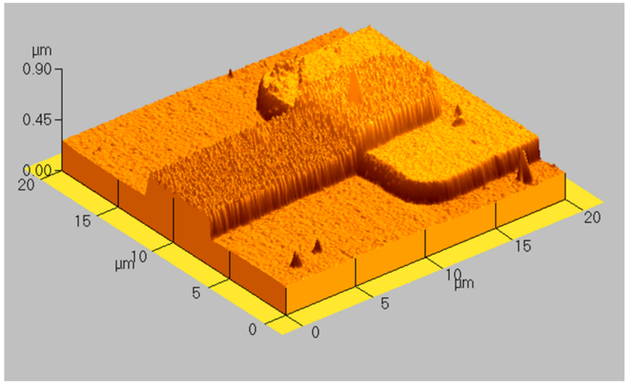

Superconductivity at oxide interfaces, UK, Sept. 14-15, 2011

Energy scales and interface effects in SNS and SFS ramp-type junctions of cuprates and ferromagnets

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Outline

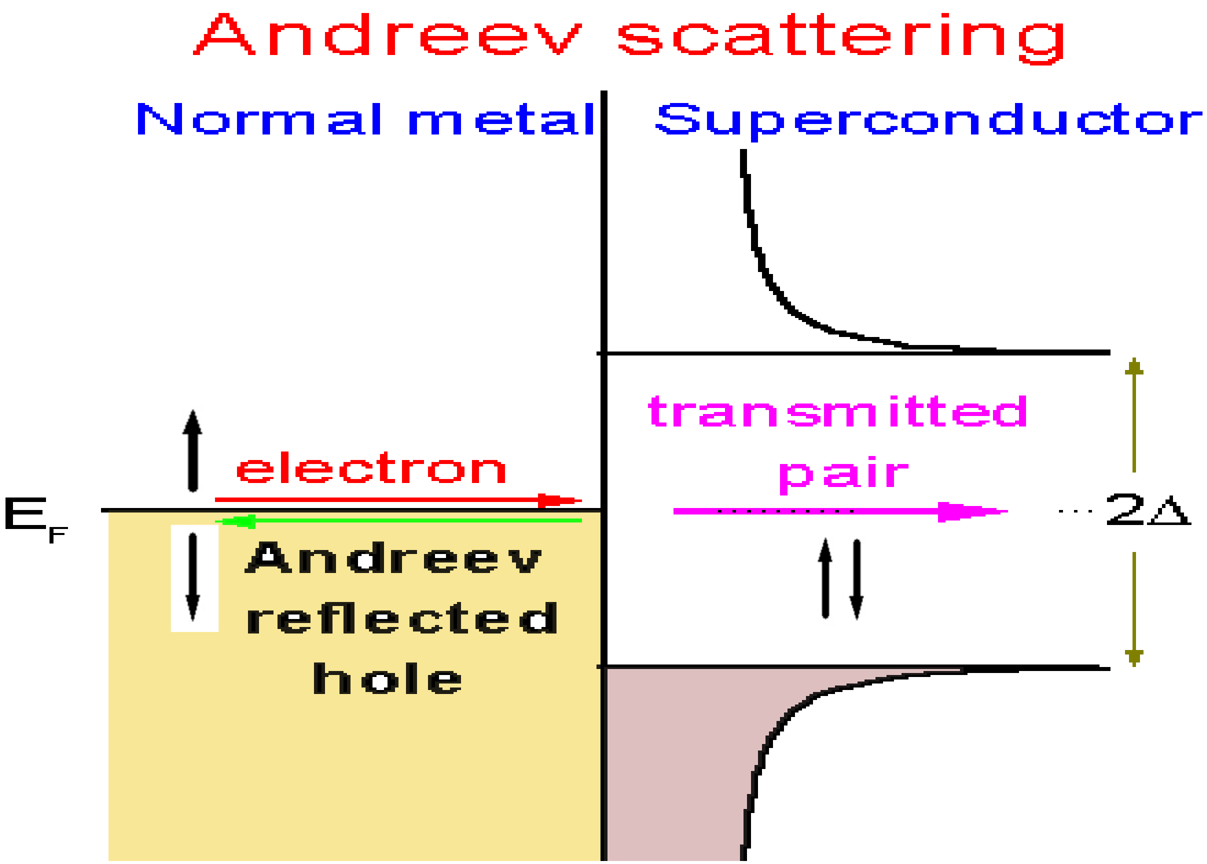
- Background: The Andreev reflection effect , and
  SNS & SFS ramp-type junctions

- $YBa_2Cu_3O_y$-$SrRuO_3$-$YBa_2Cu_3O_y$ junctions:
  Evidence for a crossed Andreev reflection effect (CARE)
  No dominant proximity induced triplet SC (PITS) in F

- $La_{2-x}Sr_xCuO_4$-$La_{1.65}Sr_{0.35}CuO_4$ -$La_{2-x}Sr_xCuO_4$ junctions:
  Observation of Two energy scales (Δ_1 and Δ_2)

- $YBa_2Cu_3O_y$-$La_{0.67}Ca_{0.33}MnO_3$-$YBa_2Cu_3O_y$ junctions:
  No CARE, no PITS
- $La_{1.9}Sr_{0.1}CuO_4$–$La_{0.67}Ca_{0.33}MnO_3$-$La_{1.9}Sr_{0.1}CuO_4$ junctions:
  No supercurrent (no PITS)

Transport in SN junctions below the gap is via the Andreev scattering effect



Point contact spectroscopy on LSCO single crystals

Conductance at 4.2K

Deutscher, Achsaf, Goldschmidt & Revcolevschi Physica C, **282,** 140 (1997)

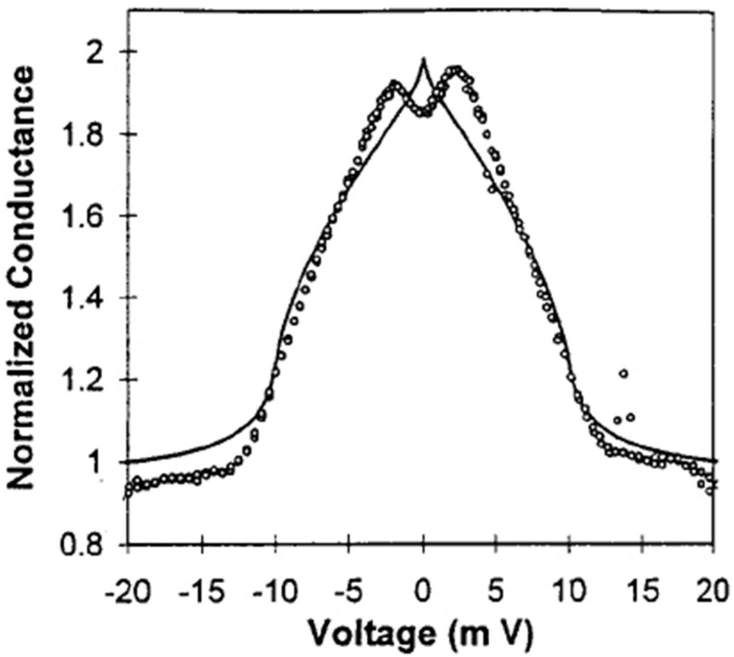
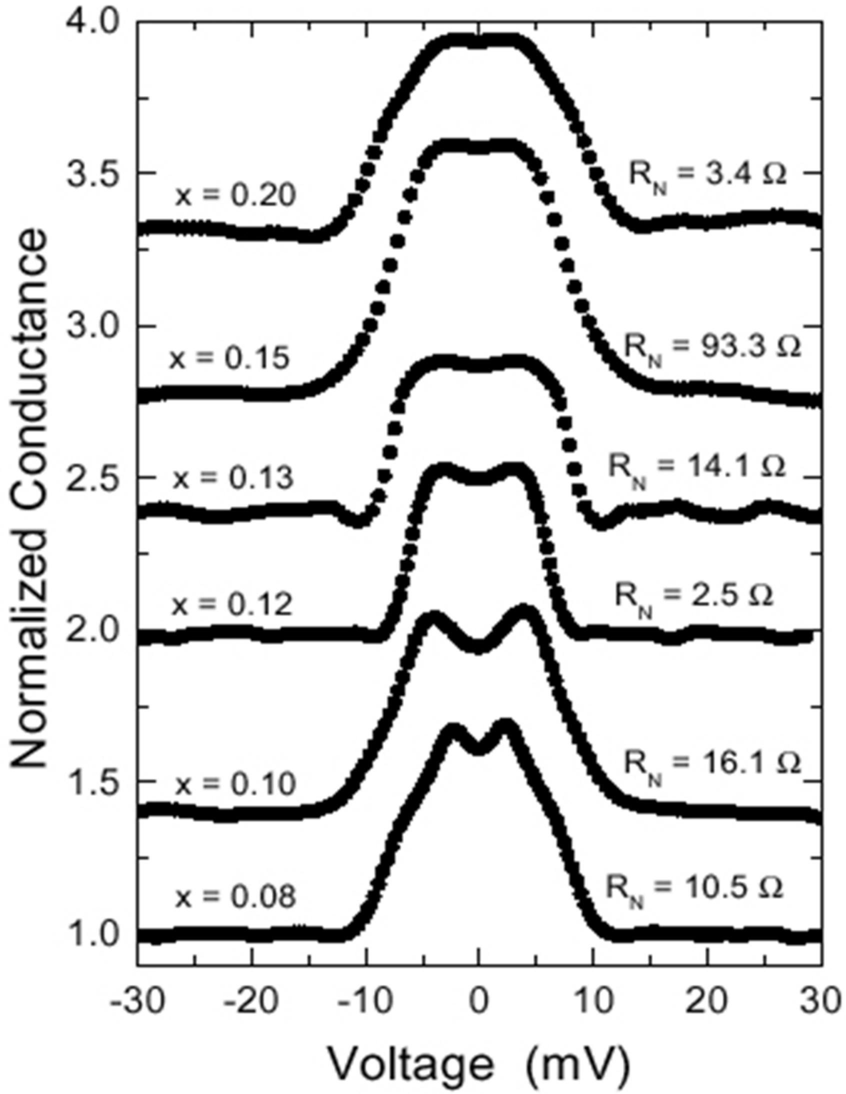
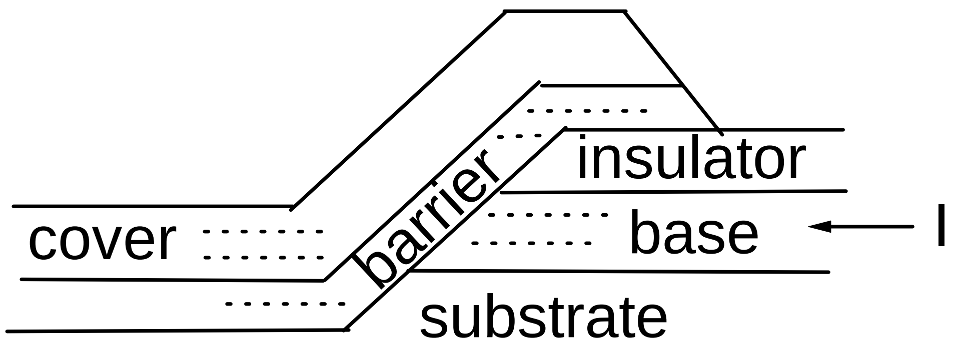


