Topological superconductivity in Pb/Co/Si(111)

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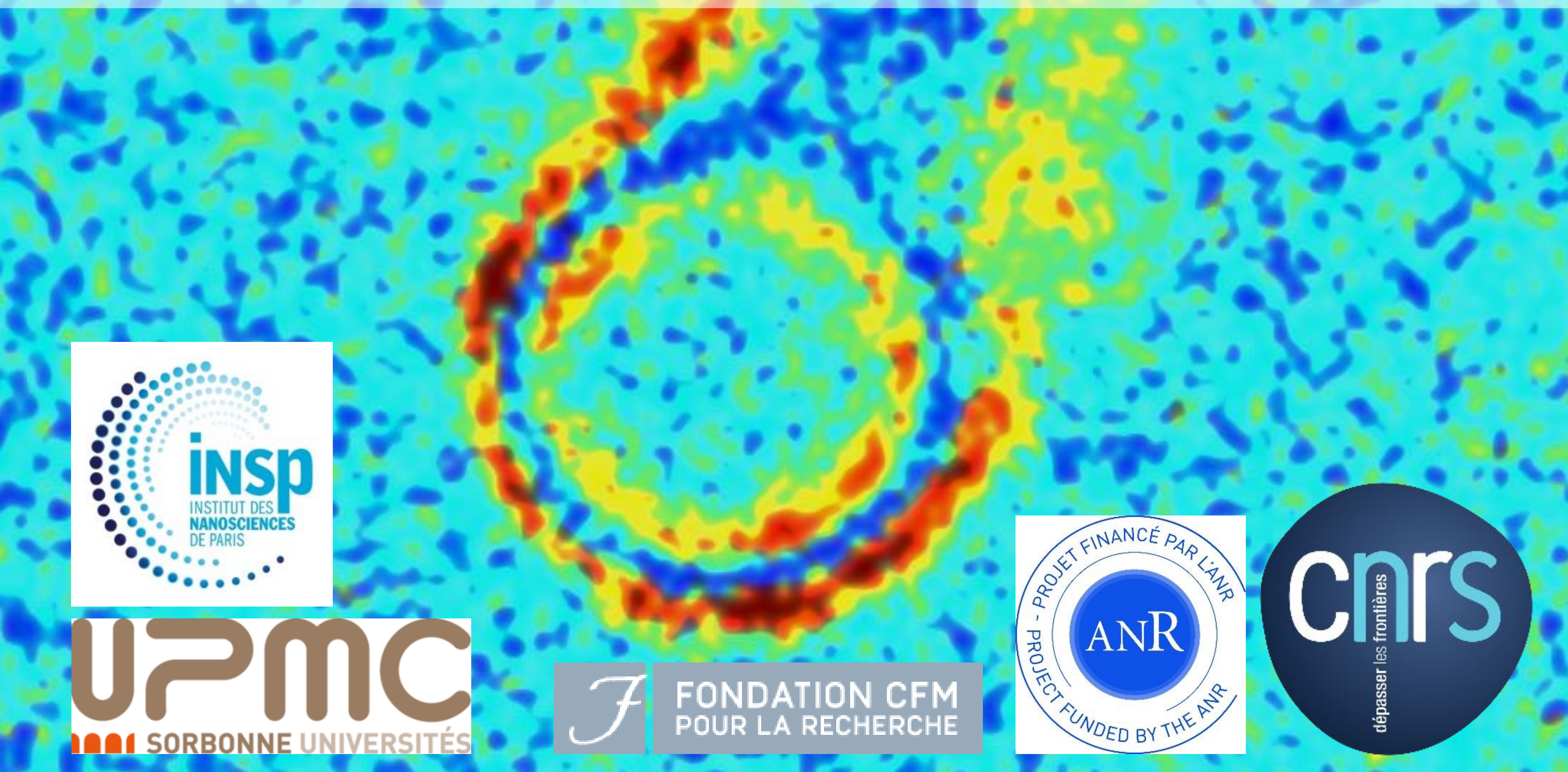

Acknowledgments

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- Dimitri Roditchev
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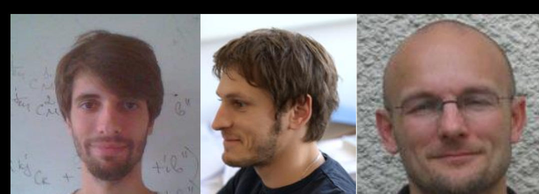
- Sébastien Guissart
- Mircea Trif
- Pascal Simon

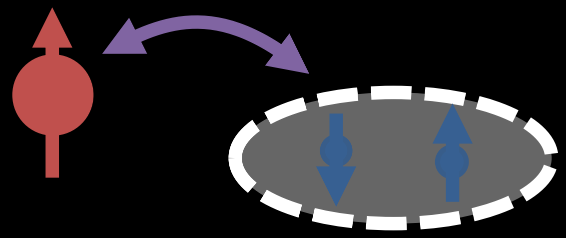


Institut Jean Rouxel
CNRS & University of Nantes

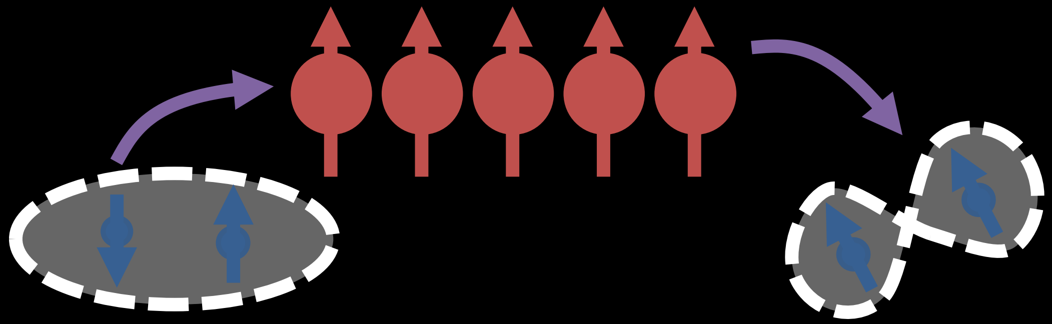
- Laurent Cario
- Étienne Janod

Outline

- **I-Magnetic bound states in superconductors**
  - Dimensionality effect
  - 2H-NbSe2
  - Pb/Si(111)



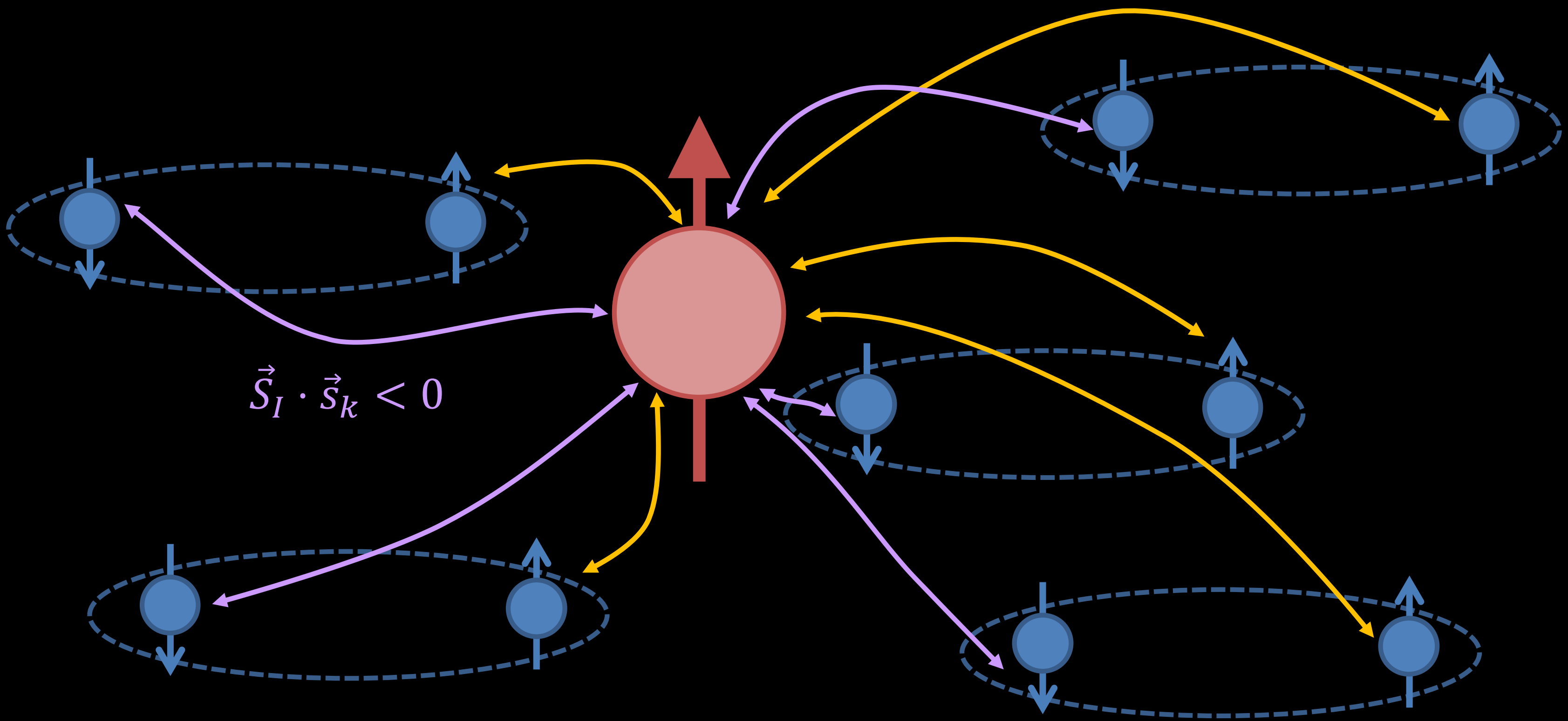
- **II-Topological superconductivity in ferromagnet-superconductor hybrid systems**
  - 1D vs 2D case
  - Majorana dispersion at the edge of a 2D system
  - Majorana bound states in vortex cores



Classical magnetic impurities in a superconductor

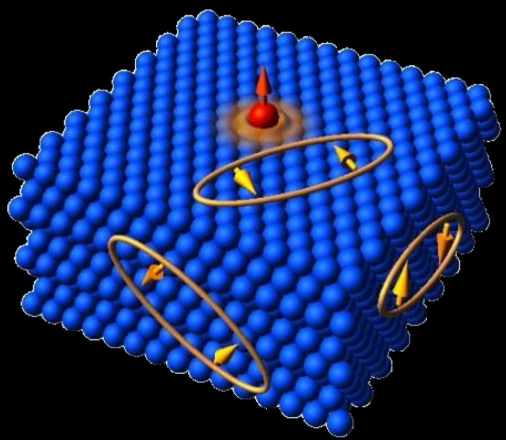
Classical impurity approximation: the impurity behaves as a local magnetic field

$$\hat{H}_{imp} = J \sum_{\vec{k}} \vec{S}_I \cdot \hat{\vec{s}}_k$$

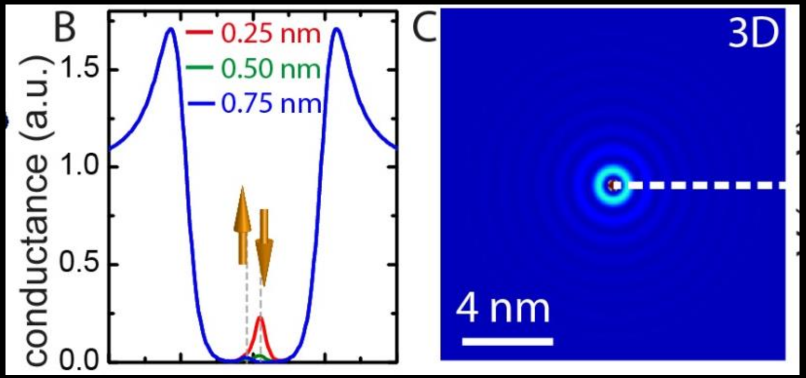


Magnetic impurities: Interaction mechanism

Appearance of in-gap Yu-Shiba-Rusinov bound states localized around the magnetic impurity



$$\widehat{H}_{imp} = J \sum_{\vec{k}} \vec{S}_I \cdot \hat{\vec{s}}_k$$



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

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

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

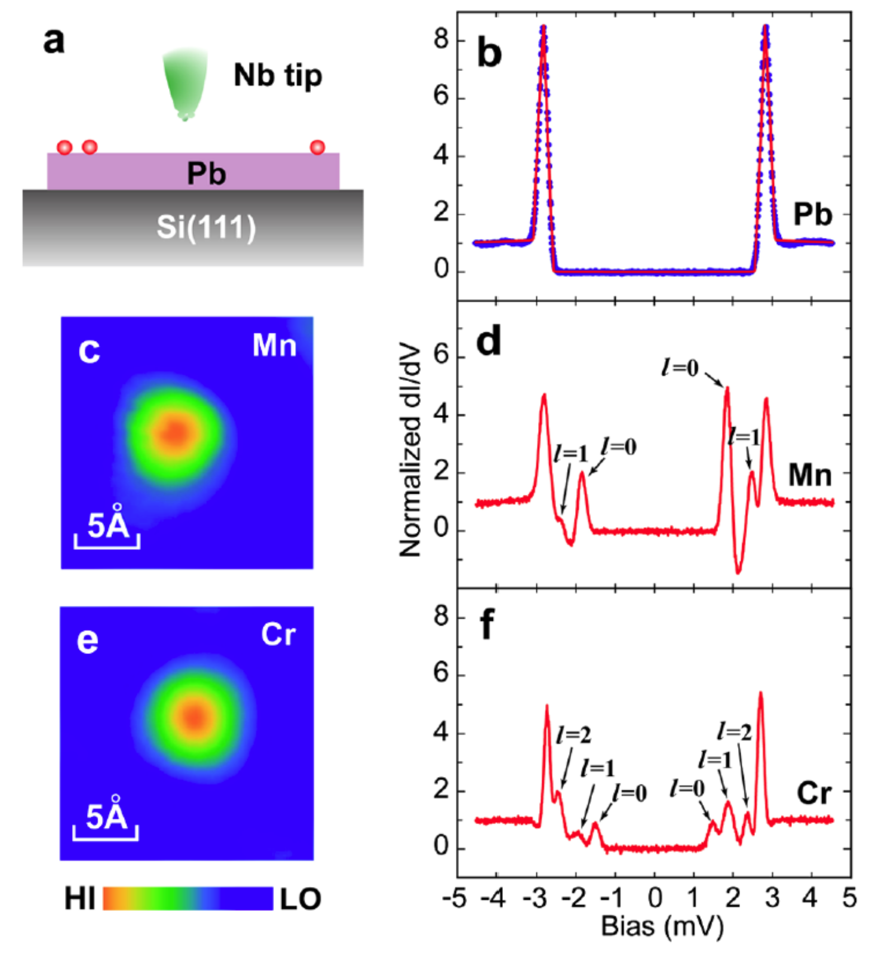
Single magnetic impurities observed by STM
Angular momentum

The number of Shiba peaks depends on the atom nature

$$Mn \rightarrow l = 0{,}1$$
$$Cr \rightarrow l = 0{,}1{,}2$$

Every peak corresponds to a different diffusion channel for the superconducting electrons.

