Charge density wave order and nematicity in cuprate superconductors

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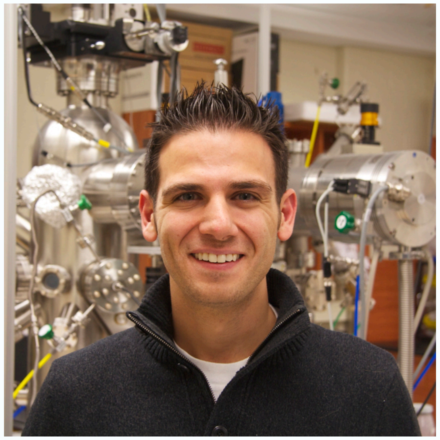
CRSNG

Canada Foundation for Innovation
Fondation canadienne pour l'innovation



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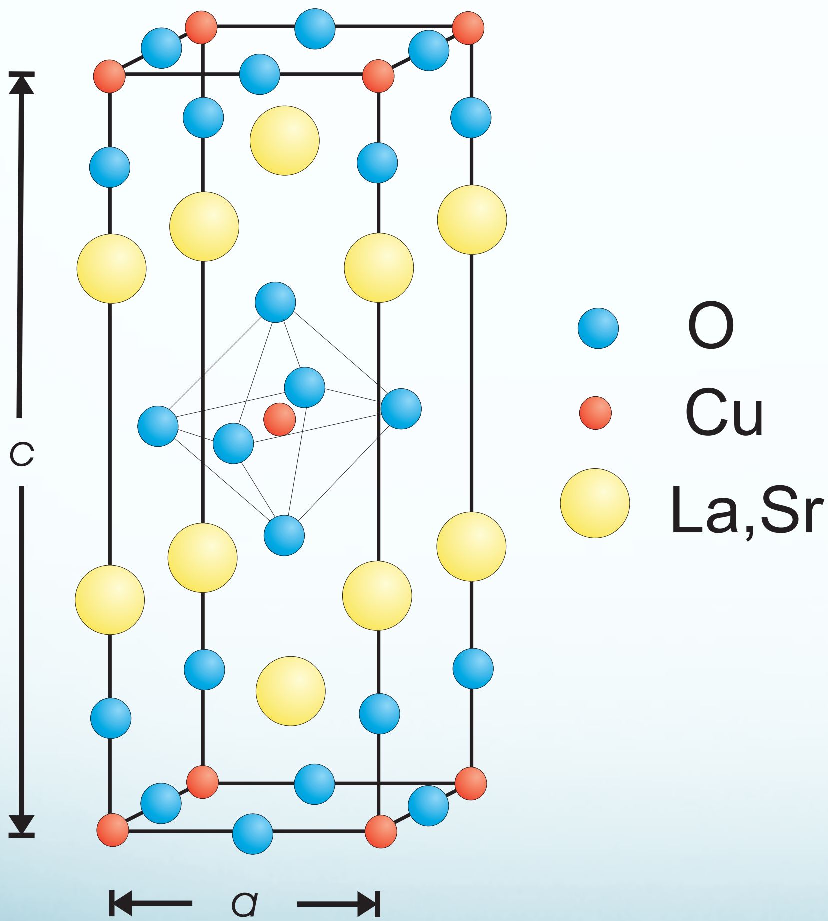
Outline

- Cuprate high temperature superconductors
- Charge density wave (CDW) order in the cuprates
- Nematicity in cuprate superconductors
    - Resonant x-ray scattering
- Symmetry of CDW order in the cuprates

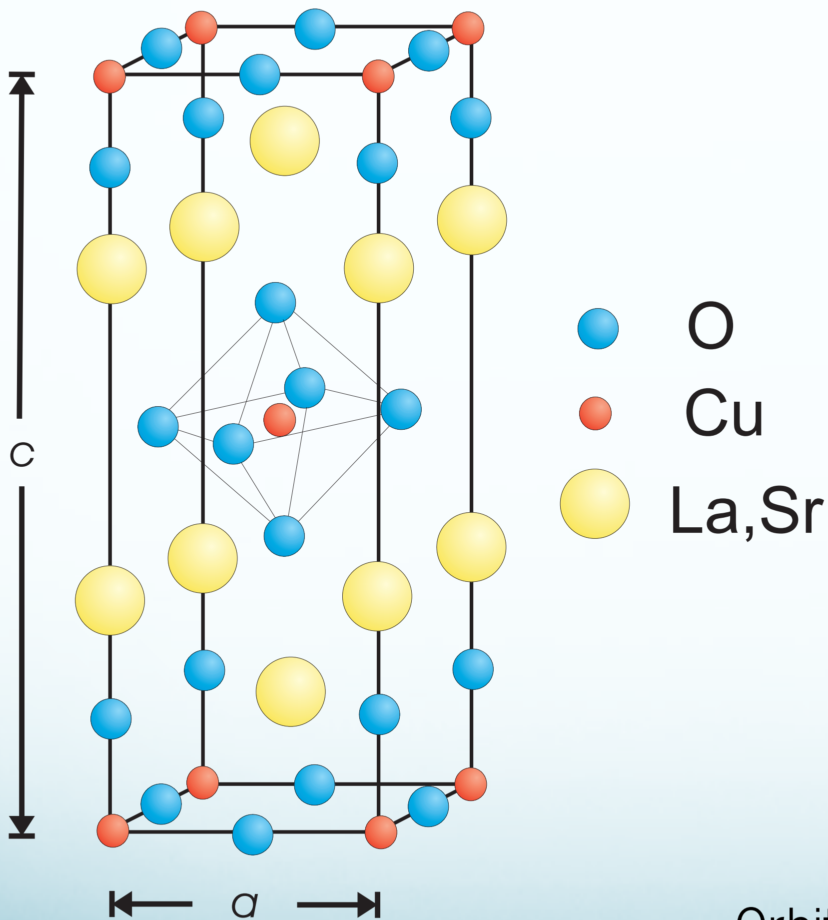
Cuprate structure and electronic structure

$La_{2-x}Sr_xCuO_4$

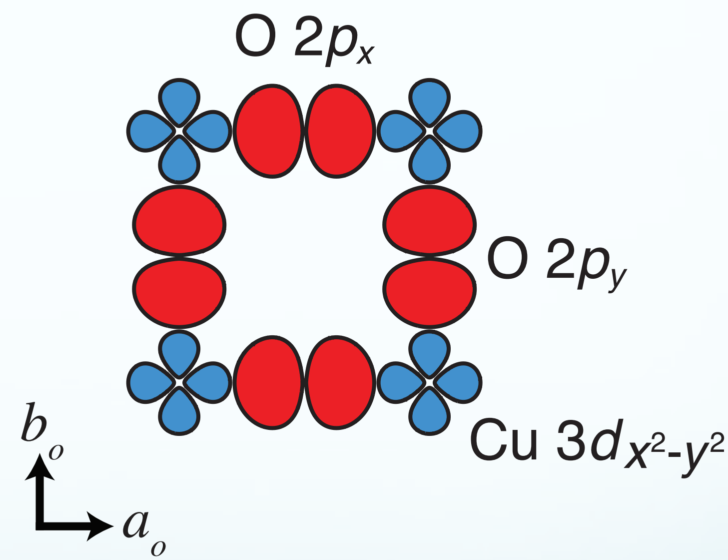


Cuprate structure and electronic structure

$La_{2-x}Sr_xCuO_4$



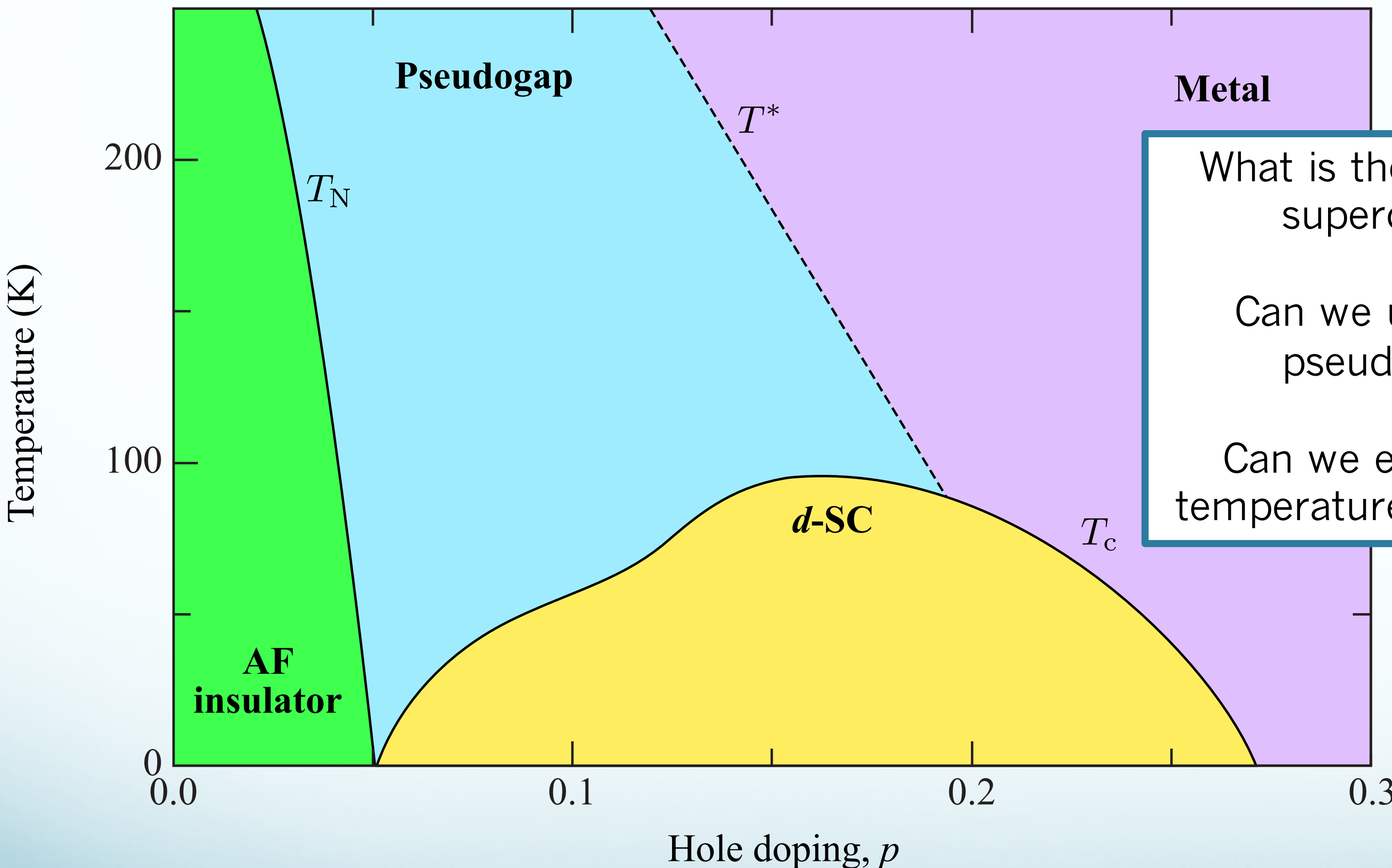
Low energy physics is dominated by the CuO_2 planes



Quasi 2D – square lattice of Cu and O

Orbital occupation (doping) of the CuO_2 planes is determined by “charge reservoir” layer

Cuprate high-temperature superconductors

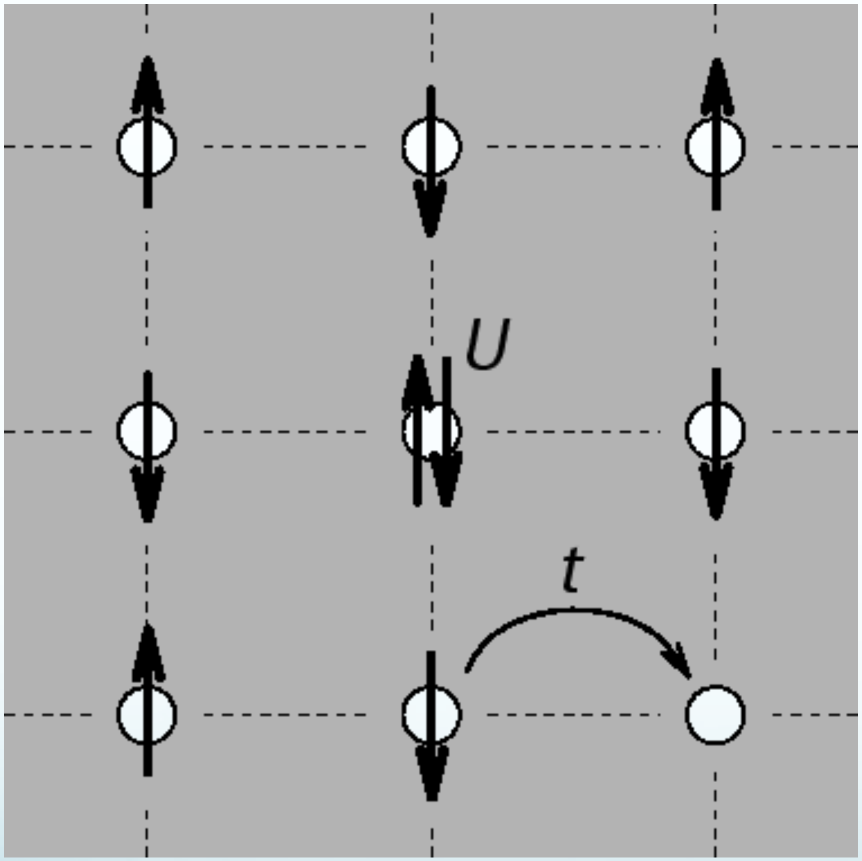


What is the mechanism for superconductivity?

Can we understand the pseudogap phase?

Can we engineer a room temperature superconductor?

Strong correlations: Why is this a hard problem?



