Static and dynamical engineering of topological superconductivity from Shiba bound states

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A magnetic impurity in a superconductor

Bogoliubov-de Gennes Ham. $\mathcal{H}_0 = \xi_p \tau_z + \Delta \tau_x$ <u>Assumes Δ constant</u> (homogeneous)

Spin impurity Ham. $\mathcal{H}_{\mathrm{imp}} = -J\mathbf{S} \cdot \sigma \; \delta(\mathbf{r})$

Consider the classical spin limit S>>1

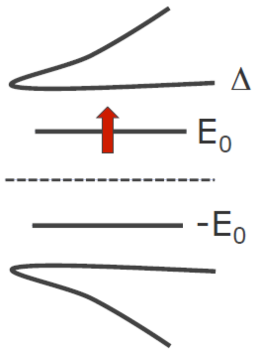
$\Rightarrow$ $\mathcal{H}_{\mathrm{imp}} = -JS\sigma^z \; \delta(\vec{r})$ Like a local magnetic field

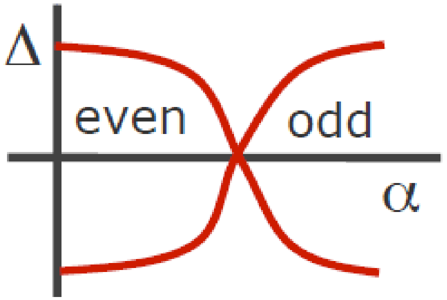
It creates an attractive potential

Shiba bound state

$$E_0 = \Delta \frac{1-\alpha^2}{1+\alpha^2}$$

$$\alpha = \pi \nu_0 J S$$

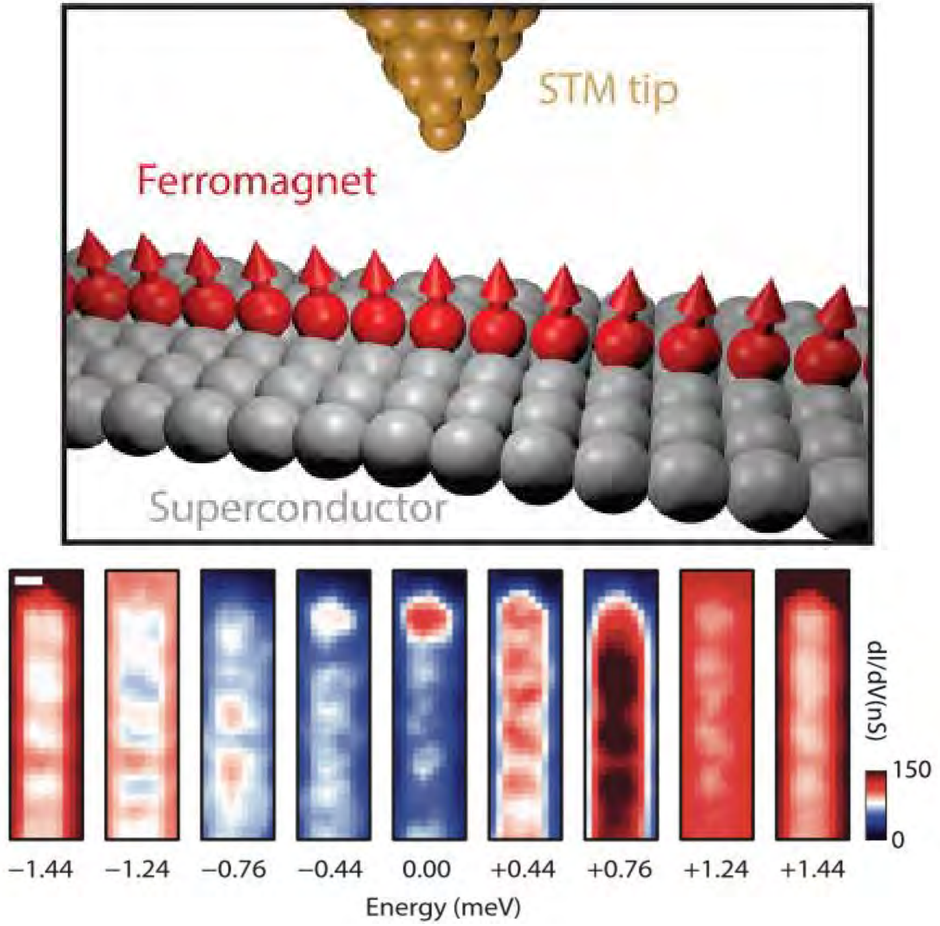




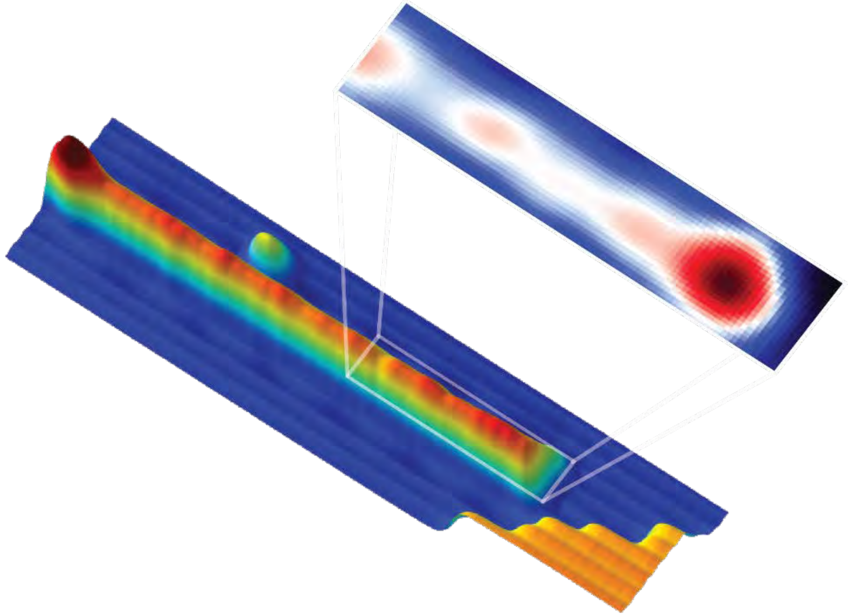
Yu Lu (1965), Shiba (1968), Rusinov (1969)

Majorana end states in magnetic chains : Fe/Pb(110)

Possible experimental realizations



Zero-bias anomaly localized on the last atoms
of the Fe chain,
almost no extension into the Pb substrate

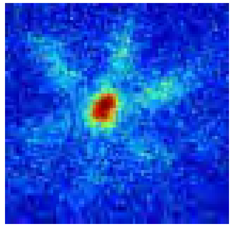


Stevan Nadj-Perge et al., Science **346,** 6209 (2014) (Princeton)
B. E. Feldman et al., Nature Physics (2016)

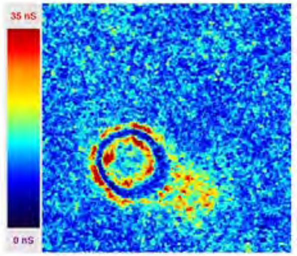
See also M. Ruby et al., PRL 2015; R. Pawlak et al., NPJ QI (2016)

Outline

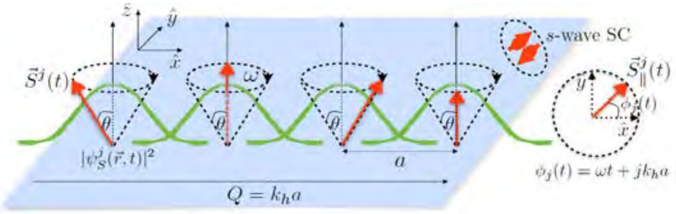
I) Determining the properties of the host superconductor using Shiba states spin polarized spectroscopy



II) Engineering topological superconductivity with Co clusters in Pb/Si(111)



III) Dynamical engineering of 1D topological superconductivity with driven magnetic adatoms.



I) Determining the properties of the host superconductor using Shiba states spin polarized spectroscopy

Asymptotics of the Shiba wave-function

Convenient paramatrization

$$E = \Delta \cos(\delta^+ - \delta^-)$$

$$\tan \delta^\pm = V\nu_0 \pm \pi\nu_0 JS$$

Rusinov (1969)

Potential scattering term

Asymptotics of the Shiba wave function

In 3D

$$\psi_\pm(r) \approx \frac{1}{\sqrt{N}} \frac{\sin\left(k_F r + \delta^\pm\right)}{k_F r} e^{-\Delta \sin(\delta^+ - \delta^-) r/\hbar v_F}$$

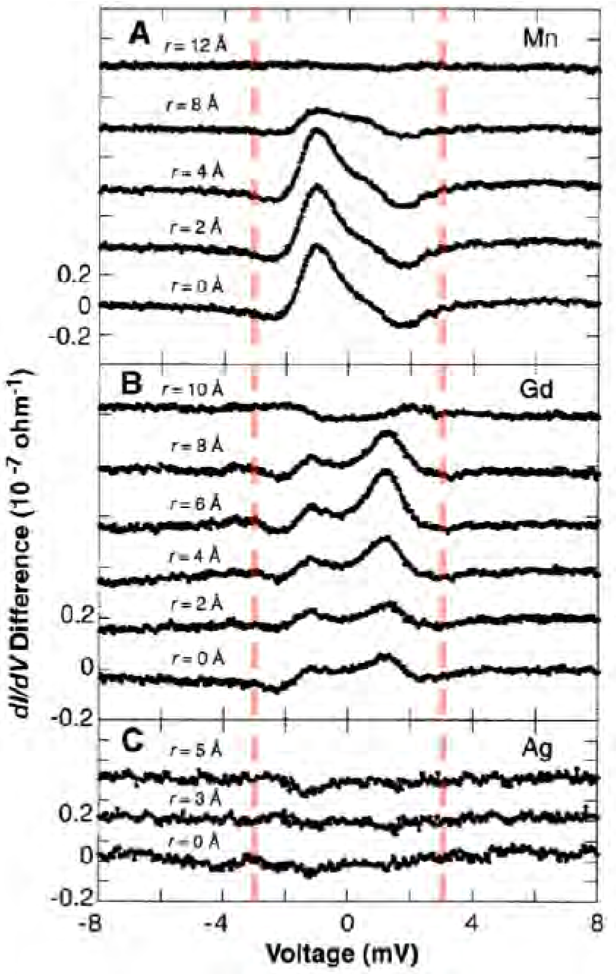
Rusinov (1969)

