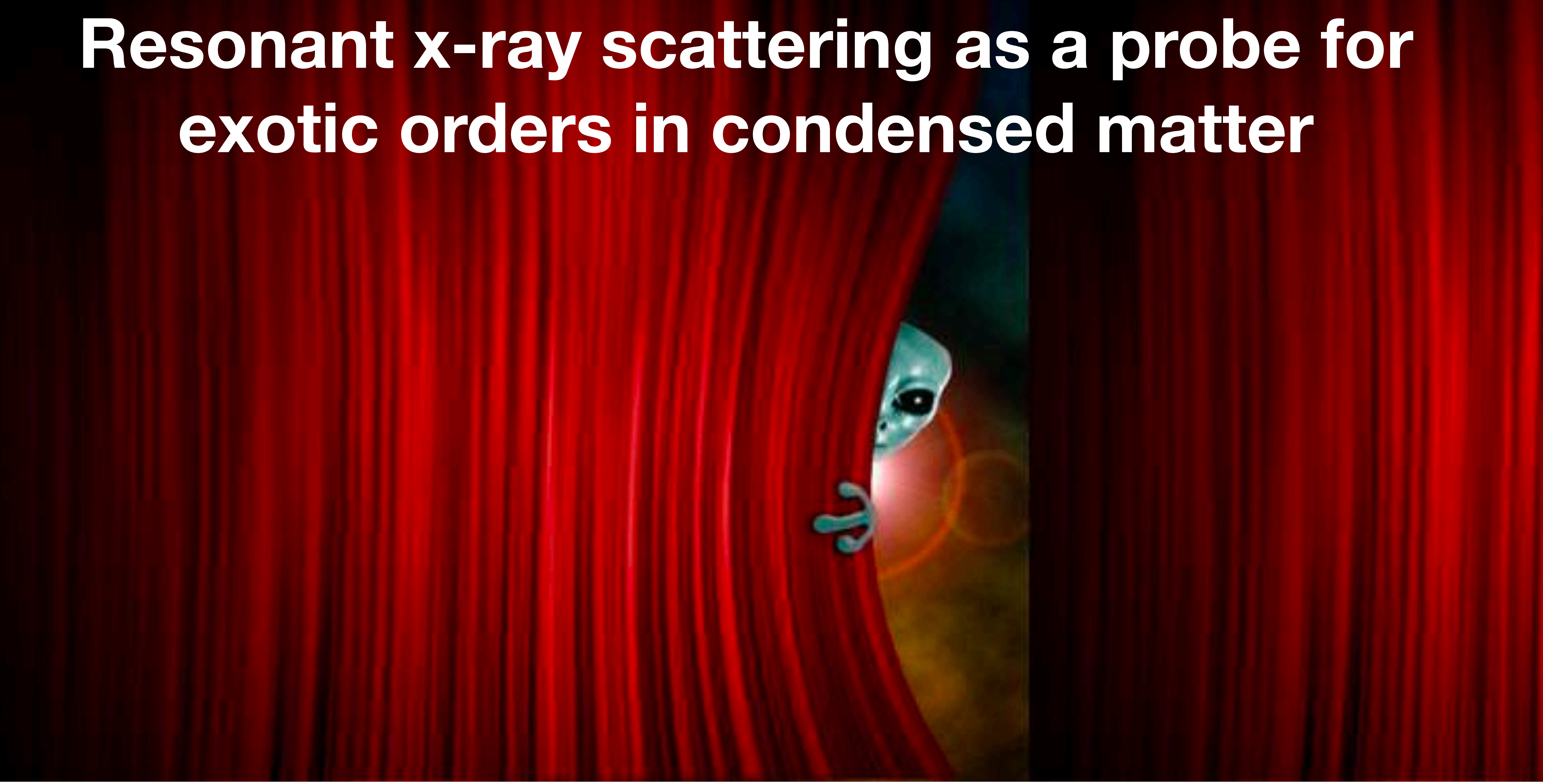
Resonant x-ray scattering as a probe for exotic orders in condensed matter



B. J. Kim

Pohang University of Science and Technology (POSTECH)

Center for Artificial Low-Dimensional Electronic Systems, Institute of Basic Science (IBS)

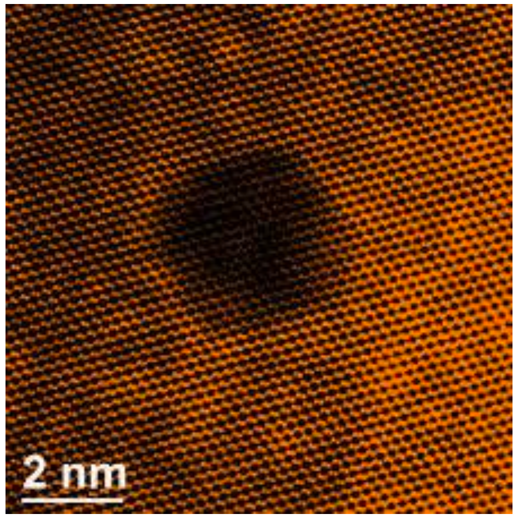
Colloquium

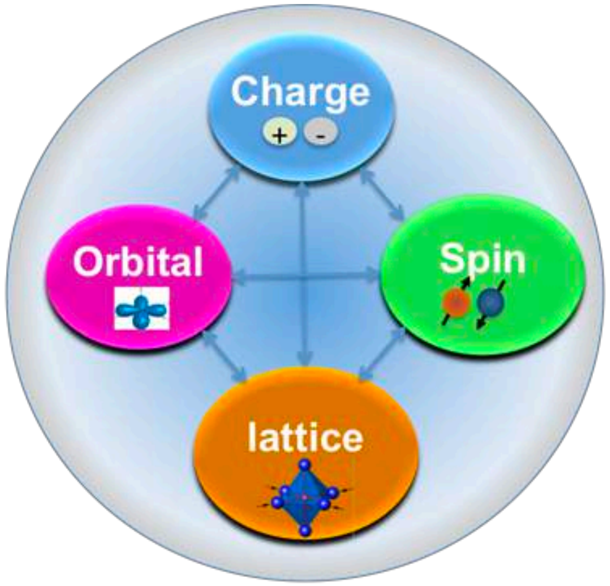
Seoul National University

Nov. 22, 2017

Condensed matter systems

- **Large number of interacting degrees of freedom**

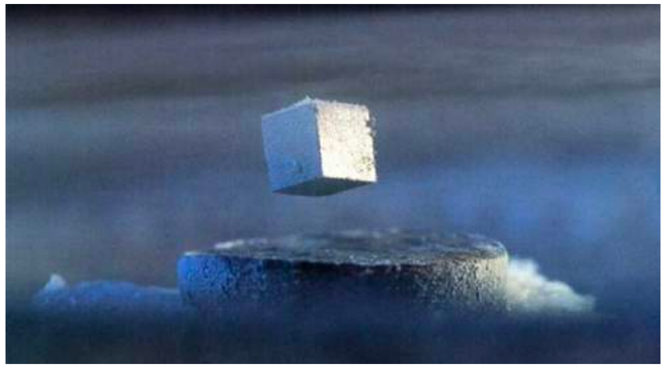




- **Symmetry of the underlying lattice (230 space groups)**

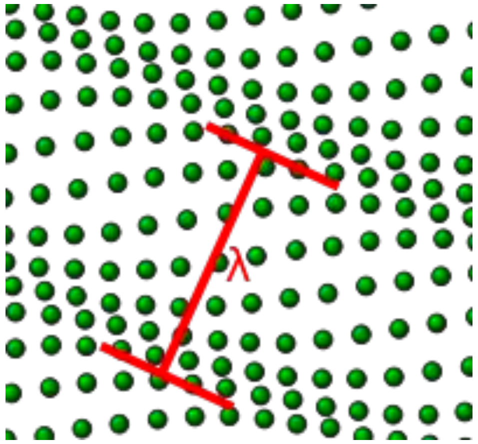
- **Spontaneous breaking of the symmetry by electronic order**

- **Emergent physics**

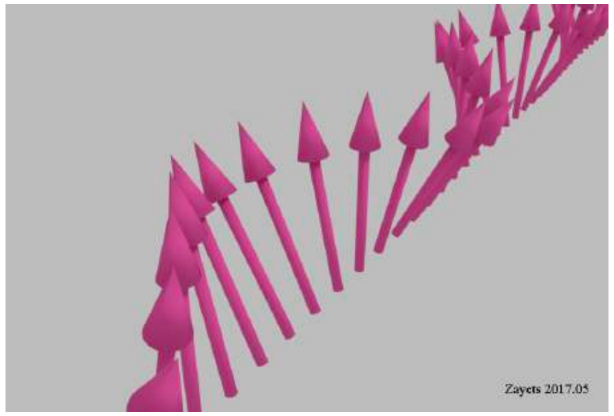


"More is different"

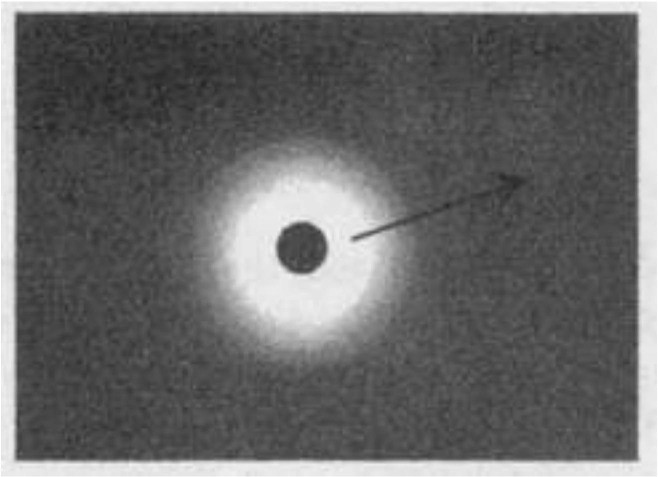
Elementary excitations in solids



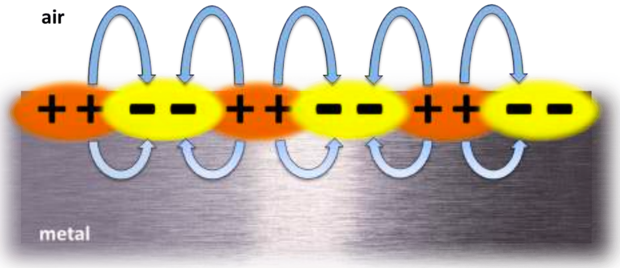
phonon



magnon

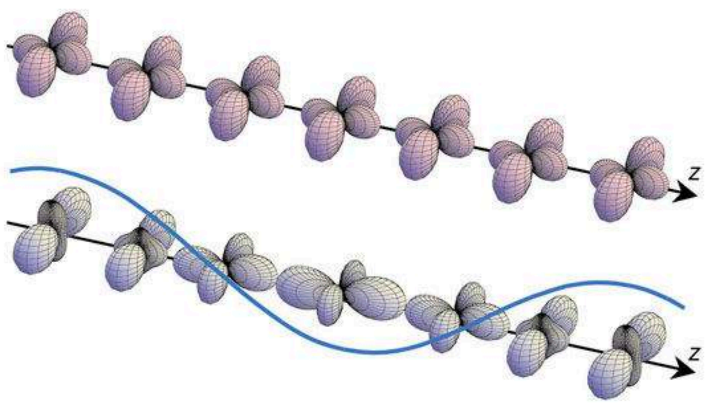


quasi-electron

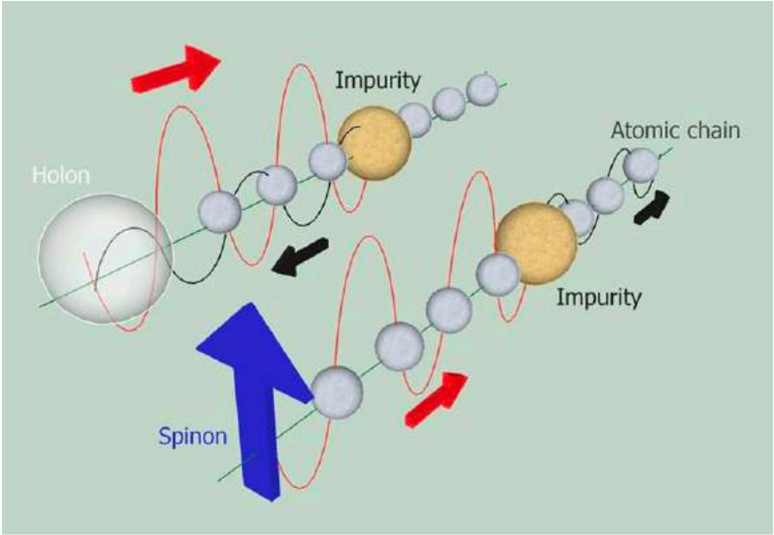


plasmon

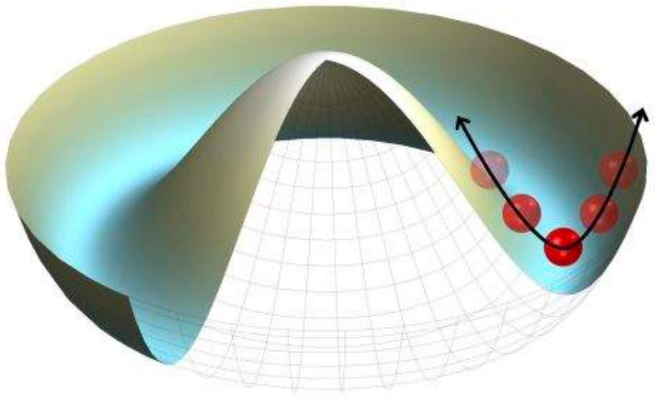
And more exotic particles..



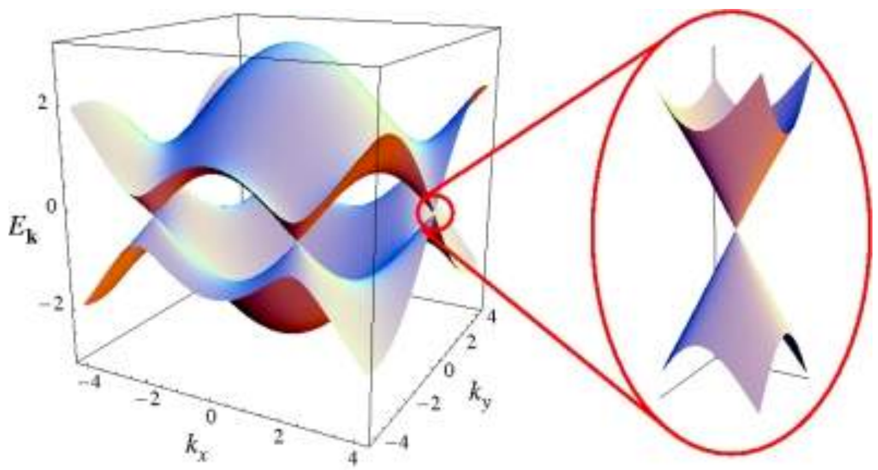
orbiton



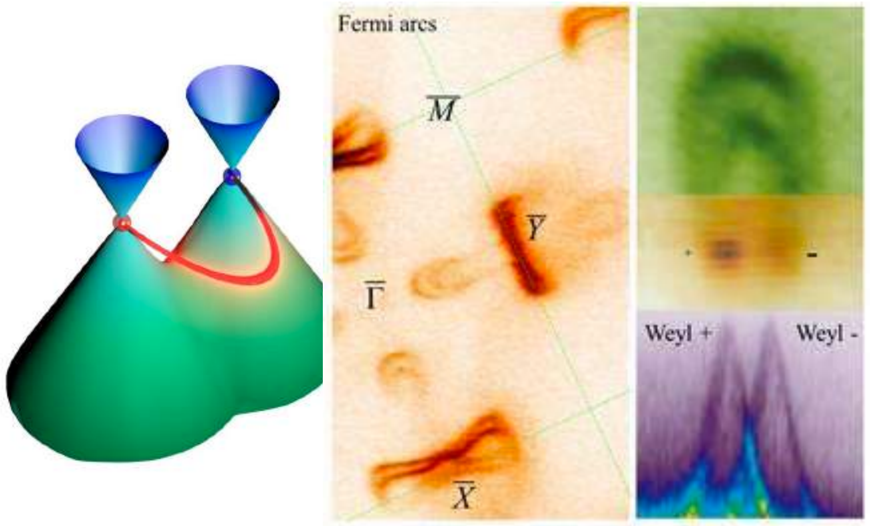
Spinon and holon



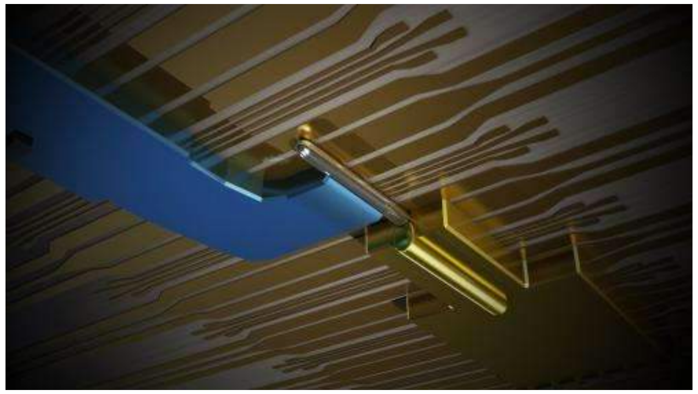
Higgs mode



Dirac fermion

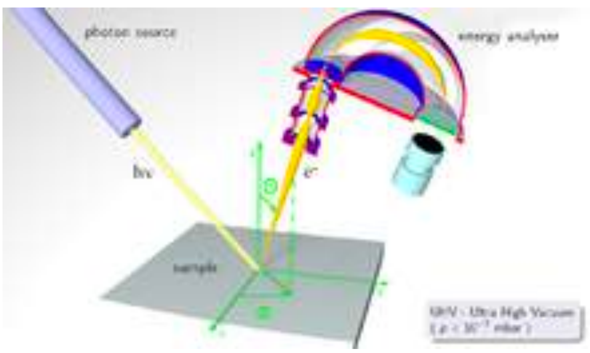


Weyl fermion

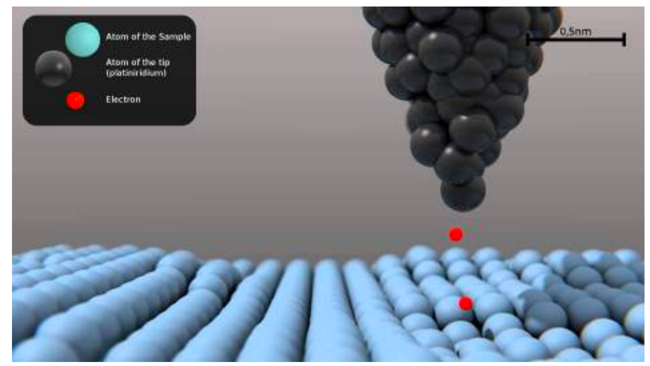


Majonara fermion

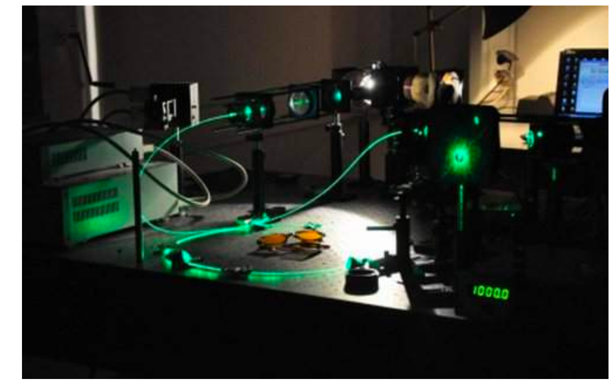
Standard probes



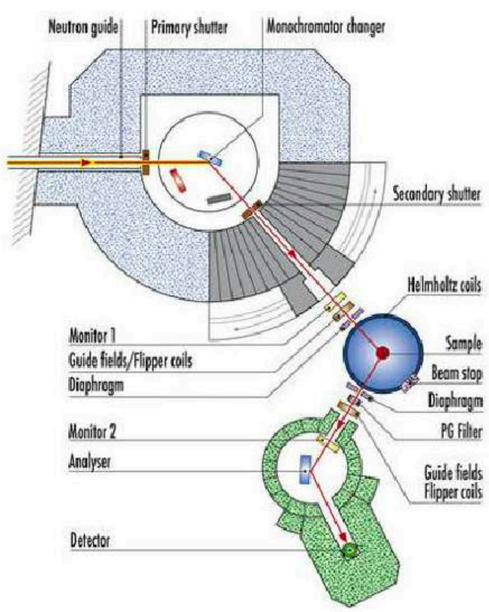
ARPES



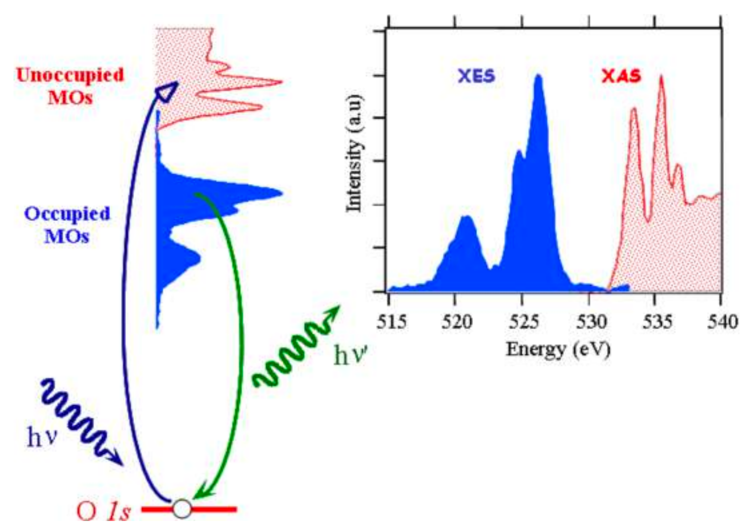
STM



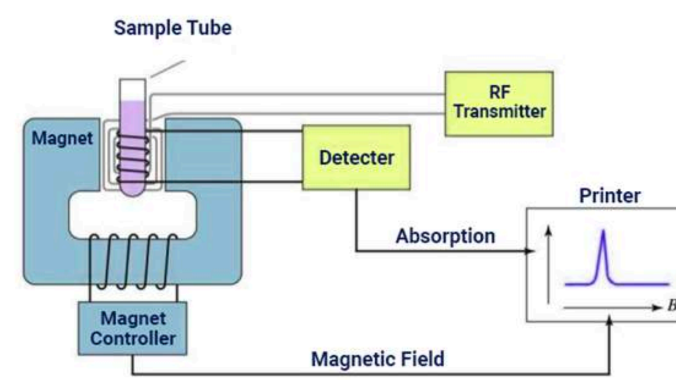
optical/Raman



INS

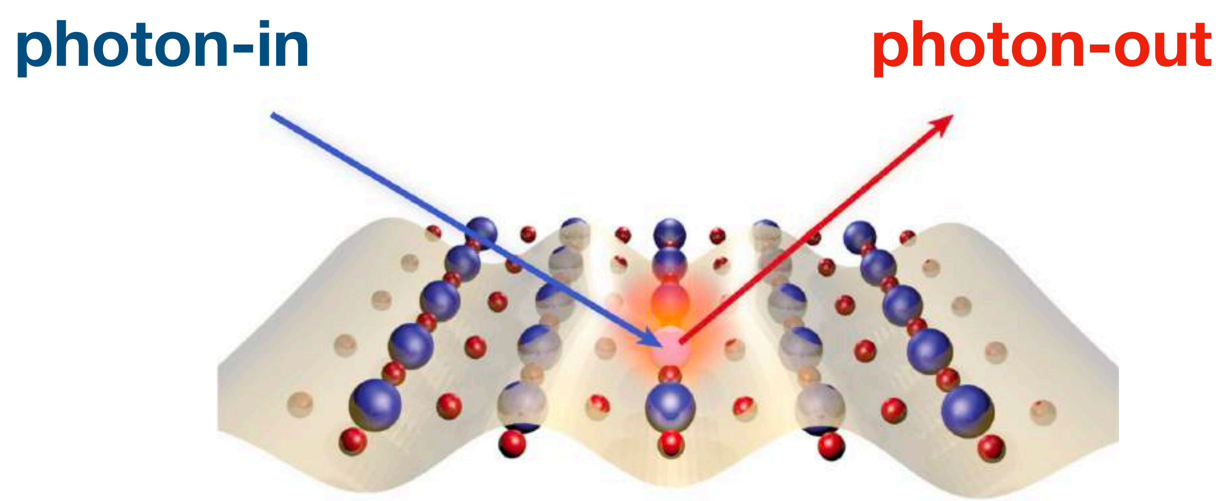


XAS/XES



NMR

Resonant inelastic x-ray scattering (RIXS)



Pros

- Sensitive to spin, orbital, charge excitations
- Sensitive to “hidden” orders
- Can measure up to hexadecapole (2^4 pole)
- Can measure tiny crystals/thin films

Cons

- Difficult to calculate the scattering cross section
- Energy resolution not as good as neutron scattering
- Difficult to get beamtime (not many user facilities)

Outline

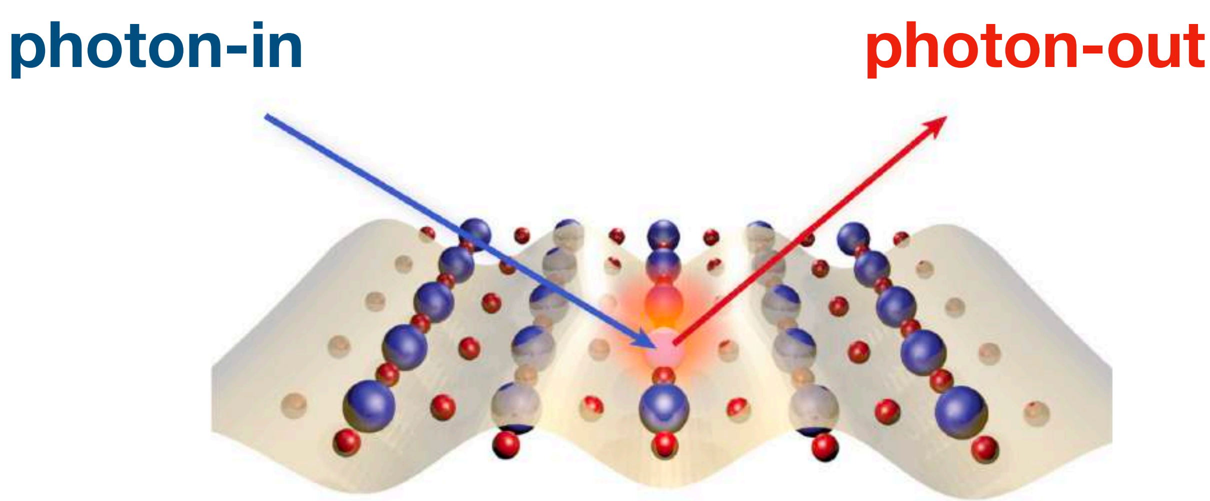
- Short introduction to RIXS
- Applications to:

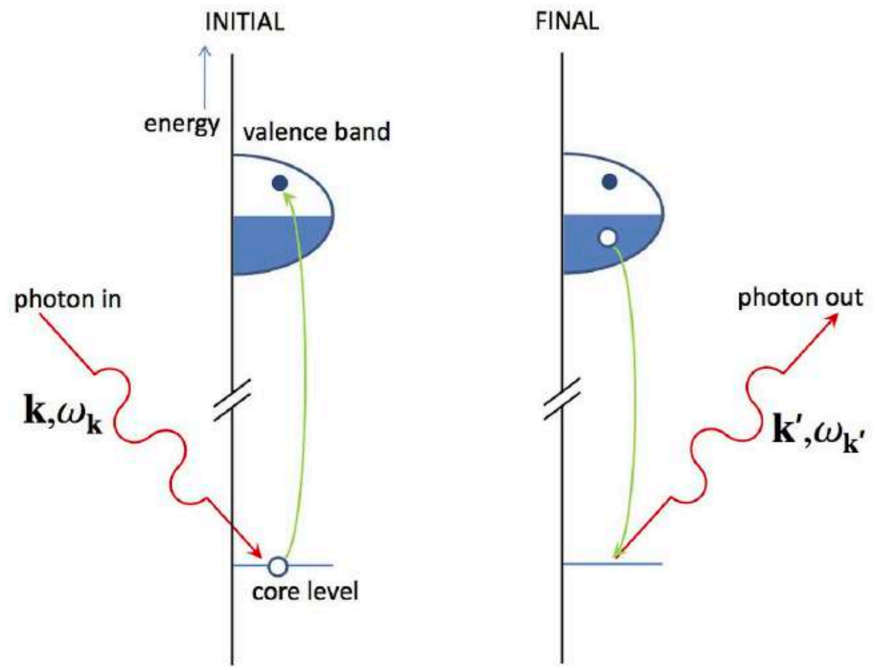
  1. Spin waves
  2. Excitons
  3. Fractional excitations
  4. Spin nematic

