Majorana fermions in superconducting nanowires without spin-orbit coupling

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(Dated: November 10, 2011)

We show that confined Majorana fermions can exist in nanowires with proximity induced *s*-wave superconducting pairing if the direction of an external magnetic field rotates along the wire. The system is equivalent to nanowires with Rashba-type spin-orbit coupling, with strength proportional to the derivative of the field angle. For realistic parameters, we demonstrate that a set of permanent magnets can bring a nearby nanowire into the topologically non-trivial phase with localized Majorana modes at its ends. Without the requirement of spin-orbit coupling this opens up for a new route for demonstration and design of Majorana fermion systems.

Journal Club

15.11.2011

Majorana bound states in nanowires

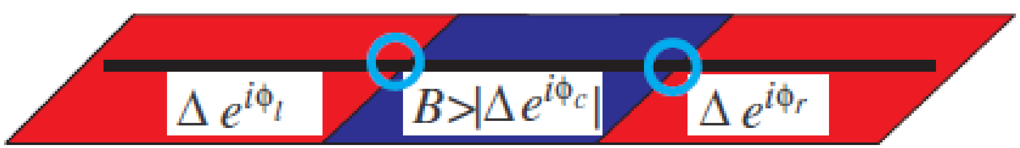
Ingredients :

- Semiconductor with strong Rashba SOI (e.g. InAs)
- Zeeman field perpendicular to SOI
- Proximity induced superconductivity

} Helical conductor

$$\mathcal{H} = [p^2/2m - \mu(y)]\tau_z + up\sigma_z\tau_z + B(y)\sigma_x + \Delta(y)\tau_x$$

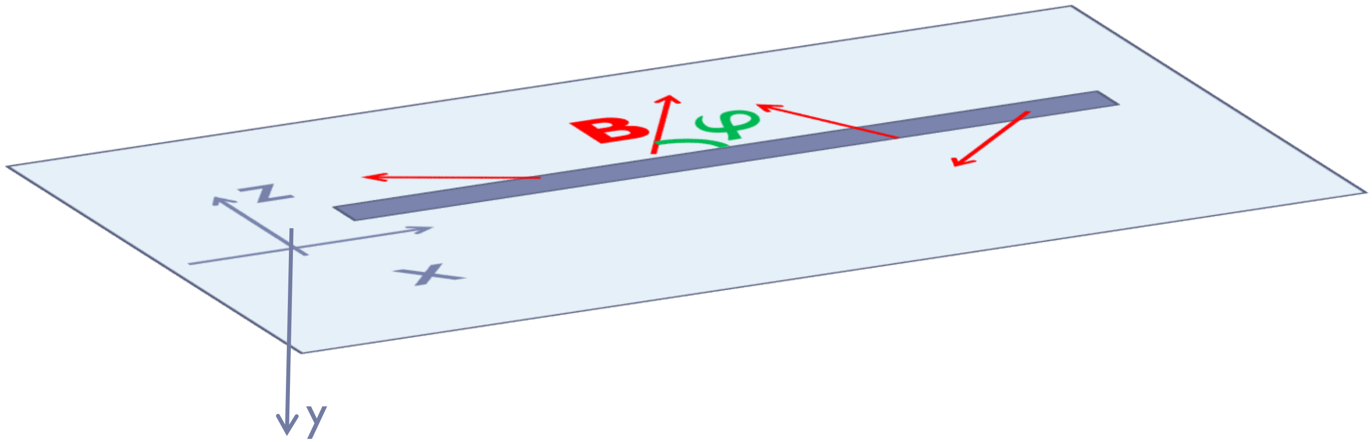
1D topological superconductor for $B^2 > \Delta^2 + \mu^2$



Majorana bound states at the interfaces

- Oreg, Refael, von Oppen, PRL **105**, 177002 (2010)

Engineering an effective Rashba SOI



Inhomogeneous field $$H = \frac{p^2}{2m} + \frac{1}{2} g \mu_B \boldsymbol{B}(x) \cdot \boldsymbol{\sigma}$$

