XIV School on Synchrotron Radiation:
Fundamentals, Methods and Applications
Muggia, Italy / 18-29 September 2017

SOCIETA' ITALIANA DI LUCE DI SINCROTRONE

Elettra Sincrotrone Trieste

RIXS for the study of strongly correlated electron systems

POLITECNICO MILANO 1863

SPIN

Consiglio Nazionale delle Ricerche

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26 September, 2017

Introducing myself...

PAUL SCHERRER INSTITUT
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Keywords:

- Soft x-rays
- Resonant spectroscopy
- RIXS
- 3d transition metal oxides
- Cuprates SC

Summary

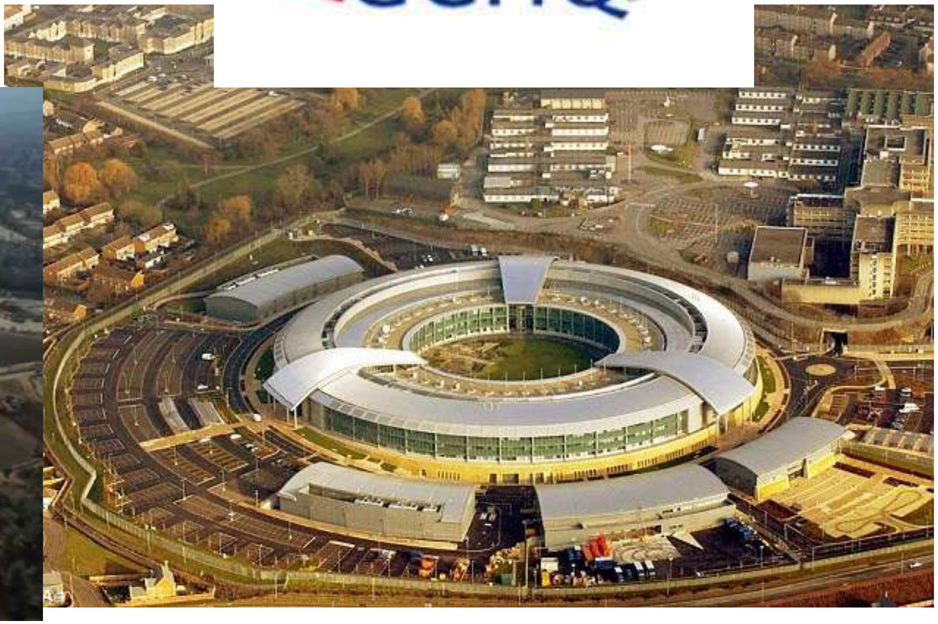
RIXS: resonant inelastic x-ray scattering

- A second order process
- *dd* excitations
- Magnetic excitations
- REXS: the elastic part of RIXS spectra

Elettra Sincrotrone Trieste

Synchrotrons: so beautiful!

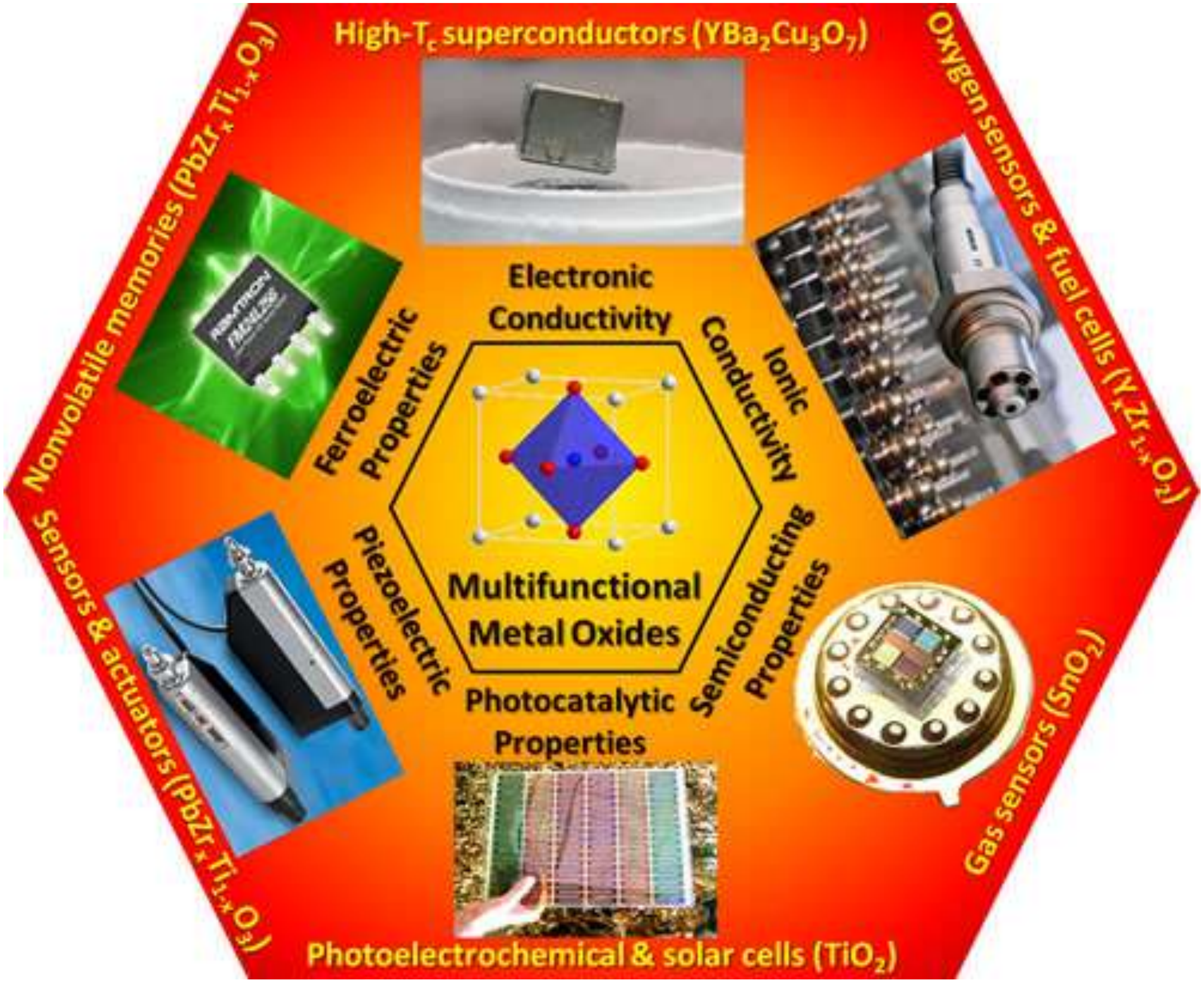
Apple new HQ in Cupertino



British intelligence agency GCHQ

(Government Communications Headquarters)

Transition metal oxides



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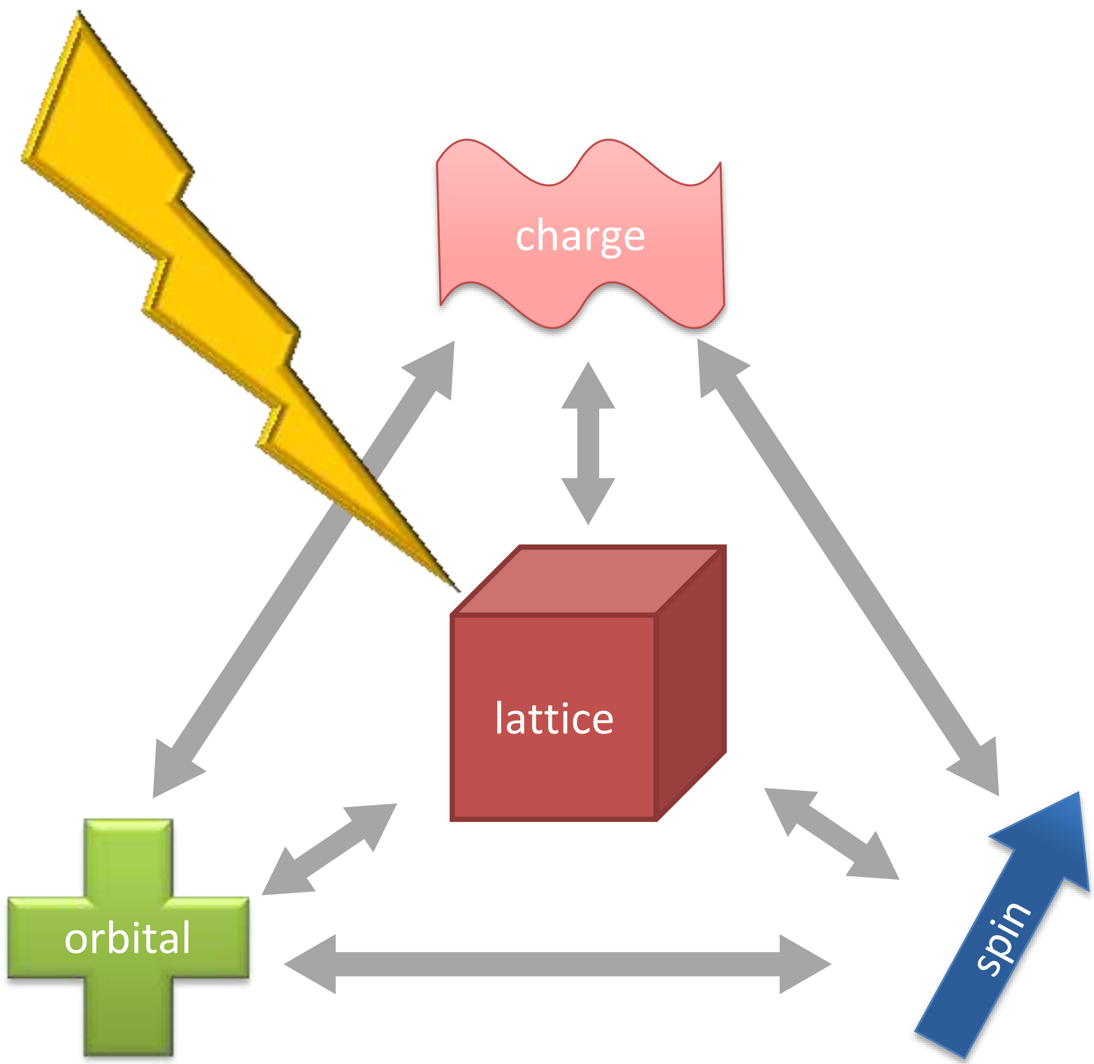
One probe for several degrees of freedom

1. Energy loss spectroscopy
2. Momentum resolution
3. Coupling to
   a. Charge
   b. Spin
   c. Orbital
   d. Lattice
4. Bulk sensitivity
5. Good energy resolution
6. Decent count rate

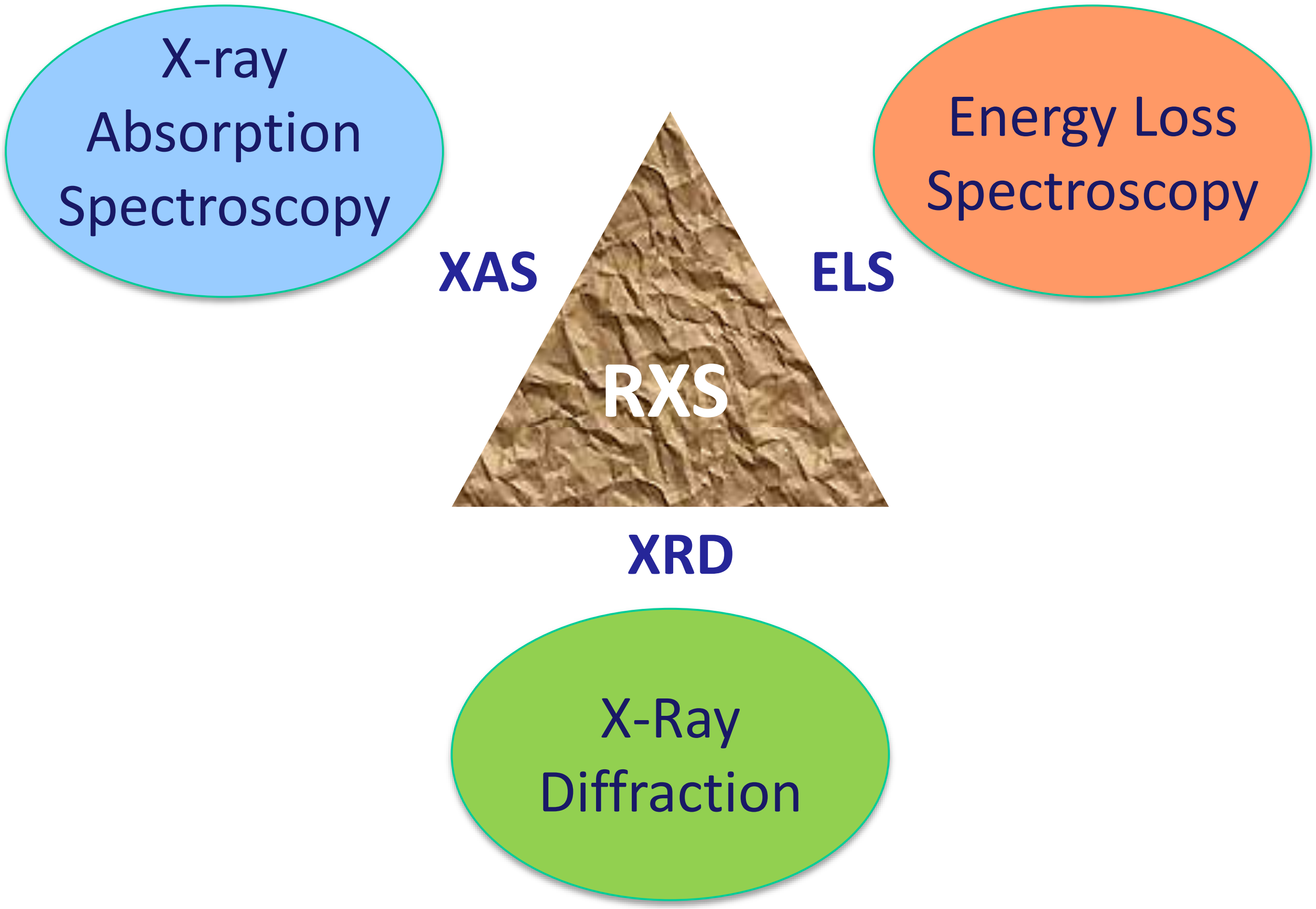


electrons (1, 2, 3, 5, 6)

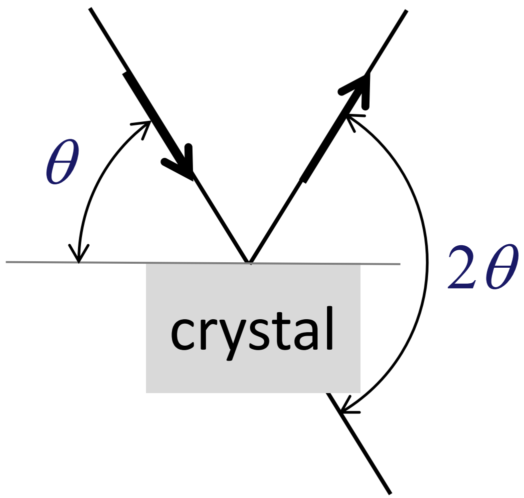
neutrons (1, 2, 3b, 3d, 4, 5)

photons (1, 2, 3a,3c, 3d, 4, 5, 6)

Introduction to Resonant X-ray Scattering



From XRD to X-ray Scattering



X-Ray Diffraction

X-Ray Scattering

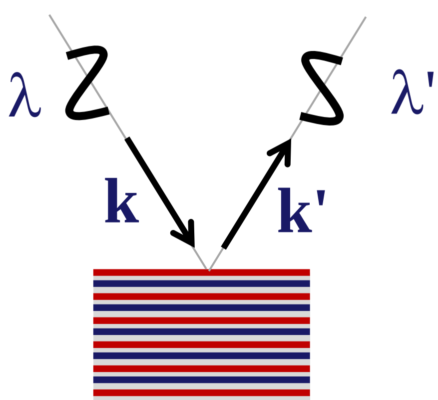
$|\mathbf{k}'|=|\mathbf{k}|$

$\lambda = \lambda'$

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

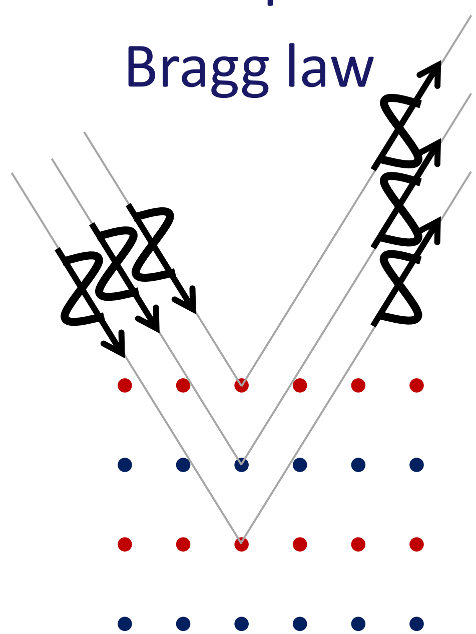
$\lambda = \lambda'$

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



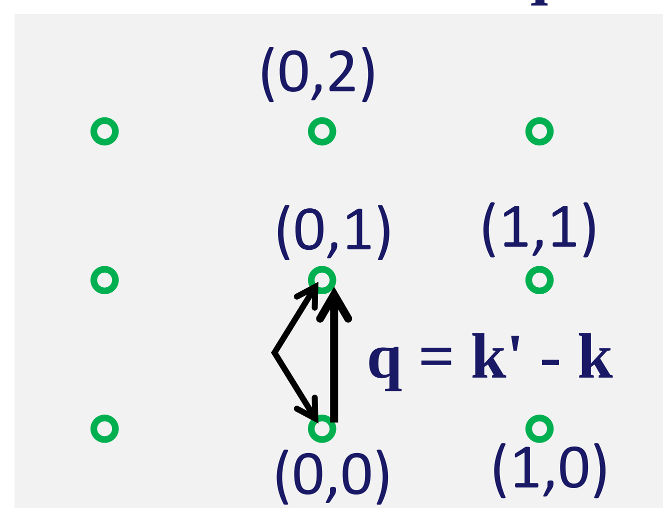
Real space

Bragg law



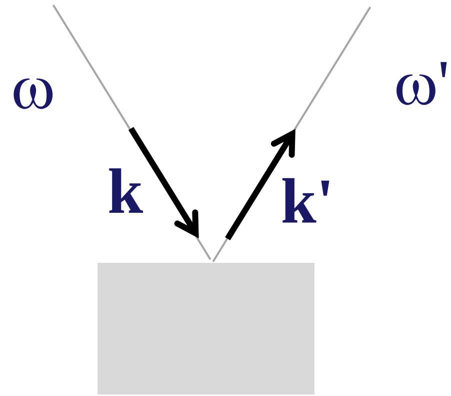
Reciprocal lattice

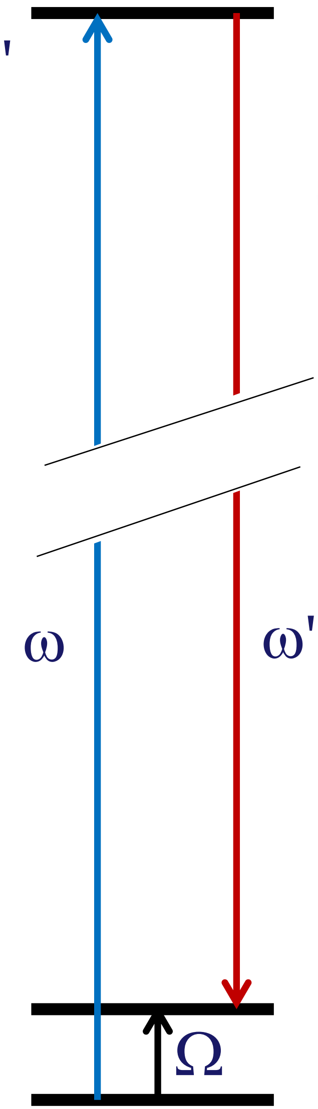
Laue condition: $\mathbf{q}=\mathbf{G}$



ELS: from Raman to Inelastic X-ray Scattering

Energy Loss Spectroscopy





Inelastic X-ray Scattering

Raman light scattering

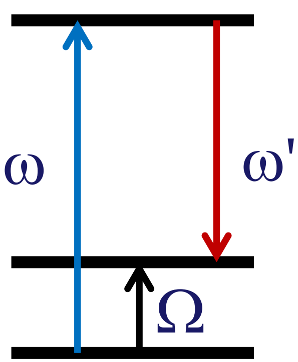
$k \approx 0$, $q \approx 0$,

$\Omega = \omega - \omega'$

X-ray photons

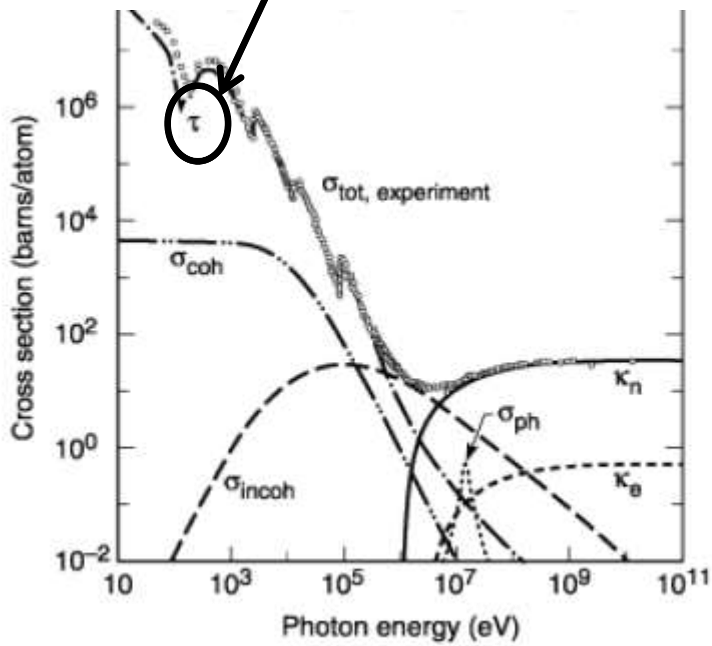
$\Omega = \omega - \omega'$

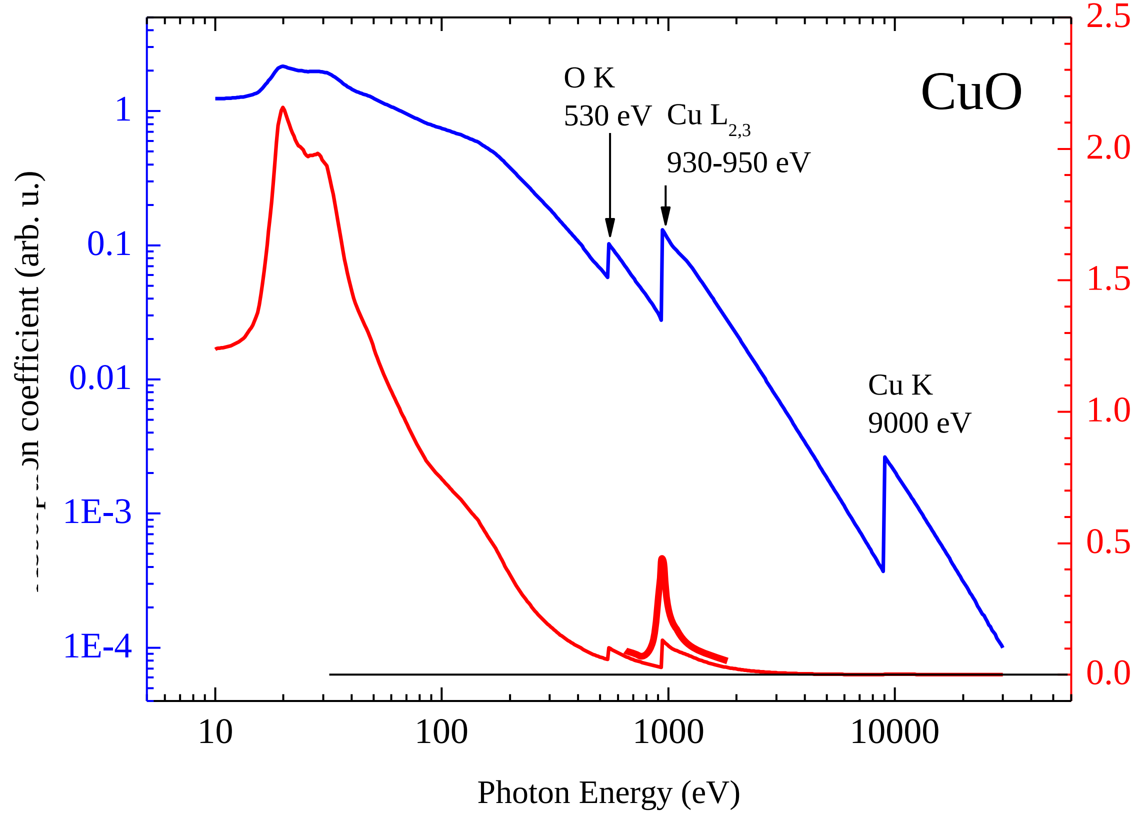
$\mathbf{q} = \mathbf{k}' - \mathbf{k}$



Resonant X-ray Absorption

Photoelectric effect dominates x-ray absorption below 100,000 eV

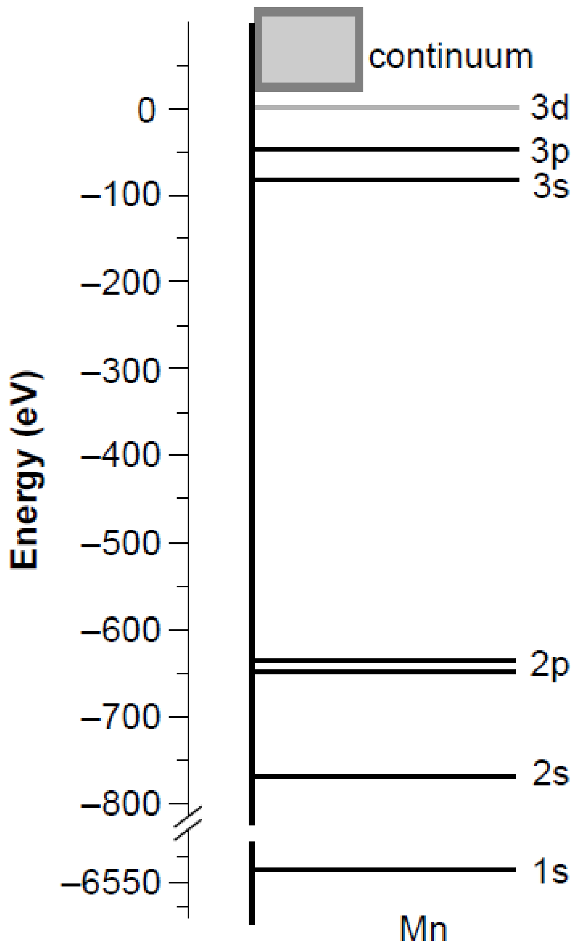


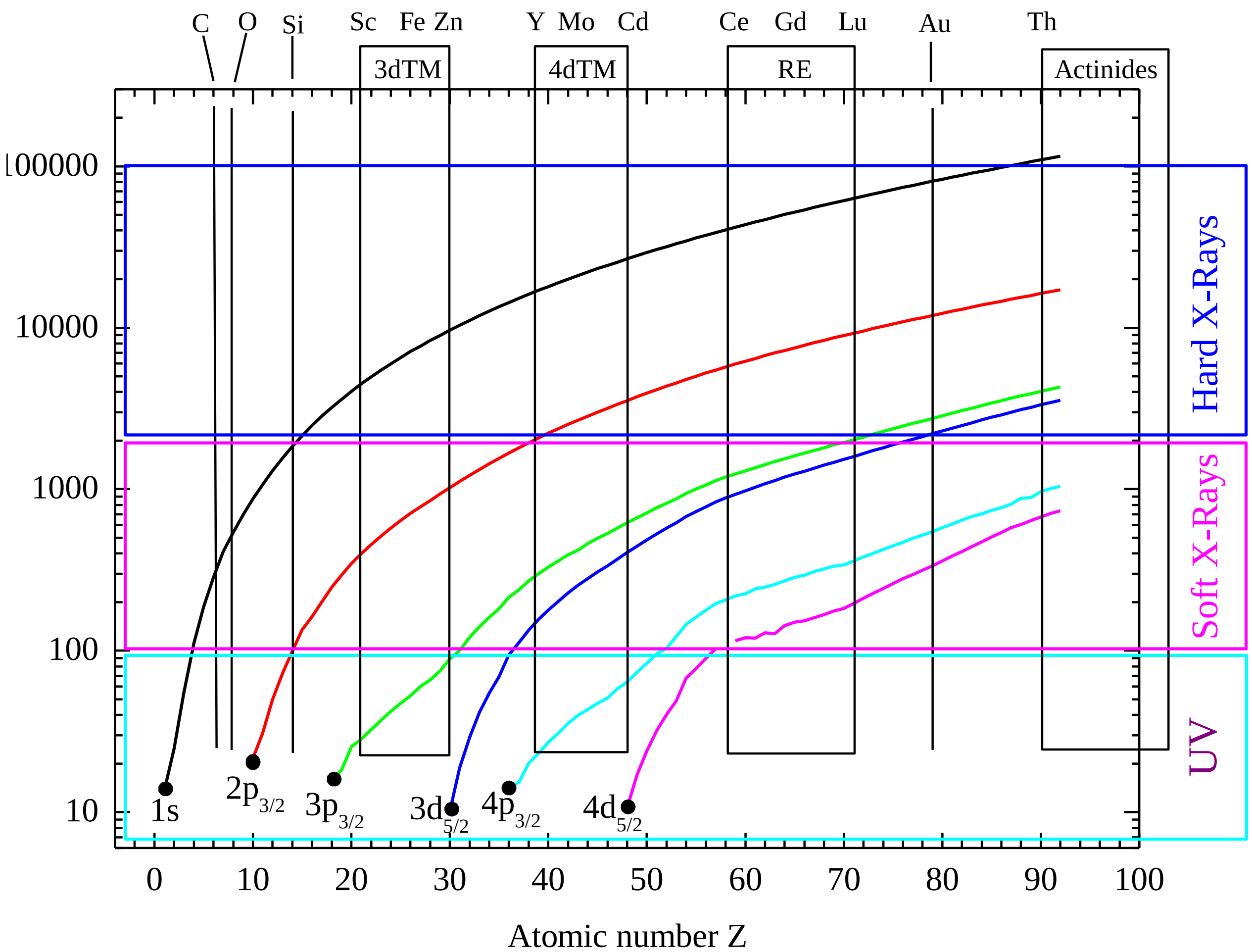


Edges are univocally element specific

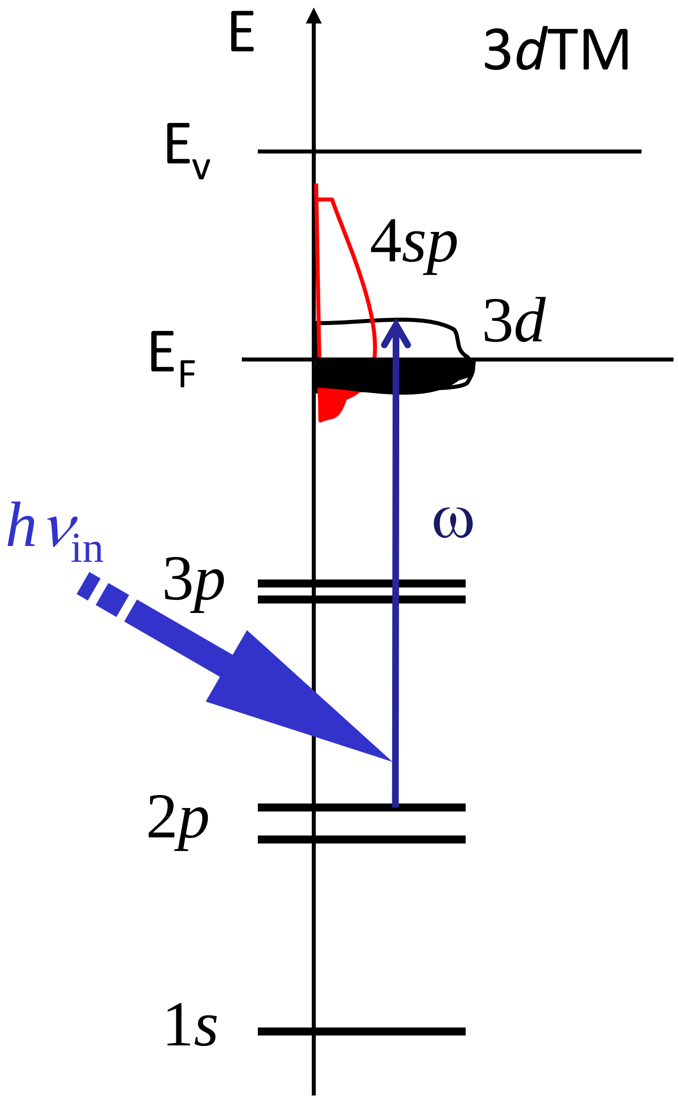
And often are dressed with a strong resonance

