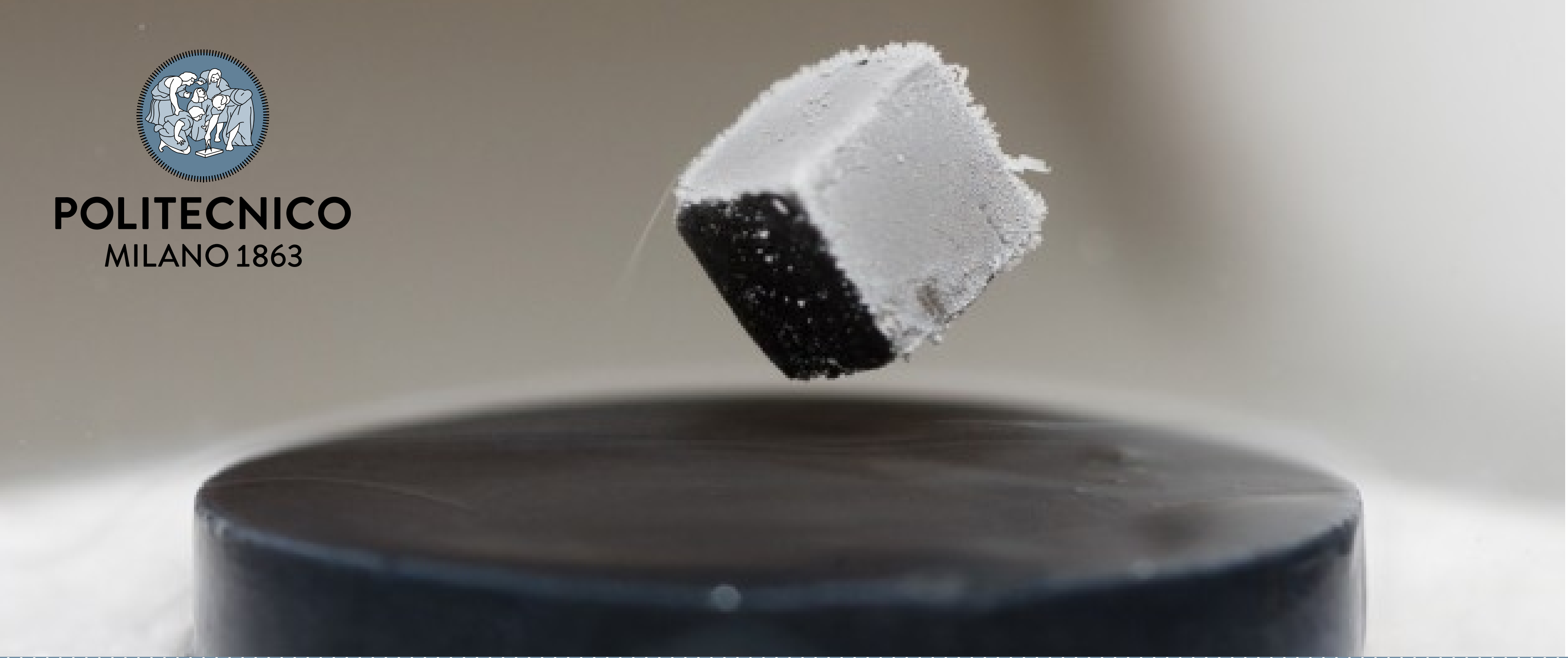


X-ray vision of High Temperature Superconductivity

Giacomo Ghiringhelli

Dipartimento di Fisica – Politecnico di Milano – Italy

Colloquium di Dottorato

Università di Pavia, Dipartimento di Fisica - 11 Maggio 2017

PAUL SCHERRER INSTITUT
PSI
SWISS LIGHT SOURCE
SLS

ESRF

POLITECNICO
MILANO 1863

European
XFEL

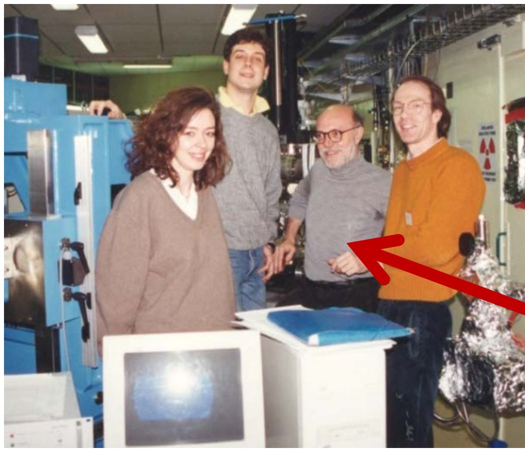
Soft x-rays, spectra and Lucio

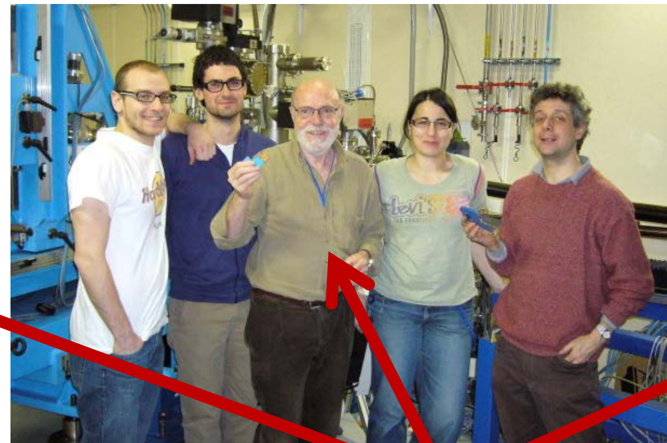
ESRF

1994 - 2000: ID12B

2001 - 2013: ID08

2015: ID32





INFM

POLITECNICO MILANO

Advanced X-Ray Emission Spectroscopy

Lucio Braicovich

POLITECNICO
MILANO 1863

ESRF

2006 - 2011: ADRESS @ SLS

POLITECNICO MILANO

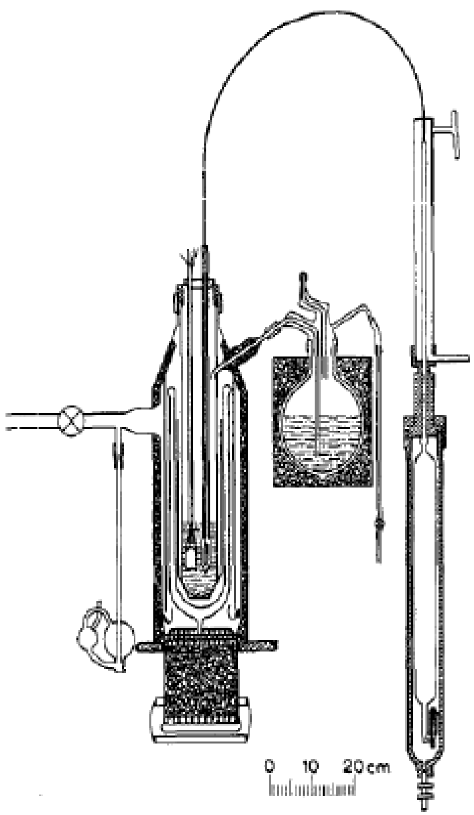
PAUL SCHERRER INSTITUT
PSI

SAXES
Swiss Light Source
&
Politecnico di Milano

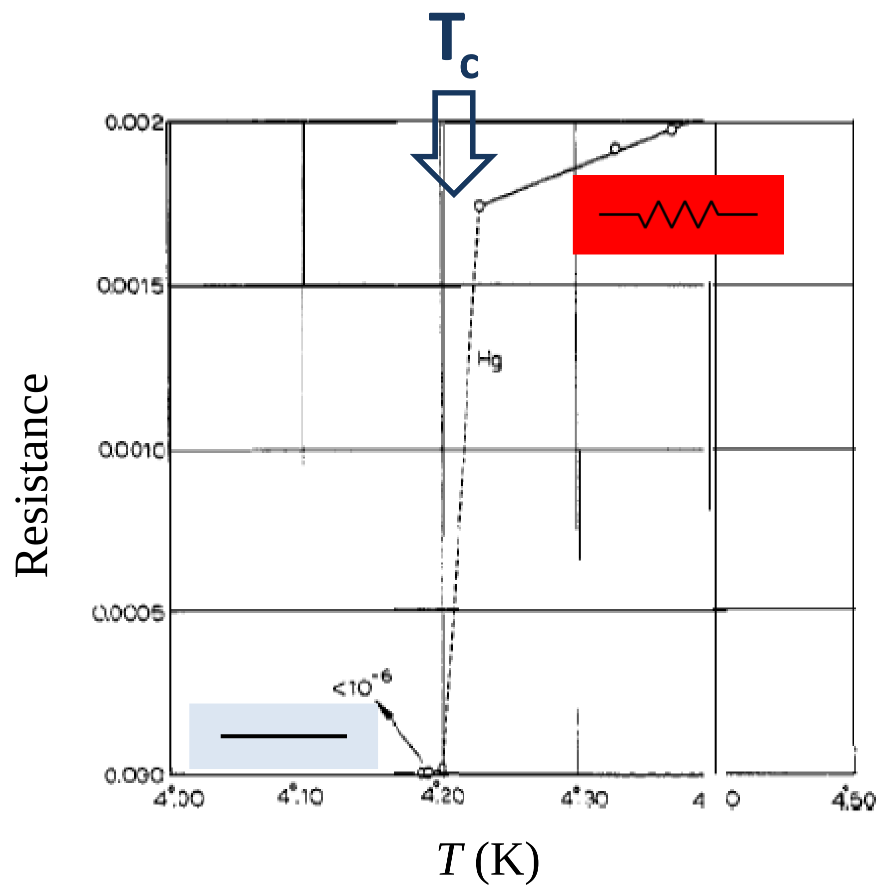
Superconductivity

Discovered in 1911 in mercury

Very low T



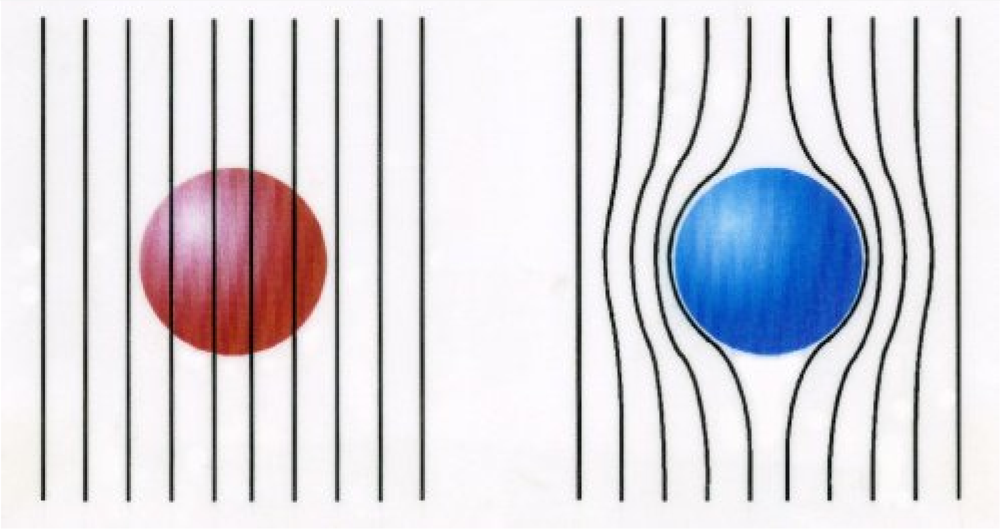
Electric **resistivity** is **ZERO** below a critical temperature

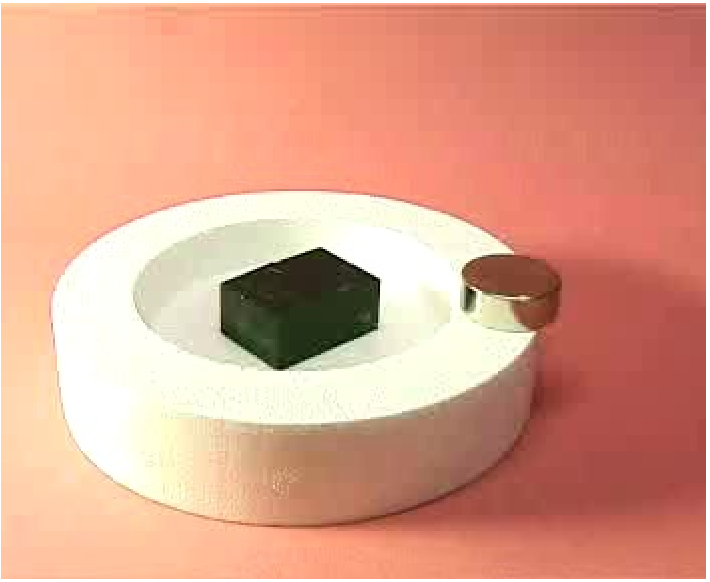


Perfect diamagnetism

Not only a perfect **conductor**, but also a perfect "**anti-magnet**":
Meissner effect

A superconductor repels magnetic fields



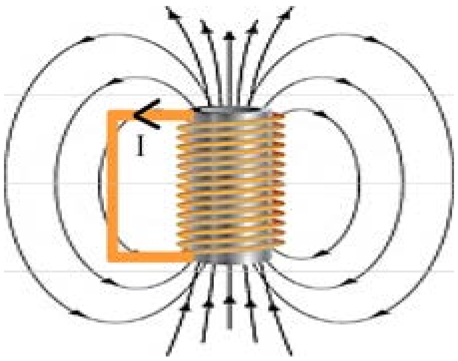


How can we use SC?

Transport and storage of electric power:
no waste of energy

Limitations

- Low T
- Critical current



High magnetic fields:
no need to dissipate heat from the coils of electromagnets

- Critical current
- Critical field
- Low T

SC technology today

Despite the difficulty due to **cryogenics**, **superconducting wires** have been developed for special applications and are currently used in commercial **medical devices** and advanced **scientific instrumentation**.

LHe

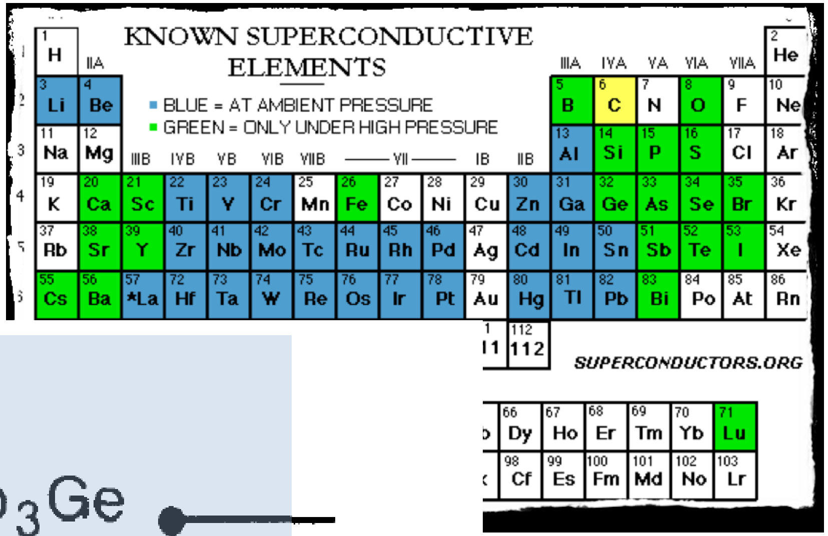
Nb alloys

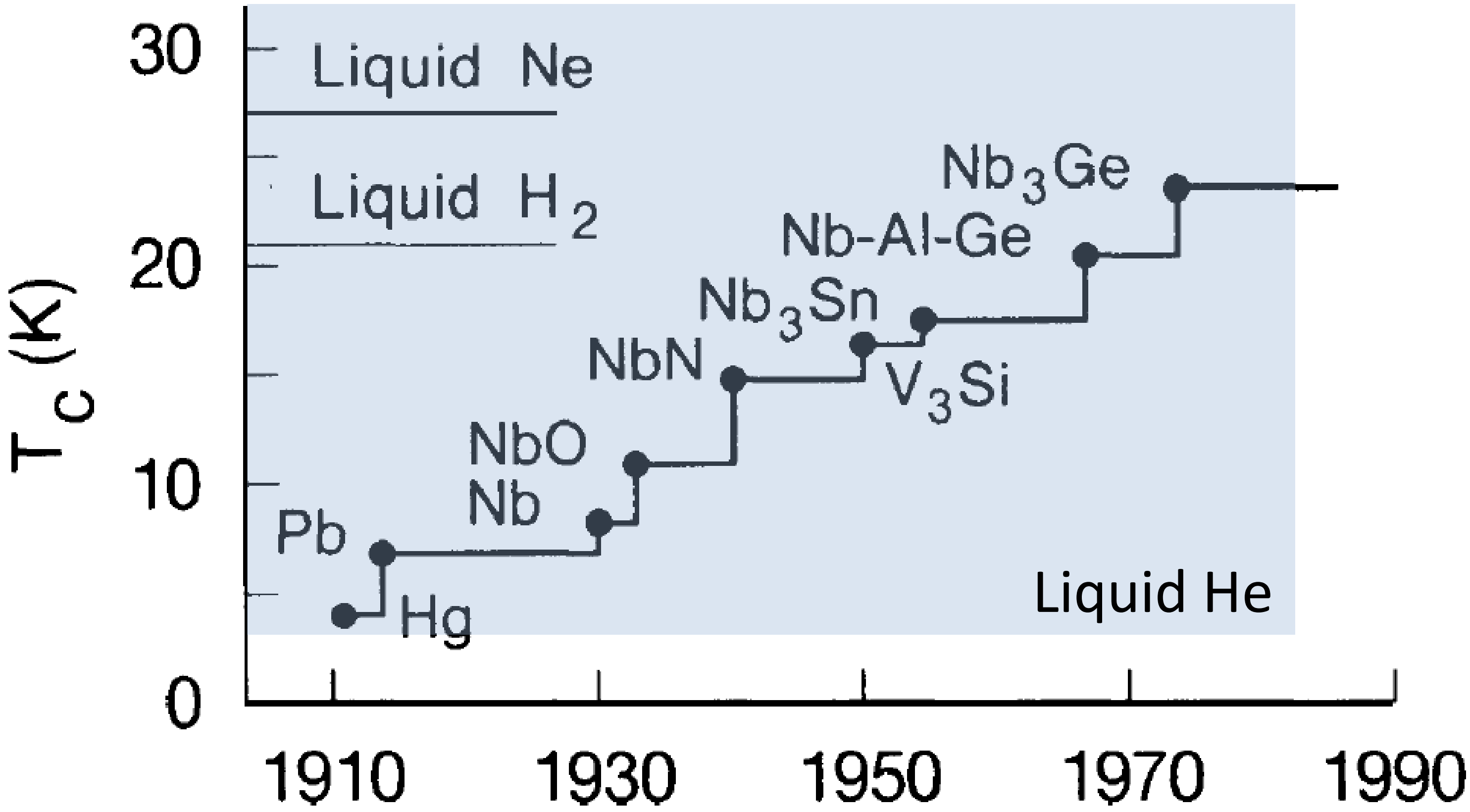
MRI

High field magnets
Particle accelerators
SQUID magnetometers

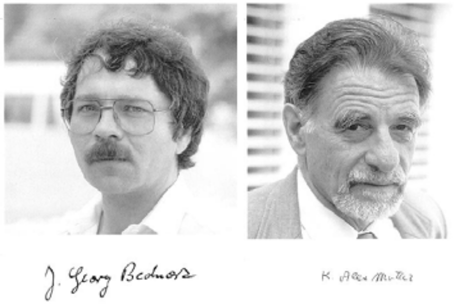
Low temperatures

For **75 years** the search for materials with higher T_c has been quite frustrating



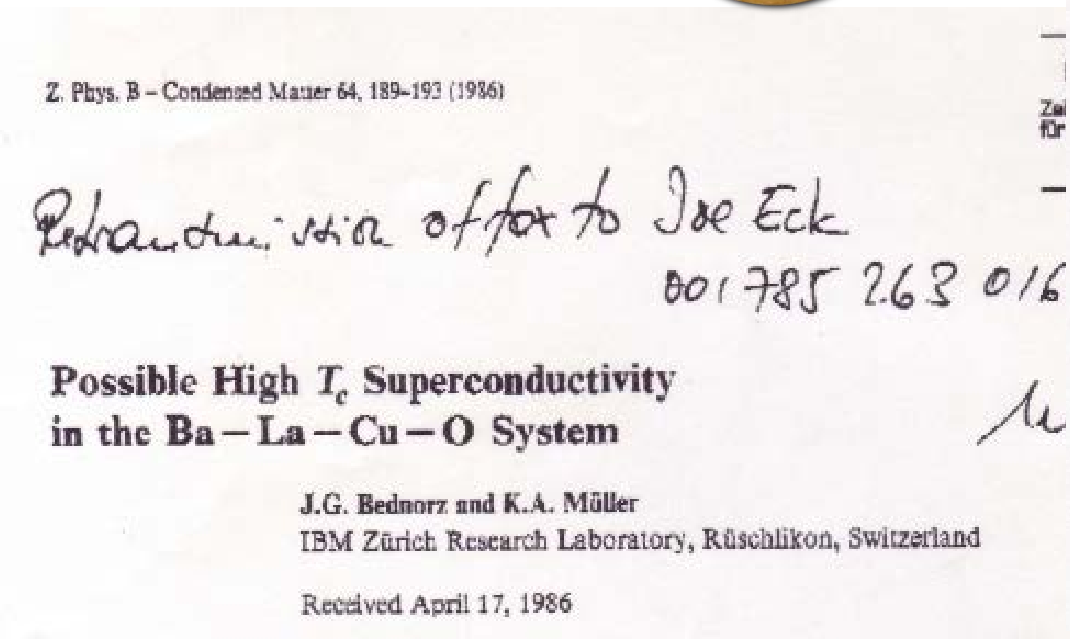


High Tc superconductors (HTS)



