POLITECNICO
MILANO 1863

Charge fluctuations and electron phonon coupling studied by very high resolution RIXS

Giacomo Ghiringhelli

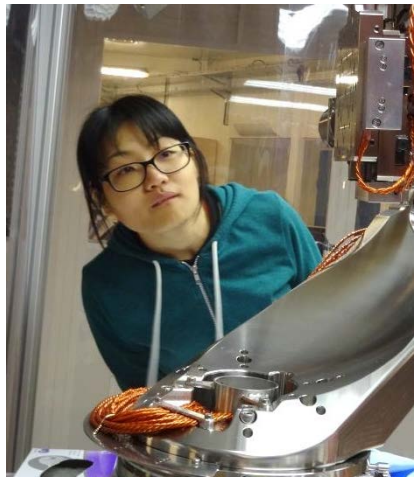
Physics Department – Politecnico di Milano – Italy

IXS 2019 – Inelastic X-ray Scattering – Stony Brook –26 June 2019

MILANO CORTINA 2026
Candidate City
Olympic Winter Games

Summary

- CDW in cuprates outside the pseudogap: overdoped Bi2201
- CDW in cuprates outside the pseudogap: (Nd/Y)123
- e-ph interaction measured by RIXS



Ying Ying Peng

Lucio Braicovich

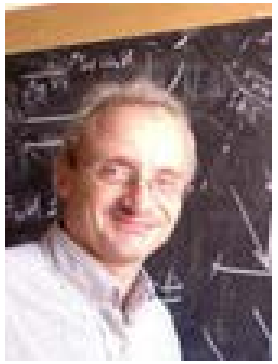
Nick Brookes

Riccardo Arpaia

Roberto Fumagalli

Matteo Rossi

Carlo Di Castro



Marco Grilli

Tom Devereaux

Jeroen van den Brink

Acknowledgements

Politecnico di Milano §now at Beijng U.	**GG, Lucio Braicovich**, **Ying Ying Peng§, Roberto Fumagalli, Matteo Rossi,** Marco Moretti Sala, Leonardo Martinelli, Mattia Pagetti, Greta Dellea, Michele Conni, Giovanni De Vecchi
ESRF	**Nick Brookes**, **Flora Yakhou, Kurt Kummer, Davide Betto**, Andrea Amorese, Christian Morawe and many others
Chalmers University	**Riccardo Arpaia**, **Eric Andersson,** Floriana Lombardi
Roma La Sapienza	**Marco Grilli, Sergio Caprara, Carlo Di Castro**
Cottbus	**Goetz Seibold**
Max Planck Institut, Stuttgart	**Matteo Minola, Bernhard Keimer**, Emilie Lefrançois, Hakuto Suzuki, Martin Bluschke
KIT, Karlsruhe	**Matthieu Le Tacon**
CNR/SPIN Napoli	**Marco Salluzzo**, Gabriella De Luca
IoP, CAS, Bejing	**Y. Ding, X. J. Zhou**
IFW Dresden U. Tennessee	**Jeroen van den Brink,** **Steven Johnston**
Stanford	**Wei-Sheng Lee, Laura Chaix, Makoto Hashimoto**, Z.X. Shen, **Tom Devereaux**, Chunjin Jia, Brian Moritz

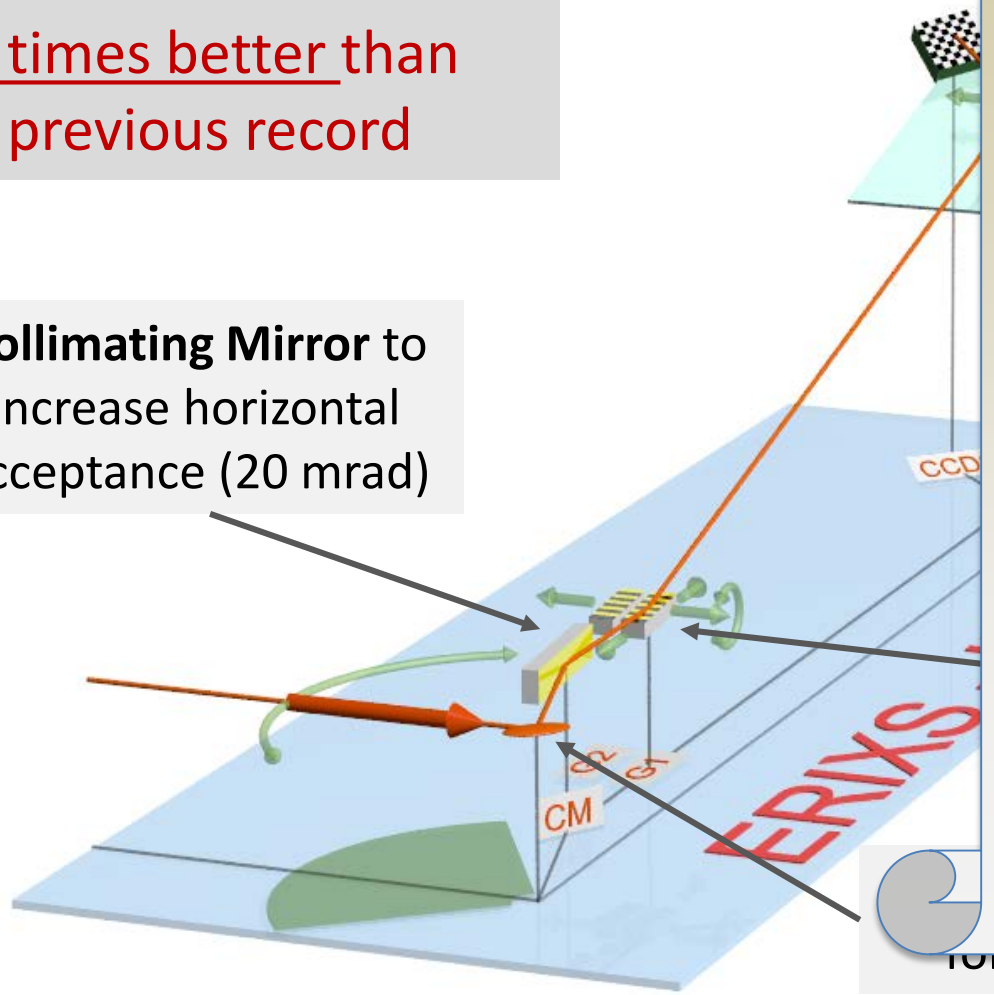
N.B. Brookes , F. Yakhou-Harris, K. Kummer, A. Fondacaro, J.C. Cezar, D. Betto, E. Velez-Fort, A. Amorese, G. Ghiringhelli, L. Braicovich, R. Barrett, G. Berruyer, F. Cianciosi, L. Eybert, P. Marion, P. van der Linden, L. Zhang, *NIM A* **903**, 175 (2018)

The merits of ERIXS at ID32

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

Two CCD **detection,**
CCD thanks to
ated beam, for
resolution [1]

Collimating Mirror to increase horizontal acceptance (20 mrad)



mirror,
ure
n of
tons [2]

eter,
for true diffraction quality scanning

Upgrade of the optics in 2020 **Combined resolving power up by 30%**

Ref: Kurt Kummer, Nick Brookes

[1] A Amorese, C Langini, G Dellea, K Kummer, NB Brookes, L Braicovich, G Ghiringhelli, *NIM A* **935**, 222 (2019)

[2] L. Braicovich, M. Minola, G. Dellea, M. Le Tacon, M. Moretti Sala, C. Morawe, J.-Ch. Peffen, R. Supruangnet, F. Yakhou, G. Ghiringhelli, and N. B. Brookes, *Rev. Sci. Instrum.* **85,** 115104 (2014)

N.B. Brookes , F. Yakhou-Harris, K. Kummer, A. Fondacaro, J.C. Cezar, D. Betto, E. Velez-Fort, A. Amorese, G. Ghiringhelli, L. Braicovich, R. Barrett, G. Berruyer, F. Cianciosi, L. Eybert, P. Marion, P. van der Linden, L. Zhang, *NIM A* **903**, 175 (2018)

Other contributions from ERIXS@ID32 in this conference

Ying Ying Peng

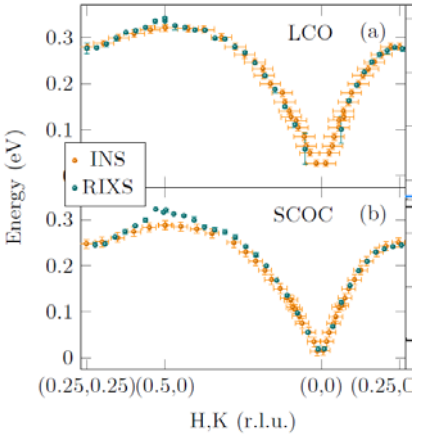
Evolution of the magnetic excitations in high Tc cuprates

next talk

Davide Betto

Bimagnon tail in the magnetic excitations of $Sr_2CuO_2Cl_2$ and La_2CuO_4

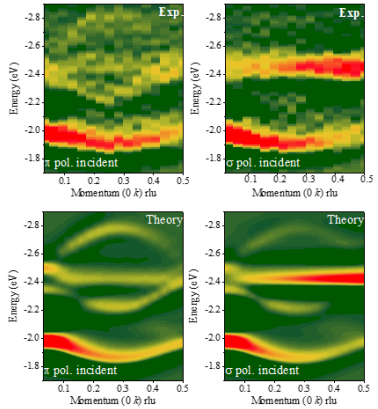
Poster PT-4



Roberto Fumagalli

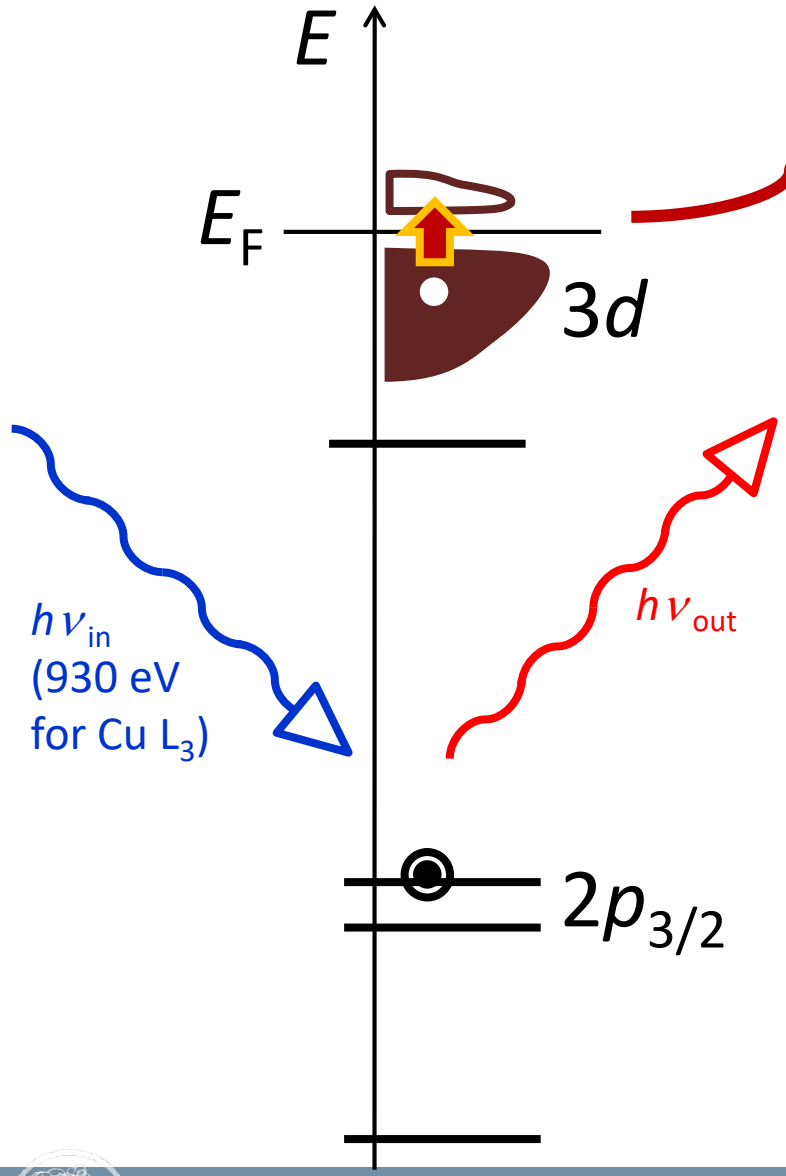
Dispersing orbital excitations in the quasi-1D and 2D cuprates

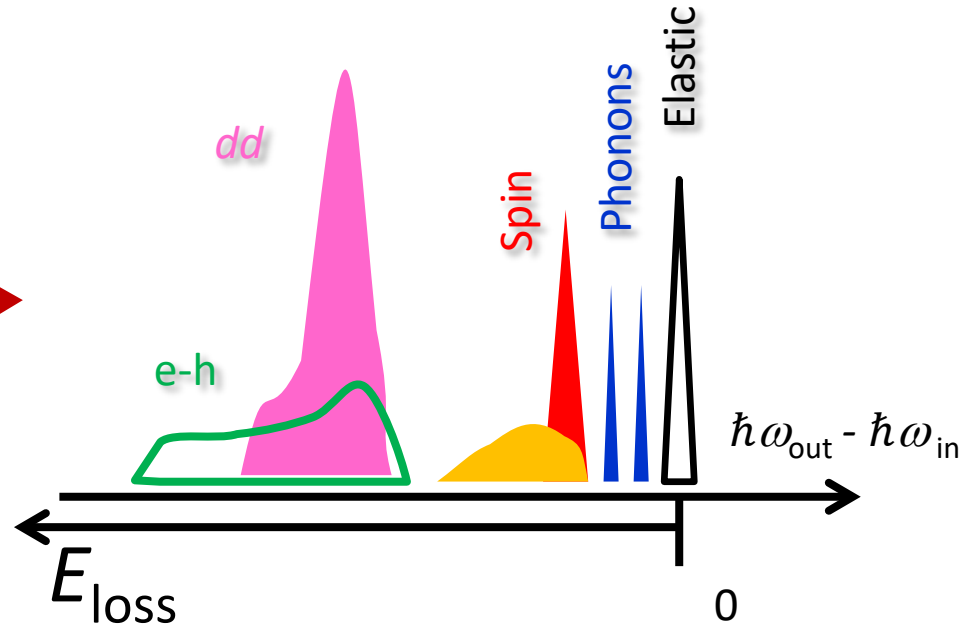
Poster PT-15



and talks by **Kurt Kummer, Andrea Amorese, Hu Miao, Wei Sheng Lee**

Cu L_3 RIXS

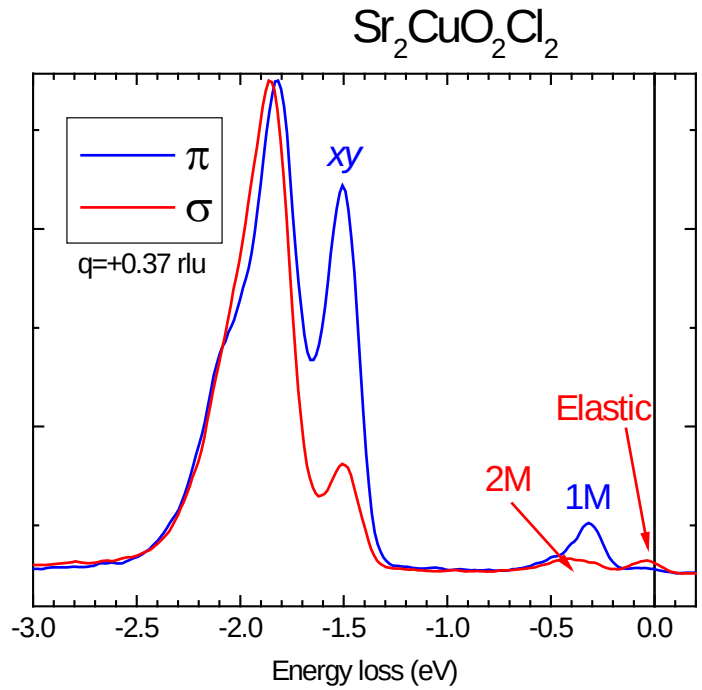


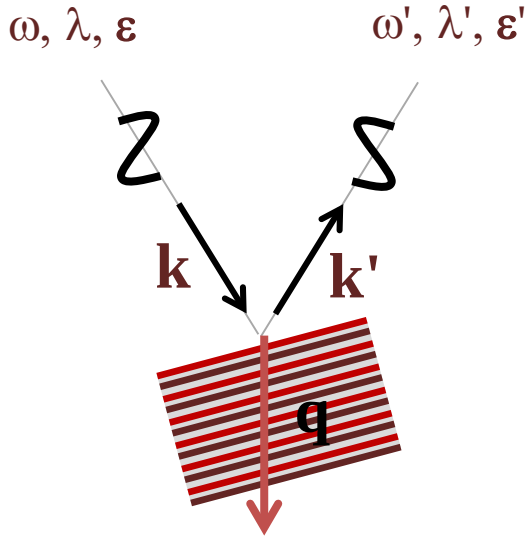


$\Omega=\omega-\omega'$

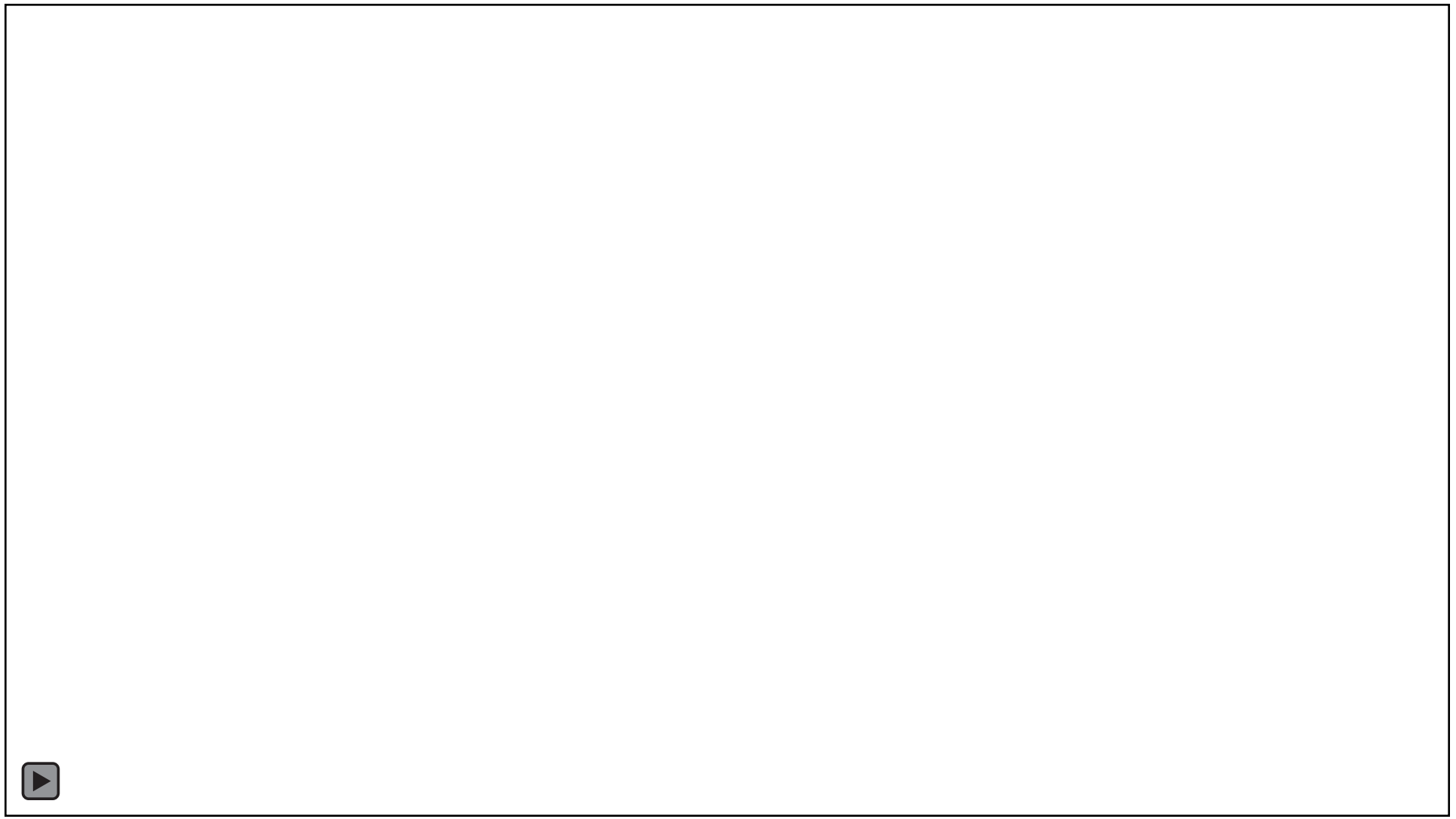
$\mathbf{q} = \mathbf{k}' - \mathbf{k}$

$\varepsilon, \varepsilon'$: polarization





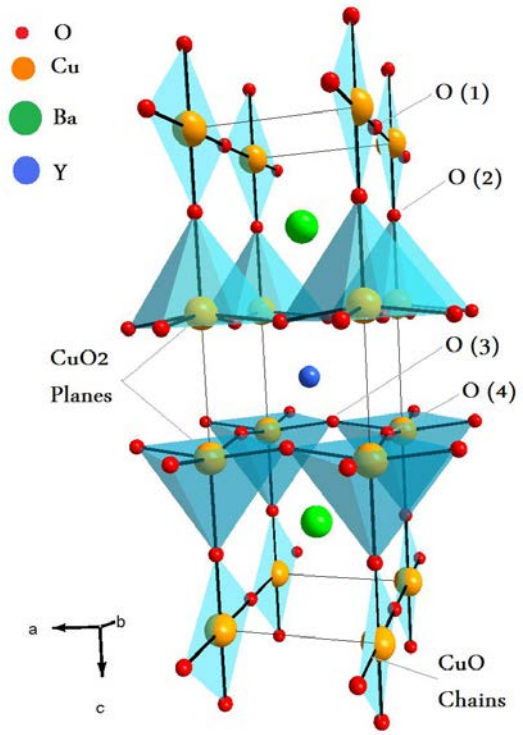
High Tc Superconducting cuprates

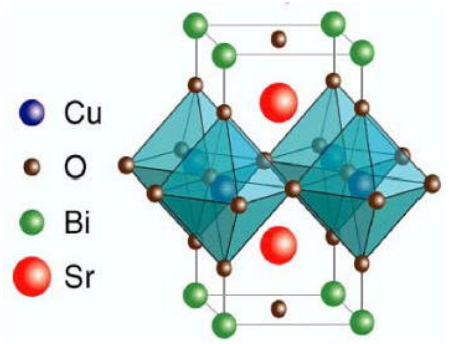


Thanks to Claudio Mazzoli

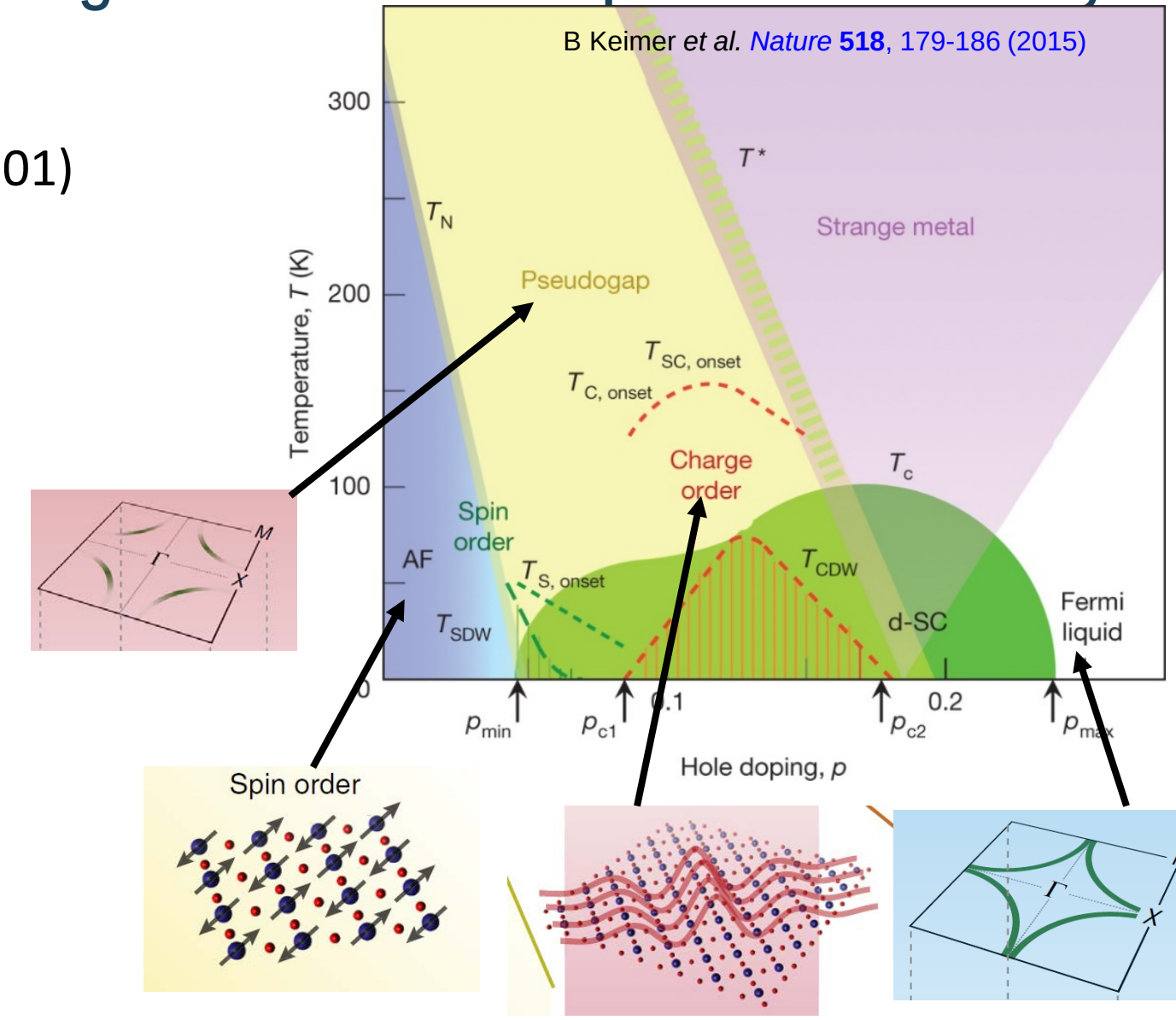
Cuprates: Magnetism, Charge Order and Superconductivity

