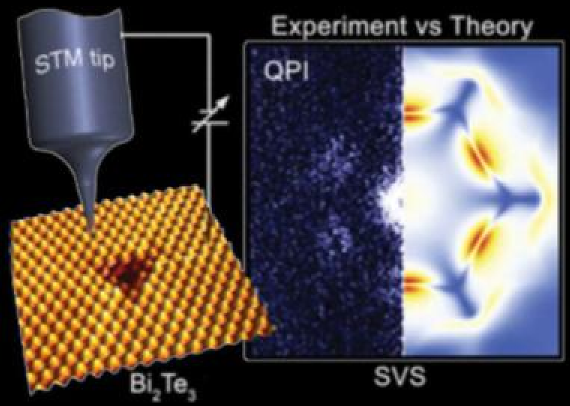
Center for Advanced Mesoscience & Nanotechnology

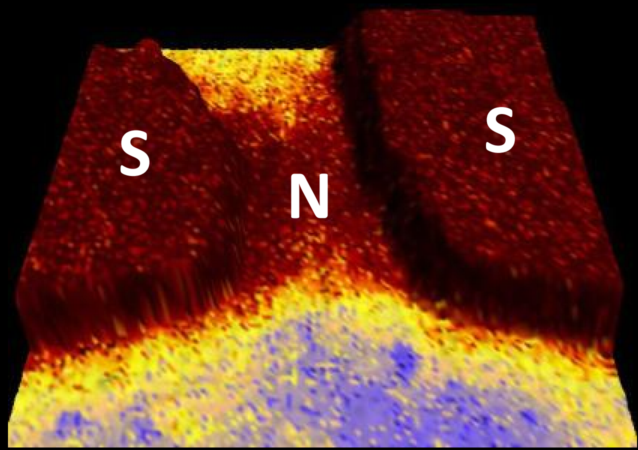
CoLab

MIPT

BIT MIPT Summer school 17-24 July 2023



Prof Vasily Stolyarov



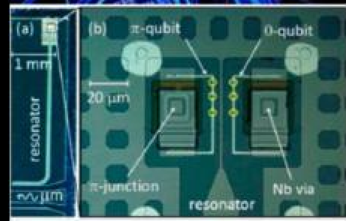
MEZO Center for Advanced Mesoscience & Nanotechnology

MIPT

Like in Manchester but Advanced …

Superconducting Quantum technology

Superconducting Digital electronics



Superconducting Neuromorphic systems

Topologically protected systems

Center for Advanced Mesoscience & Nanotechnology

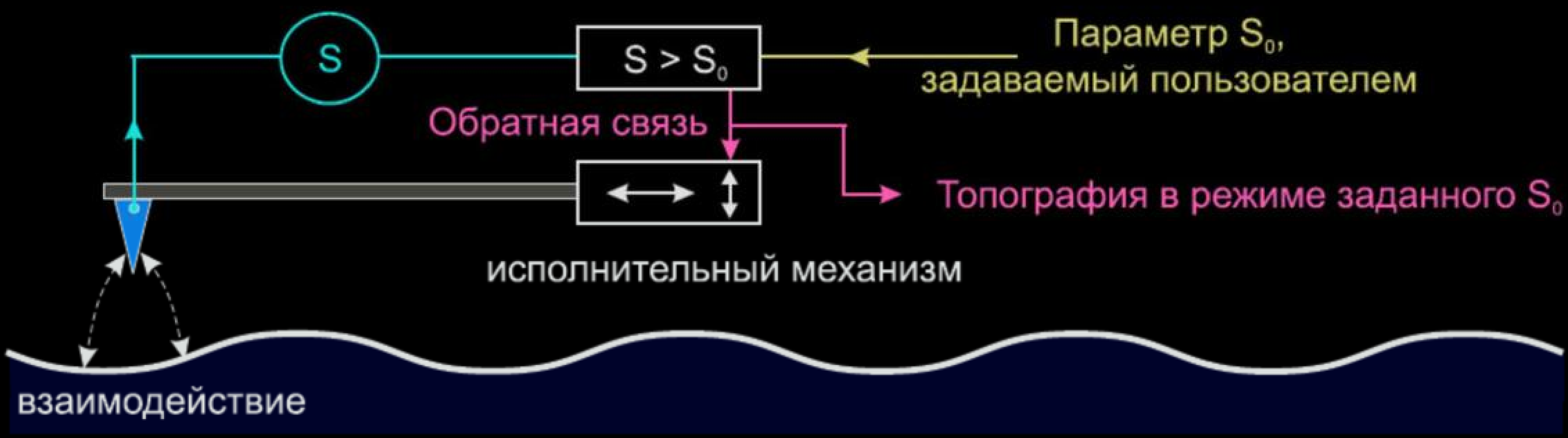
Cryogenic Scanning probe microscopy for superconducting heterostructures

Center for Advanced Mesoscience & Nanotechnology

Cryogenic Scanning probe microscopy for superconducting heterostructures

- Scanning Tunneling Microscopy: STM, STS, spin-polarized STM
- Scanning Atomic Force Microscopy: AFM, MFM, Kelvin probe, Force probe…
- Nearfield Scanning Optic Microscopy: NSOM
- Nearfield Scanning RF Microscopy
- Hall probe Microscopy or SQUID Microscopy
- Scanning Laser Microscopy
- Scanning Electron Microscopy

Cryogenic Scanning probe microscopy for superconducting heterostructures



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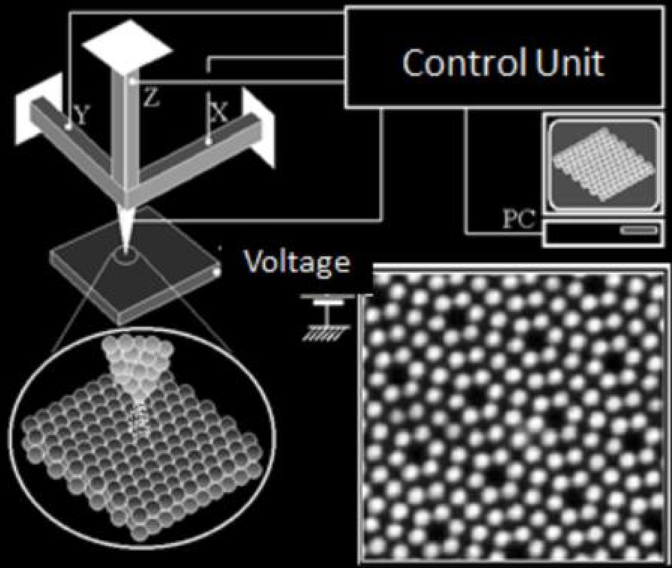
Cryogenic Scanning Tunneling Microscopy

Introduction

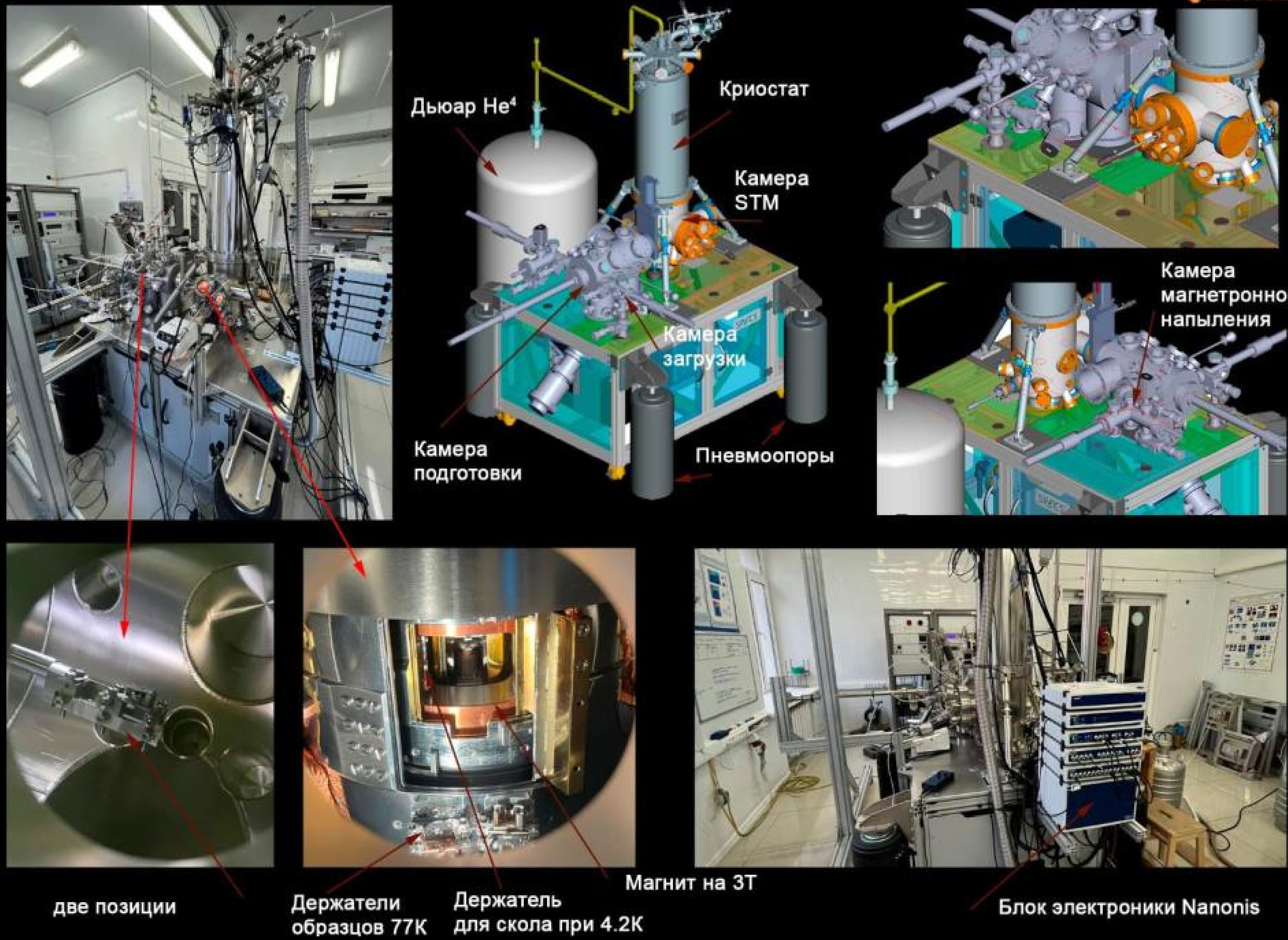
Invention of Scanning Tunneling Microscope

Ernst Ruska **Gerd Binnig** **Heinrich Rohrer**

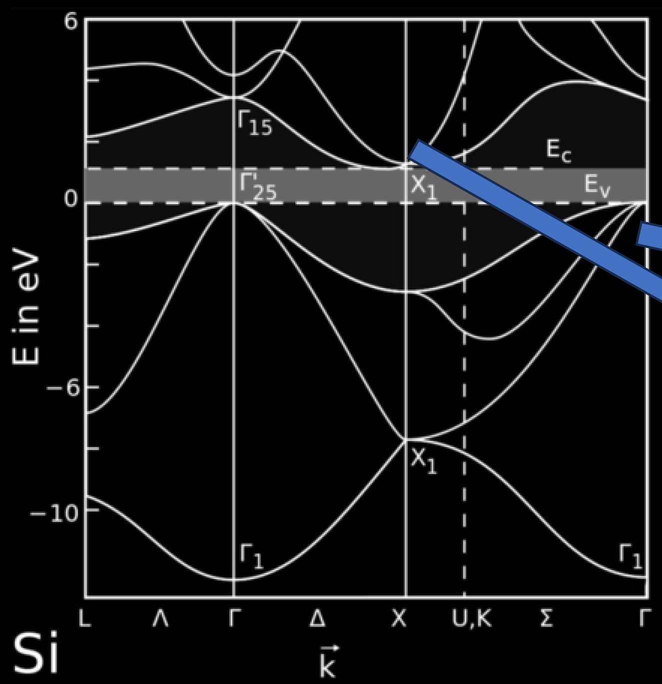


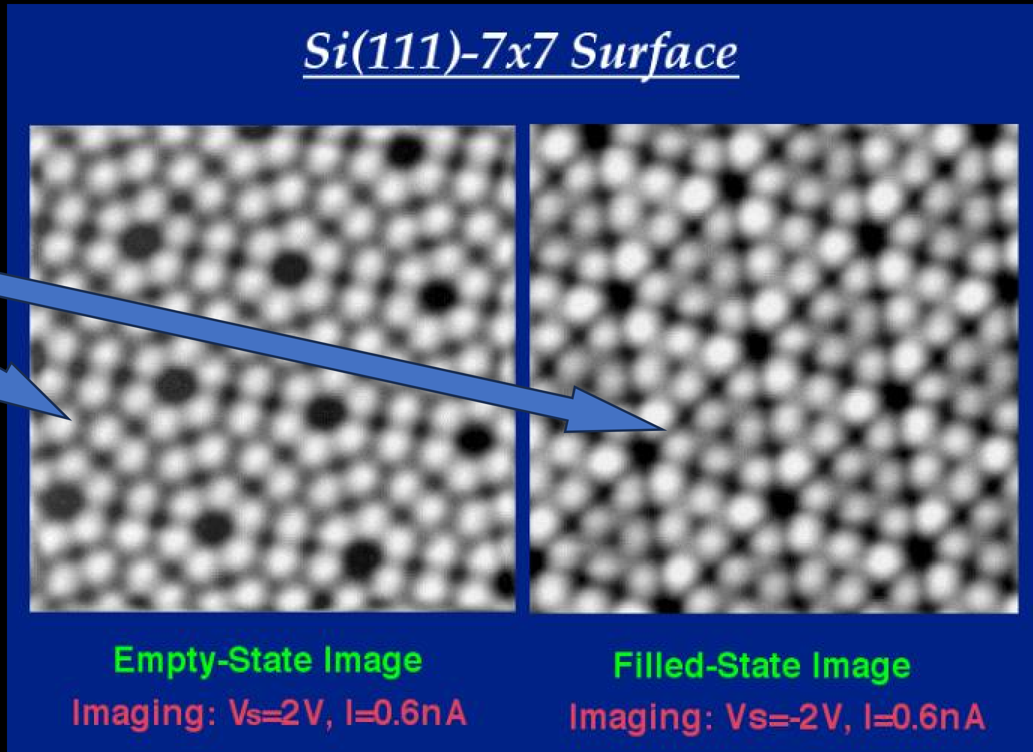
The Nobel Prize in Physics 1986: to Ernst Ruska *"for his fundamental work in electron optics, and for the design of the first electron microscope »* and to Gerd Binnig and Heinrich Rohrer *"for their design of the scanning tunneling microscope"*.

- **JT-STM SPECS (Joule-Thomson**
- **Scanning Tunneling Microscope)**
- P≤10^{-10} mbar, T = 1.2 K,
- Magnetic Field up to 3 T
- Scanning area 2 mkm^2



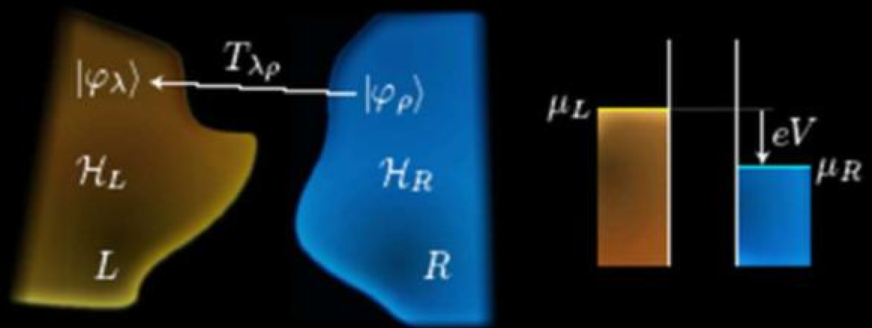
Imaging of valence and conduction states in a semiconductor





The images depend on the applied voltage.
This is a spectroscopic effect, what do we measure exactly with STM?

Tunneling spectroscopy



The Fermi golden rule is used in deriving the tunneling current.

Fermi's golden rule is a formula that describes the transition rate (the probability of a transition per unit time) from one energy eigenstate of a quantum system to a group of energy eigenstates in a continuum, as a result of a weak perturbation.

Consider the tunneling rate $t_{\lambda\rho}$ between the two state at left and right systems described by $|\varphi_\lambda>$ and $|\varphi_\rho>$.

The probability of transition from state λ to state ρ per unit time is:

$$t_{\lambda\rho} \propto \left|M_{\lambda\rho}\right| \delta(E_\lambda - E_\rho)$$

Where :

$$M_{\lambda\rho} = \langle \varphi_\lambda | V | \varphi_\rho \rangle$$

$$M_{\lambda\rho} = \int \varphi_\lambda^*(\vec{r}) V(\vec{r}) \varphi_\rho(\vec{r}) d^3\vec{r}$$

Here $V(r)$ is the mutual perturbation of the two systems

Tunneling spectroscopy

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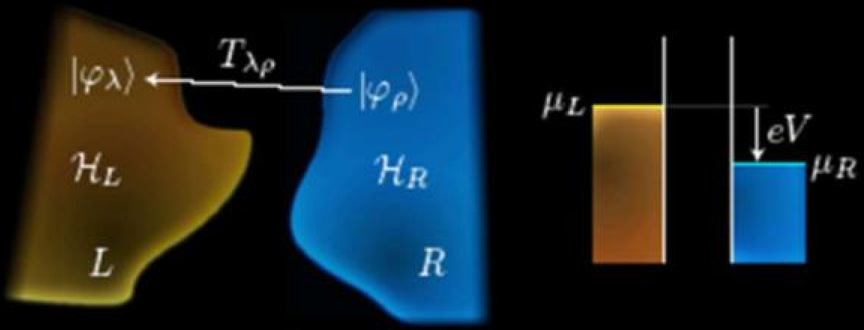

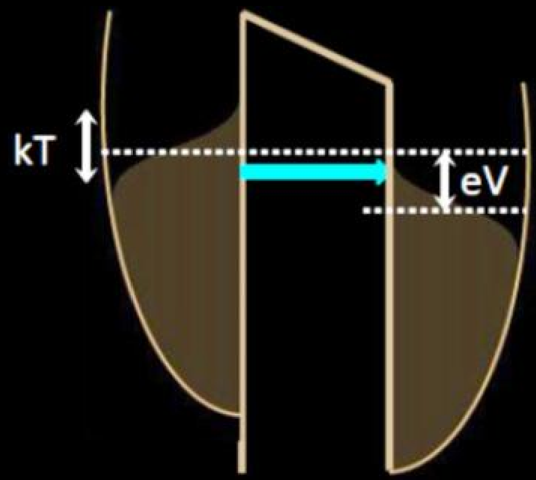

At finit temperature T, the probability of occupation of the state λ is given by the Fermi-Dirac distribution :

$$f(E_\lambda) = \frac{1}{1+\exp((E_\lambda - \mu_\lambda)/kT)}$$

– μ_λ is the chemical potentiel (Fermi level)

The current of electrons from left to right is proportional to the probability that the state λ is occupied f(Eλ) and the probability that the state ρ is empty (1-f(Eρ))

$$I_{l-r} \propto \sum_{\lambda\rho} t_{\lambda\rho} f(E_\lambda)(1 - f(E_\rho - eV))$$

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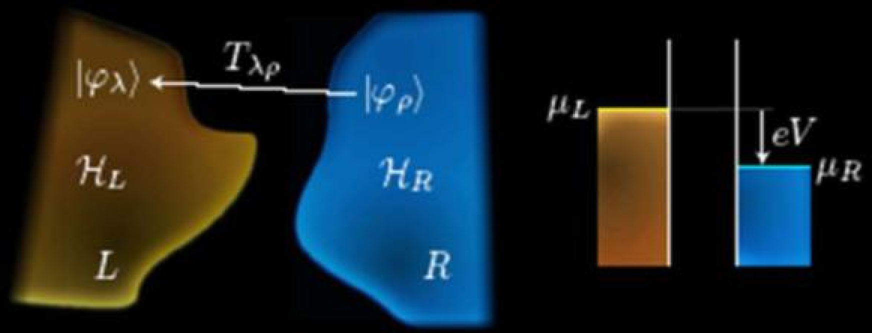
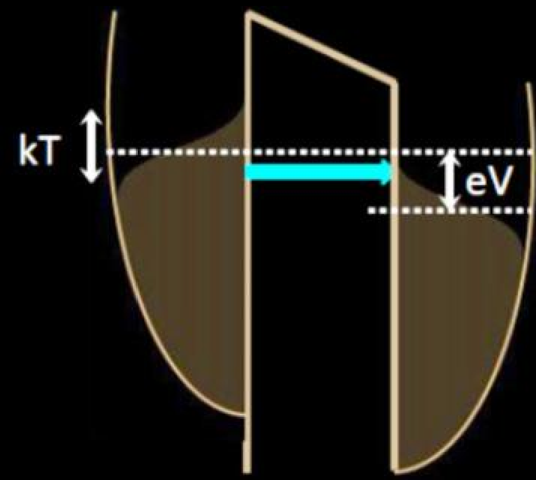
Tunneling spectroscopy





The total current $I_{total} = I_{l\text{-}r} - I_{r\text{-}l}$

$$I_{l-r} \propto \sum_{\lambda\rho} t_{\lambda\rho} f(E_\lambda)(1 - f(E_\rho - eV))$$

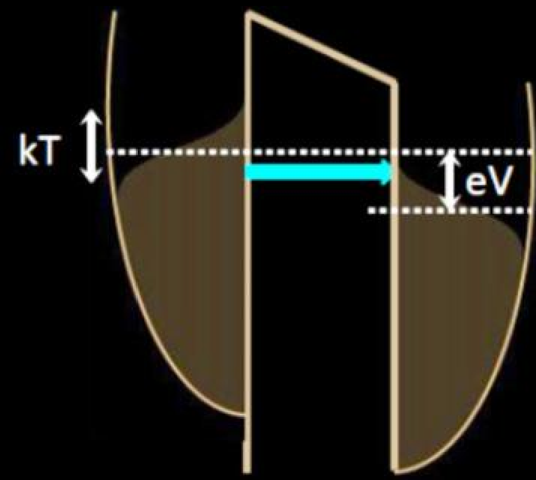
$$I_{r-l} \propto \sum_{\lambda\rho} t_{\lambda\rho} (1 - f(E_\lambda)) f(E_\rho - eV)$$

$$t_{\lambda\rho} \propto |M_{\lambda\rho}| \delta(E_\lambda - E_\rho)$$

$$I_{total} \propto \sum_{\lambda\rho} |M_{\lambda\rho}| (f(E_\lambda) - f(E_\rho - eV)) \delta(E_\lambda - E_\rho)$$

Calculation of the matrix element for an idealized STM tip

The problem is how to calculate $M_{\lambda\rho} = \int \phi_\lambda^*(\vec{r})V(\vec{r})\,\phi_\rho(\vec{r})d^3\vec{r}$?



