POLITECNICO
MILANO 1863

Consiglio Nazionale delle Ricerche

Una nuova spettroscopia di raggi X per lo studio dei “materiali quantistici”

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ACCADEMIA NAZIONALE DEI LINCEI
CLASSE DI SCIENZE FISICHE, MATEMATICHE E NATURALI
Venerdì 14 gennaio 2021 ore 11

Introduction

Career

Milano – Laurea Ingegneria. Nucleare
Paris – ENSTA Diplome d'Engenieur

2001 – Grenoble
ESRF – PhD in physics

Milano POLIMI (RTI, PA, PO)

Since 2001 – ESRF (collab.)

2005-2012 – PSI (collab.)

2011, 2019 – Stanford

XFEL.EU – Hamburg

2018 - Europhysics Prize CMD-EPS

Scientific interests

Synchrotron radiation

X-ray resonant spectroscopy

X-ray instrumentation

Strongly correlated electrons

Cuprate superconductors

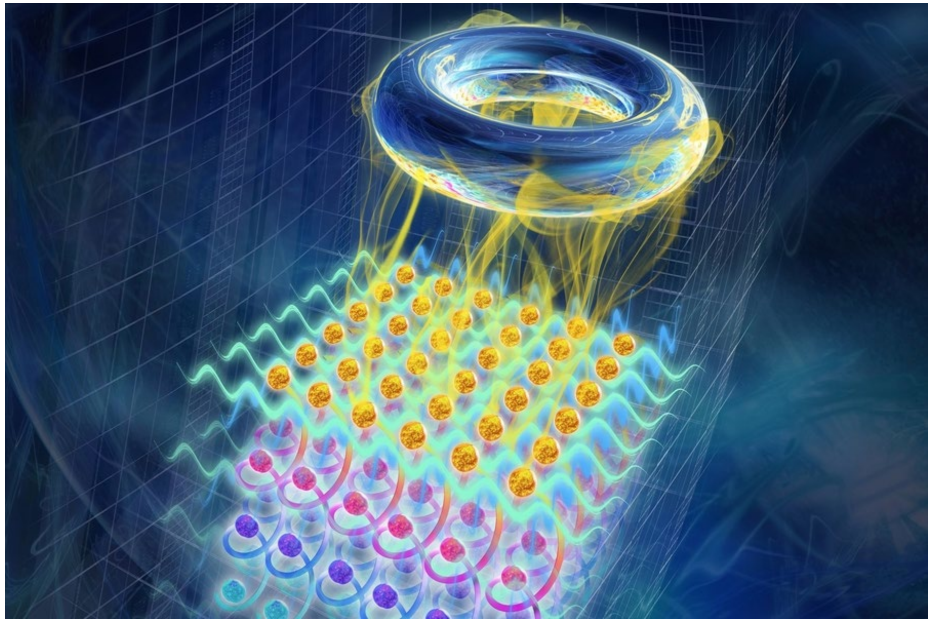
RIXS

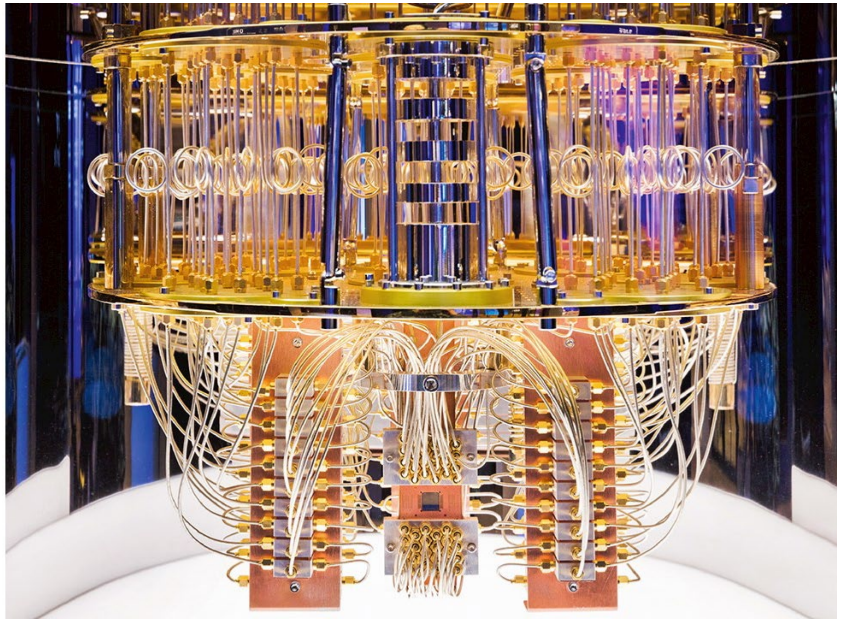
Resonant
Inelastic
X-ray
Scattering

Diffusione
Anelastica
Risonante di
Raggi X

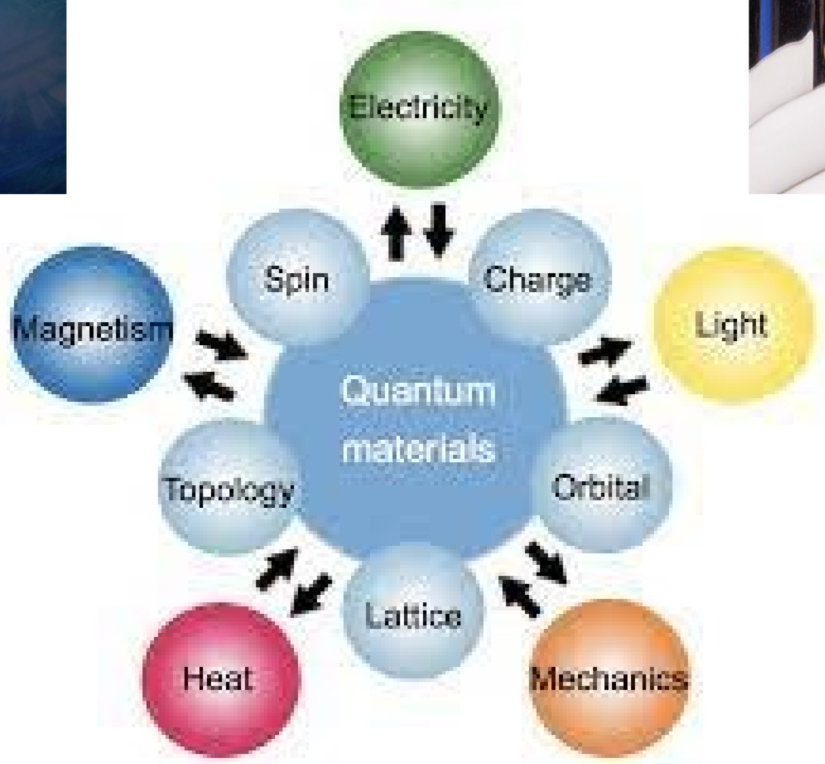
- Una spettroscopia per i materiali complessi
- Luce, Raggi X e neutroni
- Come funziona il RIXS
- Le difficoltà tecniche nella strumentazione per RIXS
- 2 risultati sui cuprati superconduttori ad alta Tc

Quantum matter, quantum materials, quantum technology



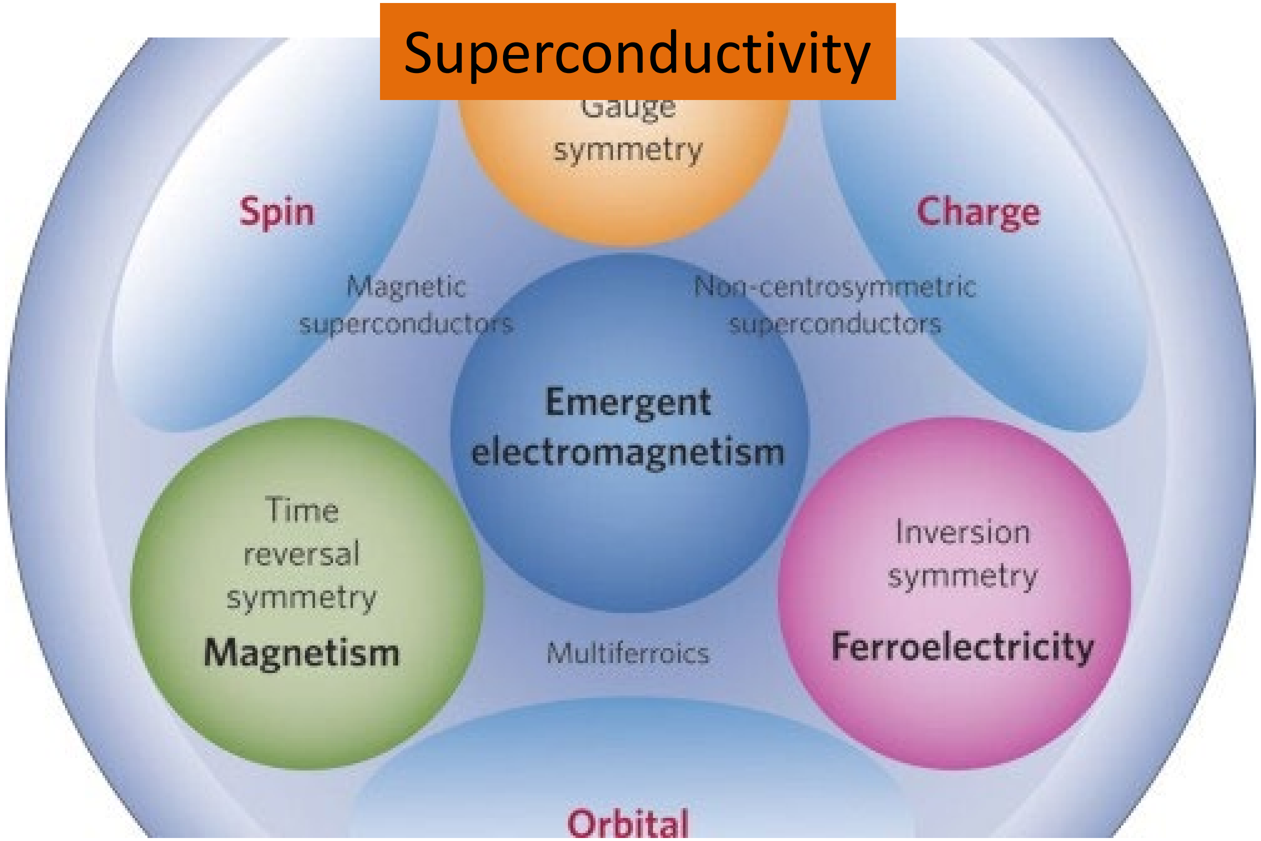


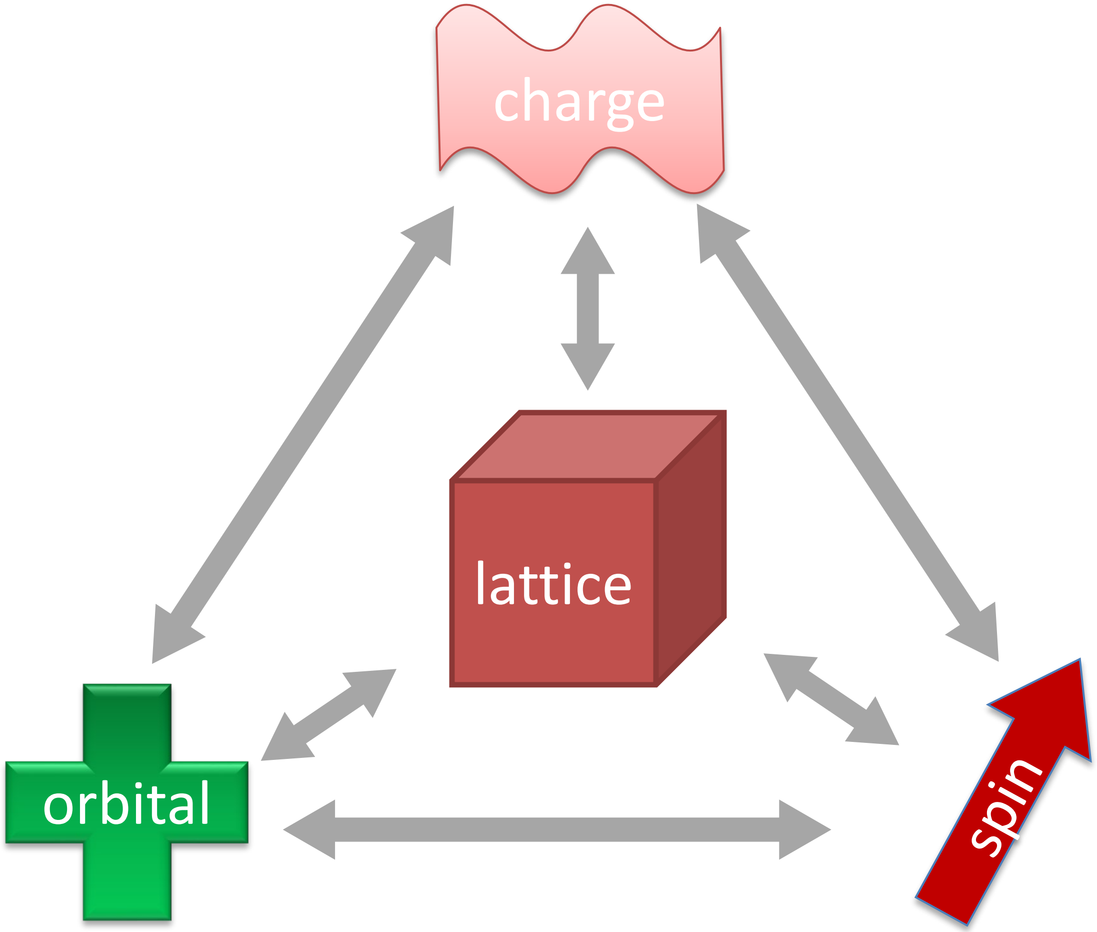
All matter, all materials, all technologies are ultimately governed by quantum physics laws, at microscopic level.
But often quantum aspects can be hidden in macroscopic laws proper to classical physics (eg semiconductor electronics)



QUANTUM-SOMETHING
When particle-wave duality is unresolved
When typical quantum mechanical phenomena emerge at macroscopic scale
When wave-physics is purposely exploited

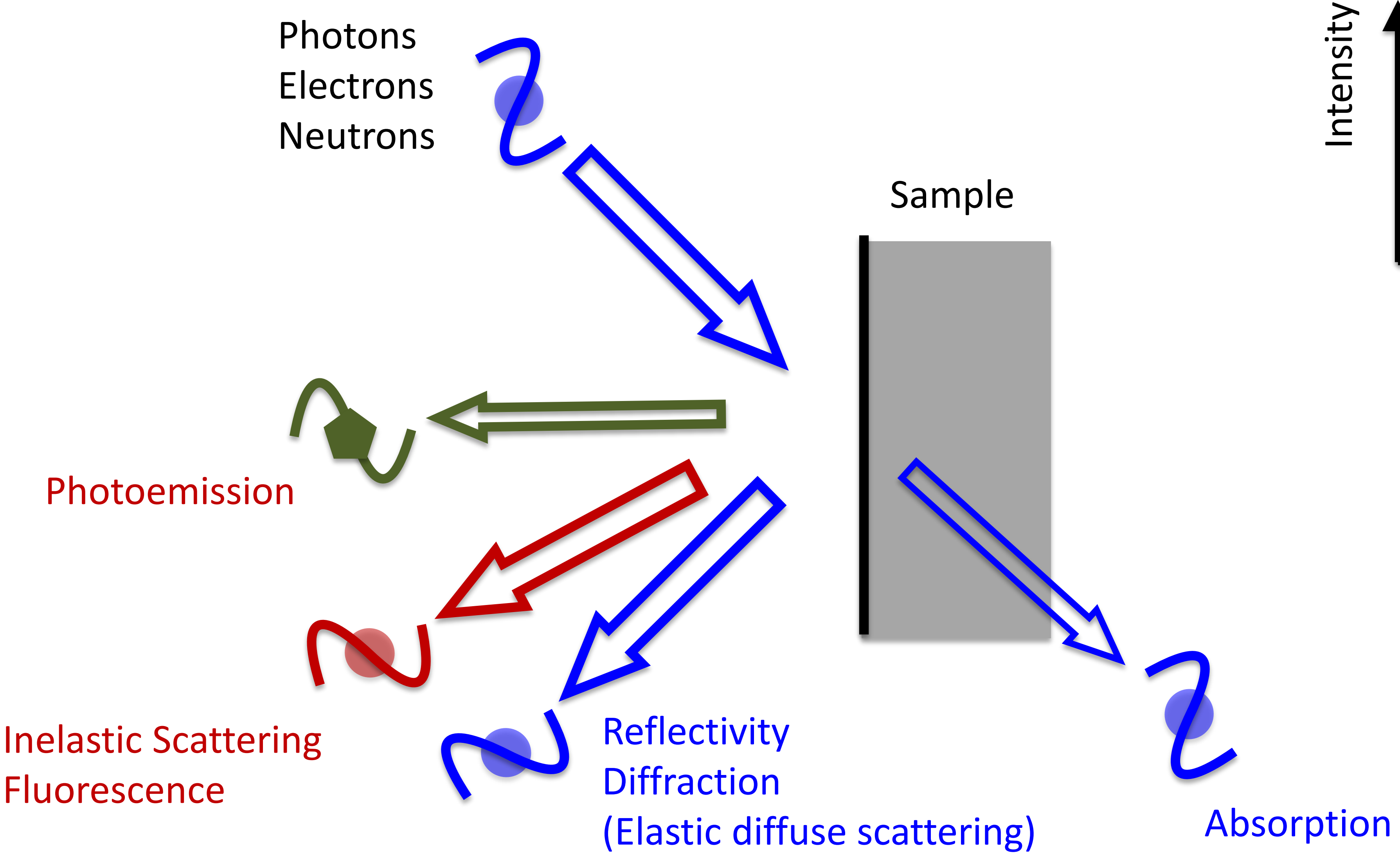
Electronic correlation in condensed matter

