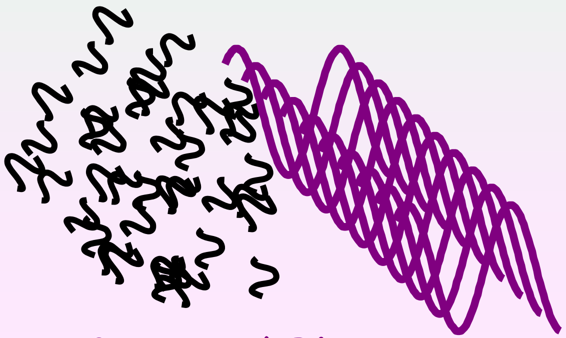
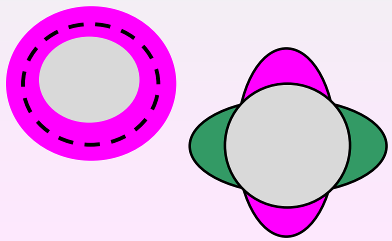
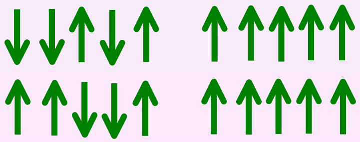
High-Temperature Superconductors: Playgrounds for Broken Symmetries



Gauge / Phase



Reflection



Time

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Outline:

- ❖ Superconductivity
- ❖ Broken Symmetries
- ❖ Andreev Reflection
- ❖ Planar Tunneling Spectroscopy
- ❖ Controversies in observing Andreev Bound State splittings (tunneling cone and atomic-scale disorder?)
- ❖ Open questions

Superconductivity (Webster):

"An electronic state of matter characterized by
zero resistance,
perfect diamagnetism, and
long-range quantum mechanical order."

This means phase coherence, which can be thought of as broken gauge symmetry

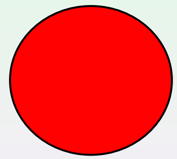
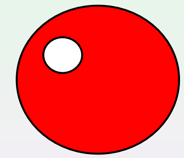
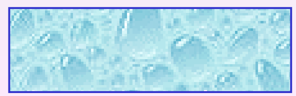
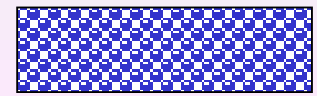
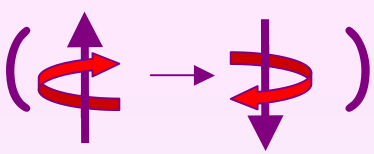
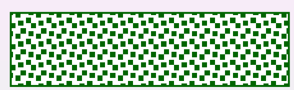
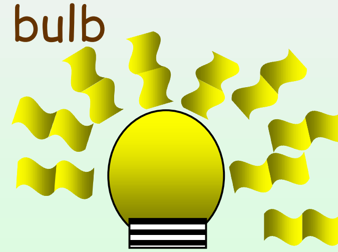
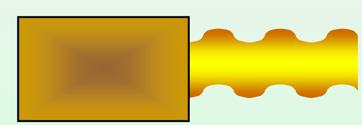
Definitions of Symmetry and Broken Symmetry

Symmetry State	***Broken Symmetry State:***
Homogeneous *w.r.t. coordinate*	*Typically* ***inhomogeneous*** *w.r.t. coordinate*

(distance, angle, phase, time, ..)

"The symmetry of the state is the ***same*** *as that of the Hamiltonian"*	*"The symmetry of the state is* ***lower*** *than that of the Hamiltonian".*
Changing the coordinate does ***not*** *produce a measurable change*	*Changing a coordinate produces a measurable change*

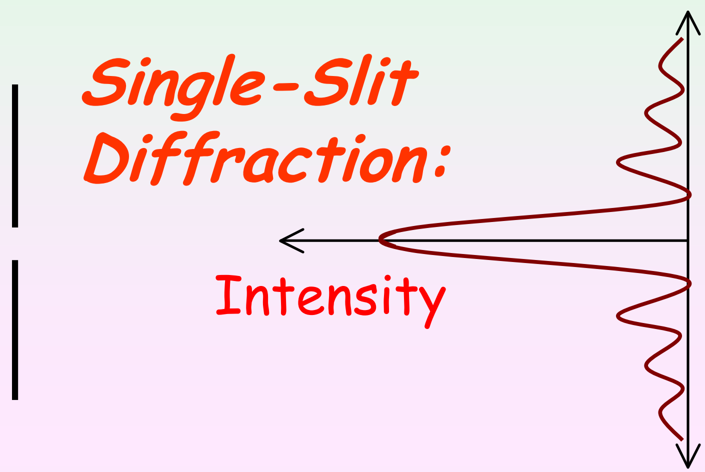
Some examples of Broken Symmetries

Symmetry:	Symmetric State	Broken Symmetry State
Circular		
Translational:	Fluid 	**Solid** 
Time Reversal: 	Paramagnet ($T>T_c$) ↑↓↑↑↓↑↓↓	**Ferromagnet** ($T<T_c$) ↑↑↑↑↑↑↑↑
Gauge *(spontaneous)*	Metal ($T>T_c$) 	**Superconductor** ($T<T_c$) 
Gauge *(driven, not spontaneous)*	Light bulb 	**Laser** 

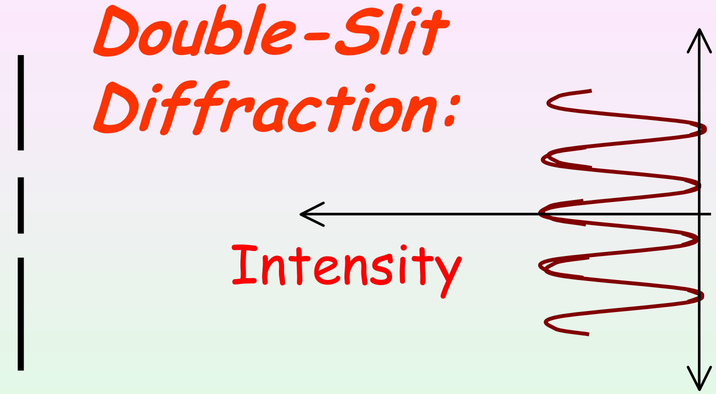
Some Ramifications of Broken Gauge Symmetry

Photons (driven)	Electrons (spontaneous)

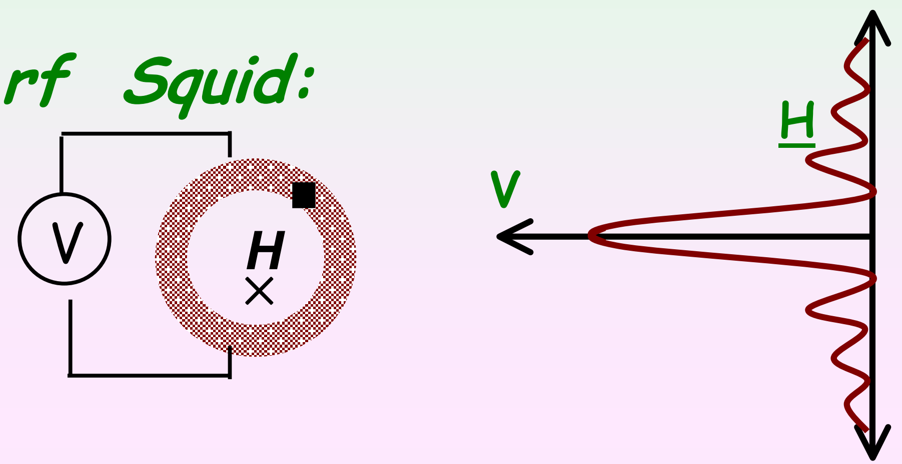
Single-Slit Diffraction:



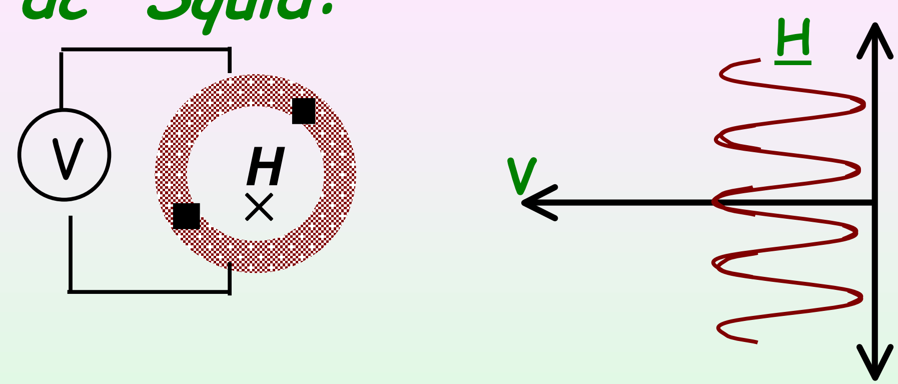
Double-Slit Diffraction:



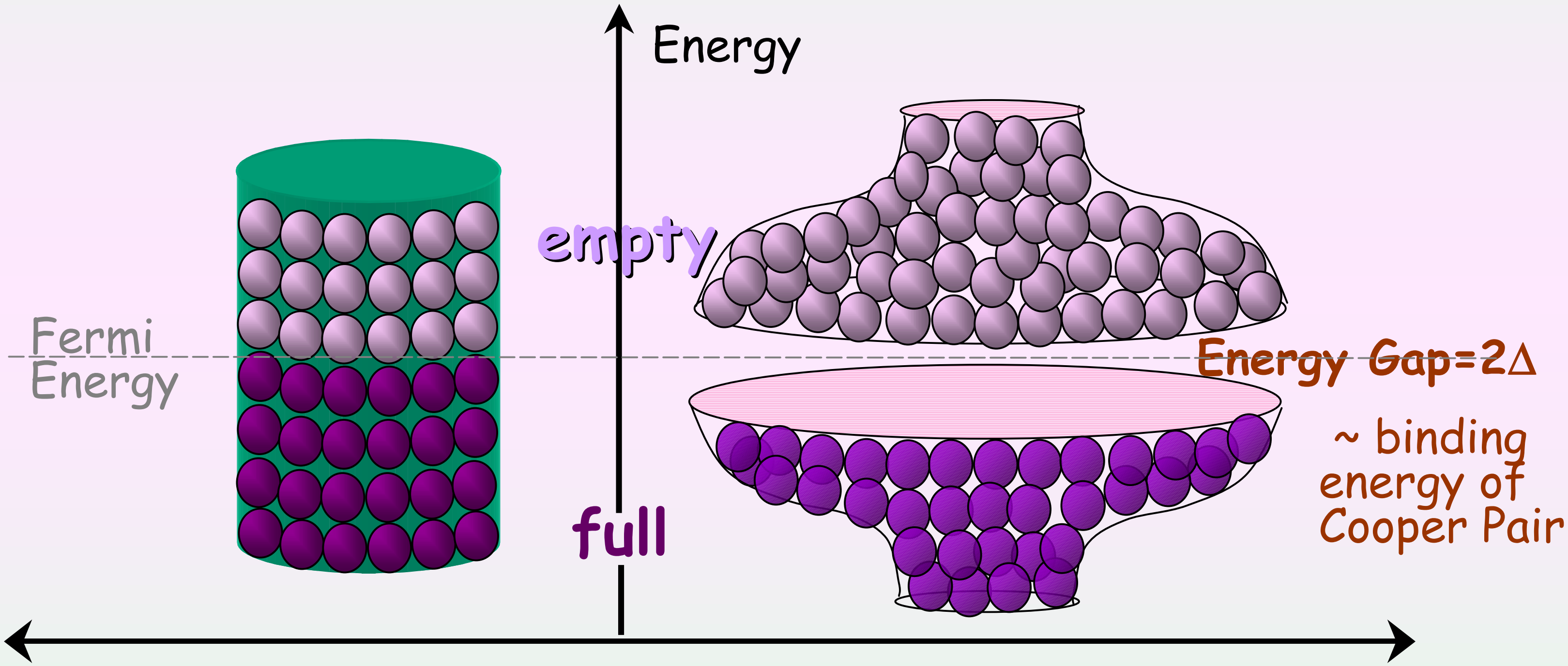
rf Squid:



dc Squid:

