Spin-orbit coupling in an ultracold gas of Dysprosium: prospects towards topological superfluidity

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Ultracold Dy experiment
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Outline

1. Artificial spin-orbit coupling with ultracold atoms
2. Ultracold Dysprosium gases
3. Creating and studying a topological superfluid

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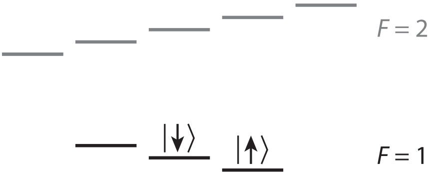
Artificial spin-orbit coupling with ultracold atoms

Definition of a spin-orbit coupling

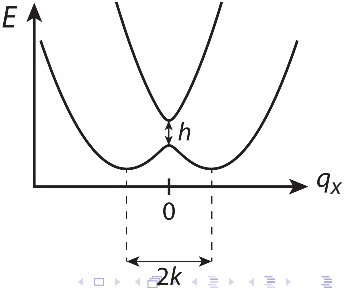
- An effective spin 1/2

example of ^{87}Rb

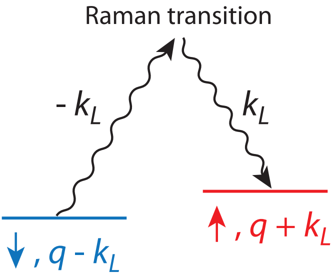


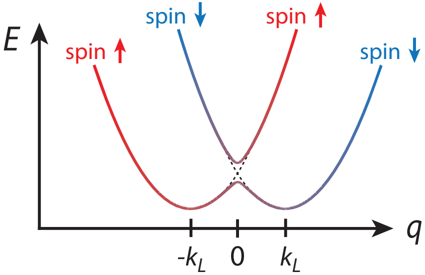
- A momentum-dependent spin coupling

$$\hat{H} = \sum_{\mathbf{q}} \frac{\hbar^2 q^2}{2m} \mathbb{1} + \frac{\hbar^2 k}{m} \hat{q}_x \hat{\sigma}_z + h \hat{\sigma}_x$$



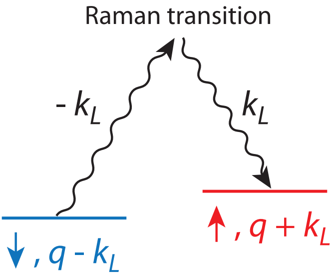
Spin-orbit coupling from laser coupling

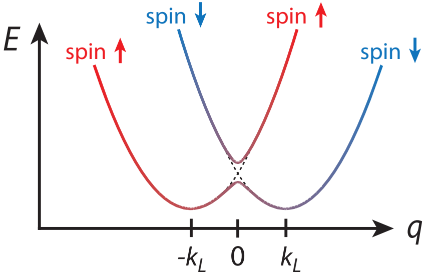




Coupling between $|\downarrow, \mathbf{q} - k_L \mathbf{e_x}\rangle$ and $|\uparrow, \mathbf{q} + k_L \mathbf{e_x}\rangle$, with a Rabi frequency h.

Spin-orbit coupling from laser coupling





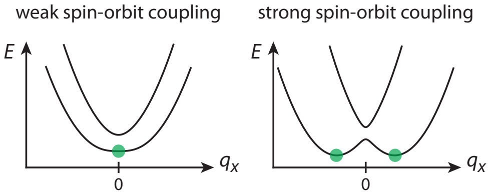
Coupling between $|\downarrow, \mathbf{q} - k_L \mathbf{e_x}\rangle$ and $|\uparrow, \mathbf{q} + k_L \mathbf{e_x}\rangle$, with a Rabi frequency h.

Can be rewritten as

$$\hat{H} = \sum_{\mathbf{q}} \frac{\hbar^2 q^2}{2m} \mathbb{1} + \frac{\hbar^2 k_L}{m} \hat{q}_x \hat{\sigma}_z + h \hat{\sigma}_x$$

Spin-orbit coupled Bose-Einstein condensates

2 degenerate single-particle ground states for strong spin-orbit coupling.



