Planar Tunneling and Andreev Reflection: Powerful probes of the superconducting order parameter

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Outline:

Lecture 1 (Tunneling spectroscopy on HTS):

- **Promo**: Grand statement / DoE-BES report / new SCs
- **Broken symmetries** (gauge, reflection and time-reversal)
- **Tunneling** and order parameter (OP) symmetry
- **Andreev reflection** (AR)
- **Tunneling** into Andreev bound states: Broken symmetries

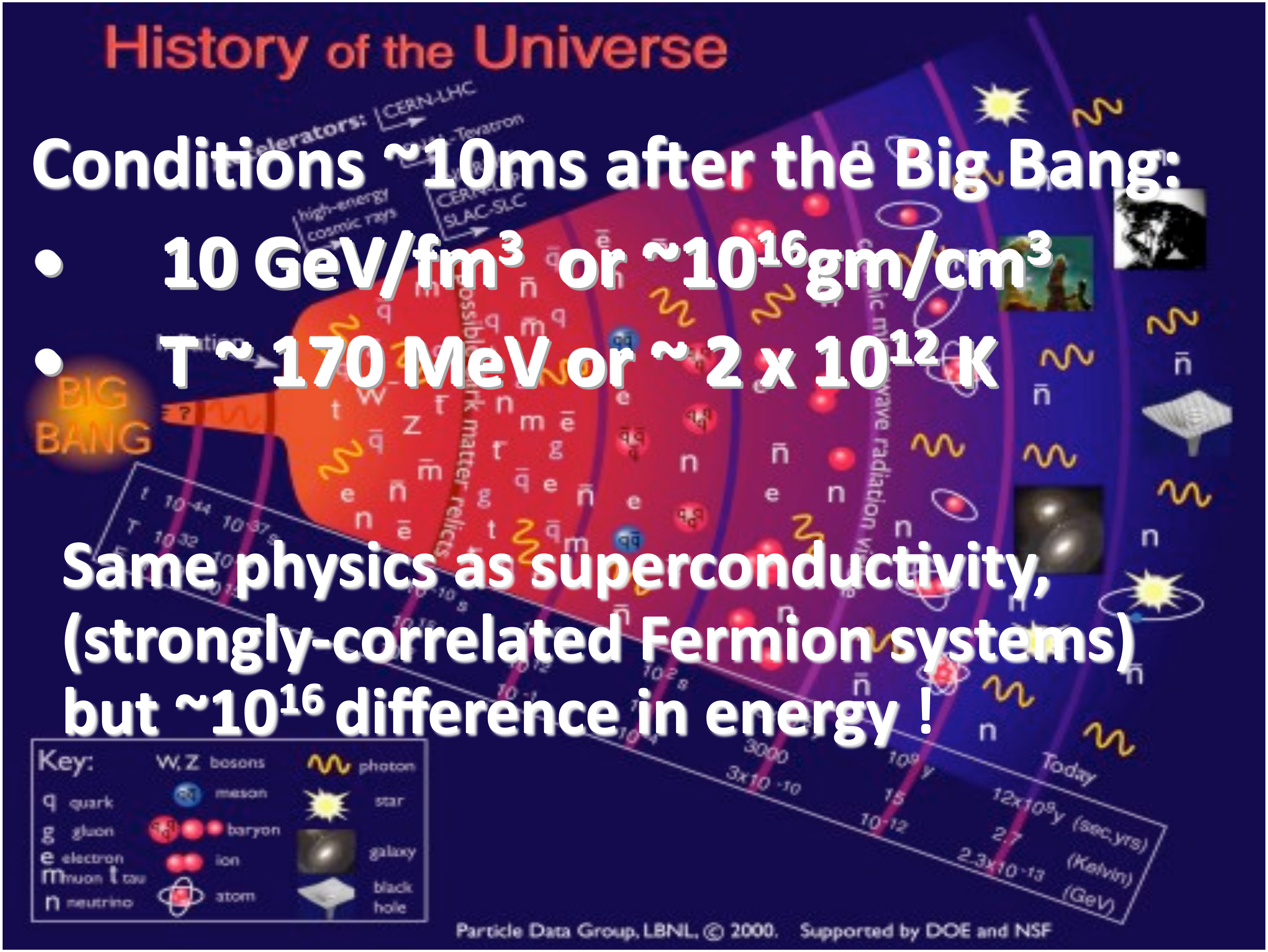
Lecture 2 (Andreev reflection spectroscopy on HFs):

- Point Contact Andreev Reflection Tunneling Spectroscopy (PCARTS)
- Blonder-Tinkham-Klapwijk (BTK) theory and it's extension to d-wave
- Definition of the issues (AR at HFSs and spectroscopy of HFs)
- CeCoIn5 and related HFs
- Describe data with a two-fluid model and Fano resonance in an energy-dependent DoS

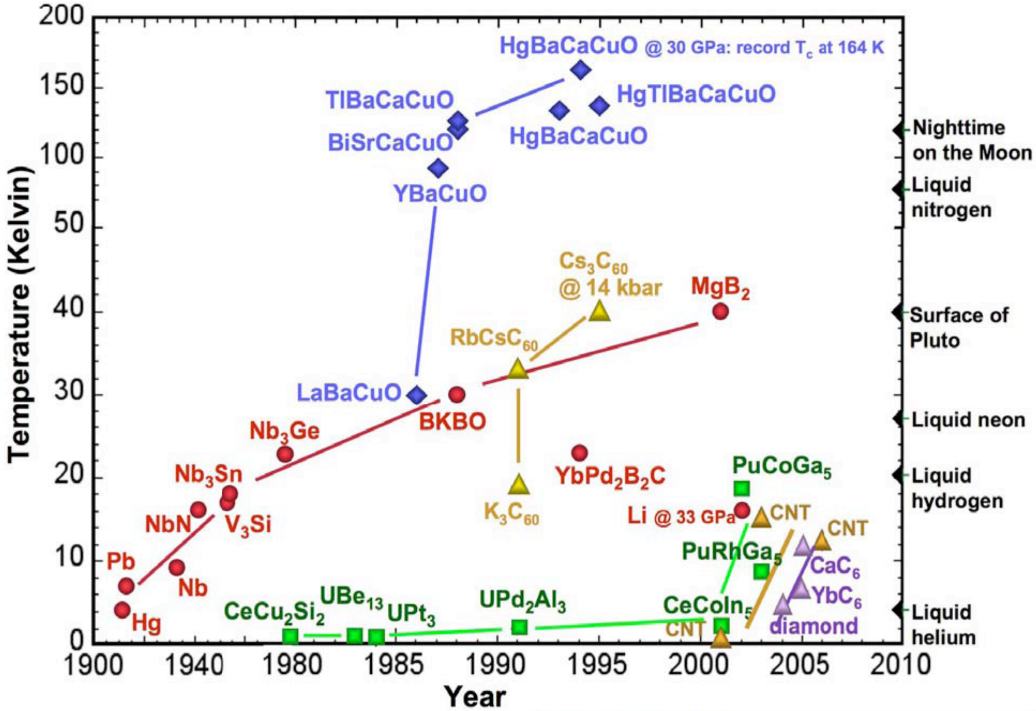
Conditions ~10ms after the Big Bang:

- 10 GeV/fm^3 or ~10^{16}gm/cm^3
- T ~ 170 MeV or ~ 2 x 10^{12} K

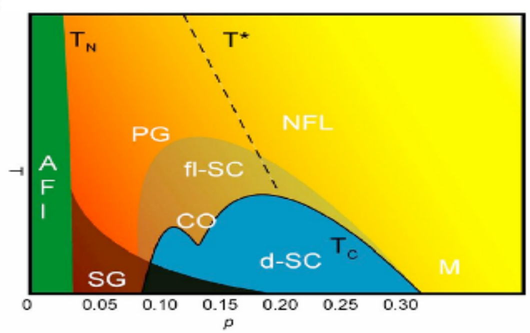
Same physics as superconductivity, (strongly-correlated Fermion systems) but ~10^{16} difference in energy !

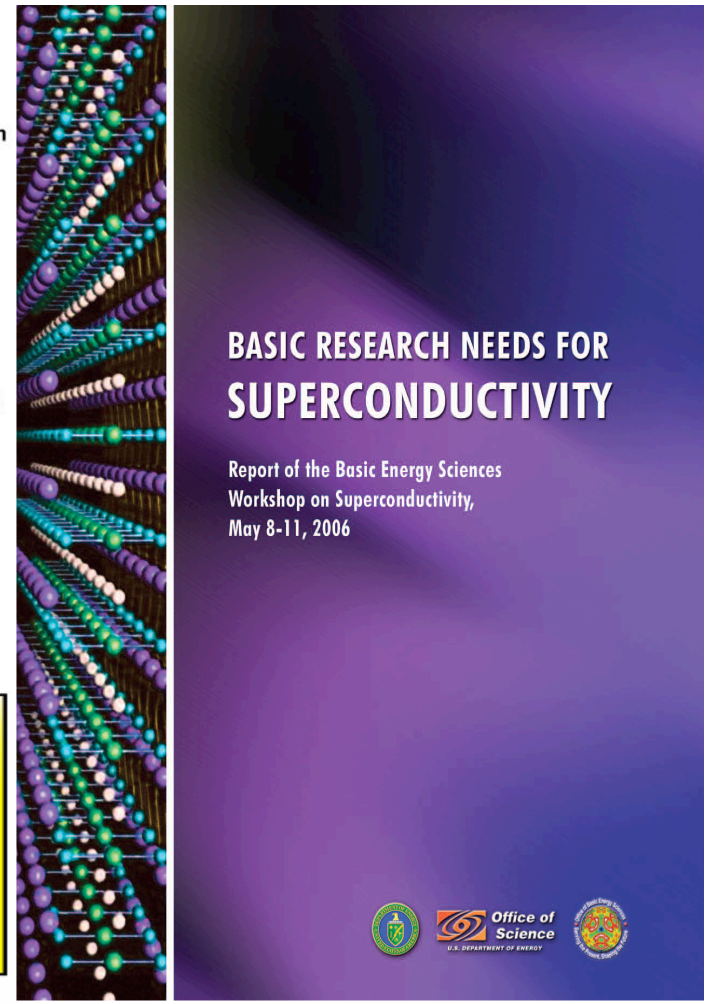


Our **2006** REPORT (with "Tc vs. Time")



Includes HOW to search for the next HTS:

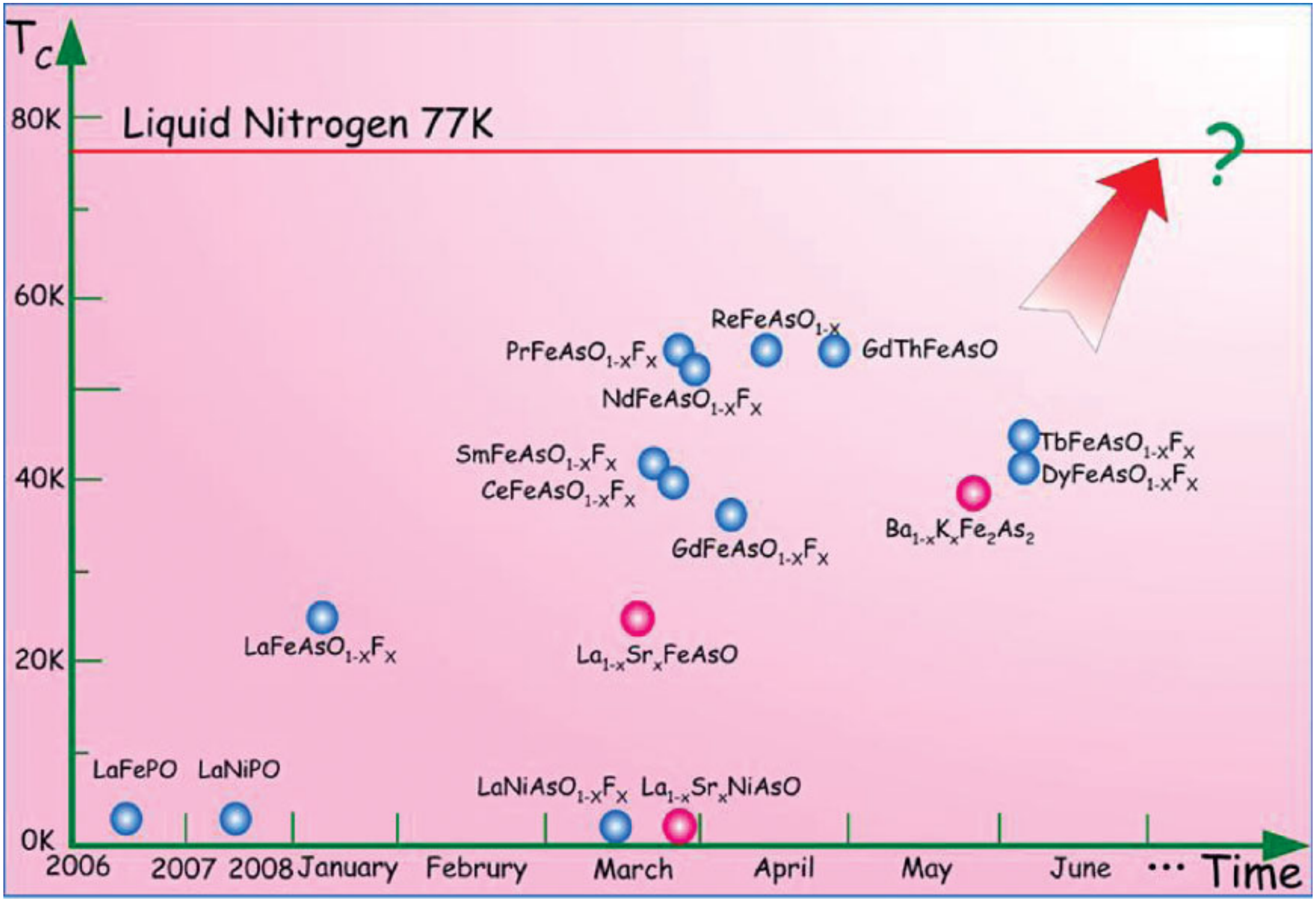




http://www.sc.doe.gov/bes/reports.lists.html

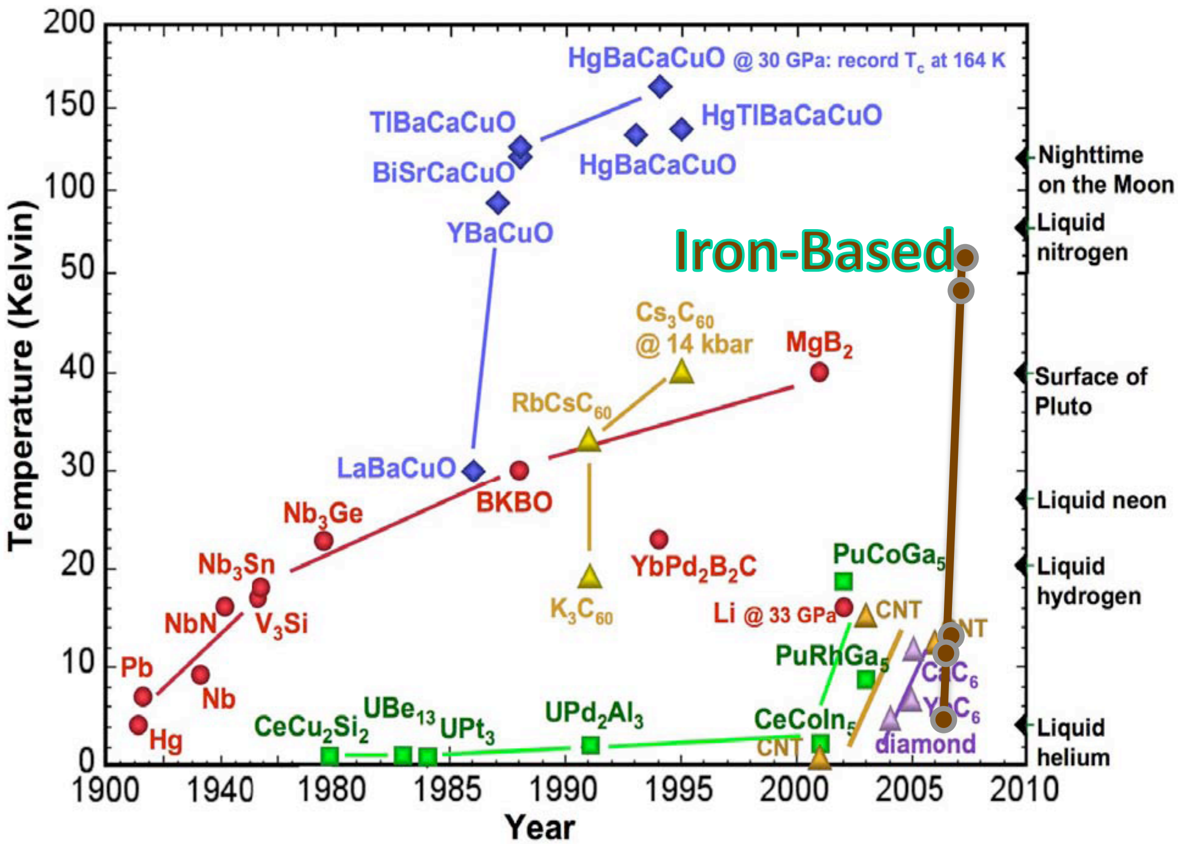
2008 Surprise

Iron-based HTS !!!