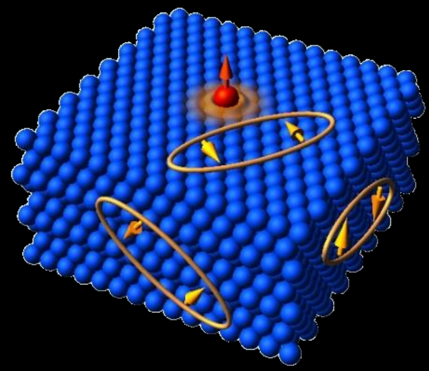
Extremely local effect of the impurities (a few Å)



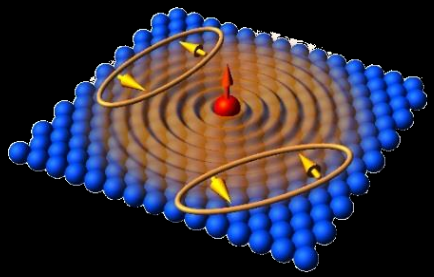
Shuai-Hua Ji et al. *PRL* **100**, 226801 (2008)

Yu-Shiba-Rusinov bound states in 2D superconductors

$$\psi_{\pm}^{3D}(r) = \frac{1}{\sqrt{N}} \frac{\sin(k_F r + \delta^{\pm})}{k_F r} e^{-\Delta \sin(\delta^{+}-\delta^{-}) r/\hbar v_F}$$



$$\psi_{\pm}^{2D}(r) = \frac{1}{\sqrt{N}} \frac{\sin\left(k_F r + \delta^{\pm} - \frac{\pi}{4}\right)}{\sqrt{k_F r}} e^{-\Delta \sin(\delta^{+}-\delta^{-}) r/\hbar v_F}$$

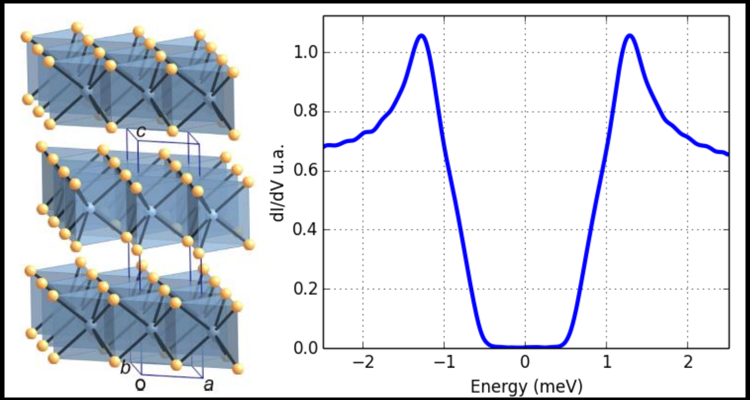


Lower dimensionality leads to **larger extents** of YSR bound states

Two-dimensionnal superconductors

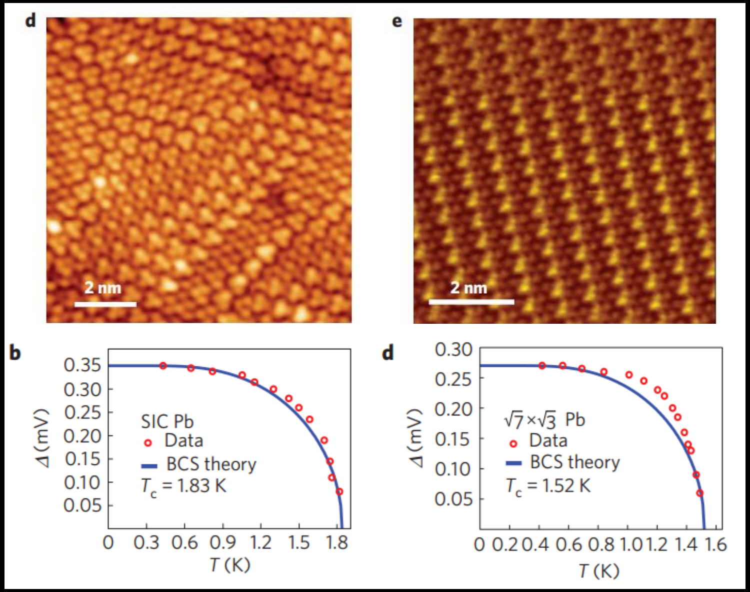
Bulk superconductor with 2D electronic structure:

- **Lamellar material 2H-$NbSe_2$**
- **Multi gap BCS**
- $T_c \simeq 7,2\ K$



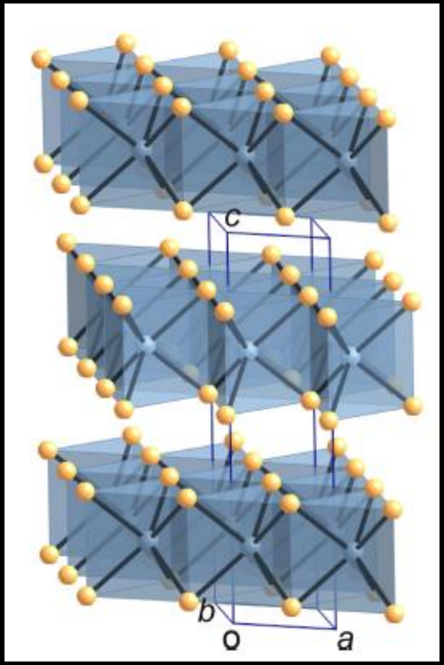
Ultimately thin superconductor :

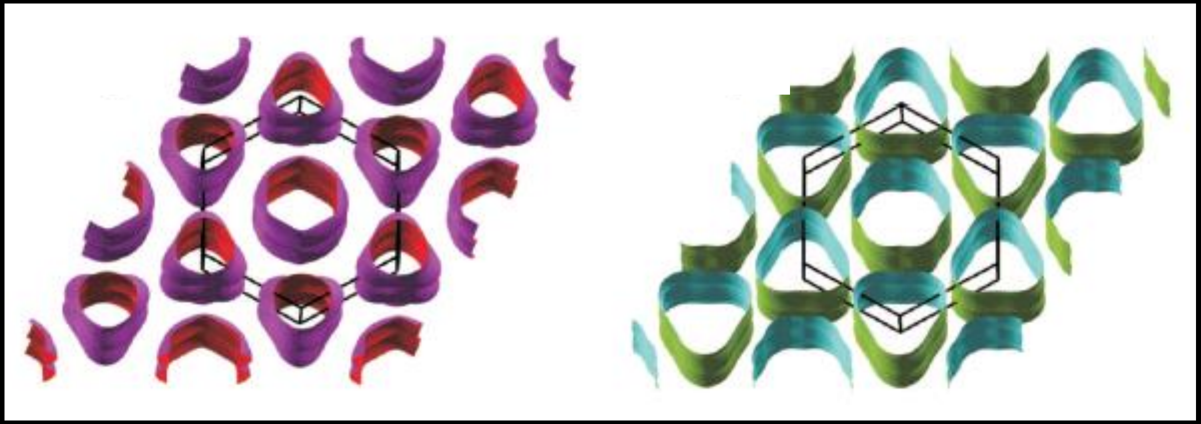
- **Single atomic layer of Pb/Si(111)**
- $T_c \simeq 1,5\ K - 1,8\ K$
- **Discovered to be superconducting in 2010**



Zhang et al. Nature Physics (2010

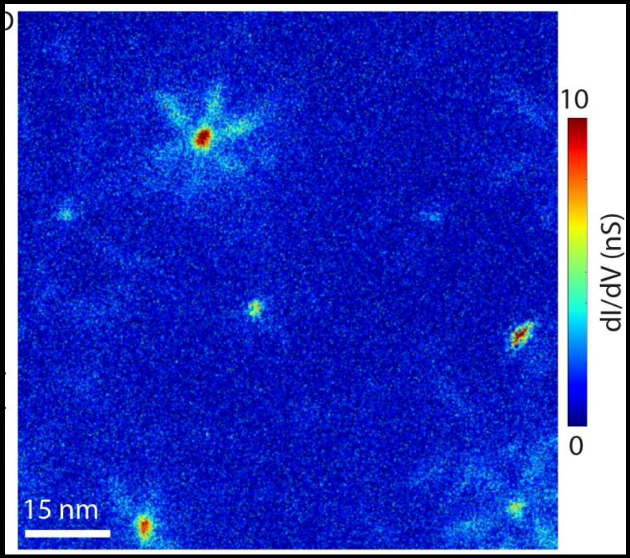
2H-$NbSe_2$ as a two-dimensional superconductor





Two-dimensional like bands structure due to the weak Van der Waals interlayer coupling.

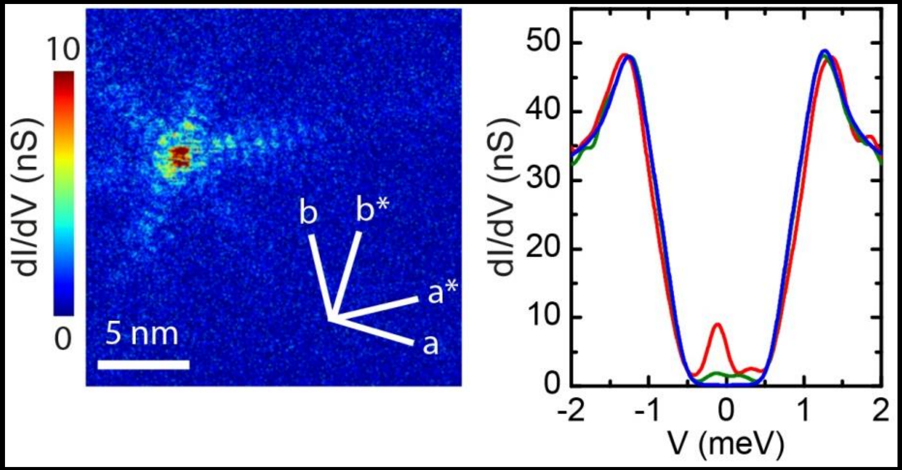
Observation of bound states around magnetic impurities in 2H-$NbSe_2$

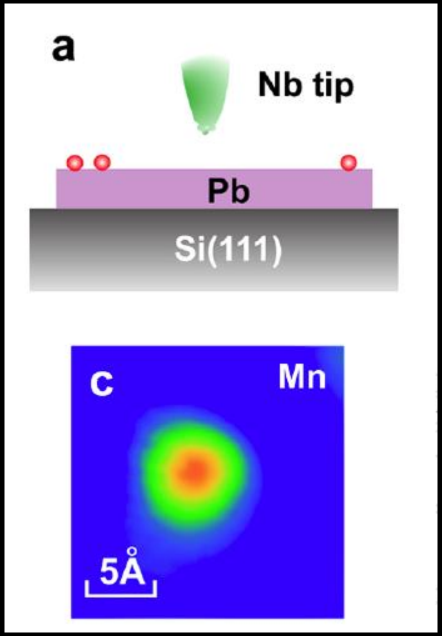


The Nb used for the crystal growth contains magnetic impurities :

