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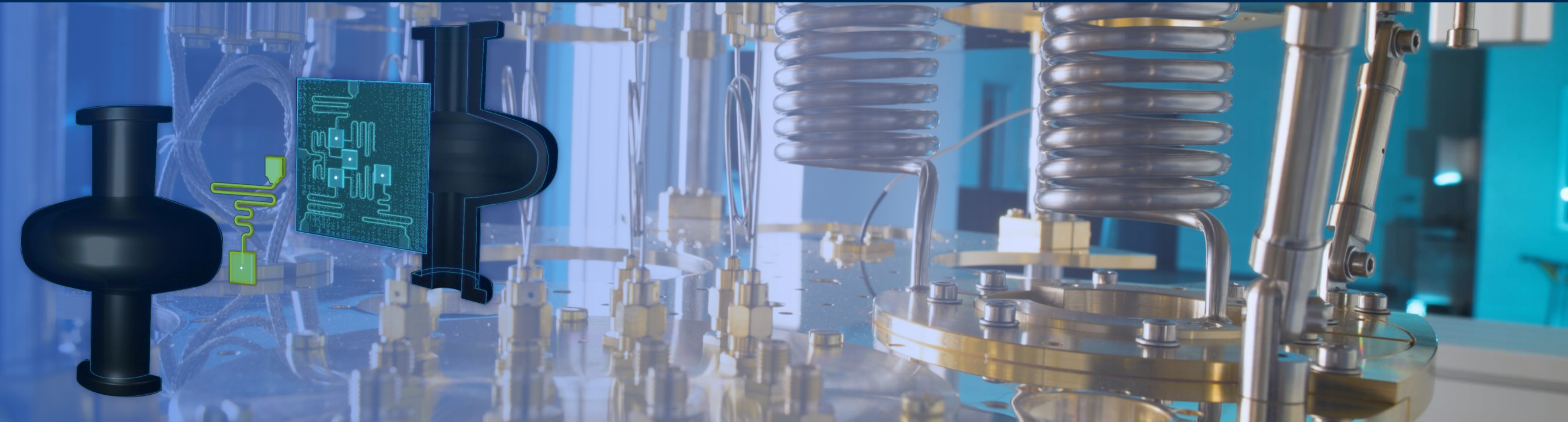

Superconducting Characterization Tools and Techniques (Part II)

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08/11/2023

U.S. Quantum Information Science Summer School
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Fermi National Accelerator Laboratory

Outline

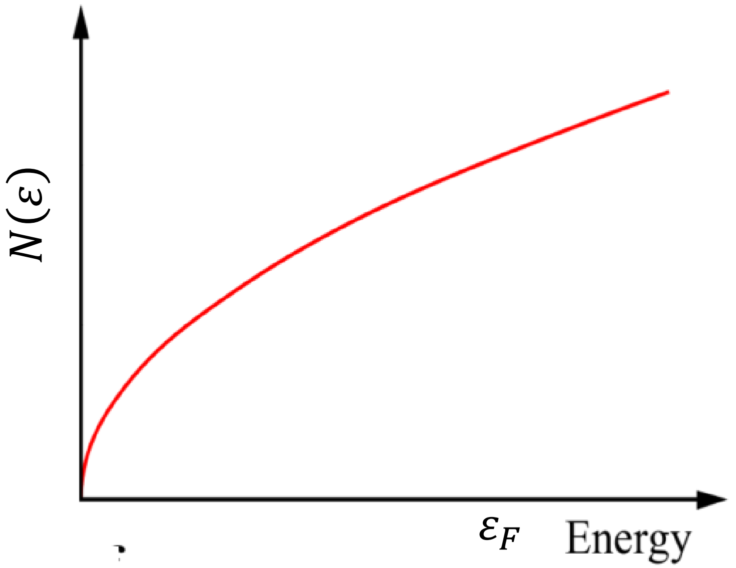
- ❑Density of States
- ❑Superconducting Gap Equation
- ❑Electron Tunneling
- ❑Application: planar tunnel junction
- ❑Principle of STM/STS
- ❑STM and Superconductors
- ❑Vortices in Type II Superconductors
- ❑STM application to Superconducting Qubits

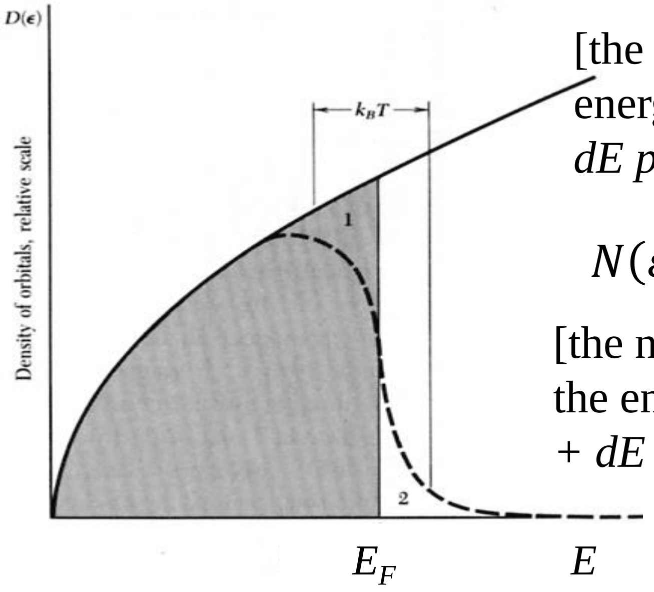
Density of States of Metals

For free electrons: $$\varepsilon_k = \frac{\hbar^2 k^2}{2m}$$

The density of states, i.e. the number of available states between ε and $\varepsilon + d\varepsilon$ is:

$$N(\mathcal{E}) = \frac{(2m)^{3/2}\varepsilon^{1/2}}{2\pi^2\hbar^3}$$





$N(\varepsilon)d\varepsilon =$

[the number of states in the energy range from E to $E + dE$ *per unit volume*]

$N(\varepsilon)f(\varepsilon)d\varepsilon =$

[the number of filled states in the energy range from E to $E + dE$ *per unit volume*]

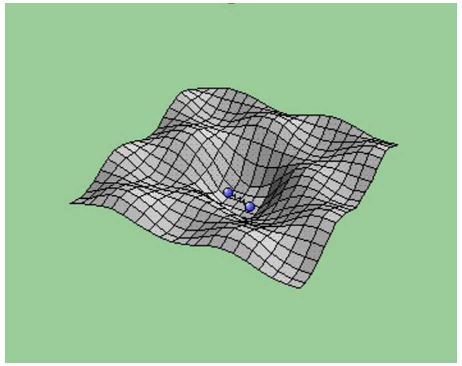
- Very important result, but note that the E dependence is different for different dimension (1D, 2D, 3D).
- Normally $k_BT \ll \varepsilon_F$ even at room T
- For most metals $N(\varepsilon_F) \approx constant$

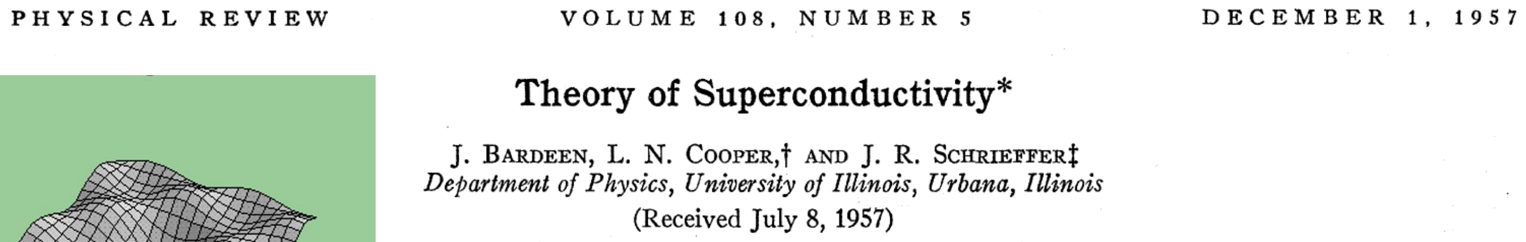
Key-ideas of the BCS theory of 1957 (Bardeen, Cooper, Schrieffer)

- The interaction of the electrons with lattice vibrations (phonons) must be important (isotope effect, high transition temperature for some metals which are poor conductors at room temperature).
- The electronic ground state of a metal at 0 K is unstable if one permits a net attractive interaction between the electrons, no matter how small.
- The electron-phonon interaction leads to a new ground state of Bosonic electron pairs (Cooper pairs) which shows all the desired properties.

BCS: Microscopic Theory of Superconductivity

1957: Bardeen, Cooper, Schrieffer
Nobel:1972

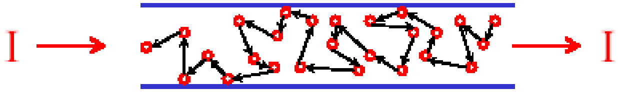



PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

J. BARDEEN, L. N. COOPER,† AND J. R. SCHRIEFFER‡
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 8, 1957)

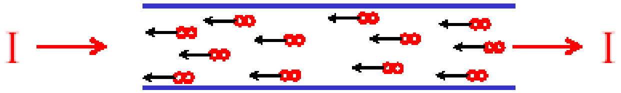
Electron has charge -e



Scattering of electrons produces resistance.

A current generates a voltage, and hence cause dissipation

Electrons are paired together:
Cooper pairs have charge -2e



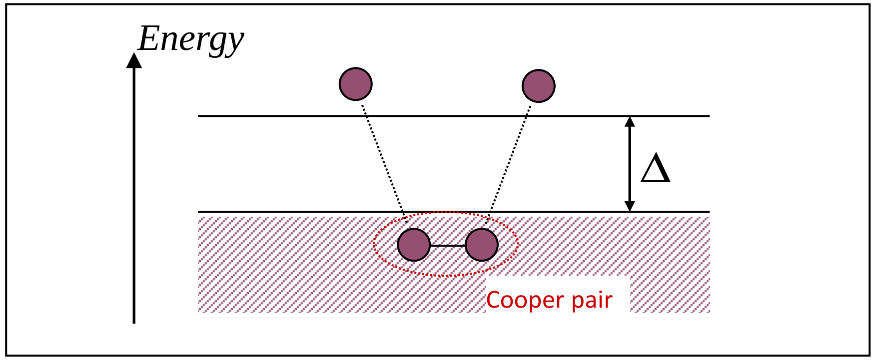
Cooper pairs carry a supercurrent, which encounters no resistance

A supercurrent generates no voltage, and hence cause no dissipation

Superconductors: Gap Equation

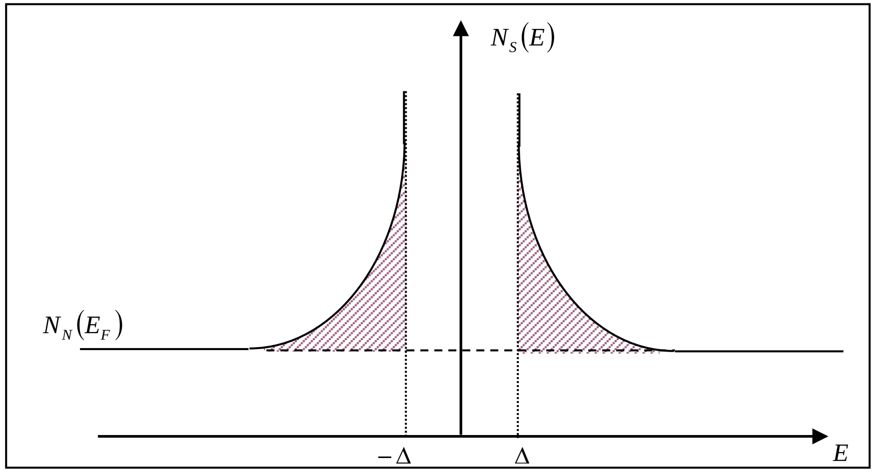
NORMAL METAL: $$\varepsilon_k = \frac{\hbar^2 k^2}{2m}$$

SUPERCONDUCTOR: $$E = \sqrt{\varepsilon_k^2 + \Delta^2}$$



SUPERCONDUCTING QUASIPARTICLE DENSITY OF STATES:

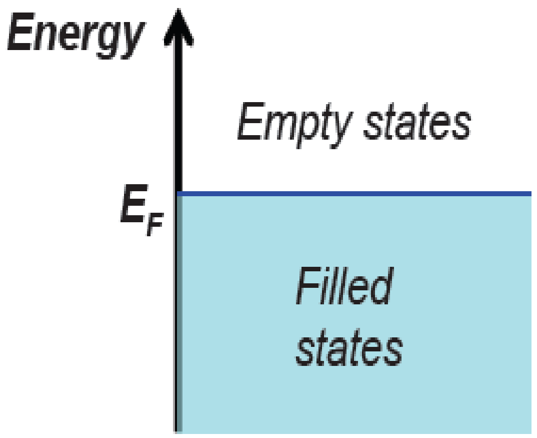
$$N_S(E) = N_N(E_F)\frac{|E|}{\sqrt{E^2 - \Delta^2}}$$



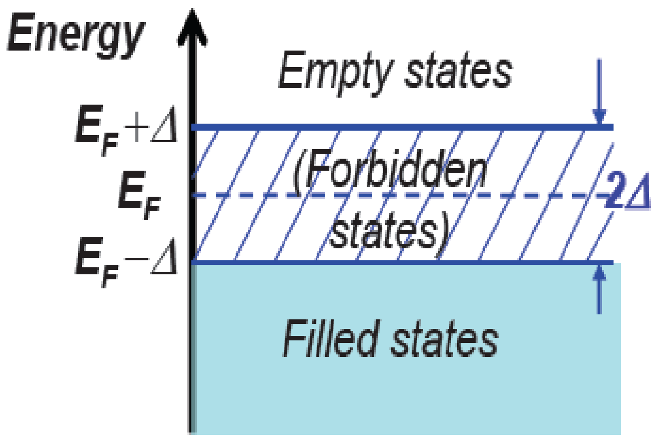
Microscopic theory of superconductivity: Bardeen, Cooper, Schrieffer (BCS) 1957

- In a normal metal, electrons obey the Fermi statistics and the Pauli exclusion principle

- In a superconductor, electrons are paired in Cooper Pairs. They all condense in the ground state. An energy gap D opens above the Fermi energy.



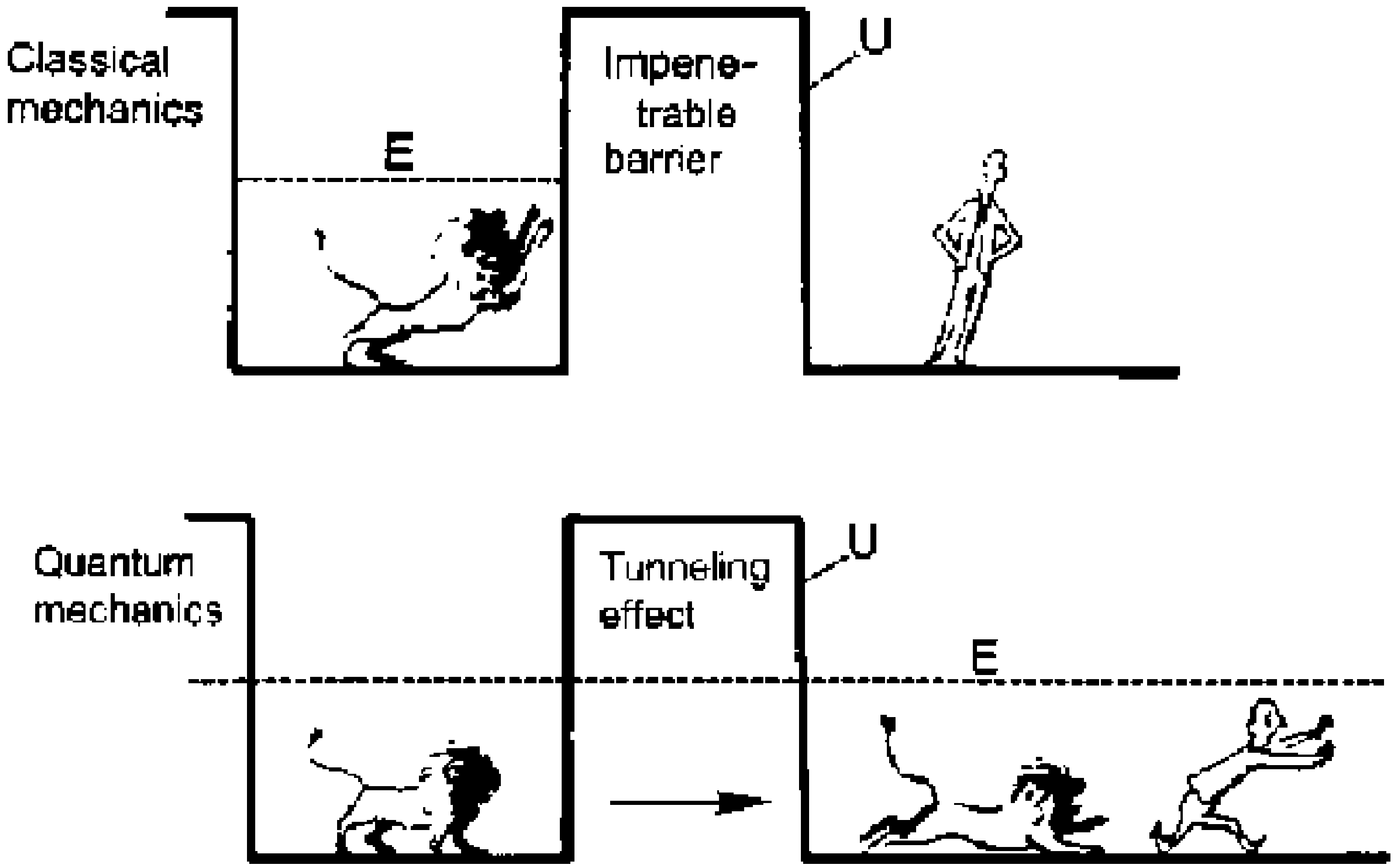
(Normal Metal)



(Superconductor)

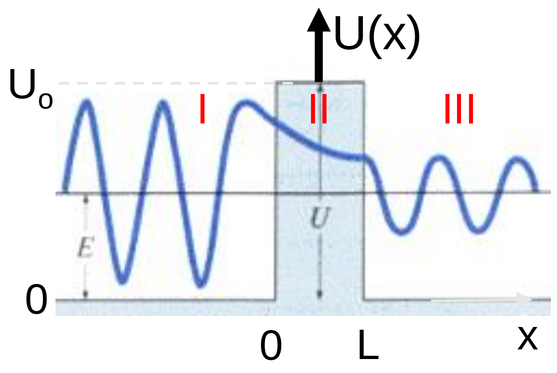
Electron Tunneling

Electron tunneling through a potential barrier



In quantum mechanics a particle can penetrate into a barrier where it would be classically forbidden.

Electron tunneling through a potential barrier



What is the probability that an incident particle tunnels through the barrier?

Time-independent Schrödinger equation

$$\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + U(z)\right)\psi(x) = E\psi(x)$$

Getting an exact result requires applying the boundary conditions at x=0 and x=L

Free electron solutions in region I and III

$$\psi_I = e^{ikx} + Ae^{-ikx}$$
$$\psi_{III} = De^{ikx}$$

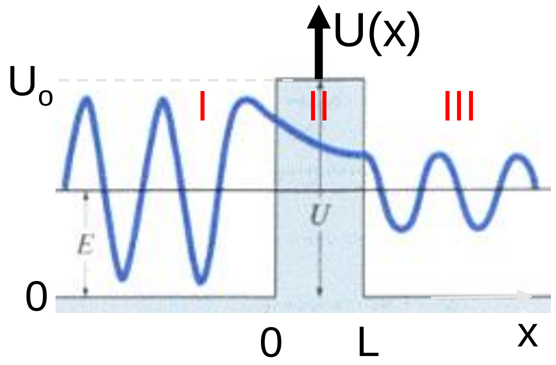
Exponential decay in the barrier (region II)

$$\psi_{II} = Be^{-Kx} + Ce^{Kx}$$

The electron tunnels through the barrier.

$$k^2 = 2mE/\hbar^2$$
$$K^2 = 2m(U_0 - E)/\hbar^2$$

Electron tunneling through a potential barrier



What is the probability that an incident particle tunnels through the barrier?

