CENTRE NATIONAL
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LPEM Physique Quantique
Paris (France)

ESPCI

Direct probe of pairing fluctuations in the pseudogap regime of underdoped cuprates

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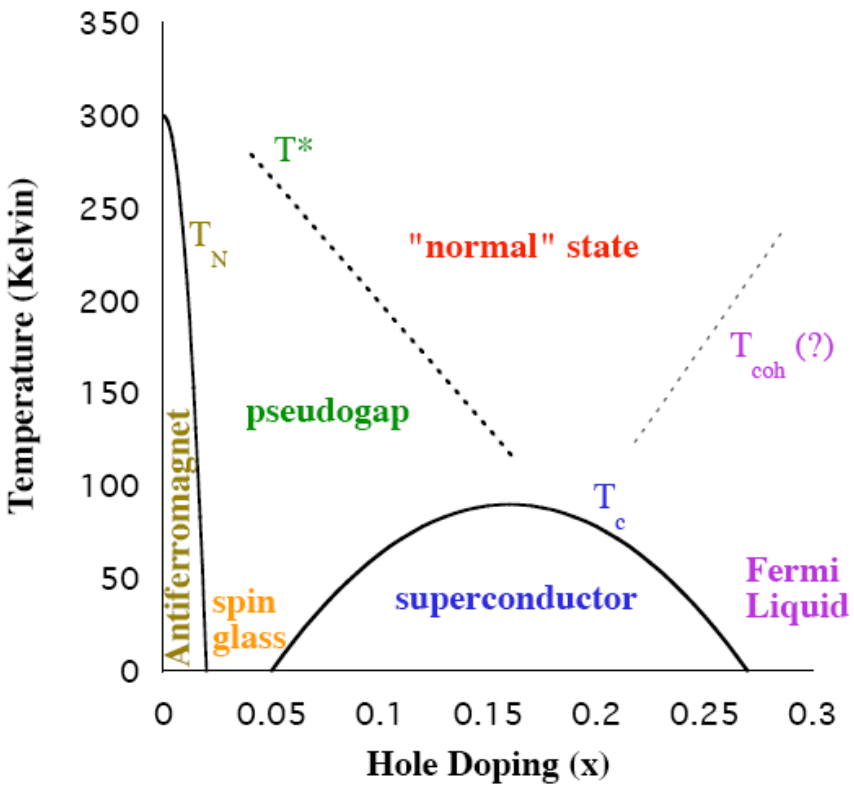
J-P. Contour UMR THALES/CNRS

N. Bergeal et al Nature Physics 4, 608 (2008)

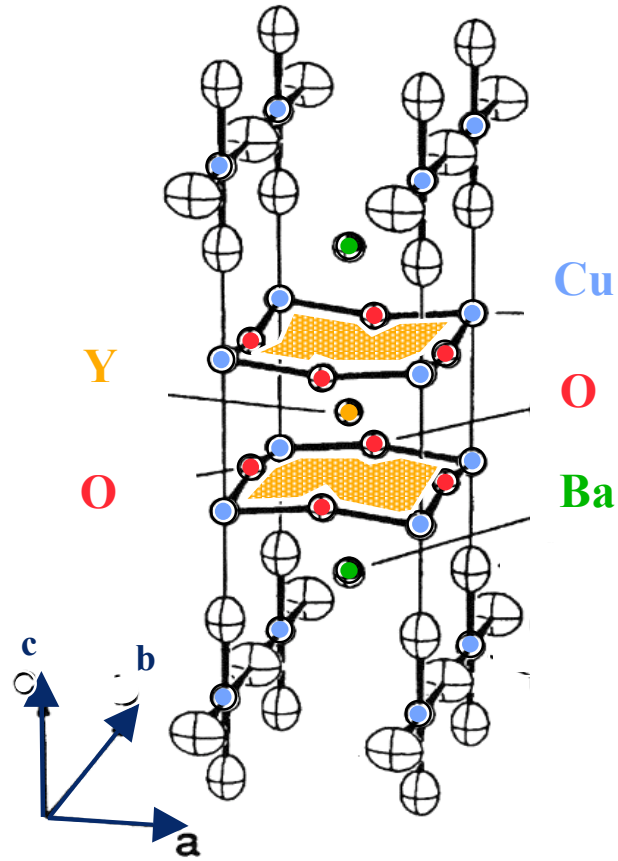
Cuprates phase diagram

- High Tc superconductors
- Hole-doped in the CuO_2 plane

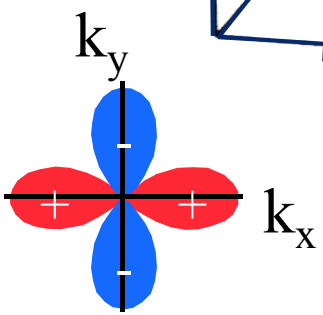


$YBa_2Cu_3O_{6+x}$

T_c=90K



- Order parameter symmetry : d_{x2-y2}



Outline

1. The pseudogap in underdoped cuprates

   Single particle probes (spin and charge channels)

   Different scenarios ; pairing fluctuations ?

2. Probing pairs above Tc : a Josephson like experiment

   Standard Josephson experiments

   Pair susceptibility above Tc in BCS superconductor

   Designing an experiment to directly probe pairs in UnderDoped Cuprates

   How do we make junctions ?

3. Only gaussian pair fluctuations between Tc and T*

   Josephson behavior at low temperature

   Electronic transport through localized states

   Gaussian fluctuations … that's all folks !

4. Conclusion

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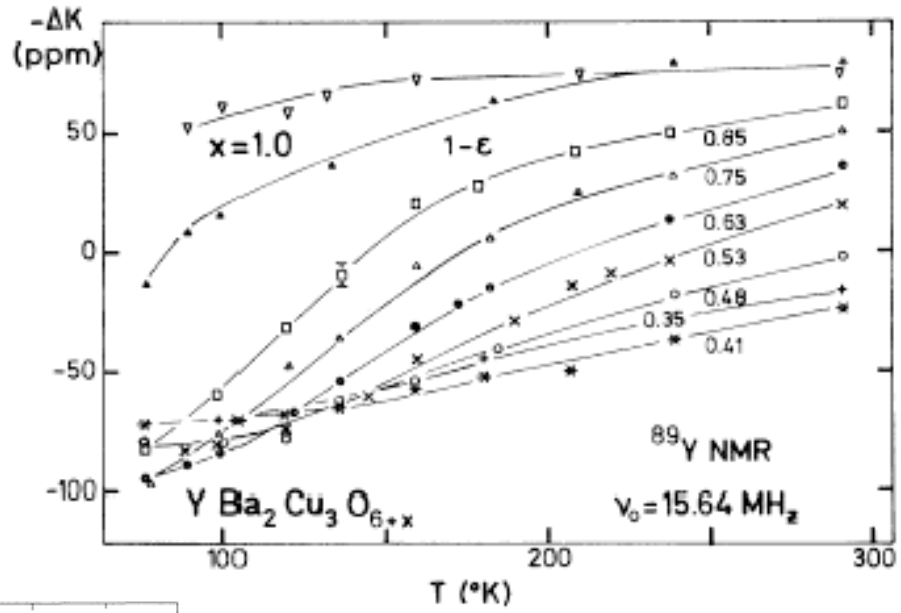
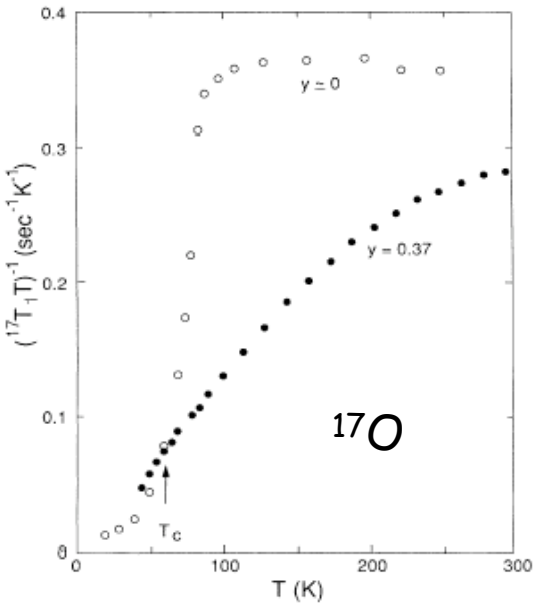
Pseudogap in the spin channel (NMR)

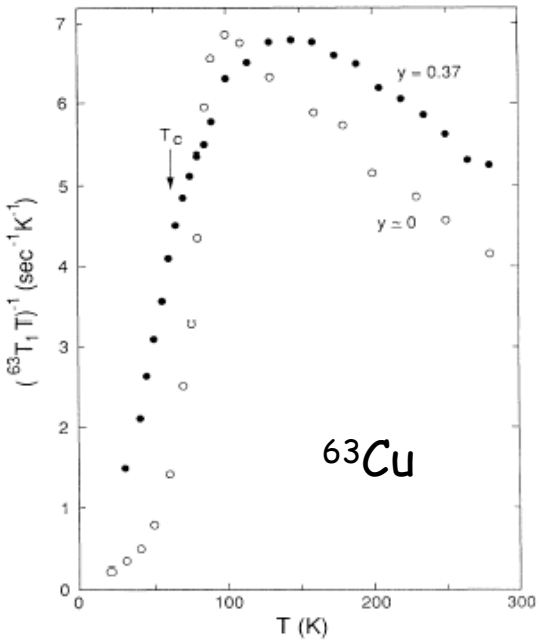
➢ Knight-shift (Alloul '89)

UnderDoped YBCO



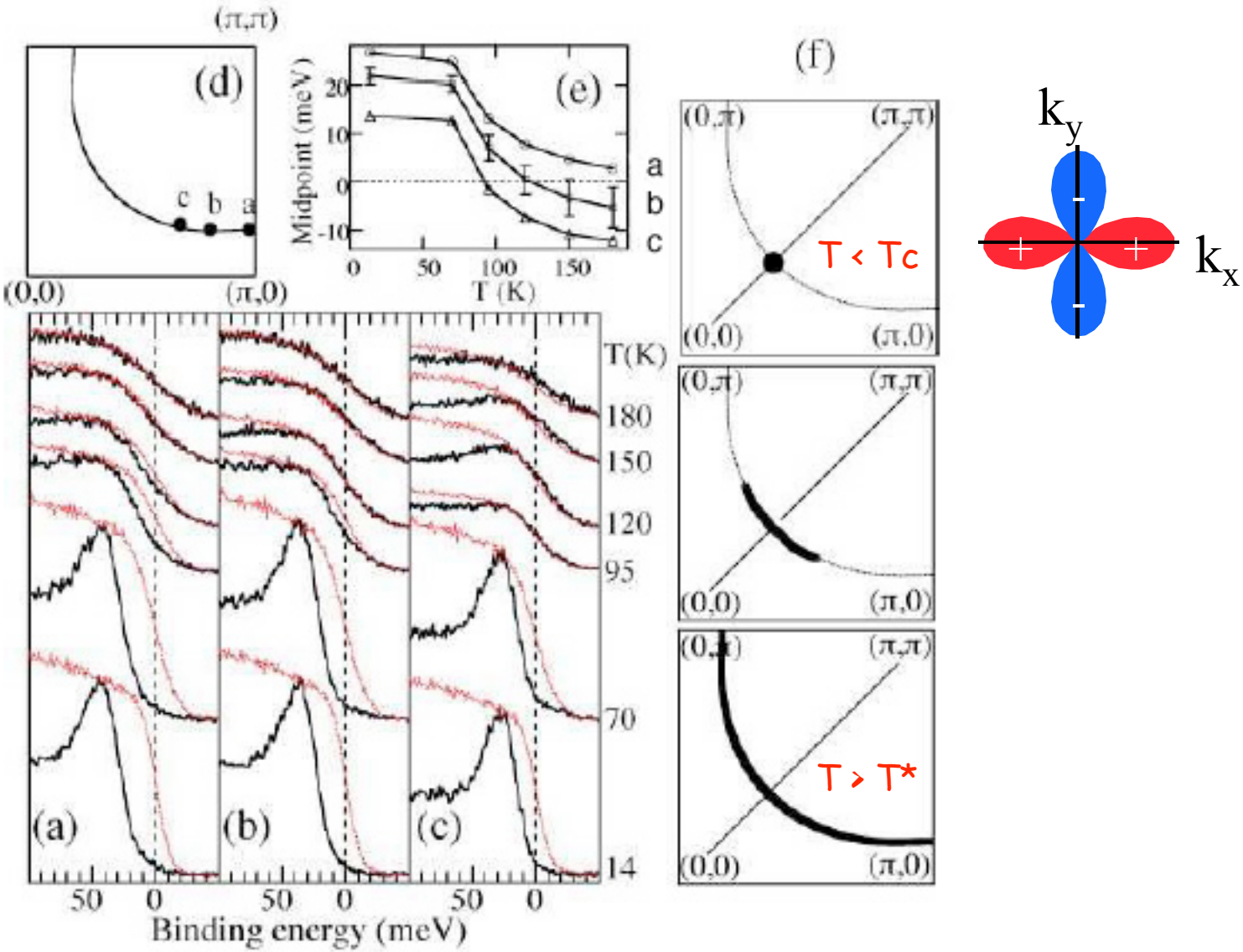
b)





➢ 1/T1T (Takigawa '91)