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

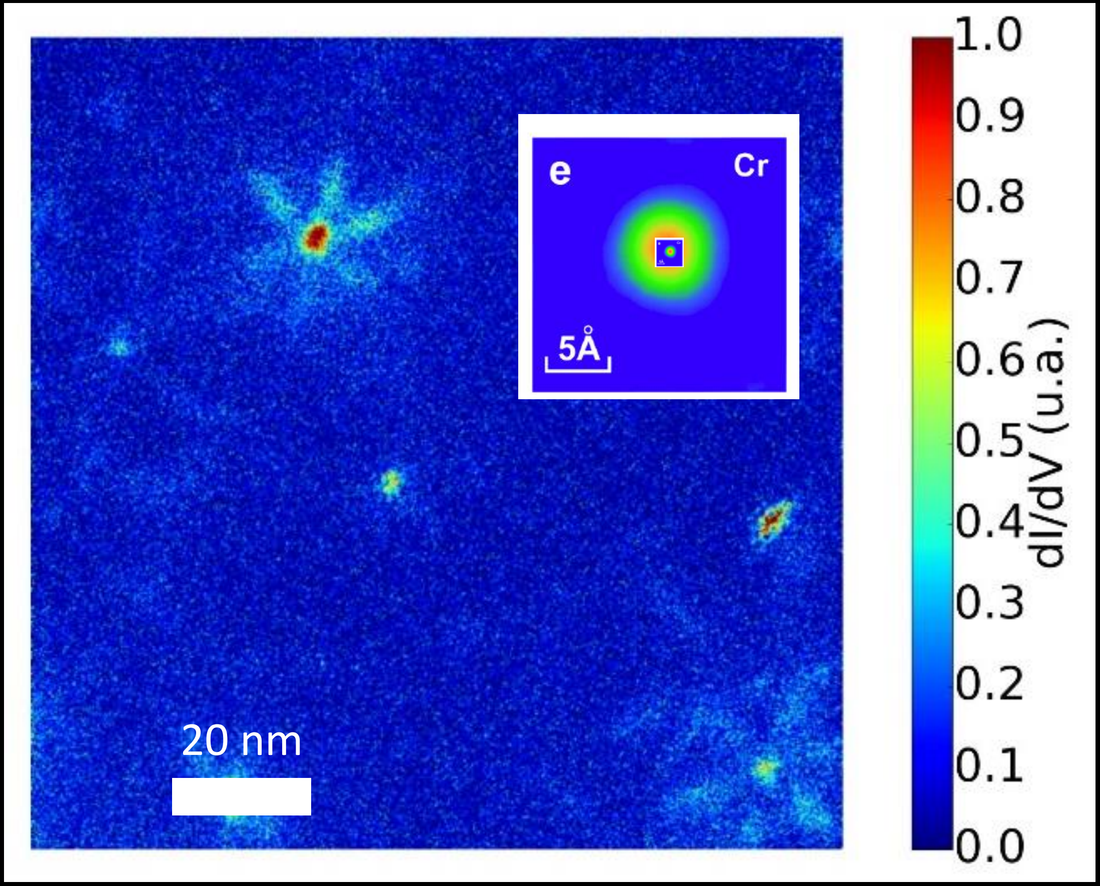
dI/dV maps at -0.13 mV (320 mK)





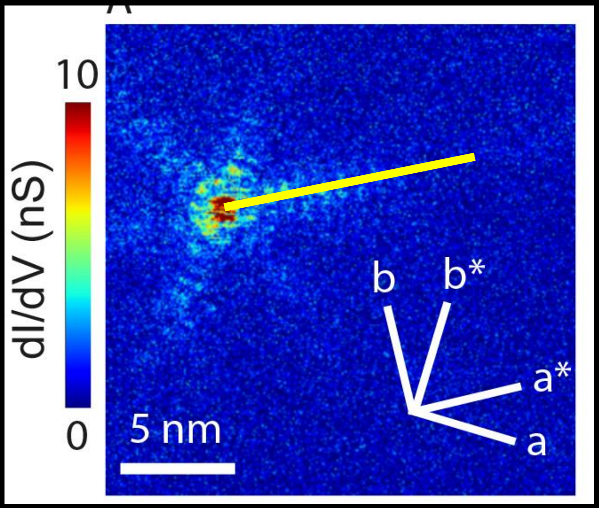
G. Ménard et al. arXiv:1506.06666, Nature Physics (2015)

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



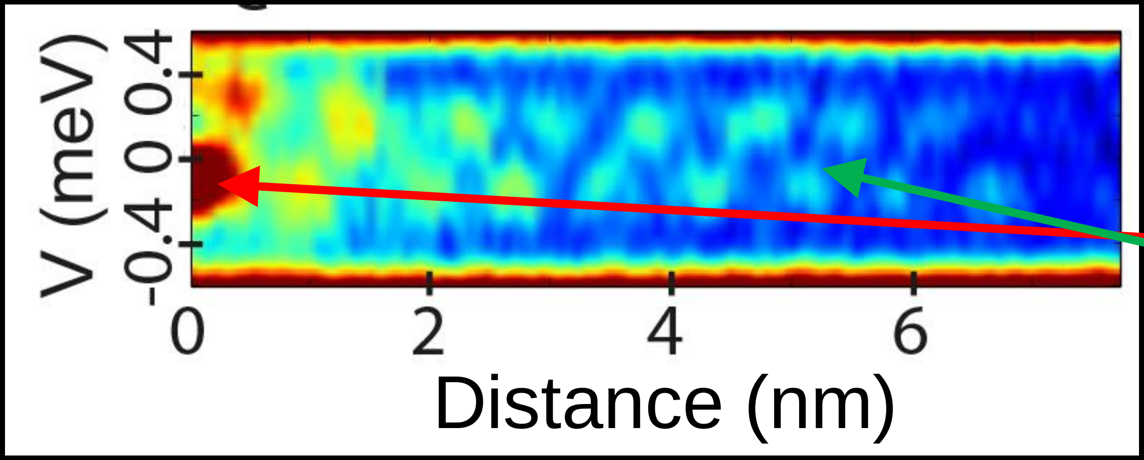
Shiba bound states observed over scales of the order of **10nm**

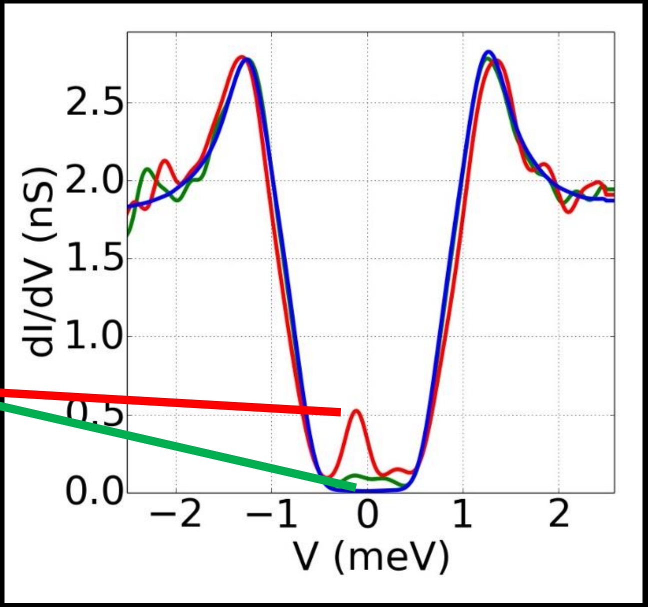
Spatial oscillation of Shiba bound states
Electron-hole asymmetry



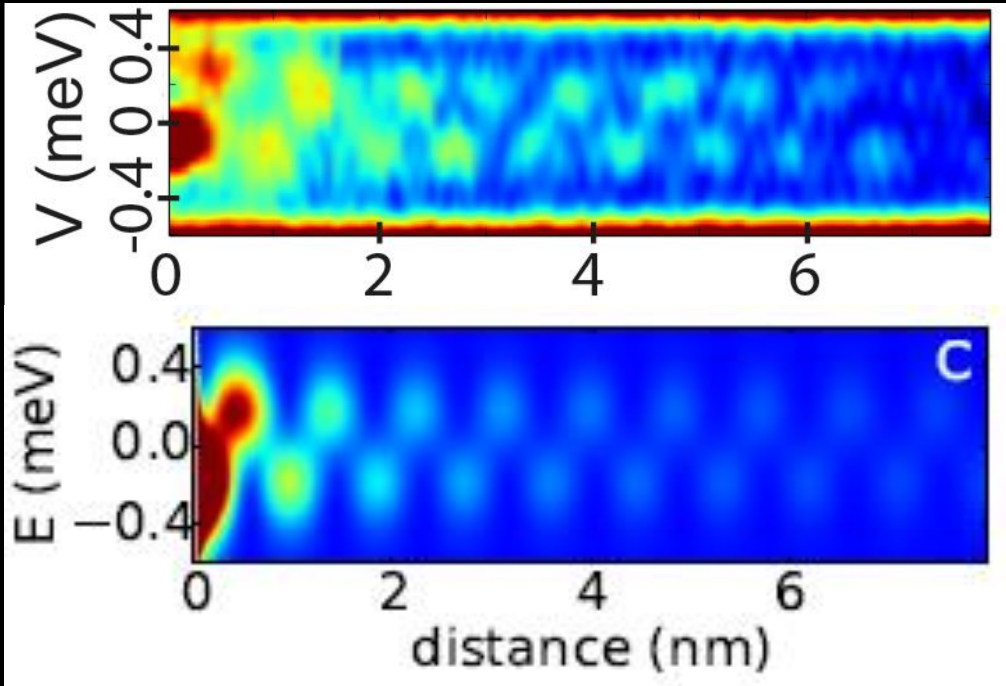
•Oscillations of the local density of states with a phase opposition between positive and negative energy states

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





Spatial oscillations and electron-hole asymmetry



Good agreement with theoretical calculations for 2D case in the asymptotic limit.

Two relevant length scales: k_F & ξ

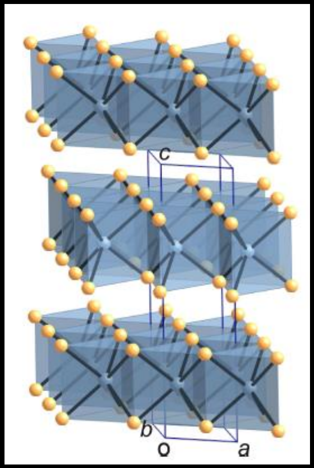
$$\psi_{\pm}(r) = \frac{1}{\sqrt{N\pi k_F r}} \sin\left(k_F r - \frac{\pi}{4} + \delta^{\pm}\right) e^{-\Delta \sin(\delta^+ - \delta^-) r/\hbar v_F}$$

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

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

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

Two-dimensionnal superconductors

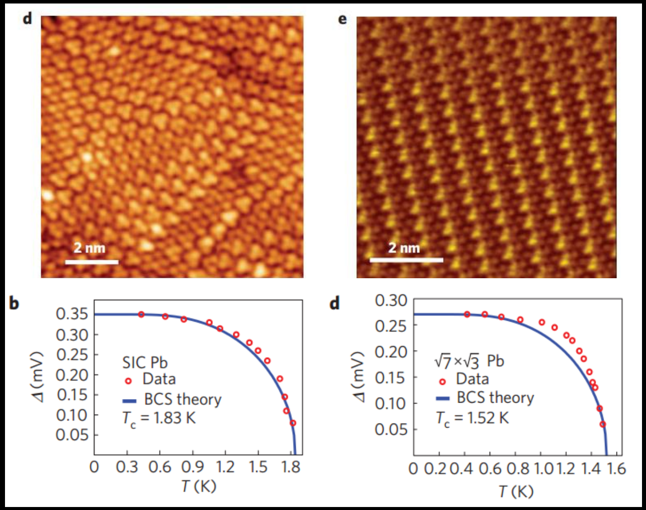


•Bulk superconductor with 2D electronic structure:

Lamellar material 2H-$NbSe_2$

•Ultimately thin superconductor :

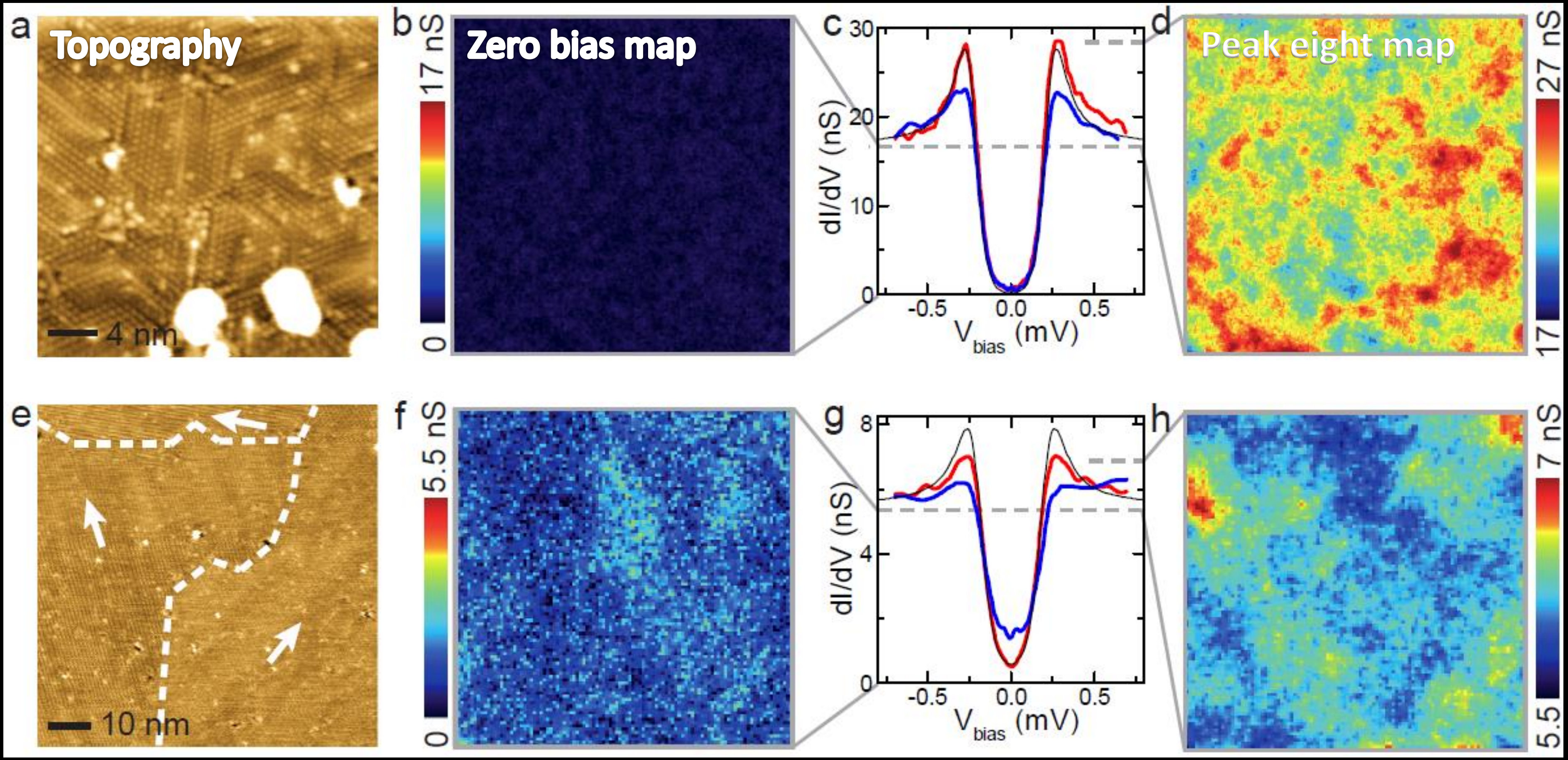
Single atomic layer of Pb/Si(111)



