The Pseudogap regime in the high temperature superconductors (HTSC)

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A special colloquium in memory of my late PhD student - Tal Kirzhner

Presented on Jan. 23, 2014, in the Faculty of Physics at the Technion

Outline

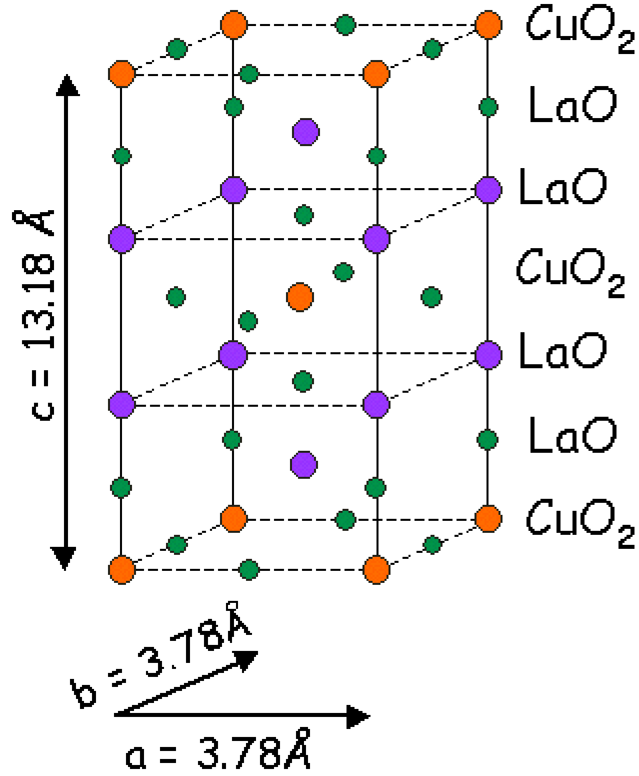
- What is the pseudogap regime? and what is T*?
- Basic experimental measurements of T* & Δ*
- Theoretical models for T* and Tc
    - Precursor superconductivity (pre-formed pairs)
    - Competing orders
- Tal's contribution to this field

Some background on the HTSC

.....Or a crash course on the HTSC

- The HTSC are oxide superconductors (the cuprates for instance, with their CuO_2 planes)

- Their "parent" compound is insulating [for example La_2CuO_4 where La is 3 valent]



- By "doping" them with some other atoms they can become superconducting [in our example, doping by Sr where Sr is 2 valent, yields $La_{2-x}Sr_xCuO_4$ which is a superconductor, (x is the "hole" doping level)]

