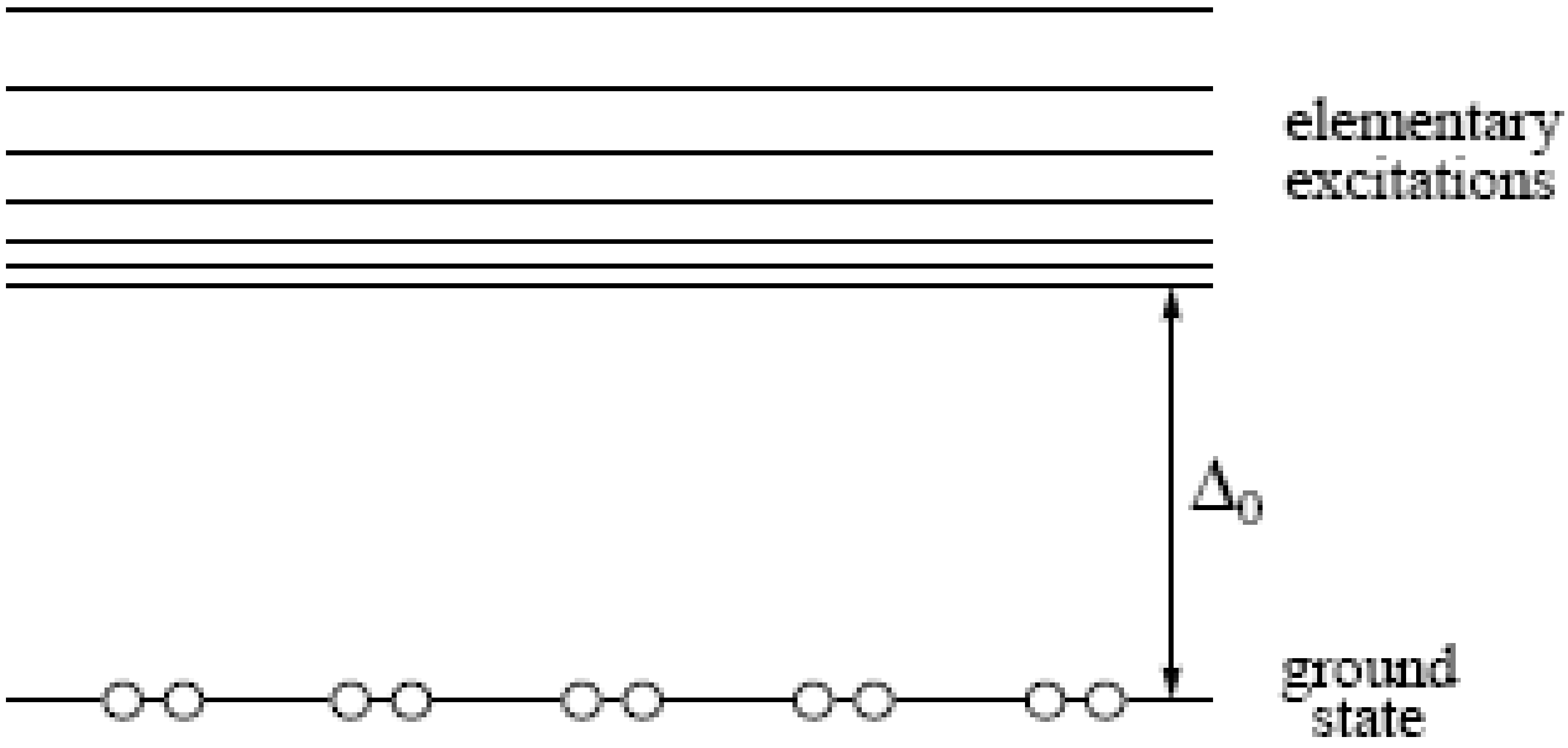
The origin of pseudogap in HTSC

Yuval Lubashevsky

Prof. Amit Keren

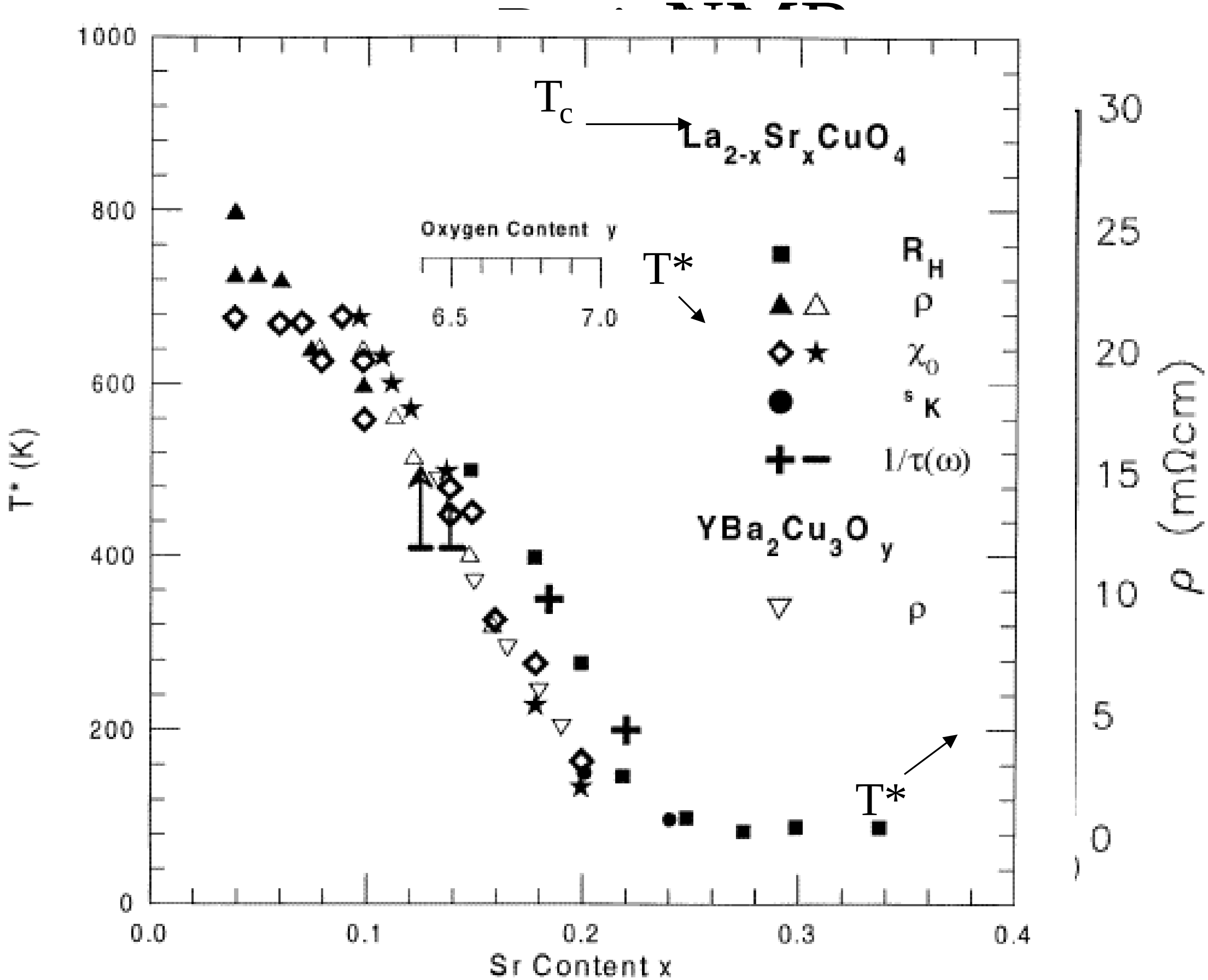
The superconductor energy gap

The BCS superconductor



The pseudogap temperature

Timusk Rep. Phys. 62 61-122 1999

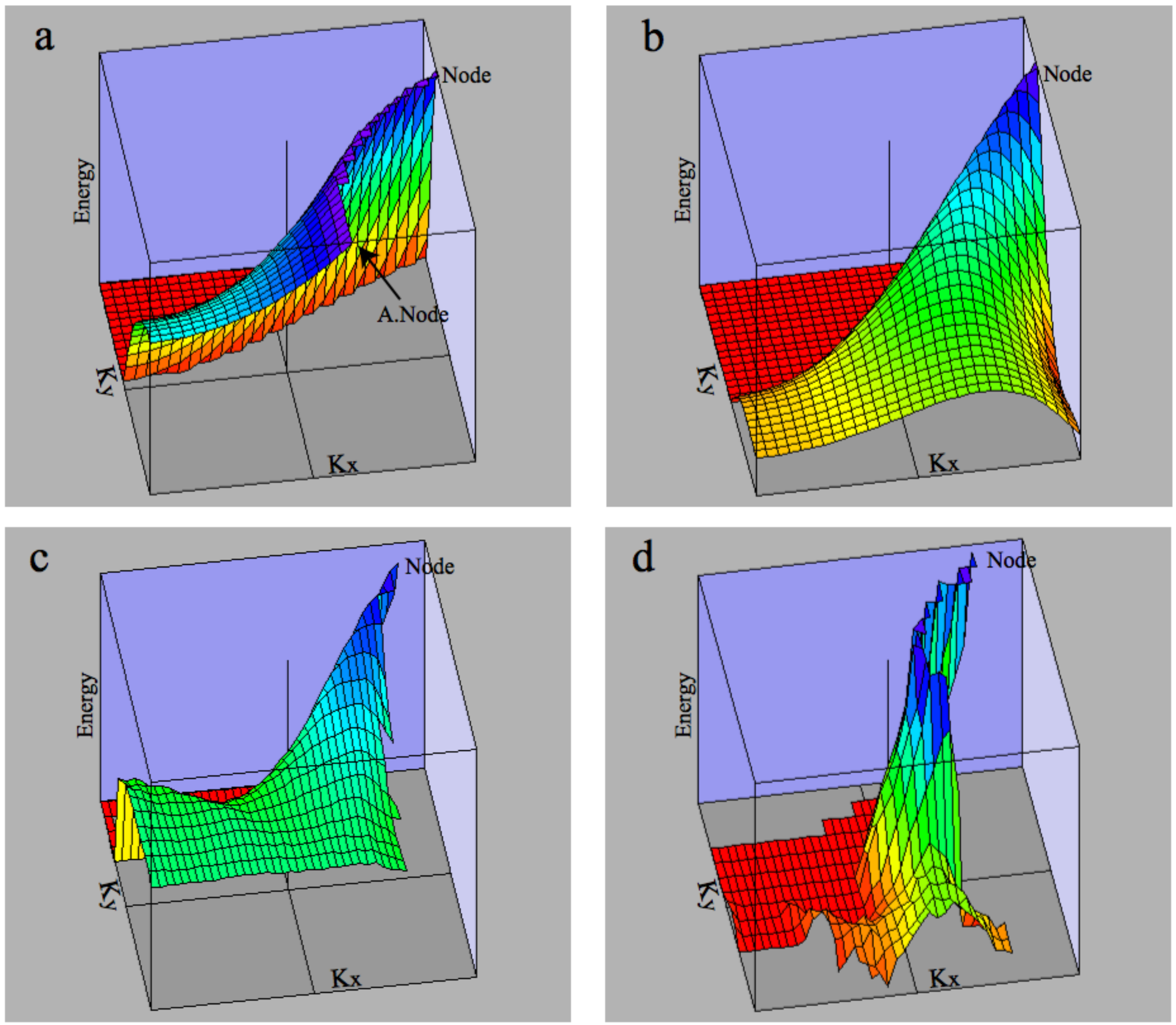


ific heat

ARPES measurements

Theory
Normal state

Theory
dSC state



Experiment
dSC

Experiment
PG state

Kanigel

