Hard x-ray RIXS study on high-Tc cuprates and related compounds

Charge excitation associated with charge ordered state

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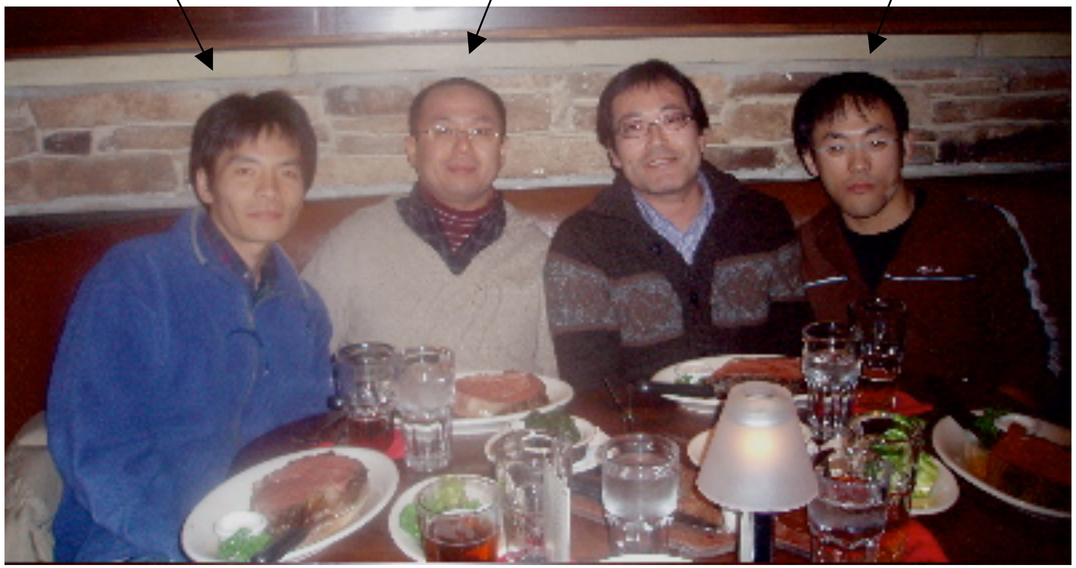

@ Wild Fire Steak House

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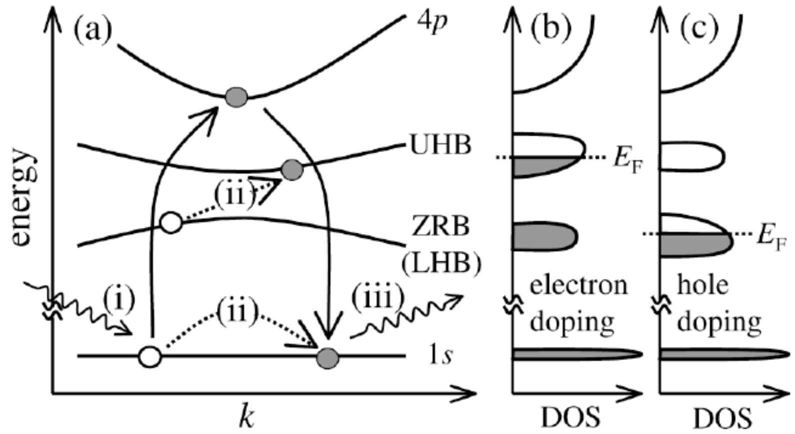
Tadashi Adachi, Youji Koike, Yukio Noda (Tohoku Univ.)
Aimon Said, Yuri Shvyd'ko (APS)

CONTENTS

Hard x-ray RIXS (Cu, Ni, … K-edge)

Principle

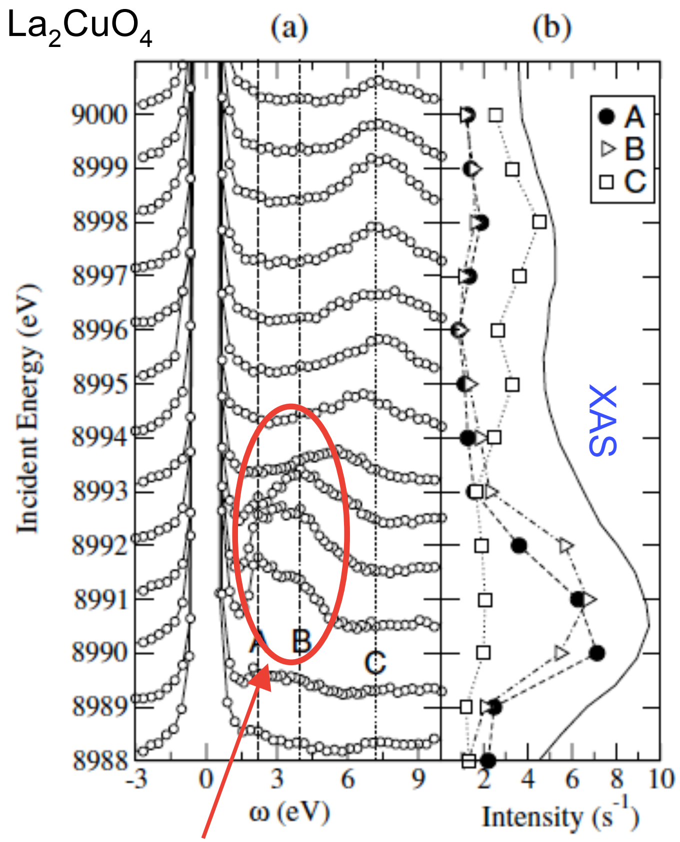
Tsutsui et al.



- The RIXS process involves an intermediate state where 1s electron is excited to 4p.
- In this process, many type of charge excitations are induced.
- Charge transfer (CT) type insulator -CT excitation (O2p to Cu3d) is very sensitive to this process.

Observation

Y.-J. Kim et al.

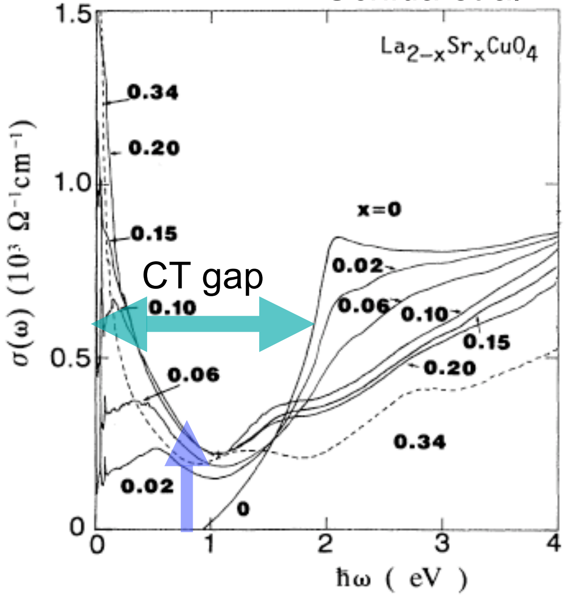


CT excitation resonates near the photon energy where XAS peak appears.

Charge transfer excitation

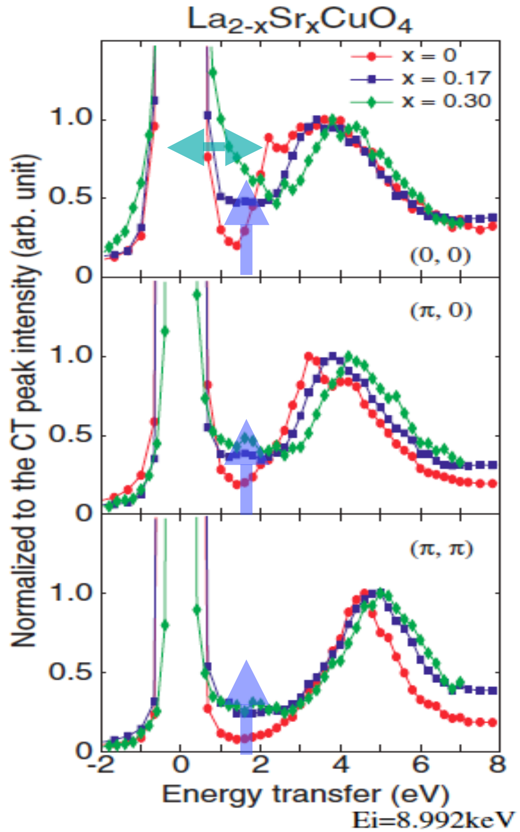
◆Optical measurement
one of the most important probes to study CT gap.

Uchida et al.



◆Clear CT gap in the non-doped sample.
◆Spectral weight shifts to lower energy as doping increases.

◆Cu-K edge RIXS observes …



◆Consistent CT gap in the non-doped sample at (0 0).

◆As doping increases, continuum-like excitation at the lower energy.

◆q-dependences of charge transfer excitations.

Wakimoto, Kim et al.

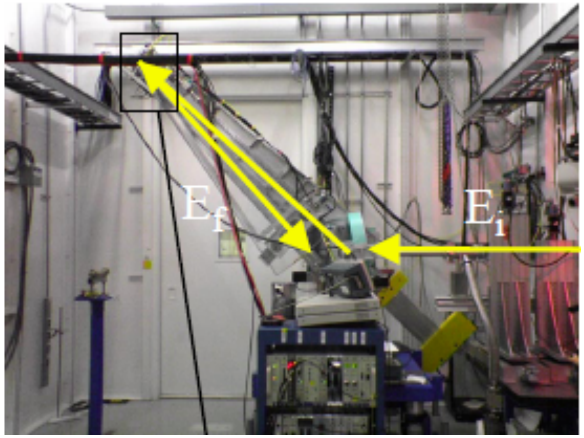
Advantage of RIXS
Being able to study q-dependence

Recent development

Typical energy resolution of RIXS Instruments : 300 ~ 400 meV
(APS 9ID-B with 1m-arm, SP8 BL11XU, BL12XU, …)

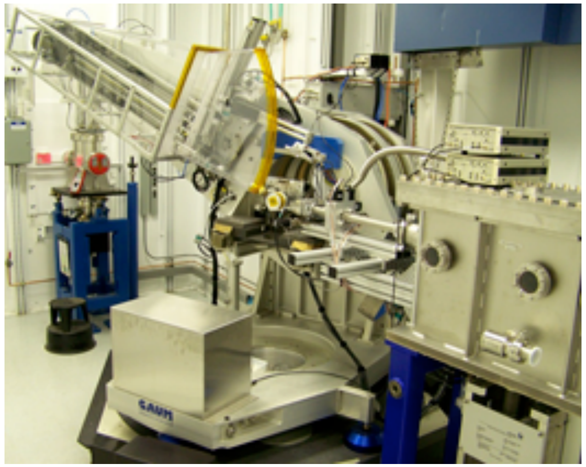
◆Recent development
towards finer energy resolution

APS 9ID-B with 2m-arm



Cu K-edge :
ΔE=118 meV

APS 30ID MERIXS



Cu K-edge :
ΔE=110 meV

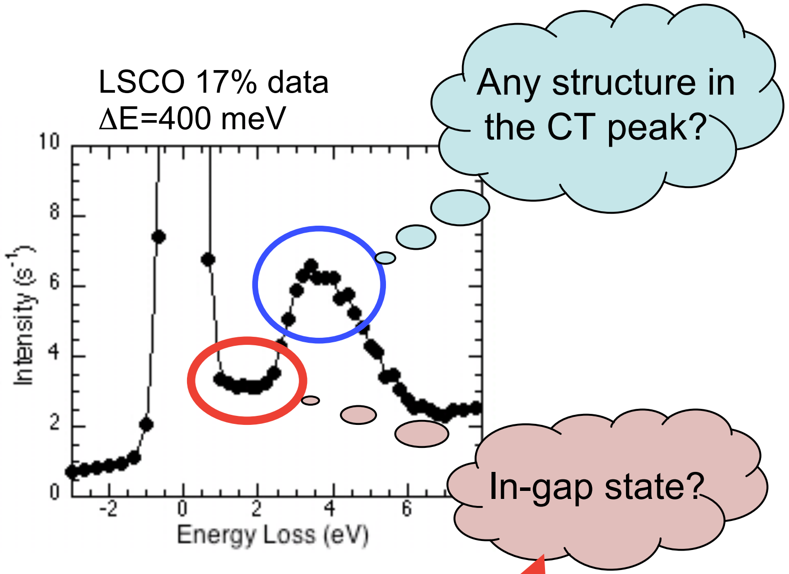
Ni K-edge :
ΔE=150 meV

⋮

Small ΔE will …

- ◆ reduce the elastic tail.
- ◆ help us to see smaller structure.

