Coherent long range magnetic bound states in two-dimensional superconductors

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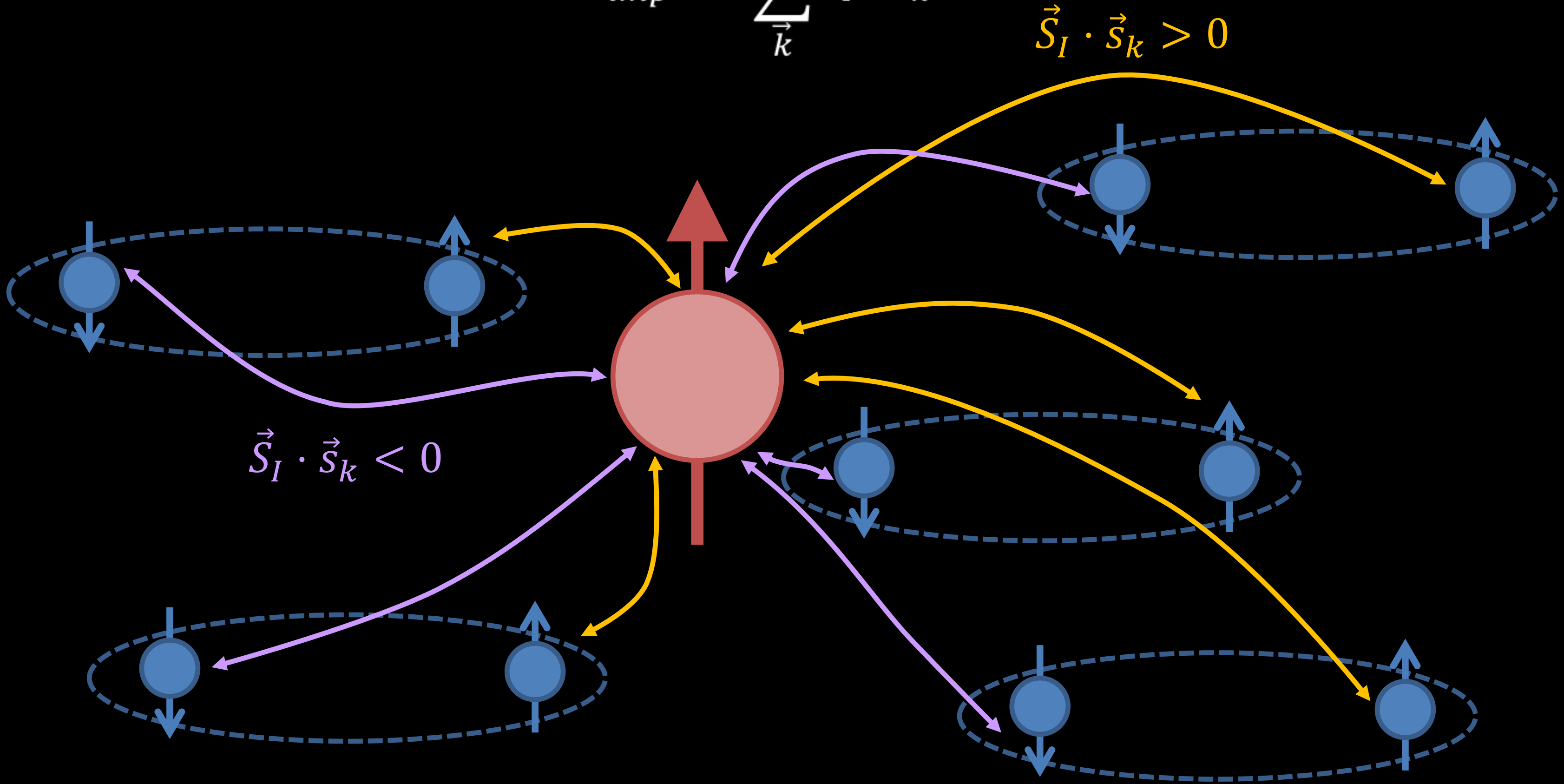
Classical magnetic impurities in a superconductor

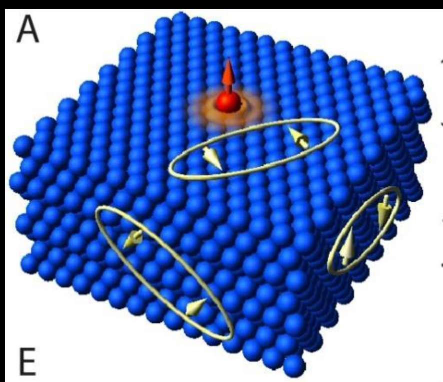
Classical impurity approximation: the impurity behaves as a local magnetic field

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

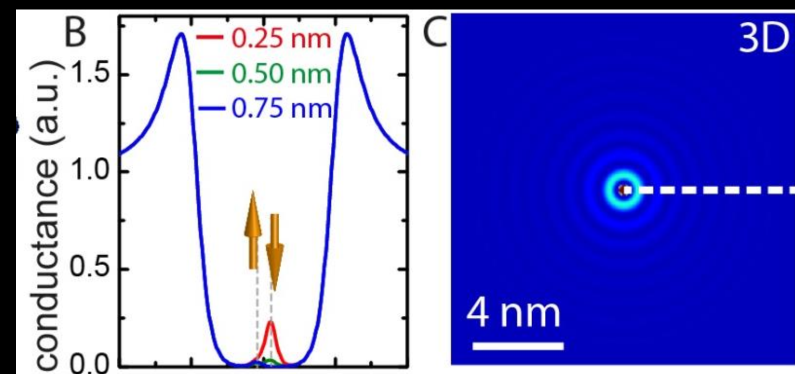


Magnetic impurities: Interaction mechanism

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



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



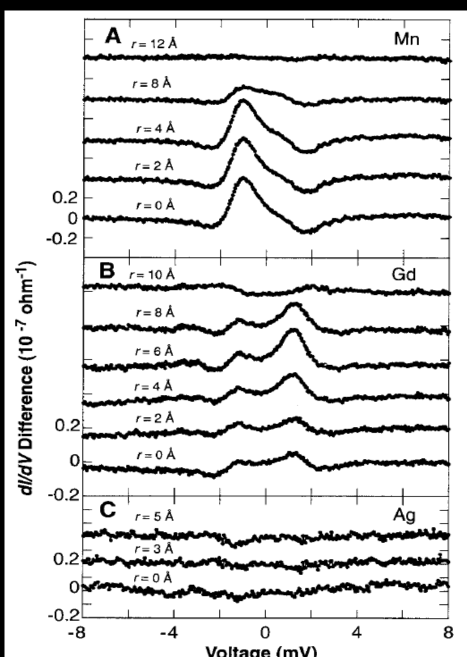
$$\psi_\pm(r) = \frac{1}{\sqrt{N}} \frac{\sin(k_F r + \delta^\pm)}{k_F r} e^{-\Delta \sin(\delta^+ - \delta^-) r / \hbar v_F}$$

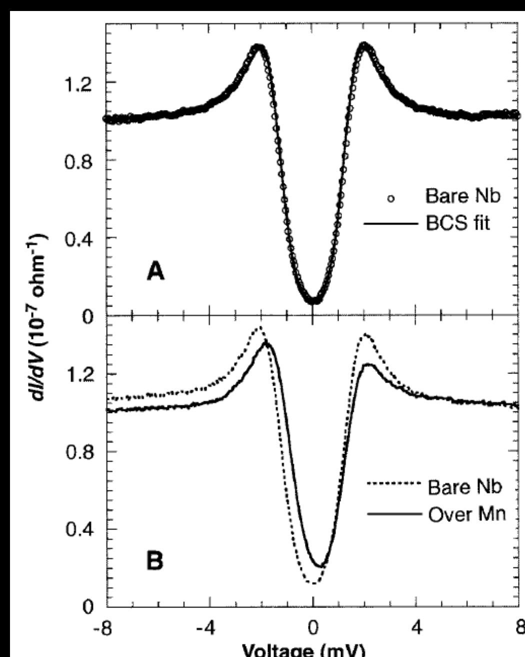
$$E = \Delta \cos(\delta^+ - \delta^-)$$

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

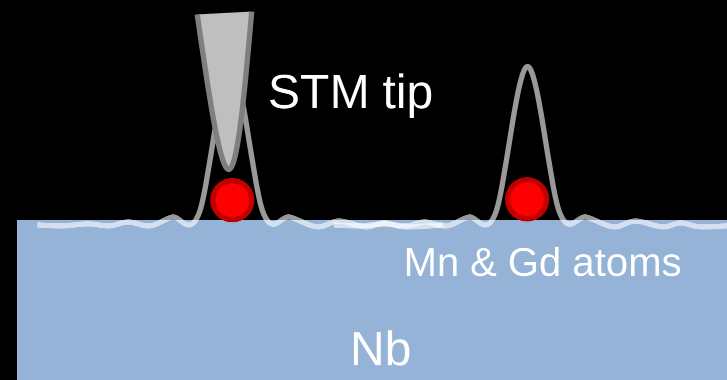
Single magnetic impurities observed by STM

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





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



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

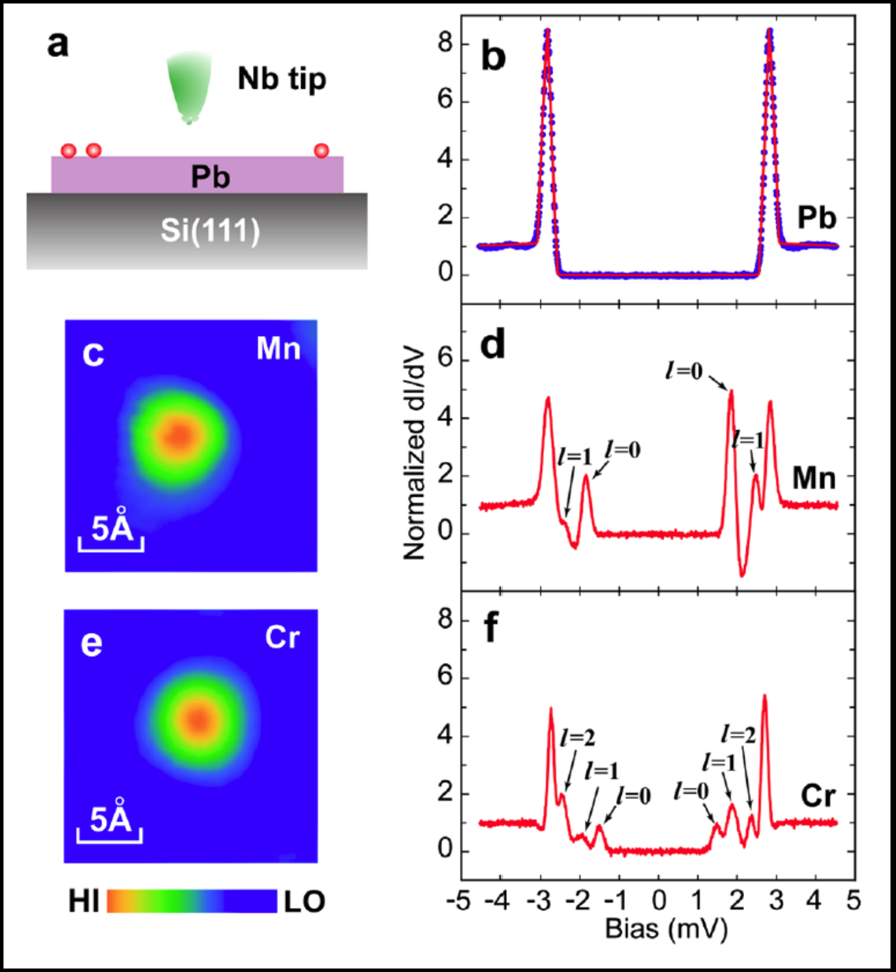
Single magnetic impurities observed by STM
Angular momentum

The number of Shiba peaks depends on the atom nature

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

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

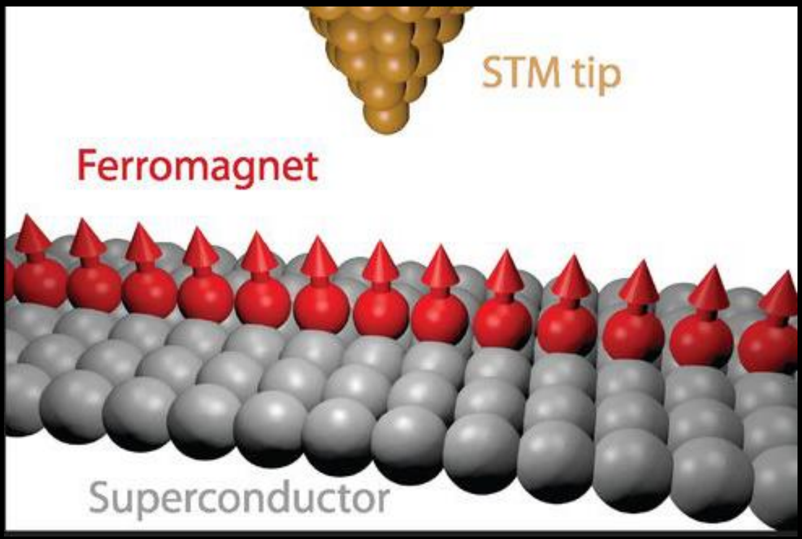
Extremely local effect of the impurities (a few Å)