Today's "Tc vs. Time" with NEW HTS

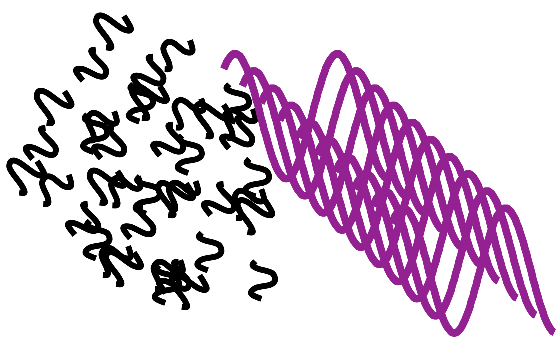
The First HTS are NOT UNIQUE!!!



A SECOND class of HTS found, so there MUST be a THIRD!?

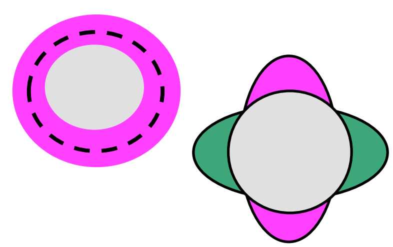
Broken Symmetries - 1 (overview)

High-temperature (and any unconventional) superconductors are playgrounds for broken symmetries



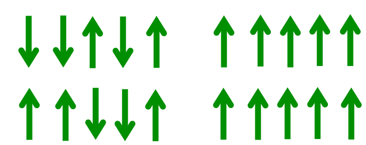
Gauge / Phase

Superconductivity



Reflection

d-wave



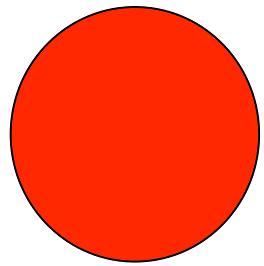
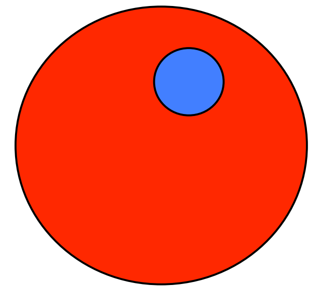
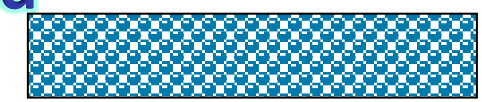
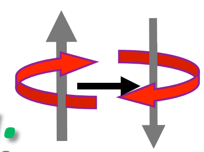
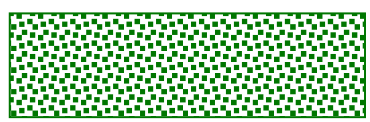
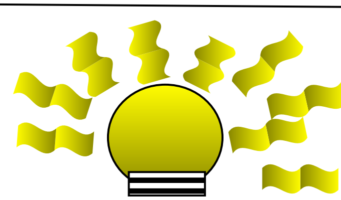
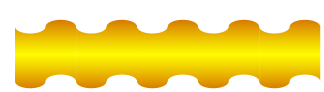
Time Reversal

Ferromagnetism

Broken Symmetries – 2 (definitions)

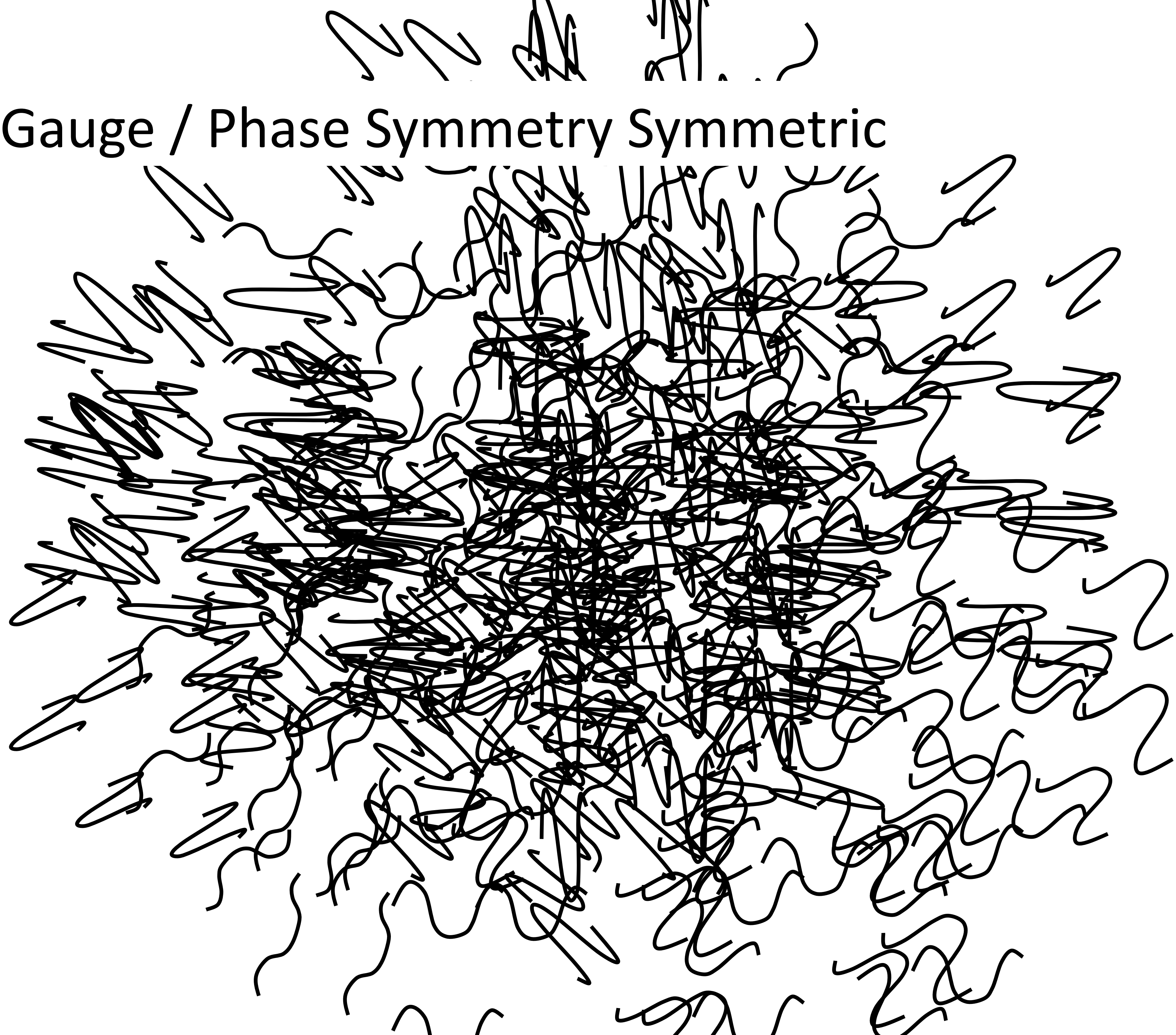
	Symmetry State	***Broken Symmetry State***
1.	***Homogeneous*** *w.r.t. coordinate*	***Inhomogeneous*** *w.r.t. coordinate*
	(distance, angle,	*phase, time, ..)*
2.	*"The symmetry of the state is the* ***same*** *as that of the Hamiltonian"*	*"The symmetry of the state is* ***lower*** *than that of the Hamiltonian".*
3.	*Changing the coordinate* ***does not*** *produce a measurable change*	*Changing a coordinate* ***does*** *produce a measurable change*

Broken Symmetries – 3: Symmetry vs. Broken Symmetry

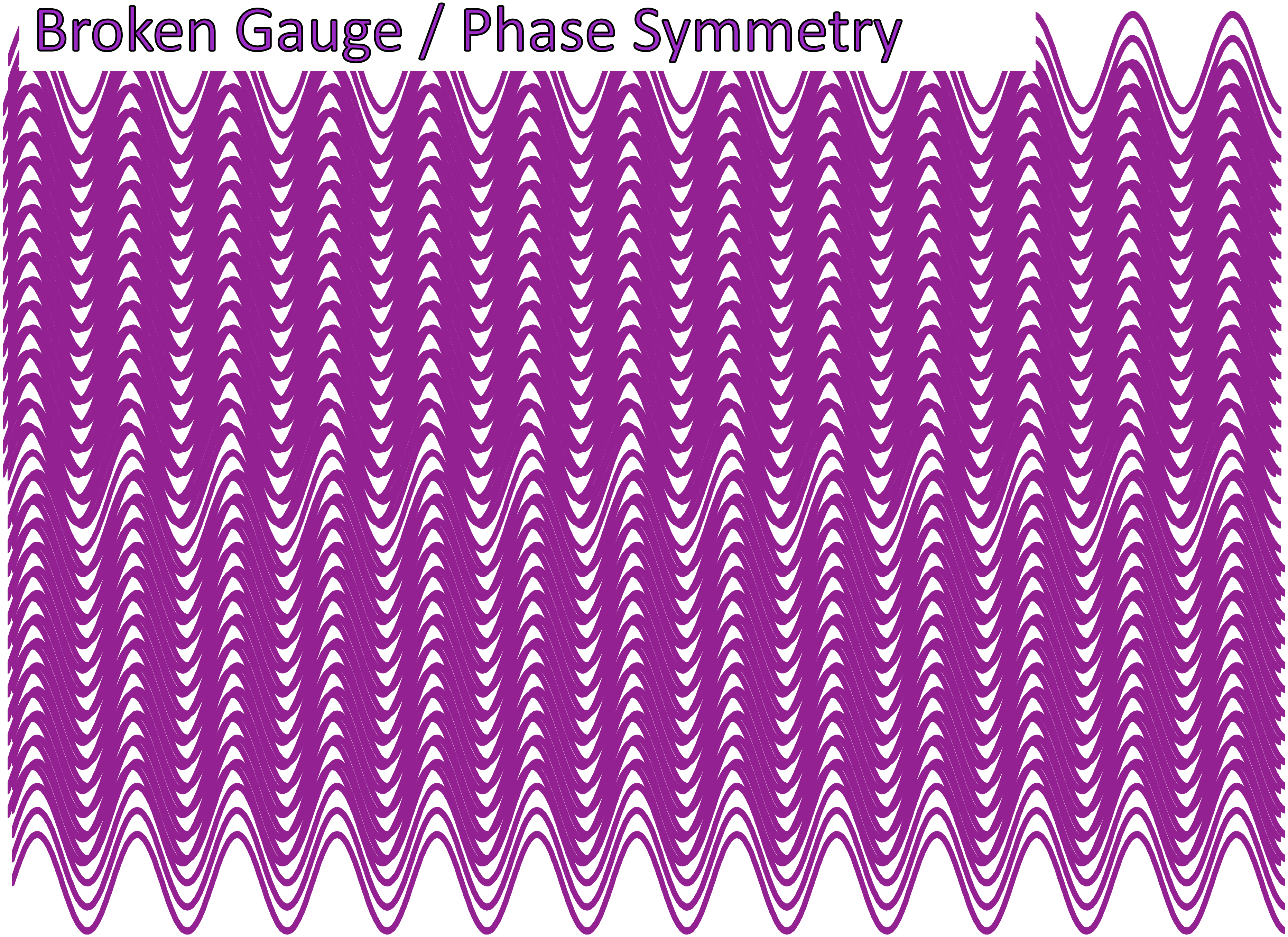
Symmetry:	Symmetry State	**Broken Symmetry**
Circular		
Translational:	**Fluid** 	**Solid** 
Time Reversal: 	Paramagnet 	**Ferromagnet** 
spontaneous ***Phase / Gauge***	Metal 	**Superconductor** 
driven	Light bulb 	**Laser** 

Broken Time-Reversal Symmetry

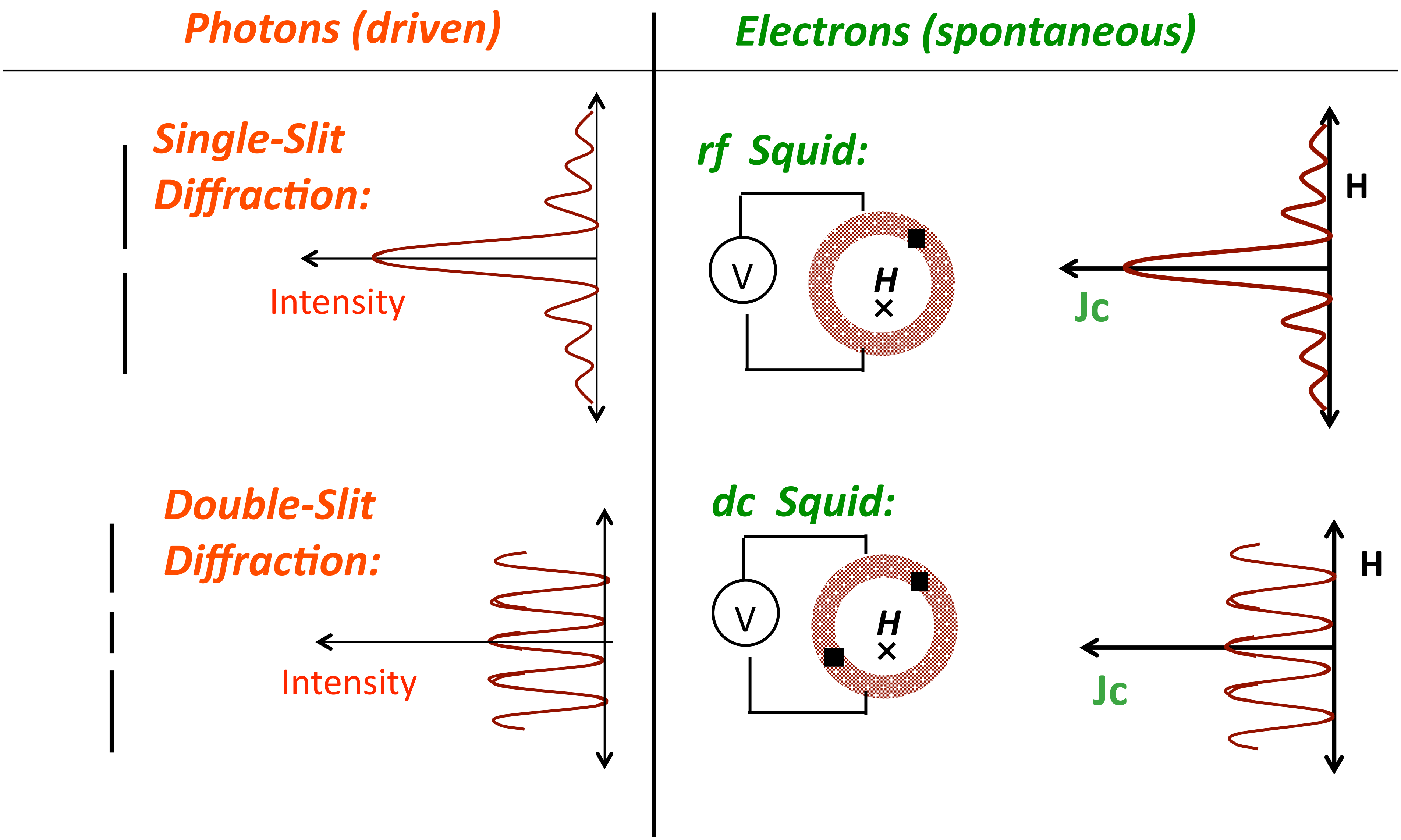
Gauge / Phase Symmetry Symmetric



Broken Gauge / Phase Symmetry

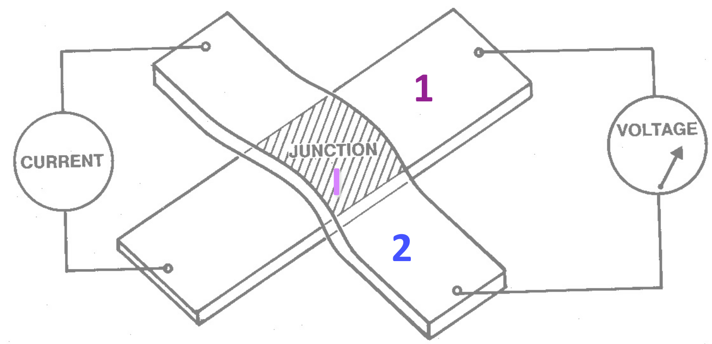


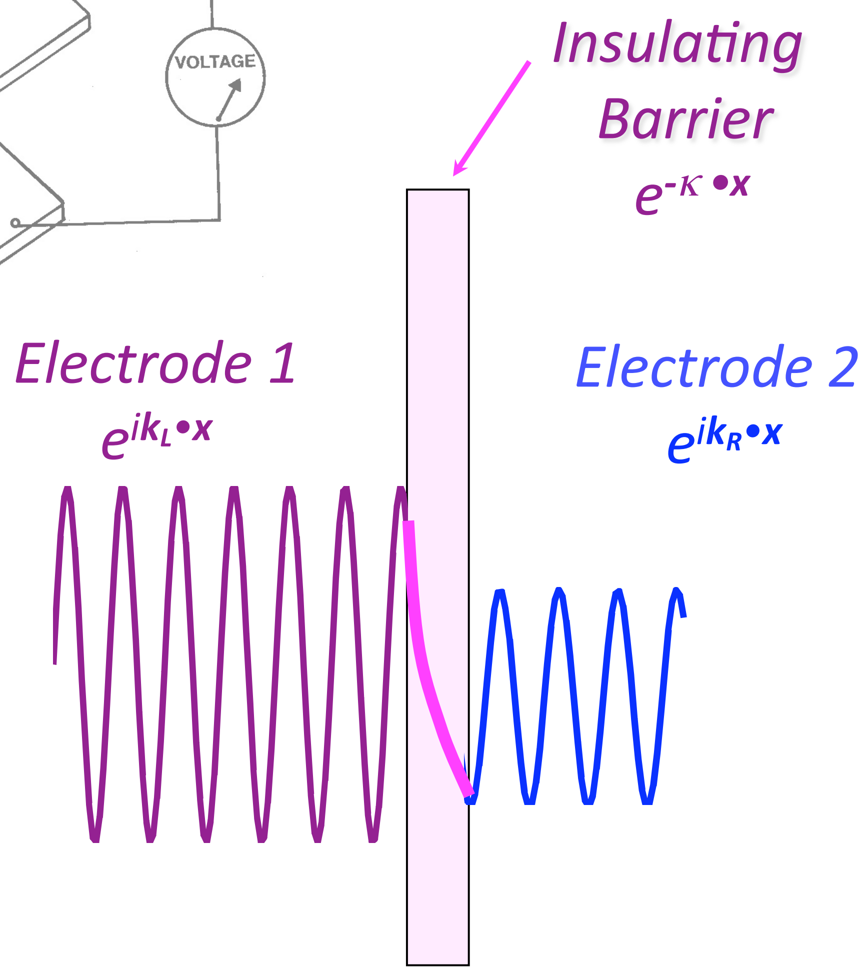
Broken Symmetries – 4 (some ramifications of broken gauge symmetry)