Fig.2 d-wave symmetry fit.

Gonneli et al. Eur. Phys. J. B**22**, 411 (2001)



Ramp-type junction cross-section



- Base & Cover – LSCOx or YBCO (S)
- Barrier – LSCO35 (N), SRO or LCMO (F)

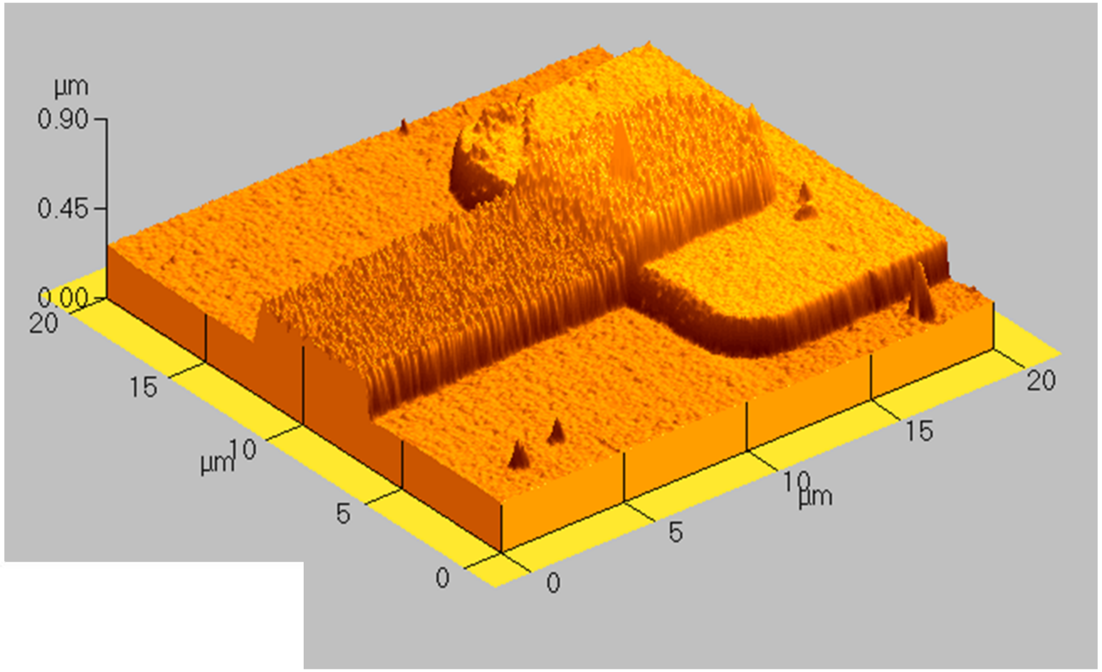
- All epitaxial structure (Laser ablation deposition, deep UV photolithography, and ion beam milling)
  avoids GBJ, and preserves structural orientation.

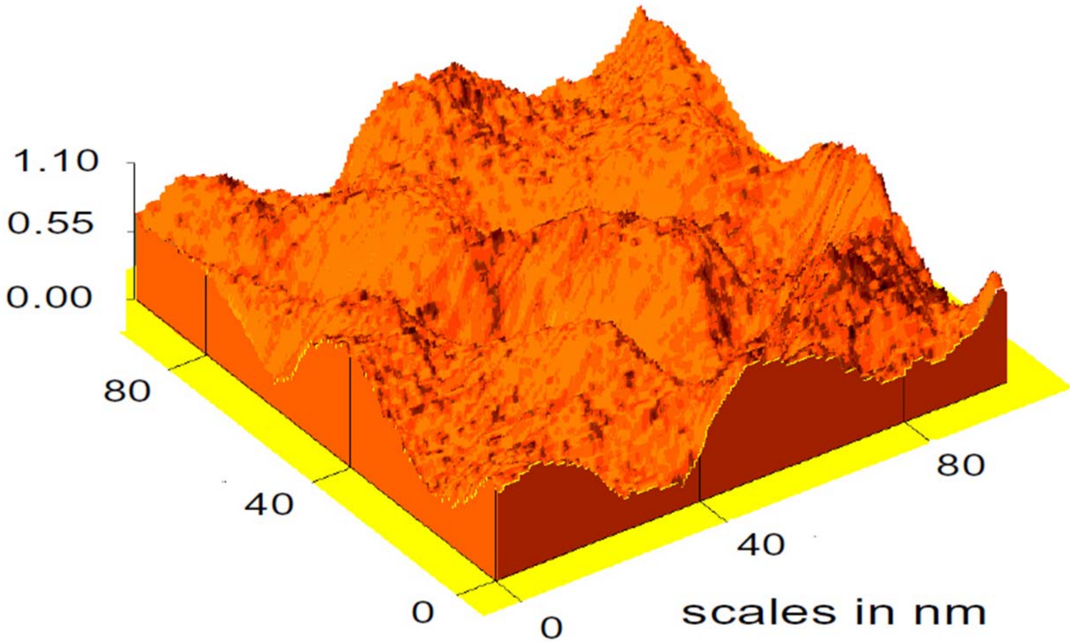
- *a*-*b* plane coupling
  with the longer coherence length ξ~2-3 nm

AFM image of a ramp type junction
& the interface topography

Base electrode:
insulator (55 nm STO) /77 nm S

Cover electrode:
gold /77 nm S / barrier of N or F

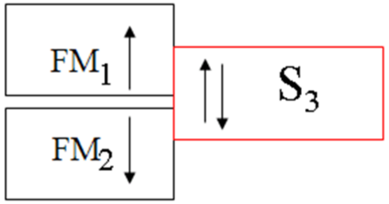




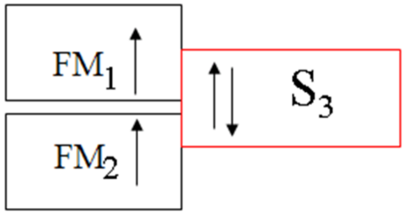
The exposed ramp
interface topography

CARE vs Proximity induced triplet superconductivity (PITS) in S-F junctions

- CARE – crossed Andreev reflection effect -is possible when polarization of the two FM electrodes are anti-parallel

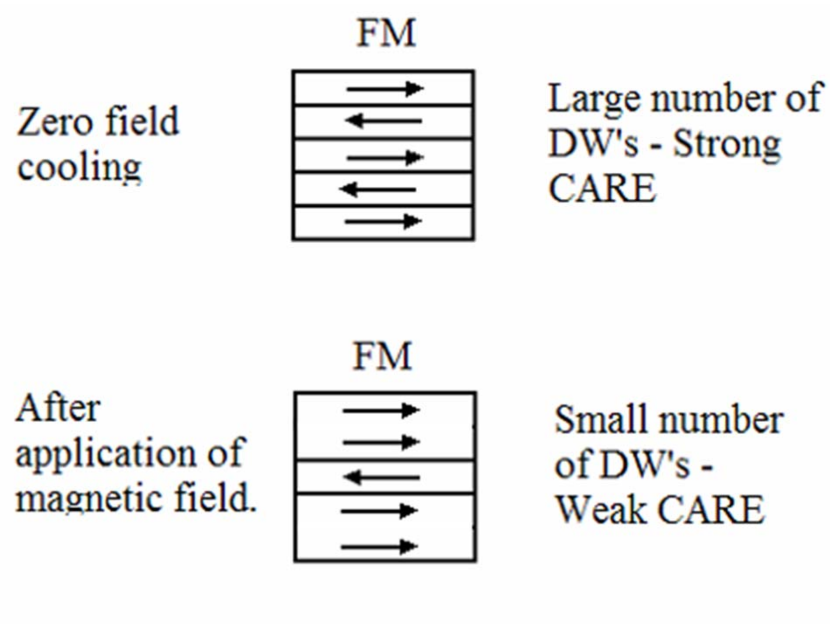


- CARE is not possible in the parallel spin configuration



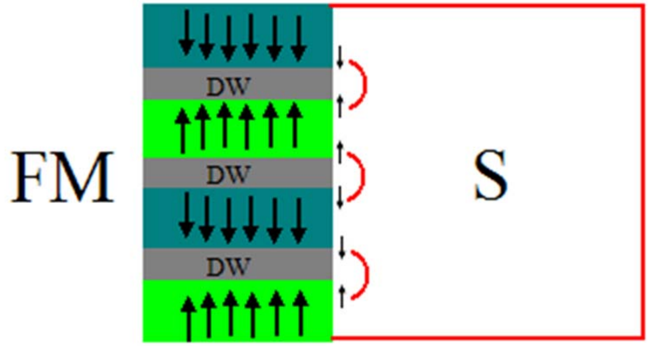
- But if induced triplet pairs are formed in F near the interface, LRPE – long range proximity effect - is possible

