ELECTROSTATIC MODULATION OF THE SUPERFLUID DENSITY OF ULTRATHIN SUPERCONDUCTING $La_{2-x}Sr_xCuO_4$ FILMS

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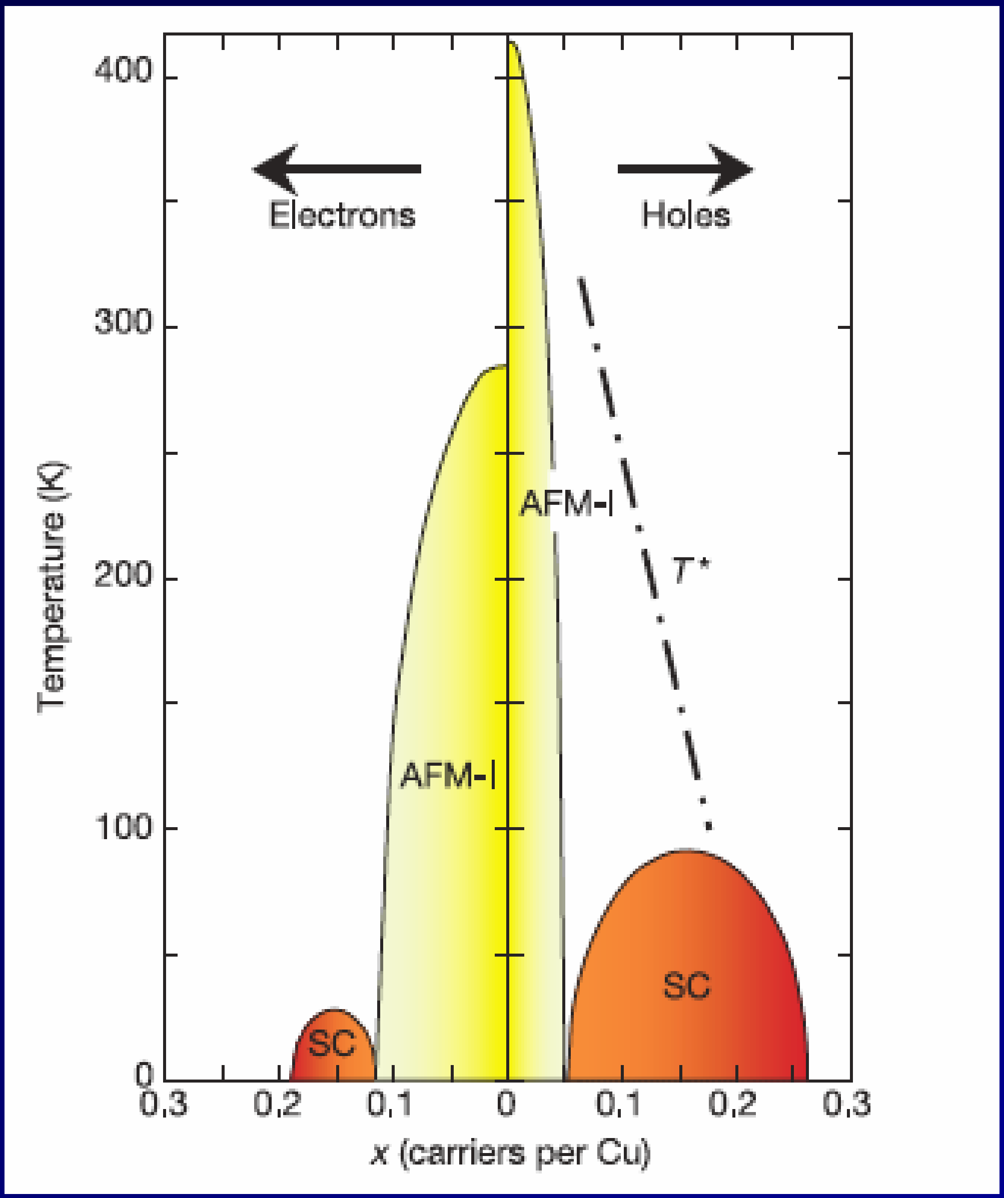
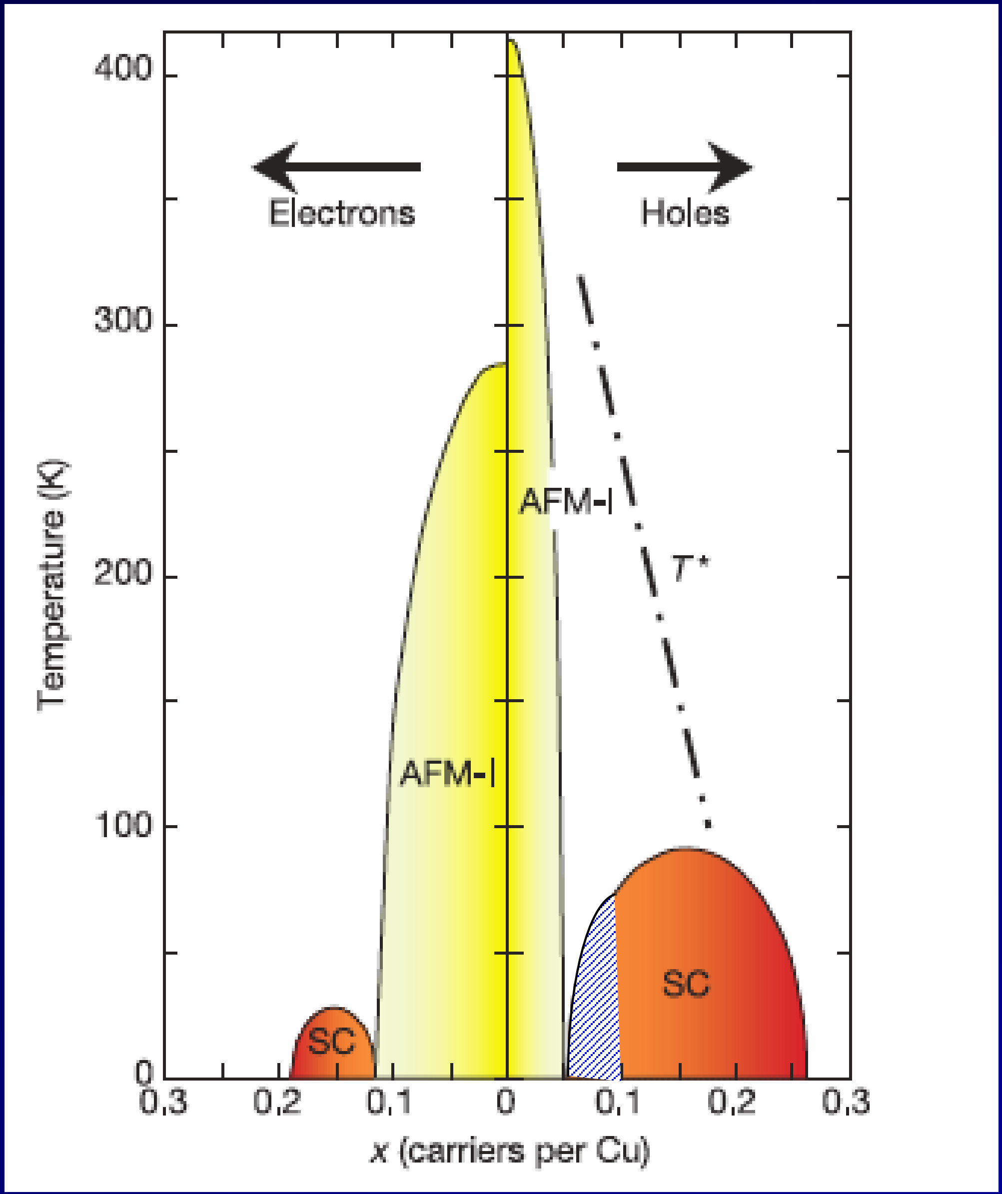
Generic Phase Diagram of High-T_c Superconductors



C.H. Ahn *et al.*, Nature (2003)

Generic Phase Diagram of High-T_c Superconductors



C.H. Ahn *et al.*, Nature (2003)

Underdoped regime
(doped Mott insulator) :

