novel SuperConductors and Synchrotron Radiation:
state of the art and perspectives
SCSR2014
Adriatico Guesthouse, Trieste, Italy / 10-11 December 2014

Elettra Sincrotrone Trieste

10 December, 2014

Charge density order and magnetic fluctuations in cuprate superconductors studied with Resonant (Inelastic) X-ray Scattering

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Summary

◊ The case of high Tc superconductors for resonant x-ray scattering

◊ Persistence of magnetic excitations in HTcS

◊ Charge Density Waves in HTcS

◊ New instrumentation, new experiments

Acknowledgements

GG, Lucio Braicovich, **Matteo Minola*, Greta Dellea,** Andrea Amorese°, Claudio Mazzoli, Mauro Fanciulli	Politecnico di Milano (* now at MPI Stuttgart; ° now at ESRF)
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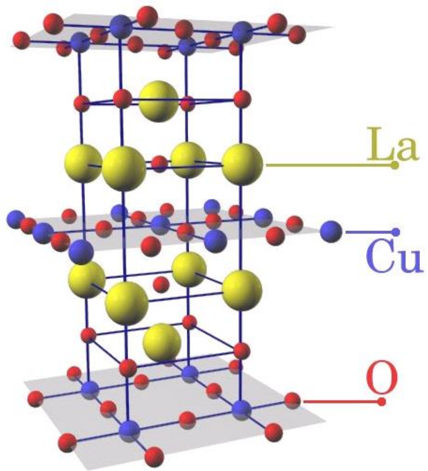
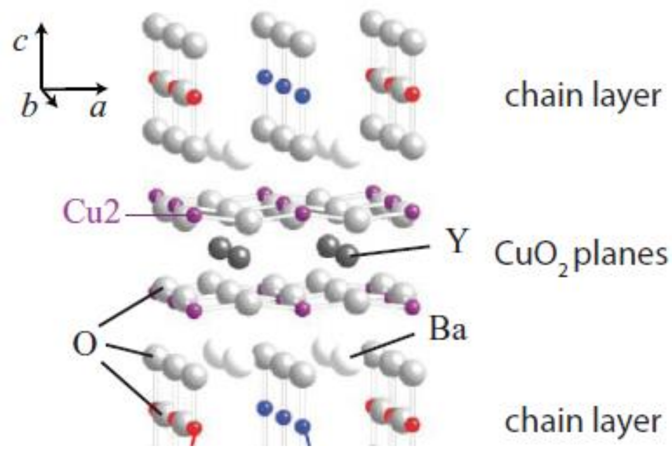
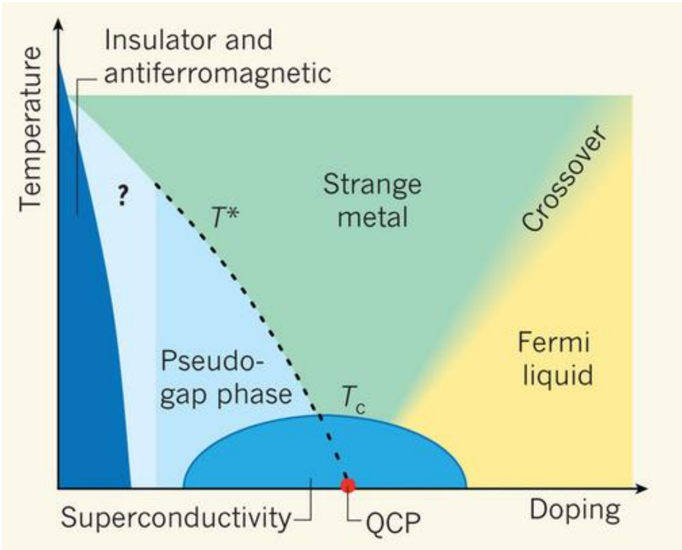
Daniele Di Castro, Giuseppe Balestrino, Lina Aruta, Antonello Tebano	CNR/SPIN Roma Tor Vergata
Gino Maritato, Pasquale Orgiani, Alice Galdi	CNR/SPIN Salerno
D. G. Schlom	Cornell
Mark Dean, John Hill, Stuart Wilkins, I. Bozovic, R. M. Konik, G. D. Gu, X. Liu, Y.-J. Sun, J. Strle,	Brookhaven Natl. Lab.
Makoto Hashimoto, W.-S. Lee, Z.X. Shen, **Tom Devereaux**, Chunjin Jia, Brian Moritz	Stanford
K. Ishii, M. Fujita, T. Tohyama,	Spring8, Tohoku, Kyoto

High Tc superconducting cuprates





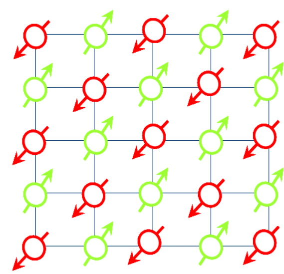
$La_{2-x}Sr_xCuO_4$ (LSCO) $YBa_2Cu_3O_{6+\delta}$ (YBCO)



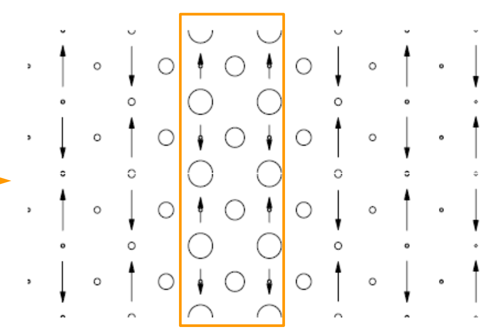
CuO$_2$ planes → Doping (by substitution) → High-T_c superconductivity

Evidence of **ordering phenomena**:

- ***Uniform* 2D AntiFerroMagnetism (AFM)** in undoped insulating samples

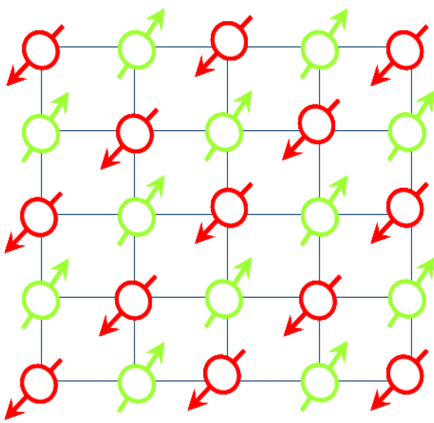


- ***Uniaxially modulated* spin** and **charge** order (**stripes**) in the 214-family: $La_{2-x-y}(Sr,Ba)_x(Nd,Eu)_yCuO_4$

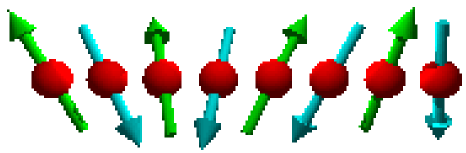


Cuprates: spin waves in the 2D AF lattice

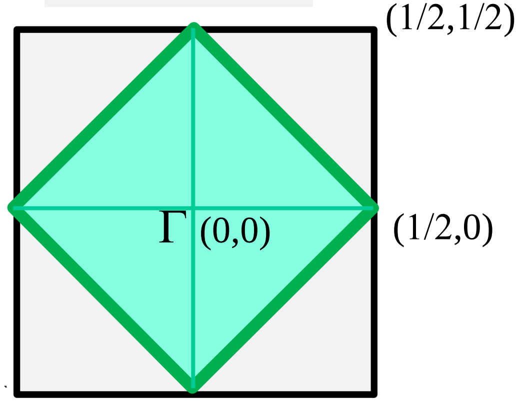
Undoped AF square lattice, long range order due to large superexchange intercation *J*

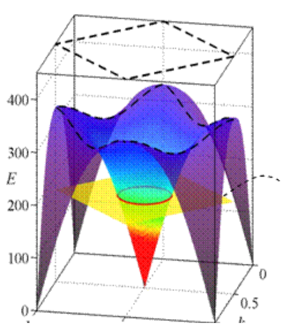


Flipping one spin gives rise to a spin wave (magnon)...



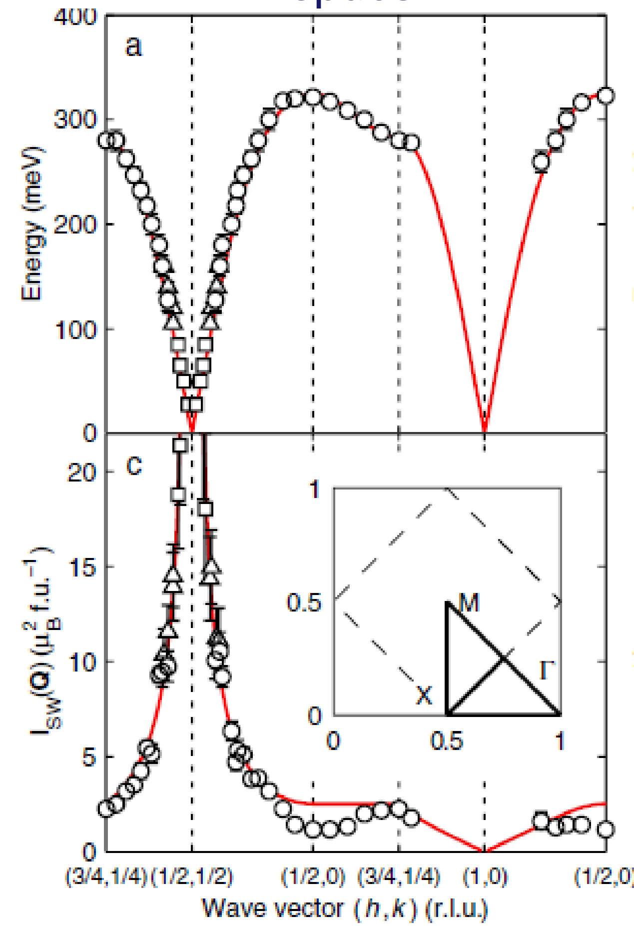
nuclear BZ





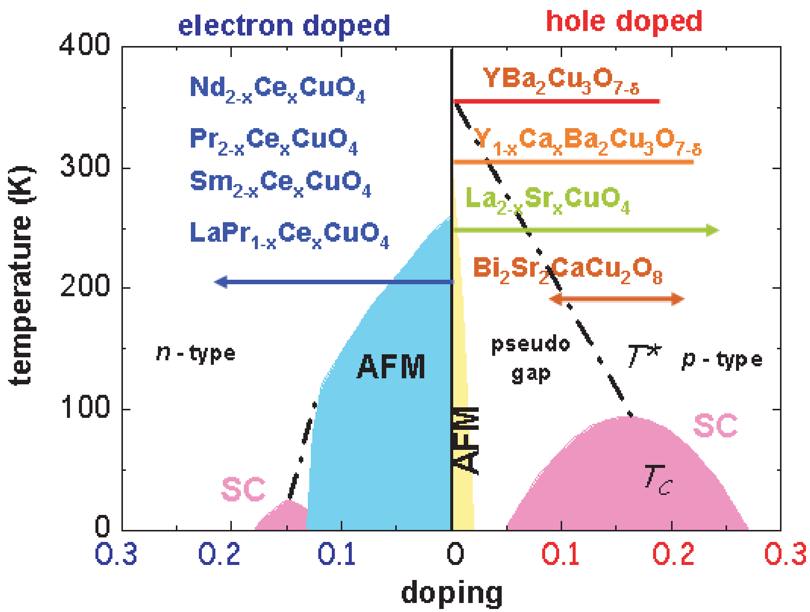
magnetic BZ

... with a well defined dispersion in reciprocal space

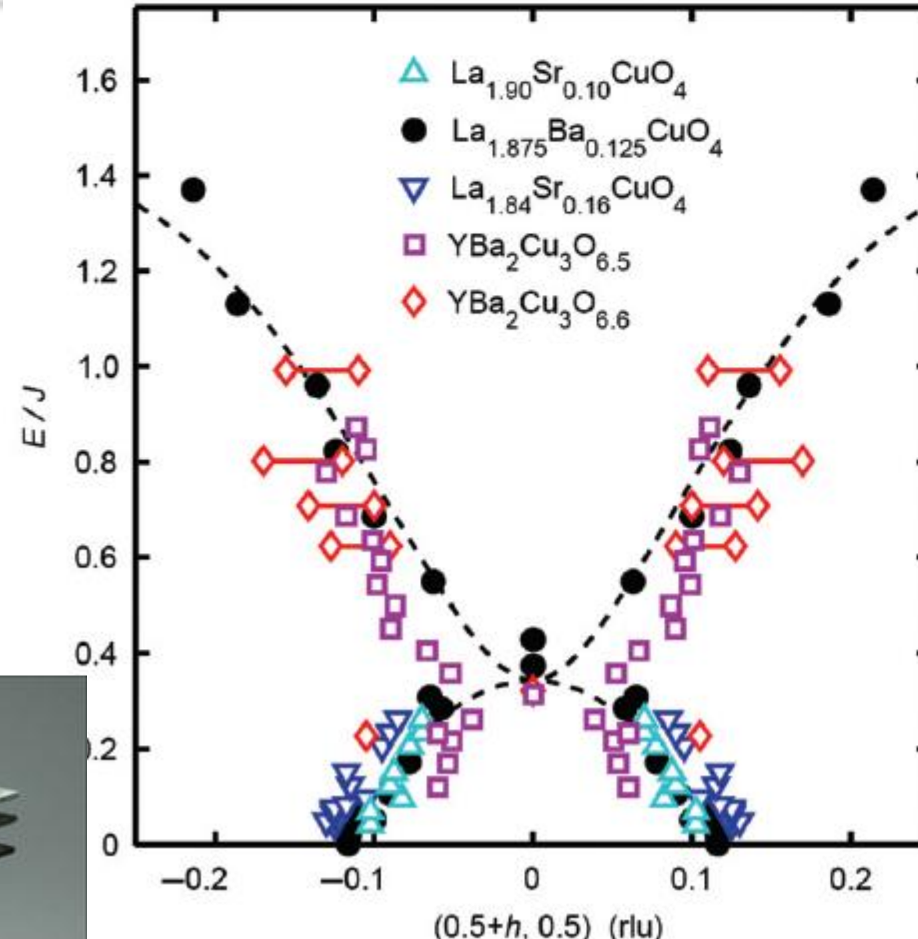


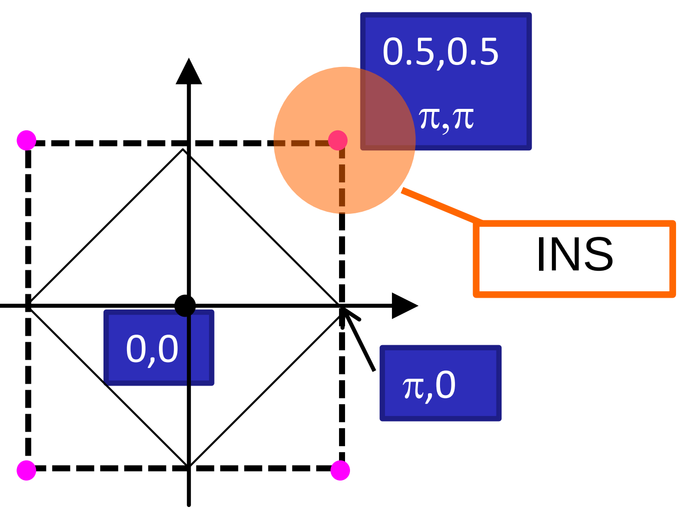
N. S. Headings, S. M. Hayden, R. Coldea, and T. G. Perring, Phys Rev Lett. **105** 247001 (2011)

Spin excitations in HTcS: doped SC



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





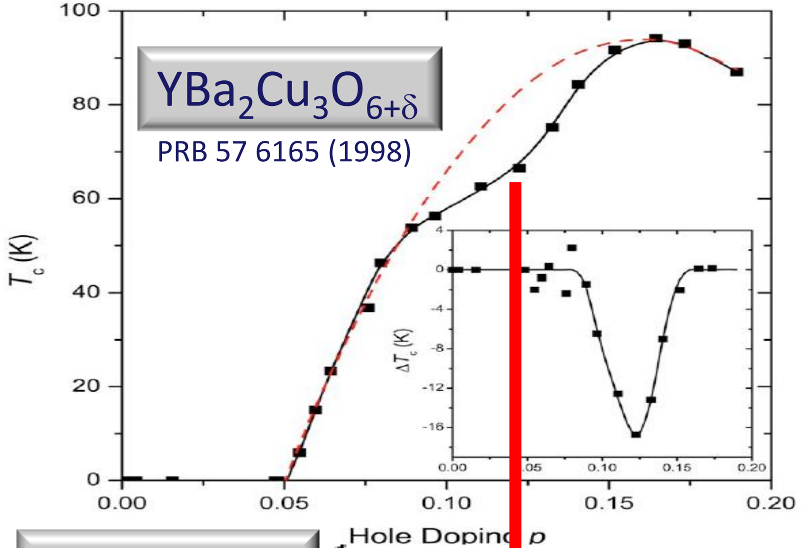
J.M. Tranquada, in *Handbook of High-Temperature Superconductivity: Theory and Experiment*, J.R. Schrieffer and J.S. Brooks, eds., Springer, 2007,

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

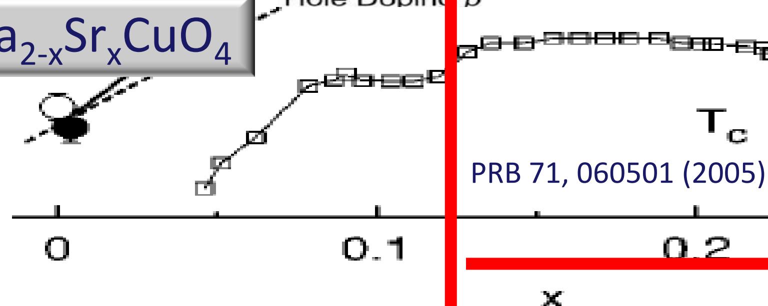
LSCO vs YBCO (214 vs 123)

$YBa_2Cu_3O_{6+\delta}$

PRB 57 6165 (1998)

