Study of “spin-charge separation” using resonant inelastic x-ray scattering

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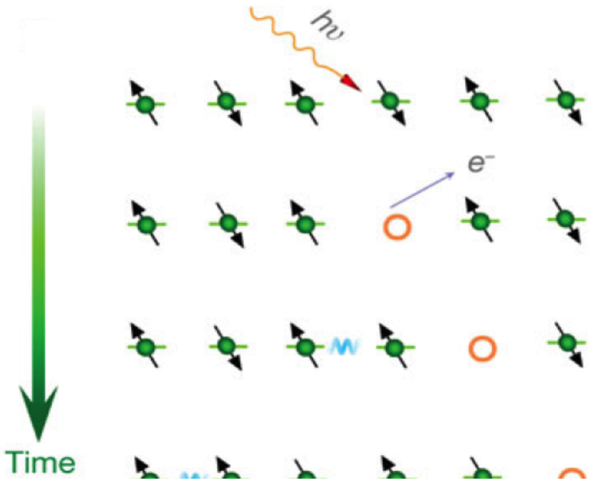
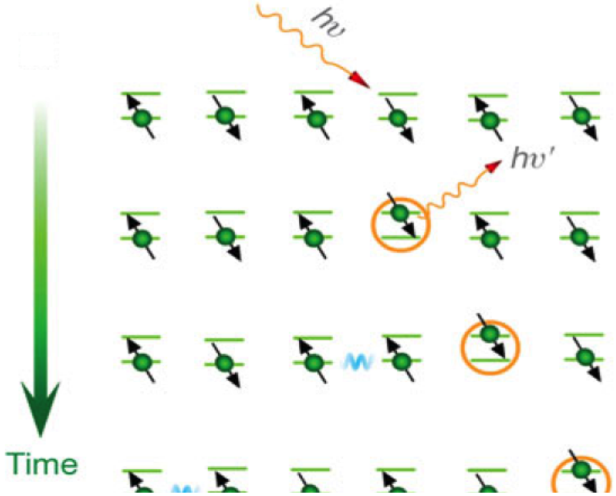
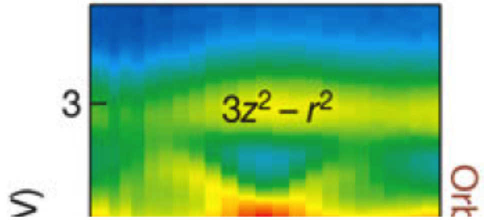
Outline

- Fractionalization in 1D
- RIXS as a probe technique
- Sr_2CuO_3 as 1D material
- Spin-charge separation using RIXS

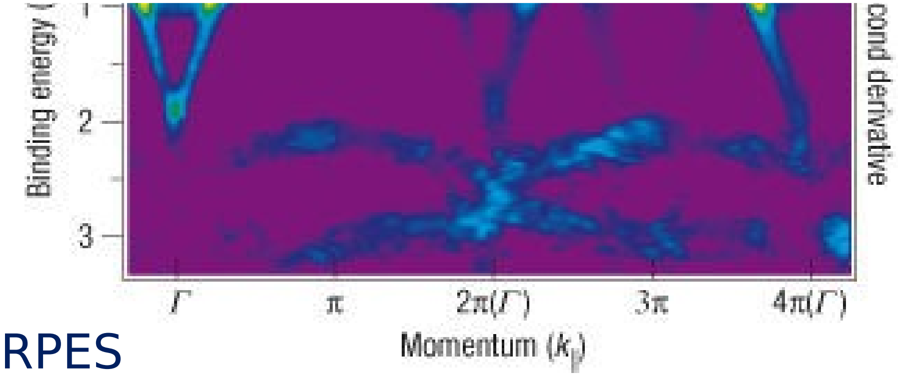
Fractionalization in 1D: *Spin, orbit and charge*

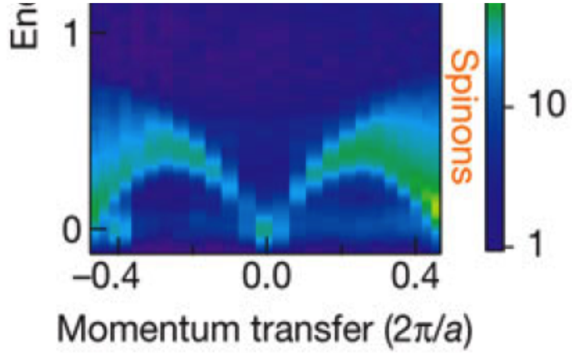






Can one observe Spin and charge separation using RIXS?