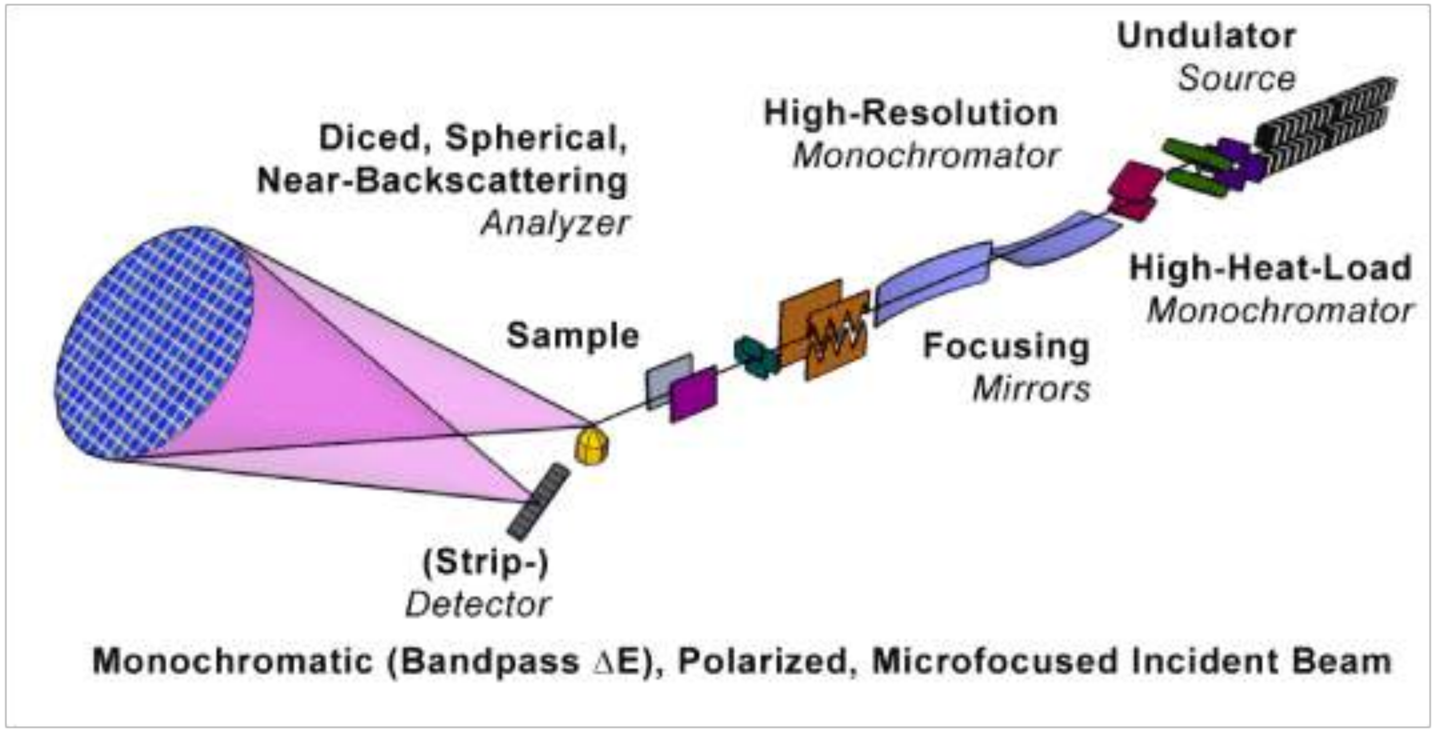
- Other interesting theoretical proposals to measure:

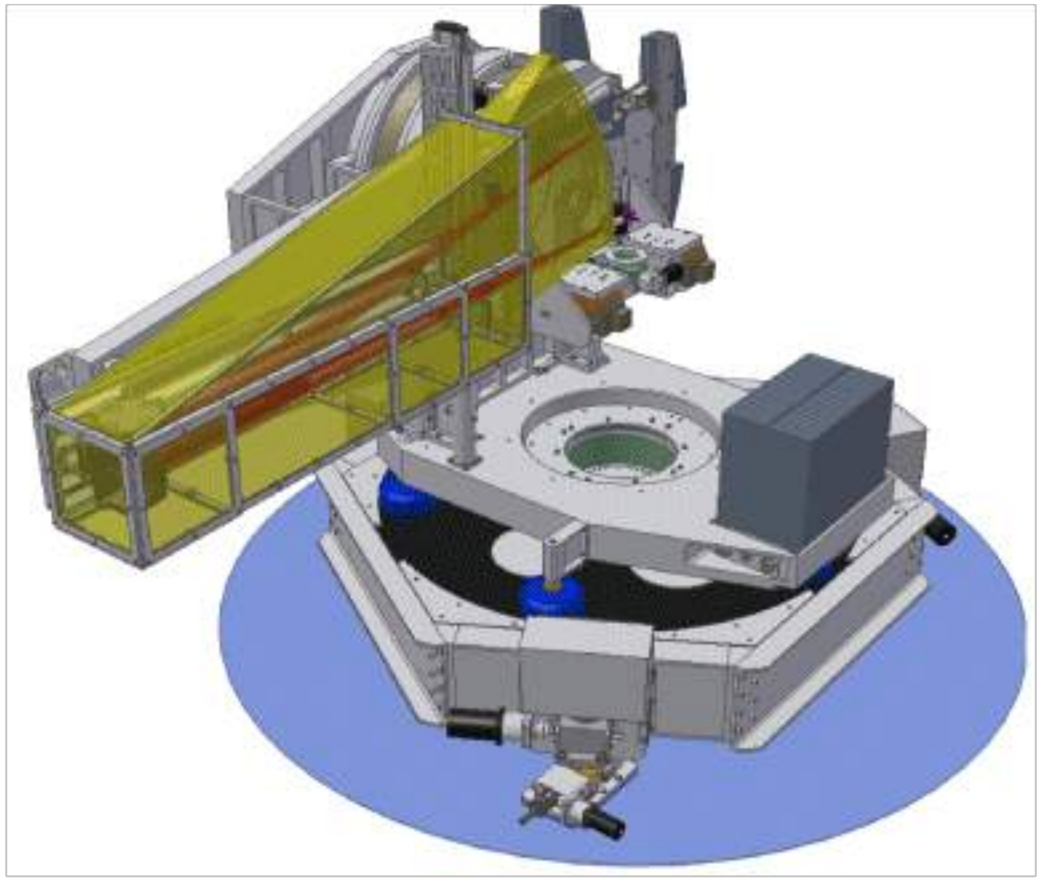
  5. Majorana fermions
  6. Gauge fields

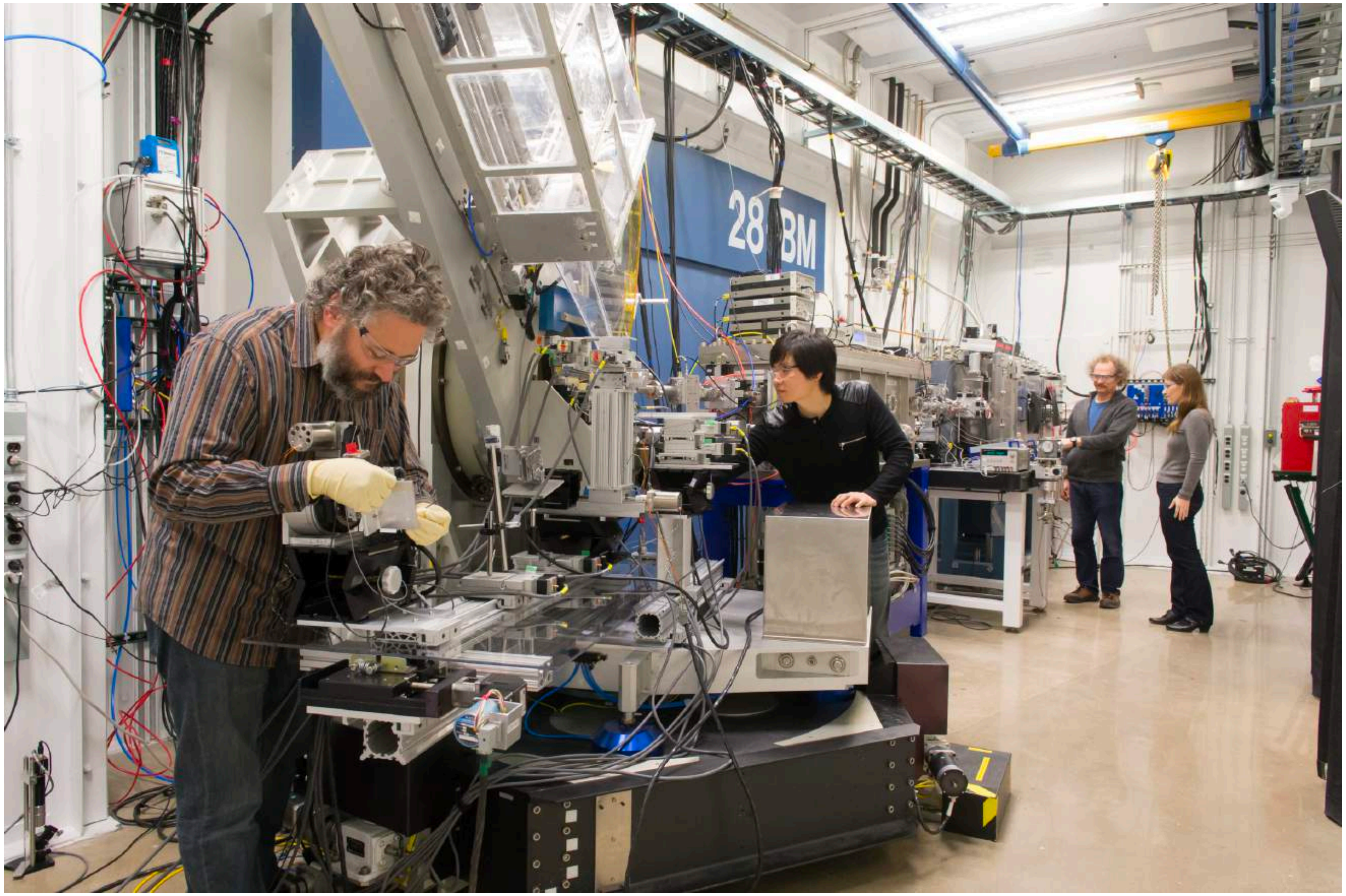
Resonant inelastic x-ray scattering (RIXS)







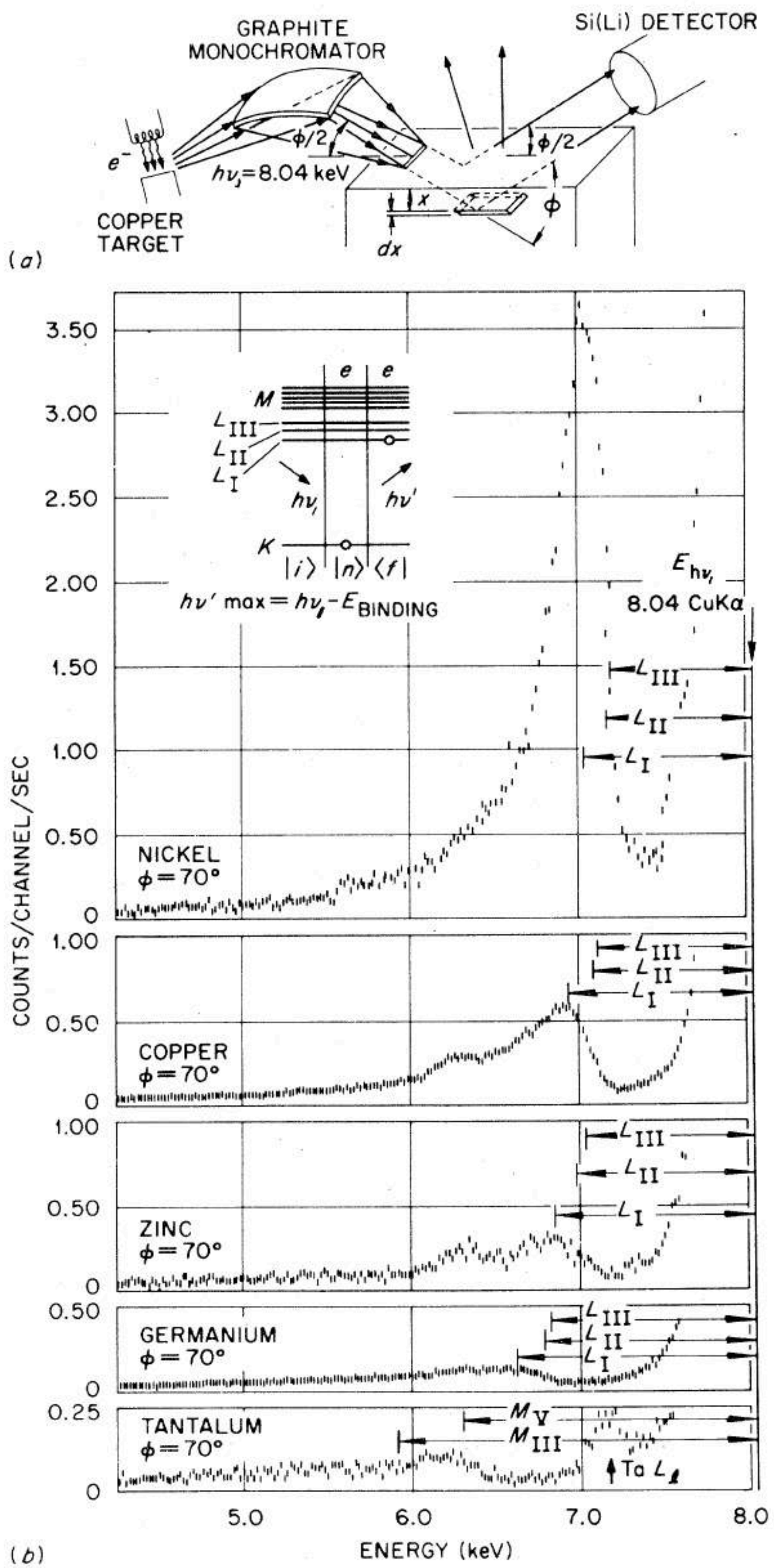




Advanced Photon Source
ARGONNE NATIONAL LABORATORY

ESRF
The European Synchrotron

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

Brief history

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

2017: <10 meV
2012: 25 meV

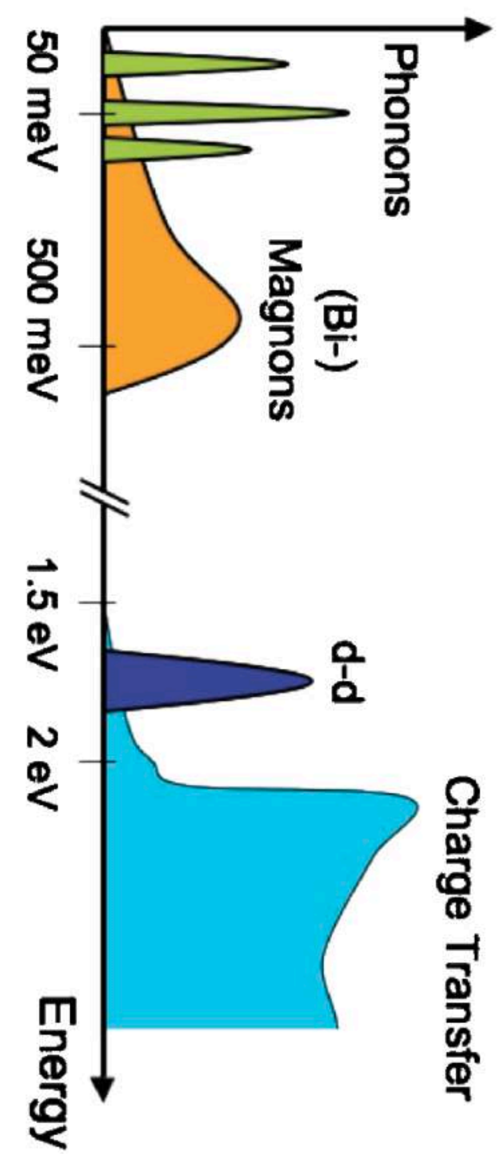
2010: 130 meV, 3000 cps

2010 — our first experiment on iridate (hard x-ray)

2007: 90 meV, 600 cps — first observation of single magnon (soft x-ray) (Braicovich & Ghiringhelli)

2002: 300 meV, 6 cps

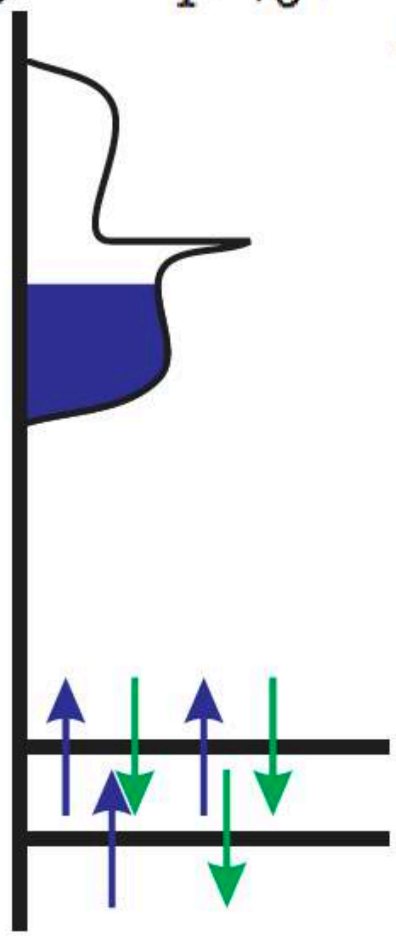
1999: 1500 meV, 1cps



L. Ament et al., Rev. Mod. Phys. (2011)

RIXS process

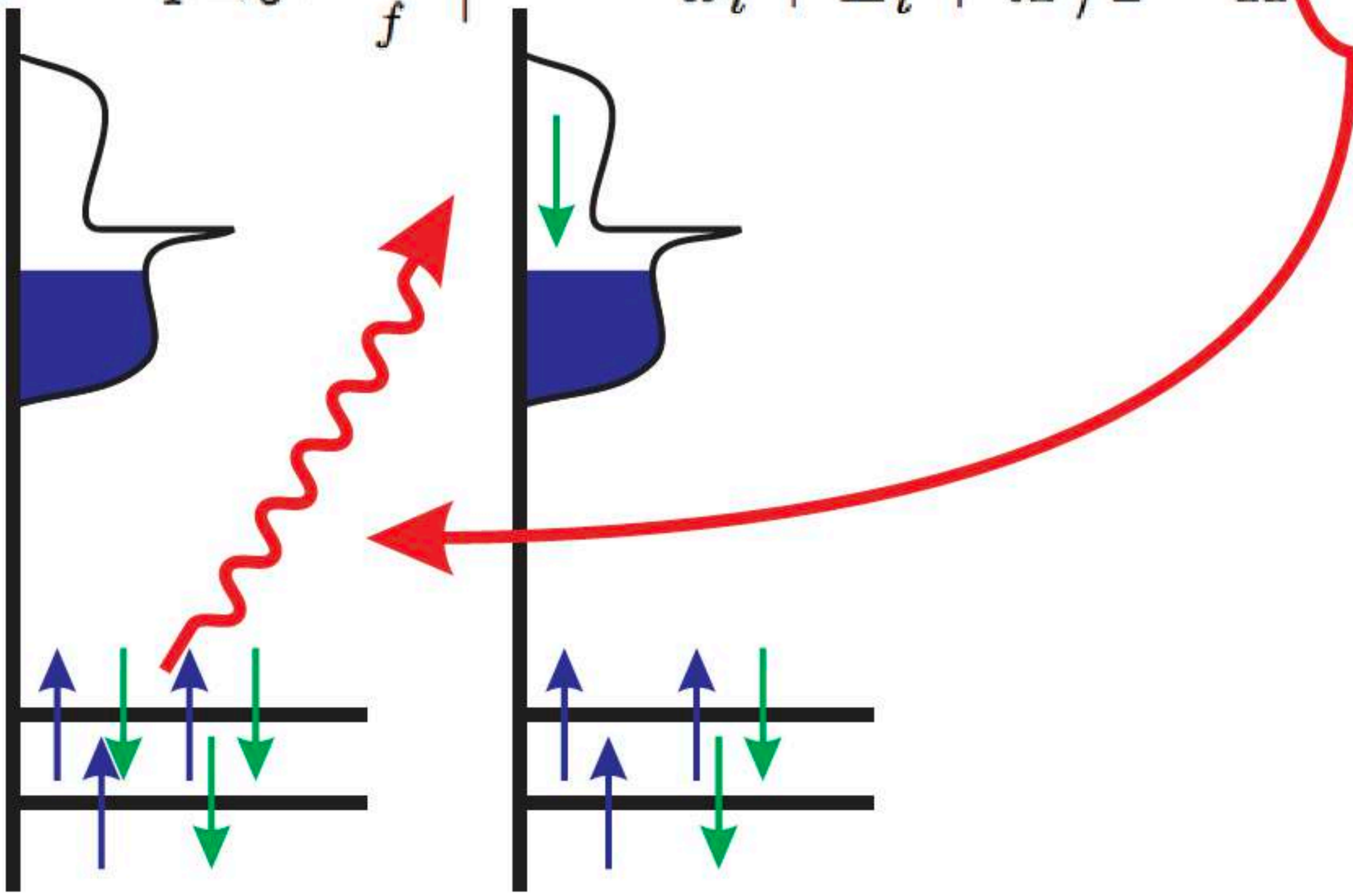
$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+} \sum_f \left| \langle f | T^\dagger_{\varepsilon_o} \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\varepsilon_i} |i\rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$



courtesy of M. Haverkort

RIXS process

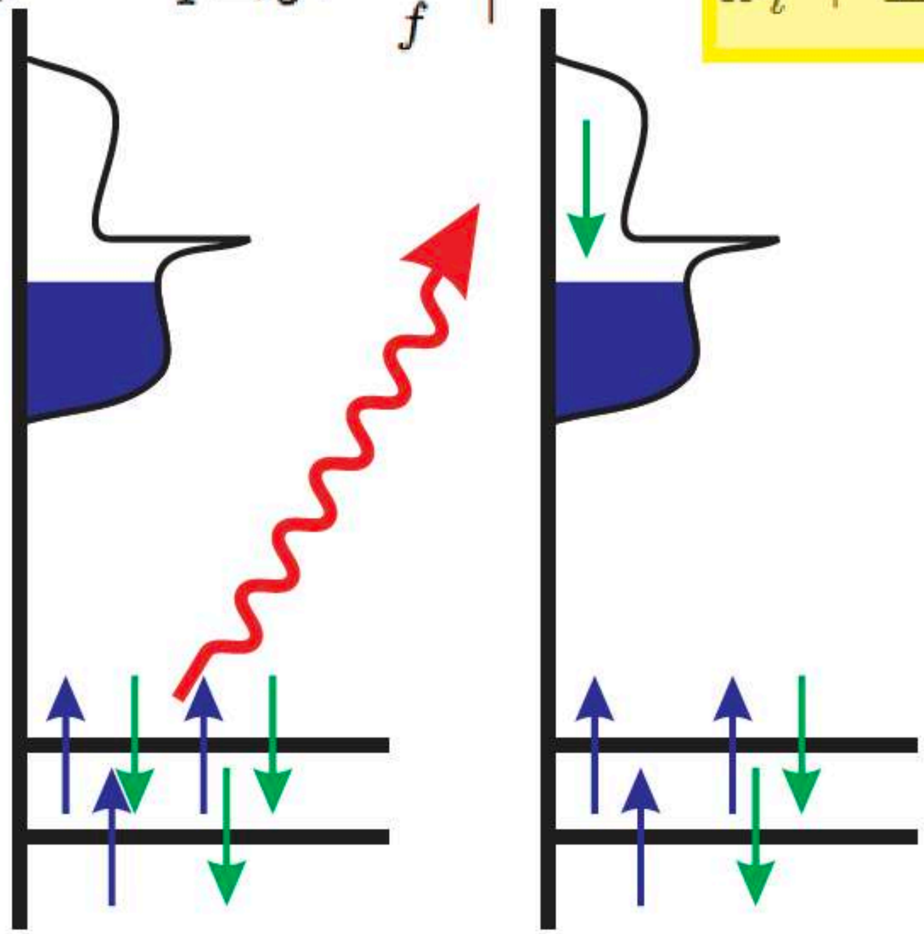
$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+} \sum_f \left| \langle f|T^\dagger_{\varepsilon_o} \frac{1}{\omega_i + E_i + \imath\Gamma/2 - H} T_{\varepsilon_i} |i\rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$



courtesy of M. Haverkort

RIXS process

$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+} \sum_f \left| \langle f | T^\dagger_{\varepsilon_o} \boxed{\frac{1}{\omega_i + E_i + i\Gamma/2 - H}} T_{\varepsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$



