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

Jérôme Lesueur

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G. Faini, LPN
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Collège de France 2010

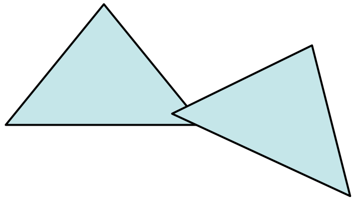
N. Bergeal et al Nature Physics 4, 608 (2008)

Cuprates superconductors : a consensus ?

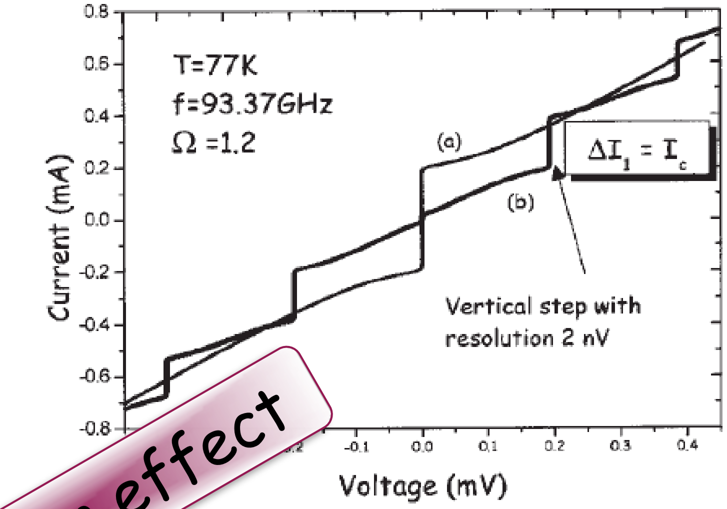
Cooper Pairs

$$\boxed{\Phi_0 = \frac{h}{2e}}$$

Esteve et al, EPL '87

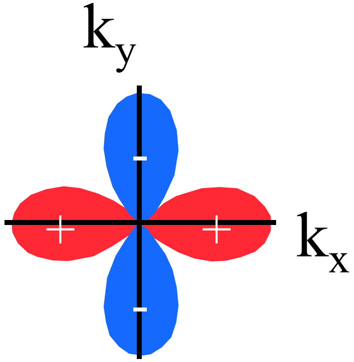


LSCO break junction



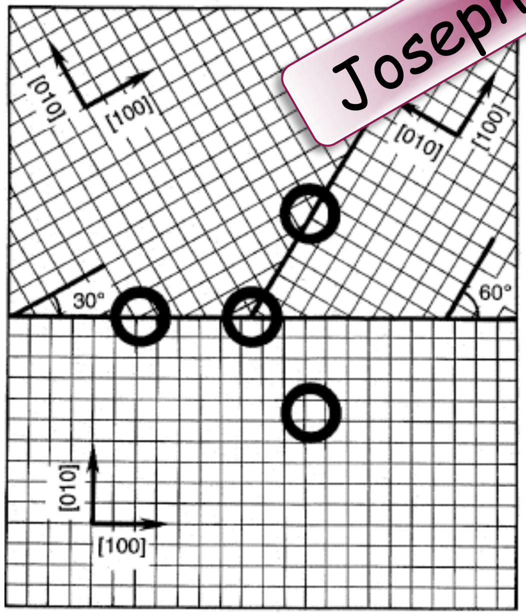
Josephson effect

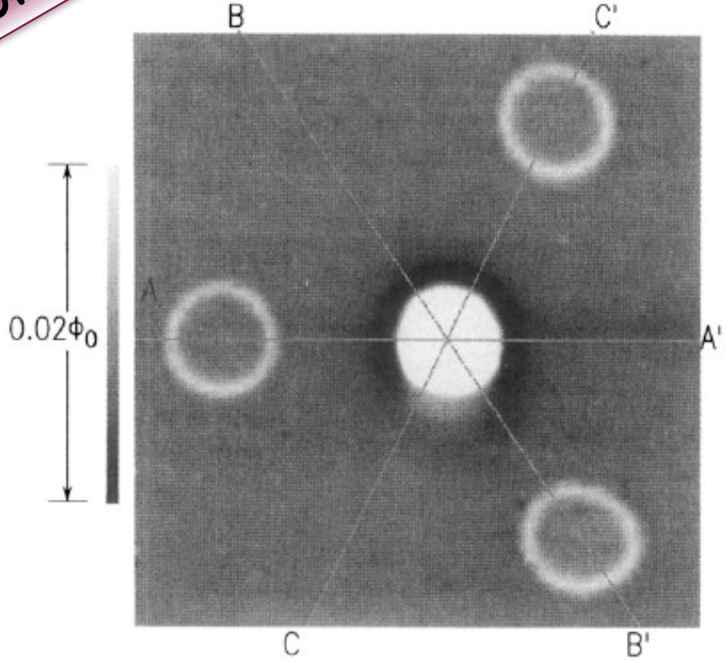
D wave order parameter



$$\boxed{d_{x^2-y^2}}$$

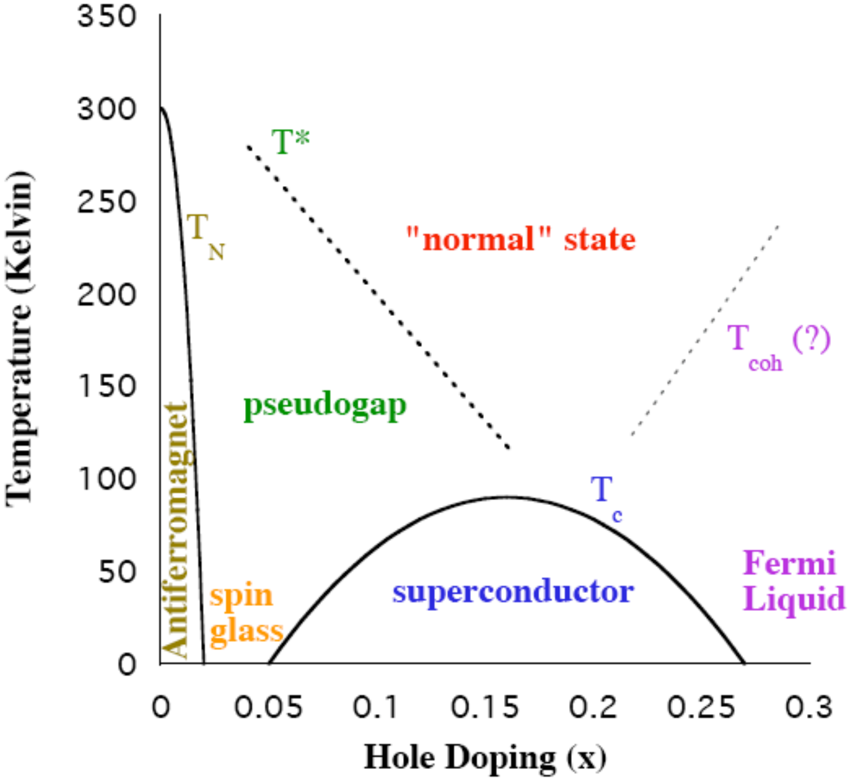
Tsuei et al, PRL '94



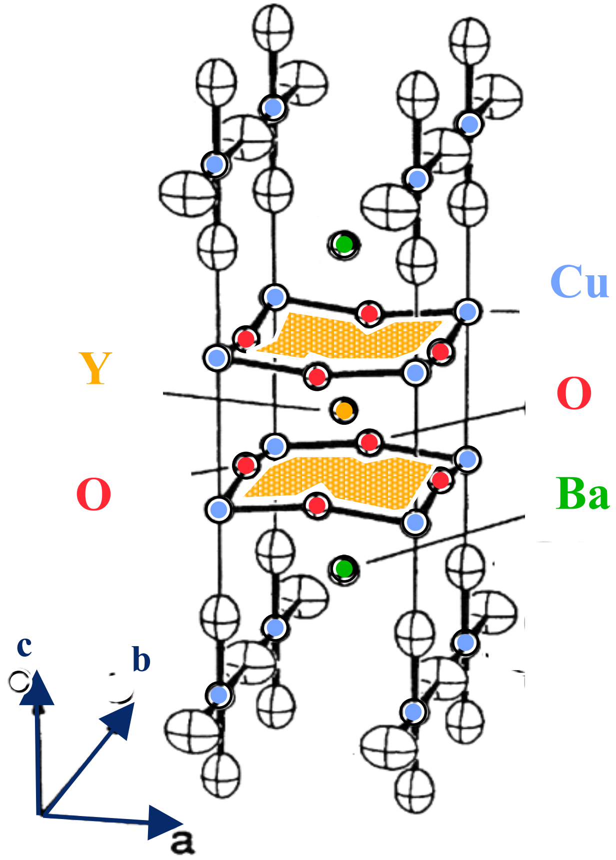


Cuprates phase diagram

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



$YBa_2Cu_3O_{6+x}$ T_c=90K



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. Fluctuations in cuprates
    - Amplitude fluctuations
    - Phase fluctuations
5. Conclusion

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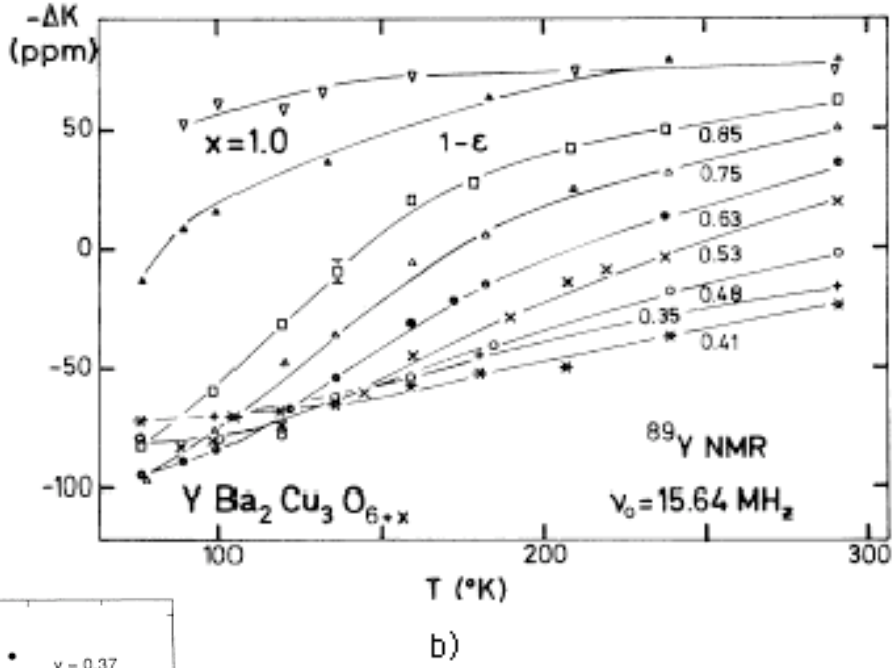
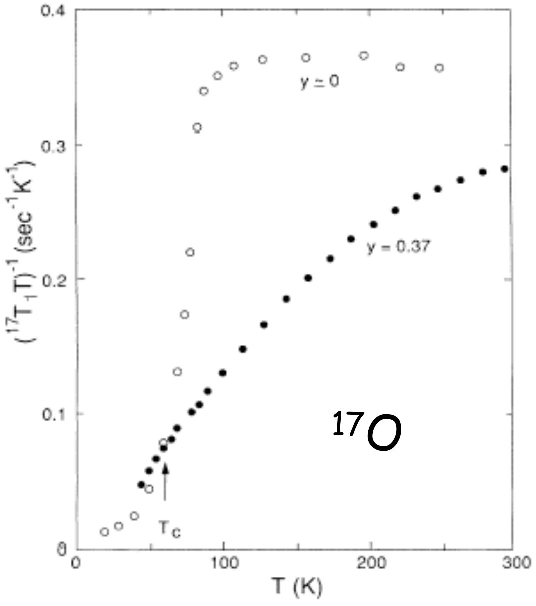
Pseudogap in the spin channel (NMR)

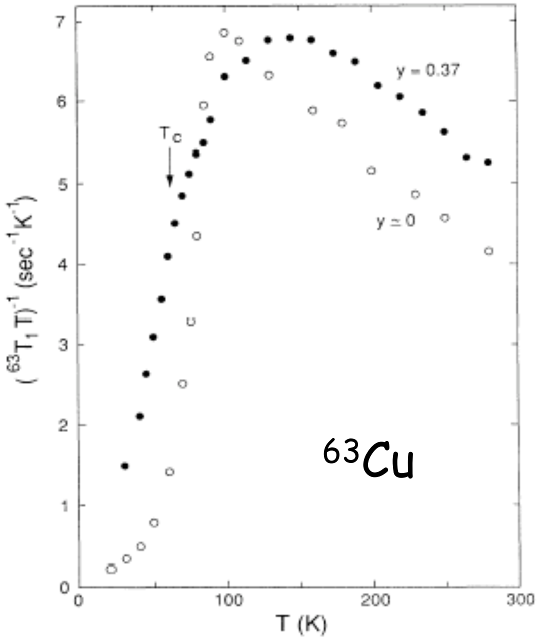
- Knight-shift (Alloul ‘89)