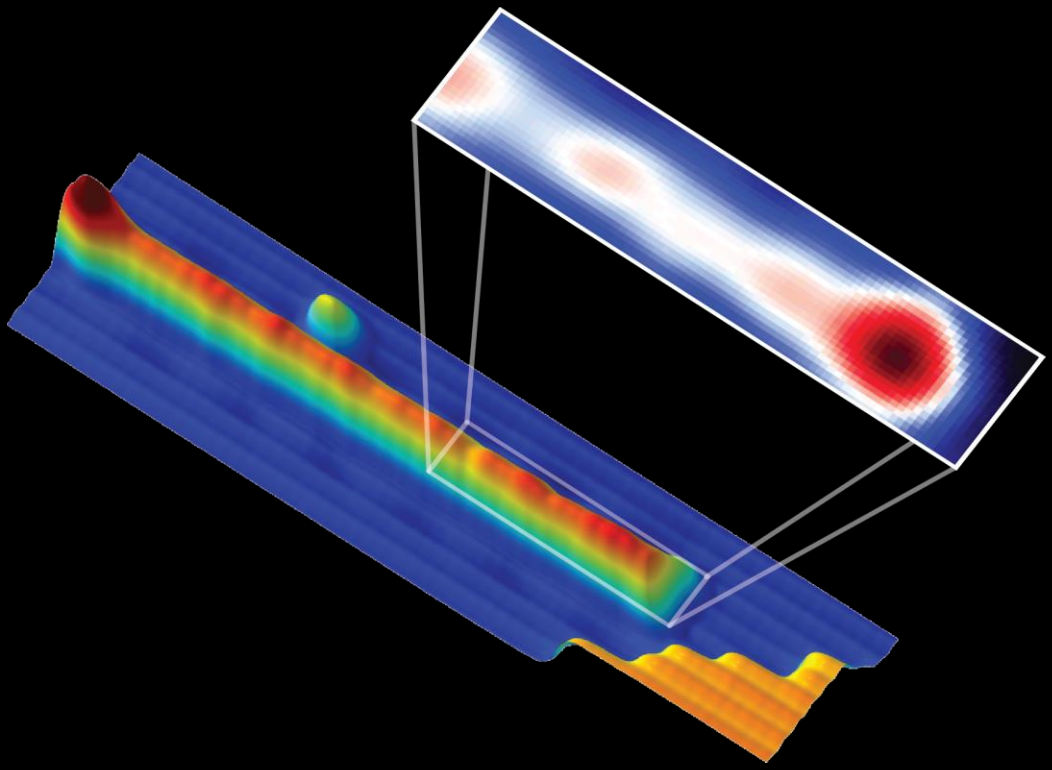


Shuai-Hua Ji et al. *PRL* **100**, 226801 (2008)

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

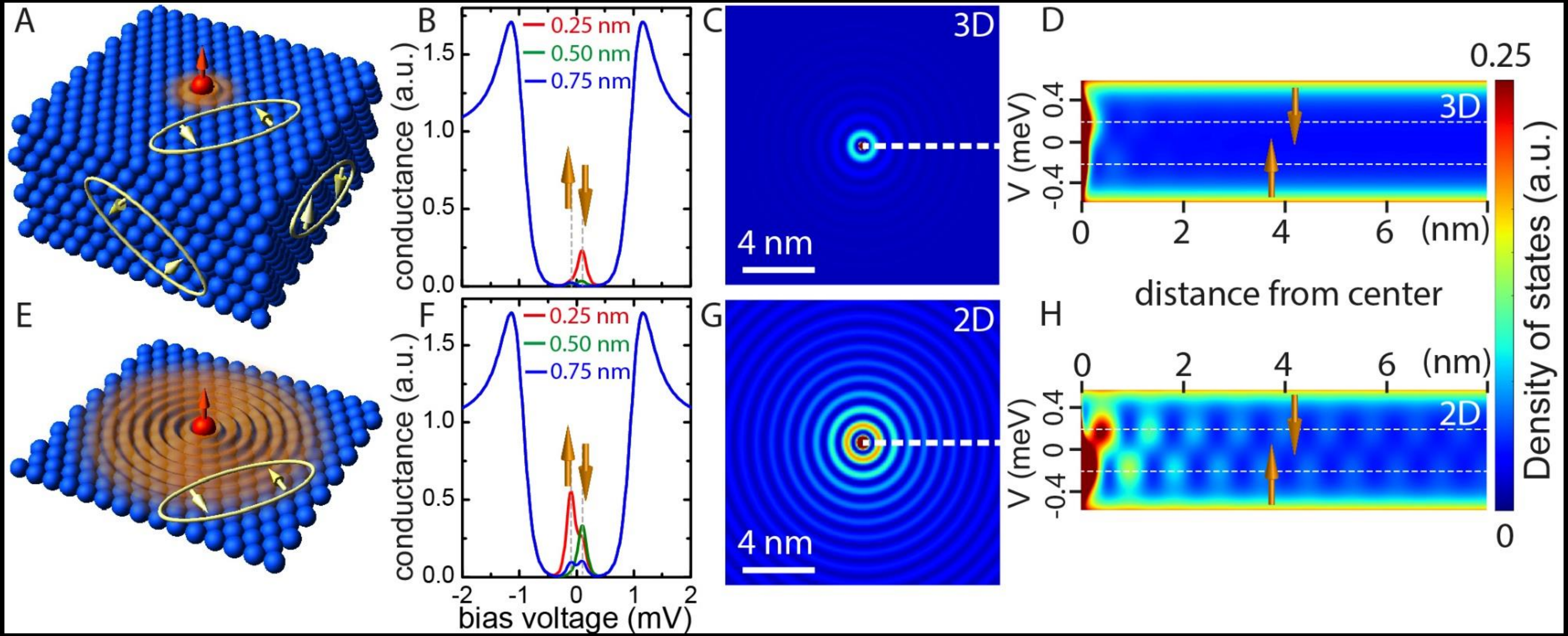
Zero-bias anomaly localized on the last atomes of the Fe chain, almost no extension into the Pb substrate





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

Spatial structure of the Yu-Shiba-Rusinov states
3D vs. 2D materials



At 3D : $1/r^2$ law for amplitude decrease of the density of states

At 2D : $1/r$ law for amplitude decrease of the density of states

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

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

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

Outline

Very large spatial extent of Yu-Shiba-Rusinov bound states in two-dimensionnal superconductors

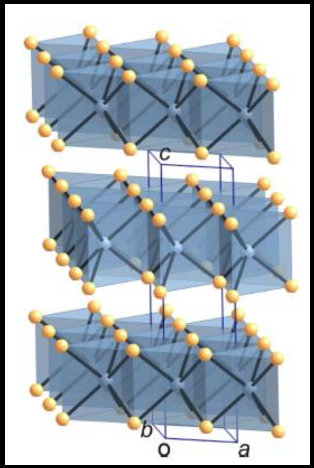
Oscillating electron-hole asymmetry

Star-shape wave-function of Shiba bound states

Two-dimensionnal superconductors

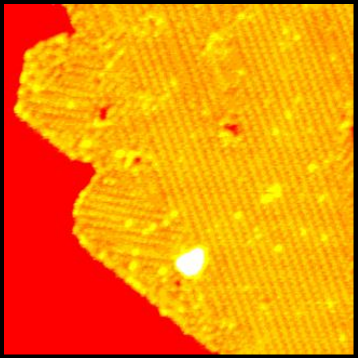
•**Bulk superconductor with 2D electronic structure:**

Lamellar material 2H-$NbSe_2$

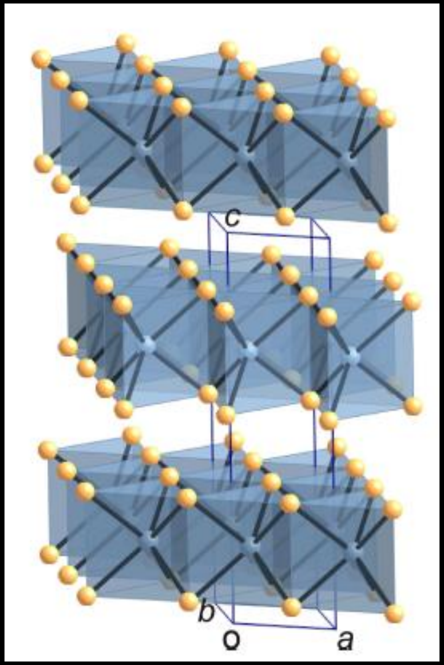


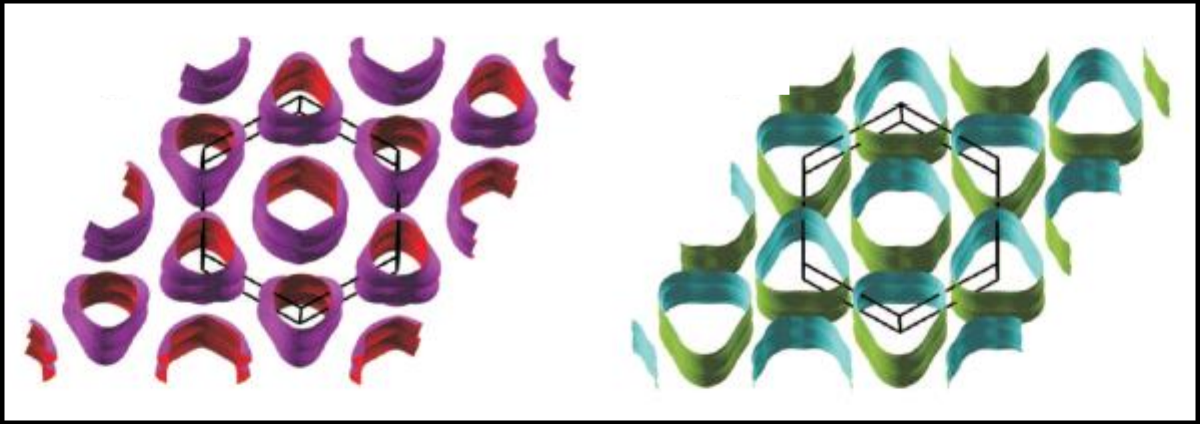
•**Ultimately thin superconductor :**

Single atomic layer of Pb/Si(111)



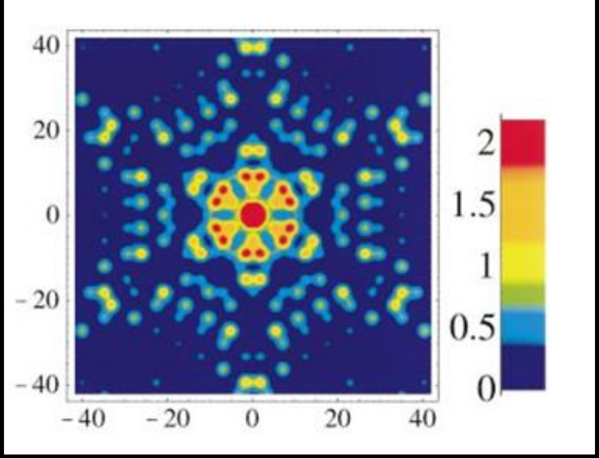
2H-$NbSe_2$ as a two-dimensional superconductor

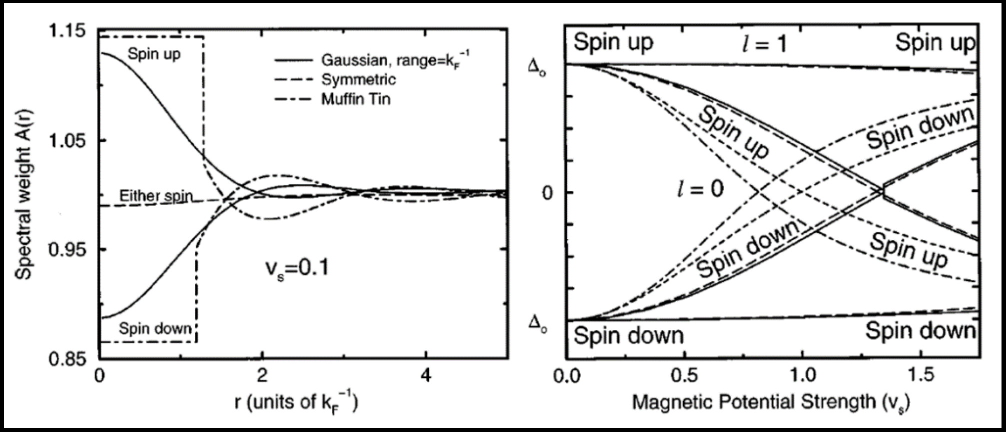




Two-dimensional like bands structure due to the weak Van der Waals interlayer coupling.