Rotate locally the spin basis $$U = e^{i\sigma_y \varphi/2}$$

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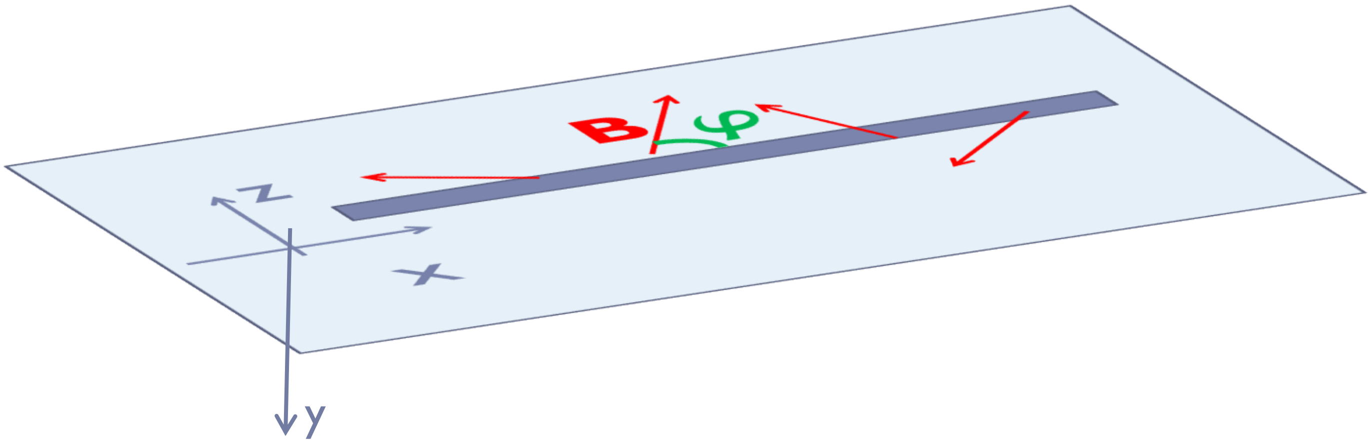

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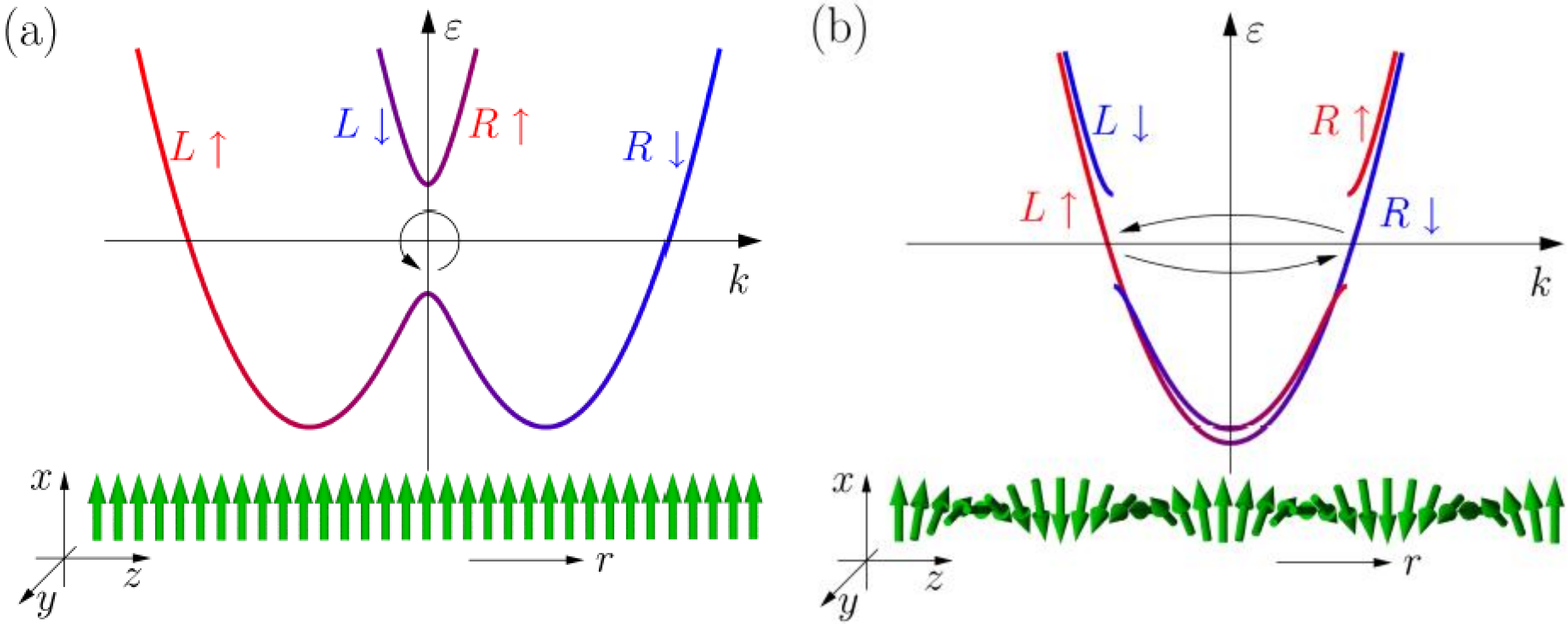
$$\tilde{H} = \frac{p^2}{2m} + \frac{\hbar^2 \varphi'^2}{2m} + \frac{\hbar^2 \varphi''}{4m}\sigma_y + \frac{1}{2} g \mu_B B \sigma_z + \frac{\hbar \varphi'}{2m} p \sigma_y$$