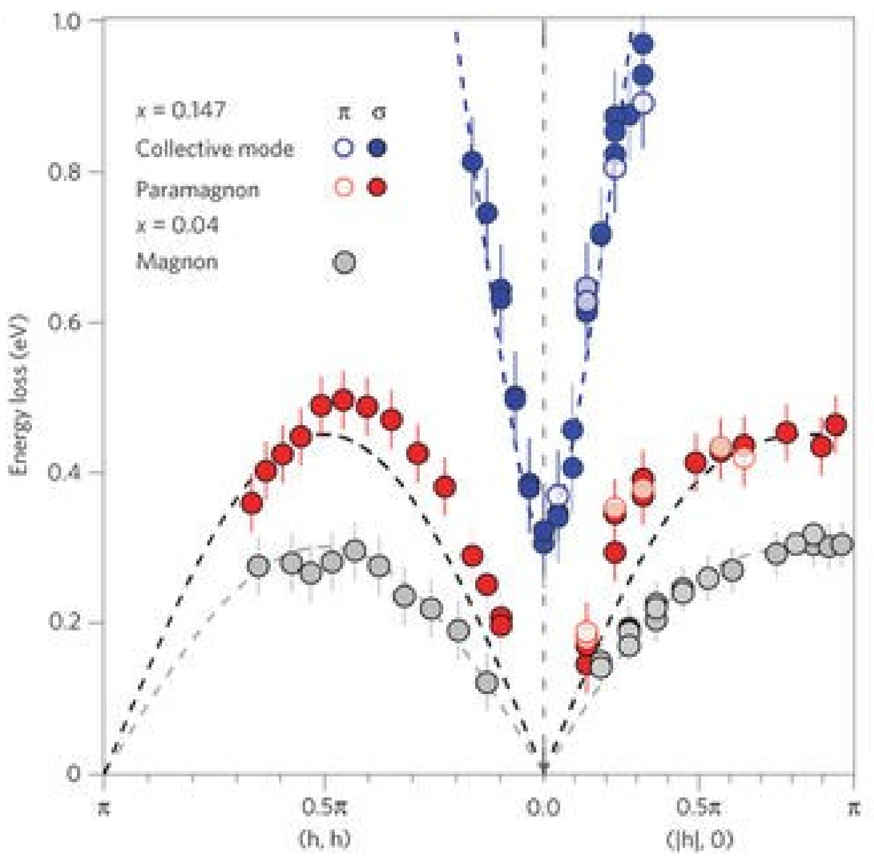




ARPES
B.J. Kim *et. al*., Nat Phys 2, 397 (2006)

RIXS
Schlappa, J. *et al*., Nature 485, 82–85 (2012)

Why understanding RIXS low energy spectra is important?



RIXS spectra of electron-doped 2D cuprates
Lee, W. S., *et al.*, Nature Phys. **10**, 883–889 (2014)

- RIXS spectra is richer compared to .
- Paramagnon persists in doped phase.
- Collective mode appears in 2D cuprate.
- Nature of these collective mode?
- Understanding 1D chain RIXS spectra might shed some light

- RIXS spectra is richer compared to S(q,ω).
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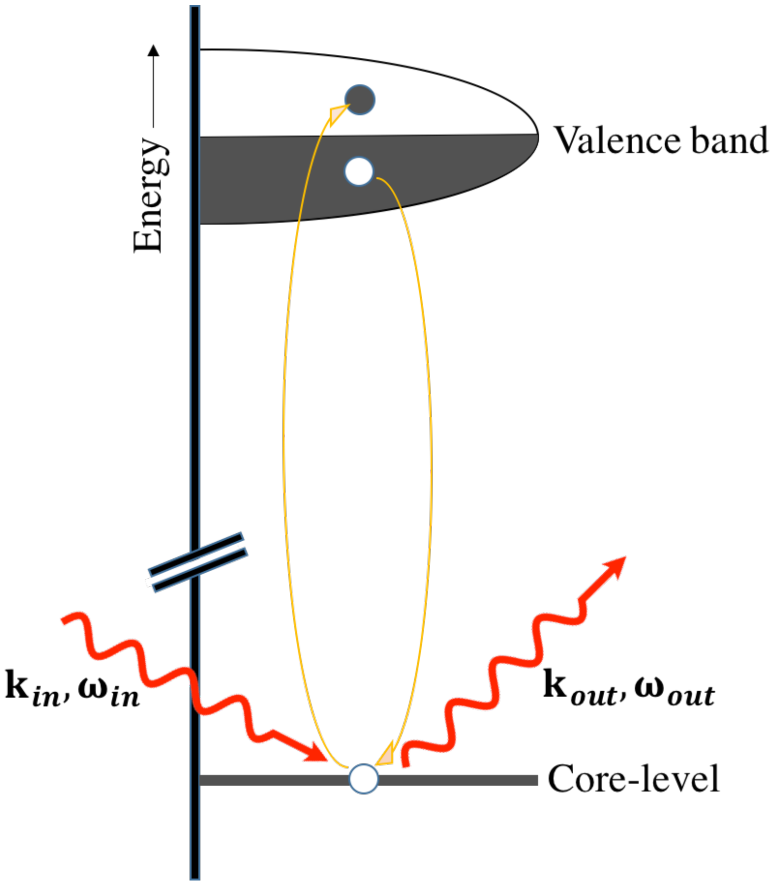
RIXS Process



