NanoEngineering of Oxide Heterostructures: The *Field Effect* & Interface Superconductivity

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The Field Effect and (Interface) Superconductivity in High-T_c and Related Films

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* in collaboration with Guy Dubuis (EPFL & BNL) & Ivan Bozovic et al. (BNL-USA)

Abstract

In the past decade we have systematically probed low energy electronic structure and measured properties of high-T_c films under different degree of epitaxial (*compressive vs tensile*) strain [1-5]. In overdoped in-plane compressed LSCO-214 films we doubled T_c, from 20K to 40K, yet Fermi surface (FS) remained essentially two-dimensional (2D) [1]. In contrast, *tensile* strained films exhibit 3D dispersion; T_c is drastically reduced [2]. It seems that the in-plane compressive strain pushes the apical oxygen away from the CuO_2 plane [1-3], enhances the 2D character of the dispersion and enhances T_c, while the tensile strain seems to act in the opposite direction and the resulting dispersion is 3D [2-5]. Evidently, such studies are directly relevant for the mechanism of high-T_c, as we have also obtained the FS topology for both cases. As the actual lattice of cuprates consists of rigid CuO_2 planes that alternate with softer 'reservoir' (that strains distort differently), our results tend to rule out 2D rigid lattice mean field models [3]. We have also mapped the 3D FS topology from the observed wavevector quantization in cuprate films thinner than 18 units cells [5]. Moreover, we have successfully grown doped Bi-2201 thin films and performed XRD, transport and preliminary in-situ ARPES studies [6]. In collaboration with Ivan Bozovic and his colleagues at BNL, we have studied the field effect in new heteroepitaxial cuprate SuFET structures. Very large fields and induced changes in surface carrier density enable large shifts in the critical temperature (T_c). We were able to substantially vary T_c with the field and observed striking superconductor-insulator quantum phase transition in $La_{2-x}Sr_xCuO_4$ films that poses profound challenge to contemporary theory [7]. We briefly cricitally discuss the significance of our results in the light of the emerging understanding of High-T_c and related phenomena.

References

1. M. Abrecht et al. PRL **91**, 057002 (2003); EPFL Thesis no. 2792 (2003)
2. D. Cloetta et al., Phys. Rev. B**74**, 014519 (2006); EPFL Thesis no. 3333 (2005)
3. D. Pavuna et al., Journal of Physics **108**, 012040 (2008) and references therein
4. C. Cancellieri et al., Phys. Rev. B**76**, 174520 (2007); EPFL Thesis no. 4120 (2008)
5. D. Ariosa et al. Appl. Phys. Lett. **92**, 092506 (2008) and references therein
6. D. Oezer, M.Sc. Thesis, EPFL (2009); N. Wooding et al., unpublished (2012)
7. A.T. Bollinger et al. Nature **472**, 458 (2011) ; G. Dubuis et. al. in print (2012).

Keywords : Superconductivity, Cuprates, Heteroepitaxy, ARPES, Transport, Field effect.

Acknowledgements: The Swiss National Science Foundation, DOE and LPCM (EPFL).

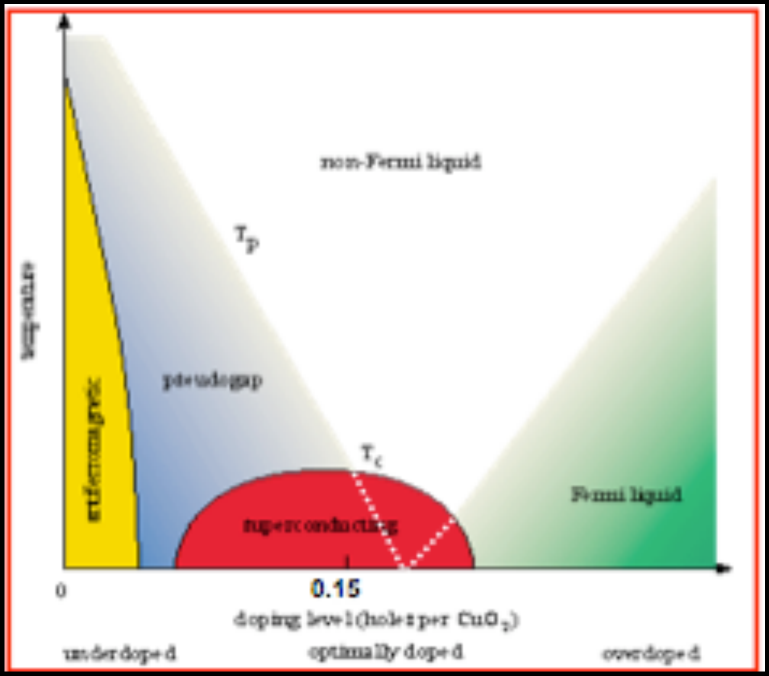
Outline

- Historic Introduction
- ***The Field Effect (Disorder) …***
- ***Interface Superconductivity***

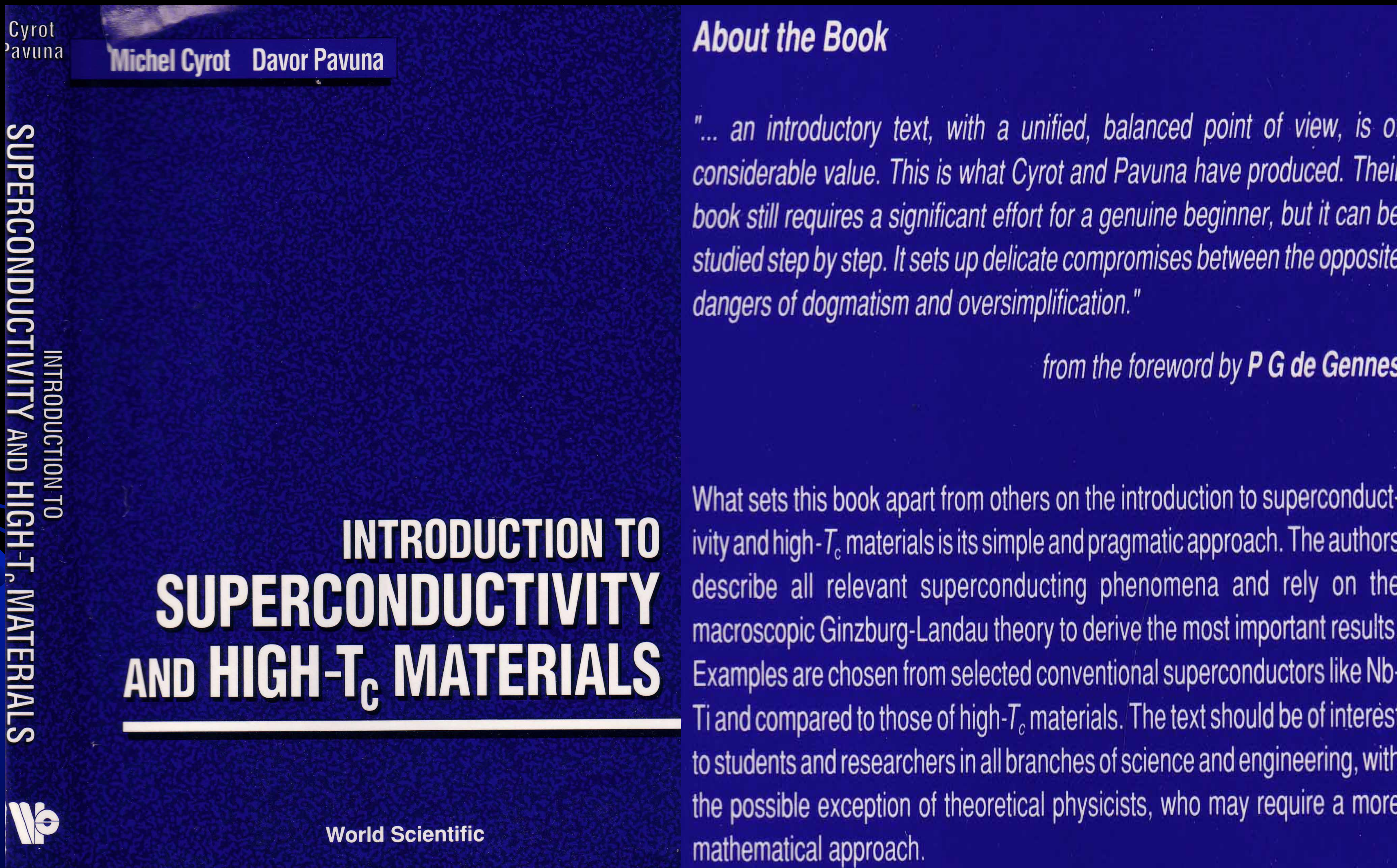
  & New Superconductors

Dedicated to the memory of Zlatko Tesanovic and Sasha Aleksandrov

Cuprates Electronic Phase Diagram:



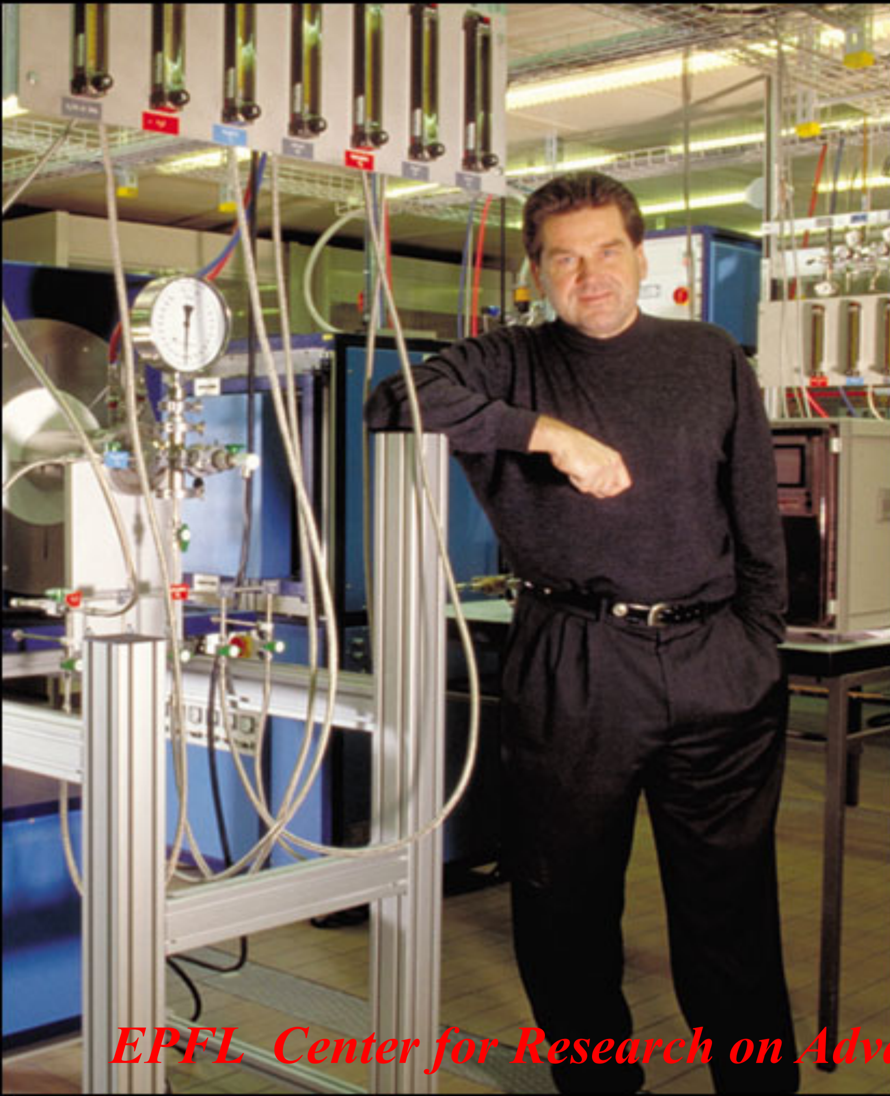
UNDERSTAND = Superconductivity Textbook

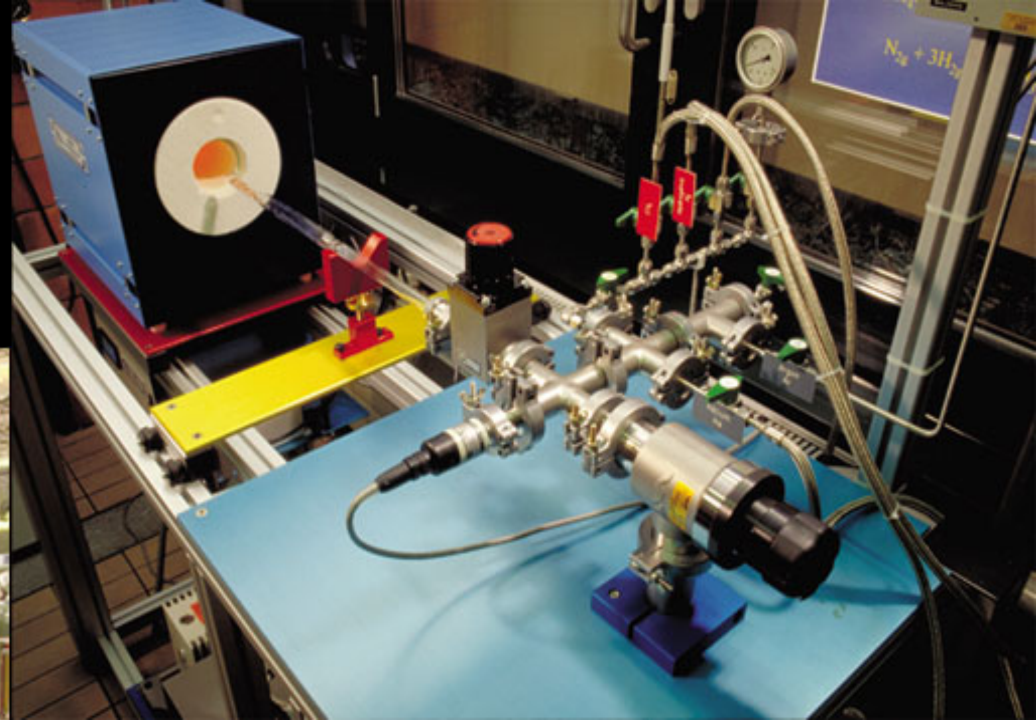


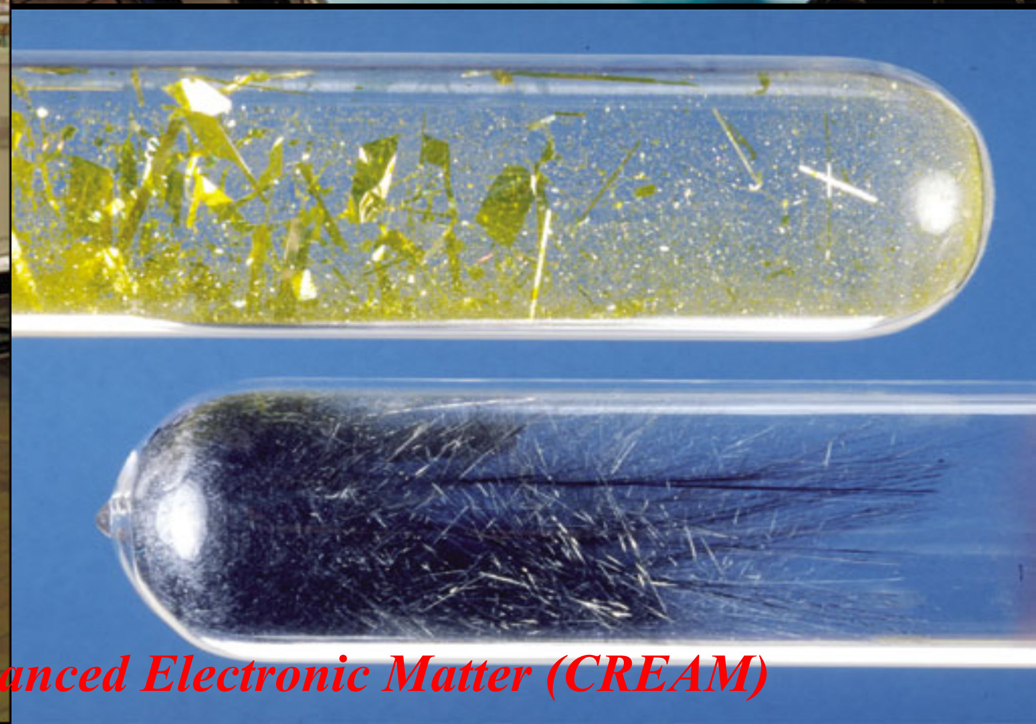
Helmuth Berger @ EPFL:

Growth of Single Crystals

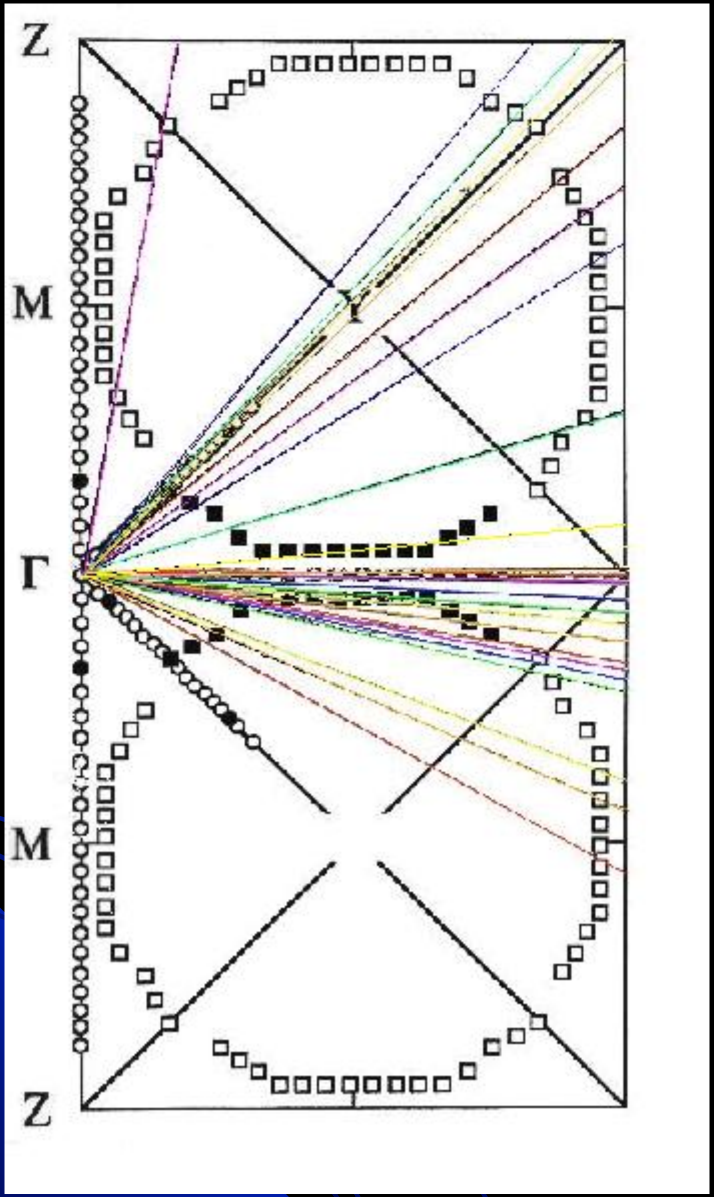
>30’000 samples’ !!!

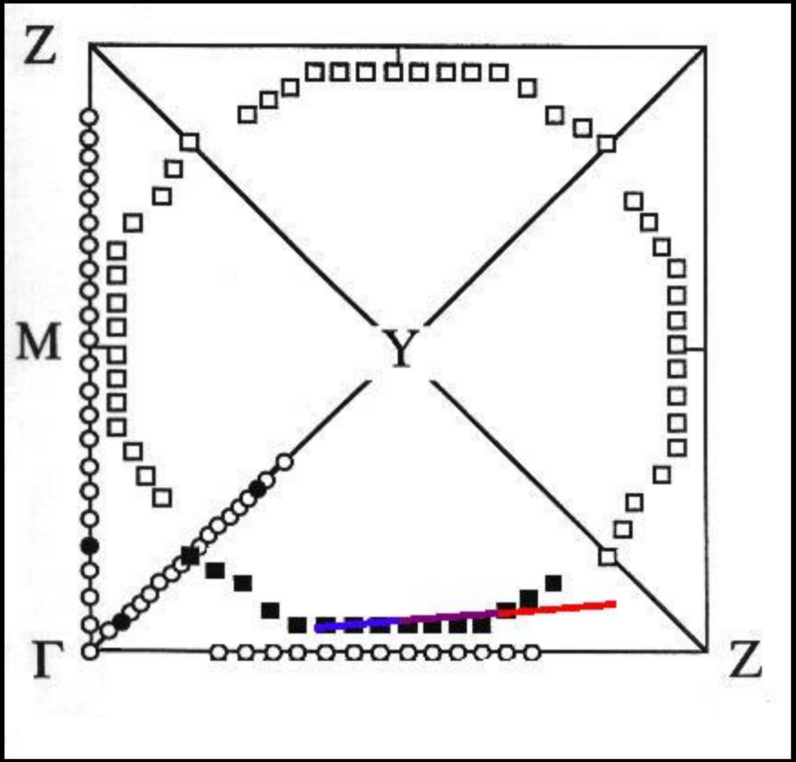






EPFL Center for Research on Advanced Electronic Matter (CREAM)