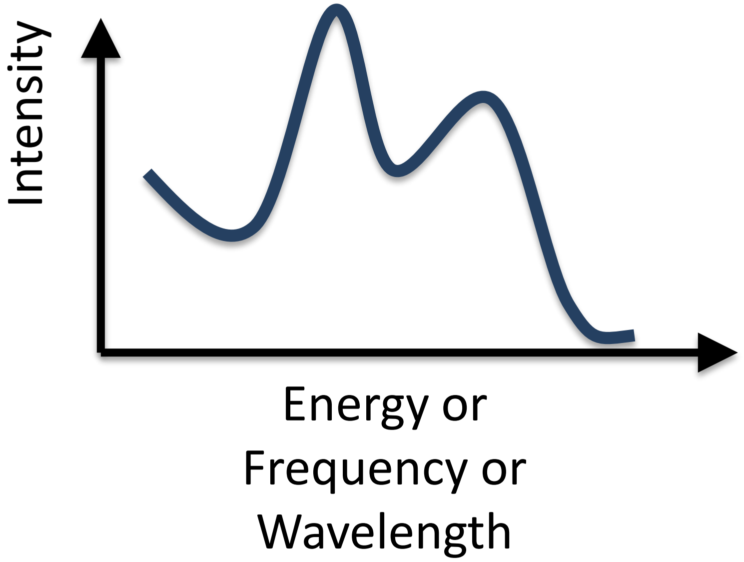




Spectroscopy for condensed matter

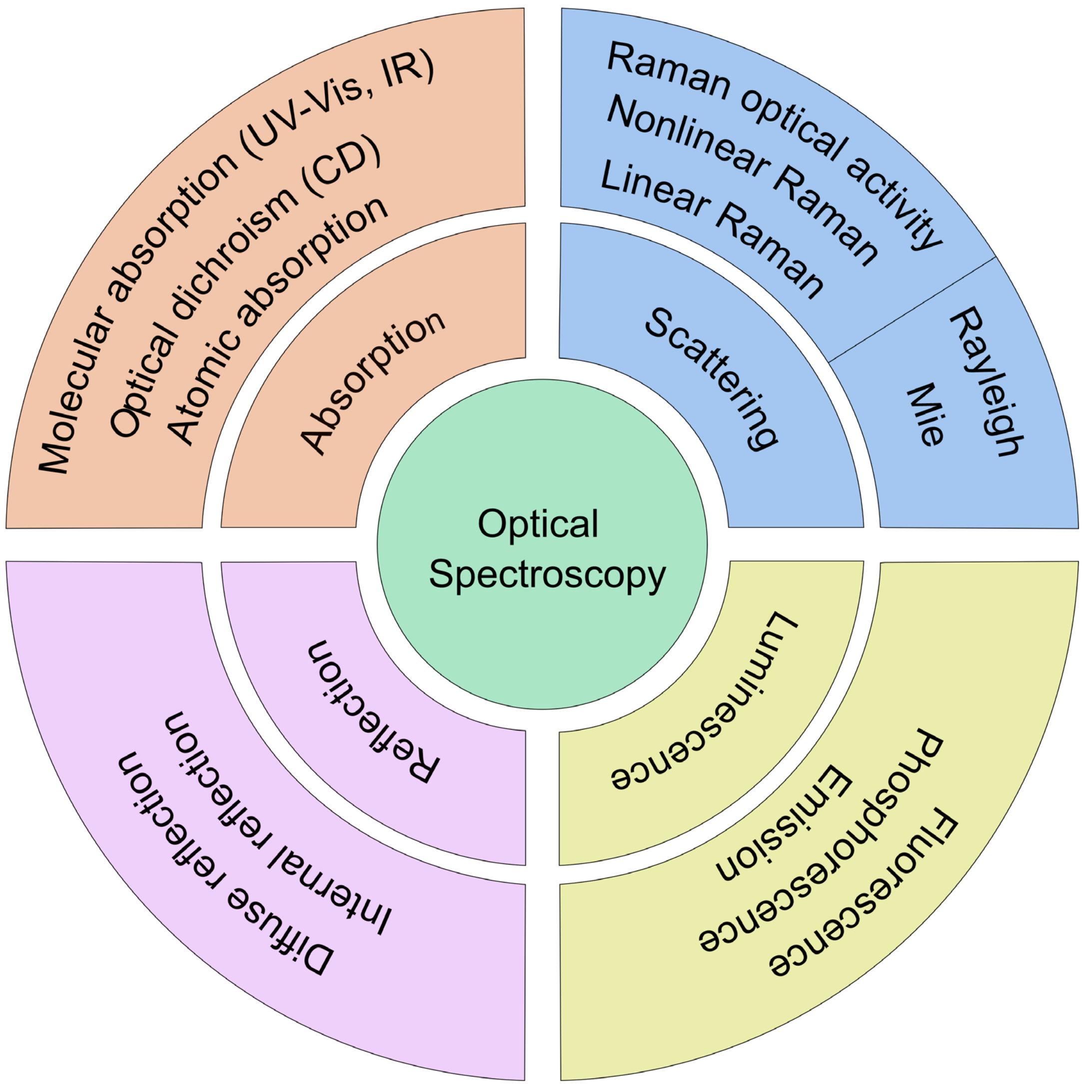
The energy/frequency dimension in the description of materials





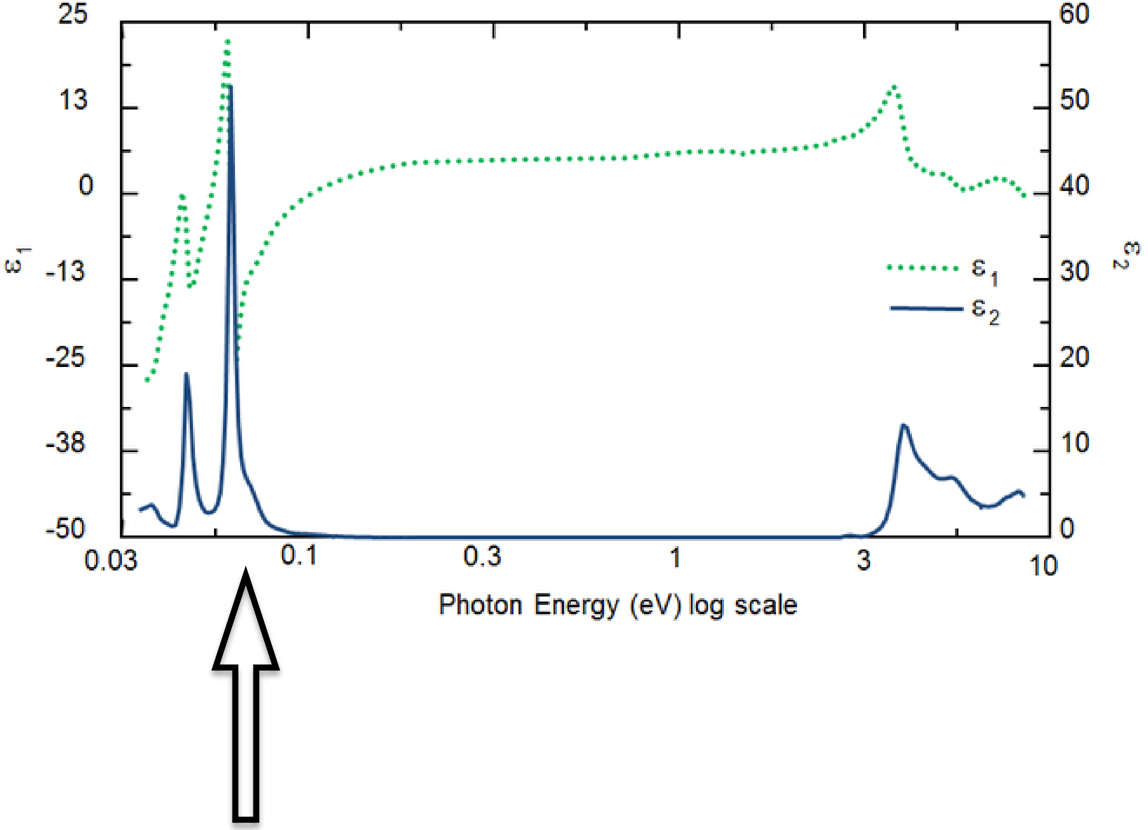
Spectra provide info on the energy of internal interactions, via the excitations.

Optical Spectroscopy



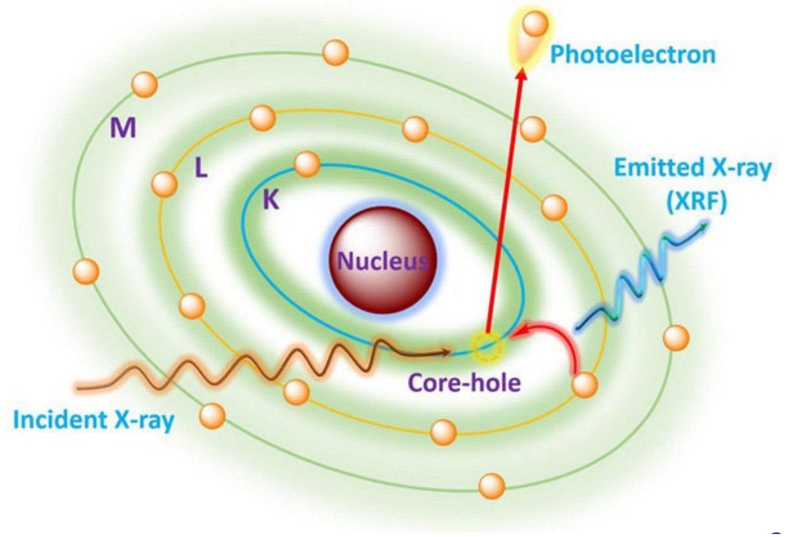
Complex optical constants:

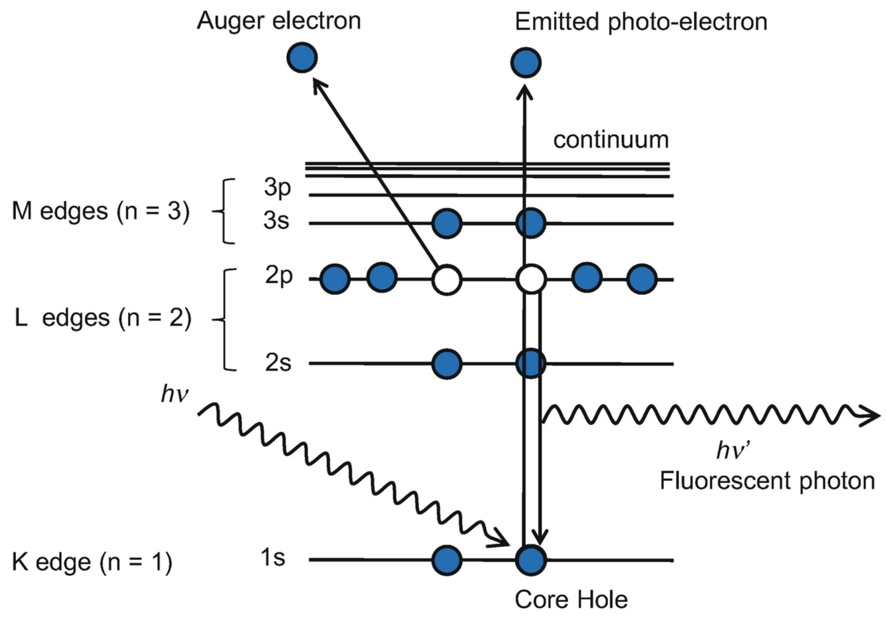
$$\varepsilon_r(\omega) = \varepsilon_1(\omega) + i\,\varepsilon_2(\omega)$$



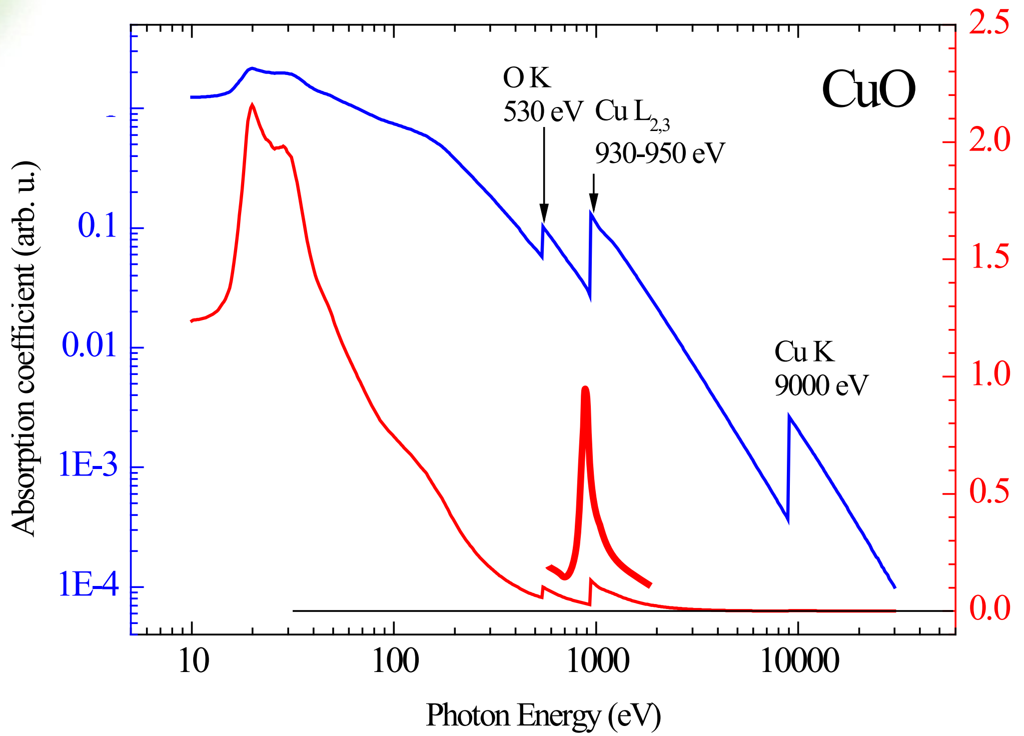
Absorption peaks
=
Excitation resonances

X-ray spectroscopy





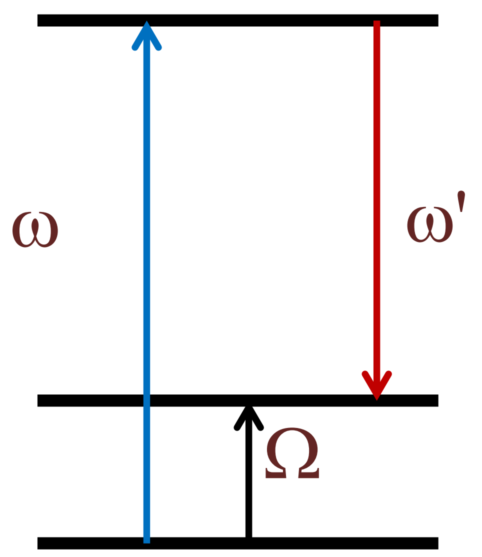
Dipole selection rule: Δl = ±1
(e.g. ns ↔ np transition)