In our conductance measurements we reduced the number of domain walls (DW) by field cycling

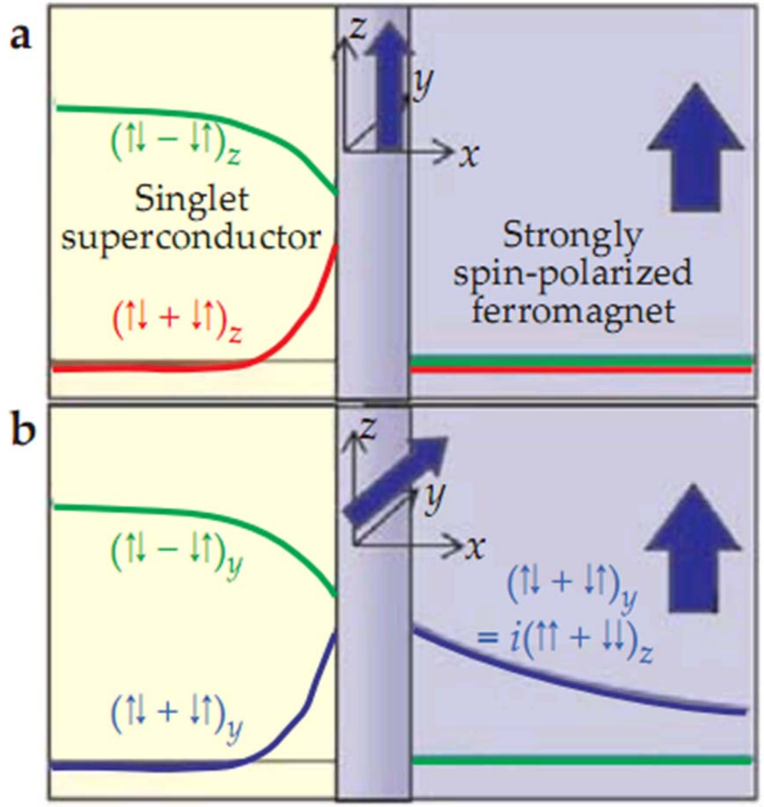


CARE vs PITS near inhomogeneiites

- CARE – In the vicinity of a Domain Walls (DW)

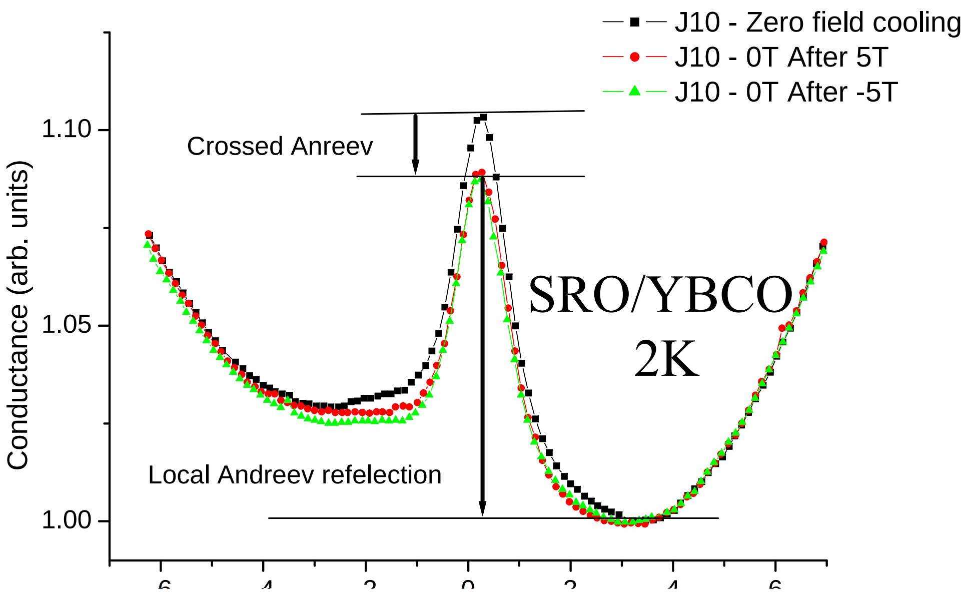


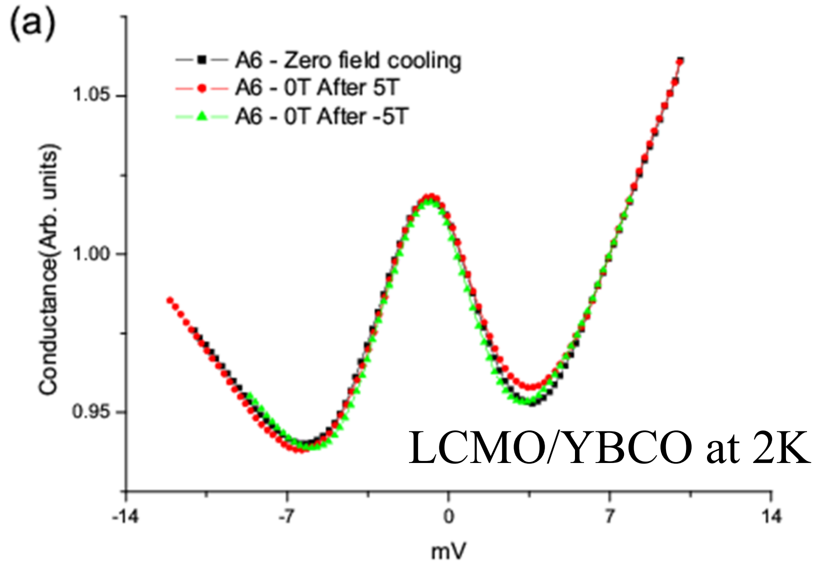
- Induced triplet SC (M. Eschrig)
- The FFLO mechanism creates m=0 triplet component in S.
- Triplet m=0 can be converted into m= ±1 by magnetic inhomogeneity.
- Different magnetization changes the quantization base, rotating the m=0 state, into m= ±1 states. (spin mixing)
- m= ±1 states penetrate deeply into the ferromagnet.



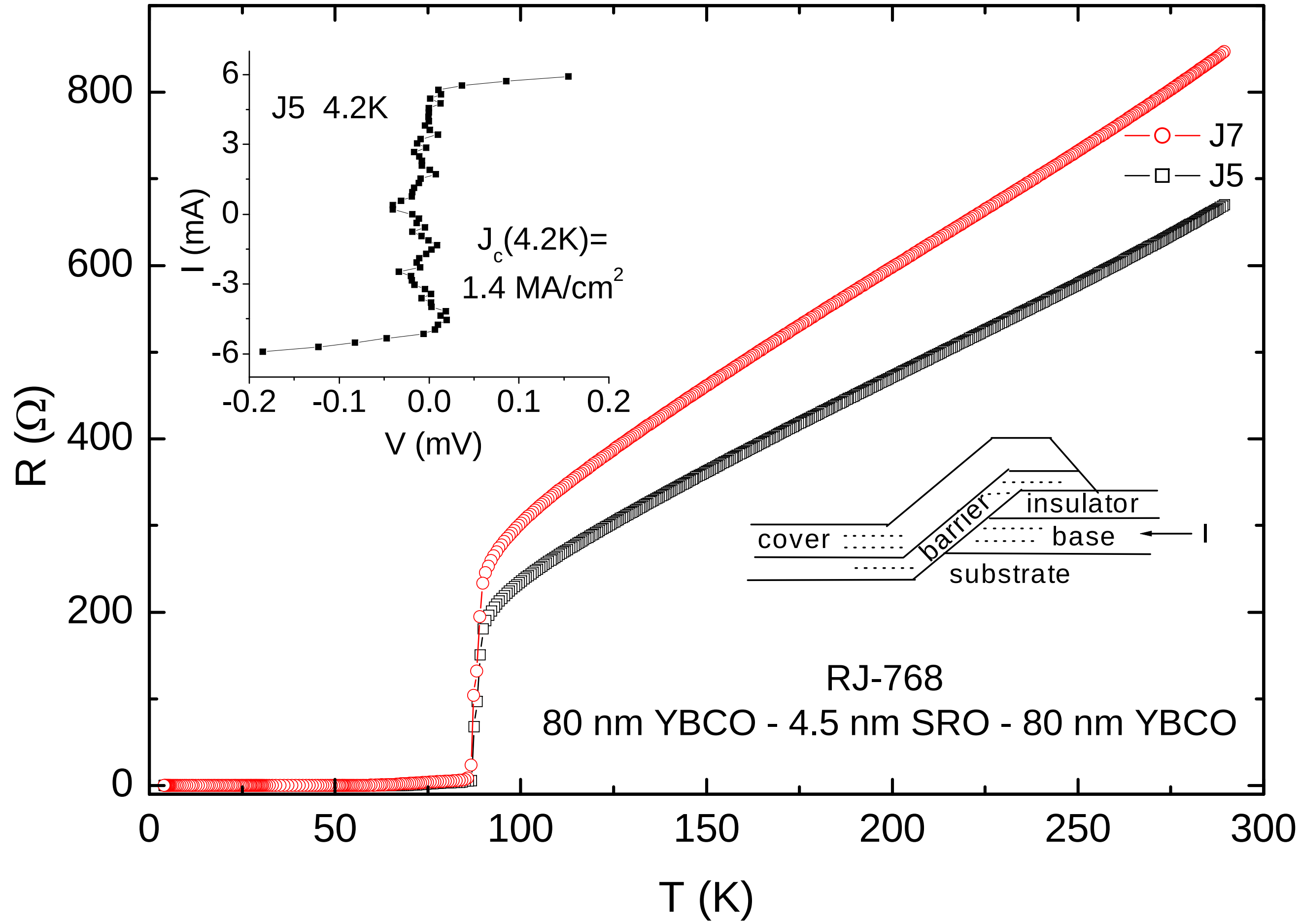
CARE vs PITS: conductance results in YBCO/SRO & YBCO/LCMO junctions