Kramers-Heisenberg Formula:

- $$I_{RIXS}(\omega, k, k', \epsilon, \epsilon') = \sum_f |F_{fg}|^2 \times \delta(E_f + \hbar\omega_{out} - E_g - \hbar\boldsymbol{\omega}_{in})$$

Outgoing Photon Energy

Incident Photon Energy

Scattering Amplitude

$$F_{fg} = \sum_{n,i} \frac{\langle f|D^{\dagger}_{i,\alpha}|n\rangle\langle n|D_{i,\alpha}|g\rangle}{E_g + \hbar\omega_{in} - E_n + i\Gamma_{n,i}}$$

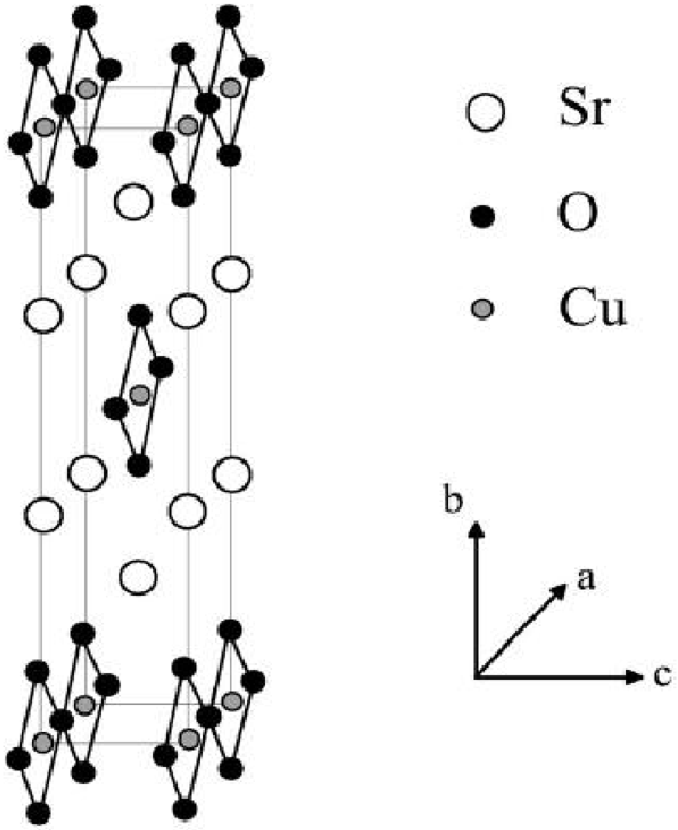
Transition Dipole Operator

$$D_{i,\alpha} = \frac{1}{\iota m_e \omega_k} \sum_i e^{\iota \boldsymbol{k}\cdot\boldsymbol{R}_i}\, \boldsymbol{\varepsilon}.\mathbf{p}_i$$

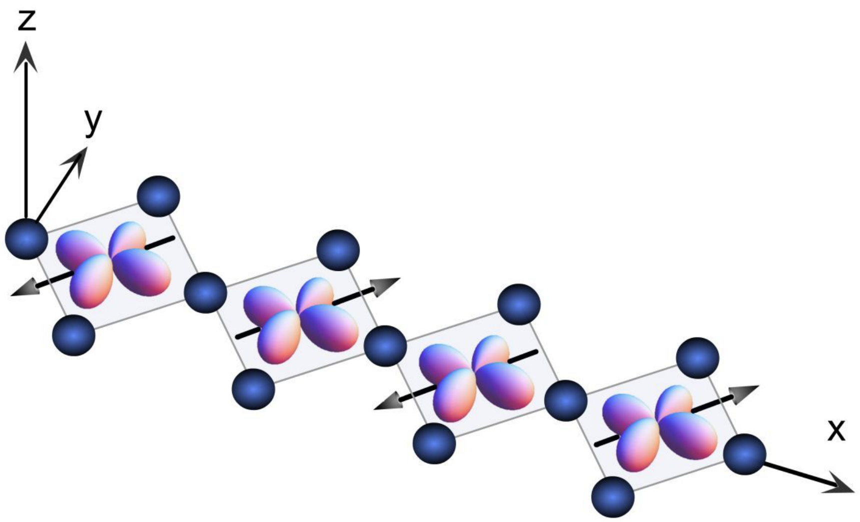
$$I_{XAS} = \sum_f |\langle f|D_i^{\alpha}|g\rangle|^2\, \delta(E_f - E_g - \hbar\boldsymbol{\omega}_{in})$$

- XAS study used to tune RIXS specific to a excitation of an atom in the crystal.

