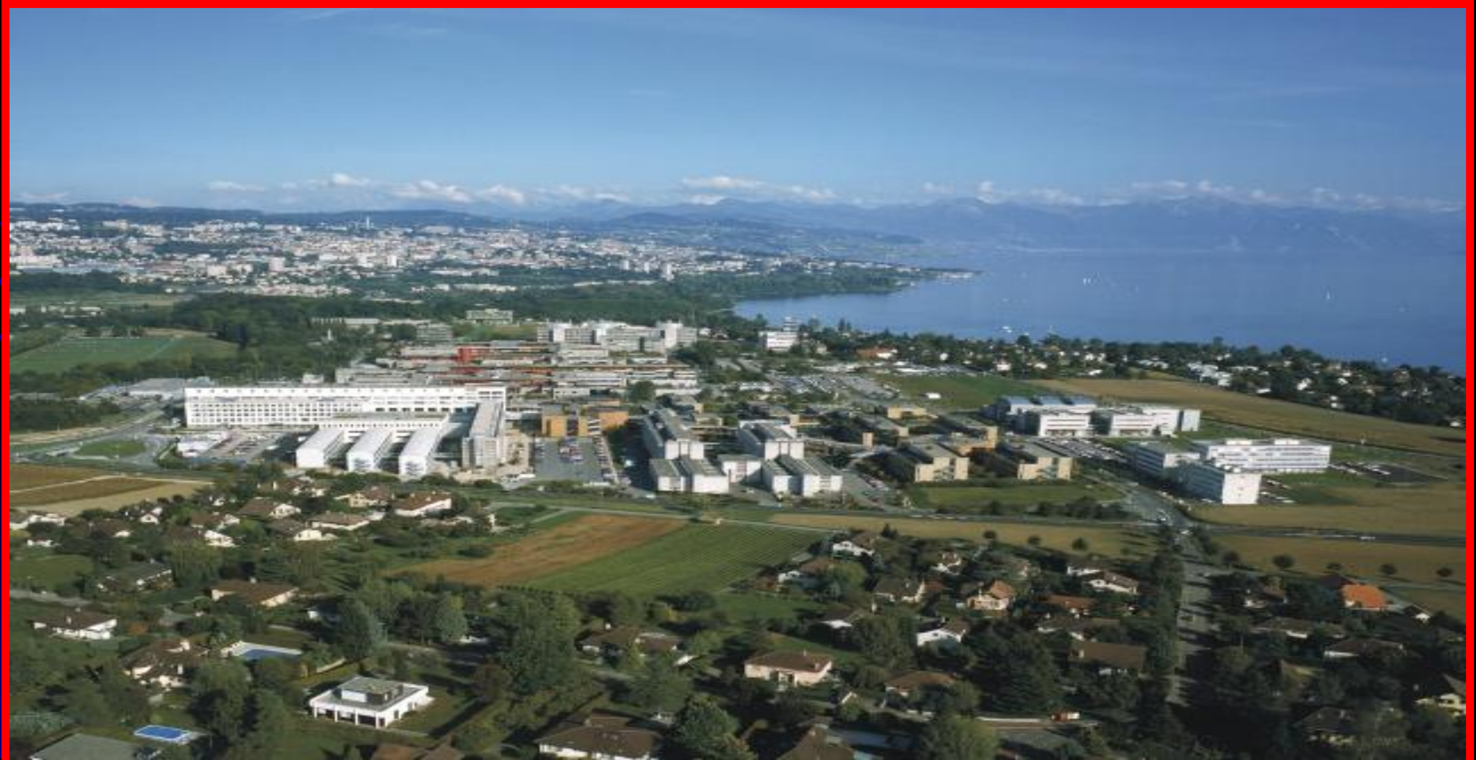
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Student Guide to RT-Superconductivity :
Physics & Nano-Engineering

Davor Pavuna

Institute of Physics of Complex Matter



SC **History, Teaching & Our Struggles**

Higher-Tc MATERIALS:

Direct ARPES on Thin High-Tc Films:

Heteroepitaxy &The Role of Strain

OUR CONVICTIONS:

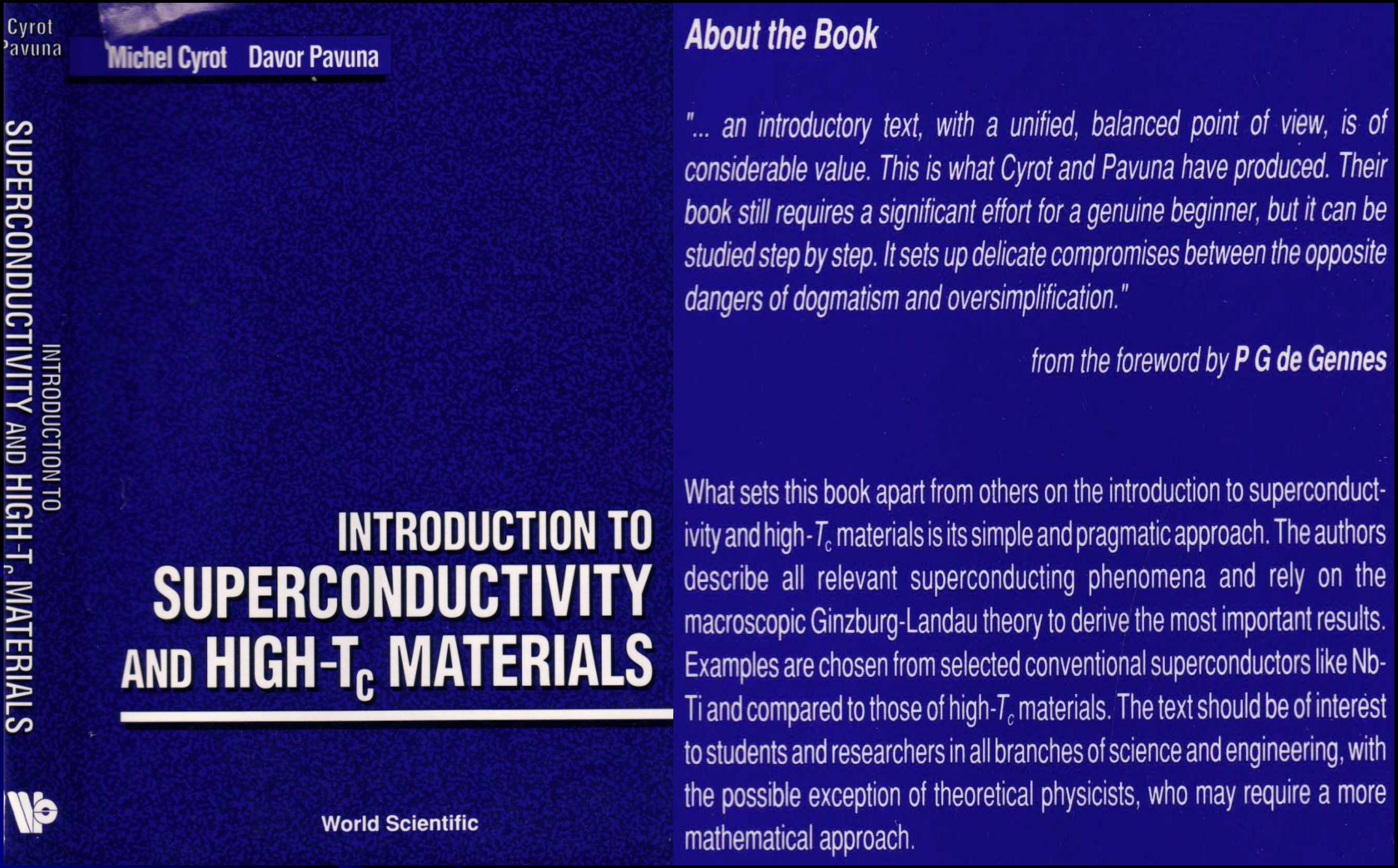
Beyond High-Tc

To All of You :

My Profound Gratitude

Pierre-Gilles de Gennes

Introductory Superconductivity Textbook (1992):



Cyrot
Pavuna

INTRODUCTION TO
SUPERCONDUCTIVITY AND HIGH-T_c MATERIALS

Michel Cyrot Davor Pavuna

INTRODUCTION TO
SUPERCONDUCTIVITY
AND HIGH-T_c MATERIALS

World Scientific

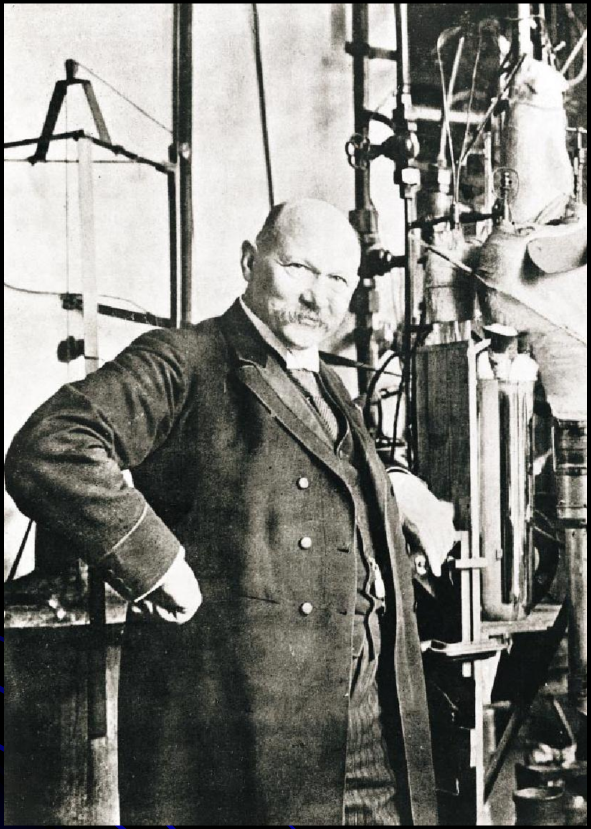
About the Book

"... an introductory text, with a unified, balanced point of view, is of considerable value. This is what Cyrot and Pavuna have produced. Their book still requires a significant effort for a genuine beginner, but it can be studied step by step. It sets up delicate compromises between the opposite dangers of dogmatism and oversimplification."

from the foreword by ***P G de Gennes***

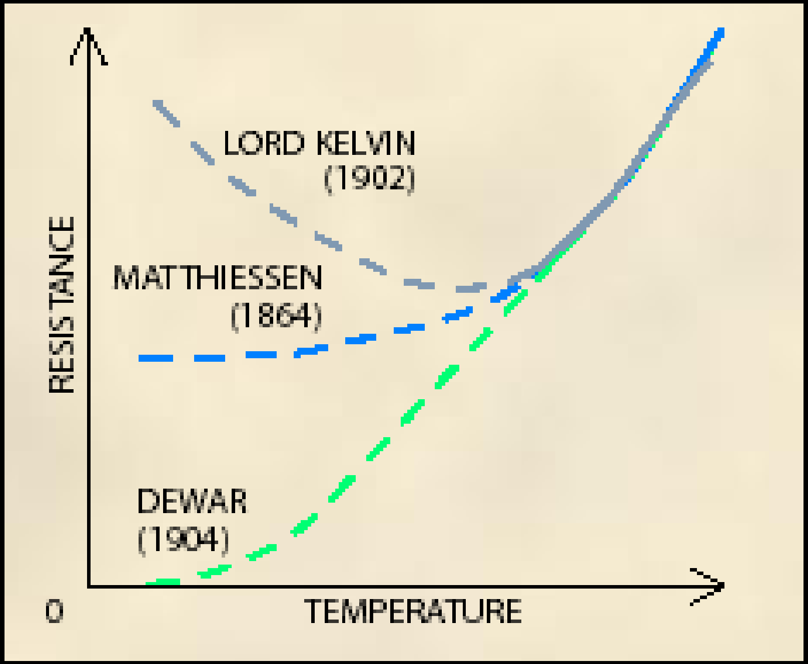
What sets this book apart from others on the introduction to superconductivity and high-T_c materials is its simple and pragmatic approach. The authors describe all relevant superconducting phenomena and rely on the macroscopic Ginzburg-Landau theory to derive the most important results. Examples are chosen from selected conventional superconductors like Nb-Ti and compared to those of high-T_c materials. The text should be of interest to students and researchers in all branches of science and engineering, with the possible exception of theoretical physicists, who may require a more mathematical approach.

Superconductivity

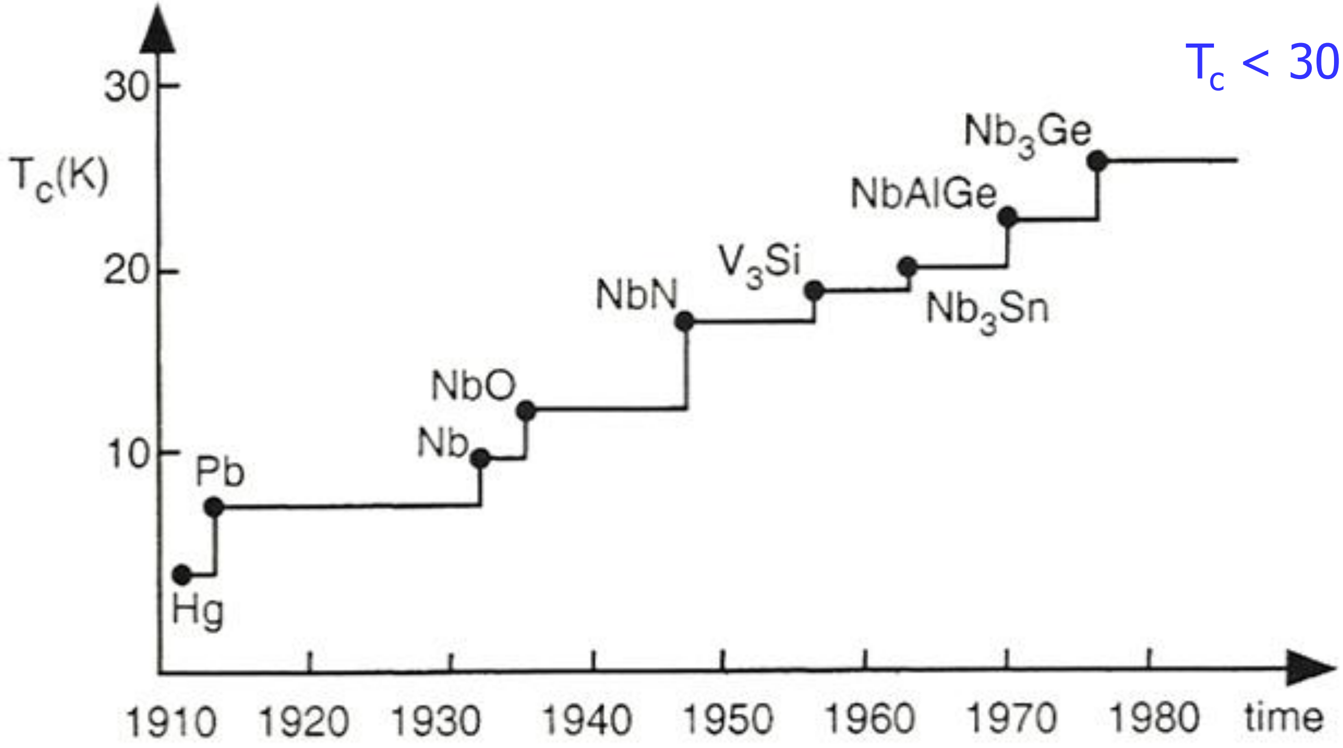


Kamerlingh Onnes, 1911

Theoretical predictions of resistivity of metals at low T



Critical temperature of superconductors



$T_c < 30$ K

conventional superconductors

21

L'équation de Schrödinger dans un contexte classique: un séminaire sur la supra-conductivité

21-1 L'équation de Schrödinger en présence d'un champ magnétique

Cette leçon a pour seul but de vous distraire. Je voudrais donner cette leçon dans un style un peu différent, juste à titre d'essai. Ce n'est pas une partie du cours, en ce sens que ce n'est pas un effort de dernière heure pour vous apprendre quelque chose de nouveau. J'imagine plutôt que je donne un séminaire ou un rapport de recherche sur le sujet, devant un auditoire plus avancé: des gens qui ont déjà été initiés à la mécanique quantique. La principale différence entre un séminaire et un cours habituel, est que celui qui fait un séminaire ne donne pas toutes les étapes, ni tous les calculs. Il dit, « si vous procédez ainsi et ainsi, voilà ce que vous obtenez », au lieu de montrer tout en détail. Ainsi j'exposerai dans cette leçon, tout le cheminement des idées, mais je ne donnerai que les *résultats* des calculs. Vous devez vous faire à l'idée que vous n'allez pas tout comprendre immédiatement, mais vous devez croire (plus ou moins) que tout s'éclairerait si vous franchissiez toutes les étapes.