- SRO domain wall width is ~3nm, comparable to the coherence length of YBCO (~2-3nm).
- LCMO domain wall size is ~20-40nm, much larger than the coherence length of YBCO.
- After application of +-5T fields and returning to zero field, get different results ==>
- Conduction drop can be due to both CARE or Triplet.
- But if triplet SC – conductance should have been decreased also in LCMO/YBCO junctions – it can occur even with large DW widths. => only CARE is consistent with both results



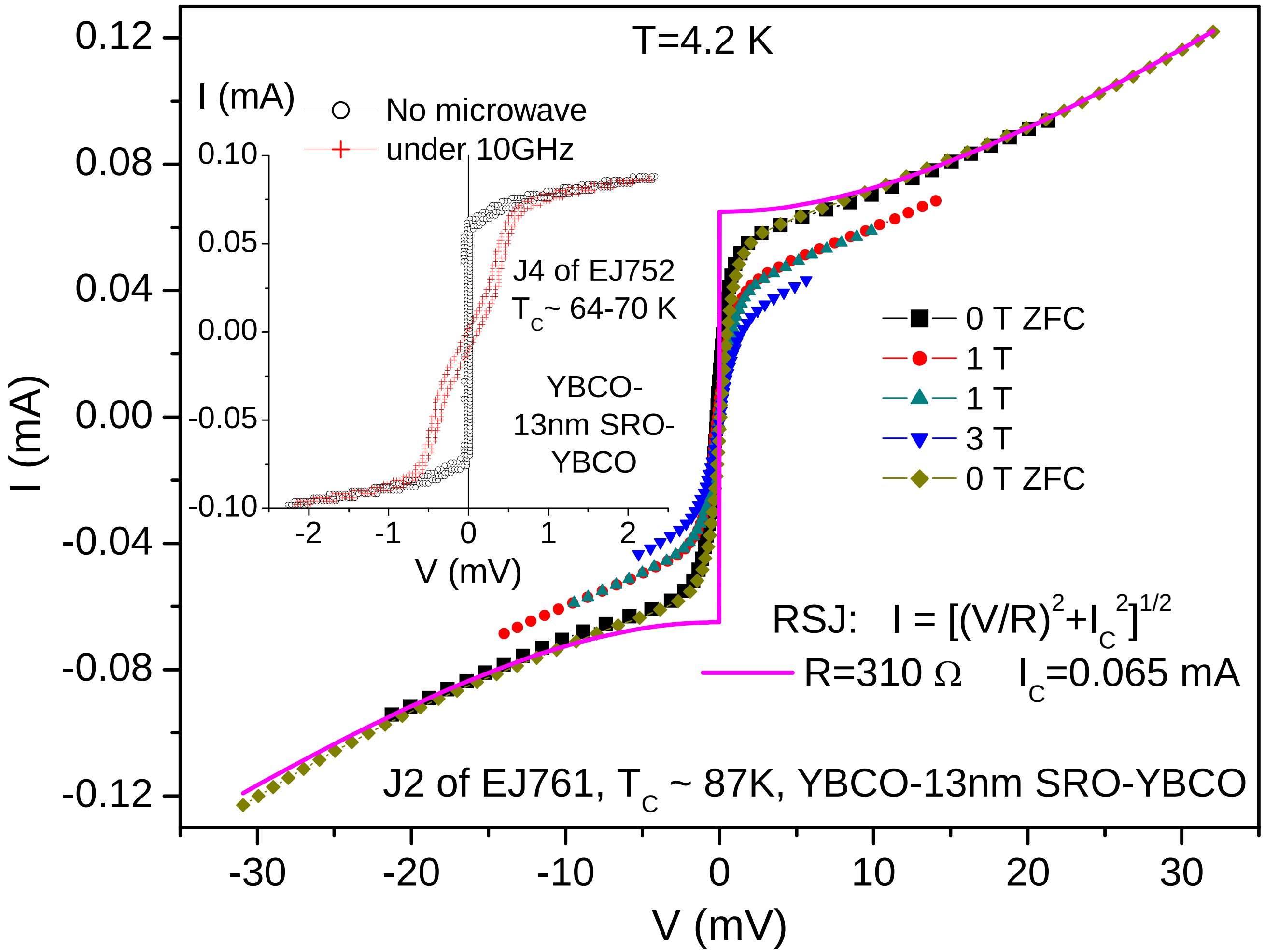


Looking for PITS in SFS junctions by I_c measurements: R vs T & I-V curve at 4.2 K in YBCO-4.5 nm SRO-YBCO junctions



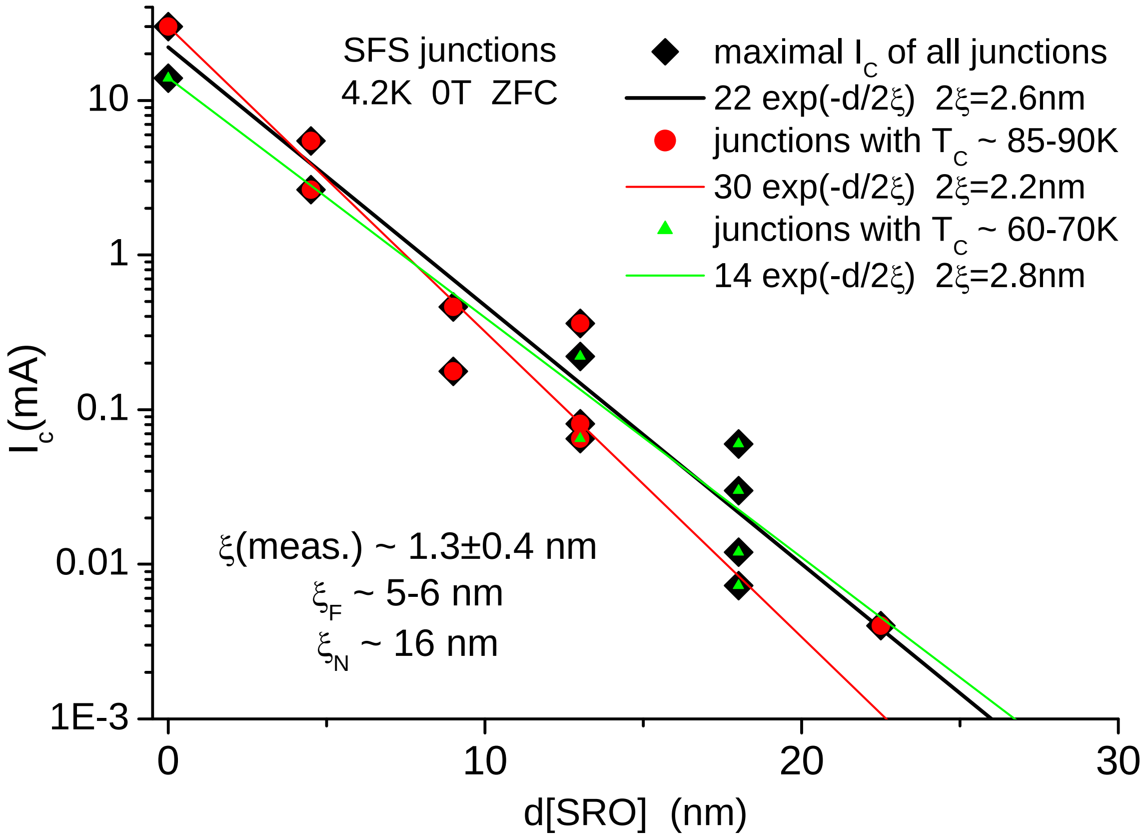
T_c~88K & the critical current I_c(4.2K)=1.4 MA/cm^2

I-V curves under fields & μ-wave radiation in YBCO-13nm SRO-YBCO junctions



Critical current is suppressed under fields and microwave radiation

Critical current vs F film thickness of YBCO-d (nm) SRO-YBCO junctions

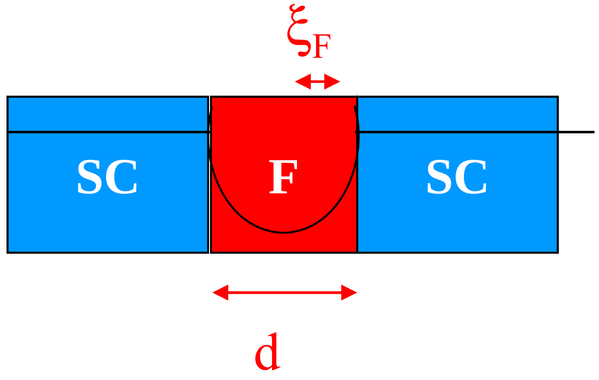


No dominant proximity induced triplet SC (PITS) in F since the decay length ξ(meas.) is much shorter than either ξ_F or ξ_N

Estimate ξ_F of SRO from band structure calculations & experiments

Clean limit: $\xi_F = \hbar v_F / 2E_{ex}$

Dirty limit: $\xi_F = (\hbar D / 2E_{ex})^{1/2}$ $D = \frac{v_F \ell}{3}$



The YBCO gap ~ 17meV, and the exchange energy in SRO ~ 13meV, are comparable.
k(T_{Curie} = 150K) ~ 13 meV, and from Faraday rotation meas., get E_{ex} ~ 10 meV**