Bednorz & Müller

Discovery: Jan. 1986
Publication: April 1986



Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Ixe Eck
001 785 263 016

Possible High T_c Superconductivity in the Ba–La–Cu–O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

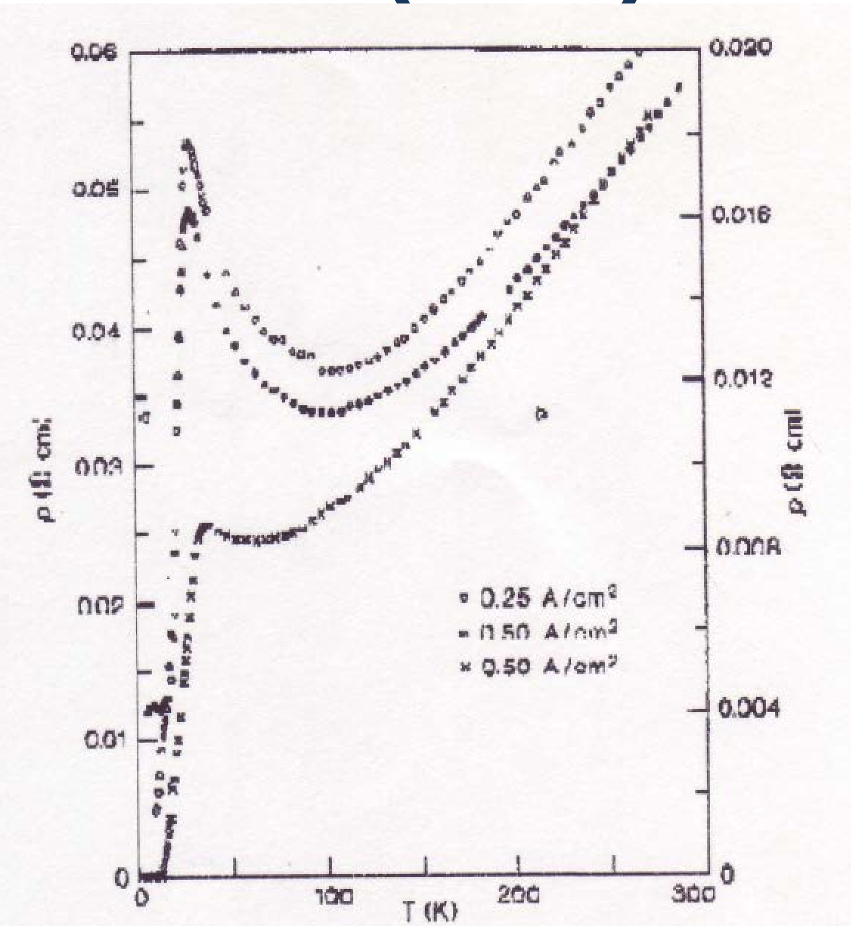


Fig. 1. Temperature dependence of resistivity in $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ for samples with $x(Ba)=1$ (upper curves, left scale) and $x(Ba)=0.75$ (lower curve, right scale). The first two cases also show the influence of current density

A new cult is born during the Woodstock of Physics (1987)

American Physical Society, **March Meeting**, New York, **1987**

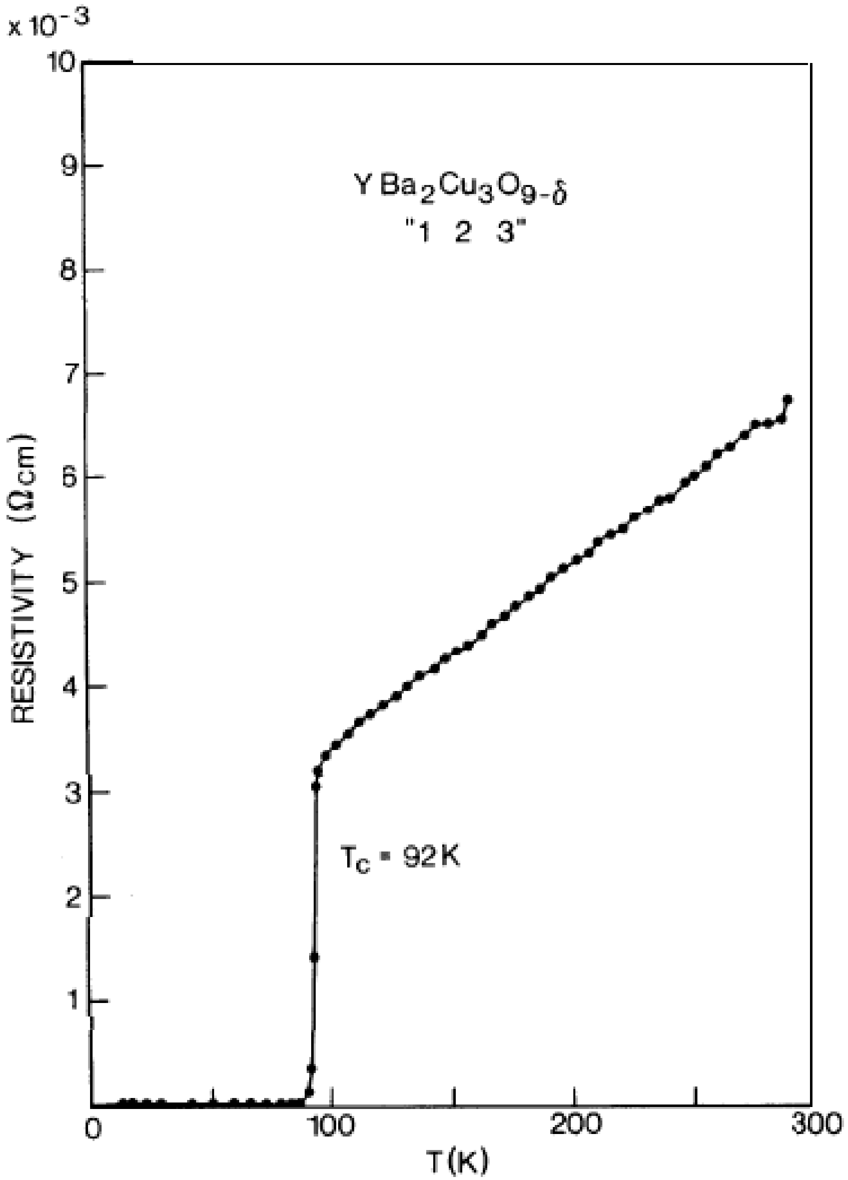
On 18 March, more than a thousand physicists jammed the outer lobbies of the ballrooms at the New York Hilton as they waited for more than an hour for the doors to open 45 minutes before the 7:30 pm panel discussion on high-T_c oxides. A brief, two-line announcement about the panel discussion had been made in the program for the annual March meeting of The American Physical Society, held in New York on 16–20 March. Of the 3080 contributed abstracts in the program for the meeting, there was only one—from IBM Yorktown Heights and Zurich—on superconductivity in Ba-La-Cu-O. But because of the growing interest in these oxides by the middle of December, Neil Ashcroft (Cornell University), then chairman of the Division of Condensed Matter Physics of the APS, told us, an effort was made to announce the panel discussion in the program even though it had already been closed.

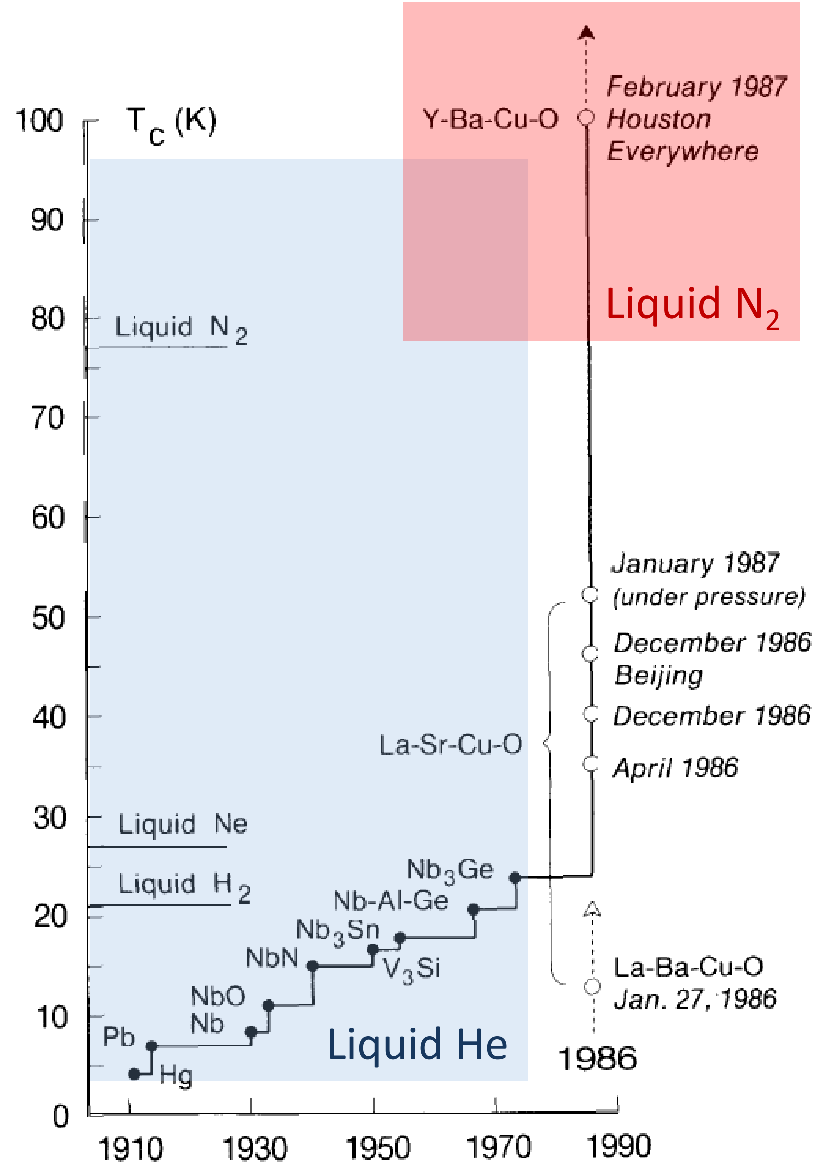
There was a thunderous applause when Ashcroft, after introducing the members of the first panel—Müller, Shoji Tanaka (University of Tokyo), Paul C. W. Chu (University of Houston), Zhongxian Zhao (Institute of Physics, Academia Sinica, Beijing) and Bertram Batlogg (AT&T Bell Laboratories)—concluded his opening remarks with "These are some of the men, ladies and gentlemen, who set this engine running." The 1140 seats in the Rendezvous Trianon Ballroom had been filled in just a few minutes after the doors opened. Several hundred physicists stood patiently in the side aisles for several hours to listen to a series of five-minute presentations; many more watched the proceedings on monitors placed in the lobbies. According to Ashcroft, more than a hundred physicists were still present when he closed the session at a quarter after three. Many remained until 6 am, when the hotel staff reclaimed the rooms.

"A Woodstock for physics" is how Michael Schluter (AT&T Bell Laboratories) described the session at a press conference the following day. Indeed, the repeated requests that Ashcroft, APS vice-president James Krumhansl and APS headquarters staff had to make, requesting their colleagues to please clear the center aisle or the hotel security staff would not let the session begin, were easy reminders of the scene at a rock concert. But the analogy to Woodstock may apply at a deeper level as well: As leaders of research teams hurriedly discussed their evidence for superconductivity above 90 K—a phenomenon unheard of until a month earlier—one could have felt as if one were a part of a ceremonial gathering organized to affirm a new cult. Of

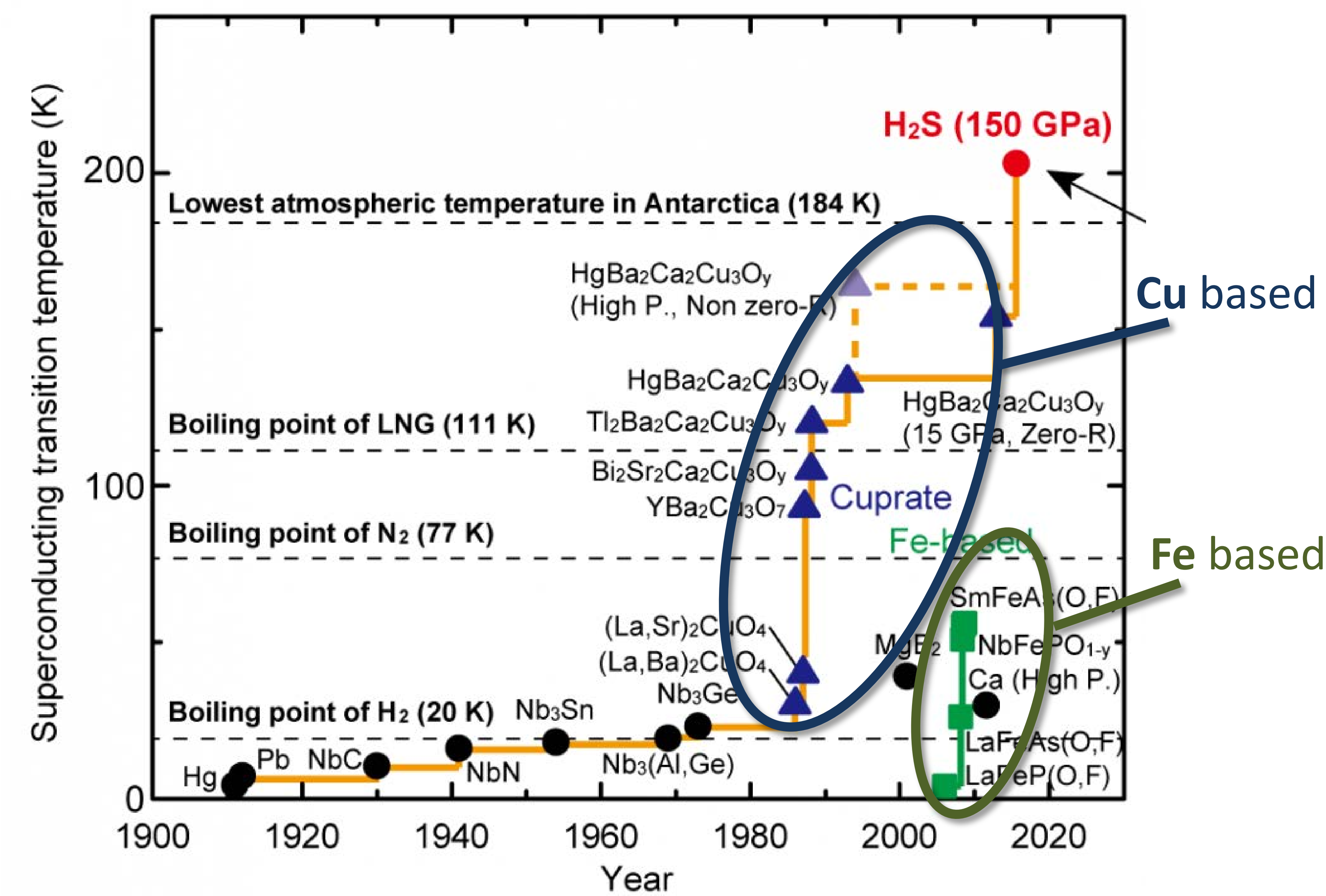
The **arXiv** was invented to keep track of discoveries on **HTS**: normal editorial procedures were too slow to guarantee priority claims

YBCO: T_c above 77 K



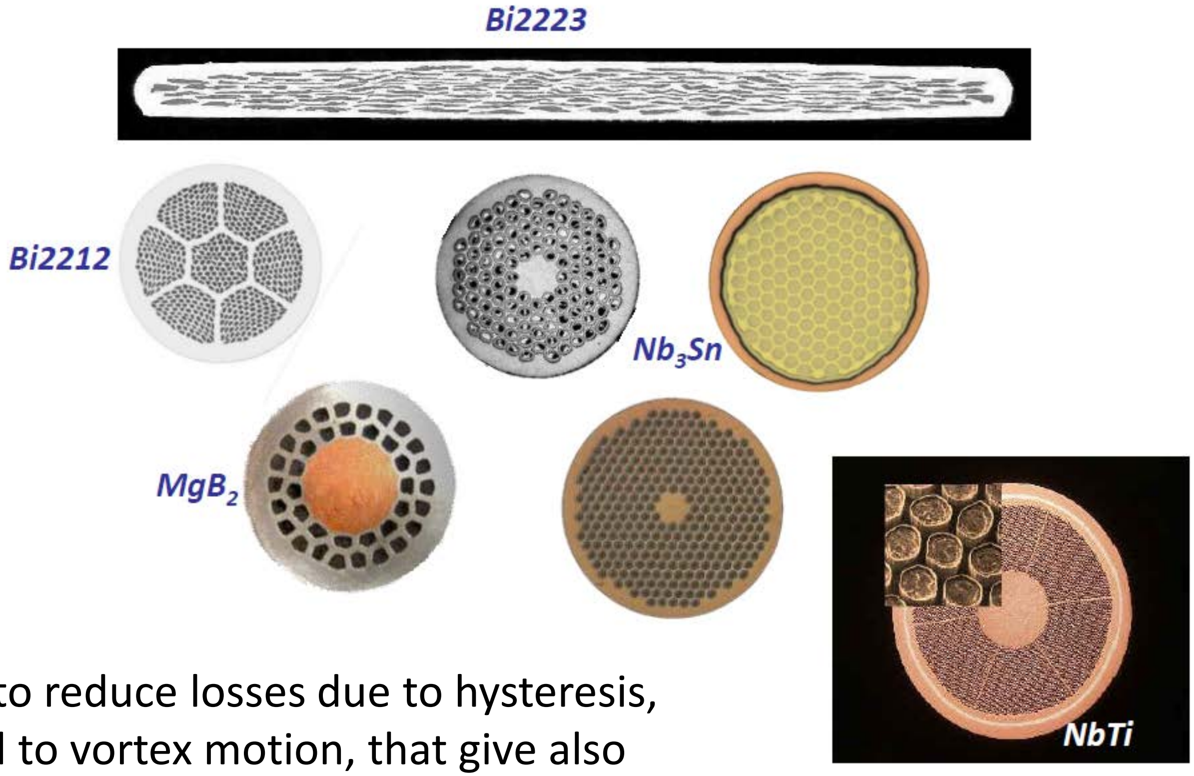


Where are we with T_c 30 years later?



New hope from Cu based HTS

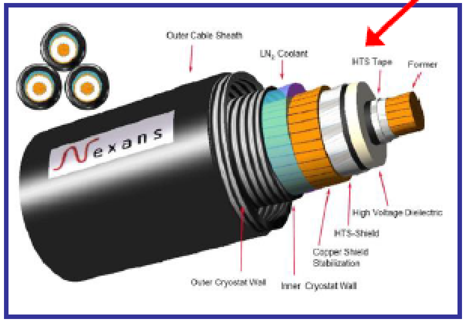
Higher T_c: above Liquid N_2, cryogenics is cheaper and simpler
Higher critical field: stronger electromagnets (potentially up to 40T)
Higher critical current, provided we learn how to make good (multifilament) wires



Multifilament: to reduce losses due to hysteresis, which is related to vortex motion, that give also energy losses

Future applications with HTS?