$T_c \propto n_s(T=0)$

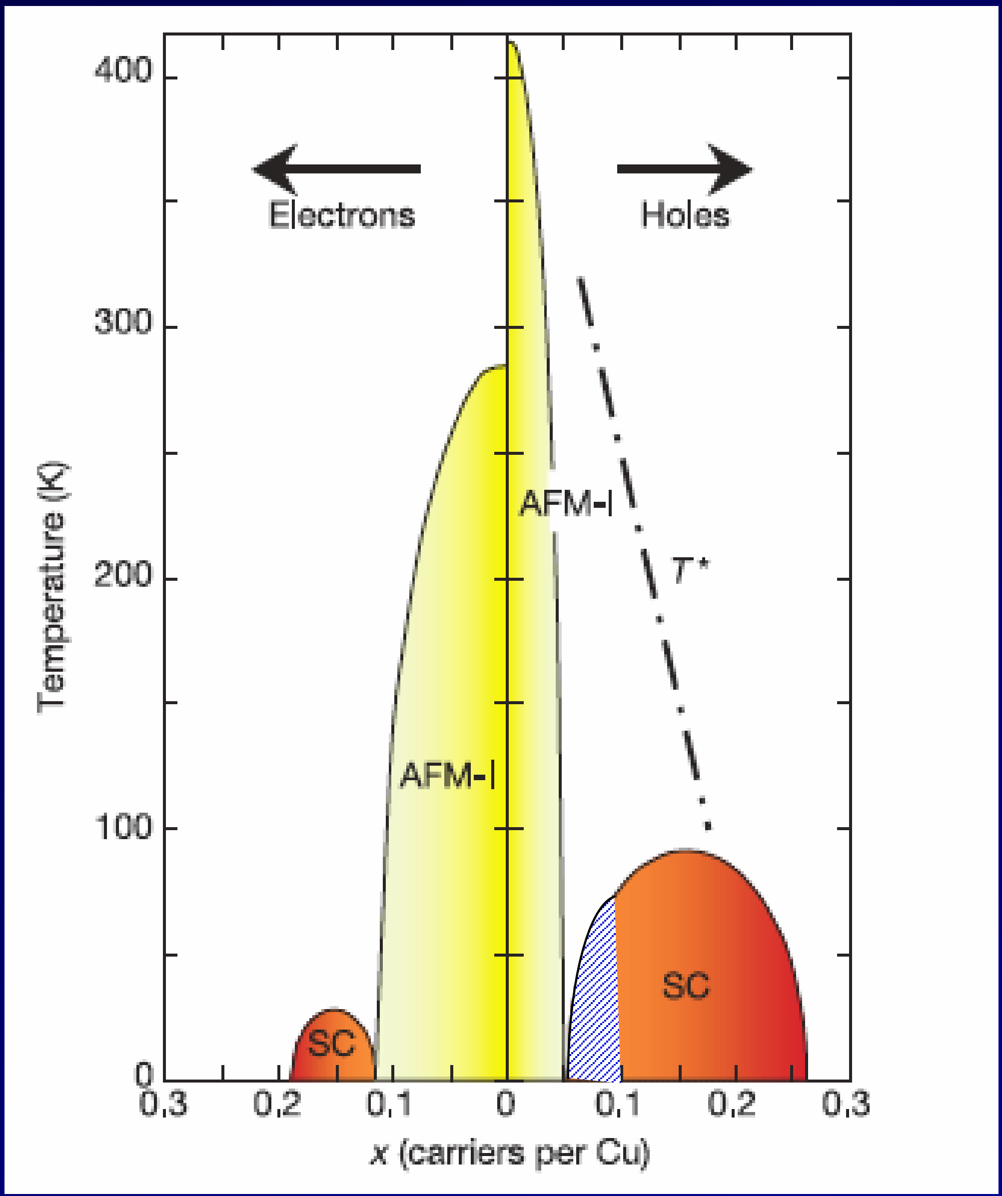
« Uemura relation »
[Y. Uemura *et al.*, PRL (89)]

Changing n_s by « chemical » doping implies sample-to-sample varying disorder, thereby complicating the interpretation of the data

$\Downarrow$

Electrostatic modulation

Generic Phase Diagram of High-T_c Superconductors



C.H. Ahn *et al.*, Nature (2003)

Underdoped regime (doped Mott insulator) :

$$T_c \propto n_s(T=0)$$

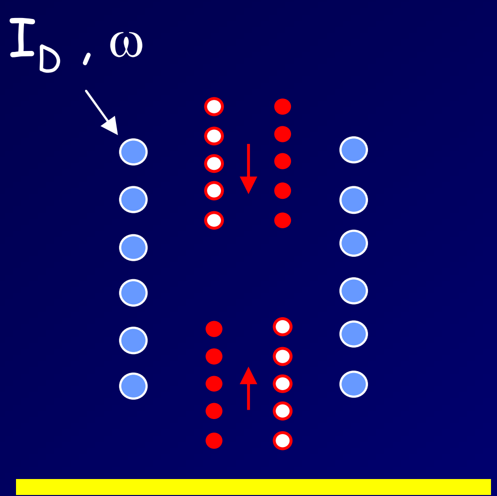
« Uemura relation »
[Y. Uemura *et al.*, PRL (89)]

Connection to experiment (thin films, thickness d) :

$$L_k^{-1} = e^2 n_s d/m^* \propto \lambda_{ab}^{-2}$$

L_k : kinetic inductance

Complex sheet impedance measurements



Sample

Drive (D)-receive (R) two-coil
SQUID-based technique

B. Jeanneret *et al.* , APL (1989)

$\Delta L \sim 1\text{pH}$, $0.1\ \text{Hz} < \omega < 10^5\ \text{Hz}$

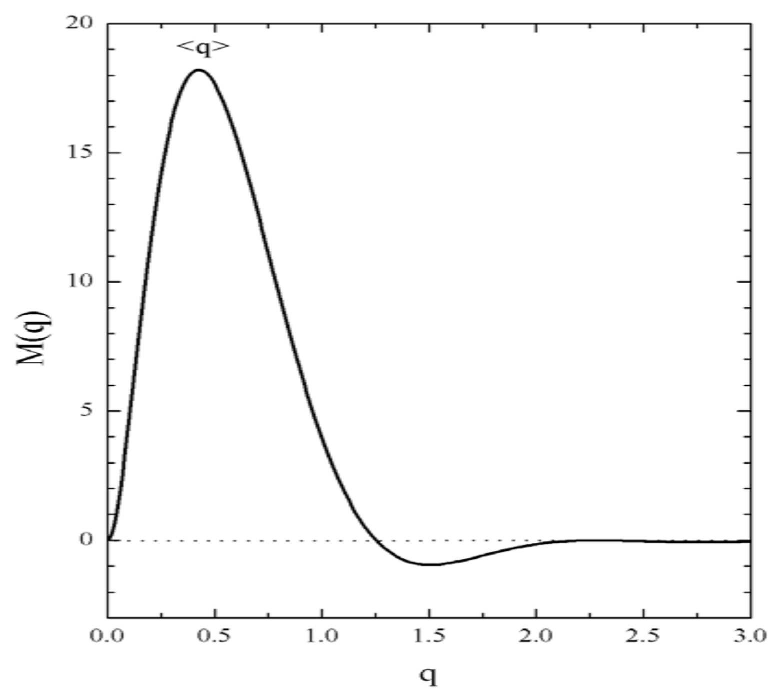
$$\delta M \propto \int_0^\infty \{1+[Z/i\omega m]q\}^{-1} M(q)\,dq$$