Magnetic impurities in 2H-$NbSe_2$
Prediction of a star shape Yu-Shiba-Rusanov bound state

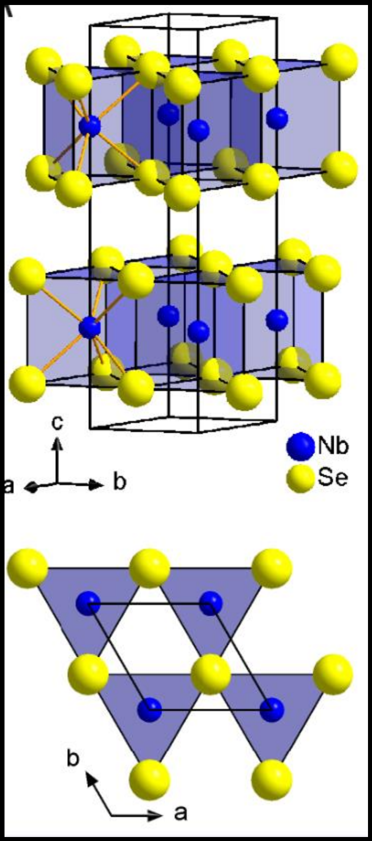


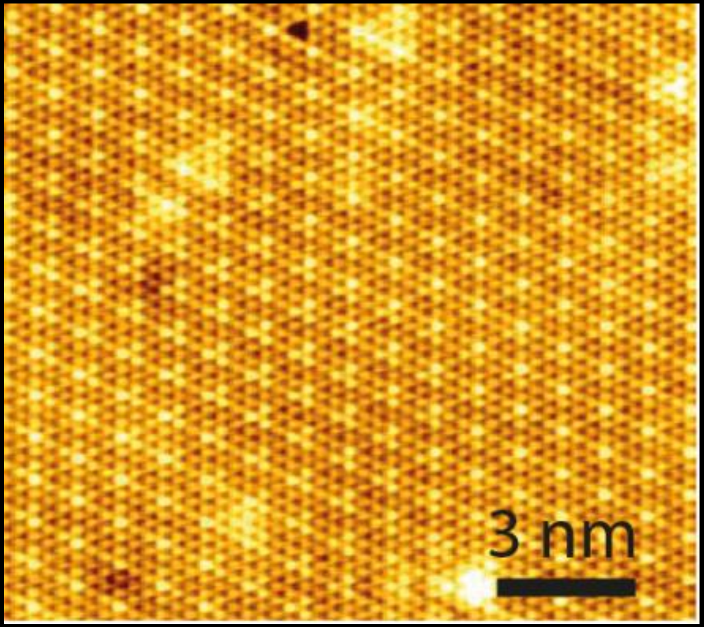


M.E. Flatté and J.M. Byers. *PRL* **78**, 3761 (1997)

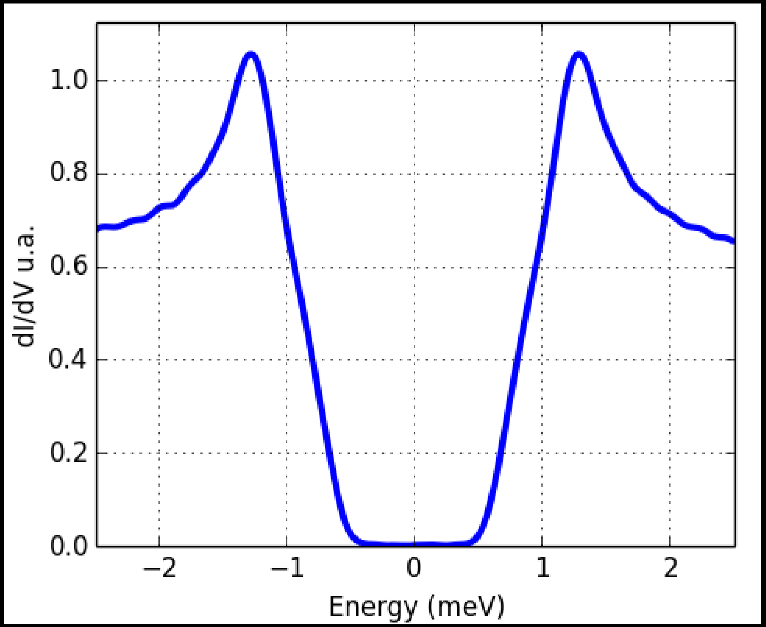
A classical spin in 2H-$NbSe_2$ may give rise to a bound state with a star shaped pattern

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



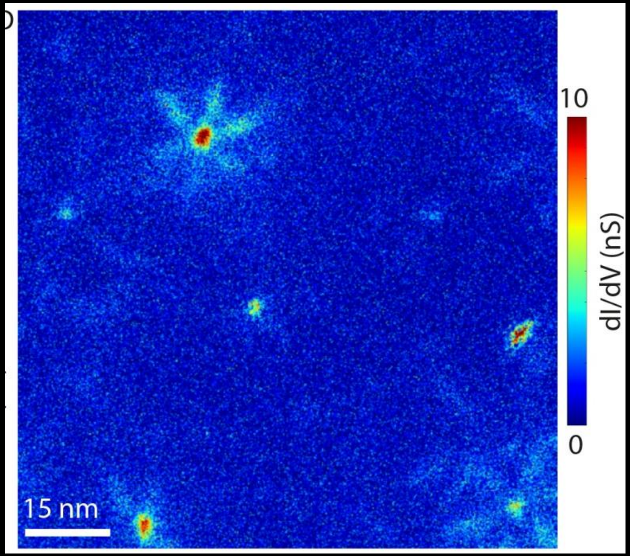


Topography
Atomic lattice and 3x3 CDW



Superconducting gap
measured at 320 mK
(multigap superconductor)

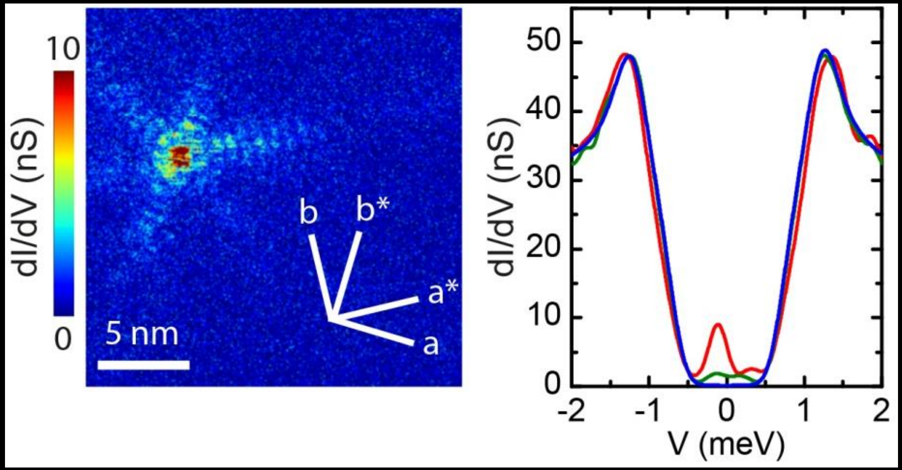
Observation of bound states around magnetic impurities in 2H-$NbSe_2$

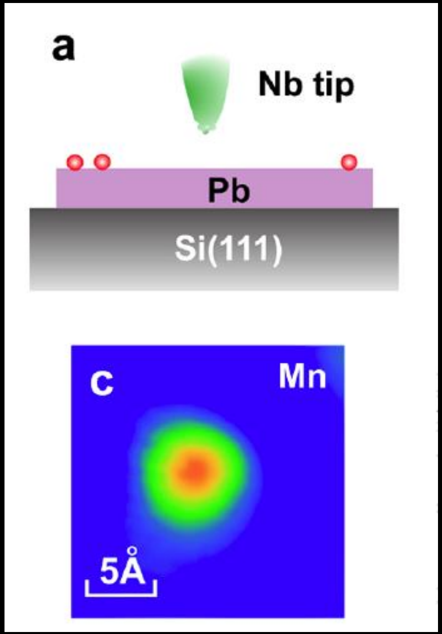


The Nb used for the crystal growth contains magnetic impurities :

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

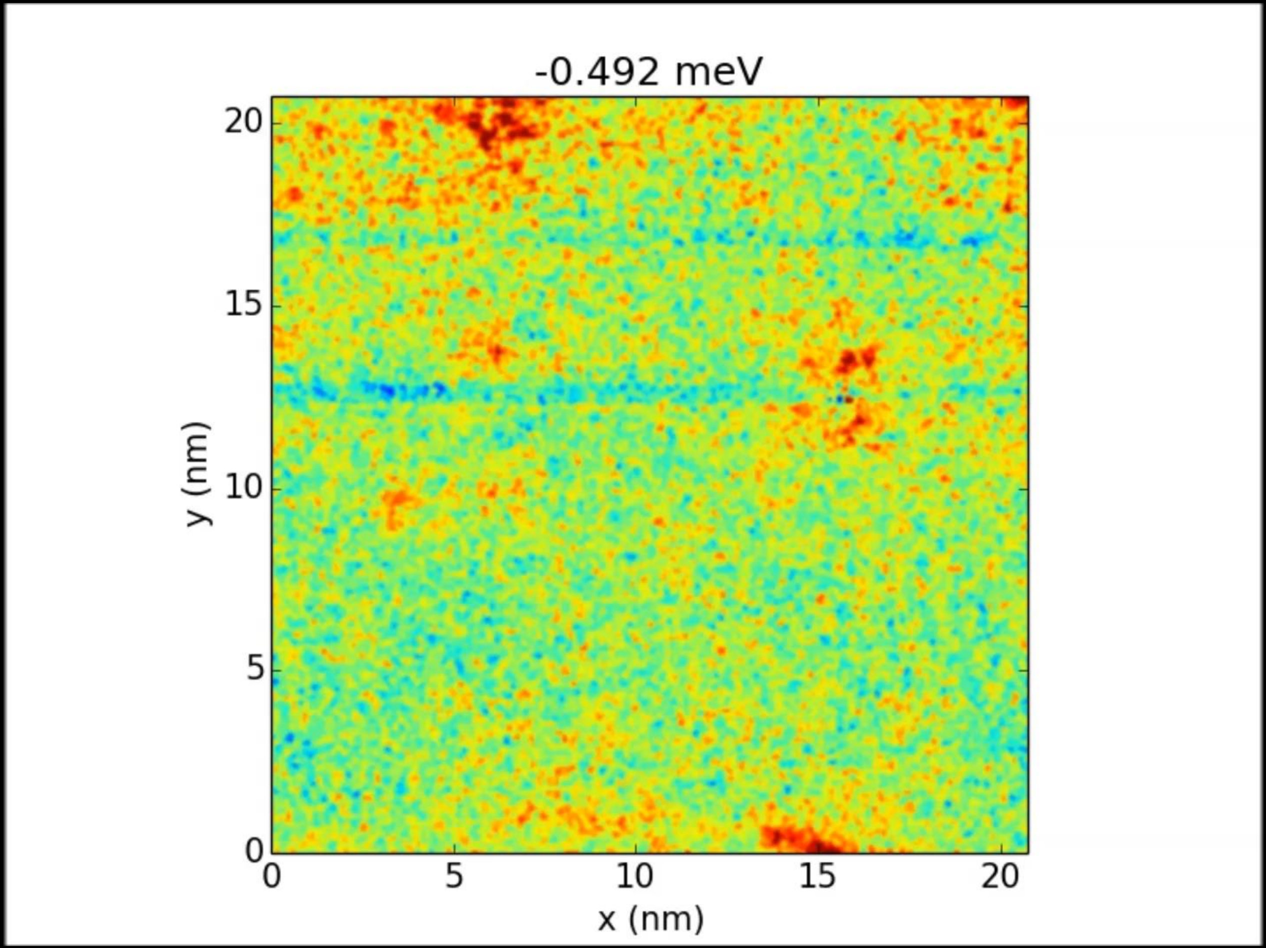
dI/dV maps at -0.13 mV (320 mK)



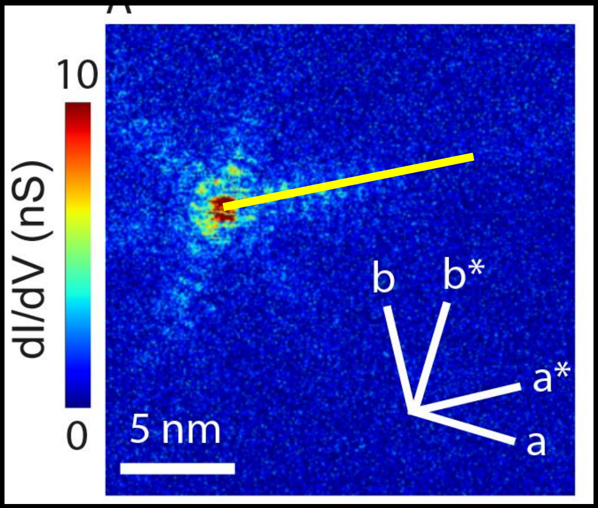


G. Ménard et al. arXiv:1506.06666, accepted Nature Physics (2015)

Observation of bound states around magnetic impurities in $2H\text{-}NbSe_2$

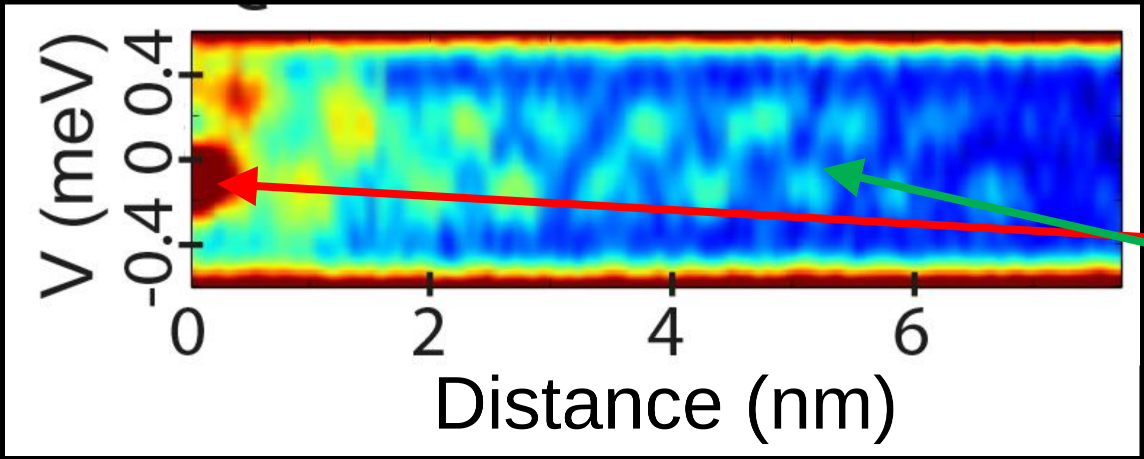


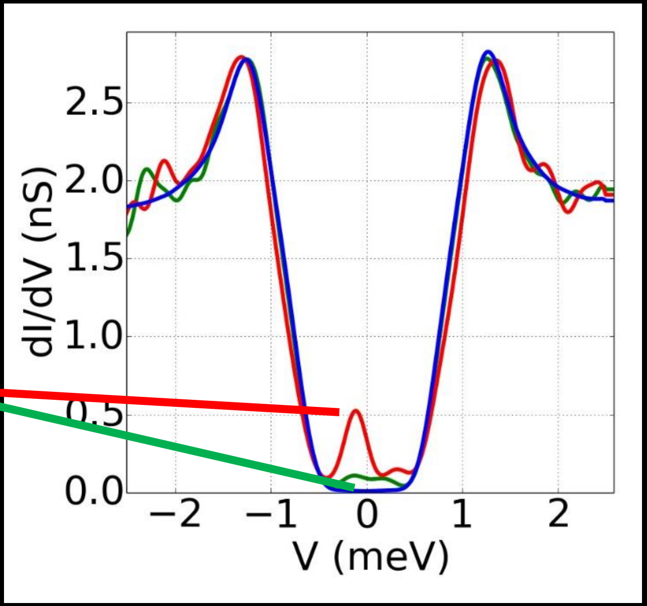
Spatial oscillation of Shiba bound states
Electron-hole asymmetry