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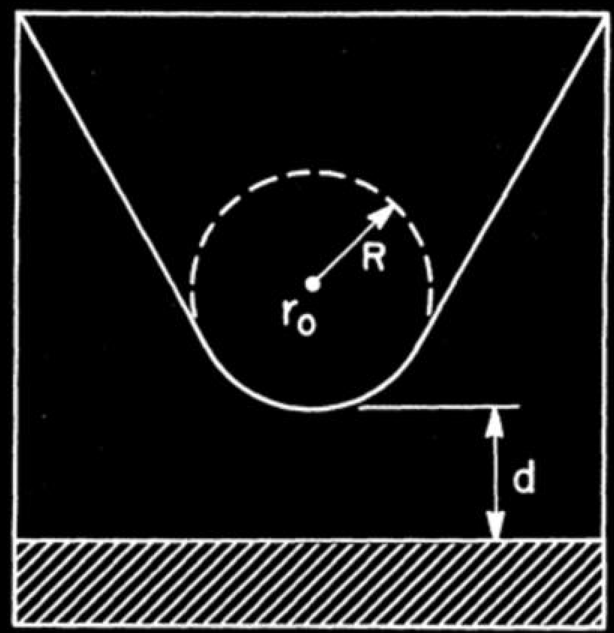
Tersoff and Hamann demonstarte that for a tip with a local spherical potencial at the apex:

$$M_{\lambda\rho} \propto M_0 \varphi_\lambda(\vec{r}_0)$$

$\vec{r}_0 = (x, y, z_0)$ -position of the las atom of the tip



(Phys. Rev. Letters 50, 1998 (1983); PRB 31, 805 (1985))

Calculation of the matrix element for an idealized STM tip

Center for Advanced Mesoscience & Nanotechnology

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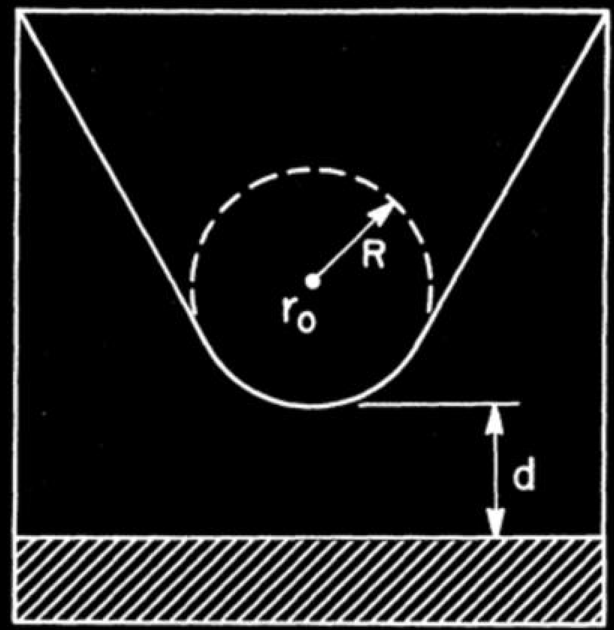
By replacing the $\sum_{\lambda\rho}$ - by the integral over all energies $d\omega$, we can write, within Tersoff and Hamann's approximation



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Calculation of the matrix element for an idealized STM tip

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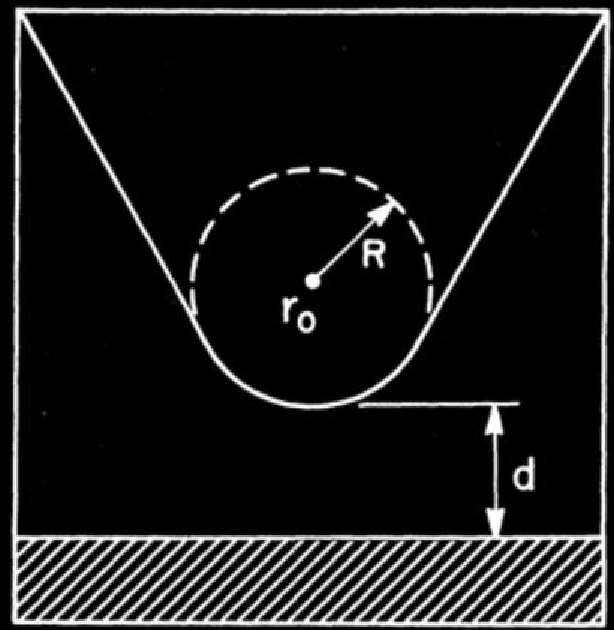
$$I_{total}(\vec{r}_0, V) \propto M_0^2 \int_{\omega} \sum_{\lambda} |\varphi_{\lambda}(\vec{r}_0)|^2 \delta(E_{\lambda} - \omega)(f(\omega) - f(\omega - eV))d\omega$$

The value

$$\rho(\vec{r}_0, \omega) \propto \sum_{\lambda} |\varphi_{\lambda}(\vec{r}_0)|^2 \delta(E_{\lambda} - \omega)$$

is known as Local Density of States (LDOS)



(Phys. Rev. Letters 50, 1998 (1983); PRB 31, 805 (1985))

!! The tunneling current vs bias contain the information about LDOS of the sample measured at the position of tip apex !!

Calculation of the tunneling current

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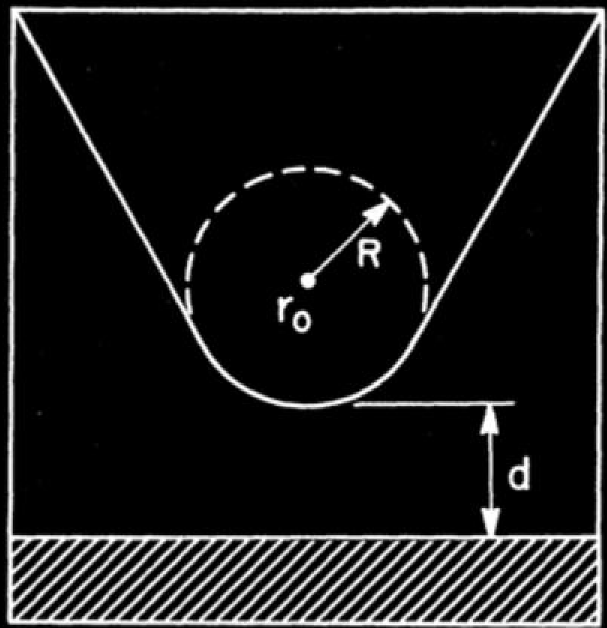
In a more general case of a non-constant LDOS of the tip $\rho(r_0, E)$, the total current can write:

$$I_T(r,V) = \frac{4\pi e}{\hbar}\int_{-\infty}^{+\infty} |M|^2 \,[f(\omega - eV) - f(\omega)]\rho_t(r_0, \omega - eV)\, \rho_s(r,\omega)d\omega$$

DOS of tip DOS of sample

Often, the tunneling conductance, $\frac{\partial I_T(r, V)}{\partial V}$ is measured/studied :

$$\frac{\partial I}{\partial V} \propto \int \rho_S(\omega)\frac{\partial \rho_T(\omega - eV)}{\partial V}[f(\omega - eV, T) - f(\omega, T)]d\omega + \\ + \int \rho_S(\omega)\rho_T(\omega - eV)\frac{\partial f(\omega - eV, T)}{\partial V}d\omega$$



(Phys. Rev. Letters 50, 1998 (1983); PRB 31, 805 (1985))

It looks complicate, but it is a folding integral within the unknown LDOS of the sample.

If in the bias window of interest $\rho_t(r_0, \omega) = cte$, then:

$$\frac{\partial I_T(r,V)}{\partial V} = \frac{4\pi e}{\hbar}\rho_t(r_0,\omega)|M|^2 \int_{-\infty}^{+\infty} \rho_s(r,\omega)\frac{\partial f(\omega - eV)}{\partial V}d\omega$$

1957: Microscopic Theory of Superconductivity (BCS)

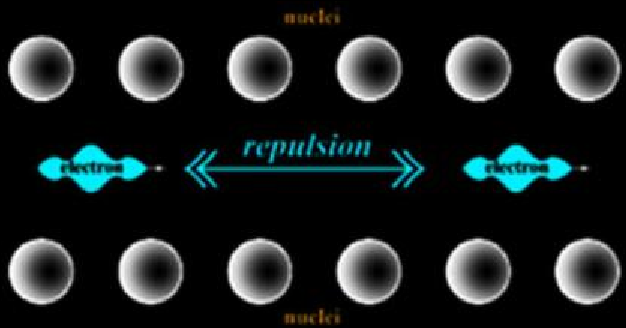
Center for Advanced Mesoscience & Nanotechnology

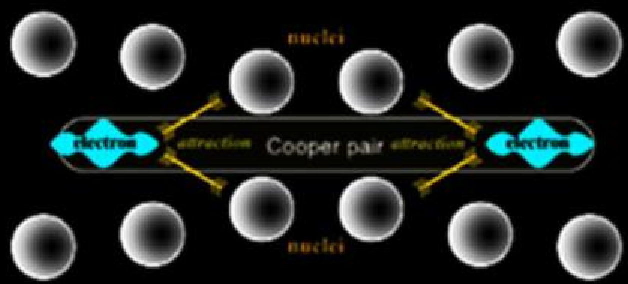
(Nobel prize: 1972)

John Bardeen

Leon Neil Cooper

John Robert Schrieffer

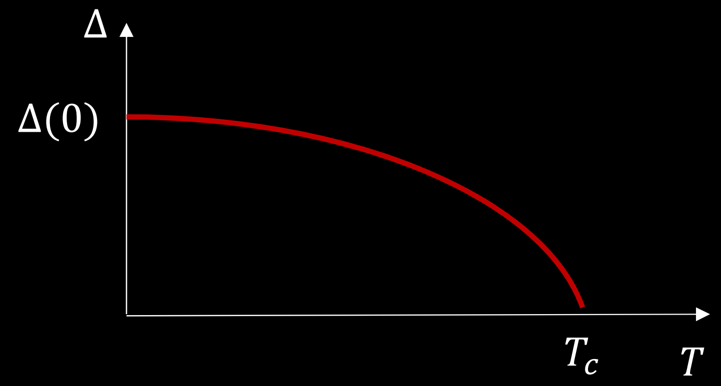




Quantum Tunneling to superconductors

Conventional (BCS) superconductor:
Gap *2Δ* in the excitation spectrum:

$$\rho_s(\omega)_{BCS} = \frac{E}{\sqrt{E^2 - \Delta(T)^2}}$$



$$\frac{2\Delta(0)}{k_B T_c} = 3.52$$

$$\frac{\partial I_T(r,V)}{\partial V} = \frac{4\pi e}{\hbar}\rho_t(r_0,\omega)|M|^2 \int_{-\infty}^{+\infty} \rho_s(r,\omega)\frac{\partial f(\omega - eV)}{\partial V} d\omega$$

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1960: Quantum Tunneling, Gap, Signatures of Electron-Phonon Interaction

Leo Esaki

Ivar Giaever

Brian Josephson

The Nobel Prize in Physics 1973 *"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively"* and *"for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"*.

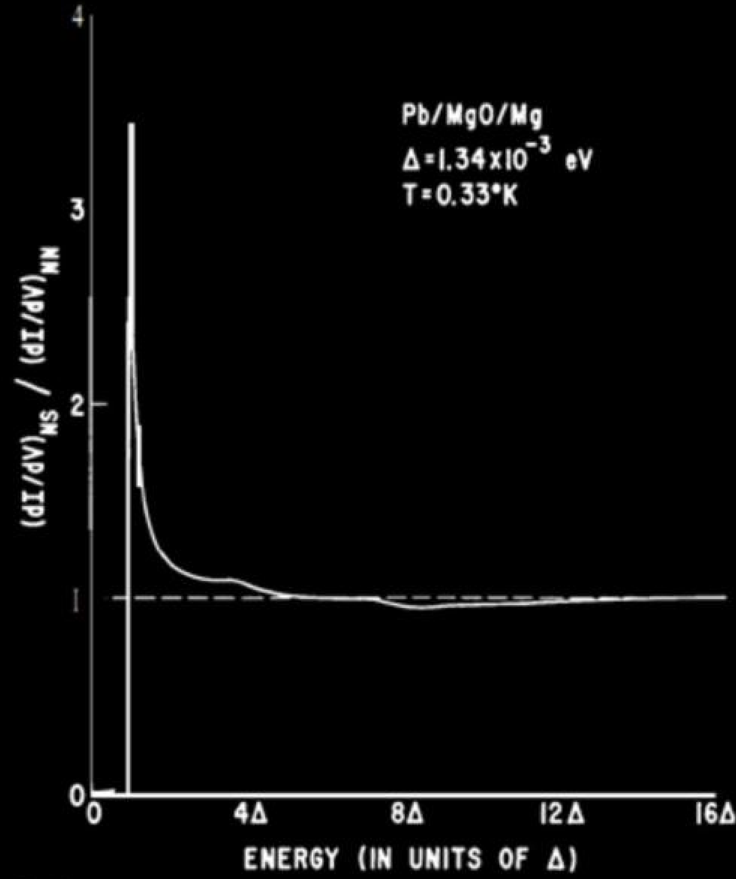
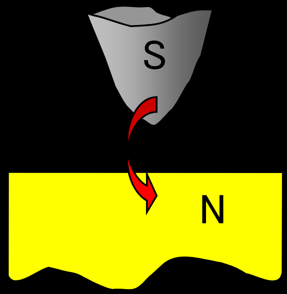


Fig. 12.
A normalized derivative of the current with respect to voltage of a lead junction at low temperature. The simple BCS-theory predicts that the derivative should approach unity asymptotically as the energy increases. Instead several wiggles are observed in the range between 4Δ and 8Δ. These wiggles are related to the phonon spectrum in lead.

Tunneling into a Superconductor

$$\frac{dI}{dV}(V) = -\frac{2\pi e^2 T}{\hbar} N_p \int_{-\infty}^{\infty} N_S(E+eV)\, \frac{\partial f}{\partial E}(E)\, dE$$

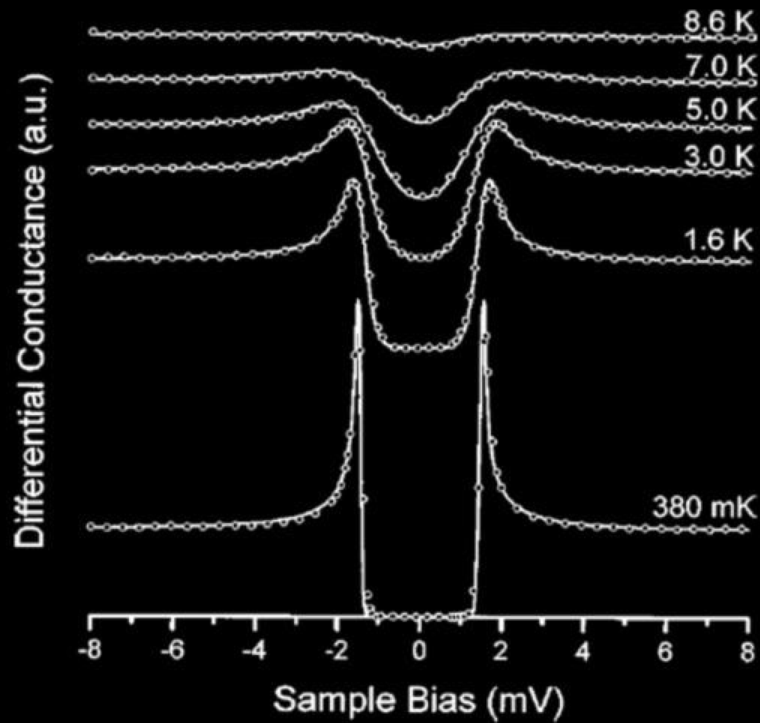


BCS-kind Superconductor:
Gap 2Δ in the excitation spectrum:

$$N_s(E) = N(0)\frac{E}{\sqrt{(E^2-\Delta^2)}}$$

BCS

$$\frac{2\Delta(0)}{k\,T_c} \approx 3.5$$



Pan, Davis, Univ. de Berkeley.(APL,1998)

Tunneling spectroscopy of superconductors

157003 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

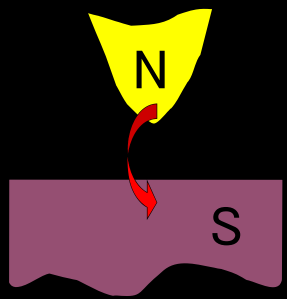
Scanning Tunneling Spectroscopy Study of the Proximity Effect in a Disordered Two-Dimensional Metal

L. Serrier-Garcia,[1] J. C. Cuevas,[2] T. Cren,[1,*] C. Brun,[1] V. Cherkez,[1] F. Debontridder,[1] D. Fokin,[1,3] F. S. Bergeret,[4] and D. Roditchev[1]

[1]*Institut des Nanosciences de Paris, Université Pierre et Marie Curie (UPMC) and CNRS-UMR 7588, 4 place Jussieu, 75252 Paris, France*

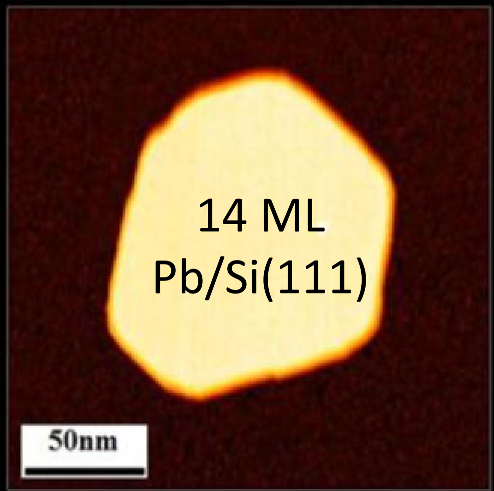
$$dI/dV(\mathbf{r}) = \int_{-\infty}^{\infty} N_s(E,\mathbf{r})\left[\frac{-\partial f(E+eV)}{\partial (eV)}\right] dE$$

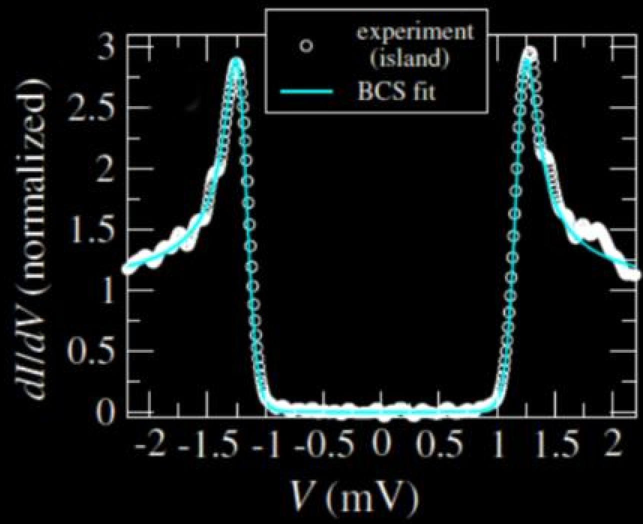
Convolution



BSC DOS

$$N_S(E) = N_N(E)\frac{E}{\sqrt{E^2-\Delta^2}}$$

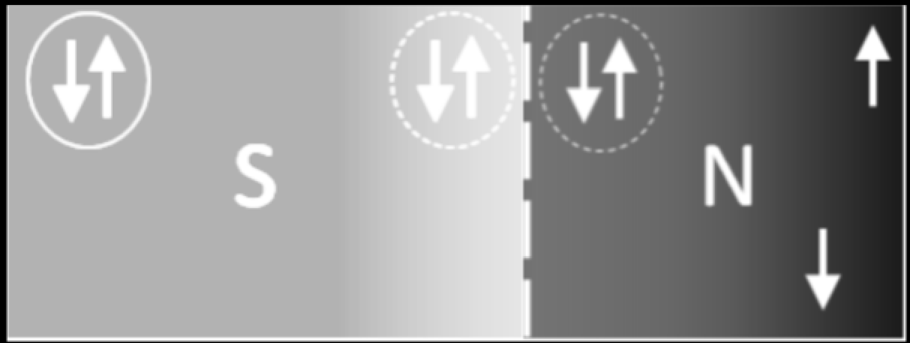




$\Delta = 1.20$ meV $T_{eff} = 0.38$K

Superconducting proximity effect

boundary



Superconductor Non supercond. metal

First experimental evidences

Holm and Meissner (1932)
Bedard and Meissner (1956)
Meissner (1958), (1960)

First theory

De Gennes (1964)
McMillan (1968)
Clarke (1969)
Deutscher and De Gennes (1969)

Superconducting proximity effect

Center for Advanced Mesoscience & Nanotechnology

boundary

Superconductor Non supercond. metal

In case of diffuse metal

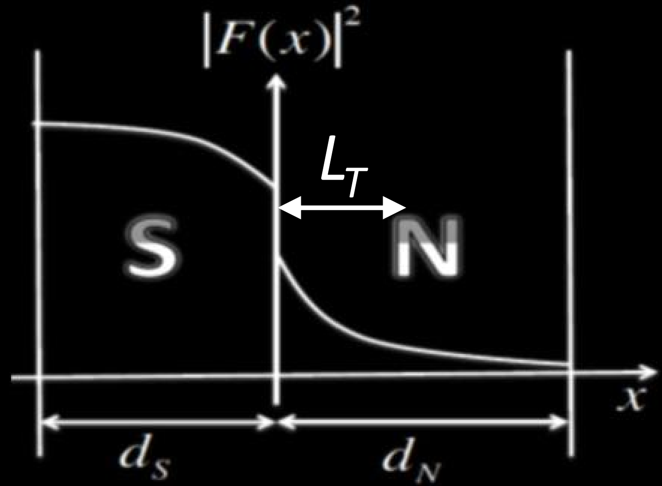
$$L_T = \sqrt{\hbar D_N / (2\pi k_B T)}$$

Cooper pair density

$$F(\vec{r}) = \langle \hat{\psi}_\uparrow(\vec{r}) \hat{\psi}_\downarrow(\vec{r}) \rangle$$

Order parametr:

$$\Delta(\vec{r}) = V(\vec{r}) F(\vec{r})$$



First experimental evidences

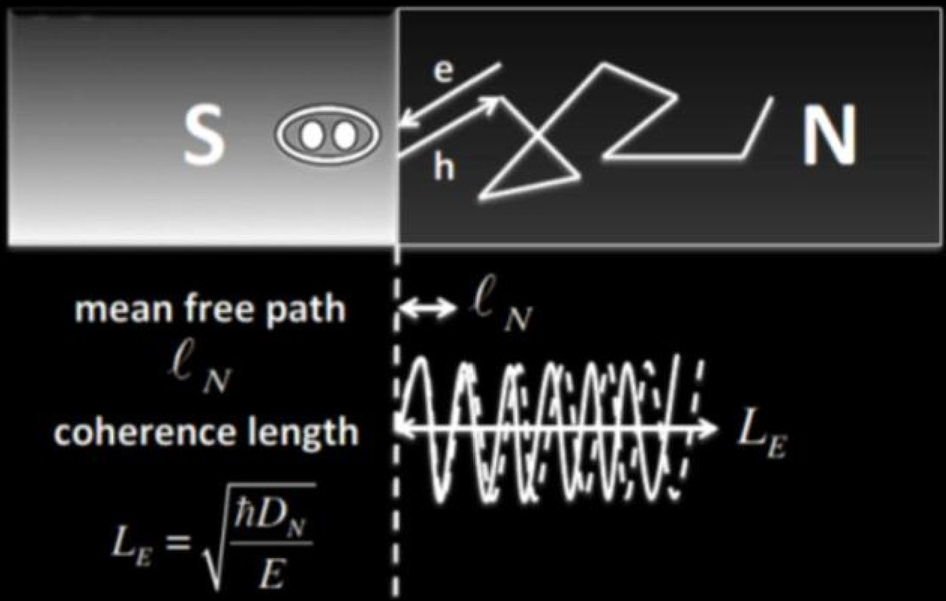
Holm and Meissner (1932)
Bedard and Meissner (1956)
Meissner (1958), (1960)

First theory

De Gennes (1964)
McMillan (1968)
Clarke (1969)
Deutscher and De Gennes (1969)

Modern description of the proximity effect

Andreev reflection at the S/N boundary + extended phase coherence in N

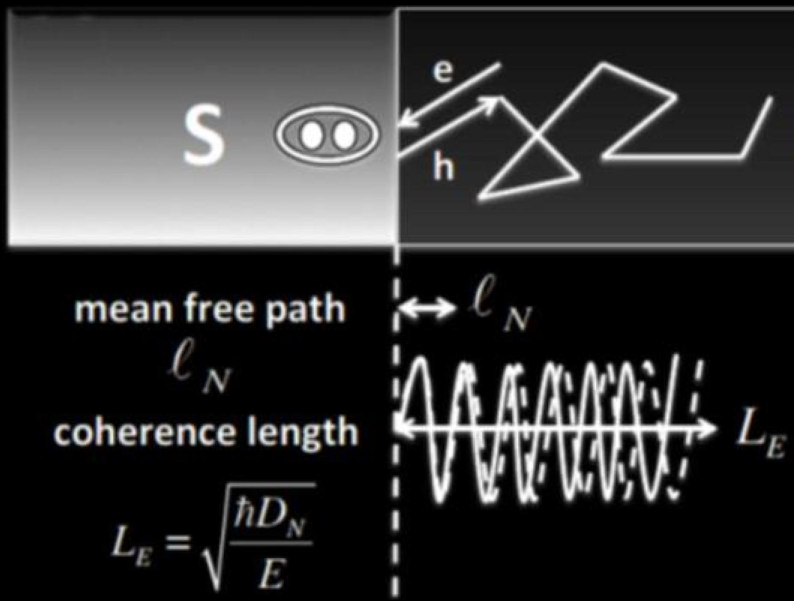


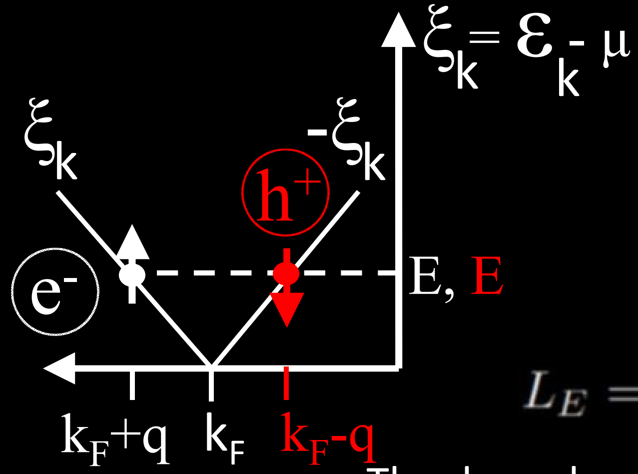
Andreev (1964),
Eilenberger (1968),
Usadel (1970),
Eliashberg (1971)

