Anisotropic dispersion of the spin excitations in a cuprate superconductor

Oleh Ivashko

University of Zurich[UZH]

Physik-Institut

Team

University of Zurich UZH

J. Chang
C. E. Matt
D. Destraz
C. Monney

EPFL – École Polytechnique Fédérale de Lausanne

C. G. Fatuzzo
N. E. Shaik
H. M. Rønnow

Paul Scherrer Institut PSI

X. Lu
M. Dantz
D. E. McNally
T. Schmitt

DTU – Technical University of Denmark

N. B. Christensen

uclan – University of Central Lancashire

P. G. Freeman

Hokkaido University

T. Kurosawa
N. Momono
M. Oda

Outline

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- Resonant Inelastic X-ray Scattering (RIXS)
- RIXS on cuprates

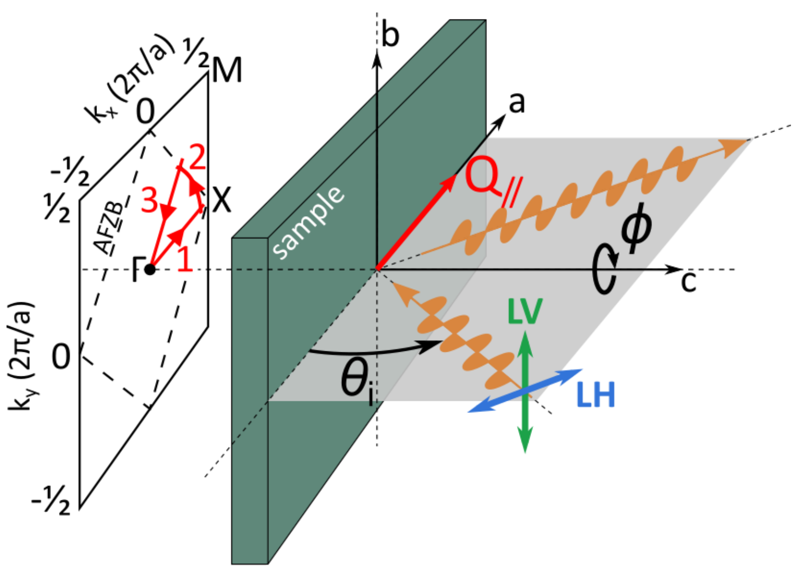
Magnetic excitations on LSCO 12%

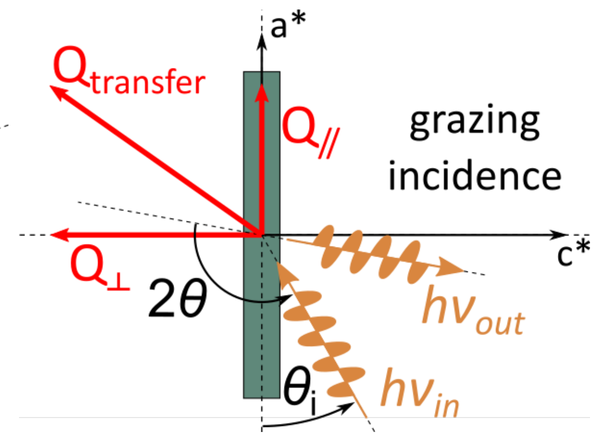
- Overview of the data
- Extraction of the magnetic-excitations dispersion
- Hubbard model
- LSCO vs. LCO comparison