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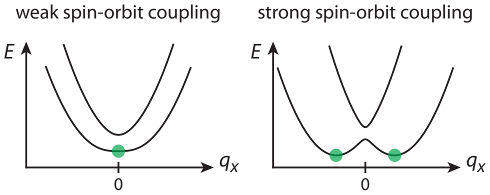
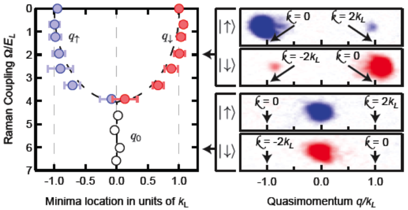


First realization in the group of I. Spielman (JQI)

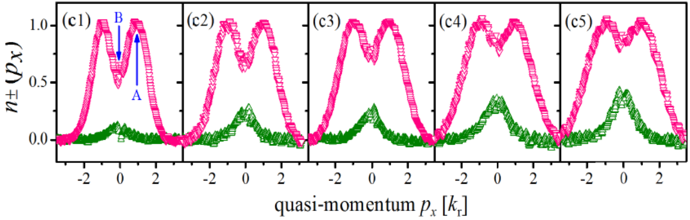


Y.-J. Lin, K. Jiménez-García, I. B. Spielman, Nature **471**, 83 (2011)

Further studies from the groups of S. Chen (UST Shanghai), C. Zhang (Univ. Texas), T. Busch (OIST), Y. Chen (Purdue Univ.)

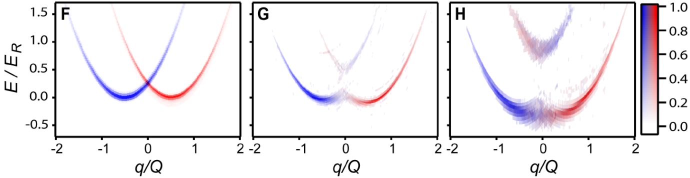
Spin-orbit coupling in fermionic alkali atoms

- Potassium ^{40}K: Spin-orbit coupled Fermi gas at thermal equilibrium



P. Wang, Z.-Q. Yu, Z. Fu, J. Miao, L. Huang, S. Chai, H. Zhai, J. Zhang, Phys. Rev. Lett. **109**, 095301 (2012)

- Lithium ^{6}Li: spin-injection spectroscopy



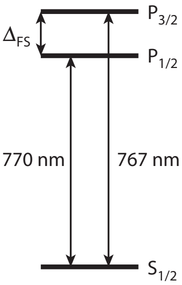
L. W. Cheuk, A. T. Sommer, Z. Hadzibabic, T. Yefsah, W. S. Bakr, and M. W. Zwierlein, Phys. Rev. Lett. **109**, 095302 (2012)

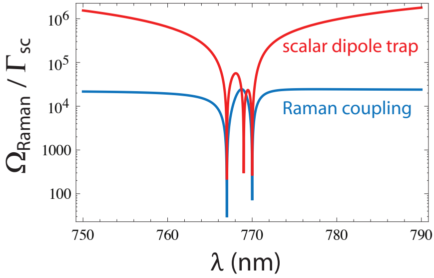
The issue of spontaneous emission for alkali atoms

The electric dipole operator is inefficient for flipping the electron/nuclear spin. Residual coupling coming from the P state $\mathbf{L}\cdot\mathbf{S}$ coupling.

- Scalar dipole potentials: $\Gamma_{\text{scattering}}/\Omega_{\text{dipole}} \simeq \Gamma/\Delta$.
- Raman coupling: the $P_{1/2}$ and $P_{3/2}$ lines tend to cancel each other

$$\Gamma_{\text{scattering}}/\Omega_{\text{Raman}} \simeq \Gamma\left(\frac{1}{\Delta_{1/2}} - \frac{1}{\Delta_{3/2}}\right).$$

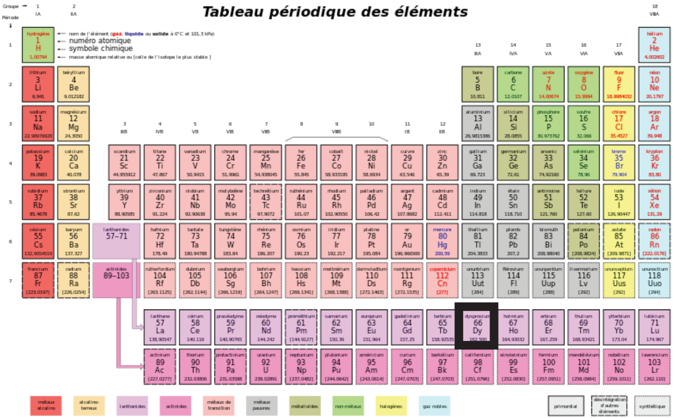




For an optimized detuning: $\Omega_{\text{Raman}} = 1\,E_r \leftrightarrow$ Heating rate of 700 nK/s.