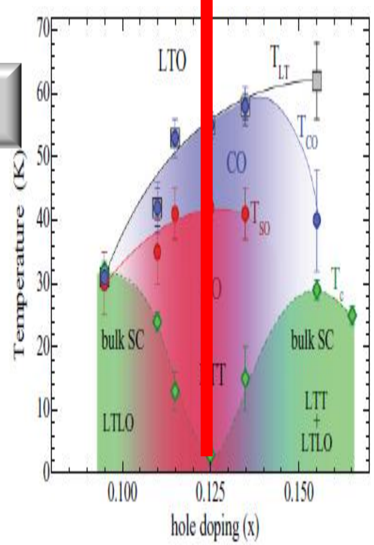


$La_{2-x}Sr_xCuO_4$

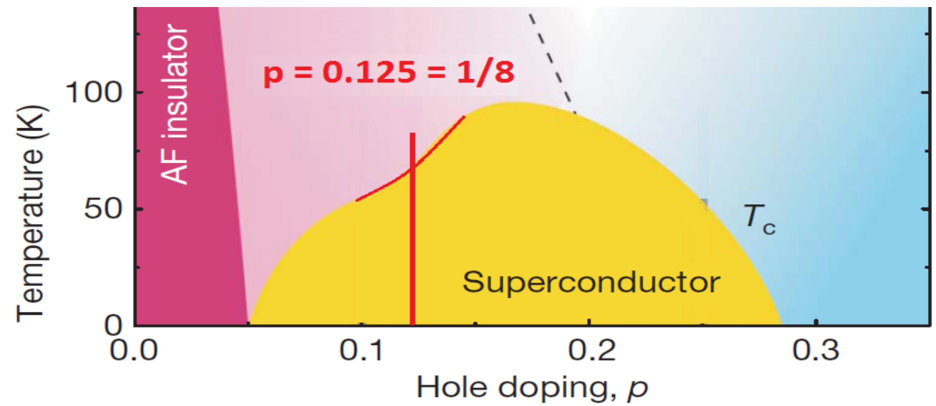


PRB 71, 060501 (2005)

$La_{2-x}Ba_xCuO_4$

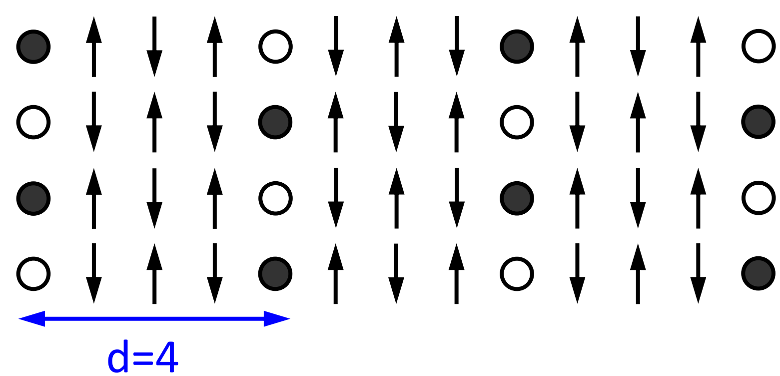


$YBa_2Cu_3O_{6+\delta}$



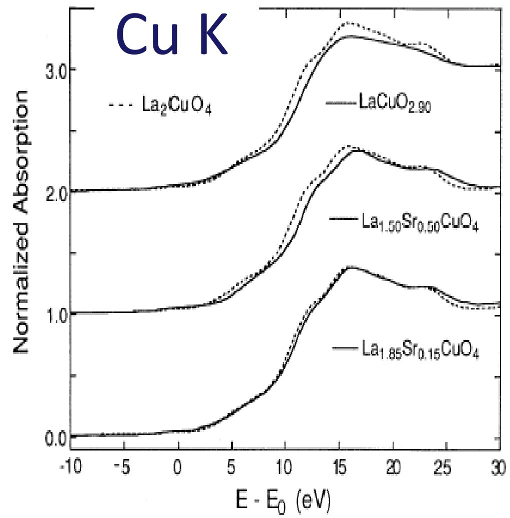
p=0.125=1/8

Static stripes in LXCO, period 4, suppress SC

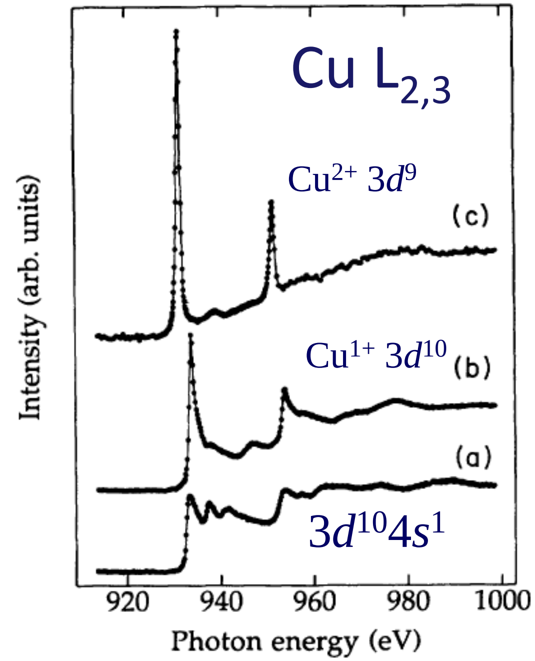


Resonant (Inelastic) soft X-ray Scattering

Soft RIXS: exploiting the 2p-3d resonant absoroption



Z. Tan *et al* Phys. Rev. B **47**, 12365 (1993)



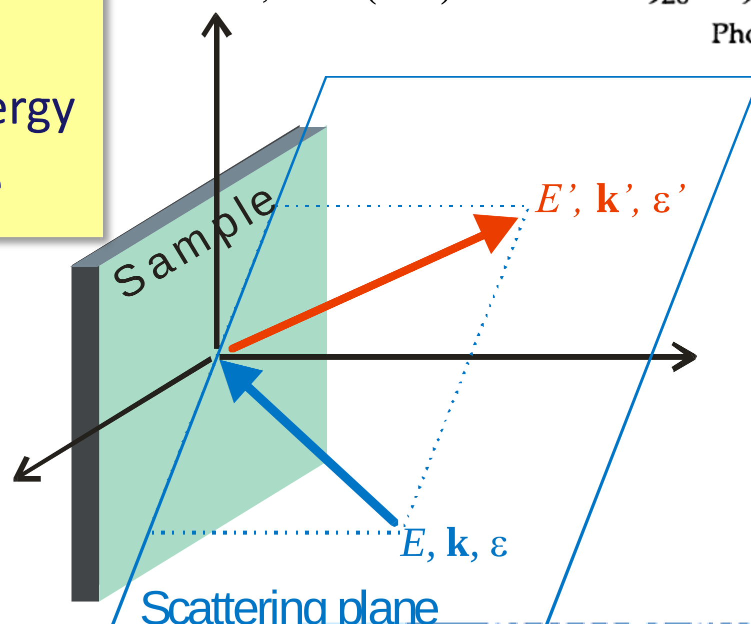
M. Grioni *et al* PRB **45**, 3309 (1992)

Resonant Inelastic X-ray Scattering:

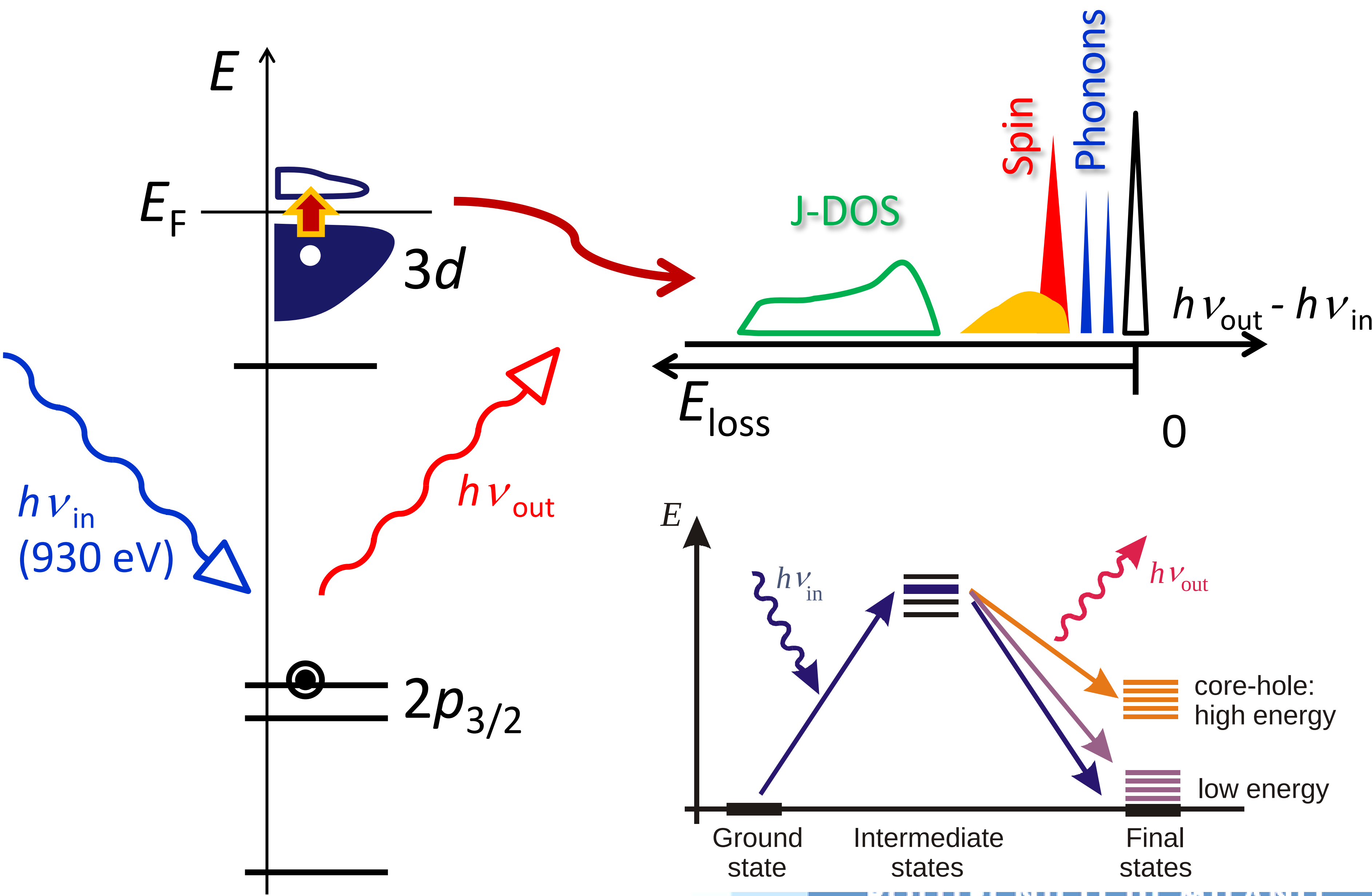
- an energy loss experiment
- made with photons of high energy
- at a core absorption resonance

Conservation laws:

- Energy
- Momentum
- "Angular momentum"

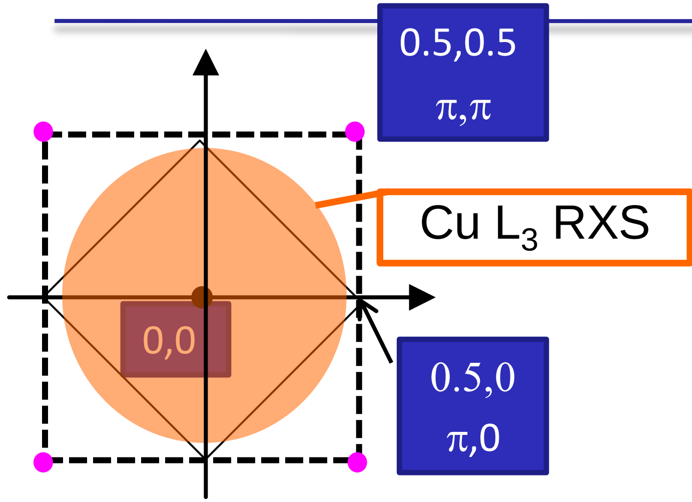


Cu L_3 RIXS



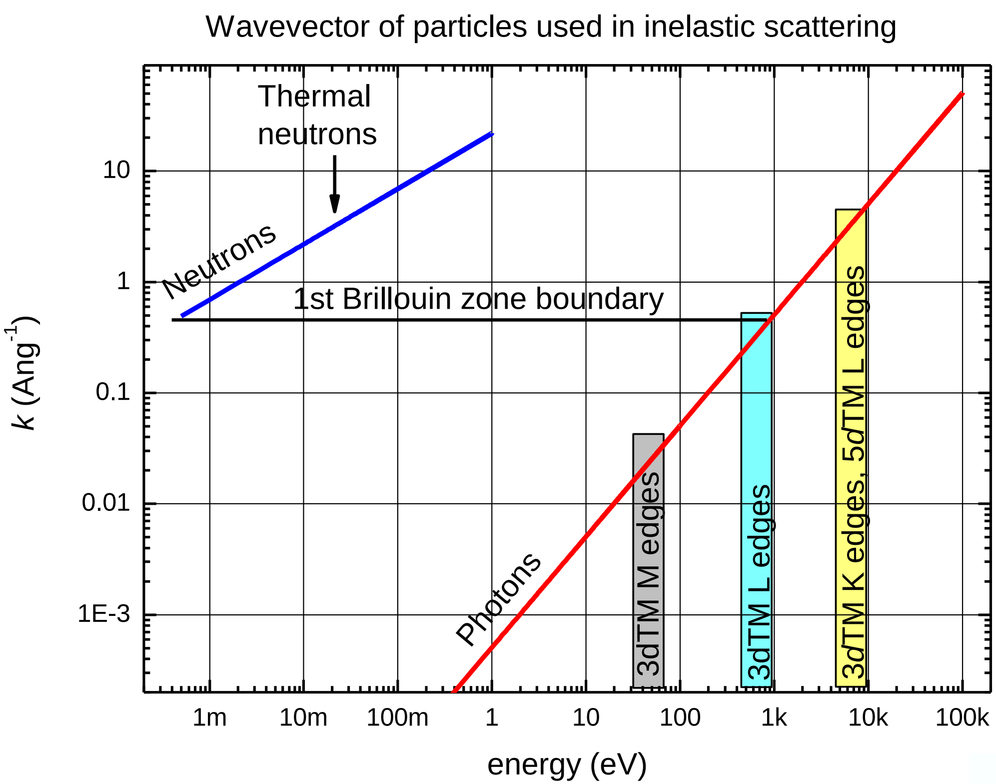
E
E_F
3d
$h\nu_{in}$
(930 eV)
$h\nu_{out}$
$2p_{3/2}$
J-DOS
Spin
Phonons
$h\nu_{out} - h\nu_{in}$
E_{loss}
0
E
$h\nu_{in}$
$h\nu_{out}$
core-hole:
high energy
low energy
Ground
state
Intermediate
states
Final
states

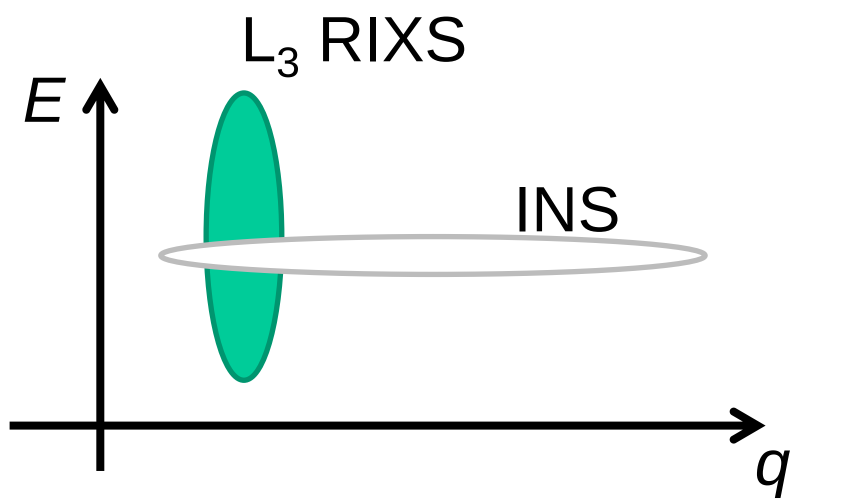
Cu L_3 RIXS: Experimental conditions



Cu L_3 resonance:

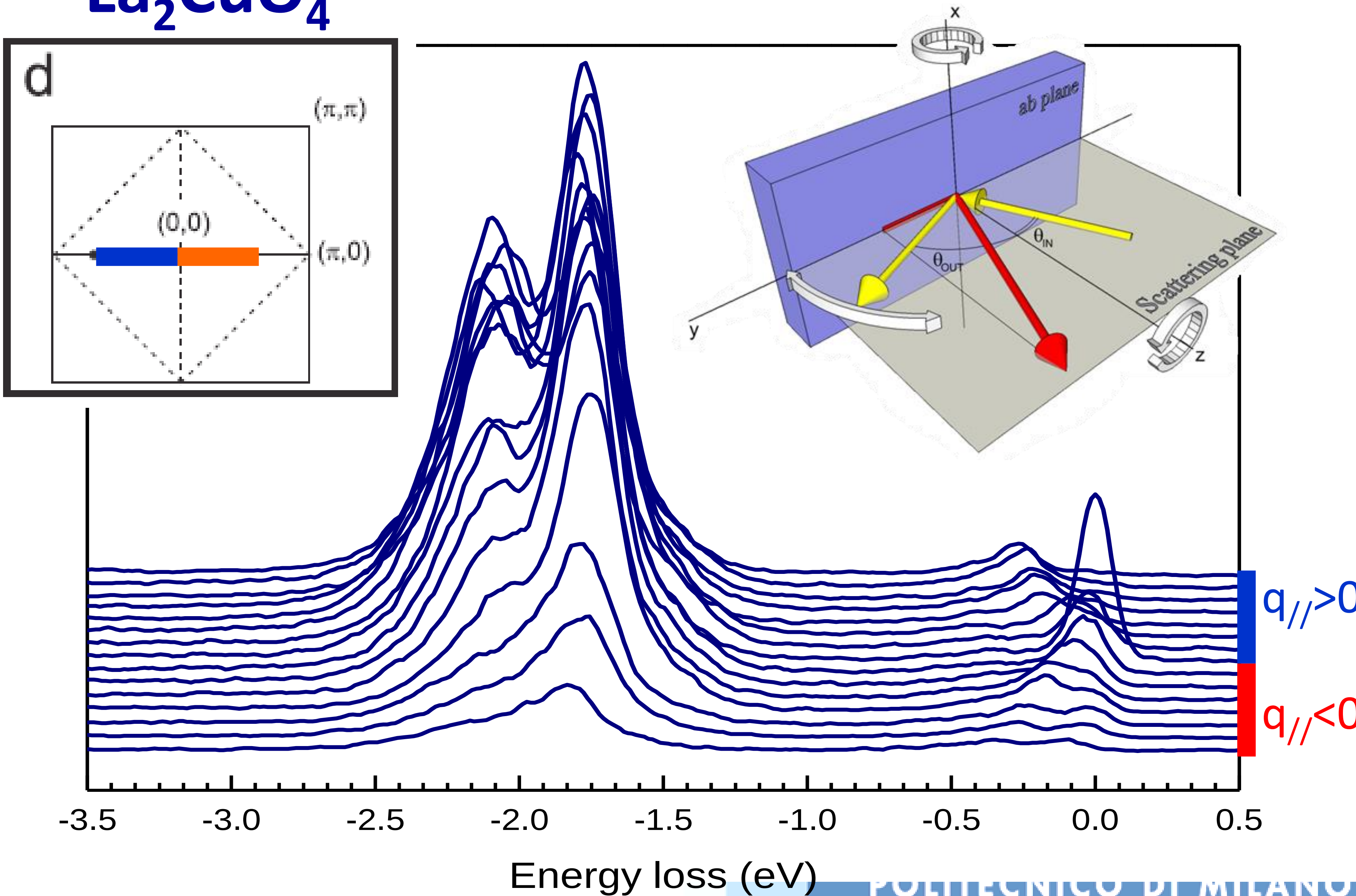
- E_0 = 930 eV
- q_{max} = 0.86 Ang^{-1}
- confined inside a region around Γ
- 2p core hole: spin-orbit interaction
- E resolution: 120-240 meV
- *q* resolution: 0.005 rlu
- ½ - 1 hour per spectrum





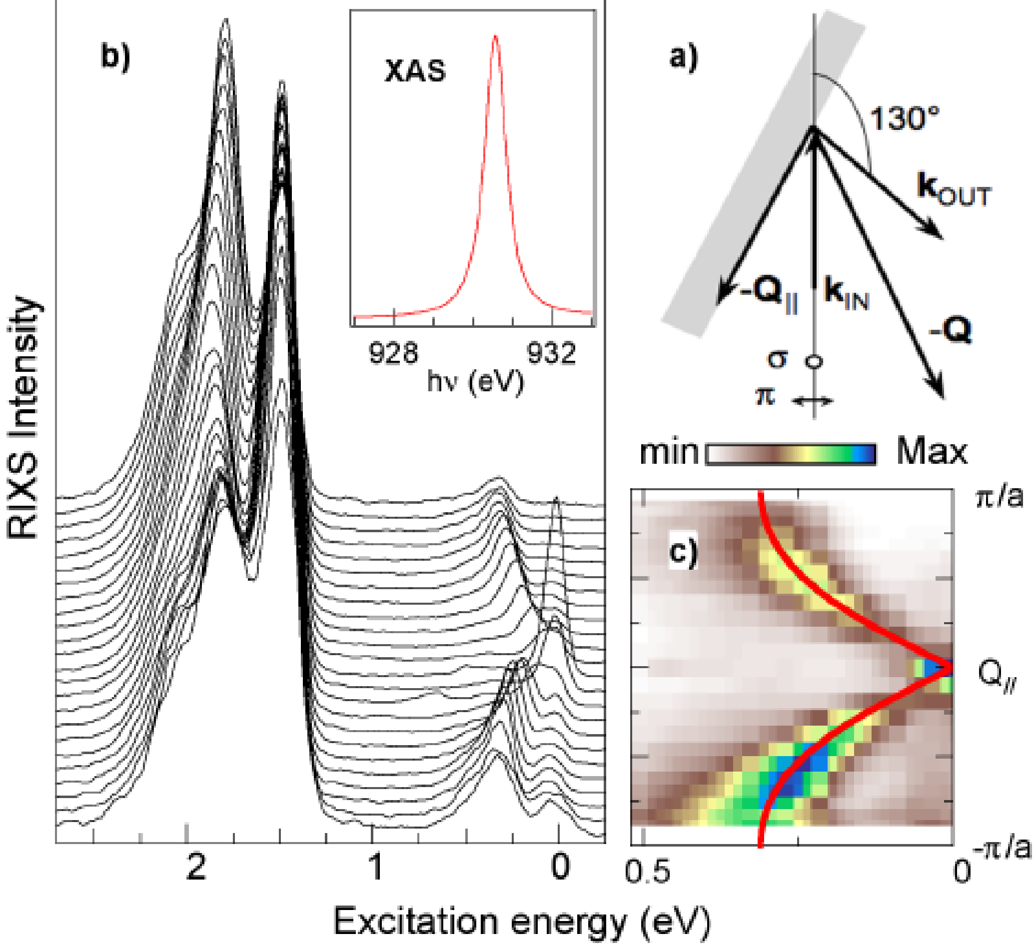
Dispersing peaks in the MIR…

La_2CuO_4

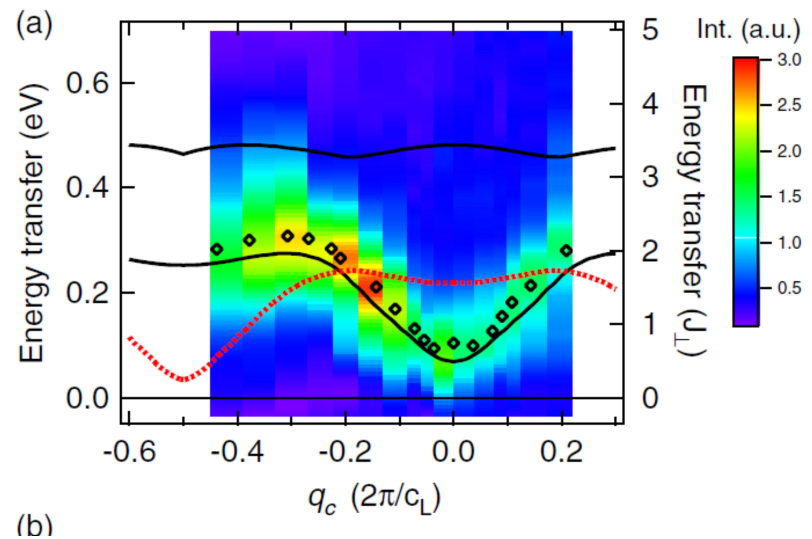


Undoped compounds

$Sr_2CuO_2Cl_2$



$Sr_{14}Cu_{24}O_{41}$



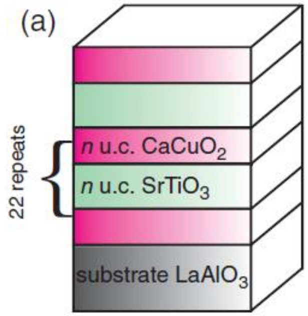
J. Schlappa et al, PRL 103, 047401 (2009)

M. Guarse et al, PRL 105 157006 (2009)

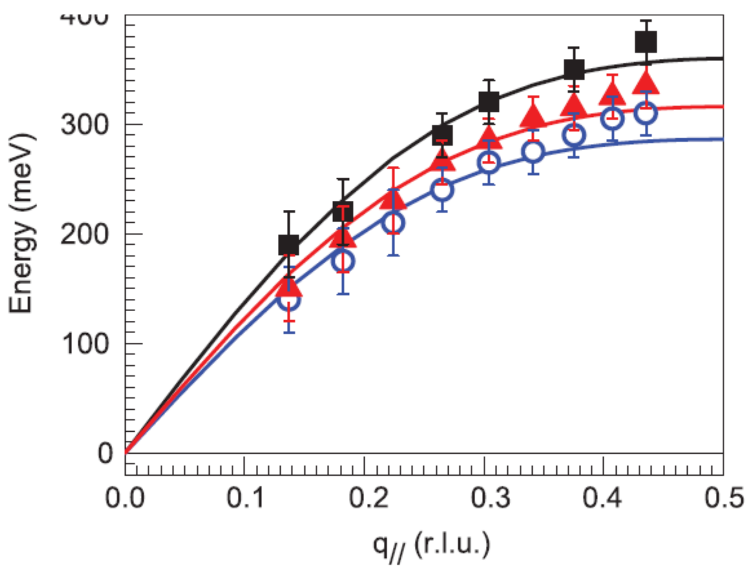
PHYSICAL REVIEW B **85**, 235138 (2012)

Magnetic and ligand field properties of copper at the interfaces of $(CaCuO_2)_n/(SrTiO_3)_n$ superlattices

M. Minola,[1] D. Di Castro,[2] L. Braicovich,[3] N. B. Brookes,[4] D. Innocenti,[2] M. Moretti Sala,[3,*] A. Tebano,[2] G. Balestrino,[2] and G. Ghiringhelli[3]



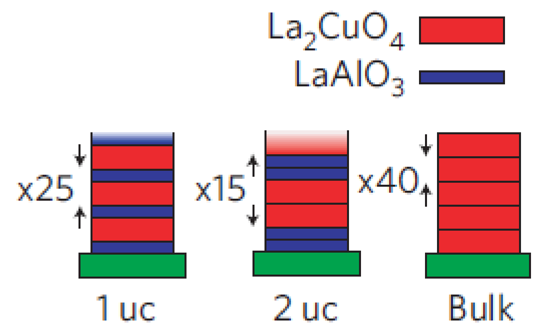
	SL ($n = 2$)	SL ($n = 3$)	$CaCuO_2$	La_2CuO_4
U	1970	2720	3010	2200
t	250	320	360	300
J	127	138	157	138
J_c	41	42	49	38
$J' = J''$	2	2	2	2

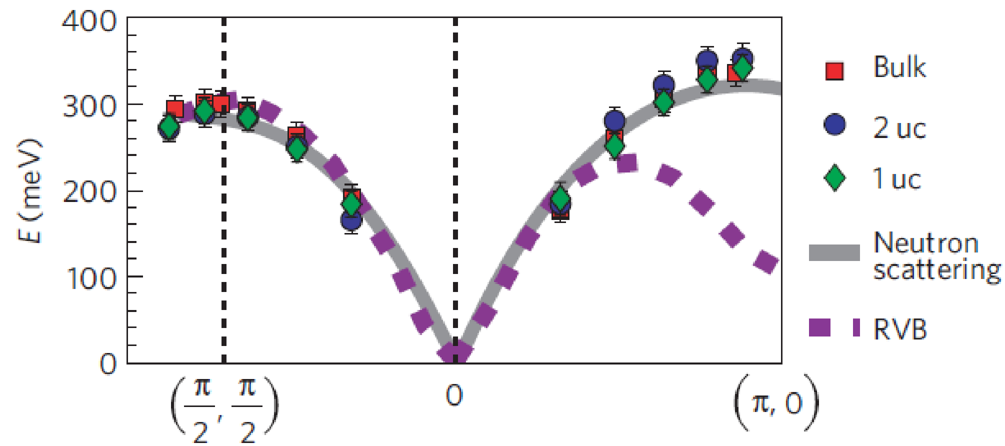


LETTERS
nature materials
PUBLISHED ONLINE: 2 SEPTEMBER 2012 | DOI: 10.1038/NMAT3409

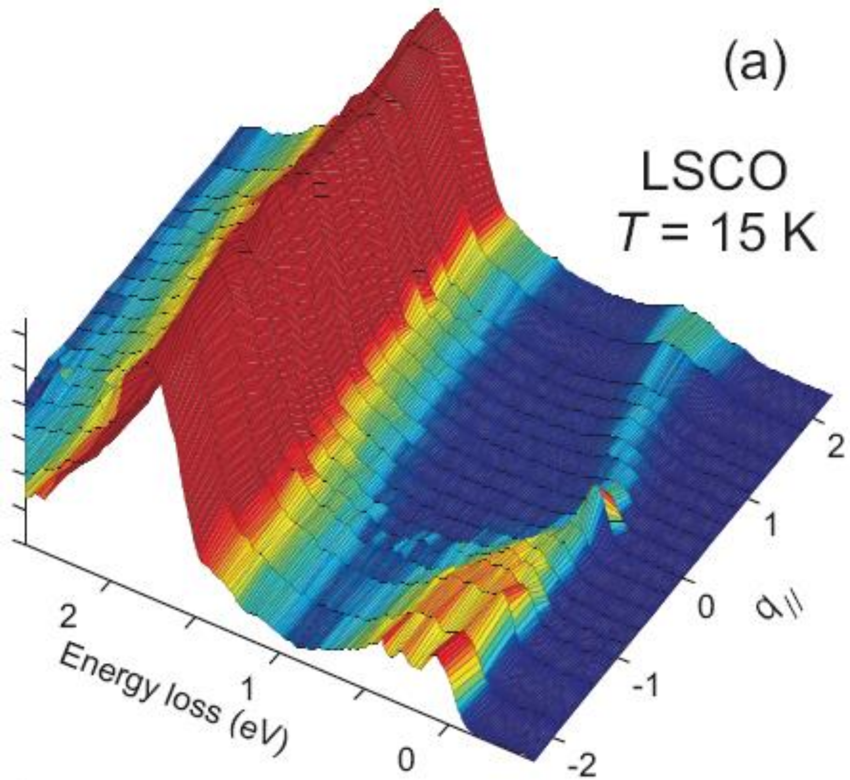
Spin excitations in a single La_2CuO_4 layer

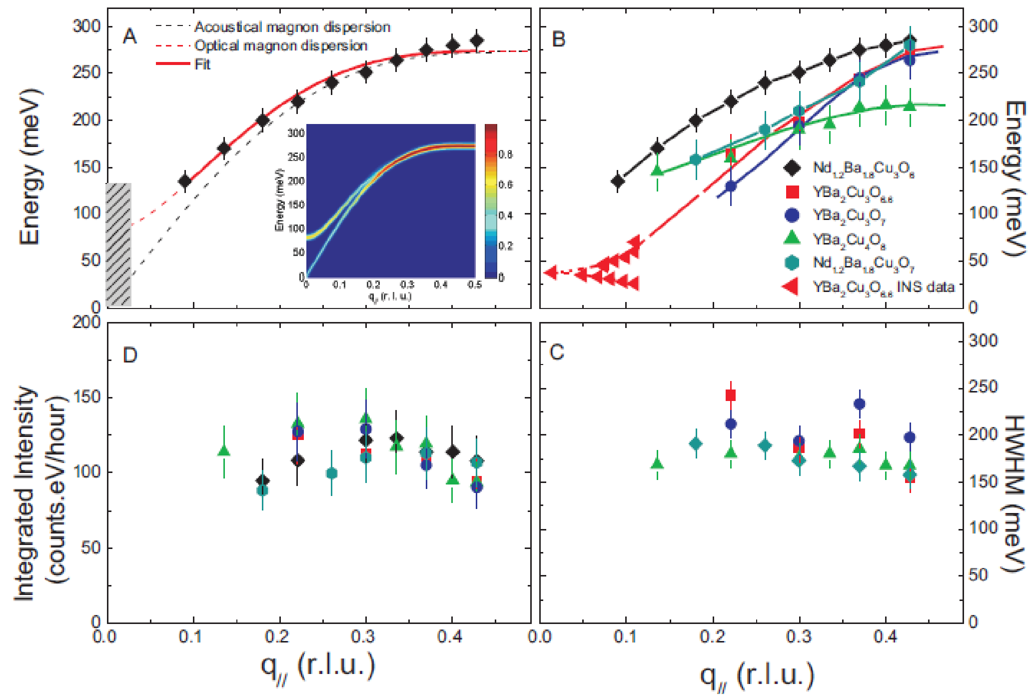
M. P. M. Dean[1]*, R. S. Springell[2,3], C. Monney[4], K. J. Zhou[4†], J. Pereiro[1†], I. Božović[1], B. Dalla Piazza[5], H. M. Rønnow[5], E. Morenzoni[6], J. van den Brink[7], T. Schmitt[4] and J. P. Hill[1]*





LSCO, YBCO and NdBCO





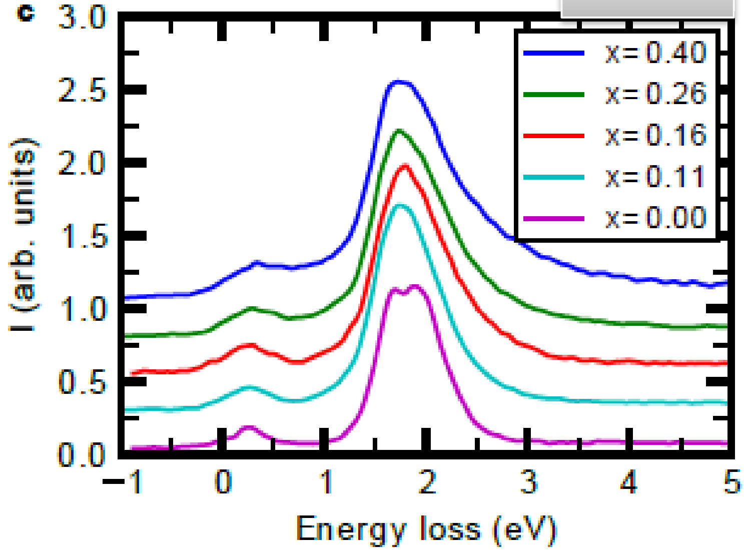
LSCO & NdBCO: 100 nm films on STO. YBCO: detwinned single crystals