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

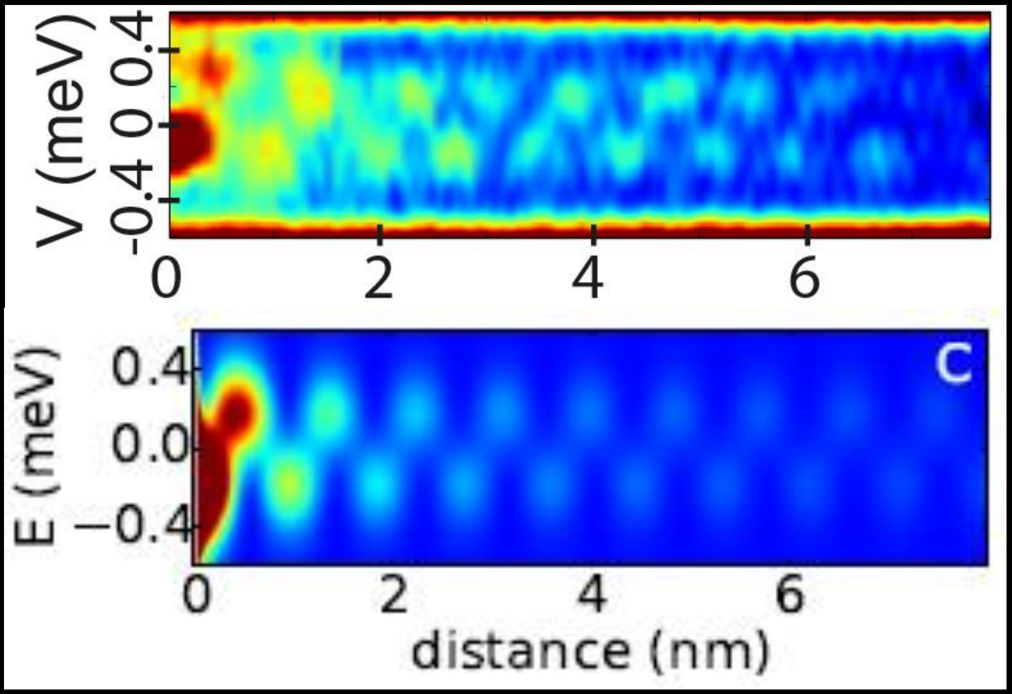
•Decrease of the Shiba bound states on a size of the order of the coherence length ξ





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

Spatial oscillations and electron-hole asymmetry



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

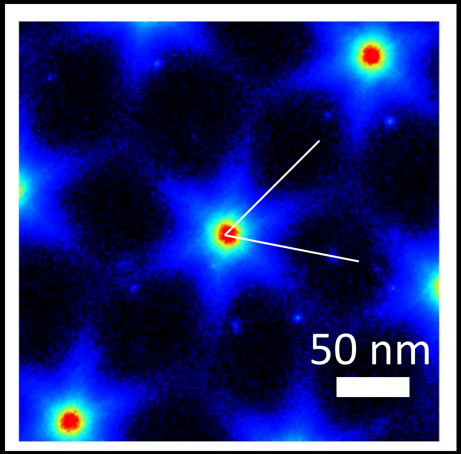
$$\psi_{\pm}(r) = \frac{1}{\sqrt{N\pi k_F r}} \sin\left(k_F r - \frac{\pi}{4} + \delta^{\pm}\right) e^{-\Delta \sin(\delta^+ - \delta^-) r/\hbar v_F}$$

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

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

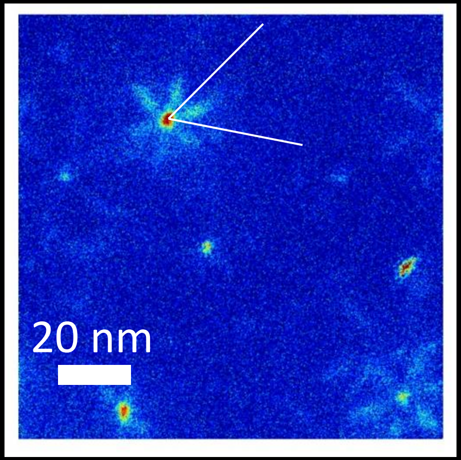
The Shiba peaks **position relatively to the gap** is directly related to the phase shift.

Six fold symmetry of the Shiba bound states



H = 100mT

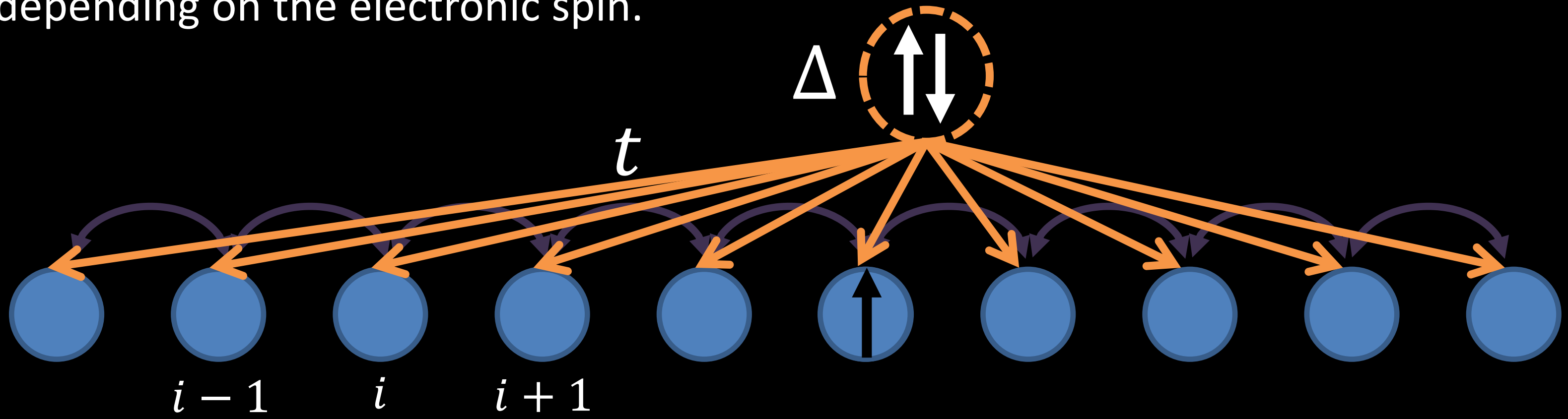
In $NbSe_2$ the star shape vortex cores are rotated 30° from the atomic lattice



The star shape structures of the magnetic bound states has the same orientation as the bound states in the vortex cores.

Theoretical model: Bogoliubov de Gennes

The magnetic interaction is modelled by an on-site energy term with a sign depending on the electronic spin.

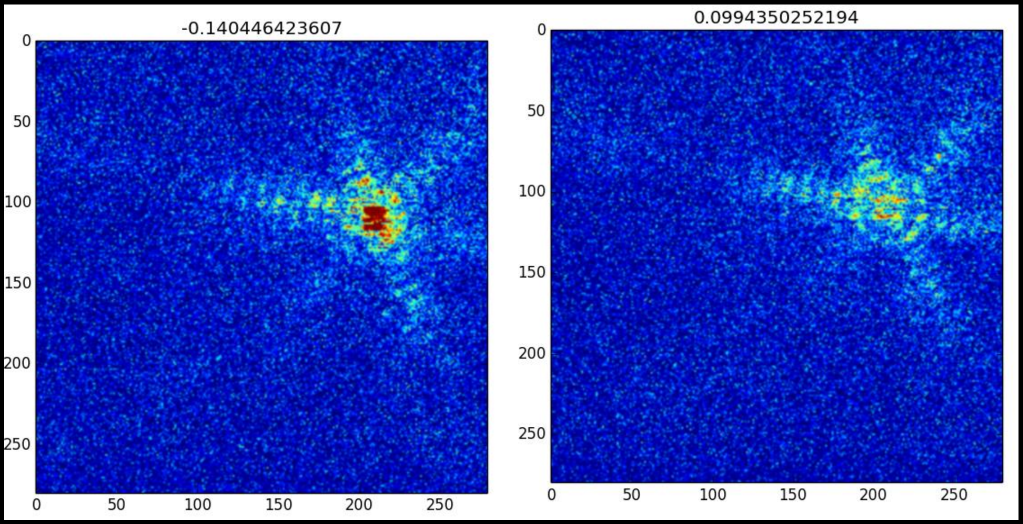


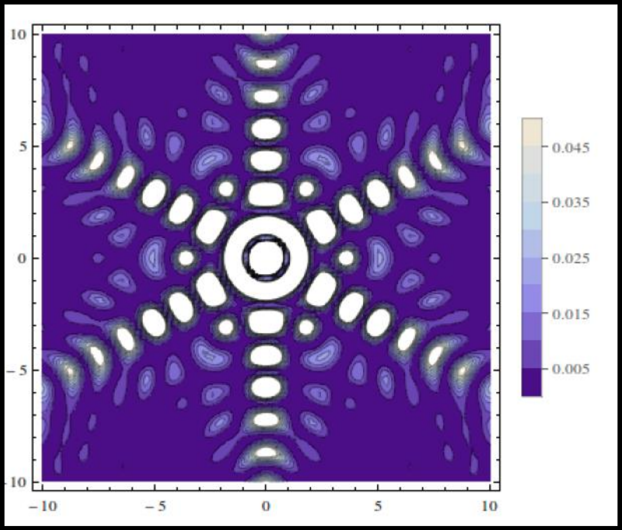
Hamiltonian expressed in the spinor basis $\psi = \begin{pmatrix} \psi_\uparrow^\dagger \\ \psi_\downarrow \\ \psi_\downarrow^\dagger \\ \psi_\uparrow \end{pmatrix}$

$$H_{BdG} = \sum_k \xi_k\left(\hat{c}_{k\uparrow}^\dagger \hat{c}_{k\uparrow} + \hat{c}_{k\downarrow}^\dagger \hat{c}_{k\downarrow}\right) + \Delta\left(\hat{c}_{k\uparrow}^\dagger \hat{c}_{k\downarrow}^\dagger + \hat{c}_{k\downarrow} \hat{c}_{k\uparrow}\right)$$

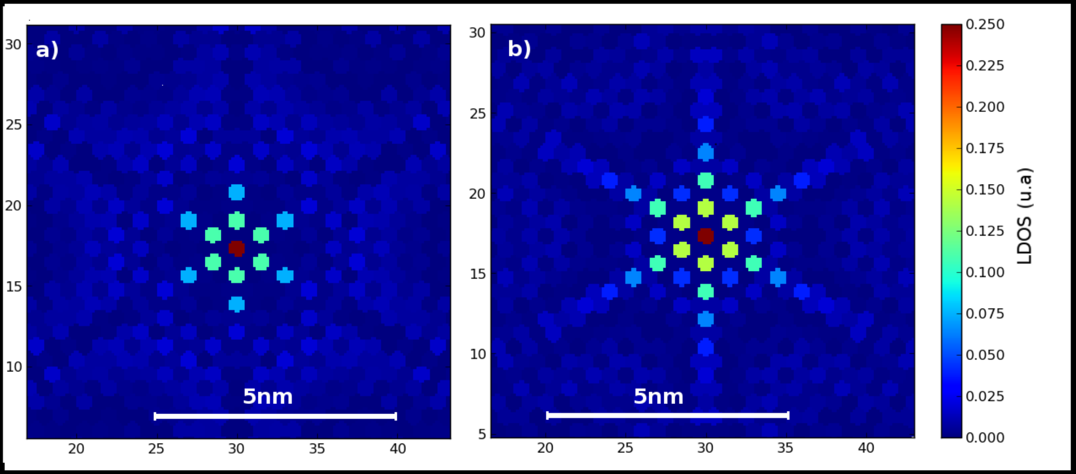
$$H_{imp} = -\frac{JS}{2}\left(\hat{c}_{0\uparrow}^\dagger \hat{c}_{0\uparrow} - \hat{c}_{0\downarrow}^\dagger \hat{c}_{0\downarrow}\right) + K\left(\hat{c}_{0\uparrow}^\dagger \hat{c}_{0\uparrow} + \hat{c}_{0\downarrow}^\dagger \hat{c}_{0\downarrow}\right)$$