Ceci mis à part, il s'agit ici d'un sujet dont je *veux* parler. C'est un sujet récent et moderne, qui pourrait fort bien être discuté dans un séminaire de recherche. Il s'agit de l'équation de Schrödinger dans un contexte classique: la supra-conductivité.

Habituellement, la fonction d'onde qui apparait dans l'équation de Schrödinger concerne une ou deux particules seulement. Et la fonction d'onde n'a pas de signification classique – contrairement au champ électrique, au potentiel vecteur ou autres. La fonction d'onde pour une seule particule *est* un champ – en ce sens que c'est une fonction de la position – mais elle n'a généralement pas une signification classique. Néanmoins, il existe des situations dans lesquelles la fonction d'onde de mécanique quantique *possède* un sens classique; c'est de celles-ci que je

---

21

The Schrödinger Equation in a Classical Context: A Seminar on Superconductivity

21-1 Schrödinger's equation in a magnetic field

This lecture is only for entertainment. I would like to give the lecture in a somewhat different style—just to see how it works out. It's not a part of the course—in the sense that it is not supposed to be a last minute effort to teach you something new. But, rather, I imagine that I'm giving a seminar or research report on the subject to a more advanced audience, to people who have already been educated in quantum mechanics. The main difference between a seminar and a regular lecture is that the seminar speaker does not carry out all the steps, or all the algebra. He says: "If you do such and such, this is what comes out," instead of showing all of the details. So in this lecture I'll describe the ideas all the way along but just give you the *results* of the computations. You should realize that you're not supposed to understand everything immediately, but believe (more or less) that things would come out if you went through the steps.

All that aside, this is a subject I *want* to talk about. It is recent and modern and would be a perfectly legitimate talk to give at a research seminar. My subject is the Schrödinger equation in a classical setting—the case of superconductivity.

Ordinarily, the wave function which appears in the Schrödinger equation applies to only one or two particles. And the wave function itself is not something that has a classical meaning—unlike the electric field, or the vector potential, or things of that kind. The wave function for a single particle *is* a "field"—in the sense that it is a function of position—but it does not generally have a classical significance. Nevertheless, there are some situations in which a quantum mechanical wave function *does* have classical significance, and they are the ones I

CONTEMP. PHYS., 1981, VOL. 22, NO. 4, 375–395

The Formation of Cooper Pairs and the Nature of Superconducting Currents†

VICTOR F. WEISSKOPF

CERN, Geneva, Switzerland, and Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

ABSTRACT. A simple physical explanation is given for the formation of Cooper pairs in a superconducting metal, for the origin of the attractive force causing the binding of the pairs, for the forming of a degenerate Bose gas by the Cooper pairs, for the finite energy gap that prevents the ensemble of electrons from changing its quantum state at low temperatures, and for the existence of permanent currents in a superconducting wire.

High-temperature superconductivity—dream or reality?

V. L. Ginzburg

P. N. Lebedev Physics Institute, USSR Academy of Sciences

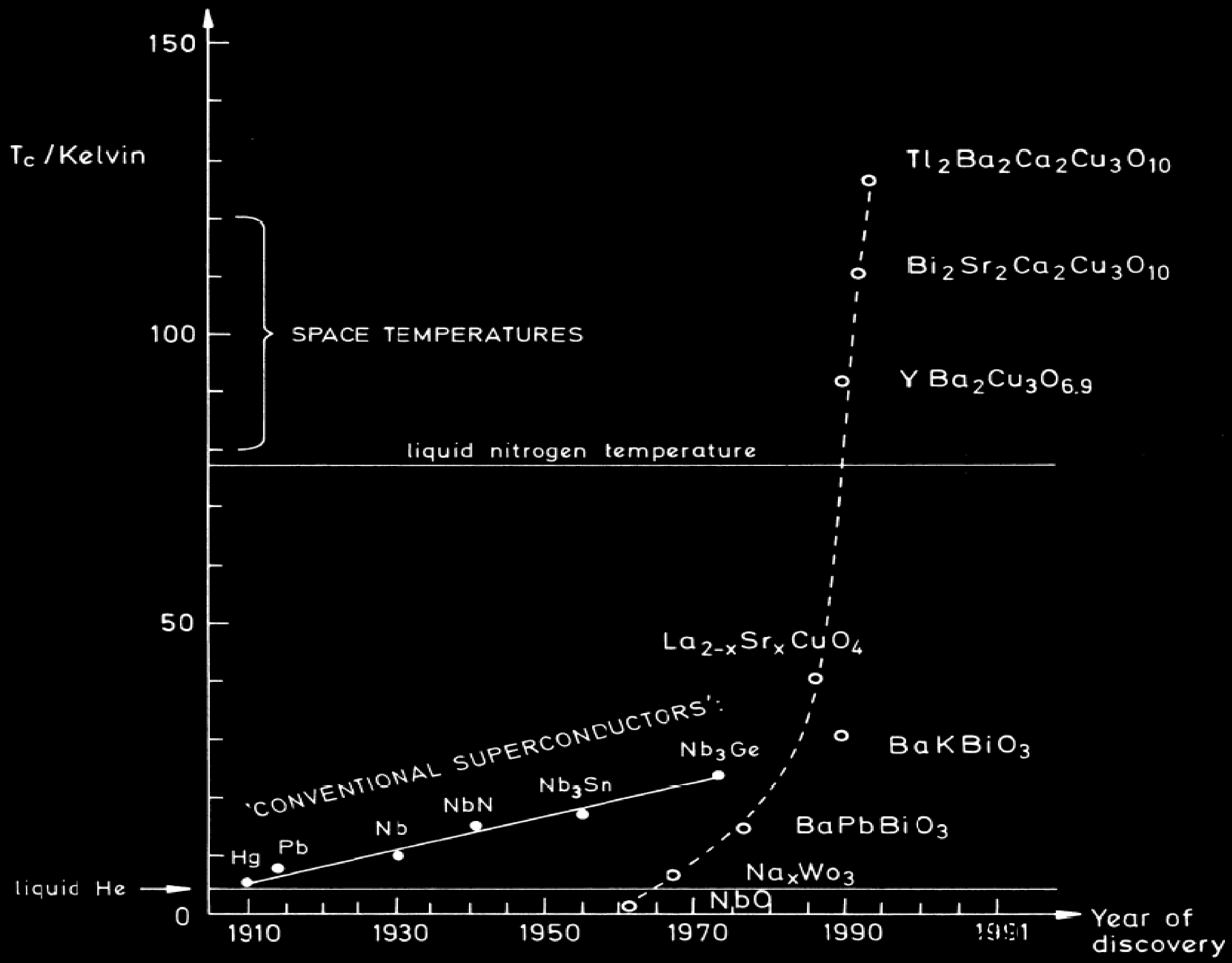
Usp. Fiz. Nauk **118**, 315–324 (February 1976)

A brief review, intended for non-specialists, of the present-day status of the problem of high-temperature superconductivity.

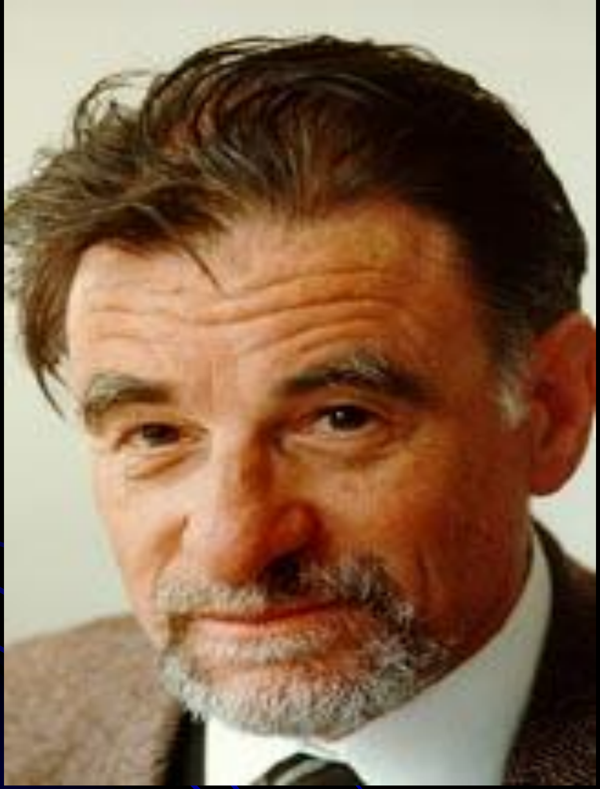
PACS numbers: 74.90.+n

CONTENTS

Sir Nevil Mott


Tc / Kelvin
150
100
50
0
SPACE TEMPERATURES
liquid nitrogen temperature
liquid He
Tl2Ba2Ca2Cu3O10
Bi2Sr2Ca2Cu3O10
Y Ba2Cu3O6.9
La2-xSrxCuO4
BaKBiO3
BaPbBiO3
NaxWo3
NbO
'CONVENTIONAL SUPERCONDUCTORS':
Nb3Ge
Nb3Sn
NbN
Nb
Pb
Hg
1910
1930
1950
1970
1990
1991
Year of discovery

Alex Müller & Georg Bednorz, 1986:



Paul Chu & **M.K. Wu**, YBCO‘123’, 1987

"Improved Low Contact Resitance to Superconducting YBaCuO Ceramics"
Nature **328**, p.603, (1987)

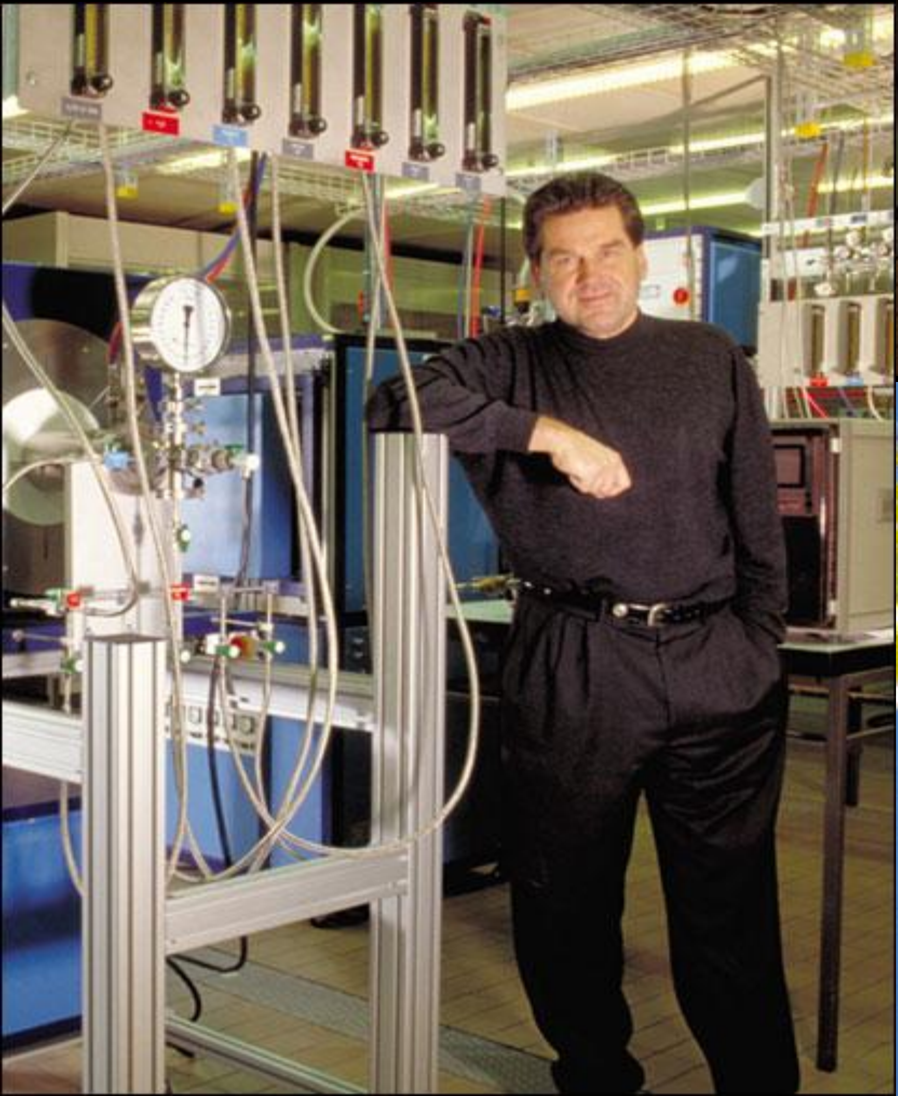
"Electronic Properties And Critical Current Densities Of $(YBCO)_{1-x}Ag_x$ Compounds",
Solid State Comm. **68**, no.6, p. 535, (1988)

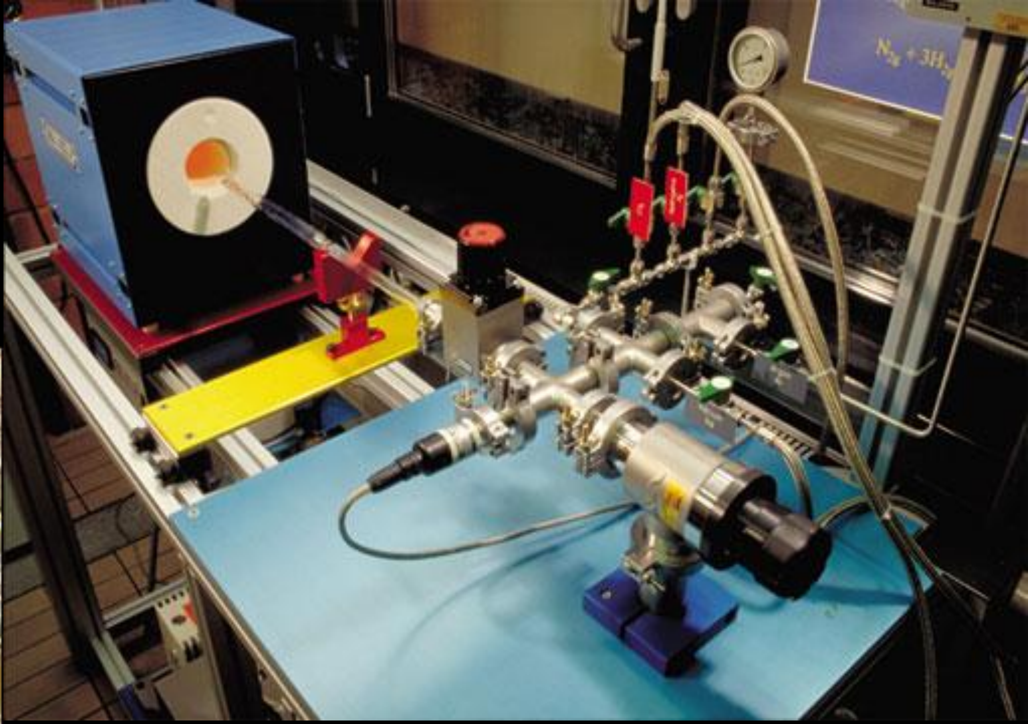
Direct ARPES on Thin High-Tc Films:
Heteroepitaxy &The Role of Strain

Helmuth Berger (EPDL):

Single Crystals Growth

>30’000 samples since 1970 !