$YBa_2Cu_3O_{6+\delta}$ (YBCO) $Bi_2Sr_2CuO_{6+\delta}$ (Bi2201)



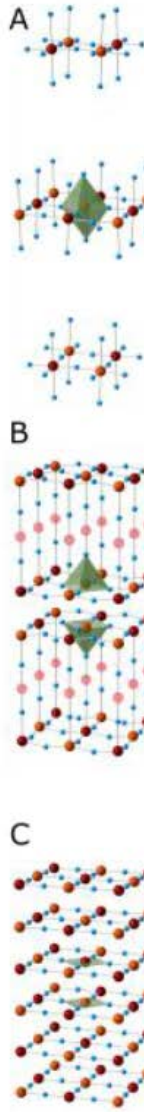


B Keimer *et al.* *Nature* **518**, 179-186 (2015)



J. Pelliciari and R. Comin *Nature Materials* **17**, 661 (2018)

Spin-waves with Cu L_3 RIXS



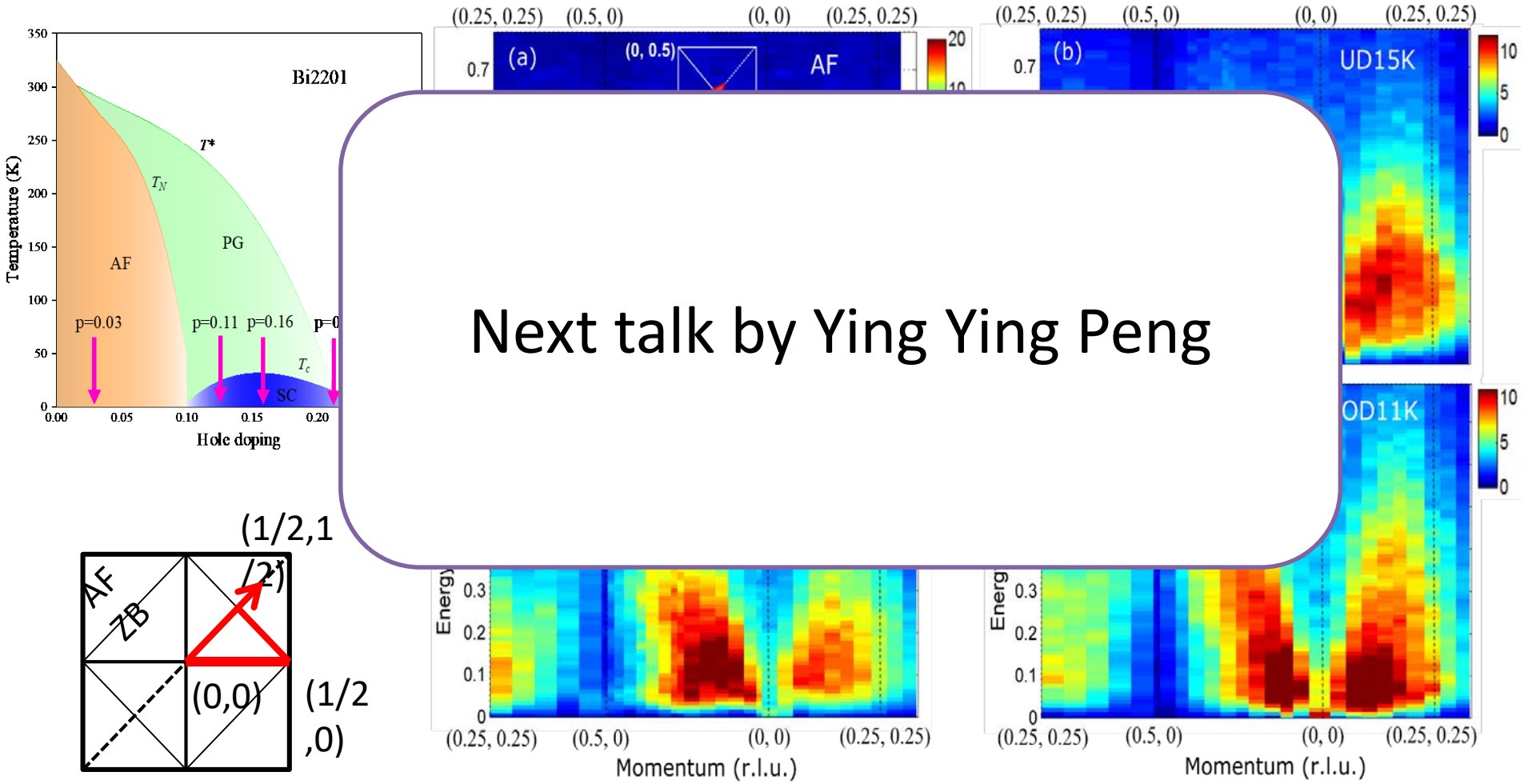
$Bi_2Sr_2CuO_6$

$NdBa_2Cu_3O_{6.1}$

$CaCuO_2$

Y. Y. Peng, G. Dellea, M. Minola, M. Conni, A. Amorese, D. Di Castro, G. M. De Luca, K. Kummer, M. Salluzzo, X. Sun, X. J. Zhou, G. Balestrino, M. Le Tacon, B. Keimer, L. Braicovich, N. B. Brookes and G. Ghiringhelli, *Nature Physics* **13** 1201 (2017)

Paramagnons in Bi2201

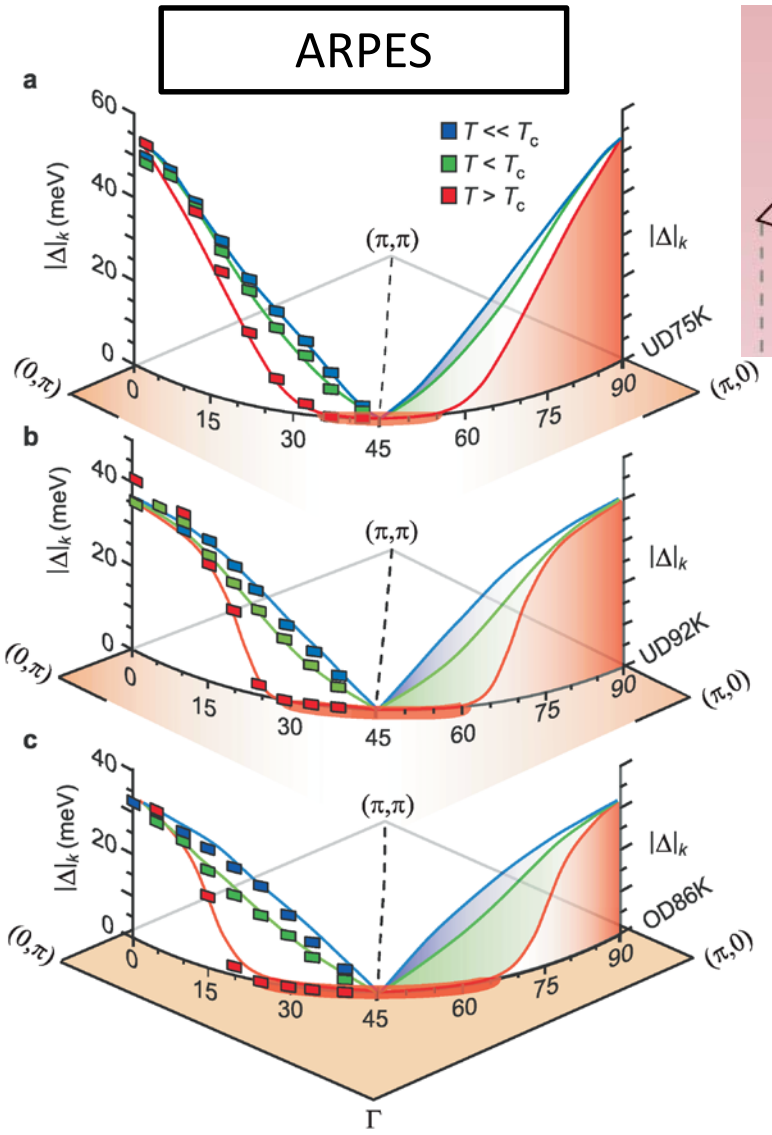


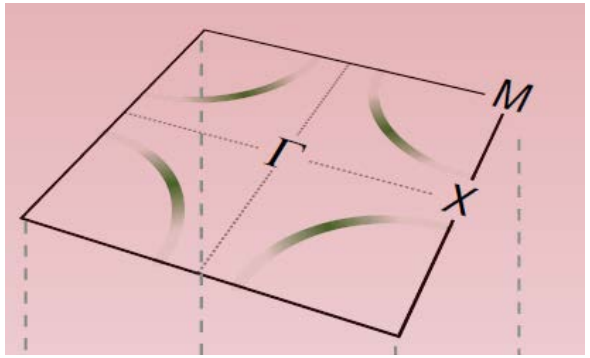
Next talk by Ying Ying Peng

Y. Y. Peng, E. W. Huang, R. Fumagalli, M. Minola, Y. Wang, X. Sun, Y. Ding, K. Kummer, X. J. Zhou, N. B. Brookes, B. Moritz, L. Braicovich, T. P. Devereaux, and G. Ghiringhelli, *Phys Rev. B* **98** 144507 (2018)

The superconducting gap

ARPES

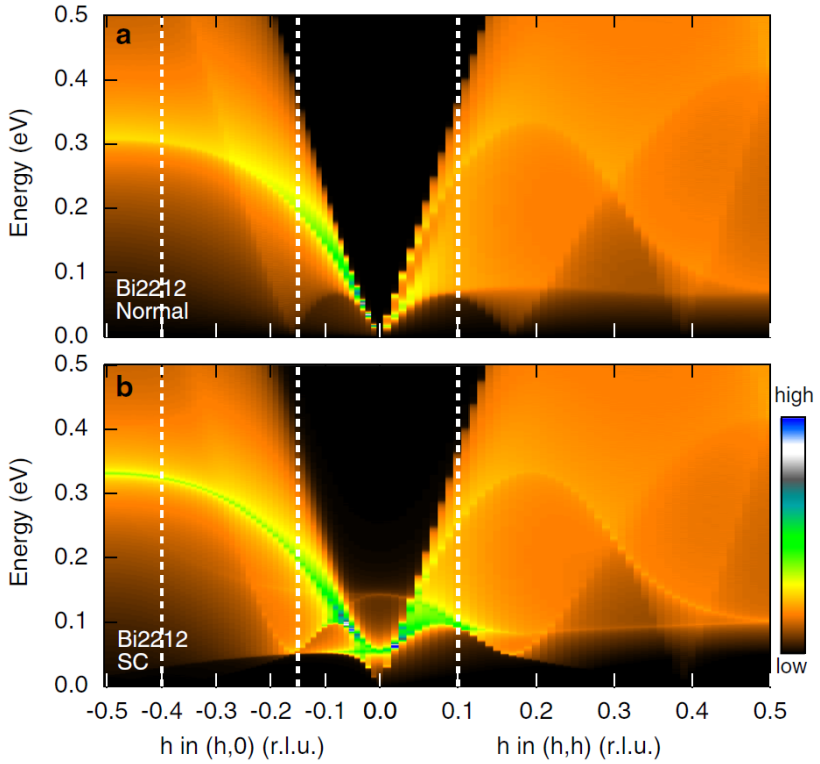


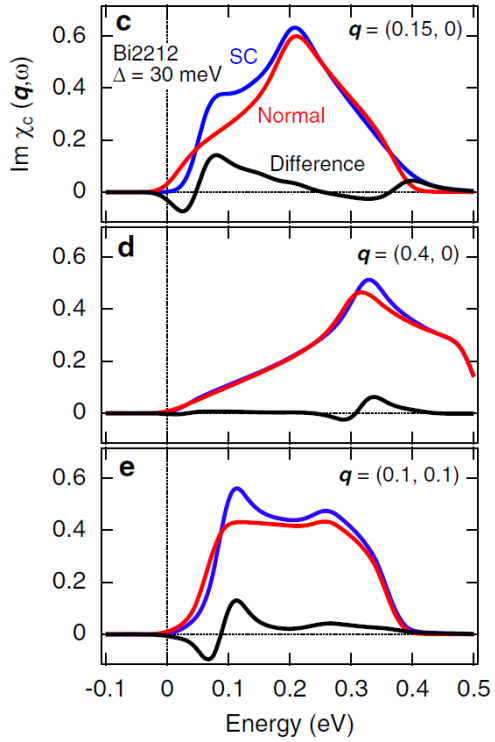


"RIXS"

Charge susceptibility:

$\mathrm{Im}\ \chi_c(\mathbf{q}, \omega)$

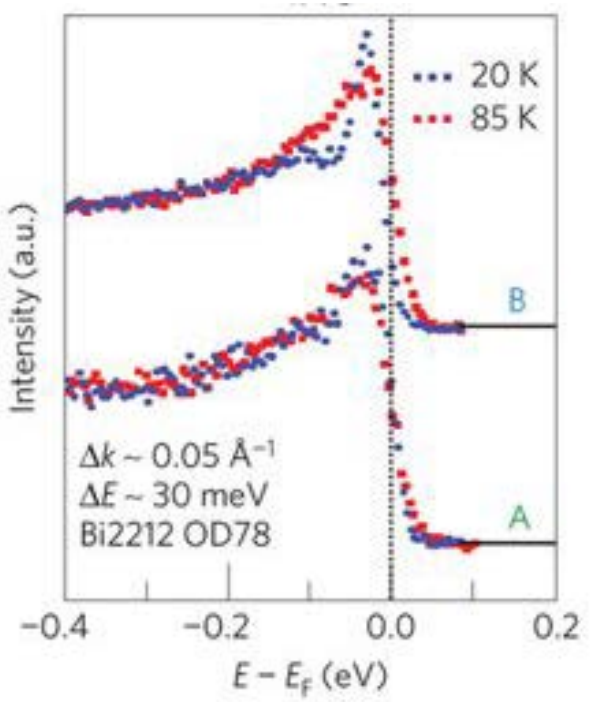




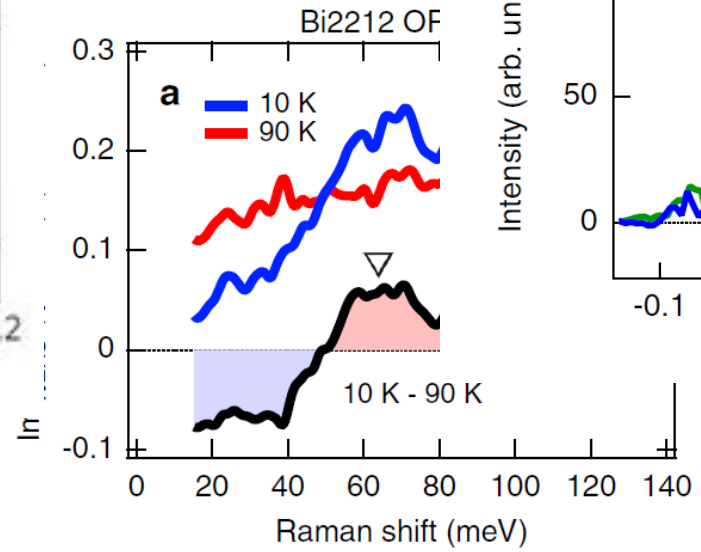
Hakuto Suzuki, Matteo Minola, Yi Lu, Yingying Peng, Roberto Fumagalli, Emilie Lefrançois, Toshinao Loew, Juan Porras, Kurt Kummer, Davide Betto, Shigeyuki Ishida, Hiroshi Eisaki, Cheng Hu, Xingjiang Zhou, Maurits W. Haverkort, Nicholas B. Brookes, Lucio Braicovich, Giacomo Ghiringhelli, Matthieu Le Tacon and Bernhard Keimer, *npj Quantum Materials* **3,** 65 (2018)

