Some
Unique Superconductive Properties of Cuprates

K. Alex Müller

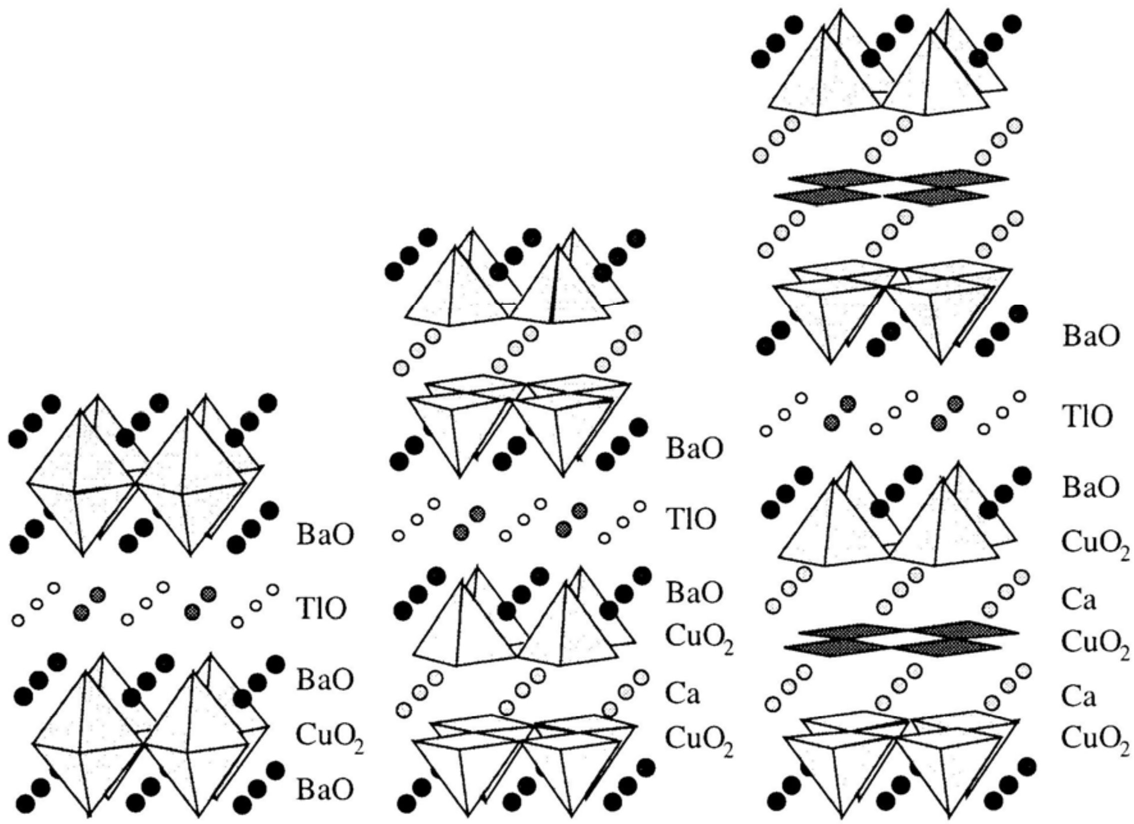
Physik-Institut der Universität Zürich,
Winterthurerstr. 190, CH-8057 Zurich, Switzerland.

Cuprates have T_c up to 163 K !