Outline

The Dysprosium atom



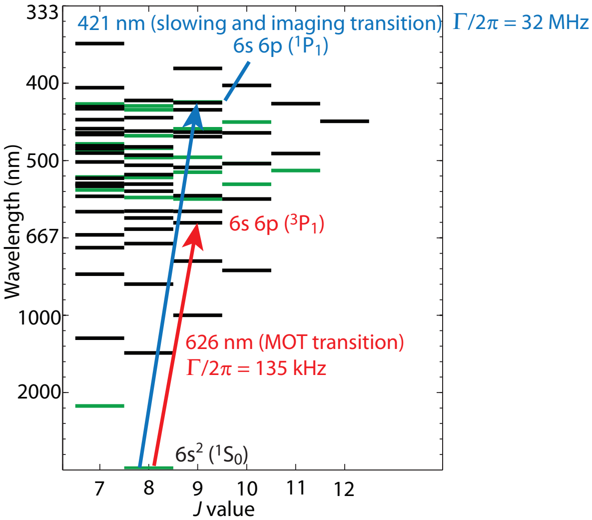
- 2 fermions, 3 bosons
- $J = 8$ ground state, electronic config. $4f^{10}(^5I_8)\,6s^2(^1S_0)$

Quantum degeneracy for bosons and fermions in the group of B. Lev

M. Lu, N. Q. Burdick, S. H. Youn, B. L. Lev, Phys. Rev. Lett. **107**, 190401 (2011)

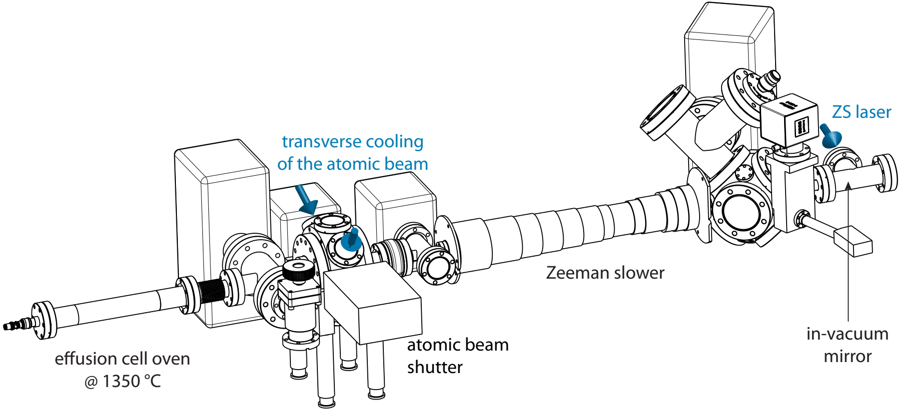
M. Lu, N. Q. Burdick, B. L. Lev, Phys. Rev. Lett. **108**, 215301 (2012)

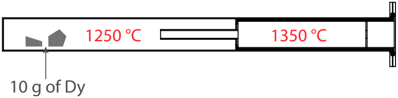
Optical transitions



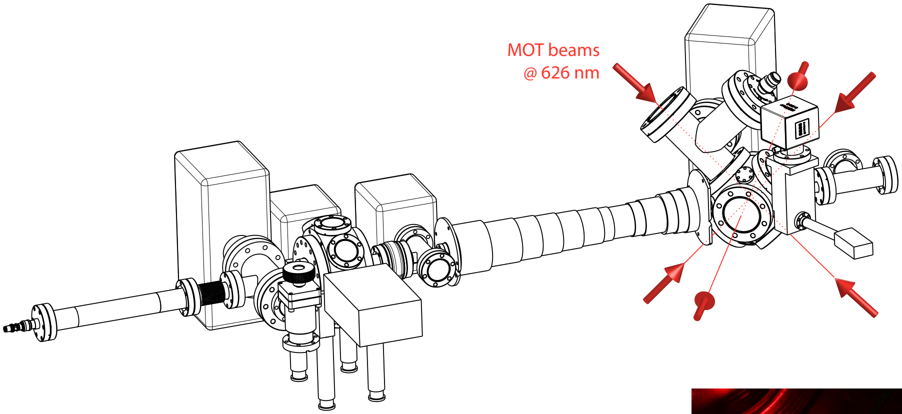
The $4f^{10}$ core electrons play no role in these optical transitions.