The SC gap in RIXS

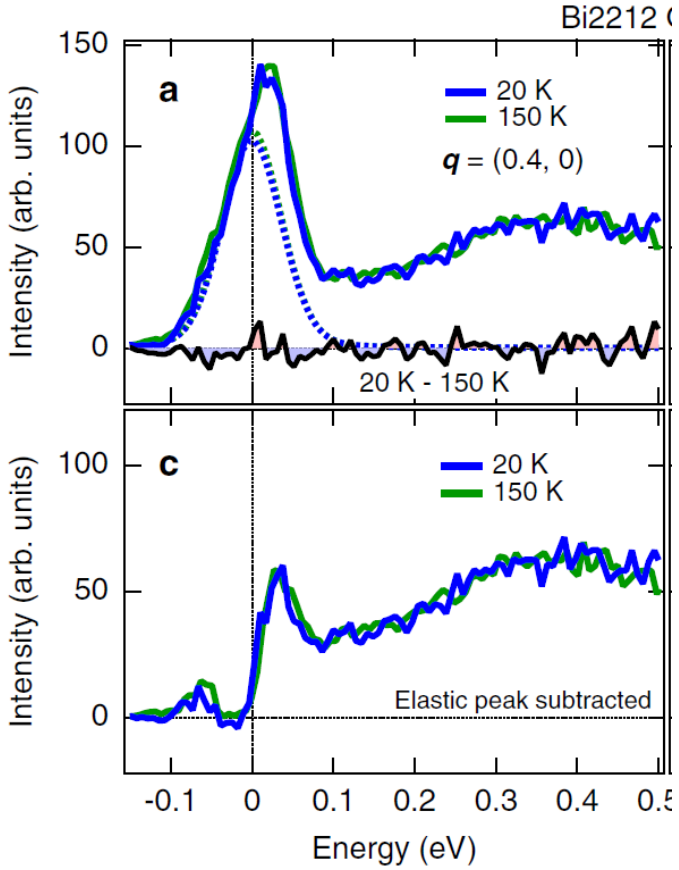
ARPES

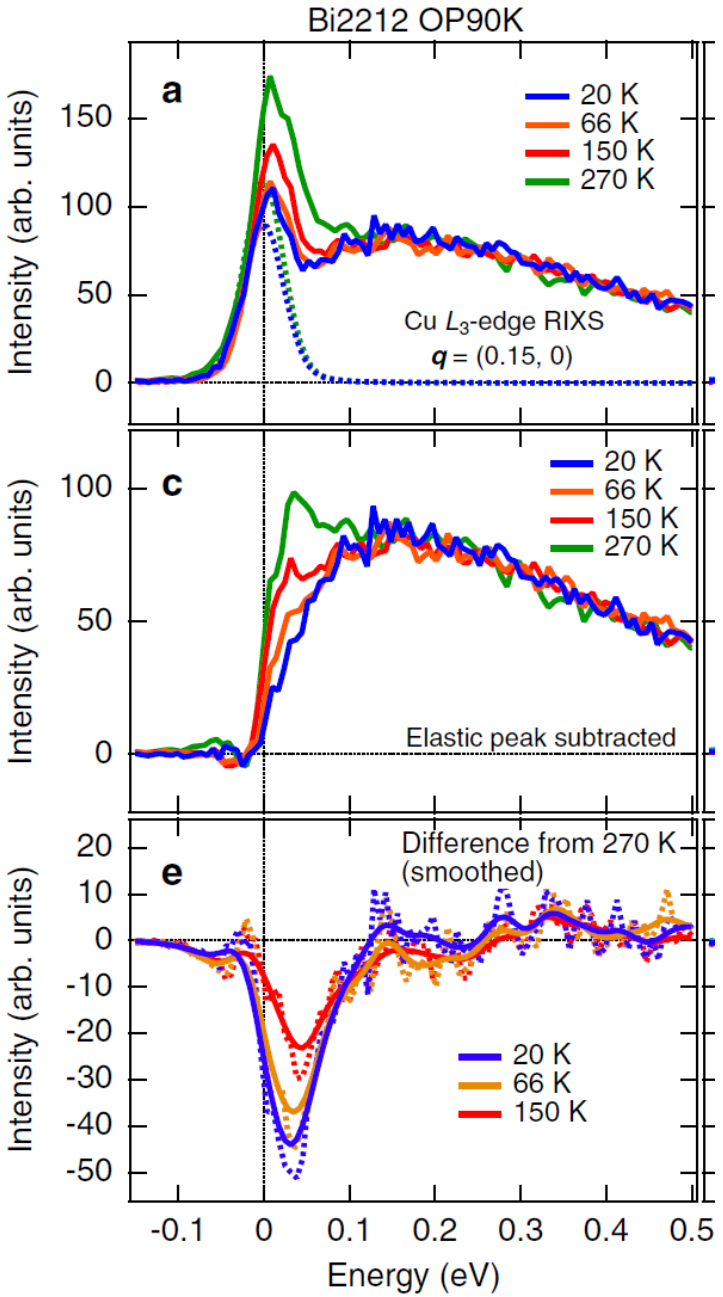


Raman: q=0



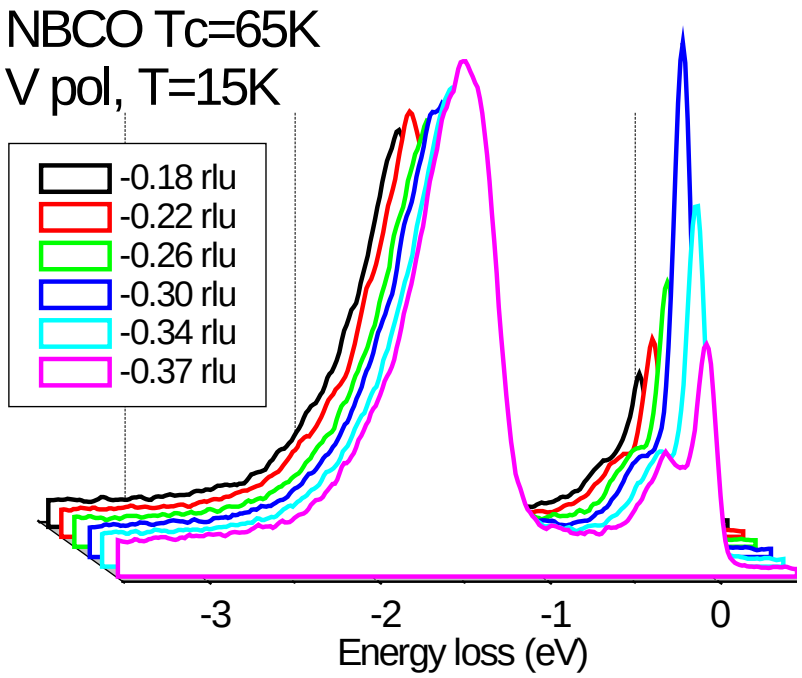
RIXS: q≠0

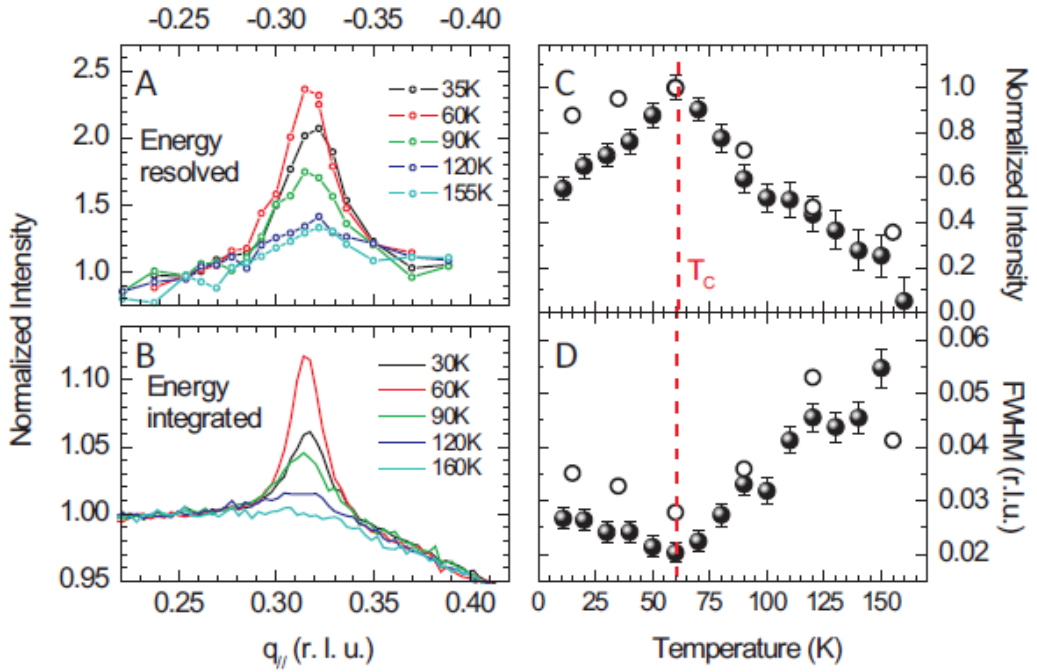




Hakuto Suzuki, Matteo Minola, Yi Lu, Yingying Peng, Roberto Fumagalli, Emilie Lefrançois, Toshinao Loew, Juan Porras, Kurt Kummer, Davide Betto, Shigeyuki Ishida, Hiroshi Eisaki, Cheng Hu, Xingjiang Zhou, Maurits W. Haverkort, Nicholas B. Brookes, Lucio Braicovich, Giacomo Ghiringhelli, Matthieu Le Tacon and Bernhard Keimer, *npj Quantum Materials* **3,** 65 (2018)

First observation of CDW in YBCO with R(I)XS





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)

Other evidences of CDW in YBCO

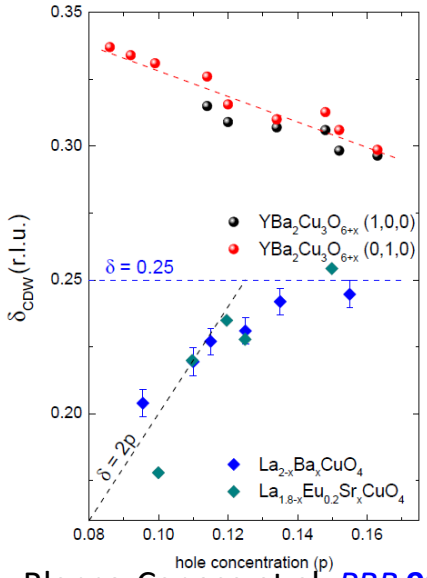
NMR, Charge modulation
at low T, high field
Wu et al. *Nature* **477** 191 (2011)

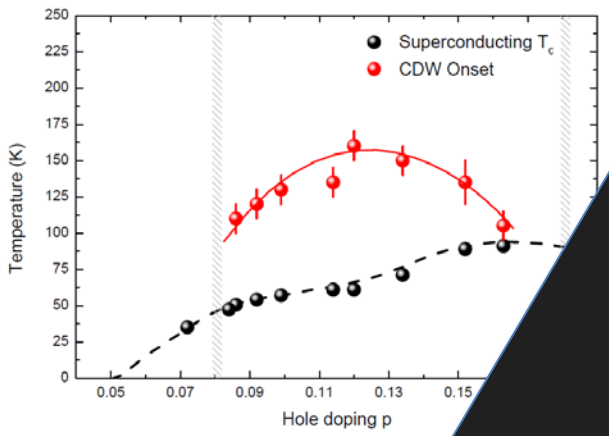
L = 0.5: Doubling of unit cell along c-axis
Field enhancement of the CDW (HXRD)
Chang et al. *Nat.Phys*. **8** 871 (2012)

Bi-axial, Static order
under high field.
Leboeuf et al. *Nat.Phys*. **9** 79 (2013)

Ubiquitous CDW in cuprates

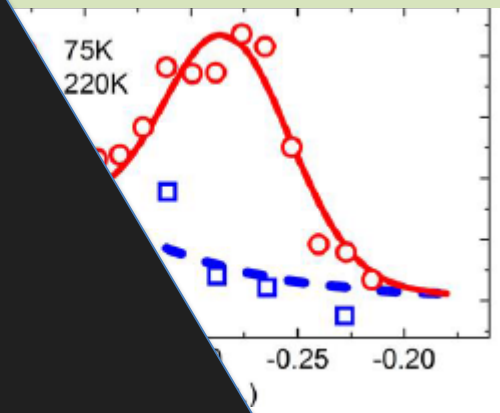
YBCO





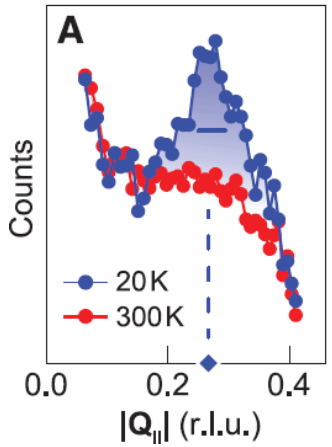
Blanco-Canosa et al. *PRB* **90**, 054513 (2014)
Huecker et al. *PRB* **90**, 054514 (2014)

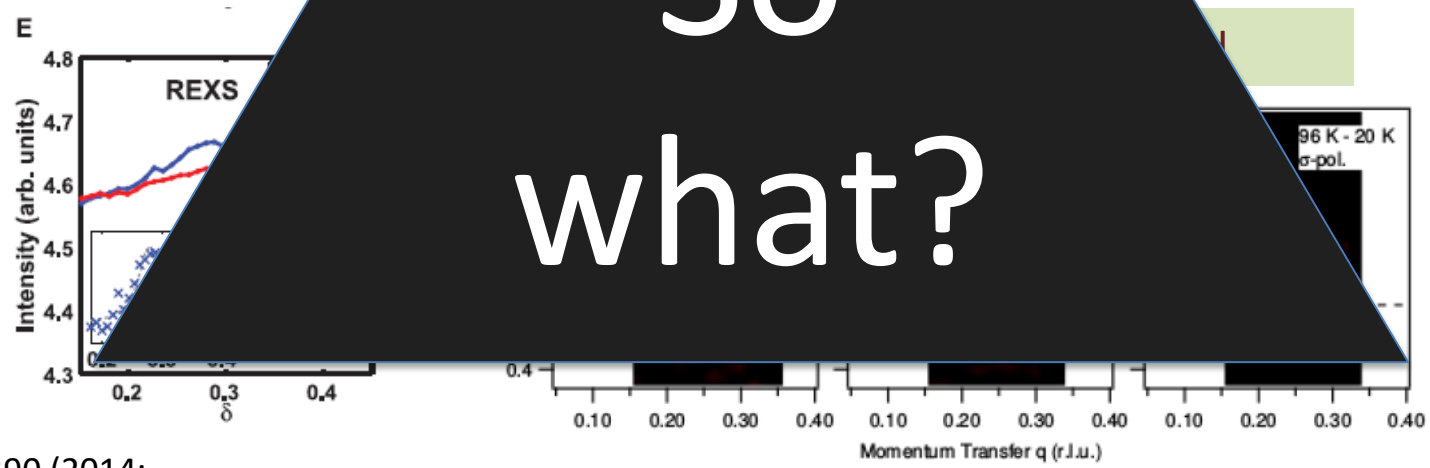
Hg1201 underdoped



5, 5875 (2014)

Bi2201 and Bi2212 underdoped



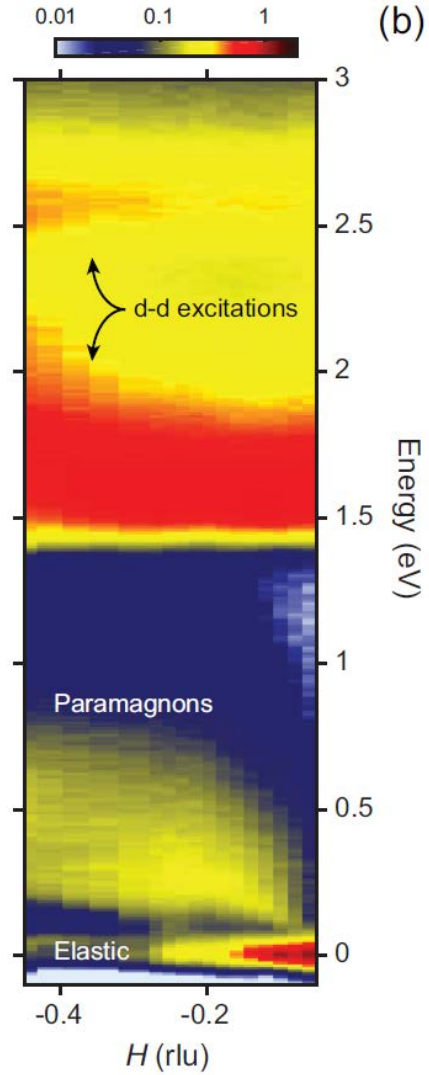


R. Comin et al, Science 343, 390 (2014);
Eduardo H. da Silva Neto et al, *Science* **343**, 393 (2014)

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

So what?

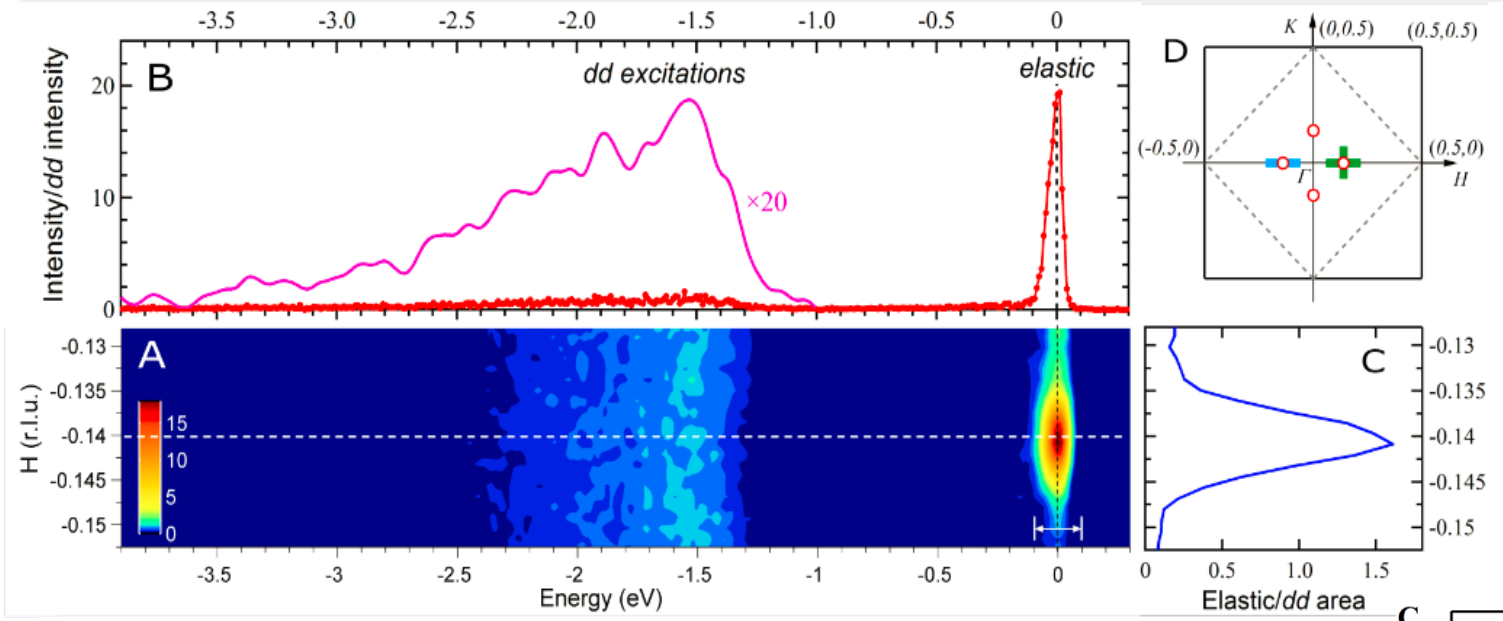
NCCO e-derdoped



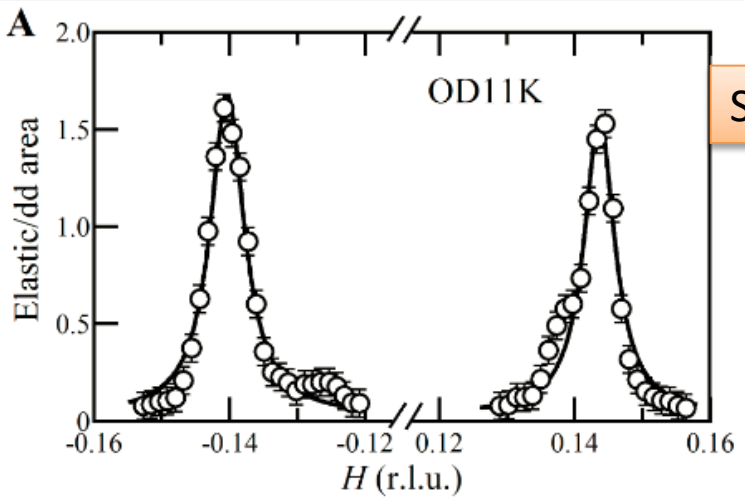
M. E. H. da Silva Neto et al,
PRB **98** 161114 (2018)

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

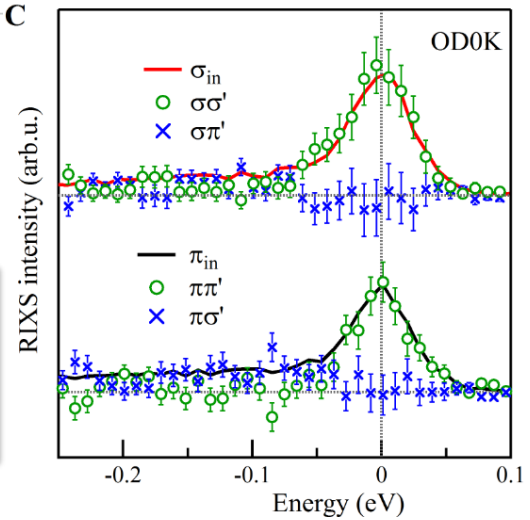
Unexpected observation of a very intense and sharp peak in pseudo-tetragonal (1,0) direction



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



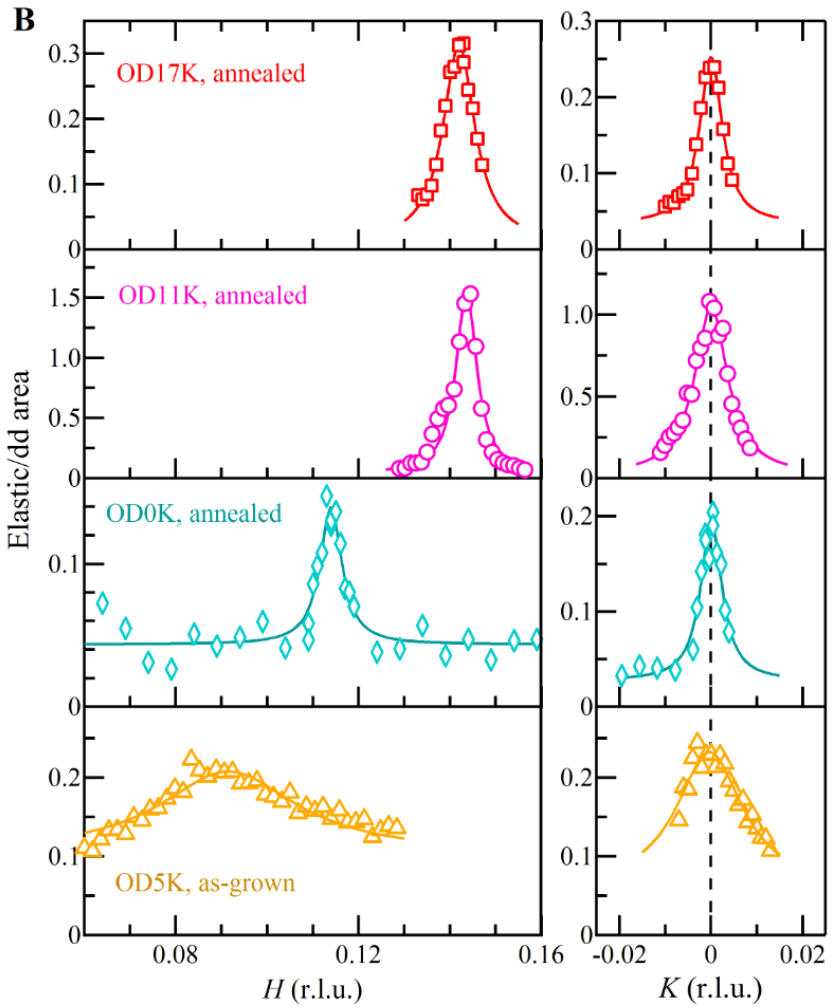
Symmetric w/r to Γ

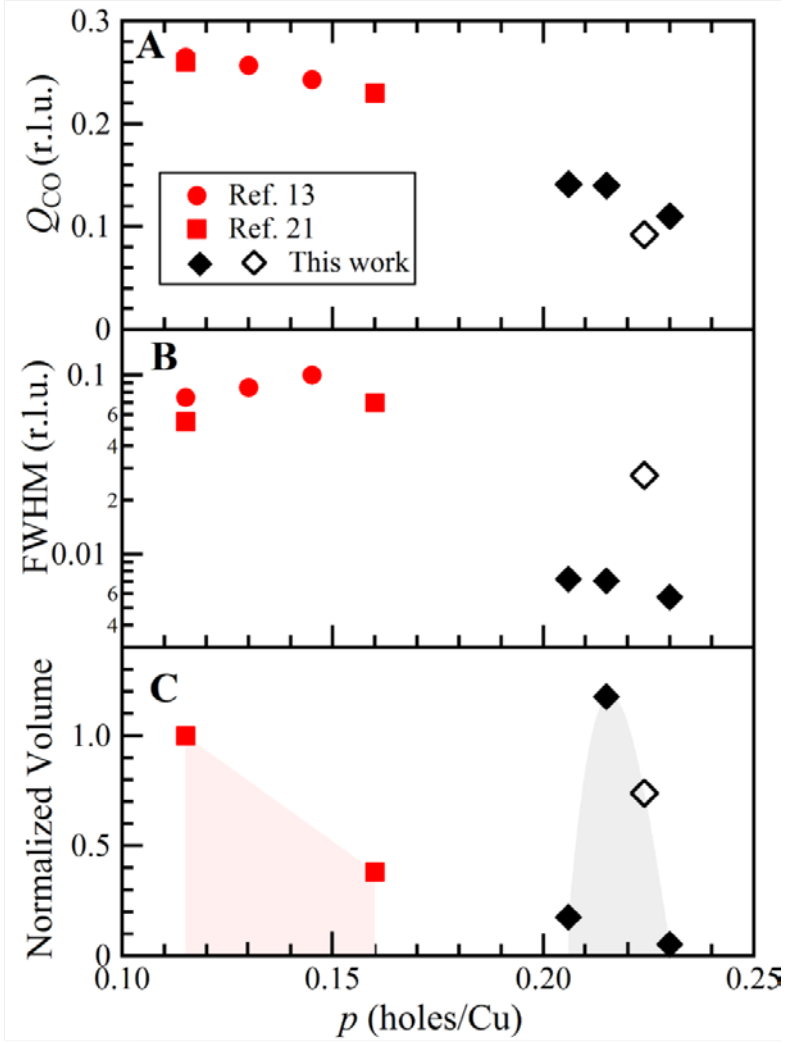


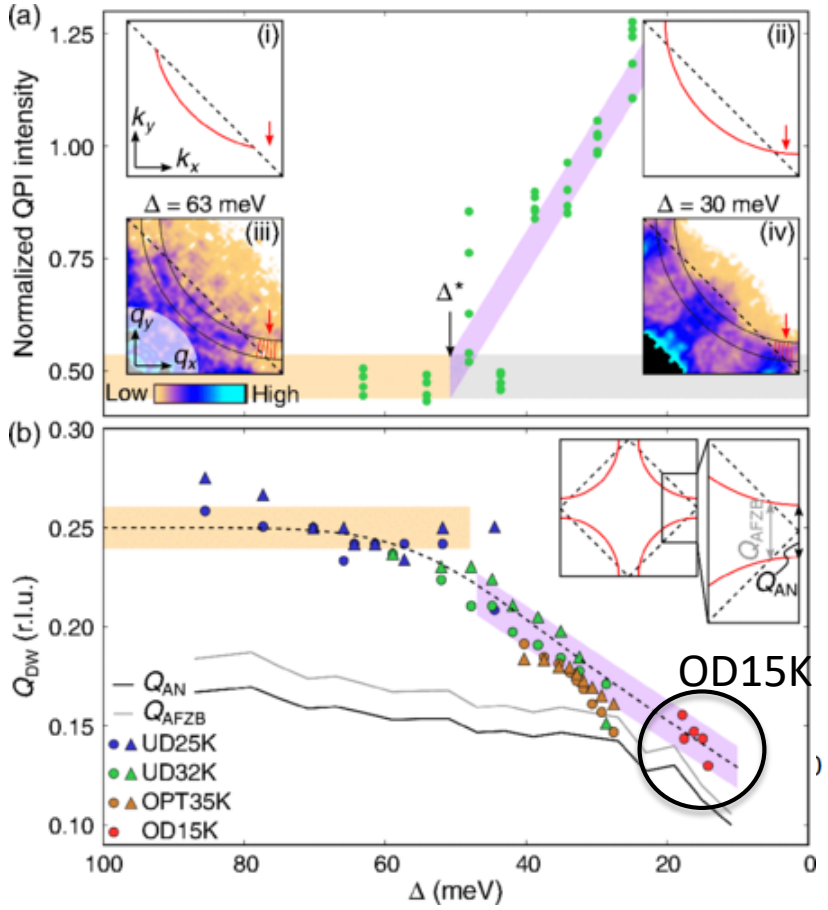
Pure charge character (no spin)