Square lattice of S =1/2 electrons

Hubbard model

$$H_H = -t \sum_{i\delta\sigma} c^{\dagger}_{i+\delta,\sigma} c_{i,\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow} \, .$$

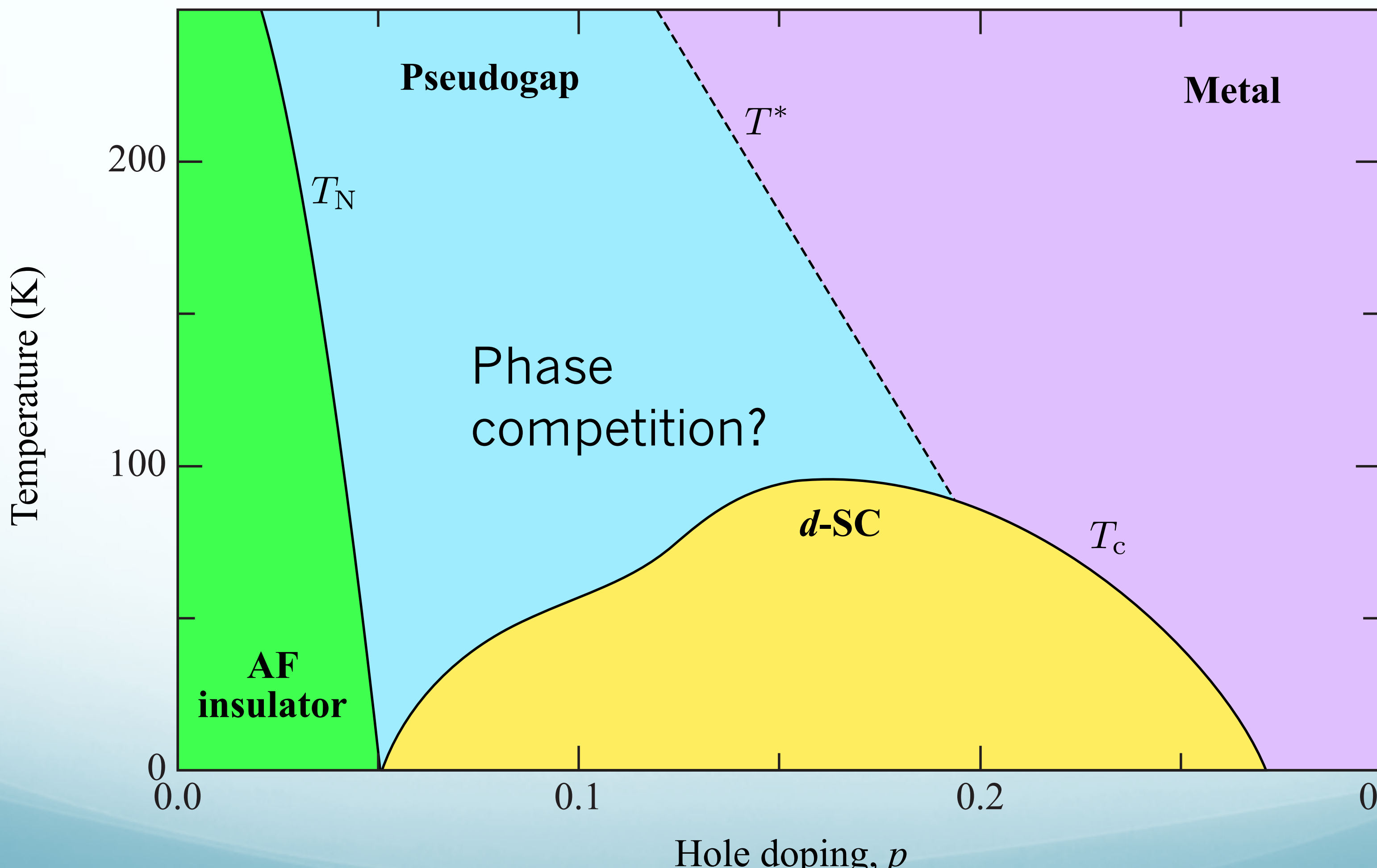
Hopping

Energy to doubly occupy a site, leaving an unoccupied site

- May not be possible to solve exactly for relevant system sizes (Hilbert space is too large)
- Real materials
    - Multiple bands model
    - 3 dimensions
    - Electronic and lattice degrees of freedom
    - …

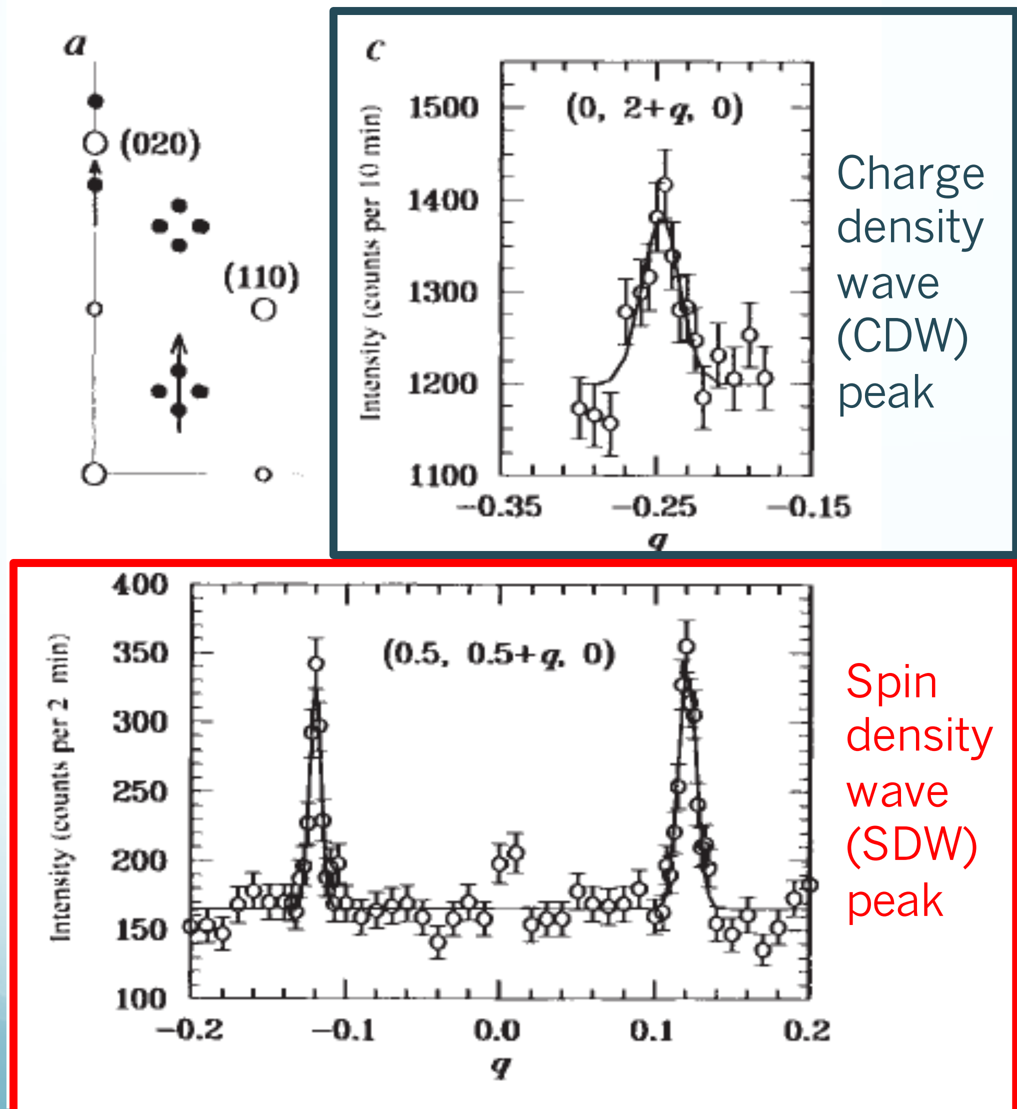
Competing states of matter

Superconductivity can compete/co-exist with other ordered phases



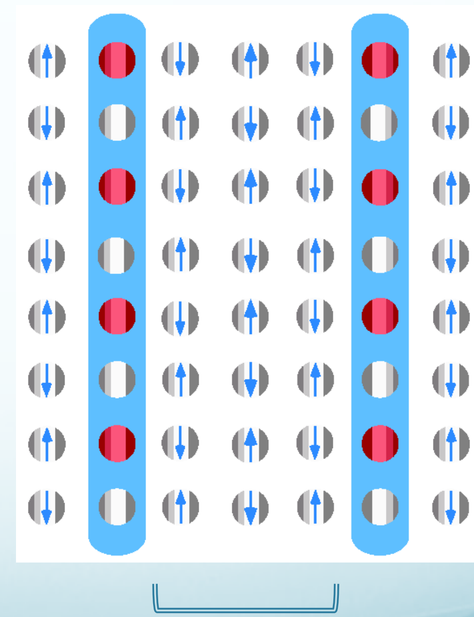
Density wave order in the cuprates

$La_{1.475}Nd_{0.4}Sr_{0.125}CuO_4$ Elastic Neutron scattering



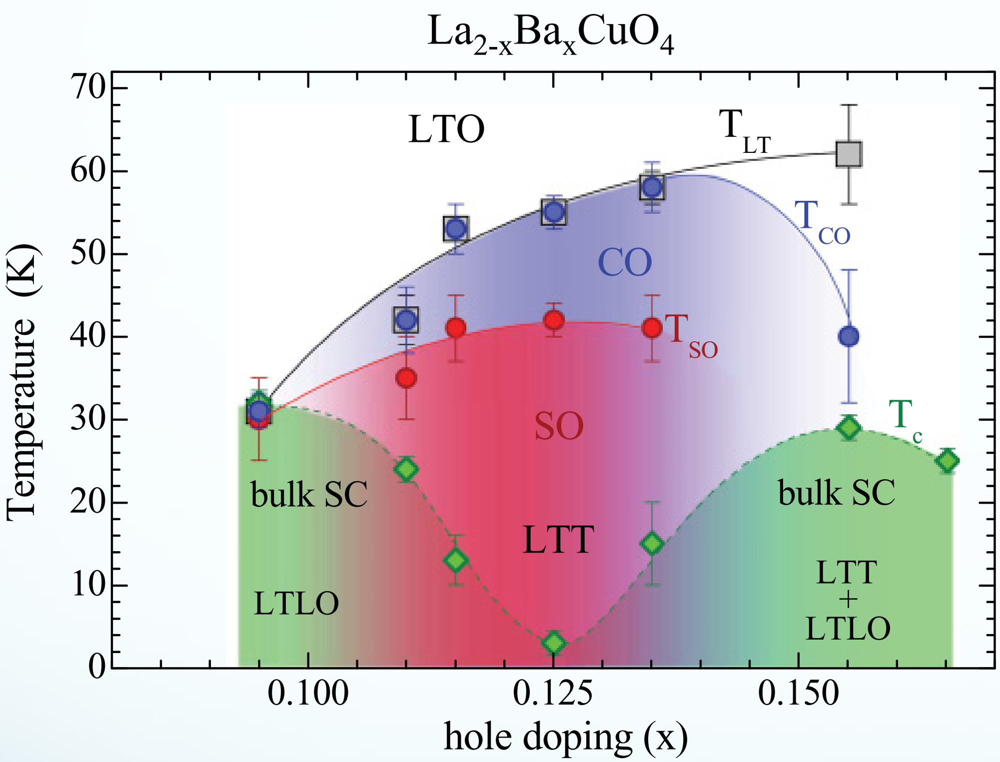
Unidirectional Spin and charge order (stripes) first observed in the cuprates by neutron scattering (Tranquada et al., Nature 1995)

Half-filled charge stripe



Undoped AF regions

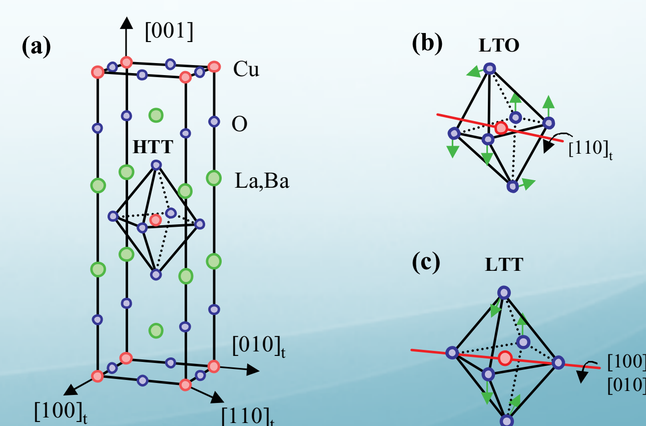
Density wave order in the cuprates



M. Hücker,
PHYSICAL REVIEW B **83**, 104506 (2011)

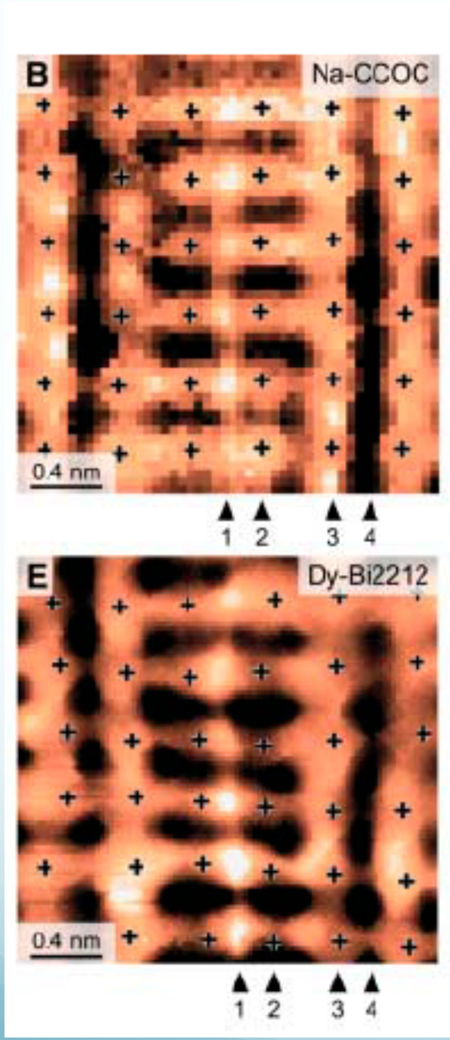
Some characteristic features of "stripes" in La-based cuprates

- Unidirectional spin order (SO) and charge order (CO)
- CDW with period ~4 lattice constants (4a)
- Associated with a suppression of superconductivity at x = 1/8
- Stabilized by LTT structural distortion



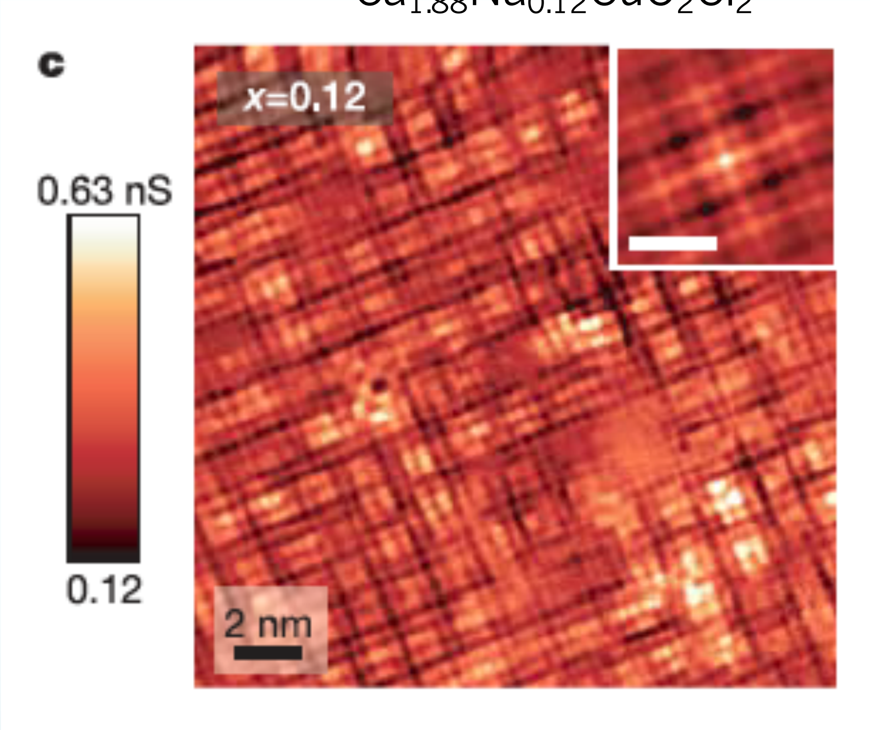
Charge order is generic to the cuprates

Scanning tunneling microscopy



Khosaka Science 2008

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$



differential tunneling conductance

Hanaguri Nature 2004

Observations of density wave order by STM

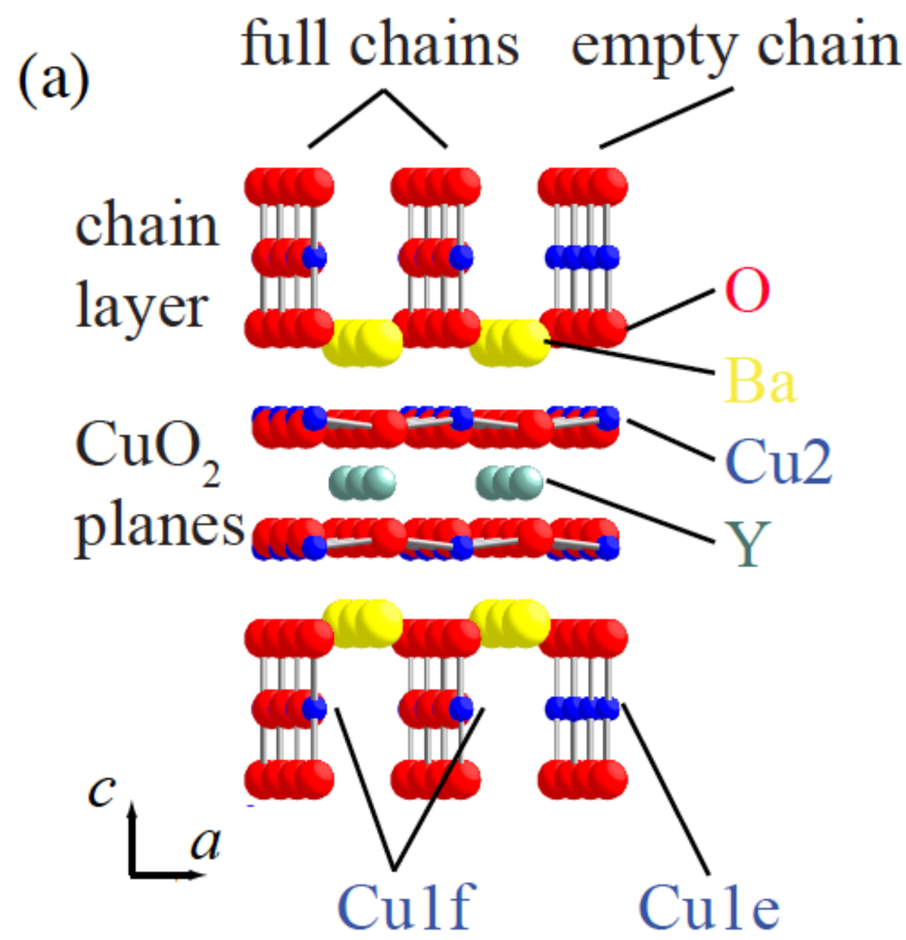
Davis group
Kapitulnik group
Yazdani group
Hoffmann group
Hudson group
...