Sr_2CuO_3 as 1D material

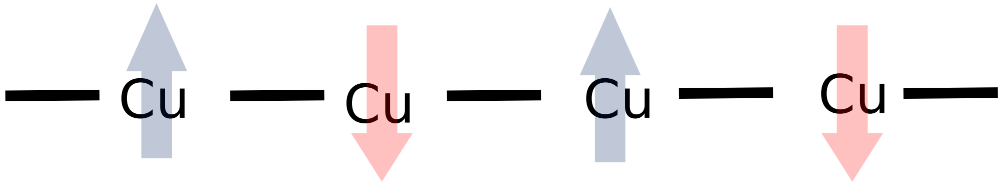


R. Neudert *et al*., PRB **62**, 10752 (2000).



$$|\psi_{gs}\rangle = \alpha|d^9\underline{L}^0\rangle + \beta|d^{10}\underline{L}^1\rangle, \qquad |\beta|^2 = 0.36$$

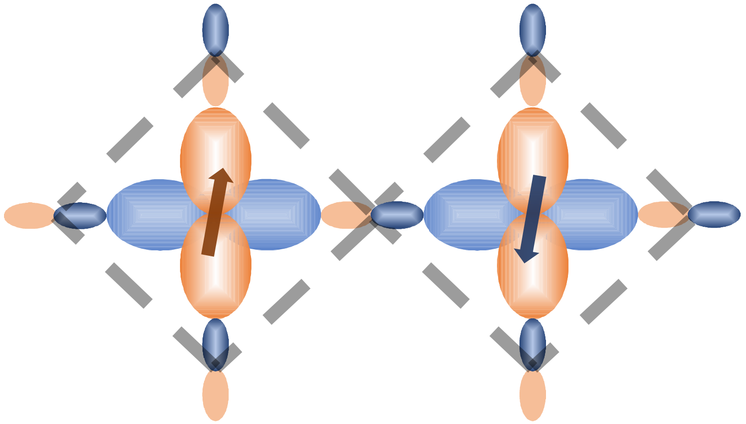
t-J Model



$$H = H_0 + H_1$$

$$H_0 = t \sum_{i,\sigma} ((1 - n_{i\sigma}) c^{\dagger}_{i\sigma} c_{j\sigma} + h.c.) + \frac{J_0}{2} \sum_i (S_i \cdot S_{i+1} + S_{i-1} \cdot S_i)$$

$$H_1 = J_{ch} \sum_i S_i \cdot S_{i+1} \, s^{\dagger}_{i+\frac{\delta}{2}} s_{i+\frac{\delta}{2}}$$



- Oxygens are integrated and mapped onto Cu sites.
- Solved using Lanczos on 20 site and DMRG on 80 sites.

