PAUL SCHERRER INSTITUT PSI

Wir schaffen Wissen – heute für morgen

The Meissner effect in a strongly underdoped cuprate well above its critical temperature

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$La_{2-x}Sr_xCuO_4$ phase diagram and pseudogap

M. Hashimoto et al., PRB 75, 140503 (2007)

Many unusual responses observed by spin and charge probes

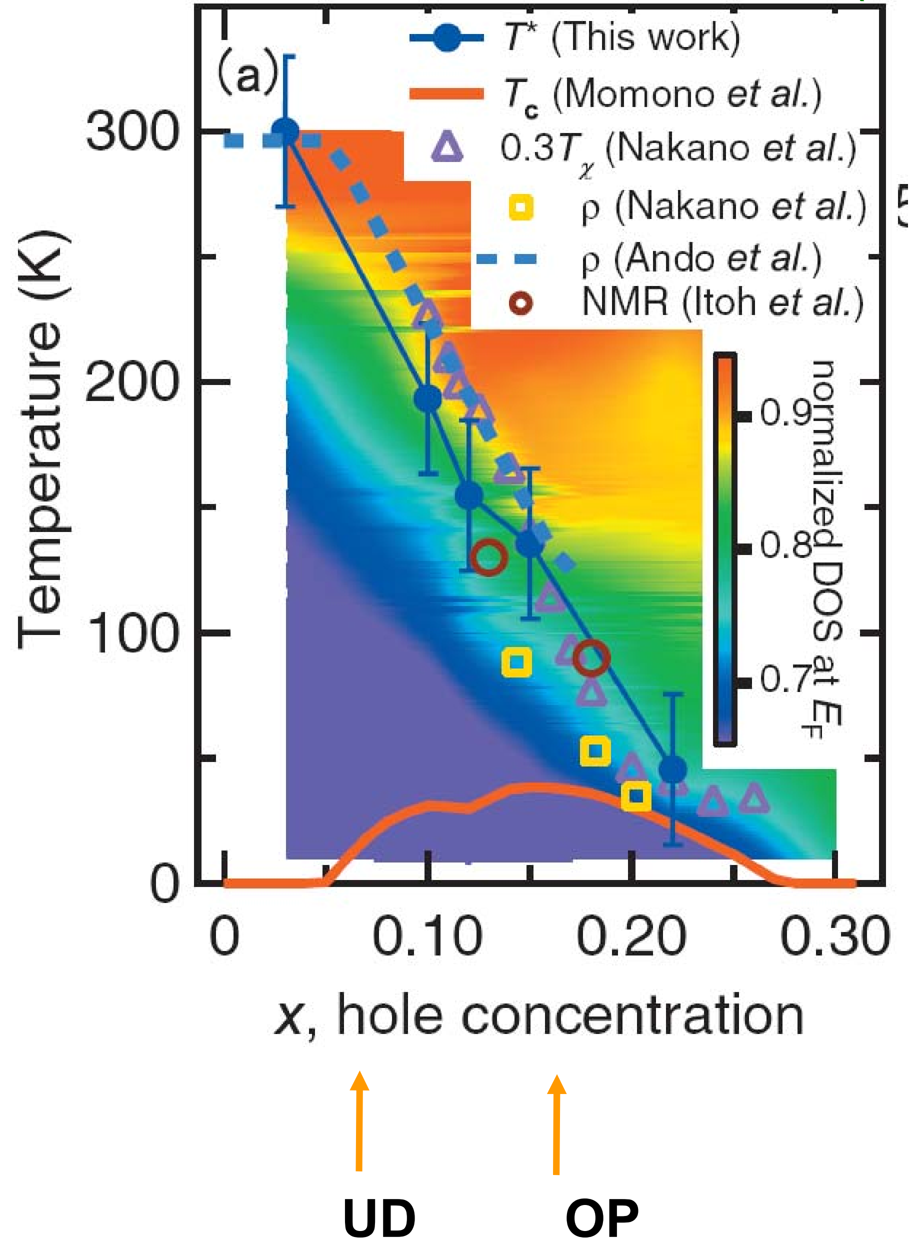
PG scenarios:

- Local pairing correlations, phase fluctuations, $T_\varphi \sim n_S/m^*$

- Ordering phenomena of charge, spin, orbital currents,…..

PG: Precursor/competing state of sc or both ?

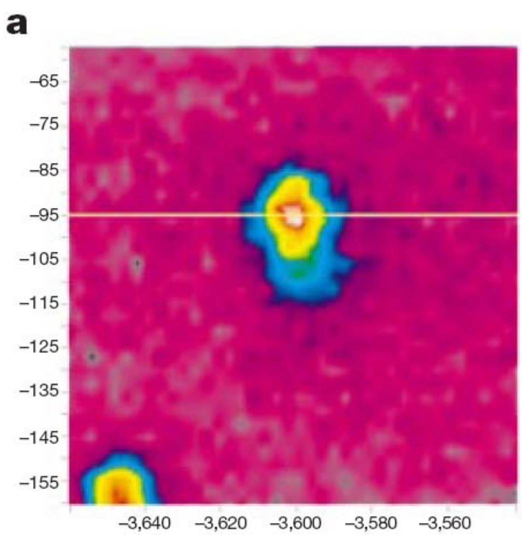
Experiments also show
anomalous diamagnetic response



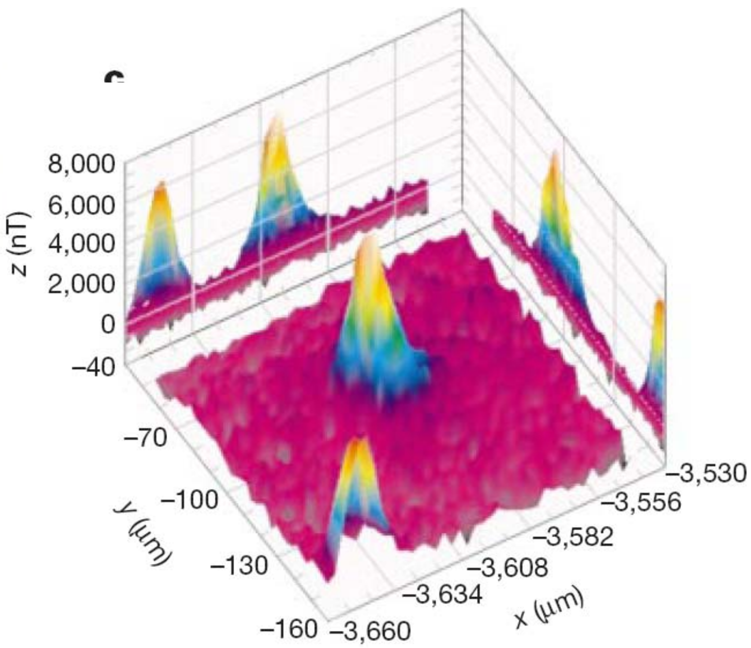
Local diamagnetism

Magnetic imaging by scanning SQUID microscopy of

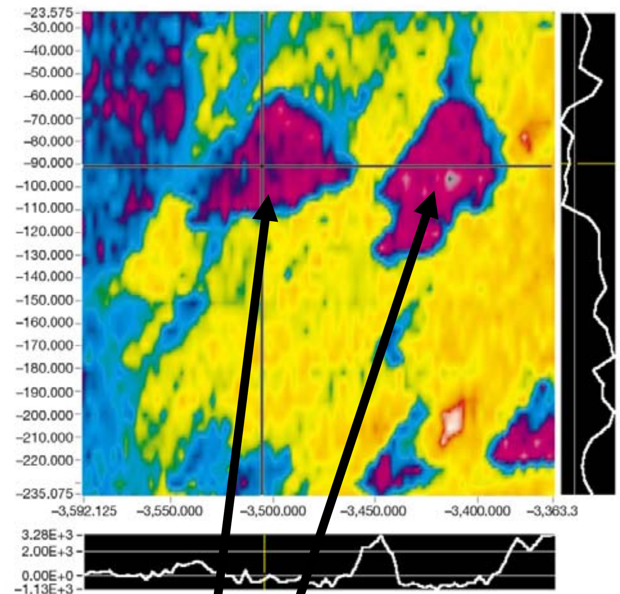
LSCO films (thickness few 100 nm) $T_c \approx 19$ K