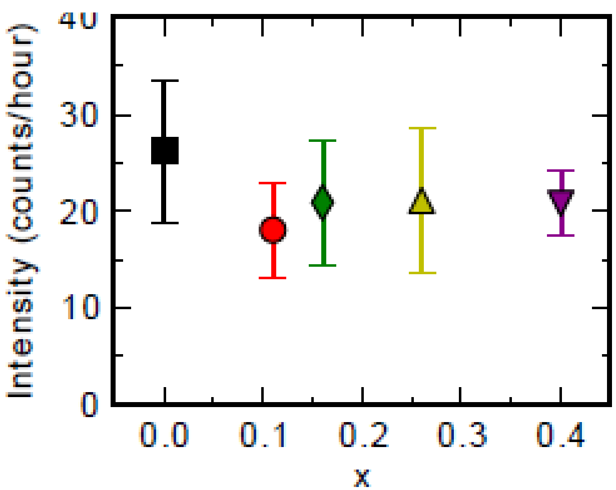
L. Braicovich, J. van den Brink, V. Bisogni, M. Moretti Sala, L. Ament, N.B. Brookes, G.M. de Luca, M. Salluzzo, T. Schmitt, and G. Ghiringhelli PRL **104** 077002 (2010)

M. Le Tacon, G. Ghiringhelli, J. Chaloupka, M. Moretti Sala, V. Hinkov, M.W. Haverkort, M. Minola, M. Bakr, K. J. Zhou, S. Blanco-Canosa, C. Monney, Y. T. Song, G. L. Sun, C. T. Lin, G. M. De Luca, M. Salluzzo, G. Khaliullin, T. Schmitt, L. Braicovich and B. Keimer, Nat. Phys. **7**, 725 (2011)

Magnetic excits in overdoped cuprates

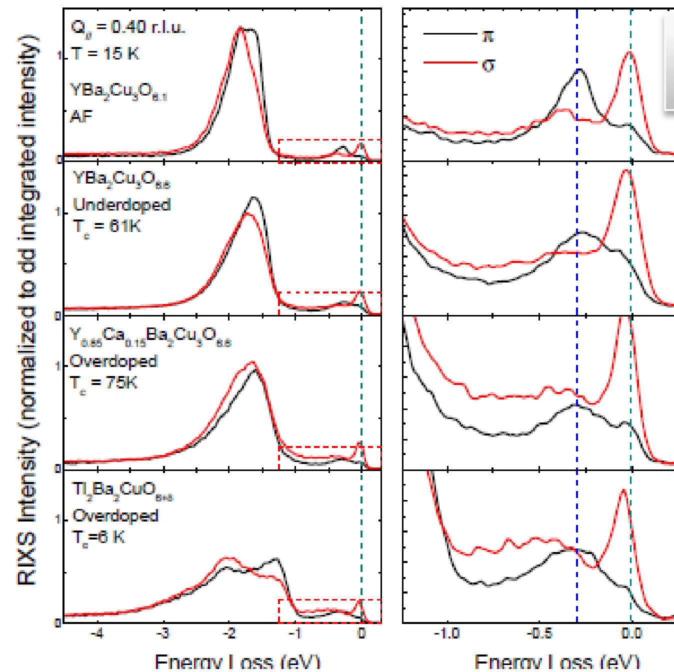
LSCO

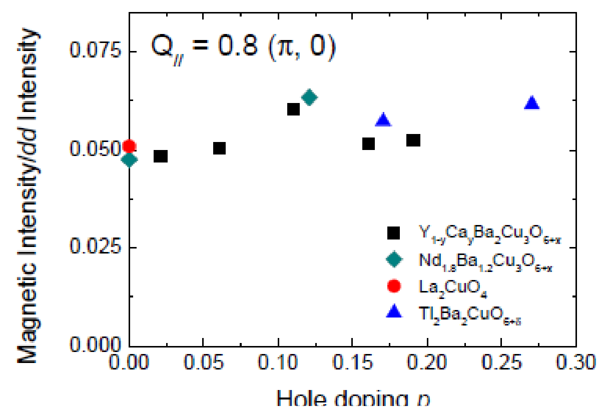




π pol

YBCO

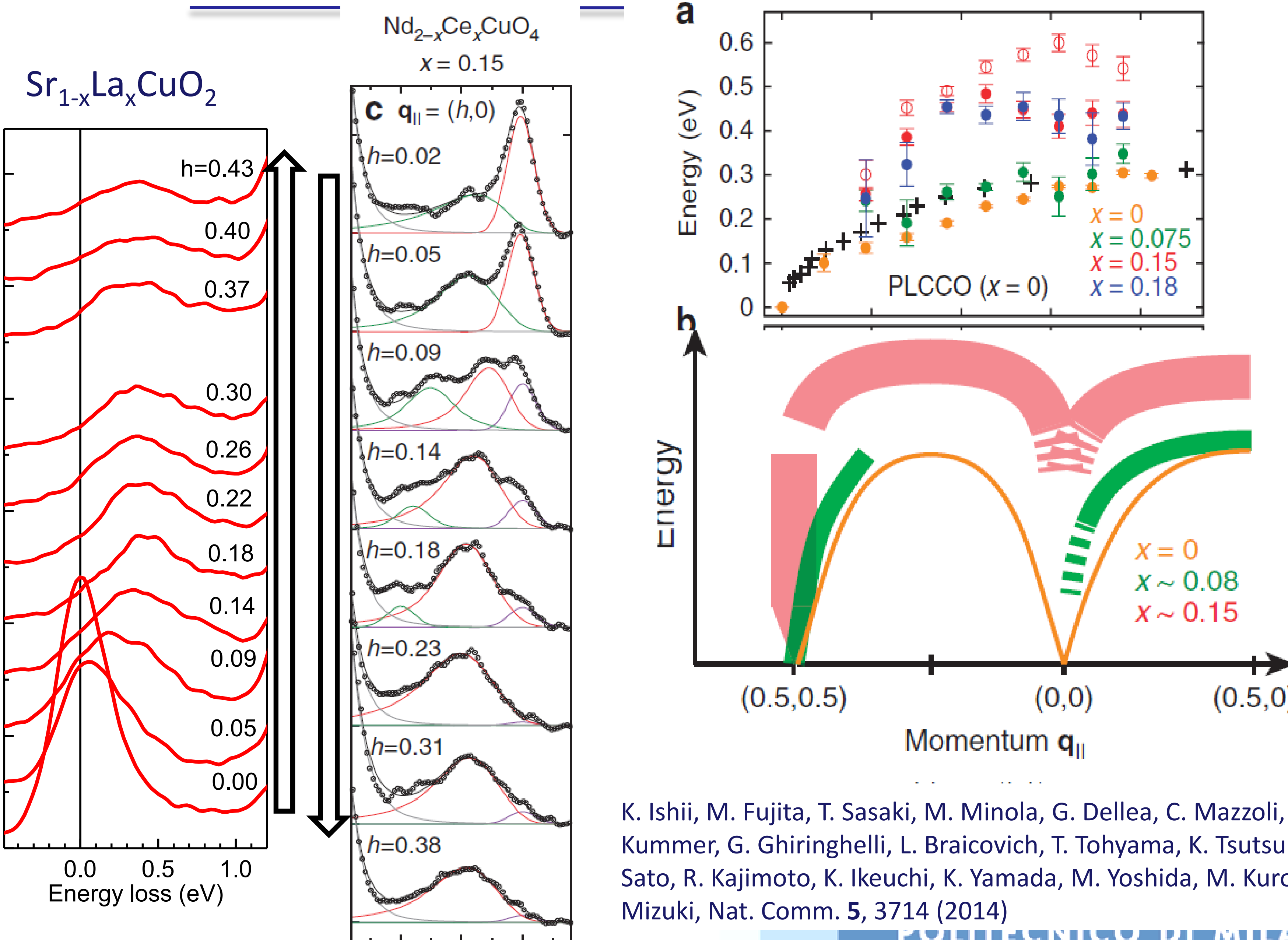




M. P. M. Dean,, . G. Dellea, R. S. Springell, F. Yakhou-Harris, K. Kummer, N. B. Brookes, X. Liu, Y.-J. Sun, J. Strle, T. Schmitt, L. Braicovich, G. Ghiringhelli, I. Bozovic, and J. P. Hill, Nat. Mater. **12**, 1019 (2013)

M. Le Tacon, M. Minola, D. C. Peets, M. Moretti Sala, S. Blanco-Canosa, V. Hinkov, R. Liang, D. A. Bonn, W. N. Hardy, C. T. Lin, T. Schmitt, L. Braicovich, G. Ghiringhelli, and B. Keimer, Phys. Rev. B 88, 020501 (2013)

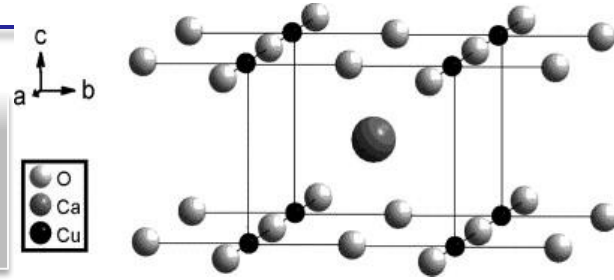
Spin excitations in e-doped SC



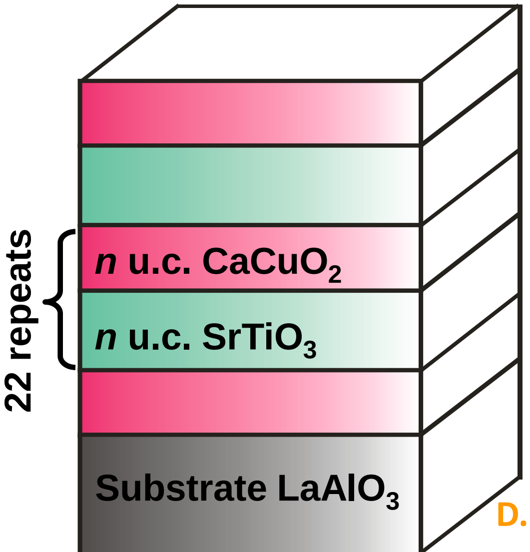
K. Ishii, M. Fujita, T. Sasaki, M. Minola, G. Dellea, C. Mazzoli, K. Kummer, G. Ghiringhelli, L. Braicovich, T. Tohyama, K. Tsutsumi, K. Sato, R. Kajimoto, K. Ikeuchi, K. Yamada, M. Yoshida, M. Kurooka & J. Mizuki, Nat. Comm. **5**, 3714 (2014)

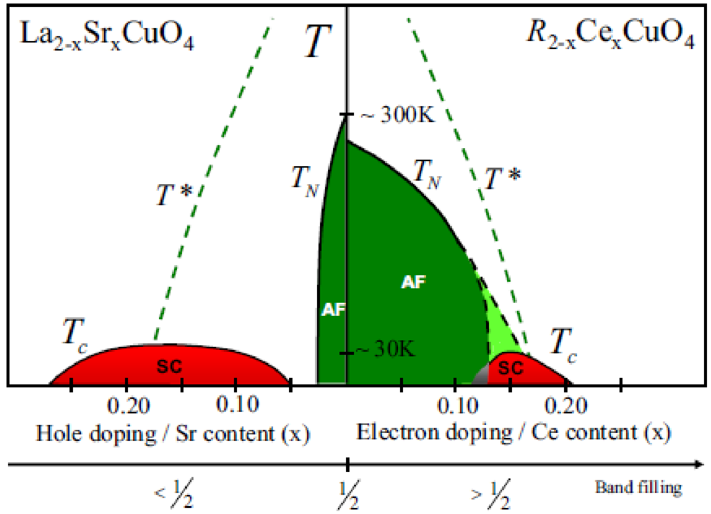
Paramagnons in e- and h-doped infinite layers

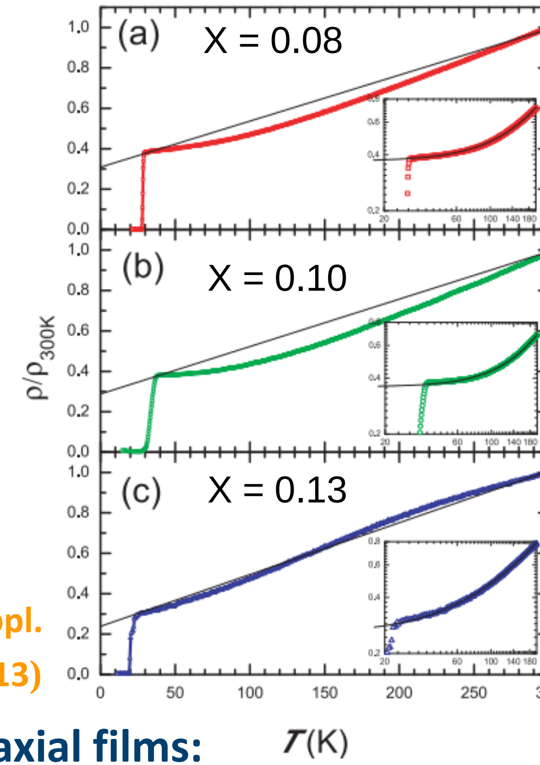
Hole-doped CCO/STO superlattices



Electron-doped: $Sr_{1-x}La_xCuO_2/GdScO_3$







D. Di Castro et al., Phys. Rev. B 86, 134524 (2012)

SLs grown in a highly **oxidizing atmosphere** → **SC**

Extra **oxygen** ions at **interfaces** → charge reservoir → hole doping CuO_2 planes

SC confined within few unit cells at interface.

L. Maritato *et al.*, J. Appl. Phys. 113, 053911 (2013)

$Sr_{1-x}La_xCuO_2$ **epitaxial films:**

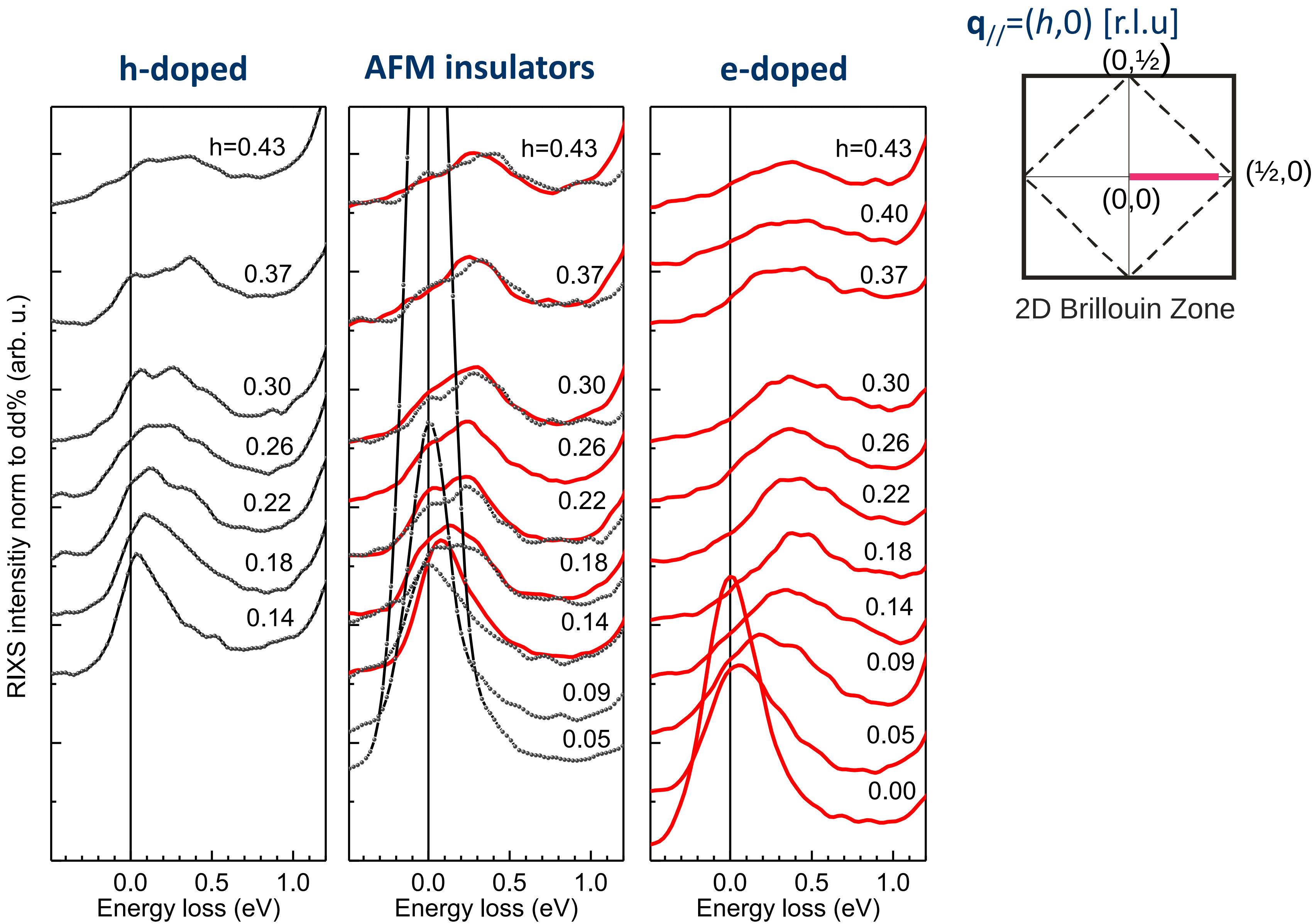
grown on a $GdScO_3$ s → **strain**

annealing → **oxygen content**

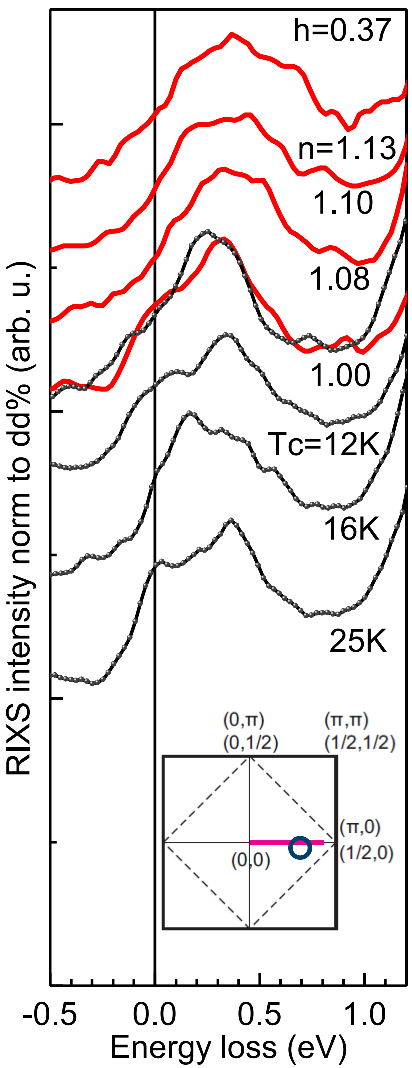
x → La stoichiometry

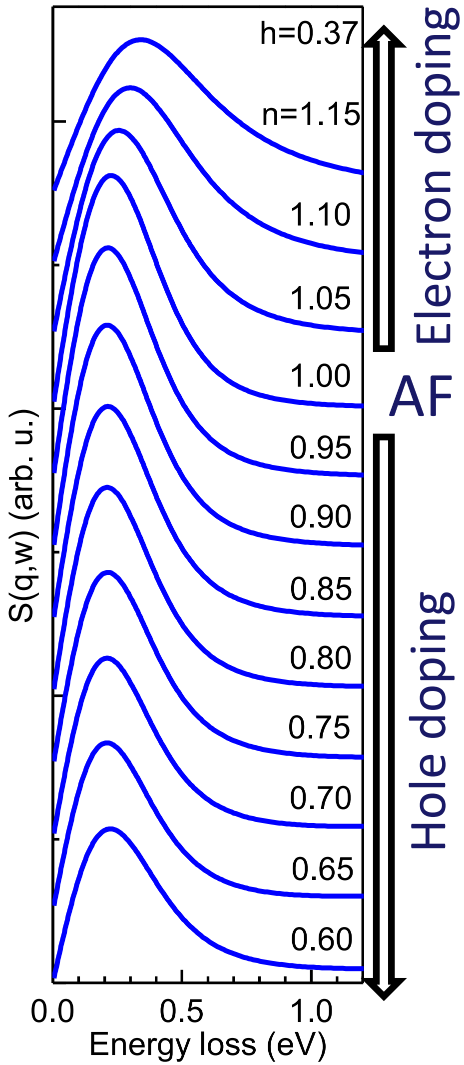
G. Dellea, M. Minola, C. Mazzoli, L. Braicovich, A. Galdi, P. Orgiani, L. Maritato, D. Di Castro, A. Tebano, G. Balestrino, C. Aruta, M. Moretti Sala, C. Jia, B. Moritz, T. Devereaux, N. B. Brookes, D.G. Schlom and G. Ghiringhelli, unpublished

