

# Vortices in superconductors & low temperature STM

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Cryocourse, 2011

## Outline

-Vortices in superconductors

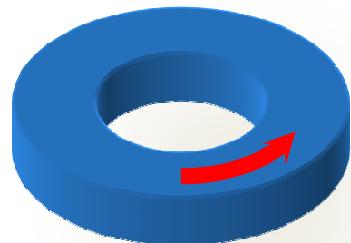
-Vortices & STM

-STM with superconducting tip

-Vortices & STM with superconducting tip

# Superconductors

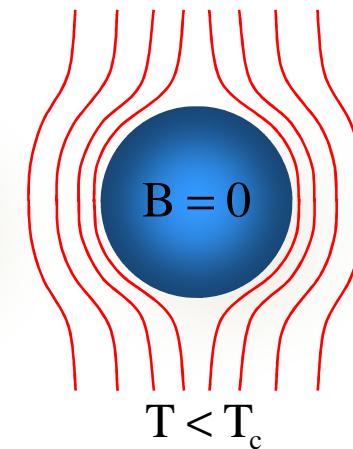
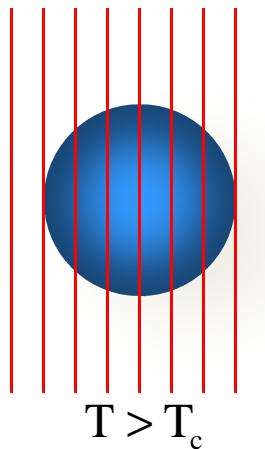
## Perfect conductor



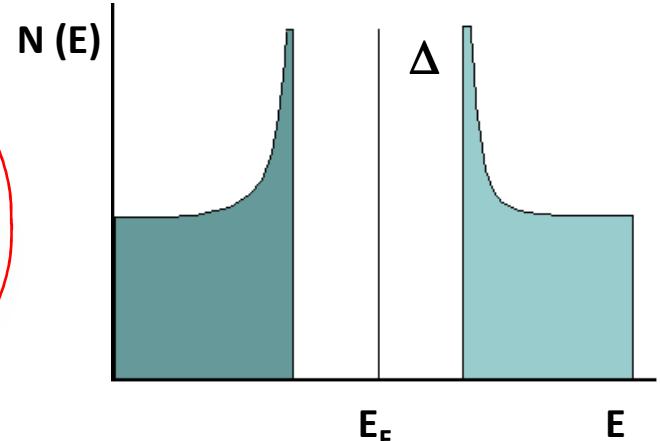
$$\rho = 0$$

$$\frac{I}{dI/dt} > 10^5 \text{ yrs}$$

## Meissner effect



$\Delta$  : gap in the electronic density of states



## Levitating magnets

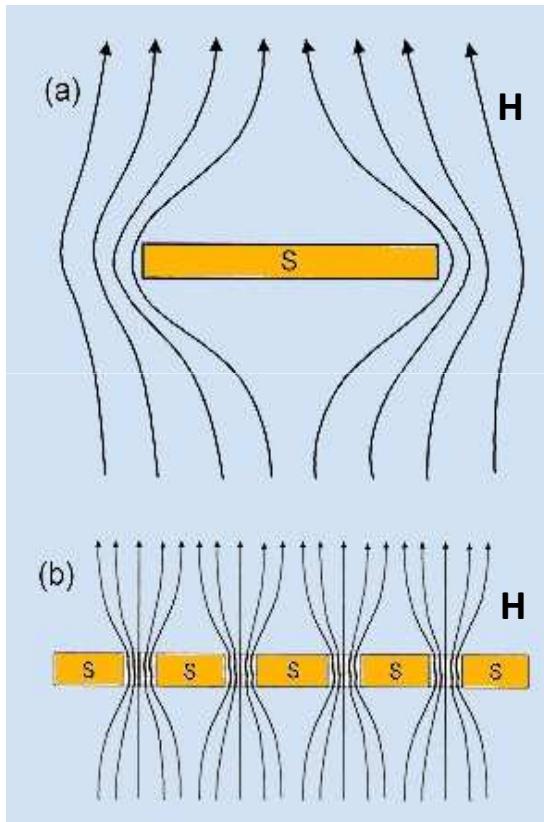


We need vortices...

# Superconductors and magnetic field

## Type I

- Meissner effect, perfect diamagnetism



## Type II

- vortices

## Magnetic flux penetration:

- energy balance
- N-S boundaries
- S-outside boundaries

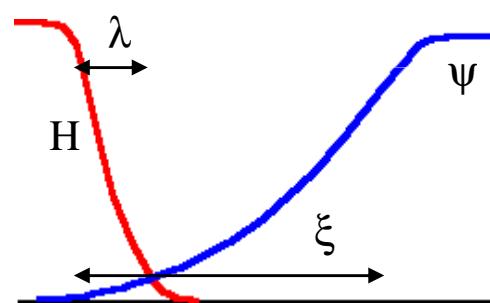
## Ginzburg-Landau parameter:

$$\kappa(T) = \lambda(T) / \xi(T)$$

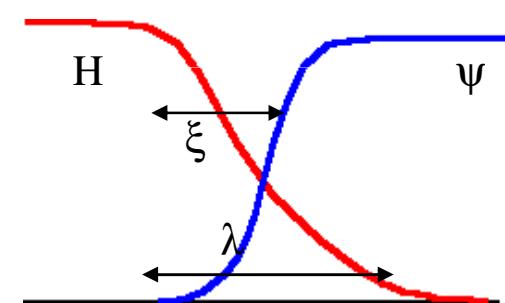
Penetration depth:  $\lambda$   
Coherence length:  $\xi$

$$\kappa = 1/\sqrt{2}$$

$\kappa \ll 1$  : type I



$\kappa \gg 1$  : type II



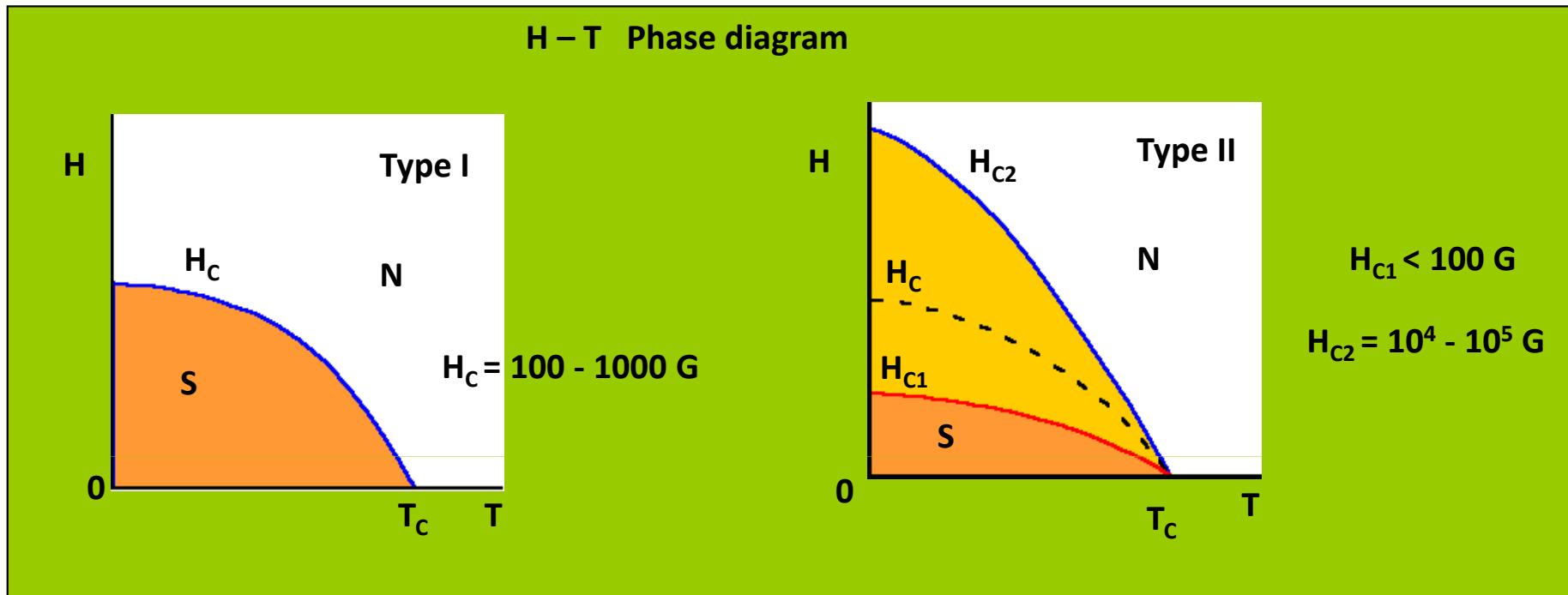
Al :

$$\begin{aligned}\lambda(0) &= 16 \text{ nm} \\ \xi(0) &= 1600 \text{ nm}\end{aligned}$$

NbSe<sub>2</sub> :

$$\begin{aligned}\lambda(0) &= 240 \text{ nm} \\ \xi(0) &= 8 \text{ nm}\end{aligned}$$

# Superconductors and magnetic field



**Critical fields in a type II superconductor:**

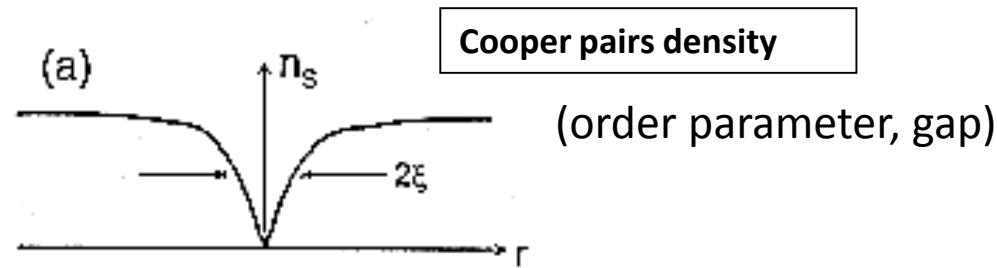
$$H_{c1} \approx \frac{\Phi_0}{4\pi\lambda^2} \quad \text{The first vortex penetrates the superconductor}$$

$$H_{c2} \approx \frac{\Phi_0}{4\pi\xi^2} \quad \text{Vortex cores overlap, everything is Normal}$$

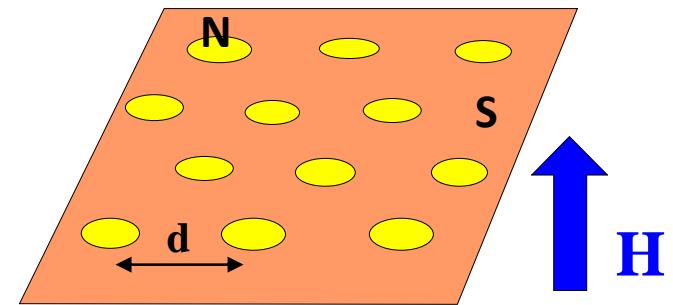
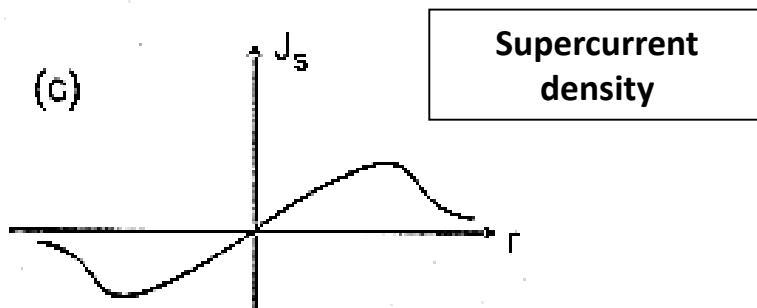
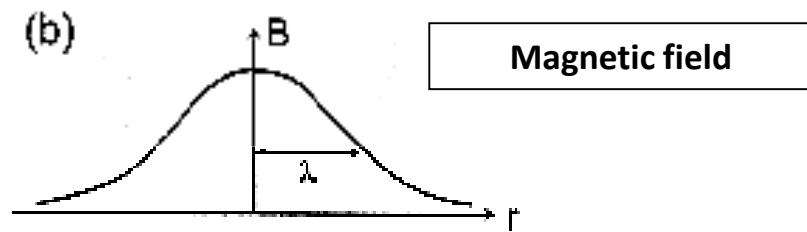
**The magnetic flux through a vortex is the quantum flux unit:**  $\Phi_0 = h / 2e \approx 2 \text{ mT} \mu\text{m}^2$

# What is a vortex?

Type II superconductor:  $\lambda > \xi$



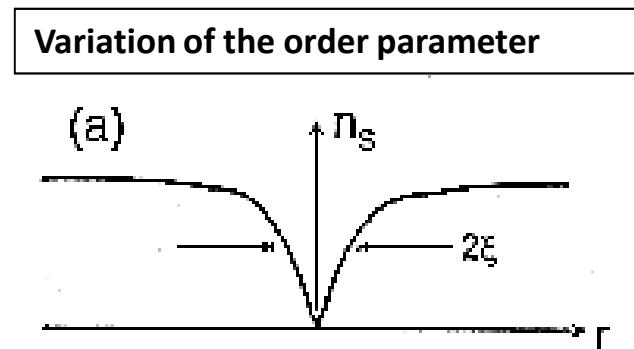
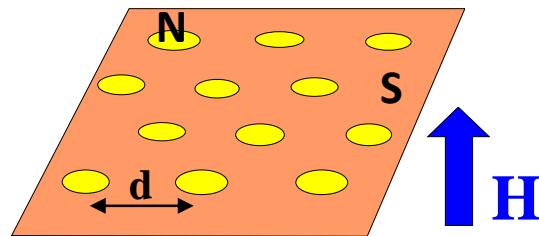
$$\Phi_0 = h / 2e \approx 2 \text{ mT} \mu\text{m}^2$$



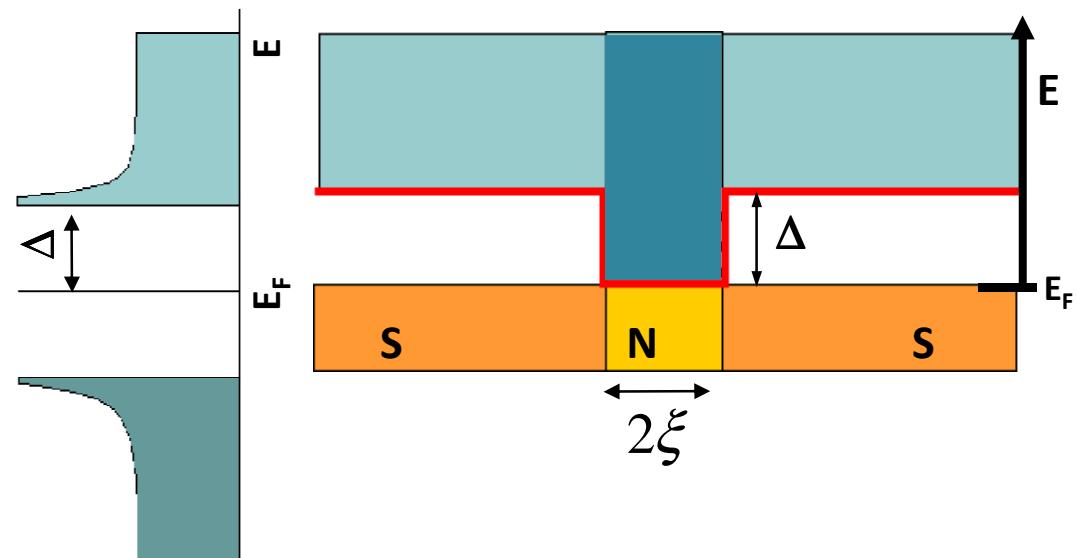
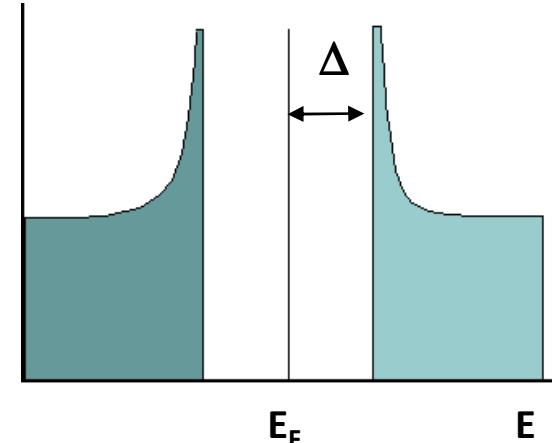
Abrikosov vortex lattice

$$d(\text{nm}) \approx 50 / \sqrt{H(\text{T})}$$

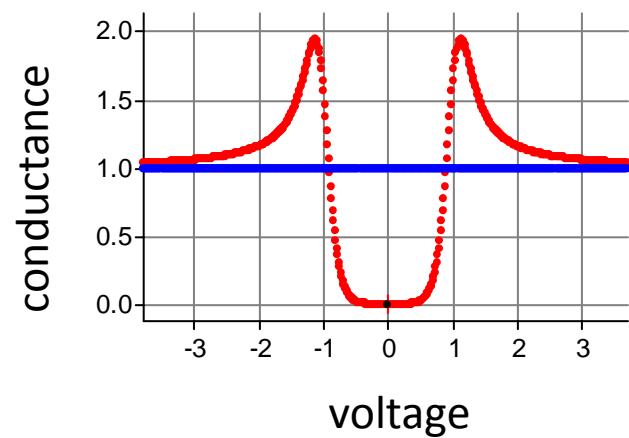
# How do we see vortices with the STM ?