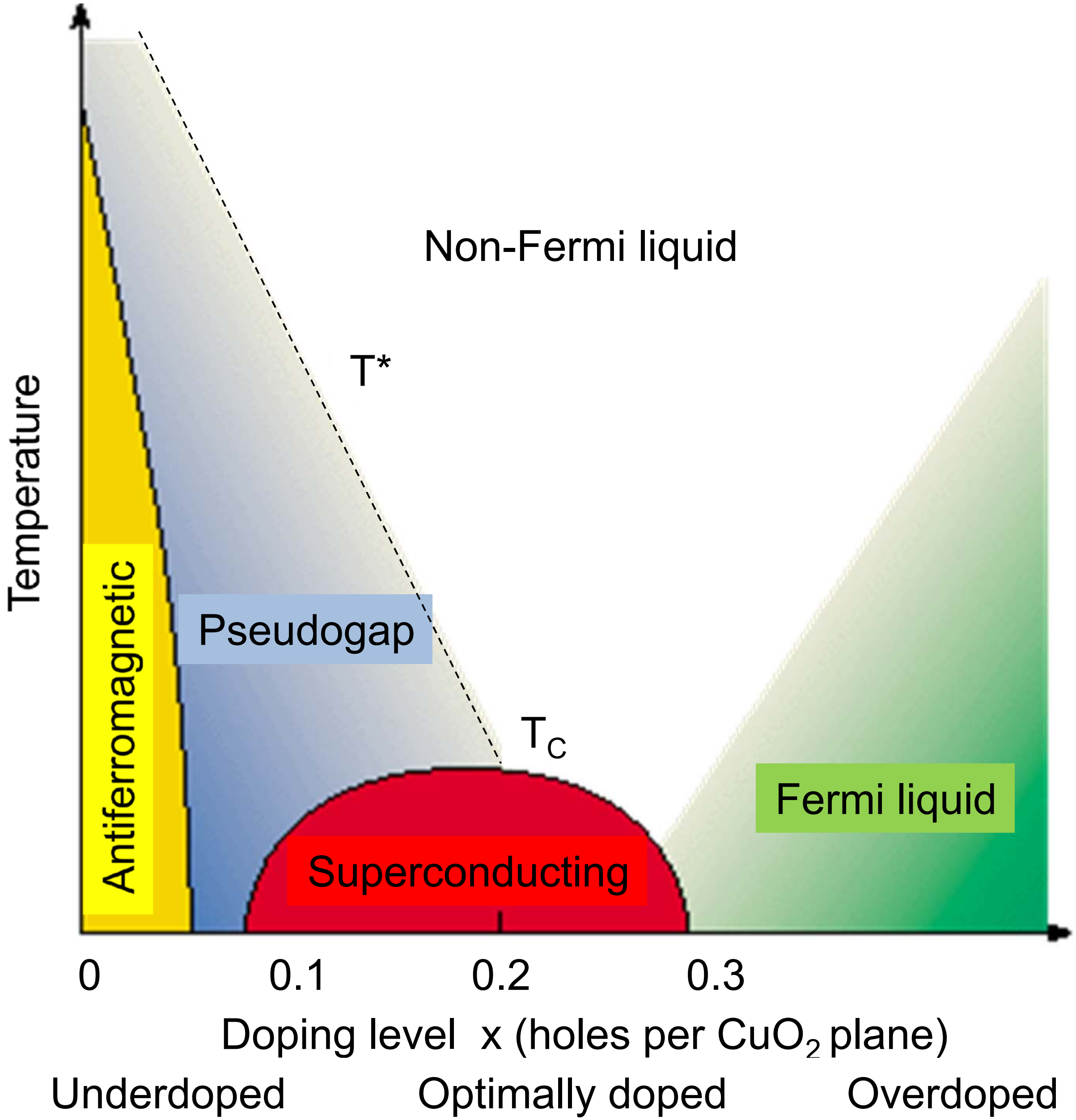
A generic phase diagram of the HTSC

At low T,
With increased doping x
AF insulator → metal→ SC

At the critical temperature
T_C the resistance→0
& shielding of H_{mag}

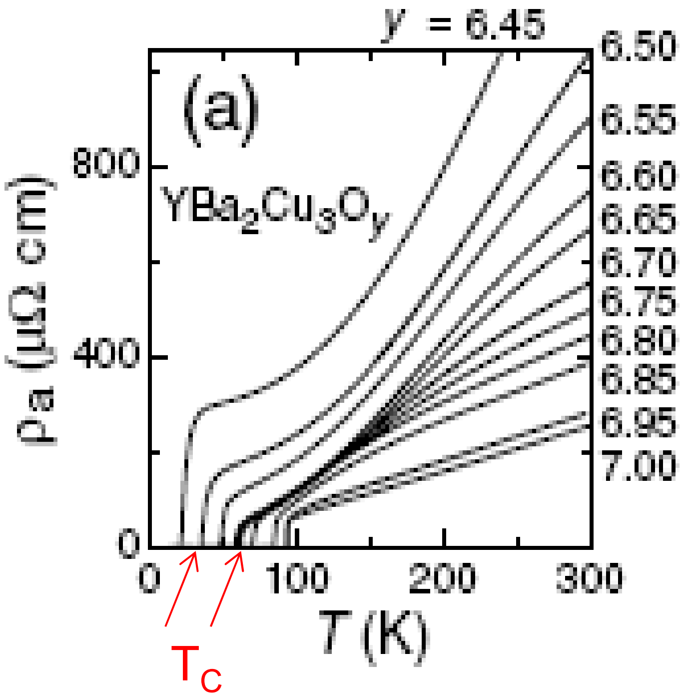
T* is the temperature of the pseudogap transition

T* and T_C are found in experiments – see next



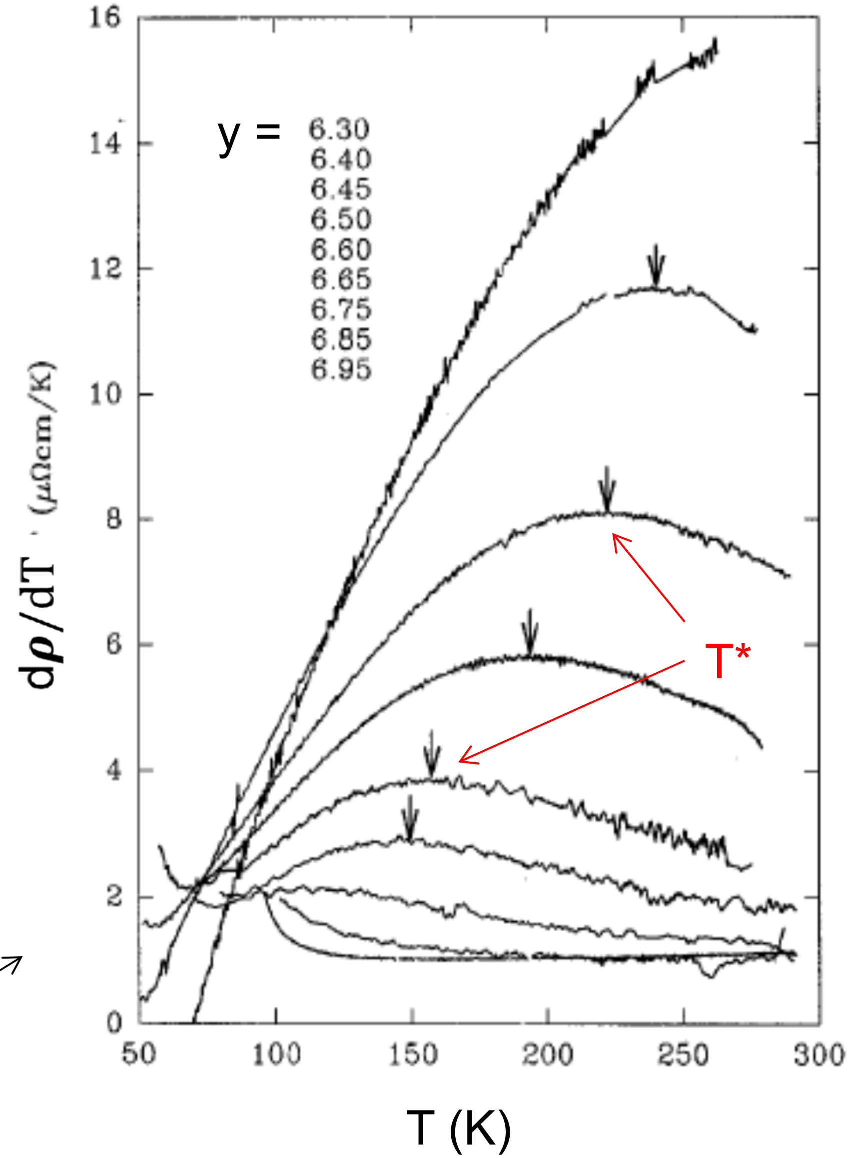
Tc & T* from R vs. T measurements

Ando & Segawa,
PRL, **88**, 167005 (2002)



