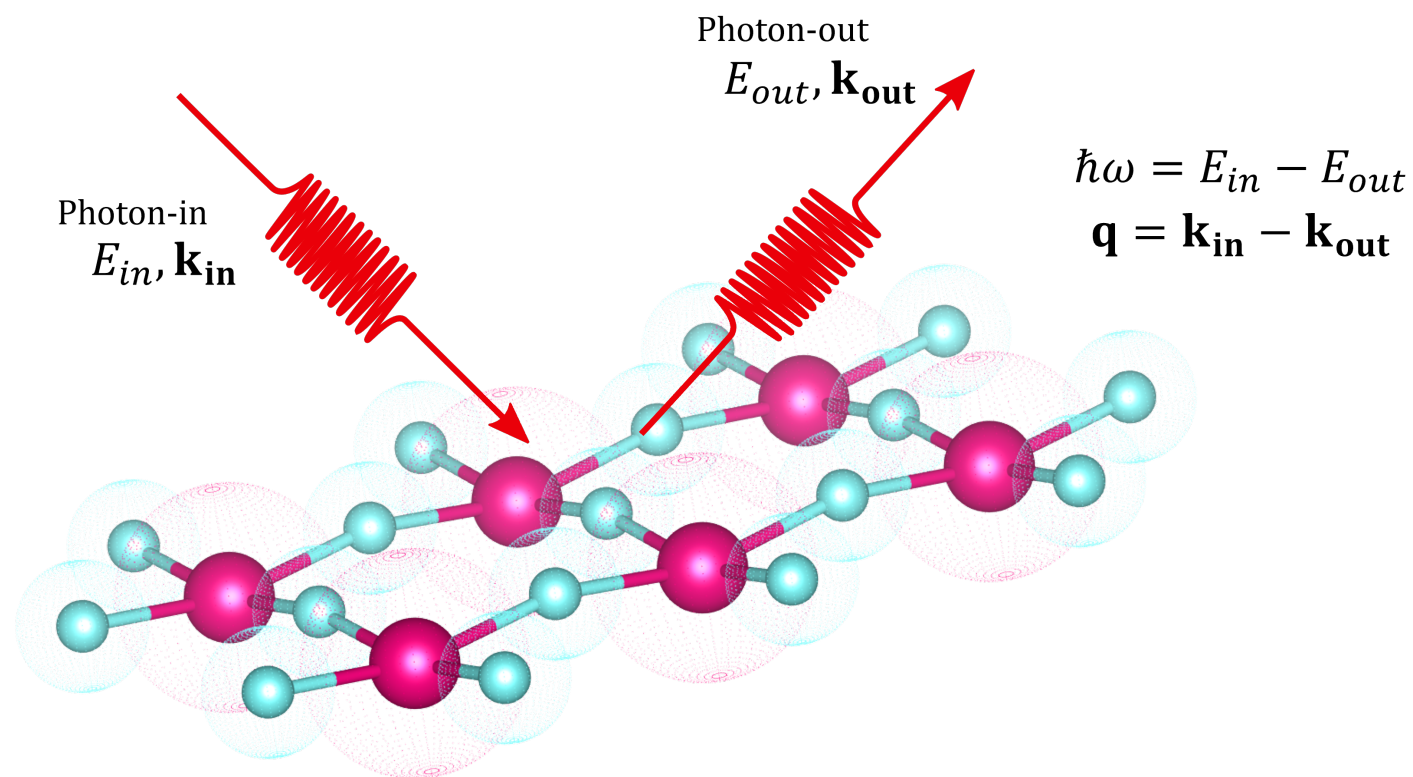


응집물리(강상관 전자계) 관점에서 바라본

Resonant Inelastic X-ray Scattering

공명 비탄성 엑스선 산란



2024 가속기 및 빔라인 미래인재 양성 교육단 여름학교
07. 10. 2024

김범준
포항공대 (POSTECH)

Elastic vs. Inelastic

=diffraction

Static vs. Dynamic

structure factor

$$S(q)$$

$$S(q, \omega)$$

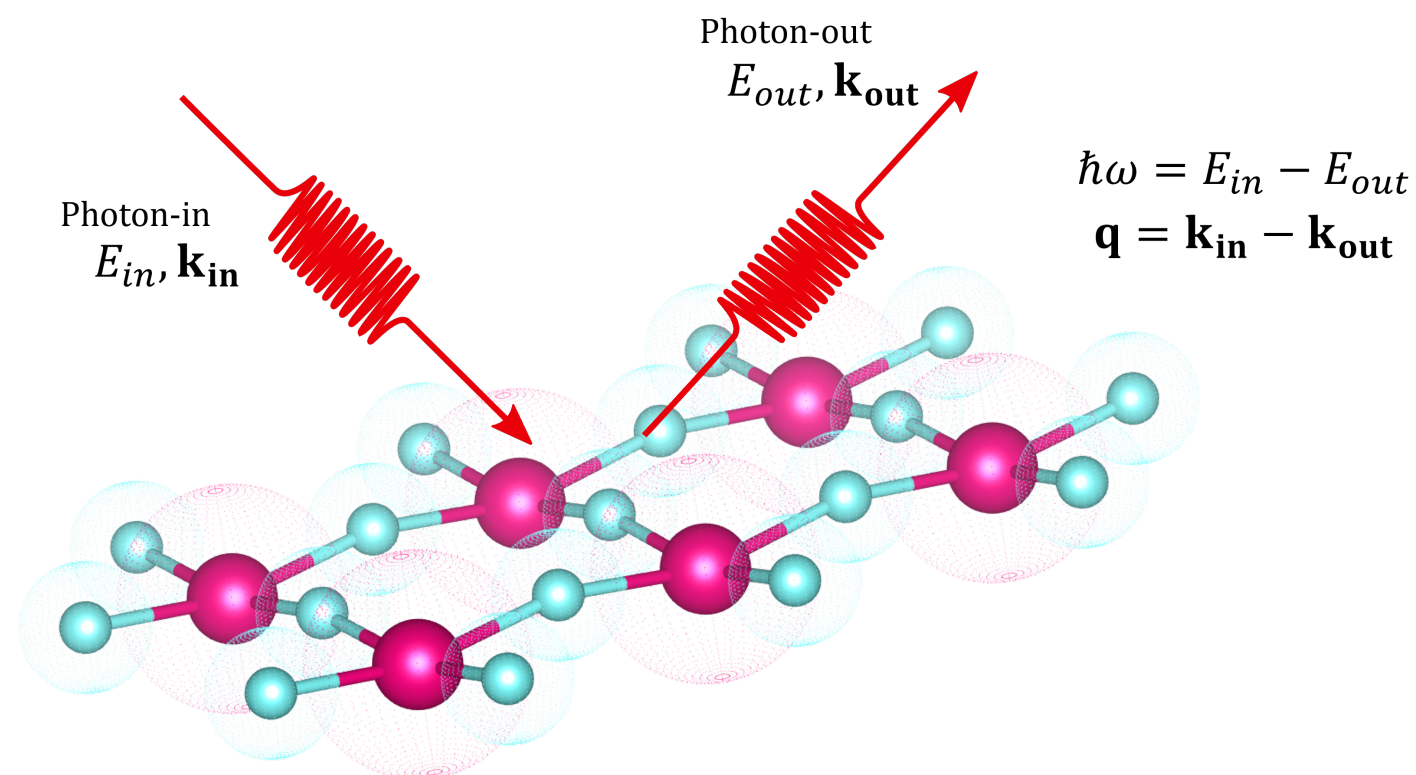
dynamic structure factor

$$q = k_f - k_i$$

momentum transfer

$$\hbar\omega = E_f - E_i$$

energy transfer



EM wave

X-ray vs. Neutron

neutral, $S=1/2$

electromagnetic force

strong force,
magnetic dipole interaction

phonon dispersion
magnon dispersion

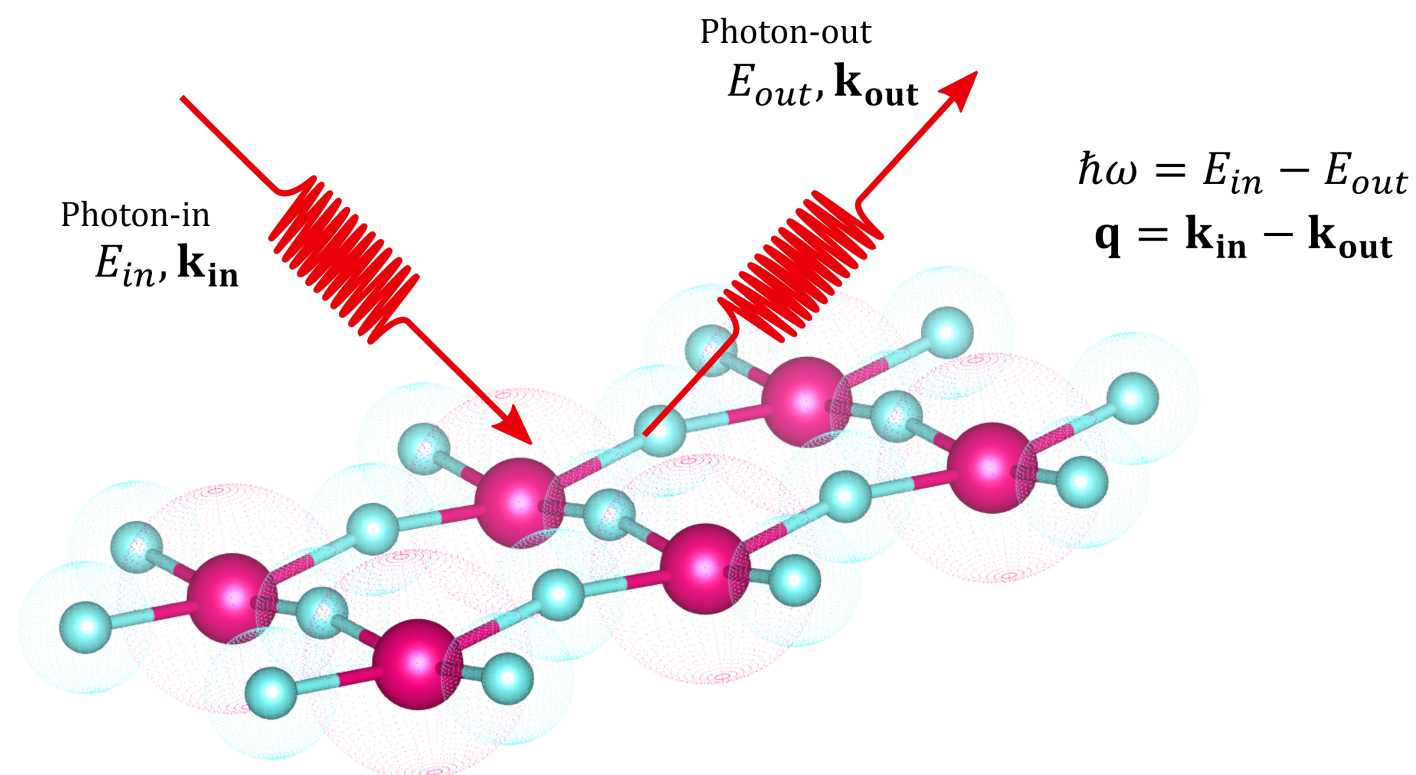
structure factor

$$S(q) = \int \rho(r) e^{-iq \cdot r} dr$$

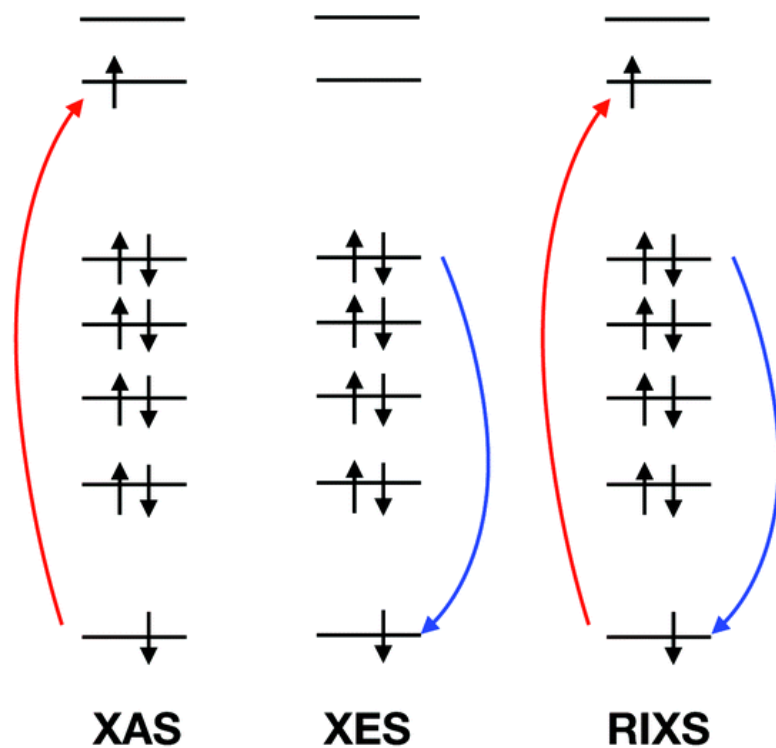
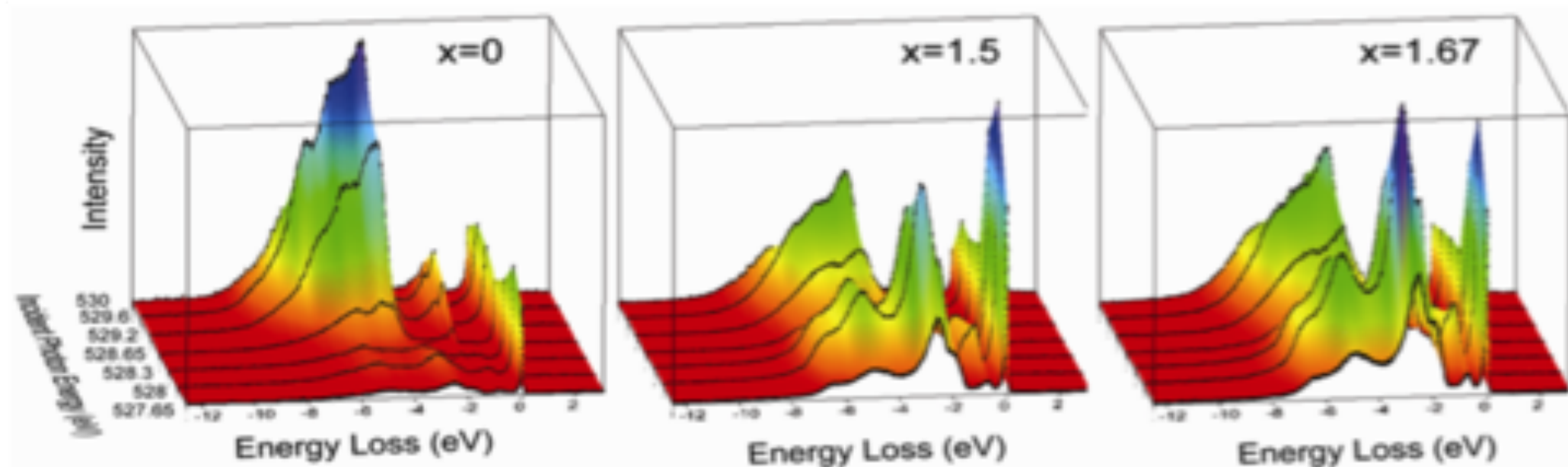
$S(q, \omega)$ dynamic structure factor

$q = k_f - k_i$ momentum transfer

$\hbar\omega = E_f - E_i$ energy transfer



Resonance



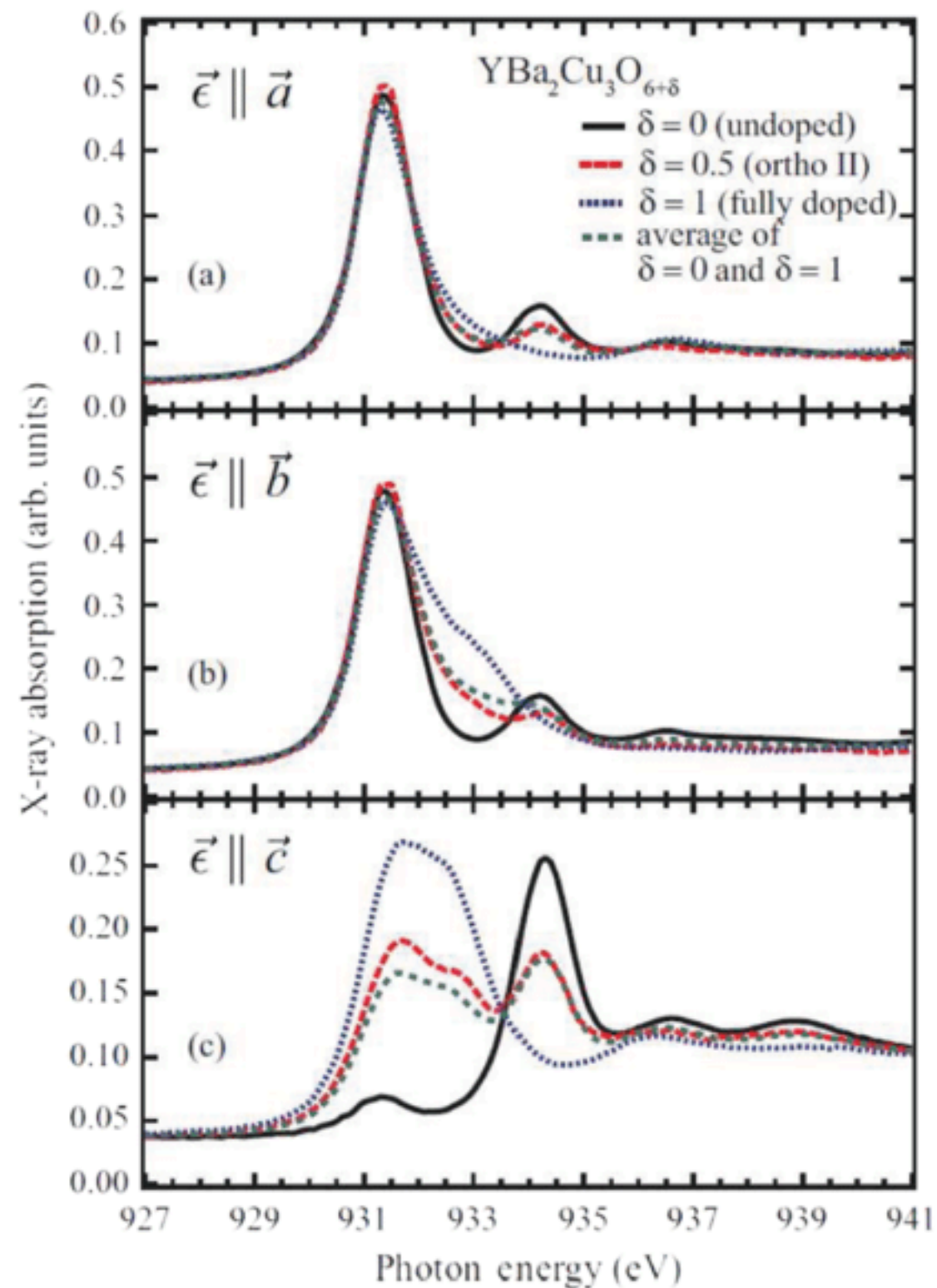
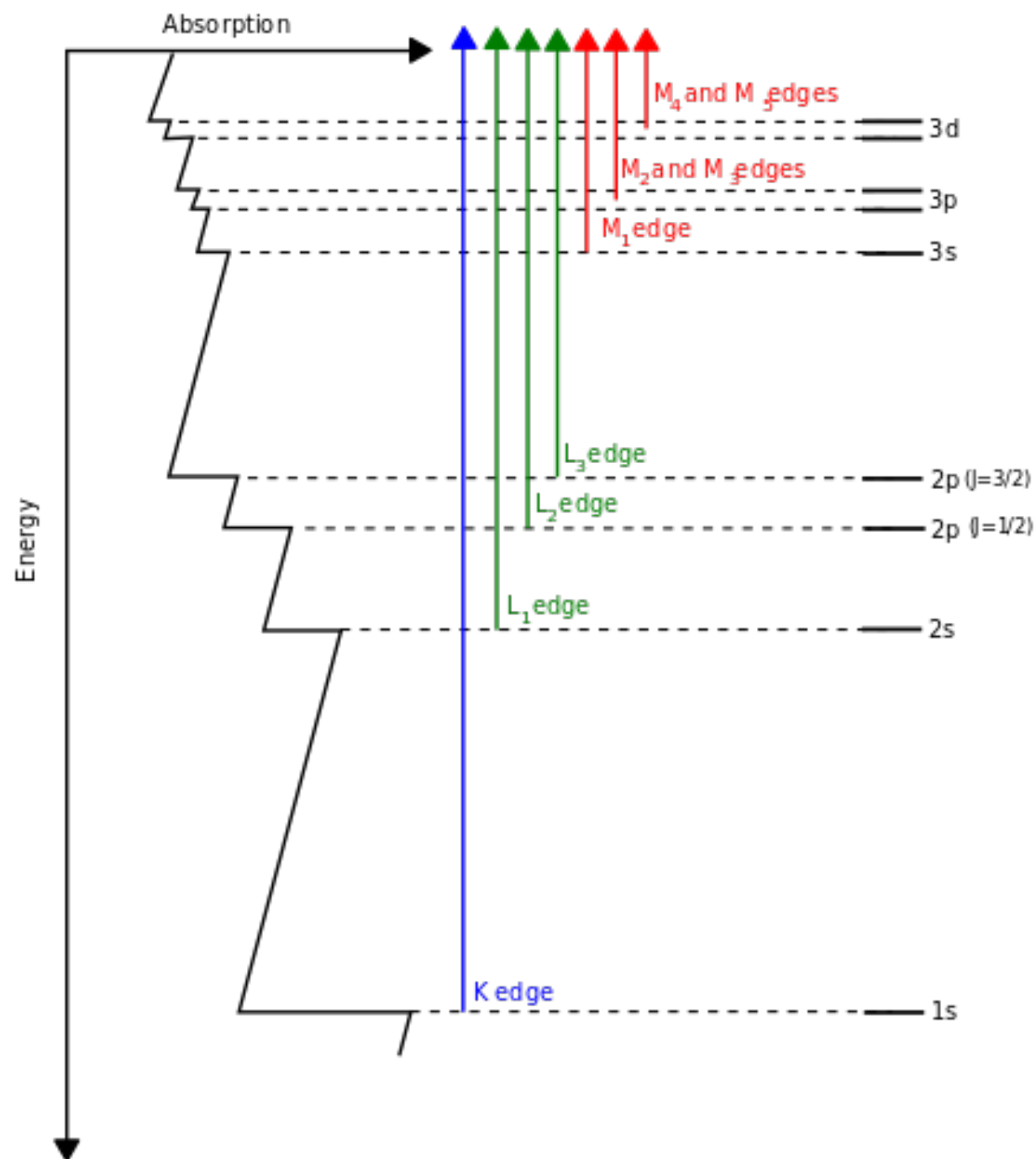
X-ray **absorption** spectroscopy (XAS)

X-ray **emission** spectroscopy (XES)

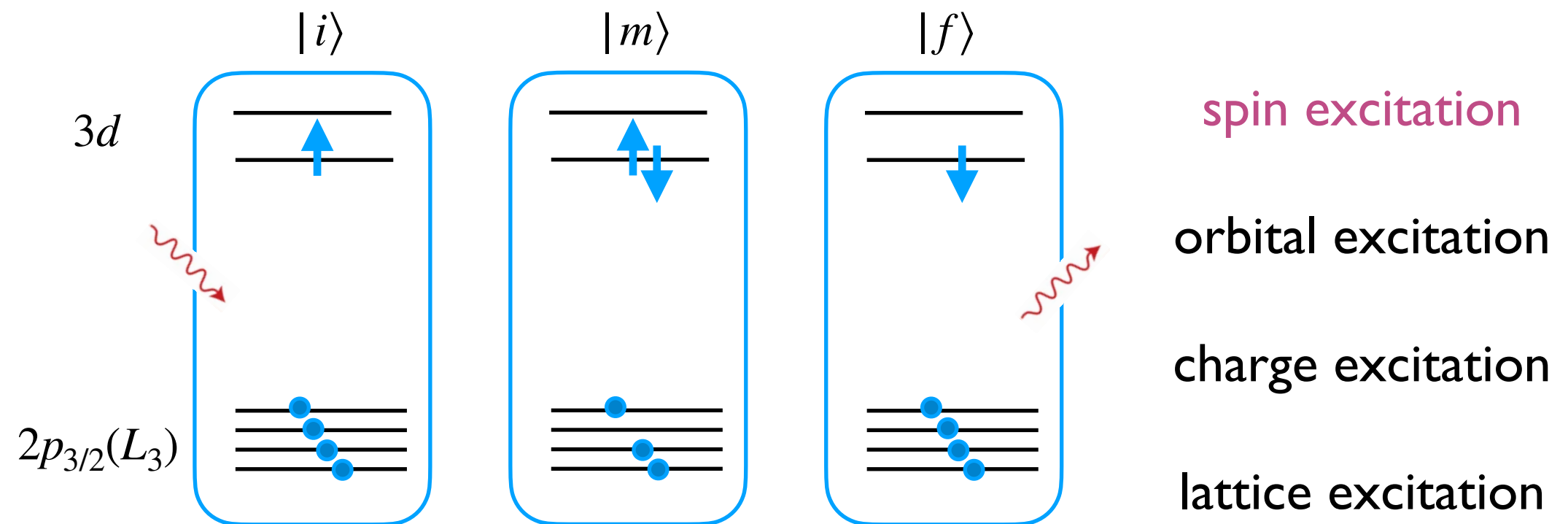
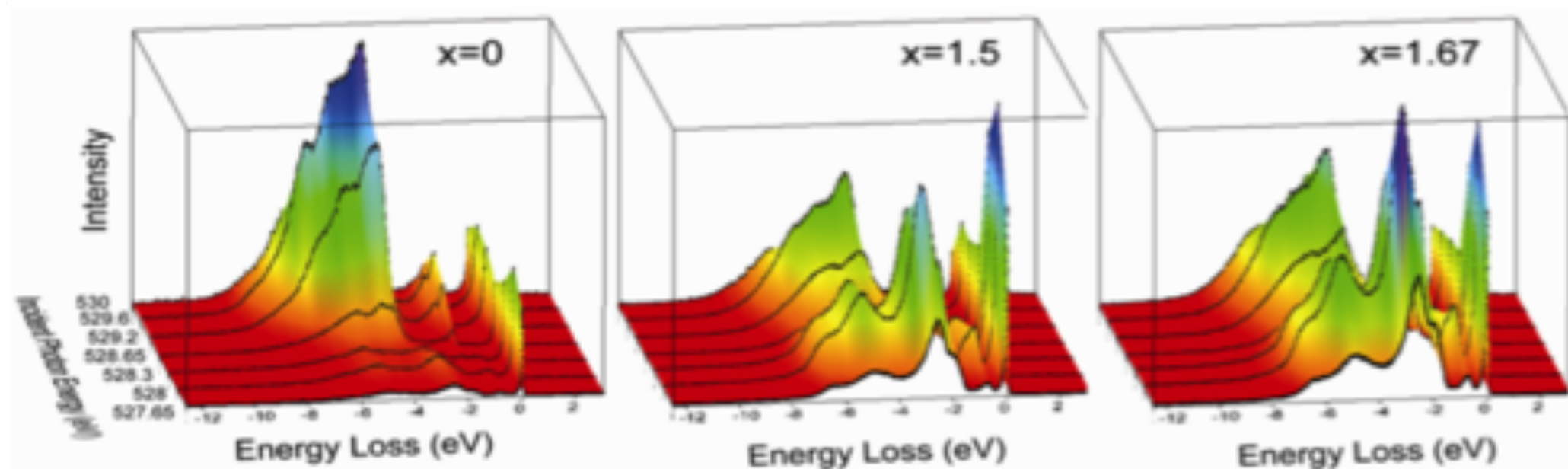
Resonant inelastic X-ray scattering