3 K



FC in 5 mG



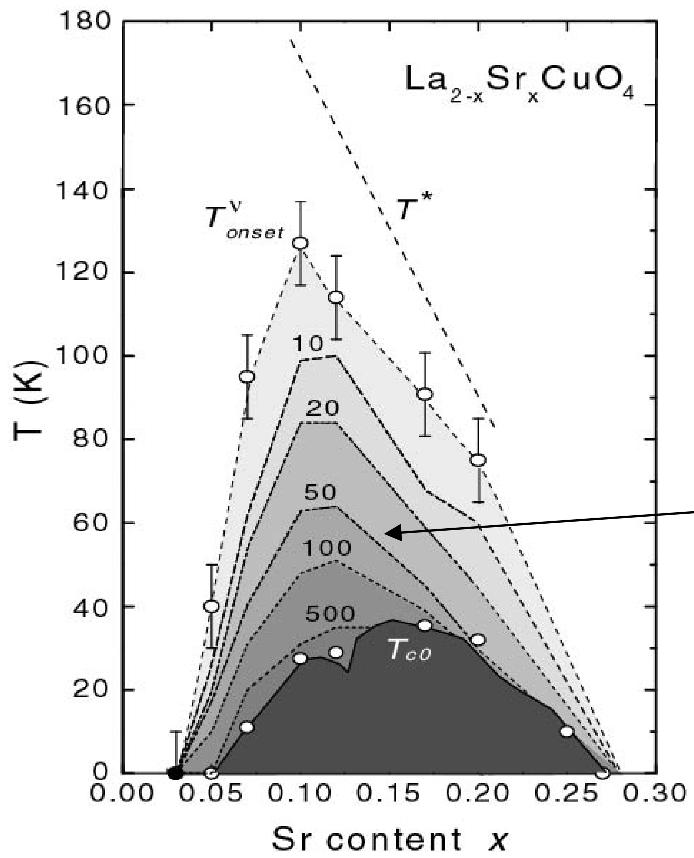
25.5 K

Diamagnetic domains

Local diamagnetism up to 30K above T_c in the pseudogap region

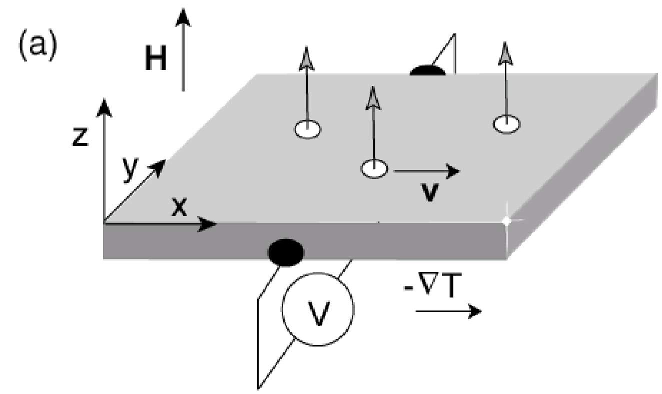
I. Iguchi, T. Yamaguchi, A. Sugimoto Nature 412, 420 (2001)

Enhanced Nernst effect



$$E_y = -e_N \nabla_x T$$

$$\nu = \frac{e_N}{B}$$

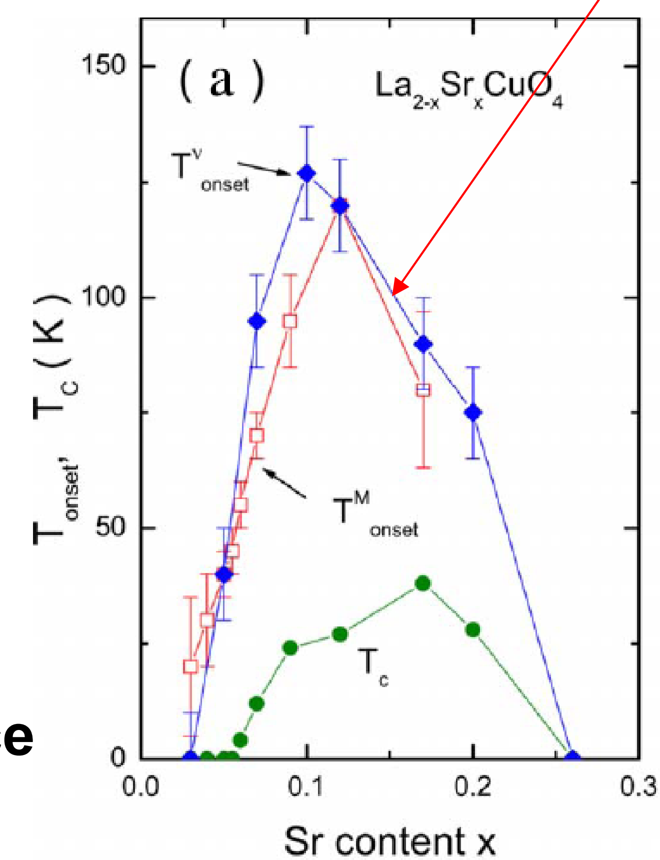


Nernst region

Y. Wang et al., PR B73, 024510 (2006)

*Z.A. Xu, N.P. Ong et al. Nature **406**, 486 (2000)*

Increased diamagnetic response

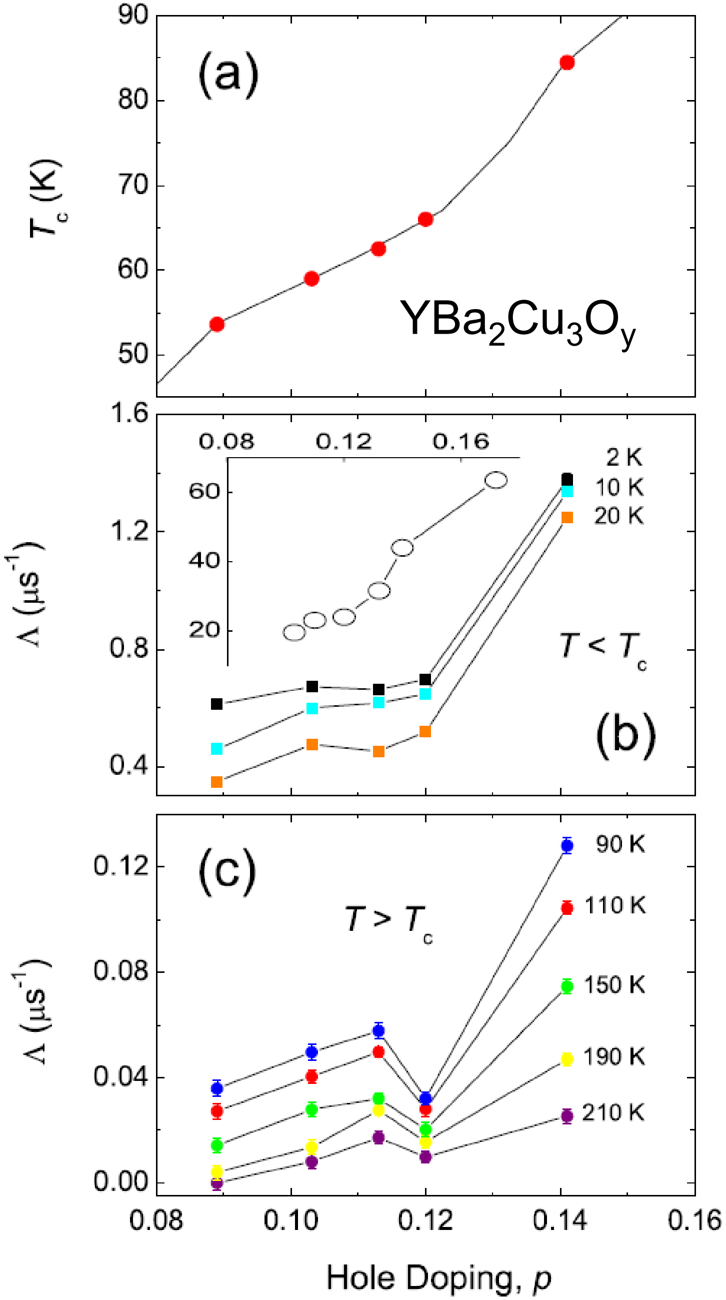


L. Li et al., PRB81, 054510 (2010)

Vorticity and superconducting correlations in Nernst region
→condensate amplitude without phase coherence for T>T$_c$, phase fluctuations