Zhang et al. Nature Physics (2010)

Effect of non-magnetic disorder on the superconductivity of a single atomic layer of Pb/Si(111)

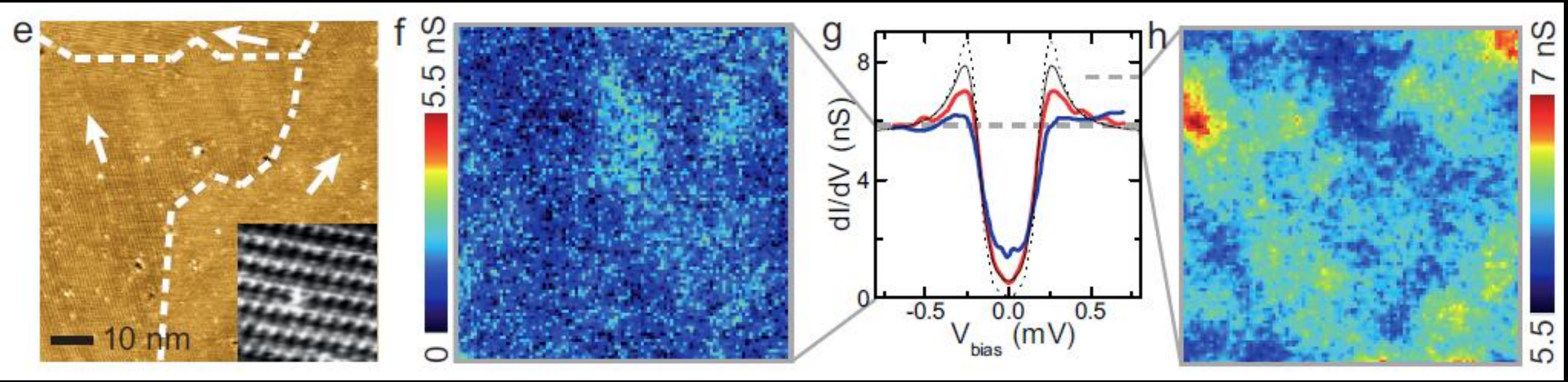
Striped-Incommensurate Pb/Si(111), 1.33 monolayer



√3 × √7-Pb/Si(111), 1.2 monolayer

C. Brun et al. Nat. Phys. 10, 444 (2014)

Effect of non-magnetic disorder on the superconductivity on √3×√7-Pb/Si(111)



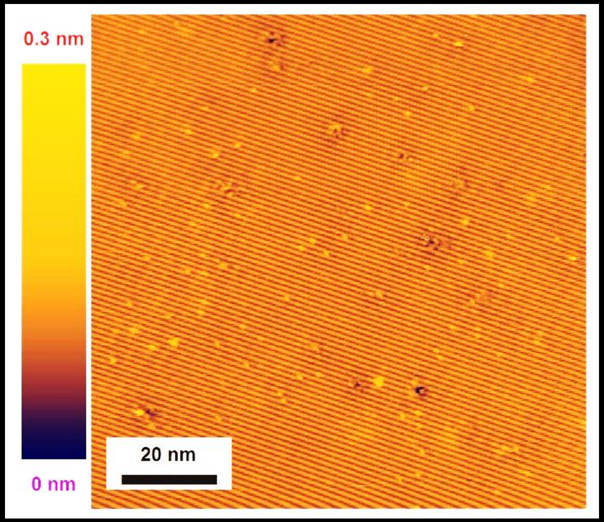
√3×√7-Pb/Si(111)
1.2 monolayer

ξ_{eff} ~ 45nm

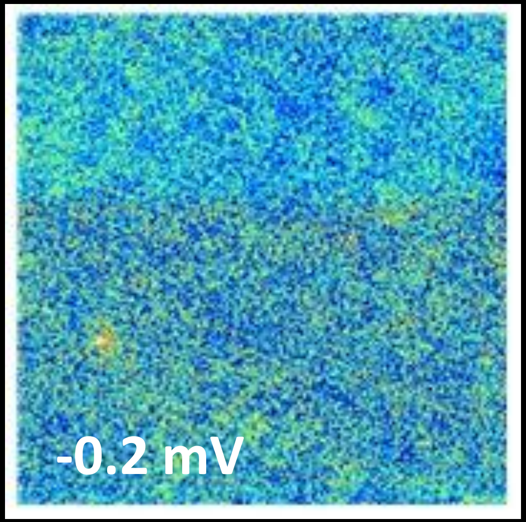
Gap filling and fluctuations of zero bias conductance:
non conventionnal superconducting order?

C. Brun et al., Nat. Phys. 10, 444 (2014)

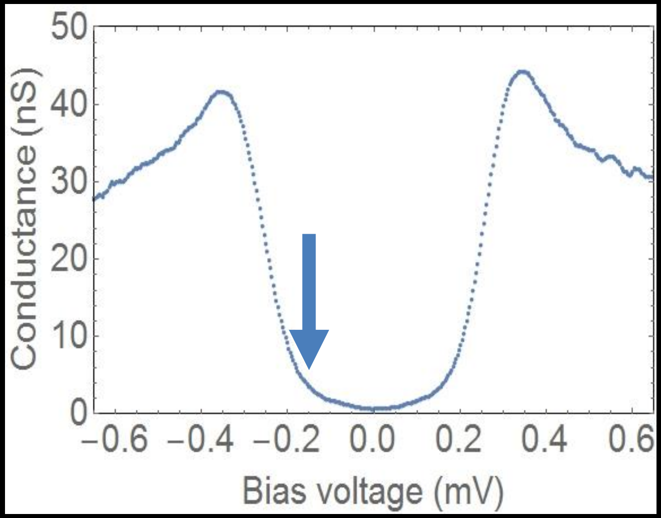
Quasiparticle interferences as a fingerprint of triplet superconducting order in √7x√3-Pb/Si(111)



Topographic map of √7x√3-Pb/Si(111)

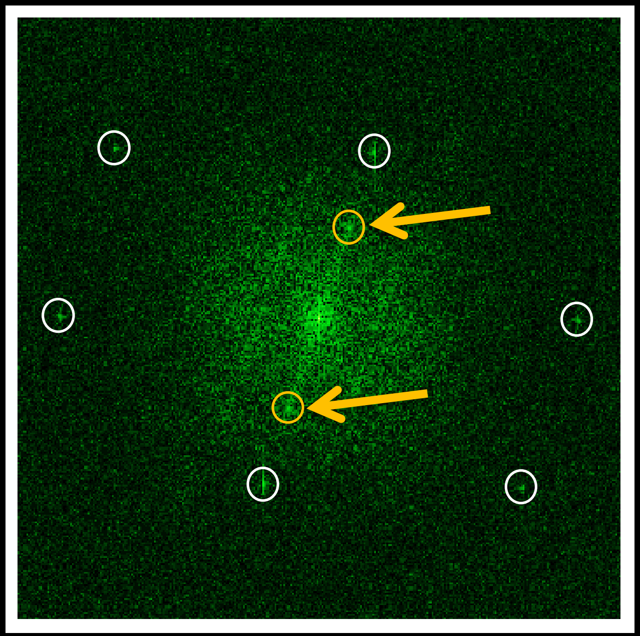


Conductances map inside the gap

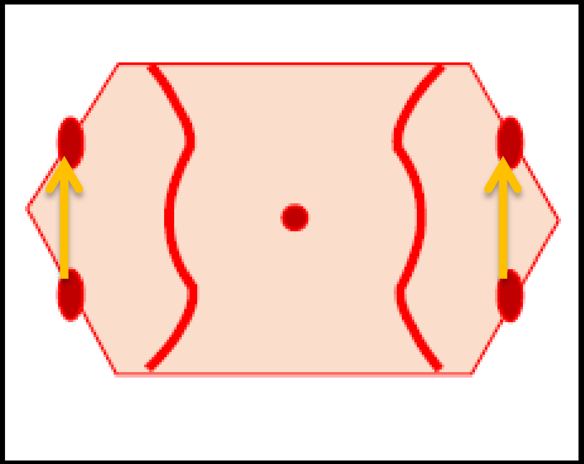


Average conductance spectrum

Quasiparticle interferences as a fingerprint of triplet superconducting order in √7x√3-Pb/Si(111)

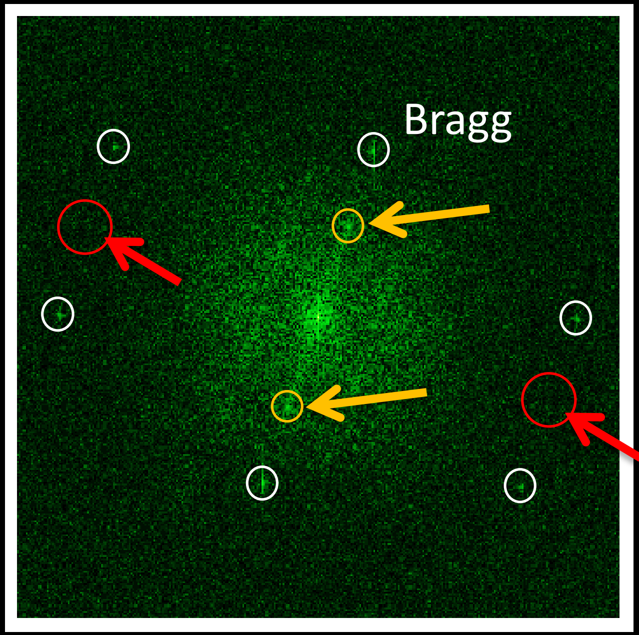


Fourier transform of the conductance map at -0.2 mV

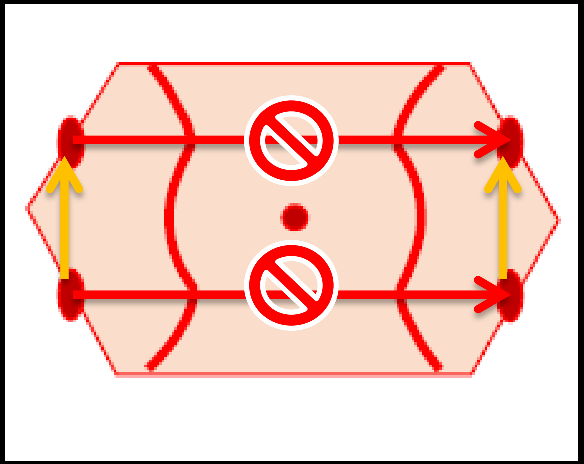


Fermi surface related scattering vectors

Quasiparticle interferences as a fingerprint of triplet superconducting order in √7x√3-Pb/Si(111)



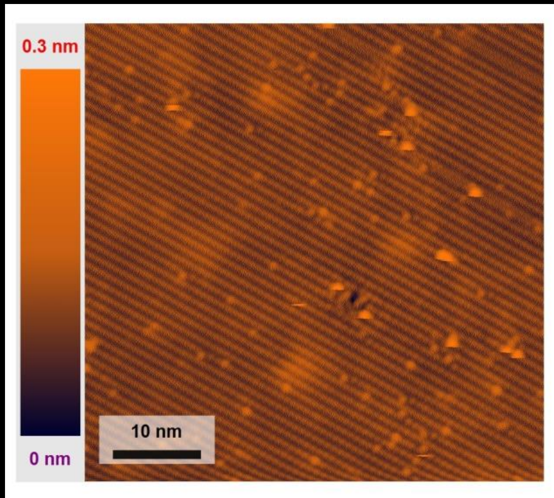
Fourier transform of the conductance map at -0.2 mV



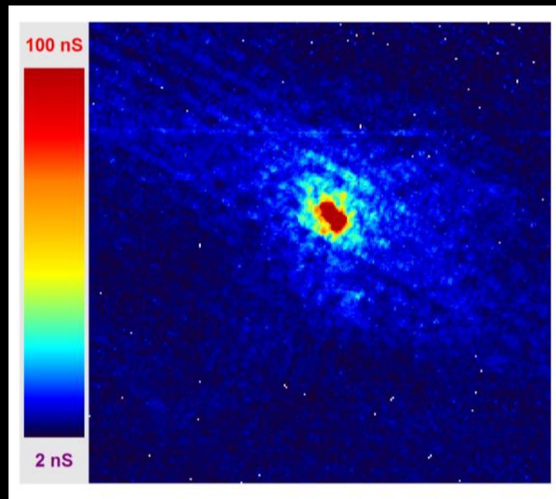
Some scattering channels are forbiden: spin selective effect?