Electron Tunneling Spectroscopy (I)

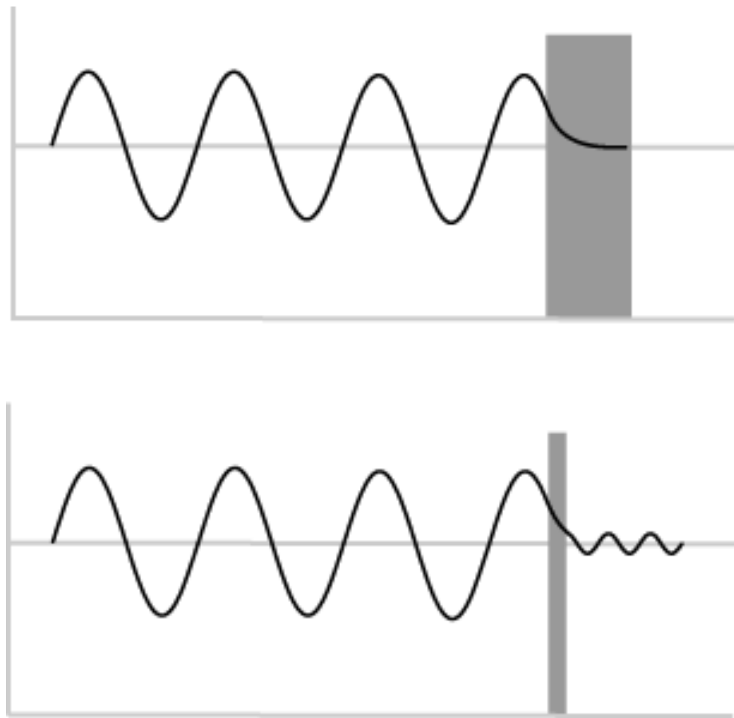
(Planar quasiparticle overview)



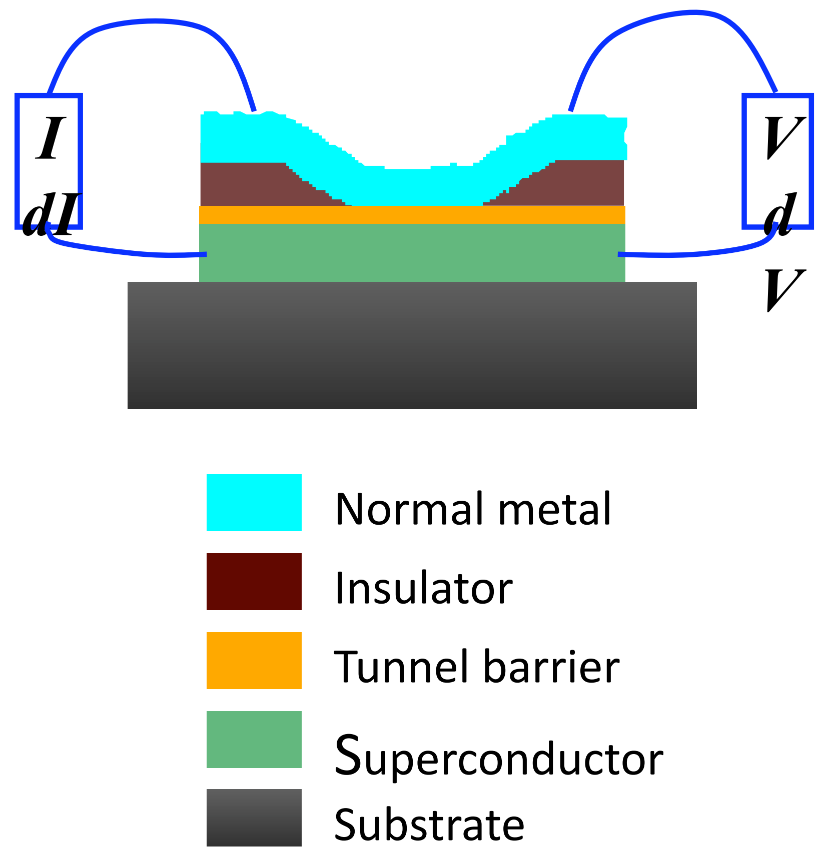


Electron Tunneling Spectroscopy (II)

Quantum Mechanical Tunneling



Planar Tunnel Junction



$Al/AlO_x/Pb$, Giaever (PRL **5** 147,1960)

Electron Tunneling Spectroscopy (III)

Tunnel Current: $I(V) = A|T|^2 eN_n(0)\int_{-\infty}^{\infty} N_s(E)\left[f(E-eV) - f(E)\right]dE$

Tunnel Conductance: $G(V) \equiv \frac{dI}{dV} = A|T|^2 e^2 N_n(0)\int_{-\infty}^{\infty} N_s(E)\frac{\partial f(E-eV)}{\partial(eV)}dE$

Tunneling matrix element: $|T|^2 \propto e^{-2\kappa d}$, $\kappa = \left[\left(2m/\hbar^2\right)\left(U-\varepsilon_z\right)\right]^{1/2}$

$f(E) = \frac{1}{\exp(E/k_B T)+1}$, Fermi function

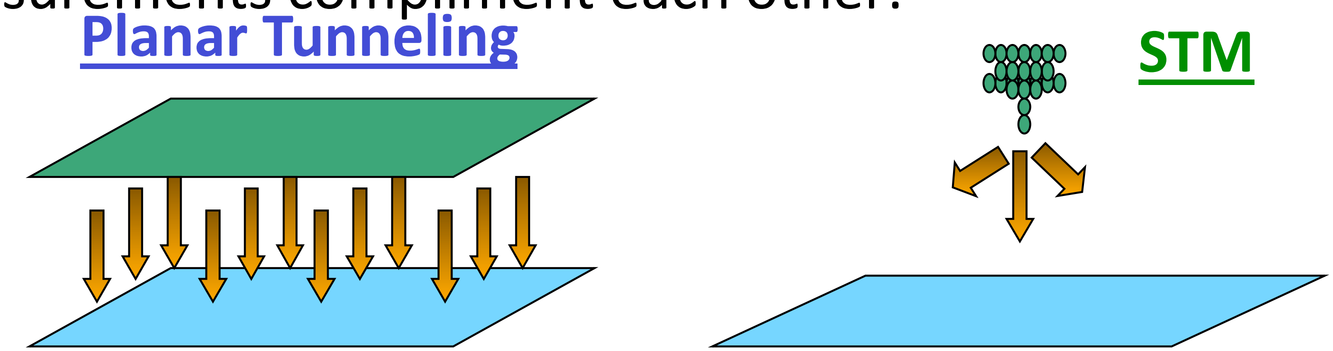
$For\ T = 0,\ \frac{\partial f(E-eV)}{\partial(eV)} = \delta(E-eV) \Rightarrow G(V) \propto N_s(eV).$

$For\ T > 0$, $G(V)$ is given as a convolution of SC DOS w.r.t. derivative of Fermi function.

Electron Tunneling Spectroscopy (IV)

(Planar vs. STM)

Measurements compliment each other:



Advantages:

I. Small tunneling cone:
Intrinsic momentum resolution for smooth surfaces

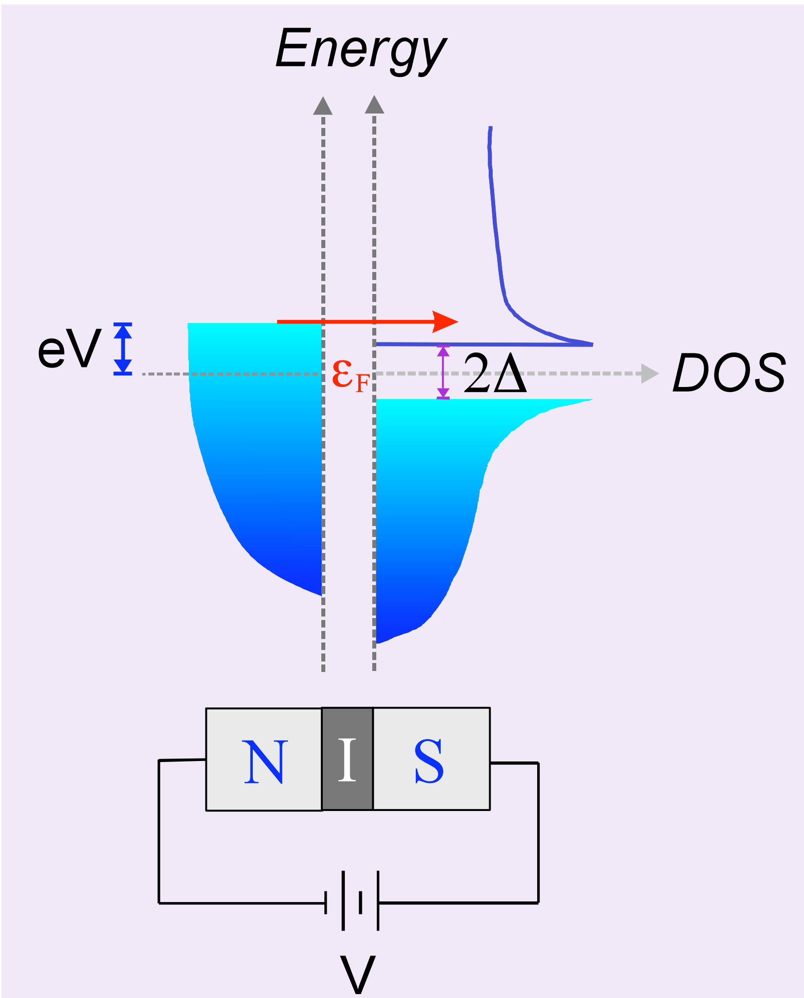
II. Stable configuration:
can easily study as a function of field, temperature, area and, most important, reproducibility.

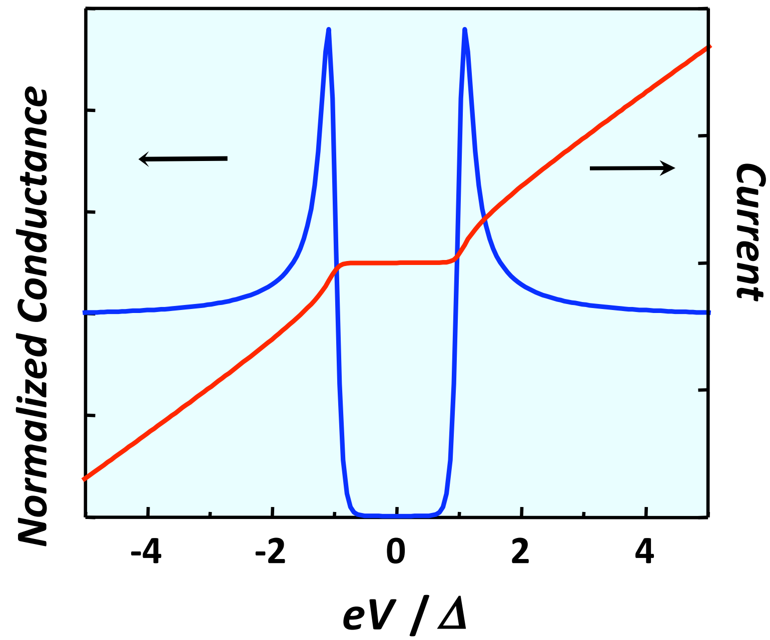
Drawbacks:

I. Damage to surface during junction fabrication

II. Low spatial resolution

Electron Tunneling Spectroscopy (V)

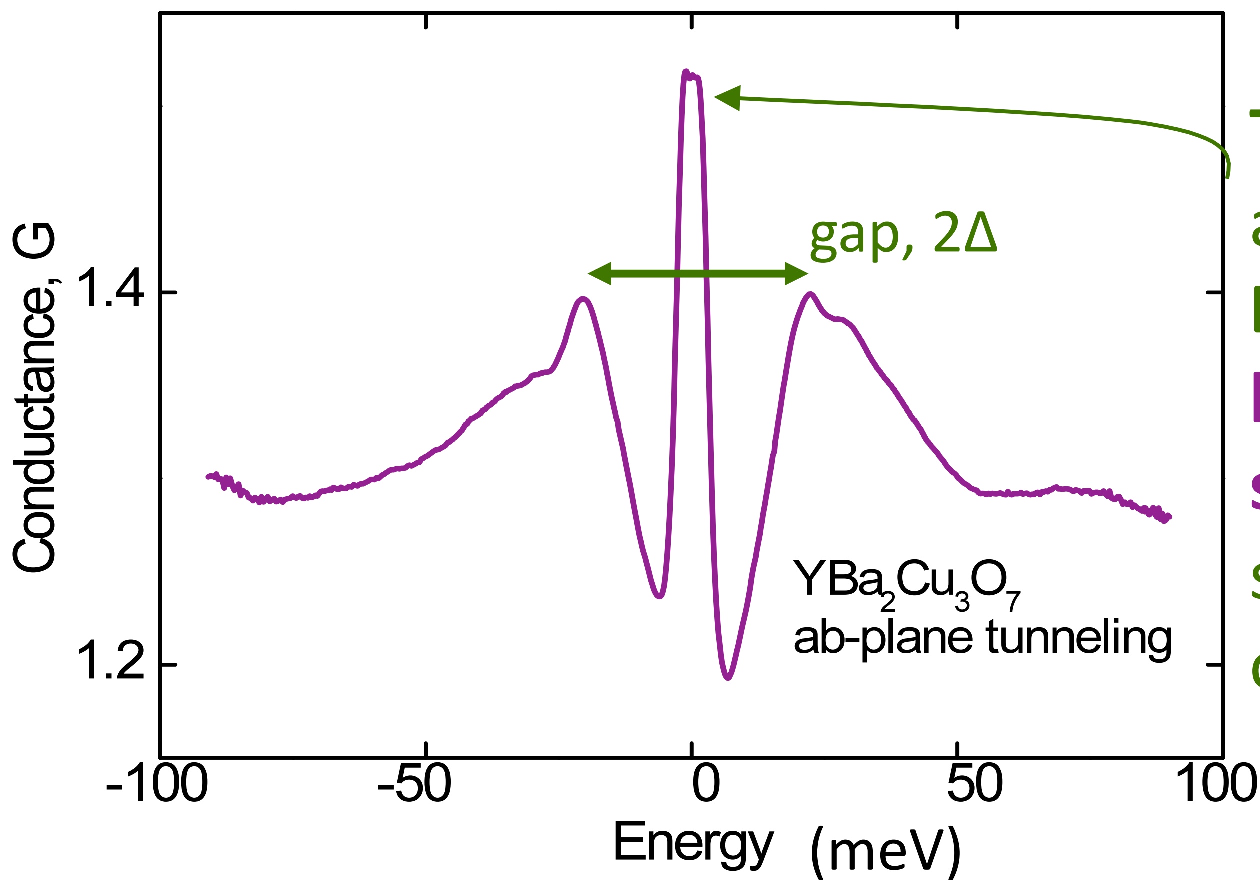




- Bias dependence of tunneling conductance directly probes DOS.
- Tunneling is a well-established technique to study SC energy gap.