Superconducting DOS



Vortices can be seen using the STM (tunneling curves)



## A “flat” type II superconductor: $\text{NbSe}_2$

Layered material, atomically flat surfaces easily obtained.

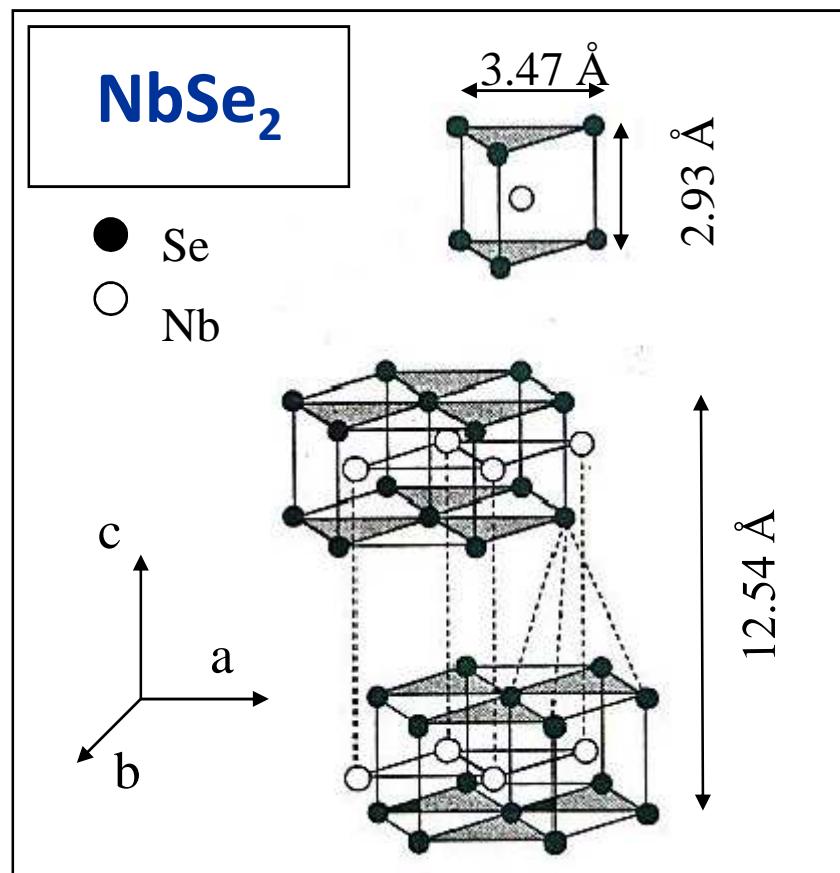
Superconductor:  $T_c = 7.2 \text{ K}$ ,

Type II:  $H_{c1} < 10 \text{ mT}$ ,  $H_{c2} = 4.5 \text{ T}$

CDW below 30K

$\lambda(0) = 70 \text{ nm}$

$\xi(0) = 8 \text{ nm}$



Schematic plot of the Fermi Surface

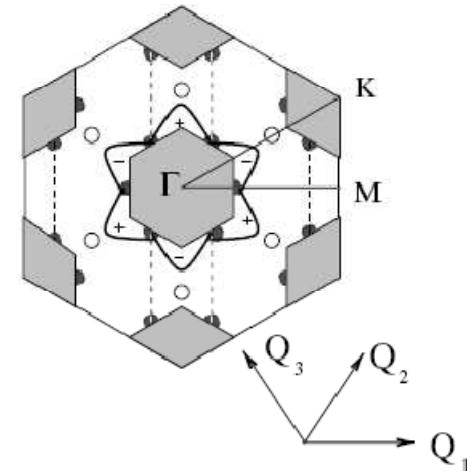
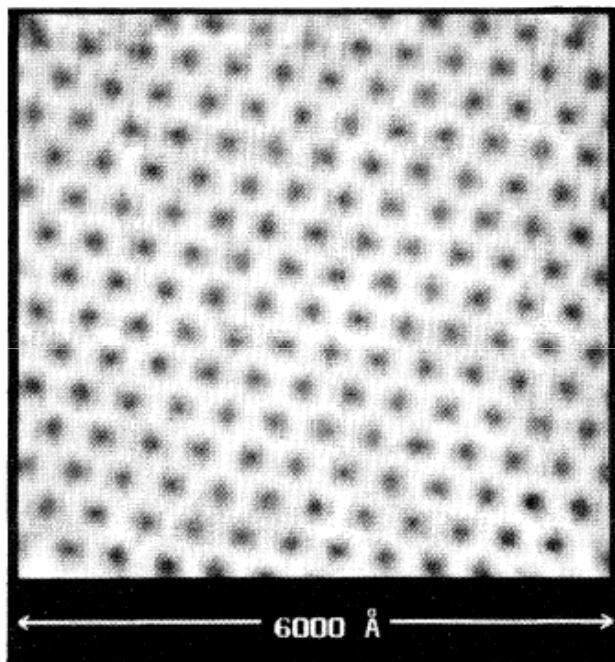


FIG. 2. Schematic plot of the Fermi surface according to [6]. Dashed lines: nodal lines associated with  $Q_1$ . Filled circles: Dirac points. Empty circles: saddle points. Thick line: proposed CDW gap.

# Observation of the vortex lattice: STM on NbSe<sub>2</sub>

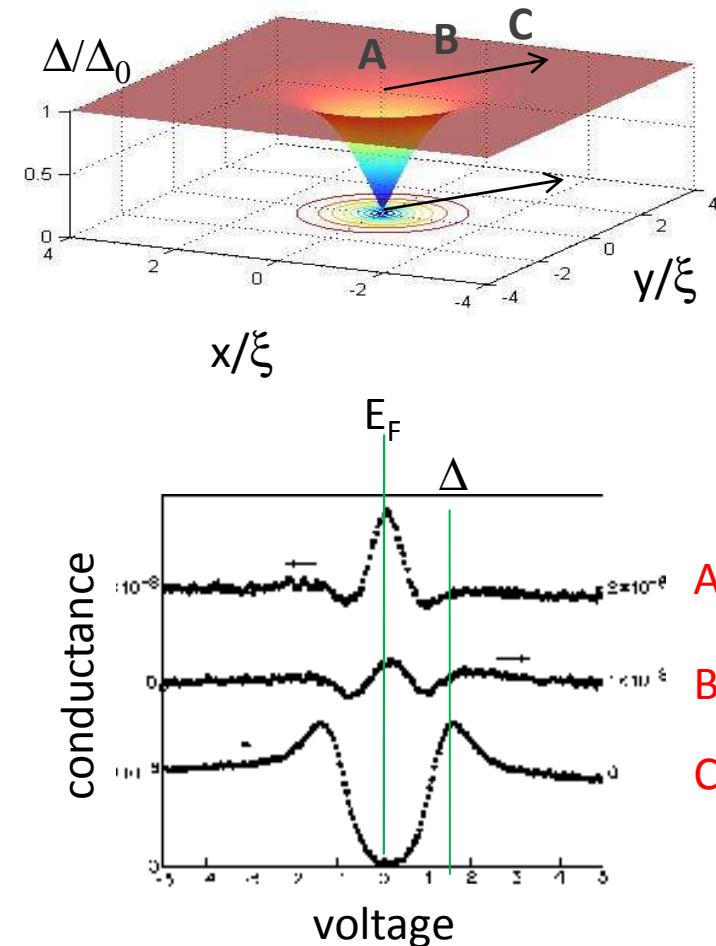
NbSe<sub>2</sub>     $T_c = 7.2$  K

$\lambda(0) = 240$  nm  
 $\xi(0) = 8$  nm



1 Tesla, T= 1.8 K

Image at V =  $\Delta$  = 1.3 mV

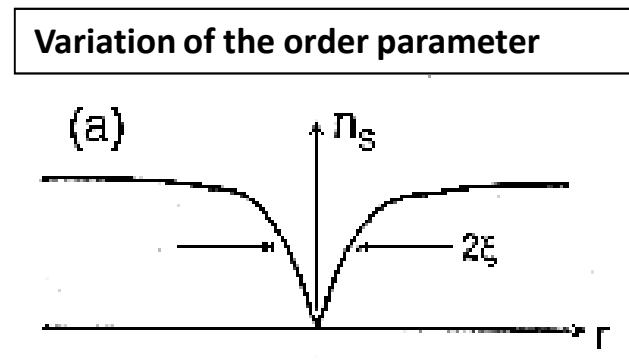
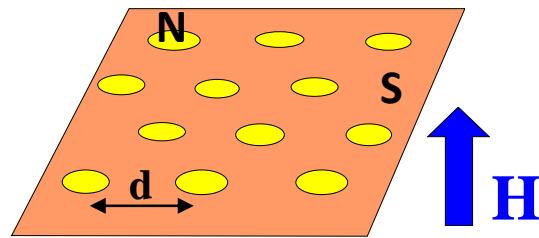


0.02 Tesla, T= 1.85 K

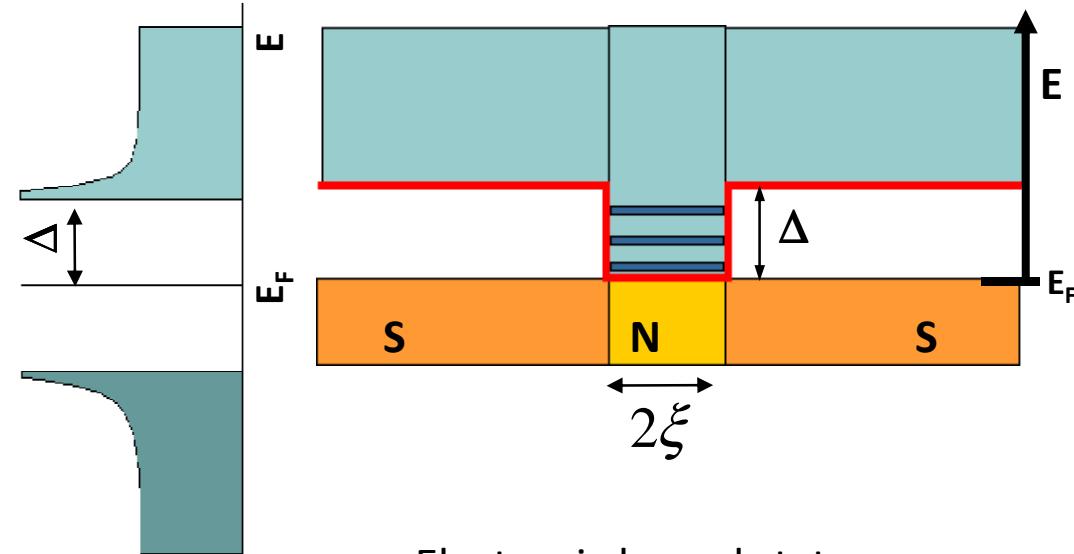
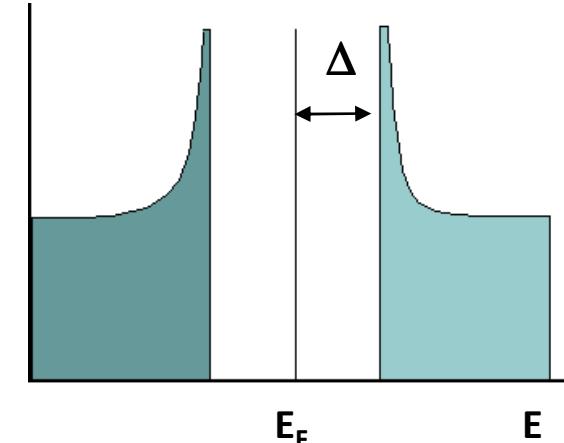
Peak: electronic states at the vortex core

H.F. Hess et al. PRL (1989)

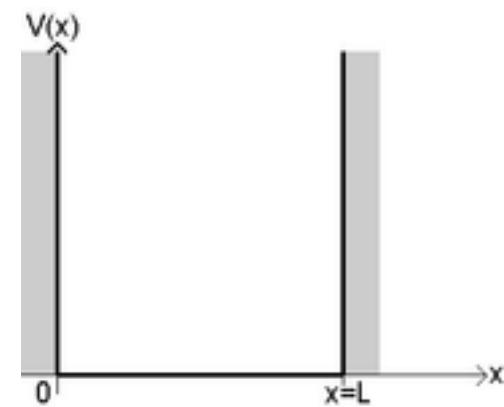
# What happens inside the vortex ?



Superconducting DOS

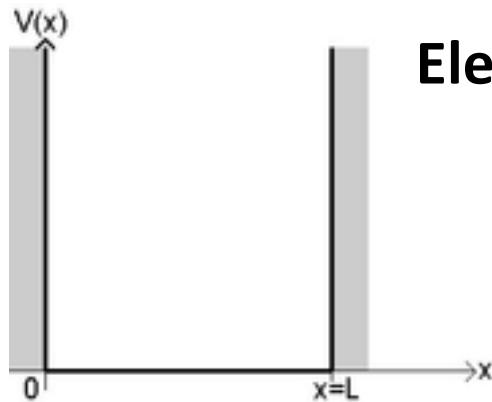


Similar to the quantum well  
Particles in a box



Can we see these electronic levels?

## Bound states: quantum well



**Electrons “in a box”**

Energy levels and wave functions of a particle in a box.