New aspect …

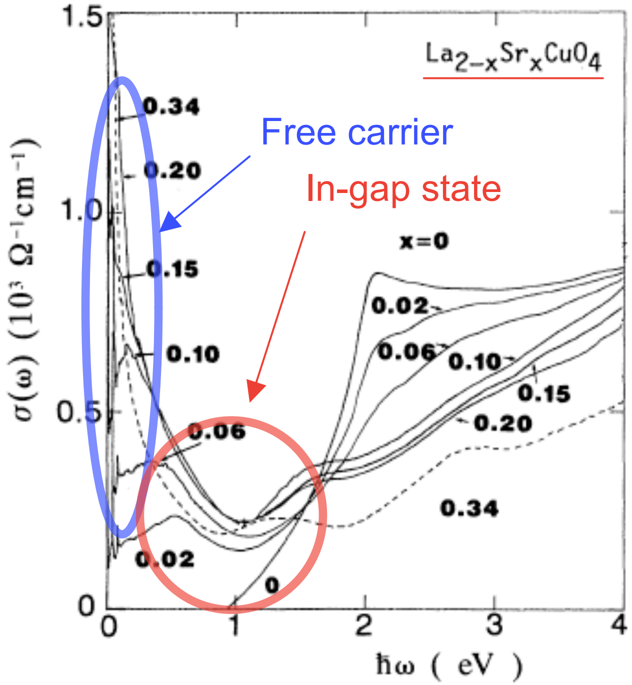


We are aiming here!

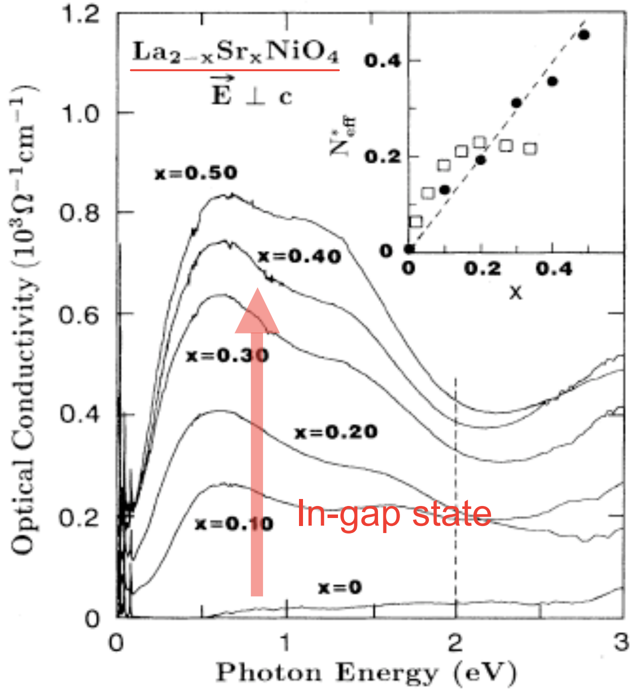
In-gap state

- Optical conductivity

Uchida et al.



Ido et al.

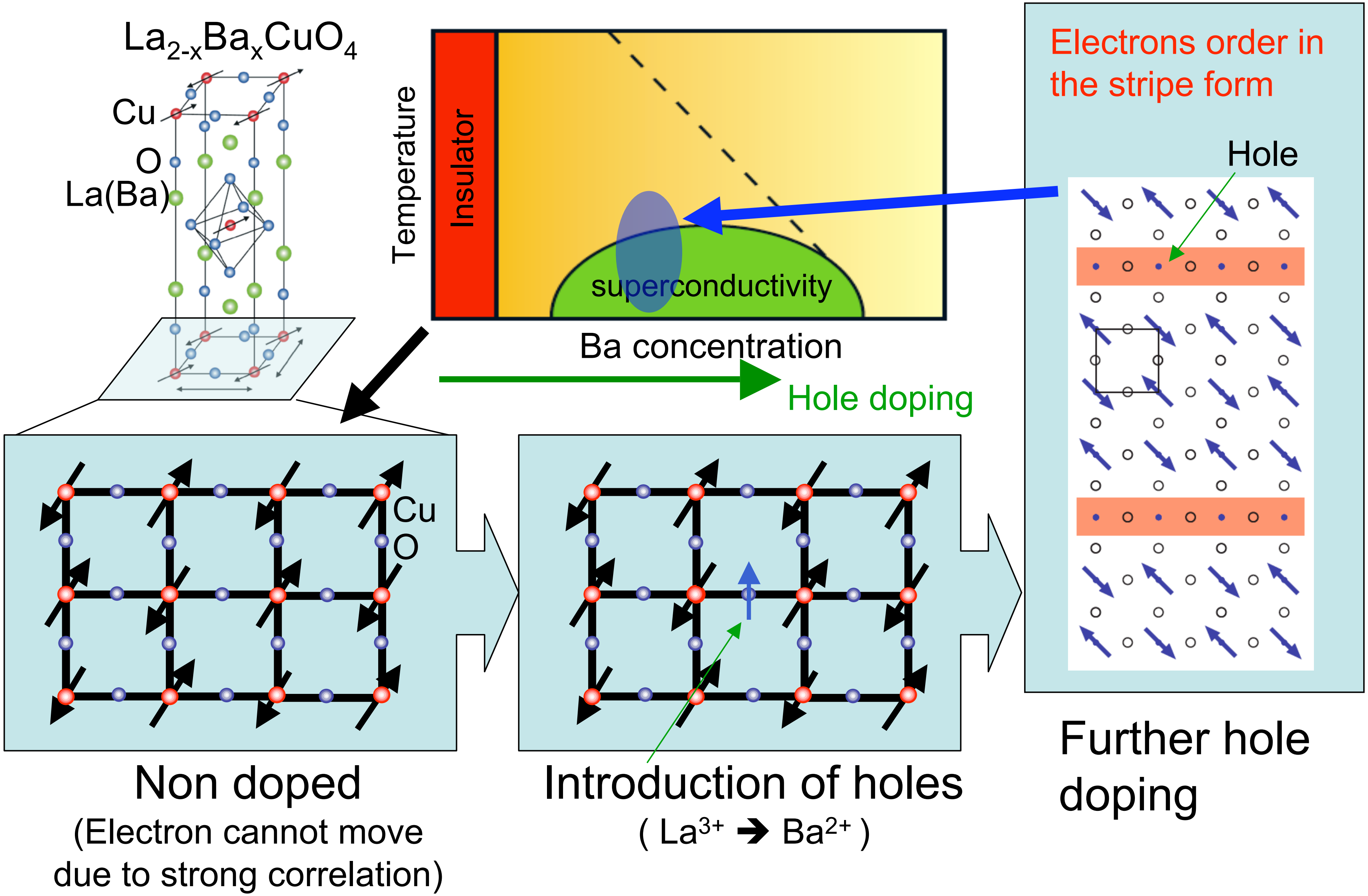


- When holes are doped into the system, in-gap state appears and grows with doping.
- This was reported by various experimental probes.
  - –Optocal measurements
  - –Photo-emission
  - –x-ray absorption

  and so on …

- Interpreted in several ways.
  - Impurity band
  - Polaron band
  - d-d excitation
  - Stripe band
  - …

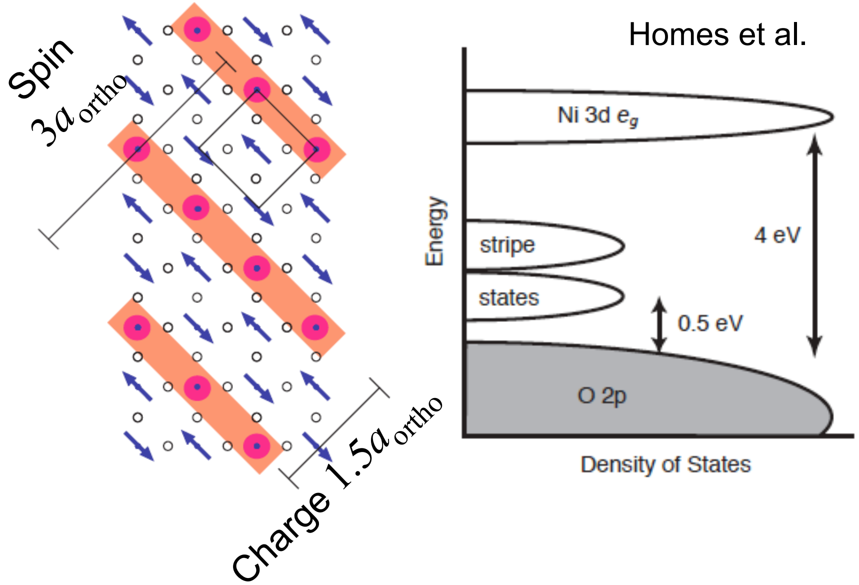
Stripe order



Schematic picture of stripe band

$La_{2-x}Sr_xNiO_4$

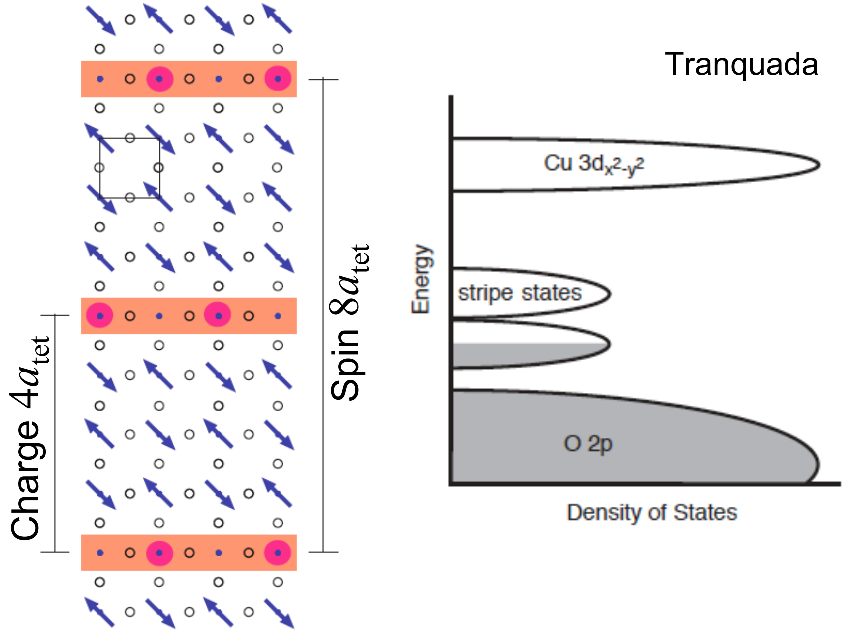
$x = \varepsilon = 1/3$



- In diagonal stripe of nickelates,
  one hole every Ni site.
- In the stripe,
  Ni^{3+} ➔ one electron in e_g
  (Mott insulator.)
- This configuration produces a stripe band which is *empty*.
- System is insulator.

$La_{2-x}Ba_xCuO_4$

$x = \delta = 1/8$



- In parallel stripe of cuprates
  one hole every 2 Cu sites.
- This configuration produces a stripe band which is *quarter-filled*.
- System is metallic.

Can we detect charge excitations to the stripe band?

Motivation

- Ingap state by stripe order?

- Dynamics of stripes?
  - relation to the superconductivity
  - strongly correlated electron system
    - cf. CDW by electron-phonon coupling

Experiments

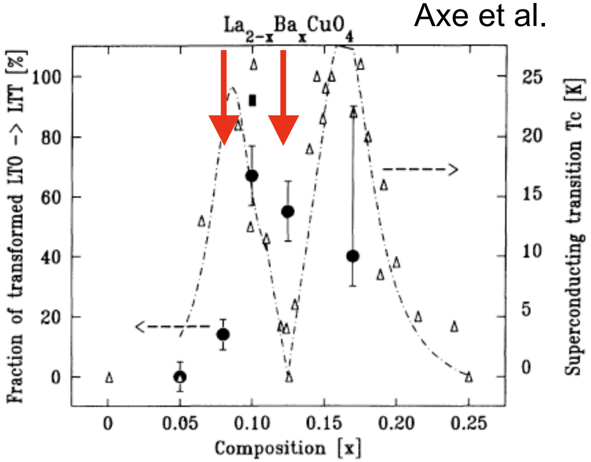
Samples

$La_{5/3}Sr_{1/3}NiO_4$ — *Robust stripe order*

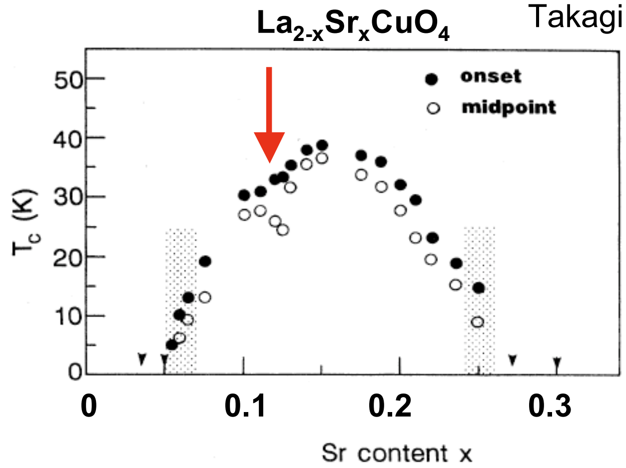
$La_{1.875}Ba_{0.125}CuO_4$ — *Robust stripe order*

$La_{1.92}Ba_{0.08}CuO_4$ — *No stripe order*

$La_{1.88}Sr_{0.12}CuO_4$ — *Stripe order expected*



Axe et al.