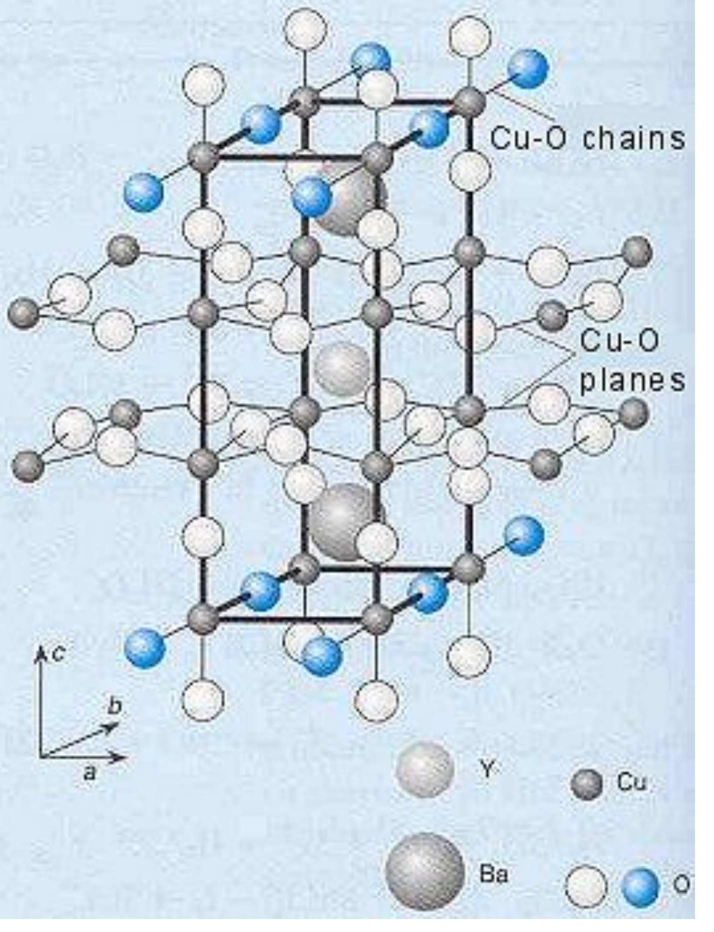
Main question

What are the interactions that affect the T*?

The CLBLCO system

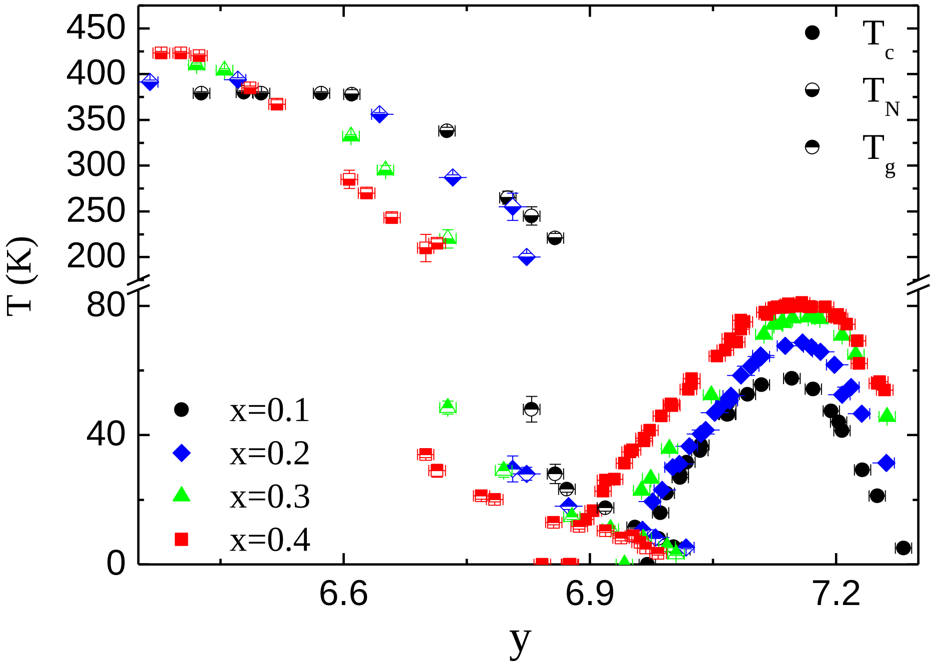
$$(Ca_x La_{1-x})(Ba_{1.75-x} La_{0.25+x})Cu_3O_y$$

- Similar structure as the well known YBCO
- 1:2:3 atomic ratio
- The main structure doesn't change with the families
- Controllable doping level (y parameter)
- **Controllable magnetic coupling (x parameter)**