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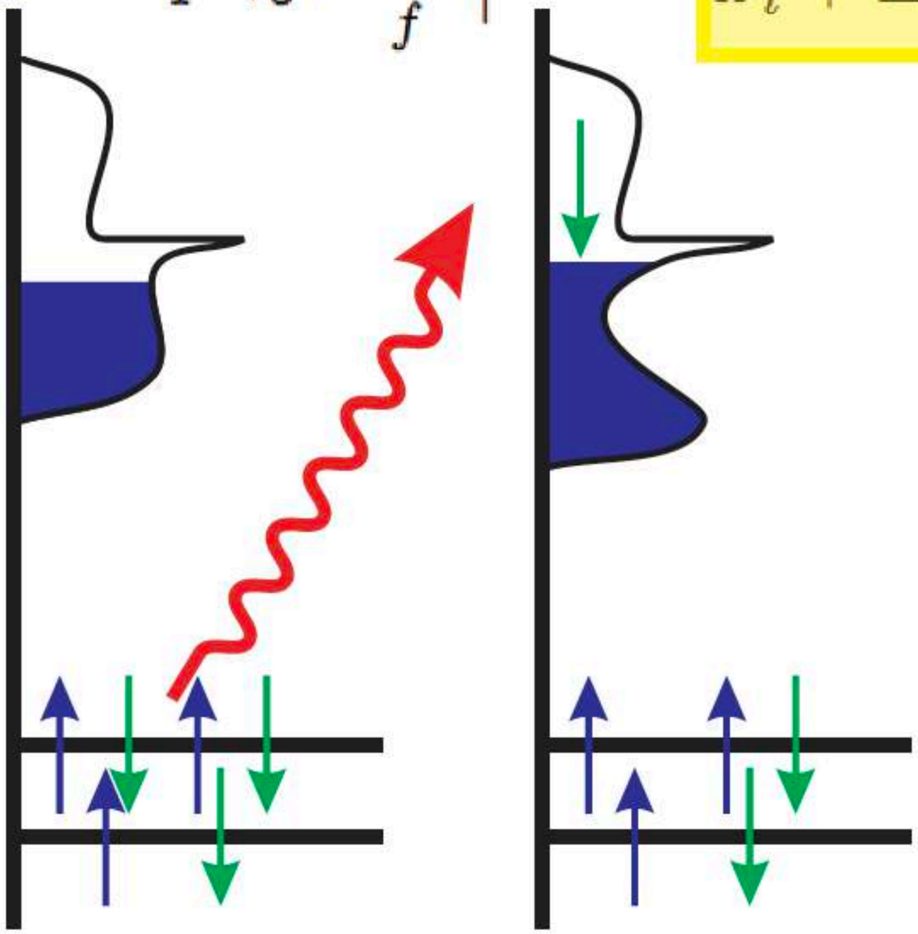

courtesy of M. Haverkort

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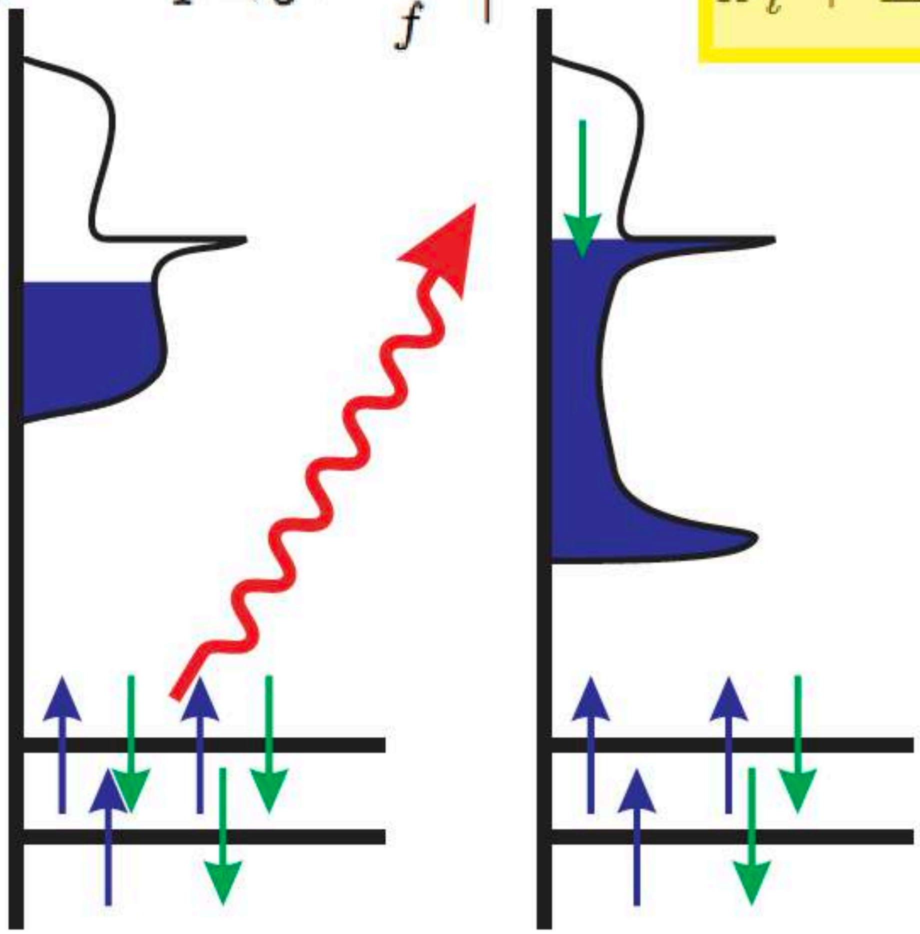

courtesy of M. Haverkort

RIXS process

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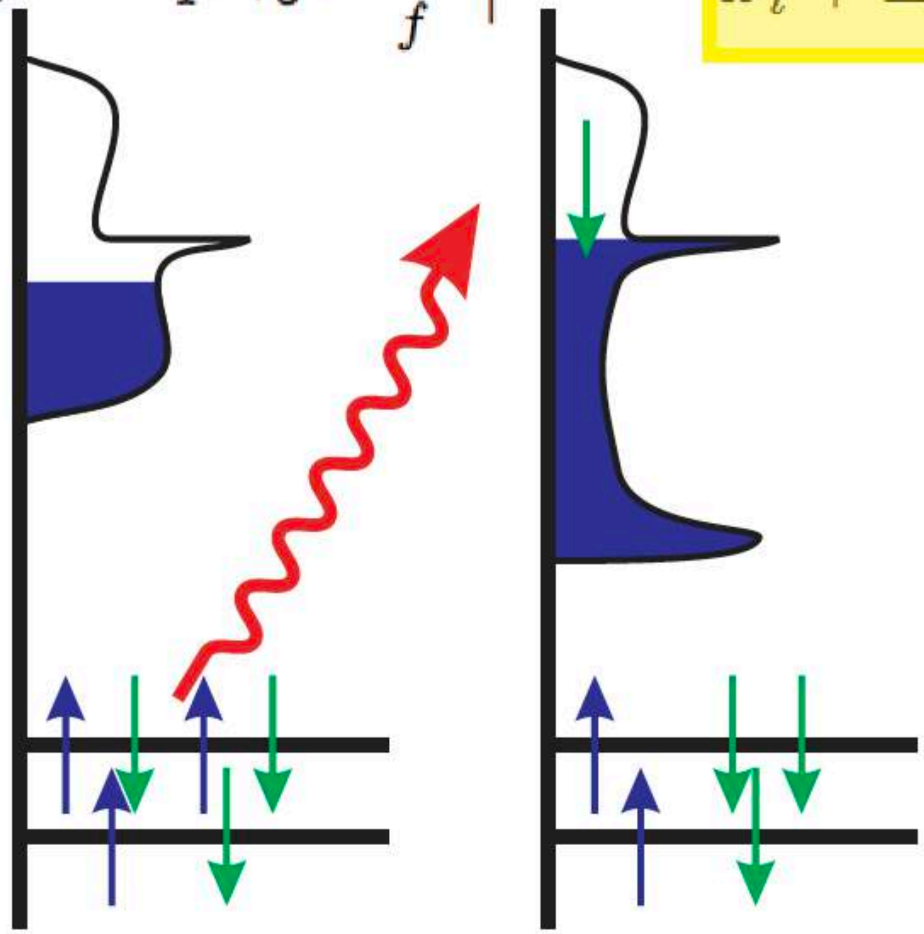
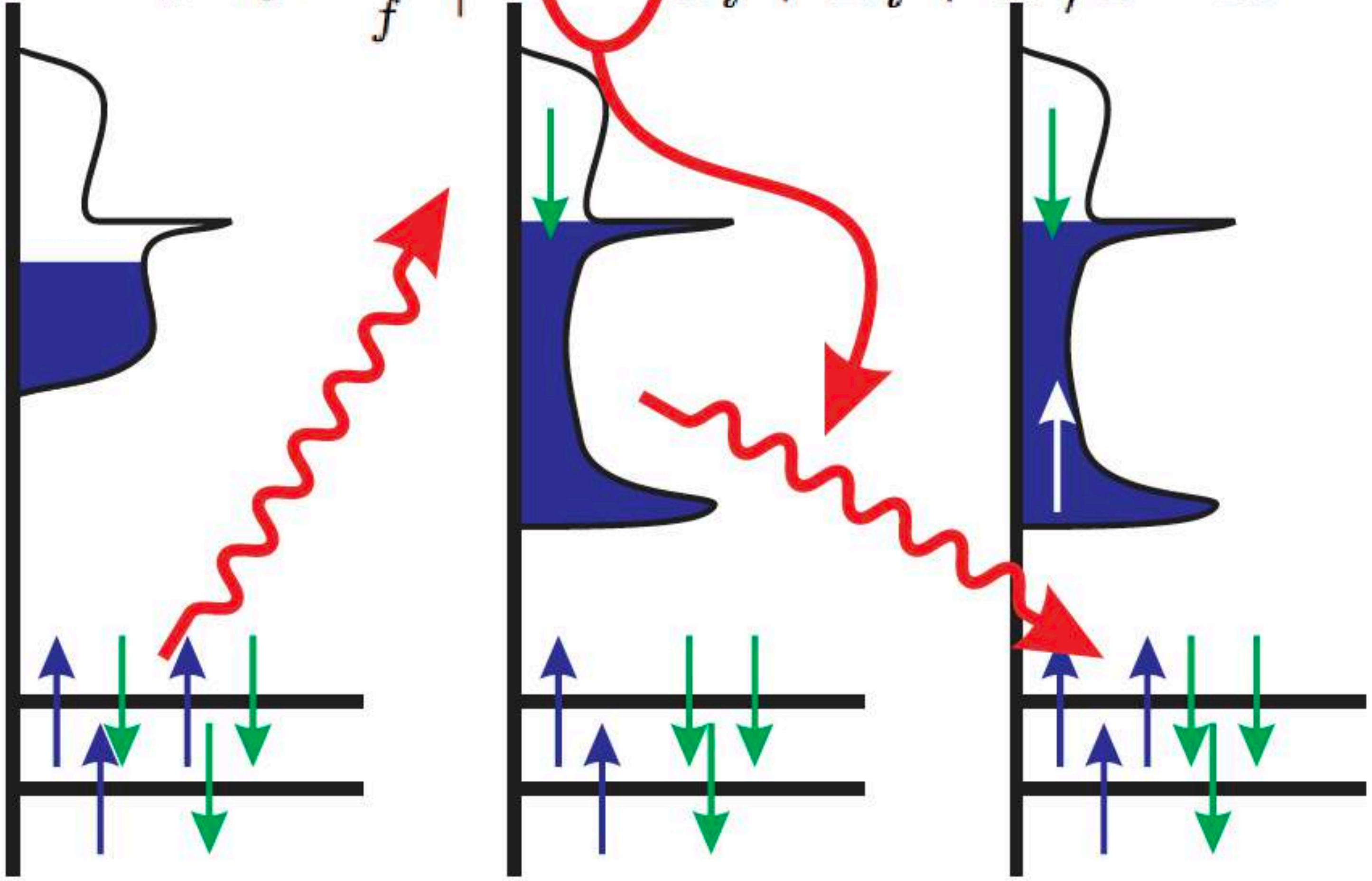


courtesy of M. Haverkort

RIXS process

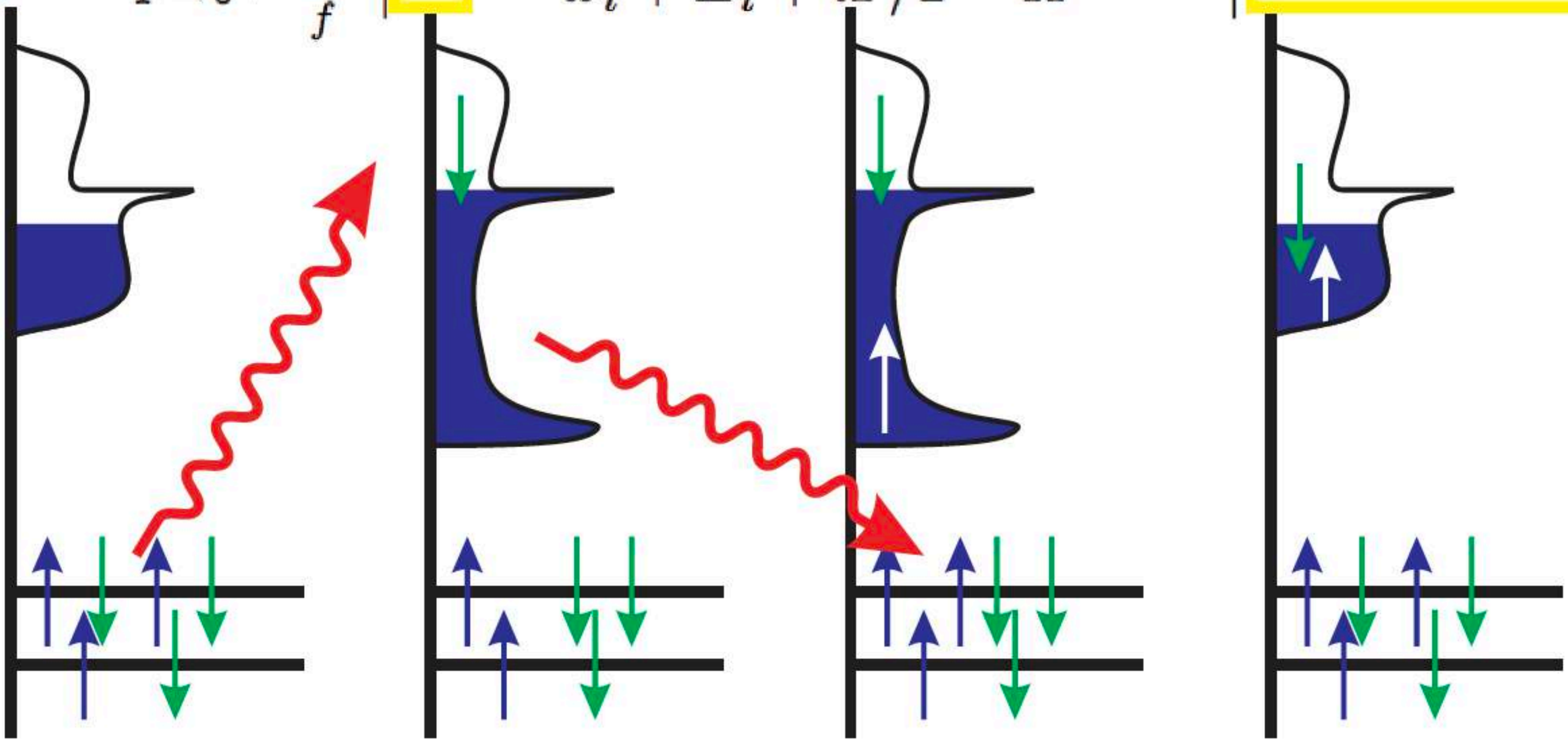
$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+} \sum_f \left| \langle f | T^\dagger_{\varepsilon_o} \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\varepsilon_i} | i \rangle \right|^2 \delta(\omega_i - \omega_o + E_i - E_f)$$



courtesy of M. Haverkort

RIXS process

$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+} \sum_f \left| \boxed{\langle f|} T^\dagger_{\varepsilon_o} \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\varepsilon_i} |i\rangle \right|^2 \boxed{\delta(\omega_i - \omega_o + E_i - E_f)}$$

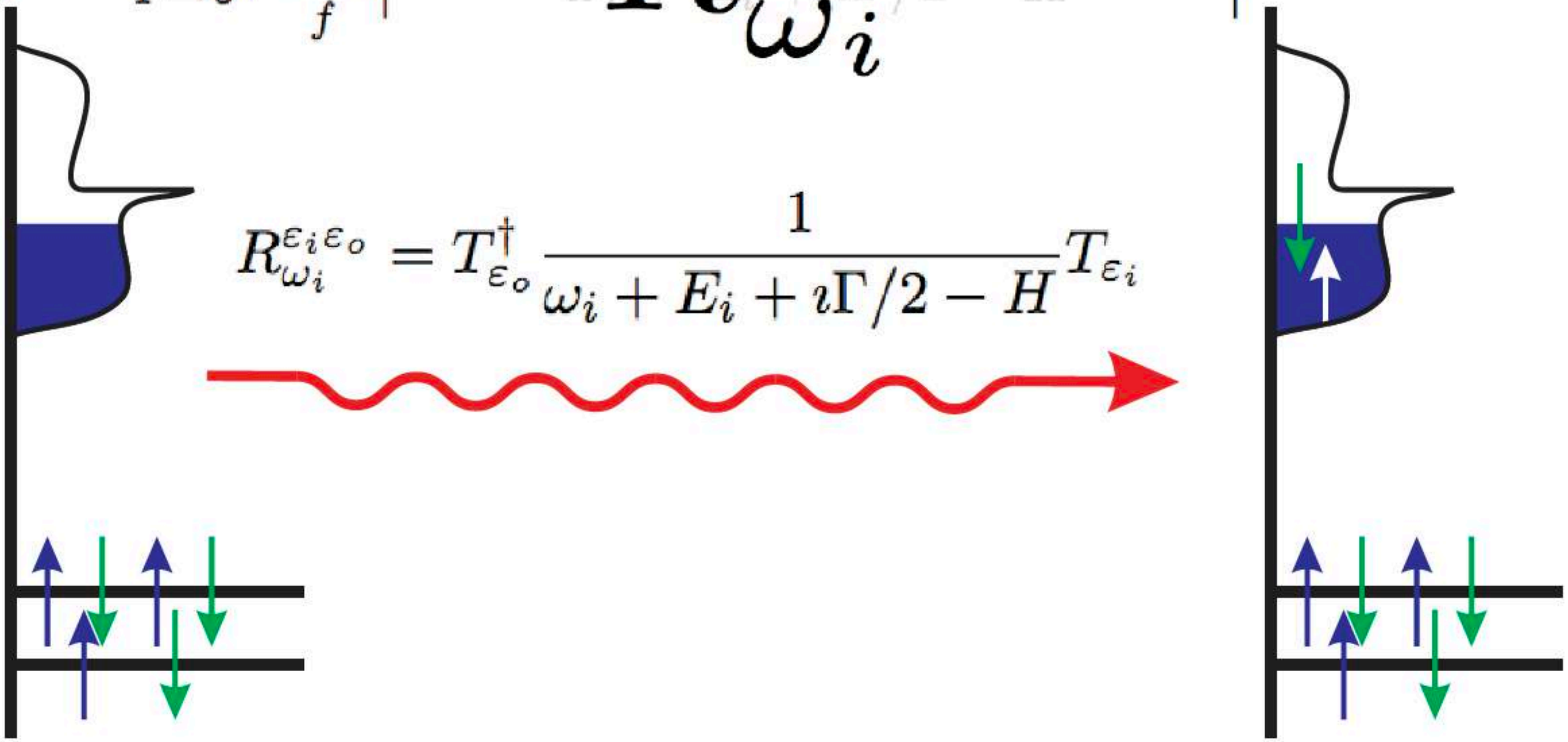


courtesy of M. Haverkort

RIXS process

$$\frac{\delta^2\sigma}{\delta\Omega\delta\omega} \propto \lim_{\Gamma\to 0^+}\sum_f \left|\langle f| R^{\varepsilon_i\varepsilon_o}_{\omega_i} |i\rangle\right|^2 \delta(\omega_i-\omega_o+E_i-E_f)$$

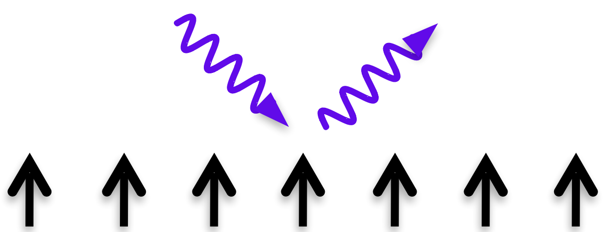
$$R^{\varepsilon_i\varepsilon_o}_{\omega_i} = T^\dagger_{\varepsilon_o}\frac{1}{\omega_i+E_i+\imath\Gamma/2-H}T_{\varepsilon_i}$$



antisymmetric	$(\epsilon_\alpha\epsilon'_\beta - \epsilon_\beta\epsilon'_\alpha)$	dipole
symmetric	$(\epsilon_\alpha\epsilon'_\beta + \epsilon_\beta\epsilon'_\alpha)$	quadrupole

courtesy of M. Haverkort

Spin waves (or magnons)



Spin waves (or magnons)

$$\uparrow \; \uparrow \; \uparrow \; \downarrow \; \uparrow \; \uparrow \; \uparrow$$

Spin waves (or magnons)

$$\uparrow\ \uparrow\ \uparrow\ \uparrow\ \downarrow\ \uparrow\ \uparrow$$

Spin waves (or magnons)

$$\uparrow \; \uparrow \; \uparrow \; \uparrow \; \uparrow \; \downarrow \; \uparrow$$

Spin waves (or magnons)

$\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \downarrow$

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

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

RIXS operators for t_{2g} orbital systems

unquenched orbital angular momentum

"fast collision approximation"

$$R^{\varepsilon_i \varepsilon_o}_{\omega_i} = T^{\dagger}_{\varepsilon_o} \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\varepsilon_i}$$

c number

$$R \propto D^{\dagger} D = \tfrac{1}{3}(R_Q + i R_M)$$

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

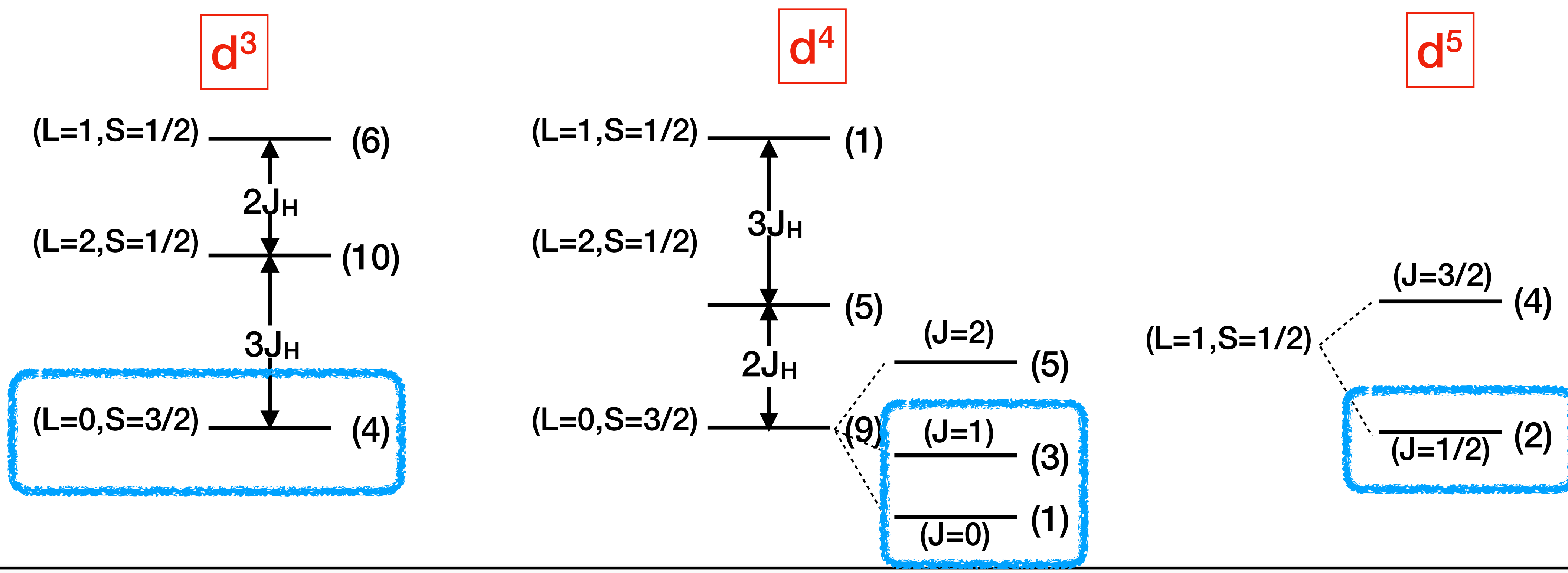
$$R_M = \tfrac{1}{2}(\boldsymbol{\epsilon} \times \boldsymbol{\epsilon}') \cdot \mathbf{N}.$$

Q_{zz} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_z^2 + 2L_zS_z$	$-L_z^2 - 2L_zS_z$
$d^2,(-1)d^4$	$2L_z^2 + L_zS_z$	$L_z^2 - L_zS_z$
Q_{xy} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_xL_y - 2L_yL_x + 2L_xS_y + 2L_yS_x$	$-L_xL_y - L_yL_x - 2L_xS_y - 2L_yS_x$
$d^2,(-1)d^4$	$2L_xL_y + 2L_yL_x + L_xS_y + L_yS_x$	$L_xL_y + L_yL_x - L_xS_y - L_yS_x$
N_z (magnetic)	L_3 edge	L_2 edge
d^1,d^5	$2L_z - 4S_z + 8L_z^2S_z - 2L_z(\mathbf{L}\cdot\mathbf{S}) - 2(\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4S_z - 8L_z^2S_z + 2L_z(\mathbf{L}\cdot\mathbf{S}) + 2(\mathbf{L}\cdot\mathbf{S})L_z$
d^2, d^4	$2L_z - 4L_z^2S_z + L_z(\mathbf{L}\cdot\mathbf{S}) + (\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4L_z^2S_z - L_z(\mathbf{L}\cdot\mathbf{S}) - (\mathbf{L}\cdot\mathbf{S})L_z$
d^3	$(4/3)S_z$	$-(4/3)S_z$

BJK & G. Khaliullin PRB (2017)

RIXS operators for t_{2g} orbital systems

Energy levels in cubic symmetry



Q_{zz} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_z^2+2L_zS_z$	$-L_z^2-2L_zS_z$
$d^2,(-1)d^4$	$2L_z^2+L_zS_z$	$L_z^2-L_zS_z$
Q_{xy} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_xL_y-2L_yL_x+2L_xS_y+2L_yS_x$	$-L_xL_y-L_yL_x-2L_xS_y-2L_yS_x$
$d^2,(-1)d^4$	$2L_xL_y+2L_yL_x+L_xS_y+L_yS_x$	$L_xL_y+L_yL_x-L_xS_y-L_yS_x$
N_z (magnetic)	L_3 edge	L_2 edge
d^1,d^5	$2L_z-4S_z+8L_z^2S_z-2L_z(\mathbf{L}\cdot\mathbf{S})-2(\mathbf{L}\cdot\mathbf{S})L_z$	$L_z+4S_z-8L_z^2S_z+2L_z(\mathbf{L}\cdot\mathbf{S})+2(\mathbf{L}\cdot\mathbf{S})L_z$
d^2,d^4	$2L_z-4L_z^2S_z+L_z(\mathbf{L}\cdot\mathbf{S})+(\mathbf{L}\cdot\mathbf{S})L_z$	$L_z+4L_z^2S_z-L_z(\mathbf{L}\cdot\mathbf{S})-(\mathbf{L}\cdot\mathbf{S})L_z$
d^3	$(4/3)S_z$	$-(4/3)S_z$

BJK & G. Khaliullin PRB (2017)

RIXS measures (pseudo) spin-spin correlations

$$R_M = \frac{1}{2}(\epsilon \times \epsilon') \cdot \mathbf{N} \qquad N_\alpha = f_\alpha \tilde{S}_\alpha$$

"Spin-Orbit Mott insulator"

Iridates

L$_3$

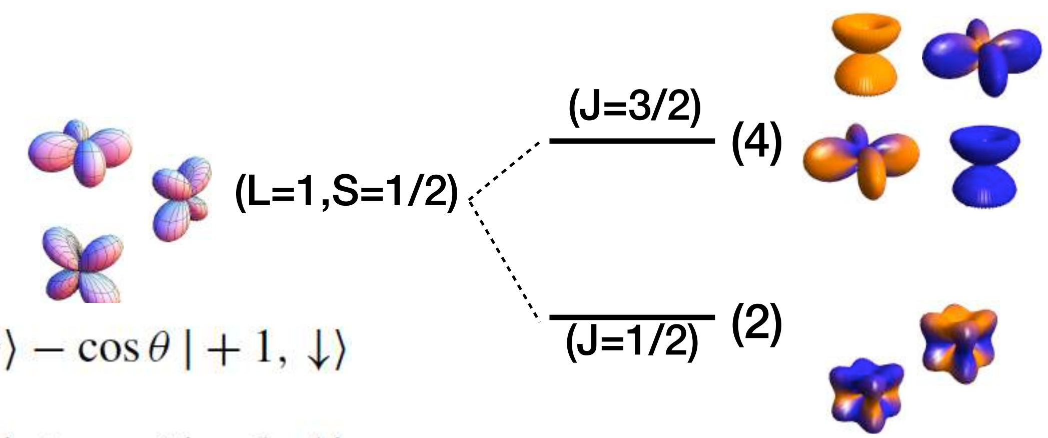
$$f_{x/y} = -3\sqrt{2}\sin 2\theta,$$

$$f_z = -2\sqrt{2}(\sin 2\theta + \sqrt{2}\cos 2\theta)$$

L$_2$

$$f_{x/y} = 0,$$

$$f_z = -3 + \cos 2\theta + 2\sqrt{2}\sin 2\theta$$



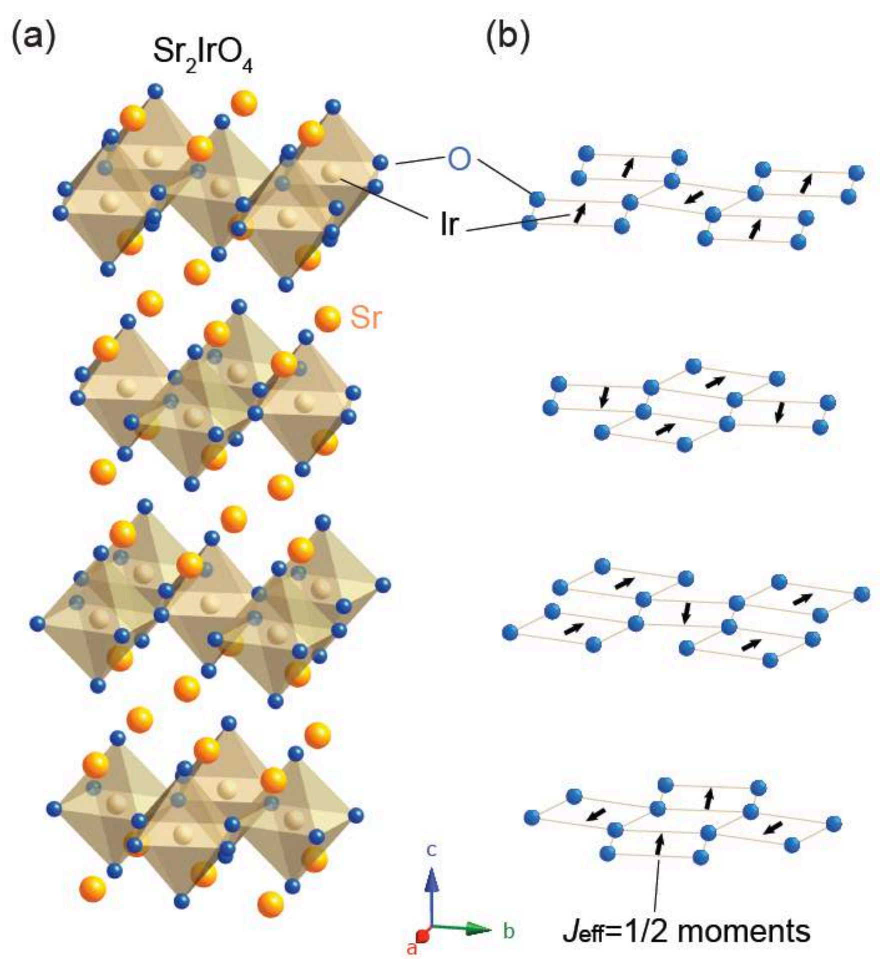
$$|\tilde{\uparrow}\rangle = +\sin\theta\,|0,\uparrow\rangle - \cos\theta\,|+1,\downarrow\rangle$$

