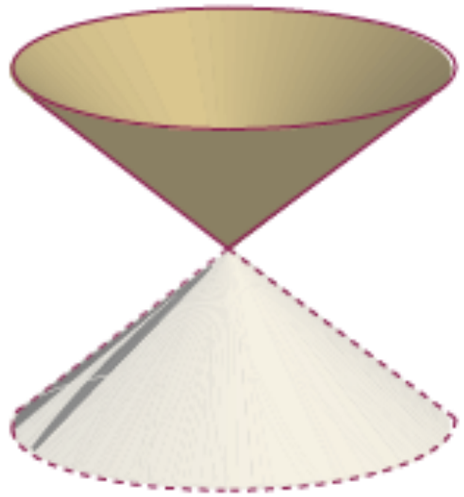
- Opposite surfaces of TI have opposite spin-momentum locking
  Opposite surfaces of TSC have $\psi_\sigma + \psi_\sigma^\dagger$ Majorana on one
  $\psi_\sigma - \psi_\sigma^\dagger$ Majorana on the other

Qualitative feature of 3He-B Majorana surface

(**SBC**, Zhang PRL '09)

$$\begin{bmatrix} \hat{\psi}_{\rightarrow}(\mathbf{r}) \\ \hat{\psi}_{\leftarrow}(\mathbf{r}) \\ \hat{\psi}^{\dagger}_{\rightarrow}(\mathbf{r}) \\ \hat{\psi}^{\dagger}_{\leftarrow}(\mathbf{r}) \end{bmatrix} = \sum_{\mathbf{k}} (\hat{\gamma}_{\mathbf{k}} e^{i\mathbf{k}_{\parallel}\cdot\mathbf{r}_{\parallel}} + \hat{\gamma}^{\dagger}_{\mathbf{k}} e^{-i\mathbf{k}_{\parallel}\cdot\mathbf{r}_{\parallel}}) \begin{bmatrix} \cos\frac{\phi_{\mathbf{k}}+\pi/2}{2} \\ \sin\frac{\phi_{\mathbf{k}}+\pi/2}{2} \\ \cos\frac{\phi_{\mathbf{k}}+\pi/2}{2} \\ \sin\frac{\phi_{\mathbf{k}}+\pi/2}{2} \end{bmatrix}$$

$$\times \quad u_{\mathbf{k}} \sin(k_{\perp} z) e^{\Delta z/\hbar v_F} + (\text{gapped modes})$$



- Momentum eigenstates NOT particle number or spin eigenstates!

- Surface state of $\psi_\sigma + \psi_\sigma^\dagger$ for any in-plane spin quantization
  ← 3He-B spin-orbit rotation symmetry

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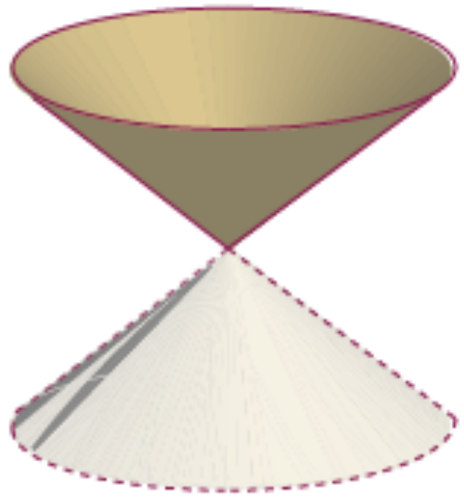