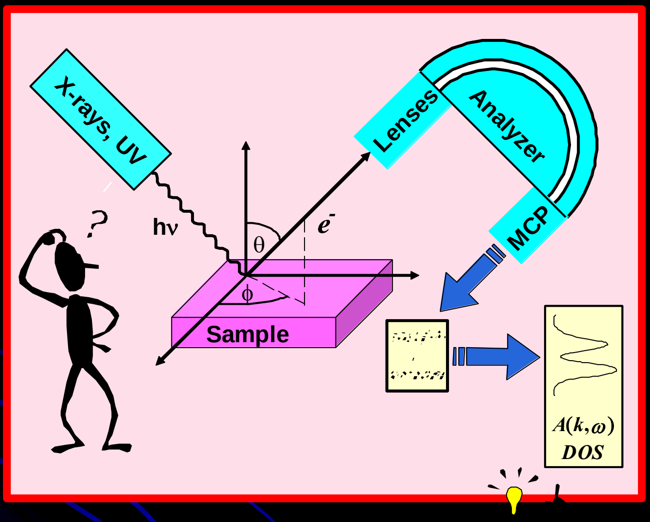




Crystals obtained from chemical transport experiments.

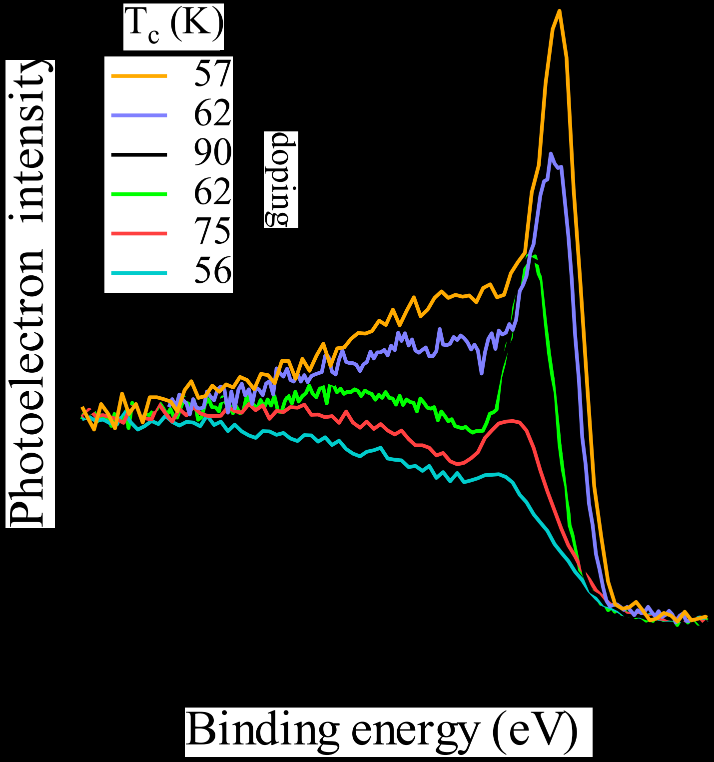
ARPES on cleaved cuprates

ARPES :

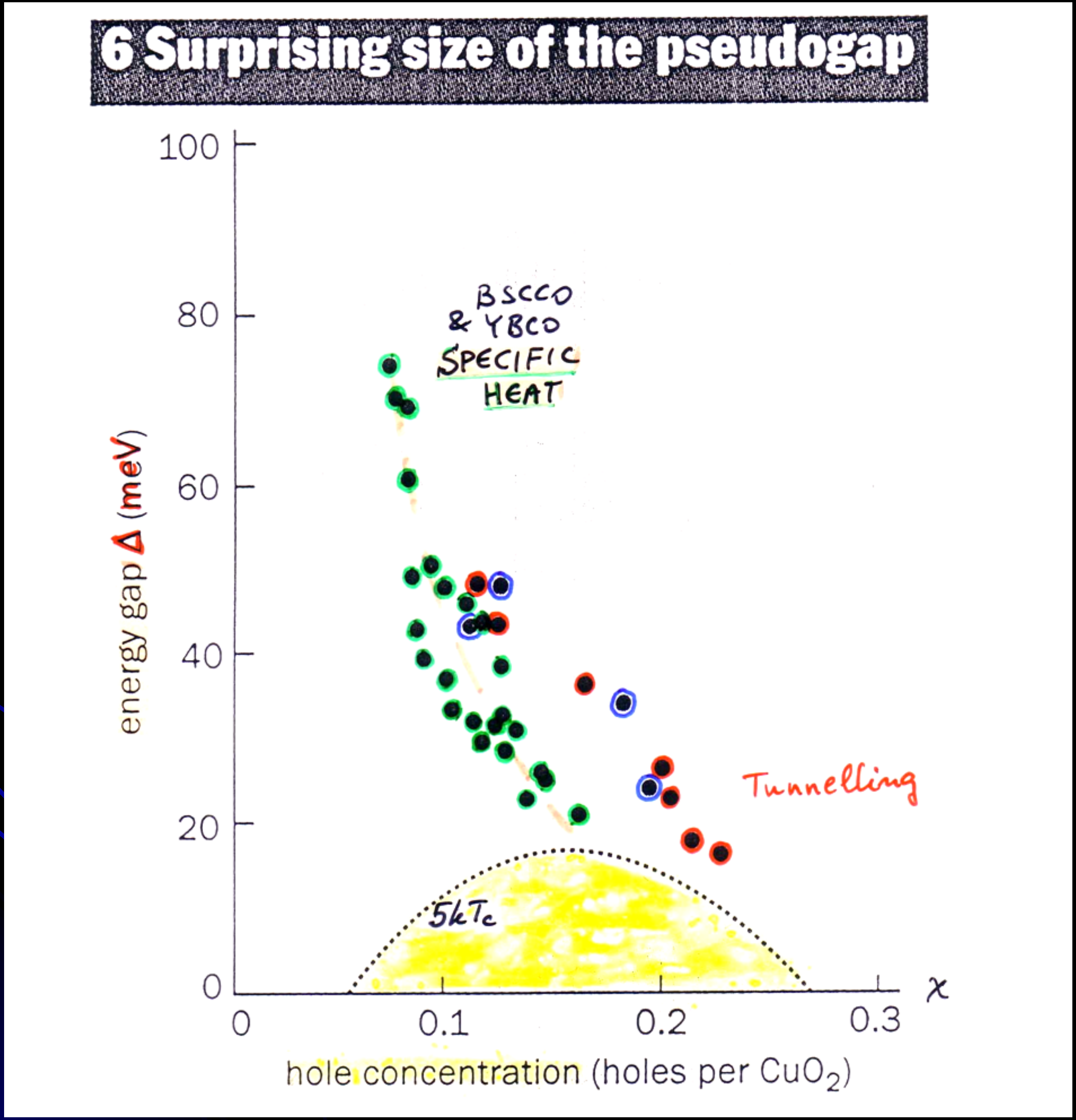


$I(\vec{k}, \omega) \sim f(\omega)\, A(\vec{k}, \omega)$

EDC on cleaved Bi-2212



Batlogg & Varma, Physics World 2000



Lev Gor'kov, 1987 : phase separation

Jim Phillips / Jacques Friedel:

(1987) : Pseudogap

… Erice, Santa Fe, SPIE meetings …

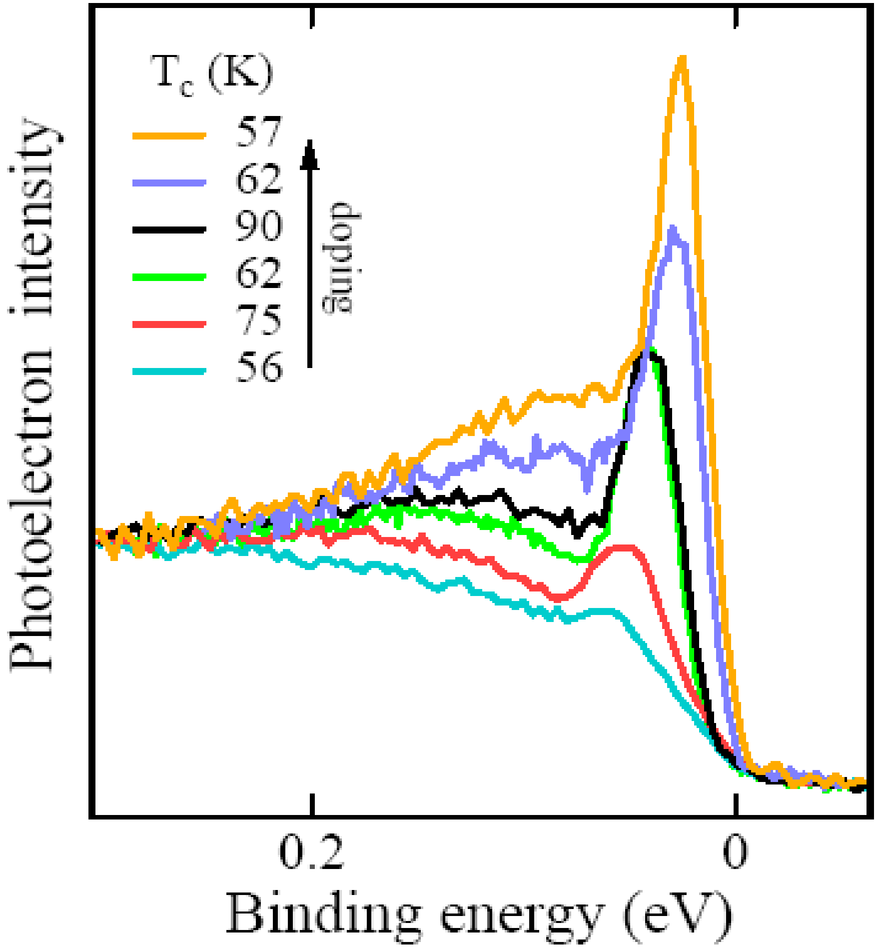
Stripes (1996)