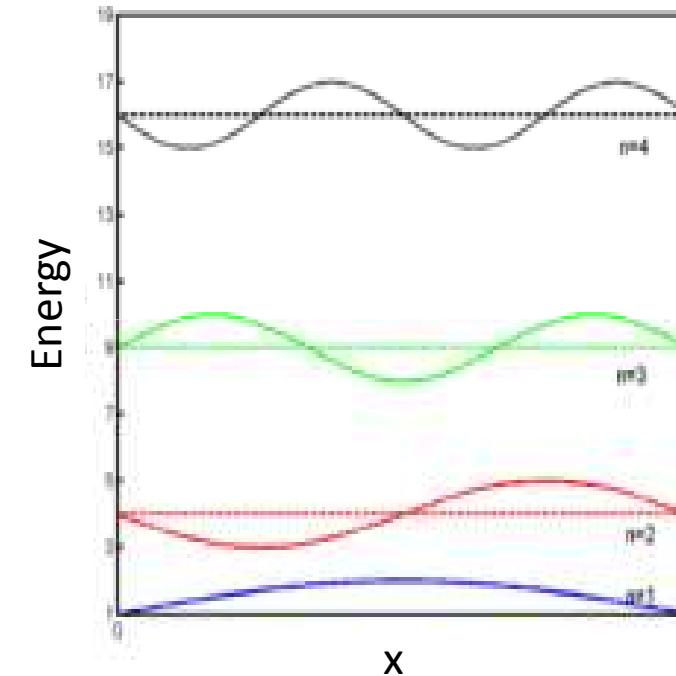
$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)$$

$$E_n = \frac{n^2 \hbar^2 \pi^2}{2mL^2} = \frac{n^2 h^2}{8mL^2}$$

Can we see these electronic states?  
How?

$$\Delta E \approx E_F \left( \frac{\lambda_F}{L} \right)^2$$

$$\begin{aligned} E_F &= 10 \text{ eV} \\ L &= 2 \text{ nm} \\ \lambda_F &= 0.2 \text{ nm} \end{aligned}$$

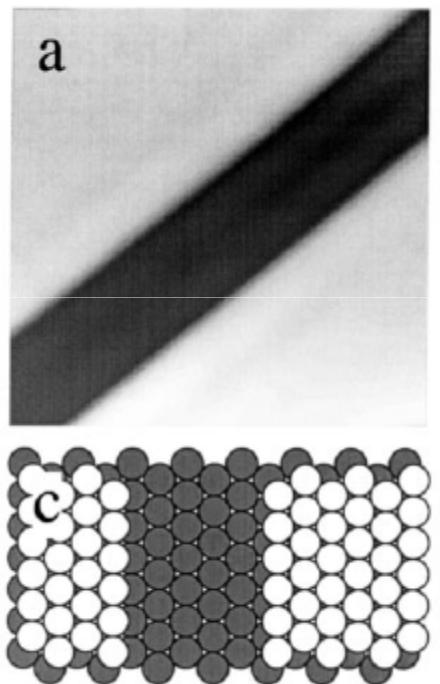


$$\Delta E = 100 \text{ meV}$$

$$(10 \text{ K} \rightarrow k_B T = 1 \text{ meV})$$

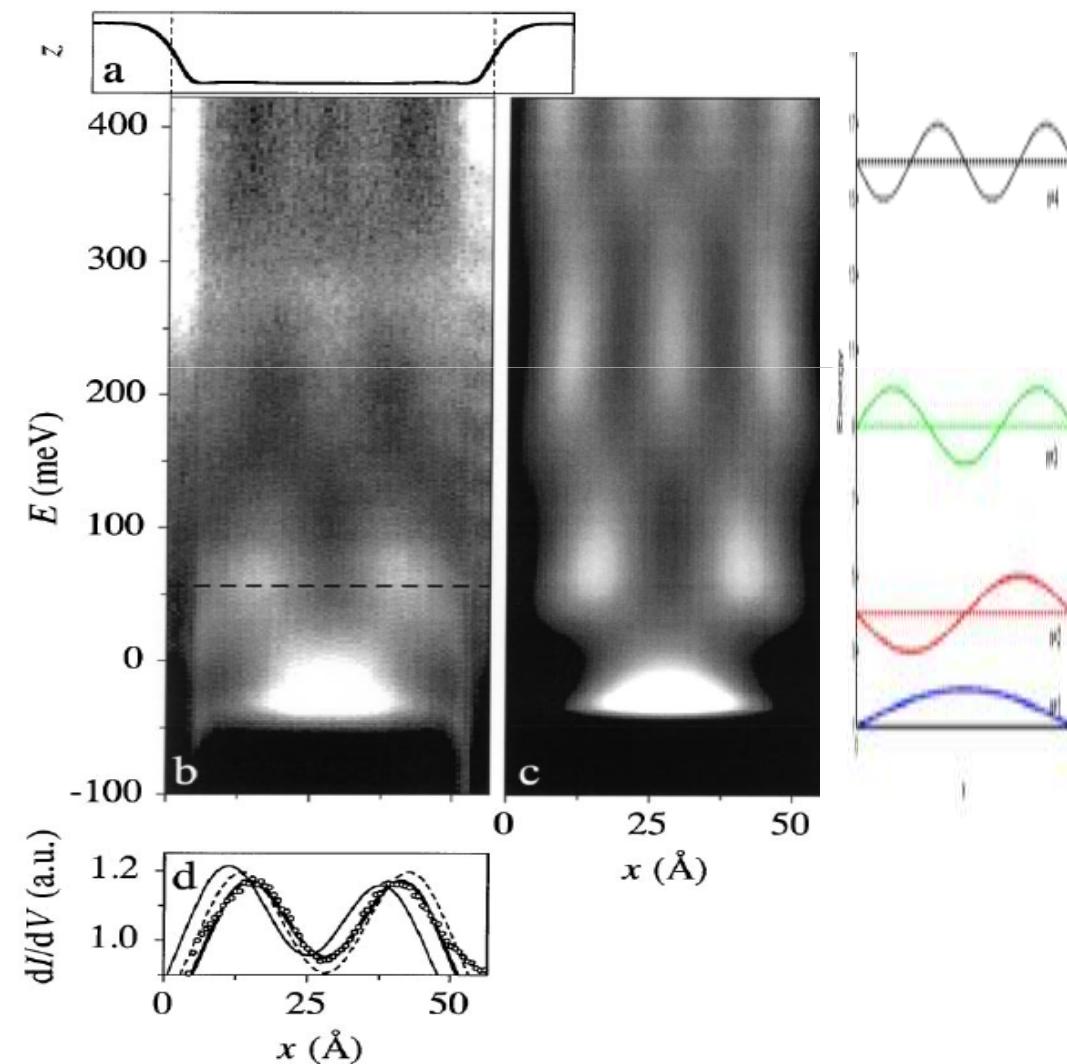
# Bound electronic states: quantum well seen by STM

T=4.9K  
Sample : Ag  
Tip: W

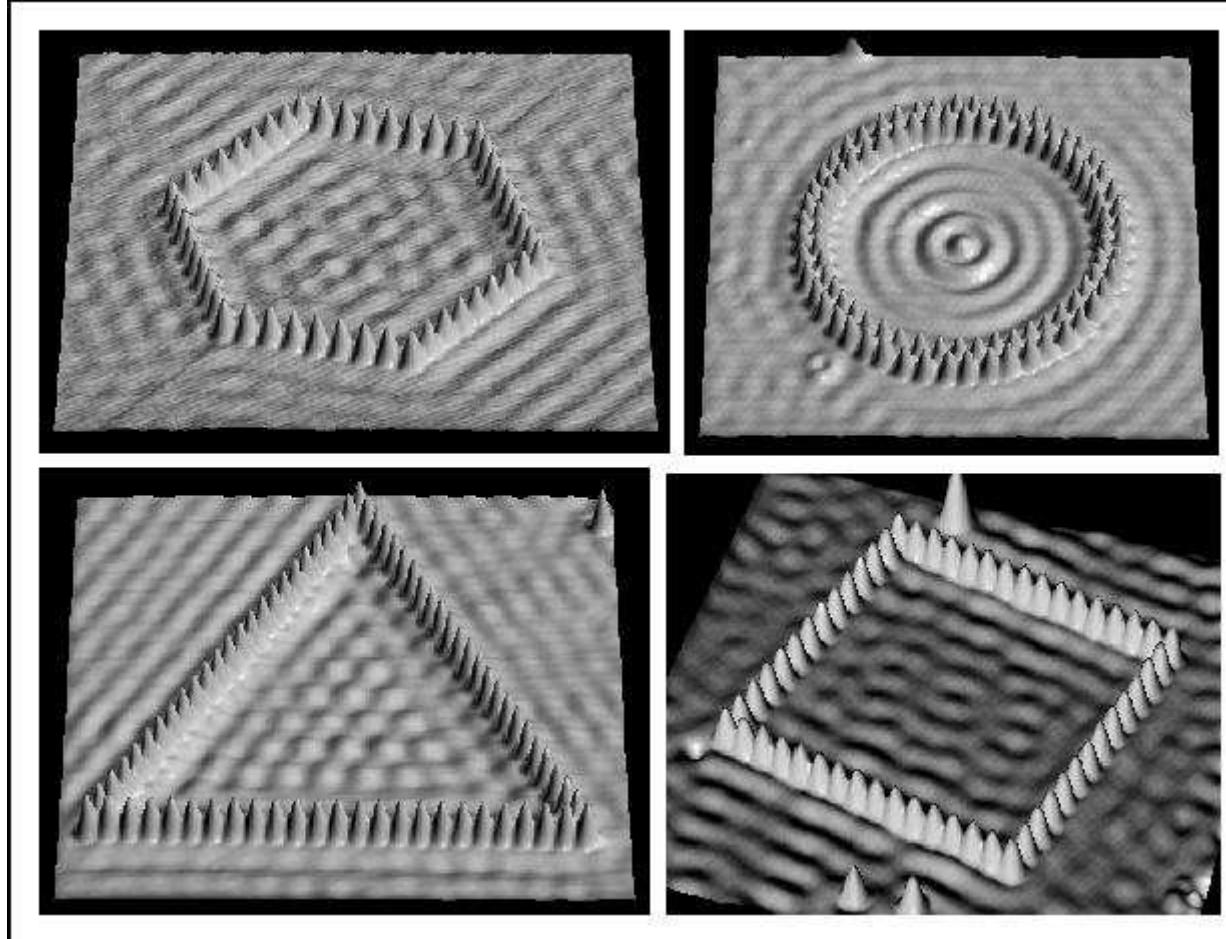


Bürgi et al. PRL, 1998

$$dI / dV(E) \Big|_x \quad (\text{Bias modulation : } 5\text{mV})$$

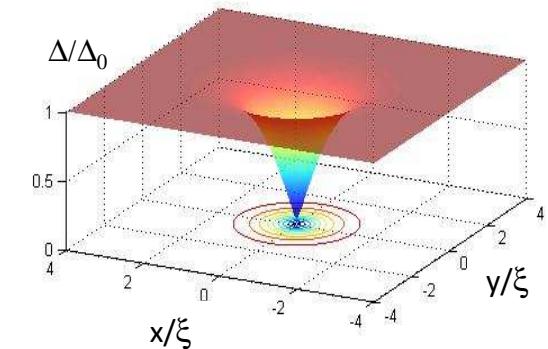


## Bound electronic states: quantum “corral” seen by STM



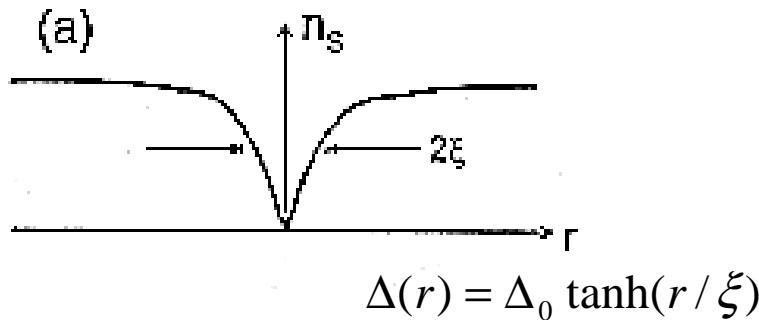
Electronic surface states in Cu(111) confined by barriers made of Fe atoms.