For v_F~2×10^5 m/s then ; ξ_F(clean limit) ~ $\frac{10^{-34}\times 2\times 10^5}{2\times 0.013\times 1.6\times 10^{-19}} = 4.8$ nm
The mean free path here is ~14 nm at low T*, so the clean limit is OK.

$$D = \frac{v_F \ell}{3} = \frac{2\times 10^5 \times 1.4\times 10^{-8}}{3} = 9.3\times 10^{-4}\ m^2 s^{-1} \Rightarrow \xi_F(\text{dirty limit}) = 6.2\,nm$$

$$\xi_N(\text{dirty limit}) = \sqrt{\frac{\hbar v_F \ell_N}{6\pi k_B T}} = \sqrt{\frac{6.626\times 10^{-34}\times 2\times 10^5\times 1.4\times 10^{-8}}{12\times \pi^2\times 4.2\times 1.38\times 10^{-23}}} = 16.44\ nm$$

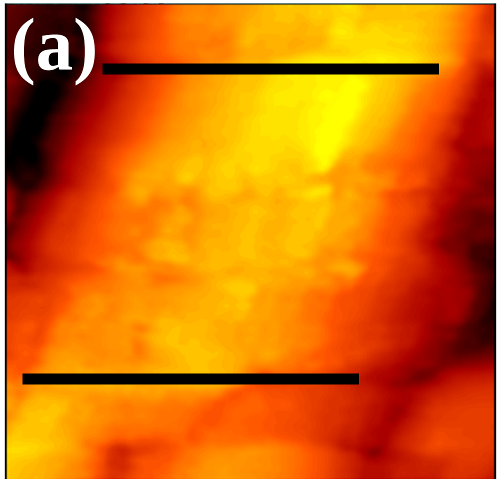
And certainly our measured ξ ~ 1 – 1.5 nm is much shorter than ξ_N ~ 16 nm

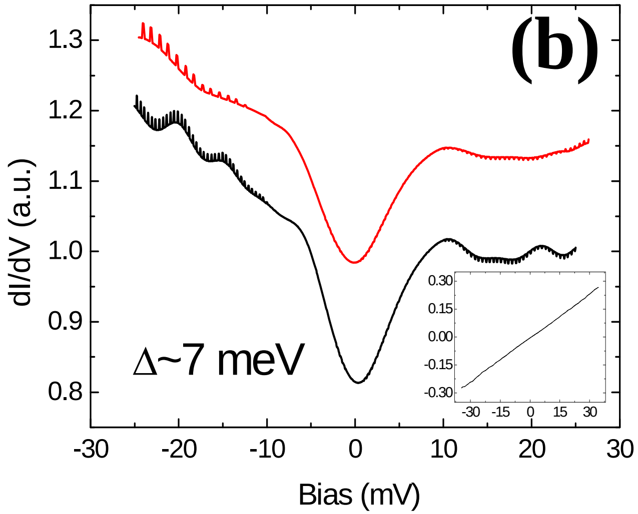
*Santi, JPCM **9**, 9563 (1997), **Dodge, PRB **60,** R6987 (1999),

Buzdin, Rev. Mod. Phys. **77**, 935 (2005)

Origin of the critical current in YBCO-SRO-YBCO junctions

- Since SRO is only 50% polarized, local Andreev reflection is the dominant transport mechanism for the supercurrent here, and it is short ranged (present results).
- STM results show long range penetration of the SC order into SRO near domain walls. [I. Asulin et al., PRB **74,** 092501(2006)]





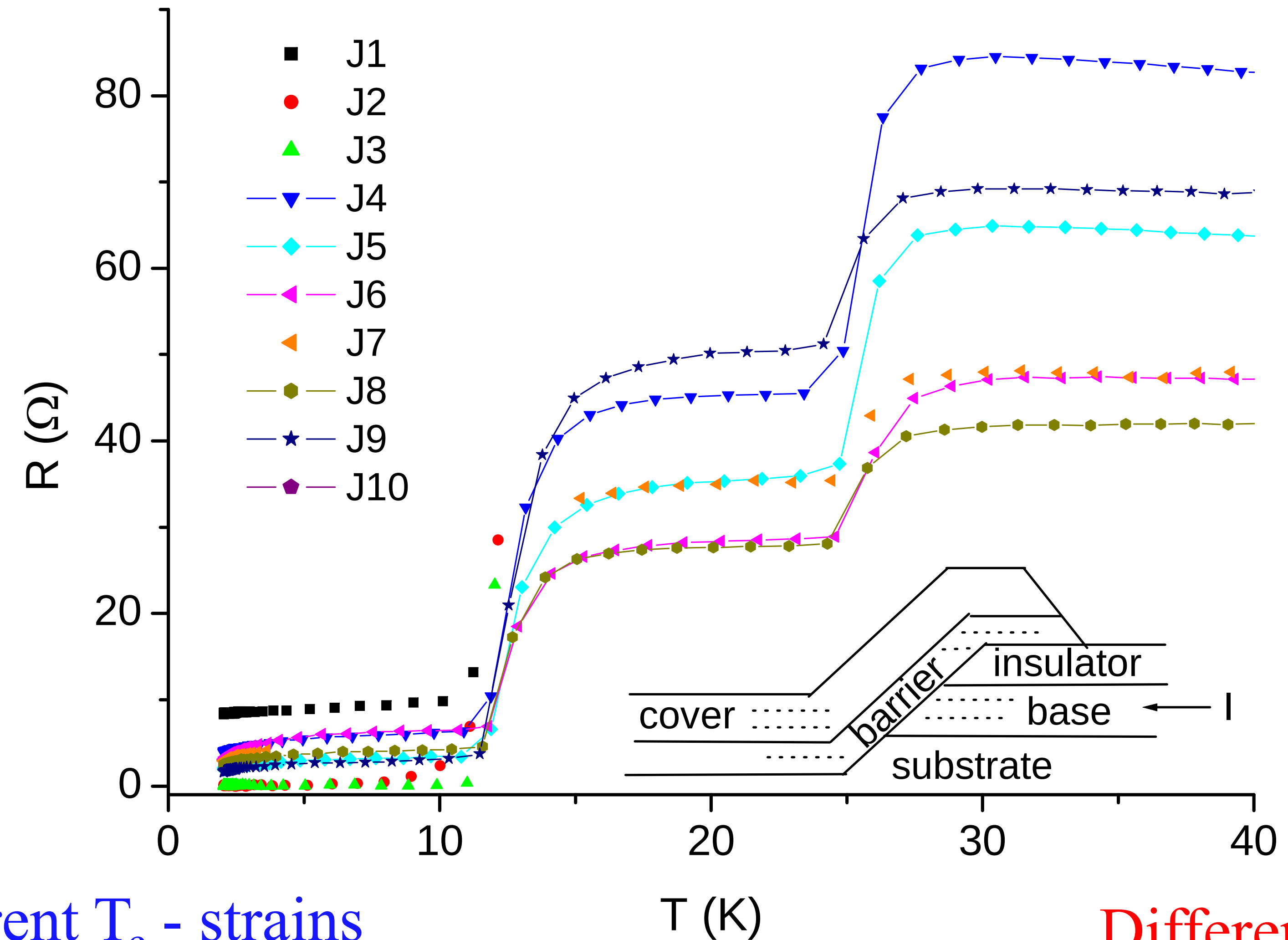
9nm SRO/(100)YBCO
300x300 nm^2
Gapped - along DW lines
Ohmic - elsewhere

Similar results up to 26 nm SRO thickness

- Thus a long range PITS can contribute to I_c in our junctions, but only along the DW lines (3nm wide), which leads to a small effect.

Similar LRPE STM results in LCMO/YBCO bilayers [Y. Kalcheim et al. PRB **83**, 064510 (2011)] But since the DW width in LCMO is ~40nm vs 3nm in SRO, a long range PITS contribution to I_c is expected to be much enhanced (no data yet)