Electron Tunneling Spectroscopy (VI)

Measured Tunneling Conductance of a High-Temperature Superconductor



The central peak arises from **Andreev Bound States**, from **broken reflection symmetry** of the superconducting order parameter

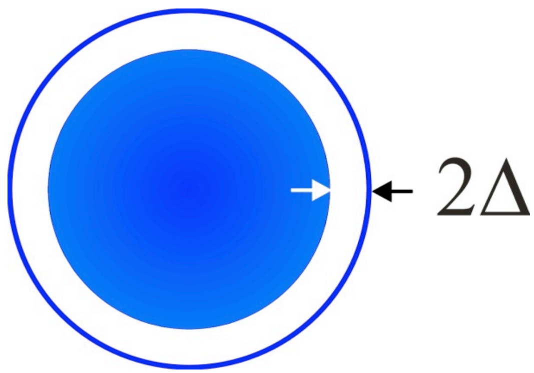
Review: d-wave SC and Andreev reflection …

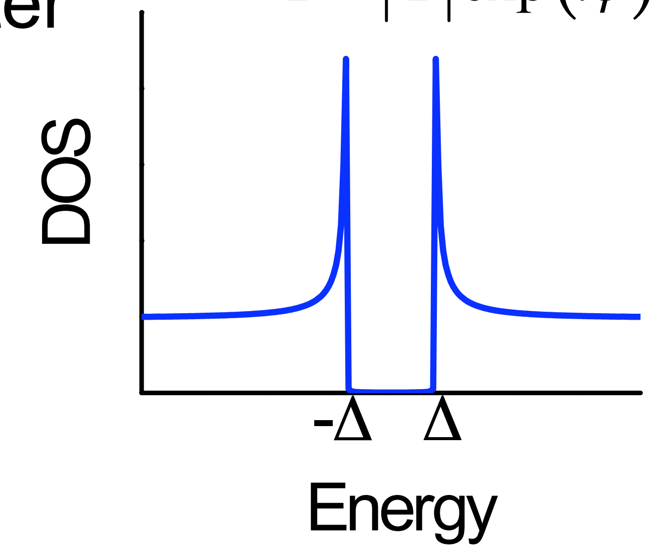
Electron Tunneling Spectroscopy (VII)

Superconducting Order Parameter

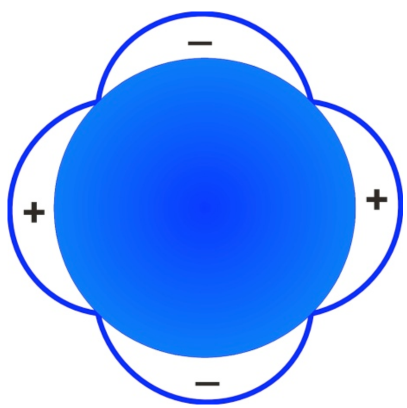
$$\Psi = |\Psi| \exp(i\phi)$$

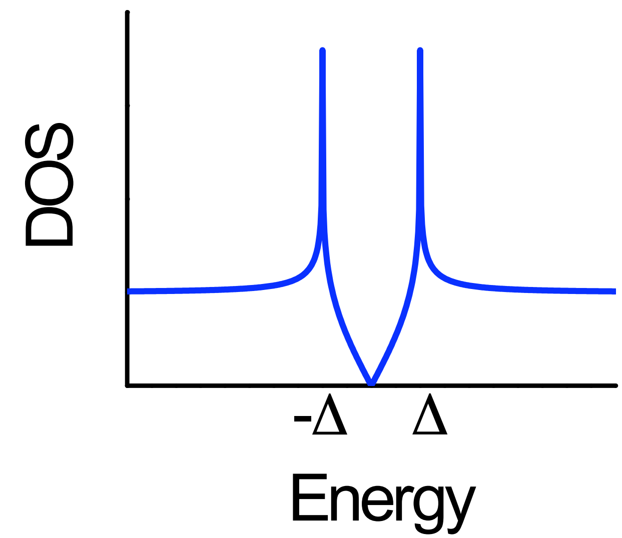
s-wave





d-wave

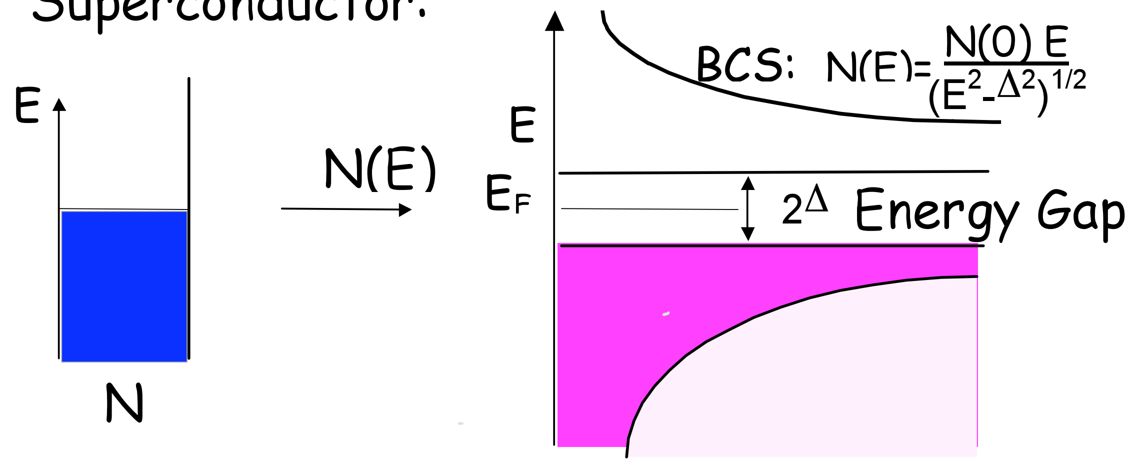




Electron Tunneling Spectroscopy (VIII)

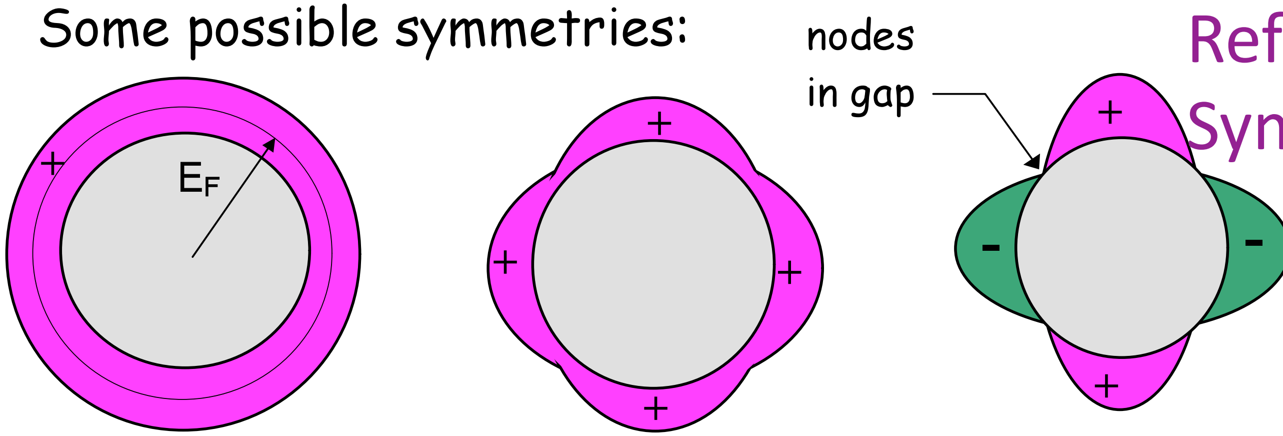
(Gap / OP symmetry)

Superconductor:



Broken Reflection Symmetry

Some possible symmetries:



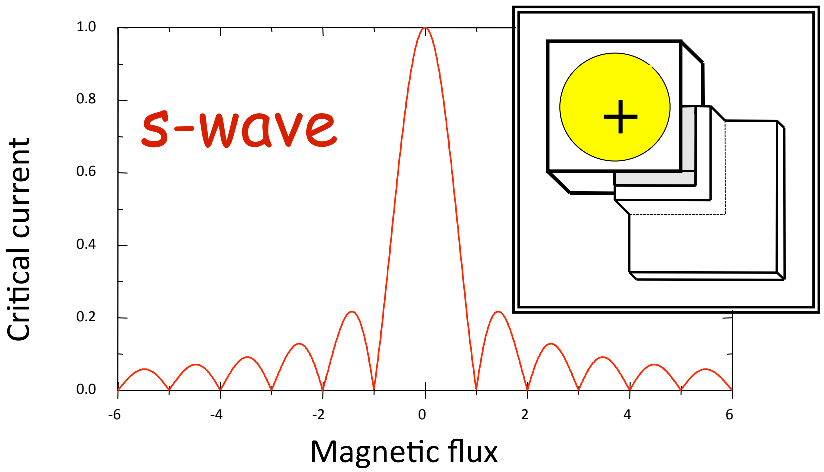
s-wave   anisotropic s-wave   d-wave

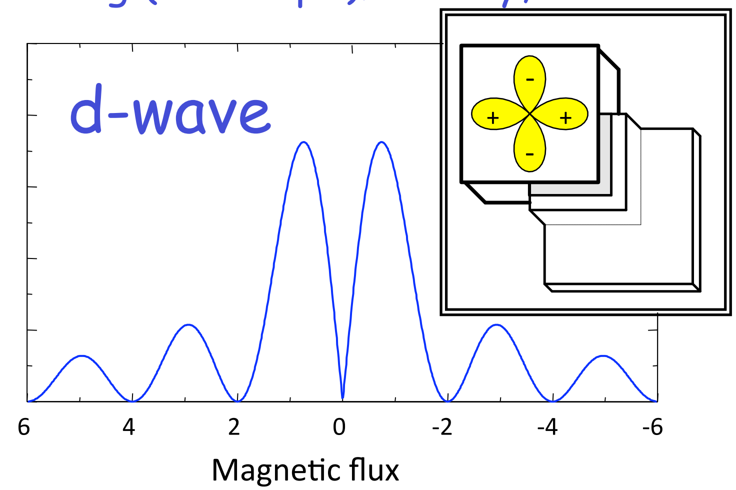
"Conventional"   "Unconventional"

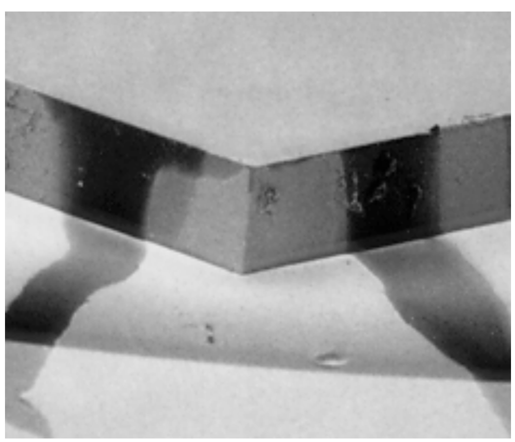
D-wave was already shown:

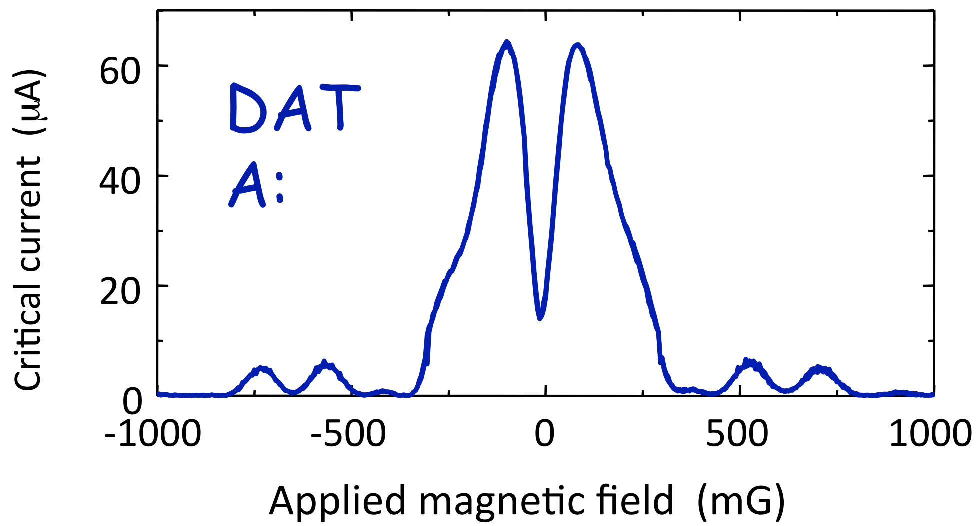
Josephson Junction (Wollman et al.)

1997 Buckley Prize: Van Harlingen, Ginsberg (this exp't); Kirtley, Tsui



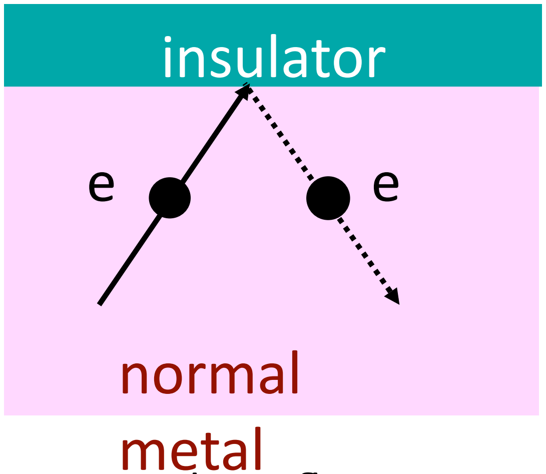






Andreev Reflection (I)

What will happen to an electron with E < Δ and no tunnel barrier?



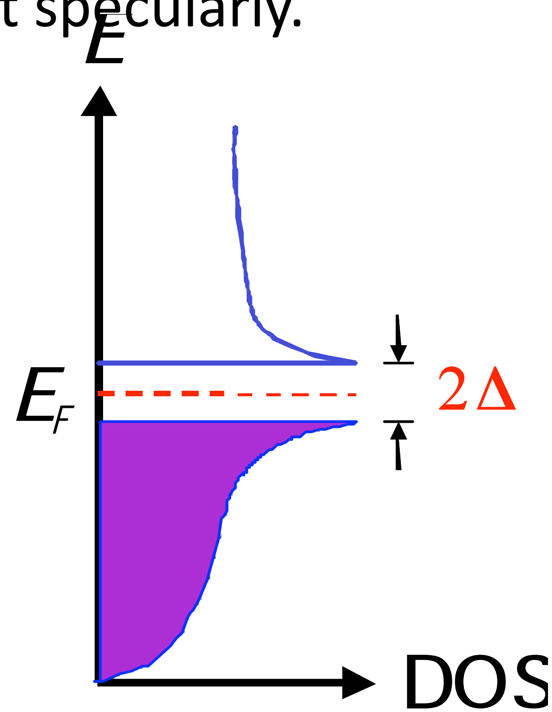
specular reflection

cf. At an interface with huge potential barrier that is translationally invariant along the transverse direction, incoming electrons reflect specularly.

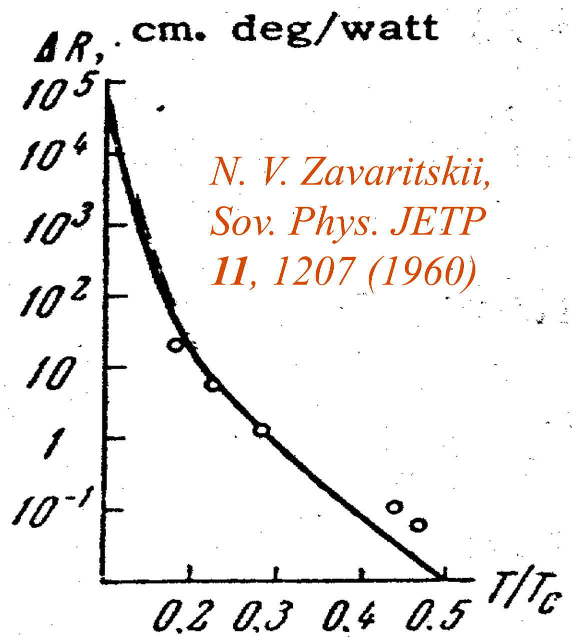
- Within the gap, no quasiparticle states available, no single particles can enter S.

- Will a normal-metal/ superconductor (N/S) system be less conductive that a single N?

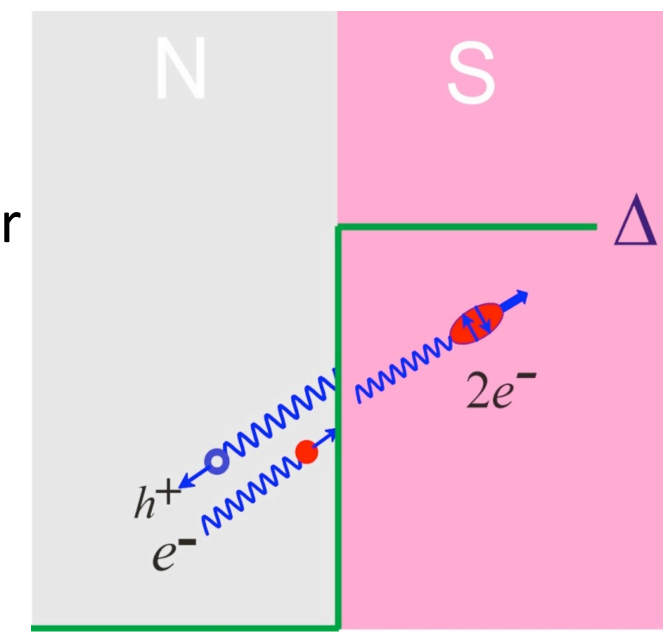
- No!