T=4.2 K  
Dimensions: 10 nm  
Corrals: 50 átomos

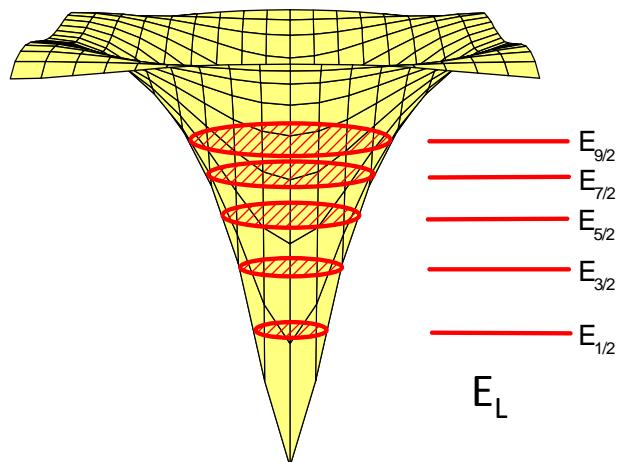


Crommie, Lutz & Eigler, IBM, Almaden, USA

# Bound electronic states: the vortex core

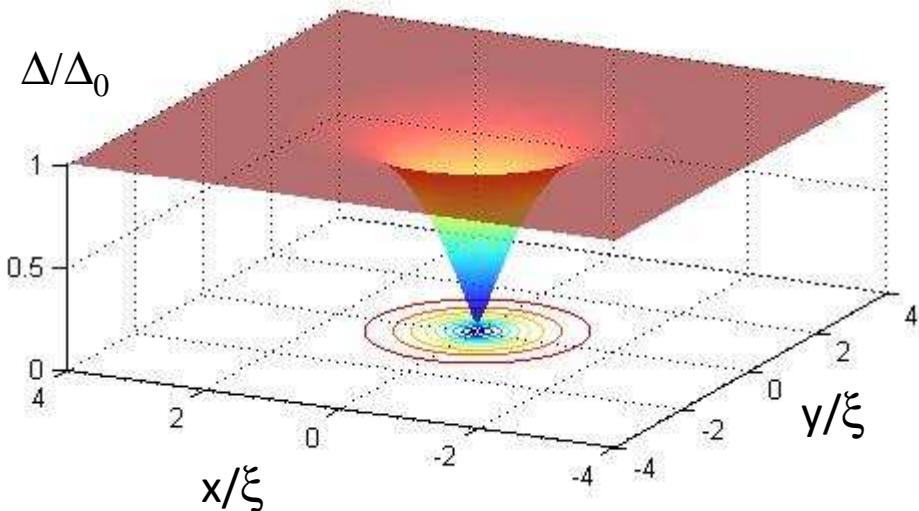


Quantized levels,  $E_L$

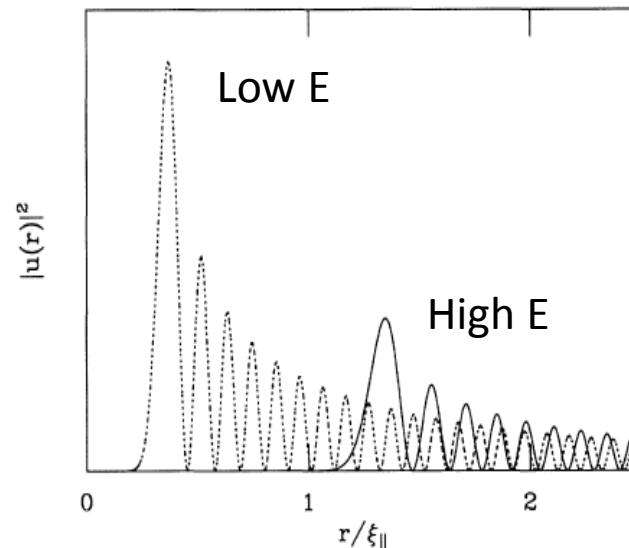


$$\Delta E \approx \frac{\hbar^2}{m\xi} \approx \frac{\Delta_0^2}{E_F}$$

$$\xi = \frac{\hbar v_F}{\pi \Delta}$$



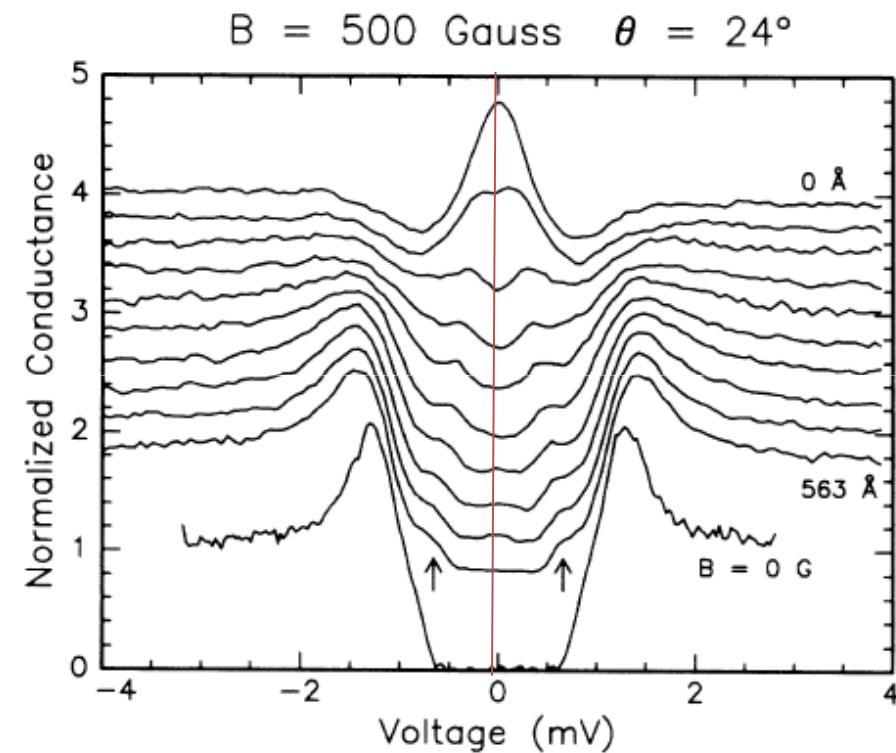
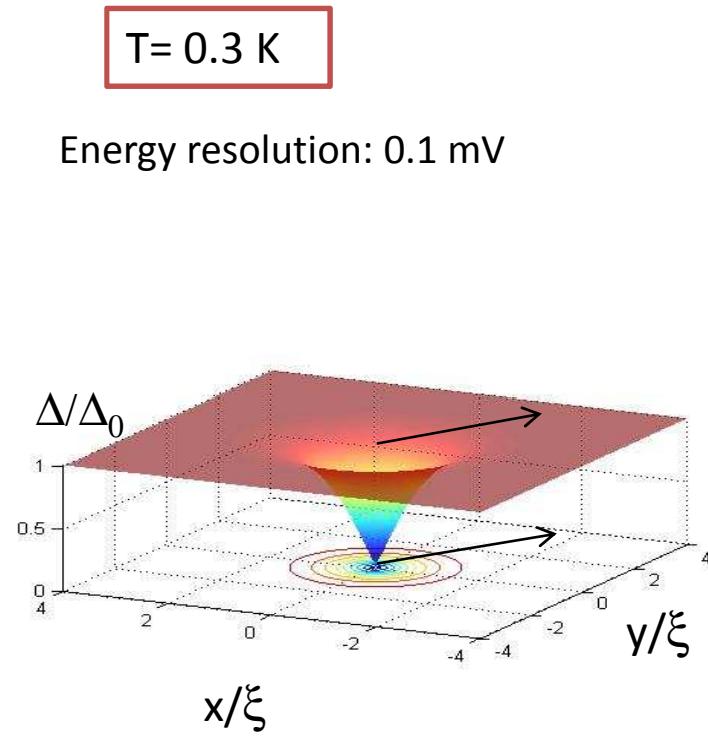
Wave function



$\xi = 10 \text{ nm}$   
 $\Delta = 1 \text{ meV}$   
 $E_F = 1 \text{ eV}$   
 $\Delta E = 1 \mu\text{eV}$   
 $(1 \text{ K} \rightarrow k_B T = 0.1 \text{ meV})$

# Bound electronic states: the vortex core. STM on NbSe<sub>2</sub>

H.F. Hess et al. PRL (1990)



# Observation of the vortex lattice: STM on NbSe<sub>2</sub>

## Reducing temperature, increasing resolution

H.F. Hess et al. PRL (1990)

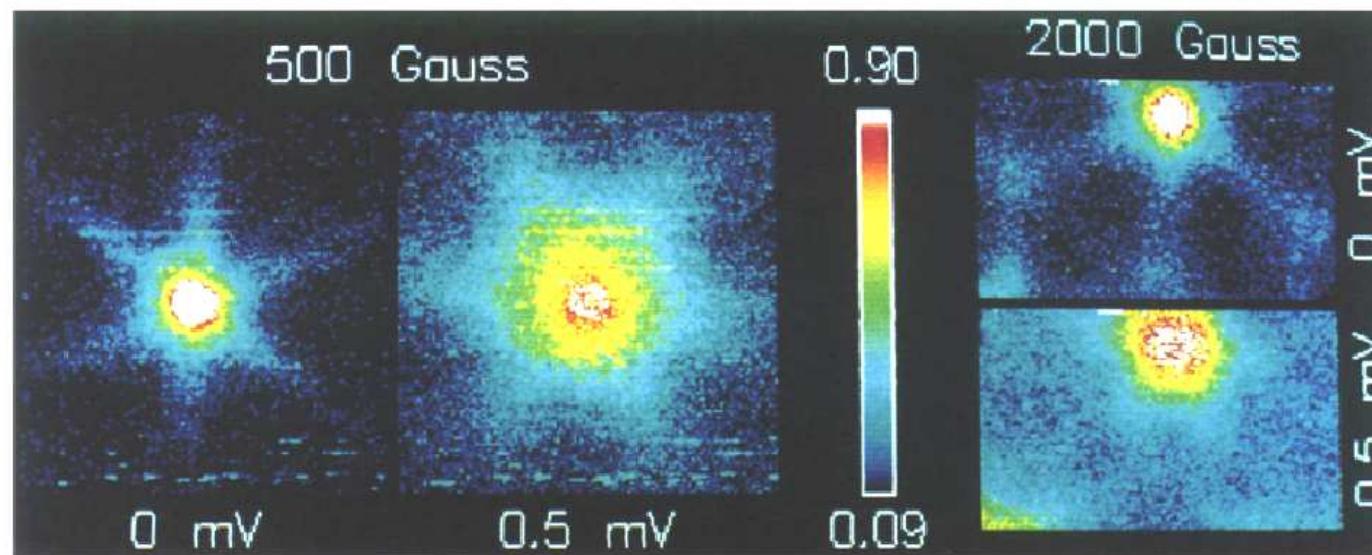
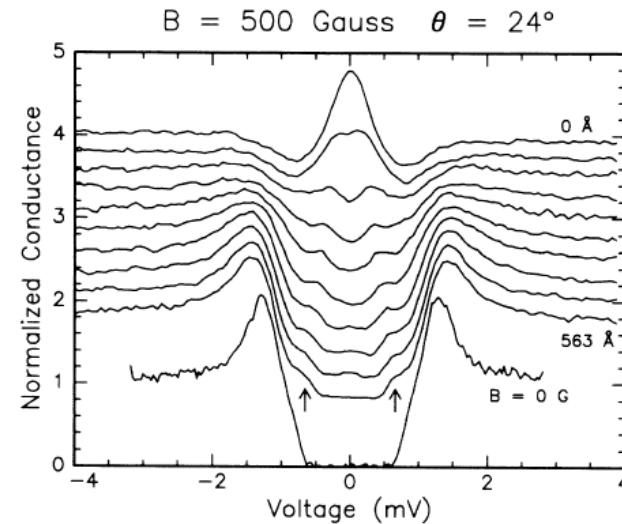
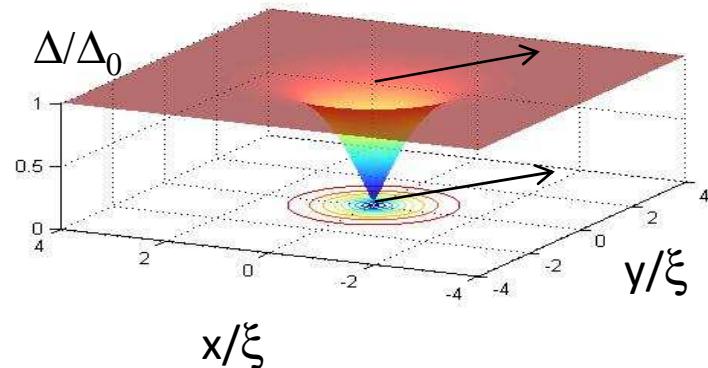


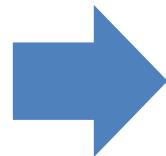
FIG. 4. Simultaneously taken XY images of  $dI/dV(0 \text{ mV}, x, y)$  and  $dI/dV(0.5 \text{ mV}, x, y)$  with  $B = 500 \text{ G}$  and the same for  $2000 \text{ G}$ . The width of all images is  $1500 \text{ \AA}$ . Differential tunneling conductance of 0.9 and larger in normalized units is shown as white.

# Observation of the vortex lattice: STM on NbSe<sub>2</sub> Conductance patterns around the vortex

Six-fold star-like pattern:

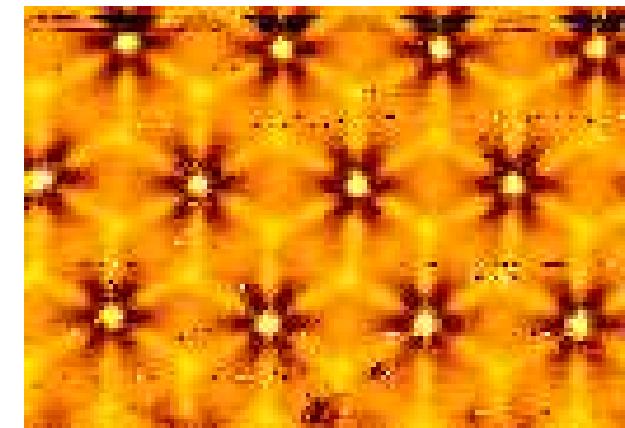
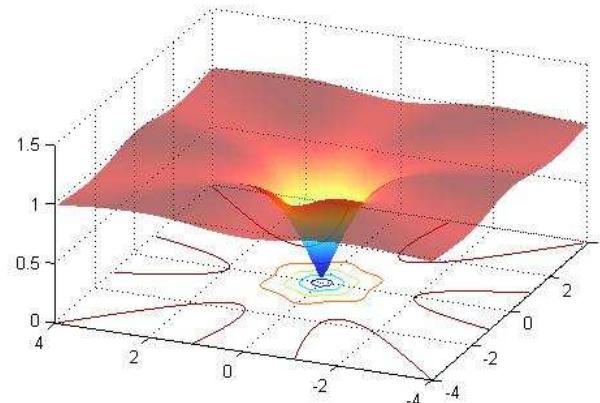
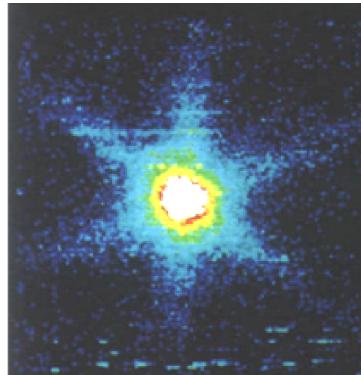
- Intrinsic phenomenon of the vortex?
- Anisotropy of the order parameter ?
- Effect of the vortex lattice ?

$$\Delta(r) = \Delta_0 \tanh(r/\xi)$$



$$\Delta(r, \theta) = \Delta_0 (1 + b \cos(6\theta)) \times \tanh(r/\xi)$$

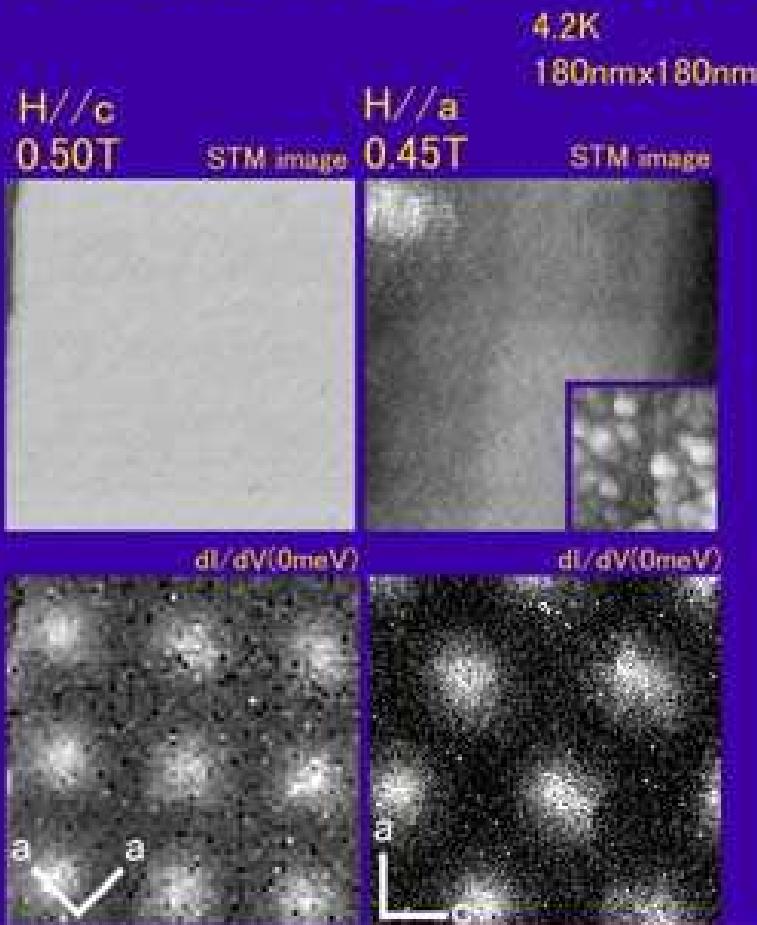
N. Hayashi, M. Ichioka, and K. Machida, PRL77, 1996.