Theoretical model: Bogoliubov de Gennes



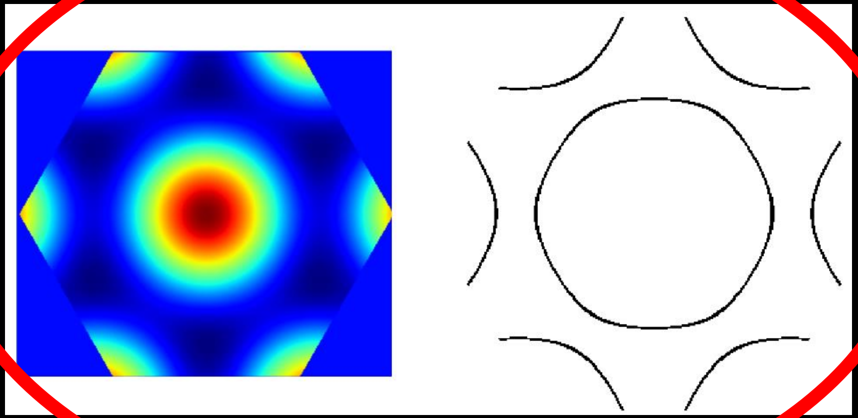


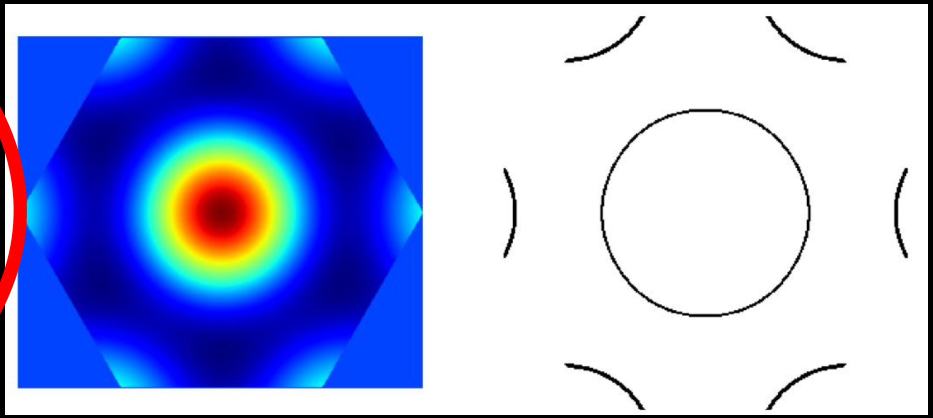
Continuous asymptotic model



Ongoing calculations using Wannier functions

Six fold symmetry of the Bound states

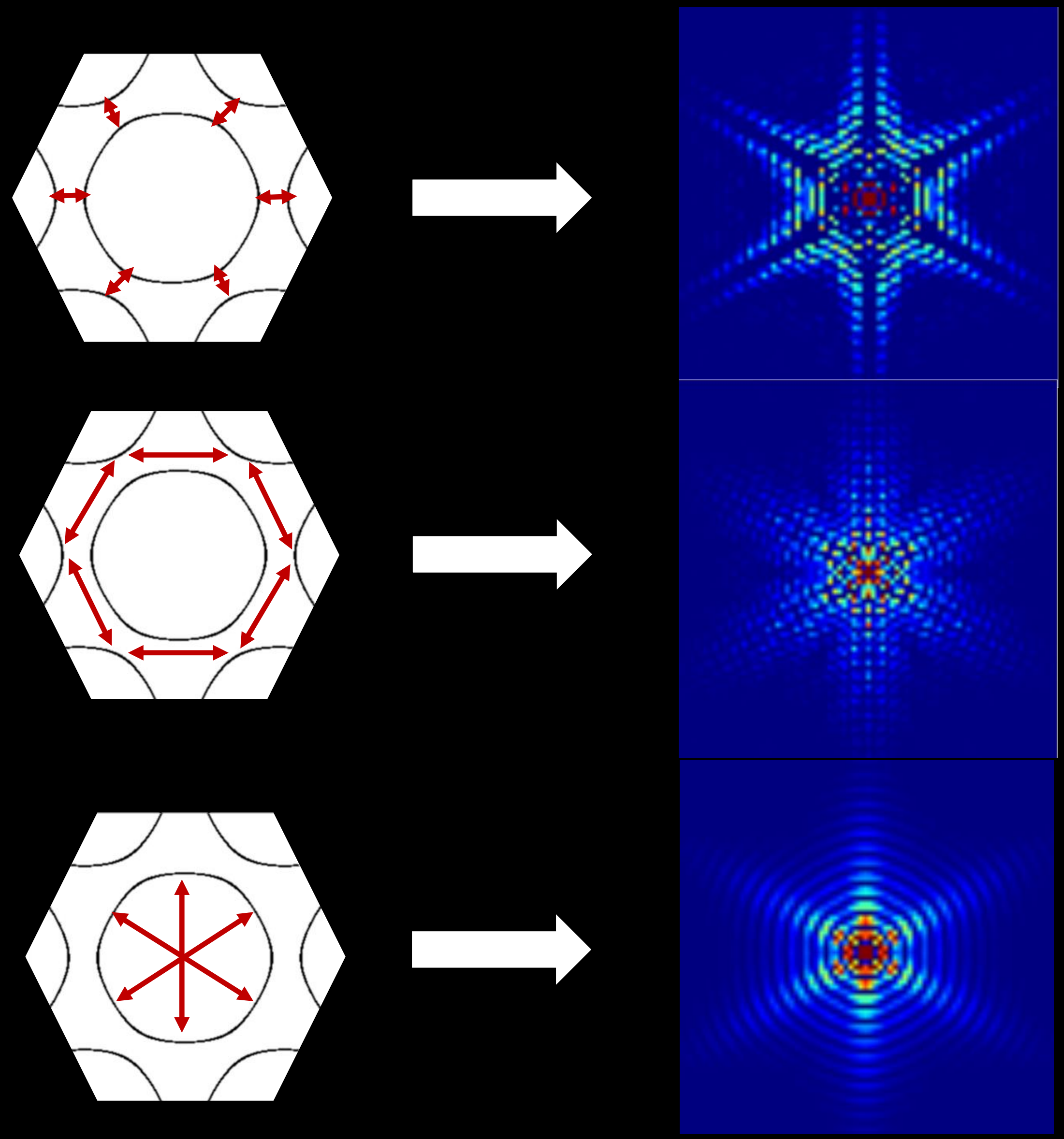




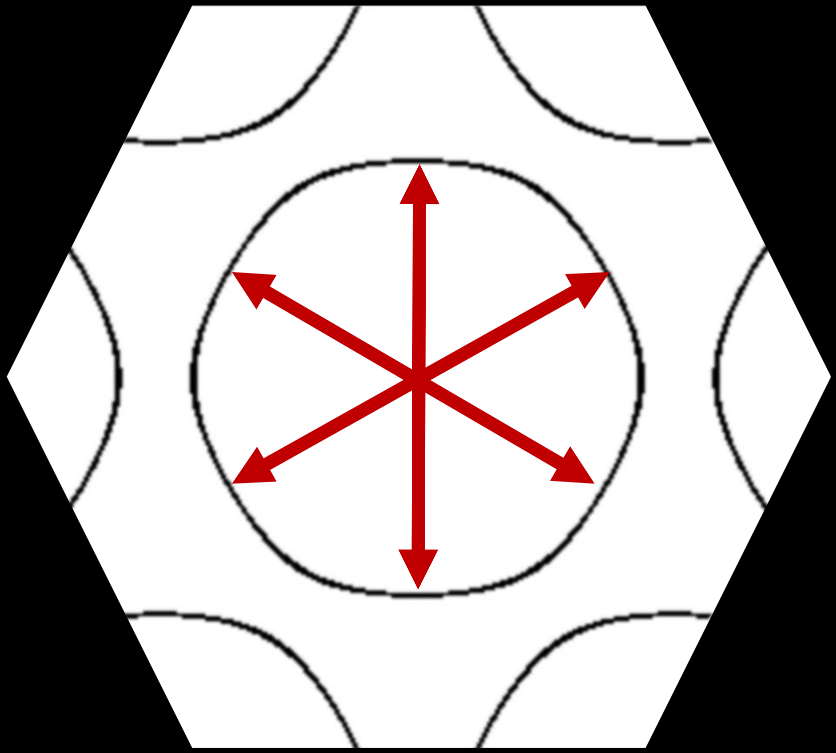
- Band structure from tight binding model (fit from ARPES data)
- No inter-plan interactions

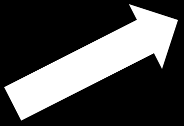
$$H_{BdG} = \sum_{\langle i,j \rangle} t_{ij}\left(\hat{c}_{i\uparrow}^{\dagger}\hat{c}_{j\uparrow} + \hat{c}_{i\downarrow}^{\dagger}\hat{c}_{j\downarrow}\right) + \sum_{i} \Delta\left(\hat{c}_{i\uparrow}^{\dagger}\hat{c}_{i\downarrow}^{\dagger} + \hat{c}_{i\downarrow}\hat{c}_{i\uparrow}\right)$$