Andreev Reflection (II)



- While trying to explain the rapid increase of thermal resistance of Sn in the intermediate state, Andreev discovered that an additional scattering must be involved. *A. F. Andreev, Sov. Phys. JETP **19**, 1228 (1964)*



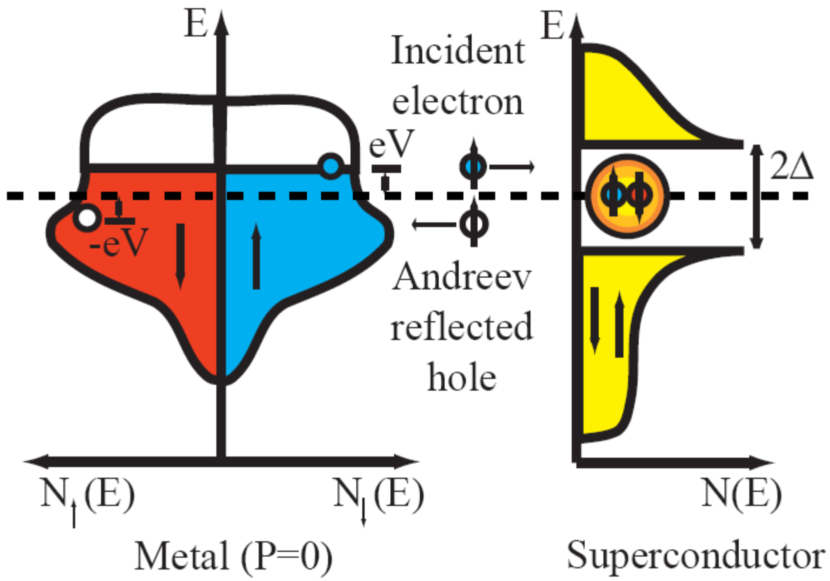
- QM scattering off SC pair potential near N/S

- Particle-hole conversion process

  multi-particle (AR) vs. single particle (tunneling)

- Retro-reflection $\mathbf{v}_h = -\mathbf{v}_e$

Andreev Reflection (III)

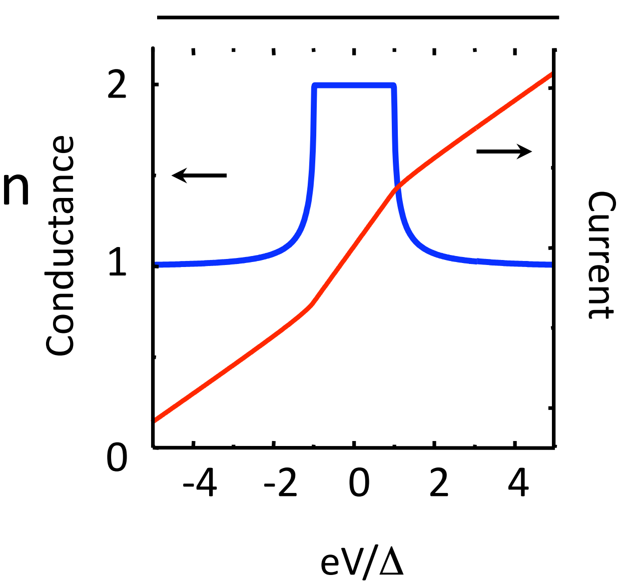


- Conserved quantities
  - Energy (E)
  - Momentum (***hk***) ($\Delta << E_F$)
  - Spin (***S***)
  - Charge inc. Cooper pairs

- Sub-gap conductance is doubled.

- Andreev reflected hole carries information on the phase of electron state and macroscopic phase of SC. phase change = Φ + arccos (ε/Δ)

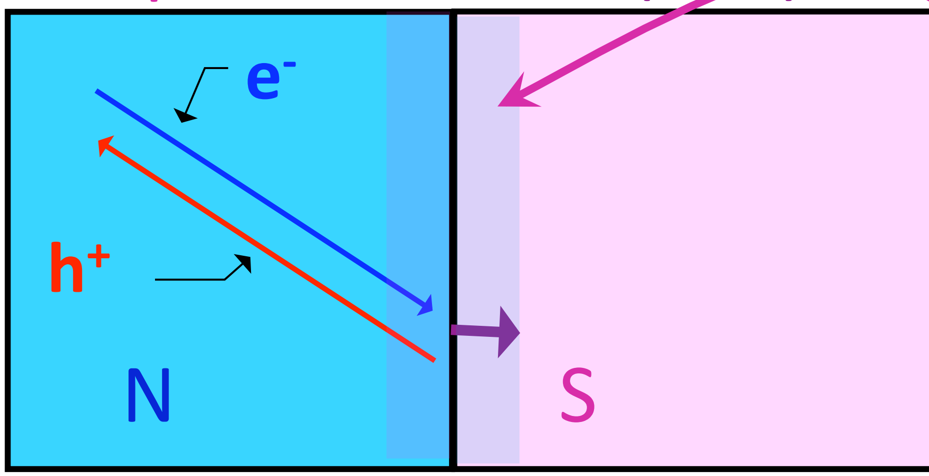
- Inverse process (S $\Rightarrow$ N): AR of a hole or
  - emission of a Cooper pair ("Andreev pairs"): **proximity effect**



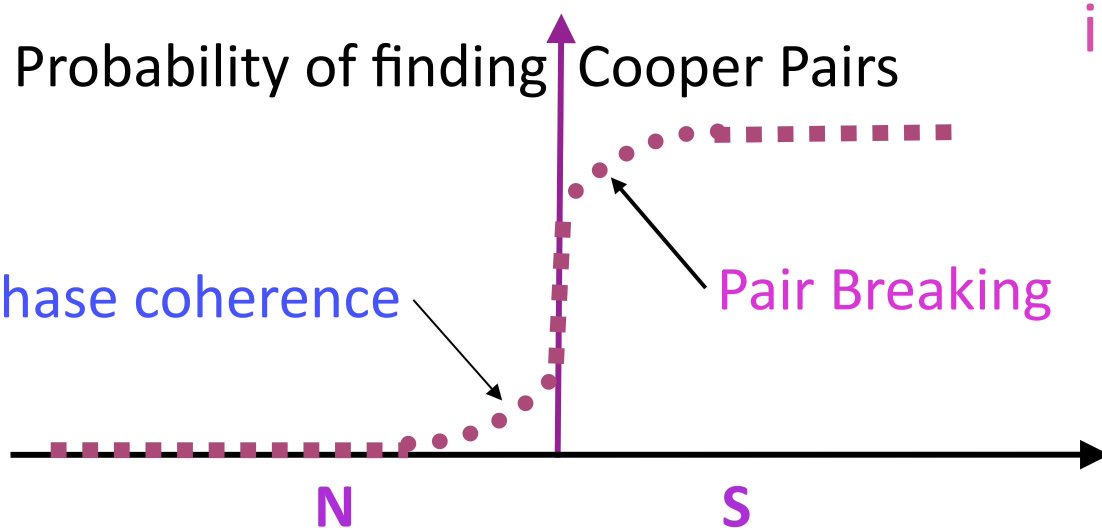
Andreev Reflection (IV)
(definition)

Normal Metal/Superconductor (N/S) interface

In N: Electrons retro-reflected as holes

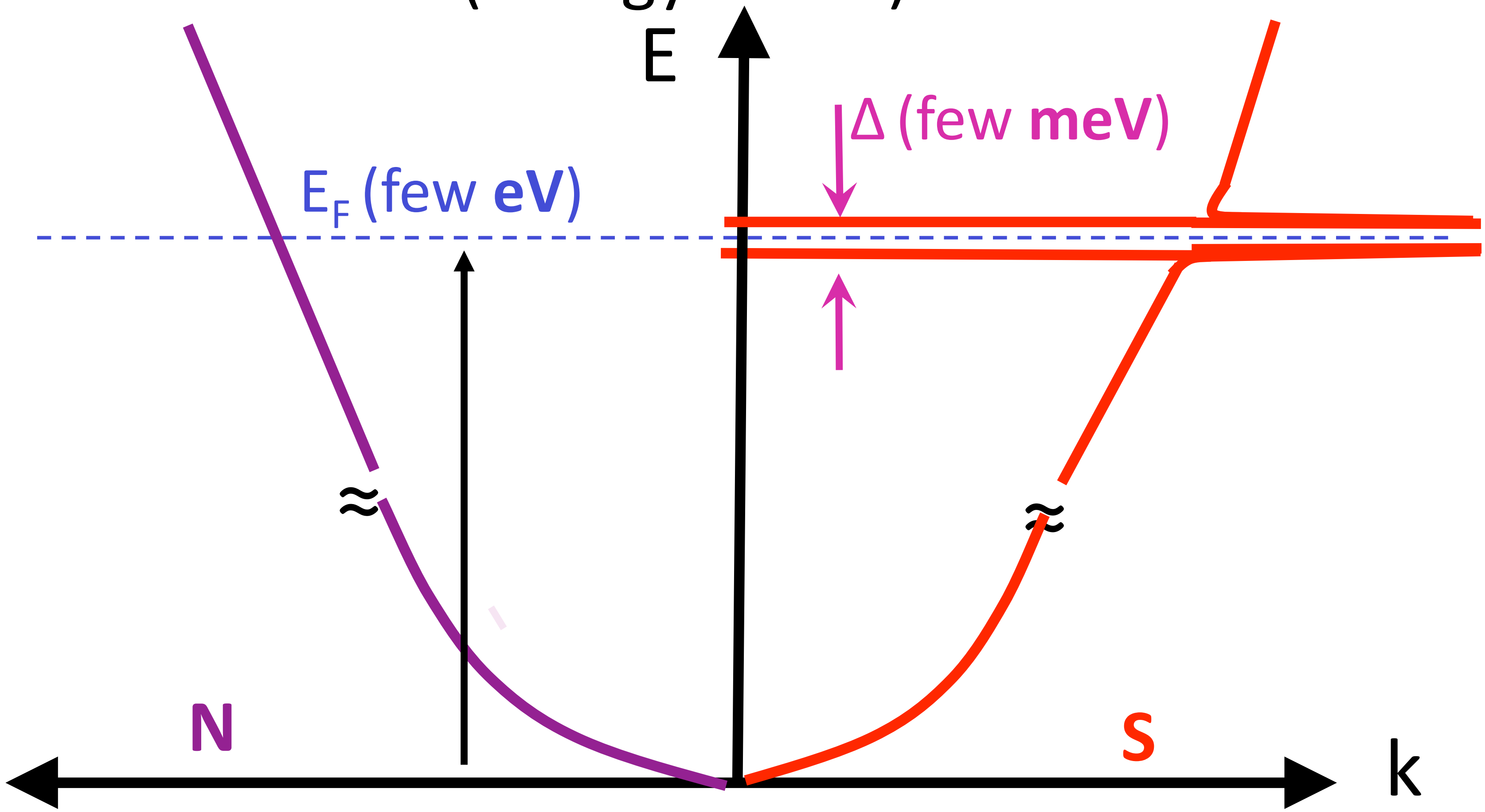


In S: Cooper Pairs Broken near interface



Andreev Reflection (V)

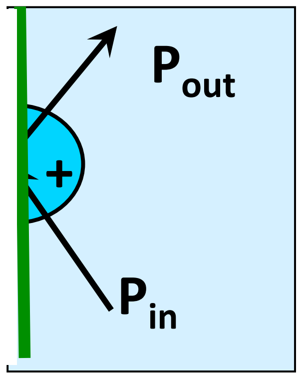
(energy scales)

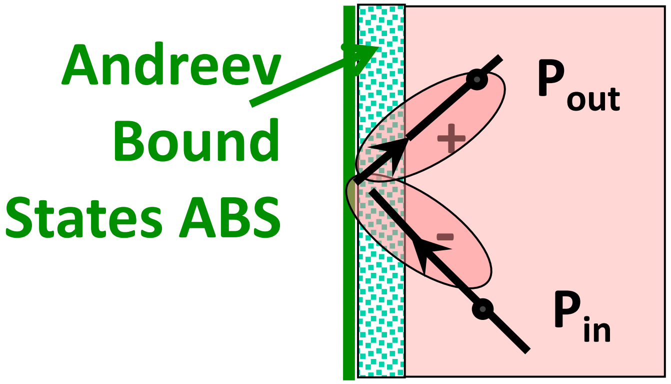


Particle conversion process that conserves charge, energy and momentum!

Andreev Reflection (VI)

(**within** a superconductor)





s-wave:

No Andreev Reflection

(order parameter isotropic)

⇒ **Cooper Pairs not Broken**

d-wave:

Strong Andreev Reflection

(order parameter sign change)

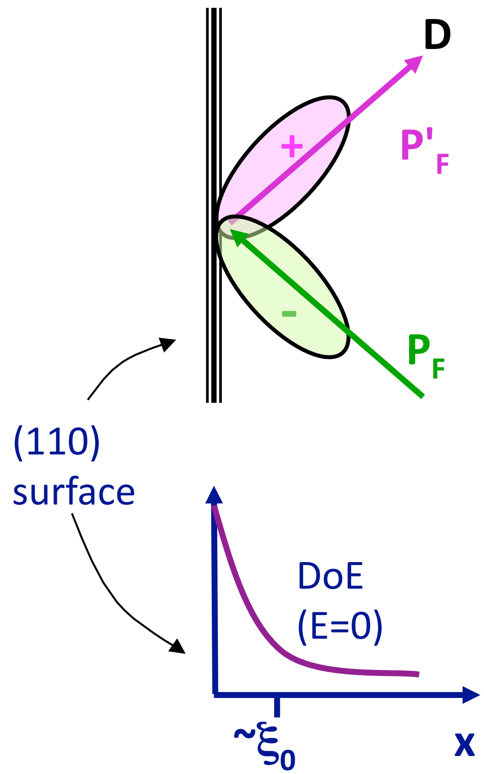
⇒ **Cooper Pairs Broken**

Quasiparticles nucleate at surface forming

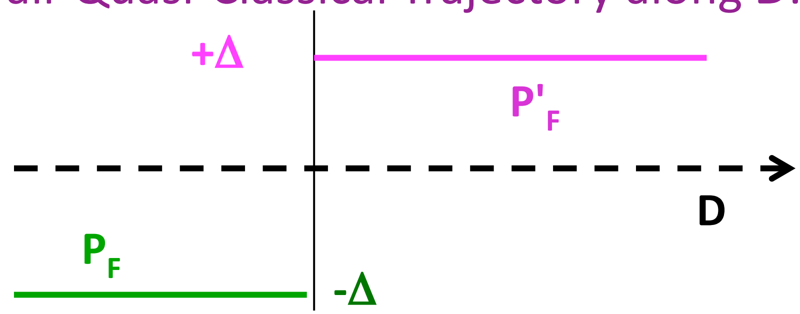
Andreev Bound States

(Bound w/in ~coherence length of surface)

Andreev Reflection (VII)
(Andreev bound states, ABS)

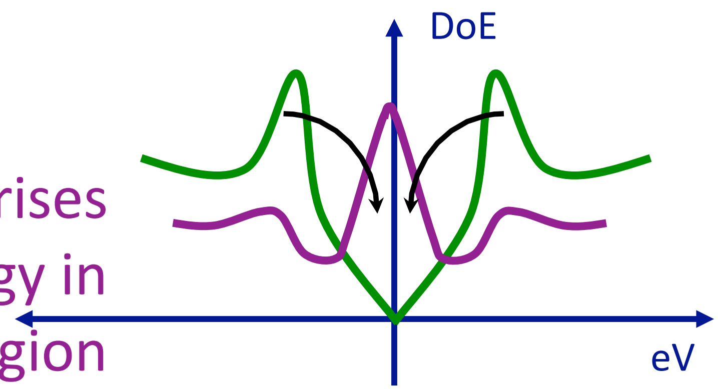


Cooper Pair Quasi-Classical Trajectory along **D**:



Sign-change of OP is only Boundary Condition in the Solution to Andreev Equations: Quasiparticle Bound States at surface (decay ~ξ_0)

Peak at zero bias (Fermi energy) arises from quasiparticles at Fermi energy in near-surface region



Electron Tunneling Spectroscopy (IX)

(Diagnostics of ZBCP - a)

Several phenomena will produce a ZBCP
(zero-bias conductance peak) in tunneling

1. Magnetic scattering (spin-flip, Kondo)
2. Proximity effects
3. Josephson current
4. Shorts / pinholes through tunnel barrier
5. Cooper-pair tunneling
6. Reflectionless tunneling
7. Inelastic processes
8. ABS (Andreev bound states)

.....etc., etc.,.....