= XAS (**absorption**) + XES (**emission**)

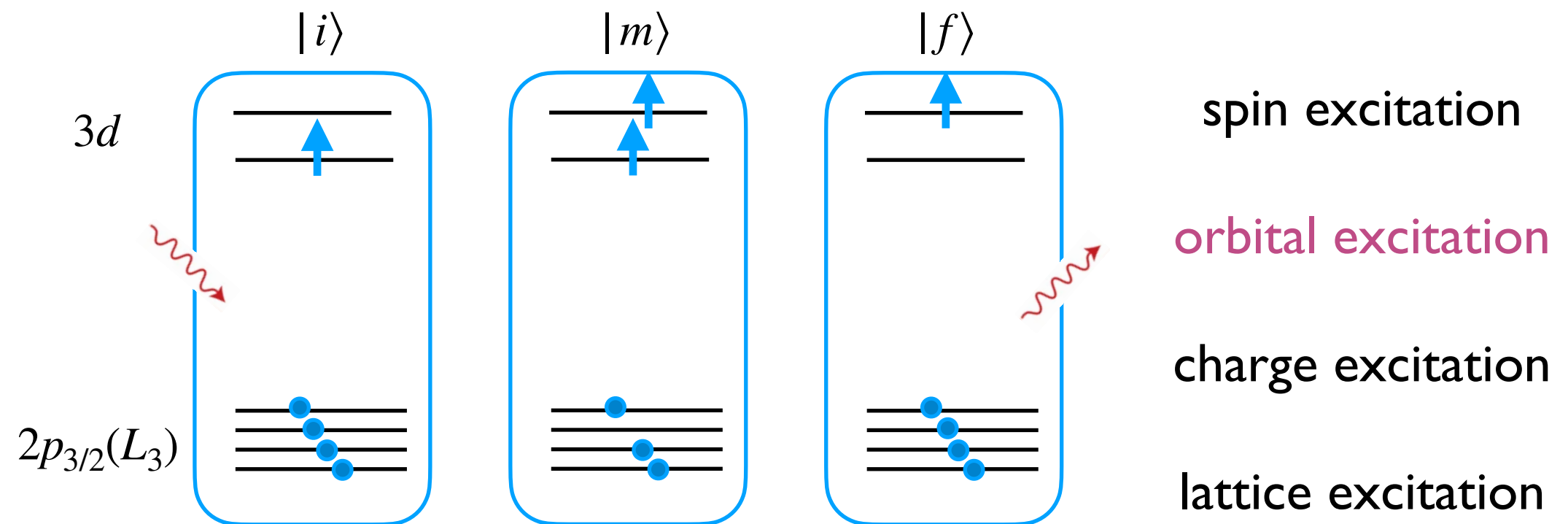
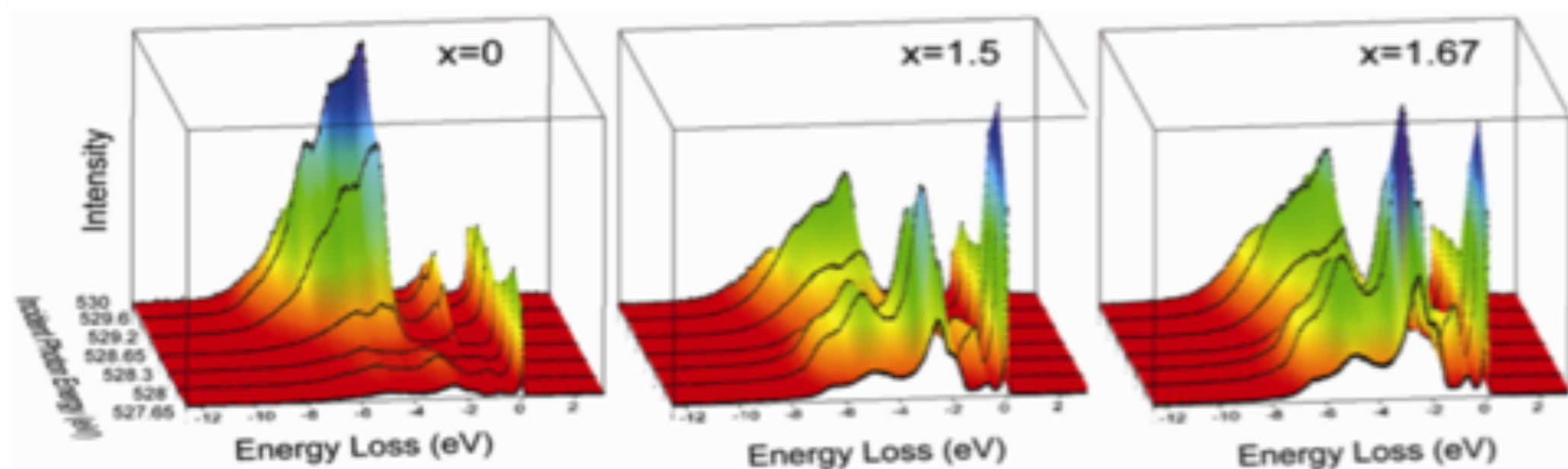
X-ray Absorption Spectroscopy



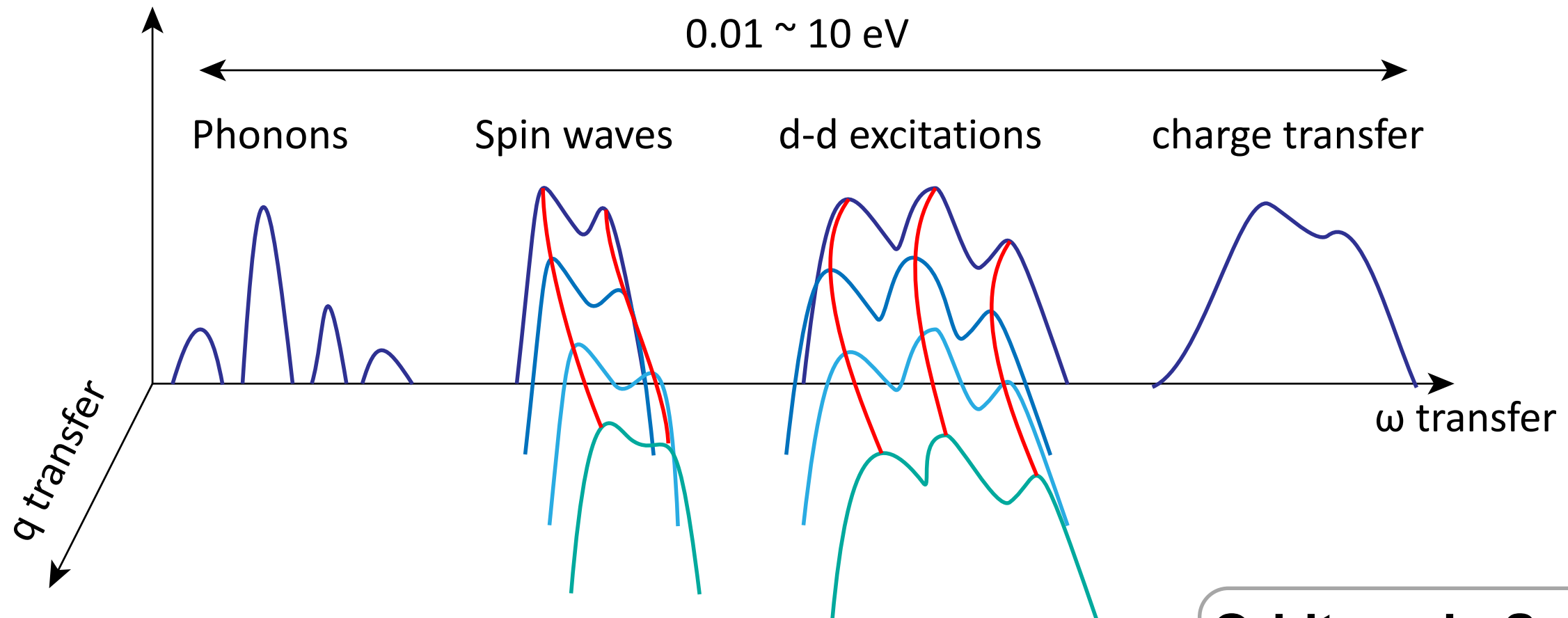
Resonance



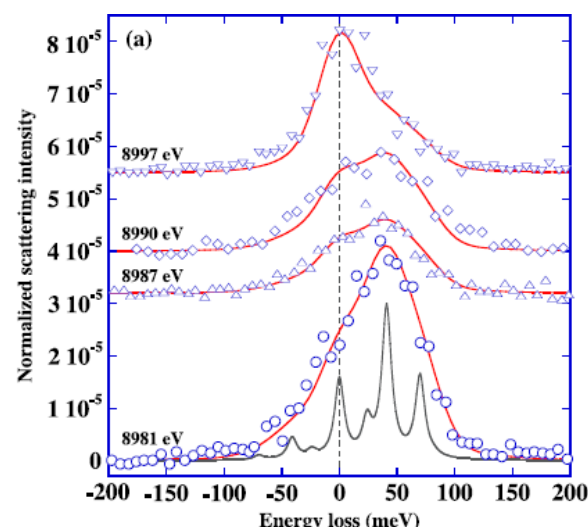
Resonance



Resonant inelastic x-ray scattering

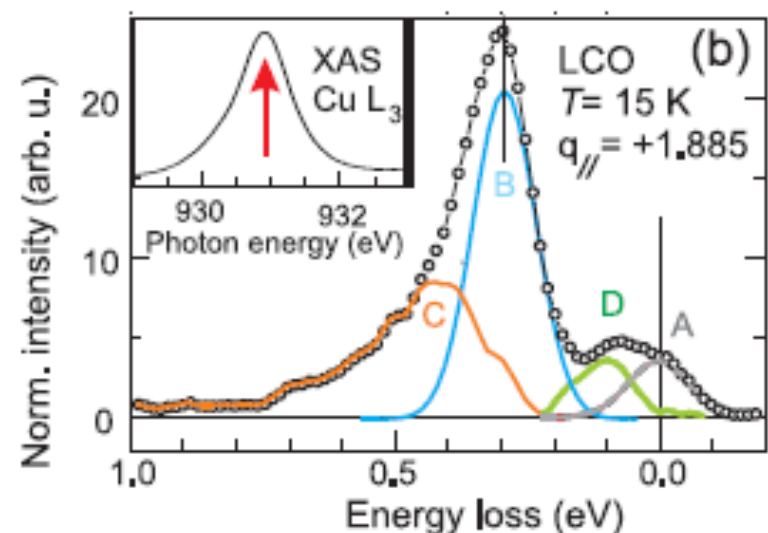


Phonons in CuO



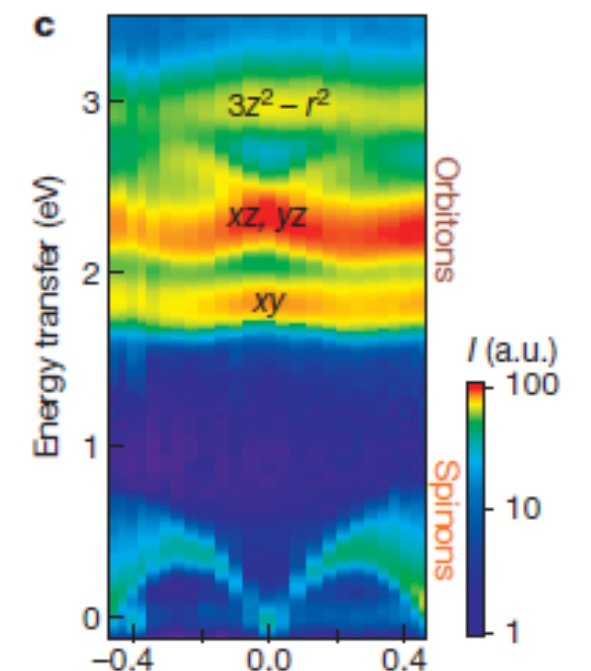
Yavas et al. JPCM 2010

Magnon in La_2CuO_4



Braicovich et al. PRL 2010

Orbitons in Sr_2CuO_3



Schlappa et al. Nature 2012

RIXS

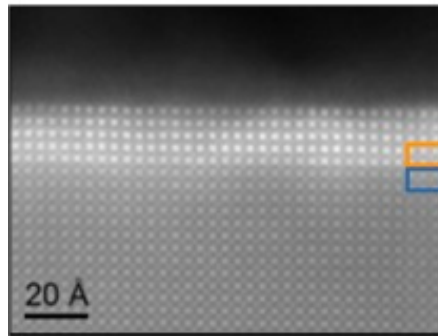
$$S(\mathbf{q}, \omega)$$

dynamic structure factor

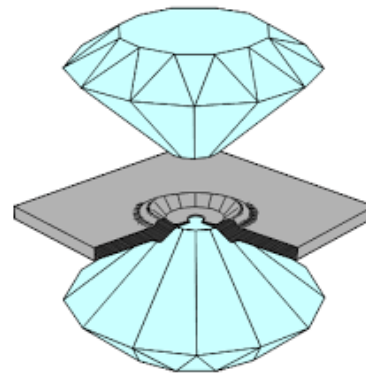
INS



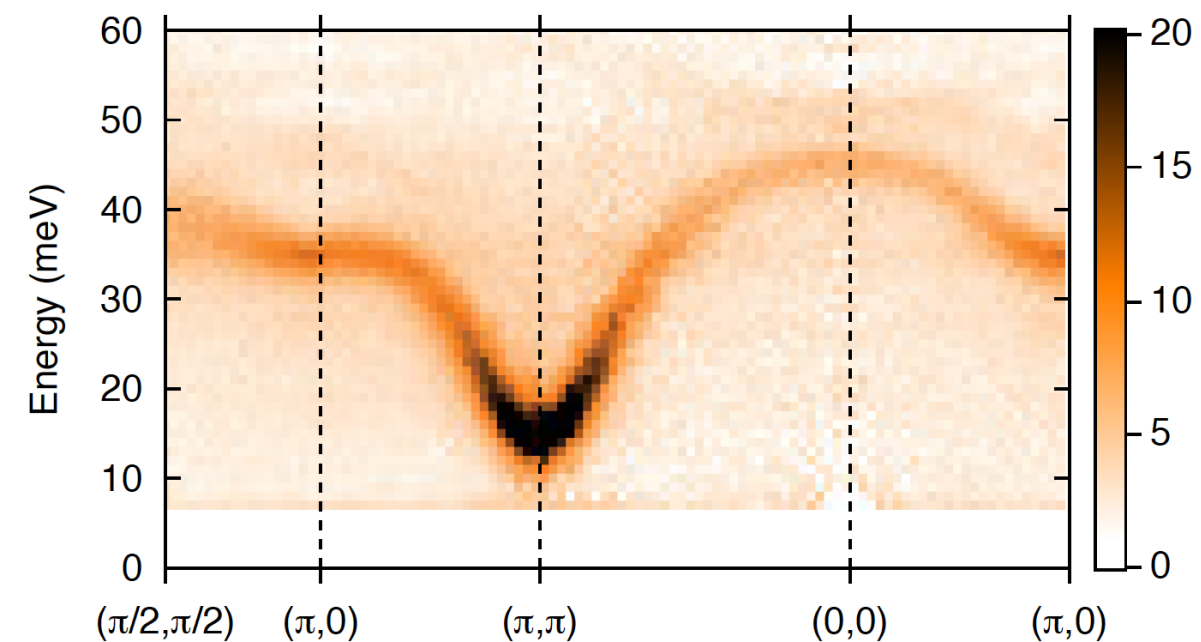
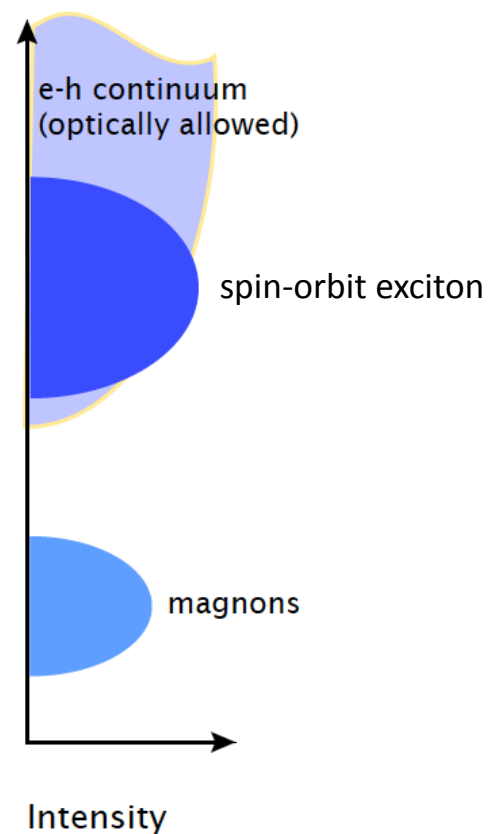
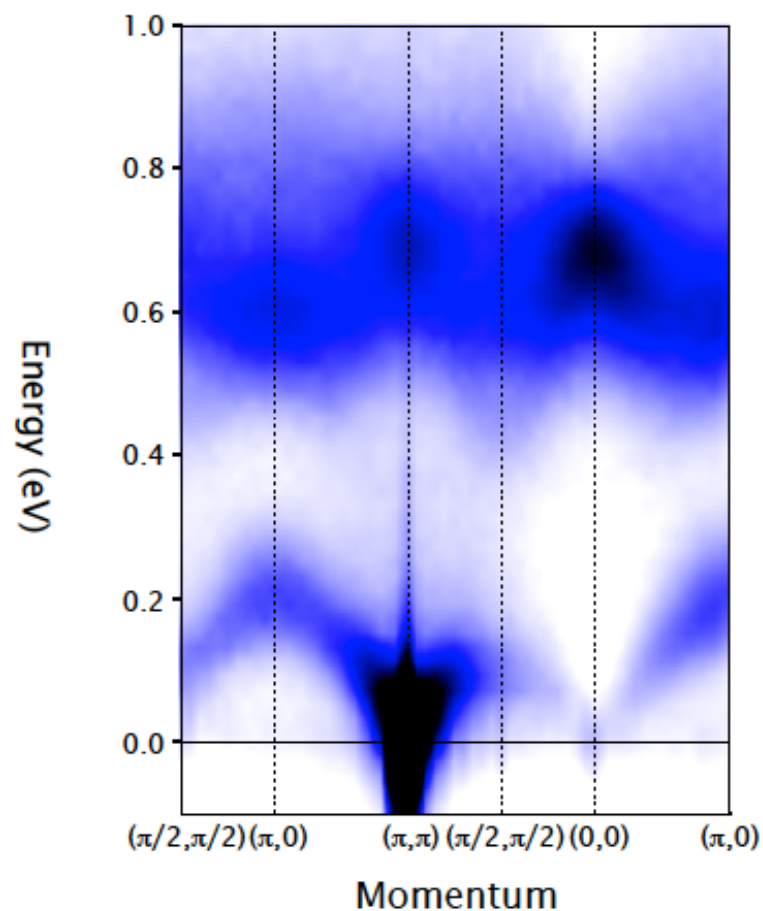
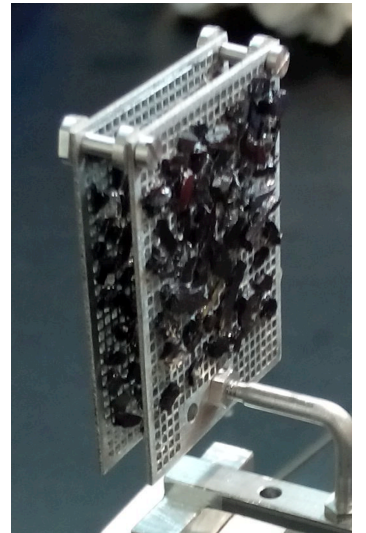
tiny crystals



thin films



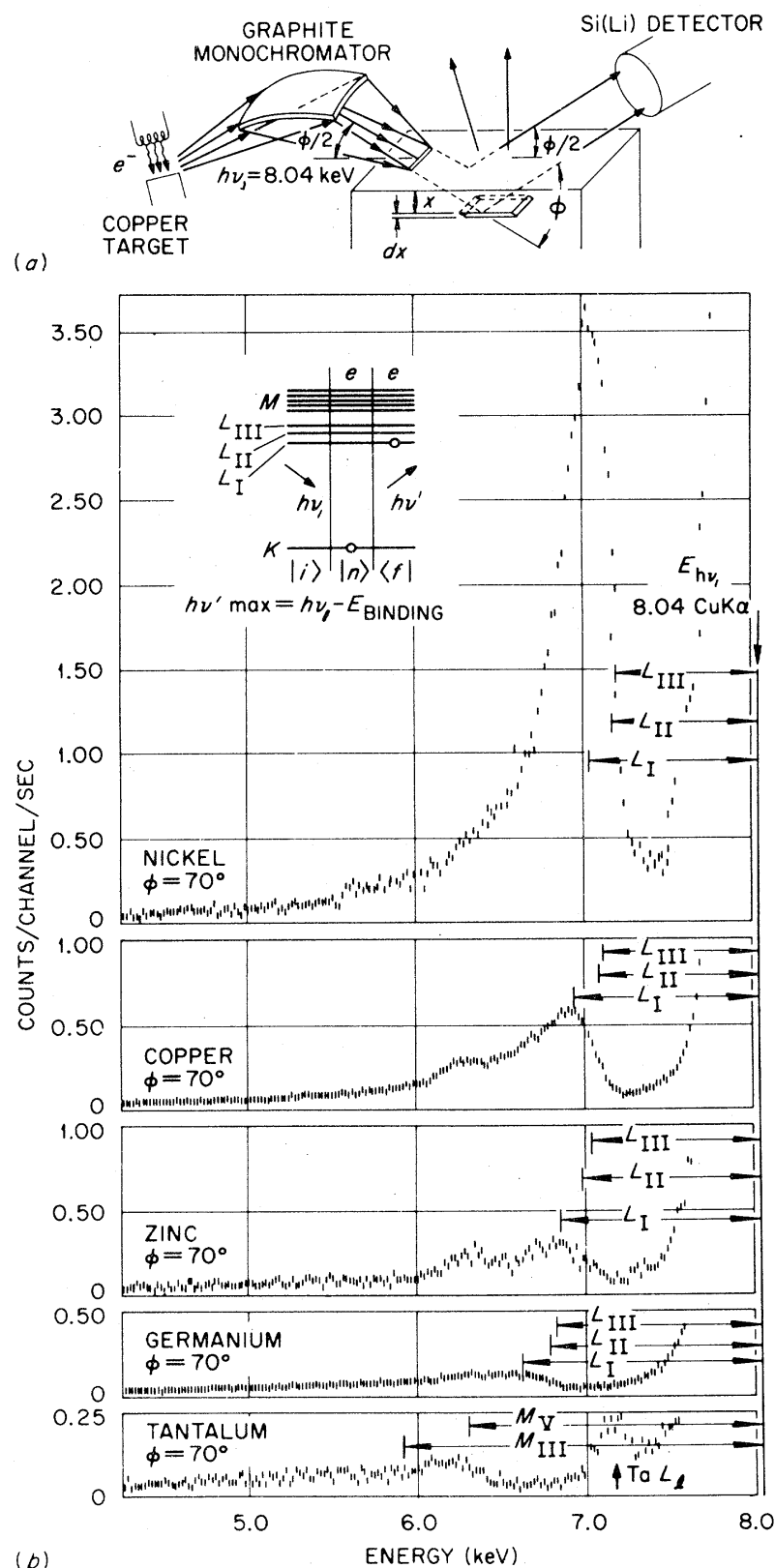
high pressure



J. Kim & BJK et al. PRL (2012)

A. Jain & BJK et al. Nature Phys. (2017)

Brief history



VOLUME 33, NUMBER 5

PHYSICAL REVIEW LETTERS

29 JULY 1974

Inelastic Resonance Emission of X Rays: Anomalous Scattering Associated with Anomalous Dispersion*

Cullie J. Sparks, Jr.