Larkin *et al.* (1968,75,77),
Schmid & Schön (1975),
Blonder *et al.* (1982),
Zaitsev (1984)

Modern description of the proximity effect

Andreev reflection at the S/N boundary + extended phase coherence in N





$$\Delta\phi = 2Et/\hbar$$

$$t_D = \hbar/E$$

$$L_E = \sqrt{Dt_D} = \sqrt{\hbar D/E}$$

The decay length of pair correlations depends on the energy

Andreev (1964),
Eilenberger (1968),
Usadel (1970),
Eliashberg (1971)

Larkin *et al.* (1968,75,77),
Schmid & Schön (1975),
Blonder *et al.* (1982),
Zaitsev (1984)

Modern description of the proximity effect

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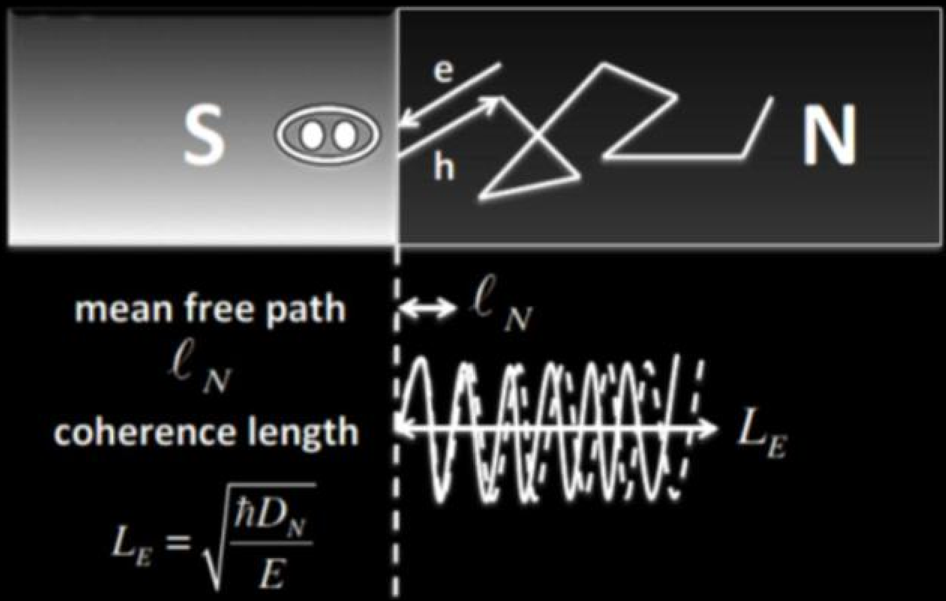
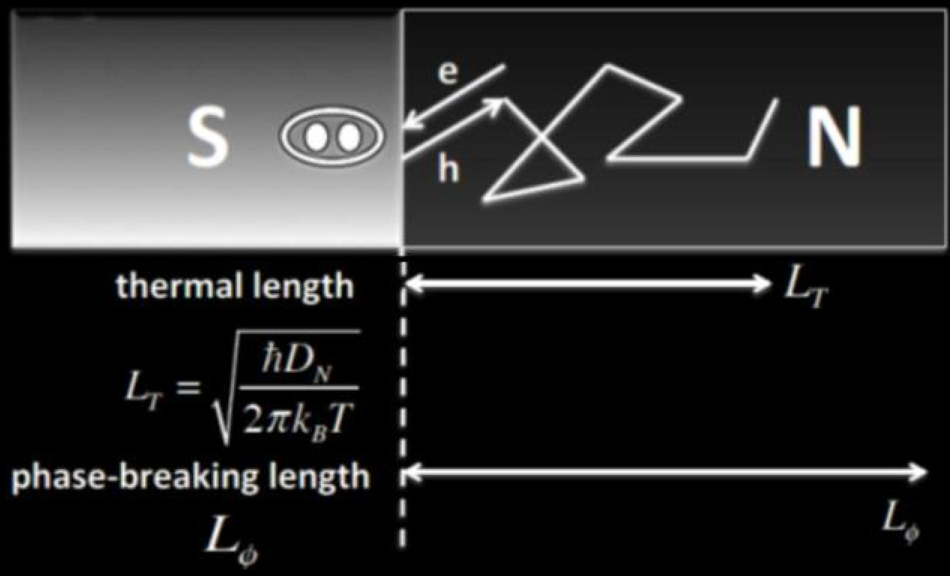
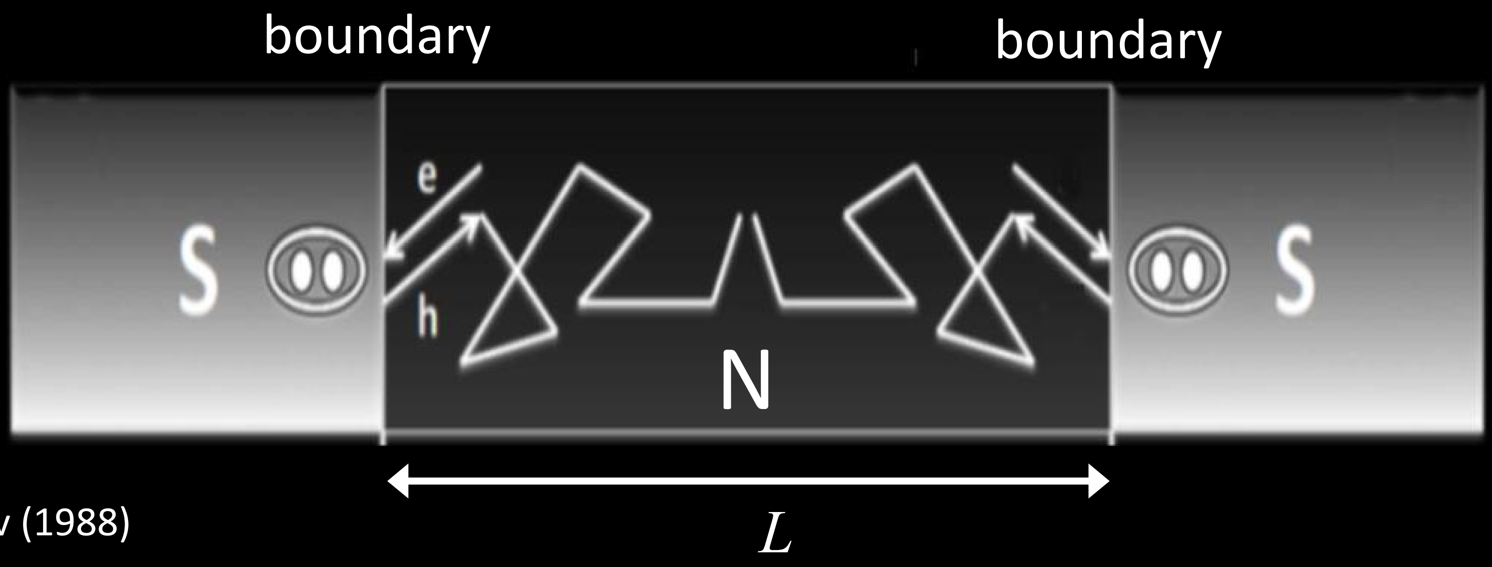




Andreev (1964),
Eilenberger (1968),
Usadel (1970),
Eliashberg (1971)

Larkin *et al.* (1968,75,77),
Schmid & Schön (1975),
Blonder *et al.* (1982),
Zaitsev (1984)

Proximity effect for S-N-S connection



Golubov & Kupriyanov (1988)
Zhou *et al.* (1998)

$$L_E > L \Leftrightarrow E < E_{\mathrm{Th}} = \hbar D_N / L^2$$

Superconducting correlations propagate for $E < E_{Th}$

minigap Δ_g connected with E_{Th}

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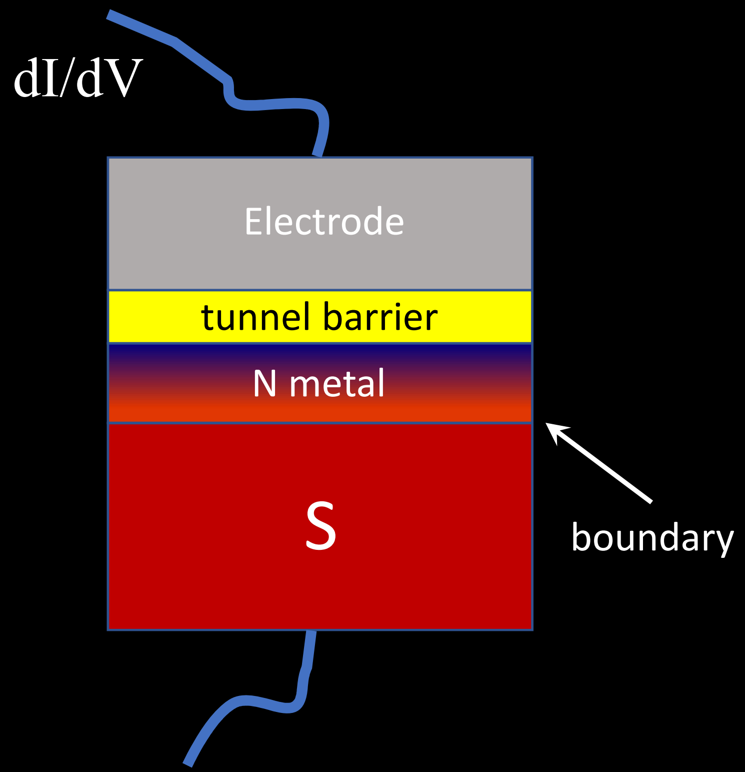
Cryogenic Scanning Tunneling Microscopy

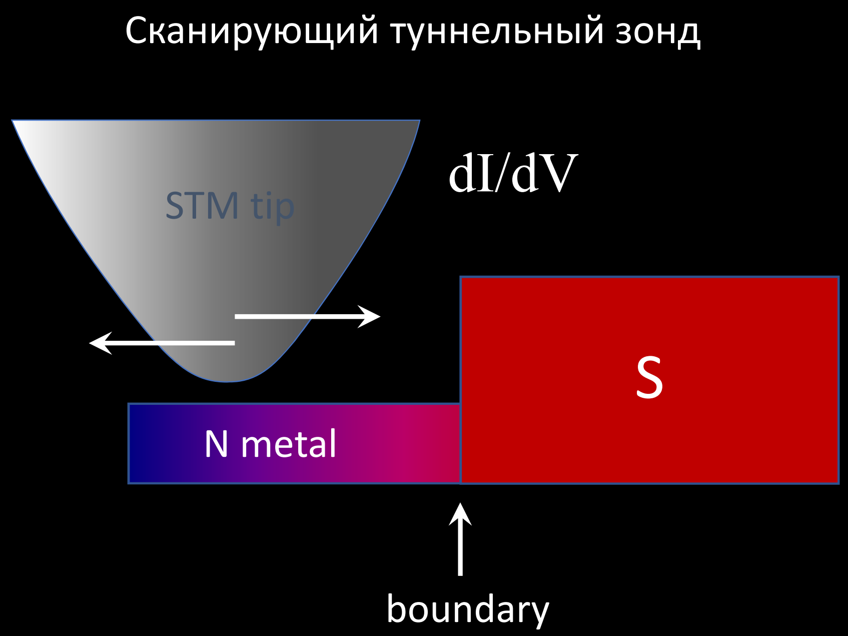
Experiments

Tunneling as a way to study the proximity effect

Lithographic technologies
Fixed tunnel contact



Development: Direct information on the spatial evolution of the density of states

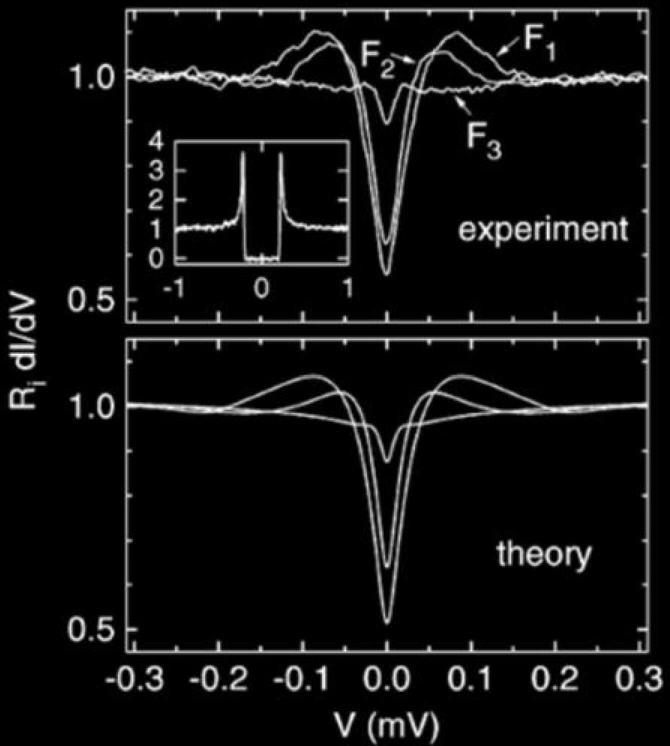


Proximity effect in devises

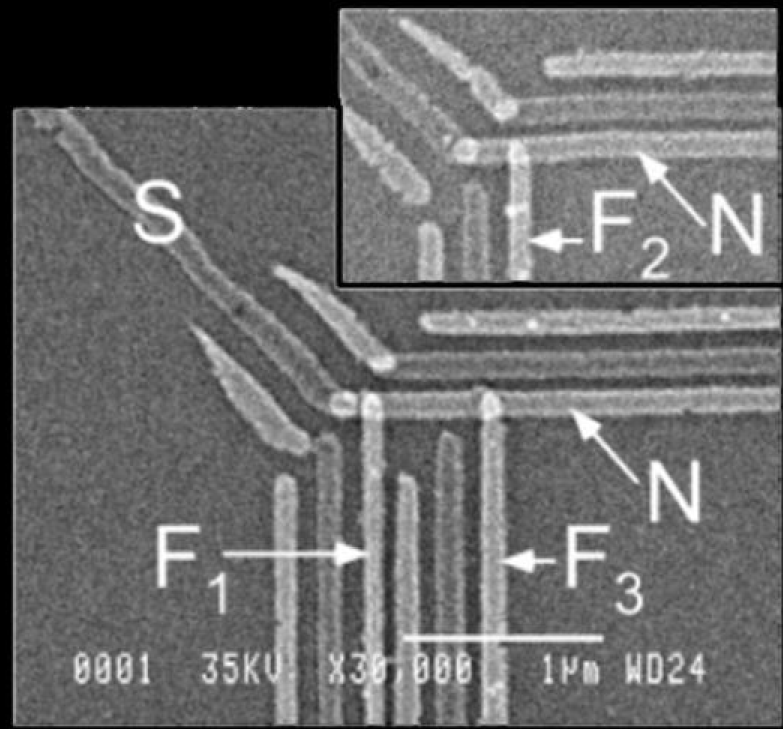
VOLUME 77, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1996

Superconducting Proximity Effect Probed on a Mesoscopic Length Scale

S. Guéron, H. Pothier, Norman O. Birge,* D. Esteve, and M. H. Devoret
Service de Physique de l'Etat Condensé, Commissariat à l'Energie Atomique, Saclay, F-91191 Gif-sur-Yvette Cedex, France
(Received 12 April 1996)



First Study of Spatial Dependency: Nanolithography

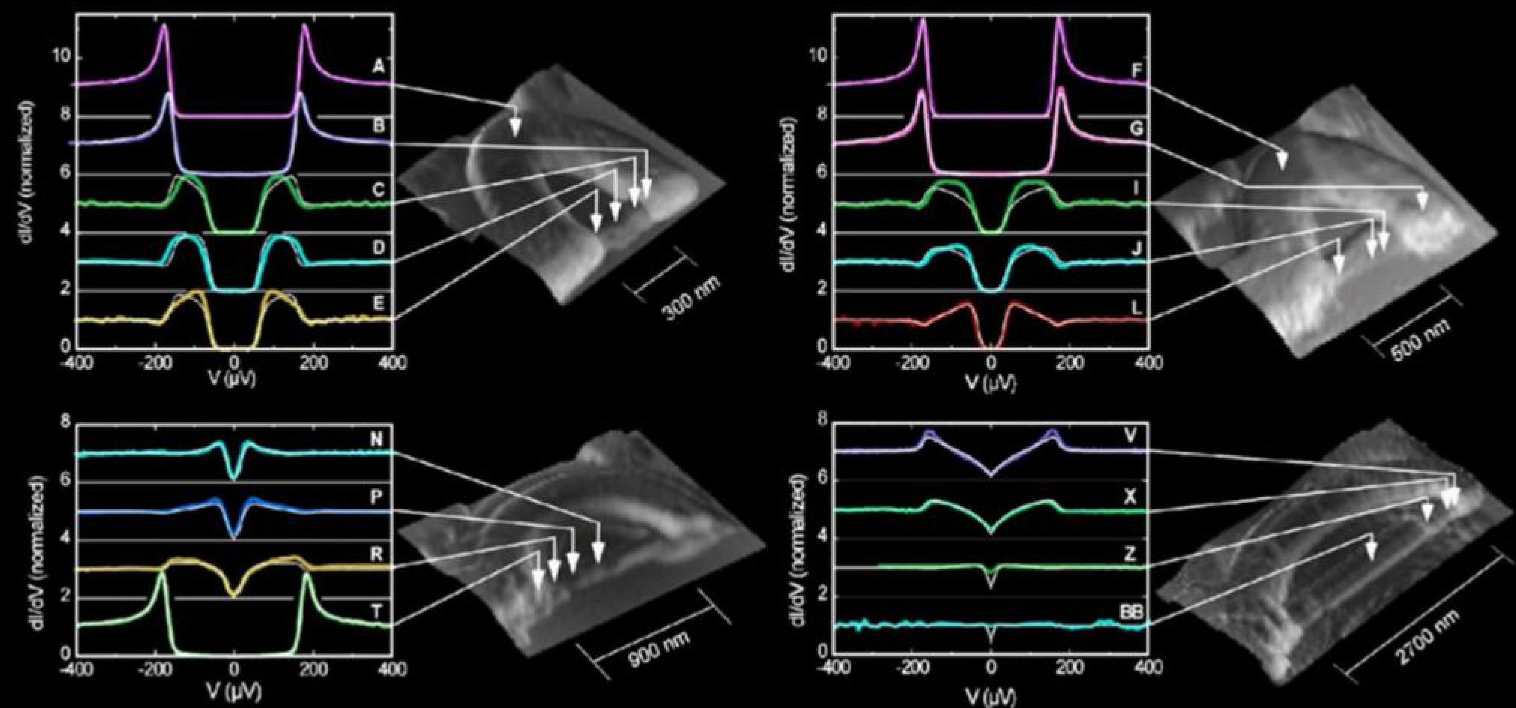


Proximity effect in devises

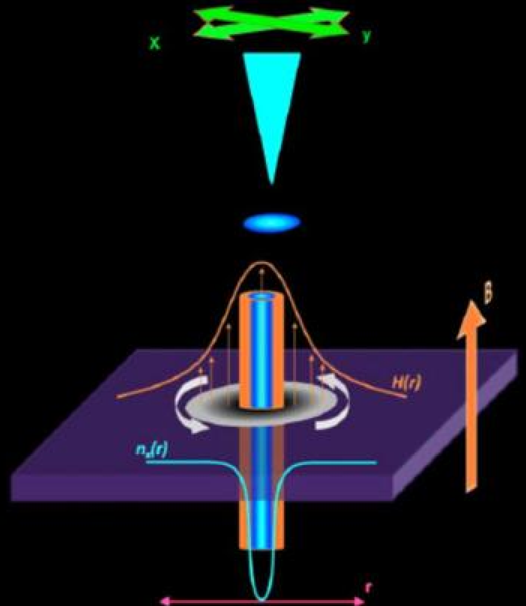
PRL 100, 197002 (2008) PHYSICAL REVIEW LETTERS week ending 16 MAY 2008

Phase Controlled Superconducting Proximity Effect Probed by Tunneling Spectroscopy

H. le Sueur, P. Joyez, H. Pothier, C. Urbina, and D. Esteve



Flux quantization by a superconductor



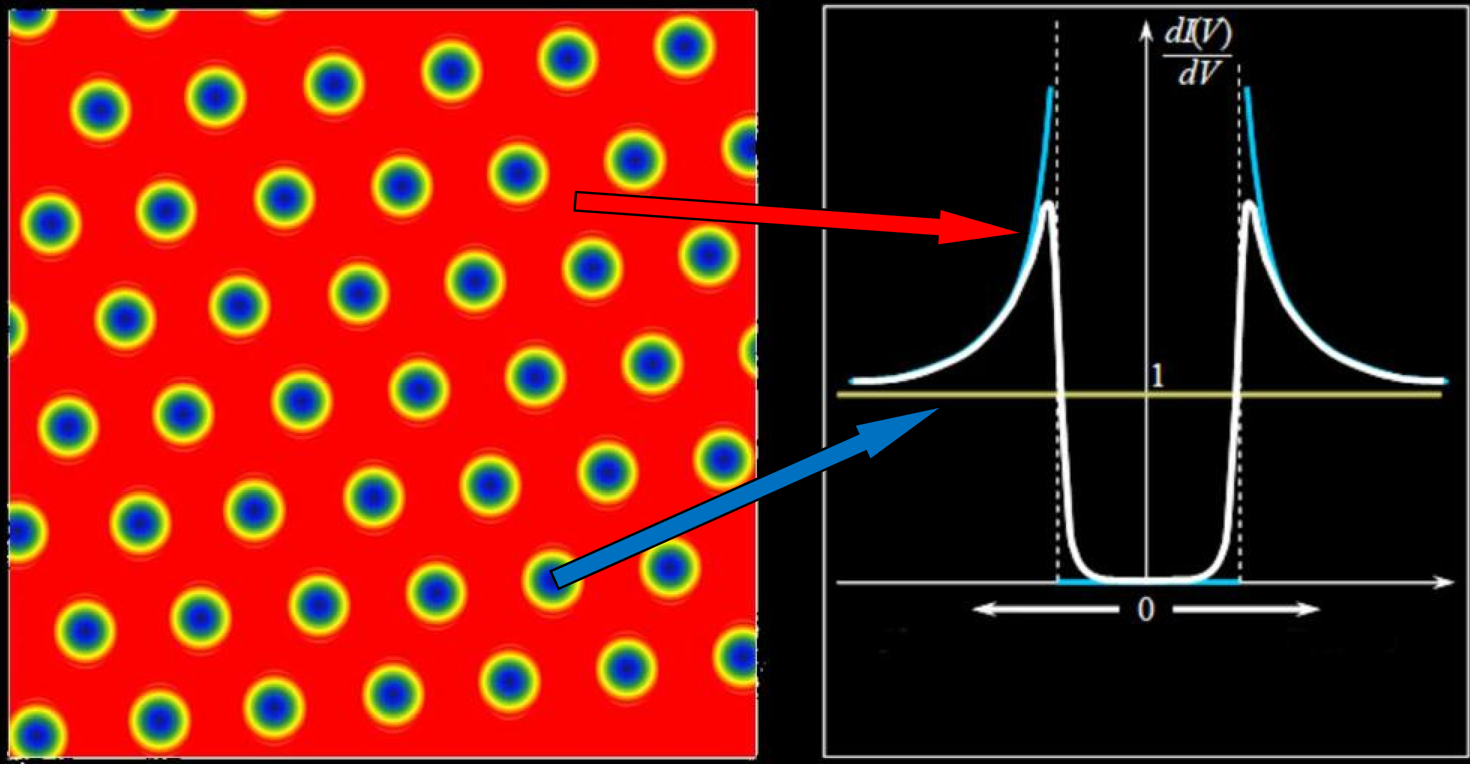
IOP Publishing
Superconductor Science and Technology
Supercond. Sci. Technol. 27 (2014) 063001 (32pp)
doi:10.1088/0953-2048/27/6/063001