inhom. TF-μSR broadening

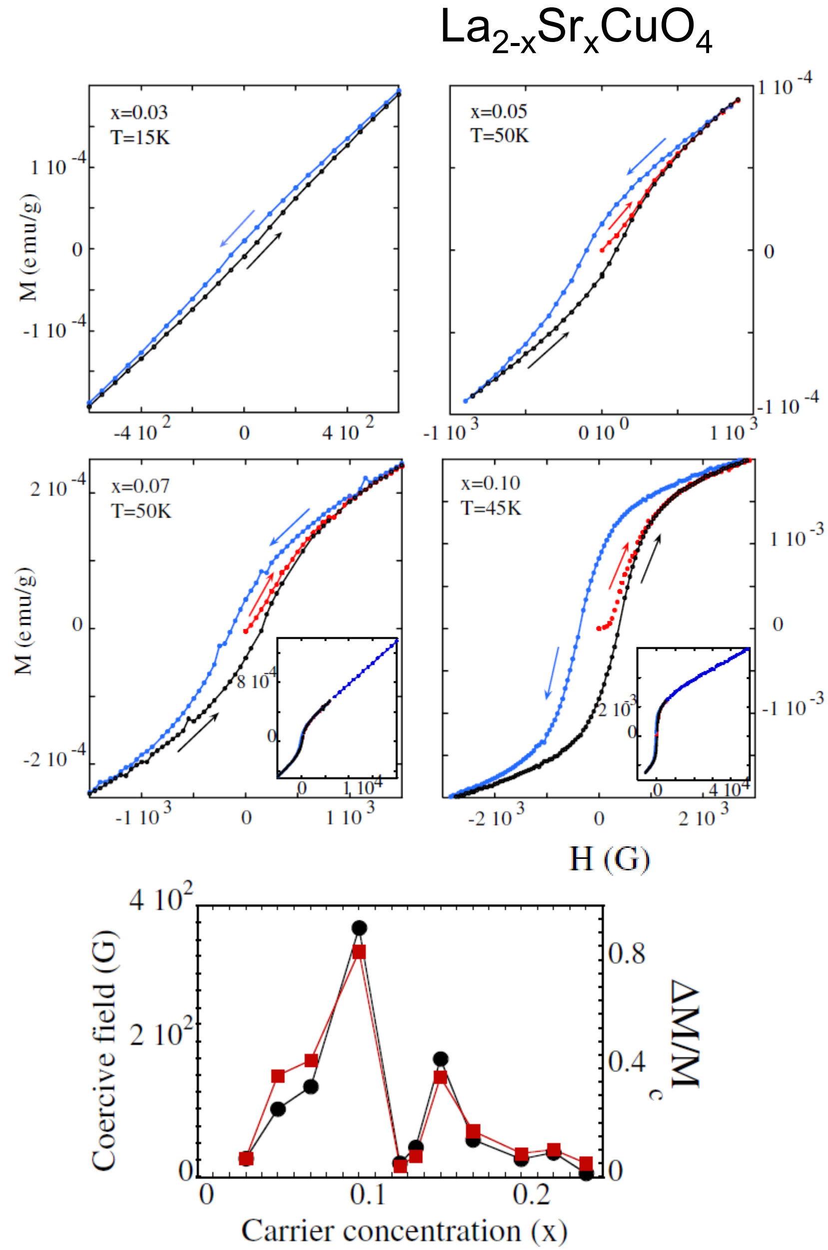
$\Lambda \propto H$ in high fields



J. Sonier et al, Phys. Rew. Lett., (2008)

(Indirect) indication of local superconductivity above T_c

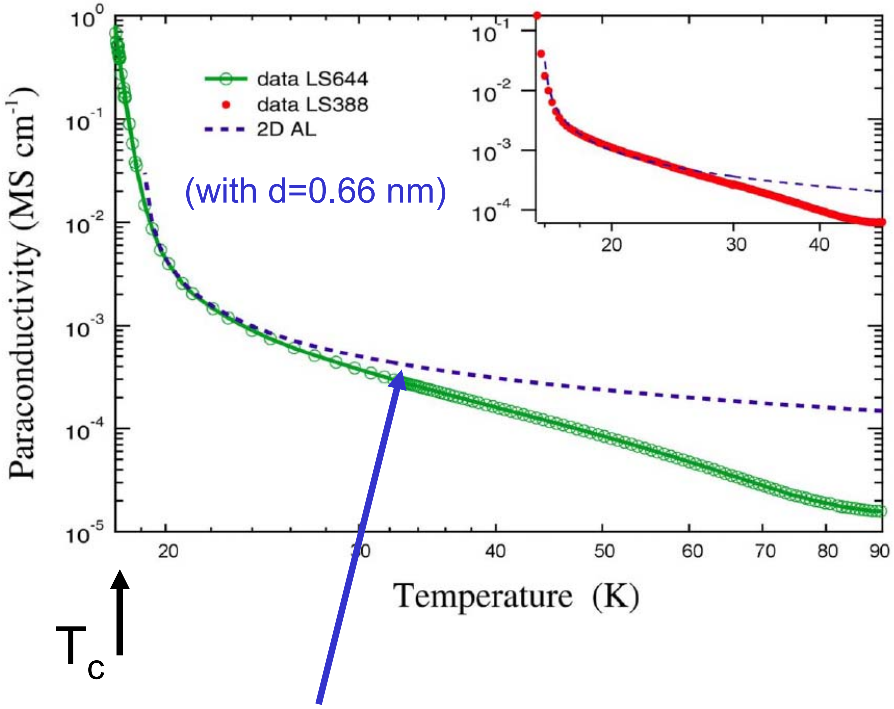
Hysteresis in low-field magnetization curves



C. Panagopoulos et al, Phys. Rew. Lett., (2006)

Paraconductivity

$La_{2-x}Sr_xCuO_4$, x=0.08-0.09, ≈ 200 nm



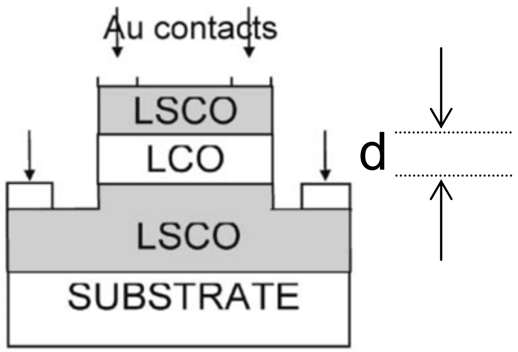
Amplitude Fluctuations (Gaussian)

Aslamazov-Larkin formula:

$$\Delta\sigma_{2D} = \frac{e^2}{16\hbar d\varepsilon} \cong \frac{e^2 T_c}{16\hbar d(T - T_c)}$$

B. Leridon et al., Phys. Rev. B 87, 012503, (2007)

Josephson effect in LSCO devices

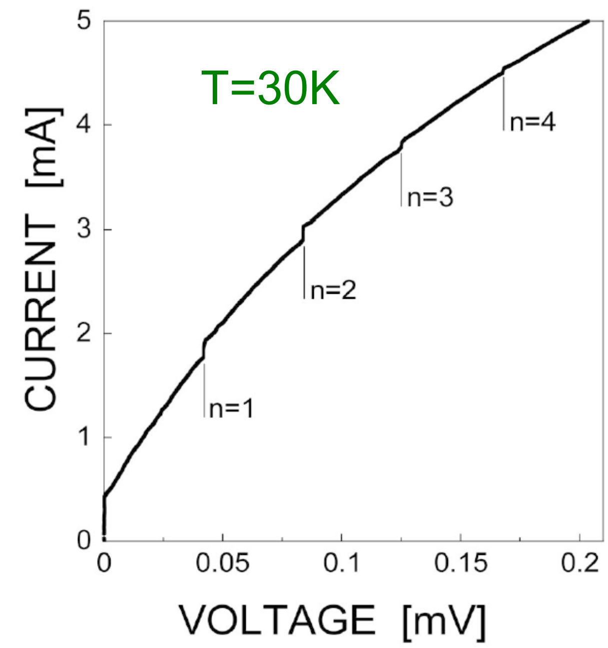


OP/UD/OP junction (≈ SS'S)

OP: $La_{1.85}Sr_{0.15}CuO_4$ T_c = 45 K

UD: La_2CuO_{4+d} $T_c' \approx$ 25 K

OP: $La_{1.85}Sr_{0.15}CuO_4$ T_c = 45 K

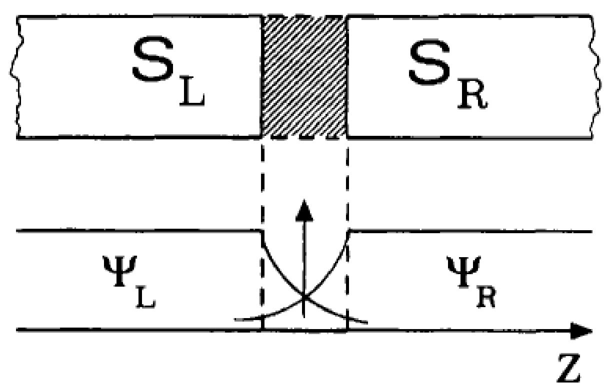


Observation of Josephson current over non-superconducting barrier in pseudogap with d ≅ 20 nm

d >> $\xi_c \approx$ 0.1- 0.3 nm

d > $\xi_N = \sqrt{\dfrac{\hbar v_F \ell}{6\pi k_B T}} \approx$ 2 nm

"Classical" range of proximity effect,
(V_N=0 and T_c'=0 !)

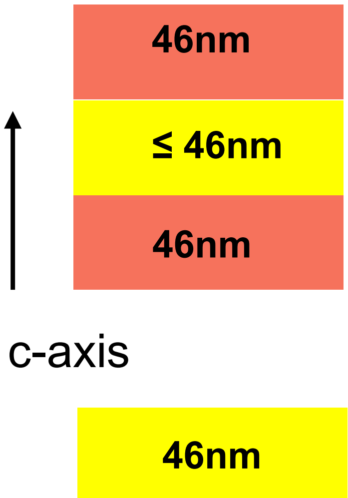


→ Giant proximity effect

I. Bozovic et al, Phys. Rew. Lett., (2004)

R.S. Decca et al., Phys.Rev. Lett. (2004) **(YBCO)**

LSCO Tri- and Single Layers

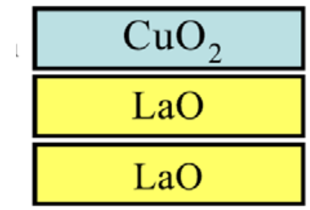


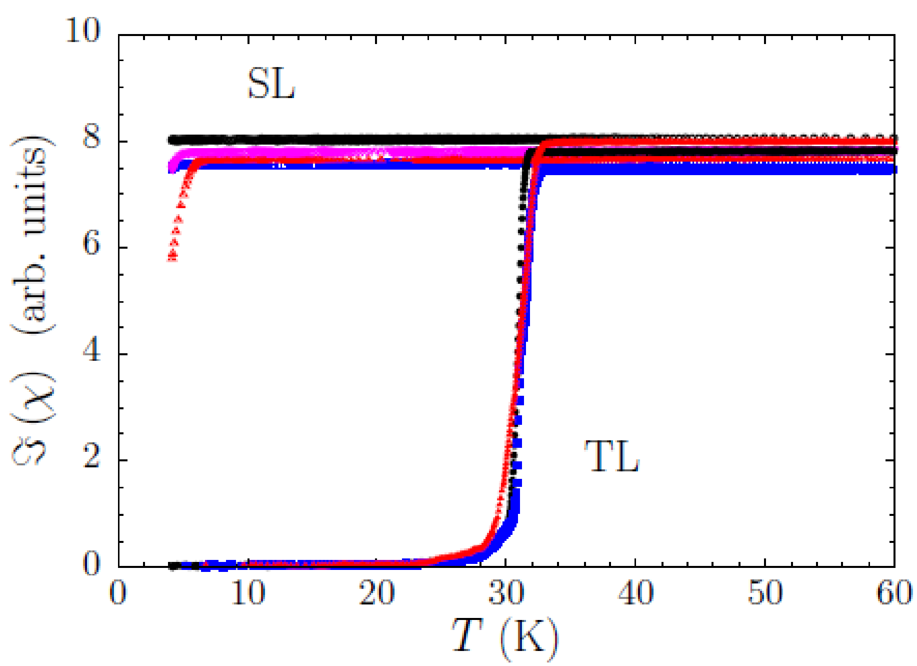
OP: $La_{1.84}Sr_{0.16}CuO_4$ $T_c \cong 32$ K