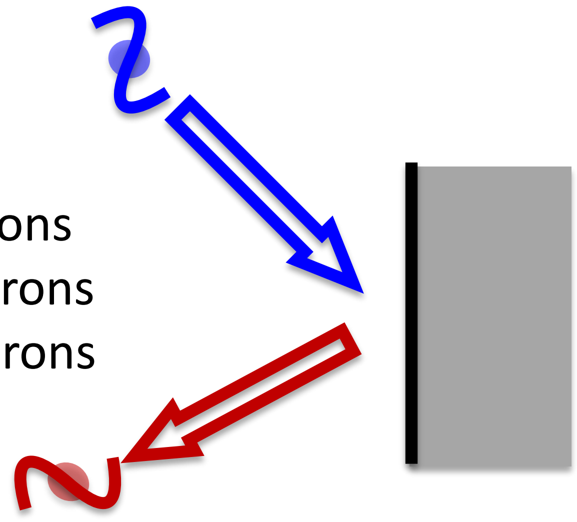
Peaks and edges in absorption provide info on the electron binding energies. And resonance to enhance scattering

Energy loss spectroscopy

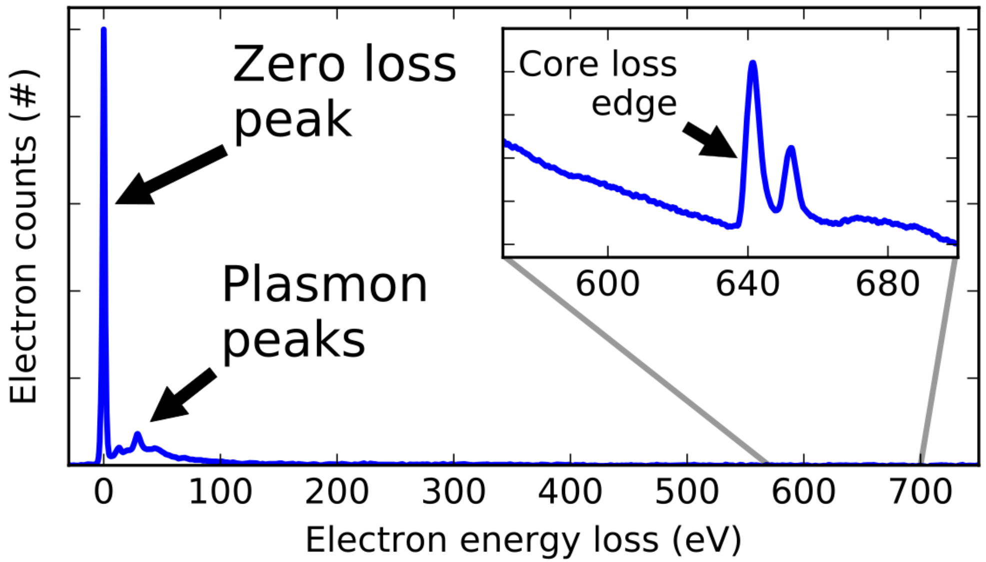
Raman light scattering

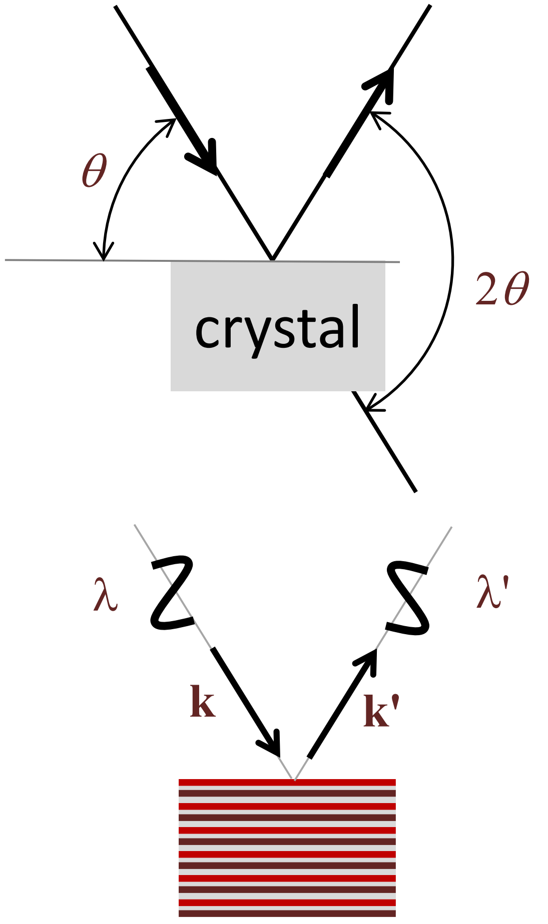


Photons
Electrons
Neutrons



Electron Energy Loss Spectroscopy (EELS)





Energy and momentum!

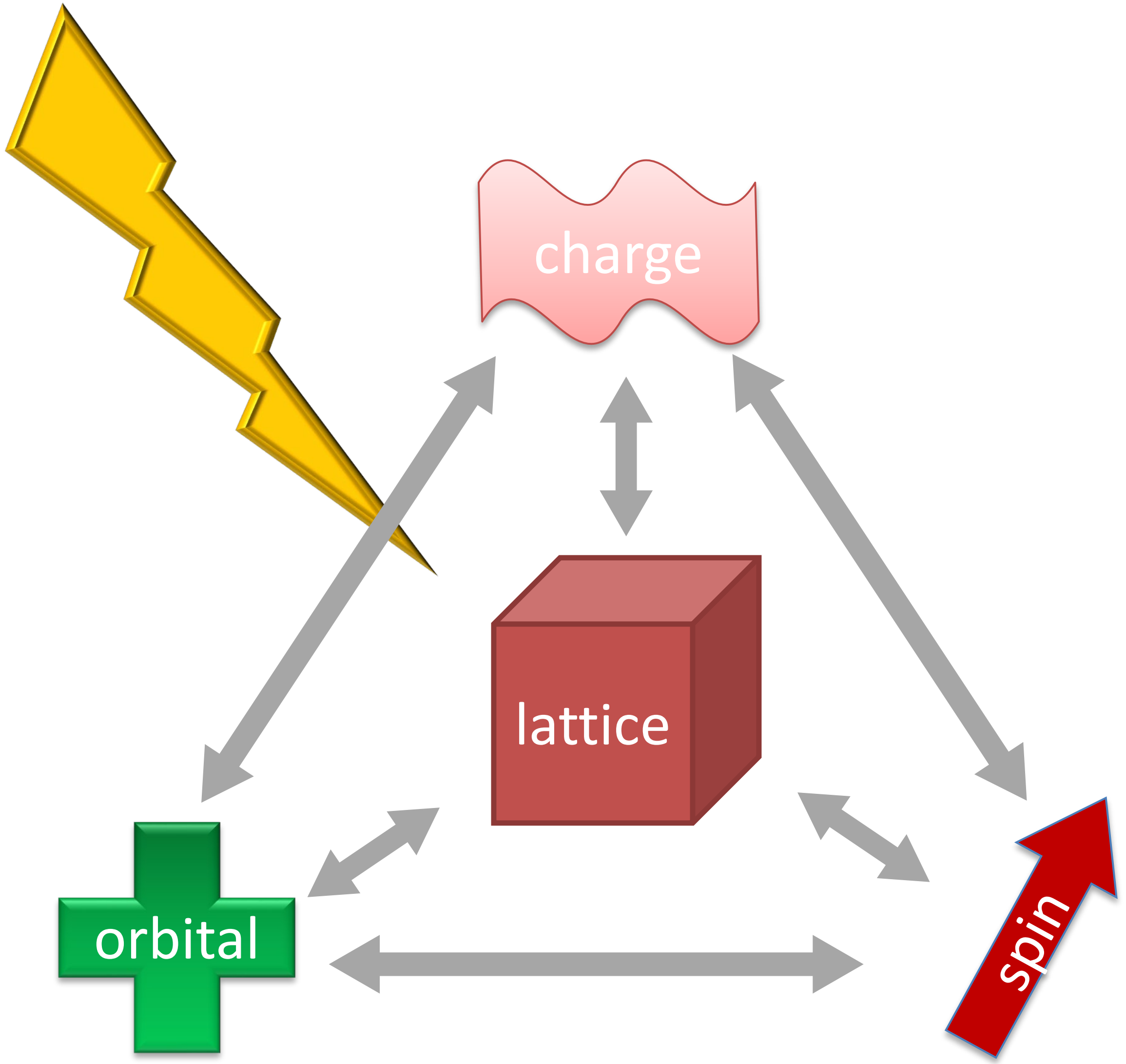
One probe for several degrees of freedom

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

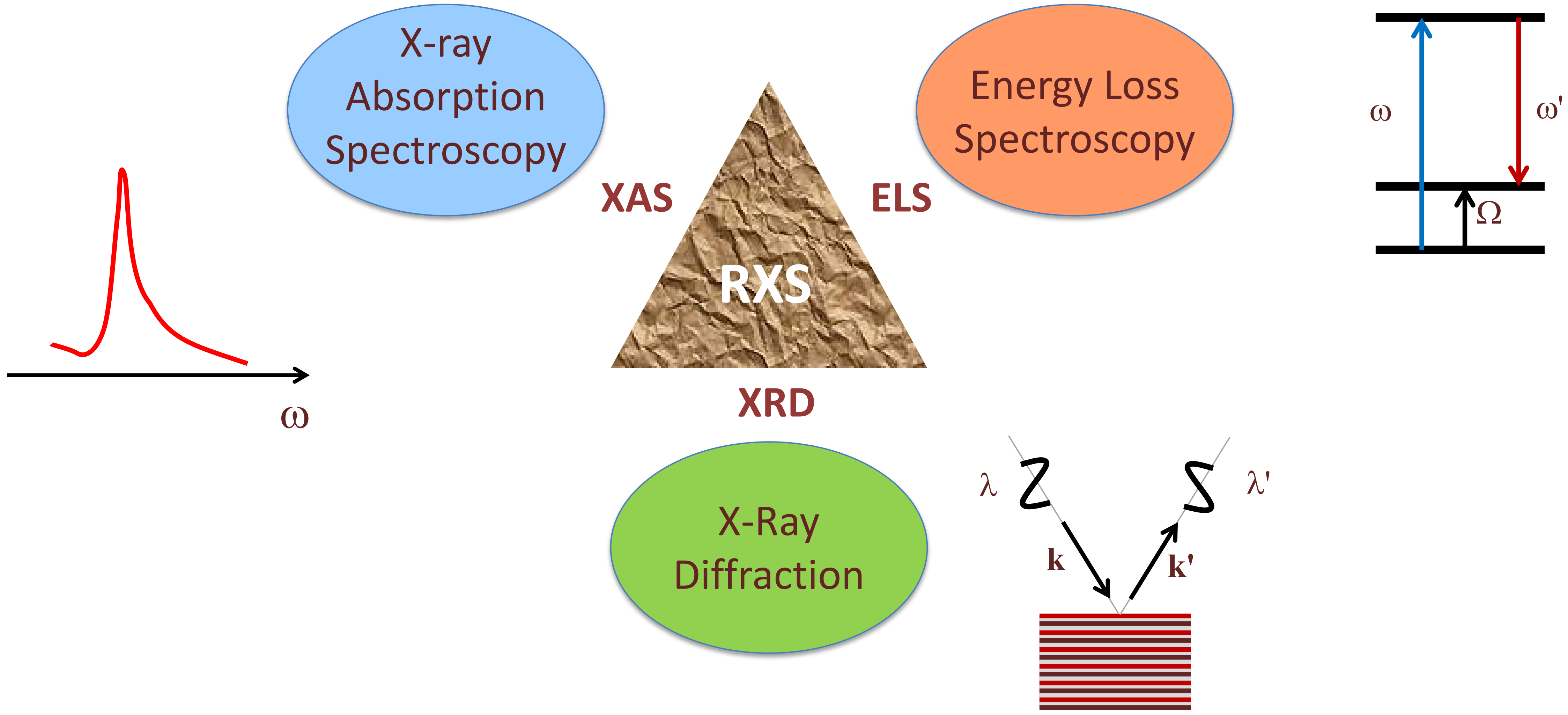
electrons (1, 2, 3, 5, 6)

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

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

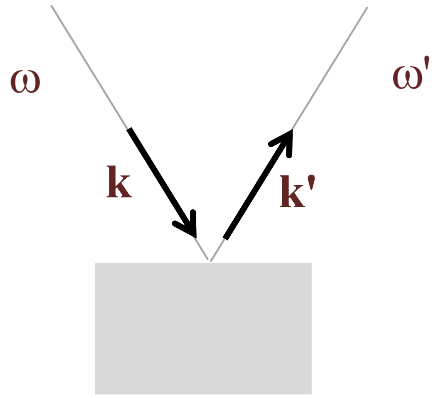


Resonant X-ray Scattering



A Raman scattering with X-rays

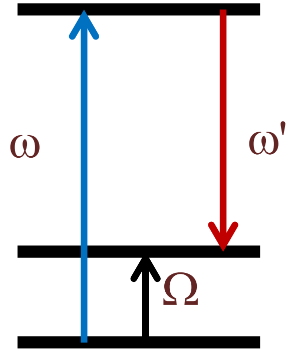
Energy Loss Spectroscopy



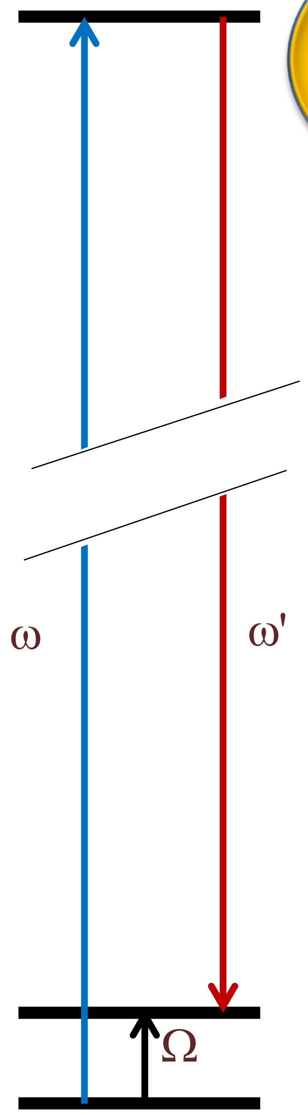
Inelastic X-ray Scattering

Raman light scattering

k≈0, q≈0,
Ω=ω−ω'