Rashba SOI!

Renormalizes μ

Effective Zeeman field

Rashba SOI == helical magnetic field



- Braunecker, Japaridze, Klinovaja, Loss, PRB **82**, 045127 (2010)

$$\tilde{H} = \frac{p^2}{2m} + \frac{\hbar^2 \varphi'^2}{2m} + \frac{\hbar^2 \varphi''}{4m}\sigma_y + \frac{1}{2} g \mu_B B \sigma_z + \frac{\hbar \varphi'}{2m} p \sigma_y$$

Side effect : effective Zeeman field is tilted toward SOI field

Optimal case

$$\boldsymbol{B} = B_0(\cos(x/R), 0, \sin(x/R)) \qquad \varphi' = 1/R \qquad \varphi'' = 0$$

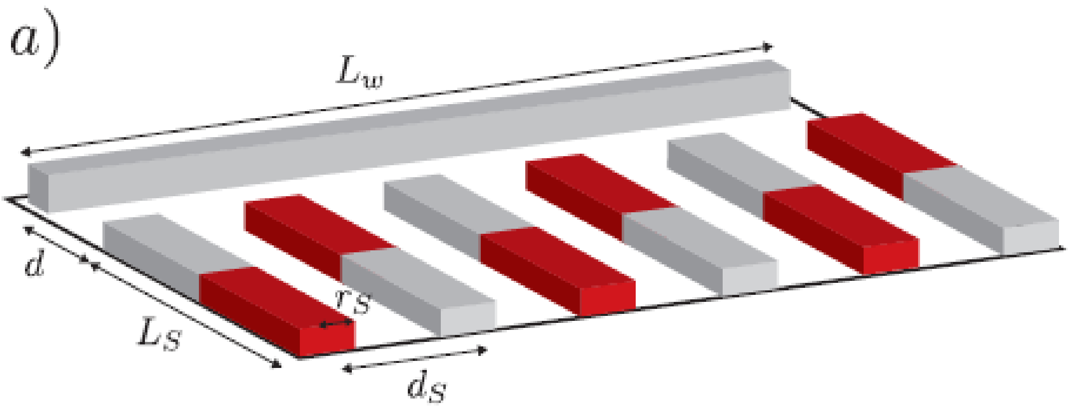
For low mass material m = 0.014 m_e (InSb) and R = 100 nm, strength of SOI is

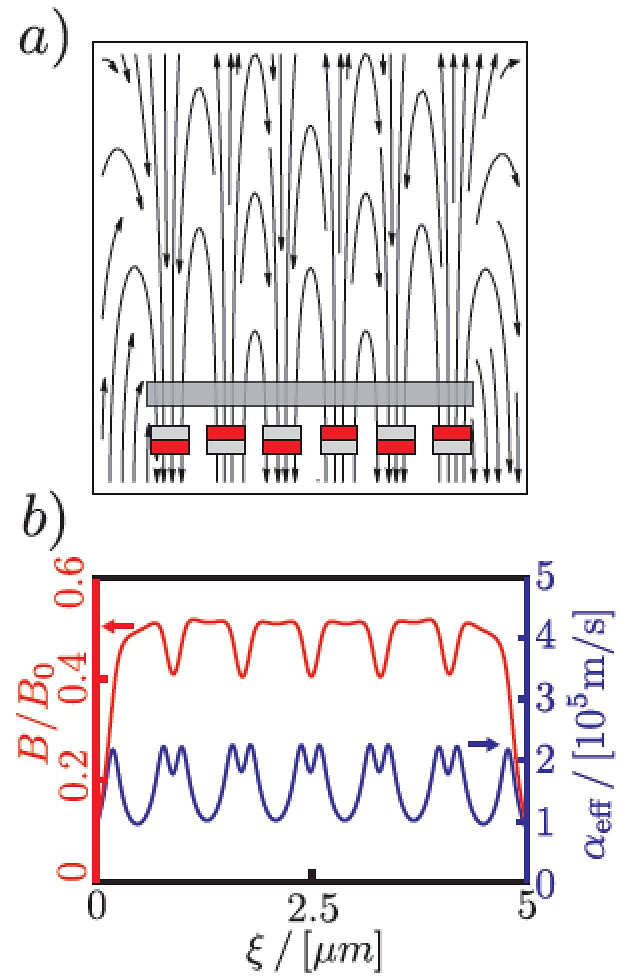
$$\alpha_{\text{eff}} = \frac{\hbar}{2mR} \approx 3 \times 10^4 \text{ m/s}$$