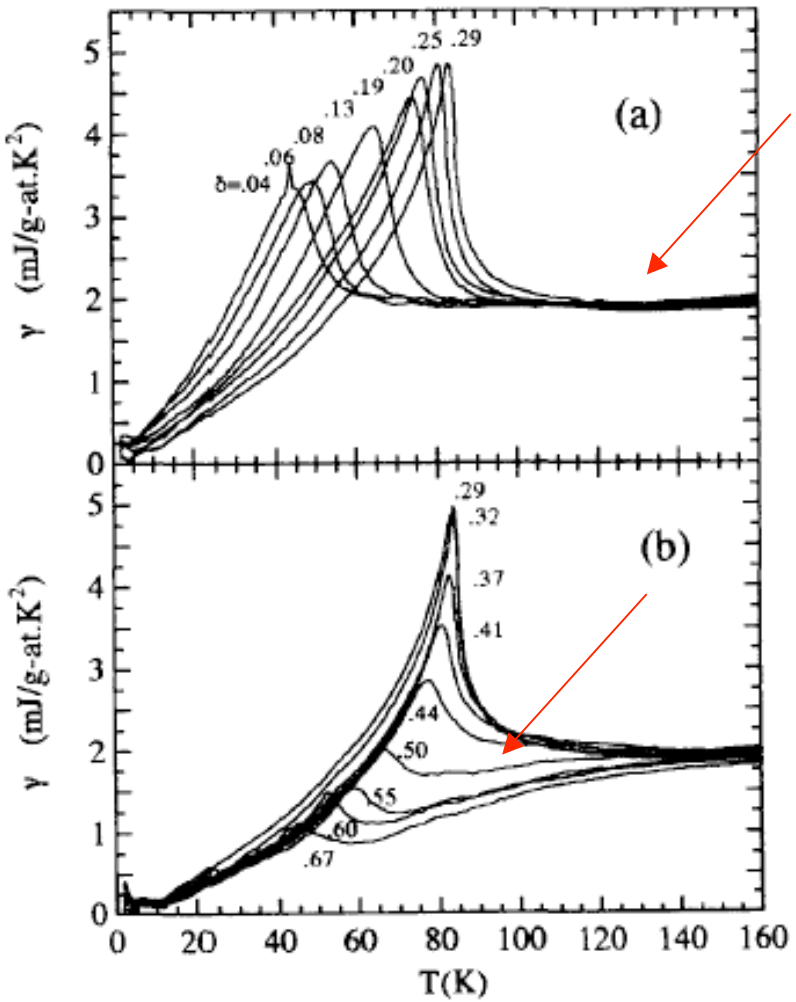
Pseudogap in the charge channel (ARPES)



UnderDoped BSCCO

➢ ARPES (Norman '98)

Pseudogap in the excitations spectrum



OverDoped YBCO

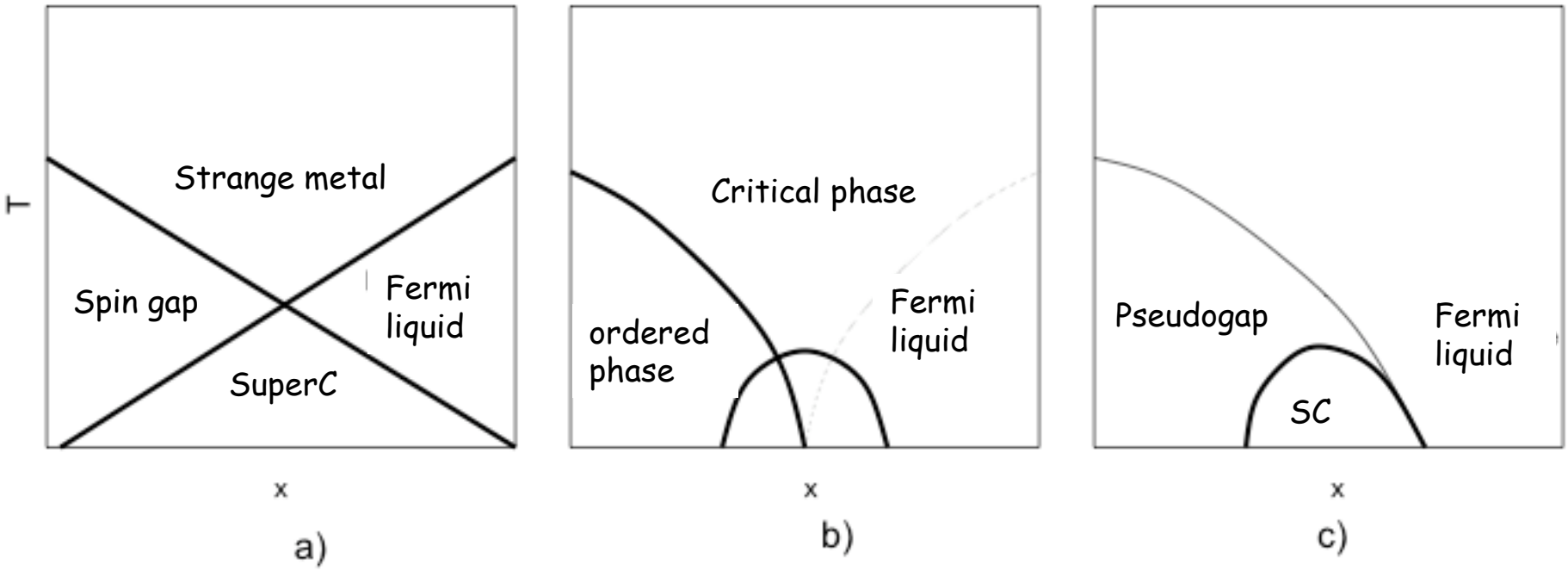
UnderDoped YBCO

➢ Specific heat (Loram '97)

➢ Lost of spectral weight

➢ Both in charge and spin channels (Entropy)

Scenarios for the Pseudogap …



- RVB like
- QCP like
- Preformed pairs

- What is the « generic » phase diagram ?
- What is T* ?
- Relation between the Pseudogap and Superconductivity ?

Are there preformed pairs ???

- Relation between the Pseudogap and Superconductivity ?

- Mostly single particle excitations probes ?

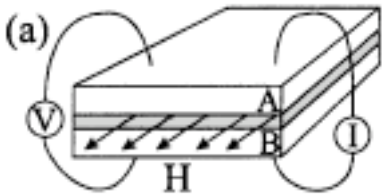
Incoherent Pair Tunneling as a Probe of the Cuprate Pseudogap

Boldizsár Jankó, Ioan Kosztin, and K. Levin
The James Franck Institute, The University of Chicago, 5640 S. Ellis Avenue, Chicago, Illinois 60637

M. R. Norman
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

Douglas J. Scalapino
Department of Physics, University of California, Santa Barbara, California 93106
(Received 19 August 1998)

- Janko et al PRL '99



- Pseudo-Josephson experiment
- Probing directly pairs
- Scenario independent

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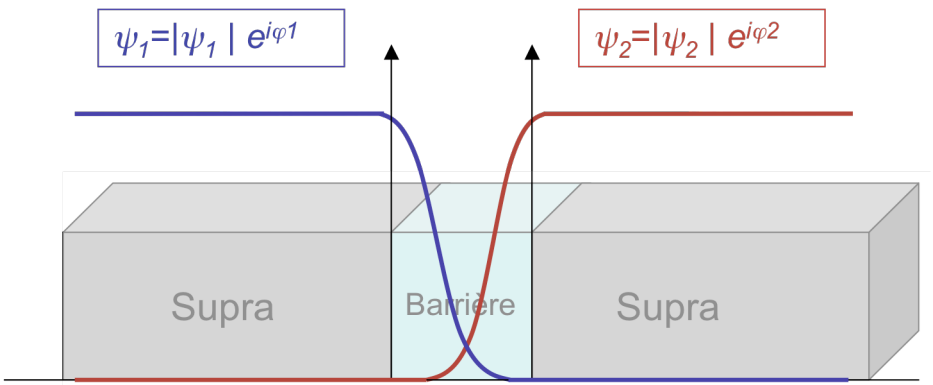
Josephson effect



➢ Josephson equations

Phase sensitive probe

$$I = I_c \sin(\varphi) \qquad \varphi = \varphi_1 - \varphi_2$$

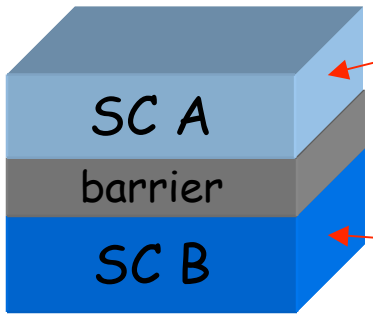
$$\frac{\partial \varphi}{\partial t} = \frac{2eV}{\hbar}$$

Time dependence

➢ Probing phase fluctuations ?

Pair susceptibility in the gaussian regime of fluctuations in a BCS superconductor

(Scalapino PRL 70)



Fluctuating pairs

Rigid pair field

$$\tau = \frac{\pi\hbar}{8k_B T_c \varepsilon}$$

$$\varepsilon = (T - T_c)/T_c$$

Tc A < T < Tc B

➢ Pair susceptibility

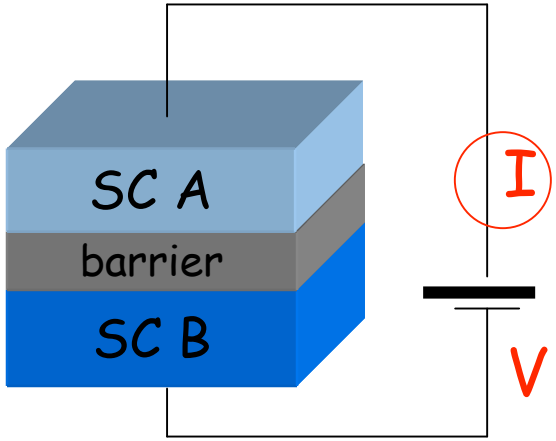
$$\chi^{-1}(q,\omega) = N_0 \varepsilon \left[i\omega\tau + (1 + \xi^2 q^2) \right]$$

Frequency $\omega = 2eV/\hbar$

Wave vector $q = (2e/\hbar c) H \left[\lambda' + d/2 \right]$

Pair susceptibility in the gaussian regime of fluctuations in a BCS superconductor

J.T.Anderson A.M. Goldman PRL (1970)

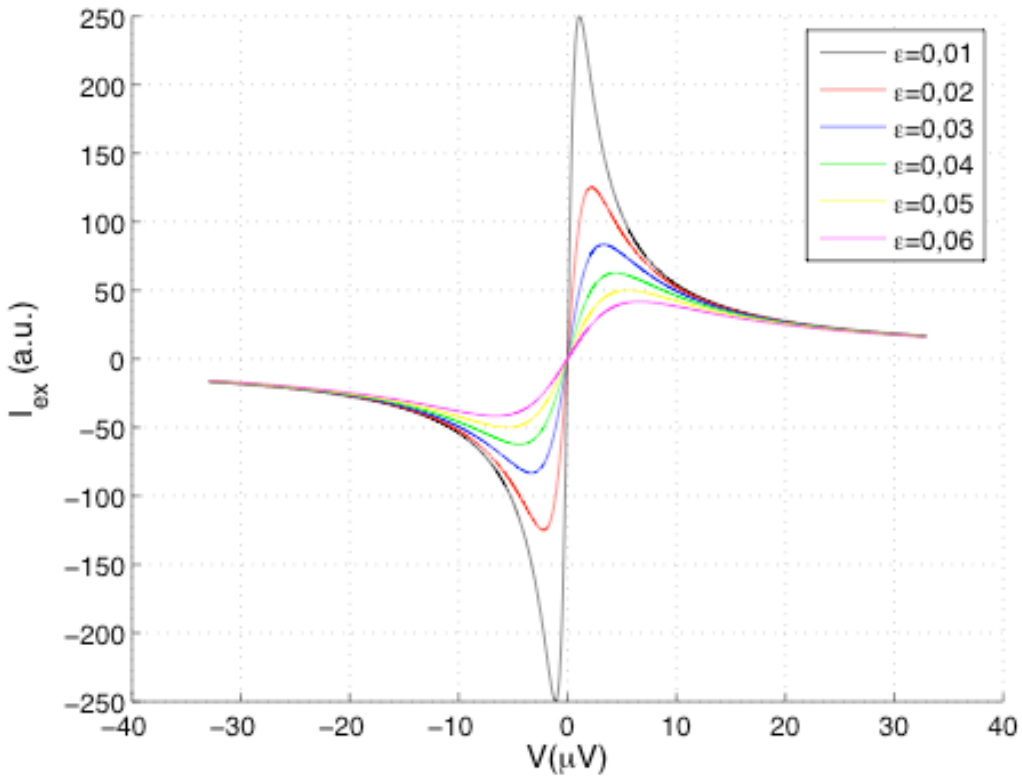


$$I_1(V,H) = \langle I_1 \rangle = (4e\,|\overline{C}|^2 A/d\hbar)\,\mathrm{Im}\chi(\omega,q),$$

$$I_{ex} = \frac{\hbar \overline{C}^2 \omega L}{4edN_0} \frac{\omega\tau}{\varepsilon\left[(\omega\tau)^2 + (1+q^2\xi^2)^2\right]}$$

Tc A < T <Tc B

➢ Excess current



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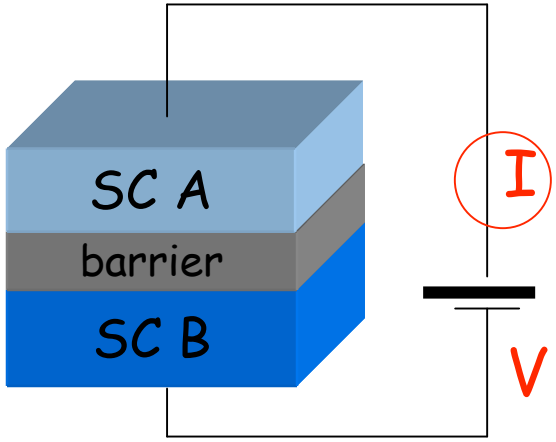


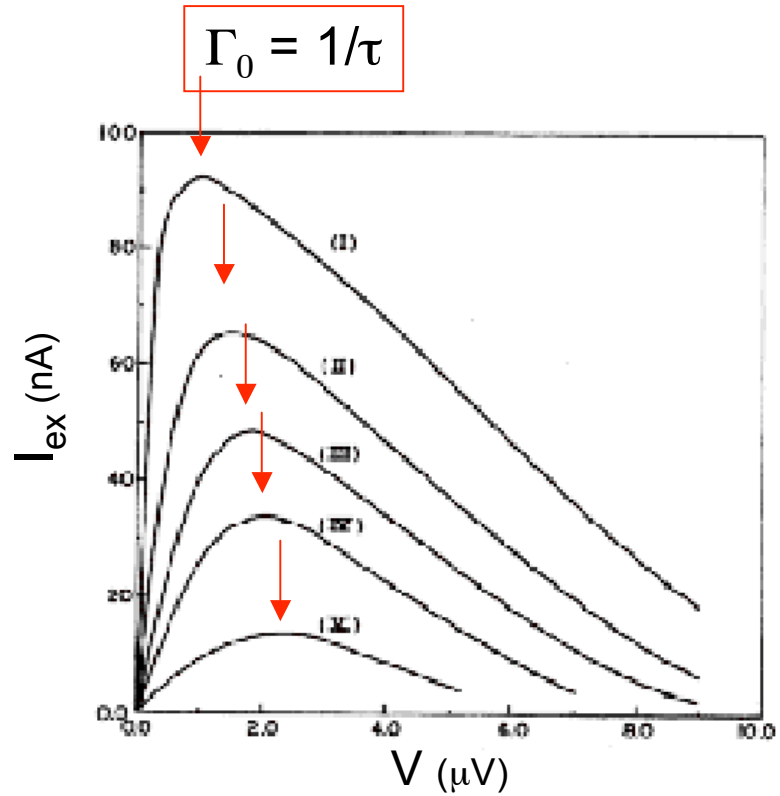
$Tc\ A < T < Tc\ B$

- Excess current

  (Im - Iqp)