Atomic beam and Zeeman slower



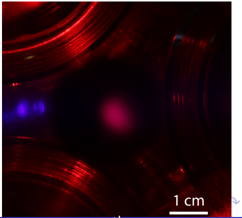


Magneto-optical trap

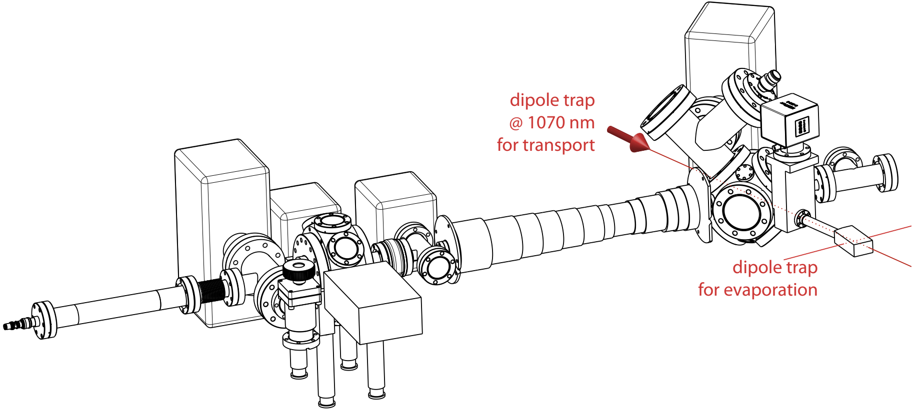


10^8 atoms at $50\,\mu$K, still under characterization

T. Maier, H. Kadau, M. Schmitt, A. Griesmaier, T. Pfau , Opt. Lett. **39**, 3138 (2014)



Optical trapping and transport

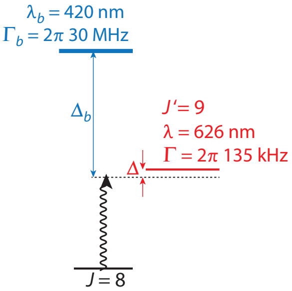


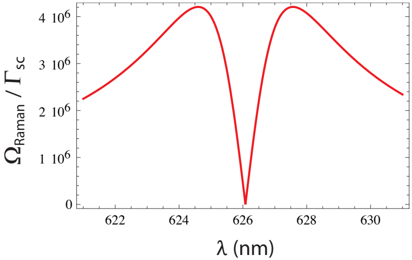
In the science cell: forced evaporation to reach quantum degeneracy

Raman coupling close to a narrow optical transition

- The $6s^2 \rightarrow 6s6p(^1P_1)$ transition at $\lambda_b \sim 400\,\text{nm}$ is spin-independent.
- Narrow $J \rightarrow J'$ transitions efficiently couple Zeeman levels.

Spin-independent light shift	$V_{\text{scalar}} \sim \alpha \left(\Gamma_b/\Delta_b + \Gamma/\Delta\right) I$
Spin-dependent light shift	$V_{\text{vector}} \sim \hbar\Omega_{\text{Raman}} \sim \alpha \left(\Gamma/\Delta\right) I$
Spontaneous emission	$\Gamma_{\text{scattering}} \sim \alpha \left(\Gamma_b^2/\Delta_b^2 + \Gamma^2/\Delta^2\right) I/\hbar$