Re-entrant CDW in OD Bi2201

STM







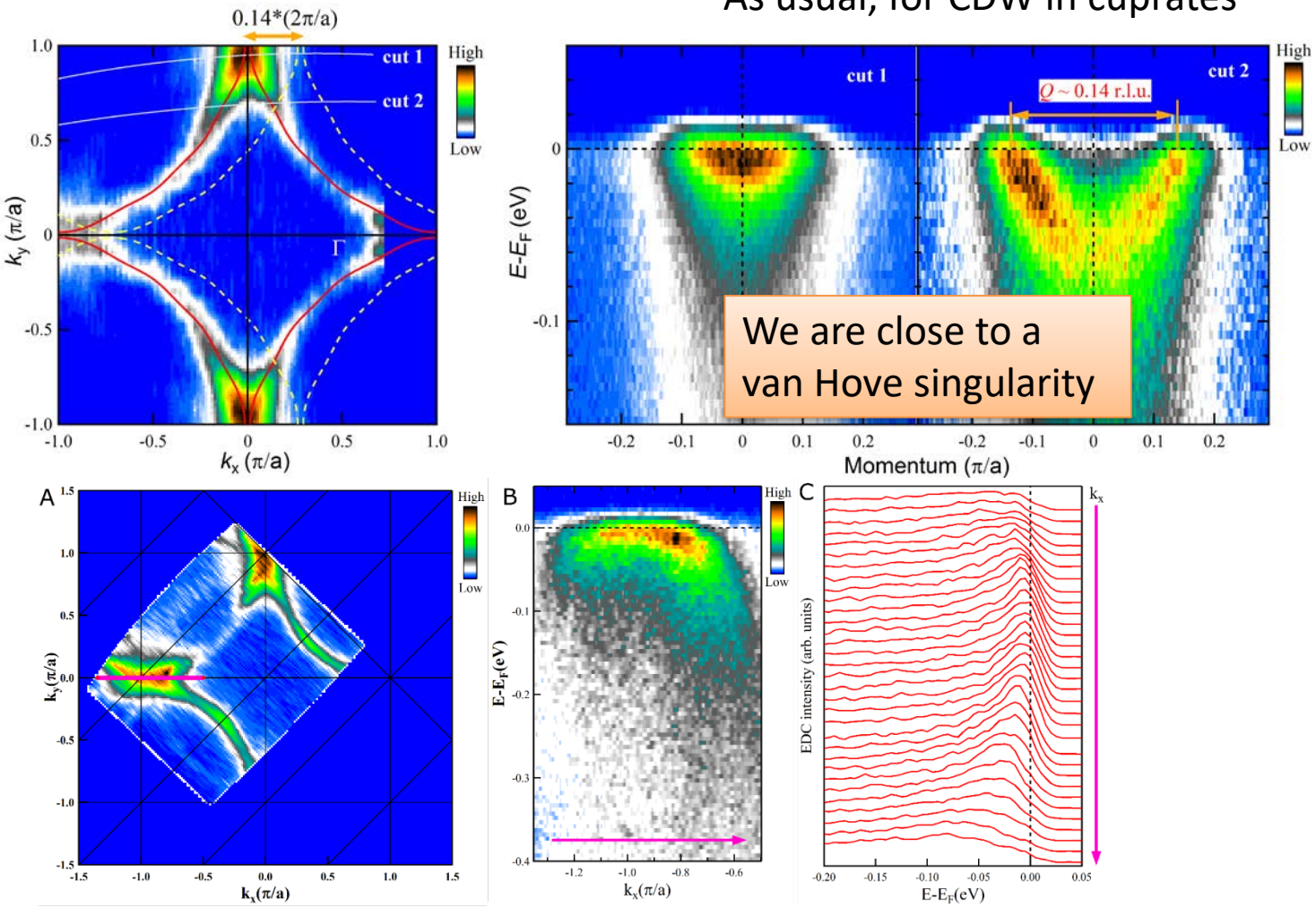
Y. Y. Peng, R. Fumagalli, Y. Ding, M. Minola, S. Caprara, D. Betto, M. Blüschke, G. M. De Luca, K. Kummer, E. Lefrançois, M. Salluzzo, H. Suzuki, M. Le Tacon, X. J. Zhou, N. B. Brookes, B. Keimer, L. Braicovich, M. Grilli, G. Ghiringhelli, *Nature Materials* **17**, 697 (2018).

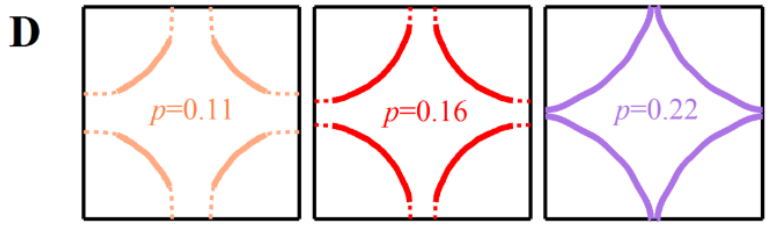
Tatiana A. Webb, Michael C. Boyer, Yi Yin, Debanjan Chowdhury, Yang He, Takeshi Kondo, T. Takeuchi, H. Ikuta, Eric W. Hudson, Jennifer E. Hoffman, and Mohammad H. Hamidian Phys. Rev. X **9**, 021021 (2019)

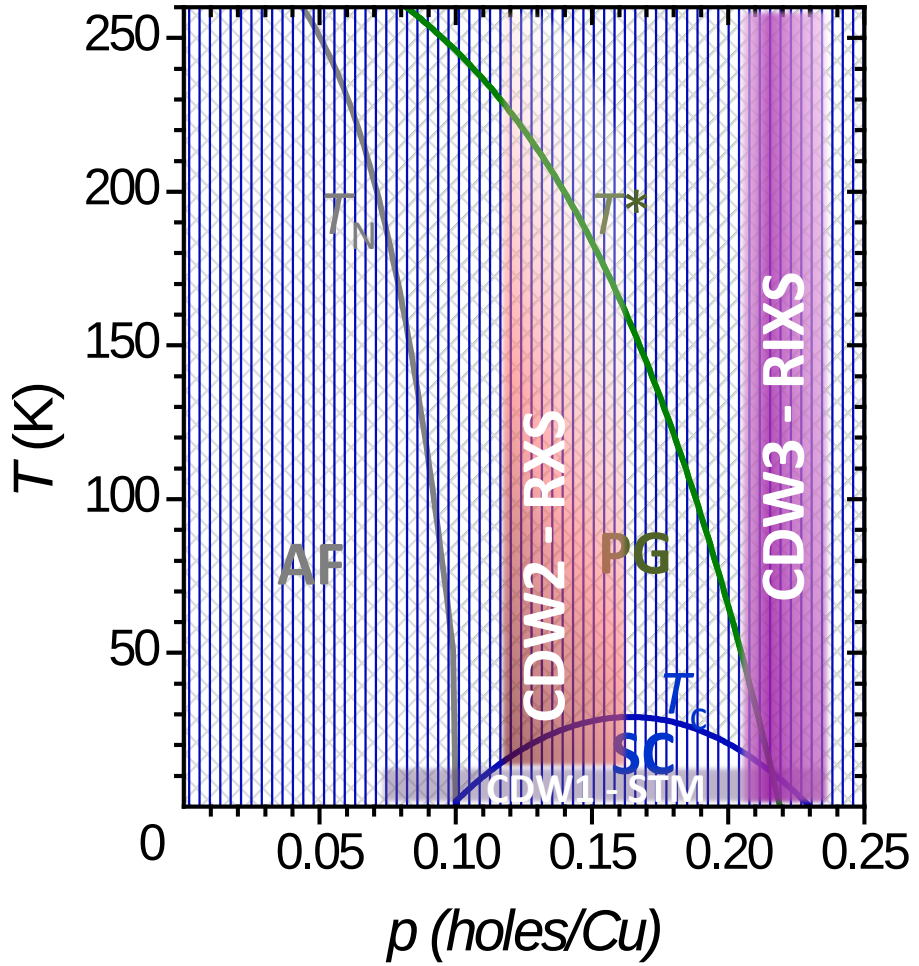
CDW in OD Bi2201: the role of electronic structure

ARPES on OD11K (T_c=11 K, p~0.215), at T=20K: no Fermi surface nesting or folding*

* As usual, for CDW in cuprates

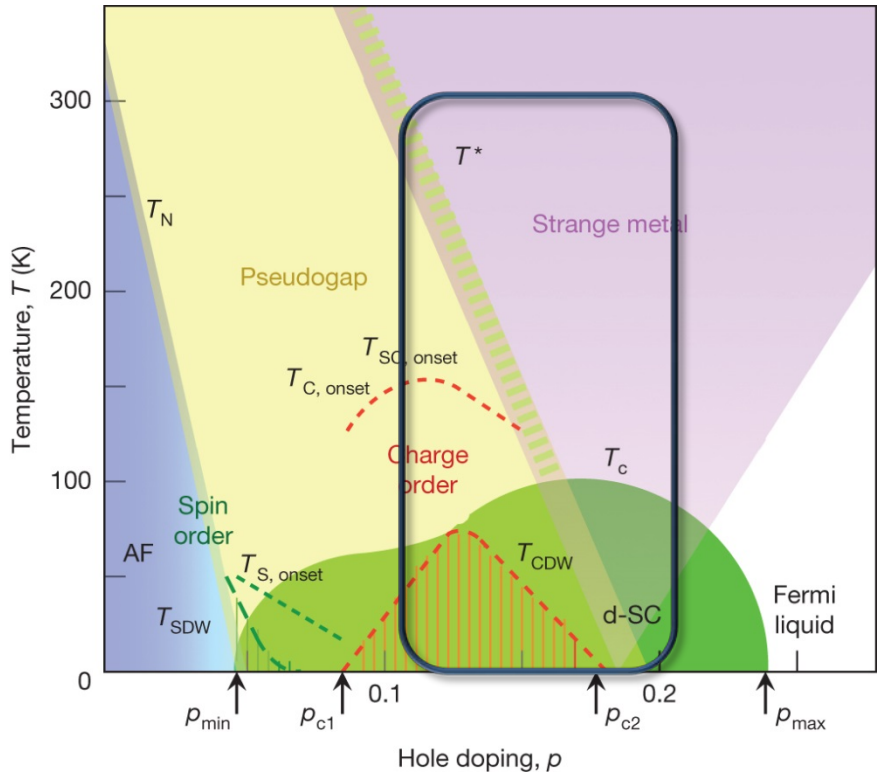






CDW T-dependence in R123

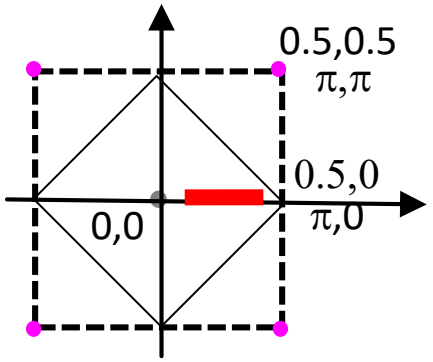
Taking a better look at CDW, at "high" T, in (Y,Nd)BCO

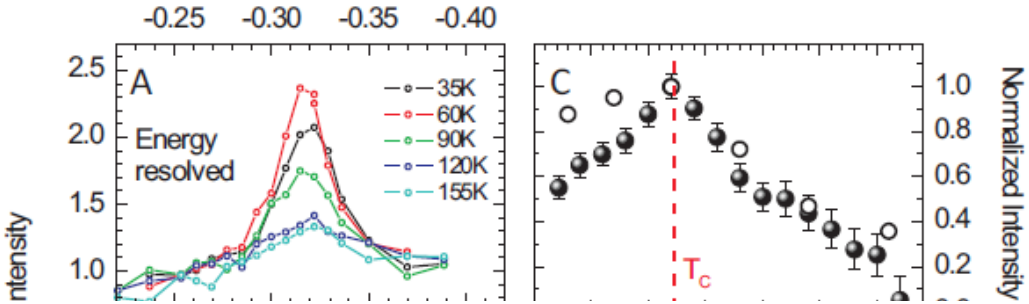


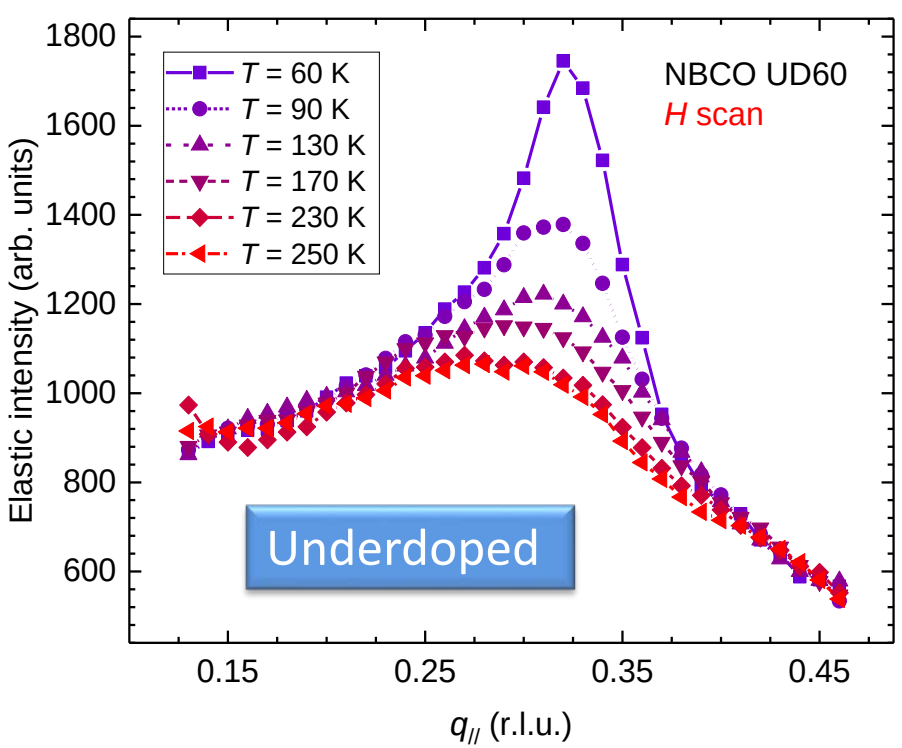
Samples
Epitaxial films grown in CNR/SPIN Napoli and Chalmers
(M Salluzzo, GM De Luca, R Arpaia, E Andersson, F Lombardi)

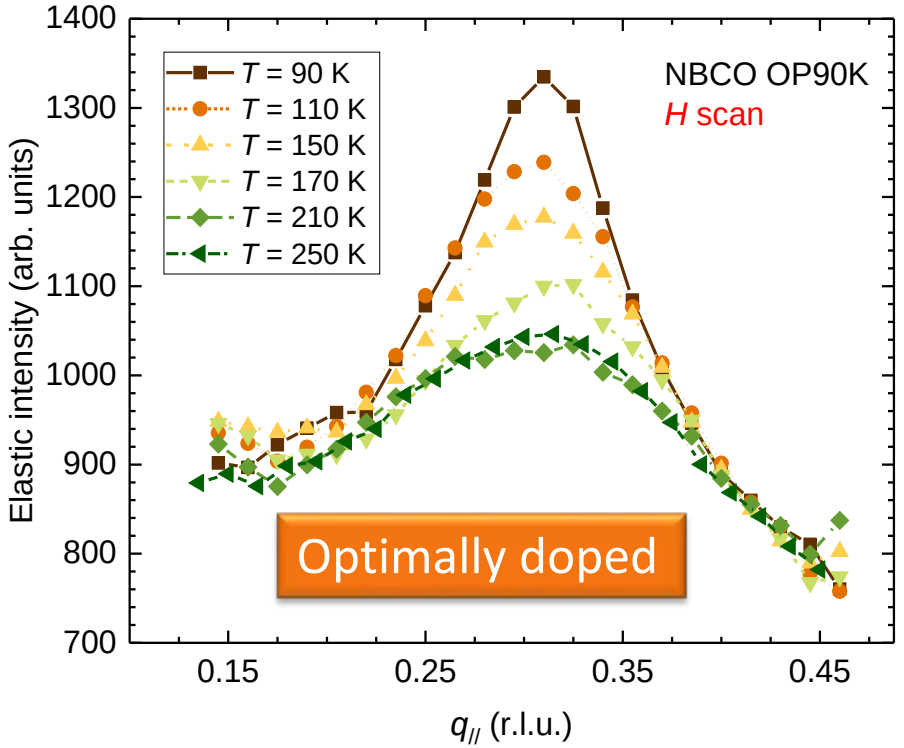
R. Arpaia, S. Caprara, R. Fumagalli, G. De Vecchi, Y.Y. Peng, E. Andersson, D. Betto, G. M. De Luca, N. B. Brookes, F. Lombardi, M. Salluzzo, L. Braicovich, C. Di Castro, M. Grilli, G. Ghiringhelli, arXiv1809.04949

What is the real T_{CDW}?

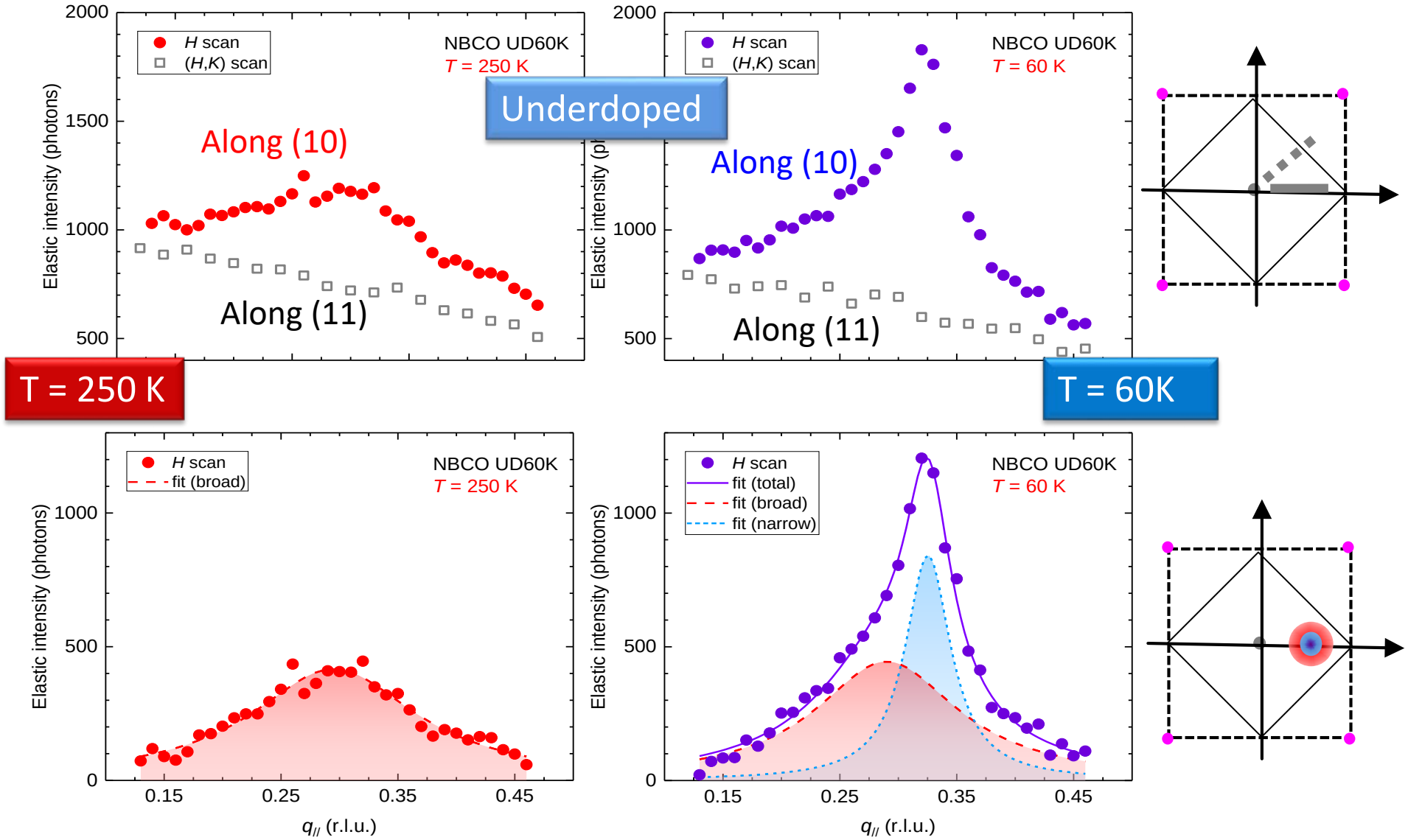








Not just one CDW peak

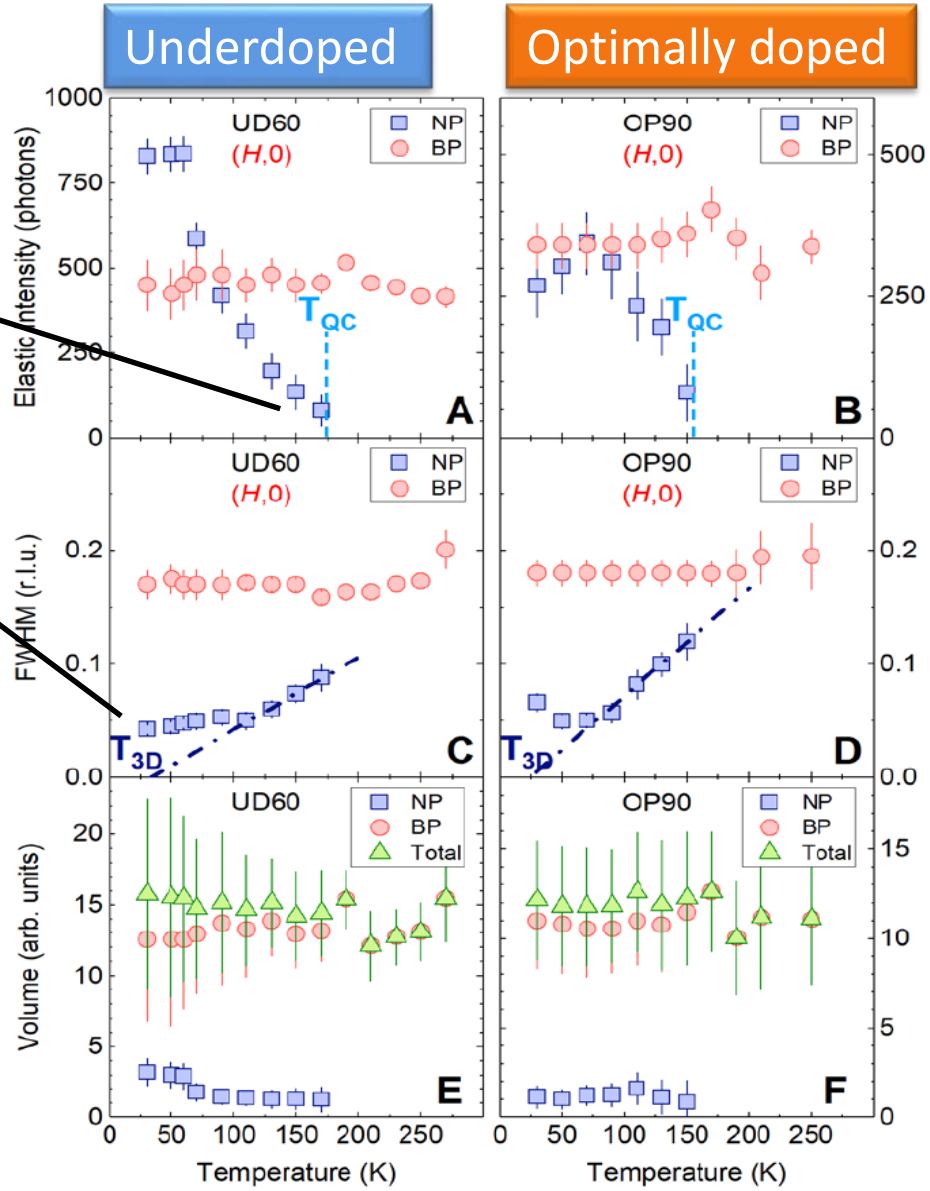


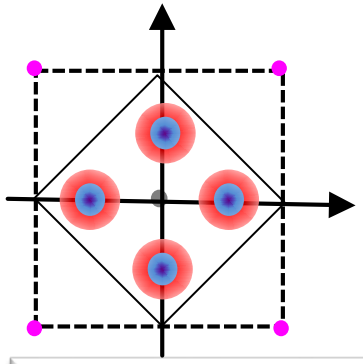
R. Arpaia, S. Caprara, R. Fumagalli, G. De Vecchi, Y.Y. Peng, E. Andersson, D. Betto, G. M. De Luca, N. B. Brookes, F. Lombardi, M. Salluzzo, L. Braicovich, C. Di Castro, M. Grilli, G. Ghiringhelli, arXiv1809.04949