Power distribution, generation and storage



superconducting cables

fault current limiters

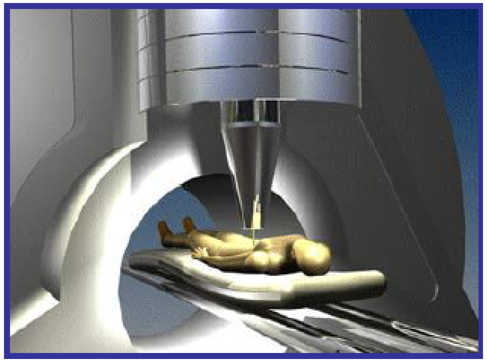
20% from renewable sources by 2020

$$E = \frac{1}{2}\frac{B^2}{\mu}$$

energy density of the magnetic field

New medical applications:

Compact accelerators for hadron therapy

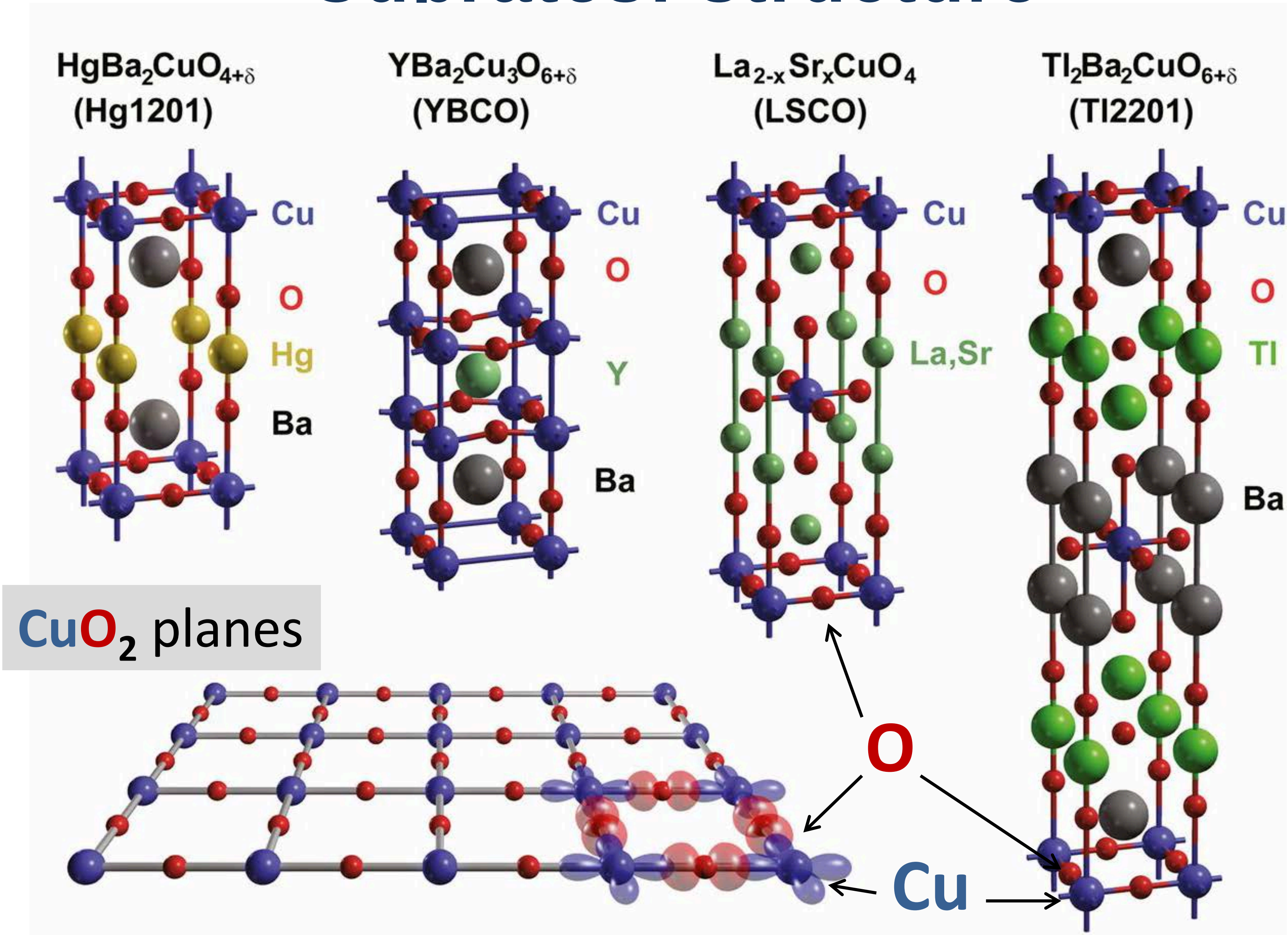


A big step to get there…

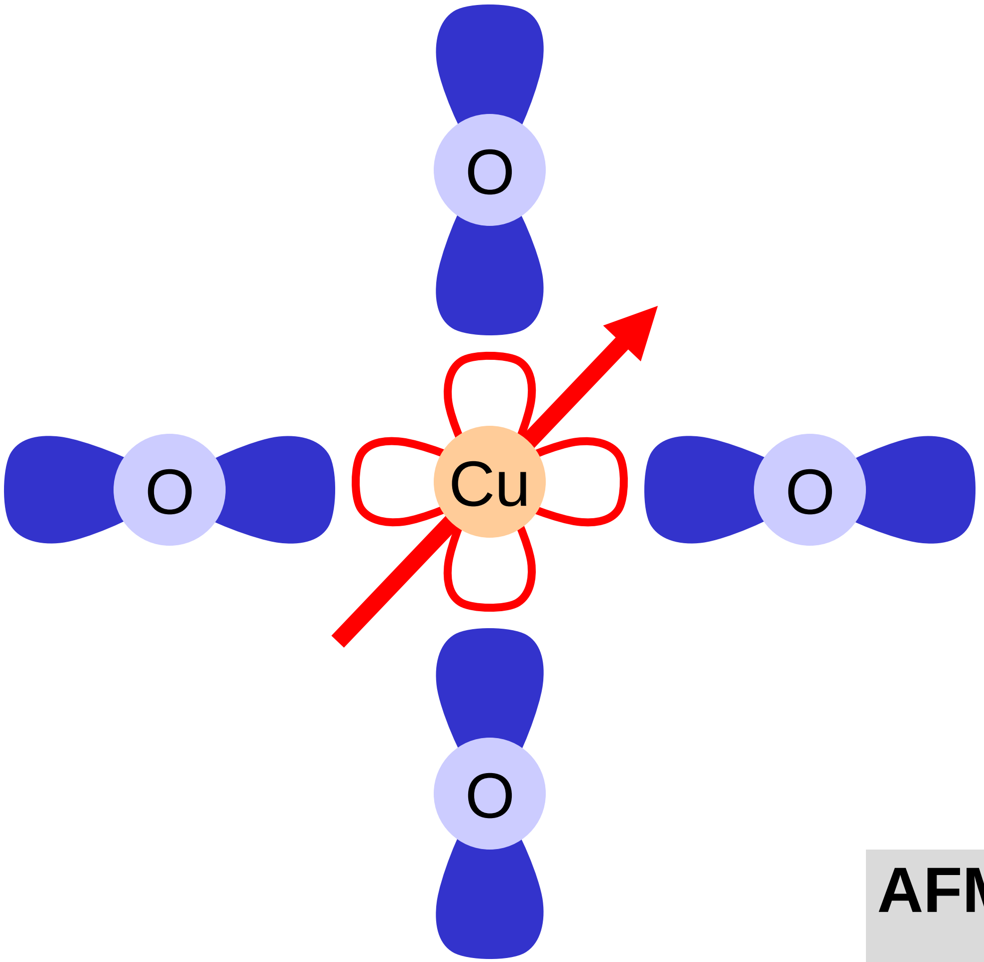
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Source*:* **Carmine Senatore***,* Université de Genève - Lectures on *Superconductivity and applications*

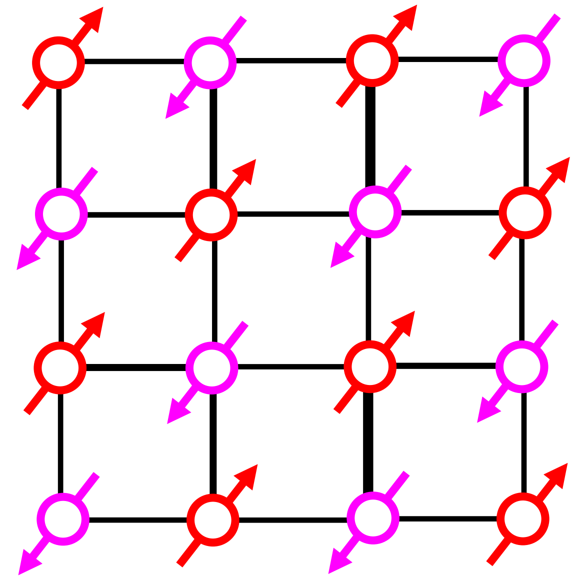
Cuprates: structure



AntiFerroMagnetic order in CuO_2 planes



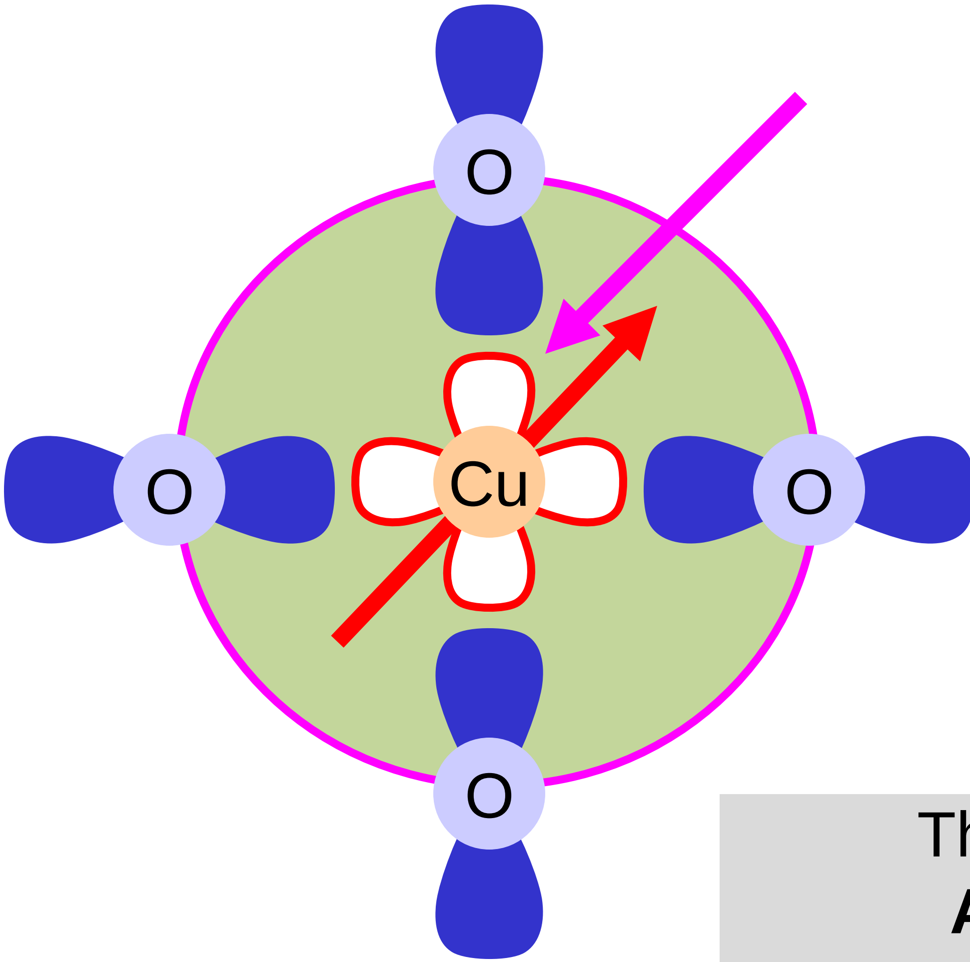
Cu^{2+}, $3d^9$



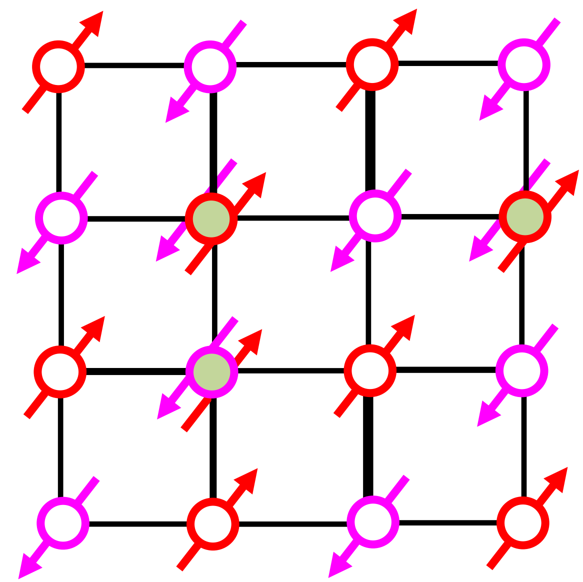
AFM order in the CuO_2 planes

INSULATOR

Doping of planes: holes

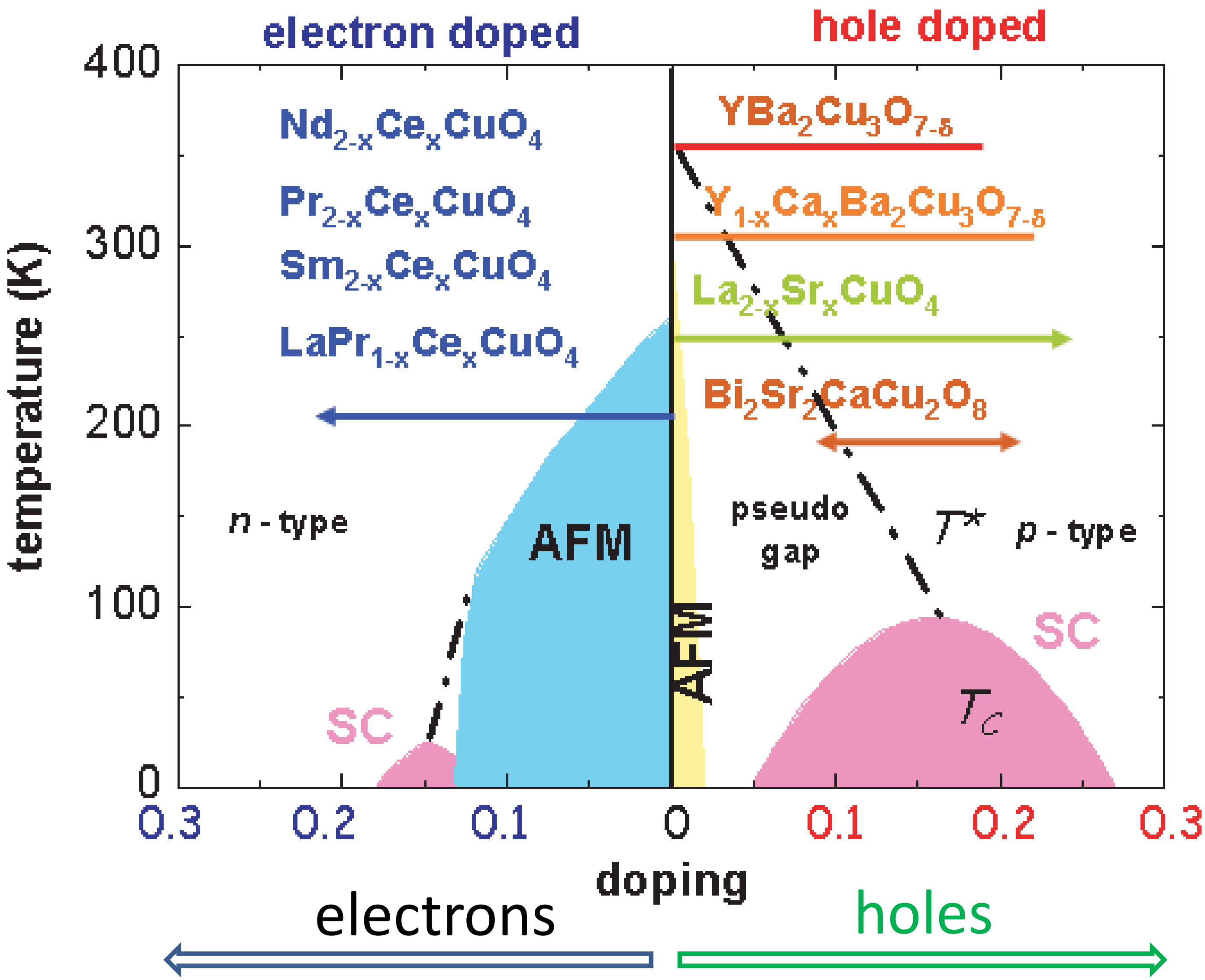


Cu^{2+}, $3d^9$

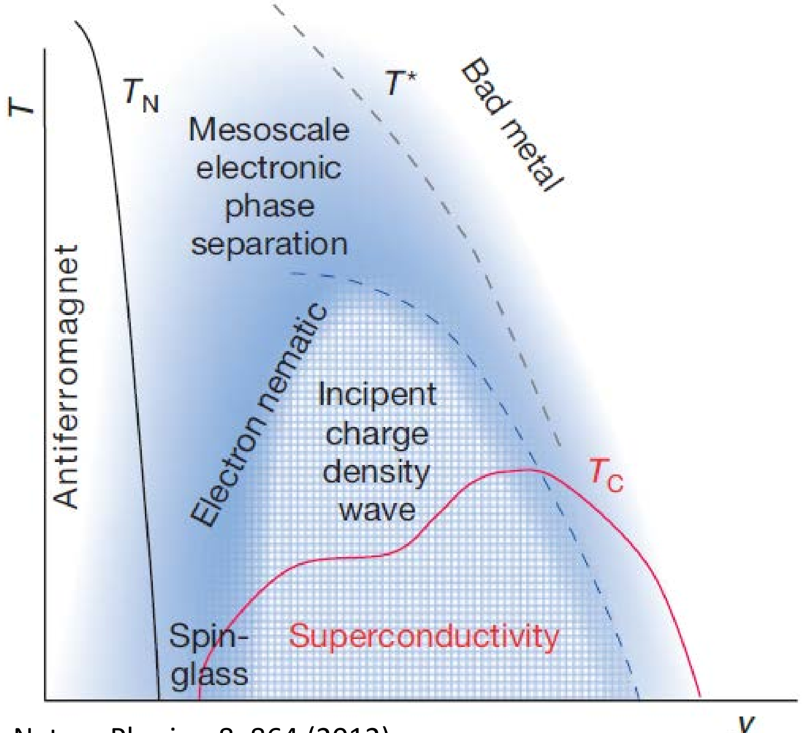


The perfect (long range)
AFM order is broken
Superconductivity becomes possible

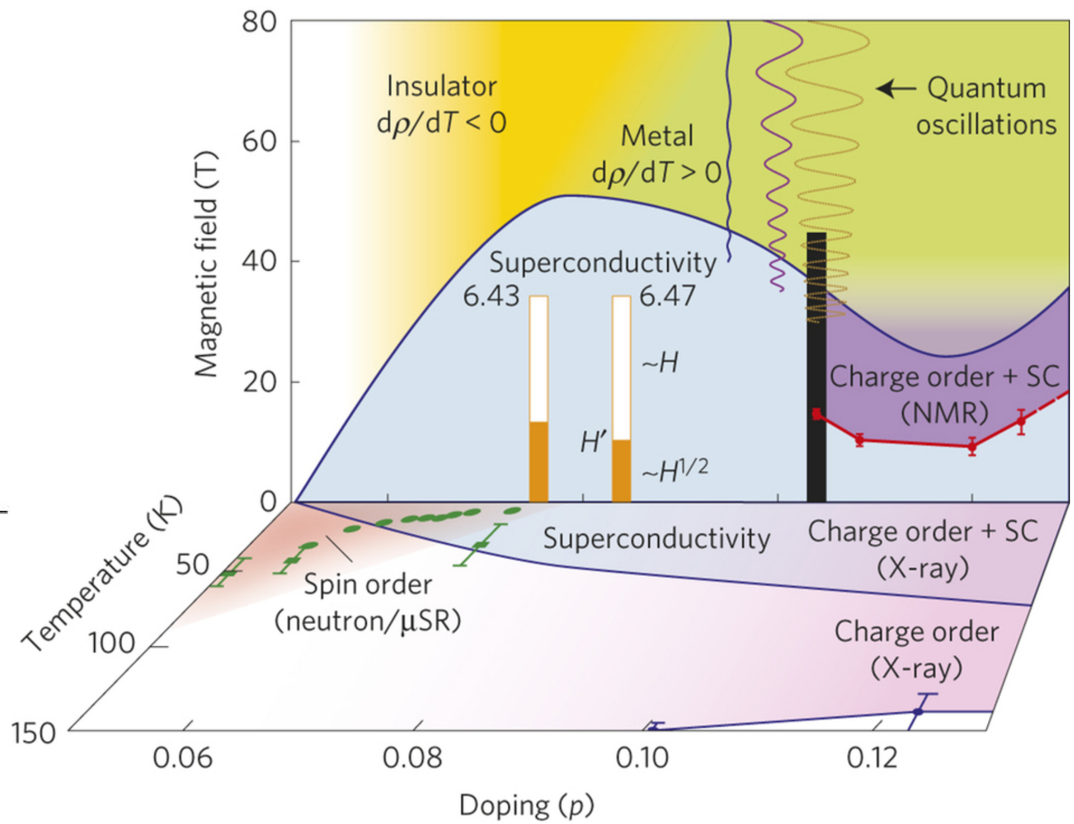
Phase diagram



Extreme Complexity



Nature Physics, 8, 864 (2012)



Nature Physics 12, 47 (2016)

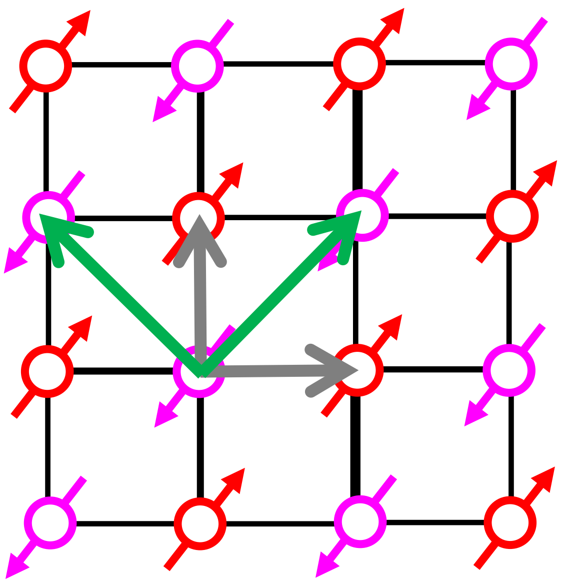
All experimental techniques have been used to unveil the secrets of cuprates, but in most cases results have added complexity rather than clarity

What is special in HTS?

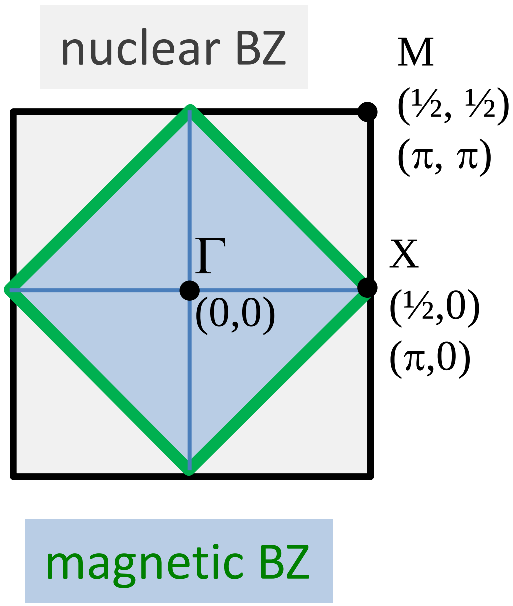
The common property is in the **CuO_2 planes**, ie the system is considered **quasi 2D**.
Thus all properties are referred to the squared **2D reciprocal lattice**.