- V sets the frequency

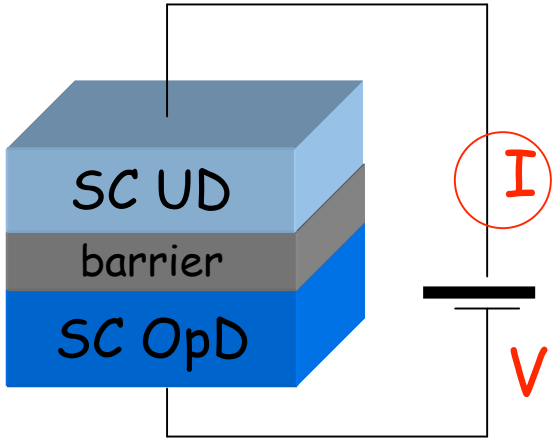
- Junctions Sn-SnO-Pb with $Tc_{Sn} < T < Tc_{Pb}$



ε=1.48 10^{-3}, 1.97 10^{-3}, 2.45.10^{-3}, 2.94 10^{-3}, 3.91 10^{-3}

Pair susceptibility in the pseudogap regime of UD cuprates

B.Janko, I.Kostin, K.Levin, M.R.Norman, D.J.Scalapino PRL 82, 4304 (1999)



Underdoped : fluctuating pairs

➢ Excess current

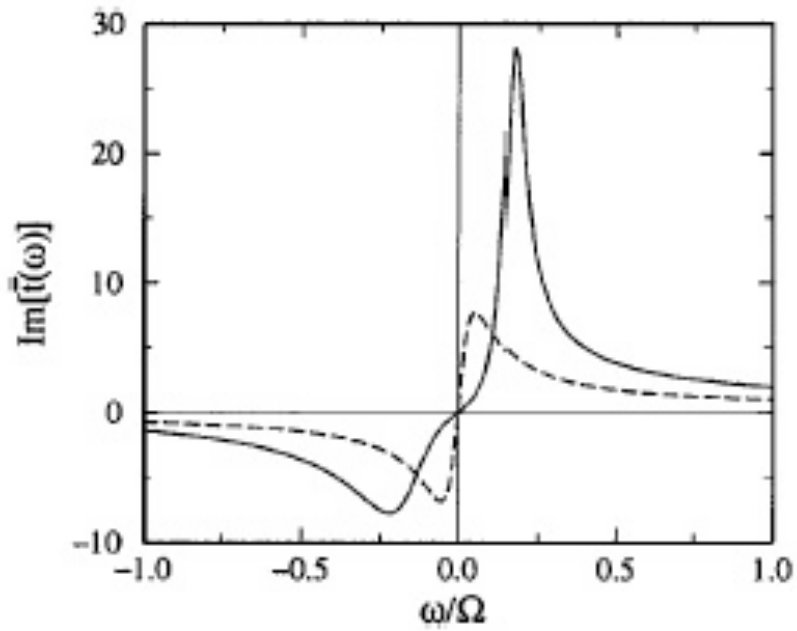
Optimally doped : rigid pair field

Tc UD < T <Tc OpD

➢ Up to T* (Tc OpD)

➢ Independent of a specific scenario !!!

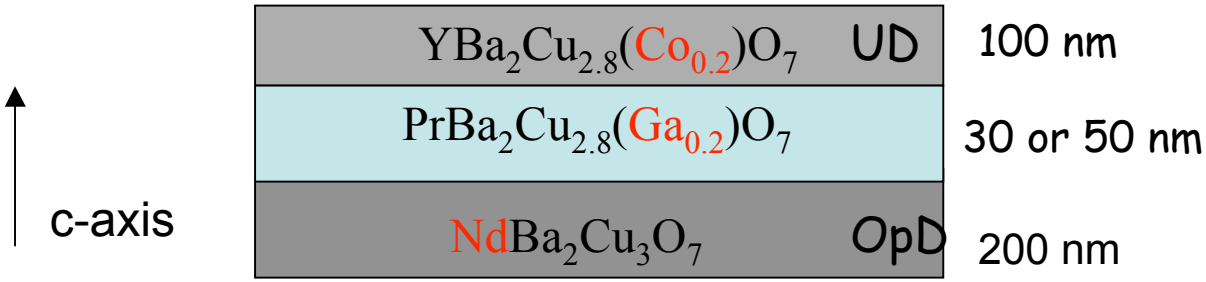
➢ Difficult !!!



Design of the experiment

➢ Requirements :

- Three different materials
- The barrier has to be compatible (epitaxy)
- Epitaxy at T~700°C --> impossible to underdope with oxygen



Tc (UD) = 61 K

Tc (OpD) = 90 K

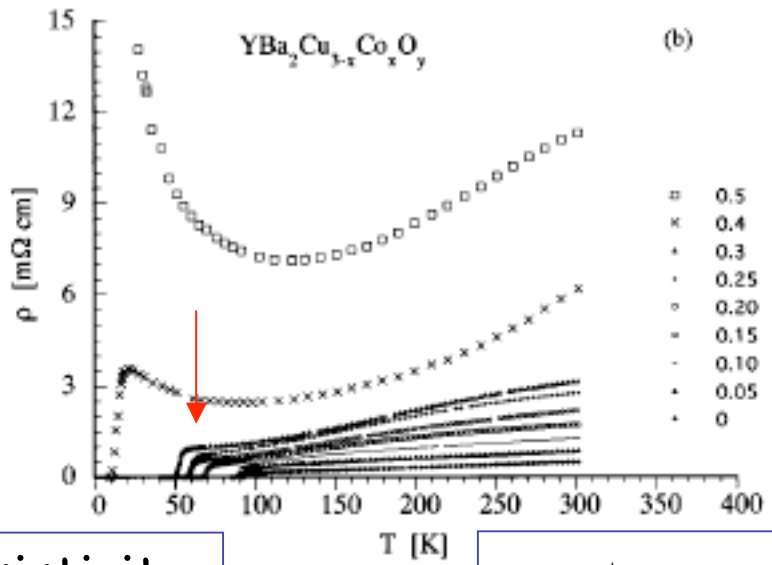
J.P Contour (Thales/CNRS)

The UnderDoped material …

➢ Carrington '92

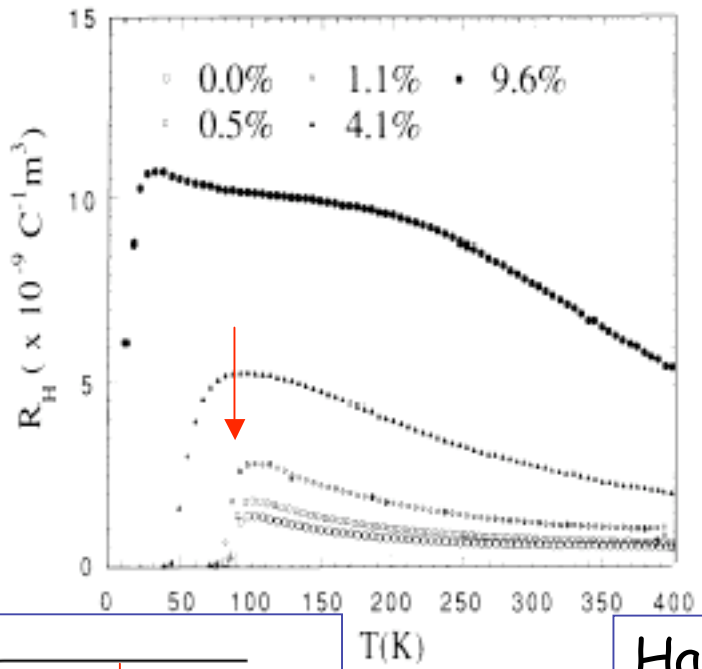
➢ Co-doped YBCO :

- Tc can be adjusted by doping (60 K)
- Small disorder (Co in the chains)



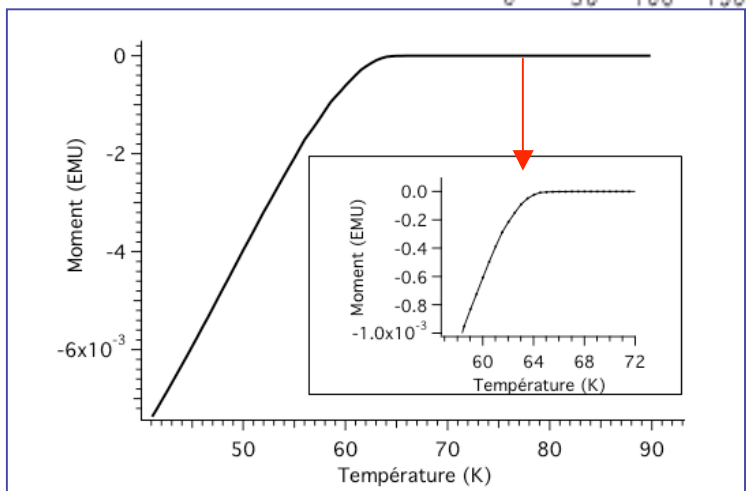
Resistivity

a)



Hall Cste

b)



Susceptibility

The Barrier ...

➢ Glazman - Matveev

➢ Ga-doped PBCO :

- PBCO : weak insulator
- Standard compound in Josephson devices
- Ga doping : higher resistivity

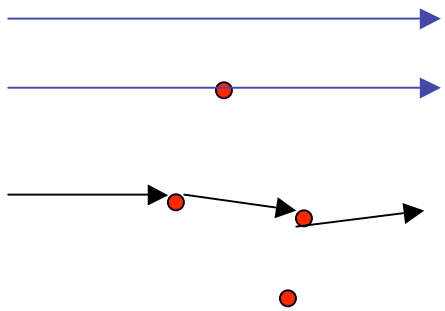
➢ Conduction in PBCO :

- Variable Range Hopping (bulk)
- Conduction through localized states (layer)
- Ga doping : reduction of their number

$$G(T) = G_{dir} + G_{res} + \sum G_n(T)$$

elastic

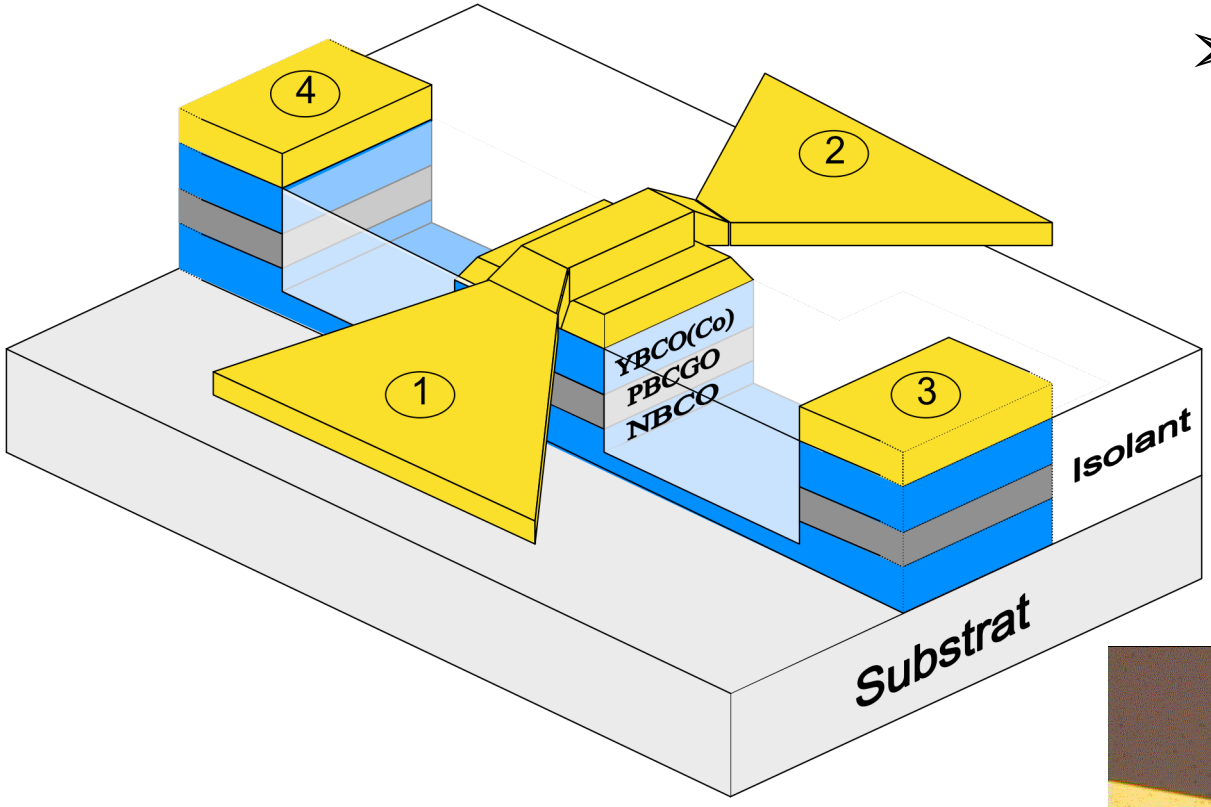
inelastic



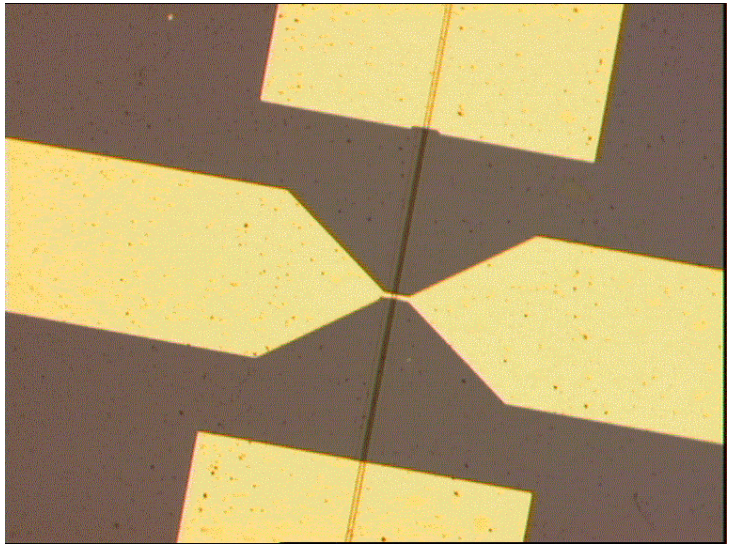
$$G(T) = G_0 + \alpha T^{4/3} + \beta T^{5/2} + \ldots$$