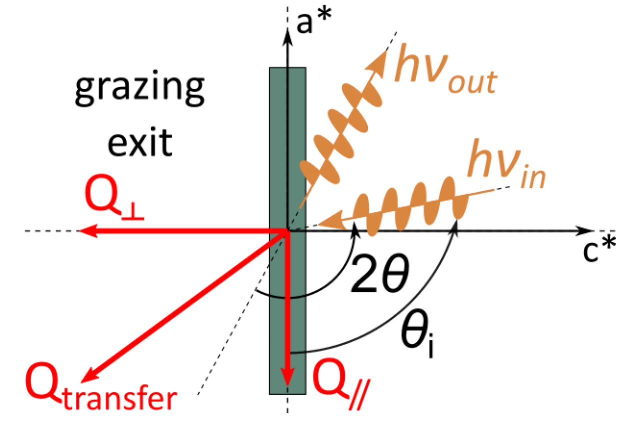
Two orbital model & data interpretation

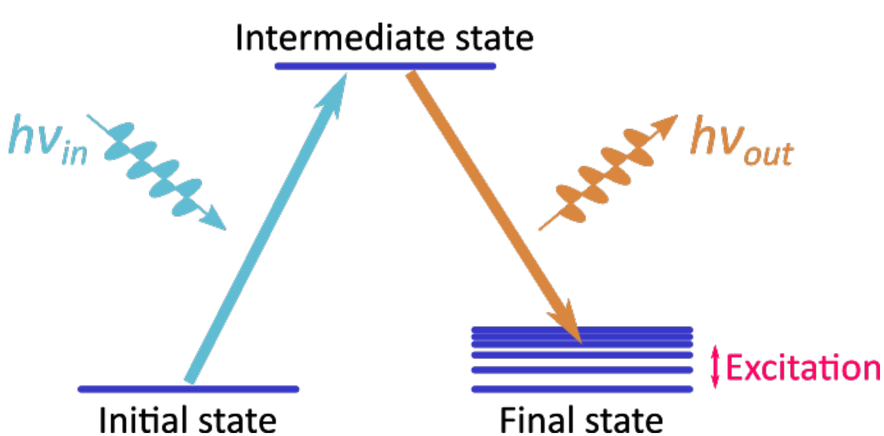
Conclusions

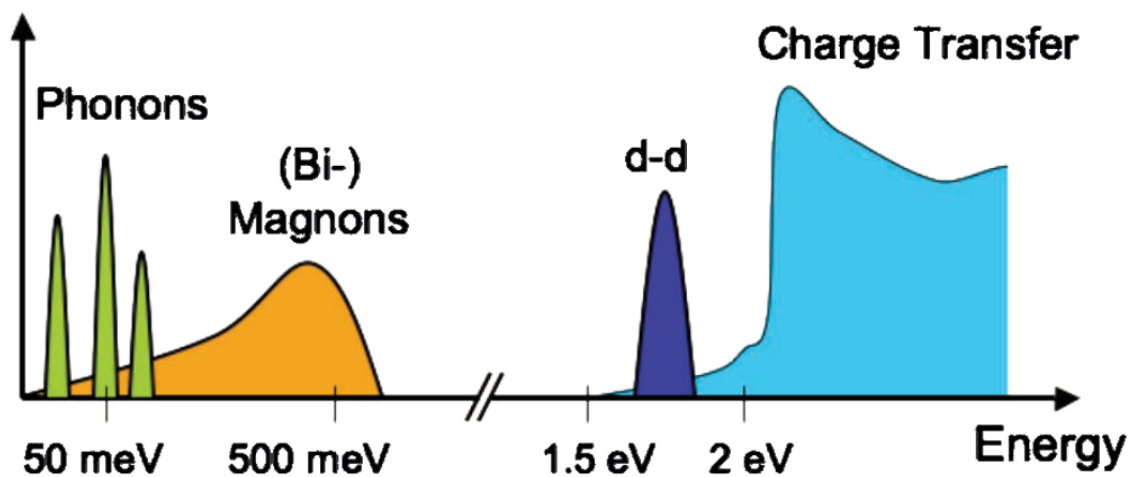
Introduction: RIXS





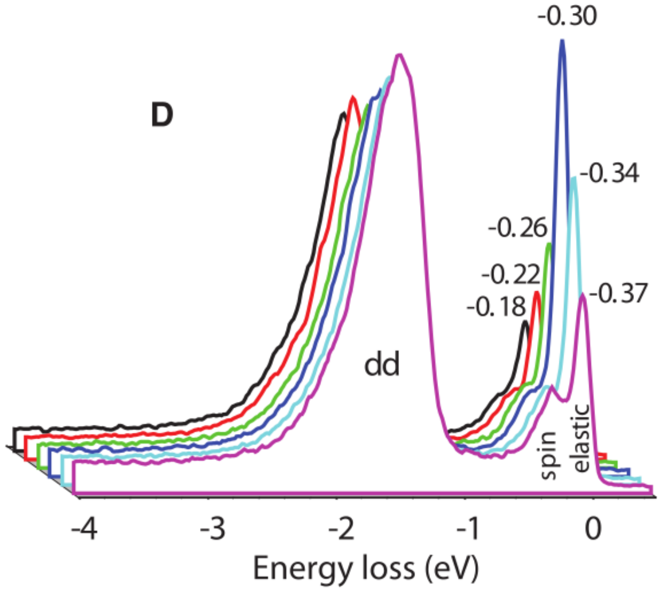




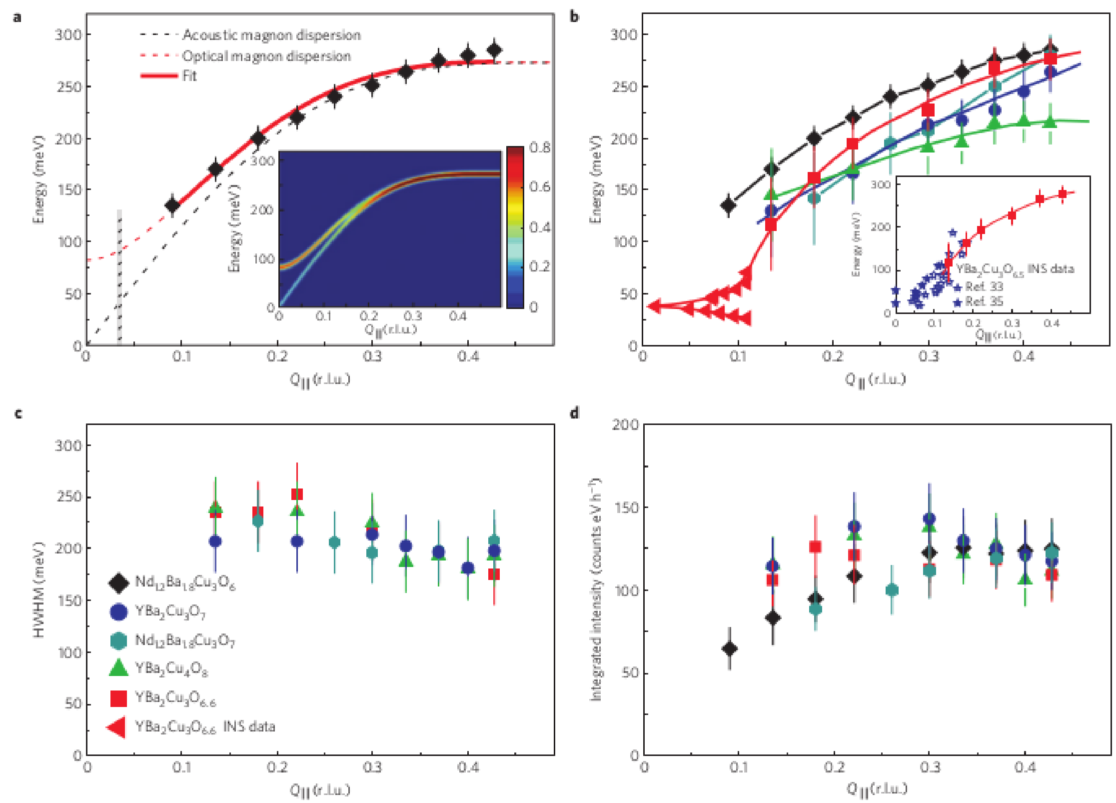


Adapted from L. J. P. Ament, *et al.*, Rev. of Mod. Phys., 83 (2011)

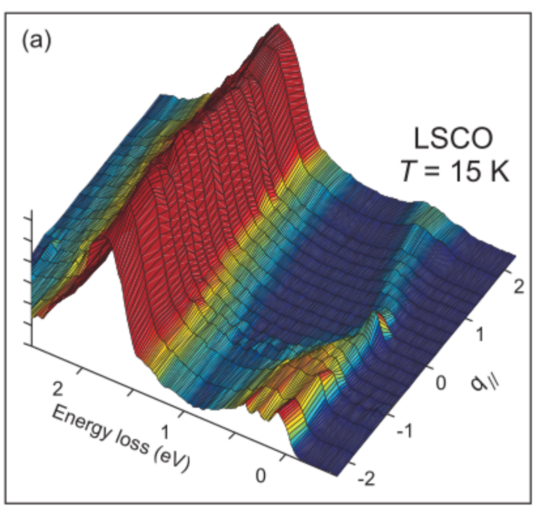
Introduction: RIXS on cuprates



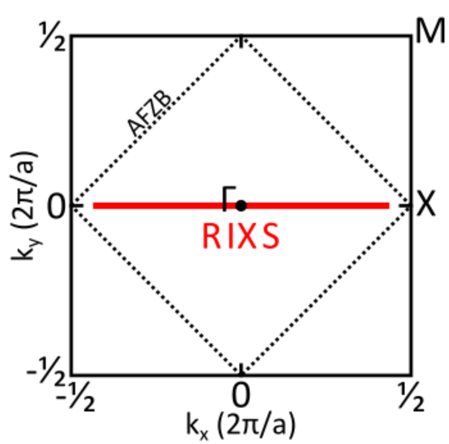
G. Ghiringhelli *et al.*, Science 6096, 821 (2012)