Shiba bound states in the stripe incommensurate monolayer of Pb/Si(111)

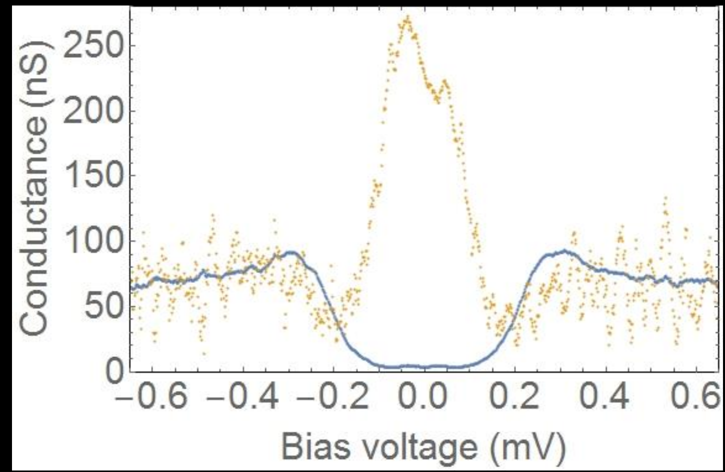
√7x√3-Pb/Si(111), *1.2 monolayer*



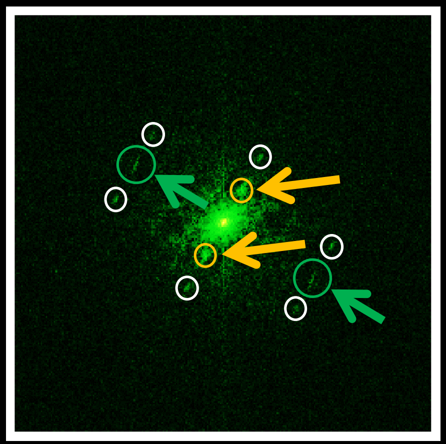
Topography

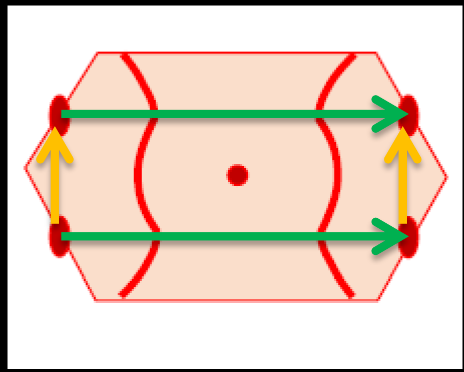


Conductance map at 0 mV

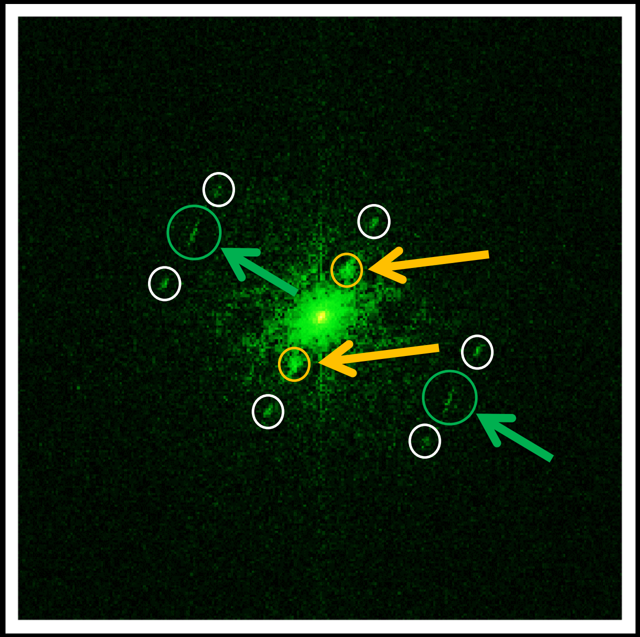


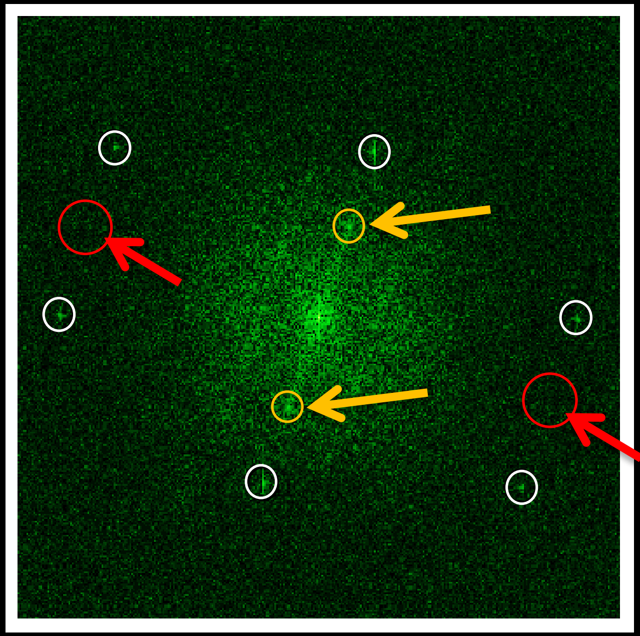
Conductance spectra on top and far from the impurity



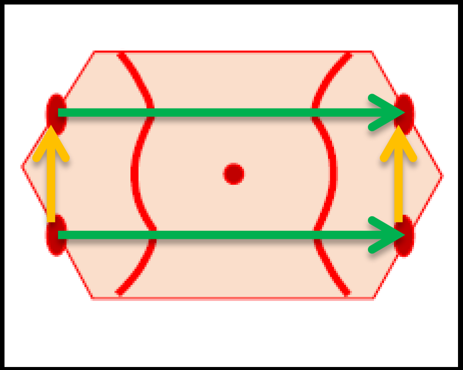


Magnetic vs non-magnetic impurities
Signature of a triplet component?

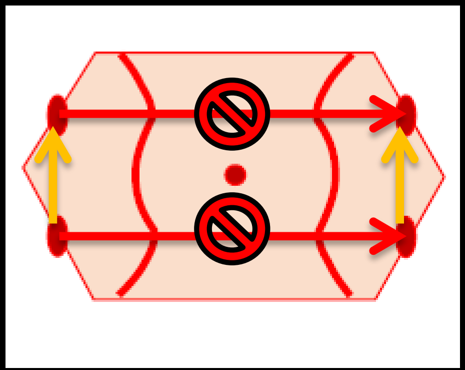




Magnetic impurities



Non magnetic impurities



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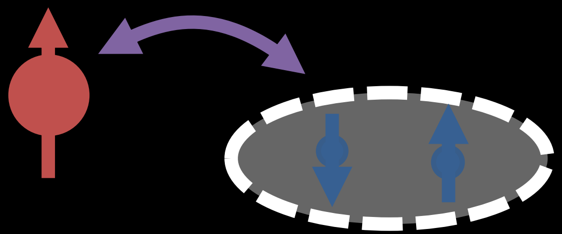
  Dimensionality effect
  2H-NbSe2
  Pb/Si(111)



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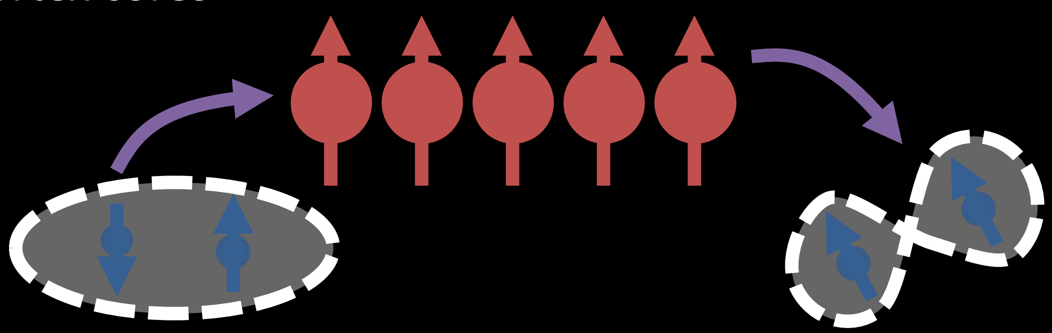
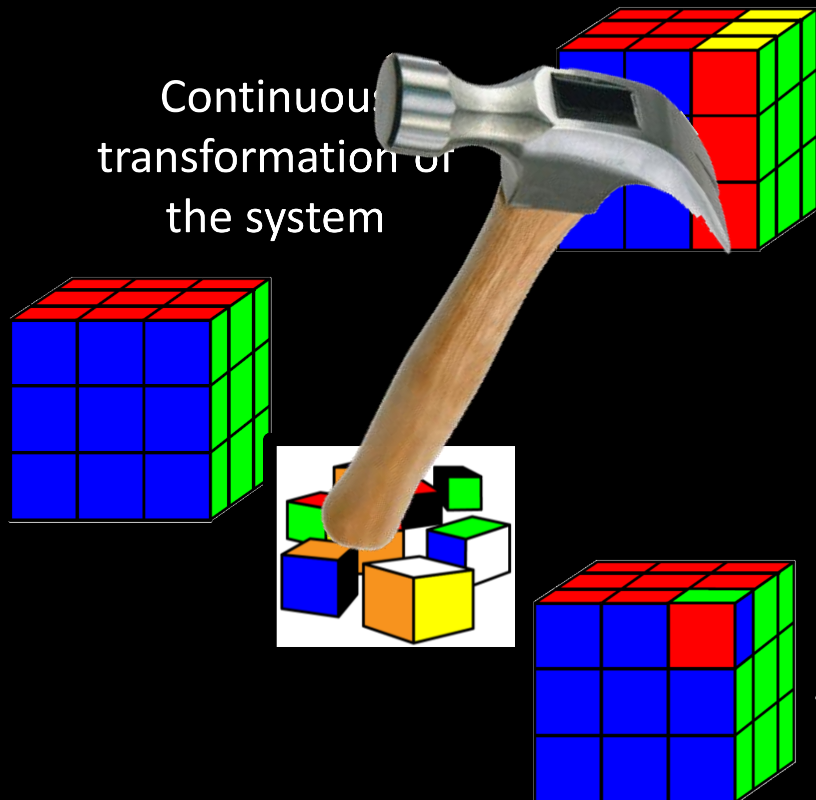
  Majorana bound states in vortex cores



Topological states



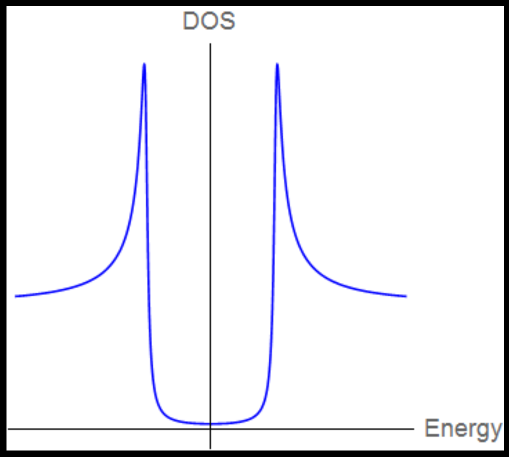
Break and rebuild the system for this configuration.
2 configurations → **2** topological indices.

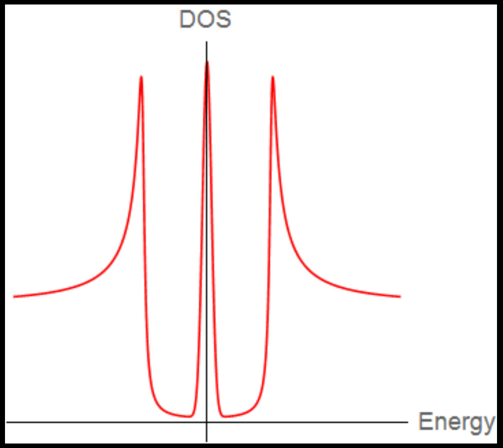
Trivial vs topologic
1D superconductor

Trivial superconductor

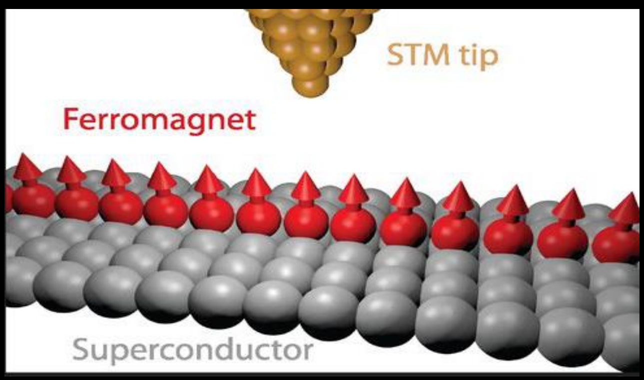
No edge states

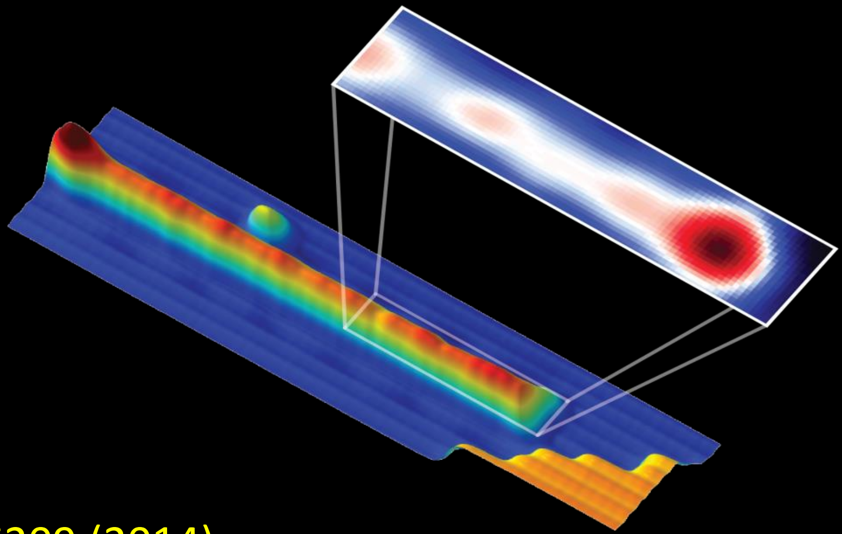
Majorana zero
energy bound state





Majorana end states in a magnetic chain on top of a superconductor Fe/Pb(110)