21.5 eV data

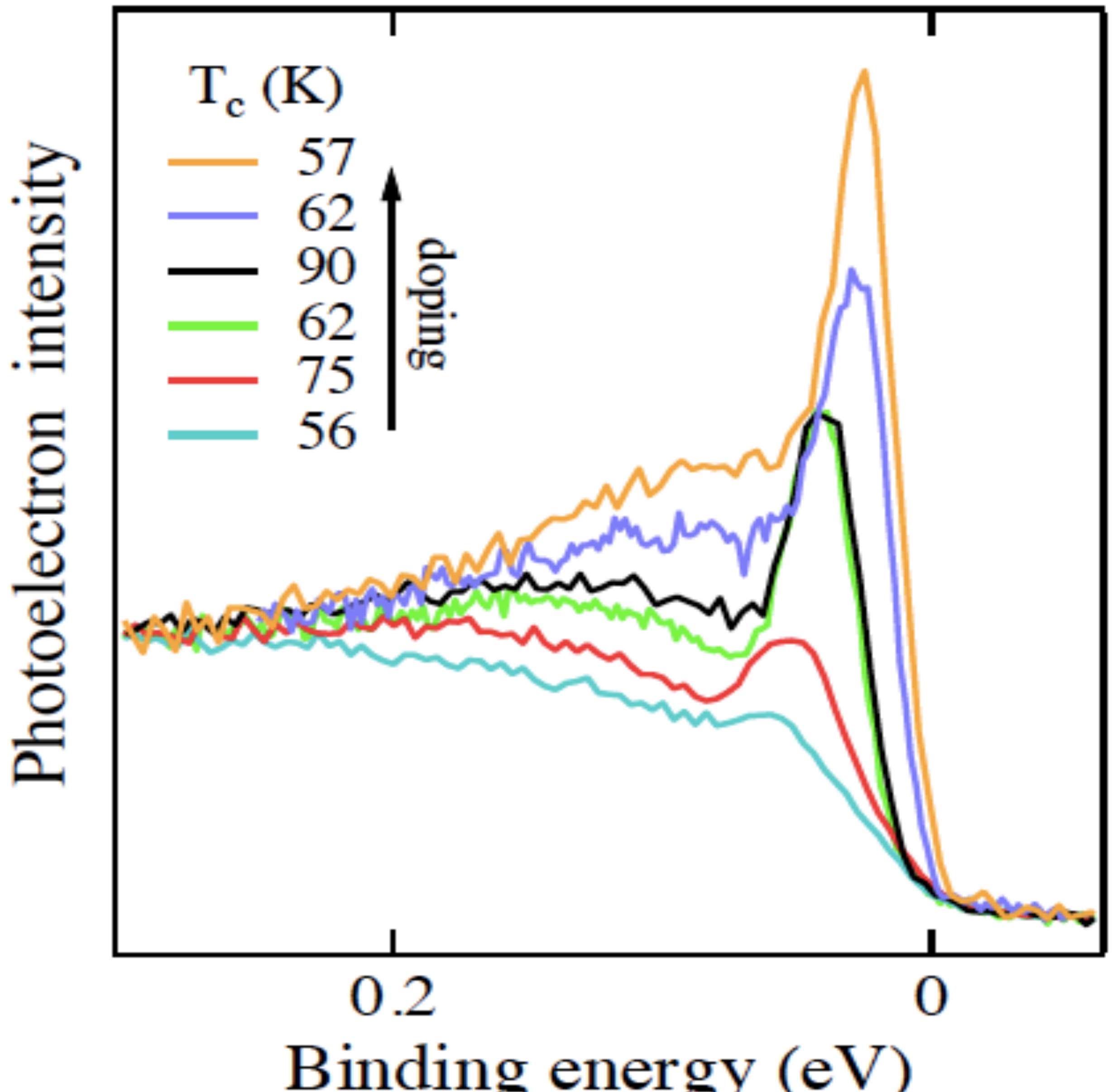
33 eV data

21.5 eV and 33 eV data

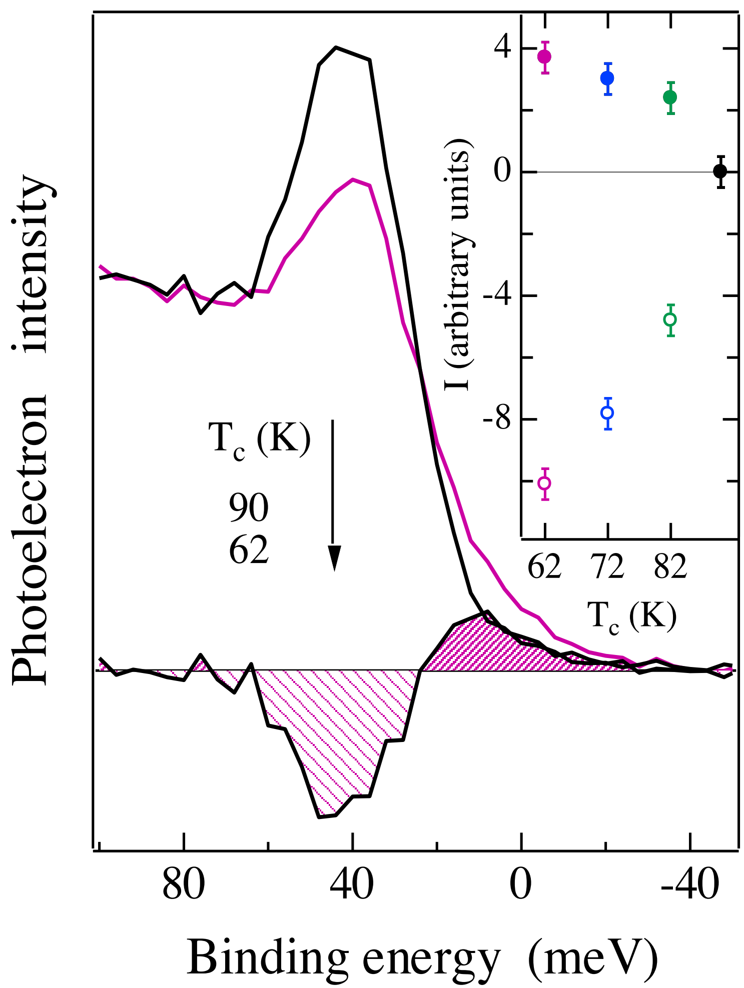
ARPES on Bi-2212 Crystals

I. Vobornik et. A (1999)l

ARPES on Cleaved Bi-2212 (I. Vobornik)



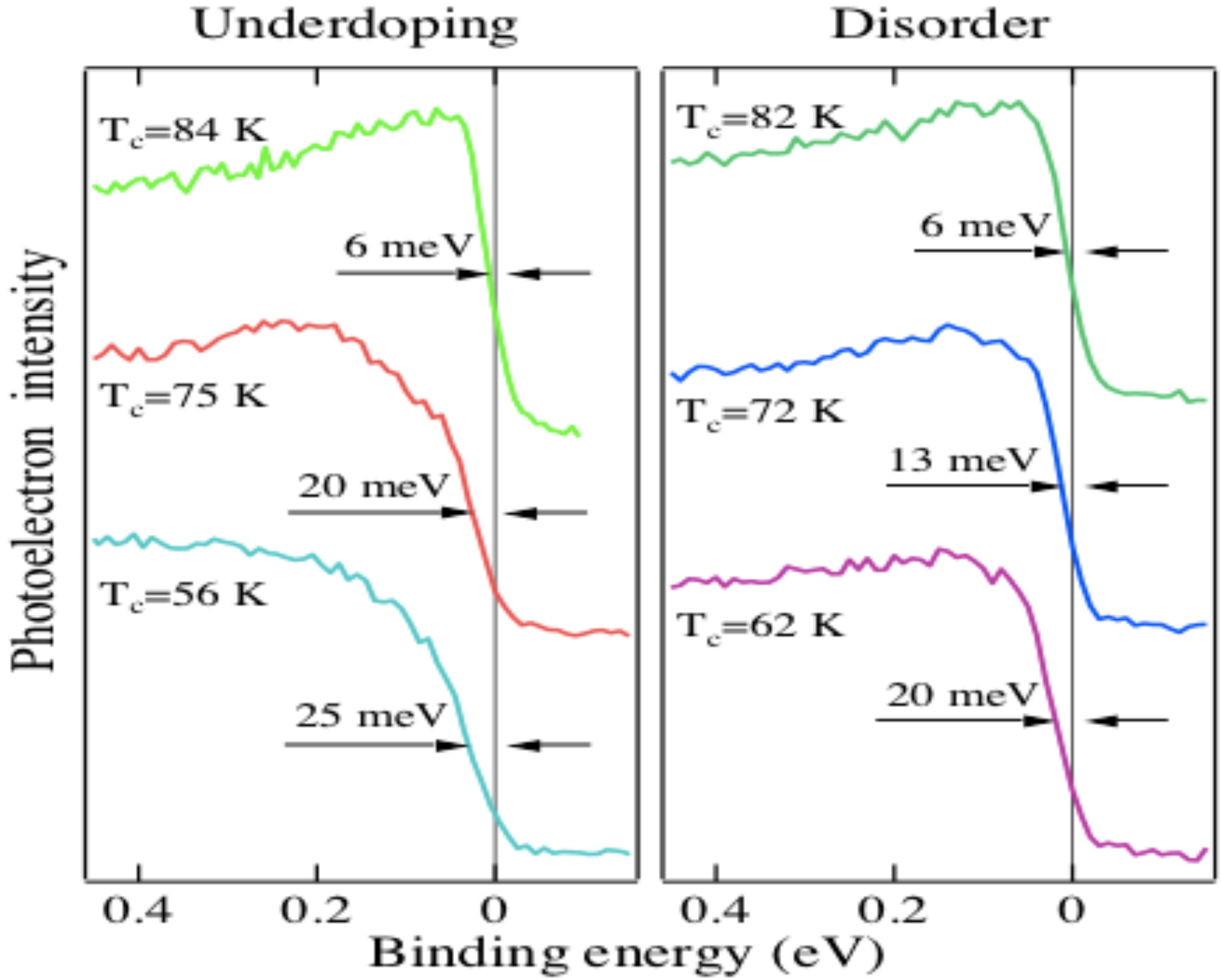
Disorder in $Bi_2Sr_2CaCu_2O_{8+x}$ SC-state:



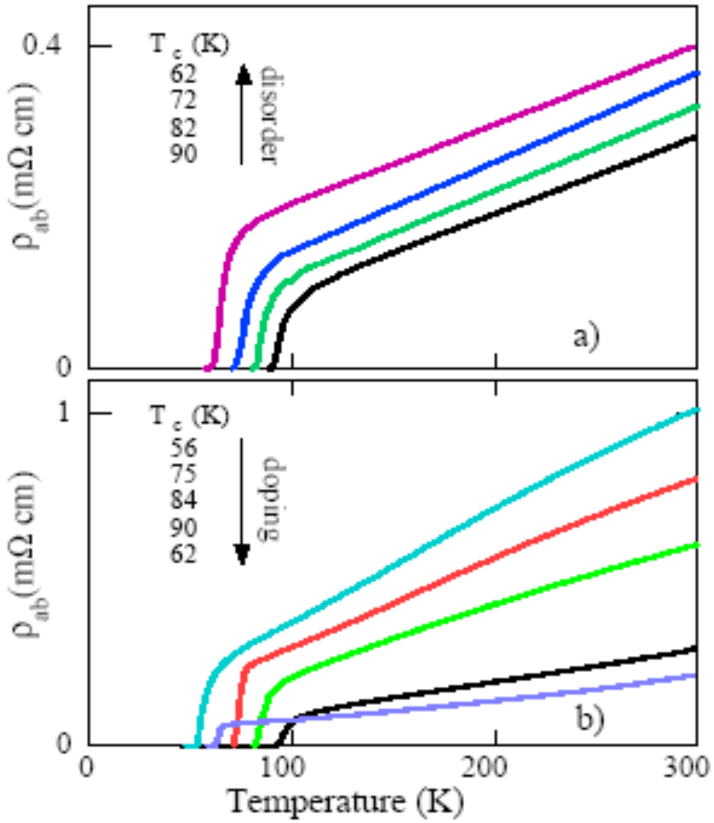
Defect-induced loss of coherence

I. Vobornik *et al.*,
PRL **82**, 3128 (1999)

ARPES Pseudogap & Disorder

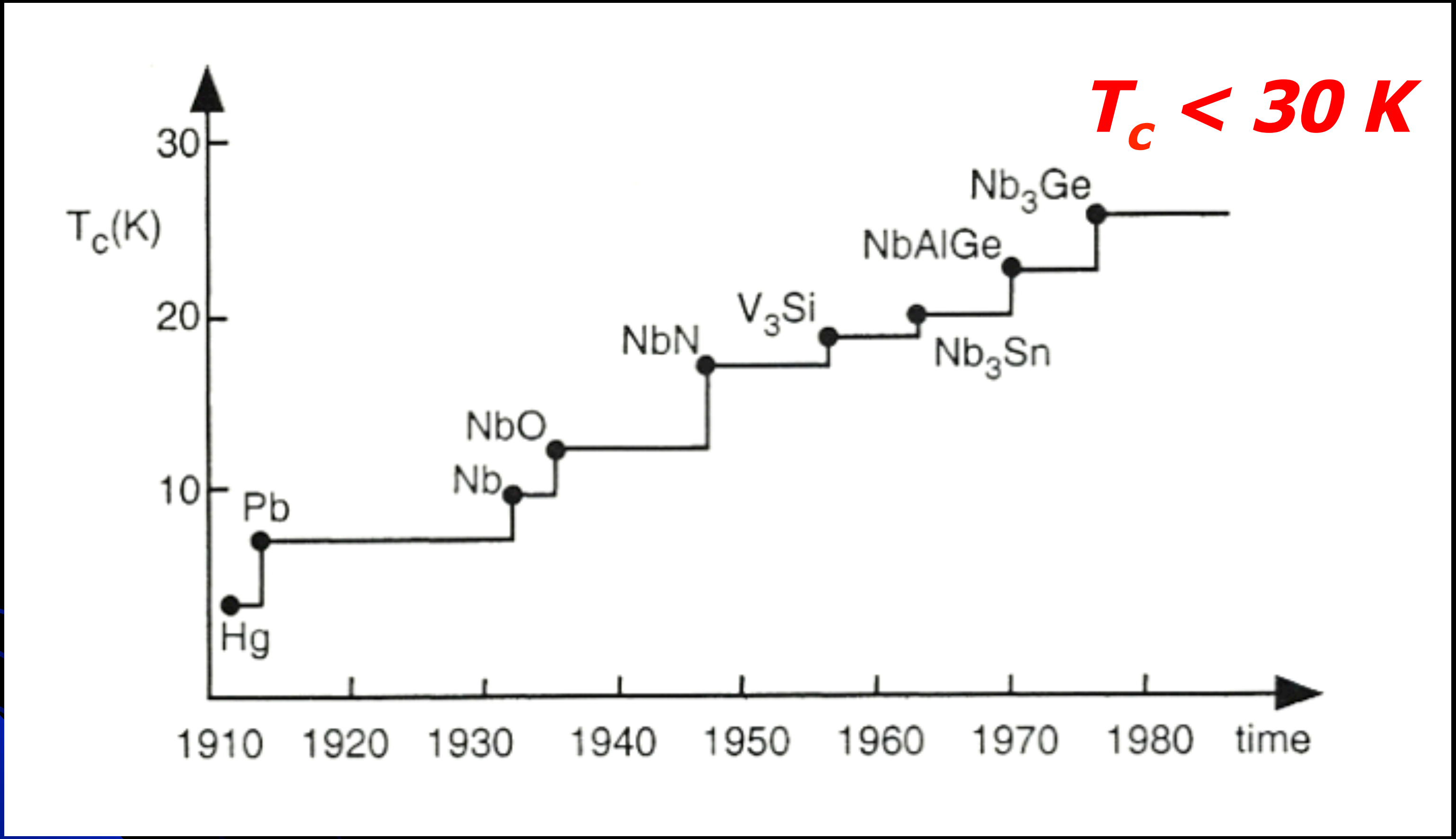


Doping vs. deliberate disorder (L.Forro):



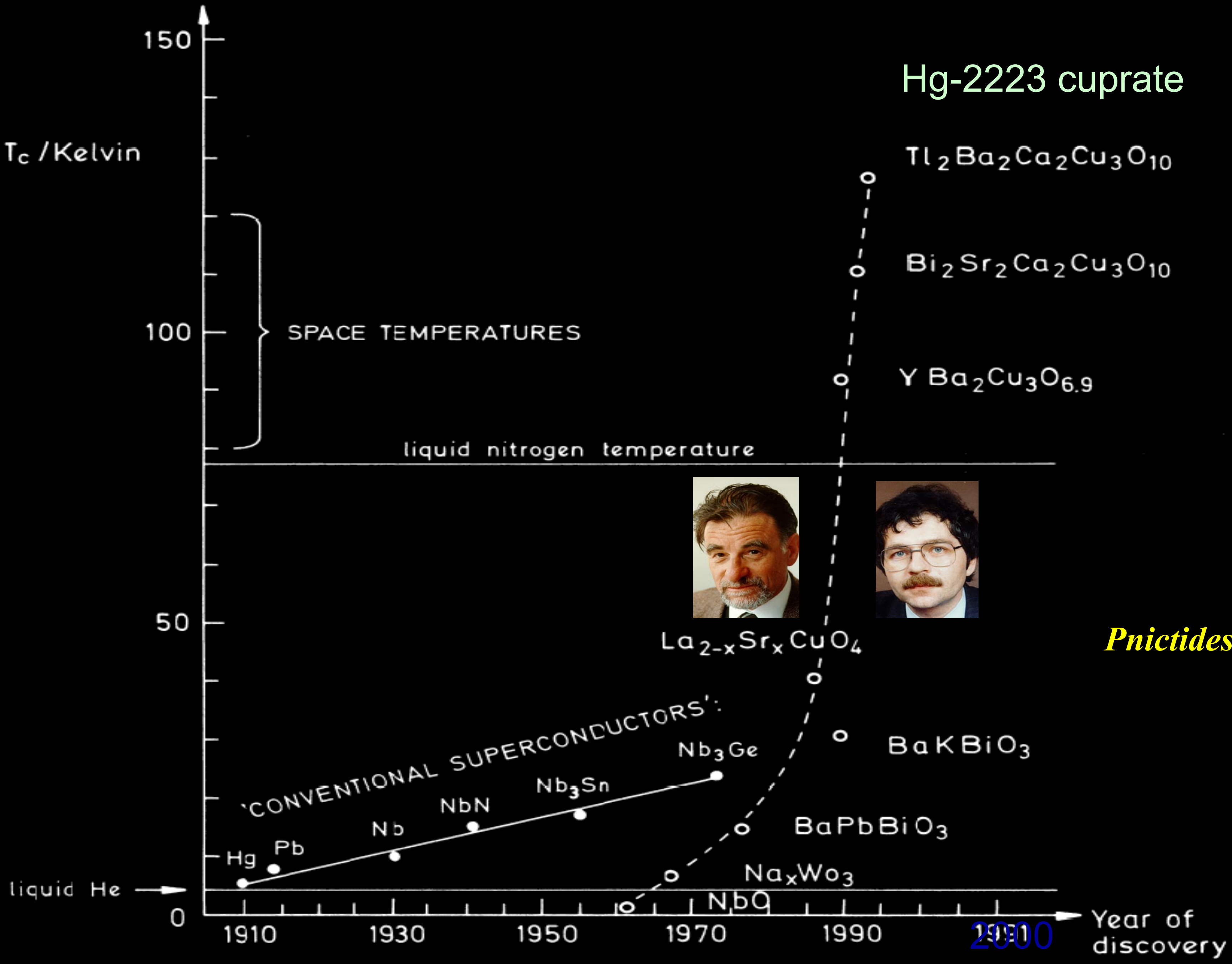
Verify the bulk properties as discussed by Alloul et al.!

Critical temperature of superconductors <1986



Conventional Superconductors

Barisic-Labbé-Friedel theory of superconductivity (1967)


Hg-2223 cuprate
T_c / Kelvin
150
100
50
0
SPACE TEMPERATURES
liquid nitrogen temperature
liquid He
$Tl_2Ba_2Ca_2Cu_3O_{10}$
$Bi_2Sr_2Ca_2Cu_3O_{10}$
$YBa_2Cu_3O_{6.9}$
$La_{2-x}Sr_xCuO_4$
Pnictides
$BaKBiO_3$
$BaPbBiO_3$
Na_xWo_3
NbO
'CONVENTIONAL SUPERCONDUCTORS':
Nb_3Ge
Nb_3Sn
NbN
Nb
Pb
Hg
1910
1930
1950
1970
1990
2000
Year of discovery

Hangzhou Workshop on Quantum Matter

Two key words:

Emergence and Control

- ***How to understand and control the remarkable emergent properties of correlated quantum matter?***

Yu Lu

Ivan Bozovic & Davor Pavuna

Control

Correlated Oxide Materials:

Physics & Nano-Engineering

I – VI

(SPIE,USA)

2. ARPES on In-Situ Grown FILMS:

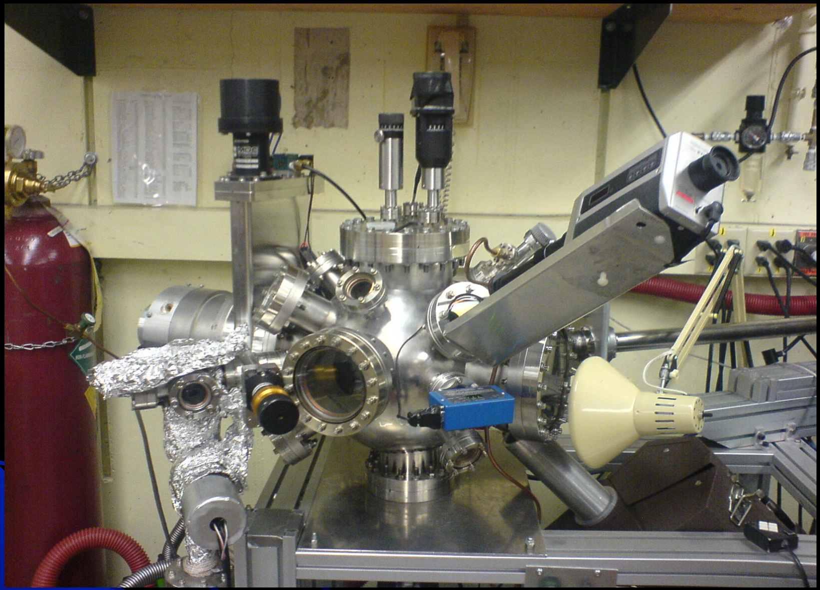
Physics <-> HeteroEpitaxy

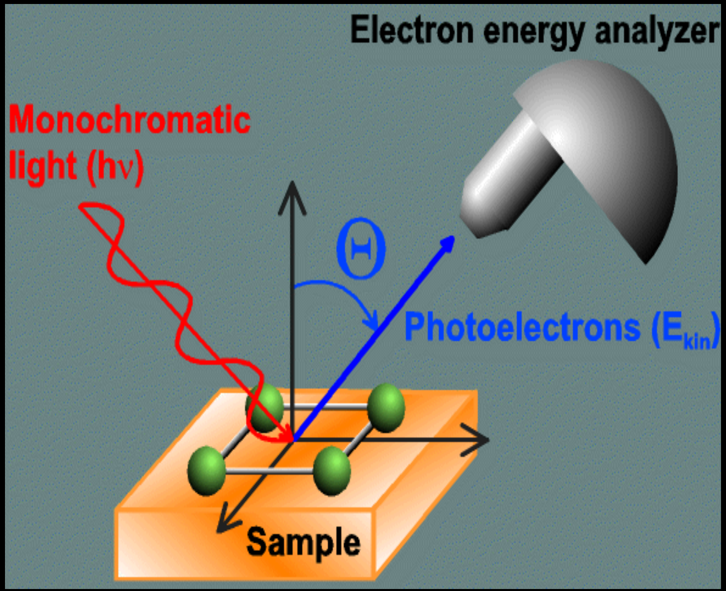
Control E(k) … (LATTICE) STRAINS

Control 'building blocks' + Functionality

In-Situ ARPES on UNCLEAVED Films

Top Surface is Crucial & INTERFACE Rules !