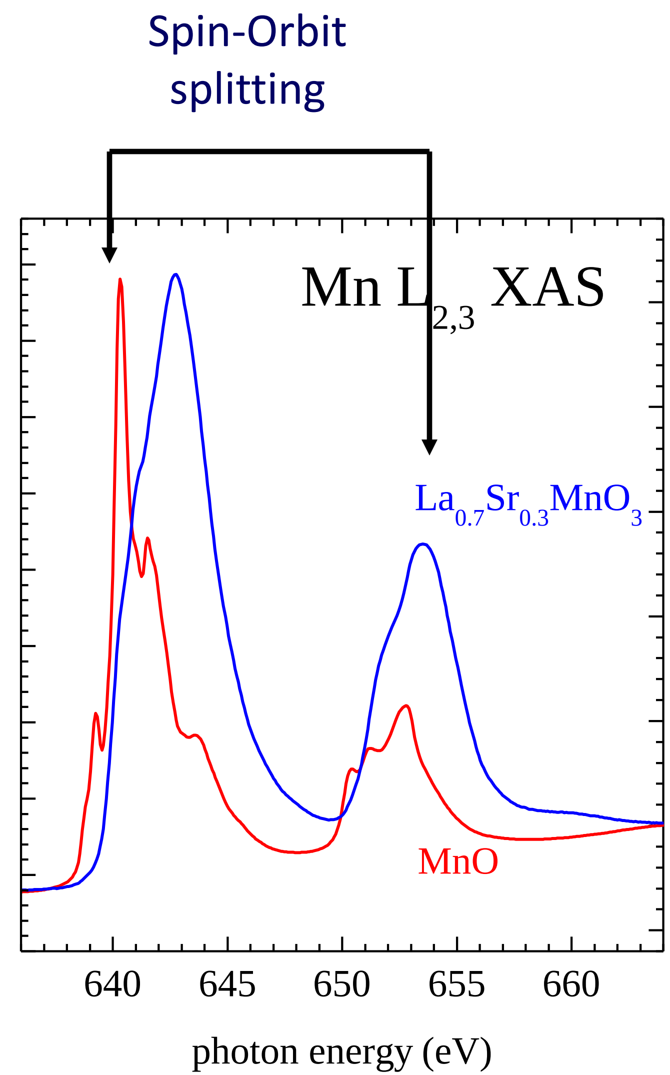
Core level binding energies and edges



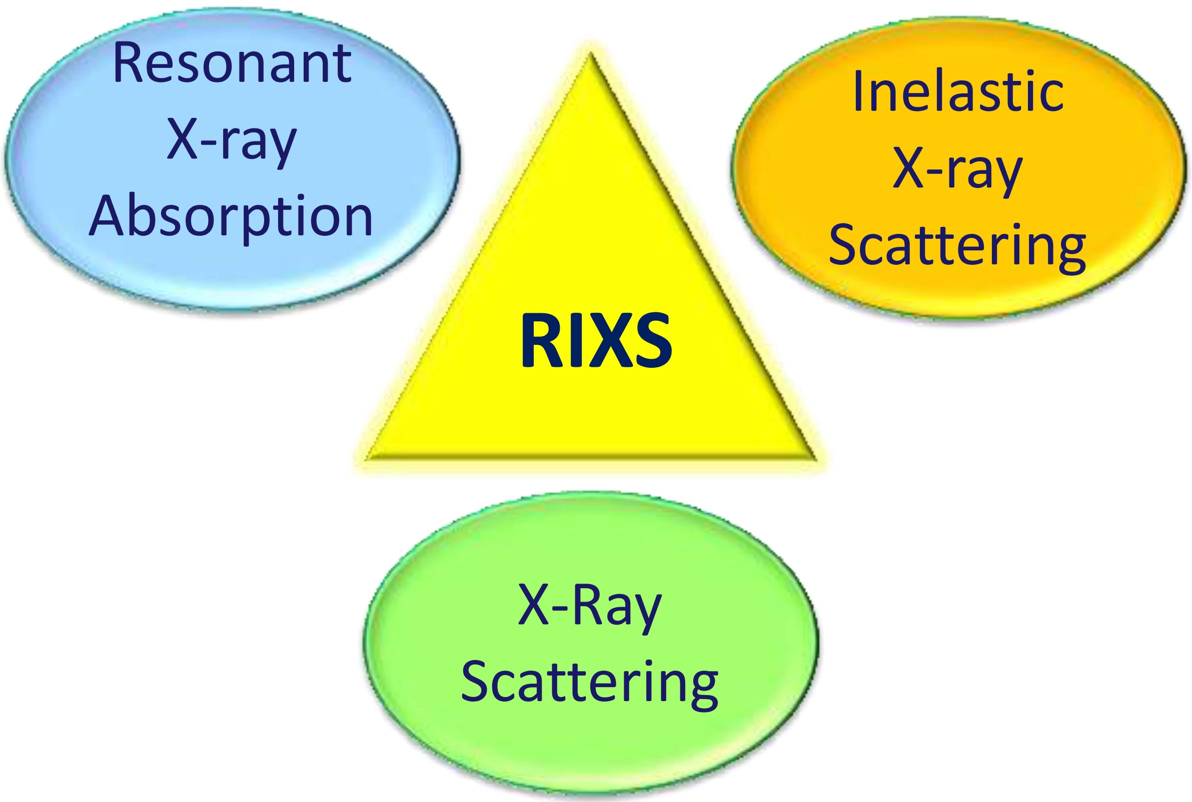


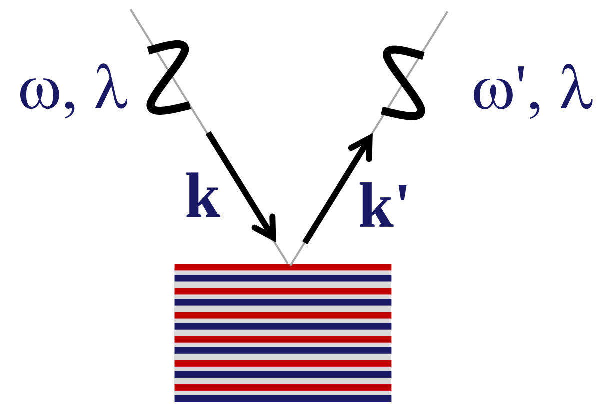
XAS of 3d transition metals





Resonant Inelastic X-ray Scattering



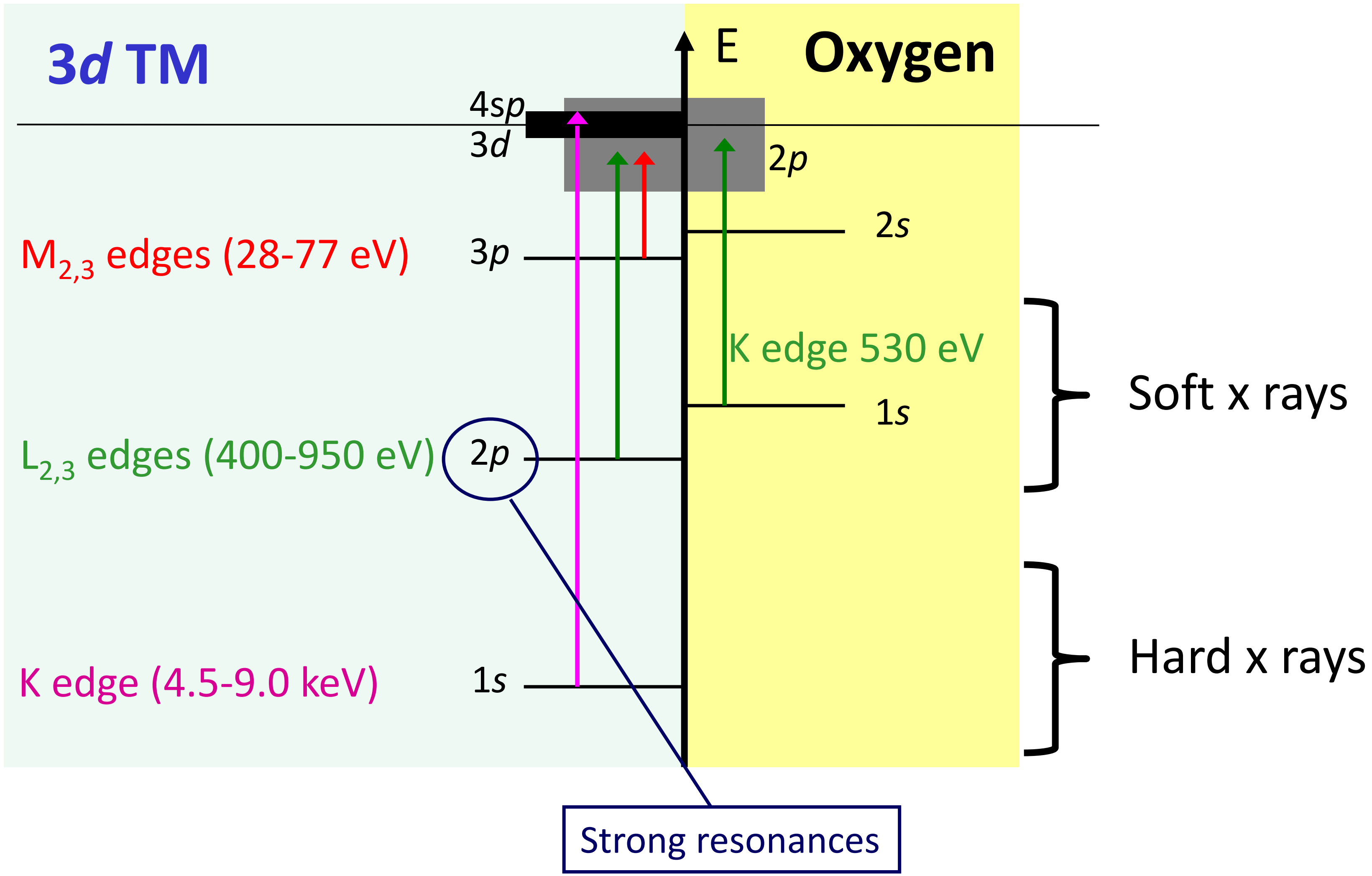


$$\Omega = \omega - \omega'$$

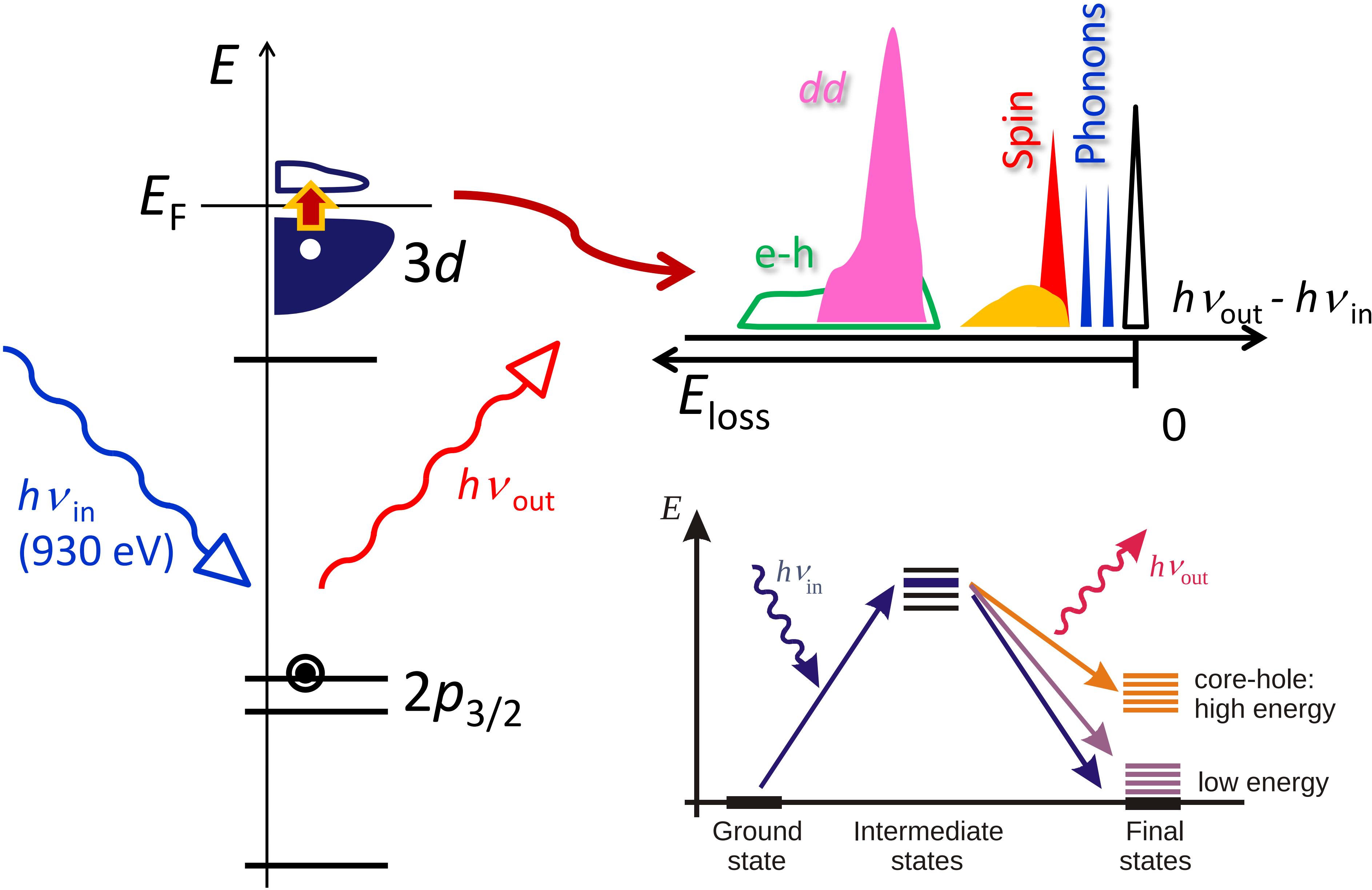
$$\mathbf{q} = \mathbf{k'} - \mathbf{k}$$

The choice of the resonance: 2*p*→3*d*, L_3 edge

3*d* Transition Metal oxides: a lucky coincidence for soft x-rays



L_3 RIXS



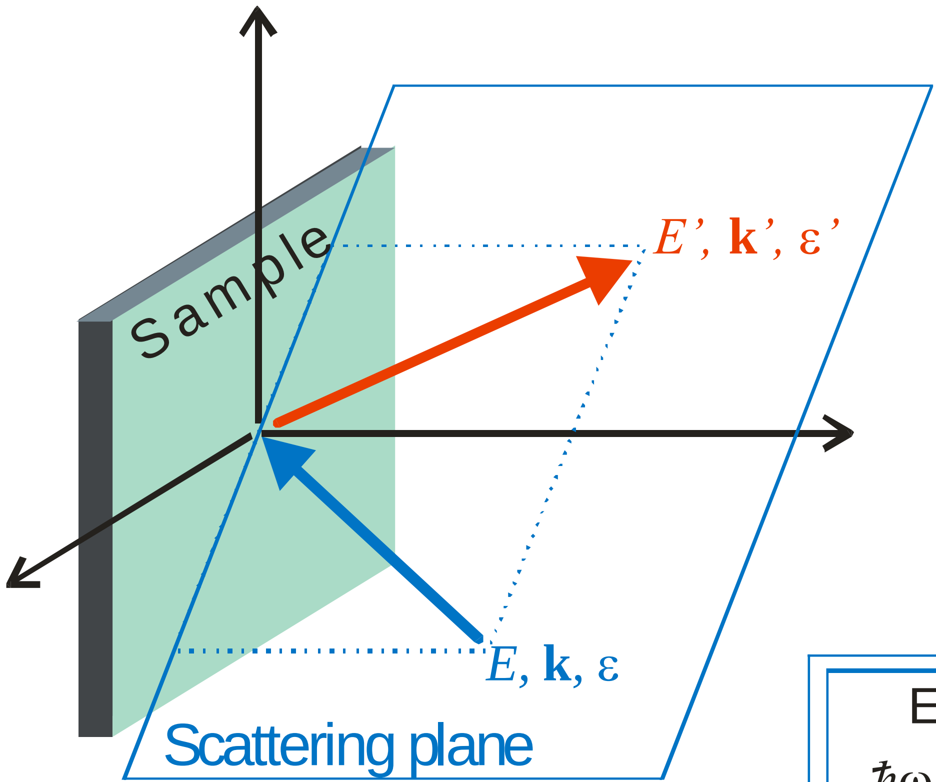
E
E_F
3d
2p_3/2
hν_in
(930 eV)
hν_out
dd
e-h
Spin
Phonons
hν_out - hν_in
E_loss
0
E
hν_in
hν_out
core-hole:
high energy
low energy
Ground
state
Intermediate
states
Final
states

Kramers-Heisenberg formula

$$\sum_f \left| \sum_i \frac{\langle f|T^{(e)}|i\rangle\langle i|T^{(a)}|g\rangle}{E_g + h\nu_{\text{in}} - E_i - i\Gamma_i} \right|^2$$

$$\times \frac{\Gamma_f/\pi}{(E_g + h\nu_{\text{in}} - E_f - h\nu_{\text{out}})^2 + \Gamma_f^2},$$

L edge RIXS : energy and momentum transfer

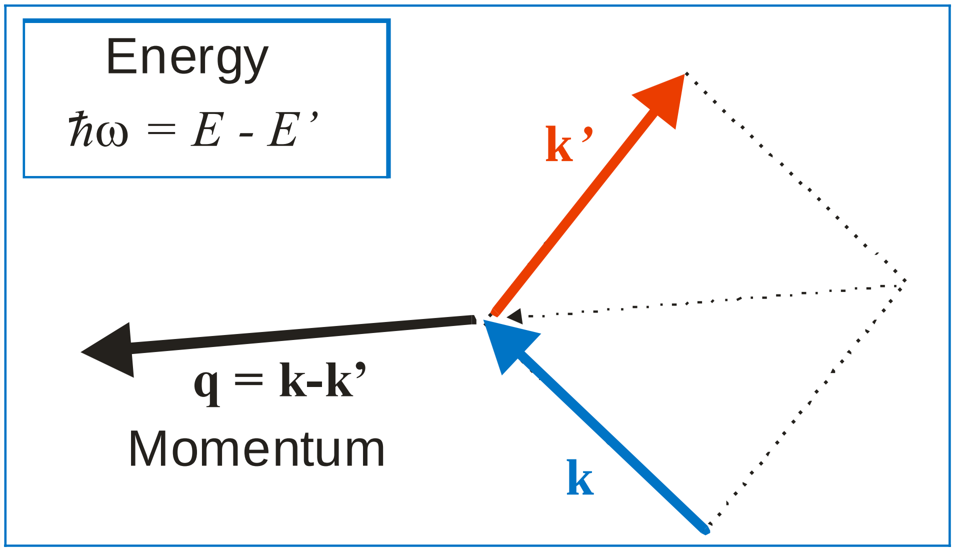


Resonant Inelastic X-ray Scattering:

- an energy loss experiment
- made with photons of high energy
- at a core absorption resonance

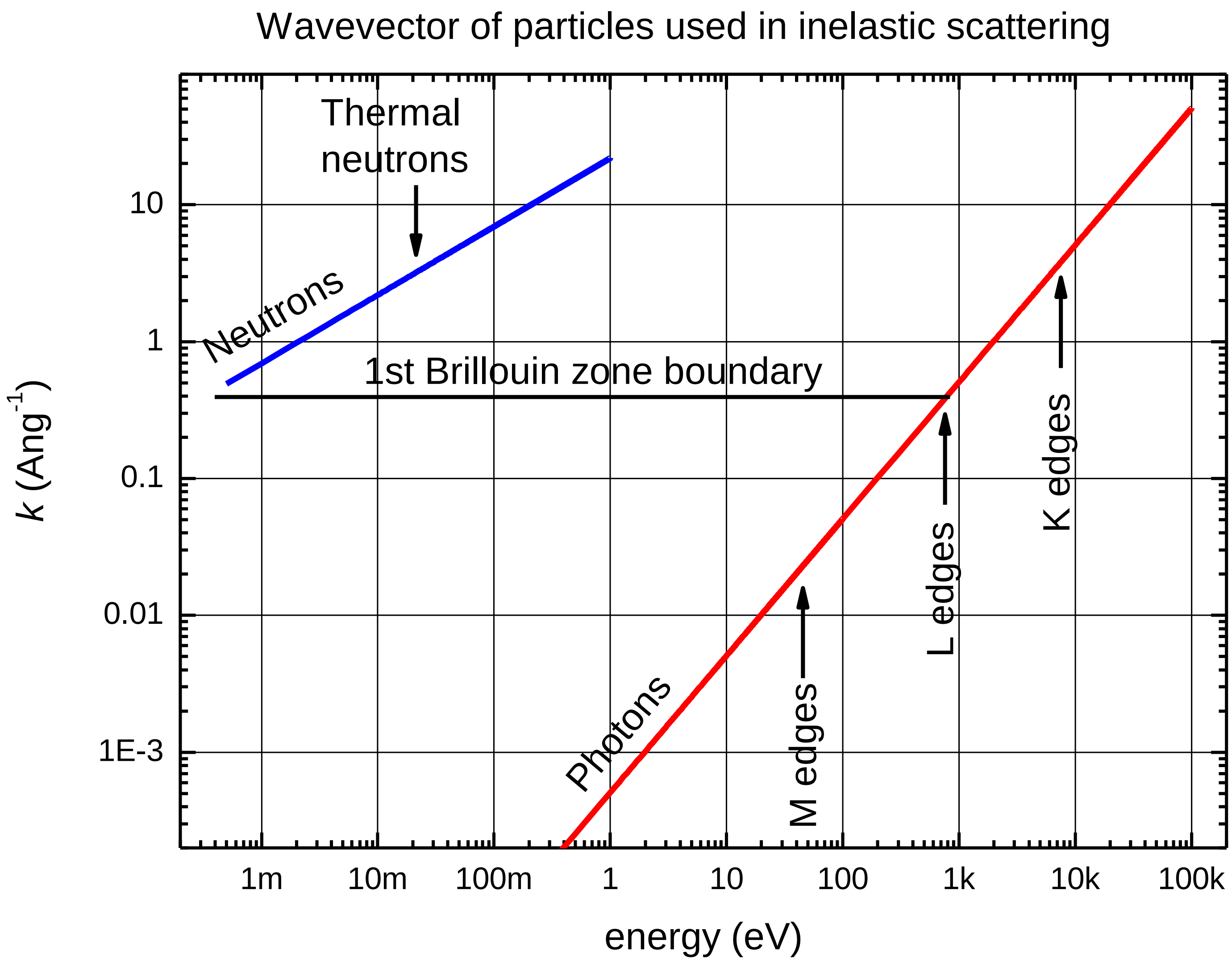
Conservation laws:

- Energy
- Momentum
- "Angular momentum"

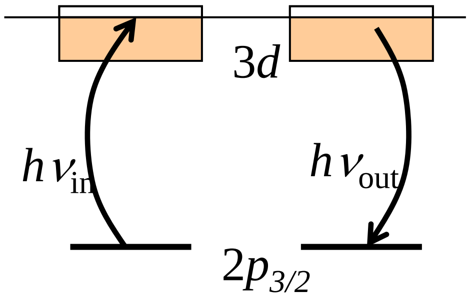


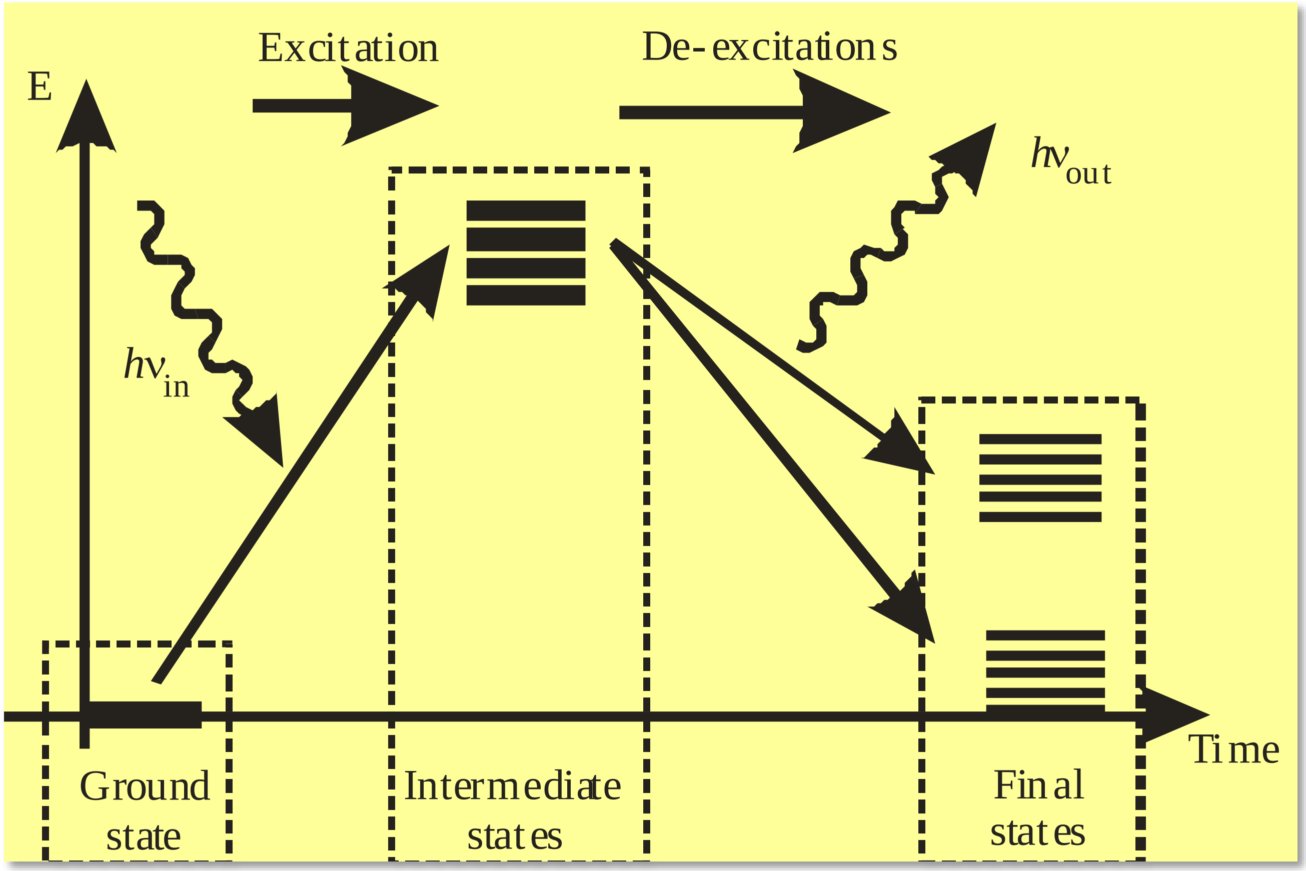
Photon momentum and kinematics

Photons vs Neutrons: energy and momentum



$L_{2,3}$ edge RIXS: intermediate and final states





$3d^n \longrightarrow 2p^5 3d^{n+1} \longrightarrow 3d^n$

The potential of soft RIXS (for 3dTM systems)

Site selective,
***q* resolved probe of**
elementary excitations

- charge excitations across the gap
- *dd* excitations
- magnetic excitations
- phonons

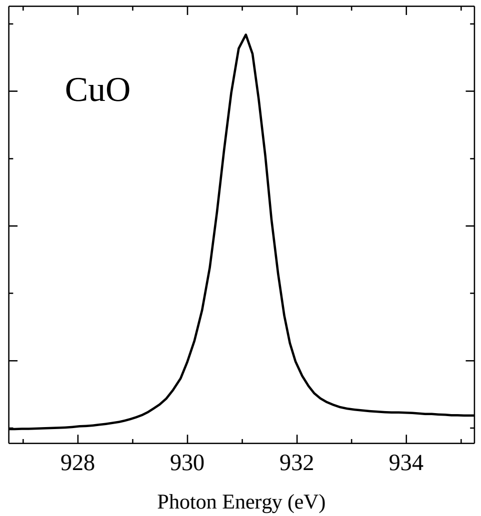
$3d^n \longrightarrow 2p^5 3d^{n+1} \longrightarrow$
- $3d^n$: elastic, magnetic and phonons
- $3d^{n*}$: *dd* excitations
- $3d^n\underline{L}$: *Charge Transfer excitations*