$$G(V) = G_0 + \alpha V^{4/3} + \beta V^{5/2} + \ldots$$

Mesas used in this study

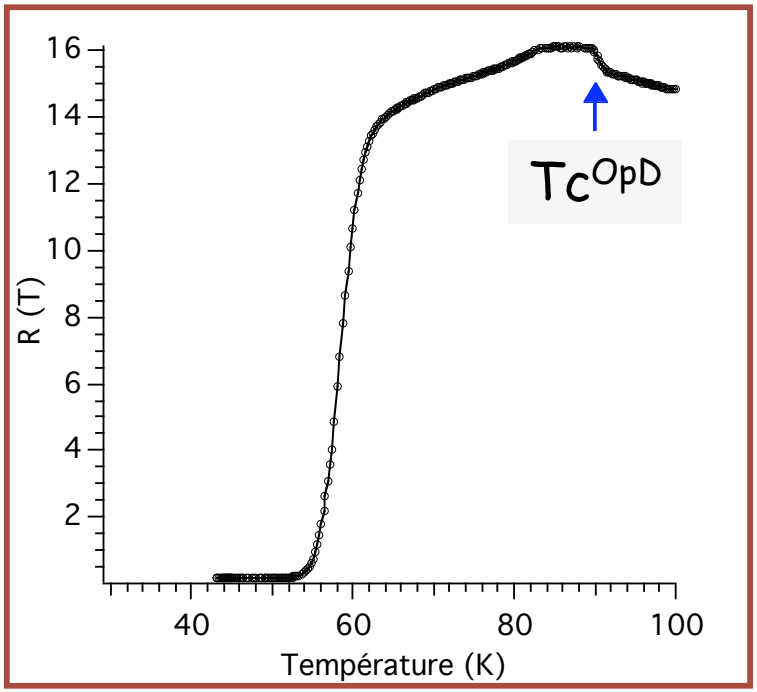


➢ Mesa structures



➢ Junctions 40μm*40μm to 5μm*5μm

R(T) curve

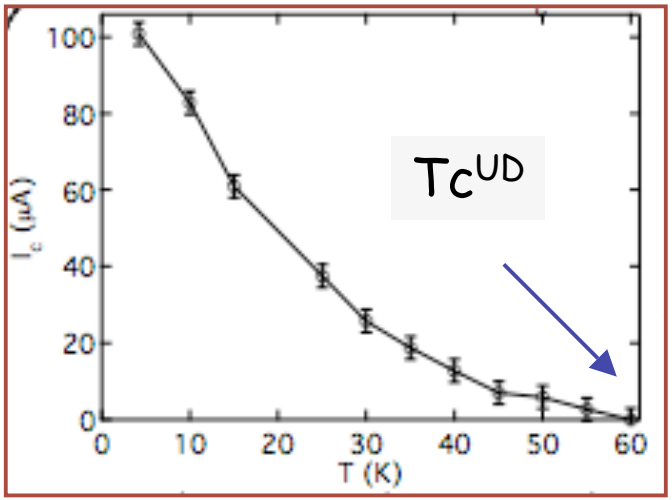


- Good equipotentials

  Gold resistance in series (150 mΩ)

  Barrier resistance >> other resistances

- Josephson coupling at $T_c^{UD} \approx 61K$



- Josephson $T < T_c^{UD} < T_c^{OpD}$
- « Normal » $T_c^{UD} < T_c^{OpD} < T$
- Pseudogap $T_c^{UD} < T < T_c^{OpD}$

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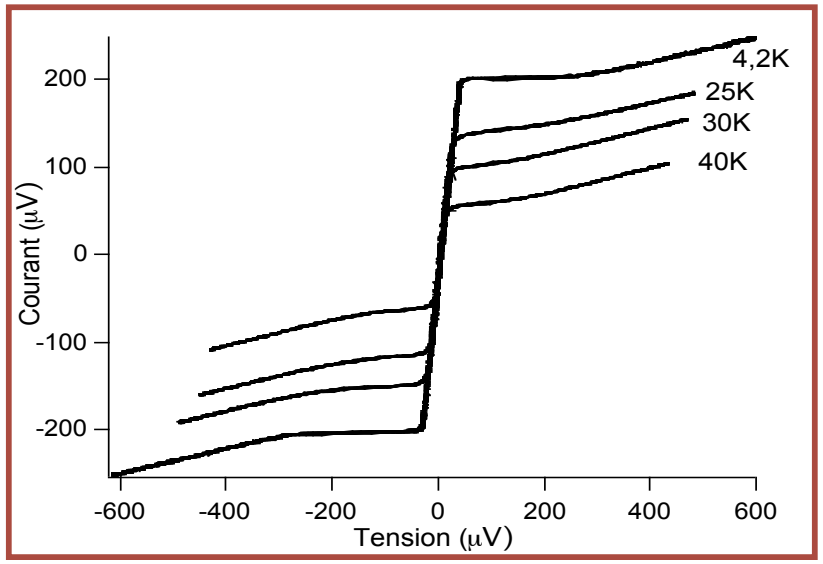
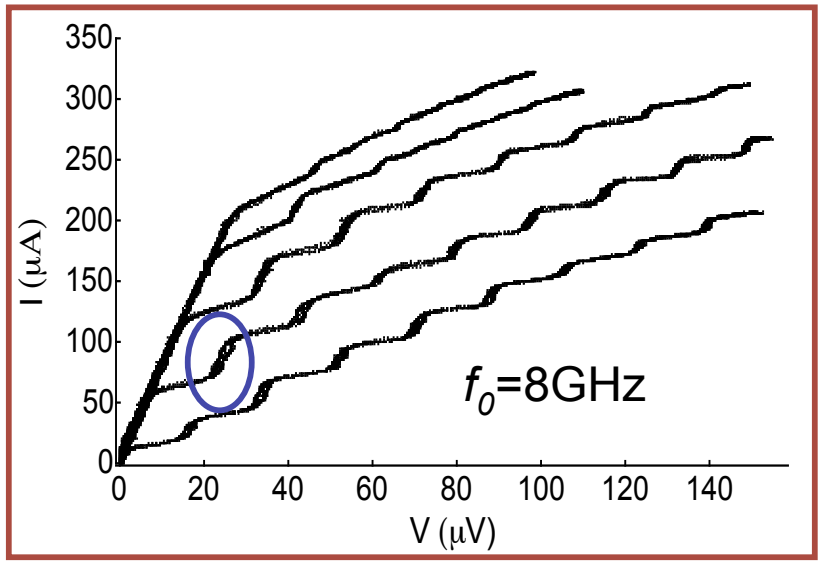
Josephson effect at low temperature ($T<T_c^{UD}<T_c^{OpD}$)

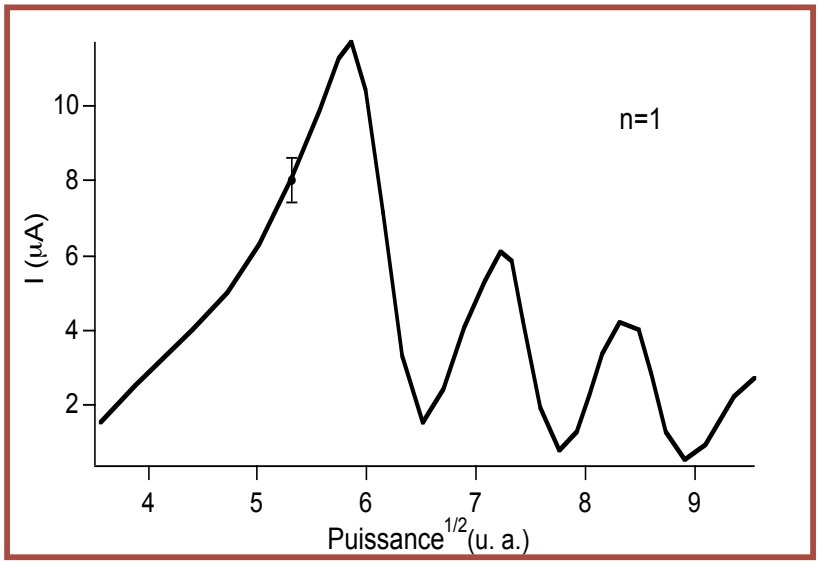


- RSJ Josephson I-V characteristics

Coupling IcRn = 2mV

- Shapiro steps $V_n = n\frac{h}{2e}f_0$



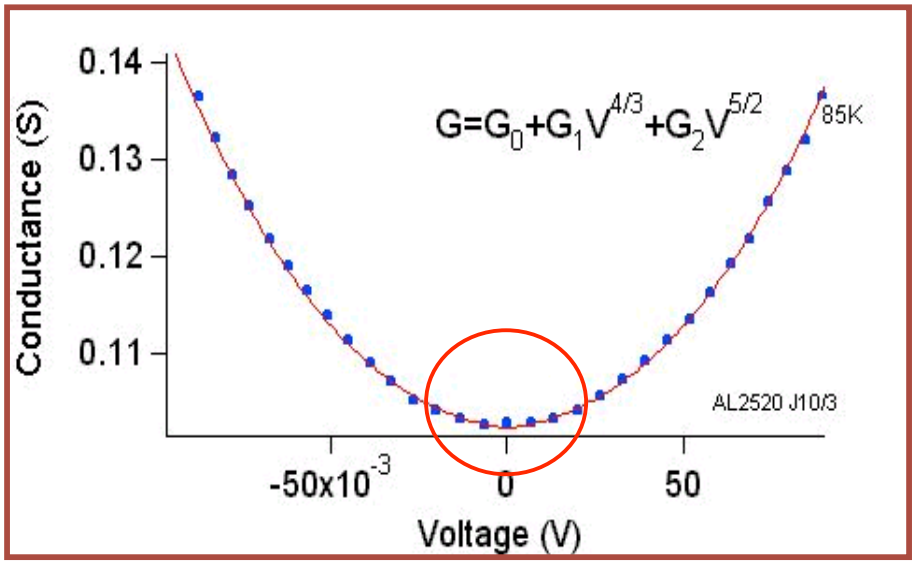


Transport through $PrBa_2Cu_{3-x}(Ga_x)O_7$ ($T_c^{UD} < T_c^{OpD} < T$)

- Quasiparticles: hopping through LS
- 50 nm : 3 LS

  30 nm : 1 or 2 LS
- Corresponding T dependence

$T_c^{UD} < T_c^{OpD} < T$

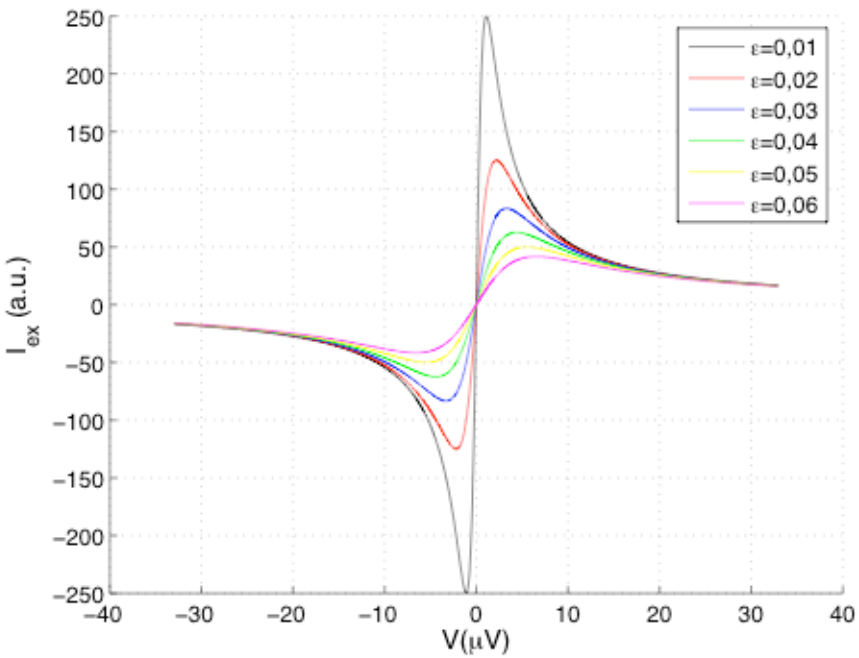


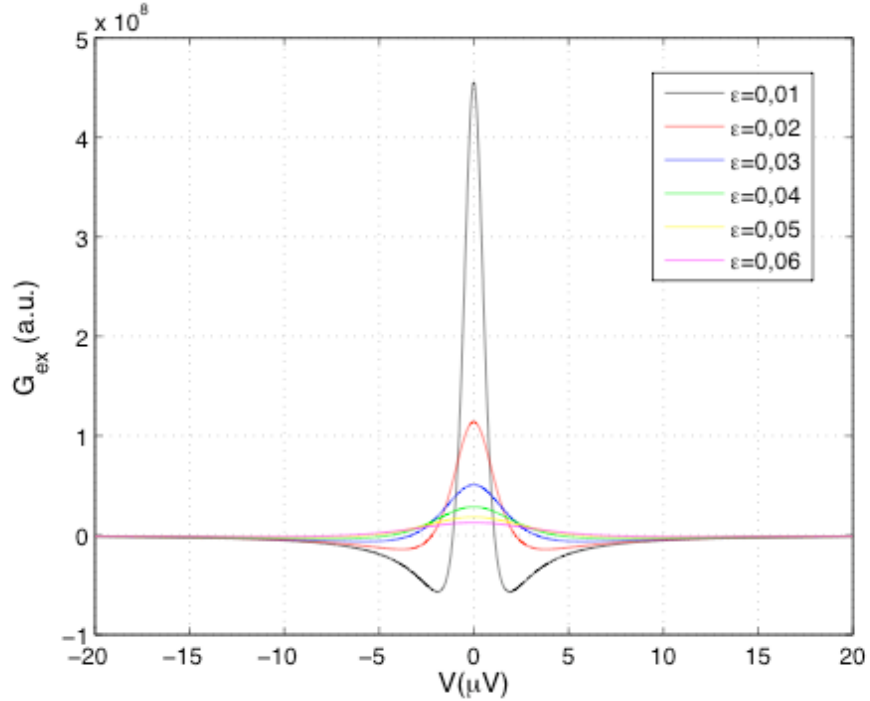
$$G(V) = G_0 + \alpha V^{\frac{4}{3}} + \beta V^{\frac{5}{2}} + \gamma V^{\frac{18}{5}} + \ldots.$$