Takagi et al.

Instruments

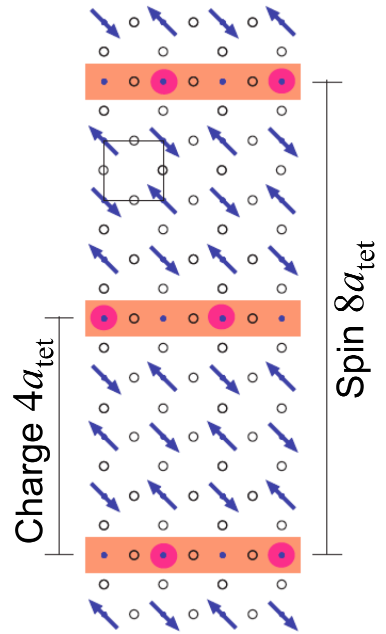
MERIX@APS Nickelate

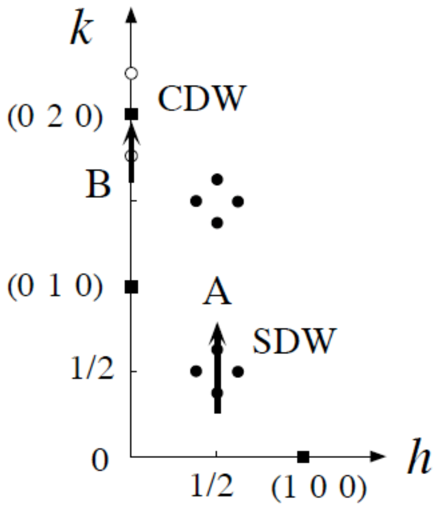
BL11XU@SP8 Cuprates

Horizontal scattering plane

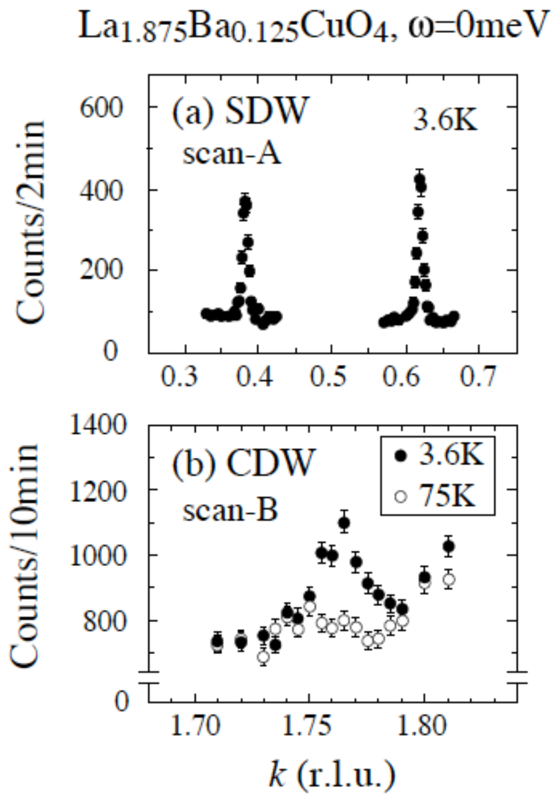
$La_{1.875}Ba_{0.125}CuO_4$ sample

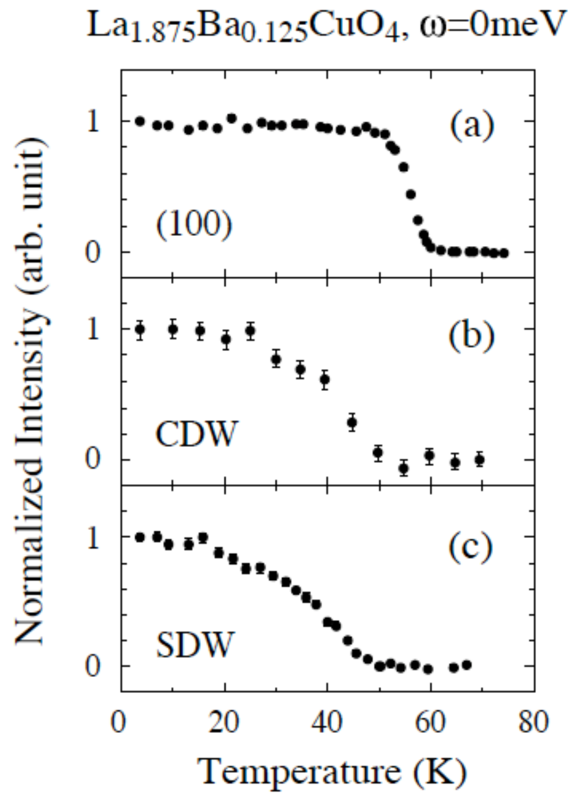
Single crystal
- Grown by TSFZ method.
- Cut in a disk shape with the c-axis normal to the disk.
- Stripe order was checked by neutron.



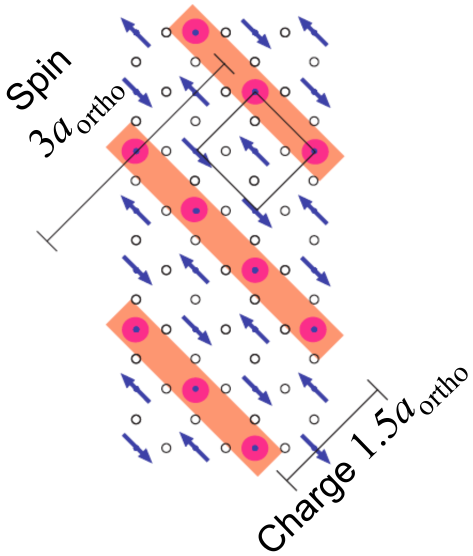


Fujita et al.





$La_{5/3}Sr_{1/3}NiO_4$ sample



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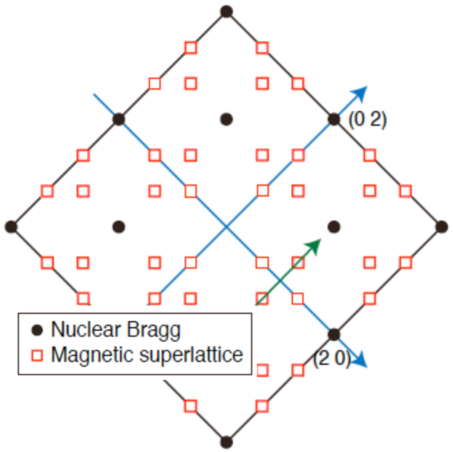
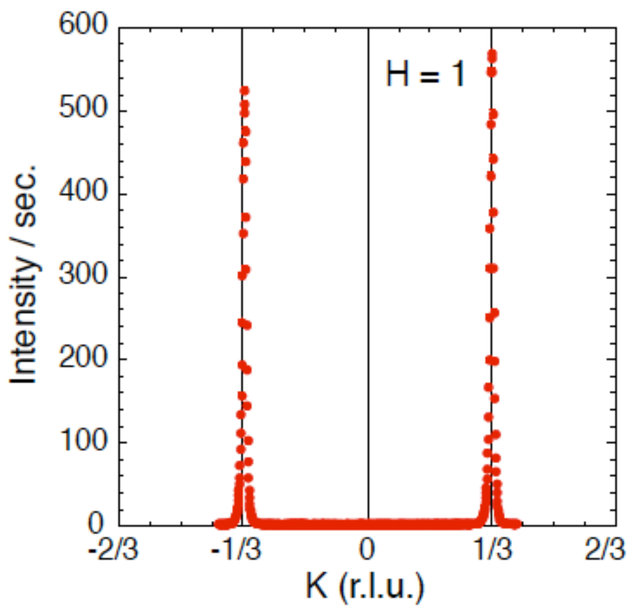
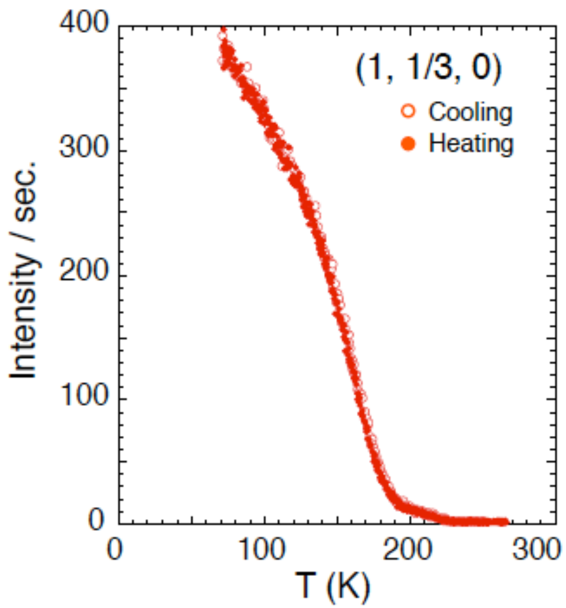


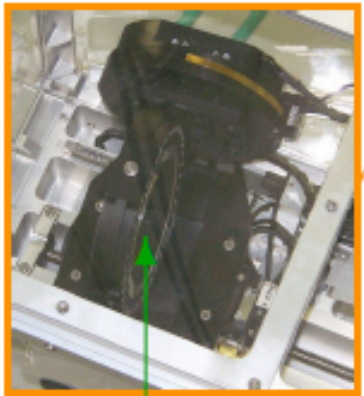


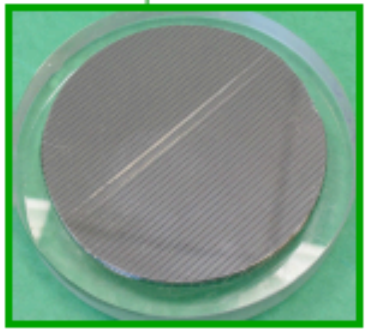


MERIX Spectrometer@30-ID.APS

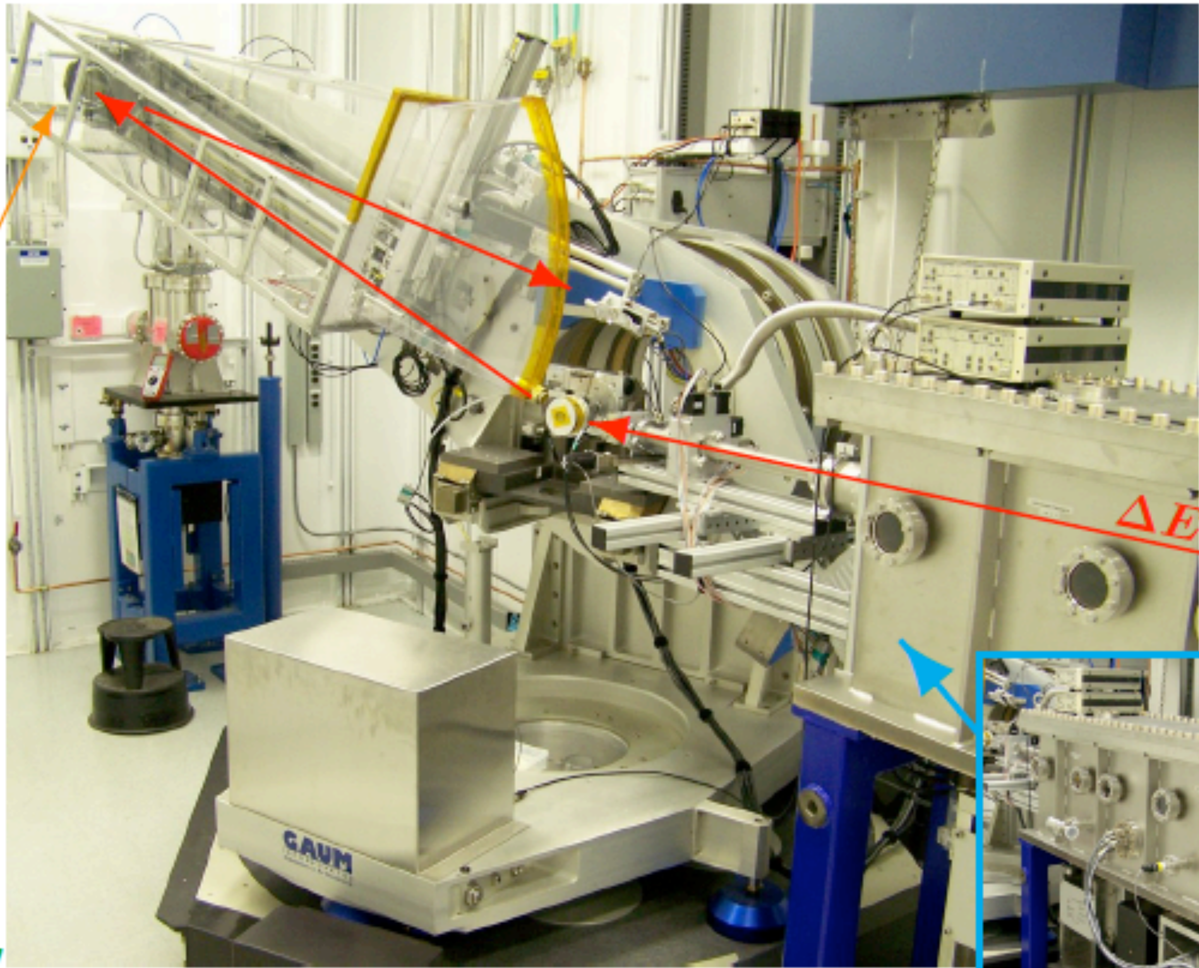
(LSNO experiments)