Cuprates: the "easy" case

In cuprates Cu is divalent: $Cu^{2+} \Leftrightarrow 3d^9$

This makes XAS almost trivial: 1 peak only

$$3d^9 \longrightarrow (2p_{3/2})^3 3d^{10}$$

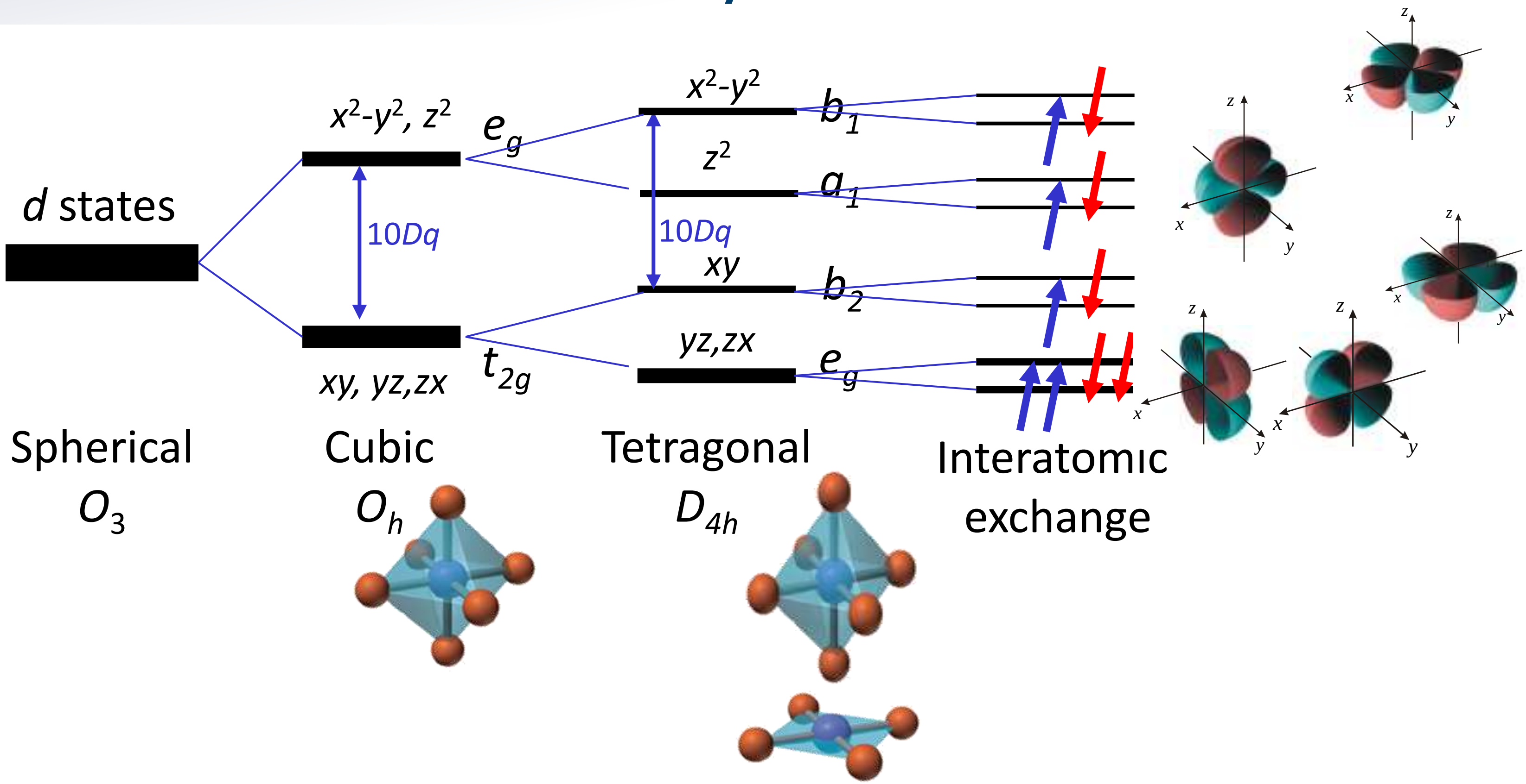


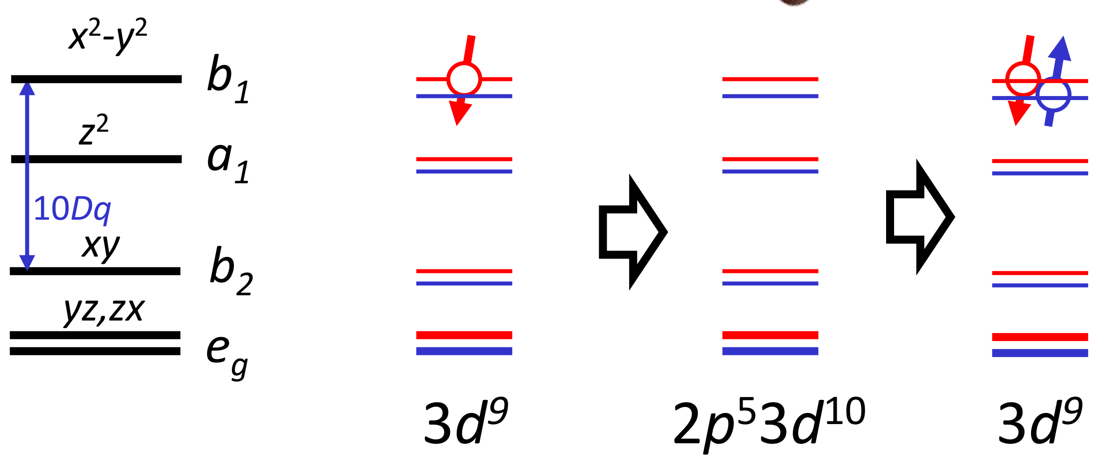
RIXS can be calculated even by hand:

$$3d^9 \longrightarrow (2p_{3/2})^3 3d^{10} \longrightarrow (3d^9)^*$$

Even for magnetic excitations (spin waves), because fast collision approximation is a very good approximation

dd excitations in Cu^{2+} systems

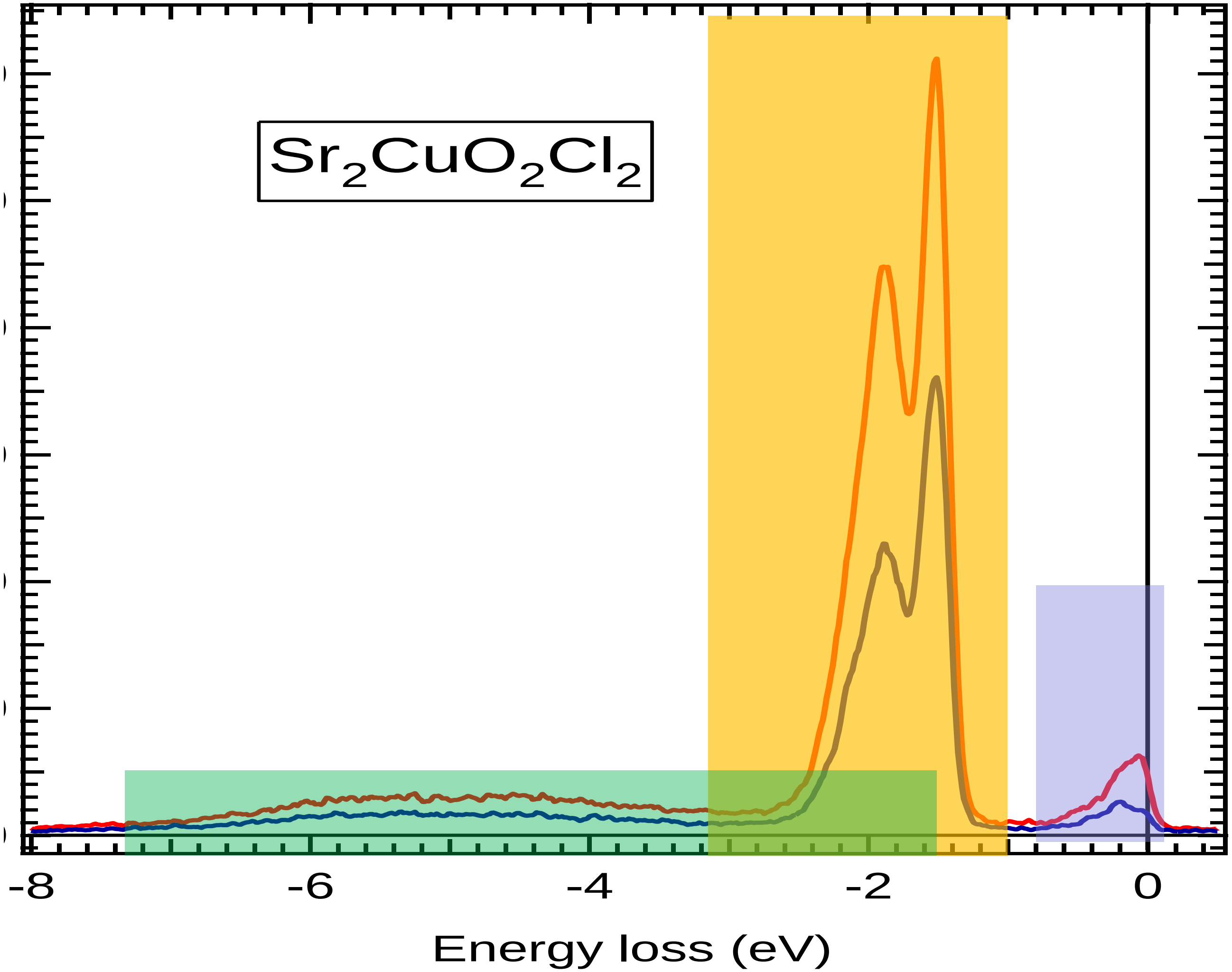




Cu L_3 RIXS of cuprates: mainly *dd* excitations

$3d^9 \longrightarrow 2p^5 3d^{10} \longrightarrow$

- $3d^9$: elastic, magnetic and phonons
- $3d^{9*}$: *dd* excitations
- $3d^{10}\underline{L}$: *Charge Transfer excitations*

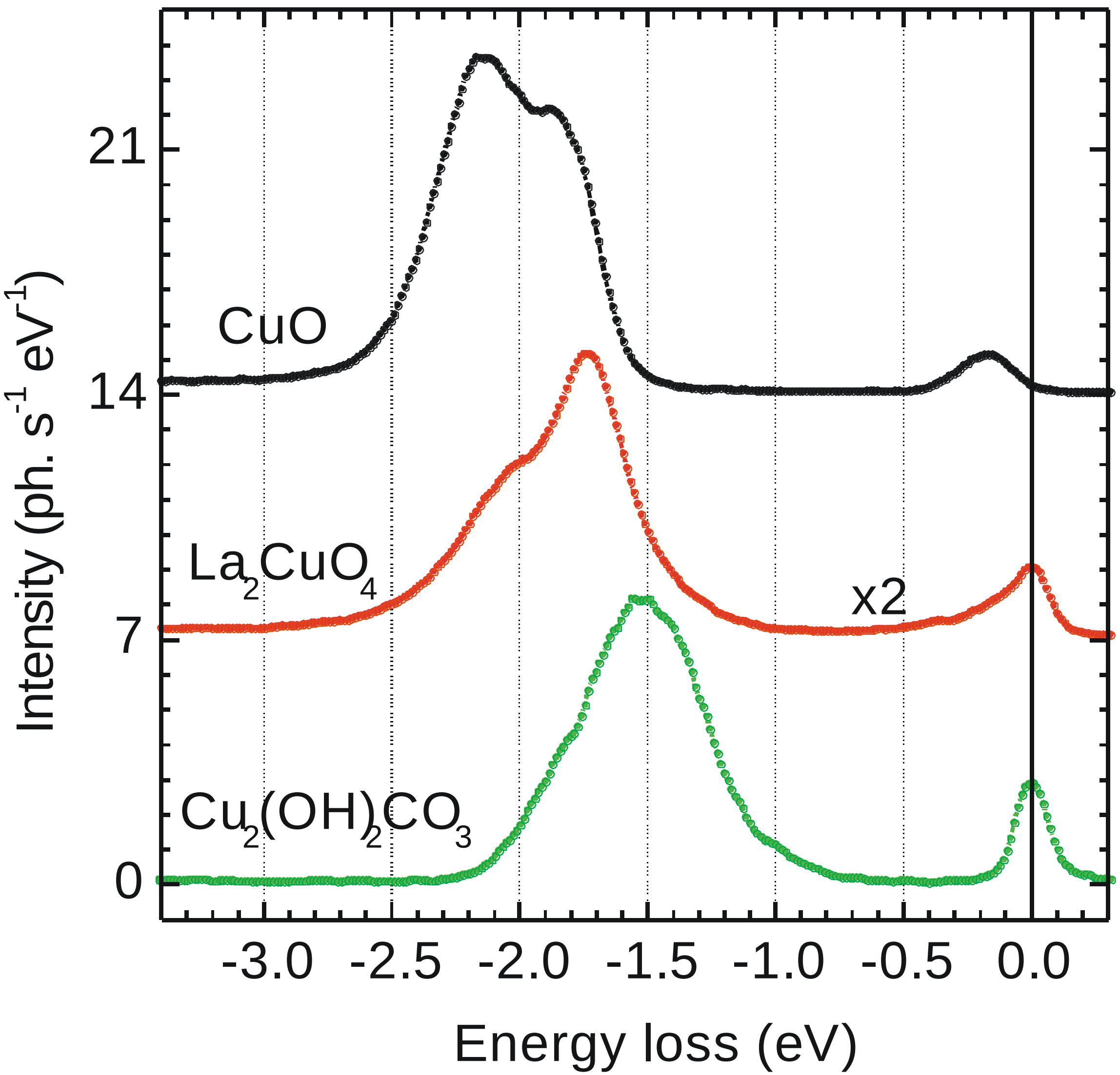


All final states are reached via 2 electric dipole allowed transitions!

Photons get coupled to electrons spin thanks to 2*p* spin-orbit interaction

At L_3 edge elastic peak is very small (not the case at K)

Cu L_3 edge: CuO, La_2CuO_4, Malachite



Cu^{2+} in square approximately planar coordination

Cu-O distances:
CuO 1.7 – 2-2 Ang
LCO 1.9 – 2.4 Ang
Malachite 1.9 – 2.6 Ang

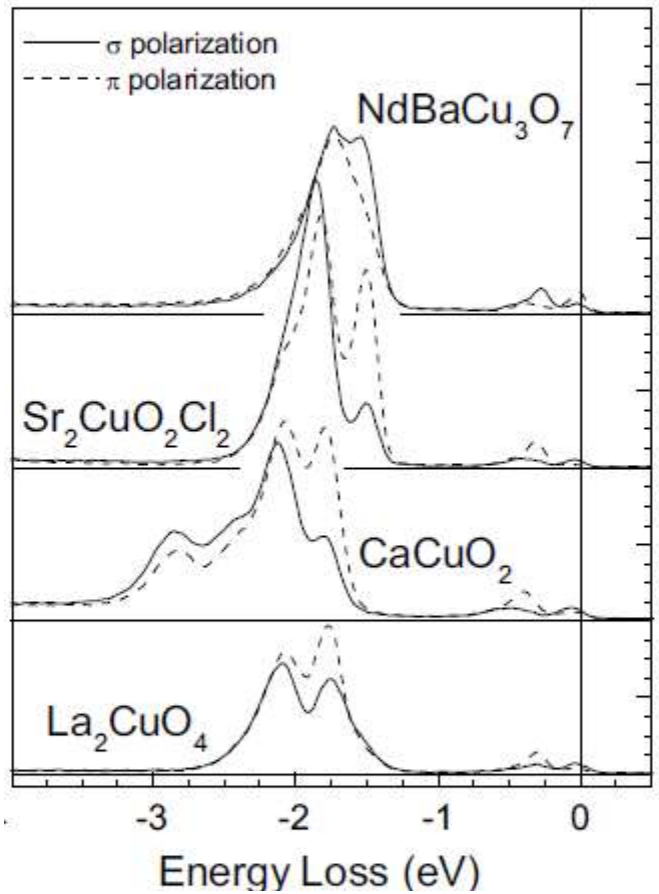
Different Cu^{2+} coordination, symmetry, hybridization

⇩

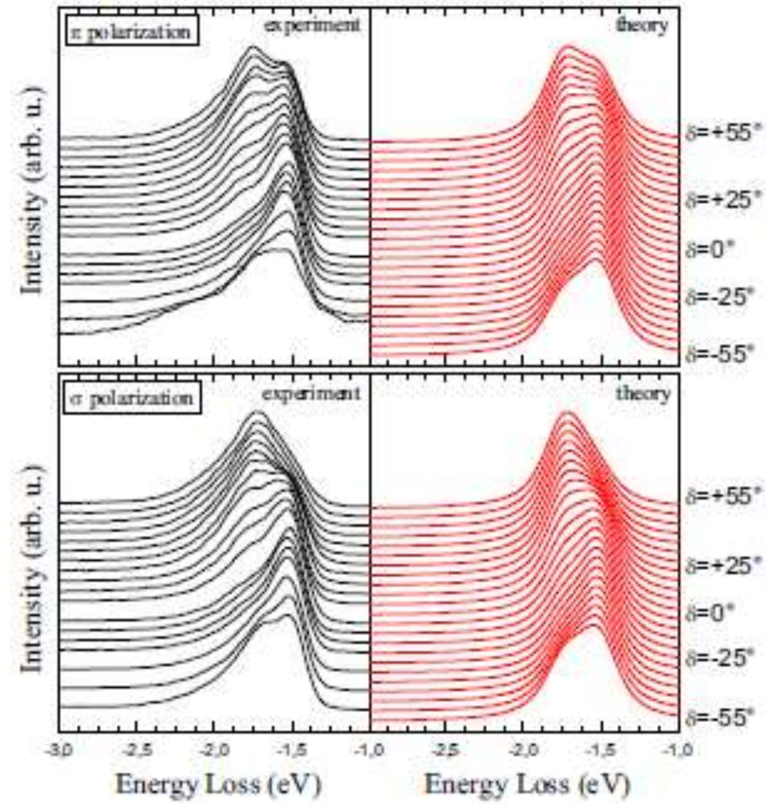
Different *dd* excitations

G. Ghiringhelli, A. Piazzalunga, X. Wang, A. Bendounan, H. Berger, F. Bottegoni, N. Christensen, C. Dallera, M. Grioni, J.-C. Grivel, M. Moretti Sala, L. Patthey, J. Schlappa, T. Schmitt, V. Strocov , and L. Braicovich, Eur.Phys. J. Special topics **169**, 199 (2009)

This is a very direct way of measuring the *dd*-excitation energies



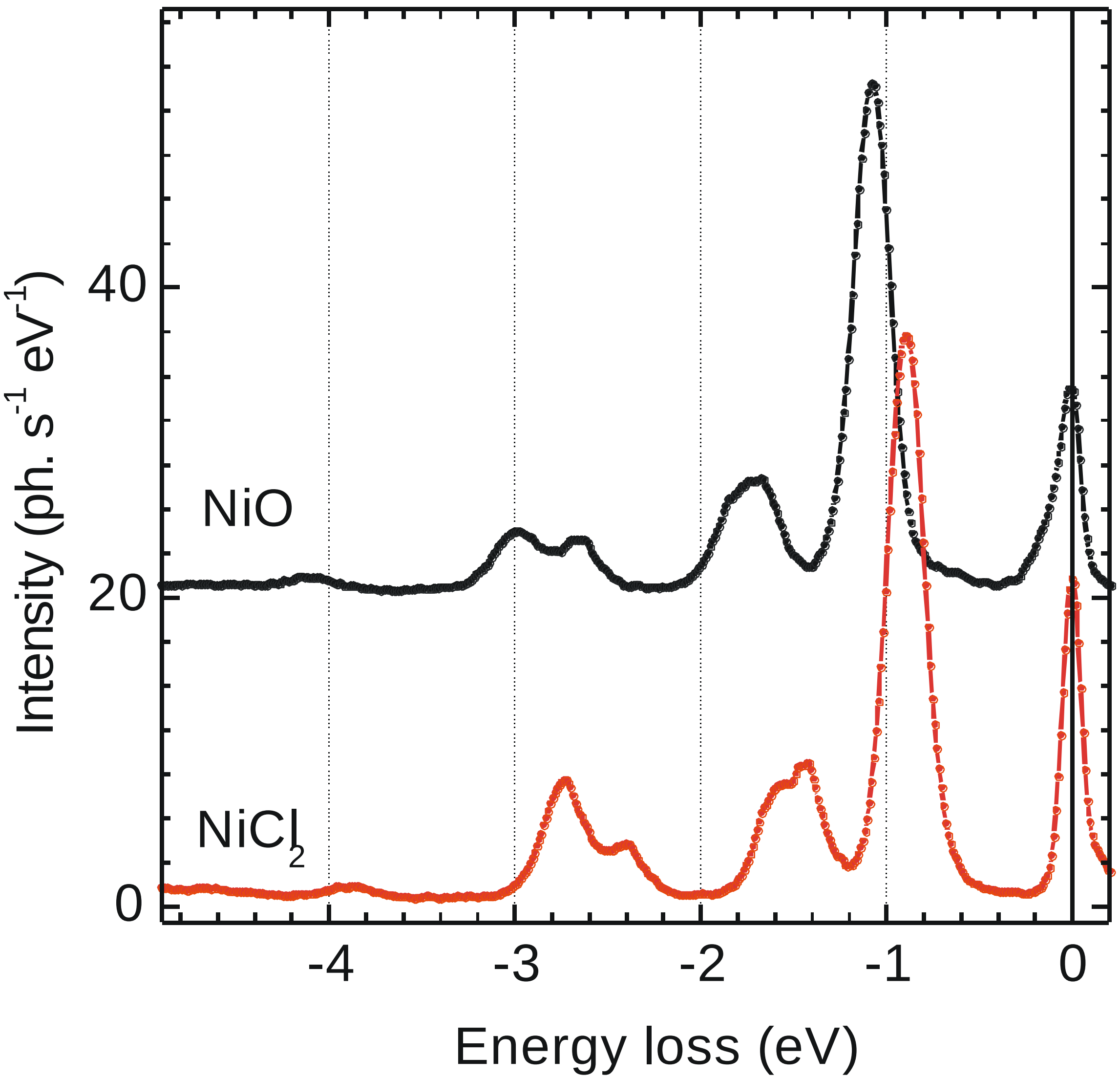
NdBCO



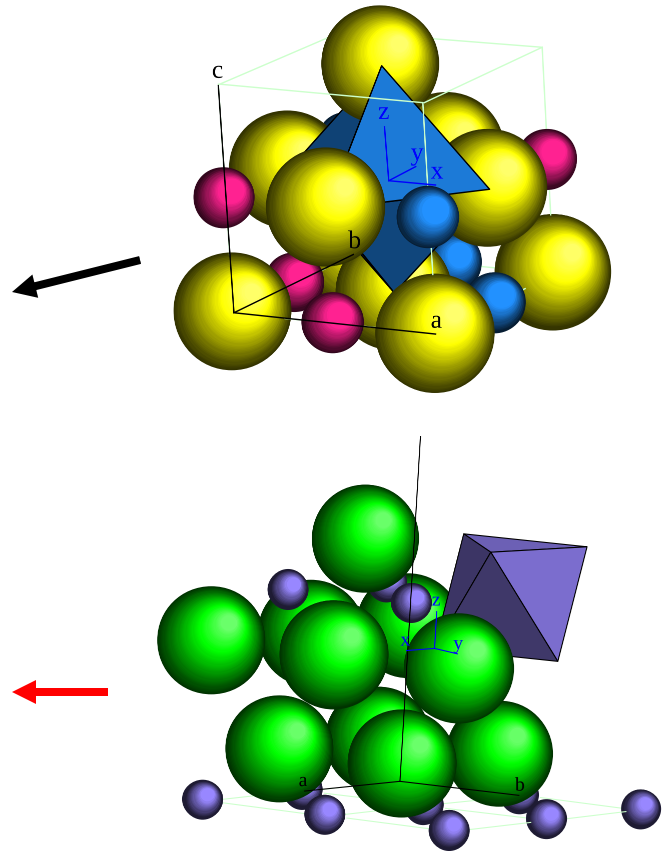
	La_2CuO_4	$Sr_2CuO_2Cl_2$	$CaCuO_2$
J [meV]	130[34,35]	130[35]	130[35]
$E_{3z^2-r^2}$ ($\Gamma_{3z^2-r^2}$) [eV]	1.70 (.14)	1.97 (.10)	2.72 (.12)
E_{xy} (Γ_{xy}) [eV]	1.80 (.10)	1.50 (.08)	1.75 (.09)
$E_{xz/yz}$ ($\Gamma_{xz/yz}$) [eV]	2.12 (.14)	1.84 (.10)	2.10 (.18)

M. Moretti Sala, V. Bisogni, L. Braicovich, C. Aruta, G. Balestrino, H. Berger, N. B. Brookes, G.M. De Luca, D. Di Castro, M. Grioni, M. Guarise, P. G. Medaglia, F. Miletto Granozio, M. Minola, M. Radovic, M. Salluzzo, T. Schmitt, K.-J. Zhou, G. Ghiringhelli, New J. Phys. **13**, 043026 (2011)

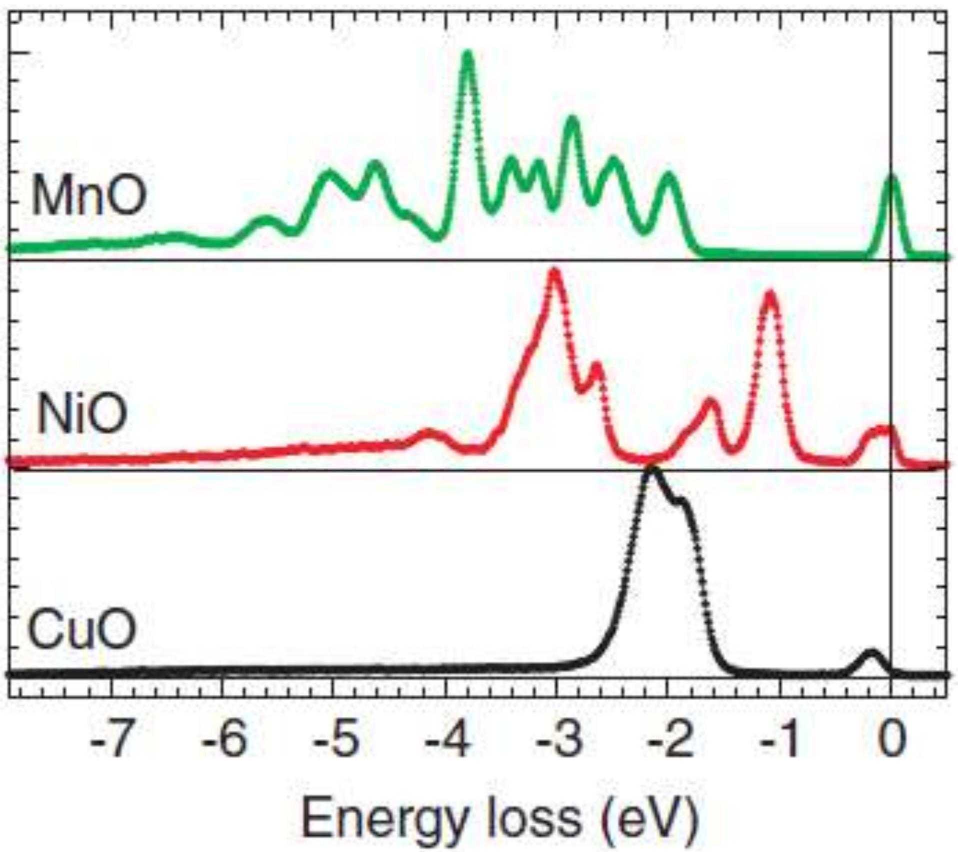
Ni L_3 edge: NiO, $NiCl_2$

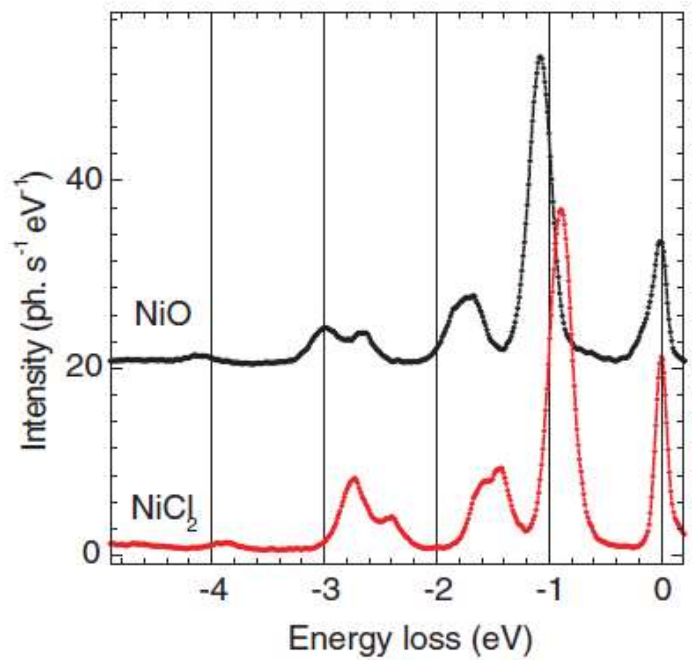


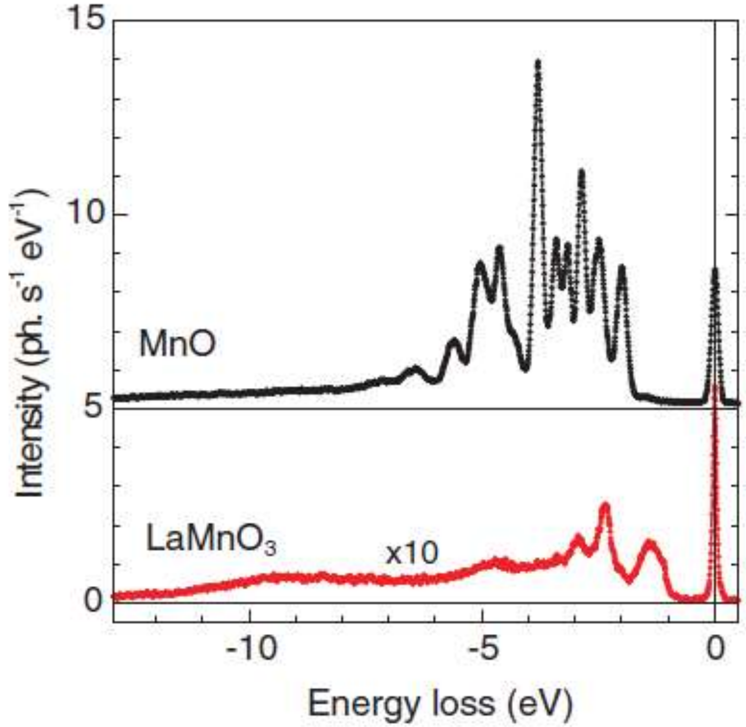
Ni^{2+} ($3d^8$) in octahedral coordination



dd and CT excitations in simple oxides

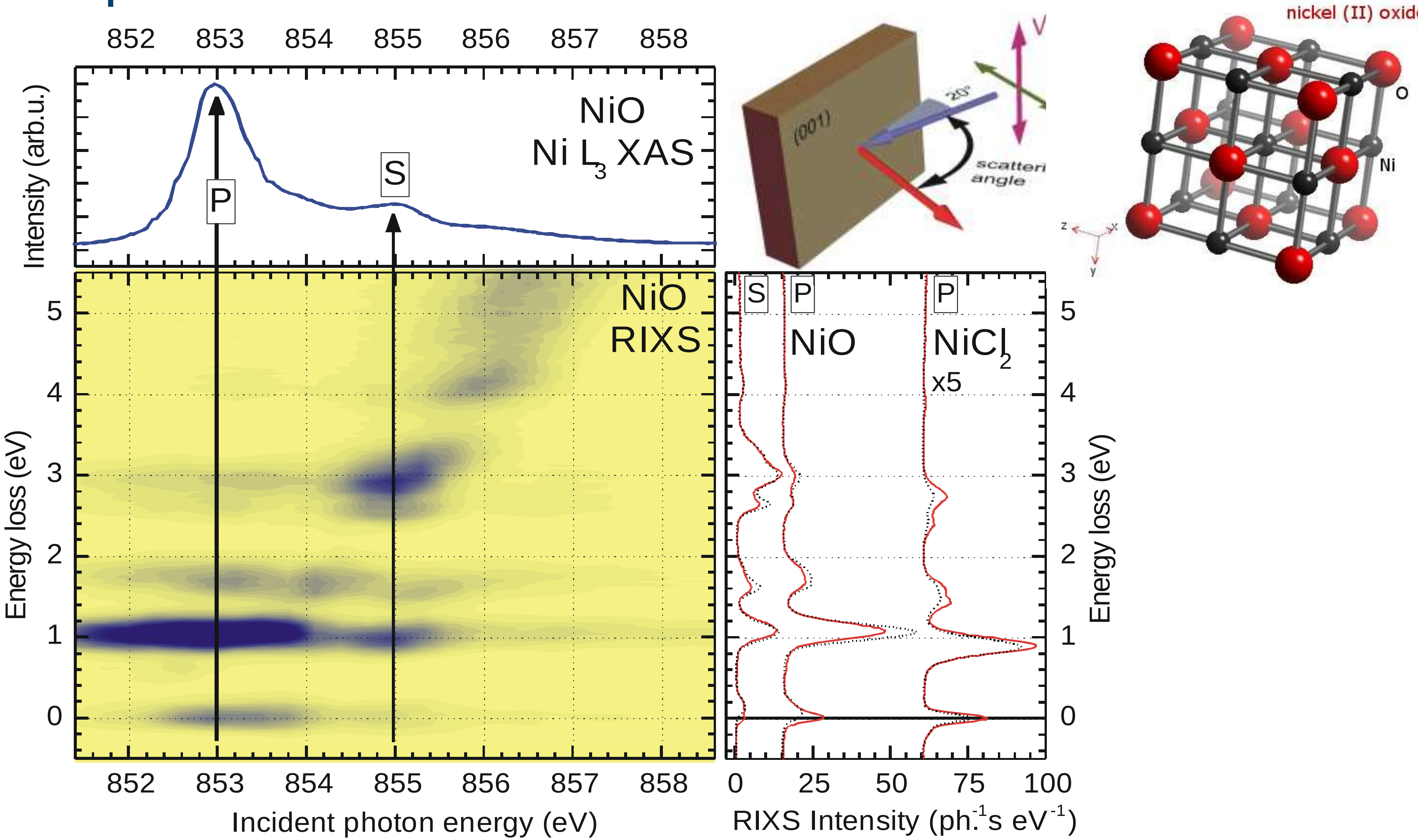






G. Ghiringhelli, A. Piazzalunga, X. Wang, A. Bendounan, H. Berger, F. Bottegoni, N. Christensen, C. Dallera, M. Grioni, J.-C. Grivel, M. Moretti Sala, L. Patthey, J. Schlappa, T. Schmitt, V. Strocov , and L. Braicovich, Eur.Phys. J. Special topics **169**, 199 (2009)

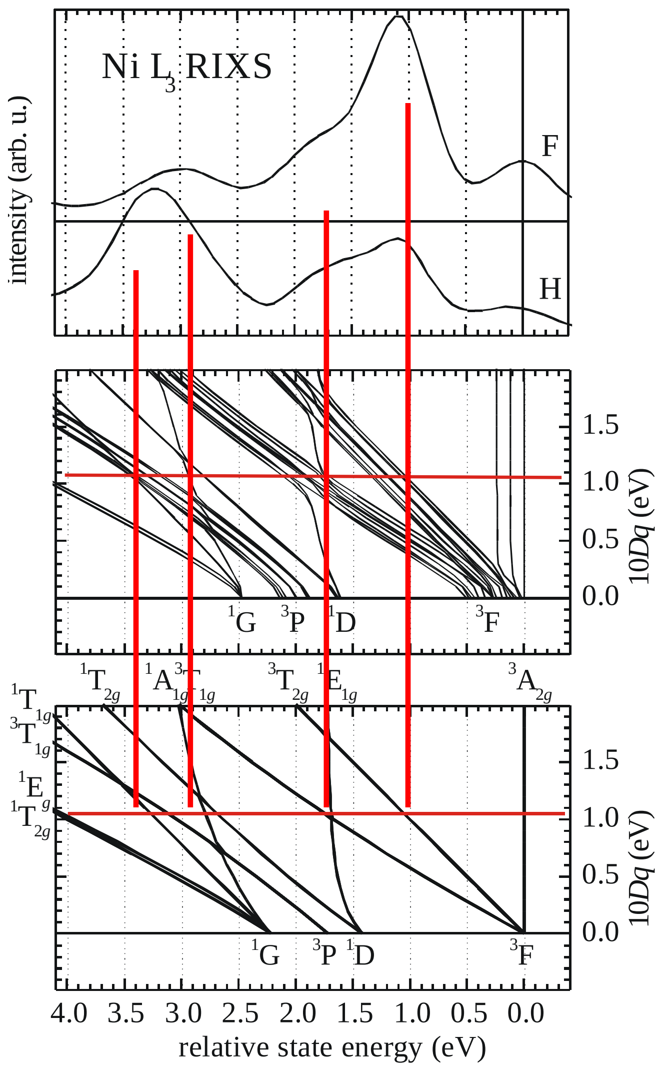
RIXS of NiO: incident photon energy depencence ...