$$Z = R + i\omega L_k$$

$$L_k^{-1} = e^2 n_{s\square}/m^*$$

$n_{s\square} = n_s d$: 2D superfluid density

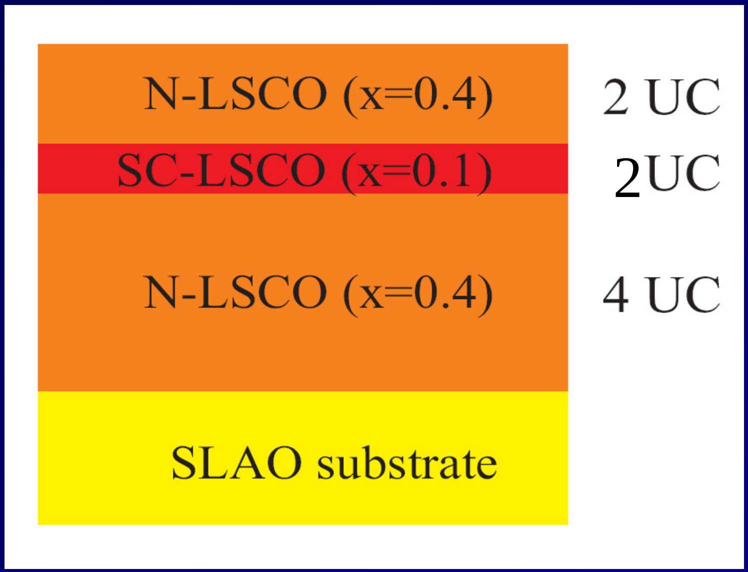
R : dissipation $\Rightarrow$ vortices

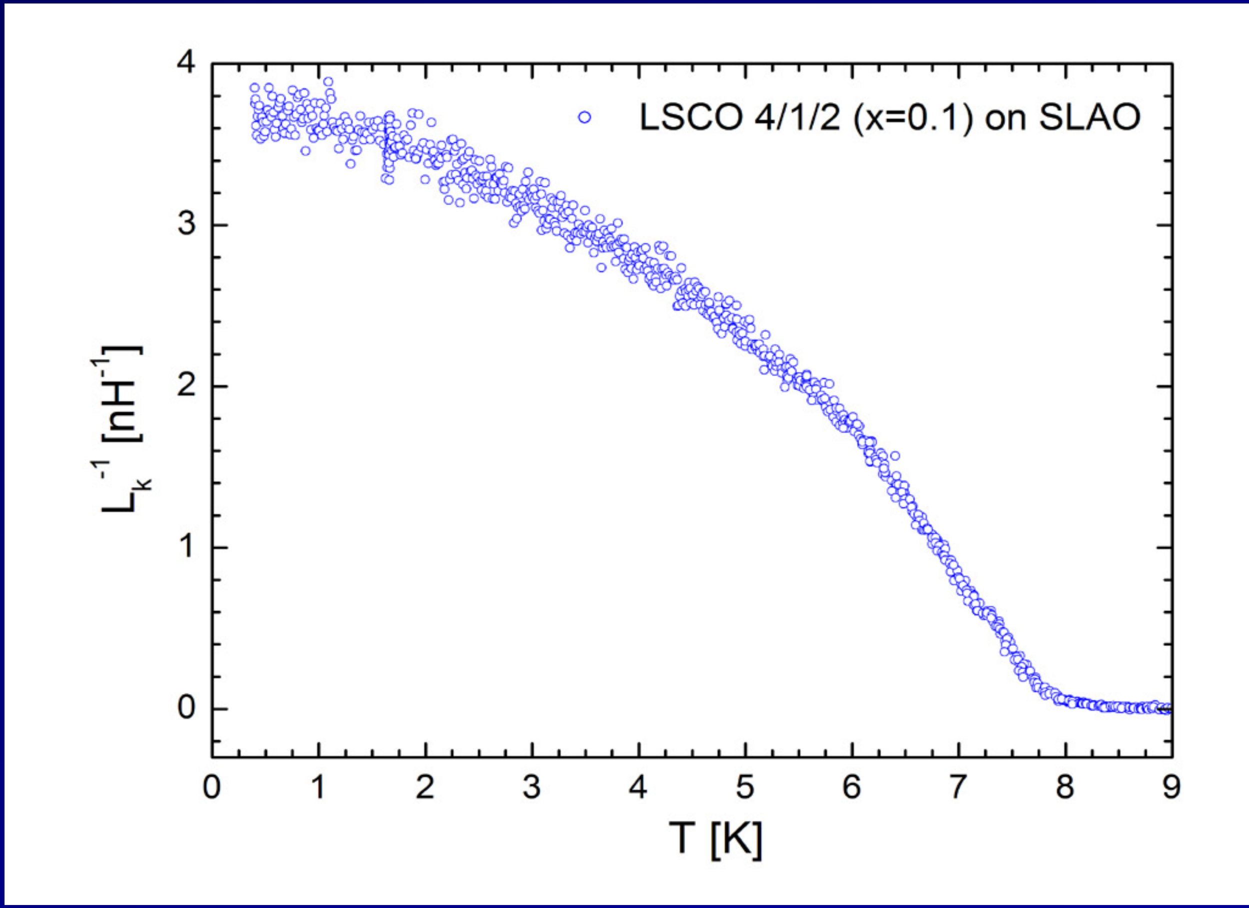


Growth of ultrathin LSCO films - Kinetic inductance $L_k^{-1}(T)$

MBE buffer method

A. Rüfenacht *et al.*, Solid-State Electronics 47, 2167 (2003)

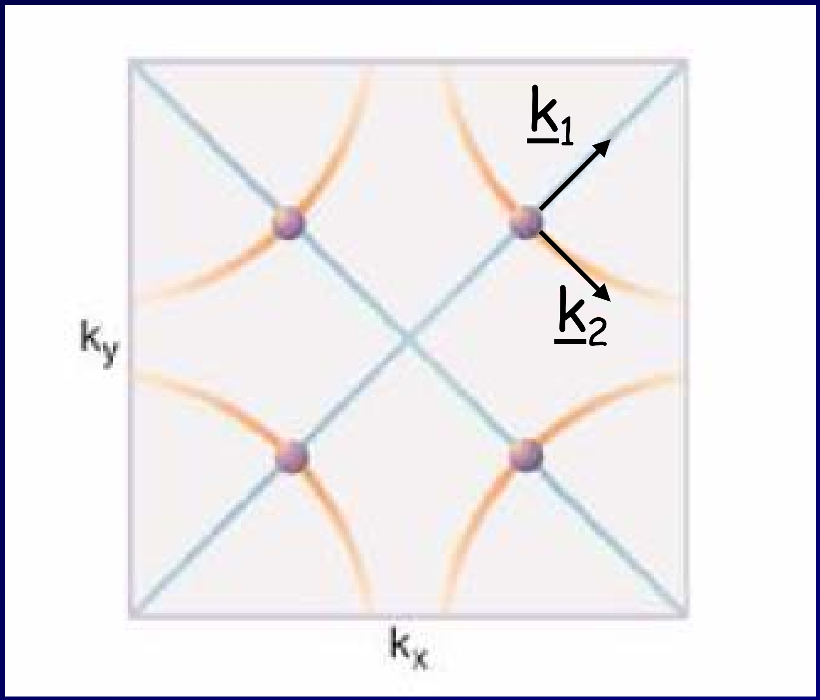




J.P. Locquet *et al.*, Nature (98)

From $L_k(0) = \mu_0\lambda_{ab}^2(0)/d$: $\lambda_{ab}(0) = 535$ nm

Superconductor with d_{x2-y2} pairing symmetry



P.A. Lee, Science (1997)

QP excitation energy :

$$E(\underline{k}) = \hbar[(k_1 v_F)^2 + [(k_2 v_\Delta)^2]^{1/2}$$

$$v_\Delta = a\Delta_0/\hbar\sqrt{2}$$

QP density of states

[A.C. Durst and P.A. Lee, PRB (2000)]

Pure superconductor :

$$N(\varepsilon) = |\varepsilon|/\pi\hbar^2 v_F v_\Delta$$

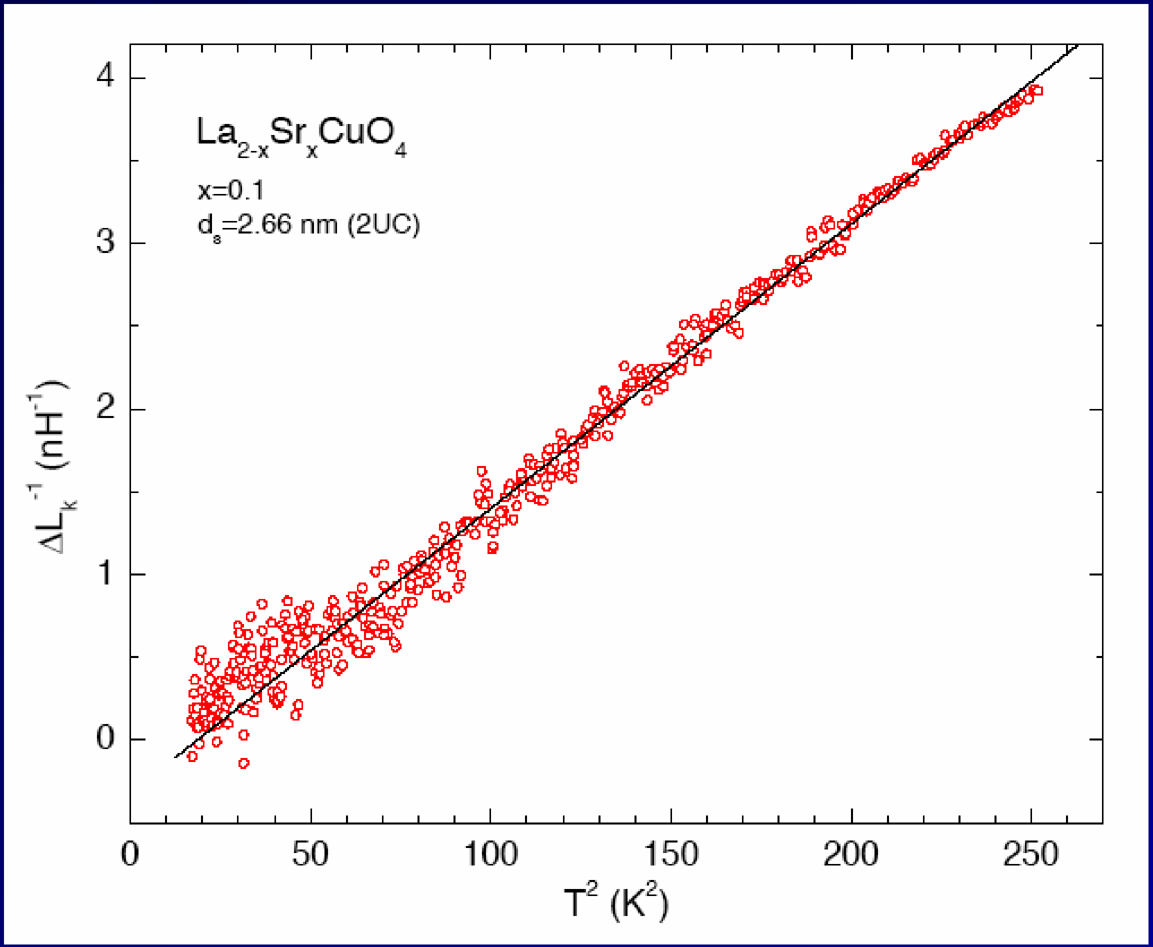
Superconductor with impurities :

$$N(0) = [4(\hbar/\tau)/\pi\hbar^2 v_F v_\Delta]\ln[E_0/(2\pi\hbar/\tau)]$$

τ : QP lifetime , $E_0 = (2E_F\Delta_0)^{1/2}$

Low-temperature ($T \ll T_c$) inverse kinetic inductance change

$$\Delta L_k^{-1} \equiv L_k^{-1}(0) - L_k^{-1}(T)$$



SC with nodal points in the order parameter (*d-wave*) and with impurities :

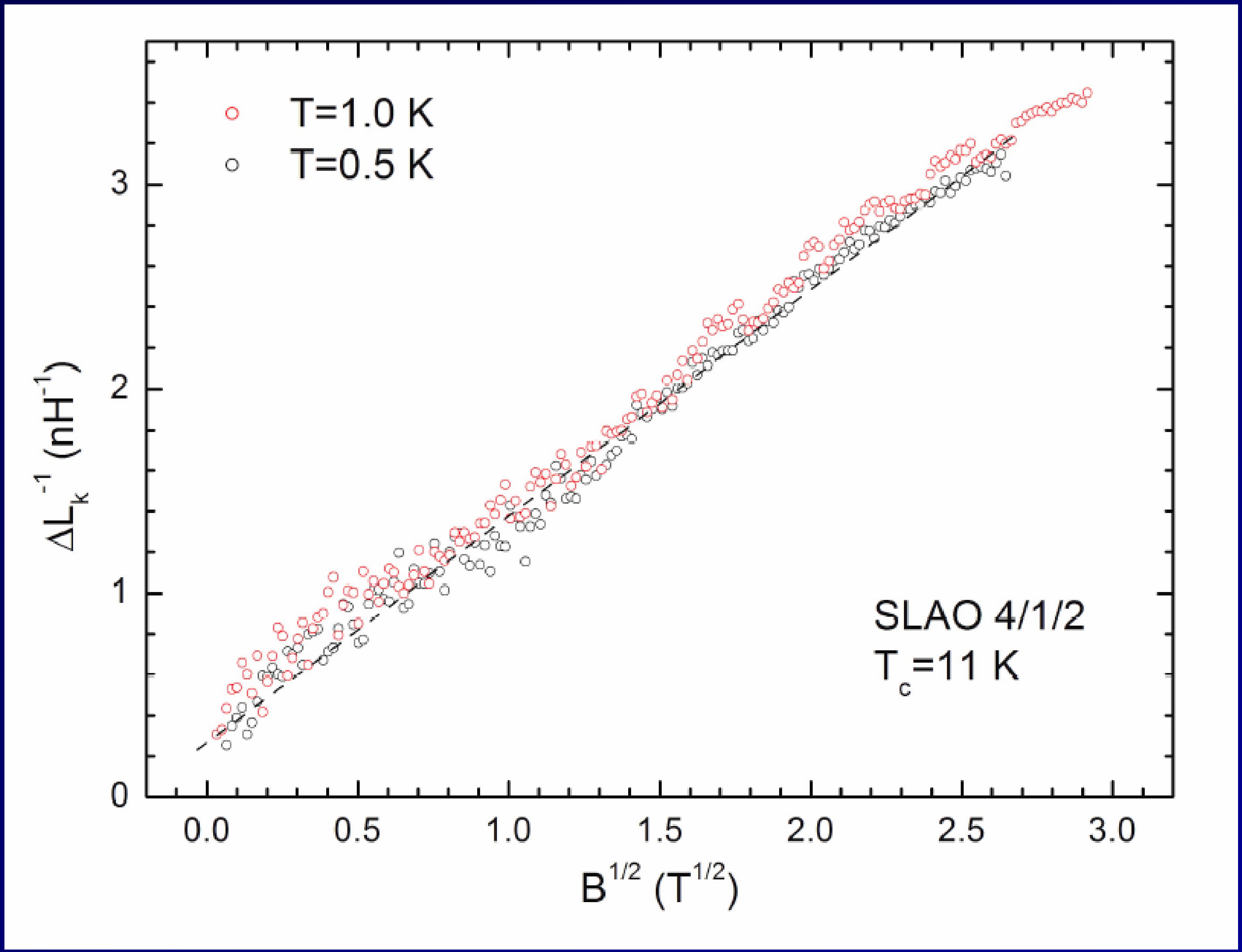
[S.G. Sharapov *et al.*, PRB (2002)]