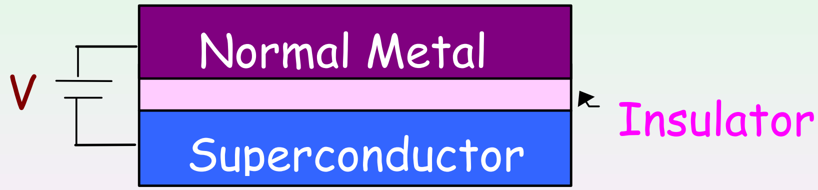


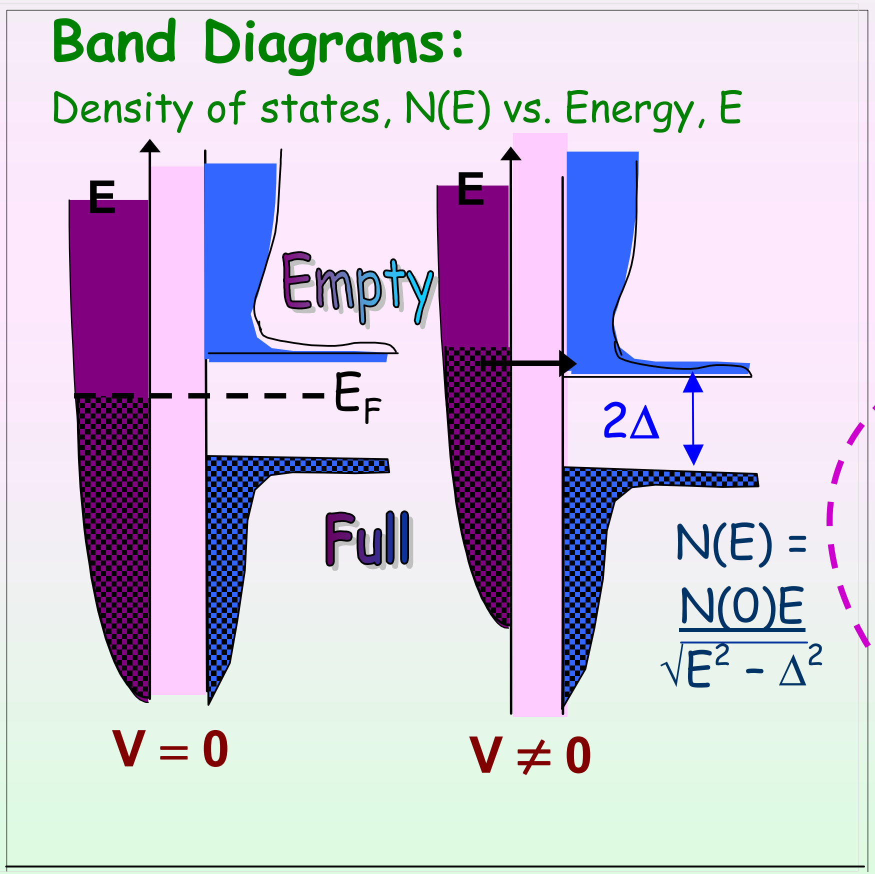
This strongly correlated electronic state results in an energy gap