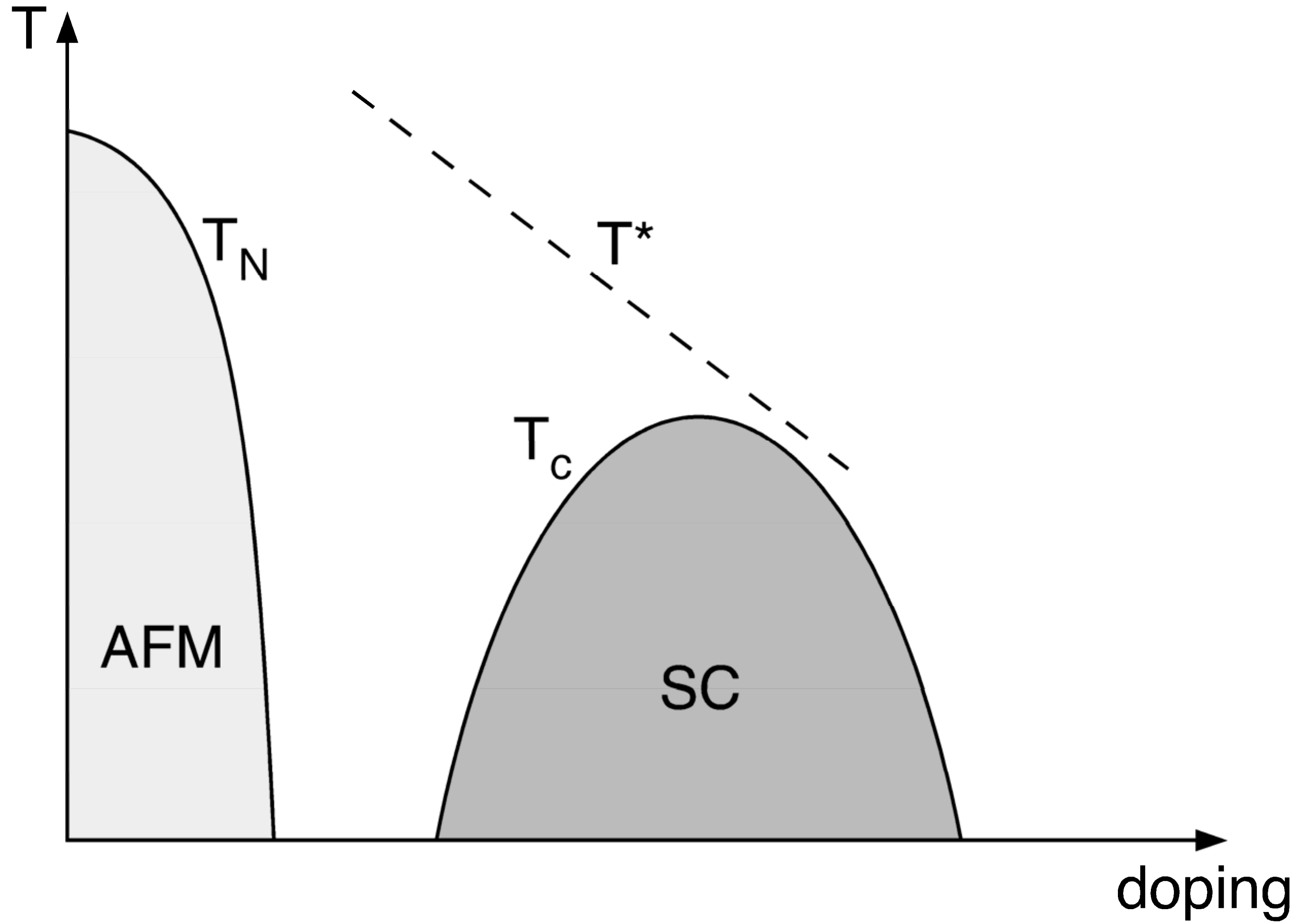
The Structure of Cuprates

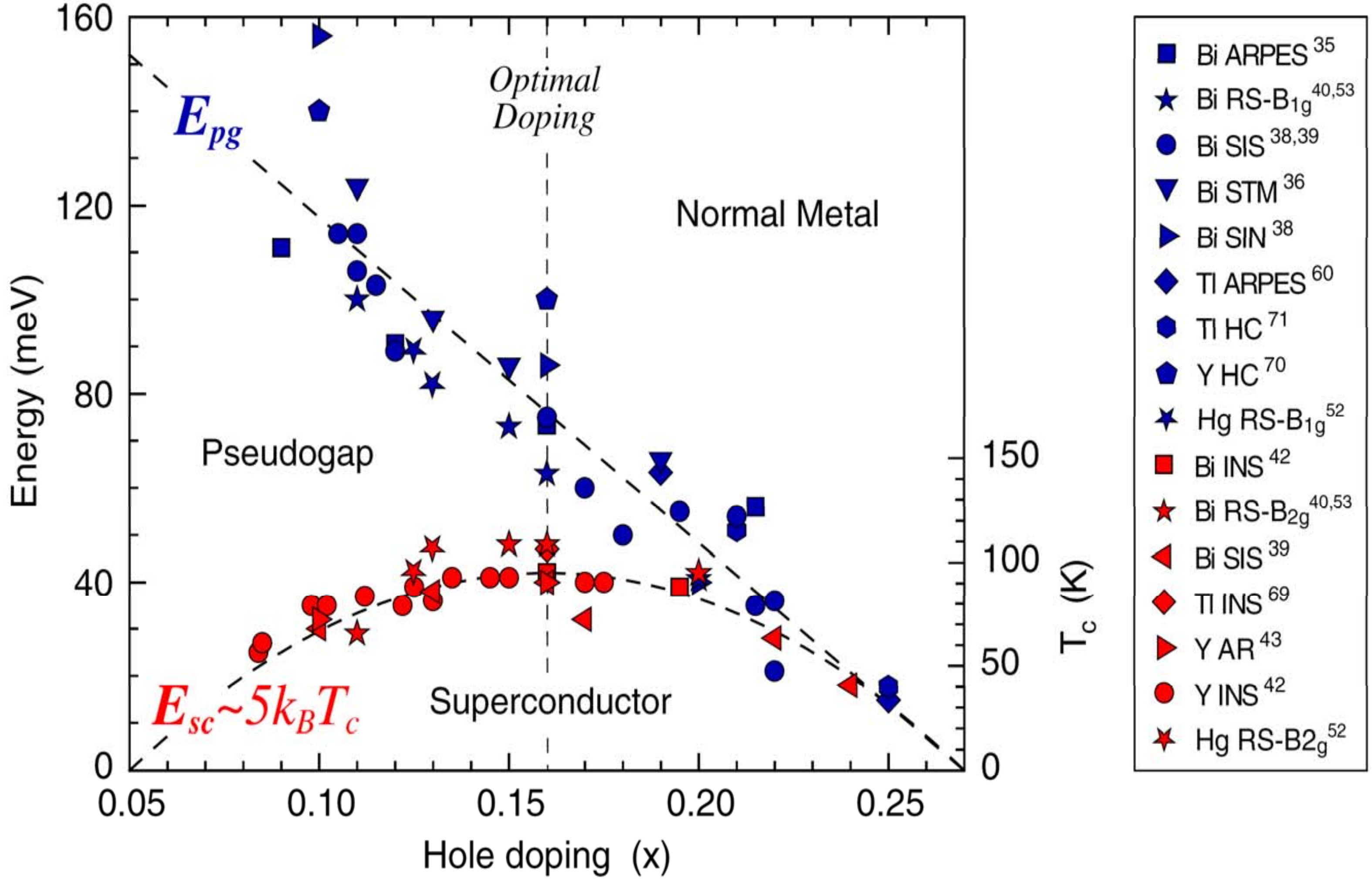
CuO_2 layer :

	O		O		O	
O	Cu	O	Cu	O	Cu	O
	O		O		O	
O	Cu	O	Cu	O	Cu	O
	O		O		O	
O	Cu	O	Cu	O	Cu	O
	O		O		O	



Generic Phase Diagram





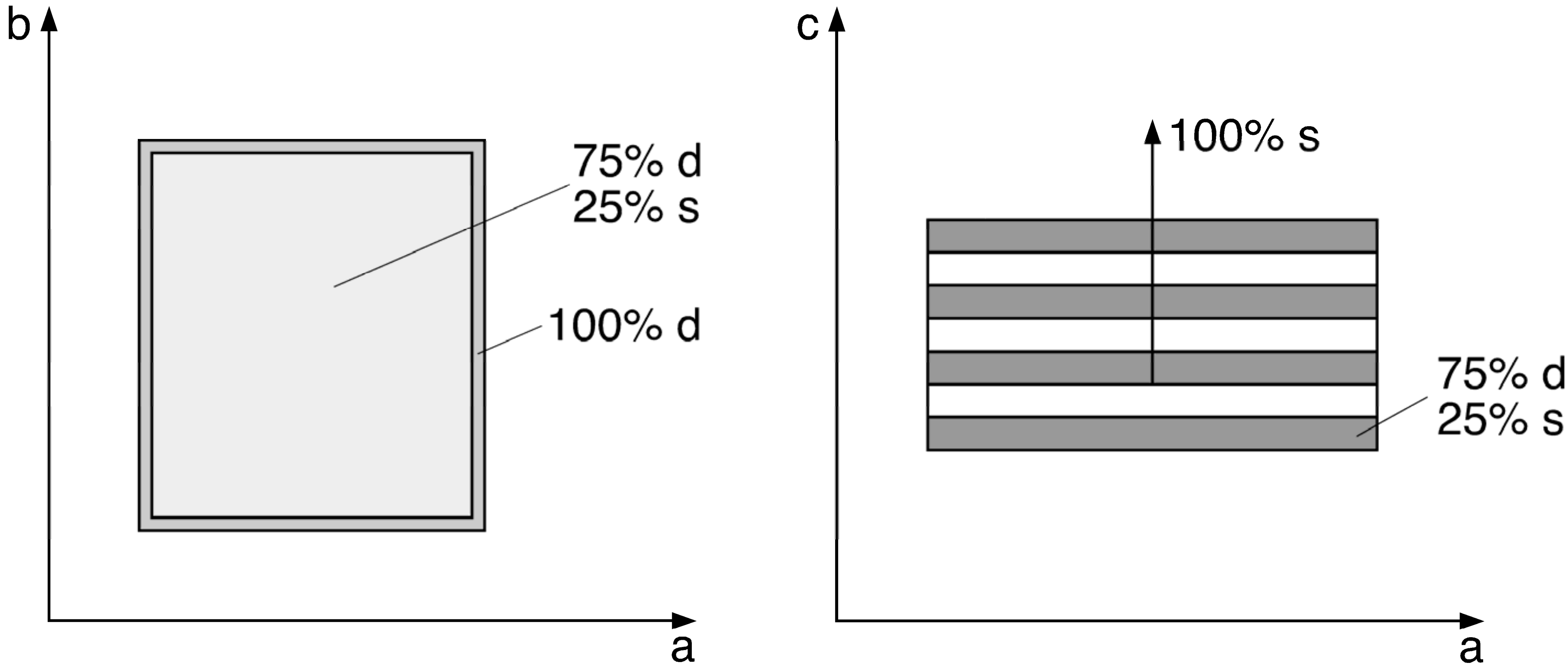
Hüfner, Hossain, Damascelli, and Sawatzky, Rep. Prog. Phys. **71**, 062501 (2008).