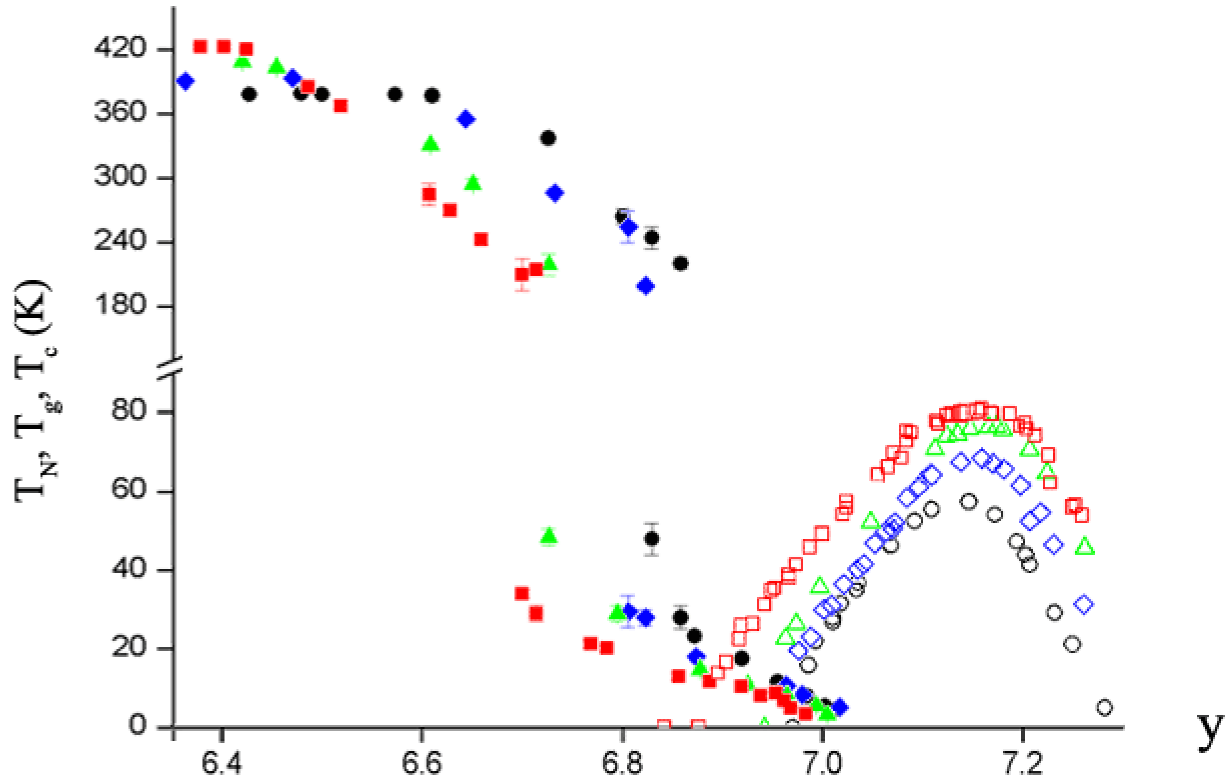


CLBLCO phase diagram

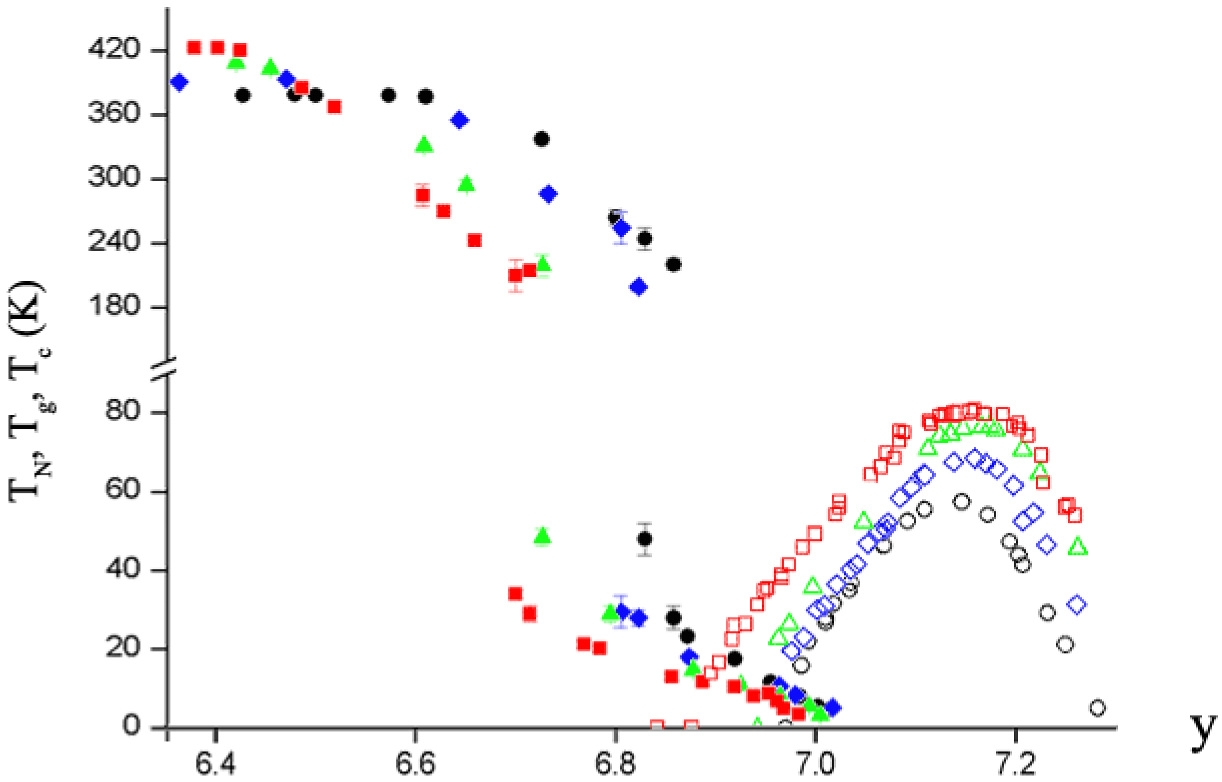
- Similar phase diagrams
- The family with the highest T_c have the highest T_N on the lowest doping.
- Big difference at T_c^{max} between the families



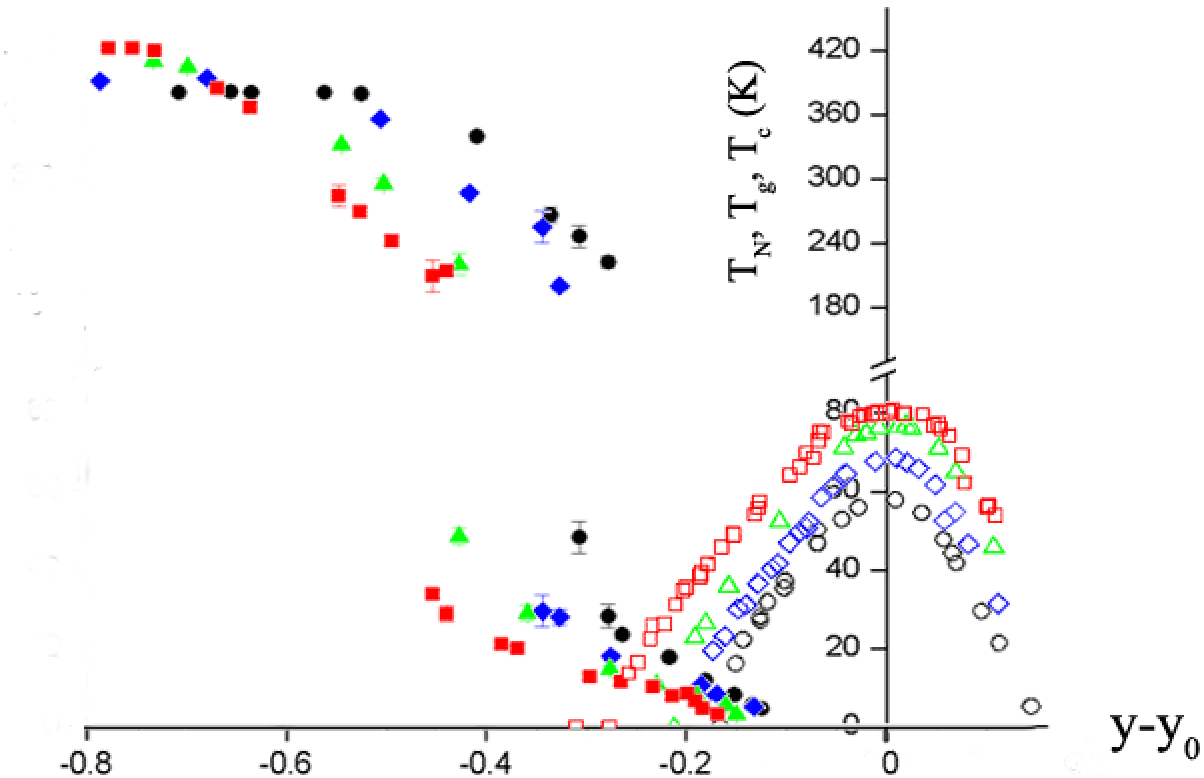
Ofer PRB 73 220508 2006



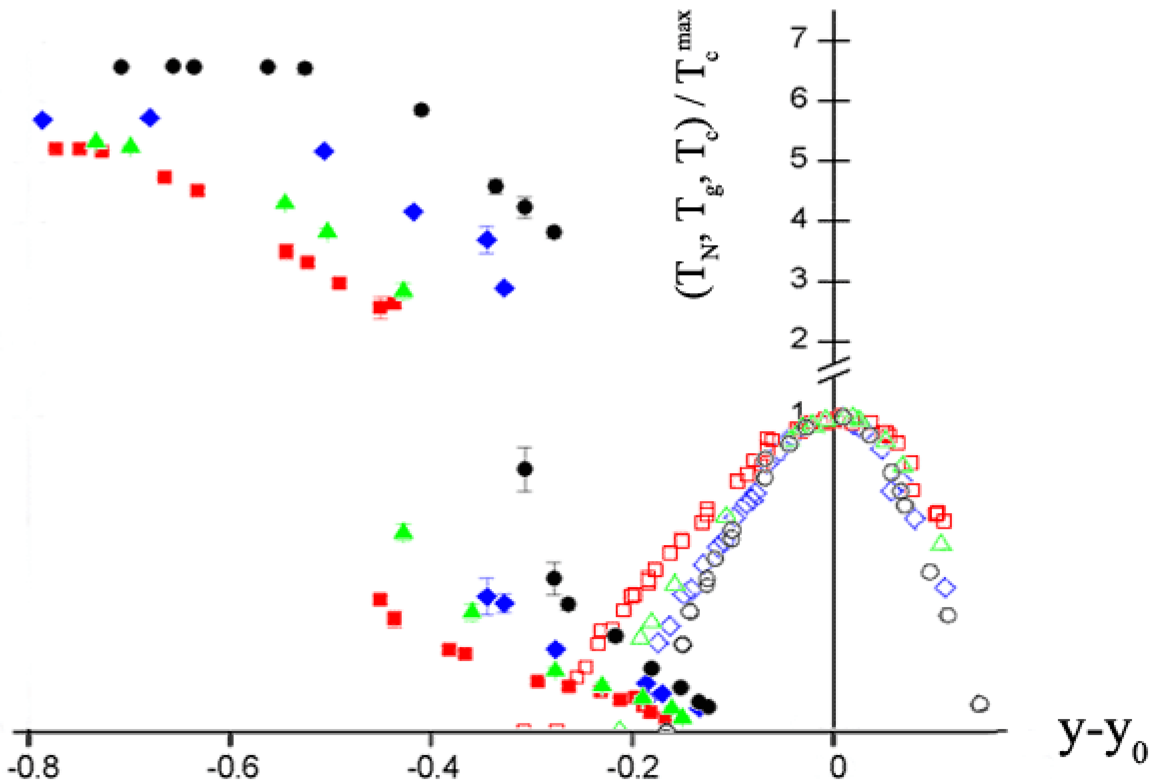
420
360
300
240
180
80
60
40
20
0
6.4
6.6
6.8
7.0
7.2
T_N, T_g, T_c (K)
y