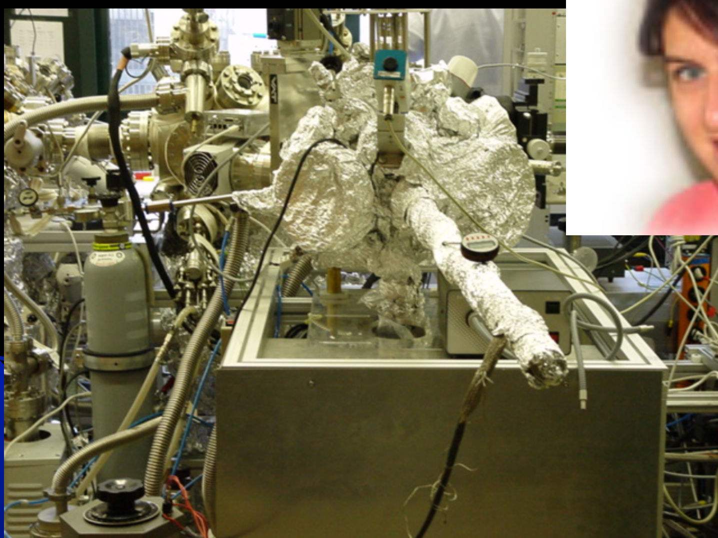


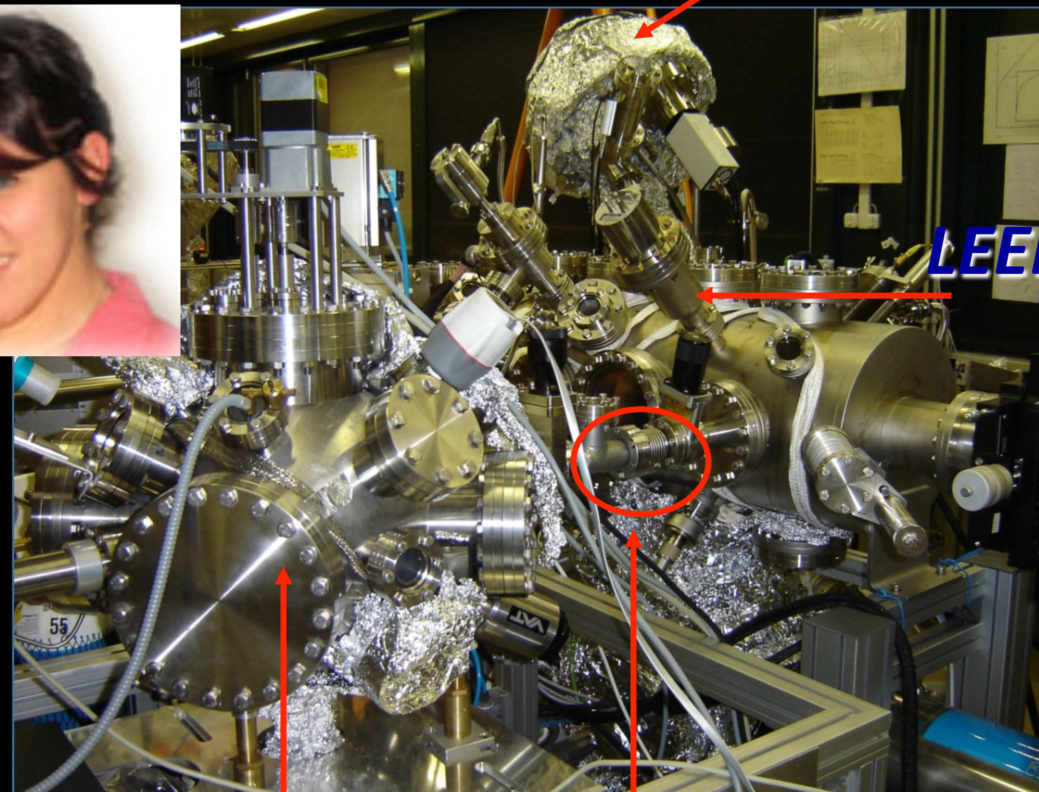
PLD Cuprates HeteroEpitaxy

DARPES on As-made UNCLEAVED thin films

DARPES on As-Grown Film Surfaces

Grioni's ARPES ← Laser ablation





Pavuna et al. J. Phys. (GB) 108, 012040 (2008)

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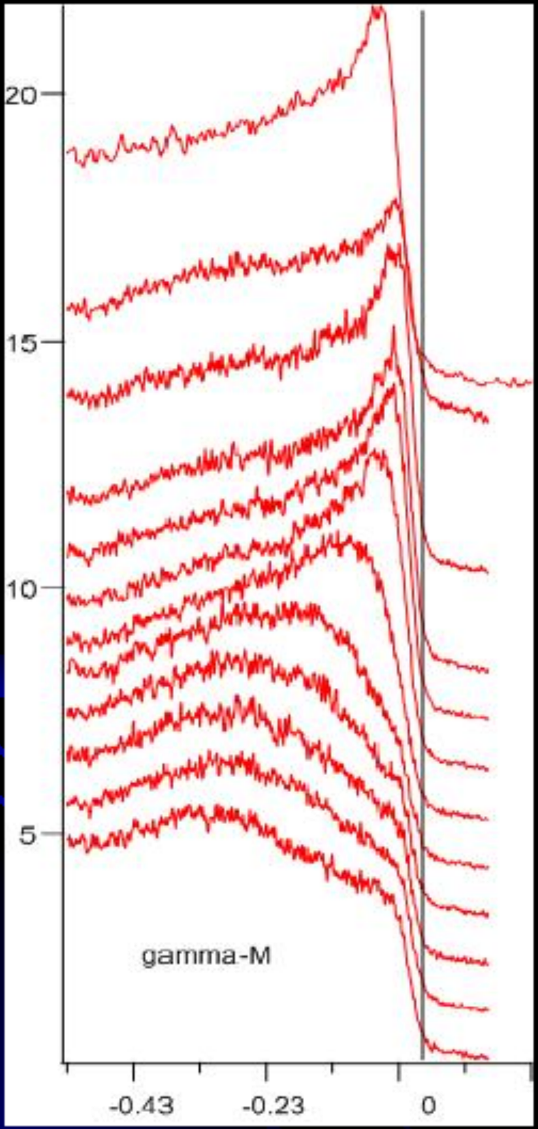
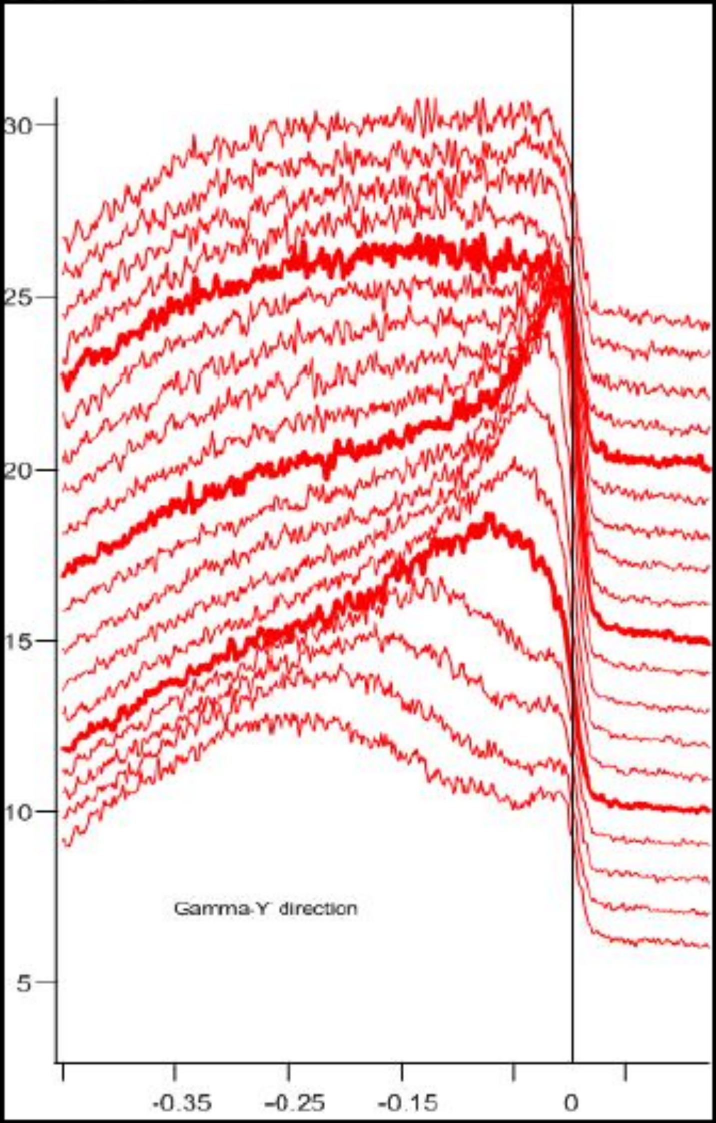
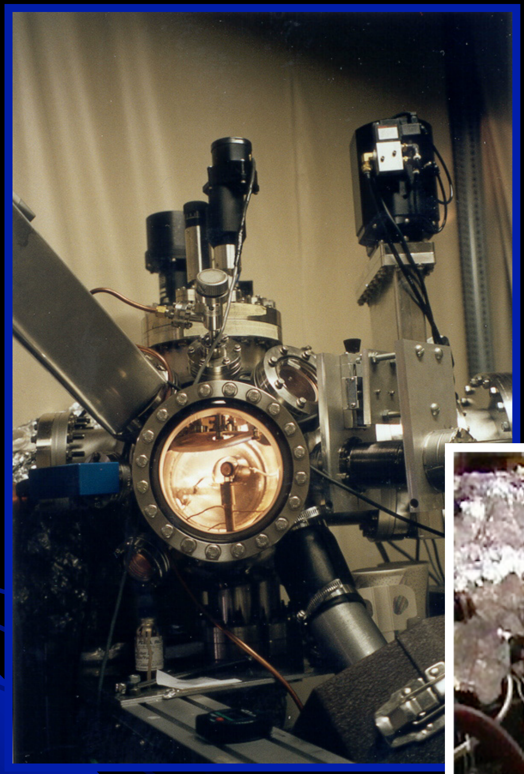
Direct ARPES on As-made La-doped Bi-2201 Film:

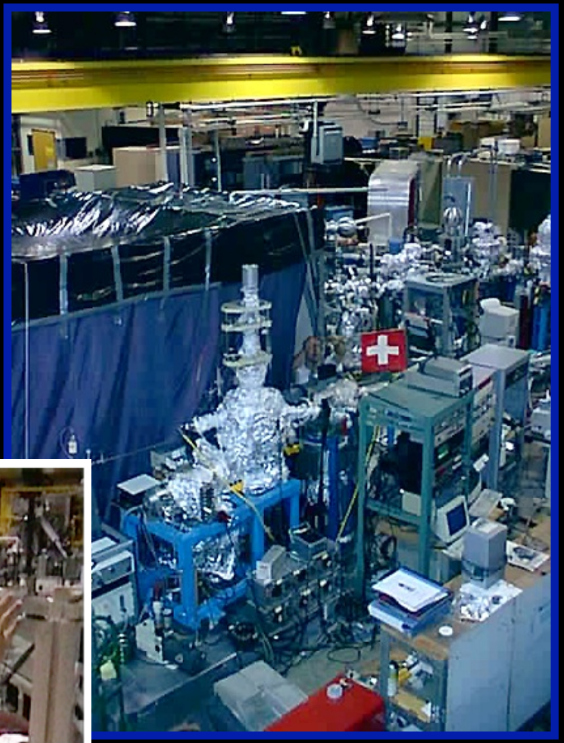
NOT Cleaved

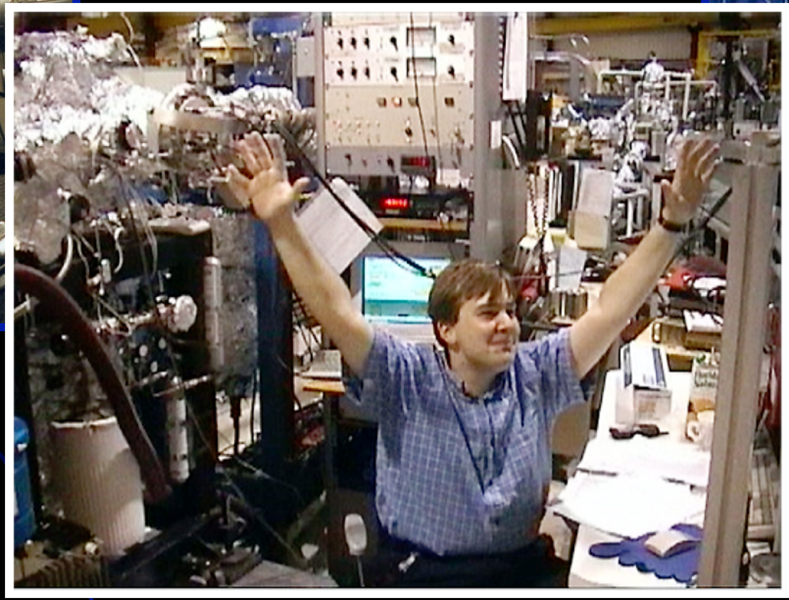




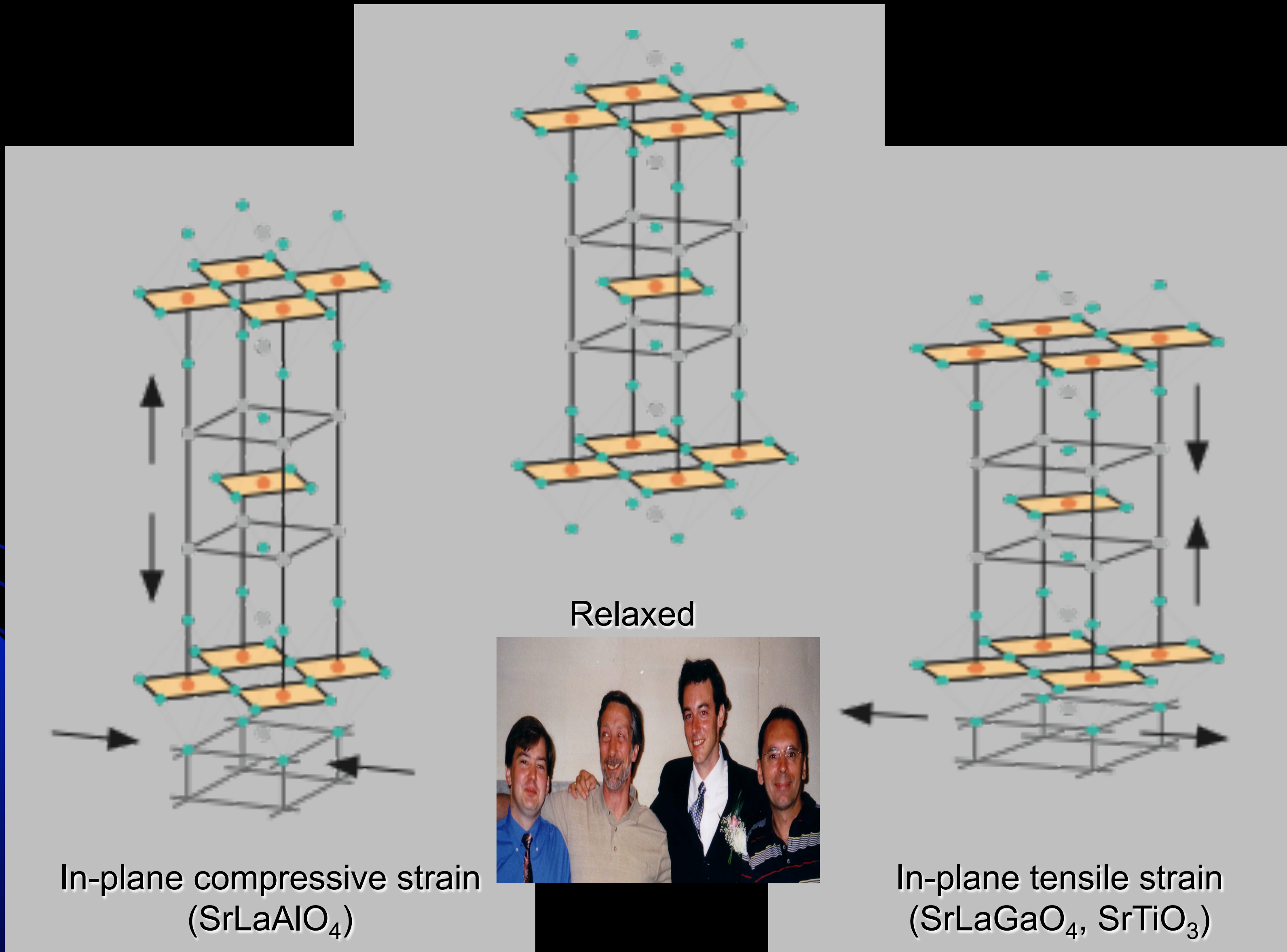
In-Situ ARPES @ Synchrotron in Wisconsin

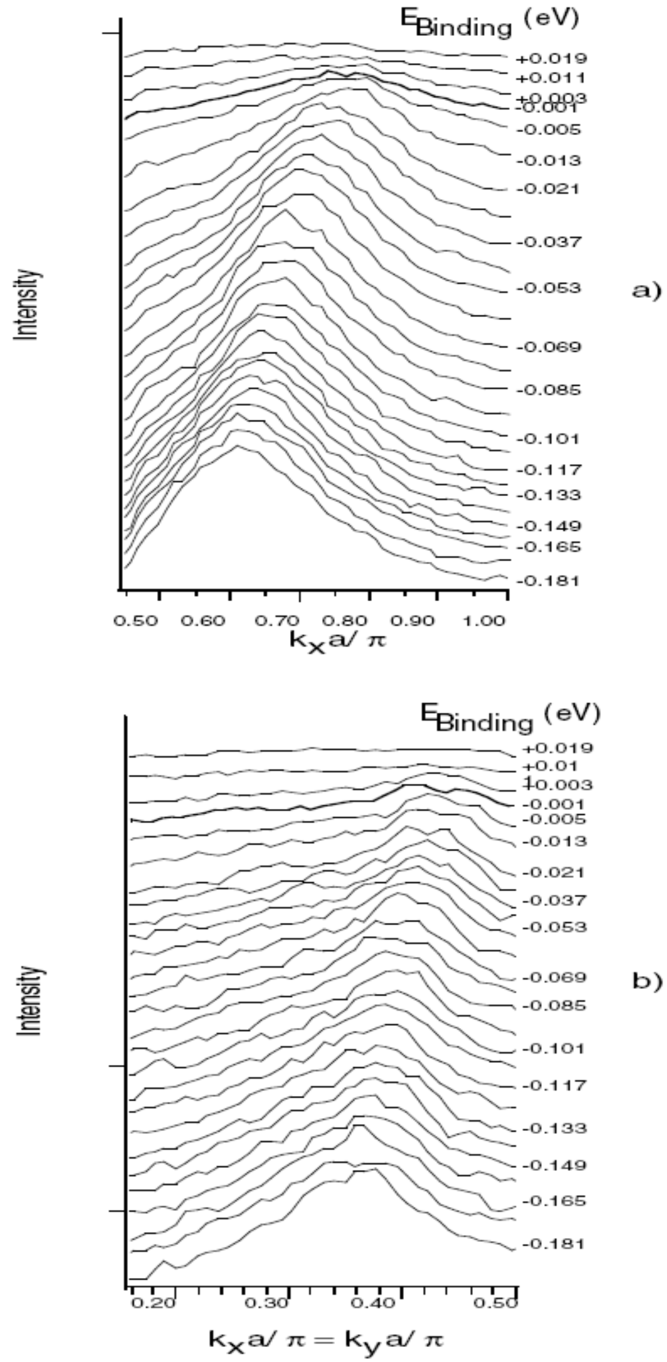






$La_{2-x}Sr_xCuO_4$ Films Under Strains





Compressive

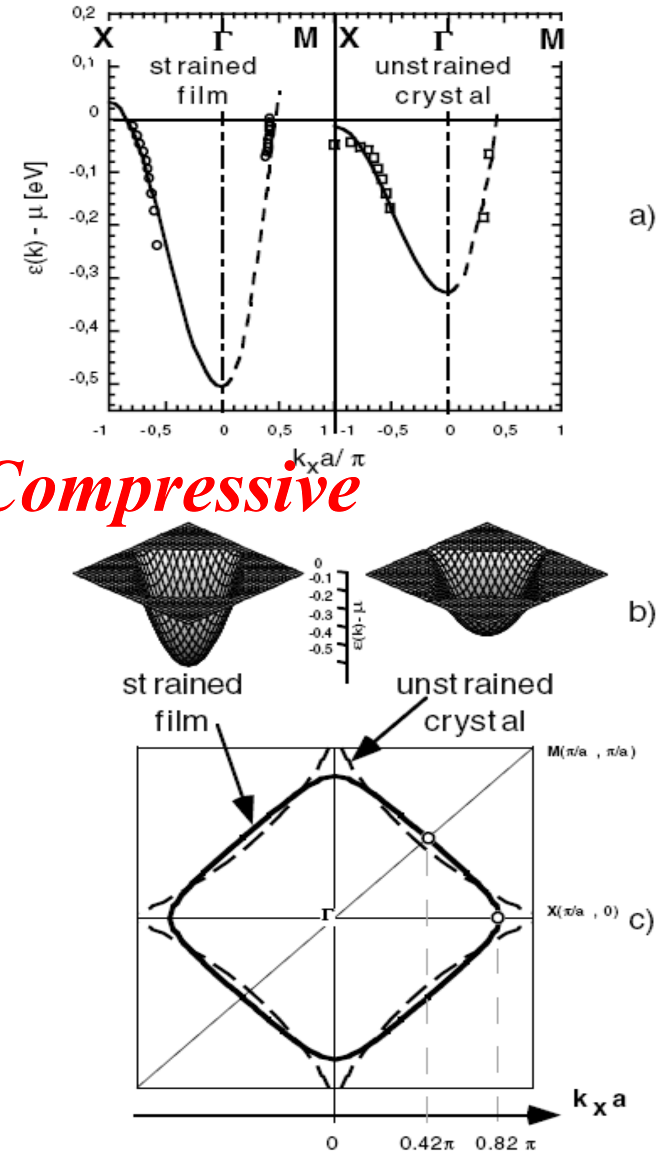
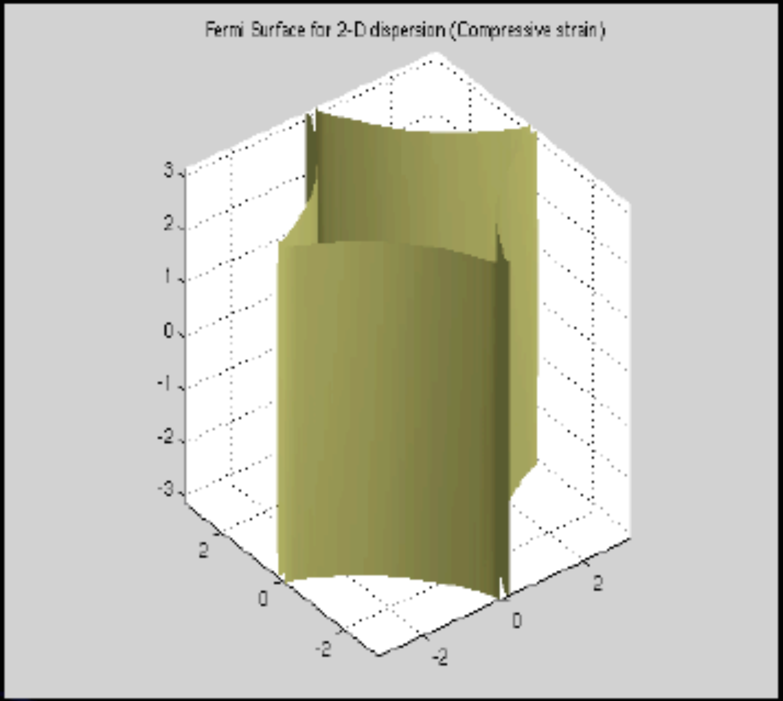
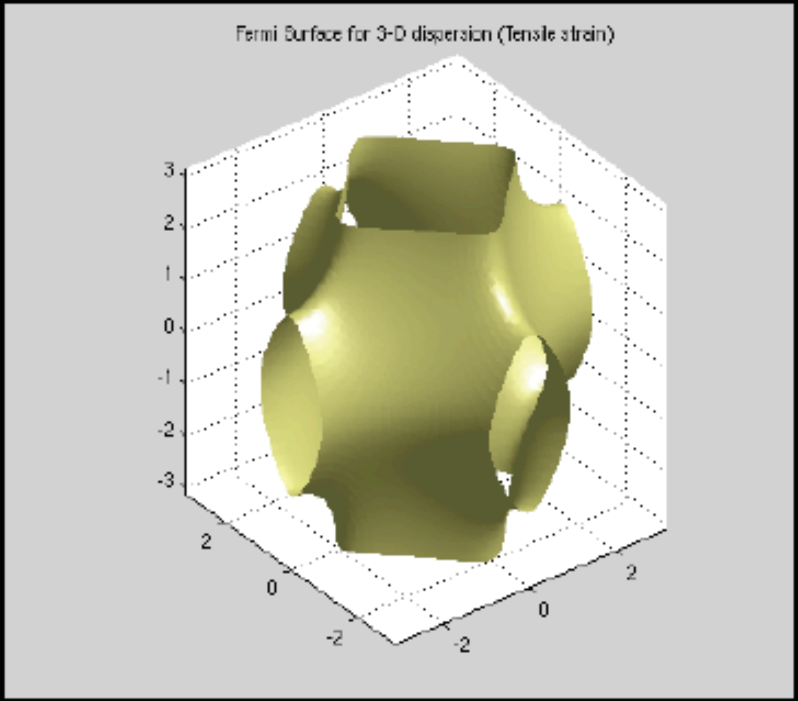


FIG. 2. (a) Fits of band dispersion for a strained film (circles, left panel) and for an unstrained single crystal (squares, right panel, data from Ref. [15]), along Γ-*X* (solid line) and Γ-*M* (dashed line). The fits are based on Eq. (1). (b) Visualization of the best-fit results: dispersion of the two-dimensional band for an optimally doped in-plane compressed film (left) and

Direct ARPES on Strained HTSC Films





An illustration of reconstructed FS for overdoped (x= 0.2) LSCO-214 films under

compressive strain and **tensile strain** .