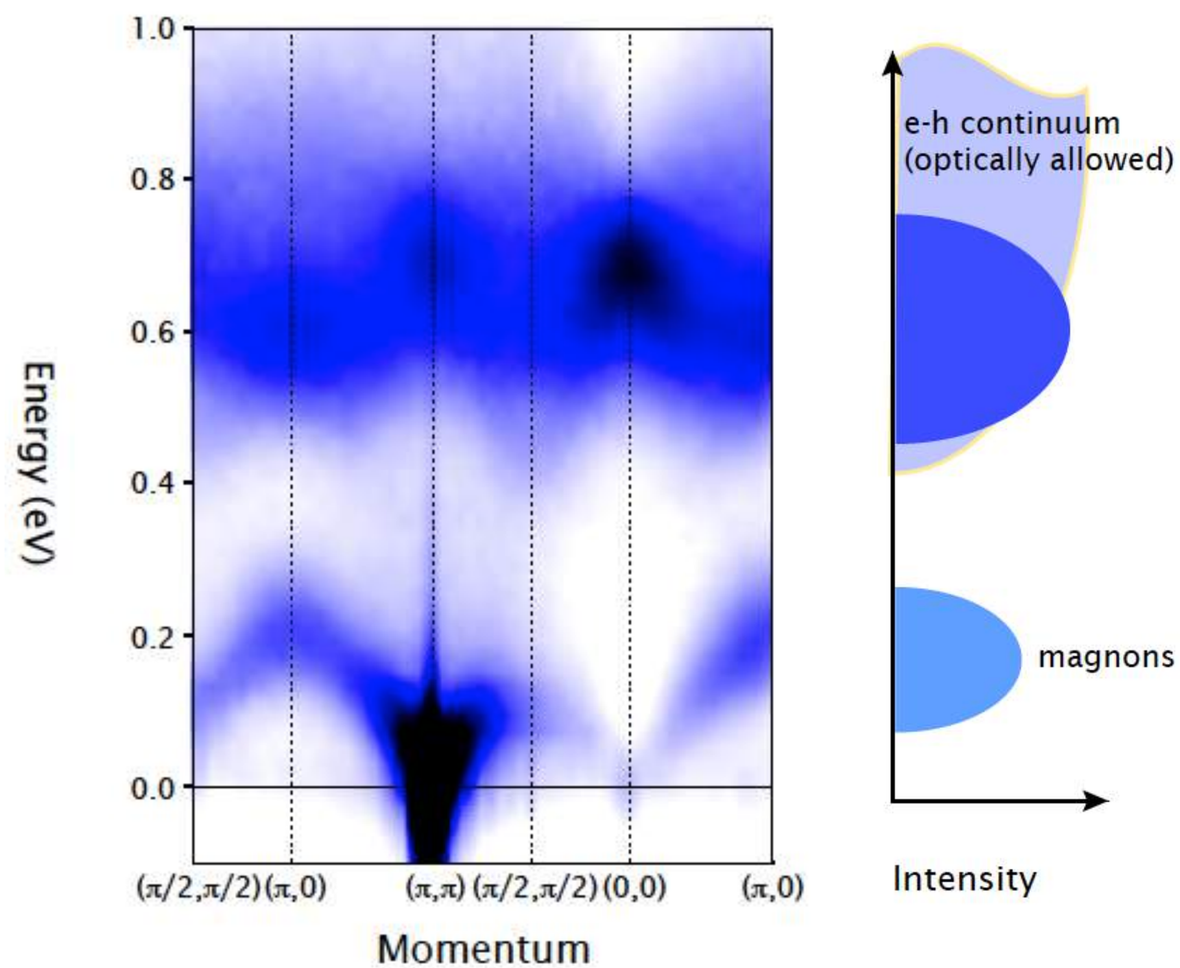
$$|\tilde{\downarrow}\rangle = -\sin\theta\,|0,\downarrow\rangle + \cos\theta\,|-1,\uparrow\rangle$$

Q_{zz} (quadrupole)	L_3 edge	L_2 edge
d^1,$(-1)d^5$	$-2L_z^2 + 2L_zS_z$	$-L_z^2 - 2L_zS_z$
d^2,$(-1)d^4$	$2L_z^2 + L_zS_z$	$L_z^2 - L_zS_z$
Q_{xy} (quadrupole)	L_3 edge	L_2 edge
d^1,$(-1)d^5$	$-2L_xL_y - 2L_yL_x + 2L_xS_y + 2L_yS_x$	$-L_xL_y - L_yL_x - 2L_xS_y - 2L_yS_x$
d^2,$(-1)d^4$	$2L_xL_y + 2L_yL_x + L_xS_y + L_yS_x$	$L_xL_y + L_yL_x - L_xS_y - L_yS_x$
N_z (magnetic)	L_3 edge	L_2 edge
d^1,d^5	$2L_z - 4S_z + 8L_z^2S_z - 2L_z(\mathbf{L}\cdot\mathbf{S}) - 2(\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4S_z - 8L_z^2S_z + 2L_z(\mathbf{L}\cdot\mathbf{S}) + 2(\mathbf{L}\cdot\mathbf{S})L_z$
d^2, d^4	$2L_z - 4L_z^2S_z + L_z(\mathbf{L}\cdot\mathbf{S}) + (\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4L_z^2S_z - L_z(\mathbf{L}\cdot\mathbf{S}) - (\mathbf{L}\cdot\mathbf{S})L_z$
d^3	$(4/3)S_z$	$-(4/3)S_z$

BJK et al. PRL (2008), BJK et al., Science (2009)

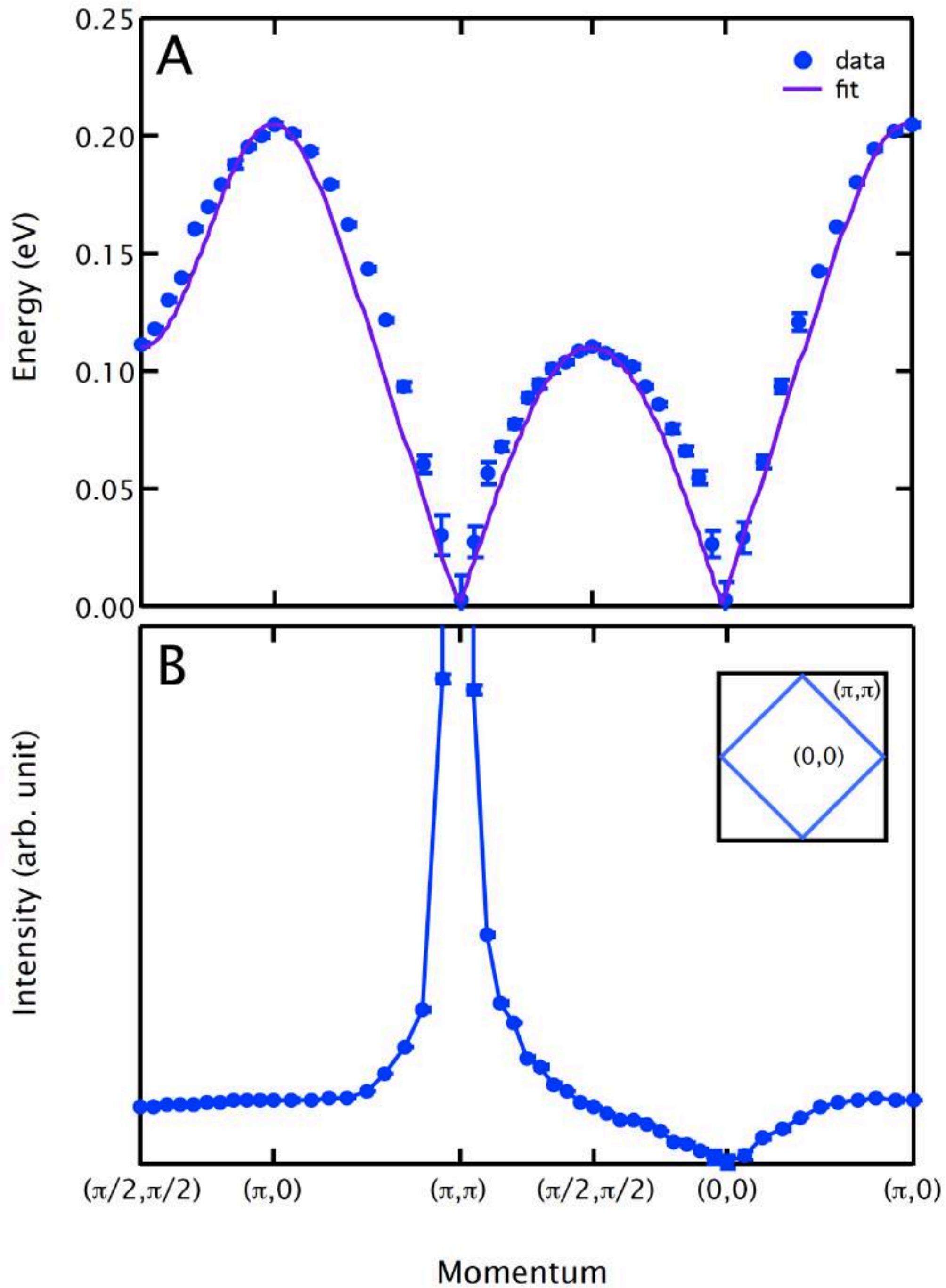
Magnetic excitations in Sr_2IrO_4

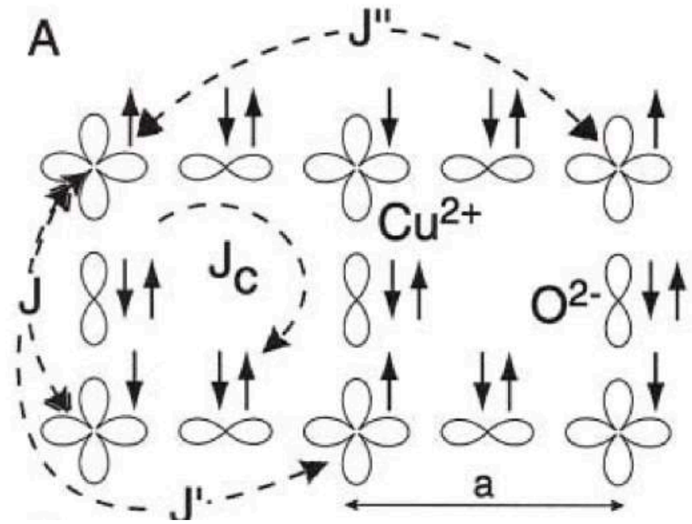




J. Kim & BJK et al. PRL (2012)

Fit to Heisenberg model





J=60

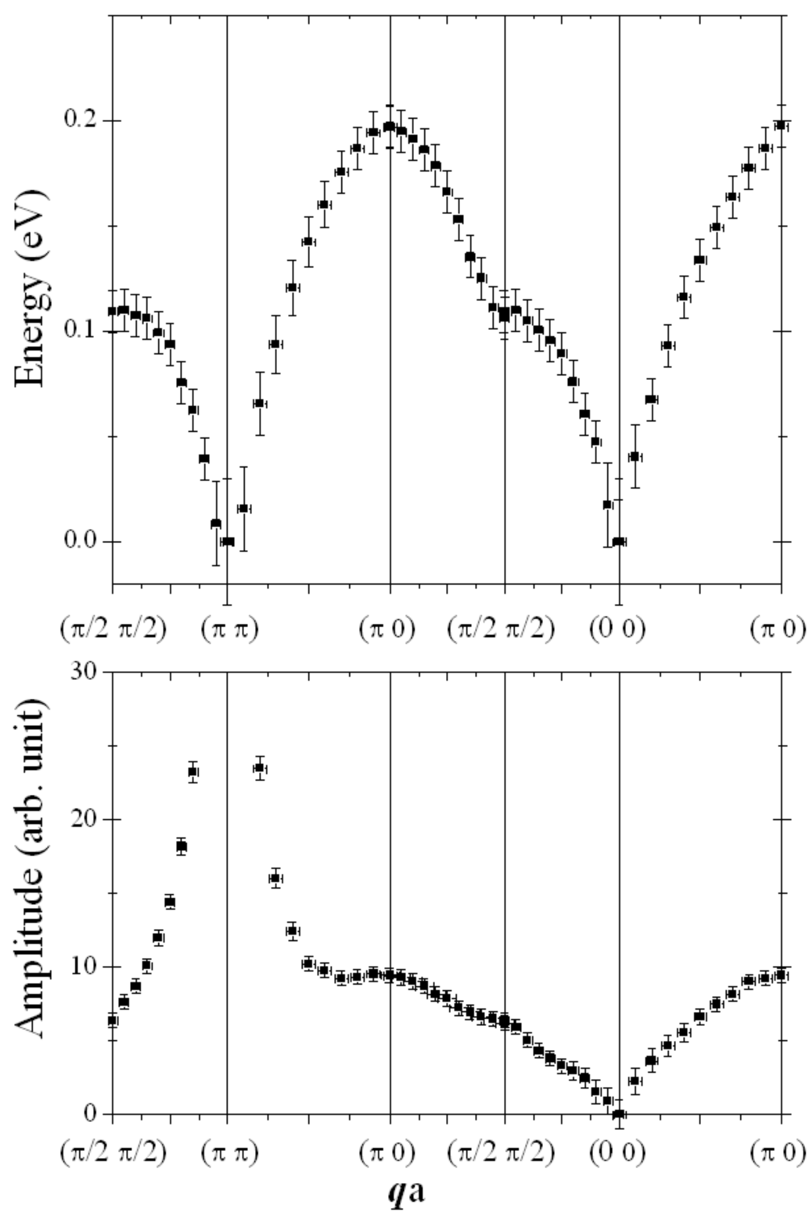
J’=-20

J”=15

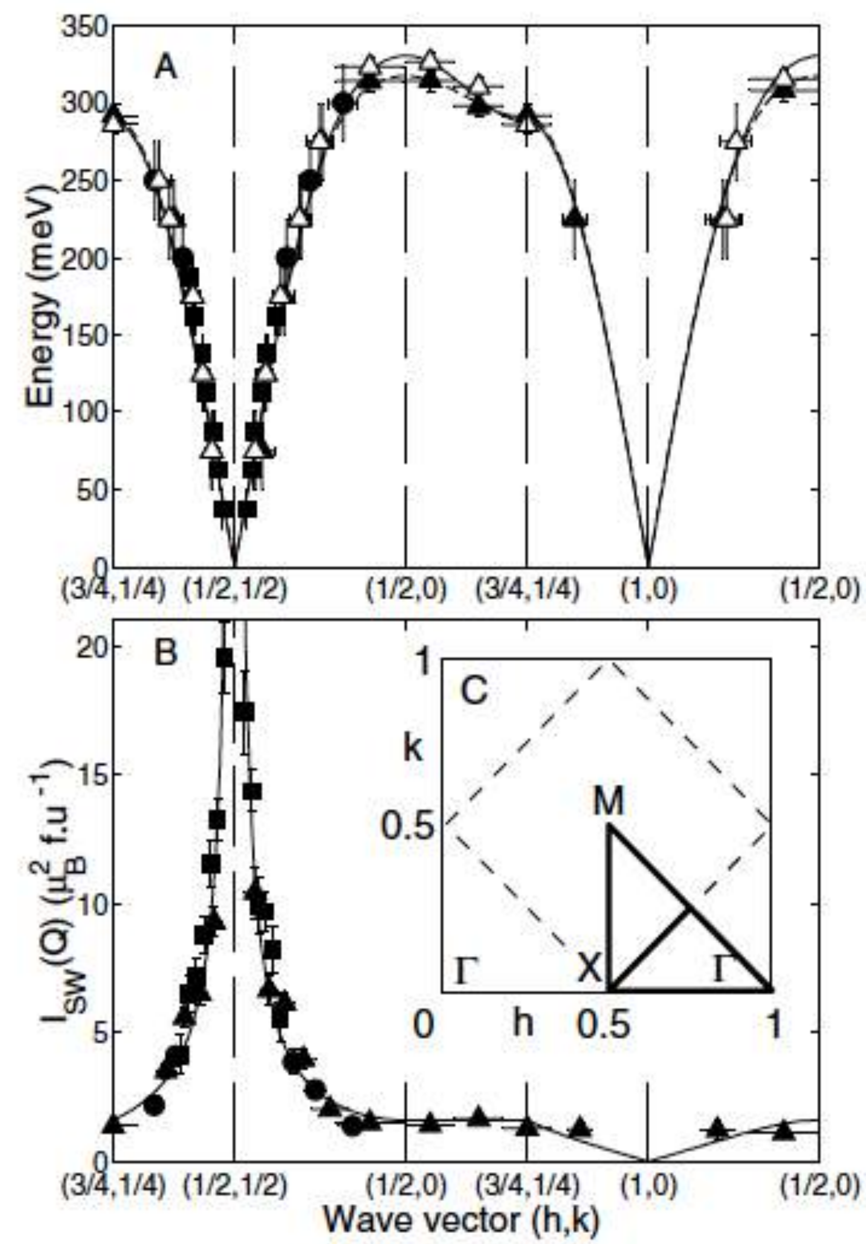
J_c=0 (suppressed)

Very similar spin dynamics

Our RIXS data on Sr_2IrO_4



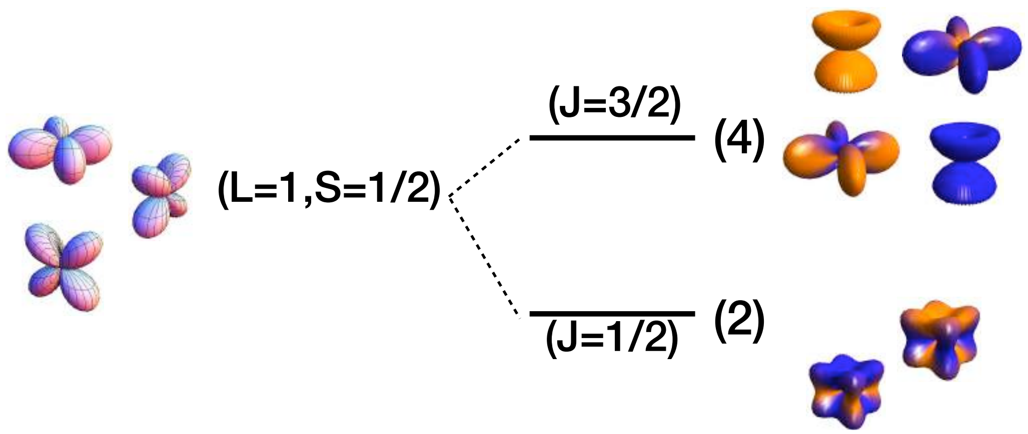
Neutron data on La_2CuO_4

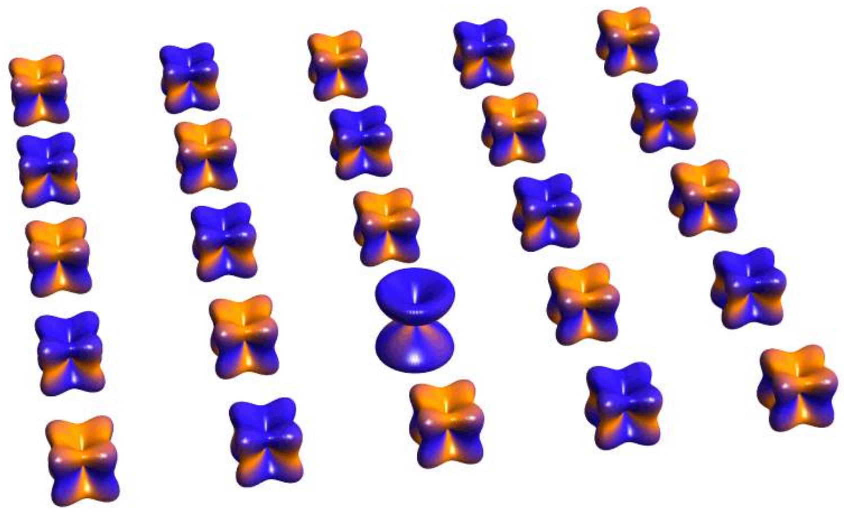


Coldea et al., PRL (2001)

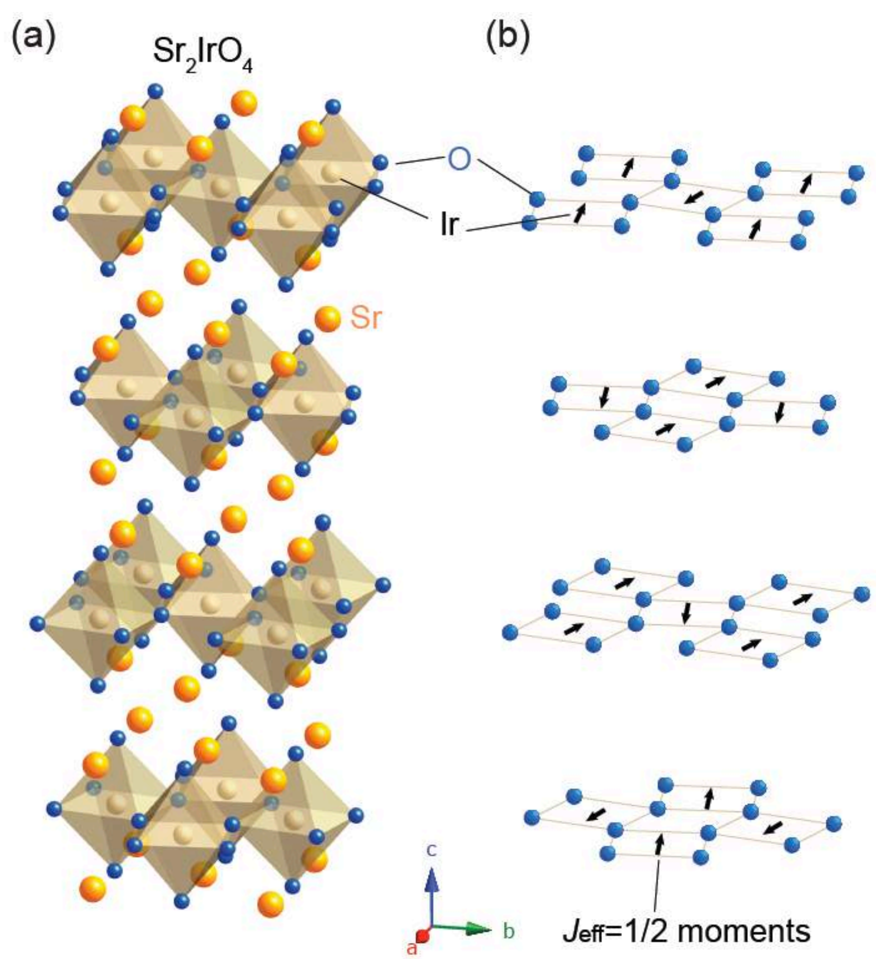
Superconductivity in Sr_2IrO_4 upon carrier doping?

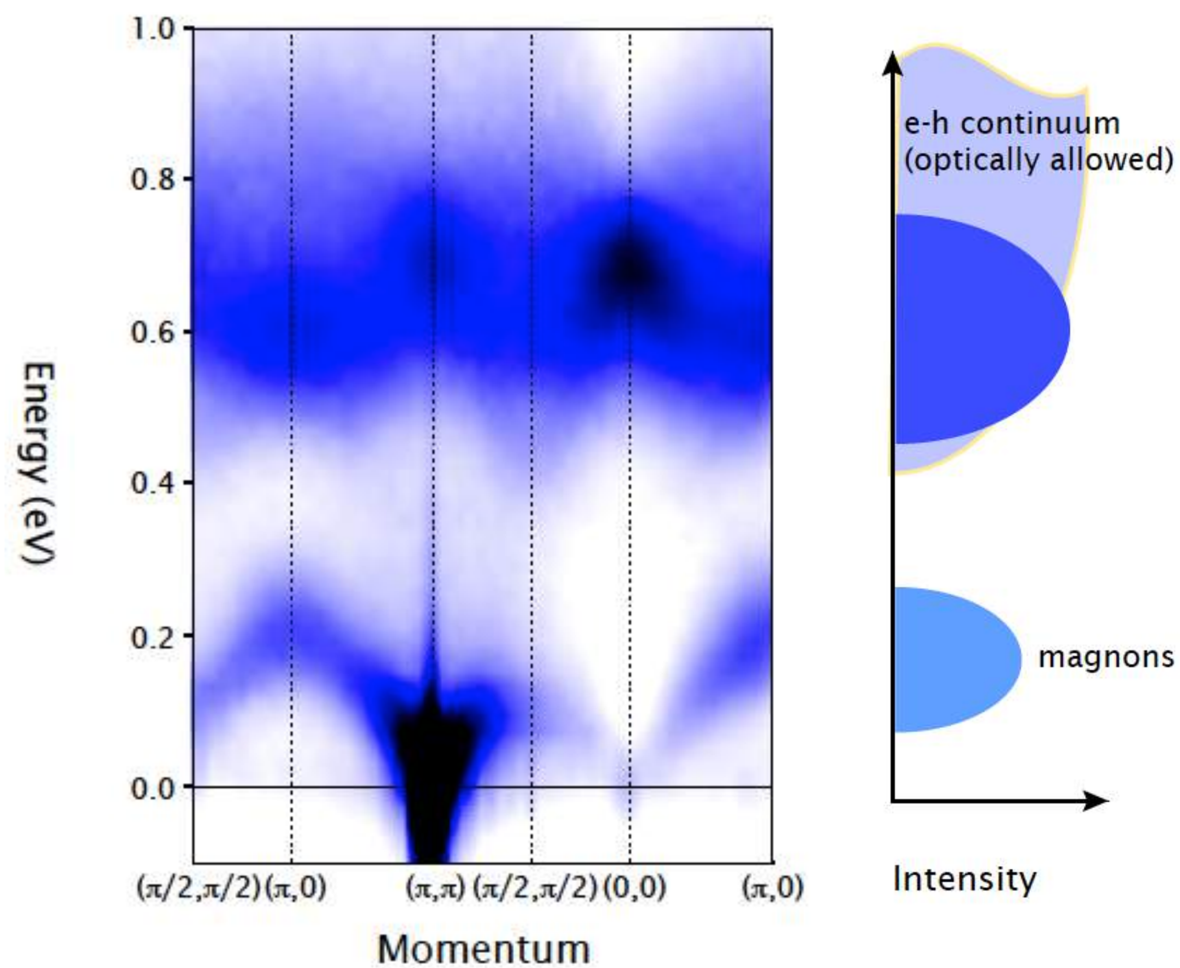
Spin-orbit exciton





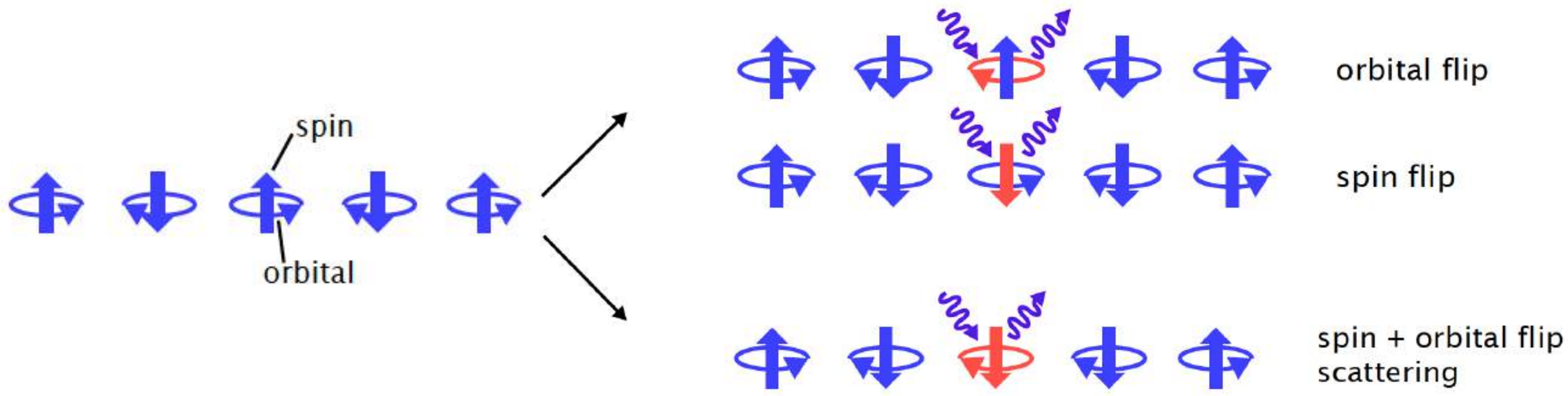
Magnetic excitations in Sr_2IrO_4

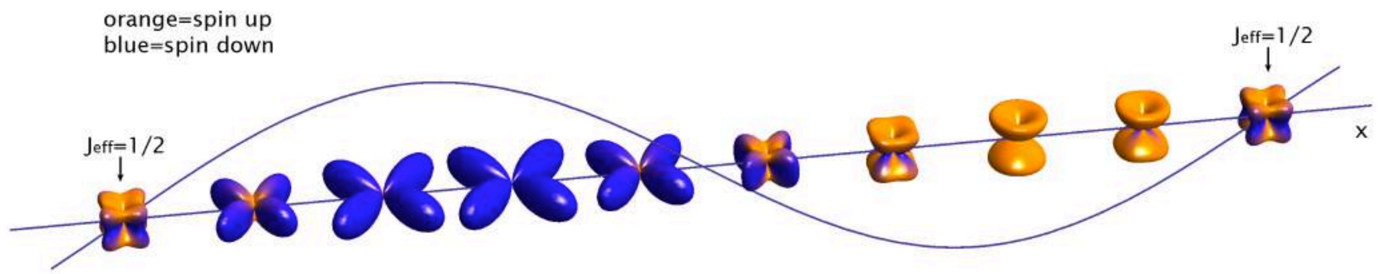




J. Kim & BJK et al. PRL (2012)

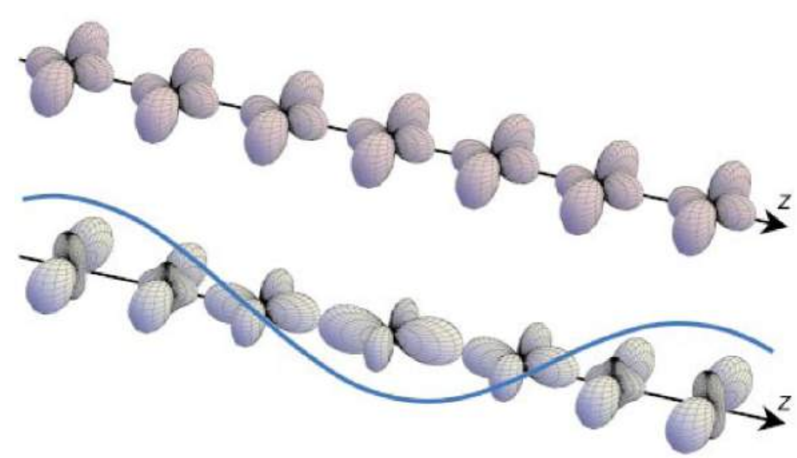
Spin-orbital waves



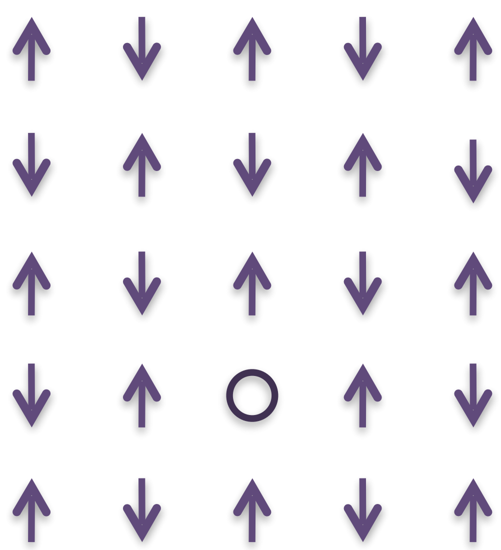


"Orbiton"