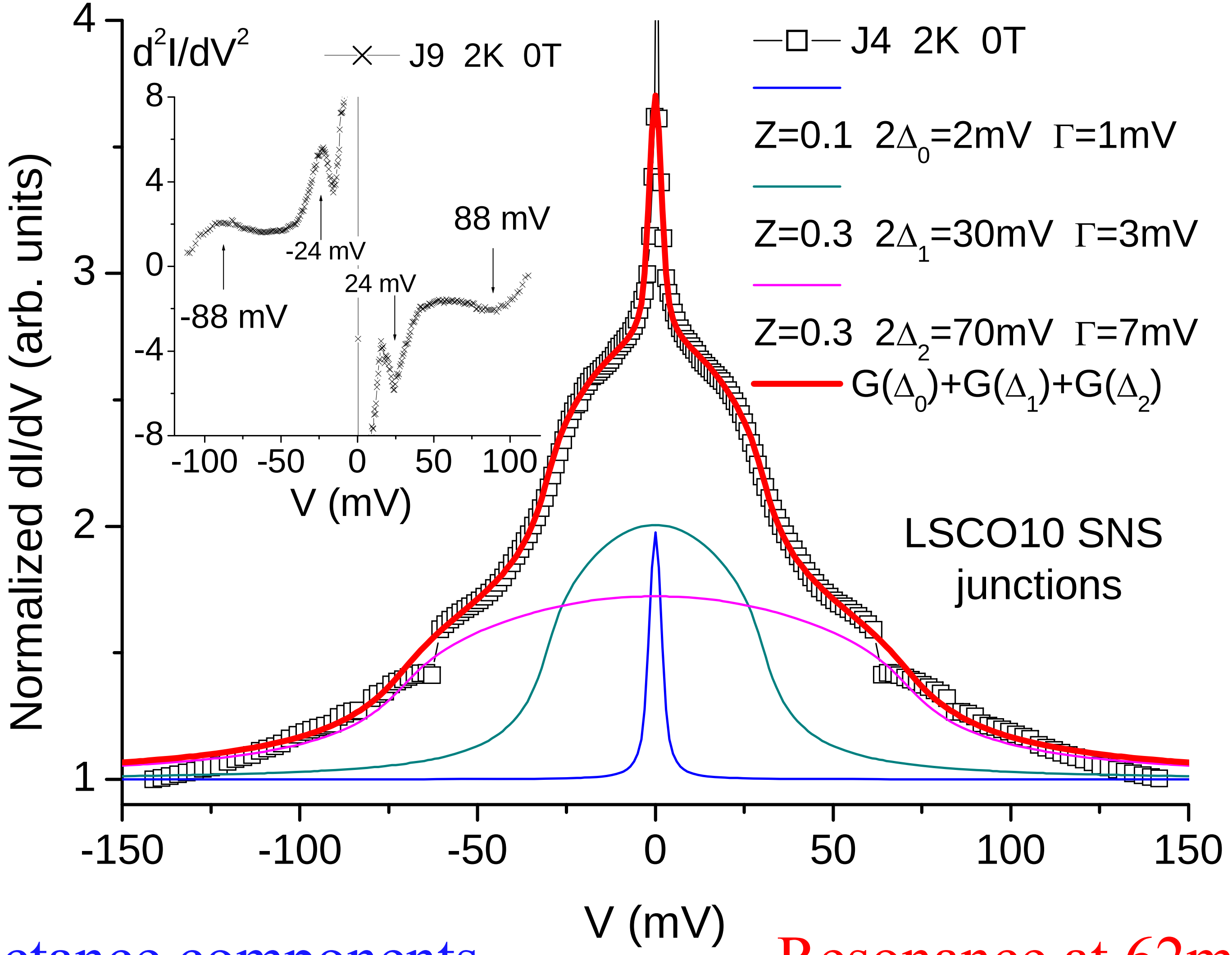
Two energy scales in SNS LSCO junctions: LSCO10-LSCO35-LSCO10 junction



Different T_c - strains

Different R_N

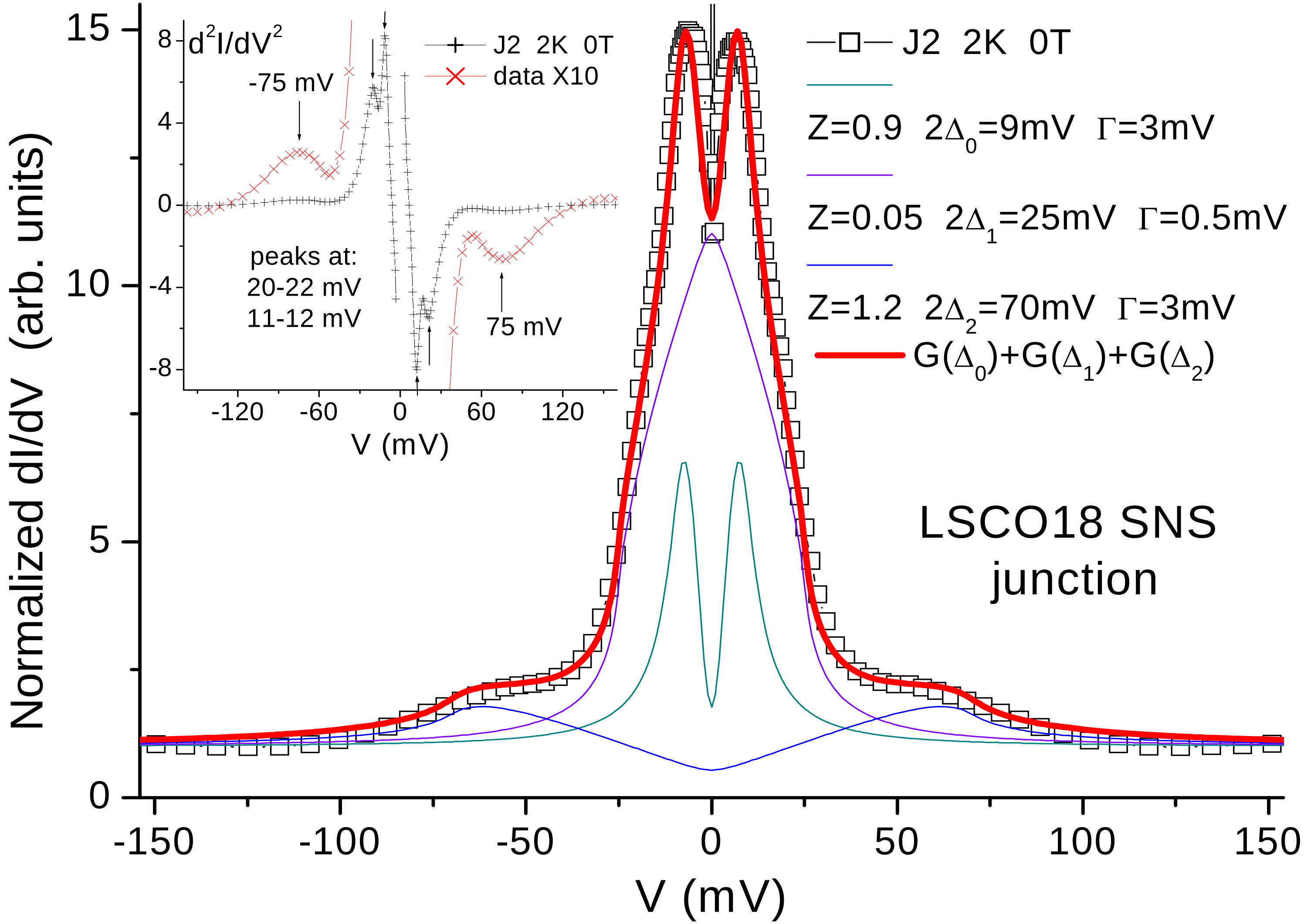
Conductance spectra of LSCO10-LSCO35-LSCO10 junctions