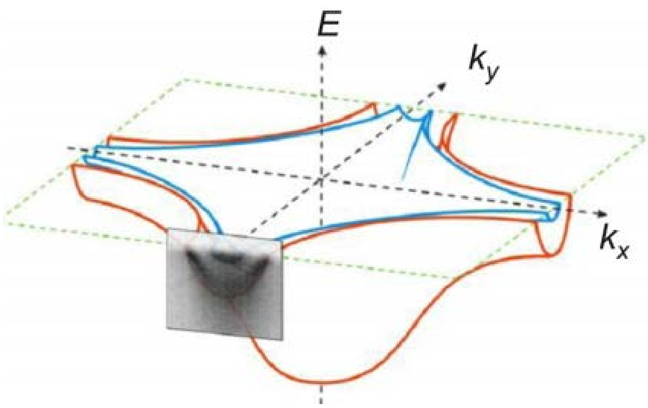
For example:
The electronic band structure as determined by Angle Resolved PhotoElectron Spectroscopy (**ARPES**)

Quasi 2D STRUCTURE



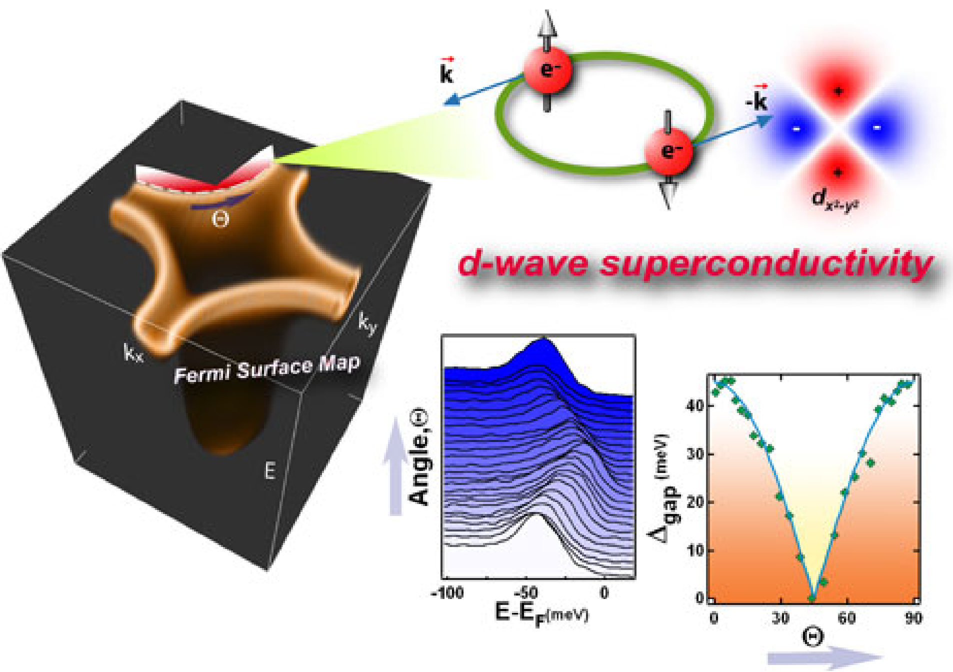
RECIPROCAL SPACE





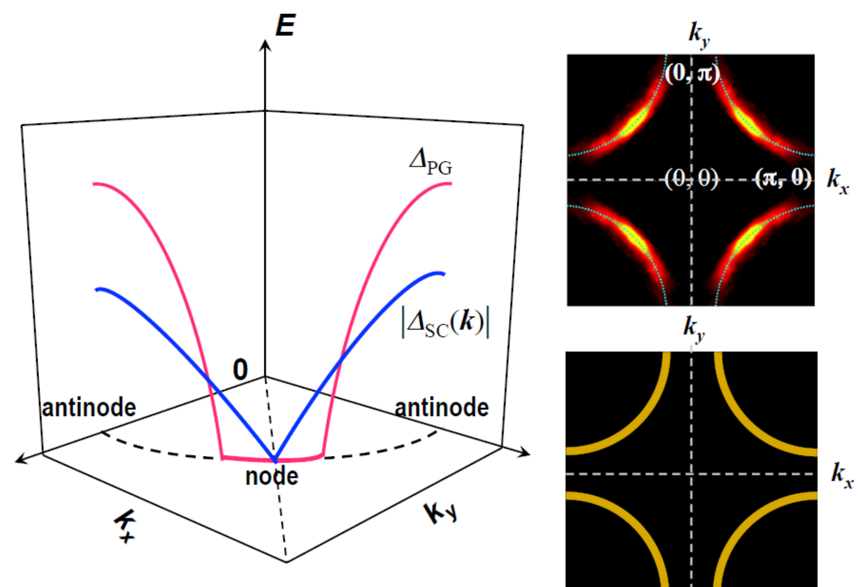
The Superconducting gap…

By ARPES we can determine the **Fermi surface shape** and the **SC gap**.
The **gap** is not constant long the Fermi surface, but has ***x*²-*y*² symmetry**



But ARPES cannot tell us what is the **glue** of **Cooper pairs**

…and Pseudo-Gap



$\Delta_{SC}(\boldsymbol{k}) = (\Delta_0/2)\,(\cos k_x a - \cos k_y a)$

Enter X-ray spectroscopy!

XAS: ground state **orbital symmetry**

XMCD: **weak ferromagnetism** and proximity effect

Spin-Resolved XPS: **spin character** of doped sites

RIXS: **crystal field** splitting

RIXS: spin excitations (**magnons**)

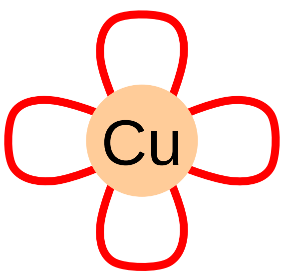
R(I)XS: **charge density waves**

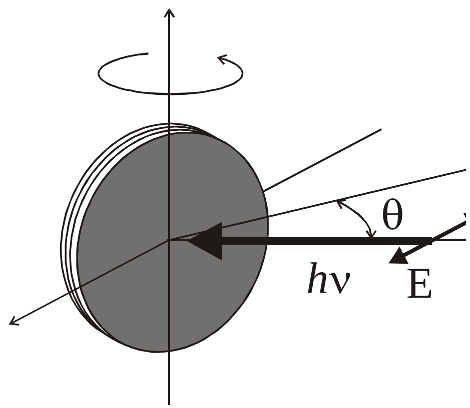
IXS: **phonon** dispersion

RIXS: **electron-phonon coupling**

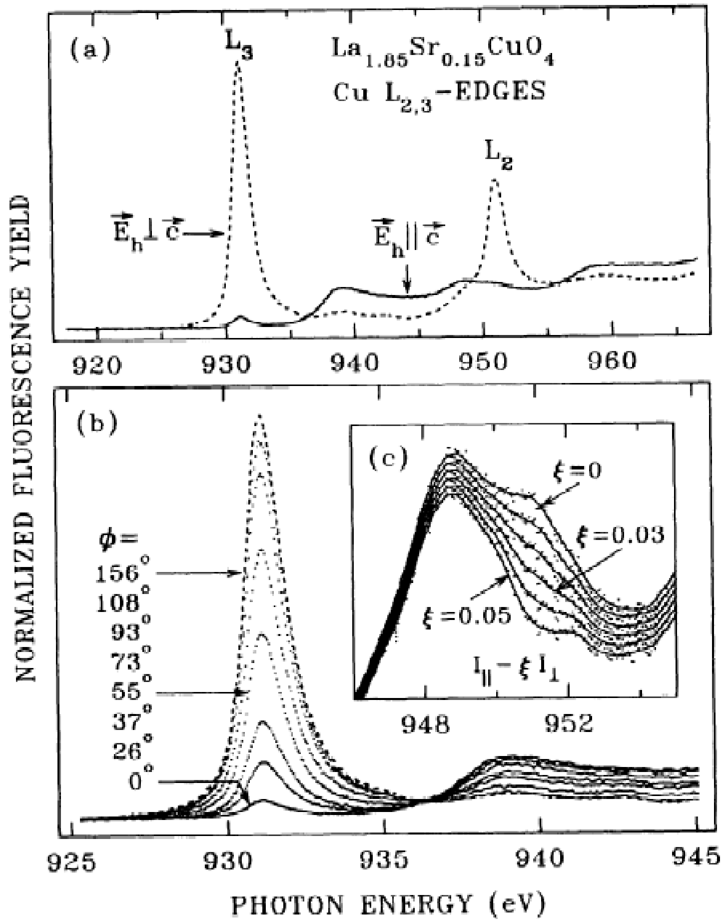
XAS: 3*d* hole symmetry

Linear dichroism of Cu $L_{2,3}$ XAS was used to probe the symmetry of the empty Cu 3*d* orbital





Result: the hole in Cu^{2+} has 100% x^2-y^2 symmetry



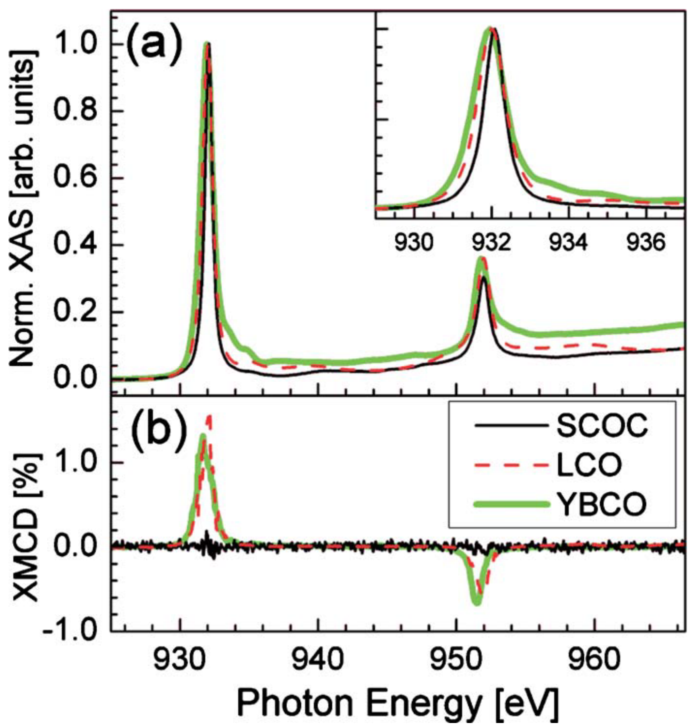
VOLUME 68, NUMBER 16 PHYSICAL REVIEW LETTERS 20 APRIL 1992

Out-of-Plane Orbital Characters of Intrinsic and Doped Holes in $La_{2-x}Sr_xCuO_4$

C. T. Chen, L. H. Tjeng, J. Kwo, H. L. Kao, P. Rudolf, F. Sette, and R. M. Fleming

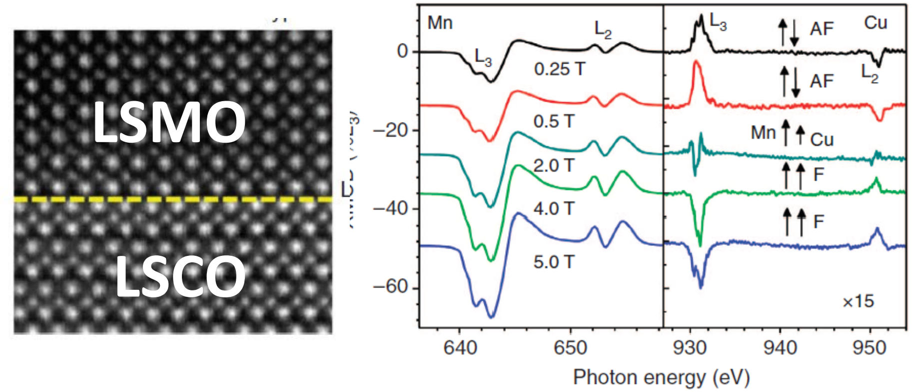
XMCD: weak ferromagnetism and proximity effect

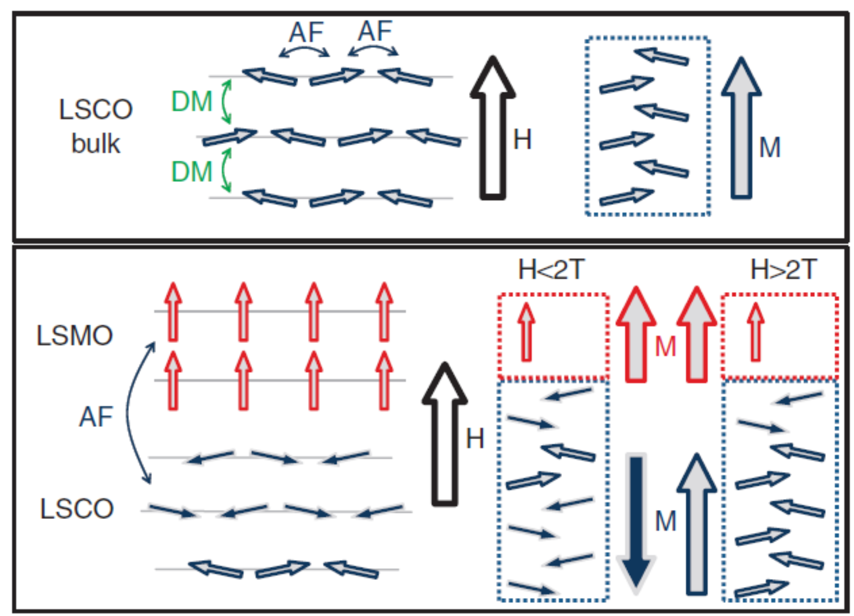
The spin moments are **not perfectly in-plane**: they are tilted by few degrees and a strong external field can orient their out-of-plane component and we can detect it with XMCD



G.M. De Luca, M. Salluzzo, GG et al, PRB 82, 214504 (2010); Nat. Comm. 6626 (2014)

A ferromagnetic oxide can act similarly (proximity effect)



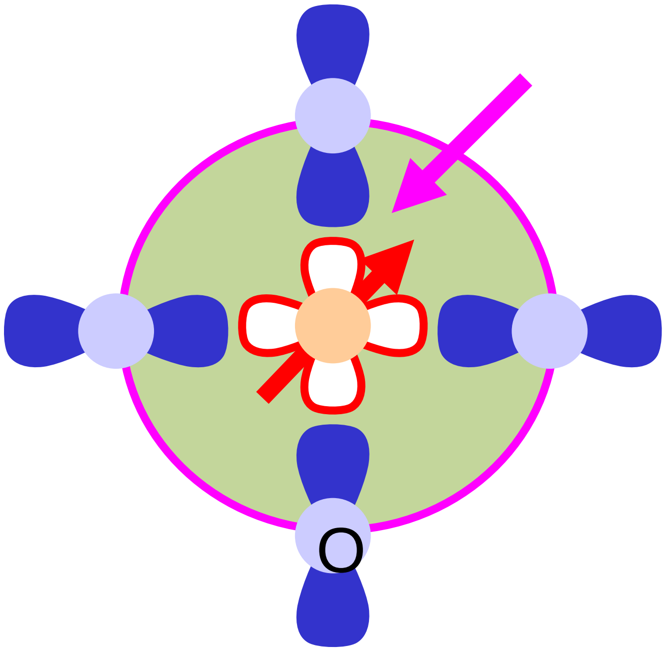


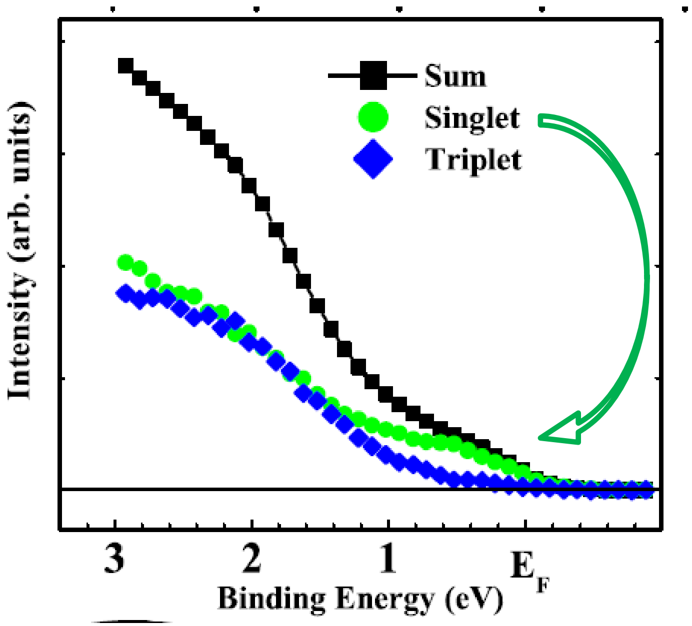
Spin-Resolved XPS: Zhang-Rice singlets

How are the spins aligned when two holes sit at the same Cu site?

Theory predict **antiparallel** configuration (Zhang-Rice singlet)

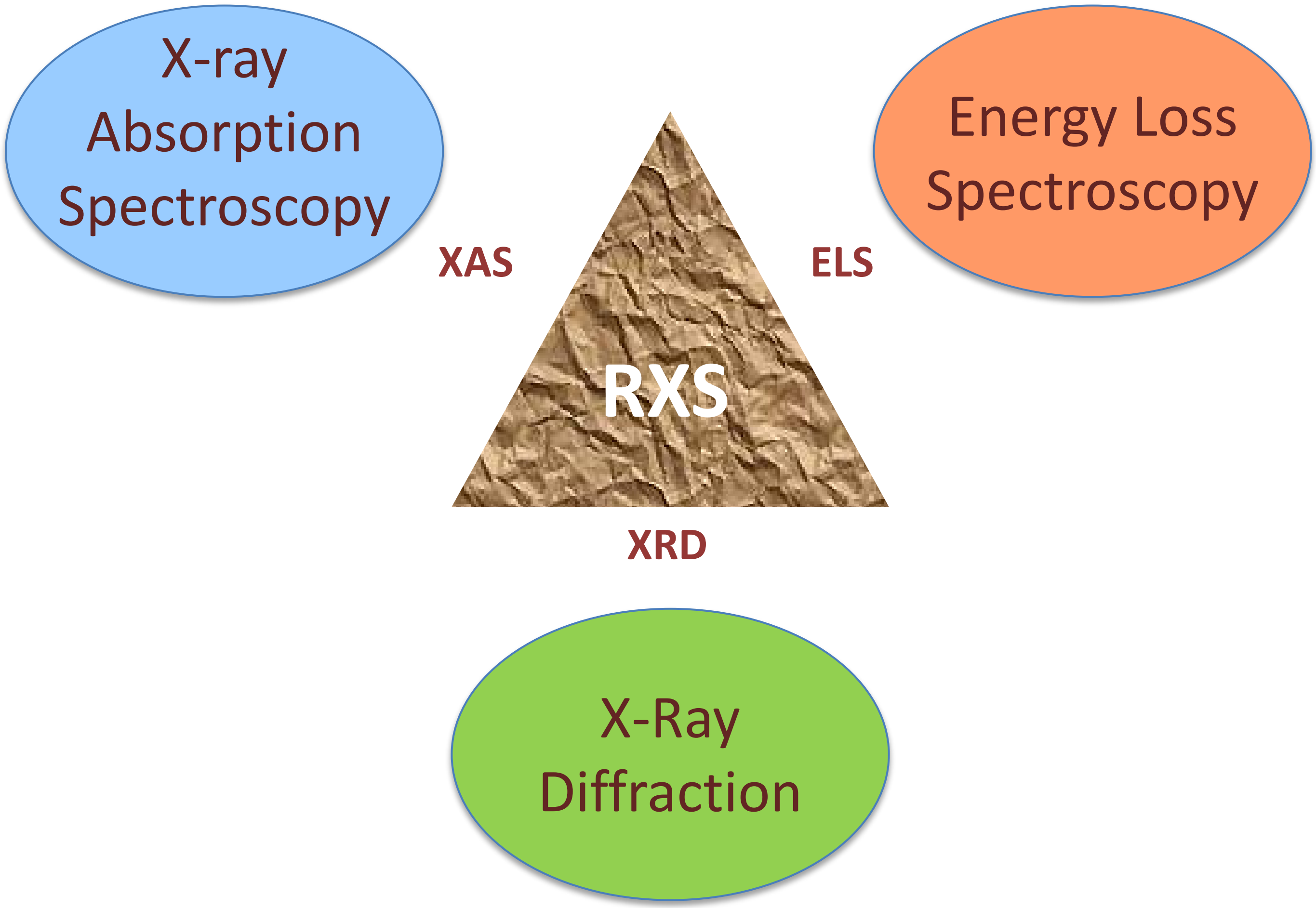
A smart combination of **resonant photoemission** made with **circularly polarized photons** and by detecting the **spin polarization** of photoelectrons has **confirmed it**.