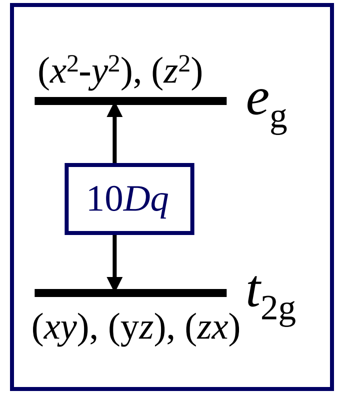


G. Ghiringhelli A. Piazzalunga, C. Dallera, L. Braicovich, T. Schmitt, V.N. Strocov, J. Schlappa, L. Patthey, X. Wang, H. Berger, and M. Grioni, PRL **102**, 027401 (2009)

Many excited states

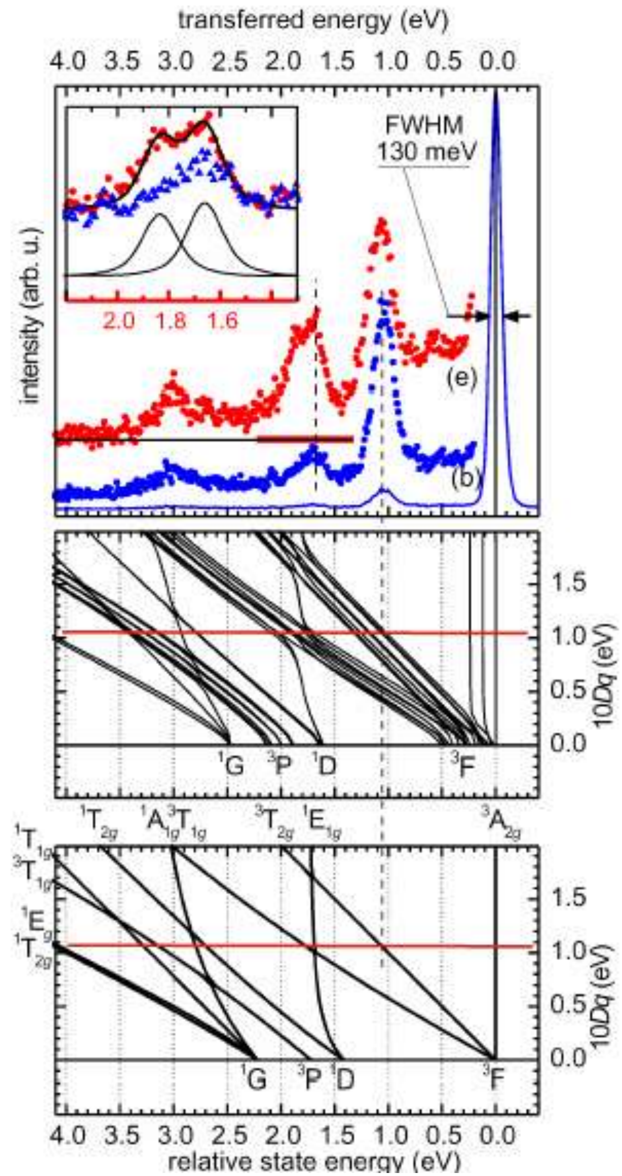
Crystal field model: Sugano-Tanabe diagrams





Single ion
Octahedral C.F.
3d spin-orbit
Exchange

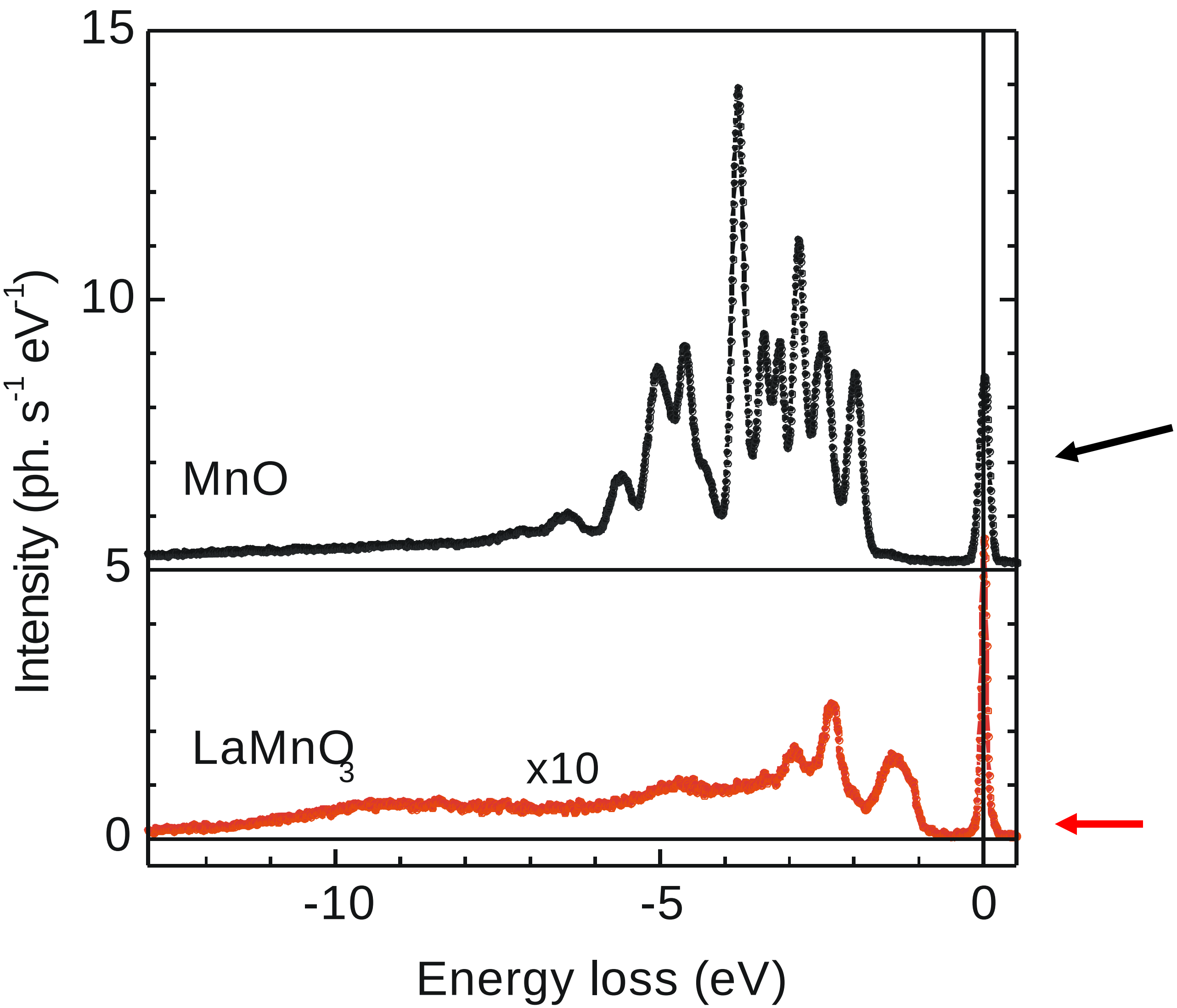
Single ion
Octahedral C.F.



G. Ghiringhelli *et al*, J. Phys. Cond. Mat. **17**, 5397 (2005)

S.G.Chiuzbaian, G. Ghiringhelli *et al*, Phys. Rev. Lett. **95**, 197402 (2005)

Mn L_3 edge: MnO, $LaMnO_3$



Mn^{2+} and Mn^{3+} in octahedral coordination

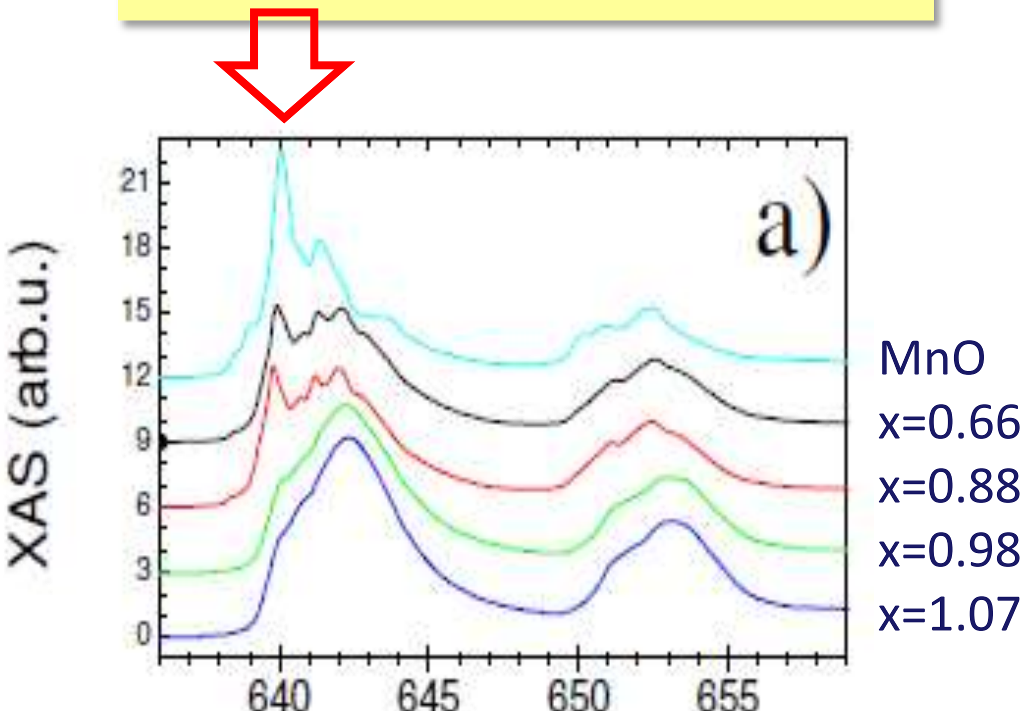
Mn^{2+}: $3d^5$

Mn^{3+}: $3d^4$

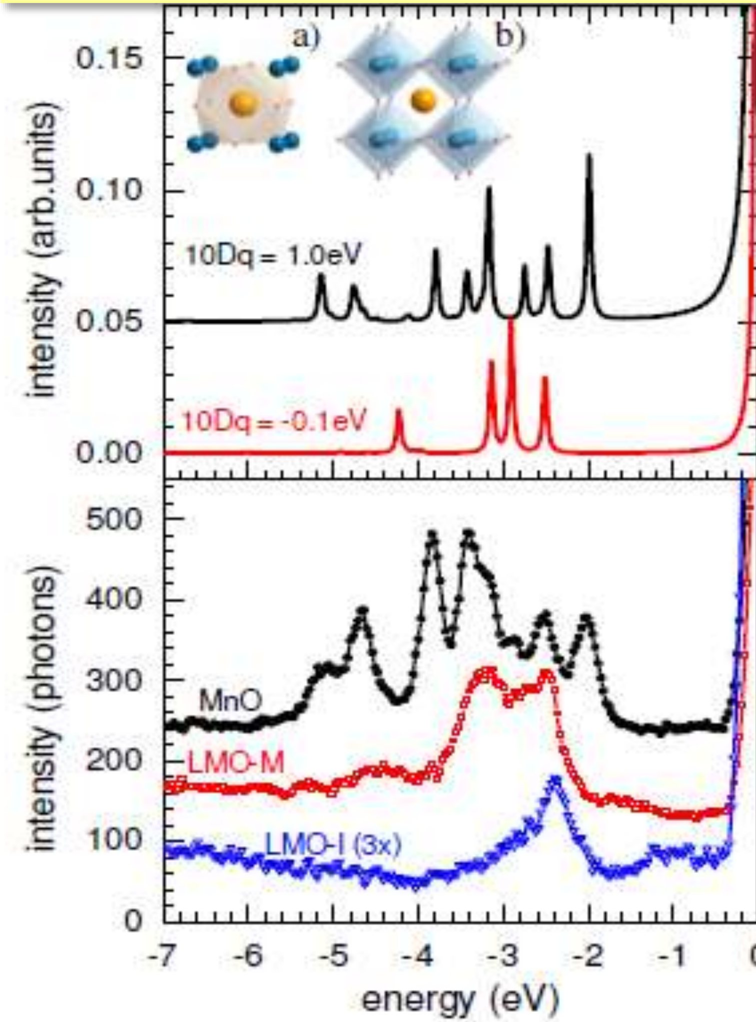
An application to thin film: Mn^{2+} in La_xMnO_3

La_xMnO_{3-d}/STO films
x=La/Mn ratio
for x<1 becomes FM (self doping)

XAS reveals the presence of Mn^{2+} for x<1



RIXS shows that Mn^{2+} is at site A, ie, it replaces La^{3+}



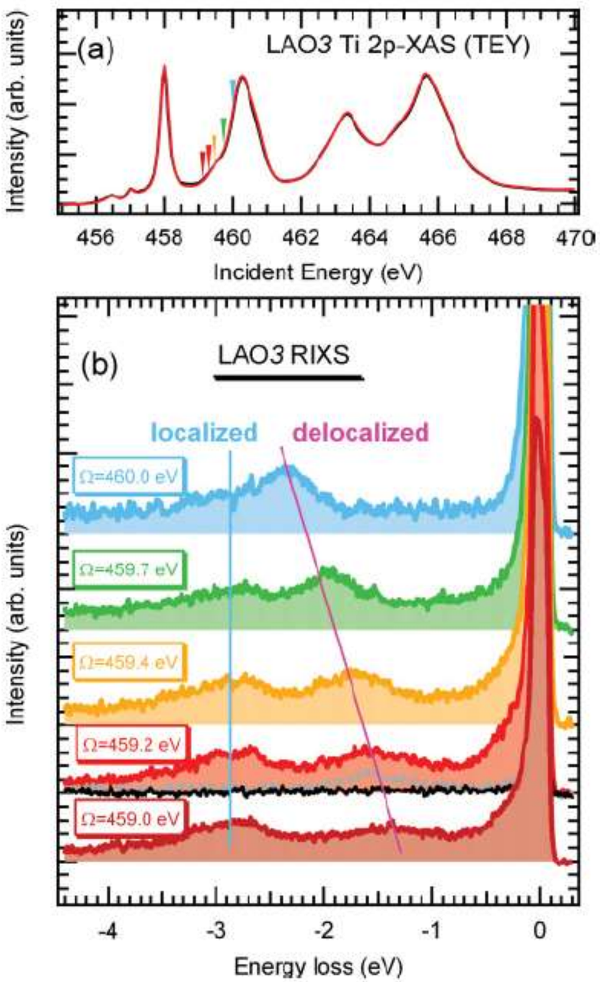
P. Orgiani, A. Galdi, C. Aruta, V. Cataudella, G. De Filippis, C.A. Perroni, V. Marigliano Ramaglia, R. Ciancio, N.B. Brookes, M. Moretti Sala, G. Ghiringhelli, and L. Maritato, Phys. Rev. B **82**, 205122 (2010)

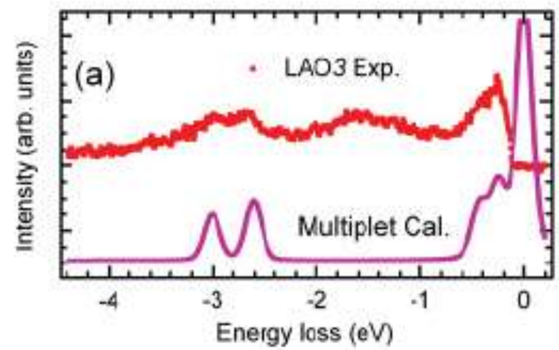
STO/LAO superlattice: RIXS at Ti L_3

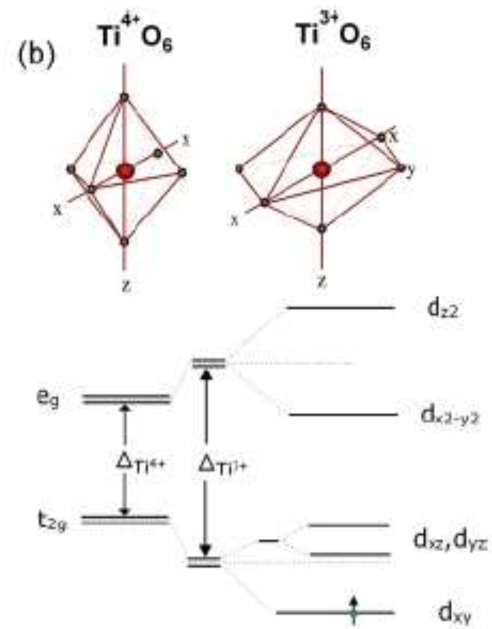
PHYSICAL REVIEW B 83, 201402(R) (2011)

Localized and delocalized Ti 3*d* carriers in $LaAlO_3/SrTiO_3$ superlattices revealed by resonant inelastic x-ray scattering

Ke-Jin Zhou,[1] Milan Radovic,[2,1] Justine Schlappa,[1,*] Vladimir Strocov,[1] Ruggero Frison,[3] Joel Mesot,[1,2] Luc Patthey,[1] and Thorsten Schmitt[1,†]





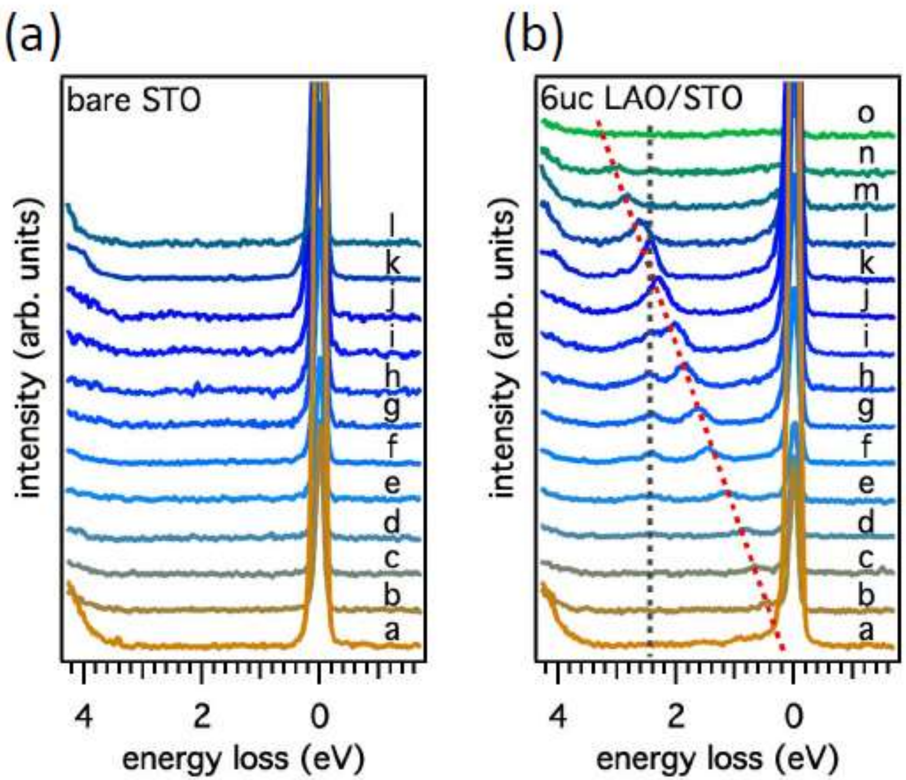


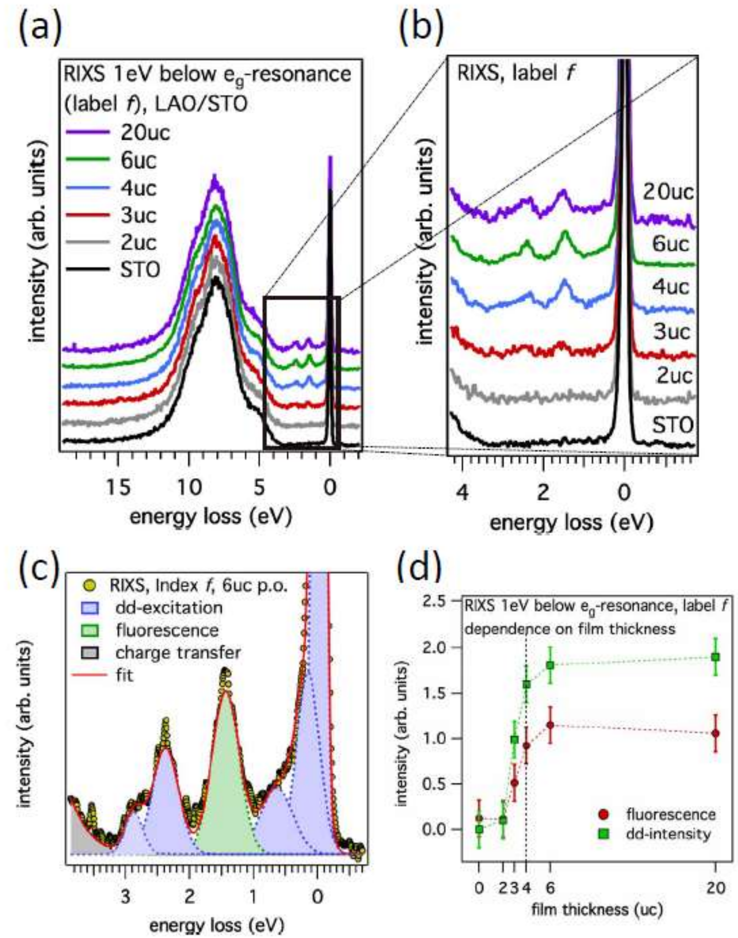
Again LAO/STO RIXS

arXiv:1705.10360v1

Raman and fluorescence contributions to resonant inelastic soft x-ray scattering on $LaAlO_3/SrTiO_3$ heterostructures

F. Pfaff[1], H. Fujiwara[2], G. Berner[1], A. Yamasaki[3], H. Niwa[4], H. Kiuchi[5], A. Gloskovskii[6], W. Drube[6], O. Kirilmaz[1], A. Sekiyama[2], J. Miyawaki[4,7], Y. Harada[4,7], S. Suga[8], M. Sing[1], and R. Claessen[1]





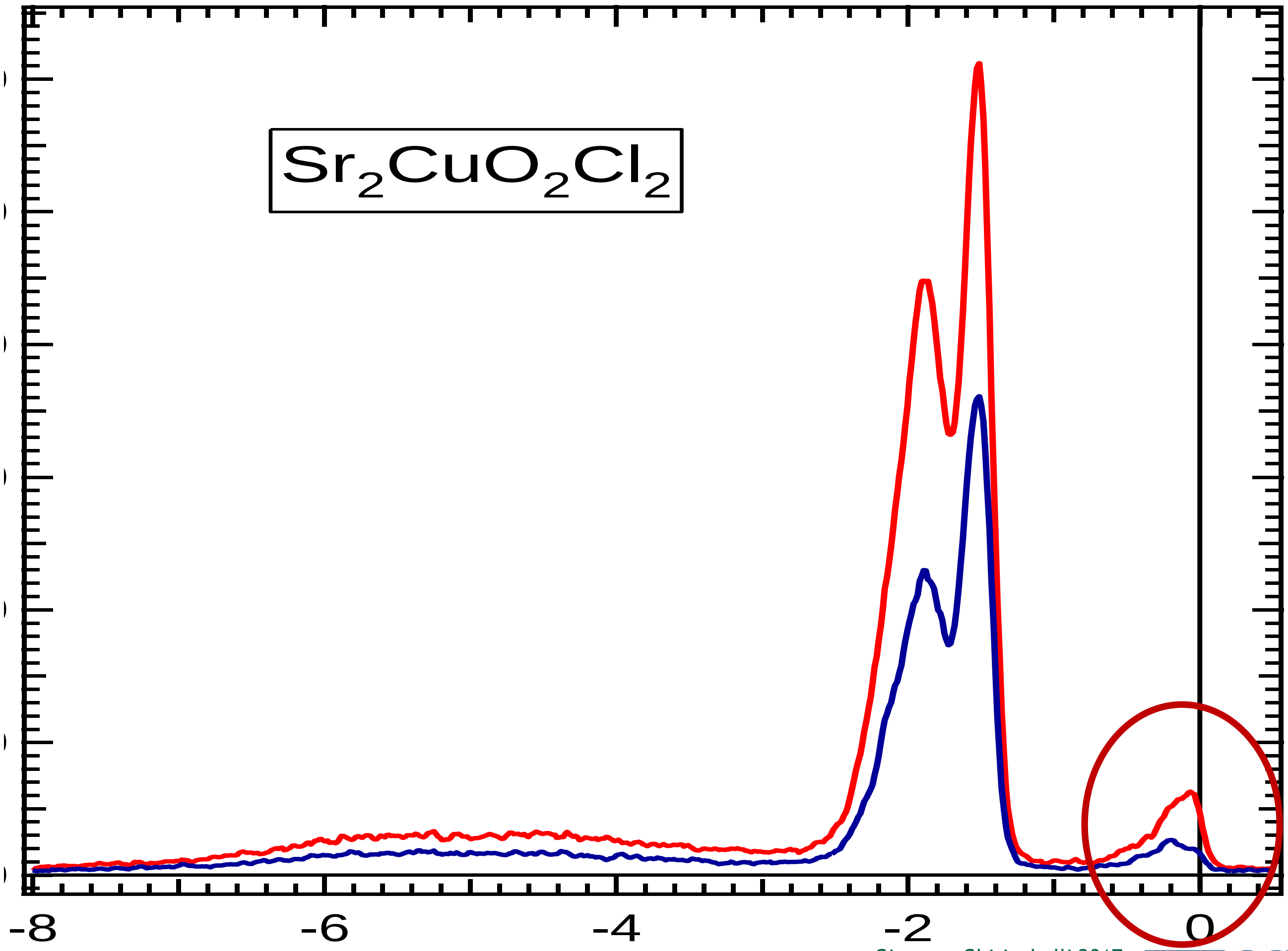
Raman and Non –Raman excitations present only above 4 uc of LAO: 2 forms of Ti-3d^1 structure?

What about the “quasi-elastic” spectral features?

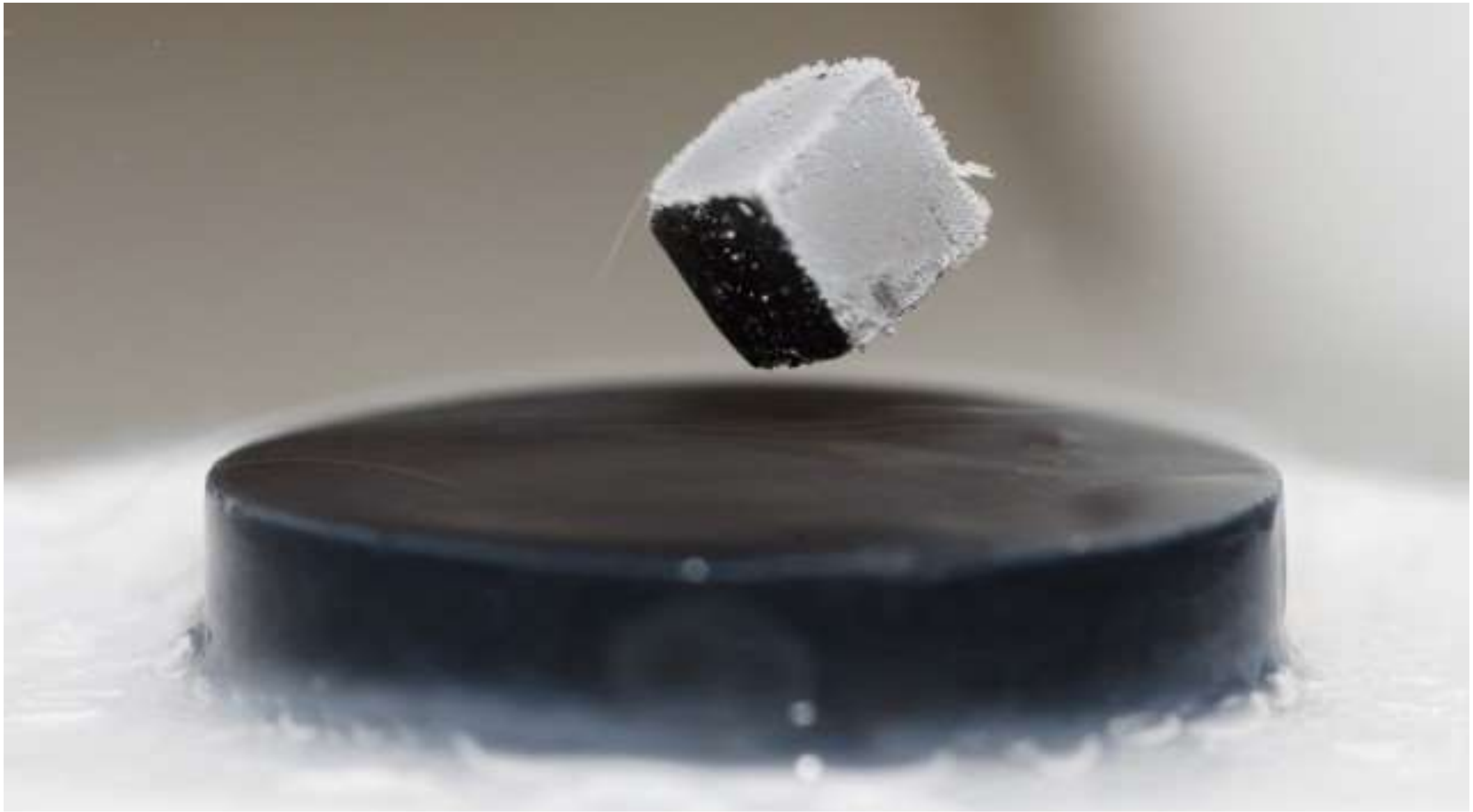
Phonons: up to 90meV

Magnons (2*J* at BZB): up to 300 meV (J_{eff} ≈ 140 meV)

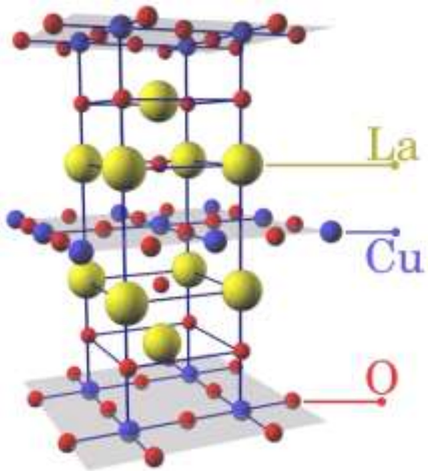
Multi mangons...