In many situations, the barrier width L is much larger that the "decay length" 1/K of the penetrating wave ($KL \ll 1$). In this case $C \approx 0$.

Transmission coefficient: transmitted/incoming amplitudes

$$T \approx Ge^{-2KL} \quad \text{where} \quad G = 16\frac{E}{U_0}\left(1 - \frac{E}{U_0}\right) = 16\frac{2m}{\hbar^2}\frac{k^2K^2}{k^2 + K^2}$$

T decays exponentially with the barrier width.

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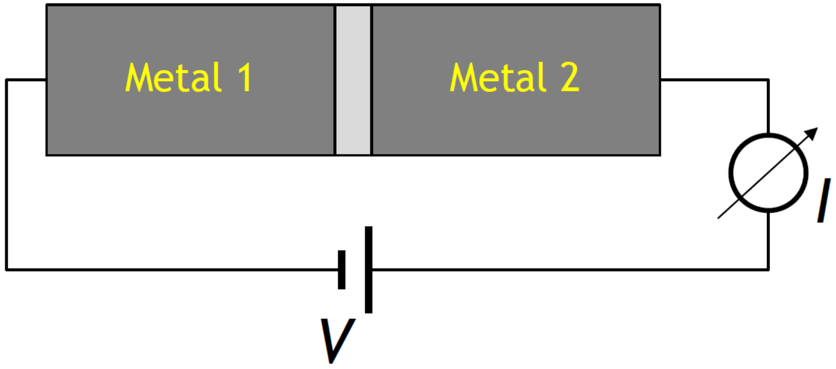
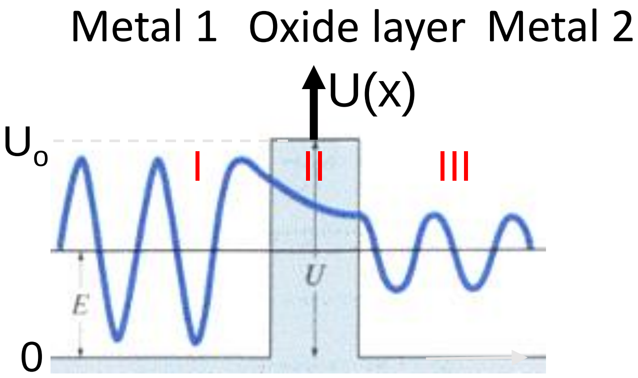
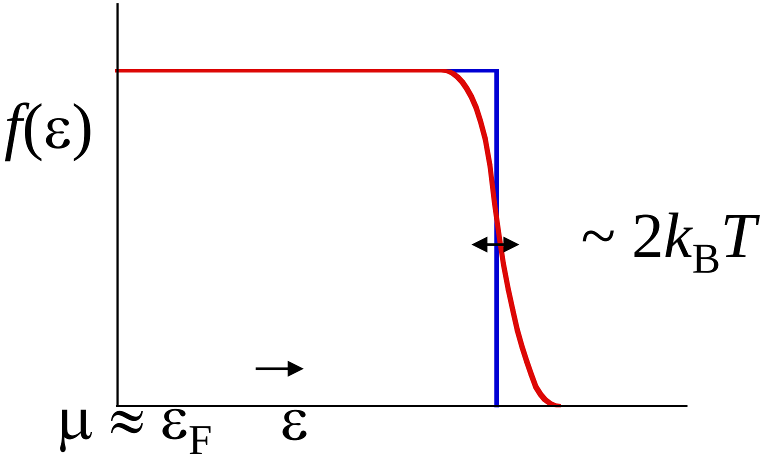
Application: planar tunnel junction





Tunneling electrons obey Fermi statistics:

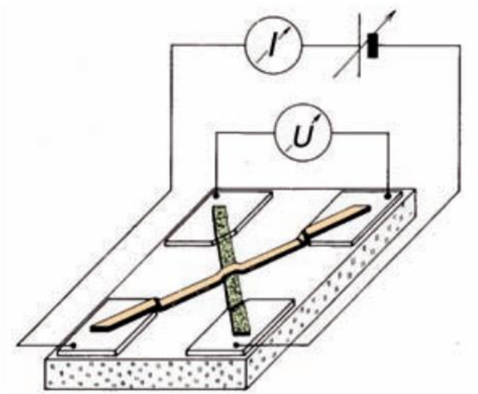
$$f(E) = \frac{1}{e^{E/k_B T+1}} \qquad E = \varepsilon - \varepsilon_F$$

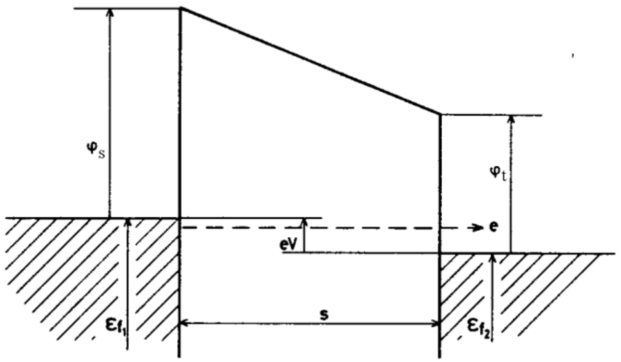


Tunneling depends on the electronic density of states (DOS) of both electrodes in the junction.

Tunneling Spectroscopy

Planar Tunnel Junctions





J. C. Fisher and I. Giaever, "Tunneling through thin insulating layers," Journal of Applied Physics, 32, 172 (1961).

$$dI_{L\rightarrow R} = \underbrace{f(E)N_L(E)}_{\text{Occupied states Metal L}}\underbrace{[1-f(E+eV)]N_R(E+eV)}_{\text{Empty states Metal R}}\,T(E,V)dE$$

$$dI_{R\rightarrow L} = \big(1-f(E)\big)N_L(E)f(E+eV)N_R(E+eV)\,T(E,V)dE$$

$$I = \int_{-\infty}^{+\infty}\{f(E)N_L(E)[1-f(E+eV)]N_R(E+eV)\,T(E,V) - \big(1-f(E)\big)N_L(E)f(E+eV)N_R(E+eV)\,T(E,V)\}dE$$

$$I = \int_{-\infty}^{+\infty} N_L(E)N_R(E+eV)T(E,V)[f(E)-f(E+eV)]dE$$

T(E,V) is the transmission factor,
N_L and N_R are the density of states in the two electrodes
f(E) is the Fermi function, which guaranties that the electrons tunnel from an occupied into an empty state

$$T(E,eV) = \exp\left(-\frac{2d\sqrt{2m}}{\hbar}\sqrt{\frac{\Phi_s+\Phi_t}{2}+\frac{eV}{2}-E}\right)$$

Tunneling Spectroscopy

$k_B T << E_F$ $$I = \int_{E_F - eV}^{E_F} N_L(E) N_R(E+eV) T(E,V)[f(E) - f(E+eV)] dE$$

2) $eV << \Phi$ $$T(E,V) \approx T(E_F, 0)$$ Transmission factor independent on energy

3) $eV << E_F$ $$N_R(E) \approx N_R(E_F)$$

$$I = N_R(E_F) T(E_F, 0) \int_{E_F - eV}^{E_F} N_L(E)[f(E) - f(E+eV)] dE$$ I is proportional to the integral of N_L in the interval E_F+eV

Measure I(V) to obtain N_L

$$\frac{dI}{dV} \propto \int_{E_F - eV}^{E_F} N_L(E) \left[-\frac{\partial f(E+eV)}{\partial (eV)} \right] dE$$

Tunneling Spectroscopy

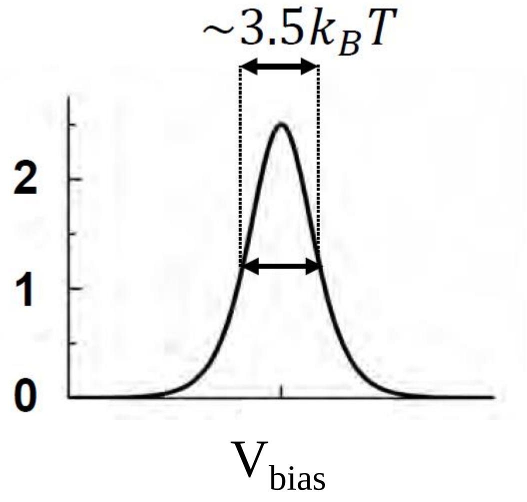
Measure I(V) to obtain N_L

$$\frac{dI}{dV} \propto \int_{E_F-eV}^{E_F} N_L(E)\left[-\frac{\partial f(E+eV)}{\partial(eV)}\right] dE$$

Energy resolution strongly dependent on temperature

Typical Energy Resolution:

T=300 K	$\Delta E = 0.1eV$
4.2 K	$\Delta E \sim 1.5\ meV$
300 mK	$\Delta E \sim 100\ \mu eV$



$$\frac{dI}{dV} \propto N_L(E_F - eV)\, N_R(E_F) T(E_F, 0)$$

Differential conductance directly proportional to the density of states in the sample

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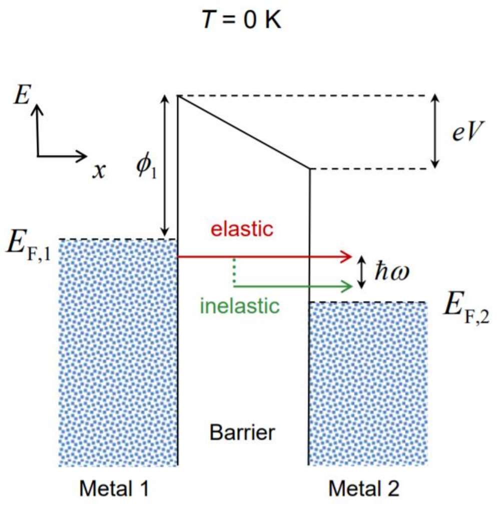
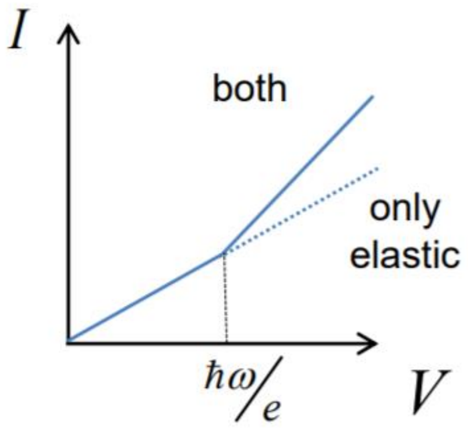
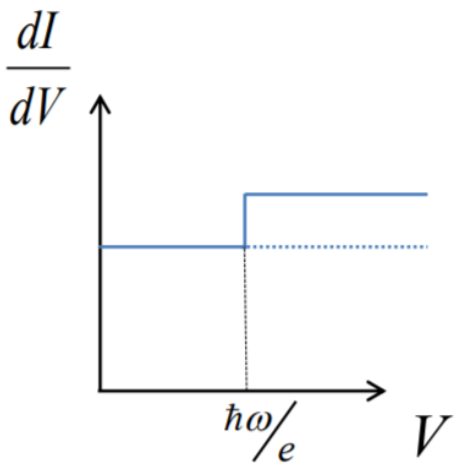
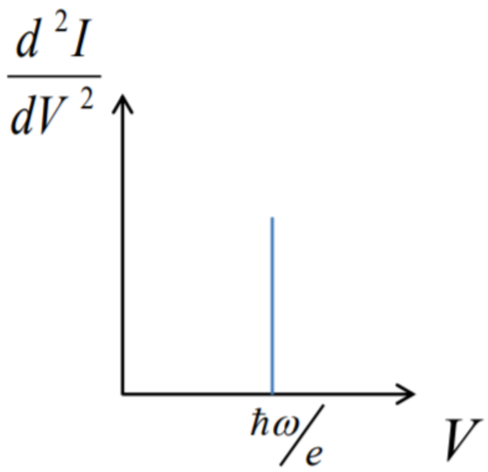
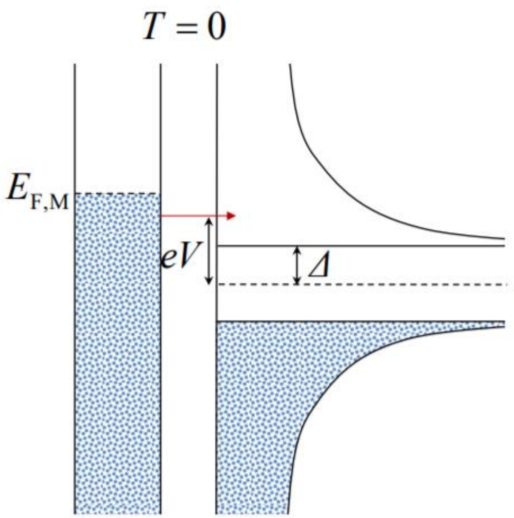
Tunneling Spectroscopy

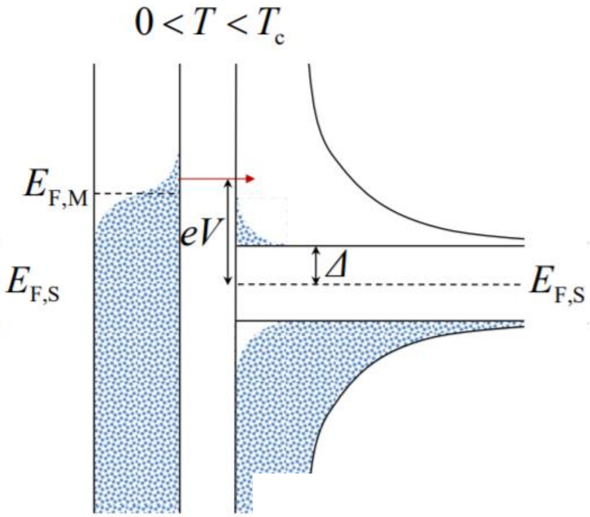


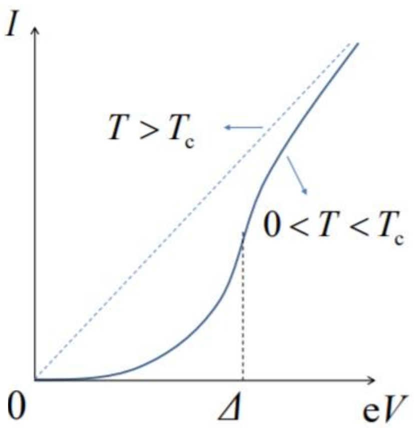


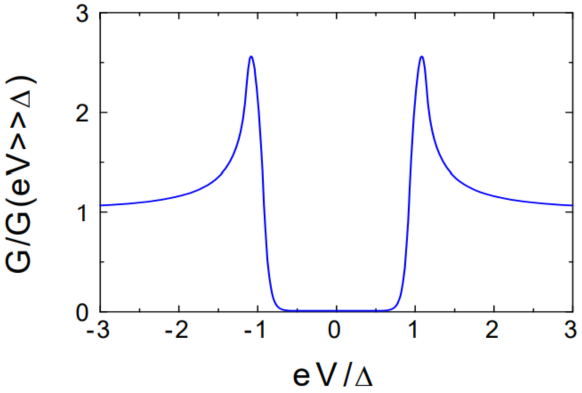












$$N(E) = \mathrm{Re}\left\{\frac{|E|}{(E^2 - \Delta^2)^{1/2}}\right\}$$

Strong-coupling – details of electron-phonon coupling important

Δ_k is complex and energy-dependent

$\mathrm{Re}(\Delta_k) \Rightarrow$ excitation energies

$\mathrm{Im}(\Delta_k) \Rightarrow$ decay of qp excitations with the emission of phonons

Theory --- Eliashberg gap equation (1960) considered the retarded nature of electron-phonon coupling (not in BCS)

Results --- phonon modes $\Leftrightarrow$ $N_S(E)$ variations

TWO PARAMETERS
- μ^* Coulomb pseudo-potential (repulsive interaction)
- $\alpha^2 F(\omega)$ electron-phonon (attractive interaction)

$\alpha^2(\omega)$ electron-phonon coupling strength

$F(\omega)$ phonon density of states

Bill McMillan

John Rowell

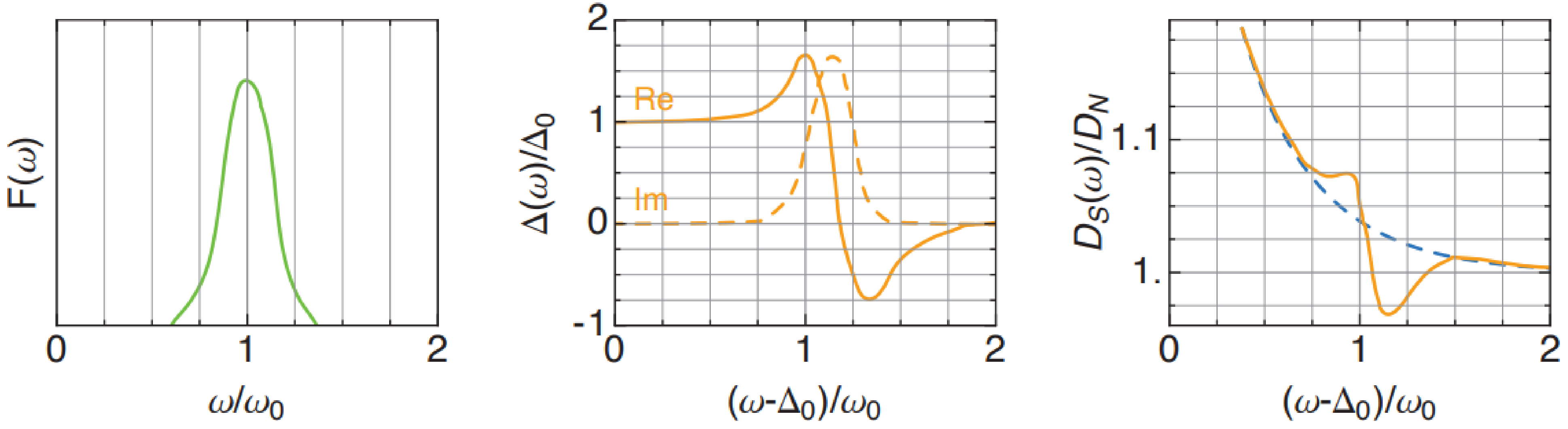
McMillan Conversion Procedure

$\mu^*, \alpha^2 F \leftrightarrow N_S(E)$ iterative solution (vary $\mu^*, \alpha^2 F$)

$$T_c = \frac{\theta_D}{1.45}\, exp\left[-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right]$$

where $\lambda = 2\int_0^\infty d\omega \left(\frac{1}{\omega}\right) \alpha^2(\omega) F(\omega)$

Experiments (Rowell & McMillan) ⟶ excellent agreement with known phonon data and fits to tunneling data



J. Scalapino, J. R. Schrieffer, and J. W. Wilkins, “Strong-coupling superconductivity. I,” Physical Review, 148, 263 (1966).