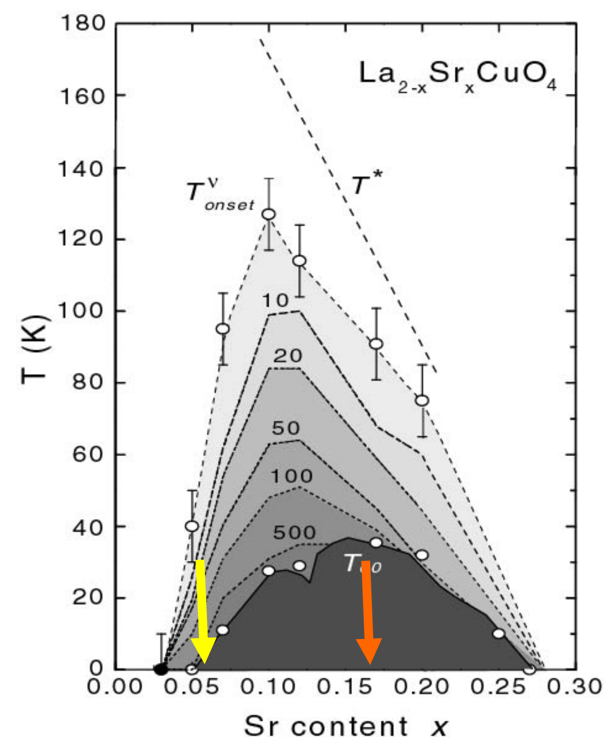
UD: $La_{1.94}Sr_{0.06}CuO_4$ $T_c' \lesssim 5$K

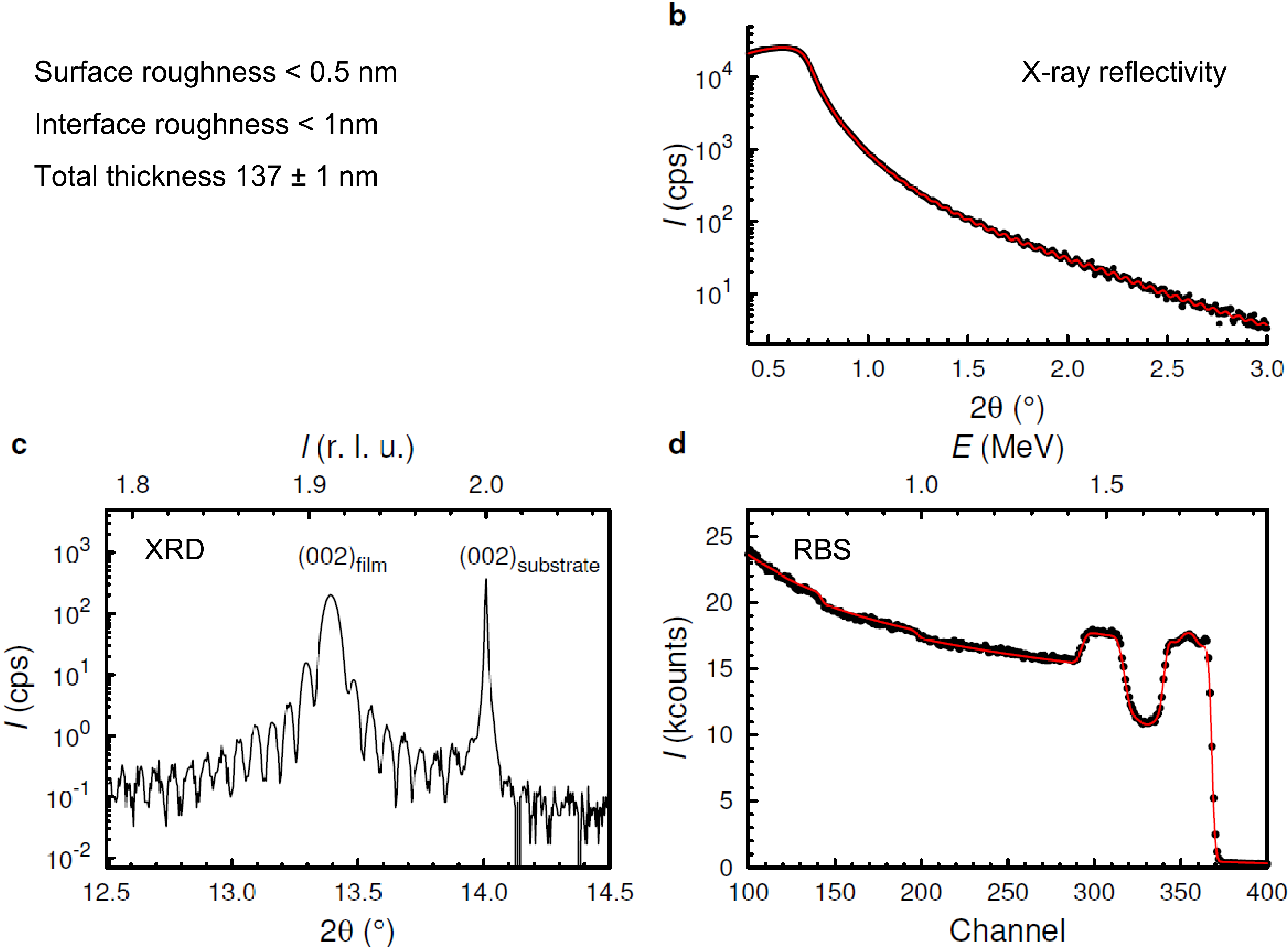
OP: $La_{1.84}Sr_{0.16}CuO_4$ $T_c \cong 32$ K

Grown at BNL by molecular beam expitaxy (I. Bozovic, G. Logvenov) → Layer by layer growth and doping control