Coherence Lengths

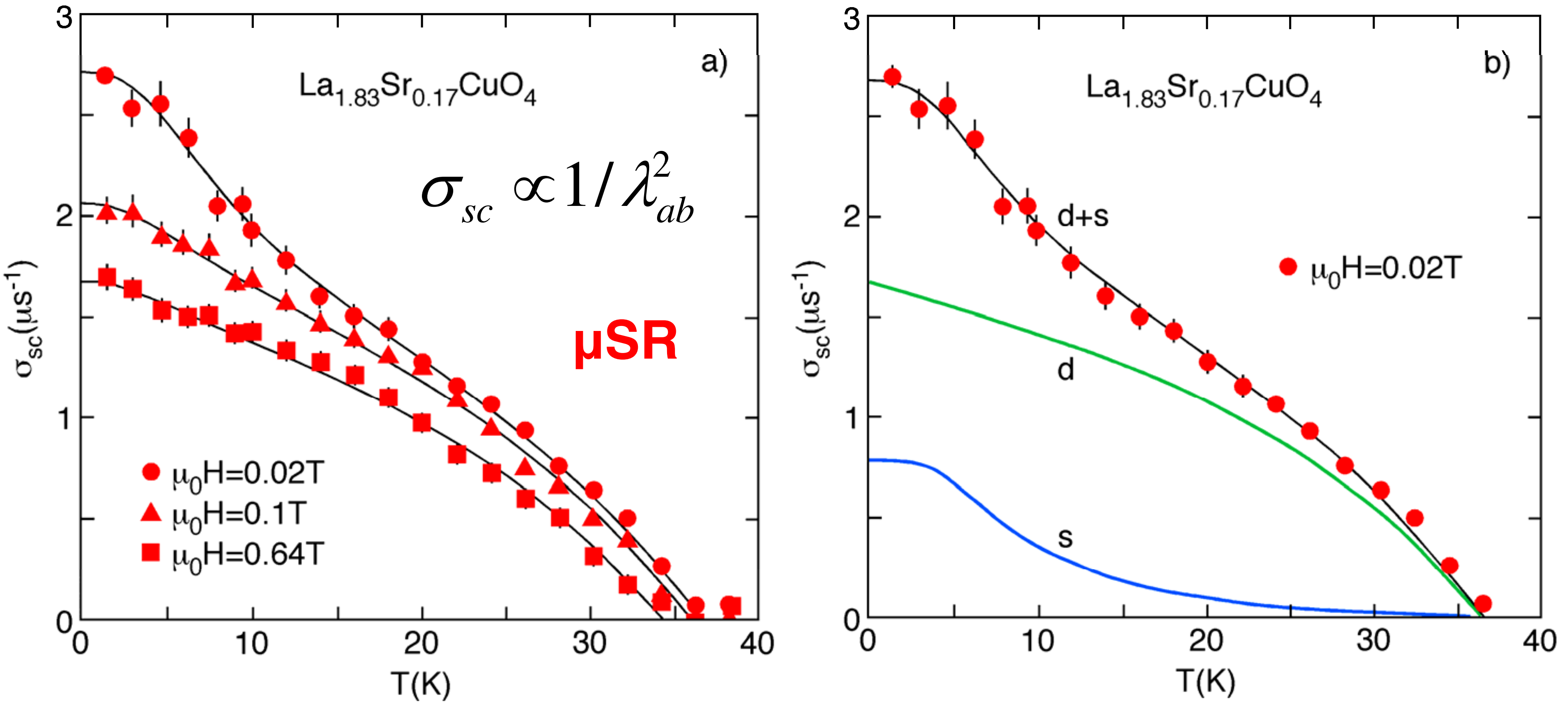
$YBa_2Cu_3O_7$ (T_c = 91 K)