Excitations in doped 1D

$$|\psi\rangle = |\psi_s\rangle \otimes |\psi_{\bar{h}}\rangle$$

Karlo Penc, et. al., Phys. Rev. B **55**, 15475

$$\omega_s(k) = \frac{\pi J}{2} |\sin(ka)|, \forall k \in [0, \pi)$$

Charge-less spin

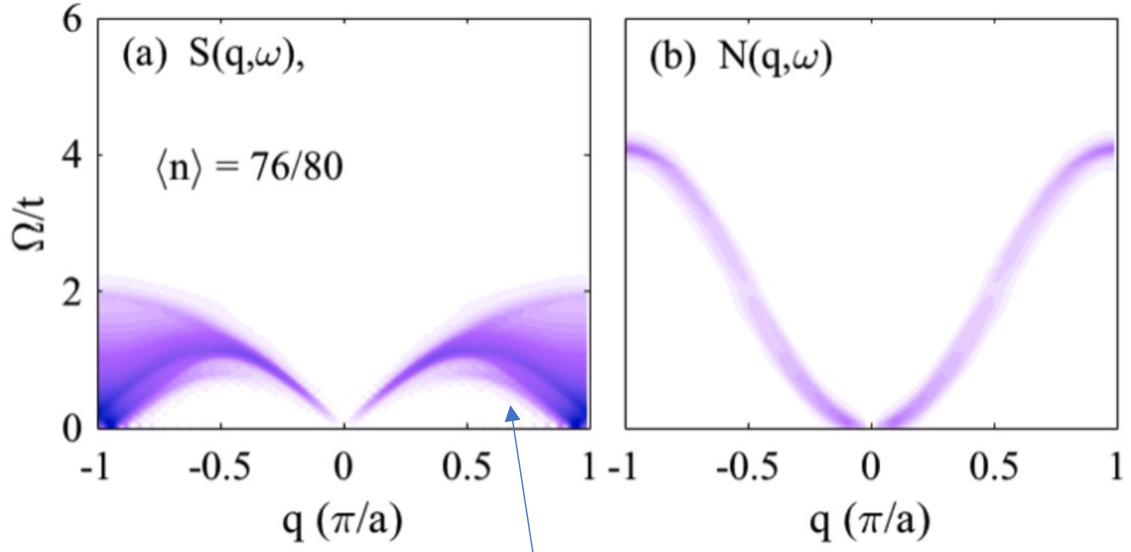
$$\omega_{\bar{h}}(k) = -2t\cos(ka + \phi)\ \forall k \in [0, 2\pi),\ \forall k \in [0, 2\pi)$$