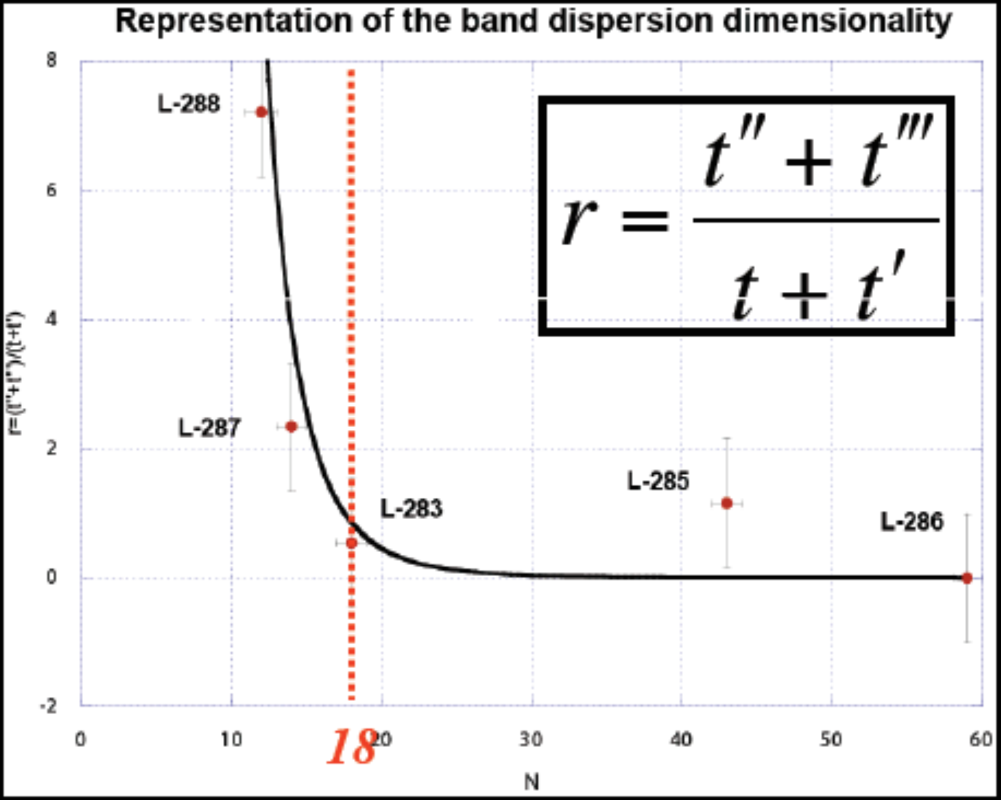
Tc is enhanced **Tc is diminished**

PRL, 2003 ***PRB, 2006***

Ultra-Thin Films: 2D-3D Crossover

Discrete generic 3D -tight-binding model

Parameter	Hopping term [mW]
t	in-plane nearest neighbor (NN)
t'	in-plane next nearest neighbor (NNN)
t''	out-of-plane NN
t'''	out-of-plane NNN



Ariosa et al.

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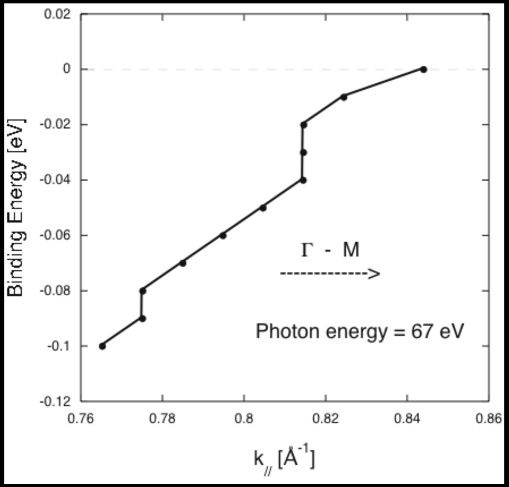
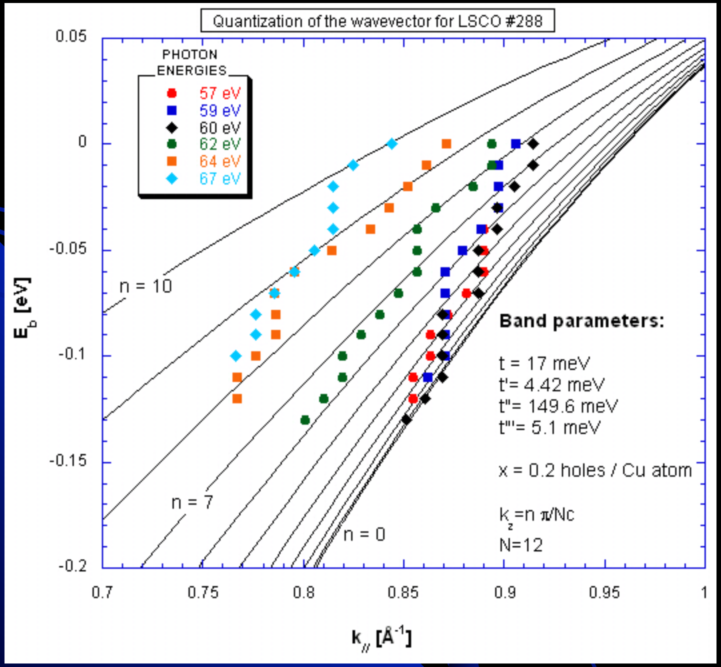
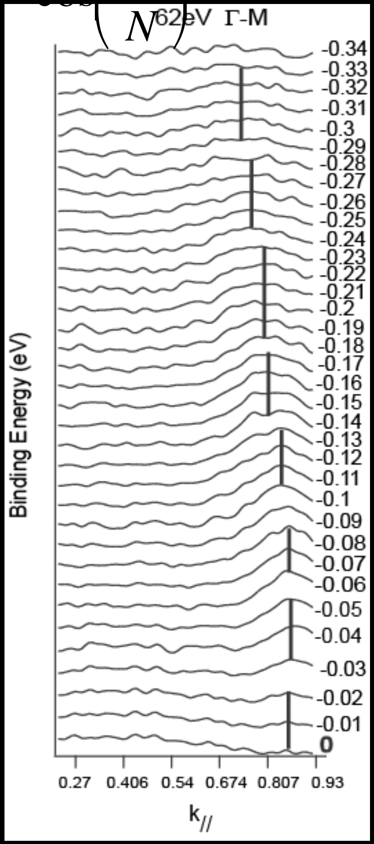
r indicates predominant dimensionality of the electronic band dispersion.

The quantization of the electron wavevector





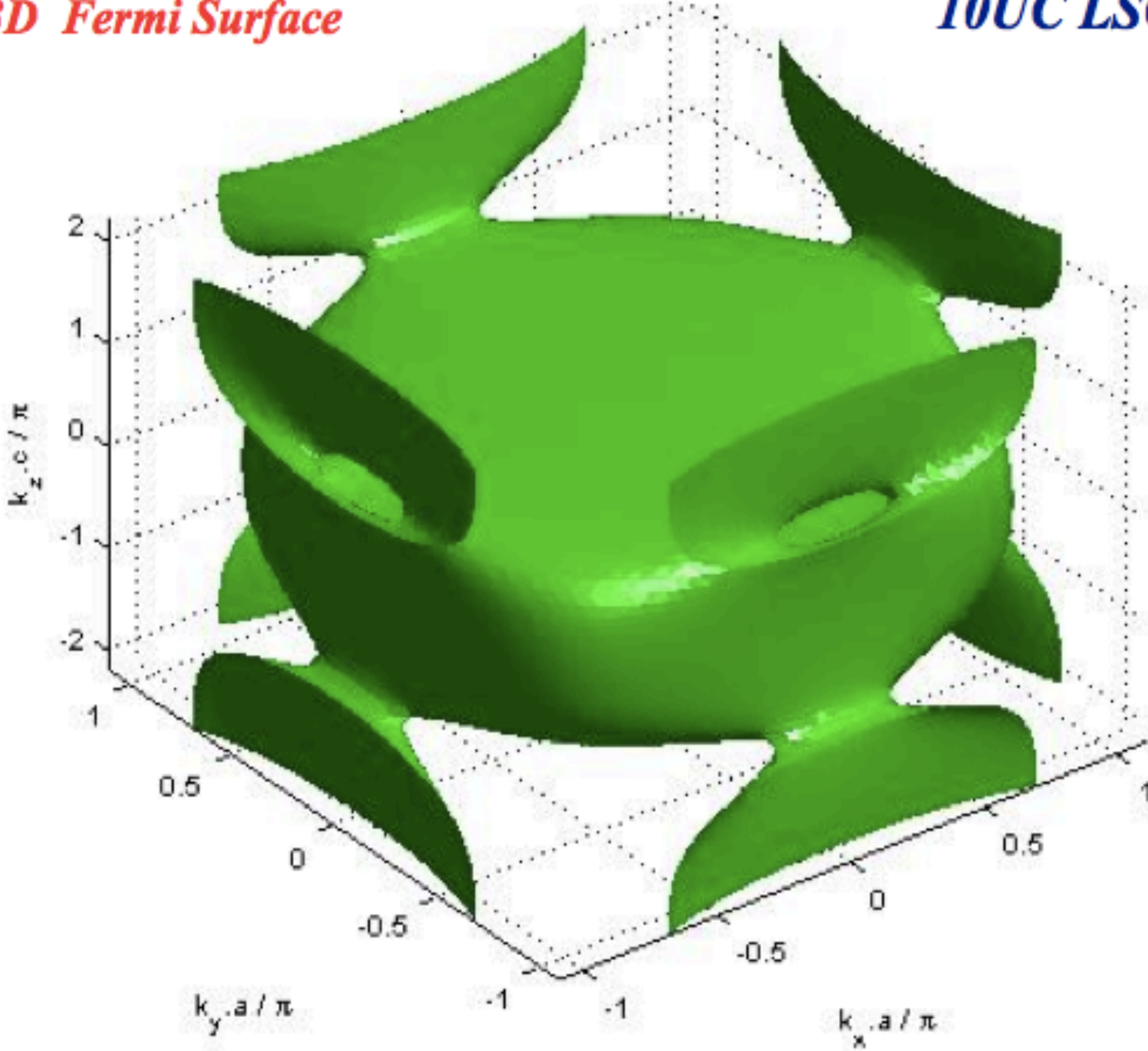
$$k_z = n\pi / Nc$$



Appl. Phys. Lett. 92, 092506 (2008)

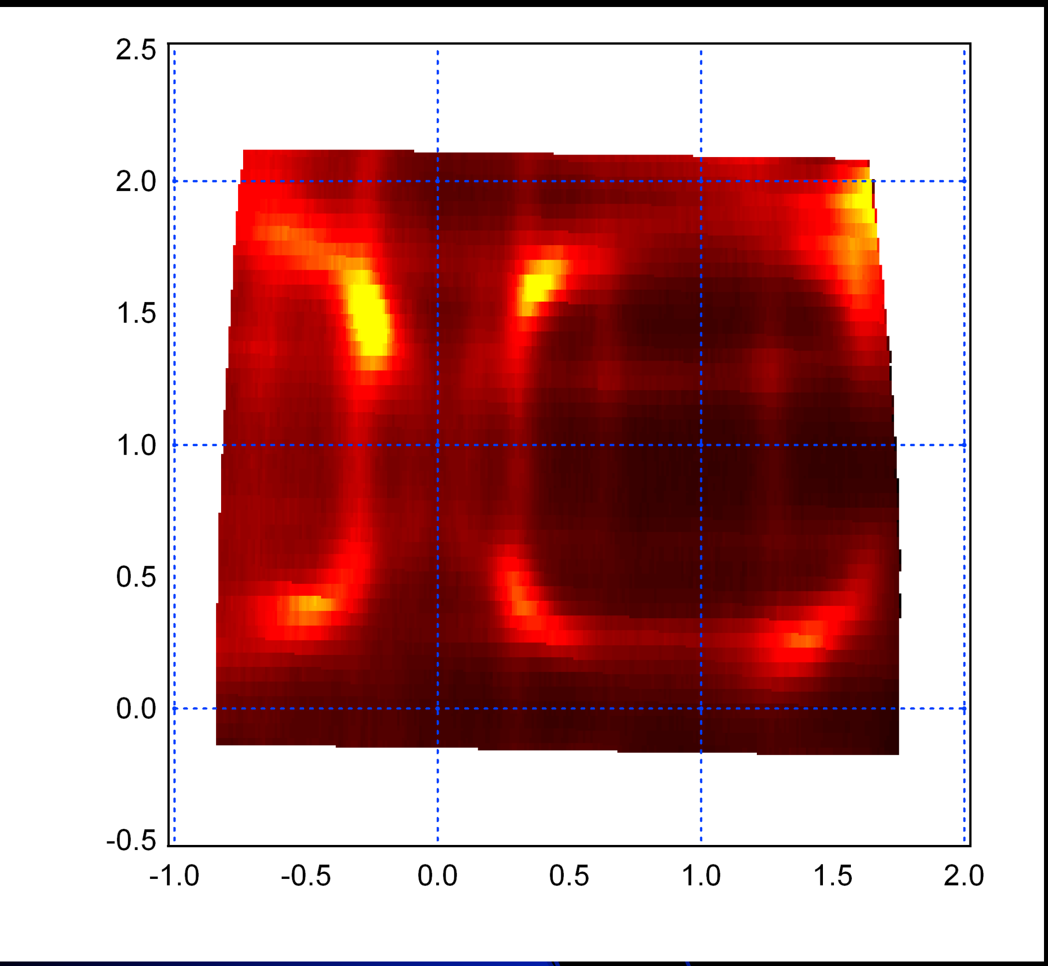
3D Fermi Surface

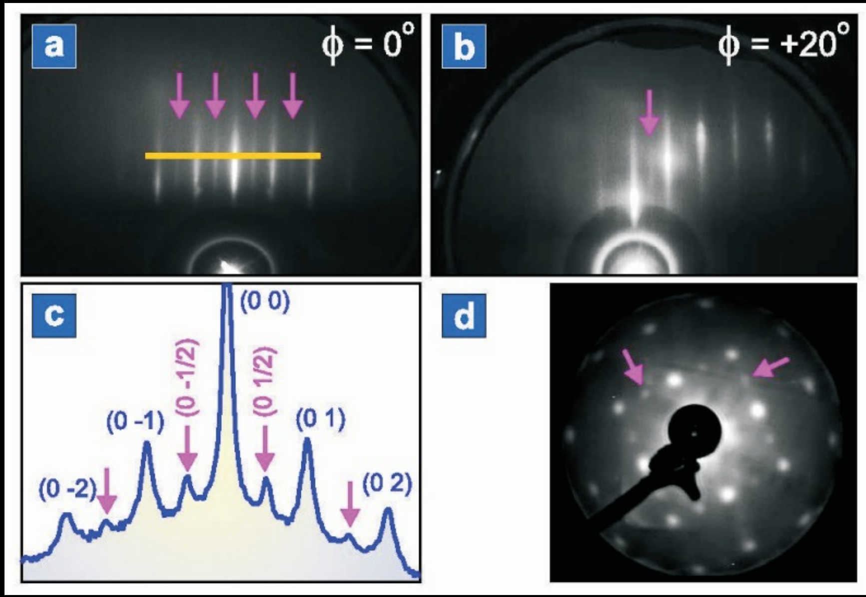
10UC LSCO Film

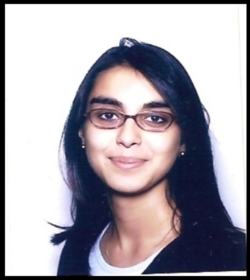


Ming Shi & Joel Mesot, PSI

Fermi surface of ortho-II YBCO(123)





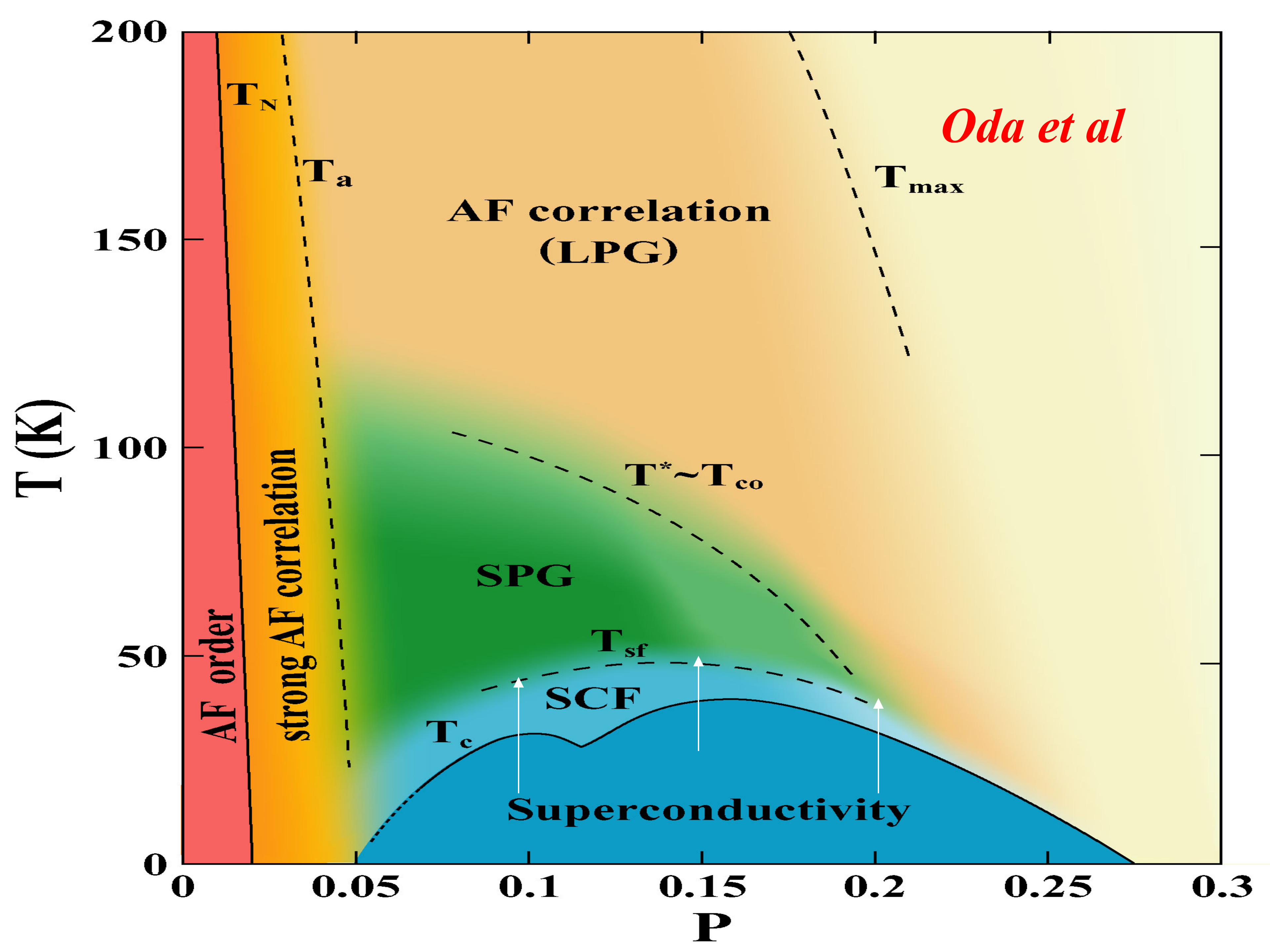


Y. Sassa & M. Radovic et al.

* In-Situ ARPES ***on As-grown Films Works !***

* ***< 18UCs LSCO-214 Strained Films Show Different Dispersions (3D FS)***

* T_c scales with c-axis (apical oxygen)



200
150
100
50
0
T (K)
0
0.05
0.1
0.15
0.2
0.25
0.3
P
T_N
T_a
AF correlation
(LPG)
T_{max}
Oda et al
T^*~T_{co}
SPG
T_{sf}
SCF
T_c
Superconductivity
AF order
strong AF correlation

T_c vs. $S(300)$ *In doped LXCO-214*

Thierry Schnyder, Jeff Tallon et al. (2010)

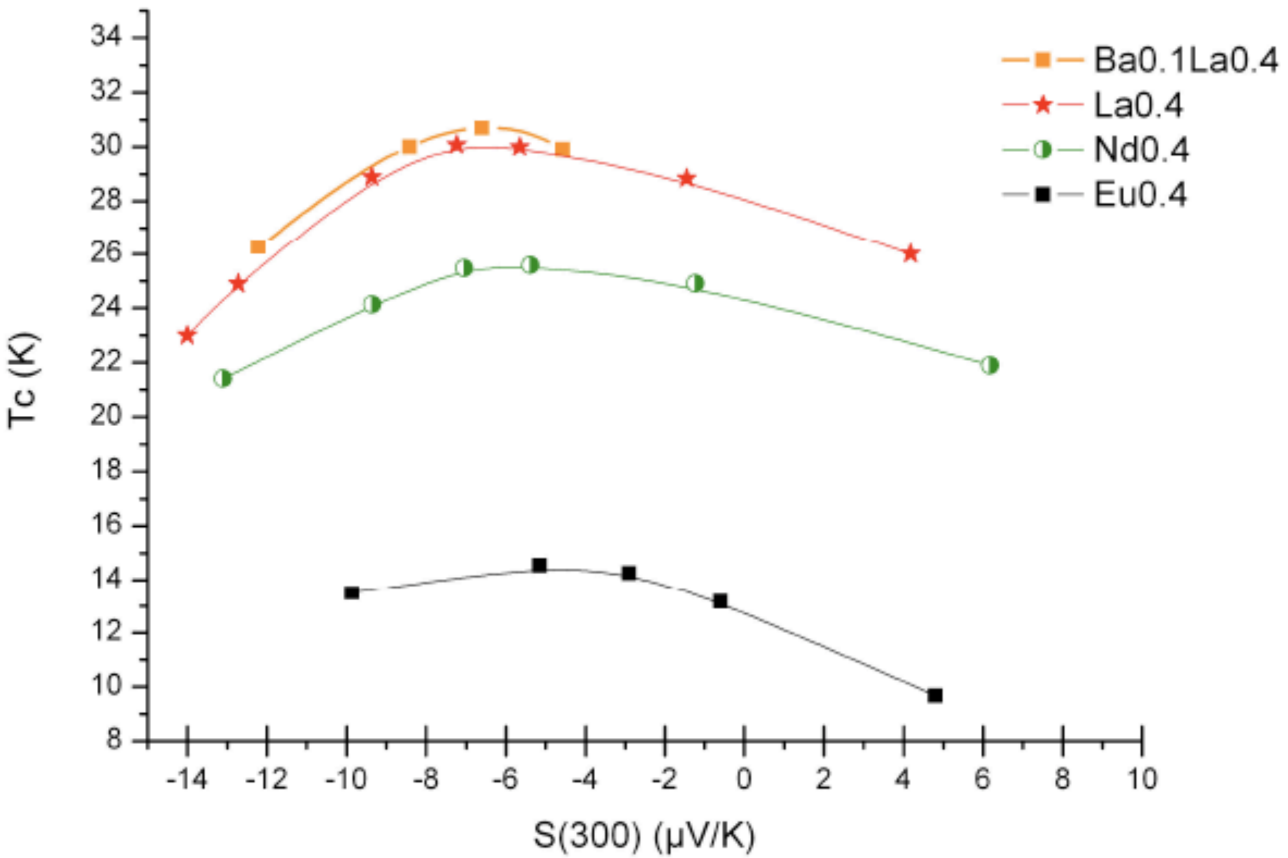
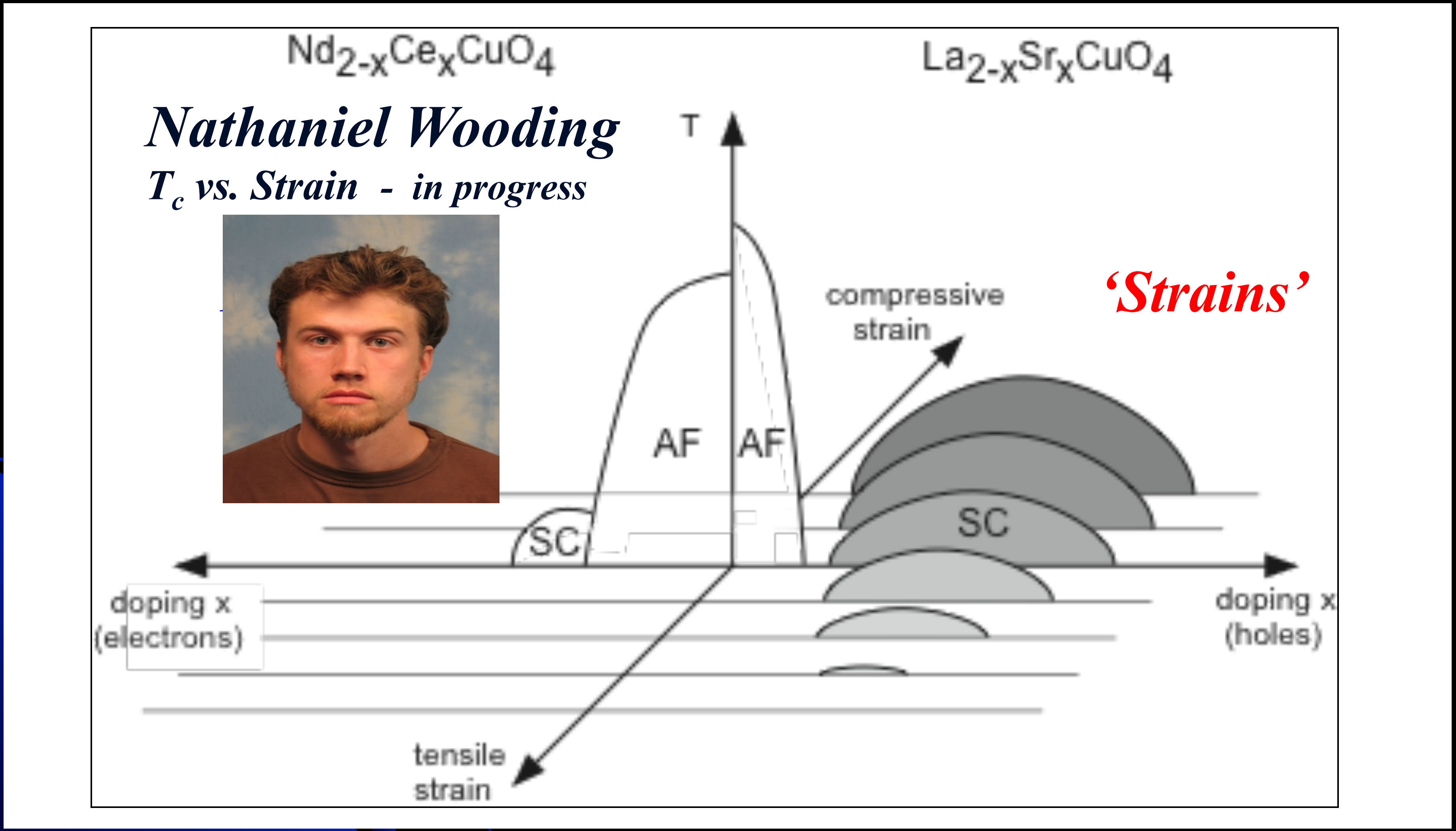