EPFL 1989: ARPES on
Cleaved BSCCO-2212 Crystals

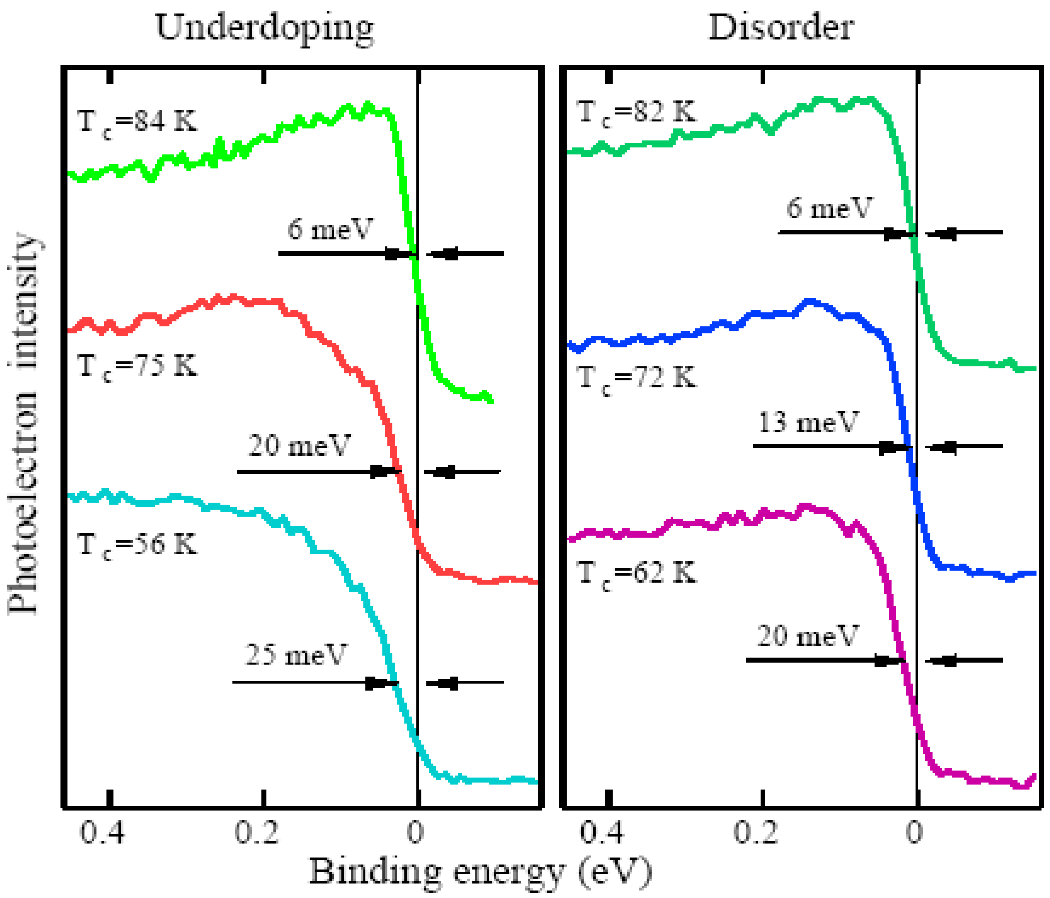
&

Deliberately Induced Disorder
by
2.5 MeV electron bombardment

ARPES on cleaved Bi-2212, I. Vobornik et al. EPFL

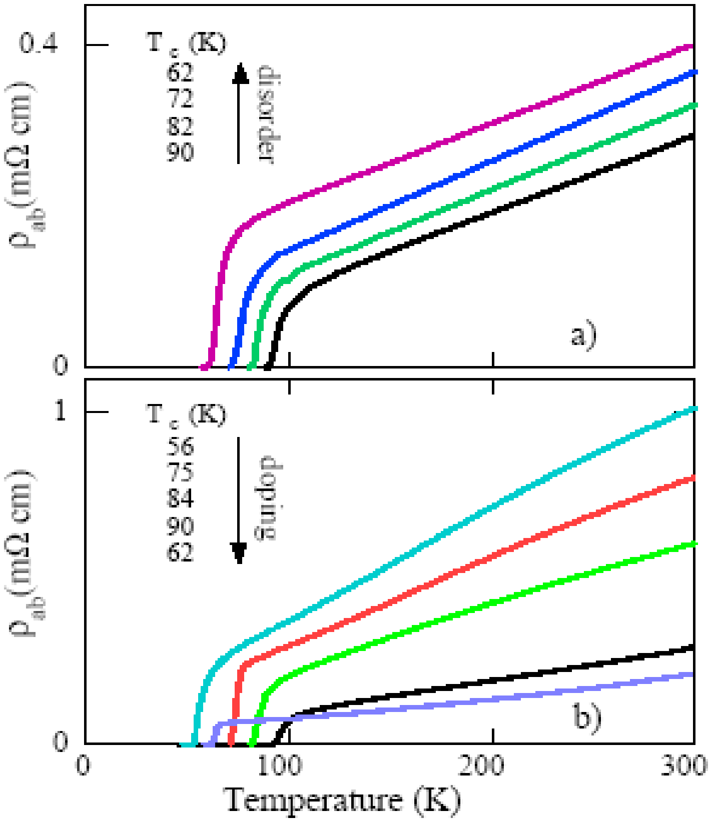


ARPES Pseudogap & Disorder

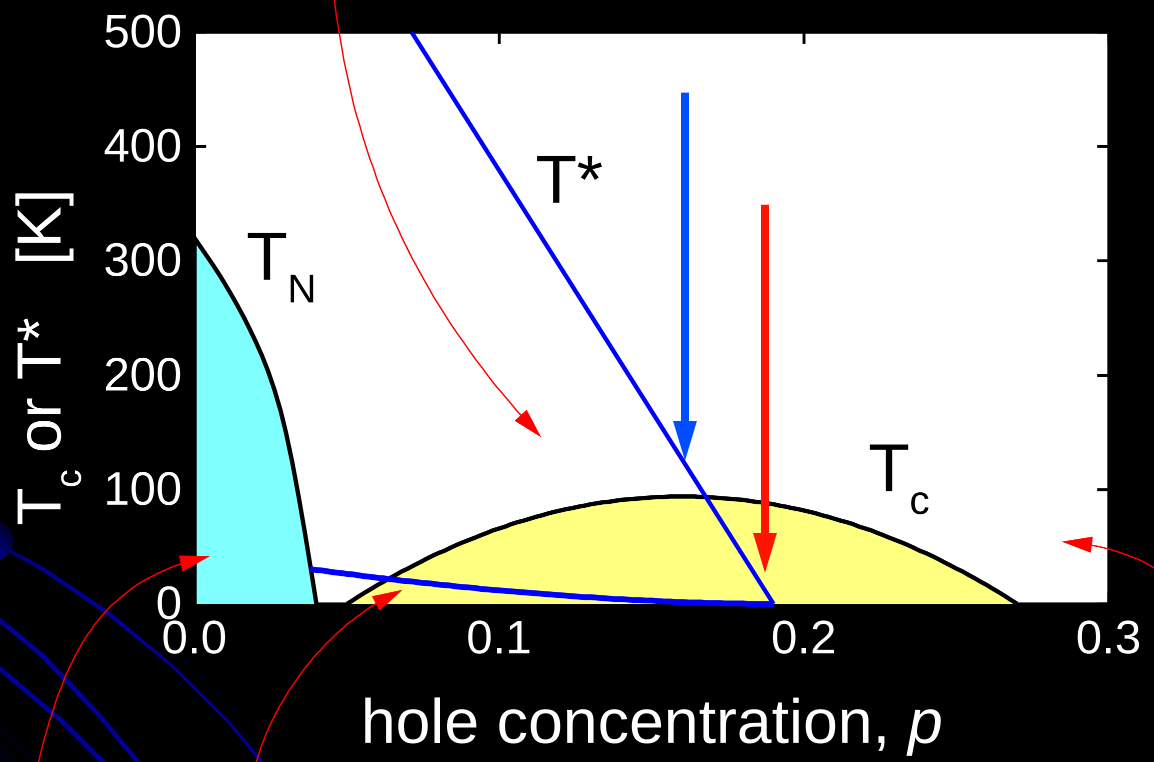


PRL 1999

Doping vs. deliberate disorder (L.Forro):



Tallon’s generic diagram…



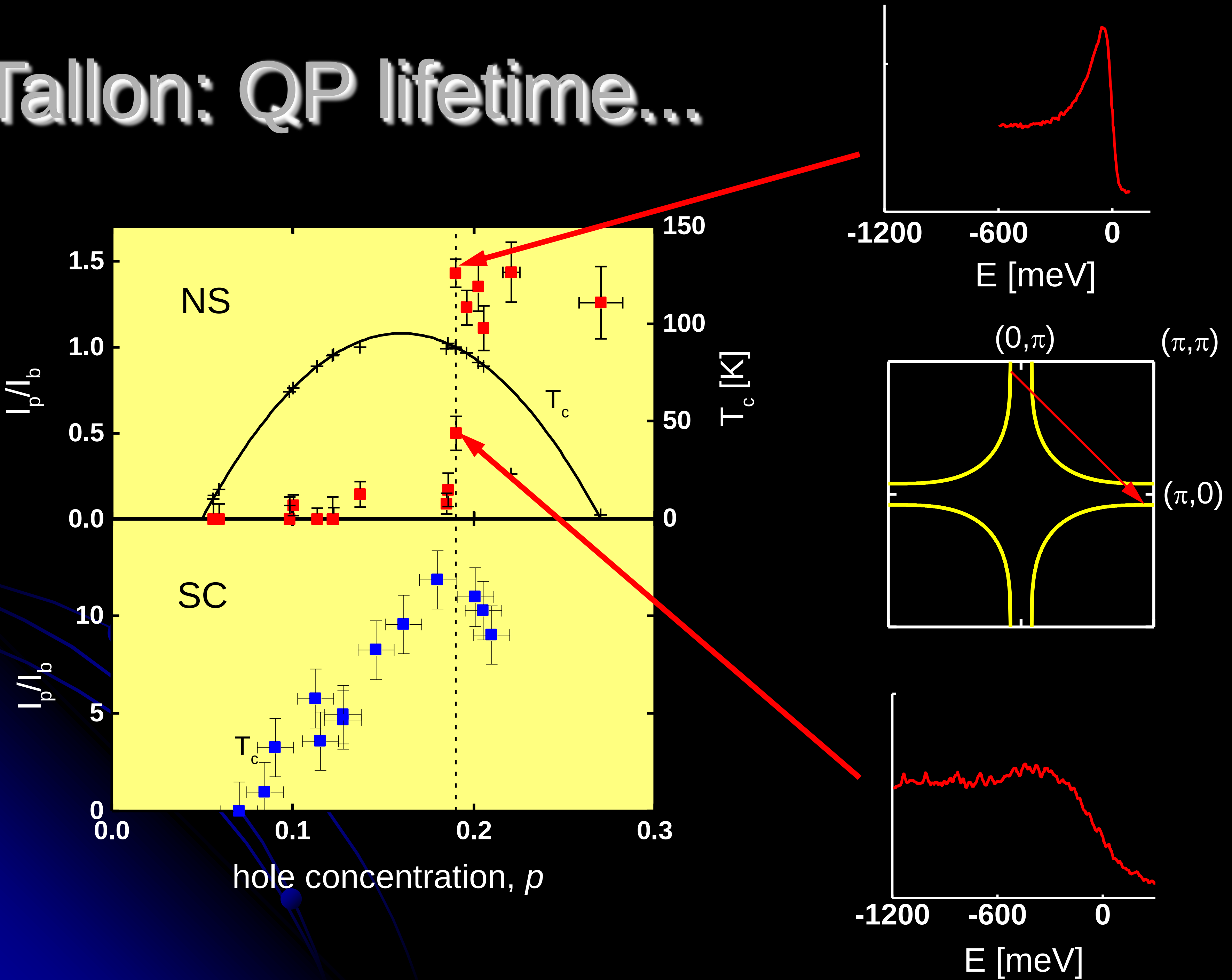
short-range AF fluctuating magnetic order

static "spin" glass

long-range AF static magnetic order

"normal" metal

Tallon: QP lifetime...



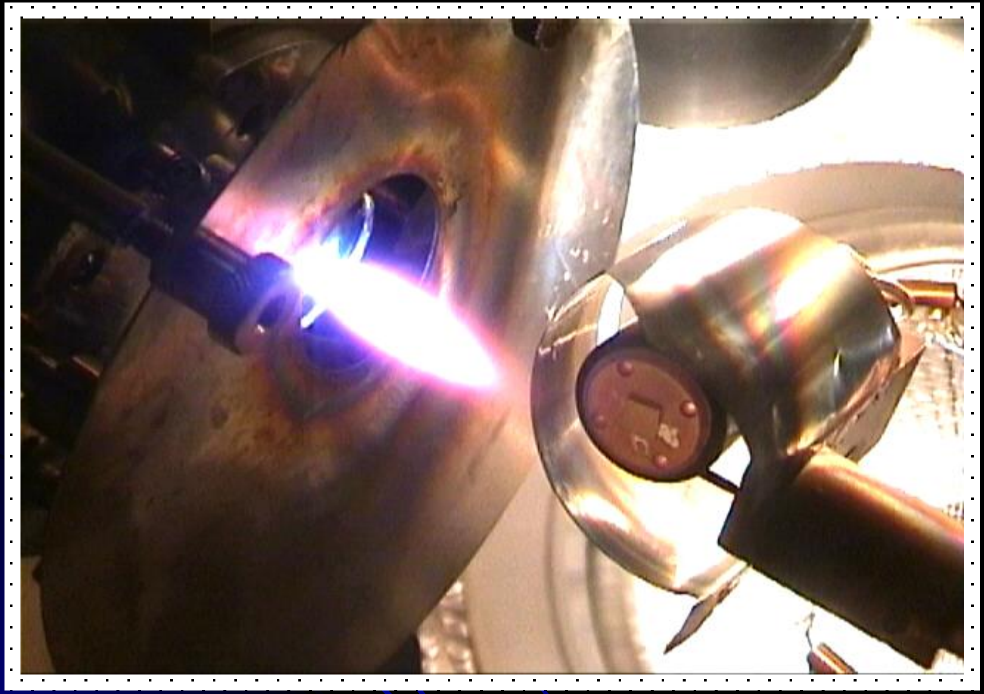
Ivan Bozovic and Davor Pavuna

Correlated Electron Materials:

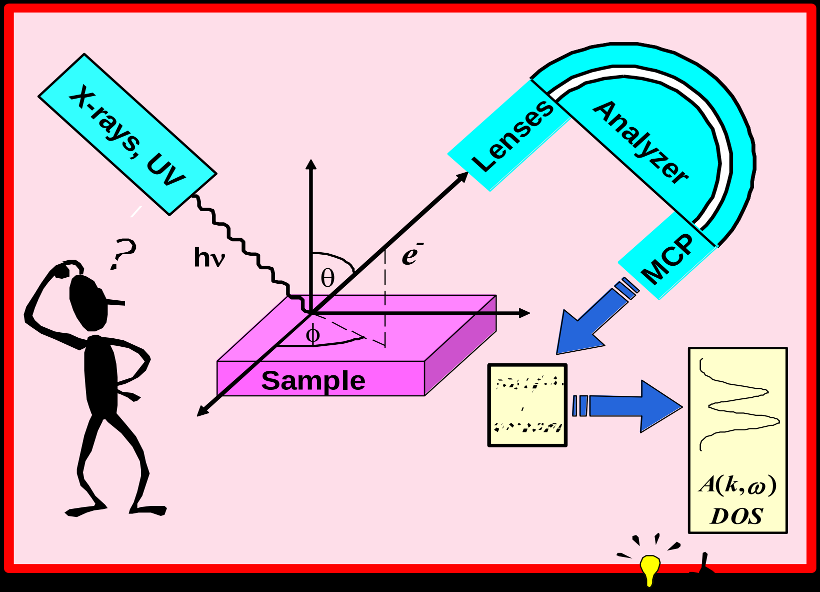
Physics & Nano-Engineering
I – VI

(SPIE,1994 – 2005)

Laser ablation -> Film --> ARPES



ARPES :



$I(\vec{k}, \omega) \sim f(\omega)\, A(\vec{k}, \omega)$

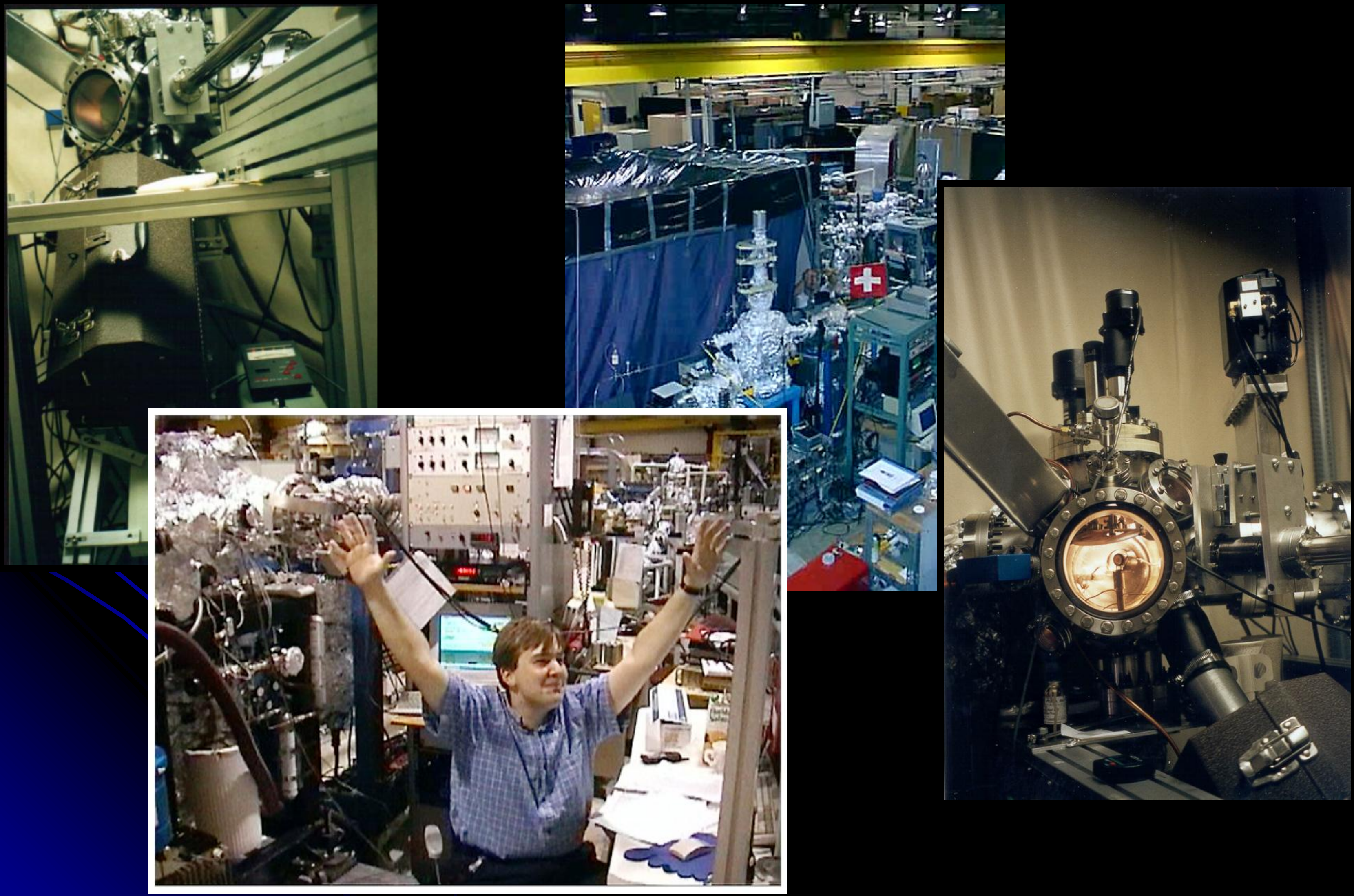
Why ARPES on FILMS ?