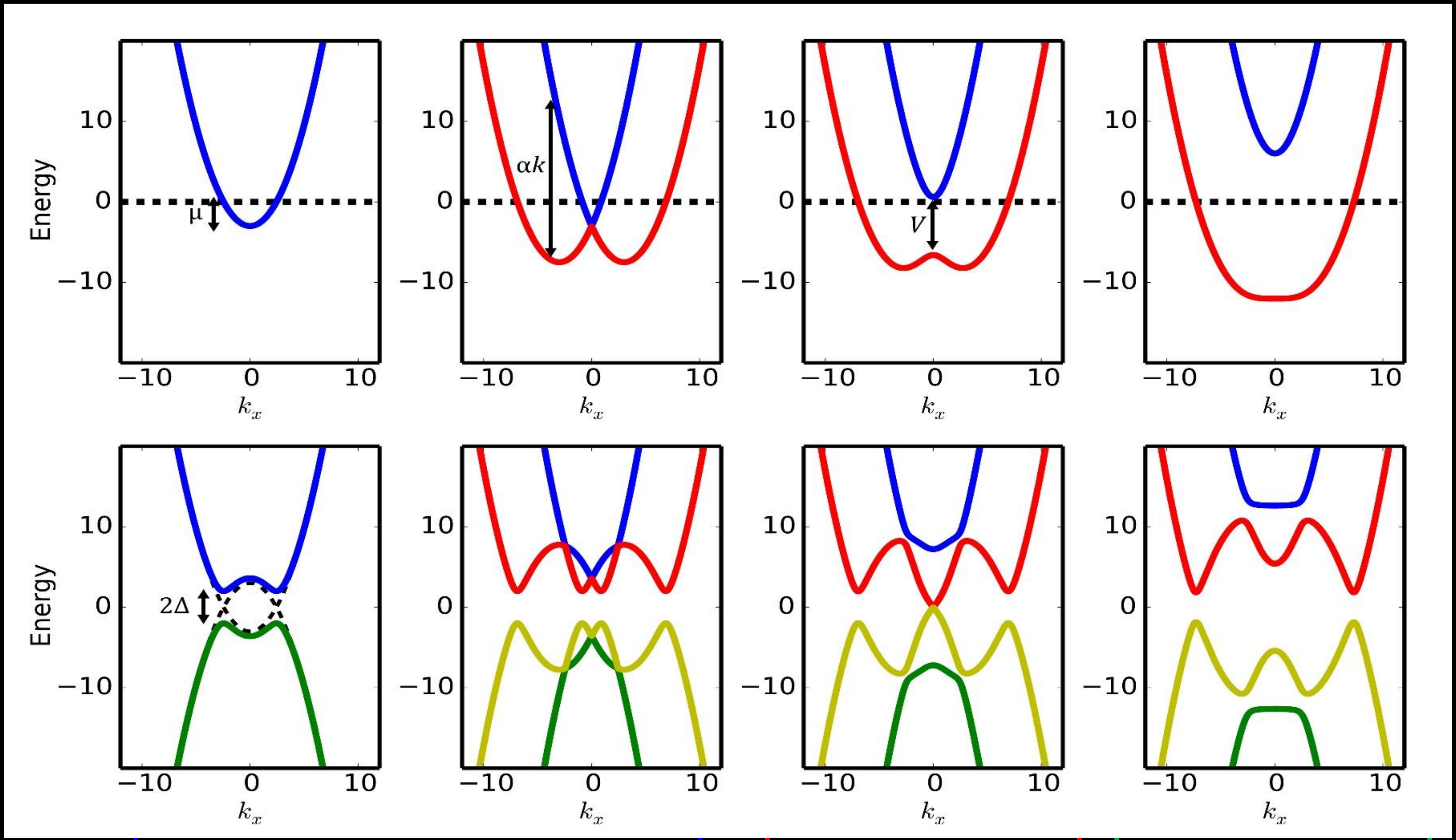


Stevan Nadj-Perge et al., Science **346,** 6209 (2014)

Vazifeh and Franz, PRL **111**, 206802 (2013)
Nadj-Perge et al, PRB **88**, 020407(R) (2013)
Braunecker and Simon, PRL **111**, 147202 (2013)

Topological transition in a Rashba superconductor in a magnetic field

Free electrons + Rashba spin-orbit coupling + Zeeman

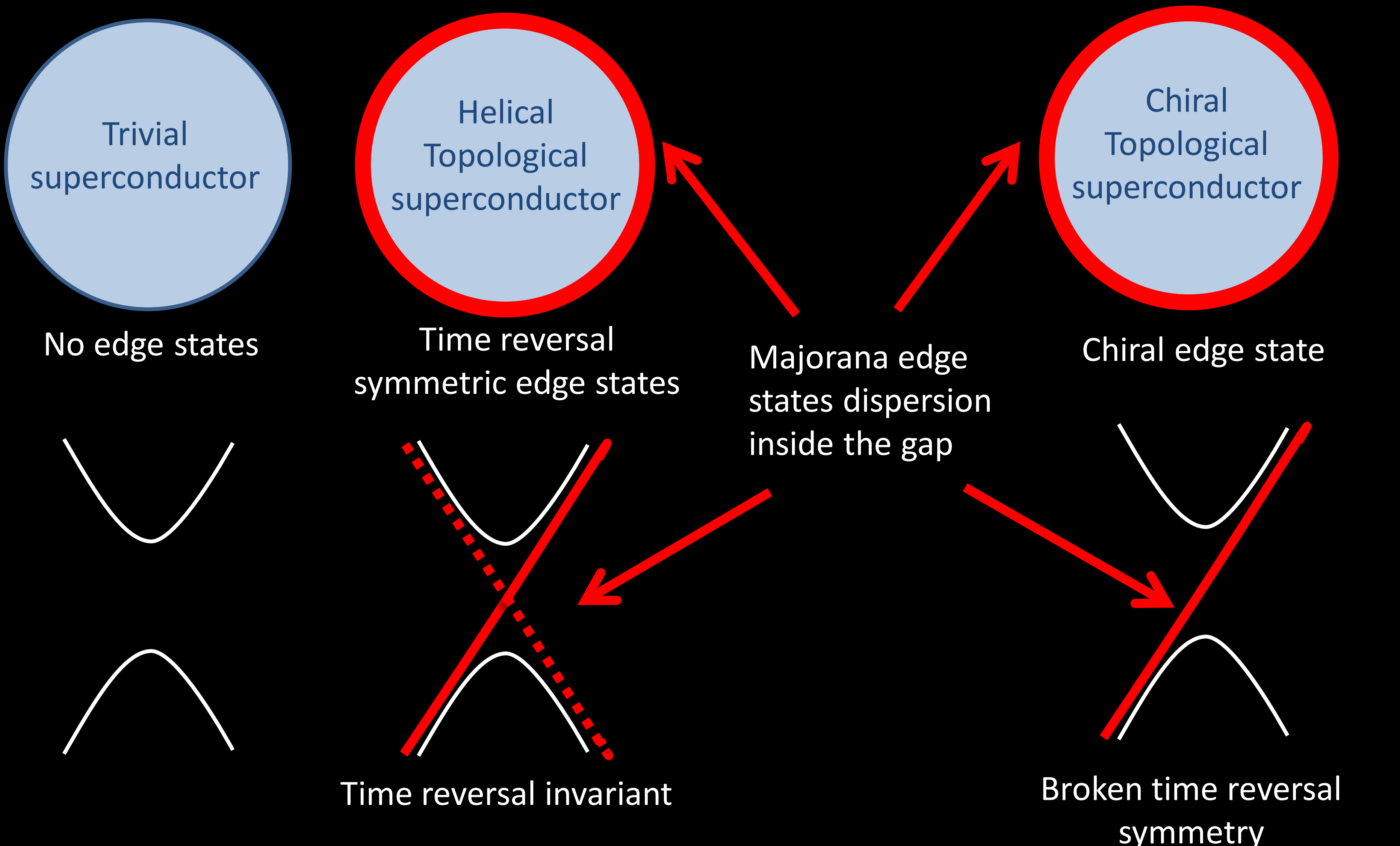


Trivial

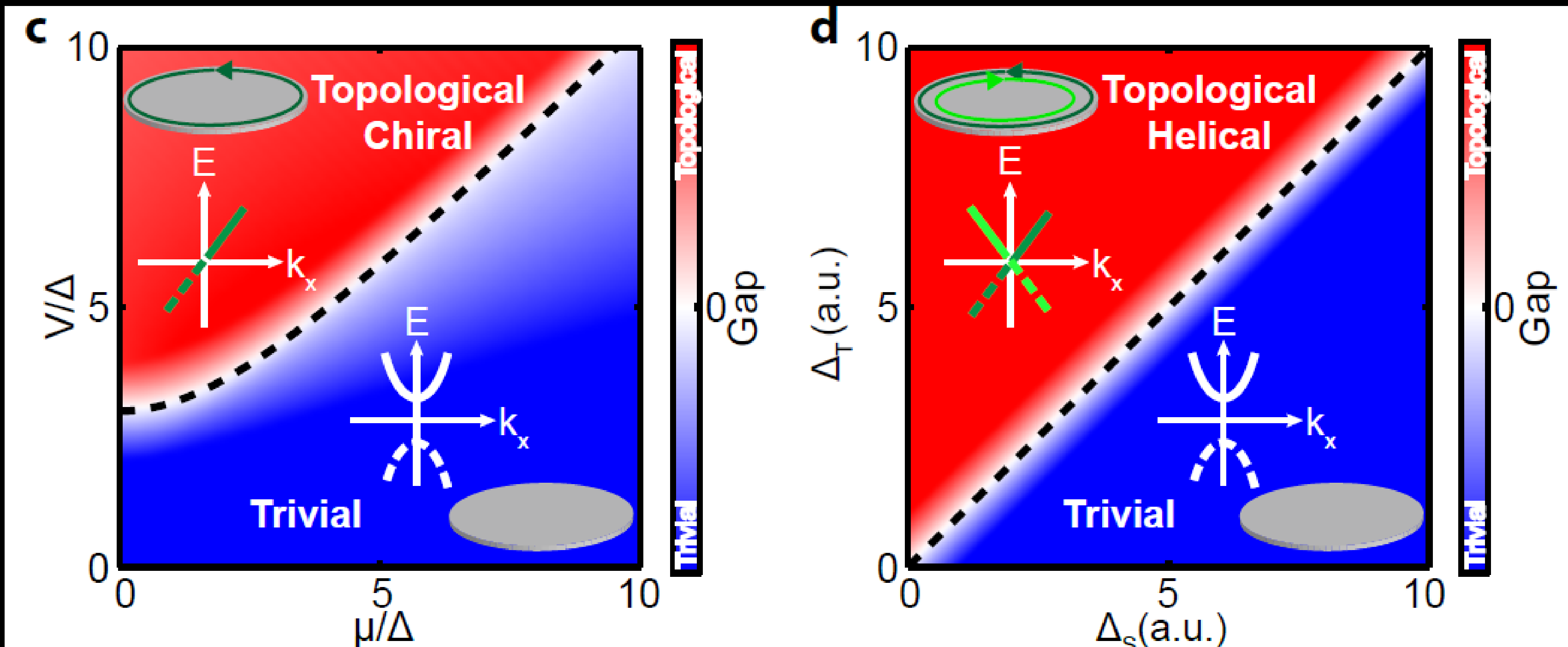
Topological transition

Topological

Majorana dispersions at the edge of 2D topological superconductors



Topological superconductivity: Chiral vs Helical



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

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

Rashba + Zeeman splitting V

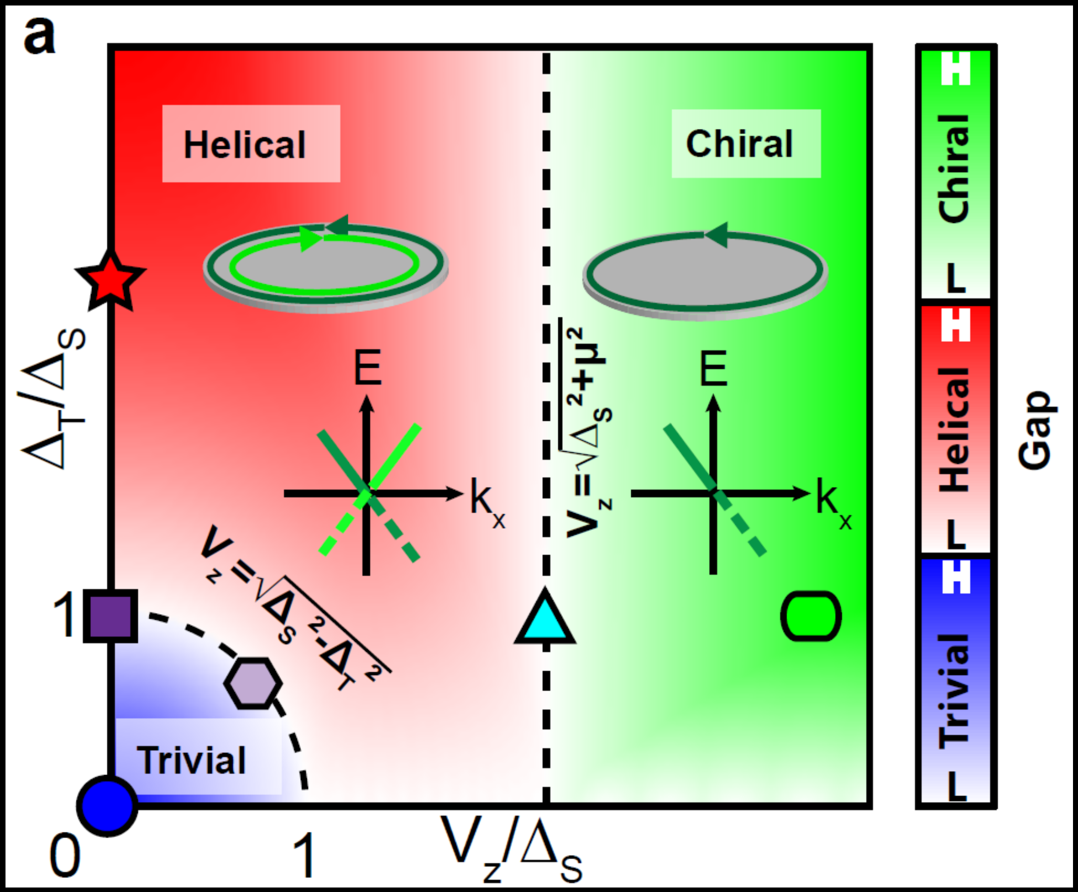
Δ_{T} is a time reversal symmetric triplet pairing