3 conductance components

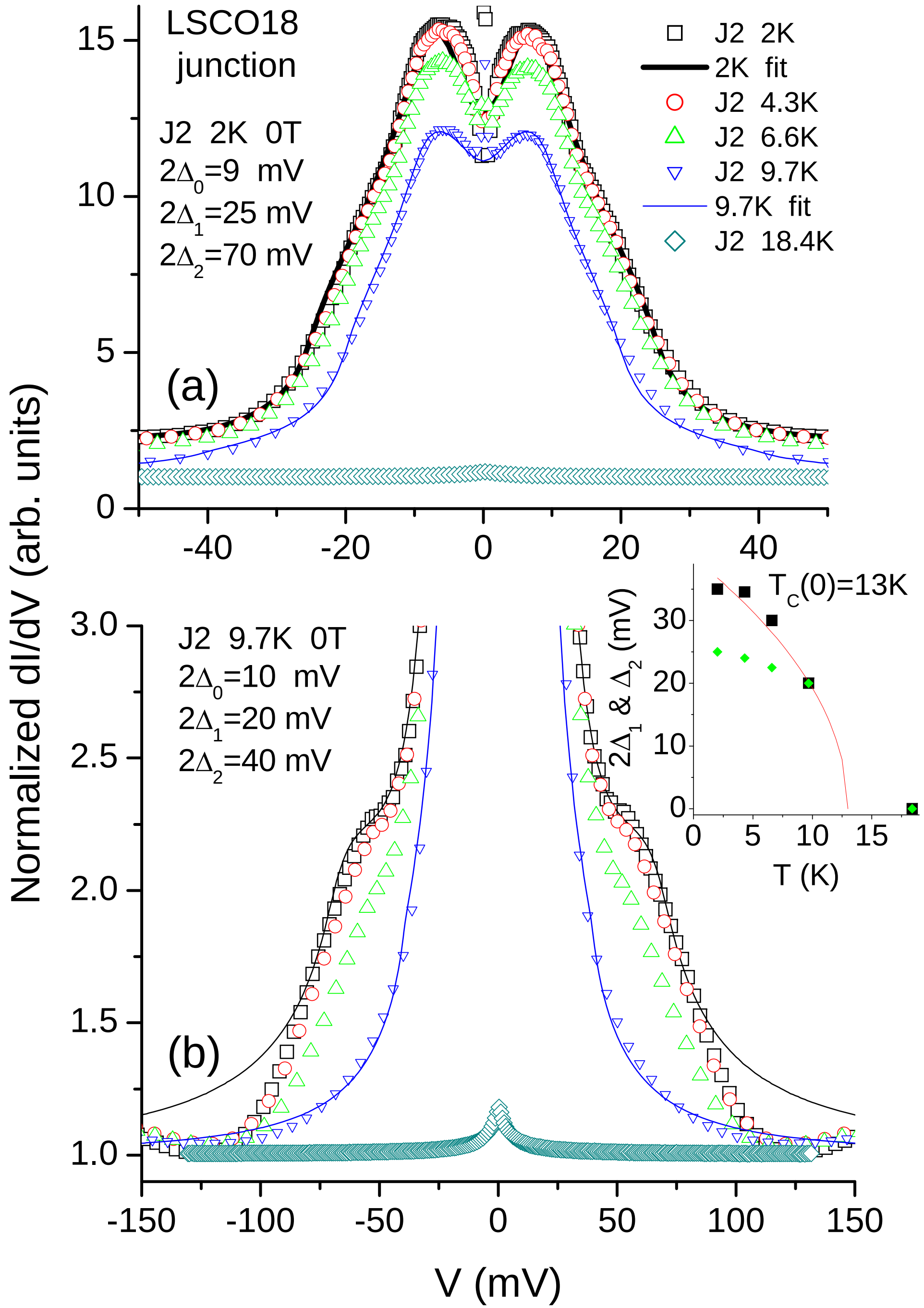
Resonance at 62mV - rare

Conductance spectrum of LSCO18 – LSCO35 – LSCO18 junction



Main contribution from Δ_1 – very transparent! Δ_2 - tunneling

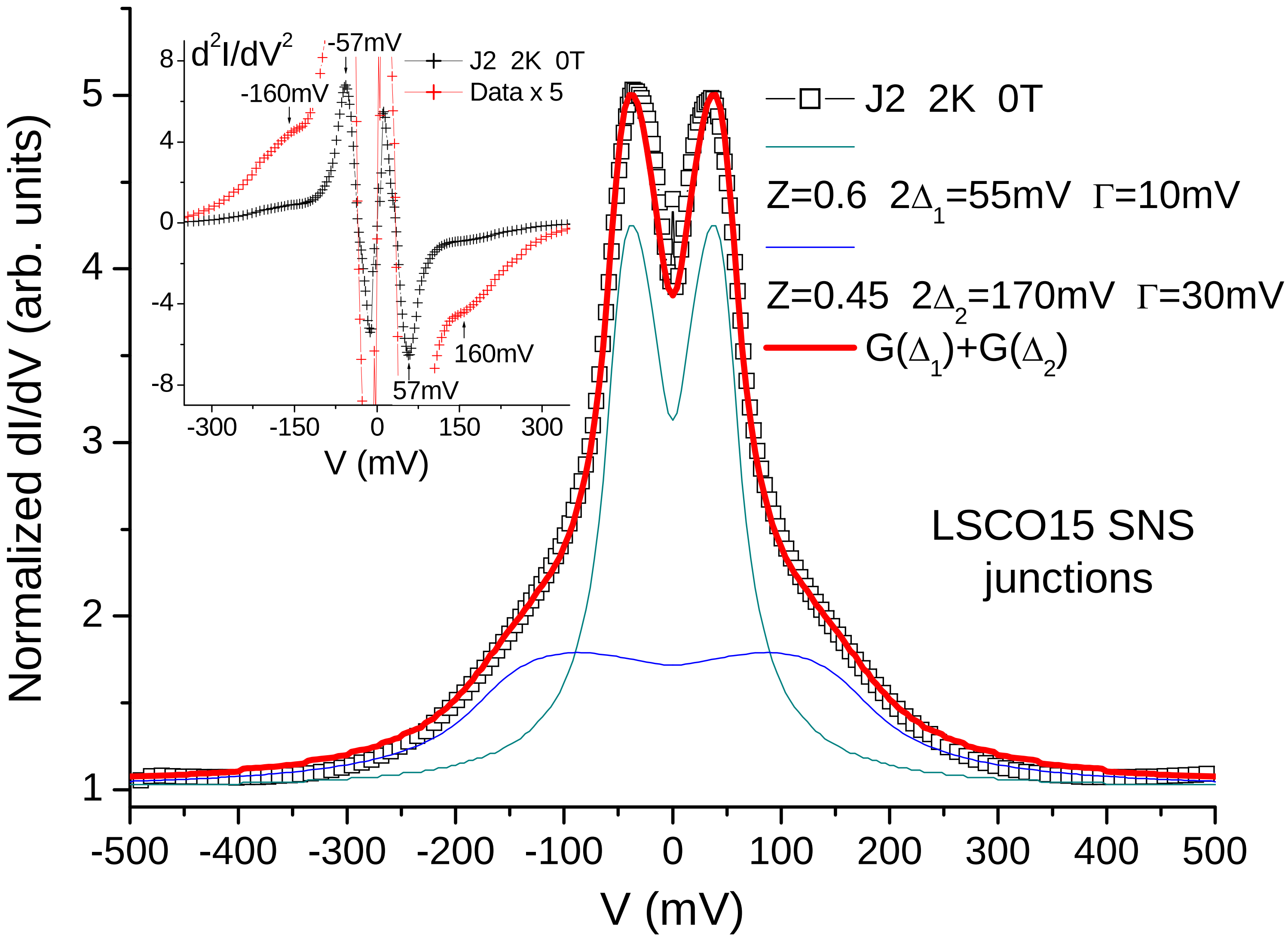
Conductance spectra of LSCO18 – LSCO35 – LSCO18 junction versus temperature



Δ_1 & Δ_2 behave like energy gaps

$$\Delta_2(T) = \Delta_2(0)\sqrt{(T_c - T)/T_c} \quad fit$$

Conductance spectra of LSCO15 – LSCO35 – LSCO15 junction



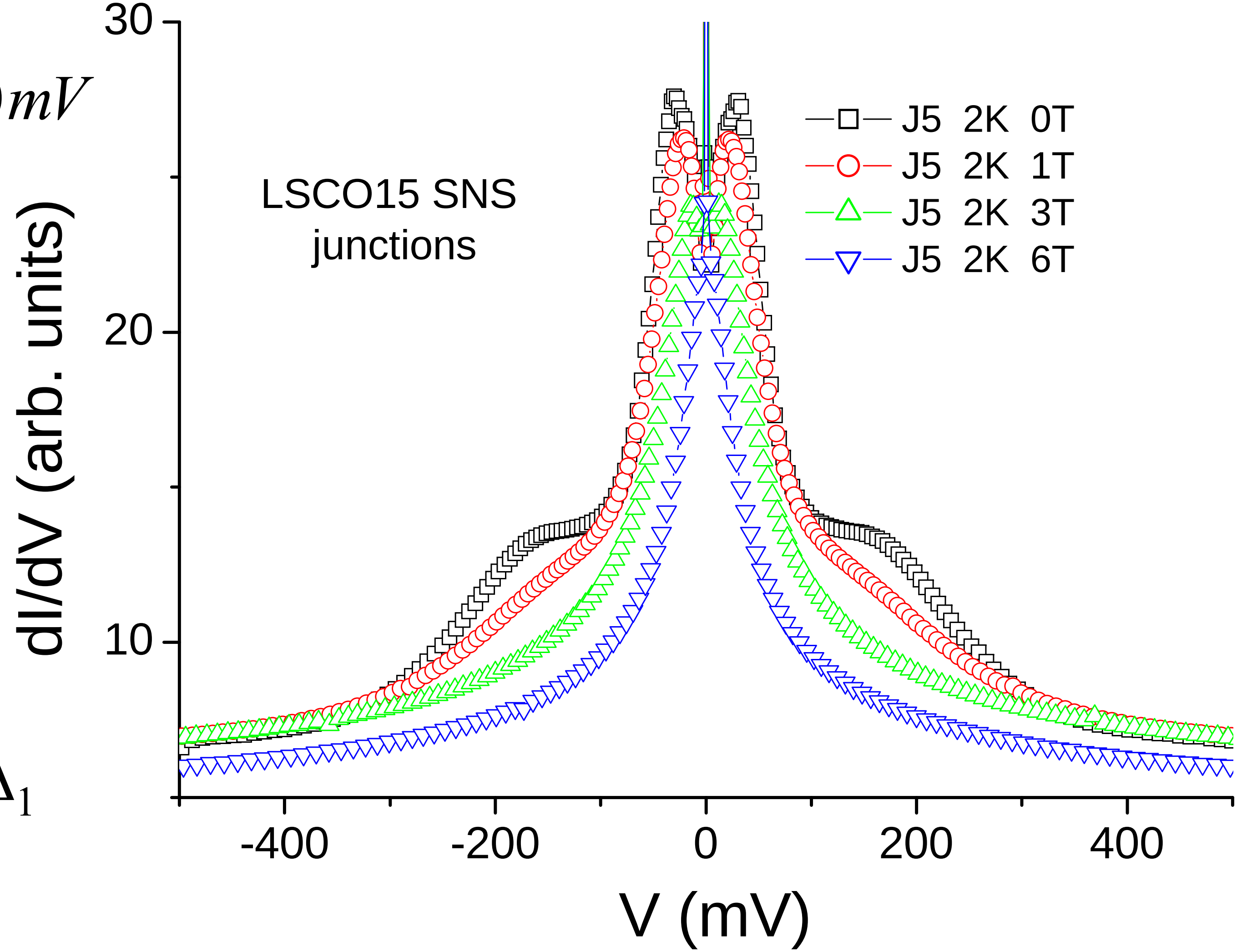
Conductance spectra of LSCO15 – LSCO35 – LSCO15 versus H