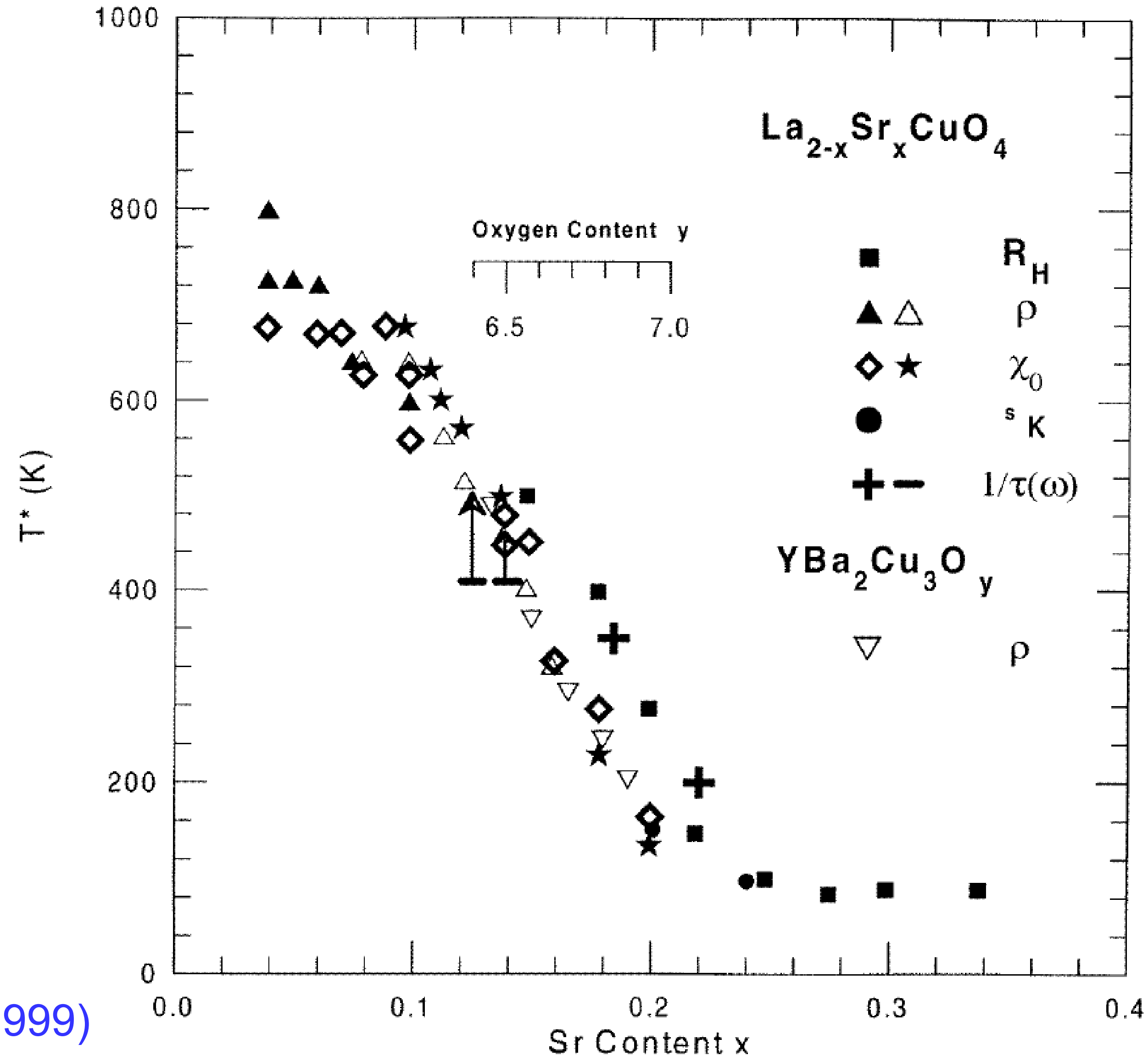
In the UD regime T_C↑x & T*↓x

Wuyts, Moshchalkov, and
Bruynseraede PRB, **53** 9418 (1996)



And more T* results using different measurement techniques

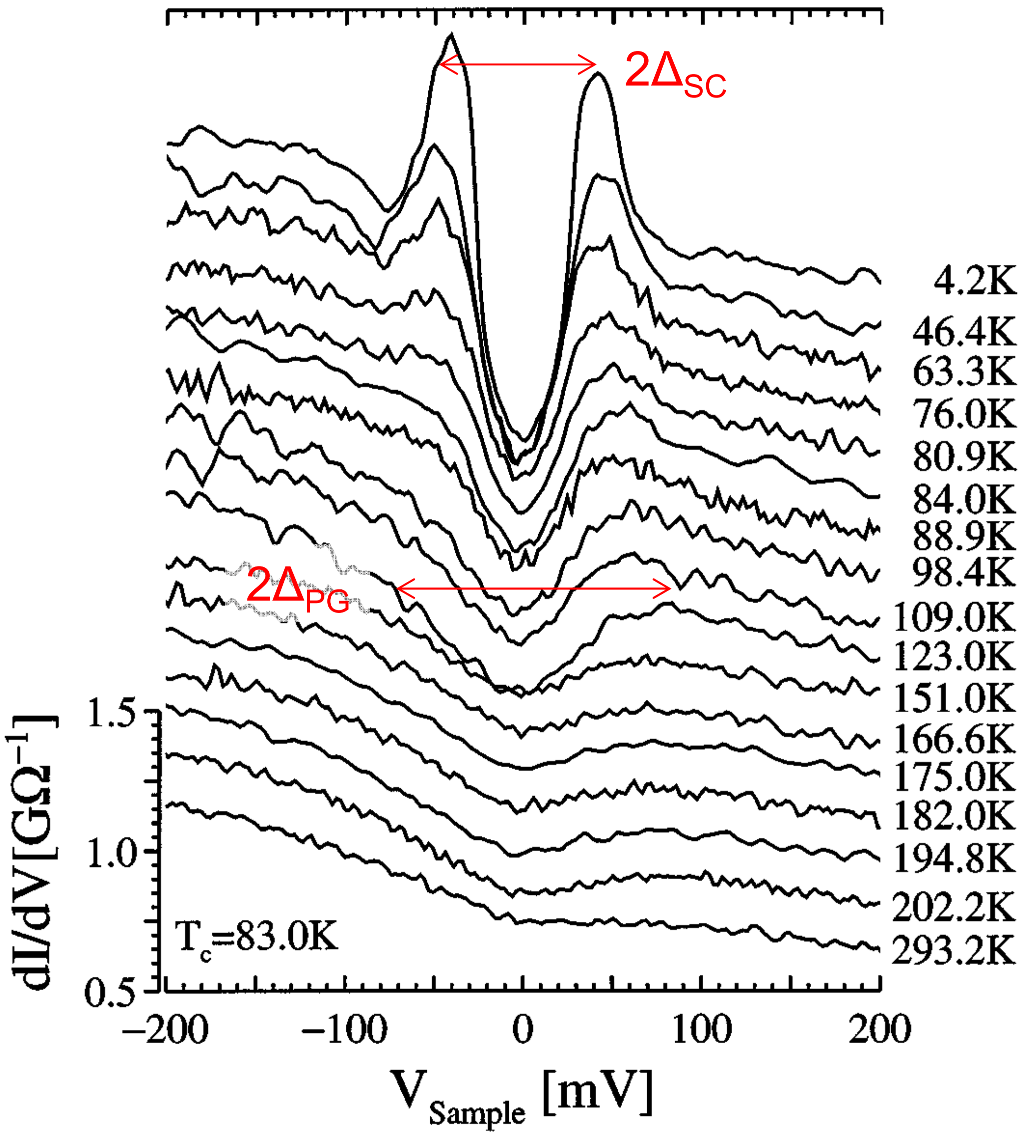
- R_H - Hall meas.
- ρ - resistivity
- χ_0 - susceptibility
- ^sK - Knight shift (NMR)
- +- IR relaxations



Timusk & Statt
Rep. Prog. Phys. **62, 61** (1999)

What is the energy-gap Δ_{PG} of the pseudogap?

- Experimental data of Scanning Tunneling Spectra in $Bi_2Sr_2CaCu_2O_{8-\delta}$ [Renner et al. PRL **80**, 149 (1998)]
- In all SC, a superconducting energy-gap Δ_{SC} exists below T_c
- There is also a Δ_{PG} (pseudo)gap below T* and above T_c in the HTSC
- Both Δ are characterized by a depletion of low-energy density of states of electrons at eV<Δ