Charge density wave order in YBCO??

$YBa_2Cu_3O_{6+x}$

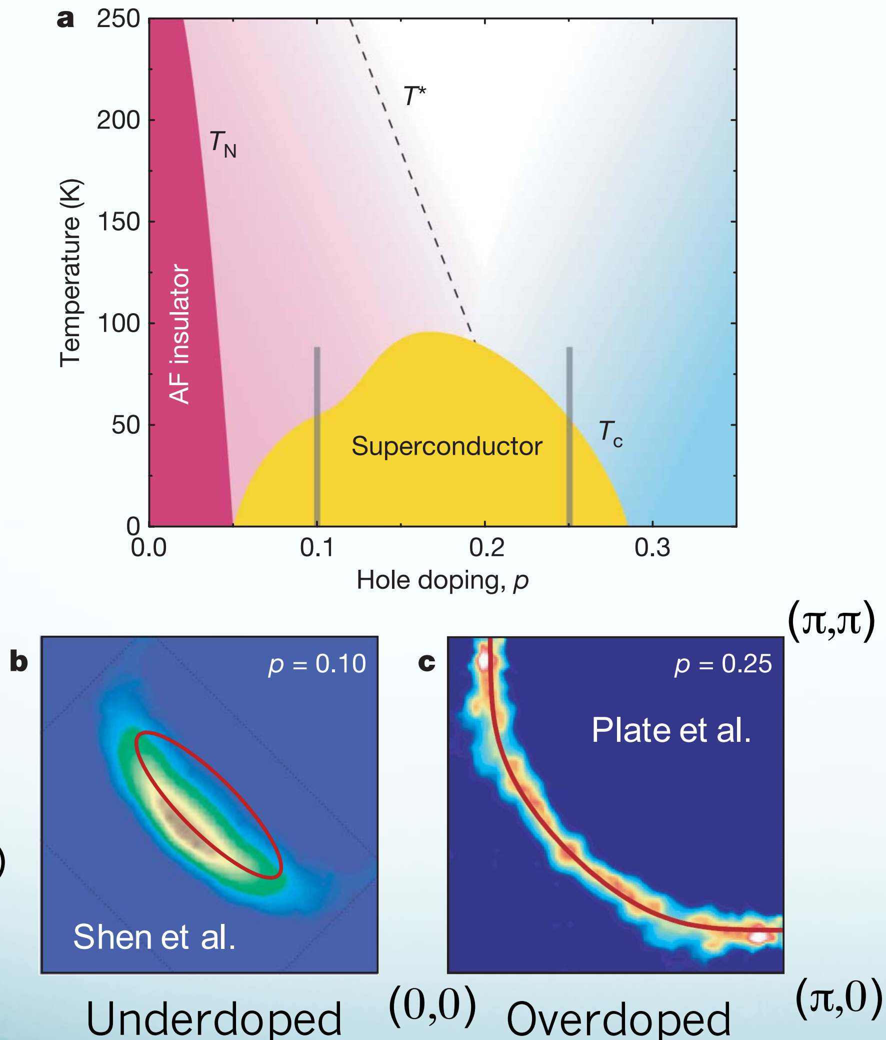
- Bilayer cuprate
- Orthorhombic structure ($a \neq b \neq c$)
- Doped by O atoms intercalated into "chain" layer far from the CuO_2 planes
- Low levels of disorder
- High $T_{c,max}$ = 94.2 K
- Oxygen orders in the chain layer

Ex: Ortho III ordered $YBa_2Cu_3O_{6.75}$



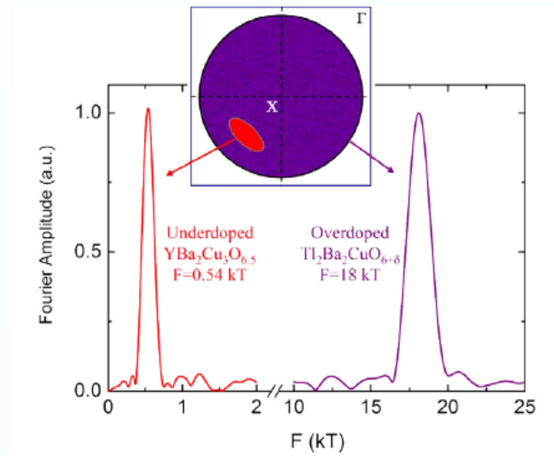
Indirect evidence of density wave order in $YBa_2Cu_3O_{6+\delta}$

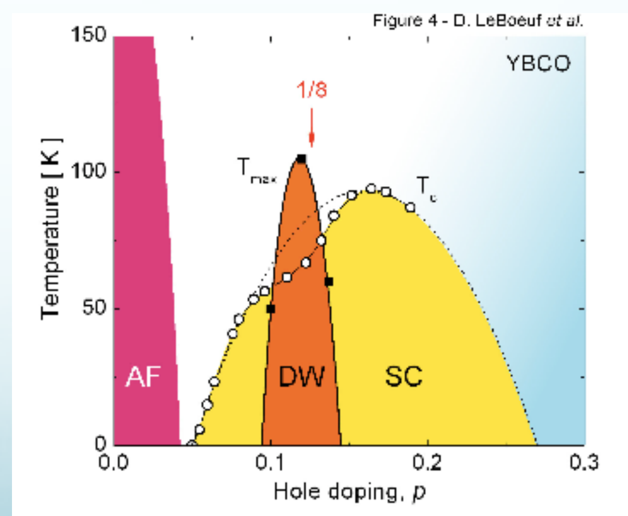
Fermi surface (ARPES)



Hole like Fermi surface measured in cuprates by angle resolved photoemission

Electron pocket from quantum oscillations in low doped YBCO



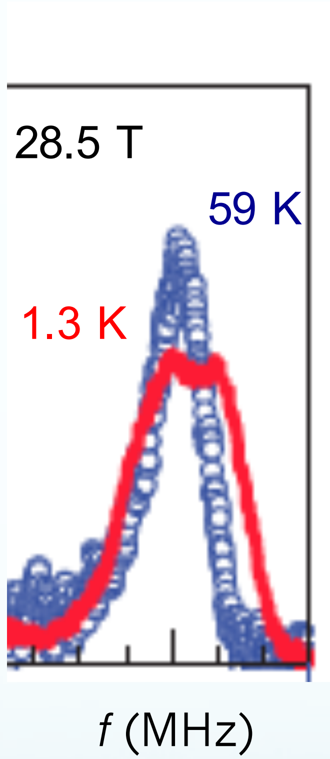


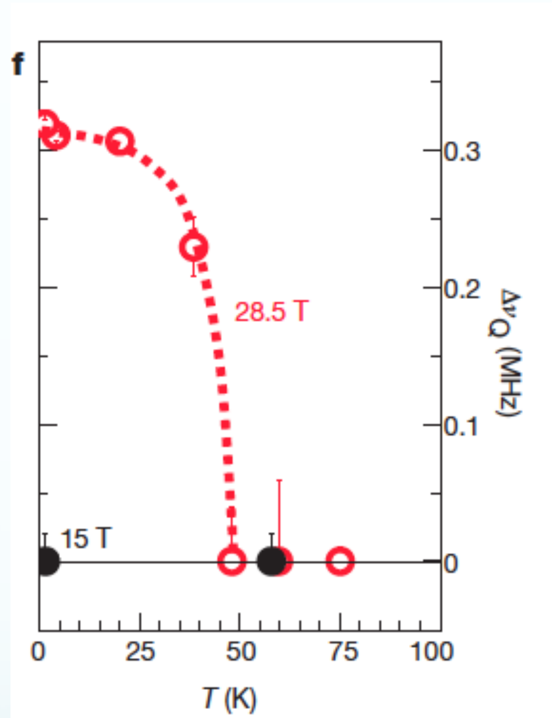
Doiron-Leyraud et al. Nature 2007

Evidence of density wave order in $YBa_2Cu_3O_{6+x}$

High magnetic field NMR in YBCO

Splitting of in plane Cu^{63} peaks associated with charge density variation





Tao Wu et al., Nature 2011

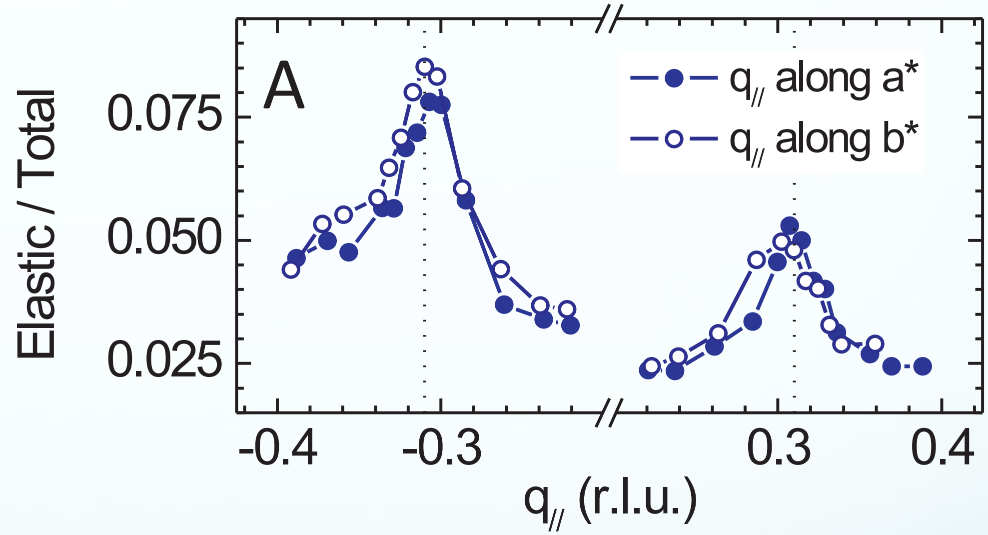
CDW order in YBCO

Long-Range Incommensurate Charge Fluctuations in (Y,Nd)$Ba_2Cu_3O_{6+x}$

G. Ghiringhelli,[1]* M. Le Tacon,[2] M. Minola,[1] S. Blanco-Canosa,[2] C. Mazzoli,[1] N. B. Brookes,[3] G. M. De Luca,[4] A. Frano,[2,5] D. G. Hawthorn,[6] F. He,[7] T. Loew,[2] M. Moretti Sala,[3] D. C. Peets,[2] M. Salluzzo,[4] E. Schierle,[5] R. Sutarto,[7,8] G. A. Sawatzky,[8] E. Weschke,[5] B. Keimer,[2]* L. Braicovich[1]

Using resonant x-ray scattering, Ghiringhelli et al. detected CDW order in underdoped YBCO

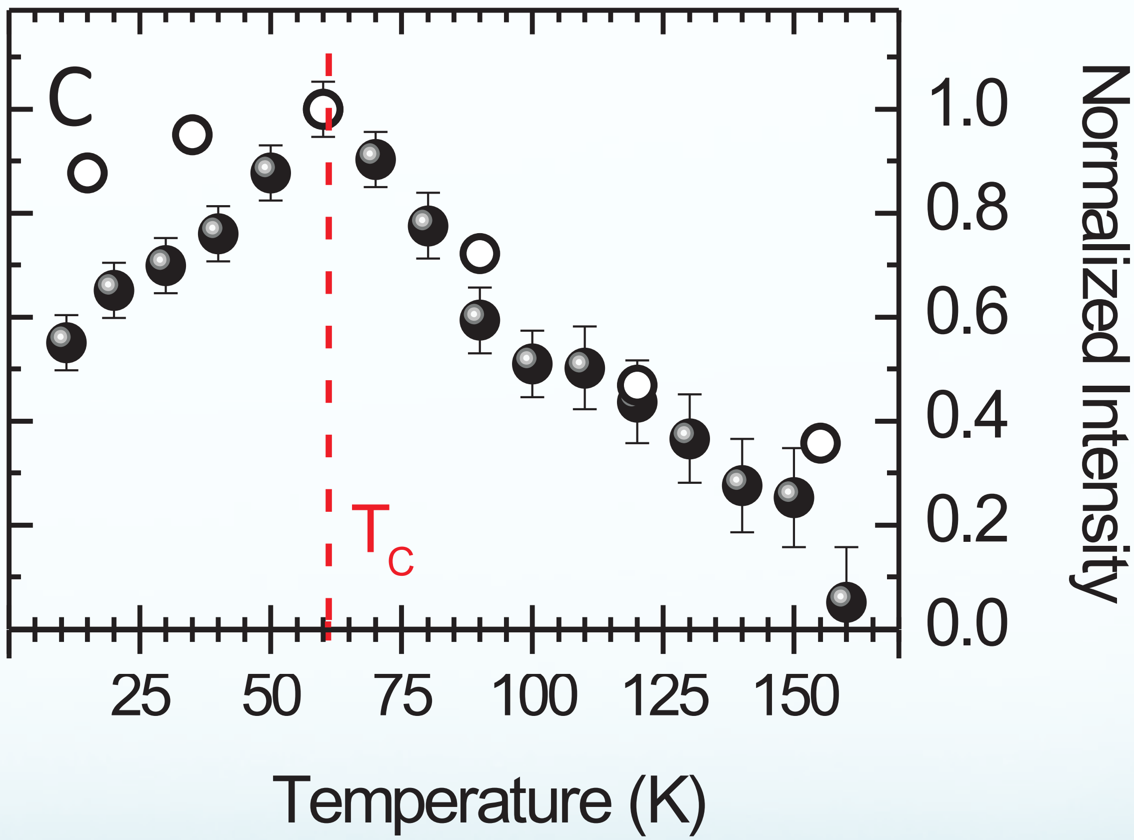
$YBa_2Cu_3O_{6.6}$



- CDW peaks at [0.3 0 *L*] and [0 0.3 *L*] in detwinned, orthorhombic samples
- Incommensurability of 0.3 (instead of 0.25 as in La-based cuprates)

Ghiringhelli et al. Science (2012).