$$\Delta L_k^{-1}(T) \propto T^2$$

«Pure» SC : $\Delta L_k^{-1}(T) \propto T$

[W.N. Hardy *et al.*, PRL (1993)]

Low-temperature magnetic-field dependence of $\Delta L_k^{-1} \equiv L_k^{-1}(0) - L_k^{-1}(B)$



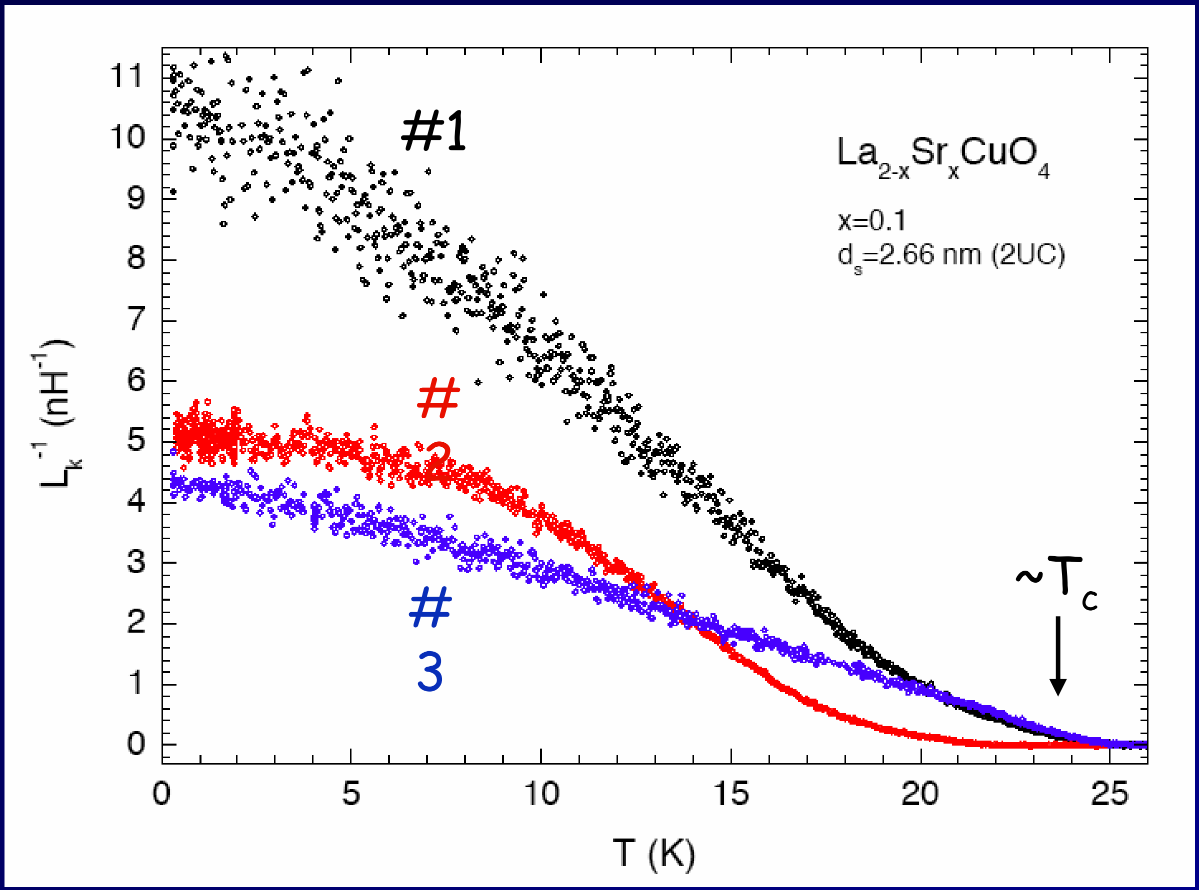
For « nodal » order parameter at T « Tc :

[G.E. Volovik, JETP Lett. (93); S.G. Sharapov *et al.*, PRB (02)]

$\Delta L_k^{-1}(B) \propto B^{1/2}$

For *s*-wave SC : $\Delta L_k^{-1}(B) \propto B$

Effect of disorder on the superfluid response $L_k^{-1} = e^2 n_{s\square}/m^*$



LSCO films with the same thickness (d_s = 2 UC) and the same doping (x = 0.1):

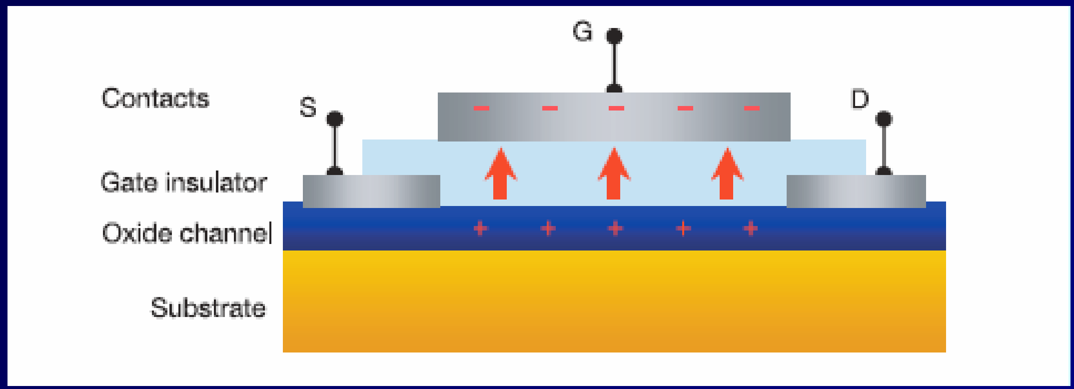
1. Have approximately the same T_c

2. But differ substantially in $L_k^{-1}(0)$

M. Franz *et al.*, PRB (97)

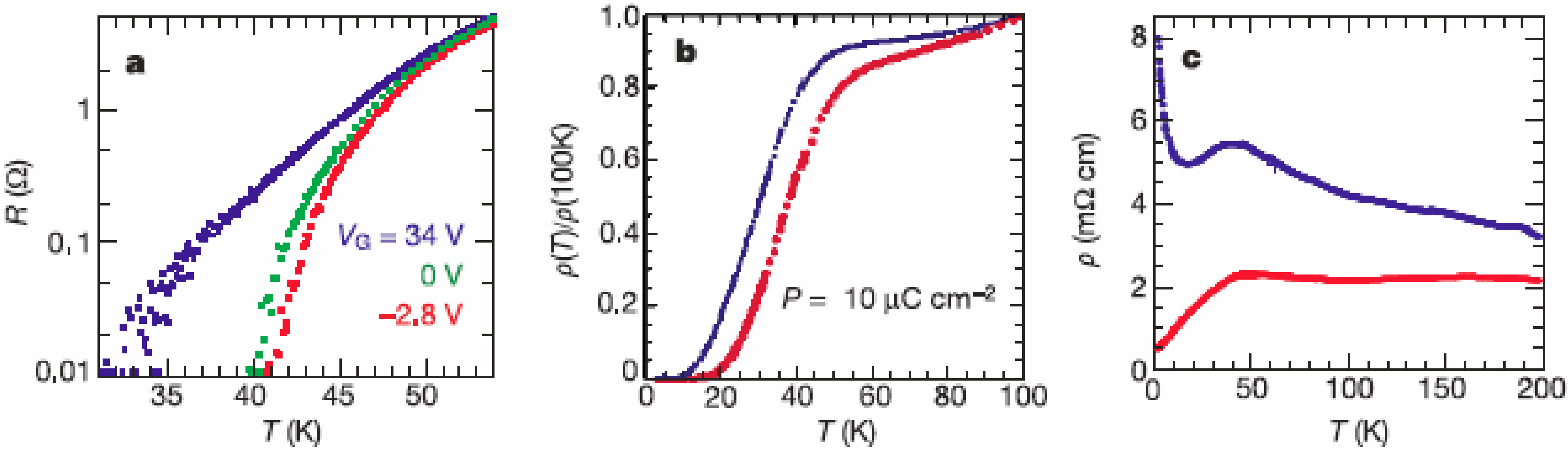
	# 1	# 2	# 3
$\tau^{-1} \times 10^{-11} [s^{-1}]$	2.0	4.1	6.0
v_F/v_Δ	37	32	25