- Weak depedence at low energy (< 10 mV)
- Josephson effect : resonant tunneling through Localized States

Finaly, the test … ($T_c^{UD} < T < T_c^{OpD}$)

➢ Conductance measurements to be more sensitive





$$I_{ex}(V) = A\frac{\omega/\Gamma_0}{\epsilon[1+(\omega/\Gamma_0)^2]}$$

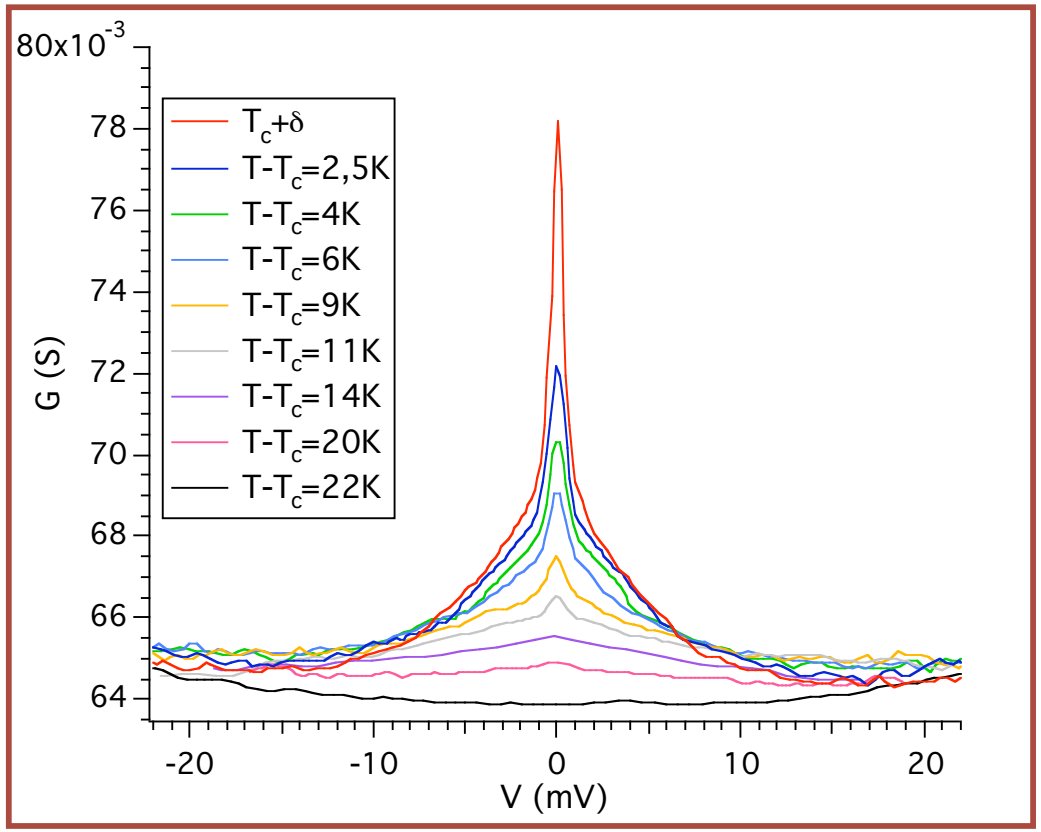
$$\Gamma_0 = (16k_B/h)(T - T_c)$$

$$\epsilon = (T - T_c)/T_c$$

$$G_{ex}(V) = A\frac{2e}{\hbar\Gamma_0\varepsilon}\frac{1-(\omega/\Gamma_0)^2}{[1+(\omega/\Gamma_0)^2]^2}$$

➢ How high in temperature will the peak survive ?

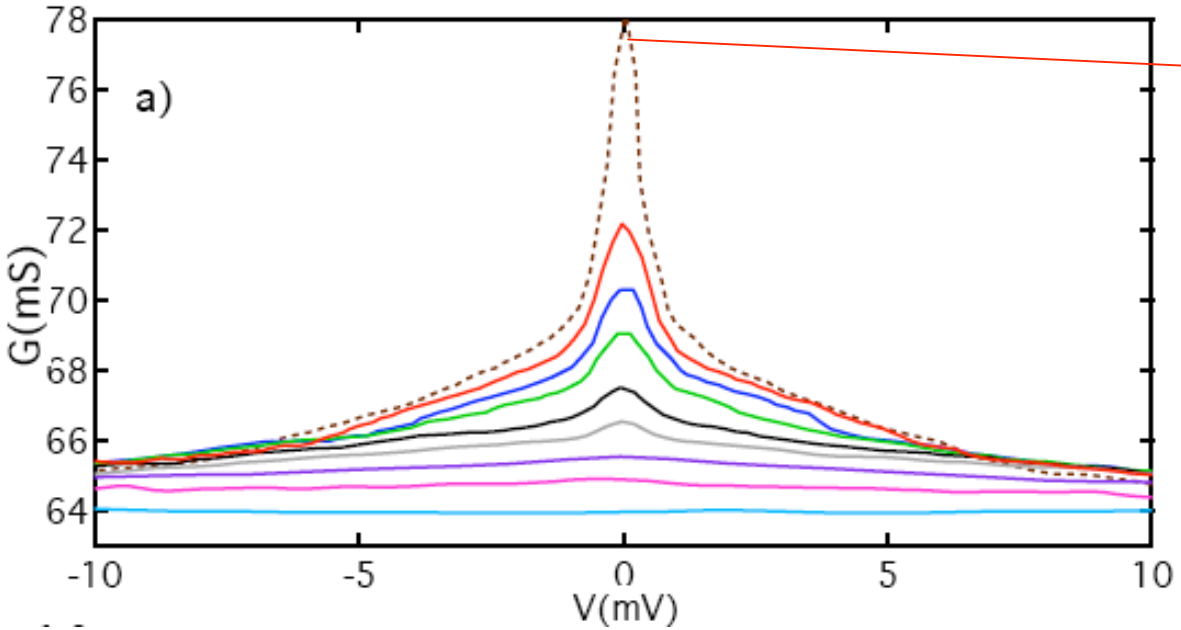
Testing the fluctuating pairs ($T_c^{UD} < T < T_c^{OpD}$)

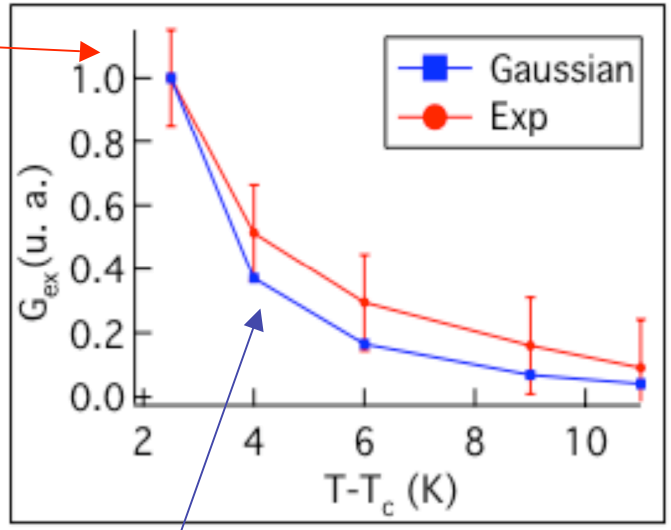


- An excess conductance peak
- Seen only 14K above Tc
- Far below Tc (OpD)

Gaussian fluctuations ?

Gaussian regime of fluctuations ($T_c^{SD} < T < T_c^{OD}$)





- Width in energy ~1mV compatible with gaussian fluctuations
- Quantitative comparison with Scalapino-Ferrel's model
- Thermal noise has to be taken into account $\Gamma = \Gamma_0 + \Gamma_1$

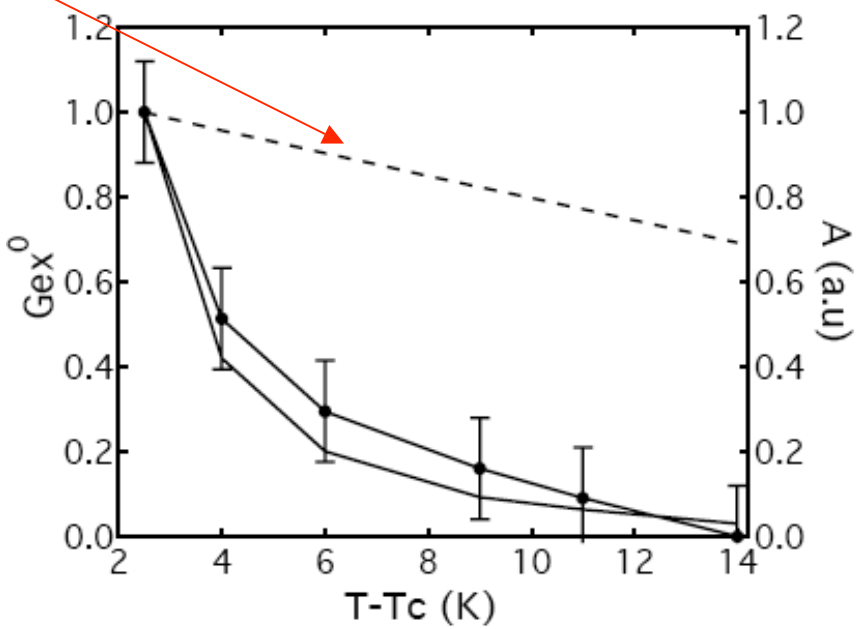
$$\Gamma_1 = 4e^2 R k_B T/\hbar^2$$

Only Gaussian fluctuations ? ($T_c^{SD} < T < T_c^{OD}$)

- The temperature dependence is controled by the barrier

- The temperature dependence of A calculated by Ferrel

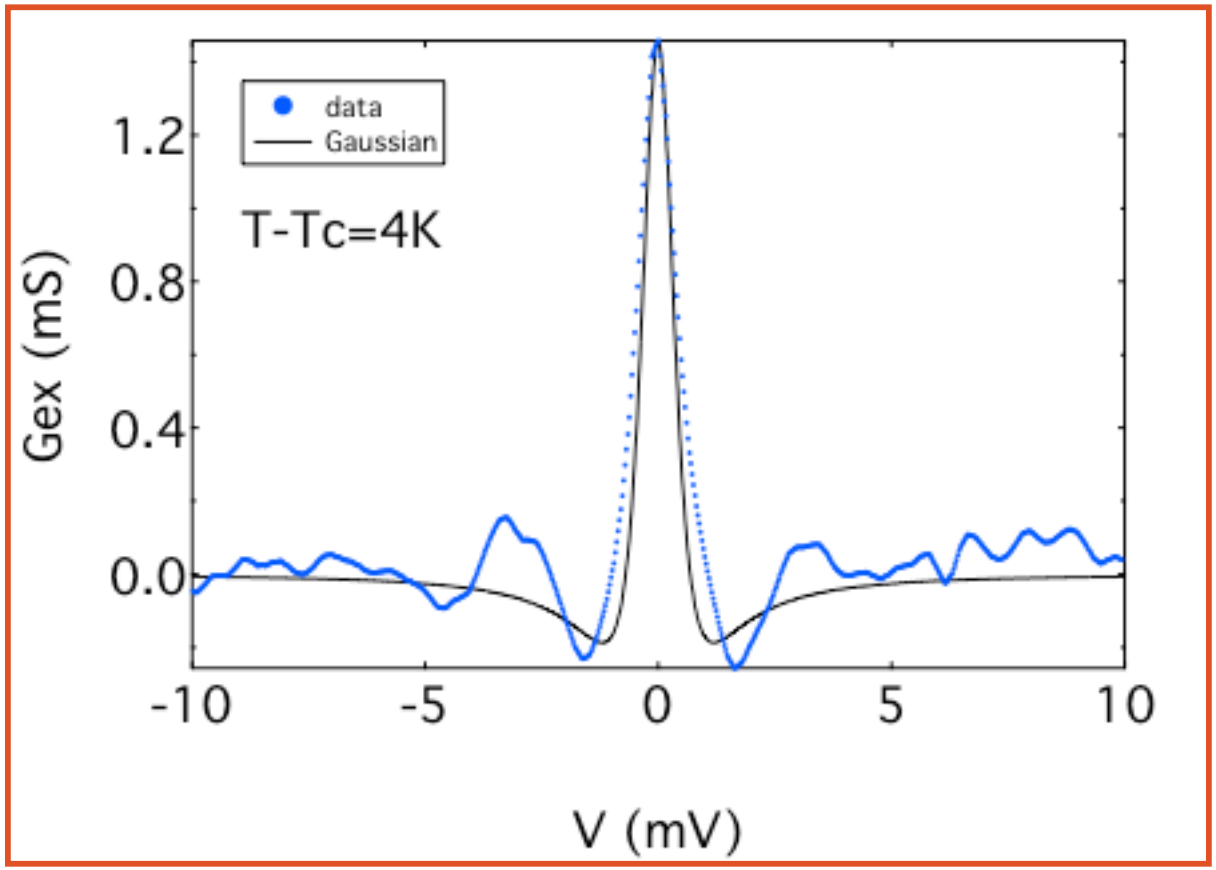
$$I_{ex}(V) = A\frac{\omega/\Gamma_0}{\epsilon[1+(\omega/\Gamma_0)^2]}$$



- What about the shape of the peak ?