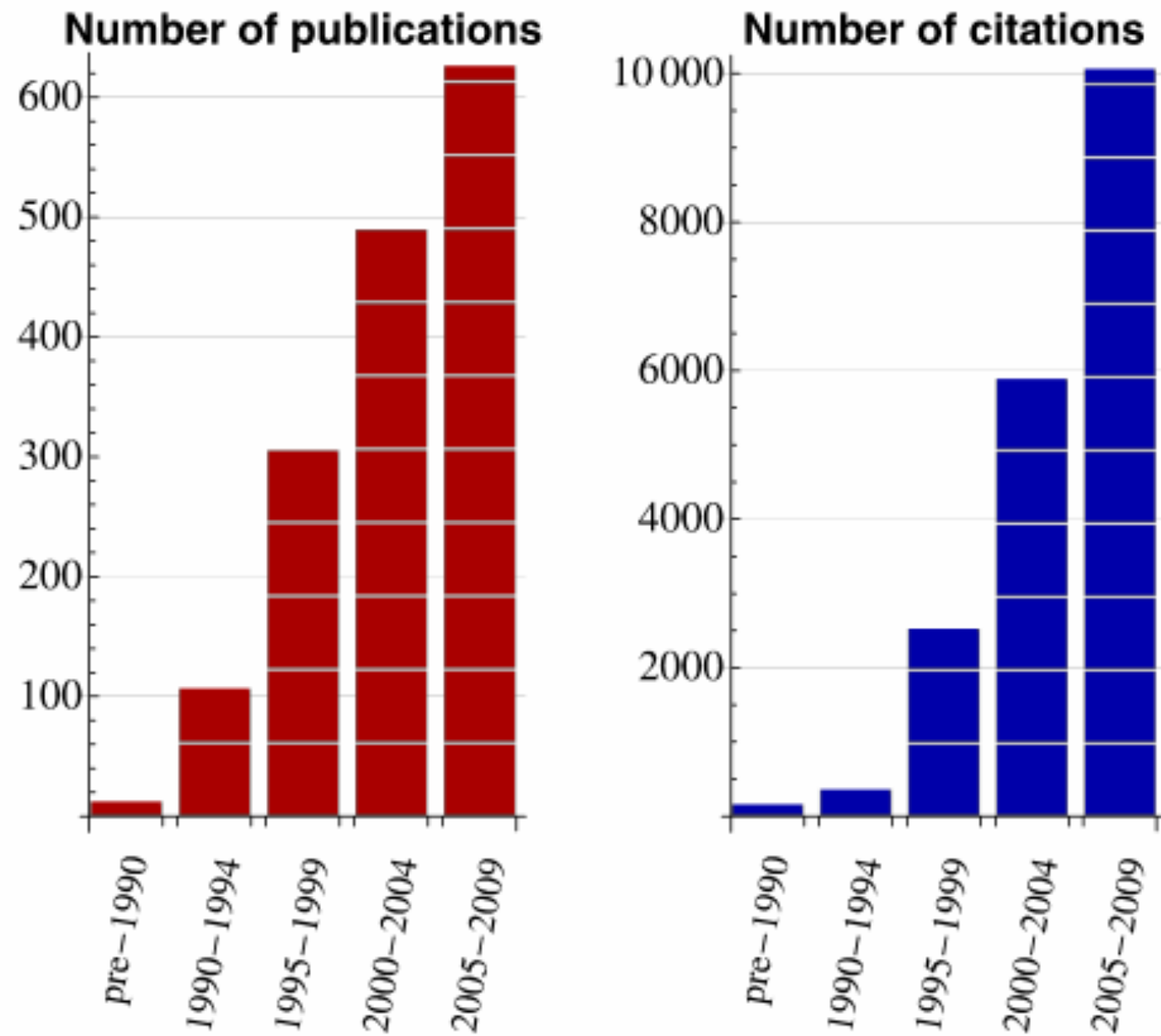
Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 13 May 1974)

190 eV resolution @ 5.9 keV

ing increases rapidly in intensity. The cross section for the observed scattering is shown to be predicted by the $\vec{P} \cdot \vec{A}$ term in second-order perturbation theory, a term previously neglected in inelastic x-ray scattering calculations.

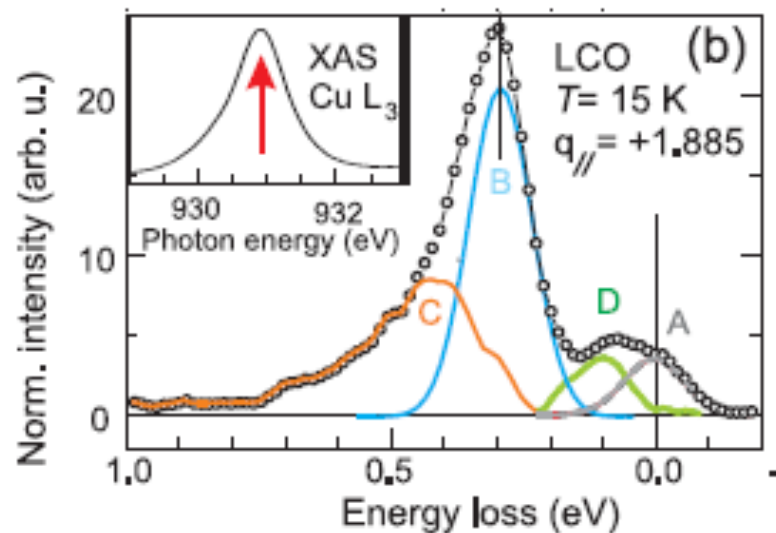
Brief history



Brief history

our first experiment on iridate (hard x-ray)
first observation of single magnon (soft x-ray)
(Braicovich & Ghiringhelli)

Magnon in La_2CuO_4



Braicovich et al. PRL 2010

2017: <10 meV
2012: 25 meV

Ir L3 edge 11.2 keV
resolving power $>10^6$

2010: 130 meV, 3000 cps

2010

2007: 90 meV, 600 cps

2002: 300 meV, 6cps

1999: 1500 meV, 1cps

Resonant inelastic x-ray scattering

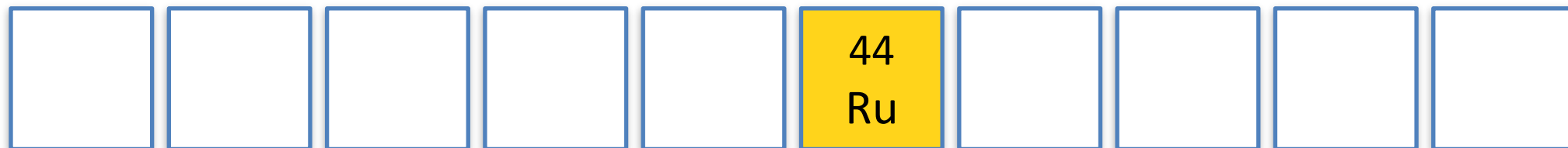
L edge

3d



Soft (<1keV)

4d

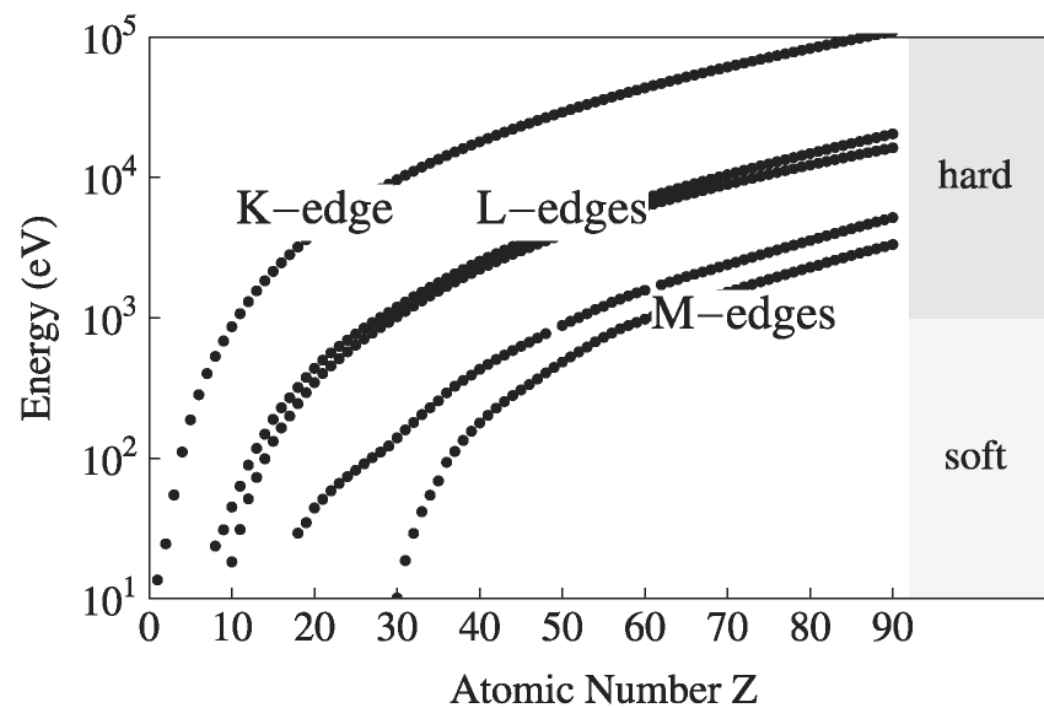


Intermediate

5d



Hard (>10 keV)



Resonant inelastic x-ray scattering

L edge

3d



Soft (<1keV)

Soft X-Ray RIXS Spectrometer at ID32, ESRF



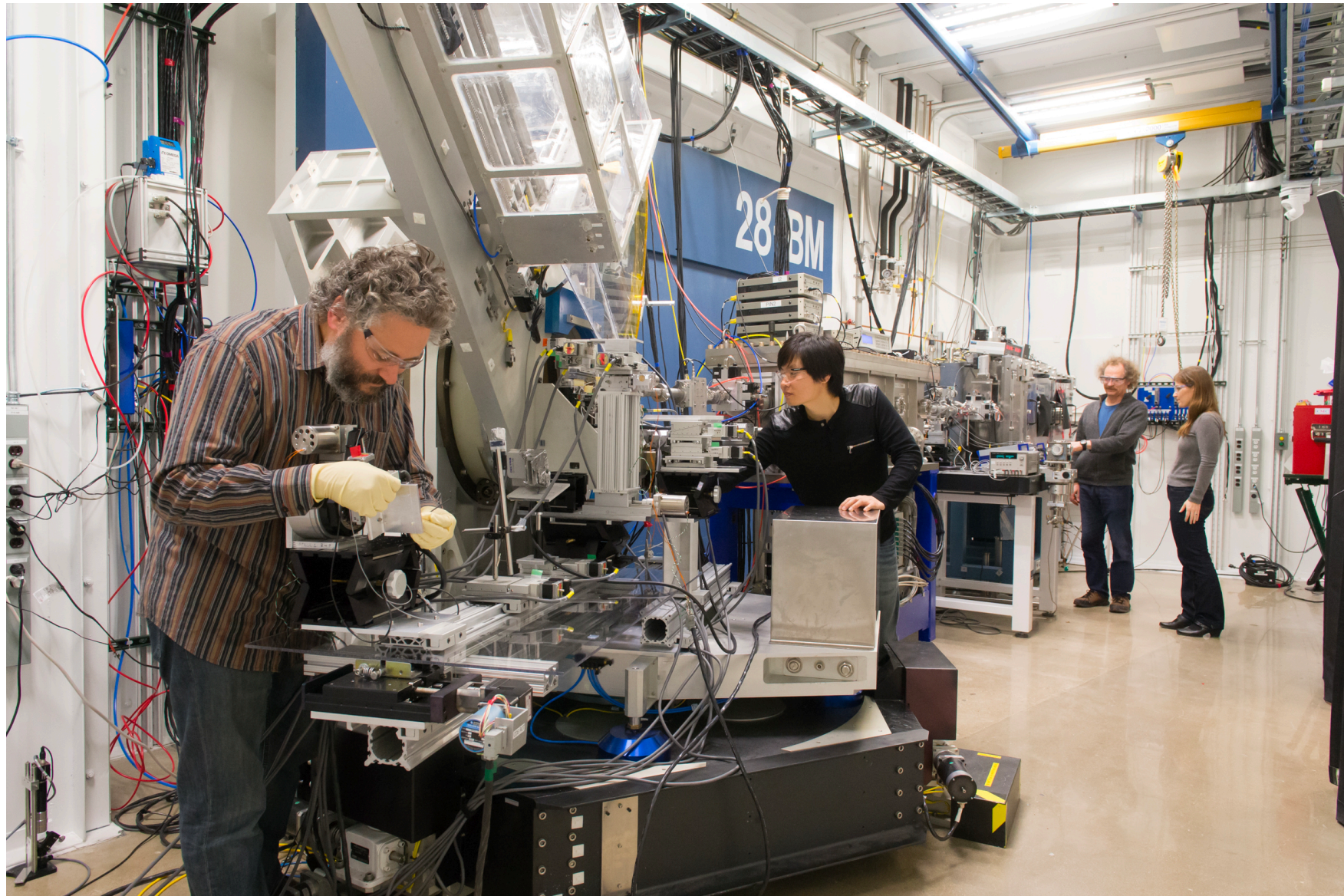
Resonant inelastic x-ray scattering

5d



77
Ir

Hard (>10 keV)



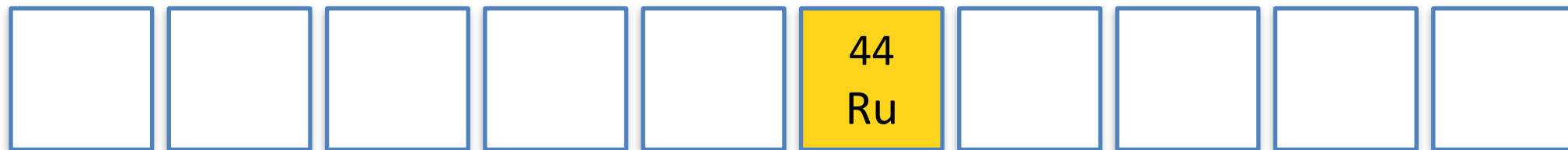
Advanced
Photon
Source

ARGONNE NATIONAL LABORATORY



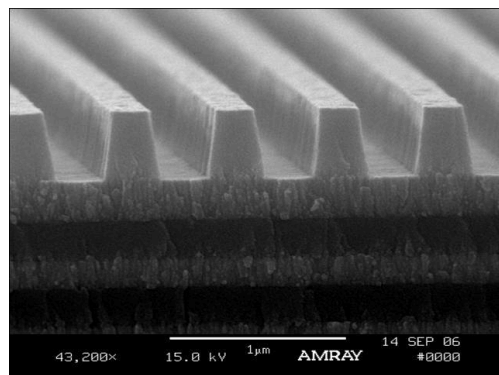
Resonant inelastic x-ray scattering

4d



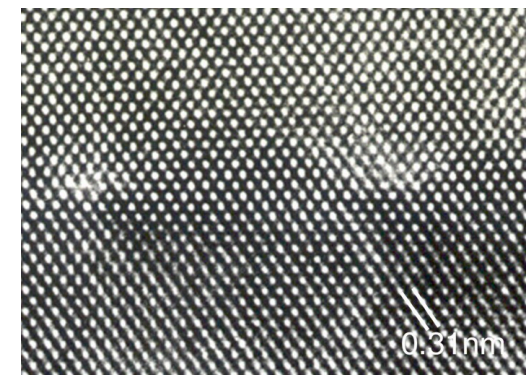
Intermediate

Grating



$$E = 2 \sim 3 \text{ keV}$$
$$\lambda = 0.4 \sim 0.6 \text{ nm}$$

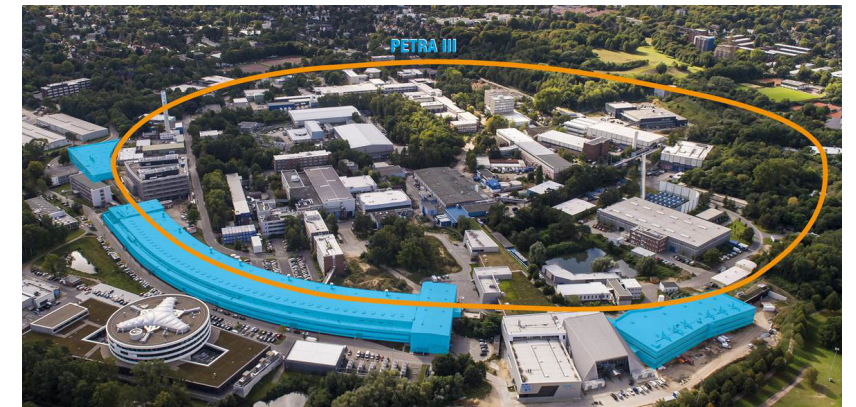
Crystal



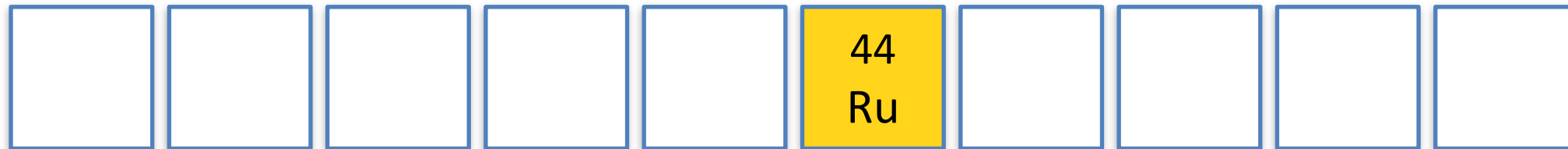
X-ray optics difficult to implement

The world's first high-resolution RIXS beamline for intermediate energy

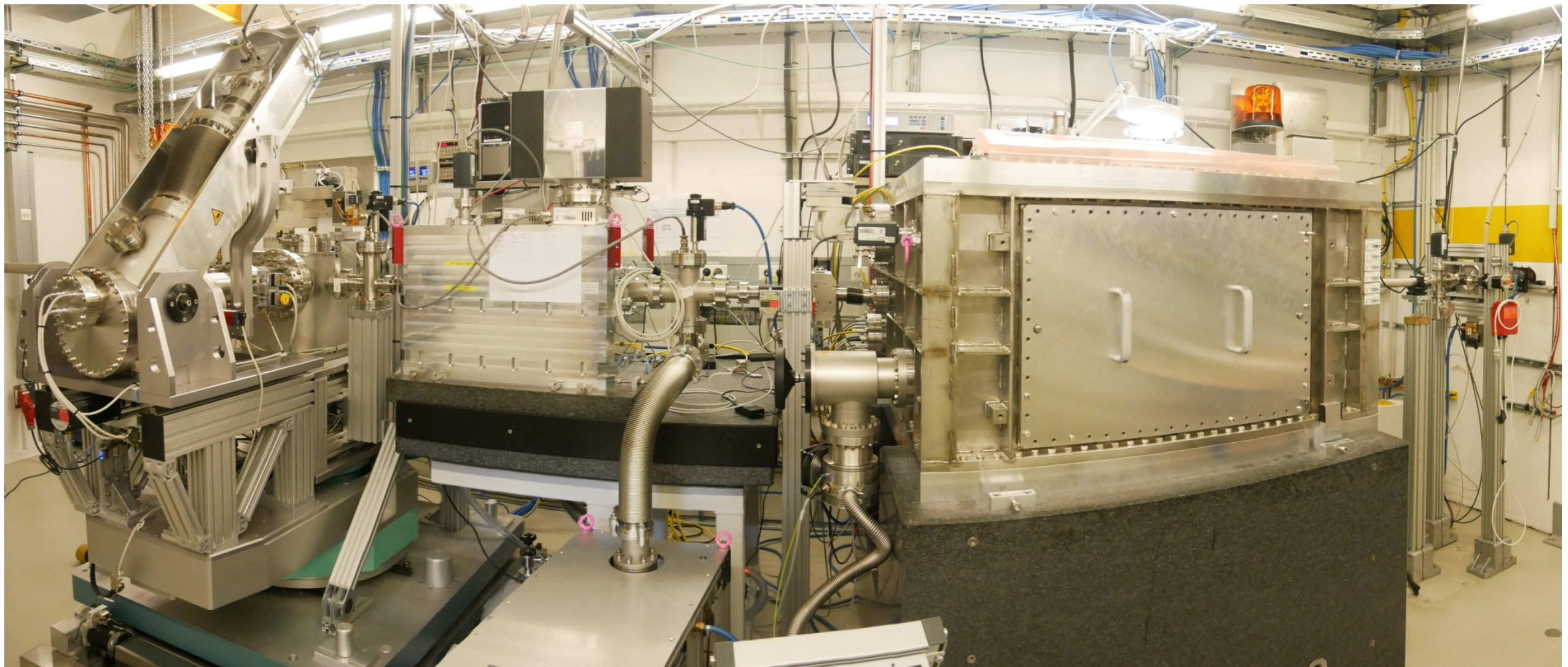
I-RIXS project at DESY - P01 (Hamburg)



4d



Intermediate



Soft x-ray RIXS beamlines

PROJECTS AROUND THE WORLD: 1

Source (country)	Scientific areas	Combined resolving power	Energy range (eV)	Time scale	Instrumentation	Contact:
ALS (USA)	Excitations in 3D materials; ultrafast phenomena	5000@540eV 2500@1keV		Spring 2016	qRIXS: time and momentum resolved RIXS	Yi-De Chaung ychuang@lbl.gov
ALS (USA)	Dispersive excitations	25000	250-1500	2017-2018	QERLIN: high throughput multiplexing for measuring dispersive excitations	Howard Padmore hapadmore@lbl.gov
BESSYII (Germany)	Solid state and molecular sciences	25000-30000	200-1500	Design finished, funded, ~2018	METRIXS: 7 m Spectrometer with momentum transfer for solid state and molecular sciences.	Alexander Föhlisch alexander.foehlich@helmholtz-berlin.de
BESSYII (Germany)	Inhomogeneous samples	5000	100-1500	In operation	μ mRIXS: PGS Spectrometer, 1 μ m Focus for inhomogeneous samples.	Justine Schlappa justine_schlappa@helmholtz-berlin.de
BESSYII (Germany)	Solids and molecules	3000	60-1500	In operation	flexRIXS: Compact transportable Rowland Spectrometers with dedicated solid and molecular sample environments.	Alexander Föhlisch
Diamond Light Source (UK)	Condensed matter physics, material science, strongly correlated systems, Catalysts	10000 - 40000 @ 1keV	250-3000	Installation: 2015-2016 First Light summer 2016 First Users Spring 2017.	13m scattering arm. Continuous angular rotation (150 degrees) - Cinel design. Polarization analysis. 4 collecting optics close to the sample. Can reach small forward scattering angles.	Kejin Zhou Kejin.zhou@diamond.ac.uk
MAX IV (Sweden)	Solids, Gases, liquids	>30000	250-1600	Beamline installation: Fall 2015 Spectrometer: Spring 2016. Comm. 2017	10m collimating Rowland spectrometer. Detector height minimised for stability. Drift correction using zero-order. Possible future polarimeter. Continuous angular rotation over 120 degrees using differentially pumped rotation system.	Marcus Agaker marcus.agaker@physics.uu.se



Soft x-ray RIXS beamlines

PROJECTS AROUND THE WORLD: 2

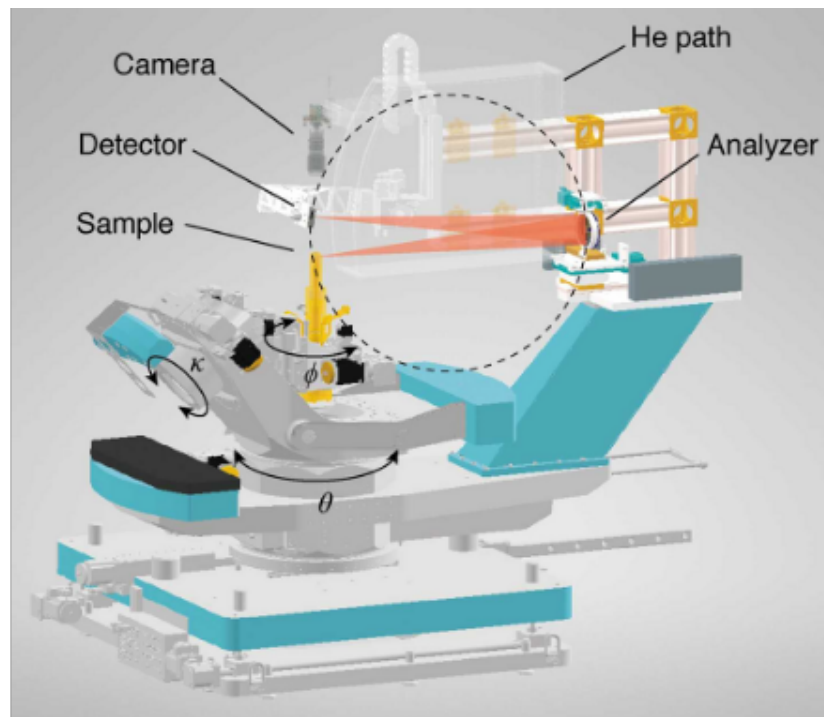
NSLSII (USA)	Correlated electron systems	10000- 70000	165- 2300	Installation: 9/2016 1st light 11/16 Users: 01/17	Piezo based diffractometer. Continuous angular rotation of 14m scattering arm with triple rotating flange system. Detector with polarimeter.	Ignace Jarrige jarrige@bnl.gov
PetraIII (Germany)	Liquids	Medium resolution	250- 2300	Operational	User instrument: Possible upgrade for higher resolution	Jens Viefhaus jens.viefhaus@ desy.de
Sirius (Brazil)	Gases, liquids, interfaces and solids Bio-molecules	~42000	400- 1200	First Users: Beginning of 2019.	CCD detector giving a spatial resolution of 3microns. Large momentum transfer Possible rotatable platform or chamber Possibly magnetic fields	Marco Guarise marco.guarise@ nls.br
SLS (Switzerland)	Correlated Materials, Molecular physics, Chemistry/ catalysis	5800- 8000 @ 930eV 7500- 11800 @530eV	400 - 1700	Operational	Q rotating girder platform 30-130 degrees 6 axis manipulator from autumn 2015. 9-350K 1 inch chip CCD camera with 13.5 micron pixels From 2016 EM-CCD with 3 one inch chips and subpixel resolution around 2-3 micron Upgrade RP: 13-14000 930eV New BL / spectrometer at PSI SLS 2.0 > 2020	Thorsten Schmitt thorsten.schmitt @psi.ch
Soleil (France)	Solid state- physics Liquids and gases.	5000- 8000	50-950	Operational + possible new project	Electric and magnetic fields (~1T) at the sample by end 2016. Liquid and gas cells. Soleil upgrade project 2020? High resolution (>20000) 8m long spectrometer.	Nicolas Jaouen nicolas.jaouen@ synchrotron- soleil.fr
SSRF (China)	Electronic structure of materials	46500 @ 930eV	250- 1700	waiting for funding.	Phase II project on Dreamline beamline 8m scattering arm	Yong Wang wangyong@ sinap.ac.cn
TPS (Taiwan)	Low-energy excitations of transition metal compounds.	42000 @ 900eV	400- 1200	Under construction (11/2015)	Dragon type beamline. Energy compensation scheme (AGS-AGM) Polarization analysis. 7.5m long scattering arm	Di-Jing Huang djhuang@ nsrrc.org.tw
CLS (Canada)						
SPRING8 (Japan)						