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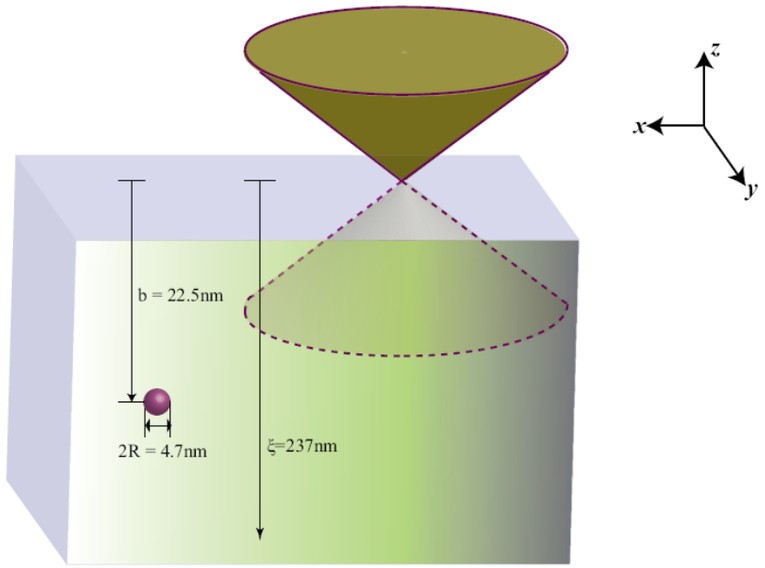
- Surface excitation change
  $I_z = i\psi_{\rightarrow}\psi_{\leftarrow}$

  Surface excitation do not change
  $\rho = \sum_\sigma \psi^\dagger_\sigma \psi_\sigma$ $\quad I_x = \psi^\dagger_{\rightarrow}\psi_{\rightarrow} - \psi^\dagger_{\leftarrow}\psi_{\leftarrow}$ $\quad I_y = \psi^\dagger_{\rightarrow}\psi_{\leftarrow} + \psi^\dagger_{\leftarrow}\psi_{\rightarrow}$

Toward qualitative Majorana detection



- Surface Majorana fermion detection through spin relaxation - shows Ising spin fluctuation of the surface state

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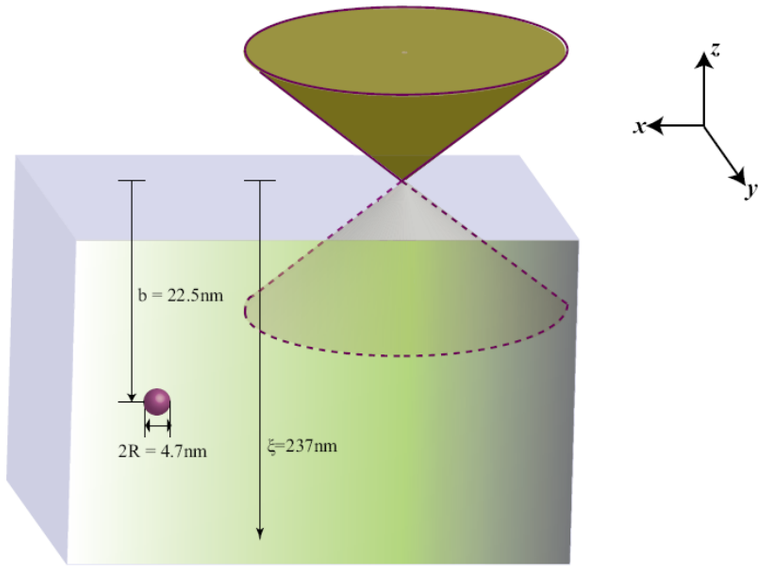