$$2\Delta_2(2K,0T) = 220\,mV$$

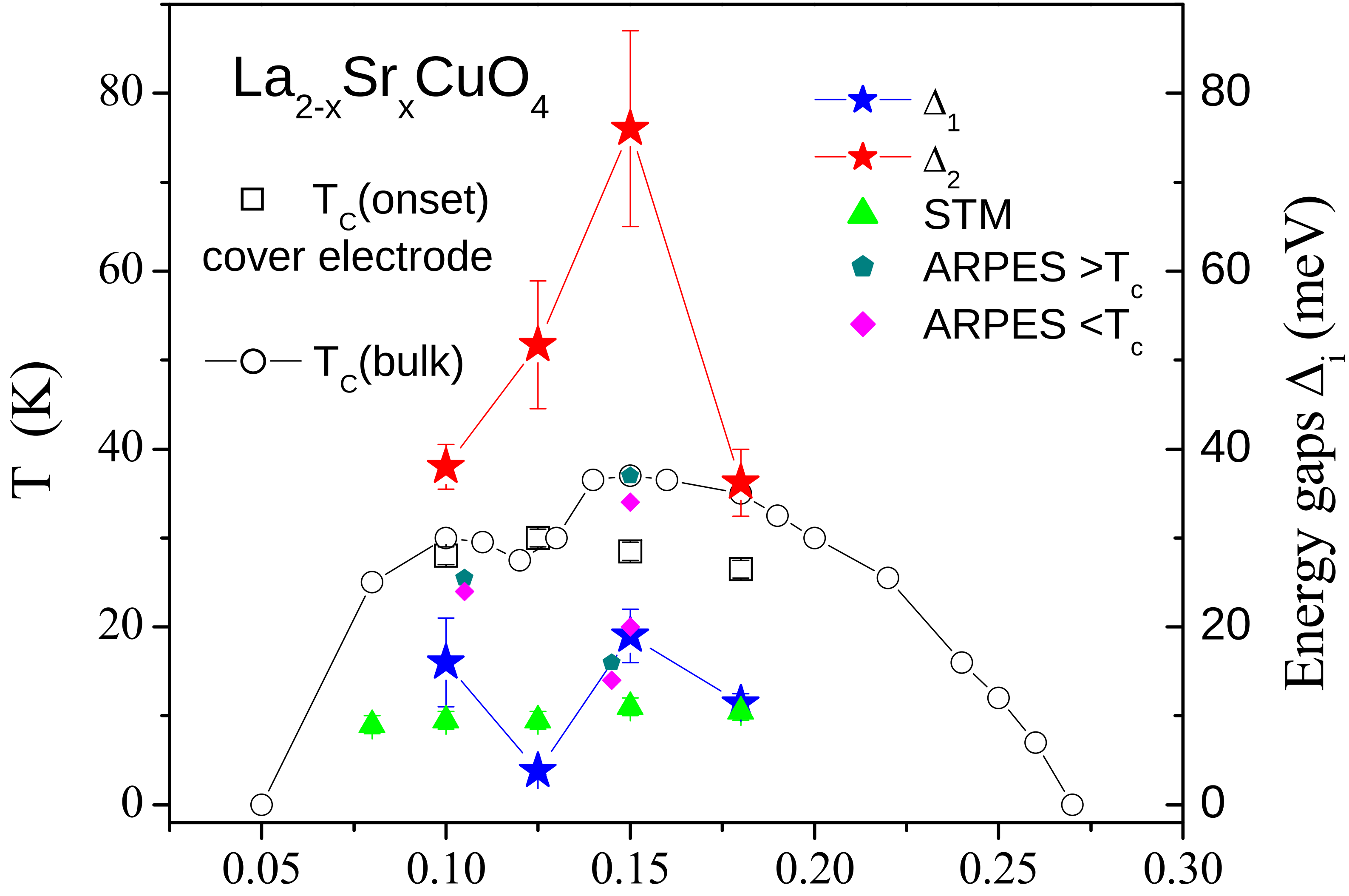
Largest Δ_2 on the wafer

Spread of Δ_2 values

Suppression versus H: Δ_2 faster than Δ_1



The phase diagram of LSCO



Δ_1 – SC gap

Δ_2 – ? gap

STM – Yuli et al., ARPES – Yohsida et al., Shi et al., Terashima et al.

What is the origin of Δ_2 ?

Y. Wang & N. P. Ong
PRB **73**, 24510 (2006)→

- Similarity to the Nernst results at T > T_c

- Possibly the same origin: 2K + current → breaking pair correlations, equivalent to T > T_c

- Hence origin in SC-fluctuations or preformed pairs, but scaling is with SC dome, not the pseudogap

PHYSICAL REVIEW B **73**, 024510 (2006)

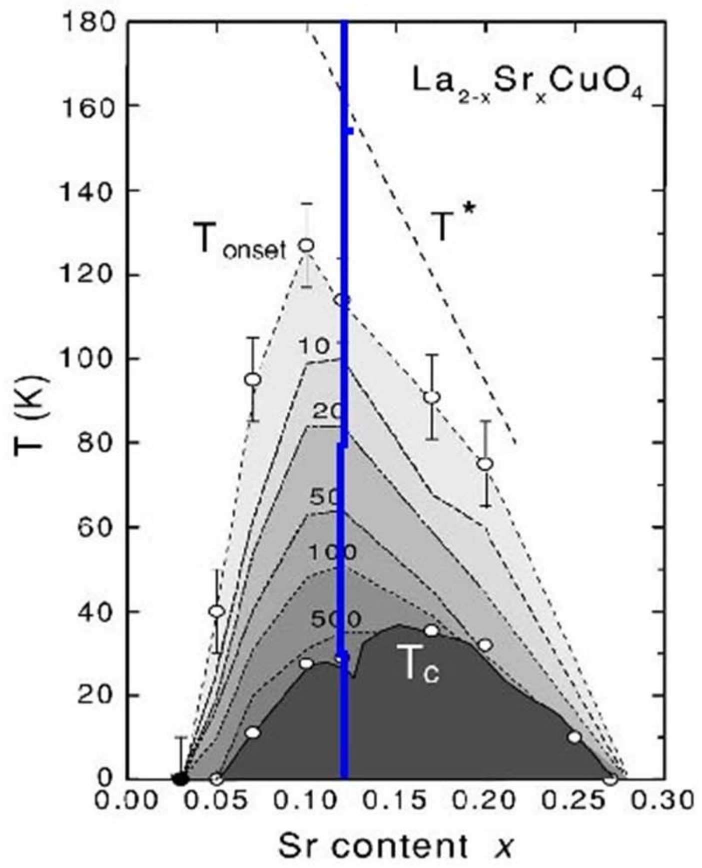
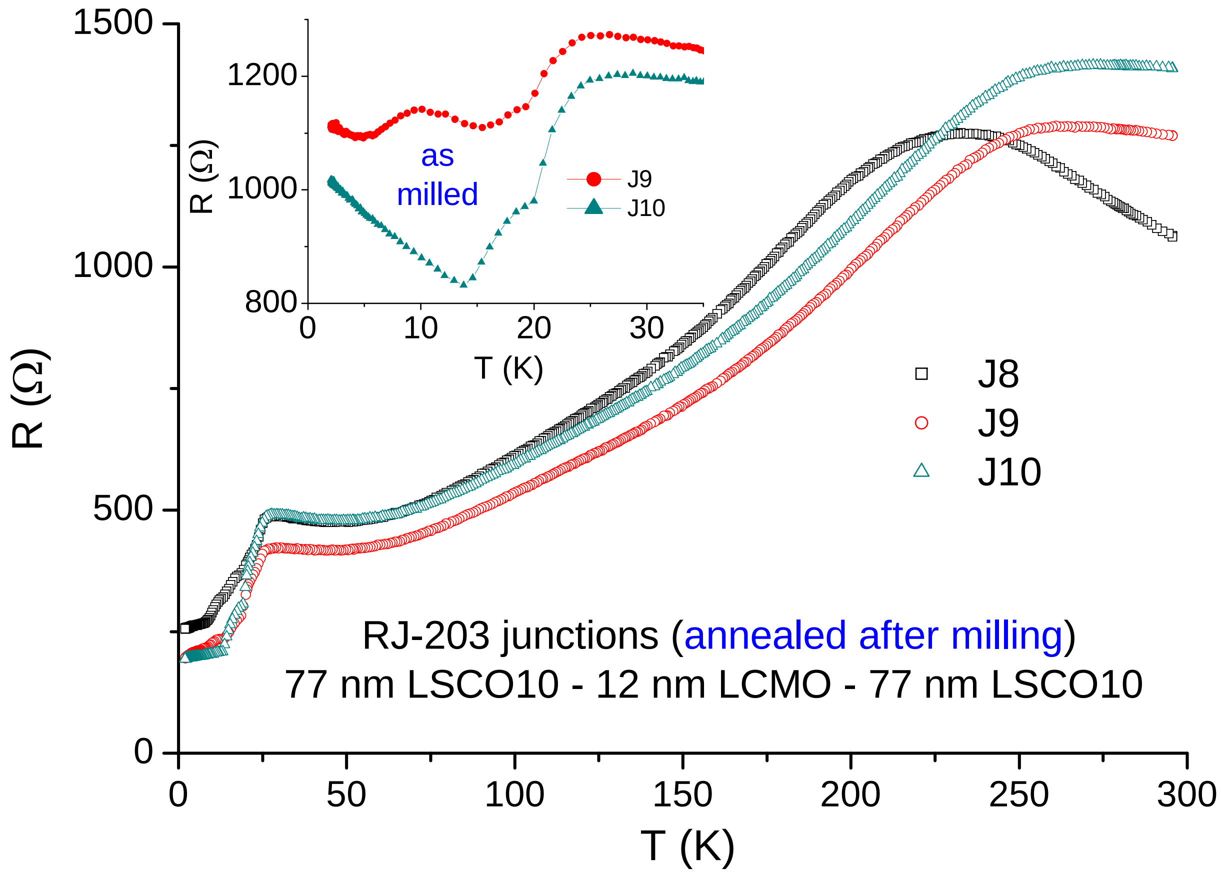


FIG. 20. The phase diagram of LSCO showing the Nernst region between T_c and T_{onset} (numbers on the contour curves indicate the value of the Nernst coefficient ν in nV/KT). The curve of T_{onset} vs x has end points at x=0.03 and x=0.26 and peaks conspicuously near 0.10. The dashed line is T^* estimated from heat-capacity measurements.

No I_c & negative MR in LSCO10-12nm LCMO-LSCO10 junctions



T_{curie}~250 K Different T_c - strains Sensitivity to oxygen in LCMO

No critical current, and we can estimate $\xi_F \sim 1$ nm (No PITS again)

Conclusions

- Observation of CARE in the conductance of YBCO-SRO junctions
- No dominant PITS in YBCO-SRO-YBCO junctions & in LSCO-LCMO-LSCO junctions
- The similarity of the Δ_2 & Nernst results supports a precursor SC scenario for Δ_2 in LSCOx-LSCO35-LSCOx junctions

T. Kirzhner & G. Koren, Phys. Rev. B **82**, 134507 (2010)

http://lanl.arxiv.org/PS_cache/arxiv/pdf/1107/1107.0808v1.pdf

G. Koren & T. Kirzhner, Phys. Rev. Lett. **106**, 017002 (2011)