Broken time reversal
1 chiral edge state

2 helical edge states
equivalent by time reversal

Topological superconductivity: Chiral vs Helical

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



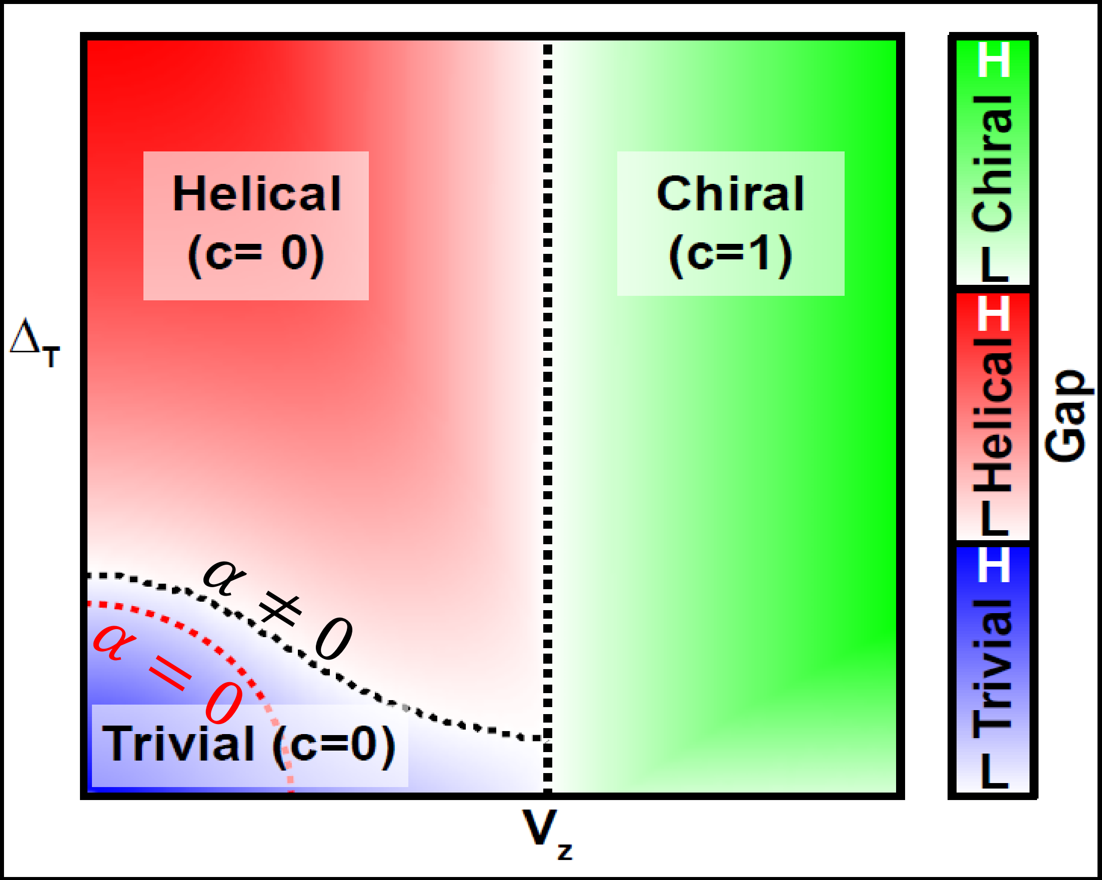
Two control parameters:
-Zeeman field
-Triplet amplitude

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

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

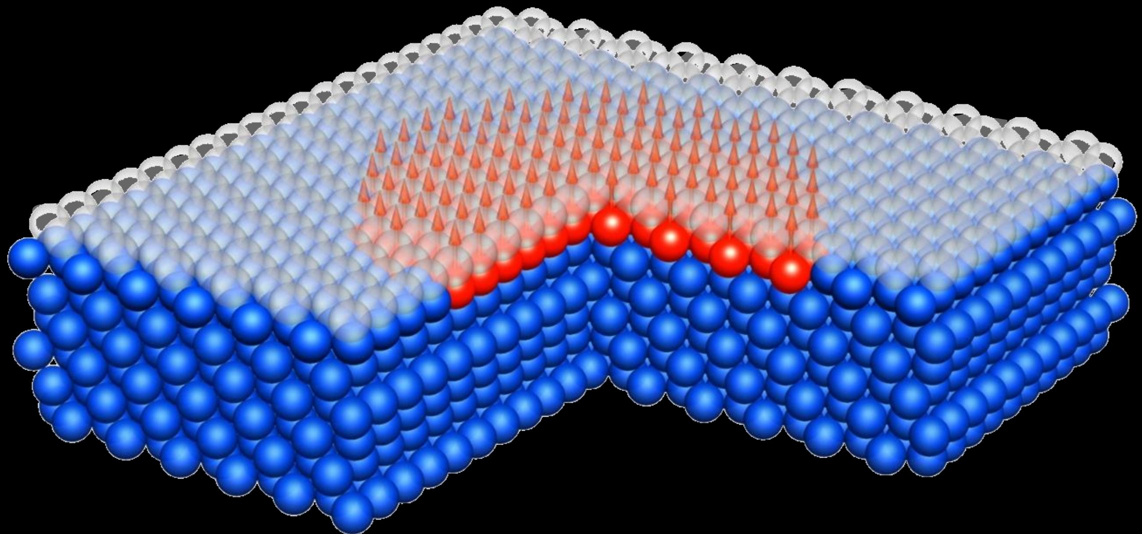
Topological superconductivity: Chiral vs Helical

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



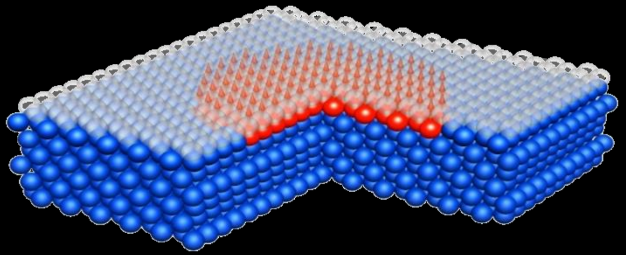
G. Ménard et al., arXiv: 1607.06353 (2016)

Towards 2D topological superconductivity

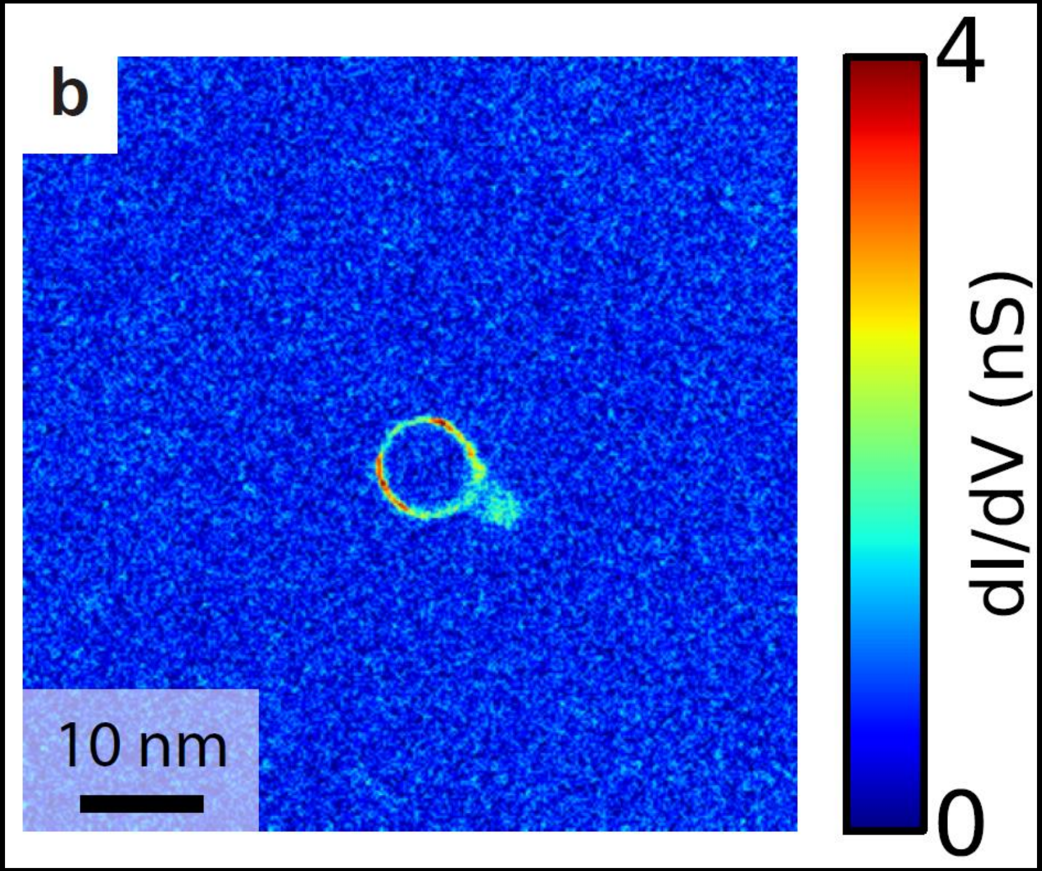


Pb/Si(111) Rashba superconductor
coupled to a ferromagnetic domain

Edge states around magnetic nanodomain in Pb/Co/Si(111)



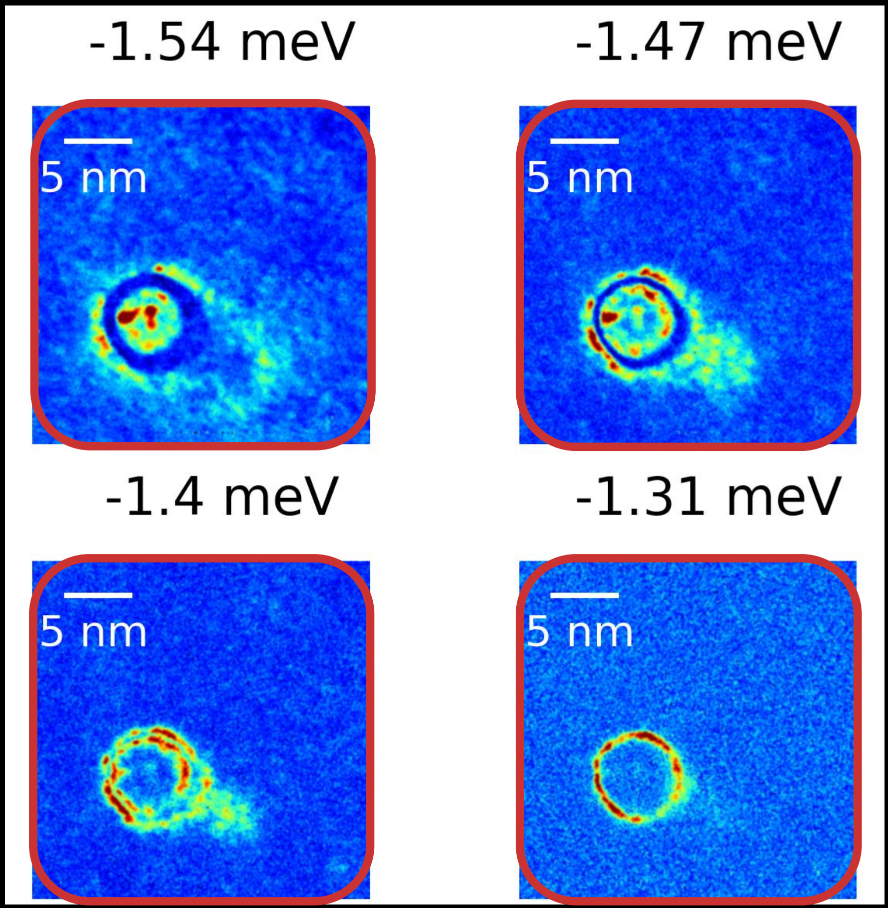
Observation of perfectly circular structure at the Fermi energy around buried Co clusters