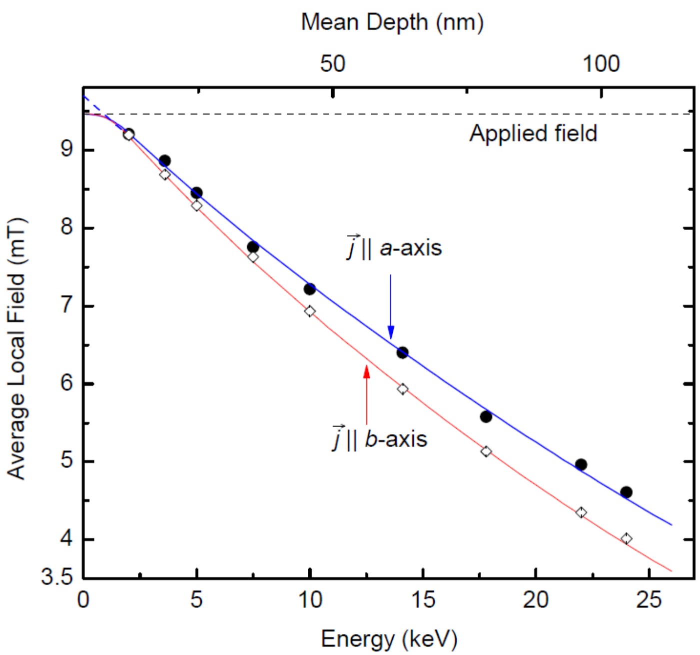


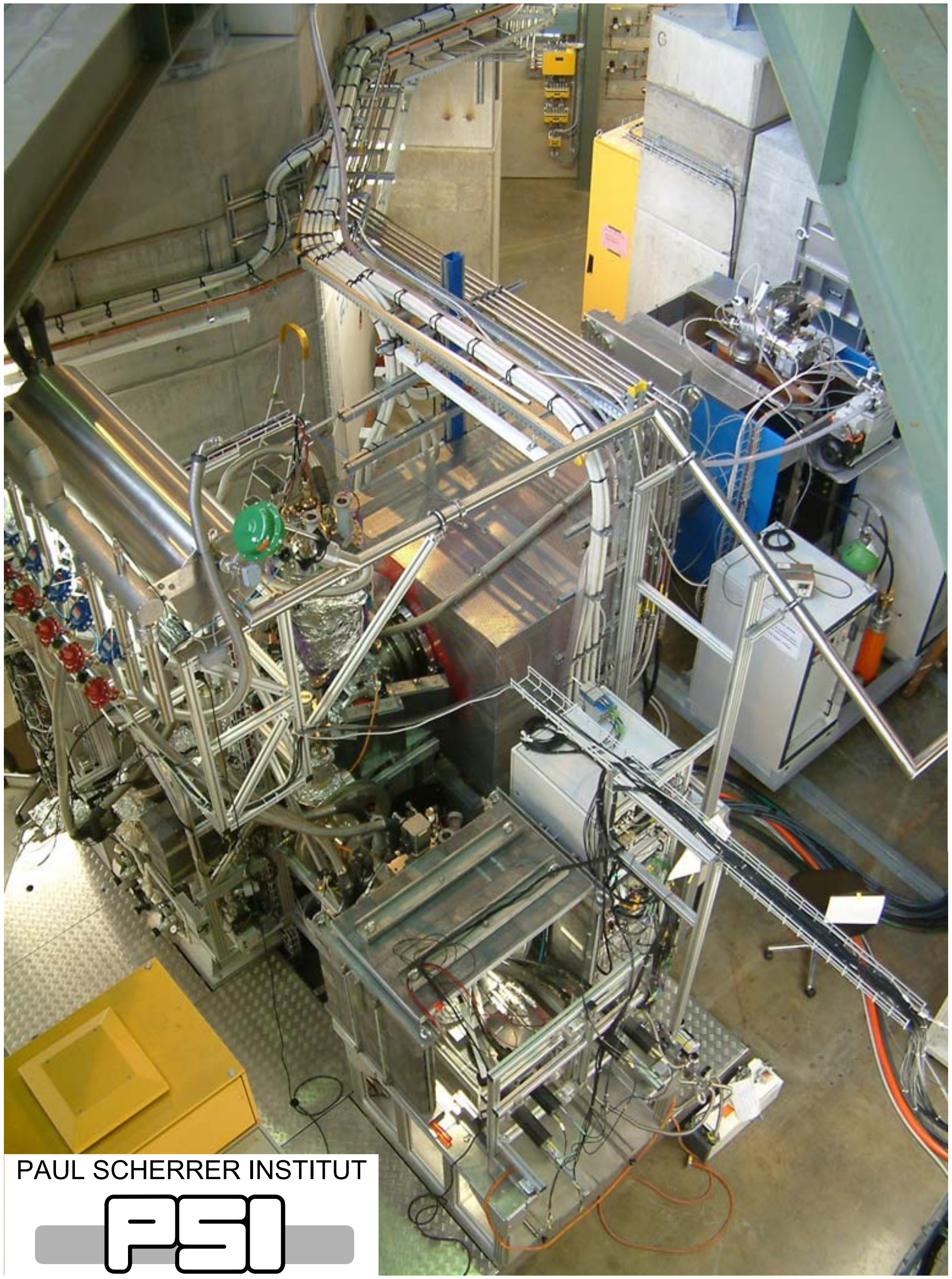
Surface roughness < 0.5 nm
Interface roughness < 1nm
Total thickness 137 ± 1 nm
b
X-ray reflectivity
I (cps)
10^4
10^3
10^2
10^1
0.5
1.0
1.5
2.0
2.5
3.0
2θ (°)
c
l (r. l. u.)
1.8
1.9
2.0
XRD
$(002)_{film}$
$(002)_{substrate}$
I (cps)
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
12.5
13.0
13.5
14.0
14.5
2θ (°)
d
E (MeV)
1.0
1.5
RBS
I (kcounts)
25
20
15
10
5
0
100
150
200
250
300
350
400
Channel

Low Energy Muon Spin Rotation/Relaxation

100% polarized positive muons of tunable energy (0.5 - 30 keV) allow depth resolved μSR on nm scale (1-200 nm range).

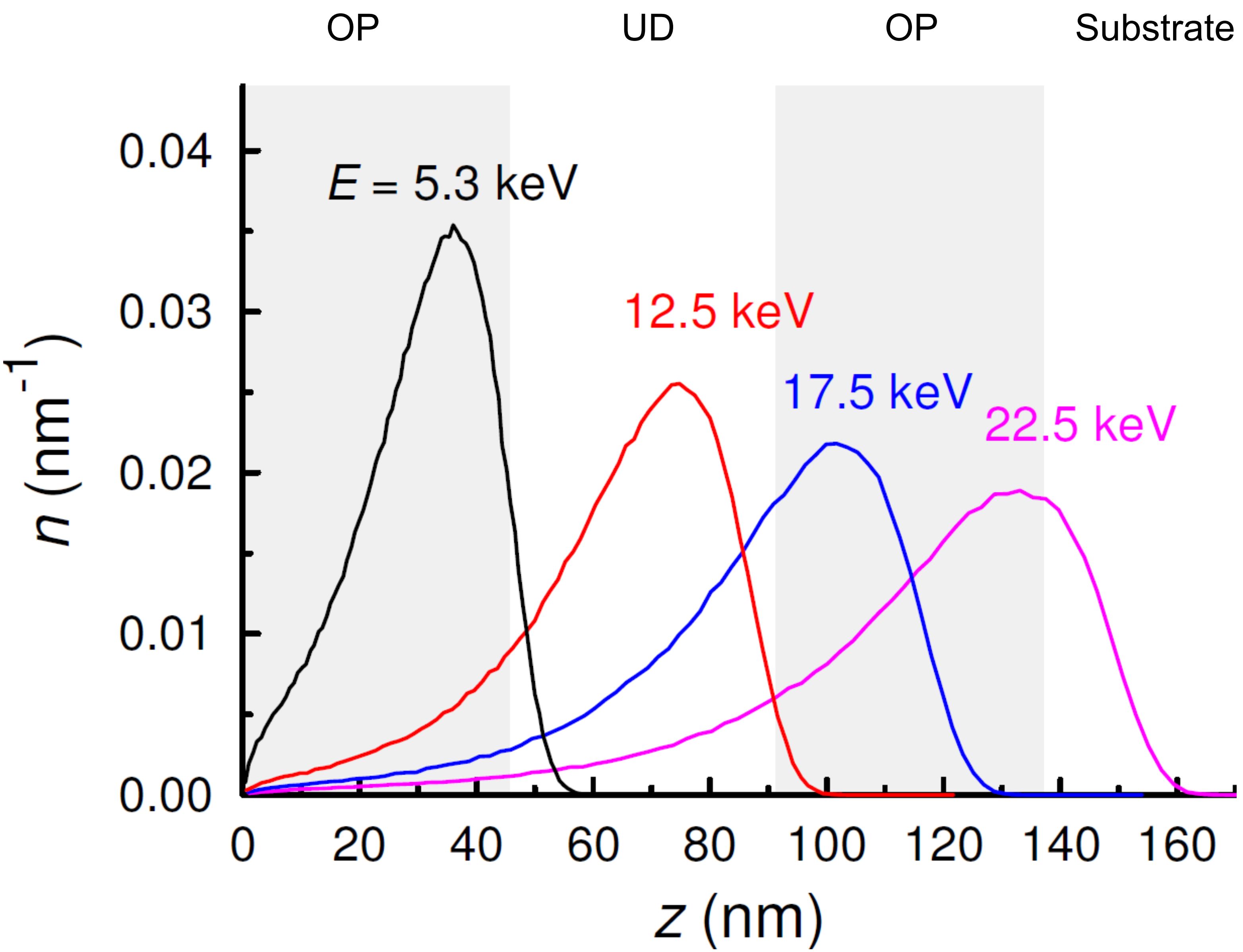
Field profile in detwinned $YBa_2Cu_3O_{6.92}$