,

Spinless charge

Spin

Charge



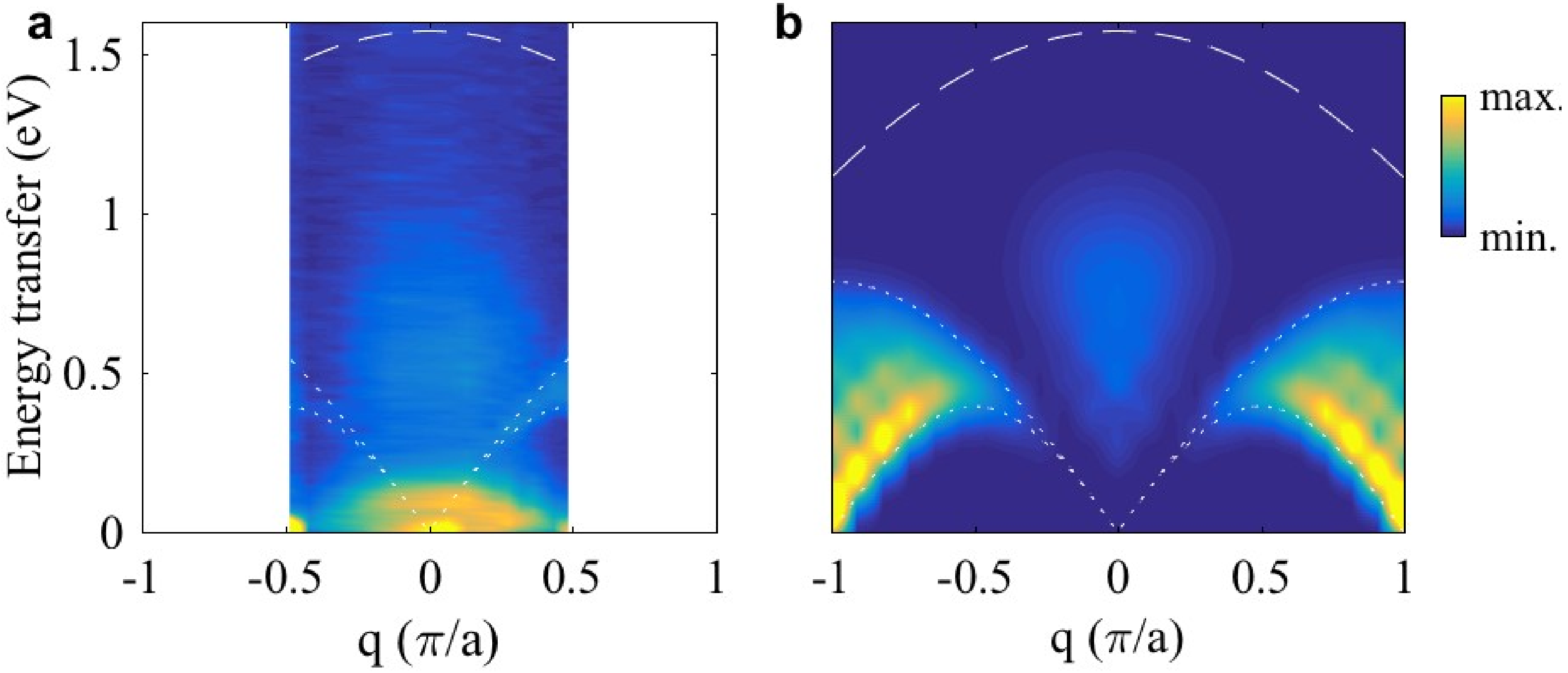
Calculated using DMRG on 80 sites

Two-spinon

RIXS: Undoped 1D chain

Experiment: O K-edge

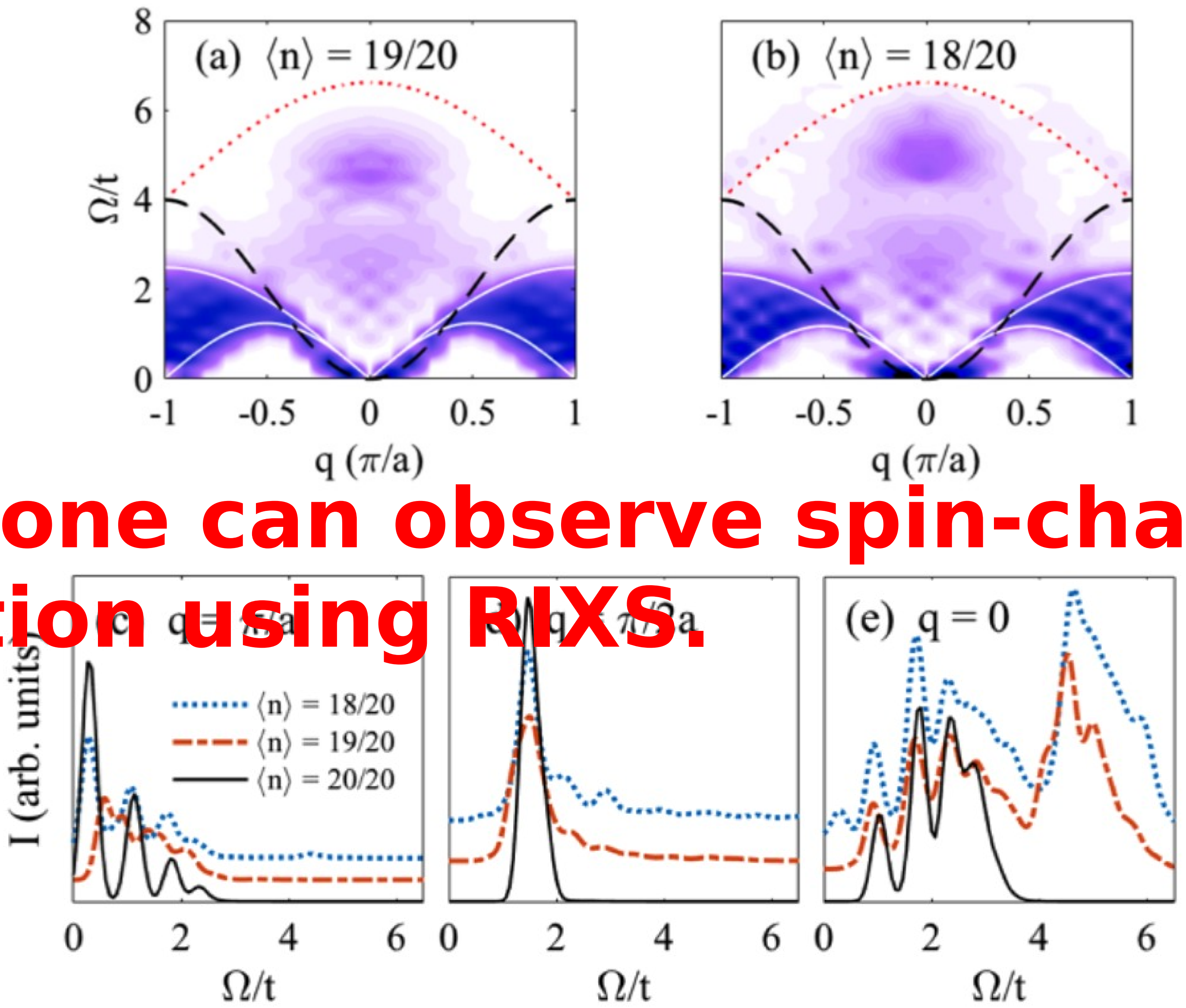
Theory: O K-edge



Schlappa, J., Kumar U., *et. al.,* [Under review]