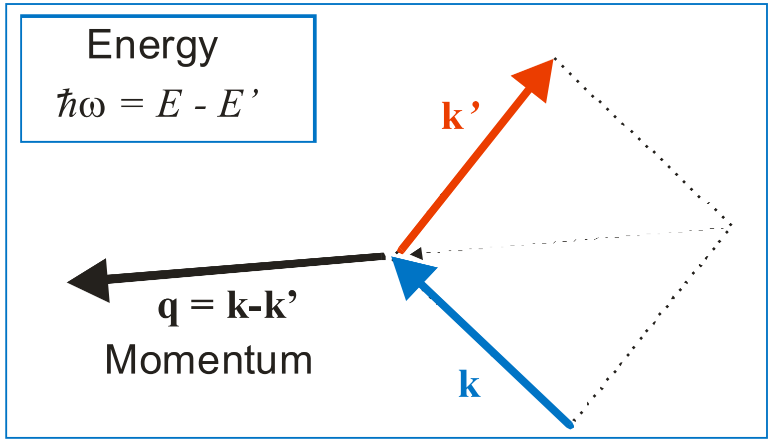


X-ray photons

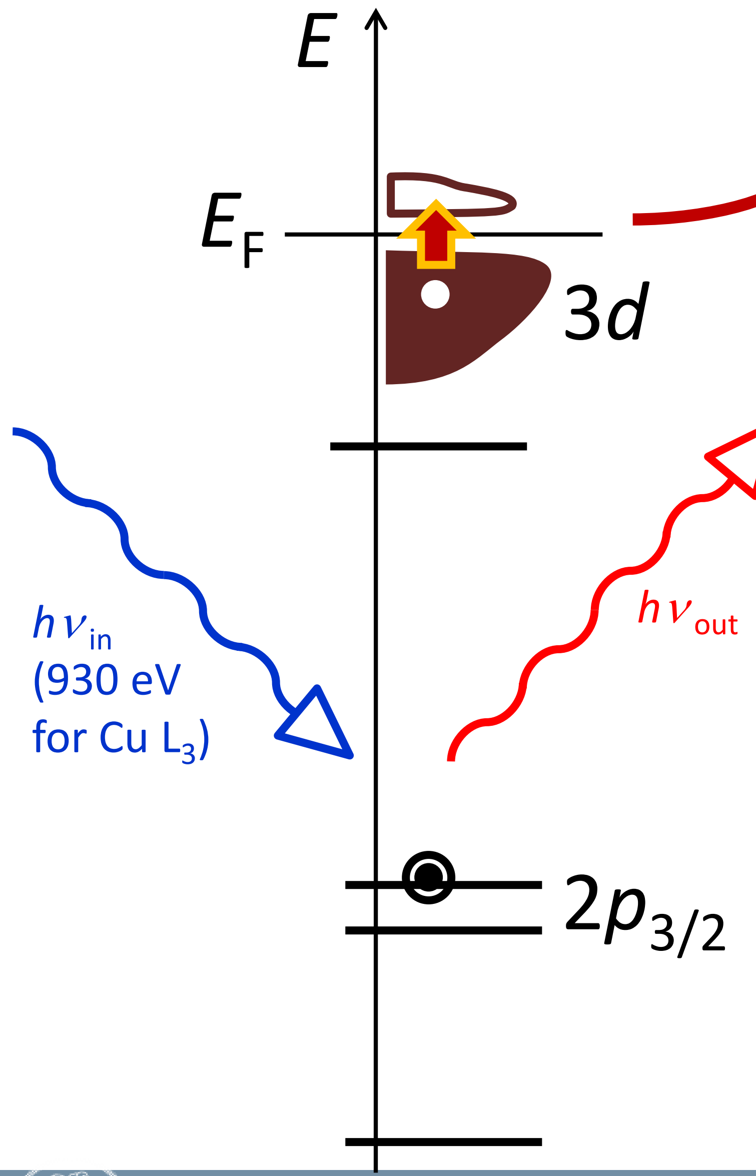


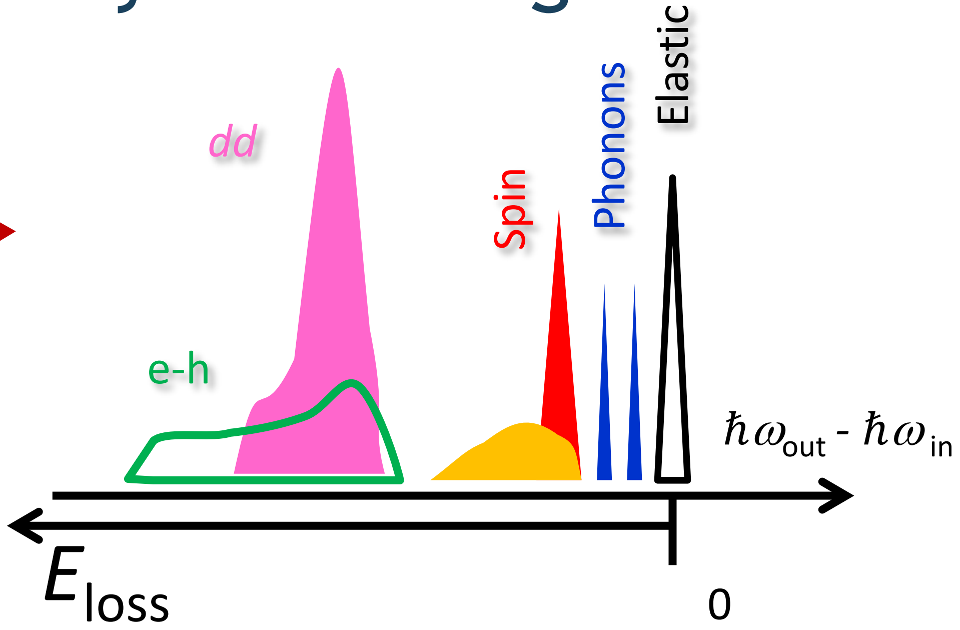
$\Omega = \omega - \omega'$

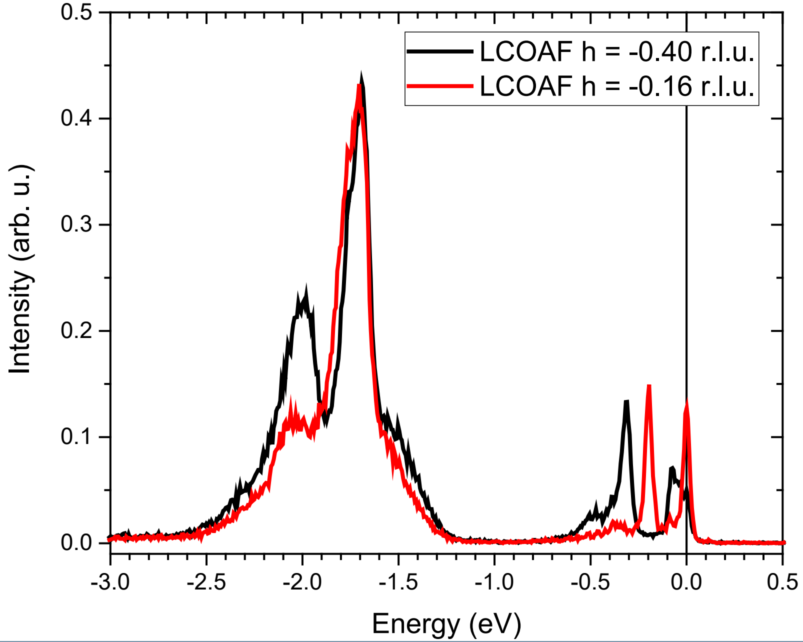
$\mathbf{q} = \mathbf{k'} - \mathbf{k}$



RIXS, Resonant Inelstic X-ray Scattering



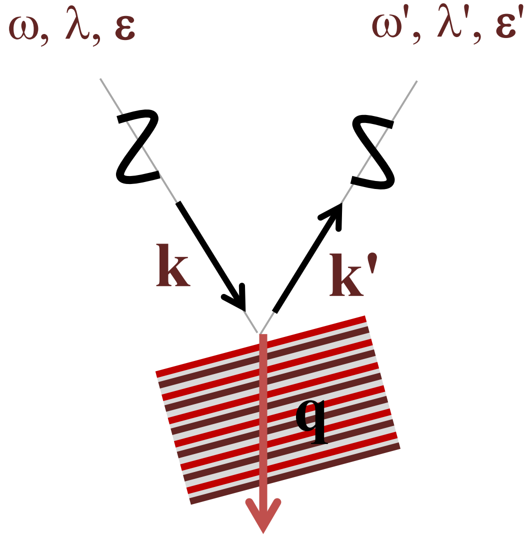




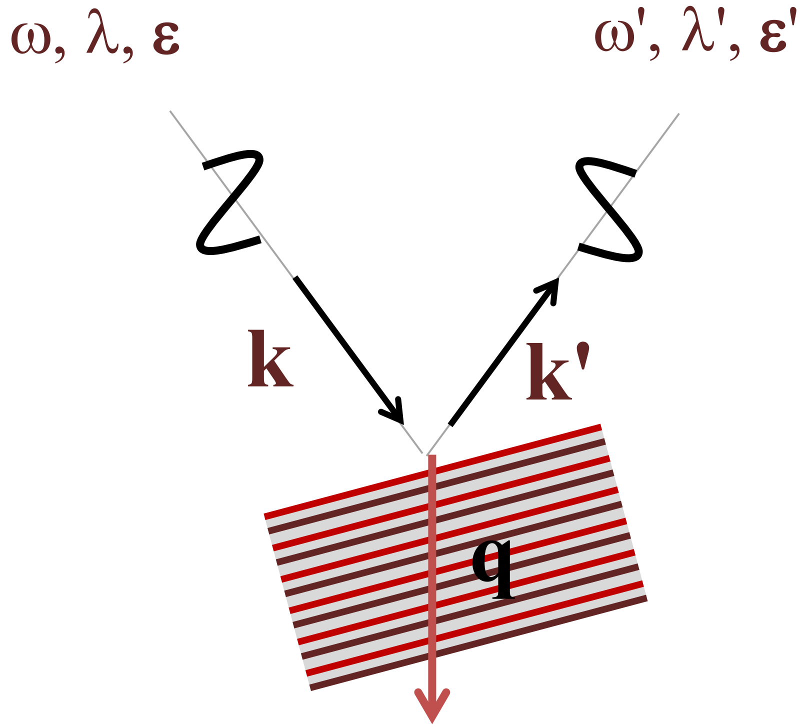
$\Omega = \omega - \omega'$

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

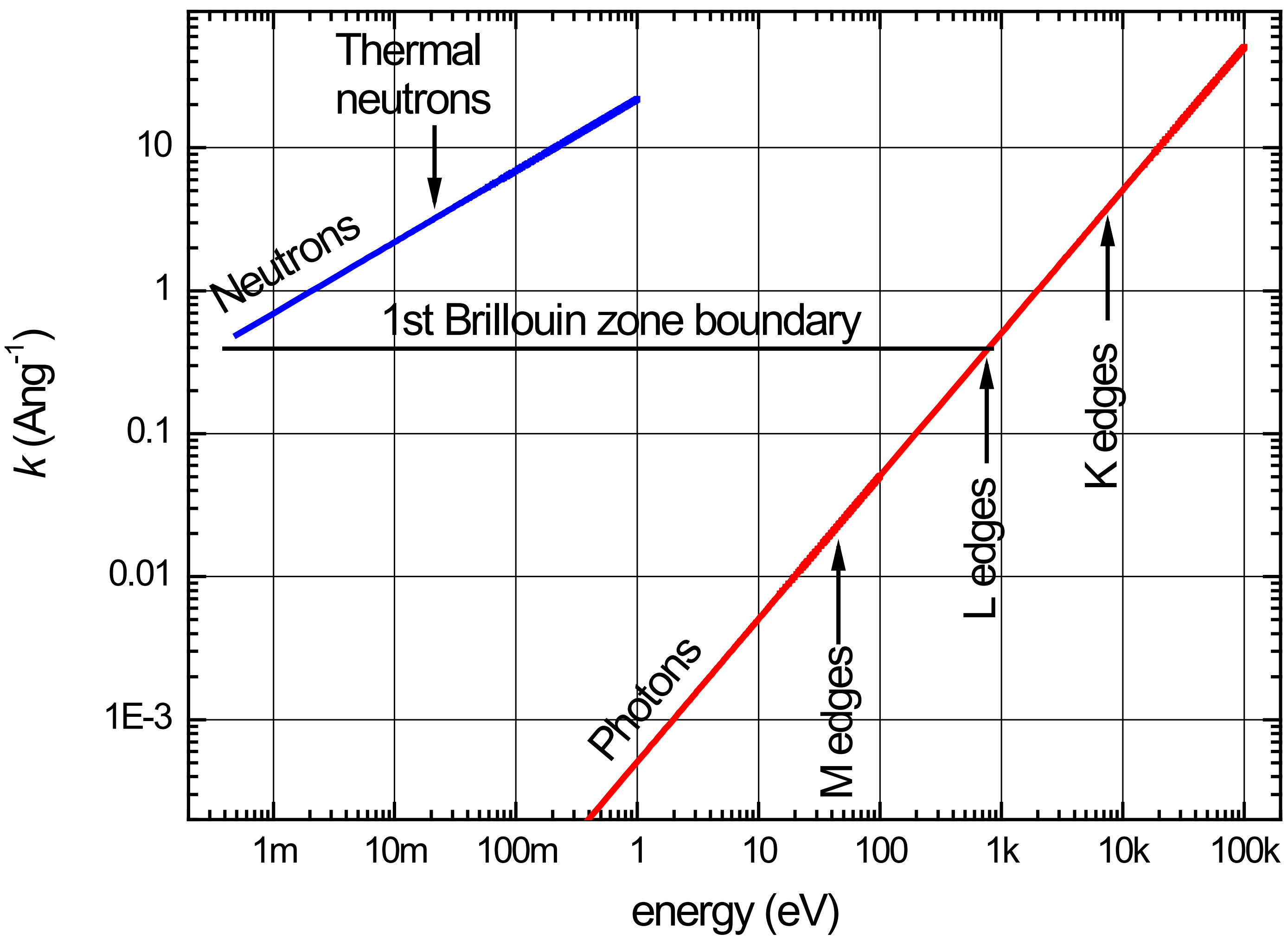
ε, ε': polarization



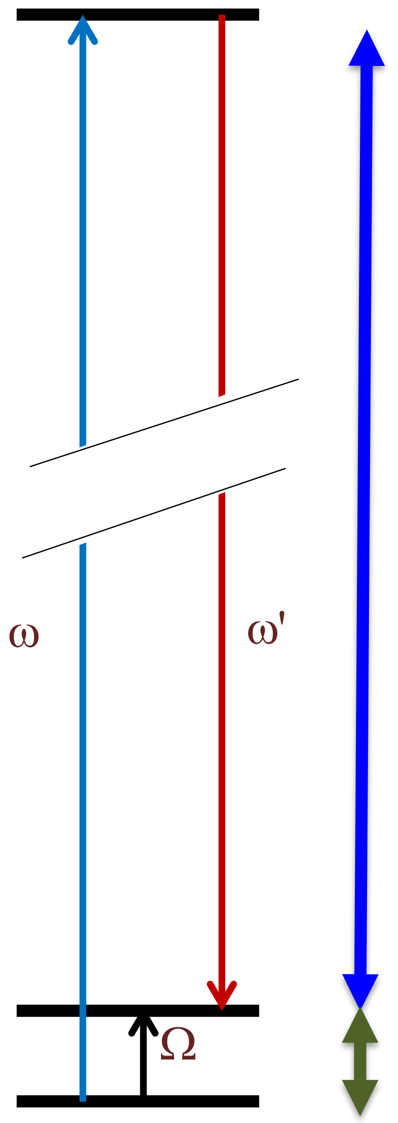
Energy and momentum



Wavevector of particles used in inelastic scattering



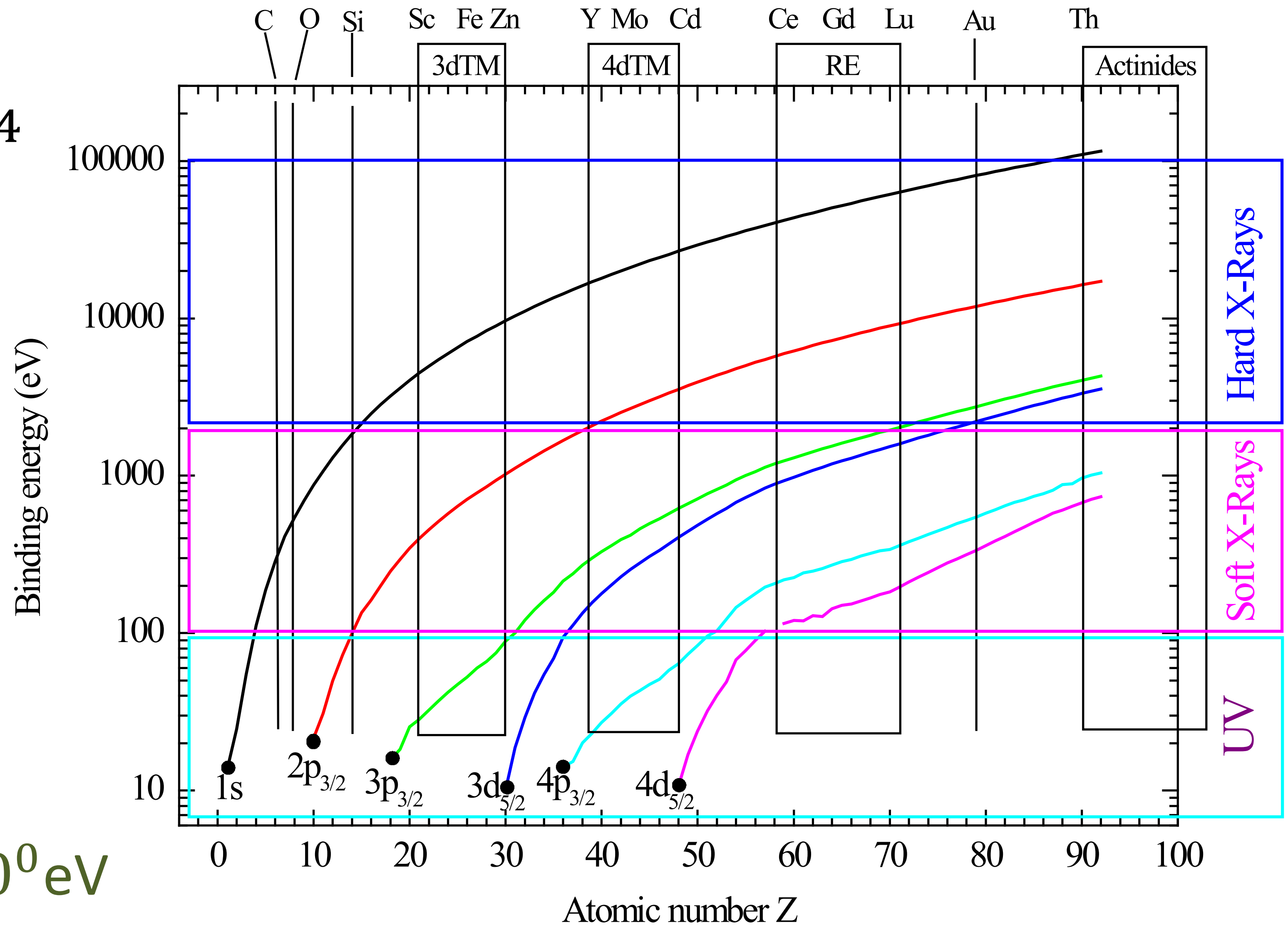
Ultra high resolving power is needed



$$\frac{E}{\Delta E} > 10^4$$

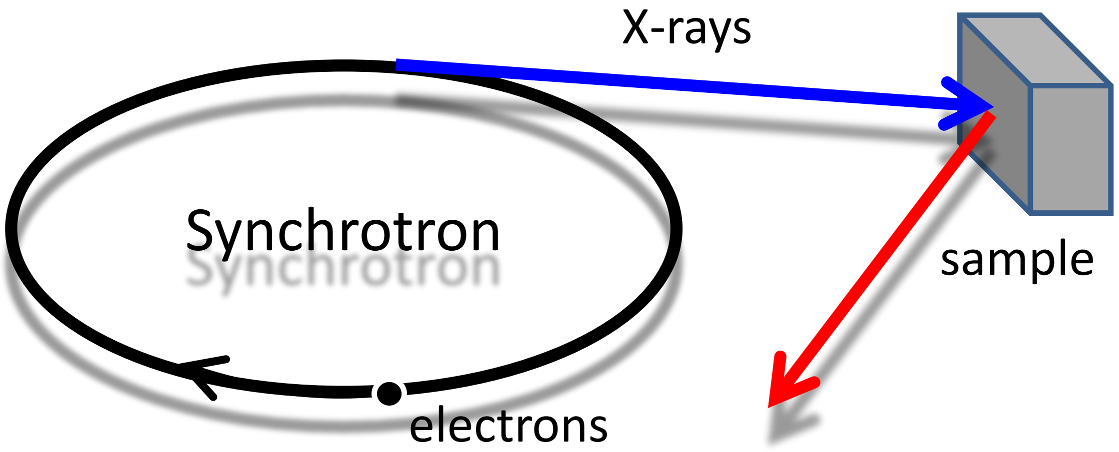
$\hbar\omega \sim 10^3\mathrm{eV}$

$\hbar\Omega \sim 10^{-2} - 10^0\mathrm{eV}$

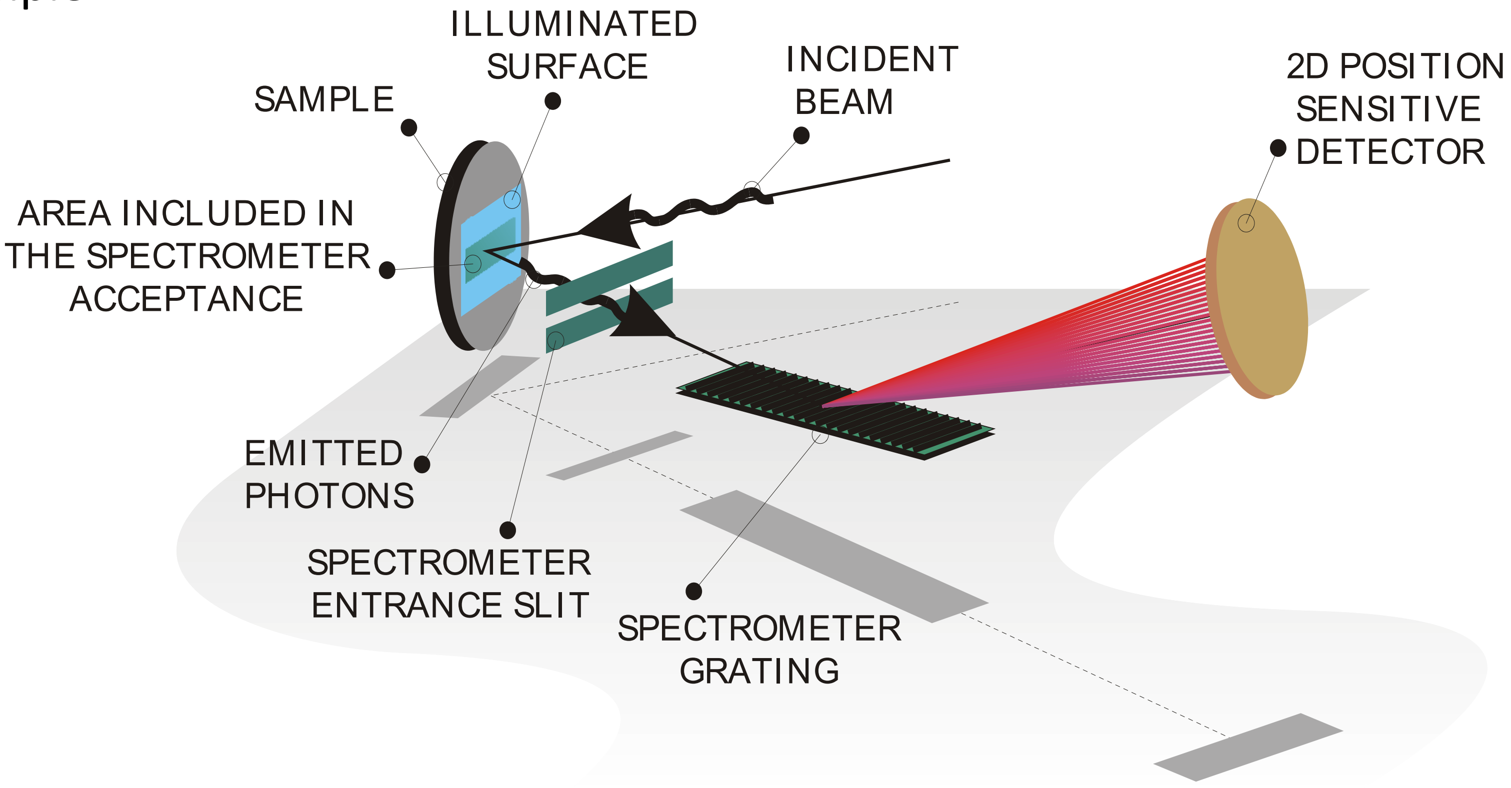


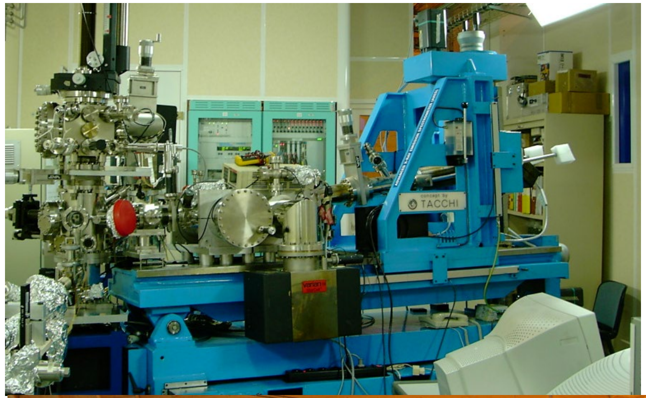
RIXS measurements: the technical challenge

Tunable and brilliant source of x-rays is needed