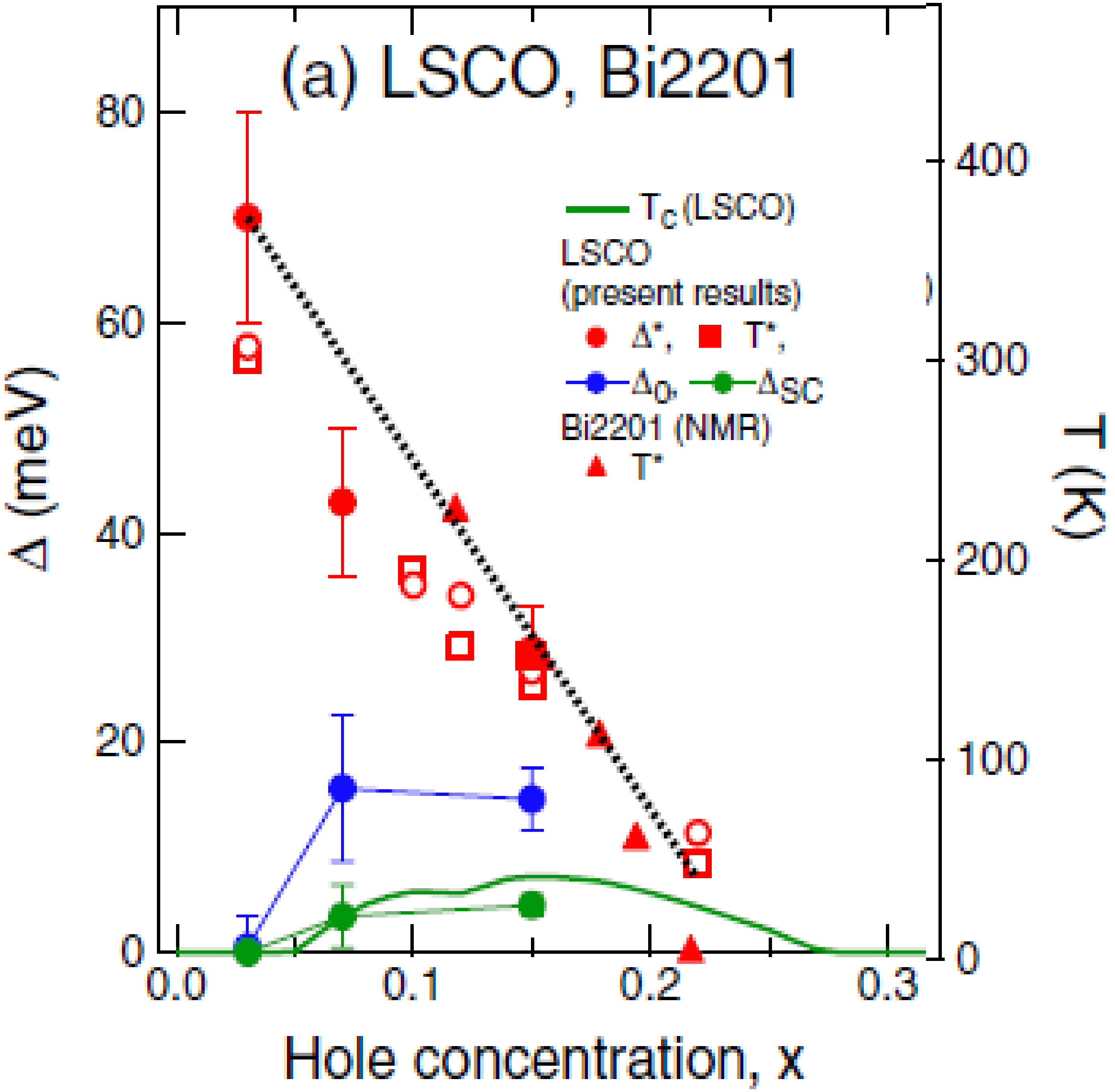


→ $\Delta_{PG} > \Delta_{SC}$

Δ_{PG} & T* from Angular Resolved Photoemission (ARPES) data

Δ^* (or Δ_{PG}) behaves like T*

Yoshida et al.
PRL **103**, 37004 (2009)



(Agrees with $2\Delta^*=4.3K_BT^*$
Close to BCS: $2\Delta_0=3.5K_BT_C$)

Modeling of T* & T_C versus x in the cuprates

- Every superconductor has a macroscopic wave function (or a complex order parameter) that describes its' pairs

$$\psi(r) = \varphi_o (r)\exp[-i\theta(r)]$$

- $\varphi_o(r)$ is related to the pairing gap $\propto$ pairing temperature T_P ($T_P \approx \Delta_0/2$)

- $\theta(r)$ is the condensate phase $\propto$ phase ordering temperature. For a 2D system, $T_\theta \propto n_S$ where n_S is the pairs' density ($T_\theta \approx h^2 n_S \xi^{d-2}/4\pi m^*$)

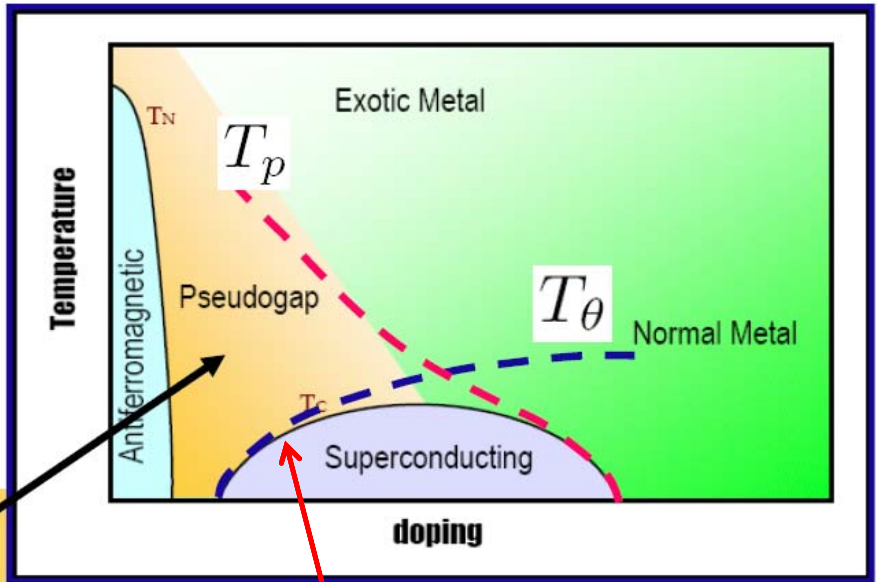
- In conventional SC, such as the elements, both pairing and phase-coherence occur simultaneously at T_C

- In the HTSC where x is low, pairing can occur at $T>T_C$ but without phase-coherence. In this case, T_C is determined by:

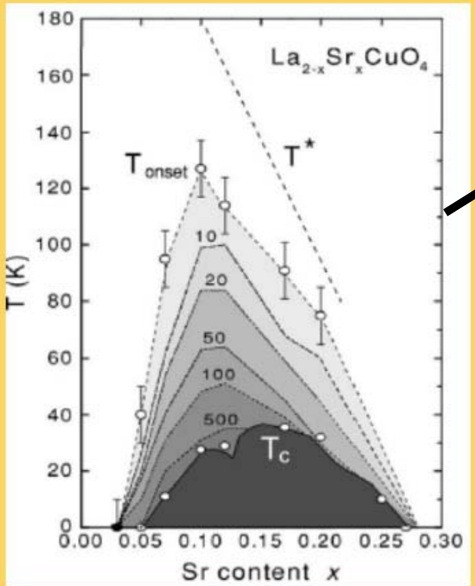
$$T_C \sim \min(T_P ; T_\theta)$$

Precursor or pre-formed pairs model for the pseudogap regime

- There are uncorrelated pairs in the PG regime that become phase-coherent at T_c



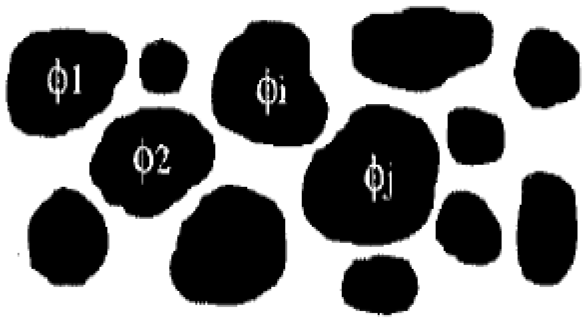
Emery and Kivelson (Nature 1995)