Previous work on electrostatic modulation



Dielectric gate

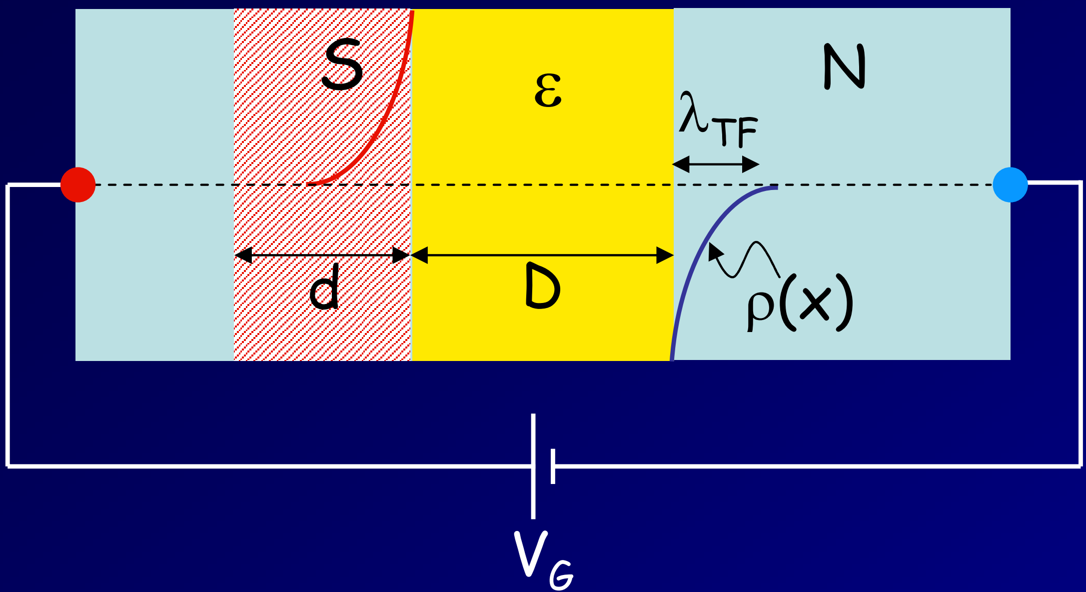
Ferroelectric (PZT) gate



J. Mannhart, Supercond. Sci. Technol. (1996)

C.H. Ahn *et al.*, Science (1999)

Electrostatic modulation of $L_k^{-1} = e^2 n_{s\square}/m^*$



$$\Delta L_k^{-1}/L_k^{-1} = \Delta Q_s/Q_s$$

$$= (CV_G/en_{s\square})[1 - \exp(-d/\lambda_{TF})]$$

$$C^{-1} = C_\varepsilon^{-1} + C_{TF}^{-1} = (D/\varepsilon\varepsilon_0) + (\lambda_{TF}/\varepsilon_0)$$

$$\lambda_{TF} = (\hbar/e)[\pi\varepsilon_s\varepsilon_0 d/m]^{1/2} \approx 0.5 \text{ nm}$$

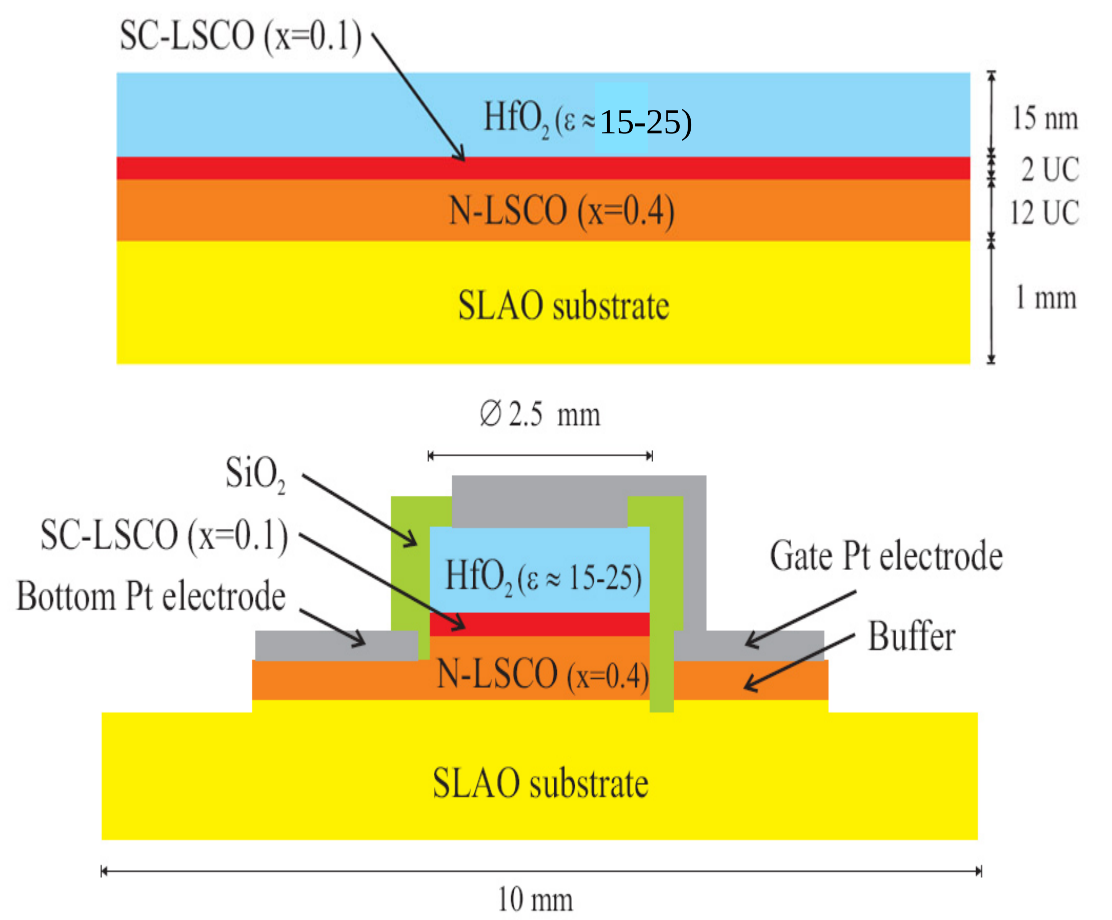
[H. Beck and D. Ariosa (95)]

Limiting cases (for $D/\varepsilon\lambda_{TF} \gg 1$, $E \equiv V_G/D$) :

$d \ll \lambda_{TF} \;\Rightarrow\; \Delta L_k^{-1}/L_k^{-1} = \varepsilon\varepsilon_0 E/en_s\lambda_{TF}$ (max. modulation for $E = E_B$)

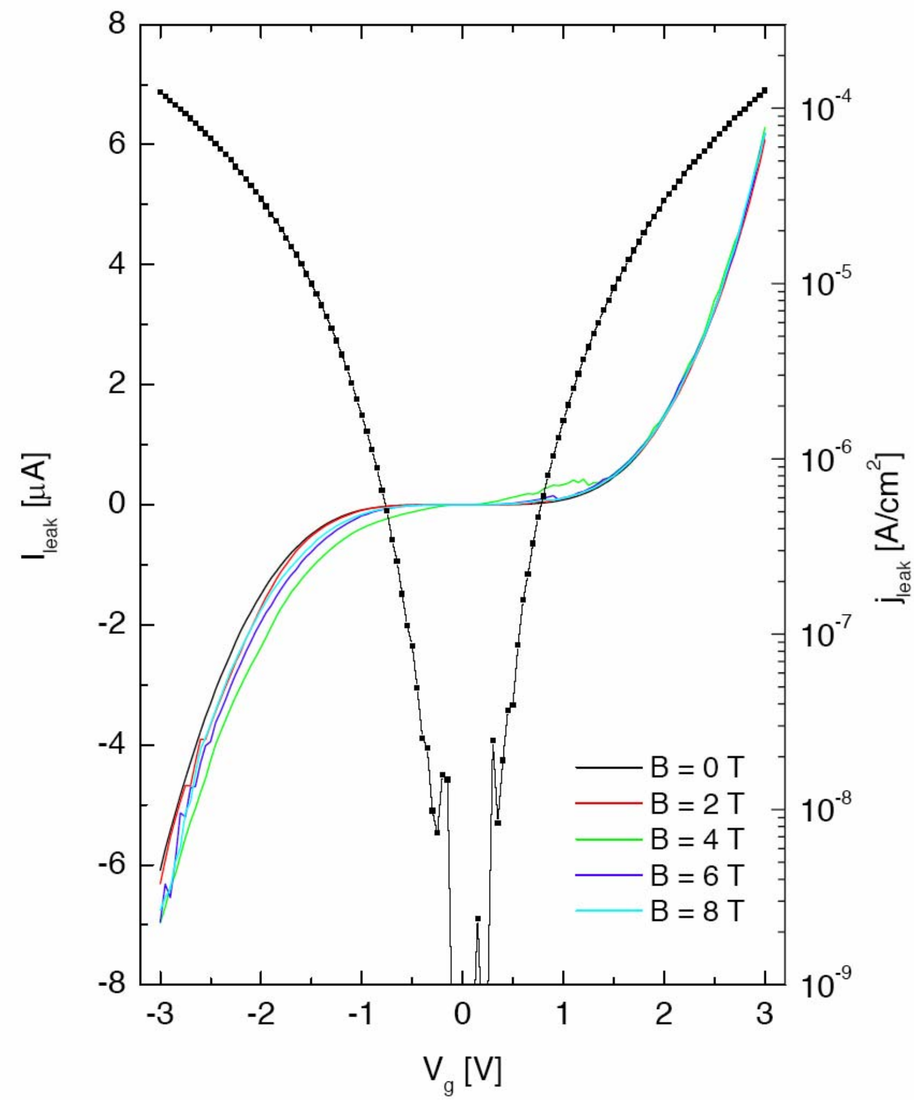
$d \gg \lambda_{TF} \;\Rightarrow\; \Delta L_k^{-1}/L_k^{-1} = \varepsilon\varepsilon_0 E/en_s d \;\Rightarrow\;$ Ultrathin Films : $d \gtrsim \lambda_{TF}$