Strong-coupling – details of electron-phonon coupling important

Strong-coupling SC

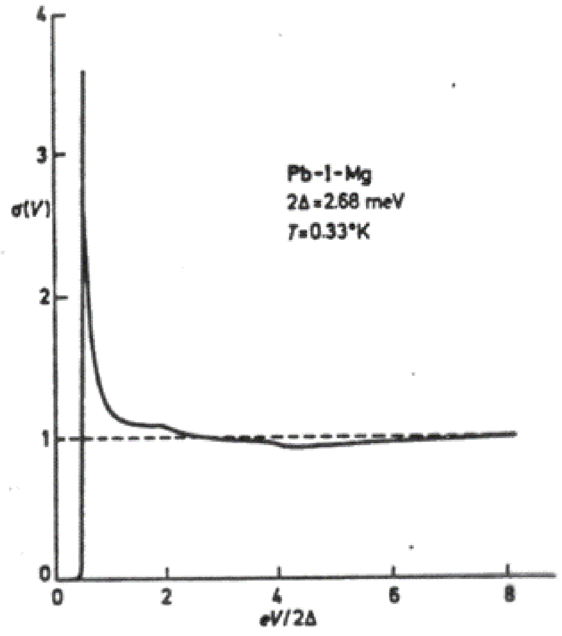
Some superconductors $\frac{2\Delta(0)}{k_B T_c} > 3.53$

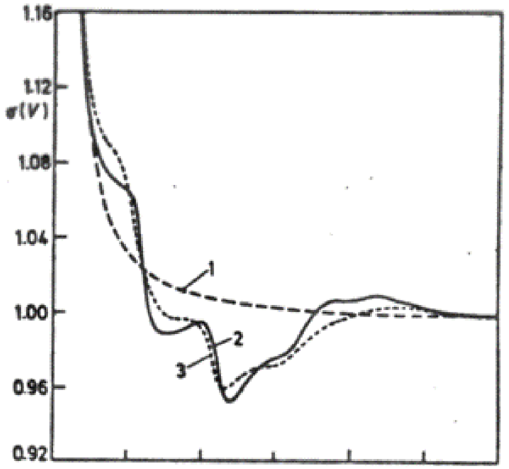
Pb ~ 4.3, Nb ~ 4.8, Hg ~ 4.6, YBCO ~ 6

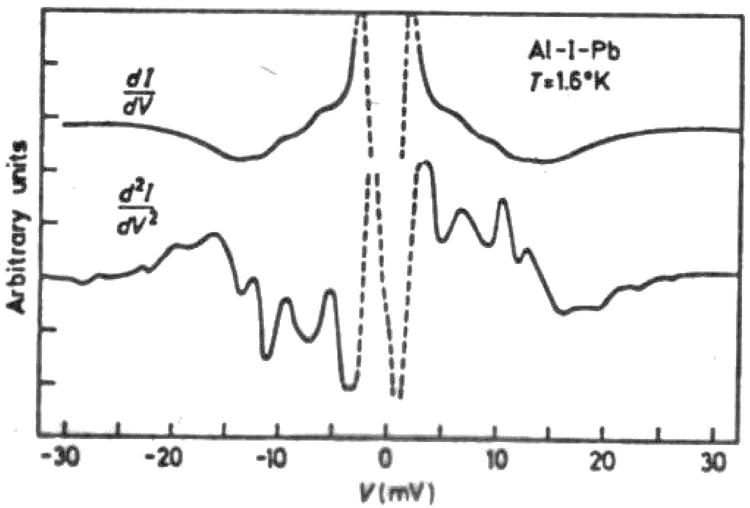
Structure in tunneling (for $eV \gg \Delta$)

For weak coupling $N(0)V \ll 1$, the details of the microscopic pairing wash out

For strong coupling $N(0)V \sim 1$, the details of the phonons responsible for the pairing are revealed





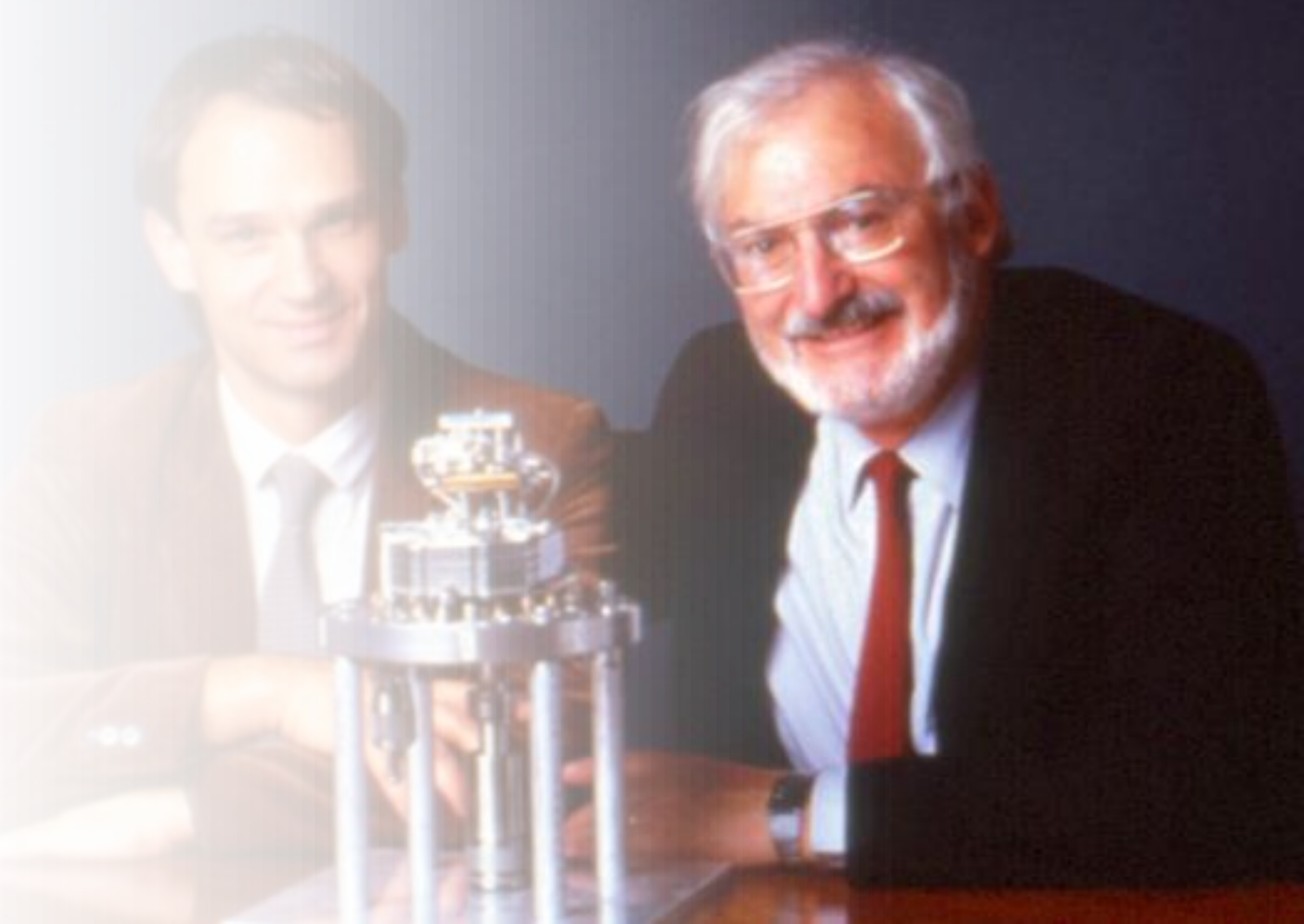


Structure near $k\theta_D$ (phonon frequencies)

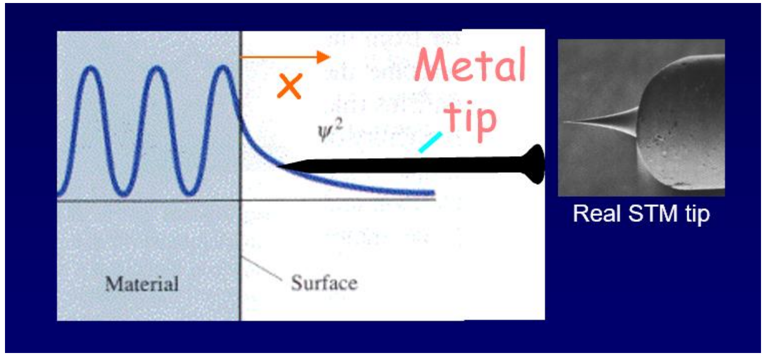
Scanning Tunneling Microscope

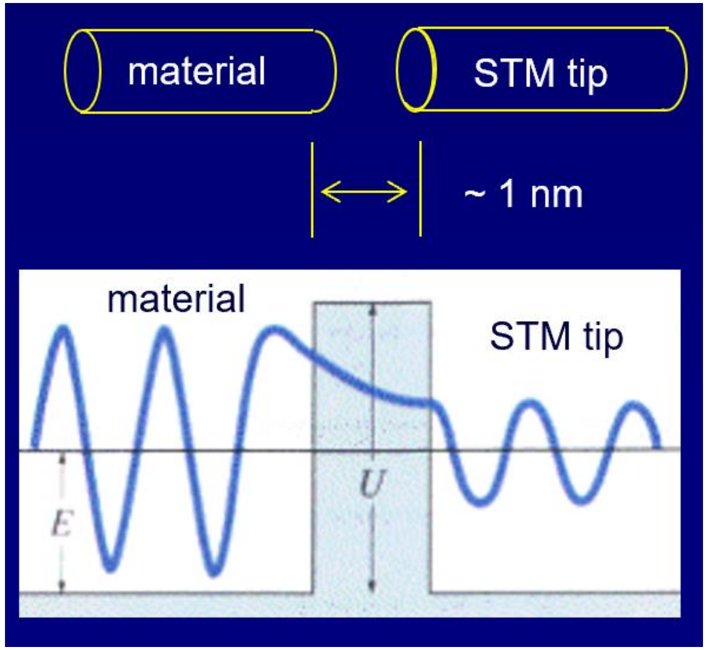
G. Binning & H. Rohrer (IBM, Zurich) Nobel Prize- 1986

The Nobel Prize in Physics 1986 was divided, one half awarded to Ernst Ruska "for his fundamental work in electron optics, and for the design of the first electron microscope", the other half jointly to Gerd Binnig and Heinrich Rohrer "for their design of the scanning tunneling microscope."



Working Principle of the Scanning Tunneling Microscope (STM)





$$I = N_R(E_F)T(E_F,0)\int_{E_F-eV}^{E_F} N_L(E)[f(E)-f(E+eV)]dE$$

WKB-approximation

$$T(E_F,0) \propto exp(-2\gamma)$$

Barrier width

$$\gamma = \int_0^L \sqrt{2m\varphi/\hbar^2}\,dz = \frac{L}{\hbar}\sqrt{2m\varphi}$$

Barrier height

$$\phi \approx \frac{\varphi_1+\varphi_2}{2}$$

Work functions

$$I \propto e^{-2kL}\int_{E_F-eV}^{E_F} N_{sample}(E)[f(E)-f(E+eV)]dE$$

Main idea of the STM is to exploit the exponential decay of the tunneling current over the distance between tip and sample

Working Principle of the Scanning Tunneling Microscope (STM)

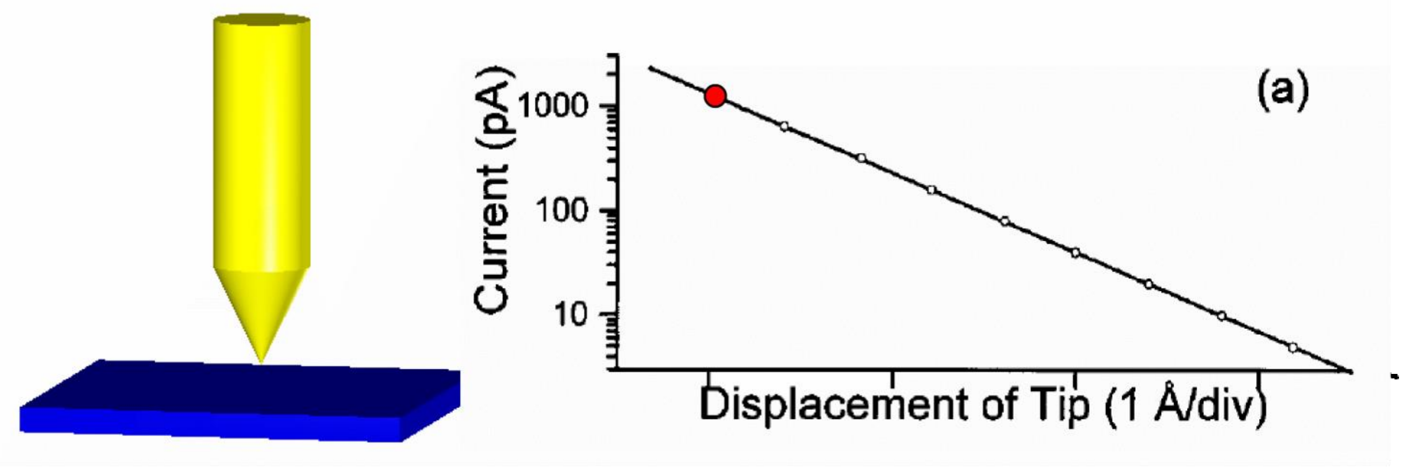
- Tunneling current

$$I \approx 18 \frac{V_s}{10000\Omega} \frac{k}{d} A_{eff} e^{-2kd}$$

$$A_{eff} = \pi \times \left(\tfrac{1}{2} L_{eff}\right)^2$$

$$L_{eff} \approx 2 \times \left[(R_t + d)/k\right]^{1/2}$$

$$2k\ [\text{Å}^{-1}] = 1.025\Phi^{1/2}\ [\text{eV}]$$



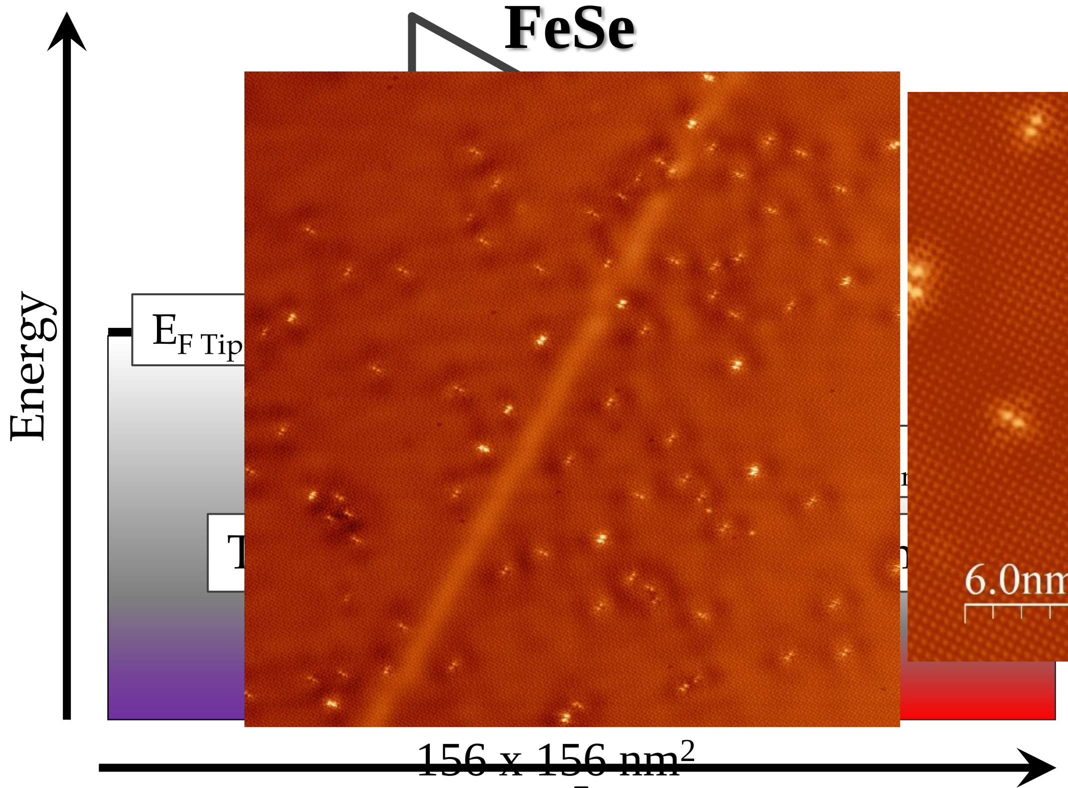
What information can be accessed by STM/STS?

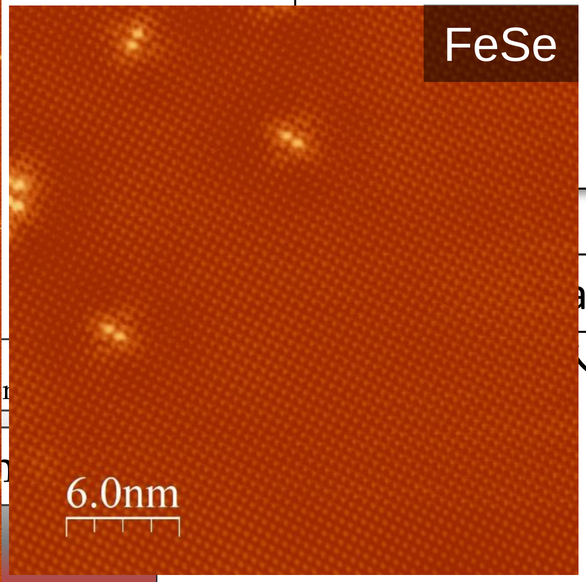
Surface Topography

$$\psi(z) = \psi(0)e^{-\kappa z} \qquad \kappa = \frac{\sqrt{m\,(\varphi_{tip} + \varphi_{sample})}}{\hbar}$$

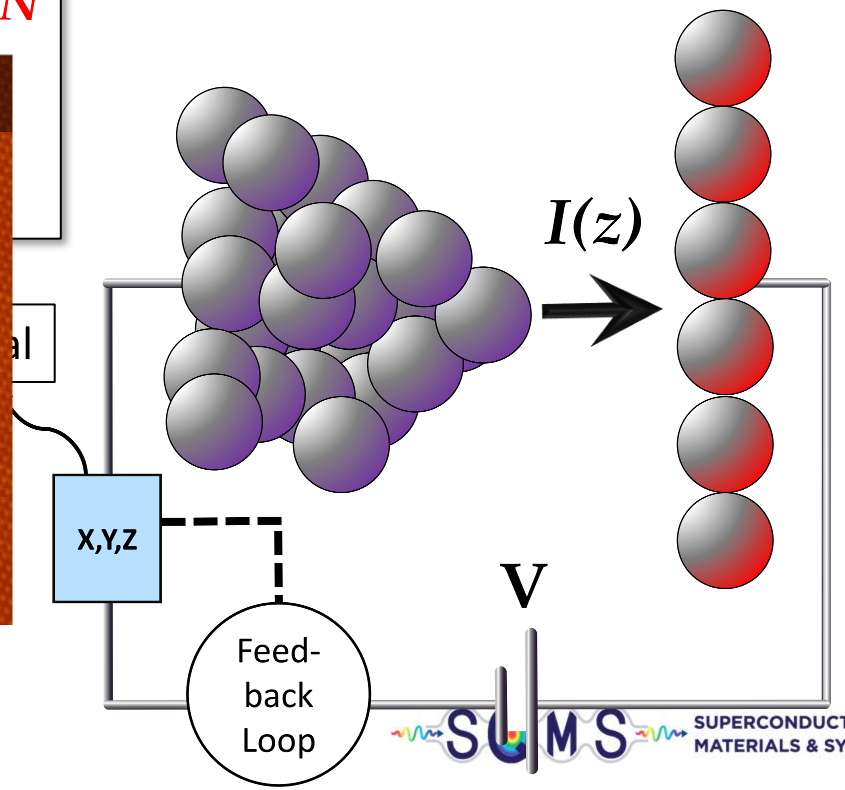
$$I\,(d) \propto \,|\psi(d)|^2 \propto e^{-2\kappa d}$$

Tunneling current *decreases* about one order of magnitude with every 1 Å *increase* in z.