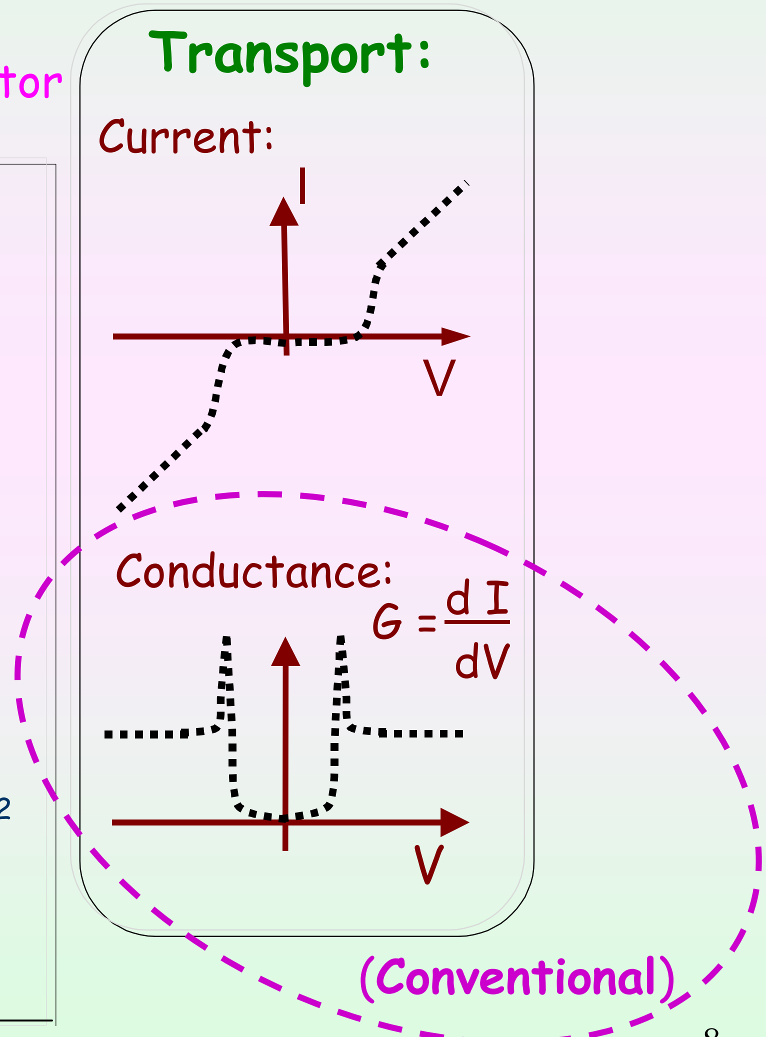


Density of electronic states

Tunneling: The SIN Tunnel Junction

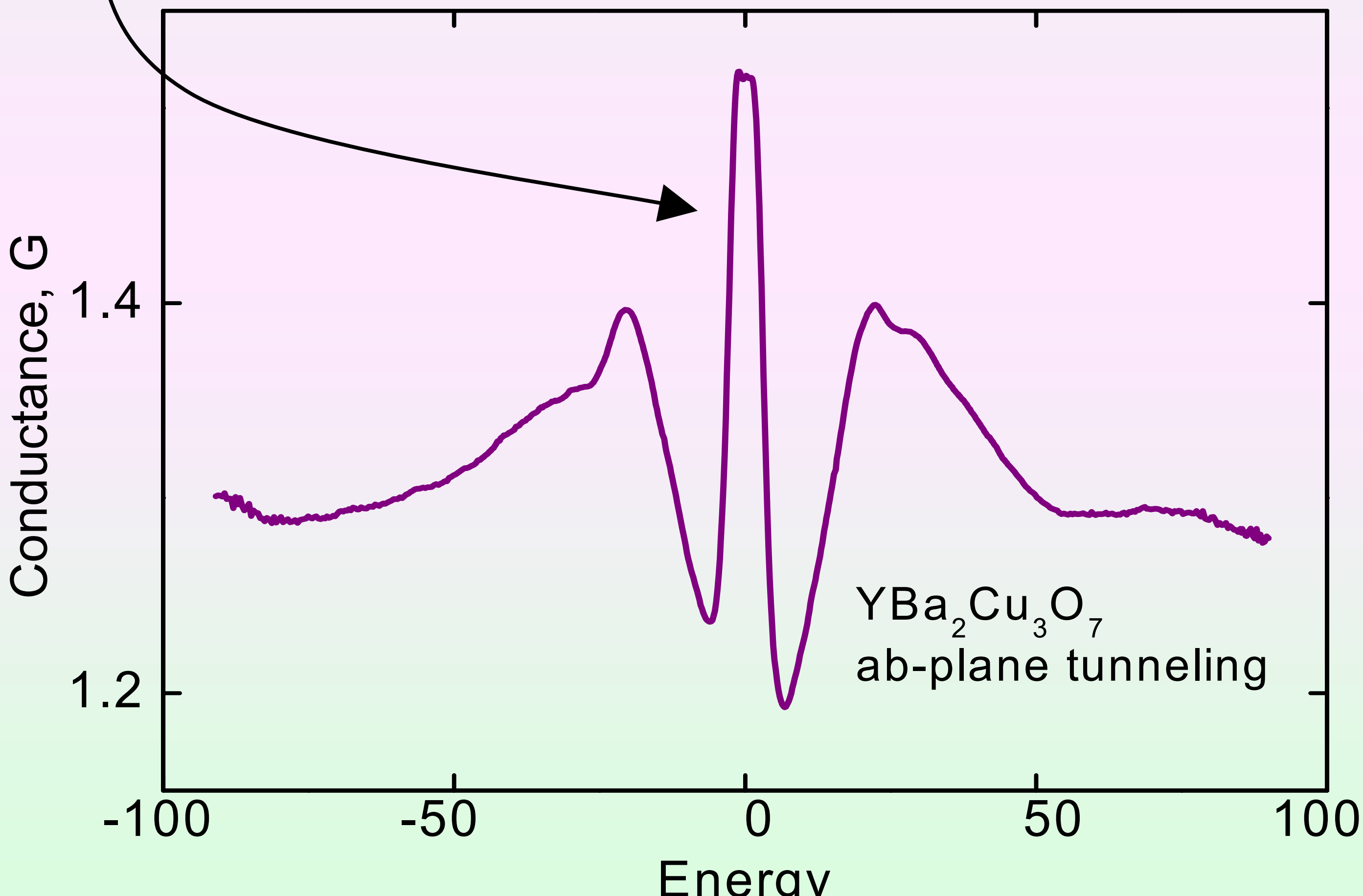




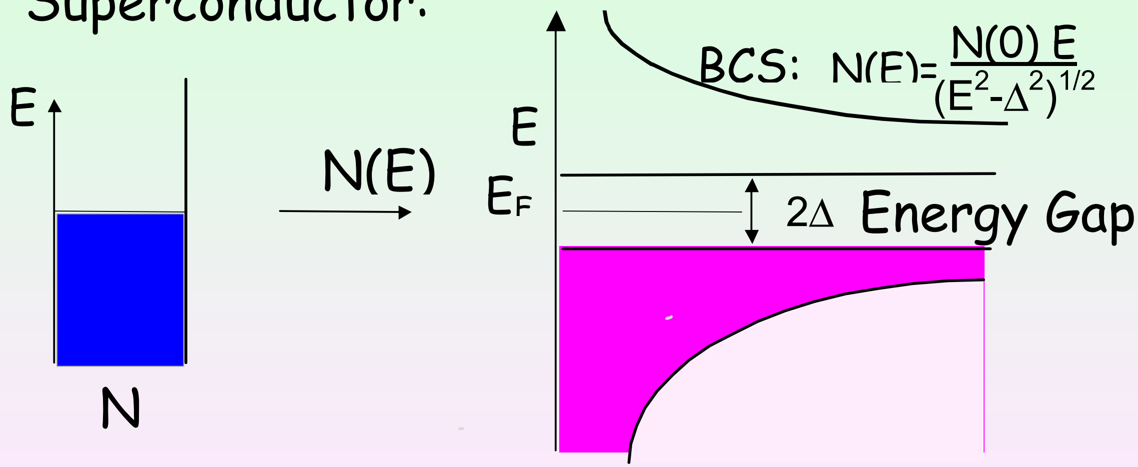


Measured Tunneling Conductance of a High-Temperature Superconductor

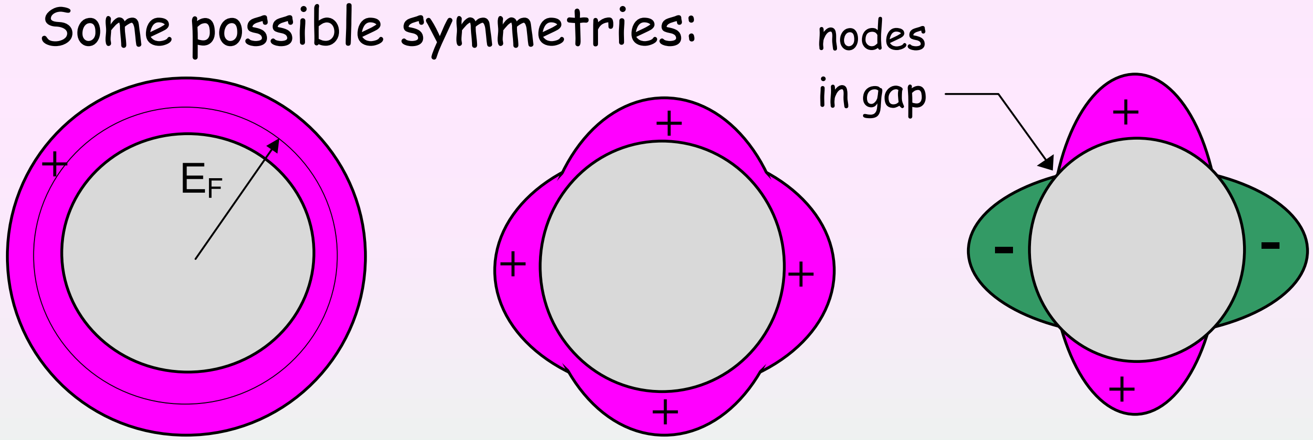
The central peak is due to the **broken reflection symmetry of** the superconducting order parameter



Superconductor:



Some possible symmetries:



s-wave

anisotropic s-wave

d-wave

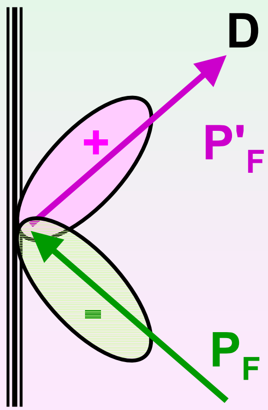
Broken Reflection Symmetry

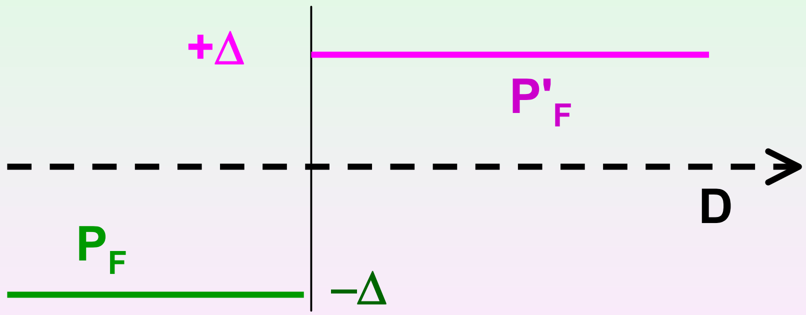
"Conventional"

"Unconventional"

ORIGIN OF ANDREEV BOUND STATE

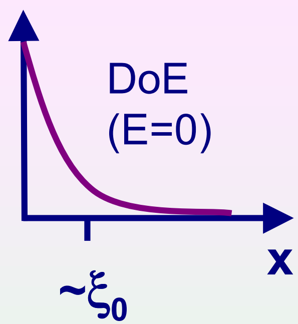
Cooper Pair Quasi-Classical Trajectory along **D**:





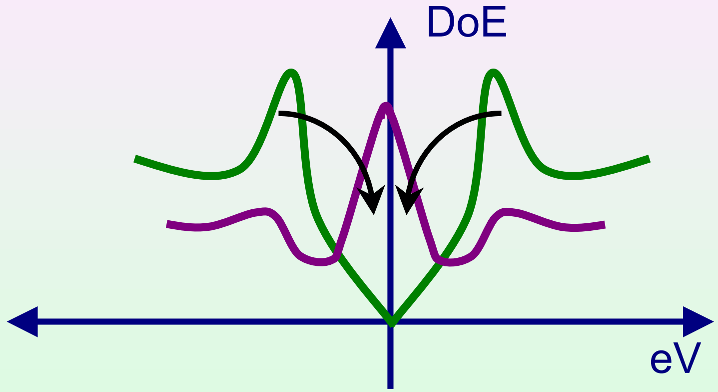
(110)
surface

Sign-change of Order Parameter is only Boundary Condition



Solution to Andreev Equations:

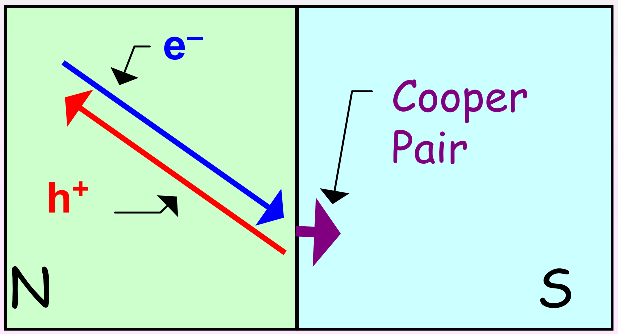
Quasiparticle Bound State at surface (decay $\sim\xi_0$)



ANDREEV REFLECTION: For an NS interface
Conventional (s-wave) superconductor:

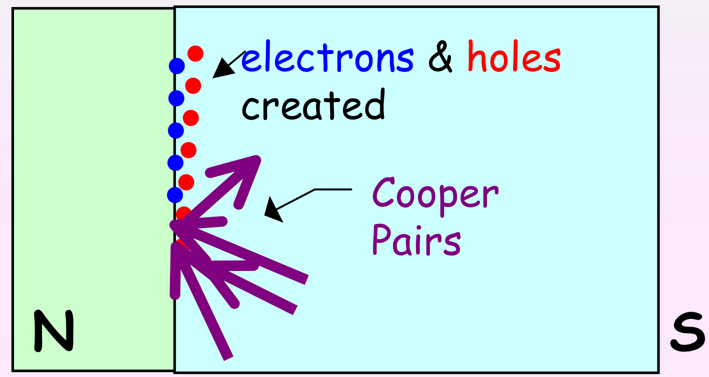
From Normal metal:

Electron Retroreflected as a hole



From Superconductor

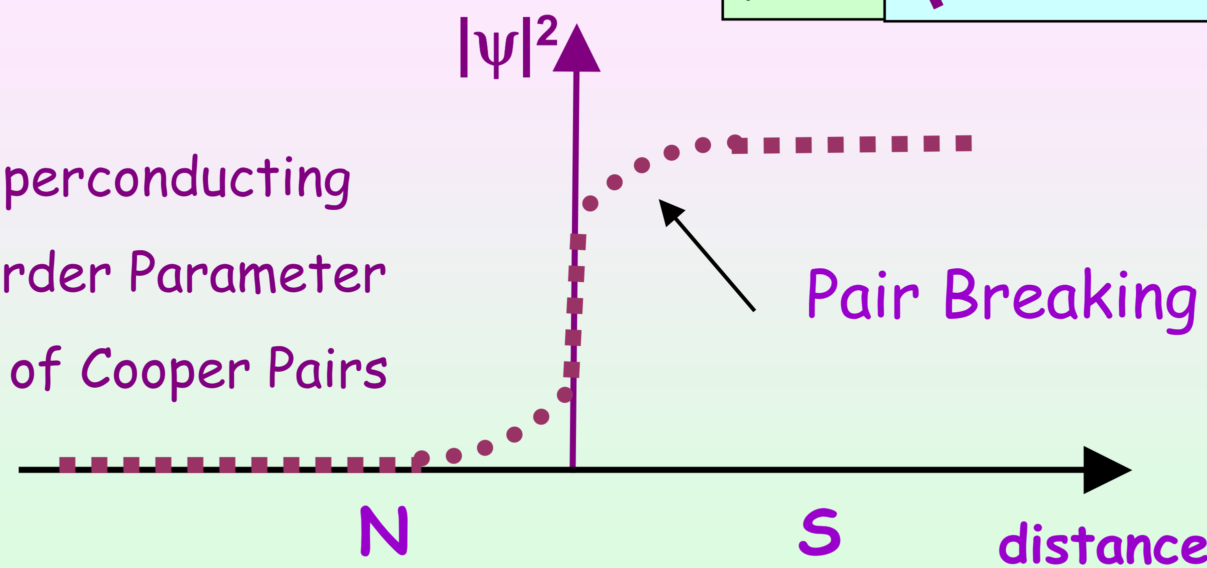
Cooper Pairs Broken



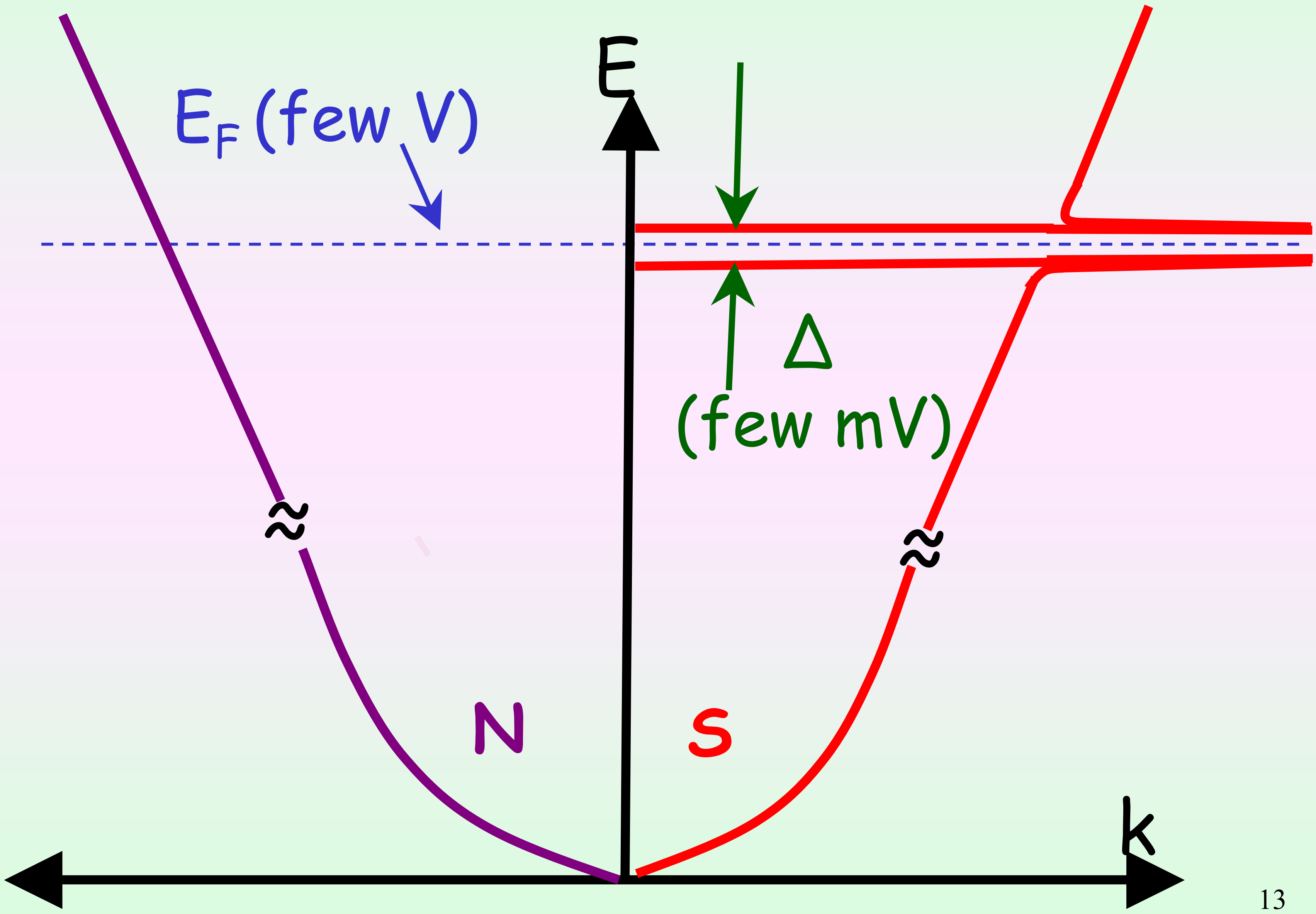
ψ = Superconducting

Order Parameter

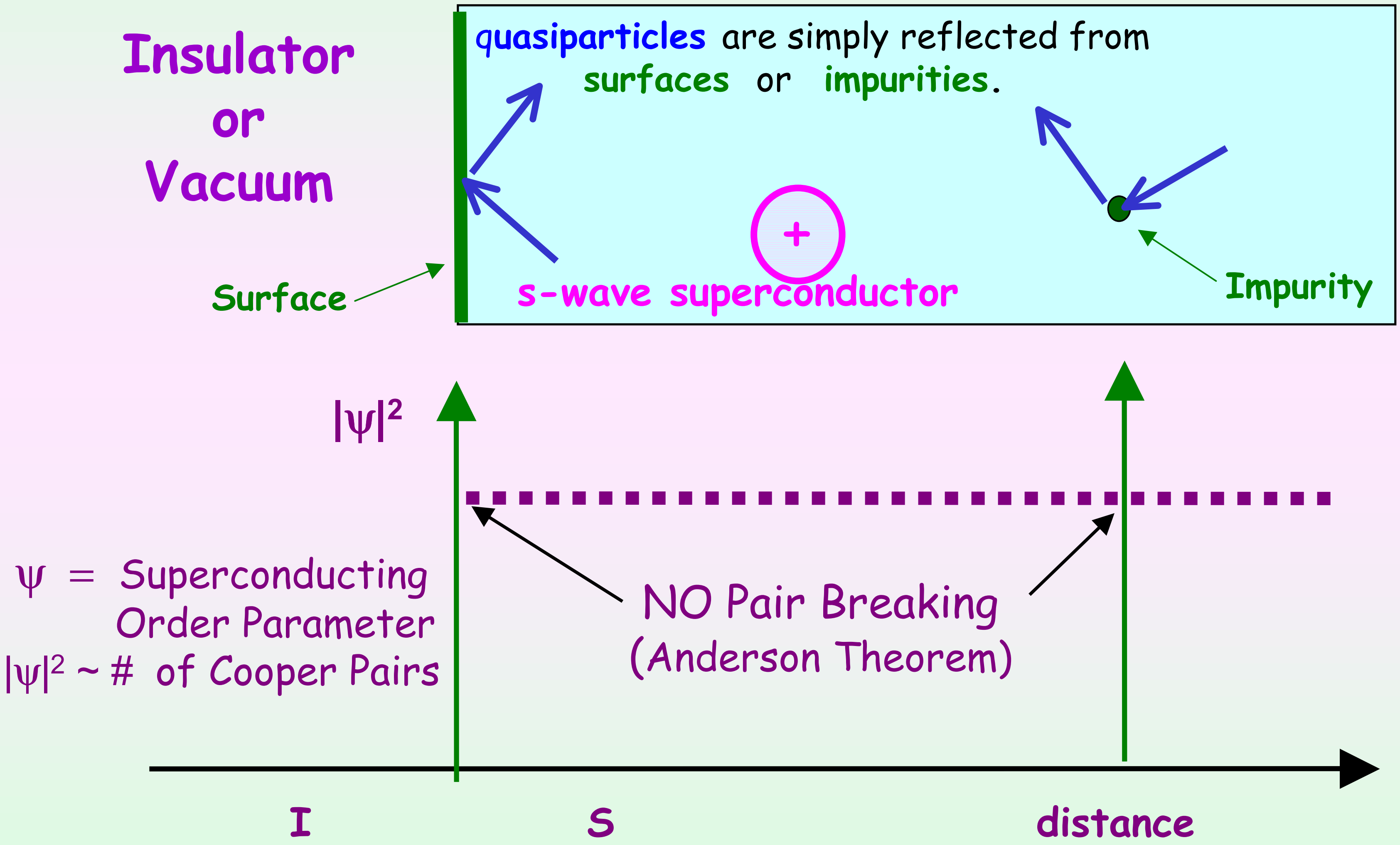
$|\psi|^2 \sim$ # of Cooper Pairs



Energy Scales for Andreev Reflection

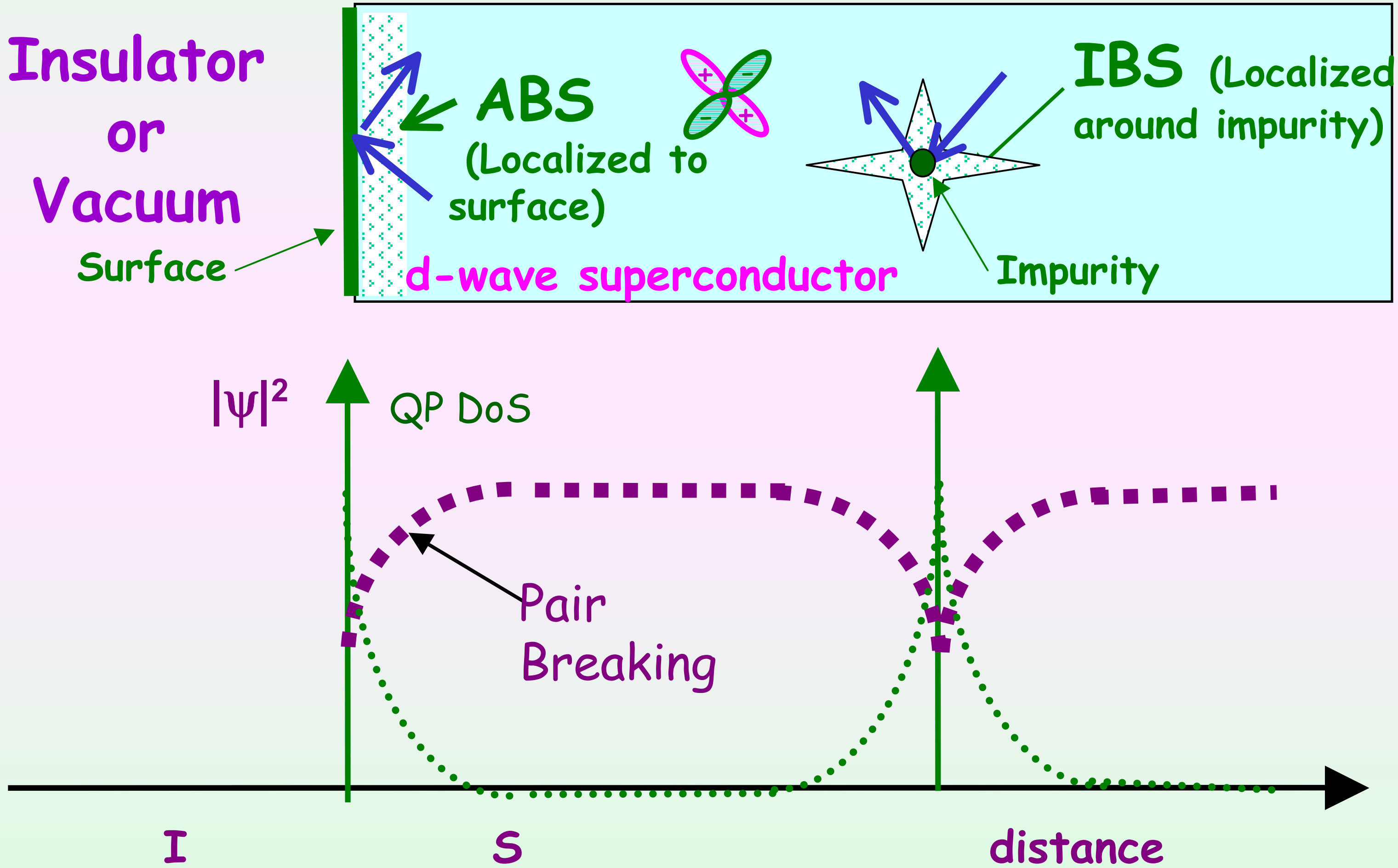


QP scattering in a conventional (s-wave) superconductor:

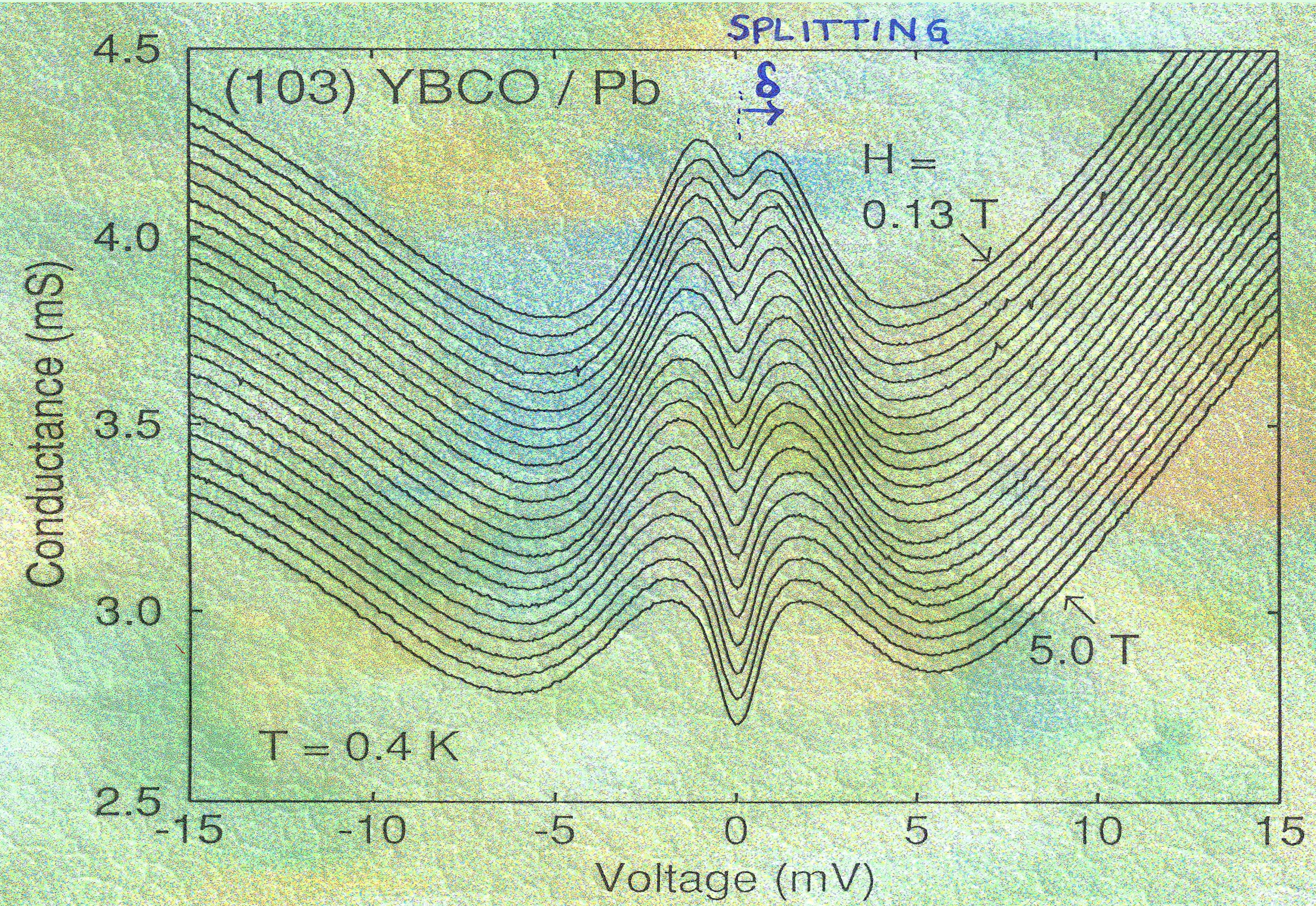


QP scattering in an unconventional (d-wave) superconductor:

Andreev Bound States and Impurity Bound States



Magnetic Field Dependence



ORIGIN OF ABS FIELD SPLITTING:

ABS carry current along the interface

Applied Magnetic field, H_{appl}, induces a Doppler Shift:

$$\delta = \delta_s + (e/c)\, v_F\, \lambda \sin\phi_c\, H_{appl}$$

δ = *ABS splitting*

λ = *penetration depth*

v_F = *of tunneling electrons*

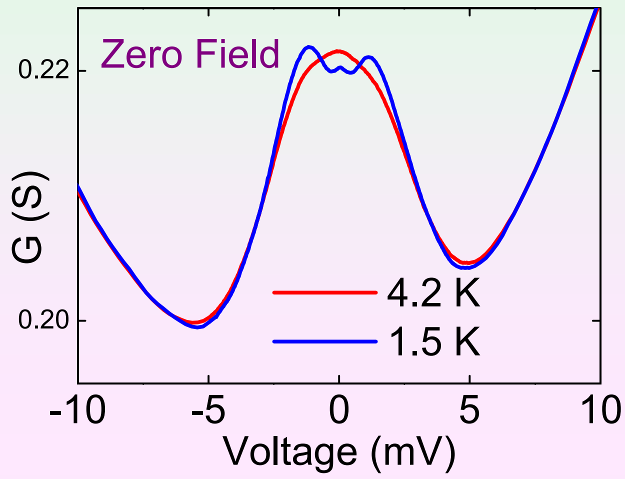
ϕ_c = *tunneling cone*

$$\boxed{\delta \propto H_{appl}}$$

Magnetic fields intrinsically break time reversal symmetry, Here, field-driven BTRS is detected by a splitting of ZBCP.

$\therefore$ ***Splitting of the ABS in ZERO field***
$\Rightarrow$ ***SPONTANEOUSLY***
Broken Time-Reversal Symmetry

Spontaneous splitting of ZBCP (H_{appl} = 0):