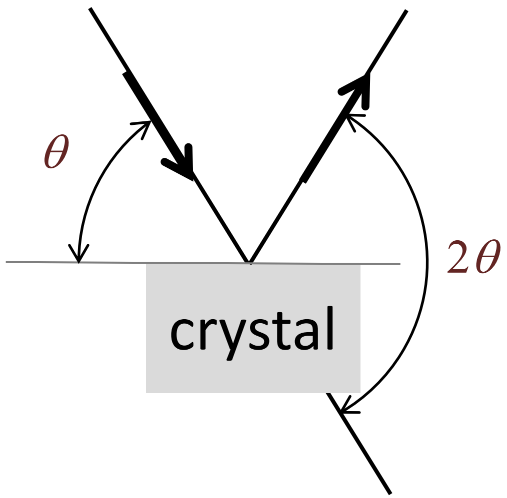


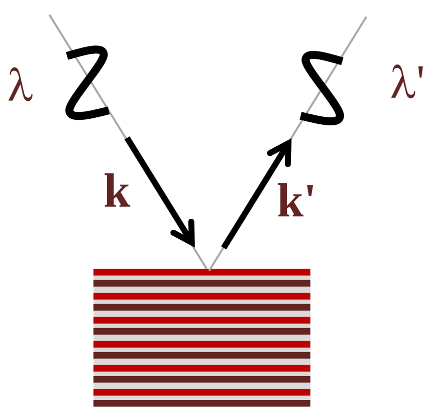
N.B. Brookes, GG et al, PRL 87 237003 (2001); PRL 115, 027002 (2015)

Introduction to Resonant X-ray Scattering



From XRD to X-ray Scattering





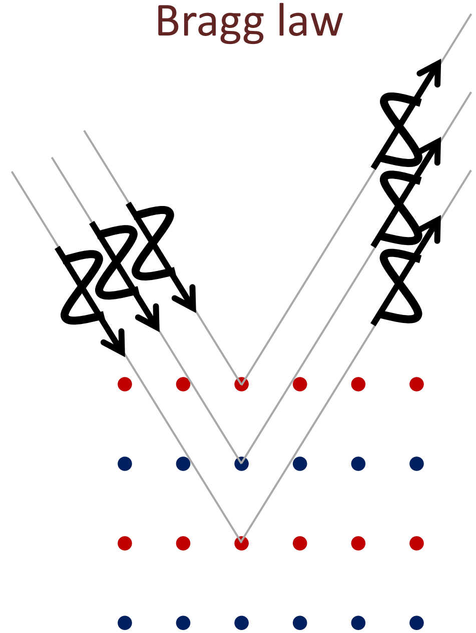
X-Ray Diffraction

$|\mathbf{k}'|=|\mathbf{k}|$

$\lambda = \lambda'$

Real space

Bragg law



X-Ray Scattering

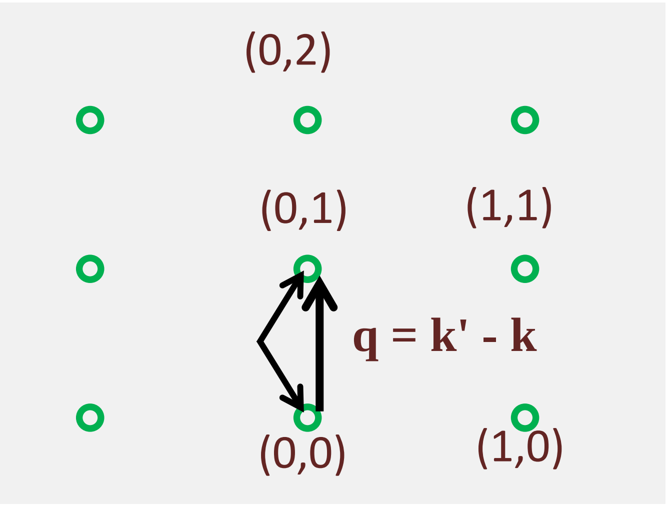
$|\mathbf{k}'|=|\mathbf{k}|$

$\lambda = \lambda'$

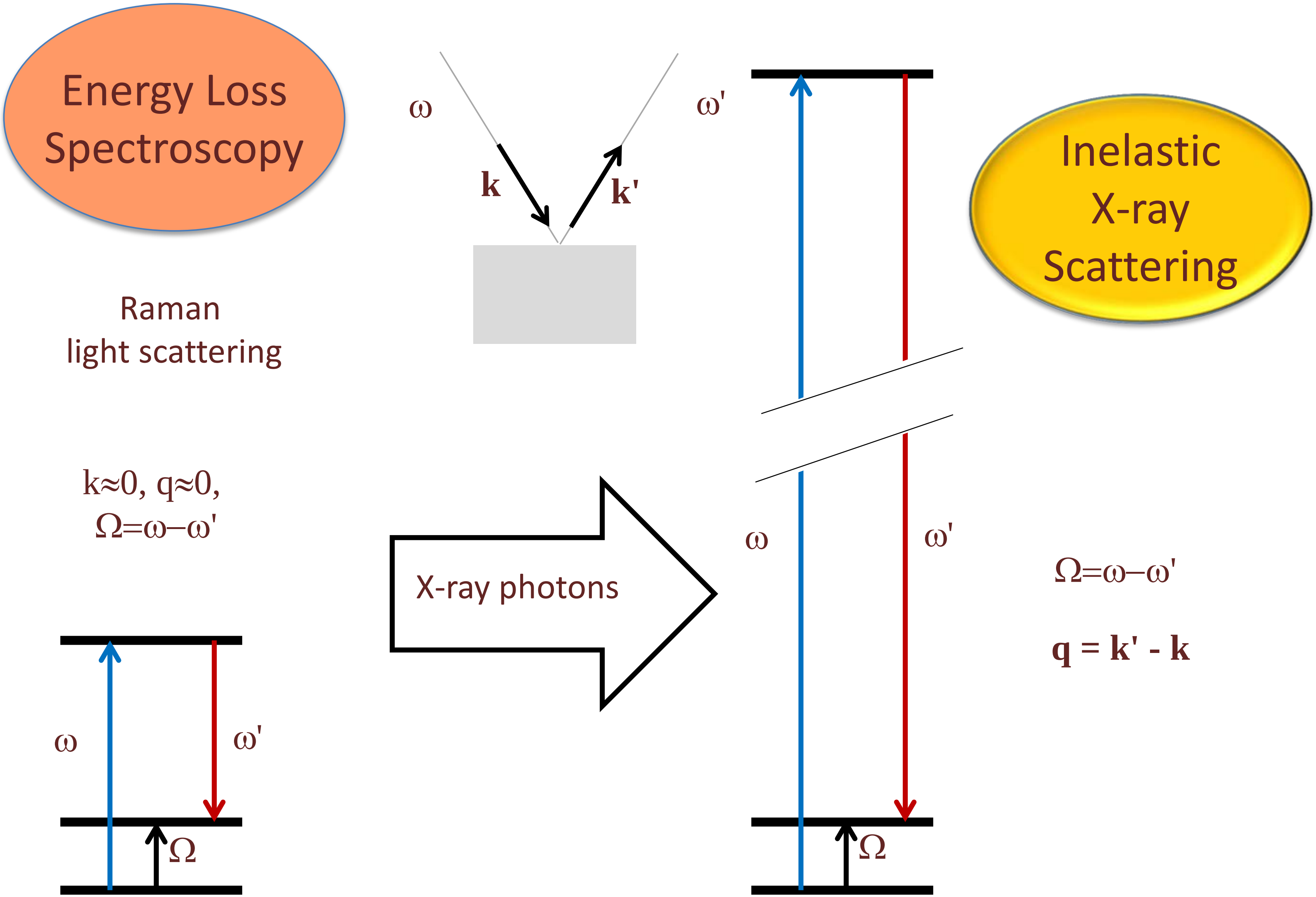
$\mathbf{q}=\mathbf{G}$

Reciprocal lattice

$\mathbf{q}=\mathbf{G}$

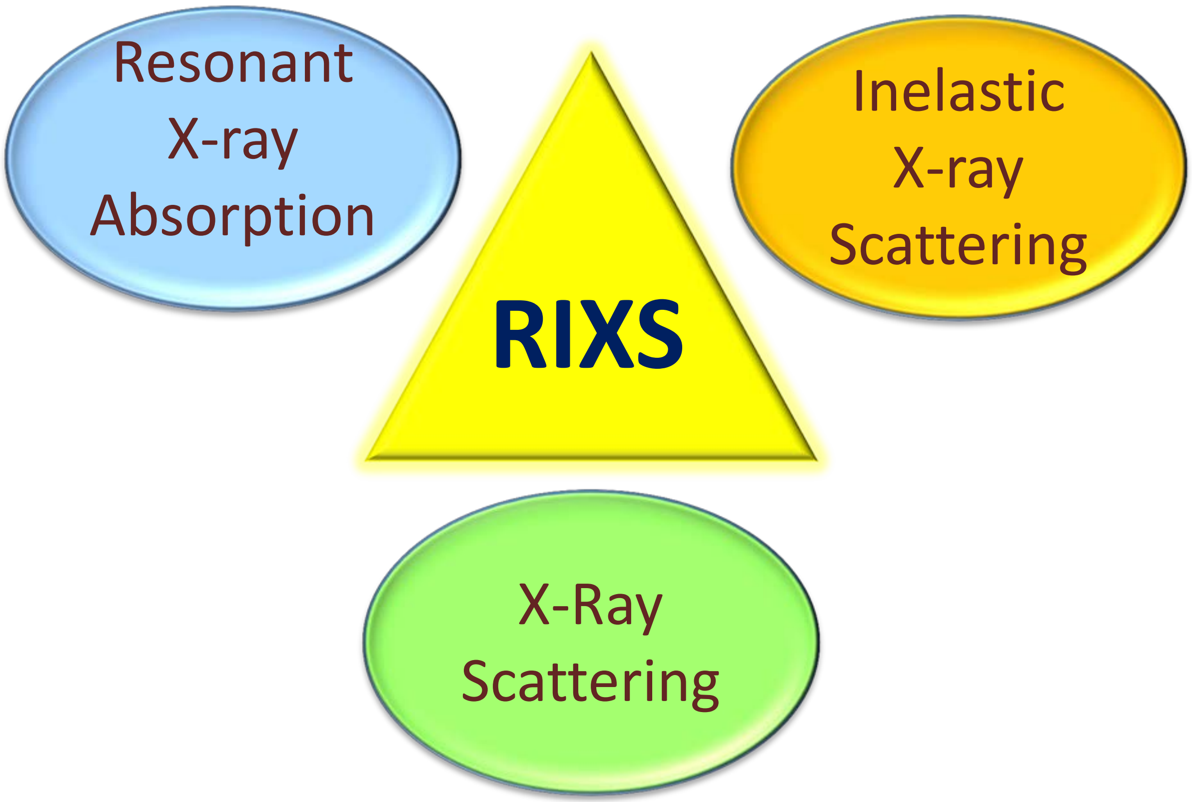


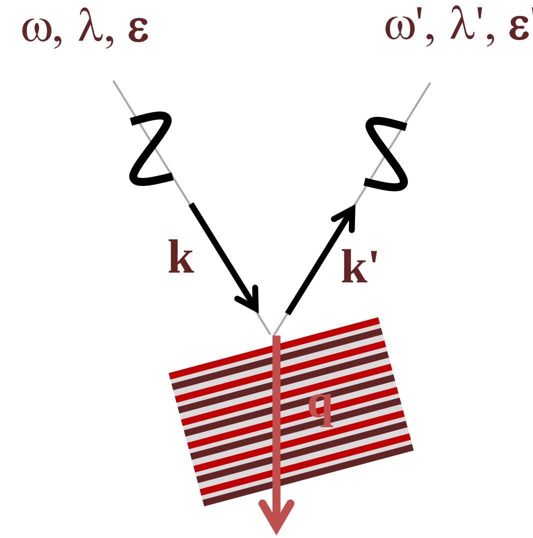
ELS: from Raman to Inelastic X-ray Scattering



RIXS

Resonant Inelastic X-ray Scattering



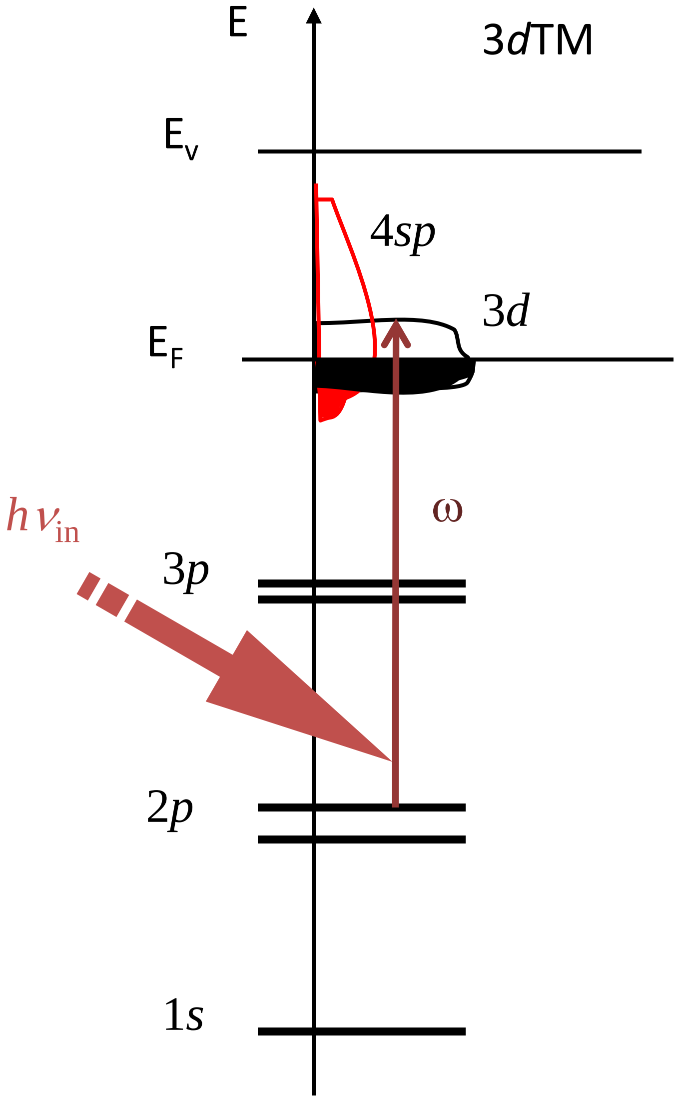


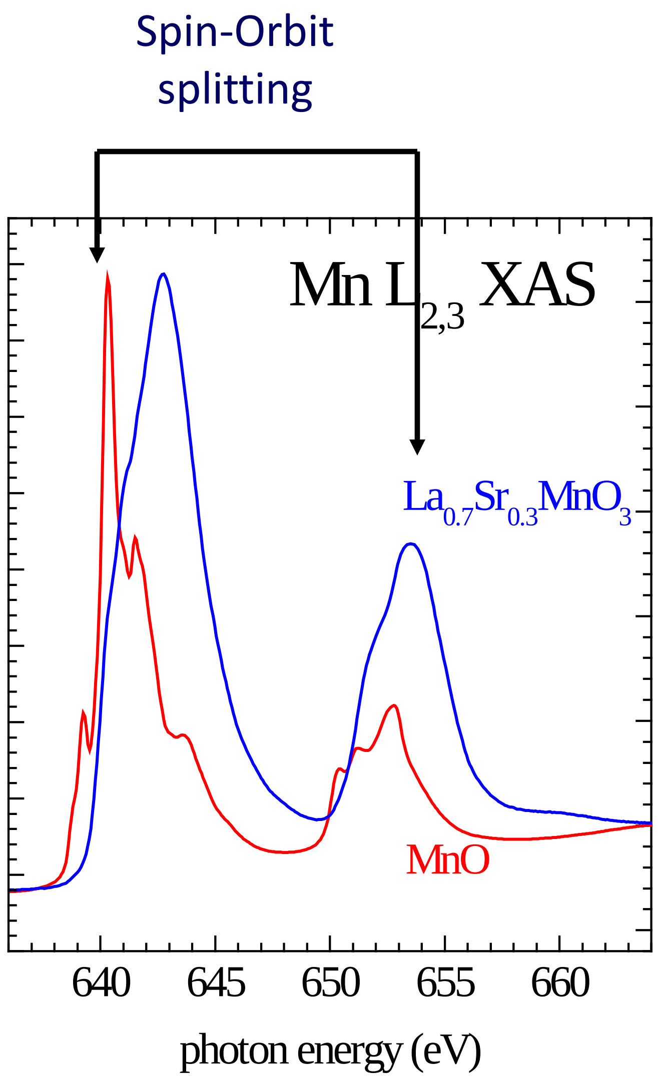
$\Omega = \omega - \omega'$

$\mathbf{q} = \mathbf{k}' - \mathbf{k}$

ε, ε ': polarization

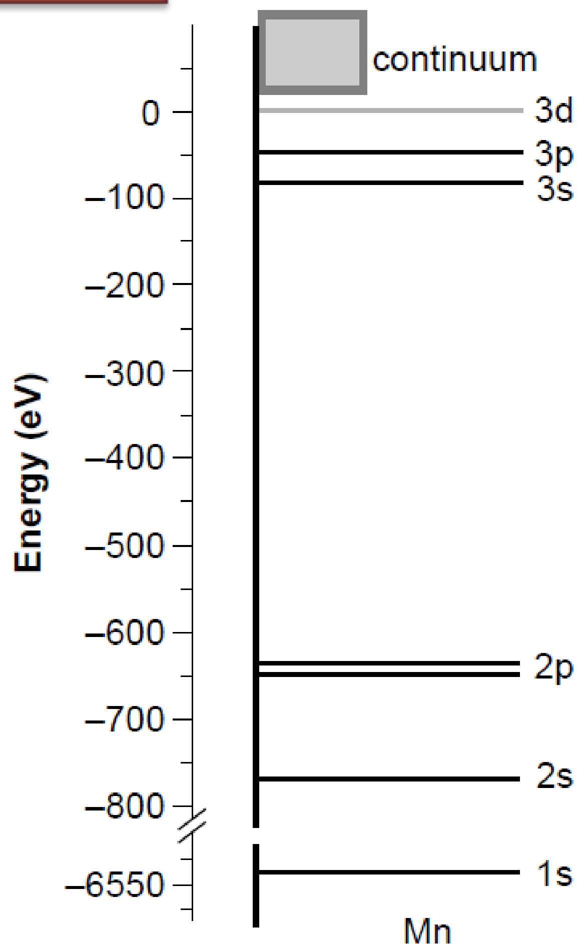
Why soft x-rays for 3d transition metals