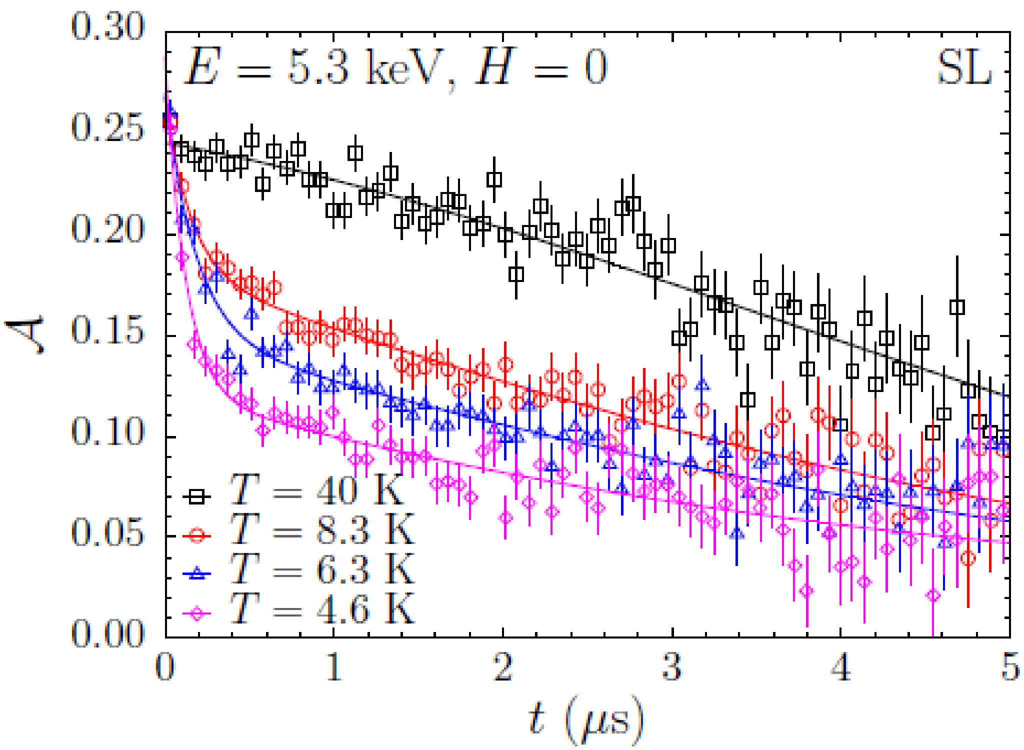


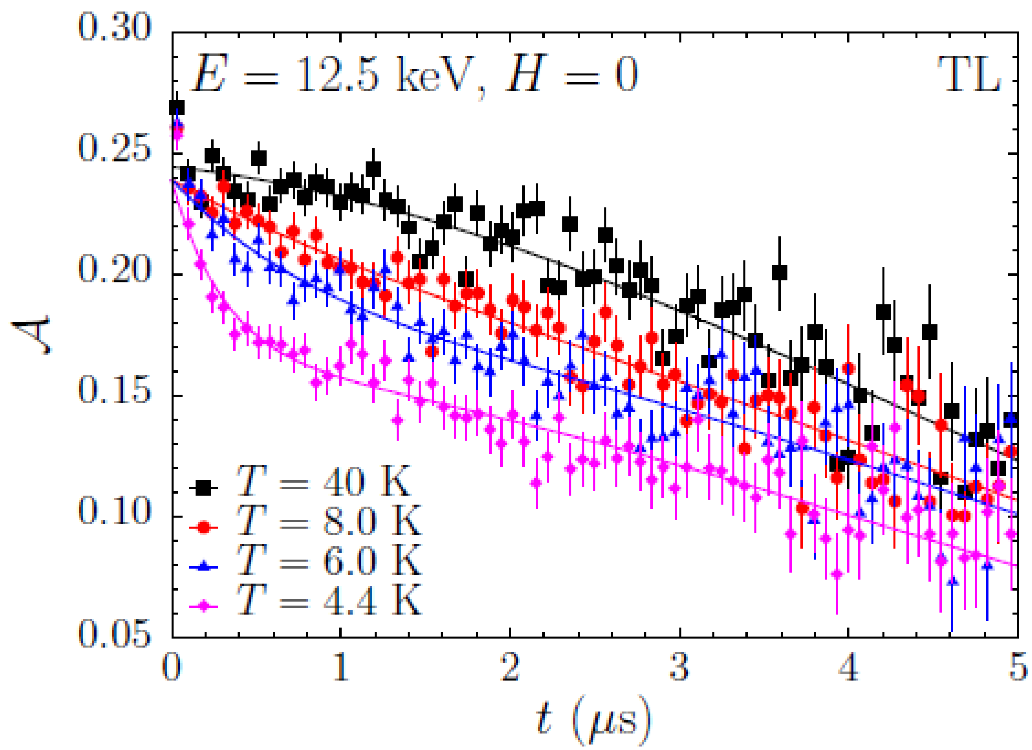
R. Kiefl et al. , Phys. Rev. B81, 180502(R) (2010)