Narrow Peak (NP) and Broad Peak (BP)

$T_{QC}=T_{CDW}$
Onset of NP

T_{3D}
Critical T for 3D order
without SC

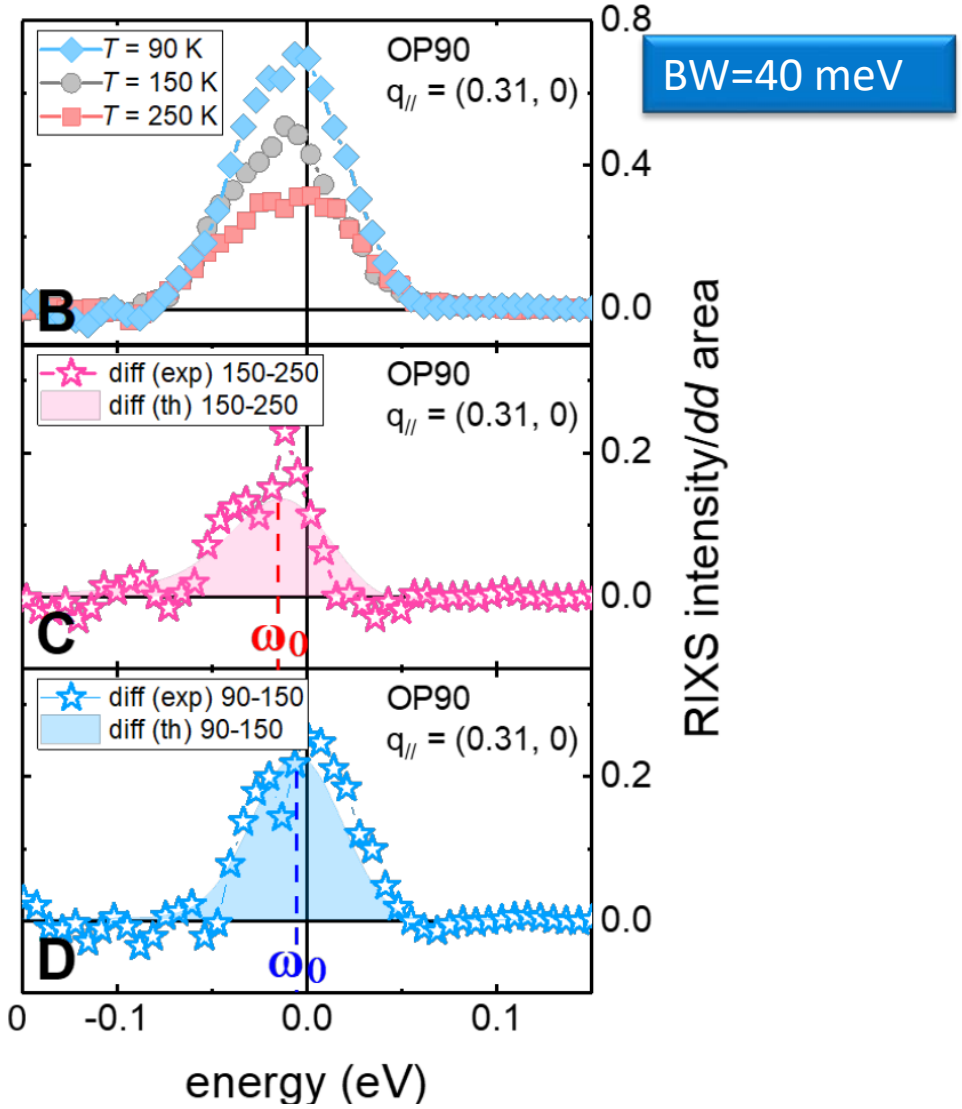




NP has critical behavior
BP is almost constant

BP is much larger in integrated amplitude than NP

Energy resolved measurements: charge density fluctuations



BW=40 meV

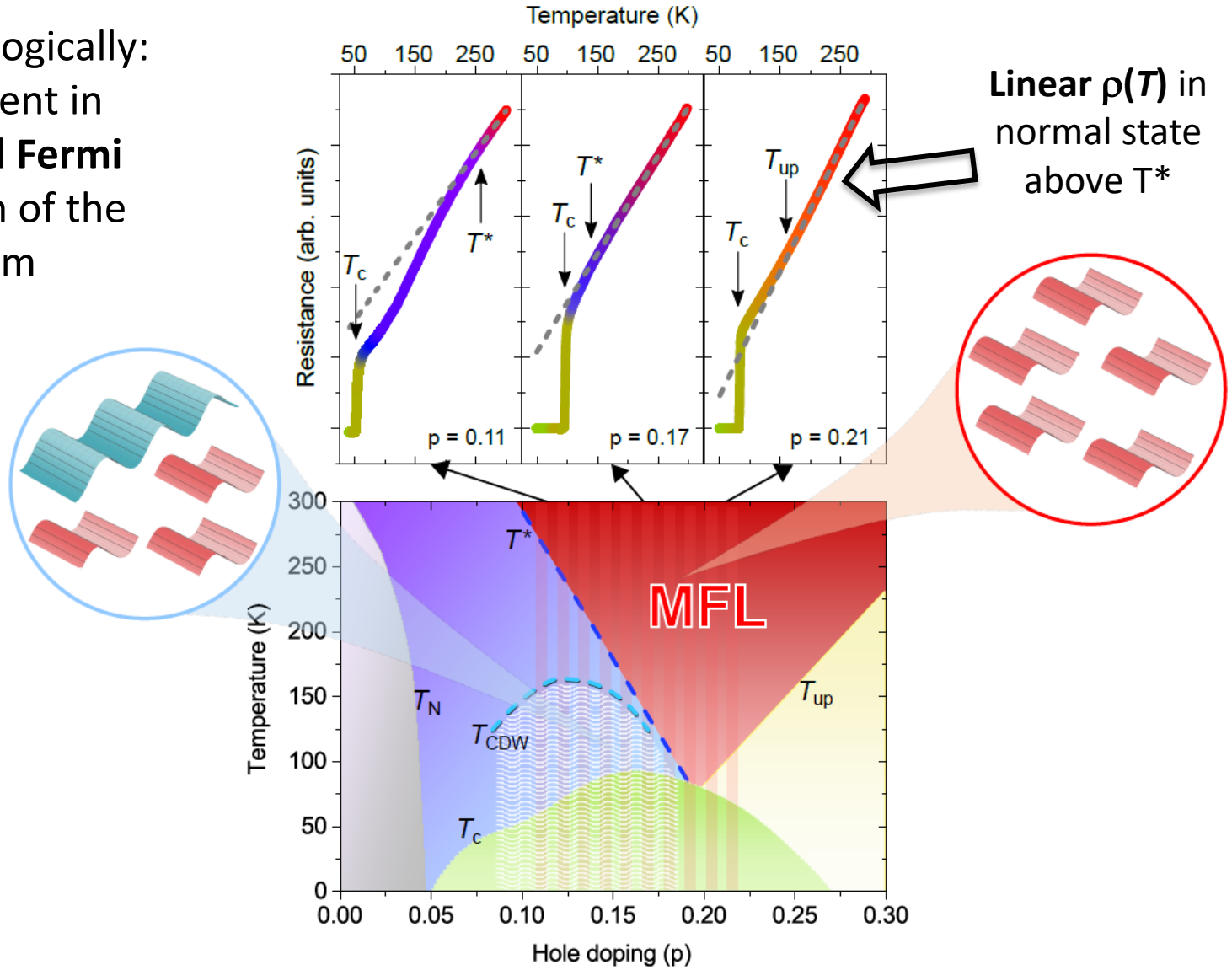
R. Arpaia, S. Caprara, R. Fumagalli, G. De Vecchi, Y.Y. Peng, E. Andersson, D. Betto, G. M. De Luca, N. B. Brookes, F. Lombardi, M. Salluzzo, L. Braicovich, C. Di Castro, M. Grilli, G. Ghiringhelli, arXiv1809.04949

CDF and Marginal Fermi Liquid picture

CDW, T dependent

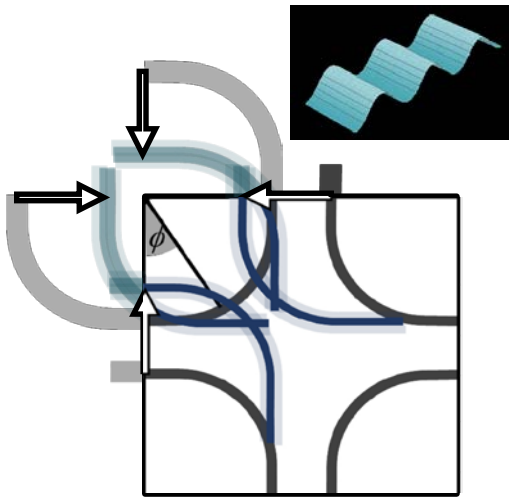
CDF,
quasi T independent

Phenomenologically: CDF are present in the **Marginal Fermi Liquid** region of the phase diagram

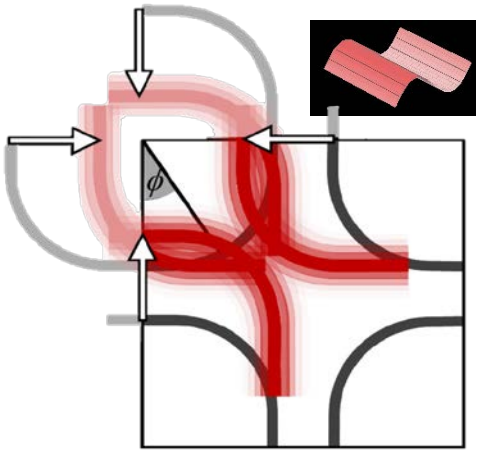


G. Seibold, R. Arpaia, Y.Y. Peng, R. Fumagalli, L. Braicovich, C. Di Castro, M. Grilli;, G. Ghiringhelli, and S. Caprara, *arXiv:1905.10232*

Scattering from CDF can lead to linear $\rho(T)$

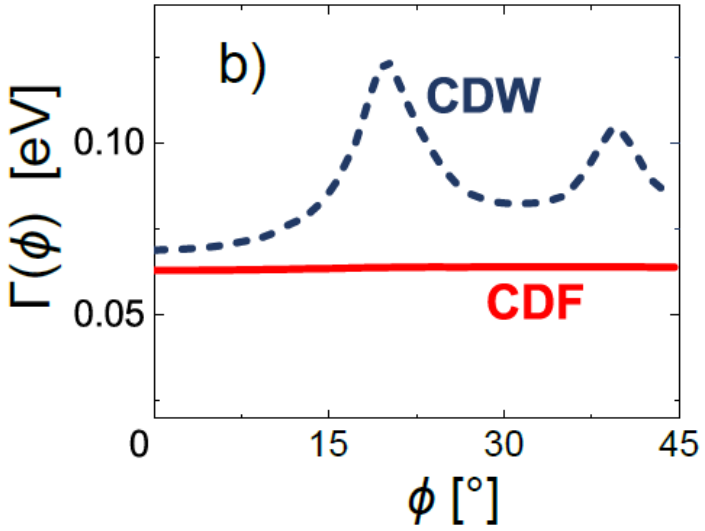


CDW scattering

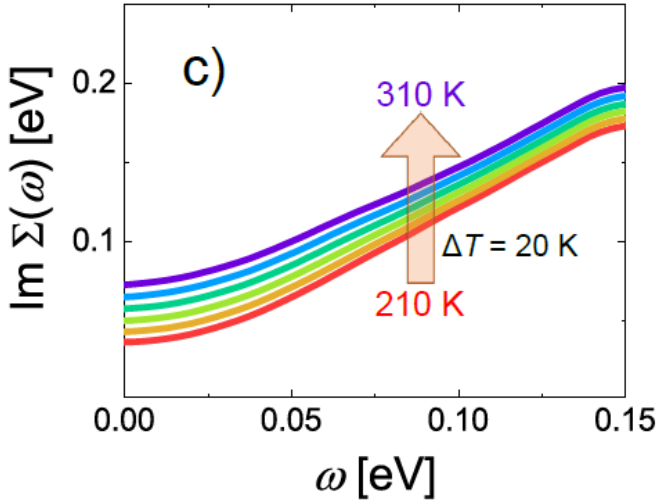


CDF scattering

Scattering rate: $\Gamma = \mathrm{Im}\,\Sigma(\phi, T, \omega = 0)$



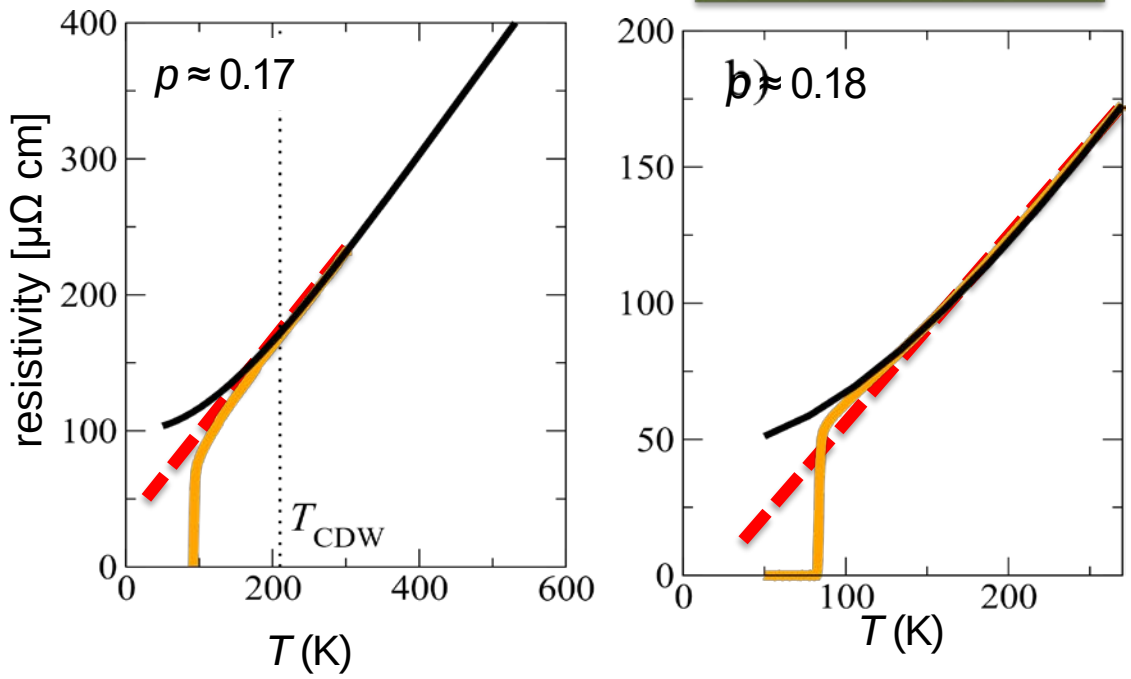
Imaginary part of el. self-energy Σ



Resistivity of OP and OD samples is quantitatively reproduced

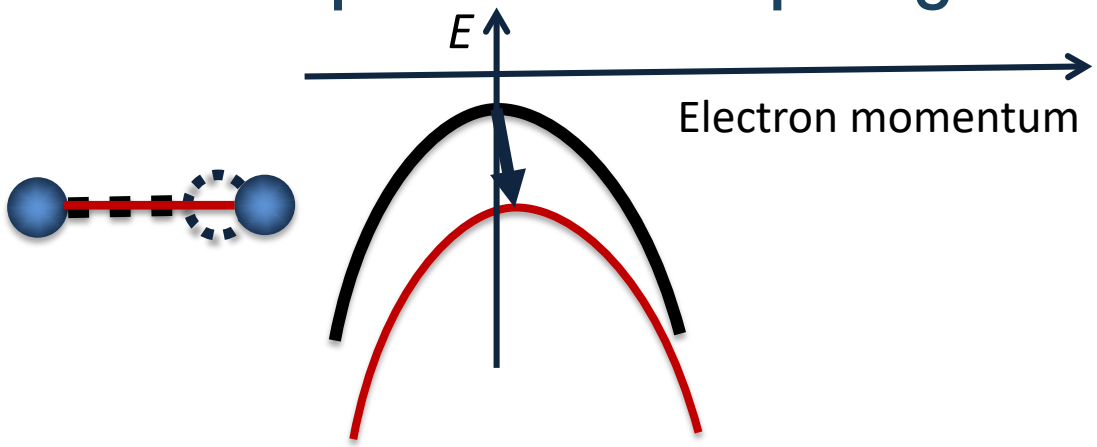
Optimally doped NBCO

Over-doped YBCO



G. Seibold, R. Arpaia, Y.Y. Peng, R. Fumagalli, L. Braicovich, C. Di Castro, M. Grilli;, G. Ghiringhelli, and S. Caprara, *arXiv:1905.10232*

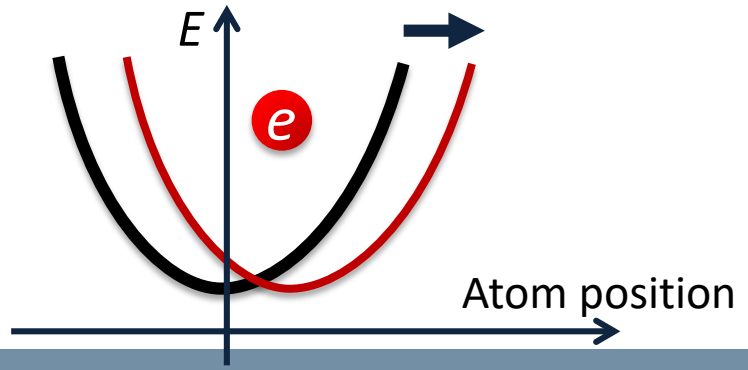
Electron phonon coupling

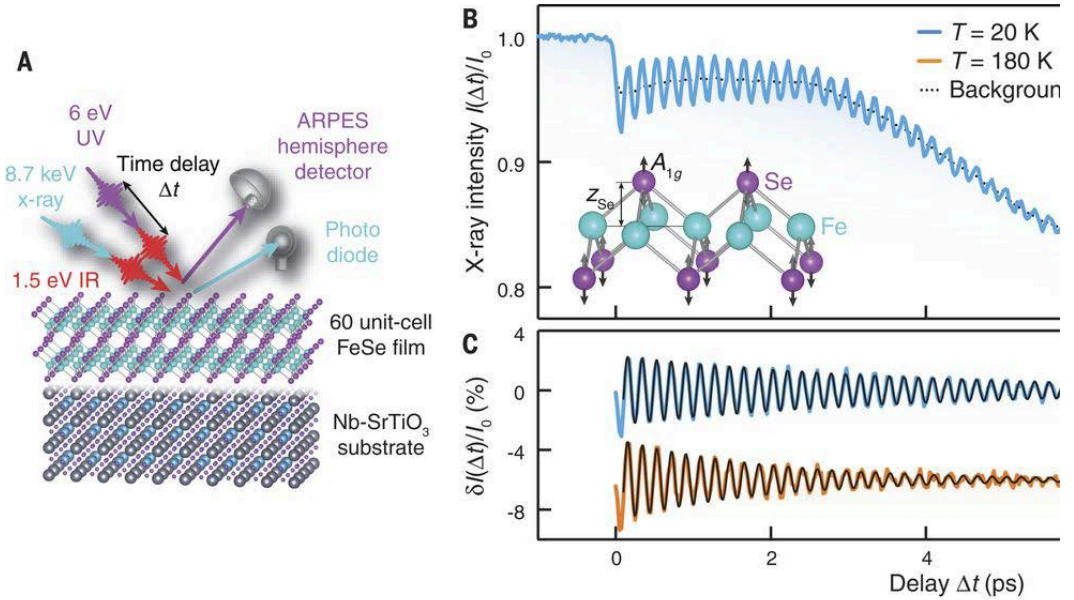


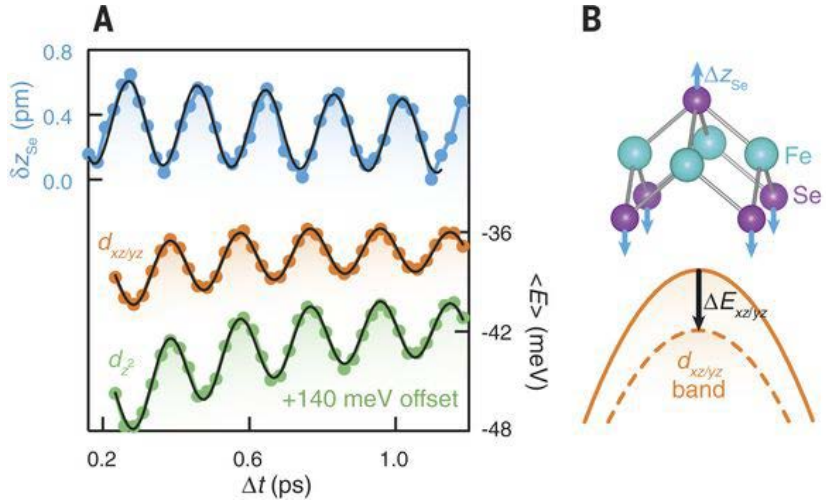
How $\mathcal{H}$ is modified by an atomic displacement