in the plane:	$\xi_{ab} \sim 1.5$ nm
perpendicular to plane:	$\xi_c \sim 0.3$ nm

Symmetry of the Superconducting Wavefunction

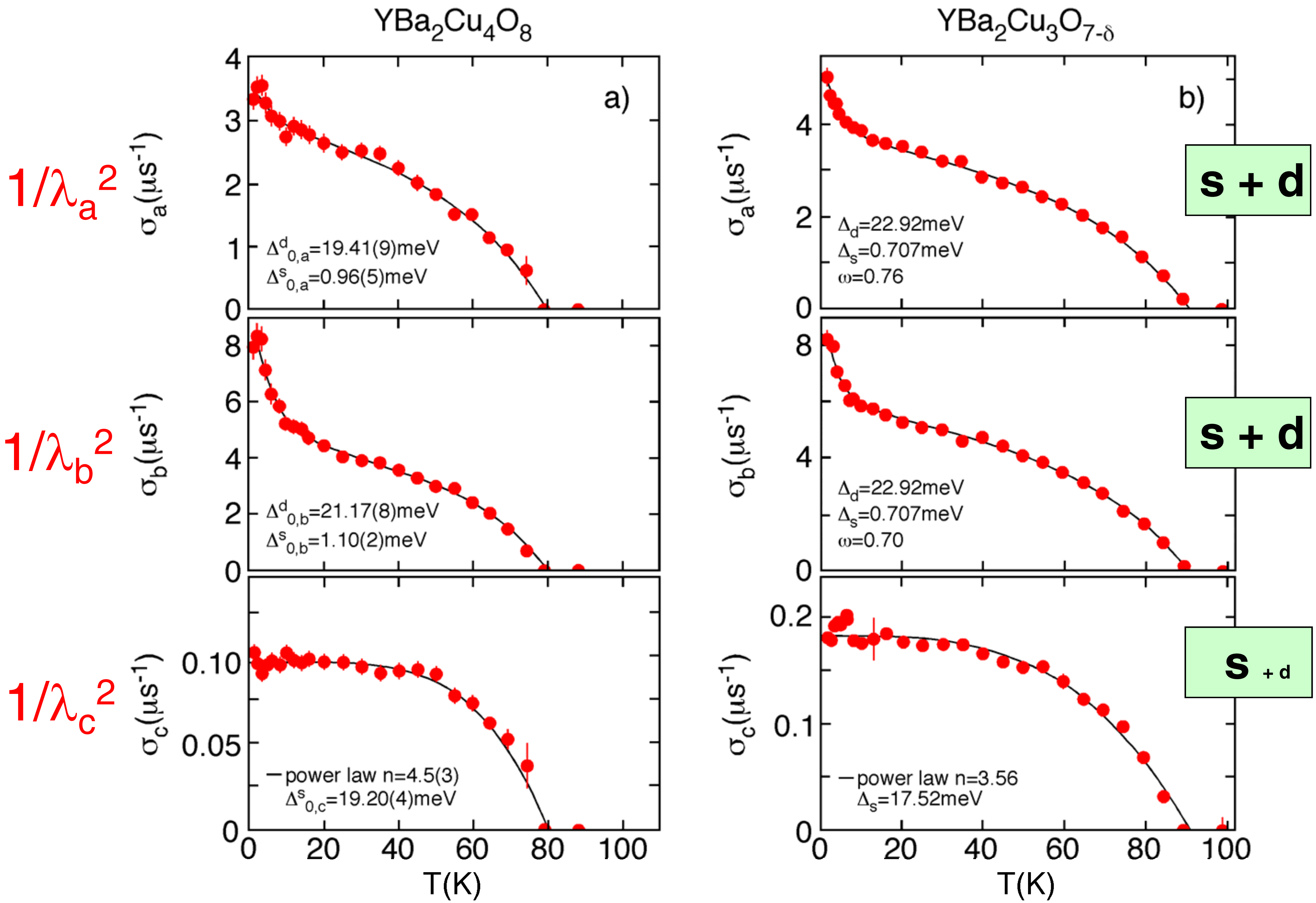


Two-gap Superconductivity in $La_{1.83}Sr_{0.17}CuO_4$ from Muon Spin Rotation



R. Khasanov *et al.*, Phys. Rev. Lett. **75**, 060505 (2007).

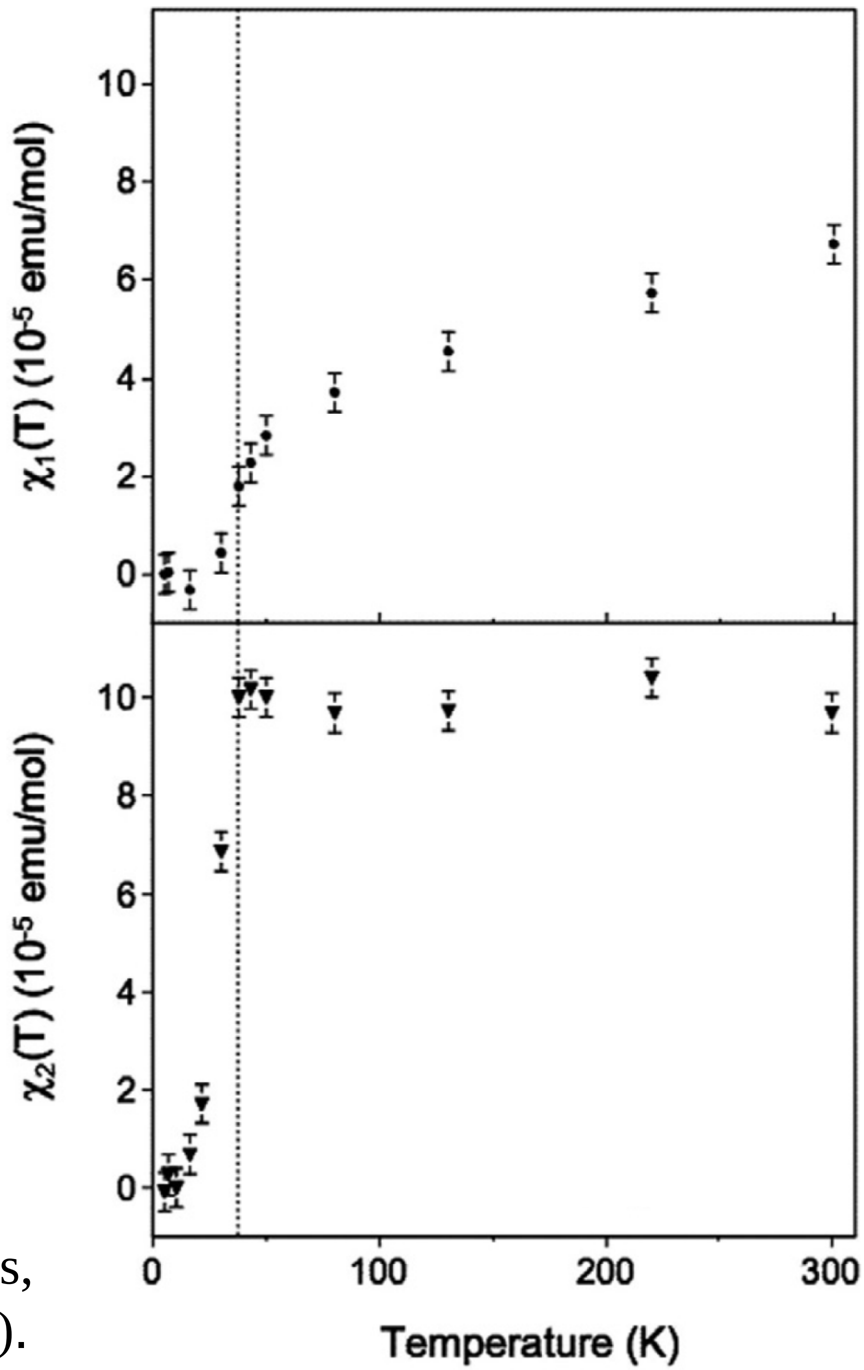
H. Keller, A. Bussmann-Holder, and K. A. Müller, Materials Today **11**, 38 (2008).



Khasanov *et al.*, J. Supercond. Nov. Magn. **21**, 81 (2008)

Khasanov *et al.*, Phys. Rev. Lett. **99**, 237601(2007)

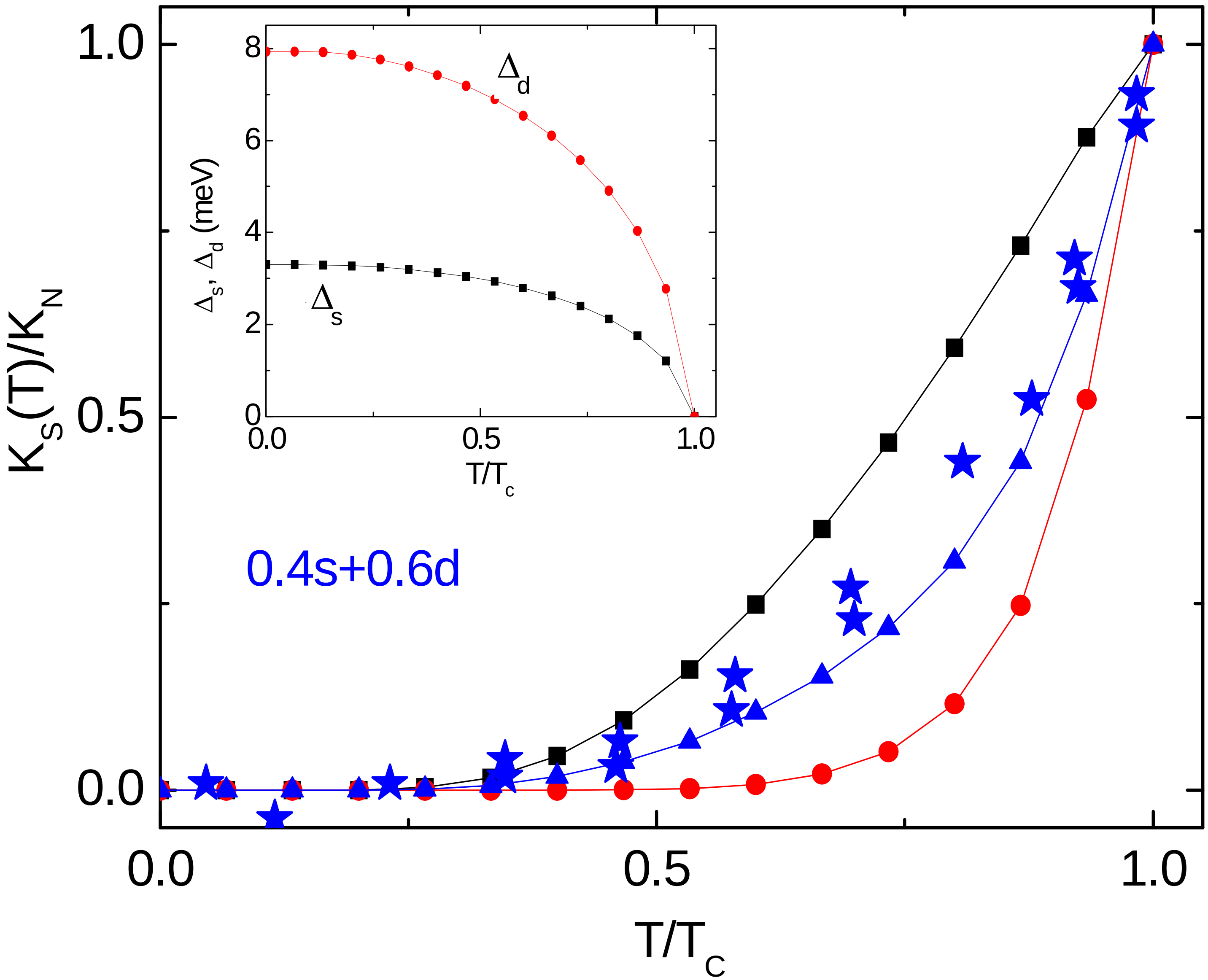
Two-component Behavior from NMR



J. Haase, C. P. Slichter and G. V. M Williams, J. Phys.: Condens. Matter **20**, 434227 (2008).

Theory of NMR with two Components

A. Bussmann-Holder



Vibronic Theory

$$H = H_1 + H_2 + H_{e-l} + H_l\,, \qquad H_l = \hbar\omega \sum_i b_i^+ b_i$$

$$H_1 = H_{\mathrm{tJ}}(d)$$

$$H_2 = H(p)$$

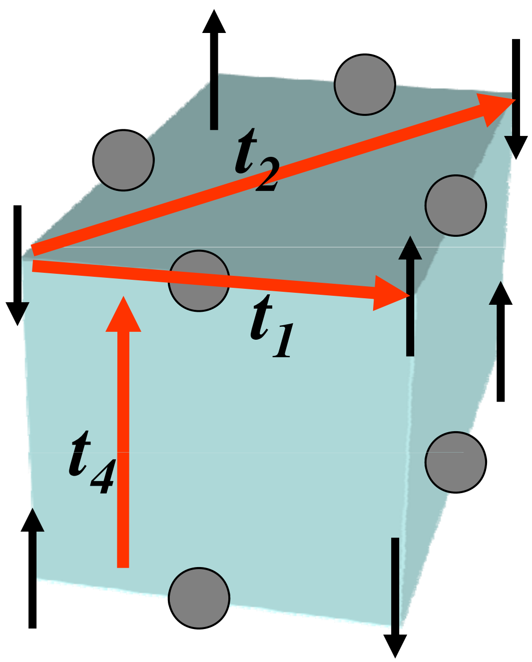
$$H_{e-l} = -\gamma \sum_{i,\sigma} [x_i n_{ip} + x_j n_{jd}] - \tilde{\gamma} \sum_{i,j} x_i (d_i^+ p_j + H.c.)$$