Paramagnon dispersion along (1,0) direction



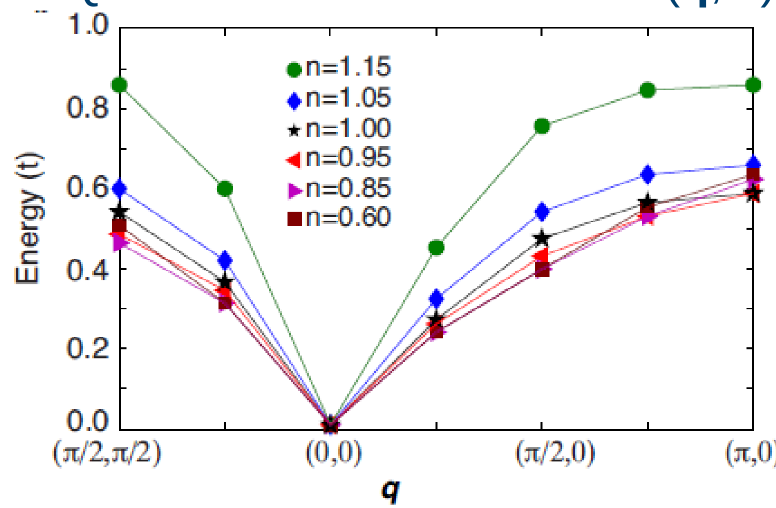
Doping dependence in exp. and theory





Single band Hubbard model in a 12-site cluster

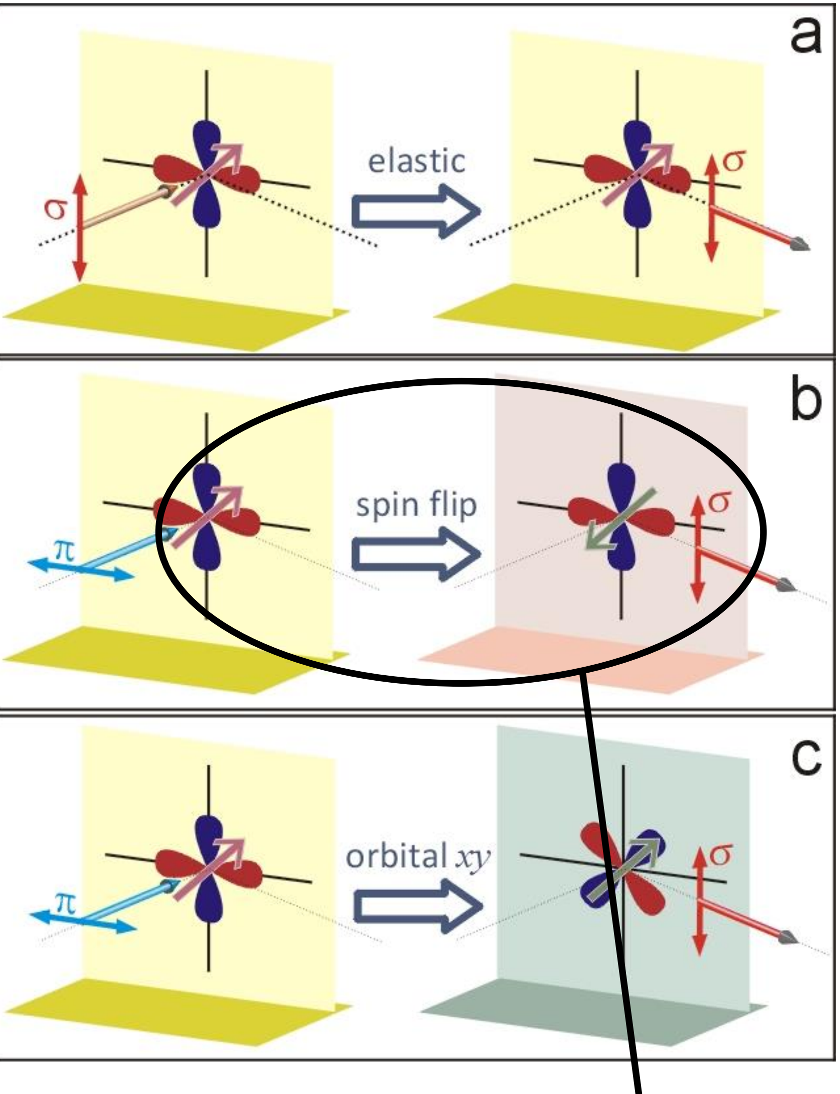
DQMC simulations used for $S(\mathbf{q},\omega)$

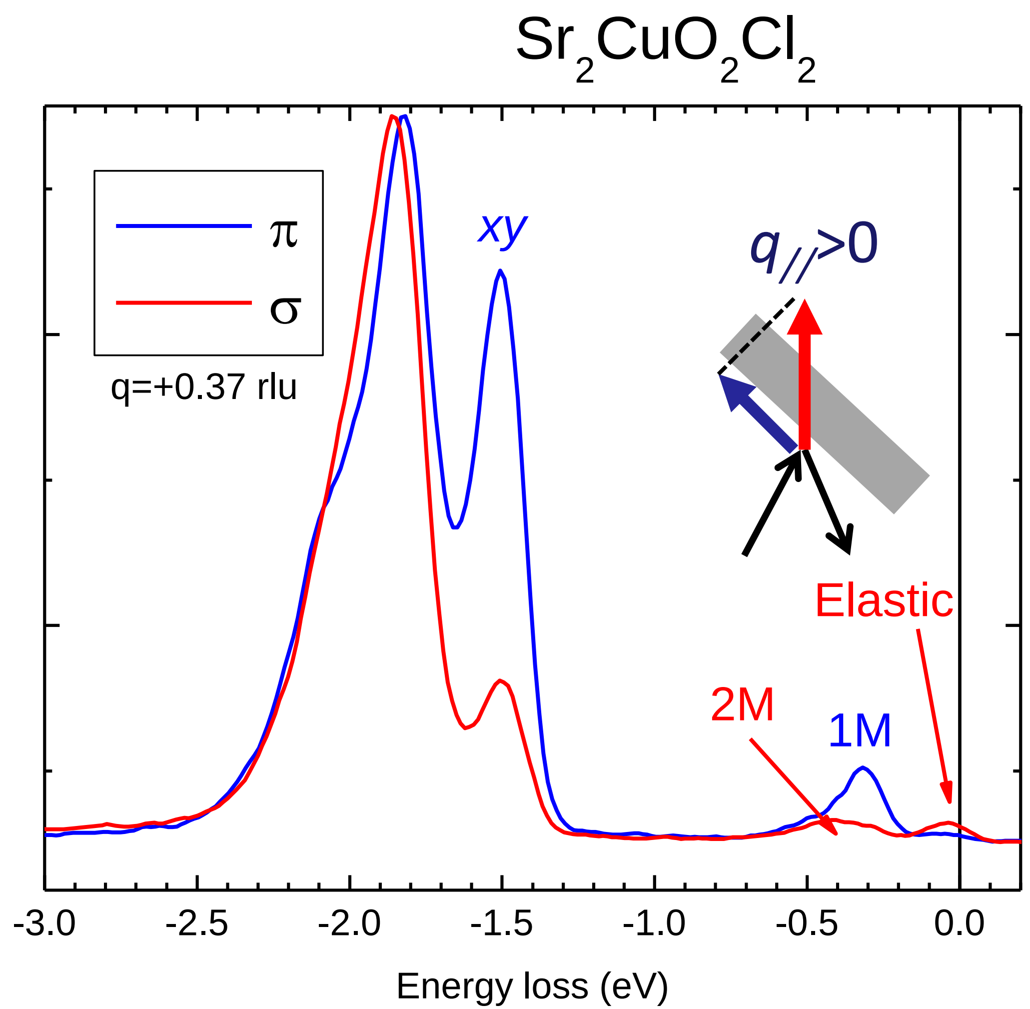


C. J. Jia, E. A. Nowadnick, K. Wohlfeld, Y. F. Kung, C.-C. Chen, S. Johnston, T. Tohyama, B. Moritz & T. P. Devereaux, Nat. Comm. 5, 3314 (2014)

G. Dellea, M. Minola, C. Mazzoli, L. Braicovich, A. Galdi, P. Orgiani, L. Maritato, D. Di Castro, A. Tebano, G. Balestrino, C. Aruta, M. Moretti Sala, C. Jia, B. Moritz, T. Devereaux, N. B. Brookes, D.G. Schlom and G. Ghiringhelli, unpublished

Polarization dep. of Cu L_3 RIXS intensity

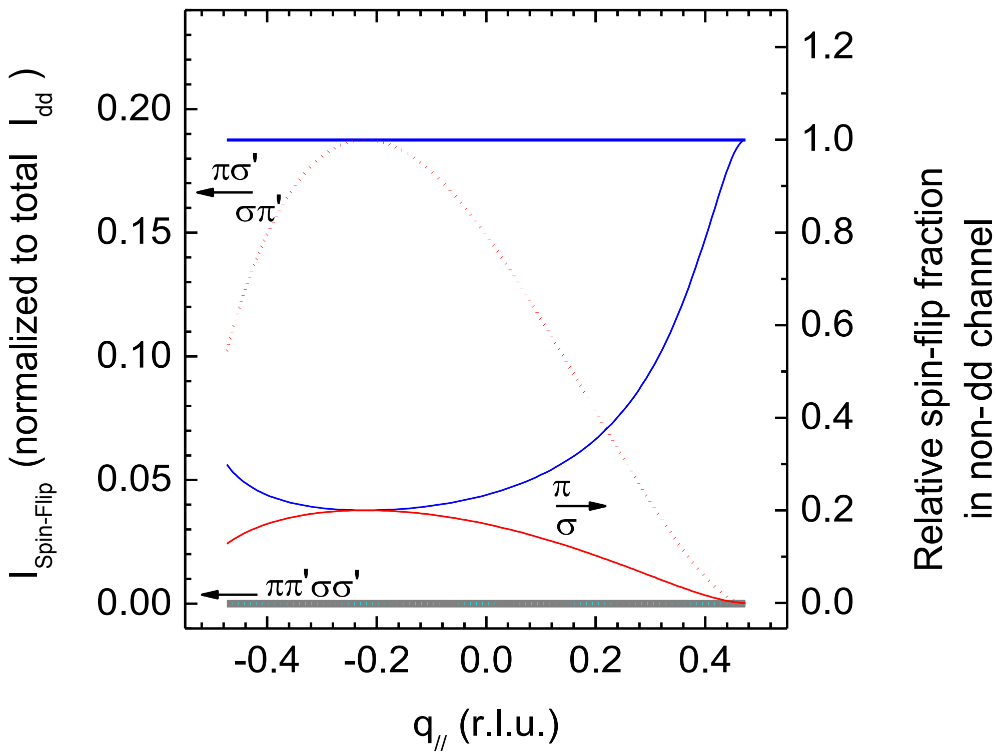


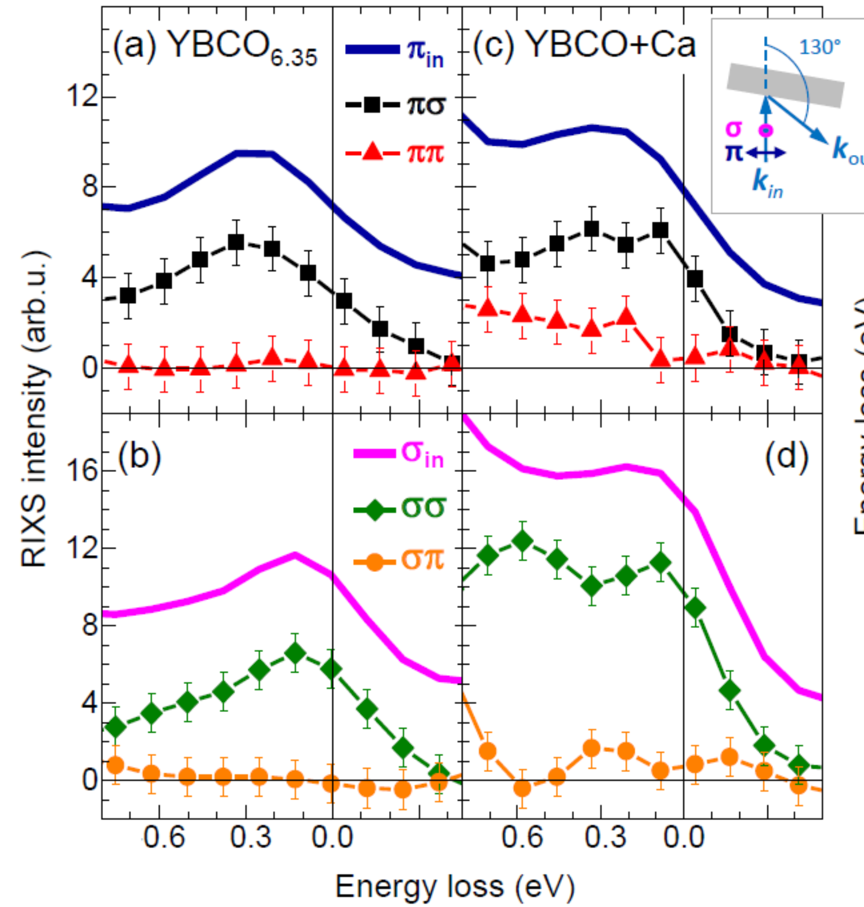


Crossed polarizations

The spin-flip cross section in doped compounds

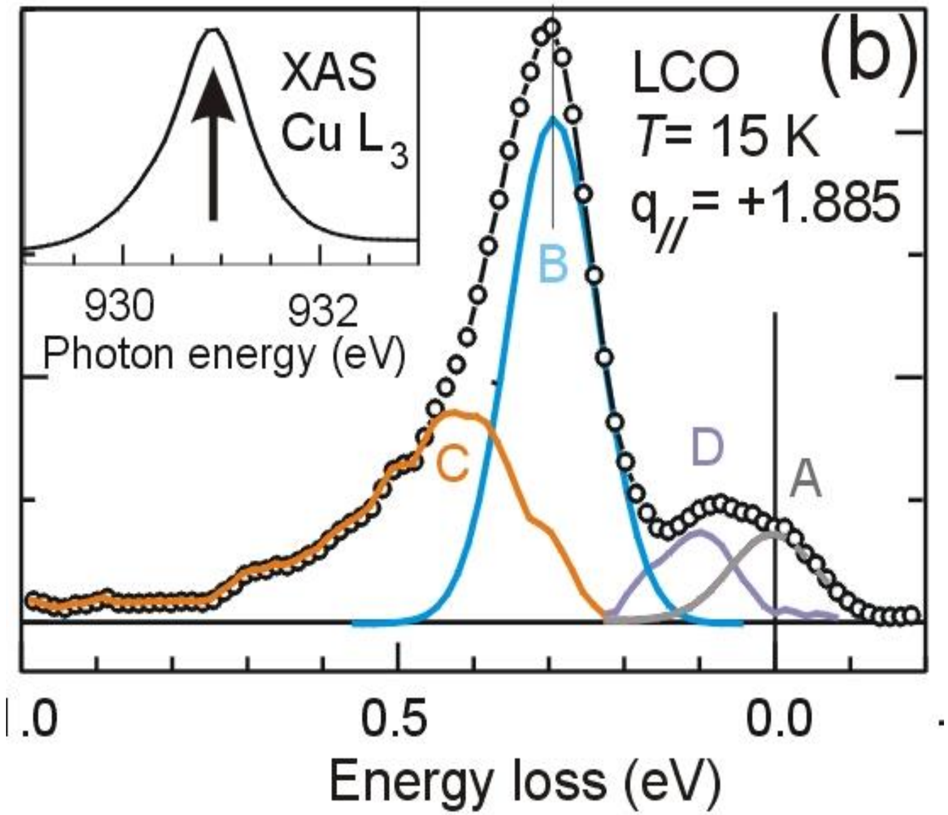
Single ion X-sections with full polarization control: only crossed polarization can give SF





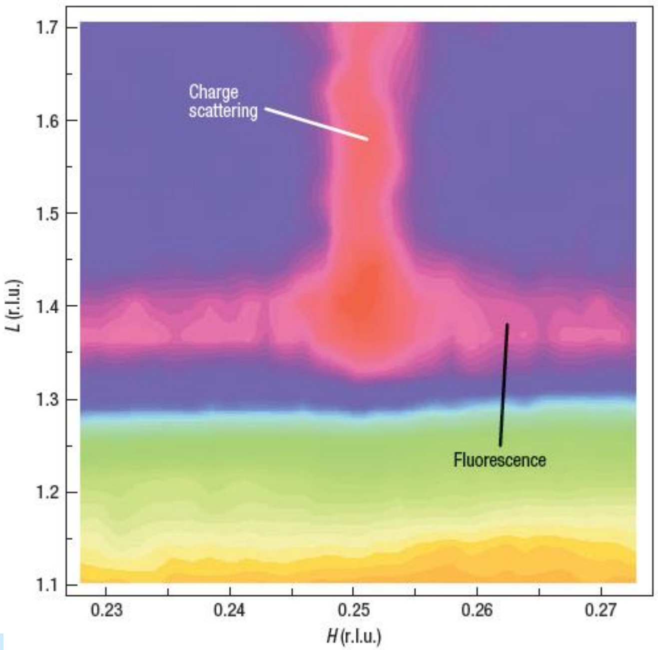
Polarimeter on AXES@ID08: ionic selection rules are confirmed for UD and OD YBCO

How about the elastic peak in RIXS?