UnderDoped YBCO





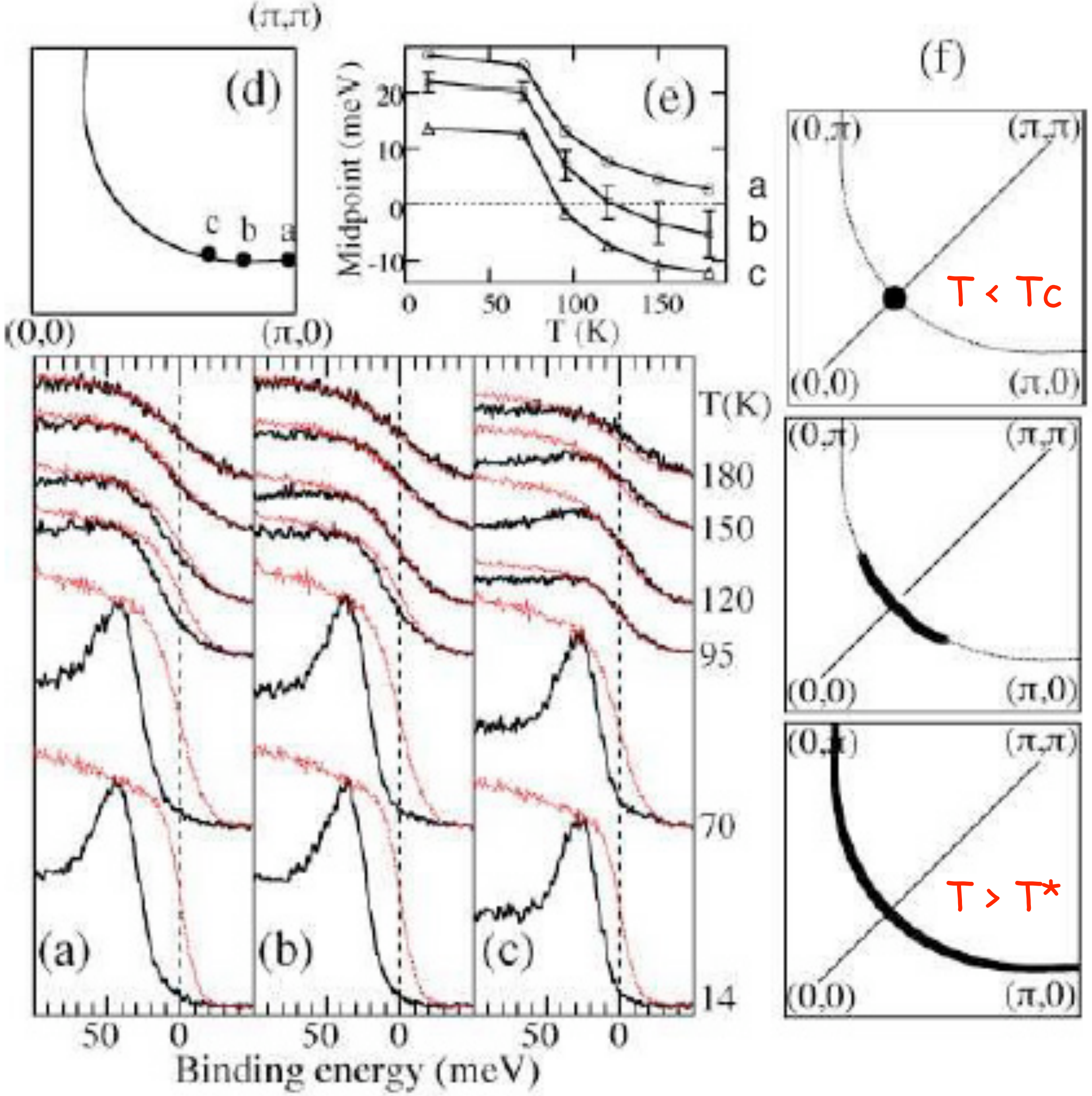
^{17}O

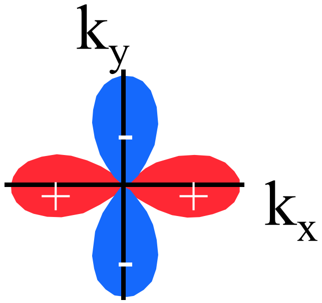


^{63}Cu

- $1/T_1T$ (Takigawa ‘91)

Pseudogap in the charge channel (ARPES)

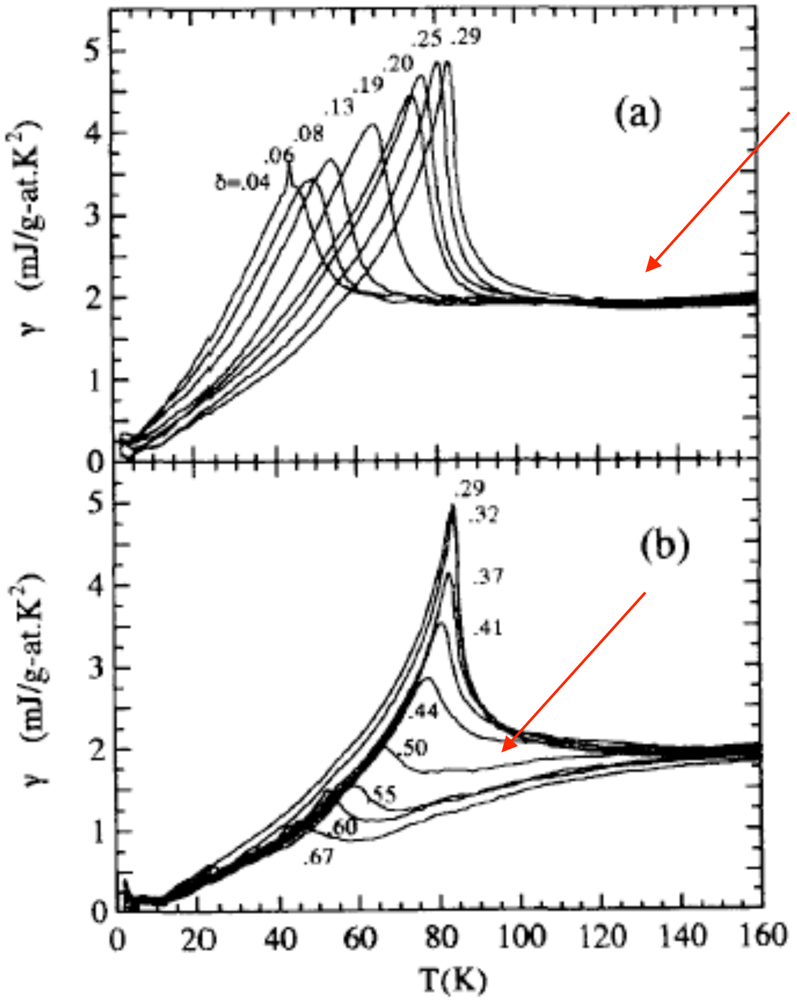




UnderDoped BSCCO

- ARPES (Norman '98)

Pseudogap in the excitations spectrum



OverDoped YBCO

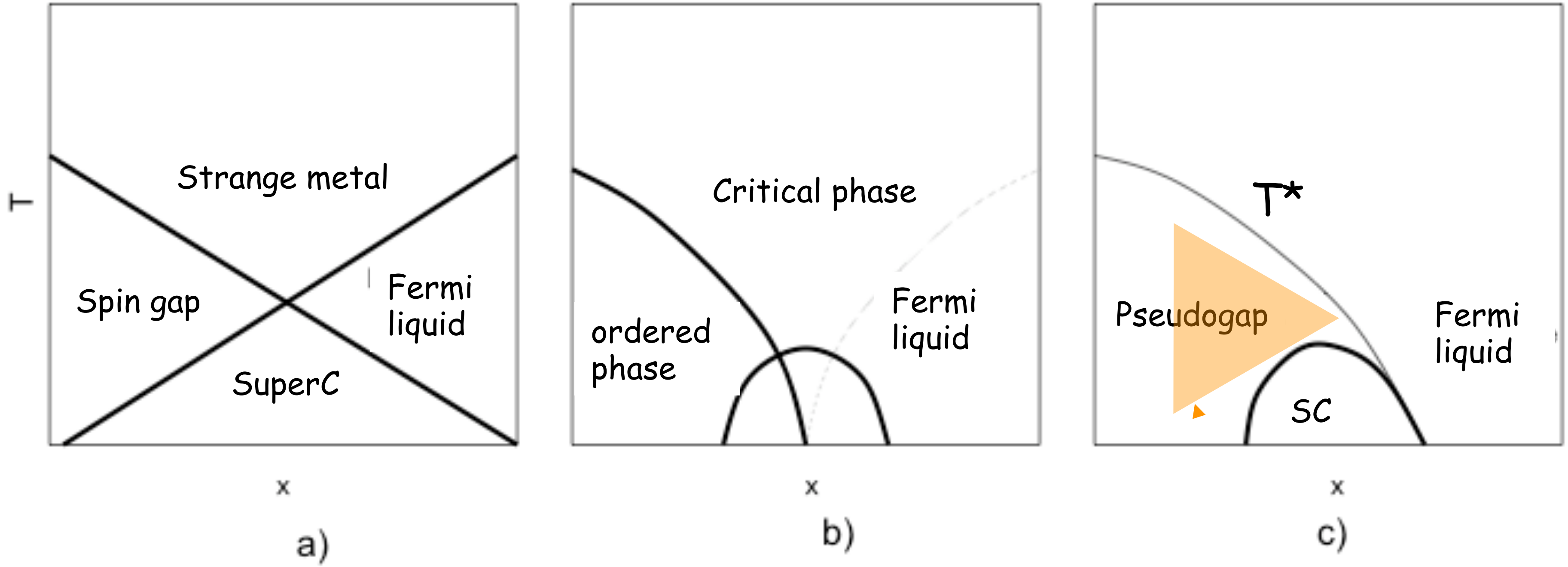
UnderDoped YBCO

- ➢ Specific heat (Loram '97)

- ➢ Lost of spectral weight

- ➢ Both in charge and spin channels (Entropy)

Scenarios for the Pseudogap …

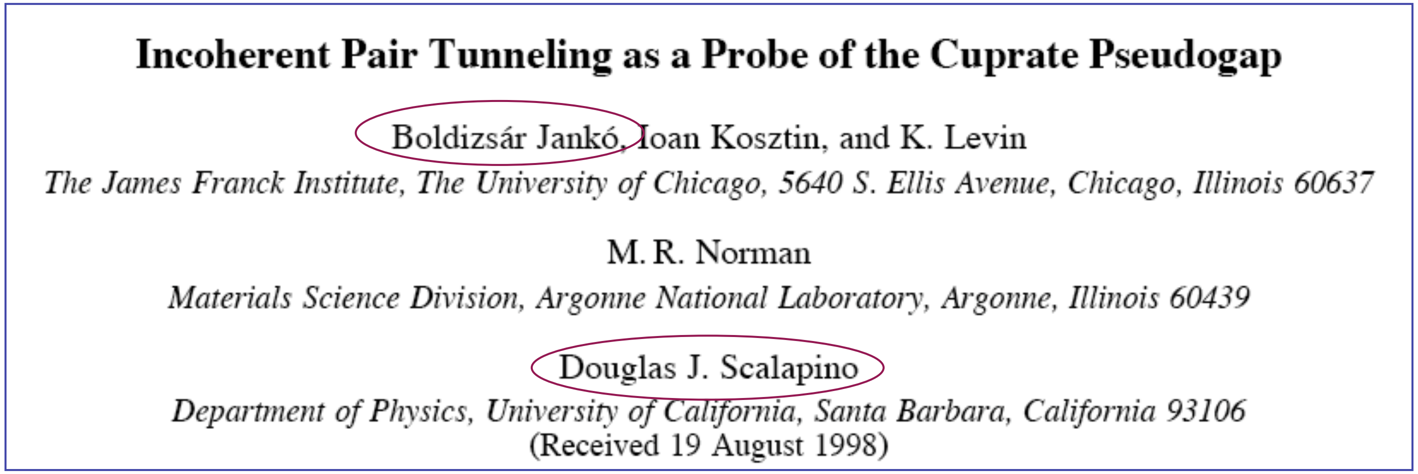


- ➢ RVB like
- ➢ QCP like
- ➢ Preformed pairs

- ➢ 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

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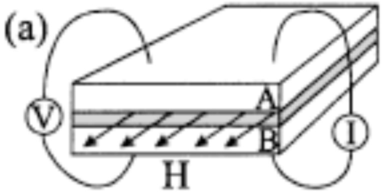
The James Franck Institute, The University of Chicago, 5640 S. Ellis Avenue, Chicago, Illinois 60637

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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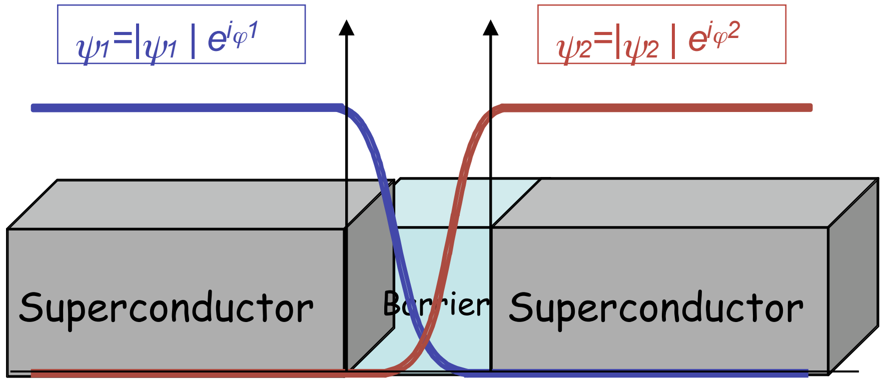
Josephson effect



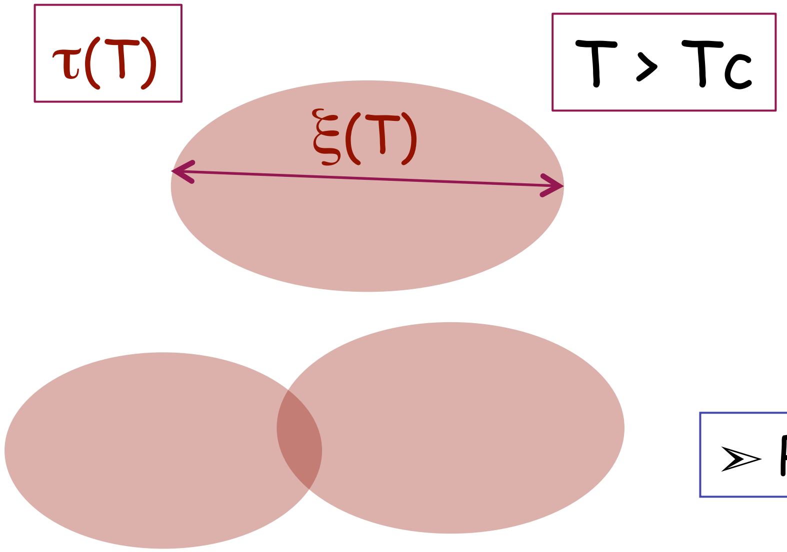
➢ Josephson equations

Phase sensitive probe

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

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

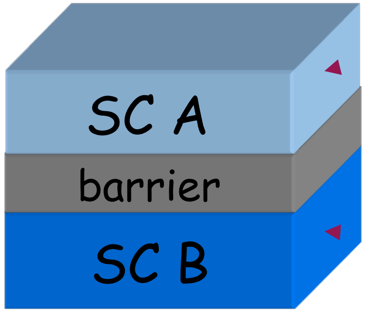
Time dependence



➢ Probing superconducting 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

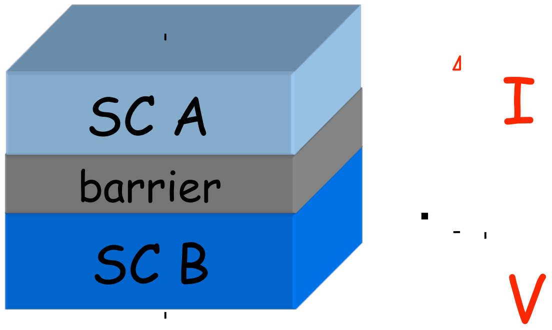
$$\chi^{-1}(q,\omega) = N_0\varepsilon\left[i\omega\tau + (1+\xi^2 q^2)\right]$$