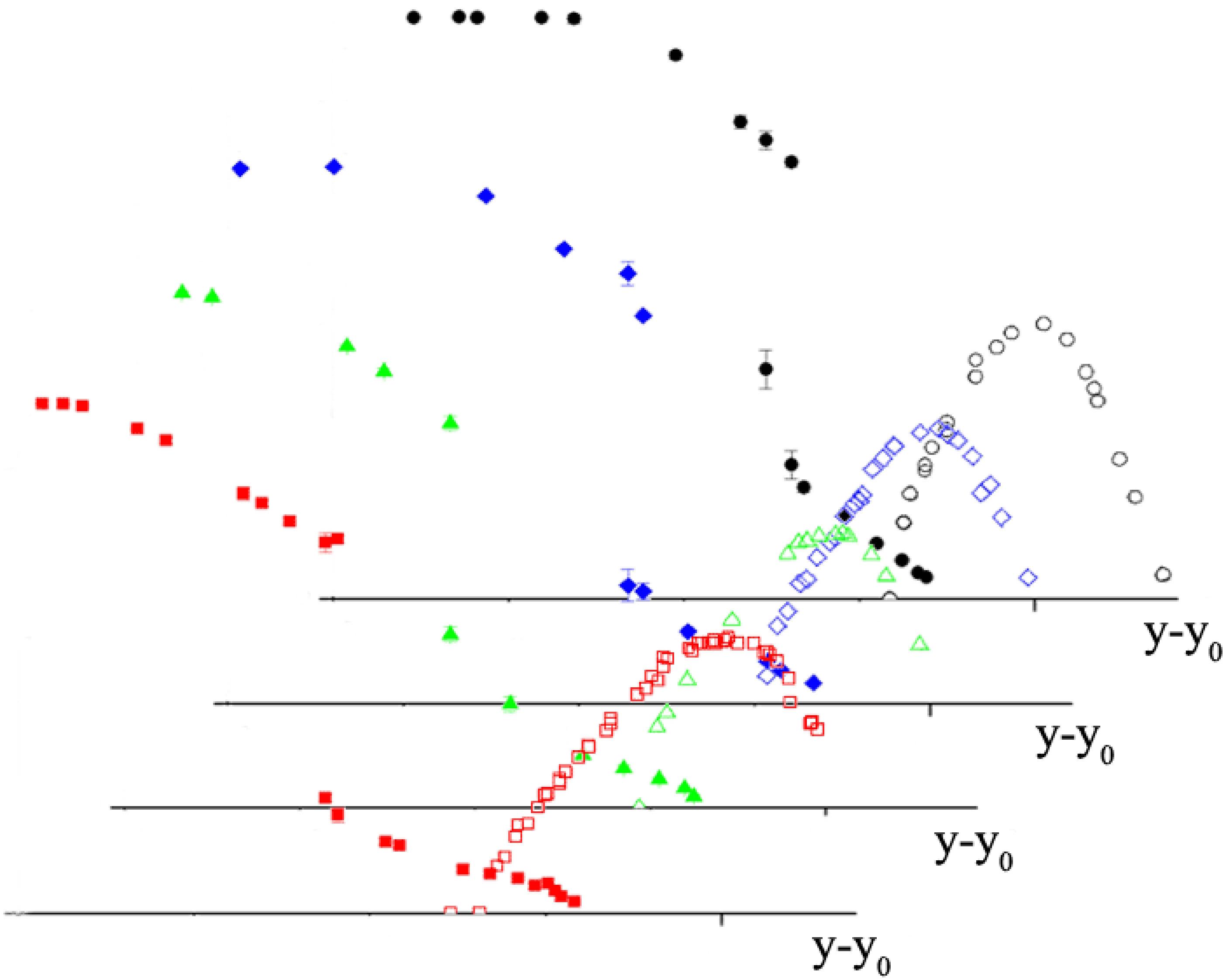
420
360
300
240
180
80
60
40
20
0
6.4
6.6
6.8
7.0
7.2
T_N, T_g, T_c (K)
y

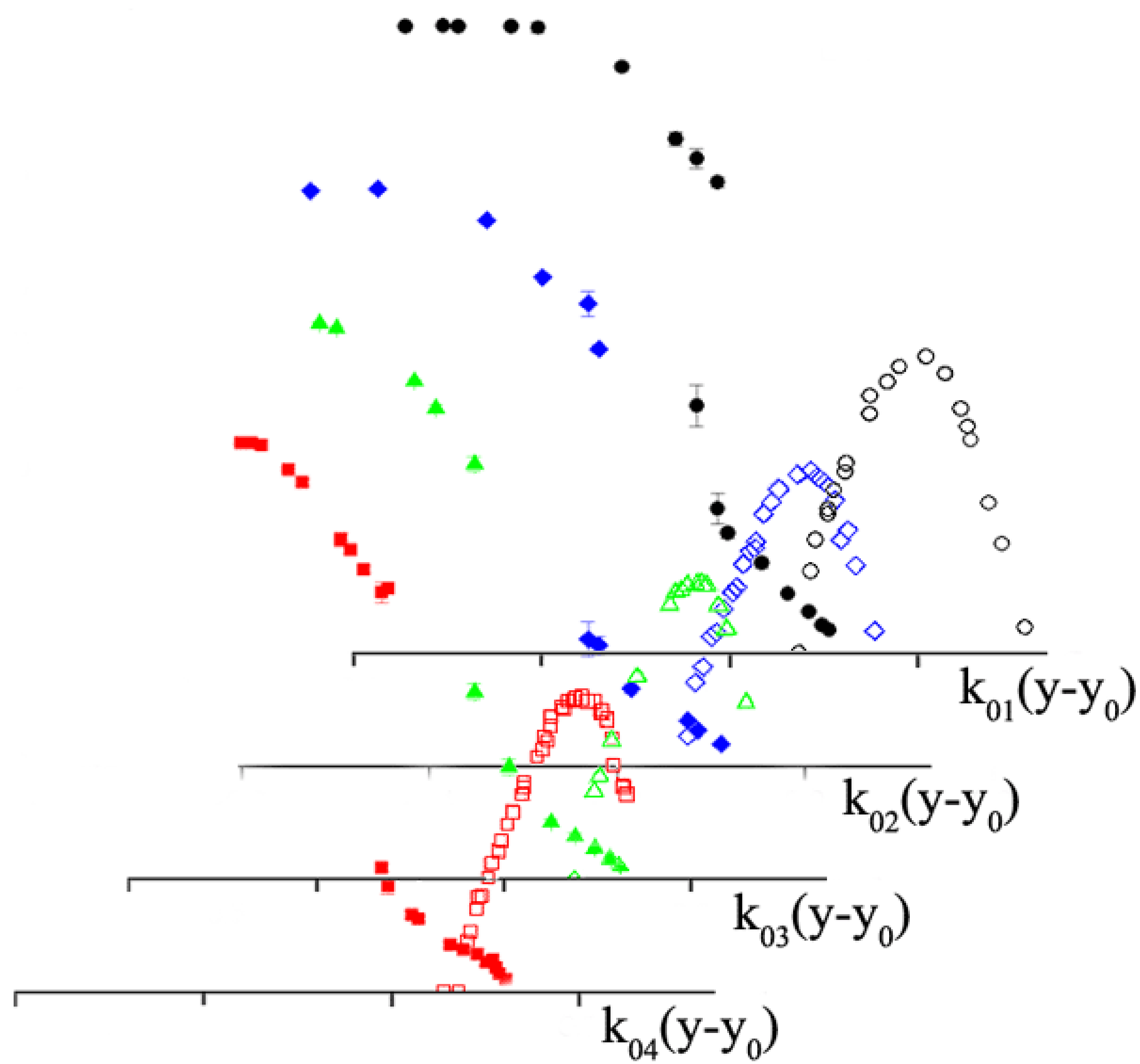


T_N, T_g, T_c (K)
420
360
300
240
180
80
60
40
20
0
-0.8
-0.6
-0.4
-0.2
0
$y-y_0$