Wang, Li, Ong. (PRB 06)

- Strong phase-fluctuations in the PG regime
- Or low phase-stiffness, like in granular material

$T_c \sim \min(T_P ; T_\theta)$

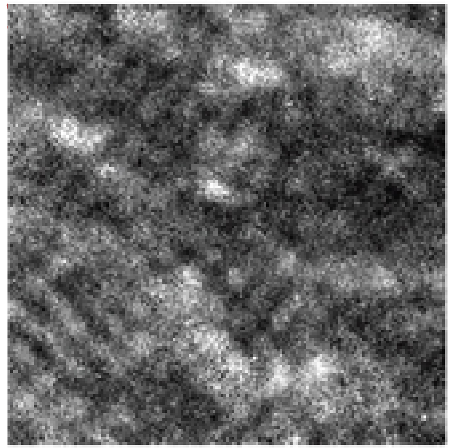


Competing orders

- SDW – spin density wave, spin stripes,
- CDW – charge density wave, charge stripes,

"Checkerboard" (STM conductance, 10mV)

Wise et al., NP 4, 696 (2008)

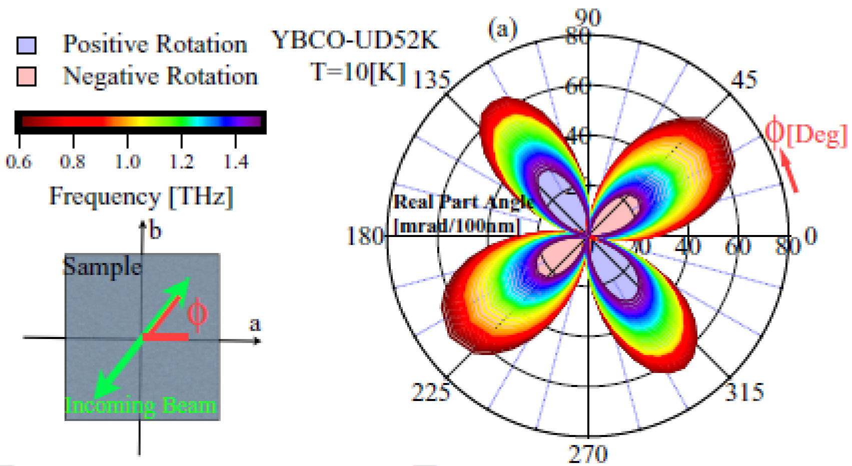


30nm, Bi-2201, ~$6a_0$ mod.
T_C=32 K, T=35 K

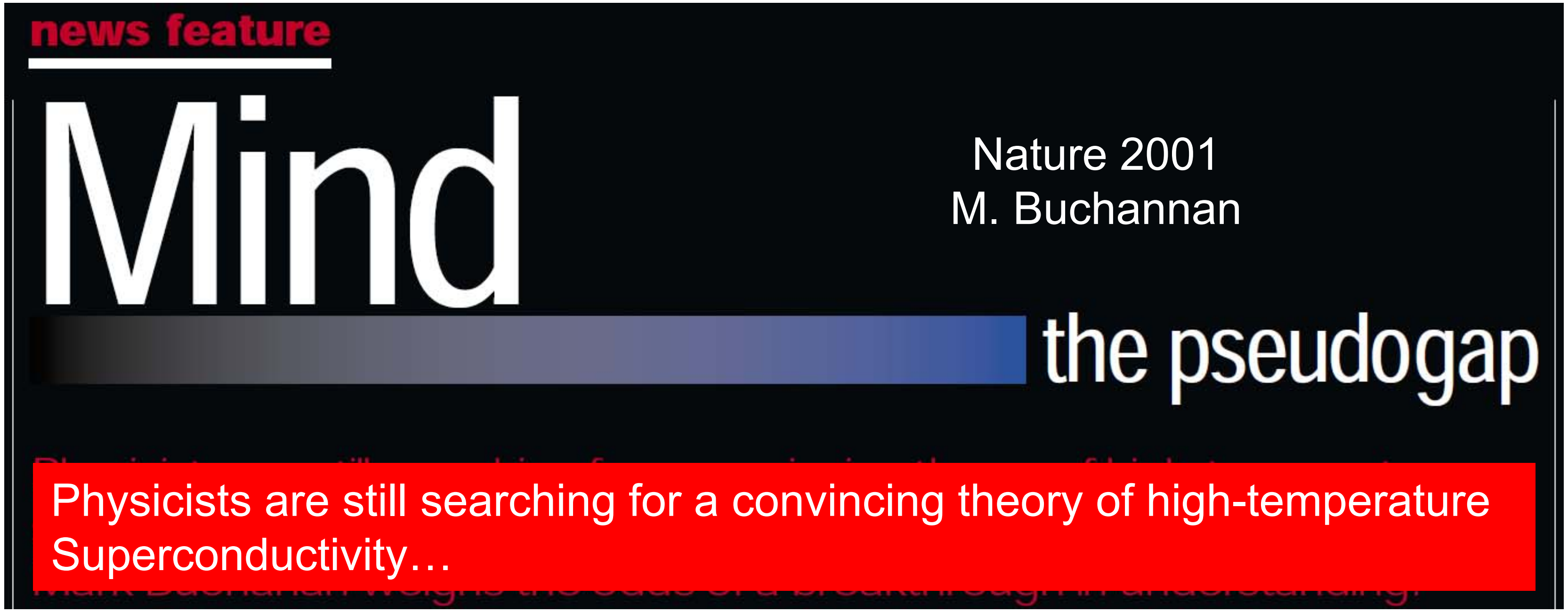
- Magnetic order (found using neutron scattering)
- Gyrotropic order (breaking C_4 rotation & mirror symmetries)

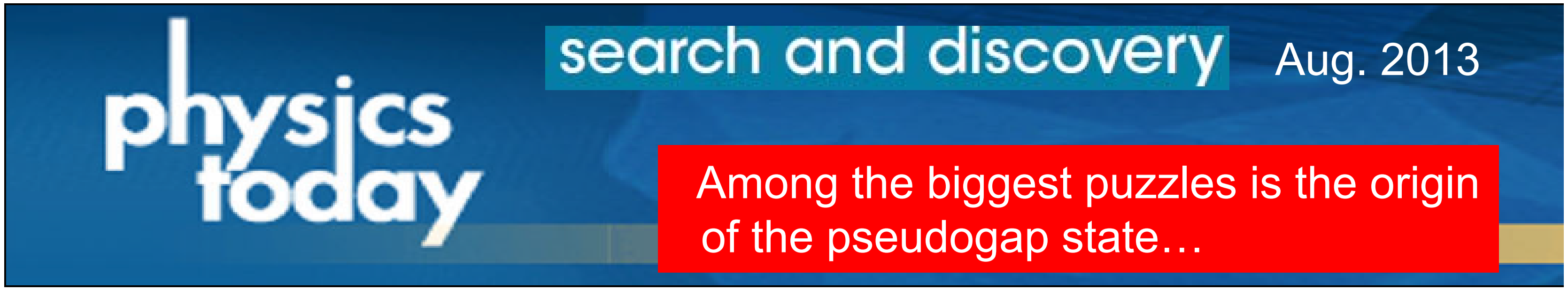
Terahertz spectroscopy – birefringence

Lubashevsky, Pan, Tal Kirzhner, Koren & Armitage, arXiv:1310.2265



The origin of the pseudogap is still a puzzle





- And still in Jan. 2014, Patrick Lee of MIT starts his recent arXiv:1401.0519 paper by:

Since the early days of cuprate superconductivity research, the pseudogap phase has been identified as a central piece of the high Tc puzzle.