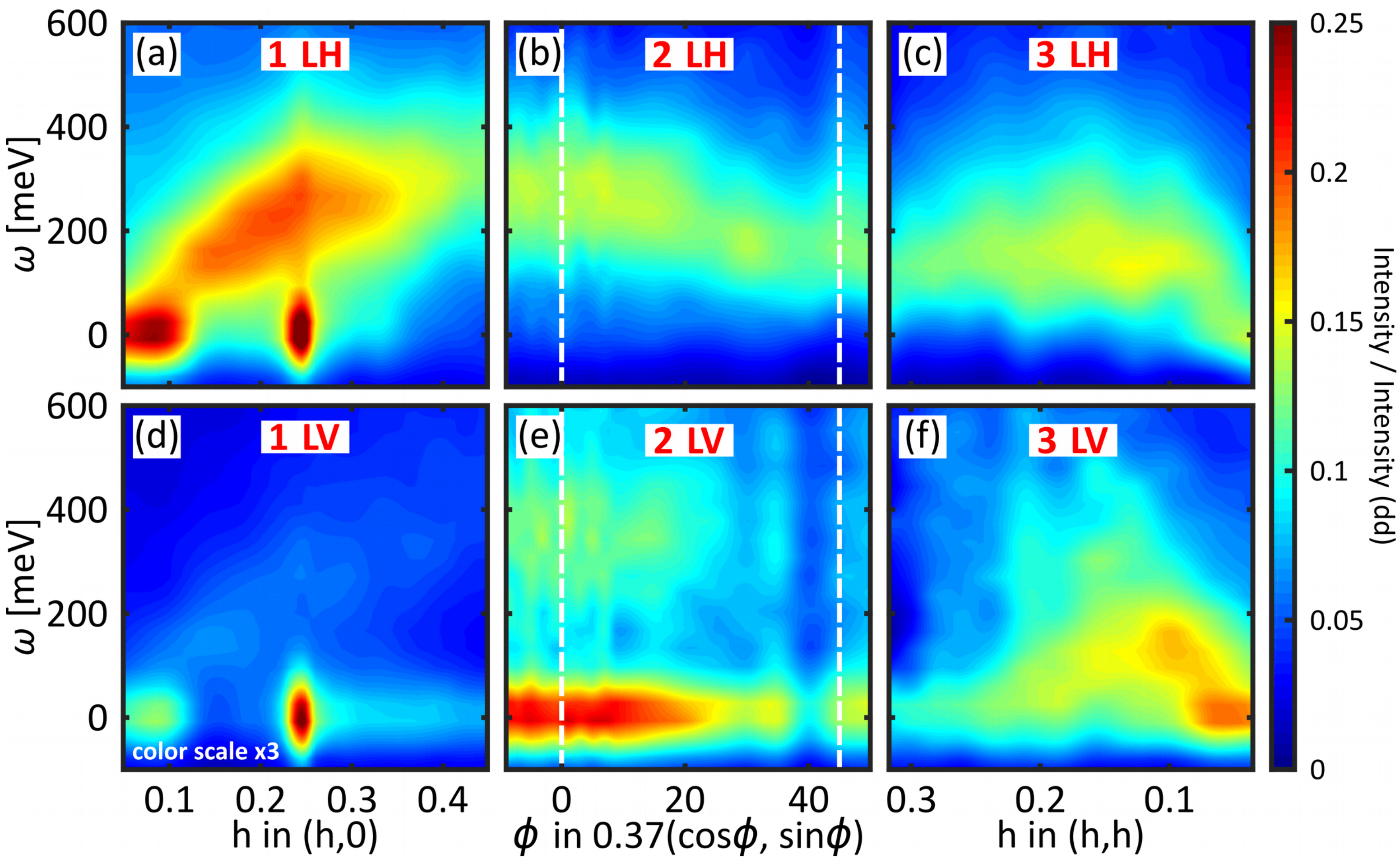
M. Le Tacon *et al.*, Nature Physics 7, 725–730 (2011)

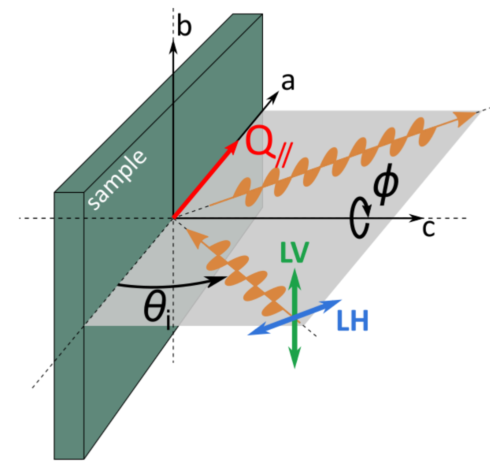


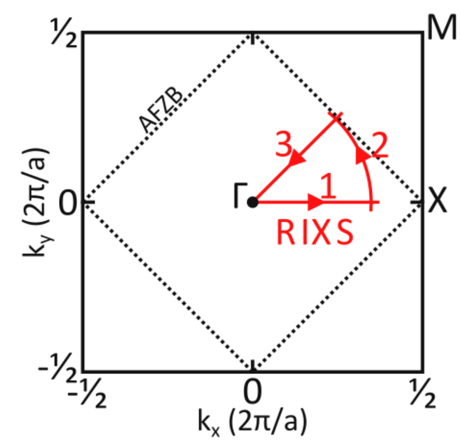
L. Braicovich *et al.*, PRL 104, 077002 (2010)