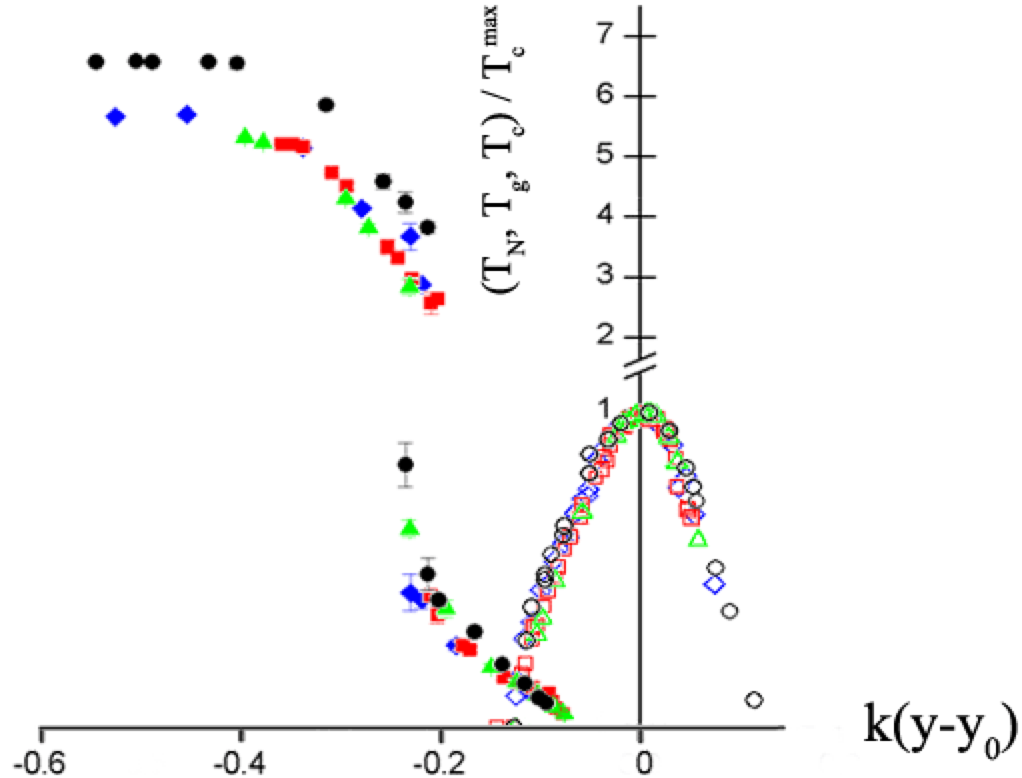


$(T_N, T_g, T_c) / T_c^{max}$
7
6
5
4
3
2
1
-0.8
-0.6
-0.4
-0.2
0
$y-y_0$


y-y0
y-y0
y-y0
y-y0



$k_{01}(y-y_0)$
$k_{02}(y-y_0)$
$k_{03}(y-y_0)$
$k_{04}(y-y_0)$

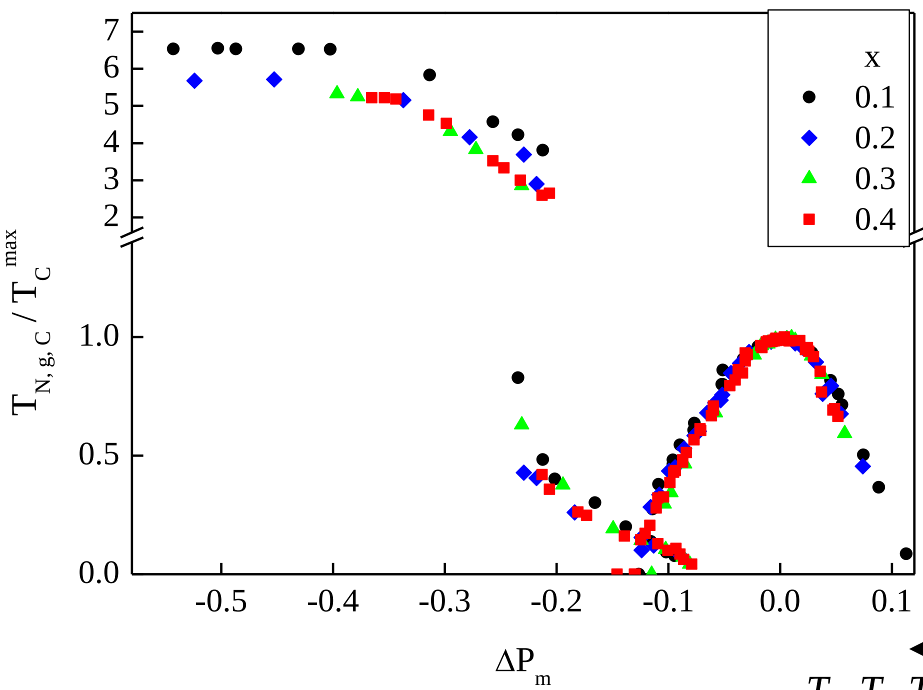


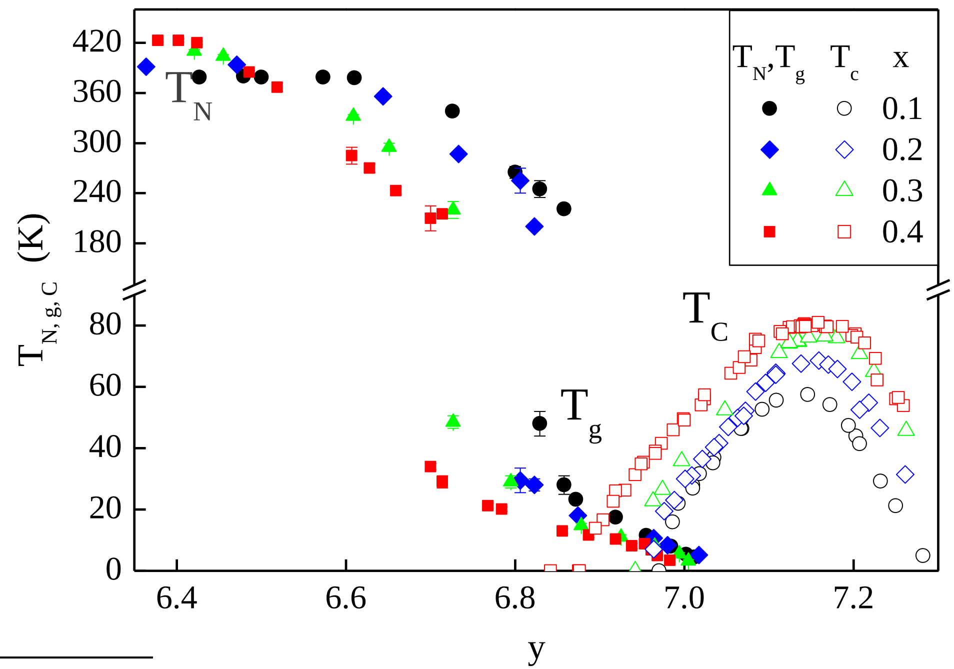
$(T_N, T_g, T_c) / T_c^{max}$
7
6
5
4
3
2
1
-0.6
-0.4
-0.2
0
$k(y-y_0)$

Transformation of the entire doping range.

$$\Delta p_m = p - p^{opt} = K_x(y - y_x^{opt})$$

$(Ca_xLa_{1-x})(Ba_{1.75-x}La_{0.25+x})Cu_3O_y$





$$T_N, T_g, T_c \Rightarrow T_N, T_g, T_c / T_c^{max}$$

$$y \Rightarrow K(x)\Delta y$$

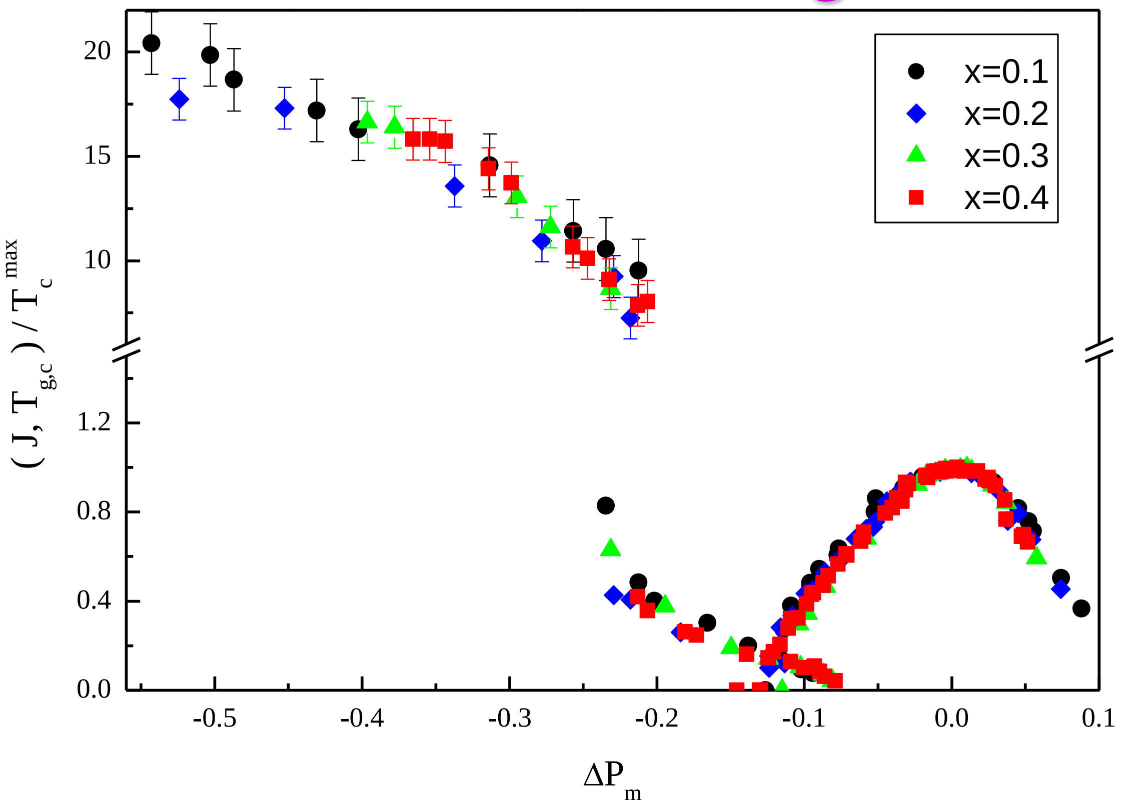
The scaling works in the entire doping range apart for *x=0.1*?

Ofer PRB 73 220508 2006

The role of anisotropies

- T_N is determined by the in-plane J and out of plane $J_\perp$ coupling.
- We extracted J out of T_N.

Unified Phase Diagram



The in-plane J is extracted from T_N.

Ofer PRB 73 220508 2006

Scaling Conclusion

- We found that T_c scale like the in-plane J therefore is a consequence of a 2D magnetic interaction.

$$T_c \propto J$$

- **Question: Does T* scales with J as T_c does, or with some other magnetic parameter?**

The experimental methods

- The SQUID (Superconducting QUantum Interference Device)
- The temperature range is 1.2K to 310K
- The field range is up to 6.5T.