CDW order in YBCO



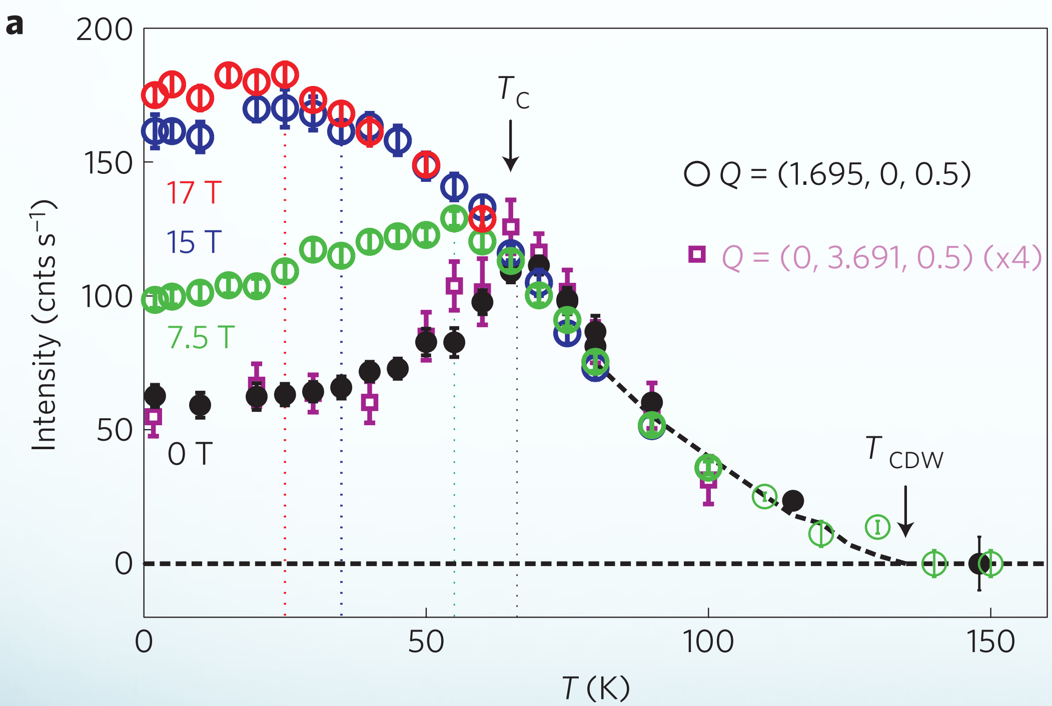
CDW order onsets at ~150 K and peaks in intensity at T_{c}, the superconducting transition temperature

Ghiringhelli et al. Science (2012).

CDW order in YBCO in magnetic field

Hard x-ray scattering

J. Chang et al., Nature Physics (2012)



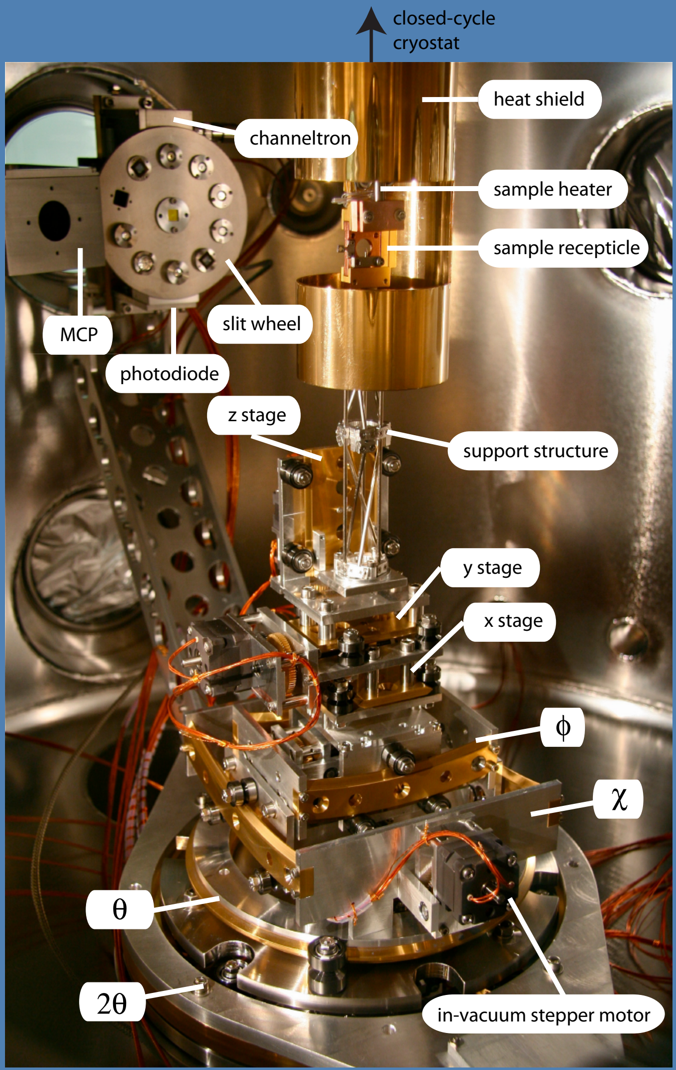
Competition between SC and CDW orders:

A magnetic field perpendicular to the planes suppresses superconductivity and enhances charge density wave order

Resonant Soft X-ray Scattering at the Canadian Light Source

http://www.lightsource.ca/experimental/reixs.php

George Sawatzky (UBC)
David Hawthorn (Waterloo)
Feizhou He (CLS)
Luc Venema (Groningen)
Harold Davis (UBC)
Ronny Sutarto (UBC)



- 4-circle diffractometer (9 in-vacuum motions)
- ultra-high vacuum ($P = 2 \times 10^{-10}$ Torr)
- Photodiode, channeltron and 2D channelplate detectors with variable slits and filters
- cooling to 18 K with closed-cycle cryostat
- Full polarization control of incident light (EPU) with unique dual EPU rapid switching of polarization mode
- 80 – 2500 eV photon energy range
- High energy resolution ($E/\Delta E > 15000$ at Nitrogen K edge)
- Attached chambers for in-situ sample growth (MBE) and characterization (XPS, AFM/STM, EELS, scanning Auger spectroscopy, SEM, UV photoemission)

The Canadian Light Source

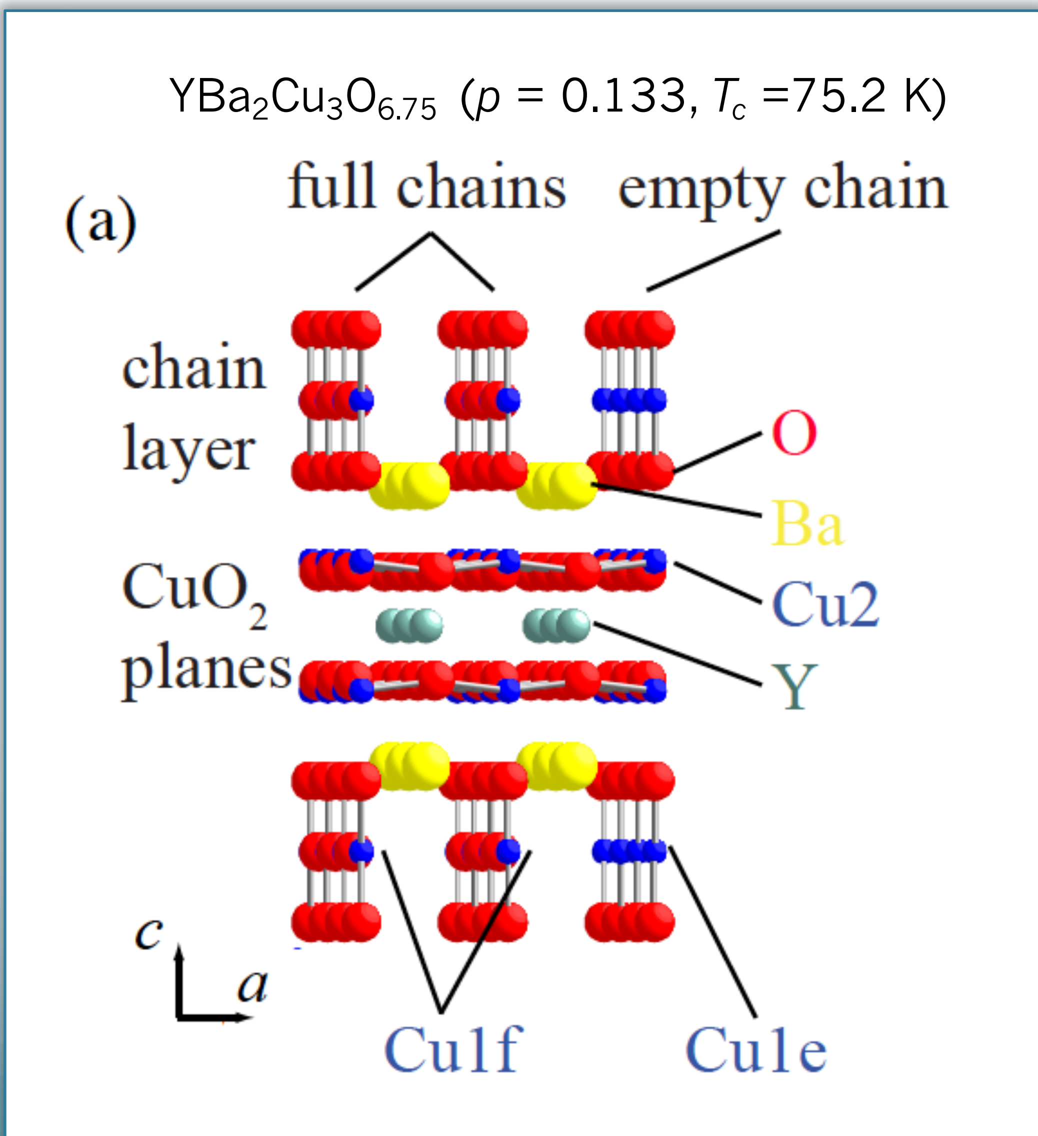
University of British Columbia

University of Waterloo

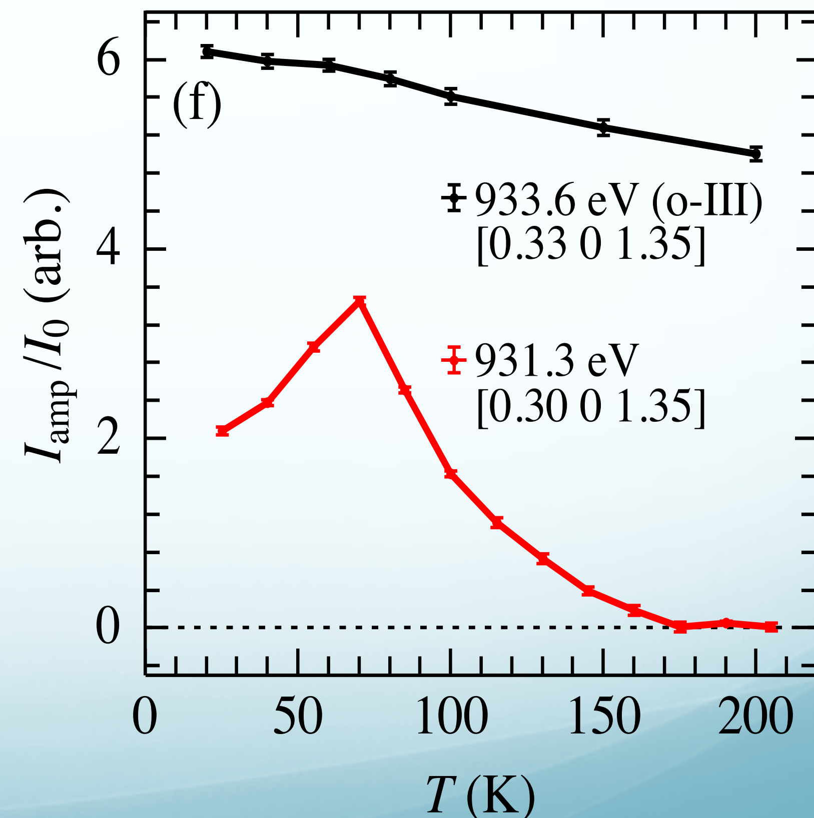
funded by Canada Foundation for Innovation, British Columbia Knowledge Development Fund and Western Economic Diversification

Hawthorn *et al.*
Rev. Sci. Instrum. 2011

Density wave order in the planes of Ortho III YBCO



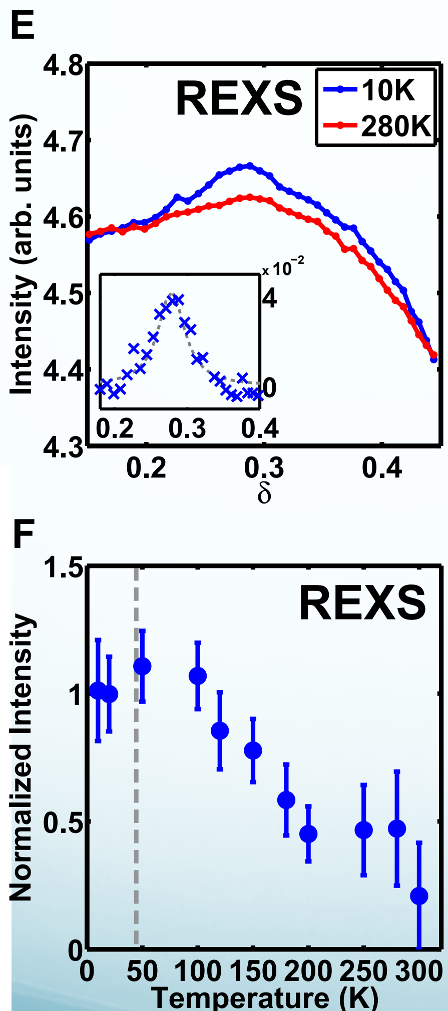
- CDW order in the CuO_2 planes
- CDW order present in high purity, oxygen-ordered samples
- Insight into microscopic character of CDW order



Achkar et al. PRL **109**, 167001 (2012)

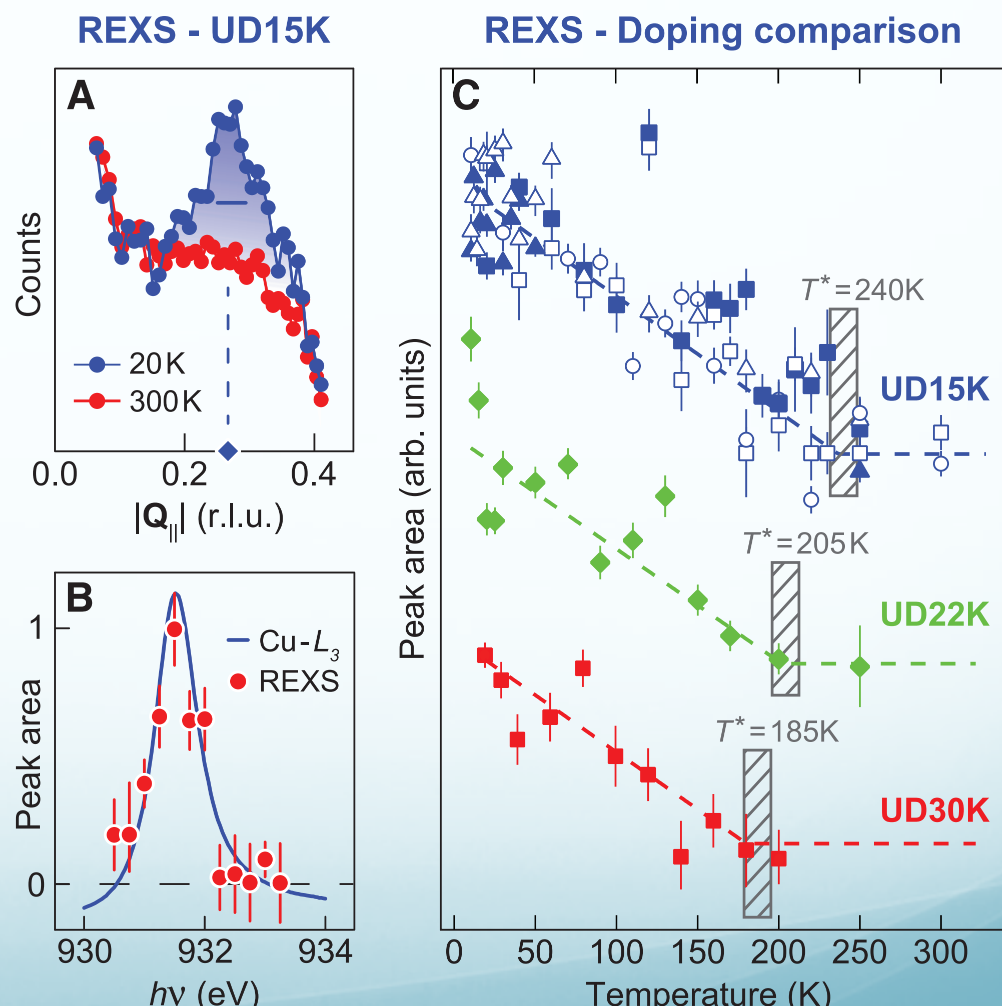
CDW order in the other cuprates

$Bi_2Sr_2CaCu_2O_{8+delta}$ (Bi2212)



da Silva Neto et al. Science (2014)