Physics <->Heteroepitaxy :

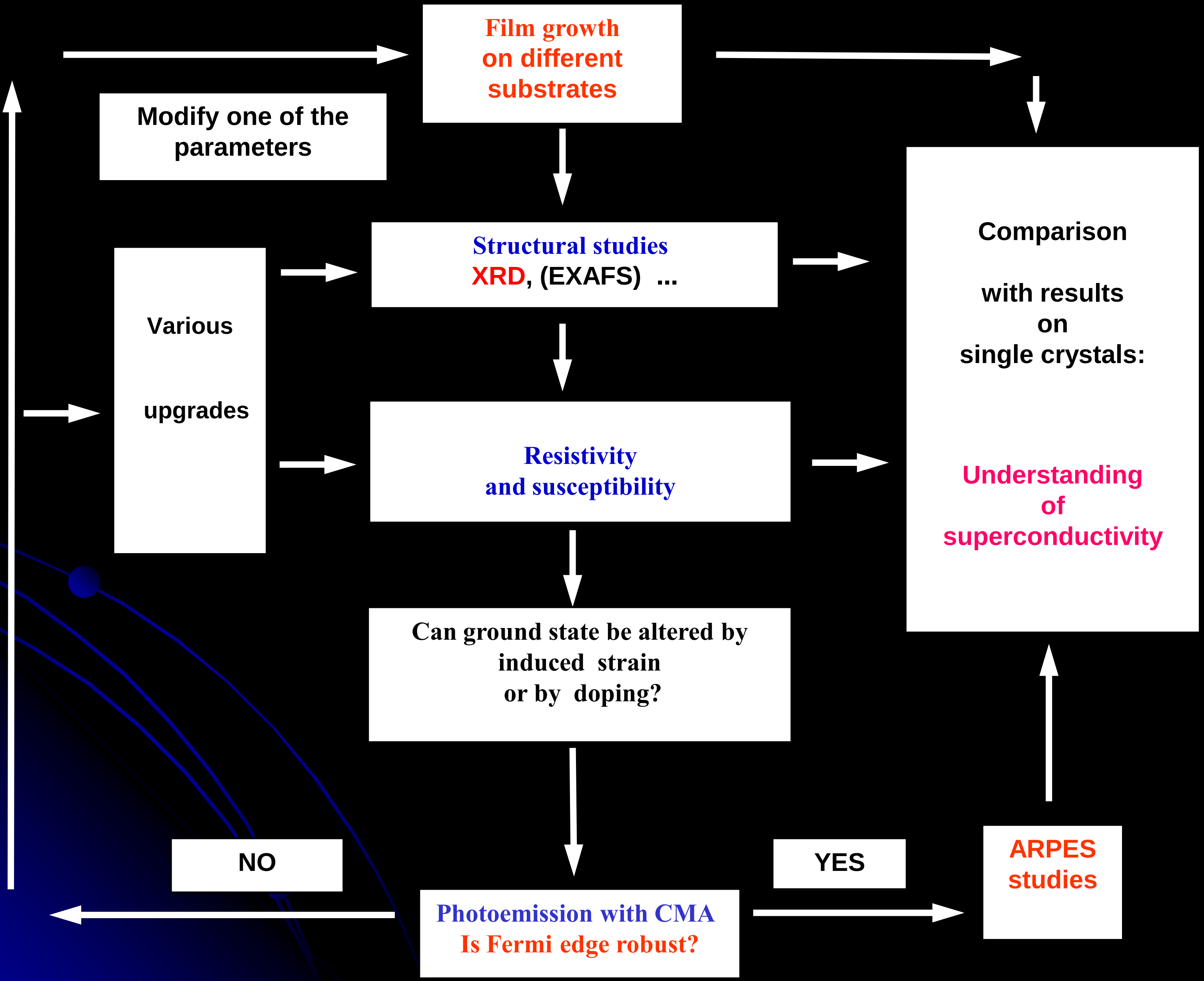
Control E(k) … and the (LATTICE) STRAIN !

Control ‘building blocks’ + **functionality**

Swiss outpost in Wisconsin: laser ablation facility for high-temperature superconductors growth



Film Optimization



Film growth
on different
substrates

Modify one of the
parameters

Various

upgrades

Structural studies
XRD, (EXAFS) ...

Resistivity
and susceptibility

Can ground state be altered by
induced strain
or by doping?

NO

YES

Photoemission with CMA
Is Fermi edge robust?

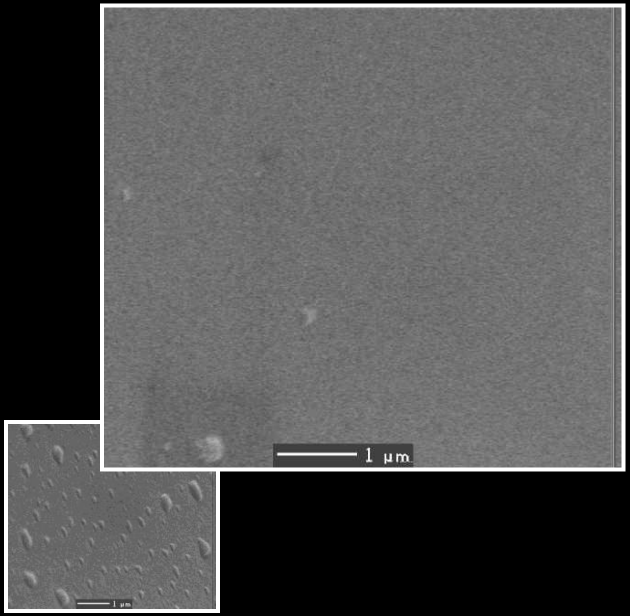
ARPES
studies

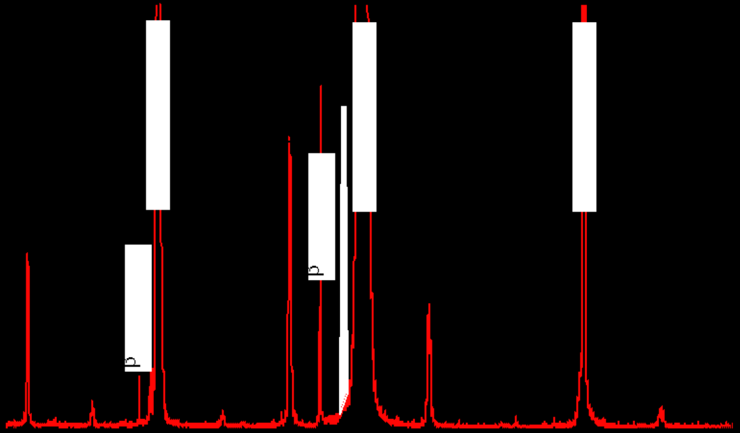
Comparison

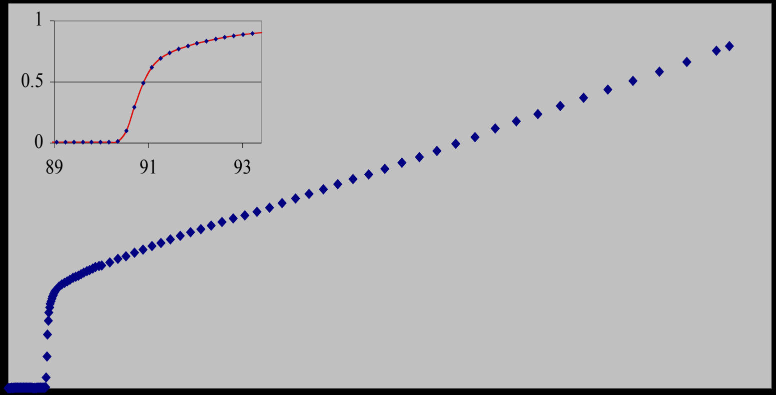
with results
on
single crystals:

Understanding
of
superconductivity

NBCO-123 Epitaxial Films on STO





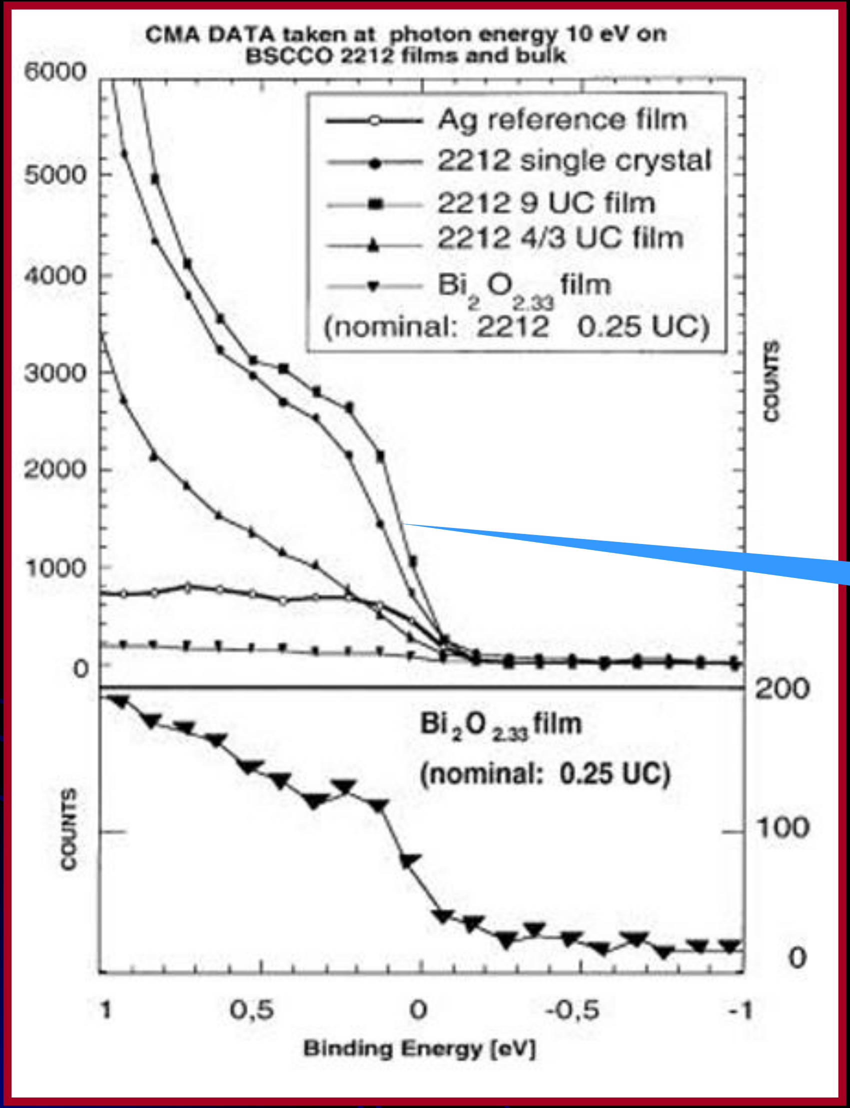


very smooth, almost outgrowth free surfaces, crystal coherence ≈0.8 μm

M. Abrecht et.al.,*Journal of Applied Physics* **91** (3), 1187 (2002)

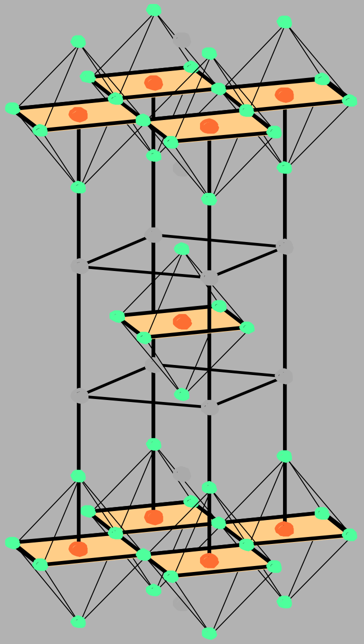
2001: As grown epitaxial films of high-Tc superconductors exhibit a clear Fermi edge

(No cleaving)