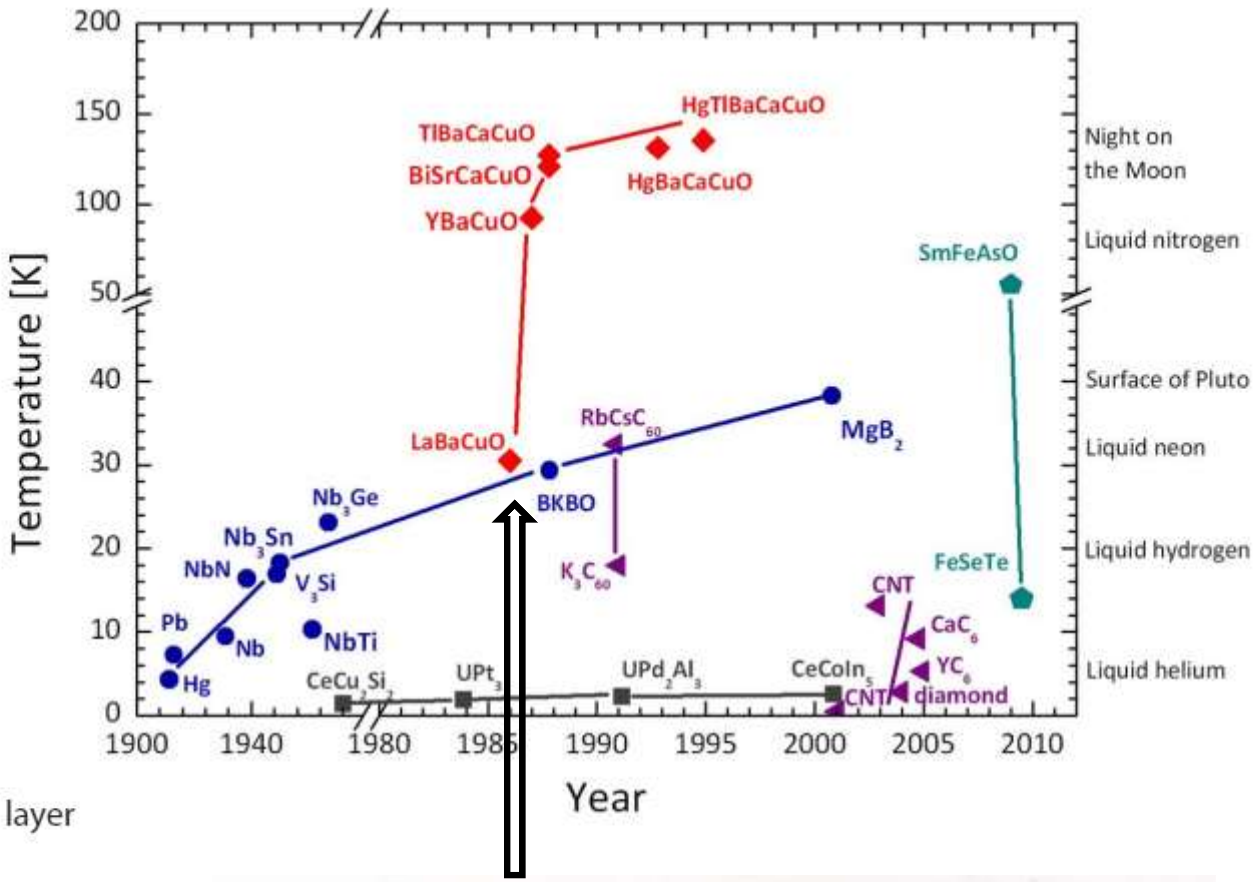
High Tc superconductors

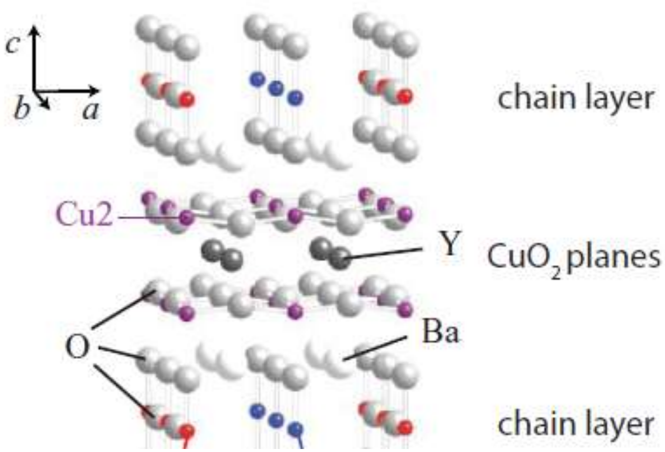


High Tc superconducting cuprates



$La_{2-x}Sr_xCuO_4$ (LSCO)





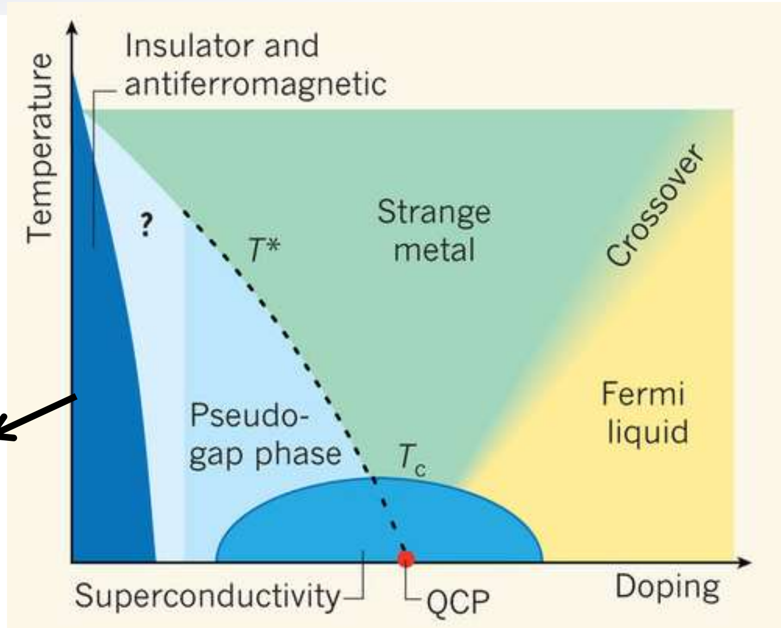
$YBa_2Cu_3O_{6+\delta}$ (YBCO)

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

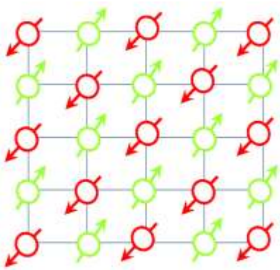
J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

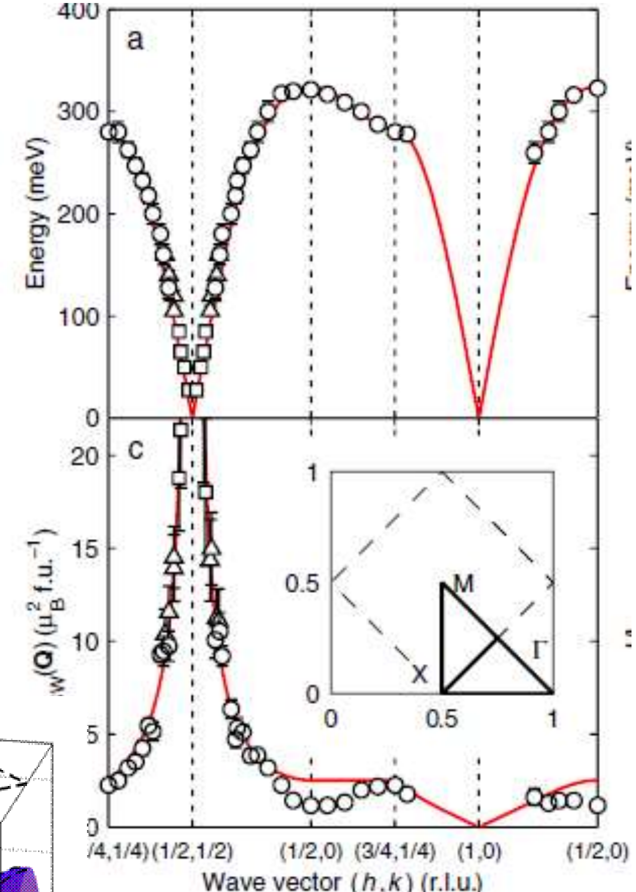
Spin excitations in HTcS: undoped AF



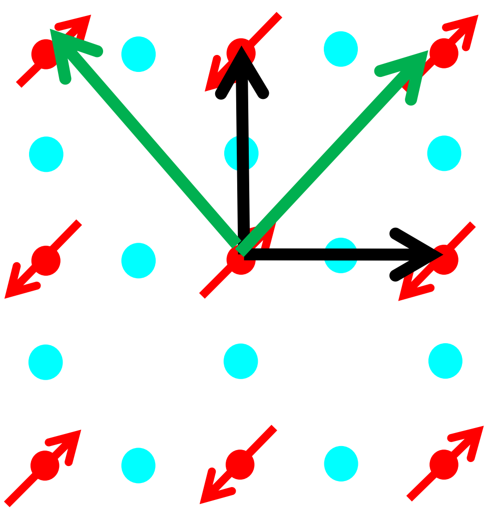
2D AF



INS: La_2CuO_4

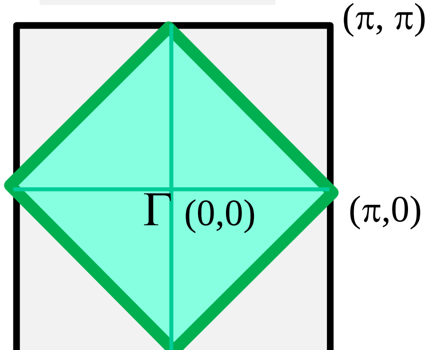


DIRECT SPACE

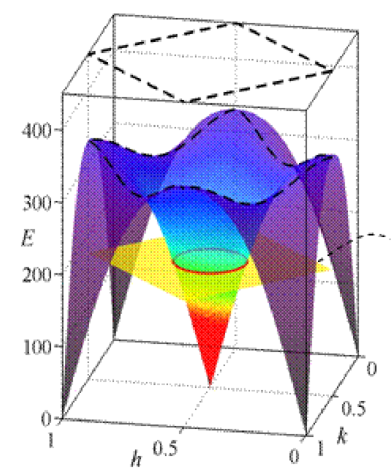


RECIPROCAL SPACE

nuclear BZ

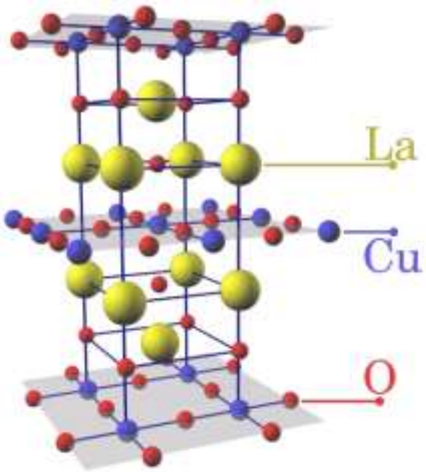


magnetic BZ

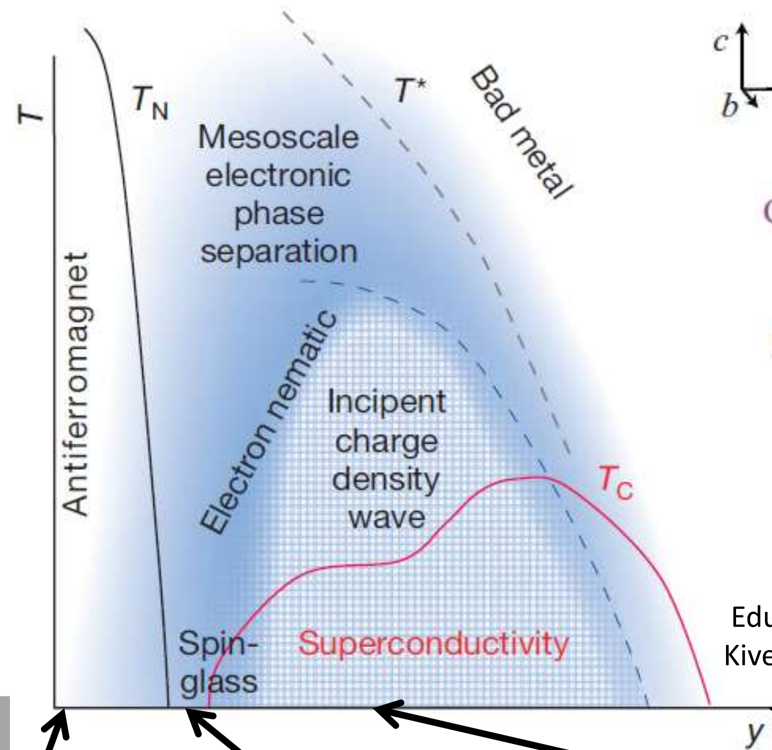


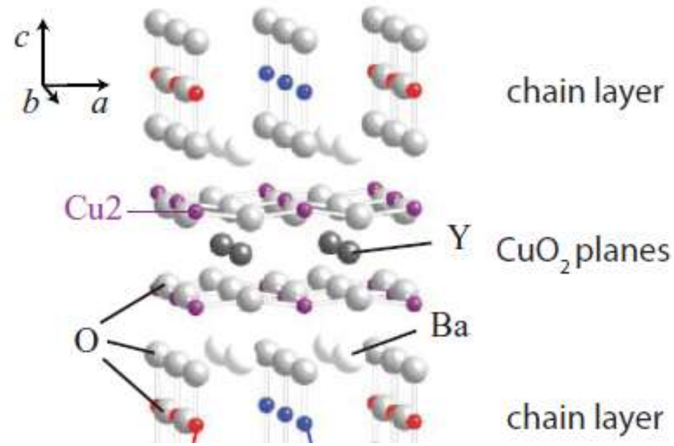
N. S. Headings, S. M. Hayden, R. Coldea, and T. G. Perring, Phys Rev Lett. **105** 247001 (2011)

The mysteries of HT_cS



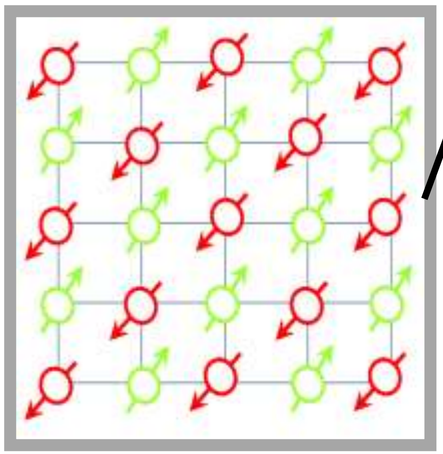
$La_{2-x}Sr_xCuO_4$ (LSCO)

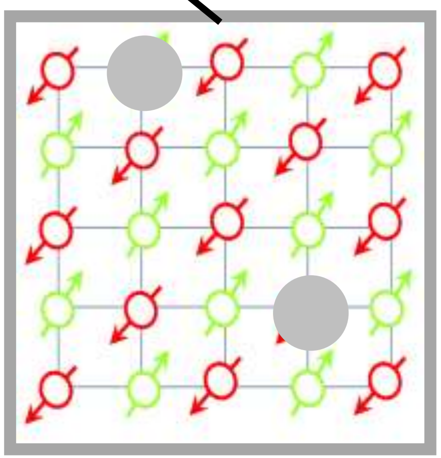


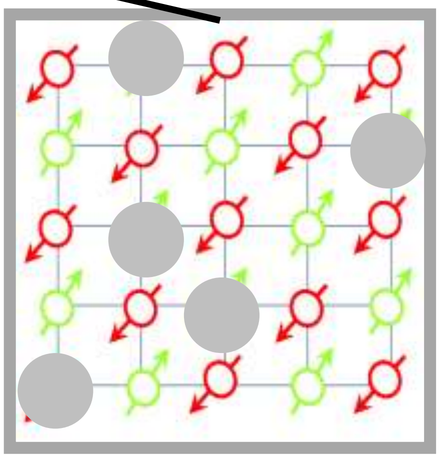


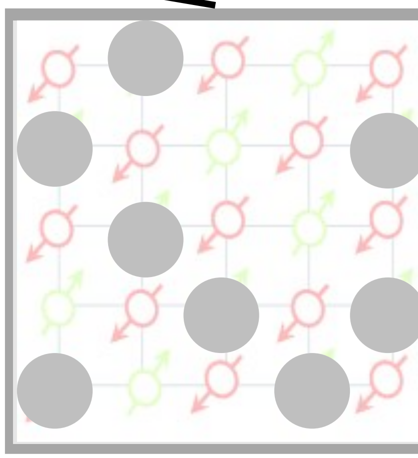
$YBa_2Cu_3O_{6+\delta}$ (YBCO)

Eduardo Fradkin and Steven A. Kivelson, Nature Physics, 8, 864 (2012)









Some questions on cuprates

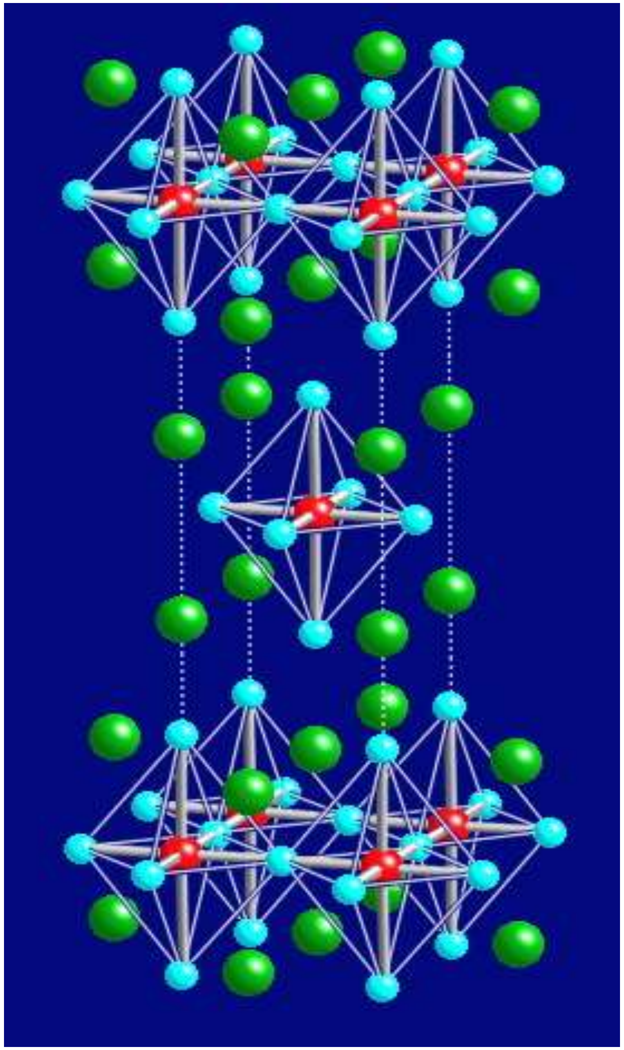
What is the role of antiferromagnetism in superconductivity?

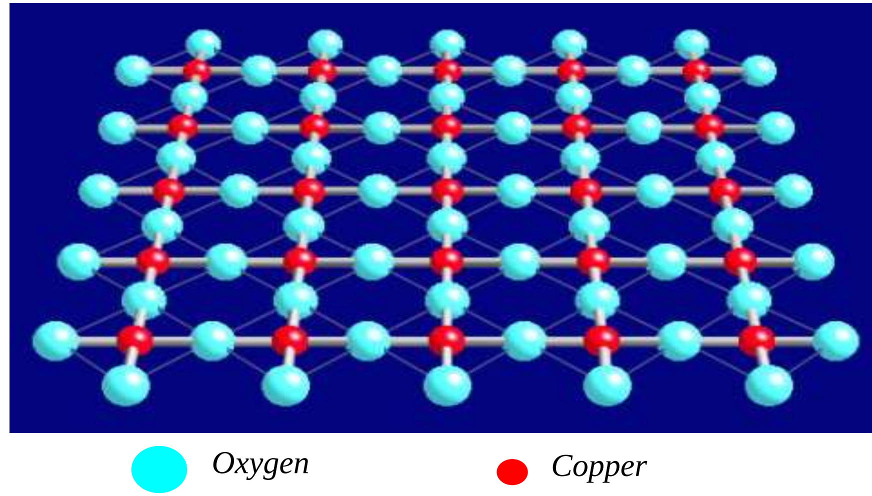
- Is AF the same in all cuprates?
- How does AF evolves with doping?

What is the role of charge order in superconductivity?

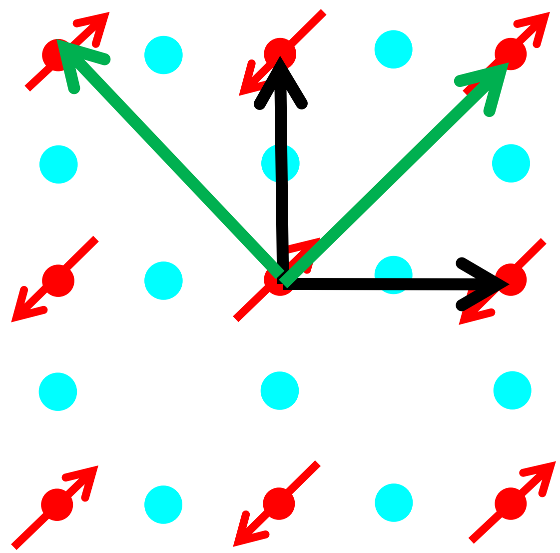
- CDW-SC: competition or collaboration?
- CDW: static or fluctuating?
- What is the between CDW and electronic structure?
- Is the pseudogap needed for CDW?

La_2CuO_4: 2D spin ½ Heisenberg AF insulator



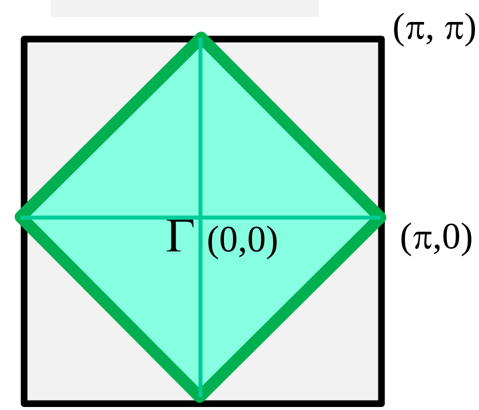


DIRECT SPACE



RECIPROCAL SPACE

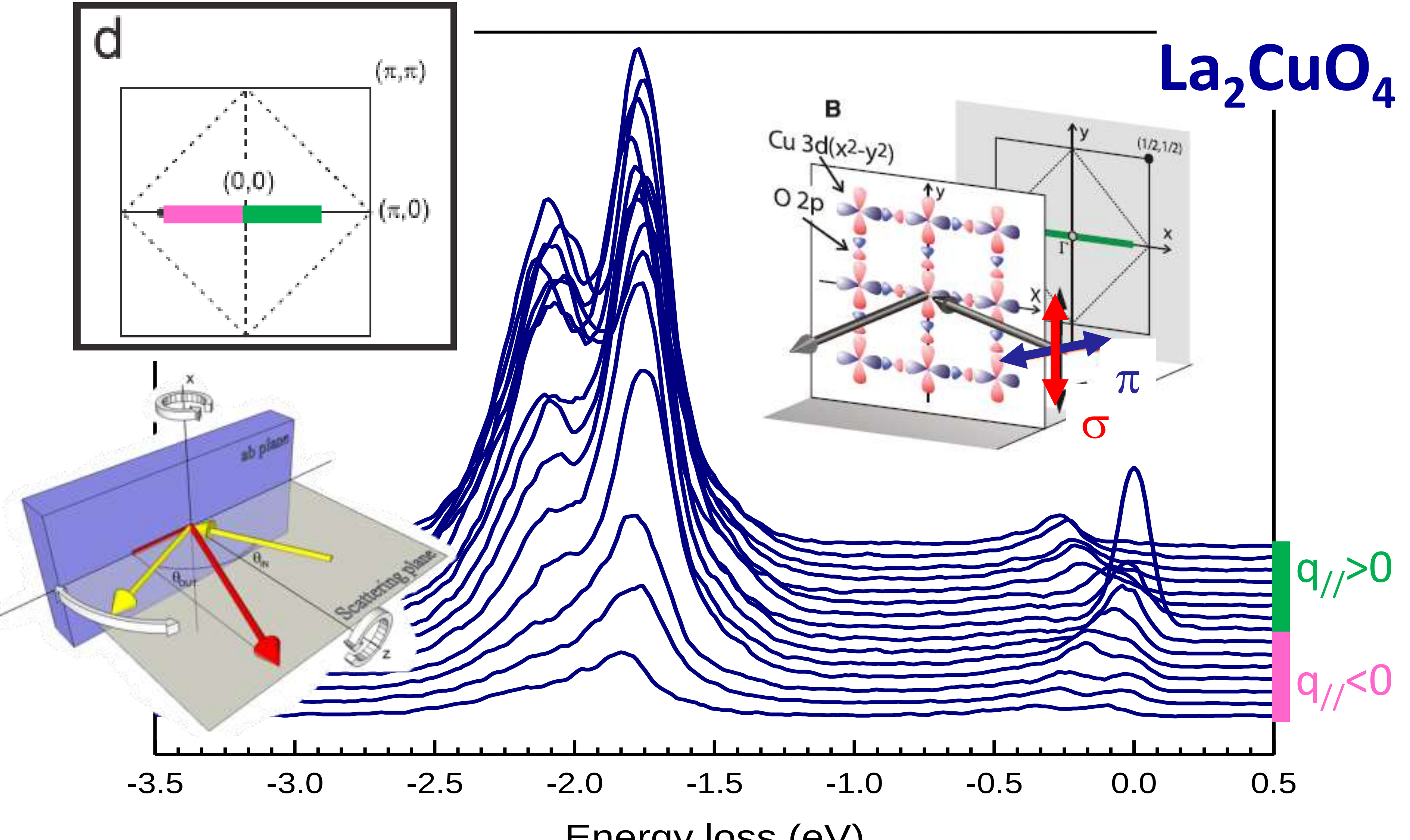
nuclear BZ



magnetic BZ

Elementary magnetic excitations are spin waves

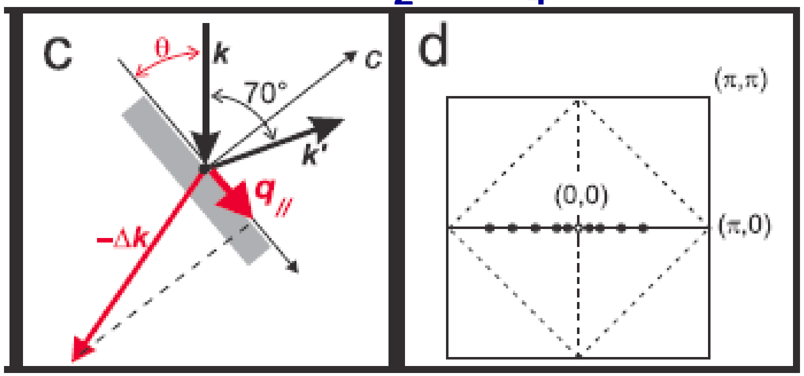
First demonstration: La_2CuO_4

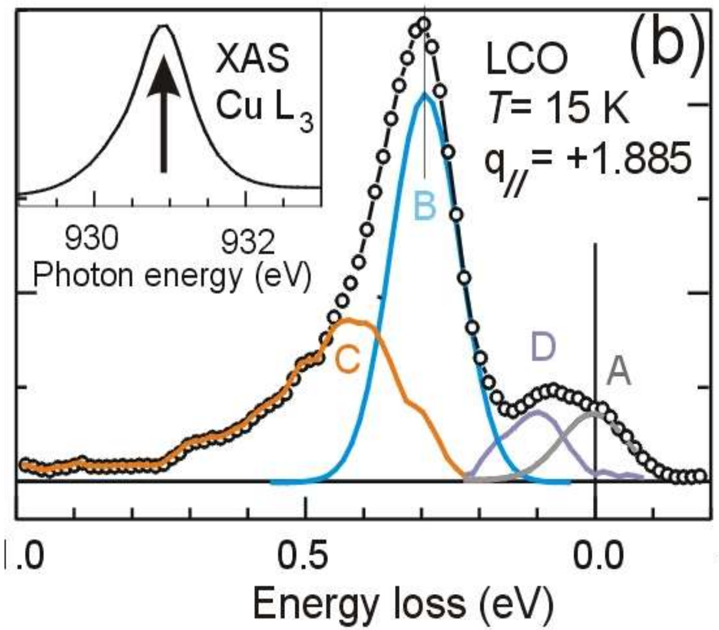


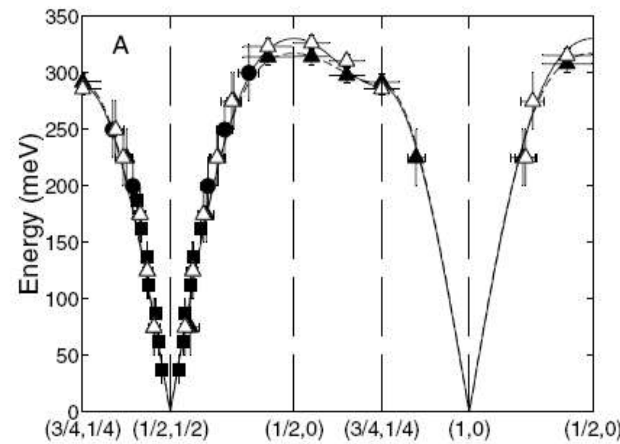
L. Braicovich, J. van den Brink, V. Bisogni, M. Moretti Sala, L. Ament, N.B. Brookes, G.M. de Luca, M. Salluzzo, T. Schmitt, and G. Ghiringhelli PRL **104** 077002 (2010)