*Feedback **ON***

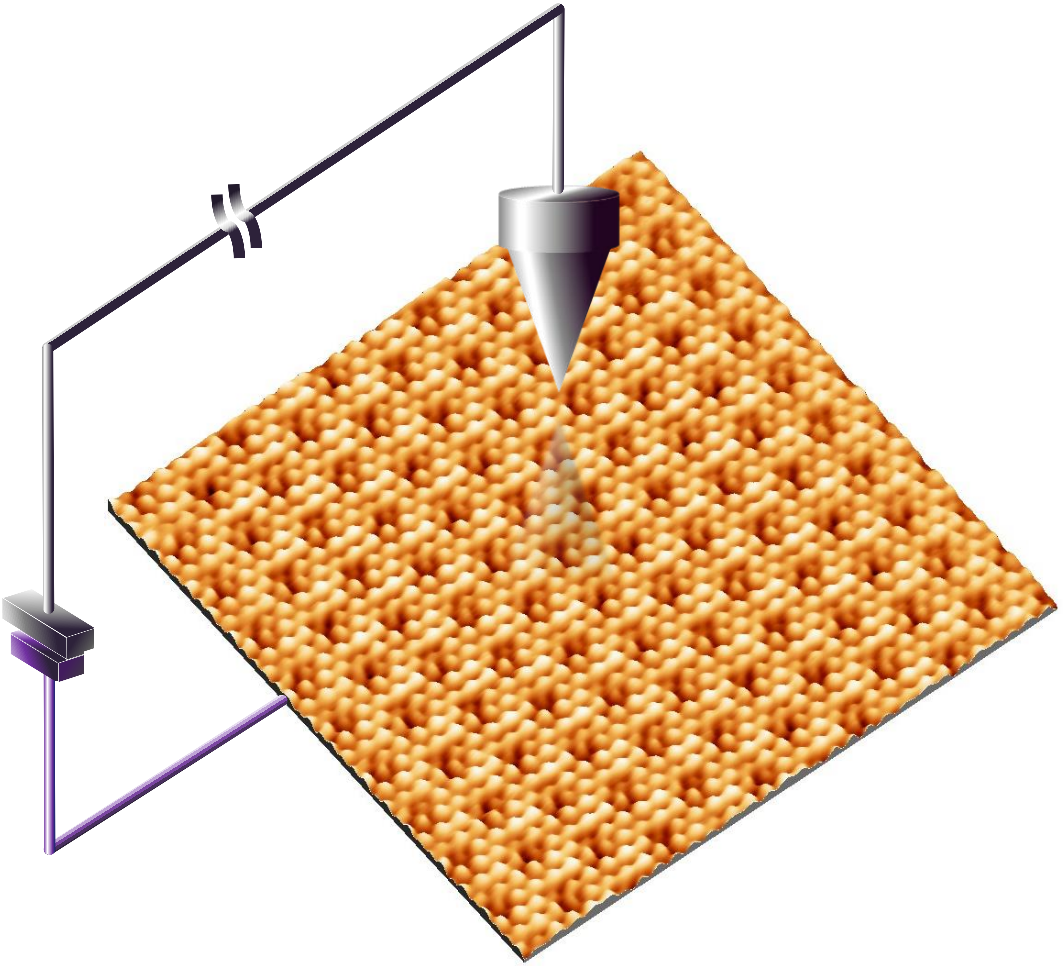


Iavarone Lab

STM/STS

$$\frac{dI}{dV} \propto T(E_F)N_{Tip}(E_F)N_{sample}(E)$$

Local Density of States

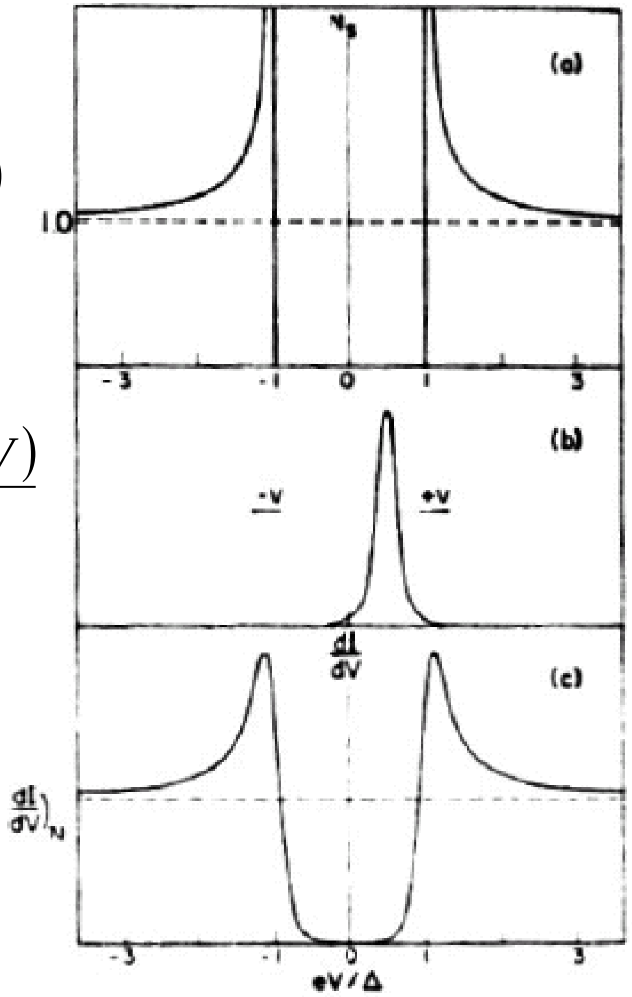


$$I(V) = A \int_0^{eV} dE\, T(E,V$$

$$N_S(E)$$

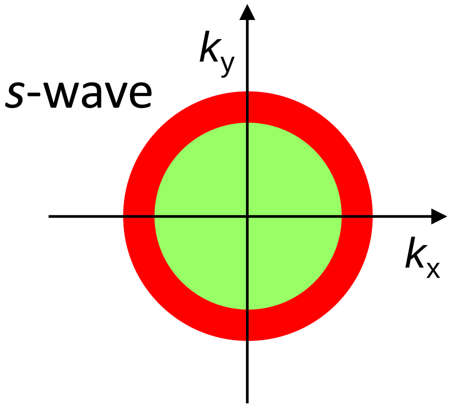
$$\frac{\partial f(E-eV)}{\partial V}$$

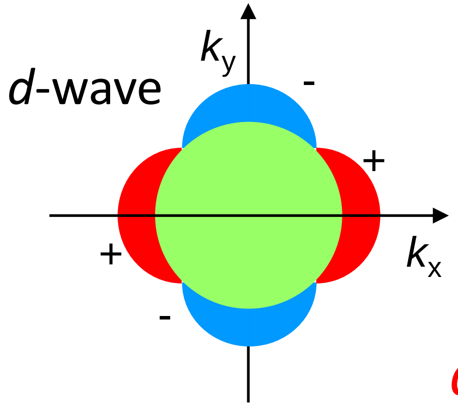
$$\frac{dI}{dV}$$



Superconducting Gap by STM

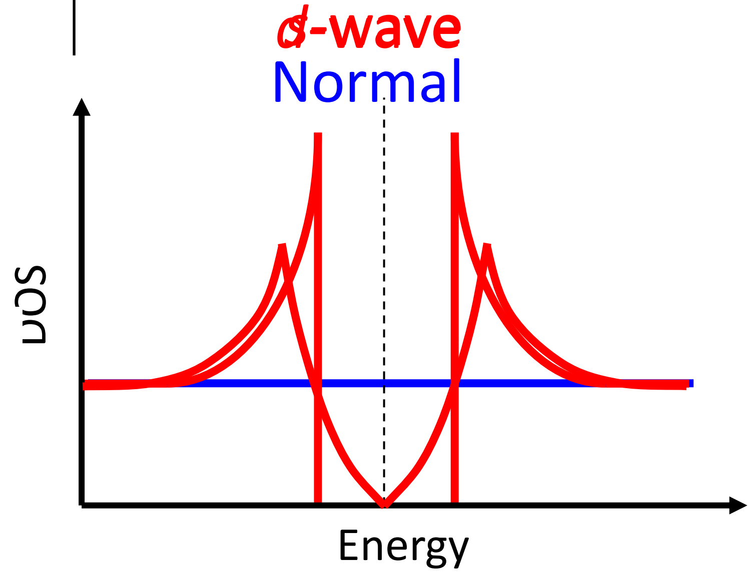
Superconducting gap



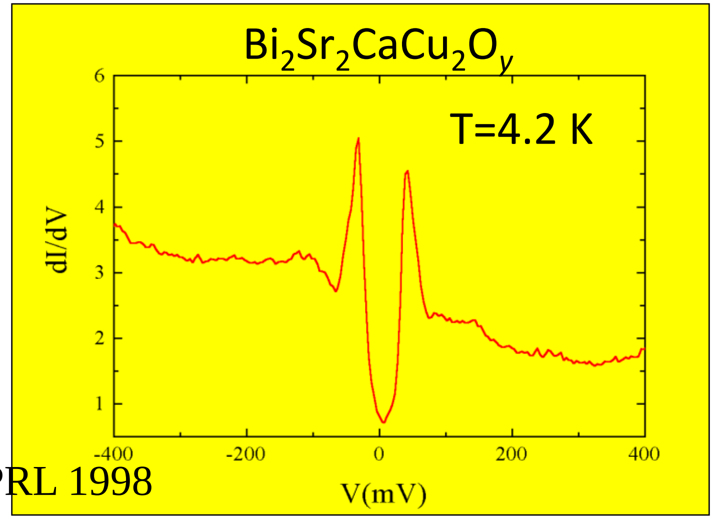


Nodal gap or full gap

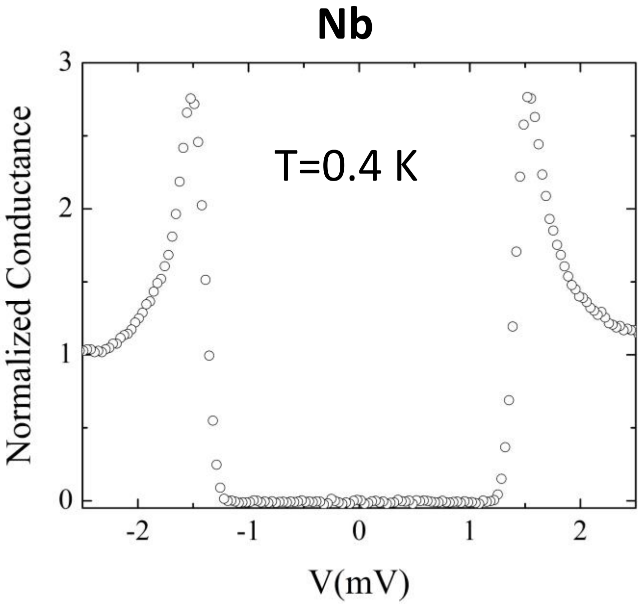
→ Tunneling spectrum



k–space structure



Y. De Wilde, PRL 1998



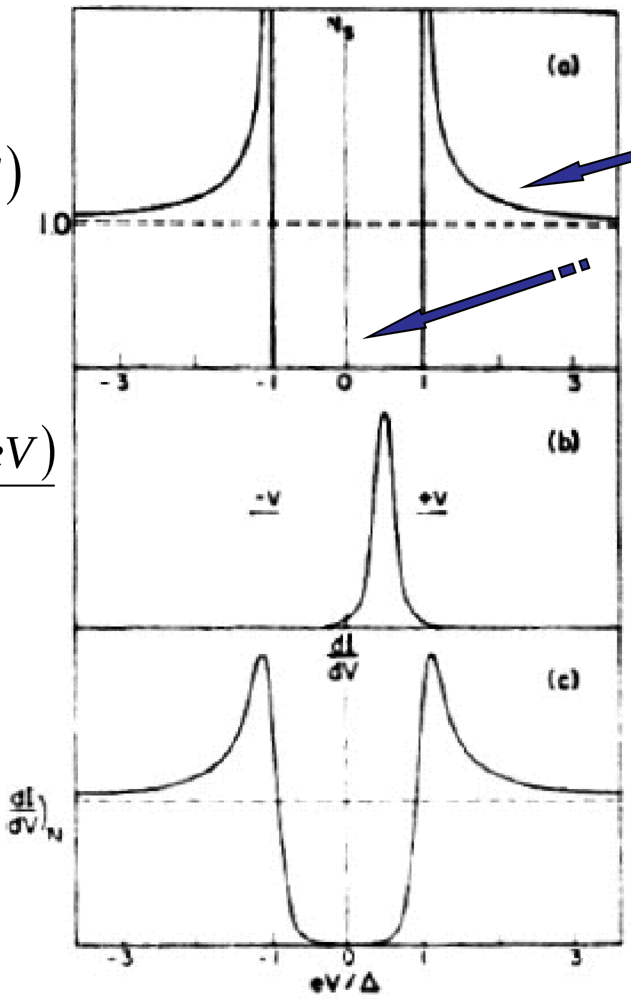
Iavarone Lab

What information can be accessed by STM/STS?

$N_S(E)$

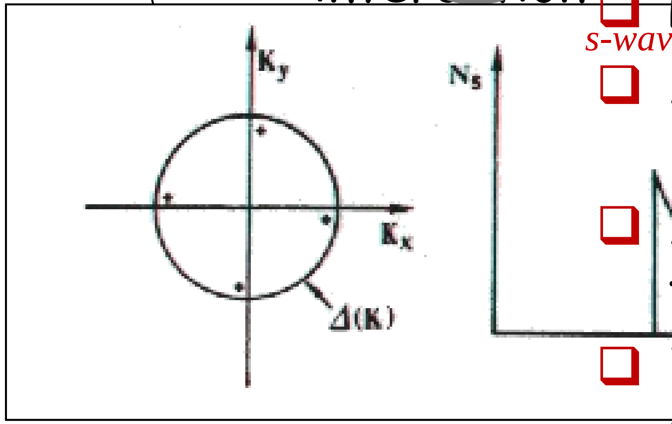
$\frac{\partial f(E-eV)}{\partial V}$

$\frac{dI}{dV}$

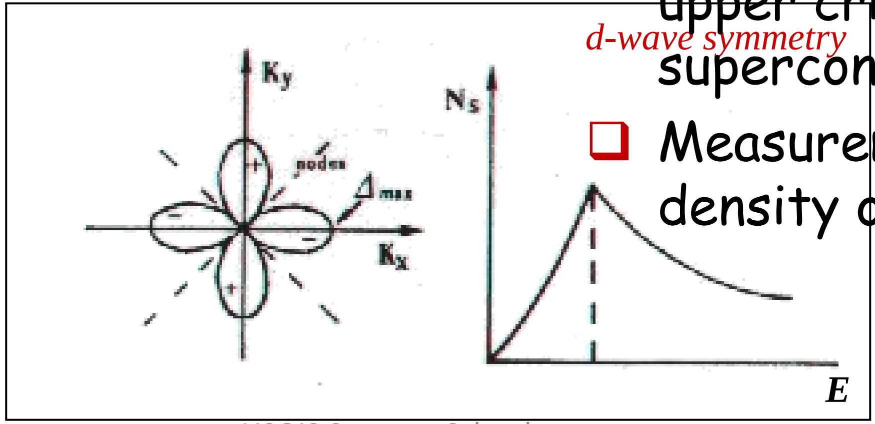


Symmetry of the pair wavefunction

s-wave symmetry

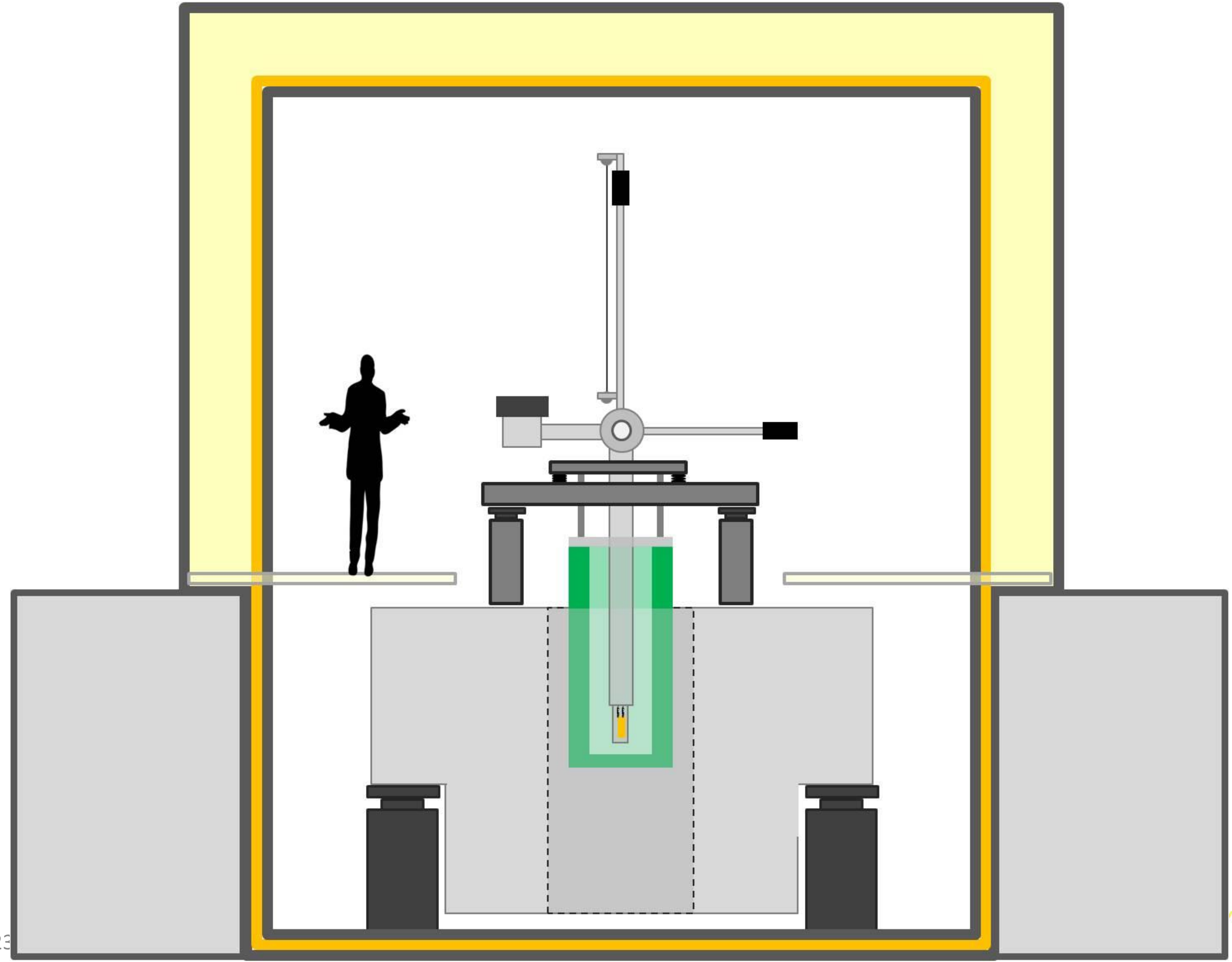


d-wave symmetry



- ❑ superconducting energy gap Δ spatially resolved.
- ❑ Low-energy quasiparticle excitations.
- ❑ Pairing symmetry.
- ❑ Atomic scale spectroscopy to resolve impurities.
- ❑ Atomic scale spectroscopy to reveal the presence of competing orders.
- ❑ Visualization of vortices up to the upper critical field and measure the superconducting coherence length ξ.
- ❑ Measurements of quasiparticle density of states in vortex cores.