Figure: T_c vs. $S(300)$

T_c scales with c-axis (apical oxygen)

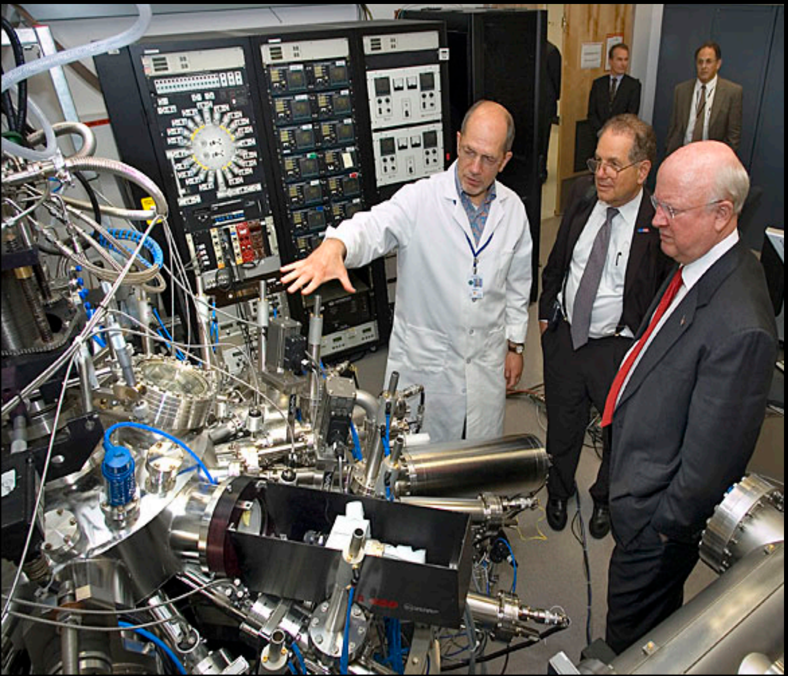
NanoEngineering & Electronic Diagram

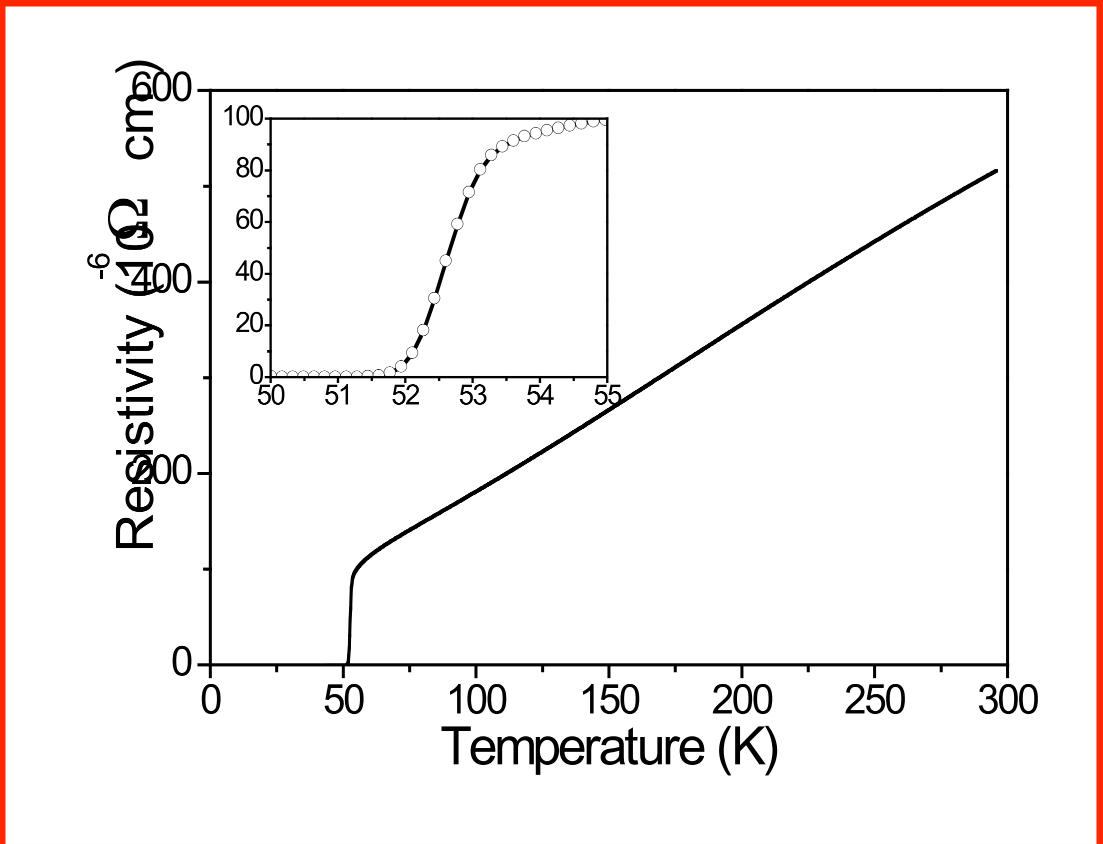


See also Cloetta et al. PRB 2006

MBE Grown Compressively Strained LSCO Film (BNL):

Resistivity of an LSCO film on LSAO substrate.

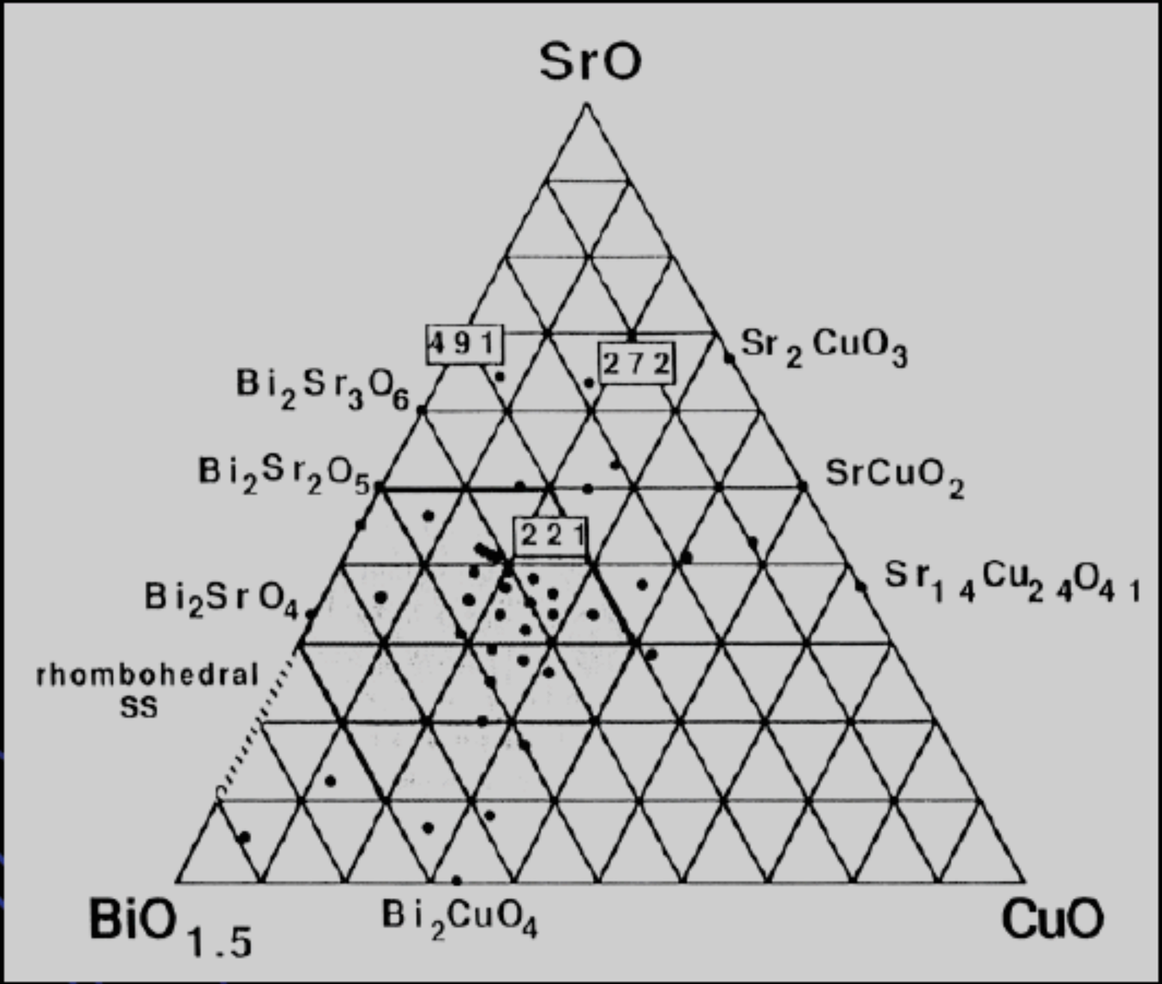




Bozovic et al. PRL 89, 107001 (2002)

High-Tc Materials COMPLEXITY: Unwanted phases

OUR MAIN PROBLEM



Phase formation in the Bi-Sr-Cu-O system
(@ 800°C, in air)

Courtesy I. Bozovic

3. Electric Field Effect in LSCO Films

Guy Dubuis @BNL with Ivan Bozovic et al.

- Use Electric Field to tune T_c

- ***Adjust carrier concentration***
  without changing disorder

* Intrinsic nature of quantum critical points ?

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BROOKHAVEN NATIONAL LABORATORY

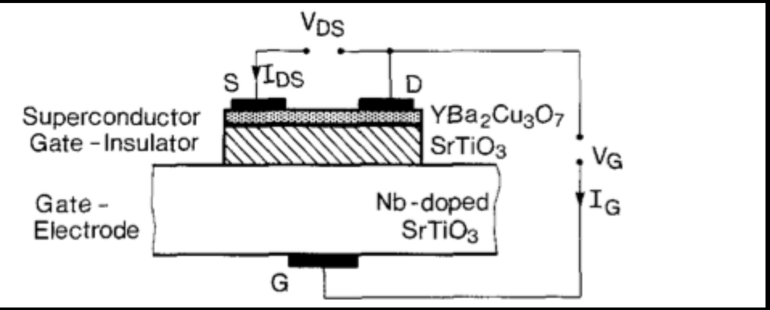
Field Effect applied to high-Tc Superconductivity (1991)

Electric field effect on superconducting $YBa_2Cu_3O_{7-\delta}$ films

J. Mannhart, J.G. Bednorz, K.A. Müller, and D.G. Schlom

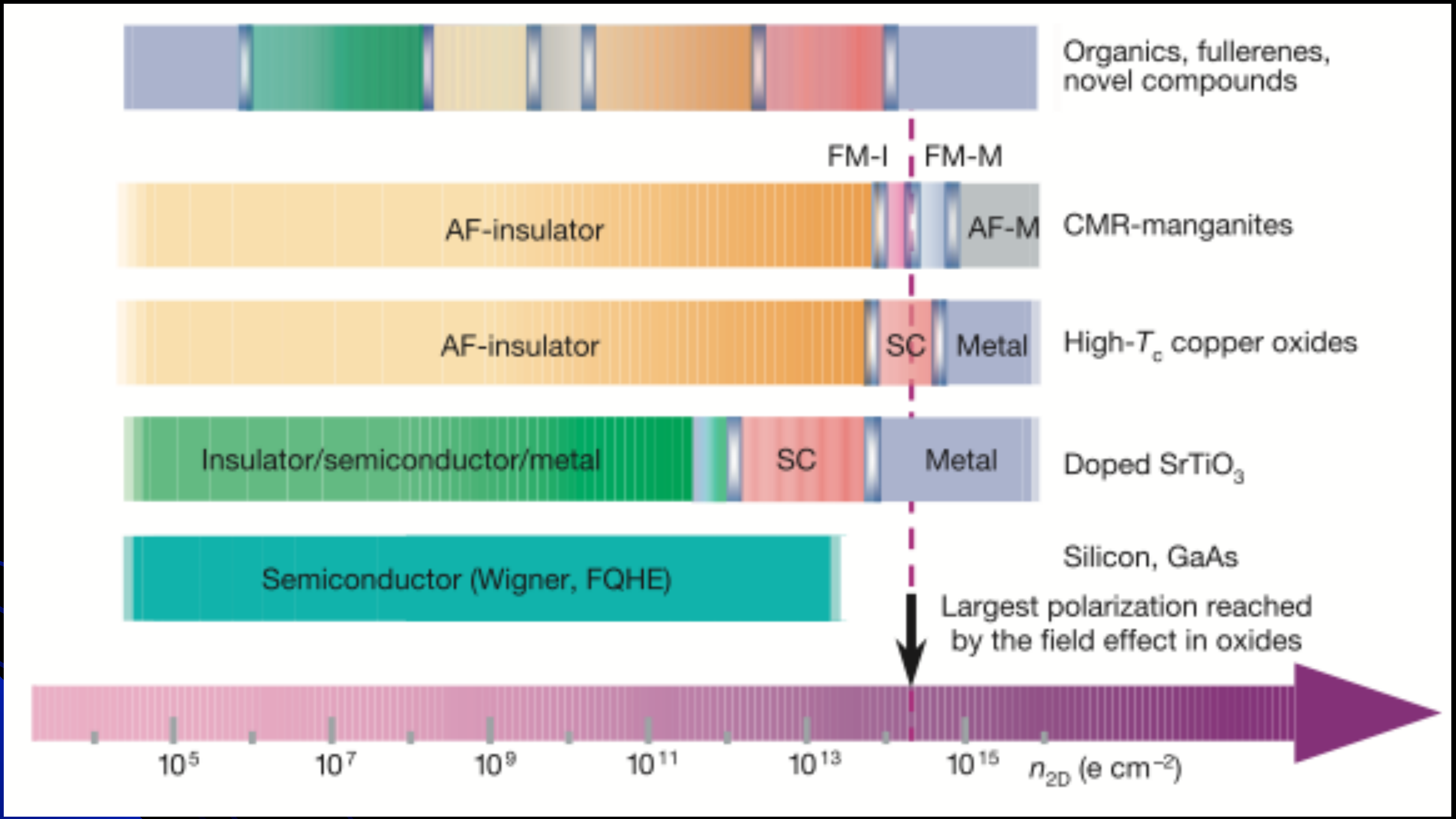
Z. Phys. B – Condensed Matter 83, 307–311 (1991)

- «… density of free carriers in the $YBa_2Cu_3O_{7-\delta}$ films can be modified by 1-2% with gate voltages smaller than 50 V. »



To induce large changes in the carrier concentration, i.e. ~ 10^{21} cm^{-3}, the breakdown field of the insulator is required to be at least 10^{8} V/cm and such an insulator does not exist.

Field effect & correlated oxydes

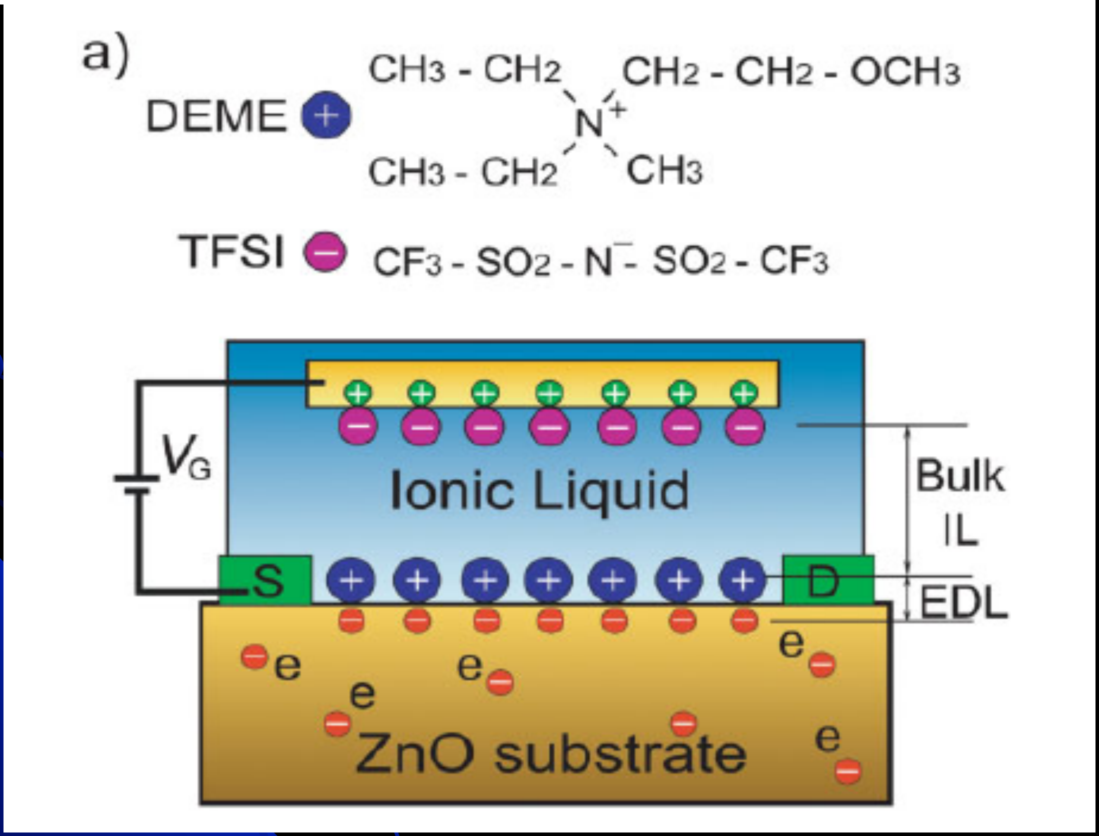


Ahn et al., Nature 424, 1015-1018(2003)

High-Density Carrier Accumulation in ZnO Field-Effect Transistors Gated by Electric Double Layers of Ionic Liquids

By *Hongtao Yuan,* Hidekazu Shimotani, Atsushi Tsukazaki, Akira Ohtomo, Masashi Kawasaki*, and *Yoshihiro Iwasa*

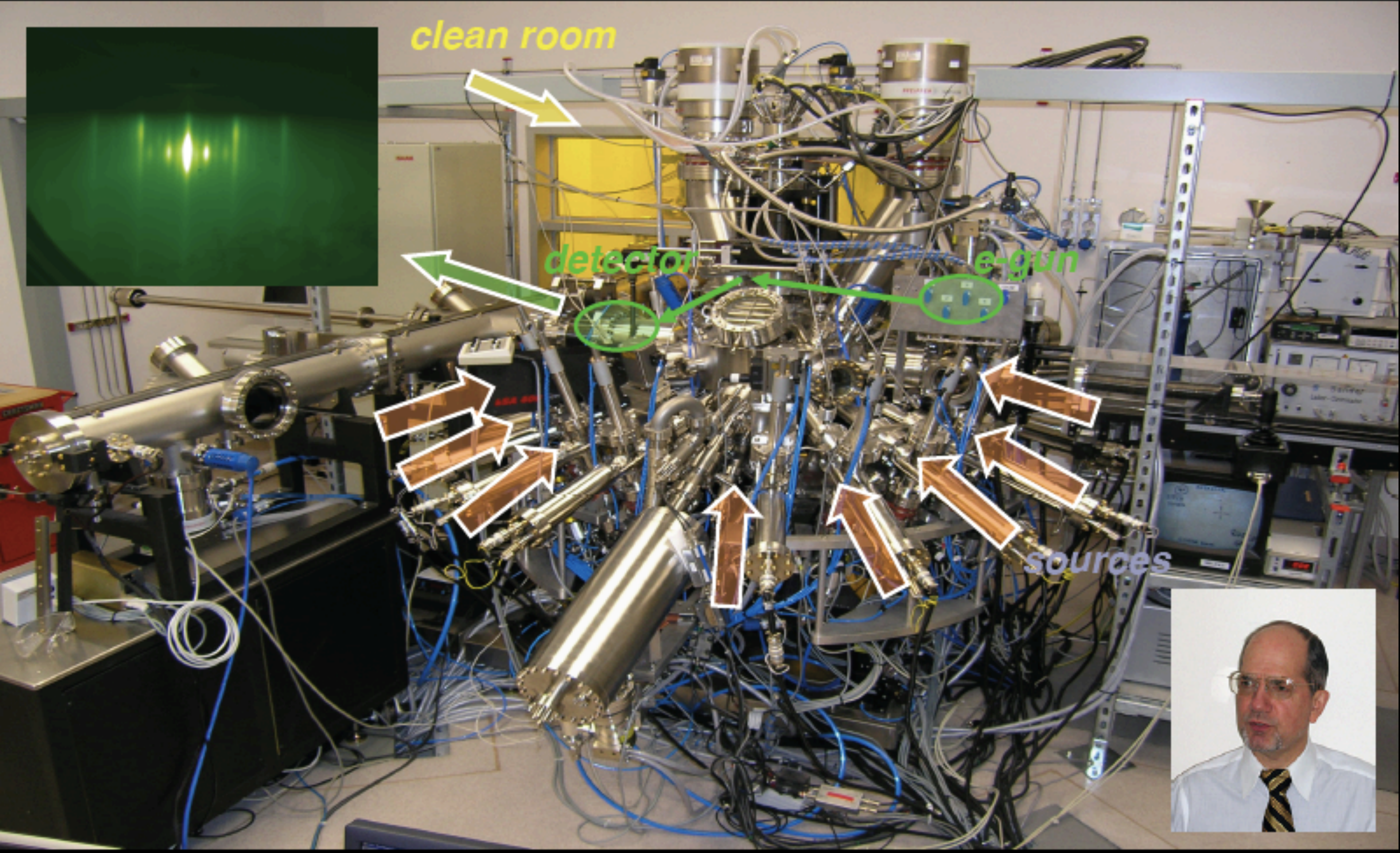
Adv. Funct. Mater. **2009**, *19*, 1046–1053