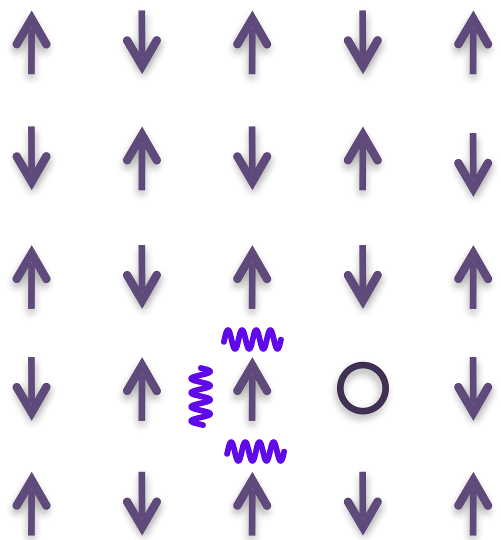
E. Saitoh et al., Nature (2001)



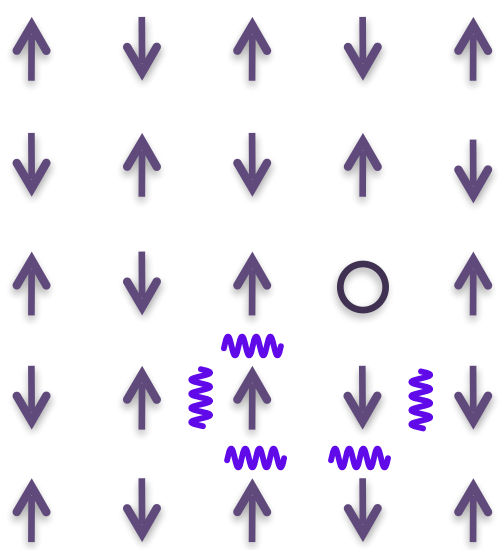
One-hole propagation



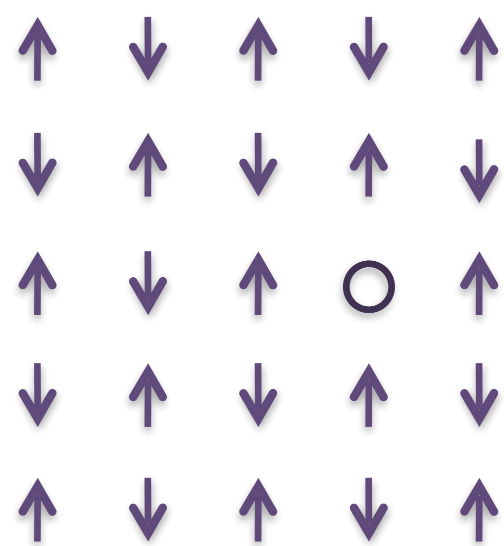
One-hole propagation



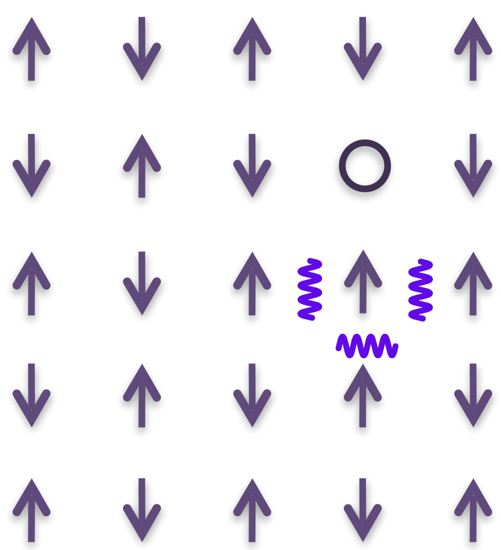
One-hole propagation

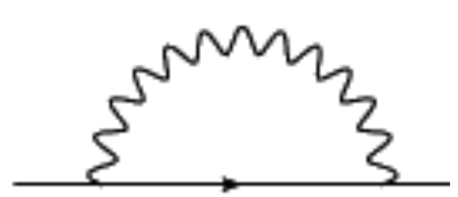


One-hole propagation

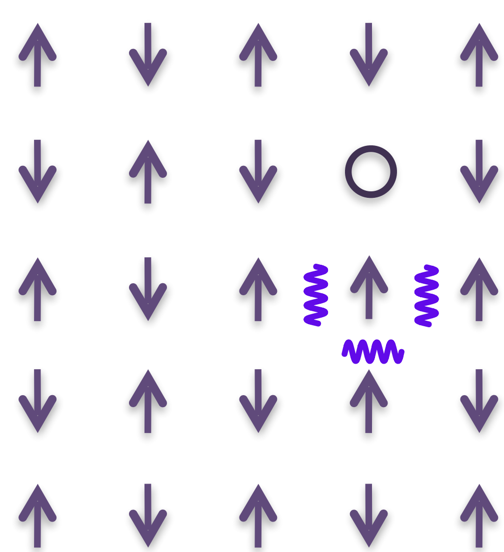


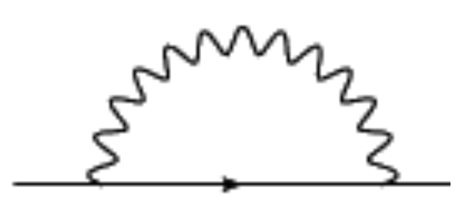
One-hole propagation



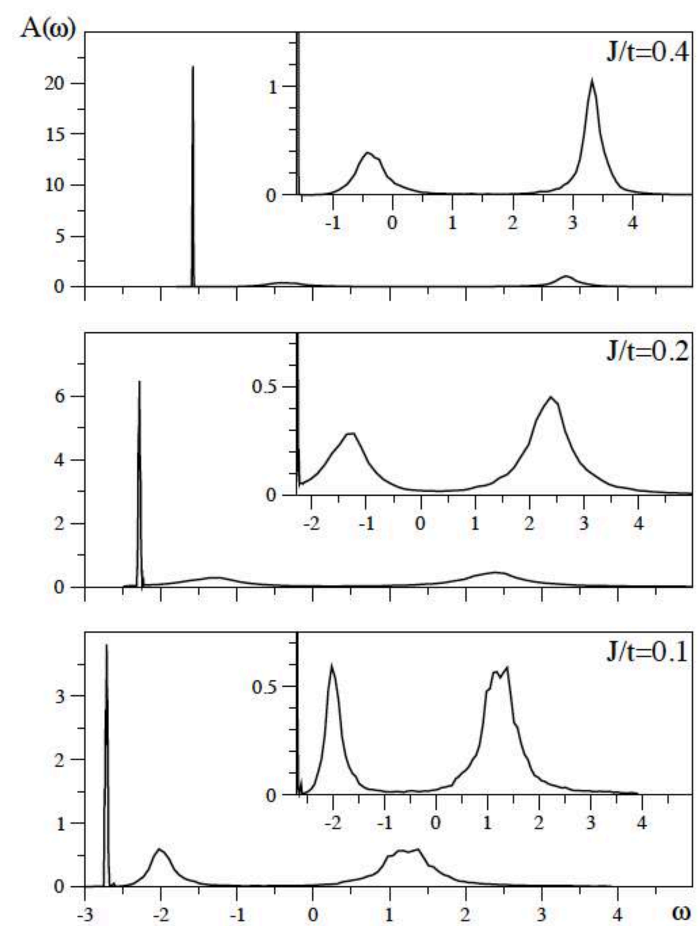


One-hole propagation



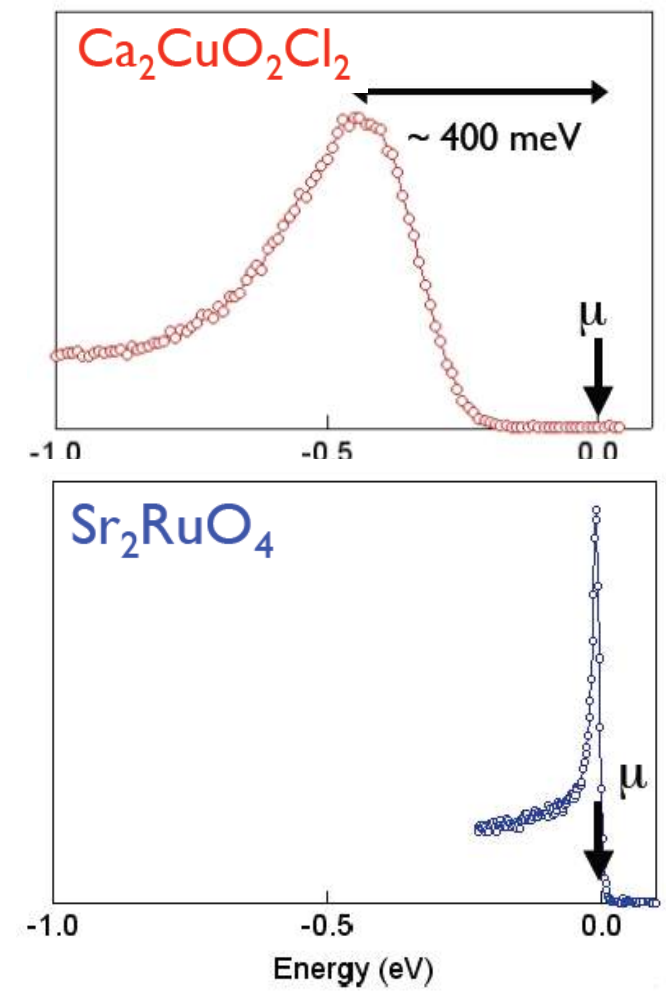


theory (t-J model)



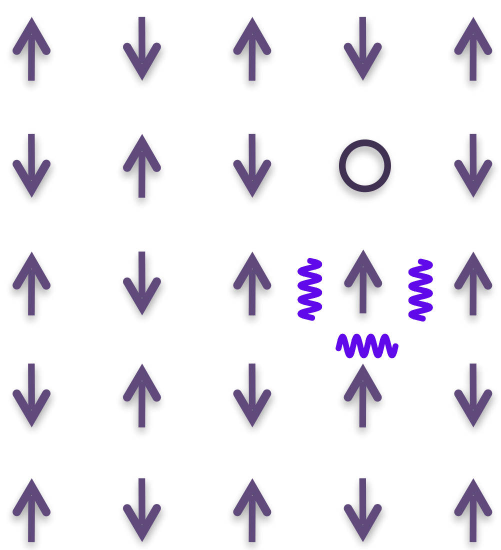
A. S. Mischenko et al. (2001)

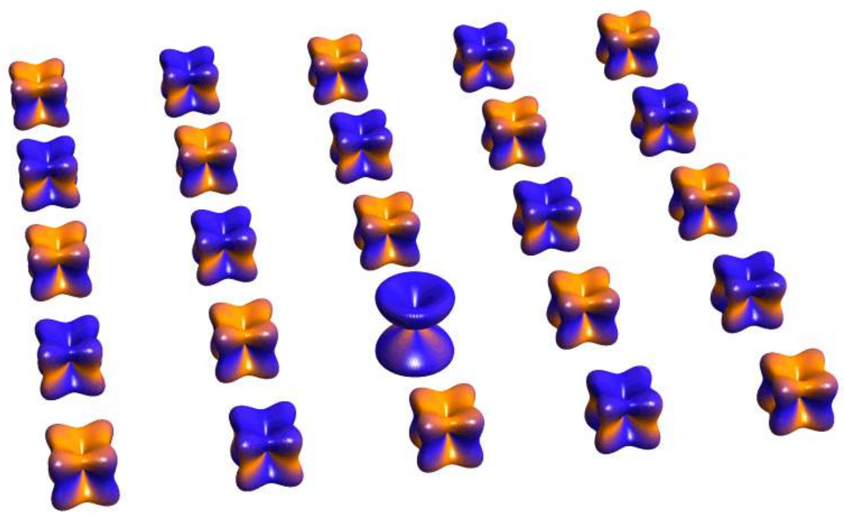
ARPES



Shen group

One-hole propagation



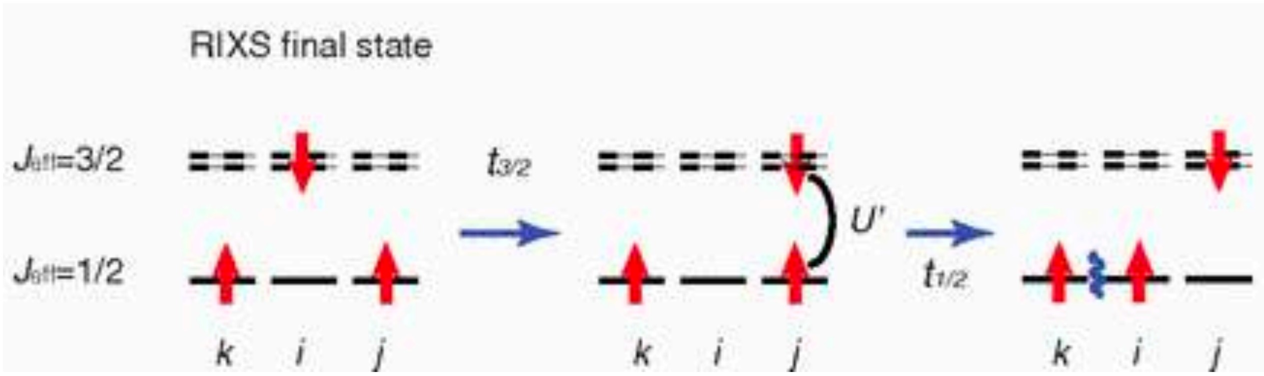


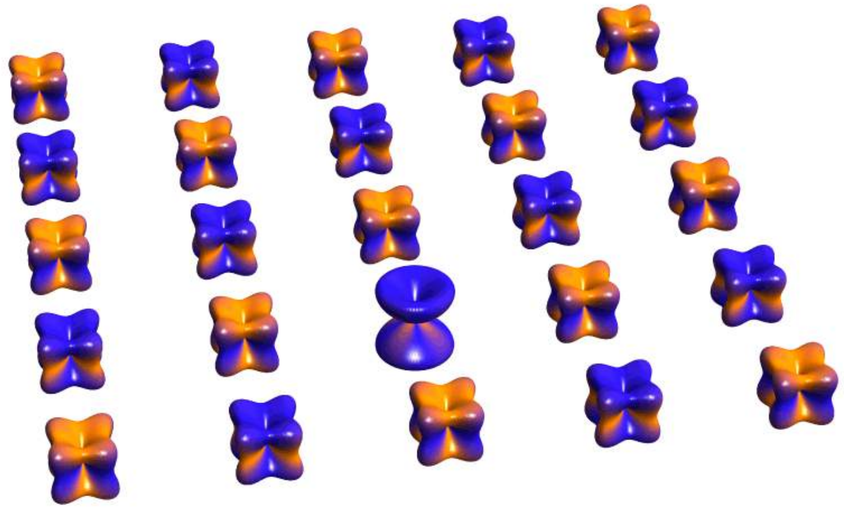
charge e-, spin-1/2 fermion

charge neutral, hard-core boson

One-hole propagation

hopping via superexchange process





charge neutral, hard-core boson

One-hole propagation

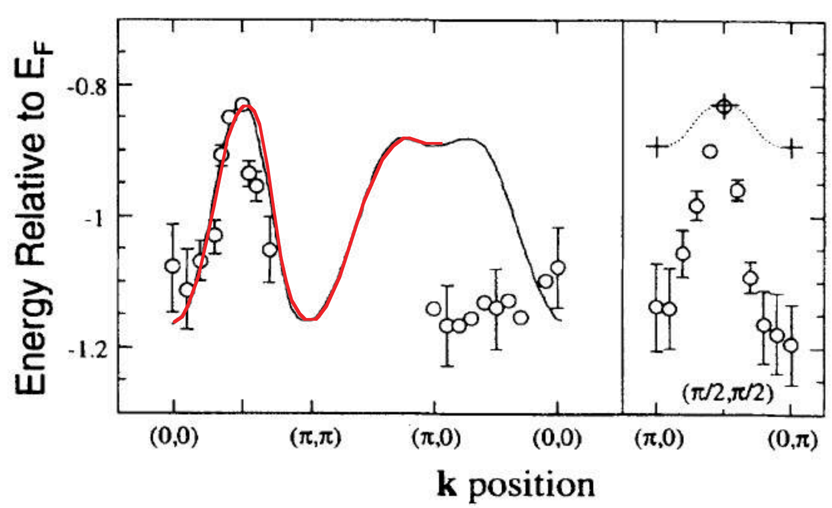
ARPES

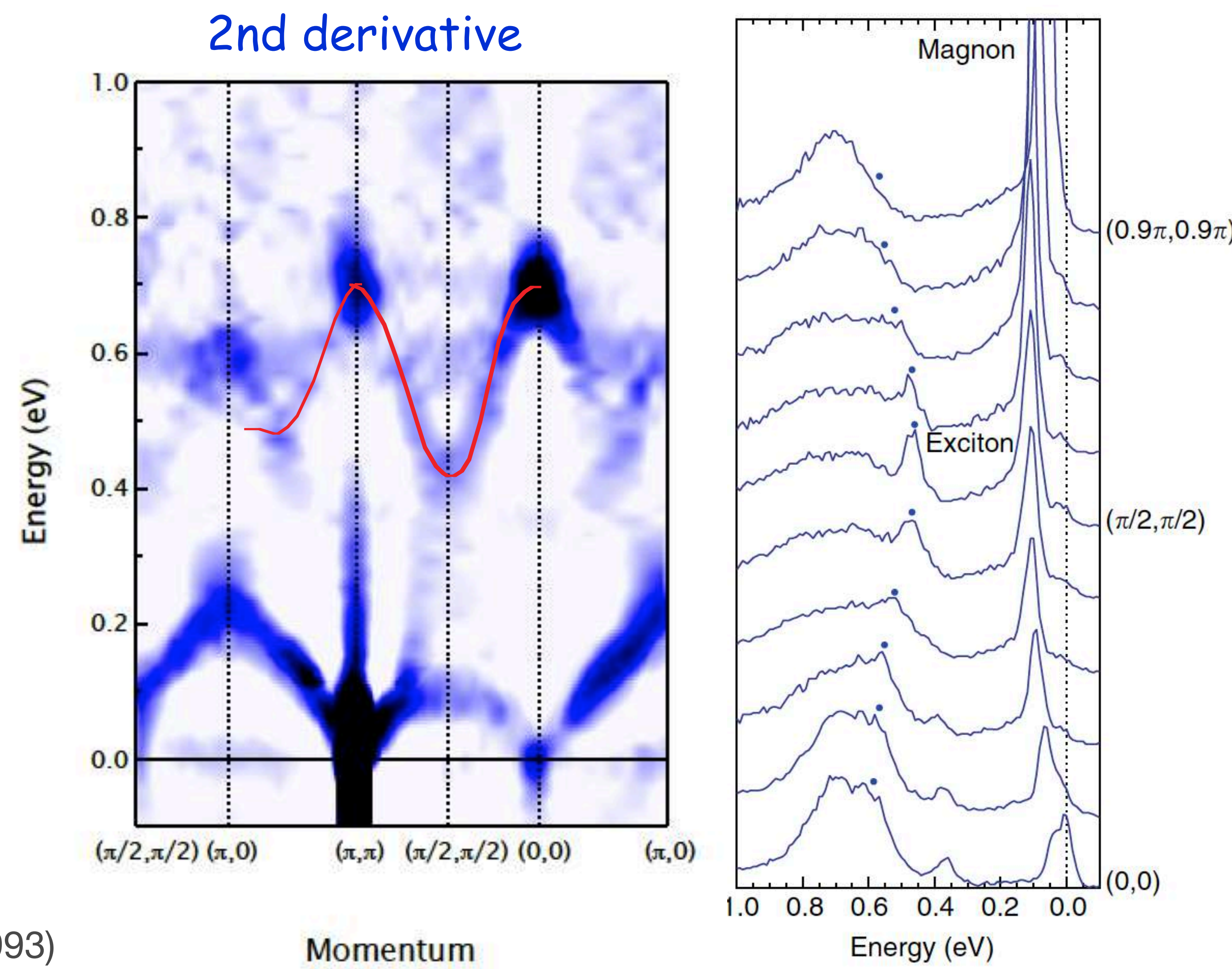
one-hole propagation in $Sr_2CuO_2Cl_2$

RIXS

one-exciton propagation in Sr_2IrO_4

B. O. Wells et al., PRL (1995)

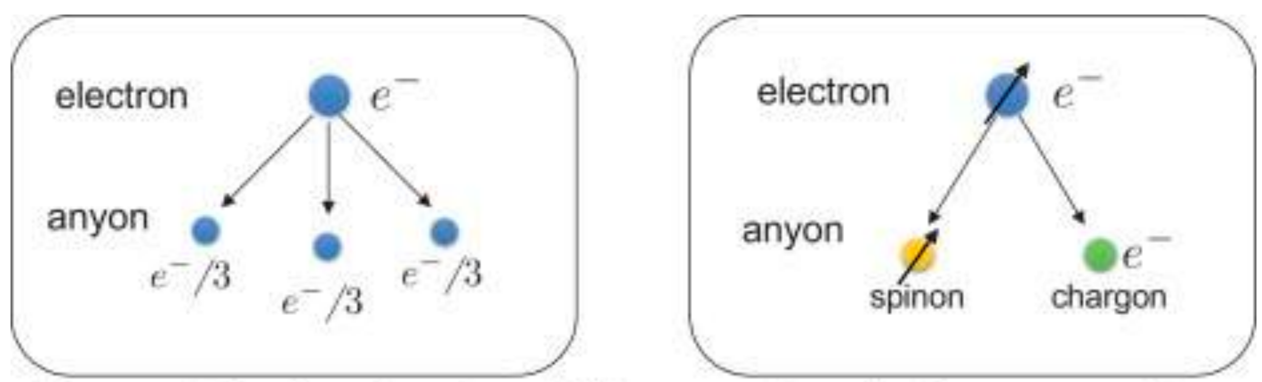




Schmitt-Rink, Varma, Ruckenstein, Phys. Rev. Lett. (1993)
Lee, Nagaosa & Wen, Rev. Mod. Phys. (2006)

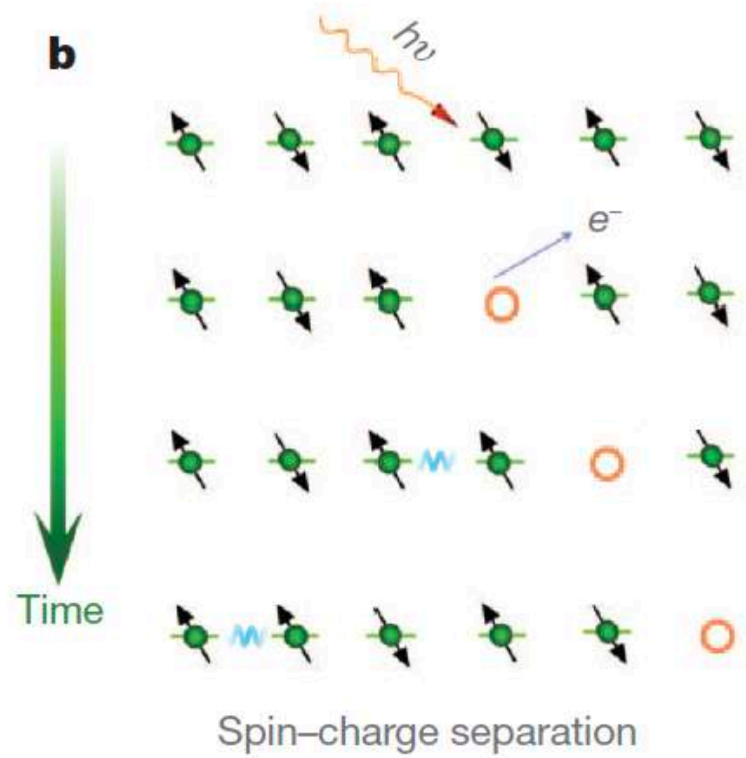
J. Kim & BJK et al. Nature Comm. (2014)