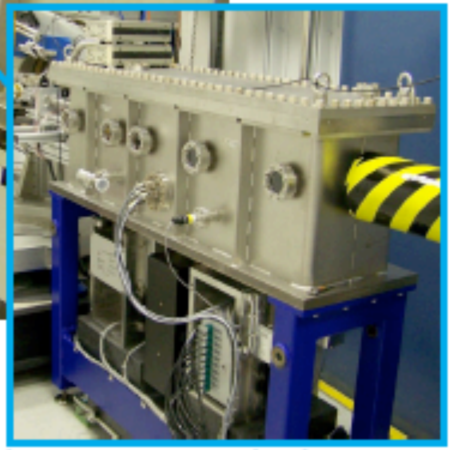
Analyzer gimbal





Ge(337)
diced analyzer:
$\Delta E = 115$ meV

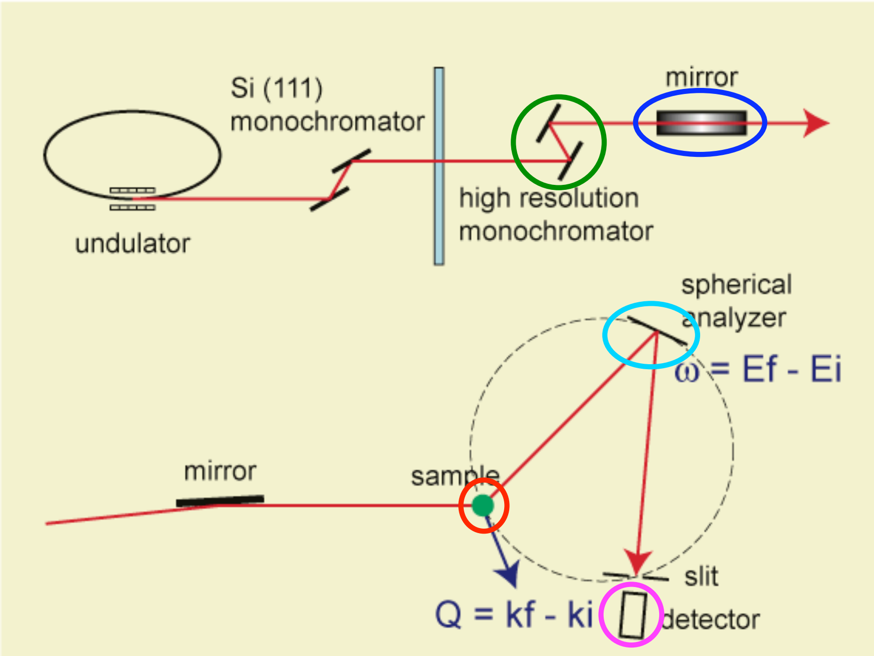


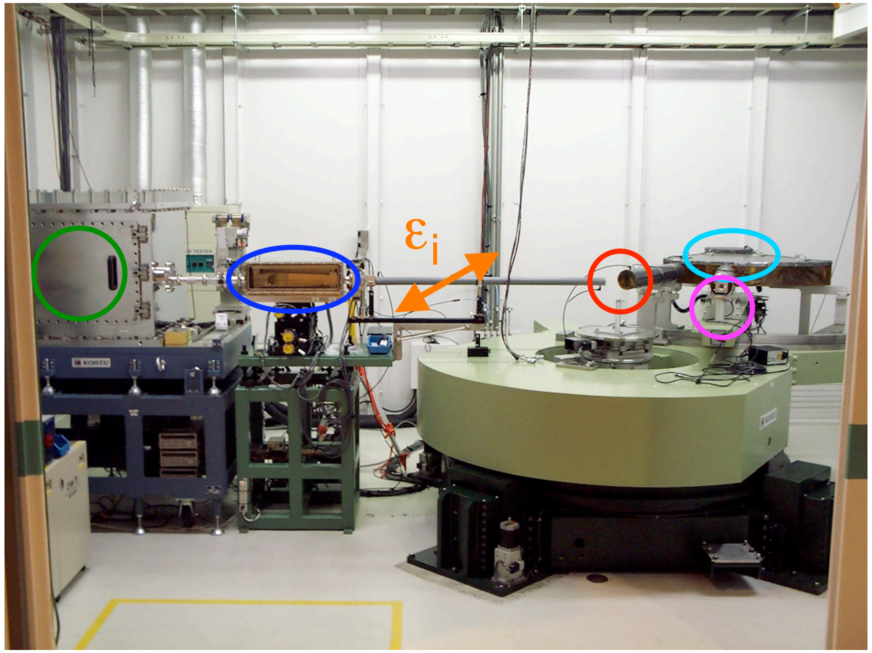


MERIX mirror.
Focus: 5 μm (V) $\times 40 \mu$m (H)

- Fine energy resolution
  - Cu K-edge : ΔE=110 meV
  - Ni K-edge : ΔE=150 meV (Ge(642) analyzer)
- High efficiency by line detector

BL11XU at SPring-8 (L(B,S)CO experiments)



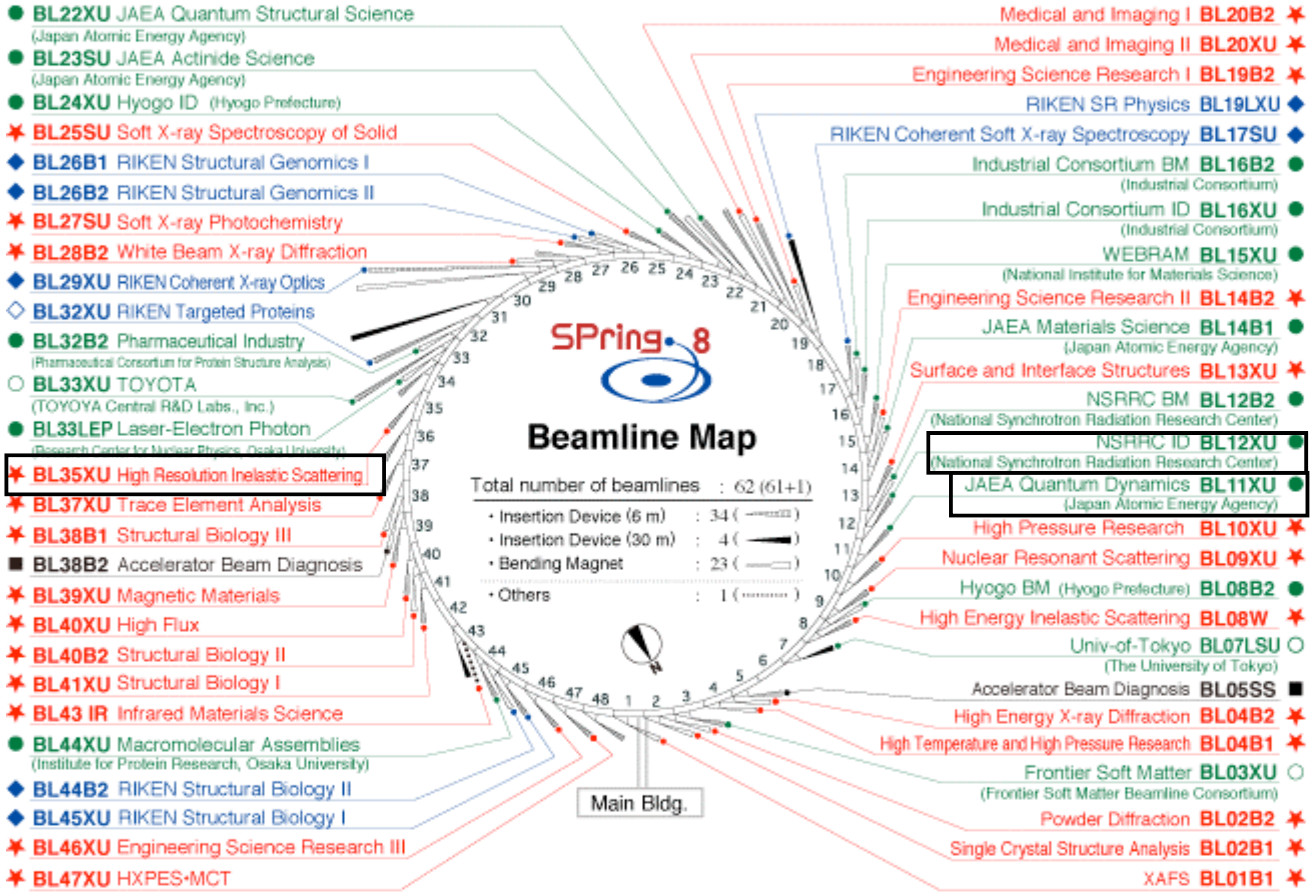


- Horizontal Scattering geometry
  (ε_i // scattering plane)
- Polarization analyzer
- Sample condition
  - ✓ Temperature 10 - 400 K
  - ✓ Magnetic Field < 8 T

Energy resolution in practical set up

element	mono.	analyzer	ΔE (meV)
Cu		Ge(733)	~ 400
Mn	Si (400)	Ge(531)	~ 300
V		Ge(422)	~ 300

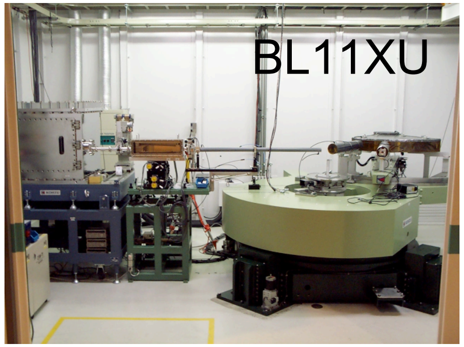
IXS beamlines at SPring-8

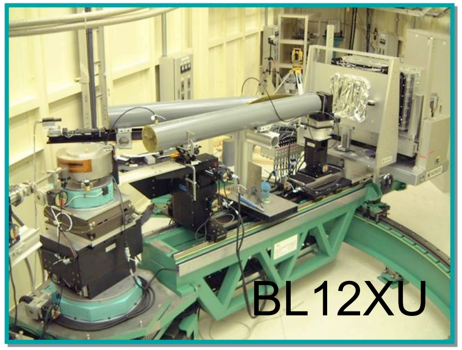


★ : Public Beamlines
● : Contract Beamlines
◆ : RIKEN Beamlines
■ : Accelerator beam diagnostic lines
☆ ○ ◇ □ : Planned or Under Construction

- high resolution
  - BL35XU … public beamline
  - ΔE ~ 1 meV
  - phonon

- medium resolution
  - BL11XU … JAEA
  - BL12XU … Taiwan NSRRC
  - (contact beamlines)
  - ΔE ~ 100 meV
  - charge excitations