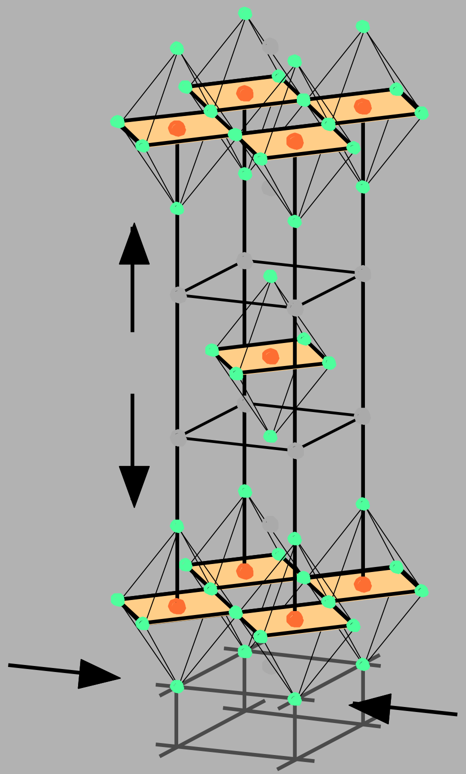


Fermi edge

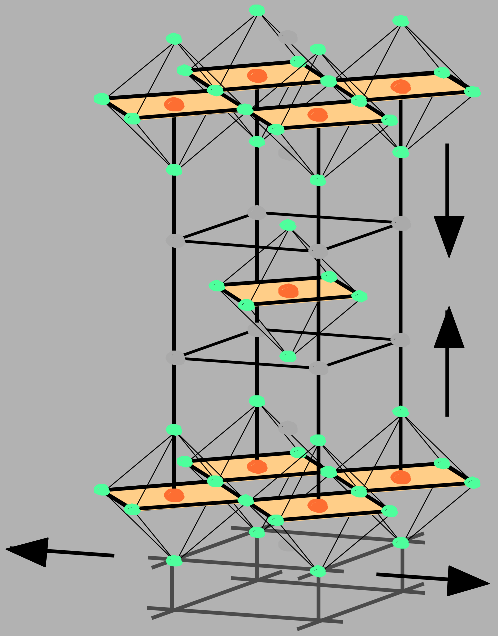
$La_{2-x}Sr_xCuO_4$ Under Strain



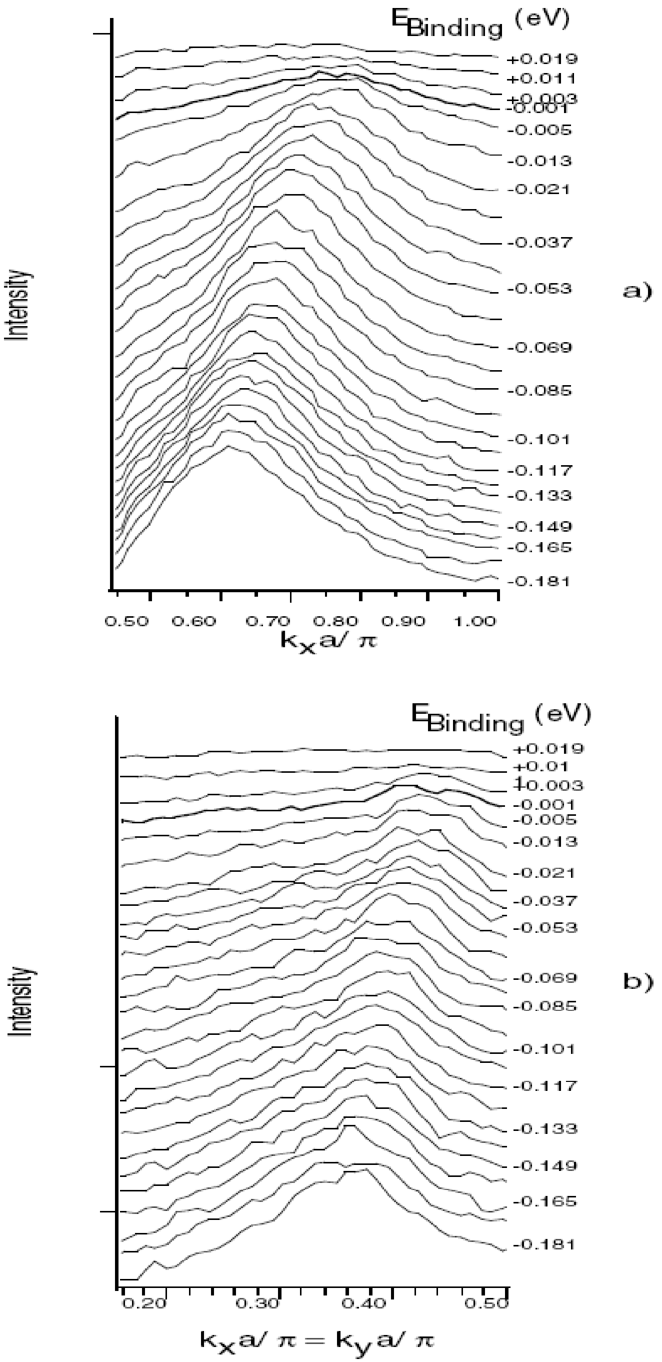
Relaxed

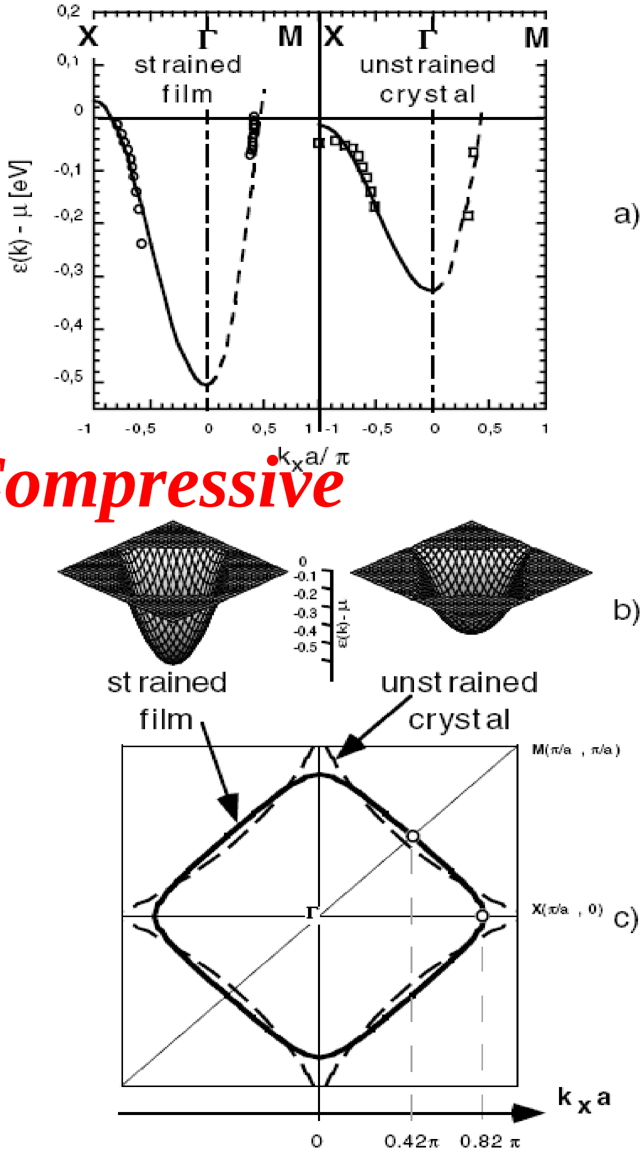


In-plane compressive strain ($SrLaAlO_4$)



In-plane tensile strain ($SrLaGaO_4$, $SrTiO_3$)

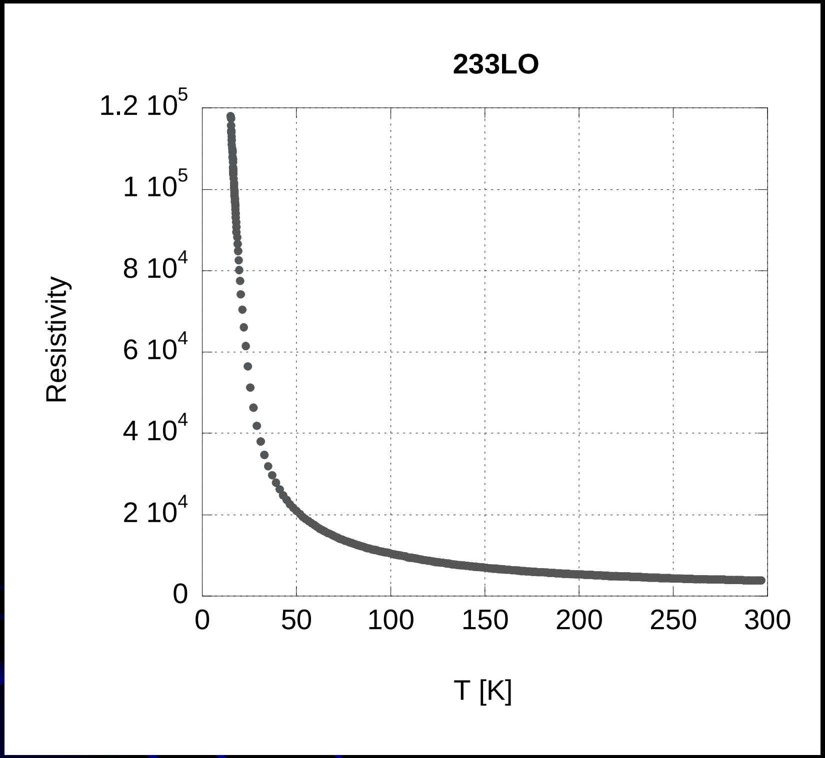


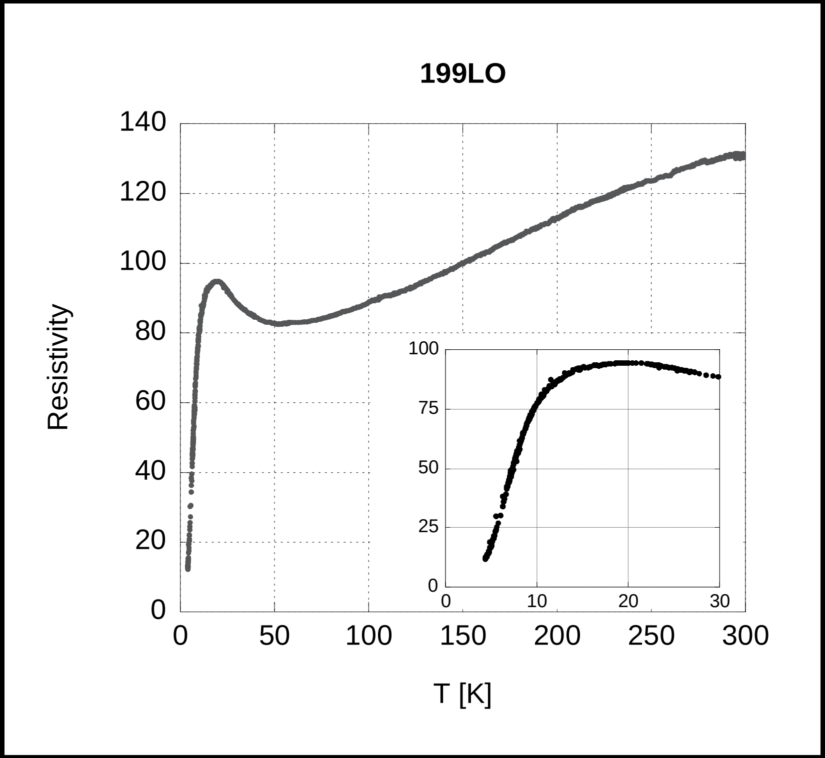


Compressive

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 for an unstrained optimally doped single crystal (right)

Tensile Strain : Resistivity



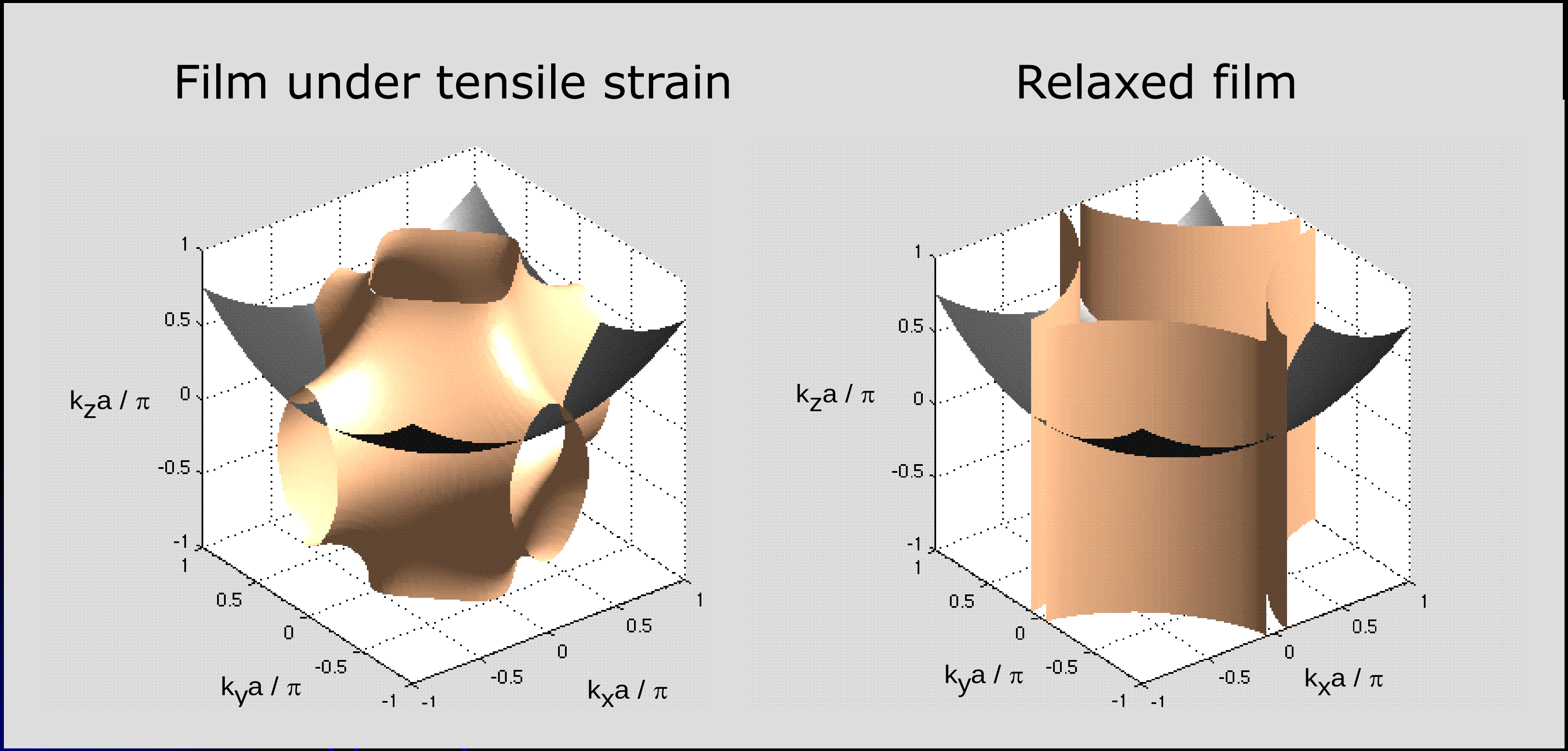


Huge tensile strain
c-axis: 13.10 Å

Tensile strain (partially relaxed)
c-axis: 13.18 Å

(Bulk c-axis: 13.23 Å)

Reconstructed Fermi Surface

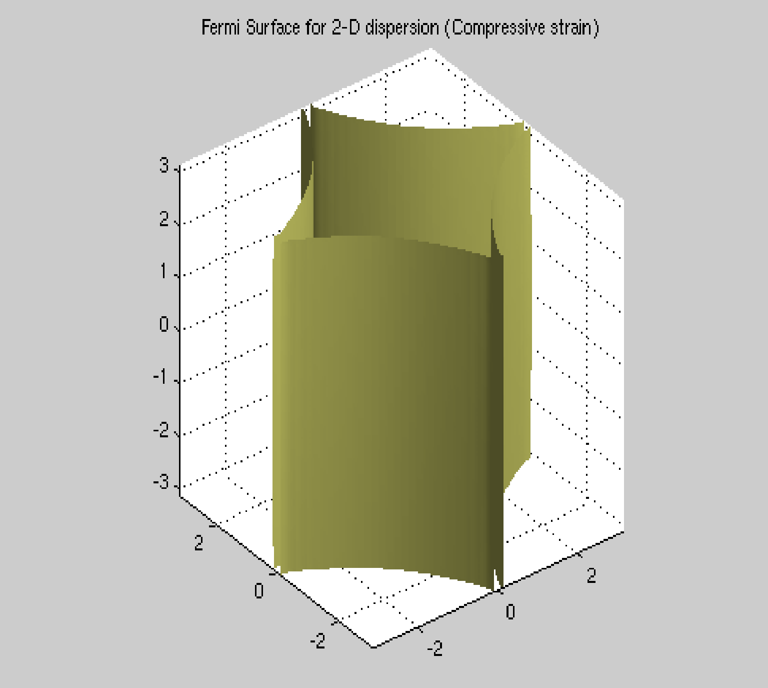


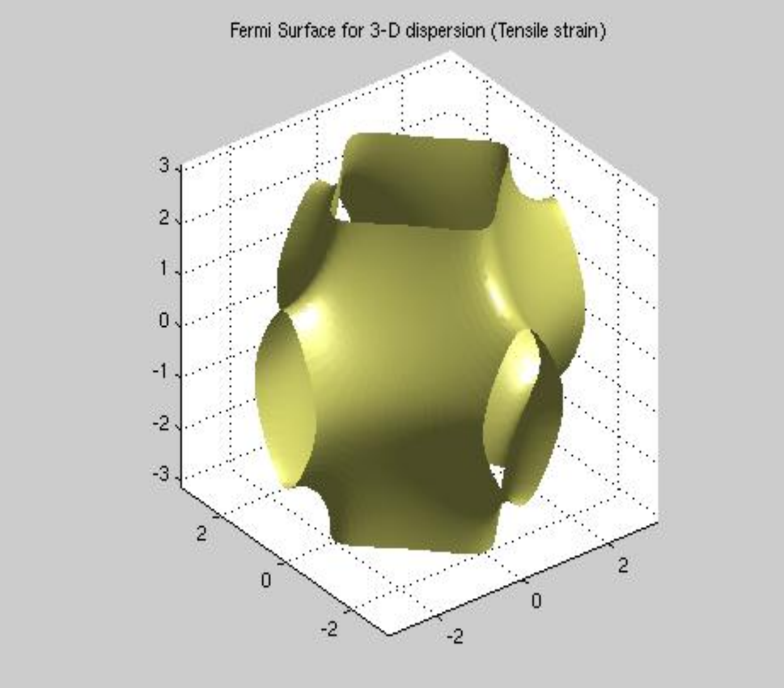
Film under tensile strain

Relaxed film

Cloetta et al. PRB 74, 014519(2006)