Topical Review

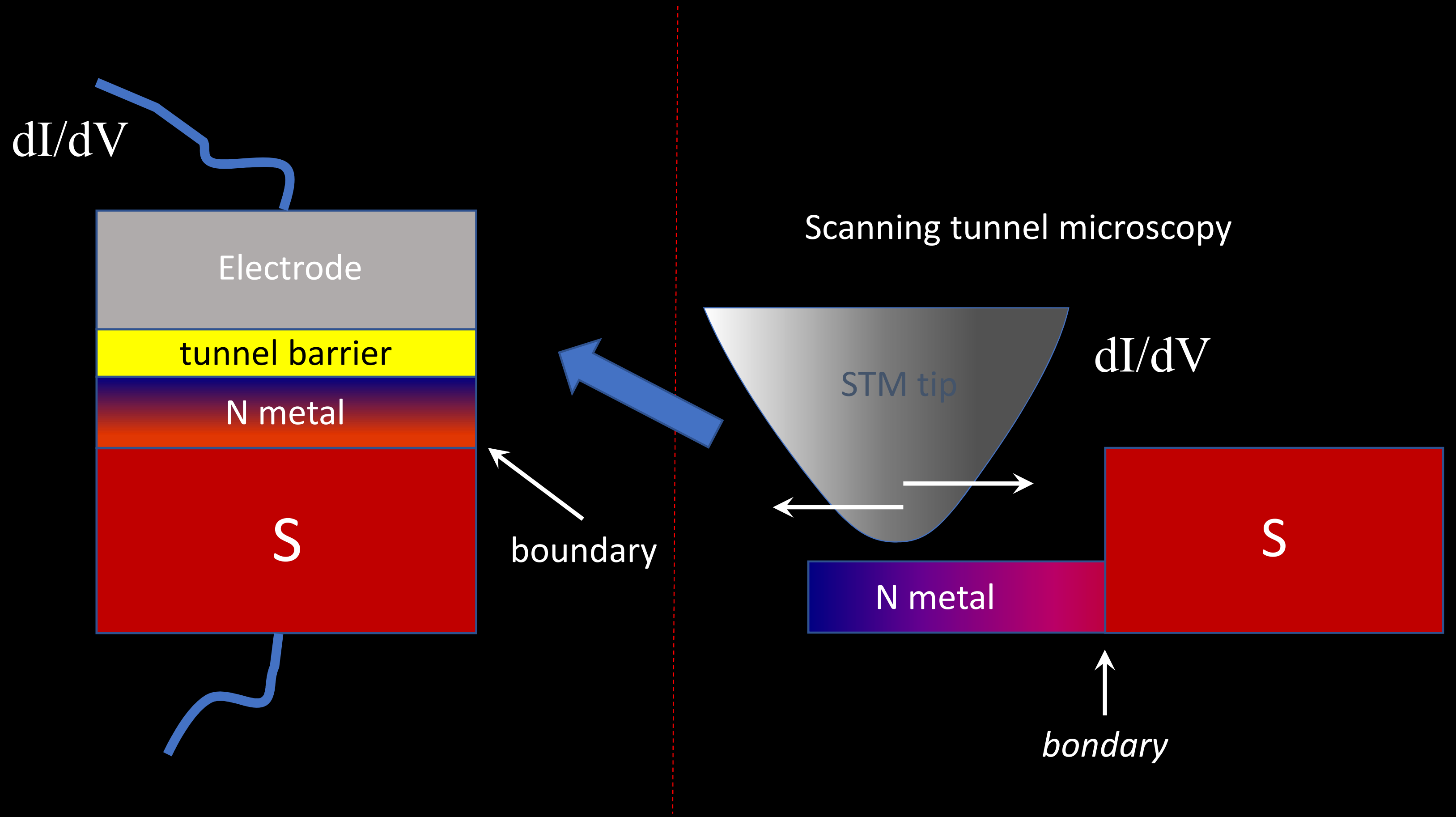
Imaging superconducting vortex cores and lattices with a scanning tunneling microscope

H Suderow[1,2], I Guillamón[1,2,3], J G Rodrigo[1,2] and S Vieira[1,2]

[1] Laboratorio de Bajas Temperaturas, Departamento de Física de la Materia Condensada, Instituto de Ciencia de Materiales Nicolás Cabrera and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049 Madrid, Spain



Proximity effect at the boundary of a superconductor with a nonsuperconducting metal in the diffuse limit



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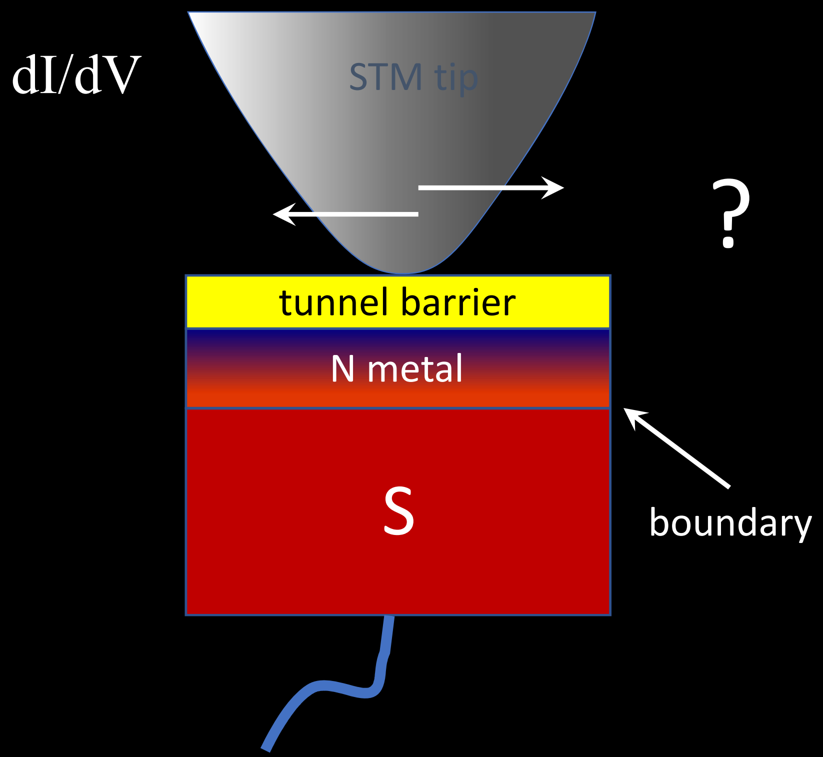

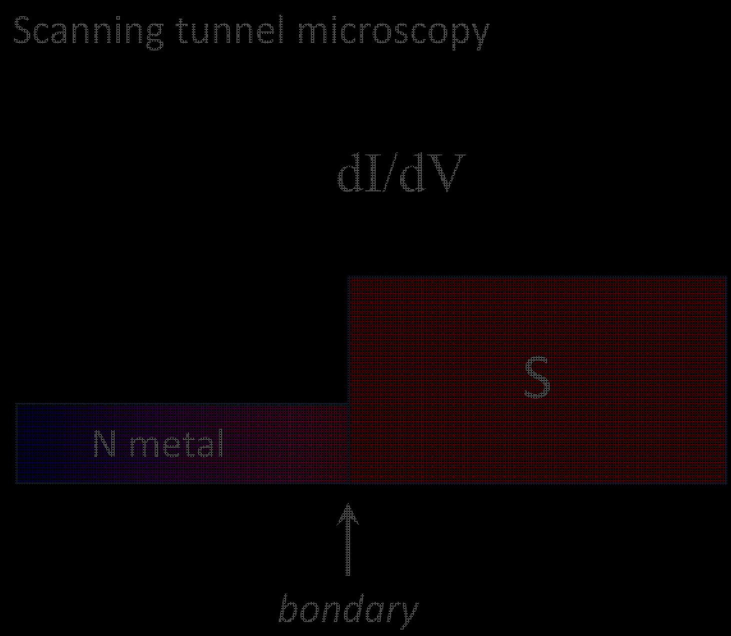

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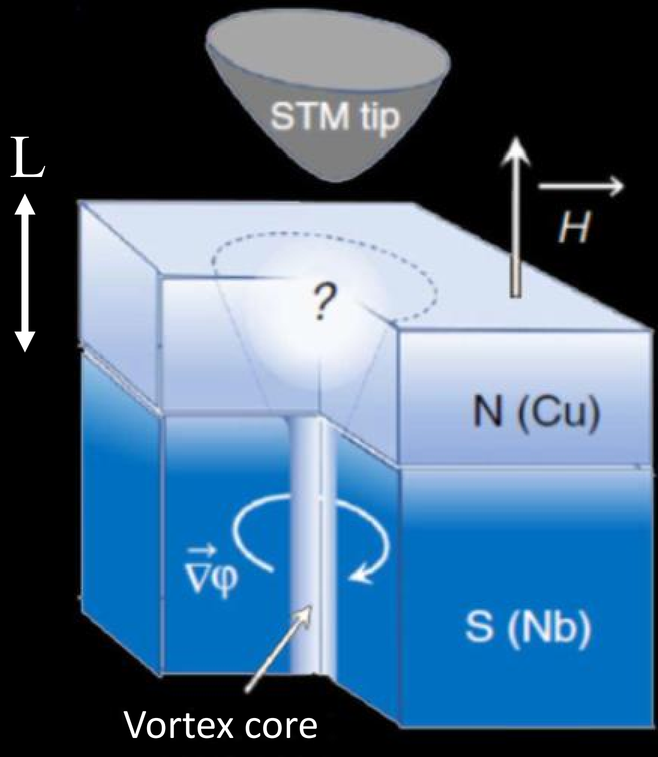


ARTICLE

DOI: 10.1038/s41467-018-04582-1 OPEN

nature COMMUNICATIONS

Expansion of a superconducting vortex core into a diffusive metal

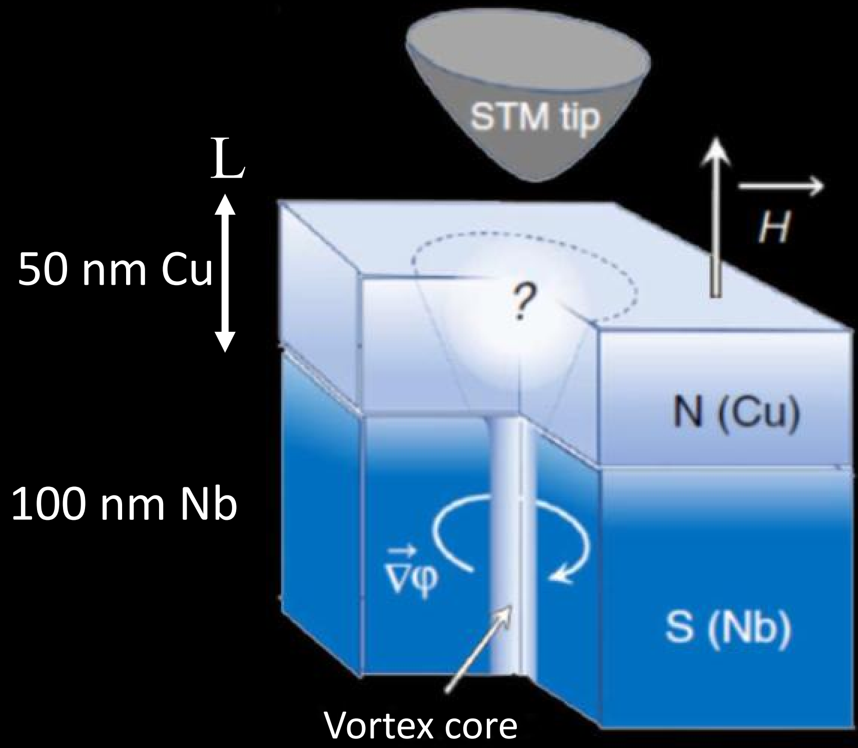
Vasily S. Stolyarov[1,2,3,4,5], Tristan Cren[2], Christophe Brun[2], Igor A. Golovchanskiy[1,5], Olga V. Skryabina[1,3], Daniil I. Kasatonov[1], Mikhail M. Khapaev[1,6,7], Mikhail Yu. Kupriyanov[1,7,8], Alexander A. Golubov[1,9] & Dimitri Roditchev[1,2,10,11]

Vortex size?

3D- proximity effect

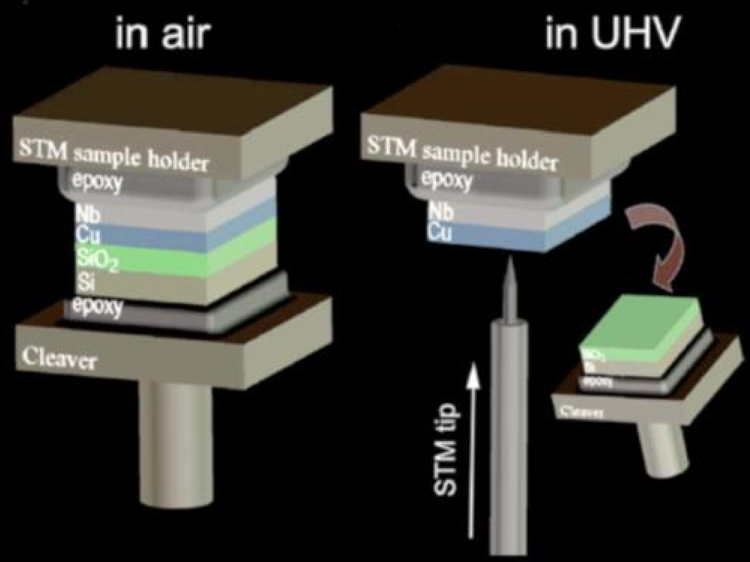
minigap Δ, related to $\hbar D_N / L^2$

Proximity effect at the boundary of a superconductor with a nonsuperconducting metal in the diffuse limit



Cu, Nb:
Magnetron sputtering

d_{Nb} = 100 nm
d_{Cu} = 50 nm
d_{SiO2} = 270 nm
d_{Si} = 0.3 mm



APPLIED PHYSICS LETTERS **104**, 172604 (2014)

Ex situ **elaborated proximity mesoscopic structures for ultrahigh vacuum scanning tunneling spectroscopy**

V. S. Stolyarov,[1,2,3,4,5,6] T. Cren,[1,2,a)] F. Debontridder,[1,2] C. Brun,[1,2] I. S. Veshchunov,[7,3] O. V. Skryabina,[3] A. Yu. Rusanov,[8] and D. Roditchev[1,2,9]
[1]*UMR 7588, Institut des Nanosciences de Paris, UPMC Univ Paris 06, Sorbonne Universités, F-75005 Paris, France*

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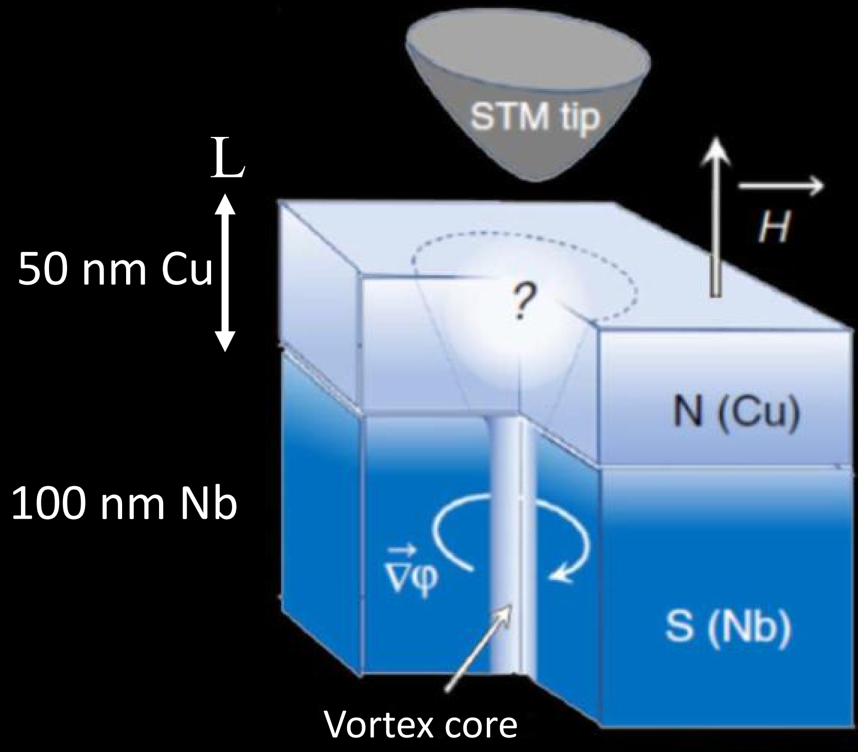
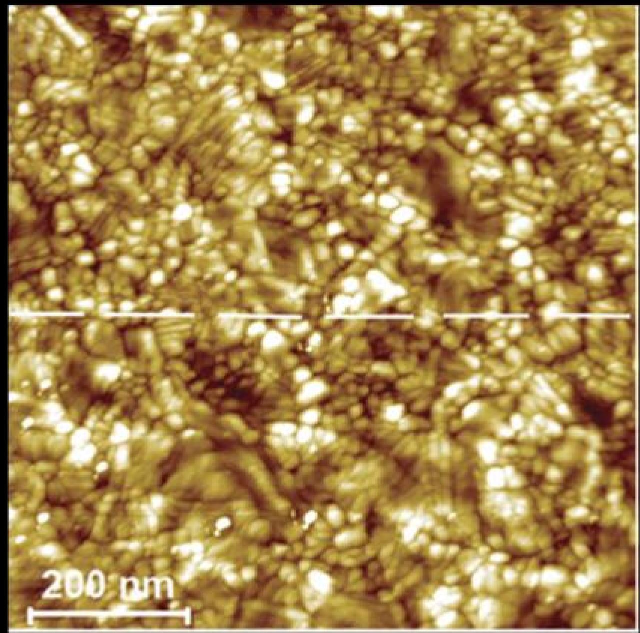


STM topography



$D_N = \ell_N v_F/3 \approx 100\ cm^2.s^{-1}$

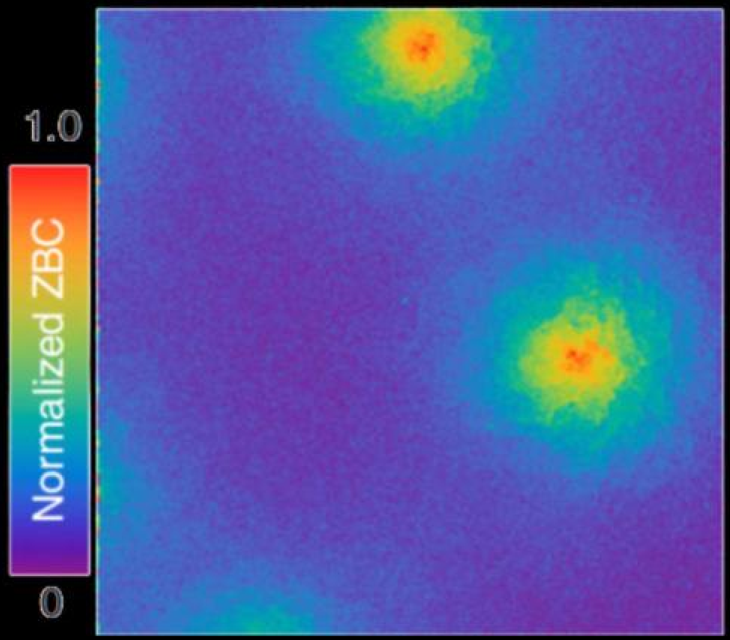
$\xi_N\ = (\hbar D_N/\Delta\ )^{1/2} \approx 37$ nm

Grain size ~ ℓ_N ~ 20 nm

Proximity effect at the boundary of a superconductor with a nonsuperconducting metal in the diffuse limit

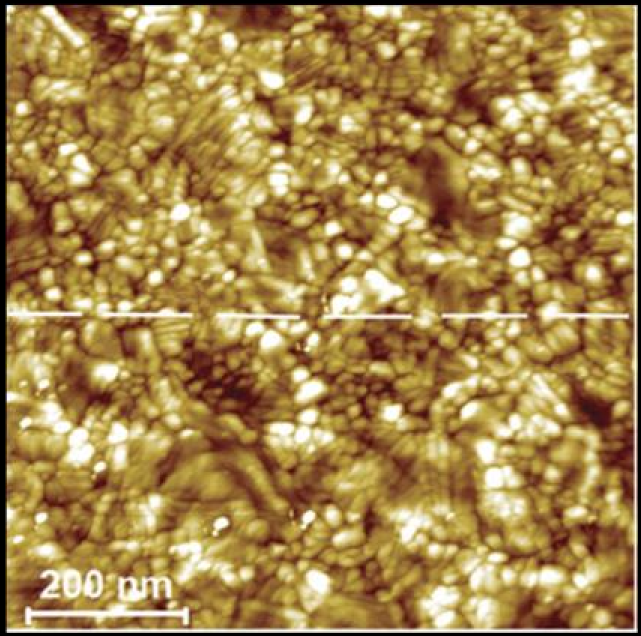
T=300 mK

STS map



B = 5 mT
dI/dV(V=0)

STM topography



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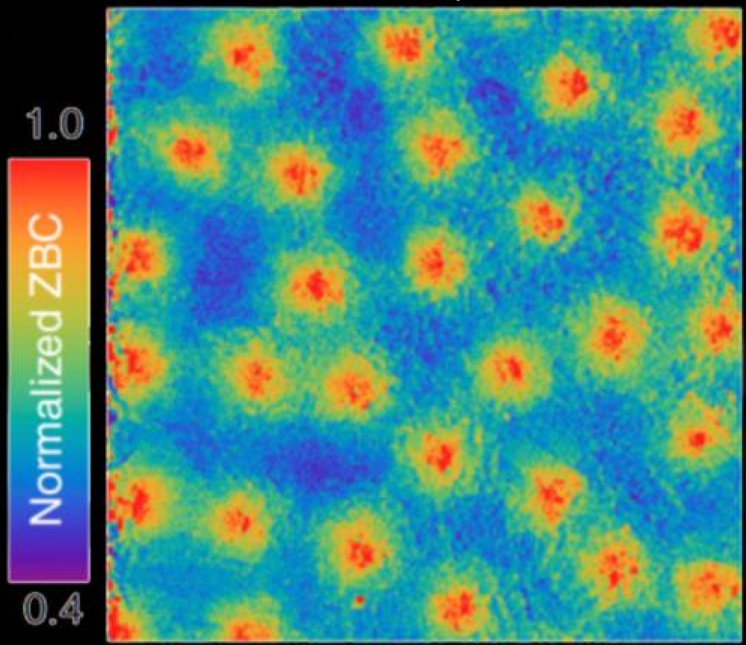
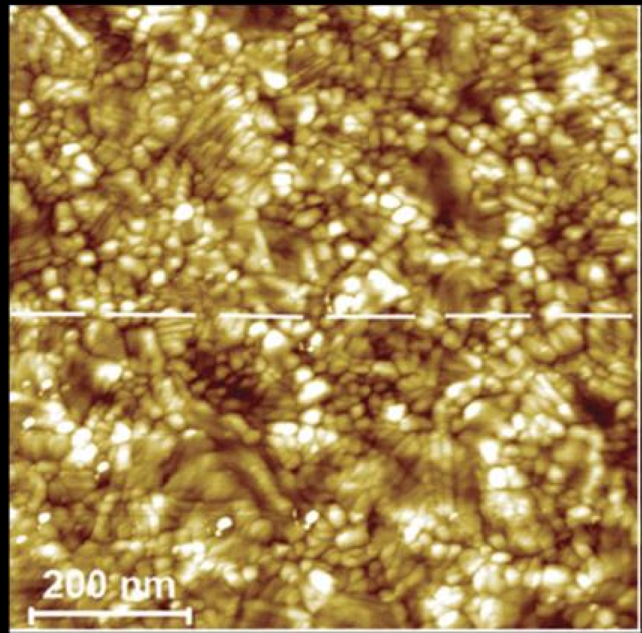


B = 55 mT
dI/dV(V=0)