$Bi_2Sr_{2-x}La_xCuO_{6+delta}$ (Bi2201)

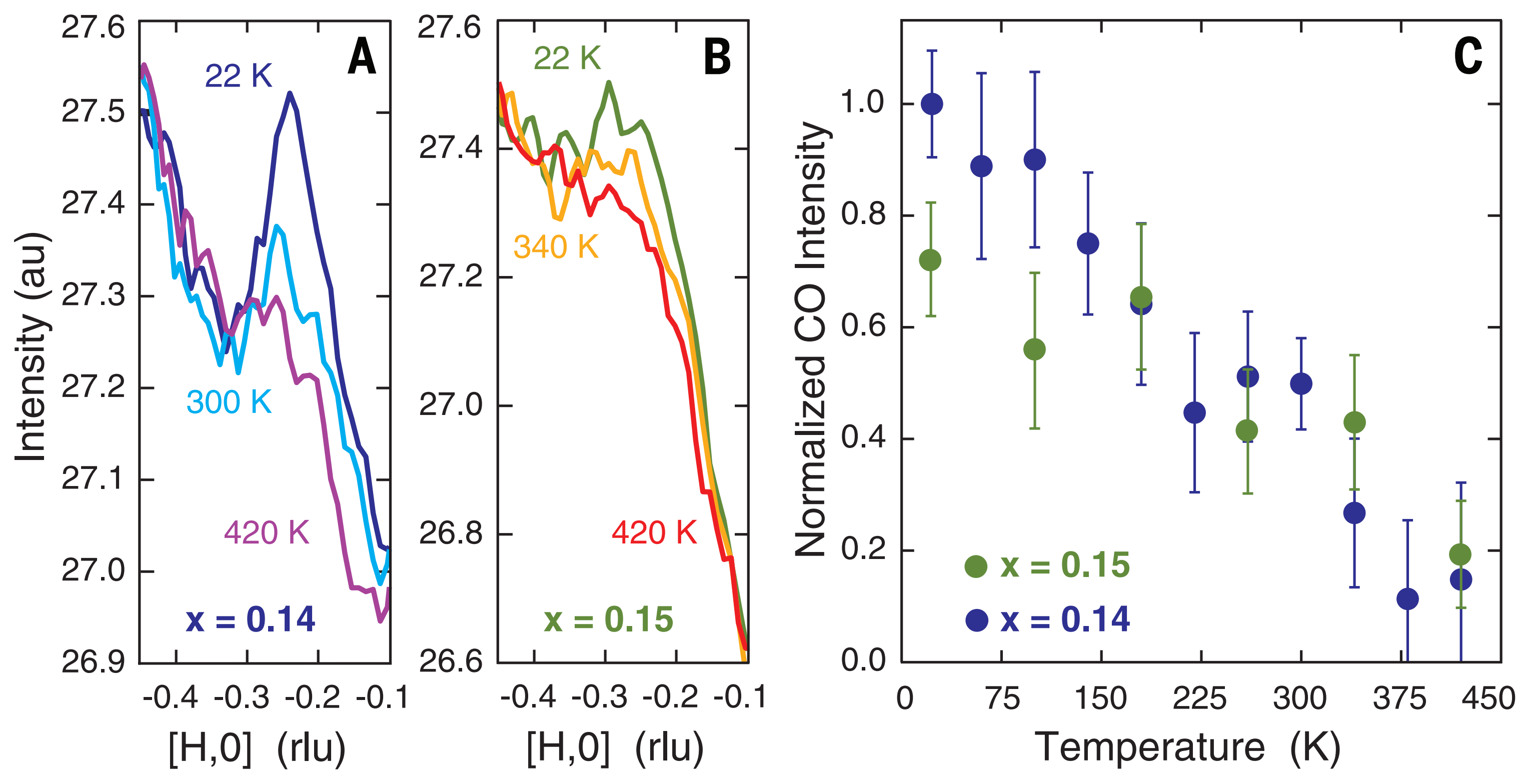


Comin et al. Science (2014)

CDW order in electron doped

Charge ordering in the electron-doped superconductor $Nd_{2-x}Ce_xCuO_4$

Eduardo H. da Silva Neto,[1,2,3,4*†] Riccardo Comin,[1,2*] Feizhou He,[5] Ronny Sutarto,[5] Yeping Jiang,[6] Richard L. Greene,[6] George A. Sawatzky,[1,2] Andrea Damascelli[1,2†]



da Silva Neto et al. Science (2015)

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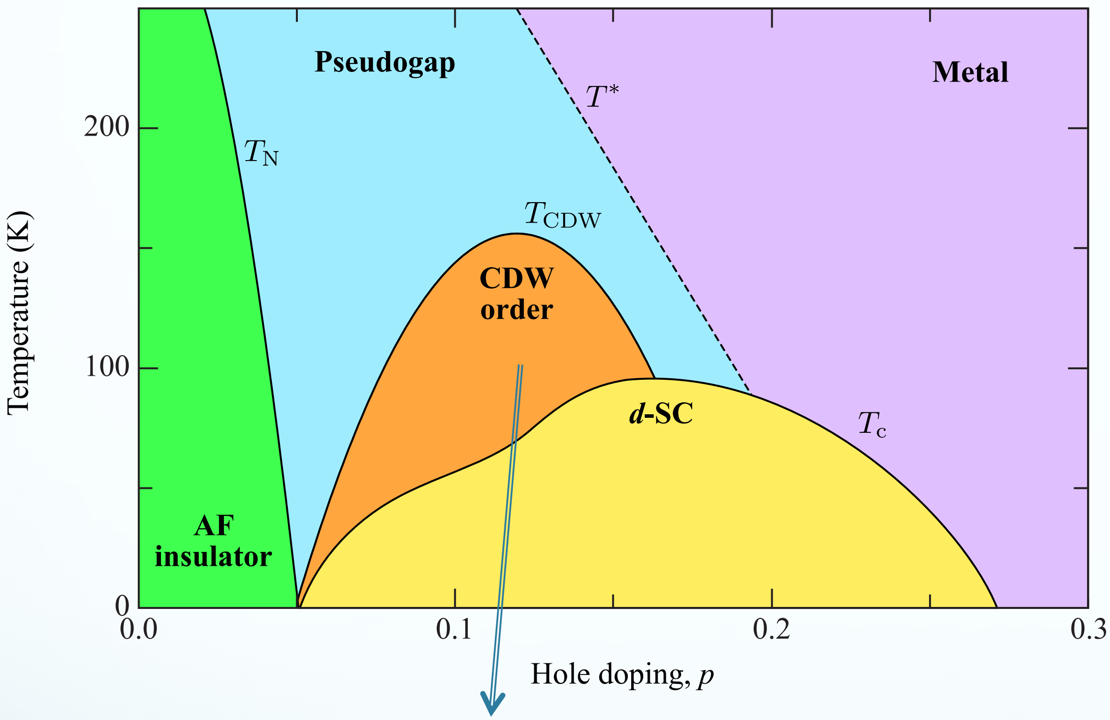
CDW order: A Central Piece of the Puzzle



Stripe-like, unidirectional CDW??

Questions

How does CDW order relate to superconductivity?

What interactions give rise to CDW order?

Are these the same interactions that lead to superconductivity?

Intertwined order?

Can we tune CDW order to maximize superconductivity?

Are there other orders present in the cuprates?

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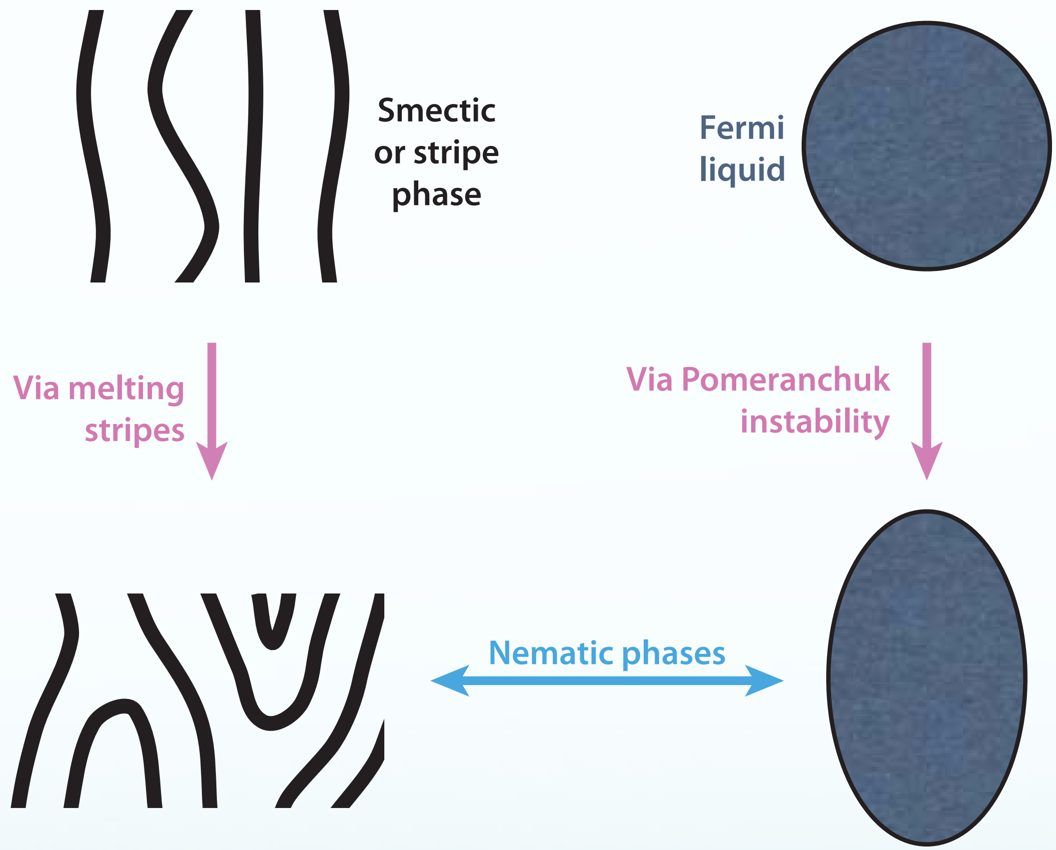
Nematicity in stripe-ordered cuprates probed via resonant x-ray scattering

A. J. Achkar, M. Zwiebler, Christopher McMahon, F. He, R. Sutarto, Isaiah Djianto, Zhihao Hao, Michel J. P. Gingras, M. Hücker, G. D. Gu, A. Revcolevschi, H. Zhang, Y.-J. Kim, J. Geck, D. G. Hawthorn

Science **351**, 576 (2016).

Nematicity: Rotational symmetry breaking

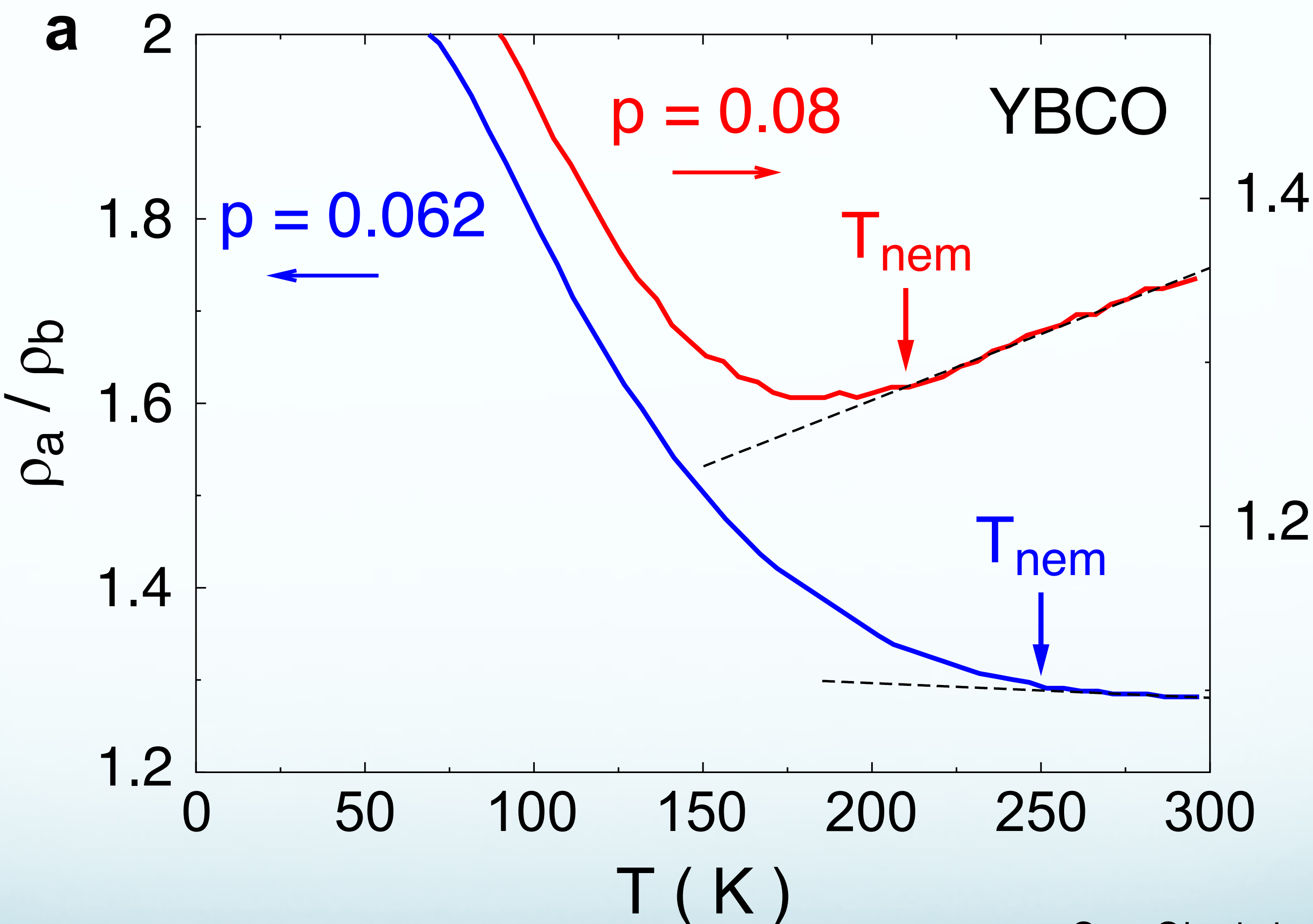


Possible nematic order parameters: $\mathcal{N} = \dfrac{\rho_{xx} - \rho_{yy}}{\rho_{xx} + \rho_{yy}}$ $\quad N(\boldsymbol{Q}) = S(\boldsymbol{Q}_x) - S(\boldsymbol{Q}_y)$