Fabrication of electric-field-effect heterostructures



d = 2.66 nm (2UC)

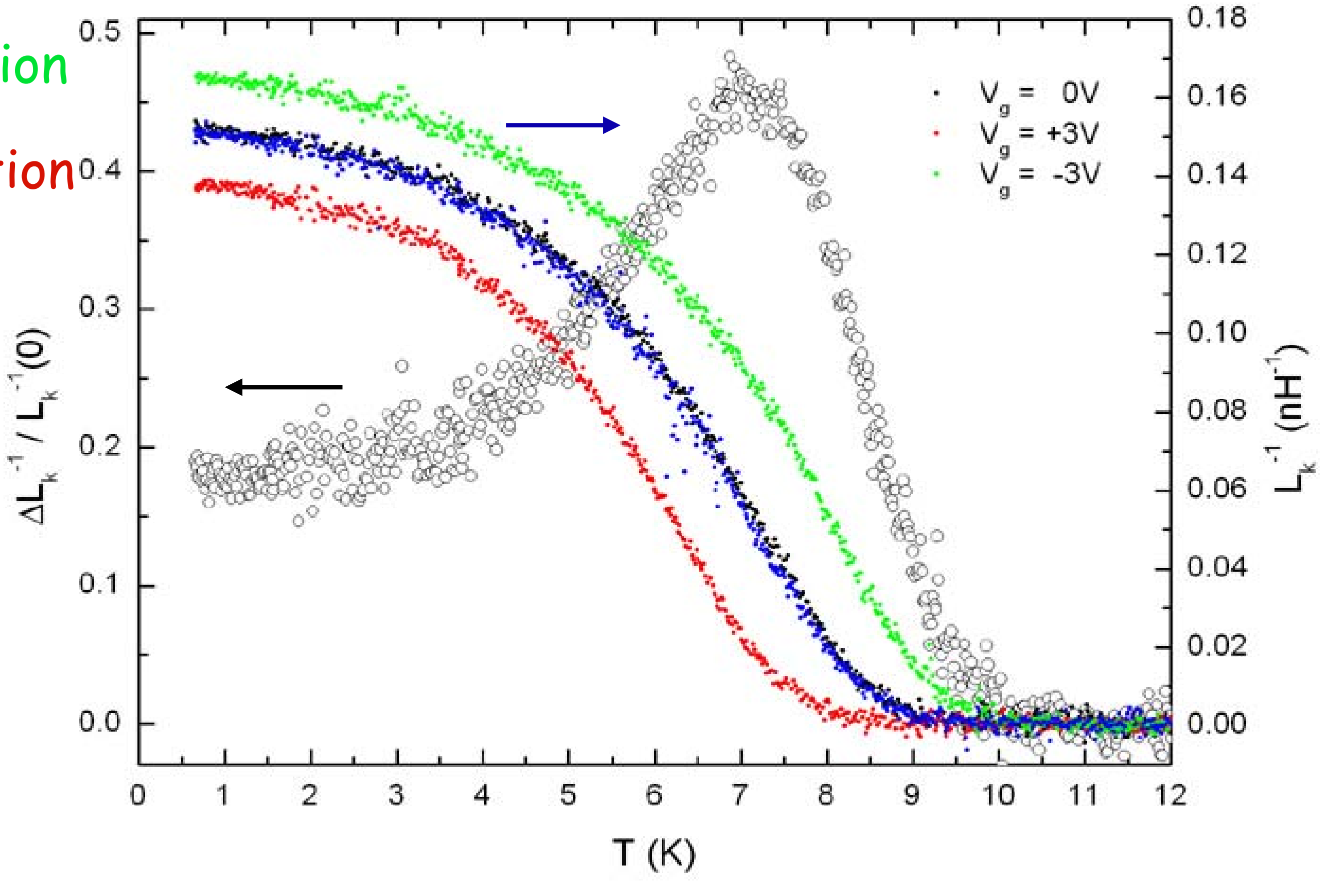
Leakage current vs V_G



Absolute and relative electrostatic modulation of $L_k^{-1}(T)$

hole injection

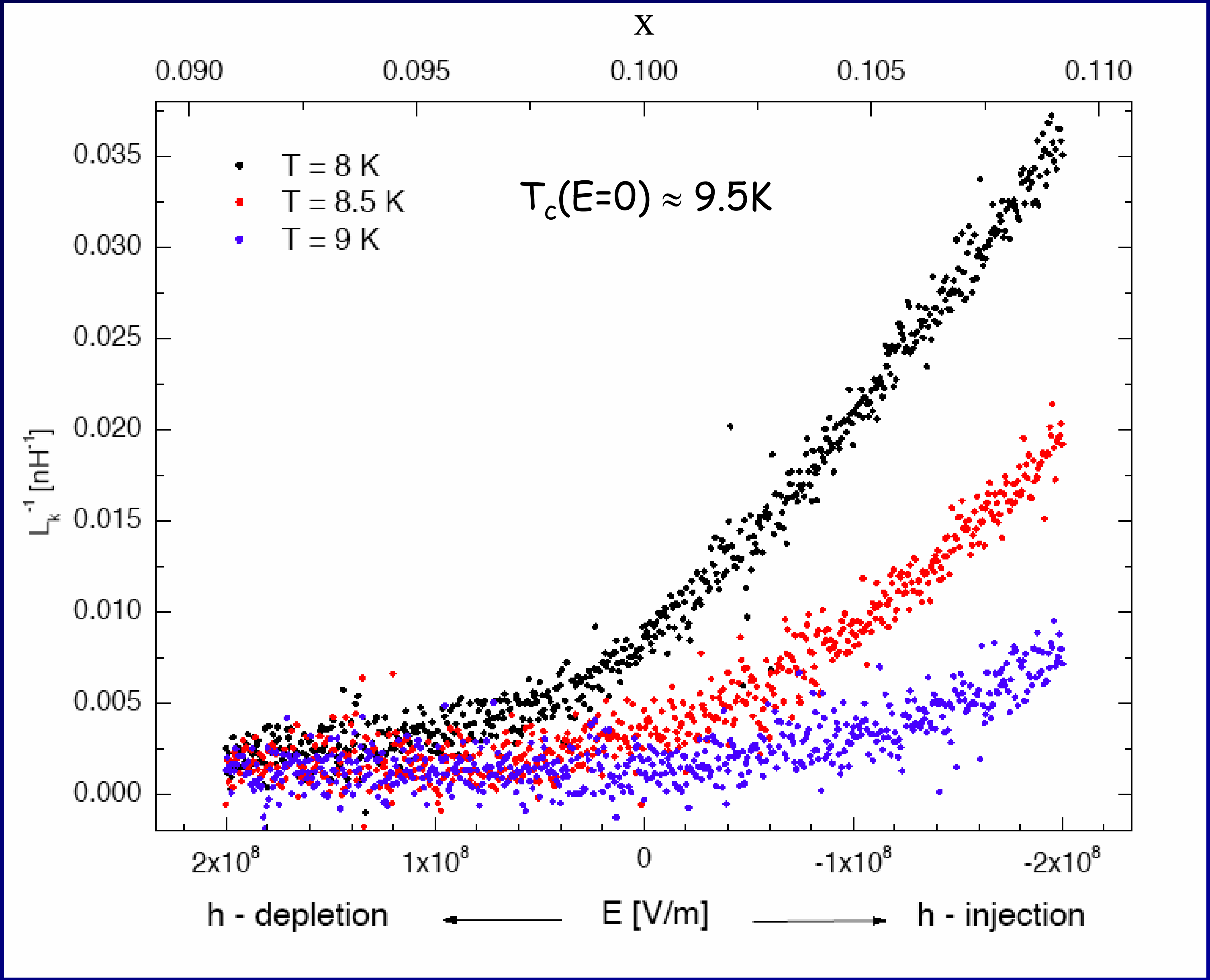
hole depletion



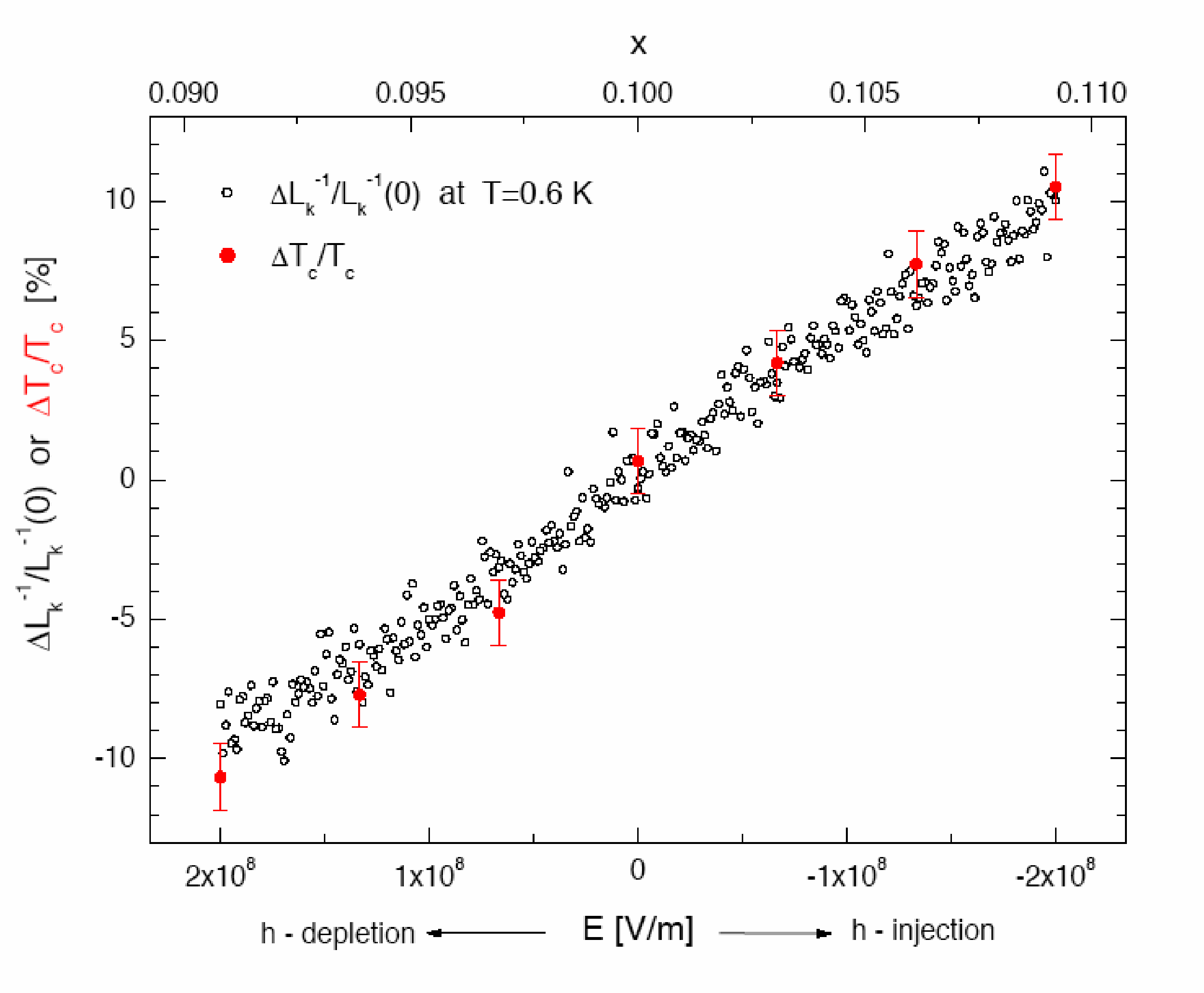
At T = 0: $\Delta L_k^{-1}/L_k^{-1}(0) \approx \pm 9\%$ for $E = V_g/D \approx \pm 2 \times 10^8$ V/m

A.T. Fiory *et al.*, PRL (90) : $\Delta L_k^{-1}/L_k^{-1}(0) \approx 10^{-5}$; A.T. Findikoglu *et al.*, APL (93)

Electric-field-induced superconductivity : $L_k^{-1}(E)$ isotherms near T_c



Comparison of $\Delta T_c(E)/T_c(0)$ and $\Delta L_k^{-1}(E)/L_k^{-1}(0)$ for $T \rightarrow 0$



Unambiguous evidence for the « Uemura relation » :

$$L_k^{-1}(T=0) \propto T_c$$