Direct ARPES on Strained HTSC Films

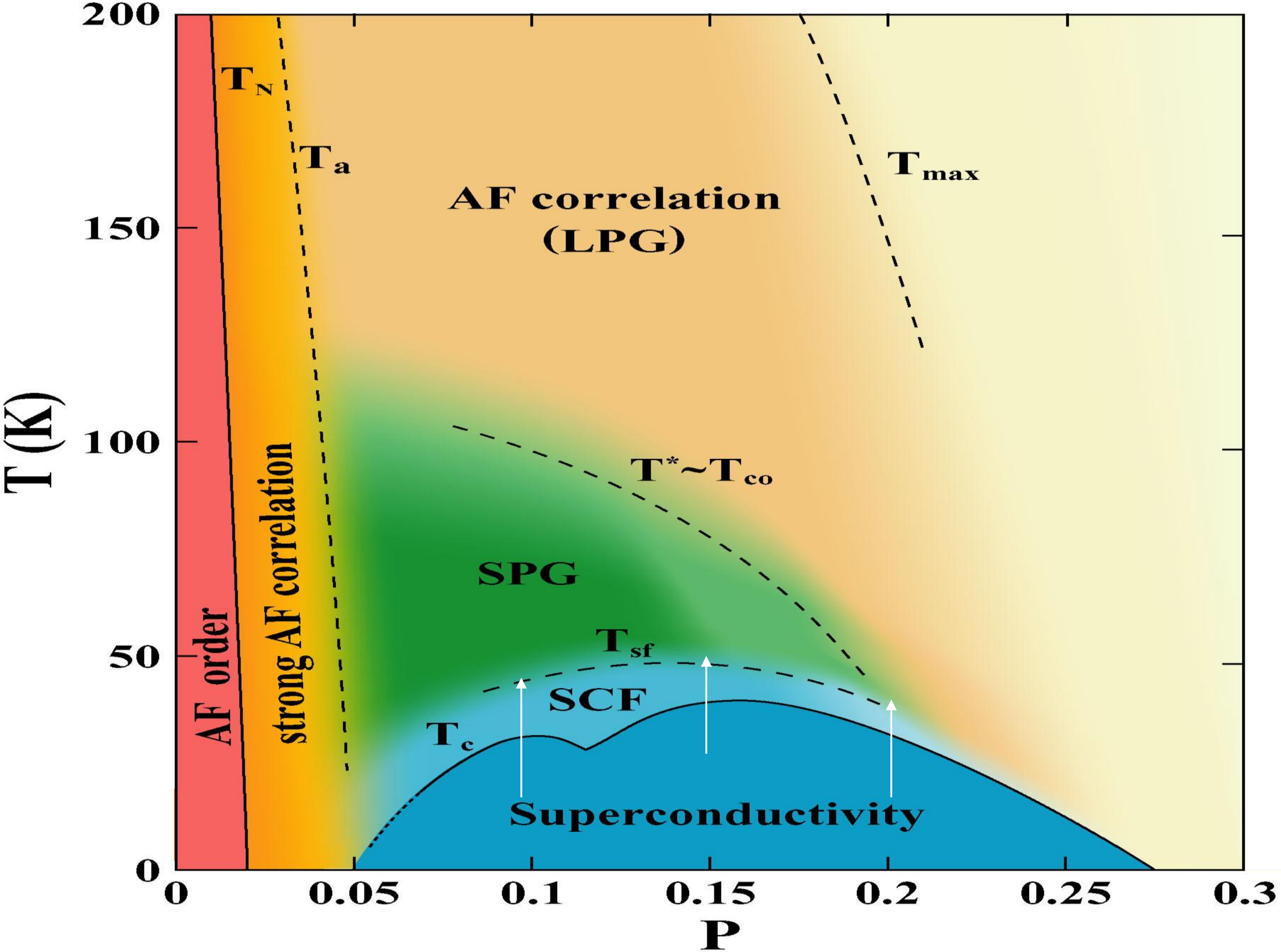




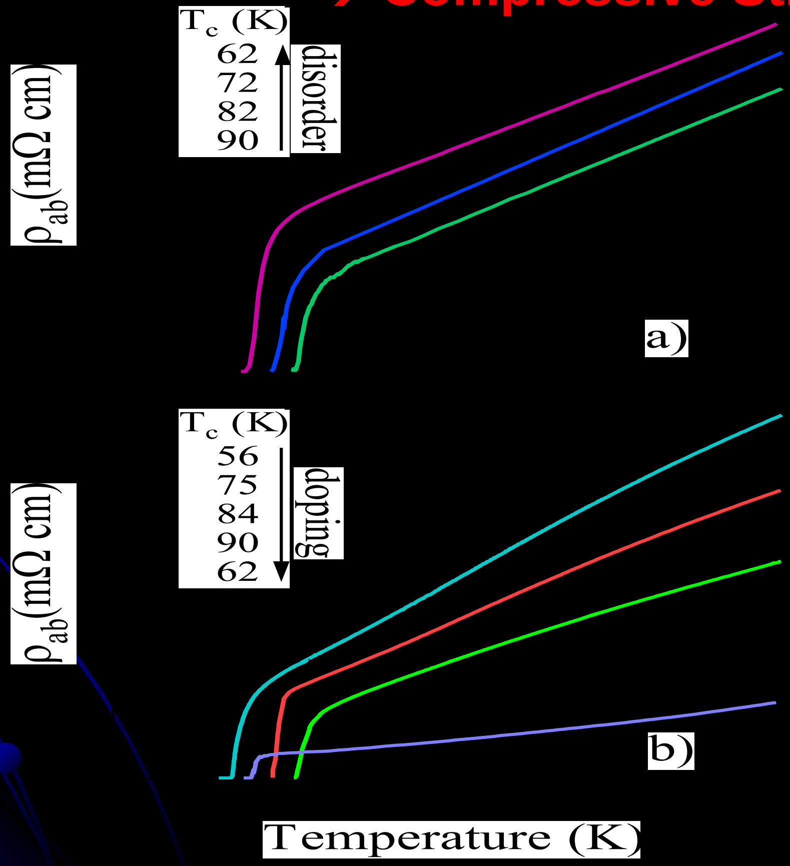
An illustration of reconstructed FS for overdoped (x= 0.2) LSCO-214 films under

compressive strain and **tensile strain** .

Tc is enhanced **Tc is diminished**

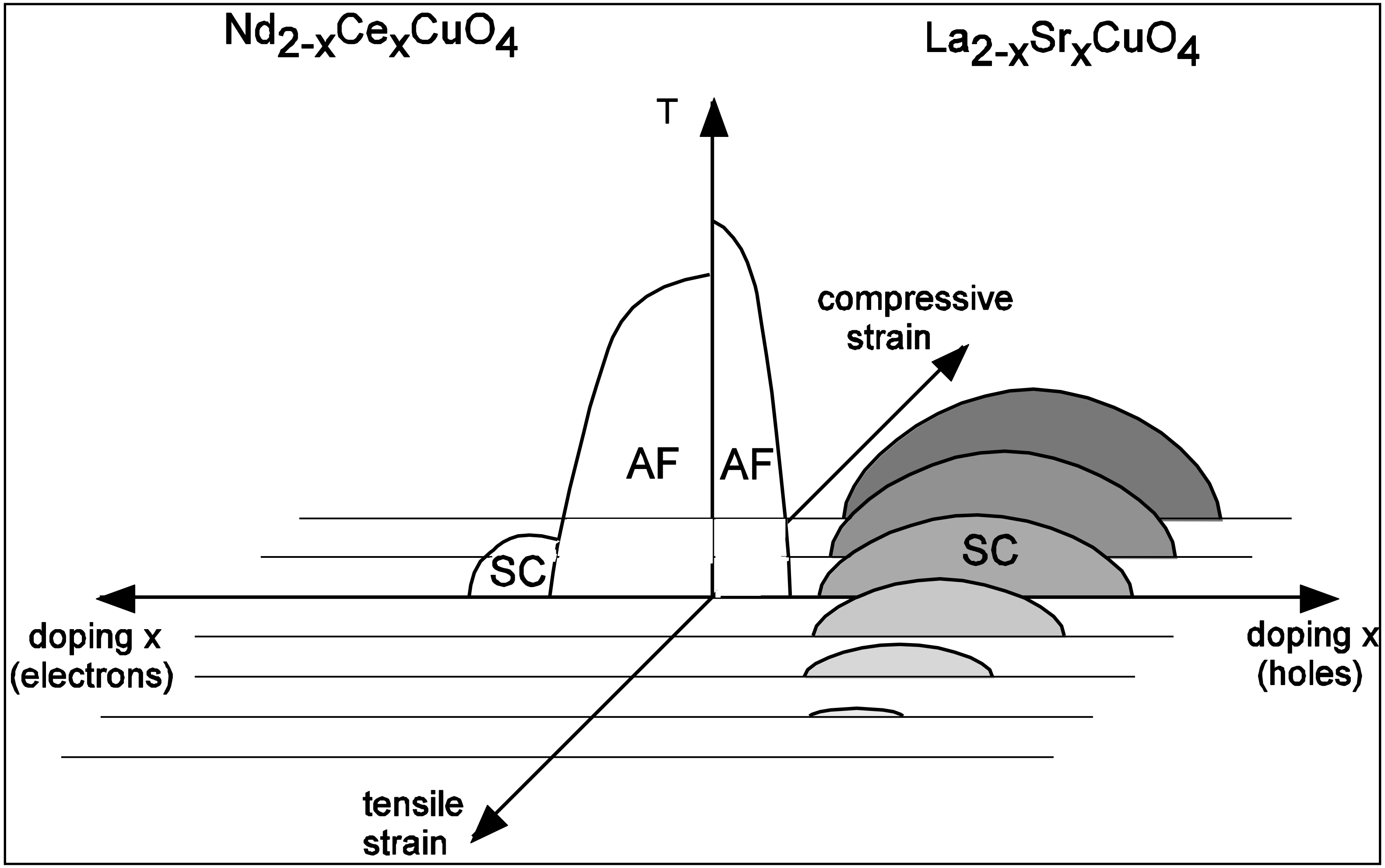

200
150
100
50
0
T (K)
0
0.05
0.1
0.15
0.2
0.25
0.3
P
T_N
T_a
T_{max}
AF correlation
(LPG)
AF order
strong AF correlation
$T^{*}\sim T_{co}$
SPG
T_{sf}
SCF
T_c
Superconductivity

Compressive strain in LSCO acts OPPOSITE to the deliberately induced disorder :



→ Compressive Strain

Schematic Electronic Phase Diagram



LSCO-214 is like a Napoleon Cake

Reminder:

I. Bozovic:

Soft La-O coordinate

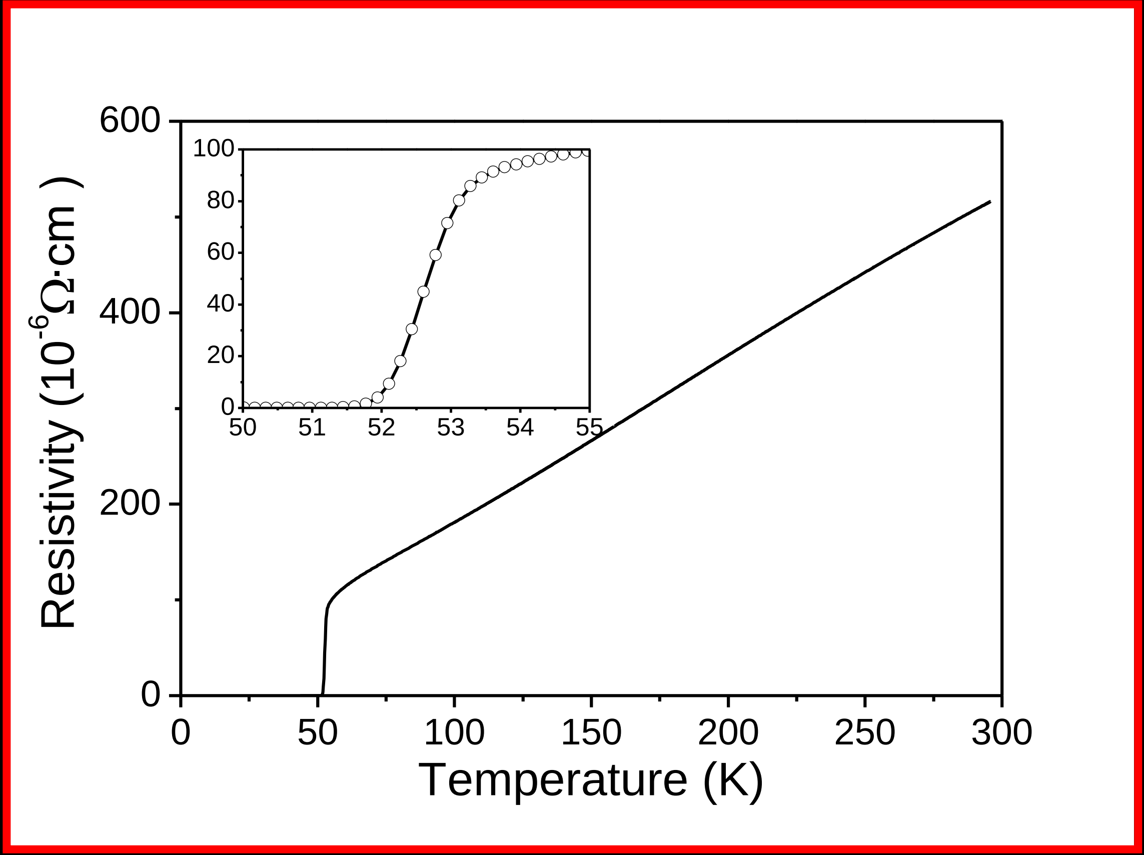
S. Uchida:

Role of Apical Oxygen Disorder

LSCO Films: Transport properties

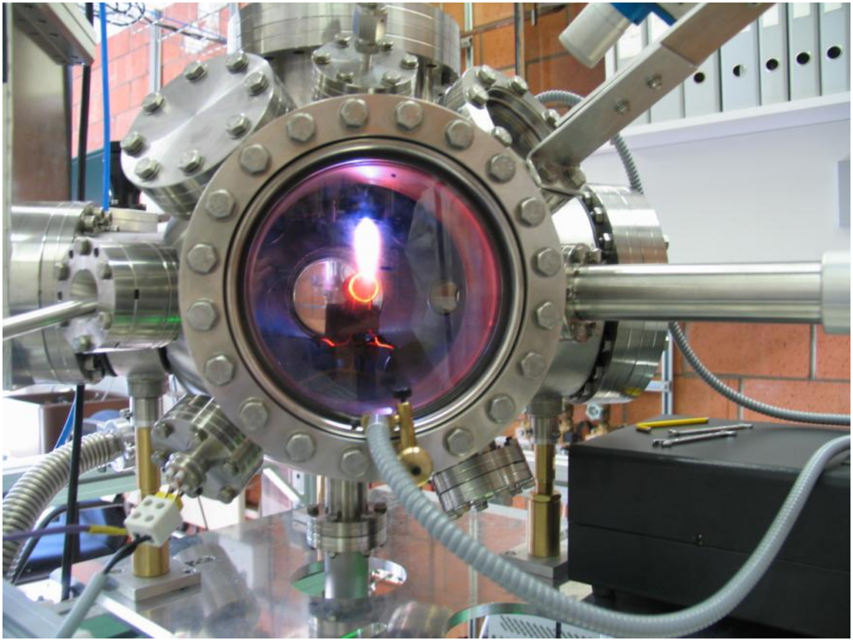
Resistivity of an LSCO film on LSAO substrate.