Covington, *et al.*, PRL **79**,277 (1997).

verified by:

- Kashiwaya *et al.* J. Phys. Chem. Sol. **59**, 2034 (1997).
- Lesueur *et al.* Proc. SPIE **3481** , 419 (1998)
- Krupke & Deutscher PRL **83**, 4364 (1999)
- Grison *et al.* Physica B **284-288**, 559 (2000)

Consistent with **Broken Time Reversal Symmetry** (BTRS) arising from the formation of a **sub-dominant OP** (at low temperature, the QPs in the ABS condense into a Cooper channel that is not $d_{x^2-y^2}$, discussed next)

Other models for the spontaneous splitting exist:

Higashitani, J. Phys Soc Jap 66, 2556 (1997)
Honerkamp et al, Physica B 291-282, 888 (2000)
Barash et al PRB 62, 6665 (2000)
Lofwander et al, PRB 62, 414653 (2000)

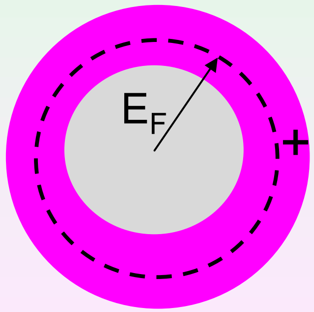
$\Bigg\}$ Intrinsic instabilities lead to a spontaneous Doppler Shift

Morr & Demler, cond-mat/0010460:

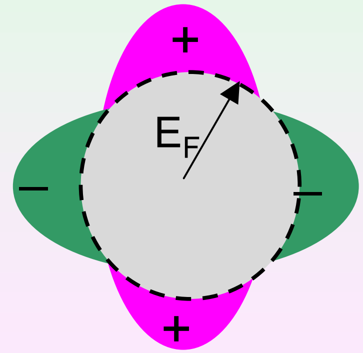
Caroly gap (Full QM calc.)

Mixed States:

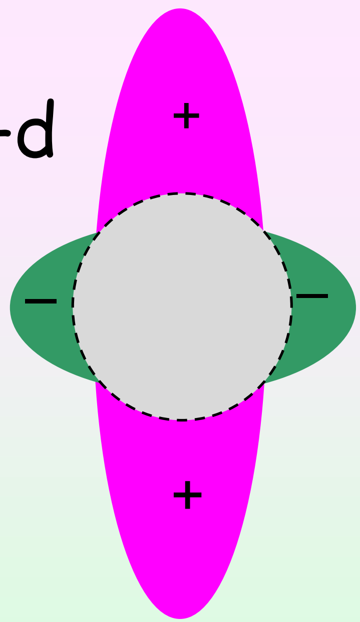
- *s*



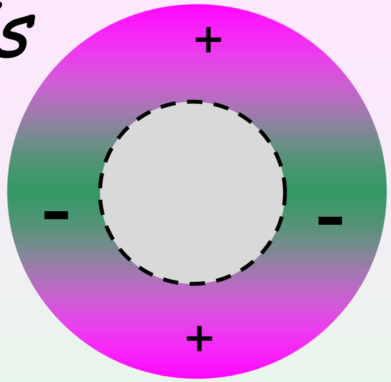
- *d*



- *s+d*



- *d+is*



Broken Time-Reversal Symmetry
(magnetism)

Comments / observations on zero-bias conductance peak splittings

A. For nominally-doped materials, the spontaneous and field-induced splittings are either seen together or no (they go hand-in-hand).