In the soft x-rays (100-1500 eV) a grating spectrometer is used

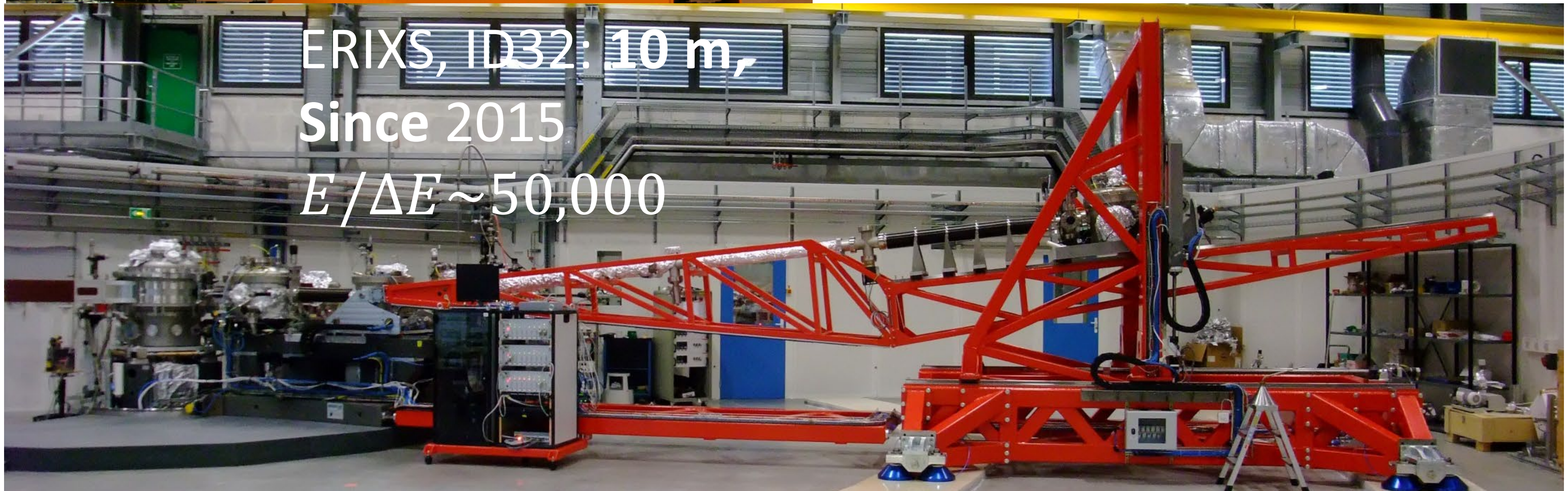




AXES, ESRF: **2.2 m**
1994 – 2012
$E/\Delta E \sim 3000$

Lucio Braicovich

SAXES, SLS: **5 m**
Since 2007
$E/\Delta E \sim 10{,}000$



ERIXS, ID32: **10 m,**
Since 2015
$E/\Delta E \sim 50{,}000$

ENERGY RESOLUTION: progress in 20 years

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).

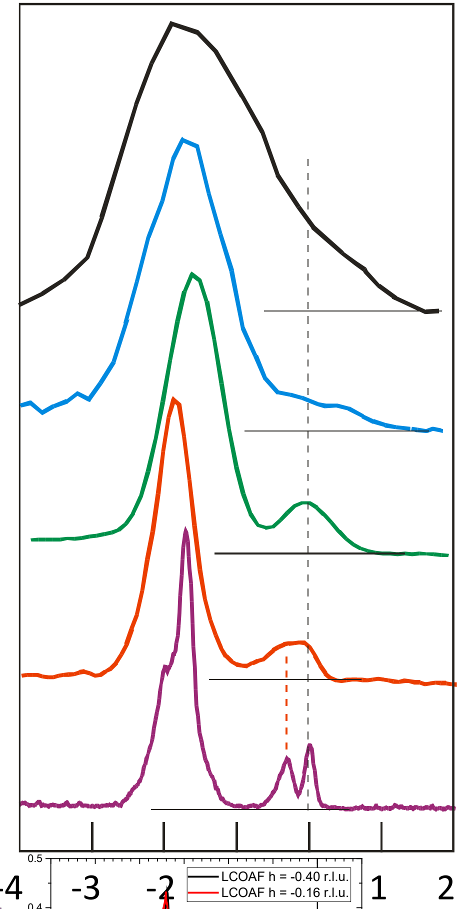
Δ*E* ~0.13 eV

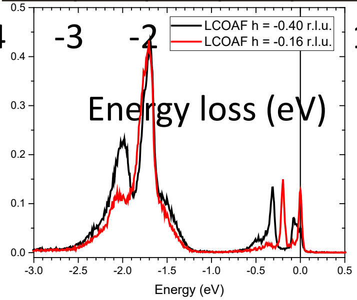
SAXES @ SLS, 2008. G. Ghiringhelli, L. Braicovich, T. Schmit *et al.*, unpublished

Δ*E* ~0.050 eV

Δ*E* ~0.030 eV

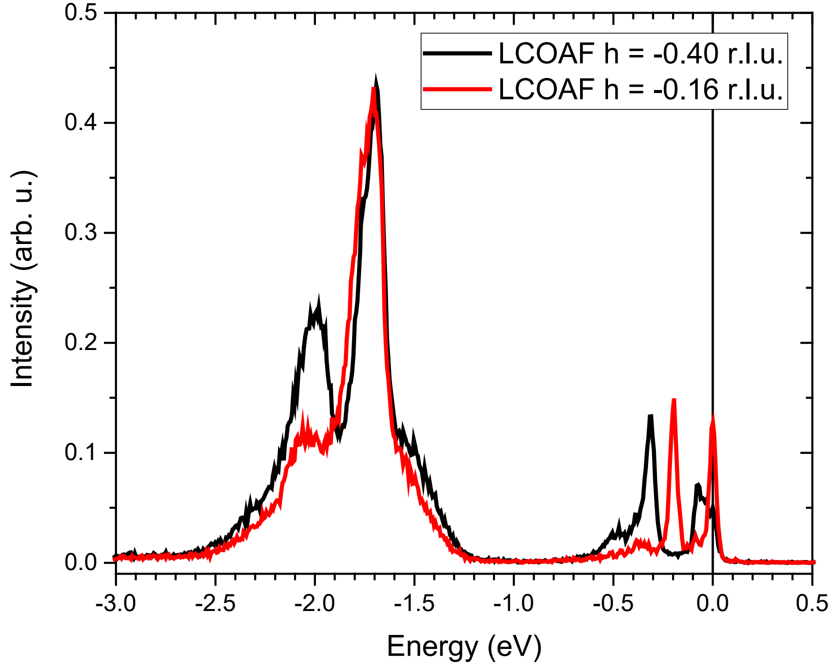
Δ*E* ~0.023 eV





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

2000	Uppsala
2003	ESRF + AXES
2007	ESRF + AXES
2008	SLS + SAXES
2015	ESRF + ERIXS
2016	ESRF + ERIXS
2019	NSLS II + SIX
2021	ESRF + ERIXS



Combined resolving power has increased by a factor 70

RIXS instruments growing in many synchrotrons

Some high level projects

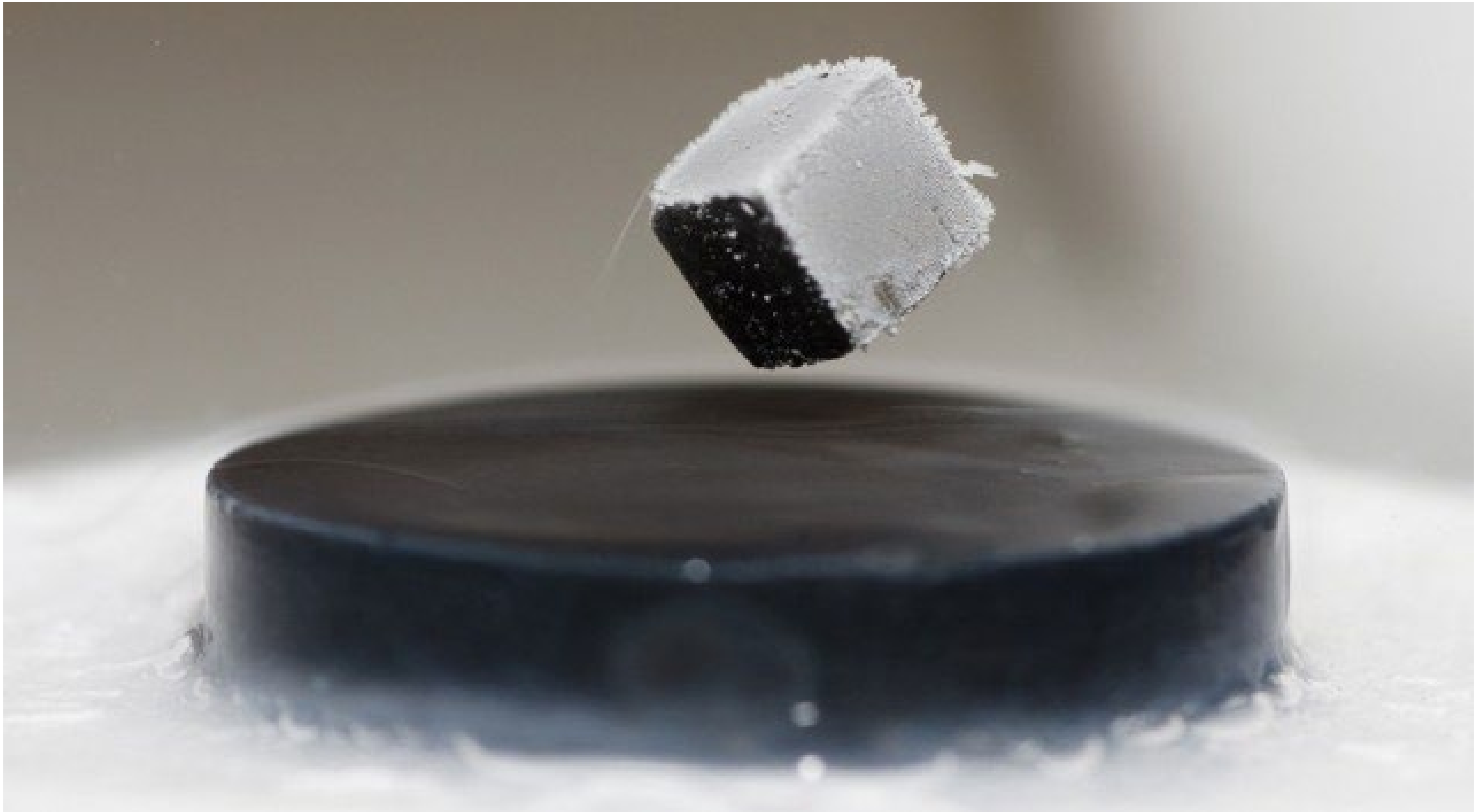
Soft X-rays:

ESRF
Diamond Light Source (UK)
MAX IV (Sweden)
SLS-PSI (Switzerland)
BESSY II (HZB, Berlin)
European XFEL
Taiwan Photon Source
Brookhaven NSLS II (US)
Stanford LCLS II (US)

Hard/Intermediate X-rays:

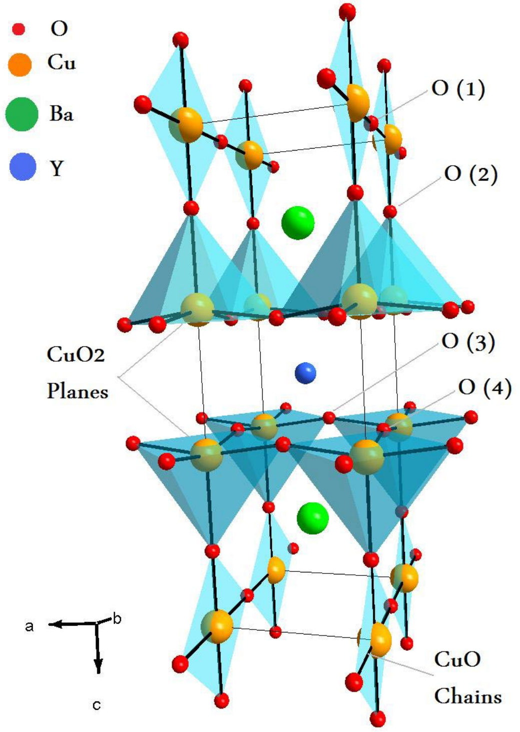
ESRF
APS (US)
DESY (Hamburg)

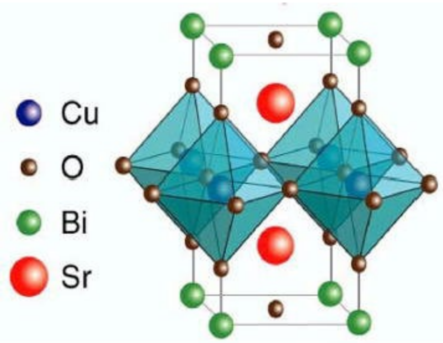
High Tc Superconducting cuprates

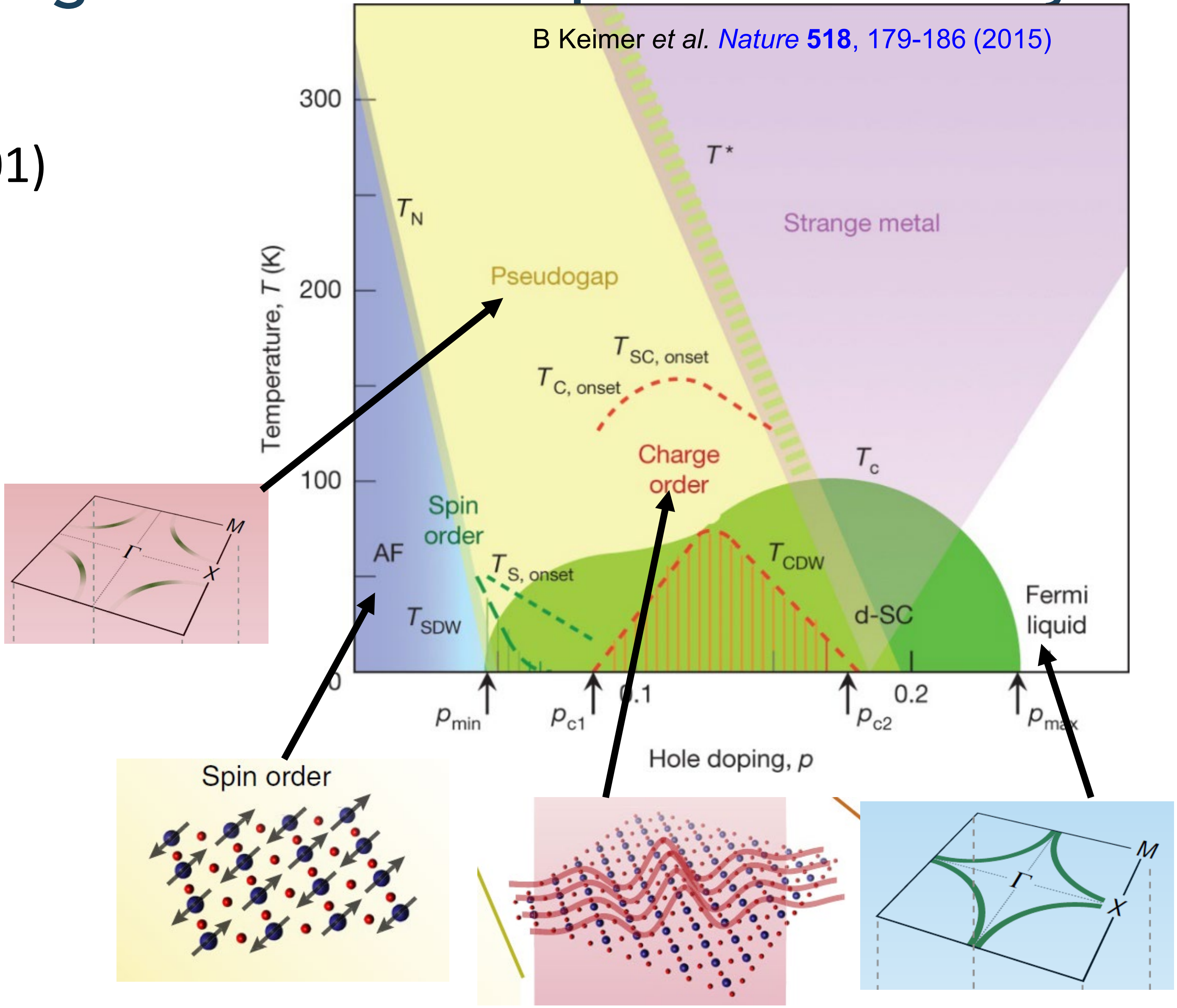


Cuprates: Magnetism, Charge Order and Superconductivity

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

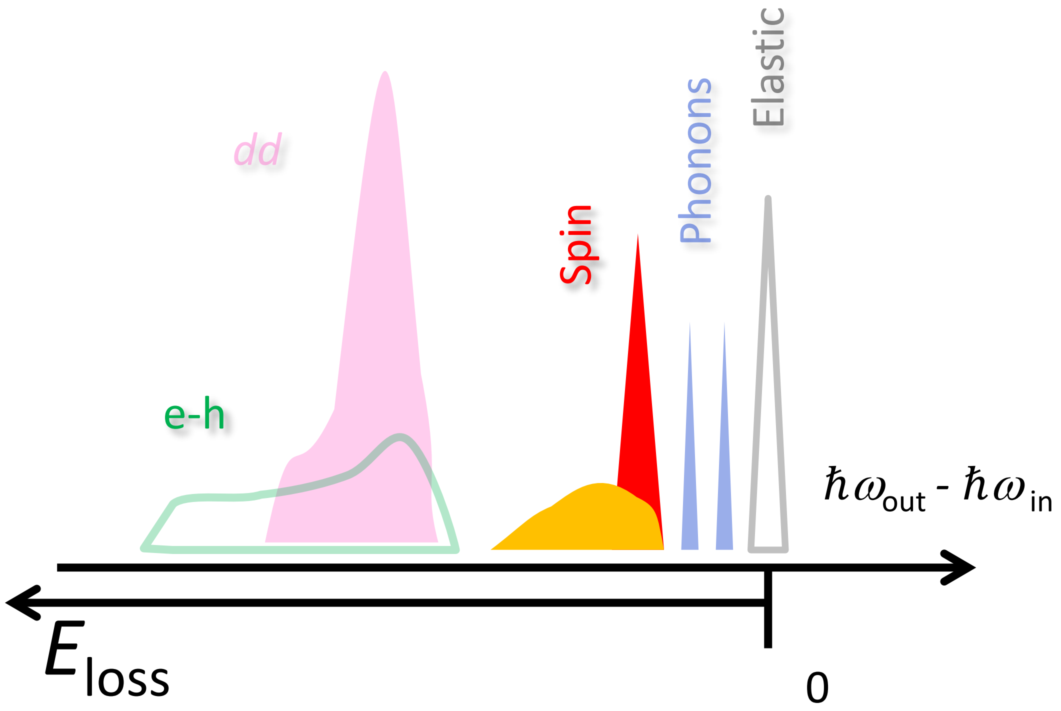


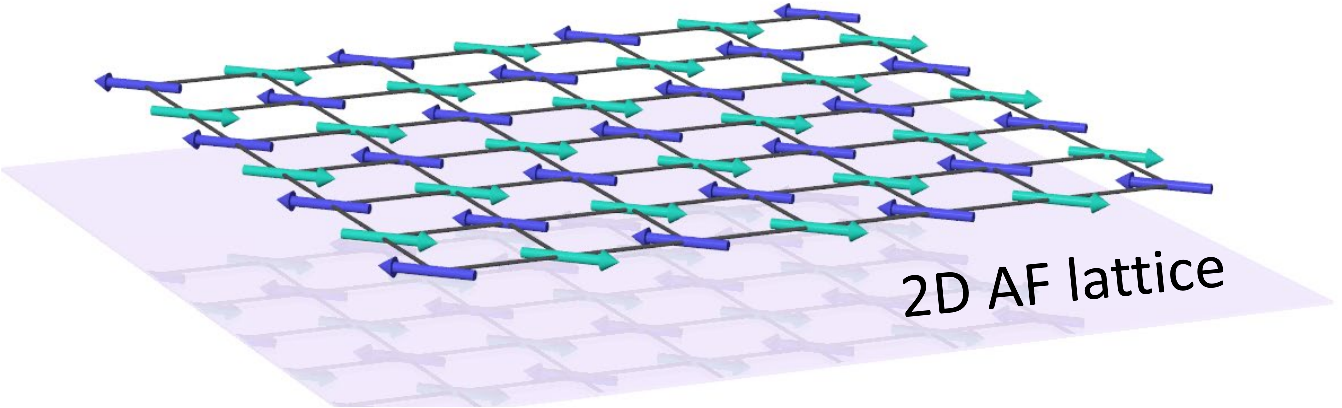


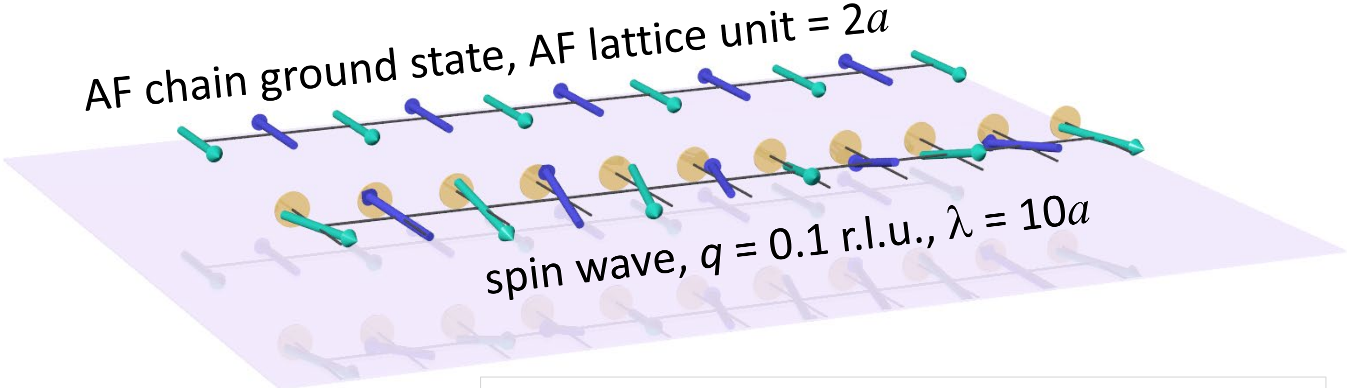


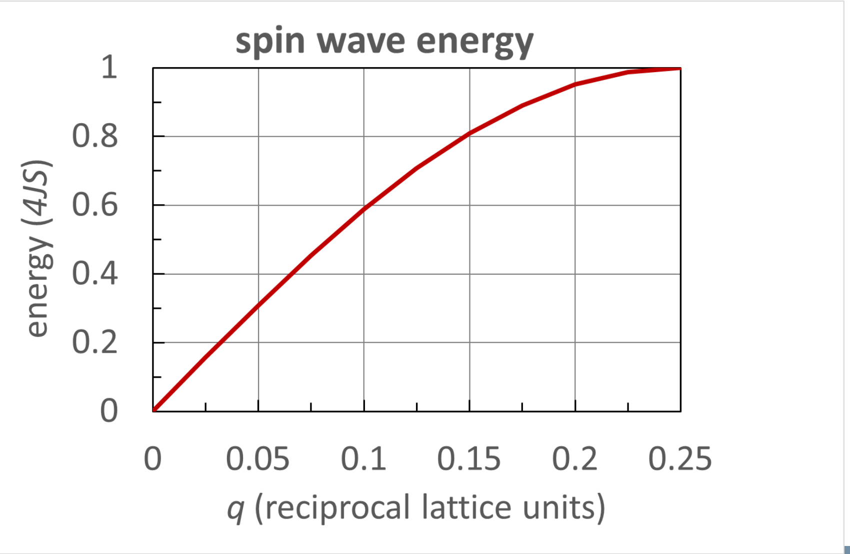
J. Pelliciari and R. Comin *Nature Materials* **17**, 661 (2018)

Spin excitations









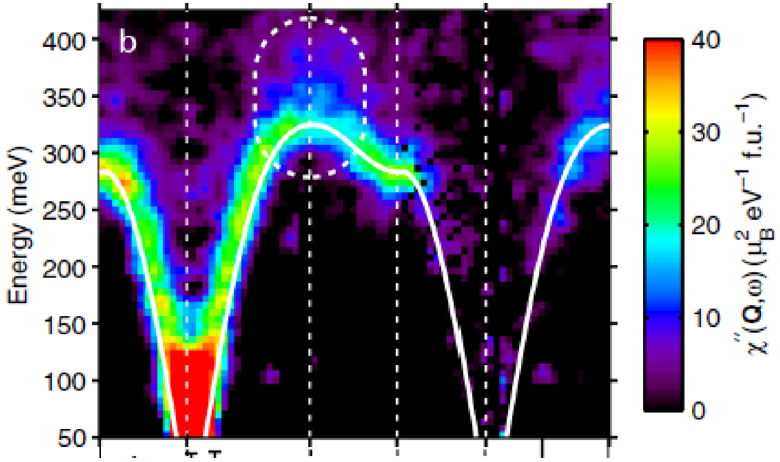
Single magnon: Lorentzian peak

Double magnons: continuum

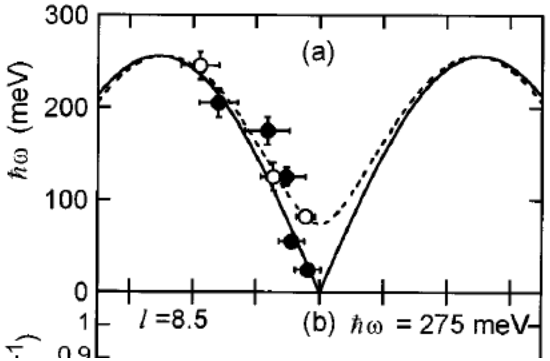
Spin excitations: neutron vs x-ray scattering