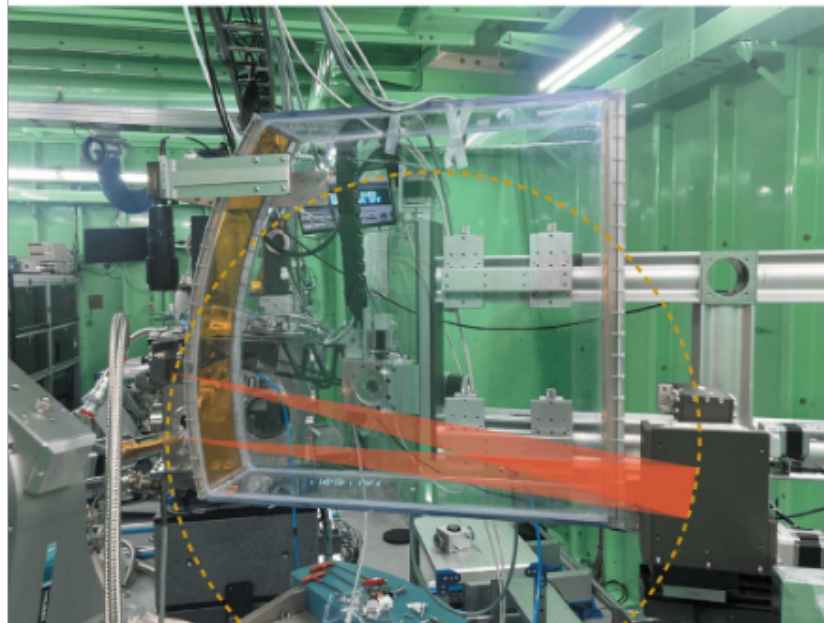
Hard x-ray RIXS beamlines

Facility	Beamline	Energy	Resolution	Analyzer	Spectrometer	Materials	Contact
APS (US)	Sector 27	6~15 keV	25~ 200 meV	Single analyzer	Vertical/ Horizontal scattering	3d and 5d TM and RE, etc	J. Kim
Spring-8 (Japan)	BL 11 XU	6~10 keV	0.1~1 eV	Single analyzer	Horizontal scattering	3d and 5d TM and etc	Kenji Ishii
Spring-8 (Japan)	BL 12 XU	8~32 keV	1 eV	Single analyzer	Horizontal scattering	3d TM	Nozomu Hiraoka
ESRF (France)	ID 20	4~20 keV	25 meV~ 2eV	Five analyzers	Vertical/ Horizontal scattering	3d and 5d TM and etc	Marco Moretti
Desy (Germany)	P 01	5~20 keV	25 meV ~ 1eV	Single analyzer	Vertical/ Horizontal scattering	3d TM	Hasan Yavas
SSRF (China)	Planned						Xuerong Liu

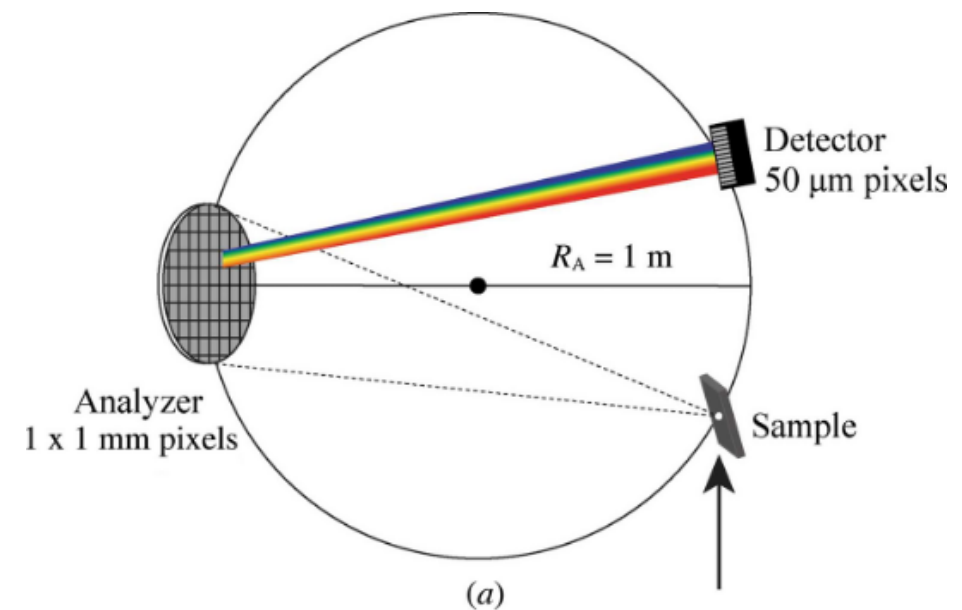
Hard x-ray RIXS @ IC beamline of PLS-II



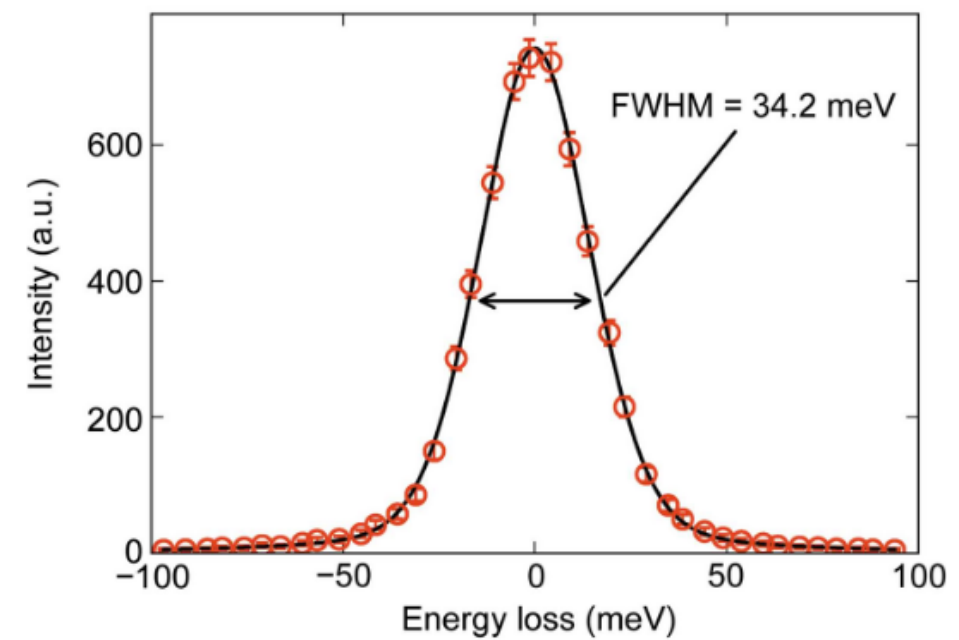
(a)



(b)



(a)



(b)

Basic Principles

Photon-electron interaction

$$H' = \frac{e^2}{2m_e c^2} \sum_i A(\mathbf{r}_i)^2 - \frac{e^2 \hbar}{2m_e^2 c^4} \sum_i \mathbf{s}_i \cdot \left(\frac{\partial \mathbf{A}}{\partial t} \times \mathbf{A} \right) - \frac{e}{m_e c} \sum_i A(\mathbf{r}_i) \cdot \mathbf{p} - \frac{e^2 \hbar}{2m_e^2 c^4} \sum_i \mathbf{s}_i \cdot (\nabla \times \mathbf{A}(\mathbf{r}_i))$$

$$\begin{aligned} \langle \phi_n | e^{-i\vec{k} \cdot \vec{r}} \hat{\epsilon} \cdot \vec{p}_e | \phi_i \rangle &\approx \hat{\epsilon} \cdot \langle \phi_n | \vec{p}_e | \phi_i \rangle \\ &= \frac{im}{\hbar} \hat{\epsilon} \cdot \langle \phi_n | [H, \vec{r}] | \phi_i \rangle \\ &= \frac{im}{\hbar} (E_n - E_i) \hat{\epsilon} \cdot \langle \phi_n | \vec{r} | \phi_i \rangle \\ &= \frac{im(E_n - E_i)}{\hbar} \langle \phi_n | \hat{\epsilon} \cdot \vec{r} | \phi_i \rangle \end{aligned}$$

Quadrupole transition (E2)

$$\Delta L=2$$

$$e^{-i\vec{k} \cdot \vec{r}} \approx 1 - i\vec{k} \cdot \vec{r} + \dots$$

$$\Delta L=1$$

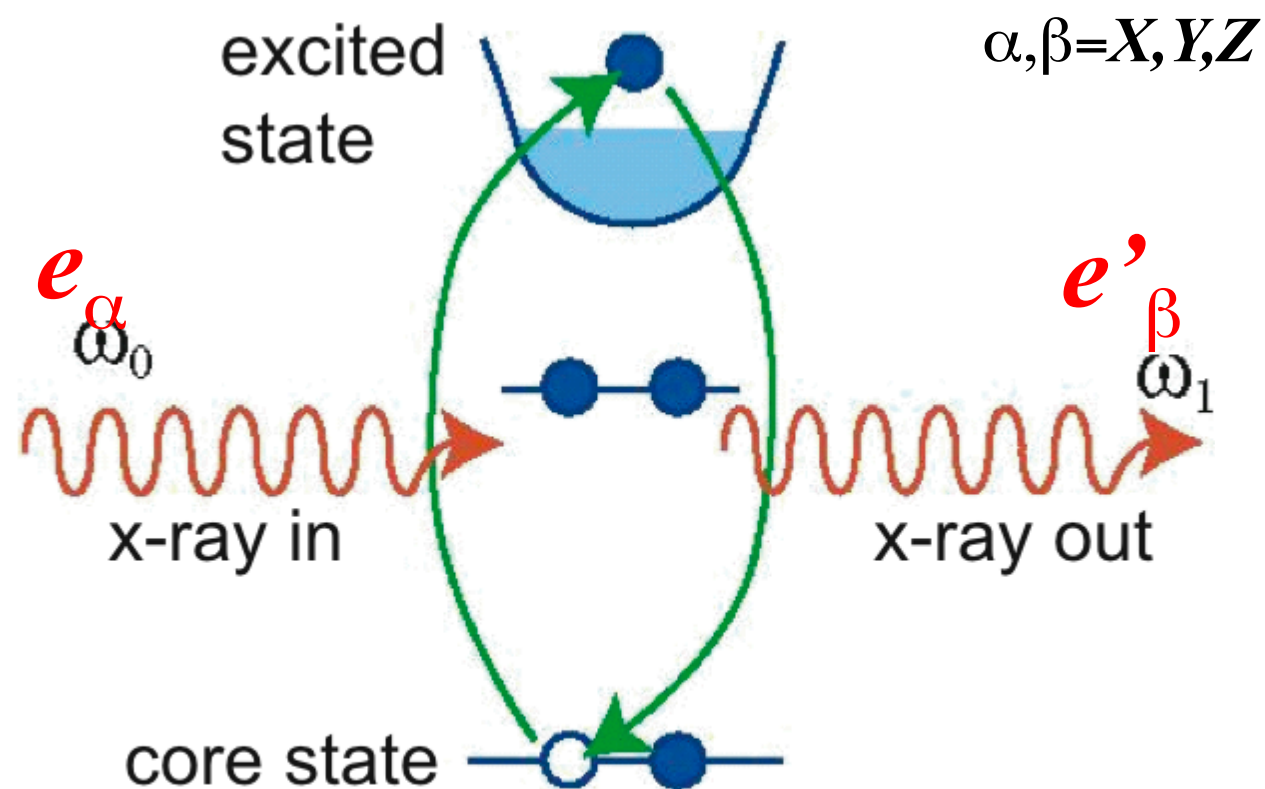
Dipole transition (E1)

X-ray absorption intensity

$$I \propto |\langle \phi_n | \vec{\epsilon} \cdot \vec{r} | \phi_i \rangle|^2$$

Resonance scattering

Second-order process



ray absorption + X ray emission
in one coherent quantum process.

$$I \propto \left| \frac{\langle \phi_f | \vec{\mathcal{E}}^* \cdot \vec{r} | \phi_n \rangle \langle \phi_n | \vec{\mathcal{E}} \cdot \vec{r} | \phi_i \rangle}{\omega - E_n + E_i + i\Gamma/2} \right|^2$$

What does RIXS measure?

Correlation functions

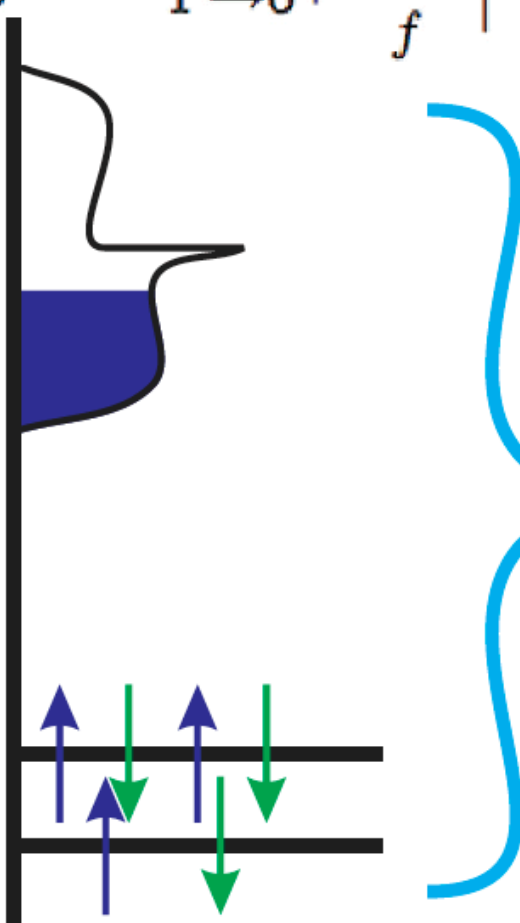
Experiments measure correlation functions

Ex: Neutron and x-ray measure spin and density correlation functions, respectively.

$$S_s(q, \omega) = \int dr dt \langle S^+(r, t) S^-(0, 0) \rangle \quad S_\rho(q, \omega) = \int dr dt \langle \rho(r, t) \rho(0, 0) \rangle$$

$$S_s(q, \omega) = \sum_f |\langle f | S | i \rangle|^2 \delta(E_i - E_f + \hbar\omega)$$

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$


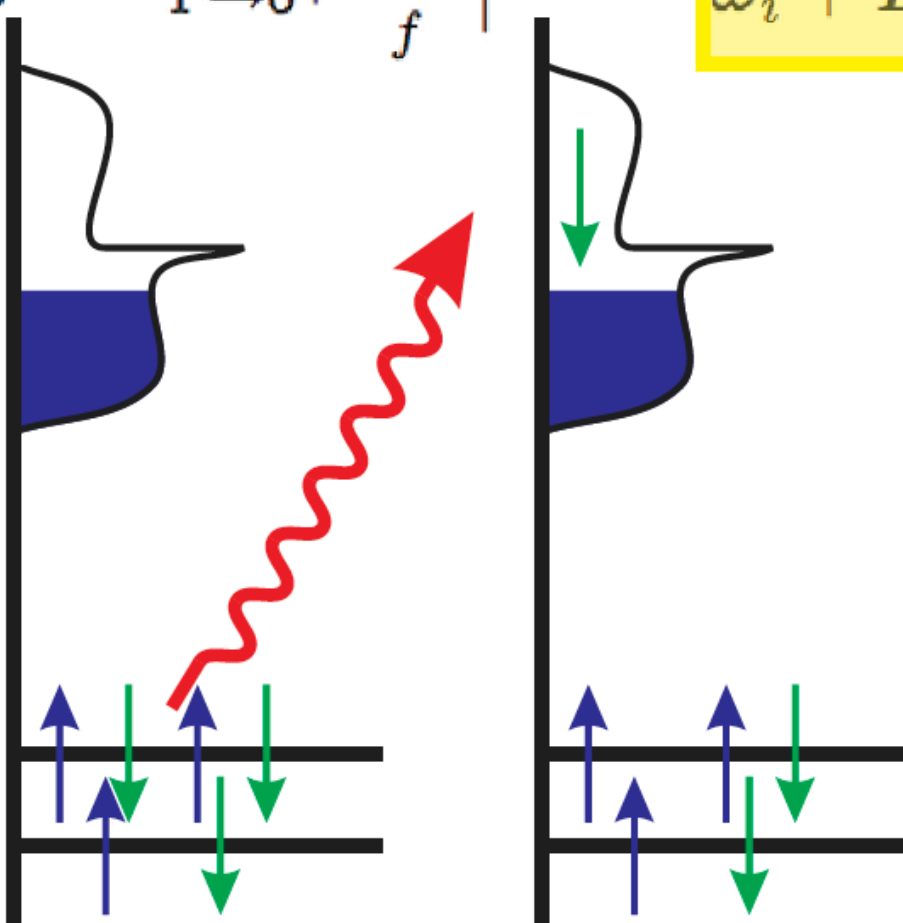
The diagram illustrates the RIXS process. On the left, a vertical line represents the energy axis. A blue shaded region indicates the initial state energy distribution. Below it, two horizontal lines represent the final state energy levels. Green arrows point upwards from the lower level to the upper level, representing the absorption of an incident photon. Blue arrows point downwards from the upper level to the lower level, representing the emission of a scattered photon. A large blue bracket connects the initial state energy distribution to the final state energy levels, indicating the energy transfer process. A blue circle highlights the term $|i\rangle$ in the equation, which represents the initial state of the system.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$

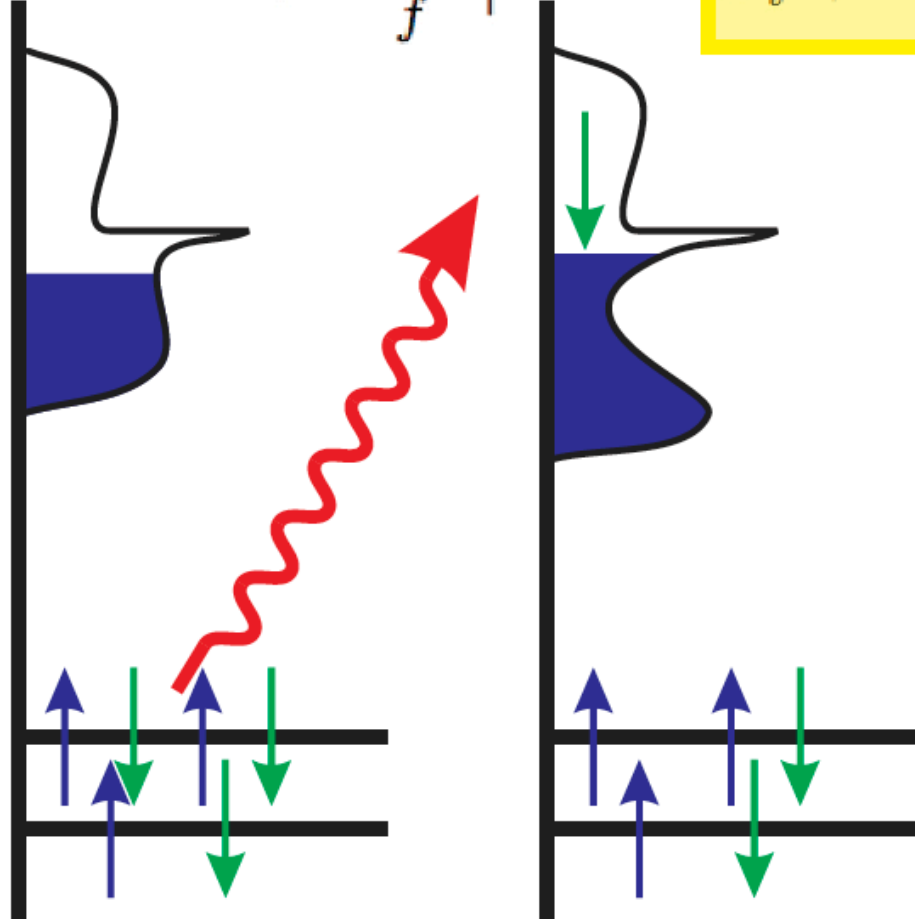
The diagram illustrates the RIXS process. It shows two electronic band structures, one on the left representing the initial state $|i\rangle$ and one on the right representing the final state $|f\rangle$. Blue arrows indicate electron transitions between bands, while green arrows indicate hole transitions. A red wavy arrow represents the outgoing scattered photon. A red curved arrow points from the T_{ϵ_i} operator in the equation to the initial state band structure.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$


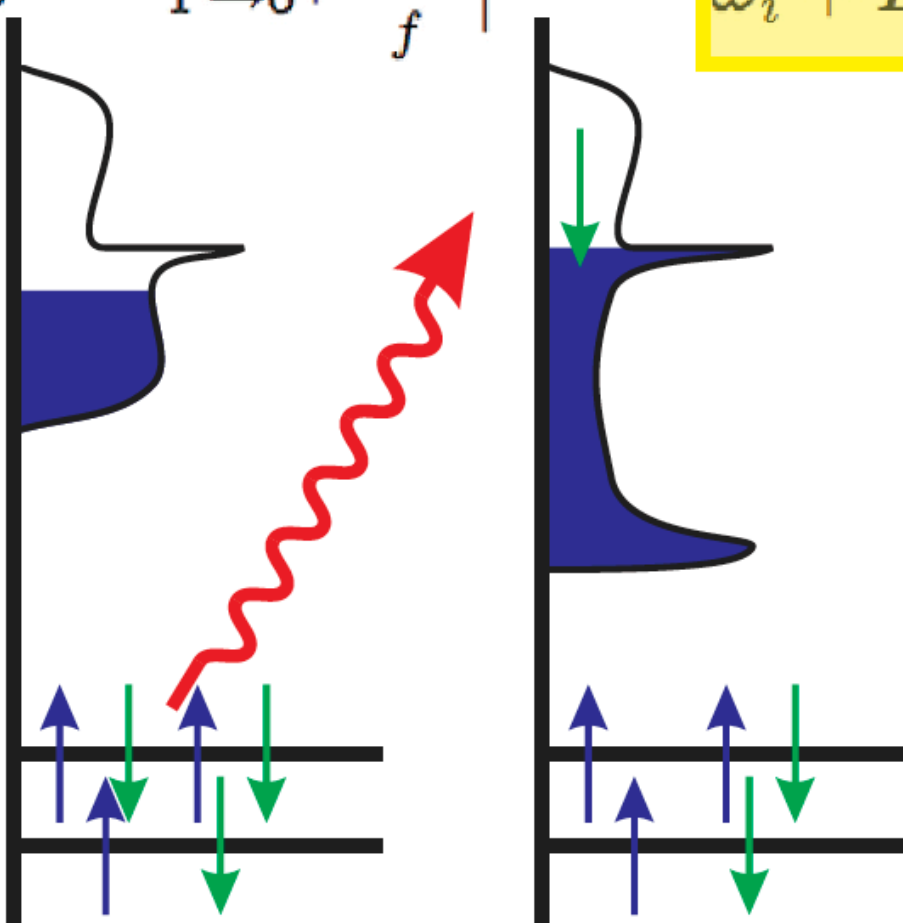
The diagram illustrates the RIXS process. It shows two energy levels, each represented by a vertical line with a blue shaded region at the top. The left energy level has a red wavy arrow pointing upwards, indicating an incoming photon. The right energy level has a green arrow pointing downwards, indicating an outgoing photon. Below each energy level, there are two horizontal lines representing electronic states. On the left, there are four blue arrows pointing up and four green arrows pointing down. On the right, there are four blue arrows pointing up and four green arrows pointing down. The red wavy arrow and the green arrow are connected by a red wavy line, representing the exchange of energy between the two energy levels.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$