Fractional excitations

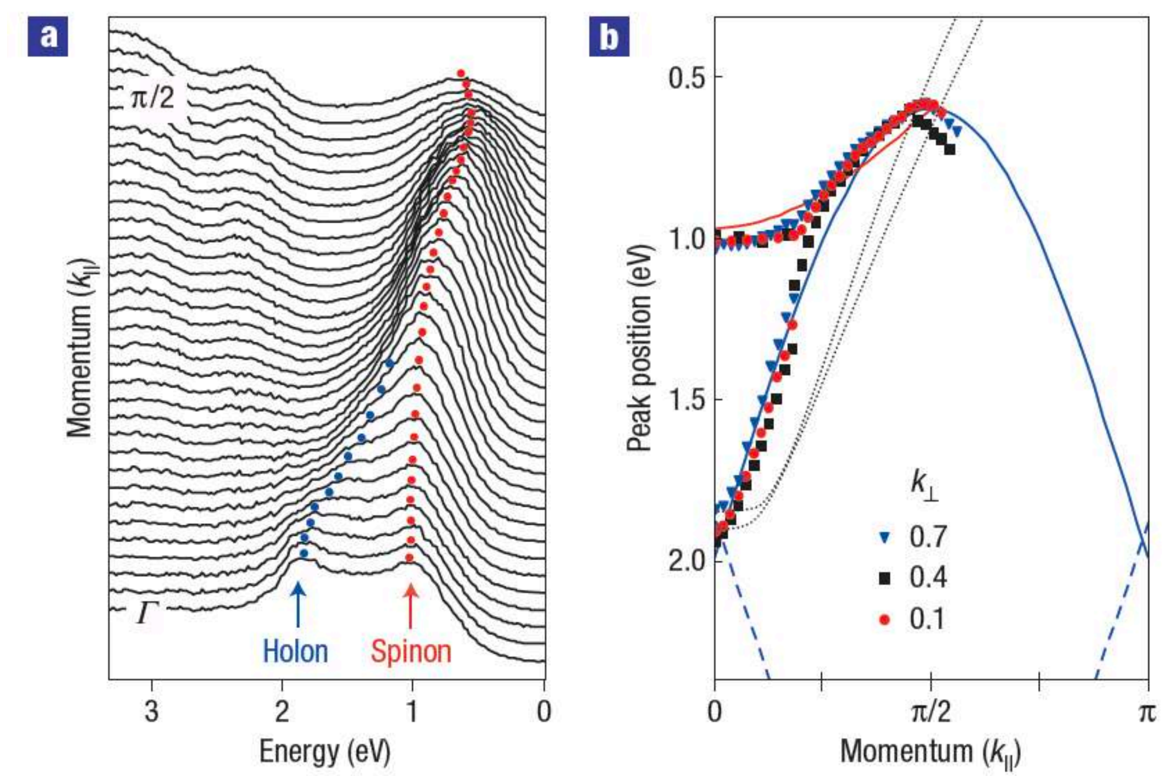


(a) $\nu = 1/3$ fractional quantum Hall (b) spin-charge separation

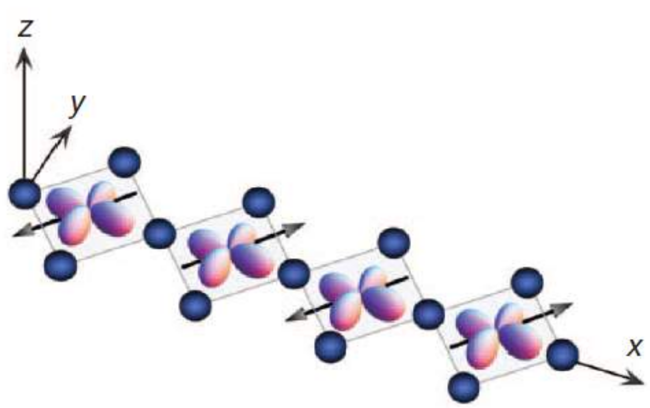
Spin-charge separation



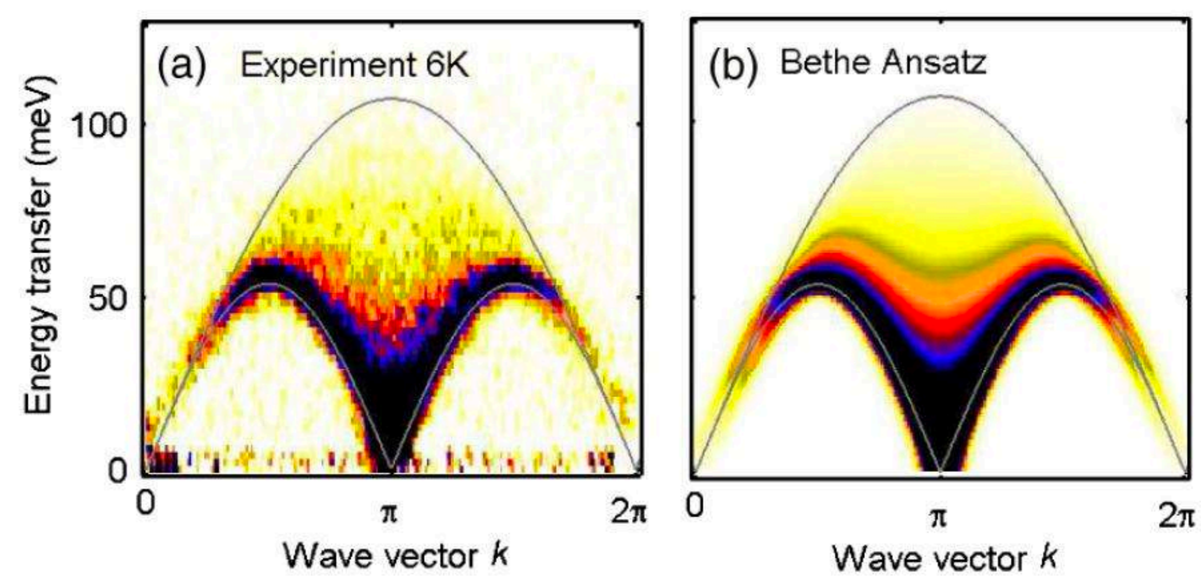
ARPES



1D chain structure in Sr_2CuO_3

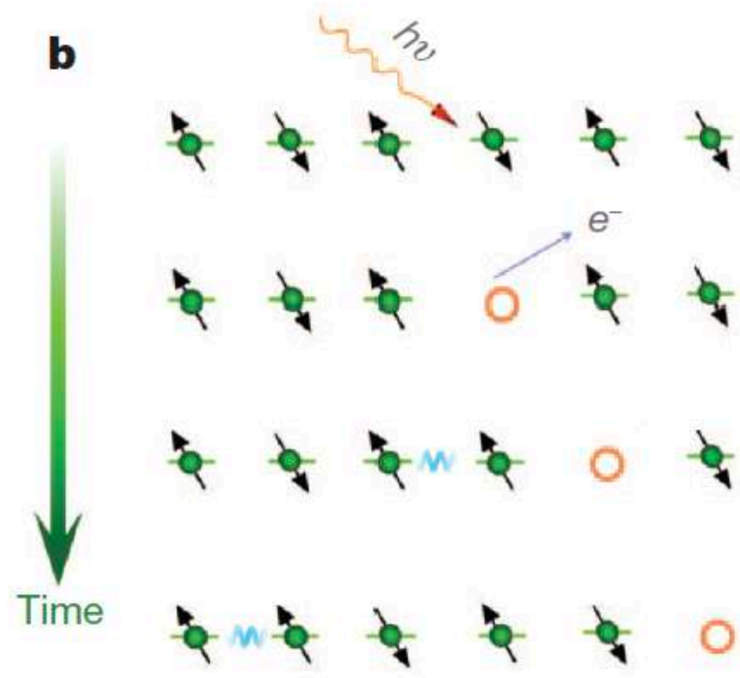


INS



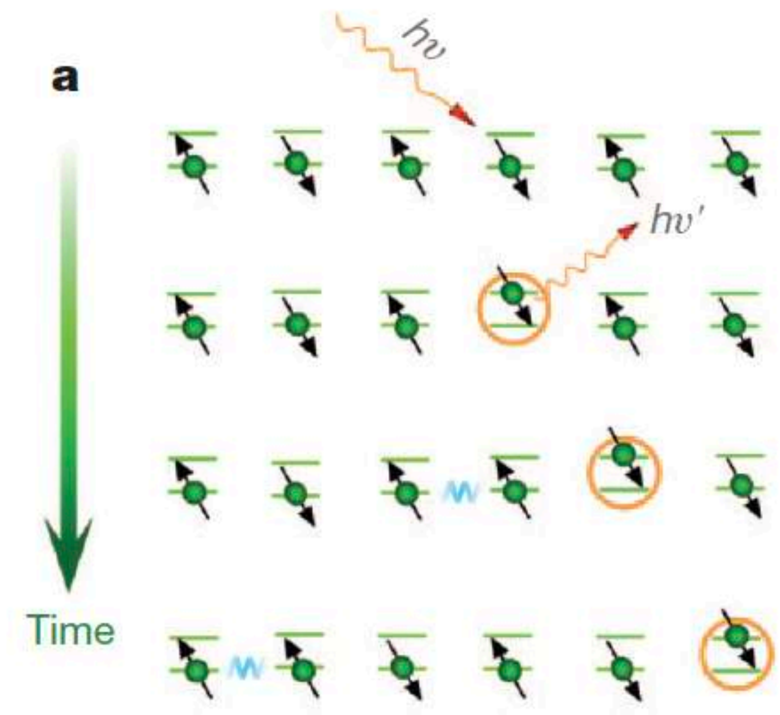
C. Kim et al. PRL (1996)
BJK, C. Kim et al. Nature Phys. (2006)

Spin-charge separation

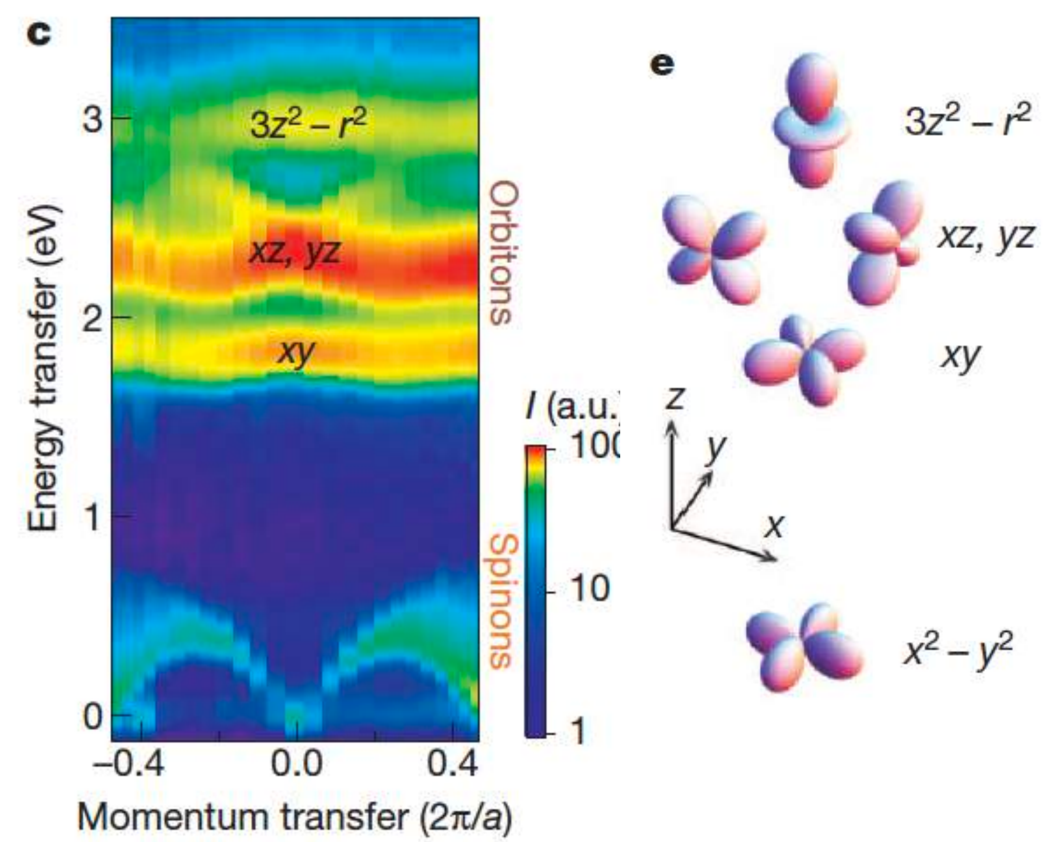


Spin–charge separation

Spin-orbital separation



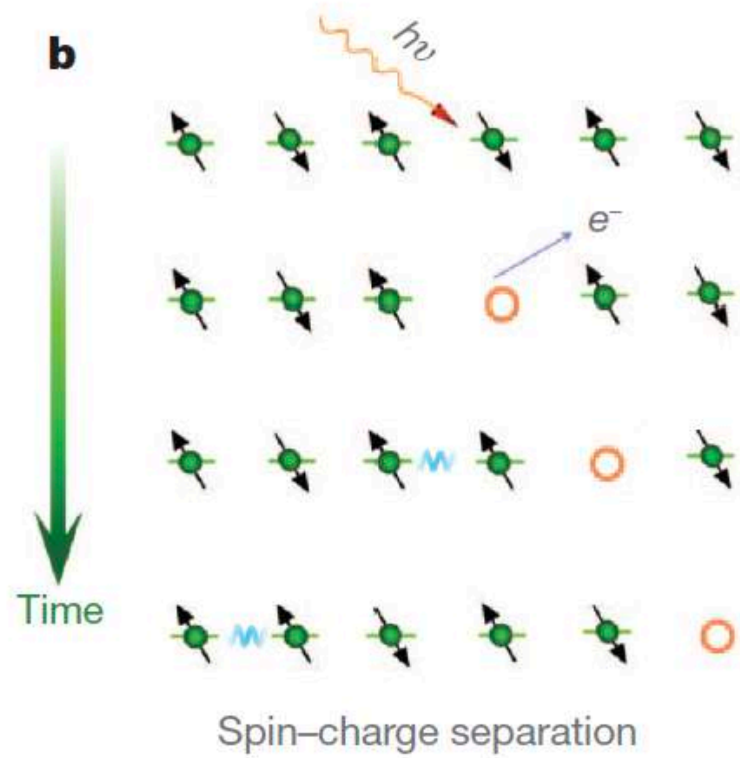
Spin–orbital separation

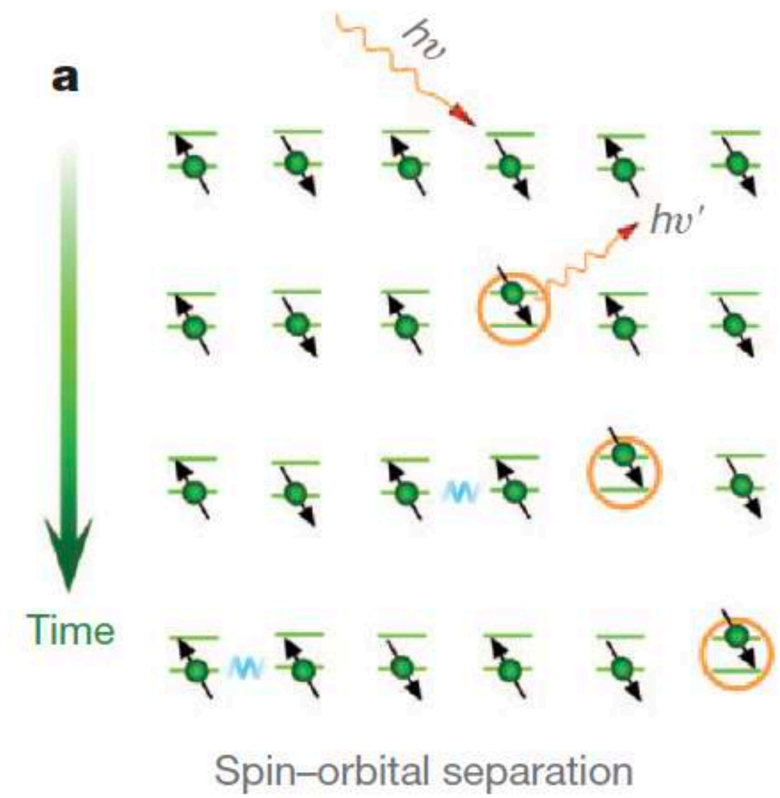


J. Schlappa et al. Nature (2012)

Spin-charge separation

Spin-orbital separation

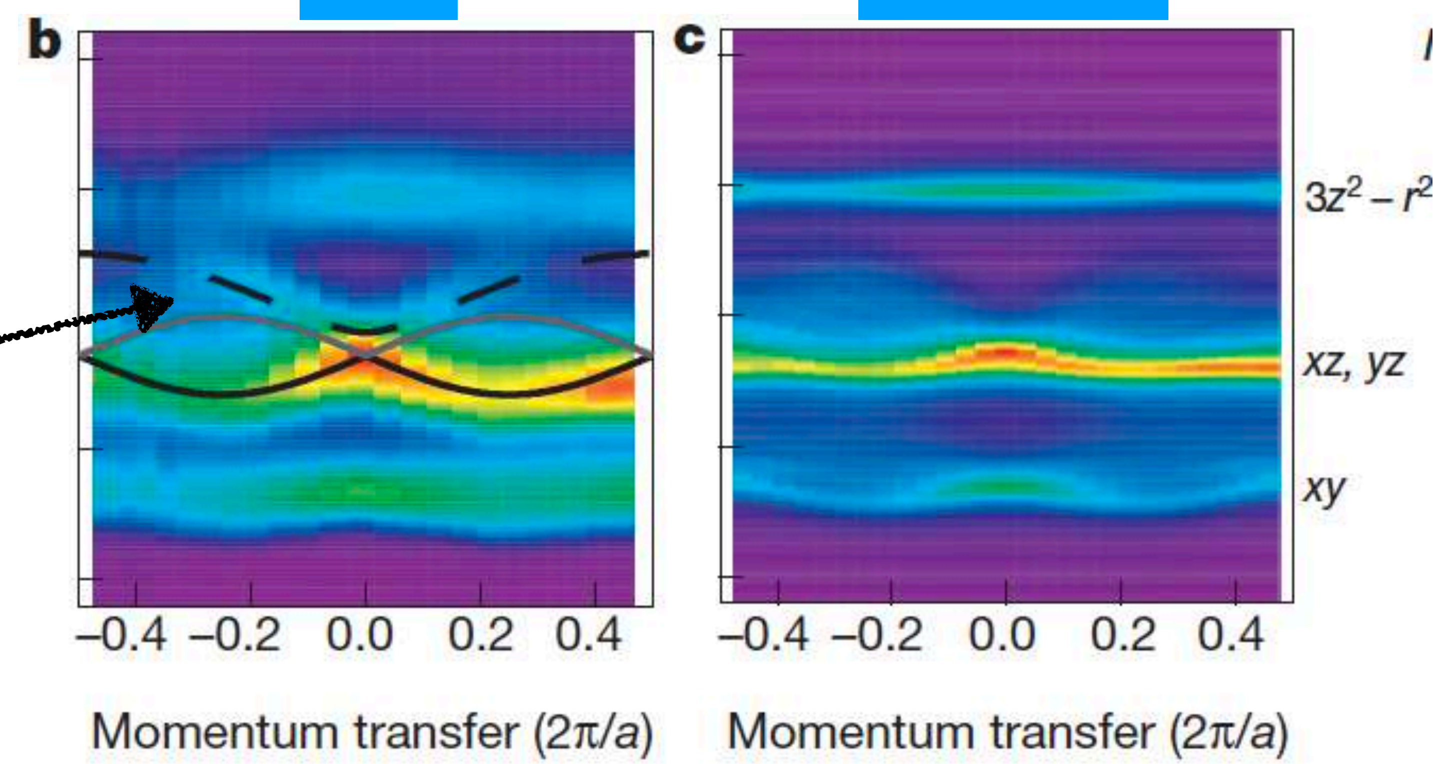




RIXS

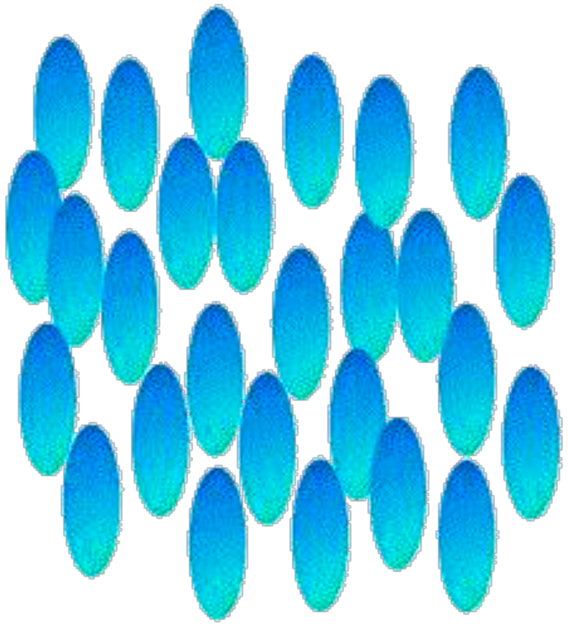
Simulation

Spinon-orbiton continuum

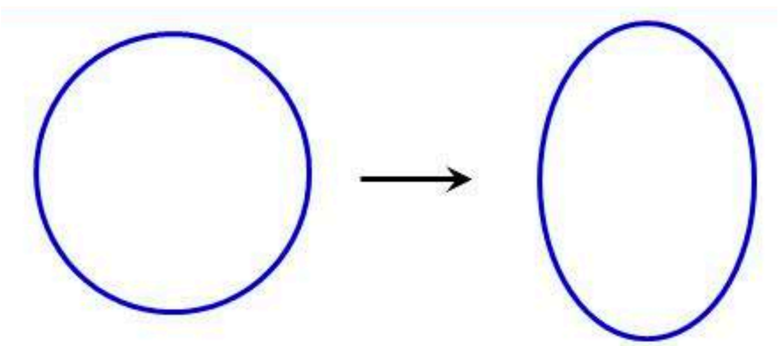


J. Schlappa et al. Nature (2012)

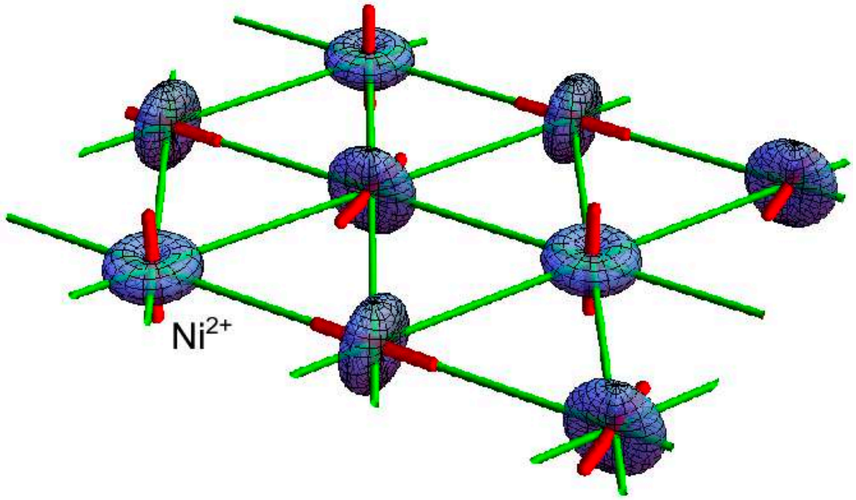
Spin nematic



Liquid crystal



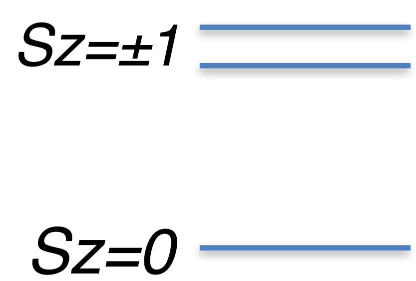
Fermi surface
anisotropic distortions

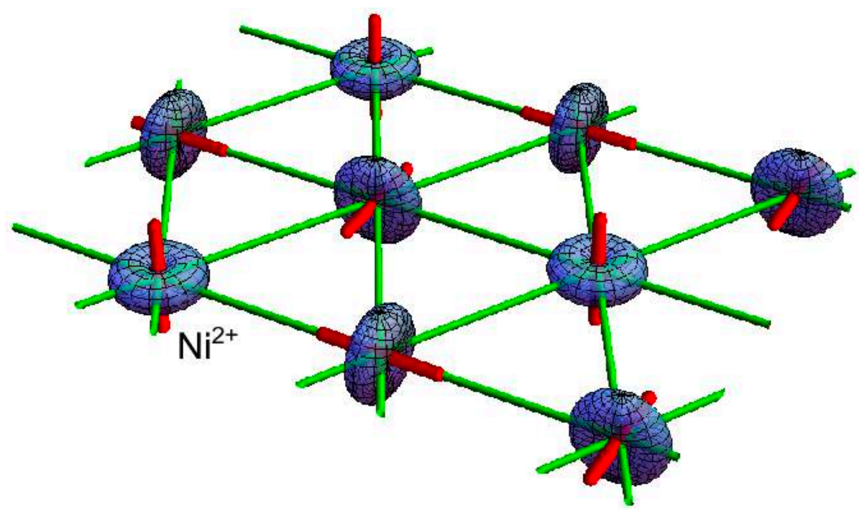


spin nematic

Spin nematic

$$H = J\sum_{\langle ij\rangle} \mathbf{S_i}\cdot\mathbf{S_j} + E\sum_i S_{zi}^2.$$





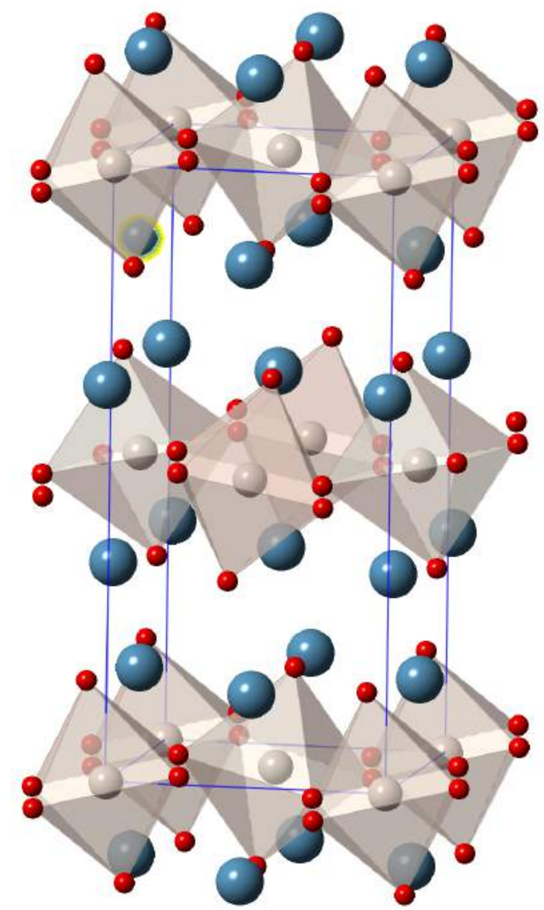
spin nematic

breaks rotational symmetry but preserves time-reversal symmetry

$\langle S\rangle=0$ and $\langle S^2\rangle\neq 0$

4d Mott insulator Ca_2RuO_4

- Metal-to-insulator transition at T=360 K
- (π,π) antiferromagnetic below T_N=110 K
- d^4 low-spin configuration, nominally S=1