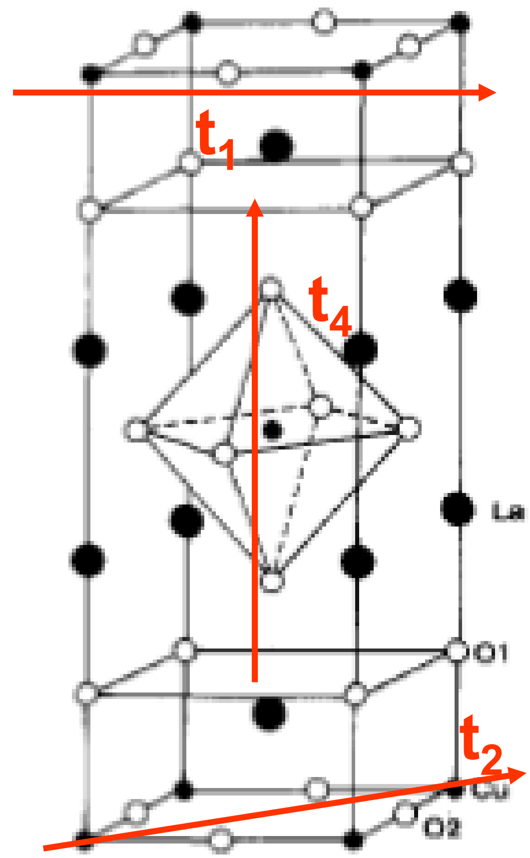
Polaron binding energy: $E_b = \gamma^2 / 2M\omega^2$

$$t_i \to \tilde{t}_i = t_i \exp[-E_b / \hbar\omega]$$

$$U^{eff} = U - 2\gamma^2 / M\omega^2 , \omega \to 0 : U_{eff} \ attractive$$

$$+ n_p n_d \ mixing \ \ from \ \tilde{\gamma}$$





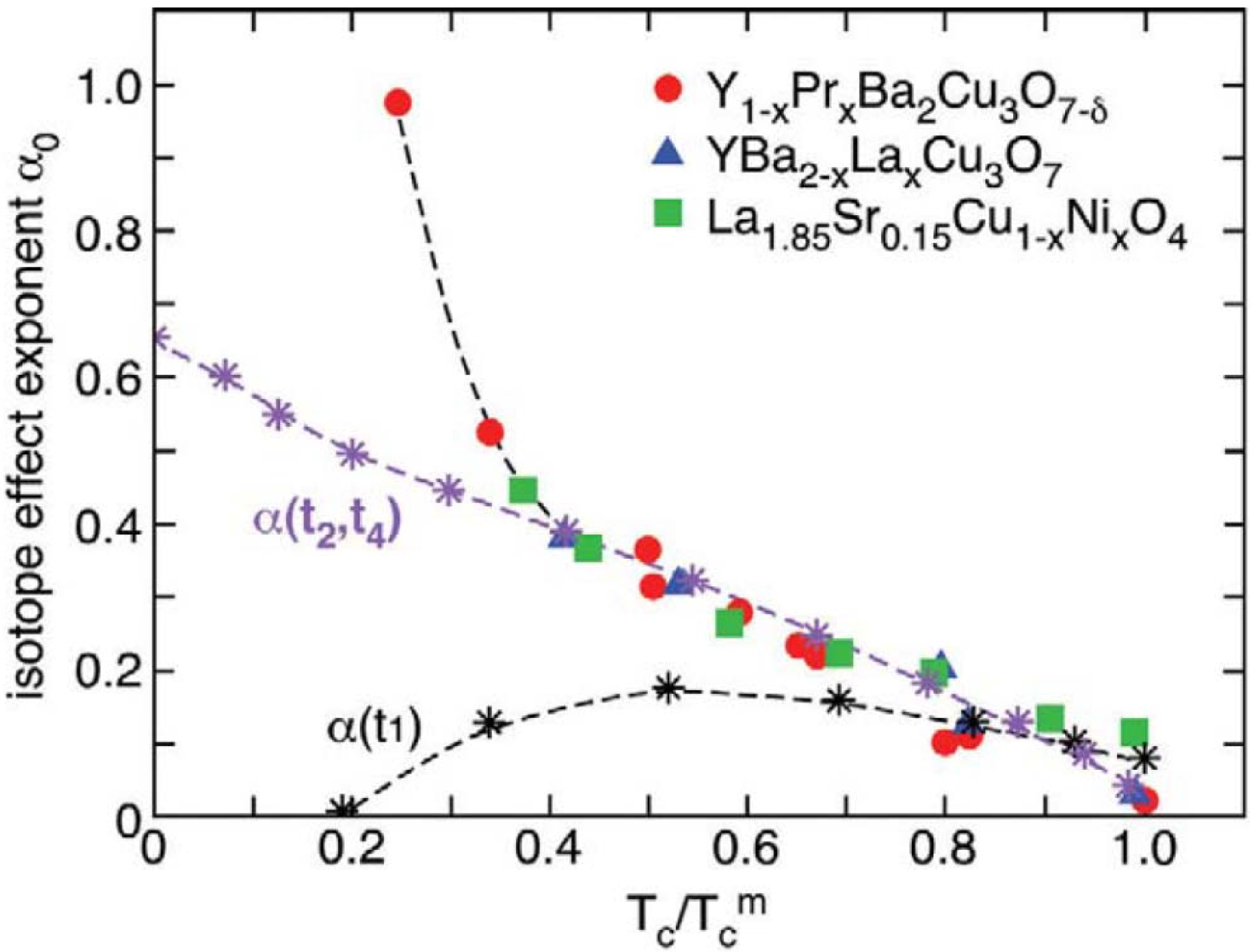
Isotope Effects

$$T_c \propto M^{-\alpha}$$

Isotope effect exponent: $\alpha = -\dfrac{\Delta T_c / T_c}{\Delta M / M} = \dfrac{d \ln(T_c)}{d \ln(M)}$