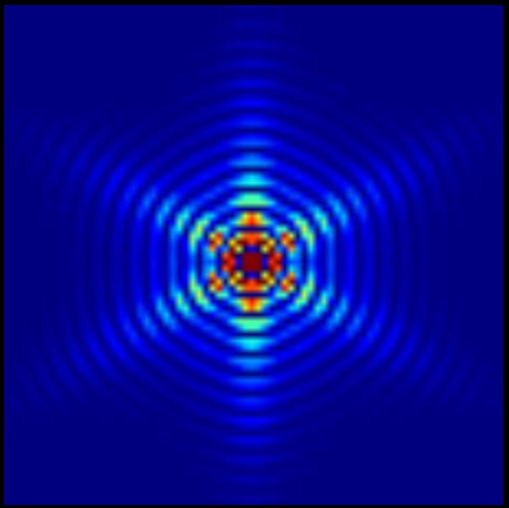
Comparison with joint-DOS calculations



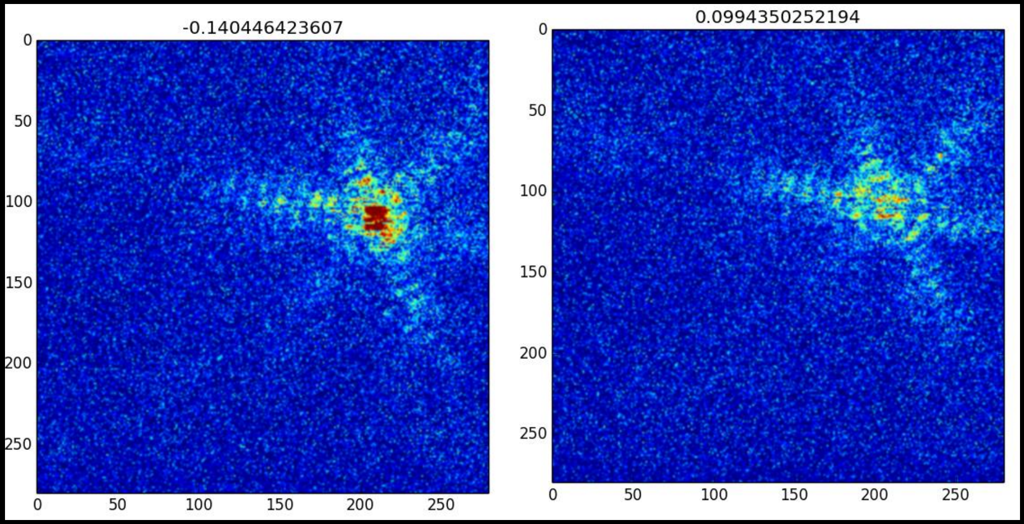
Comparison with joint-DOS calculations







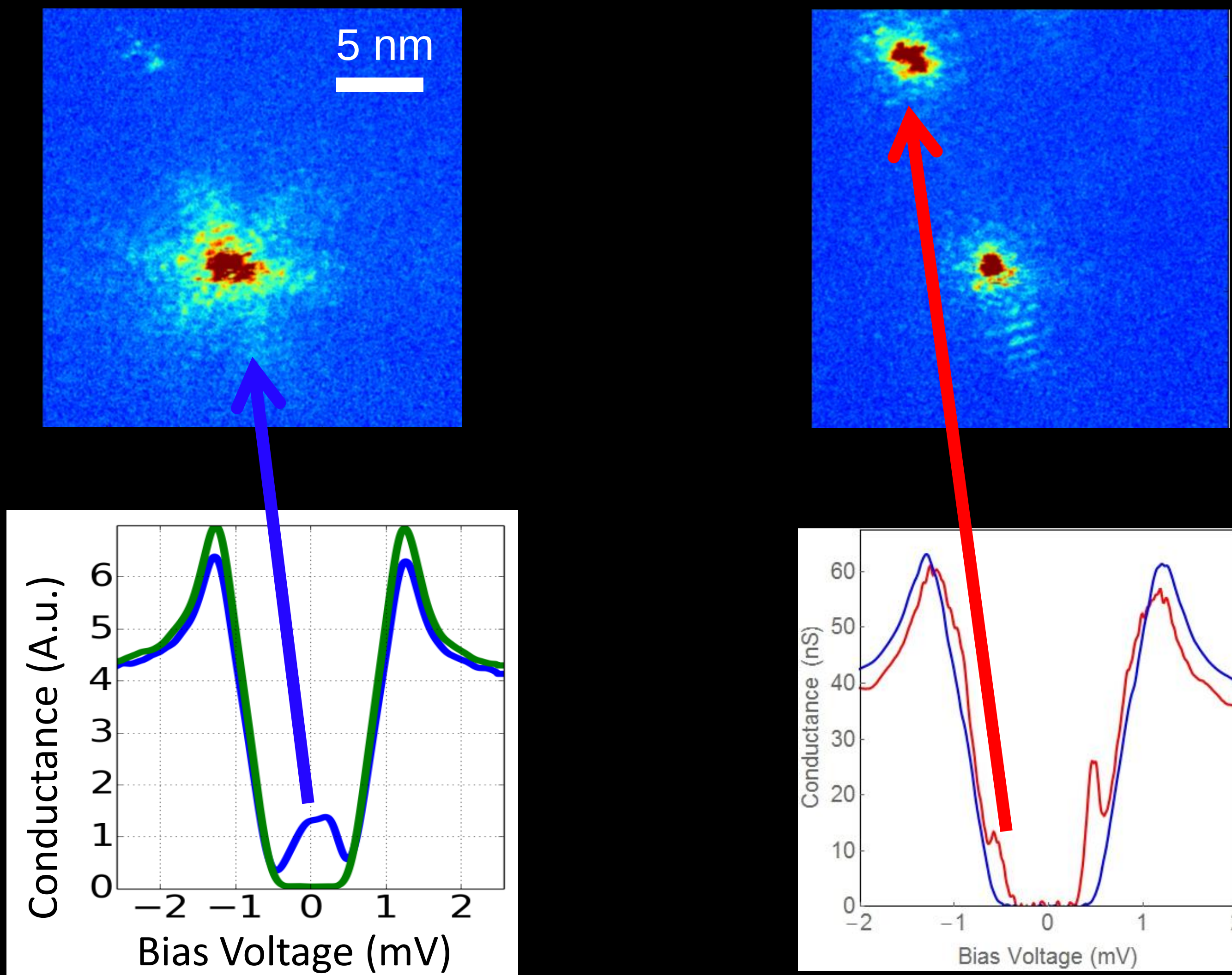
Joint DOS calculation indicate that the relevant part of the Fermi surface is the inner pocket.



Two different impurities

-0,12 meV

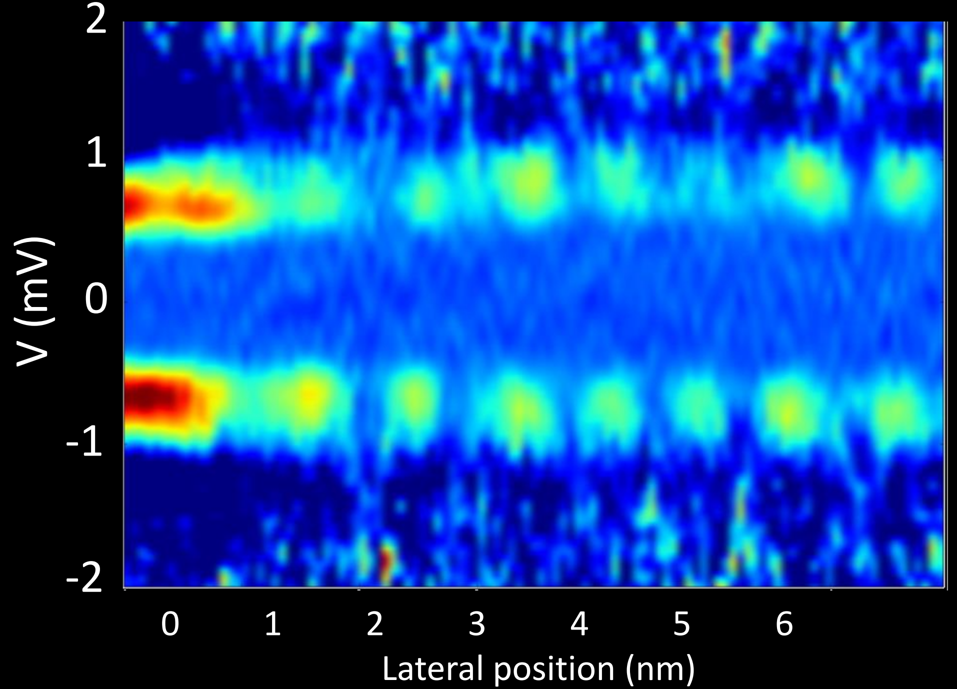
-0,34 meV

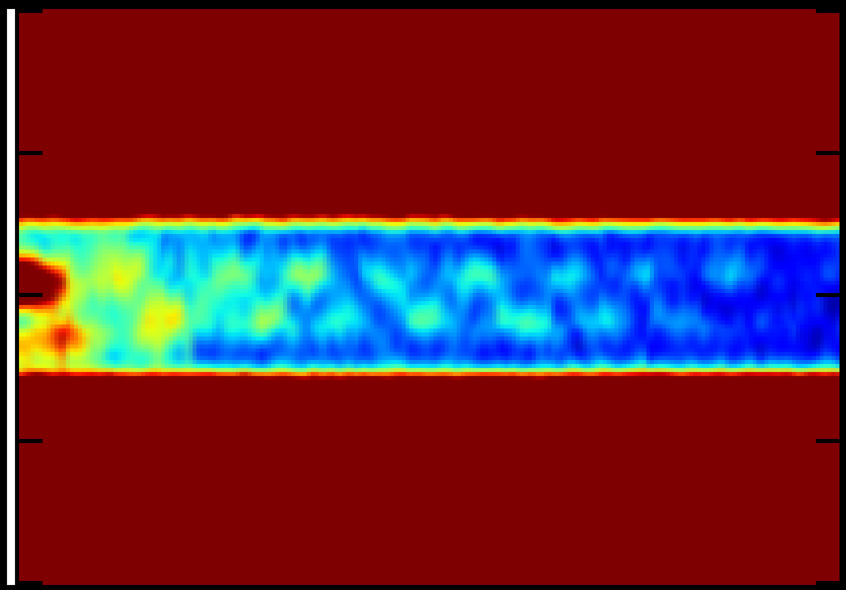


Cr?

Mn?

Impurity with bound states at gap edge: in phase electron-hole oscillations





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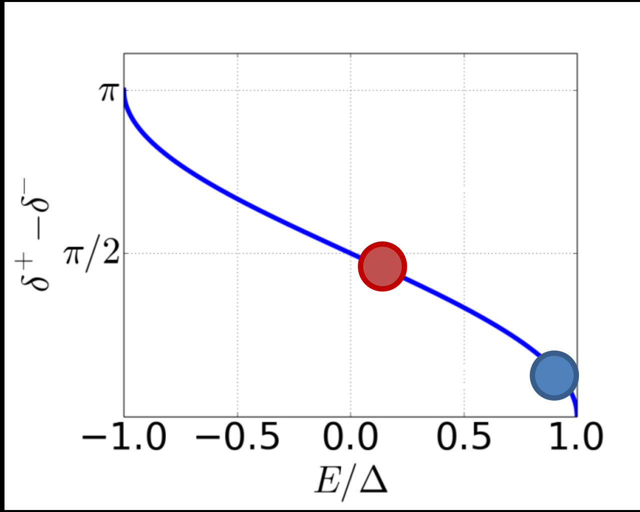
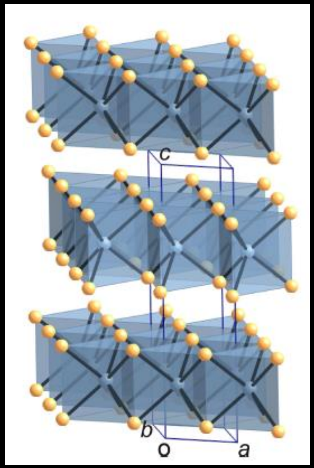


Two-dimensionnal superconductors

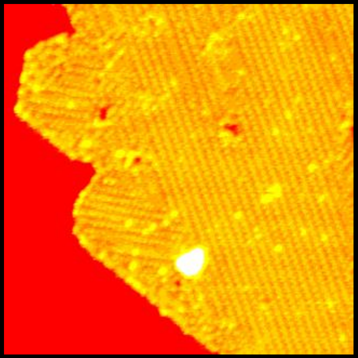
- Bulk superconductor with 2D electronic structure:

  Lamellar material 2H-$NbSe_2$



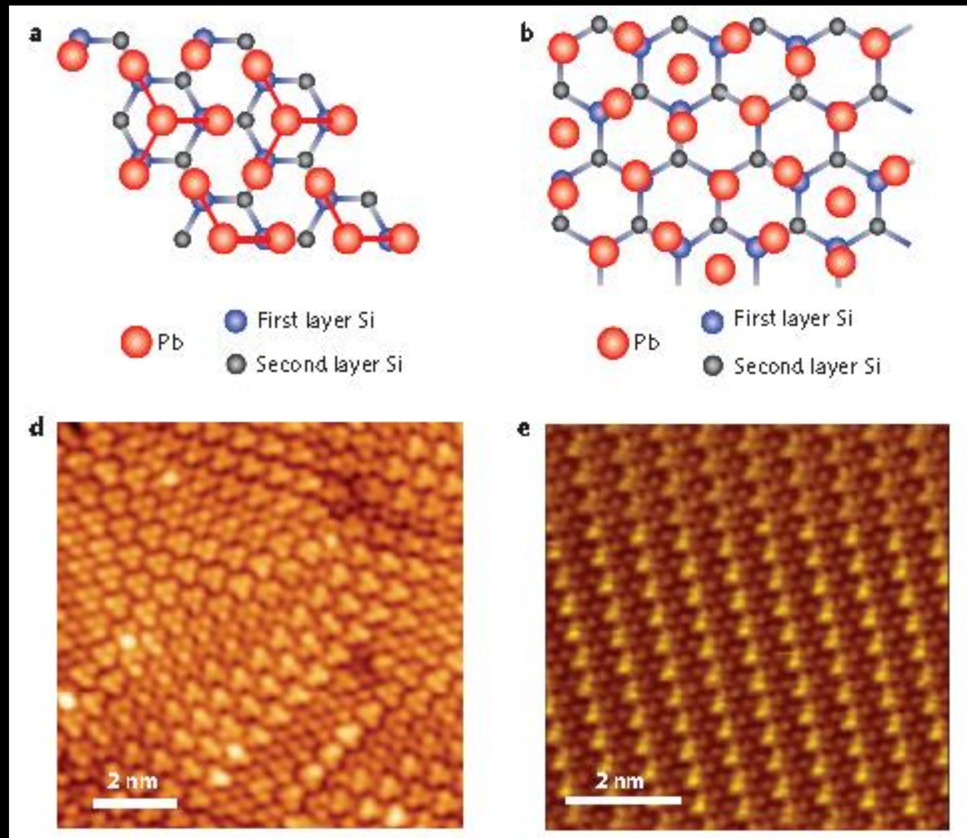
- Ultimately thin superconductor :

  Single atomic layer of Pb/Si(111)



Superconductivity in a monolayer of Pb/Si(111)

S. Zhang et al. Nature Physics 6, 104 (2010)

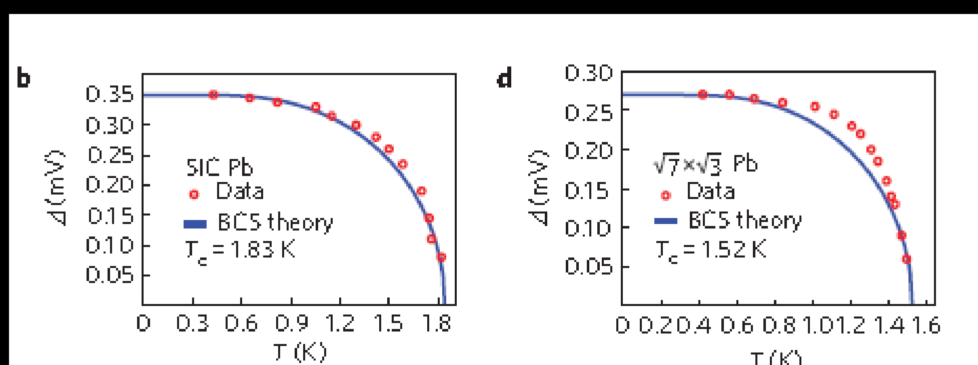


Striped-incommensurate Pb/Si(111)

1.33 monolayer

√7 × √3 reconstruction of Pb/Si(111)