DIAGNOSTICS are REQUIRED to determine
if the zero bias conductance peak arises from ABS
(intrinsic to any unconventional superconductor)

Electron Tunneling Spectroscopy (X)

(Diagnostics of ZBCP - b)

1. **Crystallographic orientation**

- Only seen in ab-plane tunneling (not in c-axis)
- Not seen in specular (100) a-axis tunneling
- Magnitude depends upon ab-plane crystallographic orientation

2. **Temperature**

- Split in ZBCP below T_s
- Zero-bias conductance ~1/T below 40K, above T_s

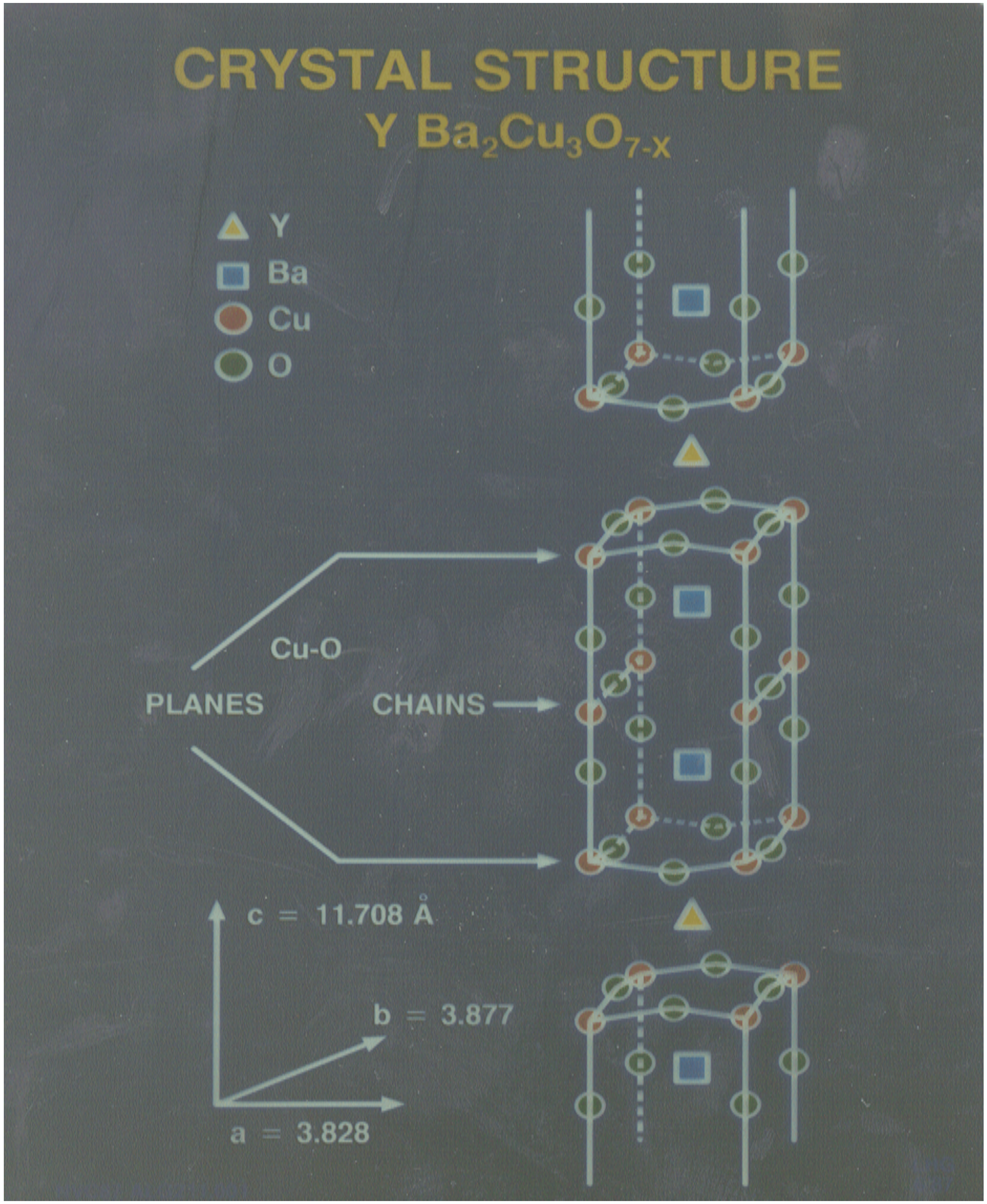
3. **Magnetic Field**

- Field Evolution
- Saturation effects
- Field Scale
- Angular or orientational dependence of the applied field
- Hysteresis

4. **Doping and disorder**

- ZBCP reduces in size and disappears with increased doping and ion-induced damage.
- This is shown to be a DoS effect (follows gap disorder dependence)

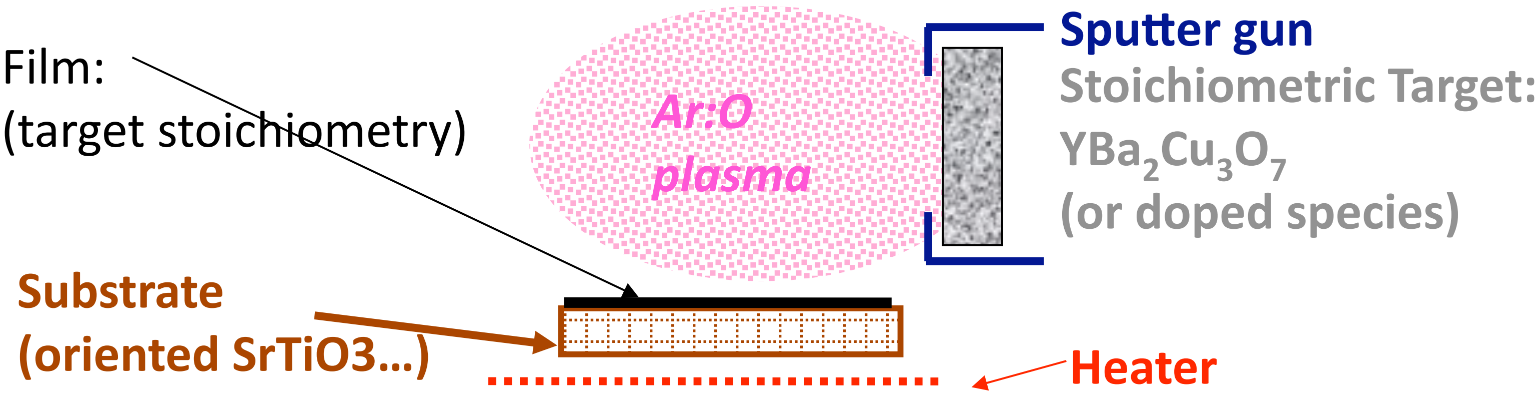
∴ Observed Zero Bias Conductance Peaks arise from ABS


CRYSTAL STRUCTURE
Y $Ba_2Cu_3O_{7-X}$
Y
Ba
Cu
O
Cu-O
PLANES
CHAINS
c = 11.708 Å
b = 3.877
a = 3.828

Electron Tunneling Spectroscopy (XI)

(Film growth and diagnostics)

Off-Axis Planar Magnetron Sputter Deposition:



Reproducible films of (001), (100) and (103) and (110)-oriented $YBa_2Cu_3O_7$, $(Y_xPr_{1-x})Ba_2Cu_3O_7$, $YBa_2(Cu_xNi_{1-x})_3O_7$, $YBa_2(Cu_xZn_{1-x})_3O_7$

Materials Analysis includes:

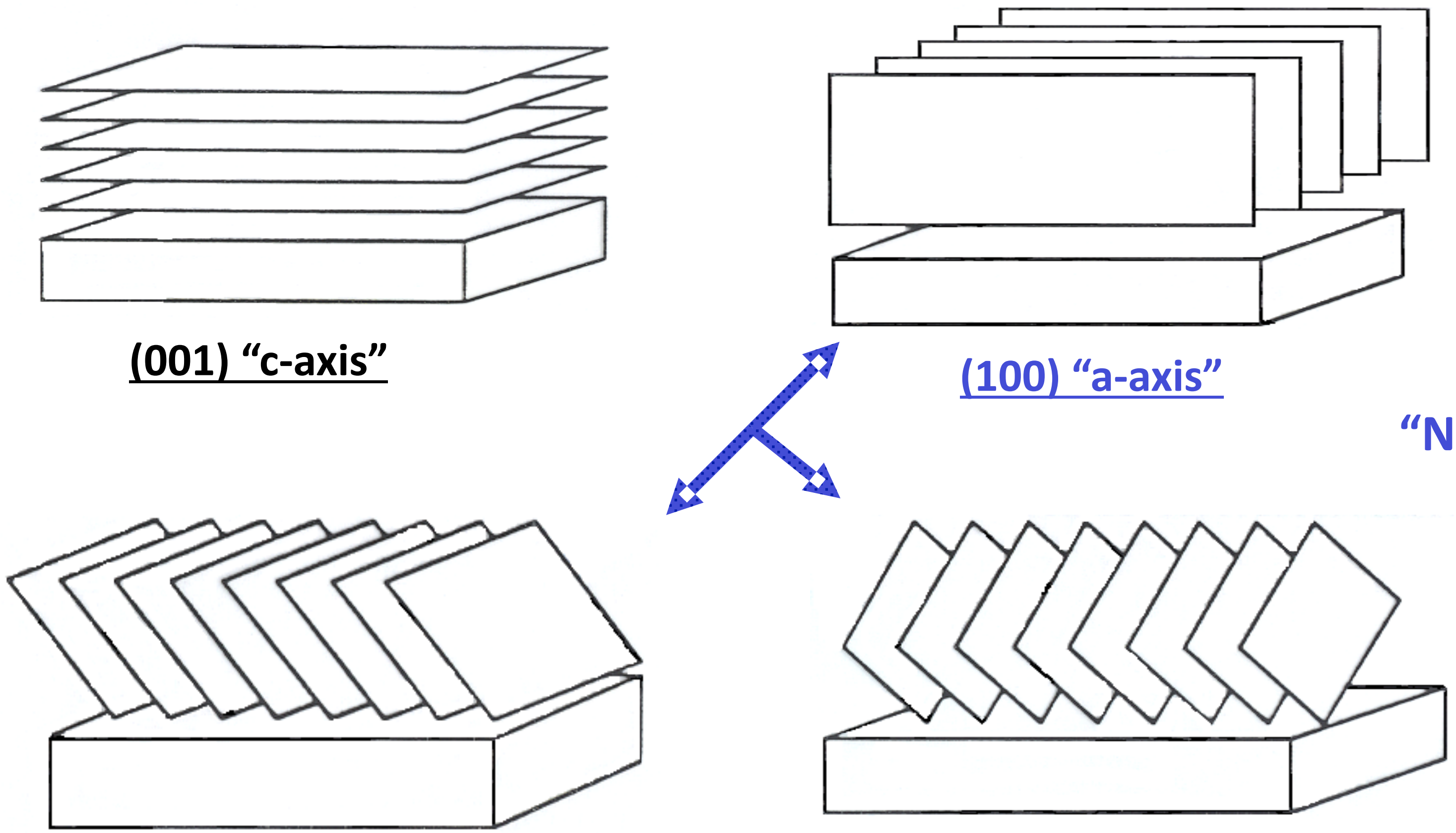
Electronic transport (resistivity vs. temperature, tunneling)

Magnetization (susceptibility vs. temperature)

Structural analysis (XRD, RBS, SEM, AFM, etc.,…)·

Electron Tunneling Spectroscopy (XII)

Possible Orientations of CuO_2 Planes



(001) "c-axis"

(100) "a-axis"

"Non-C-axis"

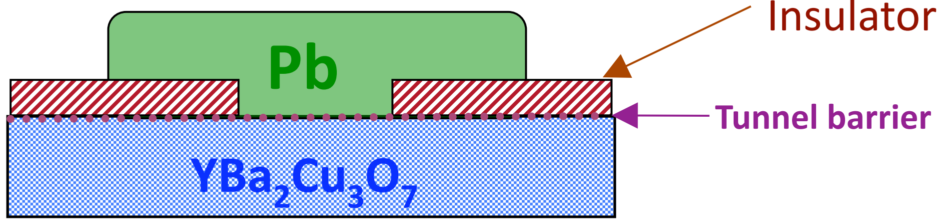
(103) or (013)

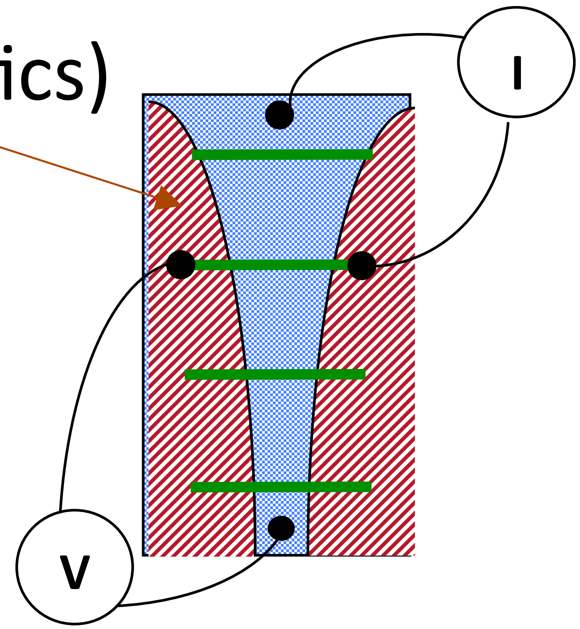
(110) "a-b axis"

YBCO thin films, or cut crystal faces

Electron Tunneling Spectroscopy (XIII)

(junction growth and diagnostics)





· Pb counter-electrodes evaporated *ex-situ*.

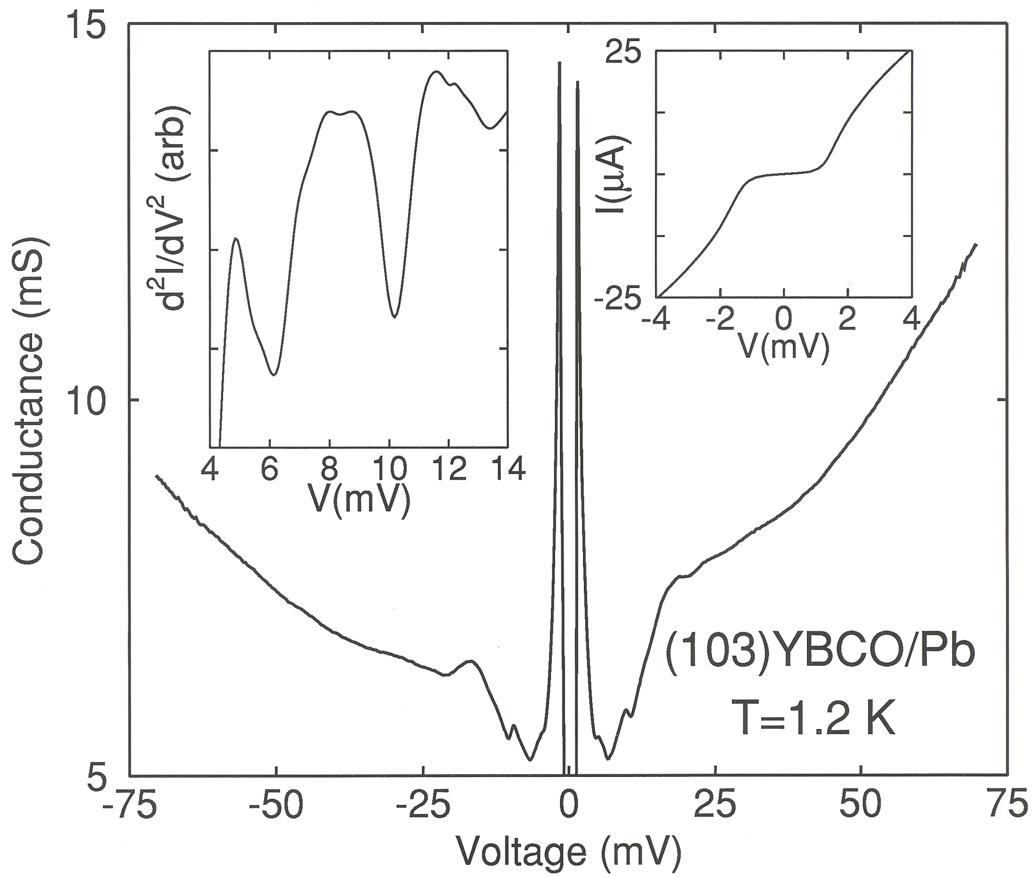
TUNNELING VERIFIED by:

1. Quality of the observed Density of States (DoS) of the superconducting Pb counter electrode, OR the now well-known YBCO DoS
2. Junction resistance: scales with $1/A_{junction}$
3. Little to no temperature dependence
4. **<u>REPRODUCIBLITY</u>**

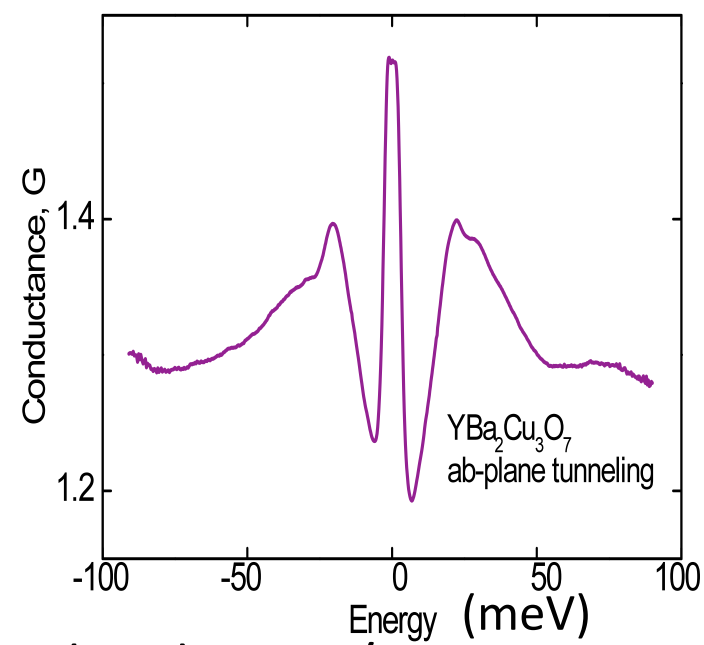
Electron Tunneling Spectroscopy (XIV)

(Junction diagnostics: DoS)