Frequency $\omega = 2eV/\hbar$

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

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

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

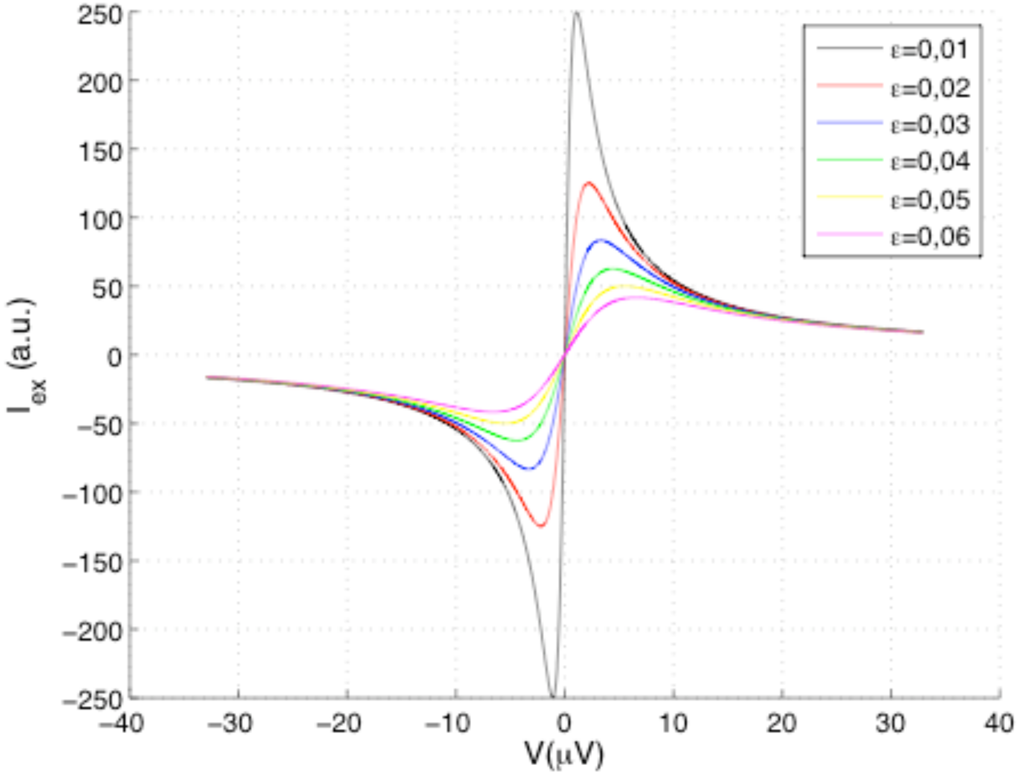


$$I_1\left(V,H\right) \propto \operatorname{Im}\chi(\omega,q)$$

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

- Tc A < T <Tc B

- ➢ Excess current



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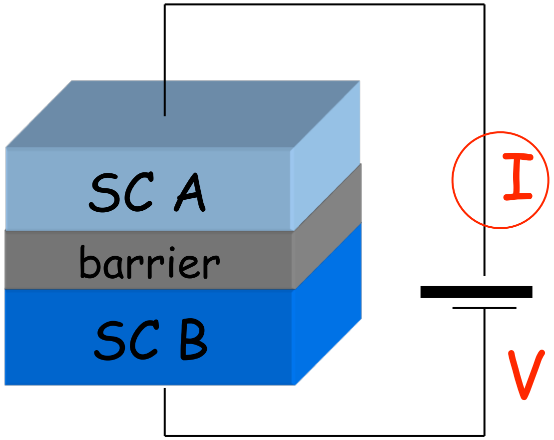


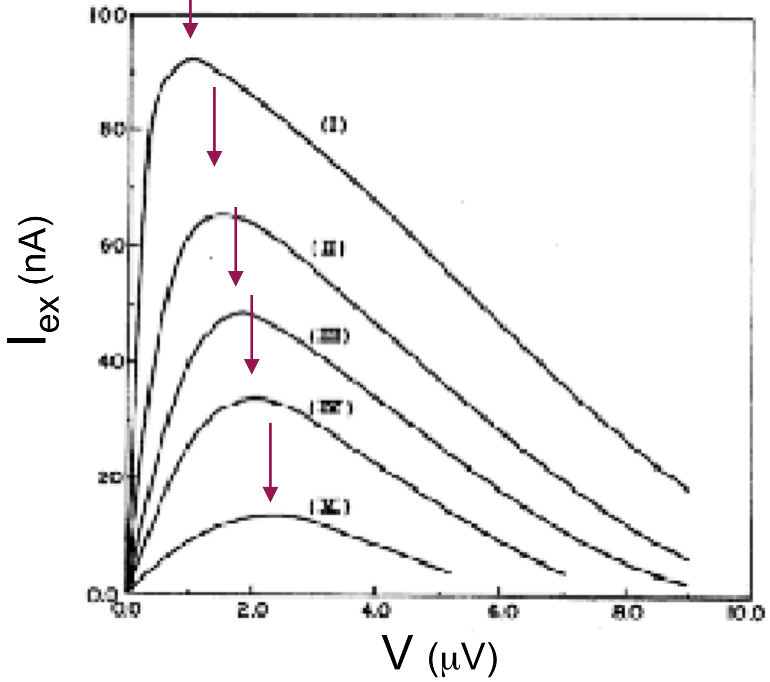
$Tc\ A < T < Tc\ B$

- ➢ Excess current (Im - Iqp)
- ➢ V sets the frequency

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

$$\boxed{\Gamma_0 = 1/\tau}$$

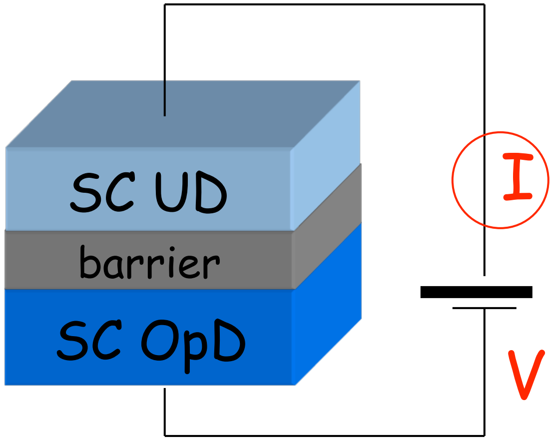
$$\Gamma_0 = \frac{16k_B}{h}(T-T_c)$$



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)



Tc UD < T <Tc OpD

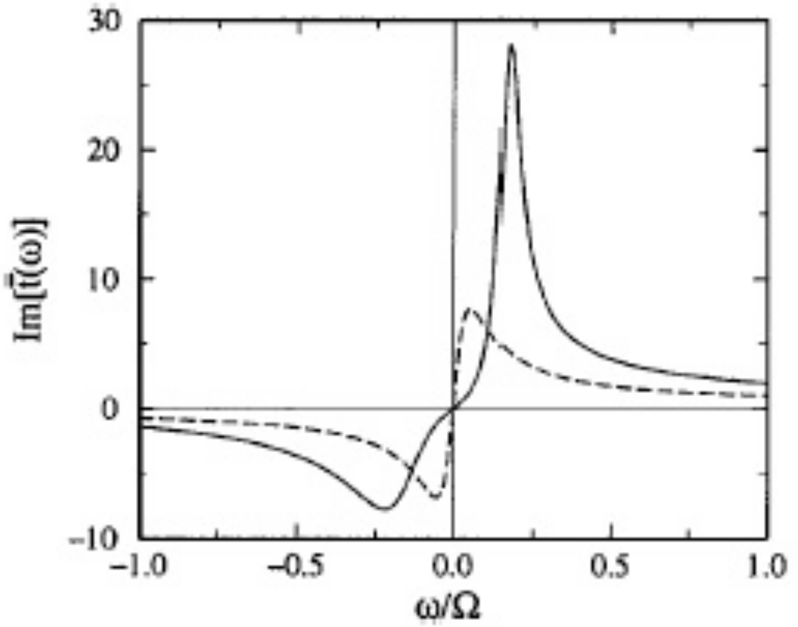
Underdoped : fluctuating pairs

- Excess current

Optimally doped : rigid pair field

- Up to T* (Tc OpD)
- Independent of a

  specific scenario !!!
- Difficult !!!

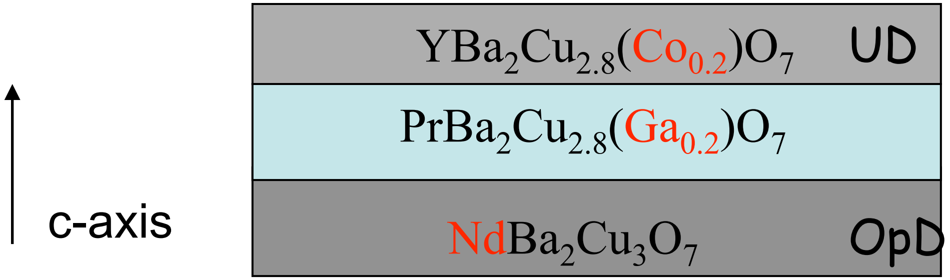


Design of the experiment

➢ Requirements :

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

T* (UD) = 250 K



$YBa_2Cu_{2.8}(Co_{0.2})O_7$ UD 100 nm

$PrBa_2Cu_{2.8}(Ga_{0.2})O_7$ 30 or 50 nm

$NdBa_2Cu_3O_7$ OpD 200 nm

c-axis

Tc (UD) = 61 K

Tc (OpD) = 90 K

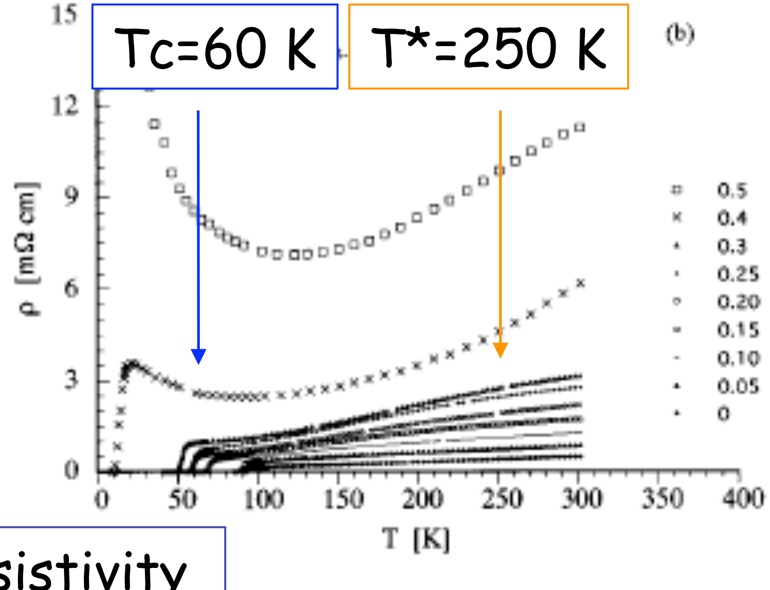
J.P Contour (Thales/CNRS)

The UnderDoped material …

➢ Carrington '92

➢ Co-doped YBCO :

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

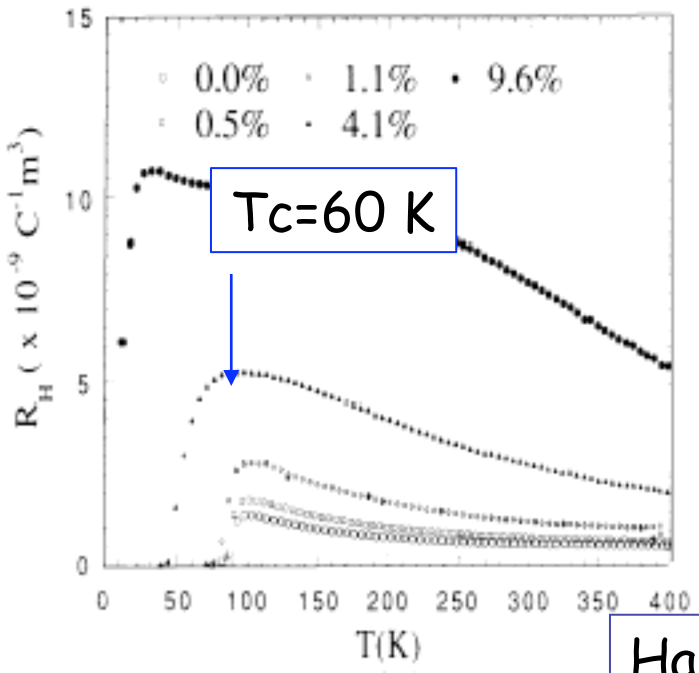


Tc=60 K

T*=250 K

Resistivity

a)



Tc=60 K

Hall Cste

b)

The Barrier ...