1.20 monolayer

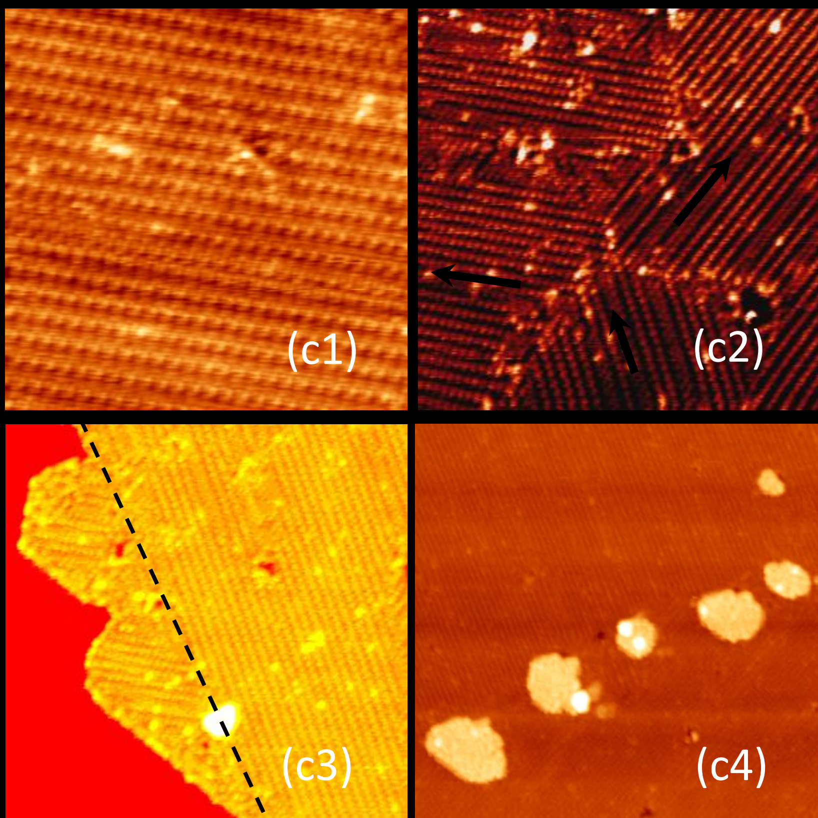


In situ transport
R <~ 1kΩ

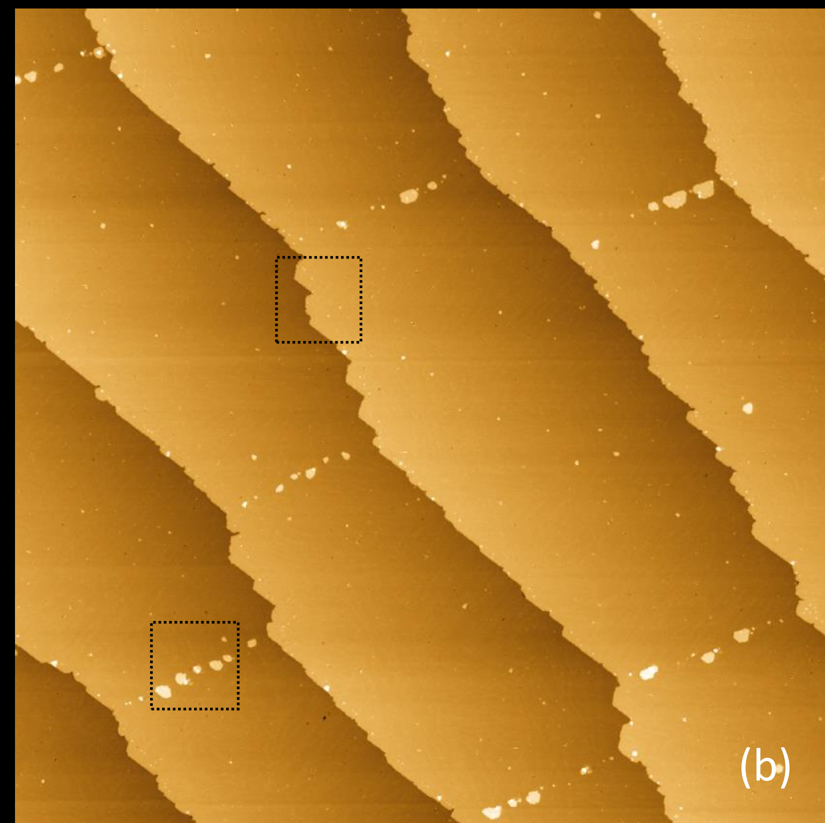
Electron Confinement in one Pb monolayer

1ML √7x √3 Pb on Si(111)

Characteristic atomic defects



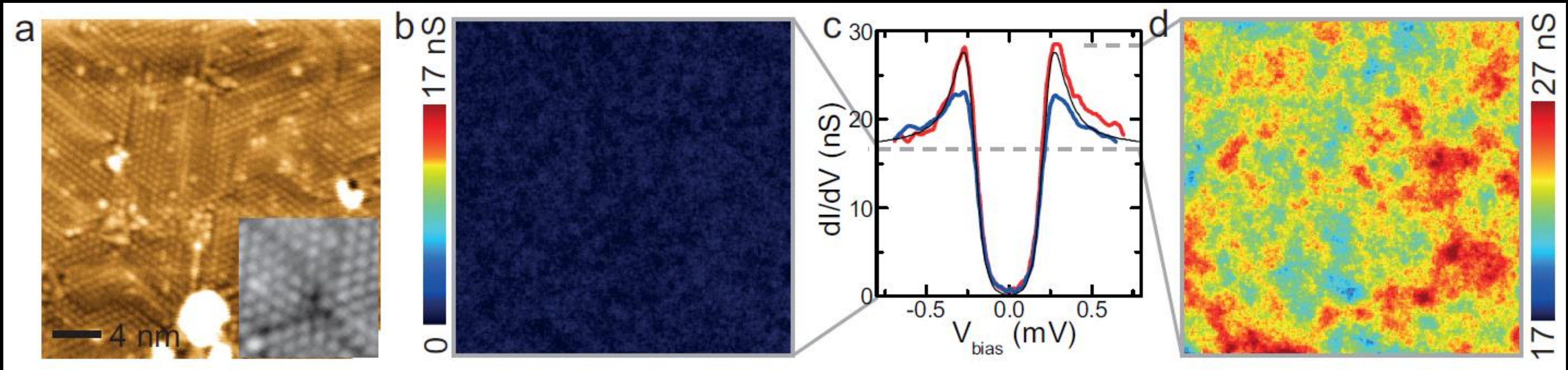
√7x √3 Pb / Si(111)



600x600 nm^2

Superconductivity vs Disorder in 1ML of Pb on Si(111)

Striped-Incommensurate Pb/Si(111) 1.33 monolayer



Topography

Spectroscopic map at the Fermi level

Conductance spectra

Peak height map

Fluctuation of the coherence peaks height on

ℓ_{fluct}=5 nm < < ξ_{eff} ~ 50nm

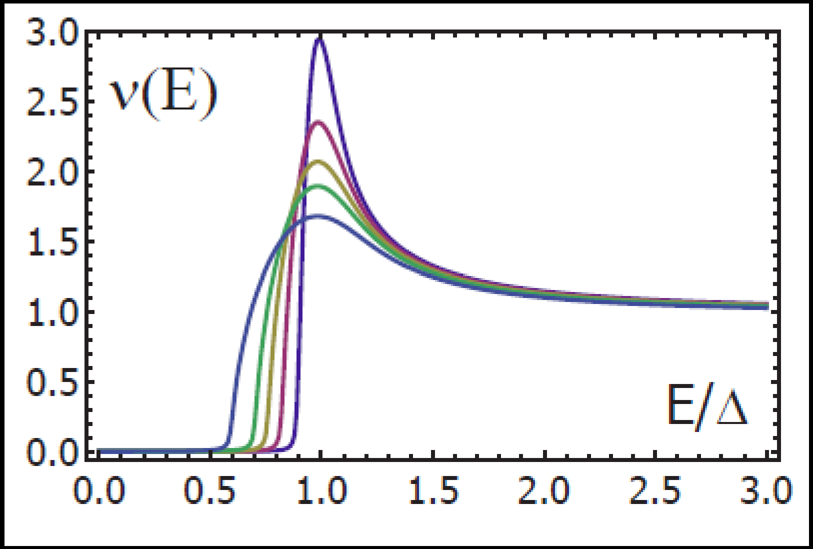
C. Brun et al. Nat. Phys. 10, 444 (2014)

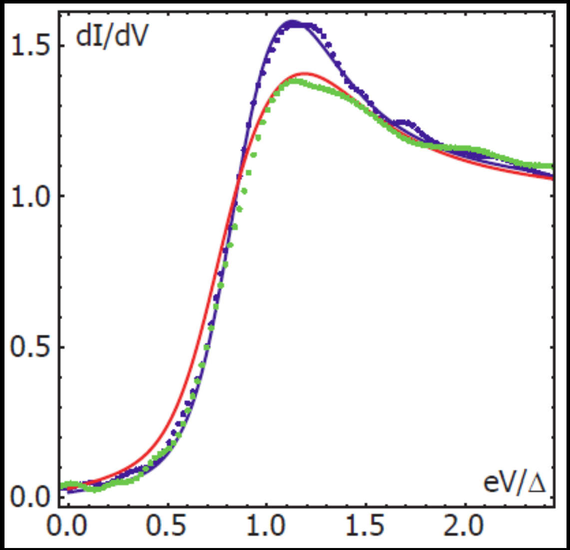
Fluctuation of the coherence peaks height

$$\ell_{fluct} = 5 \text{ nm} << \xi_{eff} \sim 50\text{nm}$$
$$\ell \sim 4 \text{ nm}, \ k_F\ell > 10\text{-}20$$

According to Lev Ioffe & Boris Altshuler:

Non BCS corrections due to the low dimensionnality and small mean free path (Real contact interaction instead of BCS reduced hamiltonian)
Indication of a possible BEC –BCS crossover



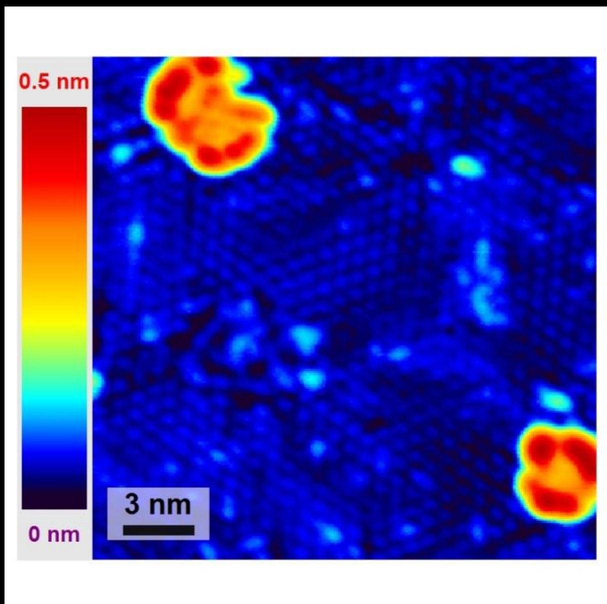


C. Brun et al. Nat. Phys. 10, 444 (2014)

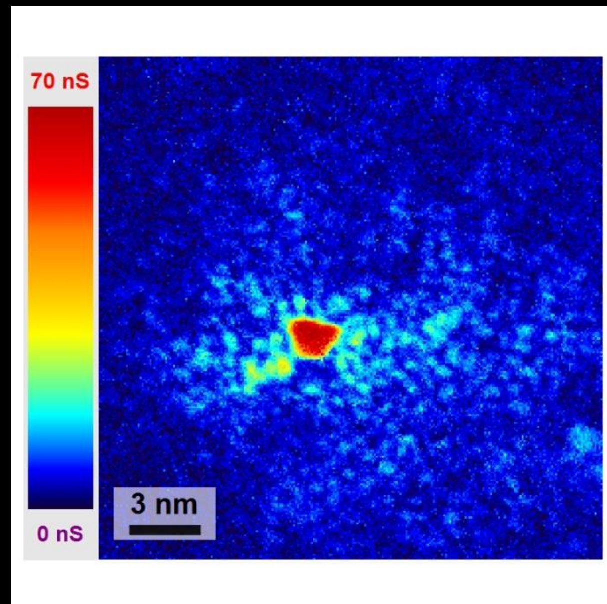
$G/G_Q \sim 30\text{-}100$

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

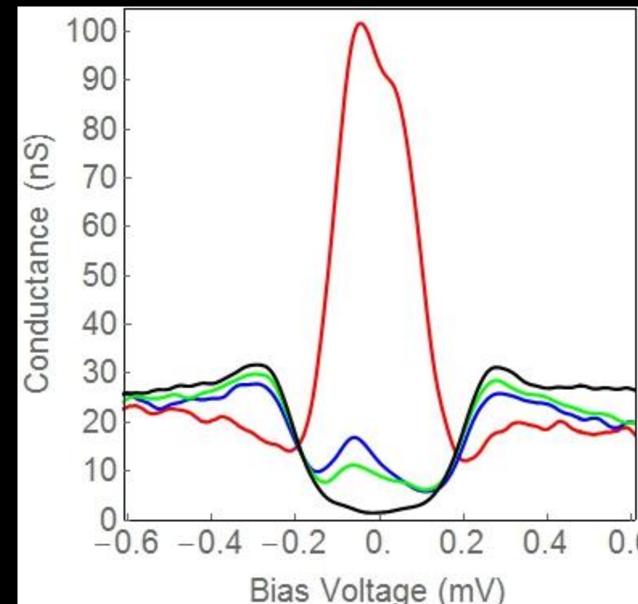
Striped-Incommensurate Pb/Si(111), 1.33 monolayer