The elastic peak is usually small at Cu L_3, and in principle the elastic intensity should all be in the Bragg peaks, i.e. in what is usually measured by RXS, without energy resolution...

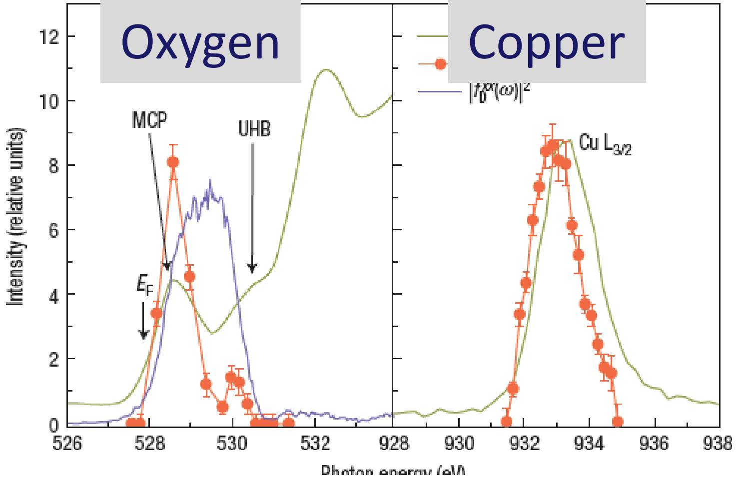
L. Braicovich, et al PRL **104** 077002 (2010)

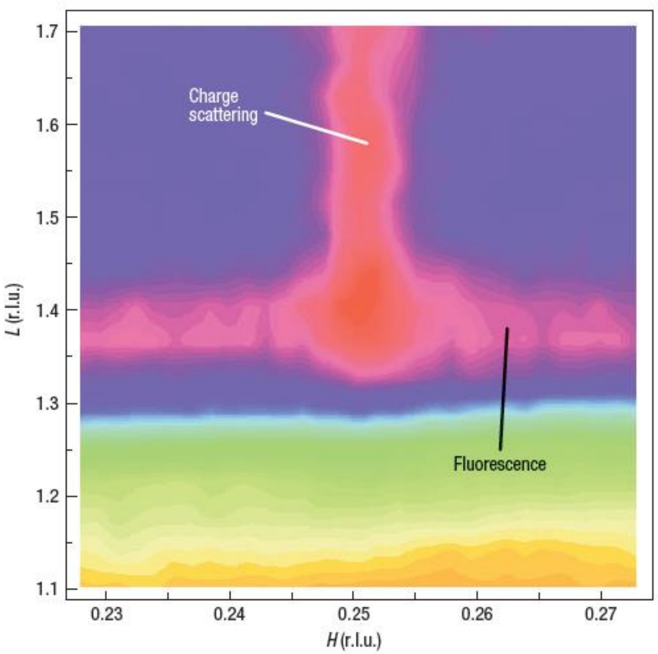


P. Abbamonte et al, Nat. Phys. 1, 155 (2005)

Cu L_3 RXS from stripes in striped cuprates

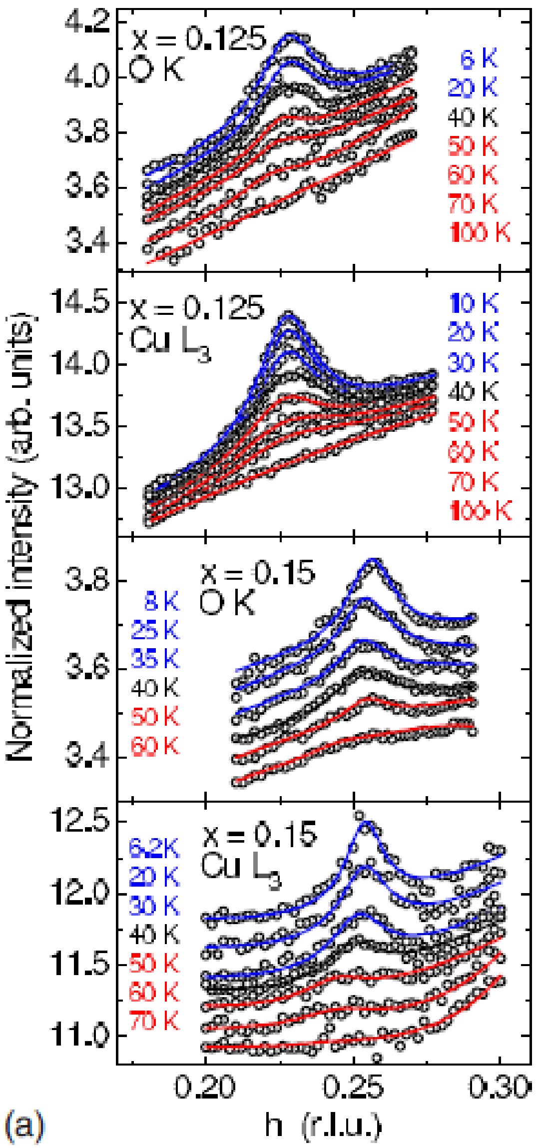
$La_{1.8-x}Ba_xCuO_4$



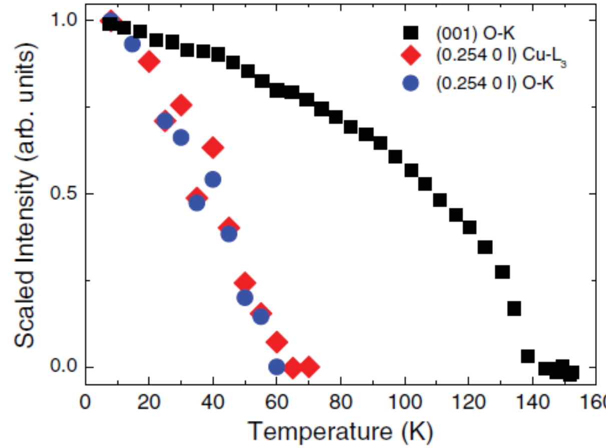


P. Abbamonte et al, Nat. Phys. 1, 155 (2005)

$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$

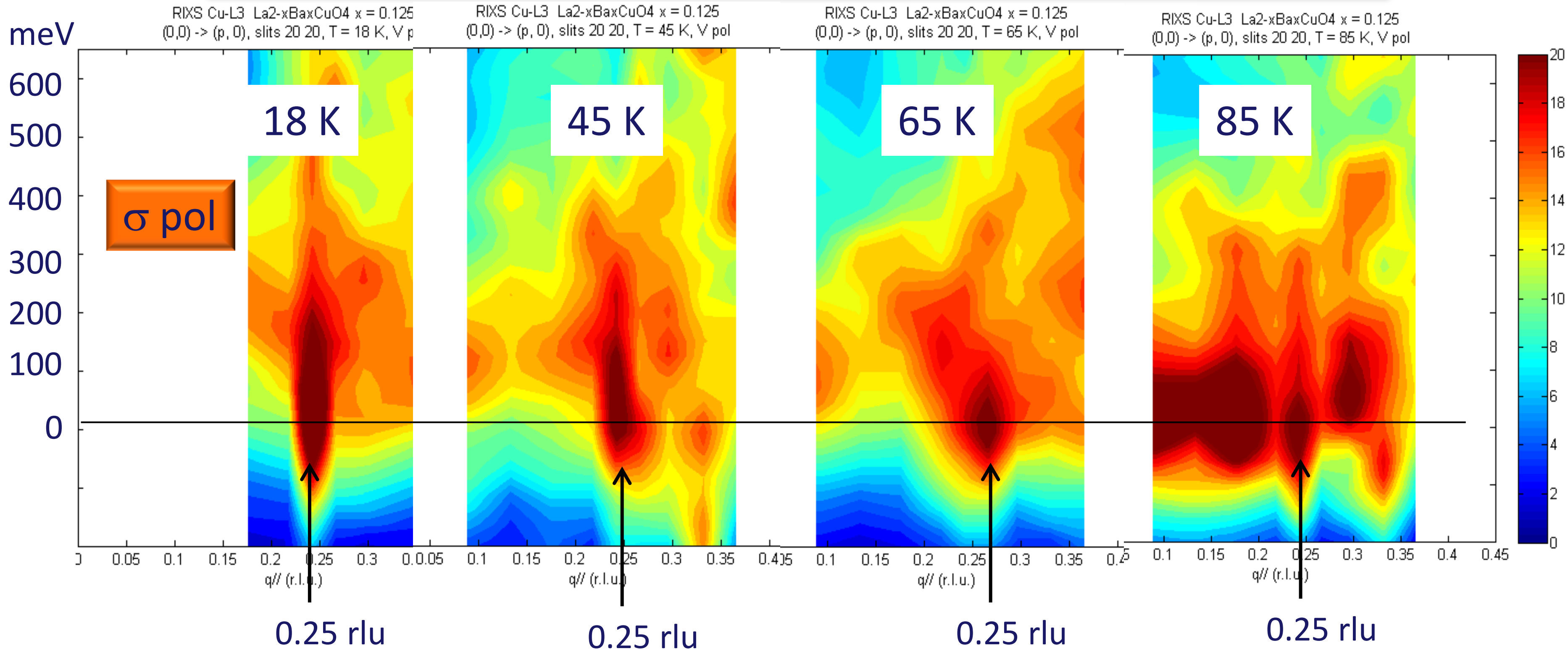


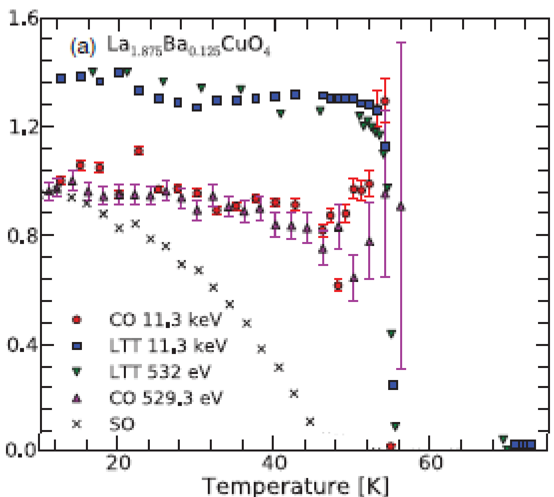
(a)



J. Fink et al, Phys Rev B 79, 100502 (2009); 83 092503 (2011)

Cu L_3 RIXS of LBCO



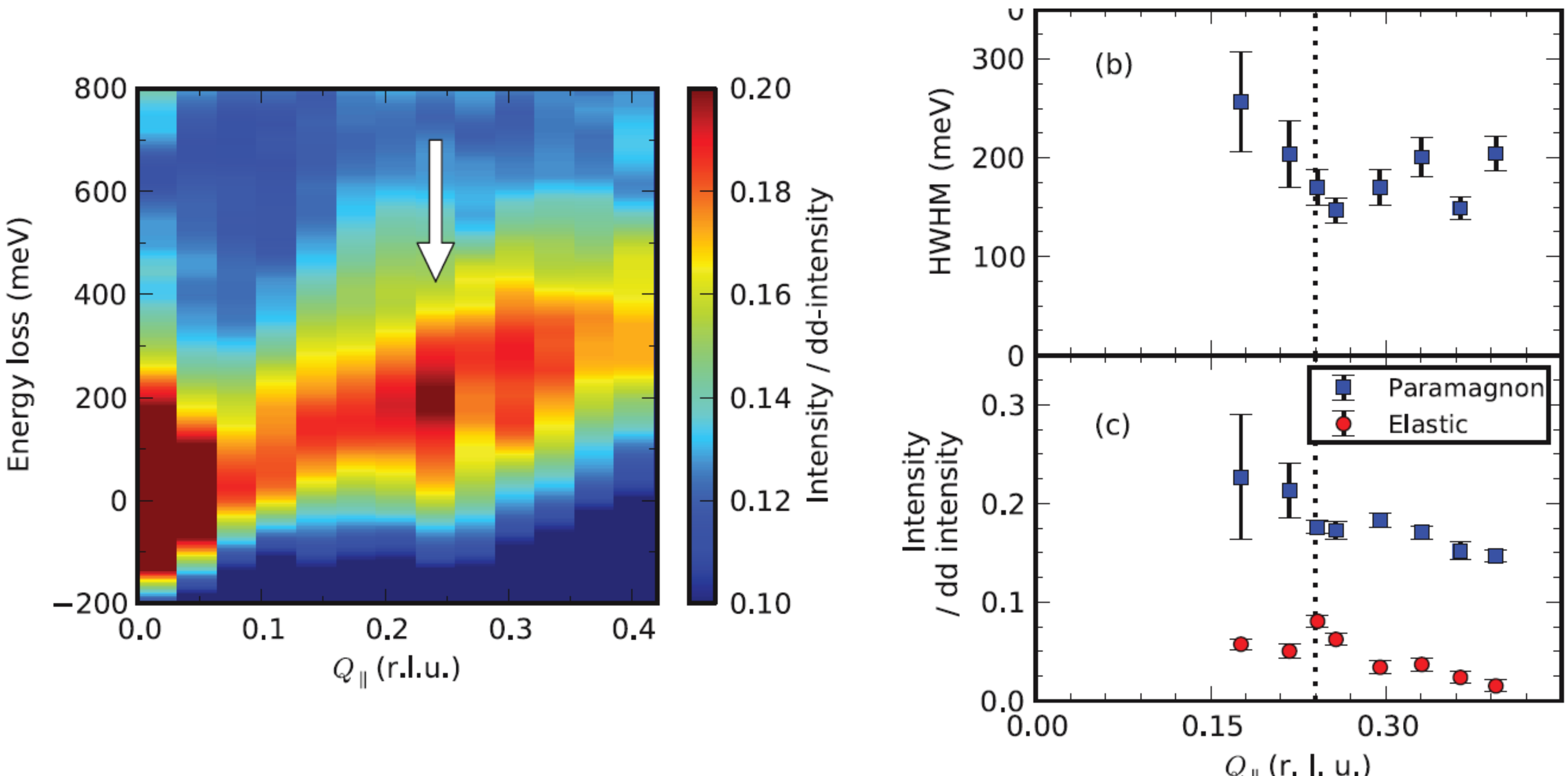


G. Dellea, M.P.M. Dean, M. Minola, N. B. Brookes, M. Le Tacon, S.B. Wilkins, L. Braicovich, J.P. Hill, G. Ghiringhelli, et al unpublished

The charge ordering peak persists above T_{struct}

S.B: Wilkins et al, Phys Rev B 84, 145111 (2011))

Cu L_3 RIXS of LBCO, x=0.125 (striped)

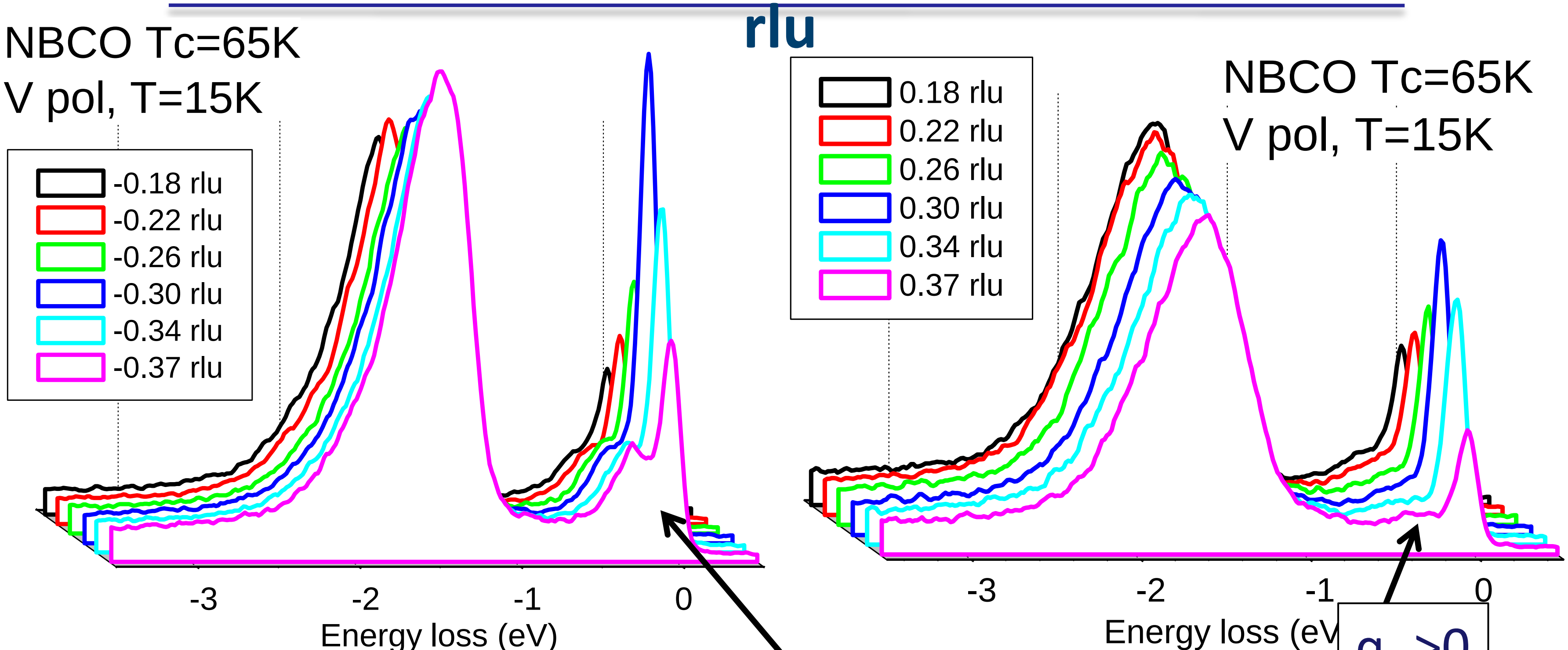


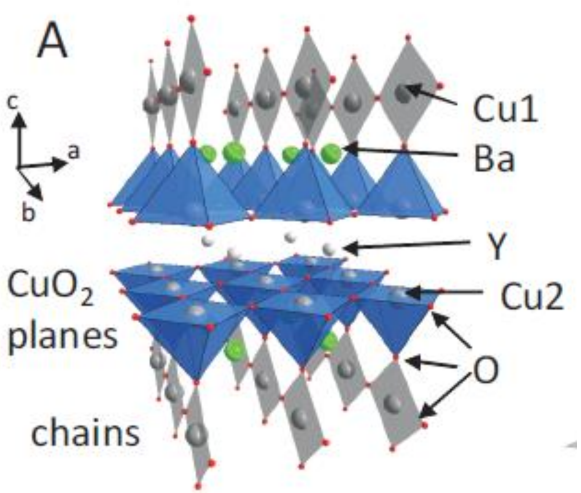
Using π polarization, which enhances spin excitations, the charge ordering wave vector remains significant. However we see no indications of spin order peaks.