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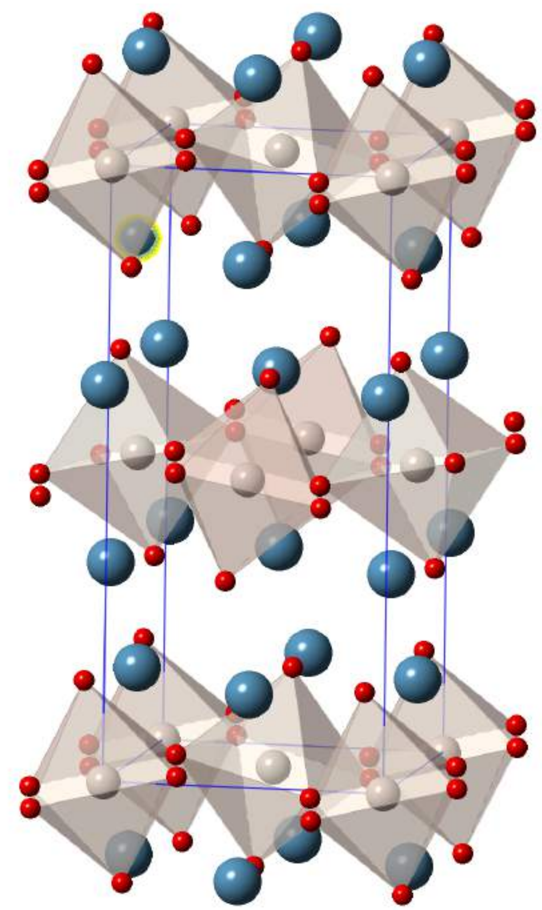
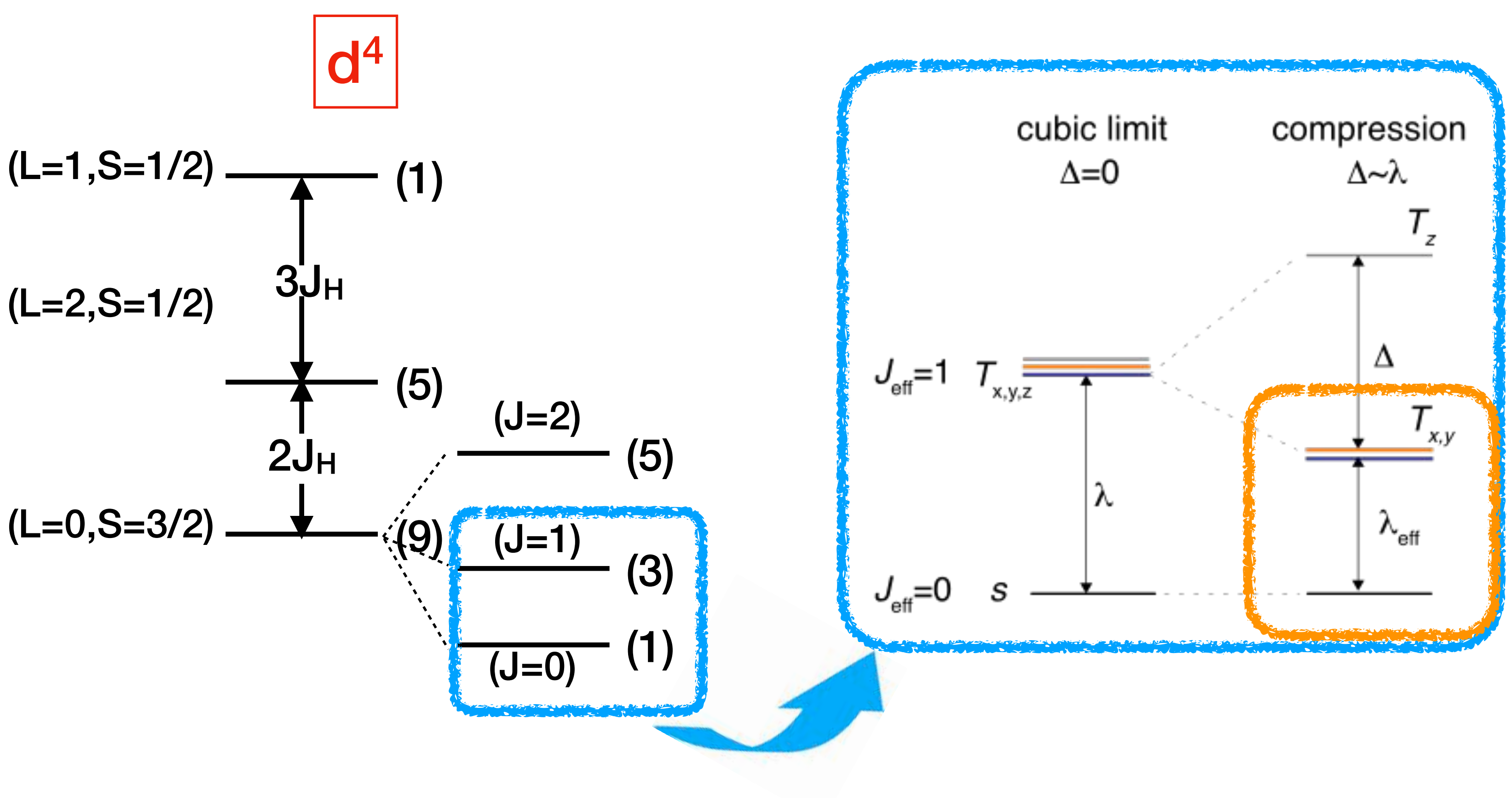




Pbca space group

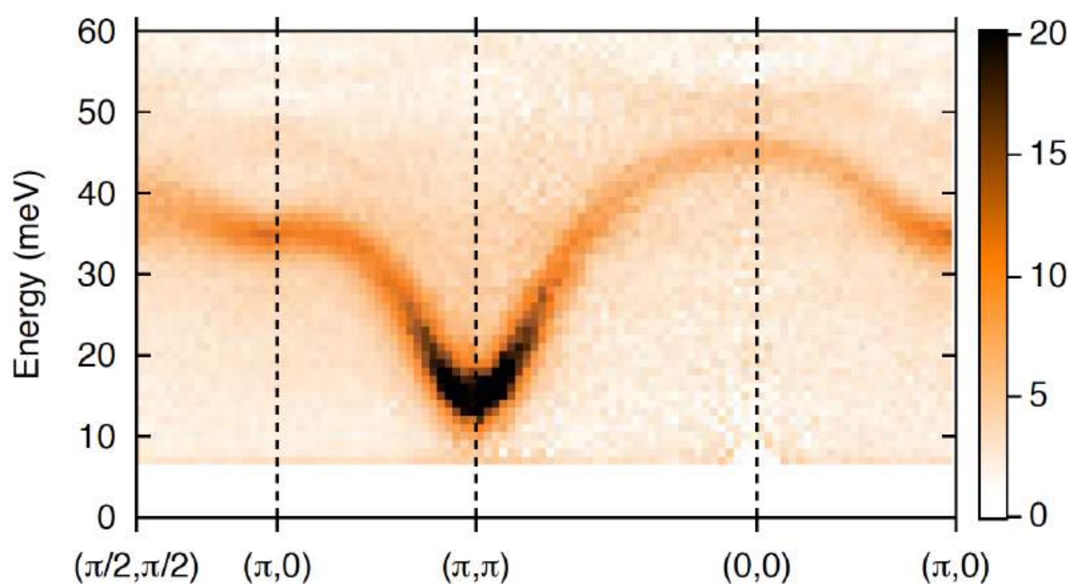
Octahedra:
rotated about c axis
tilited about b axis,
compressed along c

singlet-triplet model

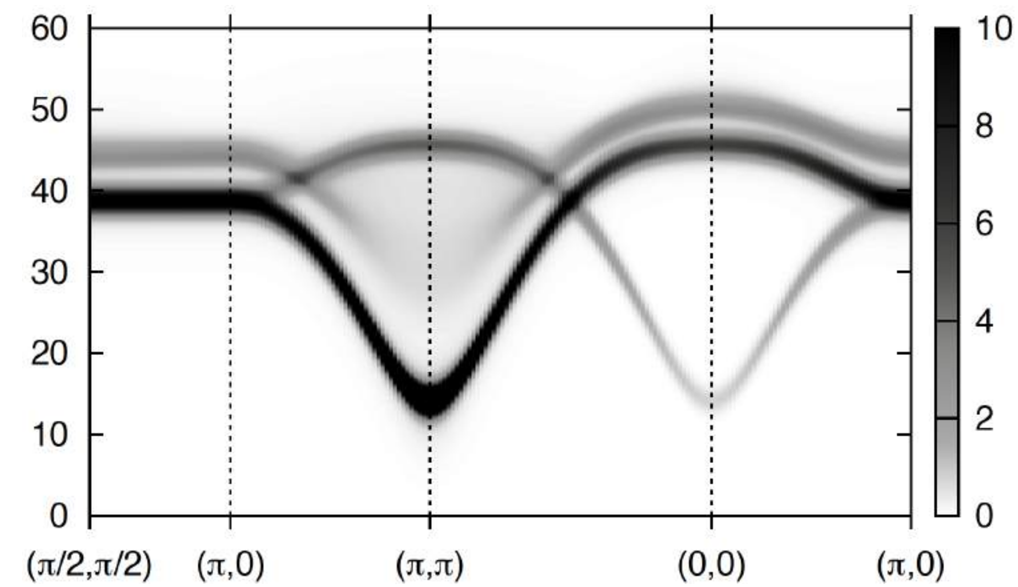
effective S=1 model

Anomalous dispersion

INS



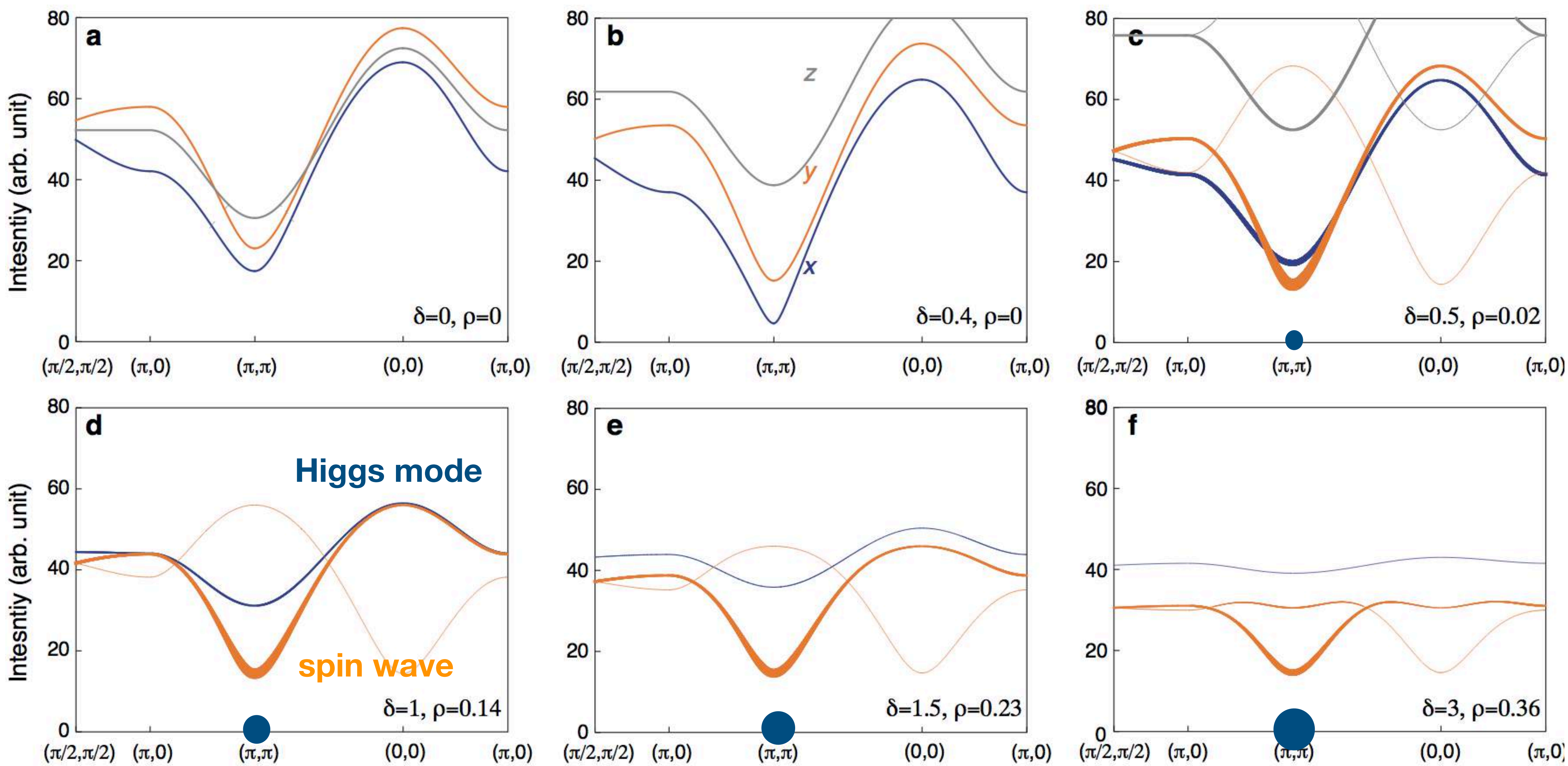
Simulation



$$H = J\sum_{\langle ij\rangle}(\mathbf{S_i}\cdot\mathbf{S_j} - \alpha S_{zi}S_{zj}) + \boxed{E\sum_i S_{zi}^2} + \epsilon\sum_i S_{xi}^2.$$

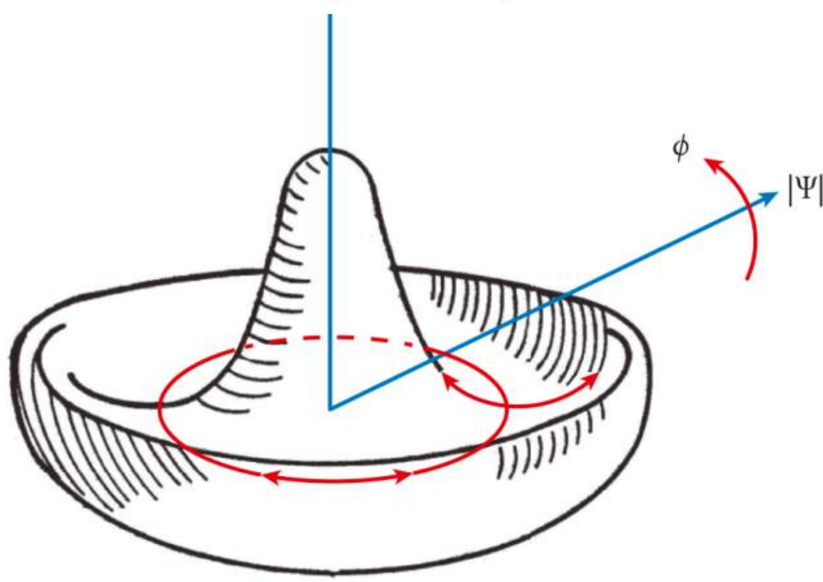
$$E \simeq 24,\ J \simeq 5.6,\ \epsilon \simeq 4.0\,\mathrm{meV},\ \text{and}\ \alpha = 0$$

Magnetic order by exciton condensation

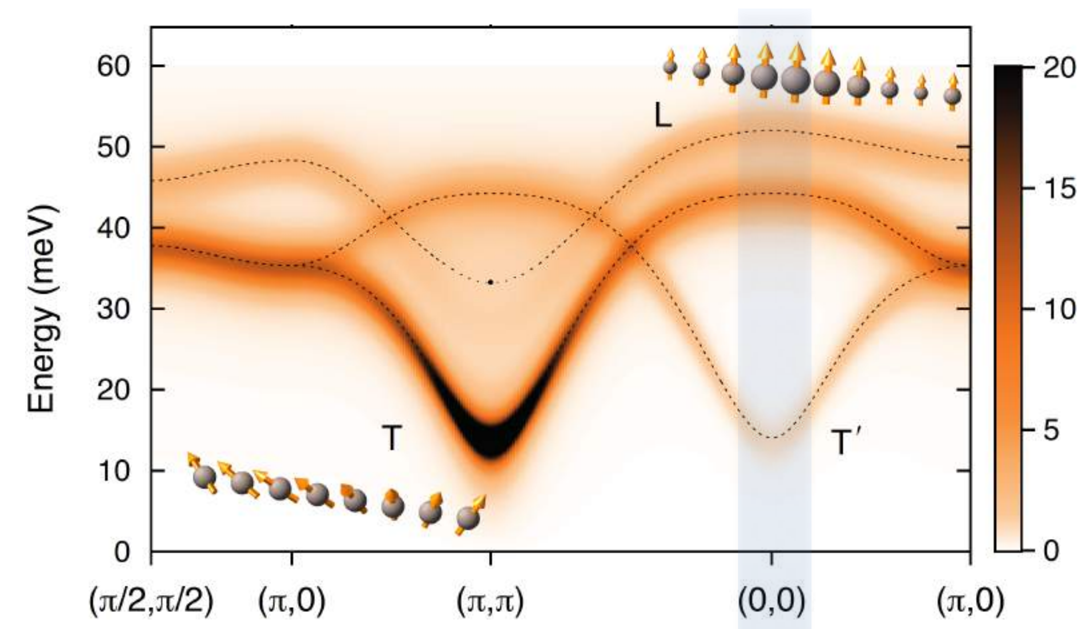


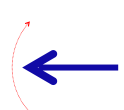
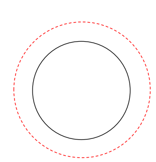
Higgs amplitude mode

$$\Psi(\mathbf{r},t) = \left|\Psi(\mathbf{r},t)\right| e^{i\phi(\mathbf{r},t)}$$



Pekker D, Varma CM. 2015.
Annu. Rev. Condens. Matter Phys. 6:269–297

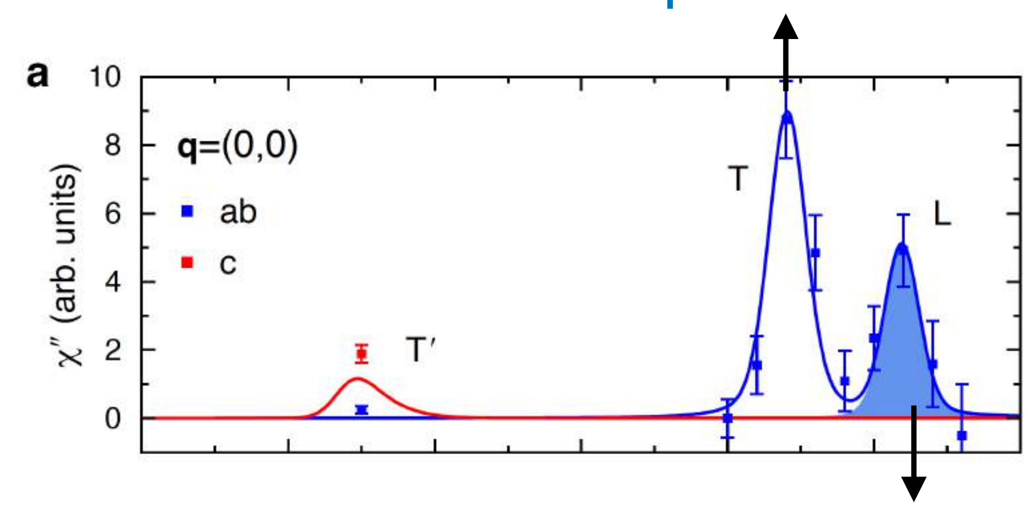



two normal modes


rotation *(phase)*

breathing *(density)*

spin wave

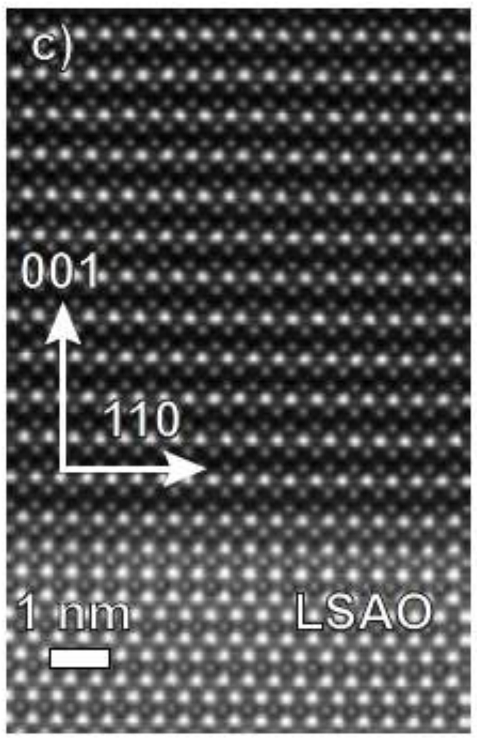


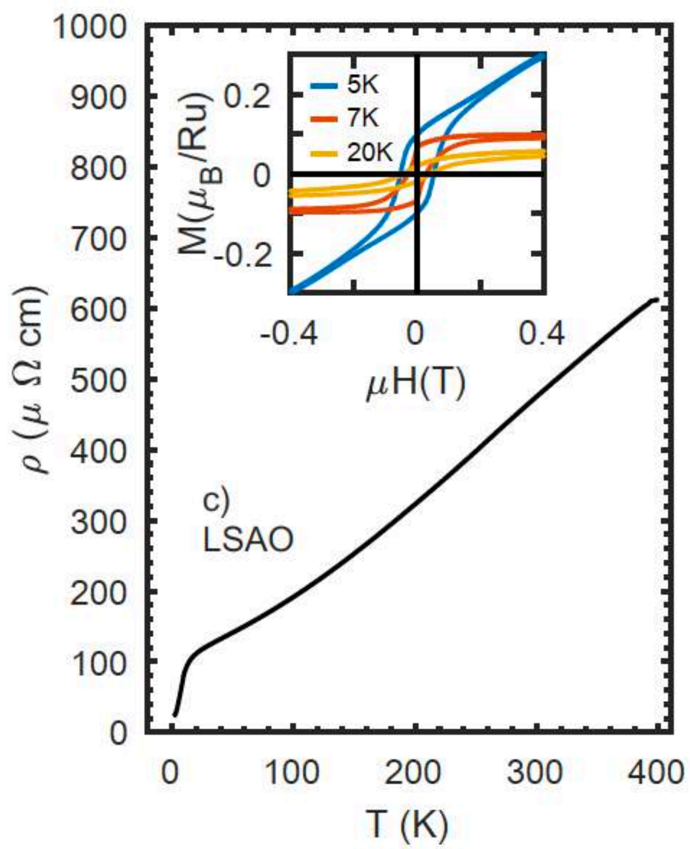
Higgs mode

A. Jain, BJK et al. Nature Physics (2017)

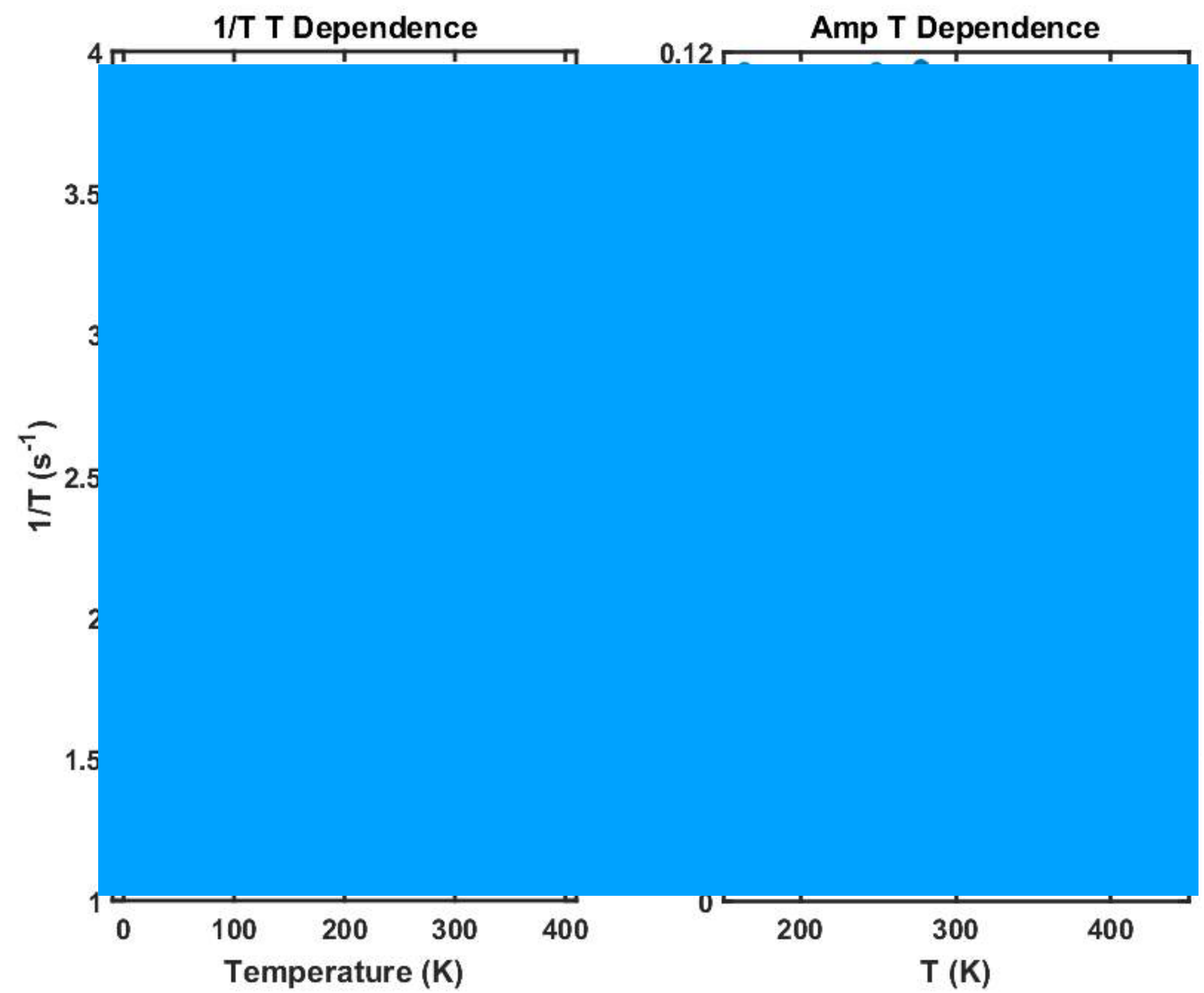
Magnetic order suppressed

CRO on LSAO





β-NMR indicates an electronic order!



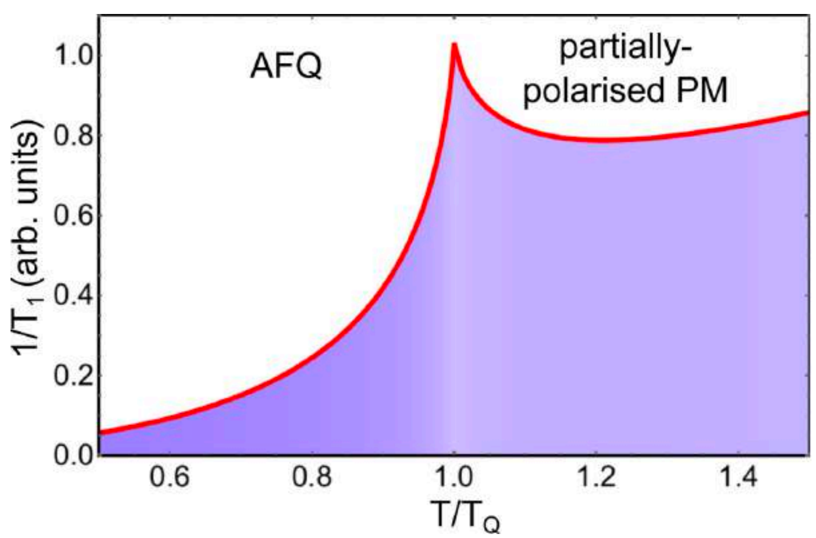
C. Dietl, BJK et al. arxiv (2017),
C. Dietl, BJK (unpublished)

Spin nematic?