300 mK STM Lab at Temple University



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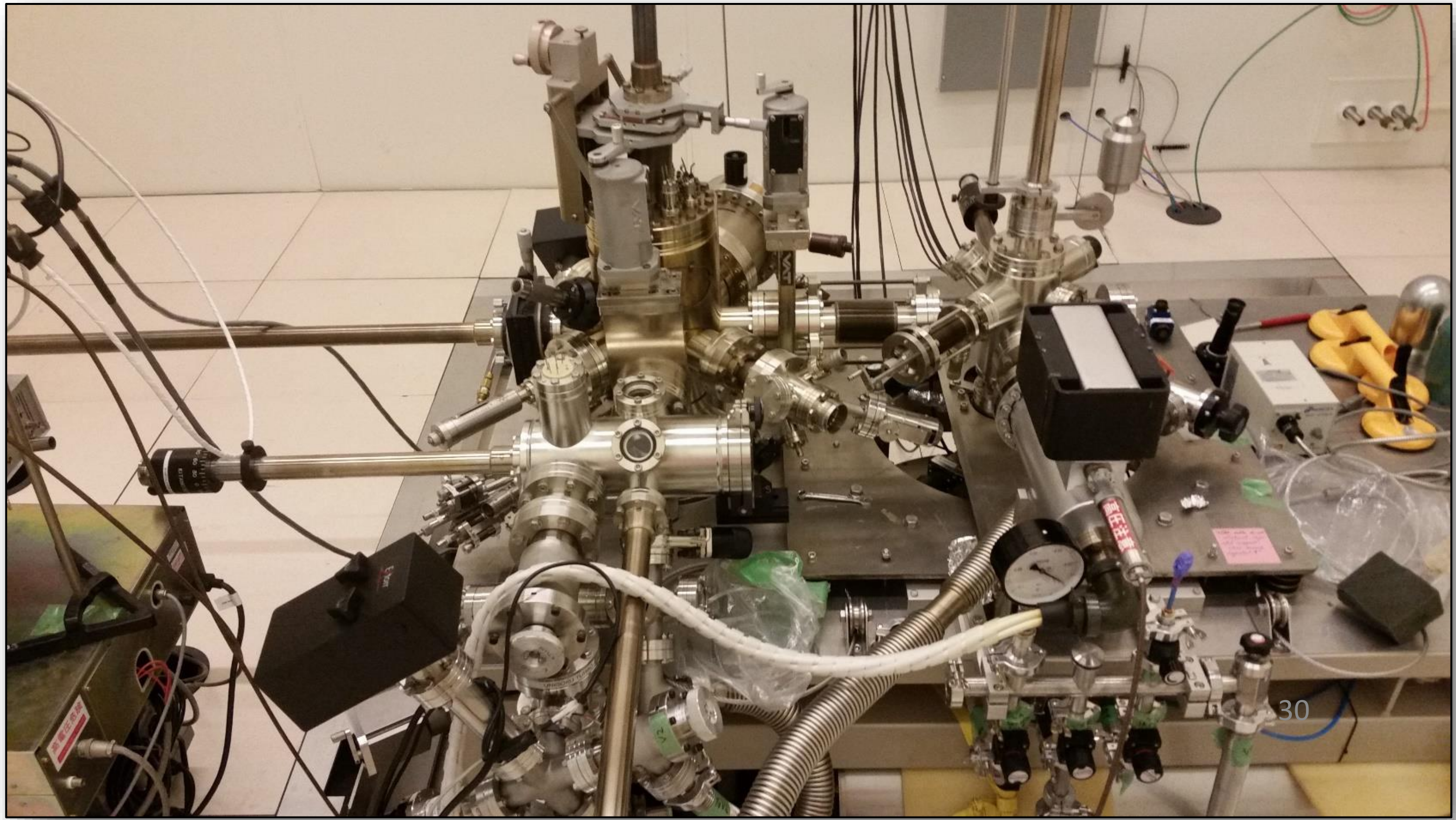
300 mK STM Lab at Temple University

STM Capabilities

Unisoku UHV-LT ^{3}He Scanning Tunneling Microscope



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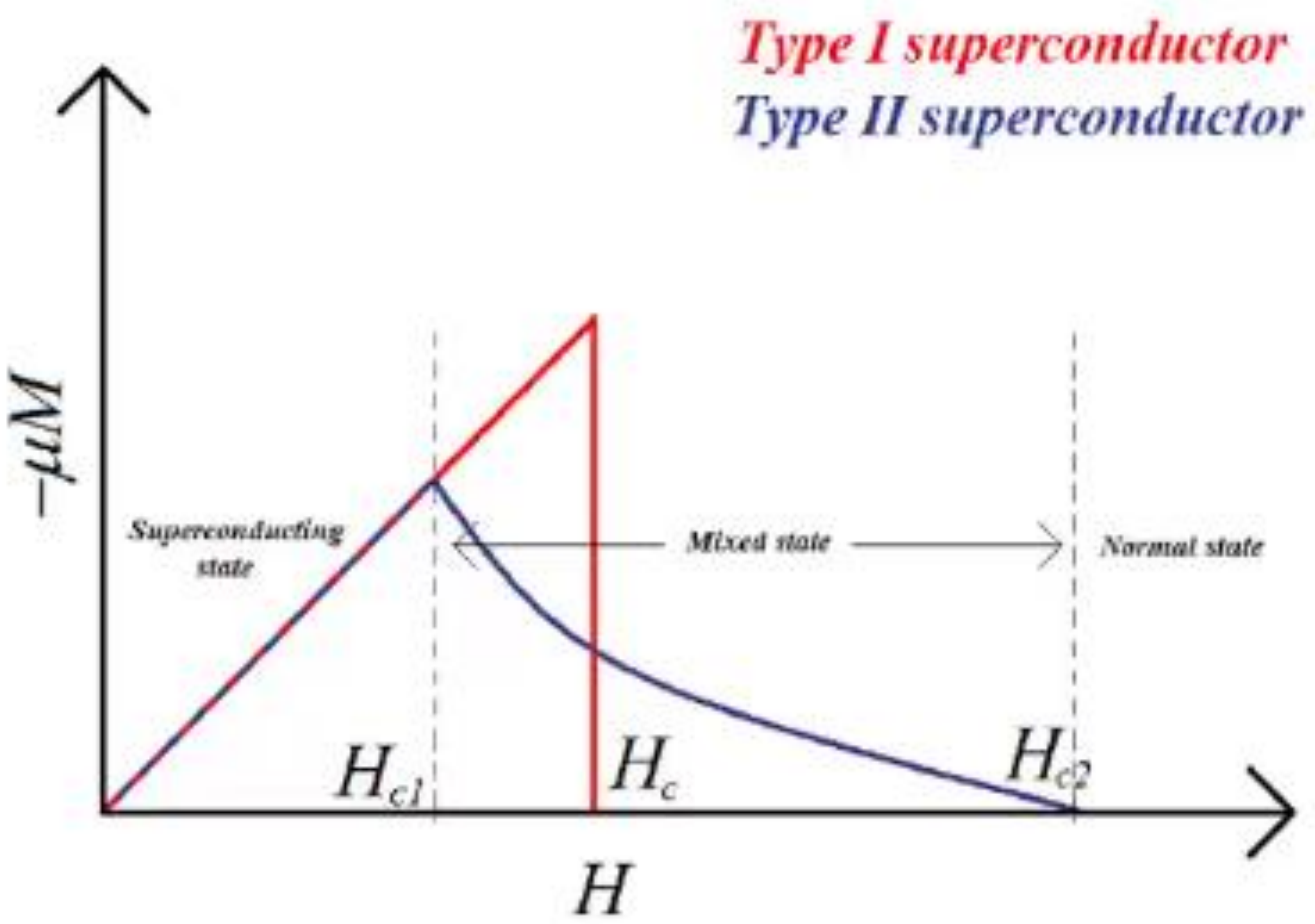
Vortices in Superconductors

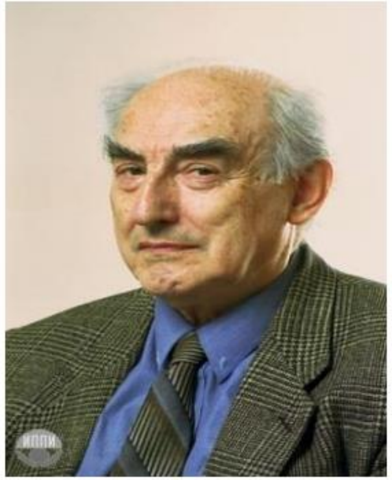
Type I and Type II superconductors



Ginzburg-Landau Theory (1950)

order parameter $\psi(r) = \psi_0(r)e^{i\varphi(r)}$

$$n_s = |\psi^*\psi| = \psi_0^2$$




V. L. Ginzburg A. A. Abrikosov
Nobel Prize in Physics 2003

Coherence length ξ is the length over which $\psi(r)$ changes appreciably

Ginzburg-Landau Theory (1950)

Free energy of the superconducting state:

$$g_s(T,H) = f_n(T,0) + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m*}|(-i\hbar\nabla - e*A)\psi|^2 + \frac{1}{2\mu_0}B^2 - B\bullet H$$

$$\alpha\psi + \beta|\psi|^2\psi + \frac{1}{2m^*}\left(\frac{\hbar}{i}\nabla - \frac{e^*}{c}\vec{A}\right)^2\psi = 0$$

$$j_s = \frac{e*\hbar}{2m*i}(\psi*\nabla\psi - \psi\nabla\psi*) - \frac{e*^2}{m*c}\psi*\psi\vec{A}$$

$$= \frac{e*}{m*}|\psi|^2(\hbar\nabla\phi - \frac{e*^2}{m*}\vec{A}) = e*|\psi|^2\vec{v}_s$$

$$\xi^2 = \frac{\hbar^2}{m^*|\alpha(T)|}$$

$$\lambda = \frac{m^*}{\mu_0 e^{*2}|\psi_0|^2}$$

L. P. Gor’kov, JETP 9, 1364(1959). A.A.Abrikosov, JETP 5, 1174(1957).

Ginzburg-Landau theory (1950)

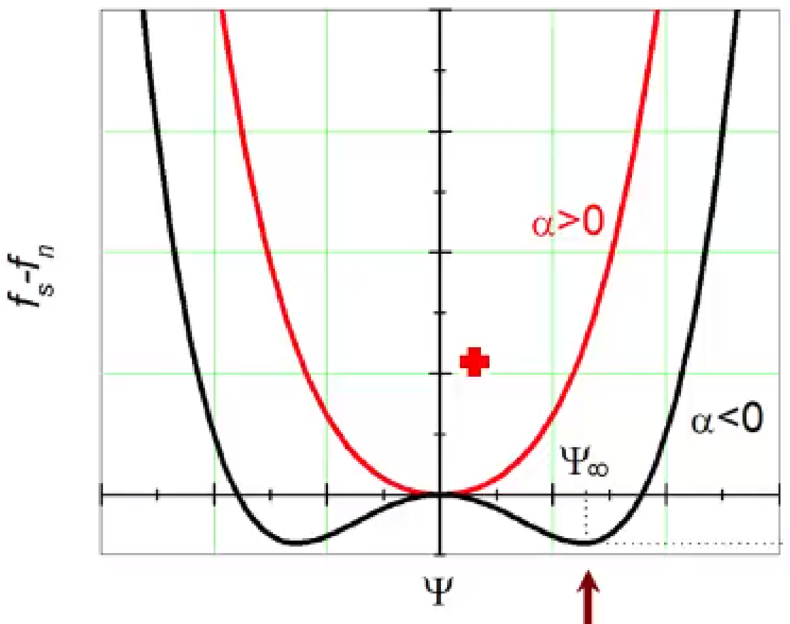
$$f_s = f_n + \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4$$

- For α < 0, solve for minimum in f_s-f_n …

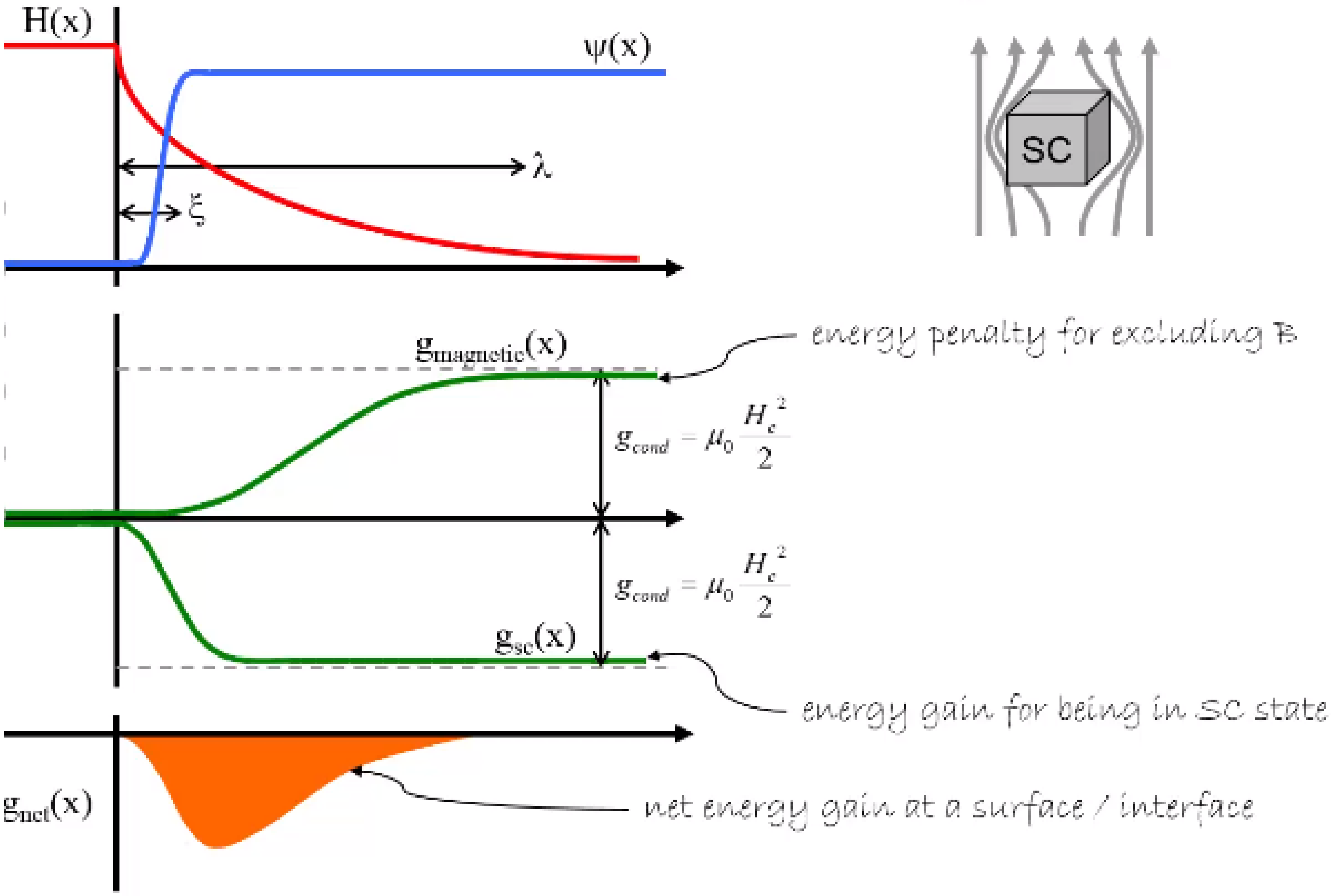
$$f_s - f_n = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4$$

$$\frac{d}{d|\psi|^2}(f_s - f_n) = \alpha + \beta|\psi|^2 = 0$$

$$\Rightarrow |\psi_\infty|^2 = \frac{-\alpha}{\beta}$$



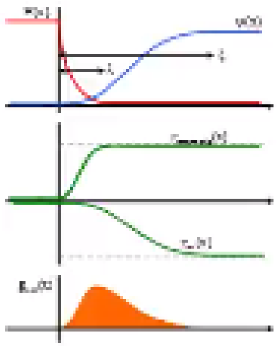
Surface Energy: $\xi < \lambda$



Type I

$$\kappa \equiv \frac{\lambda}{\xi}$$

Type II

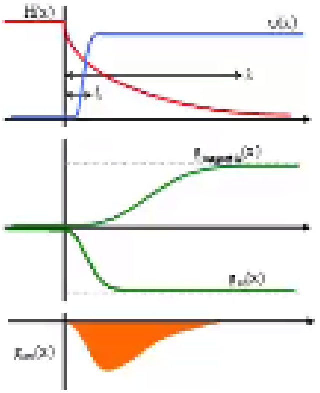


$\xi >> \lambda$

$\kappa < \frac{1}{\sqrt{2}}$

- elemental superconductors

	ξ (nm)	λ (nm)	T_c (K)	H_{c2} (T)
Al	1600	50	1.2	.01
Pb	83	39	7.2	.08
Sn	230	51	3.7	.03



$\lambda >> \xi$

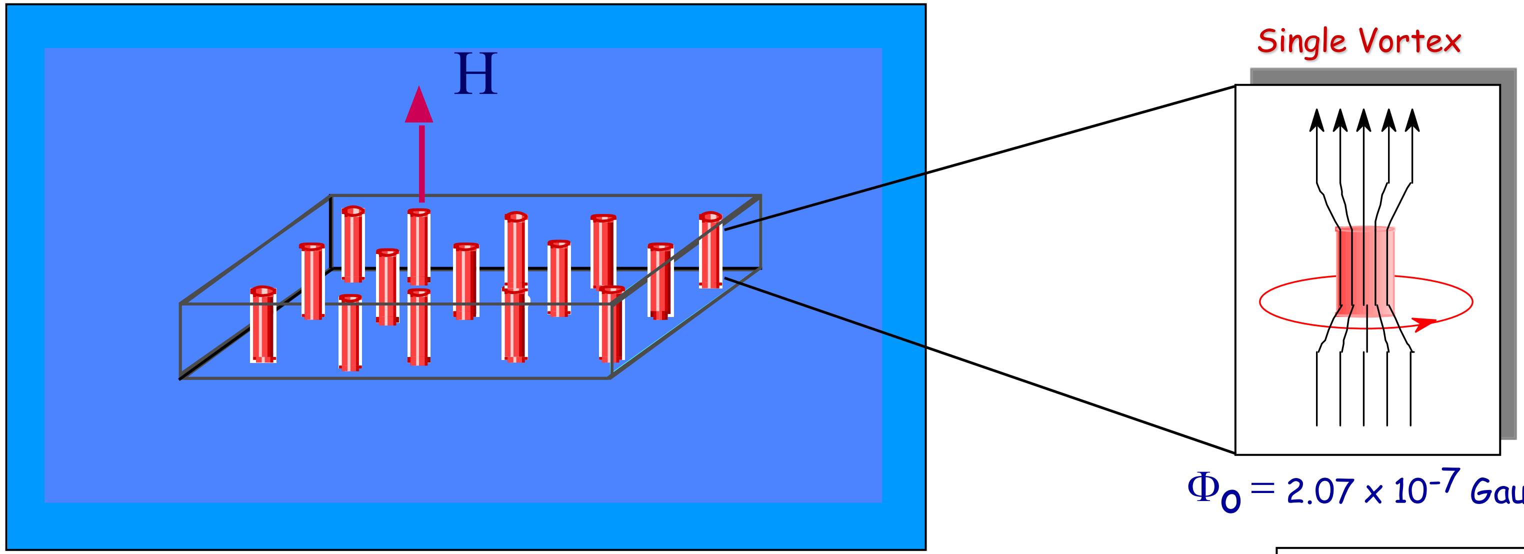
$\kappa > \frac{1}{\sqrt{2}}$

- predicted in 1950s by Abrikosov

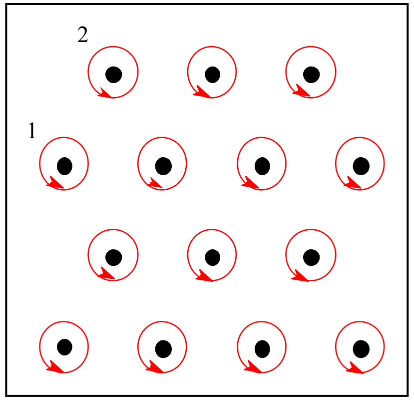
	ξ (nm)	λ (nm)	T_c (K)	H_{c2} (T)
Nb_3Sn	11	200	18	25
YBCO	1.5	200	92	150
MgB_2	5	185	37	14

Abrikosov Vortices in Superconductors

Type II superconducting sample in a magnetic field



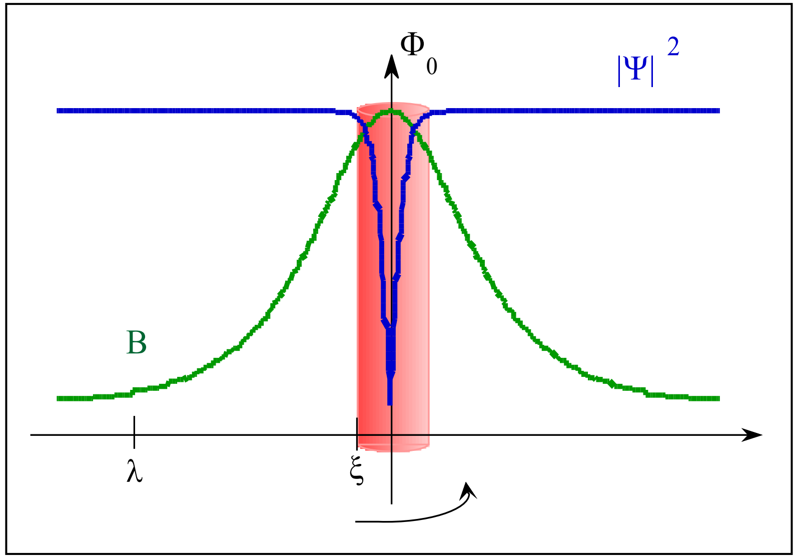
$\Phi_0 = 2.07 \times 10^{-7}$ Gauss-cm^2



$a_o \sim \sqrt{\Phi_o / B}$

$$\xi(T) = \frac{\xi(0)}{\sqrt{1-T/T_c}}$$

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-T/T_c}}$$



A.A.Abrikosov, JETP 5, 1174(1957).