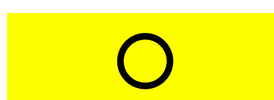
Muon stopping profiles

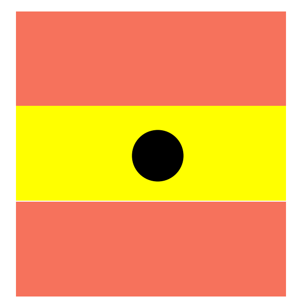


Magnetism in UD Layer x ≅ 0.06 : single vs barrier

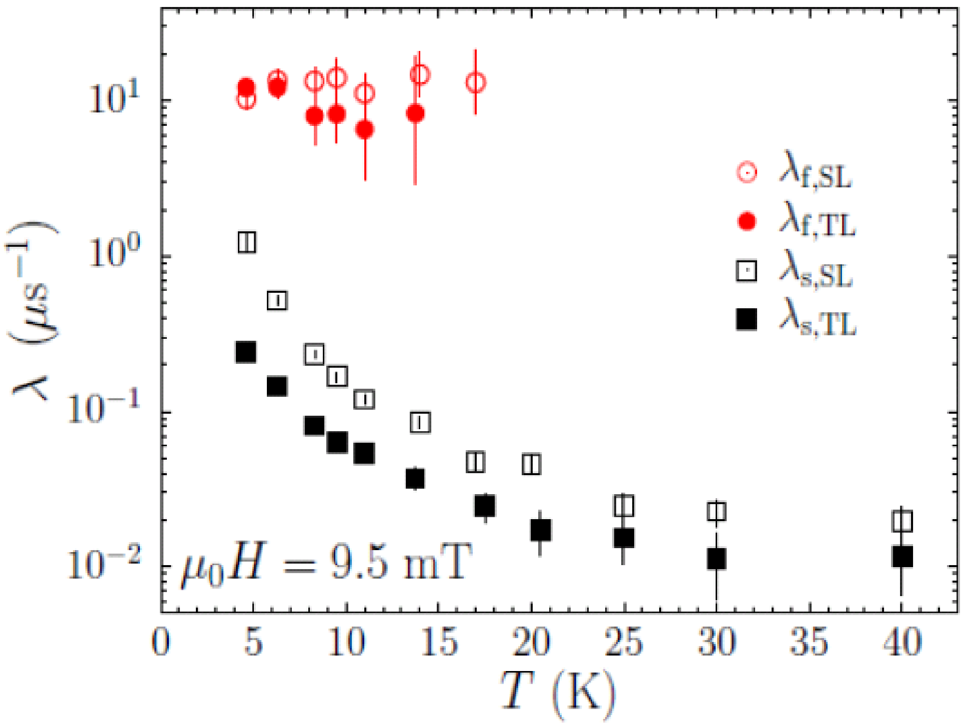


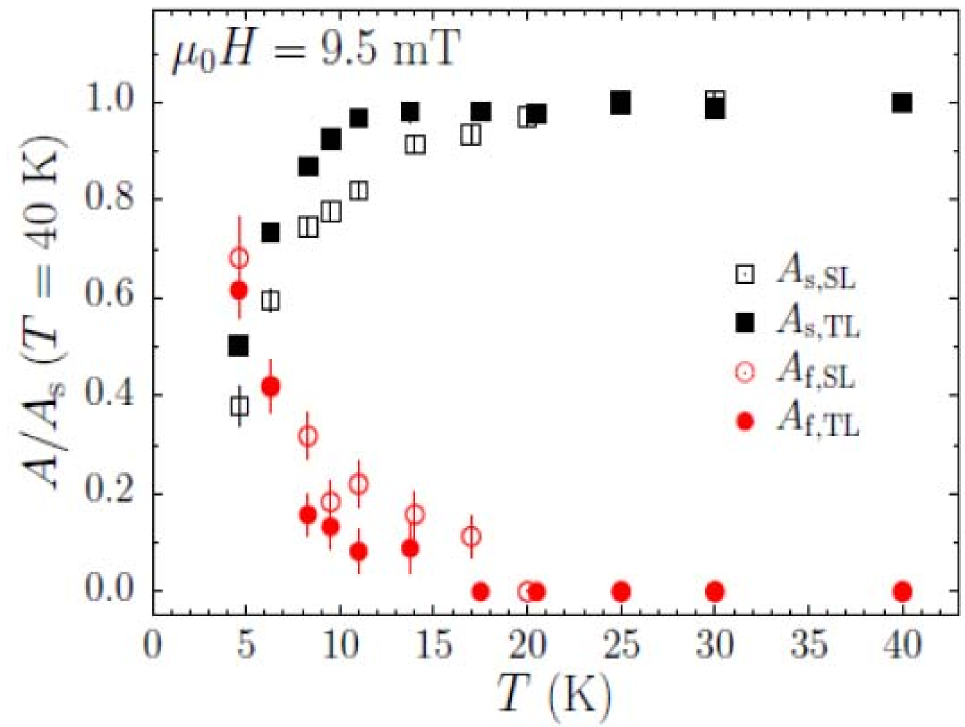






Magnetism in UD Layer x ≅ 0.06 : single vs barrier



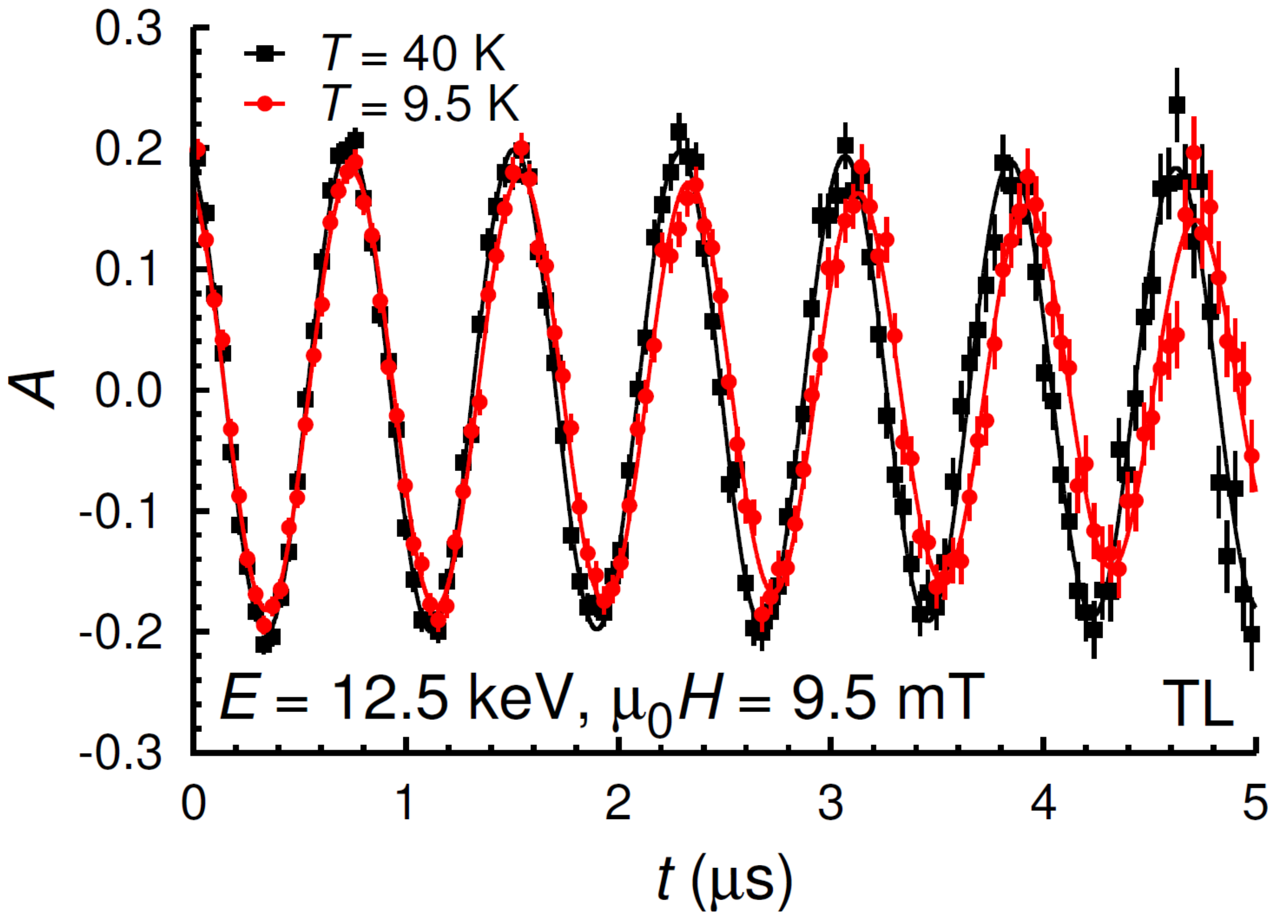


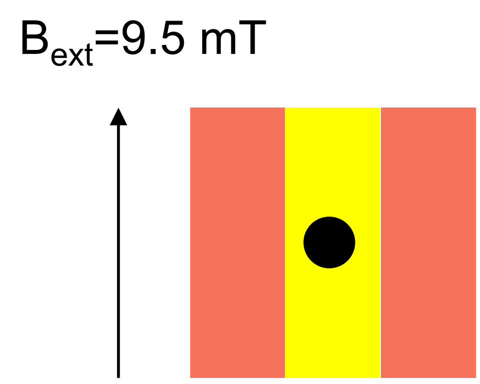
Measurement of the magnetic properties in ZF and wTF

→ Onset of magnetism at ~ 15K („spin glass“ in underdoped regime)

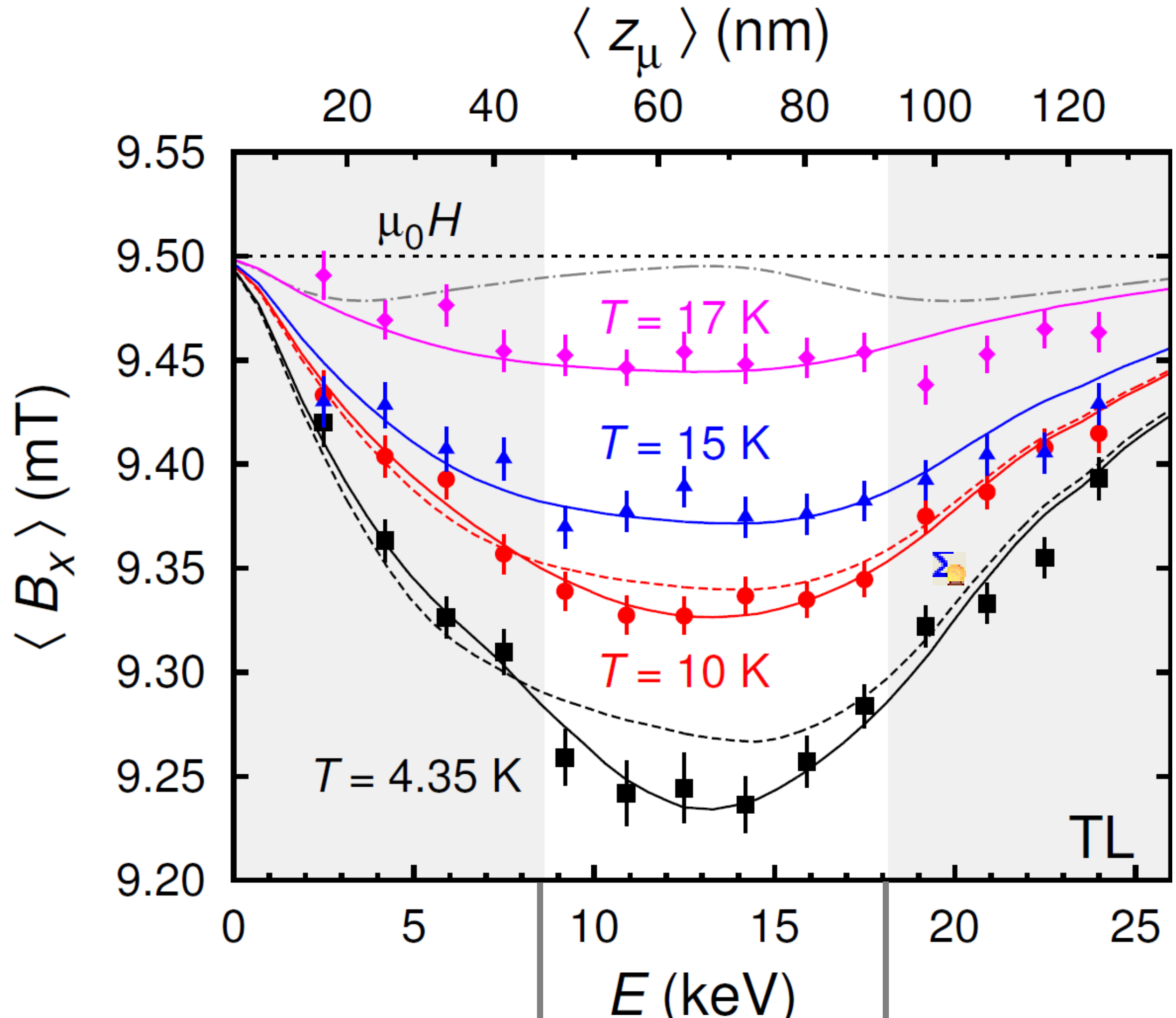
→ Integrity and doping level of barrier

Diamagnetic response





Field profile B(z) , B_{ext}=9.5 mT || ab-planes



entire ‘barrier’ layer of thickness *d* much larger than typical *c*-axis coherence exhibits Meissner effect for temperatures well above T_c’

$$d \gg \xi_c \simeq 0.3 \text{ nm},$$

$$d \gg \xi_N = \sqrt{\frac{\hbar v_c \ell}{2\pi k_B (T - T_c')}} \leq 3 \text{ nm}$$

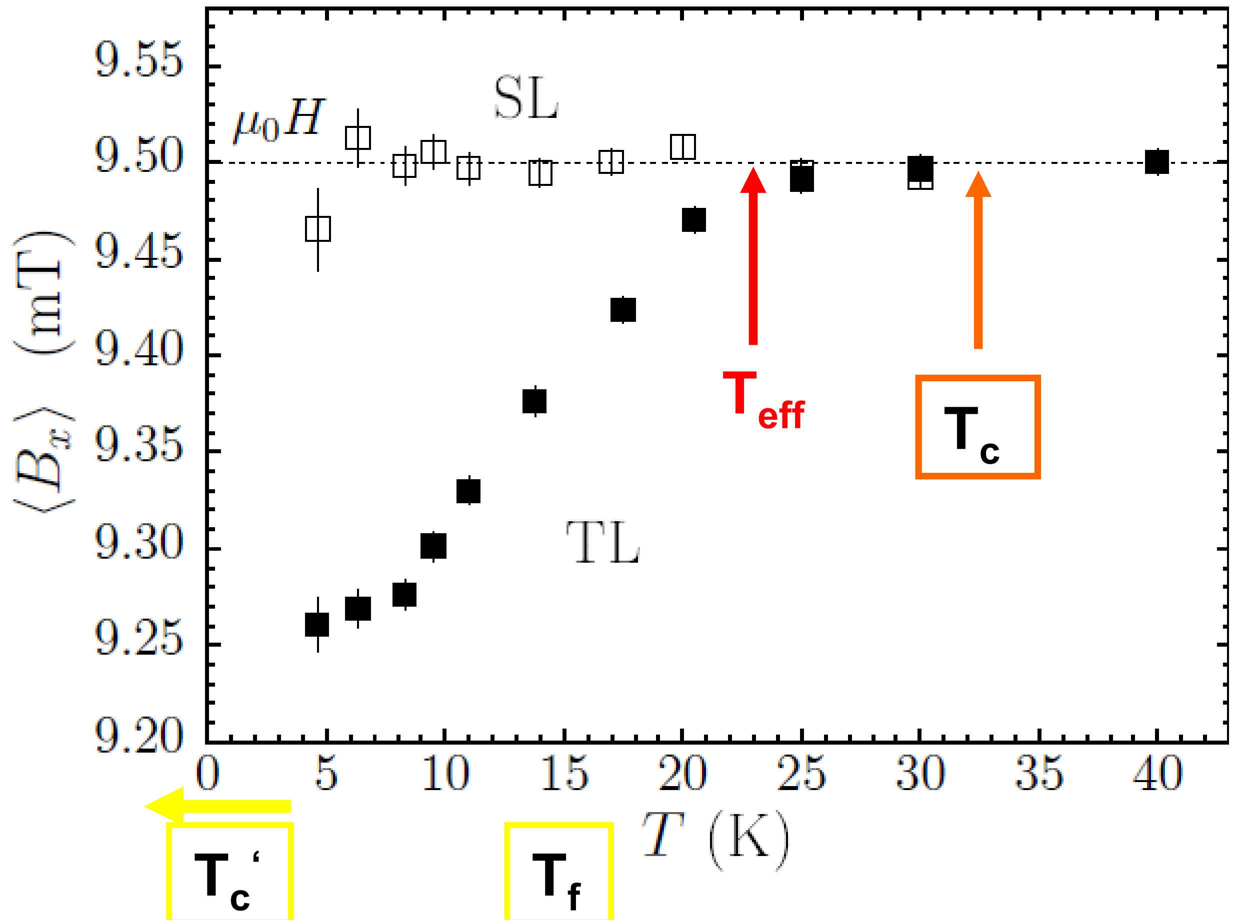
(for T ≥ 10K)

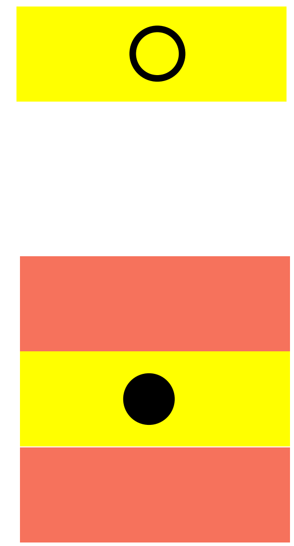
Supercurrents flow in c-direction and ab planes.