In the underdoped regime (if $\Delta n_s/n_s = \Delta n_h/n_h$) :

$$\Delta L_k^{-1}/L_k^{-1}(T=0) = \varepsilon\varepsilon_0 E/en_h d$$

n_h = # of free holes

$x \approx 0.1 \Leftrightarrow n_h \approx 1.05 \times 10^{21}\ cm^{-3}$

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$\varepsilon \approx 23$

J. Robertson, Eur. Phys. J. Appl. Phys. (2004) :

$\varepsilon \approx 25$ for HfO_2

Temperature dependence of $\Delta L_k^{-1}/L_k^{-1}(0)$

Model for the underdoped regime based on :

1. The « Uemura » relation (T = 0)

$$L_k^{-1}[T=0,\ T_c(E)] \propto T_c(E)$$

2. Factorization of temperature dependence

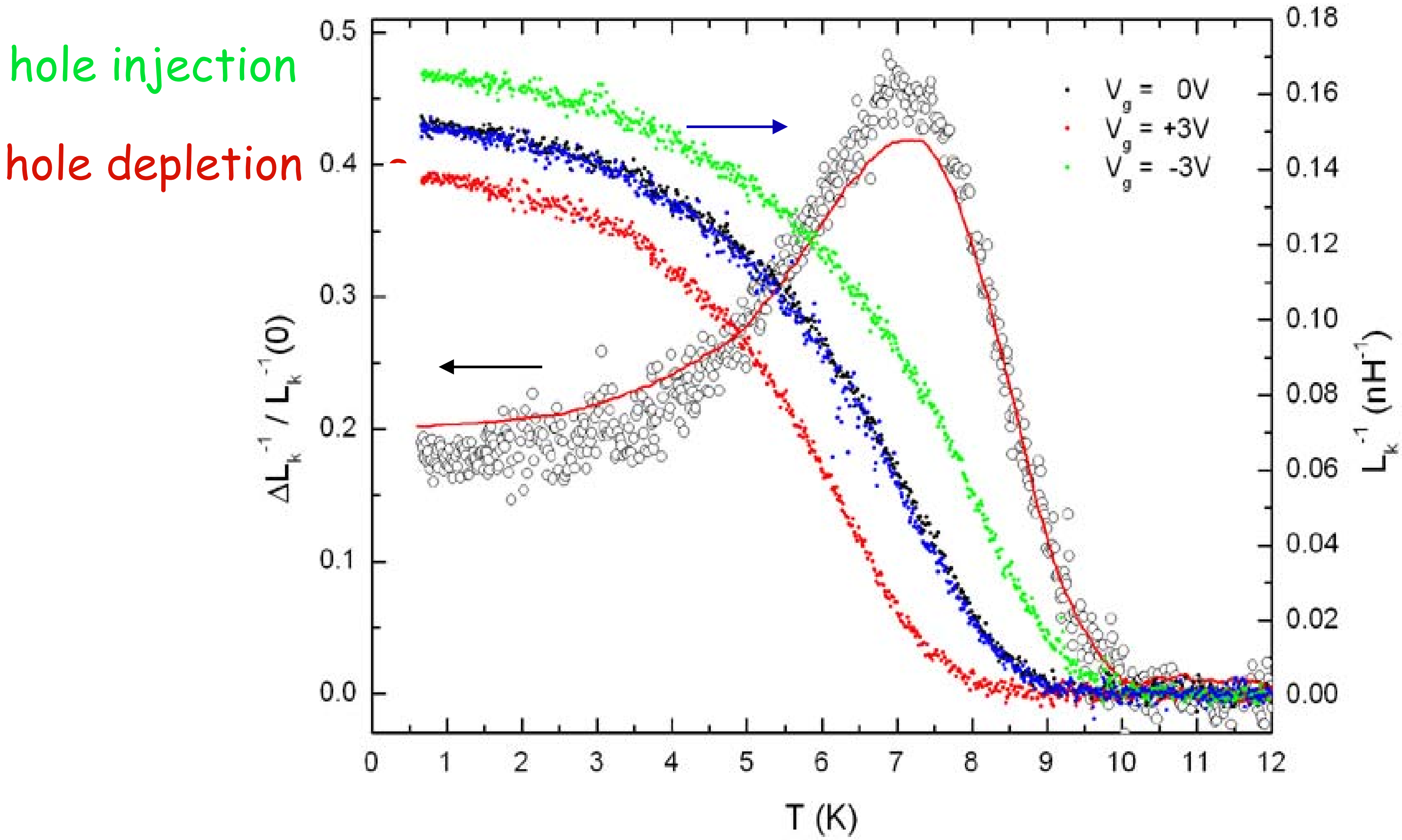
$$L_k^{-1}[T,\ T_c(E)\ ] = L_k^{-1}[0,\ T_c(E)]\ f[T/T_c(E)]$$

Then :

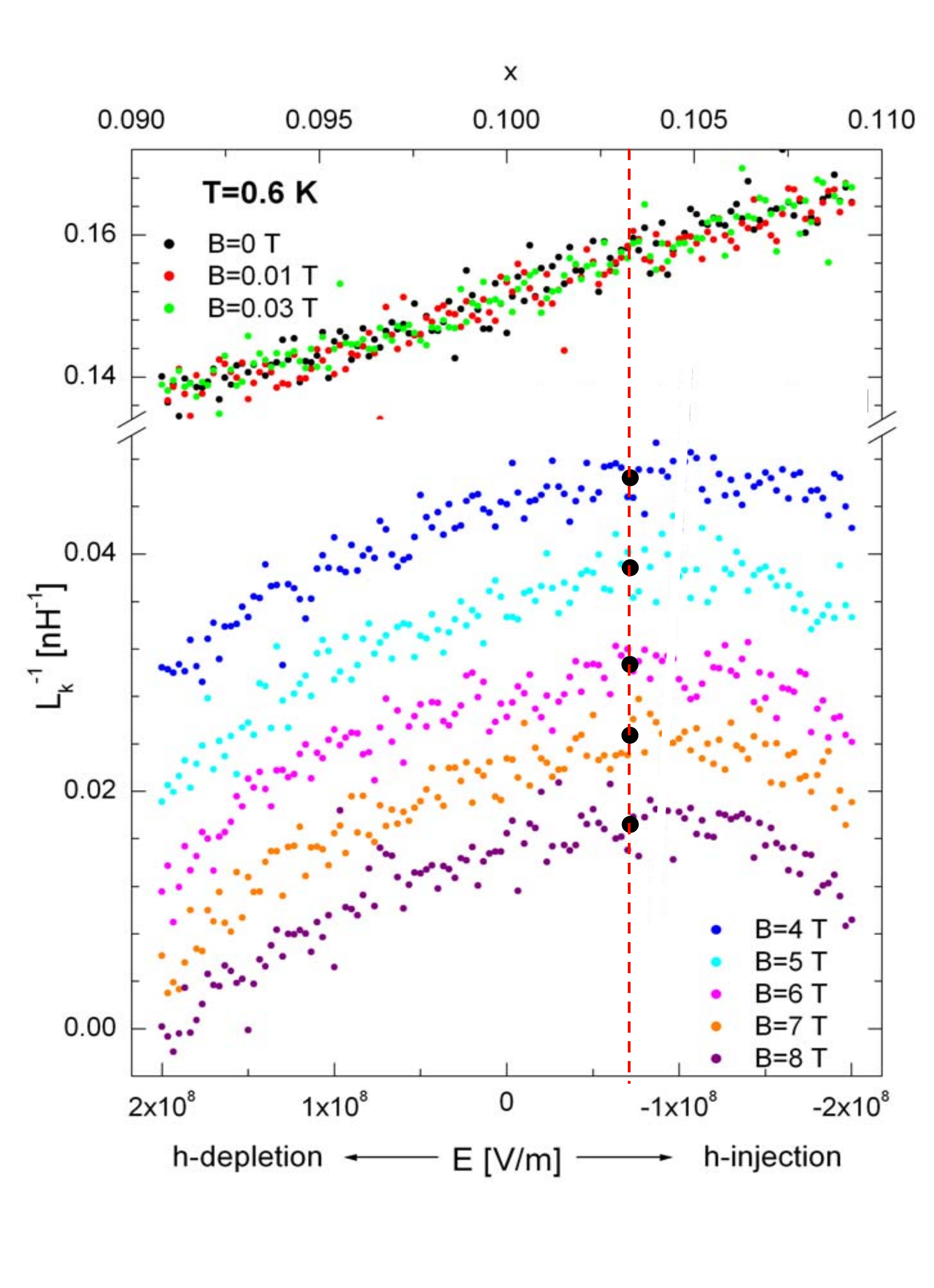
$$\Delta L_k^{-1}(T,\ E)/L_k^{-1}(0) = [f(T/T_c) - T(df/dT)]_{E=0}\Delta T_c(E)/T_c(0)$$