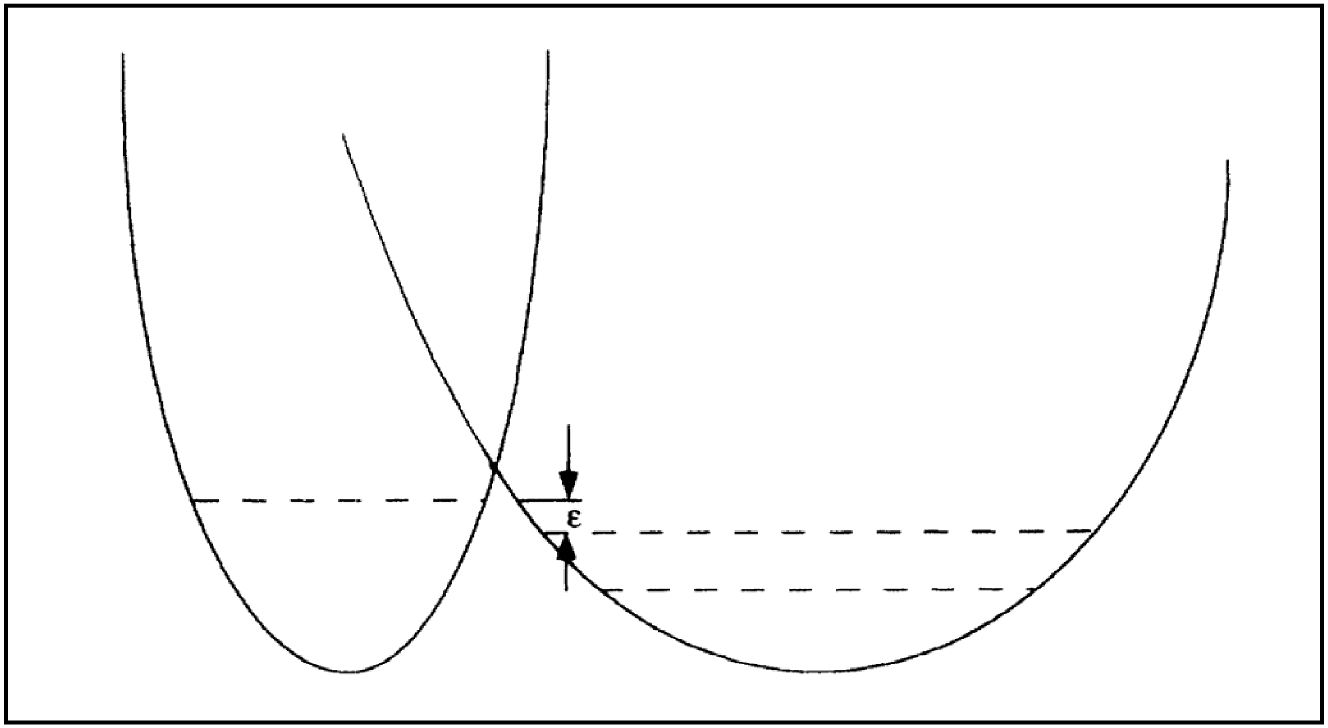
Within the BCS theory: $\alpha = 0.5$

Isotope Effects



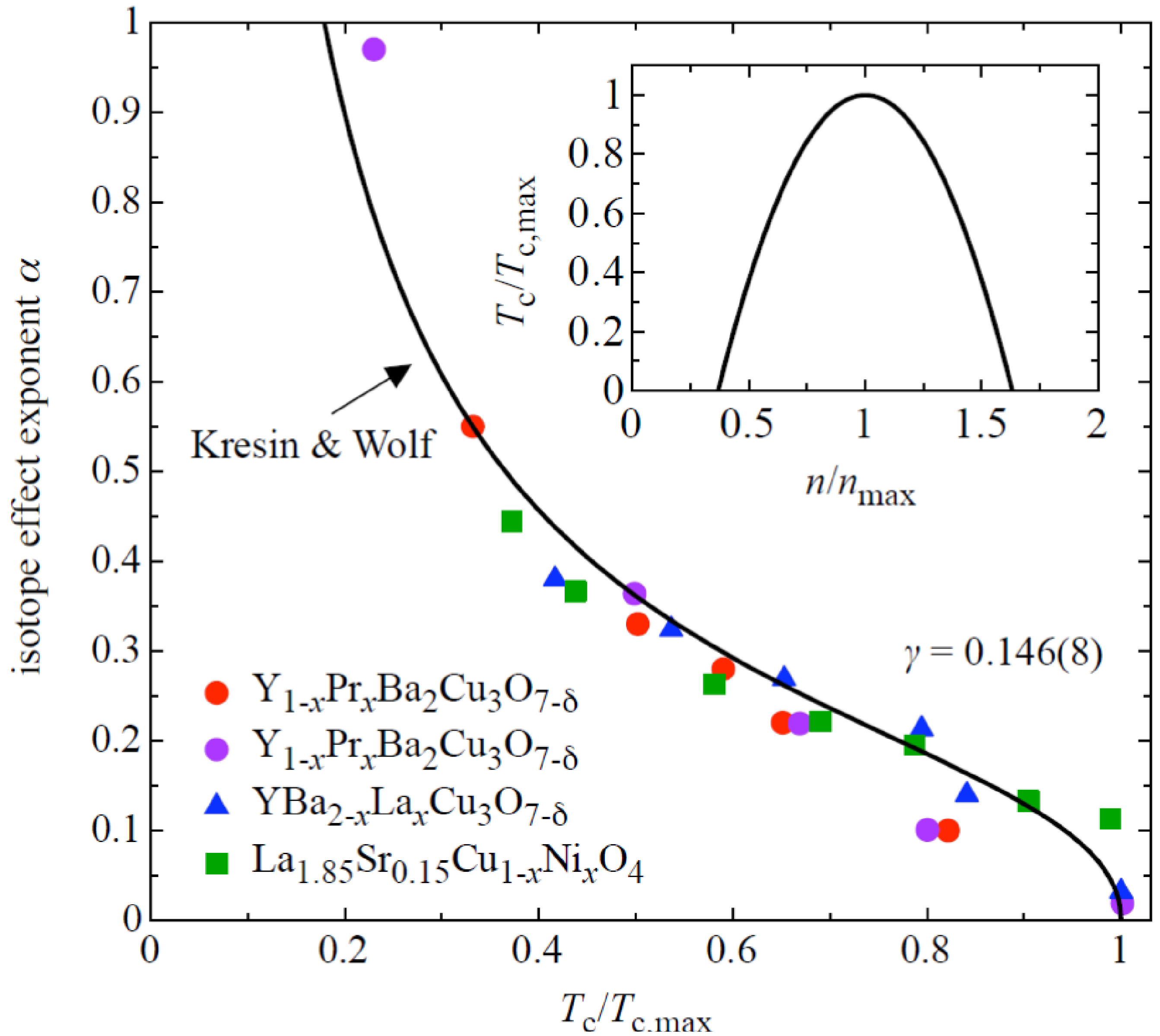
H. Keller, A. Bussmann-Holder, and K. A. Müller, Materials Today **11**, 38 (2008).

Polaronic Model of Kresin and Wolf



$$\alpha(n,T_c) = \gamma(n)\frac{n}{T_c(n)}\frac{\partial T_c(n)}{\partial n}$$

V. Z. Kresin and S. A. Wolf, Phys. Rev. B **49**, 3652 (1994).



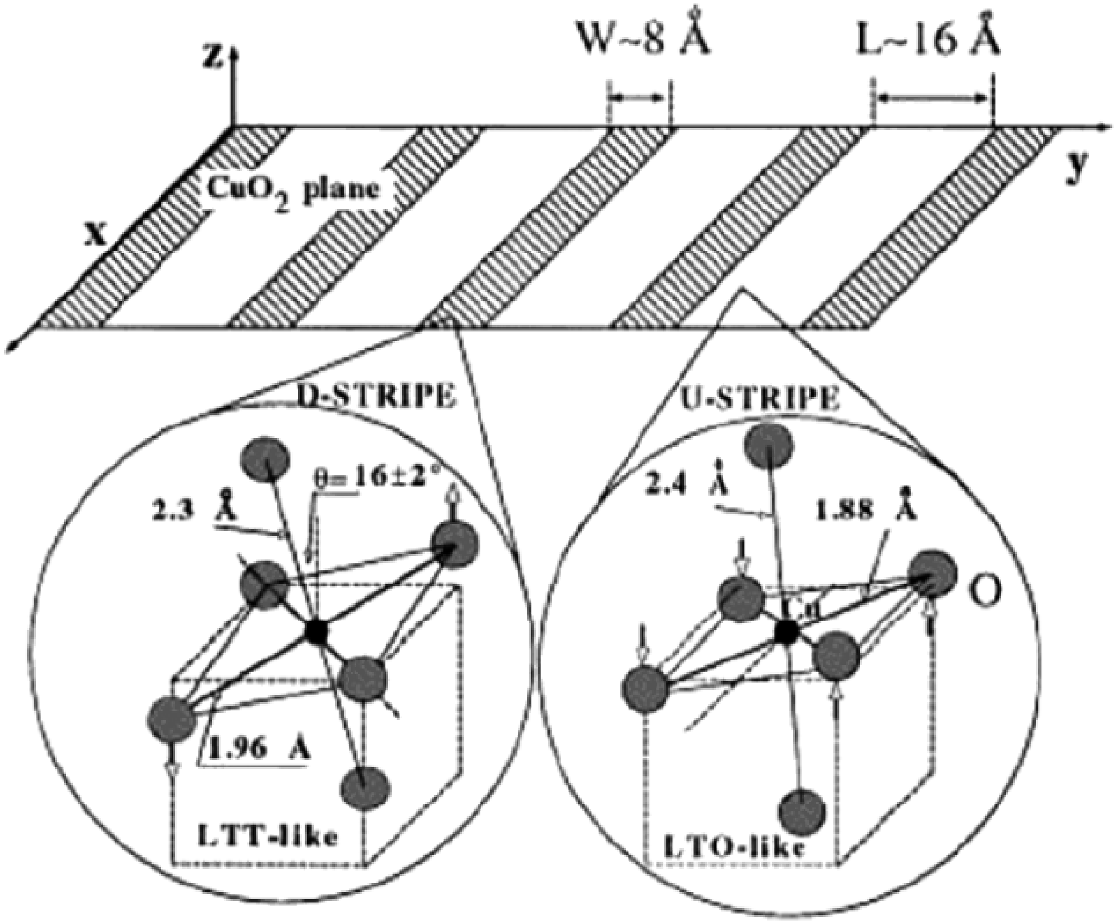
S. Weyeneth and K. A. Müller, J. Supercond. Nov. Magn. (2011).