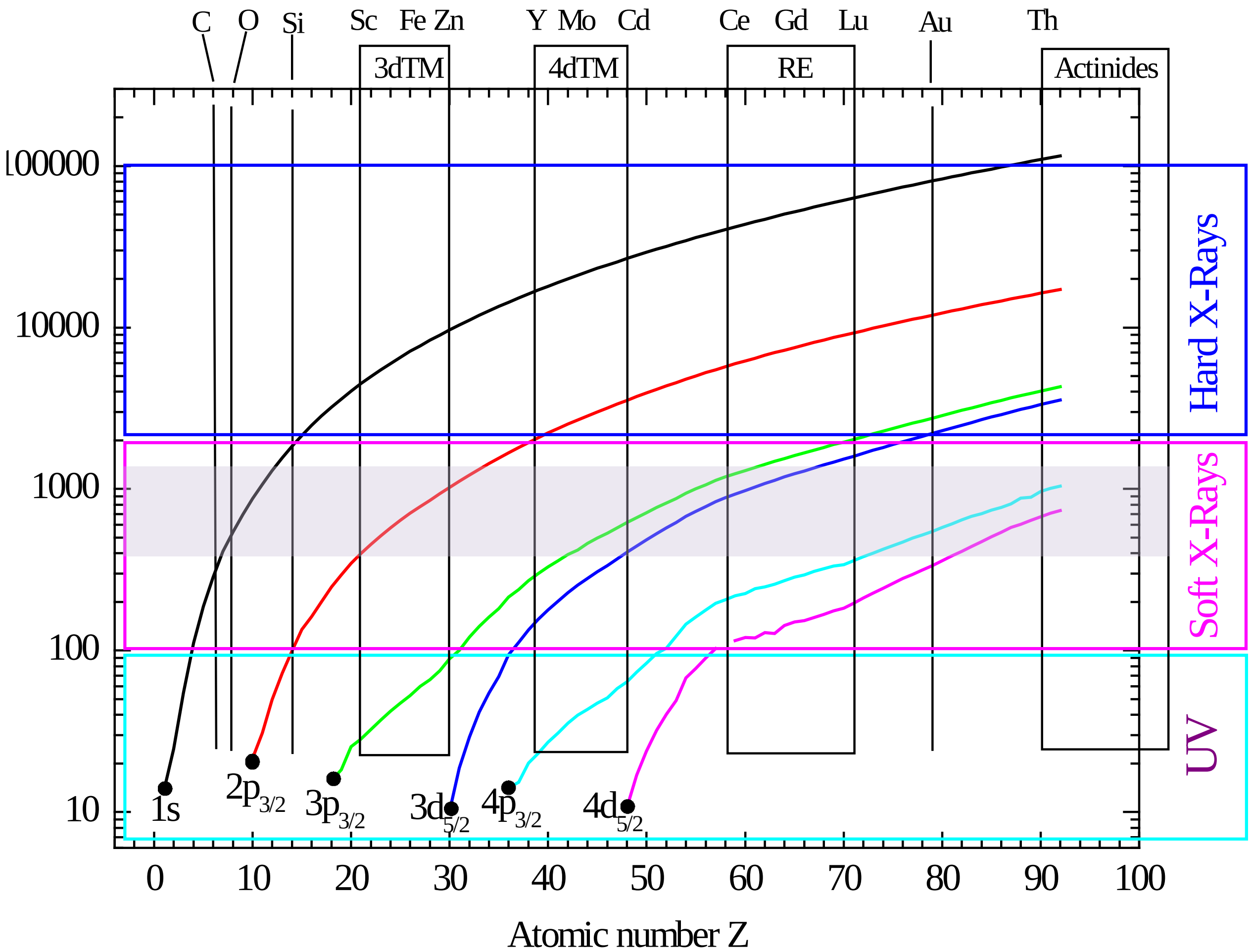




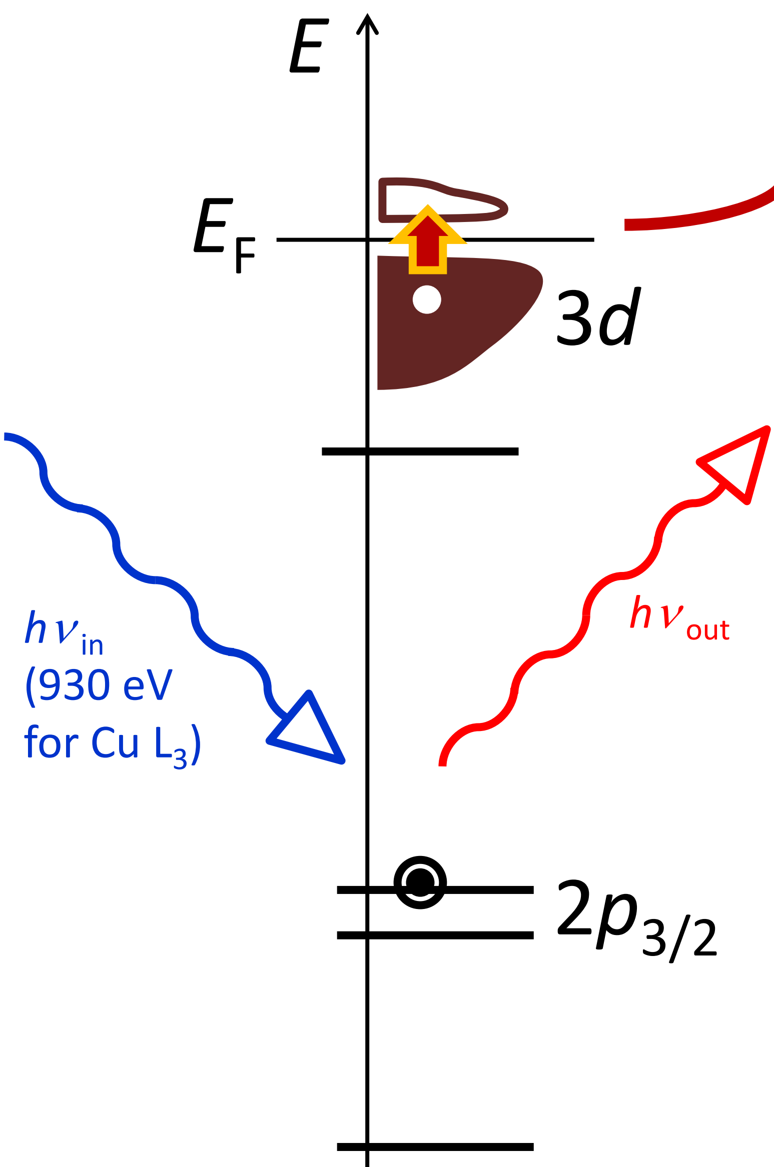
Core level binding energies and edges

3dTM

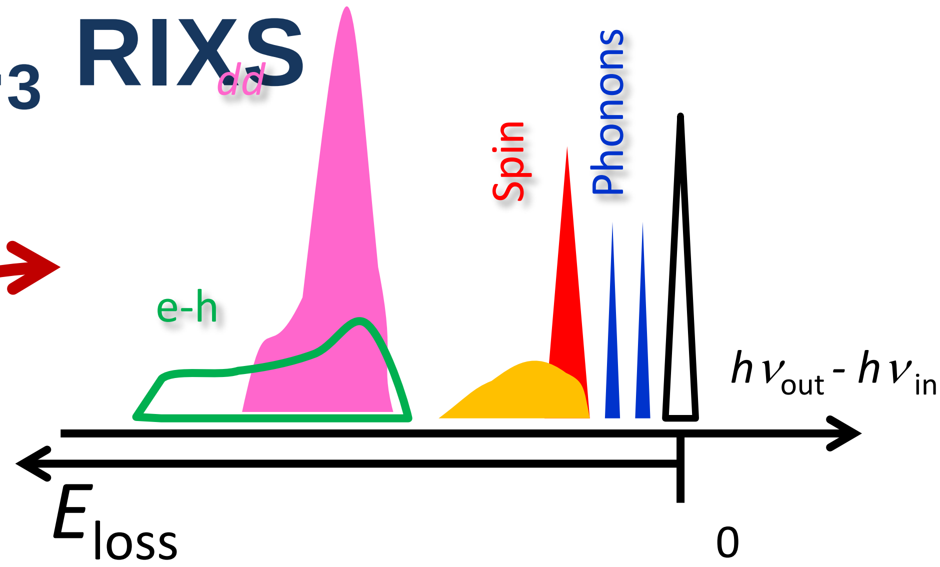




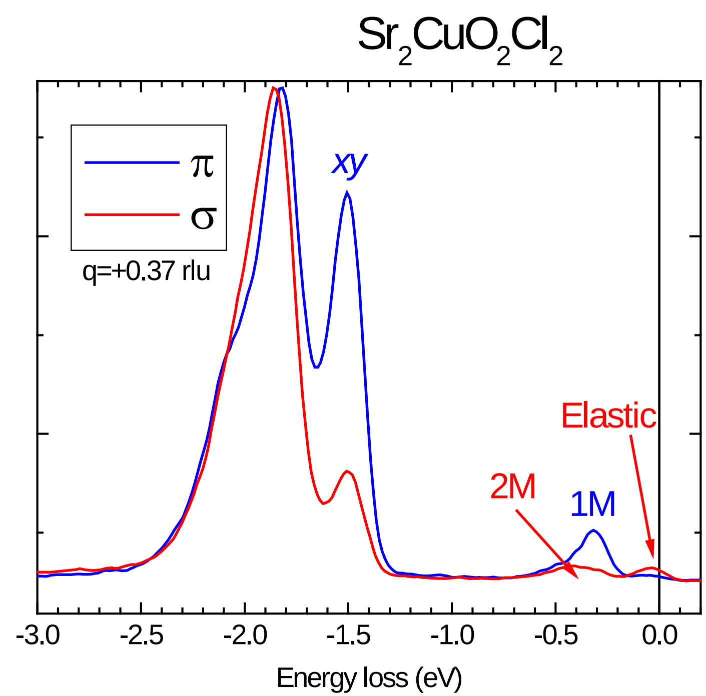
Cu L_3 RIXS



E
E_F
3d
2p_3/2
hν_in
(930 eV
for Cu L_3)
hν_out

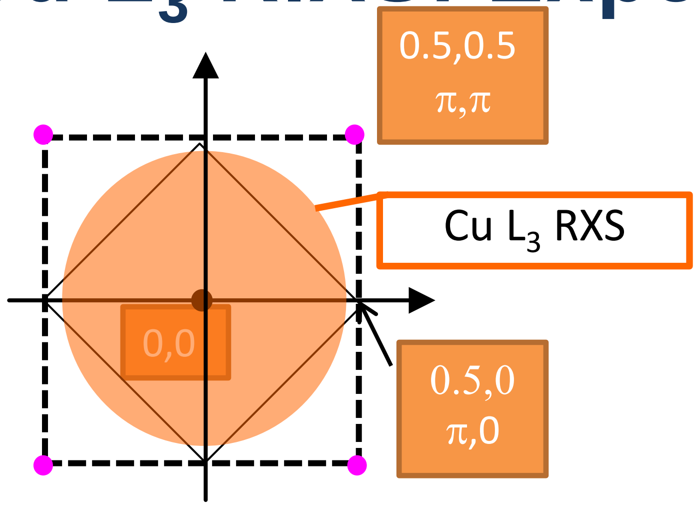


dd
e-h
Spin
Phonons
hν_out - hν_in
E_loss
0



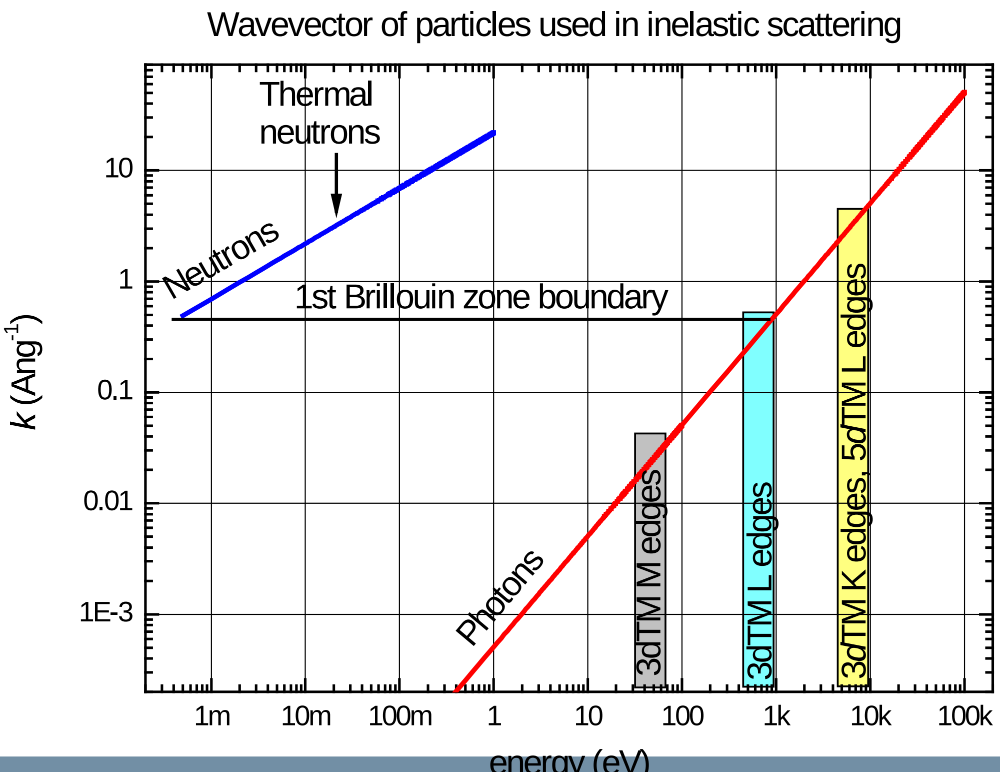
Sr2CuO2Cl2
π
σ
q=+0.37 rlu
xy
Elastic
2M
1M
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
Energy loss (eV)

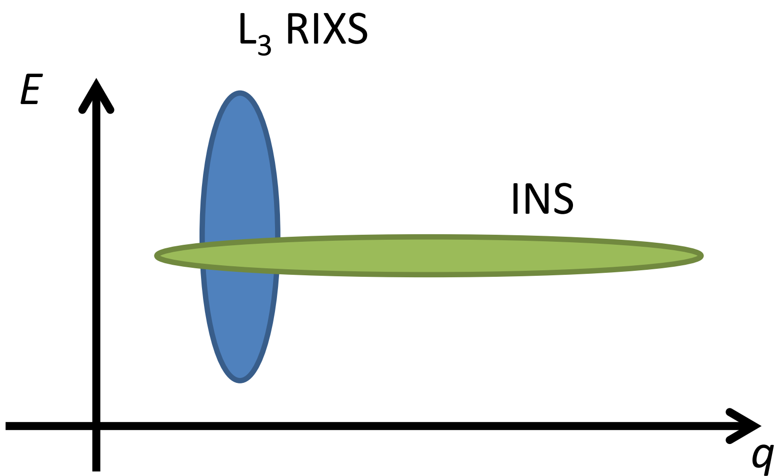
Cu L_3 RIXS: Experimental conditions



Cu L_3 resonance:

- E_0 = 930 eV
- q_{max} = 0.86 Ang^{-1}
- confined inside a region around Γ
- 2p core hole: spin-orbit interaction
- **E resolution: 20-50 meV**
- *q* resolution: 0.005 rlu
- ½ - 1 hour per spectrum



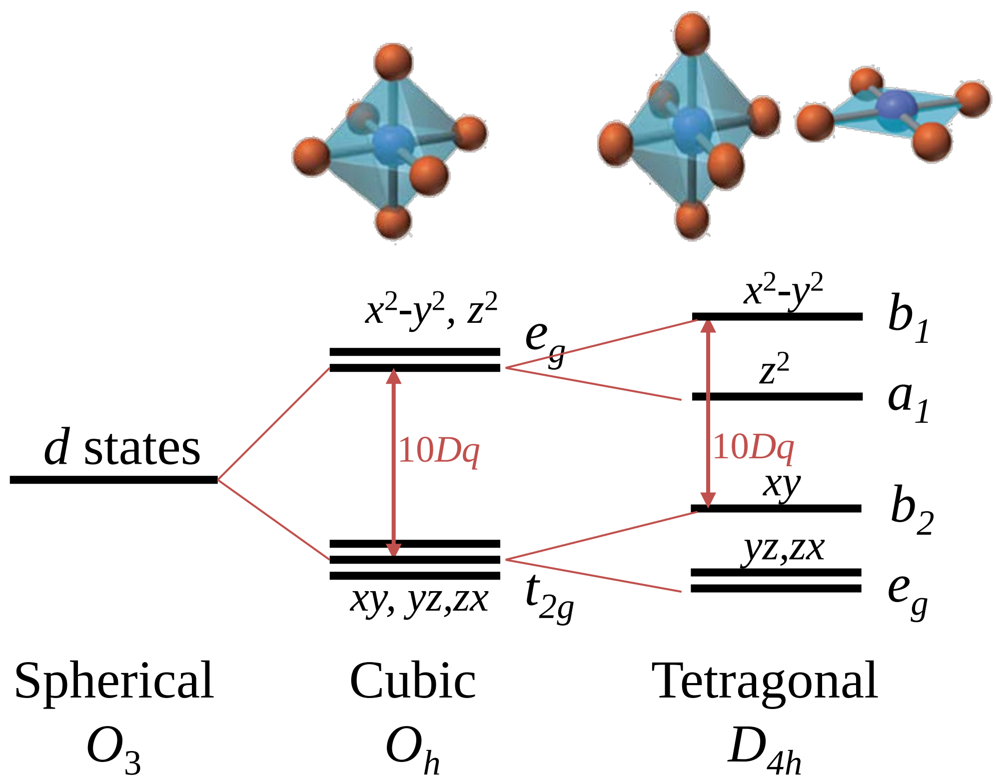


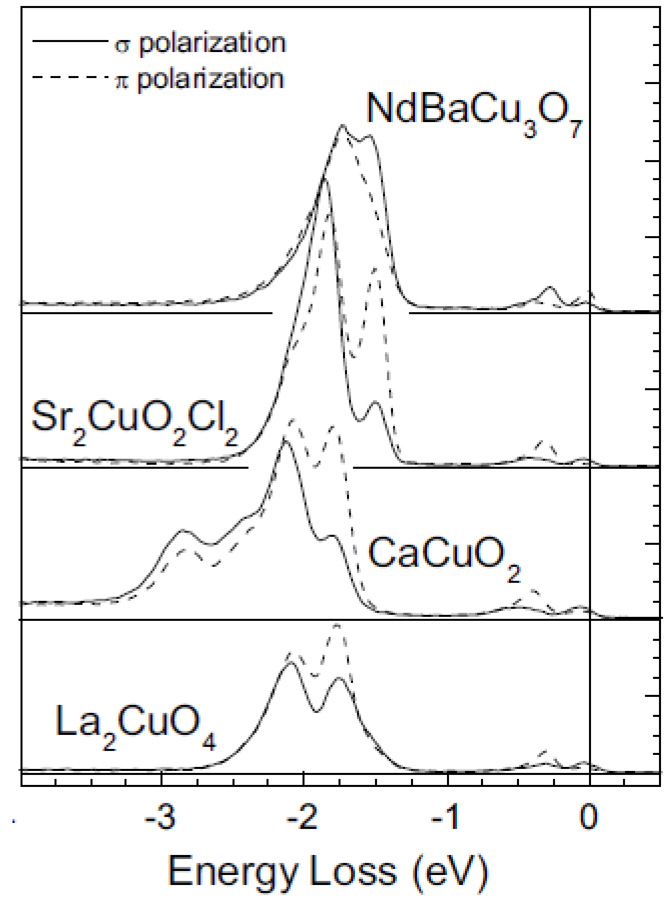
RIXS: crystal field

How much are the 3d orbitals separated in energy in the cuprates (crystal field splitting)?

What is the relation to the coordination and atomic distances?

RIXS has determined these values.

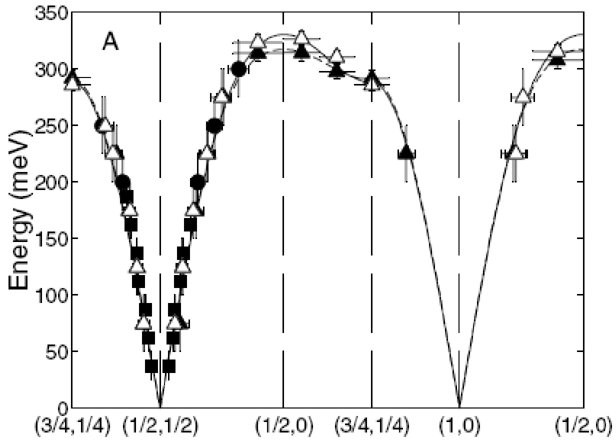




M. Moretti Sala, L. Braicovich, GG et al, New J. Phys. **13**, 043026 (2011)

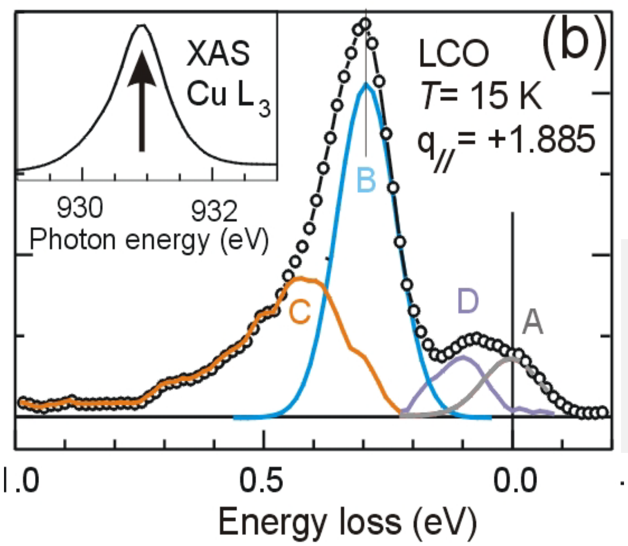
RIXS: spin excitations

RIXS can measure the **dispersion of magnons**. The energy of spin excitations tells us how strong the **exchange interaction** between Cu moments is, ie how stable the **antiferromagnetic order**.

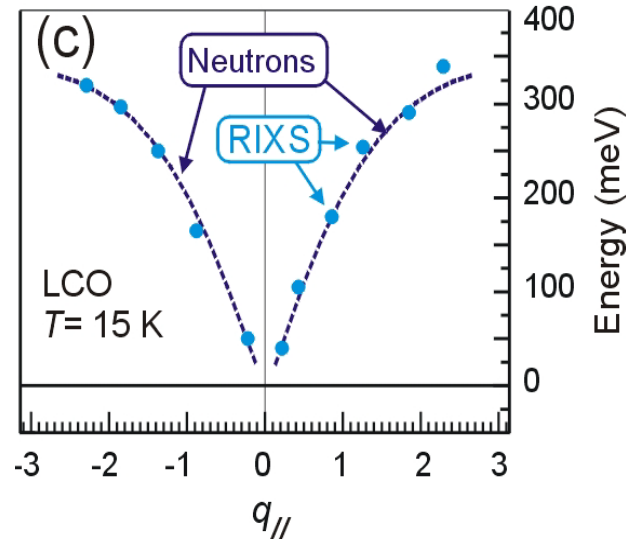


R. Coldea et al, Phys. Rev. Lett. **86**, 5377 (2001).

Until 2010 only neutrons could do that, with limitations due to tiny x-sections



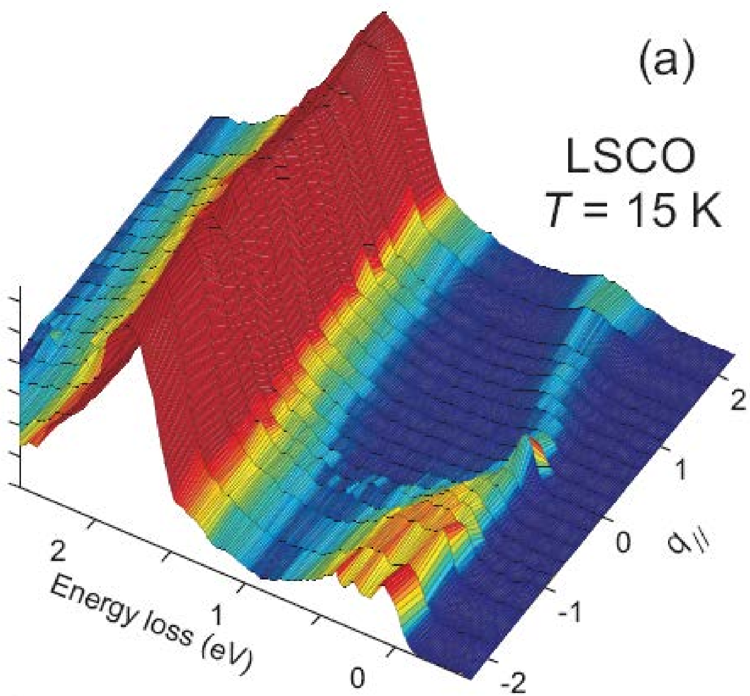
High resolution is necessary

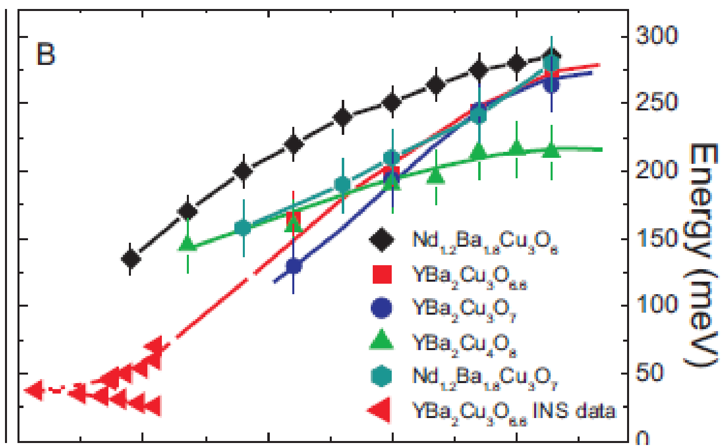


L. Braicovich, J. van den Brink, M. Moretti Sala, GG et al PRL **104** 077002 (2010)

RIXS: paramagnons

Interestingly RIXS has demonstrated that antiferromagnetism remains very strong even in doped, superconducting cuprates.





This observation makes **spin fluctuations** the best candidate for **Cooper pairing**!