Many ways to grow REPODUCIBLE junctions for planar tunneling spectroscopy



+V ➔ filling YBCO states

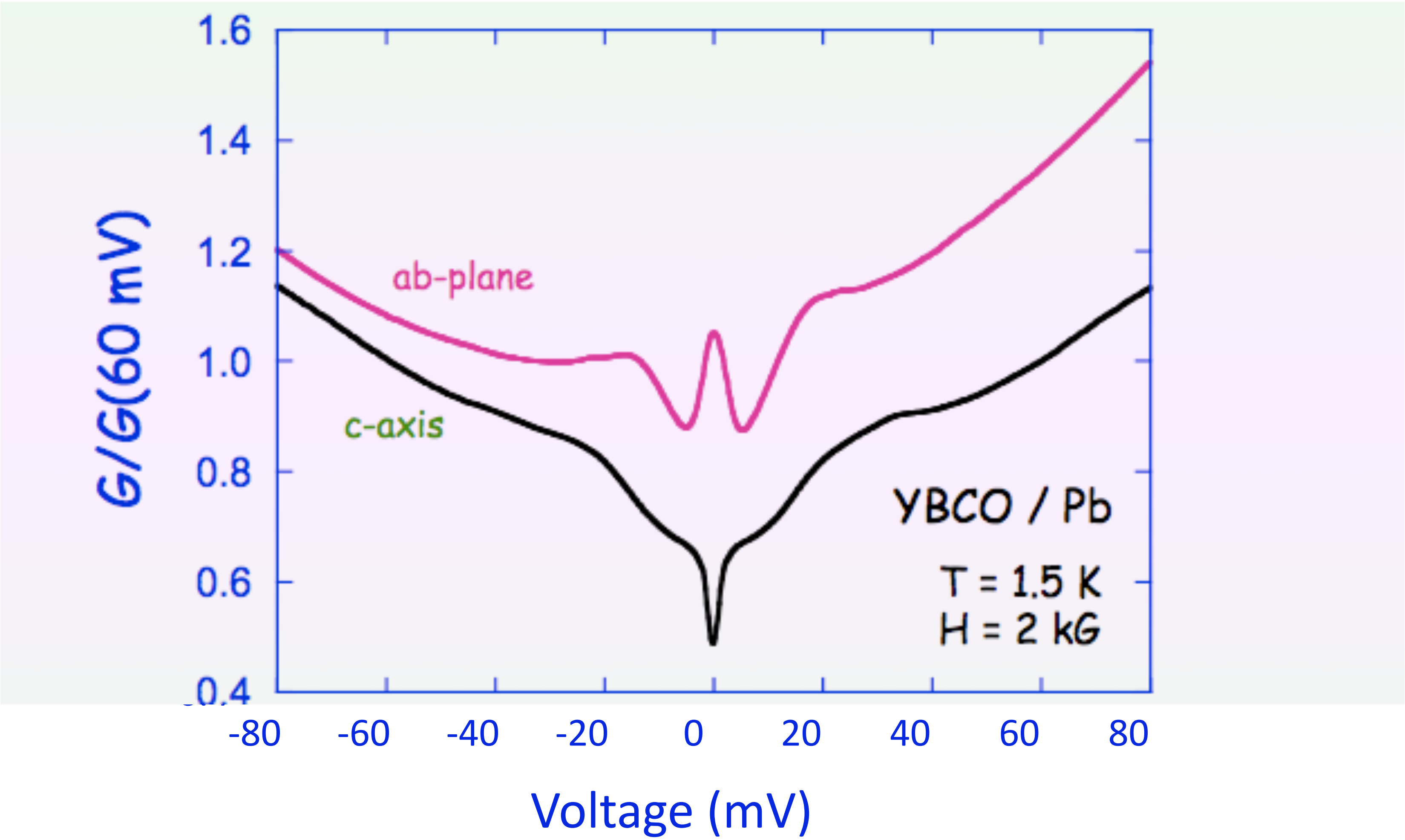


(meV)

(110) YBCO/Ag T=1.2K

Electron Tunneling Spectroscopy (XV)

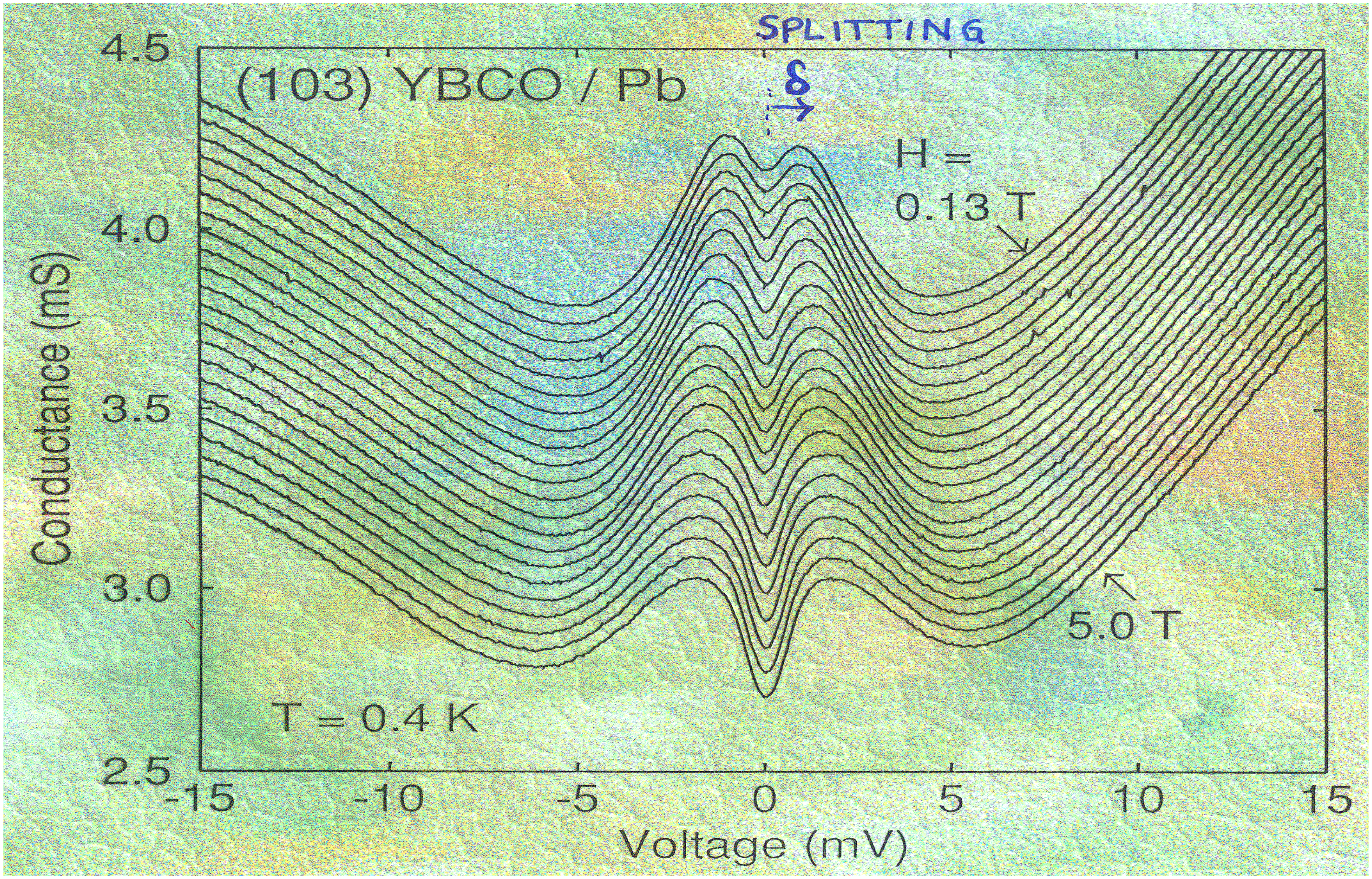
(Junction diagnostics: Crystallographic Orientation



M. Covington & LHG, PRB **62**, 12440 (2000)

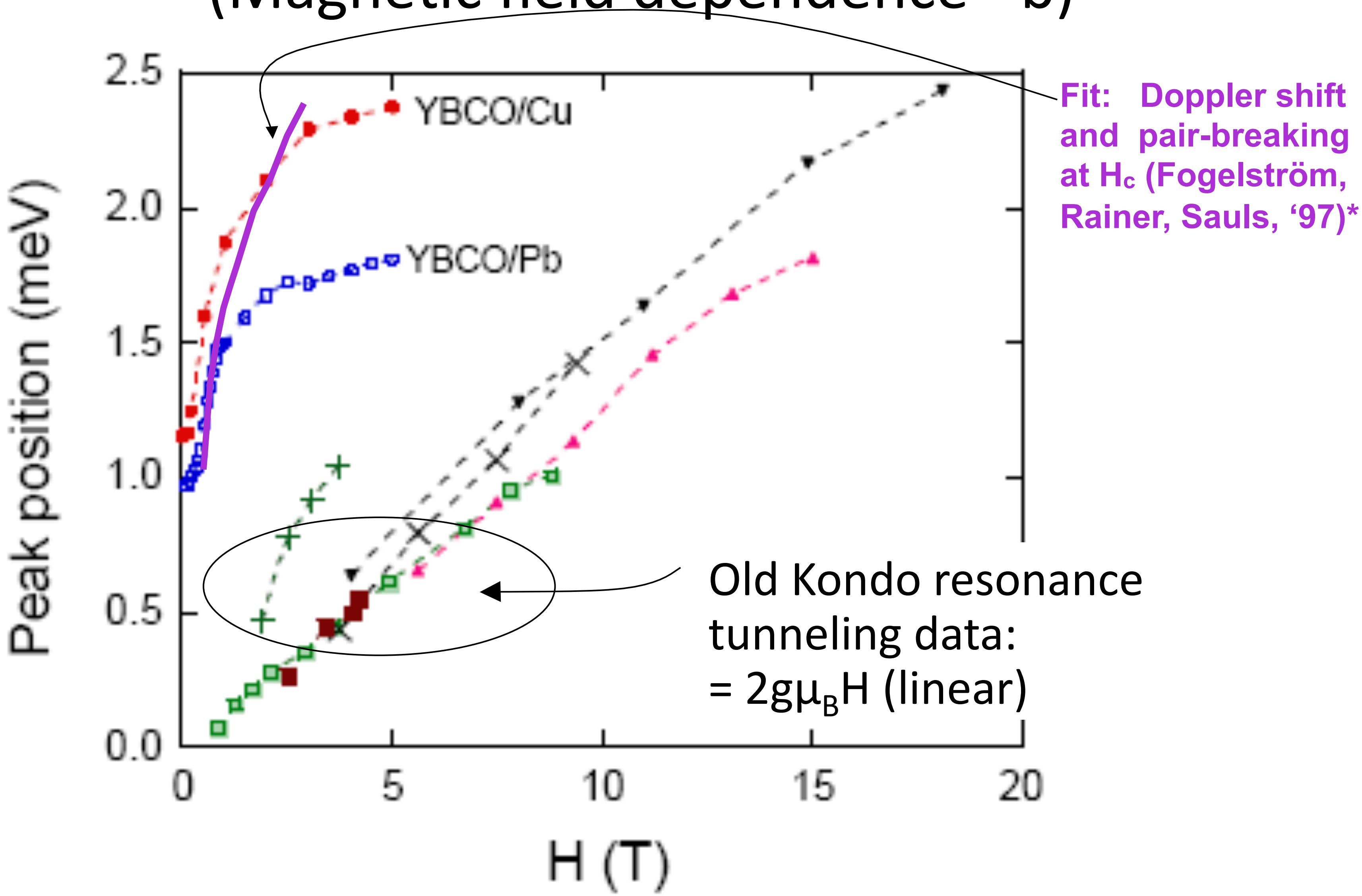
Electron Tunneling Spectroscopy (XVI)

(Magnetic field dependence - a)



J. Lesueur et al, Physics C (1992); M. Covington et al, PRB (2000)

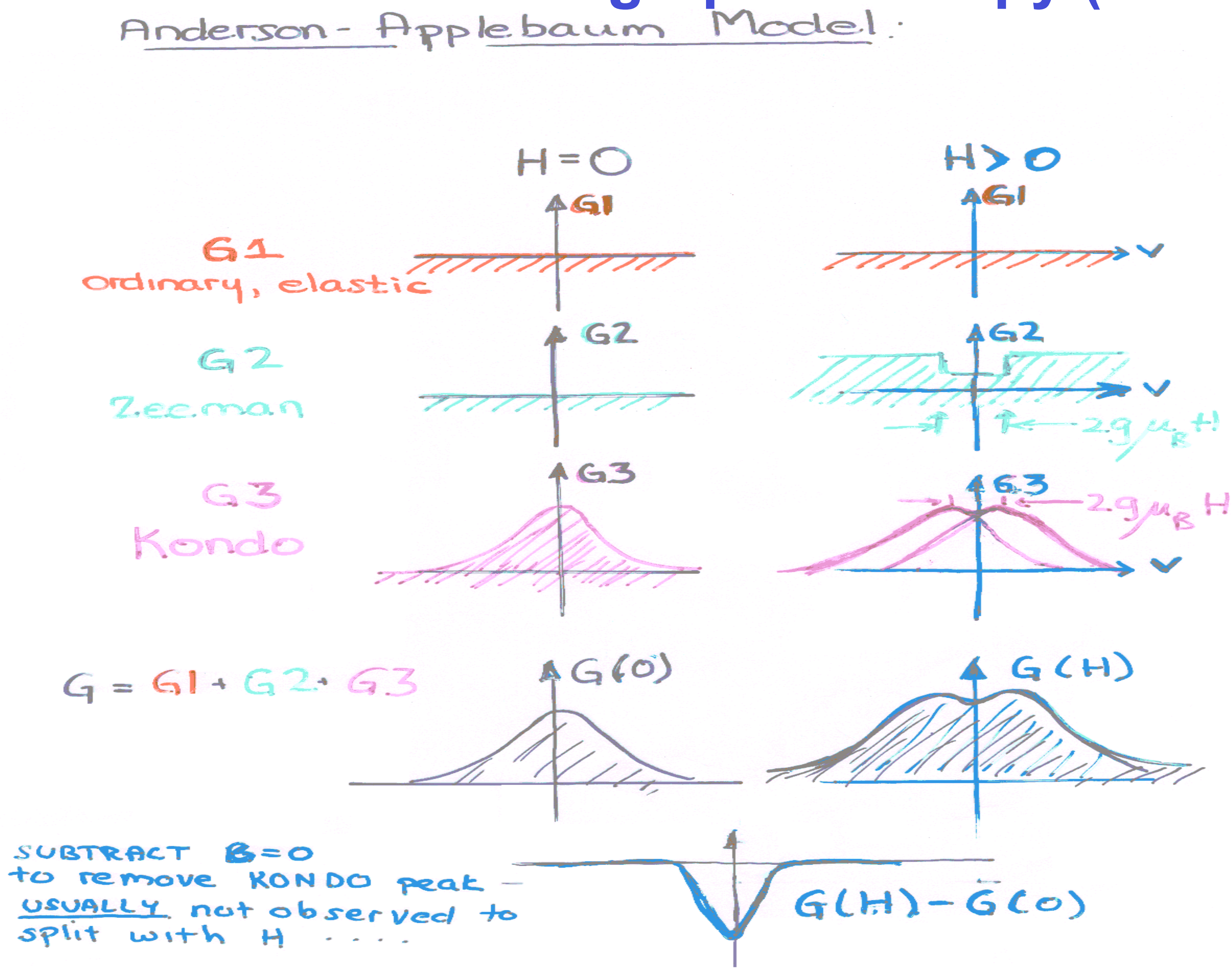
Electron Tunneling Spectroscopy (XVII)
(Magnetic field dependence - b)



Old Kondo resonance tunneling data: $= 2g\mu_B H$ (linear)

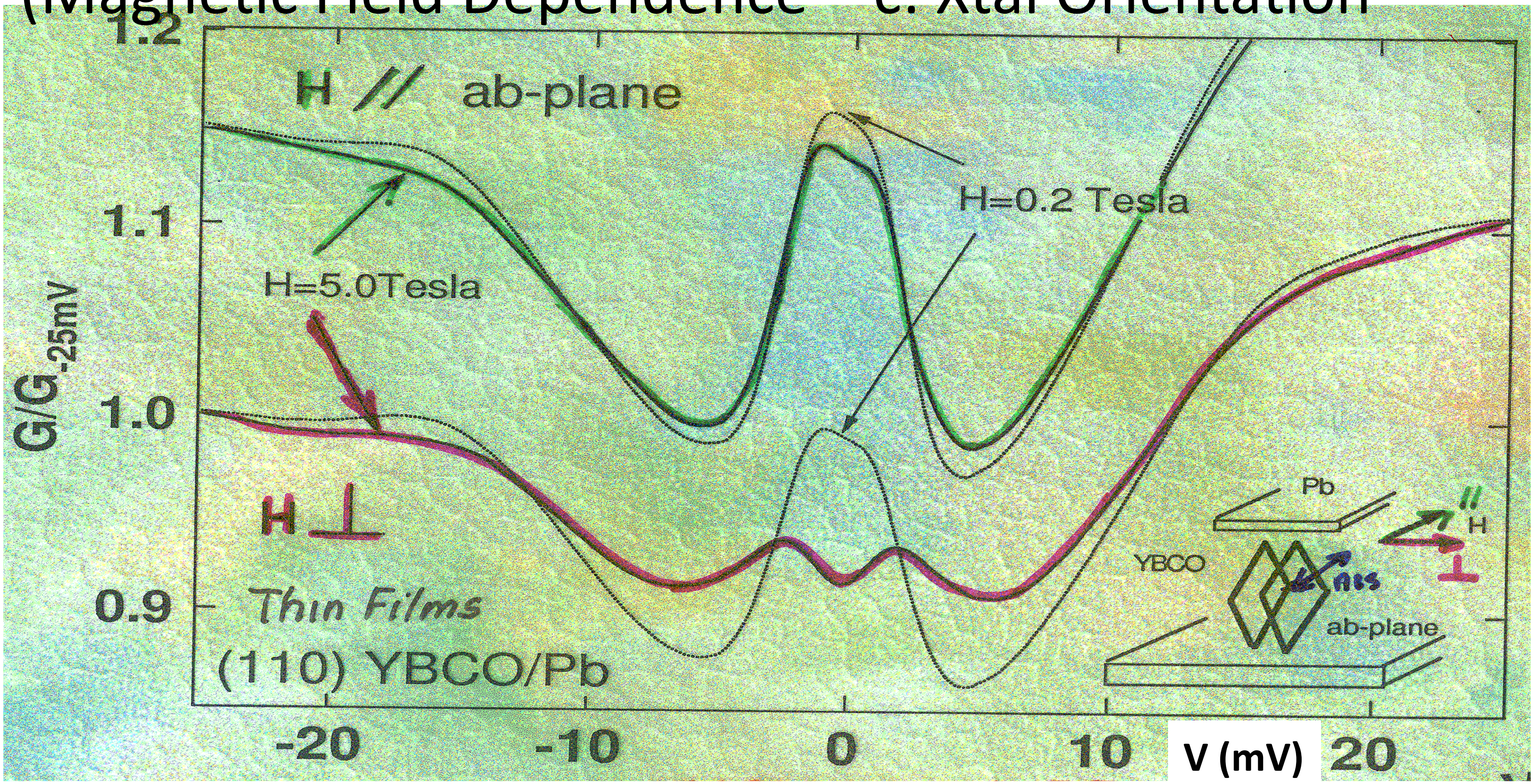
**Lesueur, (92-00); Covington (97-00); Aprili (99); Deutscher (99-05).....*