Supercurrents in the pseudogap regime of LSCO in YBCO/LSCO/YBCO junctions

Tal Kirzhner

DIP meeting, Technion, March 19, 2013

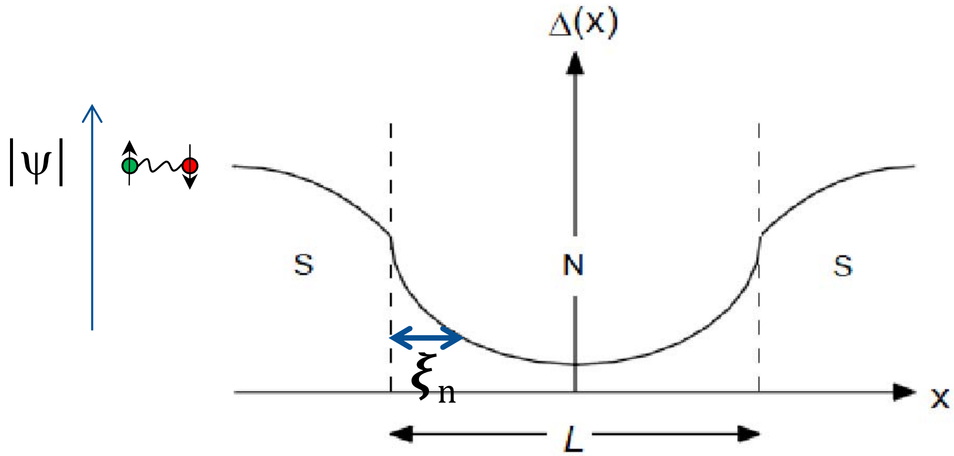
http://physics.technion.ac.il/~gkoren/DIP_Tal

SNS Junctions

- Proximity effect in SNS junctions leads to a supercurrent (Pairs' current at zero bias, via Andreev reflections).

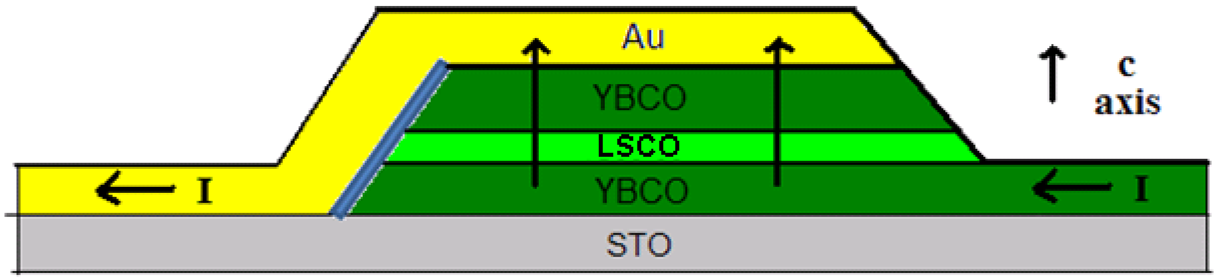
- The critical current in SNS junctions (DeGennes):
  - $J_c = \frac{\pi}{2e\rho_n\xi_n}\frac{|\Delta_0|^2}{k_bT_c}(1-\frac{T}{T_c})^2 e^{-L/\xi_n}$ or $I_c \propto e^{-L/\xi_n}$

  - Weak superconductivity in the metal barrier



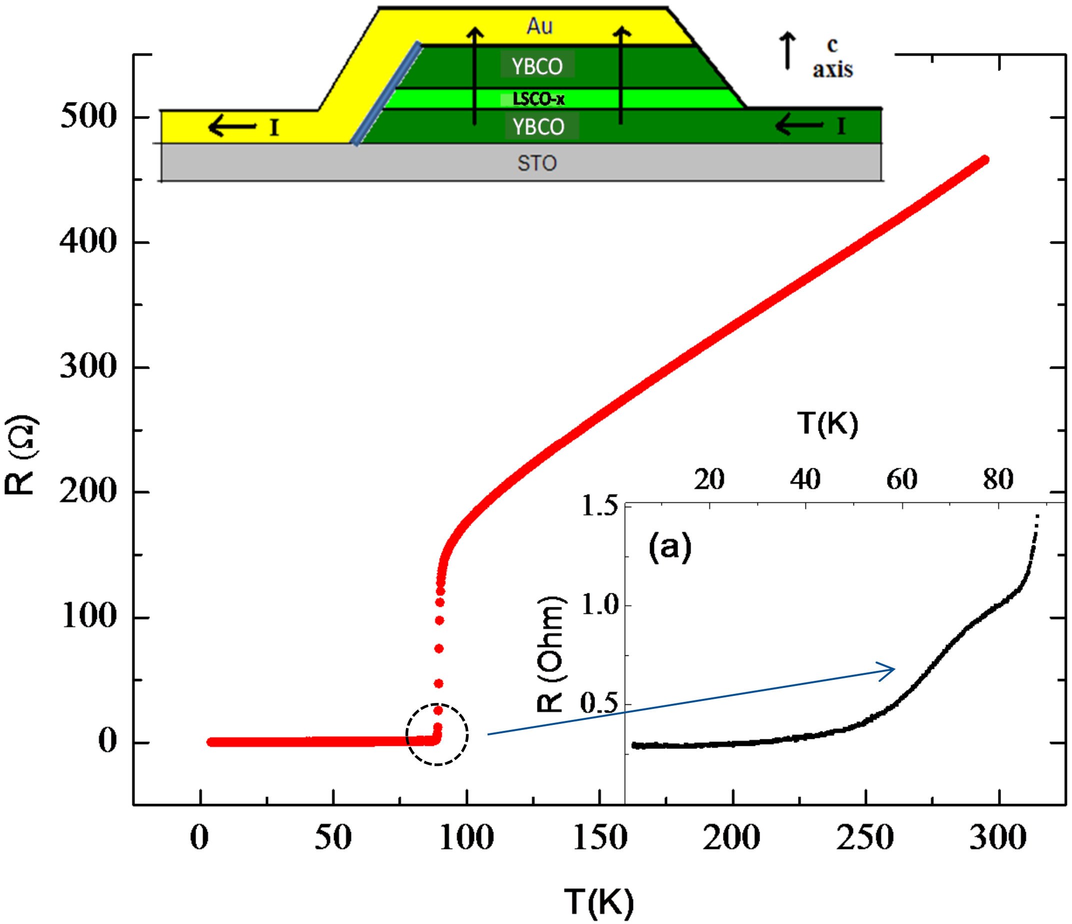
The junctions in the present experiment

- Tri-layer, c-axis Josephson junctions of the SNS type were prepared.
- (100nm **YBCO cover**) / (10-20nm **LSCO**) / (200nm **YBCO base**) junction
  - LSCO with various doping
  - 5 µm x 5 µm Area
- The I-V curves were measured as function of temperature, below T_c of YBCO (90K) and above T_c of LSCO-x (<25K) in the PG regime of LSCO-x & then the critical current was extracted.