➢ Glazman - Matveev

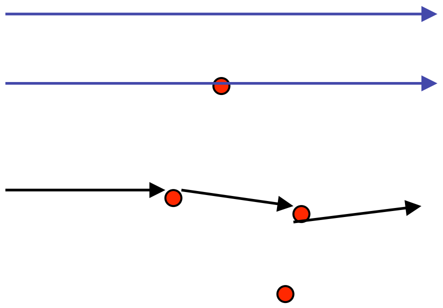
➢ Ga-doped PBCO :

- 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

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

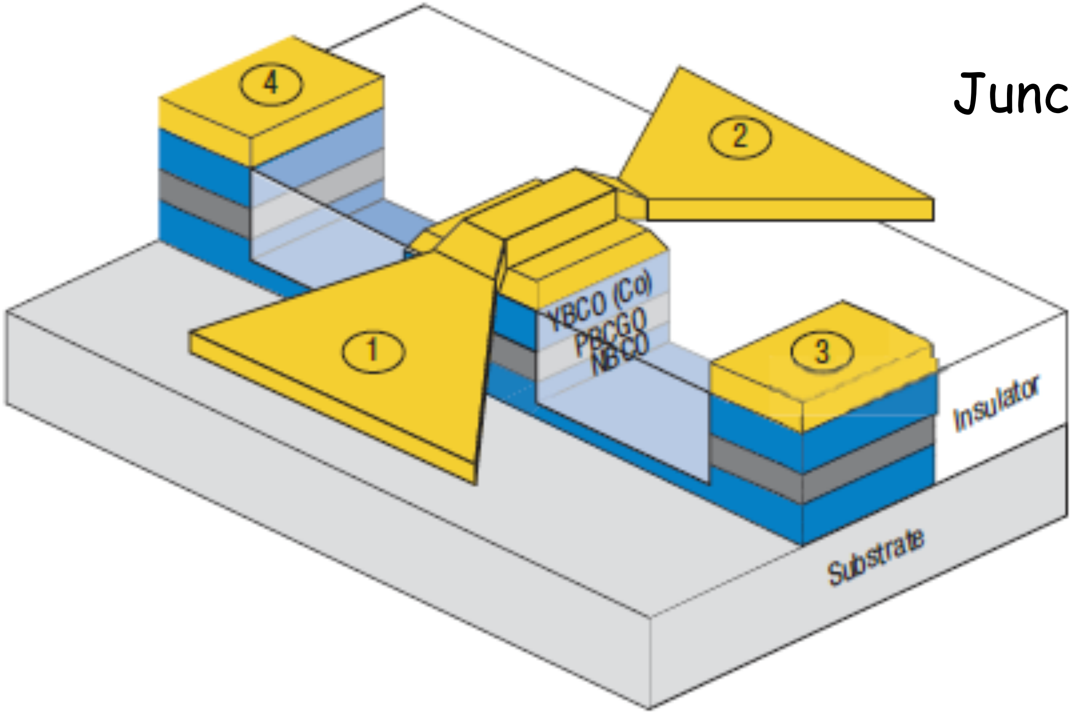


elastic

inelastic

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

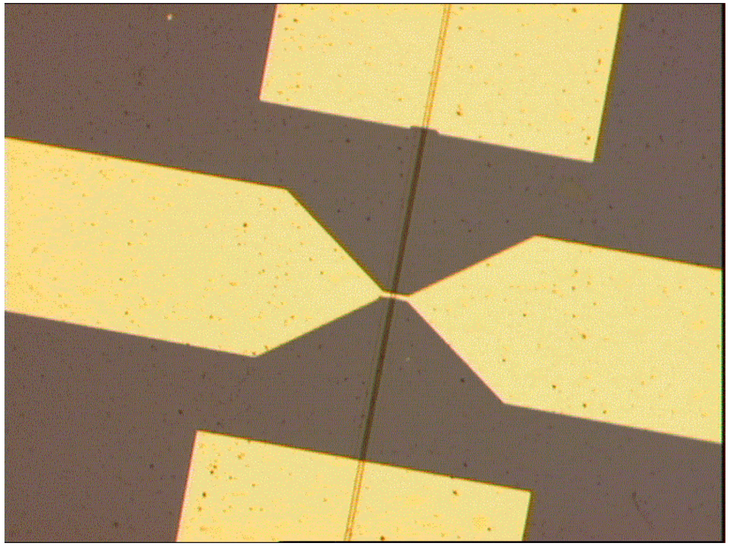
Mesas used in this study



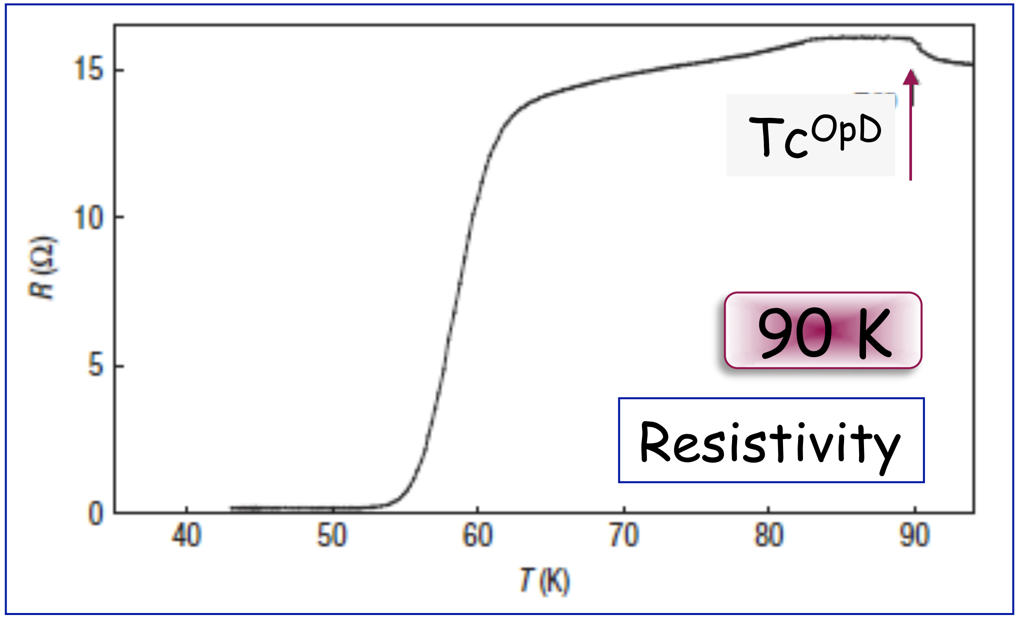
Mesa structures

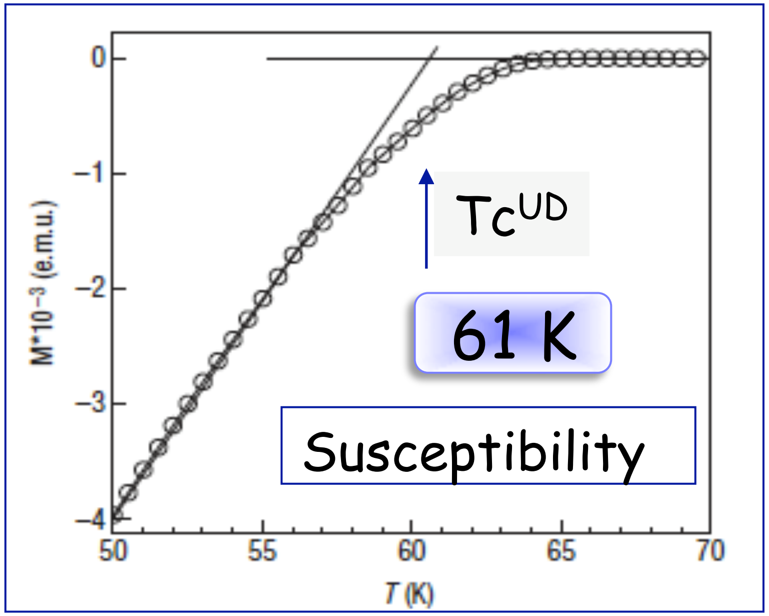
Junctions 40μm*40μm to 5μm*5μm

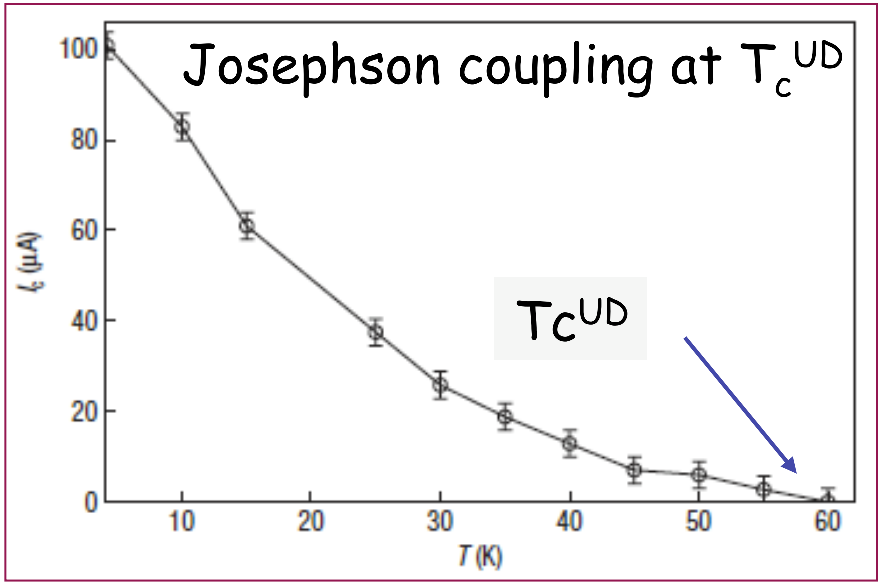
- ➢ Good equipotentials
- ➢ Gold resistance in series (150 mΩ)
- ➢ Barrier resistance >> other resistances



Caracteristic temperatures







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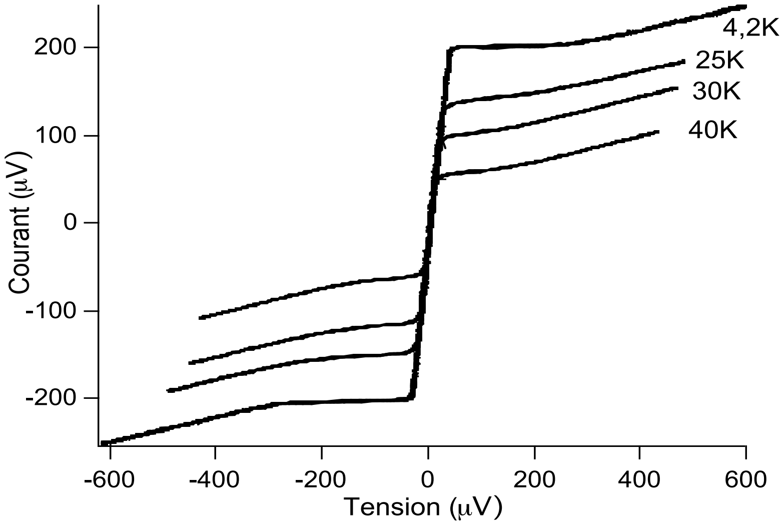
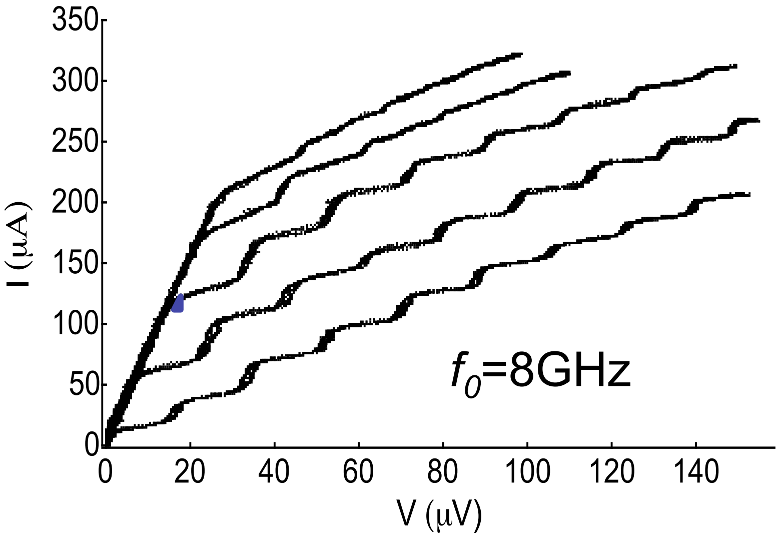
Josephson effect at low temperature ($T<T_c^{UD}<T_c^{OpD}$)

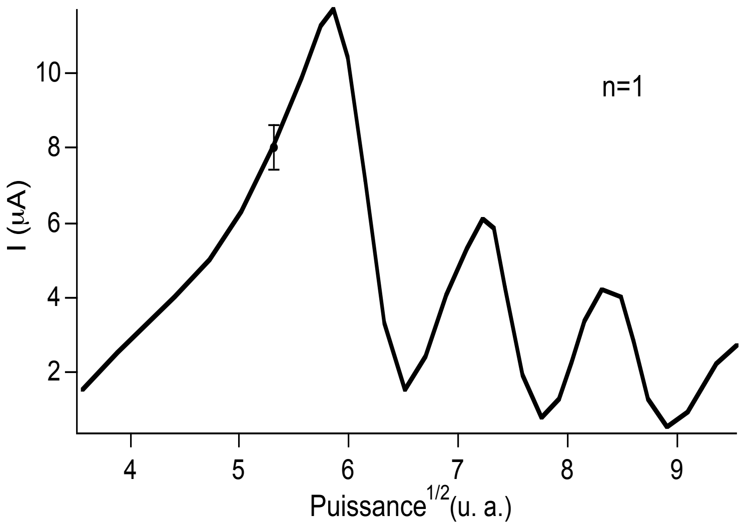


- ➢ RSJ Josephson I-V characteristics

Coupling IcRn = 2mV

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

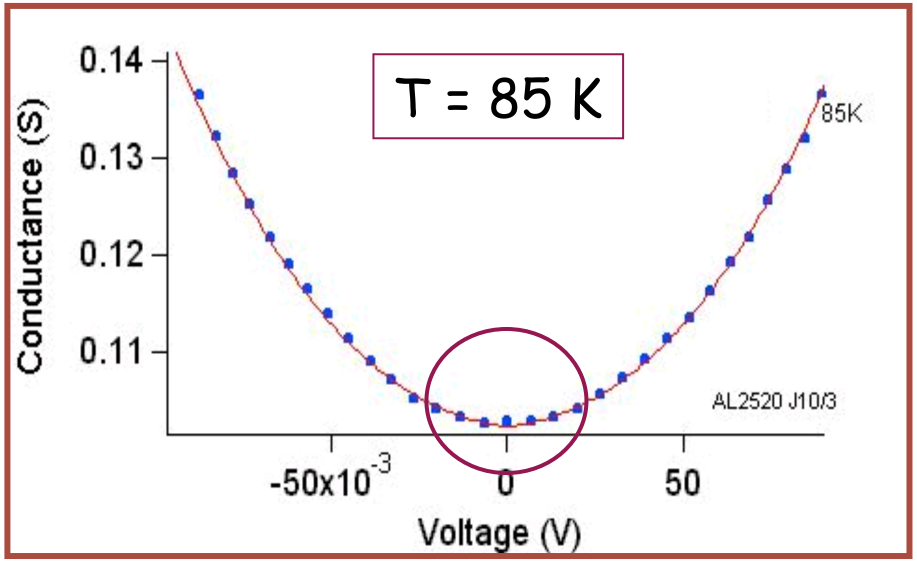




Transport through $PrBa_2Cu_{3-x}(Ga_x)O_7$ ($T_c^{UD} < T_c^{OpD} < T$)