Magnetic excitations on LSCO 12%: Overview of the data







$Q_{CDW} = (\pm\delta_1,\delta_2)$

$\delta_1 = 0.24(6)$ rlu

$\delta_2 \approx 0.01$ rlu

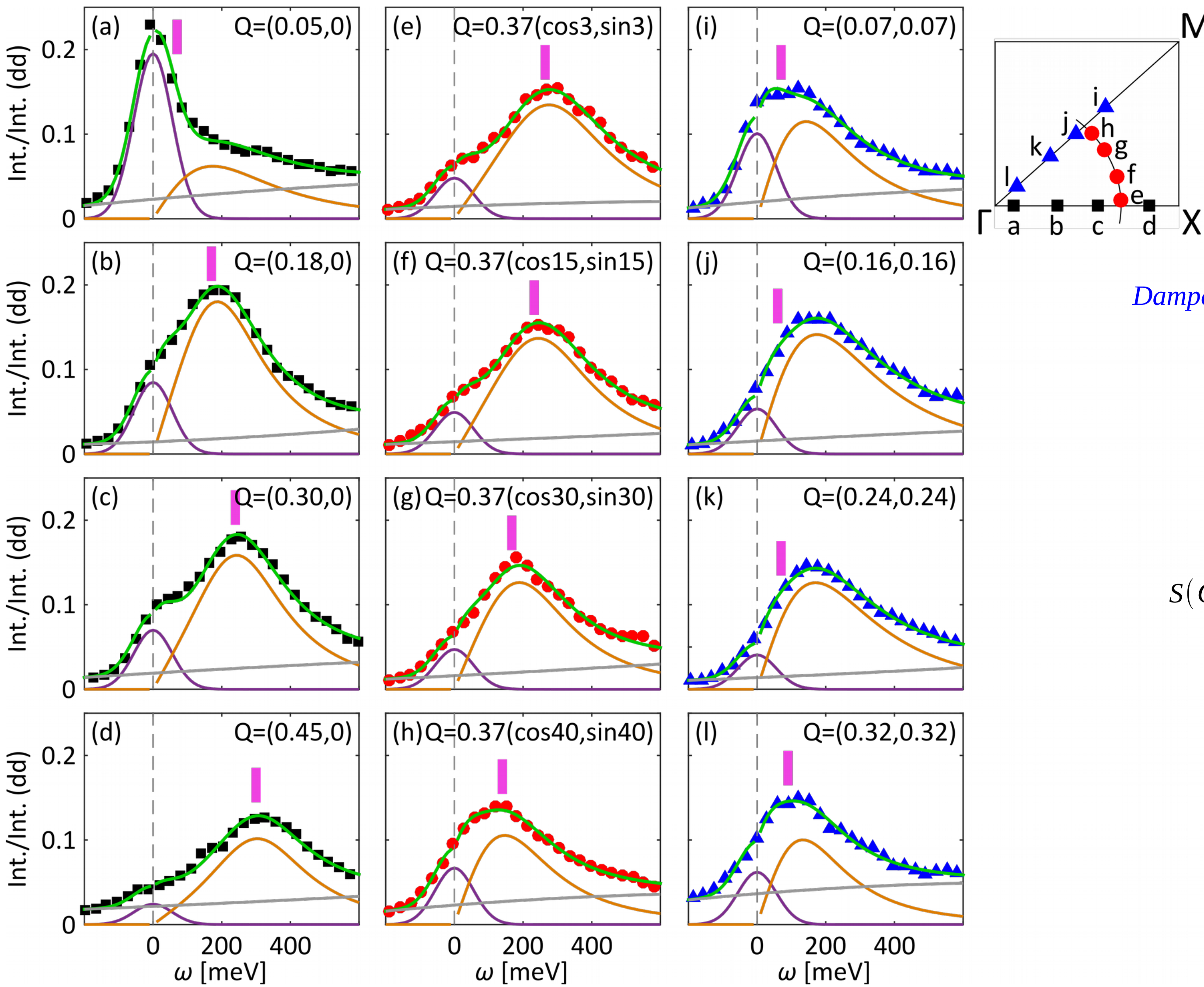
V. Thampy *et al.*, PRB 90, 100510 (2014)
T. P. Croft *et al.*, PRB 89, 224513 (2014)

Magnetic excitations stronger for LH light
under grazing exit scattering conditions

M. Le Tacon *et al.*, Nature Physics 7, 725–730 (2011)

O. Ivashko *et al.*, PRB 95, 214508 (2017)

Magnetic excitations on LSCO 12%: Paramagnons



Damped harmonic oscillator response function

$$\chi'' = \chi''_0 \frac{\gamma\omega}{\left[\omega^2-\omega_0^2\right]^2+\omega^2\gamma^2}$$

Damping coefficient

$$(\gamma/2)=\sqrt{\omega_0^2-\omega_1^2}$$

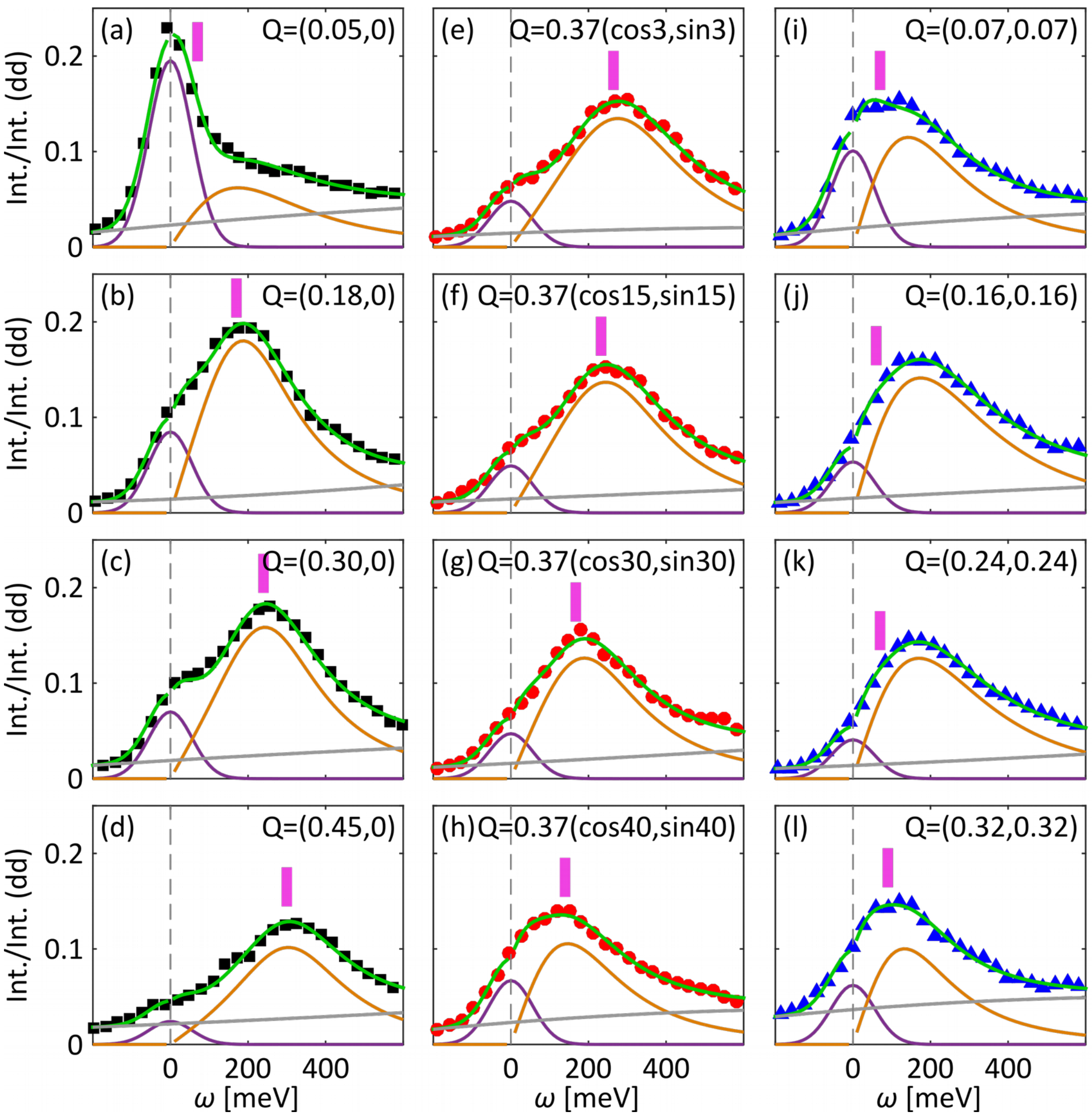
Dynamical Stucture Factor

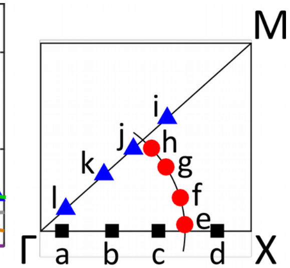
$$S(Q,\omega)=\frac{1}{1-\exp(\hbar\omega/k_B T)} * \chi''(Q,\omega)$$