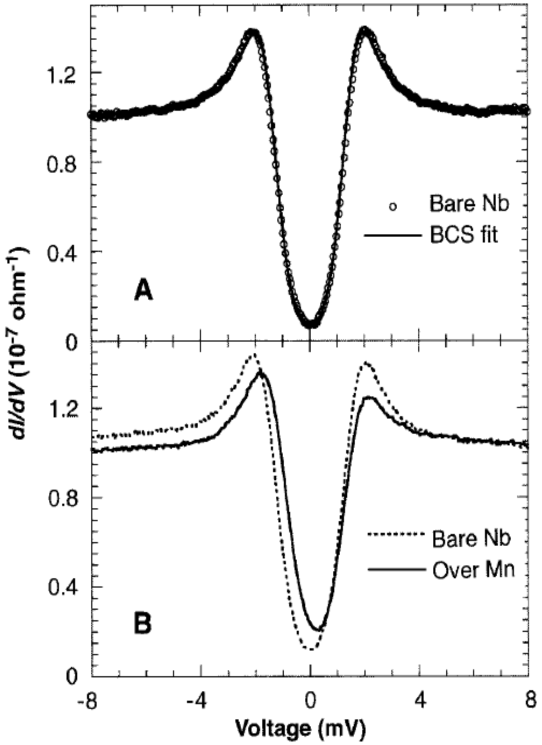
In 2D

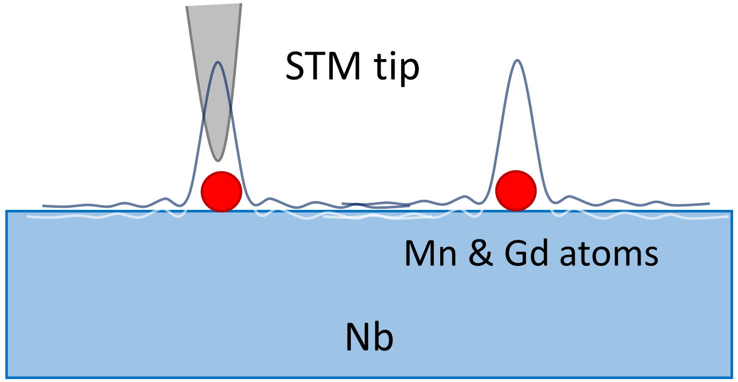
$$\psi_\pm(r) \approx \frac{1}{\sqrt{N}} \frac{\sin(k_F r - \frac{\pi}{4} + \delta^\pm)}{\sqrt{\pi k_F r}} e^{-\Delta \sin(\delta^+ - \delta^-) r/\hbar v_F}$$

Single magnetic impurities observed by STM

- Bound states for magnetic impurities (Mn & Gd) on Nb
- No bound states for non magnetic Ag adatoms on Nb



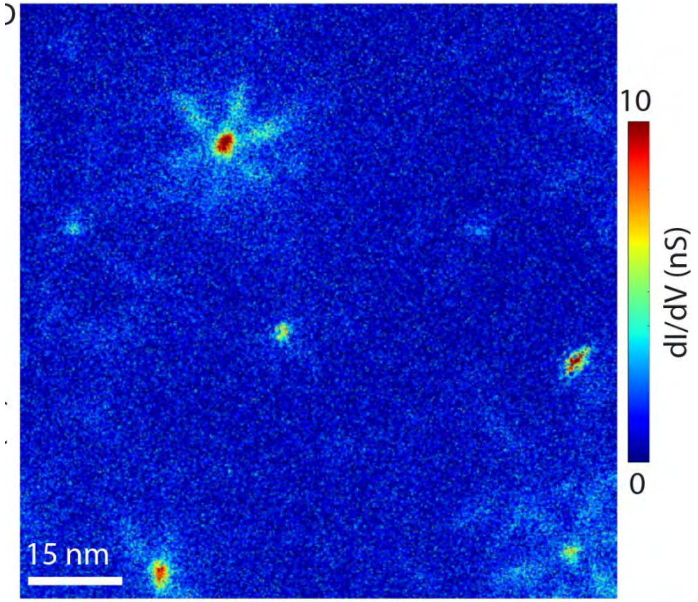




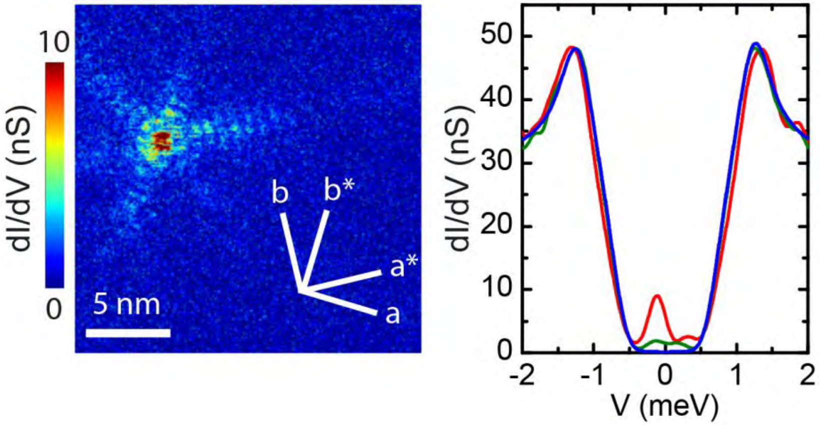
The wave function of the bound states is localized at less than 10 Å from the impurities

Yazdani et al. *Science* **275**, 1767 (1997)

Observation of bound states around magnetic impurities in 2H-$NbSe_2$



dI/dV maps at -0.13 mV (320 mK)



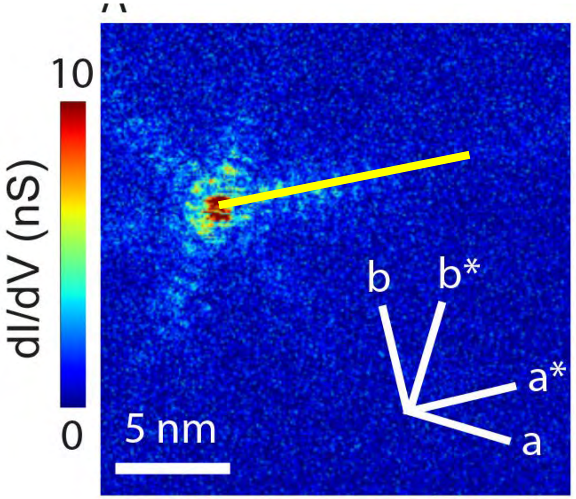
The Nb used for the crystal growth contains magnetic impurities :

- 175 ppm of Fe
- 54 ppm of Cr
- 22 ppm of Mn

G. Ménard et al., Nature Physics 2015

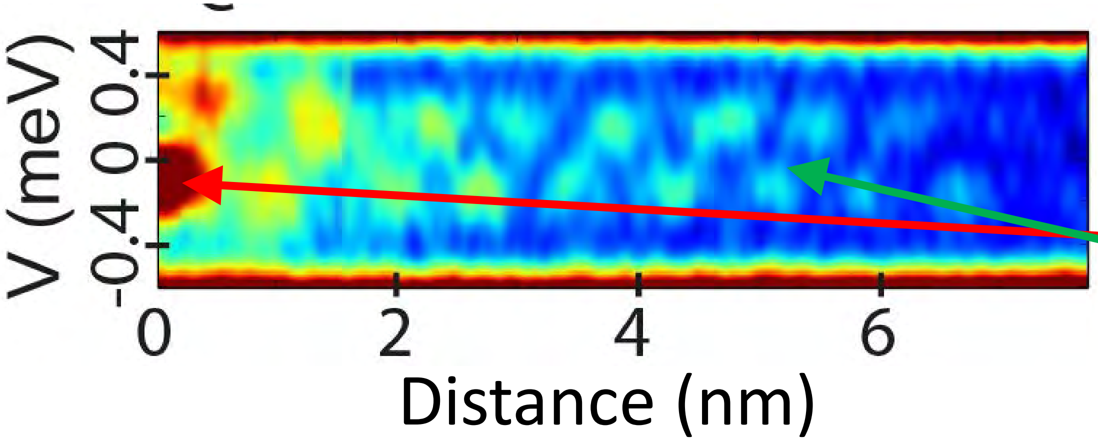
See also N. Hatter et al., Nature Commun. (2015); M. Ruby et al., PRL (2016)

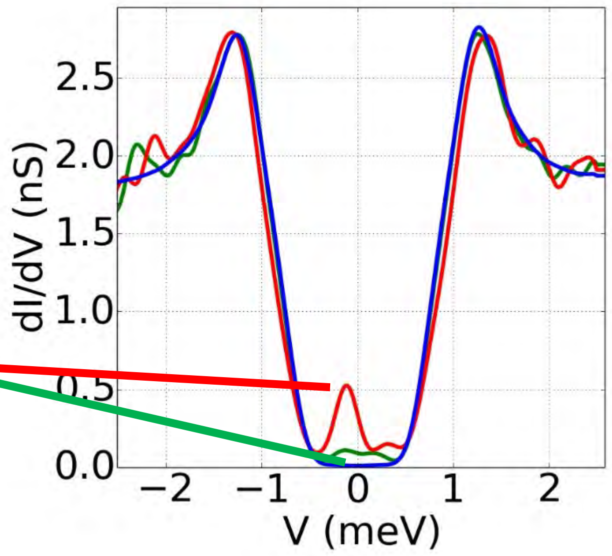
Spatial oscillation of Shiba bound states
Electron-hole asymmetry



•Oscillations of the local density of states with a phase opposition between positive and negative energy states

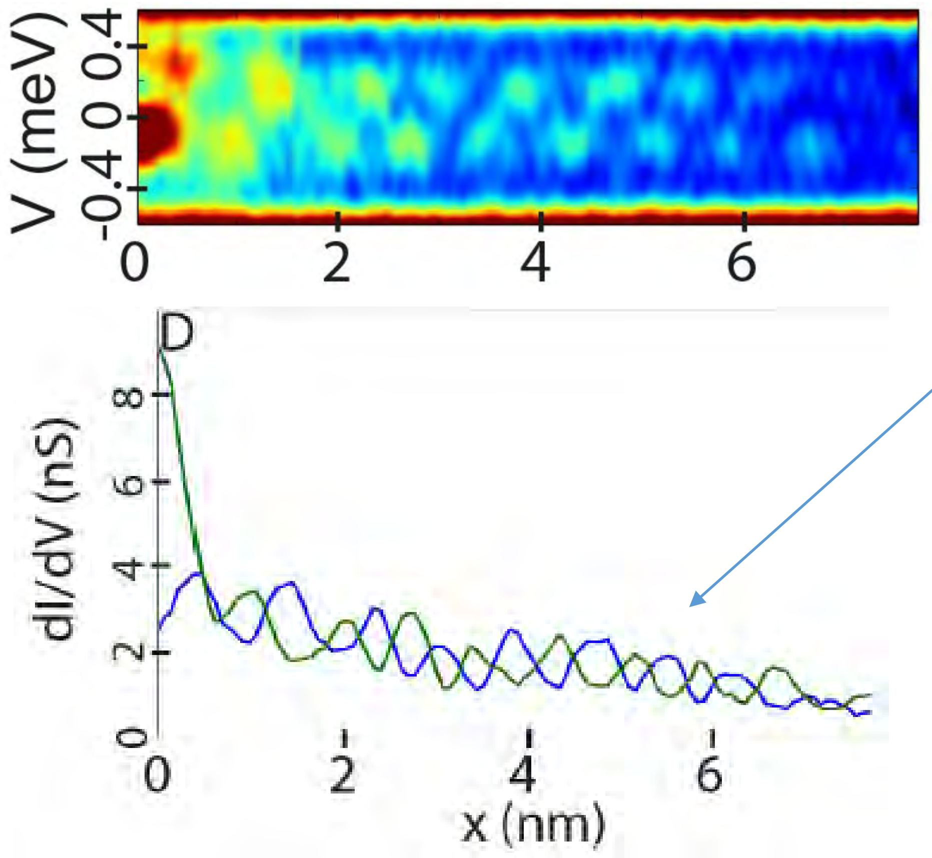
•Decrease of the Shiba bound states on a size of the order of the coherence length ξ





G. Ménard et al., Nature Physics 2015

Spatial oscillations and electron-hole asymmetry



Good agreement with theoretical calculations for Shiba state in a **2D** SC in the asymptotic limit.