B. There are two cases in which the splittings are not observed:

   1. A narrow tunneling cone
   2. Atomic scale disorder.

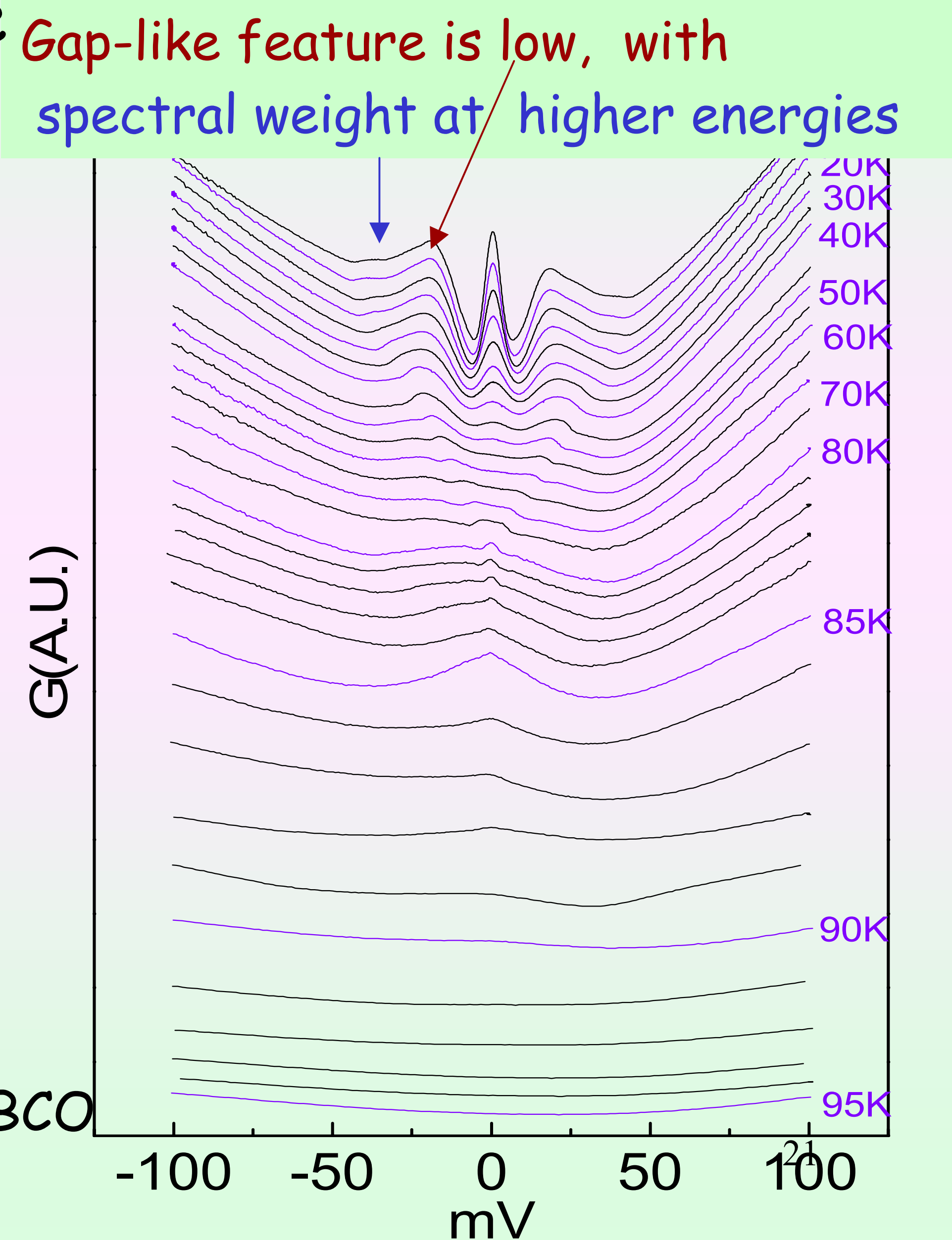
NEW junction Fabrication Technique
➔Narrow Tunneling Cone

Hydrolysis and Condensation of ultra-pure Zr2(Oprn)16

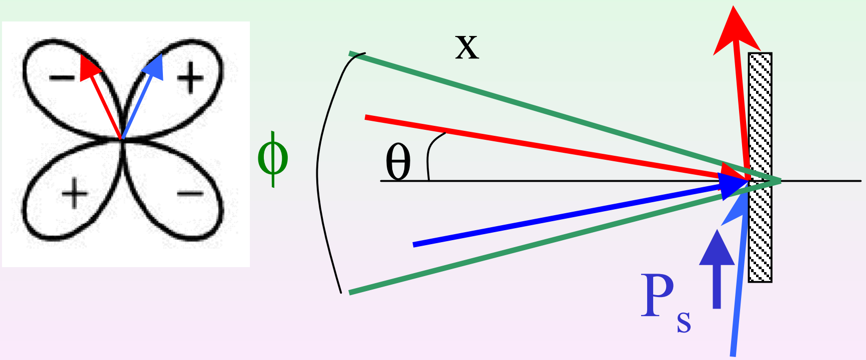
Provides ultra-thin, pinhole-free **zirconia** layer

Maintains atomic-scale smoothness on film facets

Data consistent with a **small tunneling cone**



Model I (for sharp-featured junctions): Tunneling cone can act as a filter



Fogelström *et al. PRL (1997)*

$$G_S(\varepsilon) \propto \int d\theta . N(\theta,\varepsilon) . D(\theta)$$

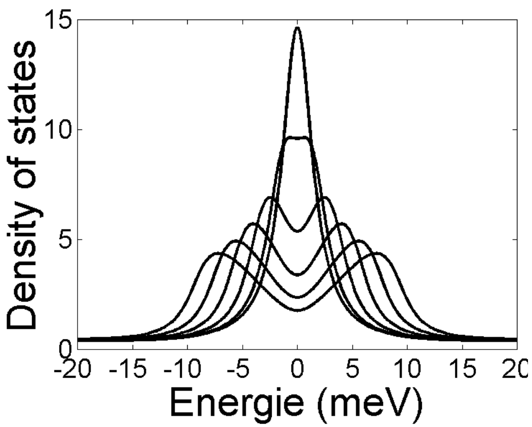
$$N(\theta,\varepsilon) = \mathrm{Im}\left(\frac{\varepsilon^R}{D^R} - \frac{|\Delta(\theta)|^2}{\varepsilon^R D^R} \right)$$