Susceptibility

- Definition $$\chi_0 = \lim_{H \to 0} \frac{\partial M}{\partial H}$$

- Practice $$M = \chi_{dc} H$$

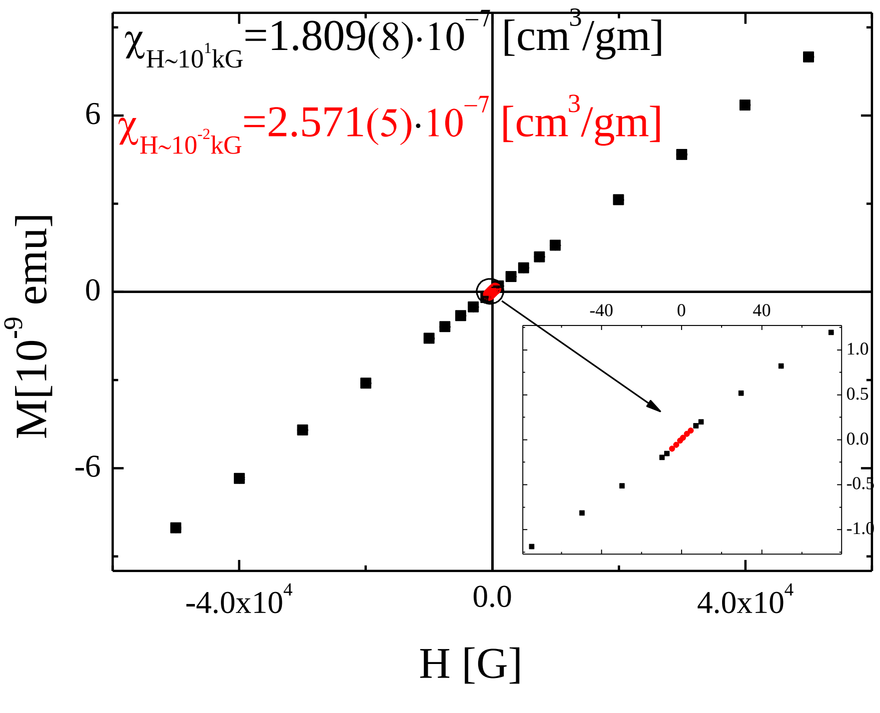
- Where D is known as the demagnetizing factor, and it get different values for different geometries.

$$\chi_{dc} = \frac{\chi_0}{1 + D\chi_0}$$

- For needle like sample D=0, then:

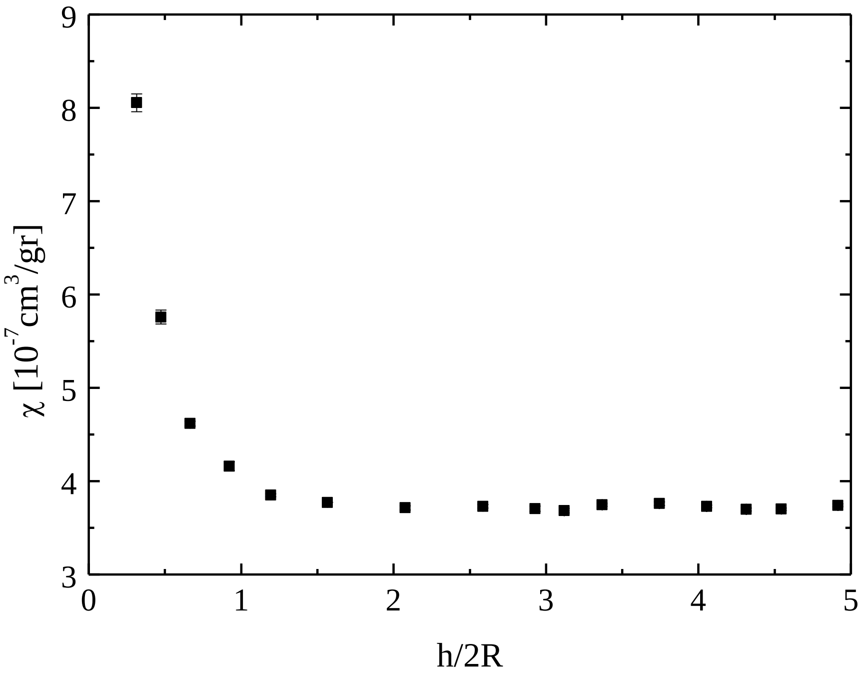
$$\chi_{dc} \approx \chi_0$$

Measurement condition



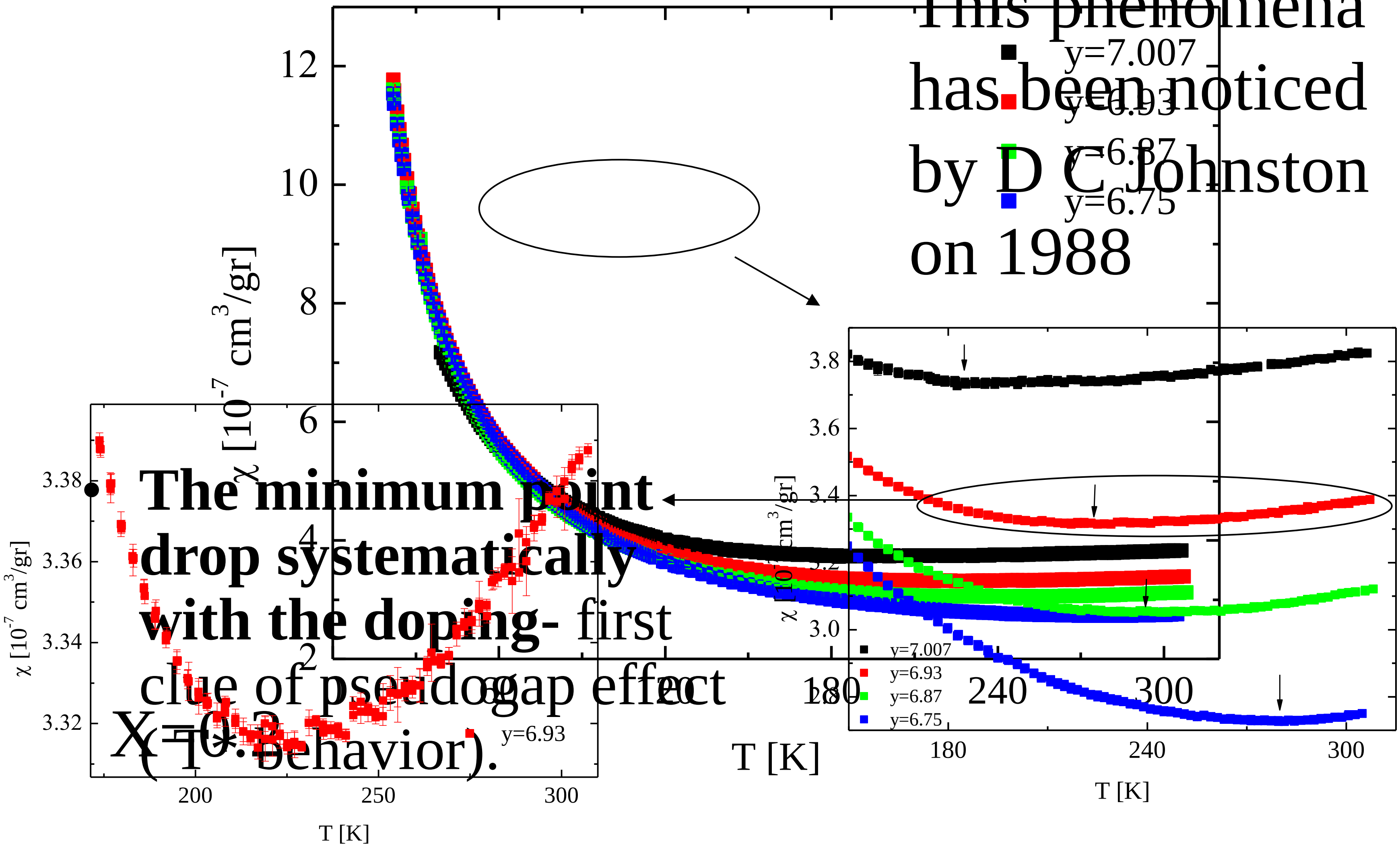
Field dependence

Geometric dependence



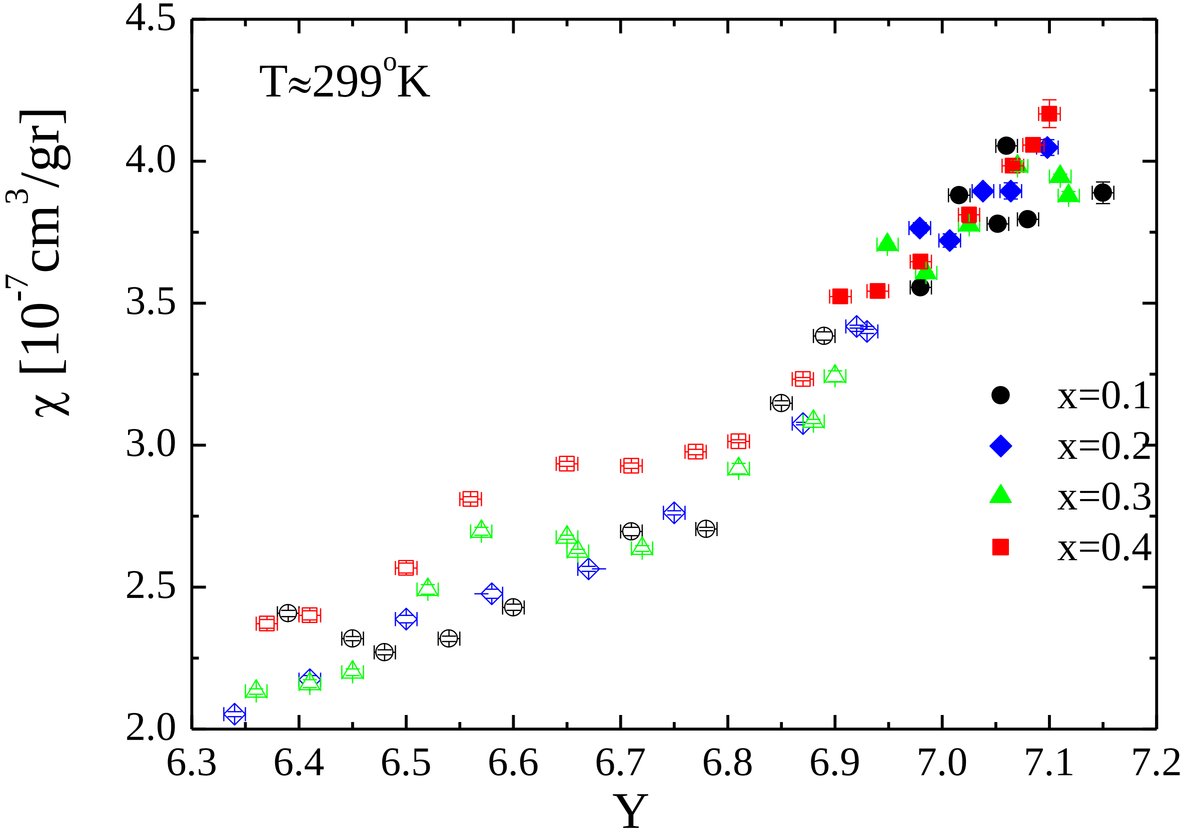
Raw data

This phenomena has been noticed by D C Johnston on 1988



- **The minimum point drop systematically with the doping-** first clue of pseudogap effect (T* behavior).

$$\chi_0 = f(y)$$



- The value of χ is increasing with the doping (Pauli susceptibility).