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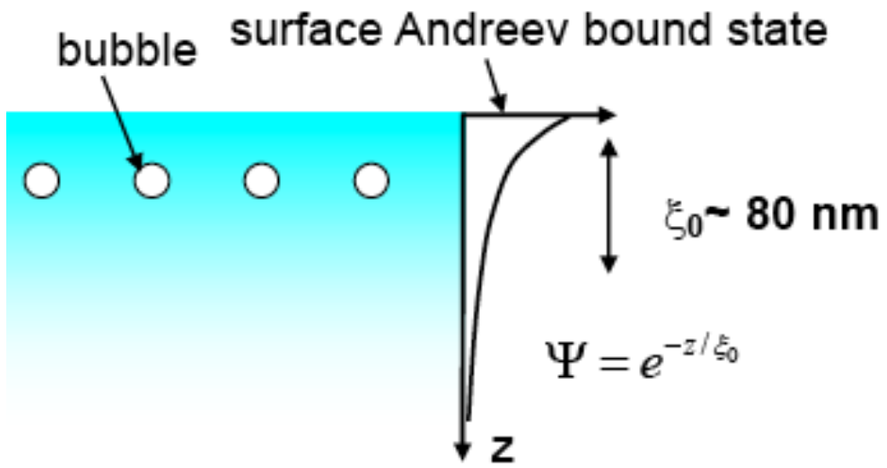
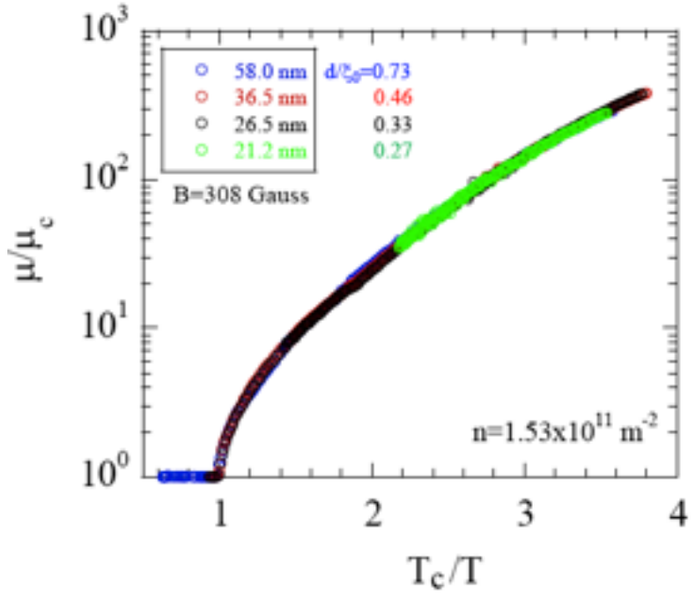
(**SBC**, Zhang PRL '09)

- Ion bubble mobility experiment with parallel electric field
  ⇒ no sign of enhanced density fluctuation at the surface





(Ikegami, **SBC,** Kono JSPJ '13)