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

  30 nm : 1 or 2 LS
- Corresponding T dependence

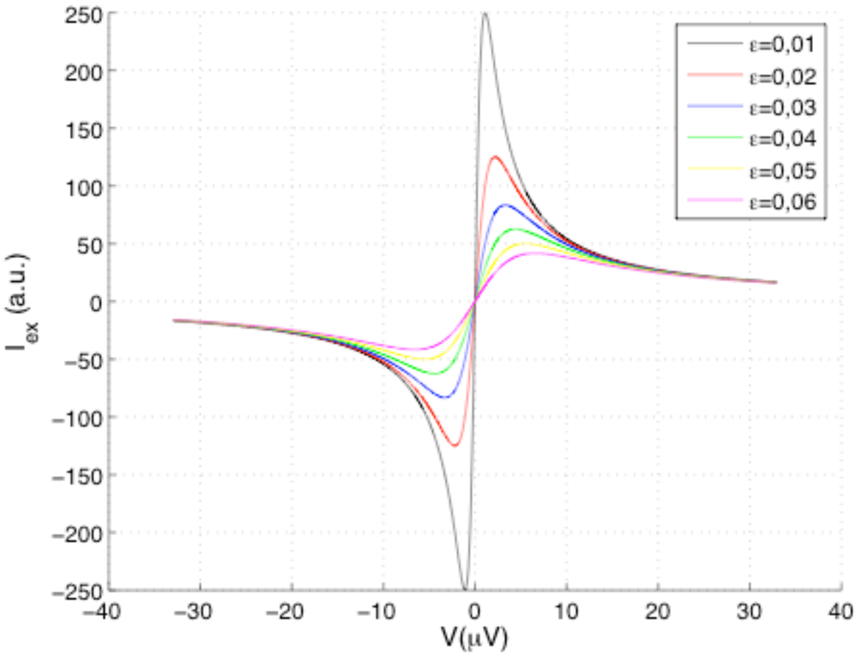


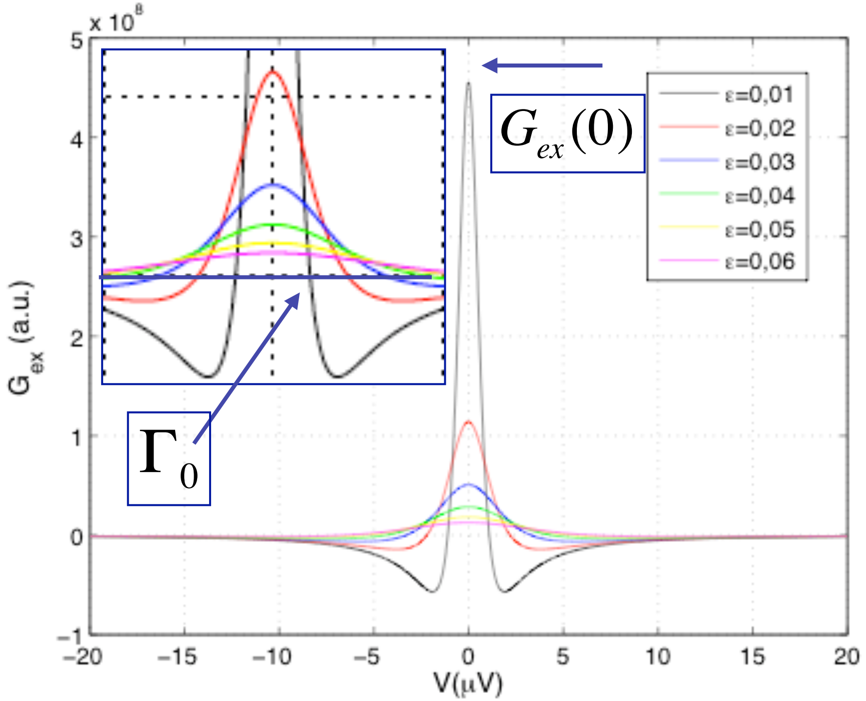
$$G(V) = G_0 + \alpha V^{\frac{4}{3}} + \beta V^{\frac{5}{2}} + \gamma V^{\frac{18}{5}} + \ldots.$$

- 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





$$\Gamma_0 = \frac{16k_B}{h}(T-T_c)$$

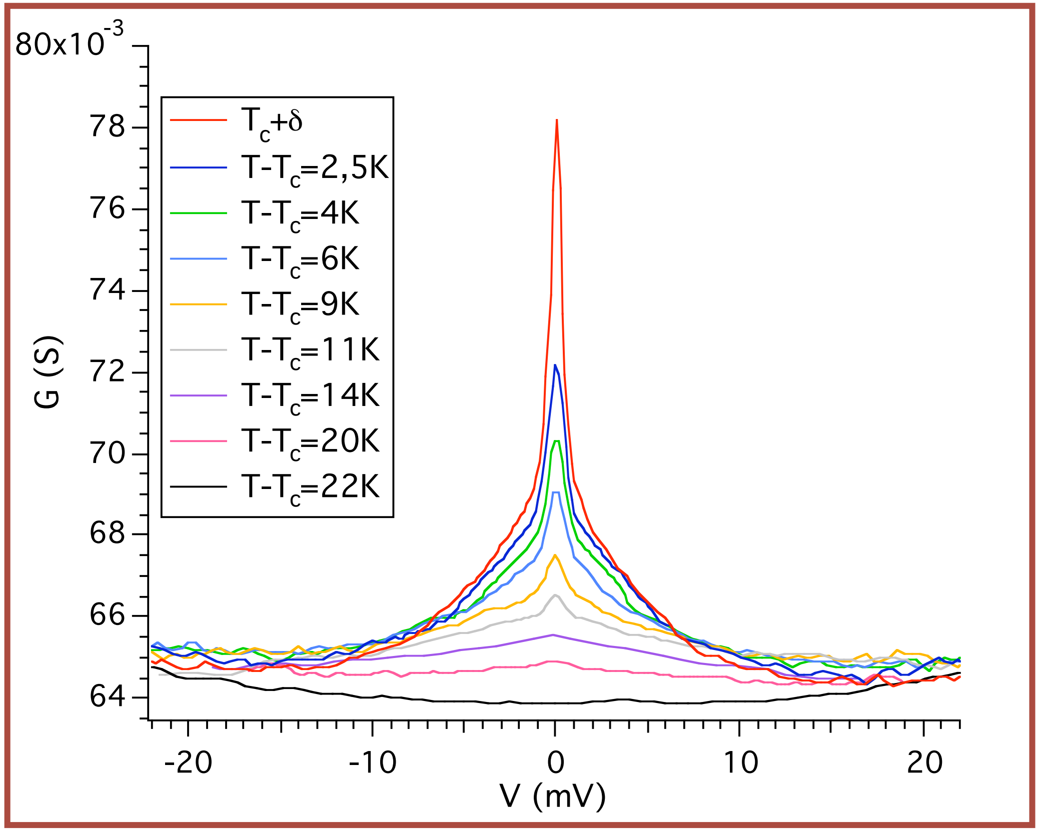
$$I_{ex}(V) = A\frac{\omega/\Gamma_0}{\varepsilon[1+(\omega/\Gamma_0)^2]}$$

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

$$\varepsilon = \frac{T-T_c}{T_c}$$

- How high in temperature will the peak survive ?

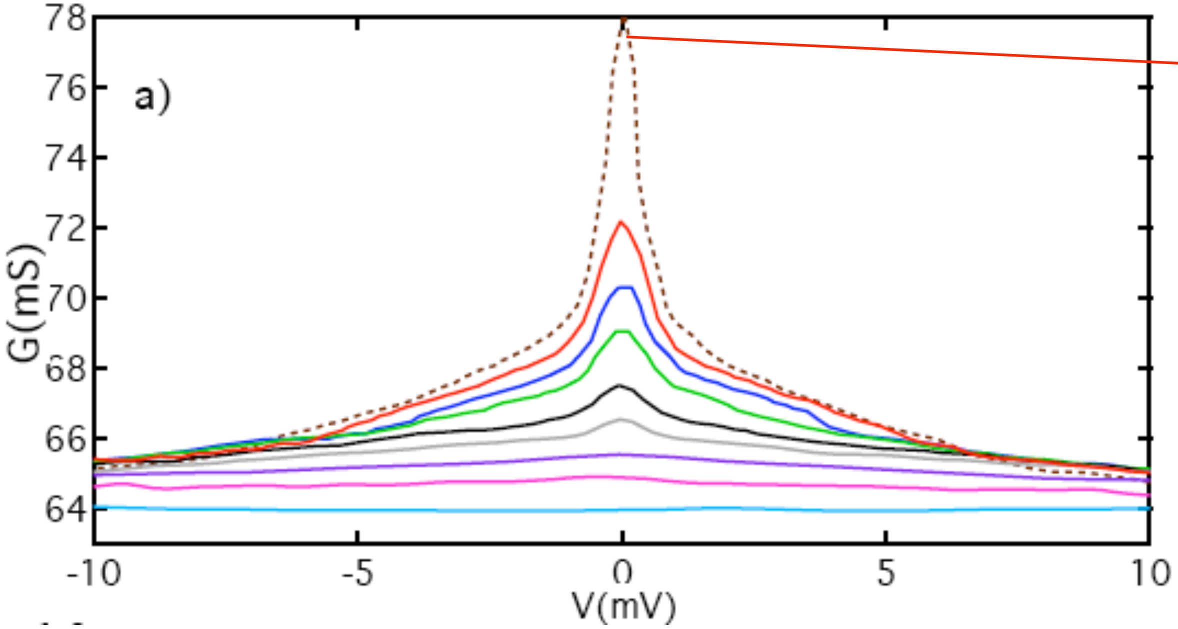
Testing the fluctuating pairs ($T_c^{UD} < T < T_c^{OpD}$)

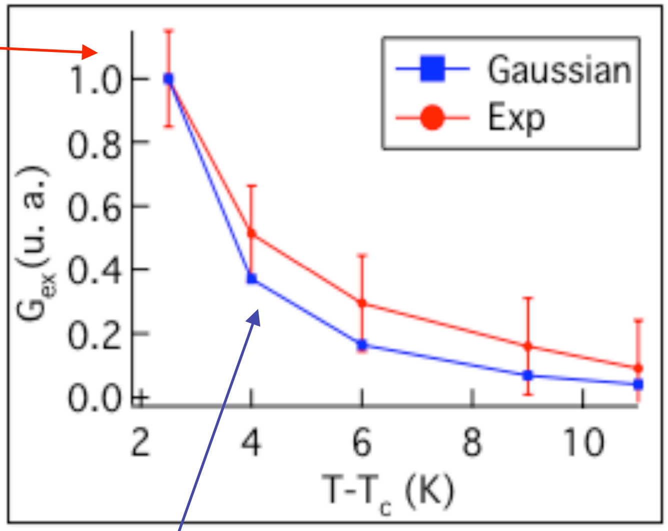


- An excess conductance peak
- Seen only 14K above Tc
- Far below Tc (OpD)
- Far below T* (250 K)

Gaussian fluctuations ?

Gaussian regime of fluctuations ($T_c^{UD} < T < T_c^{OpD}$)





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

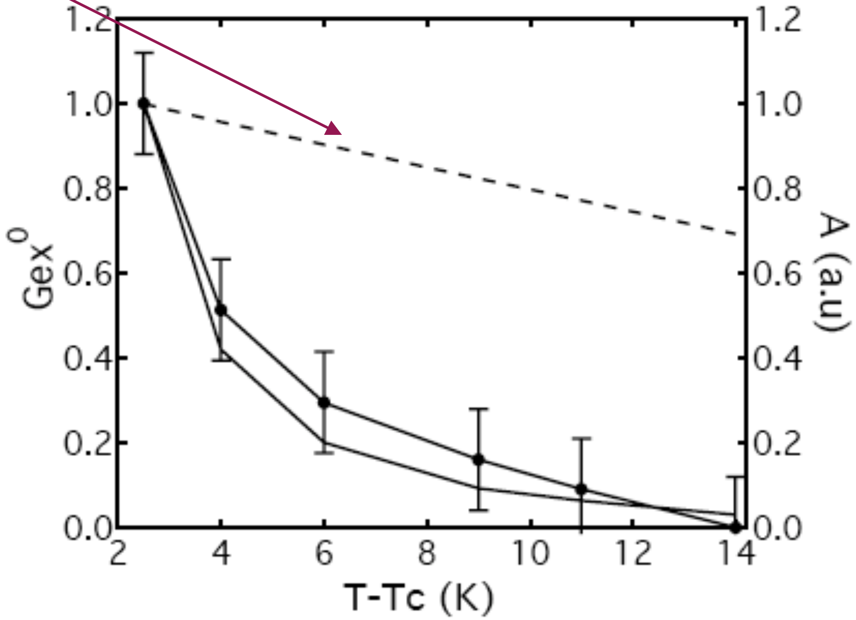
$$\boxed{\Gamma_1 = 4e^2 R k_B T / \hbar^2}$$

Only Gaussian fluctuations ? (T_c^{UD} <T<T_c^{OpD})