Topography



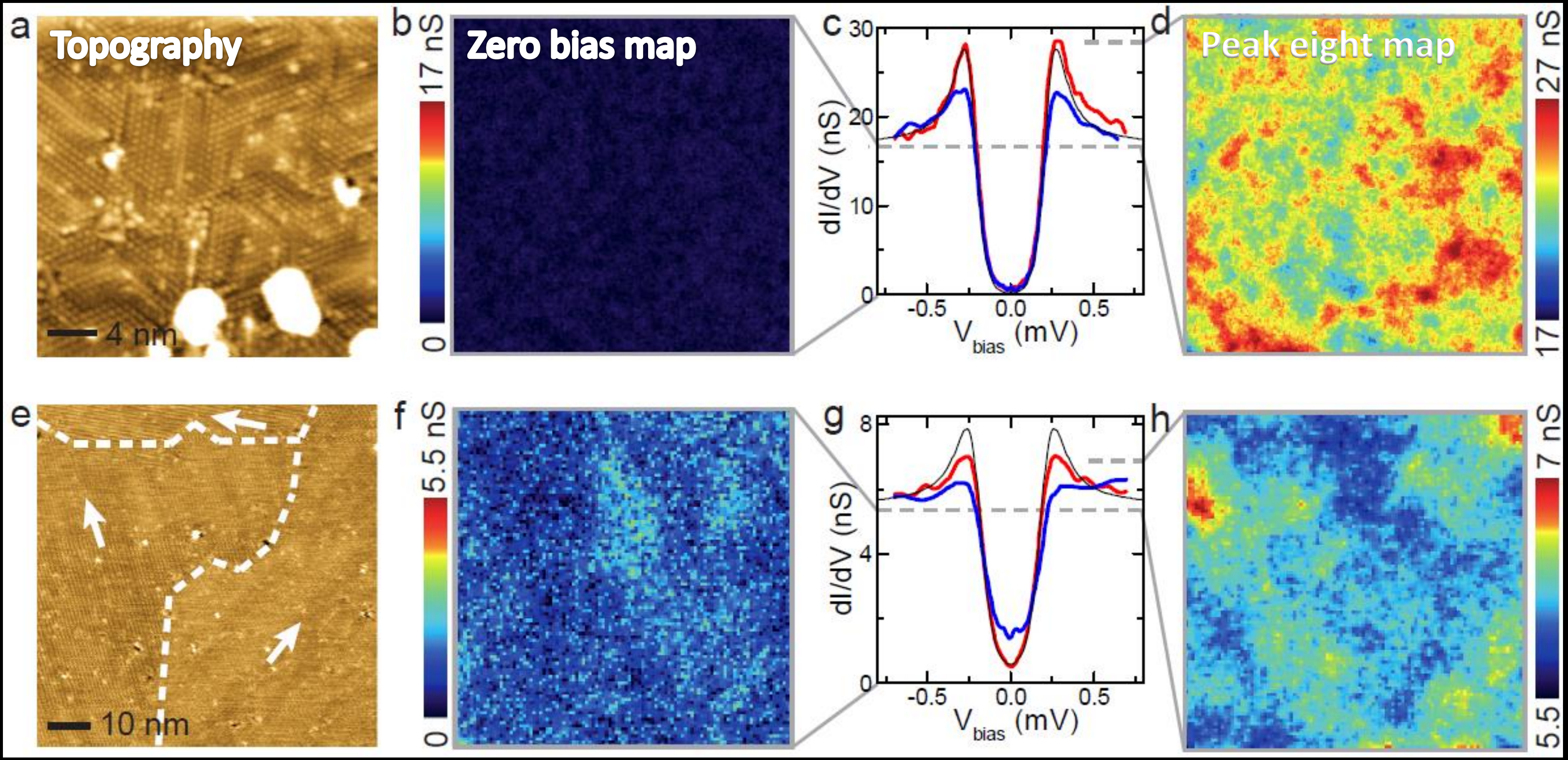
Conductance map at 0 mV



Conductance spectra on top (red), at 5 nm (blue), 10 nm (green) and far from the impurity (black)

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)

Gap filling and fluctuations of zero bias conductance in Pb$\sqrt{7}$x $\sqrt{3}$

- Strong spin-orbit coupling in Pb/Si(111) monolayer due to the non-centrosymmetry at the surface
- Superconductivity develops on a Rashba splitted ground state

Superconducting 2D System with Lifted Spin Degeneracy: Mixed Singlet-Triplet State

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(Received 20 March 2001; published 2 July 2001)

Origin of the gap filling in √7x√3-Pb/Si(111)

Superconducting 2D System with Lifted Spin Degeneracy: Mixed Singlet-Triplet State

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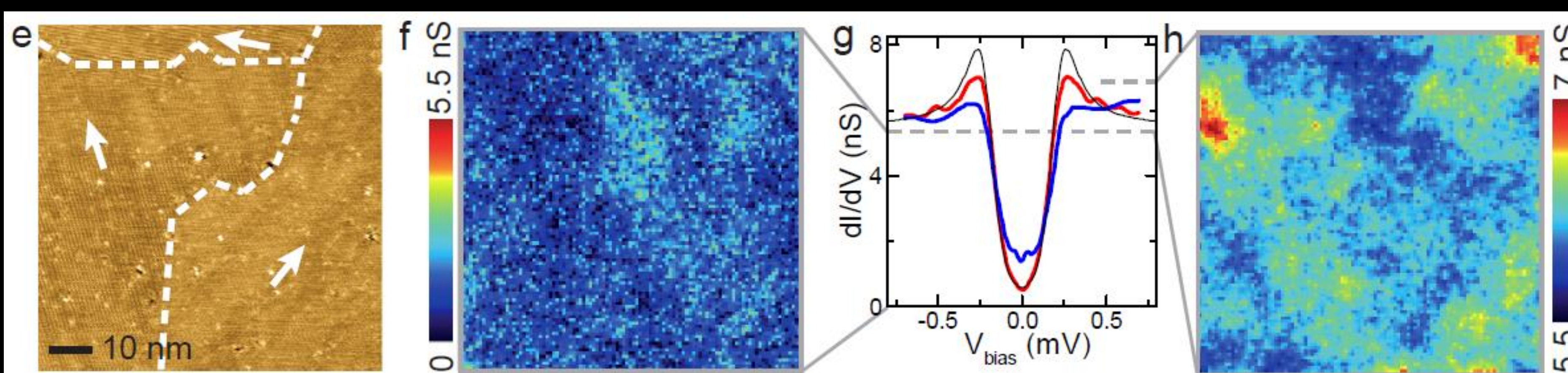
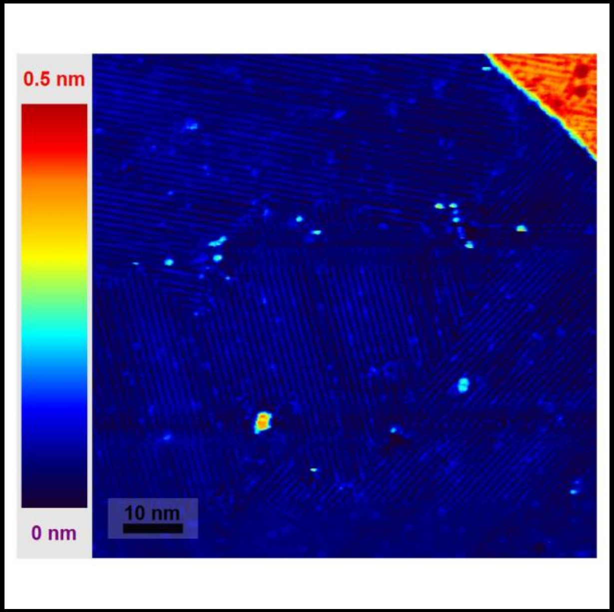
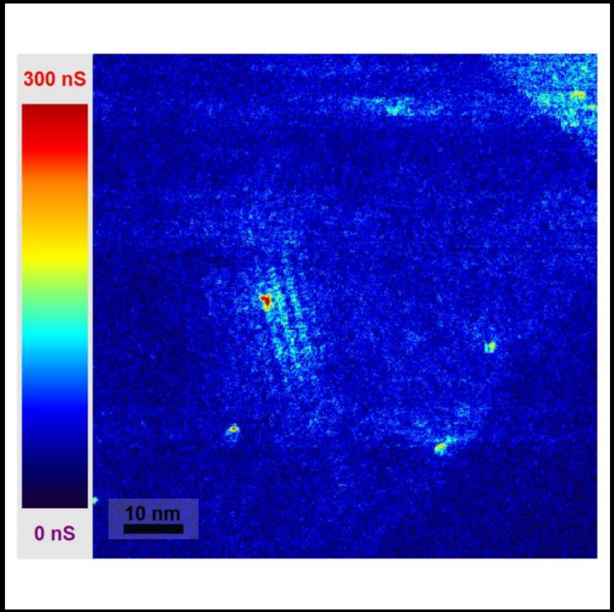
Gor'kov and Rashba PRL 87, 037004 (2001)

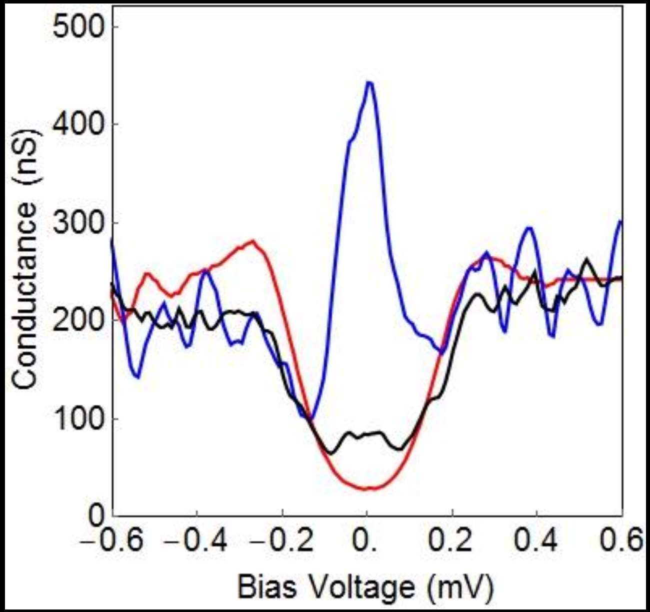
The triplet part is sensitive to non-magnetic disorder
(Analogous to weak magnetic disorder in a s-wave superconductor)



Extented bound states around magnetic defects in $\sqrt{3} \times \sqrt{7}$-Pb/Si(111)





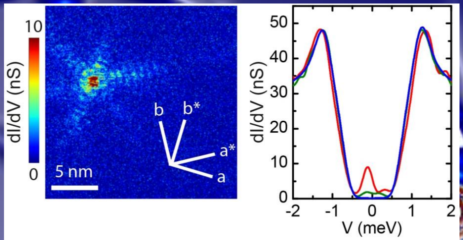


Topography

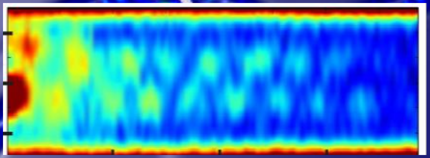
Conductance map at 0 mV

Conductance spectra on top (red), at 5 nm (blue), 10 nm (green) and far from the impurity (black)

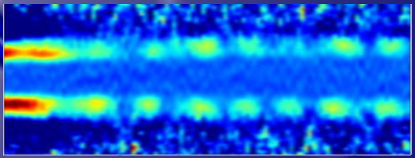
Coupling a classical spin to a 2D condensate leads to spatially extended, quantum coherent, spin polarized, bound states



•Large star shaped bound states in NbSe2

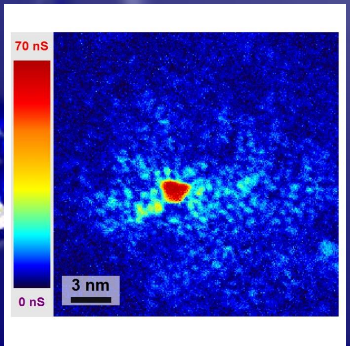


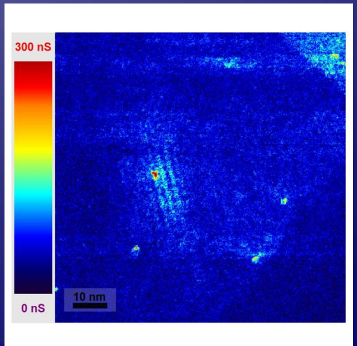
•Oscillating electron-hole asymmetry

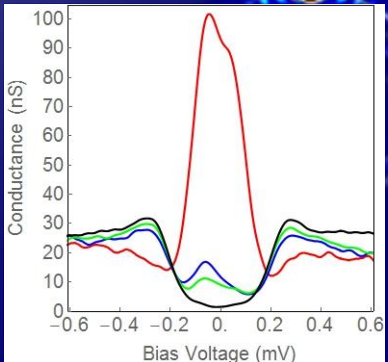


•Phase shift governed by bound state energy

•Very large extend of Yu-Shiba-Rusinov bound states in Pb/Si(111) monolayers







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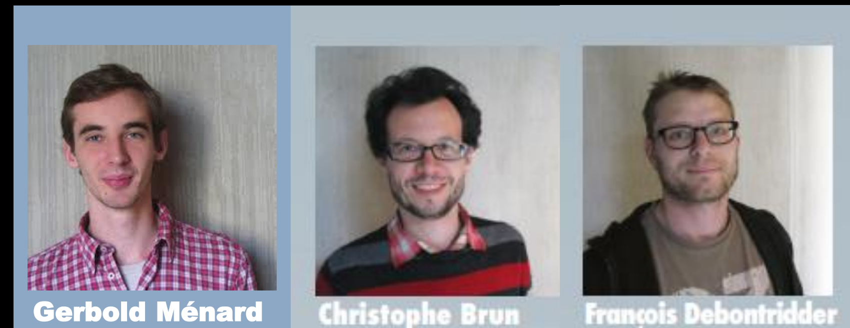
INSP team (CNRS & Sorbonne university)

- Christophe Brun
- Tristan Cren
- François Debontridder
- Matthieu Leclerc
- Vasily Stolyarov



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- Sébastient Guissart
- Pascal Simon

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- Laurent Cario
- Étienne Janod

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ANR
cnrs dépasser les frontières
FONDATION CFM POUR LA RECHERCHE
UPMC SORBONNE UNIVERSITÉS

Thank you !