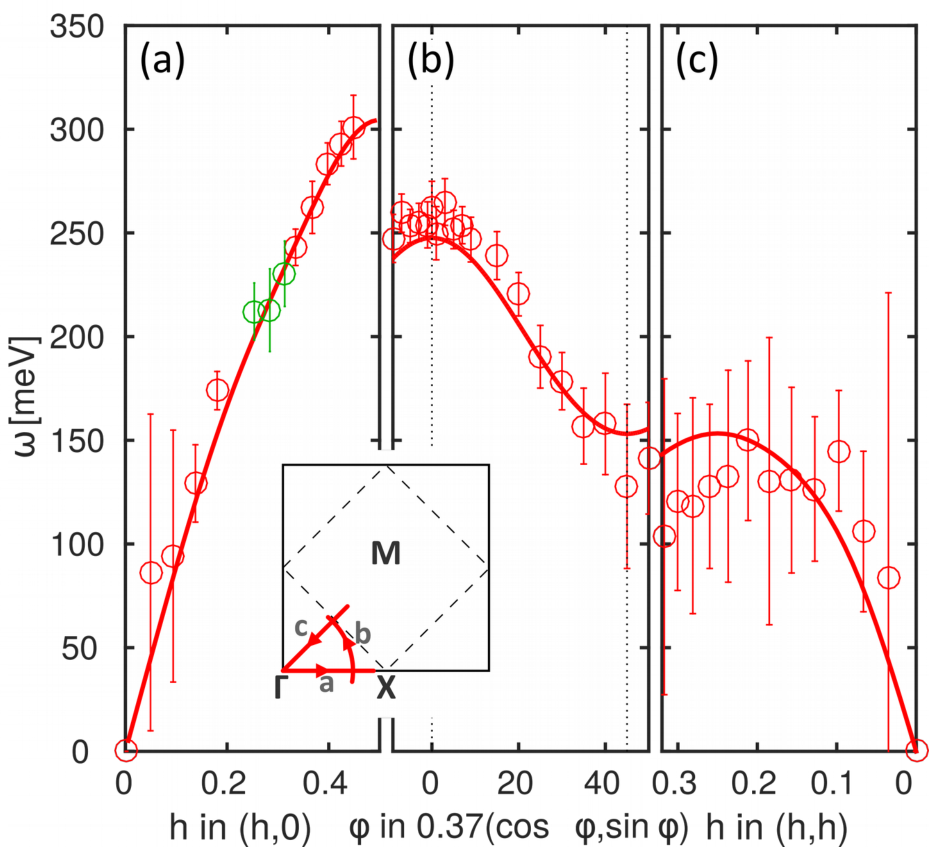
C. Monney, *et al.*, PRB 93, 075103 (2016); J. Lamsal and W. Montfrooij, PRB 93, 214513 (2016)

O. Ivashko *et al.*, PRB 95, 214508 (2017)

Magnetic excitations on LSCO 12%: Paramagnons





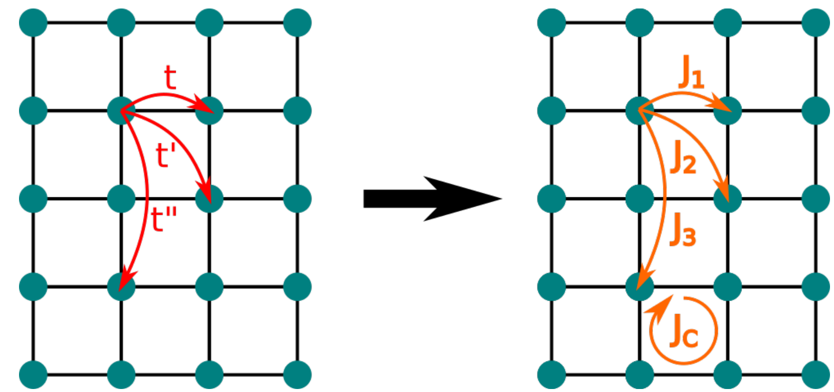


O. Ivashko *et al.*, PRB 95, 214508 (2017)

Magnetic excitations on LSCO 12%: Hubbard model

Hamiltonian

$$H_H = -t \sum_{i,j_1;\sigma} c^{\dagger}_{i,\sigma} c_{j_1,\sigma} - t' \sum_{i,j_2;\sigma} c^{\dagger}_{i,\sigma} c_{j_2,\sigma} - t'' \sum_{i,j_3;\sigma} c^{\dagger}_{i,\sigma} c_{j_3,\sigma} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$



Dispersion relation

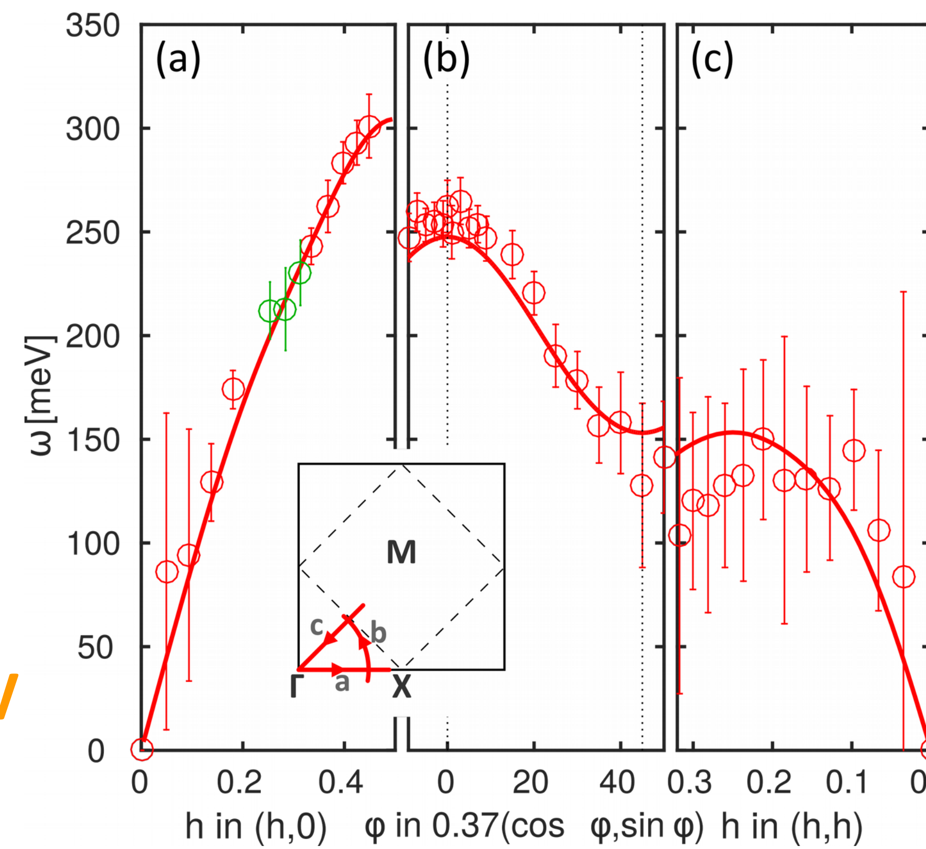
$$\omega(\boldsymbol{q}) = Z\sqrt{A(\boldsymbol{q})^2 - B(\boldsymbol{q})^2}, Z = 1.219$$