≡

How lattice is deformed by the presence of a valence electron





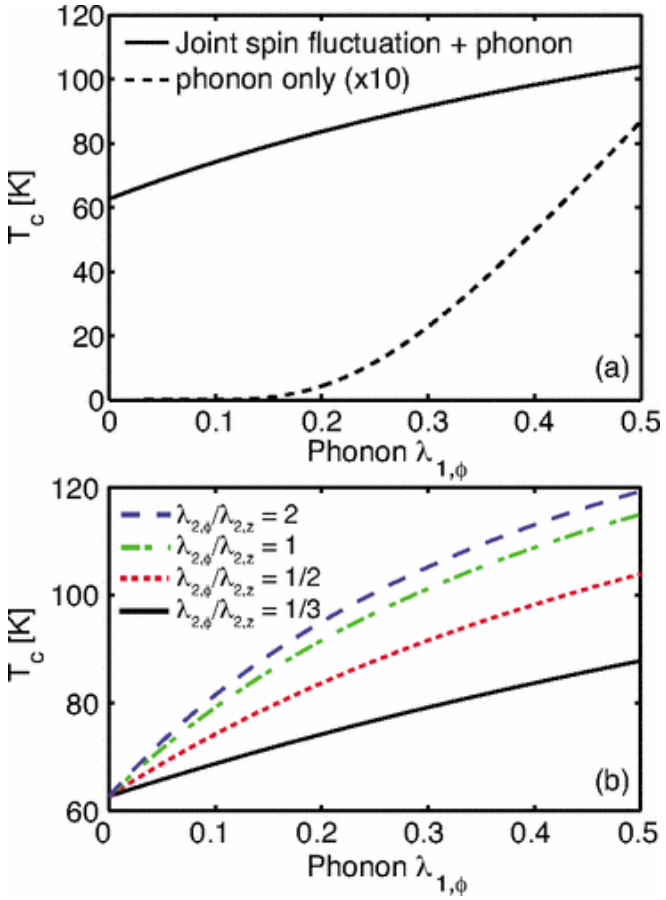


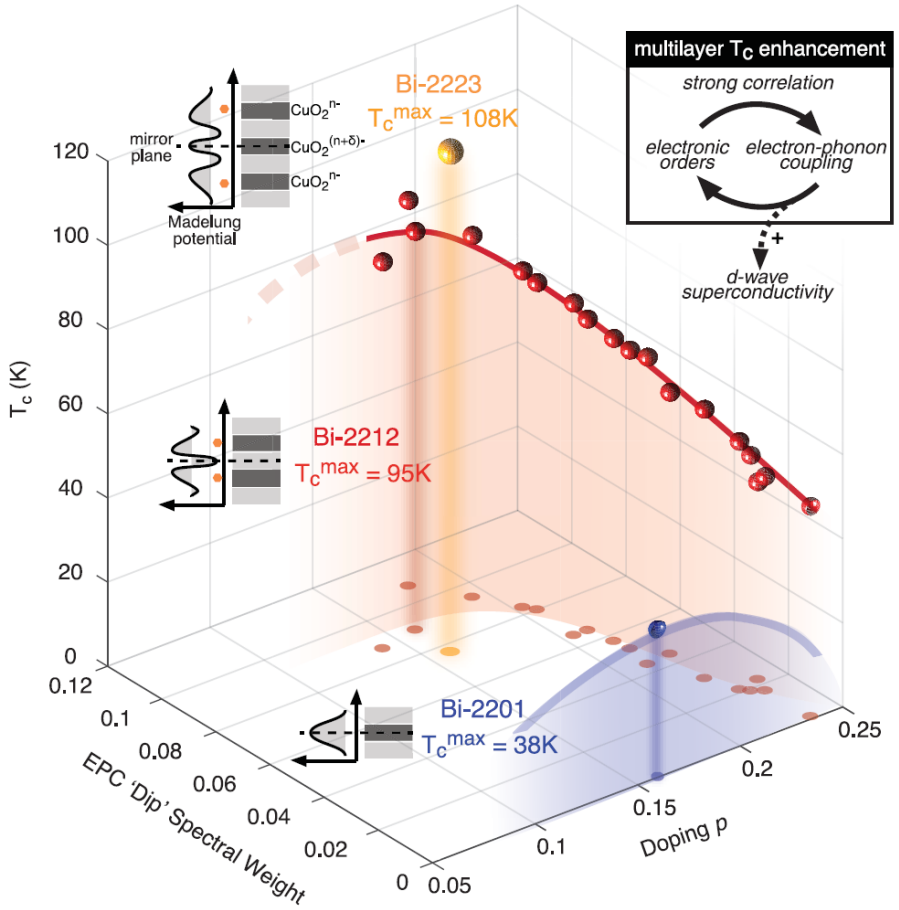
S. Gerber, S.-L. Yang, D. Zhu, H. Soifer, J. A. Sobota, S. Rebec, J. J. Lee, T. Jia, B. Moritz, C. Jia, A. Gauthier, Y. Li, D. Leuenberger, Y. Zhang, L. Chaix, W. Li, H. Jang, J.-S. Lee, M. Yi, G. L. Dakovski, S. Song, J. M. Glownia, S. Nelson, K. W. Kim, Y.-D. Chuang, Z. Hussain, R. G. Moore, T. P. Devereaux, W.-S. Lee, P. S. Kirchmann, and Z.-X. Shen, *Science* **357,** 71(2017)

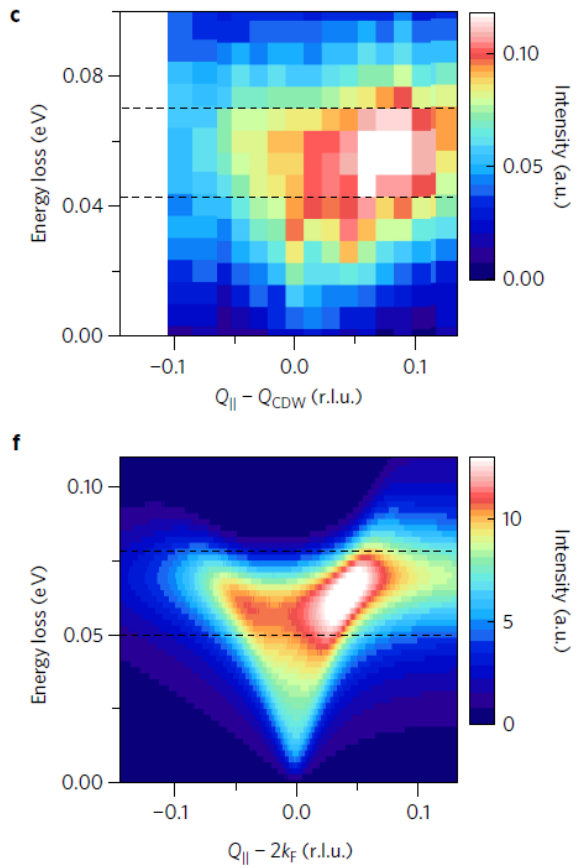
Electron phonon coupling (EPC) in cuprates

EPC: cooperative effect of phonons in SC pairing in cuprates

CDW couple with some optical modes







S. Johnston, F. Vernay, B. Moritz, Z.-X. Shen, N. Nagaosa, J. Zaanen, and T. P. Devereaux *Phys. Rev. B* **82**, 064513 (2010)

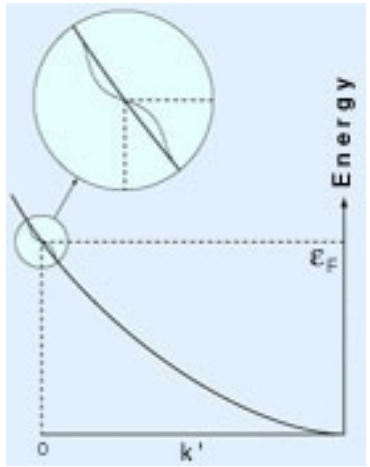
Y. He, M. Hashimoto, D. Song, S.-D. Chen, J. He, I. M. Vishik, B. Moritz, D.-H. Lee, N. Nagaosa, J. Zaanen, T. P. Devereaux, Y. Yoshida, H. Eisaki, D. H. Lu, and Z.-X. Shen *Science* **362** 62 (2018)

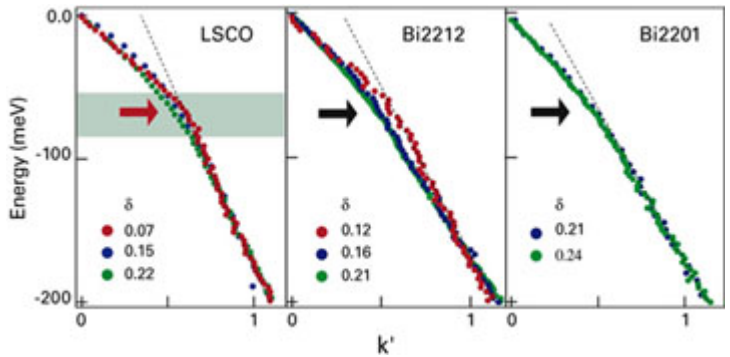
L. Chaix, G. Ghiringhelli, Y. Y. Peng, M. Hashimoto, Y. He, S. Chen, K. Kummer, N.B. Brookes, B. Moritz, S. Ishida, Y. Yoshida, H. Eisaki, L. Braicovich, Z.-X. Shen, T. P. Devereaux, W.-S. Lee, *Nature Physics* **13**, 952 (2017)

Measuring EPC with RIXS

Large parameter space: electron **k**, phonon (ω,**q**)

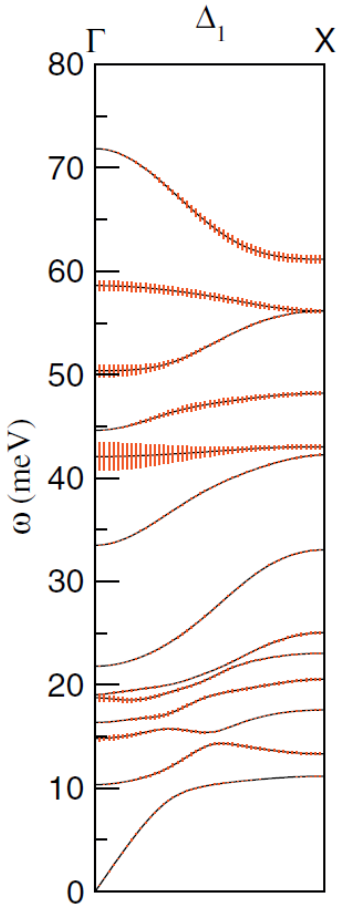
ARPES: kinks related to EPS
k and ω can be obtained
q is unknown





https://sites.google.com/a/lbl.gov/bl10_hers/news/archive/roleoflatticevibrationsinsuperconductivity

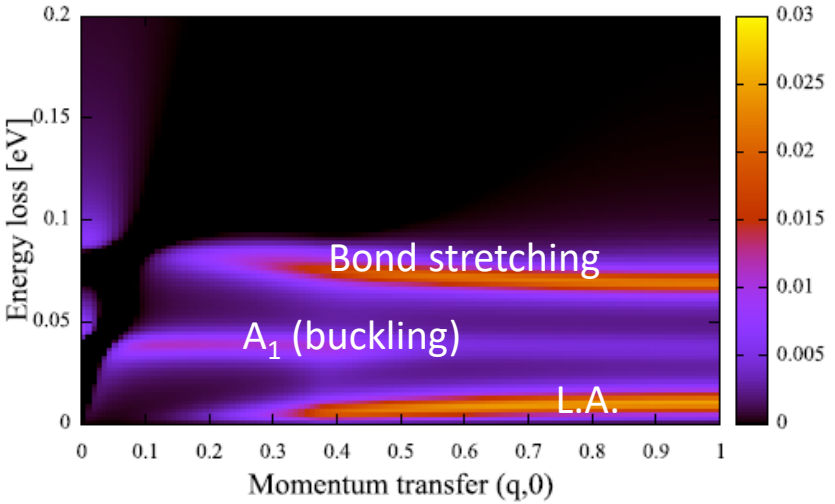
INS: linewidth related to EPC
k is unknown
ω and **q** are measured



L. Pintschovius, *phys. stat. sol. (b)* **242**, 30 (2005)

RIXS: ph peak intensity prop. to EPC
k is partly unknown
ω and **q** are measured

Theoretical phonon intensity in RIXS



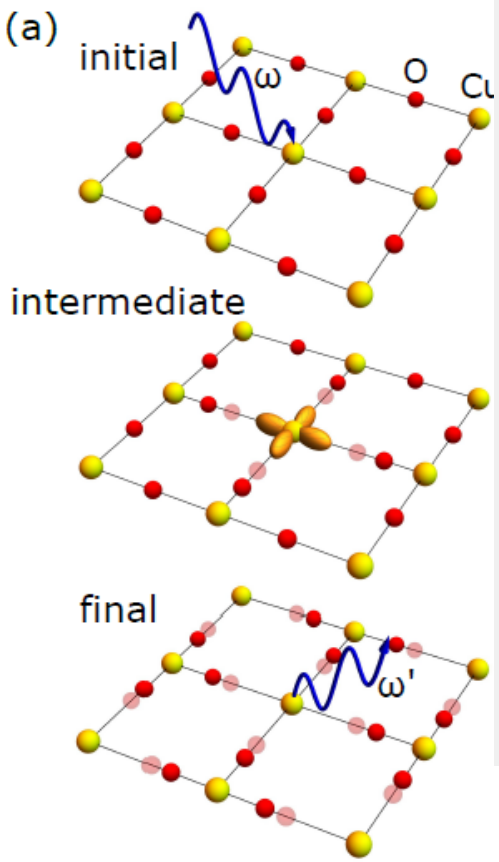
T. P. Devereaux, A. M. Shvaika, K. Wu, K. Wohlfeld, C.-J. Jia, Y. Wang, B. Moritz, L. Chaix, W.-S. Lee, Z.-X. Shen, G. Ghiringhelli, and L. Braicovich, *PRX* **6**, 041019 (2016)

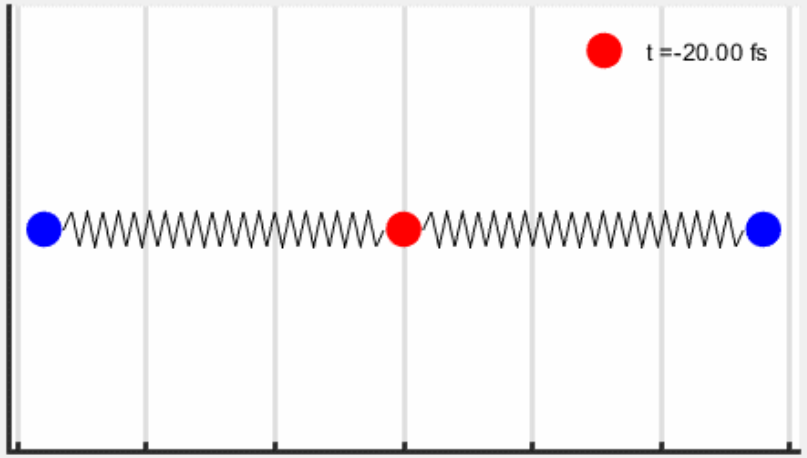
Measuring EPC with RIXS: mechanism

Theory by Ament, van den Brink

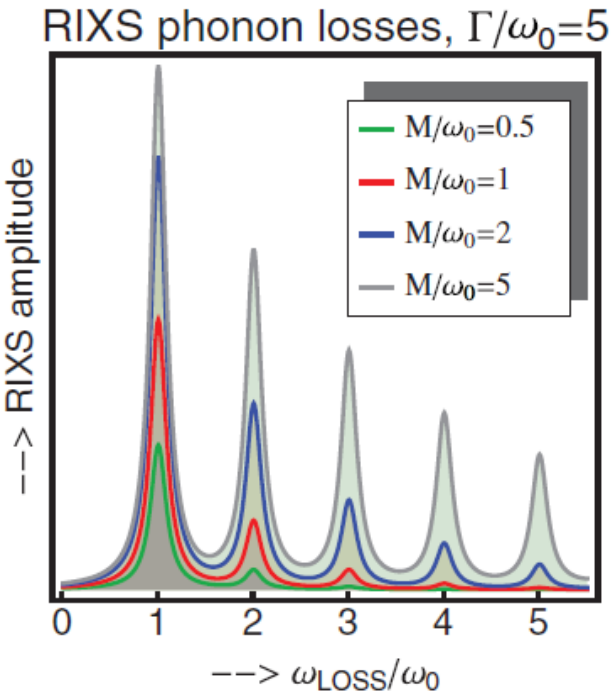
Phonon peak intensity grows with:
- EPC, i.e., M or $g = (M/\omega_0)^2$
- Intermediate state lifetime

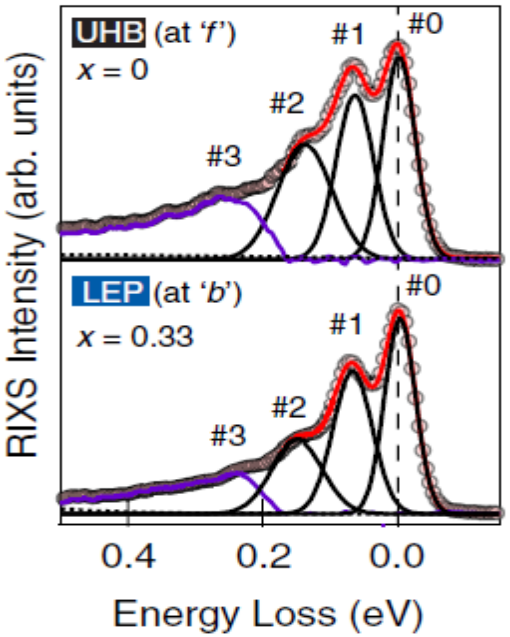
2*ph*, 3*ph* peaks





Application to 1D system (O K edge)





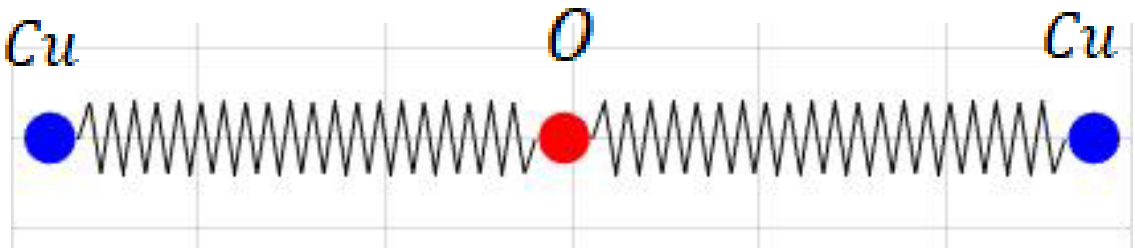
Matteo Rossi, Riccardo Arpaia, Roberto Fumagalli, Marco Moretti Sala, Davide Betto, Gabriella M. De Luca, Kurt Kummer, Jeroen van den Brink, Marco Salluzzo, Nicholas B. Brookes, Lucio Braicovich, Giacomo Ghiringhelli, arXiv:1902.09163, to appear in PRL

L. J. P. Ament, M. van Veenendaal and J. van den Brink, EPL **95** (2011) 27008

W-S Lee et al, PRL **110**, 265502 (2013)

Classical model of EPC in RIXS

Ground state

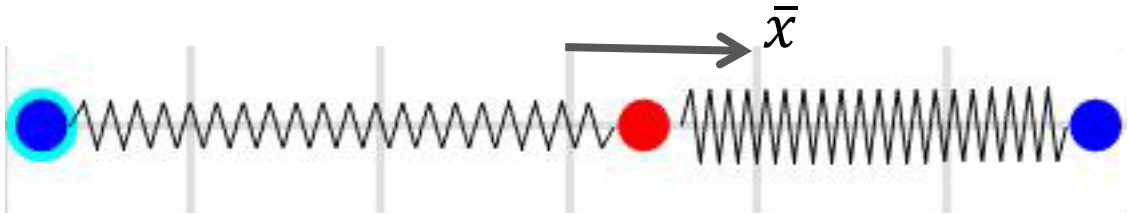


$$\omega_0 = \sqrt{\frac{2k_0}{M}}$$

$$M\ddot{x} = +k_0(\Delta x - x) - k_0(\Delta x + x)$$

Δx is the pre-deformation of springs: irrelevant in ground state, relevant in intermediate state

Intermediate state

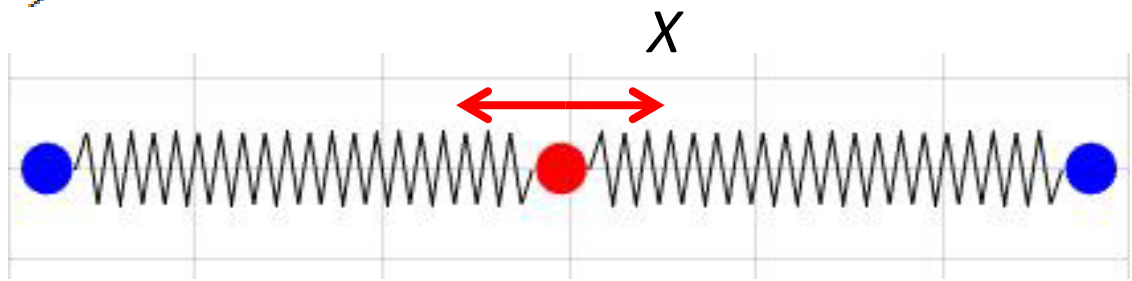


$$\omega_1 = \sqrt{\frac{2k_0 - k_{ep}}{M}}$$

New equilibrium position $\bar{x} = \dfrac{k_{ep}}{2k_0 - k_{ep}}\Delta x$

$$M\ddot{x} = +k_0(\Delta x - x) - (k_0 - k_{ep})(\Delta x + x)$$

Final state



$$\omega_0 = \sqrt{\frac{2k_0}{M}}$$

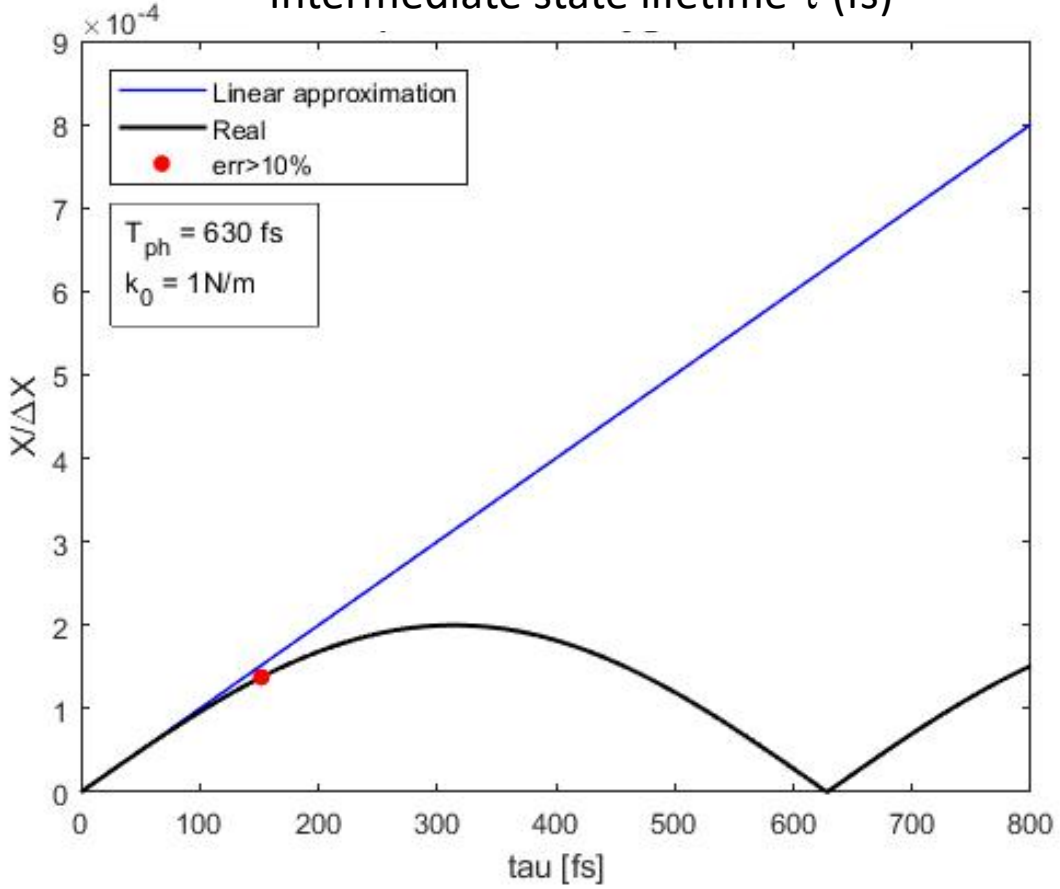
$$x(t) = X\sin(\omega_0 t + \phi)$$

$$X^2 = \bar{x}^2\left(\left(\frac{\omega_1}{\omega_0}\right)^2 \sin^2(\omega_1\tau) + (1 - cos(\omega_1\tau))^2\right)$$