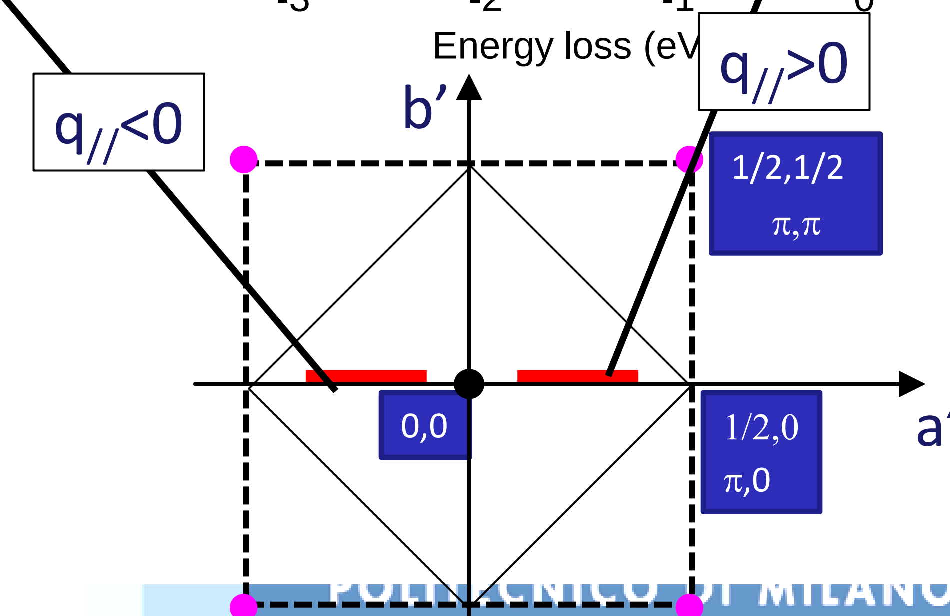
Spin excitation dispersion is visibly modified by stripes.

M. P. M. Dean, G. Dellea, M. Minola, S. B. Wilkins, R. M. Konik, G. D. Gu, M. Le Tacon, N. B. Brookes, F. Yakhou-Harris, K. Kummer, J. P. Hill, L. Braicovich, and G. Ghiringhelli, Phys. Rev. B **88**, 020403(R) (2013)

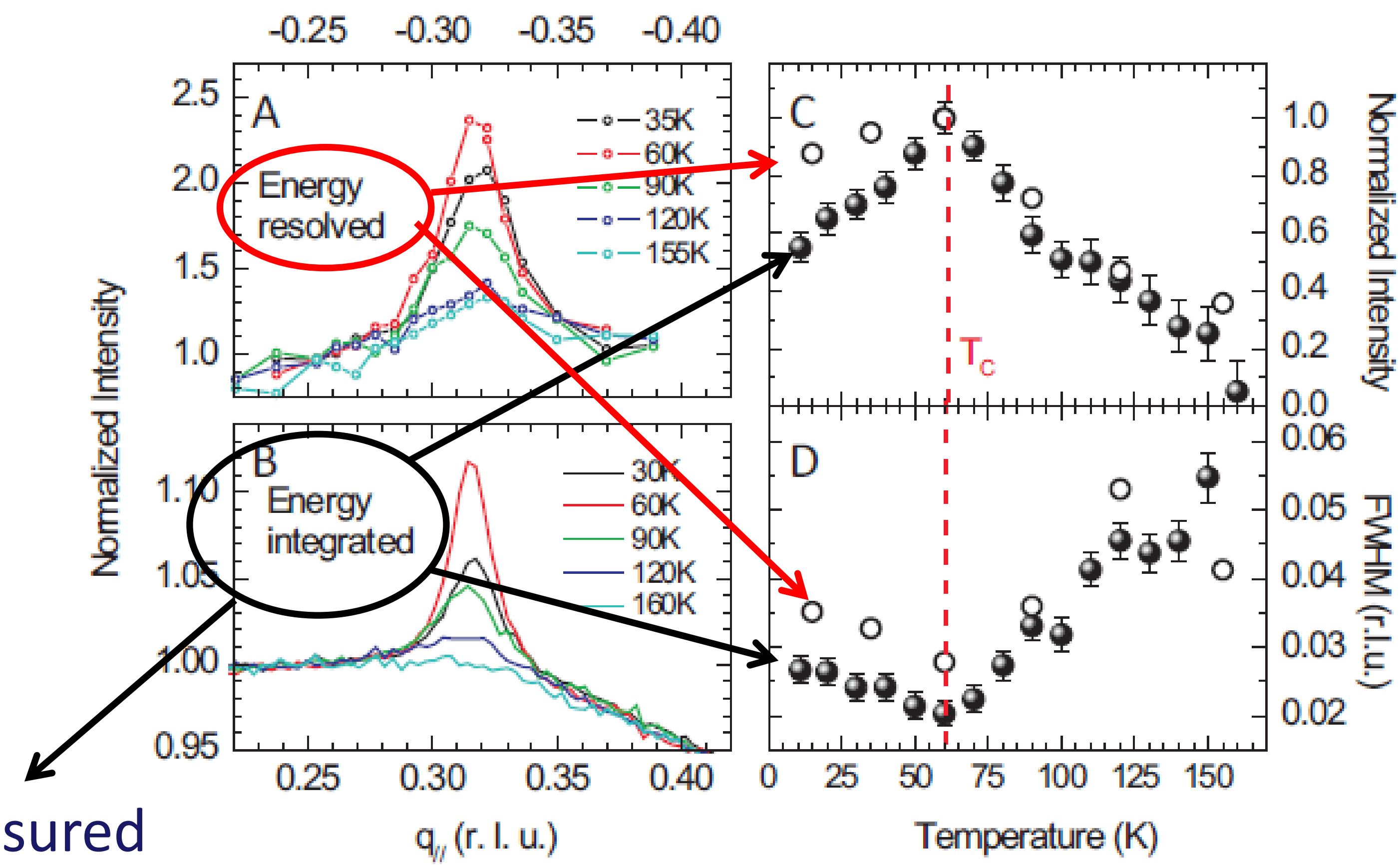
$NdBa_2Cu_3O_{6+y}$: elastic peak enhancement around 0.3 rlu







T dependence



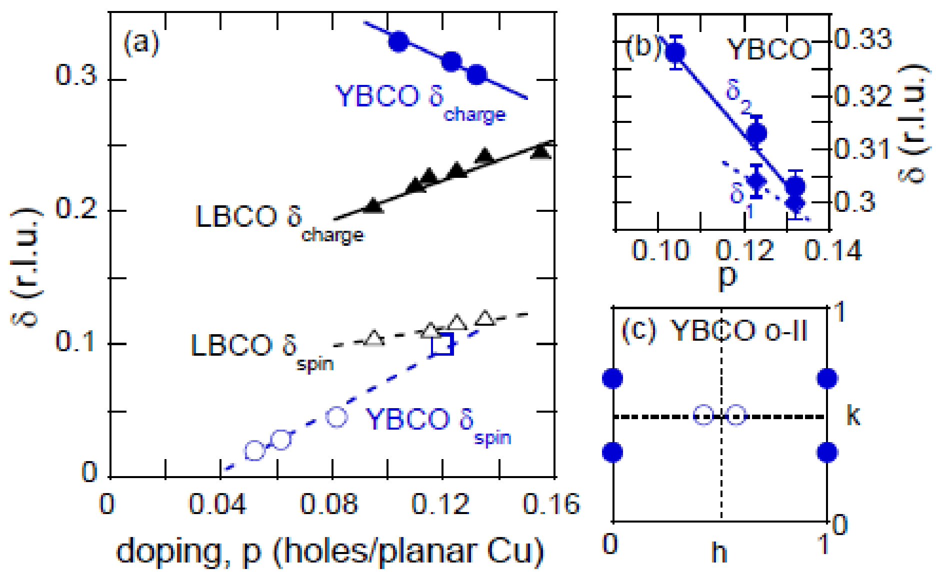
Measured at Bessy

Max intensity at Tc: CDW competes with SC

YBCO: doping dependence

Direct observation of charge density wave order at zero magnetic field in ortho-II $YBa_2Cu_3O_{6.54}$

E. Blackburn,[1] J. Chang,[2,3,*] M. Hücker,[4] A. T. Holmes,[1] N. B. Christensen,[5] Ruixing Liang,[6,7] D. A. Bonn,[6,7] W. N. Hardy,[6,7] M. v. Zimmermann,[8] E. M. Forgan,[1] and S. M. Hayden[9]



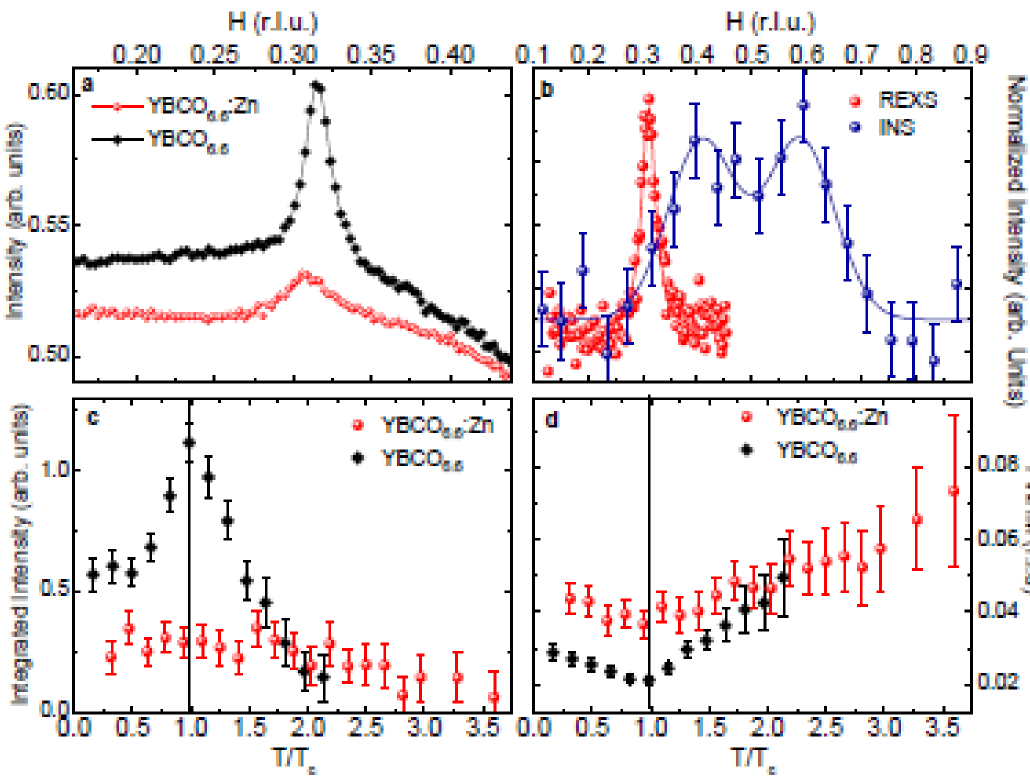
y in YBCO	Oxygen ordering	Doping level p	T_c (K)	T_{CDW} (K)
6.54	o-II	0.104	58	155(10)
6.67	o-VIII	0.123	67	140(10)
6.75	o-III	0.132	74	140(10)

arXiv:1212.3836v1

... and independence of charge and spin ordering WV

Three-phase competition in underdoped $YBa_2Cu_3O_{6+\delta}$

S. Blanco-Canosa,[1] A. Frano,[1,2] T. Loew,[1] Y. Lu,[1] J. Porras,[1] G. Ghiringhelli,[3] M. Minola,[3] C. Mazzoli,[3] L. Braicovich,[3] E. Schierle,[2] E. Weschke,[2] M. Le Tacon,[1] and B. Keimer[1]



tures. Rather than forming a coherent spin- and charge-modulated "striped" state, as in the 214 system, [3, 10–14] spin and charge order are strongly competing in $YBCO_{6+\delta}$. Stripe order is thus not a universal feature of the underdoped cuprates. We further show that

Charge ordering

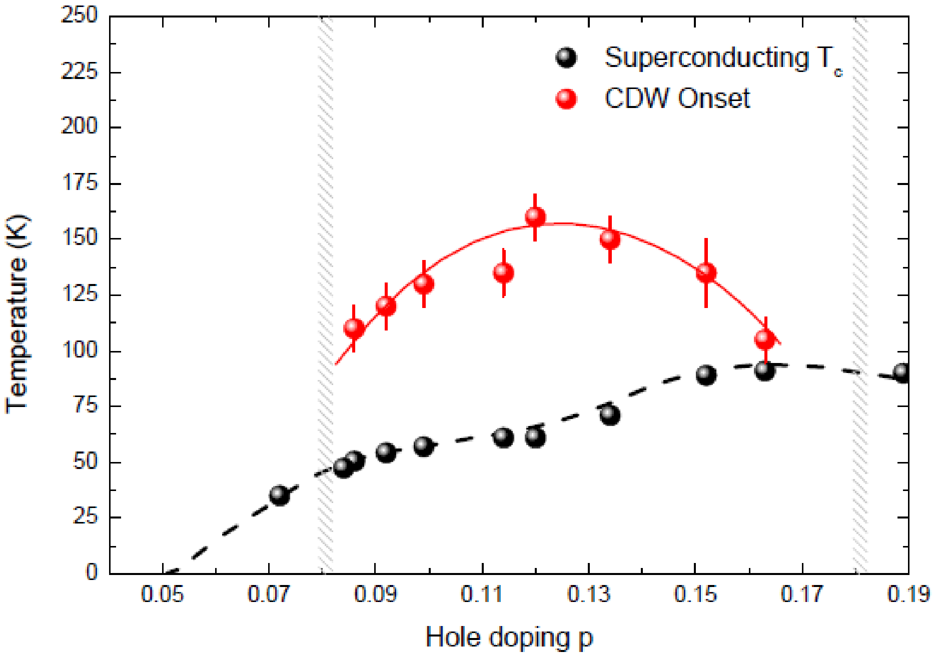
Spin ordering

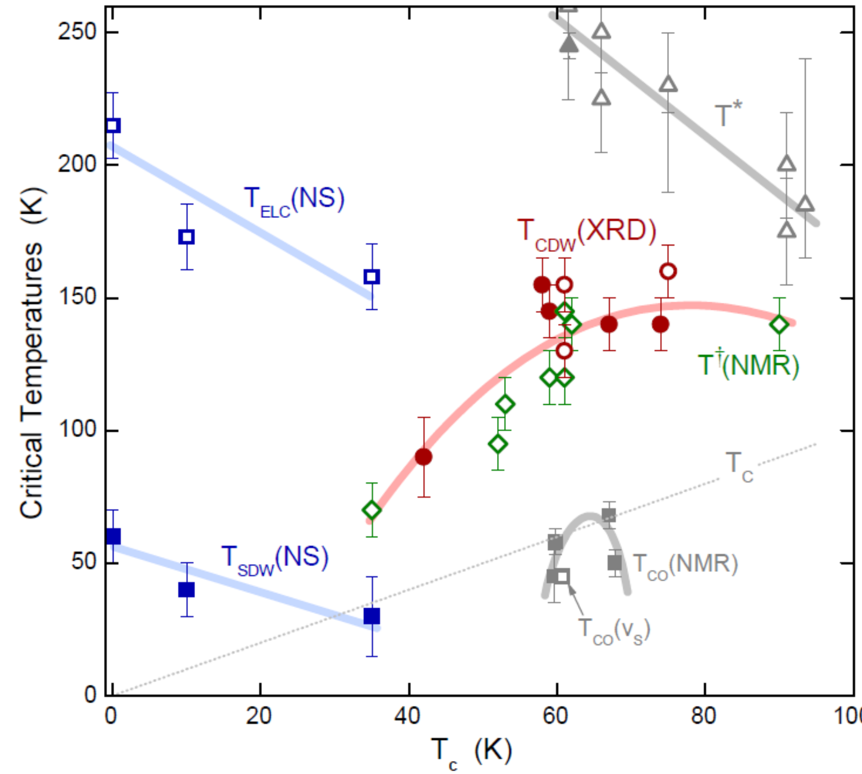
Superconductivity

YBCO6.6

Blanco-Canosa, A. Frano, T. Loew, Y. Lu, J. Porras, G. Ghiringhelli, M. Minola, C. Mazzoli, L. Braicovich, E. Schierle, E. Weschke, M. Le Tacon, and B. Keimer, Phys. Rev Lett. **110**, 187001 (2013)