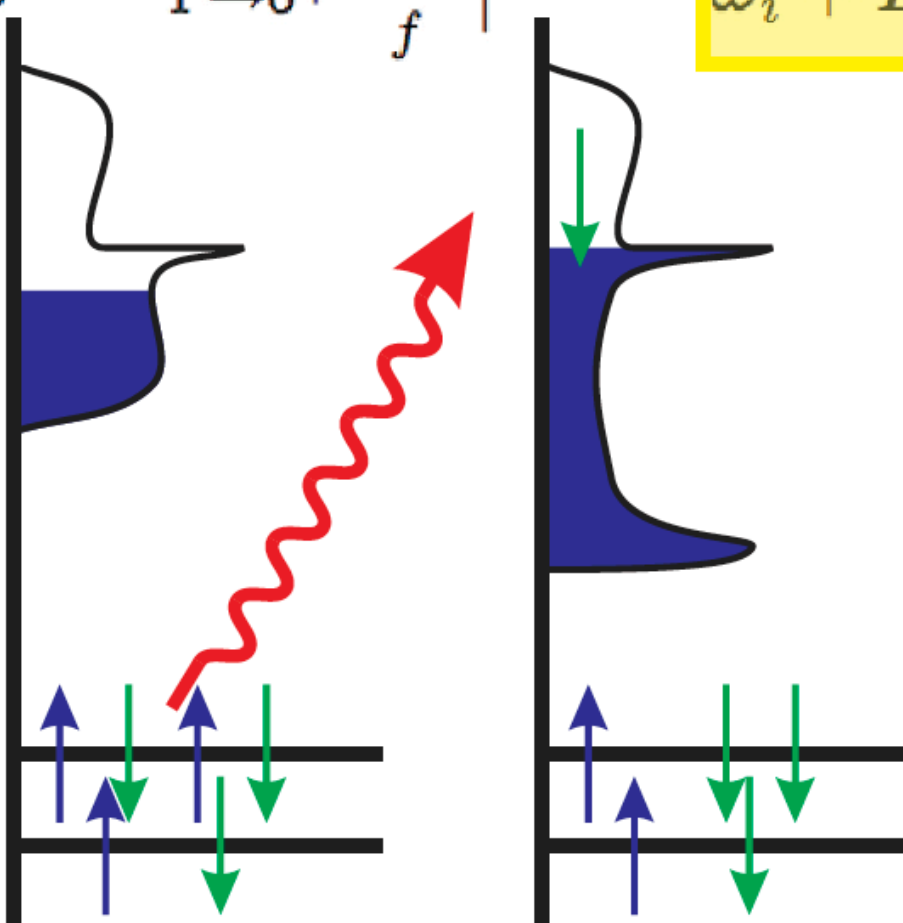
The diagram illustrates the RIXS process. It shows two vertical energy levels, each with a blue shaded region representing the core level and a black line representing the valence level. Below the valence level, there are two horizontal lines representing electronic states, with blue arrows pointing up and green arrows pointing down. A red wavy arrow points from the valence level of the left system to the valence level of the right system, representing the scattered photon.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$


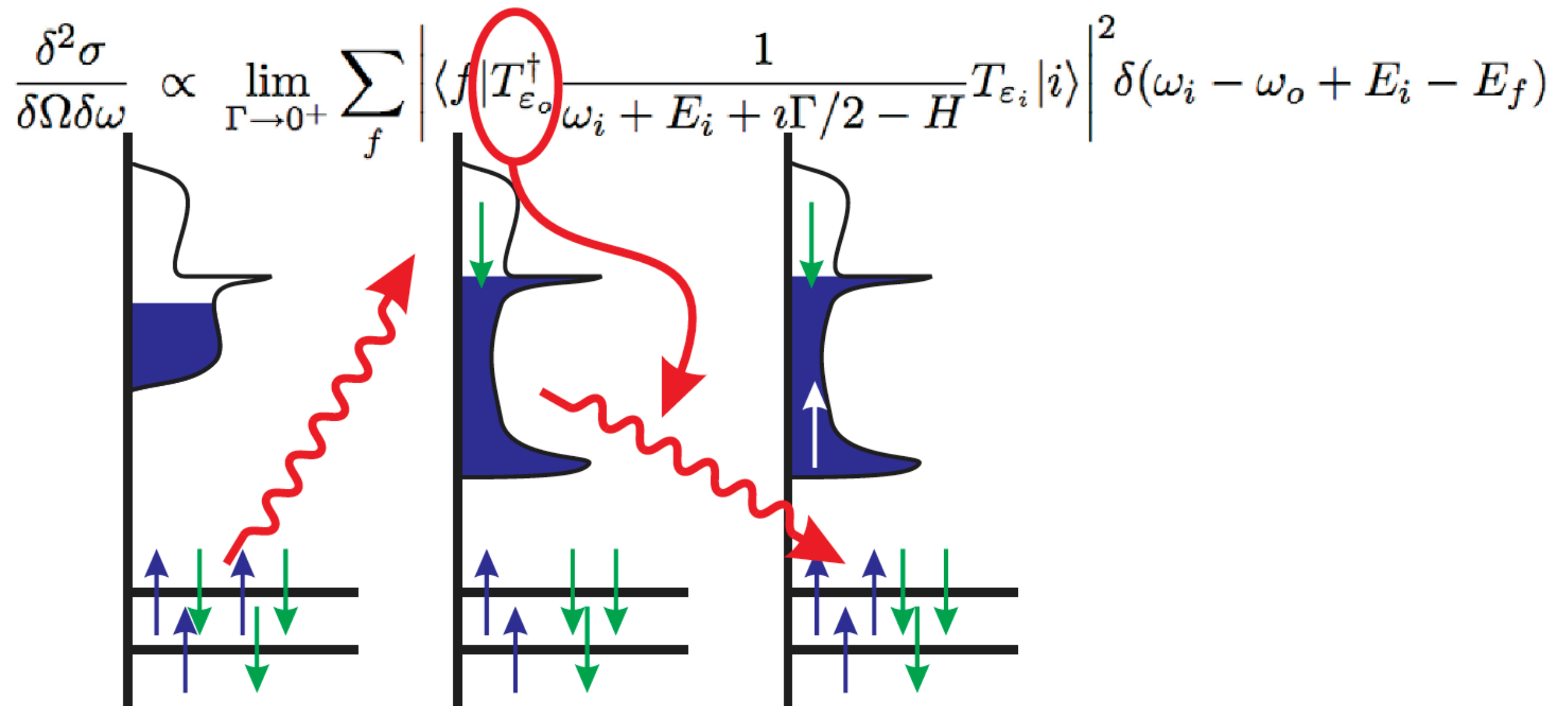
The diagram illustrates the RIXS process. It shows two energy levels, each represented by a vertical black line. The left level has a blue shaded region at the top, and the right level has a blue shaded region at the bottom. A red wavy arrow points from the left level to the right level, indicating the transfer of energy. Below each level, there are two horizontal black lines representing electronic states. Blue arrows point up and green arrows point down, indicating the movement of electrons between these states during the process.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$


The diagram illustrates the RIXS process. It shows two energy levels, each represented by a vertical black line. The left energy level has a blue shaded region at the top, and the right energy level has a blue shaded region at the bottom. A red wavy arrow points from the left energy level to the right energy level, indicating the scattering process. Below each energy level, there are horizontal black lines representing electronic states. On the left, there are four horizontal lines with blue arrows pointing up and green arrows pointing down. On the right, there are four horizontal lines with blue arrows pointing up and green arrows pointing down. The red wavy arrow originates from the bottom of the left energy level and points towards the top of the right energy level.

RIXS process



RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$

The diagram illustrates the RIXS process through four stages, each showing energy levels and electron transitions:

- Stage 1:** Initial state with two energy levels. The lower level has two electrons (blue up, green down). The upper level is empty. A red wavy arrow indicates an incoming photon.
- Stage 2:** An electron from the lower level is excited to the upper level by the incoming photon. The lower level now has one electron (blue up), and the upper level has one electron (green down).
- Stage 3:** An electron from the upper level is scattered back to the lower level by an outgoing photon (red wavy arrow). The lower level now has two electrons (blue up, green down), and the upper level is empty.
- Stage 4:** Final state with two energy levels. The lower level has two electrons (blue up, green down). The upper level is empty. A red wavy arrow indicates an outgoing photon.

RIXS process

$$\frac{\delta^2 \sigma}{\delta \Omega \delta \omega} \propto \lim_{\Gamma \rightarrow 0^+} \sum_f \left| \langle f | T_{\epsilon_o}^\dagger \frac{R_{\omega_i}^{\epsilon_i \epsilon_o}}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$

$$R_{\omega_i}^{\epsilon_i \epsilon_o} = T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i}$$



antisymmetric

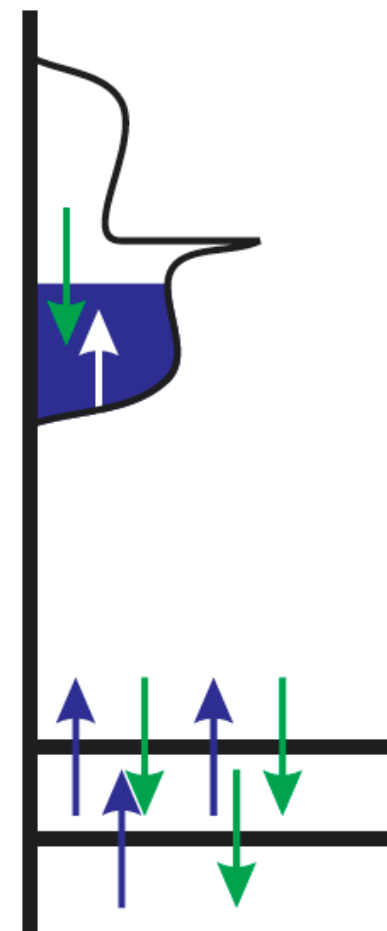
$$(\epsilon_\alpha \epsilon'_\beta - \epsilon_\beta \epsilon'_\alpha)$$

symmetric

$$(\epsilon_\alpha \epsilon'_\beta + \epsilon_\beta \epsilon'_\alpha)$$

dipole

quadrupole



courtesy of M. Haverkort

RIXS operators for t_{2g} orbital systems

unquenched orbital angular momentum

“fast collision approximation”

$$R_{\omega_i}^{\epsilon_i \epsilon_o} = T_{\epsilon_o}^\dagger \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\epsilon_i} \quad \rightarrow \quad R \propto D^\dagger D = \frac{1}{3}(R_Q + i R_M)$$

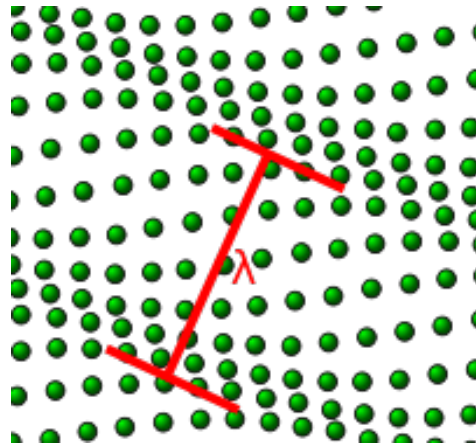
c number

$$R_Q = \sum_{\alpha} \epsilon_{\alpha} \epsilon'_{\alpha} Q_{\alpha\alpha} - \frac{1}{2} \sum_{\alpha > \beta} (\epsilon_{\alpha} \epsilon'_{\beta} + \epsilon_{\beta} \epsilon'_{\alpha}) Q_{\alpha\beta}$$

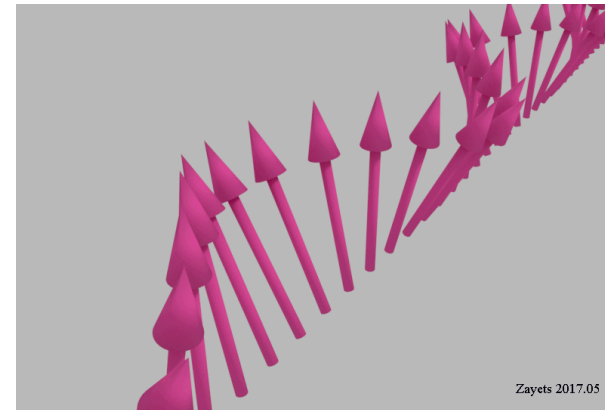
$$R_M = \frac{1}{2} (\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}') \cdot \mathbf{N}.$$

Q_{zz} (quadrupole)	L_3 edge	L_2 edge
$d^1, (-1)d^5$	$-2L_z^2 + 2L_z S_z$	$-L_z^2 - 2L_z S_z$
$d^2, (-1)d^4$	$2L_z^2 + L_z S_z$	$L_z^2 - L_z S_z$
Q_{xy} (quadrupole)	L_3 edge	L_2 edge
$d^1, (-1)d^5$	$-2L_x L_y - 2L_y L_x + 2L_x S_y + 2L_y S_x$	$-L_x L_y - L_y L_x - 2L_x S_y - 2L_y S_x$
$d^2, (-1)d^4$	$2L_x L_y + 2L_y L_x + L_x S_y + L_y S_x$	$L_x L_y + L_y L_x - L_x S_y - L_y S_x$
N_z (magnetic)	L_3 edge	L_2 edge
d^1, d^5	$2L_z - 4S_z + 8L_z^2 S_z - 2L_z(\mathbf{L} \cdot \mathbf{S}) - 2(\mathbf{L} \cdot \mathbf{S})L_z$	$L_z + 4S_z - 8L_z^2 S_z + 2L_z(\mathbf{L} \cdot \mathbf{S}) + 2(\mathbf{L} \cdot \mathbf{S})L_z$
d^2, d^4	$2L_z - 4L_z^2 S_z + L_z(\mathbf{L} \cdot \mathbf{S}) + (\mathbf{L} \cdot \mathbf{S})L_z$	$L_z + 4L_z^2 S_z - L_z(\mathbf{L} \cdot \mathbf{S}) - (\mathbf{L} \cdot \mathbf{S})L_z$
d^3	$(4/3)S_z$	$-(4/3)S_z$

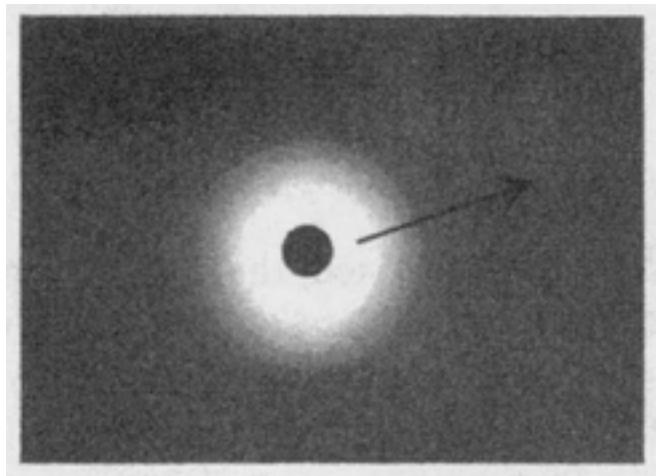
Elementary excitations in solids



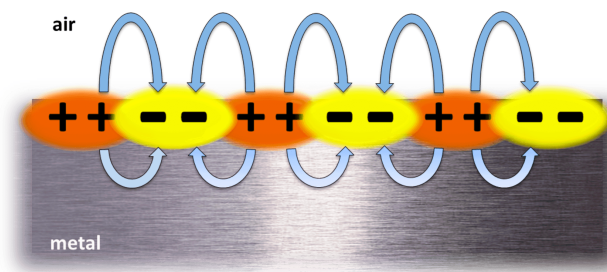
phonon



magnon

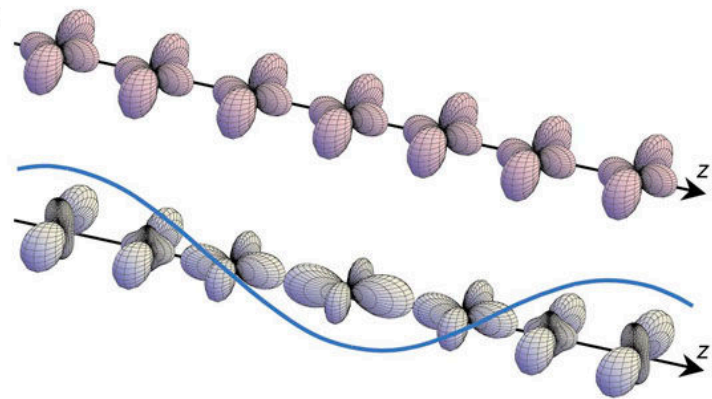


quasi-electron

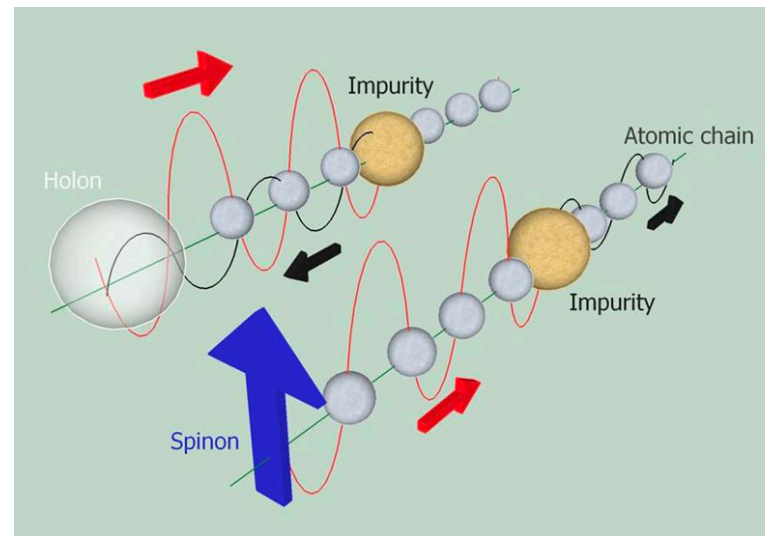


plasmon

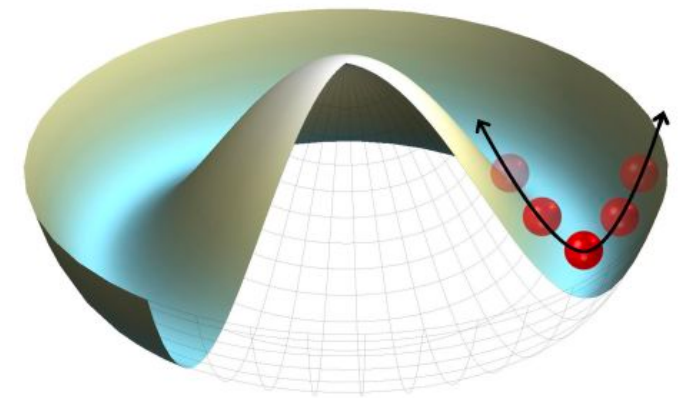
And more exotic particles..



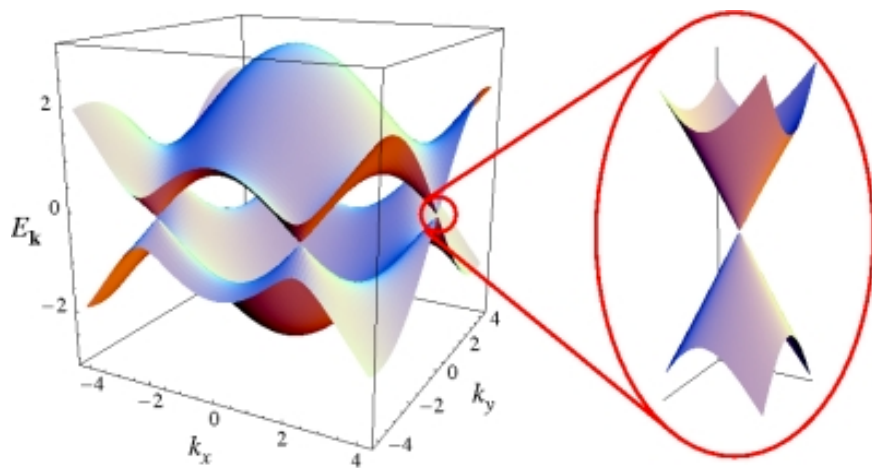
orbiton



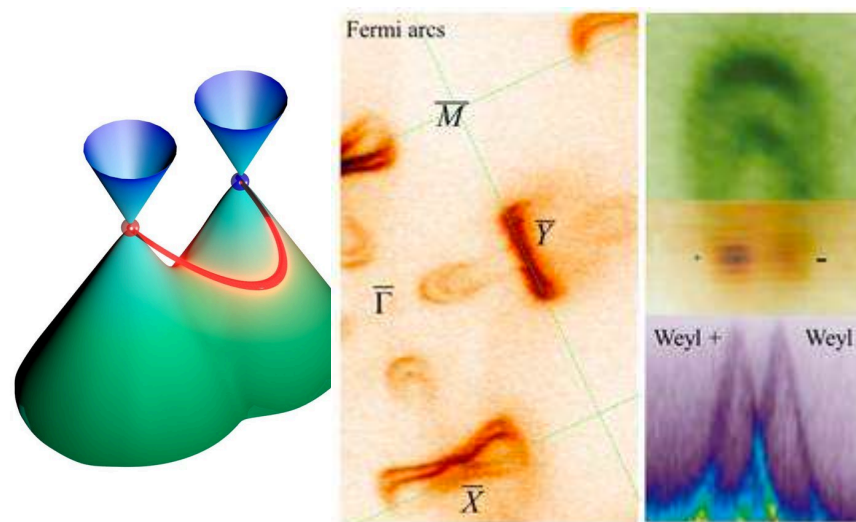
Spinon and holon



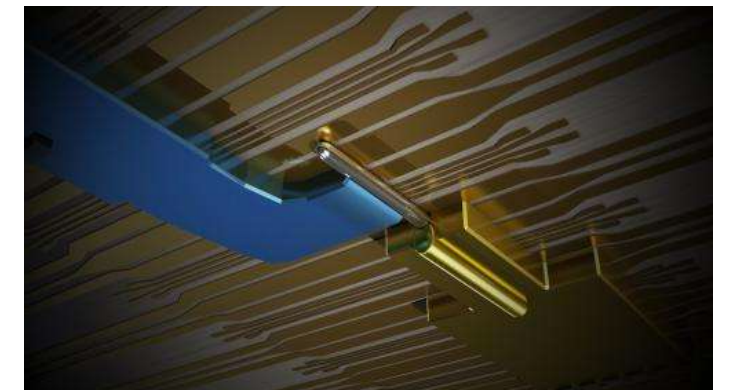
Higgs mode



Dirac fermion

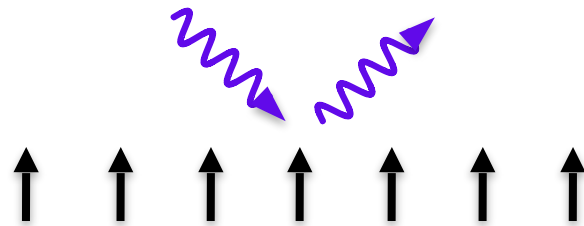


Weyl fermion



Majonara fermion

Spin waves (or magnons)



Spin waves (or magnons)



Heisenberg magnet:

$$\begin{aligned} H &= S_z^i S_z^j + S_x^i S_x^j + S_y^i S_y^j \\ &= S_z^i S_z^j + \frac{1}{2}(S_+^i S_-^j + S_-^i S_+^j) \end{aligned}$$

Spin waves (or magnons)



Spin waves (or magnons)



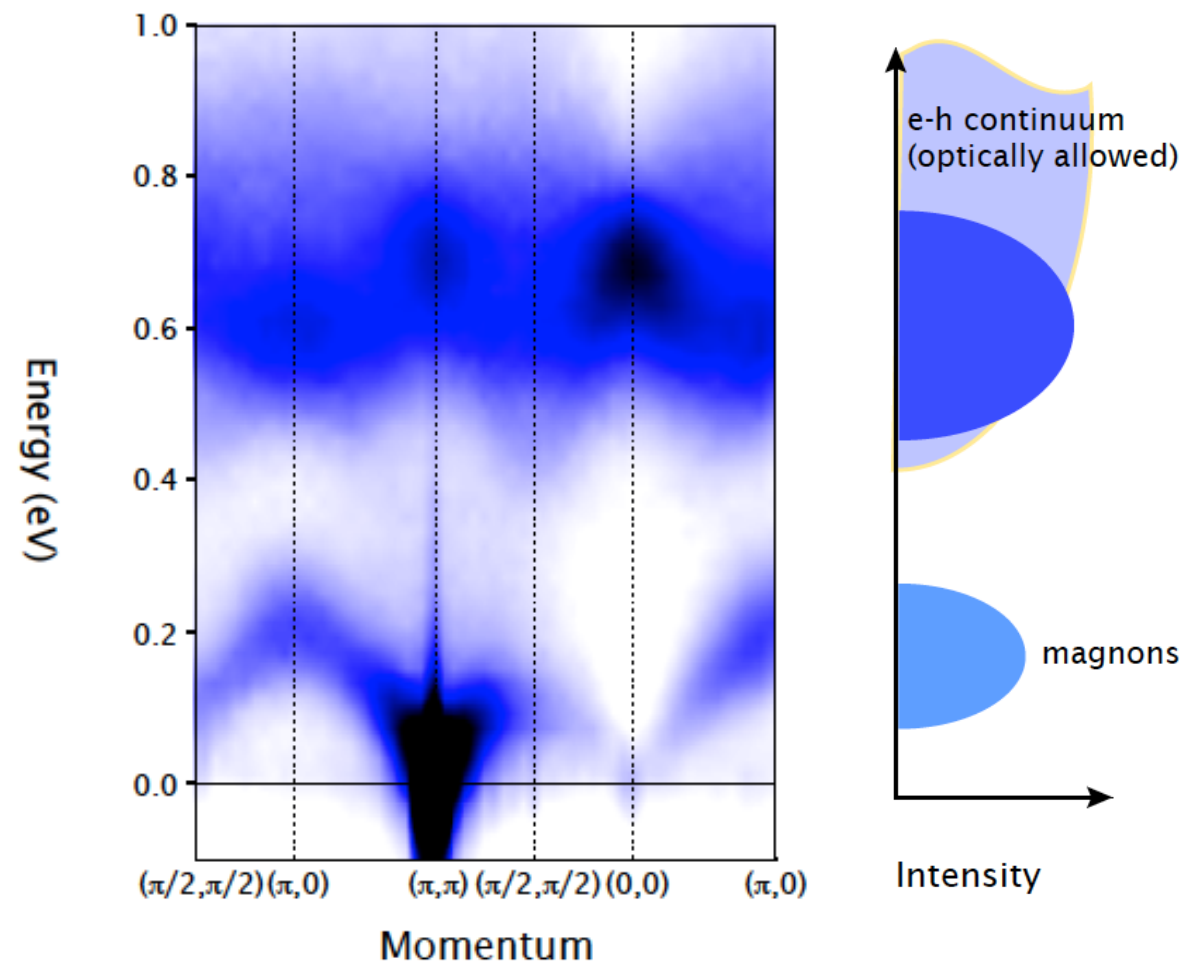
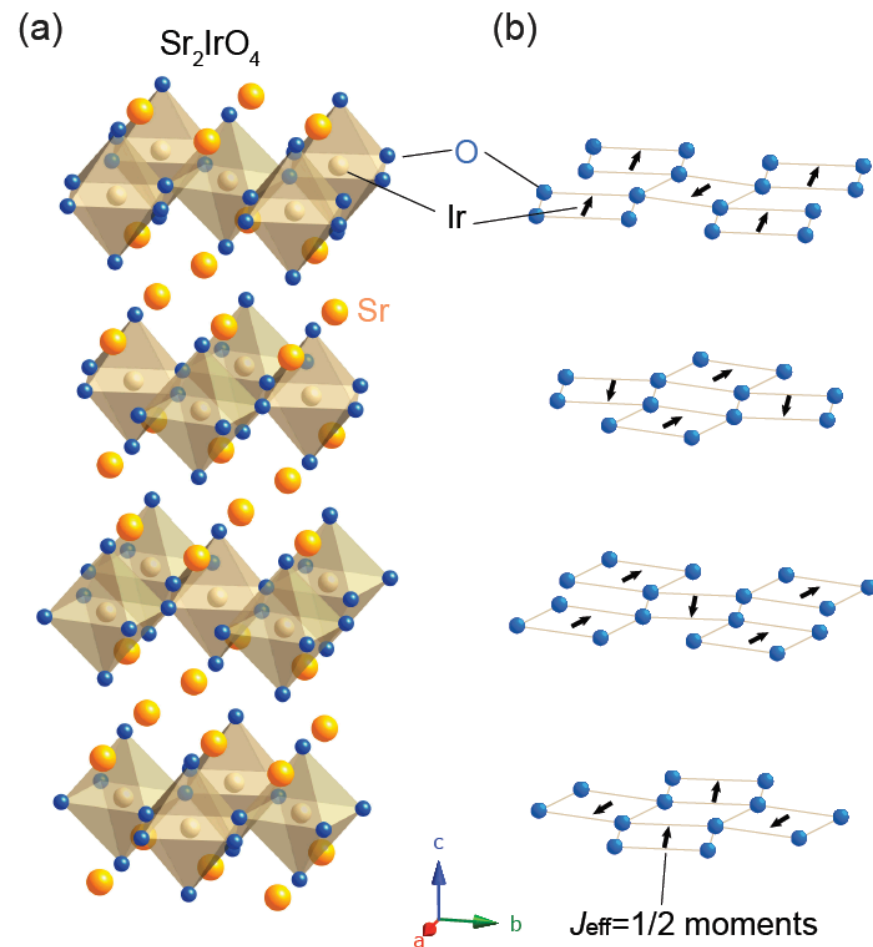
Spin waves (or magnons)