(similar to InAs)

Topological phase for $g^* \mu_B |B_c| > \sqrt{|\Delta|^2 + (\mu - \hbar^2/8mR^2)^2}$

Anti-parallel permanent micro magnets





$L_w = 5\,\mu\text{m}$

$d = 100\,\text{nm}$

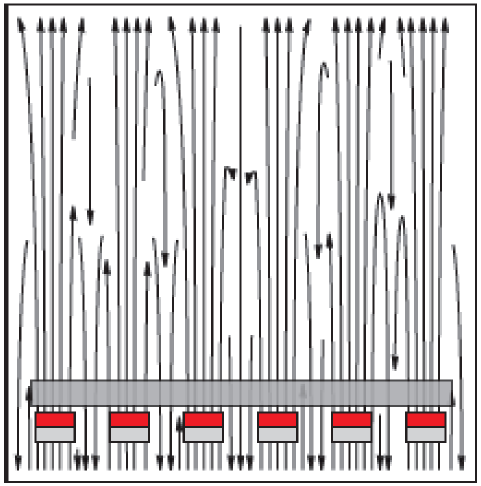
$L_S = 600\,\text{nm}$

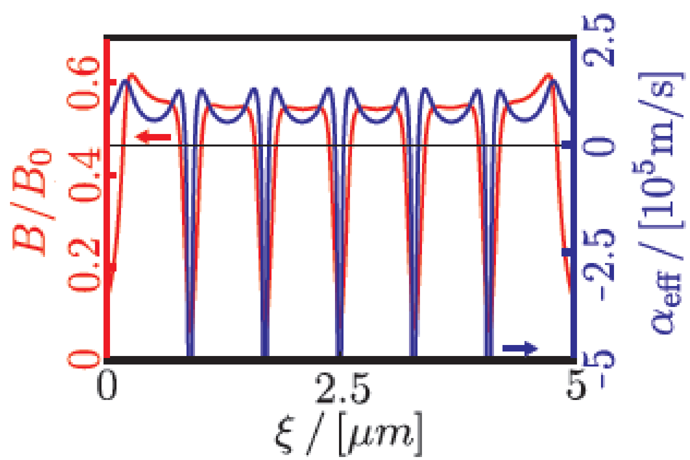
$r_S = 330\,\text{nm}$

$d_S = 860\,\text{nm}$