Kivelson et al. Annual Reviews of Condensed Matter 2010

Evidence for Electronic Nematicity in the cuprates: $YBa_2Cu_3O_{6+x}$

Ratio of electrical resistivity along *a* and *b* axes



Cyr-Choiniere arXiv 2015

Ando PRL 2002

$YBa_2Cu_3O_{6+x}$ is structurally orthorhombic

Evidence for Electronic Nematicity in the cuprates: Bi2212

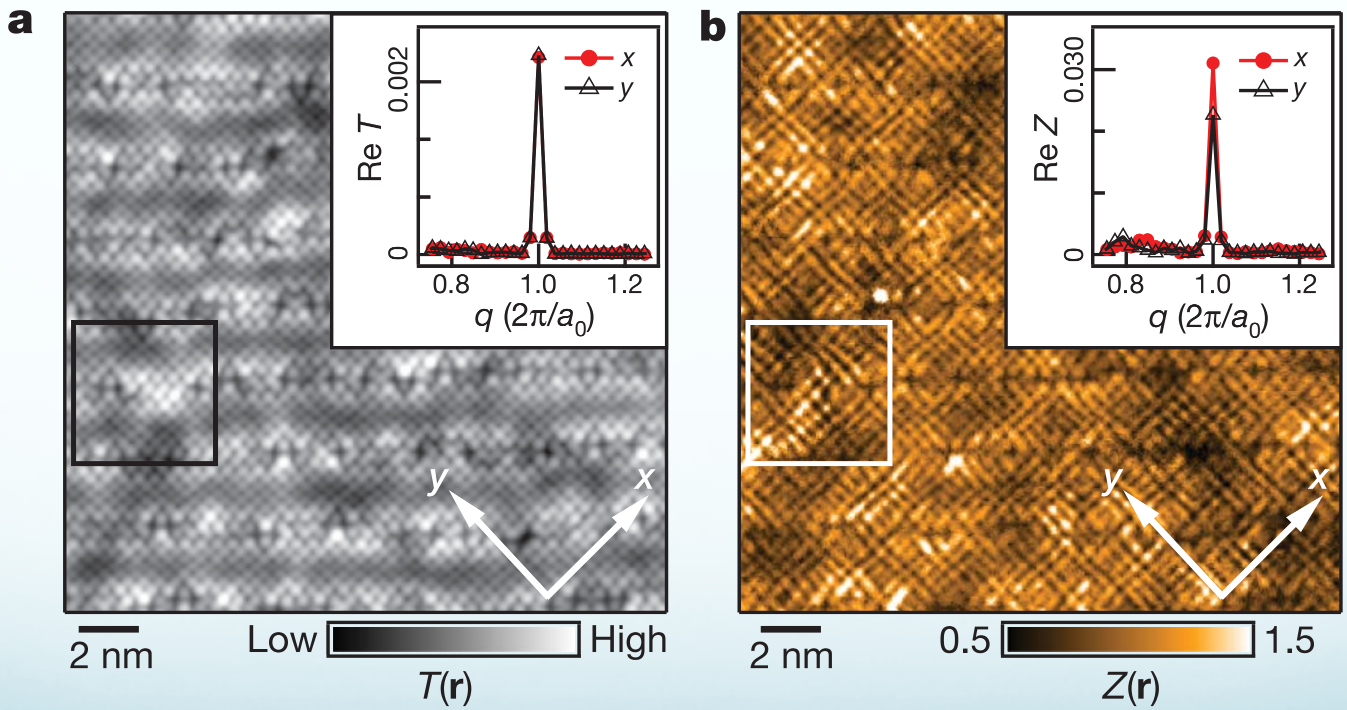
Scanning tunneling microscopy

Short-range, intra-unit-cell C_4 symmetry breaking

Bi2212

Togography

Z map (related to local density of states)

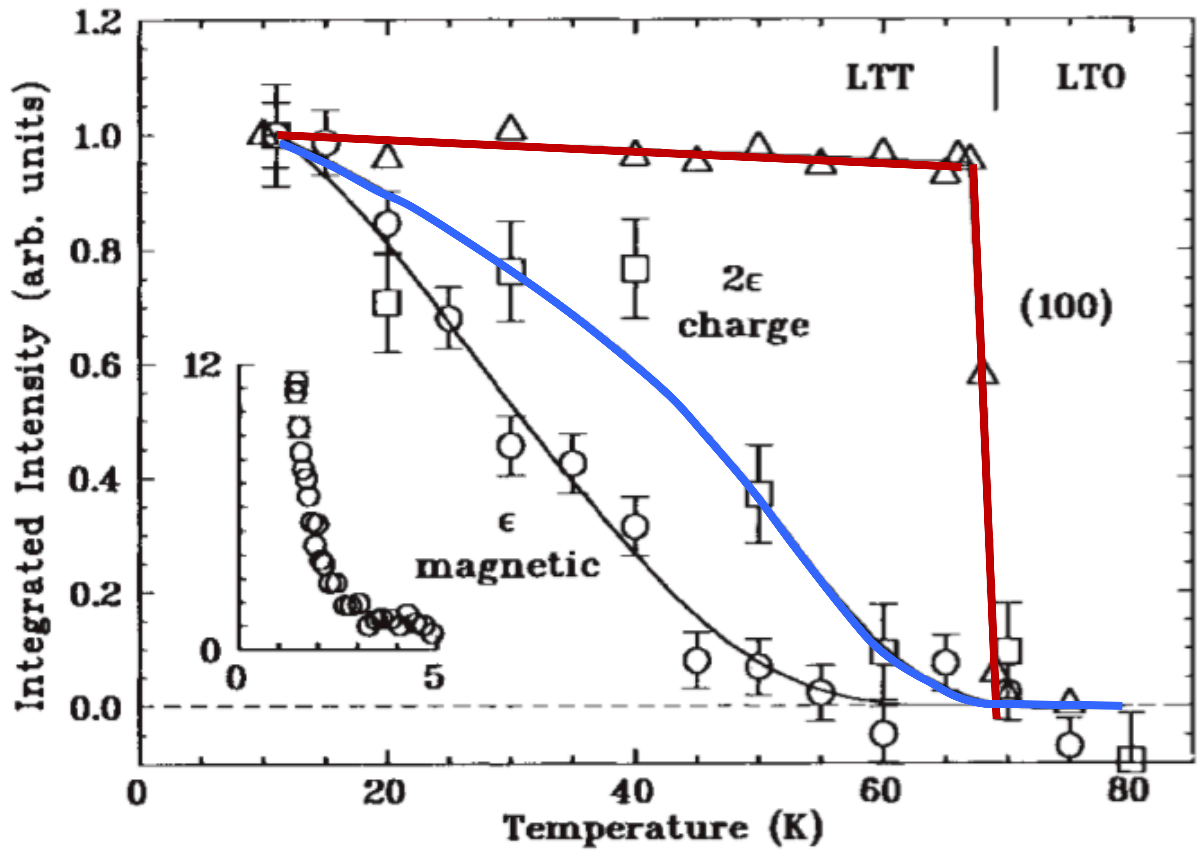


Lawler, Fujita, et al. Nature 2010

Structure, nematicity and CDW order in $(La,X)_2CuO_4$

Neutron scattering

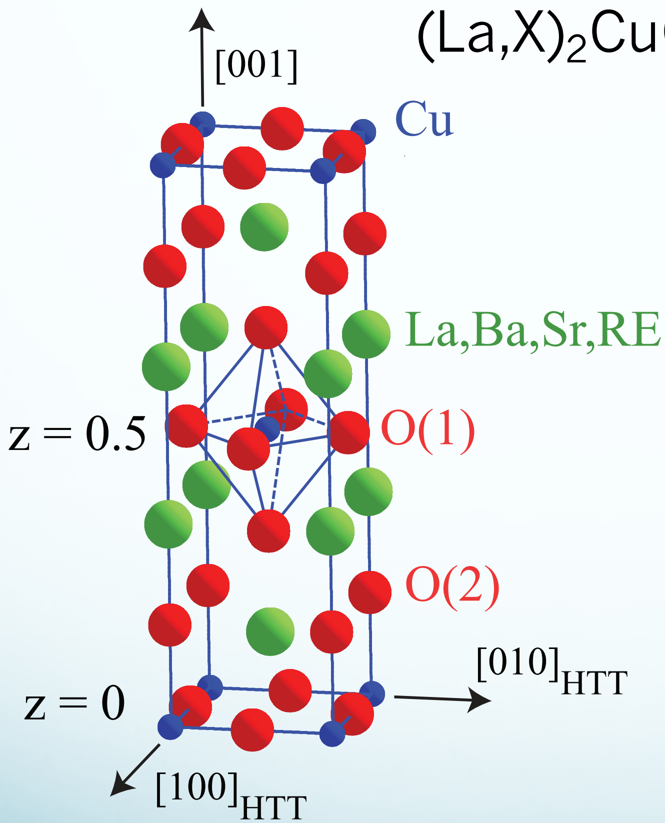
$La_{1.475}Nd_{0.4}Sr_{0.125}CuO_4$



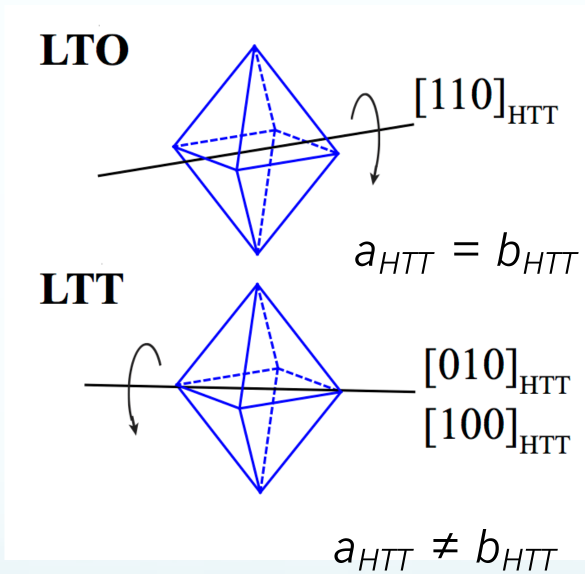
Charge density wave order onsets below 1st order low temperature orthorhombic (LTO) to low temperature tetragonal (LTT) phase transition

Tranquada Nature (1995)

Structure, nematicity and stripes in $(La,X)_2CuO_4$



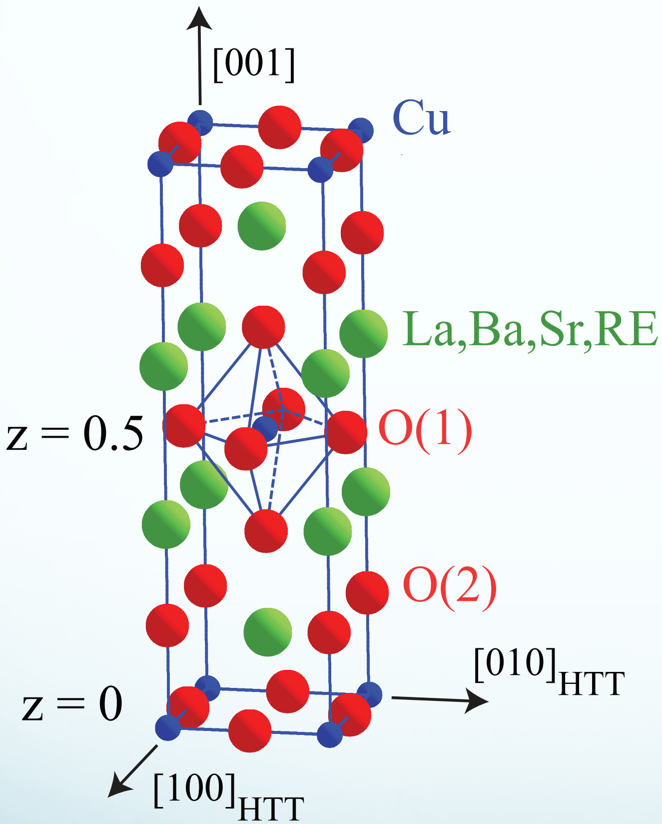
orthorhombic CuO_2 planes

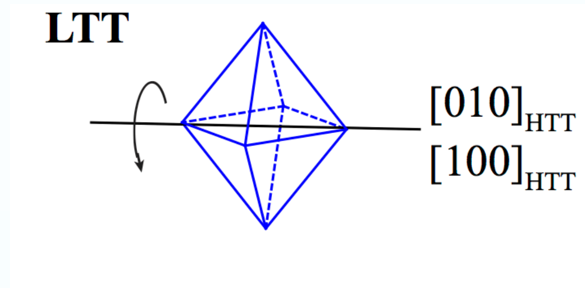


1st order LTO to LTT phase transition measured by x-ray and neutron scattering

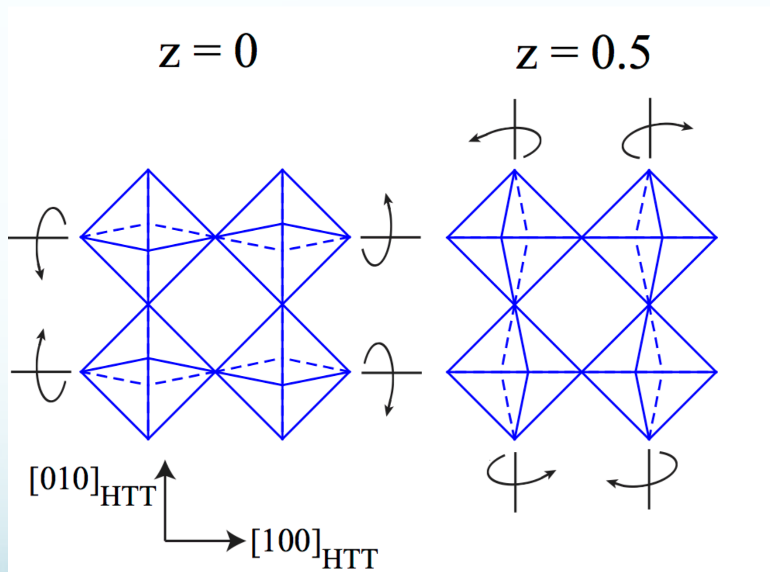
- Axe PRL 1989
- Suzuki Physica C 1989
- Tranquada 1995
- Zhao PRB 2007
- Kim PRB 2008
- Fink PRB 2011
- Wilkins PRB 2011
- Hucker PRB 2011
- ...

Low temperature tetragonal (LTT) structure





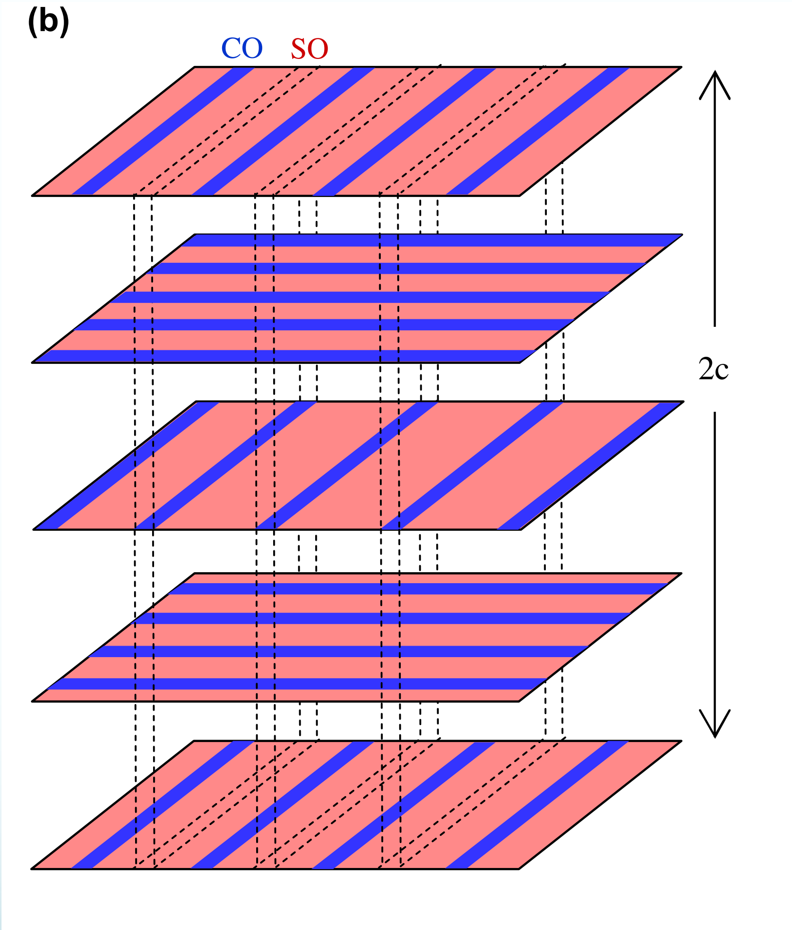
Tilt direction of octahedra alternates between neighboring planes