Two relevant length scales: k_F & ξ

$$\psi_{\pm}(r) = \frac{1}{\sqrt{N\pi k_F r}} \sin\left(k_F r - \frac{\pi}{4} + \delta^{\pm}\right) e^{-\Delta \sin(\delta^{+}-\delta^{-}) r/\hbar v_F}$$

$$E = \Delta \cos(\delta^{+} - \delta^{-})$$

$$\tan \delta^{\pm} = (K\nu_0 \pm \nu_0 JS/2)$$

The Shiba peaks **position relatively to the gap** is directly related to the phase shift.

G. Ménard et al., Nature Physics 2015

Spin-orbit coupling in 2D superconductors

Question: Shiba bound states have a long range extent in 2D superconductors

Can we use Shiba bound state spectroscopy to determine/extract properties of the host superconductor ?

Motivation: Many new (quasi) 2D superconductors with a strong spin-orbit coupling are now available: Sr_2RuO_4, Pb monolayer, etc.

Inversion symmetry is broken+ heavy elements → Strong spin orbit interaction

Similar question can be raised with 1D semiconducting wires (InAs, InSb) proximitized by a superconductor

Model Hamiltonian and bound state equations

$$\mathcal{H}_0 = \begin{pmatrix} \xi_p \sigma_0 & \Delta_s \sigma_0 \\ \Delta_s \sigma_0 & -\xi_p \sigma_0. \end{pmatrix} + \lambda (p_y \boldsymbol{\sigma}_x - p_x \boldsymbol{\sigma}_y) \otimes \boldsymbol{\tau}_z$$ in 2D

→ Rashba Spin Orbit coupling

$$\mathcal{H}_{imp} = \boldsymbol{J} \cdot \boldsymbol{\sigma} \otimes \boldsymbol{\tau}_0 \cdot \delta(\boldsymbol{r})$$ with $$\boldsymbol{J} = (J_x, J_y, J_z)$$

Consider the classical spin limit J >>1

Bound state equation

$$\begin{cases} [\mathbb{I}_4 - V G_0(E, \boldsymbol{r}=0)]\, \Phi(0) = 0 \\ \Phi(\boldsymbol{r}) = G_0(E, \boldsymbol{r}) V \Phi(0) \end{cases}$$

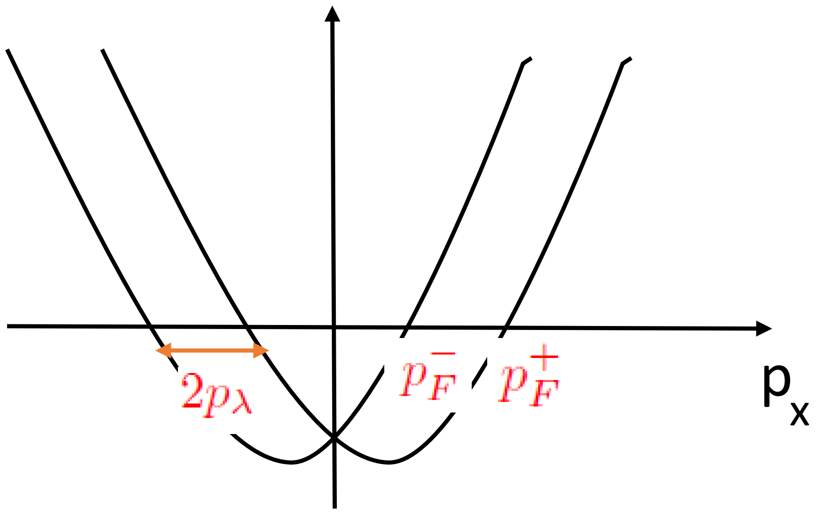
with $$G_0(E, \boldsymbol{p}) = [(E + i\delta)\mathbb{I}_4 - \mathcal{H}_0(\boldsymbol{p})]^{-1}$$

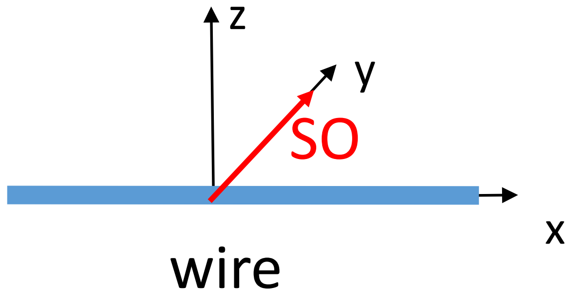
Pientka, Glazman, von Oppen, PRB (2013)

Observables

$$S(E, \boldsymbol{r}) = \Phi^\dagger(\boldsymbol{r}) \begin{pmatrix} 0 & 0 \\ 0 & \boldsymbol{\sigma} \end{pmatrix} \Phi(\boldsymbol{r})$$ and $$\rho(E, \boldsymbol{r}) = \Phi^\dagger(\boldsymbol{r}) \begin{pmatrix} 0 & 0 \\ 0 & \sigma_0 \end{pmatrix} \Phi(\boldsymbol{r})$$

Band dispersion in 1D systems





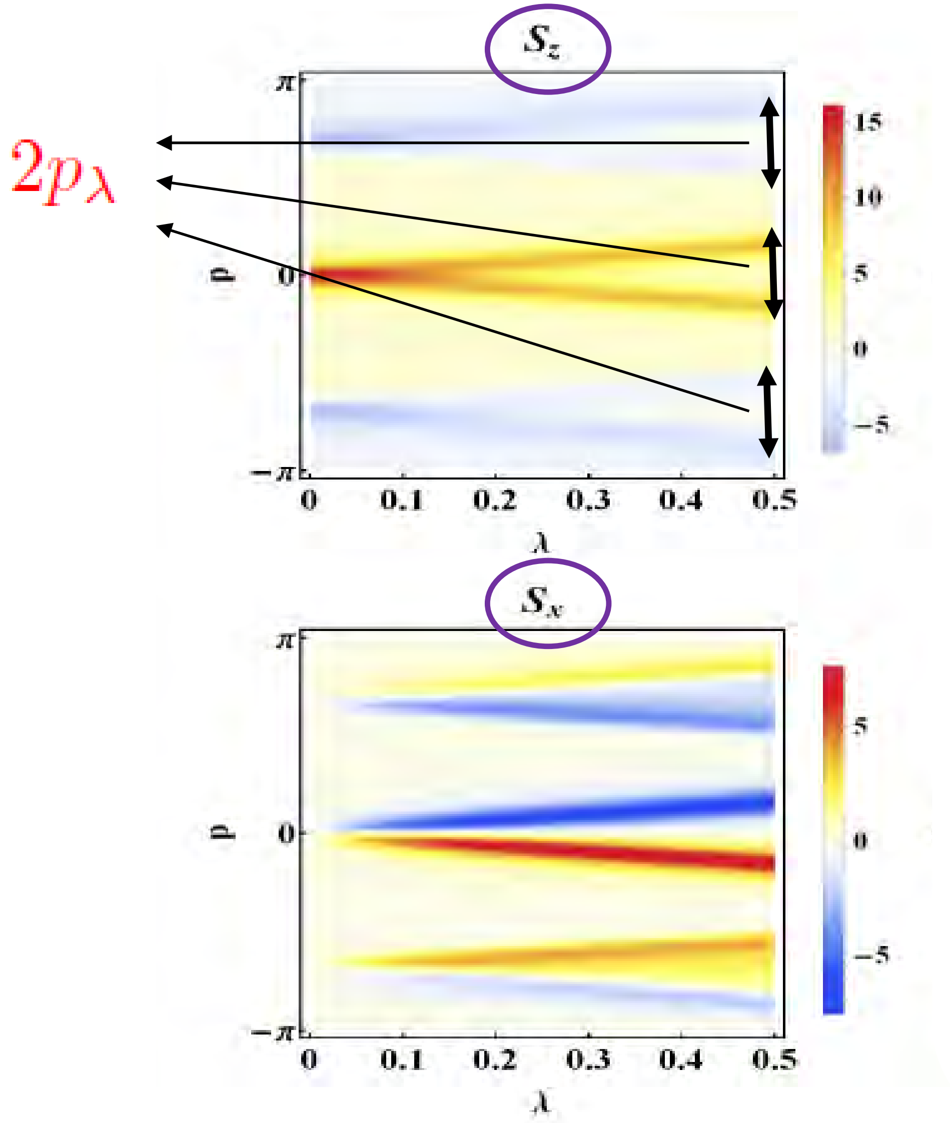
$$p_\lambda = p_{so} = m\lambda$$
$$p_F^\pm = p_F \pm p_\lambda$$

We expect the Friedel oscillations to depend on these momenta in metals.

What survives in presence of superconductivity ?

Magnetic impurity along the z axis in a 1D wire

Analyze spin polarized spectroscopy

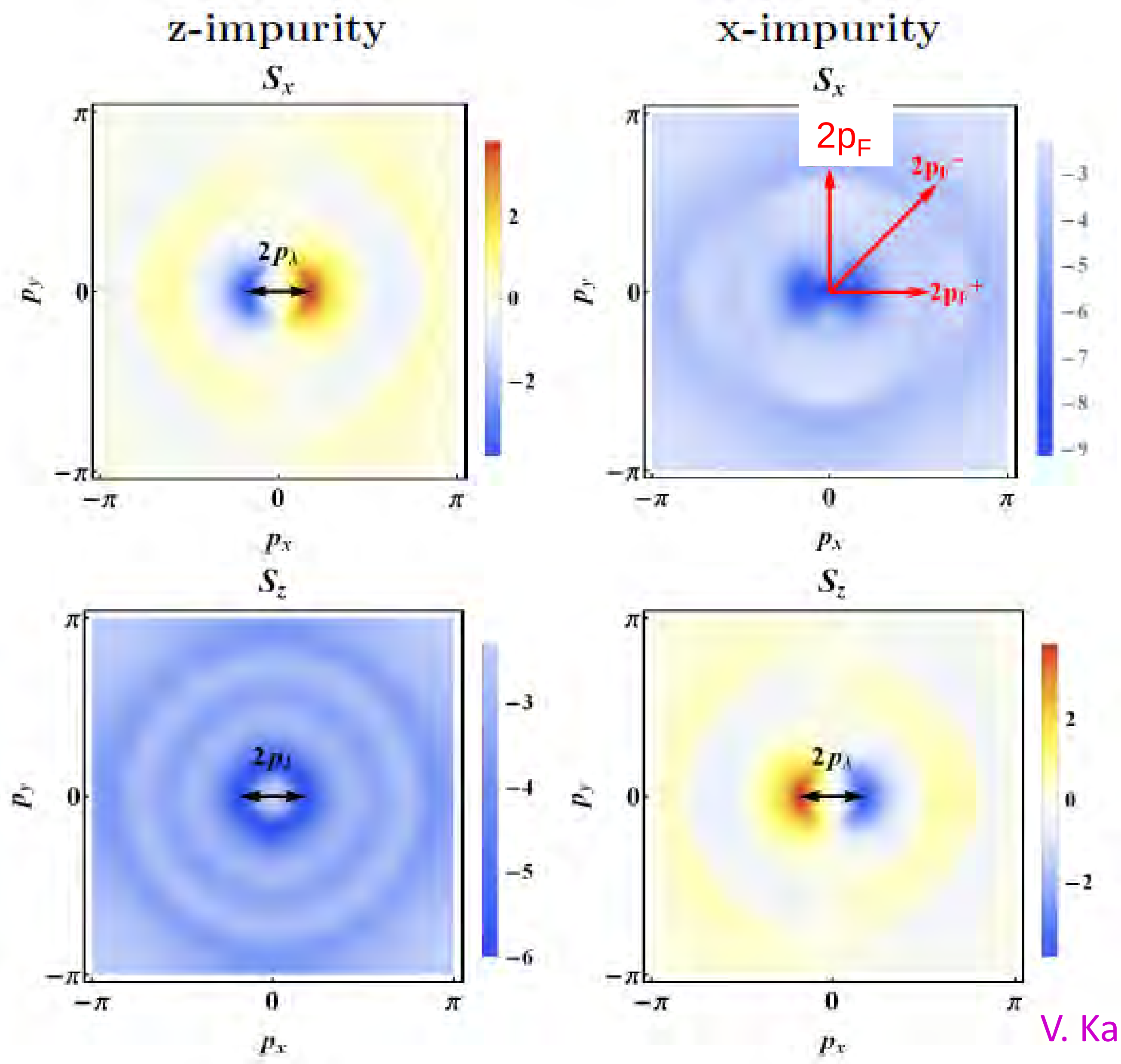


One can read off the SO coupling.
from **spin polarized spectroscopy**
of Shiba states