- The temperature dependence is controled by the barrier

- The temperature dependence of A calculated by Ferrel

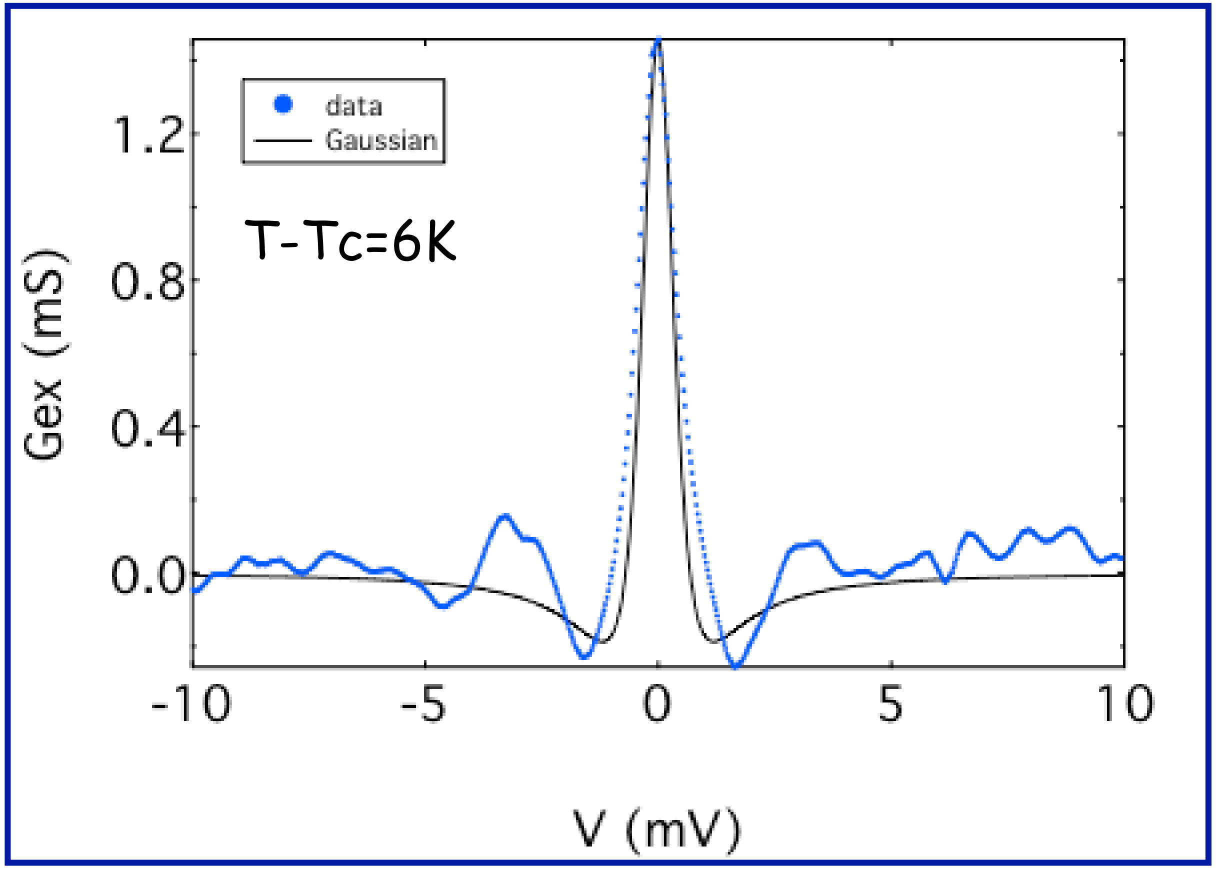
$$I_{ex}(V) = A\frac{\omega/\Gamma_0}{\varepsilon[1+(\omega/\Gamma_0)^2]}$$



- What about the shape of the peak ?

Shape of the peak ($T_c^{UD} < T < T_c^{OpD}$)

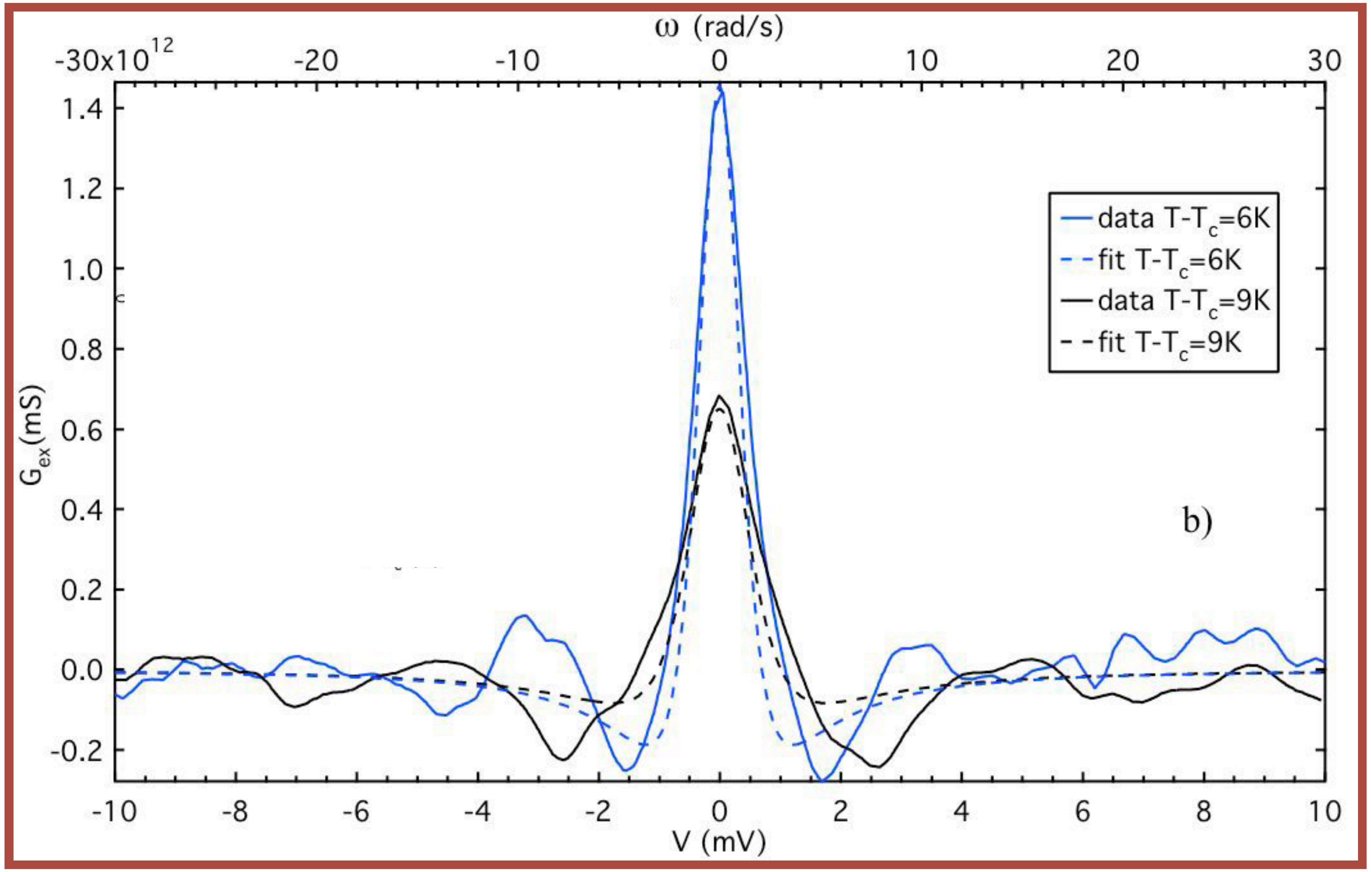
Background subtraction using microwaves



- Excess conductance consistent with gaussian fluctuations

Shape of the peak ($T_c^{UD} < T < T_c^{OpD}$)

Background subtraction using microwaves



Two different temperatures

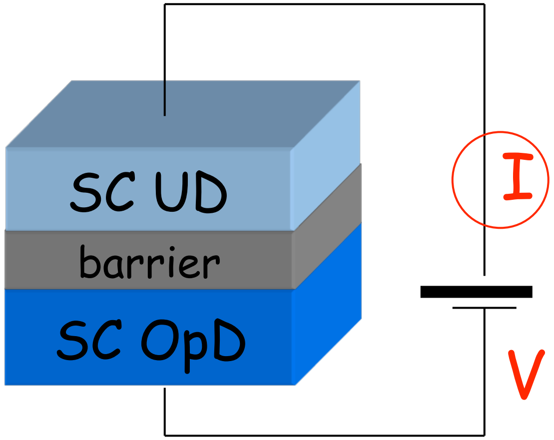
Conclusion of the experiment

61 K << 250 K

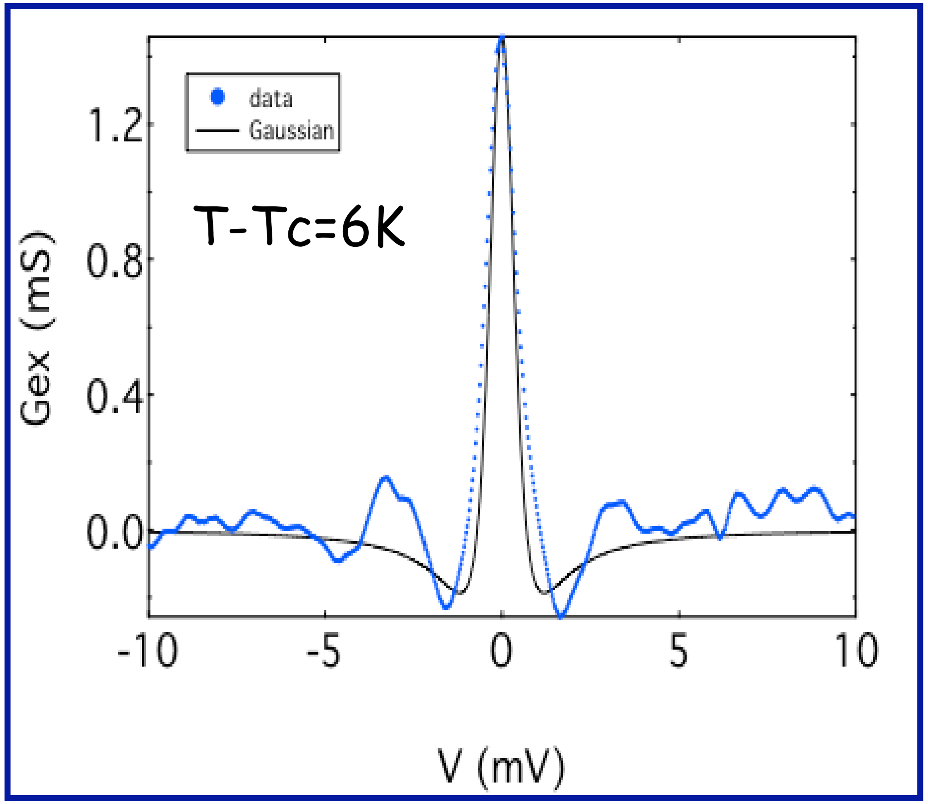
Our conclusion

Gaussian fluctuations seen 15 K above Tc <<T*

- ➢ Fluctuation of the Order Parameter Amplitude
- ➢ Only one temperature scale in the problem



Tc UD < T <Tc OpD



Outline

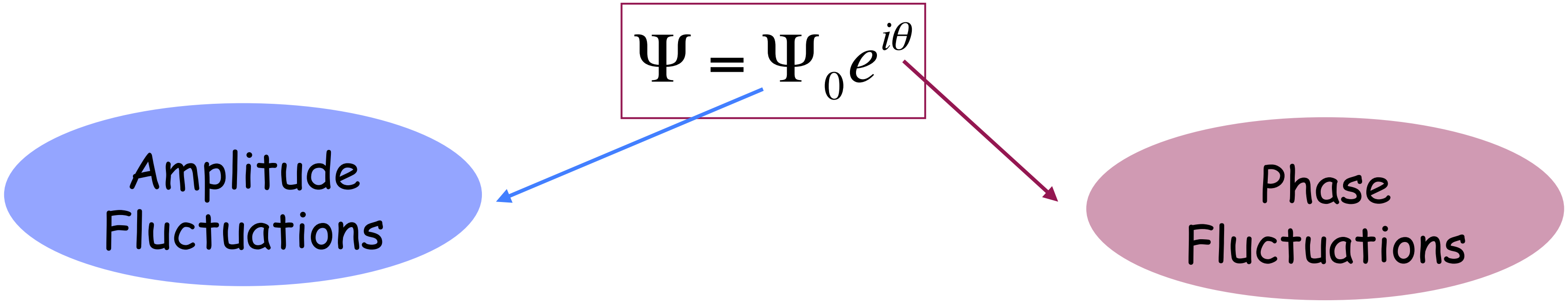
1. The pseudogap in underdoped cuprates
    - Single particle probes (spin and charge channels)
    - Different scenarios ; pairing fluctuations ?
2. Probing pairs above Tc : a Josephson like experiment
    - Standard Josephson experiments
    - Pair susceptibility above Tc in BCS superconductor
    - 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. **Fluctuations in cuprates**
    - Amplitude fluctuations
    - Phase fluctuations
5. Conclusion

Amplitude vs phase fluctuations …

Our conclusion

Gaussian fluctuations seen 15 K above Tc <<T*

- ➢ Fluctuation of the Order Parameter Amplitude
- ➢ Only one temperature scale in the problem



$$\Psi = \Psi_0 e^{i\theta}$$

Amplitude Fluctuations

Phase Fluctuations

Ginzburg-Landau

Aslamasov-Larkin

Kosterlitz-Thouless

Nelson Halperin

Lifetime of the Cooper pairs

Stiffness of the condensate

Fluctuation of the amplitude of the OP

$$\tau = \frac{\pi\hbar}{8k_B(T-T_c)}$$

Cooper pairs lifetime

- ➢ Specific form of the fluctuating pair contribution
- ➢ Infinite extension of the fluctuations (detection limit)