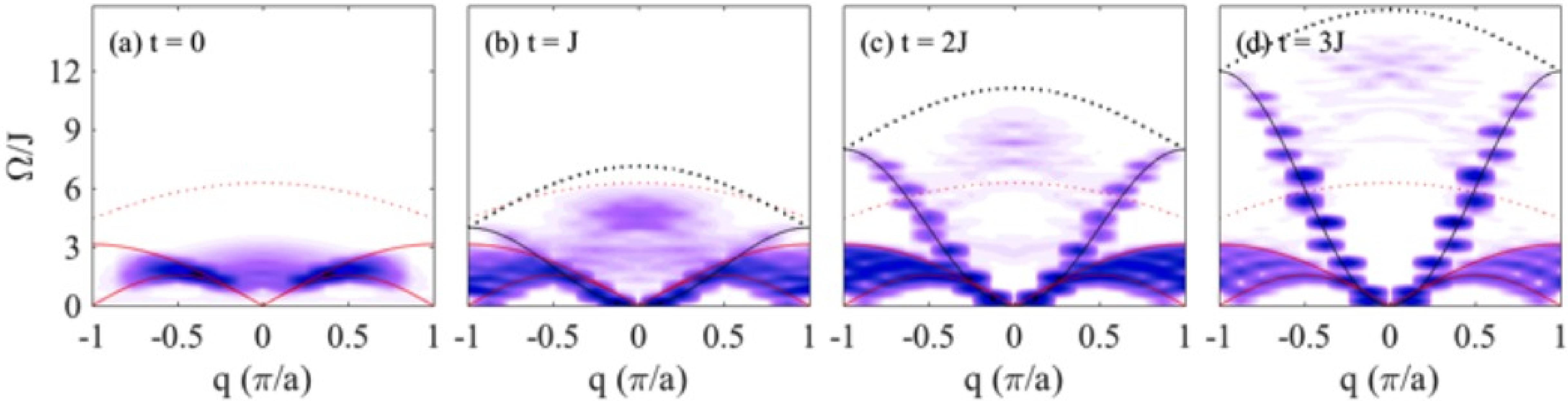
- Spinon Energy, for $\epsilon_{spinon}(k) = \frac{\pi}{2}|sin\ ka|$ for k∈ $[0,\frac{\pi}{a}]$