Susceptibility types

- Isolated spin: Langevin paramagnetism, Curie law

$$\chi_0 = \frac{N\mu_B^2}{3k_B T} = \frac{C}{T}$$

- Weakly coupled spins: Curie-Weiss

$$\chi_0 = \frac{C}{T+\theta}$$

- Pauli spin (Landau) :

$$\chi_0(T) = const = \mu_B^2 \mathbf{D}(\varepsilon_f)$$

- Core: Van Vleck and Langevin

$$\chi_0(T) = const$$

There is no traditional theory about increasing susceptibility with T

Strongly coupled spins

- Two coupled spins according to Heisenberg model.

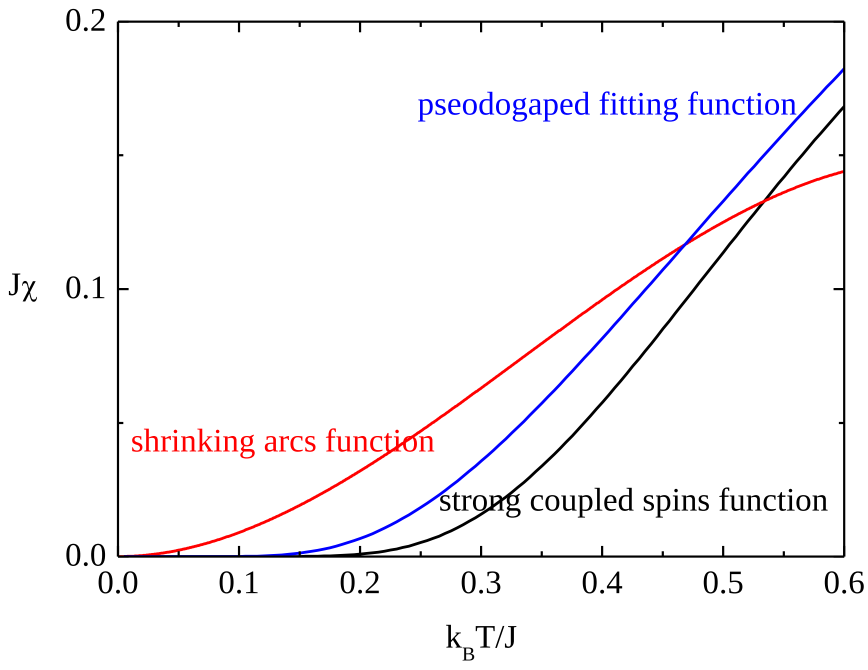
$$\chi_0 = \beta \left[e^{\frac{\beta J}{2}} \cosh\left(\frac{\beta J}{2} \right) \right]^{-2}$$

- shrinking arcs phenomena.

$$\chi_0 = A(T)\left(\frac{2T}{T*} - \left[\frac{T}{T*} \right]^2 \right)$$

- The fitting term.

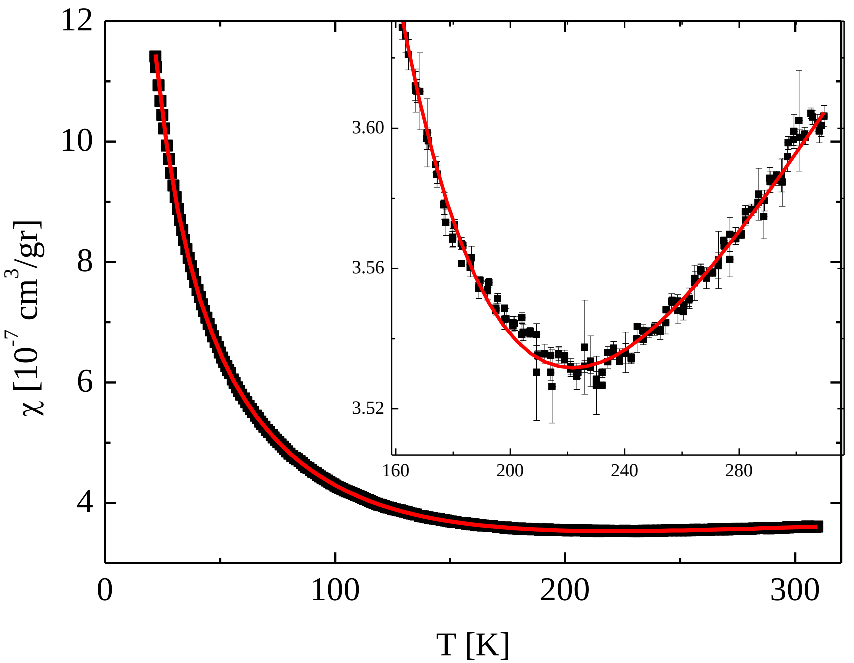
$$\chi_0 = \frac{const}{\cosh\left(\frac{T*}{T} \right)}$$

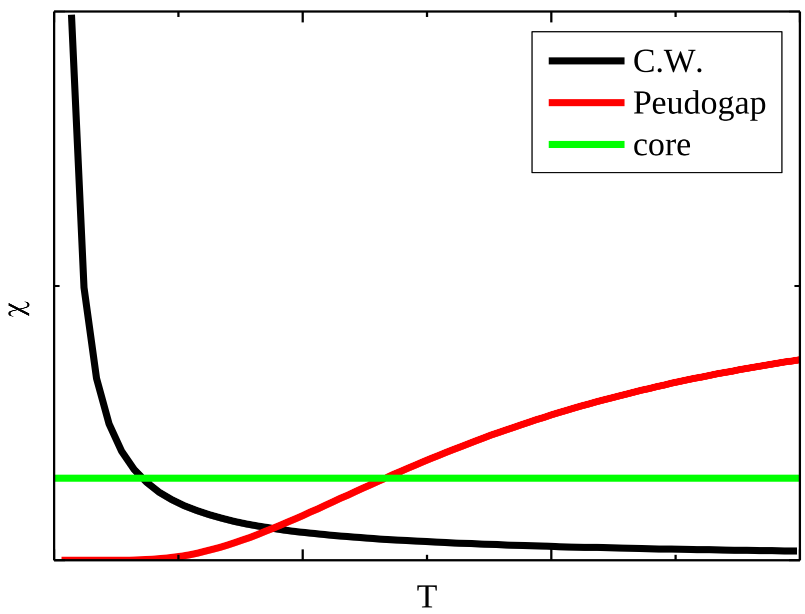


The fitting function

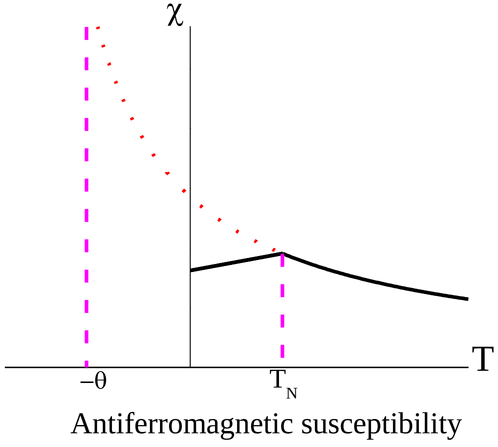
$$\chi_0 = \frac{C_1}{T+\theta} + \frac{C_2}{\cosh\left(\frac{T^*}{T}\right)} + C_3$$