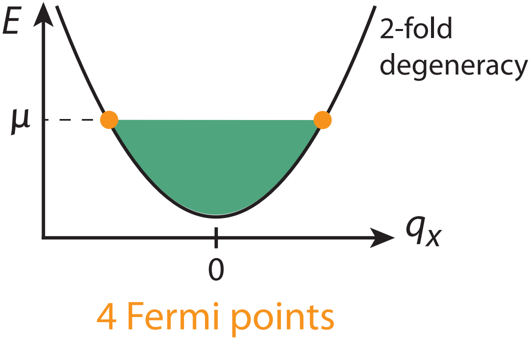
For the detuning $\Delta = (\Gamma/\Gamma_b)\Delta_b \sim 1\,\text{nm}$ one gets

$$\Omega_{\text{Raman}}/\Gamma_{\text{scattering}} \sim \Delta_b/\Gamma_b \sim 10^7 : \quad \text{negligible heating}$$

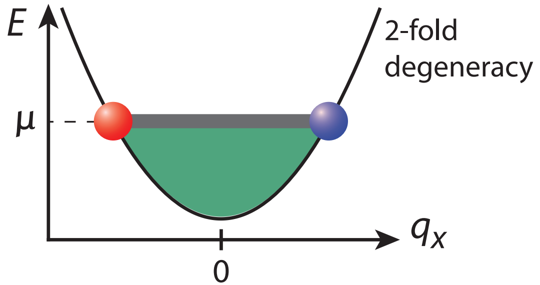
Outline

s-wave superfluidity in ultracold Fermi gases

Without spin-orbit coupling: s-wave superfluidity in spin-1/2 Fermi systems



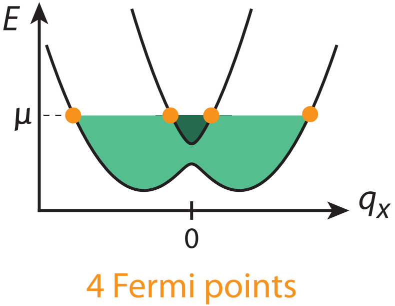
Without spin-orbit coupling: s-wave superfluidity in spin-1/2 Fermi systems



$$s\text{-wave interactions } g \sum_{k,k',q} \hat{c}^\dagger_{k+q,\uparrow} \hat{c}^\dagger_{k'-q,\downarrow} \hat{c}_{k',\downarrow} \hat{c}_{k,\uparrow}.$$

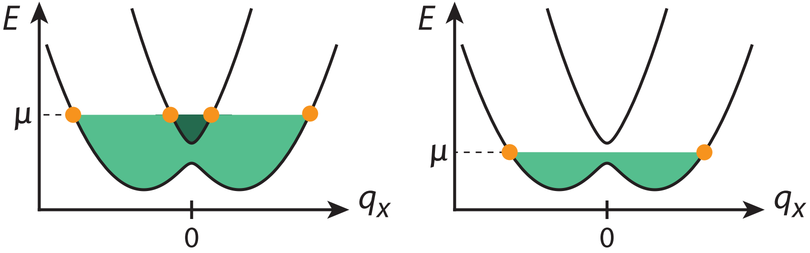
$$\Rightarrow s\text{-wave gap } \Delta \sum_k \hat{c}^\dagger_{k,\uparrow} \hat{c}^\dagger_{-k,\downarrow} + h.c.$$

Spin-orbit coupled Fermi gases



- 4 Fermi points: looks like a spin-1/2 Fermi gas
- 2 Fermi points: looks like a spinless Fermi gas

Spin-orbit coupled Fermi gases



4 Fermi points

2 Fermi points

In the 'spinless' situation, let us project interactions on the single occupied branch.

$$\sum_{k,k',q} g(k,k',q)\hat{c}^\dagger_{k+q}\hat{c}^\dagger_{k'-q}\hat{c}_{k'}\hat{c}_k$$

Dressed s-wave interactions have an odd symmetry $g(k,k',-q) = -g(k,k',q)$.

$$\Rightarrow p\text{-wave gap } \sum_k \Delta(k)\hat{c}^\dagger_k\hat{c}^\dagger_{-k} + h.c., \quad \text{with} \quad \Delta(-k) = -\Delta(k).$$

C. Zhang, S. Tewari, R. M. Lutchyn, S. Das Sarma, Phys. Rev. Lett. **101**, 160401 (2008)

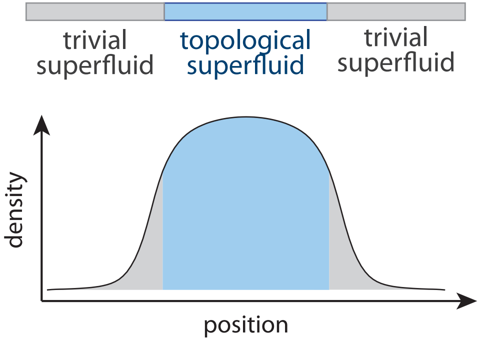
R. A. Williams et al, Science **335**, 314 (2012)

Phase diagram

Topological superfluidity when the Fermi surface is effectively ‘spinless’:

$$-h < \mu < h$$

In local density approximation: $\mu(x) = \mu_0 - \frac{1}{2} m\omega_x^2 x^2$.