V. Kaladzhyan, PS, C. Bena, PRB (2016)

Magnetic impurity in a 2D s-wave superconductor

Fourier transform of the **SPIN** resolved Local DOS



$$p_\lambda = p_{so} = m\lambda$$
$$p_F^\pm = p_F \pm p_\lambda$$

One can read off the SO coupling from **spin polarized STM**

V. Kaladzhyan, PS, C. Bena, PRB (2016)

Take home message

Suggests to use spin-polarized STM

- spin-polarized DOS is sensitive to the spin-orbit coupling

V. Kaladzhyan, PS, C. Bena, PRB 2016

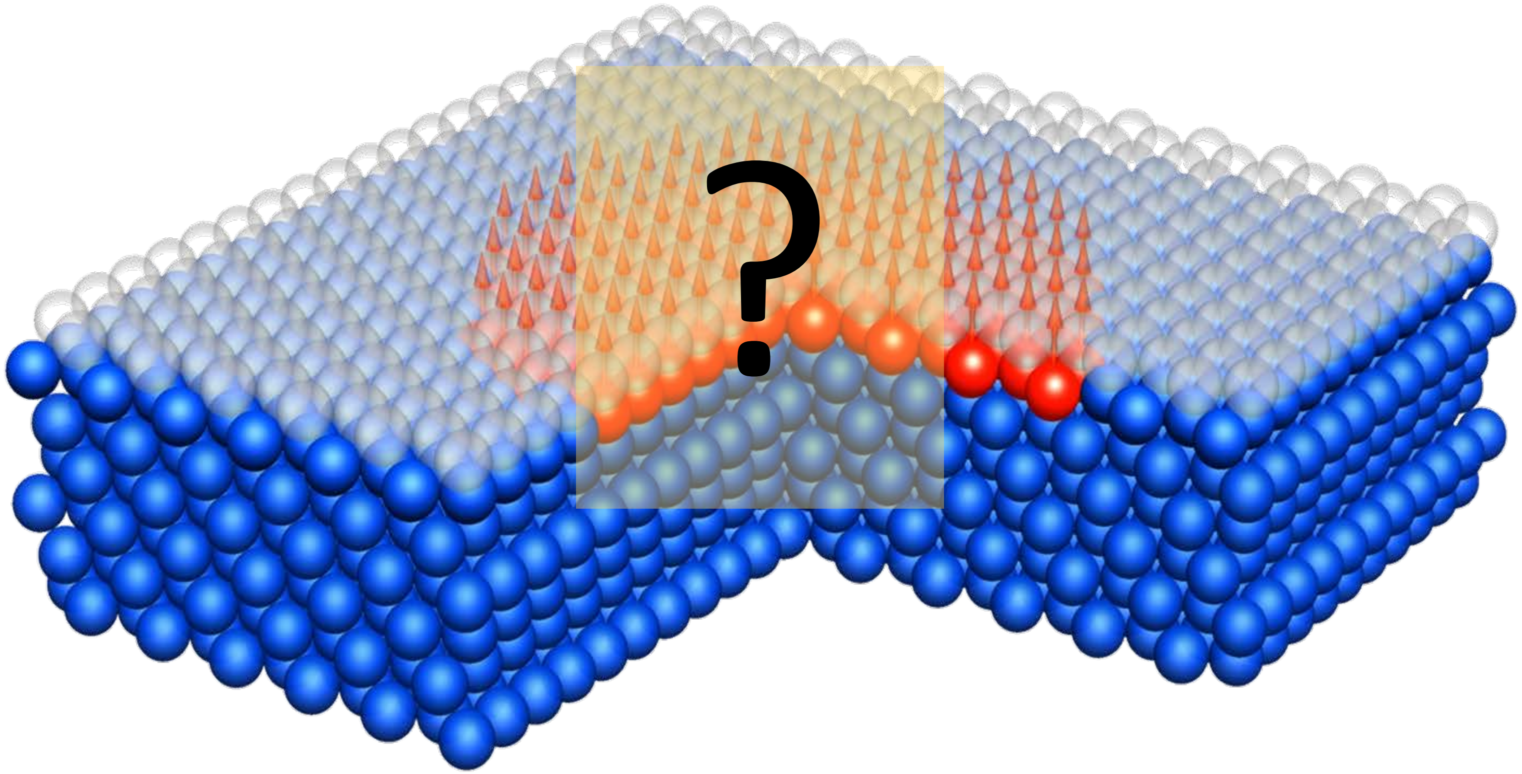
- Allows to distinguish - s-wave vs p-wave

  - in-plane d-vector vs out-of plane d-vector

V. Kaladzhyan, C. Bena, PS, 2016

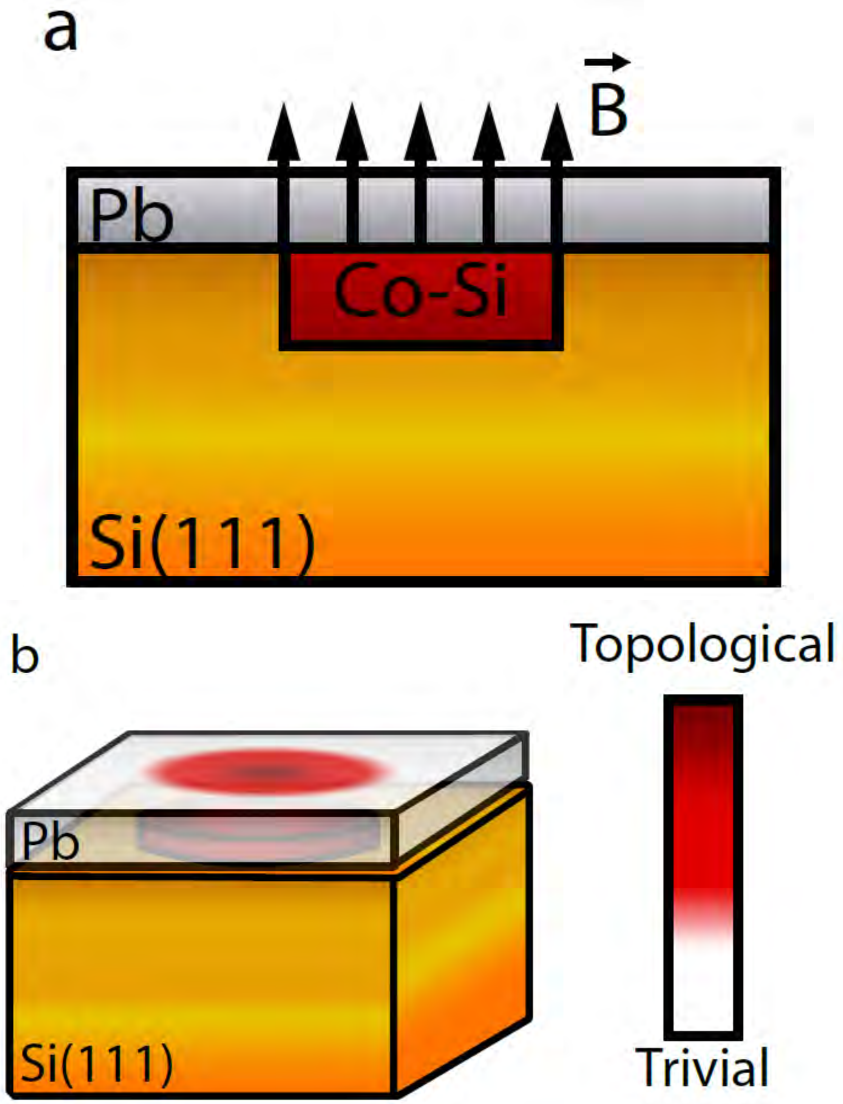
II) Engineering topological superconductivity with Co clusters in Pb/Si(111)

Magnetic impurities: Coupling the impurities

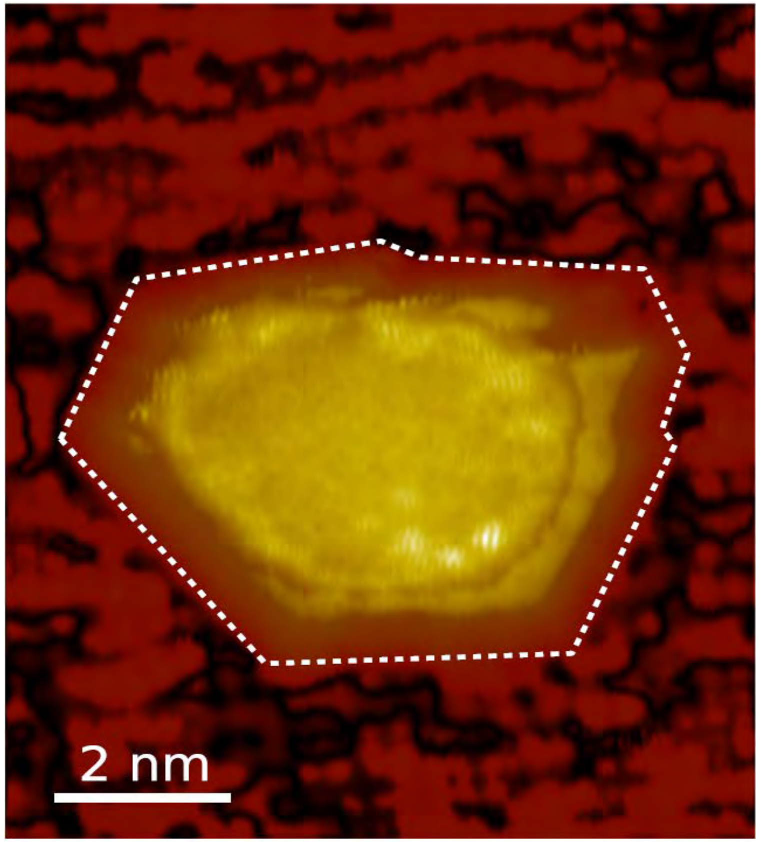


What happens for multiple impurities and ordered magnetic clusters ?