PHYSICAL REVIEW B **93**, 184419 (2016)

Theory of NMR $1/T_1$ relaxation in a quantum spin nematic in an applied magnetic field

Andrew Smerald[1,2,3] and Nic Shannon[2,3,4]



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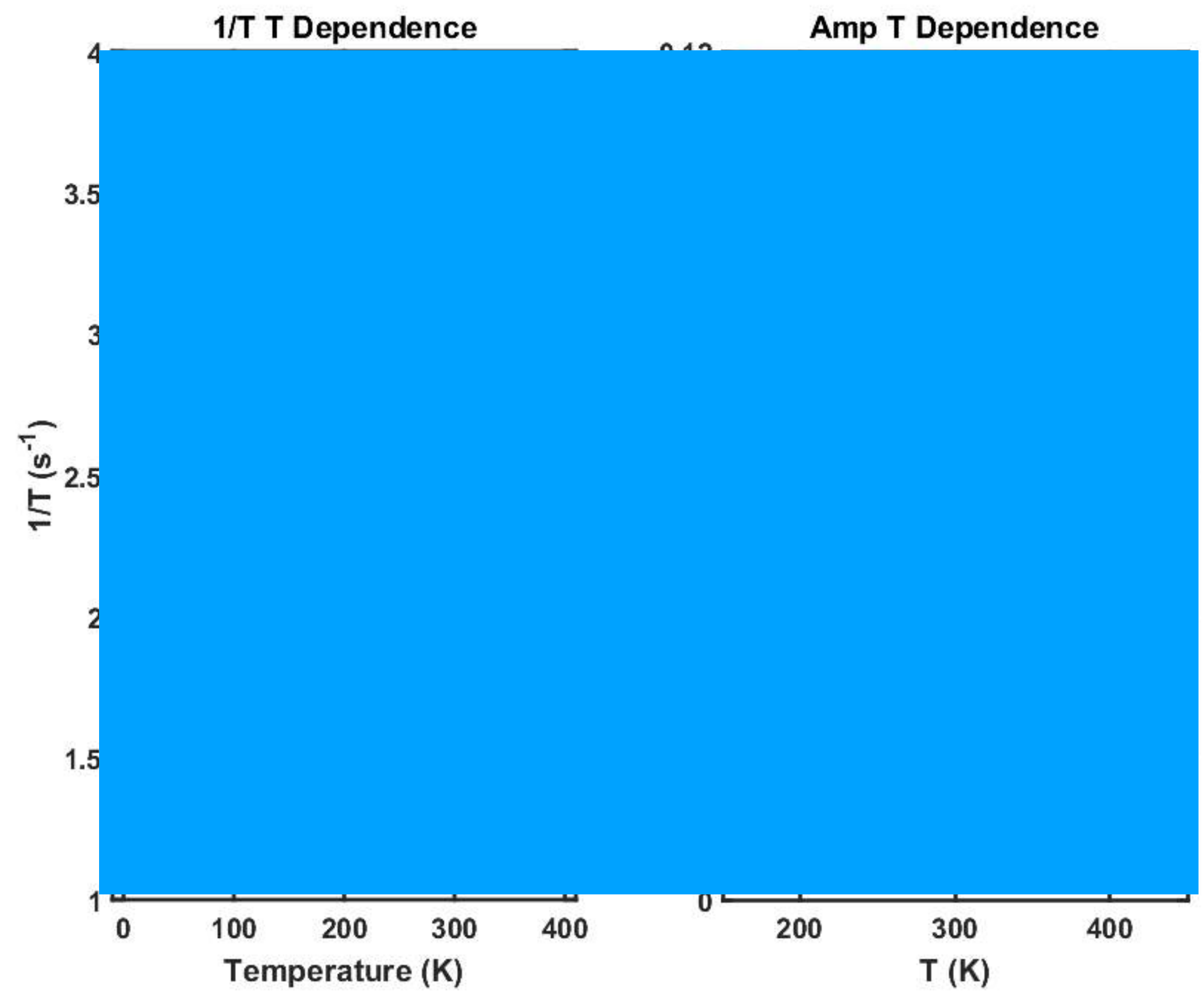


C. Dietl, BJK et al. arxiv (2017),
C. Dietl, BJK (unpublished)

RIXS operators for t_{2g} orbital systems

unquenched orbital angular momentum

"fast collision approximation"

$$R^{\varepsilon_i \varepsilon_o}_{\omega_i} = T^{\dagger}_{\varepsilon_o} \frac{1}{\omega_i + E_i + i\Gamma/2 - H} T_{\varepsilon_i}$$

c number

$$\Rightarrow \quad R \propto D^{\dagger} D = \tfrac{1}{3}(R_Q + i R_M)$$

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

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

Q_{zz} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_z^2 + 2L_zS_z$	$-L_z^2 - 2L_zS_z$
$d^2,(-1)d^4$	$2L_z^2 + L_zS_z$	$L_z^2 - L_zS_z$
Q_{xy} (quadrupole)	L_3 edge	L_2 edge
$d^1,(-1)d^5$	$-2L_xL_y - 2L_yL_x + 2L_xS_y + 2L_yS_x$	$-L_xL_y - L_yL_x - 2L_xS_y - 2L_yS_x$
$d^2,(-1)d^4$	$2L_xL_y + 2L_yL_x + L_xS_y + L_yS_x$	$L_xL_y + L_yL_x - L_xS_y - L_yS_x$
N_z (magnetic)	L_3 edge	L_2 edge
d^1,d^5	$2L_z - 4S_z + 8L_z^2S_z - 2L_z(\mathbf{L}\cdot\mathbf{S}) - 2(\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4S_z - 8L_z^2S_z + 2L_z(\mathbf{L}\cdot\mathbf{S}) + 2(\mathbf{L}\cdot\mathbf{S})L_z$
d^2, d^4	$2L_z - 4L_z^2S_z + L_z(\mathbf{L}\cdot\mathbf{S}) + (\mathbf{L}\cdot\mathbf{S})L_z$	$L_z + 4L_z^2S_z - L_z(\mathbf{L}\cdot\mathbf{S}) - (\mathbf{L}\cdot\mathbf{S})L_z$
d^3	$(4/3)S_z$	$-(4/3)S_z$

BJK & G. Khaliullin PRB (2017)

Verifying spin nematic using RXS

unquenched orbital angular momentum

"fast collision approximation"

c number

$$R^{\varepsilon_i\varepsilon_o}_{\omega_i} = T^\dagger_{\varepsilon_o}\frac{1}{\omega_i+E_i+i\Gamma/2-H}T_{\varepsilon_i}$$

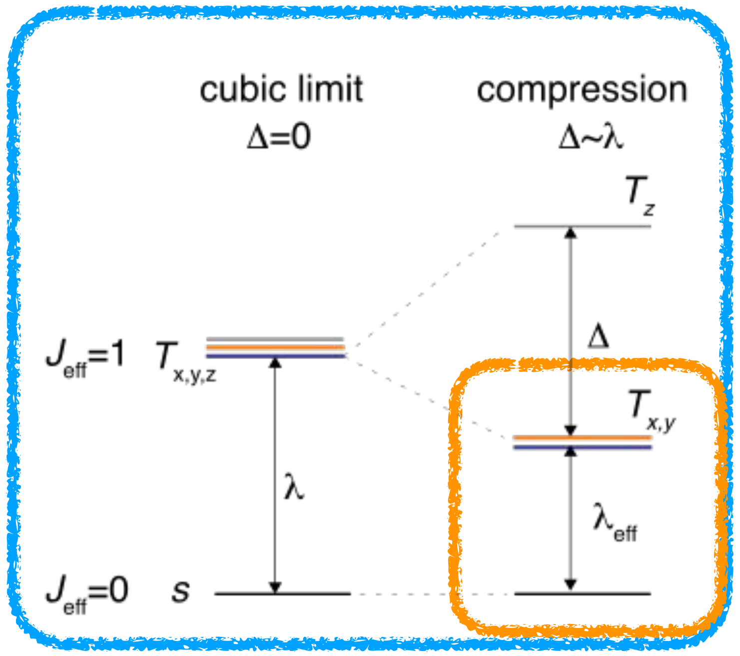
$$R \propto D^\dagger D = \tfrac{1}{3}(R_Q + i R_M)$$

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

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

$$\begin{aligned} R_Q = {} & \tfrac{1}{2}[a_{xy}(\epsilon_x\epsilon'_x + \epsilon_y\epsilon'_y) + a_z\epsilon_z\epsilon'_z]\tilde{S}_z^2 \\ & + \tfrac{1}{2}b_{xy}[(\epsilon_x\epsilon'_x - \epsilon_y\epsilon'_y)(\tilde{S}_y^2 - \tilde{S}_x^2) \\ & + (\epsilon_x\epsilon'_y + \epsilon_y\epsilon'_x)(\tilde{S}_x\tilde{S}_y + \tilde{S}_y\tilde{S}_x)] \\ & + \tfrac{1}{2}b_z[(\epsilon_y\epsilon'_z + \epsilon_z\epsilon'_y)(\tilde{S}_y\tilde{S}_z + \tilde{S}_z\tilde{S}_y) \\ & + (\epsilon_z\epsilon'_x + \epsilon_x\epsilon'_z)(\tilde{S}_z\tilde{S}_x + \tilde{S}_x\tilde{S}_z)], \end{aligned}$$

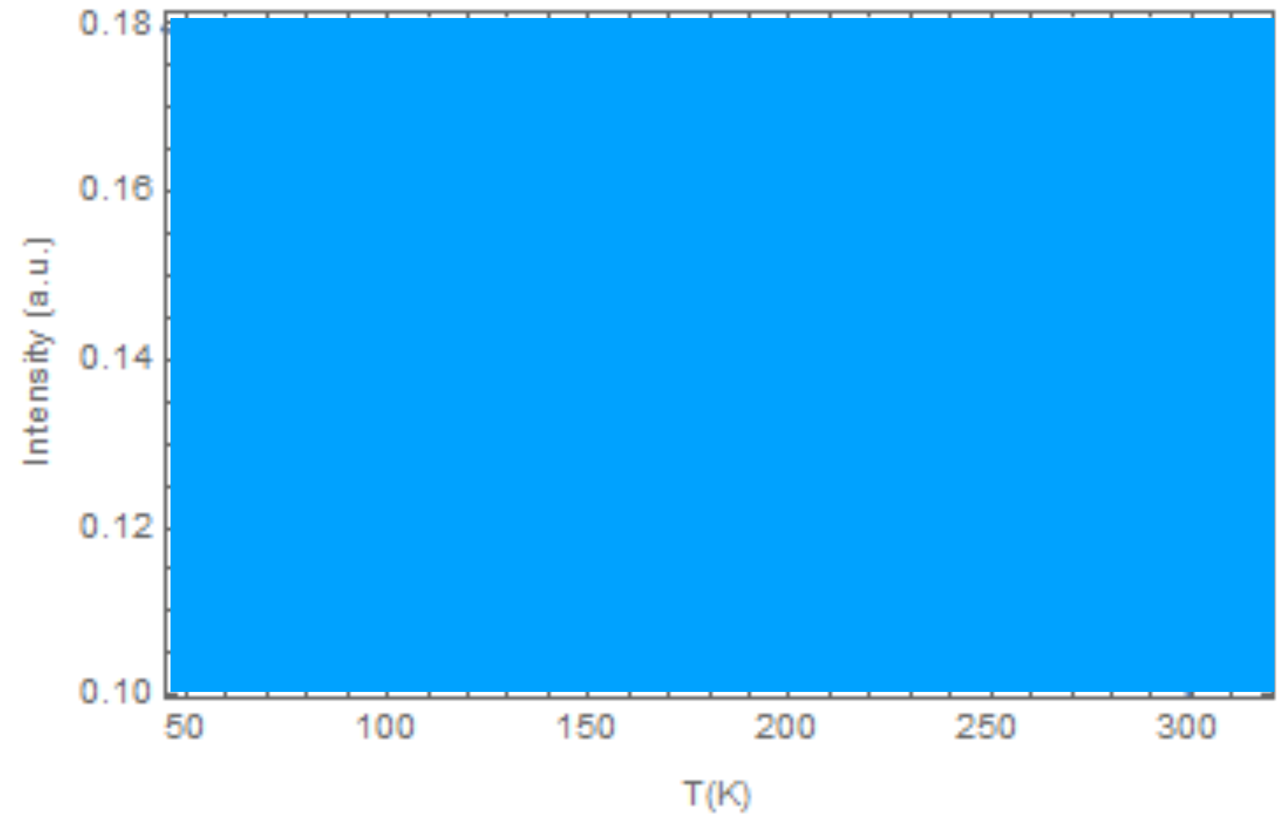
$$\begin{aligned} R_M = {} & \tfrac{1}{2}c_{xy}[(\epsilon_y\epsilon'_z - \epsilon_z\epsilon'_y)\tilde{S}_x + (\epsilon_z\epsilon'_x - \epsilon_x\epsilon'_z)\tilde{S}_y] \\ & + \tfrac{1}{2}c_z(\epsilon_x\epsilon'_y - \epsilon_y\epsilon'_x)\tilde{S}_z. \end{aligned}$$



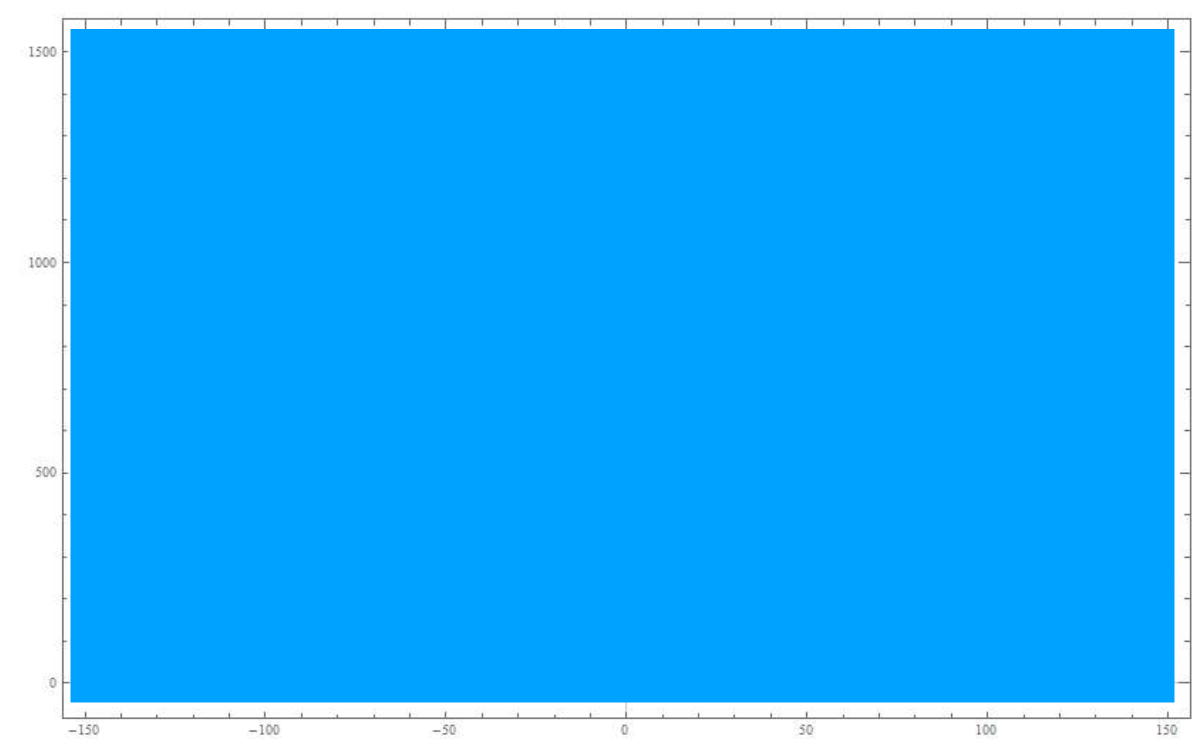
BJK & G. Khaliullin PRB (2017)

Verifying spin nematic using RXS

order parameter grows around T=300 K



xy quadrupole

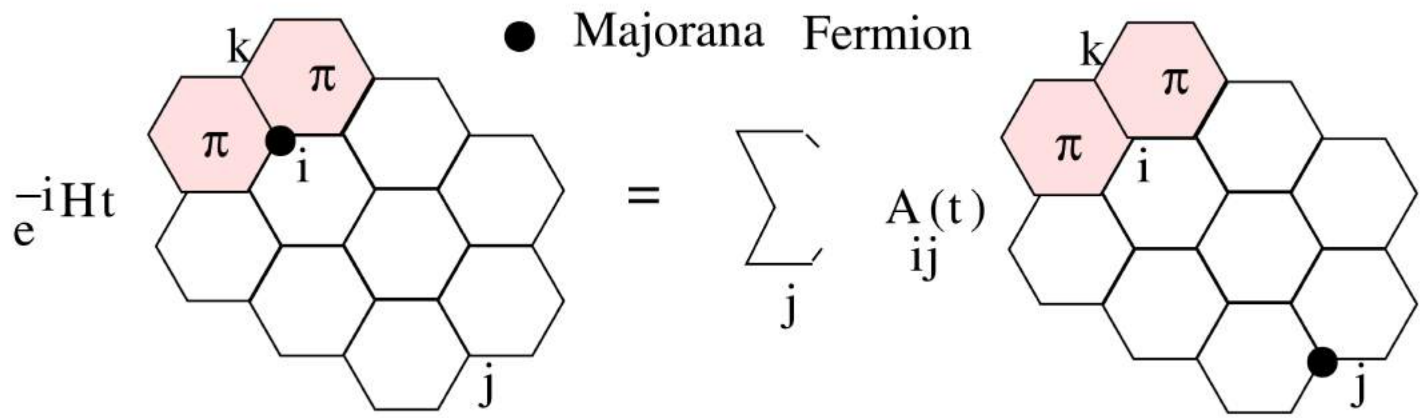


C. Dietl, BJK (unpublished)

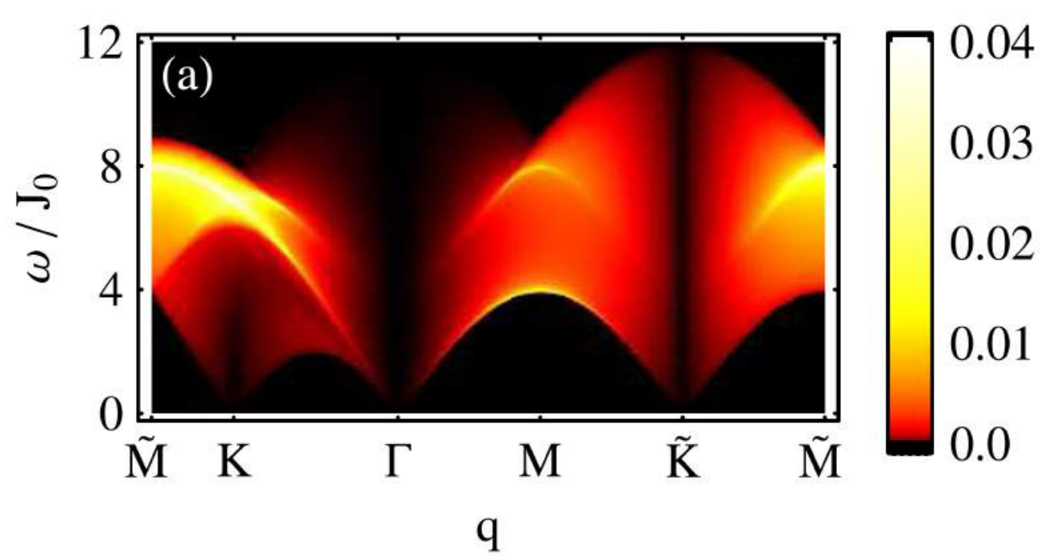
Recent theoretical proposals

Majorana fermions in Kitaev spin liquid

Spins fractionalize into Majorana fermions and emergent gauge fluxes



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)

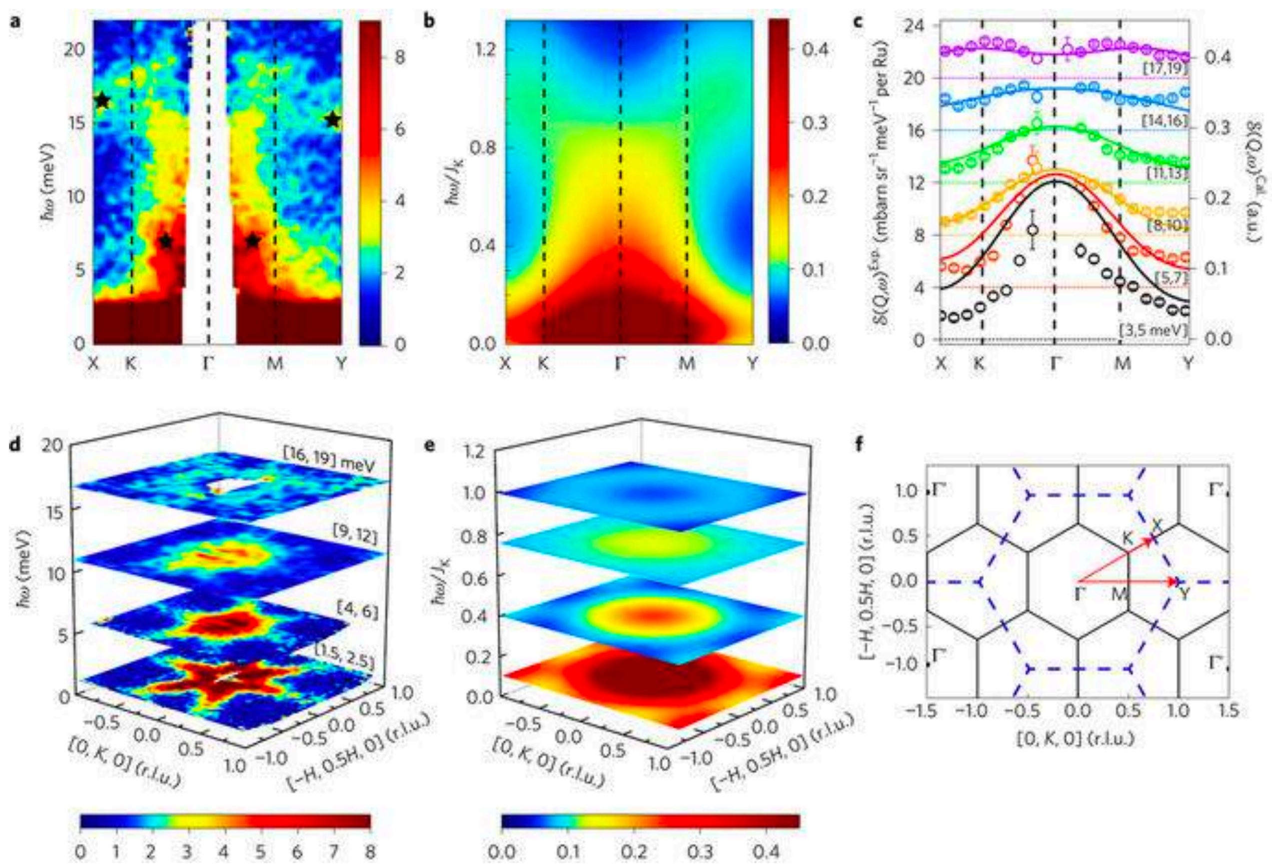


J_0~ 10-20 meV

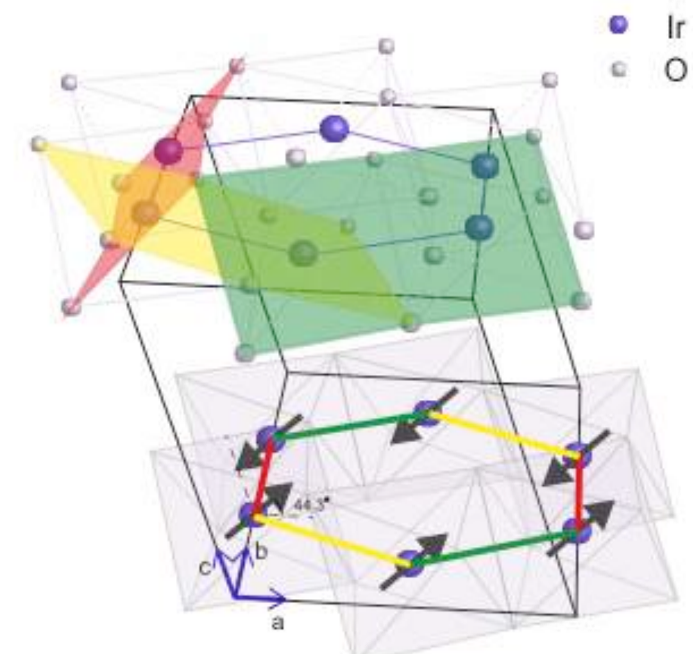
Halasz, Perkins, van den Brink, PRL (2016)

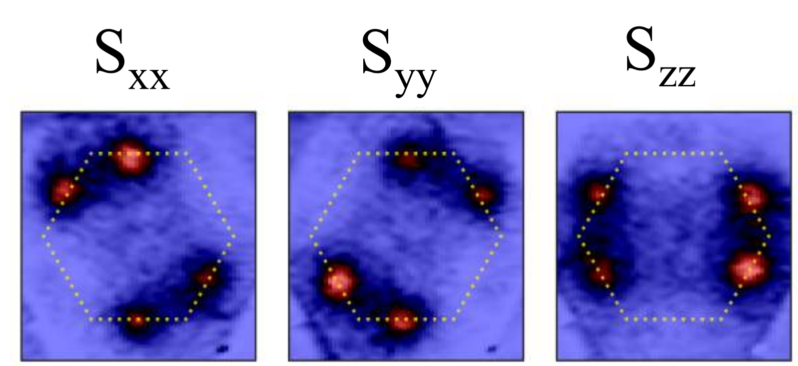
Candidate materials for Kitaev quantum spin liquid

RuCl3



Na$_2$IrO$_3$

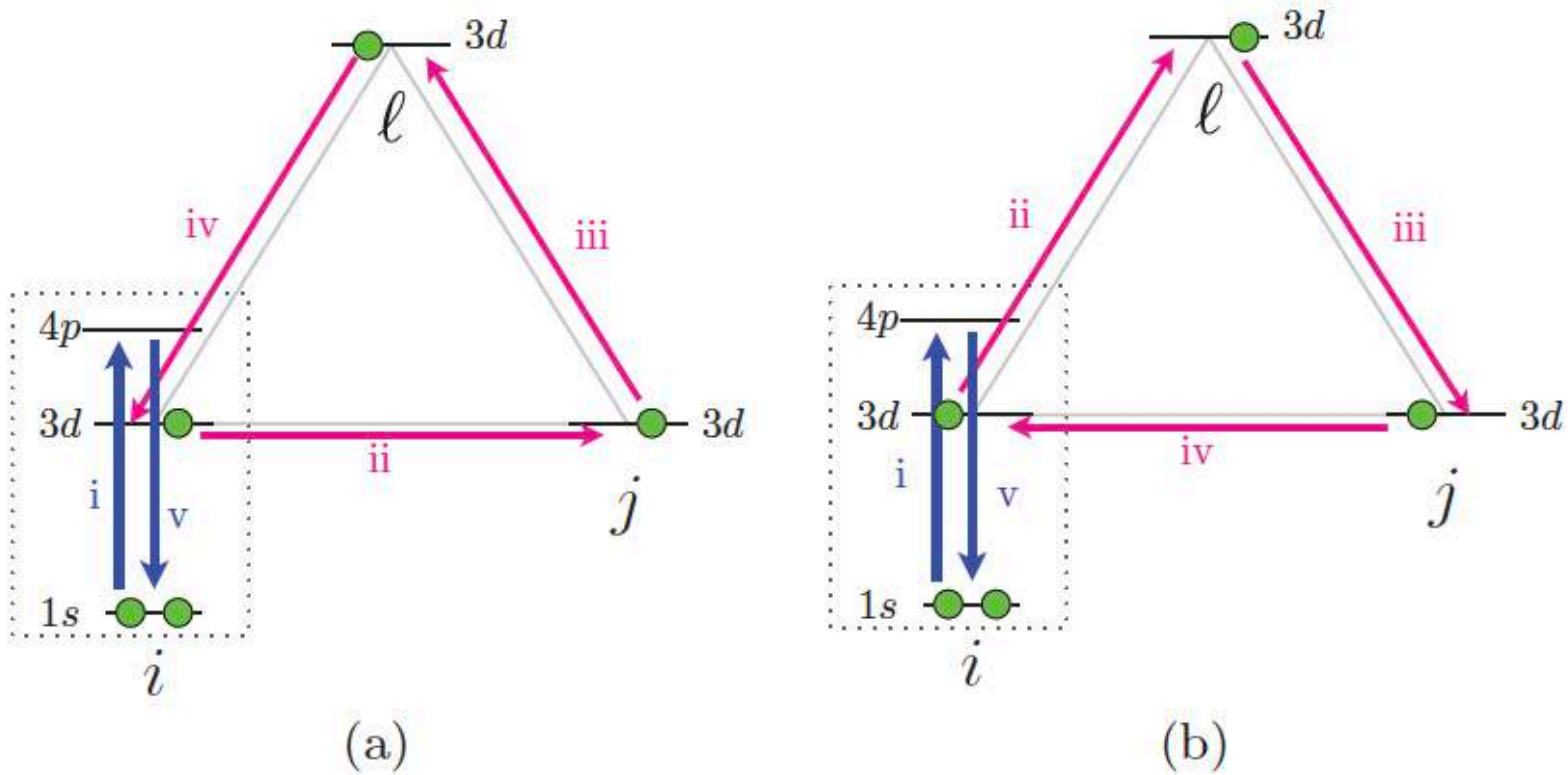




S.-H. Do et al., Nature Physics (2017)

S. H. Chun, BJK et al., Nature Physics (2015)

Gauge fields



$$
\begin{aligned}
T^{(a)}_{\text{3-sites}} &\propto \left(c^{\dagger}_{is}(J^{\dagger})^{\beta}_{sp} c_{ip}\right)(t_{i\ell} c^{\dagger}_{i} c_{\ell})(t_{\ell j} c^{\dagger}_{\ell} c_{j})(t_{ji} c^{\dagger}_{j} c_{i})\left(c^{\dagger}_{ip'} J^{\alpha}_{p's'} c_{is'}\right) \\
&= \mathrm{tr}\{J^{\alpha}(J^{\dagger})^{\beta}\} t_{i\ell} t_{\ell j} t_{ji}\, \mathrm{tr}\{\chi_{\ell}\chi_{j}\tilde{\chi}_{i}\} \\
&= N^{\alpha\beta} t_{i\ell} t_{\ell j} t_{ji} [2i\mathbf{S}_{\ell}\cdot(\mathbf{S}_{j}\times\mathbf{S}_{i}) + \cdots], \qquad (9)
\end{aligned}
$$

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

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

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

W.-H. Ko and P. A. Lee, PRB (2011)

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.

RIXS beamline @ PAL