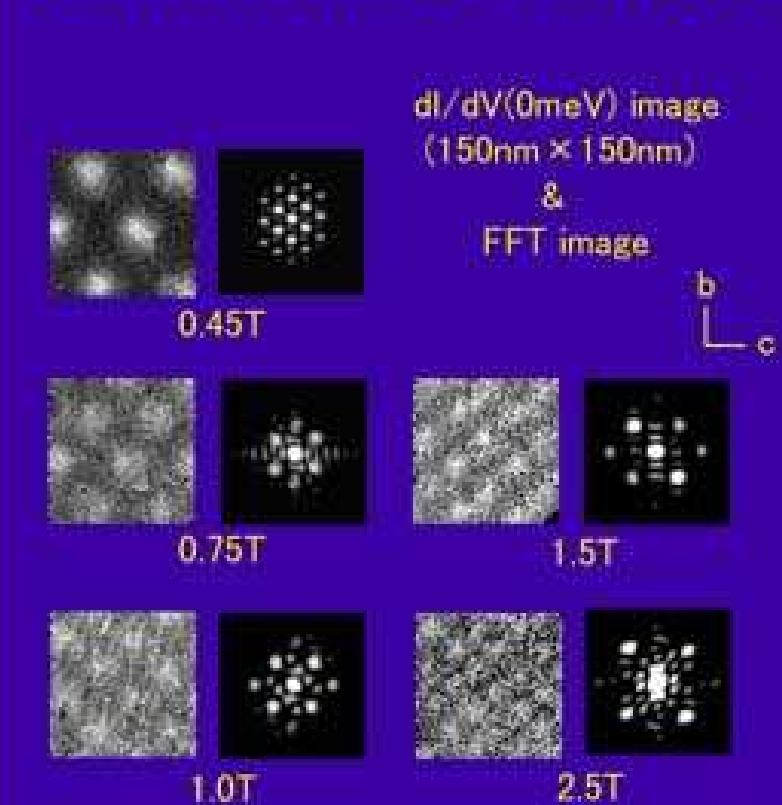
LBT-UAM T= 0.3 K

## Other superconductors, other symmetries of the order parameter

### VORTEX LATTICE in $\text{YNi}_2\text{B}_2\text{C}$



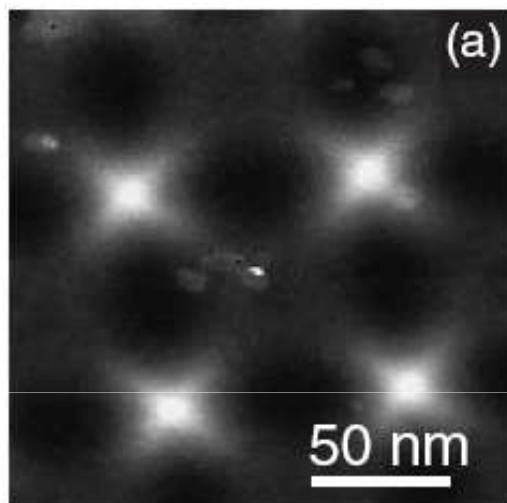
### VORTEX LATTICE in $\text{YNi}_2\text{B}_2\text{C}$



## Other superconductors, other symmetries of the order parameter

$\text{YNi}_2\text{B}_2\text{C}$        $T = 0.46 \text{ K}$

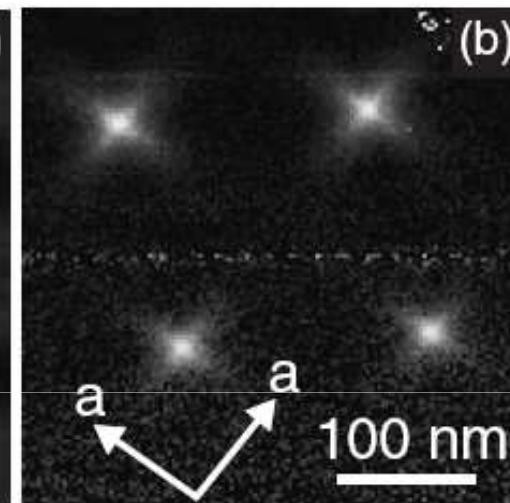
0.3 Tesla



$dI/dV$  [a.u.]

0.0 1.1

0.07 Tesla

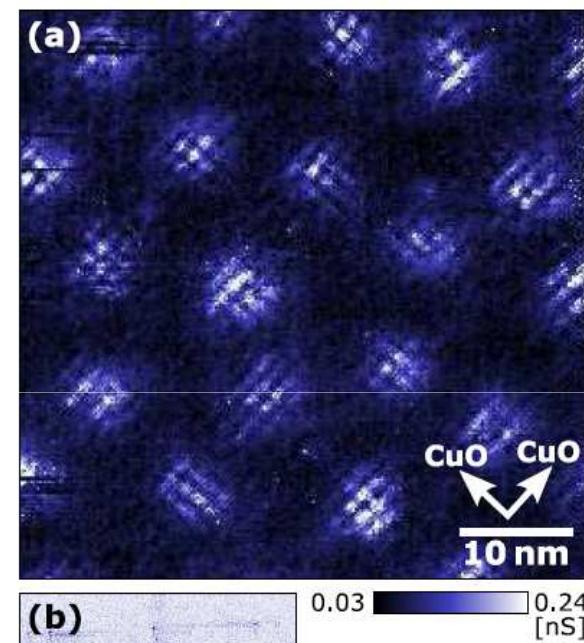


$dI/dV$  [a.u.]

0.0 1.1

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$

4.2 K  
14.5 T



$\text{CuO} \quad \text{CuO}$   
10 nm

0.03 0.24  
[nS]

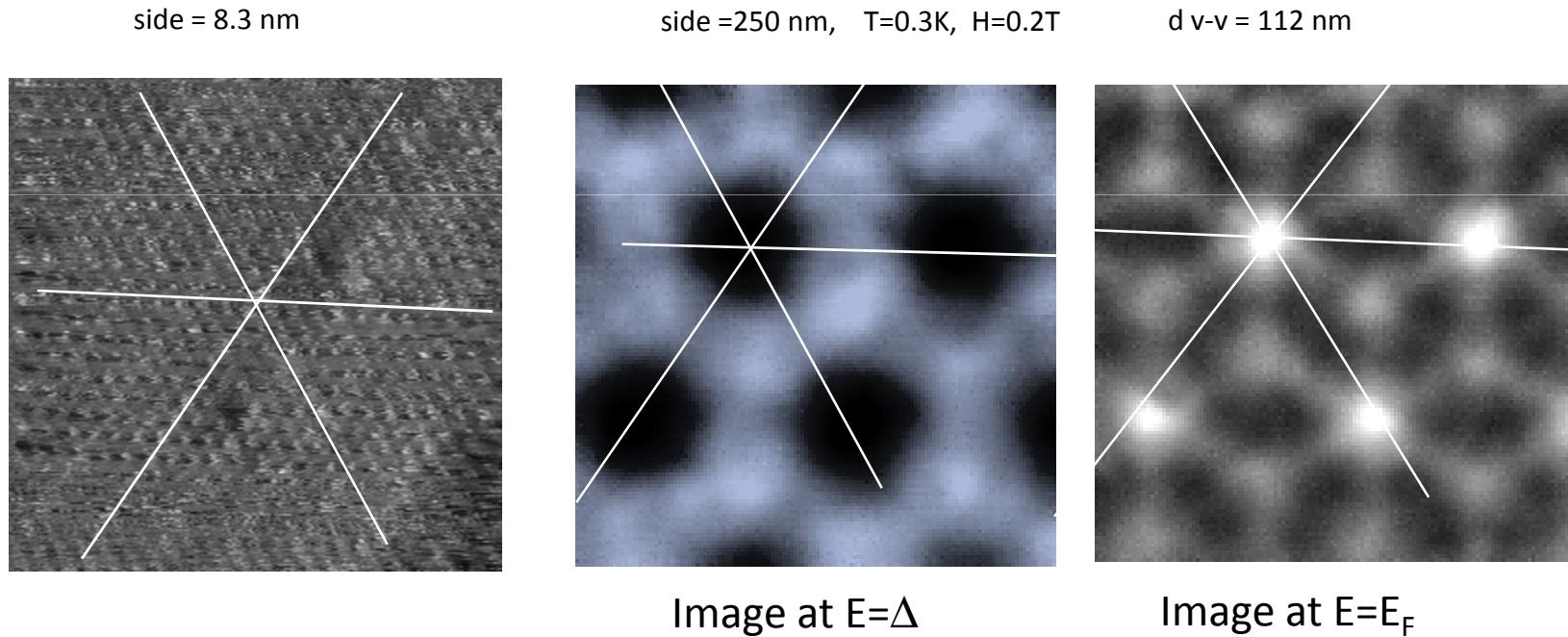
Fig. 2. Vortex lattice in  $\text{YNi}_2\text{B}_2\text{C}$  imaged by plotting  $N_s(E = 0 \text{ meV}, \mathbf{r})$  on gray scale at  $0.46 \text{ K}$  (a) in  $0.30 \text{ T}$  ( $180 \times 180 \text{ nm}^2$ ) and (b)  $0.07 \text{ T}$  ( $360 \times 360 \text{ nm}^2$ ). Arrows in (b) indicate the directions of the  $a$ -axis.

N. Nishida, Tokio Institute of Technology, 2004

**Important:** the symmetry of the order parameter & Fermi surface are reflected in the vortex core and lattice

## Observation of the vortex lattice: STM on NbSe<sub>2</sub>

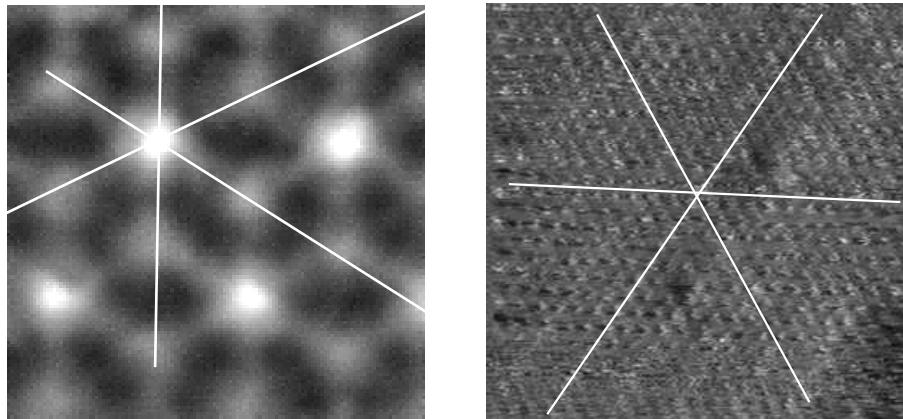
To correlate the observed variations in  $(r,\theta)$  to variations of the order parameter in Fermi Surface,  $\Delta(k_F,\theta)$ , we must check if these “macroscopic” scale (100 nm) observations have an origin at atomic scale, related to the orientation of the crystal lattice.



**The vortex lattice and the atomic lattice always present the same orientation.**

## Observation of the vortex lattice: STM on NbSe<sub>2</sub>

side = 250 nm



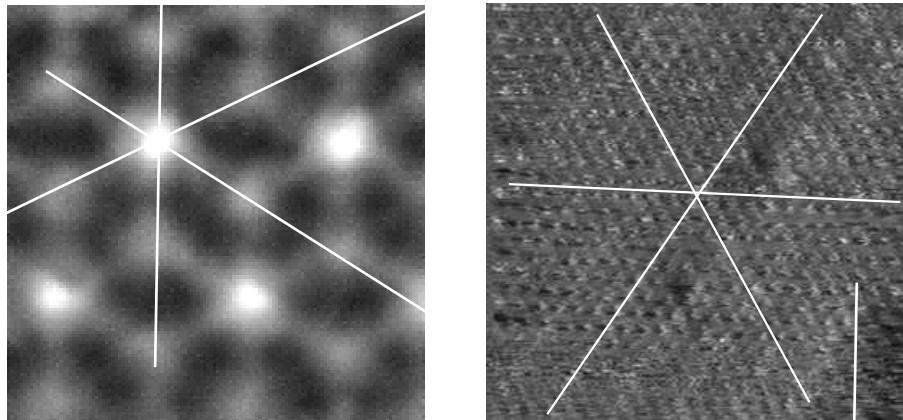
The bound states at a  $E_F$  (the rays) are **always** rotated 30° relative to the atomic lattice directions.

What happens if the vortex is not part of a lattice?

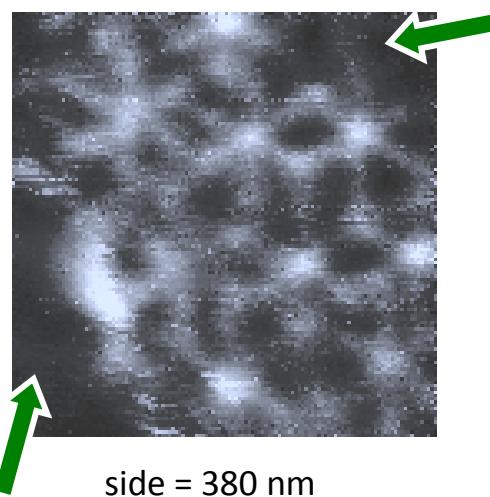
- Isolated vortex,
- Let's produce a disordered vortex lattice.

# Observation of the vortex lattice: STM on NbSe<sub>2</sub>

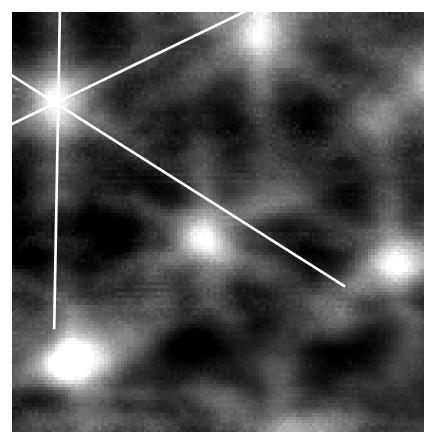
side = 250 nm



The bound states at a  $E_F$  (the rays) are **always** rotated 30° relative to the atomic lattice directions.

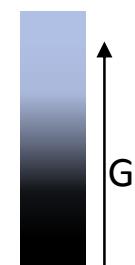


side = 380 nm



side = 250 nm

$H = 0.2 \text{ T}$   
 $T = 0.3 \text{ K}$



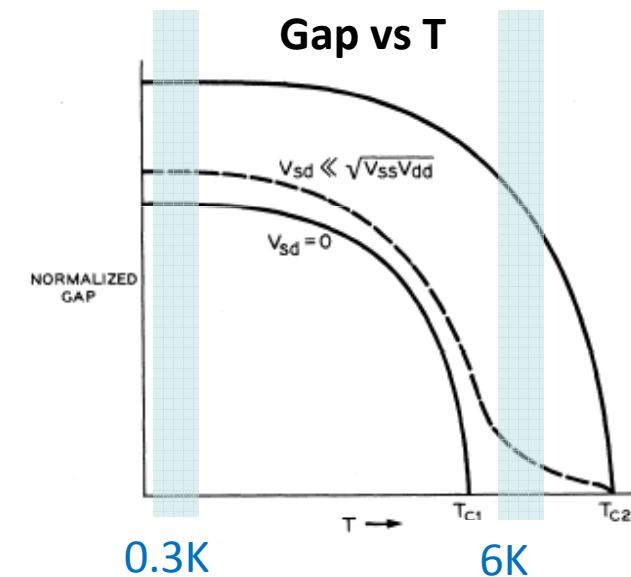
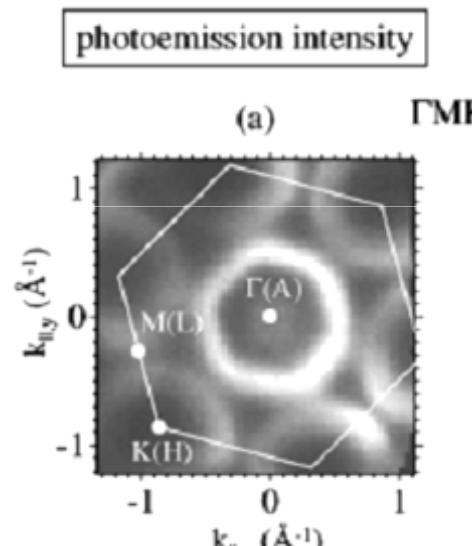
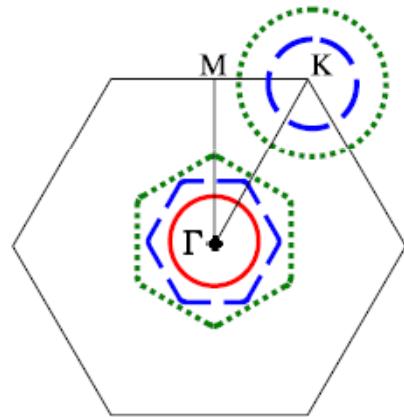
Distorted vortex lattice due to large scale defects of the sample surface.