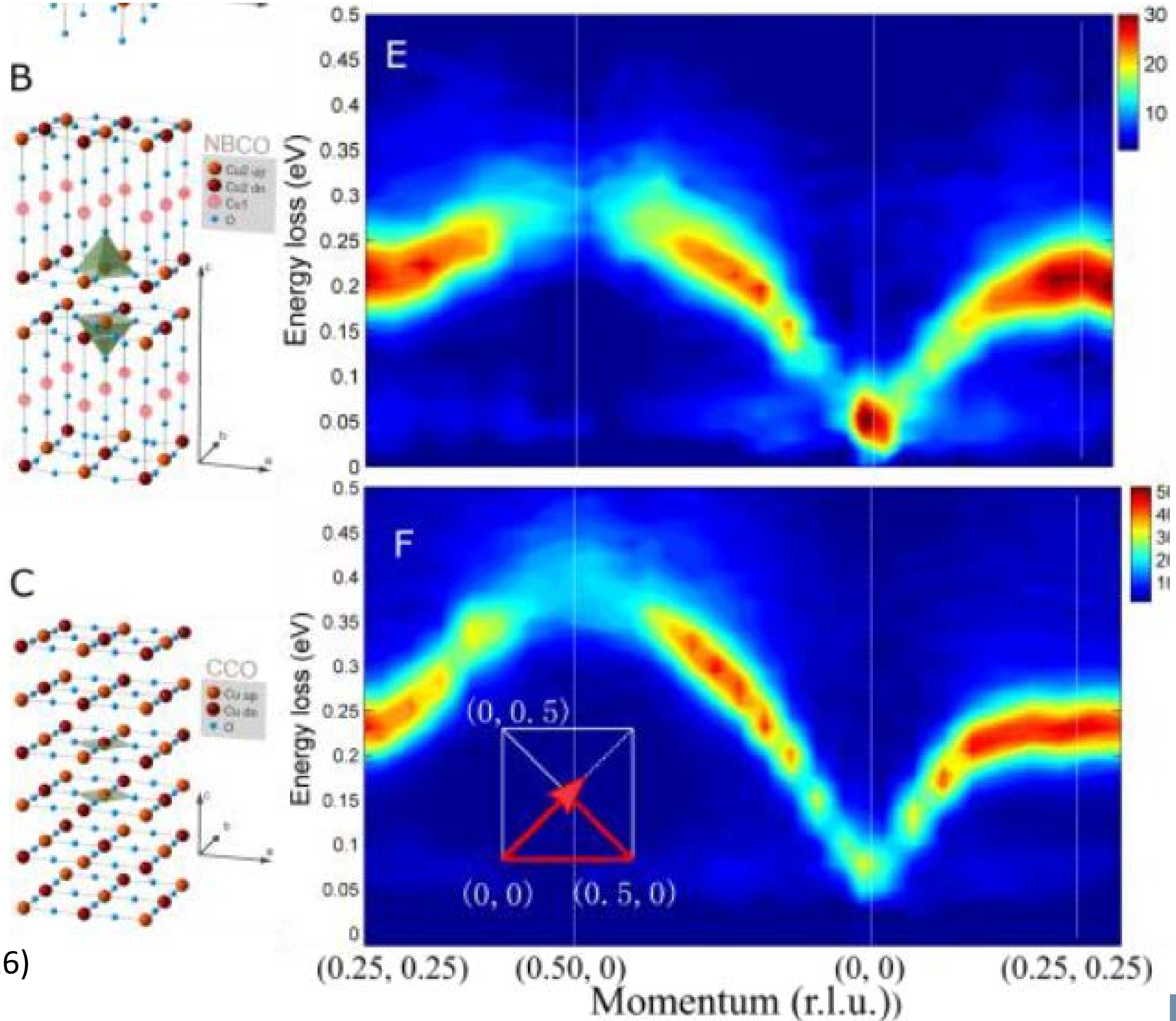
L. Braicovich, J. van den Brink, M. Moretti Sala, GG et al PRL **104** 077002 (2010)
M. Le Tacon, GG, B. Keimer et al, Nat. Phys. **7**, 725 (2011)

ERIXS at ESRF: full maps of magnons

The detailed maps of spin excitations reveal why **different families** of cuprates have **different max T_c**

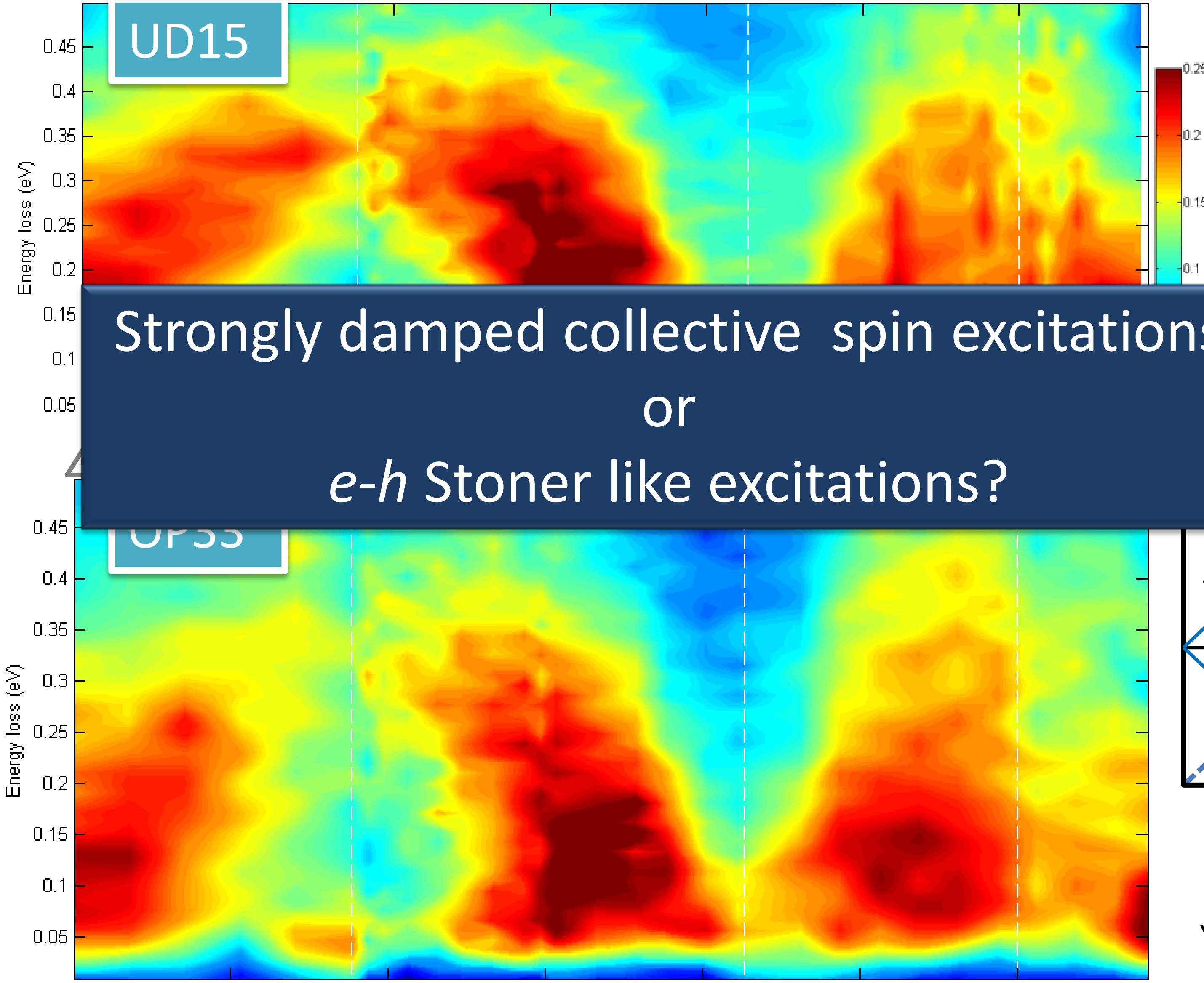
$NdBa_2Cu_3O_{6.1}$

$CaCuO_2$



Y.Y. Peng, GG et al, arXiv:1609.05405 (2016)

Paramagnons in Bi2201

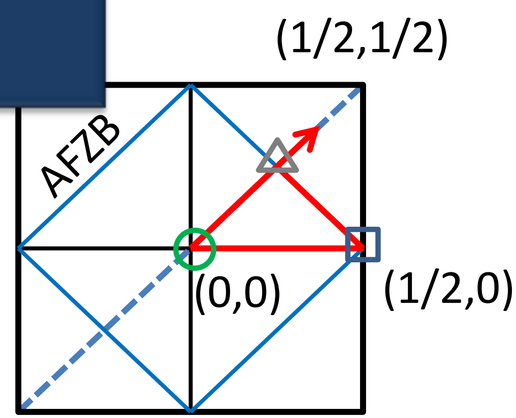


Inelastic part

Strongly damped collective spin excitations

or

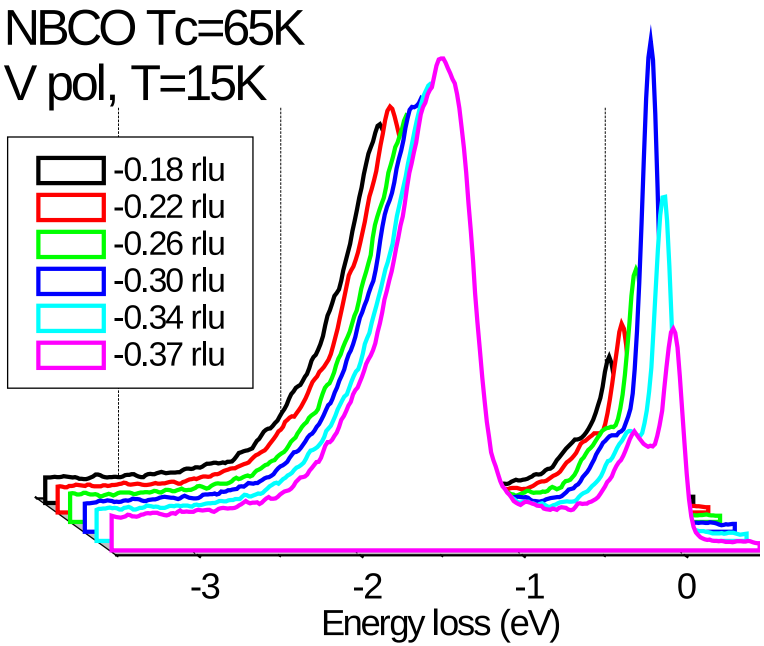
e-h Stoner like excitations?

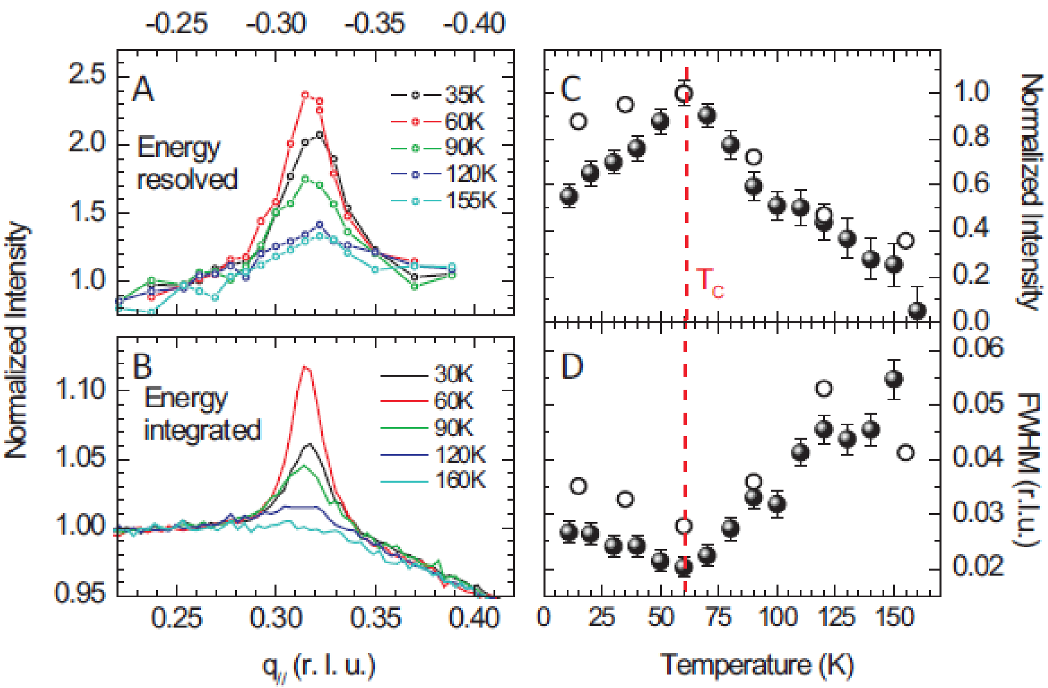


YY. Peng, GG et al, unpublished

R(I)XS: charge density waves

RIXS was used to **discover CDW in YBCO**. Within a few months, CDW were observed, with RIXS and other techniques, in many other cuprates





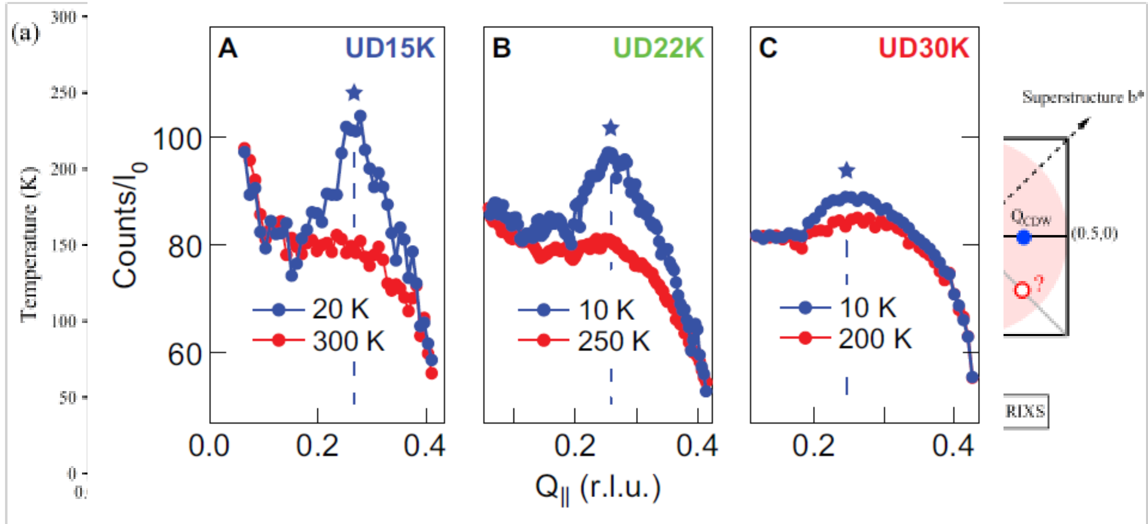
Max intensity at Tc: CDW compete with SC

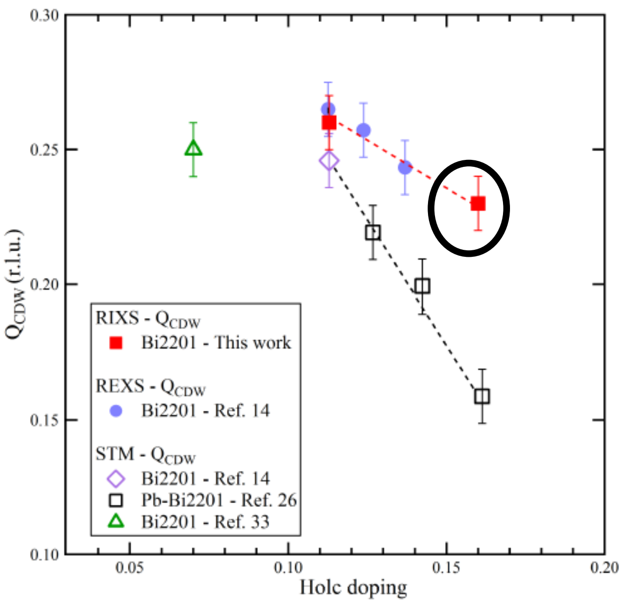
RXS (and STM, XRD and NMR) has demonstrated that CDW are present in all underdoped cuprates. Are CDW related to Superconductivity?

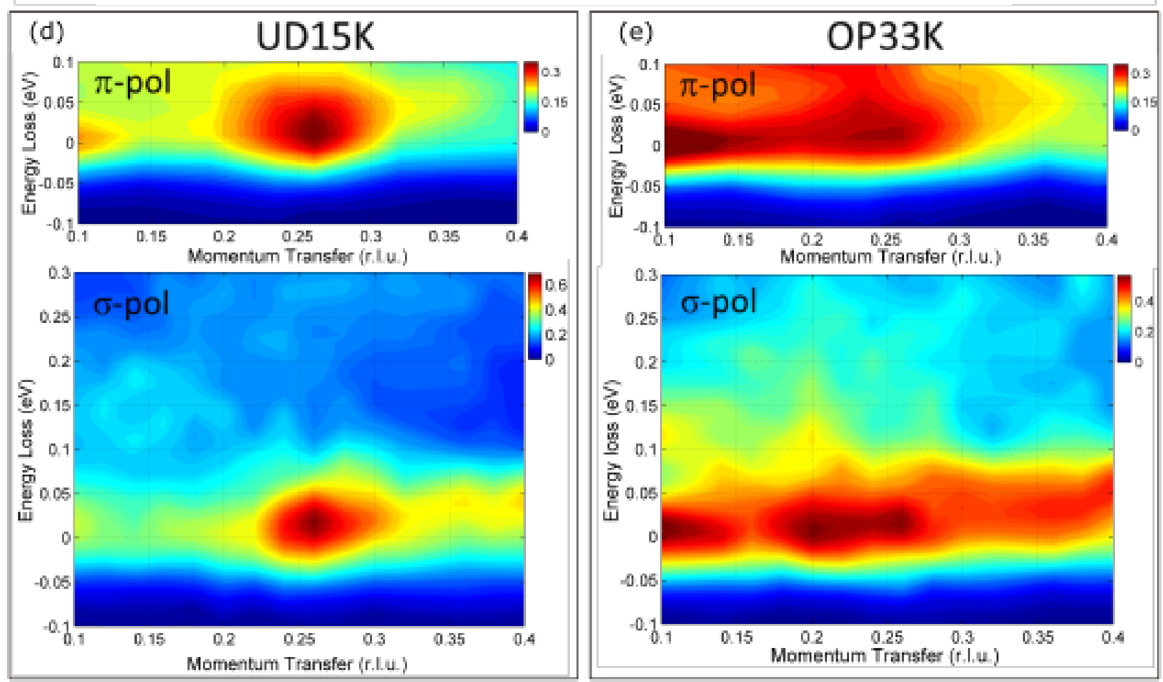
GG., M. Le Tacon, M. Minola, B. Keimer, L. Braicovich, et al Science **337**, 821 (2012)

CDW and new generation RIXS

Higher sensitivity reveals CDW in optimally doped Bi2201

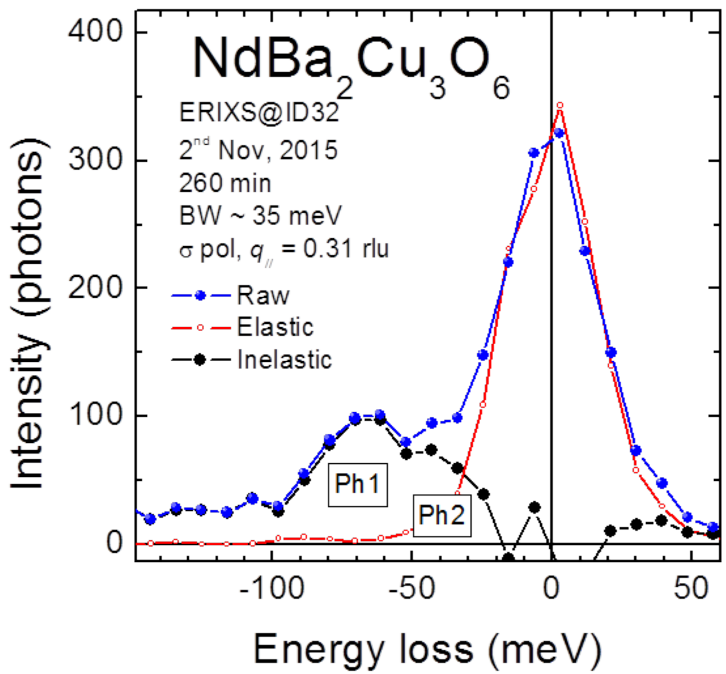






ERIXS: electron-phonon coupling

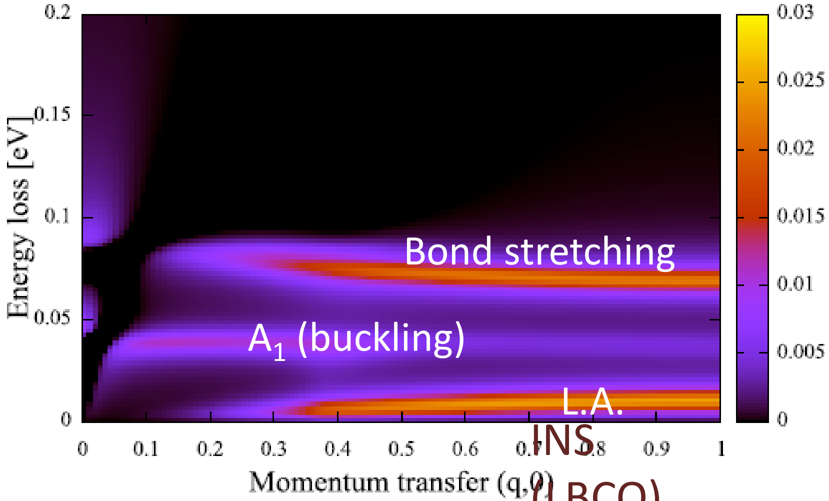
The very high resolution of ERIXS at ID32 allows the detection of phonons with RIXS. This is a very direct way of measuring the e-ph coupling.