Tilt about *a* Tilt about *b*

Unidirectional CDW order: stripes

La-based cuprates



LTT tilts and stripe order

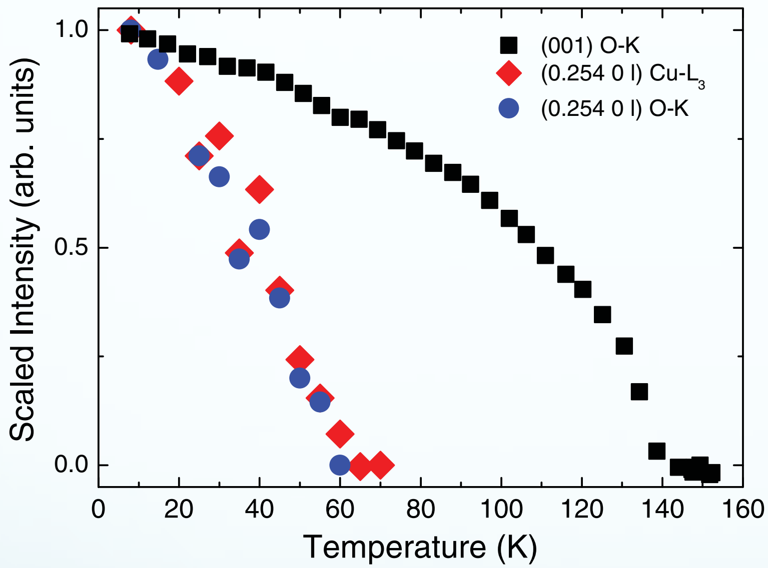
LTT distortion stabilizes stripes that alternate in direction between neighboring CuO_2 planes

Tranquada 1995
Tranquada 1996

Measuring LTO to LTT phase transition using Resonant Soft X-ray Scattering

(001) Bragg peak

$La_{1.65}Eu_{0.2}Sr_{0.15}CuO_4$

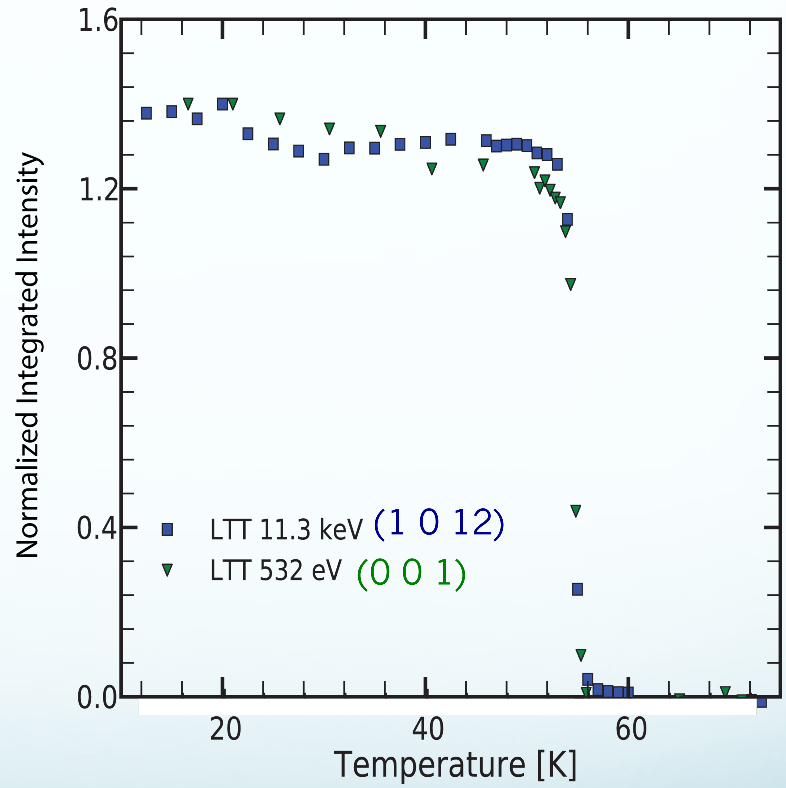


Fink et al. PRB 2011

(001) Bragg peak
only observed on resonance
(measured here at the O *K* edge)

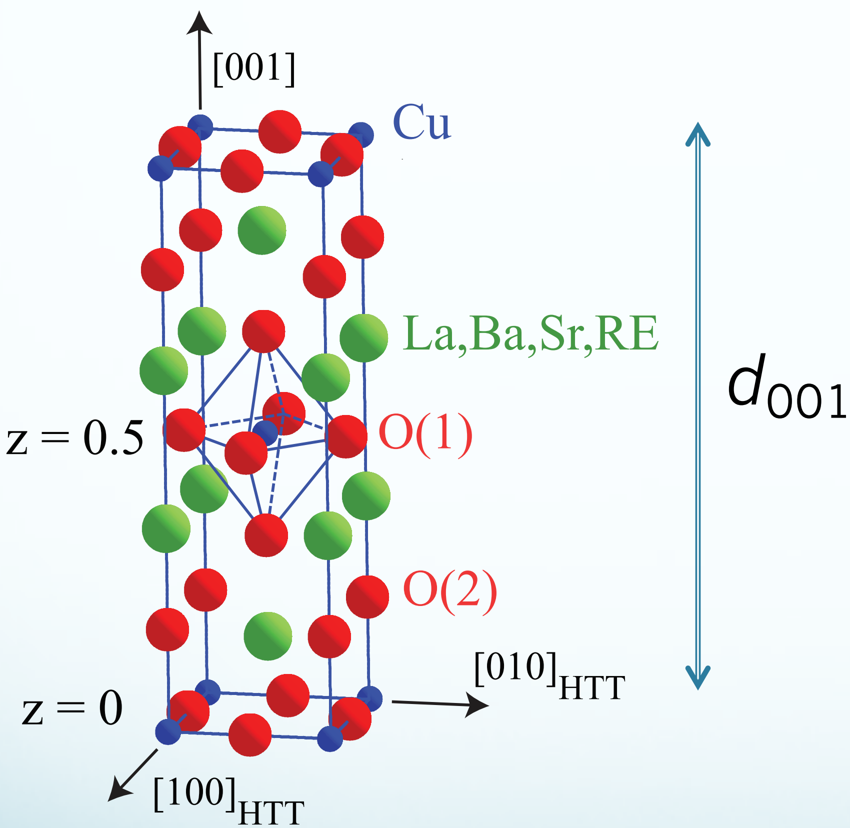
$La_{1.875}Ba_{0.125}CuO_4$

Wilkins PRB 2011



Good agreement between
hard x-ray (1 0 12) and soft x-ray (0 0 1)

Low temperature tetragonal (LTT) structure



Conventional x-ray diffraction

(001) Bragg peak is forbidden

- Scattering from neighbouring planes destructively interferes

Resonant x-ray diffraction

(001) Bragg peak is allowed

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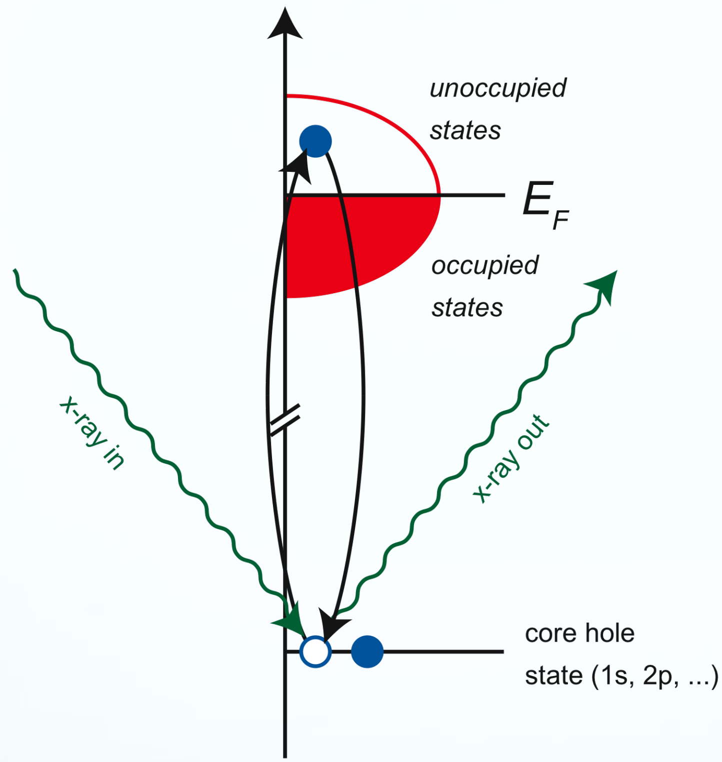
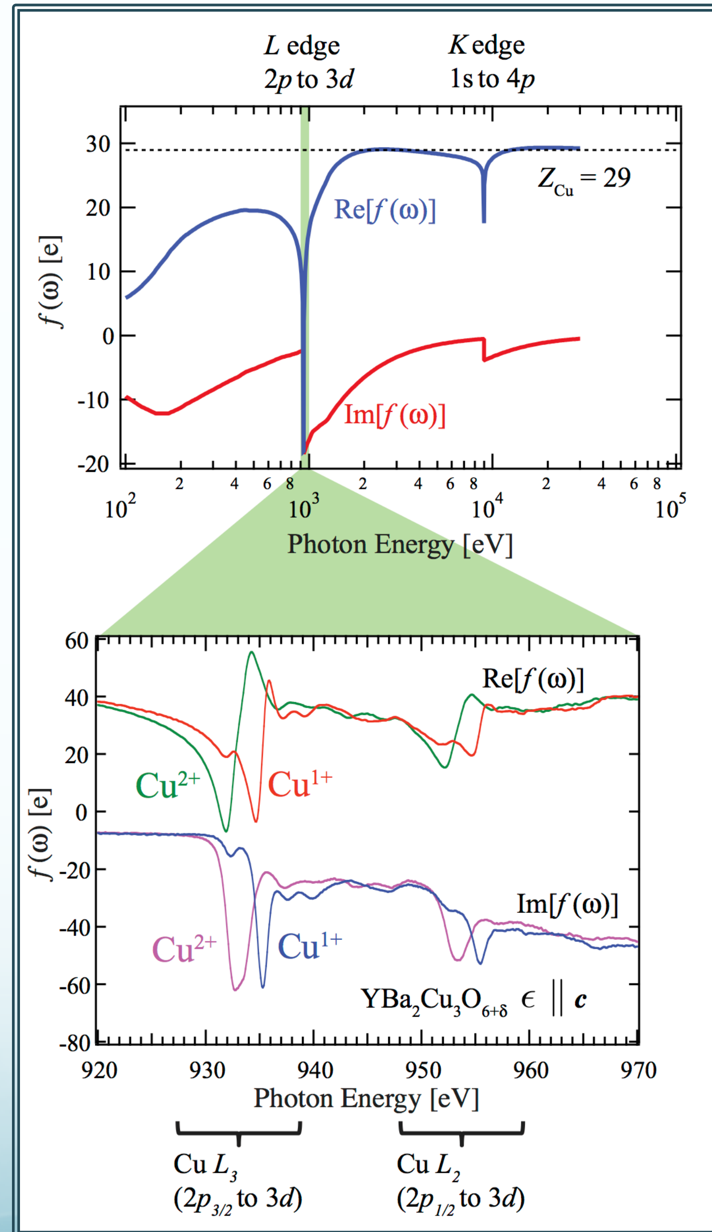
Resonant elastic x-ray scattering



$$S(\vec{Q}) = \sum_j f_j e^{-i2\pi\vec{Q}\cdot\vec{r_j}}$$

$$S(\vec{Q},\omega,\vec{e_i},\vec{e_f}) = \sum_j f_j(\omega,\vec{e_i},\vec{e_f}) e^{-i2\pi\vec{Q}\cdot\vec{r_j}}$$



Resonant X-ray Scattering

Tune photon energy to an x-ray resonance

On resonance, the atomic scattering form factor, f, is sensitive to orbital symmetry

$$I_{sc}(\vec{Q}) \propto \left| \sum_j f_j e^{-i2\pi\vec{Q}\cdot\vec{r_j}} \right|^2$$

$$I_{sc}(\vec{Q},\omega,\vec{\epsilon}) \propto \left| \sum_j (\vec{\epsilon}^{\,*} F_j(\omega)\vec{\epsilon}) e^{-i2\pi\vec{Q}\cdot\vec{r_j}} \right|^2$$

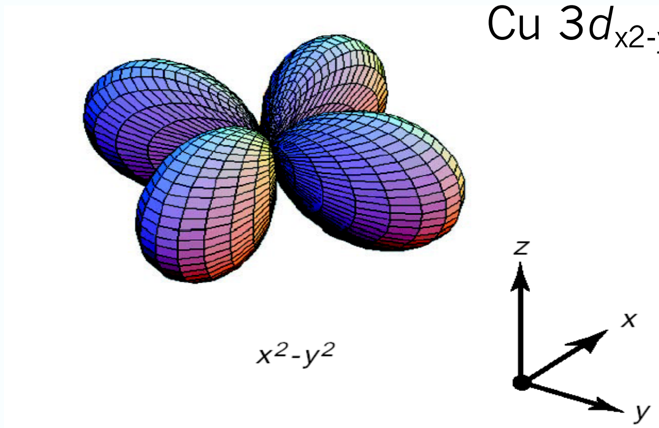
Scattered photon polarization

Incident photon polarization

$$F = \begin{bmatrix} f_{xx} & f_{xy} & f_{xz} \\ f_{yx} & f_{yy} & f_{yz} \\ f_{zx} & f_{zy} & f_{zz} \end{bmatrix}$$

Scattering form factor: polarization dependence

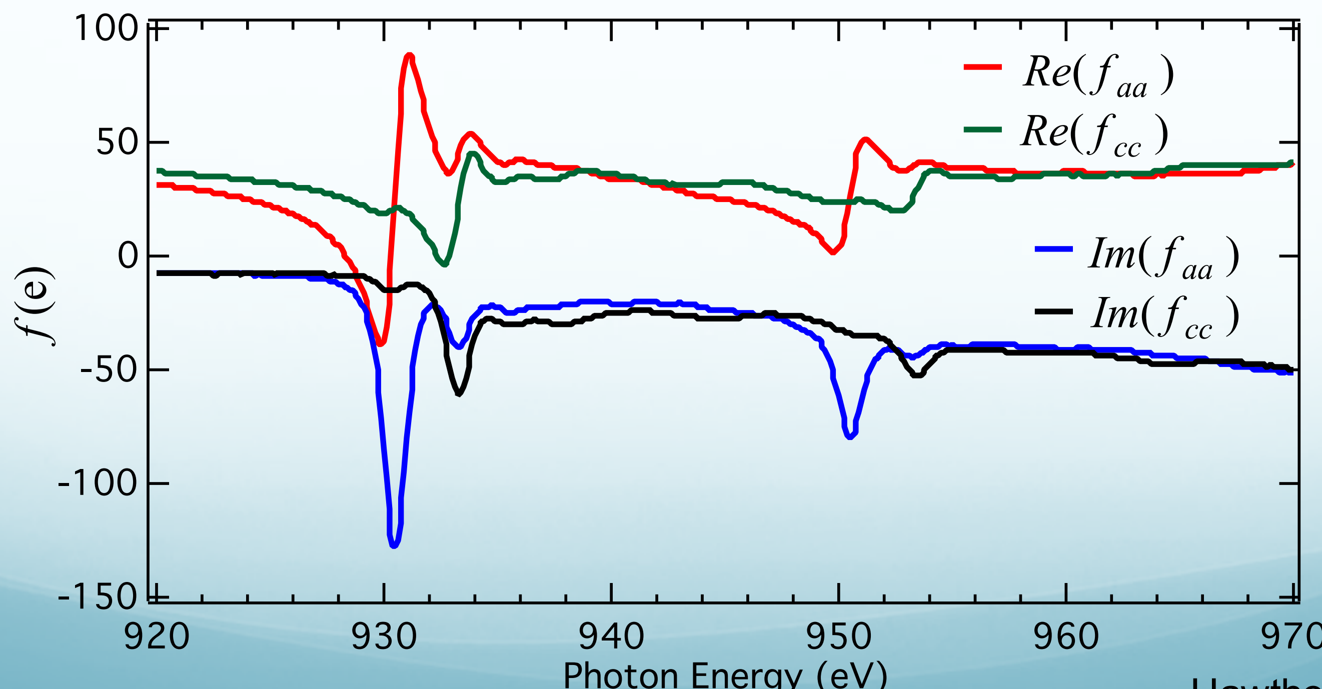
Cu $3d_{x2\text{-}y2}$ orbital



$$F = \begin{bmatrix} f_{aa} & 0 & 0 \\ 0 & f_{bb} & 0 \\ 0 & 0 & f_{cc} \end{bmatrix}$$