RIXS: doped 1D chain

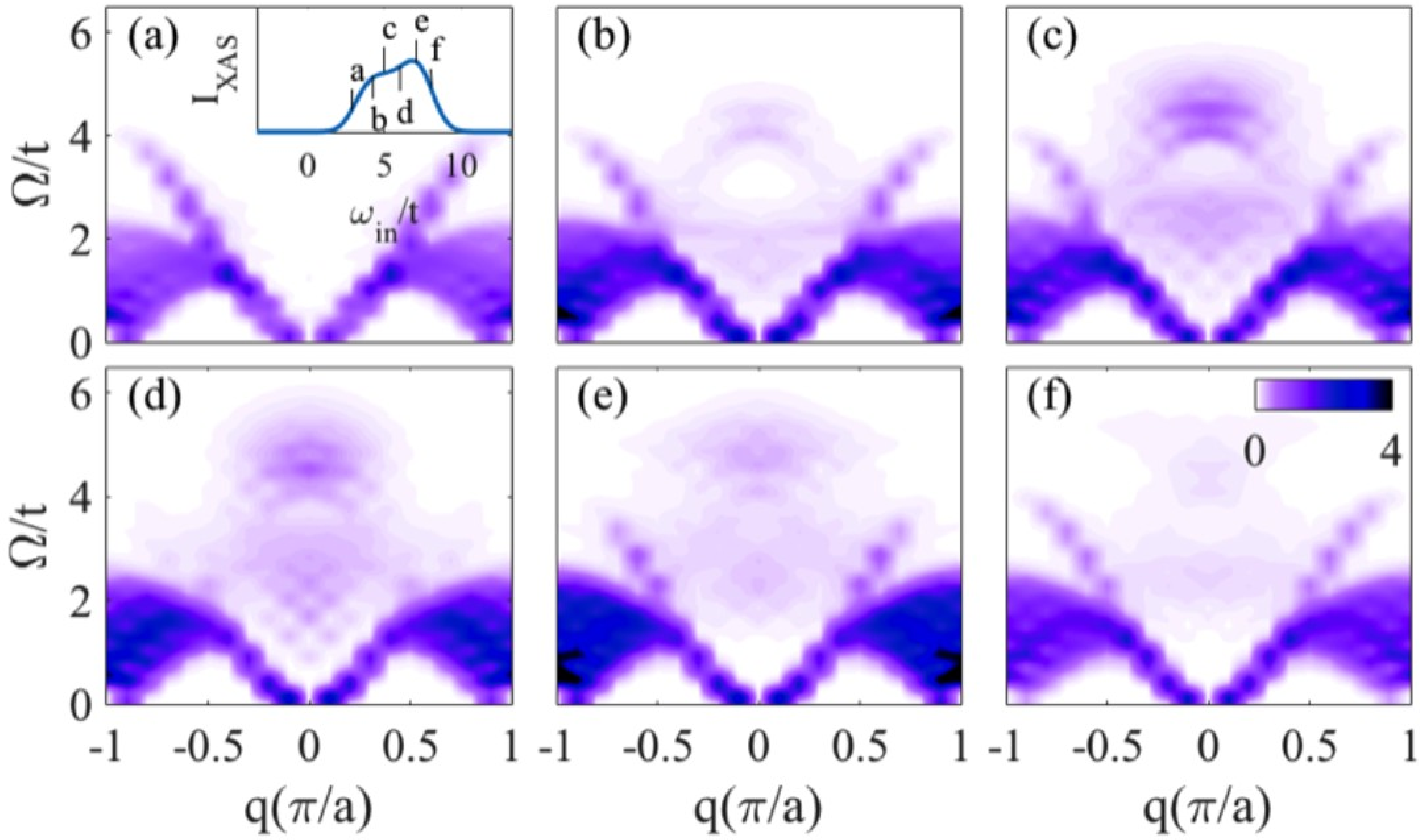


Indeed one can observe spin-charge separation using RIXS.

Dependence on t



Incidence Energy dependence



Conclusions

- We have *shown* that spin-charge separation can be observed using RIXS at oxygen K-edge of doped Sr_2CuO_3.
- We also *observed* that a new combination of spinon and anti-holon can be found in the RIXS spectra

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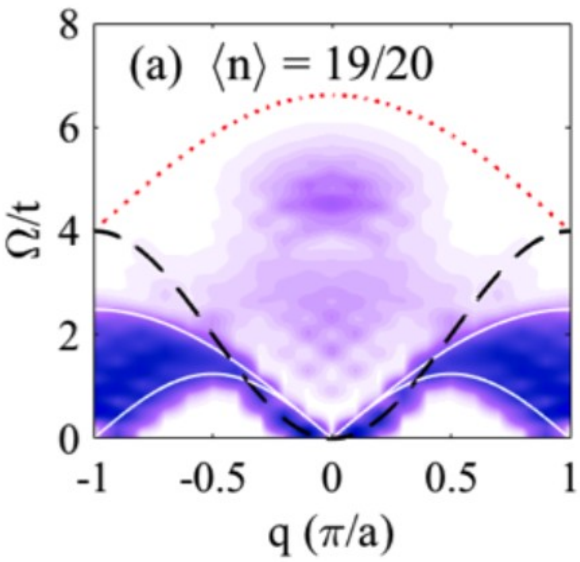

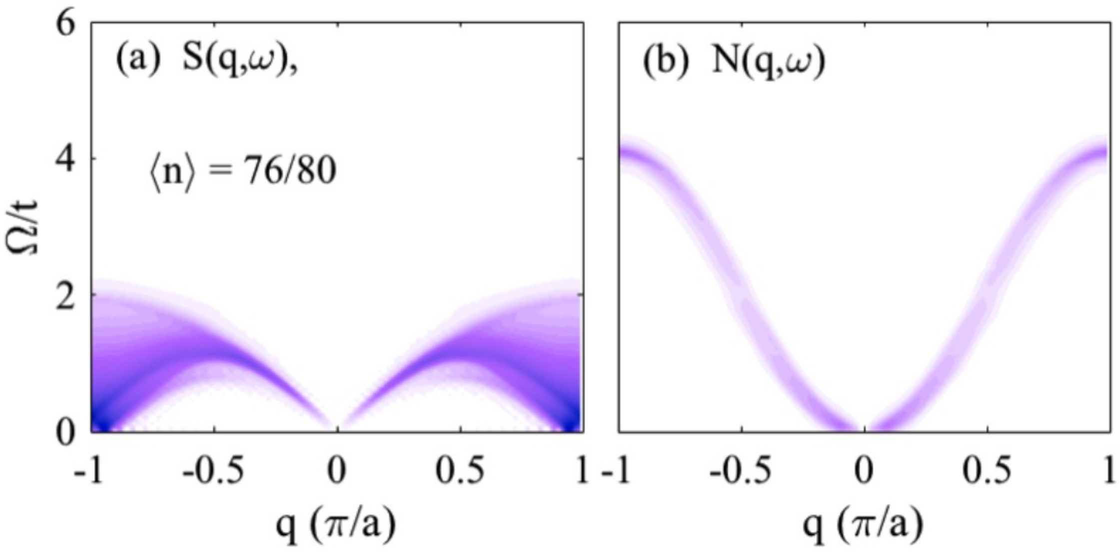

Collaborators

Prof. Steve Johnston

Dr. Alberto Nocera

Prof. Elbio Dagotto

Supplementary

- Spin-flip at O K-edge