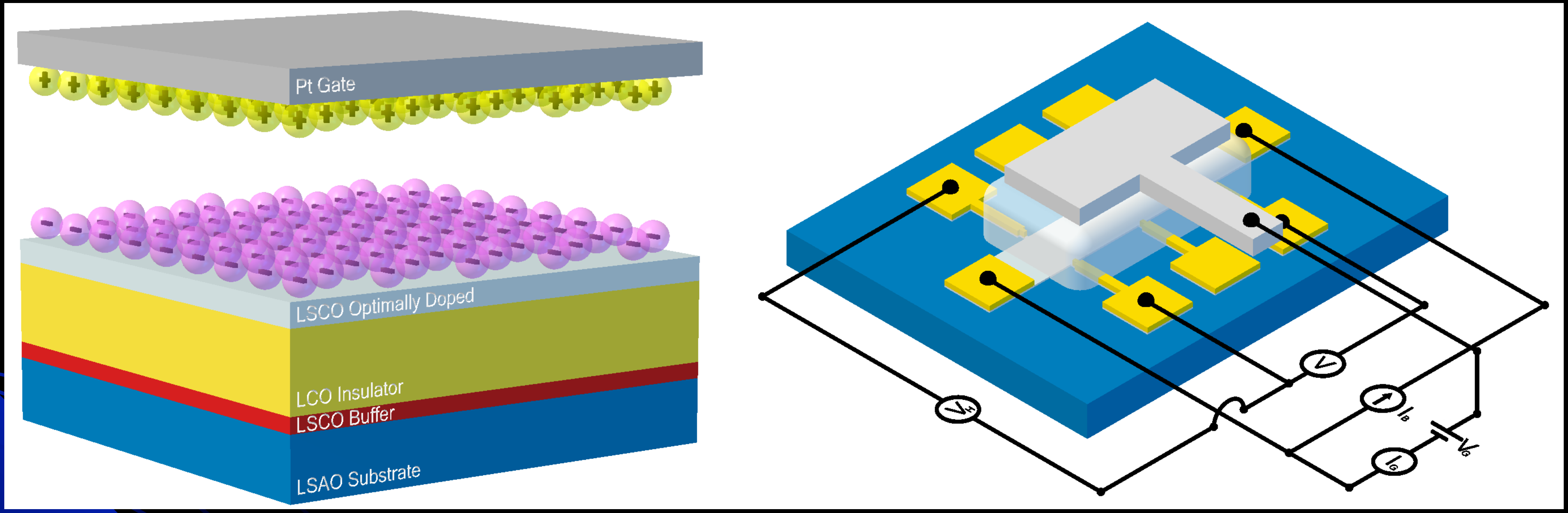
N,N-Diethyl-N-methyl-N-(2-methoxyethyl)ammonium

bis(trifluormethane sulfonyl)imide

Ivan Bozovic's ALL-MBE @BNL



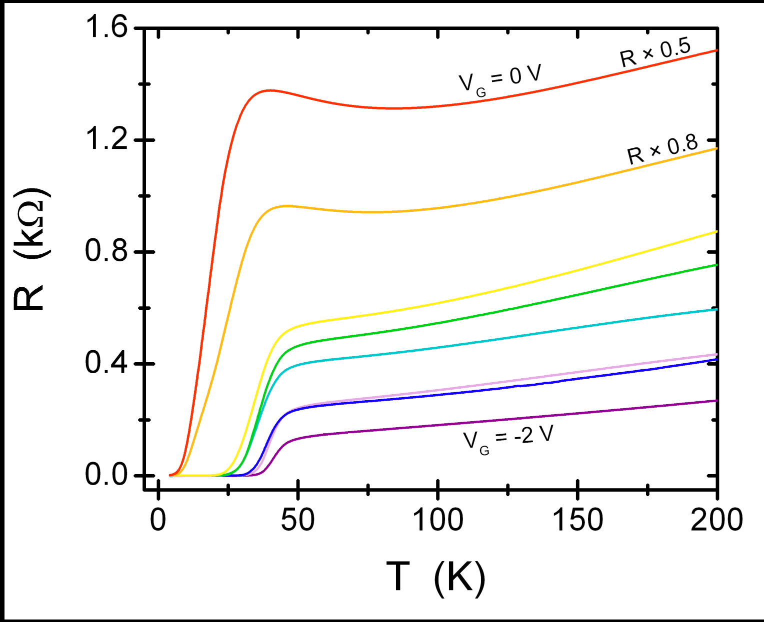
The Sample

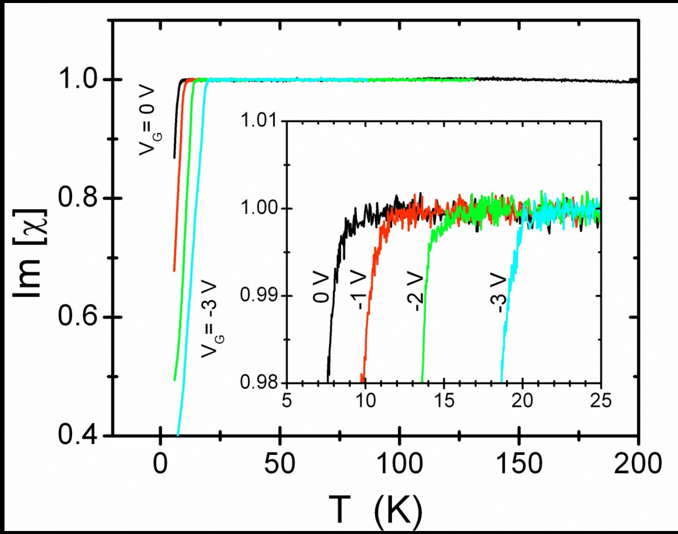


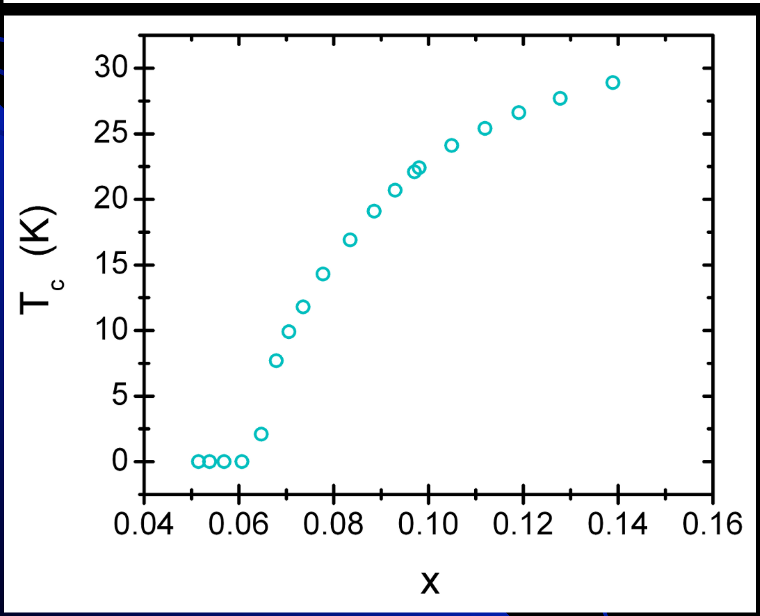
(i) 1 unit cell (UC) thick $La_{1.56}Sr_{0.44}CuO_4$ buffer layer
(ii) 5 UC of insulating La_2CuO_4 (LCO)
(iii) 1, 1.5, or 2 UC of $La_{2-x}Sr_xCuO_4$ (LSCO); x = 0.10-0.20

Nature 472, 458 (2011)

Electric field causes large changes in carrier density and T_c







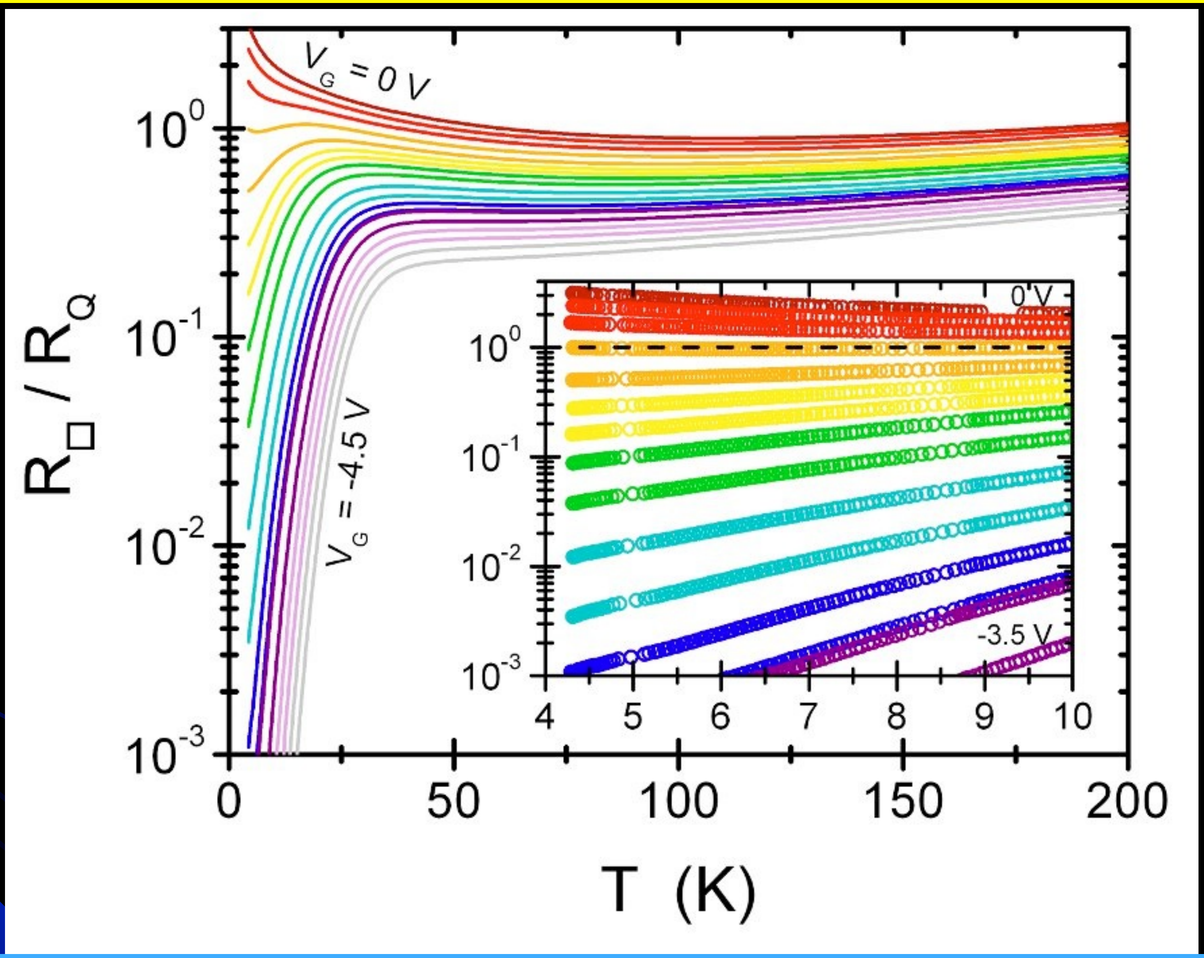
Diamagnetic response measured by 2-coil mutual inductance technique confirms the results of transport measurements

Field-induced shifts:

$\Delta x = \pm 0.04$, $\Delta T_c = 30$ K.

[Nature 2011]

S-I quantum phase transition induced by field effect in 1 UC thin LSCO layer

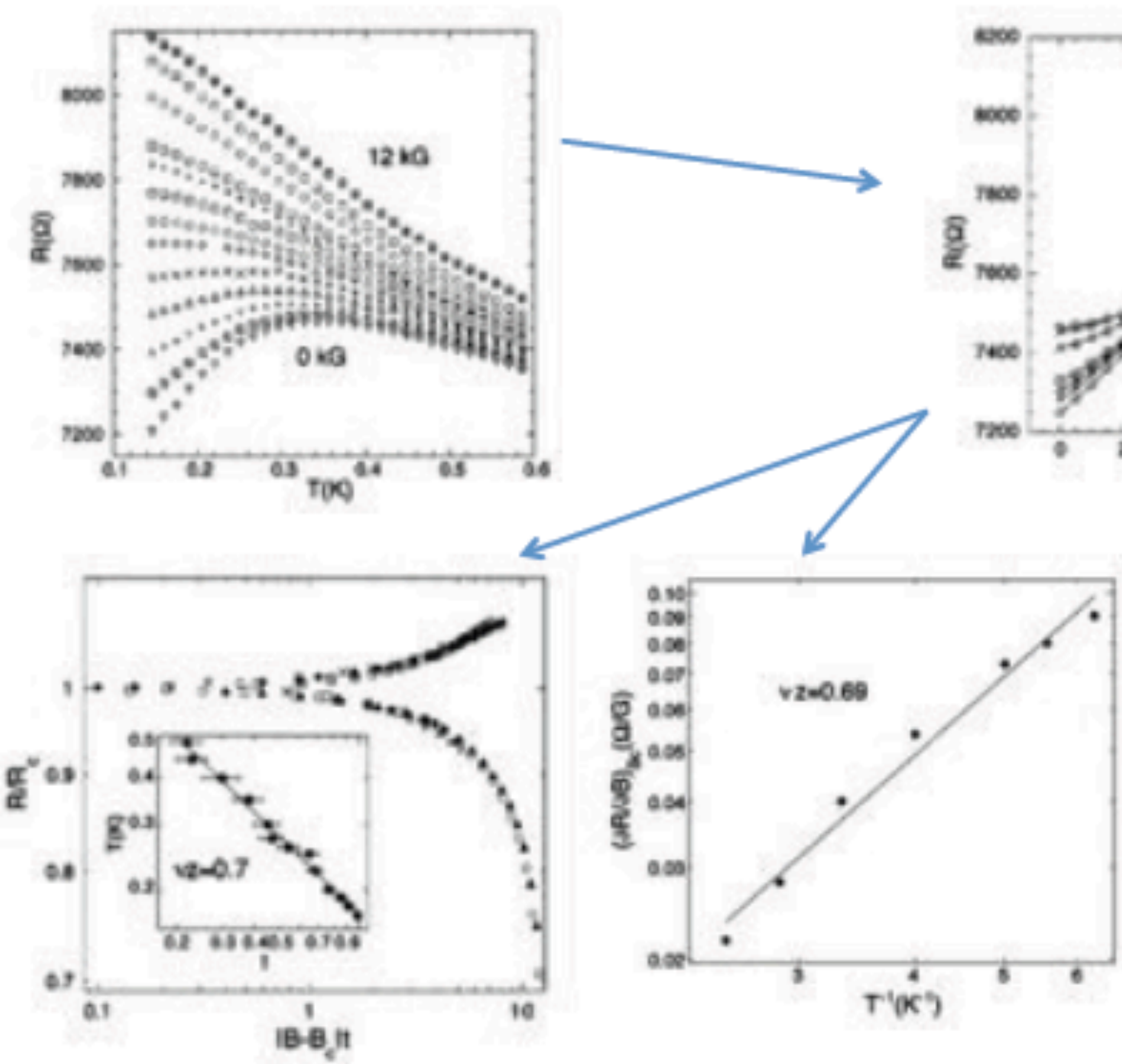


Note the T-independent separatrix at $R_\square = R_Q = 6.45\ k\Omega$; this corresponds to $\rho \approx 400\ \mu\Omega cm$

$R_Q \equiv h/(2e)^2 = 6.45\ k\Omega$

[Nature 2011]

Scaling Analysis (QPT)



z (dynamical critical exponent)
ν (correlation length exponent)

$$\delta = |K - K_C|$$

$$\xi \propto \delta^{-\nu} \quad \tau \propto \xi^{z} \propto \delta^{-z\nu}$$

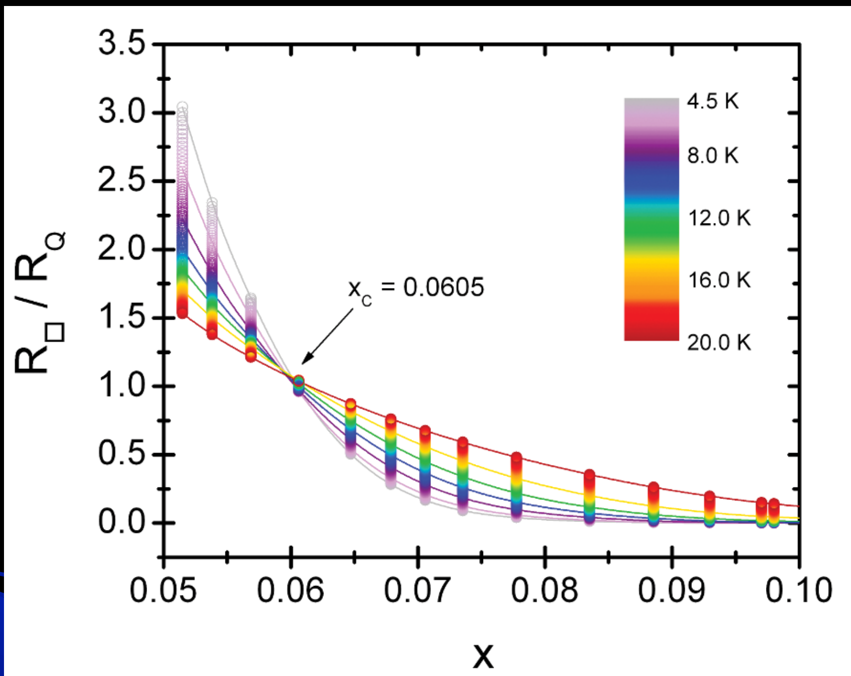
2D scaling relation of R :

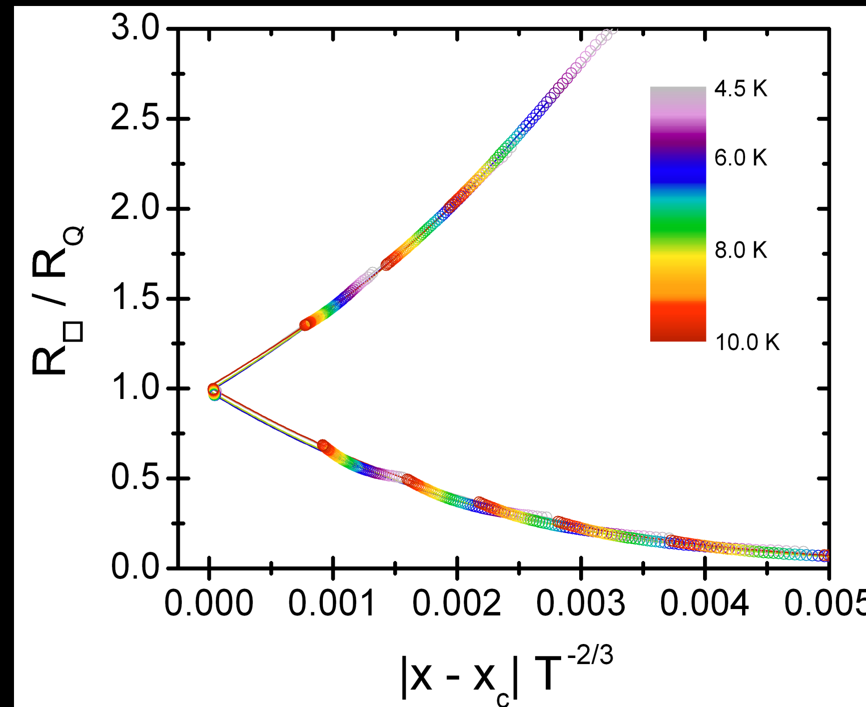
$$R(\delta, T) = R_C f\left(\delta T^{-1/\nu z}\right)$$

Markovic *et al.*, Phys. Rev. B. **60**, 4320 (1999).

The same data replot as a set of R(x) curves for finely scaled values of T

The same data scaled against a single variable $u = |x-x_c| / T^{2/3}$





Quantum critical point at $x_c = 0.06$

The critical resistance equal to $R_Q = h/(2e)^2 = 6.45$ kΩ. ➔ Existence of electron pairs on both sides of the quantum phase transition ➔ "Bosonic scenario": Cooper pair mobile and Bose-condensed, vortices localized and immobile on the S side; dual (reverse) on the I side ➔ 'Elusive Bose metal' at $x = x_c$

Good scaling to 2D S-I QPT ➔ ultrathin active layer ➔ field effect rather than chemistry

[Nature 2011]

CONCLUSIONS FROM OUR EXPERIMENTS

- ***The critical sheet resistance is equal to $R_Q = h/(2e)^2 = 6.45\ k\Omega$.***

➔ ***Existence of electron pairs on both sides of the quantum phase transition.***

➔ ***"Bosonic scenario": on the S side Cooper pairs are mobile and Bose-condensed, while vortices are bound; dual (reverse) on the I side.***

➔ ***Exact self-duality ➔ similar symmetry, interactions ➔***
➔ on-site Coulomb repulsion not sufficient?