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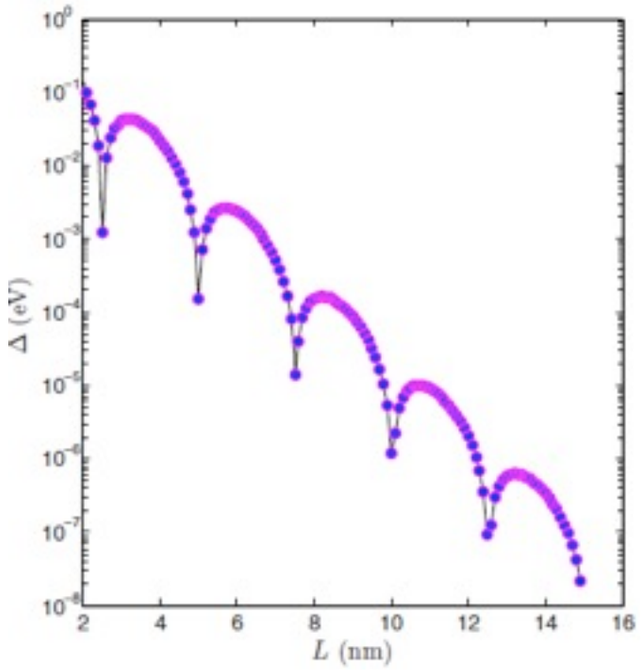
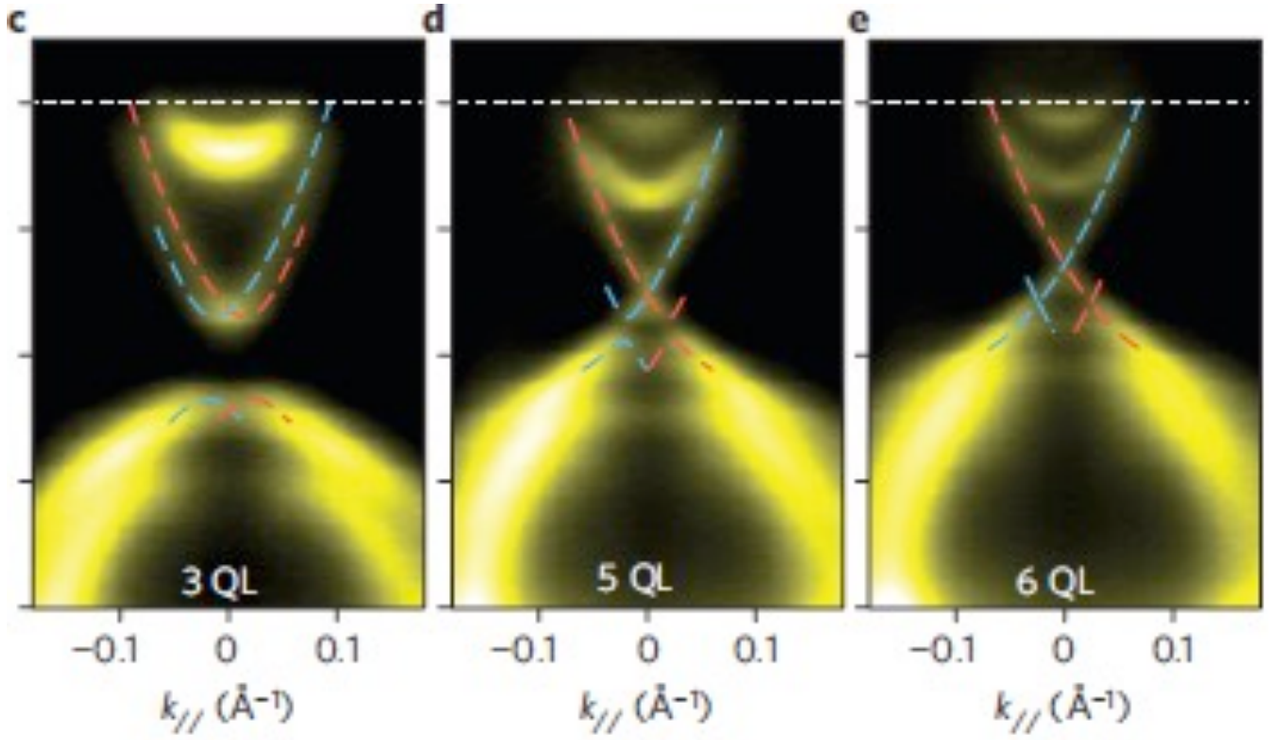
Surface state in topological insulator film



(Linder et al. PRB '09;
Liu et al PRB '09)