# How is Fermi surface in NbSe<sub>2</sub> ?

NbSe<sub>2</sub> 2-band superconductor

Scenario I :  $\Delta_{\text{Nb bonding}} = \Delta_{\text{Nb anti-bonding}} = 1.26\text{meV}$   
 $\Delta_{\text{Se}} = 0.73\text{meV}$

Scenario II :  $\Delta_{\text{Se}} \sim \Delta_{\text{Nb anti-bonding}} = 1.26\text{meV}$   
 $\Delta_{\text{Nb bonding}} = 0.73\text{meV}$



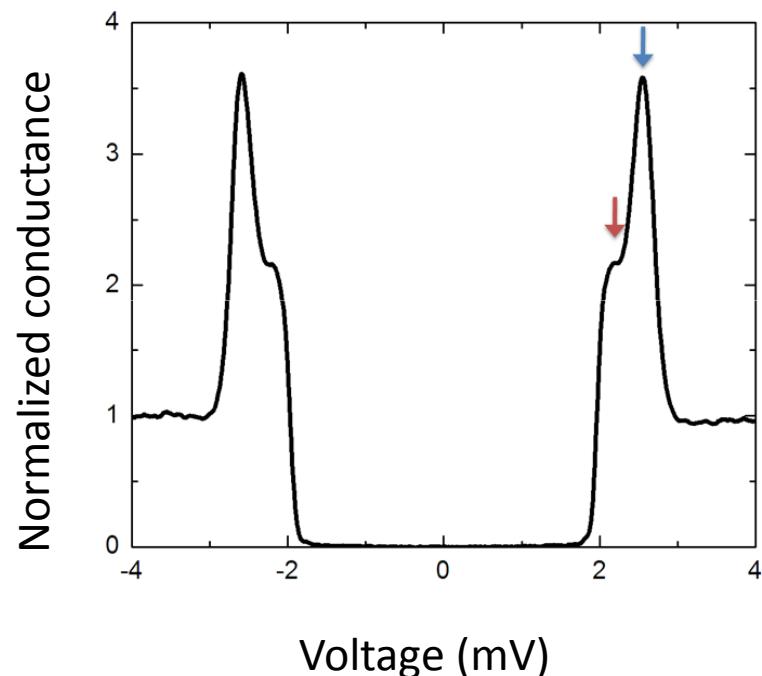
Huang et al, PRB 76 (2007);  
Yokoya et al., Science 294 (2001);  
Rodrigo and Vieira, Physica C 404 (2004)  
Boaknin et al., PRL 90 (2003)

# How are tunneling curves in $\text{NbSe}_2$ ?

$R_N = 10 \text{ M}\Omega$

Pb -  $\text{NbSe}_2$

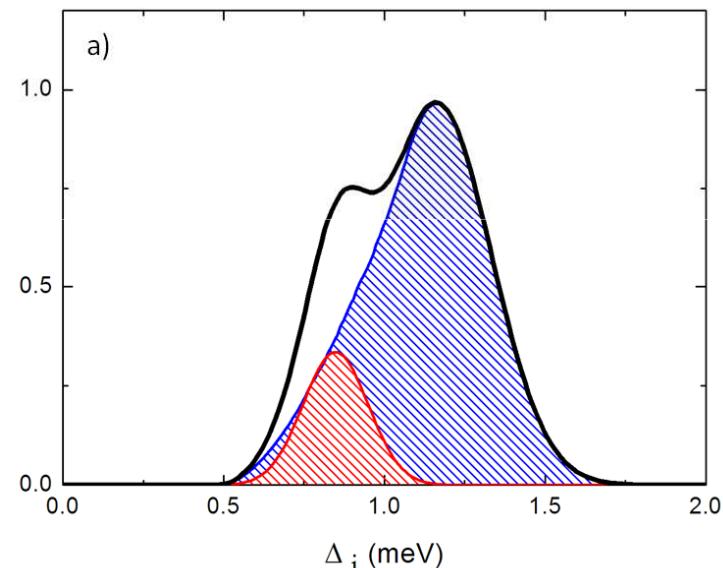
$T=0.3 \text{ K}$



$\text{NbSe}_2$

2-band superconductor

Gap distribution

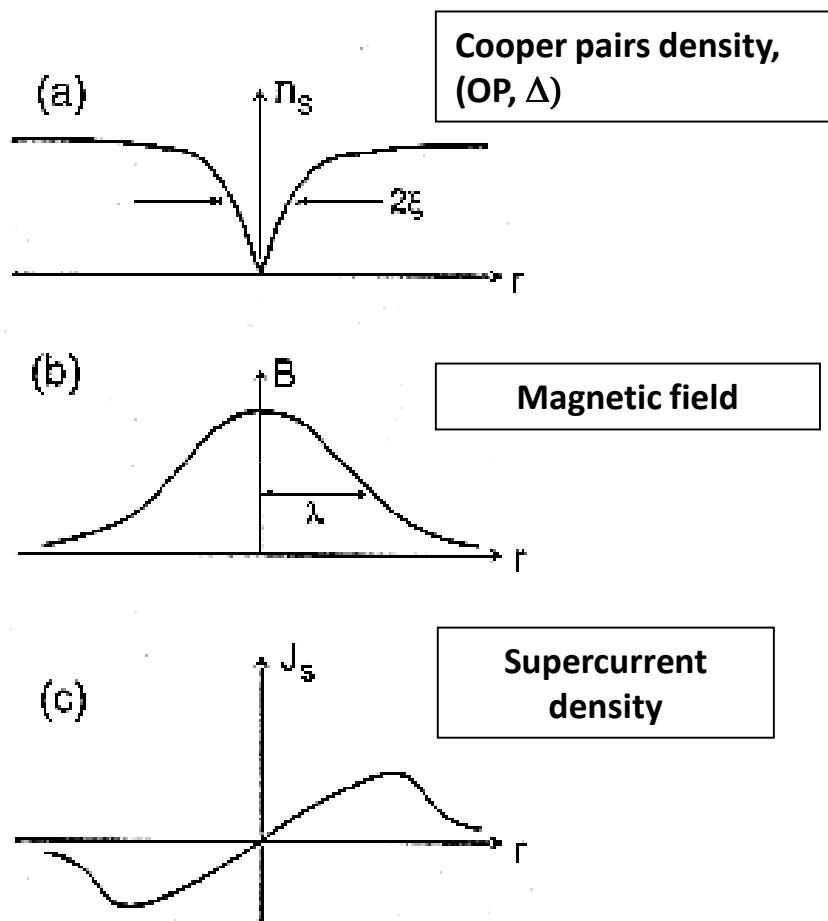


$$\Delta_{\text{Pb}} = 1.35 \text{ mV}$$

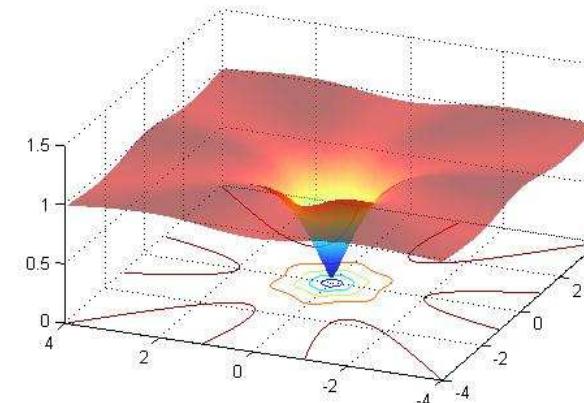
$$\begin{aligned} \text{NbSe}_2 & \quad \Delta_s = 0.7 \text{ mV} \\ & \quad \Delta_l = 1.2 \text{ mV} \end{aligned}$$

80% from band with “large gap”  
20% from band with “small gap”

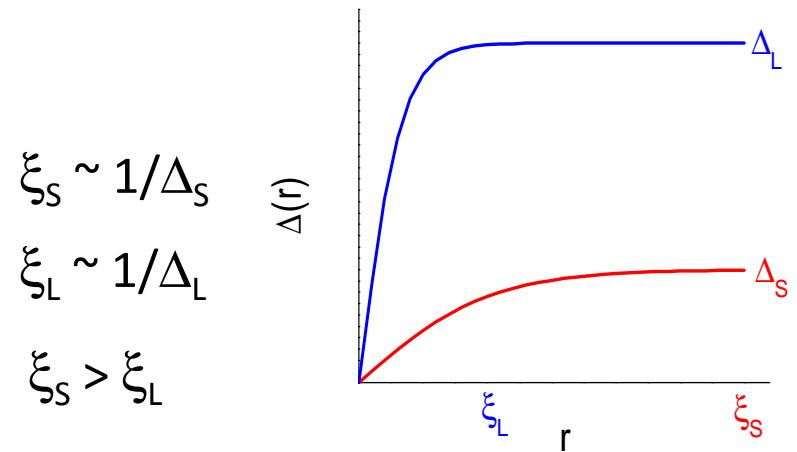
# “Double well” in the vortex in NbSe<sub>2</sub> ?



$$\Delta(r, \theta)$$



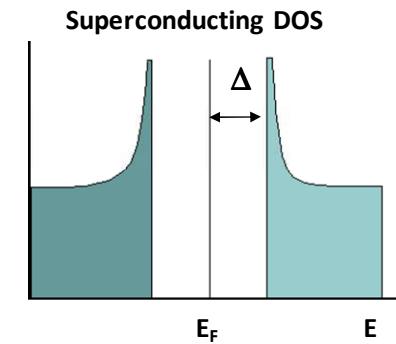
$$\xi_0(\hat{k}) = \frac{\hbar v_f}{\pi \Delta \hat{k}}$$



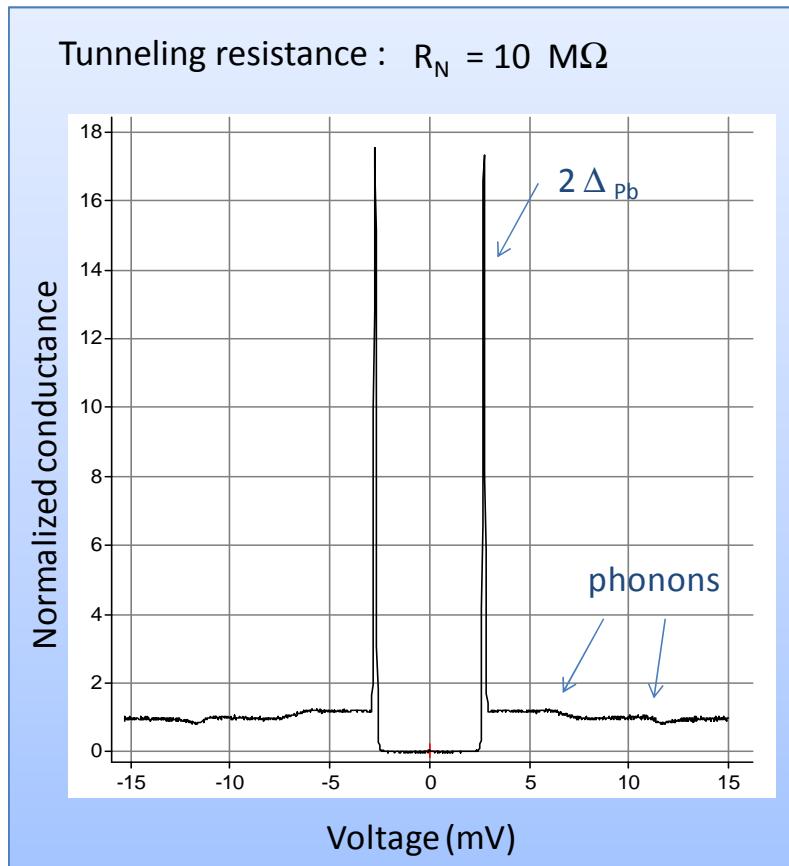
## STM/S of the vortex core

Let's use a superconducting tip. Why?

- Enhanced energy sensitivity. We probe with a sharp DOS. (Is it well defined?)
- We have 2 superconductors: Josephson current. Atomic scale probe of the superconducting condensate of the sample (without interference of the electronic bound states from quasiparticle tunneling)
- Sensitive to magnetic field
- But... is it still a good STM tip? Can we “see” atoms?



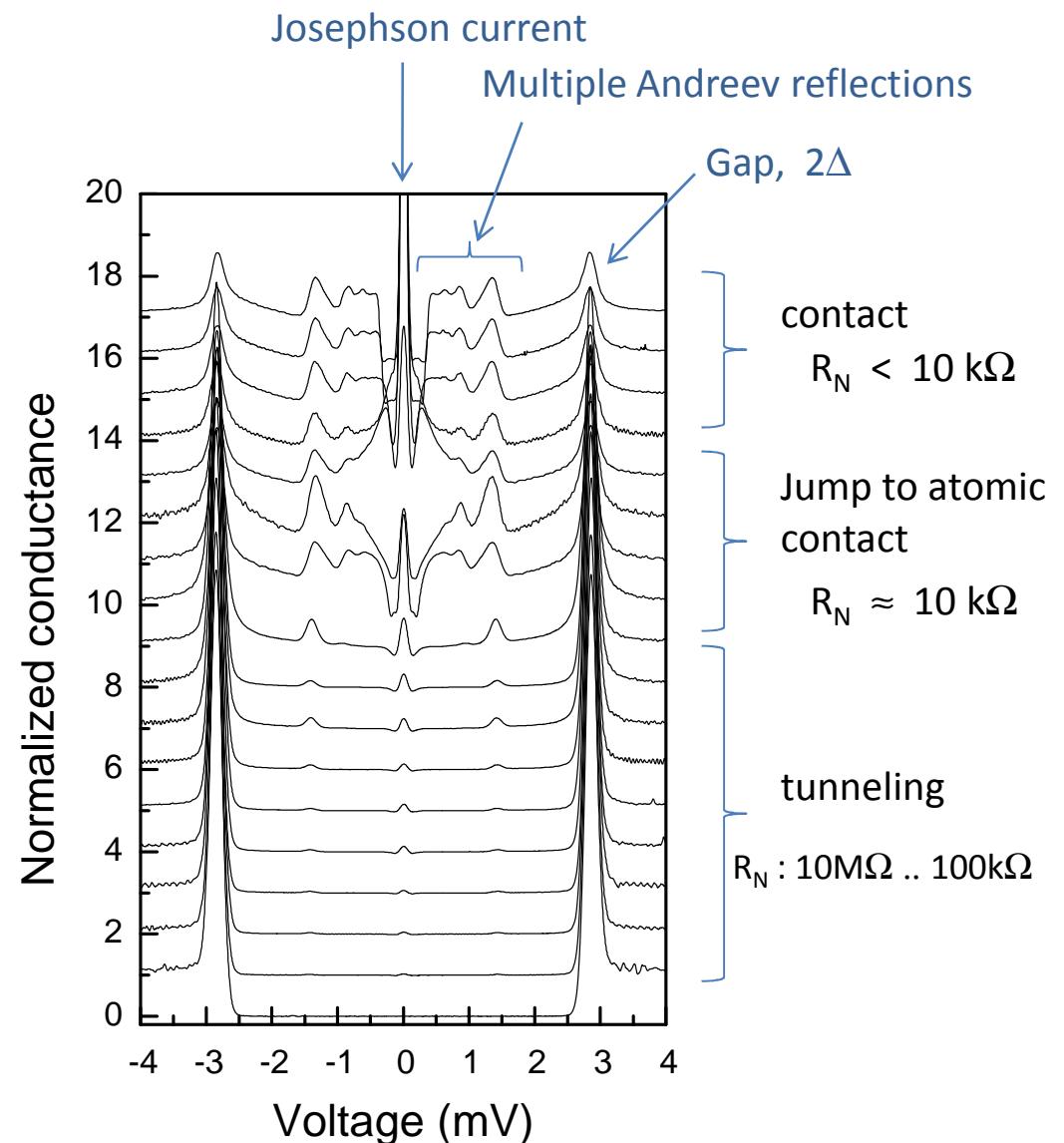
# Using the STM with a superconducting tip. How good is the tip?