➔ ***'Elusive Bose metal' at $x = x_c = 0.0605$***

+ ***several experiments in progress …***

nature nanotechnology

LETTERS

PUBLISHED ONLINE: 22 MAY 2011 | DOI: 10.1038/NNANO.2011.78

Discovery of superconductivity in $KTaO_3$ by electrostatic carrier doping

K. Ueno[1,2], S. Nakamura[3,4], H. Shimotani[5], H. T. Yuan[5], N. Kimura[4,6], T. Nojima[3,4], H. Aoki[4,6], Y. Iwasa[5,7] and M. Kawasaki[1,5,7]*

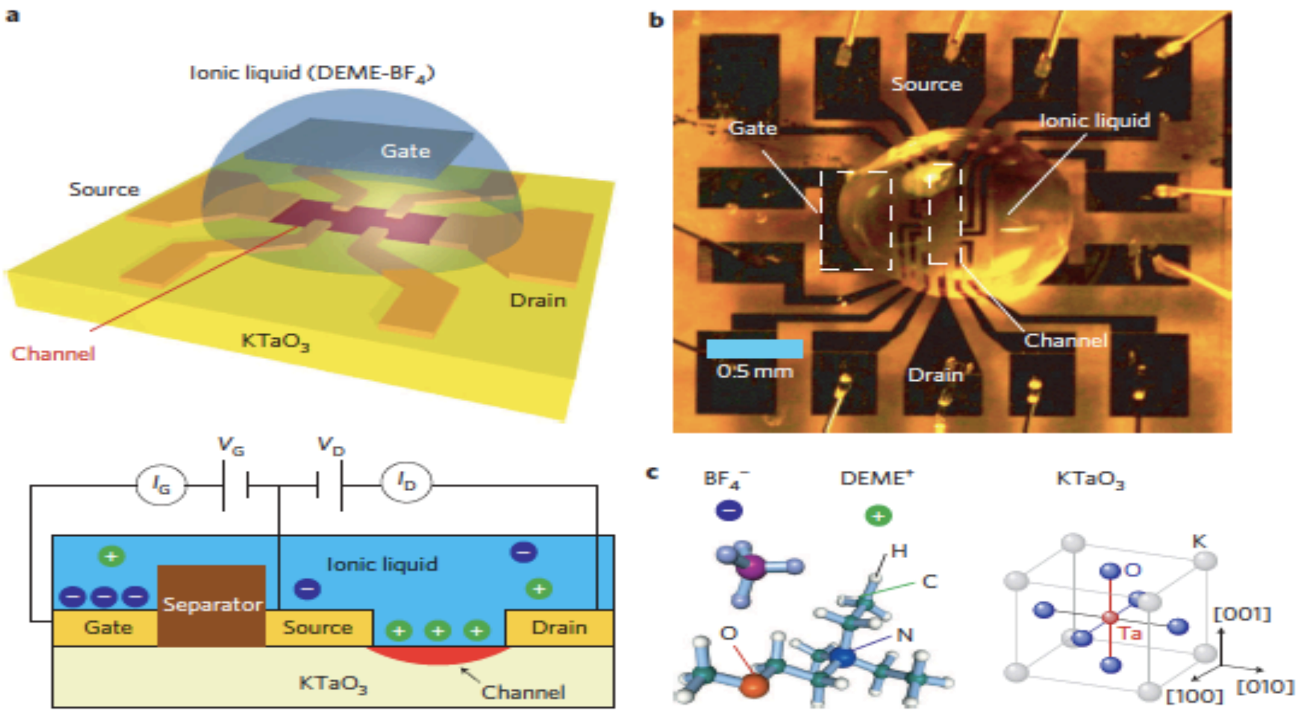
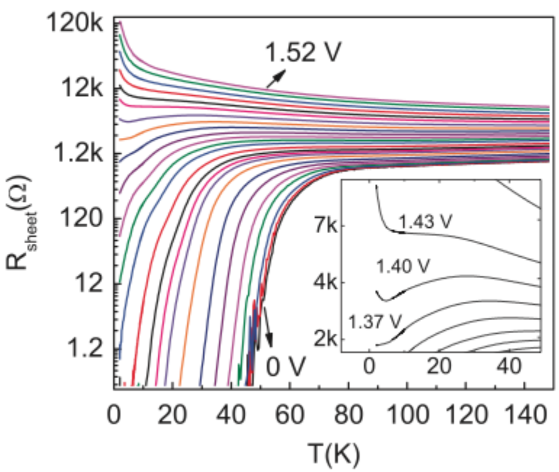
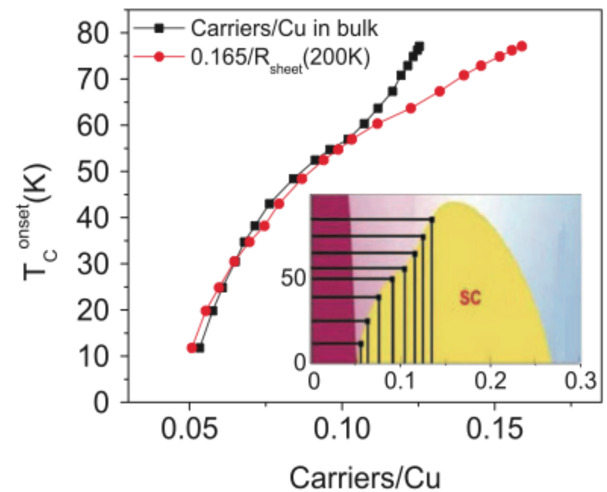


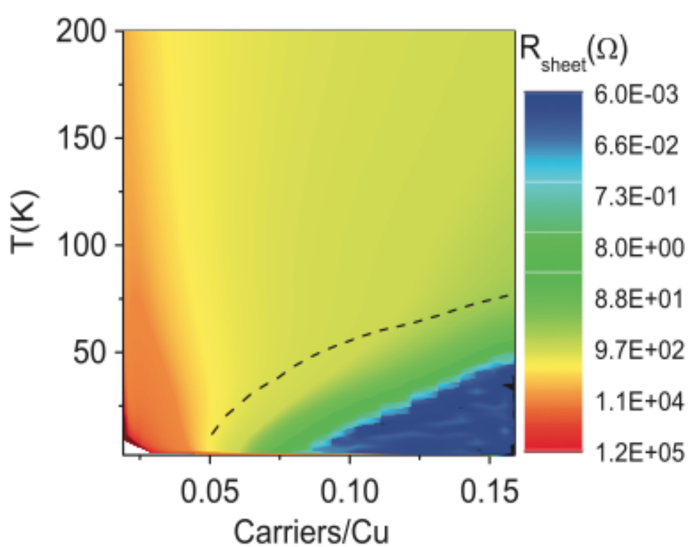
Figure 1 | Electric double-layer (EDL) transistor. a,b, Schematic diagrams (**a**) and photograph (**b**) of the EDL transistor with an ionic liquid electrolyte, DEME-BF_4. $DEME^+$ ions comprise the cations and BF_4^- ions are the anions. The device was fabricated on a $KTaO_3$ single crystal. Source, drain and gate electrodes were fabricated on the crystal (black area in the photograph), and the entire surface of the crystal, except for the channel area and electrodes, was covered by separator layer (yellow area in the photograph). A small amount of the ionic liquid was dropped on the crystal so that it covered the channel region ($KTaO_3$ surface) and the gate electrode. **c**, Molecular and crystal structures for the anion, cation and $KTaO_3$.

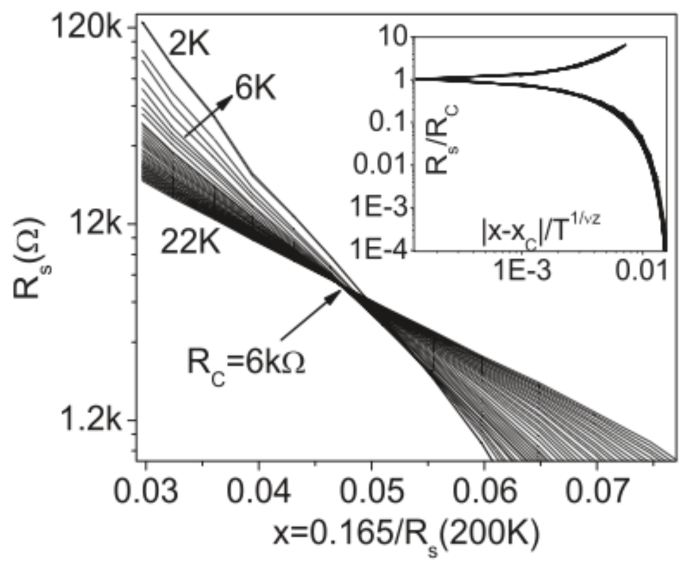
Electrostatic Control of the Evolution from a Superconducting Phase to an Insulating Phase in Ultrathin $YBa_2Cu_3O_{7-x}$ Films

Xiang Leng,[1] Javier Garcia-Barriocanal,[1] Shameek Bose,[2] Yeonbae Lee,[1] and A. M. Goldman[1]







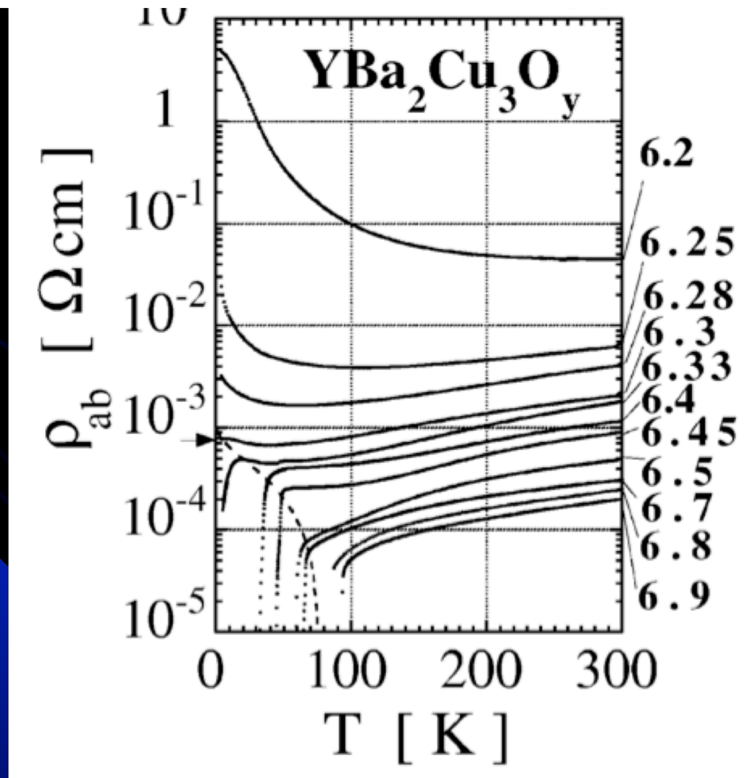


VOLUME 86, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JANUARY 2001

Superconductor-to-Insulator Transition and Transport Properties of Underdoped $YBa_2Cu_3O_y$ Crystals

Kouichi Semba and Azusa Matsuda
NTT Basic Research Laboratories, 3-1, Morinosato Wakamiya, Atsugi-shi Kanagawa 243-0198, Japan
(Received 30 November 1998; revised manuscript received 5 July 2000)

The *carrier-concentration-driven* superconductor-to-insulator (SI) transition as well as transport properties in underdoped $YBa_2Cu_3O_y$ twinned crystals is studied. The SI transition takes place at $y \simeq 6.3$, carrier concentration $n_H^{SI} \simeq 3 \times 10^{20}\ \mathrm{cm}^{-3}$, anisotropy $\rho_c/\rho_{ab} \simeq 10^3$, and the threshold resistivity $\rho_{ab}^{SI} \sim 0.8\ \mathrm{m\Omega\ cm}$ which corresponds to a critical sheet resistance $\frac{h}{4e^2} \simeq 6.5\ \mathrm{k\Omega}$ per CuO_2 bilayer. The evolution of a carrier, $n_H \propto y - 6.2$, is clearly observed in the underdoped region. The resistivity and Hall coefficient abruptly acquire strong temperature dependence at $y \simeq 6.5$ indicating a radical change in the electronic state.



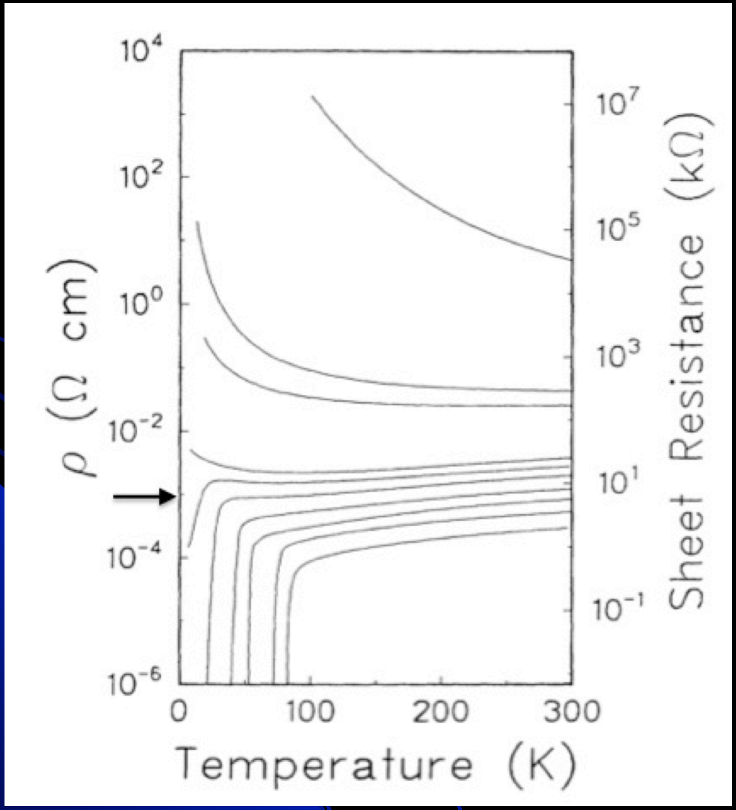
Again
Rc ≈ h/(2e)² (Arrow)

PHYSICAL REVIEW B VOLUME 44, NUMBER 5 1 AUGUST 1991-I

Two-dimensional electron localization in bulk single crystals of $Bi_2Sr_2Y_xCa_{1-x}Cu_2O_8$

D. Mandrus, L. Forro,* C. Kendziora, and L. Mihaly
Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794-3800
(Received 25 February 1991; revised manuscript received 16 May 1991)

The temperature dependence of the *ab*-plane electrical transport was investigated on a series of single-crystal $Bi_2Sr_2Y_xCa_{1-x}Cu_2O_8$ samples with a wide range of yttrium content. The observed metal-insulator transition is discussed in terms of two-dimensional localization. The Hall-effect and thermopower results indicate that the driving force of the localization is the random impurity potential.



One of the first observations of Rc ≈ h/(2e)² (Arrow)

Interface Superconductivity & New Superconductors

Ivan Bozovic (BNL)

Interface superconductivity: *a modern classic*

D. Saint-James and P. G. De Gennes	Phys. Lett. **7** 306 (1963)
V. L. Ginzburg	Phys. Lett. **13**, 101 (1964)

M. Strongin	Phys. Rev. Lett. **10**, 442 (1964)

Web of Science: "**Interface superconductivity**"

1973-2012 **1006** papers

1973-1976 **3** papers (*Overton '73, Tsuei '74, Ickson '75)*

2009-2012 **292** papers
(*Nature* 12, *NM* 8, *NP* 4, *NC* 2, *Science* 6, PRL 40, PRB 188; $\Sigma = 260$)

Why is *IS* difficult?

Conventional metals - BCS superconductors:

n ~ 1023 cm-3 $\Rightarrow$ l_{TF} ~ 2-3 Å

ξ ~ 100-1,000 Å (870 Å in lead, 16,000 Å in Al,…)

$\Rightarrow$ the modified (interface) layer is too thin for SC to occur!

Plus, reduction in carrier density generally *decreases* T_c.

Cuprates: $n \sim 1\text{-}5{*}10^{21}$ cm^{-3} $\Rightarrow$ l_{TF} ~ 5-10 Å

high T_c $\Rightarrow$ short coherence length

extreme anisotropy $\Rightarrow$ ξ_c ~ 1-2 Å

in OD cuprates, reduction in n *increases* T_c.

$SrTiO_3$:

$n \sim 10^{18}\text{-}10^{19}$ cm^{-3} $\Rightarrow$ l_{TF} ~ 5-10 nm

$\Rightarrow$ a chance to realize interface superconductivity!

$LaAlO_3$ / $SrTiO_3$ & related

2004: Discovery of high-mobility 2DEG *(Ohtomo & Hwang)*

2007: Discovery of interface superconductivity *(Triscone & Mannhart)*

2008: Electric field control *(Triscone & Mannhart)*

2009: Thickness of 2DEG measured by cross-section AFM *(Basletic)*

2009: Quantum oscillations *(Hwang)*

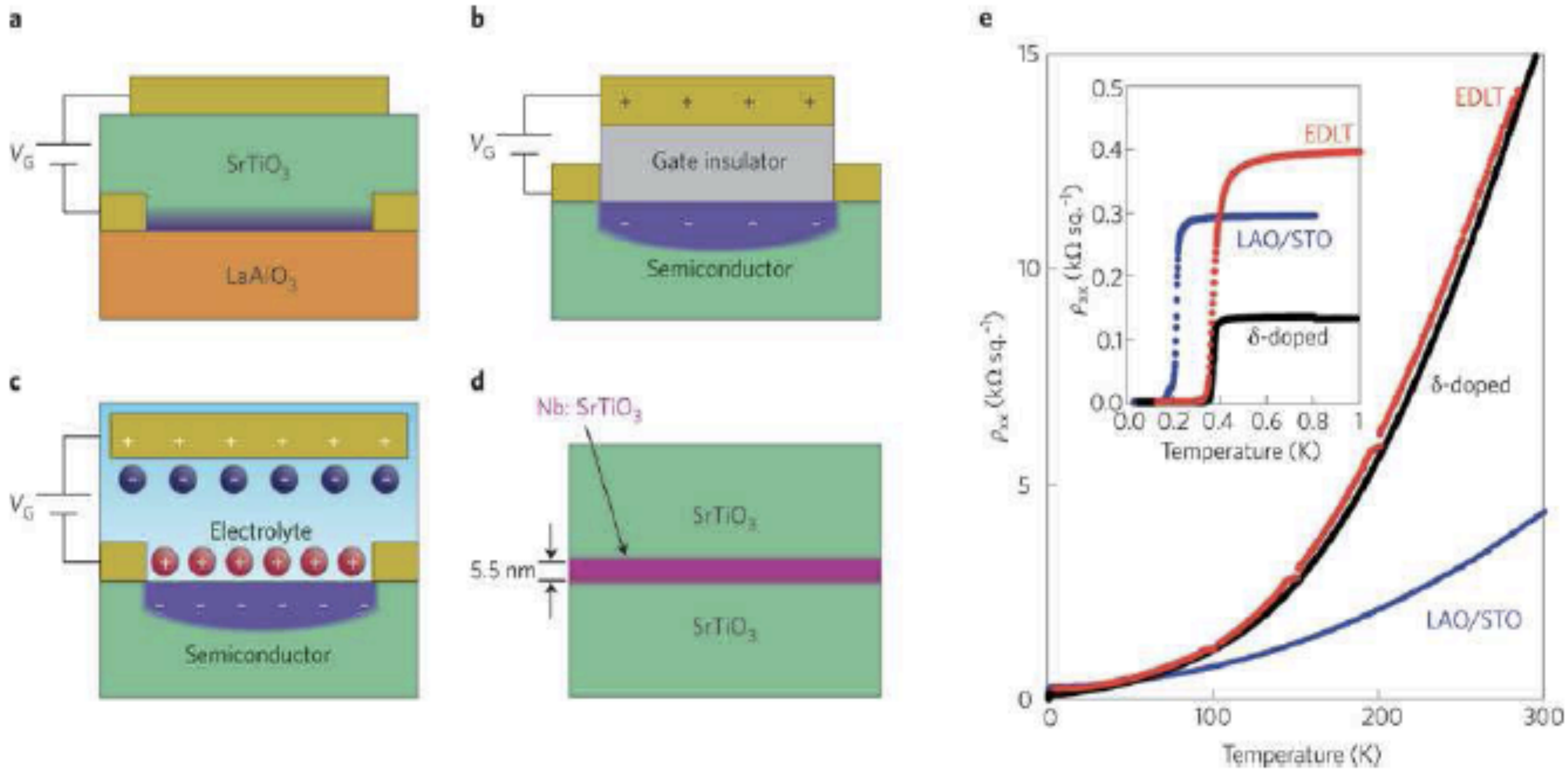
2009-11: Ferromagnetism *(Hilgenkamp, Ashoori, Moller, Mannhart, Eom, Schuller)*

2010: Tunable Rashba Spin-Orbit coupling *(Triscone, Dagan, Hwang)*

2010: Interface superconductivity in $LaTiO_3$ / $SrTiO_3$ *(Lesueur)*

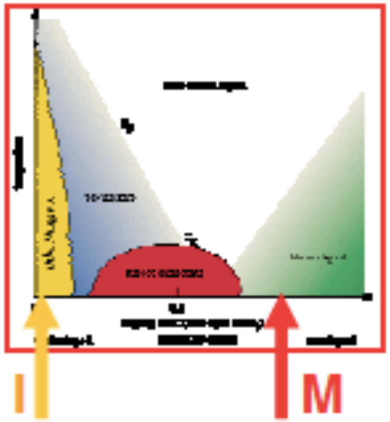
2011: Enhancement of T_c in $H_{||}$ *(Schlom)*

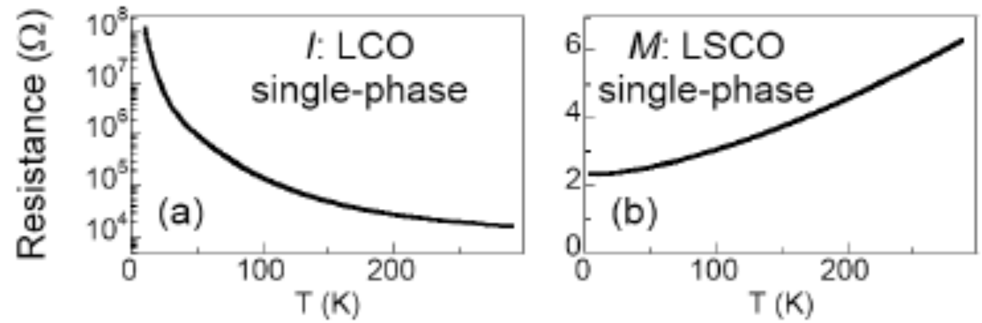
Devices used to produce 2D or interface superconductivity



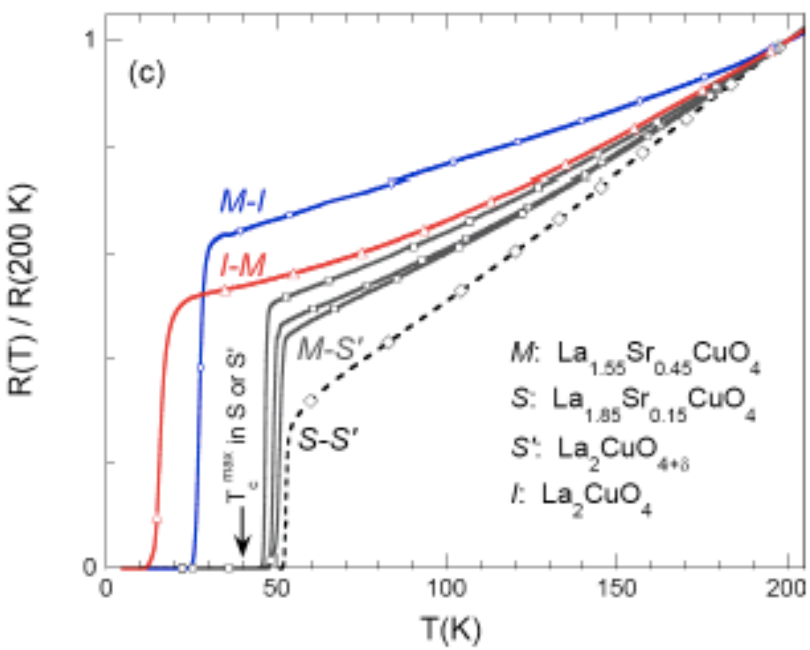
Hwang, Iwasa, Kawasaki, Keimer, Nagaosa & Tokura, *Nature Matter.* 11, 108 (2012)

INTERFACE SUPERCONDUCTIVITY IN CUPRATES





R(T) for single-phase layers of *I* and *M*.



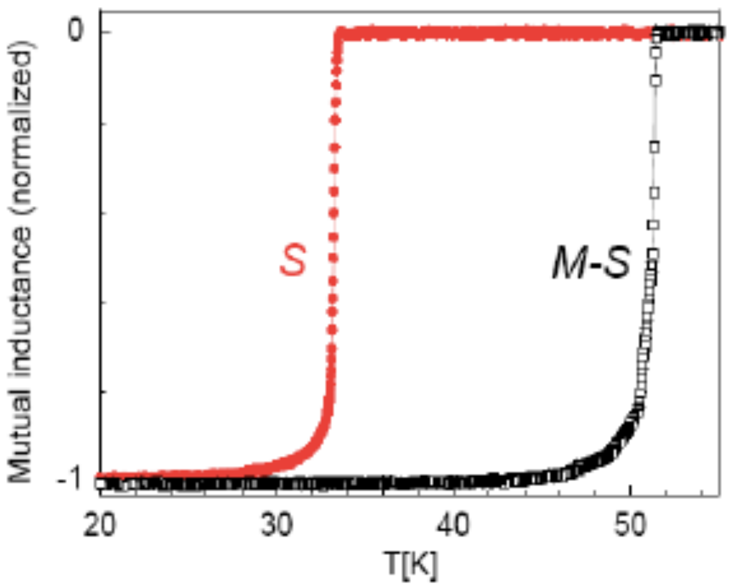
R(T) for various bilayers.

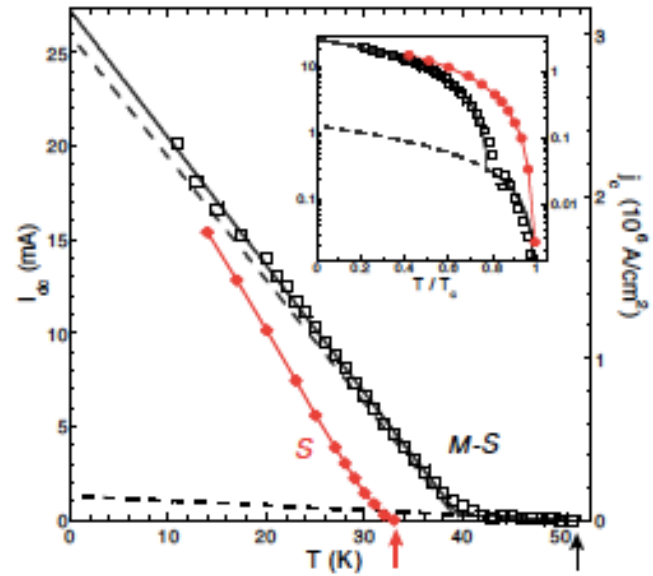
I-M and *M-I* bilayers show superconductivity even though neither of the two constituents does.