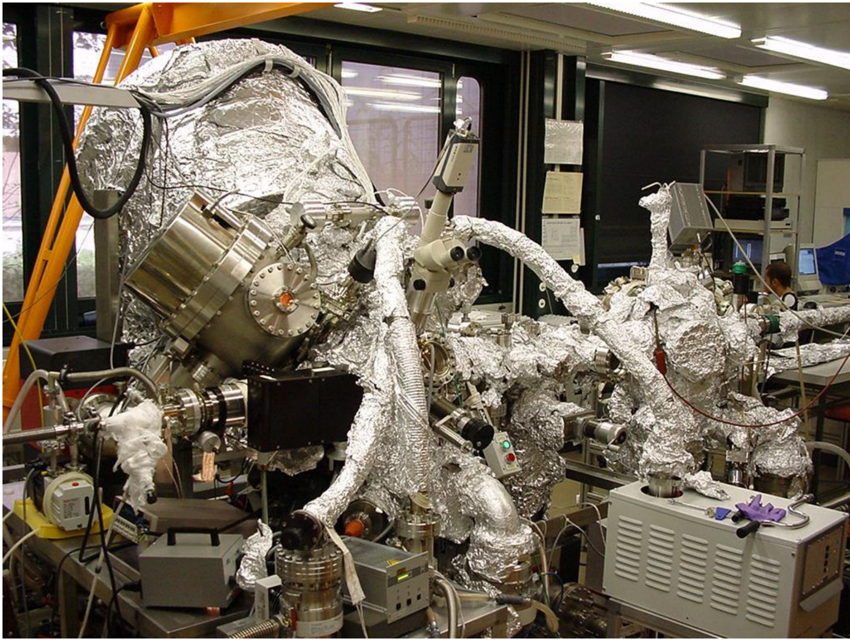
It shows T_c = 51.5 K, the record for LSCO in any form.



Bozovic et al. Phys. Rev. Lett. **89**, 107001 (2002)

Laser ablation (EPFL) → Scienta (EPFL)





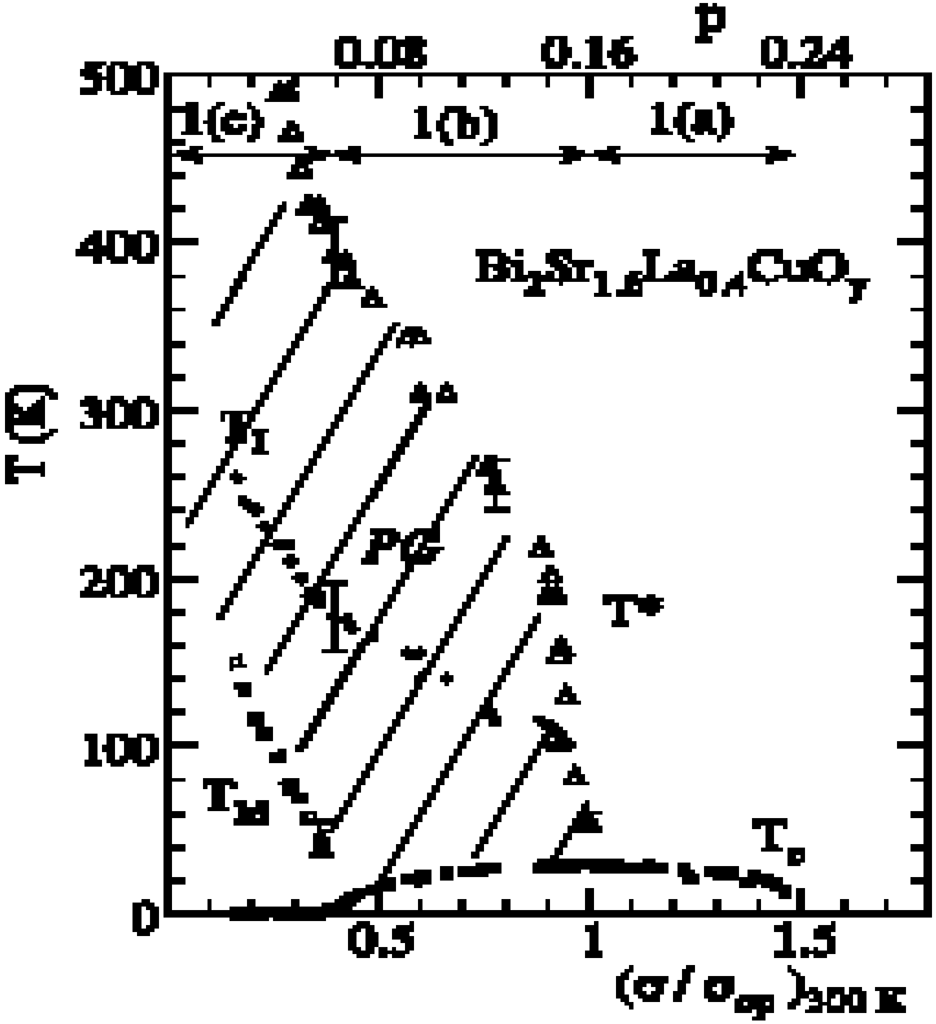


Fig. 4. Phase diagram of $Bi_2Sr_{1.6}La_{0.4}CuO_y$ films as a function of the parameter $(\sigma/\sigma_{op})_{300\,K}$ (see text). Some characteristic p values are indicated on the upper horizontal axis. Marks 1(a), 1(b) and 1(c) indicate the corresponding regions of in-plane resistivities (see Fig. 1). The open symbols correspond to the results obtained for the film of Fig. 1, while the solid symbols are for another sample. The hatched area indicates the pseudogap region (PG). T^*, T_M and T_1 are defined in Figs. 1 and 3.

← H. Raffy et al.

Bi-2001 films:

T^* is enormous !

Can we enhance
T_c to ≈50K
by
optimized growth ?

ARPES on LSCO-214 films and on cleaved crystals – agree !

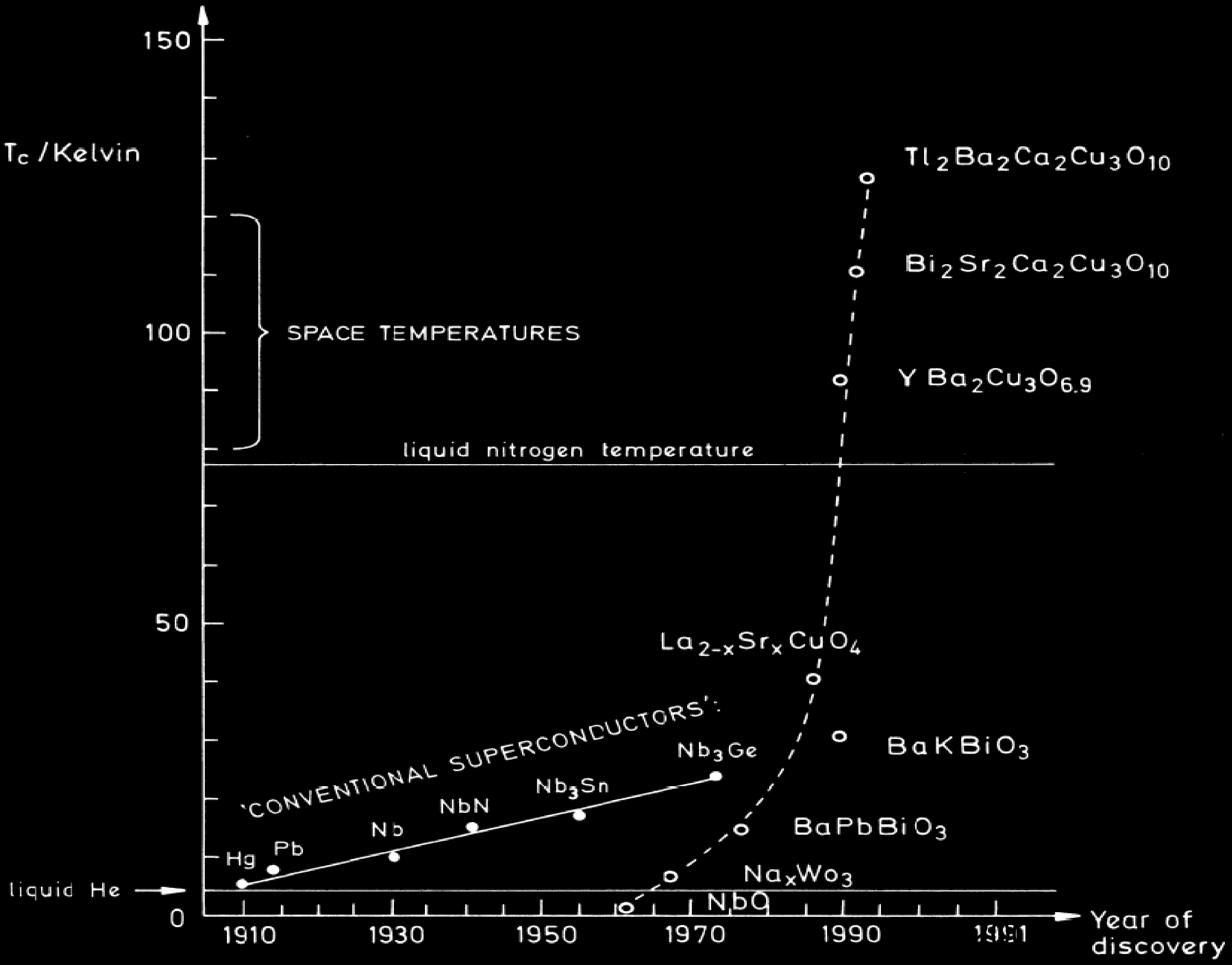
Compressive strain: FS changes from hole-like to electron-like
T_c is enhanced by compressive strain for all dopings
it correlates with apical oxygen & c-axis.

Tensile strain: Dispersion along the c-axis becomes important.
Superconductivity diminishes under huge tensile strain.

The "Napoleon-Cake" lattice important

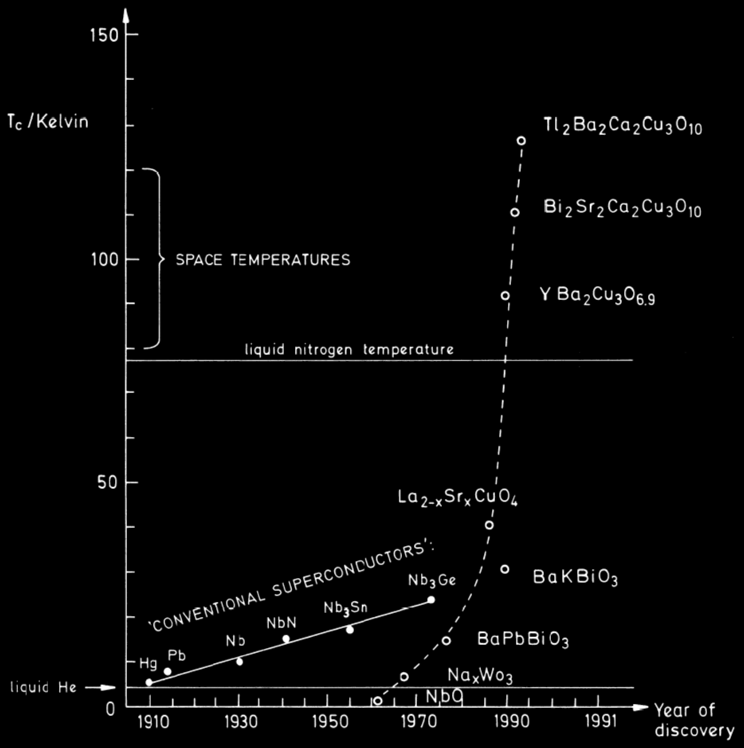
Work on Bi-2201 and LBCO in progress

Beyond High-Tc Superconductivity


Tc / Kelvin
150
100
50
0
SPACE TEMPERATURES
liquid nitrogen temperature
liquid He
Tl2Ba2Ca2Cu3O10
Bi2Sr2Ca2Cu3O10
Y Ba2Cu3O6.9
La2-xSrxCuO4
BaKBiO3
BaPbBiO3
NaxWo3
NbO
'CONVENTIONAL SUPERCONDUCTORS':
Hg
Pb
Nb
NbN
Nb3Sn
Nb3Ge
1910
1930
1950
1970
1990
1991
Year of discovery

300 K

Our Challenge



2050

Some RTSC Candidates:

Hydrogen under 400GPa

ALL MBE (or PLD) Heterostructures:

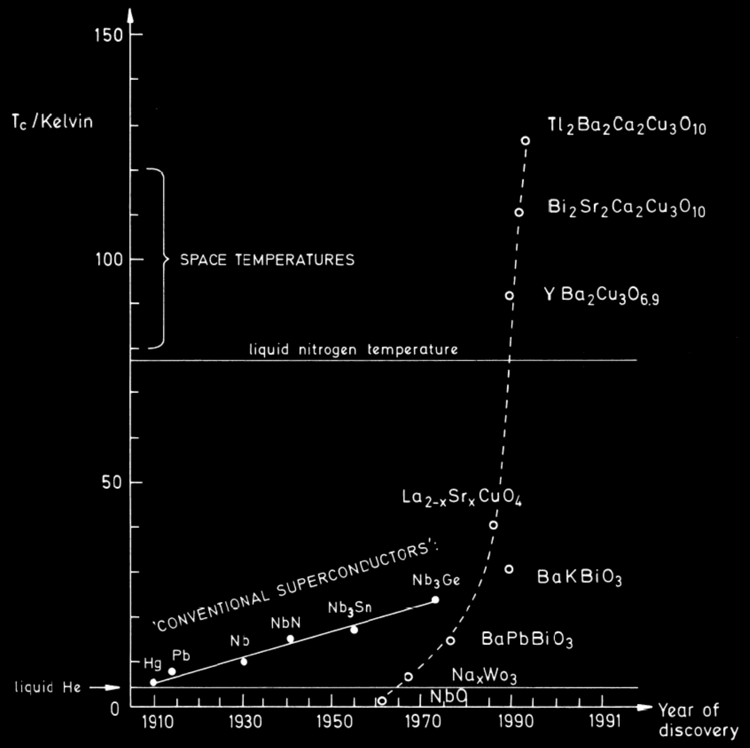
Li-doped Berillium Hydride

Interface Superconductivity (AgO-STO)

…

500 K

Colossal Superconductivity



2100

George Bernard Shaw:

… all progress is due to the man who is non-reasonable !

… there are many unknown
researchers worldwide
all the time trying to make
a RT-superconductor !?!