10 orders of magnitude higher sensitivity than INS

La_2CuO_4 – 10^3 mm^3 single crystal



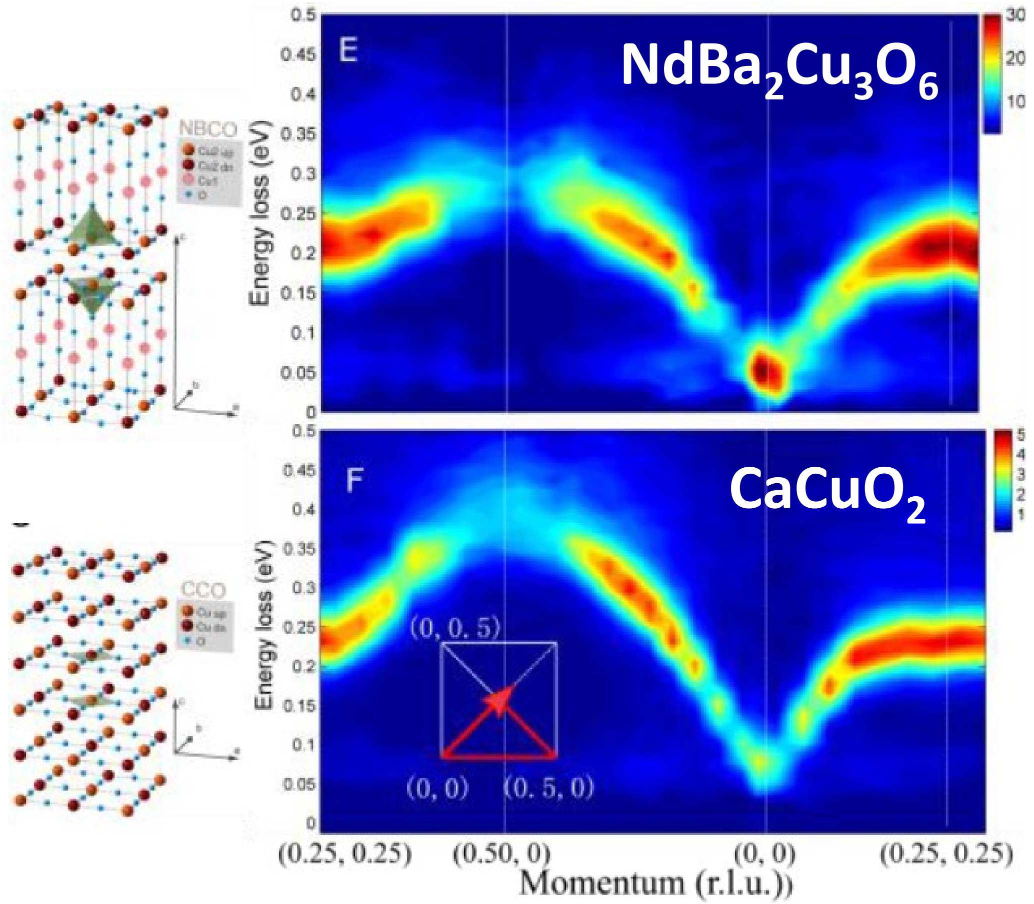
$YBa_2Cu_3O_6$ – 1 mm^3 single crystal



Inelastic Neuron Scattering (since 1960s)

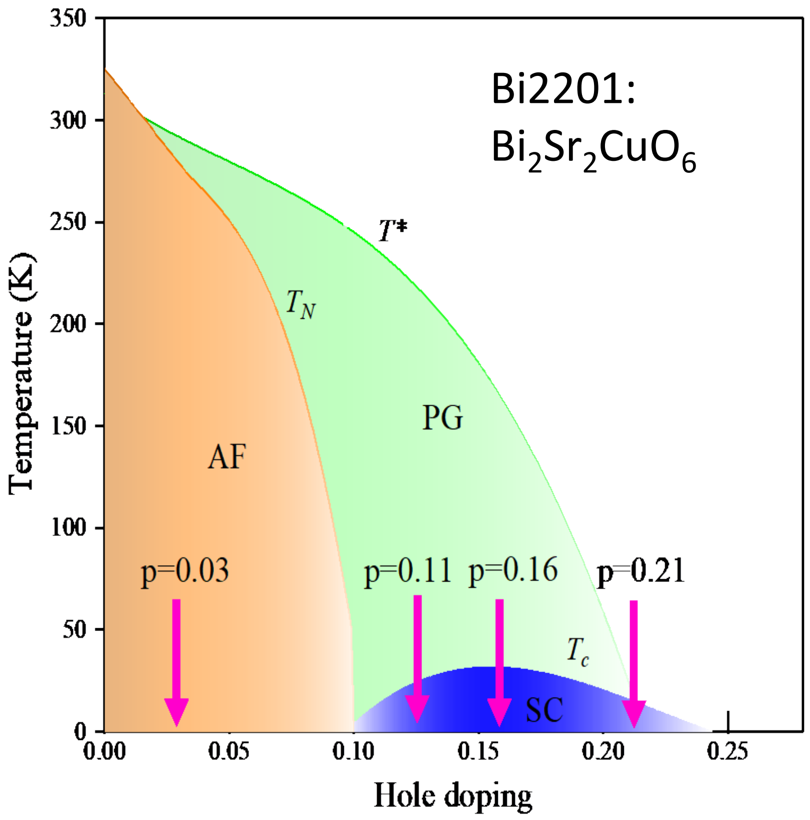
RIXS (since 2010s)

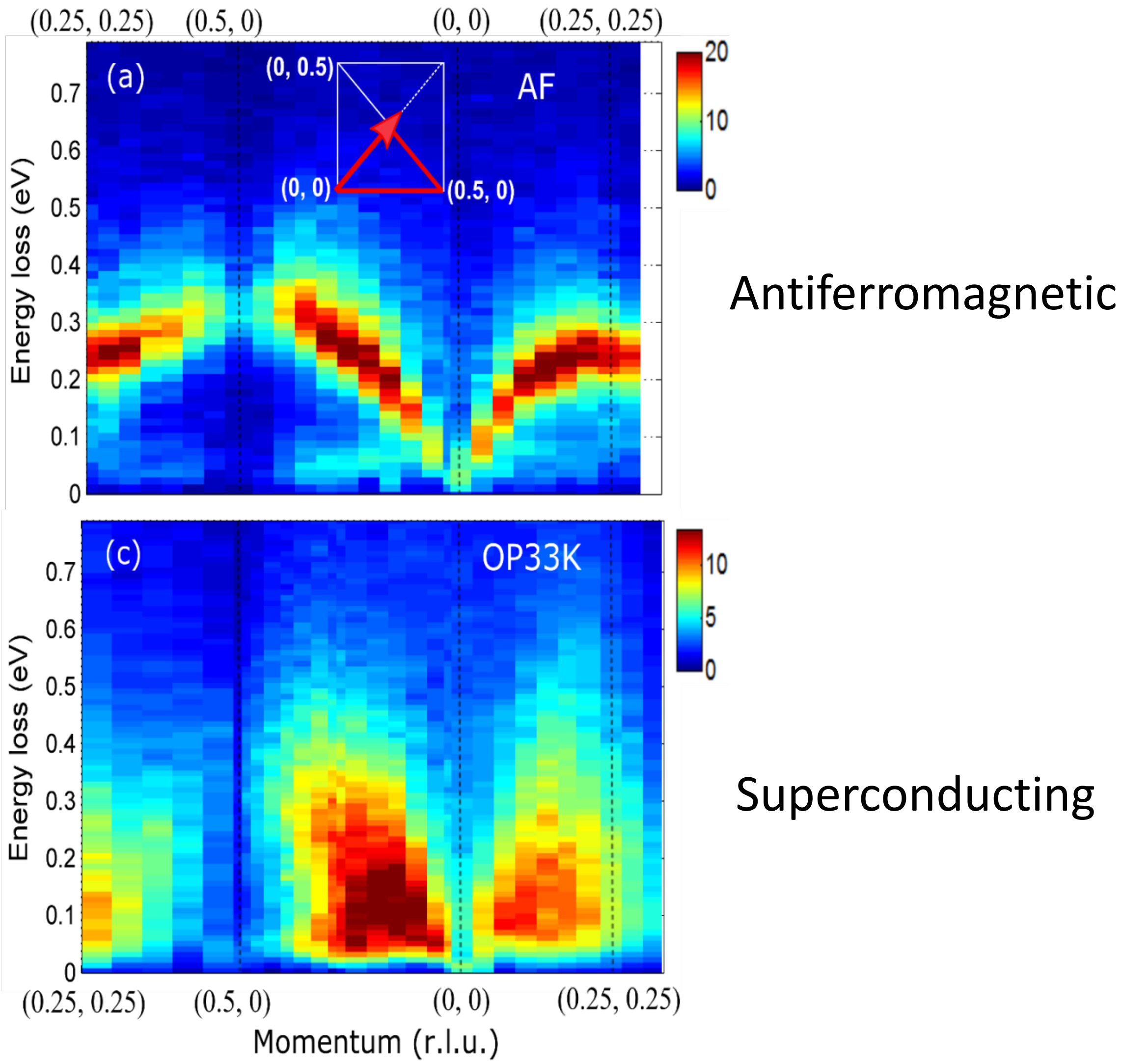
Thin films - 10^{-7} mm^3 interaction volume



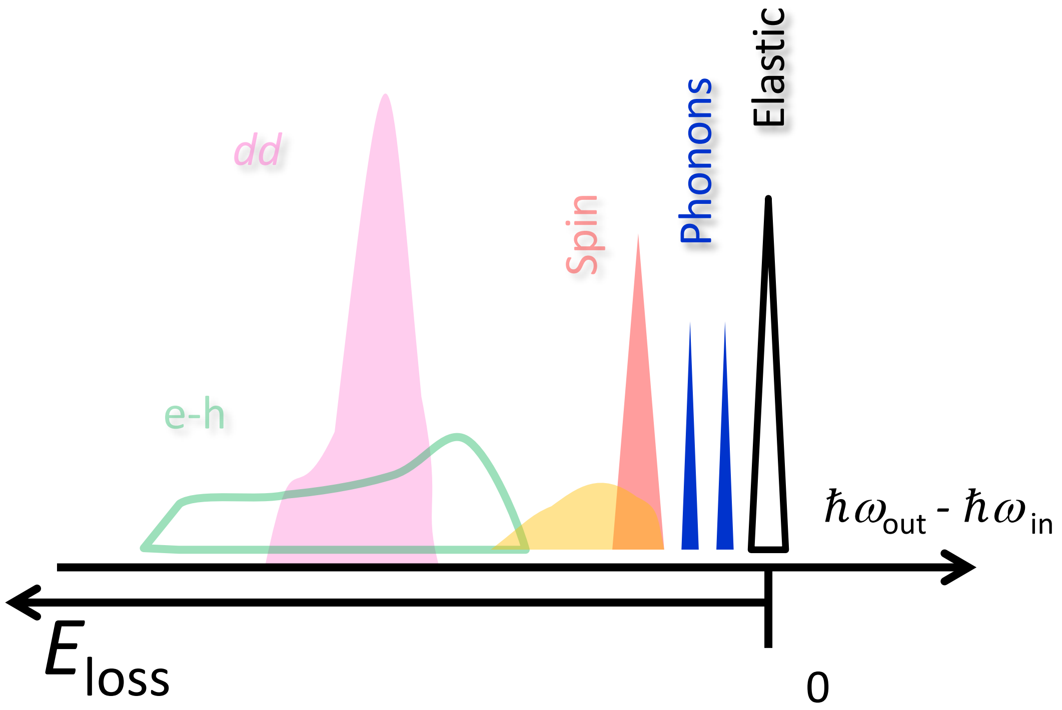
RIXS demonstrated that magnetism is present also in the superconducting state of cuprates

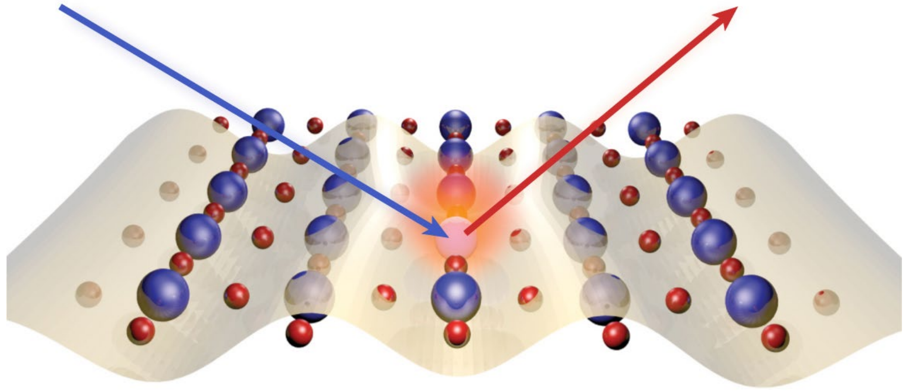
Doping destroys AF order, but not spin excitations: damped magnons = paramagnons





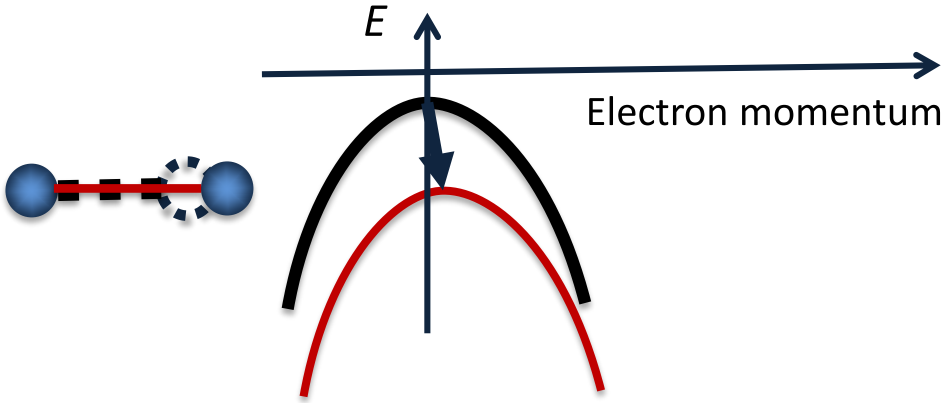
RIXS for phonons and charge order





- Elastic scattering is related to order parameters
- RXS: enhancing charge-order scattering

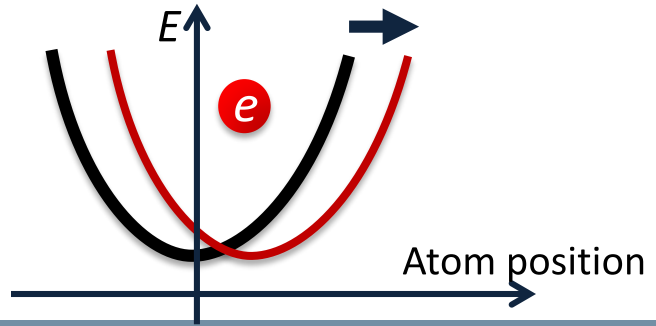
Phonons: Electron phonon coupling in cuprates



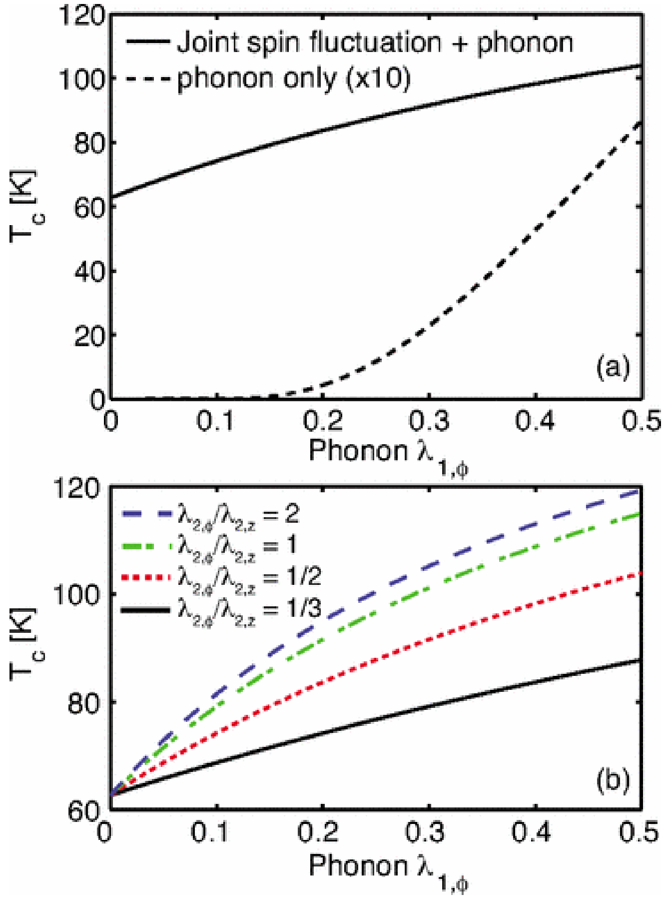
How $\mathcal{H}$ is modified by an atomic displacement