The Groundstate of a Polaronic Wavefunction

$$\Psi = \sum \Psi_n^i \, \Psi_e^i \qquad\qquad i \geq 2$$

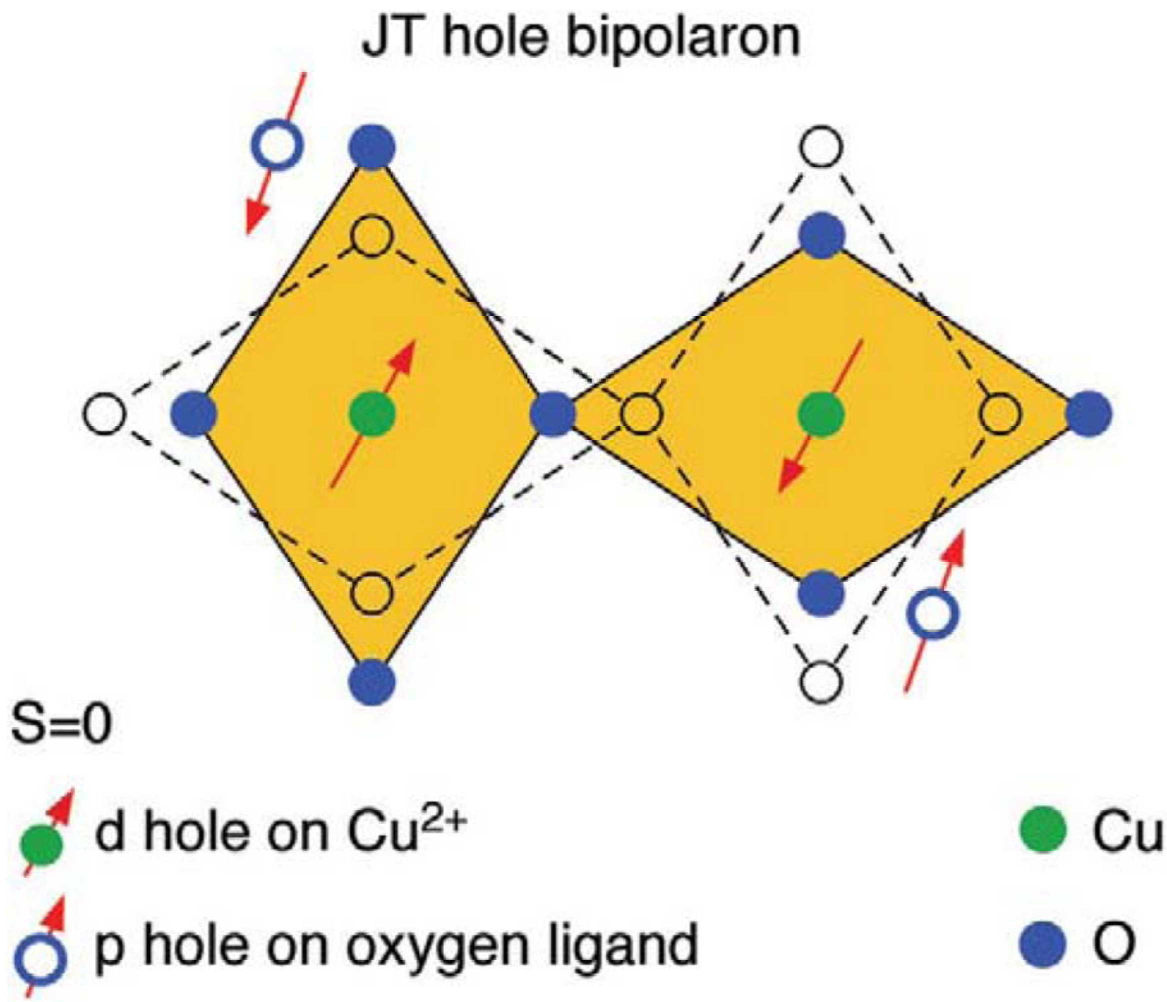
Therefore $\Psi_n{}^i$ and $\Psi_e{}^i$ are not separable as in the Born-Oppenheimer approximation.

Cuprates are Intrinsically Dynamic and Heterogenous



A. Bianconi *et al.*, Phys. Rev. Lett. **76**, 3412 (1996).

At low Doping: Jahn-Teller Bipolarons

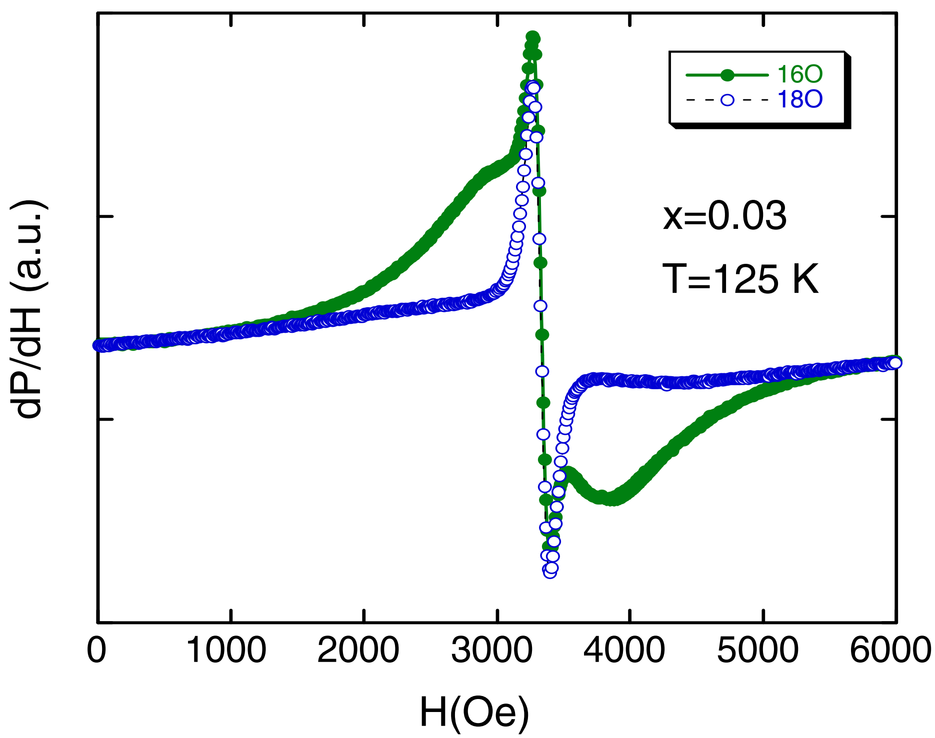


V. V. Kabanov and D. Mihailovic, J. Supercond. **13**, 959 (2000).
D. Mihailovic and V. V. Kabanov, Phys. Rev. B **63**, 054505 (2001).