Order parameter and magnetic field profile of a single vortex

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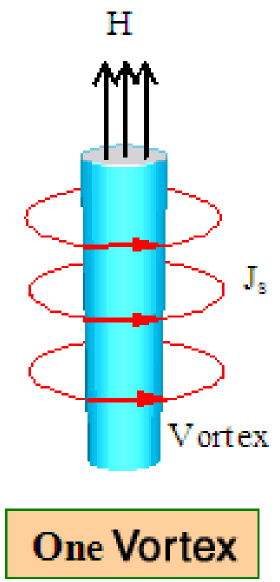
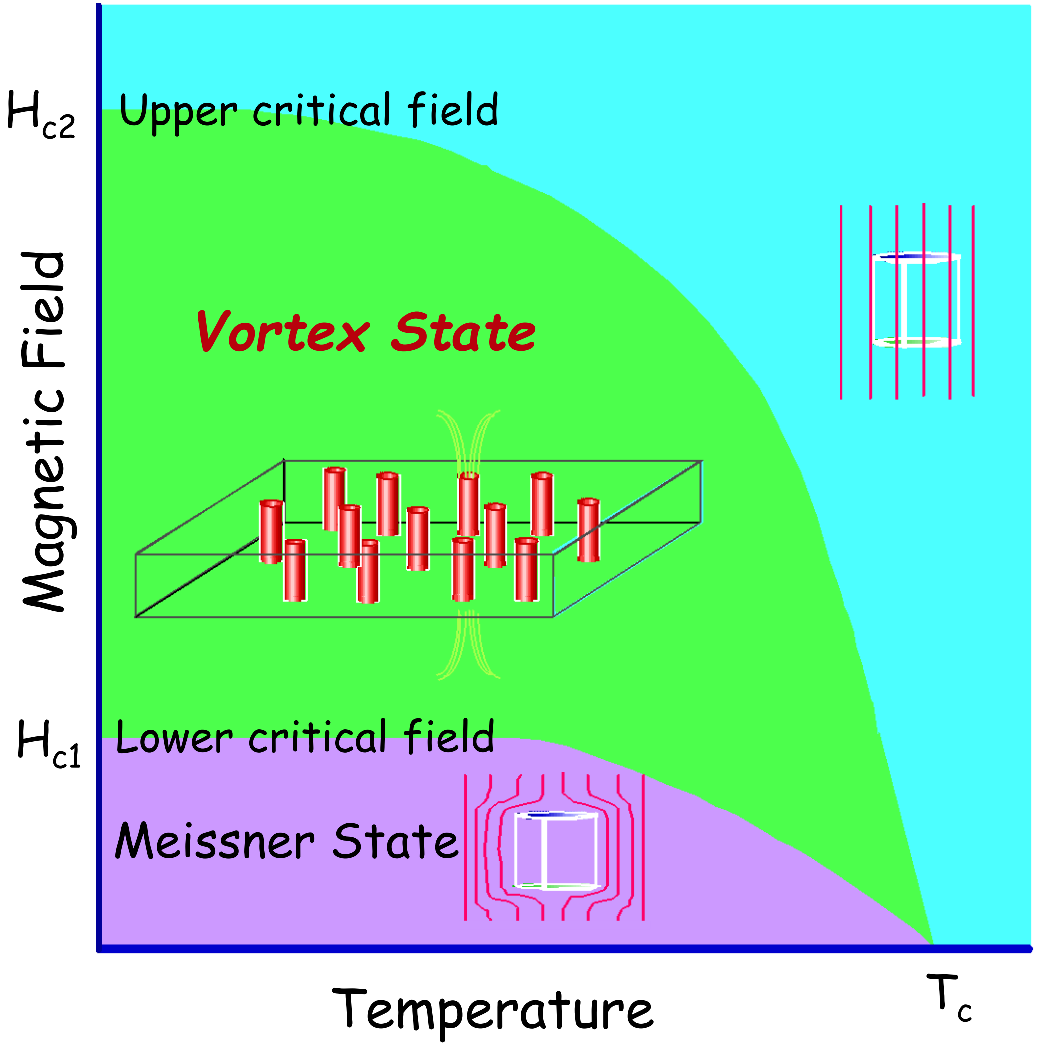
- What are vortices in superconductors?
- Why are they important?
- What can we learn from them?
- How do we study and visualize them?

Single vortex

- Has a core circled by supercurrents
- Bogoliubov QPs are confined with the vortex core with size of ξ, leading to the vortex bound states.
- Outside the core there are superconducting electron pairs (Cooper pairs)



Phase Diagram of Type II Superconductors

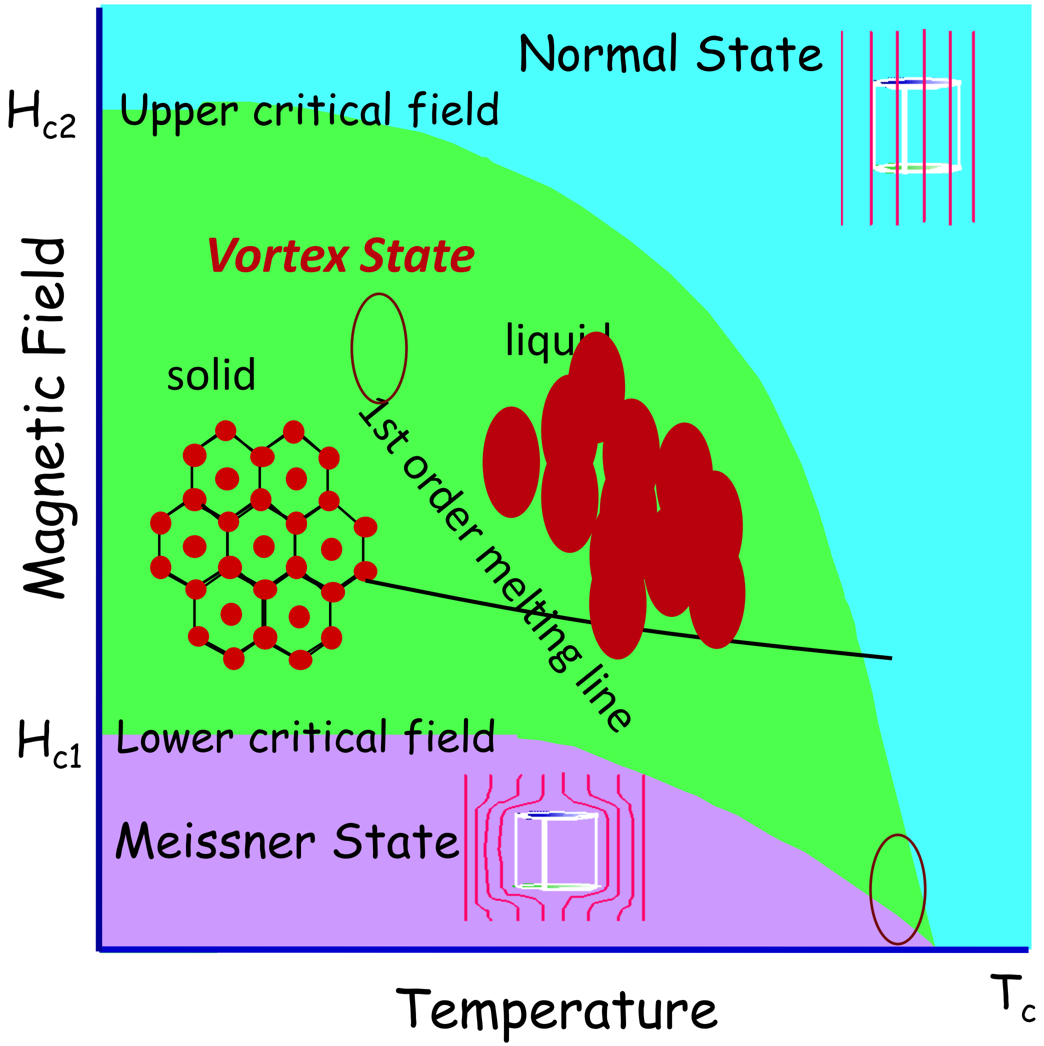


$$H_{c1} \approx \frac{\Phi_0}{4\pi\lambda^2}$$

$$H_{c2} = \frac{\Phi_0}{2\pi\xi^2}$$

Alex Abrikosov
Nobel Prize in Physics 2003

Phase Diagram of High Tc Superconductors

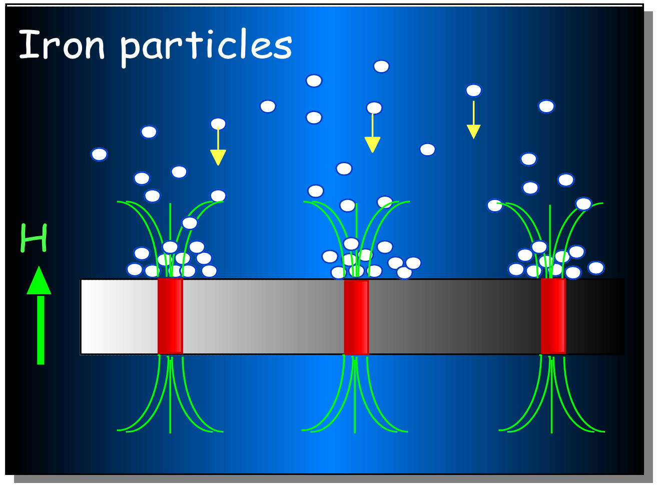


In high Tc SC due to higher Tc, smaller x and high anisotropy thermal fluctuations are not negligible. Thermally induced vibrations of the flux lattice can melt it into a "vortex liquid".

- How can we see vortices and what can we learn?

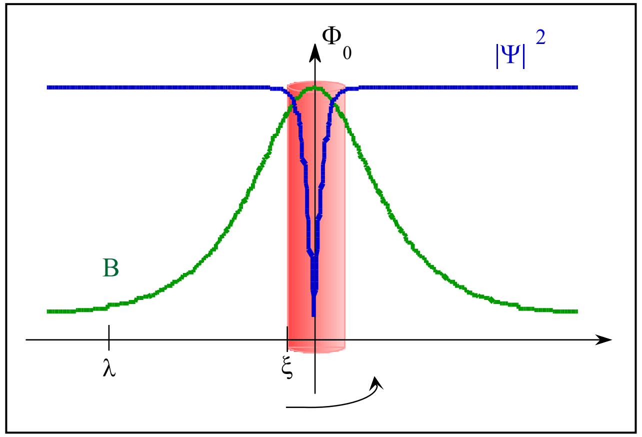
Imaging of Vortices in Type II Superconductors

Magnetic Decoration

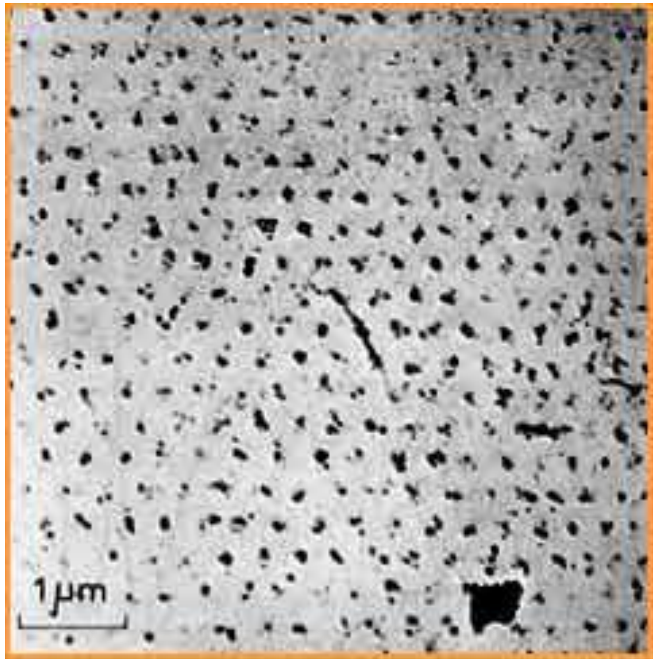


$$\xi(T) = \frac{\xi(0)}{\sqrt{1-T/T_c}}$$

$$\lambda(T) = \frac{\lambda(0)}{\sqrt{1-T/T_c}}$$



Order parameter and magnetic field profile of a single vortex



First image of Vortex lattice, 1967
Bitter Decoration
Pb-4at%In rod, 1.1K, 195G
U. Essmann and H. Trauble
Physics Letters **24A**, 526 (1967)

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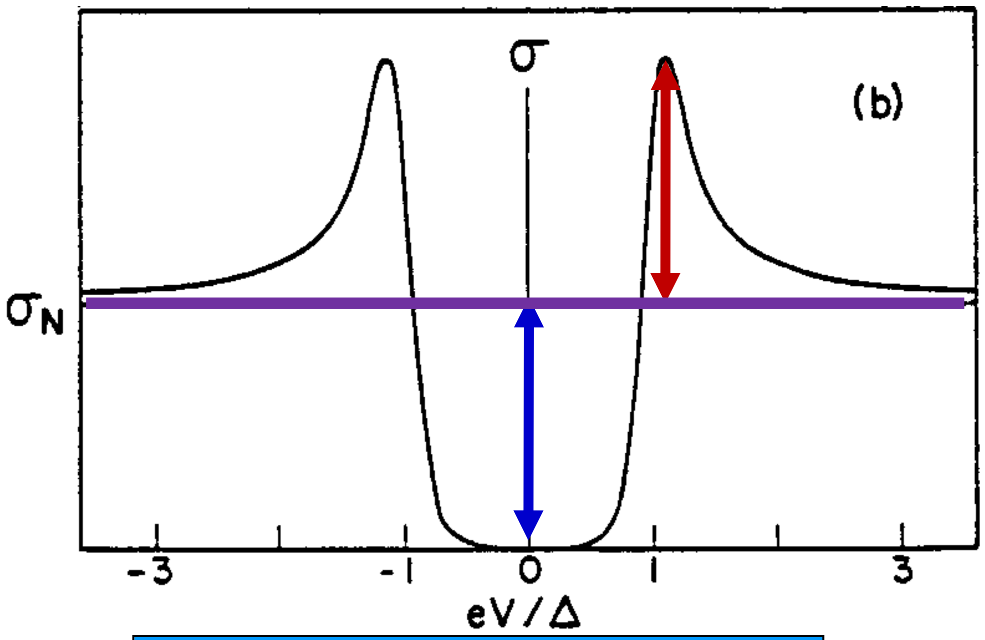
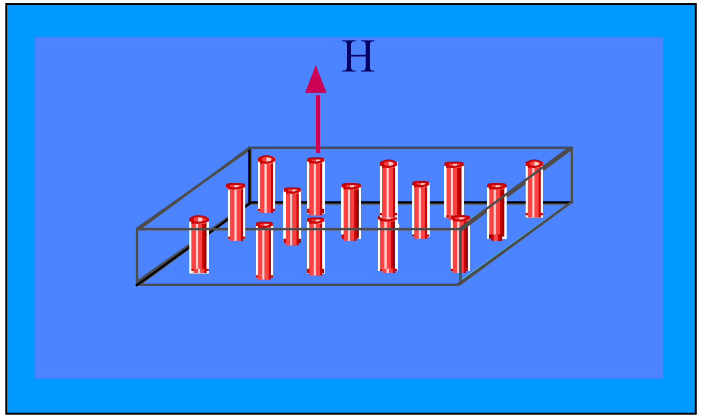
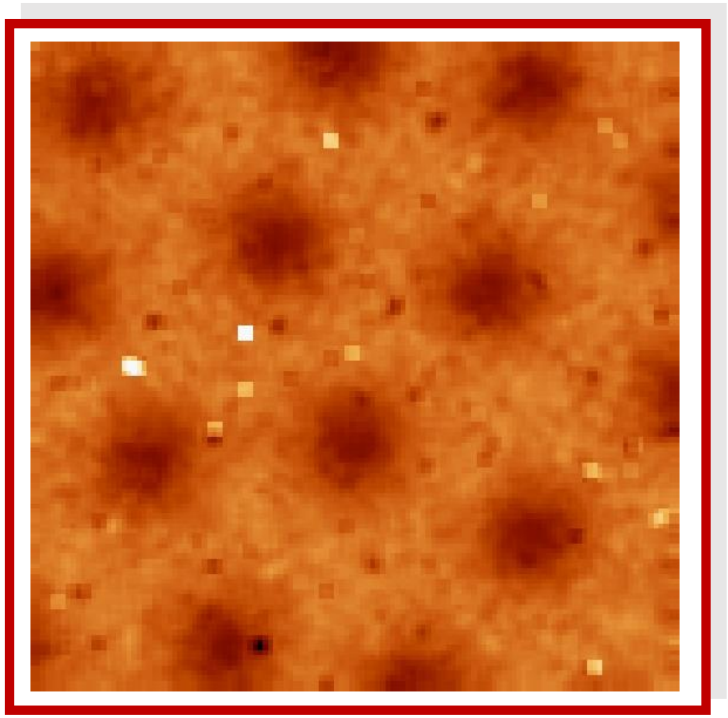
How Vortices can be imaged by STM?