T=300 mK

STM topography



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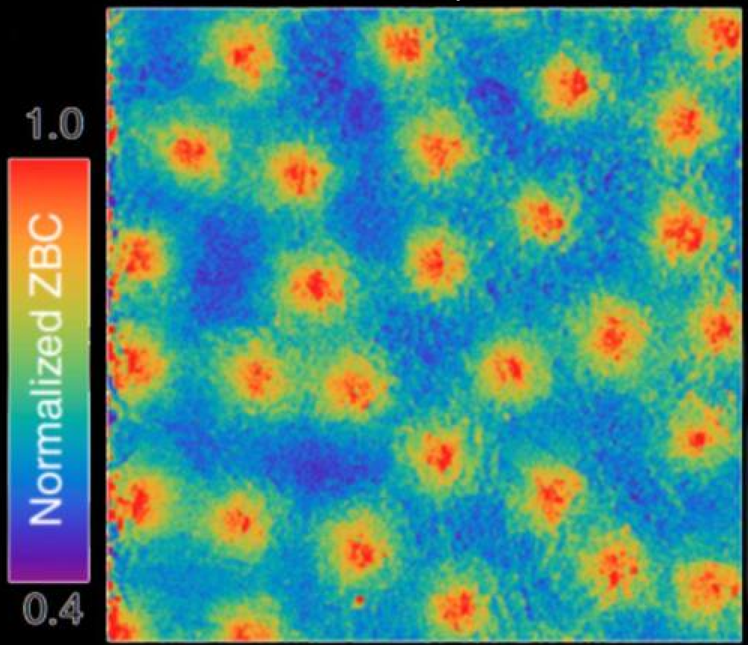

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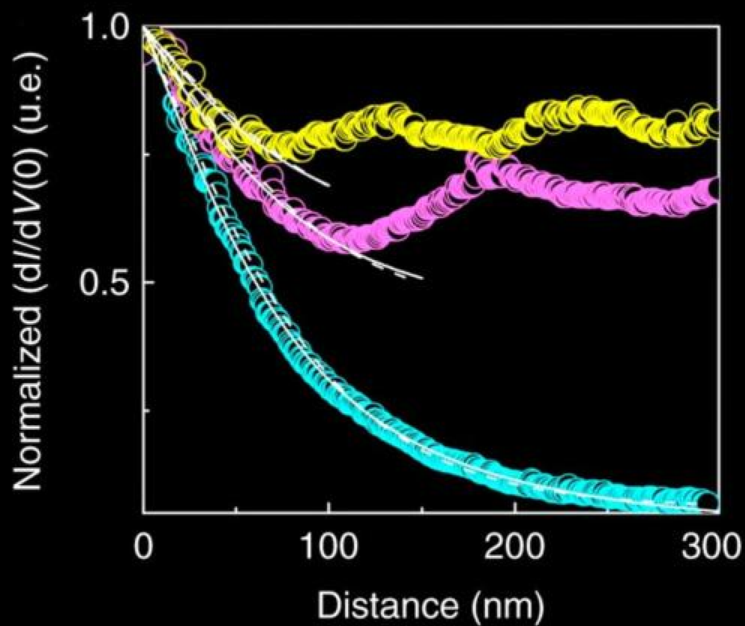

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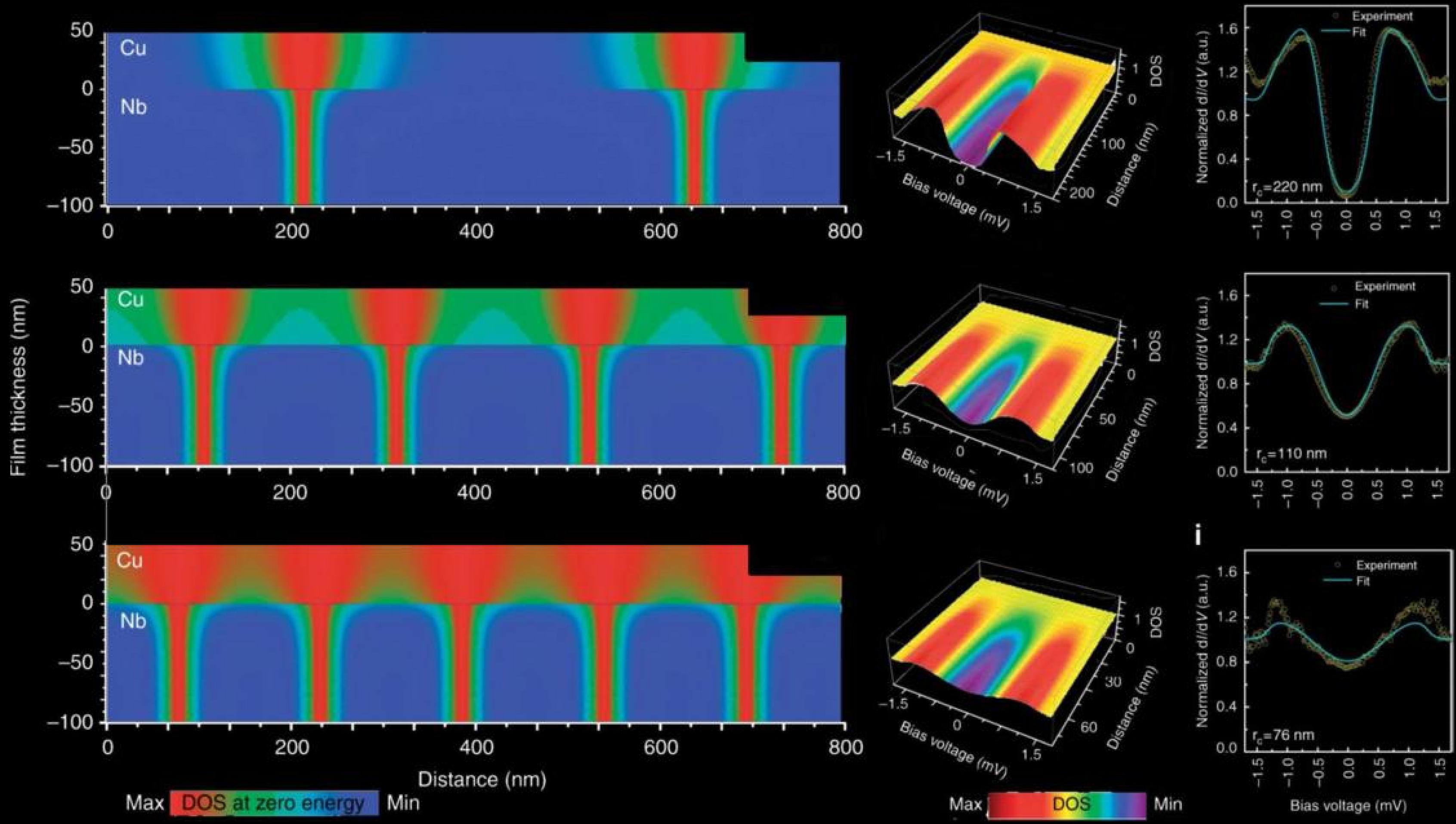
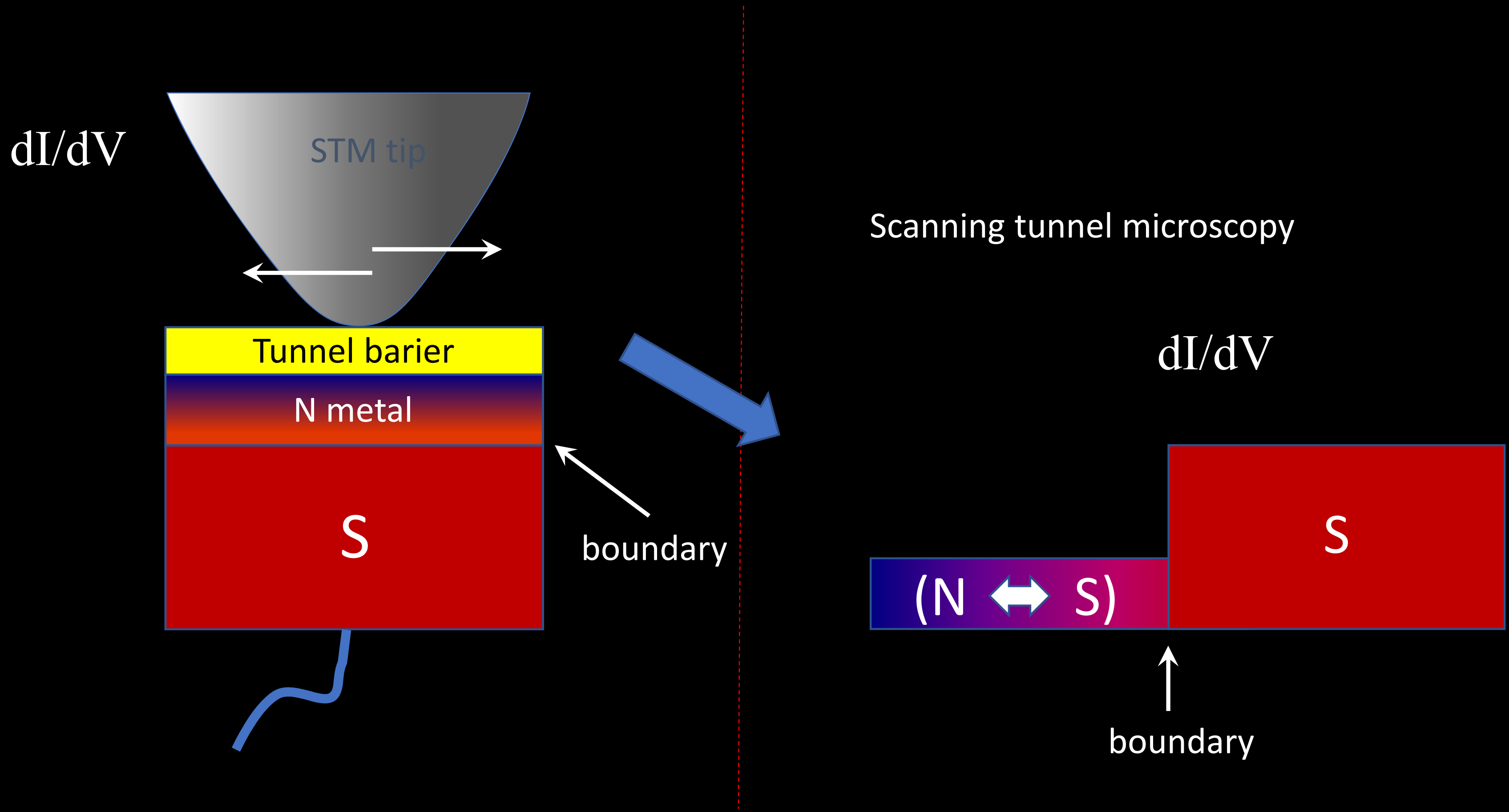
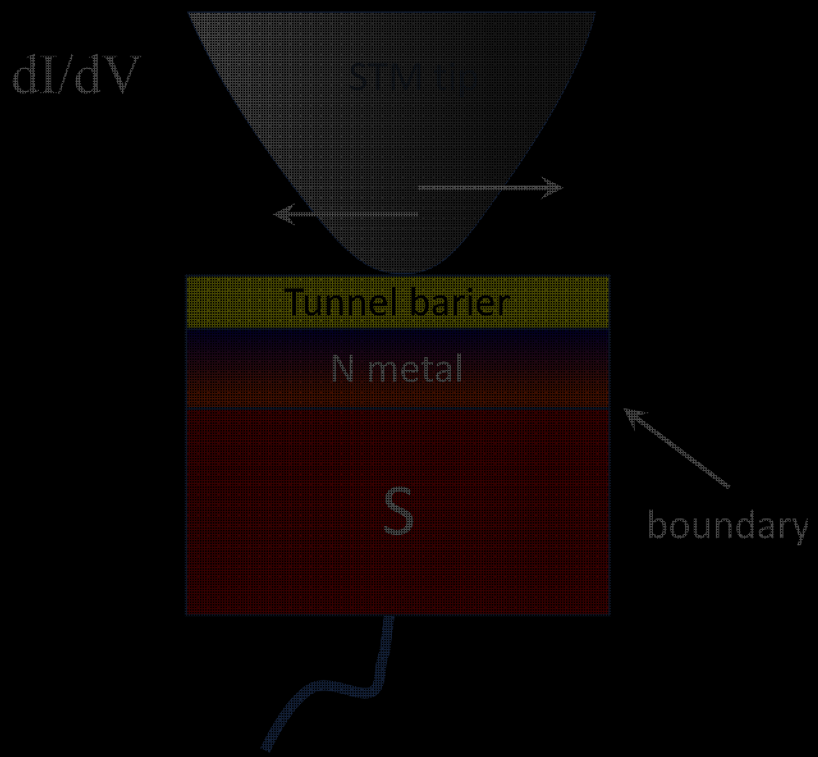


Rb = 150 Ohм

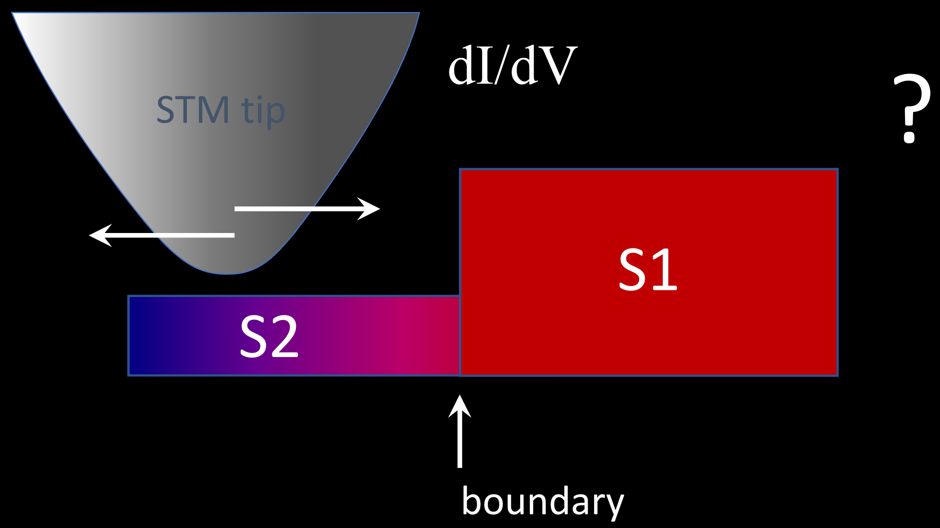
Proximity effect between two superconductors



Proximity effect between two superconductors



Scanning tunnel microscopy



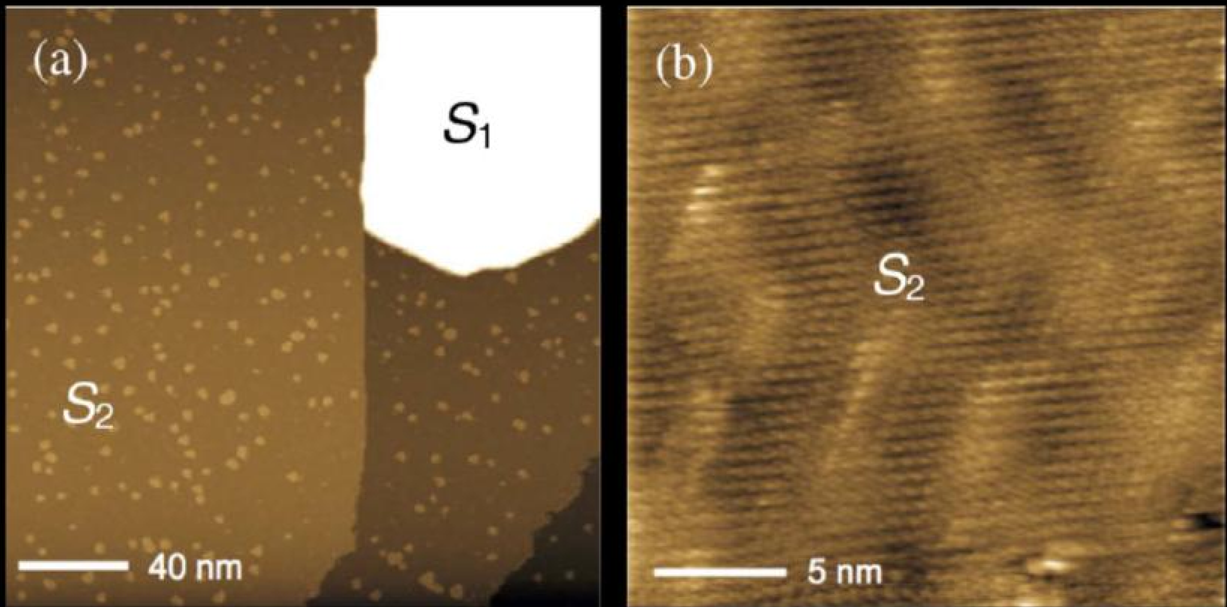
Proximity effect between two superconductors

PHYSICAL REVIEW X 4, 011033 (2014)

Proximity Effect between Two Superconductors Spatially Resolved by Scanning Tunneling Spectroscopy

V. Cherkez,[1,2] J. C. Cuevas,[3,*] C. Brun,[1,2,†] T. Cren,[1,2] G. Ménard,[1,2] F. Debontridder,[1,2] V. S. Stolyarov,[1,2,5,6] and D. Roditchev[1,4]

[1]*Institut des Nanosciences de Paris, Sorbonne Universités, UPMC Université Paris 06, UMR 7588, F-75005 Paris, France*



фаза √7x√3-Pb/Si(111)

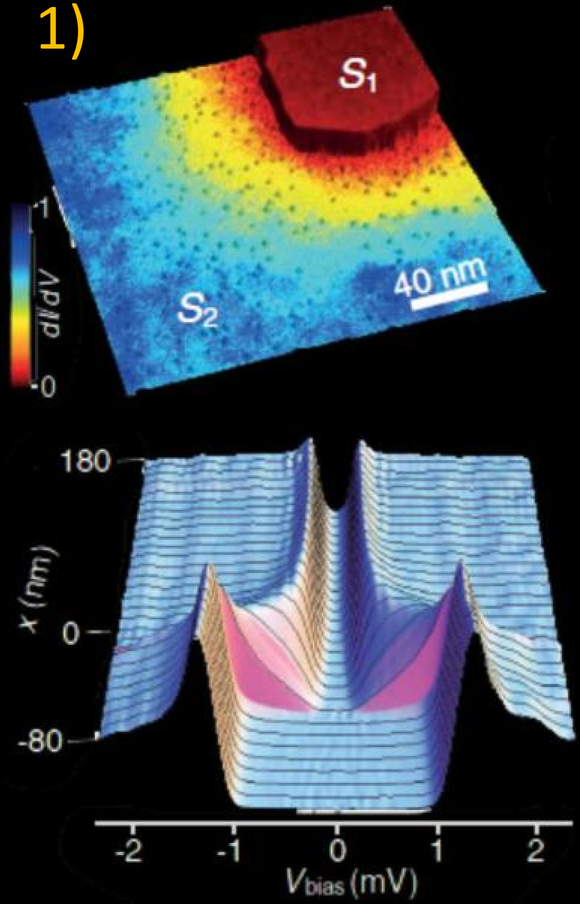
Δ_1=1.2 мВ Δ_2= 0.23 мВ

T_{C1}=6.2 K, T_{C2}= 1.8 K

T=0.3K <T_{C1},T_{C2}

Proximity effect between two superconductors

1)



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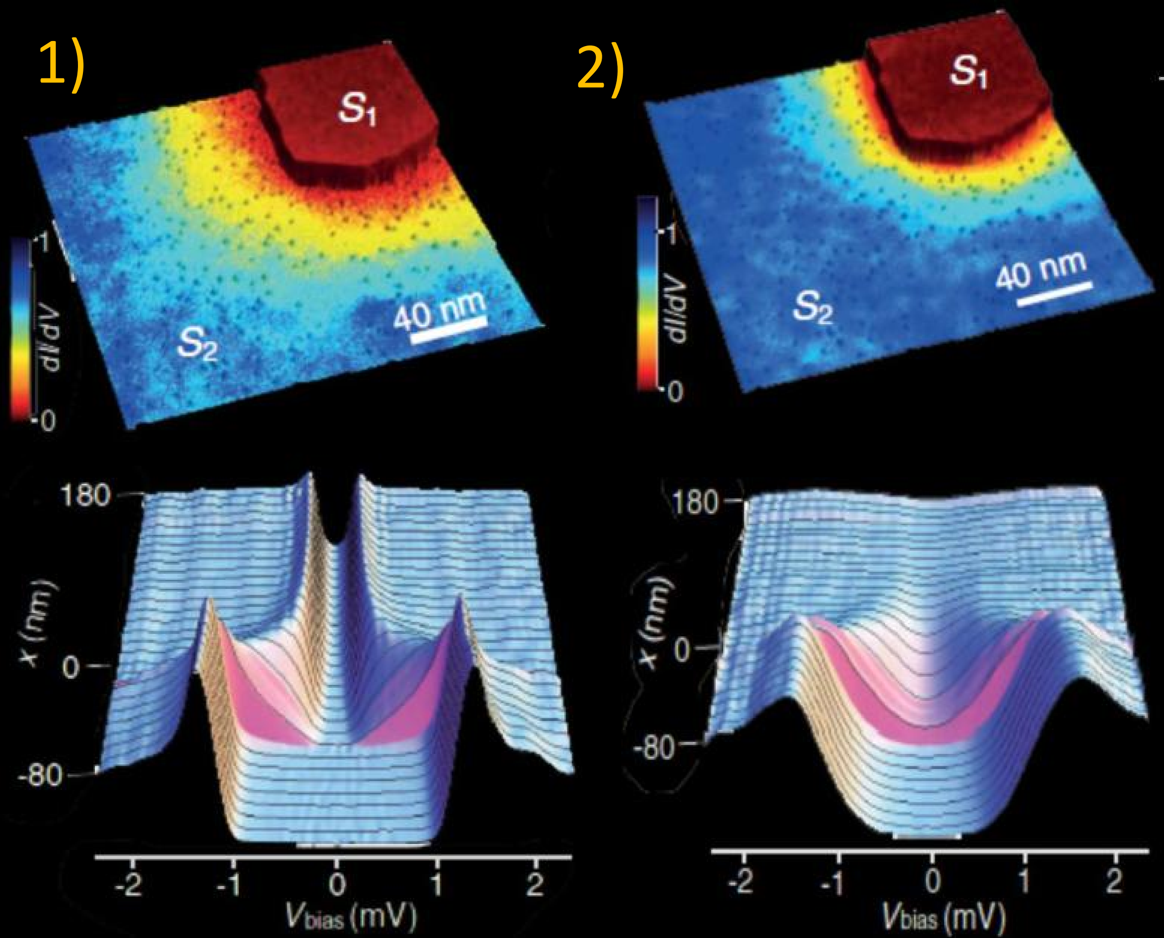

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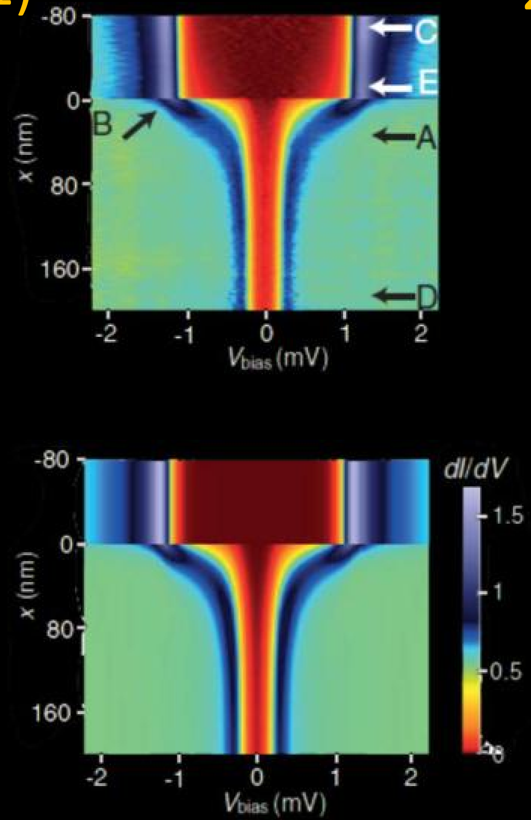
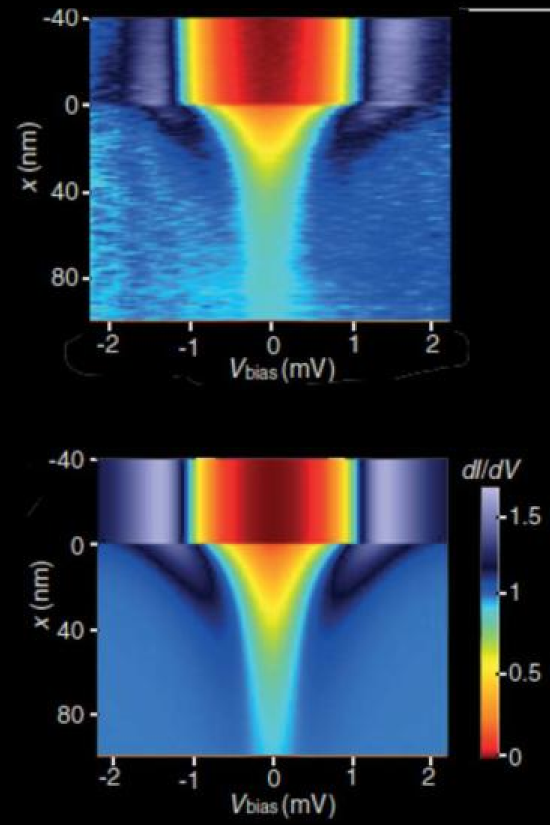