System studied: Magnetic nano-cluster embedded in Pb/Si(111)

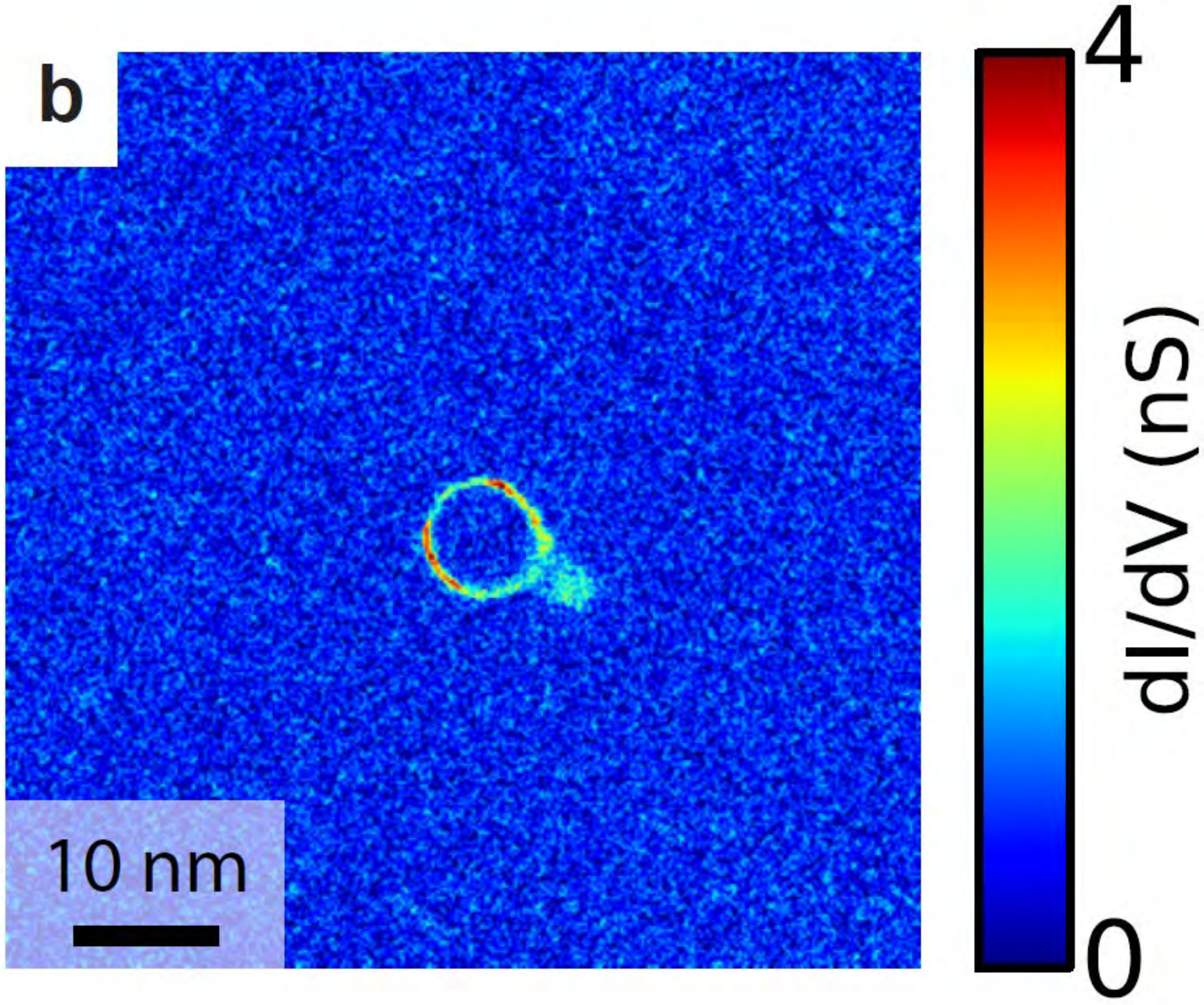


Magnetic clusters under the Pb layer to create topological superconductivity over the cluster



Magnetic nano-cluster: Majorana dispersive state ?

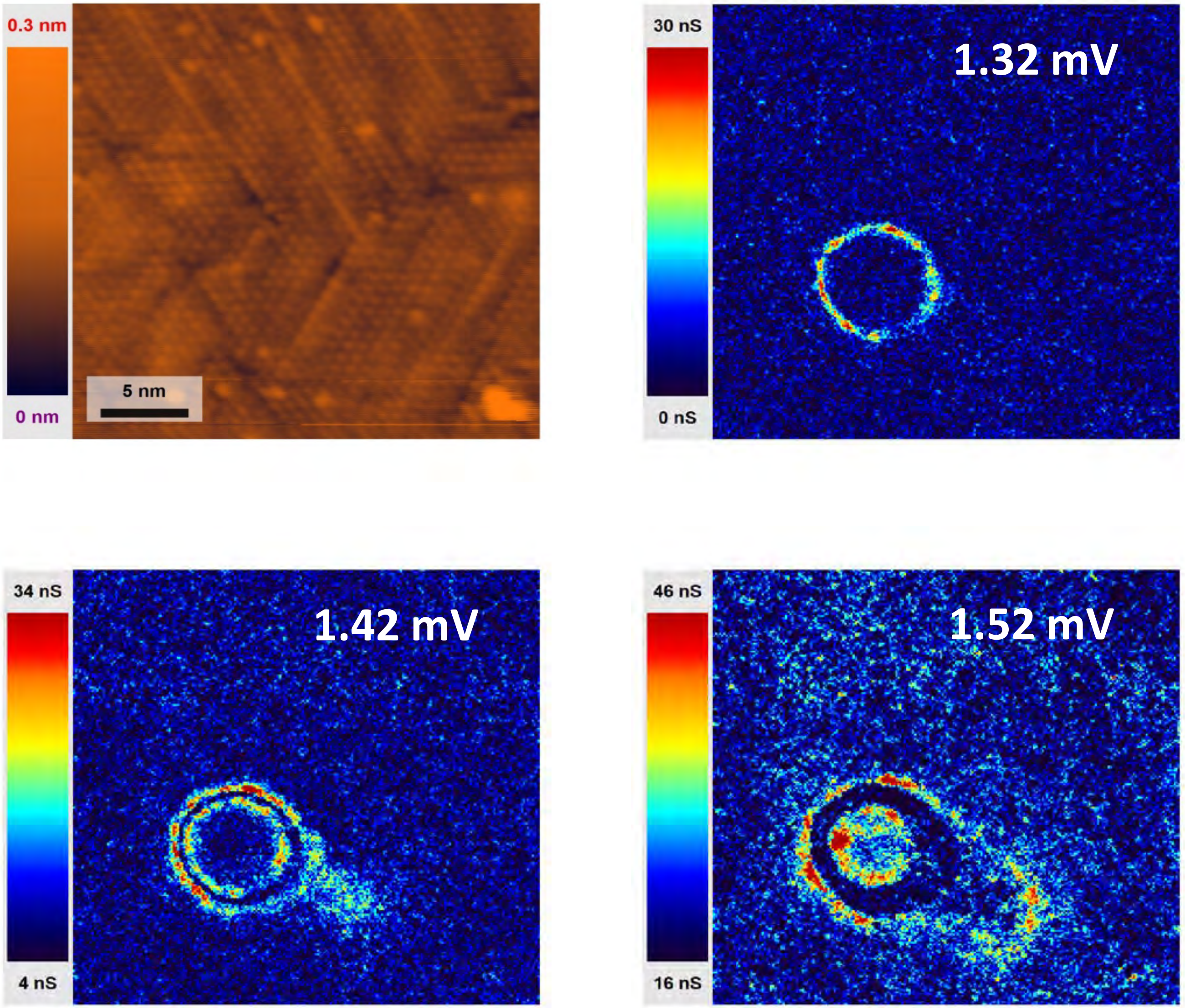
Observation of perfectly circular structure at the Fermi energy



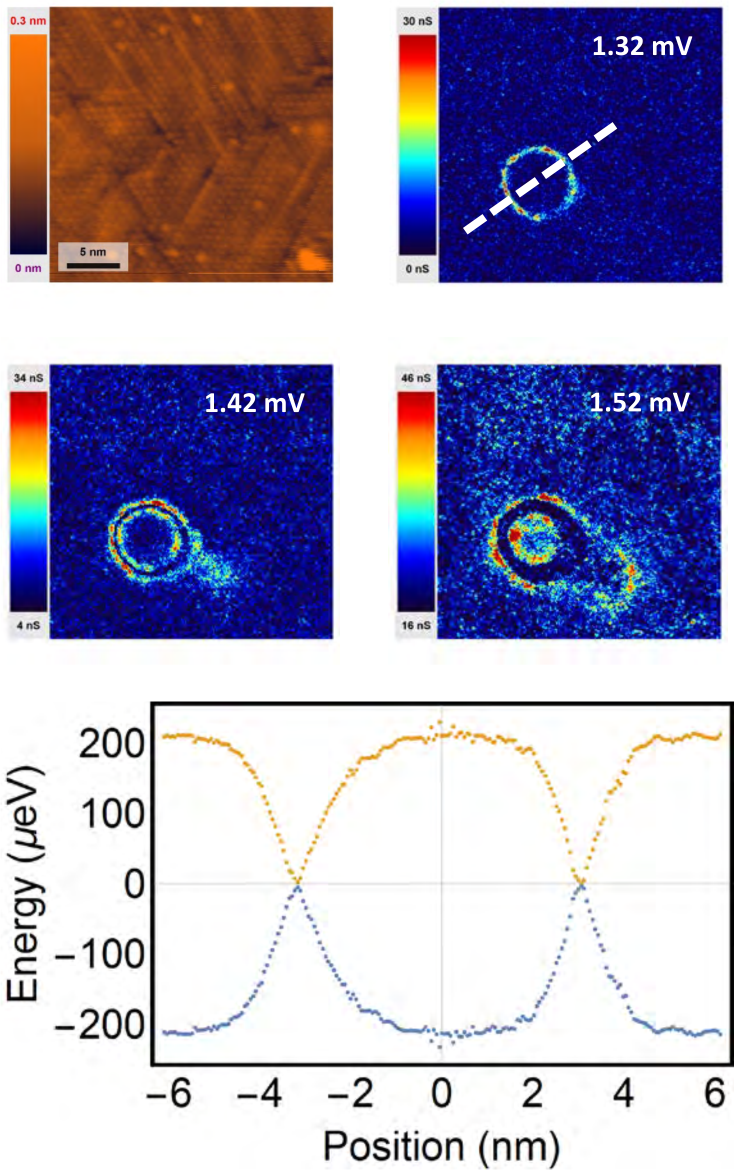
300 mK conductance map at V=0 meV using a superconducting tip