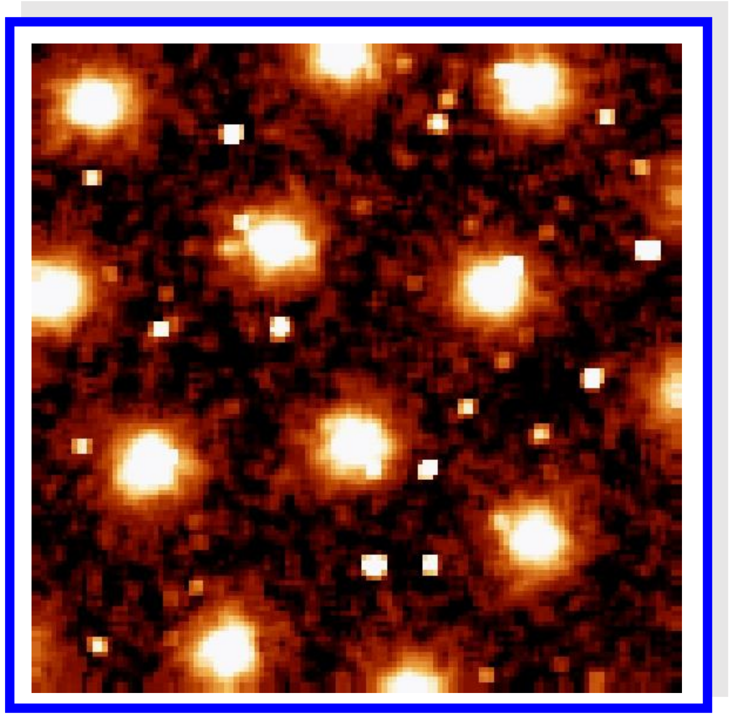
Tunneling conductance spectra in superconductor and normal metal





Conductance Maps at fixed energy





390 x 390 nm^2

H=0.15 T
T=1.5 K

Nb Film
Thickness=100 nm

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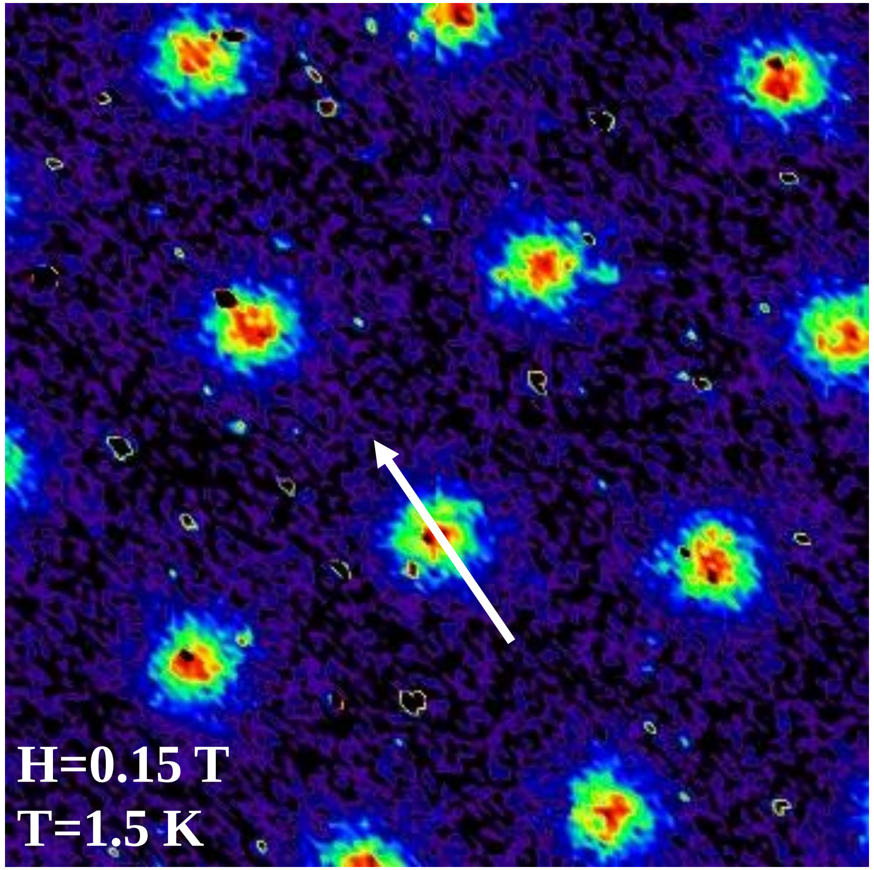
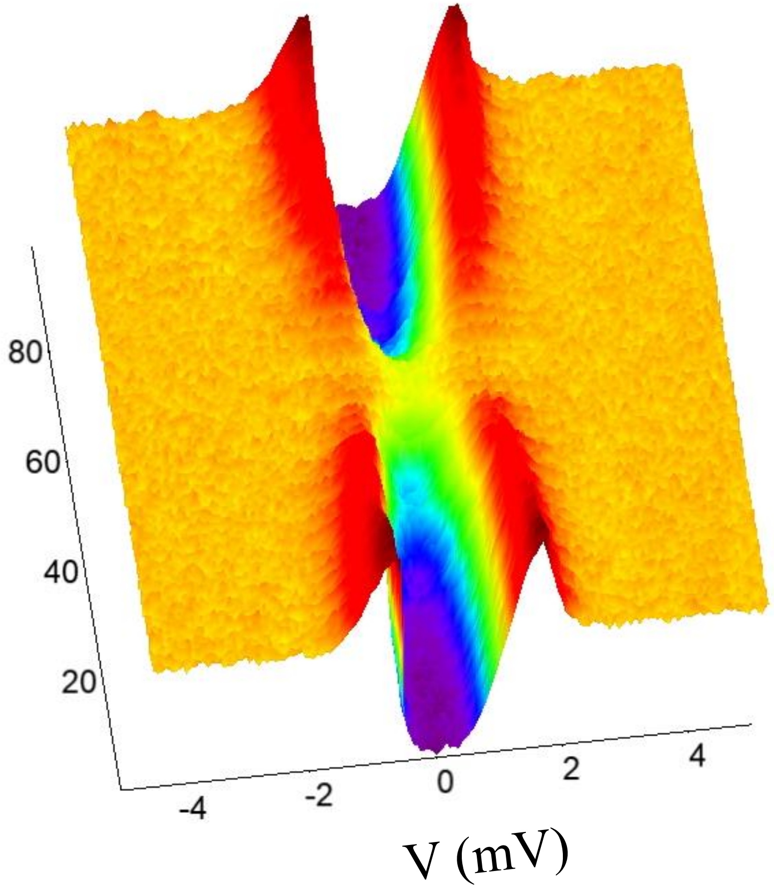
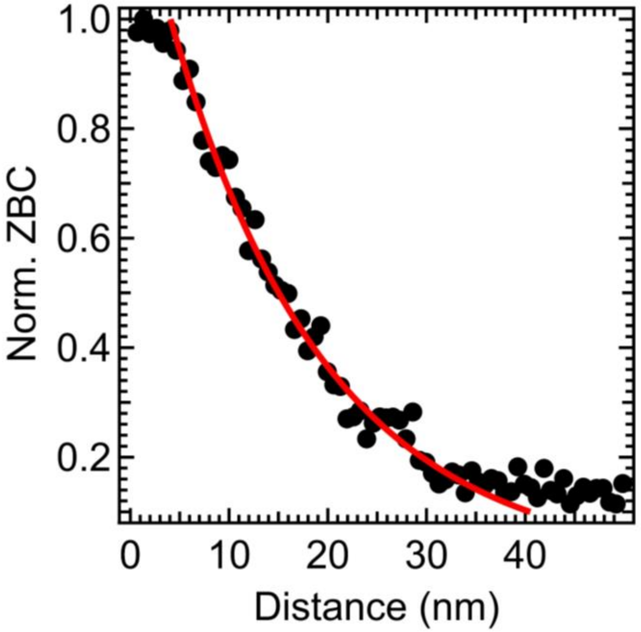
Determination of the coherence length



390 x 390 nm²





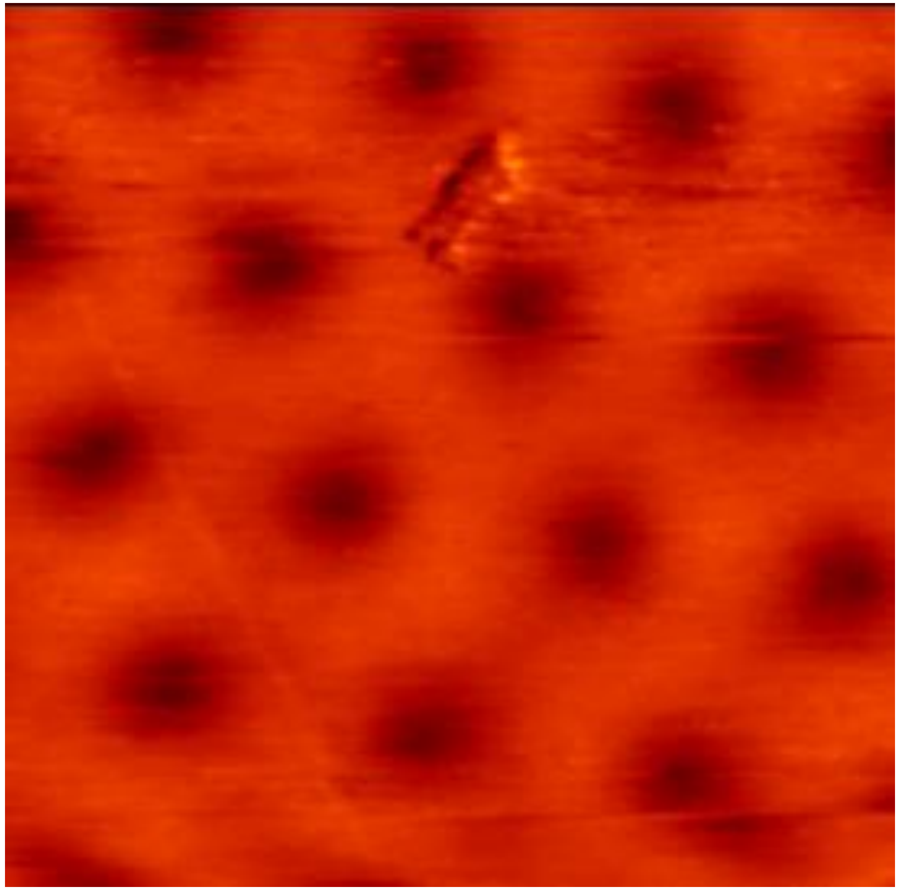
ξ = 15±1 nm

H_{c2} = 1.8 T

Different geometries and transitions of the Vortex Lattice

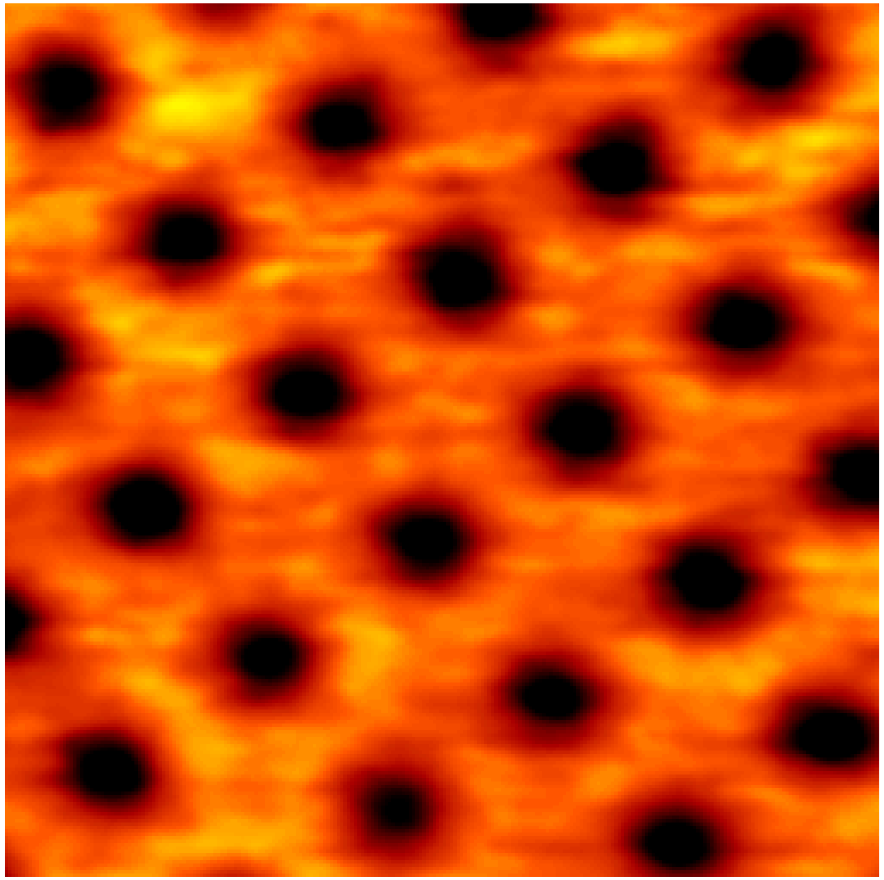
$NbSe_2$

T= 4.2 K
B=0.25 T



$LuNi_2B_2C$

T= 4.2 K
B=1.5 T



170 nm × 170 nm

The vortex lattice is oriented along the (110) direction of the crystal.

Y. De Wilde, M. Iavarone, *Phys. Rev. Lett.* **78**, 4273 (1997)

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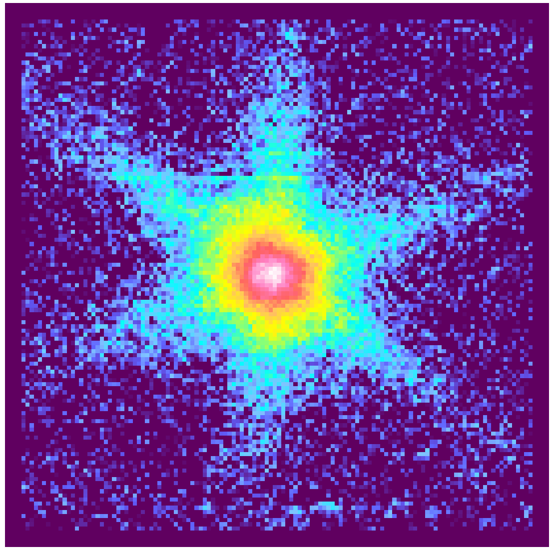
Shape of a single vortex: the case of $NbSe_2$



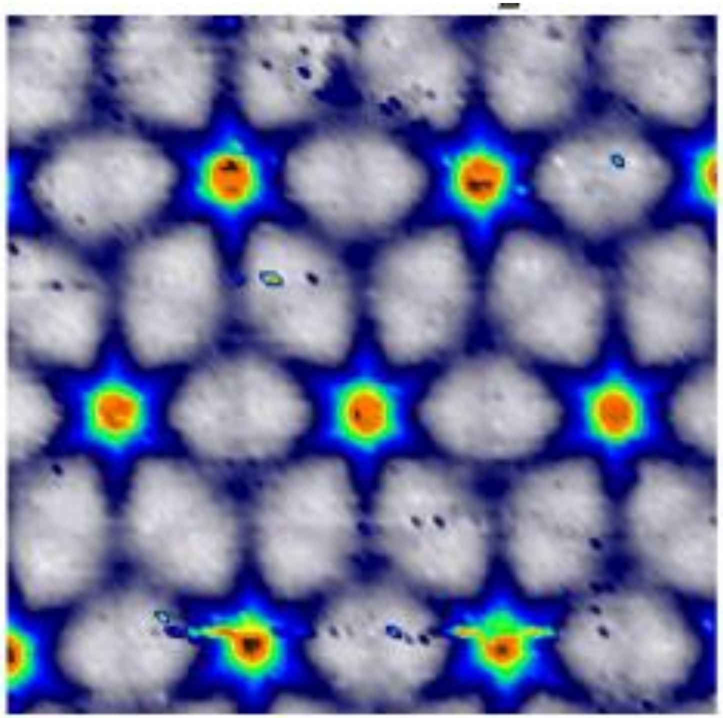
H. Hess *Phys. Rev. Lett.* **62**, 214 (1989)

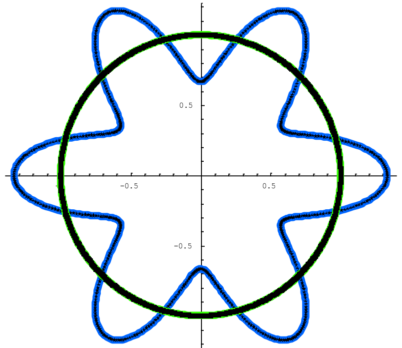
- Anisotropy of the superconducting gap
- Anisotropy of the Fermi surface
- Vortex lattice

$$\xi_{BCS} = \frac{\hbar v_F}{\pi \Delta}$$

$$\Delta(\vec{k}) \neq const$$

$$v_F(\vec{k})$$



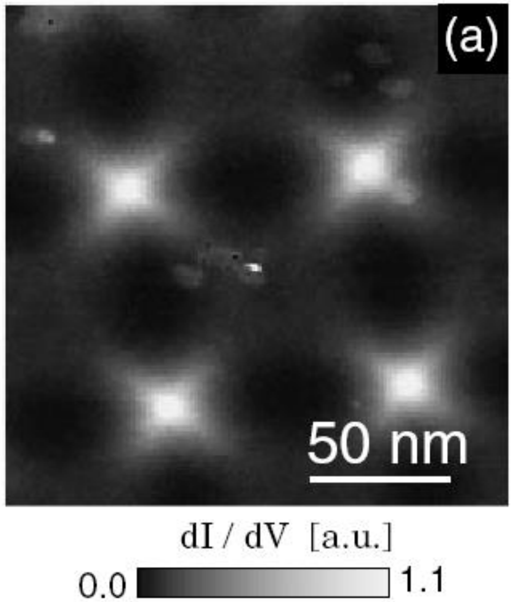


Gaps modulated in the ab-plane by the CDW

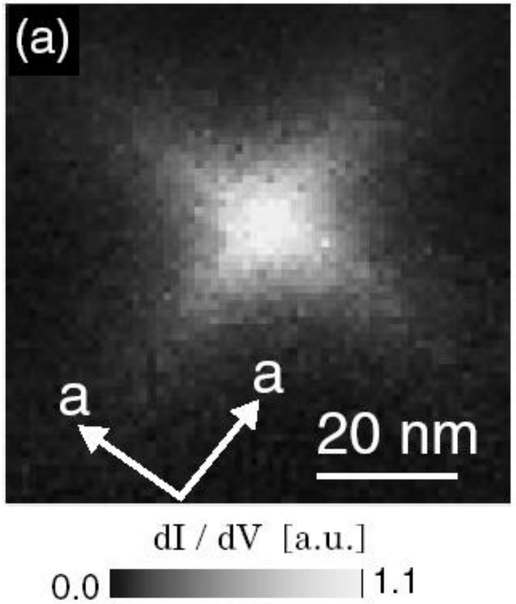
I. Guillamon et al. *PRB* **77**, 134505 (2008)

$\Delta = \Delta_0(1 + a\cos(6\varphi))$

Gap Anisotropy in borocarbides: YNi_2B_2C



T=0.46 K, B=0.3T



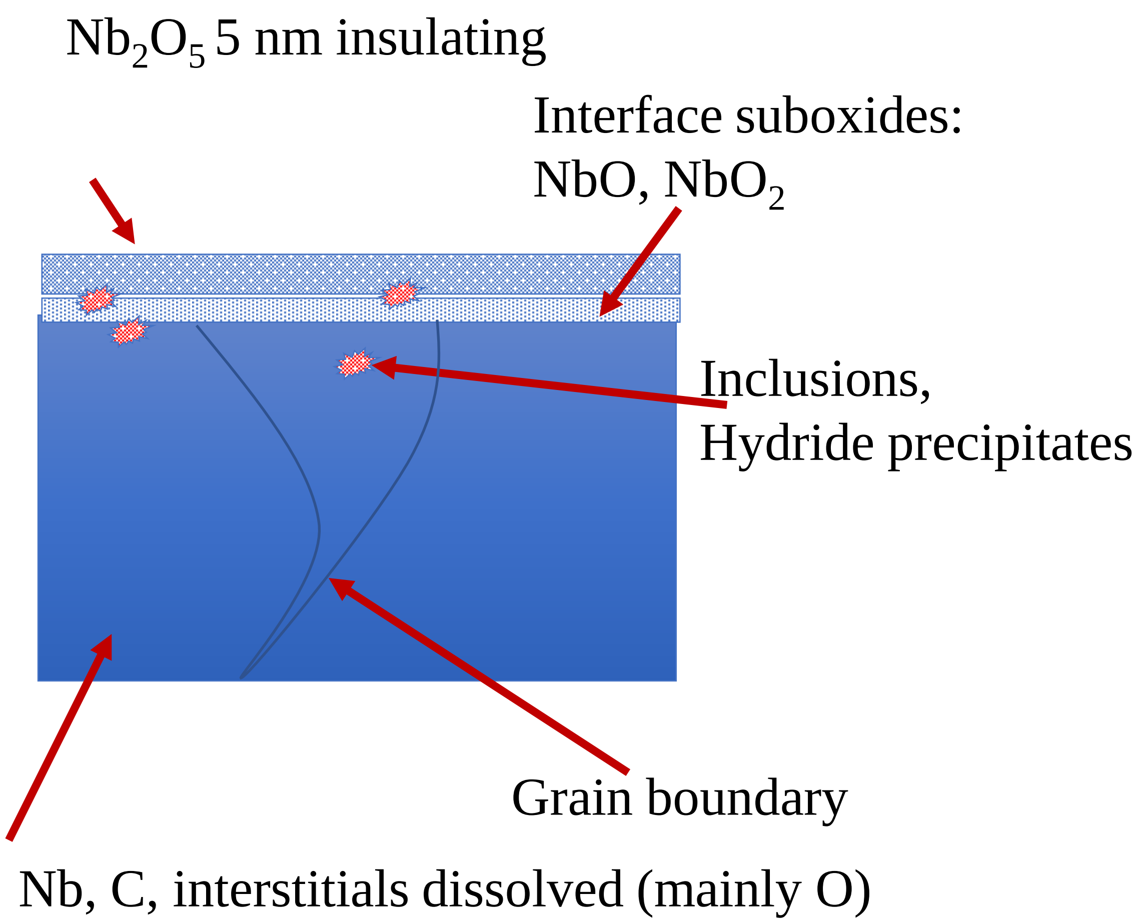
T=0.46 K, B=0.07T

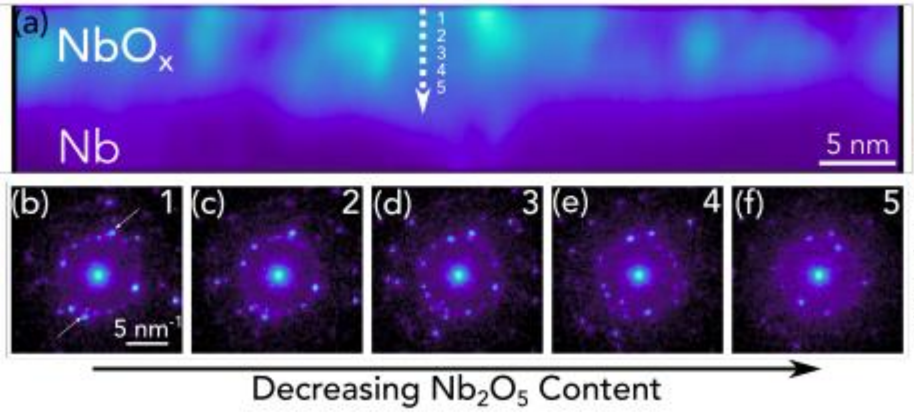
Δ(r) is fourfold-symmetric with the minima along the a-axis.