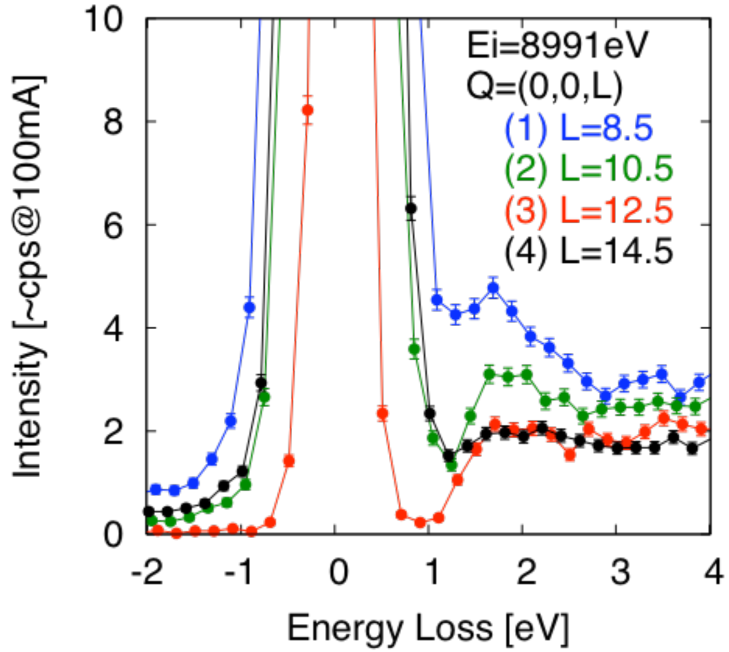


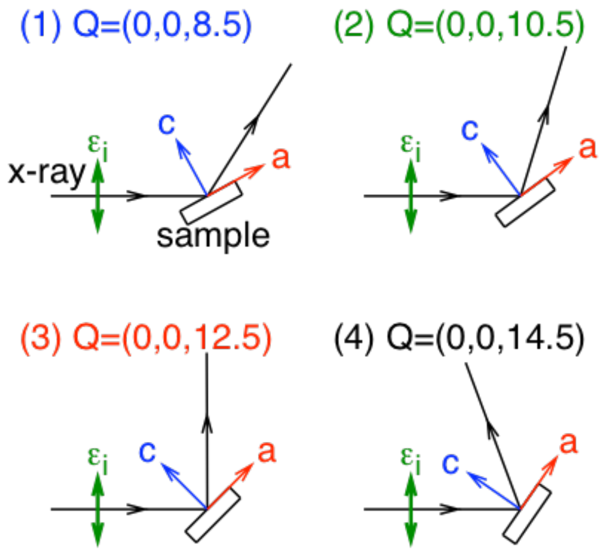


Scattering Geometry

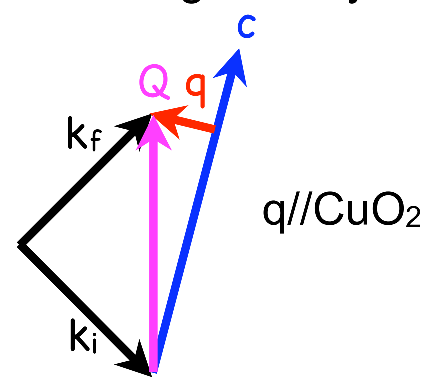
Ishii et al.

Nd_2CuO_4 momentum scan along c*-direction





Transverse geometry



- Elastic intensity is minimum at 2θ = 90°.

  Clear gap feature at Q = (0,0,12.5).

  q-scan in transverse geometry

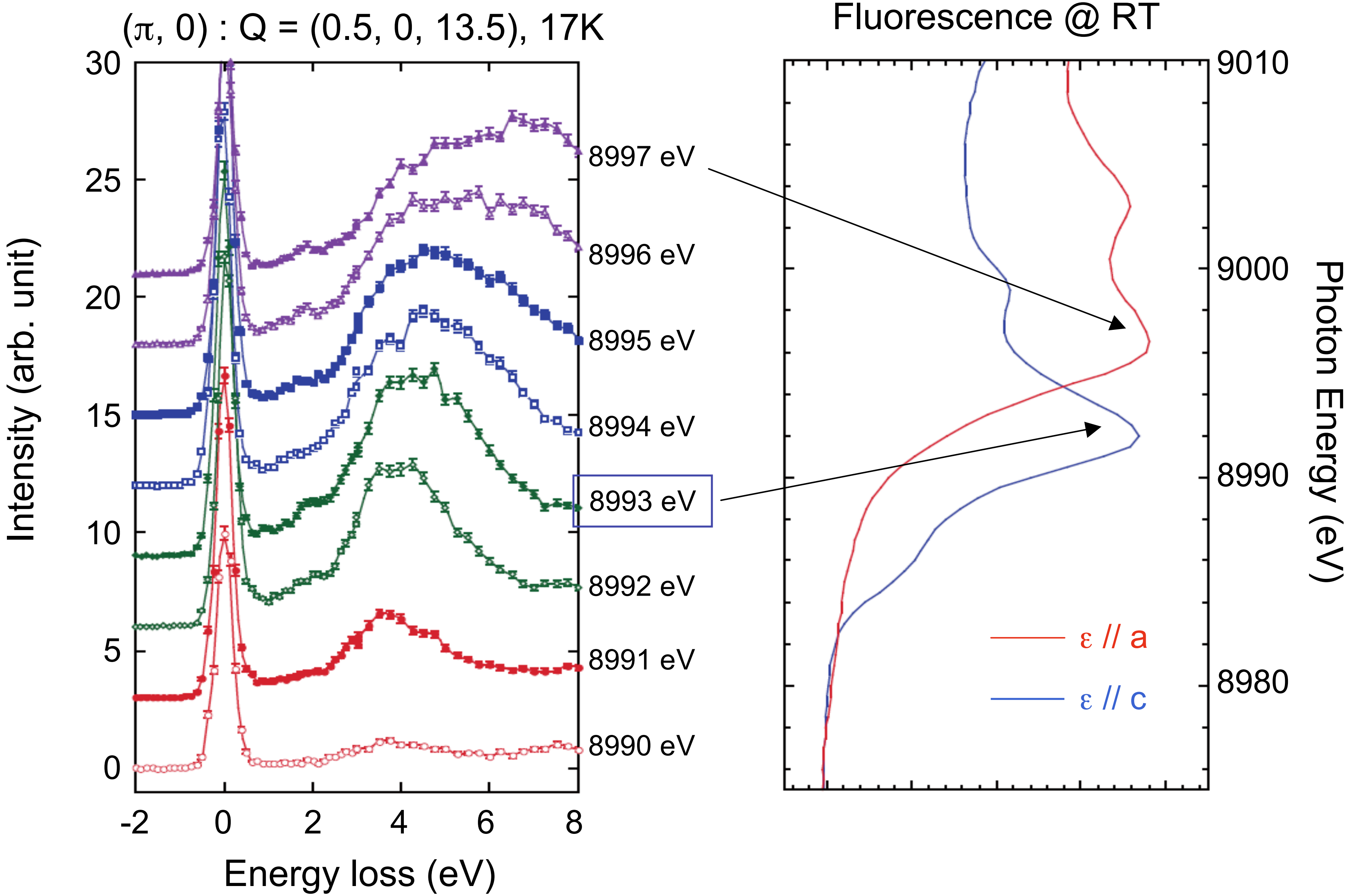
  ⇒ work well for low-dimensional materials

$La_{1.875}Ba_{0.125}CuO_4$

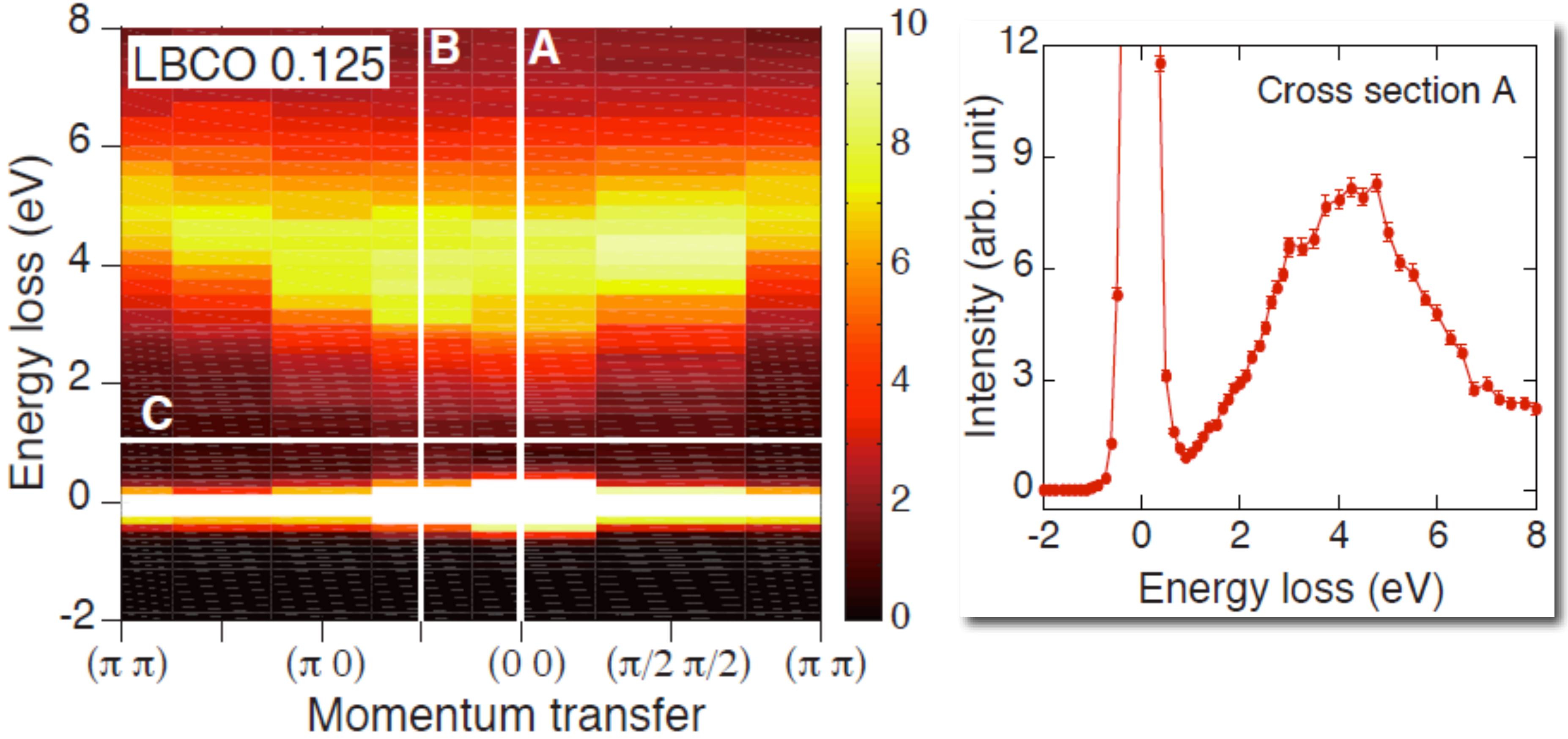
$La_{1.92}Ba_{0.08}CuO_4$

$La_{1.88}Sr_{0.12}CuO_4$

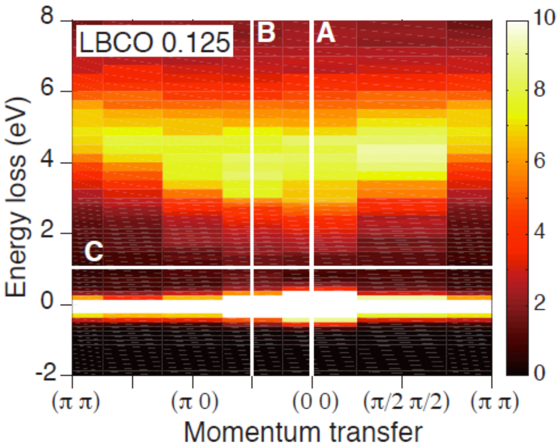
E_i - dependence : $La_{1.875}Ba_{0.125}CuO_4$