**Josephson current:**  $E_J = \frac{\Delta}{4} \frac{R_Q}{R_N}$

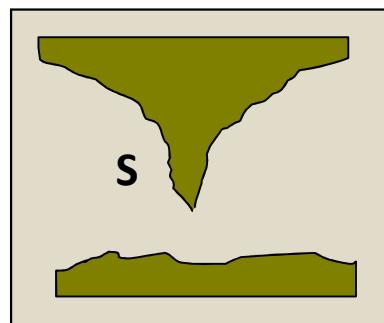
If the tunneling resistance is reduced,  $E_J$  increases, and the Josephson signal will increase. (compare  $E_J$  with  $kT$  !!)

Pb-Pb 300mK

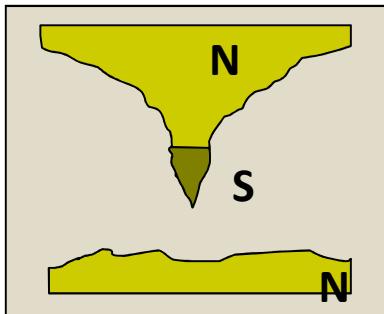


# Using the STM with a superconducting tip. How good is the tip?

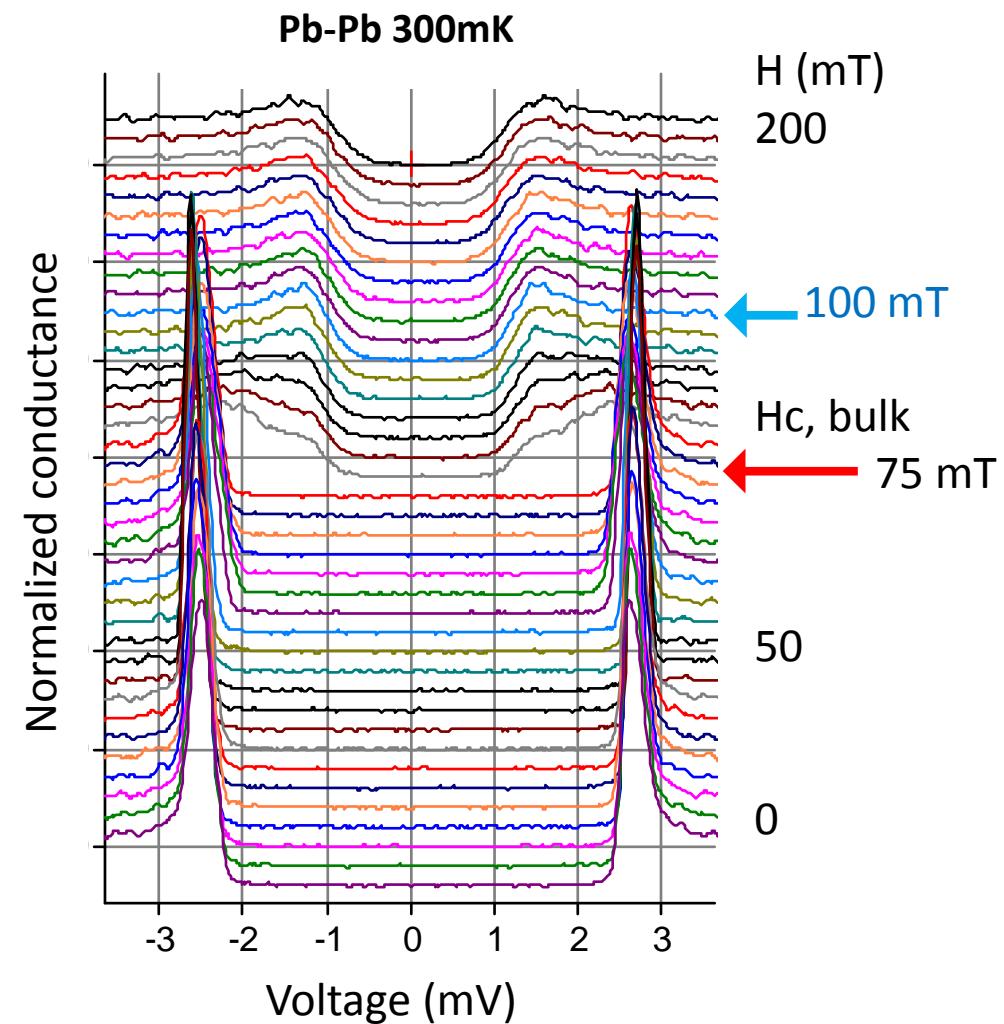
The Pb nanotip remains superconducting, with a well defined DOS at 100 mT



$H < H_{c,bulk}$ :  
both electrodes are  
superconducting.  
**S-S curves**



$H > H_{c,bulk}$ :  
Only the nanotip  
remains  
superconducting.  
**N-S curves**



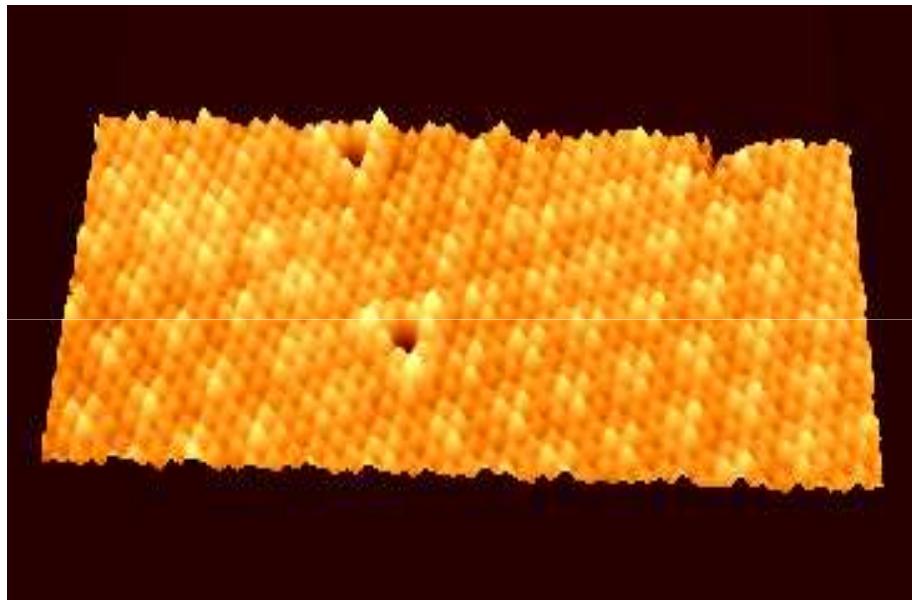
Rodrigo et al., Eur. Phys. J. B **40**, 483 (2004)

Rodrigo et al., Physica C 468 (2008)

# Using the STM with a superconducting tip. How good is the tip?

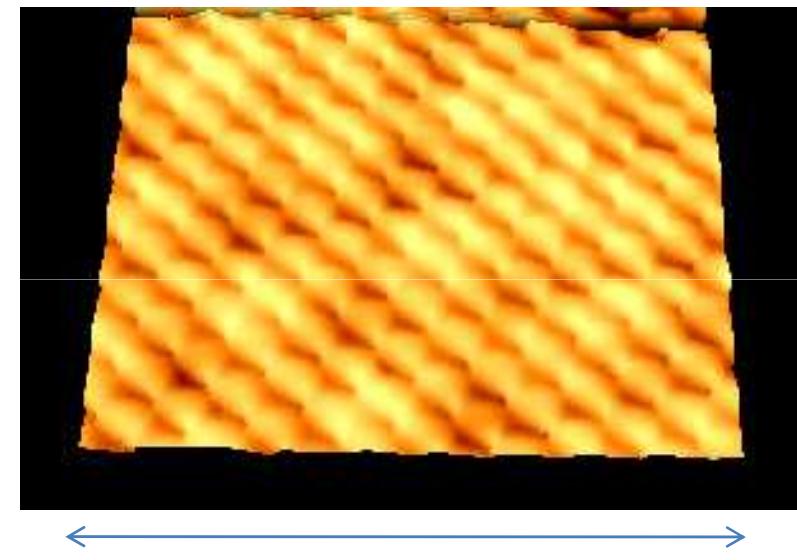
Pb tip: Atomic resolution on NbSe<sub>2</sub>      T=0.3 K

$$R_N = 10 \text{ M}\Omega$$



12 nm

$$R_N = 75 \text{ k}\Omega$$



4 nm

Apparent heights:

- Atoms : 0.10 angstrom
- CDW : 0.15 angstrom
- Hole : 0.30 angstrom

# Using the STM with a superconducting tip. How good is the tip?

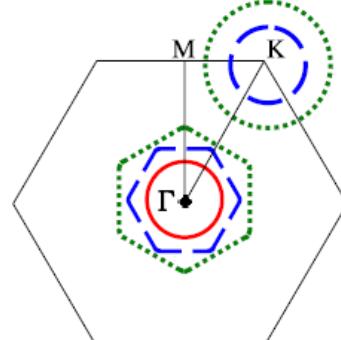
NbSe<sub>2</sub>

2-band superconductor

T<sub>c</sub>=7.2 K

Scenario I :  $\Delta_{\text{Nb bonding}} = \Delta_{\text{Nb anti-bonding}} = 1.26\text{meV}$   
 $\Delta_{\text{Se}} = 0.73\text{meV}$

Scenario II :  $\Delta_{\text{Se}} \sim \Delta_{\text{Nb anti-bonding}} = 1.26\text{meV}$   
 $\Delta_{\text{Nb bonding}} = 0.73\text{meV}$

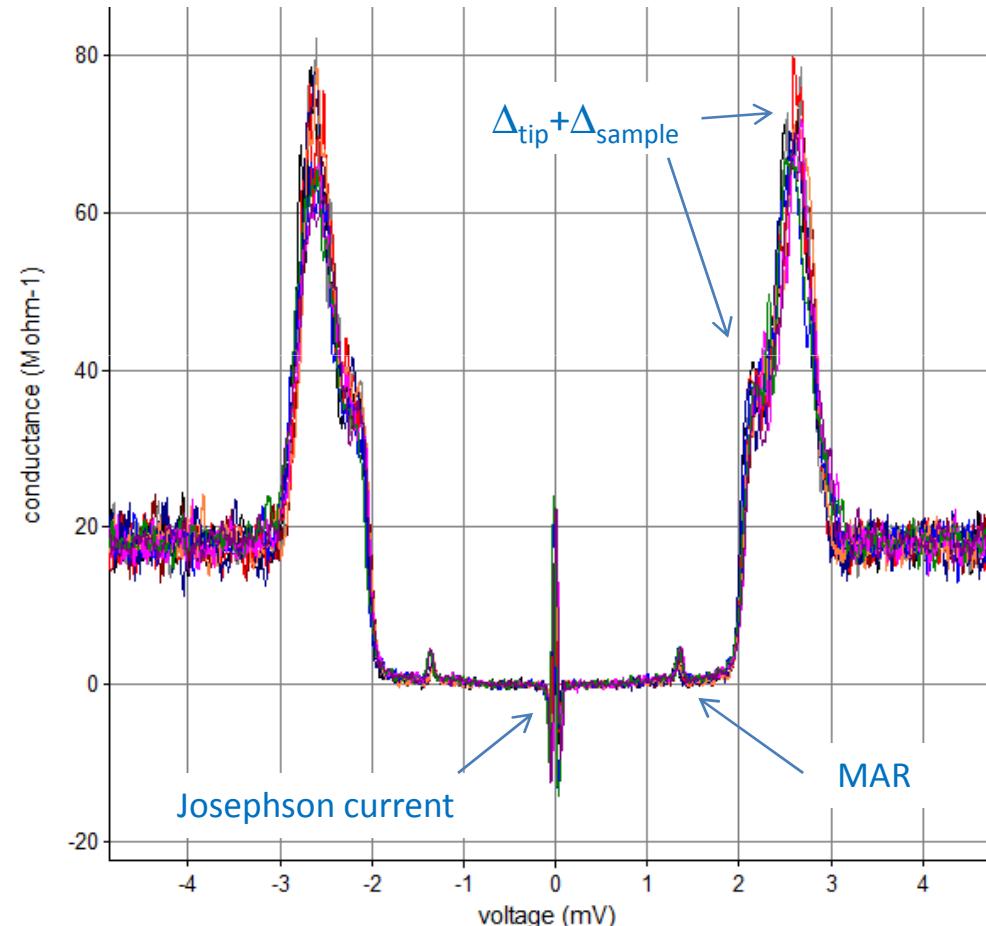


Huang et al, PRB 76 (2007);  
Yokoya et al., Science 294 (2001);  
Rodrigo and Vieira, Physica C 404 (2004)  
Boaknin et al., PRL 90 (2003)