La_2CuO_4, RIXS vs INS

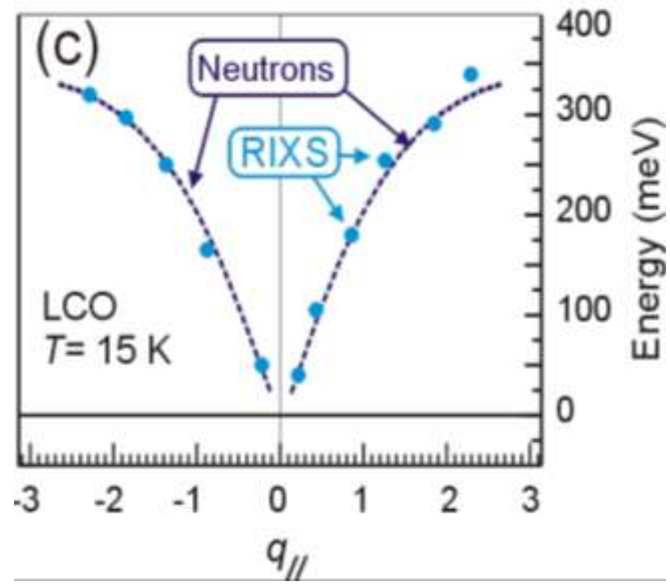
La_2CuO_4





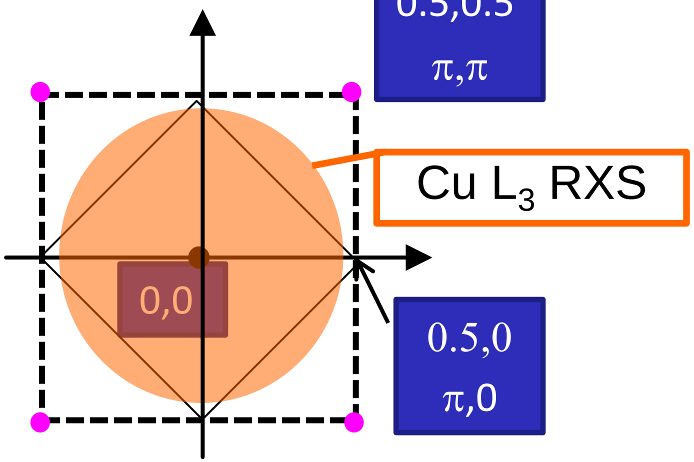


R. Coldea et al, Phys. Rev. Lett. **86**, 5377 (2001).



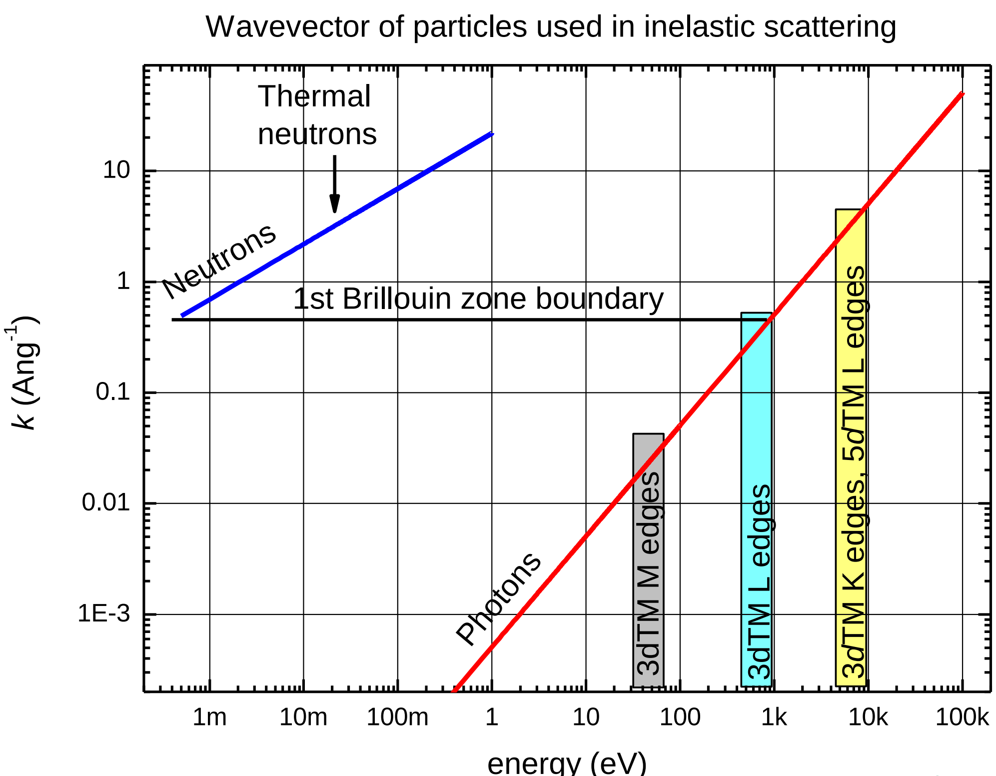
L. Braicovich, J. van den Brink, V. Bisogni, M. Moretti Sala, L. Ament, N.B. Brookes, G.M. de Luca, M. Salluzzo, T. Schmitt, and G. Ghiringhelli PRL **104** 077002 (2010)

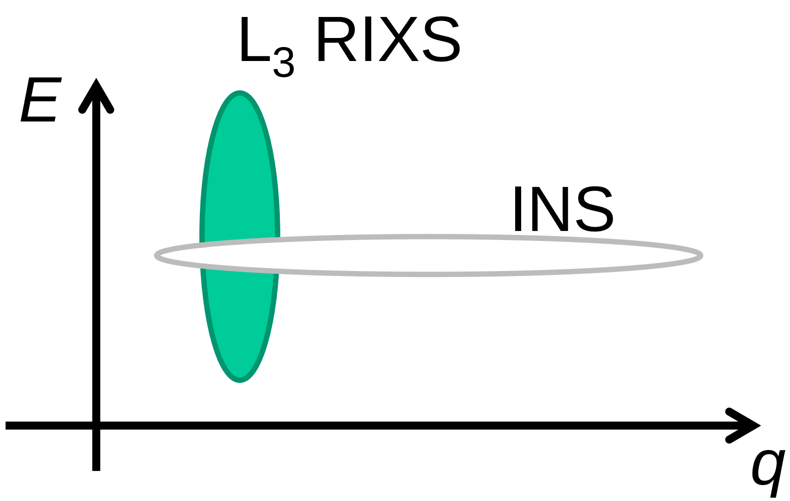
RIXS: Experimental conditions



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: 120-240 meV
- *q* resolution: 0.005 rlu
- ½ - 1 hour per spectrum



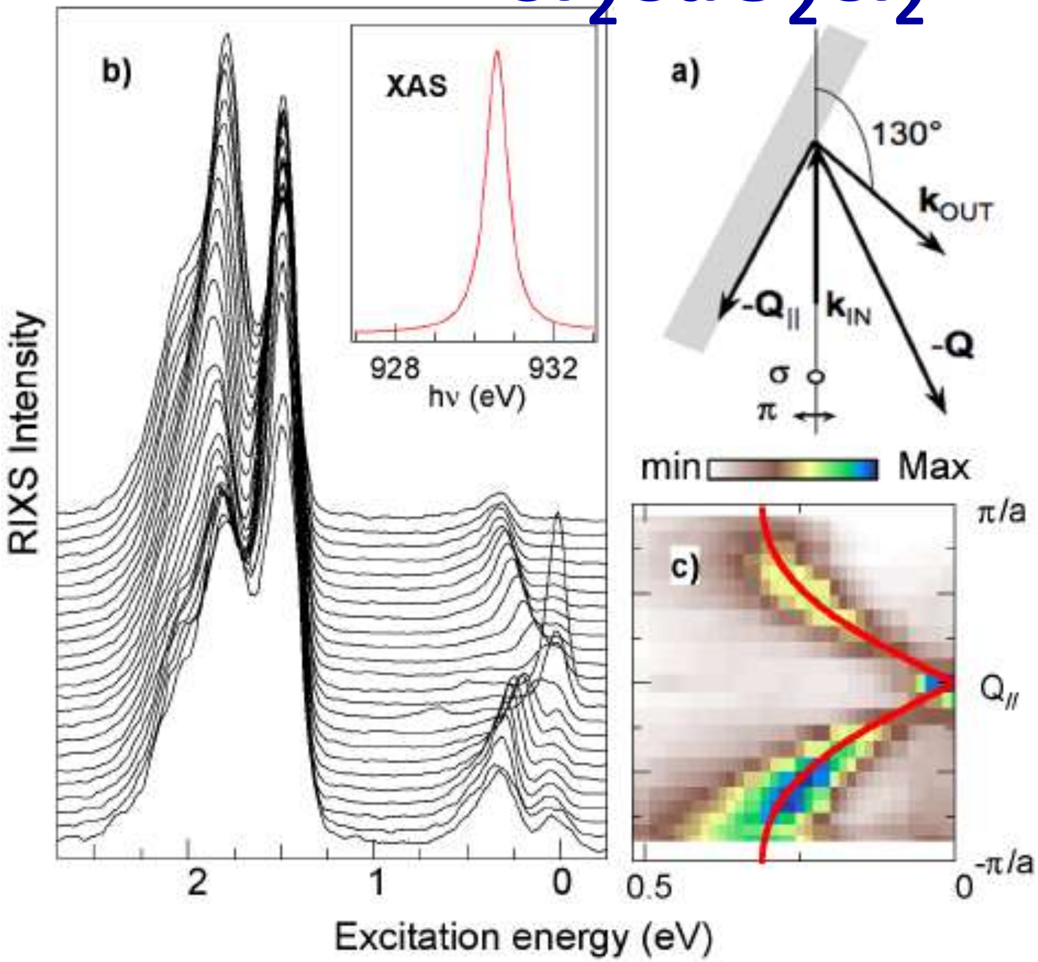


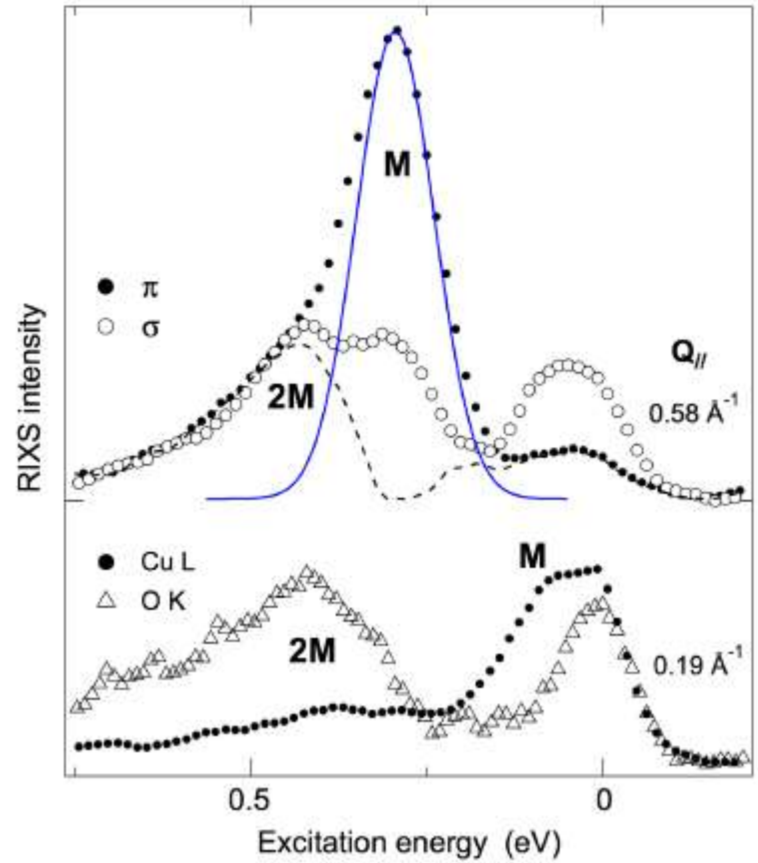
Magnetic excitations in AF cuprates

2008

$Sr_2CuO_2Cl_2$

ΔE 0.12 eV





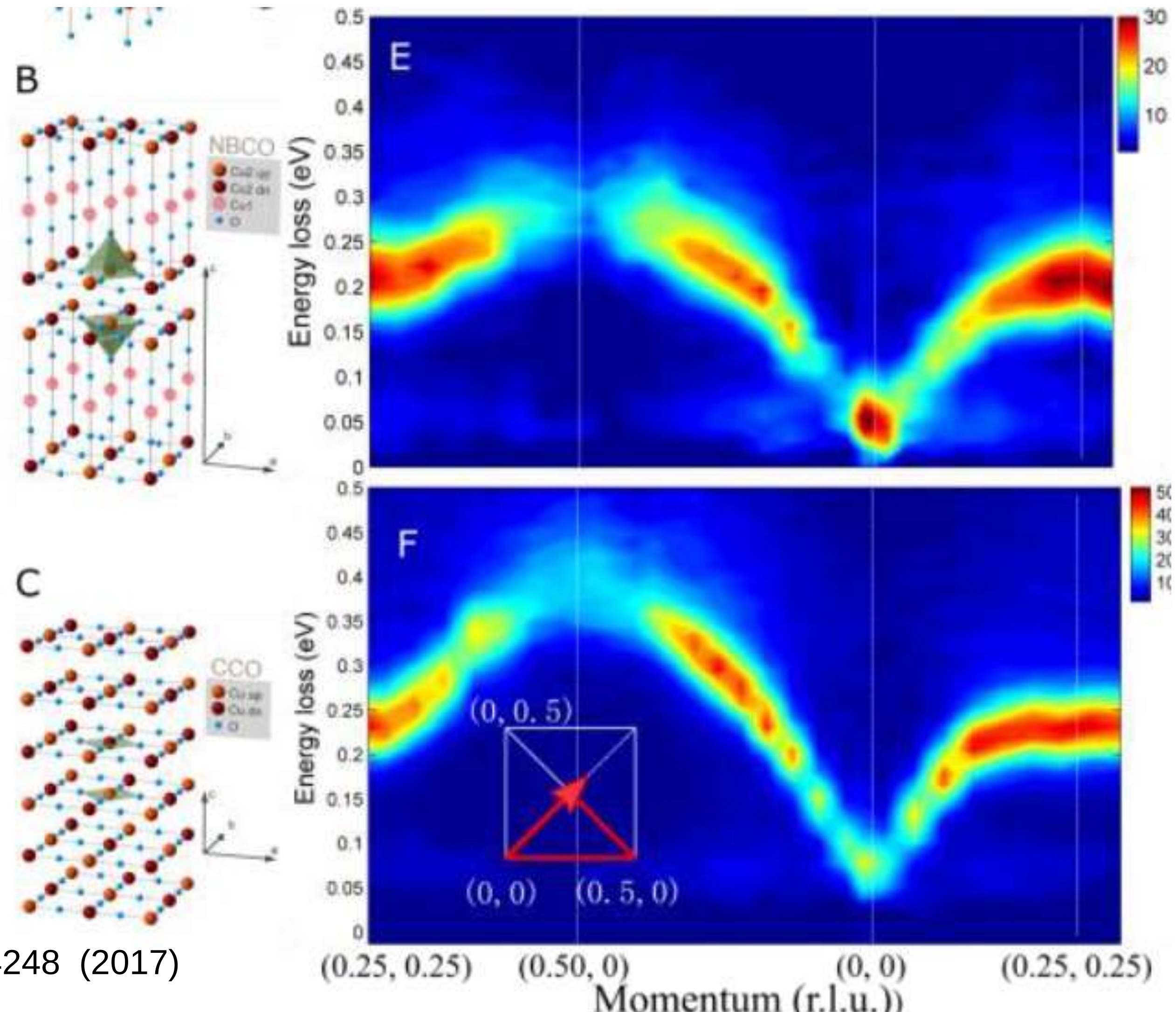
M. Guarise, B. Dalla Piazza, M. Moretti Sala, G. Ghiringhelli, L. Braicovich, H. Berger, J.N. Hancock, D. van der Marel, T. Schmitt, V.N. Strocov, L.J.P. Ament, J. van den Brink, P.-H. Lin, P. Xu, H. M. Rønnow, and M. Grioni. Phys. Rev. Lett. **105**, 157006 (2010)

ERIXS at ESRF: full maps of magnons

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

$NdBa_2Cu_3O_{6.1}$

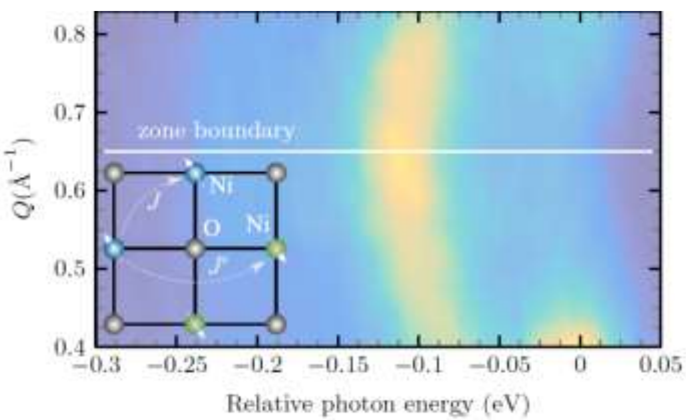
$CaCuO_2$

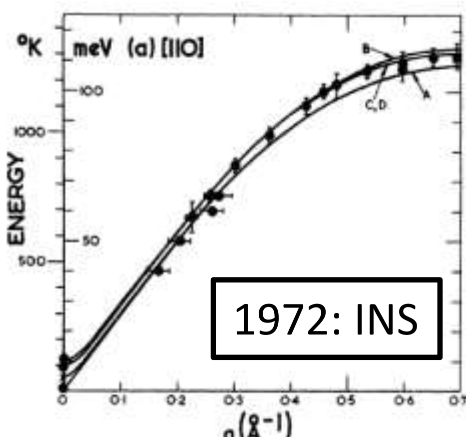


Y.Y. Peng, GG et al, Nature Physics 4248 (2017)

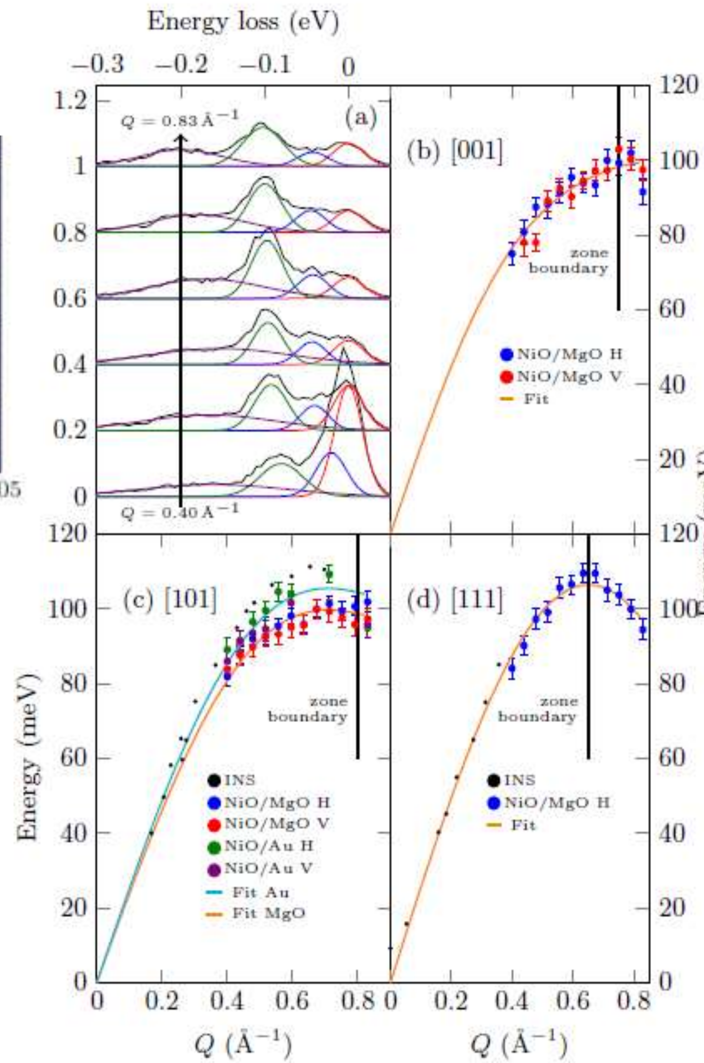
Spin-waves in NiO

Thanks to the goniometer and the scattering arm rotation we can do a real 3D scan

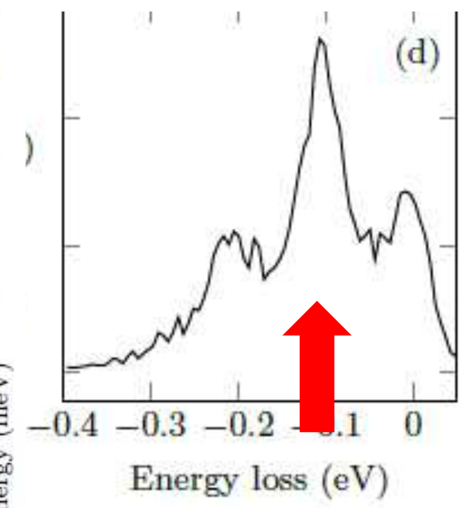




M.T. Hutchings and E.J. Samuelsen, Phys. Rev. B **6**, 3447 (1972).



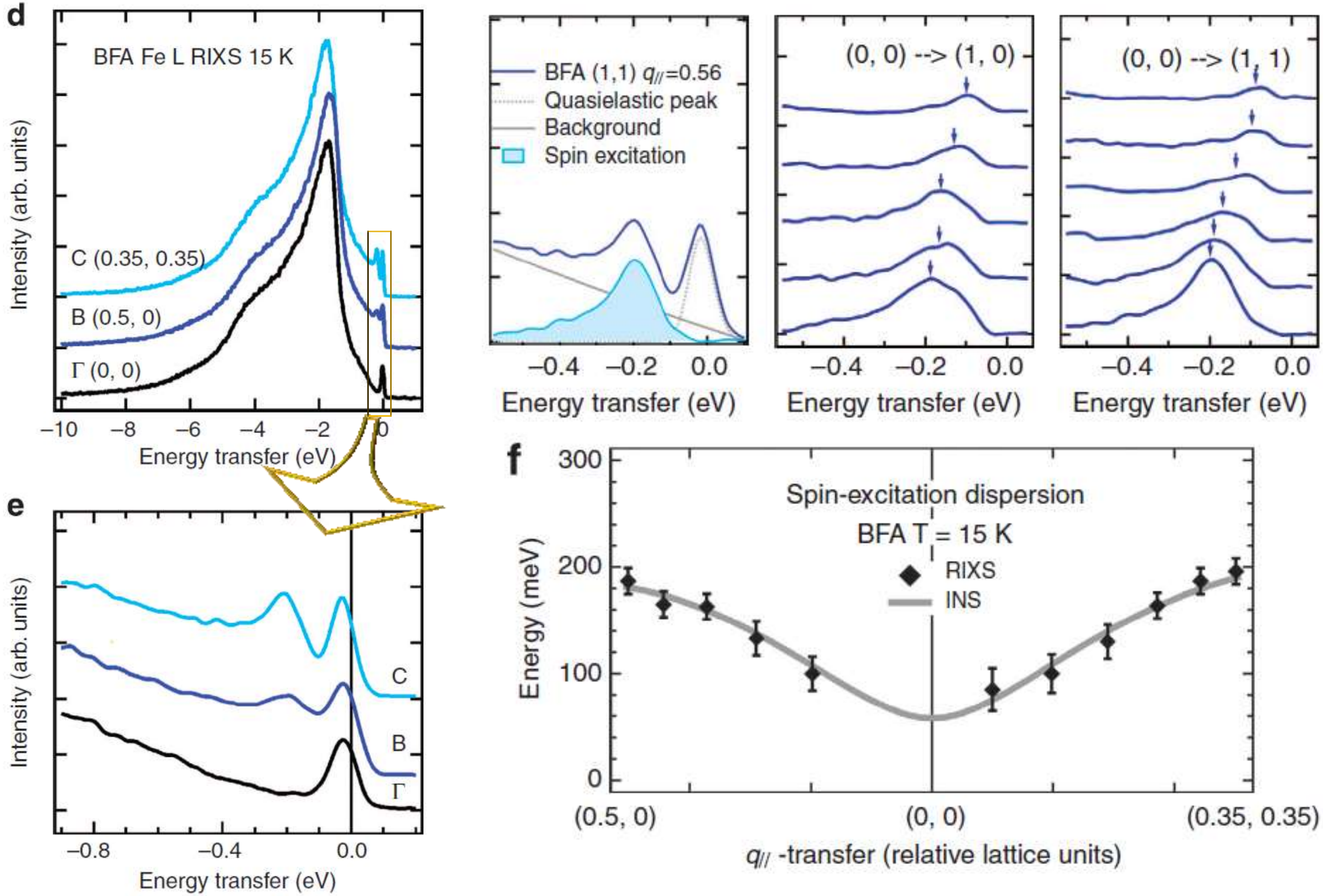
2016: RIXS (ESRF)



40 meV resolution

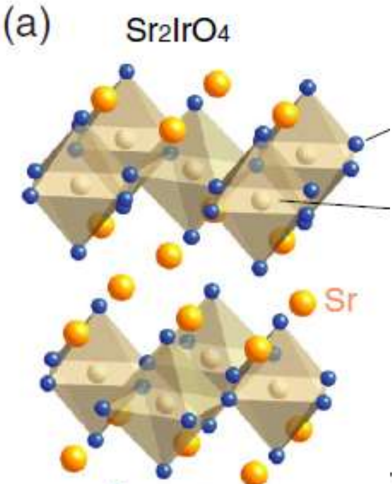
D. Betto, Y. Y. Peng, S. B. Porter, G. Berti, A. Calloni, G. Ghiringhelli, and N.B. Brookes, Phys Rev B **96** 020409 (2017)

Magnons at Fe L_3 edge in $BaFe_2As_2$



Ke-Jin Zhou, Yao-Bo Huang, Claude Monney, Xi Dai, Vladimir N. Strocov, Nan-Lin Wang, Zhi-Guo Chen, Chenglin Zhang, Pengcheng Dai, Luc Patthey, Jeroen van den Brink, Hong Ding & Thorsten Schmitt, Nature Comm. **4**, 1470 (2013)

Magnetic and orbital excitations in Sr_2IrO_4



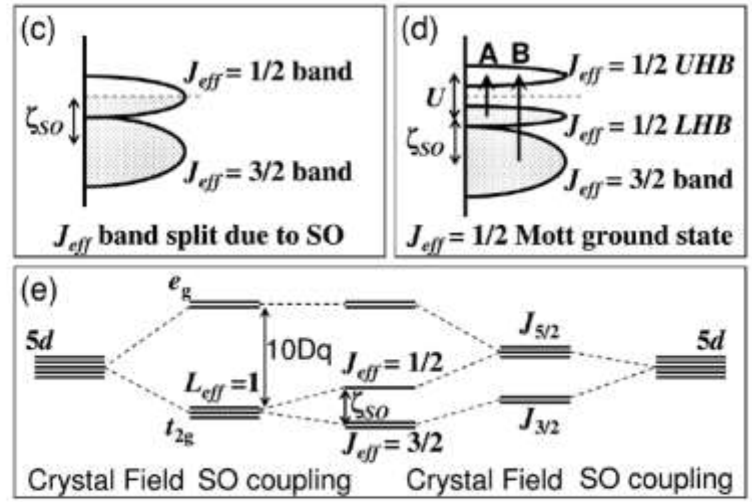
Ir^{4+}

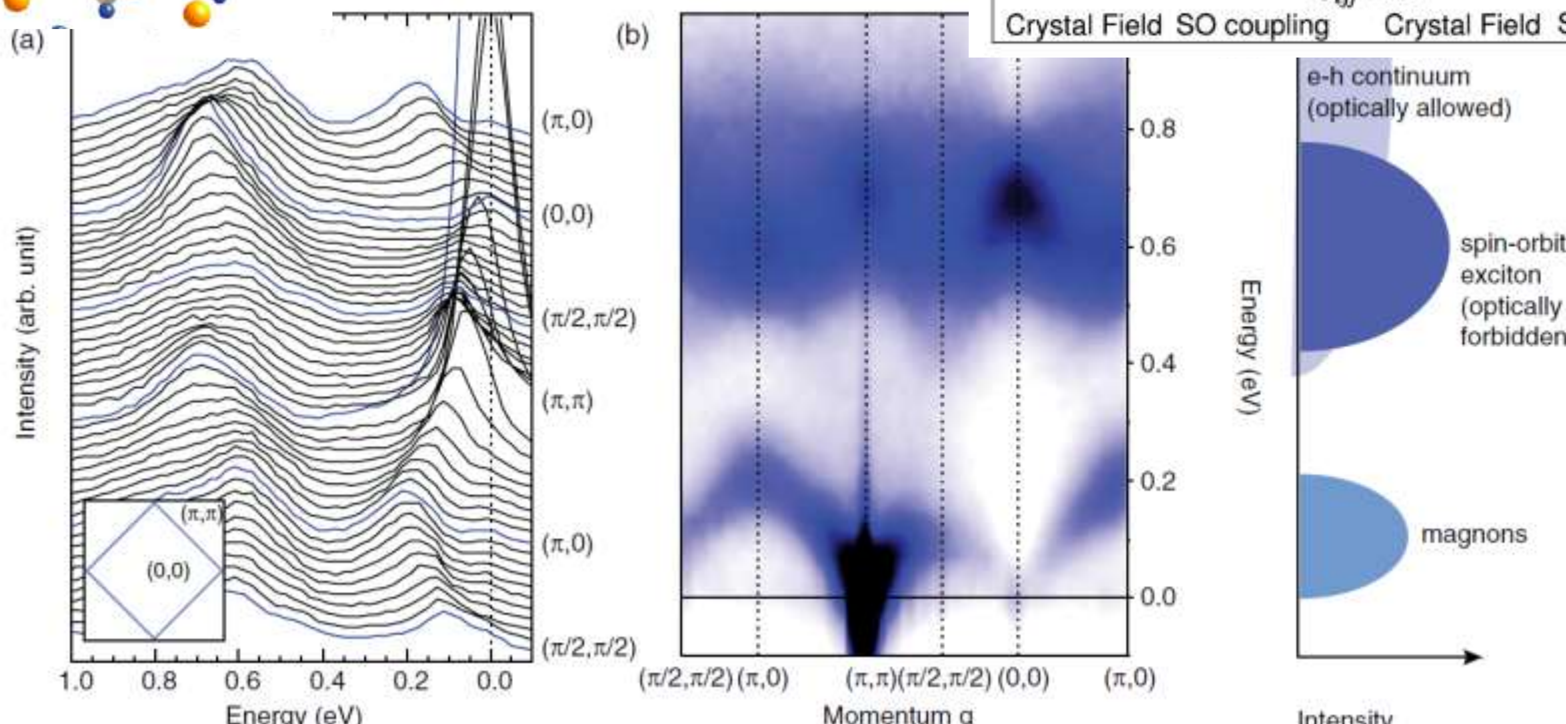
$5d^5$ ⇨

Strong spin-orbit in the 5*d*

$(\zeta_{SO} \sim 0.4$ eV

L_3 at 11.2 keV





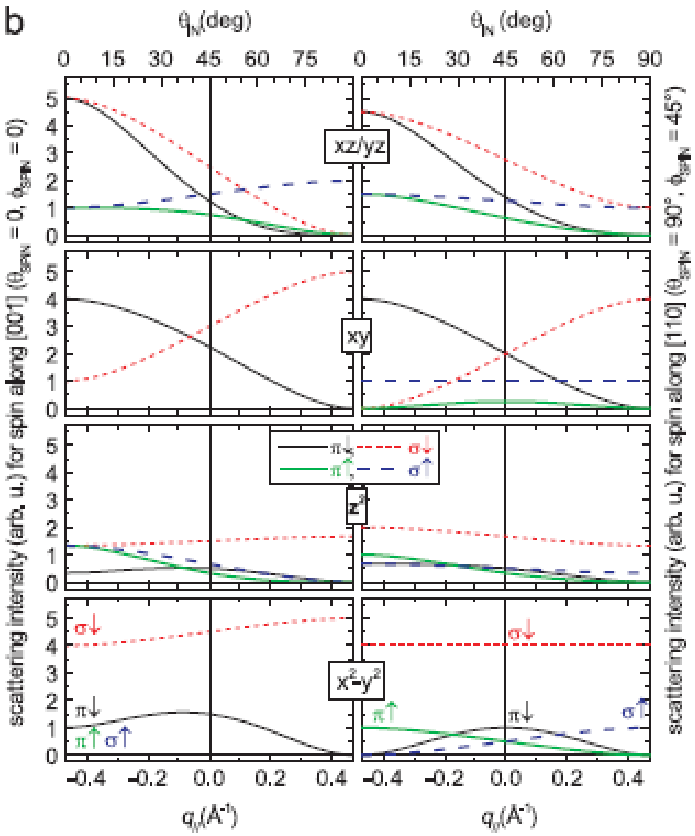
Jungho Kim, D. Casa, M. H. Upton, T. Gog, Young-June Kim, J. F. Mitchell, M. van Veenendaal, M. Daghofer, J. van den Brink, G. Khaliullin, and B. J. Kim, Phys. Rev. Lett. **108**, 177003 (2012)