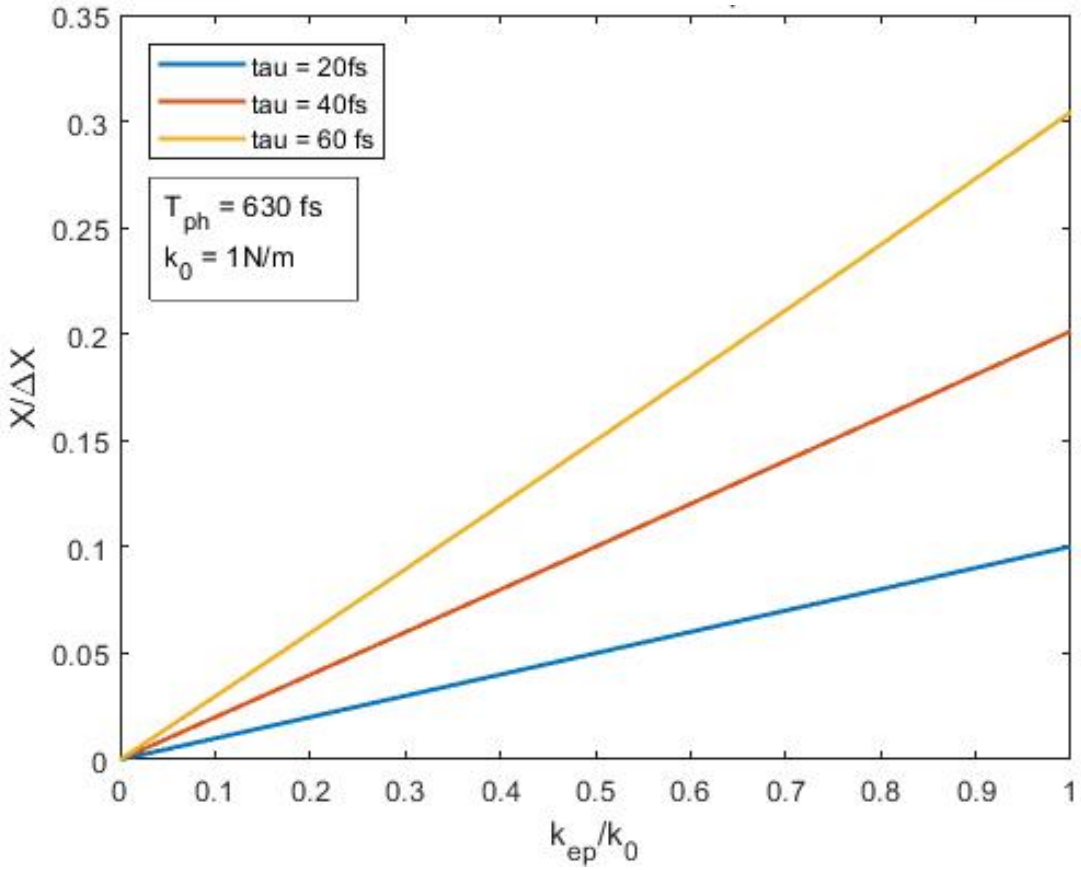
$$\frac{X}{\Delta X} = \frac{k_{ep}}{2k_0 - k_{ep}}\sqrt{\left(\left(\frac{\omega_1}{\omega_0}\right)^2 \sin^2(\omega_1\tau) + (1 - cos(\omega_1\tau))^2\right)}$$

Trends in classical oscillator model

Intermediate state lifetime τ (fs)



Change of elastic constant in I.S. k_{ep}

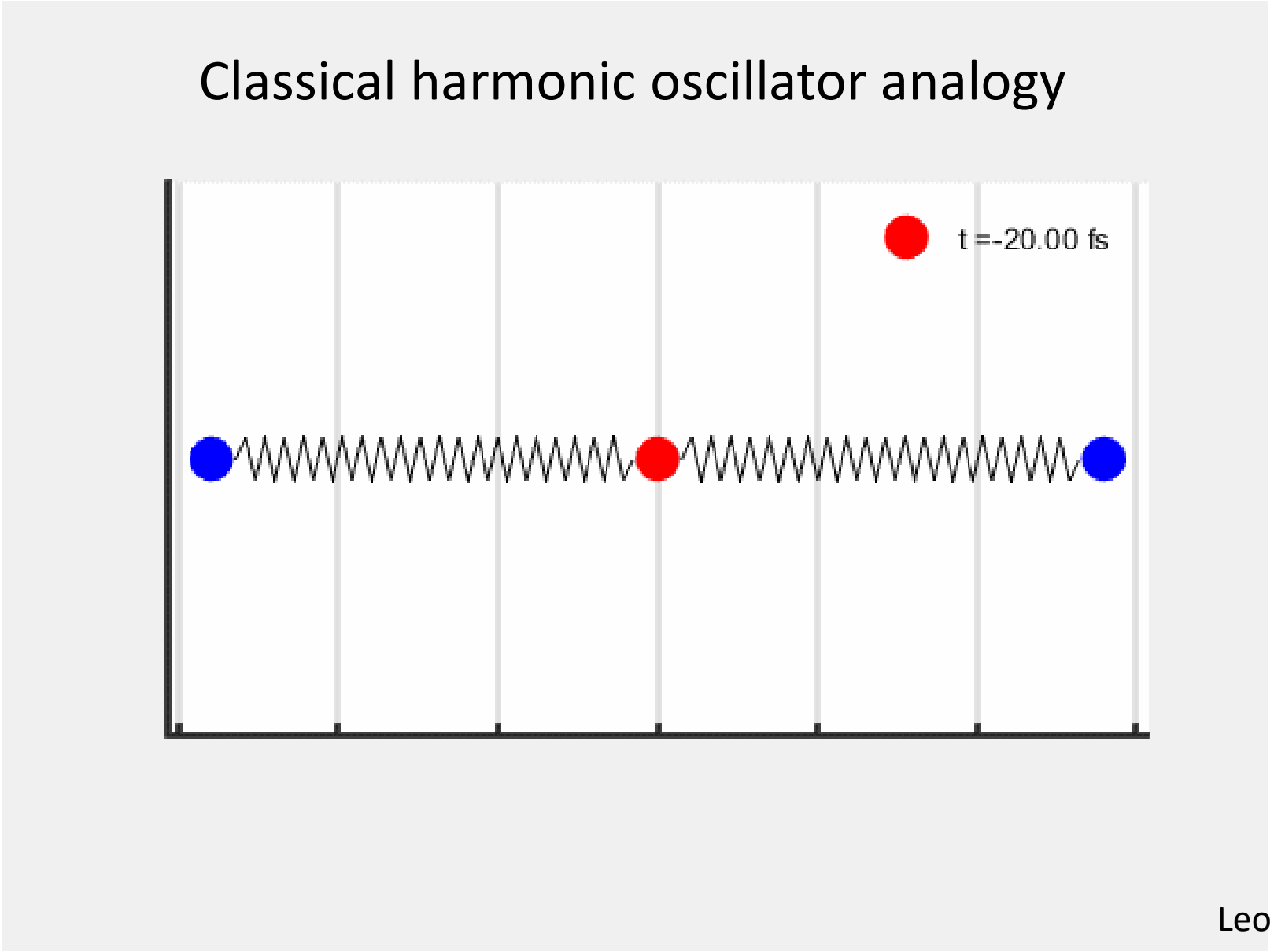


Amplitide of oscillations:

$$\frac{X}{\Delta X} = \frac{k_{ep}}{2k_0 - k_{ep}} \sqrt{\left(\left(\frac{\omega_1}{\omega_0}\right)^2 \sin^2(\omega_1\tau) + (1 - cos(\omega_1\tau))^2\right)}$$

Leonardo Martinelli, GG et al

The movie



Leonardo Martinelli, GG et al

Ament / van den Brink / van Veenendaal model

epl A Letters Journal Exploring the Frontiers of Physics

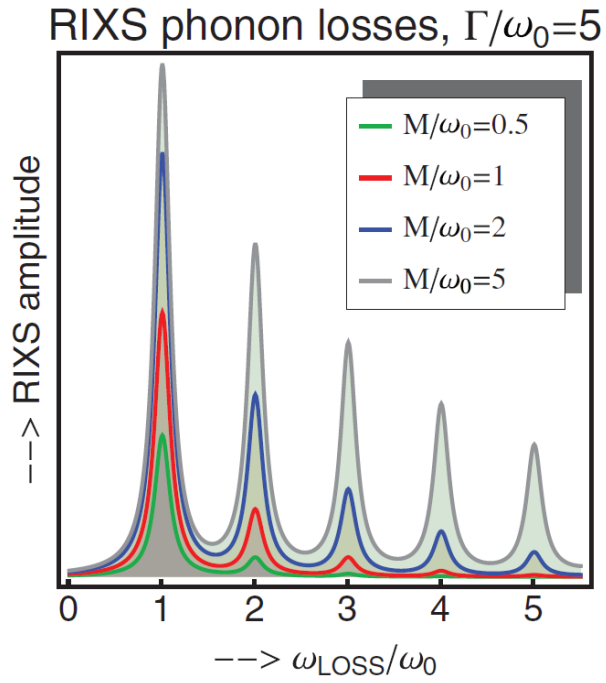
July 2011

EPL, **95** (2011) 27008
doi: 10.1209/0295-5075/95/27008

www.epljournal.org

Determining the electron-phonon coupling strength from Resonant Inelastic X-ray Scattering at transition metal L-edges

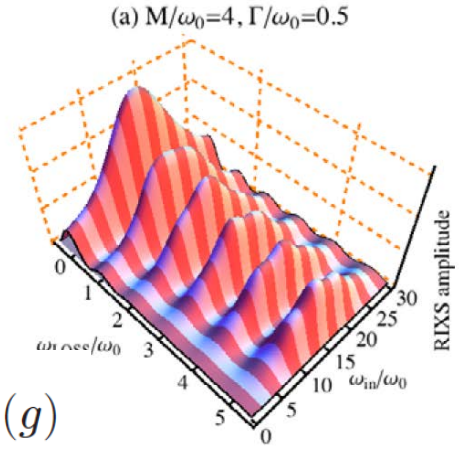
L. J. P. Ament[1,2], M. van Veenendaal[3,4] and J. van den Brink[2]

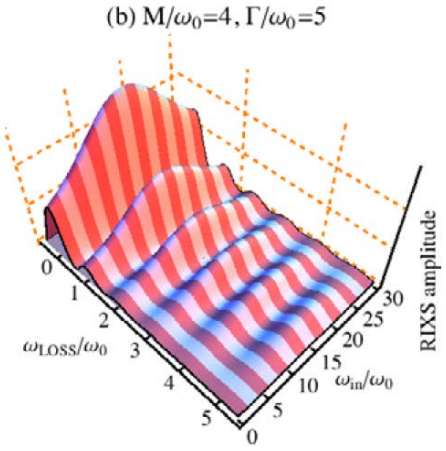


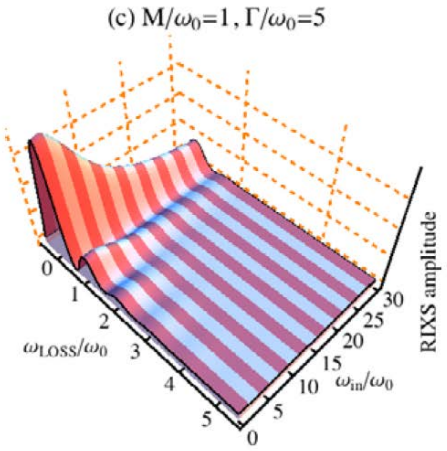
$$A_{\mathbf{q}}^{\text{Einstein}} = \sum_{n=0}^{\infty} \frac{B_{\max(n',n),\min(n',n)}(g) B_{n0}(g)}{z + (g-n)\omega_0}.$$

$$B_{mn}(g) = (-1)^m \sqrt{e^{-g} m! n!} \sum_{l=0}^{n} \frac{(-g)^l \sqrt{g}^{m-n}}{(n-l)!l!(m-n+l)!}$$

$$g = M^2/\omega_0^2.$$



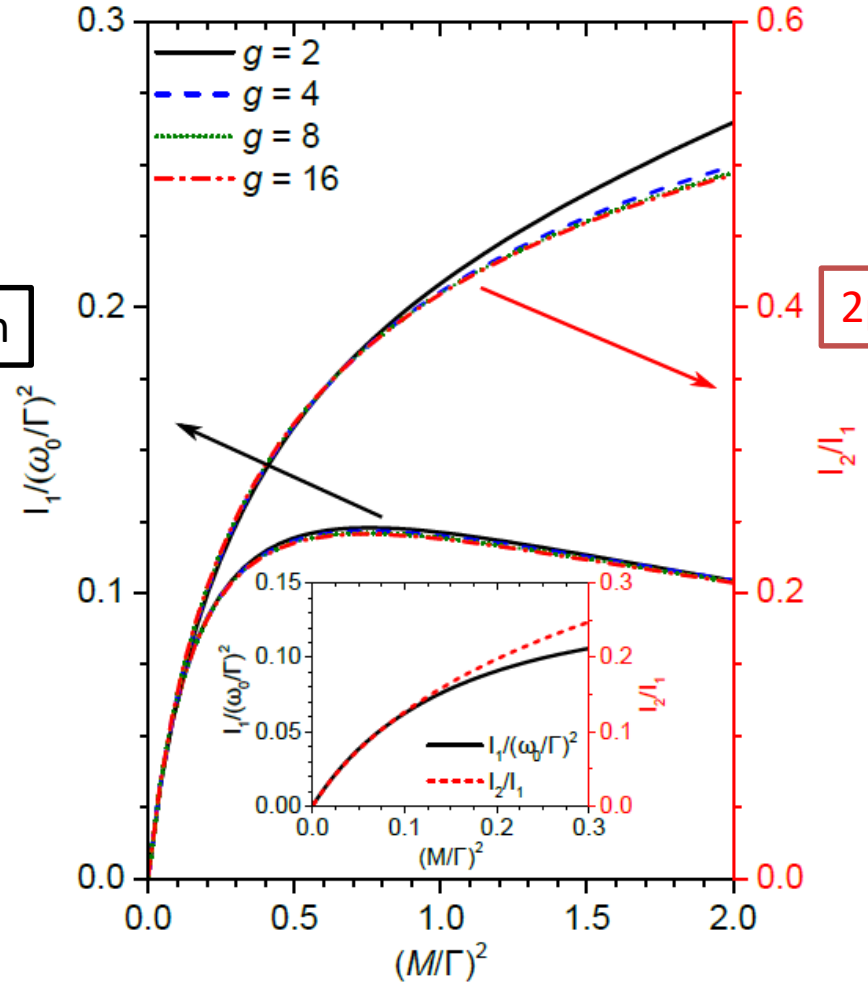




Scaling laws

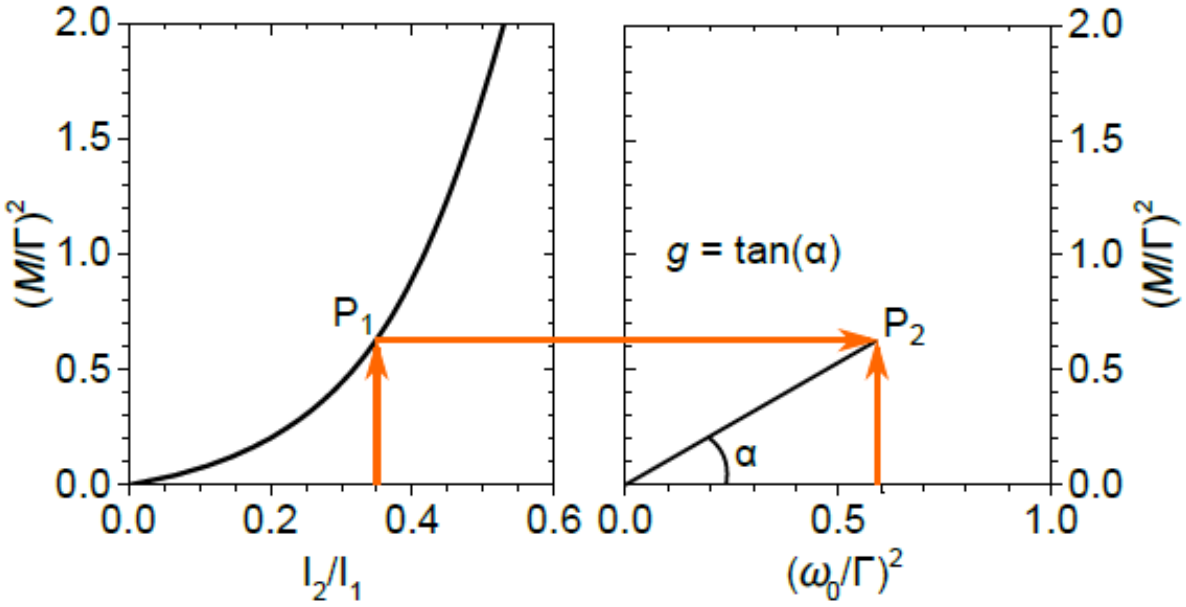
We scale all parameter on Γ, the inverse of intermediate sate lifetime

1 ph



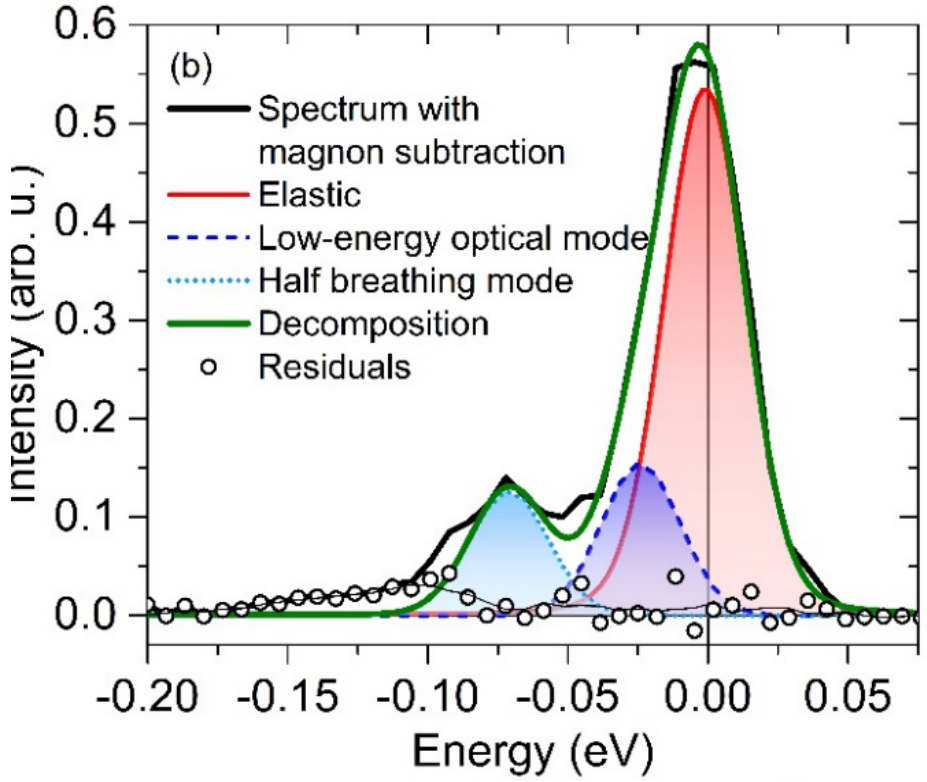
2ph / 1ph

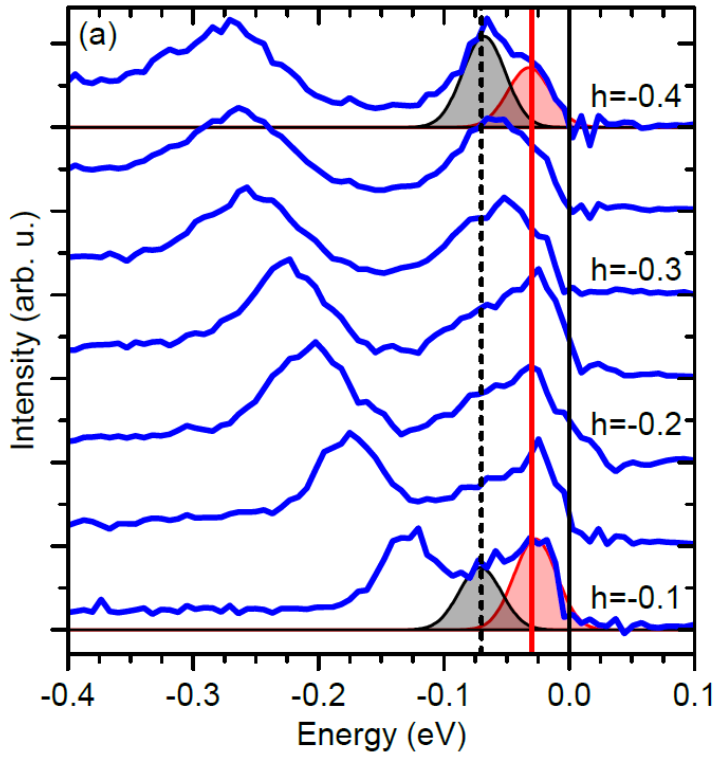
If one can measure I_2/I_1, one can get $g=M^2/\omega_0^2$ by knowing ω_0 and Γ



Lucio Braicovich, Matteo Rossi, Roberto Fumagalli, Yingying Peng, Yan Wang, Riccardo Arpaia, Davide Betto, Gabriella M. De Luca, Daniele Di Castro, Kurt Kummer, Marco Moretti Sala, Mattia Pagetti, Giuseppe Balestrino, Nicholas B. Brookes, Marco Salluzzo, Steven Johnston, Jeroen van den Brink, Giacomo Ghiringhelli, arXiv:1906.01270