2)



PHYSICAL REVIEW X **4**, 011033 (2014)

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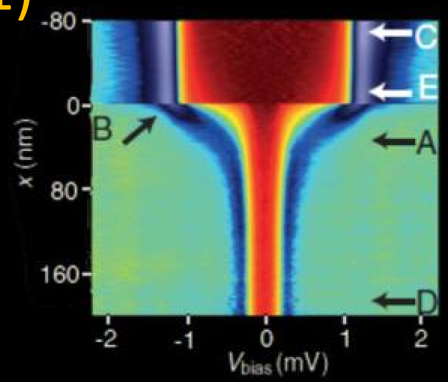
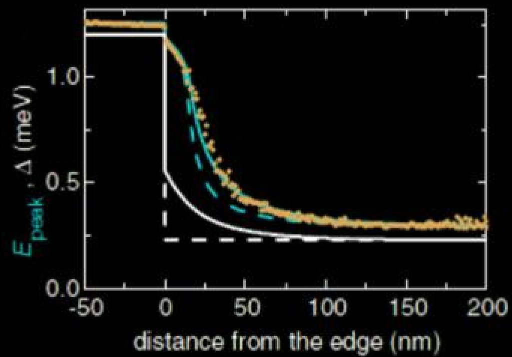
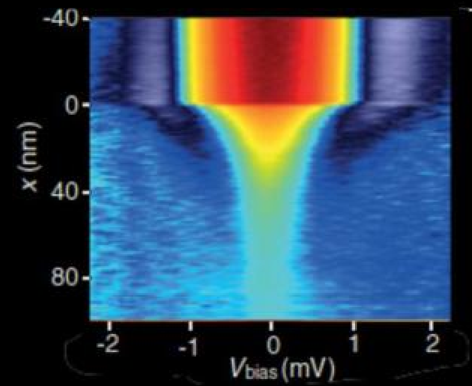
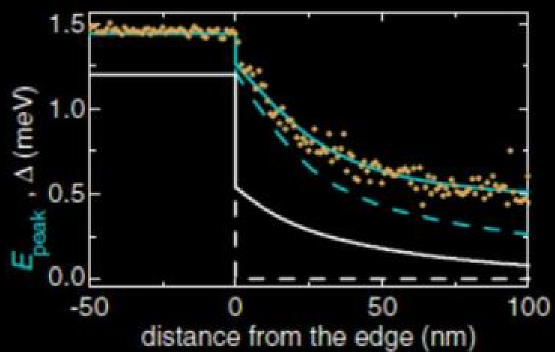




2)





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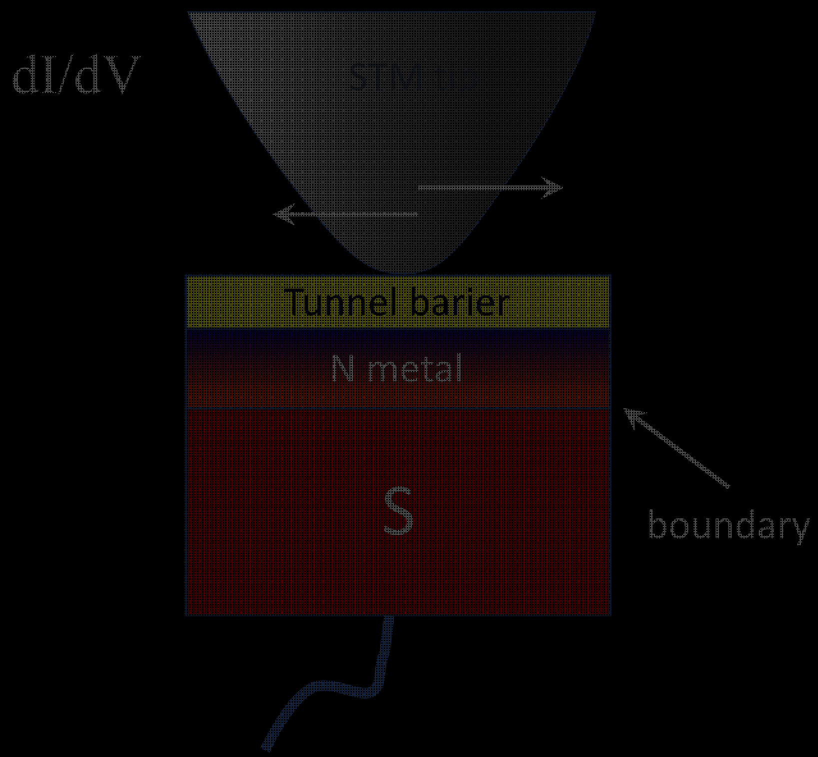
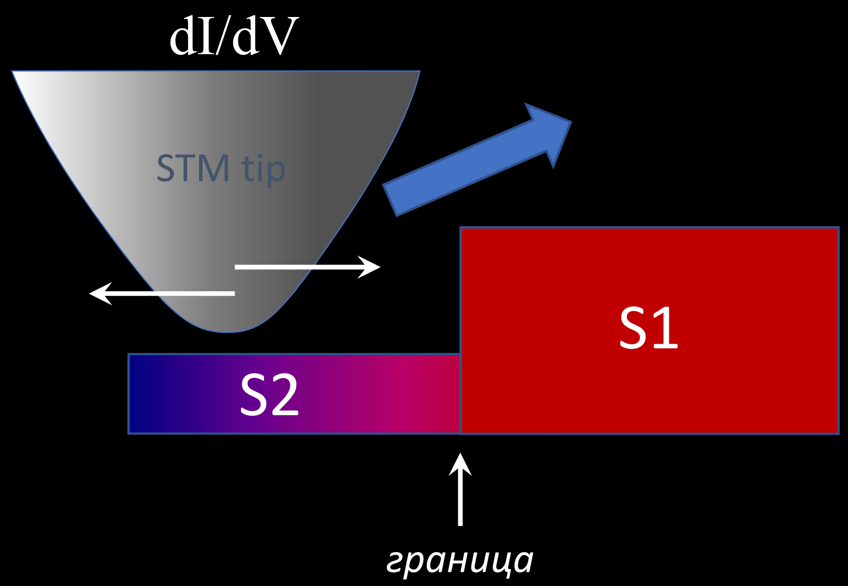
Proximity effect in a superconductor in the ballistic limit



Scanning tunnel microscopy



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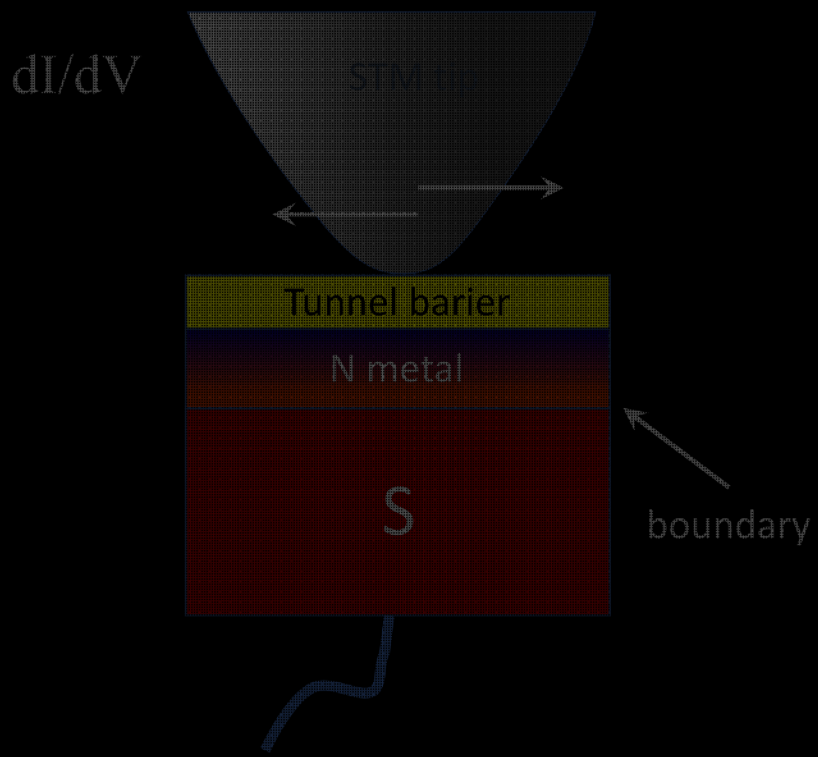

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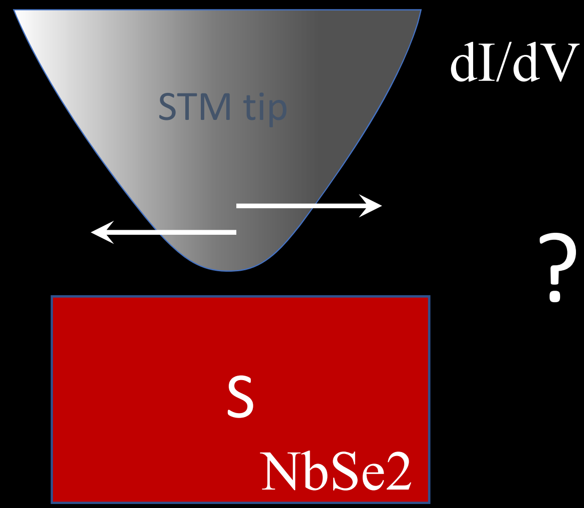

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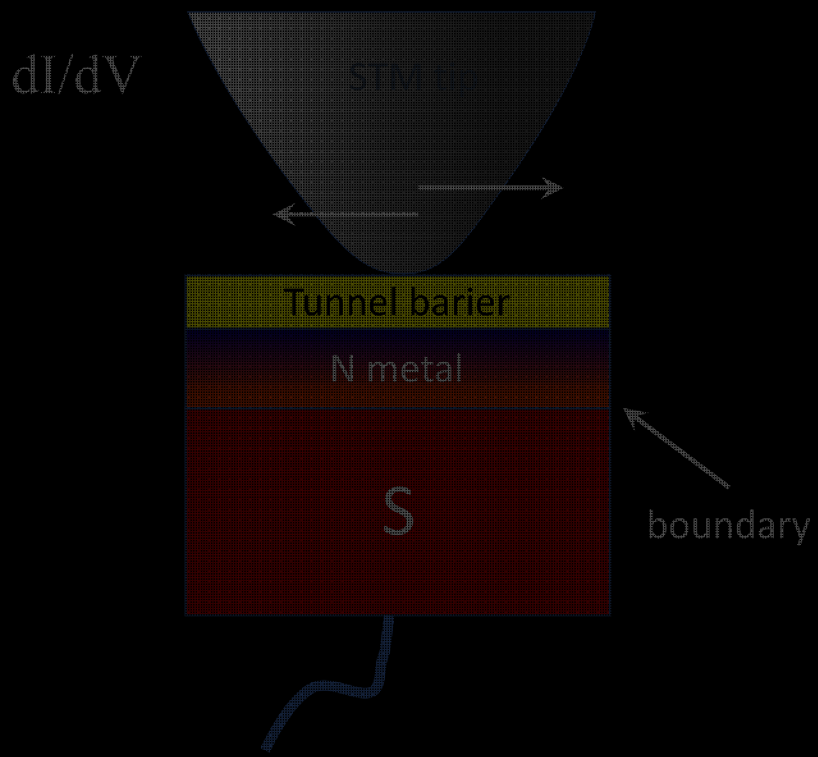

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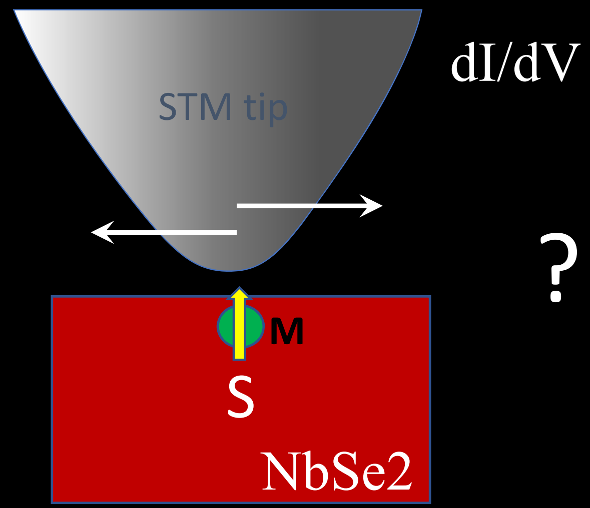


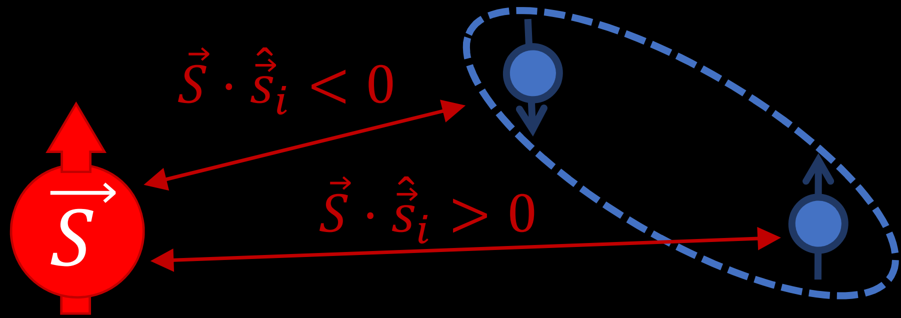
Long-range Shiba bound states

Yu-Shiba-Rusinov (YSR) problem:
3D scattering on a classical spin $\vec{S}$

L. Yu. Acta Phys. Sin (1965)

H. Shiba. Prog. Th. Phys. (1968)

A. I. Rusinov JETP Lett. (1969)



Two terms hamiltonian: magnetic and non-magnetic scattering

$$H_{Imp} = -\frac{JS}{2}(c^\dagger_{0\uparrow}c_{0\uparrow} - c^\dagger_{0\downarrow}c_{0\downarrow}) + K(c^\dagger_{0\uparrow}c_{0\uparrow} + c^\dagger_{0\downarrow}c_{0\downarrow})$$

$$E_{Shiba} = \pm\Delta\cos(\delta^+ - \delta^-)$$ where $$\tan\delta^\pm = K\nu_0 \pm \frac{JS}{2}\nu_0$$

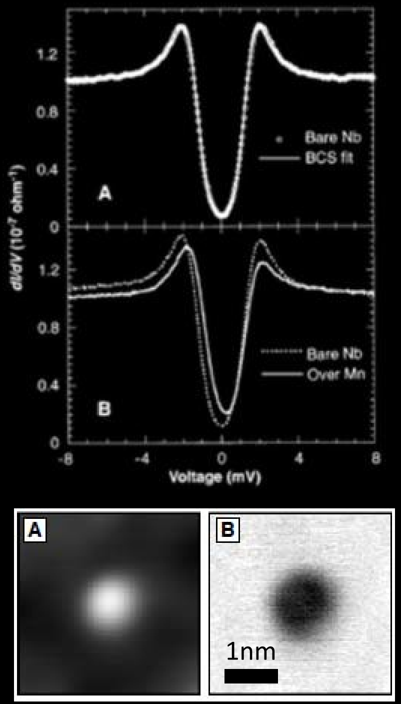
$$\psi_\pm(r) = \frac{1}{\sqrt{N}}\frac{\sin(k_F r + \delta^\pm)}{k_F r}e^{-\Delta\sin(\delta^+ - \delta^-)r/\hbar v_F}$$

$$\frac{\Delta}{\hbar v_F} \approx \xi^{-1}$$

valid for $k_F\, r \gg 1$

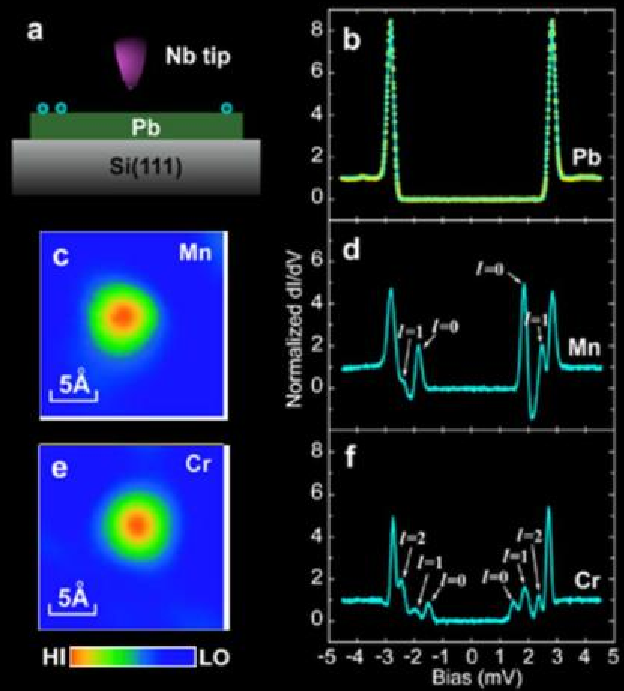
Long-range Shiba bound states

Mn on Nb(110) (bulk)



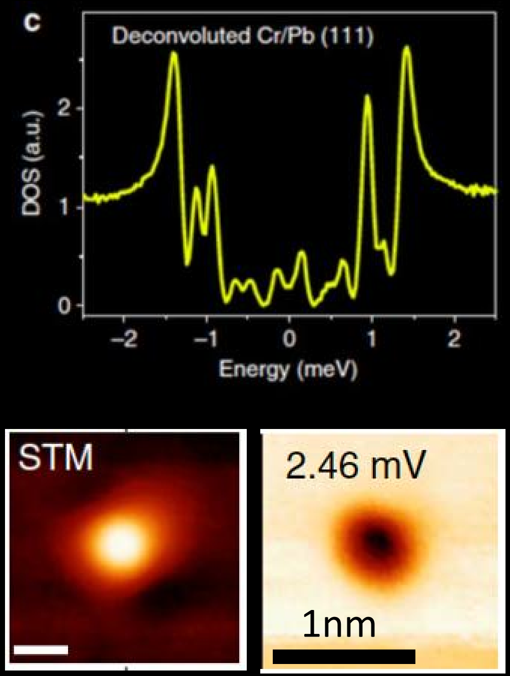
A. Yazdani et al. Science (1997)

Mn and Cr on Pb(111) (20ML)



Shuai-Hua Ji, PRL (2008)

Cr on Pb(111) (300nm)

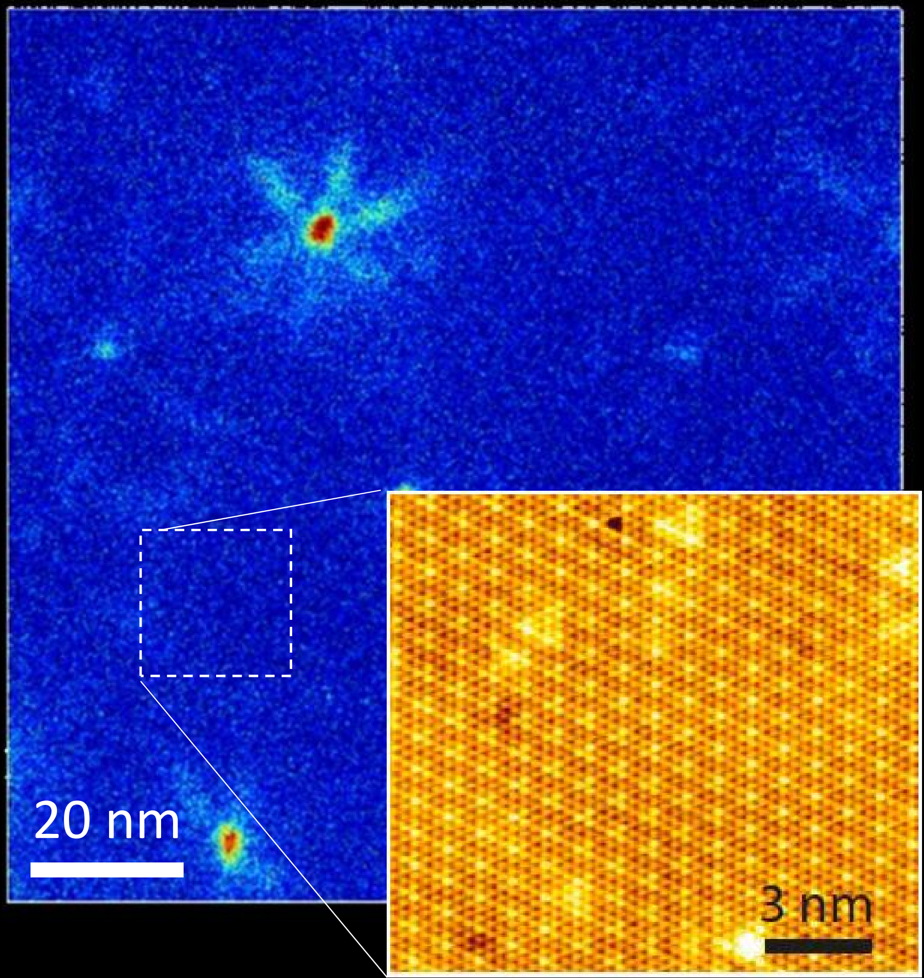


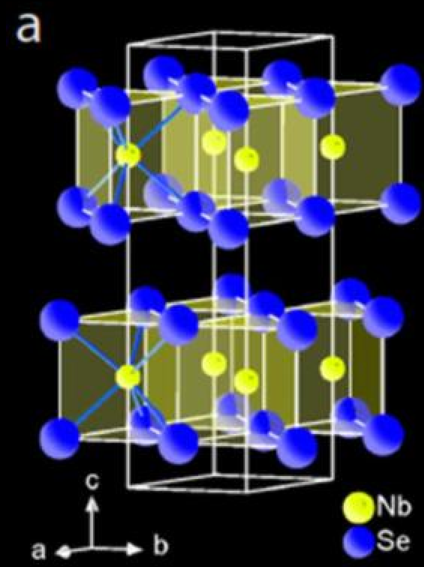
D.-J. Choi et al. Nat. Comm. (2017)