$$\varepsilon^R(\theta,\varepsilon) = \varepsilon + i\gamma + (e/c) v_f . A(R)$$

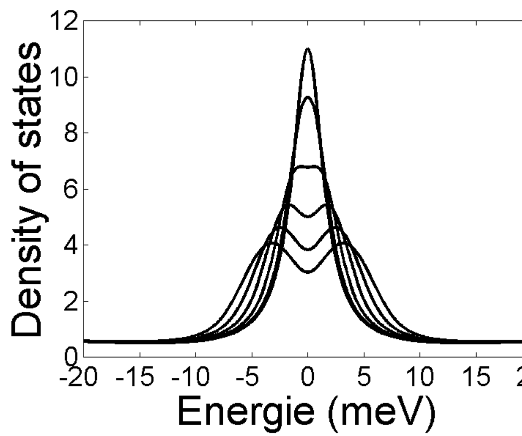
Large tunneling cone

If D(θ)=1,

φ=180°

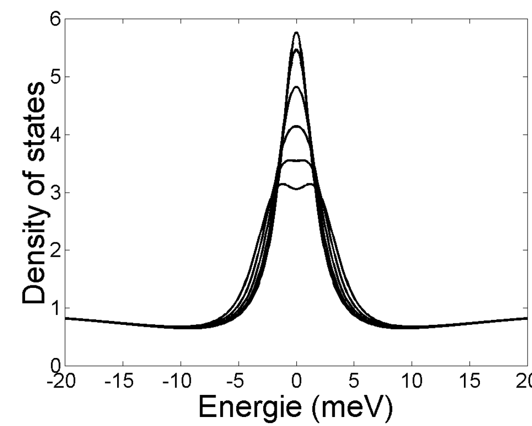


φ=50°



Small tunneling cone,

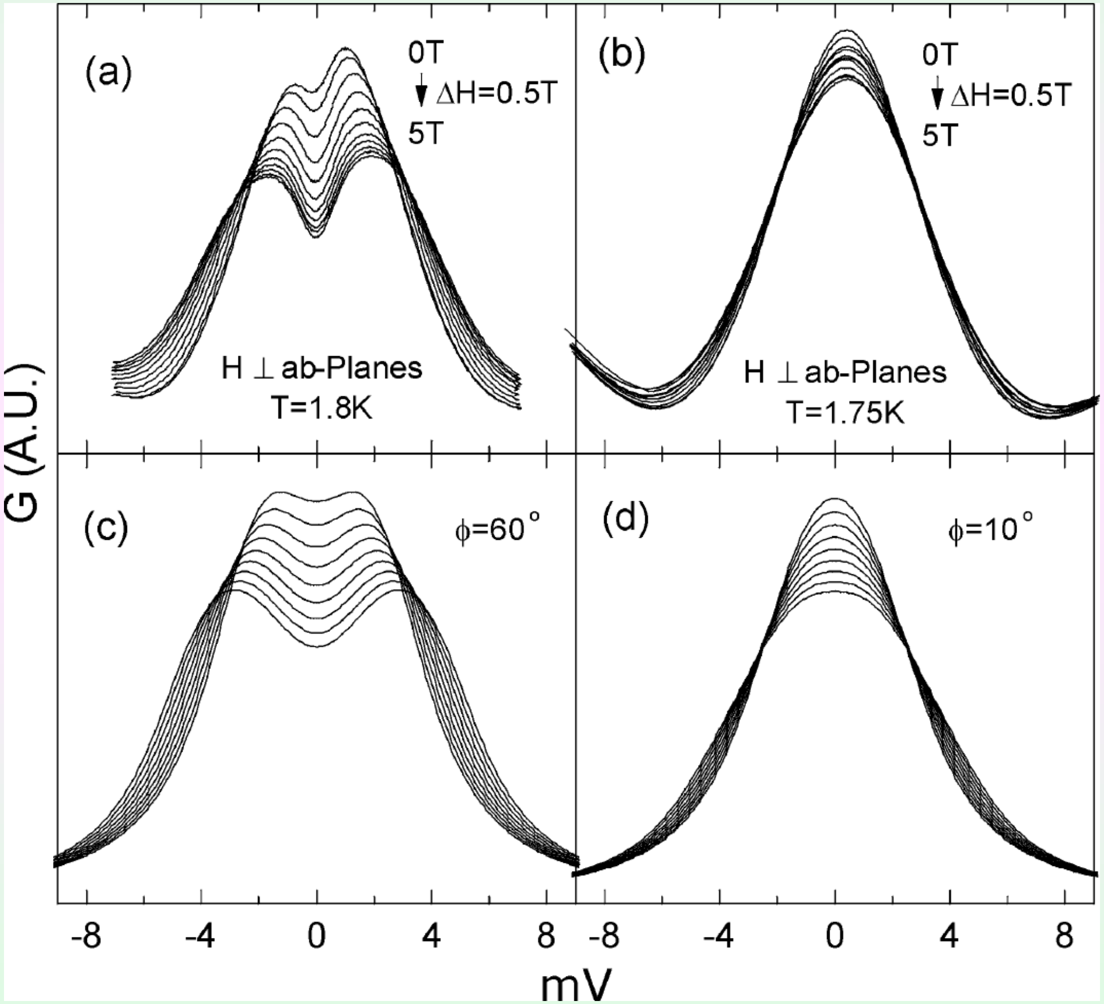
φ=20°



Tunneling cone filter: Data and Calculations

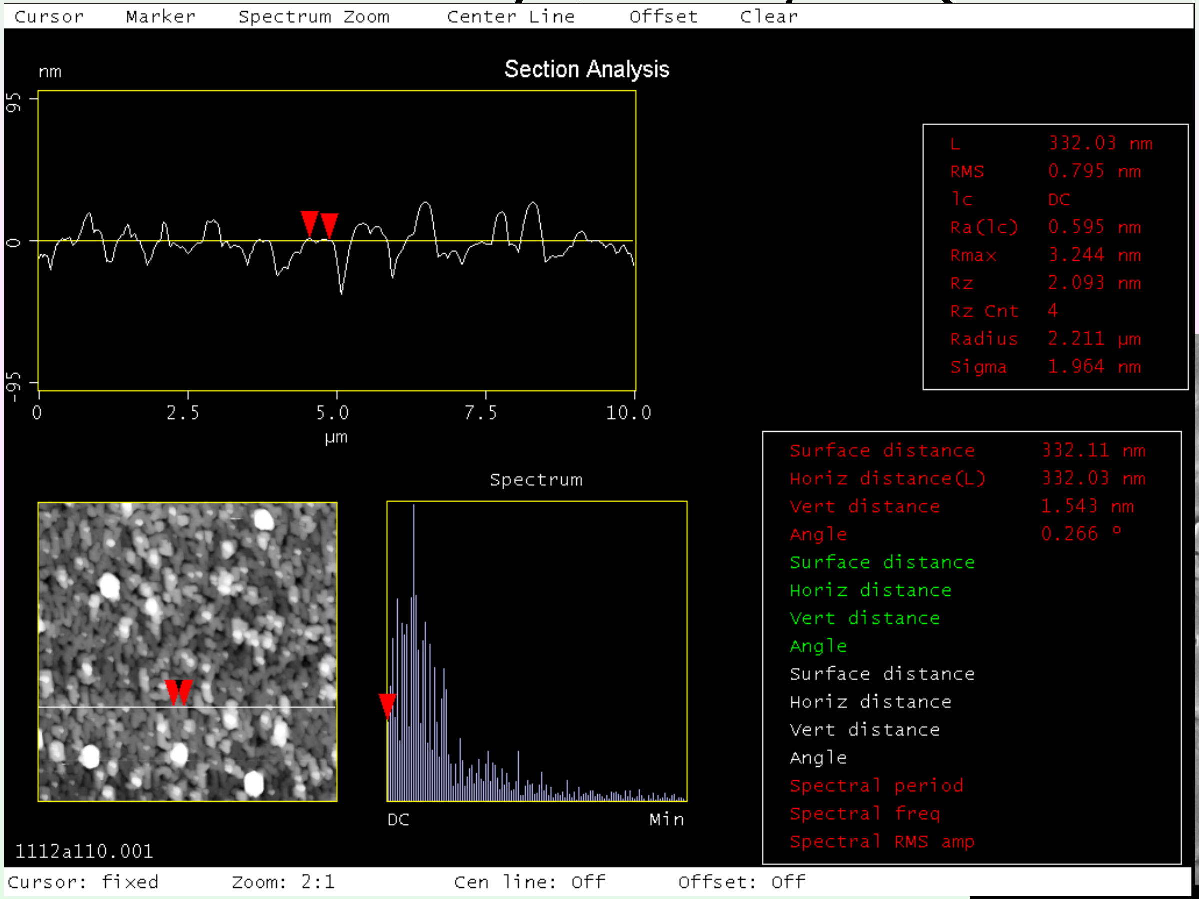
Data:
(zirconia-based junctions)

Calculations:

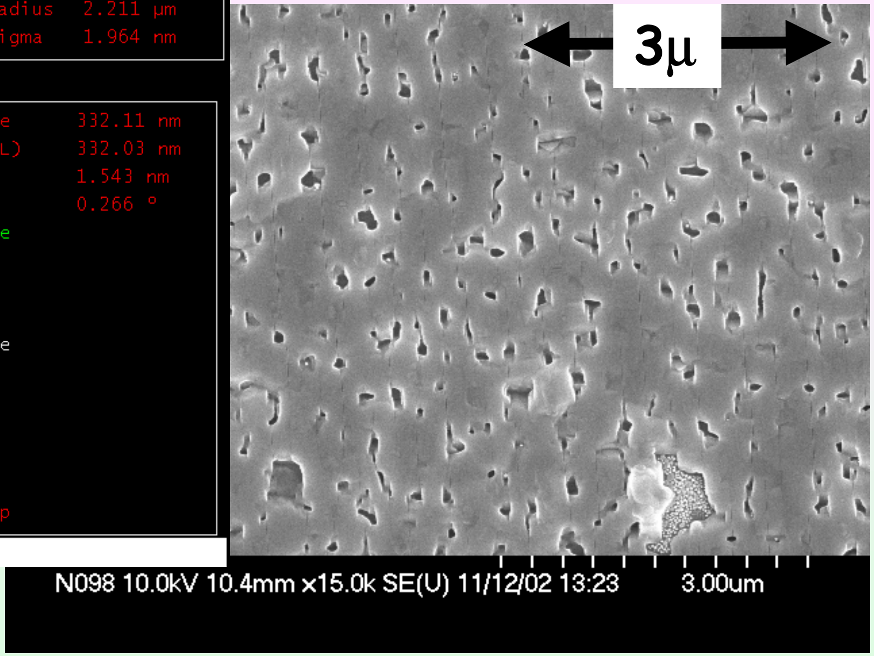


(110) YBCO Thin Film

AFM: RMS roughness ~few nm over ~.5 μ
Some ~atomically-flat regions (red arrows)



SEM

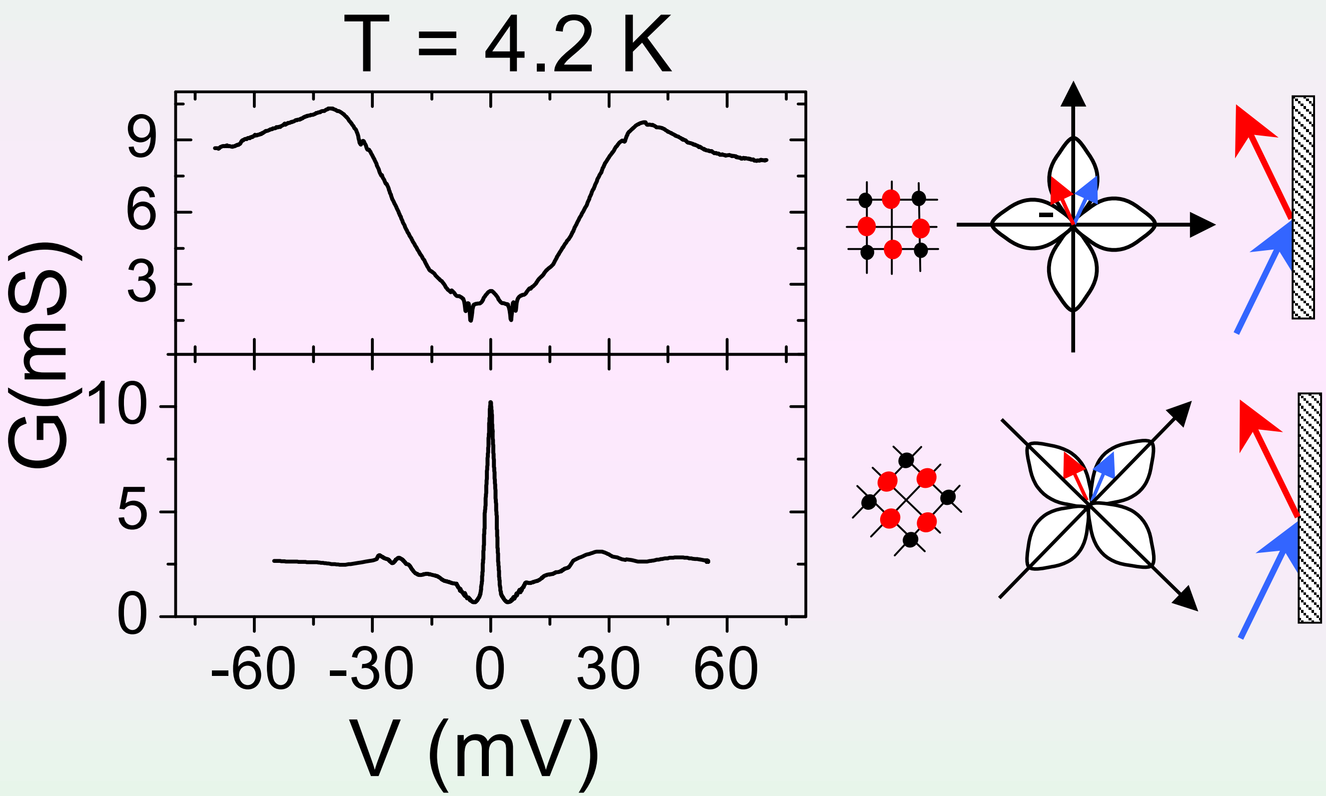


In-plane Quasi-particle Tunneling into $Bi_2Sr_2CaCu_2O_8$ Single Crystals

NEW junction Fabrication Technique:

1. Cut and Polish to RMS Roughness ~ 80 Å (AFM)
   ➔ **No Faceting and Atomic Scale Damage**
2. Evaporation of ultra-thin (1nm) CaF_2 insulating layer
3. Ag counter electrodes

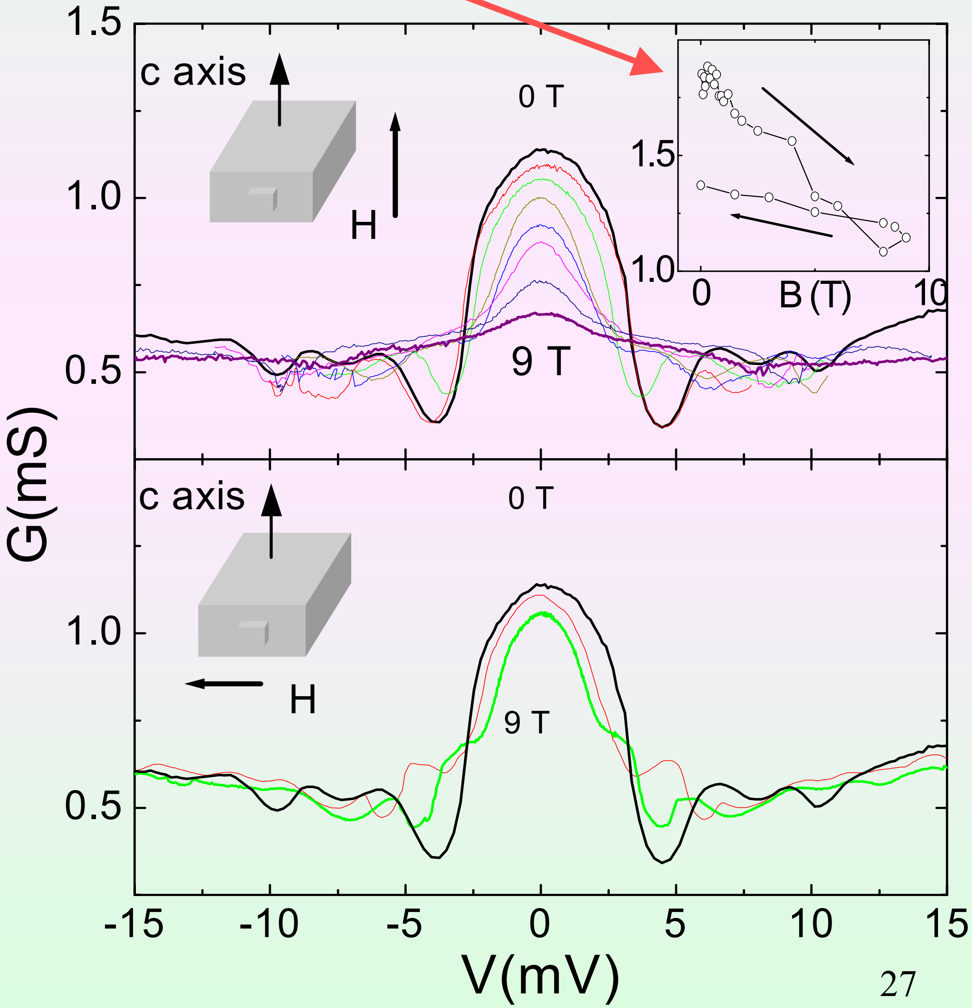
BSCCO Single Crystals:
in-plane Crystallographic Orientation Dep.



H. Aubin, LHG, S. Jian and D. G. Hinks. PRL, **89**, 177001 (2002)

BSCCO Single Crystals: Magnetic Field Dependence
Magnitude and orientation:

Anisotropic QP Transport & Hysteresis

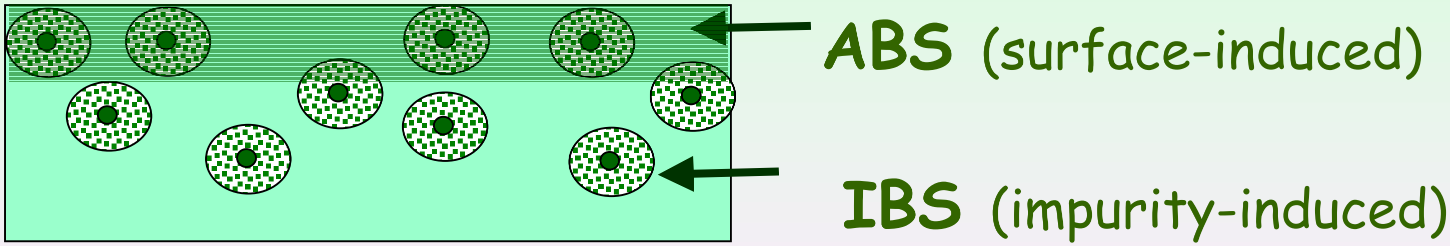


Suppression of ZBCP with applied field, field orientation dependent.

DoS spectral weight conserved within 5%

No splitting observed !

II. The IBS effect on ABS



One Idea: Samokhin and Walker, PRB, 2001:
<u>Showed that a ZBCP due to IBS does not split in a field, only broadens</u> (like the grain-boundary, ramp and single-crystal junctions).
[e.g.,IBS swamp IBS, and the IBS are localized around the scattering centers]

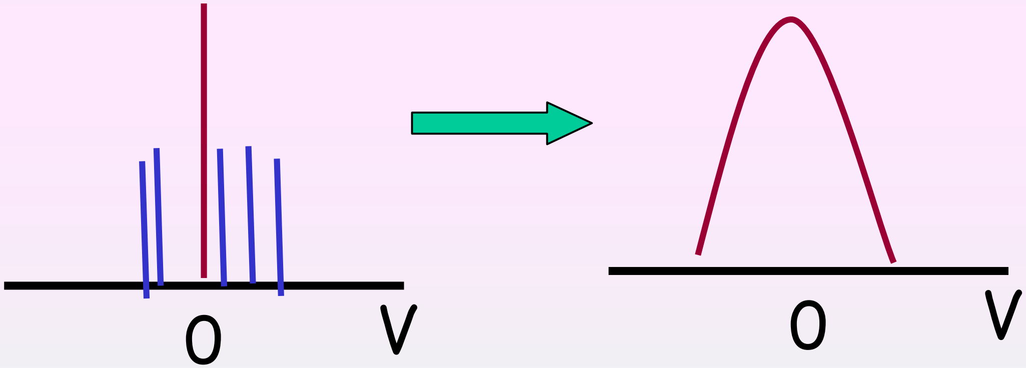
But: This model requires the IBS to <u>swamp</u> the ABS. The spectral weight of the IBS is much lower than that of the ABS, and with so many impurities, phase coherence (d-wave sc) would be lost.

And: If the IBS dominates the ABS in the ZBCP, there should be no orientation dependence!

Preliminary Model

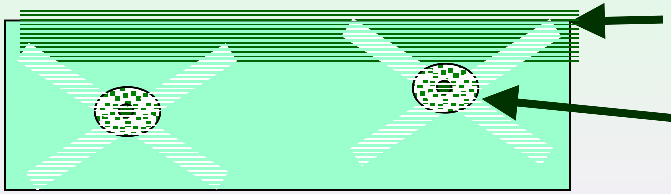
ABS plus some surface disorder creating some IBS (impurity bound state), near the ABS, both spatially and in energy, cause ABS to be **Homogeneously Broadened**

Cartoon:



Homogeneously broadened peak will split

Add some IBS near interface:



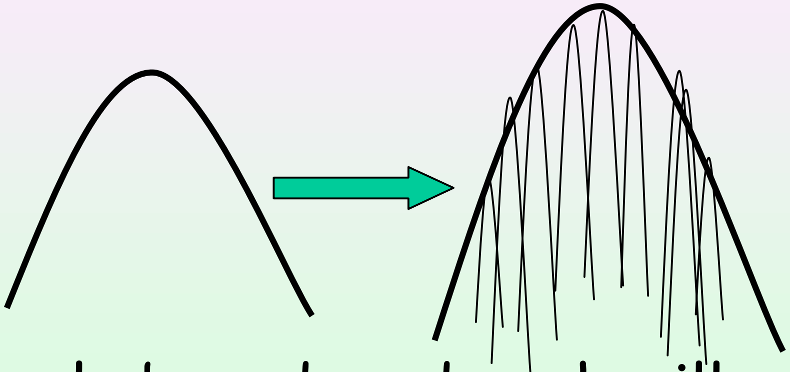
ABS (surface-induced)

IBS (impurity-induced)

<u>IBS act as scattering centers</u>
to scatter ABS along different trajectories:

*ZBCP is now an **<u>inhomogeneously-broadened</u>** band of quasiparticles:*

Cartoon:



Inhomogeneously broadened peak will not split, will only suppress and broaden.

Outstanding questions in high-temperature and unconventional superconductivity:

Finding the mechanism for superconductivity.

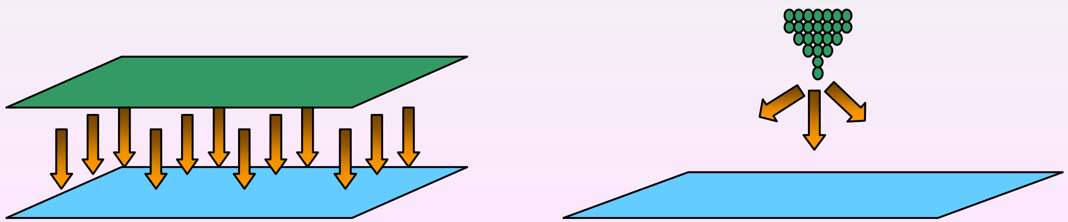
Finding reliable ways to measure if a superconductor is unconventional, and the symmetry of its pairing state.

Understanding the role of disorder, including interfaces. Conventional superconductors are typically metals or alloys, but the unconventional superconductors tend to be compounds. Therefore, they are more fragile, i.e., are more sensitive to structural disorder. In unconventional superconductors, even a small change in physical structure can cause a profound effect on their electronic structure, so this remains an important question, both for the basic understanding of the physical state, and for applications.

Finding reliable ways to measure if time-reversal symmetry is broken. This is a challenging, because the magnetism can occur in a very small fraction of the superconductor, and is buried within the superconducting state.

Planar Tunneling Spectroscopy vs. STM:
(measurements compliment each other)

Planar Tunneling STM



Advantages:

I. Can obtain high momentum resolution (tunneling cone)

II. Stable configuration:
can easily study as a function of field, temperature, area and, most important, reproducibility.

Drawbacks:

I. Damage to surface during junction fabrication

II. Low spatial resolution