Theory of magnetic RIXS (1)

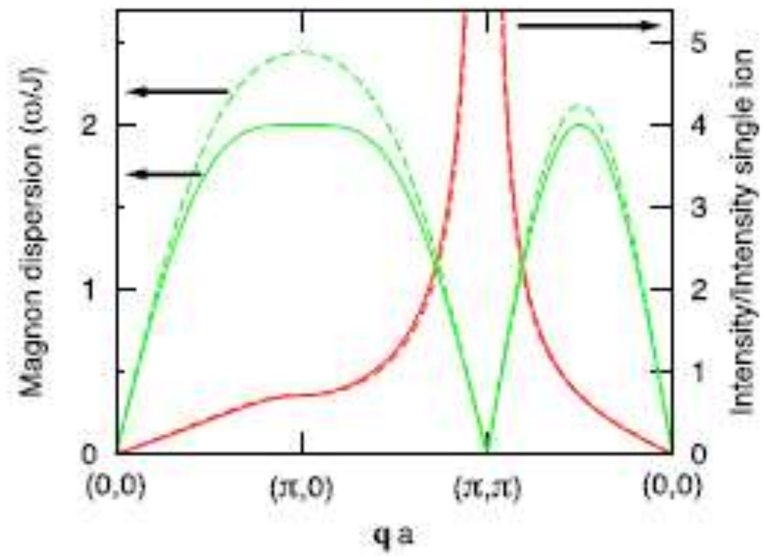
PRL 103, 117003 (2009) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2009

Theoretical Demonstration of How the Dispersion of Magnetic Excitations in Cuprate Compounds can be Determined Using Resonant Inelastic X-Ray Scattering

Luuk J.P. Ament,[1,4] Giacomo Ghiringhelli,[2] Marco Moretti Sala,[2] Lucio Braicovich,[2] and Jeroen van den Brink[1,3,4]



Single ion cross section



Linear spin wave theory

Theory of magnetic RIXS (2)

PRL 105, 167404 (2010) PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2010

Theory of Resonant Inelastic X-Ray Scattering by Collective Magnetic Excitations

M. W. Haverkort

Max Planck Institute for Solid State Research, Heisenbergstraße 1, D-70569 Stuttgart Germany

(Received 9 October 2009; published 15 October 2010)

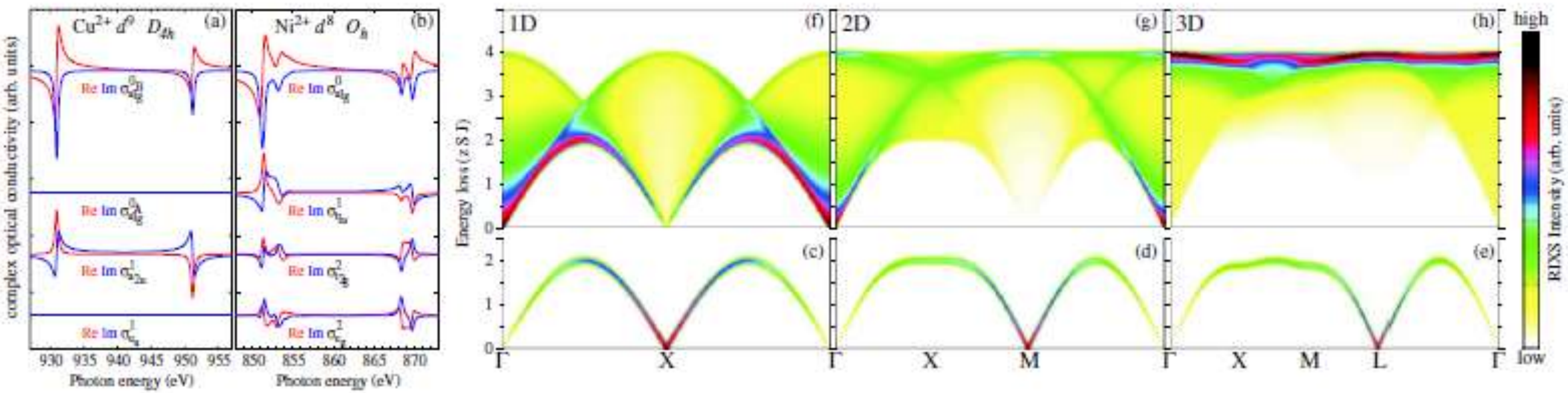
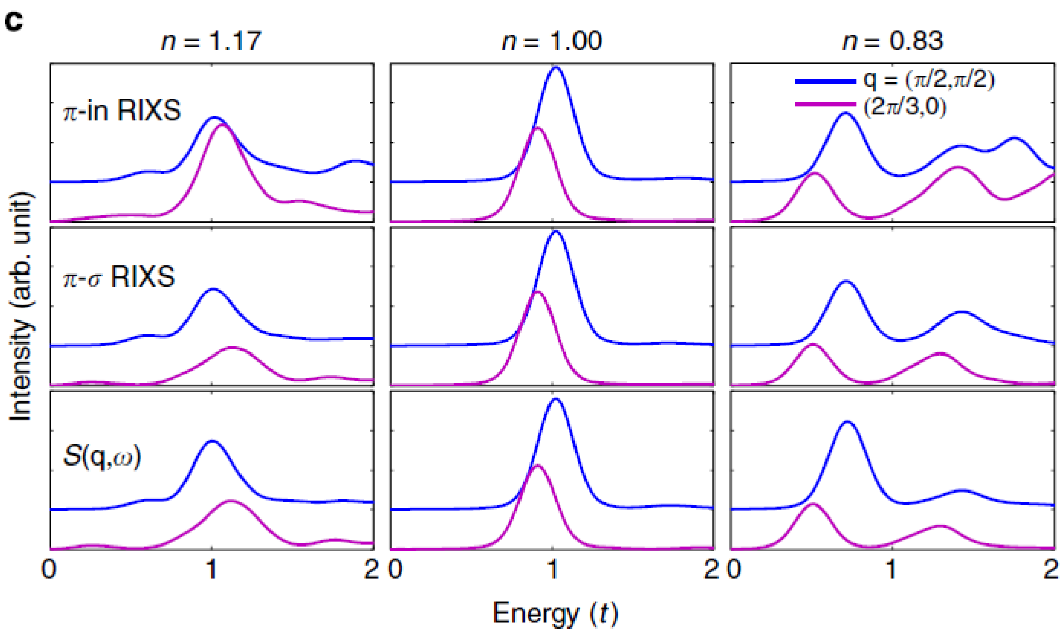


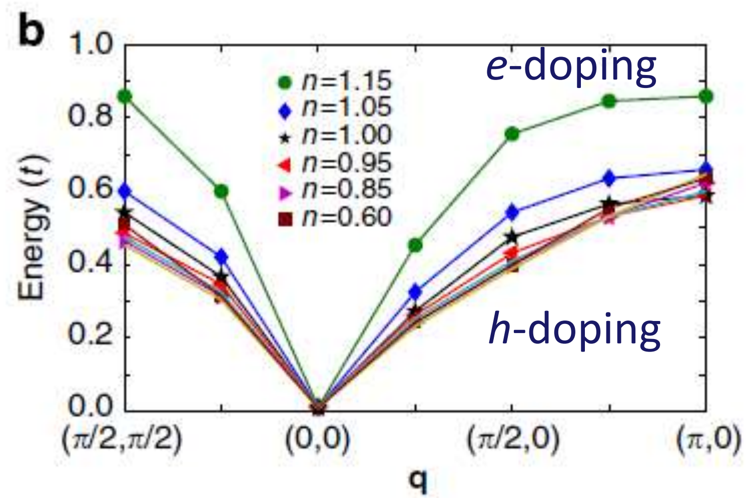
FIG. 1 (color online). Left: Fundamental x-ray absorption spectra that enter into the RIXS transition operator as energy dependent complex matrix elements calculated for (a) Cu^{2+} and (b) Ni^{2+}. Right: The Cu^{2+} and Ni^{2+} one magnon (c)–(e) and Ni^{2+} two magnon (f)–(h) RIXS spectral function, calculated using linear spin-wave theory for a 1D chain (c),(f), a 2D square (d),(g), and a 3D cubic (e),(h) Heisenberg model in energy loss units of zSJ (number of neighbors × spin × exchange constant).

Theory of magnetic RIXS (3)

What is the relation between RIXS and $S(\mathbf{q},\omega)$?



$S(\mathbf{q},\omega)$ vs p

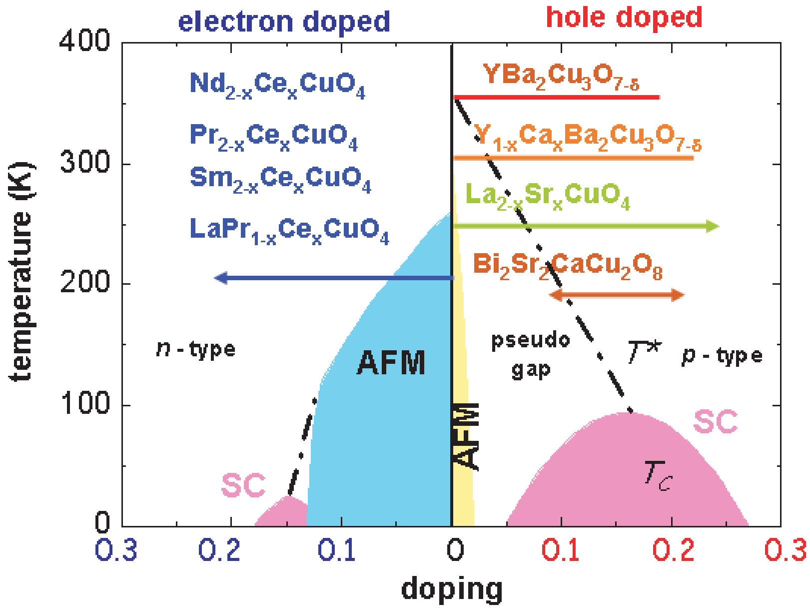


RIXS measures $S(\mathbf{q},\omega)$ quite well

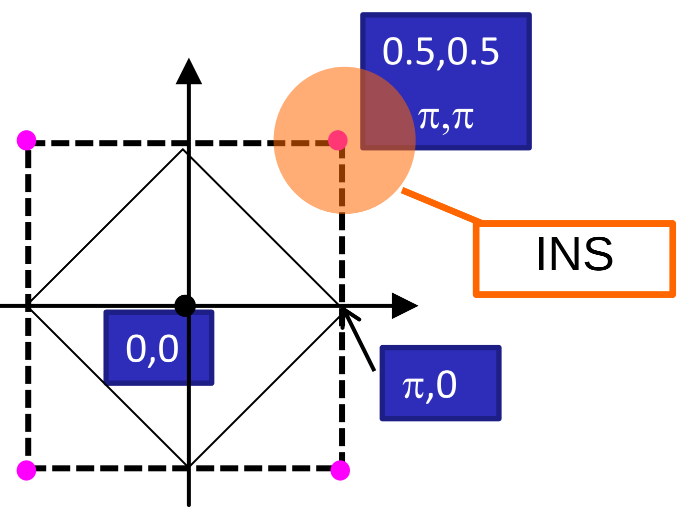
Spin excitations harden with *e*-doping, and change very little with *h*-doping.

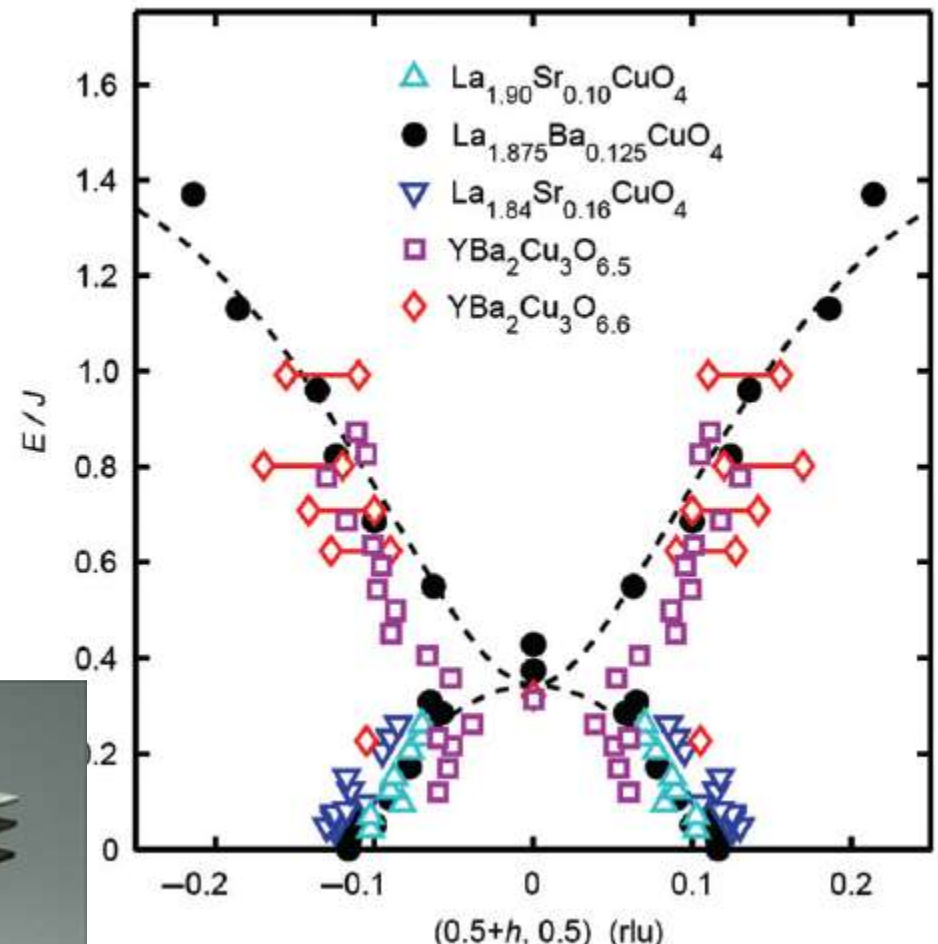
C.J. Jia, E.A. Nowadnick, K. Wohlfeld, Y.F. Kung, C.-C. Chen, S. Johnston, T. Tohyama, B. Moritz & T.P. Devereaux, NATURE COMMUNICATIONS , 5:3314 (2014)

Spin excitations in HTcS: doped SC



http://for538.wmi.badw.de/projects/P4_crystal_growth/index.htm



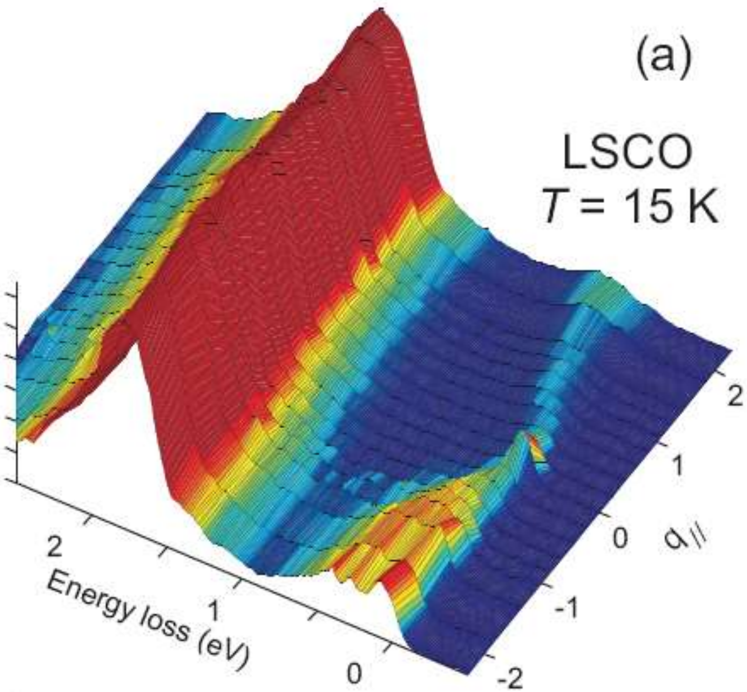


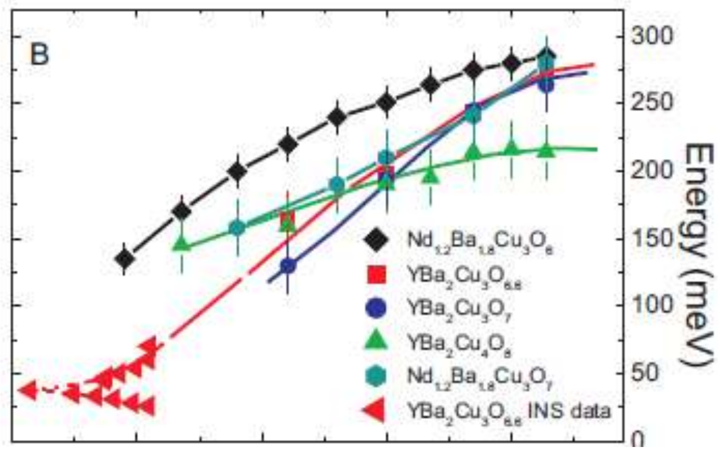
J.M. Tranquada, in *Handbook of High-Temperature Superconductivity: Theory and Experiment*, J.R. Schrieffer and J.S. Brooks, eds., Springer, 2007,

V. Hinkov et al, Eur. Phys. J. Special Topics 188, 113–129 (2010)

What happens in doped, SC cuprates? Paramagnons

Interestingly RIXS has demonstrated that short range AF correlation remains very strong even in doped, superconducting cuprates.



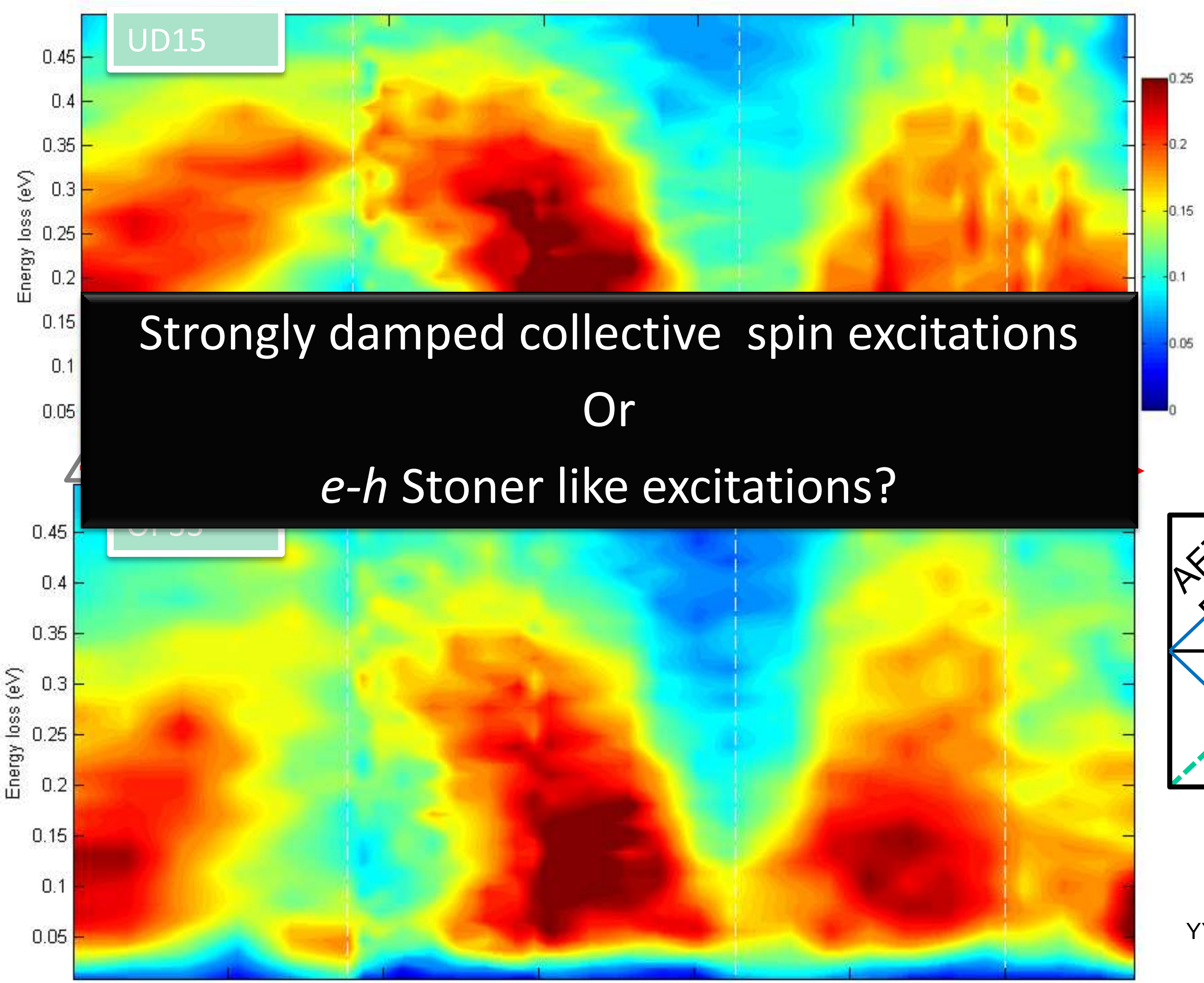


This observation makes **spin fluctuations** the best candidate for **Cooper**

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)

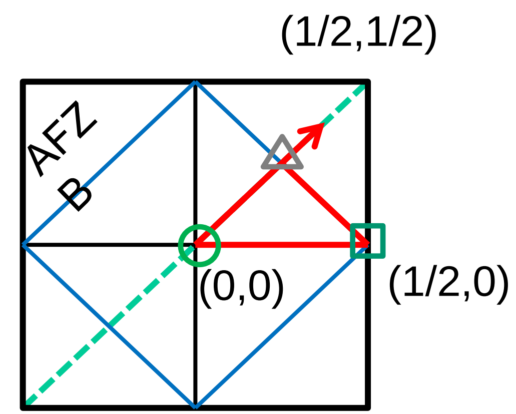
Paramagnons in Bi2201



Strongly damped collective spin excitations

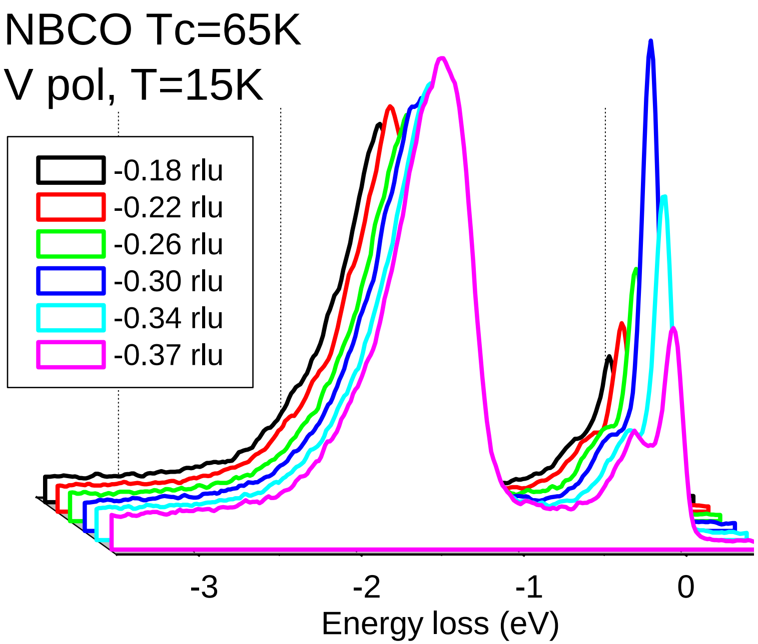
Or

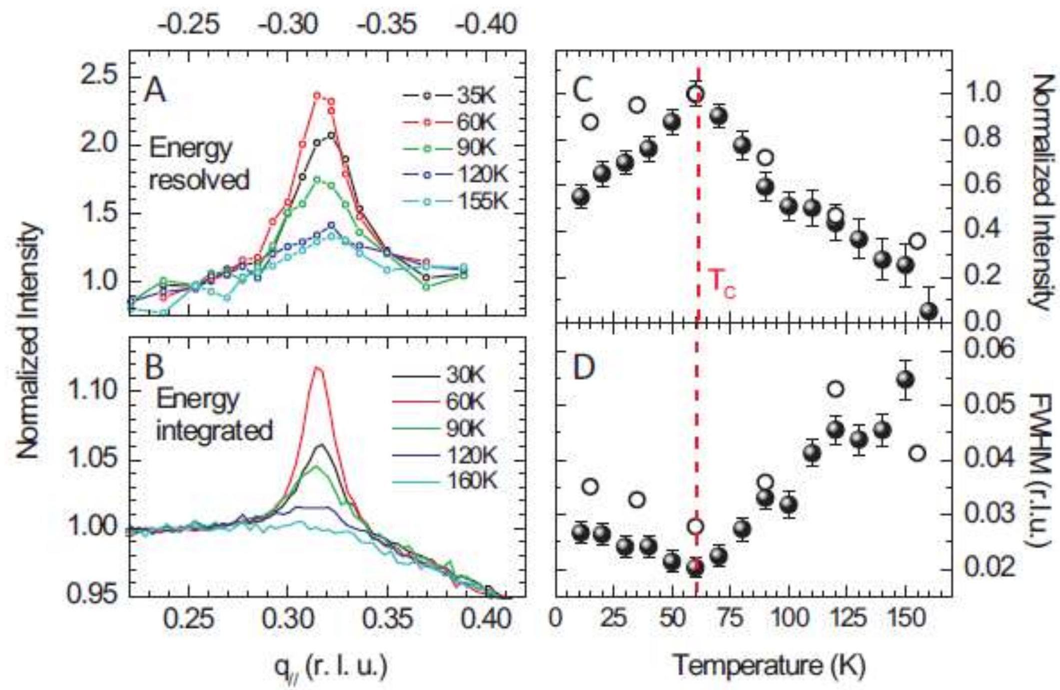
e-h Stoner like excitations?



YY. Peng, GG et al, unpublished

RIXS revealed Charge Order in HTcS





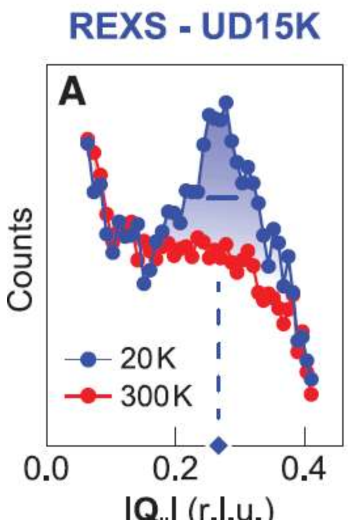
Max intensity at Tc: CO compete with SC

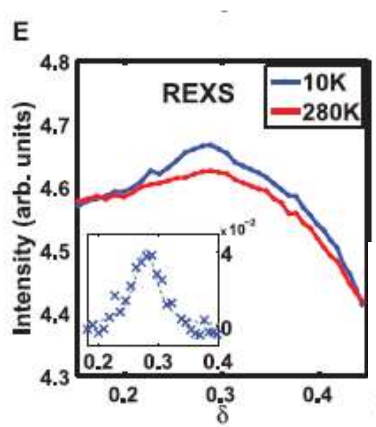
G. Ghiringhelli, M. Le Tacon, M. Minola, S. Blanco-Canosa, C. Mazzoli, N.B. Brookes, G.M. De Luca, A. Frano, D. G. Hawthorn, F. He, T. Loew, M. Moretti Sala, D.C. Peets, M. Salluzzo, E. Schierle, R. Sutarto, G. A. Sawatzky, E. Weschke, B. Keimer, L. Braicovich, Science **337**, 821 (2012)

RXS (at Cu L_3 and O K) in combination with STM, XRD and NMR has demonstrated that CO is ubiquitous in cuprates

UD Bi2201, Bi2212, Hg1201 and OPD Bi2212

Bi2201 and Bi2212 underdoped

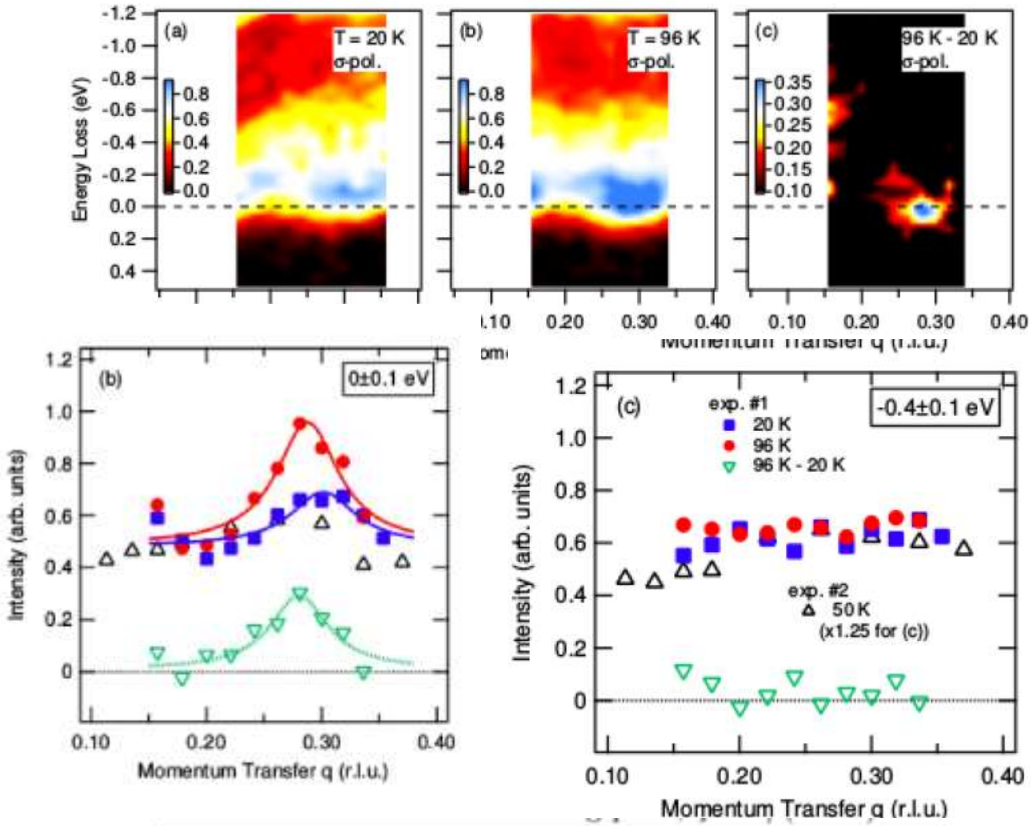




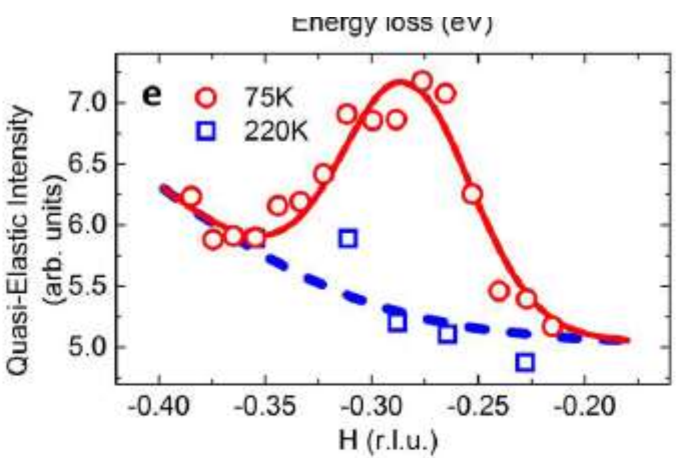
R. Comin et al, Science 343, 390 (2014;