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

valid for $k_F\, r \gg 1$

Long-range Shiba bound states – *2H-NbSe$_2$*



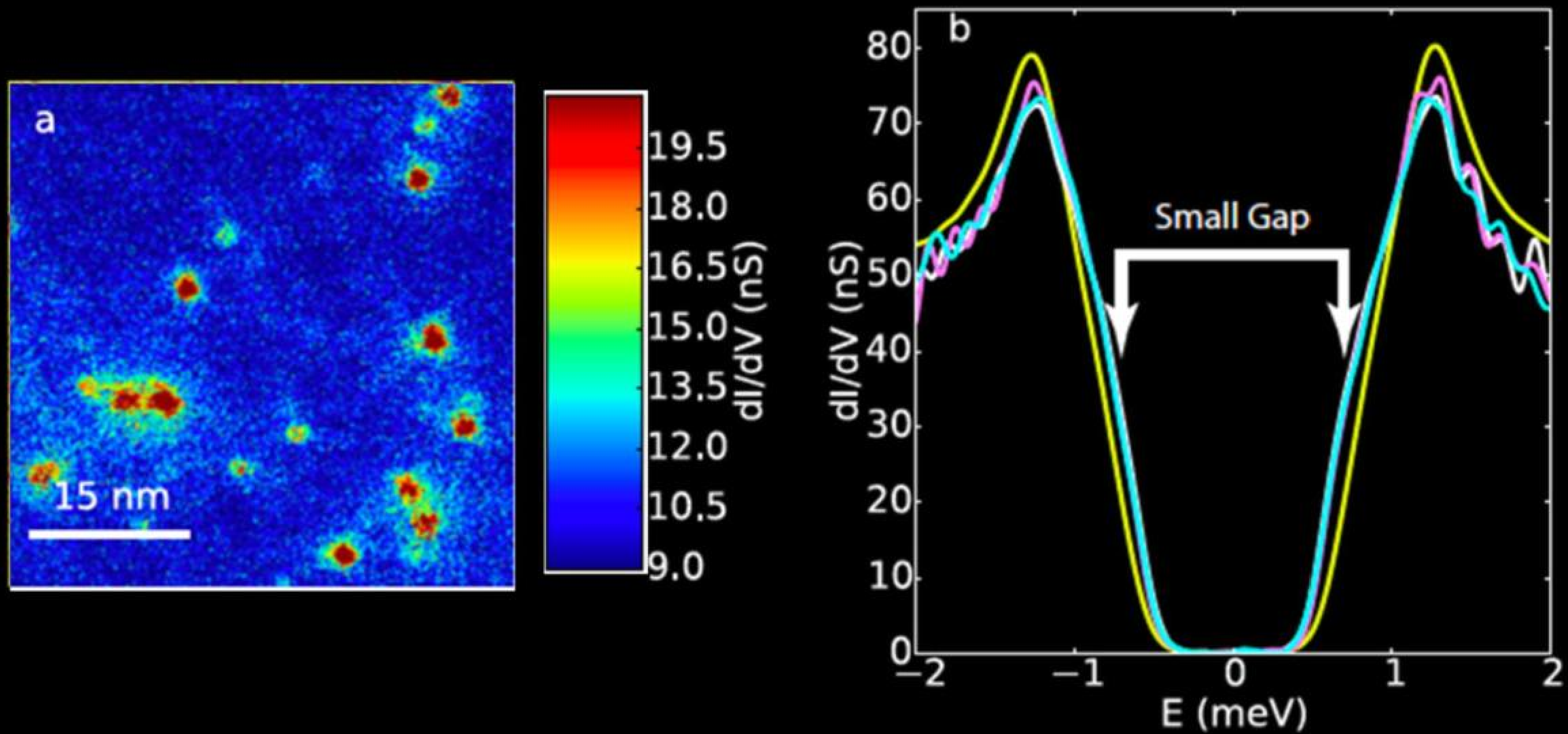


Magnetic impurities:
175 ppm of Fe,
54 ppm of Cr
22 ppm of Mn

G. Ménard et al. Nat. Phys. (2015)

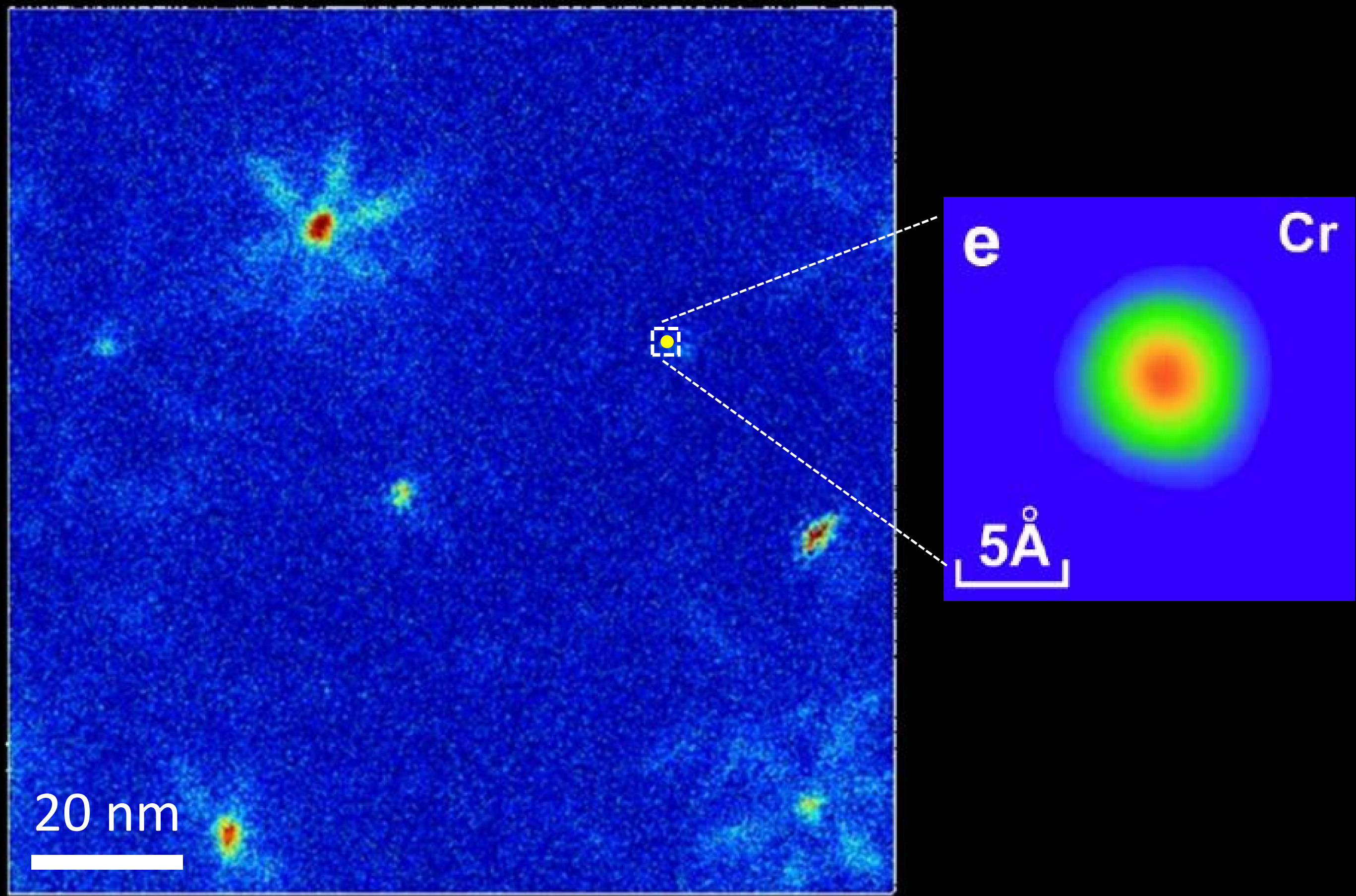
Long-range Shiba bound states – *2H-NbSe$_2$*

Non-magnetic Ta impurities in 2H-NbSe2



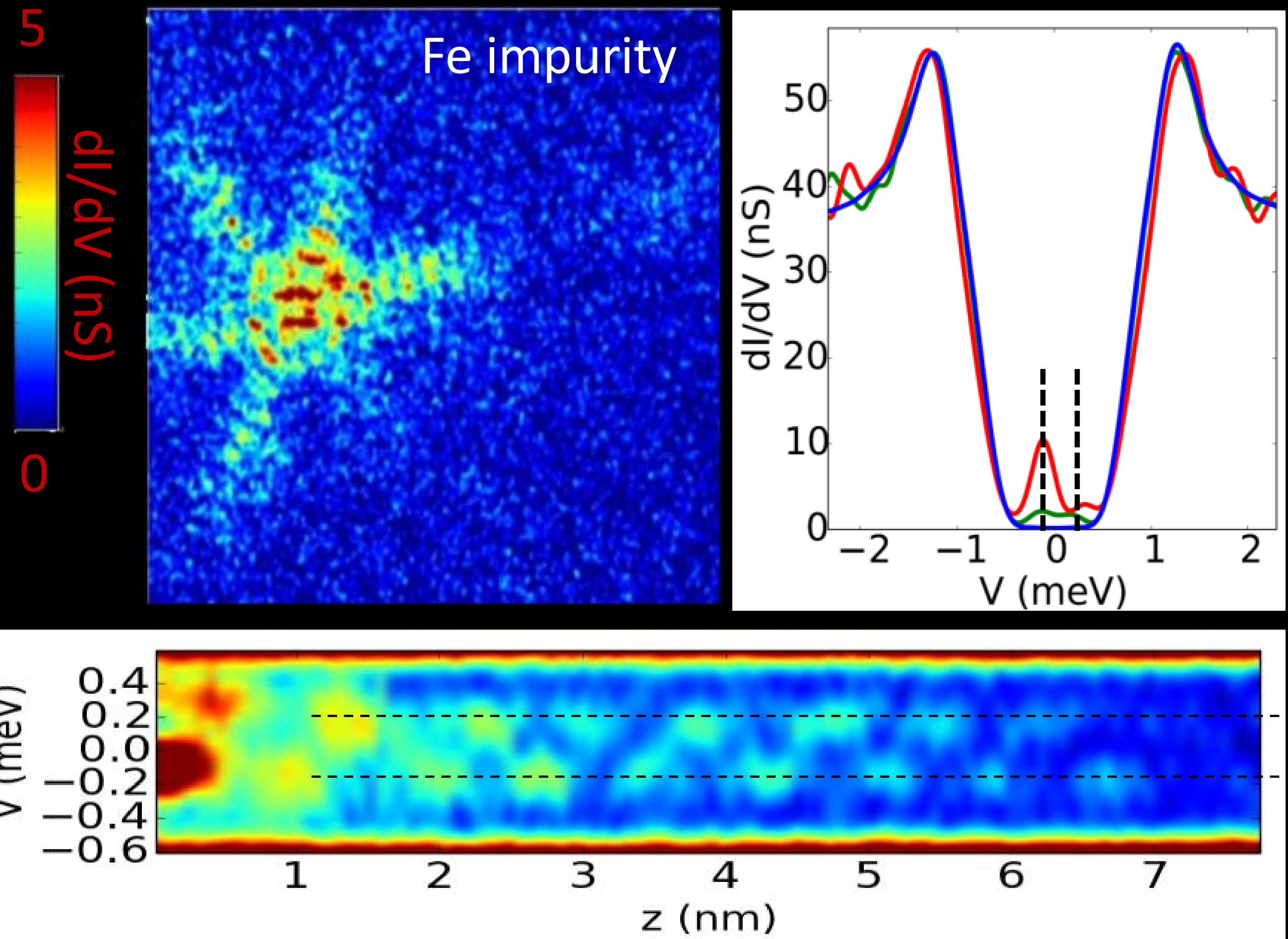
Non-magnetic impurities promote inter-band scattering channel – two band SC

Long-range Shiba bound states – *2H-NbSe$_2$*



In-gap spectroscopy reveals large scale star shaped features

Long-range Shiba bound states – *2H-$NbSe_2$*

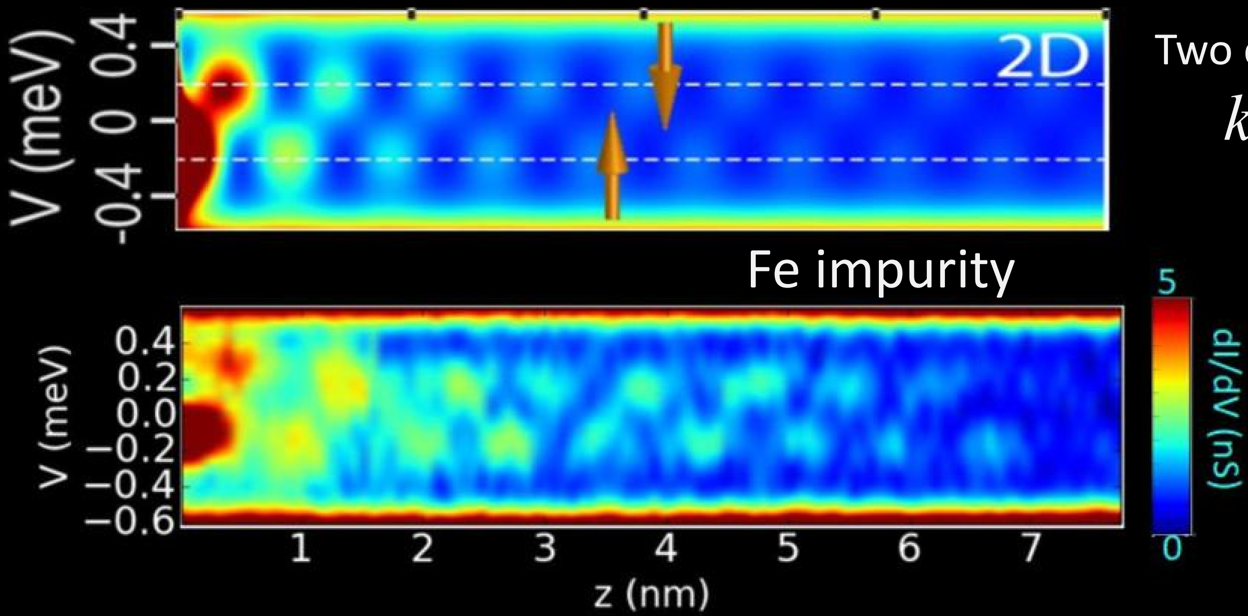


There are 2 Shiba peaks. They oscillate in space with a phase shift.

Long-range Shiba bound states – *2H-NbSe$_2$*

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

$$E_S = \Delta\cos(\delta^+ - \delta^-)\,; \quad \tan\delta^{\pm} = K\nu_0 \pm \frac{JS}{2}\nu_0$$



Two char. scales:

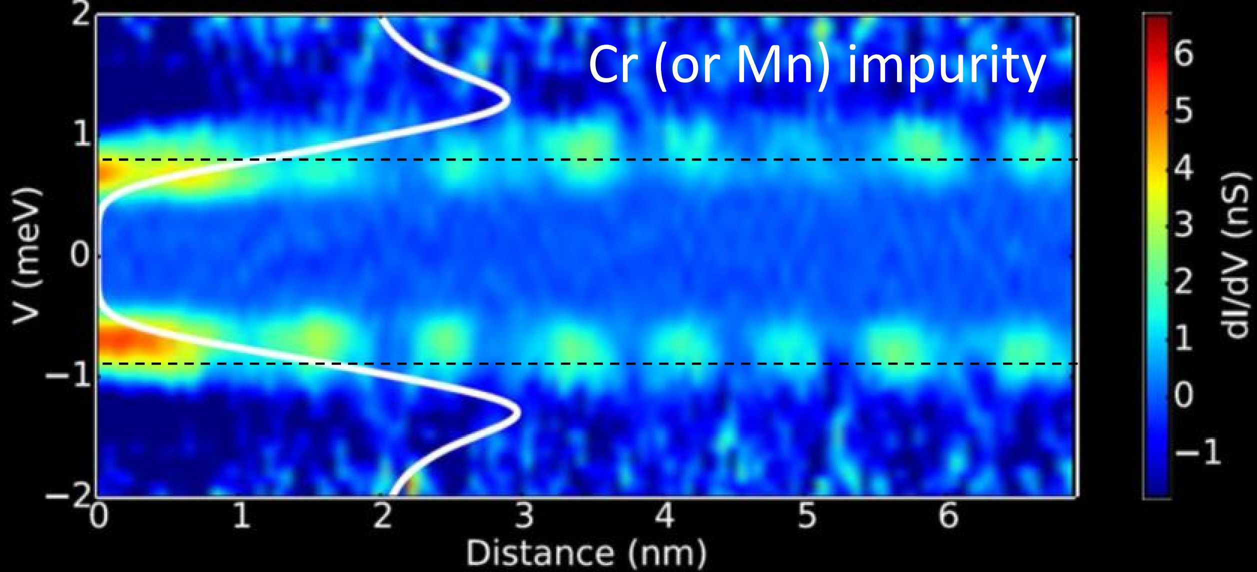
k_F and ξ

The phase shift is directly related to the position of the Shiba peaks.

Long-range Shiba bound states – *2H-NbSe₂*

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

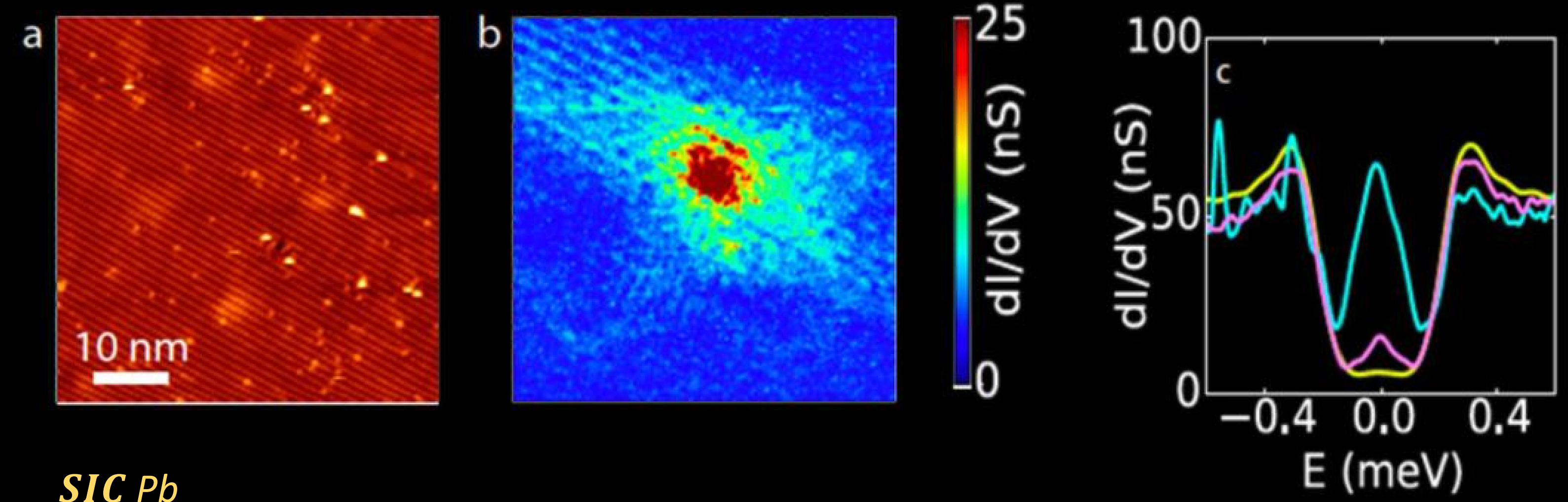
$$E_S = \Delta\cos(\delta^+ - \delta^-)\,; \quad \tan\delta^{\pm} = K\nu_0 \pm \frac{JS}{2}\nu_0$$



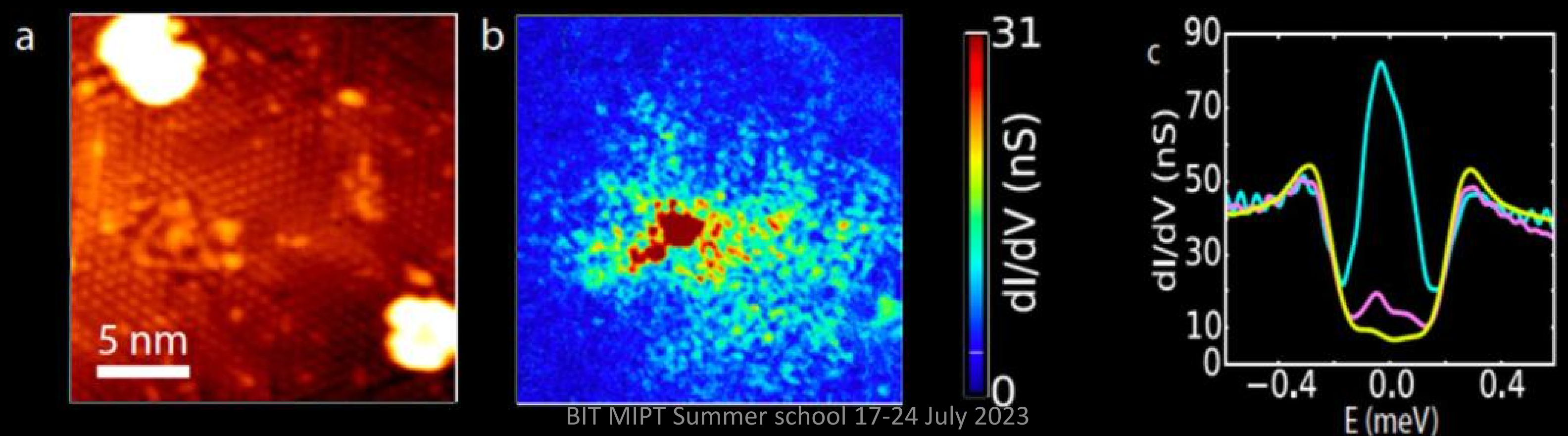
The phase shift is directly related to the position of the Shiba peaks.

Long-range Shiba bound states – *Pb-ML/Si(111)*

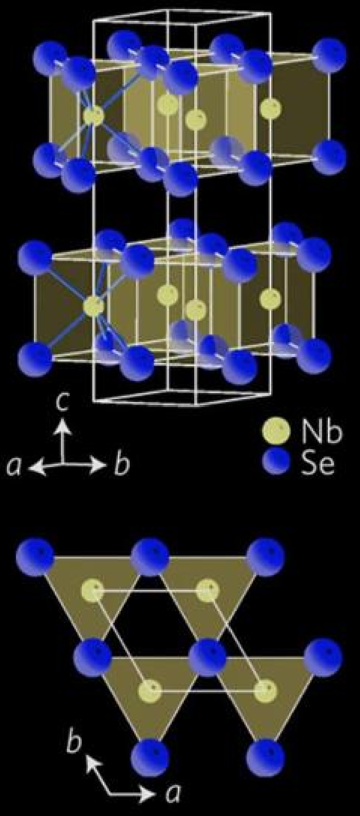
$\sqrt{7} \times \sqrt{3}$ *Pb*

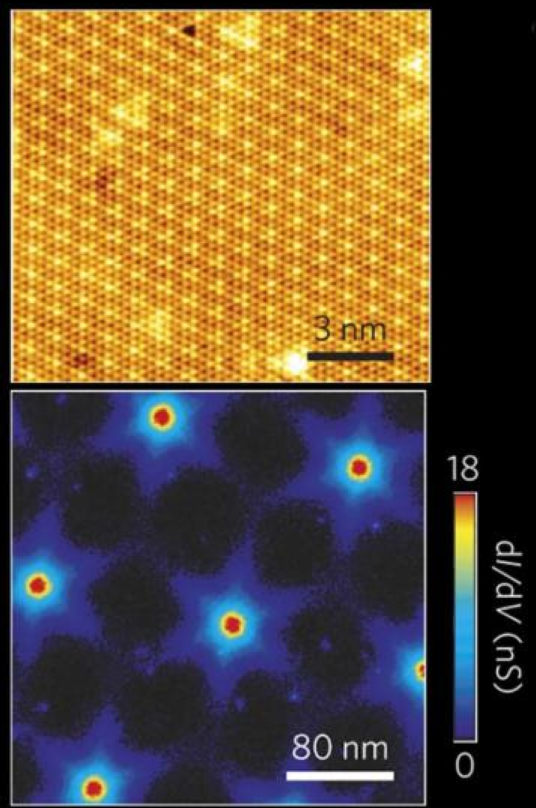


SIC *Pb*



Long-range Shiba bound states – *2H-NbSe$_2$*





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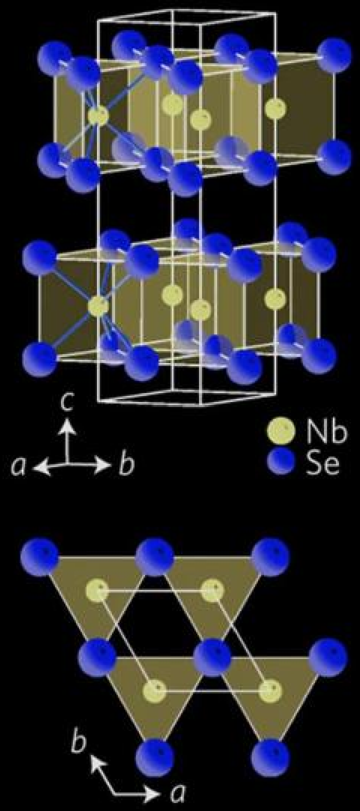
Coherent long-range magnetic bound states in a superconductor

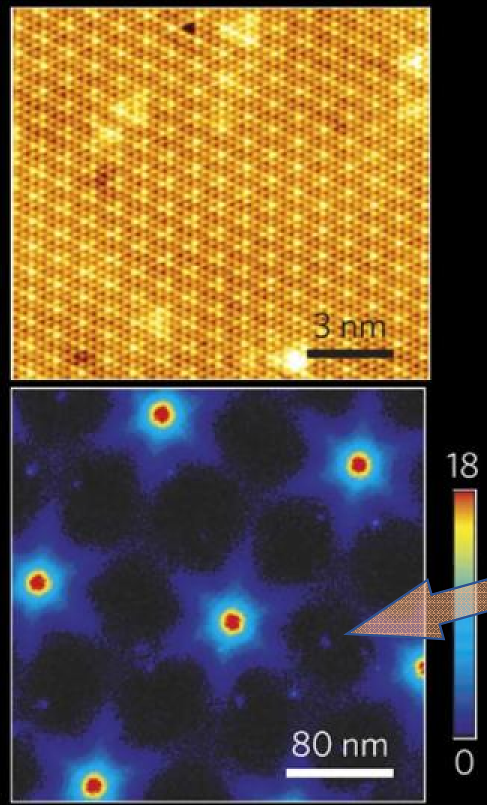
Gerbold C. Ménard[1], Sébastien Guissart[2], Christophe Brun[1], Stéphane Pons[1,3], Vasily S. Stolyarov[1,4], François Debontridder[1], Matthieu V. Leclerc[1], Etienne Janod[5], Laurent Cario[5], Dimitri Roditchev[1,3], Pascal Simon[2*] and Tristan Cren[1*]