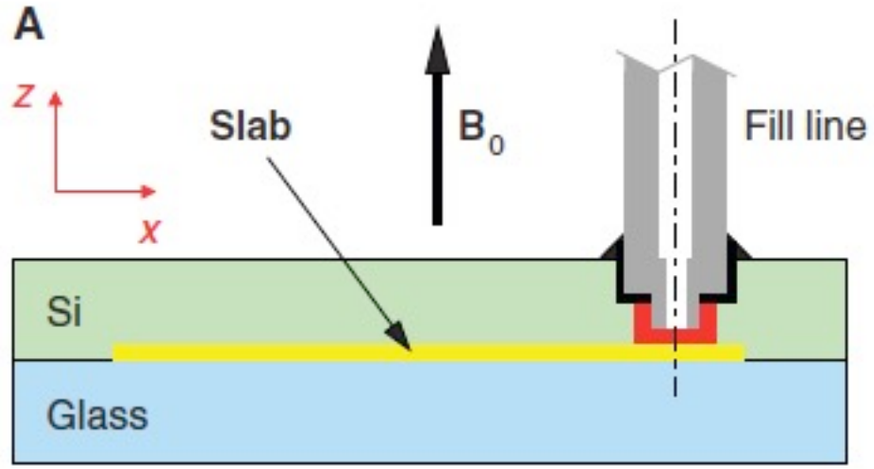


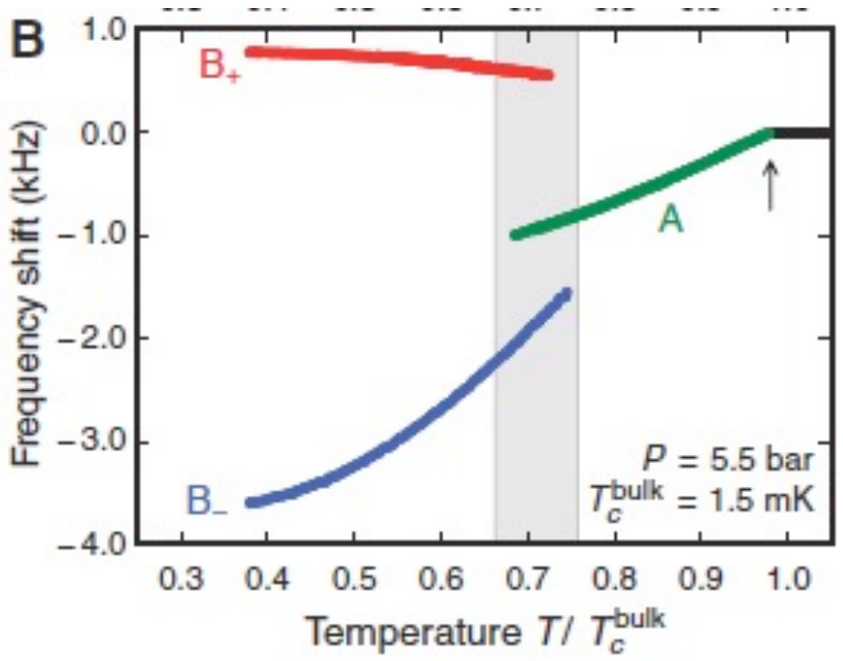
(Y Zhang, Xue et al. Nat Phys '10)

- Tunneling between two TI surfaces gaps out the surface state
  ⇒ momentum / spin locking gone for k=0

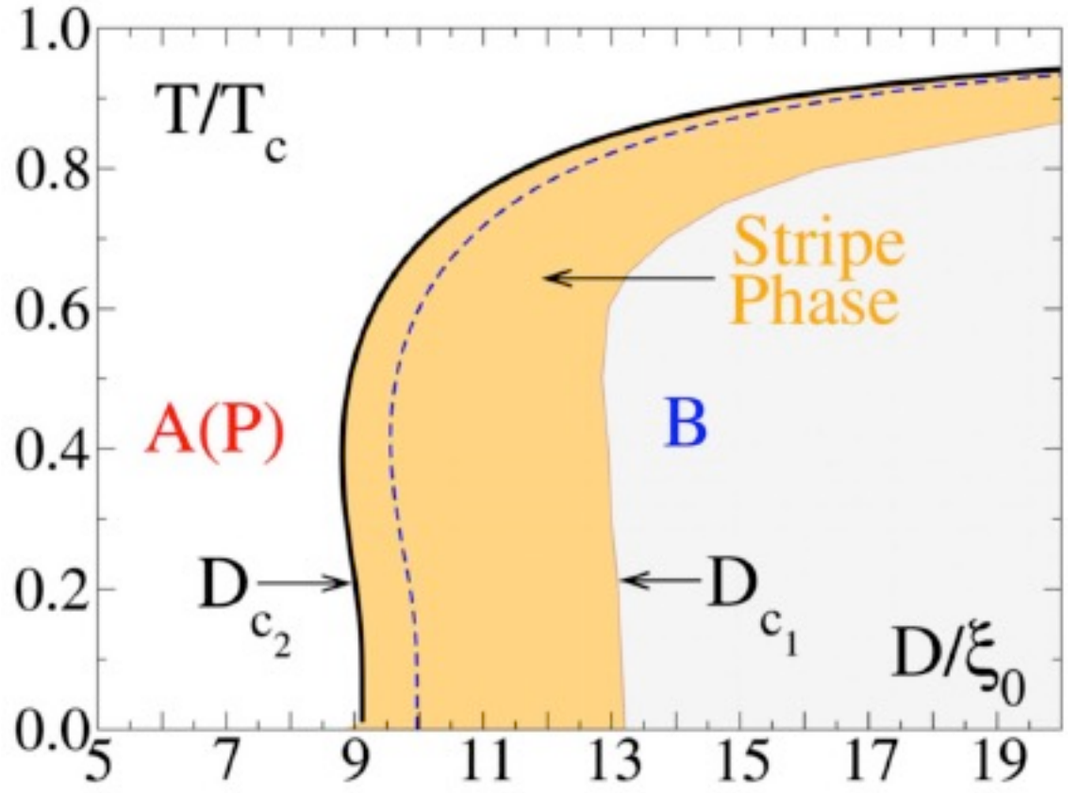
- Tunneling between two Majorana surfaces mean fusing back
  $\psi_\sigma + \psi_\sigma^\dagger$ and $\psi_\sigma - \psi_\sigma^\dagger$