Electron Tunneling Spectroscopy (XVIII)



Electron Tunneling Spectroscopy (XIX)

(Magnetic Field Dependence – c: Xtal Orientation



Highly - anisotropic QP transport: ABS carry current <u>parallel ab-planes</u> (*<u>not in c-axis direction</u>*)! **Splitting ∝ $V_F \bullet P_s$**

M. Aprili et al, PRL (1999); Krupke et al PRL (1999)

Electron Tunneling Spectroscopy (XX)

(Origin of field splitting)

Andreev bound states carry current along the interface

Applied Magnetic field, *Happl* , induces a Doppler Shift:

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

splitting $\propto H_{applied}$

δ = ***ABS*** *splitting*

λ = *penetration depth*

v_F = *of tunneling electrons*

ϕ_c = *tunneling cone*

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

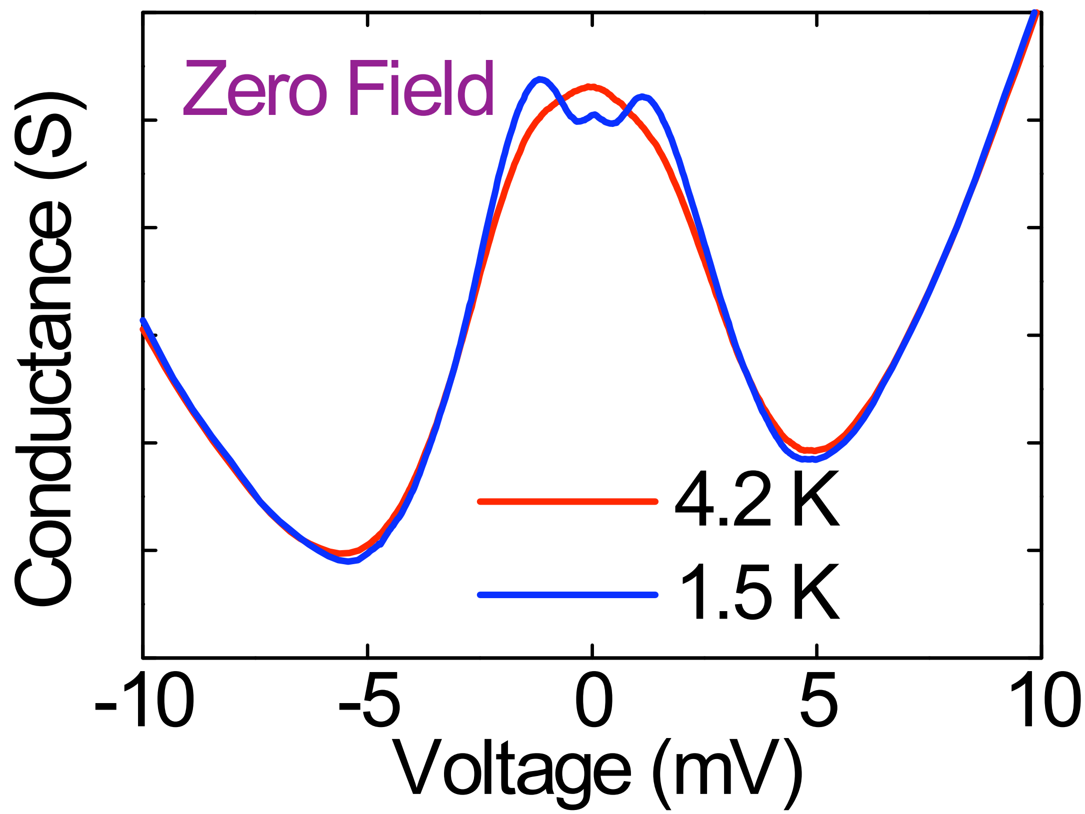
Electron Tunneling Spectroscopy (XXI)

(Zero-field splitting)

Consistent with

⇒ Spontaneous Surface Currents

⇒ Spontaneously Broken Time Reversal Symmetry



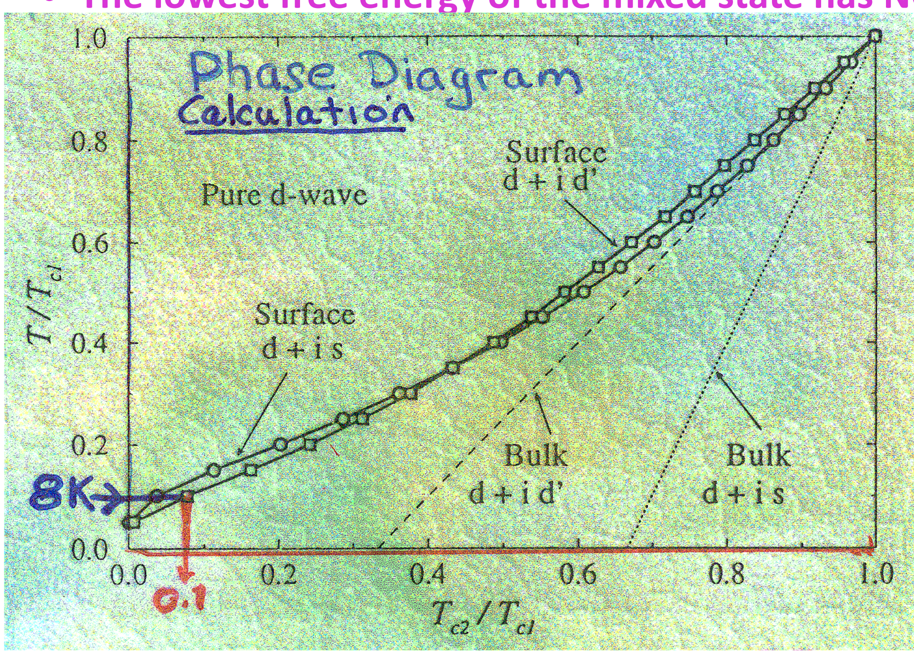
Electron Tunneling Spectroscopy (XXII)

(BTRS – a: Phase diagram)

Mechanism (Laughlin; Matsumoto & Shiba) and
Phase Diagram (Fogelström, Rainer, and Sauls

- **QUASIPARTICLES form near surface (Andreev bound state)**
  (Due to the reflection symmetry breaking of d-wave)
- **At T_s, these QUASIPARTICLES condense into Cooper pairs**
  (Into a sub-dominant SUPERCONDUCING order parameter: s-wave likely)
- **The lowest free energy of the mixed state has NO NODES** ⟹ ***d+is ?***

Ts (Transition temp of sub-dominant OP)



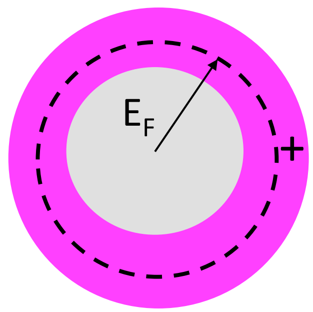
Strength of sub-dominant OP

We measure T_s = 8.1K
At T_s, phase diagram predicts splitting, δ=1.05 meV
We measure δ=1.16 meV

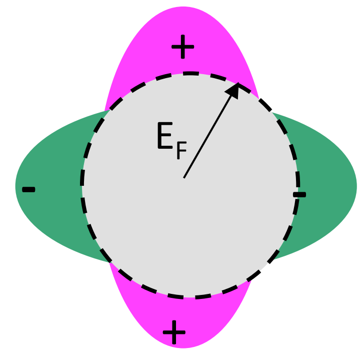
Electron Tunneling Spectroscopy (XXIII)

(BTRS –b: Mixed States)

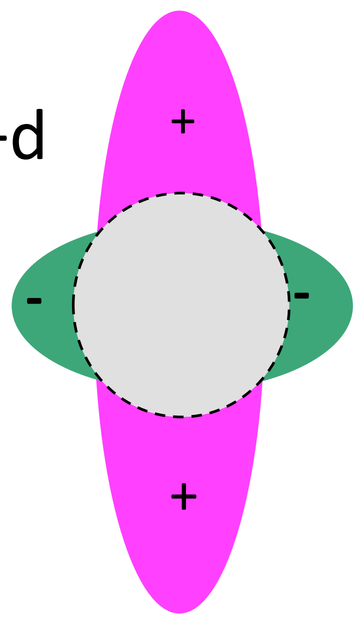
- s



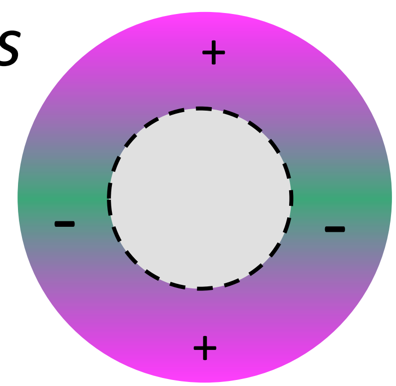
- *d*



- s+d

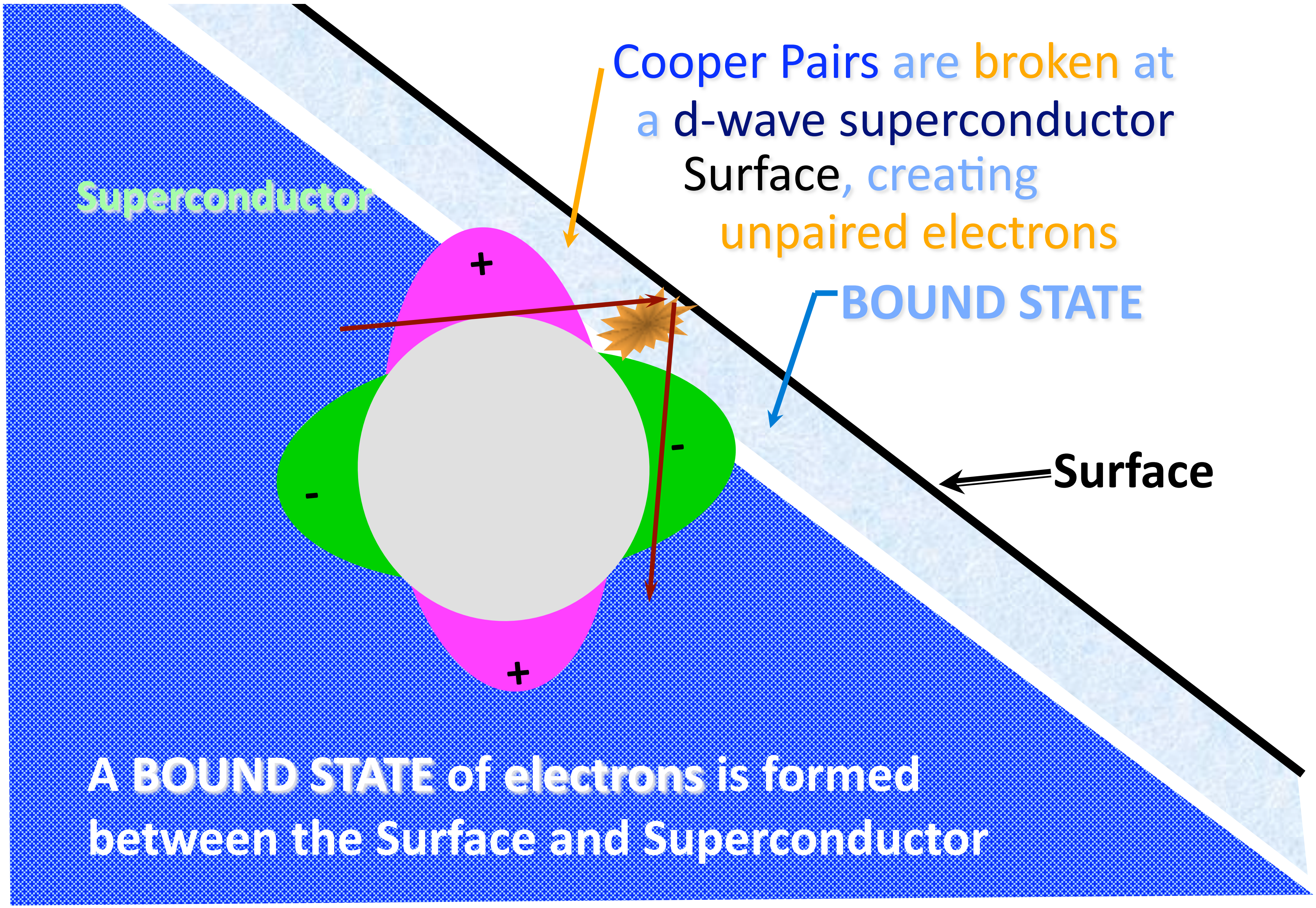


- *d+is*

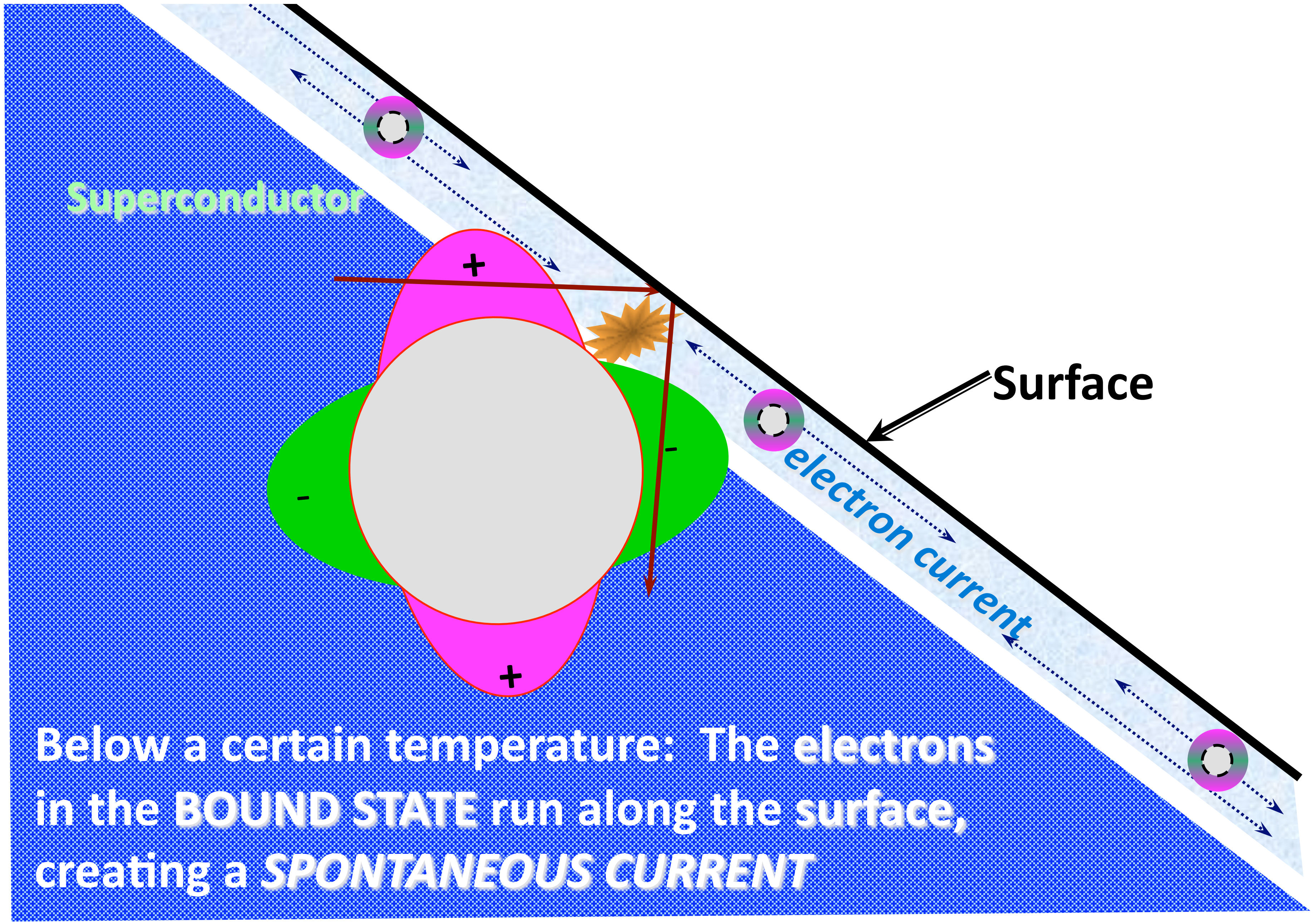


Breaks Time-Reversal Symmetry

(Cartoon of ABS: T<Tc; T>Ts)



(Cartoon of BTRS T<Ts (~8K))



Conclusions

Careful control/growth of materials, systematic diagnostics and reproducibility are crucial in the study of the physics of novel materials

High-Tc Superconductors Spontaneously Break Three Symmetries:

Gauge	(superconducting)
Reflection	(d-wave)
Time-Reversal	(spontaneous magnetic fields)

Planar Tunneling is Powerful Phase-Sensitive Probe of Unconventional Superconductivity

Cast of Characters (best part)

Wan Kyu Park
Patrick Hentges (Intel,OR)
Herve Aubin (ESPCI, Paris)
Marco Aprili (ESPCI, Orsay)
Jerome Lesueur (ESPCI, Paris)
Elvira Badica (U. VA)
Mark Covington (Seagate)

Physics UIUC

Margaret Pafford (Rohm & Hass)
Glenn Westwood
Walter G. Klemperer

Chemistry UIUC

Chad Mirkin

Chemistry NWU

Sha Jian
David G. Hinks

MatSci ANL

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