Nishimori *et al.*, Journal of the Physical Society of Japan, **73** (12) 3247 (2004)

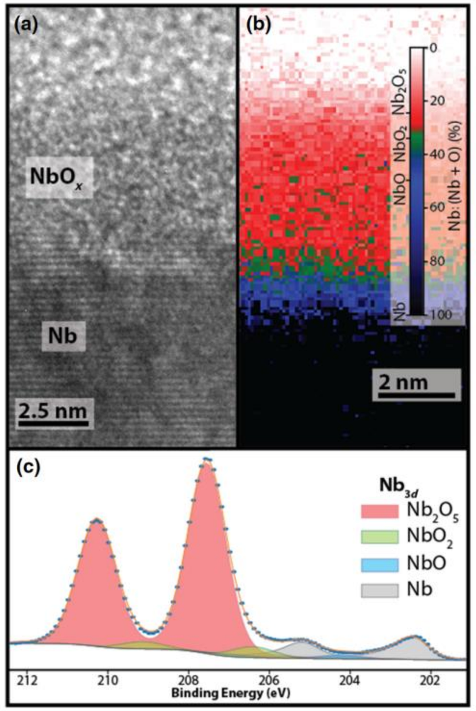
STM applied to Superconducting Qubits

Nb Surface and Surface Treatments





A. Murthy et al. ACS Nano **16**, 17257 (2022)

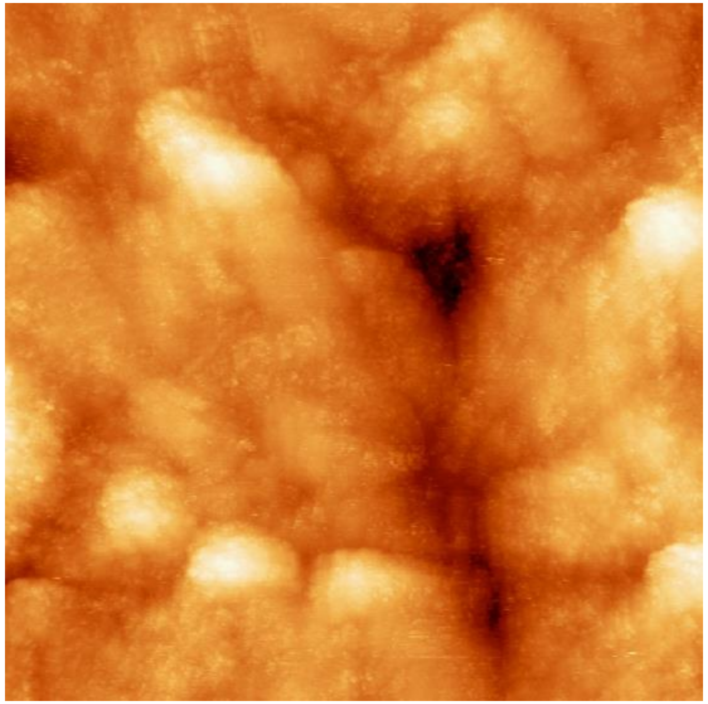


M. Virginia et al. *PRX Quantum* **3**, 020312 (2022)

- ❑ Native Surface
- ❑ Backsputtering with Ar

Nb Thin Films- Local Gap Variation

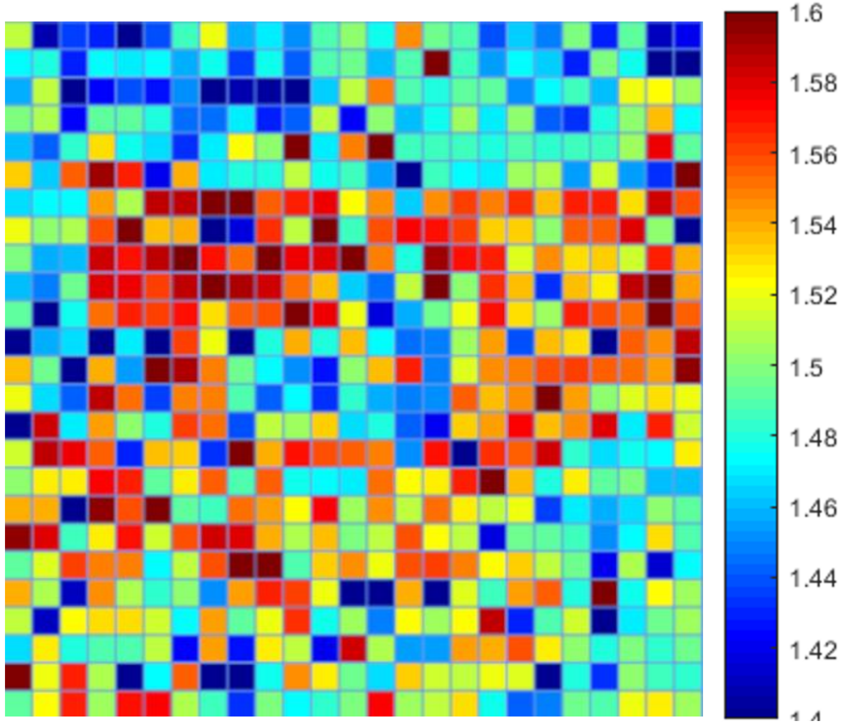
TOPOGRAPHY

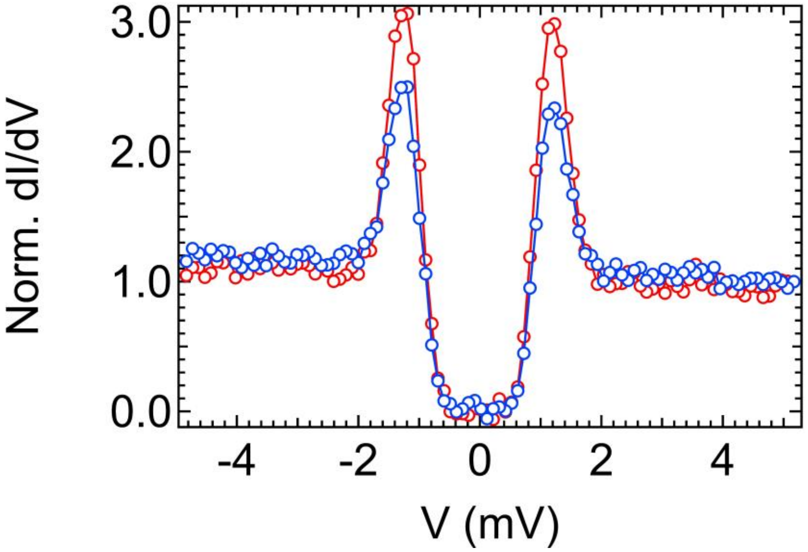


195 nm x 195 nm

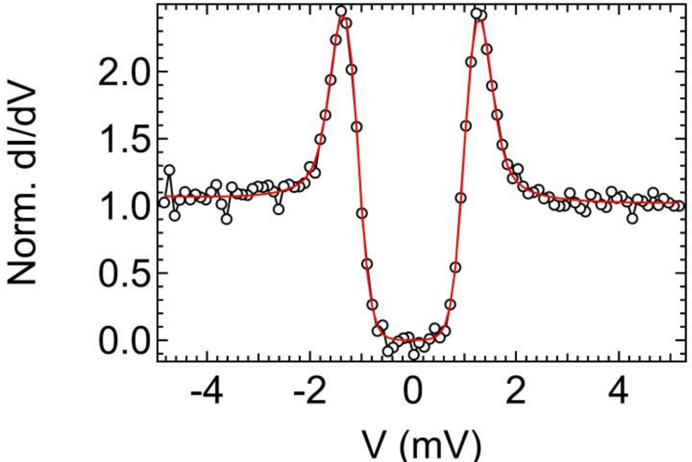
GAP MAP

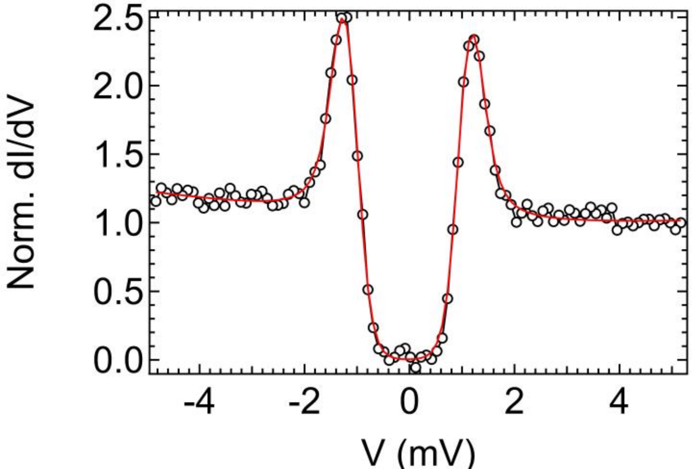
Δ (meV)





Δ=1.58 mV
Γ=0.001
α=0.138
β=0.18

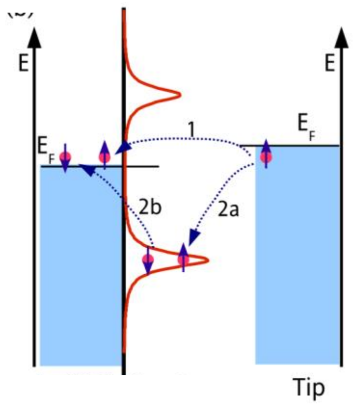




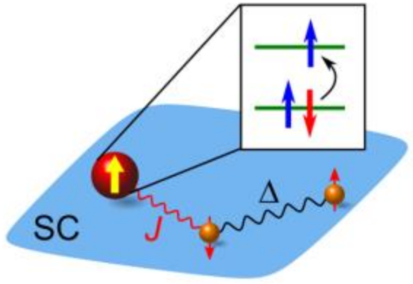
Δ=1.41mV
Γ=0.001
α=0.06
β=0.4

Presence of Magnetic Moments

Kondo spin-flip tunneling

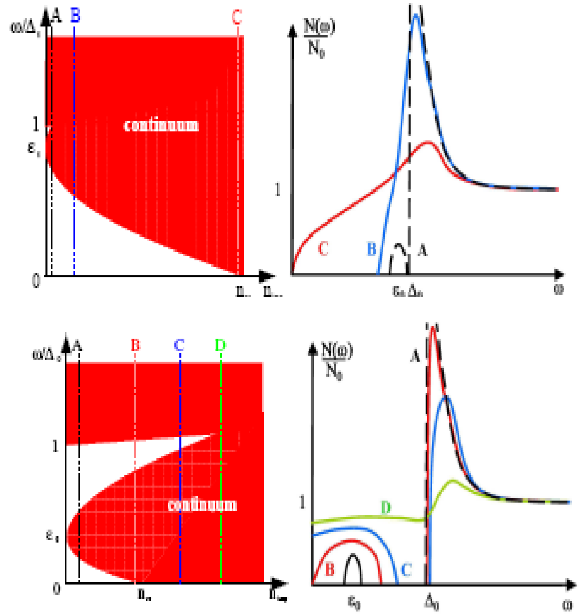


$$E_{exchange} = J\bar{S}_{impurity} \cdot \bar{s}_e$$



Exchange interaction breaks pairs!

Shiba Bands

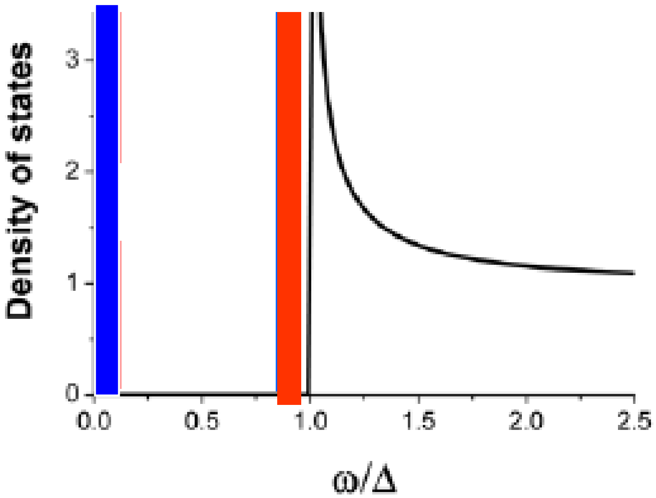


Time-reversal violated:
new states in the gap

$$\varepsilon_0 = \frac{E_0}{\Delta_0} = \frac{1-(JS\pi N_0/2)^2}{1+(JS\pi N_0/2)^2}$$

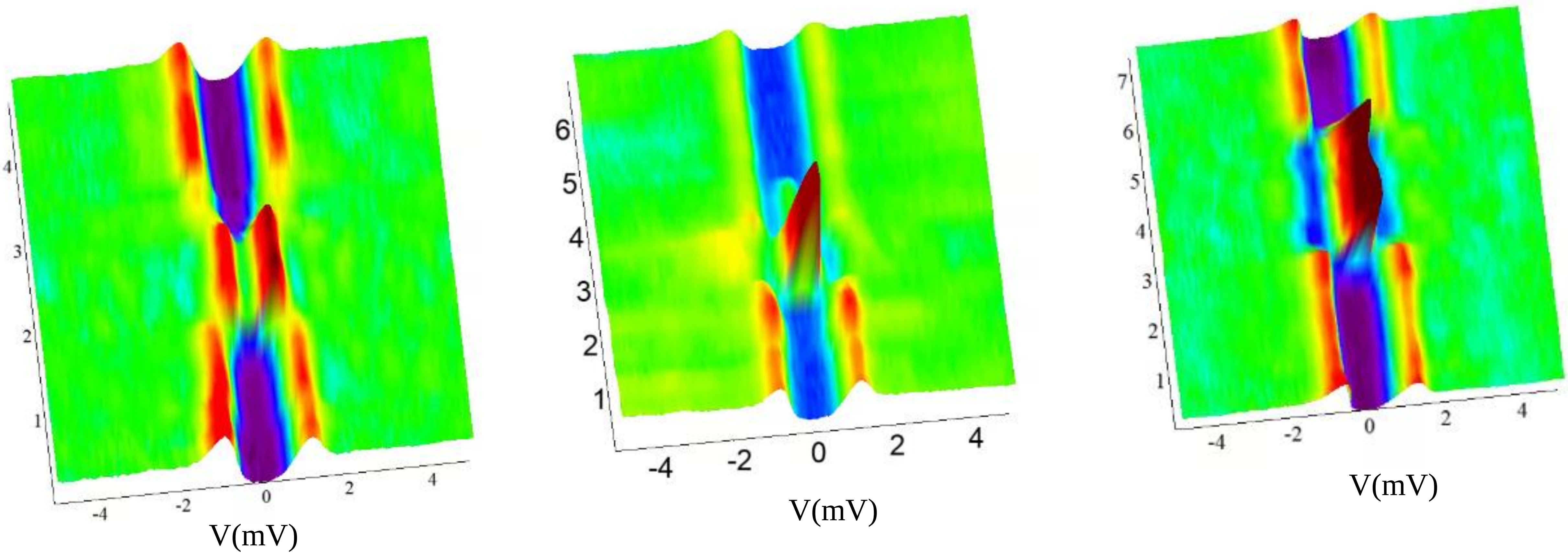
$JSN_0 \approx 1$ state in midgap $E_0 \approx 0$

$JSN_0 << 1$ state near gap edge $E_0 \approx \Delta_0$



Rusinov, A. I., 1968, Zh. Eksp. Teor. Fiz. Pis'ma Red. 9, 146 JETP Lett. 9,851969
Shiba, H., 1968, Prog. Theor. Phys. 40, 435.
Yu, L., 1965, Acta Phys. Sin. 21, 75.
A. V. Balatsky et al. , *Rev. Modern Phys.* **78**, 373 (2006)

In-gap States

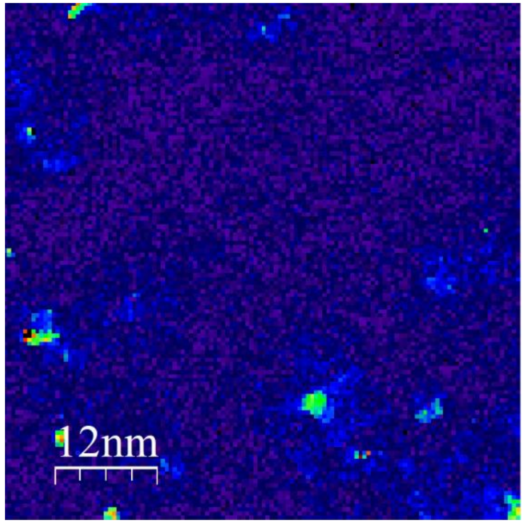


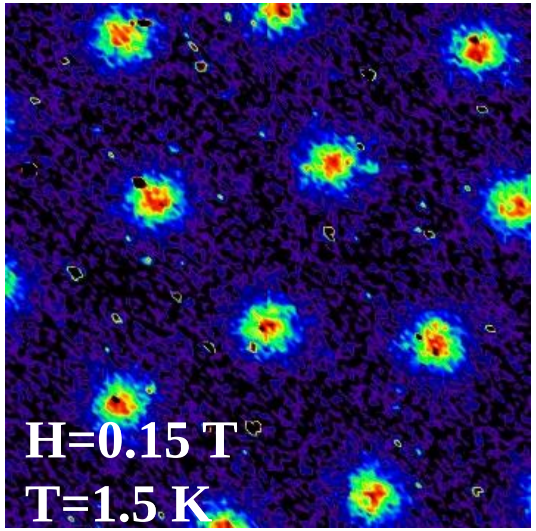
Conclusions

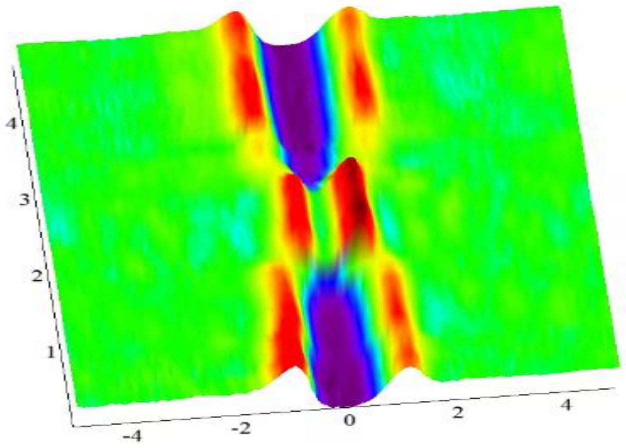
- Measurements of the quasiparticle density of states spatially resolved (gap maps, localized and extended defects…)

- Visualization of vortices up to the upper critical field and allows to extract the superconducting coherence length ξ.

- Correlate superconducting parameters Δ, ξ with surface treatments and qubit measurements.







V(mV)