Eduardo H. da Silva Neto et al, Science 343, 393 (2014

Bi2212 optimally doped



Hg1201 underdoped



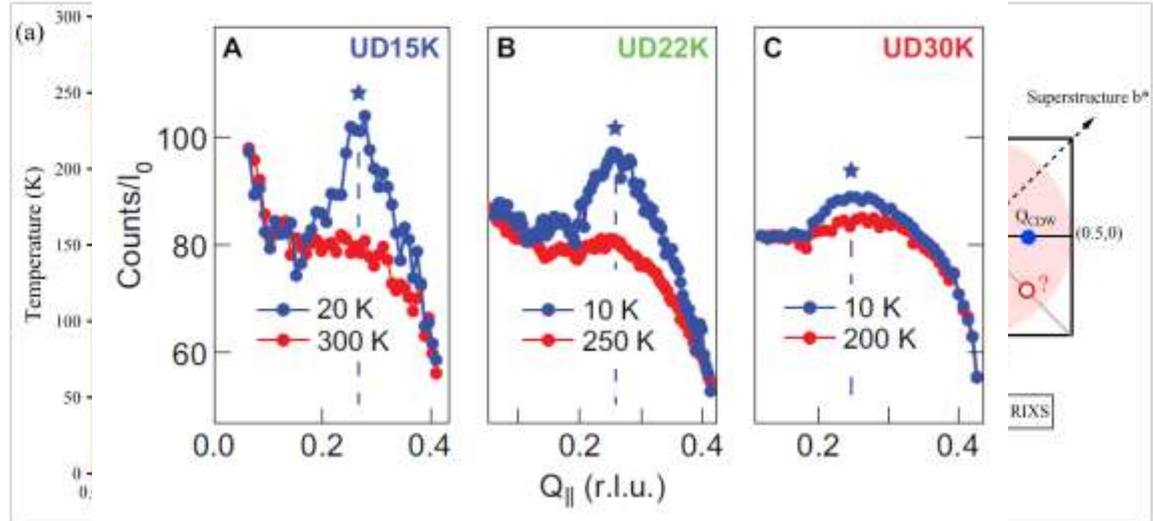
Sample	p	T_c	$q_{\parallel}$ (r.l.u.)	ξ (Å)	refs.
Bi2201	0.115	15	0.265	26	[16]
Bi2201	0.130	22	0.257	23	[16]
Bi2201	0.145	30	0.243	21	[16]
Bi2212	0.09	45	0.30	24	[15]
Bi2212	0.160	98	0.28	<24 (at T_c)	this work
YBCO	0.115	61	0.32	~60 (at T_c)	[8, 10]
LBCO	0.125	2.5	0.236	~200	[4, 6–8]
LBCO	0.155	30	0.244	~240 (15 – 25 K)	[4, 6–8]

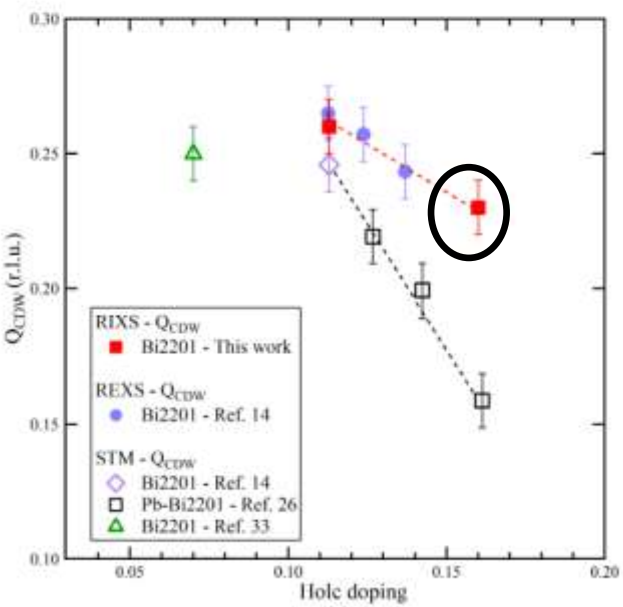
W. Tabis et al, Nat. Comm. 6875 (2014)

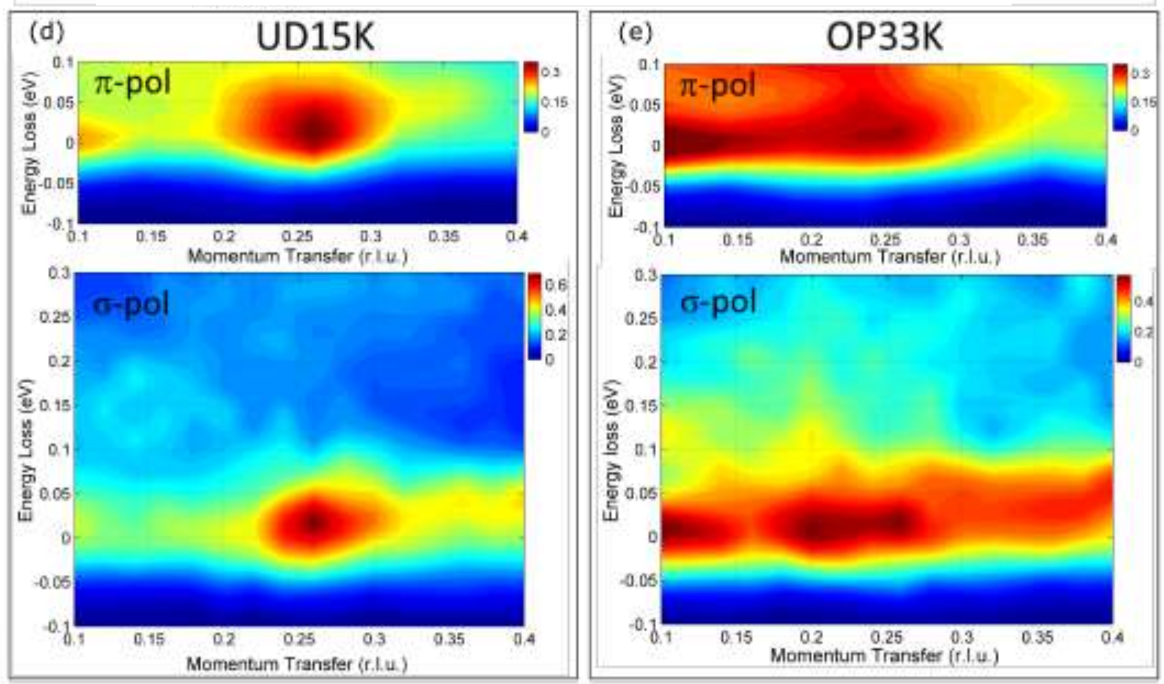
M. Hashimoto, G. Ghiringhelli et al, PRB 89 220511 (2014)

CDW measured with ERIXS at ID32

Higher sensitivity reveals CDW in optimally doped Bi2201



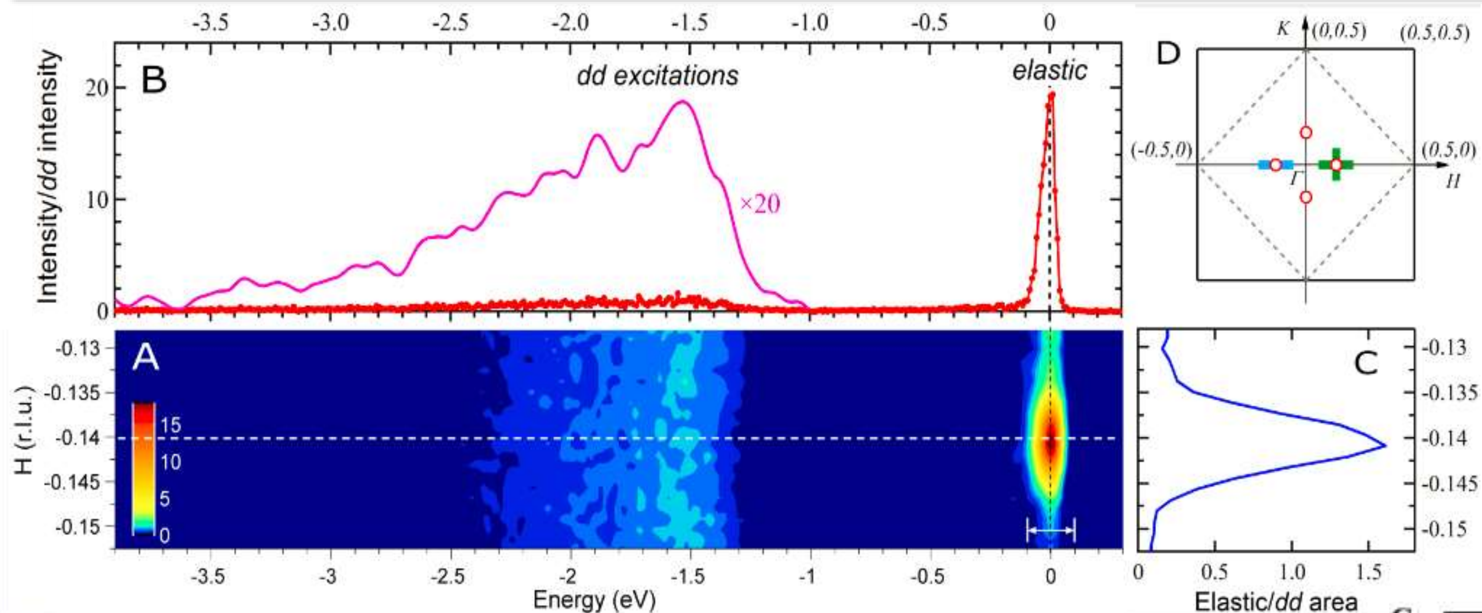




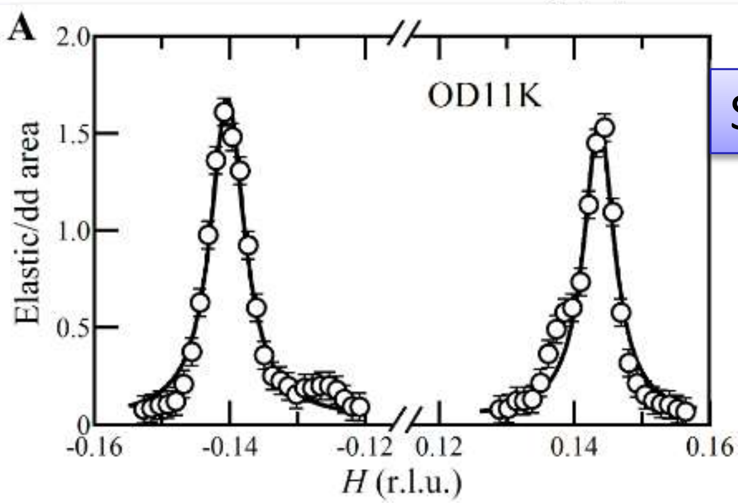
YY. Peng, GG et al, Phys. Rev. B **94,**184511 (2016)

Overdoped $(Bi,Pb)_{2.12}Sr_{1.88}CuO_{6+\delta}$

Unexpected observation of a very intense and sharp peak in pseudo-tetragonal (1,0) direction

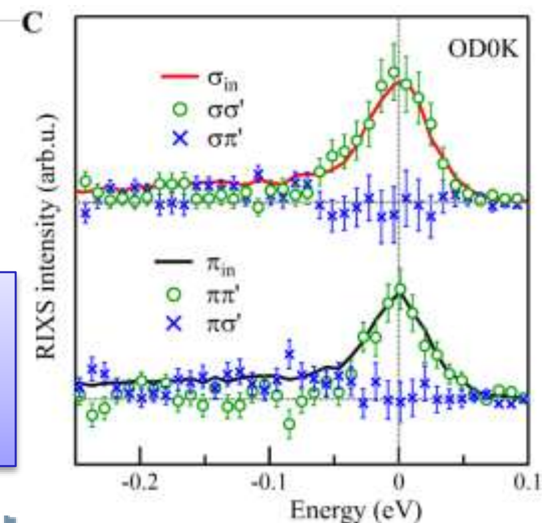


OD11K (T_c=11 K, p~0.215), Cu L_3 edge RIXS, measured at T=20K

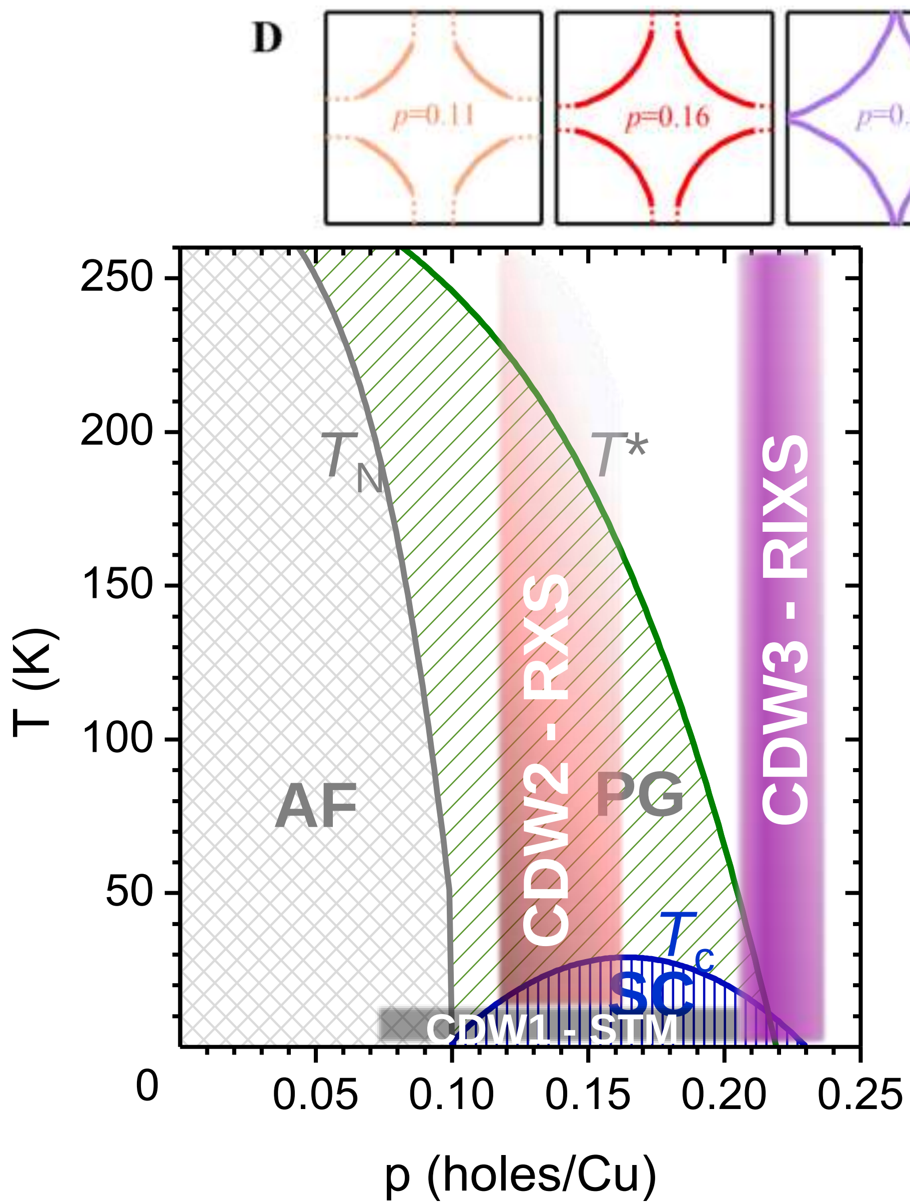


Symmetric w/r to Γ

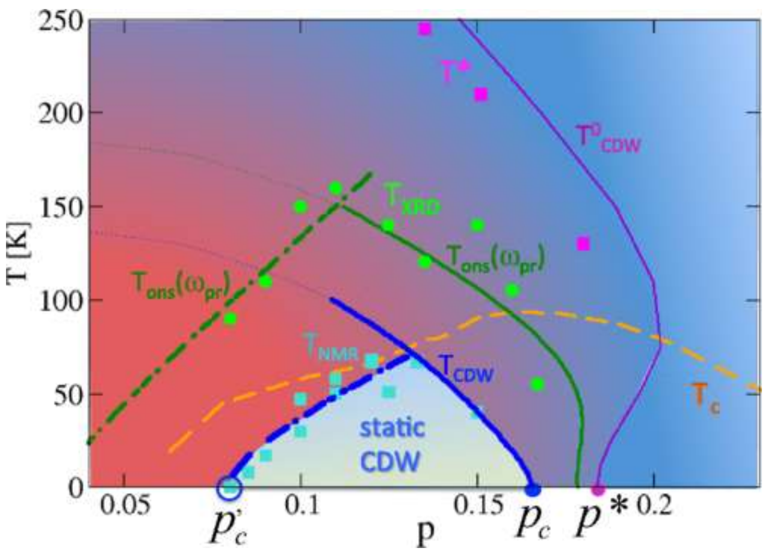
Pure charge character (no spin)



Revising the CDW landscape



The fluctuating CDW scenario seems compatible with this discovery



Y. Y. Peng, R. Fumagalli, Y. Ding, M. Minola, S. Caprara, D. Betto, G. M. De Luca, K. Kummer, E. Lefrançois, M. Salluzzo, H. Suzuki, M. Le Tacon, X. J. Zhou, N. B. Brookes, B. Keimer, L. Braicovich ,M. Grilli, G. Ghiringhelli, arXiv:1705.06165 (2017).

ENERGY RESOLUTION: progress in the last 20 years

La_2CuO_4
Cu 2*p* → 3*d*
Photon energy ~ 931 eV

Δ*E* ~1.6 eV

K. Ichikawa *et al.*, J. Electron Spectrosc. Relat. Phenom.**78**, 183 (1996).

Δ*E* ~1.2 eV

L. C. Duda *et al.*, J. Electron Spectrosc. Relat. Phenom. **110–111**, 275 (2000).

Δ*E* ~0.8 eV

AXES @ ID08, 2003. G. Ghiringhelli *et al.*, Phys Rev Lett. **92**, 117406 (2004).

Δ*E* ~0.45 eV

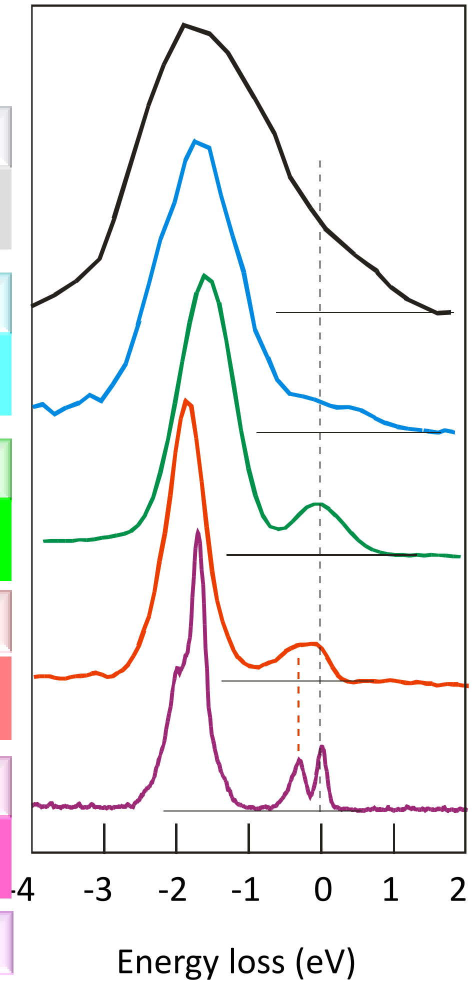
AXES @ ID08, 2007. L. Braicovich *et al.*, arXiv:0807:1140v1, (2008).

Δ*E* ~0.13 eV

SAXES @ SLS, 2008. G. Ghiringhelli, L. Braicovich, T. Schmit *et al.*, unpublished

Δ*E* ~0.050 eV

Δ*E* ~0.030 eV



2000 Uppsala

2003
2007 ESRF + AXES

2008 SLS + SAXES

2015
2016 ESRF + ERIXS

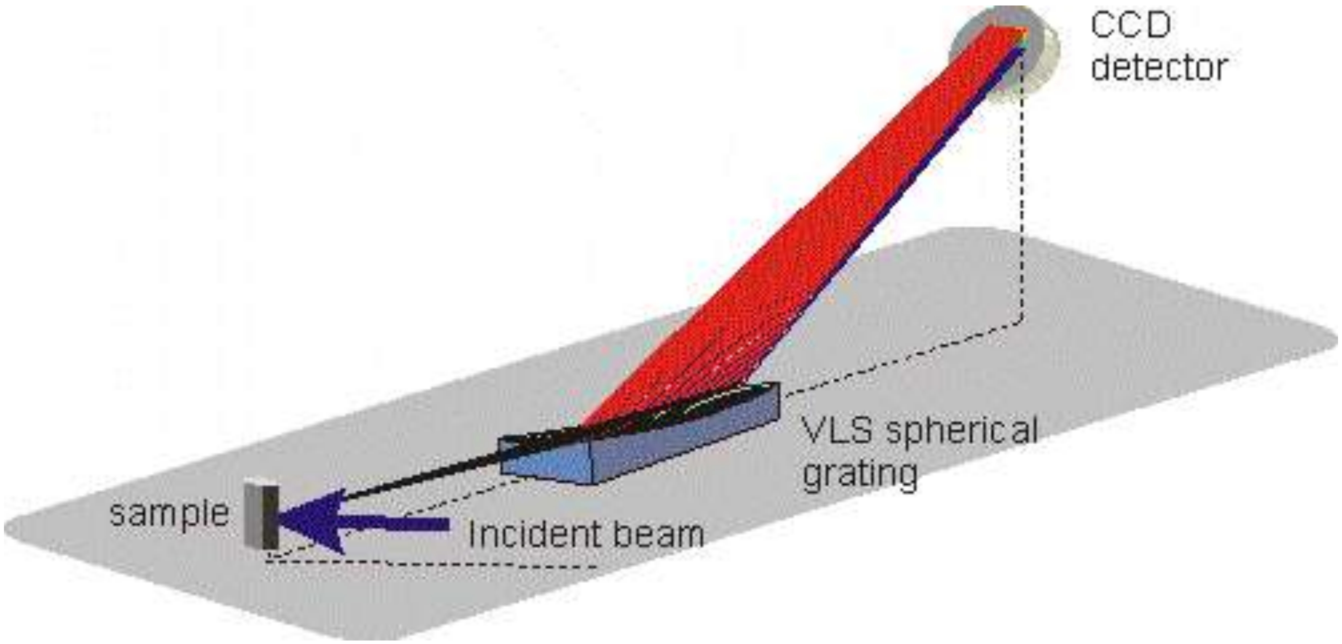
Combined resolving power has increased by a factor 30

Soft x-ray RIXS instrumentation

High resolution mono, small x-ray spot on the sample

Grating spectrometer: optimized efficiency, high resolution

The main limiting factor is INTENSITY!!!!



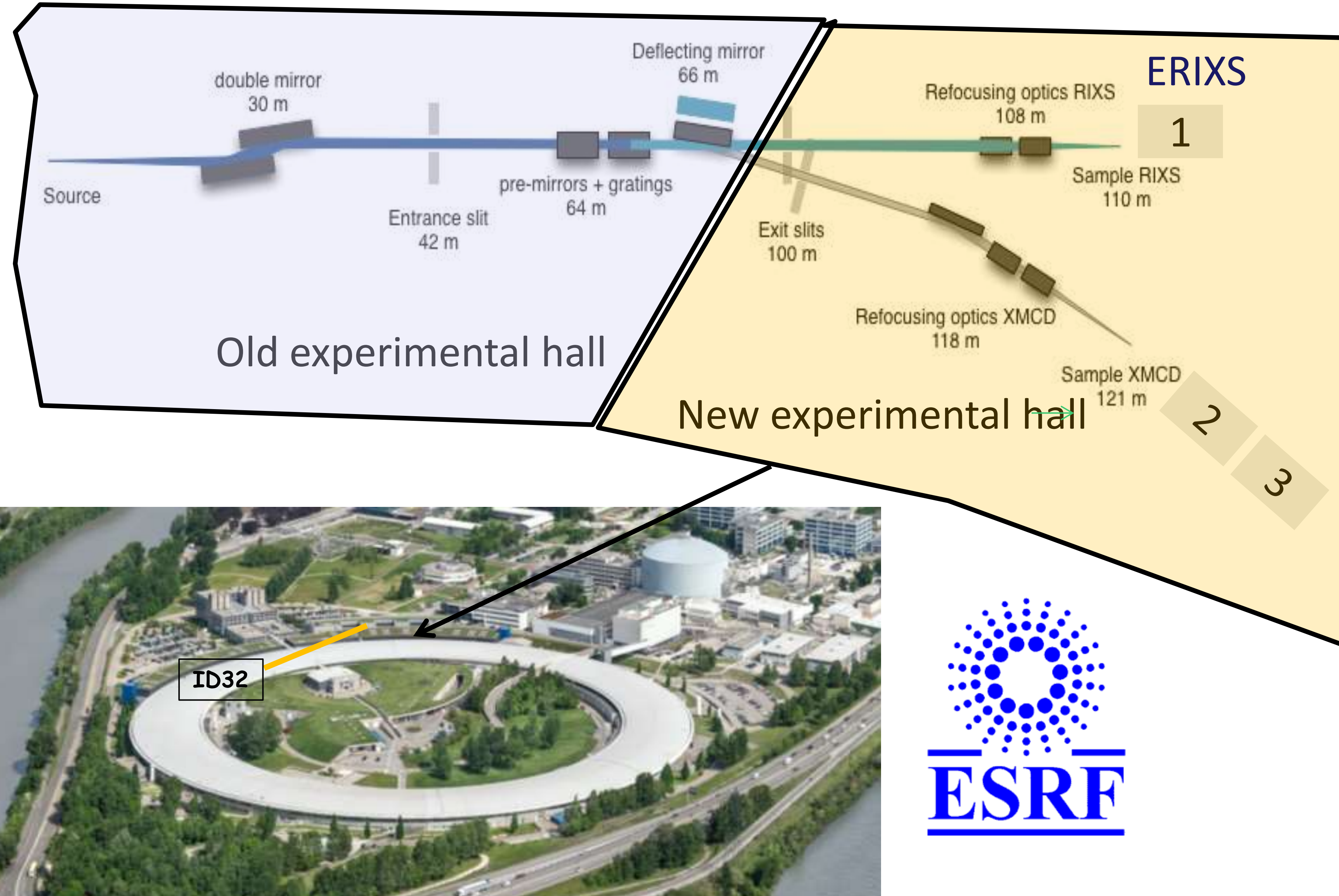
AXES: **2.2 m**

ID12B and ID08

SAXES, SLS: **5 m**

ERIXS, ID32: **10 m**

New ID32 at the ESRF



ERIXS at ID32

POLITECNICO
MILANO 1863

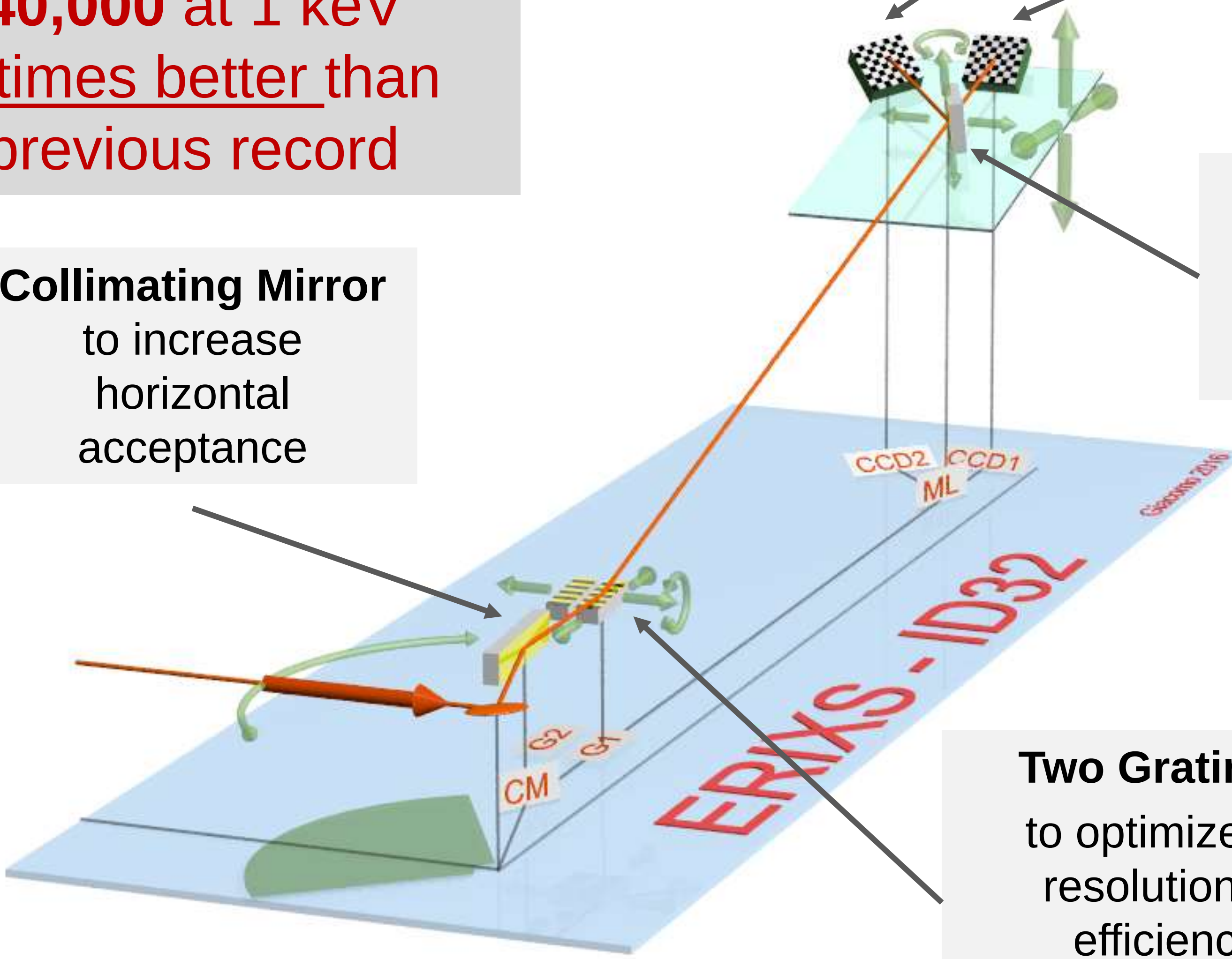
ESRF

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


ERIXS, 27/04/2014

ERIXS and the other HR soft-RIXS projects

SR FACILITY	E/ΔE (combined)	Length	YEAR	NOTES
ESRF, ERIXS@ID32	30,000	11 m	2015	With Polarimeter
DIAMOND, IXS	40,000	14 m	2017	
MAX IV, Veritas	40,000	12 m	2018	Rowland Geometry
NSLS II, Centurion@SIX	70,000	15 m	2018	Hettrick-Underwood, 50 nrad slope error, 1 um spot on sample
European XFEL	20,000	5 m	2019	For non linear RIXS and pump-probe time-resolved RIXS

Bibliography

REVIEWS OF MODERN PHYSICS, VOLUME 83, APRIL–JUNE 2011

Resonant inelastic x-ray scattering studies of elementary excitations

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Thanks

Insights into the high temperature superconducting cuprates from resonant inelastic X-ray scattering

M.P.M. Dean

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