Δ=1.1 мВ

T=0.3K < T$_C$= 7.2K

Long-range Shiba bound states – *2H-NbSe$_2$*





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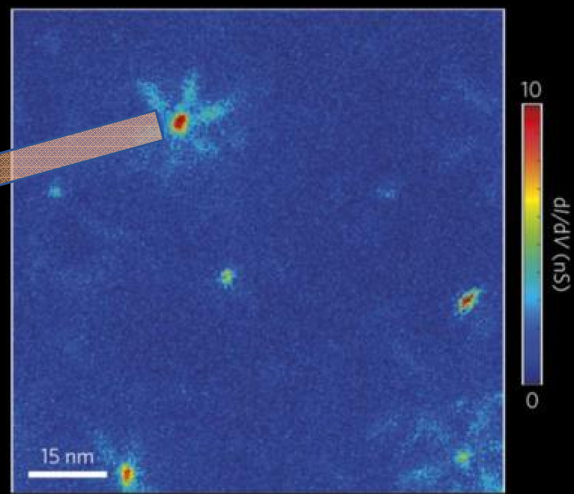
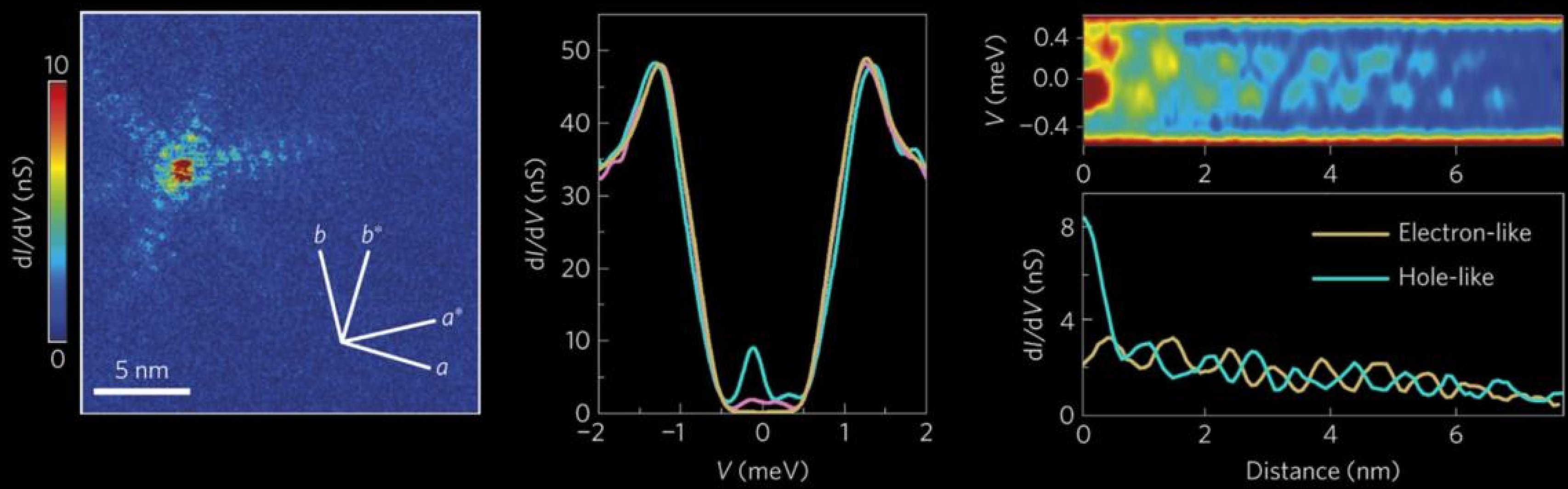
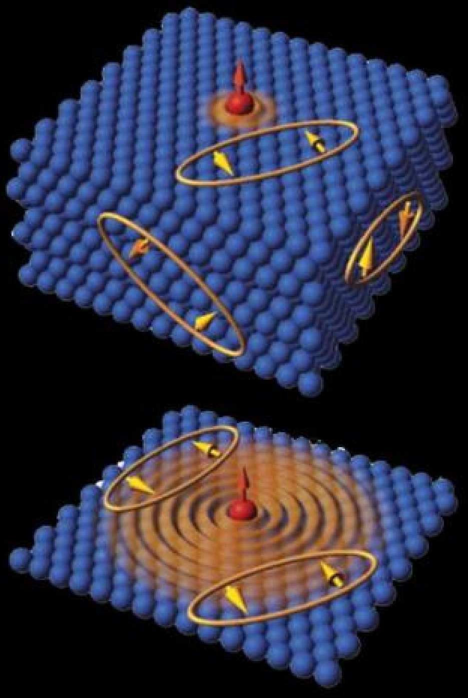
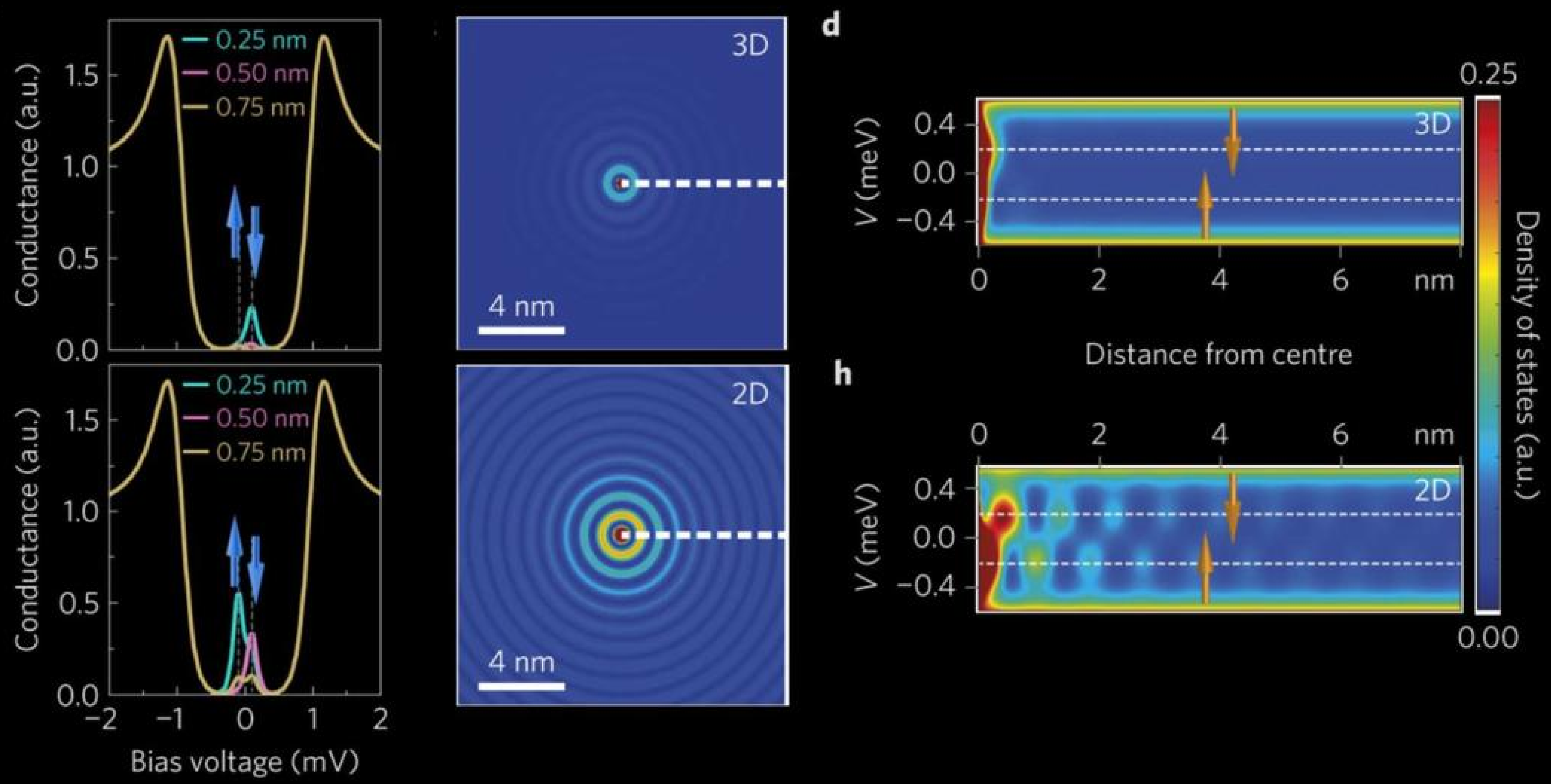


Long-range Shiba bound states – *2H-NbSe₂*



Long-range Shiba bound states – *2H-NbSe₂*

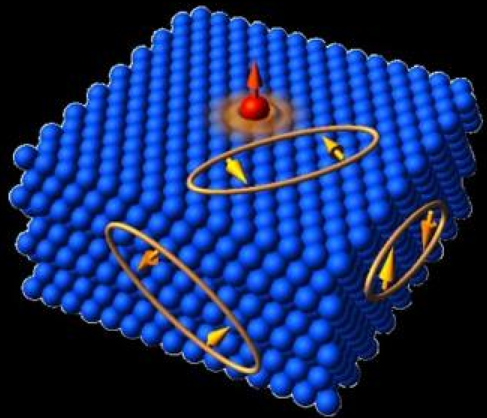




Long-range Shiba bound states – *2H-NbSe*$_2$

Experimental geometry (coupling, screening):

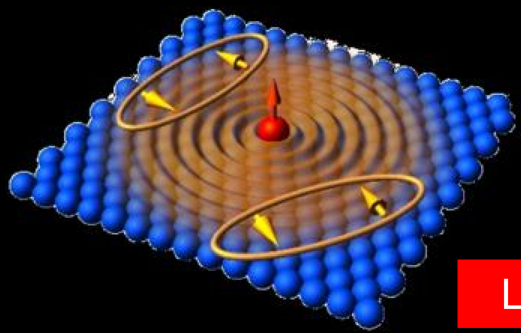
3D SC, magnetic atoms at the surface



3D

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

2D SC, magnetic atoms in the matrix

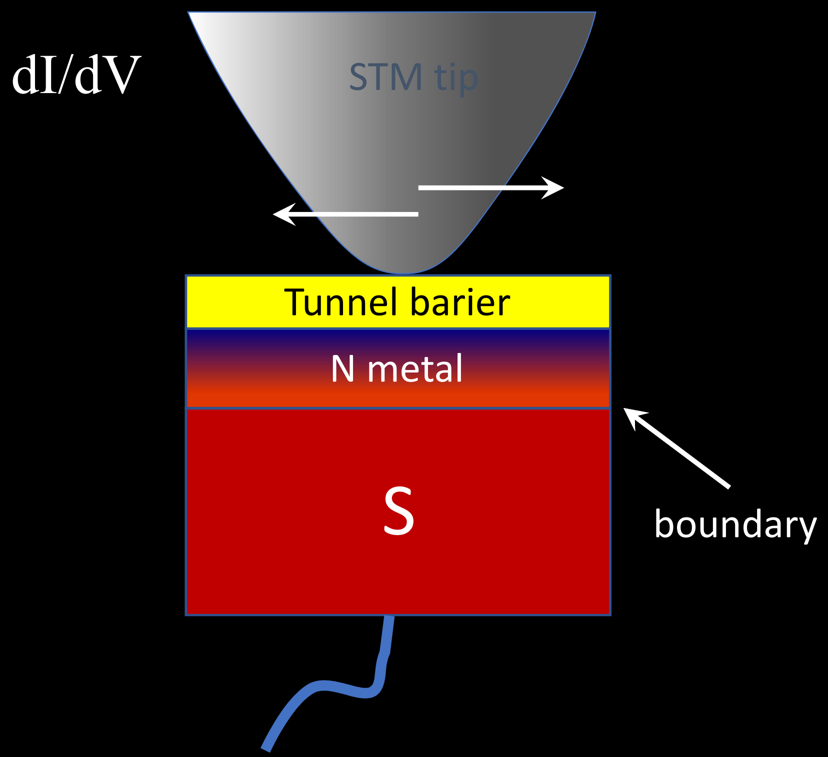


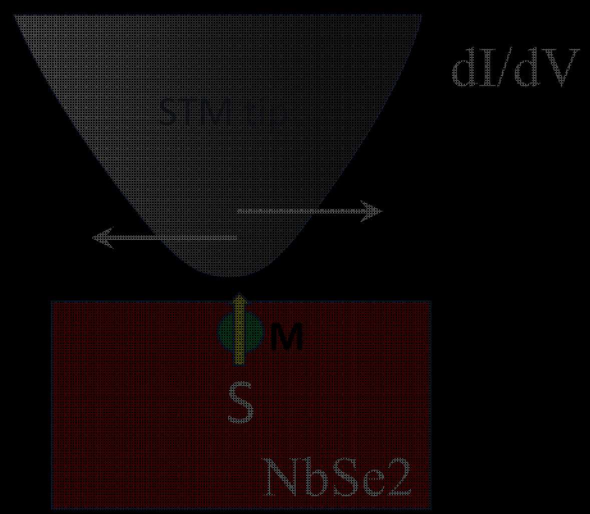
2D

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

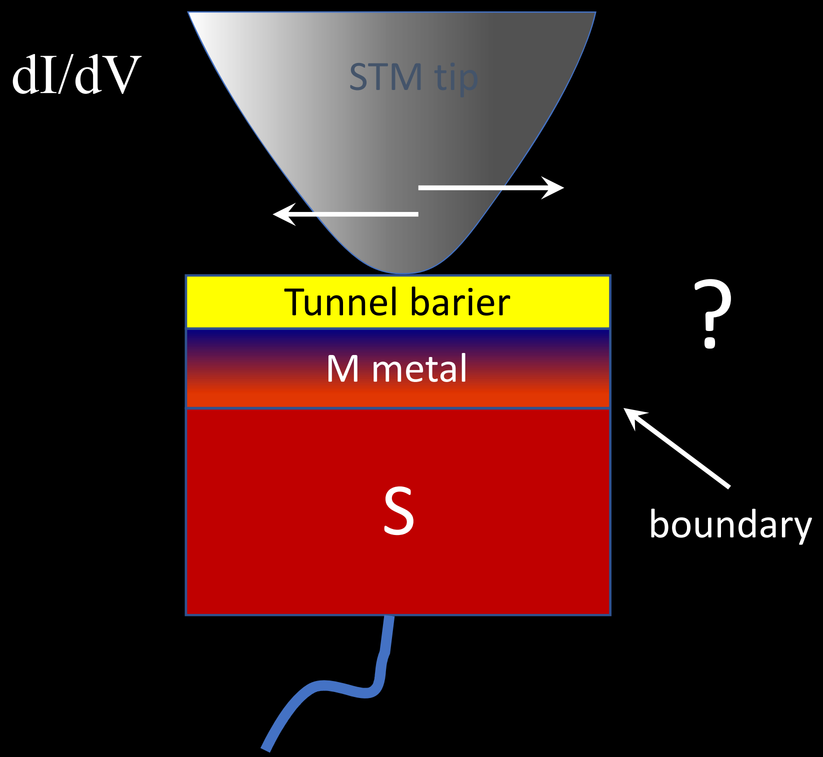
Lower dimensionality -> larger extents of YSR bound states

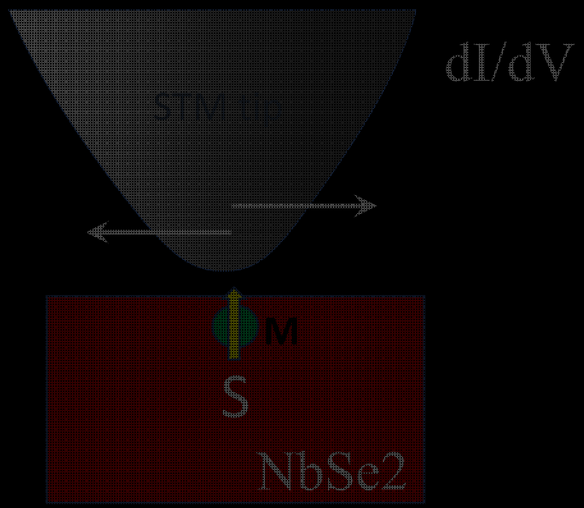
Proximity effect at the superconductor ferromagnet boundary





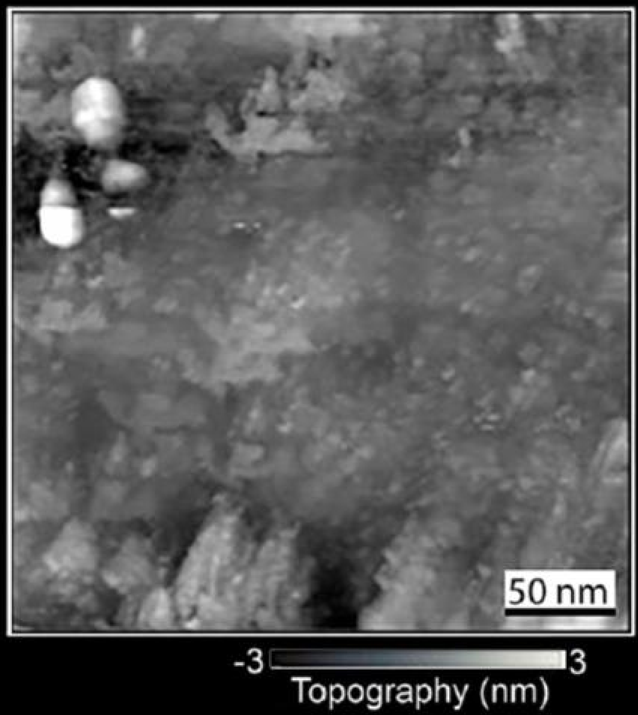
Proximity effect at the superconductor ferromagnet boundary





Proximity effect at the superconductor ferromagnet boundary

STM



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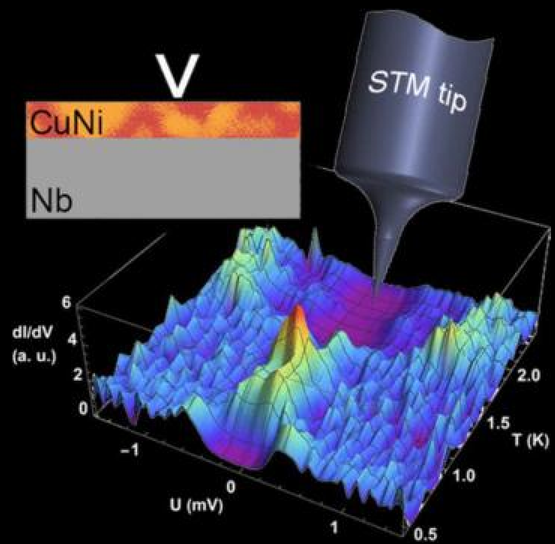
Letter

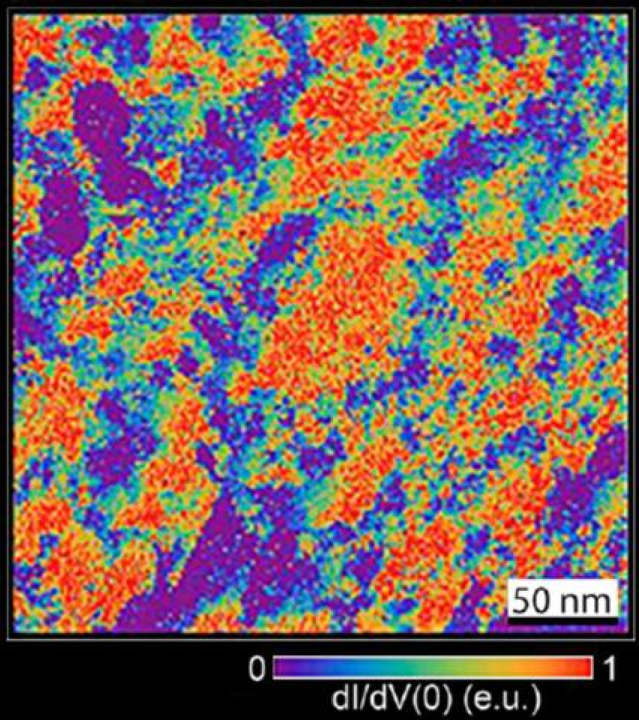
Effective Exchange Energy in a Thin, Spatially Inhomogeneous CuNi Layer Proximized by Nb

Vasily Stolyarov,* Vladimir Oboznov, Daniil Kasatonov, Alexey Neilo, Sergey Bakurskiy, Nikolay Klenov, Igor Soloviev, Mikhail Kupriyanov, Alexander Golubov, Tristan Cren, and Dimitri Roditchev



Proximity effect at the superconductor ferromagnet boundary

STS карта



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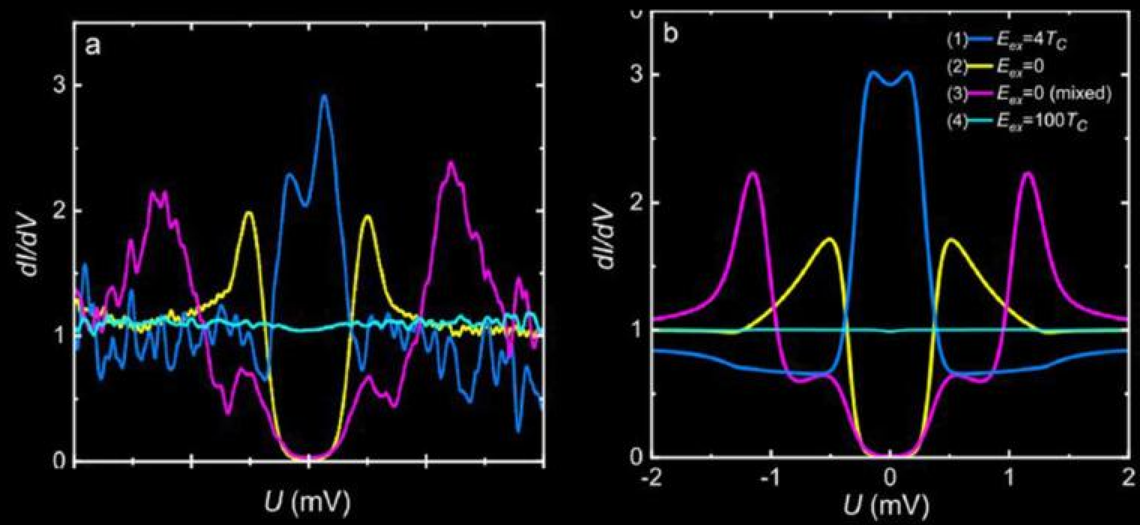

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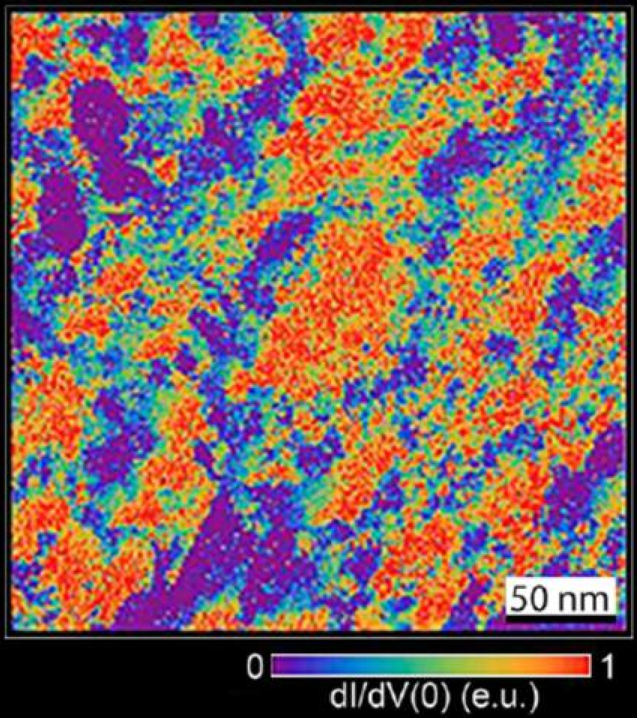

curve number	d_F, nm	E_{ex}	ξ_F, nm	ρ_F, $\mu\Omega$ cm	γ_B
1	7	$4T_c$	35	12.9	3
2	11	0	20	3.8	0.1
3(0.6)	11	0	20	3.8	0.1
3(0.4)	7	0	20	9.1	0.1
4	7	$100T_c$	35	12.9	3