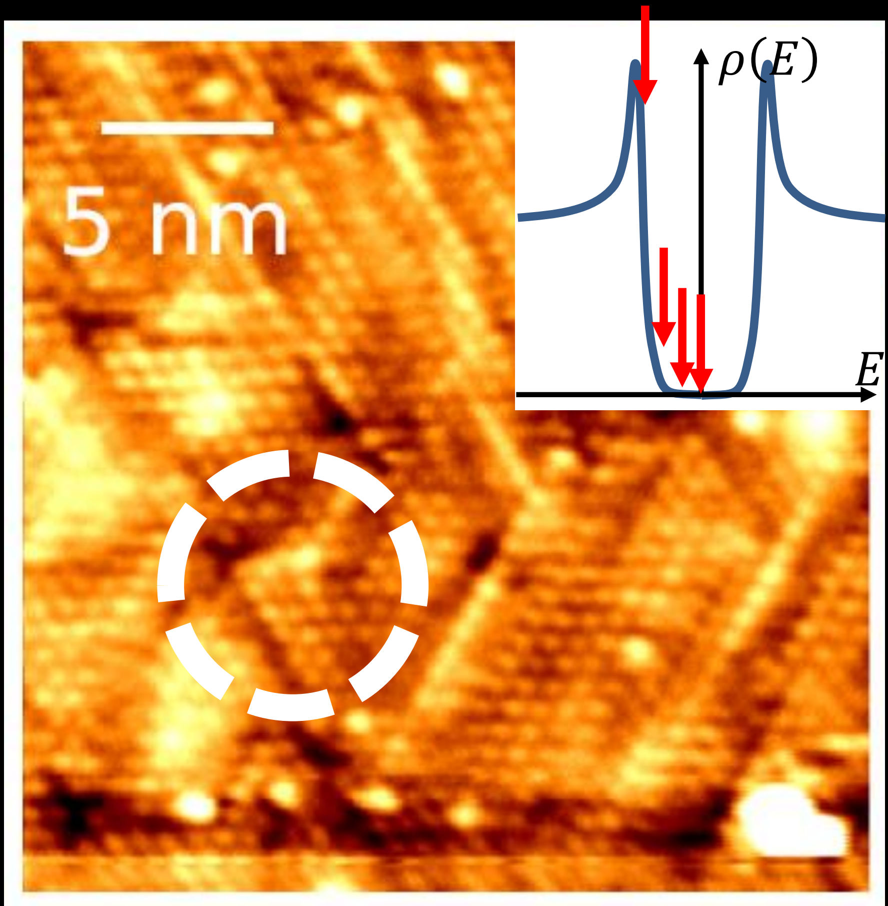


300 mK conductance map at E_F using a superconducting tip

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

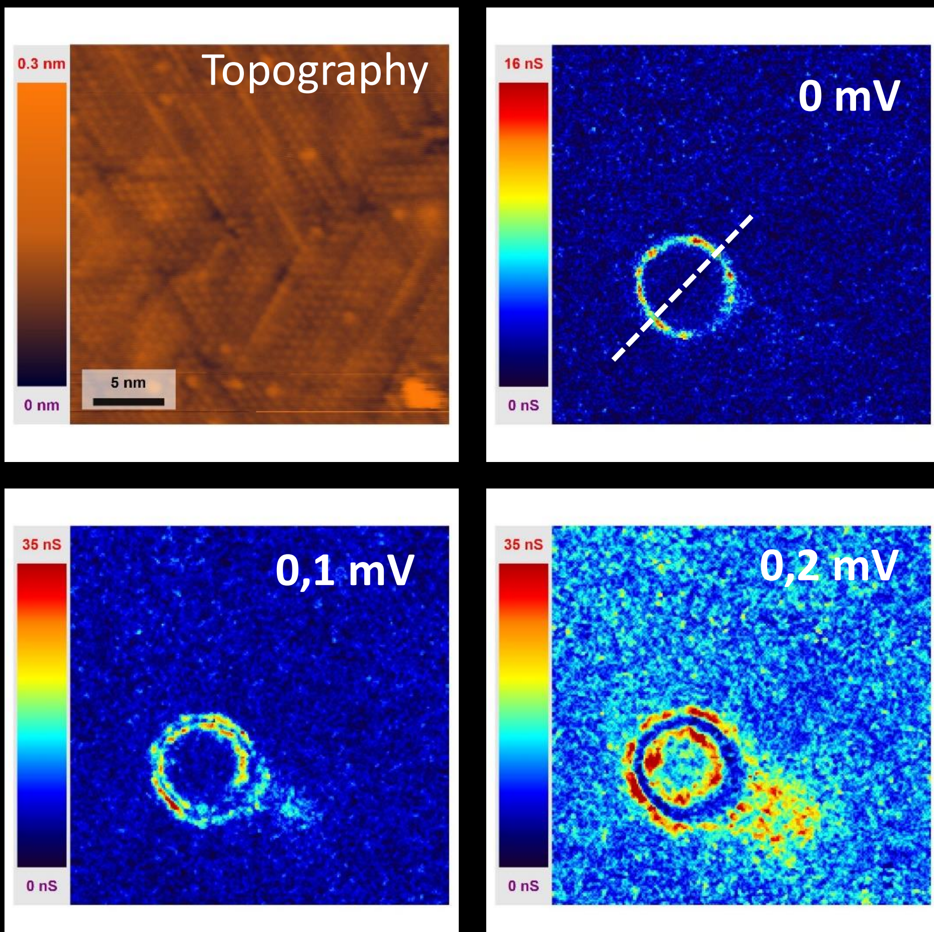
Splitting of helical edge states due to broken time reversal

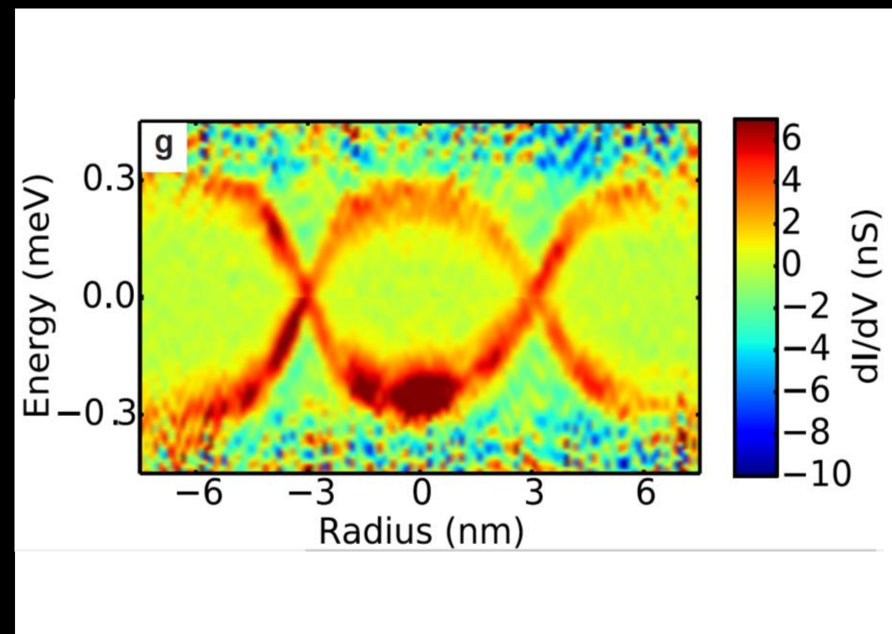




G. Ménard et al., arXiv: 1607.06353 (2016)

Majorana dispersions in Pb/Co/Si(111)

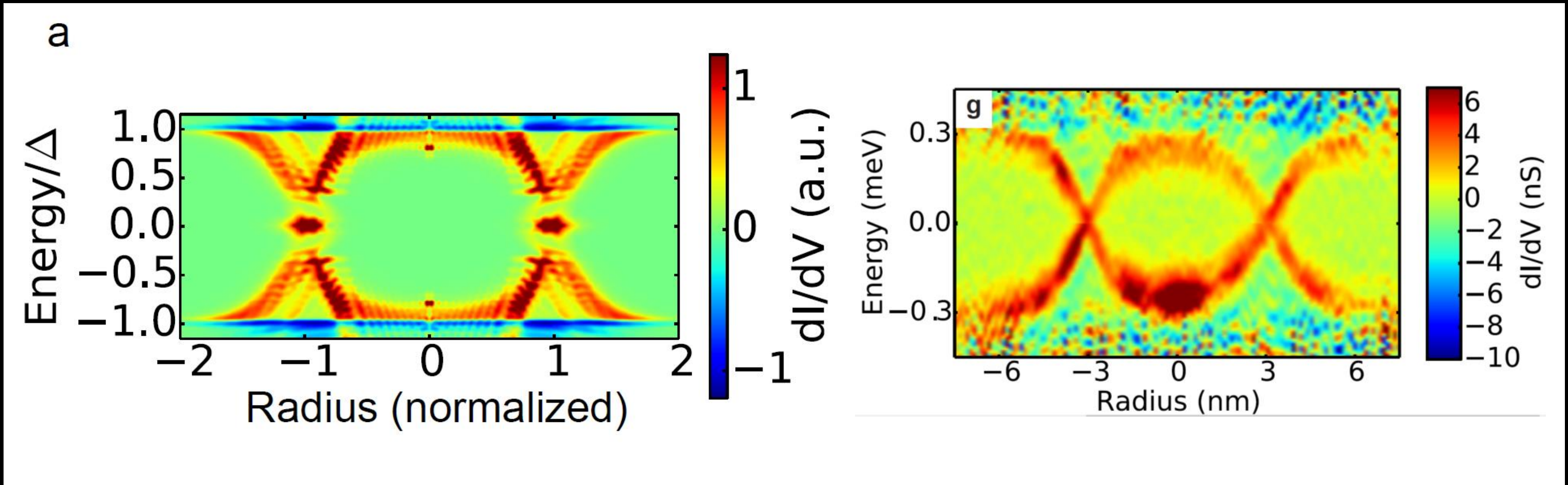




Cross section of a Majorana edge states dispersion

Theoretical modelling of Majorana dispersion

Slowly varying magnetic field defining a chiral area surrounding by a trivial area on top of singlet-triplet mixed superconductor with Rashba spin-orbit interaction



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

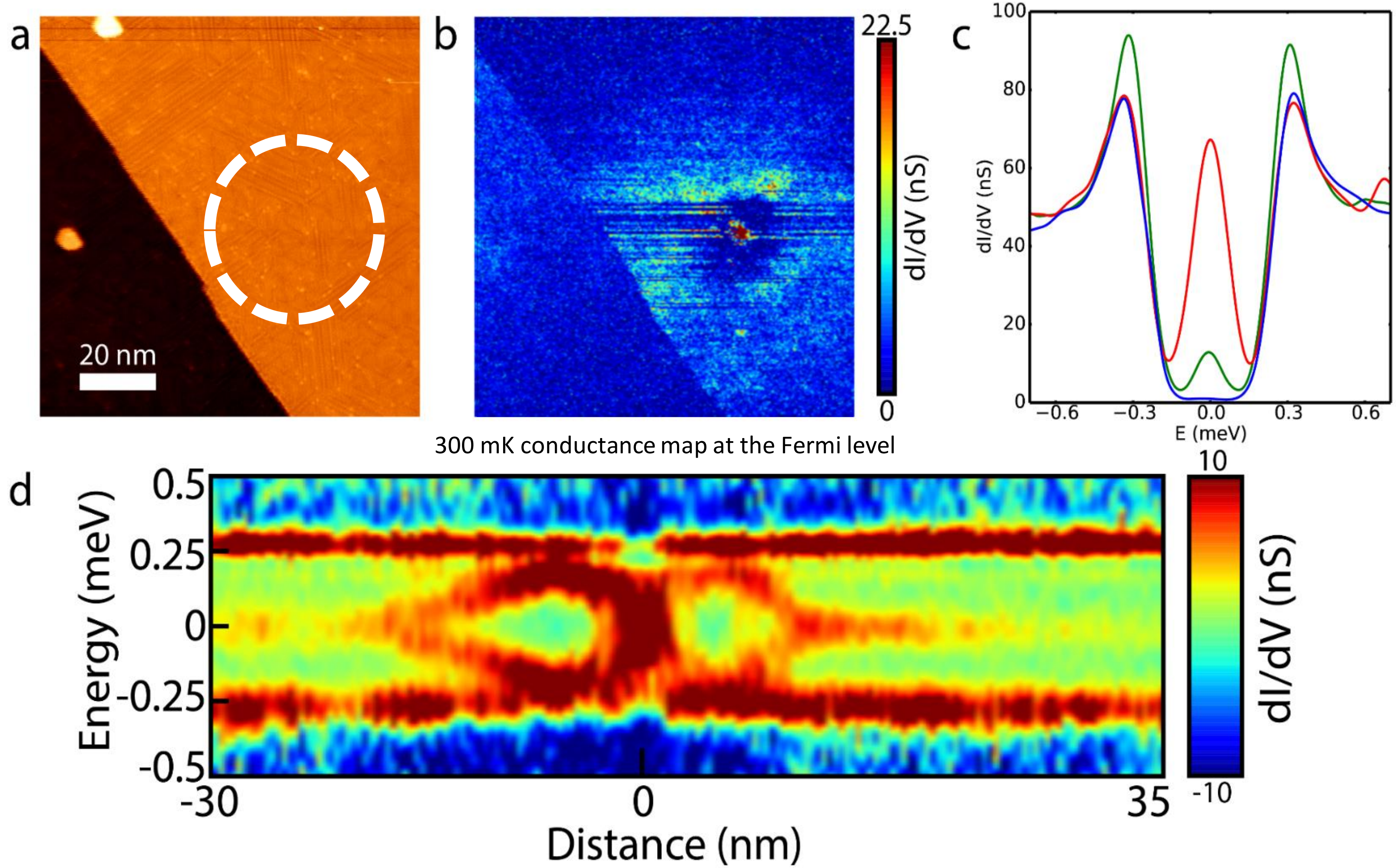
Majorana bound states

Majorana dispersive states are fine but braiding experiments require Majorana zero energy bound states

How to obtain Majorana bound states with a 2D topological superconductor?

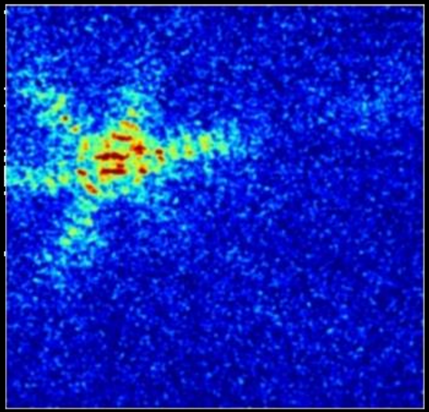
Vortex

Majorana bound state in a vortex core

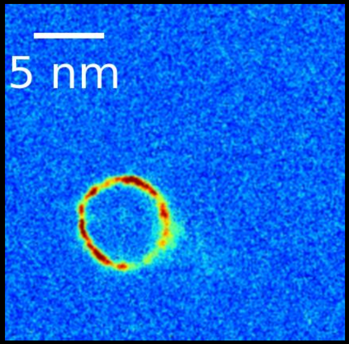


300 mK conductance map at the Fermi level

Conclusion

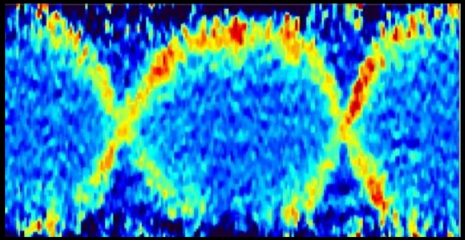


Role of dimensionality and Fermi surface for Shiba bound states

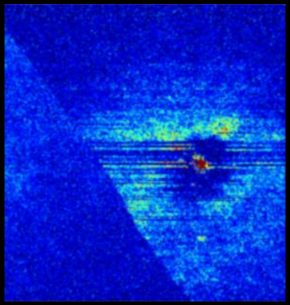


Topological superconductivity induced by a ferromagnetic domain

Hybrid helical-chiral topological state



Majorana zero-energy bound states in vortex cores



Thank you !