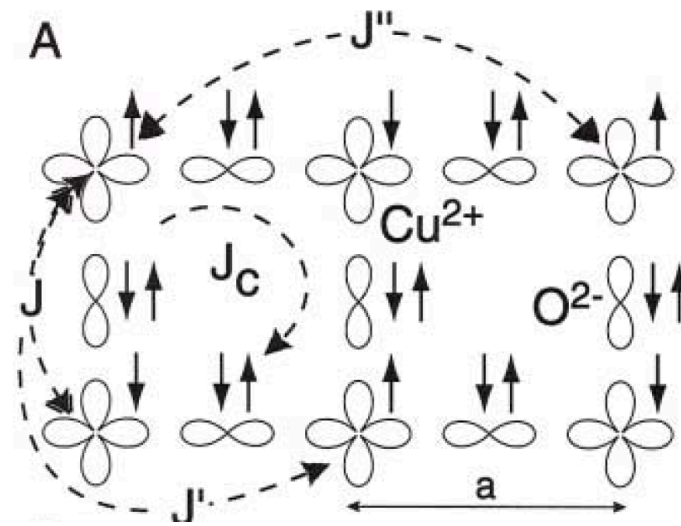
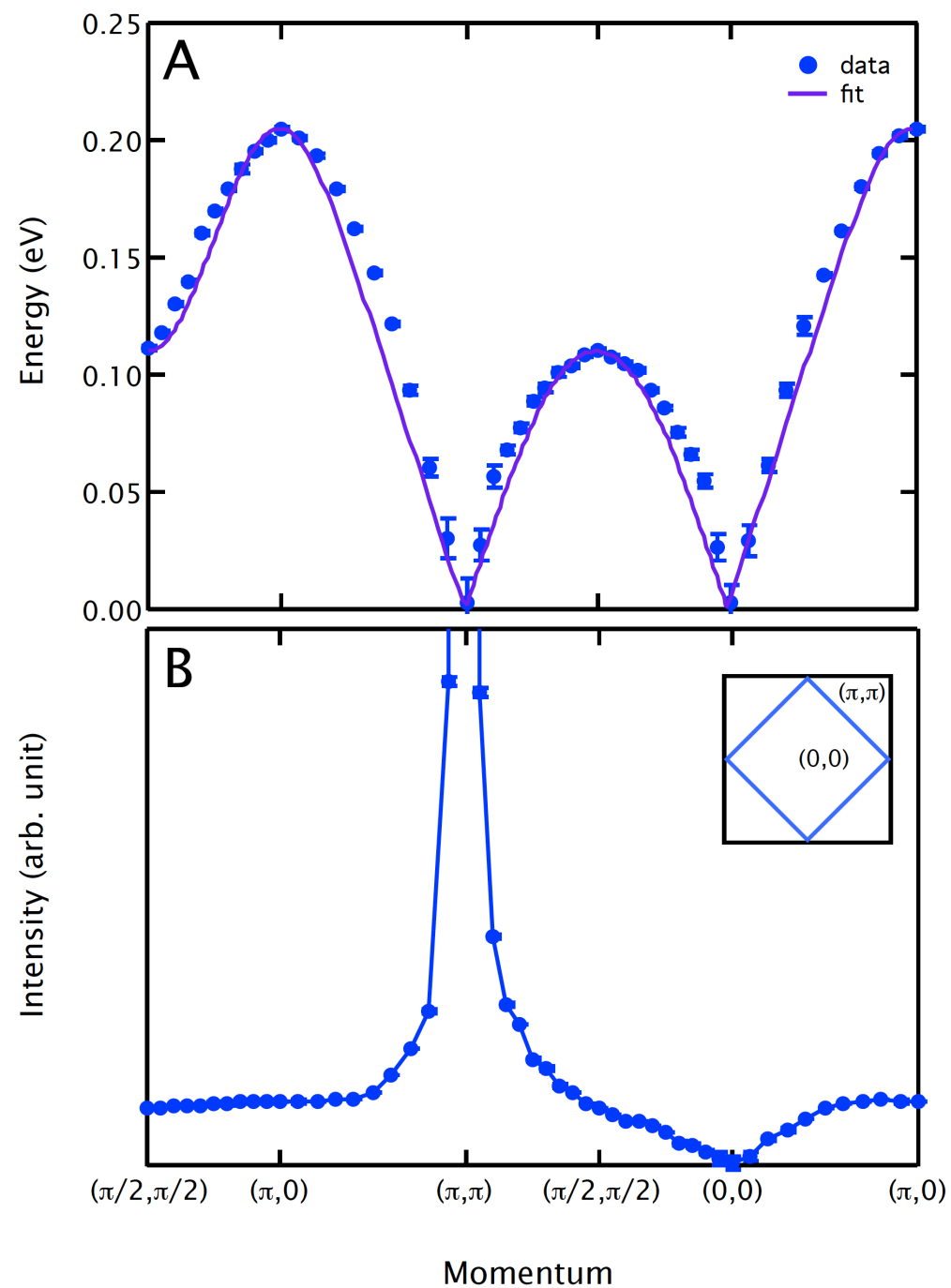
$(r, t) \rightarrow (q, \omega)$

dynamic structure factor $S(q, \omega)$

Magnetic excitations in Sr_2IrO_4



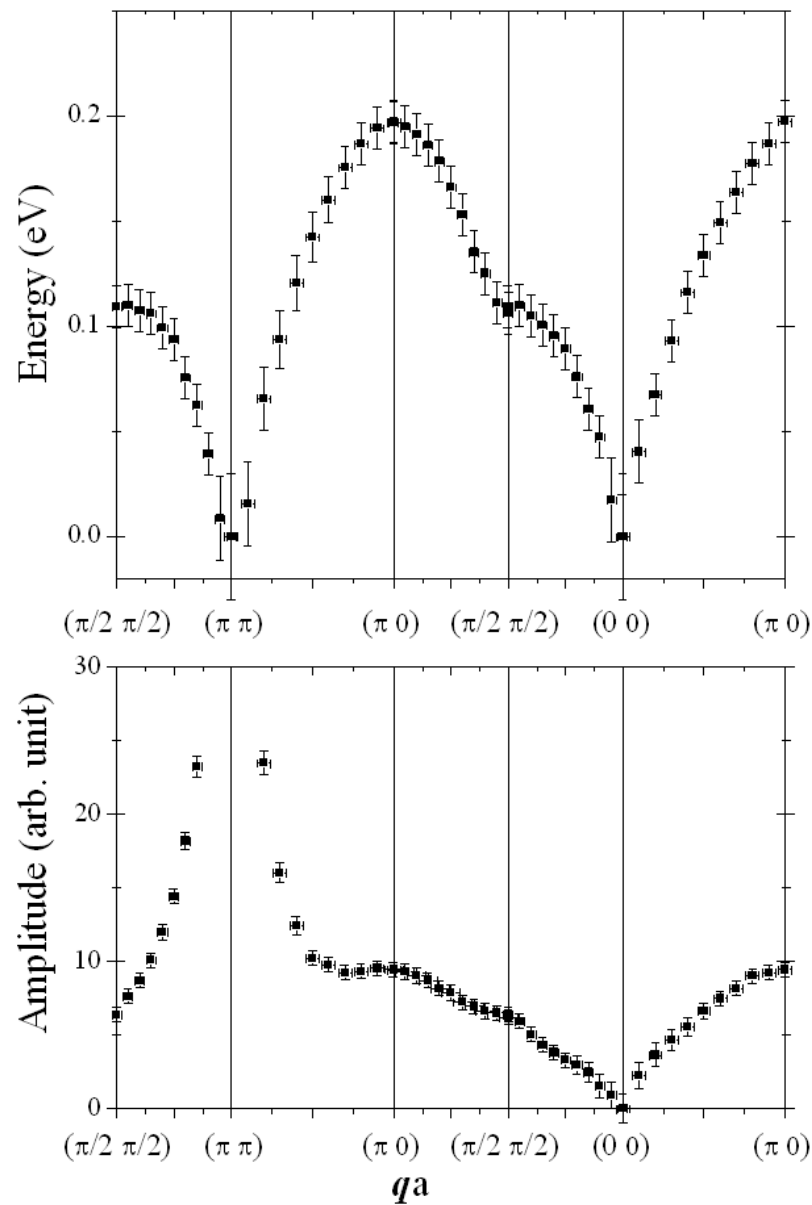
Fit to Heisenberg model



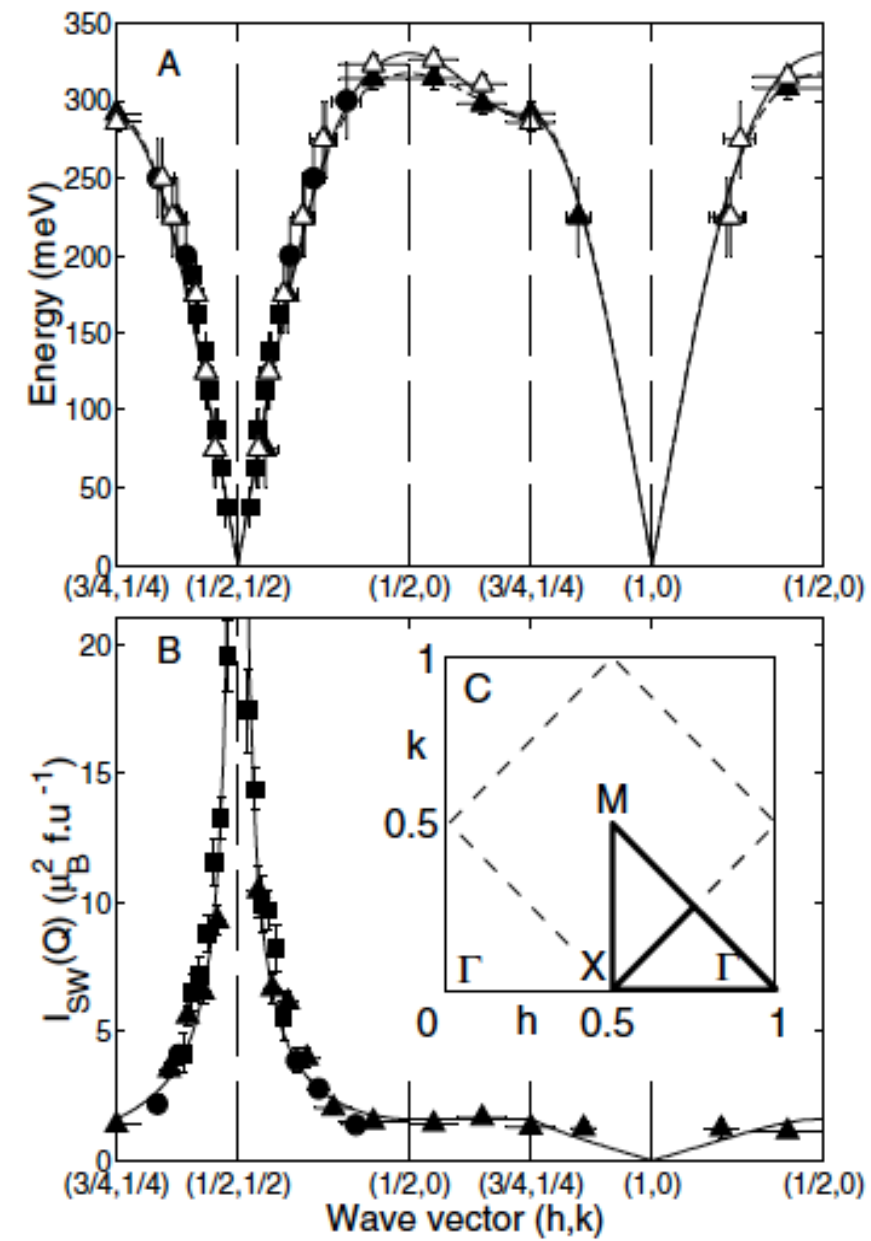
$$\begin{aligned} J &= 60 \\ J' &= -20 \\ J'' &= 15 \\ J_c &= 0 \text{ (suppressed)} \end{aligned}$$

RIXS vs. Neutron

RIXS data on Sr_2IrO_4

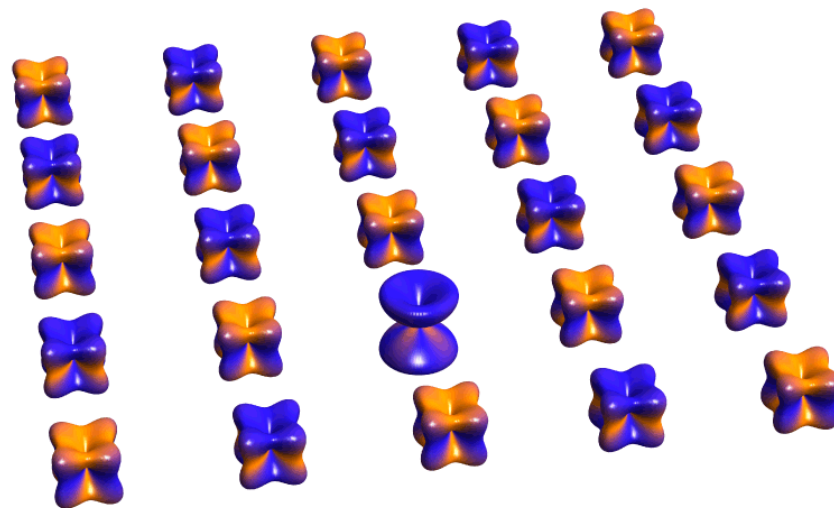
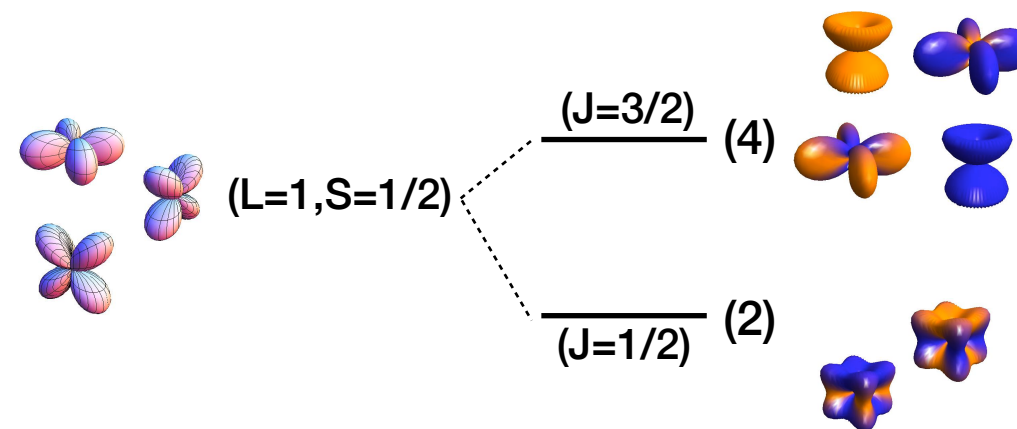


Neutron data on La_2CuO_4

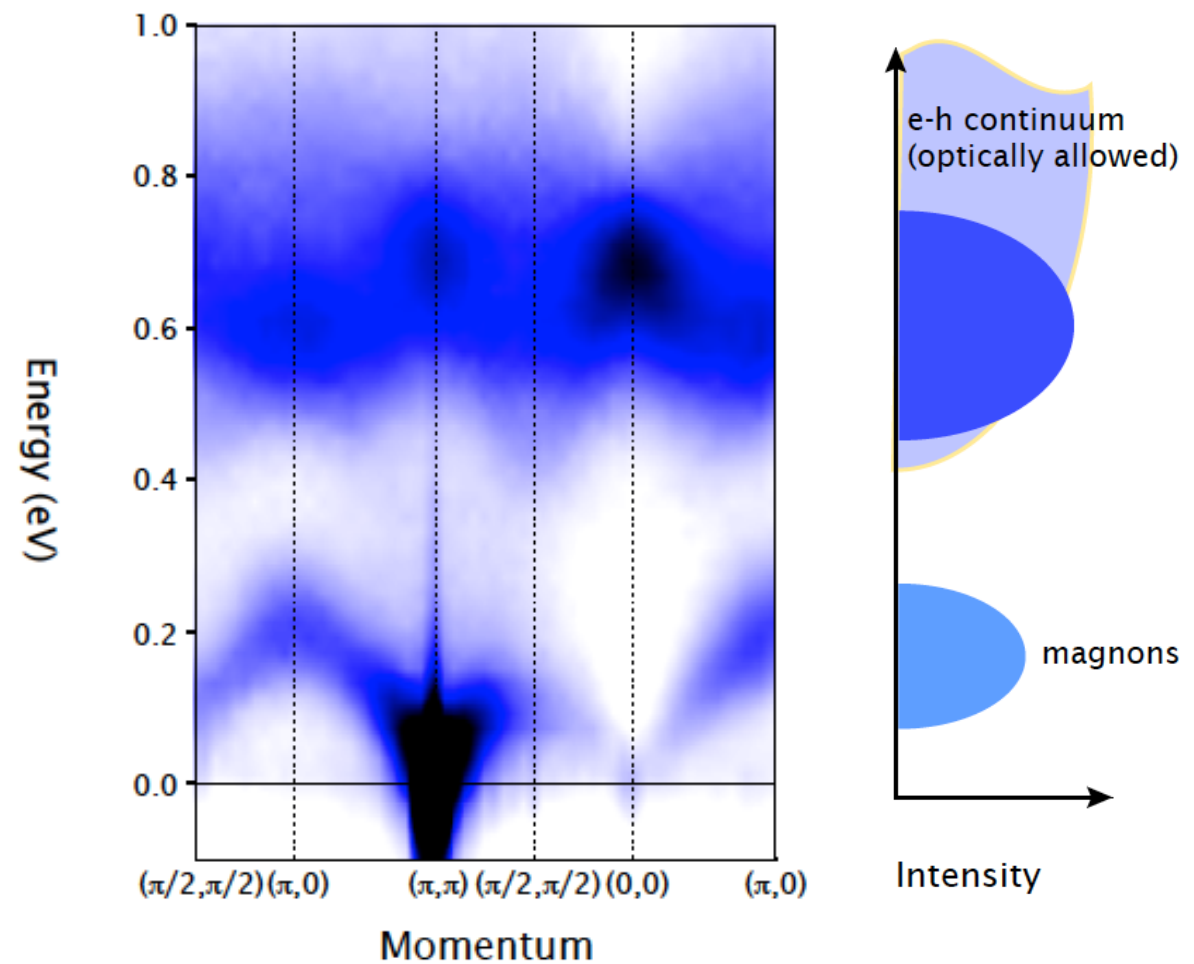
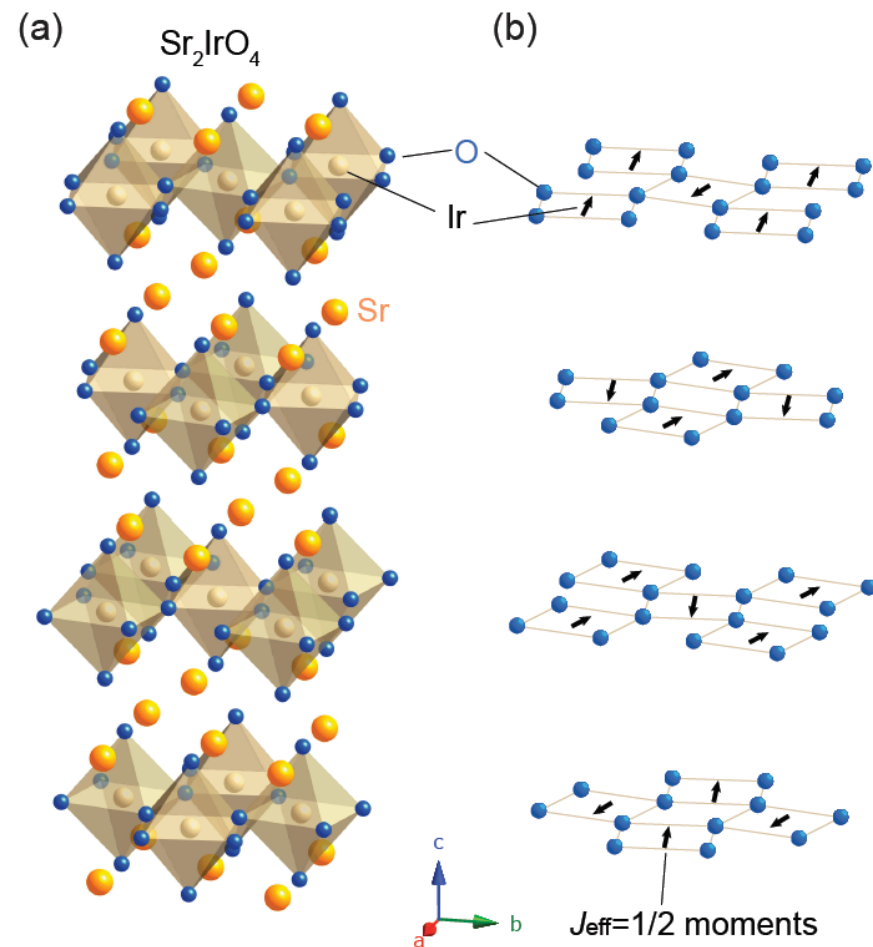


Coldea et al., PRL (2001)

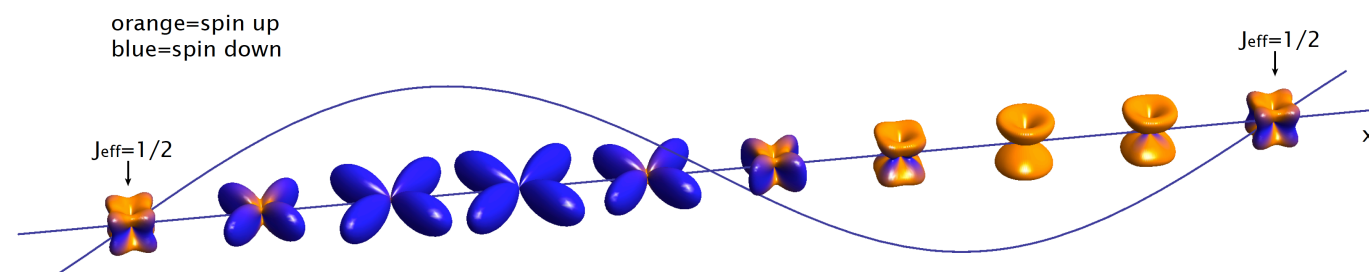
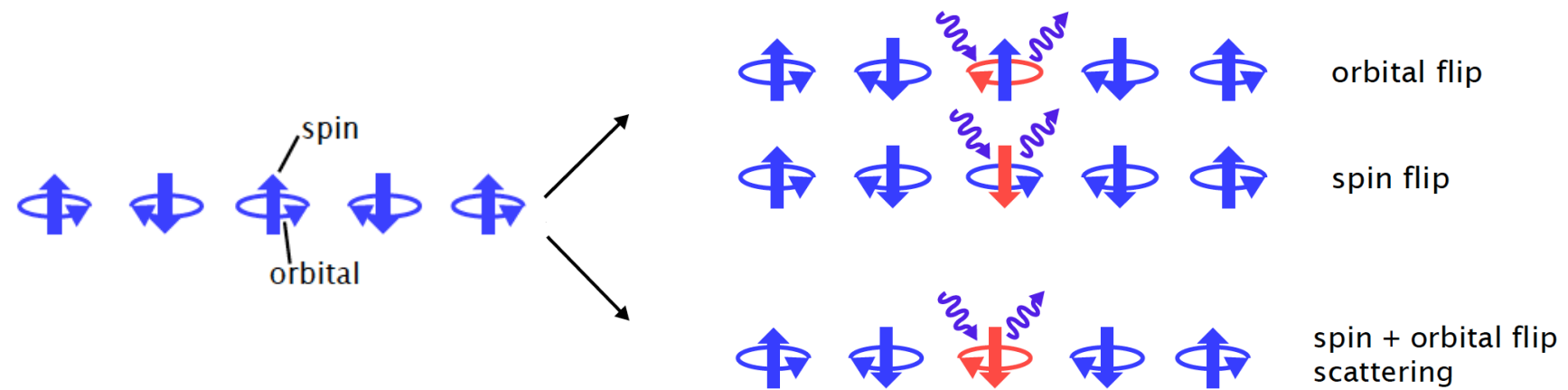
Spin-orbit exciton