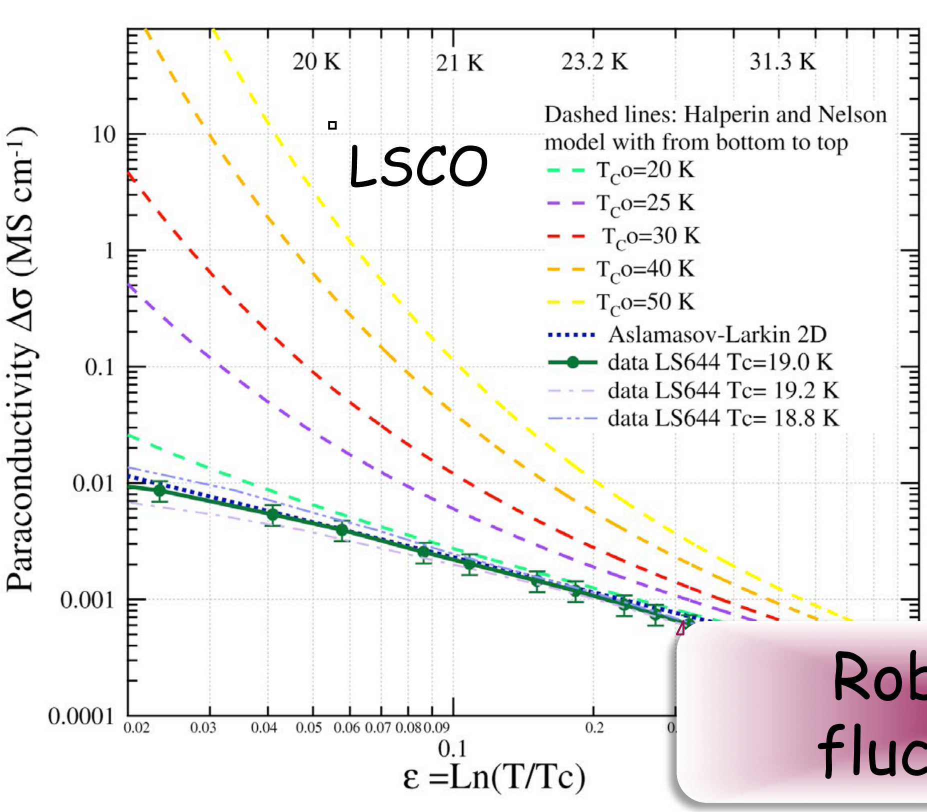
Conductivity

$$\Delta\sigma^{AL}_{D=2} = \frac{e^2}{16\hbar\, d\epsilon},$$

$$\Delta\sigma^{AL}_{D=3} = \frac{e^2}{32\hbar\xi_{c0}\sqrt{\epsilon}}.$$

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

$$\Delta\rho = -\rho^2\Delta\sigma$$



Underdoped
- YBCO
- BSCCO
- LSCO

Leridon et al PRB, 2007
Caprara et al PRB 2009

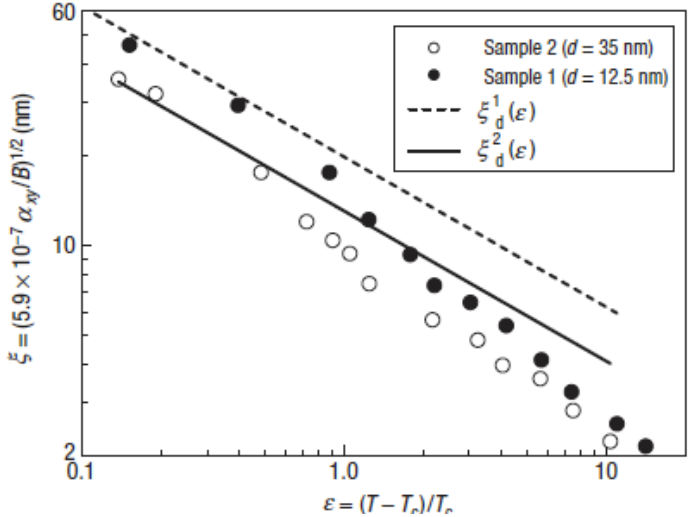
Robust AL fluctuations

Fluctuation of the amplitude of the OP

Nerst effect

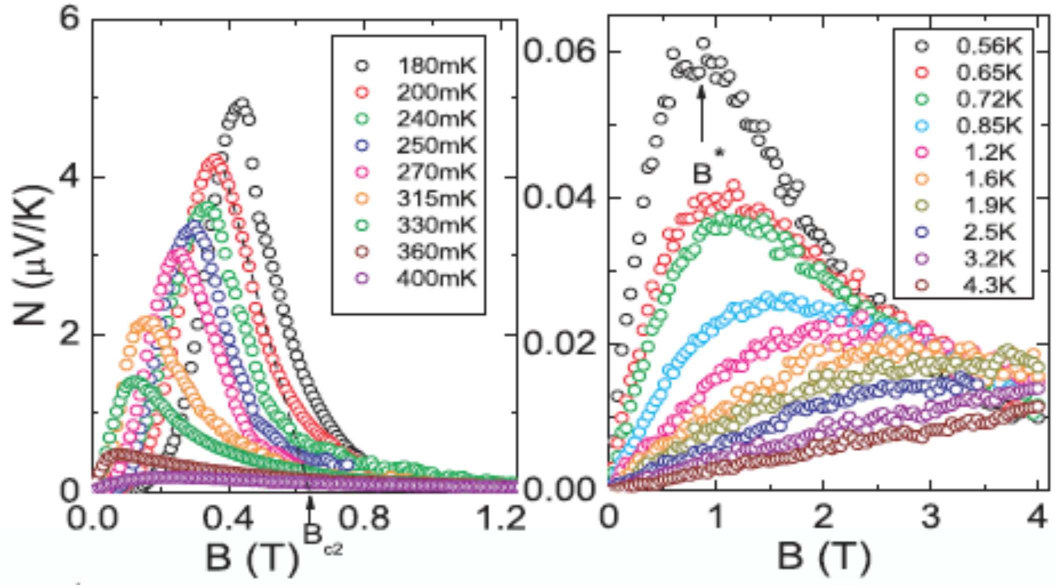
Dirty superconductor Nb_xSi_{1-x} : $\nu_{fluct} = 2000\, \nu_{norm}$

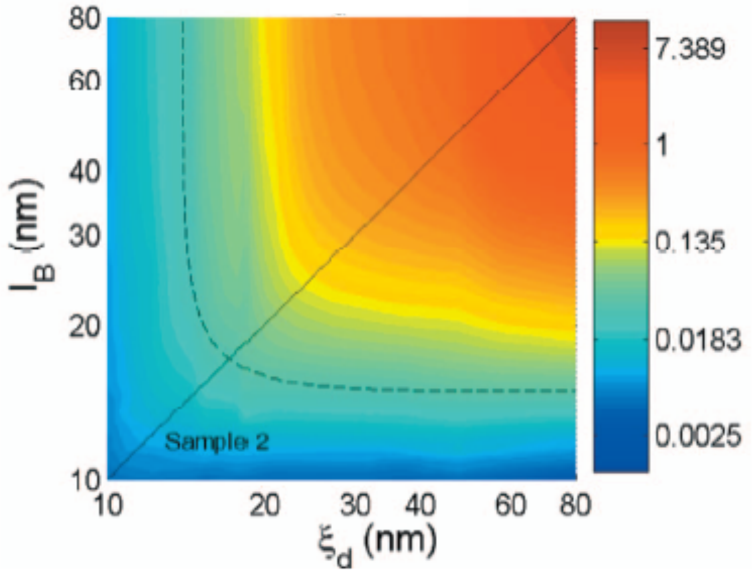
Pourret et al
Nature Phys. '06
PRB '07



$$\xi_d = \frac{1}{\sqrt{\varepsilon}} 0.36 \sqrt{\frac{3}{2}\frac{\hbar v_F \ell}{k_B T_c}}$$

$$l_B(B) = (\hbar / 2eB)^{1/2}$$

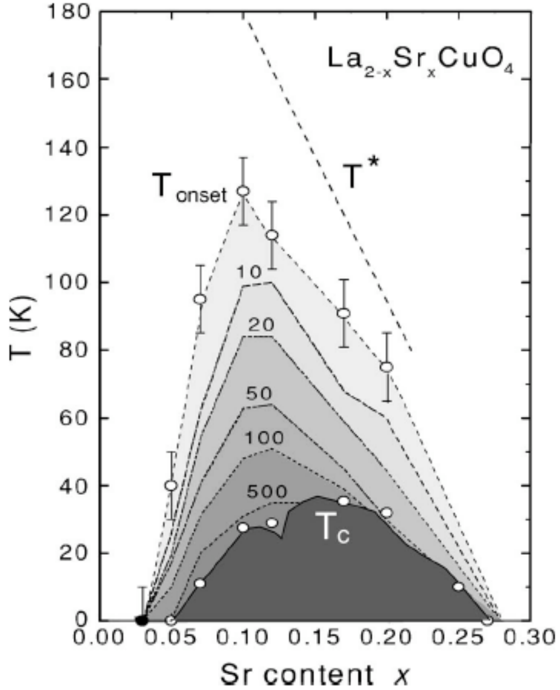




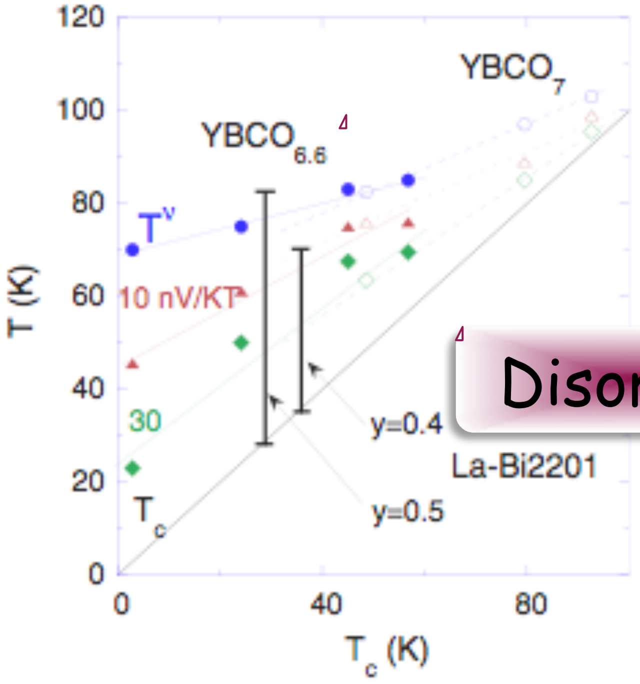
Fluctuation of the amplitude of the OP

Nerst effect

What is the situation in cuprates ?



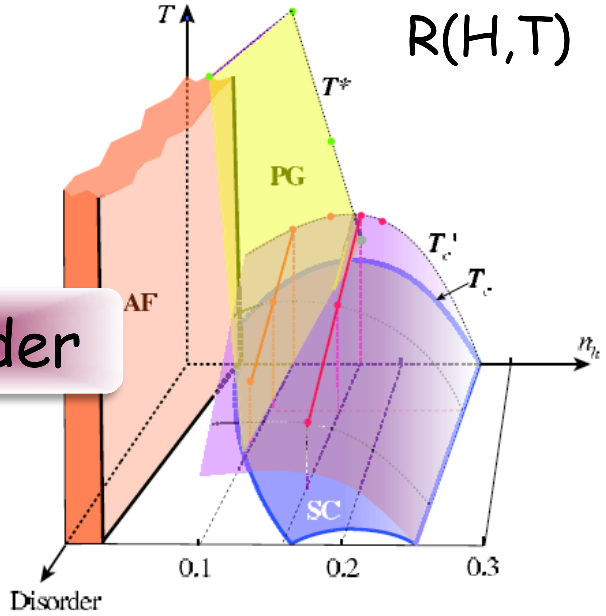
Ong's group



Rullier-Albenque et al PRL '06

Disorder

R(H,T)



Alloul et al EPL 2010

Vortex-like objects above Tc

Limited fluctuations in clean compounds

In clean samples T* < Tc'

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

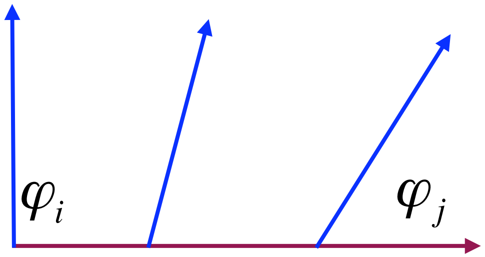
Phase transition in 2D systems : 2D XY model

$$H = -J \sum_{\langle ij \rangle} \cos(\varphi_i - \varphi_j) \Rightarrow J = \frac{\hbar^2 \rho_s}{4m} \qquad \Psi = \Psi_0 e^{i\varphi}$$

Spin system

Superfluid

Superfluid density



Bound vortices

Free vortices

$$\xi(T) \sim e^{-b|T-T_{\mathrm{KT}}|^{-1/2}}$$

Coherence length

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Phase transition in 2D systems : 2D XY model

$$H = -J \sum_{\langle ij \rangle} \cos(\varphi_i - \varphi_j) \Rightarrow J = \frac{\hbar^2 \rho_S}{4m} \qquad \Psi = \Psi_0 e^{i\varphi}$$

Spin system

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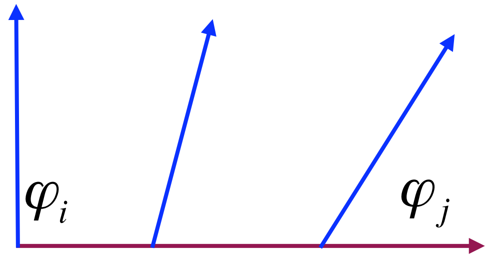
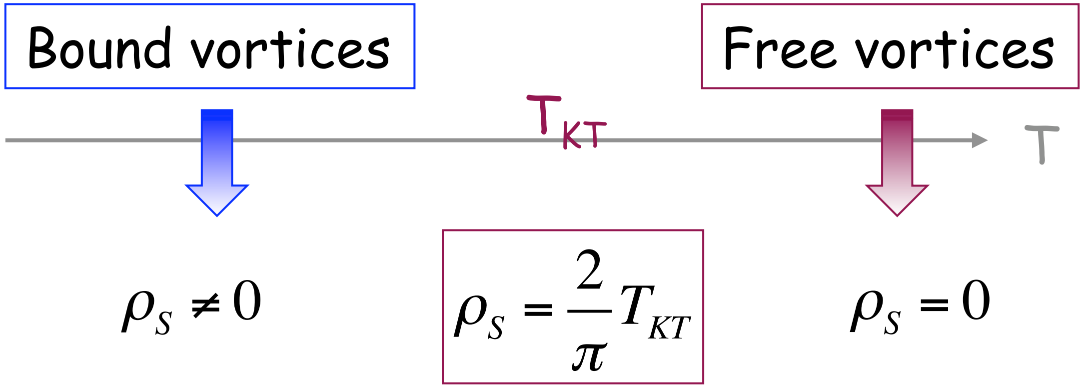
Superfluid density