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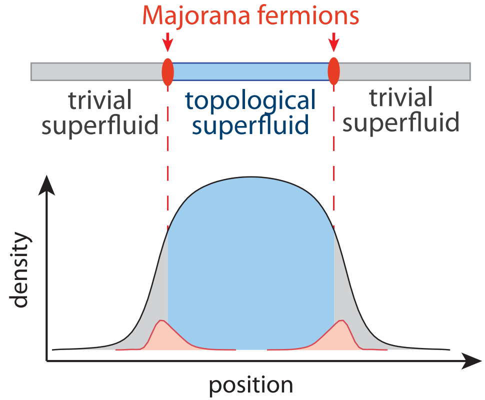
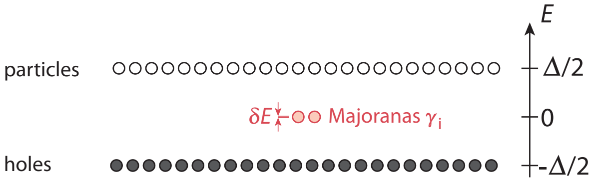


2 Majorana fermions are located at the phase separation points.

Properties of Majorana fermions

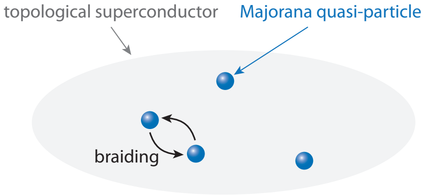
1. Their energy is locked at the Fermi level

$$\delta E/\Delta < \max\left[e^{-L/\xi}, e^{-\Delta/k_B T}, e^{-\Delta/V_{\text{perturbation}}}\right]$$



→ Topologically protected qubits

2. Non-abelian quantum statistics



Braiding operations do not commute.

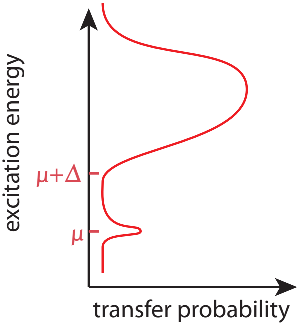
Observing the Majorana fermions using quasi-particle spectroscopy

We send a radio frequency to couple $|\uparrow\rangle$ states to a third Zeeman state initially empty.
Resonance condition:

$$\omega_{RF} = \delta_{\text{Zeeman}} + E_{\text{quasiparticle}}$$

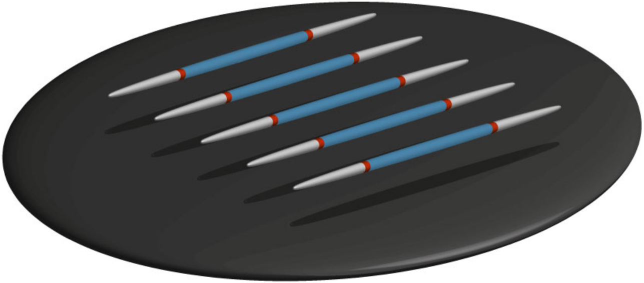
Already used for *s*-wave superfluids.

J. T. Stewart, J. P. Gaebler & D. S. Jin, Nature **454**, 744 (2008)



Conclusions

- Dysprosium is suited for simulating spin-orbit coupling
- Spin-orbit coupling + s-wave interactions $\Rightarrow$ p-wave superfluidity
- Majorana fermions located at the edges of a topological superfluid



Alternative route: using an s-wave superfluid as a Cooper pair reservoir + spin-orbit coupling

S. Nascimbene, J. Phys. B: At. Mol. Opt. Phys. **46**, 134005 (2013)

Thanks for your attention