The mapping of the e-ph coupling can clarify the role of CDW in superconductivity

L. Braicovich, S. Johnston, J van den Brink, in preparation

More work on *e-ph* coupling

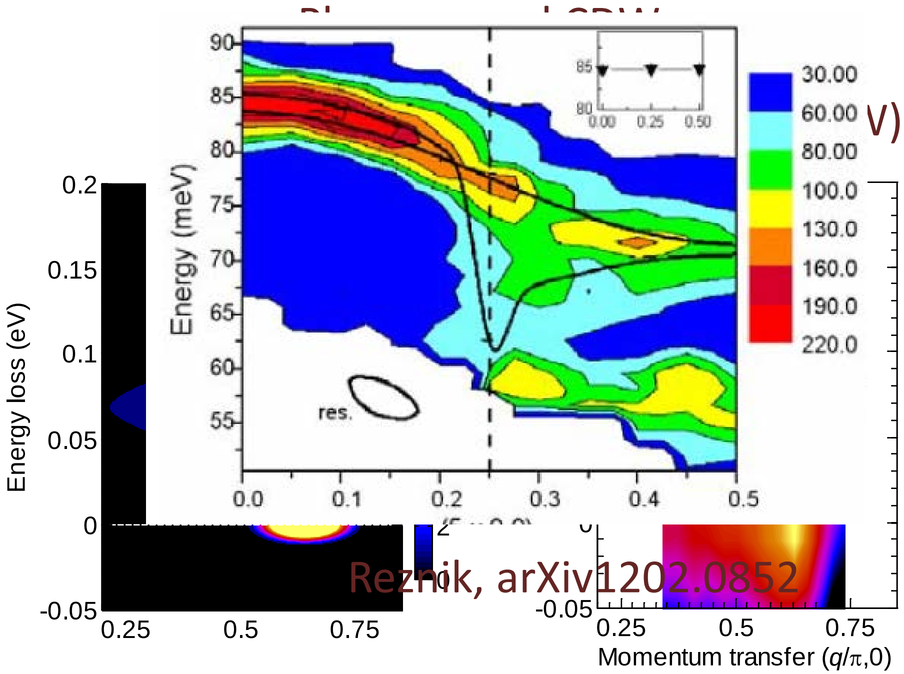


Theoretical phonon intensity in RIXS

T. P. Devereaux, A. M. Shvaika, K. Wu, K. Wohlfeld, C.-J. Jia, Y. Wang, B. Moritz, L. Chaix, W.-S. Lee, Z.-X. Shen, G. Ghiringhelli, and L. Braicovich, PRX **6**, 041019 (2016)

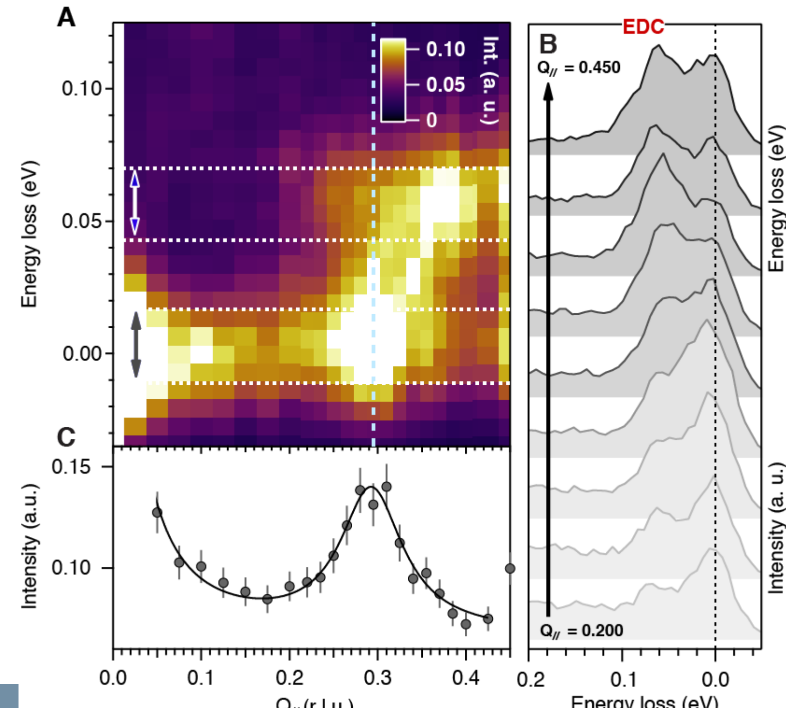
L. Chaix, G. Ghiringhelli, Y. Y. Peng, M. Hashimoto, Y. He, S. Chen, K. Kummer, N.B. Brookes, B. Moritz, S. Ishida, Y. Yoshida, H. Eisaki, L. Braicovich, Z.-X. Shen, T. P. Devereaux, W.-S. Lee, submitted

INS (LBCO)

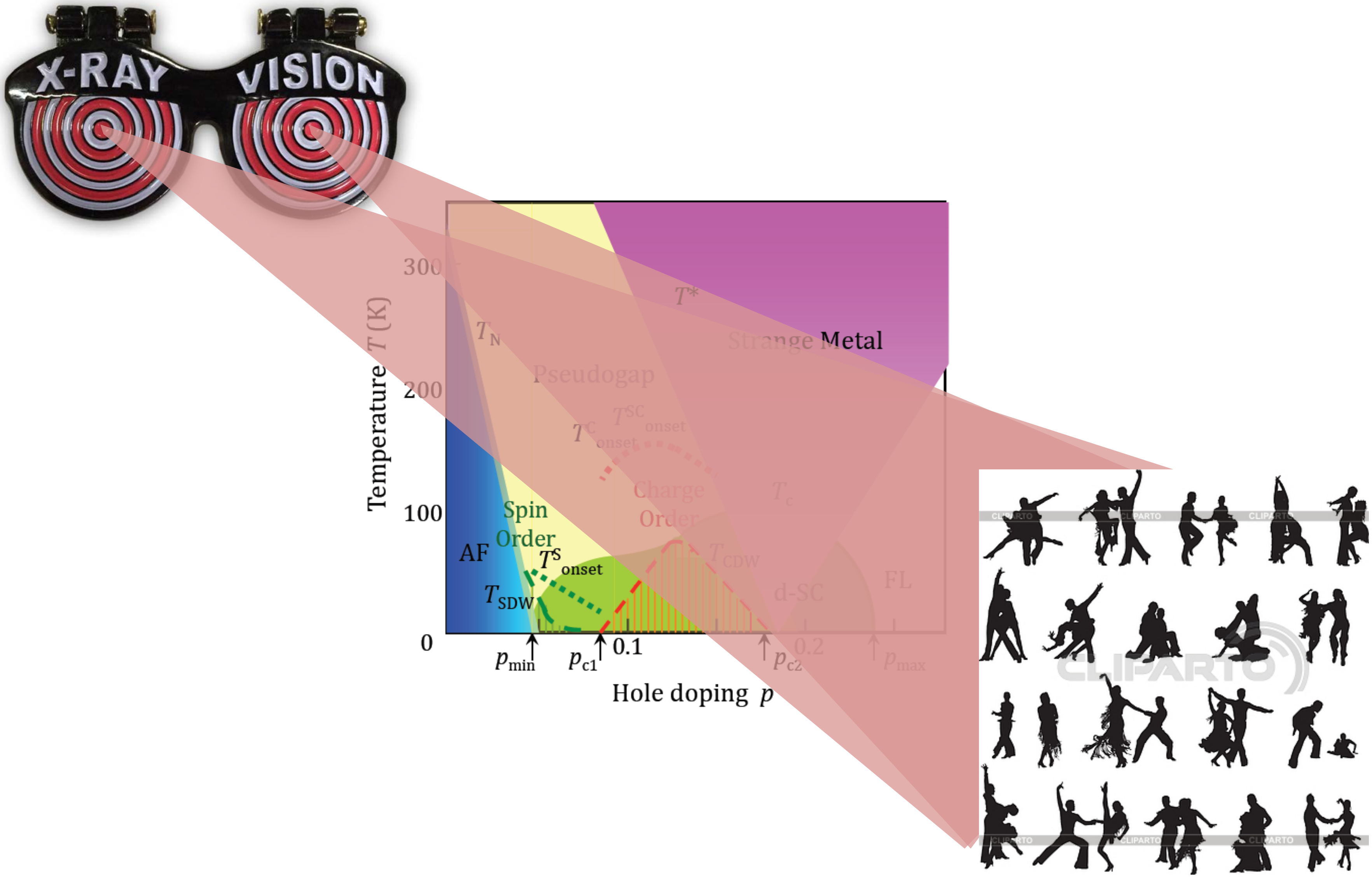


Reznik, arXiv1202.0852

Exp. (40 meV BW)



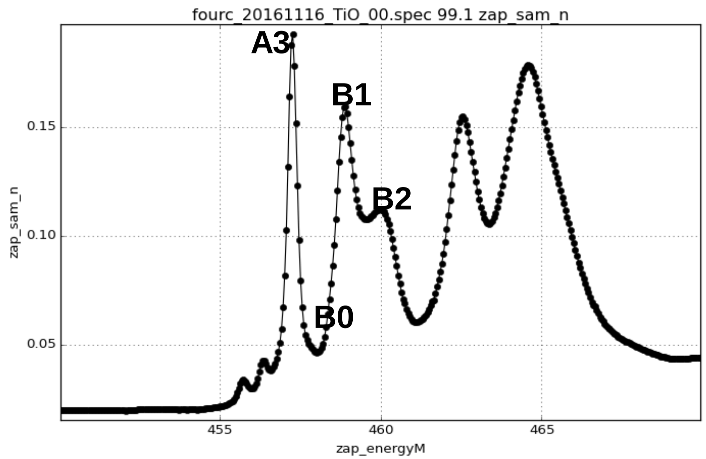
Conclusions

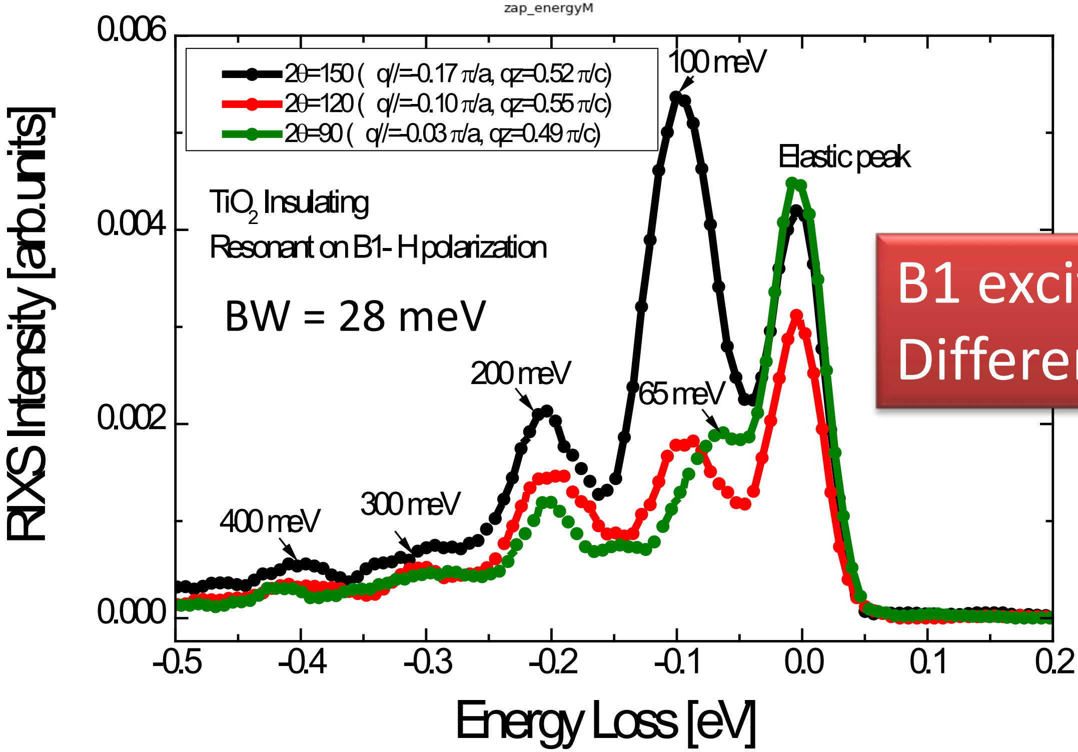


Nature 518, 179 (2015)

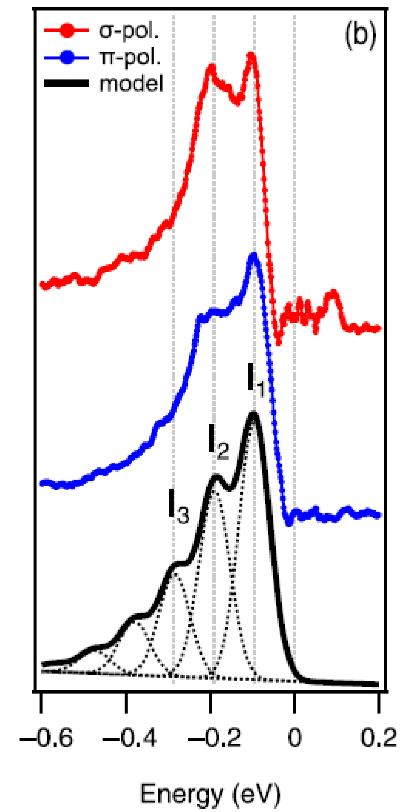

Thanks

Phonons in TiO_2





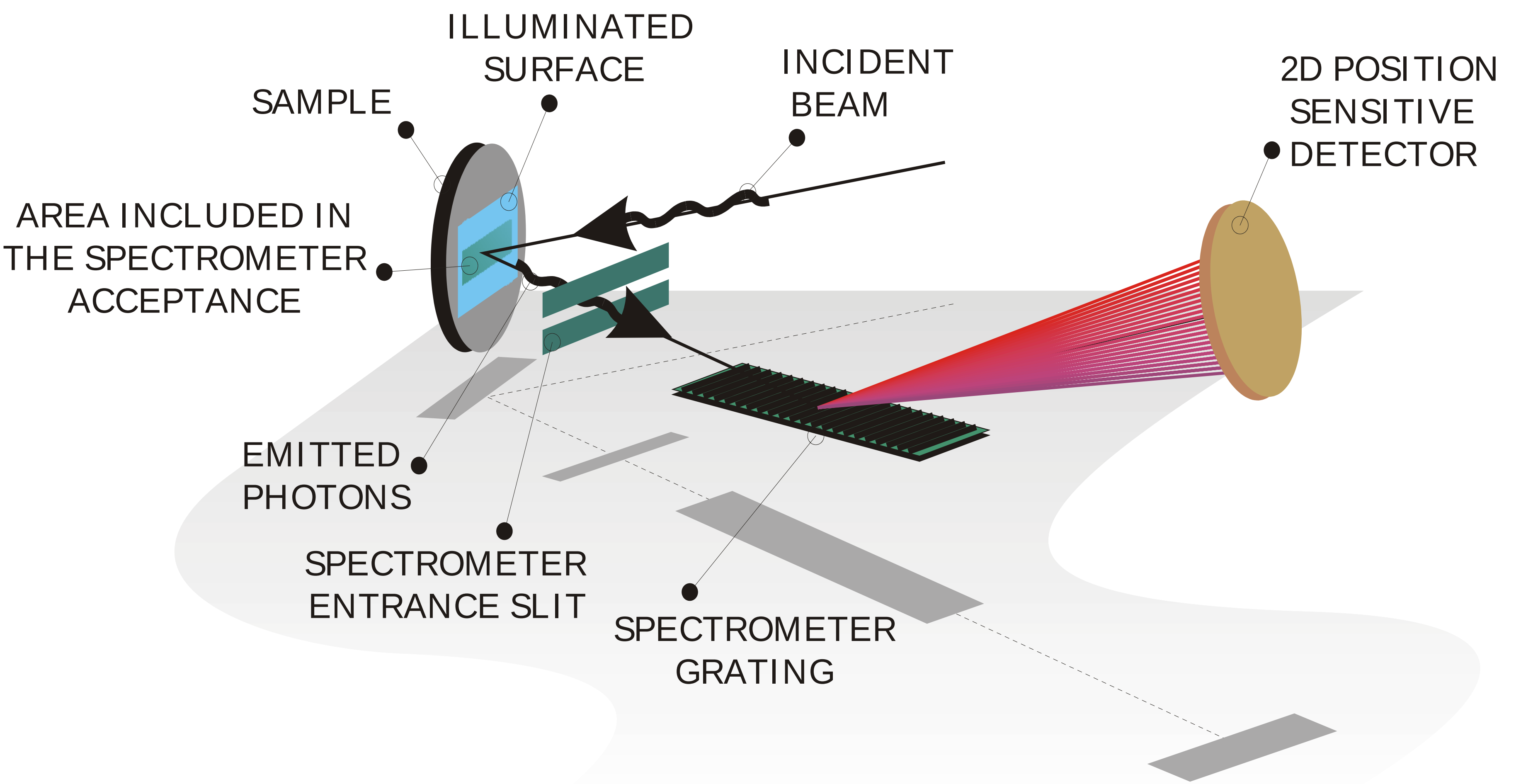
B1 excitation
Different **q**



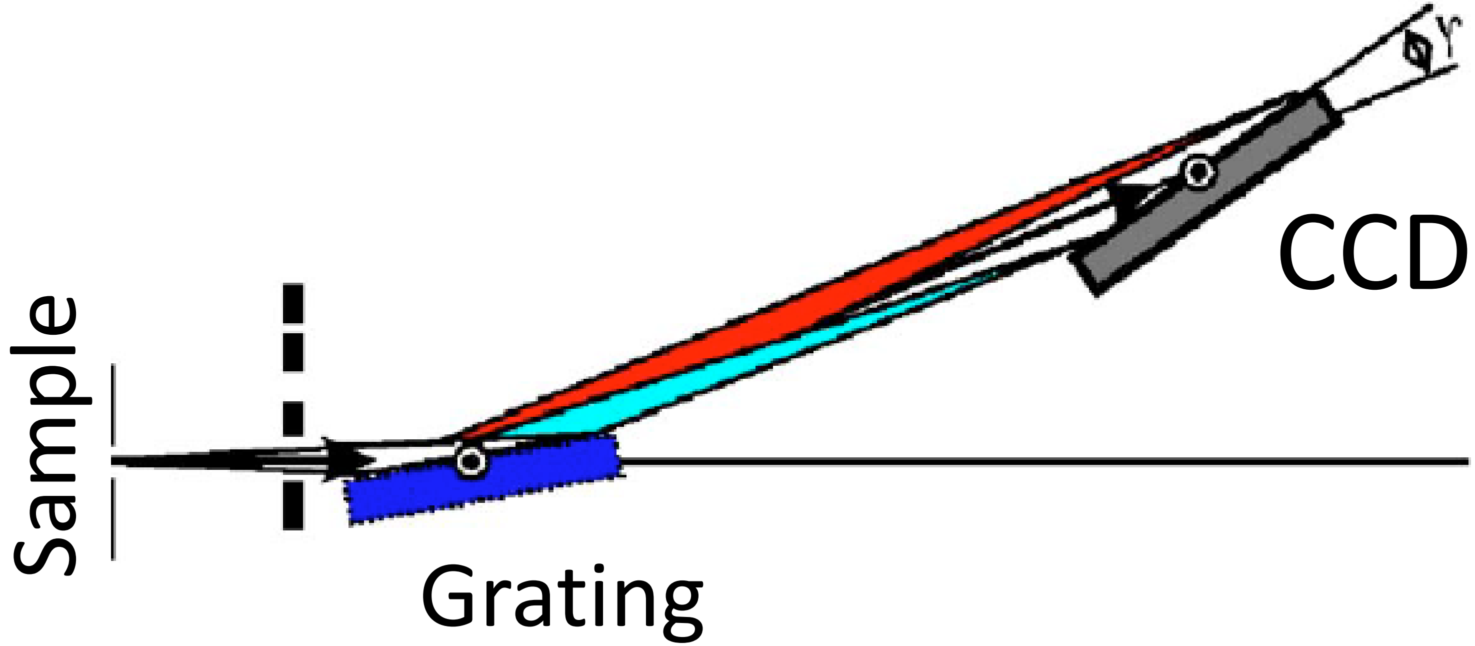
Moser et al, PRL **115**, 096404 (2015)

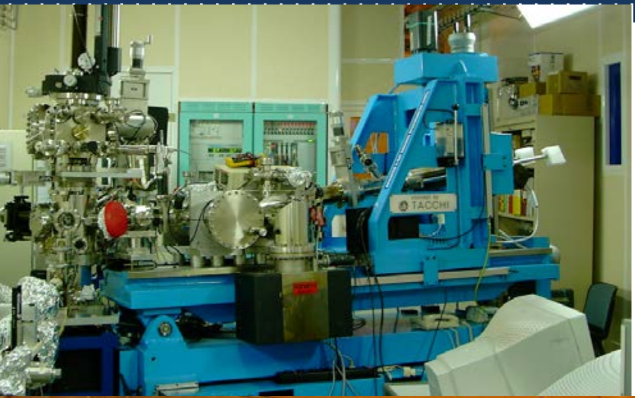
M. Salluzzo, G.M. De Luca, YY Peng, R. Fumagalli, D. Betto, L. Braicovich, G. Ghiringhelli, unpublished

Soft x-ray spectrometer



Longer instruments for better resolution





AXES: **2.2 m**

ID12B and ID08

SAXES, SLS: **5 m**

ERIXS, ID32: **10 m**

ERIXS at ID32

Resolving power: 40,000
at 1 keV
3 times better than
previous record

Two CCD detectors

Multi-layer mirror, to measure polarization of scattered photons

Collimating Mirror to increase horizontal acceptance

Two Gratings, to optimize for resolution or efficiency