Coherence Lengths

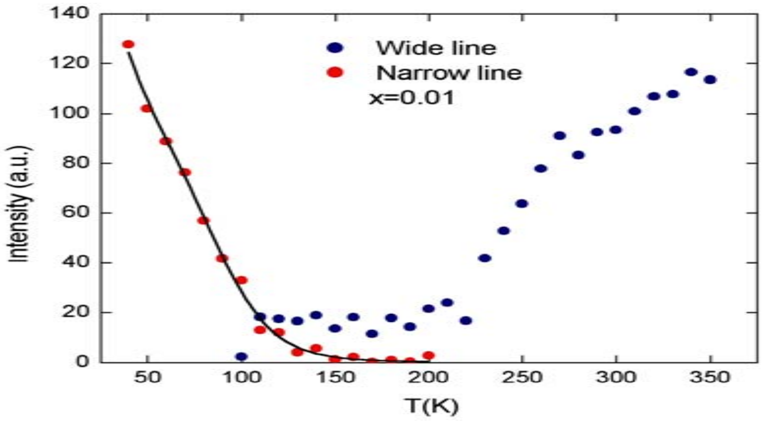
$YBa_2Cu_3O_7$ (T_c = 91 K)

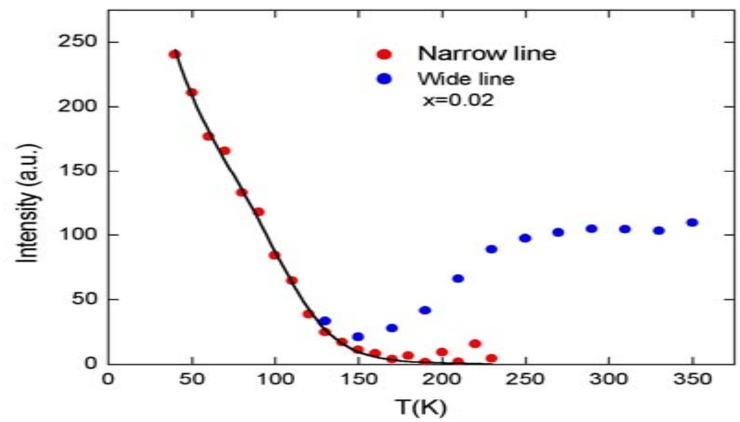
in the plane:	$\xi_{ab} \sim 1.5$ nm
perpendicular to plane:	$\xi_c \sim 0.3$ nm

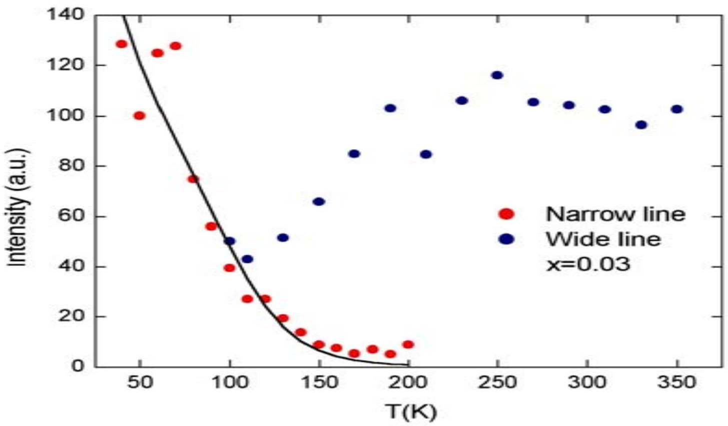


Shengelaya *et al.*, J. Supercond. **13**, 955 (2000)

EPR intensity in $La_{2-x}Sr_xCu_{0.98}Mn_{0.02}O_4$





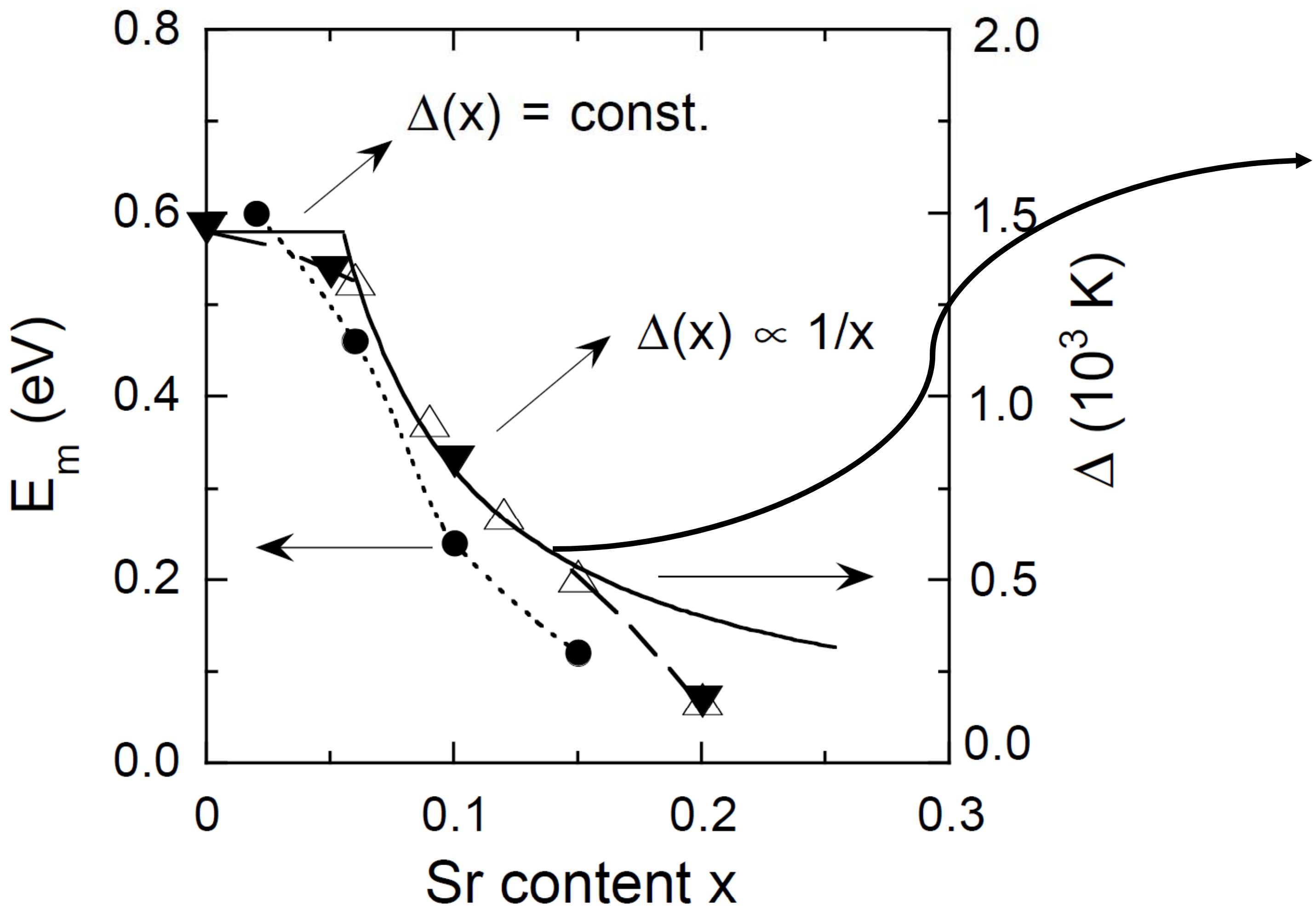


We attribute the narrow line to hole-rich regions.

Intensity of the narrow line increases exponentially below 150 K.

Activation energy Δ= 500 K within experimental accuracy the one for the bipolaron formation from Raman and Neutron scattering.

Bipolarons in $La_{2-x}Sr_xCuO_4$



A. S. Alexandrov, V. V. Kabanov, and N. F. Mott, Phys. Rev. Lett. **77**, 4796 (1996).

K.A. Müller *et al*., J. Phys.: Condens Matter **10**, L291 (1998).

Conclusions

Cuprate superconductors with unique properties have to be understood on the basis of (bi-)polaron formation and local clustering or equivalently by vibronic theory.

The separation of electronic and lattice degrees of freedom i.e. the Born-Oppenheimer approximation has to be abandoned, also with the RVB and t-J models with purely electronic degrees of freedom.