Magnetic excitations in Sr_2IrO_4

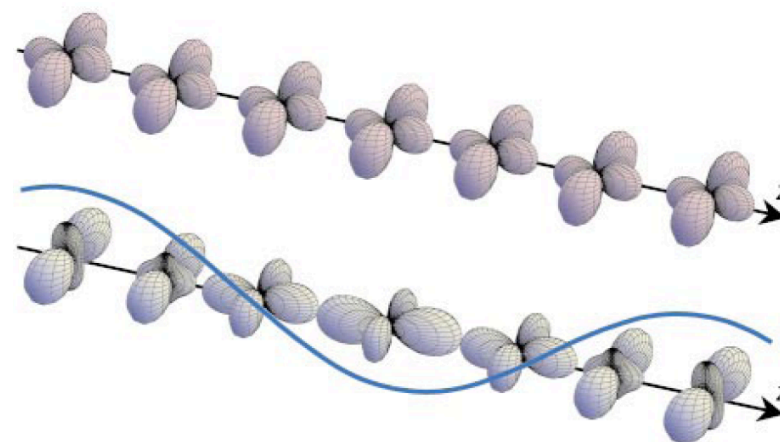


Spin-orbital waves

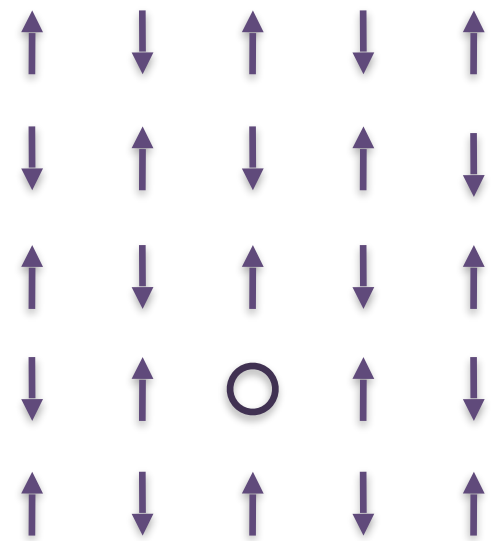


“Orbiton”

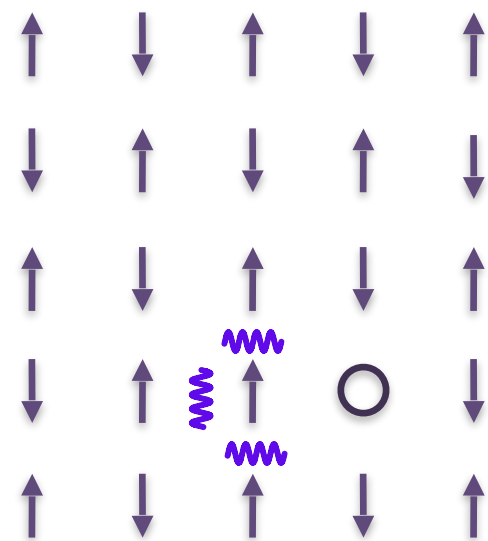
E. Saitoh et al., Nature (2001)



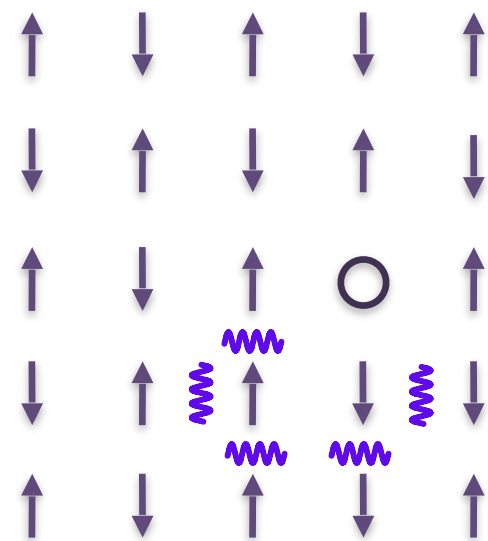
One-hole propagation



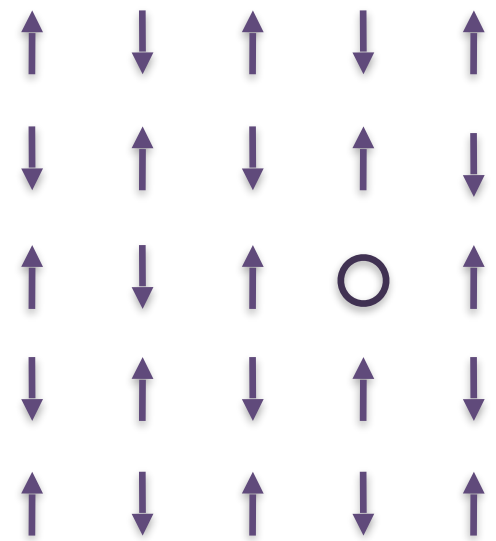
One-hole propagation



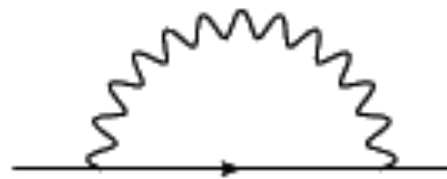
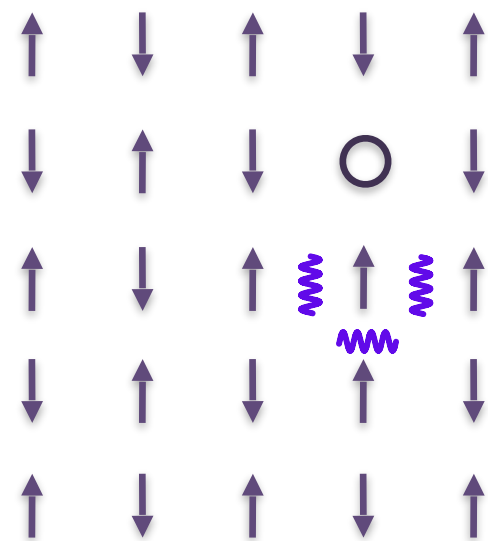
One-hole propagation



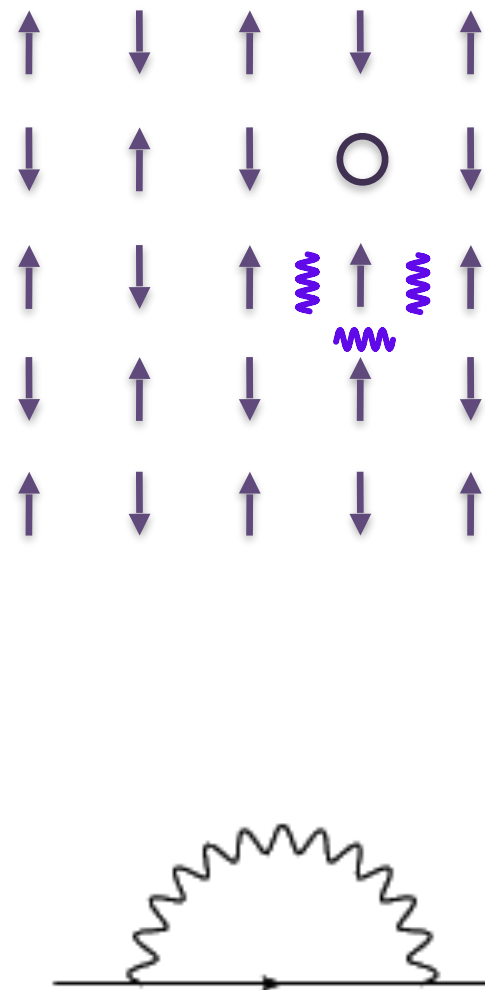
One-hole propagation



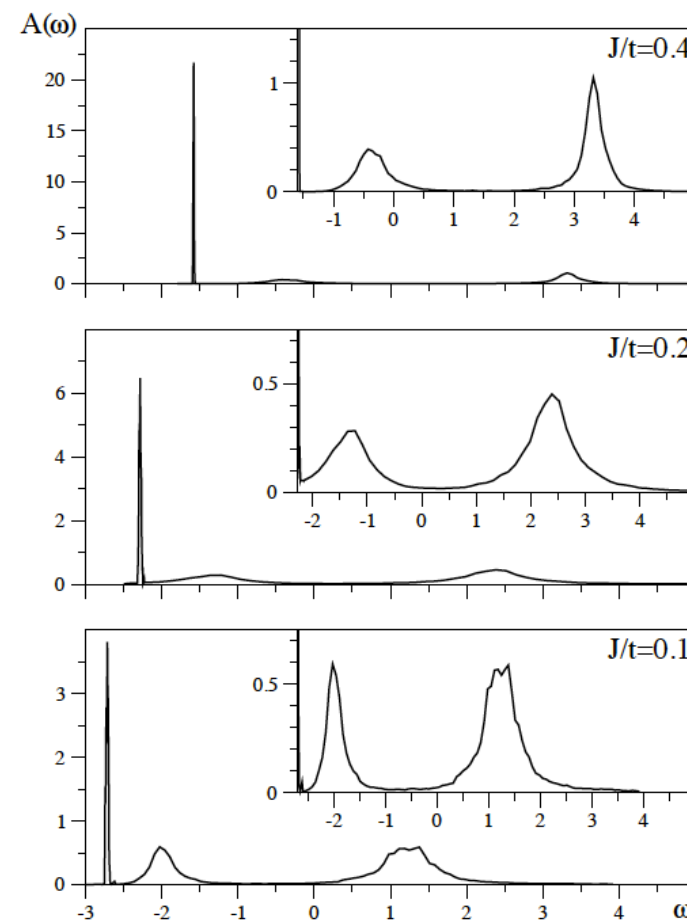
One-hole propagation



One-hole propagation

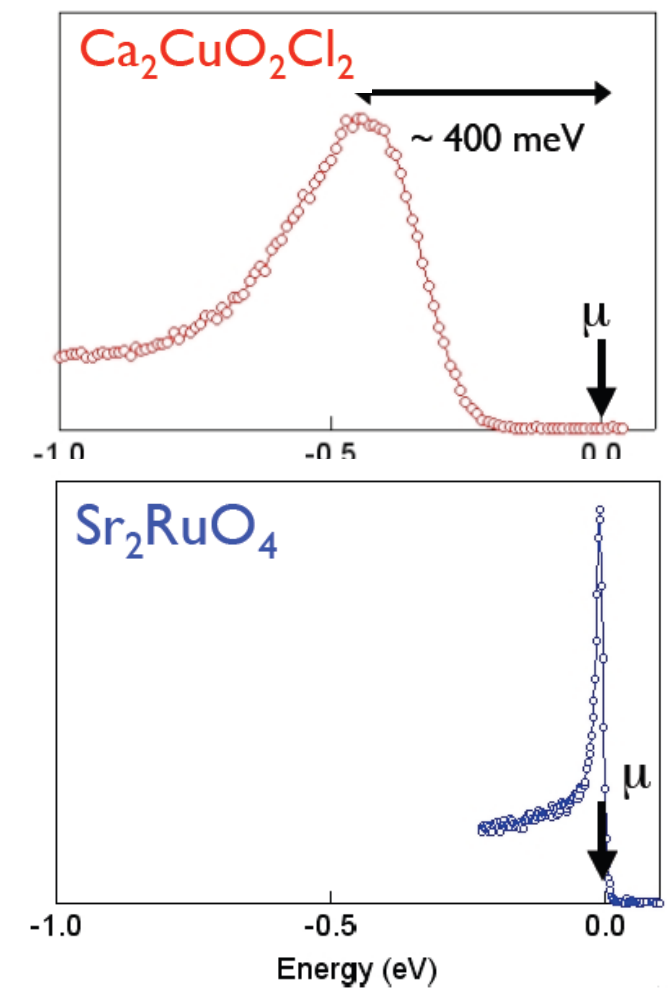


theory (t-J model)



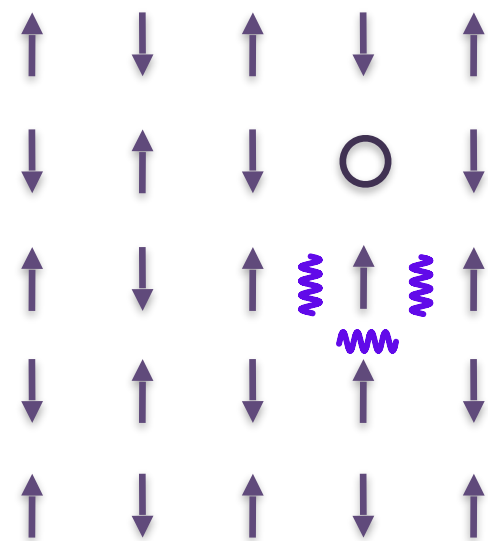
A. S. Mischenko et al. (2001)

ARPES

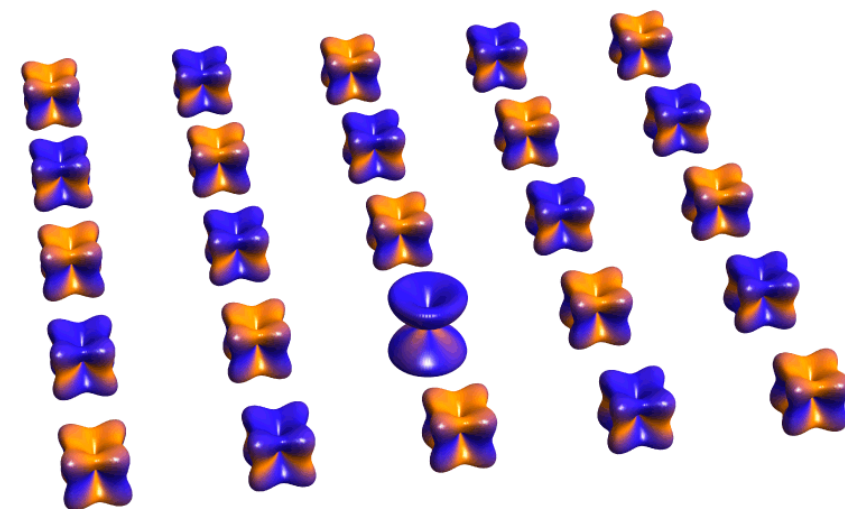


Shen group

One-hole propagation



charge e^- , spin-1/2 fermion

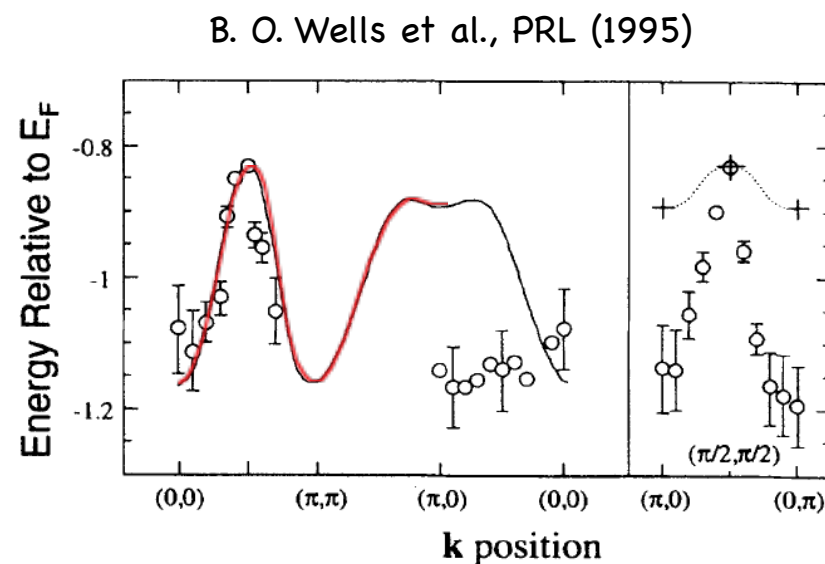


charge neutral, hard-core boson

One-hole propagation

ARPES

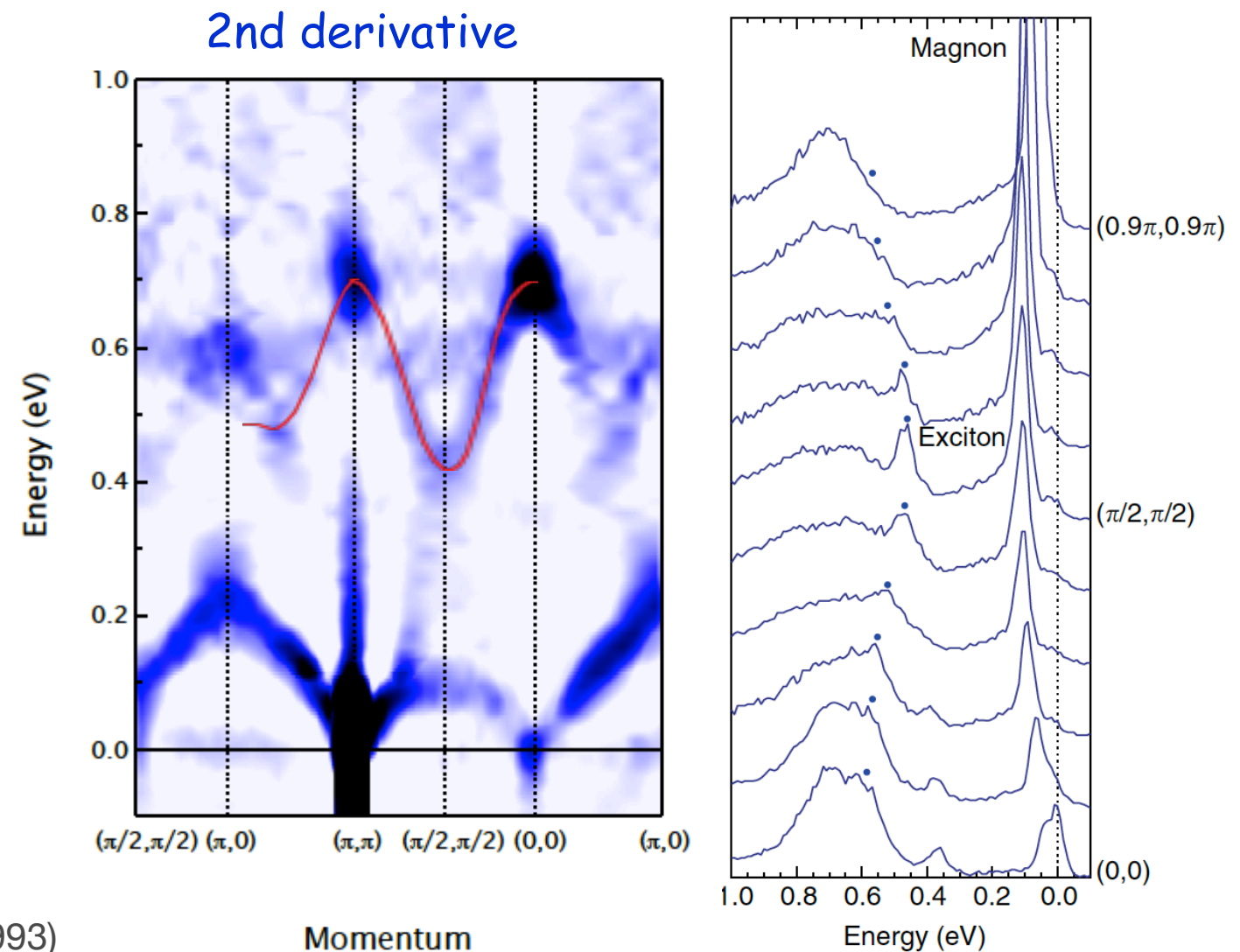
one-hole propagation in $\text{Sr}_2\text{CuO}_2\text{Cl}_2$



Schmitt-Rink, Varma, Ruckenstein, Phys. Rev. Lett. (1993)
Lee, Nagaosa & Wen, Rev. Mod. Phys. (2006)