Bound vortices

T_{KT}

Free vortices

$\rho_S \neq 0$

$$\rho_S = \frac{2}{\pi} T_{KT}$$

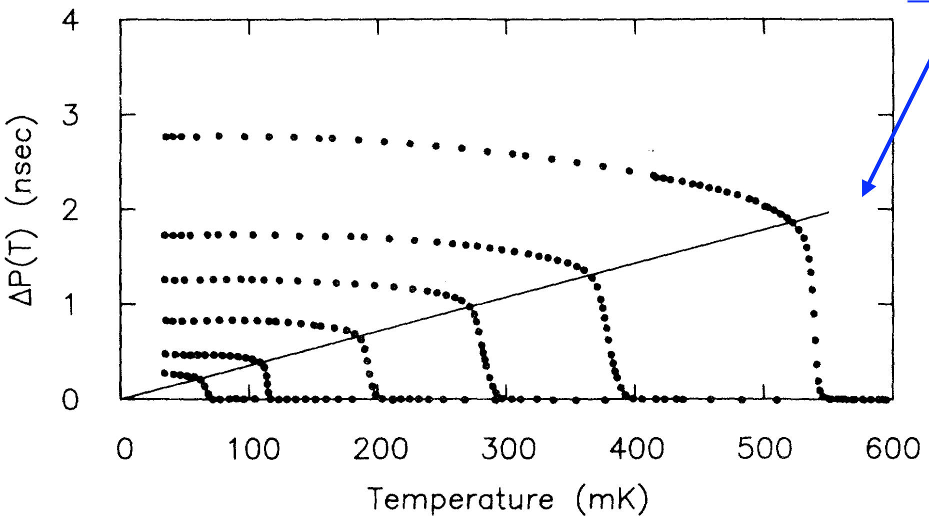
$\rho_S = 0$

Universal stiffness jump

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Universal jump

$$\frac{2T}{\pi}$$

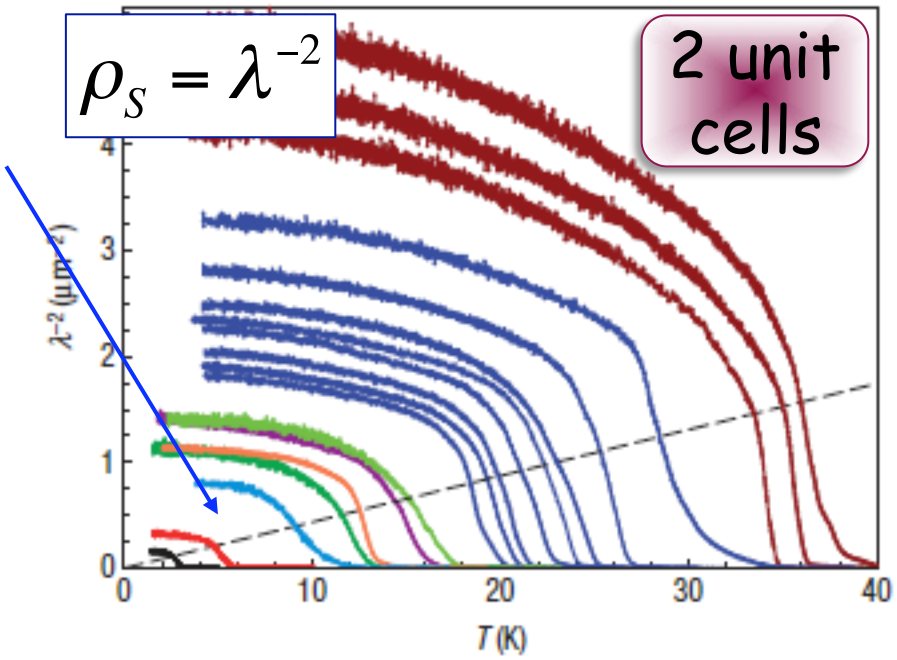


McQueeney et al
PRL '84

He$_3$-He$_4$ mixture

$$\rho_S = \lambda^{-2}$$

2 unit cells



Underdoped Ca-YBCO

Hetel et al Nature Phys. '07

- ➢ The actual thickness (2 u.c.) controls T_{KT}
- ➢ Thicker films do not show KT physics
- ➢ Scaling points towards a QCP at low doping

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Universal jump

$$\frac{2T}{\pi}$$

$$\rho_S = \lambda^{-2}$$

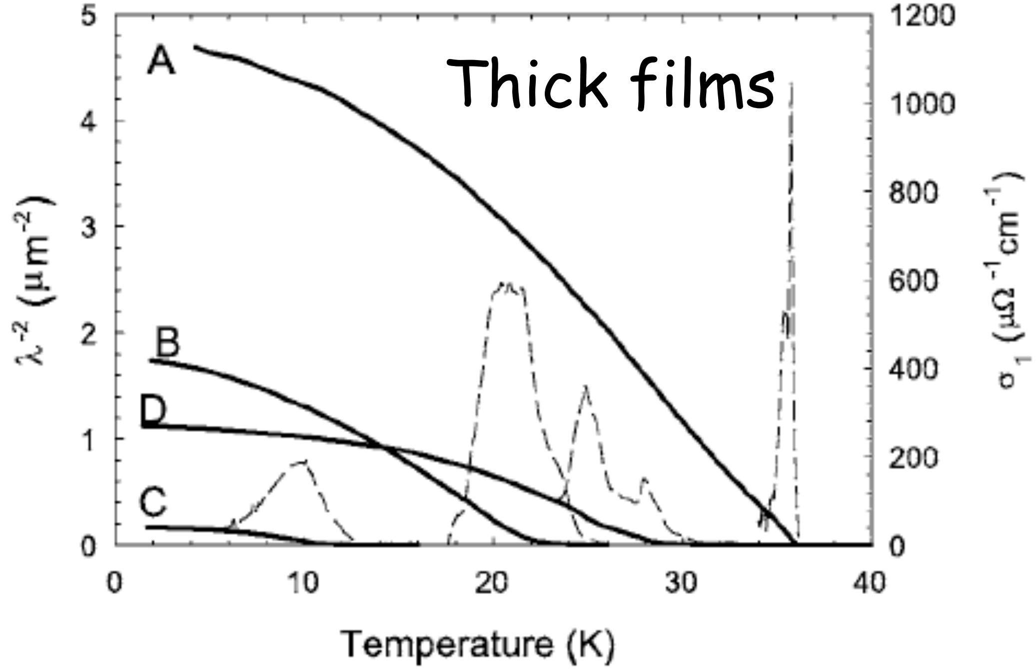
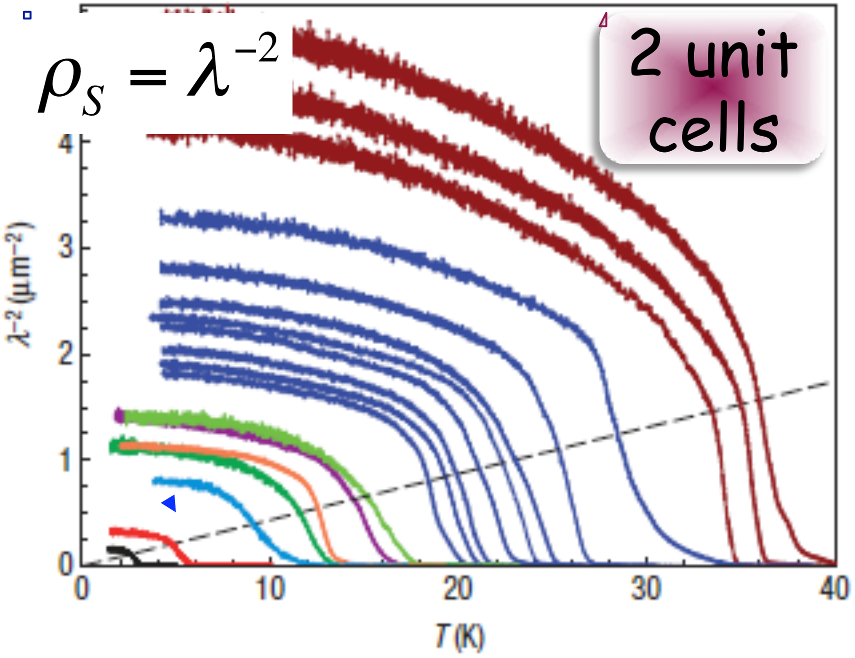


FIG. 1. Superfluid density $\rho_s \propto \lambda^{-2}$ (solid curves) and σ_1 (dashed curves) vs T for four films used in the present study.



2 unit cells

Underdoped Ca-YBCO

Hetel et al Nature Phys. '07

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Coherence length

Two characteristic temperatures : Tc & T_{KT}

Halperin-Nelson, JLTP '79

$$\tau = \frac{T - T_{KT}}{T_{KT}}$$

$$\tau_c = \frac{T_c - T_{KT}}{T_{KT}}$$

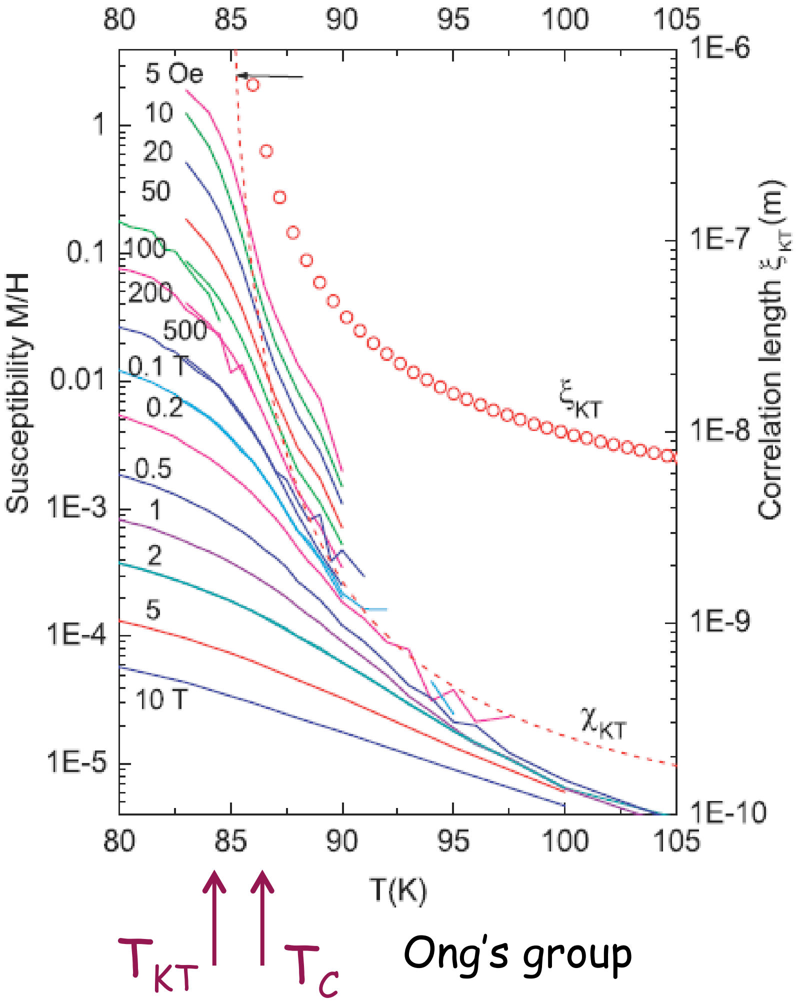
$$\Delta\sigma = 0.37 b^{-1} \sigma_N^{squ} \sinh^2[(b\tau_C/\tau)^{1/2}]$$

$$\chi = \frac{M}{H} = -\left(\frac{k_B T}{d\Phi_0^2}\right) \xi_{KT}^2$$

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

Coherence length

Two characteristic temperatures : Tc & T_{KT}



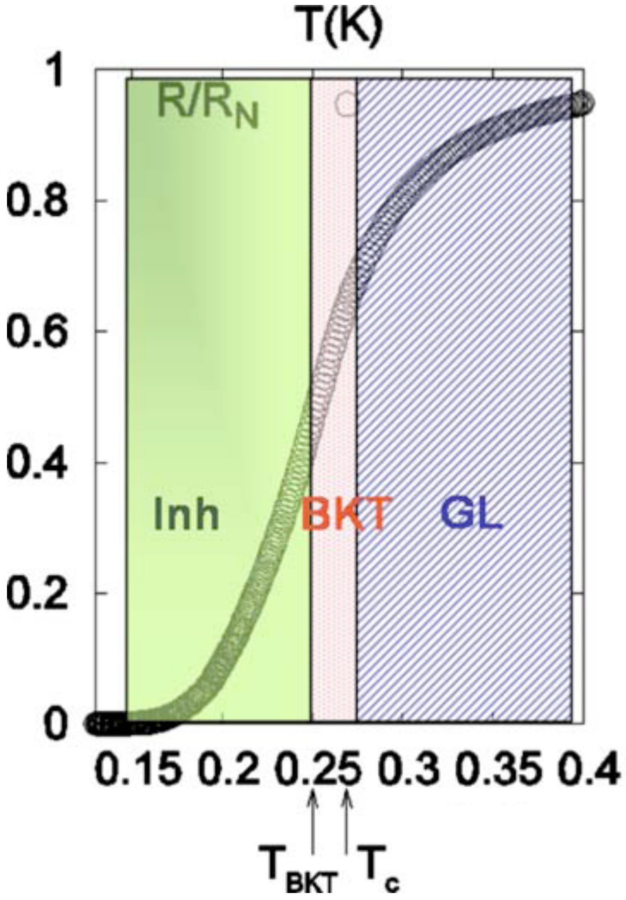
Ong's group

$$\chi = \frac{M}{H} = -\left(\frac{k_B T}{d\Phi_0^2}\right)\xi_{KT}^2$$

Fluctuation of the phase of the OP (Kosterlitz-Thouless)

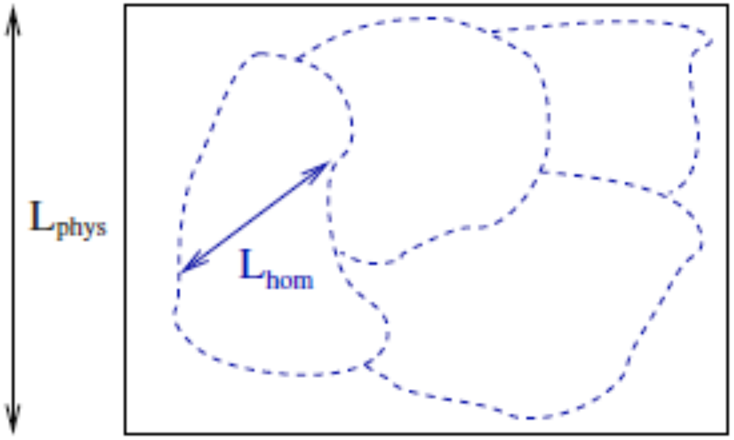
Non-universal

Finite size effects & vortex-core energy



Benfatto et al,
PRL '07, PRB '09

Cut-off in the long-range vortex interactions



No evidence of bulk KT physics

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)