YBCO doping dependence, up to optimal doping





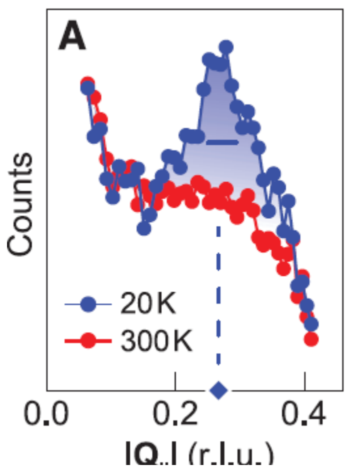
S. Blanco-Canosa, A. Frano, E. Schierle, J. Porras, T. Loew, M. Minola, M. Bluschke, E. Weschke, B. Keimer,, and M. Le Tacon, arXiv 1406.1595v1

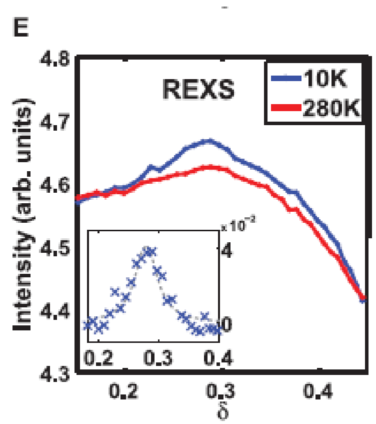
M. H¨ucker, N. B. Christensen, A. T. Holmes, E. Blackburn,3 E. M. Forgan, Ruixing Liang, D. A. Bonn, W. N. Hardy, O. Gutowski, M. v. Zimmermann, S. M. Hayden, and J. Chang, arXiv:1405.7001v1

UD Bi2201, Bi2212, Hg1201 and OPD Bi2212

Bi2201 and Bi2212 underdoped

REXS - UD15K

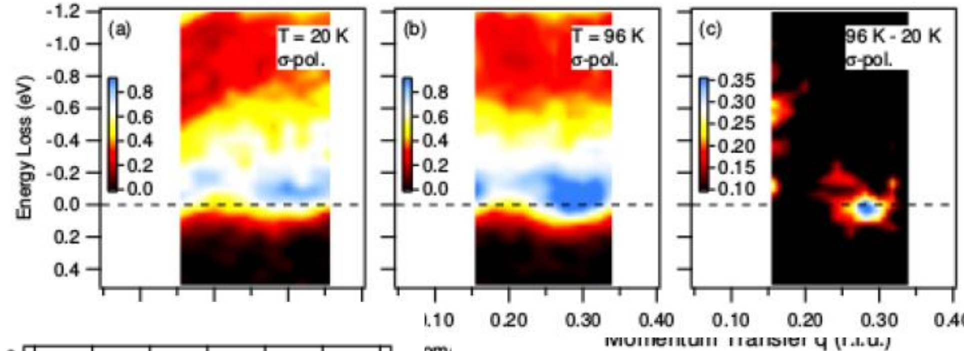


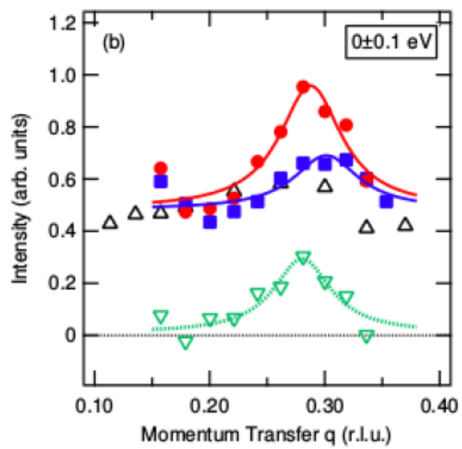


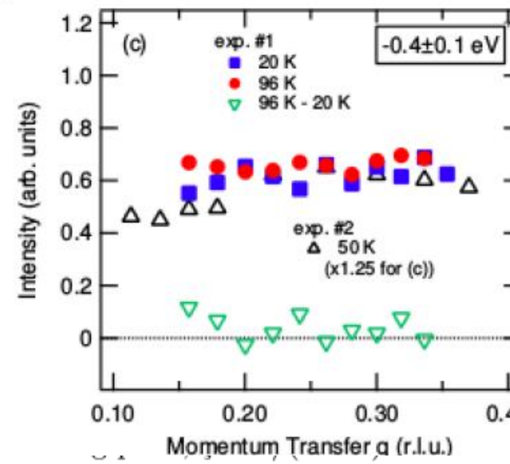
R. Comin et al, Science 343, 390 (2014;

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

Bi2212 optimally doped

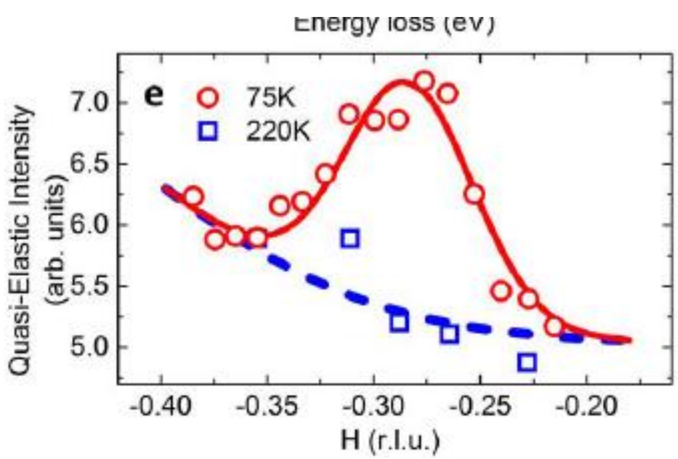






Sample	p	T_c	$q_{\parallel}$ (r.l.u.)	ξ (Å)	refs.
Bi2201	0.115	15	0.265	26	[16]
Bi2201	0.130	22	0.257	23	[16]
Bi2201	0.145	30	0.243	21	[16]
Bi2212	0.09	45	0.30	24	[15]
Bi2212	0.160	98	0.28	<24 (at T_c)	this work
YBCO	0.115	61	0.32	∼60 (at T_c)	[8, 10]
LBCO	0.125	2.5	0.236	∼200	[4, 6–8]
LBCO	0.155	30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

Hg1201 underdoped



W. Tabis et al, Nat. Comm. In press (2014)

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

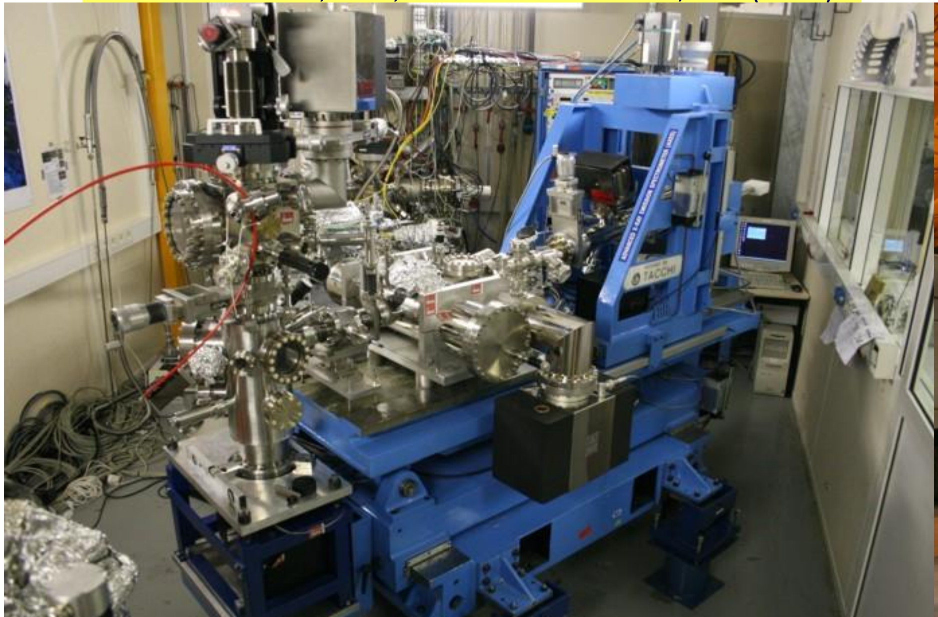
AXES (ESRF, ID08) and SAXES (SLS, ADRESS)

Since 1994: AXES at beam line ID08 of the ESRF
L = 2.2 m
Design: ***E*/Δ*E* = 2,000 at Cu L_3 (930 eV)**
2010: ***E*/Δ*E* = 5,000 at Cu L_3**

Since 2007: SAXES at beam line ADRESS of the SLS
L = 5.0 m
Design: ***E*/Δ*E* = 12,000 at Cu L_3**
2008: ***E*/Δ*E* = 10,000 at Cu L_3**

C. Dallera *et al*. J. Synchrotron Radiat. **3**, 231 (1996)
G. Ghiringhelli *et al.*, Rev. Sci. Instrum. **69**, 1610 (1998)
M. Dinardo *et al.*, Nucl, Instrum. Meth A **570**, 176 (2007)

G. Ghiringhelli, et al Rev. Sci. Instrum. **77**, 113108 (2006)
V. Strocov, T. Schmitt, L. Patthey et al, J. Synch. Rad., 17, 631 (2010).

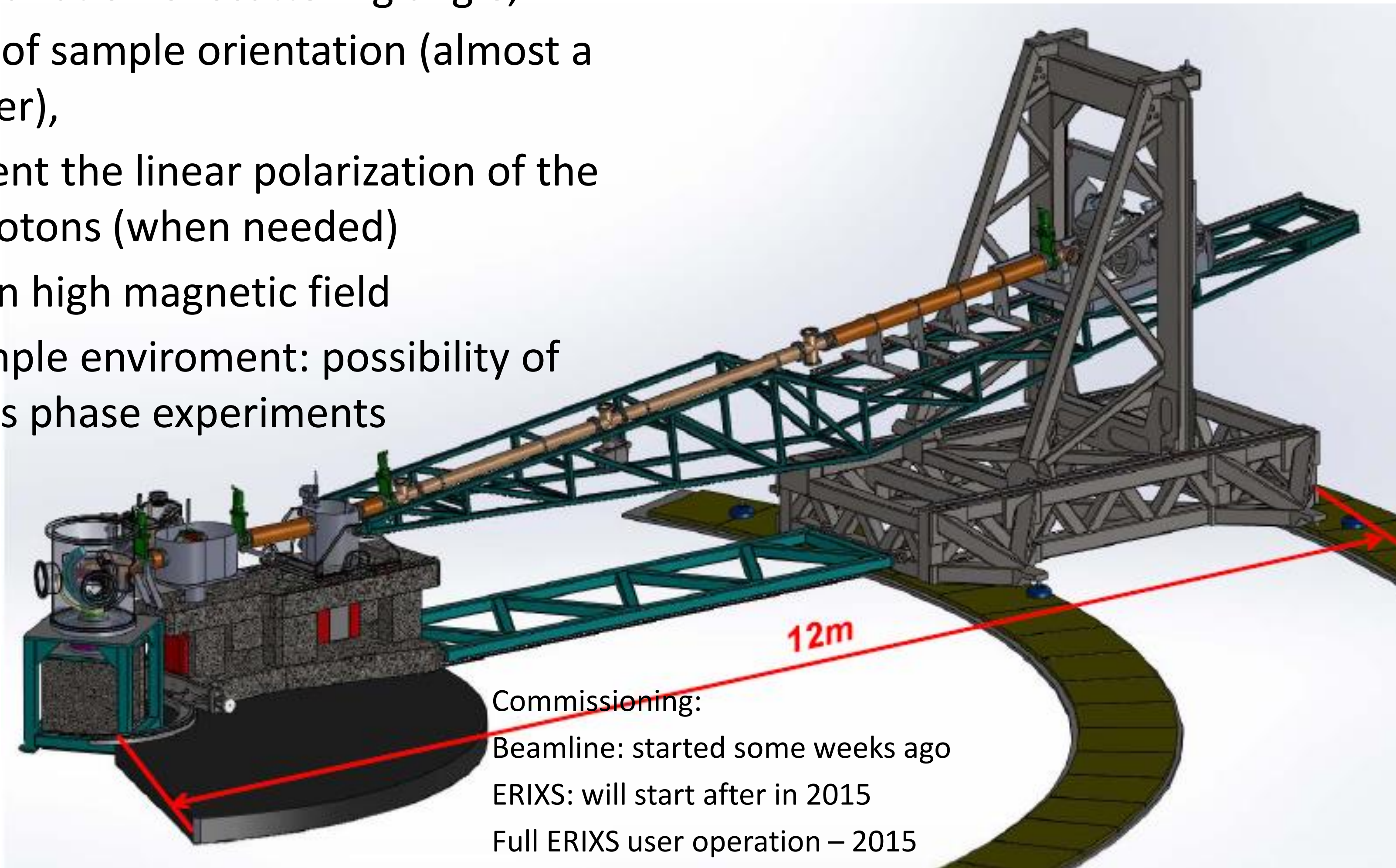


ERIXS spectrometer at the new ID32

FEATURES:

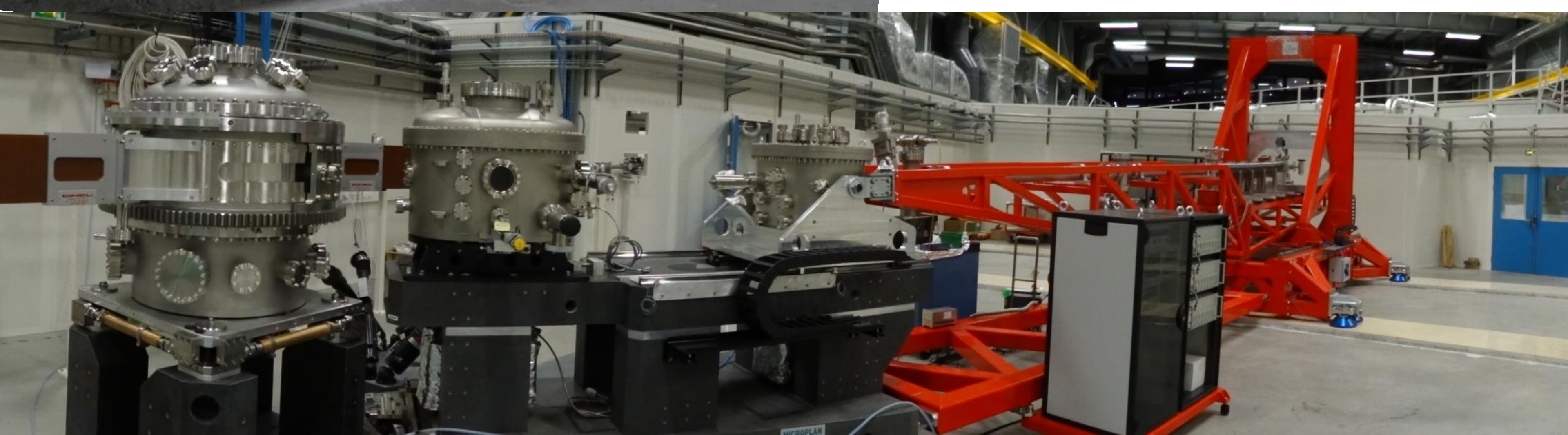
- *E/ΔE* > 20,000 below 1000 eV from day one (50 meV at Cu L_3) and *E/ΔE* > 30,000 ultimate
- continous variation of scattering angle,
- full control of sample orientation (almost a diffractometer),
- measurement the linear polarization of the scattered photons (when needed)
- optionally in high magnetic field
- flexible sample enviroment: possibility of liquid and gas phase experiments

ESRF Upgrade programme,
N.B. Brookes, F. Yakhou, GG



Commissioning:
Beamline: started some weeks ago
ERIXS: will start after in 2015
Full ERIXS user operation – 2015

ERIXS, 21/10/2014



The European Users Consortium Heisenberg RIXS at XFEL

Alexander Föhlisch, Helmholtz-Zentrum Berlin and Uni Potsdam

Giacomo Ghiringhelli, Dip. Fisica, Politecnico di Milano
Marco Grioni, Ecole Polytechnique Fédérale de Lausanne
Rafael Abela, Paul-Scherrer-Institute
Torsten Schmitt, Paul-Scherrer-Institute
Bernhard Keimer, Max-Planck-Institut für Festkörperf
Simone Techert, Max-Planck-Institut für biophysikalis
Jan-Erik Rubensson, Uppsala University
Joseph Nordgren, Uppsala University
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Matias Bargheer, Uni Potsdam
Jeroen van den Brink, IFW Dresden
Simo Huotari, Oulu, Finland
Maurits W. Haverkort, Max-Planck-Institut für Festkör
Frank de Groot, Utrecht University
Stefan Eisebitt, Technische Universität Berlin
Andrea Cavalleri, CFEL Hamburg, Oxford U.
Marc Simon, Laboratoire Chimie-Physique-Matière et
Alexei Erko, Helmholtz-Zentrum Berlin
Alexander Föhlisch, Helmholtz-Zentrum Berlin and U

XFEL SASE3: Andreas Scherz, Serguei Molodtsov

Recent expression of interest by STFC and UK scientific community

Working Group DESY/HZB/POLIMI/XFEL:
A. Foehlisch
Giacomo Ghiringhelli
Tim Laarmann
Simone Techert
Andreas Scherz
Wilfried Wurth

hRIXS: RIXS at the European XFEL

5-6 m scattering arm

Continuous rotation in backscattering (2θ = 60° - 150°)

Possibility of full forward scattering (2θ = 0° - 20°)

Up to 20,000 resolving power

TR-RIXS non-linear RIXS

Conclusions

Cu L_3 RIXS tells us that:

- Magnetic excitations perist up to very OVD regime
- Their dependence on E_{in} indicate they are collective excitations, rather than SF particle-hole excitations
- Charge ordering in HTS is rather ubiquitous, but difficult to observe
- RXS can be used to learn more on CO, but some info can come only from XRD
- Spin-order modulations are even more difficult to detect with x-rays, but signatures might be found in the paramagnon dispersion measured by RIXS
- RIXS can probe the relevant phonons too: we will study them with higher resolution

Thanks