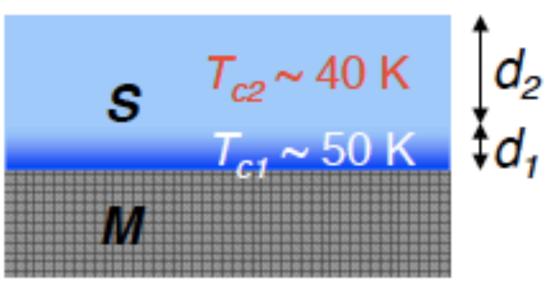
In single-phase *S* or *S′* films grown under the same conditions $T_c \leq$ 40 K.

Gozar et al., *Nature* **455**, 782 (2008)

INTERFACE-ENHANCED SUPERCONDUCTIVITY





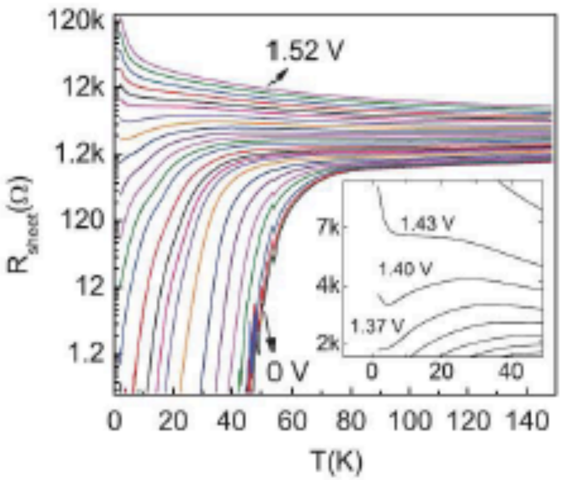


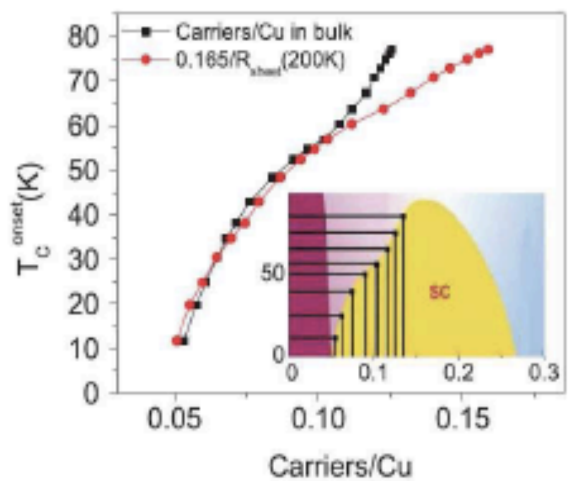
$d_1 \sim$ 1-2 UC (~2 nm)

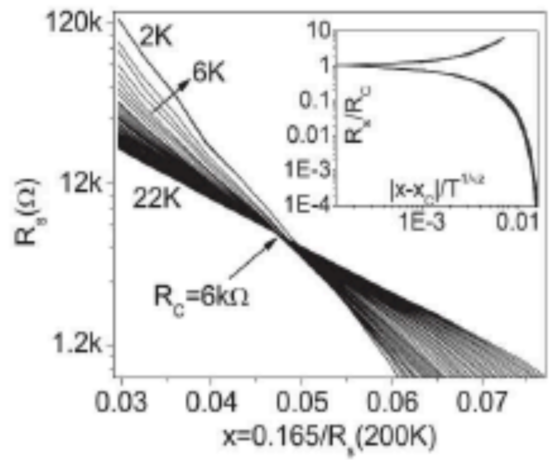
the 25% enhancement in T_c is an interface effect

Bollinger et al., *Nature* **472**, 458 (2011)

Superconductivity at ELT / $YBa_2Cu_3O_{7-x}$ Interface







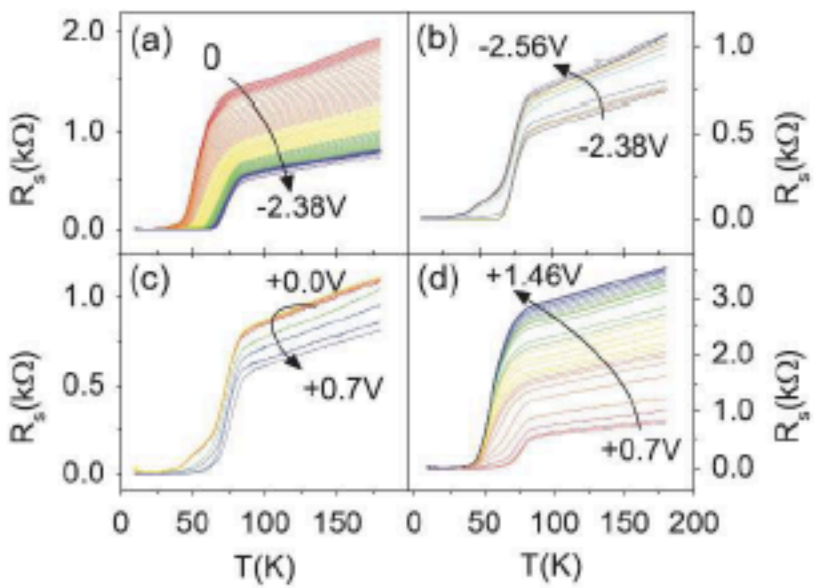
Sheet resistance vs temperature, tuned by the gate voltage.

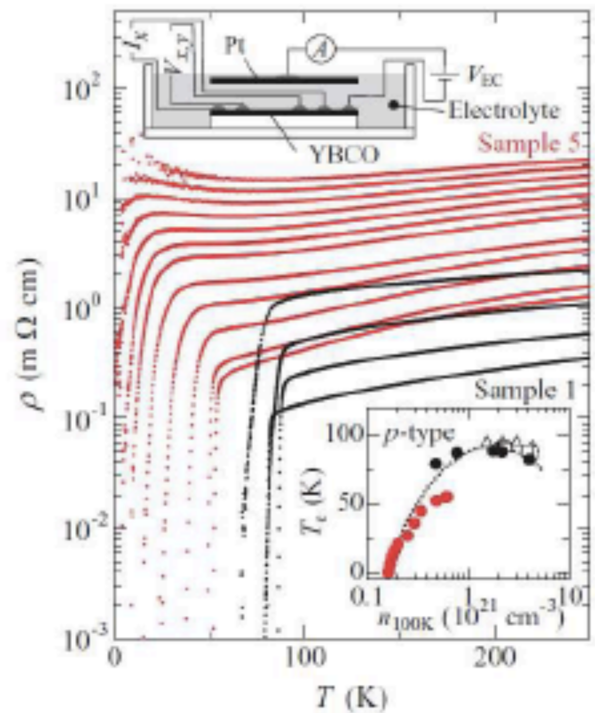
T_c vs carrier density

R(x) isotherms. Inset: 2D QCP scaling, for $R_c = h/4e^2$; $\nu z = 2.2$.

Leng et al., *PRL* **107**, 027001 (2011)

Field effect reveals new physics in $YBa_2Cu_3O_{7-x}$





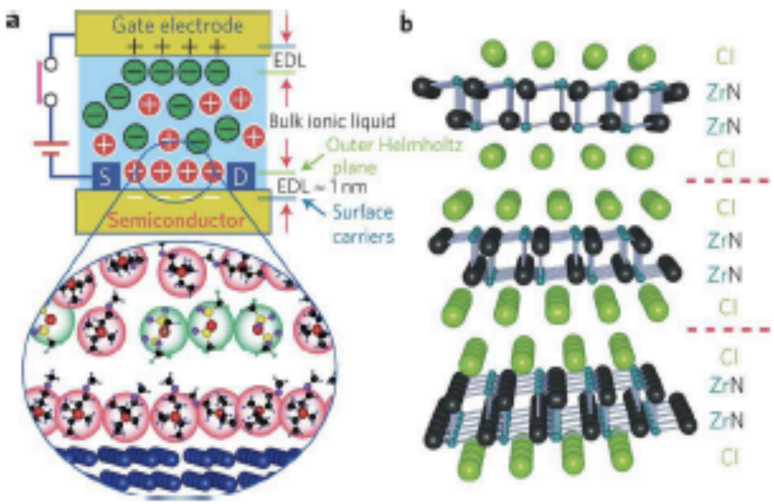
Electronic phase transition in the Fermi surface near the optimal doping level.

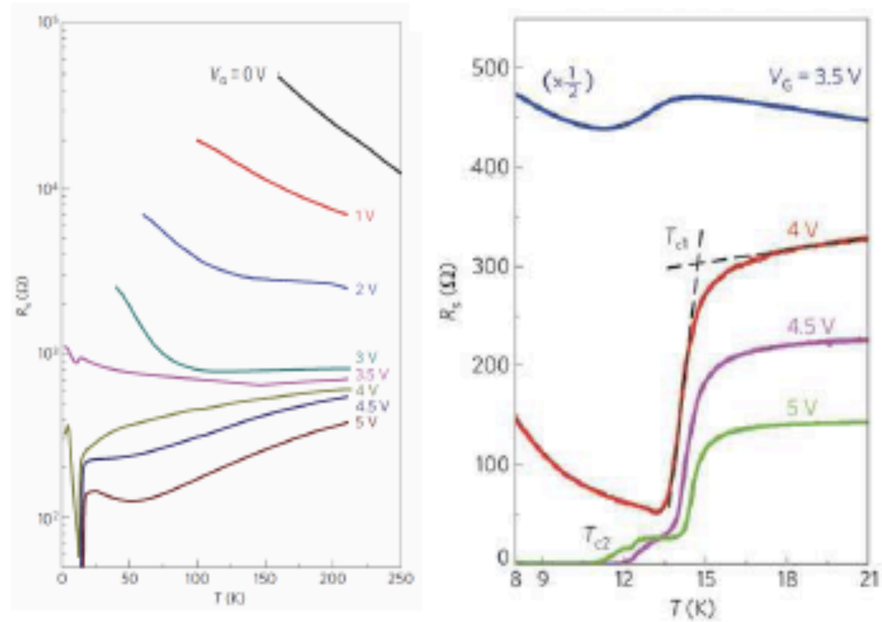
Metallic but non-superconducting YBCO, doped n-type by electrolyte field-effect

Leng et al., *PRL* **108**, 067004 (2012)

Nojima et al., *PRB* **84**, 020502 (2011)

Superconductivity at ELT / ZrNCl Interface





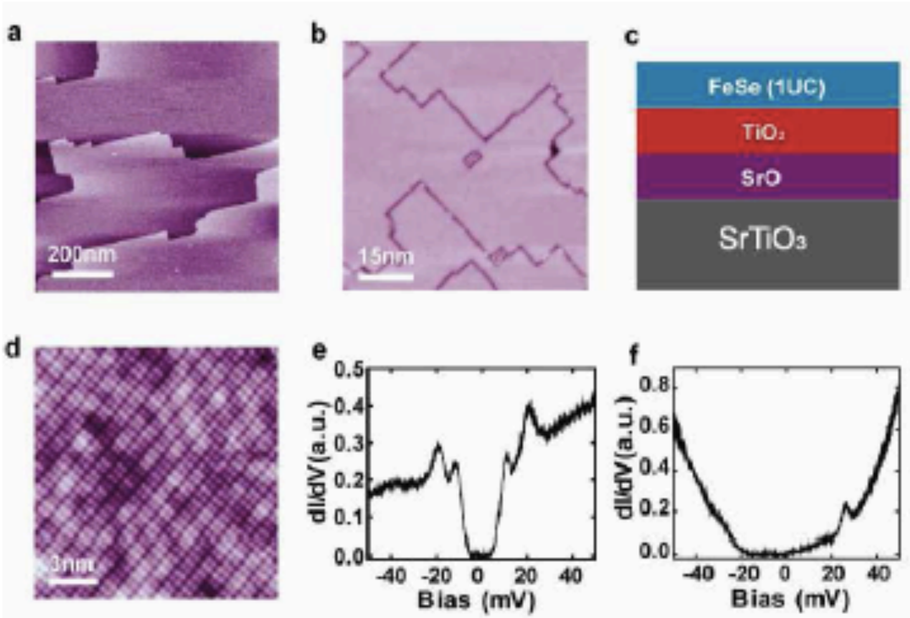
(a) Schematics of EDLT

(b) The crystal structure of ZrNCl

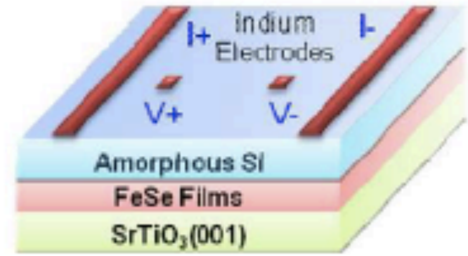
Temperature dependence of the channel sheet resistance at different gate voltages for a ZrNCl/$SrTiO_3$ bilayer.

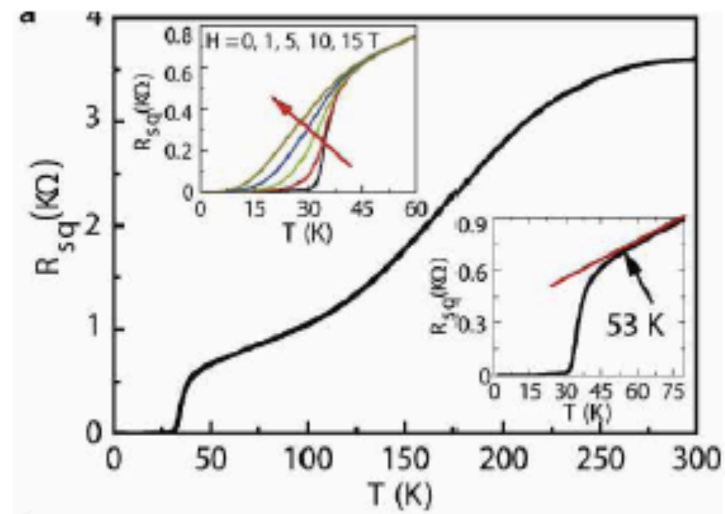
Ye et al, *Nature Matter.* 9, 125 (2010)

INTERFACE-ENHANCED SUPERCONDUCTIVITY IN FeSe



a) $SrTiO_3$ substrate, b) FeSe film, c) schematics, d) topograph showing Se termination, e) 1 UC film, f) 2UC film.



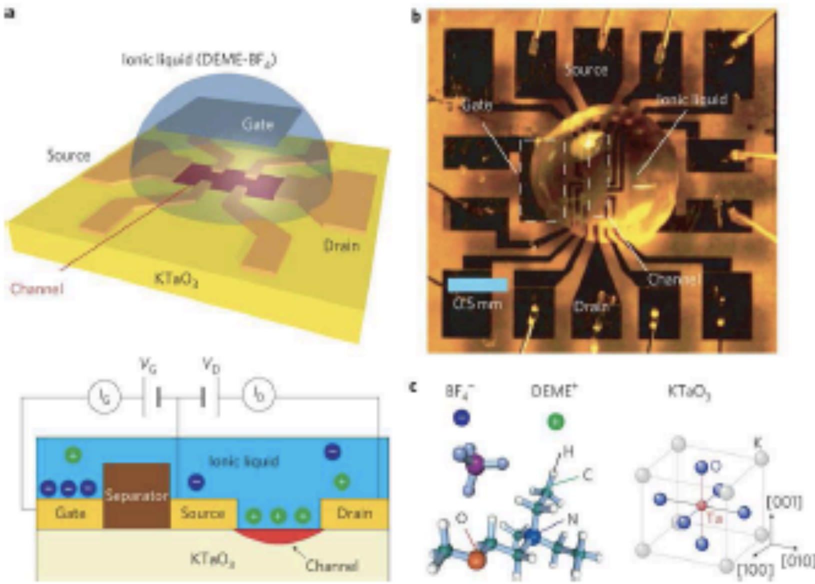


NB: In bulk FeSe, $T_c = 9.4$ K

Yan et al., *Chin. Phys. Lett.* 29, 037402 (2012)

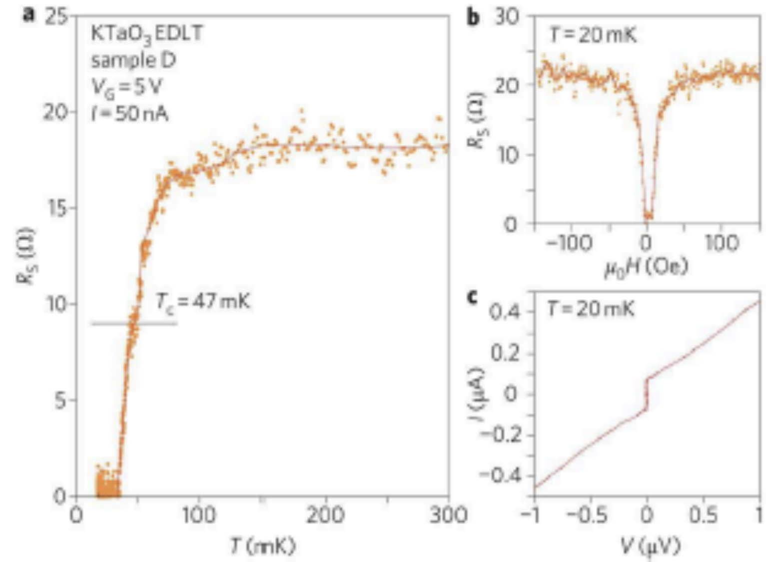
New Superconductors

Superconductivity at ELT / $KTaO_3$ interface



(a) EDLT schematics; (b) EDLT photo.

(c) the structure of BF^{4-}, $DEME^{+}$ and $KTaO_3$.



(a) Sheet resistance vs temperature, for $V_G = 5$ V.

(b) R_s *vs H,* at T = 20 mK.

(c) *I-V* characteristics, at T = 20 mK.

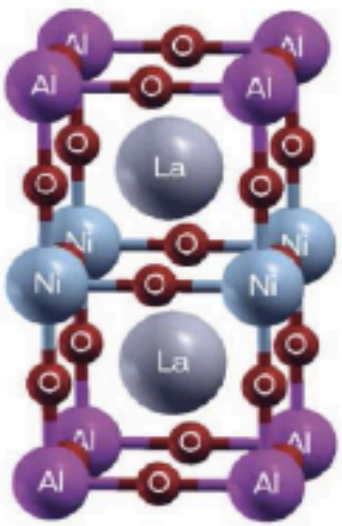
Ueno et al., *Nature Nanotech.* **6**, 408 (2011)

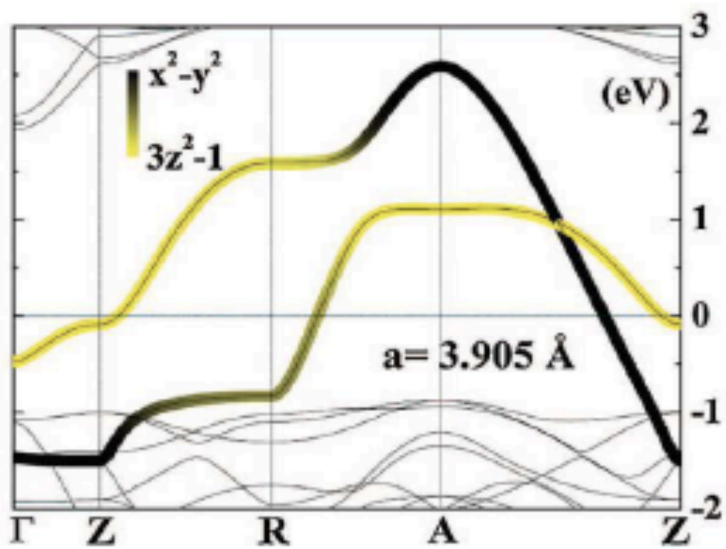
Prediction of HTS in $LaMO_3/LaNiO_3$ (M = Al, Ga, Ti,…)

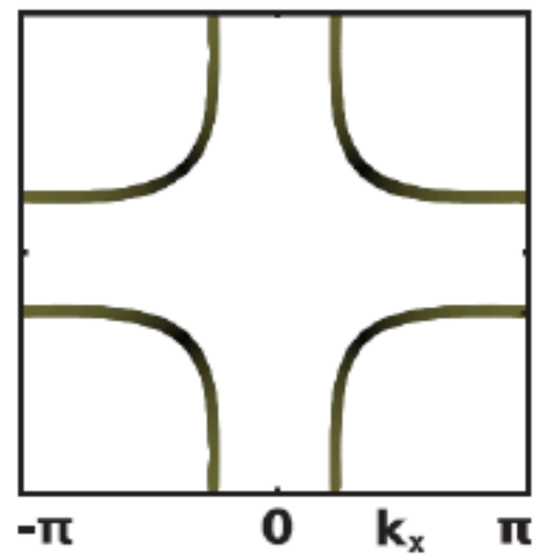
PRL **100,** 016404 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

Orbital Order and Possible Superconductivity in $LaNiO_3/LaMO_3$ Superlattices

Jiří Chaloupka[1,2] and Giniyat Khaliullin[1]







Hansmann et al, *PRL* 103, 016401 (2009)

Summary: What have we learned so far?

1. Interface superconductivity has been realized by (a) atomic-layer synthesis, and (b) electric-field effect (mainly using electrolytes).

2. New techniques have been developed to measure profiles of chemical composition, crystallographic structure, mobile carrier concentration, and superfluid density across the interfaces, with atomic resolution.

3. In the cleanest samples, the predominant mechanism is electronic reconstruction and ionic displacements.

4. quasi-2D superconductivity has been observed in $SrTiO_3$, LSCO, YBCO, etc., with T_c as high as in bulk samples.

5. A new superconductor, $KaTaO_3$ ($T_c = 0.047$ K), has been created by field effect.

6. Enhanced superconductivity has been observed at LSCO/LCO (+25%), $SrTiO_3$/FeSe (+200%), and PbTe/PbS (+600%) interfaces.

Outlook: some open questions

A. $SrTiO_3$

Inhomogeneity: electronic or atomic (e.g. oxygen vacancies)?

Role of ferromagnetism, Rashba spin-orbit coupling, Kondo effect?

Partners other than $LaAlO_3$: band, Mott, FM, AF, FE, etc.

Other titanates: $BaTiO_3$, $CaTiO_3$, $DyTiO_3$, $LaTiO_3$; $Sr_3Ti_2O_7$, ...?

The mechanism of superconductivity – conventional?

B. Cuprates

Cuprates other than LSCO and YBCO: $CaCuO_2$, $SrCuO_2$, n-type?

Non-cuprate partner materials (insulators, metals)?

C. Other superconductors

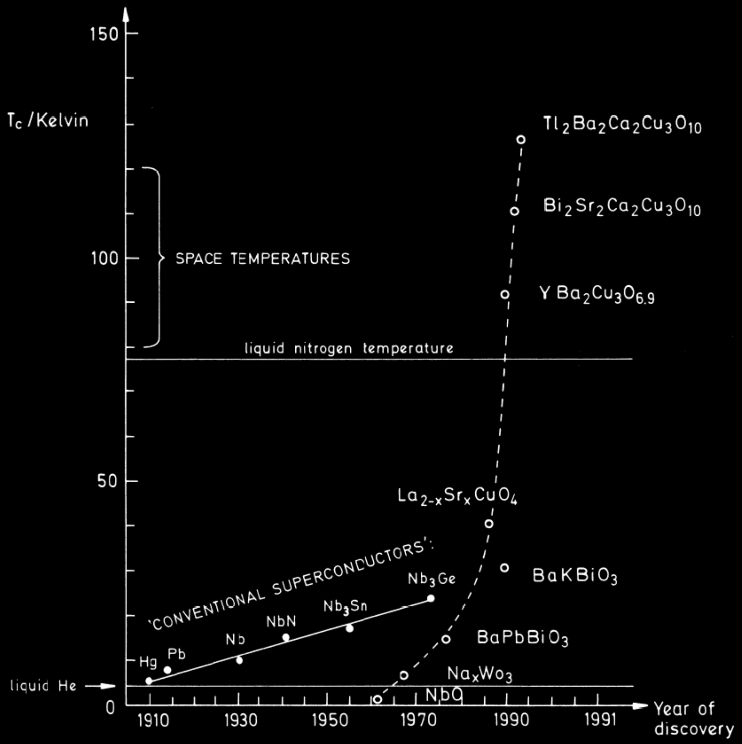
Heterostructures based on other known superconductors?

Electric-field tuning of S-I and S-M quantum phase transitions?

Beyond 2012:
‘*Gate Every Electronic Material*’

>300 K

Our (Students') Dream !



2100


Pavuna Group