Zone-boundary dispersion

$$E_{ZB} = \omega\left(\frac{1}{2}, 0\right) - \omega\left(\frac{1}{4}, \frac{1}{4}\right)$$

Case (1) $E_{ZB} = 12 Z J_B, \quad J_B = \frac{4t^4}{U^3}$

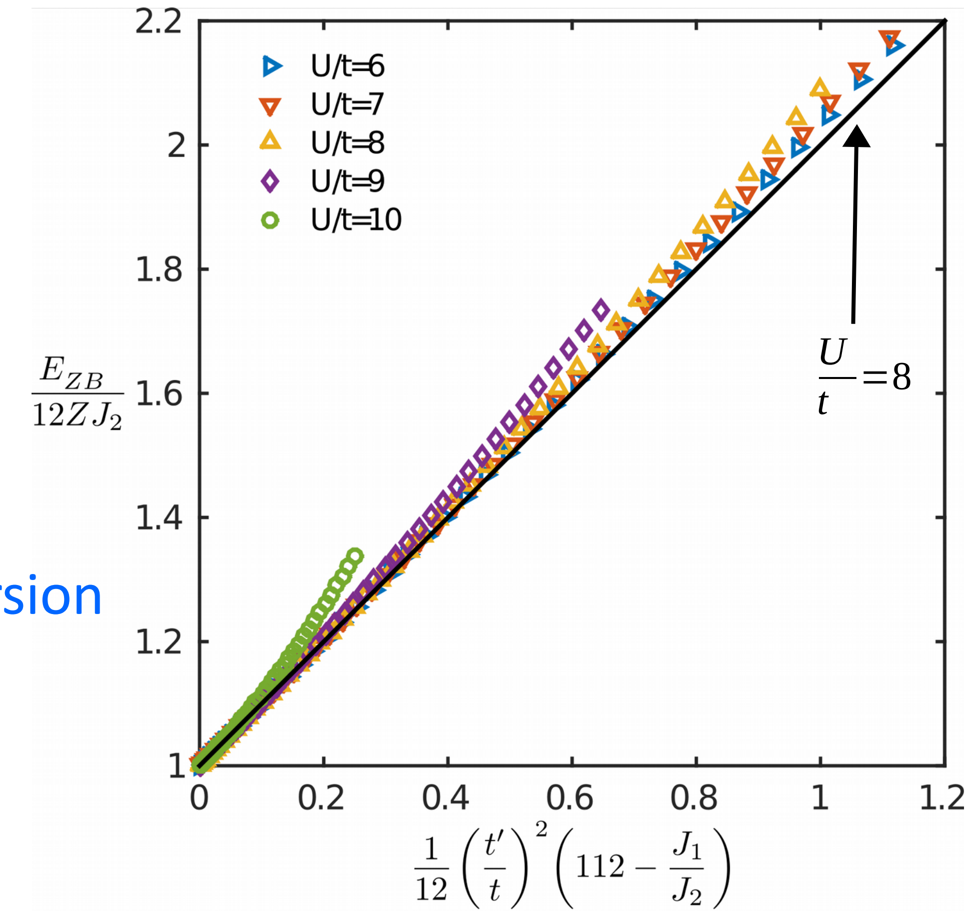
for $t' = t'' = 0$

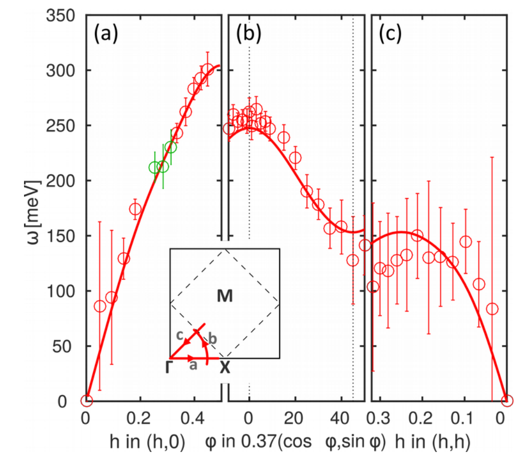


If *t* = 430 meV, *U/t* = 8 ⟶ E_{ZB} ≈ 50 meV

J.-Y. P. Delannoy *et al.*, PRB 79, 235130 (2009); O. Ivashko *et al.*, PRB 95, 214508 (2017)

Magnetic excitations on LSCO 12%: Hubbard model





Zone-boundary dispersion

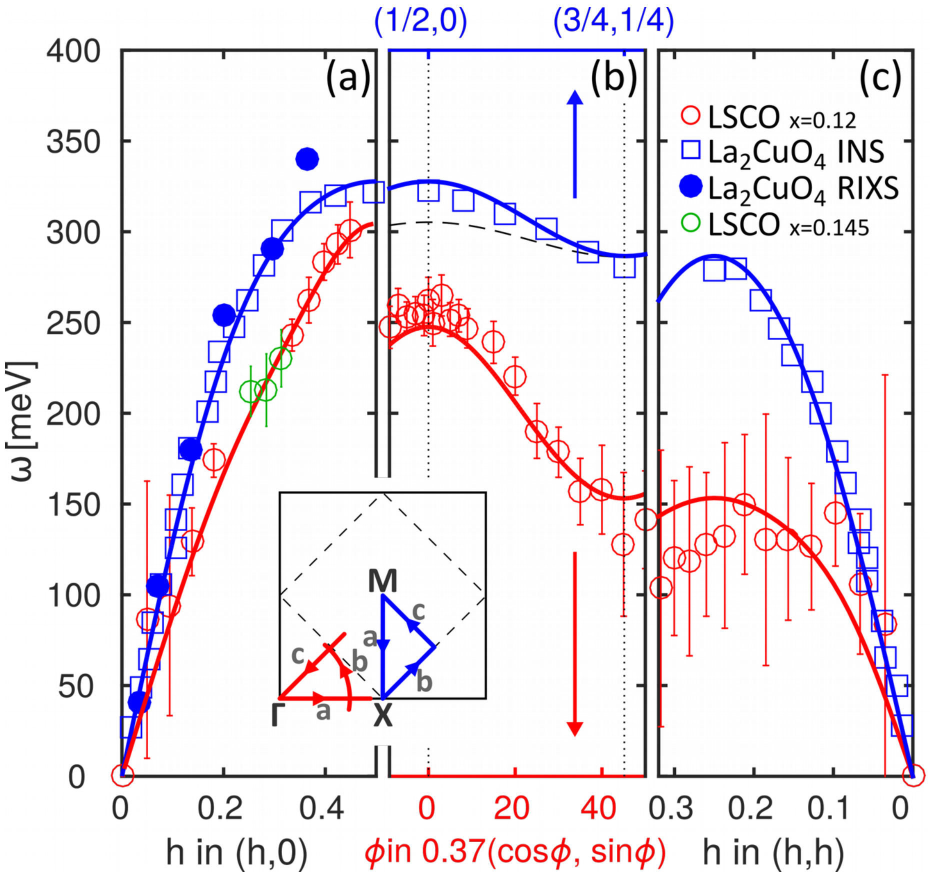
$$E_{ZB}=\omega\left(\frac{1}{2},0\right)-\omega\left(\frac{1}{4},\frac{1}{4}\right)$$