C.W. + PG + CORE

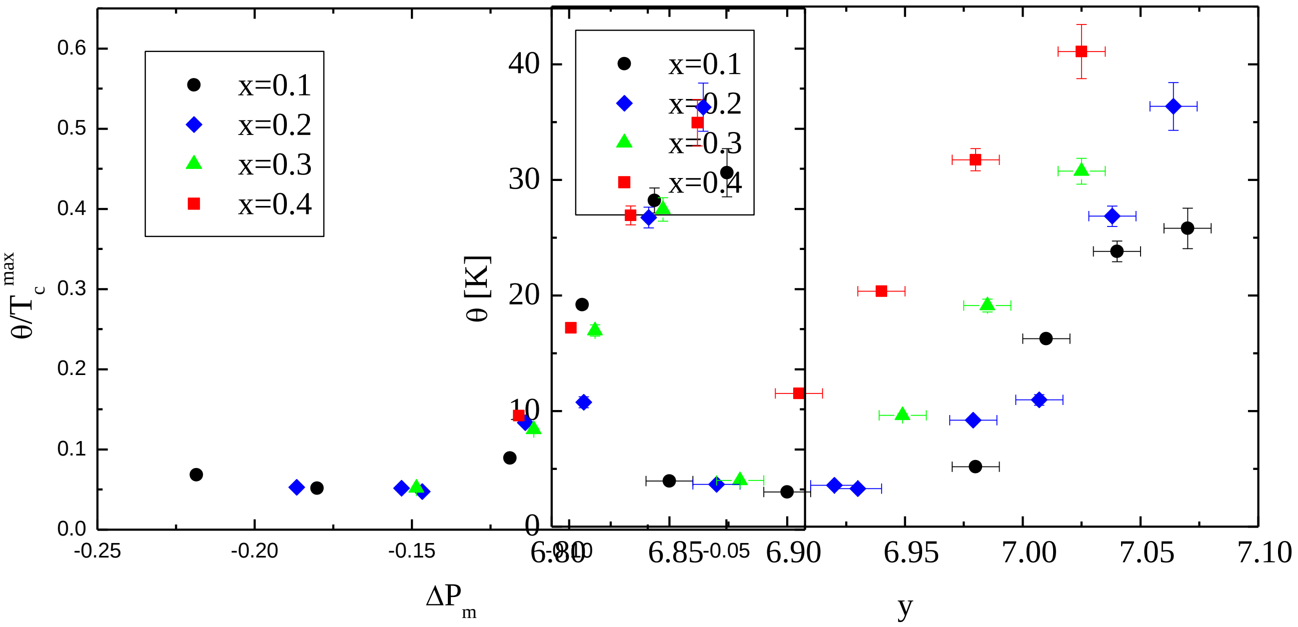




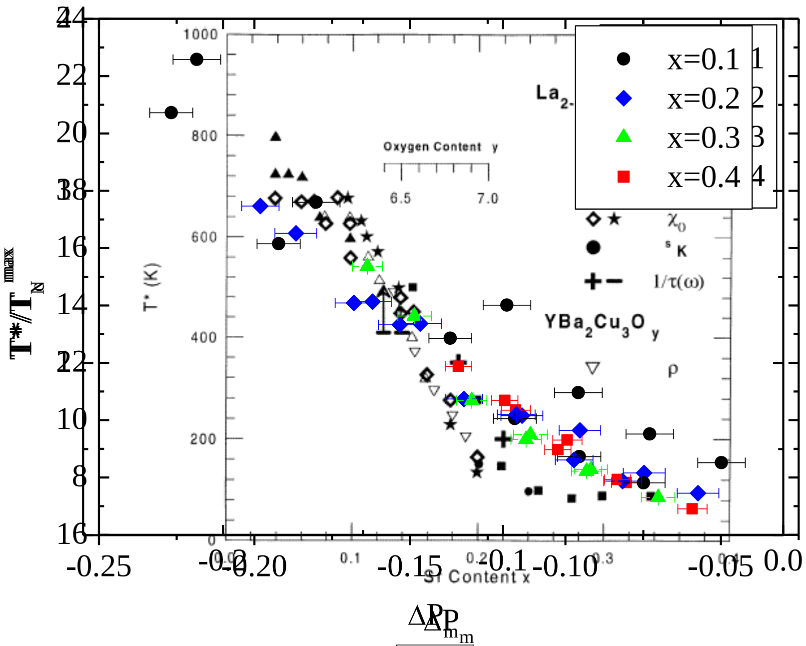
Curie-Weiss temperature

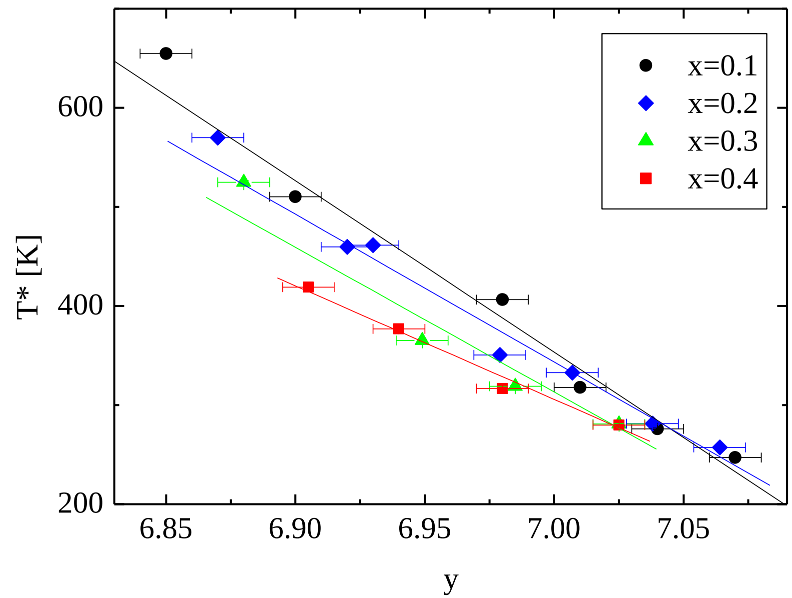


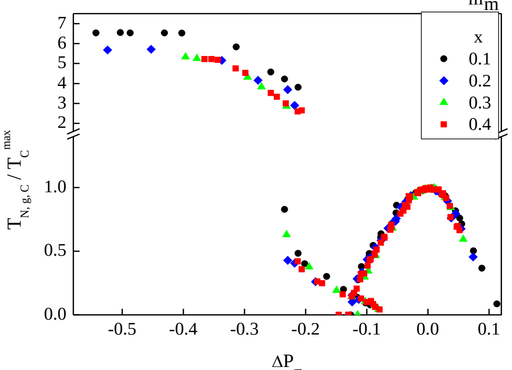
$$\theta = \left[\frac{2S(S+1)}{3K_B}\right]\sum_i Z_i J_i$$



T*







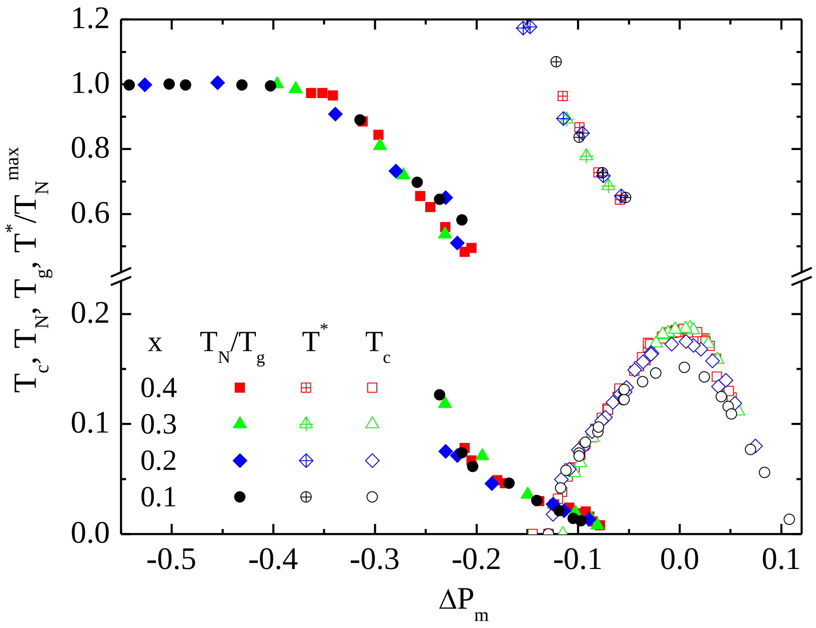
The T* doesn't scale well with T_c.

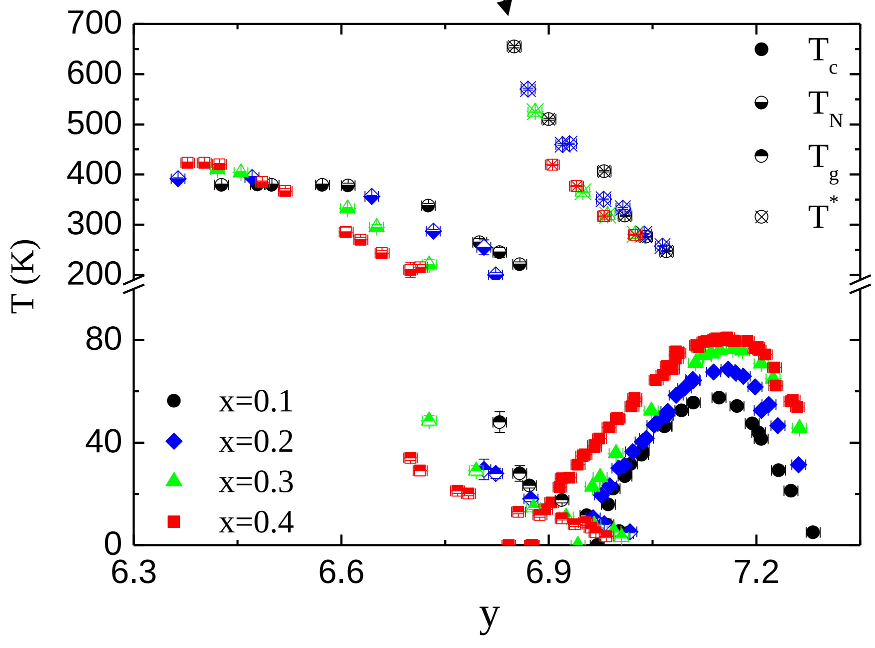
T* scale with T_N

Very similar to the T_c/T_N scaling.

Conclusions

We added the T* to the phase diagram
T* scale like T_N, and it is a 3D magnetic phenomena.
T_c is a 2D magnetic phenomena.





Acknowledgment

I’m grateful to Prof. Amit Keren

Thanks to:

Dr. Arkady Knizhnik, Avi Post, Dr.Michael Reisner, Dr. Leonid Iomin

And the lab’s fellow-students:

Orenstein, Oren, Eran, Meni, Oshri, Daniel, Maniv, Gil, Yoash, Ana

Specially to Rinat Ofer for her help