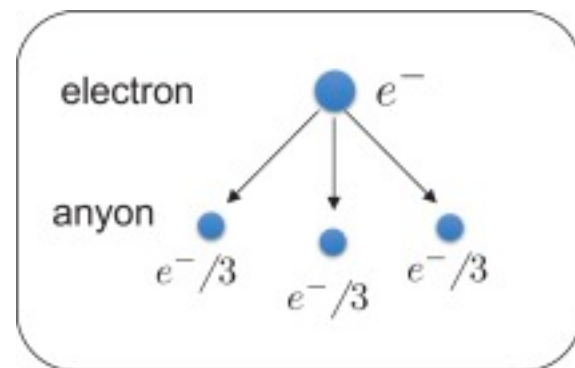
RIXS

one-exciton propagation in Sr_2IrO_4

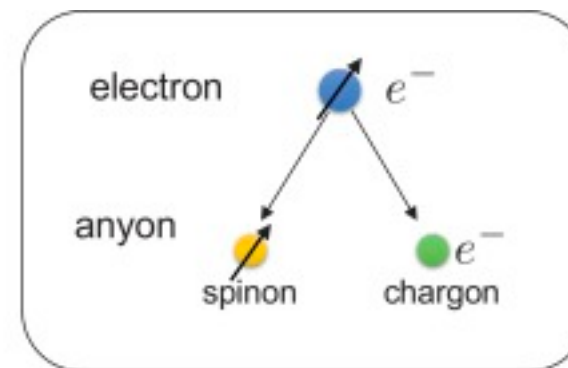


J. Kim & BJK et al. Nature Comm. (2014)

Fractional excitations

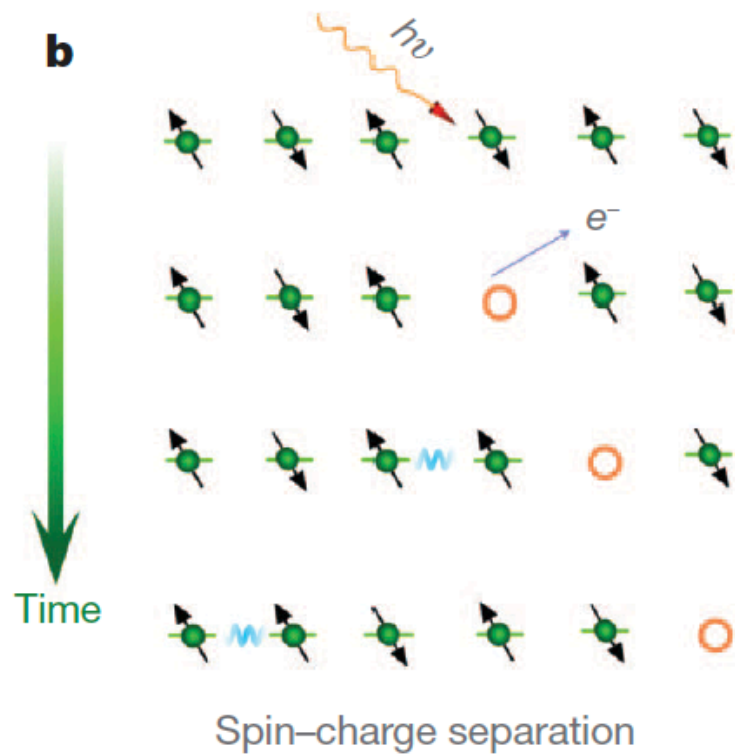


(a) $\nu = 1/3$ fractional quantum Hall

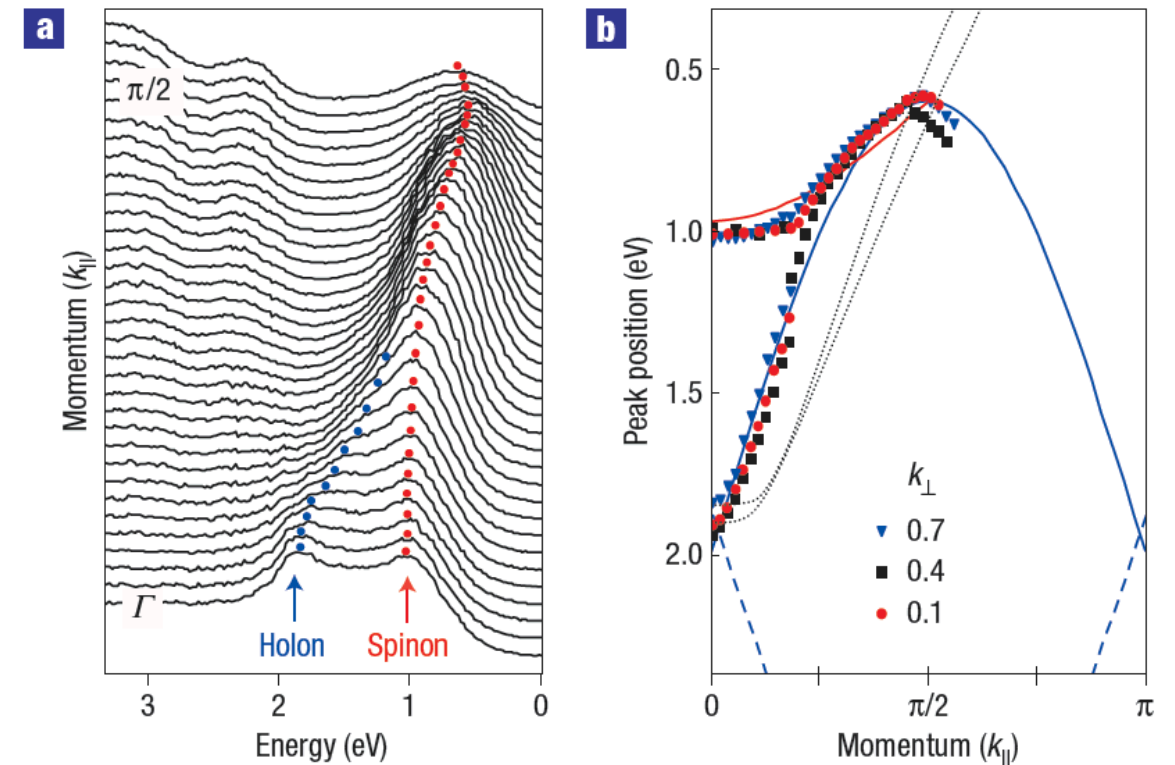


(b) spin-charge separation

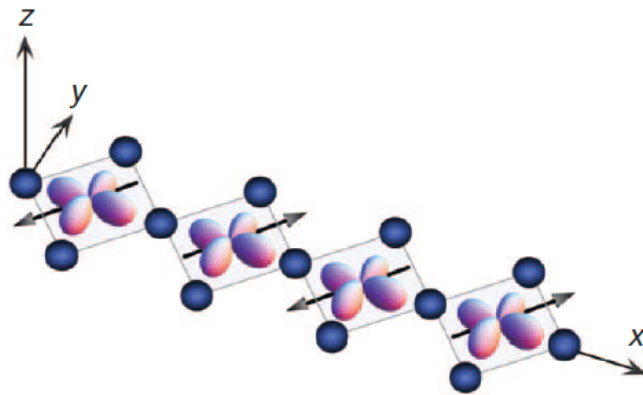
Spin-charge separation



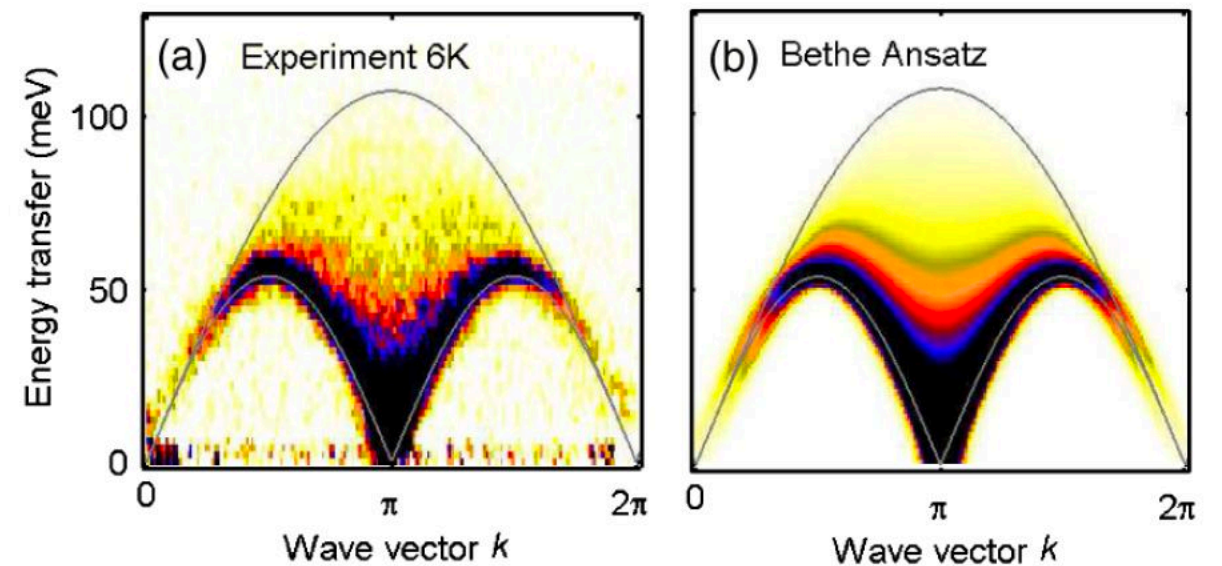
ARPES



1D chain structure in Sr_2CuO_3



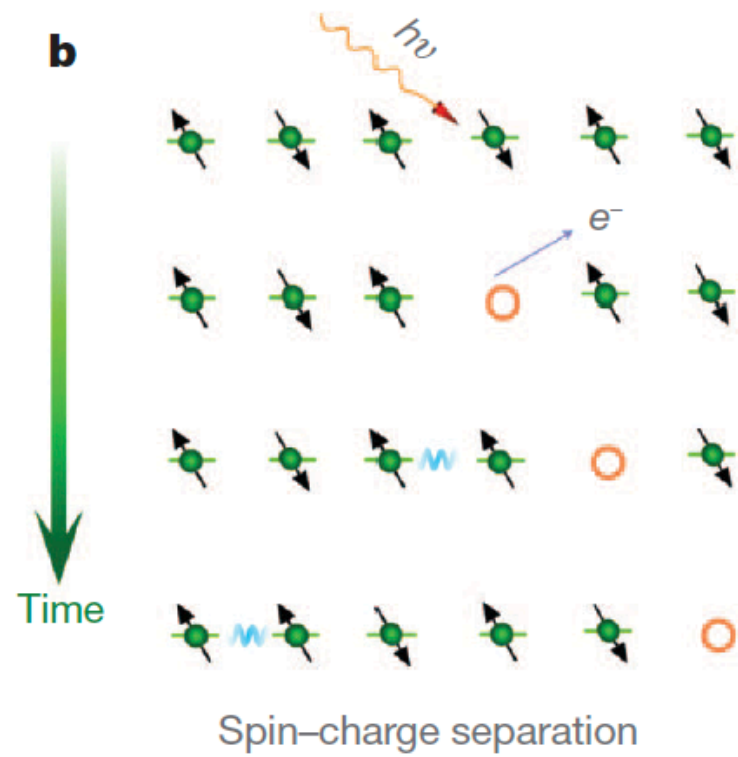
INS



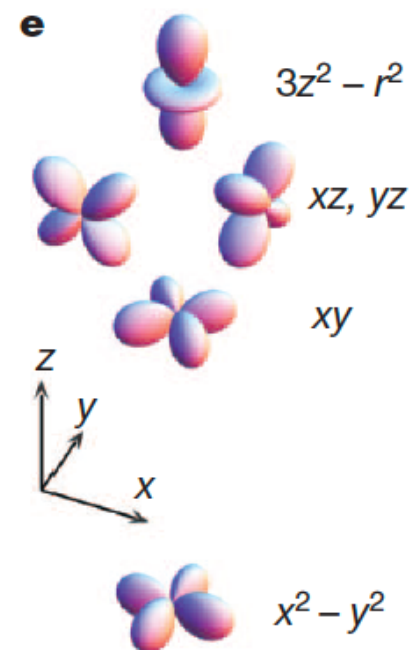
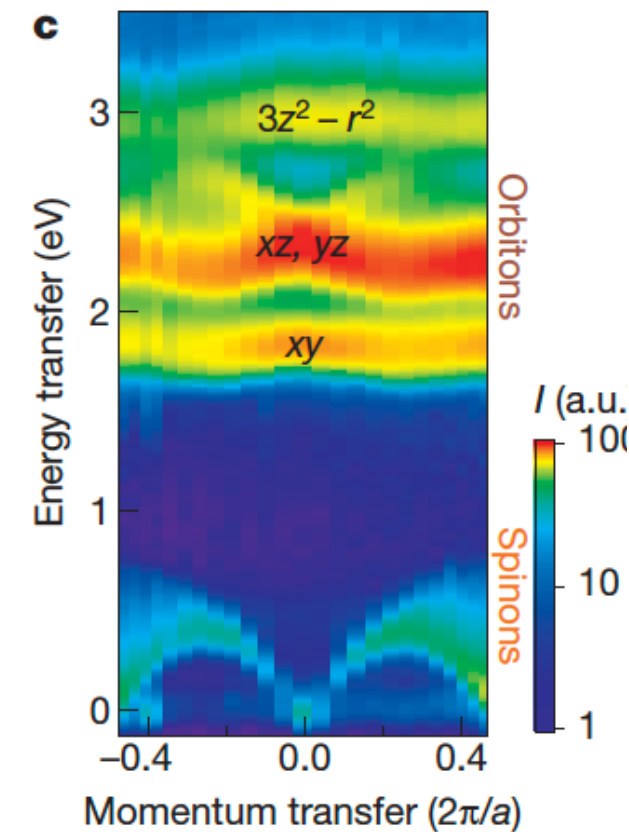
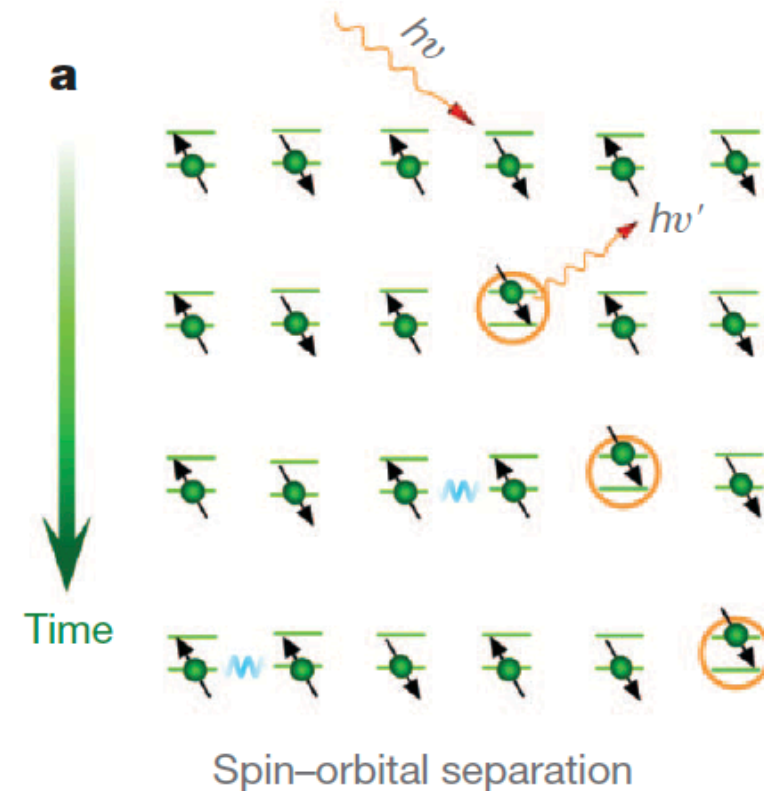
C. Kim et al. PRL (1996)

BJK, C. Kim et al. Nature Phys. (2006)

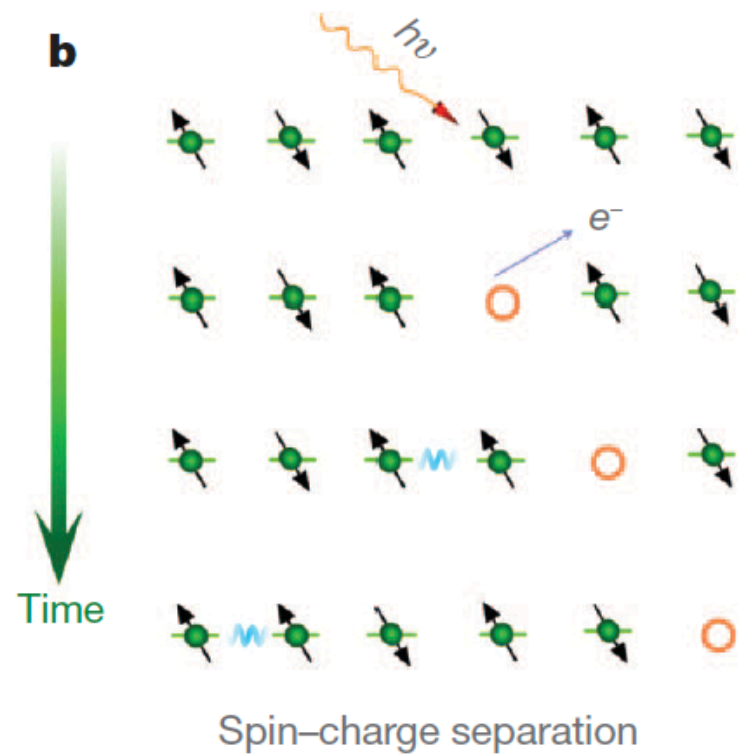
Spin-charge separation



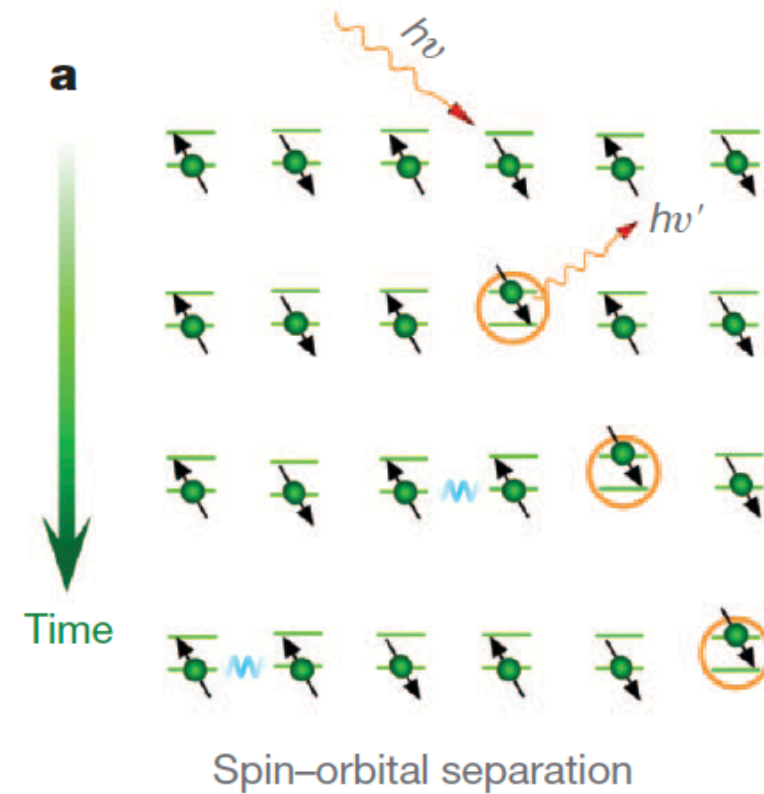
Spin-orbital separation



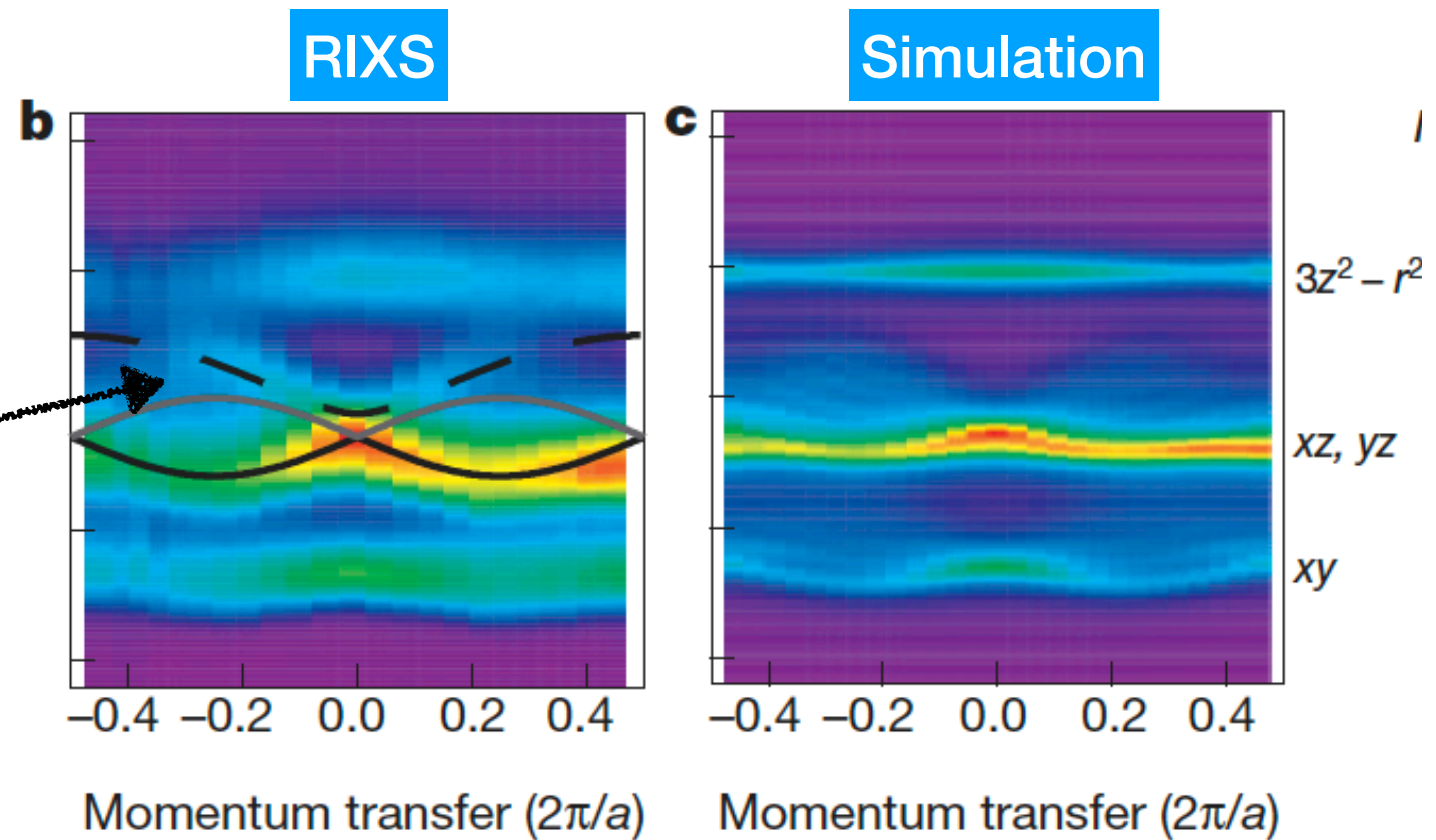
Spin-charge separation



Spin-orbital separation



Spinon-orbiton continuum



Recent theoretical proposals

Majorana fermions in Kitaev spin liquid

Spins fractionalize into Majorana fermions and emergent gauge fluxes

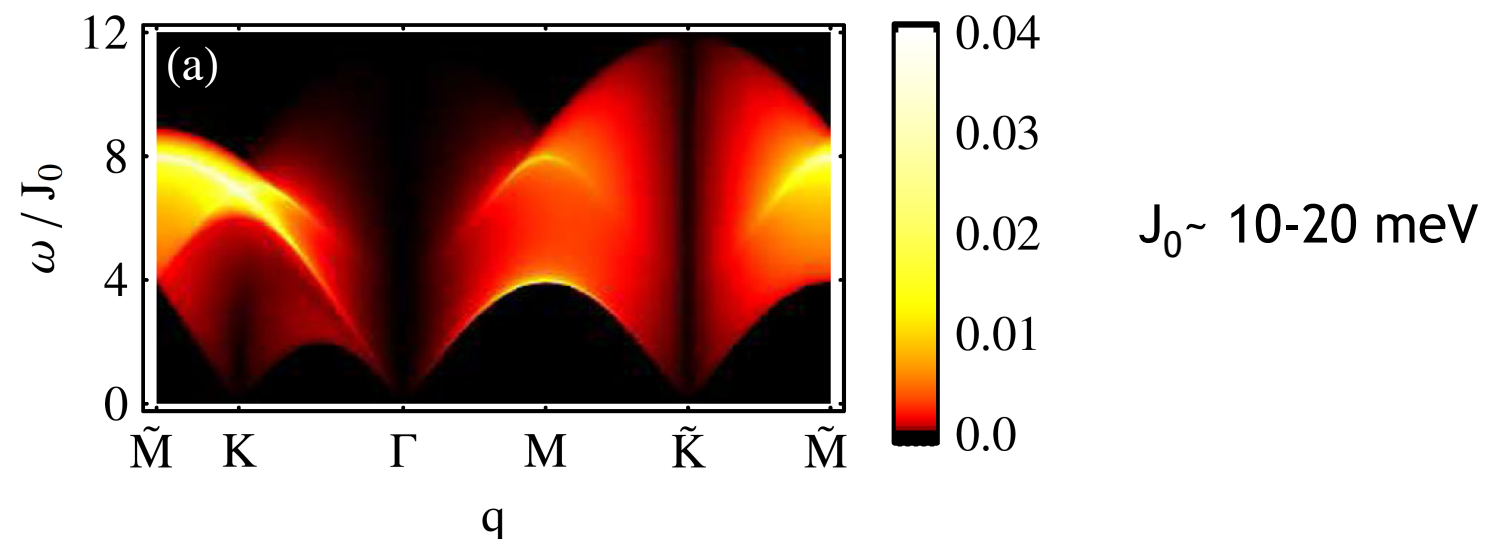
$$e^{-iHt} \text{ (on a honeycomb lattice with sites } i, j \text{ and fluxes } \pi) = \sum_j A_{ij}(t) \text{ (on a honeycomb lattice with sites } i, j \text{ and fluxes } \pi \text{ and a Majorana Fermion at } j \text{)}$$

● Majorana Fermion

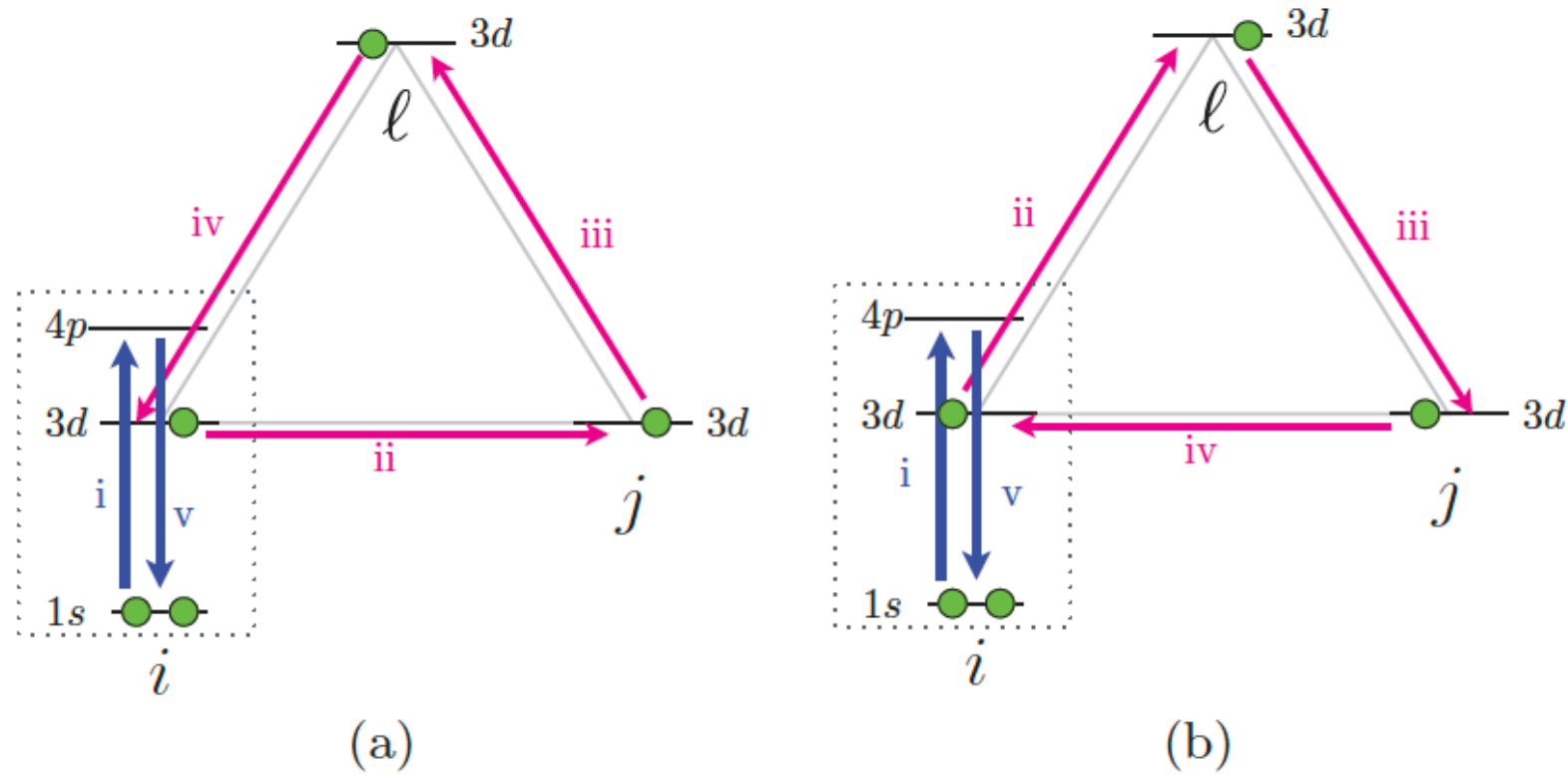
INS: dominated by static flux excitations

Raman scattering: two Majorana excitations but only at $q=0$

RIXS: Majorana (SC channel) and flux excitations (NSC channel)



Gauge fields



$$\begin{aligned}
 T_{3\text{-sites}}^{(a)} &\propto (c_{is}^\dagger (J^\dagger)_{sp}^\beta c_{ip}) (t_{i\ell} c_i^\dagger c_\ell) (t_{\ell j} c_\ell^\dagger c_j) (t_{ji} c_j^\dagger c_i) (c_{ip'}^\dagger J_{p's'}^\alpha c_{is'}) \\
 &= \text{tr}\{J^\alpha (J^\dagger)^\beta\} t_{i\ell} t_{\ell j} t_{ji} \text{tr}\{\chi_\ell \chi_j \tilde{\chi}_i\} \\
 &= N^{\alpha\beta} t_{i\ell} t_{\ell j} t_{ji} [2i \mathbf{S}_\ell \cdot (\mathbf{S}_j \times \mathbf{S}_i) + \dots], \tag{9}
 \end{aligned}$$

In a U(1) spin liquid, spin chirality translates into

$$\sim \langle i | b(\Delta \mathbf{k}, \Delta \omega) b(\mathbf{0}, 0) | i \rangle + \dots$$

where b is effective magnetic field associated with the emergent gauge boson

Summary

- RIXS is a powerful tool sensitive to charge, spin, and orbital degrees of freedom.
- As such, it is useful for measuring spin-wave (magnon) dispersions, but can also be used to detect more exotic particles not readily measured by conventional probes.