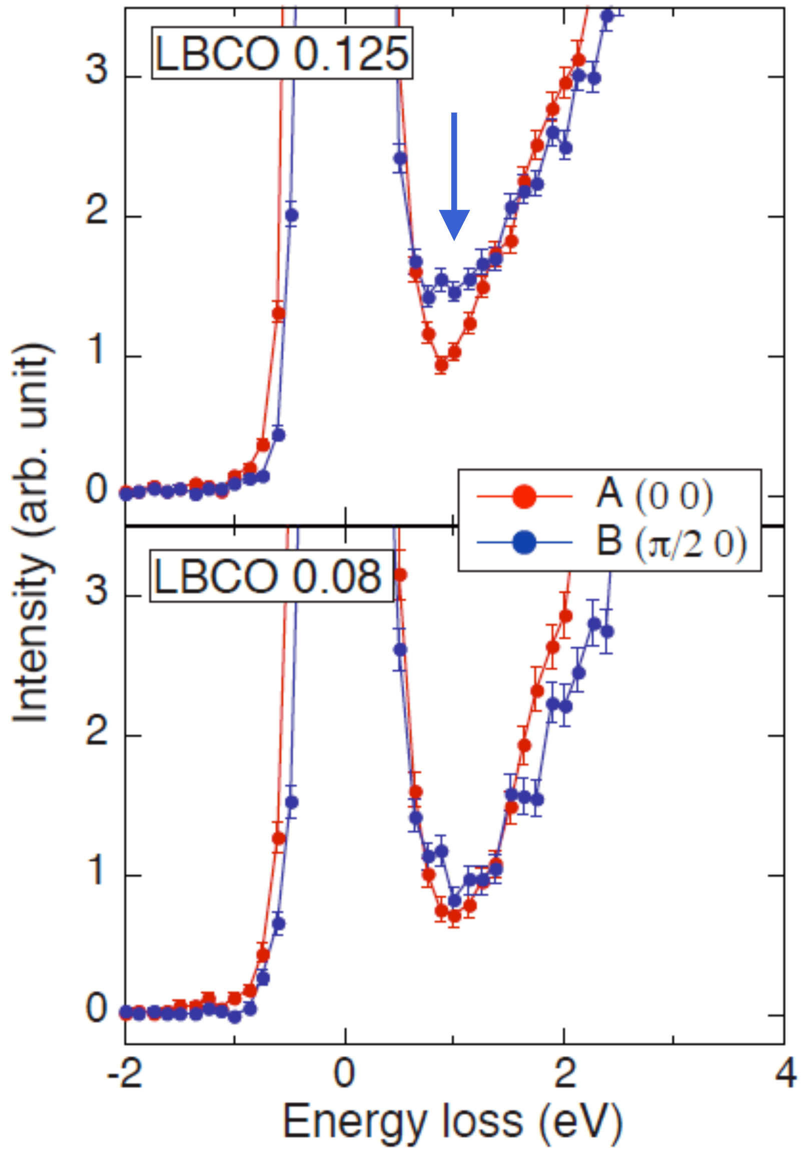


Overall spectra

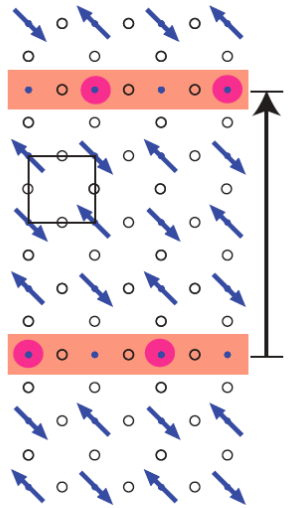


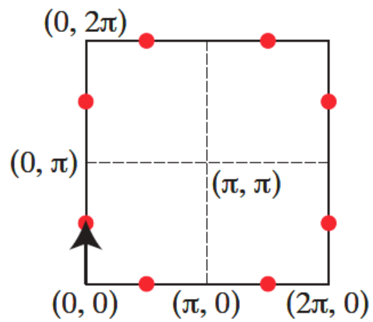
Comparison between (0, 0) & q_s



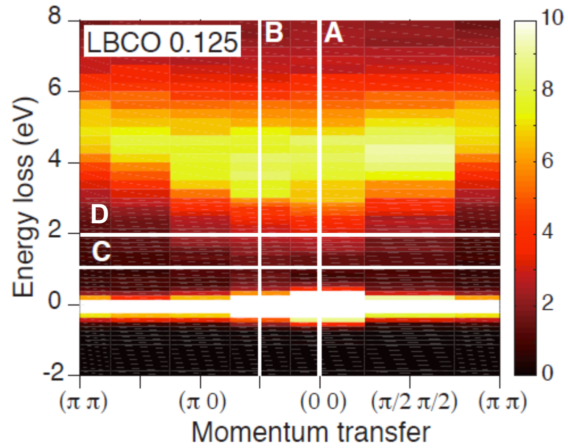


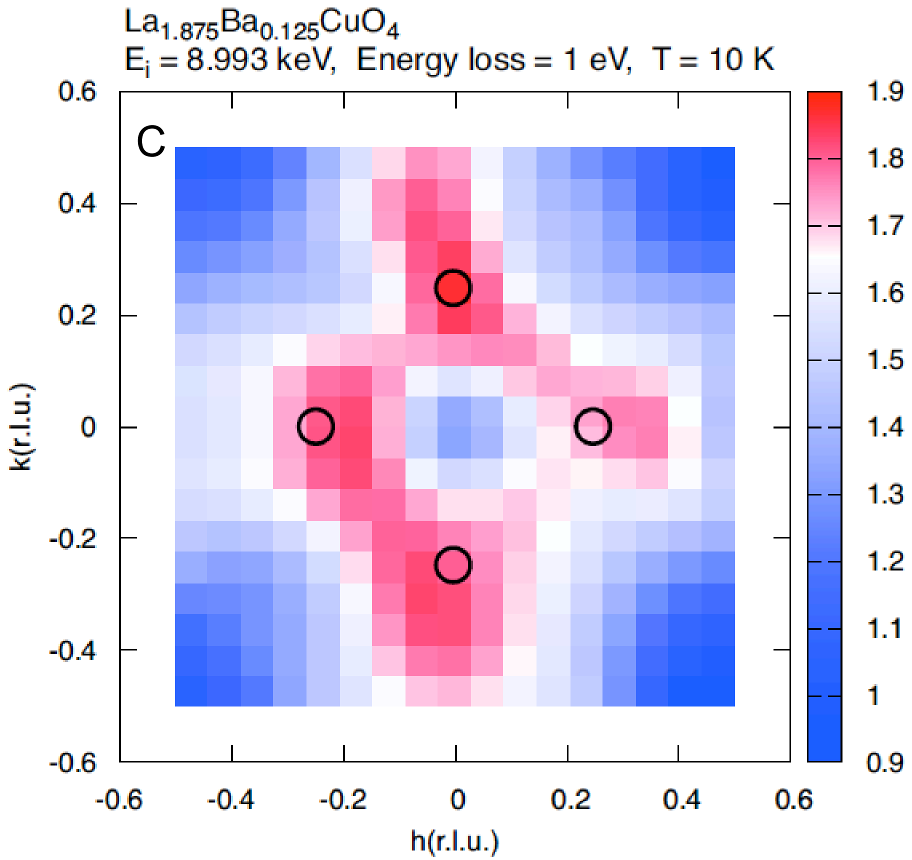
Stripe spacing :
$d_s = (0, 4a)$
Stripe q :
$q_s = 2\pi(0, 1/4)$