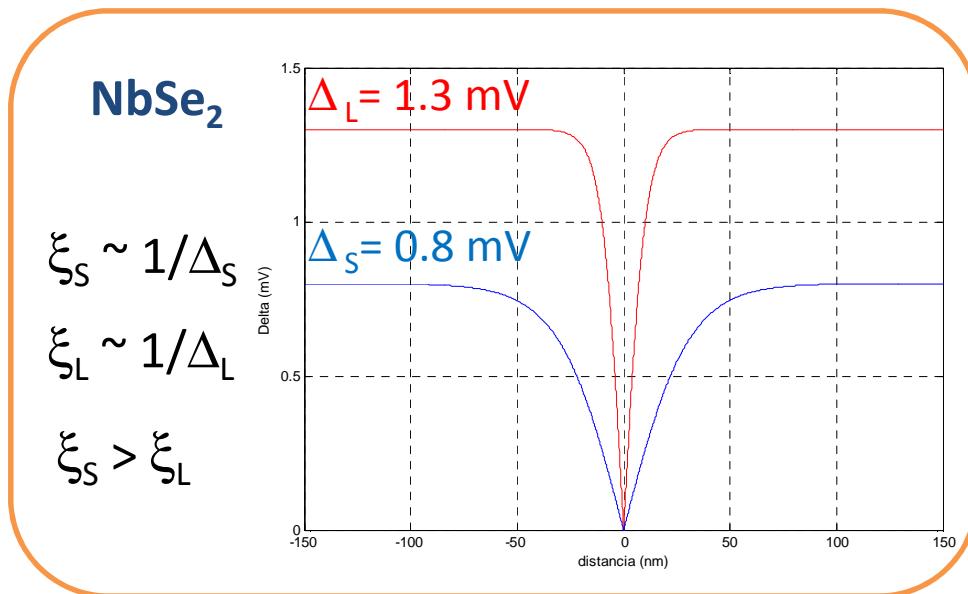
Pb-NbSe<sub>2</sub>

300 mK

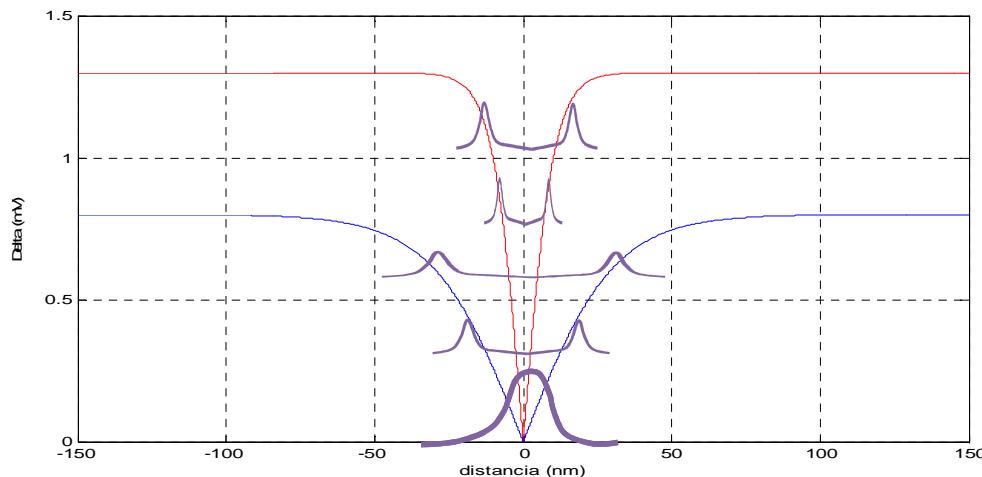
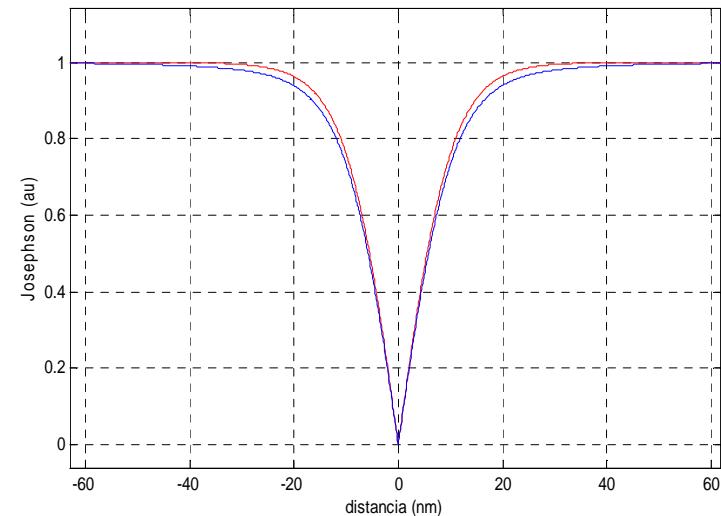
Rn=50 kohm



# Studying the vortex in NbSe<sub>2</sub> with the superconducting tip.



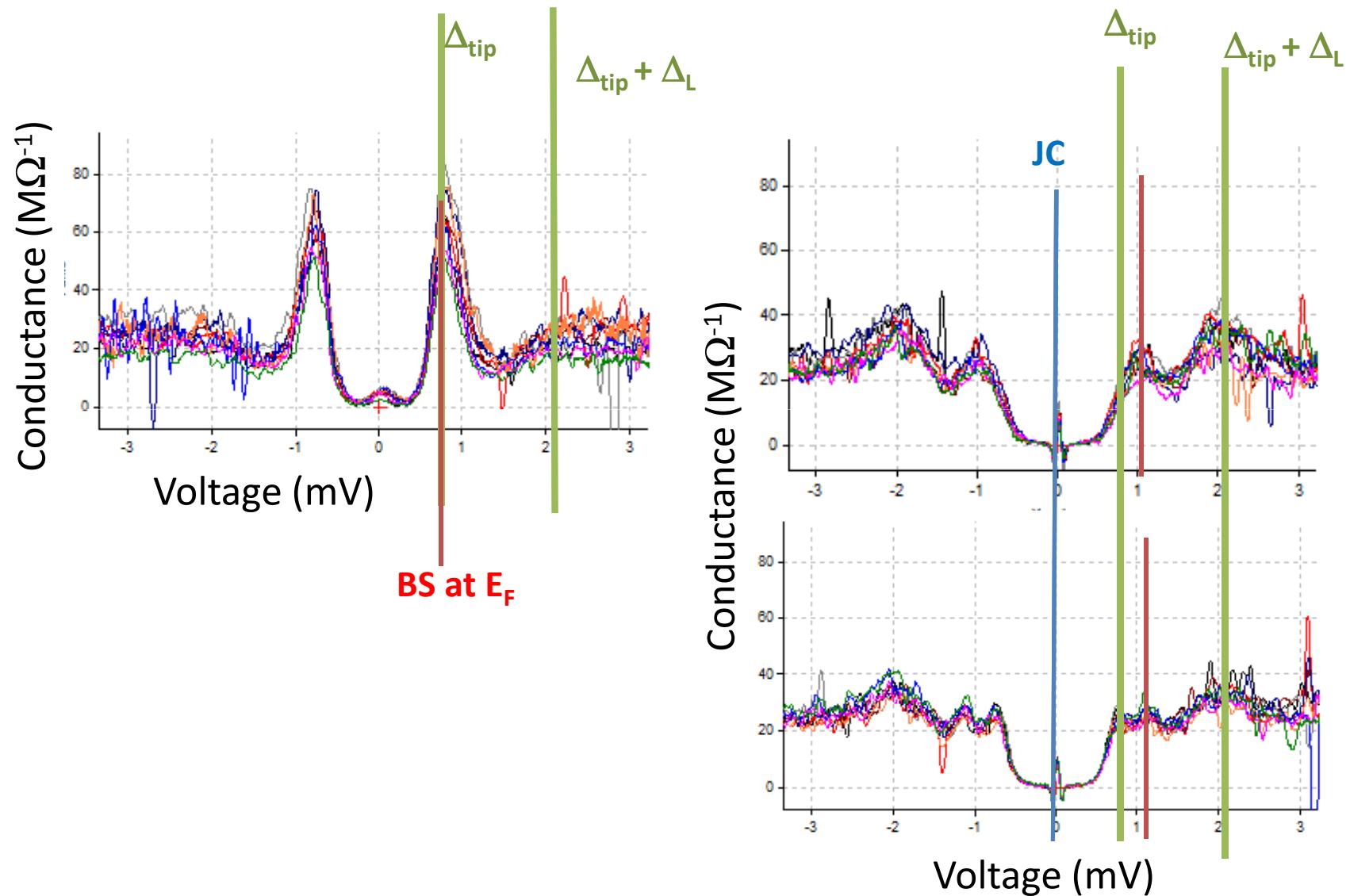
JC profile (blue), compared to  
 $\Delta_L$  profile (red)



I will follow the spatial evolution of  
the electronic bound states

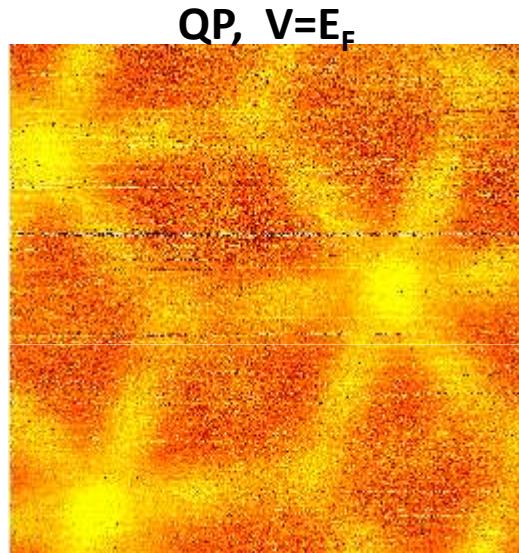
80% from band with “large gap”  
20% from band with “small gap”

# Studying the vortex in $\text{NbSe}_2$ with the superconducting tip.

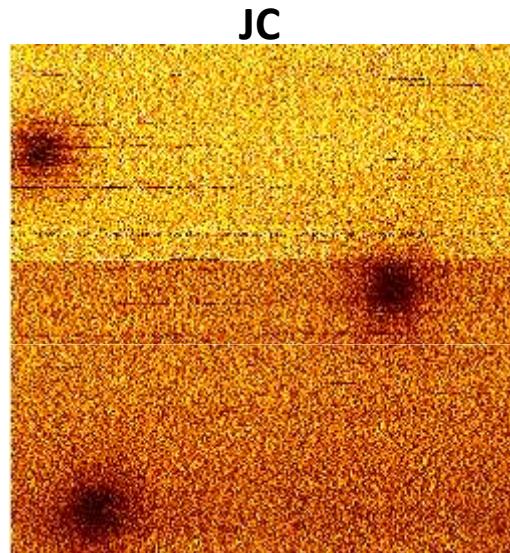


# Studying the vortex in NbSe<sub>2</sub> with the superconducting tip.

@0.3K

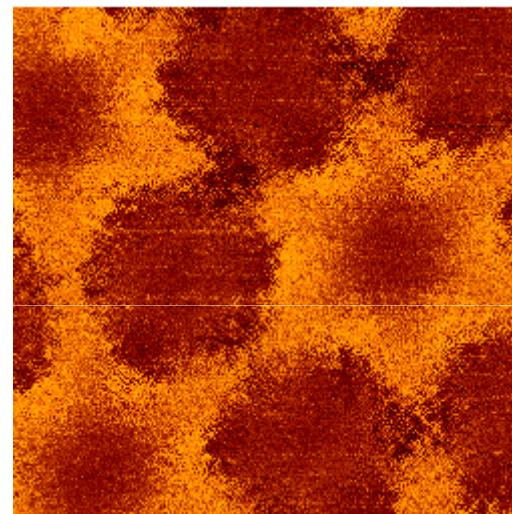


— 20 nm



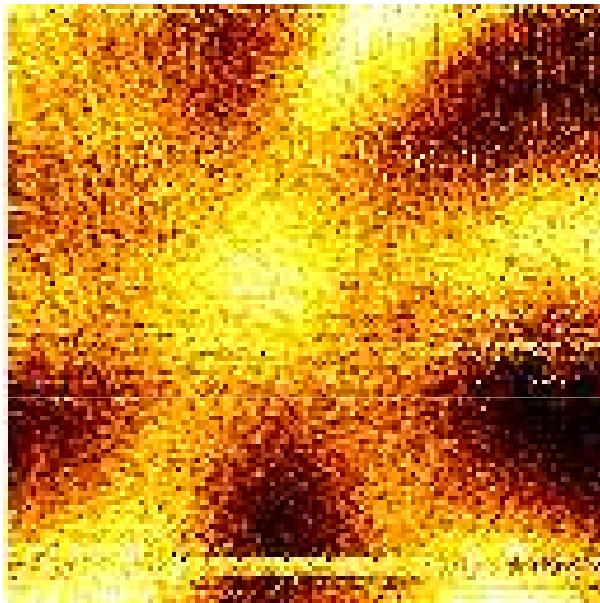
Profile of the  $\Delta_L$   
potential well

BQP: spatial evolution  
of the peak

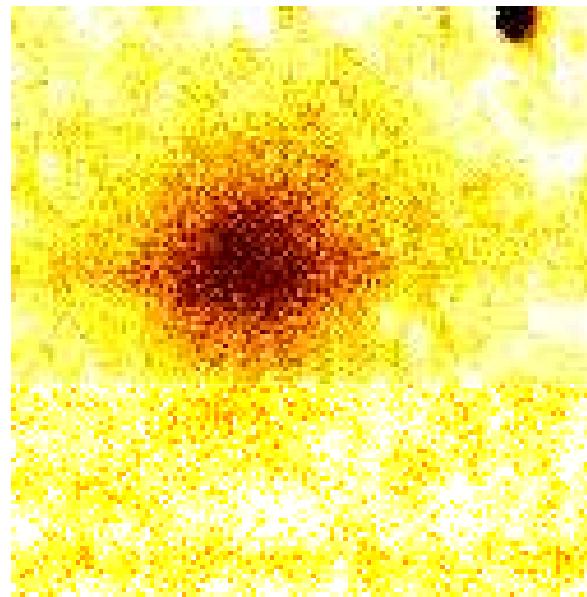


Profile of the  $\Delta_S$   
potential well

## Studying the vortex in $\text{NbSe}_2$ with the superconducting tip.



Conductance image at  
 $V = \Delta_{\text{tip}} = E_F$  sample  
(Lowest E bound state)

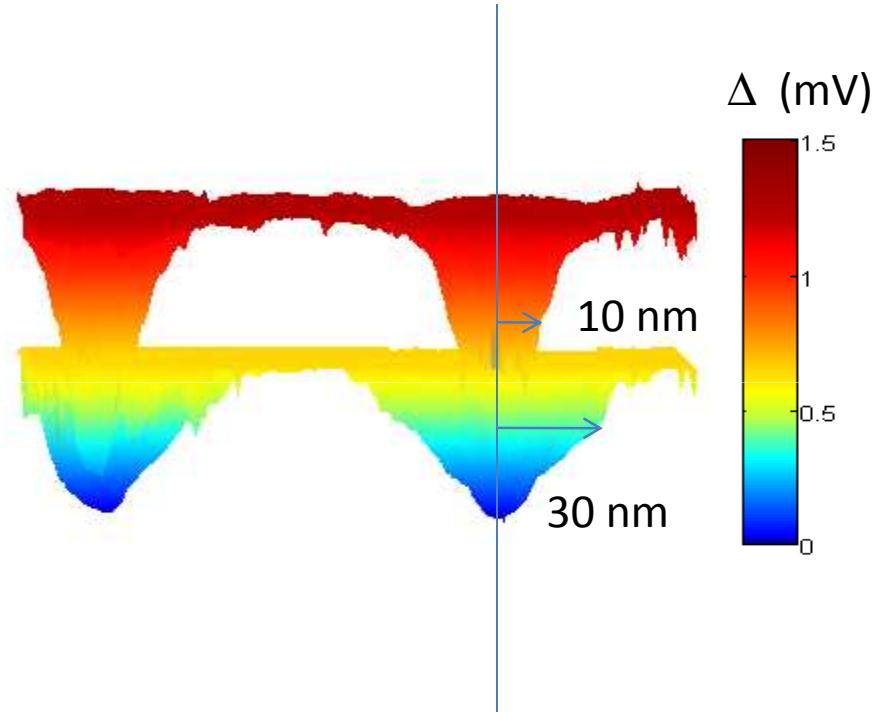


Conductance image at  
 $V = 0$ , Josephson current  
(Profile of the  $\Delta_L$  potential well)

The hexagonal shape of the potential well is observed

## Studying the vortex in $\text{NbSe}_2$ with the superconducting tip.

“The double vortex”



A vortex is not a “simple” object:

Studying a vortex, at low temperatures, with a superconducting tip, we get information about the gap and Fermi surface. (2-band SC)

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- FIS2008-00454)

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