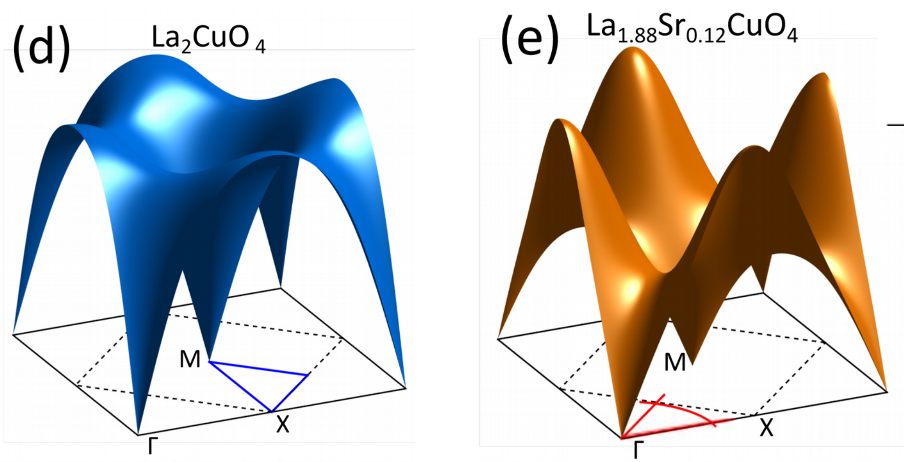
Case (2) $$\frac{E_{ZB}}{12ZJ_B}\approx 1+\frac{1}{12}\left(112-\frac{J_A}{J_B}\right)\left(\frac{t'}{t}\right)^2, \quad J_A=\frac{4t^2}{U}, \quad J_B=\frac{4t^4}{U^3}$$

$$for\ \frac{U}{t}\simeq 8, \left|\frac{t'}{t}\right|\leqslant 0.5, -\frac{t''}{t'}=0.5$$

O. Ivashko *et al.*, PRB 95, 214508 (2017)

Magnetic excitations on LSCO 12%: LSCO vs. LCO





ARPES

4t = 1720 meV and -t'/t = 0.16 (-t''/t = 0.5)

C. G. Fatuzzo *et al*, PRB 89, 205104 (2014); J. Chang *et al.*, Nat. Comm. 4, 2559 (2013); T. Yoshida *et al.*, PRB 74, 224510 (2006)

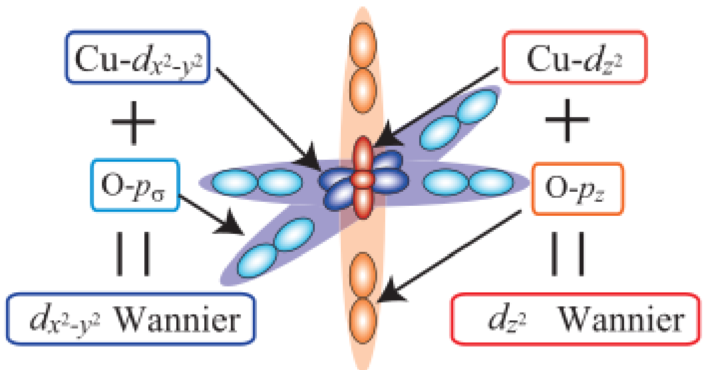
~~U/t ~ 5 & Z ~ 0.7~~

4t = 1720 meV and Z = 1.219 (-t''/t = 0.5)

$La_{2-x}Sr_xCuO_4$	U (eV)	U/t	t'/t	t''/t	Z	**Ref.**
$x = 0$	2.2	7.4	0	0	1.18	1
$x = 0$	3.6	8.3	-0.313	0.167	1.219	2
$x = 0$	3.9	9.1	-0.308	0.154	1.219	3
$x = 0.12$	2.9	6.8	-0.405	0.202	1.219	3

1 N. S. Headings *et al.*, PRL 105, 247001 (2010)
R. Coldea *et al.*, PRL 86, 5377 (2001)
2 J.-Y. P. Delannoy *et al.*, PRB 79, 235130 (2009)
3 O. Ivashko *et al.*, PRB 95, 214508 (2017)

Two orbital model & data interpretation



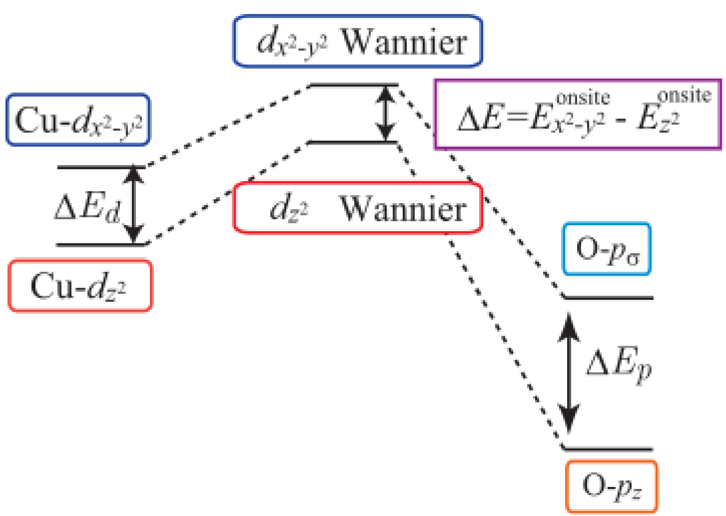
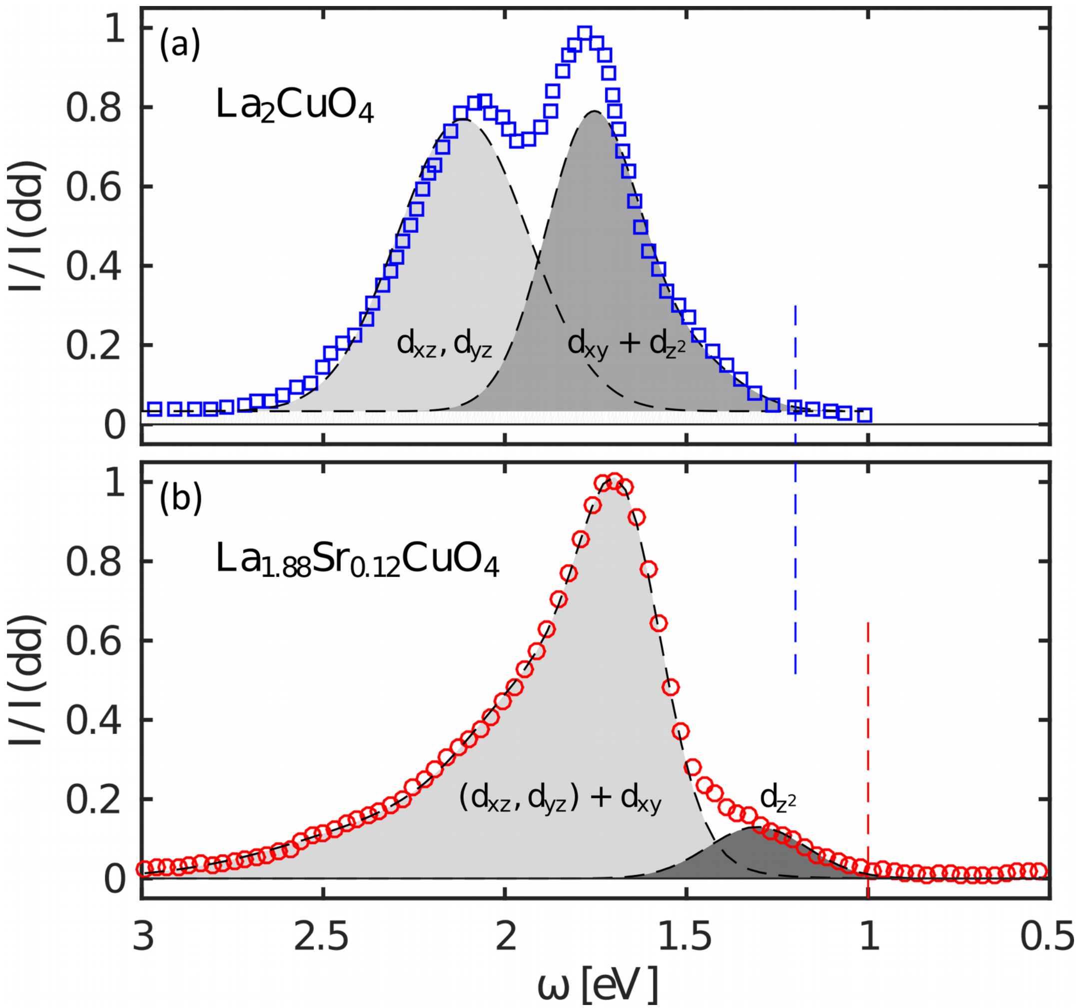