Helium-3 in thin slab





(Levitin, Saunders et al. Science ’13)

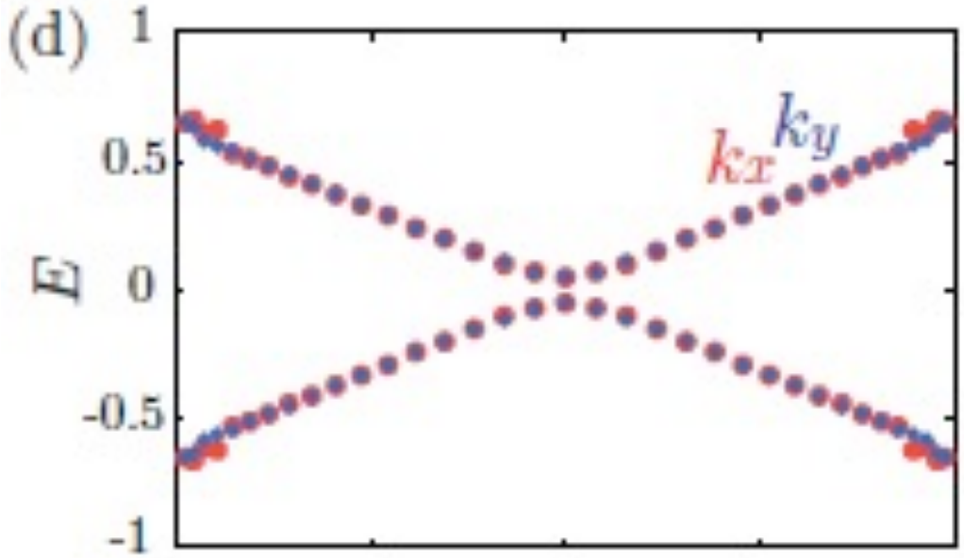


(Vorontsov, Sauls PRL ’07)