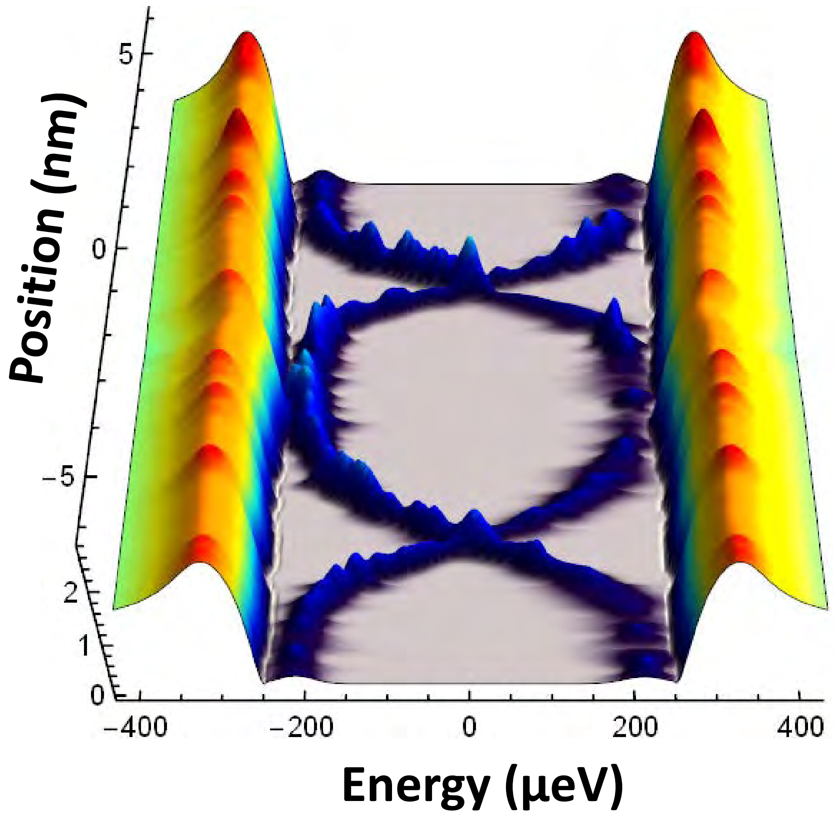
G. Ménard et al., arXiv: 1607.06353 (2016)

Splitting of rings at finite energy

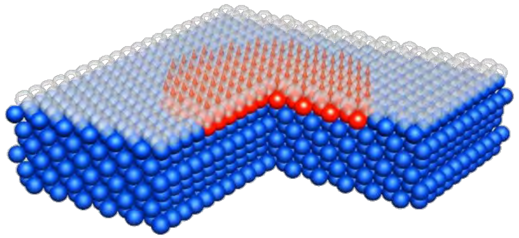


Edges dispersions in Pb/Co/Si(111)





Modeling of the cluster area



Let us first consider an **homogeneous** situation :

$$H = \xi_k \tau_z + \Delta_S \tau_x + V_z \sigma_z + \left(\alpha \tau_z + \frac{\Delta_T}{k_F} \tau_x \right) (\sigma_x k_y - \sigma_y k_x)$$

Zeeman

Rashba SO

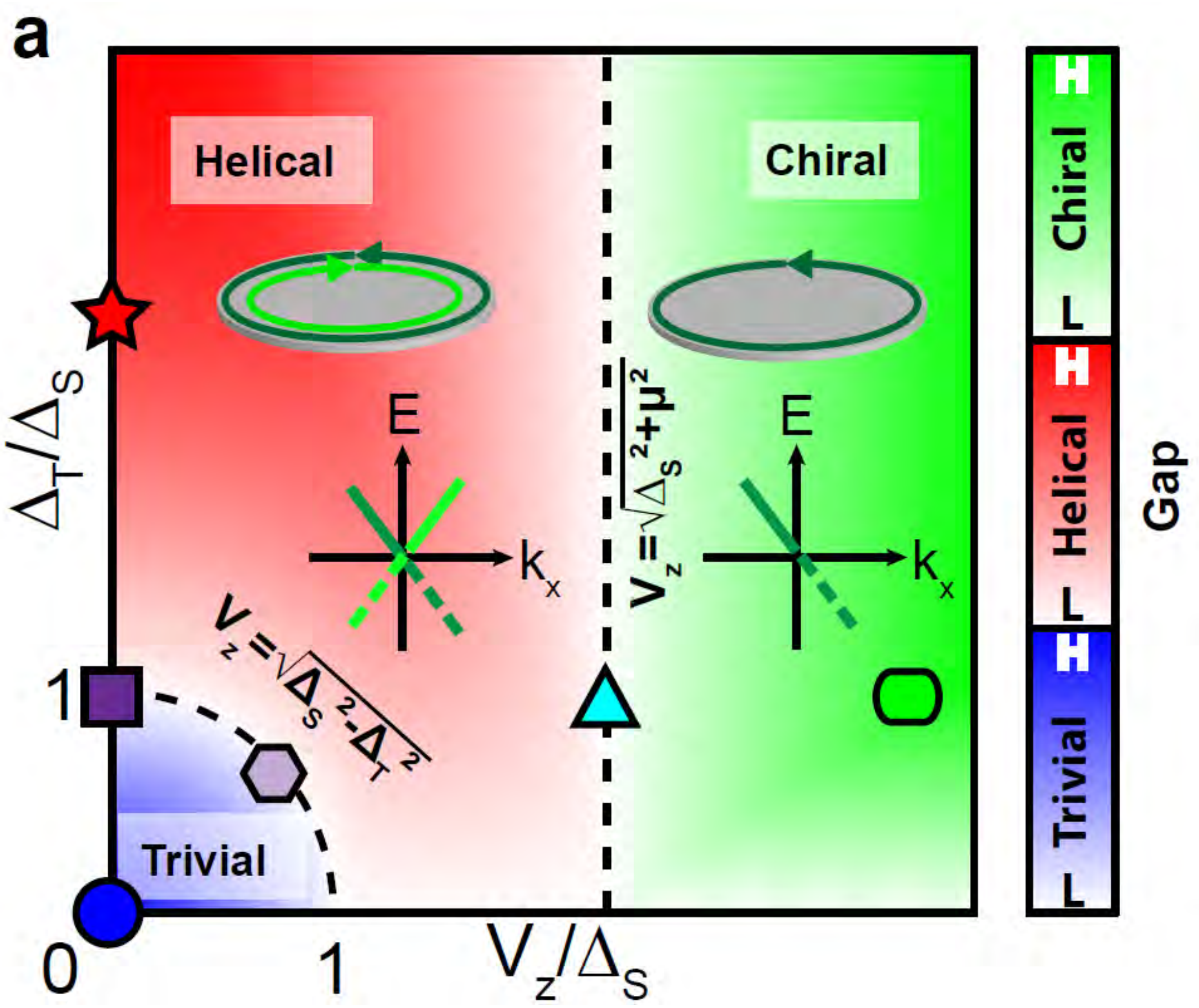
Triplet superconducting order parameter

Spectrum:

$$E_{\pm}^2(k) = V_z^2 + (\alpha k)^2 + \Delta_S^2 + \Delta_T^2 \frac{k^2}{k_F^2} + \xi_k^2 \pm 2\sqrt{V_z^2(\Delta_S^2 + \xi_k^2) + \frac{k^2}{k_F^2}(\Delta_S \Delta_T + \alpha k_F \xi_k)^2}$$

Ghosh, Sau, Tewari, Das Sarma, PRB (2010)
Tanaka, Sato, Nagaosa, JPSJ (2012)

Topological superconductivity: phase diagram based on Band structure topology



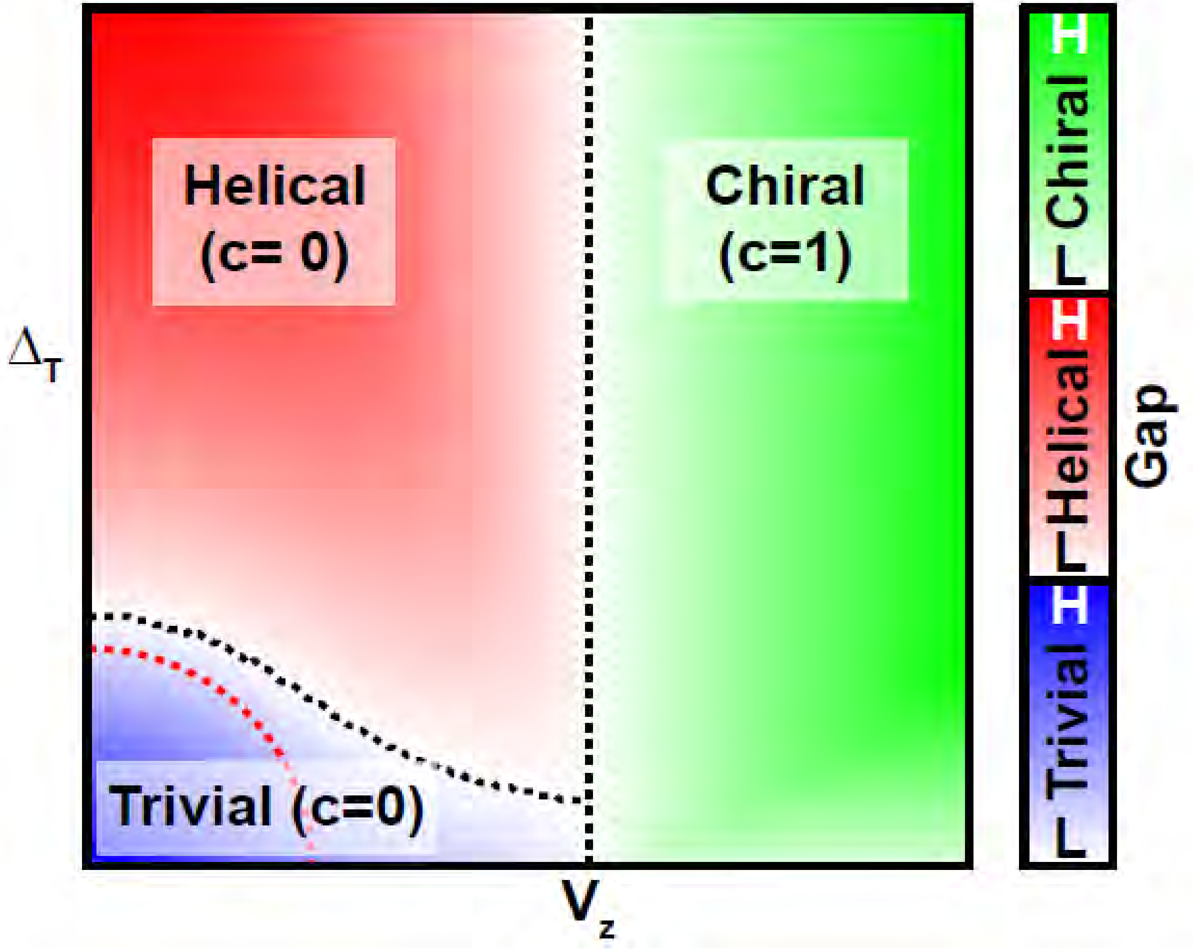
$\alpha = 0$

Two control parameters:
-Zeeman field
-Triplet amplitude

Two topological regimes:
-Chiral (one edge state) ≡ quantum Hall effect
-``Quasi'' helical (two edge states) ≡ quantum spin Hall effect