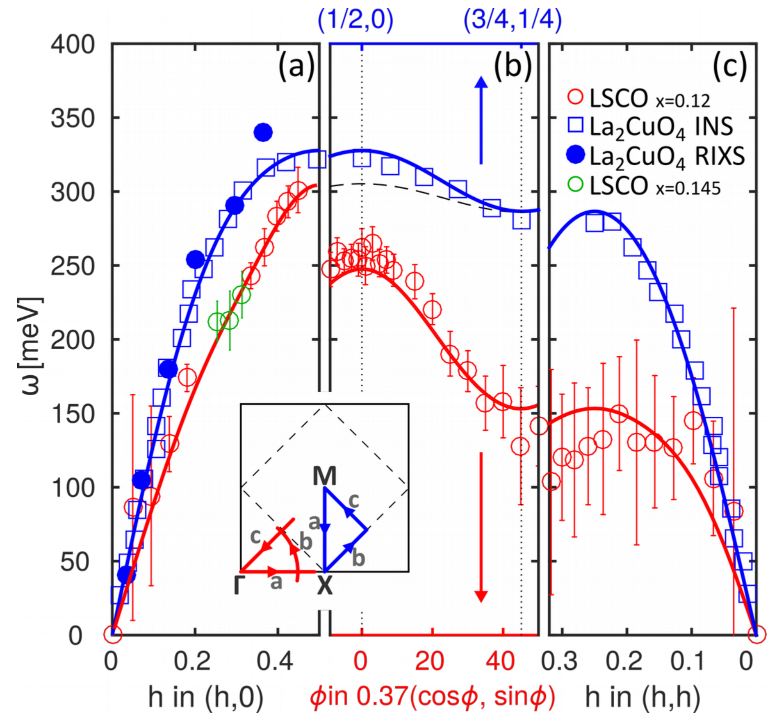
TABLE I. Hopping integrals within the $d_{x^2-y^2}$ orbital for the single- and two-orbital models (upper half), interorbital hopping (middle), and $\Delta E \equiv E_{x^2-y^2} - E_{z^2}$ (bottom).

	One-orbital		Two-orbital	
	La	Hg	La	Hg
$t(d_{x^2-y^2} \rightarrow d_{x^2-y^2})$				
t_1 (eV)	−0.444	−0.453	−0.471	−0.456
t_2 (eV)	0.0284	0.0874	0.0932	0.0993
t_3 (eV)	−0.0357	−0.0825	−0.0734	−0.0897
$(\|t_2\| + \|t_3\|)/\|t_1\|$	0.14	0.37	0.35	0.41
$t(d_{x^2-y^2} \rightarrow d_{z^2})$				
t_1 (eV)			0.178	0.105
t_2 (eV)			Small	Small
t_3 (eV)			0.0258	0.0149
ΔE (eV)			0.91	2.19

H. Sakakibara *et al.*, PRL 105, 057003 (2010)
H. Sakakibara *et al.*, PRB 85, 064501 (2012)

Two orbital model & data interpretation

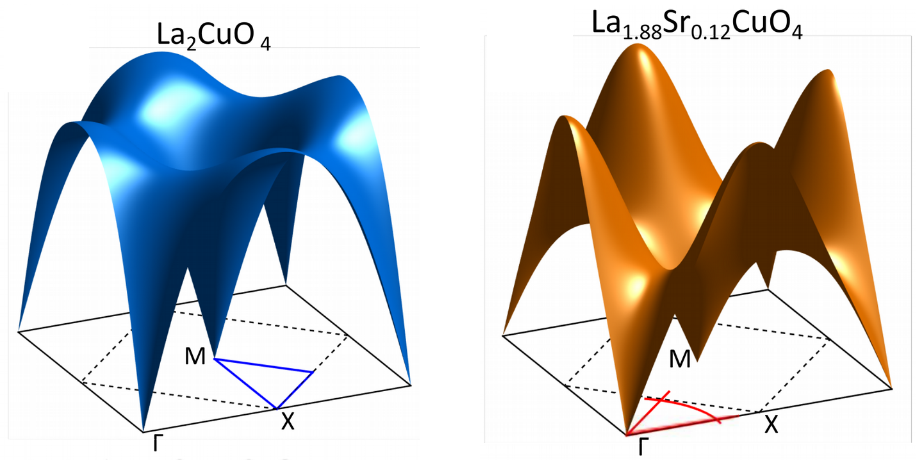




$$E_{z^2}\downarrow \Rightarrow |t'|,|t''|\uparrow \Rightarrow E_{ZB}\uparrow$$

O. Ivashko *et al.*, PRB 95, 214508 (2017)

Conclusions



- Magnetic excitations in LSCO are strongly anisotropic compared to the ones on LCO
- Hubbard type model reveals a non negligible value of t' (and t'') in contrast with ARPES data
- This discrepancy between RIXS and ARPES data is solved within the frame of two-orbital model
- Cu d_{z2} orbital reveals to be important for the description of the antiferromagnetic zone-boundary dispersion of the magnetic excitations

O. Ivashko *et al.*, PRB 95, 214508 (2017)