Results of Tal's last work - arXiv:1311.2250

- Pairing and the phase diagram of the normal coherence length $\xi_N(T; x)$ above Tc of $La_{2-x}Sr_xCuO_4$ thin films probed by the Josephson effect



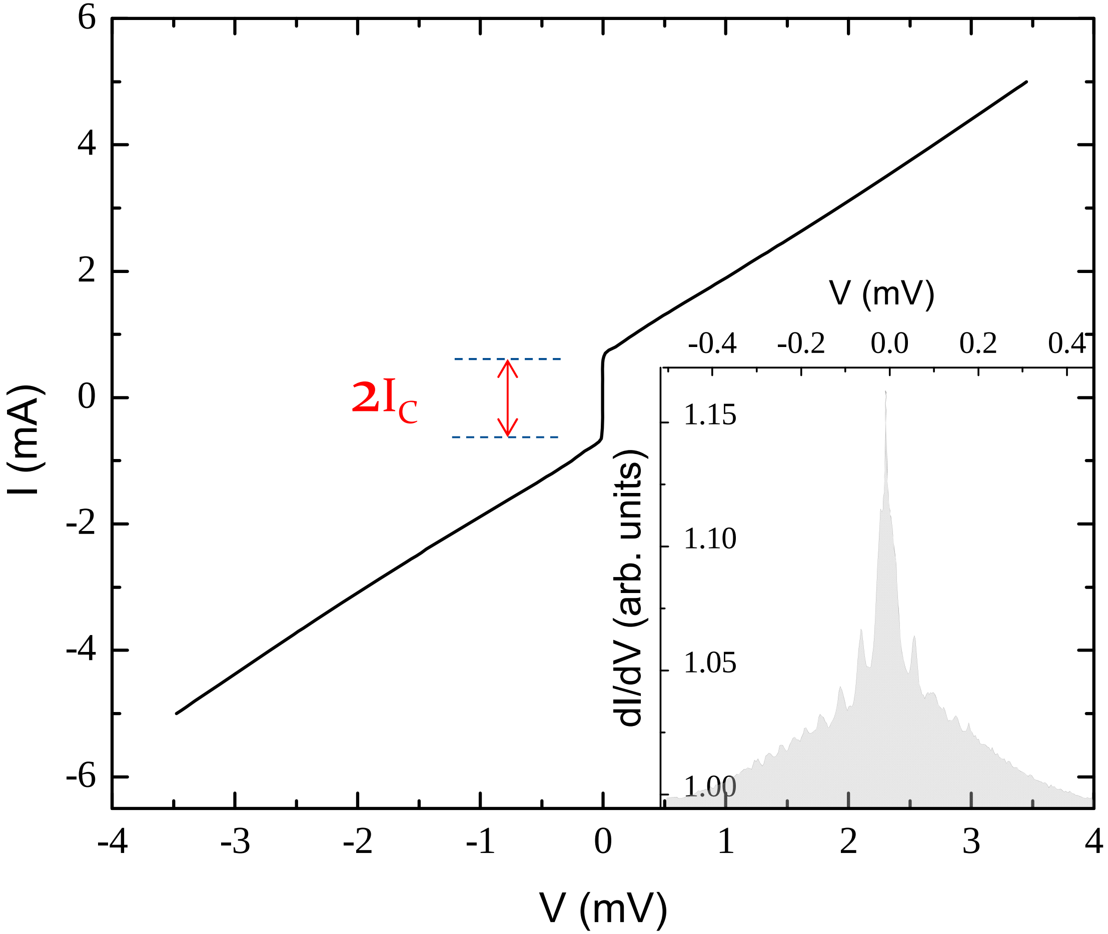
- R vs T of a junction with a 20 nm thick barrier of LSCO-0.07
- Shows mostly of the YBCO base response, T_C is ~ 90 K
- The junction resistance (before it becomes SC) is about 1 Ω

Results – 2

- I-V curve at 10 K of a typical junction with a 20 nm thick LSCO-0.07 barrier.
  $I_C \sim 0.7$ mA

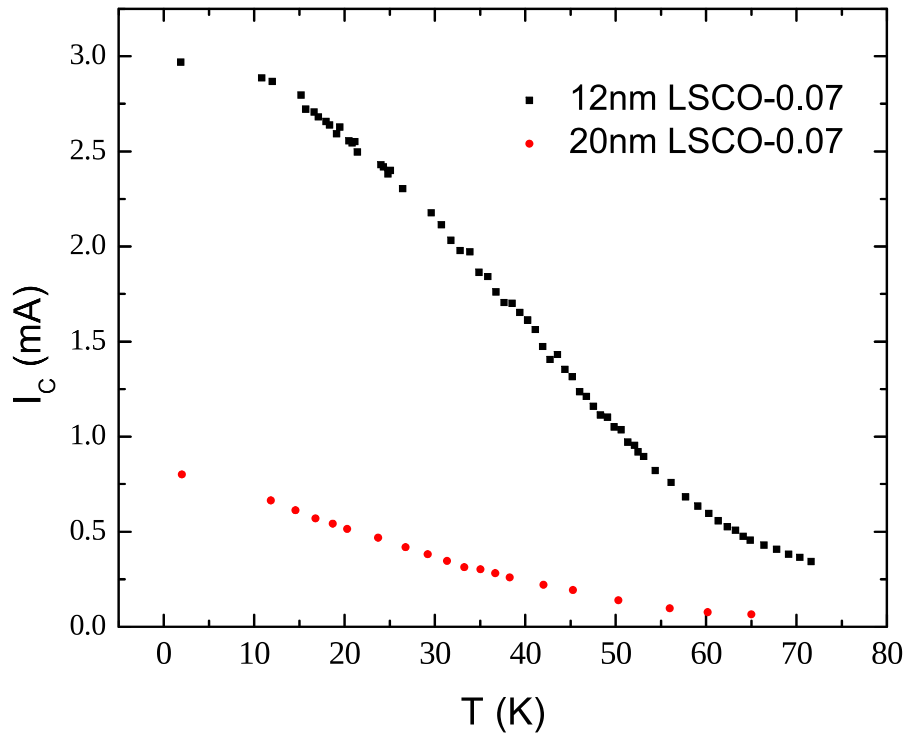
- The inset shows dI/dV at 40K under 10.7 GHz microwave irradiation.
  The "Shapiro steps", showing the AC Josephson effect, appear as peaks at spacing's of:

$$\Delta V = \frac{h\nu}{2e} \approx 20\ \mu V$$

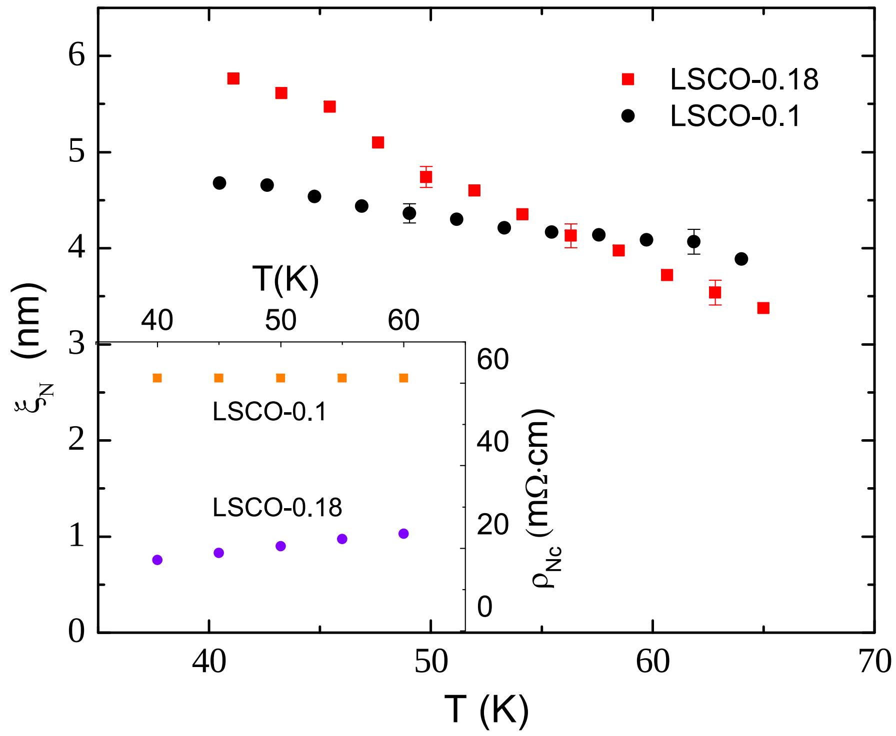


Results – 3

- I_C vs T [~$(T-T_C)^2$ near T_C]
- Larger I_C with thinner barrier



- Extract ξ_N from $I_C \propto \exp[-L/\xi_N]$ for junctions with L=12 & 20 nm & then plot ξ_N vs T
- I_C decays slowly vs T for x=0.1, →leads to crossing at 55 K



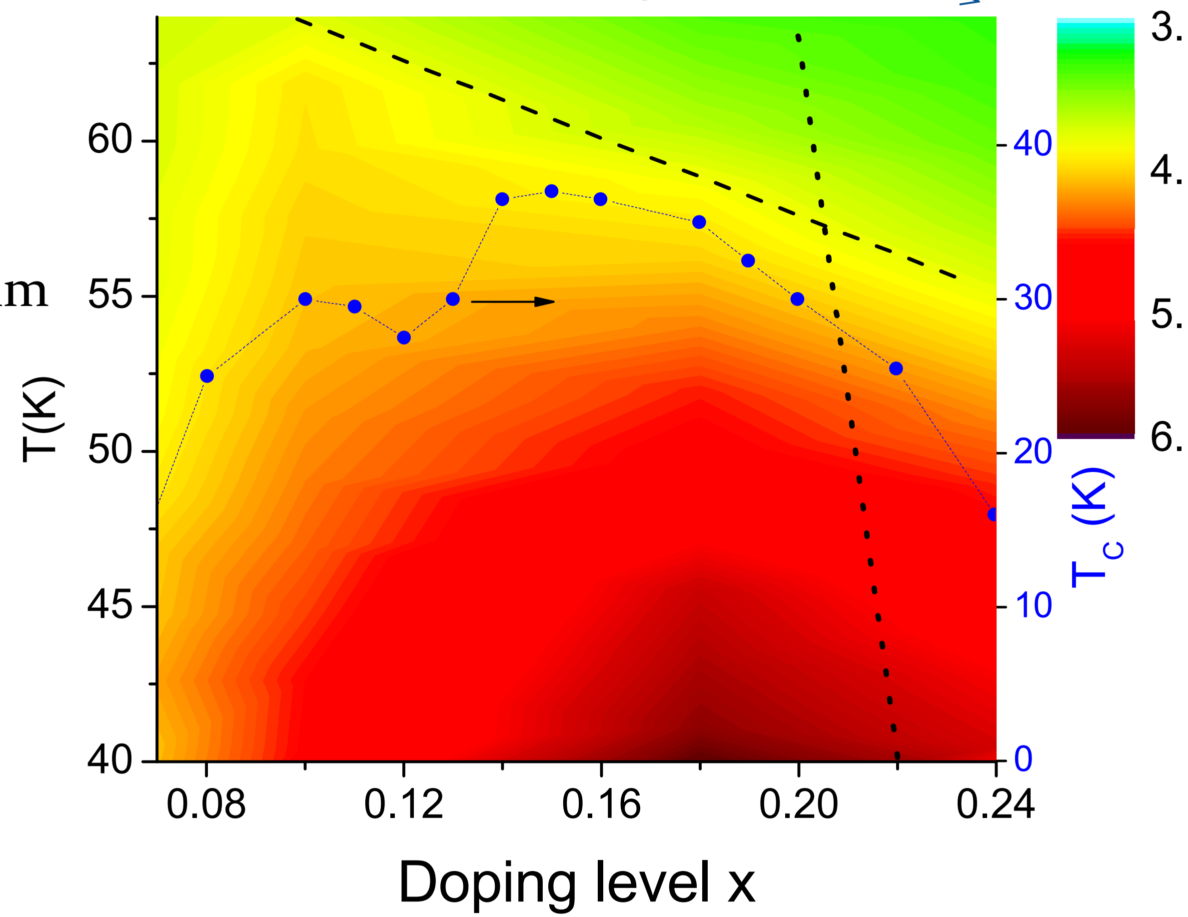
Results – 4

- All data of $\xi_N(T,x)$ for x=0.07, 0.1, 0.18 & 0.24 on a color map
- T_C of bulk LSCO vs x

- All data in the PG regime

- Long range proximity effect
ξ_N~4-5nm vs expected 0.1-0.2nm

- Enhanced ξ_N at x=0.1 compared to x=0.18 above 55 K (see dashed line) → Enhanced SC correlations → Supports the pre-formed pairs scenario in the PG regime, but at T<<T* (see dotted line)



& these are Tal's Conclusions

- We have measured the normal coherence length of an underdoped and overdoped LSCO above T_c using the Josephson effect.
- At x > 0.1 and T > 55 K the normal coherence length of underdoped LSCO is higher than that of overdoped LSCO.
  - It is in contrast to the conventional theory of the proximity effect where the opposite behavior is expected.
  - The results can be explained by the phase fluctuations scenario, and the presence of pre-formed pairs in the pseudogap regime.