$La_{1.84}Sr_{0.16}CuO_4$	$La_{1.94}Sr_{0.06}CuO_4$	$La_{1.84}Sr_{0.16}CuO_4$
46nm **T_c ≅ 32 K**	46nm **T_c’ < 5K**	46nm **T_c ≅ 32 K**

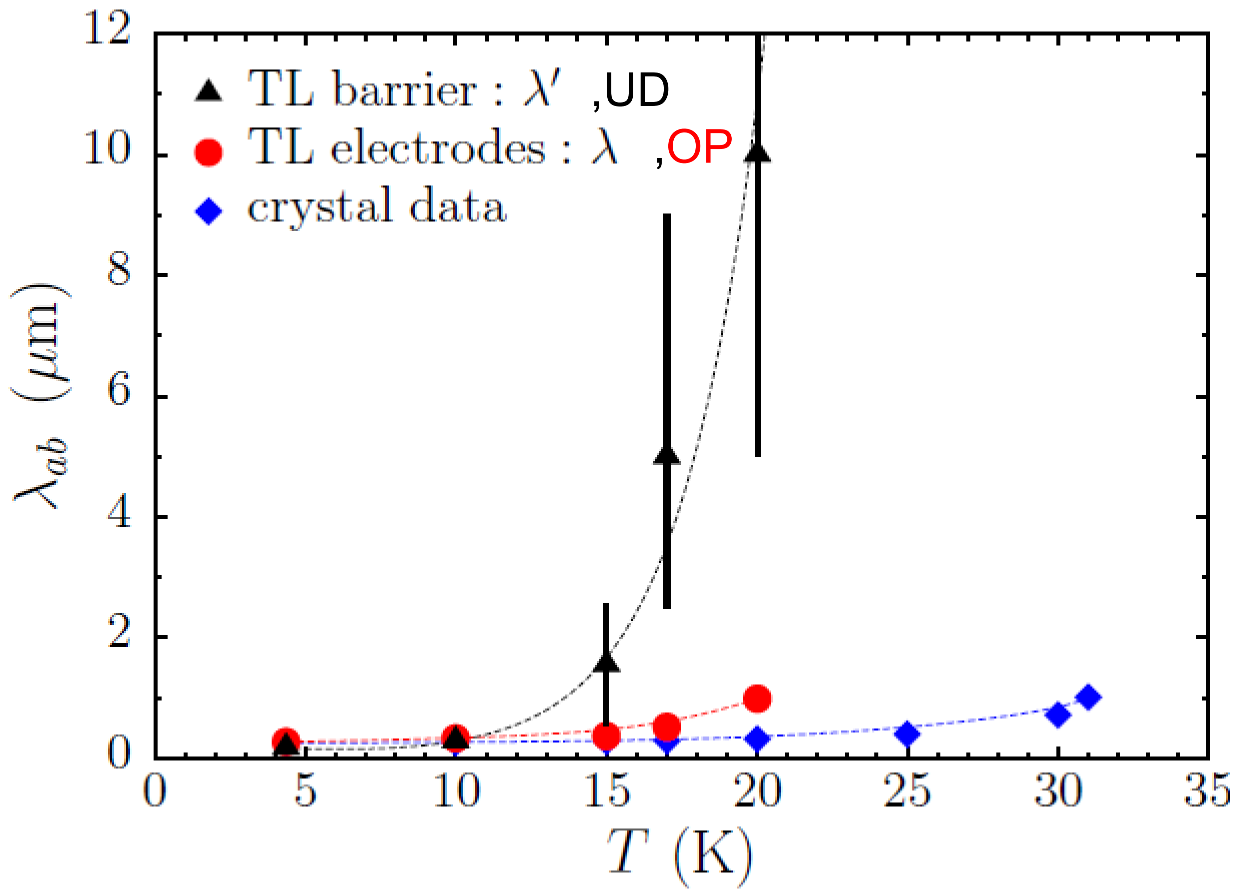
E.M. , B. Wojek A. Suter, T. Prokscha, G. Logvenov, I.Božovic, *Nat. Commun.* 2:272 doi: 10.1038/ncomms1273 (2011).

Diamagnetic shift in UD layer





Superfluid densities



$$\lambda(T) = \sqrt{\frac{m^*}{\mu_0 e^2 n_s(T)}}$$

superfluid density:

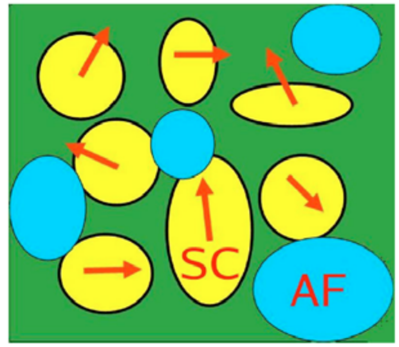
$$\frac{1}{\lambda(T)^2} \propto \frac{n_s(T)}{m^*}$$

The results indicate that up to $T_{eff} >> T_c{}'$ superfluidity with long-range phase coherence is induced in the underdoped layer by the proximity of optimally doped layers; however, this order is very sensitive to thermal excitation and disappears at $T_{eff} < T_c$, $T_{eff} < T^{\nu,M}_{Onset}$

E.M. , B. Wojek A. Suter, T. Prokscha, G. Logvenov, I. Božovic, *Nat. Commun.* 2:272 doi: 10.1038/ncomms1273 (2011).

Models

- Intrinsic inhomogeneity in cuprates → superconducting clusters and Josephson coupling (V. Kresin et al., E. Dagotto et al.)

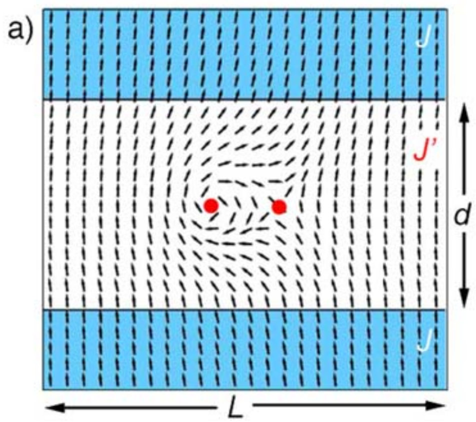


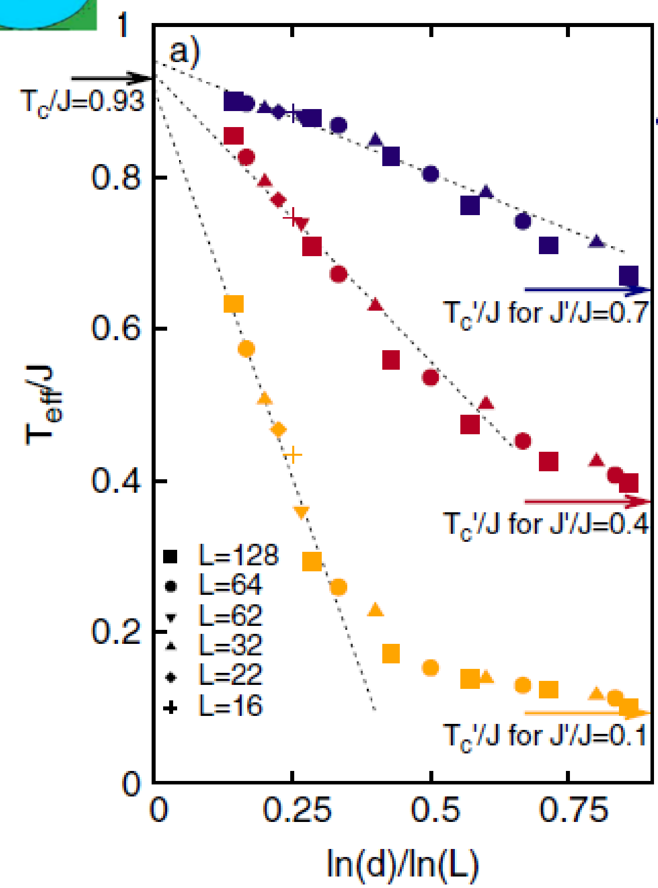
- Quenching of phase fluctuations by phase field (M. Franz et al.)

$$H_{XY} = -\frac{1}{2}\sum_{i,j} J_{i,j}\cos(\varphi_i - \varphi_j)$$

$$T_c = cJ$$

$$T'_c = cJ'$$





D. Marchand, L. Covaci, M. Berciu and M. Franz, Phys. Rev. Lett. **101**, 097004 (2008)

- Extension of conventional proximity theory including Andreev reflections (X-Z Yan, C.S. Ting)

- …..