Microwave ($T_c^{SD} < T < T_c^{OD}$)

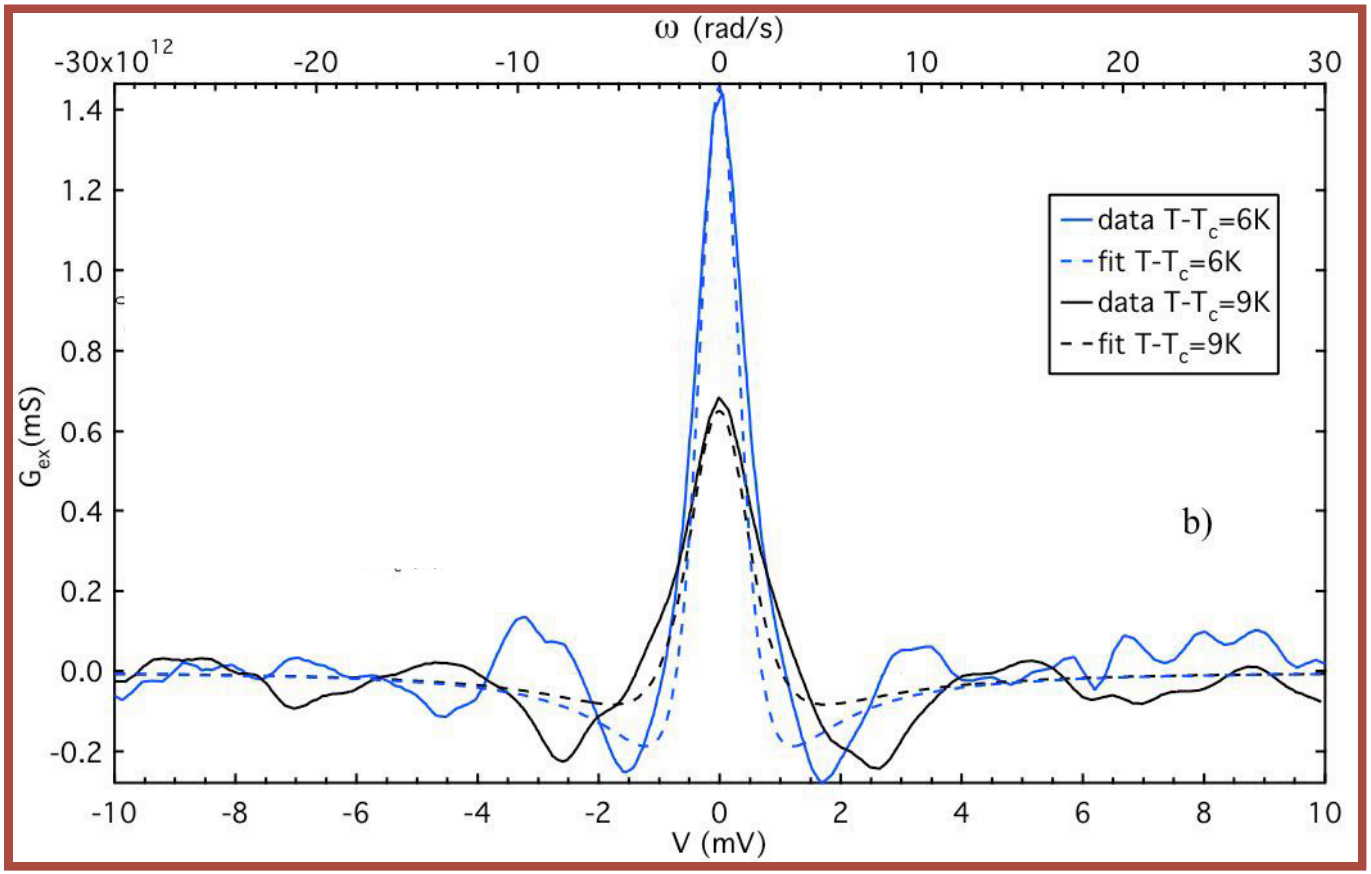
- Background substraction using microwave



- Excess conductance consistent with gaussian fluctuations

Microwave ($T_c^{SD} < T < T_c^{OD}$)

- Background substraction using microwave



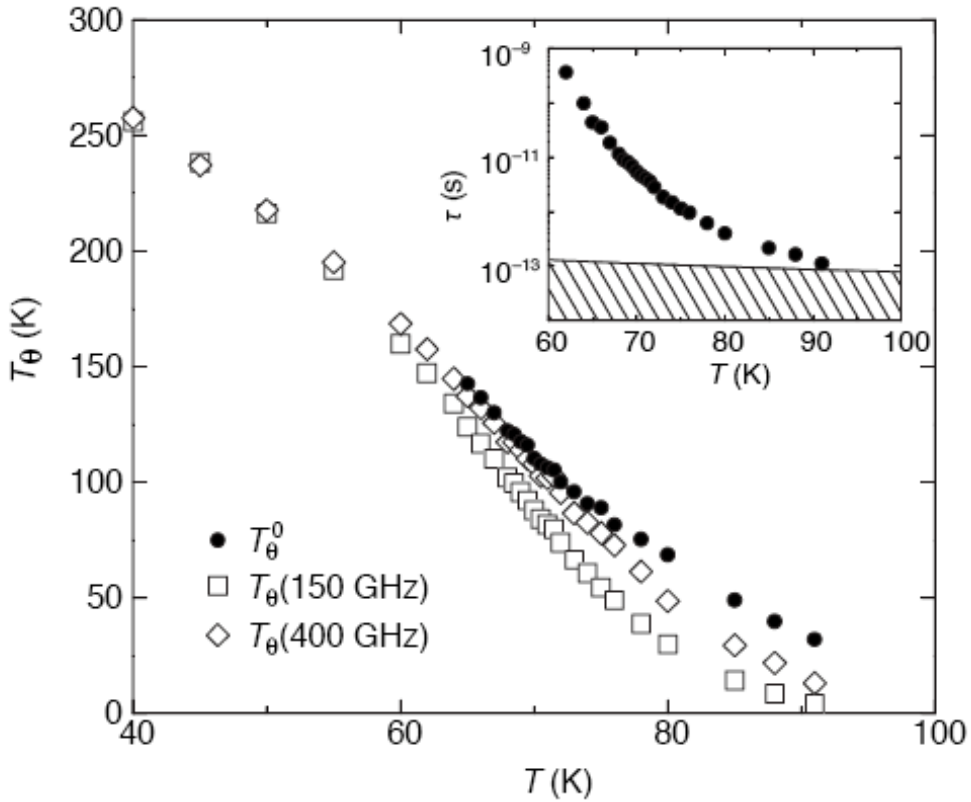
- Two different temperatures

Related experiments …

➢ Microwave conductivity and the K-T scenario

Vanishing of phase coherence in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$

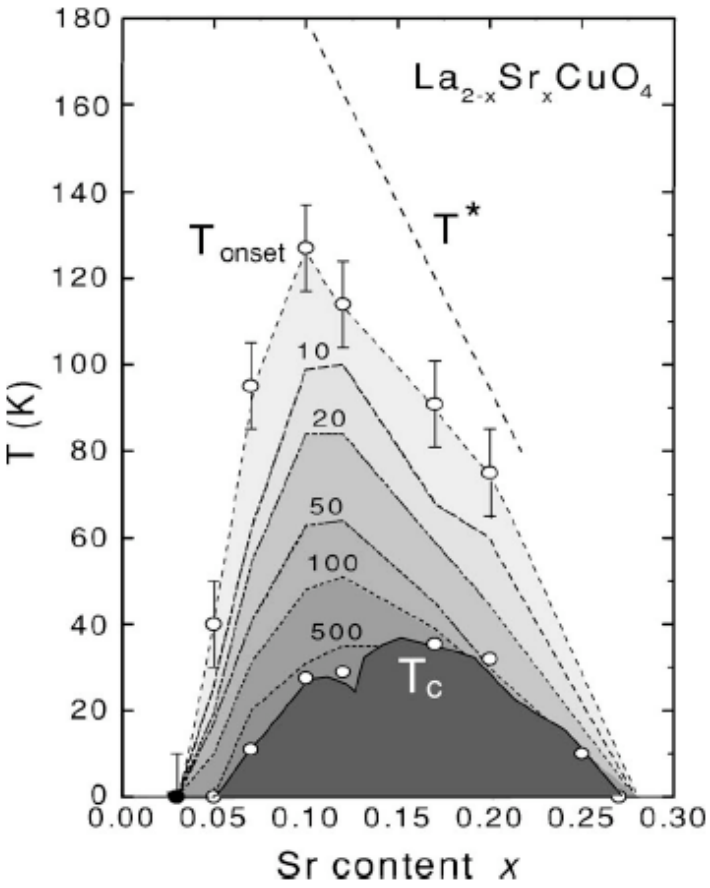
J. Corson*, R. Mallozzi*, J. Orenstein*, J. N. Eckstein† & I. Bozovic‡

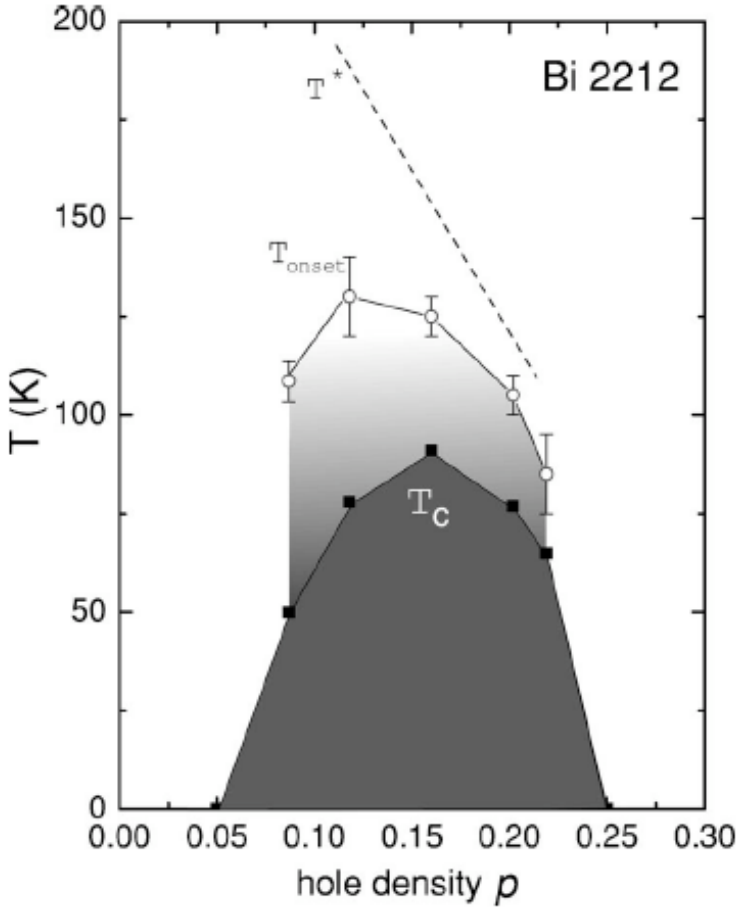


The parameters displayed in Fig. 4 suggest that while phase correlations indeed persist above T_c, they vanish well below T^*.

Related experiments … ???

➢ Nernst effect from Ong's group





Related experiments … ???

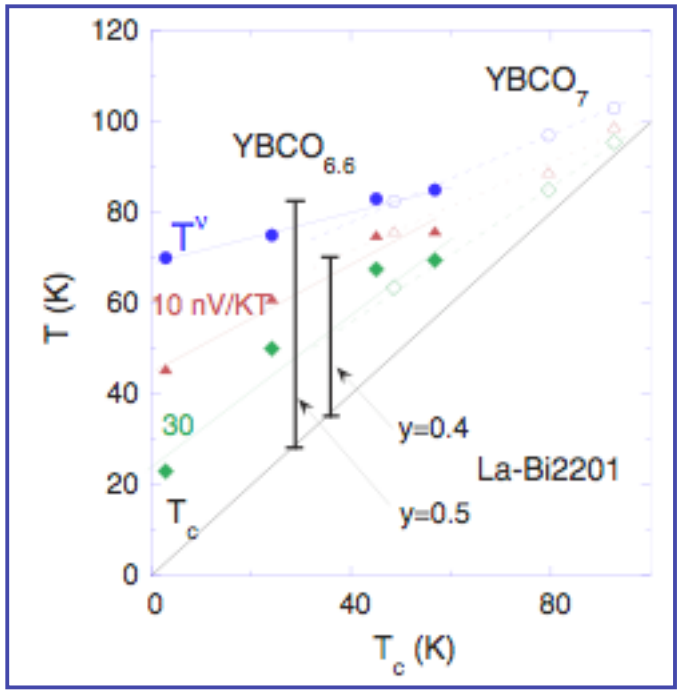
➢ But not the case in clean YBCO crystals (Rullier-Albenque PRL 2006)

PRL 96, 067002 (2006) PHYSICAL REVIEW LETTERS week ending 17 FEBRUARY 2006

Nernst Effect and Disorder in the Normal State of High-T_c Cuprates

F. Rullier-Albenque,[1] R. Tourbot,[1] H. Alloul,[2] P. Lejay,[3] D. Colson,[1] and A. Forget[1]

➢ Disorder plays a role



Nernst signal in dirty BCS superconductors above Tc …

➢ Theory : Ussishkin et al

VOLUME 89, NUMBER 28 PHYSICAL REVIEW LETTERS 31 DECEMBER 2002

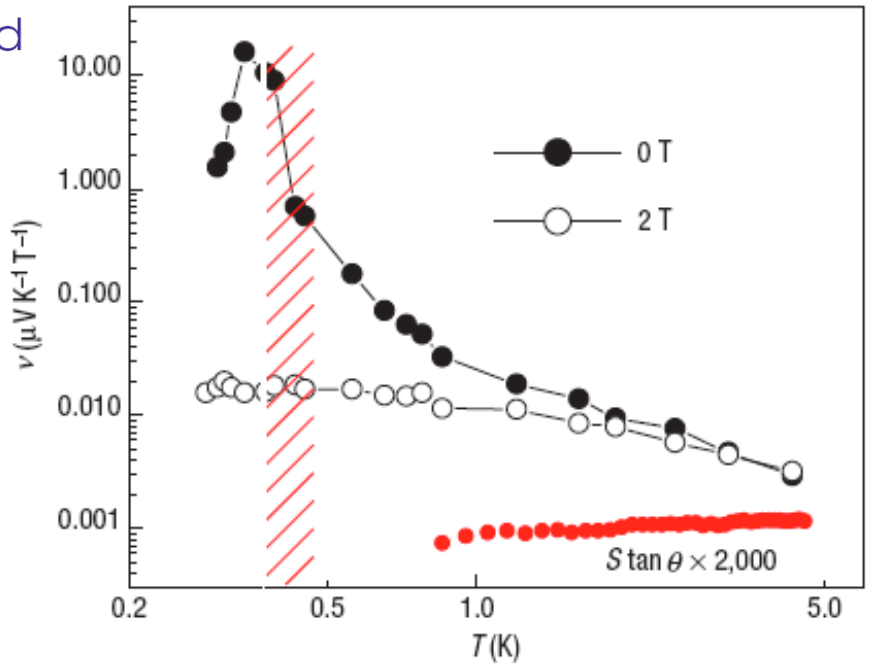
Gaussian Superconducting Fluctuations, Thermal Transport, and the Nernst Effect

Iddo Ussishkin, S. L. Sondhi, and David A. Huse

➢ Experiments : Pourret et al (Nature Physics 2006)

Observation of the Nernst signal generated by fluctuating Cooper pairs

A. POURRET[1], H. AUBIN[1]*, J. LESUEUR[1], C. A. MARRACHE-KIKUCHI[2], L. BERGÉ[2], L. DUMOULIN[2] AND K. BEHNIA[1]*



➢ Signal up to 30 x Tc

➢ Dirty limit !