Realization : magnets with different hysteresis loops

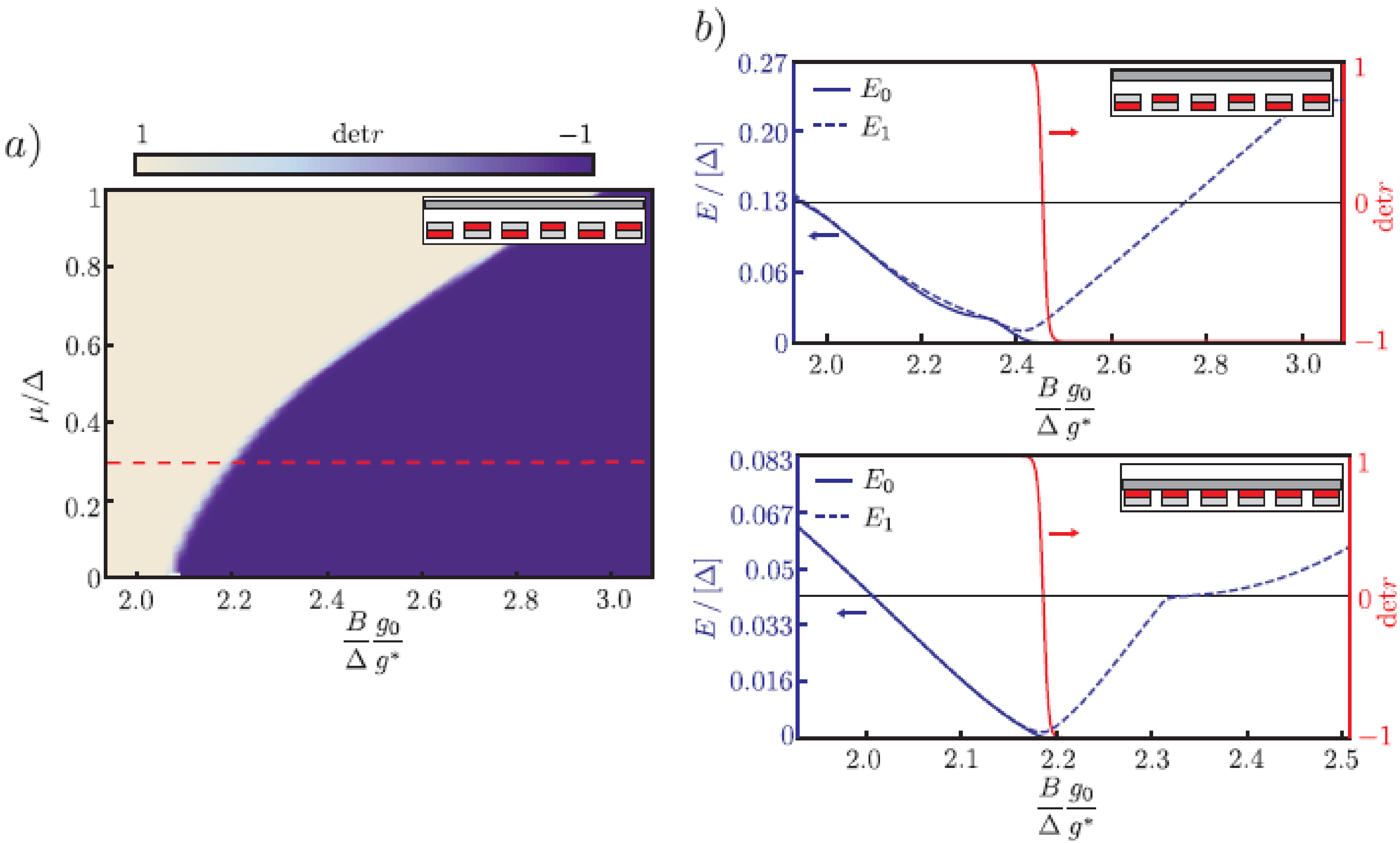
Parallel configuration



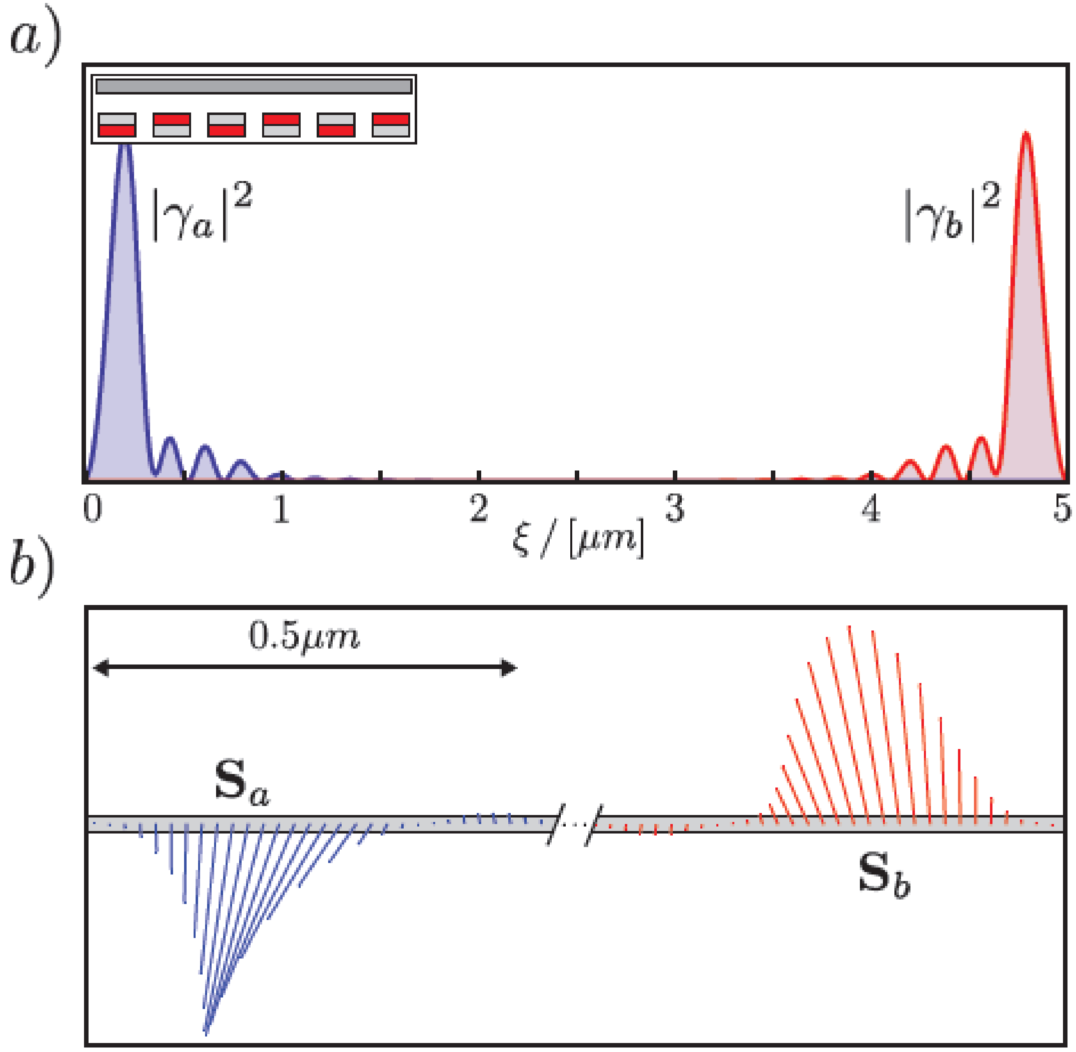


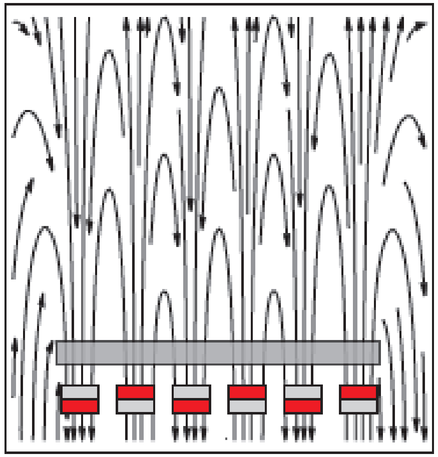
SOI and Zeeman go through zero;
Does the topological phase survive ?

Phase diagram

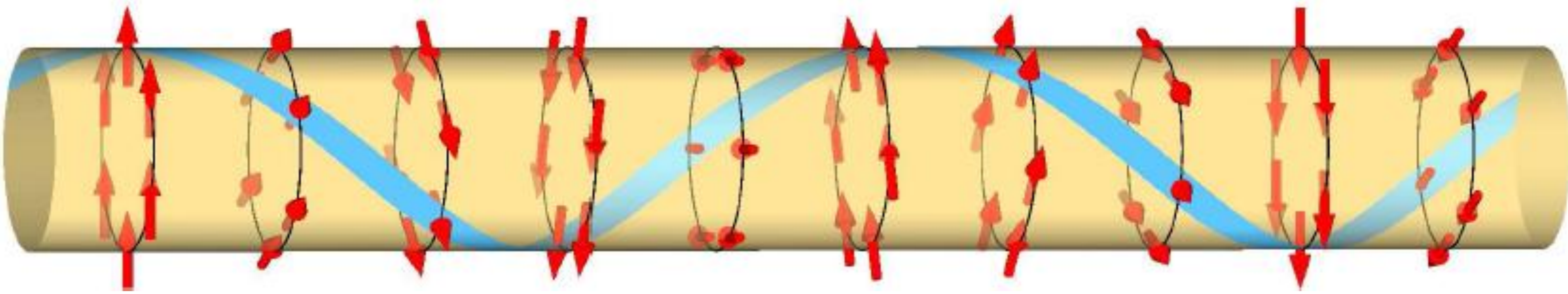


Structure of the Majorana bound states





Helical Overhauser field



Braunecker, Simon, Loss, PRB **80**, 165119 (2009)

Already suggested as a candidate for Majorana fermions :

Gangadharaiah, Braunecker, Simon, Loss, PRL **107**, 036801 (2011)

Conclusion

- Helical magnetic field can replace SOI

➔ Focus on materials optimizing other properties (e.g. g-factor)