No adjustable parameters !

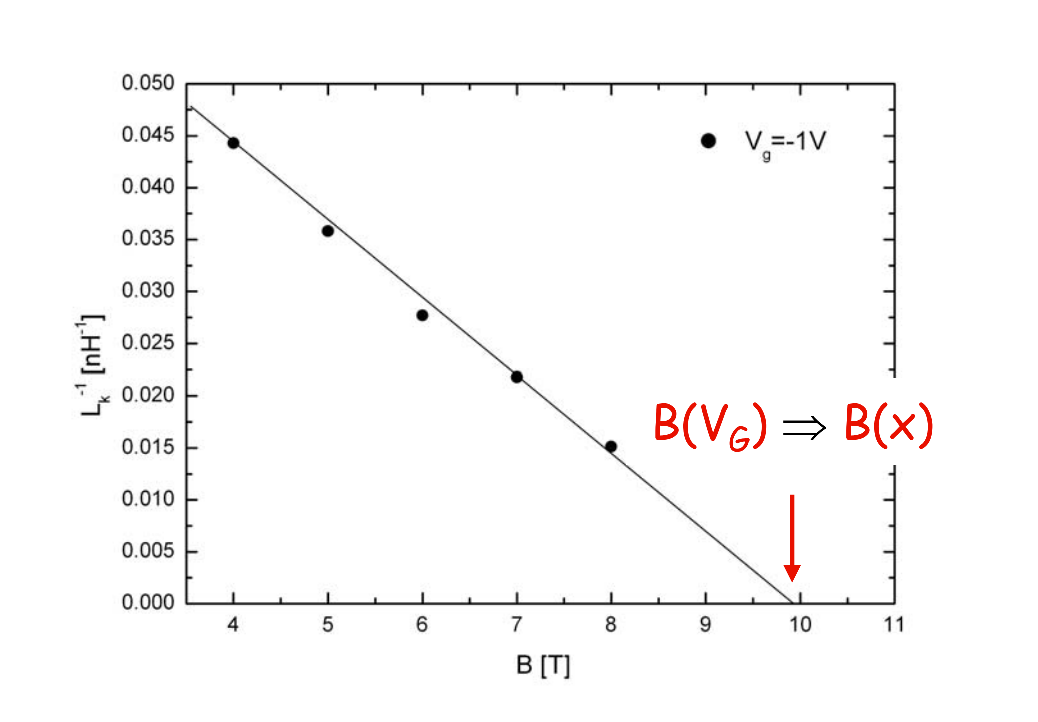
Relative electrostatic modulation $\Delta L_k^{-1}(T)/L_k^{-1}(0)$: Comparison with model calculation



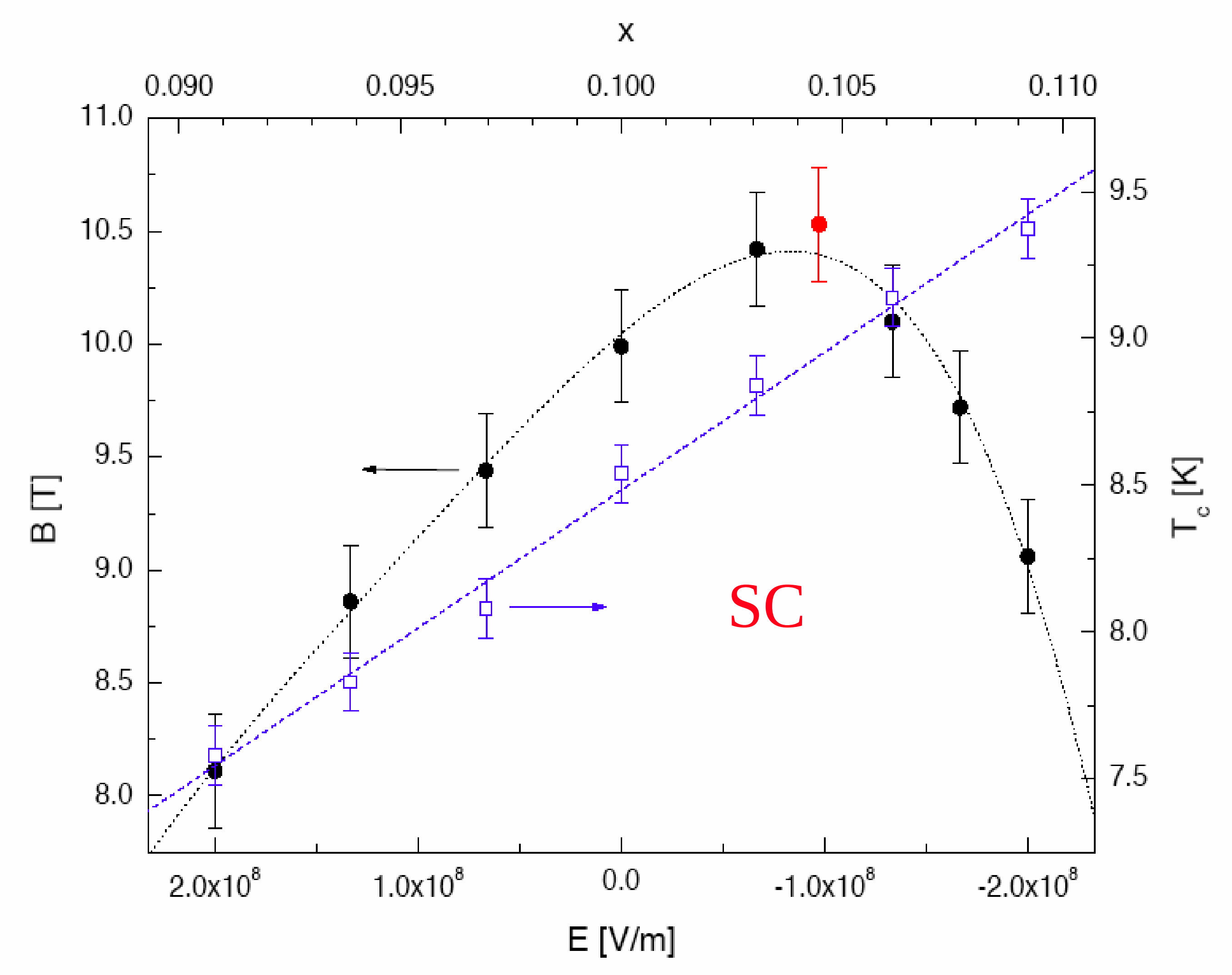
Low-temperature electrostatic modulation of L_k^{-1} in a magnetic field



Regime crossover (reentrant behavior) at high magnetic fields



Phase Diagrams : B(T = 0) and T_c vs carrier concentration x



Why maximum below the B=0 optimum doping (x=0.16) ?

- 1/8-anomaly in LSCO [T_c depression at x = 0.125] ?
- B-induced shift of optimun doping to lower x ?
- B-dependence of ε ?

Free carrier effective mass m^*

$$m^*/m_e = (e/m_e)\varepsilon\varepsilon_0(\Delta V_G/D)L_{kL}(0)[\Delta L_k^{-1}/L_k^{-1}(0)]^{-1}$$

$L_{kL}(0) \equiv \mu_0\lambda_{ab}^2(0)/d = 43.7$ pH   using (bulk) $\lambda_{ab}(0) = 304$ nm

[A.J. Zaleski and J. Klamut, J. Phys.: Cond. Matt. 11, 9371 (1999)]

$\varepsilon \approx 23$ $\Delta L_k^{-1}/L_k^{-1}(0) \approx 9\%$ (for $\Delta V_G/D = 2 \times 10^8$ V/m)

$$m^*/m_e \approx 3.5$$

CONCLUSIONS AND OUTLOOK

1. Observation of the first large (~10%) electrostatic modulation of the (areal) superfluid density (magnetic penetration depth) in ultrathin films of cuprate superconductors (LSCO).

2. Compelling evidence for the validity of the « Uemura relation » [$T_c \propto \lambda_{ab}^{-2}(0)$] in the underdoped regime.

3. Observation of an intriguing regime crossover at high B-fields.

Outlook :

SC-Insulator (quantum) phase transition in the extreme underdoped regime, overdoped regime, magnetic field effects, …