➢ Quantitative agreement with calculation

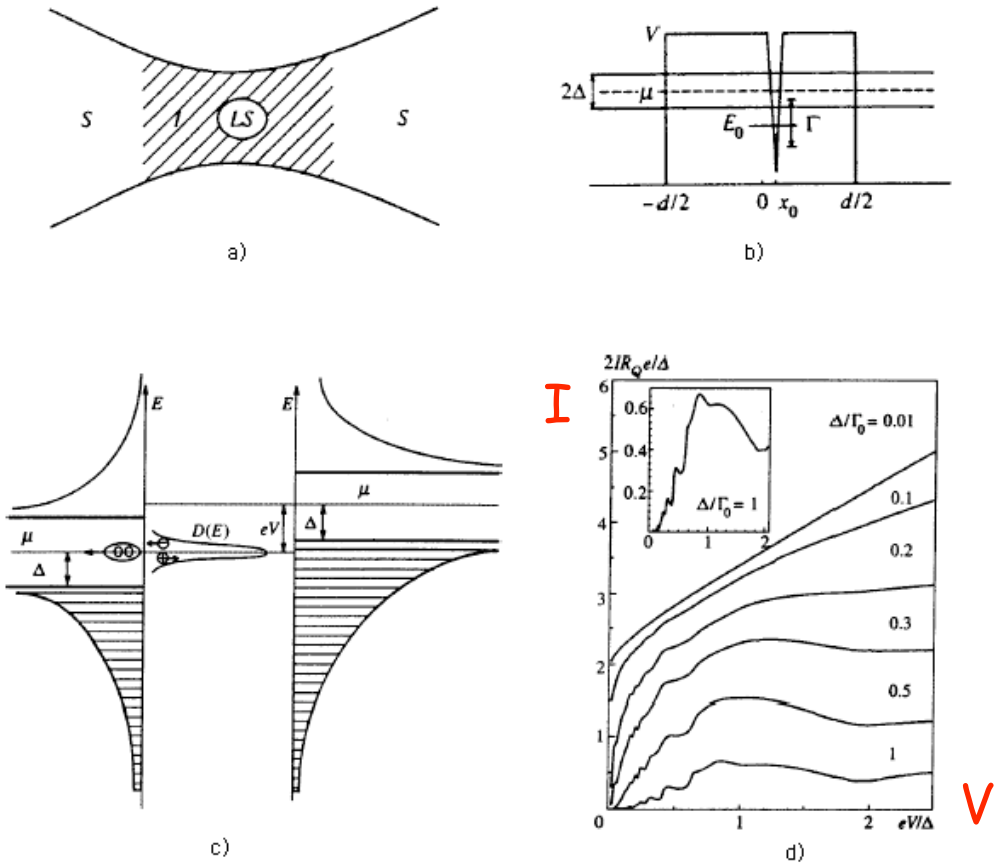
Conclusion

- Direct probe of pairing fluctuations above TC
- New type of junctions including UD and OpD layers
- Clear observation of a gaussian regime of fluctuations
- No signature of fluctuating pairs well above Tc (UD)
- Pseudogap : order in competition ???

N. Bergeal et al Nature Physics 4, 608 (2008)

Pair transport through Localized States

Devyatov '98



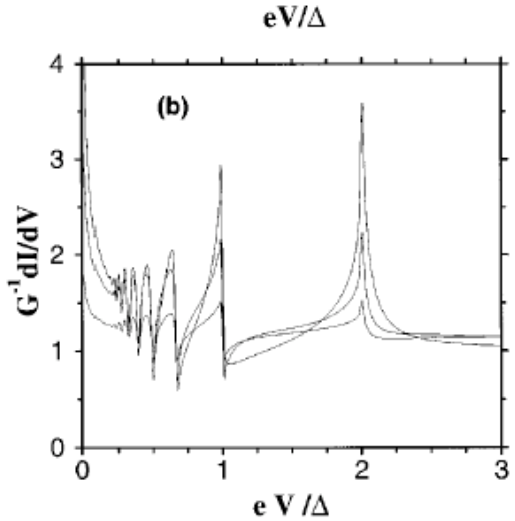


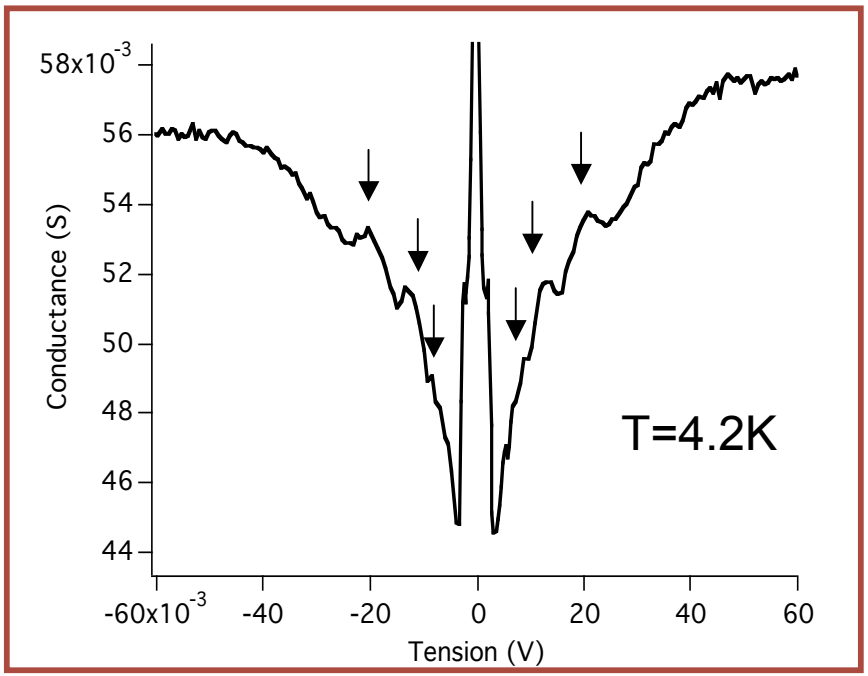
FIG. 2. The quasiparticle current (a) and the differential conductance (b) versus voltage at various temperatures, for a disordered SNS junction. From top to bottom $T = 0,1,2,3\Delta$. At low voltages, the dc current (a) has a square root dependence on voltage, while at high voltages exhibits excess current. The conductance (b) possesses subharmonic singularities, diverges at low voltages, and at high voltages asympotically tends to the normal state conductance of the disordered region.

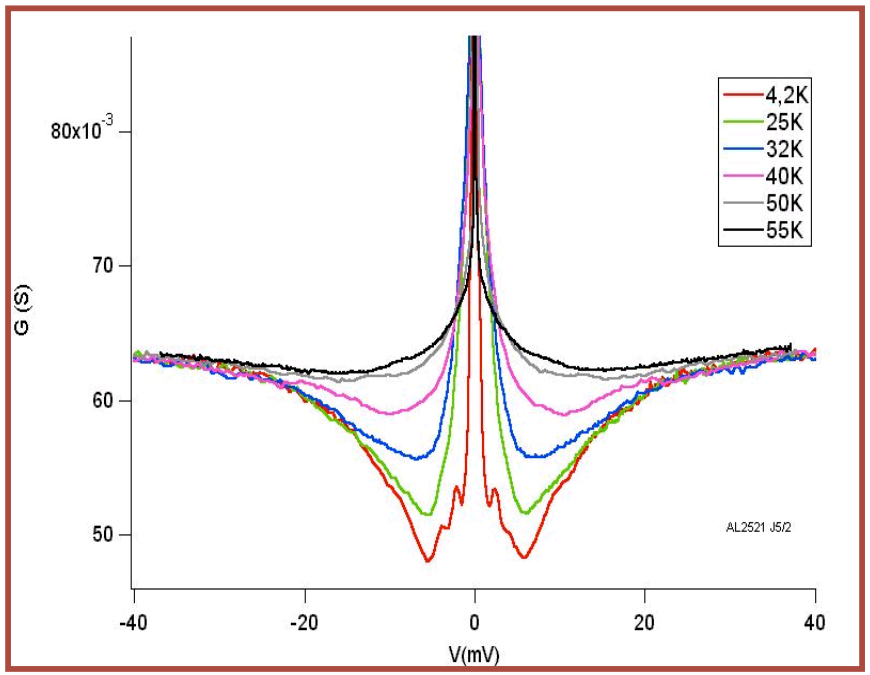
Localized States (Devyatov '98)

Mesoscopic junction (Averin '97)

Measurements at low temperature ($T<T_c^{UD}<T_c^{OpD}$)

- Transport through $PrBa_2Cu_{3-x}(Ga_x)O_7$
- Peak at low energy and resonances
- Multiple Andreev Reflection



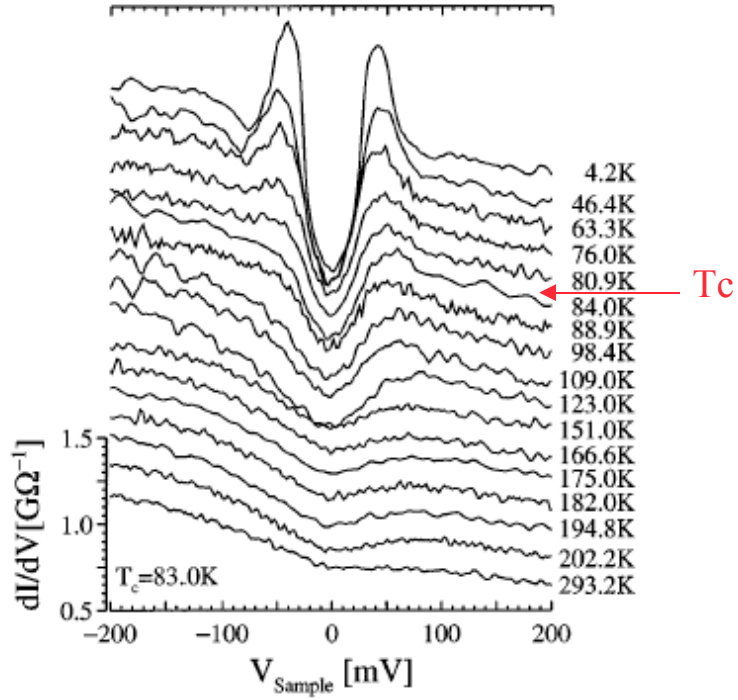


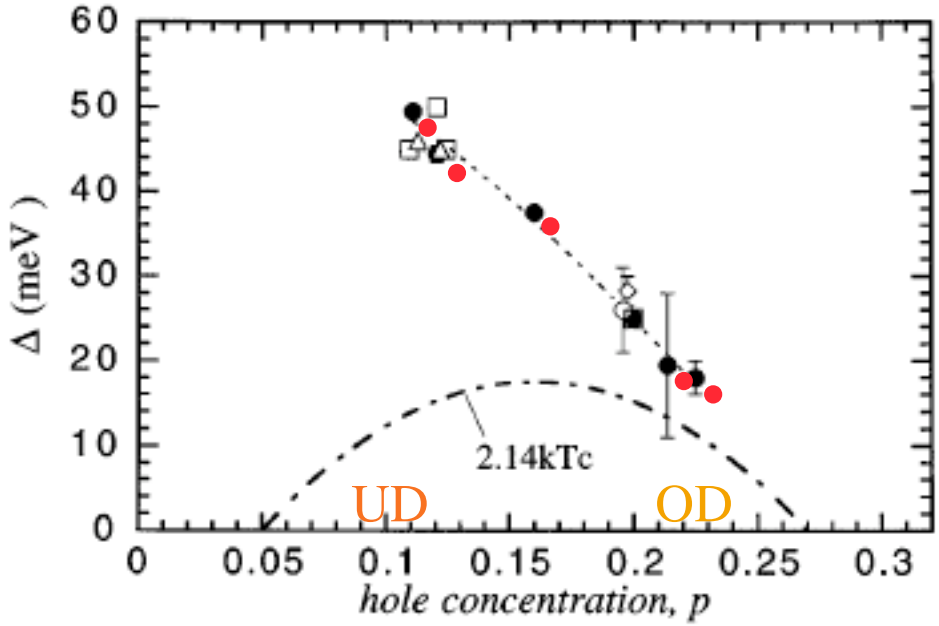
Pseudogap in the charge channel (STM)

➢ STM (Renner '98)