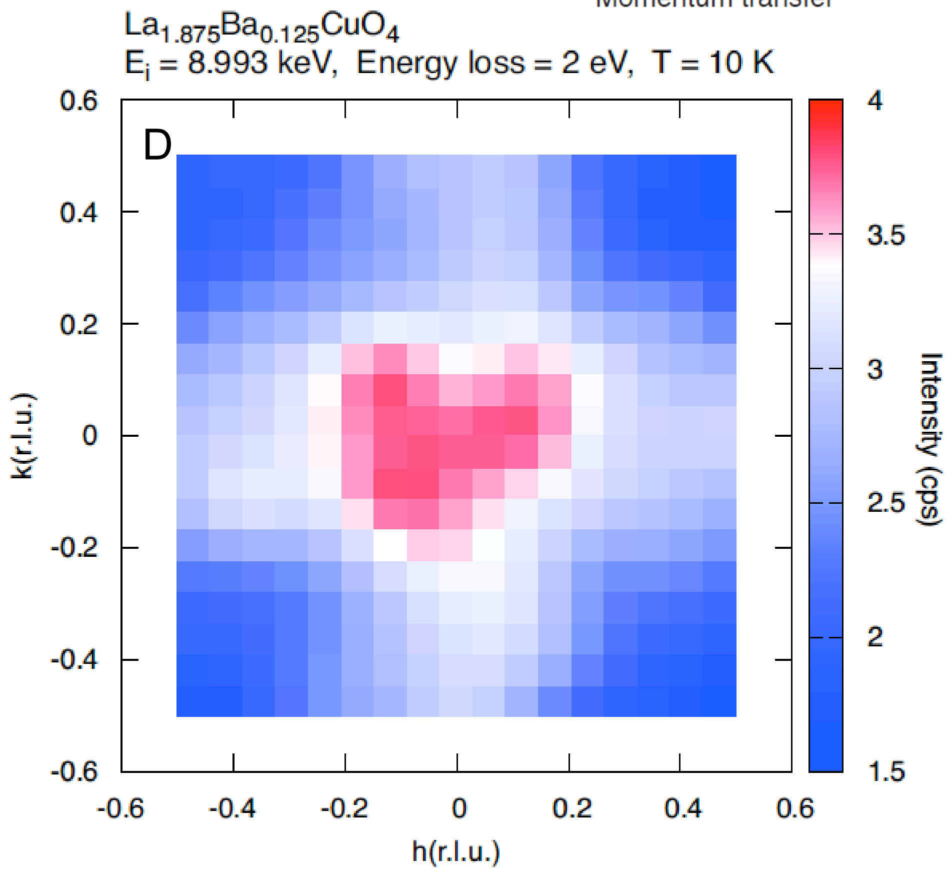


Excitation at q_s



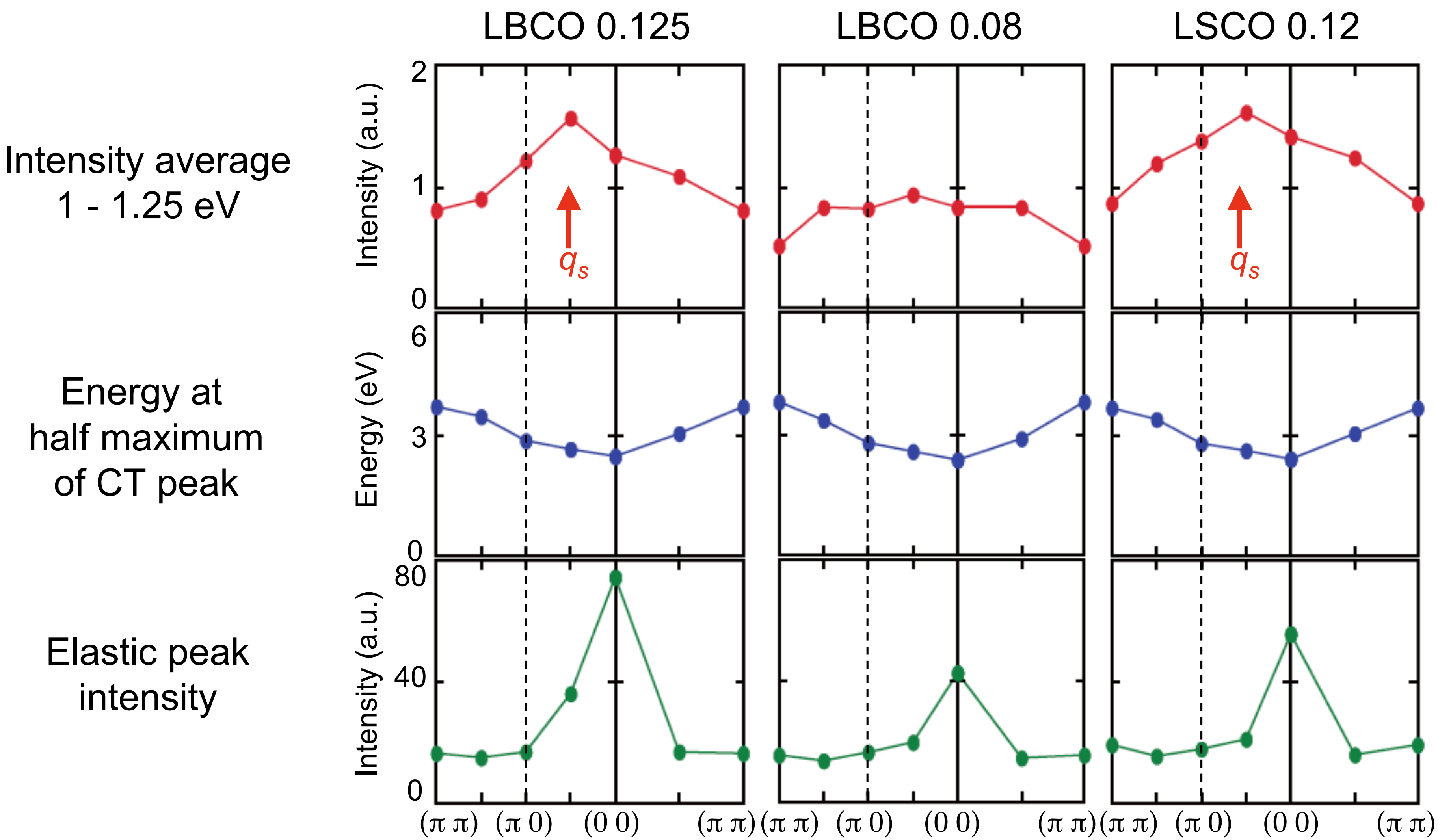


1 eV



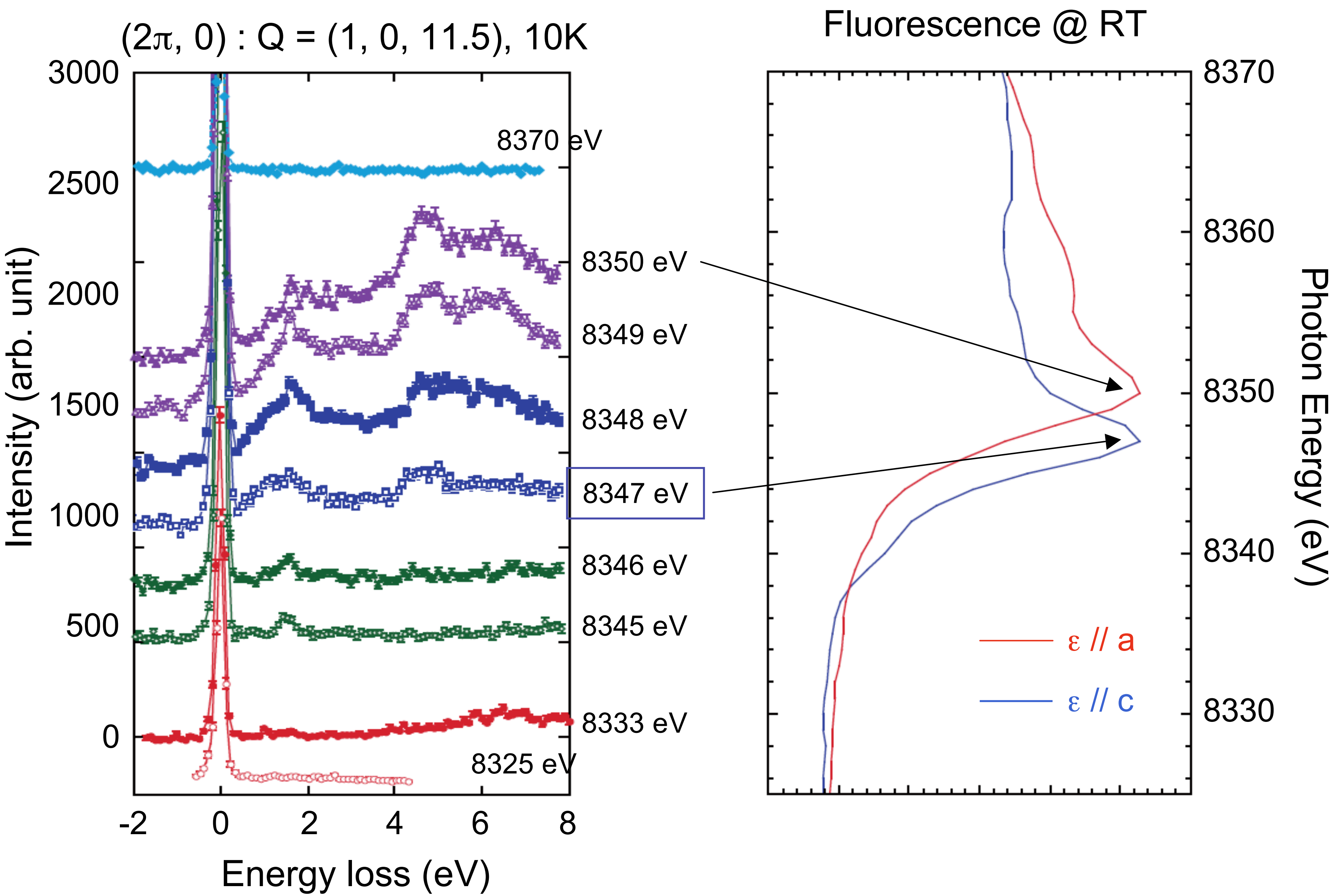
2 eV

q - dependence (2)