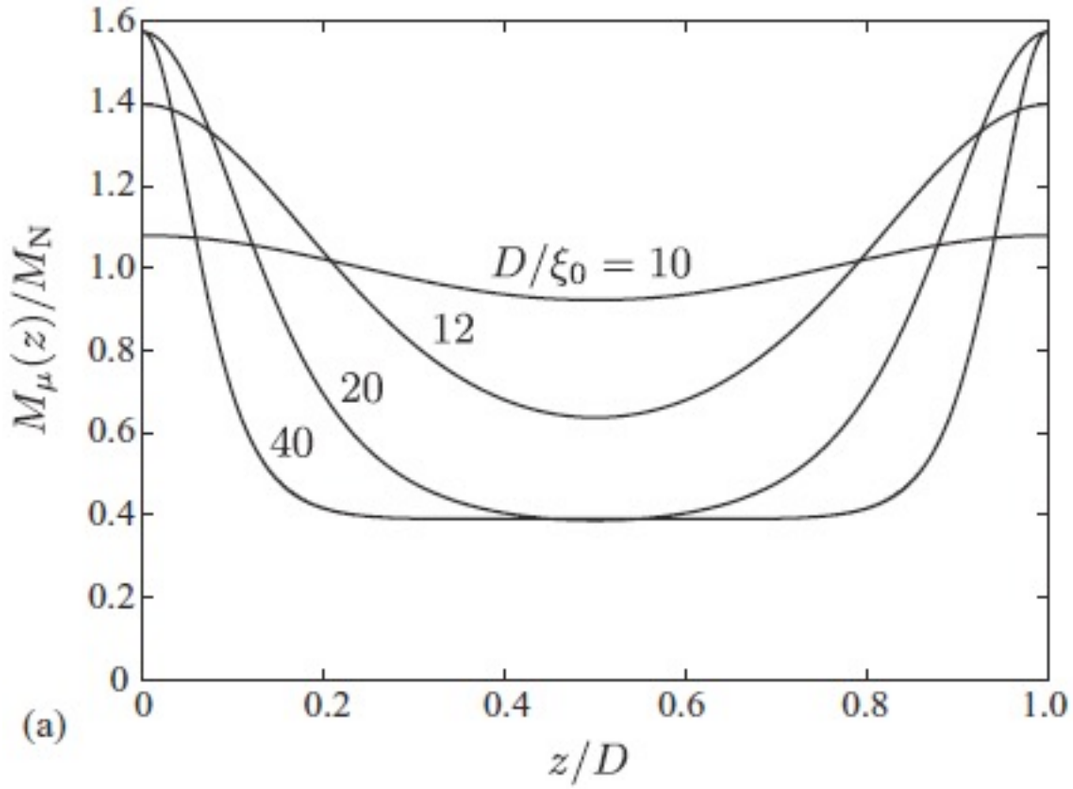
- Experiments on slab thin enough ($D \approx 650nm$, $\xi_0 \approx 77nm$) to see transition between different superfluid states

Majorana detection in thin slab

(D / ξ_0 = 14)



(Tsutsumi et al PRB ’10)



(Mizushima PRB ’12)

- Significant tunneling between the $\psi_\sigma + \psi_\sigma^\dagger$ surface and the $\psi_\sigma - \psi_\sigma^\dagger$ surface within the B-phase
  - ▶ Ising spin fluctuation ⟶ Isotropic spin fluctuation
  - ▶ Zero density fluctuation ⟶ Non-zero density fluctuation

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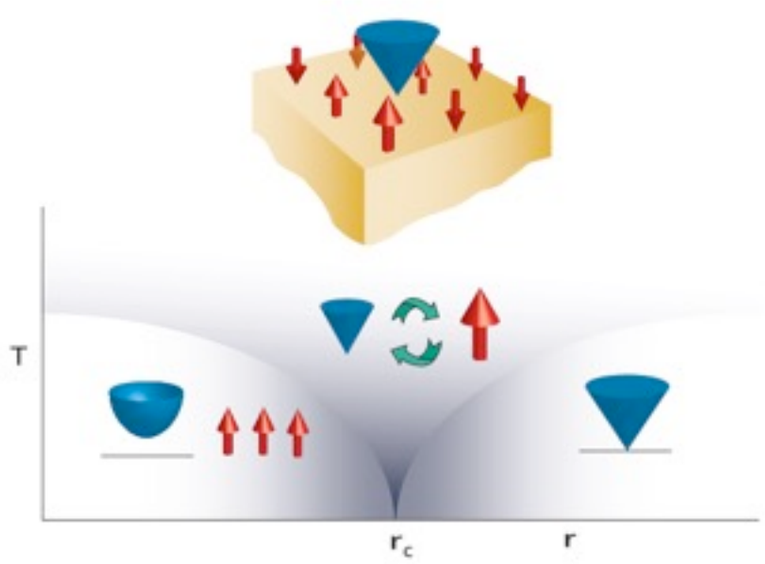
Interaction effect on Majorana surface

- Interaction alters TSC classification: $\mathbb{Z} \to \mathbb{Z}_8$

(Fidkowski, Kitaev PRB ’10; Yao, Ryu, PRB ’13;
Qi, New J Phys ’13; You, Xu ’14)