Topological superconductivity: phase diagram based on Band structure topology

$$k_F\alpha/\Delta_S \approx 0.5$$



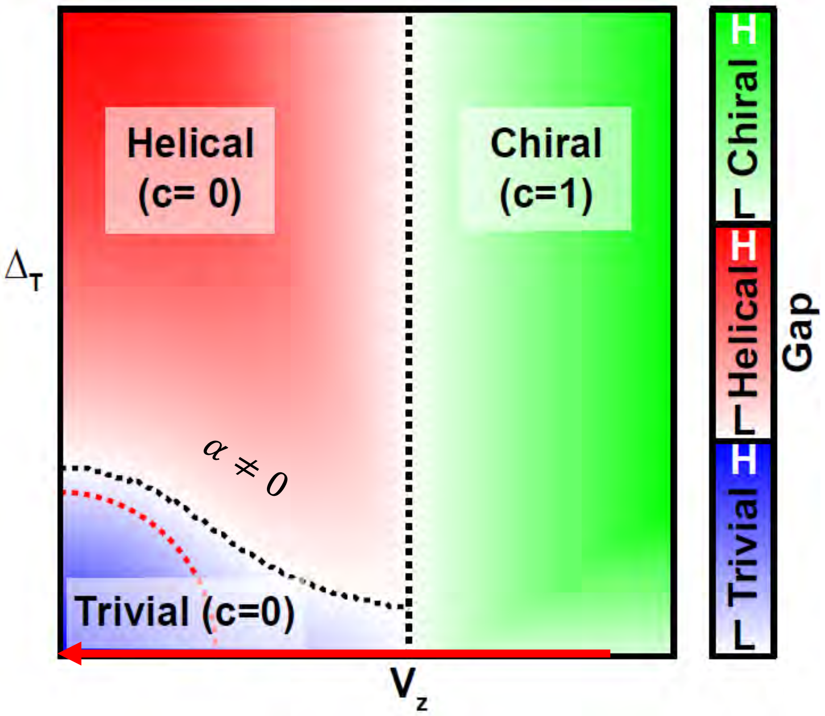
Two control parameters:
-Zeeman field
-Triplet amplitude

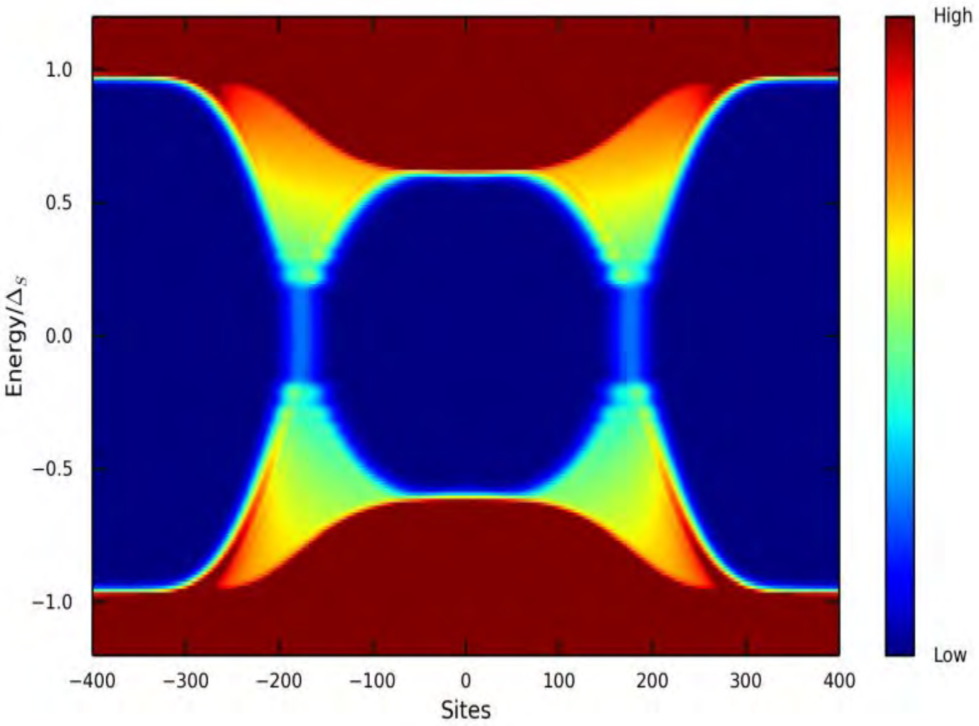
Two topological regimes:
-Chiral (one edge state) ≡ quantum Hall effect
-Helical (two edge states) ≡ quantum spin Hall effect

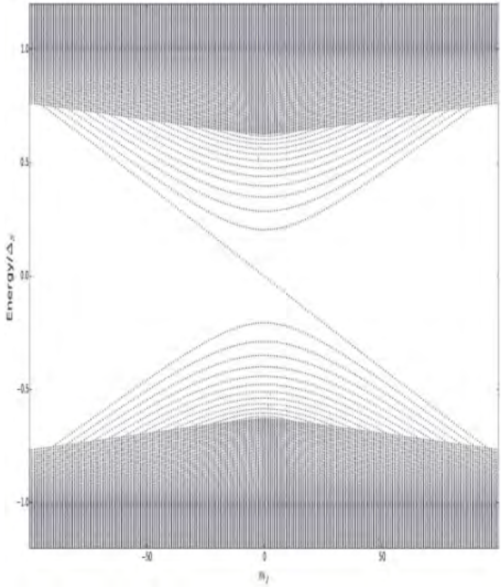
G. Ménard et al., arXiv: 1607.06353 (2016)

Simplest model: purely chiral case
(Singlet pairing, Rashba and Zeeman)

$$H = \xi_k \tau_z + V_Z \sigma_z + \alpha \tau_z + \Delta_S \tau_x$$



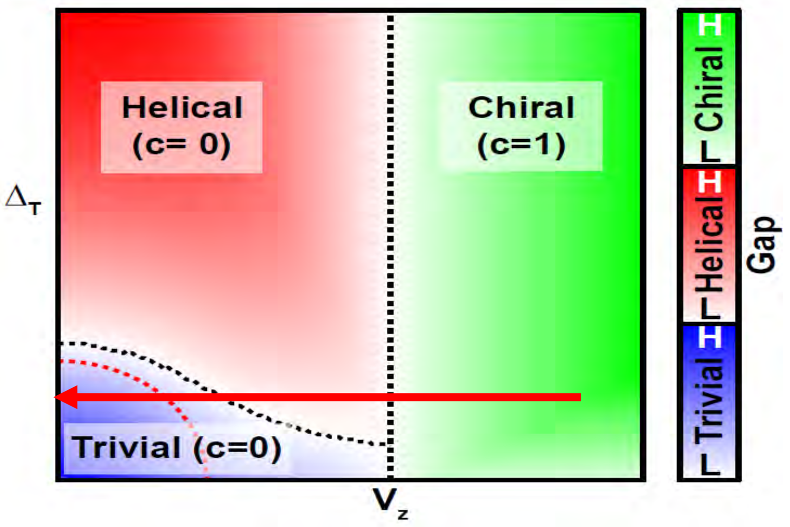


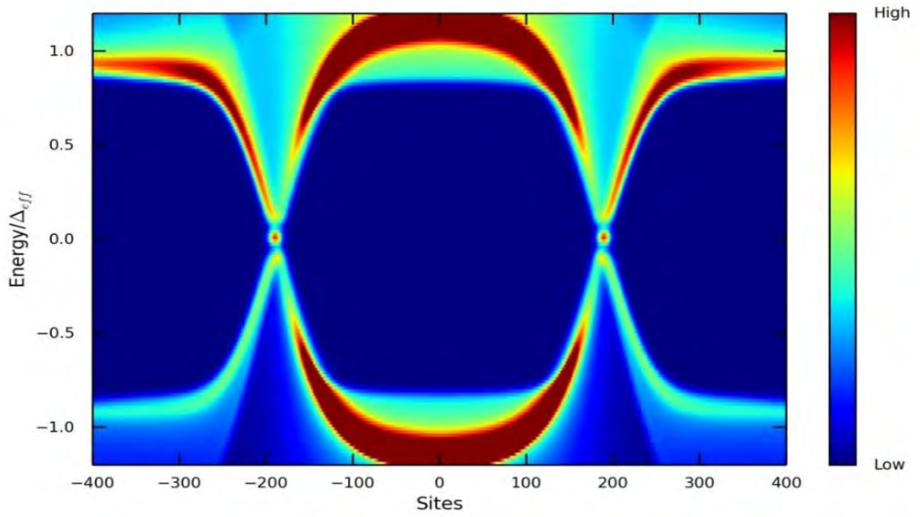


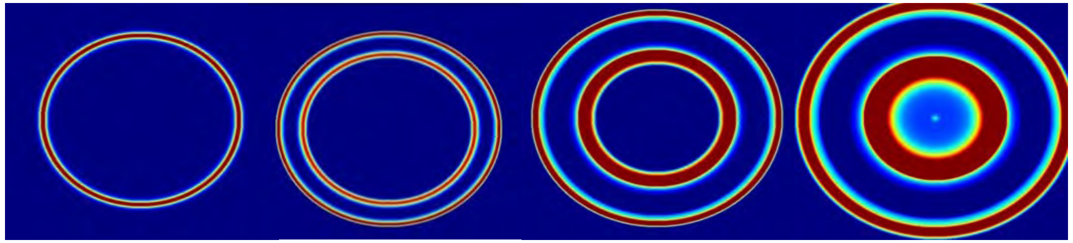
G. Ménard et al., arXiv: 1607.06353 (2016)

Time reversal broken helical state
(Singlet & triplet pairing and Zeeman)

$$H = \xi_k \tau_z + V_Z \sigma_z + \alpha \tau_z + \Delta_S \tau_x + \frac{\Delta_T}{k_F} \tau_x (\sigma_x k_y - \sigma_y k_x)$$



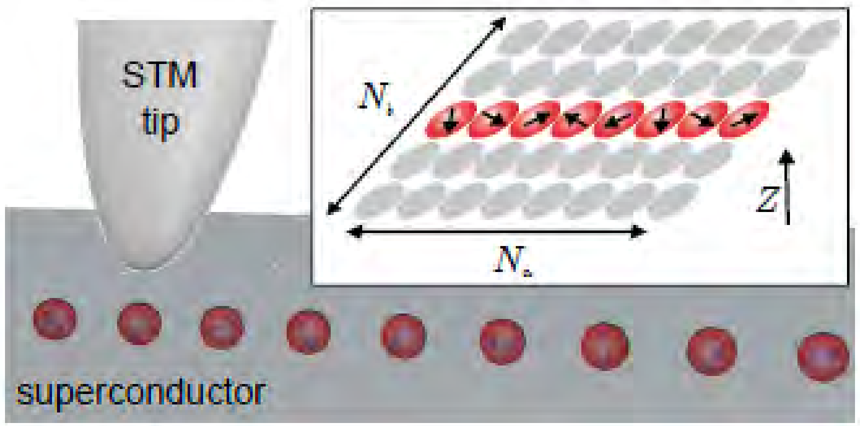




G. Ménard et al., arXiv: 1607.06353 (2016)

III) Dynamical engineering of 1D topological superconductivity with driven magnetic adatoms.