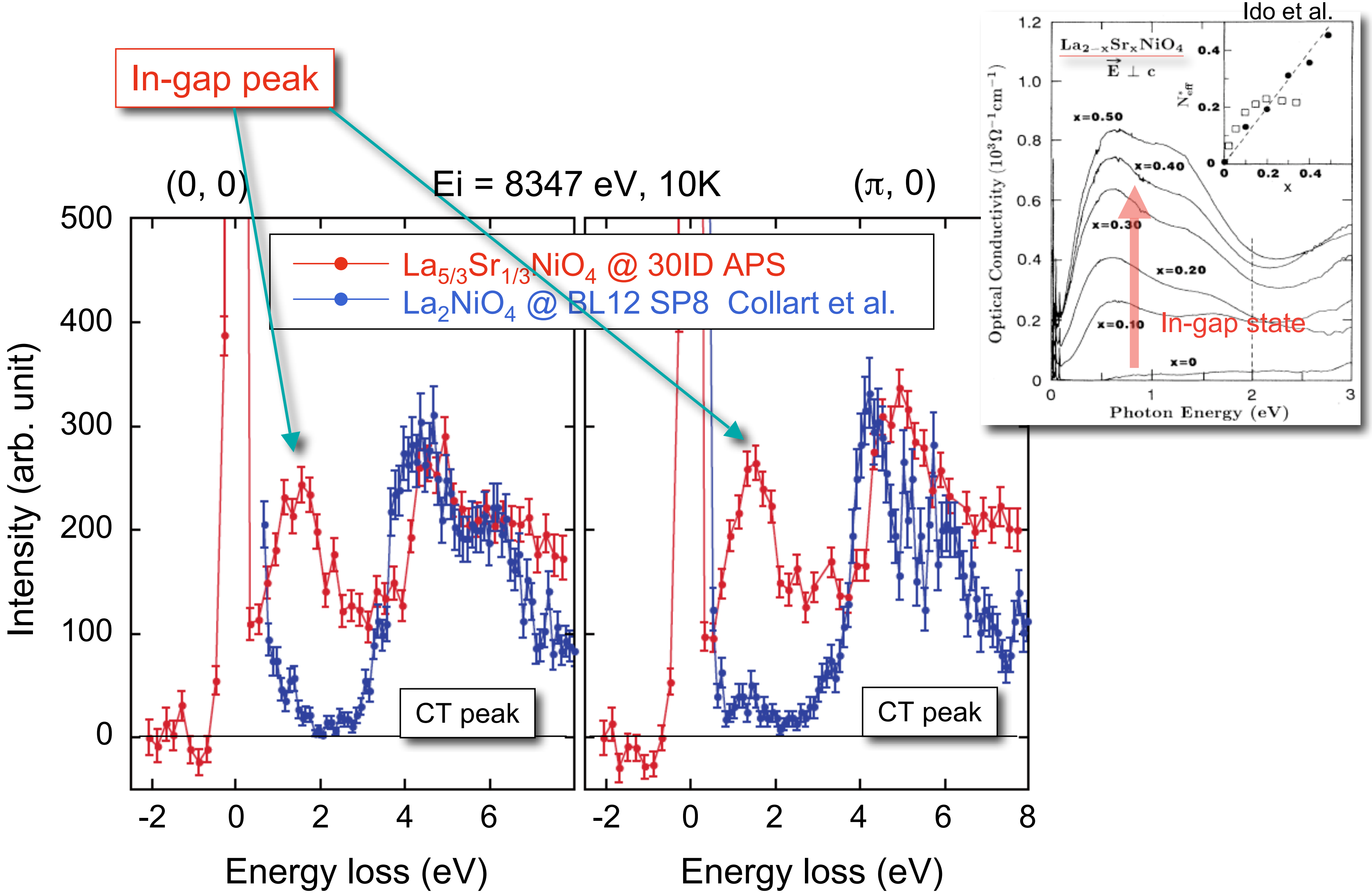


$La_{5/3}Sr_{1/3}NiO_4$

E_i - dependence

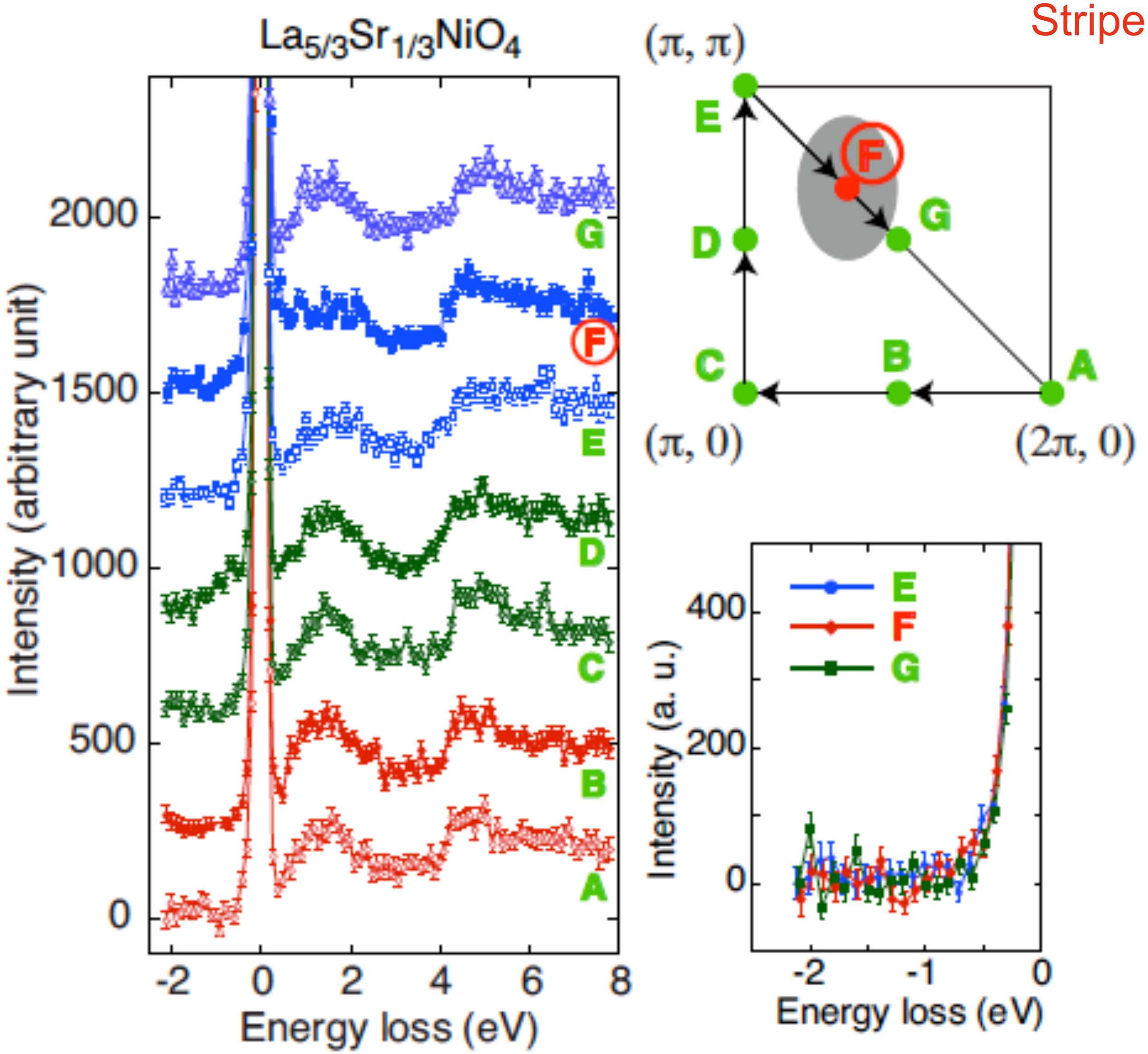


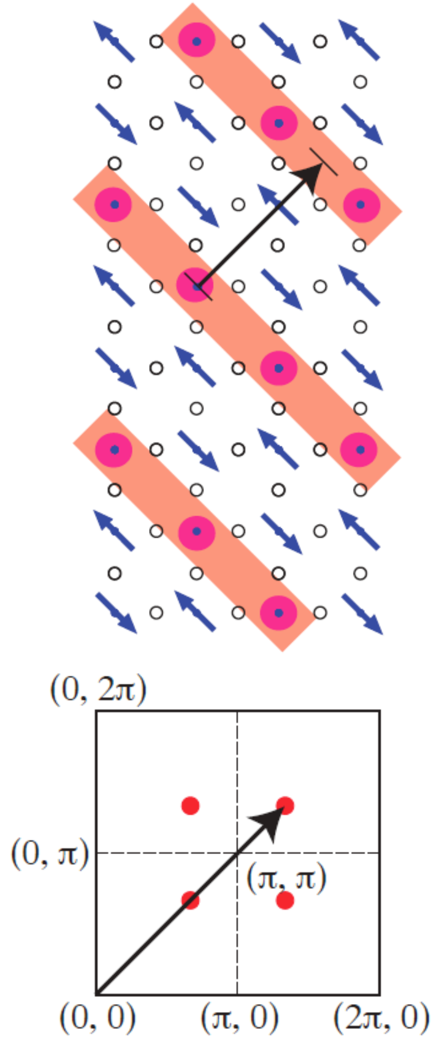
Comparison to the non-doped La_2NiO_4



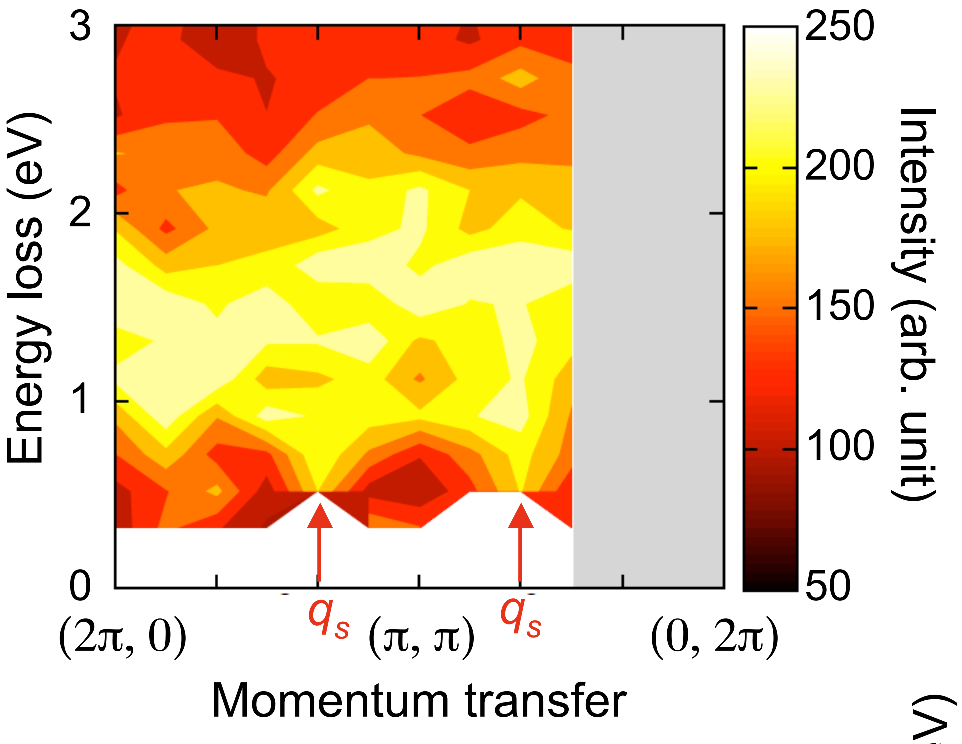
q - dependence (1)

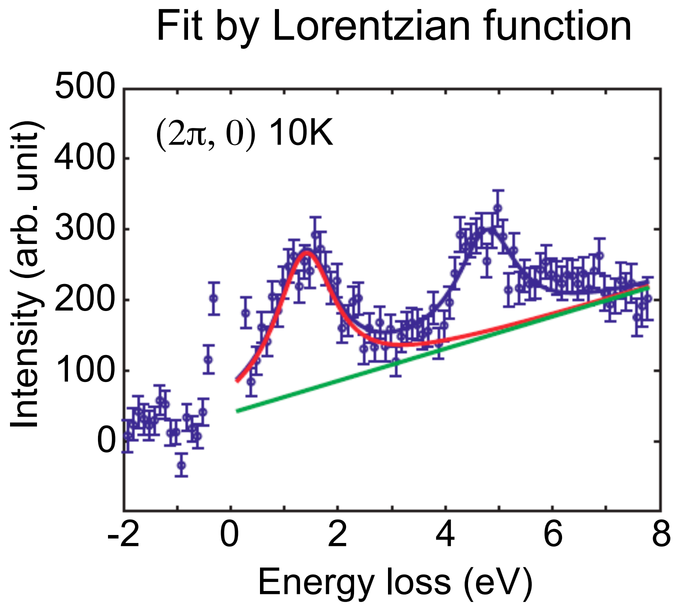
Stripe spacing : d_s = (3a/2, 3a/2)
Stripe q : q_s = 2π(2/3, 2/3)

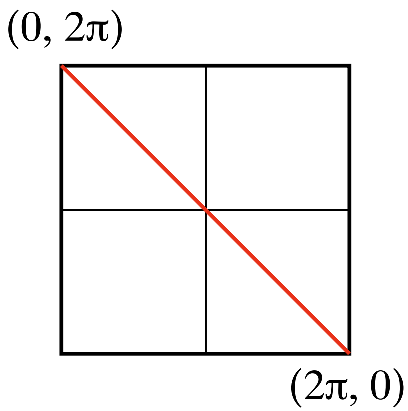


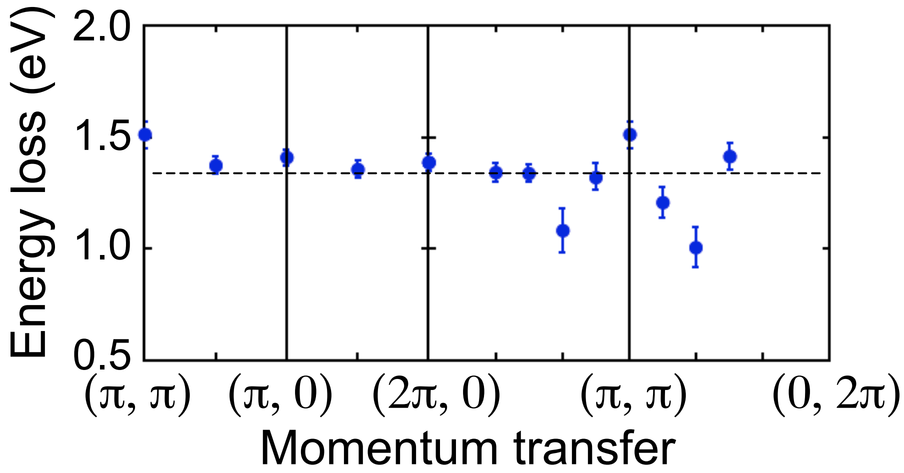


q - dependence (2)

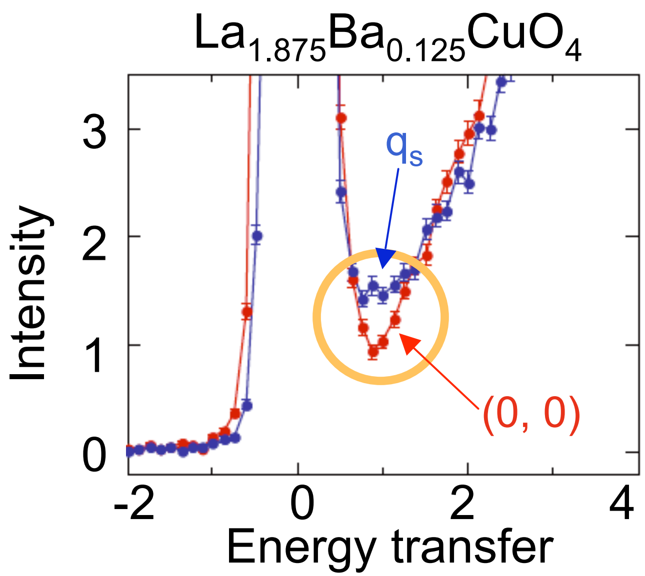


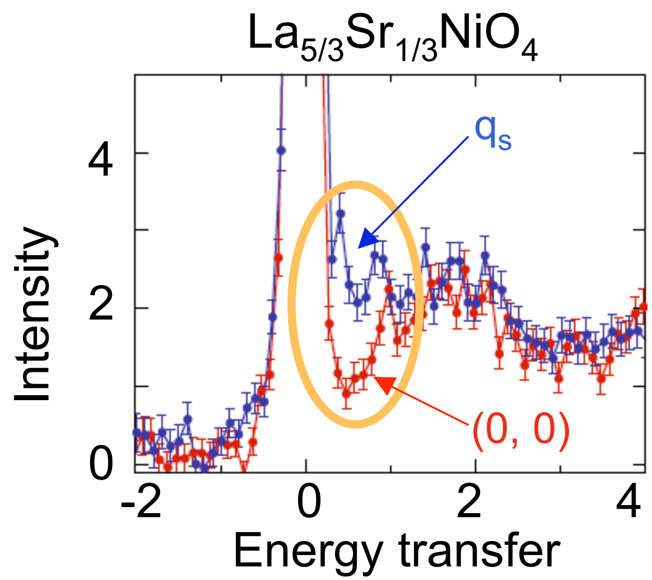






Experimental results summary





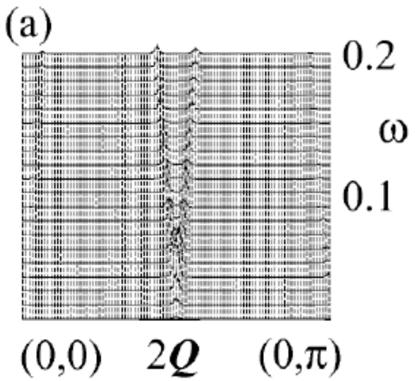
Cuprates
BL11XU 300meV resolution
- In-gap state is not observed.
- Continuum intensity increases at q_s for LBCO 0.125 and LSCO 0.12.

LSNO 1/3
MERIX 150meV resolution
- In-gap state is clearly observed.
- Gap-like structure is absent at q_s.

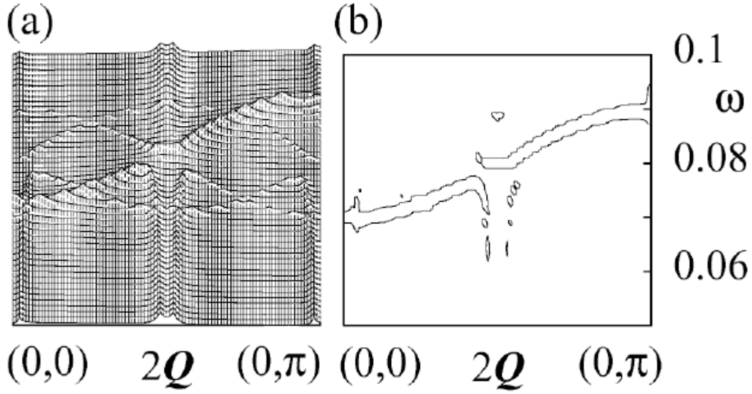
Both nickelate and cuprate, stripe order gives additional spectral weight at q_s around 1 eV.

Possibilities

Collective charge excitation?

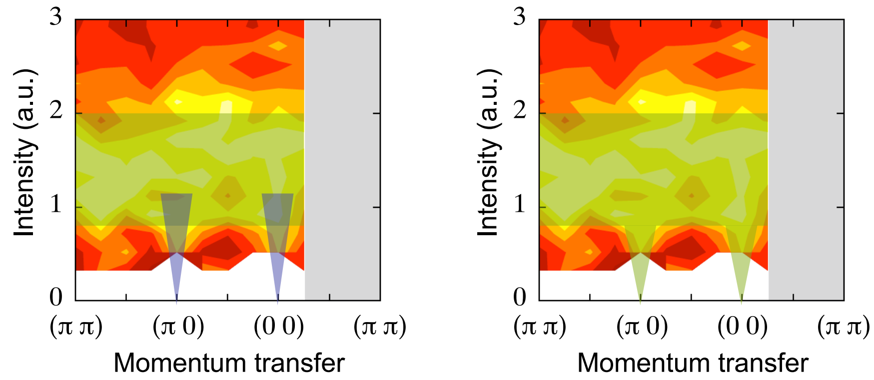


Cuprae case
Kaneshita et al.
PRL 88,115501.



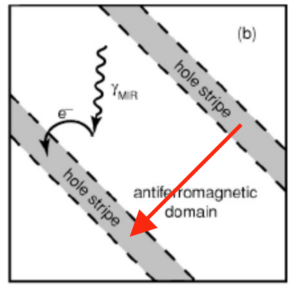
- Dynamic fluctuation of charge stripes produces collective charge excitation.
- In principle, this should be observed in non-renonant scattering.

Same or diifferent ?



Stripe band excitation?

Homes et al.



- The excitation at the stripe-*q* corresponds to the charge excitation between charge stripes.

May such excitation produces small gap??
(Gap < 340 meV)

Other origin?

Does introduction of the stripe structure into the models account for the observation?

Summary

- Hard x-ray RIXS on charged ordered system.
- Charge ordered compounds show additional RIXS spectra at q_s at ~1eV.

- More doping dependence, more material dependence will be studied soon.
- Soft x-ray RIXS can be an candidate to study this feature.