Underdoped Tc = 83 K

UnderDoped BSCCO

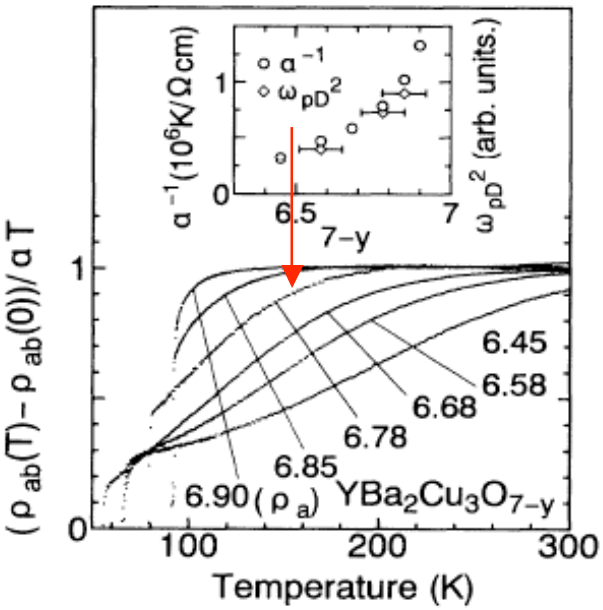




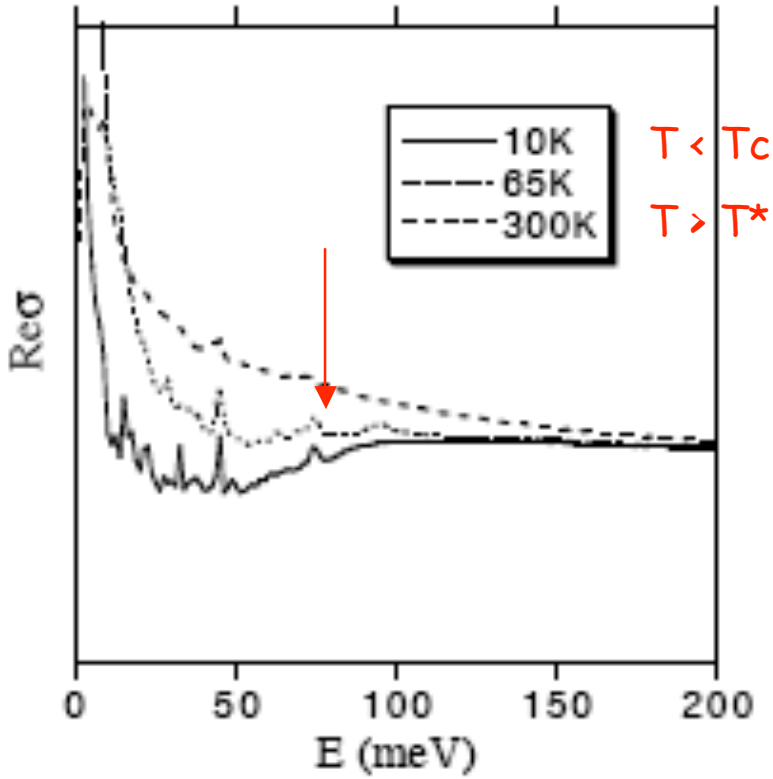
●this experiment ▫ARPES ▵ other experiments

Pseudogap in the charge channel (conductivity)

UnderDoped YBCO



a)

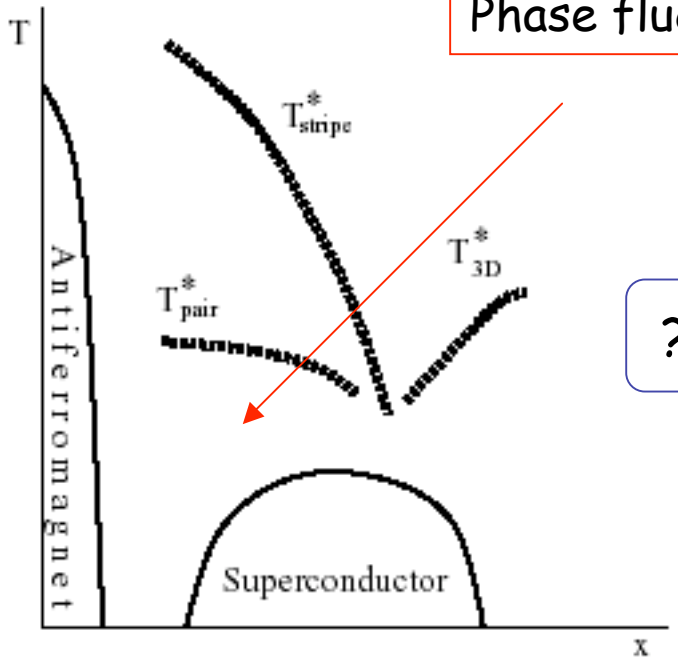


➢ DC resistivity (Itoh '93)

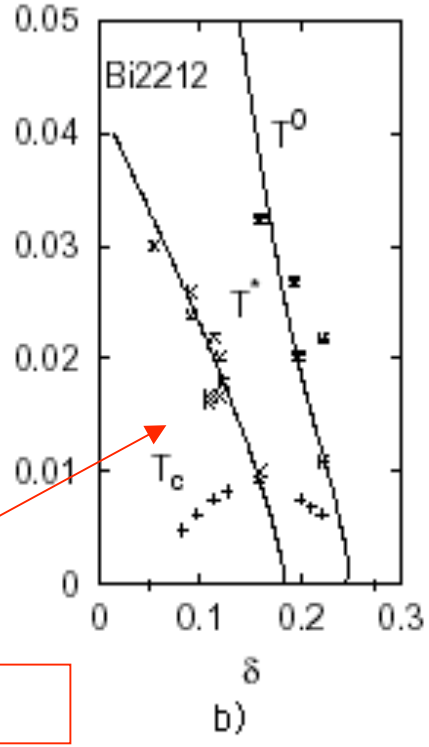
➢ AC conductivity (Homes '93)

Scenarios for the Pseudogap …

Phase fluctuations



? Stripes ?



➢ Emery-Kivelson '97

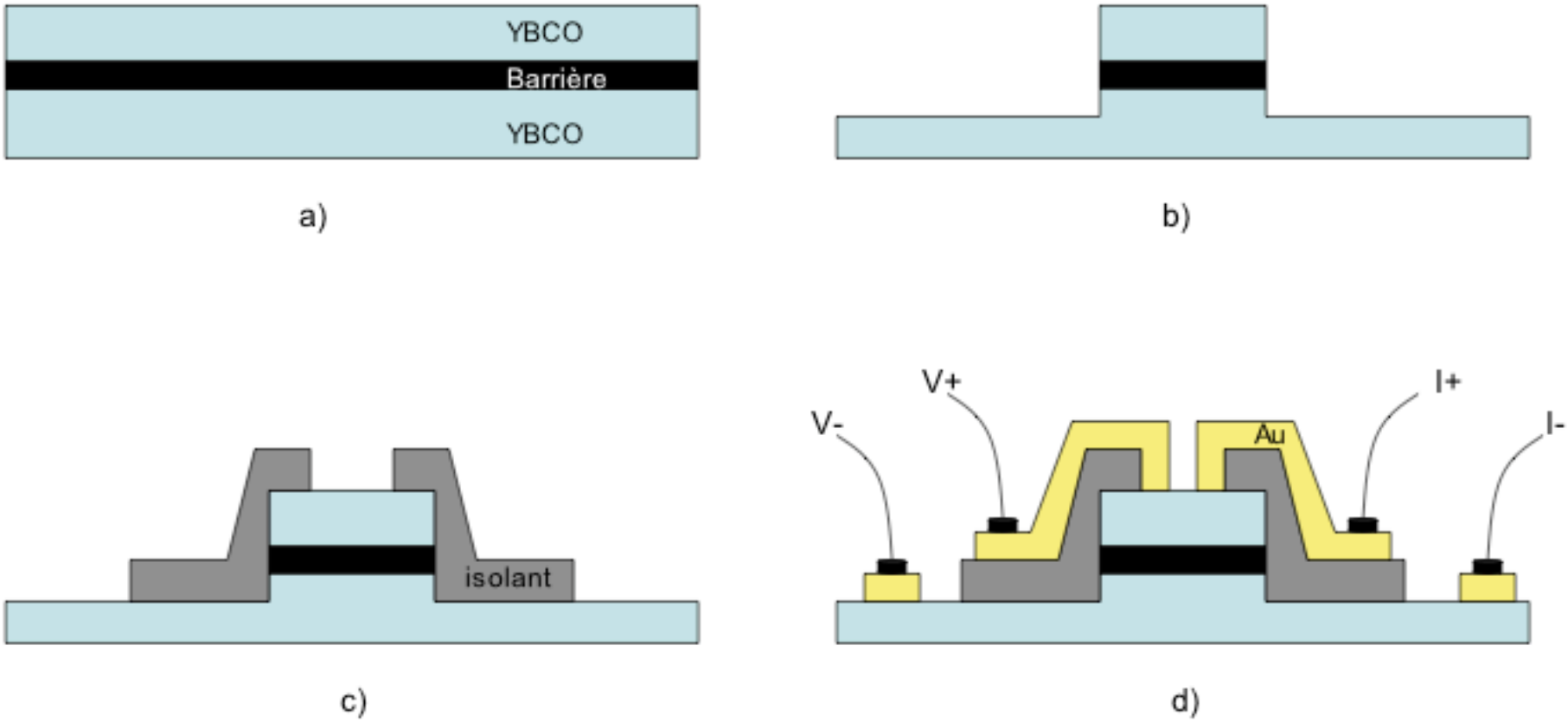
Competing order

➢ Rome's group '95

➢ Relation between the Pseudogap and Superconductivity ?

How to define the junction ? mesa structure ...

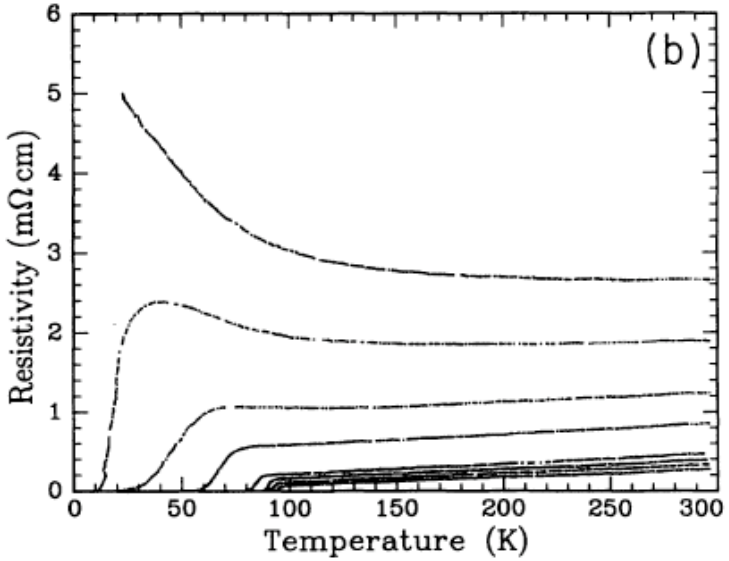
➢ Standard mesa structure

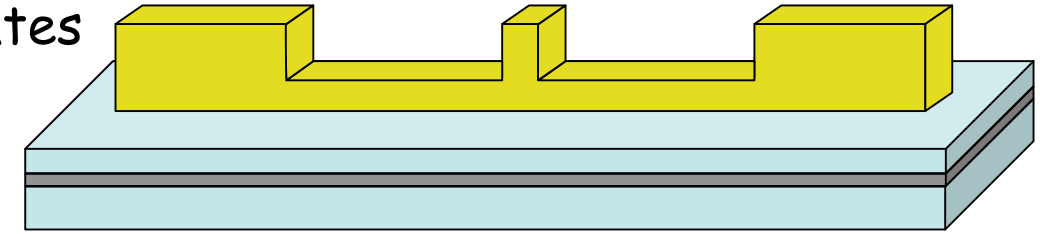


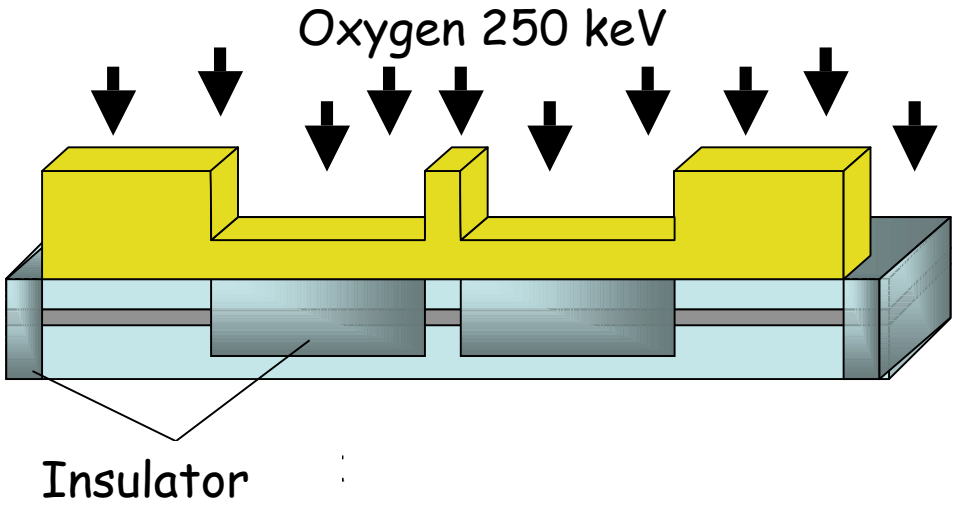
➢ Delicate ; difficult to make very small structures

New method to design mesa structures

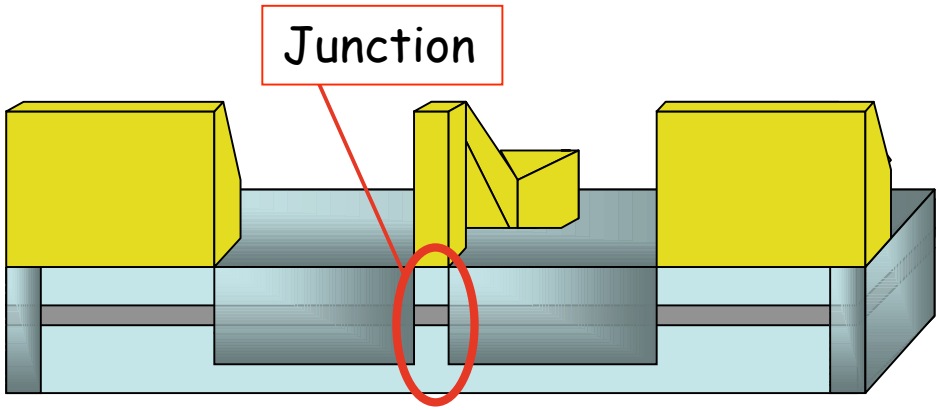
➢ Ion beam irradiation of cuprates







Dose : 5 10^{15} at/cm^2



Areas : 5 μm*5μm
to 40μm*40μm