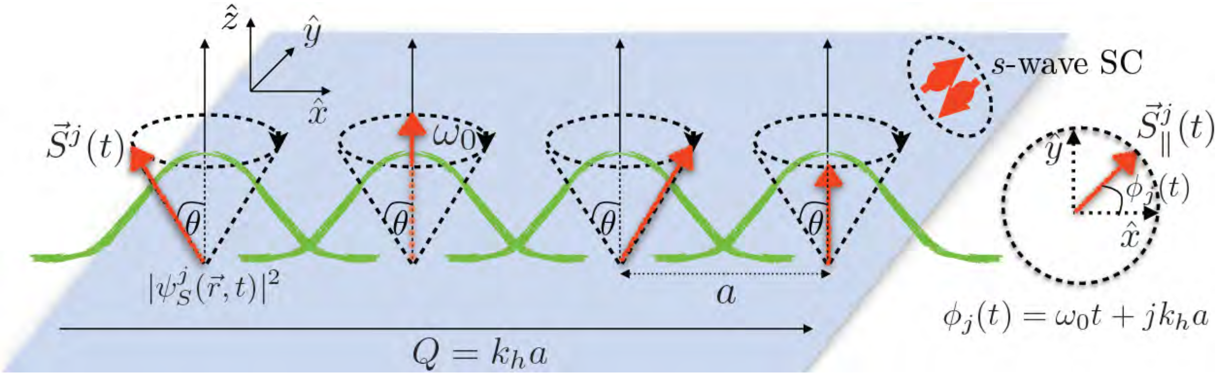
A static chain: host for topological superconductivity



s-wave SC + chain of Shiba states = p-wave SC

Nadj-Perge, Drozdov, Bernevig, Yazdani, PRB (2013)

Dynamical Shiba chain



$$i\partial_t \Psi(\boldsymbol{r},t) = \mathcal{H}(t)\Psi(\boldsymbol{r},t)$$

$$\mathcal{H}(t+T) = \mathcal{H}(t), \quad T = 2\pi/\omega_0$$

Rotating wave transformation

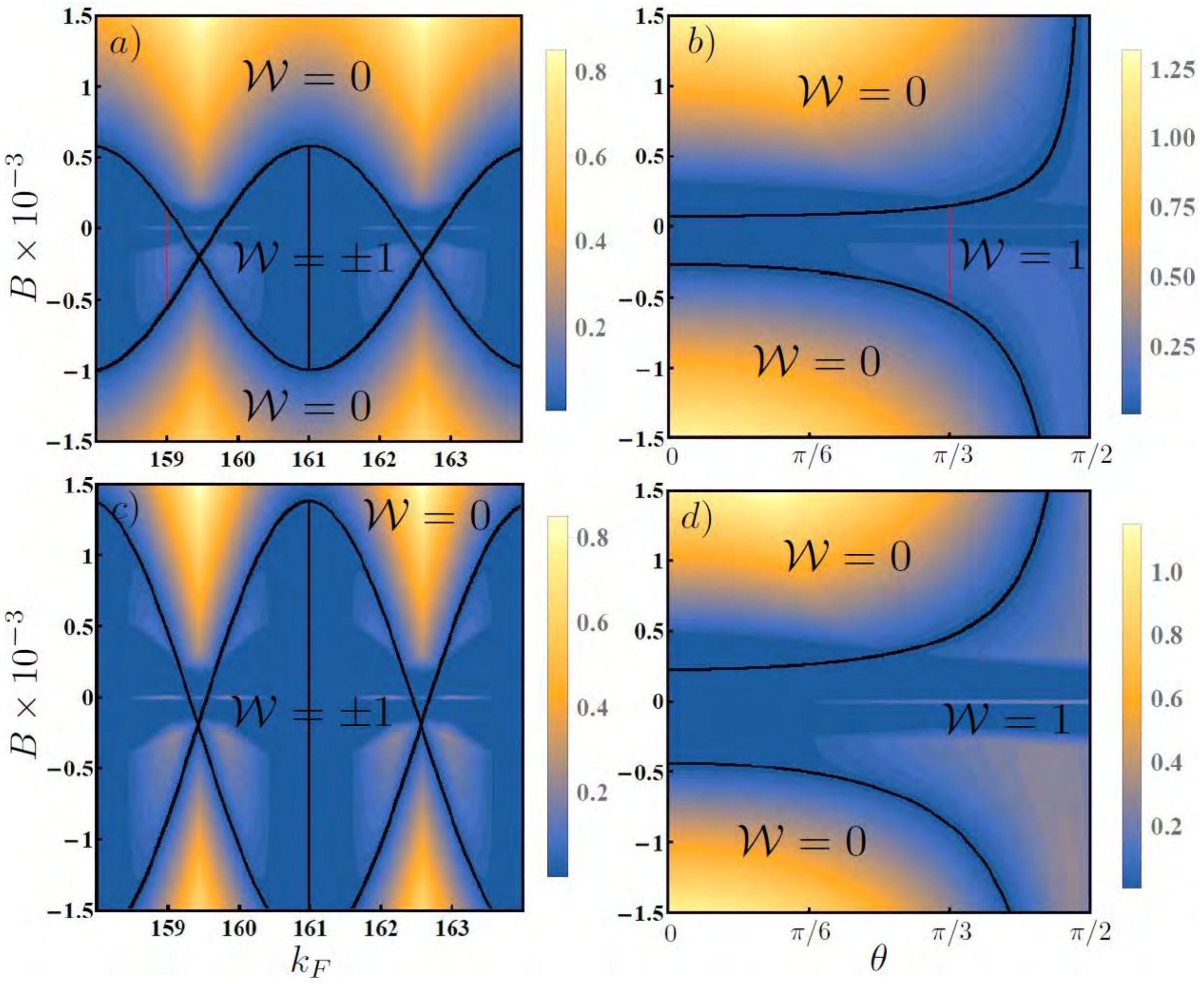
$$\Psi(\boldsymbol{r},t) = e^{-i\omega_0 t \sigma_z/2}\Phi(\boldsymbol{r})\, e^{-iEt}$$

➡ $$[\mathcal{H}(0) - B\sigma_z]\,\Phi(\boldsymbol{r}) = E\Phi(\boldsymbol{r}), \quad B \equiv \omega_0/2$$
(4×4)

➡ Deep Shiba limit: Effective 2-band model $\mathcal{H}(k) = d_0(k) + \mathbf{d}(k)\cdot\tau$
(2×2)

$$d_0(k) = \left[\Delta_s\cos\theta - B(1-\alpha\sin^2\theta)\right] F_0(B, ka, k_F a)$$
$$d_x(k) = (\Delta_s - \alpha B\cos\theta)\, F_x(B, ka, k_F a)\sin\theta\,,$$
$$d_z(k) = -\epsilon_0(B) + (\Delta_s - B\cos\theta)\, F_z(B, ka, k_F a)\,,$$

Shiba band gap in the spectrum

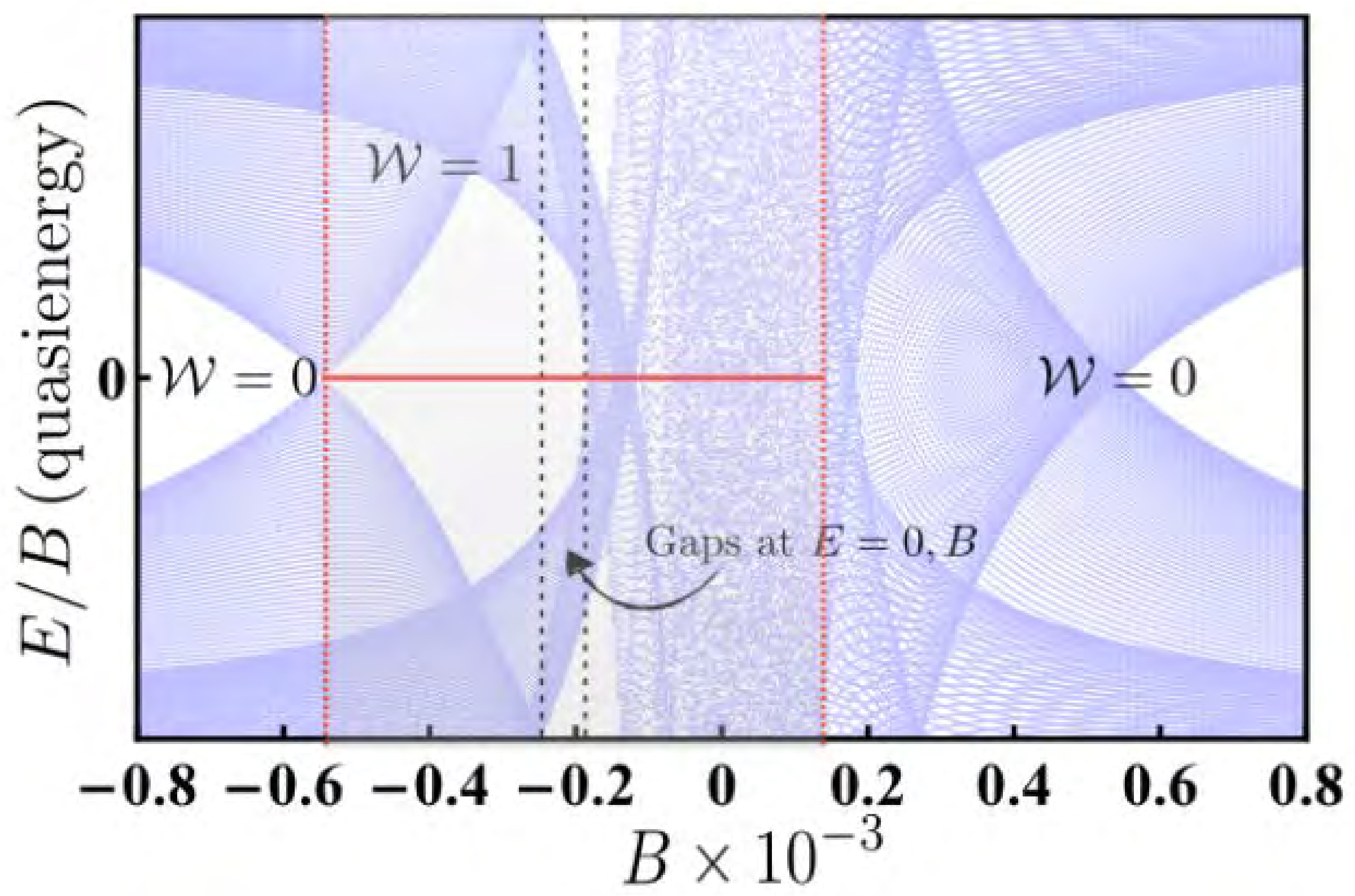


Short coherence length, $\xi \ll a$

Long coherence length, $\xi \gg a$

Gap and topology can be controlled by driving!

Open BC: edges modes



Majorana zero energy modes emerging

Summary

- Spectral analysis of the long-range extension of the Shiba state in 2D 2H-NbSe2
    - Oscillating electron-hole asymmetry

G. Ménard et al., Nature Physics (2015)

- Using spin-polarized spectroscopy of Shiba states to extract the properties of the host superconductor

V. Kaladzhyan, PS, C. Bena, PRB (2016)

V. Kaladzyan, C. Bena, PS, PRB (2016), JPCM (2016)

- Observation of dispersive in-gap states around a Co cluster interpreted as a spatial topological-non topological superconducting transition

G. Ménard et al., arXiv:1607.06353

- Dynamical engineering of 1D topological superconductivity with driven magnetic adatoms.

V. Kaladzyan, PS, M. Trif, arXiv:1703.01870

My precious collaborators

Properties of the host SC
Via Shiba spin-polarized STM

V. Kadadzhyan (PhD, Orsay&Saclay)
C. Bena (Saclay)

V. Kadadzhyan, C. Bena, PS, PRB (2016)

V. Kaladzhyan, PS, C. Bena, PRB (2016) & JPCM (2016)

Experiments (Paris)

G. Ménard (Paris→Copenhagen)
C. Brun, S. Pons, V. Stolyarov, F. Debontridder, D. Roditchev, T. Cren

Theory (Orsay)

S. Guissart (PhD Orsay), M. Trif

G. Ménard et al., Nature Physics (2015)
G. Ménard et al., arXiv:1607.06353

Dynamical engineering on topological superconductivity

V. Kadadzhyan (PhD, Orsay&Saclay)
M. Trif (Orsay → Tsinghua)

V. Kadadzhyan, PS, M. Trif, , arXiv:1703.01870