≡

How lattice is deformed by the presence of a valence electron



EPC: cooperative effect of phonons in SC pairing in cuprates



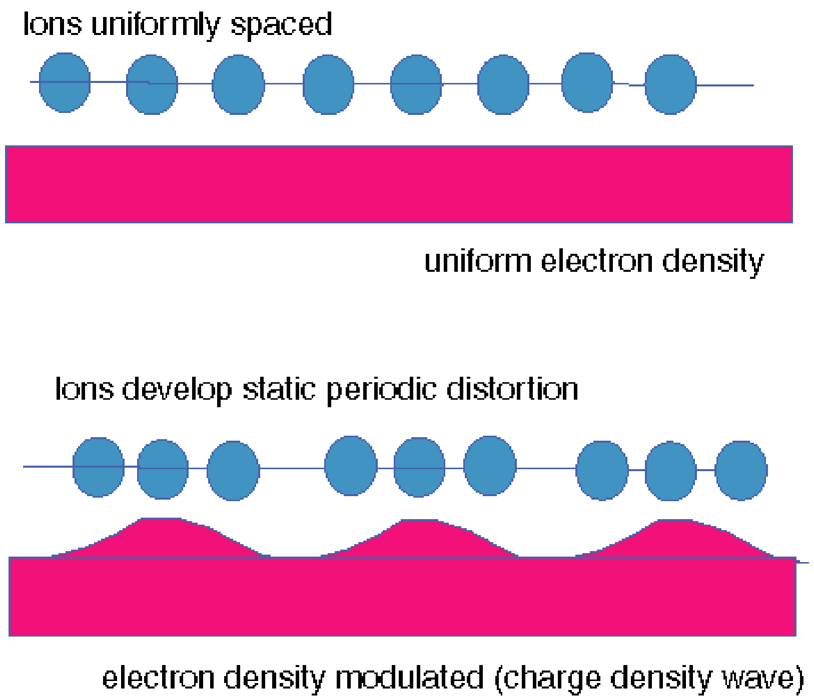
Phys. Rev. B **82**, 064513 (2010)

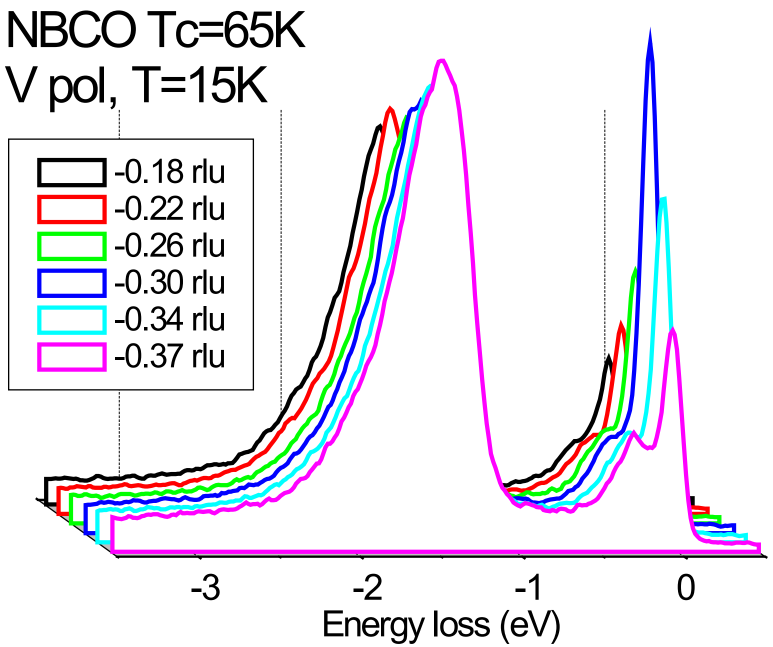
Charge order and phonons

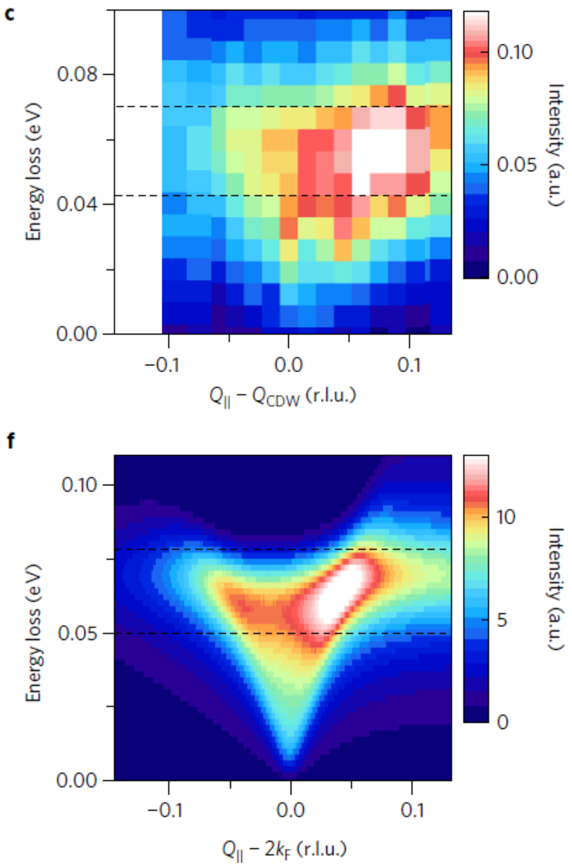
Charge density waves emerge because the atom position is influenced by the non uniform distribution of valence charge

With R(I)XS charge order was observed directly in all hole doped cuprates

RIXS can see also that charge order couples with phonons



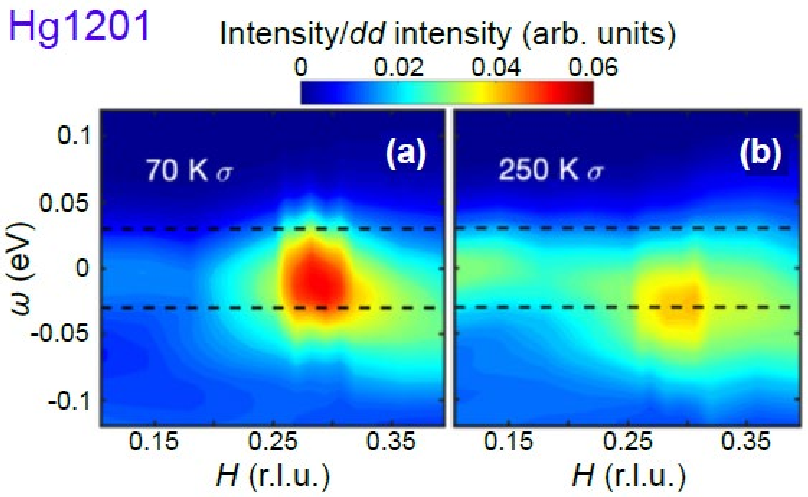


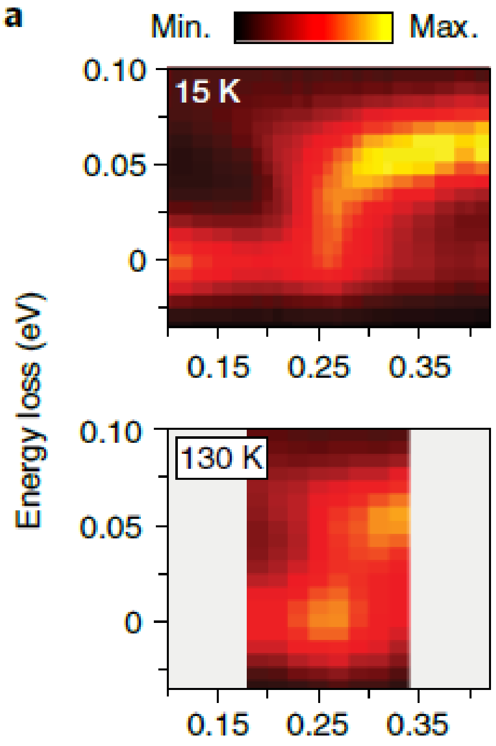


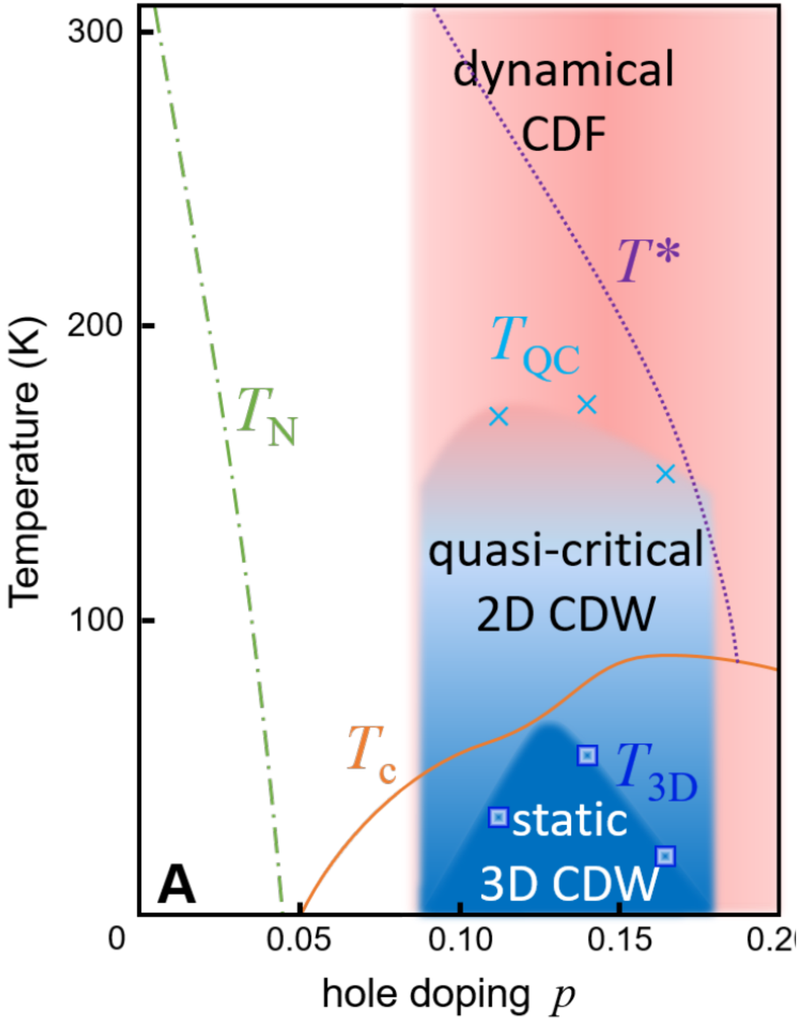
RIXS has redefined the phase diagram of cuprates

RIXS was used to determine:

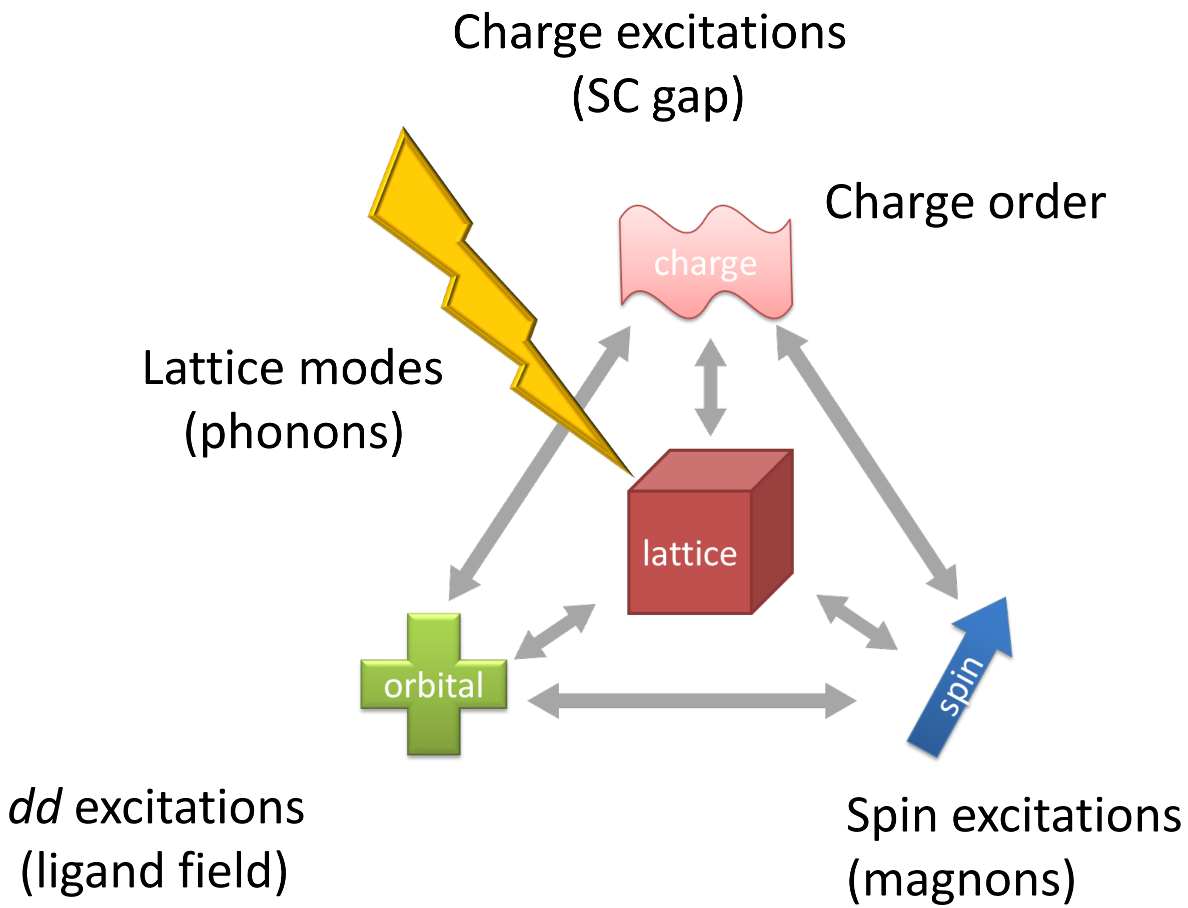
1) that charge order is a general property of cuprates
2) how charge order is coupled to phonons
3) that charge order is dominated by charge density fluctuations







RIXS outlook

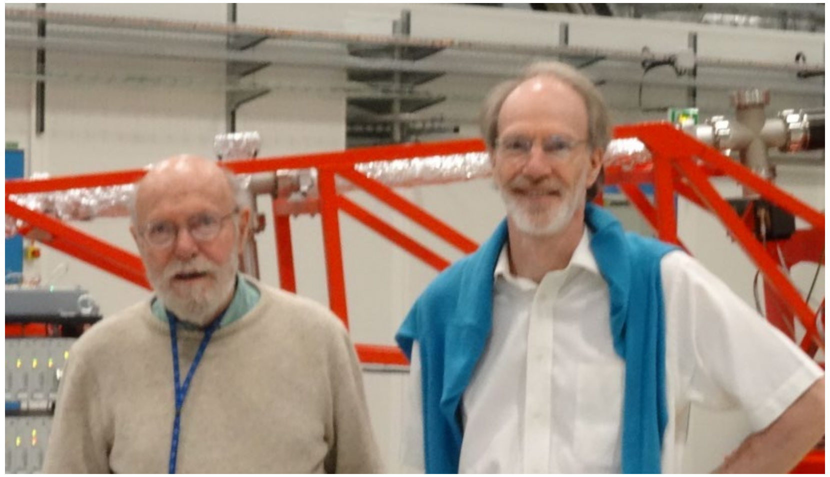


RIXS is sensitive to all degrees of freedom and can be used to determine interplay and entwining that are at the origin of the complex behavior of quantum materials

RIXS research has been driven by remarkable technical improvements, leading to several discoveries.

Better resolution, polarization dependence and time dependence will bring more

Special acknowledgements



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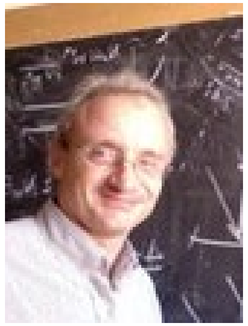

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