At Cu L_3 it does not work directly: no 2*ph* peak

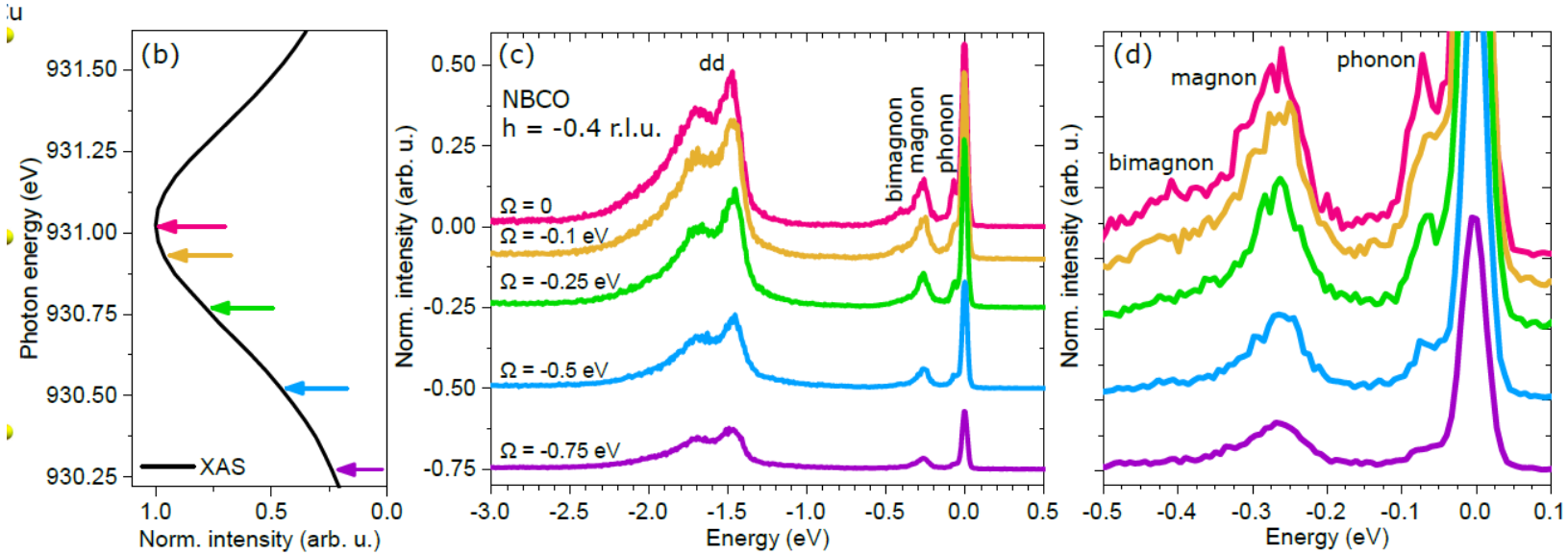


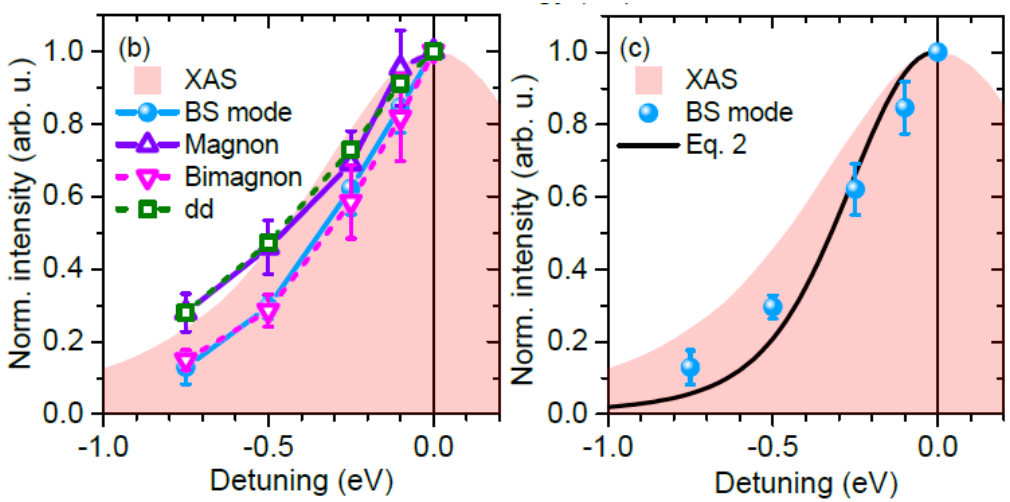


We need alternative methods to measure *M*

New method to obtain *M* from RIXS data: detuning

By detuning the incident x-ray phonon energy with respect to max of XAS, the effective lifetime decreases, reducing the phonon peak intensity more than XAS is reduced.



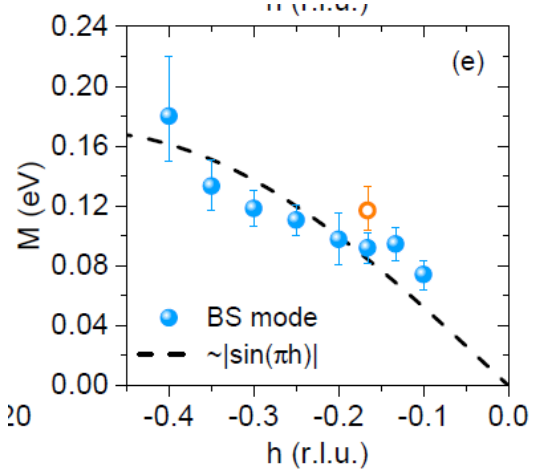


Fitting to simple equation allows estimate of

M =160 meV

at (0.40,0,L)

q dependence

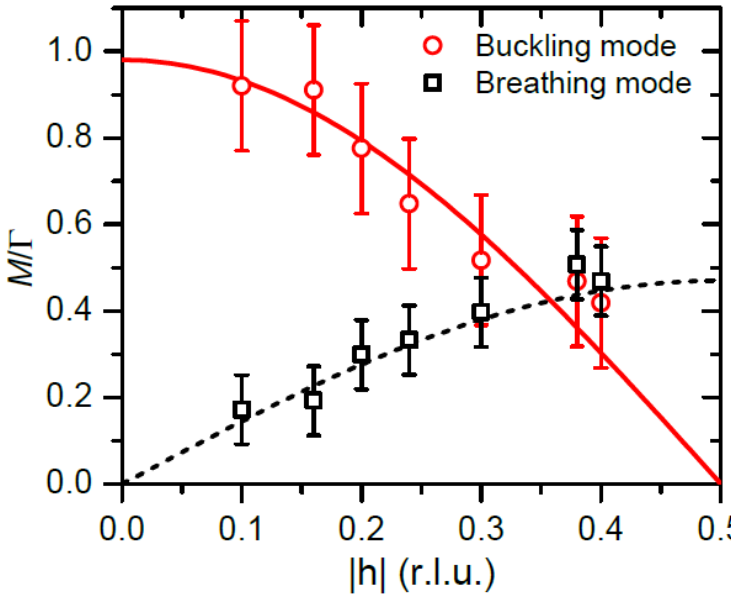


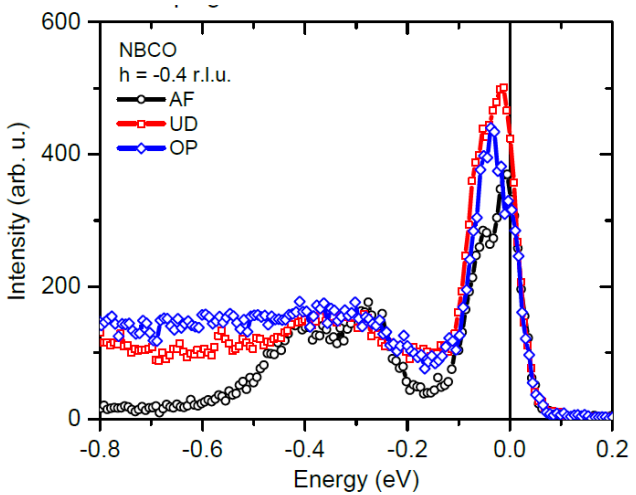
Matteo Rossi, Riccardo Arpaia, Roberto Fumagalli, Marco Moretti Sala, Davide Betto, Gabriella M. De Luca, Kurt Kummer, Jeroen van den Brink, Marco Salluzzo, Nicholas B. Brookes, Lucio Braicovich, Giacomo Ghiringhelli, arXiv:1902.09163, to appear in PRL

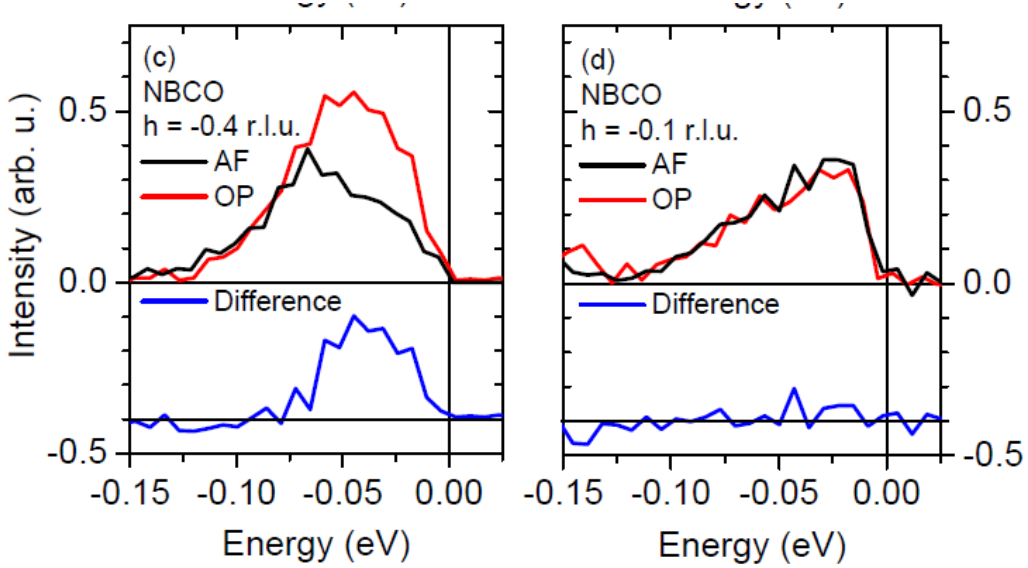
EPC in NBCO

Doping dependence: interplay with CDW at large *q* in (10)

q dependence







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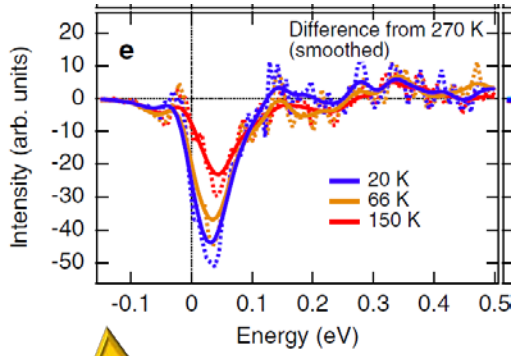
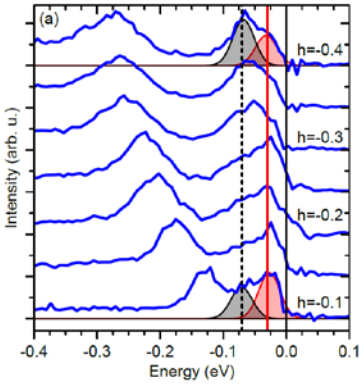
Conclusions

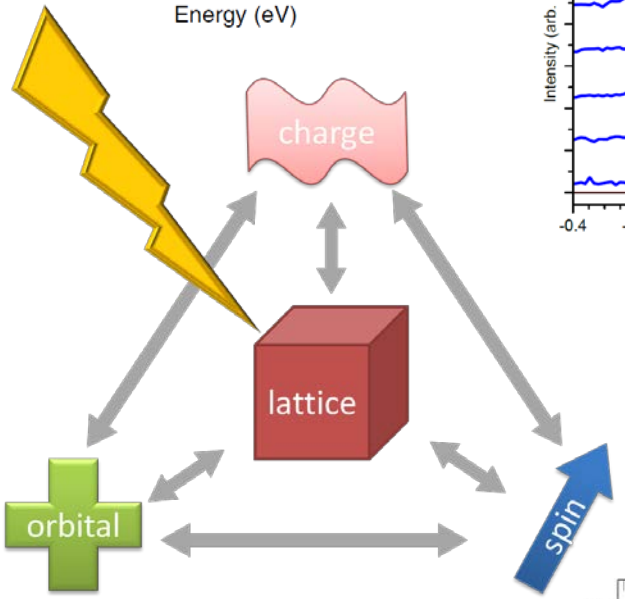
RIXS can really measure spin, charge, orbital and lattice excitations

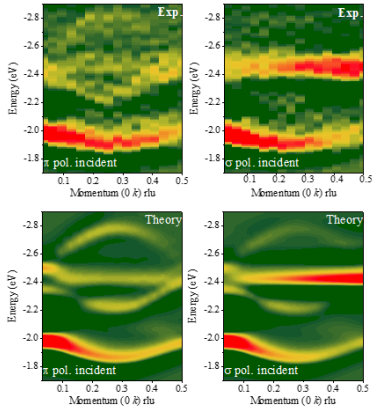
Better resolution and higher efficiency still needed

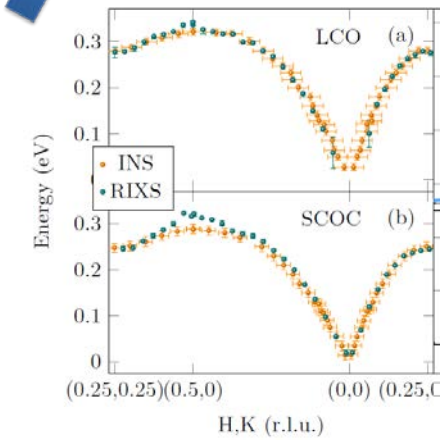
Adding the time variable will be challenging but useful to further probe interconnections











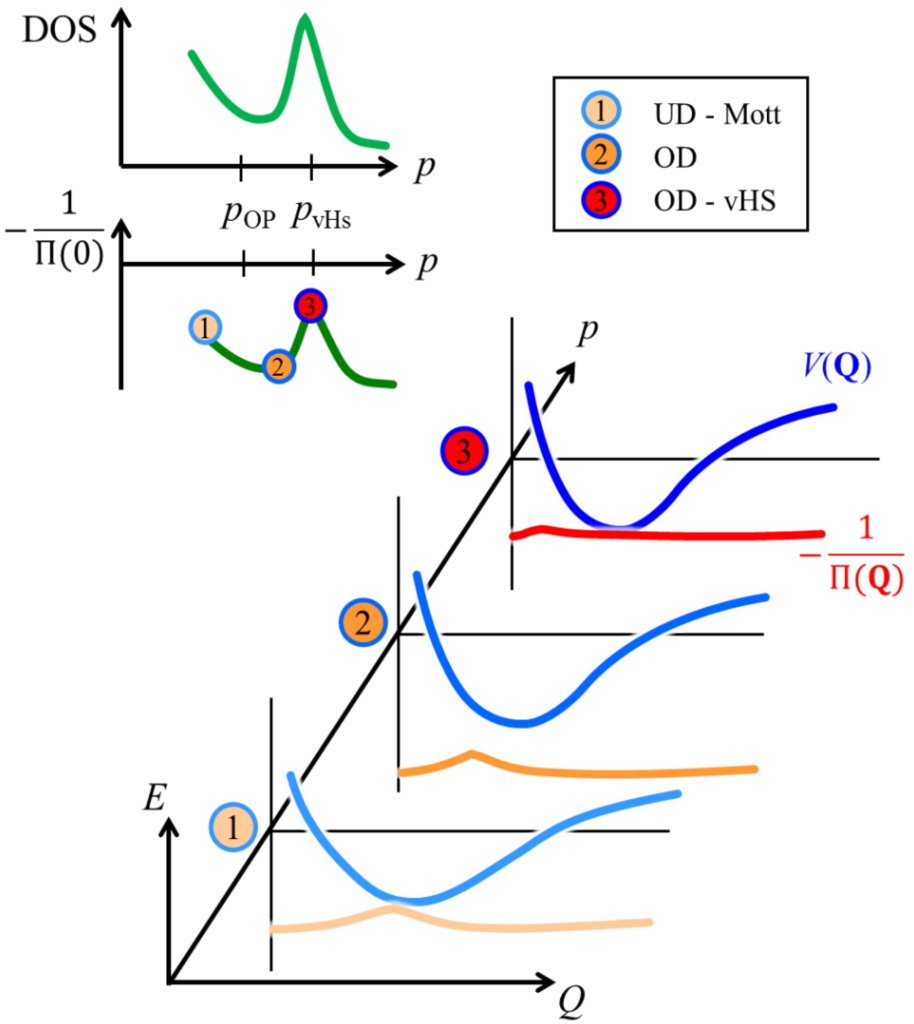
Fluctuating CDW might provide unified picture

Fermi liquid, RPA:

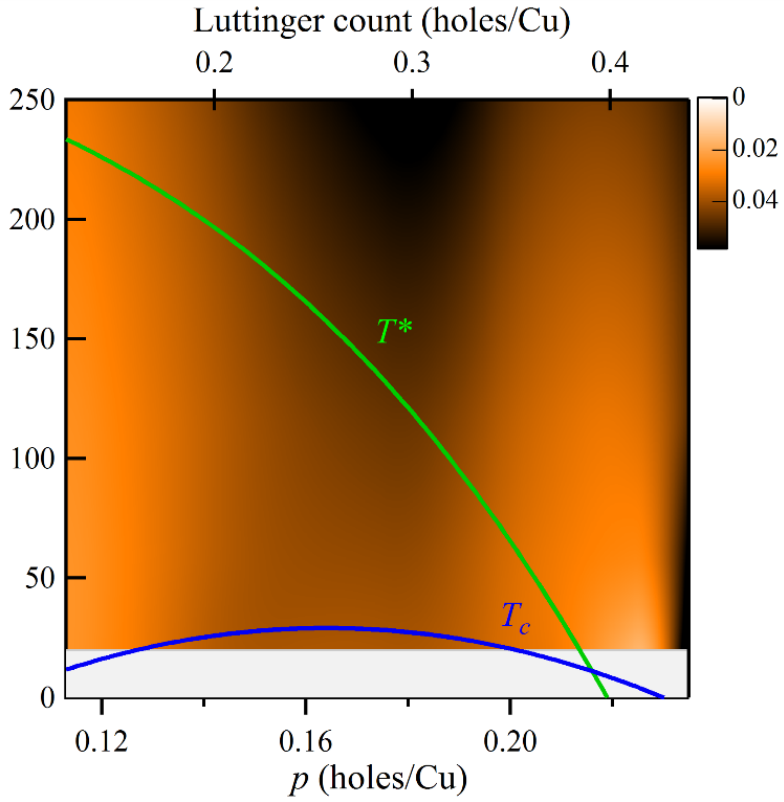
$$\chi(\mathbf{Q}) = \frac{\Pi(\mathbf{Q})}{1+V(\mathbf{Q})\Pi(\mathbf{Q})}$$

$$V(\mathbf{Q}_{co}) = -\frac{1}{\Pi(\mathbf{Q}_{co})}$$

$$\Pi(0) \propto \mathrm{DOS}$$



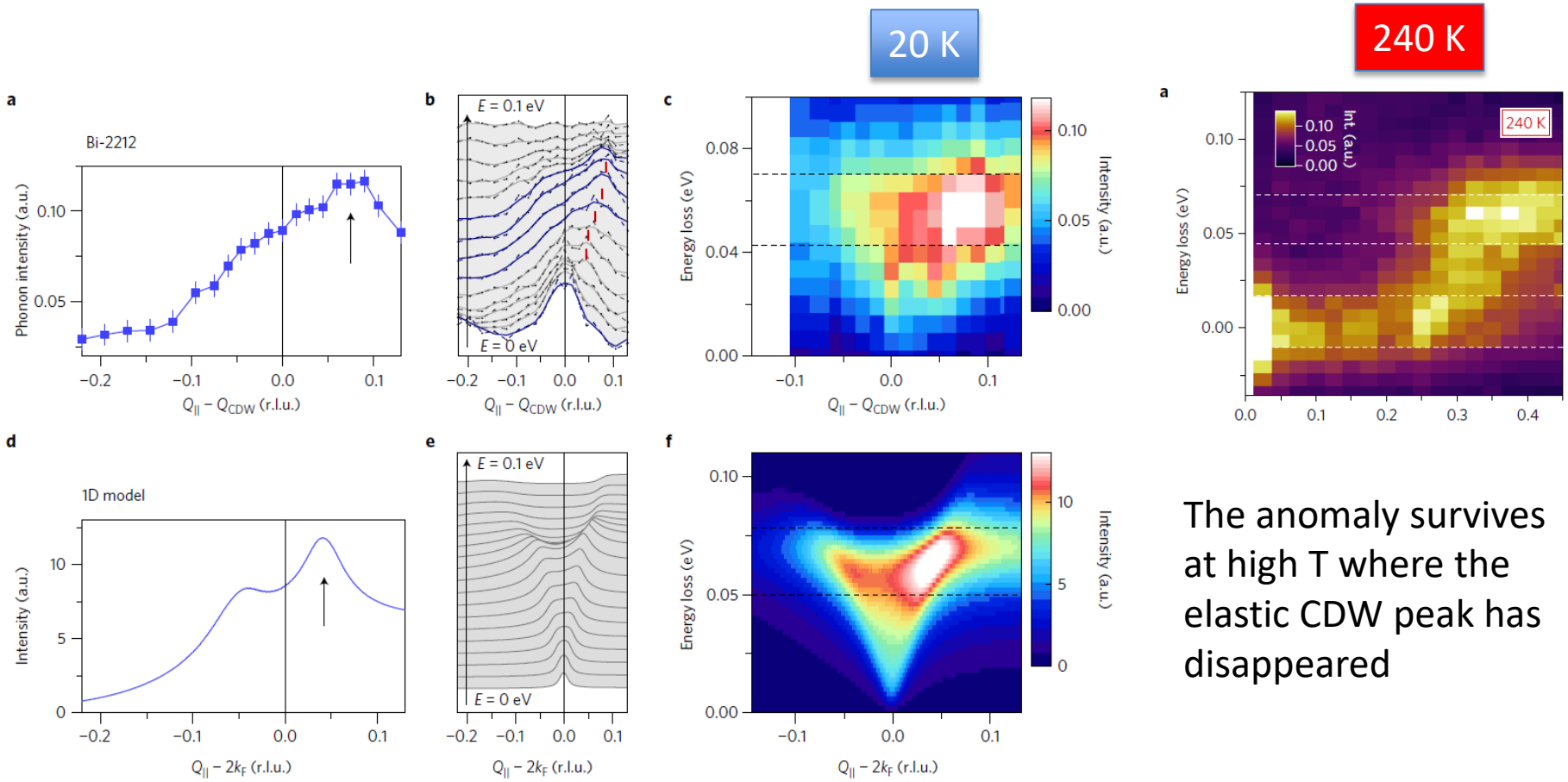
The fluctuating CDW scenario seems compatible with our discovery



S. Caprara, C. Di Castro, G. Seibold, and M. Grilli
Phys. Rev. B **95**, 224511 (2017)

Y. Y. Peng, R. Fumagalli, Y. Ding, M. Minola, S. Caprara, D. Betto, M. Blüschke, 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, Nature Materials, **17**, 697 (2018).

Phonons in RIXS reveal CDW excitation



The anomaly survives at high T where the elastic CDW peak has disappeared

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, *Nature Physics* **13**, 952 (2017)

Conclusions on CDW and CDF