- Emergent supersymmetry in symmetry breaking transition of a single Majorana cone

(Grover, Vishwanath Science ’14)

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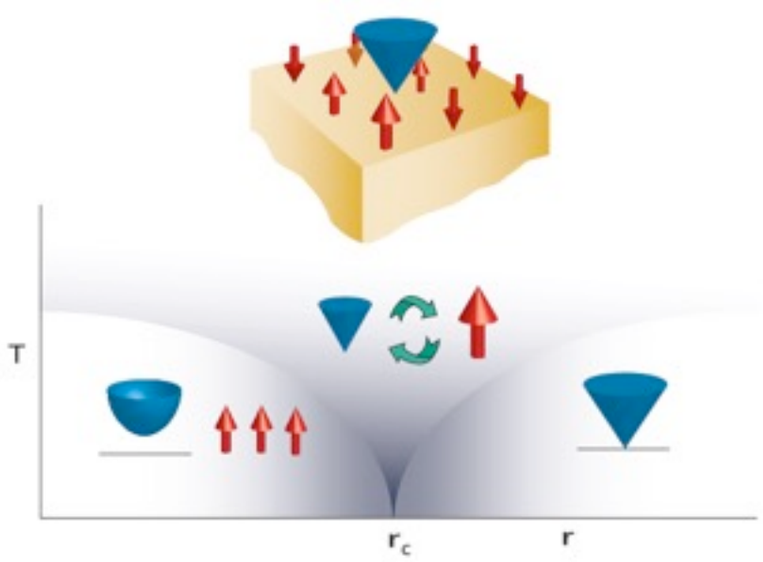


- Emergent supersymmetry in symmetry breaking transition of a single Majorana cone

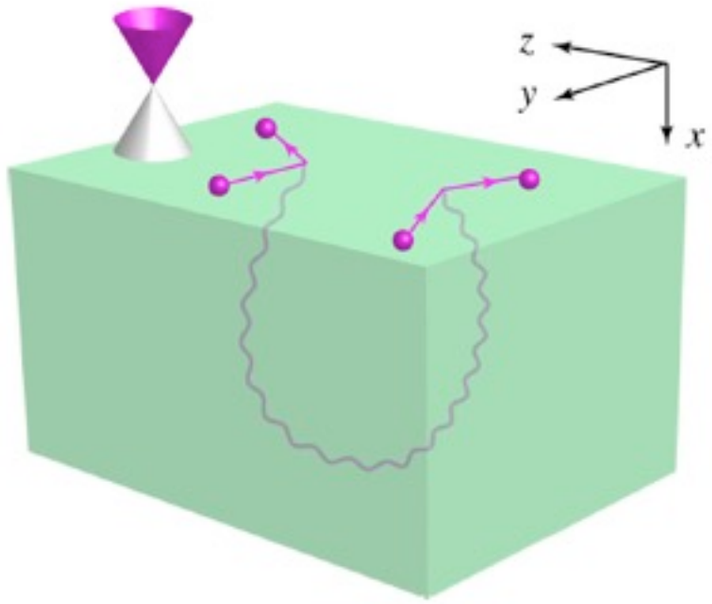
(Grover, Vishwanath Science ’14)

- 3He-B remains the only known system with the surface Majorana cone
  - ▶ Non-interacting quasiparticles insufficient for full physics as it ignores bosonic modes

Interaction on 3He-B surface

- Surface spin current renormalization from Fermi liquid correction

(Wu, Sauls PRB ’13)



- J=1 collective mode mediated interaction

(Park, **SBC**, Maciejko PRB ’15)

- Ongoing study on possible non-equilibrium interaction effect
  ⇒ detection of many-body response of Majorana surface

(Taylo, Kallin, PRB ’15;
SBC, Park, Maciejko *in progress*)

Conclusion

- There is as much experimental evidence for Majorana fermions in 3He superfluid as any solid state systems.

- There are both experimental proposals and technique available for qualitatively detecting 3He superfluid Majorana fermions.

- 3He superfluid is a good venue for studying interaction effect on Majorana fermions.