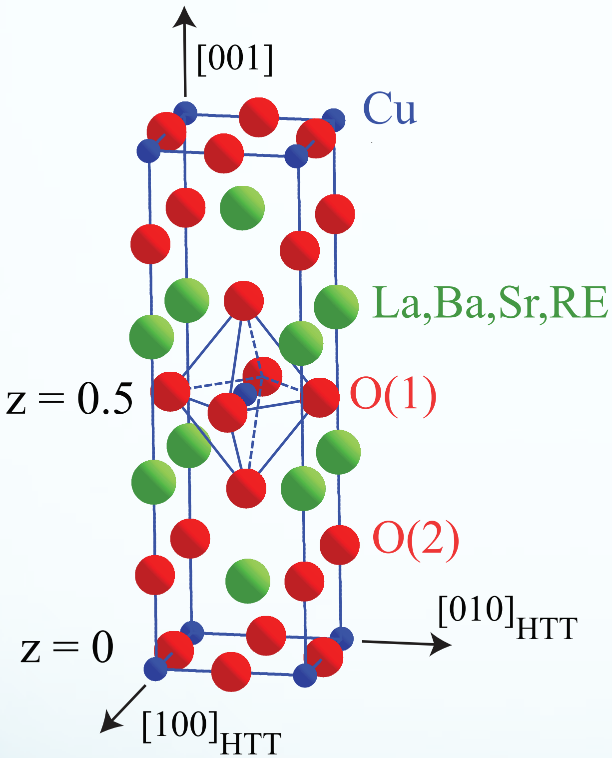
Cu L edge

$YBa_2Cu_3O_6$

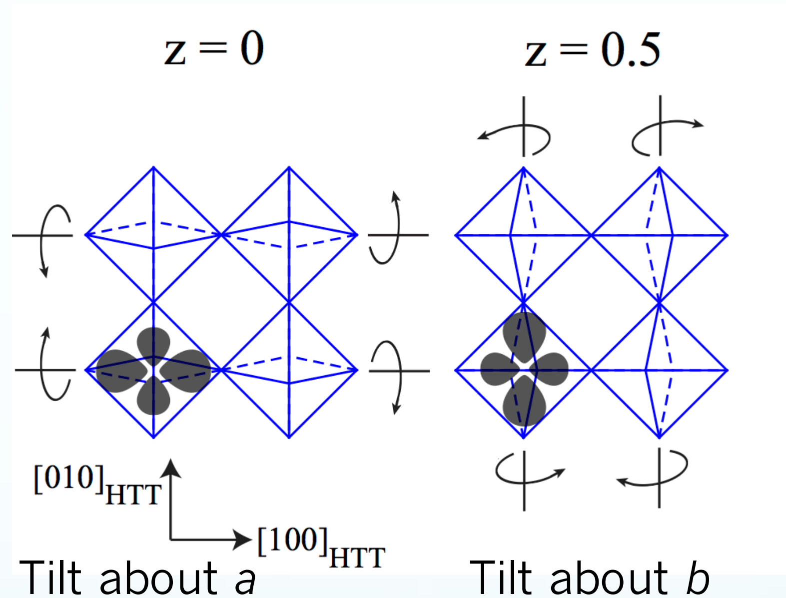


Hawthorn et al PRB 2011

Low temperature tetragonal (LTT) structure



Cu 3*d* states

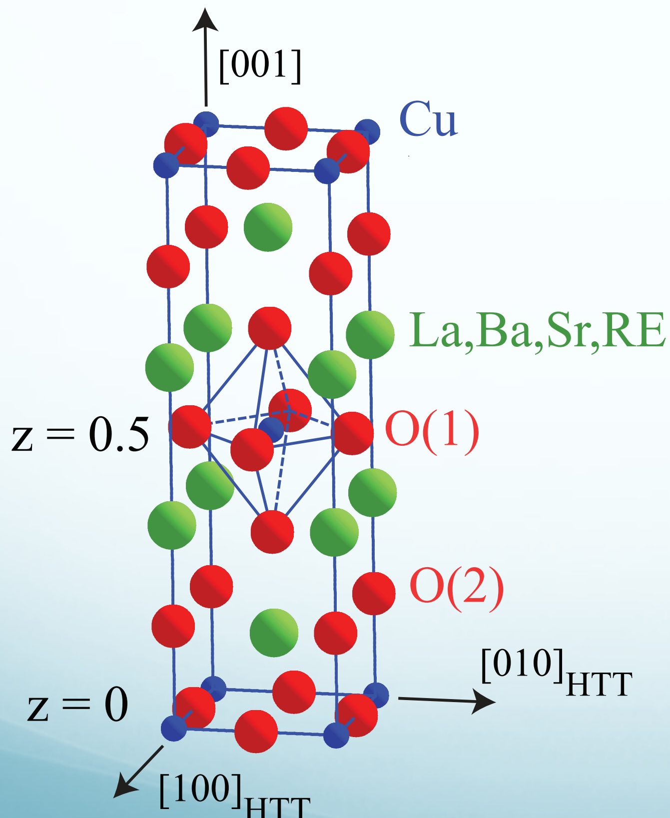


x and y components of the scattering tensor alternate between neighbouring layers

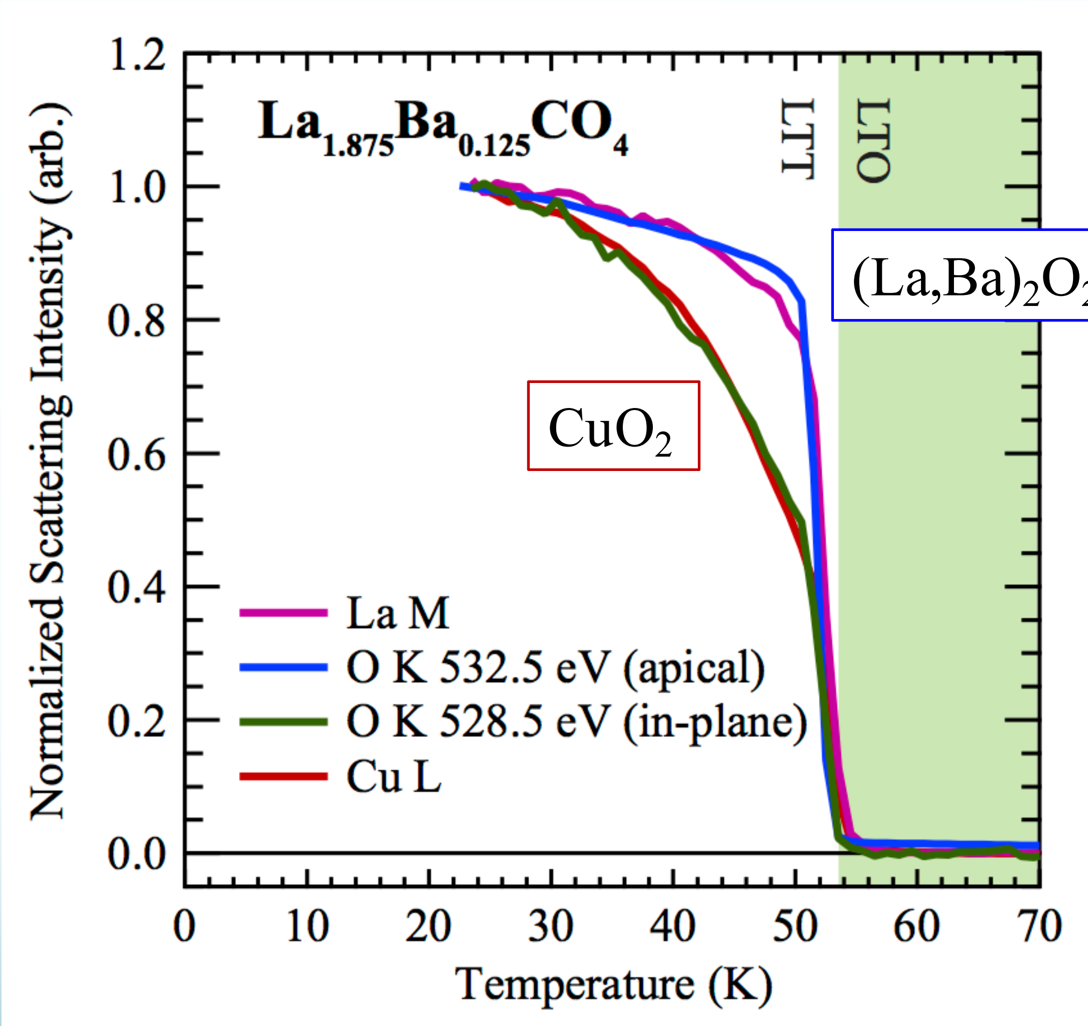
The (001) peak at the Cu *L* resonance measures electronic nematicity of the Cu 3*d* states

(0 0 1) peak at different photon energies

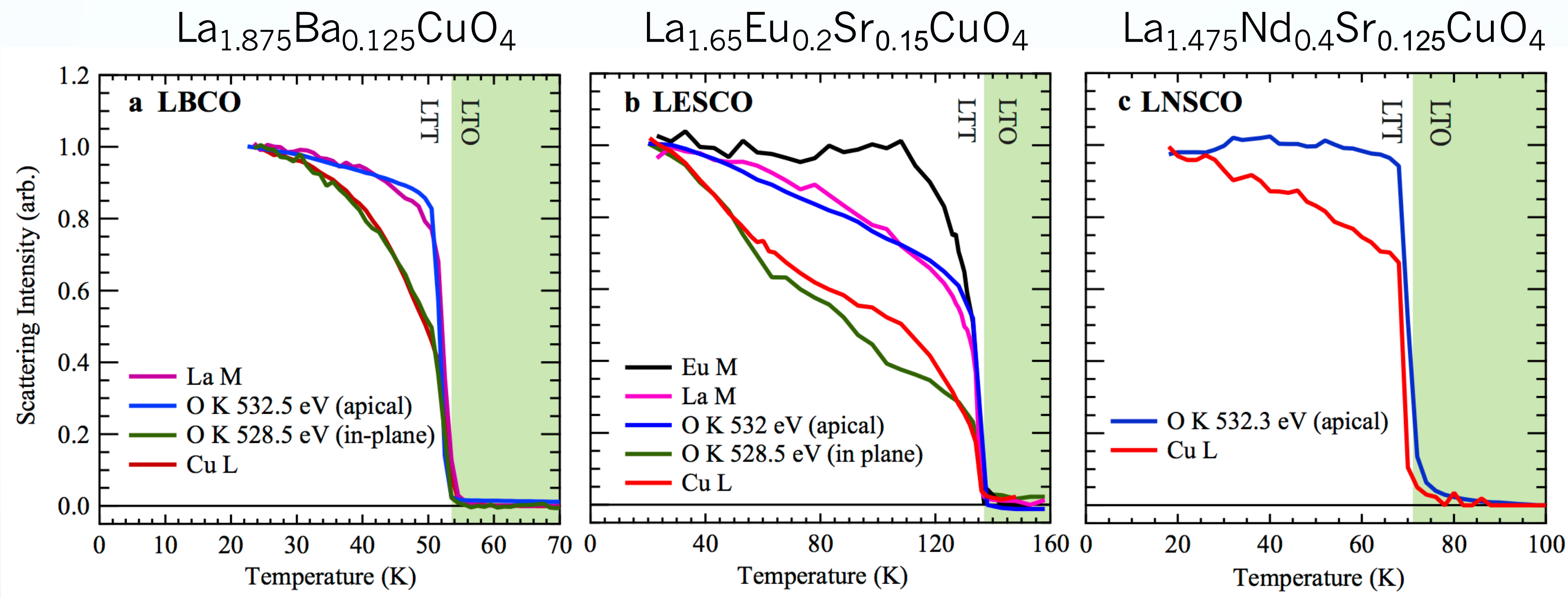
Measure (0 0 1) at different photon energies
→ Provides sensitivity to different atoms in the unit cell



Achkar Science 2016



(0 0 1) at different photon energies

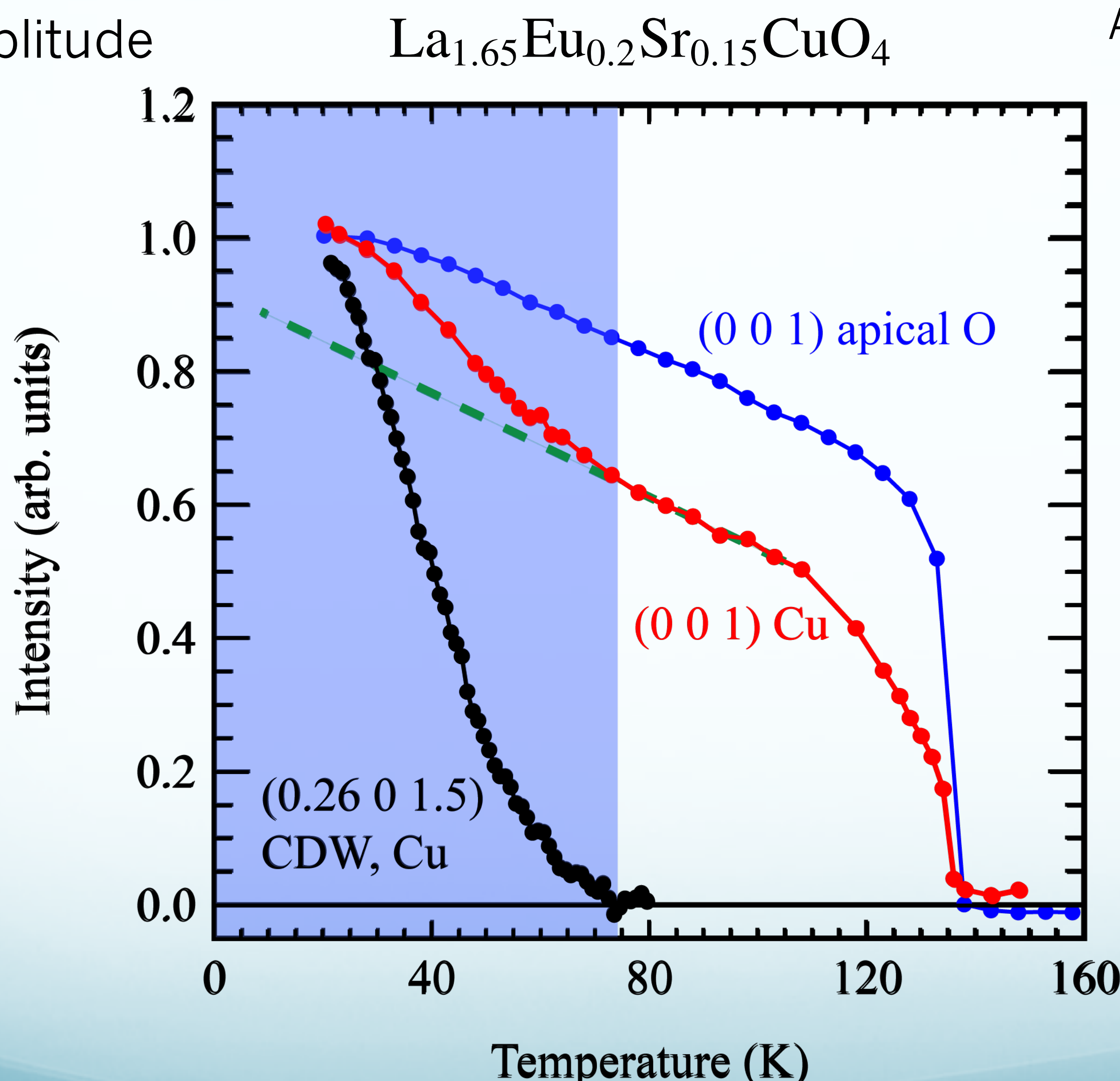


Dichotomy: CuO_2 planes relax more gradually than the $(La,X)_2O_2$ spacer layer

Relation to CDW order

Peak amplitude

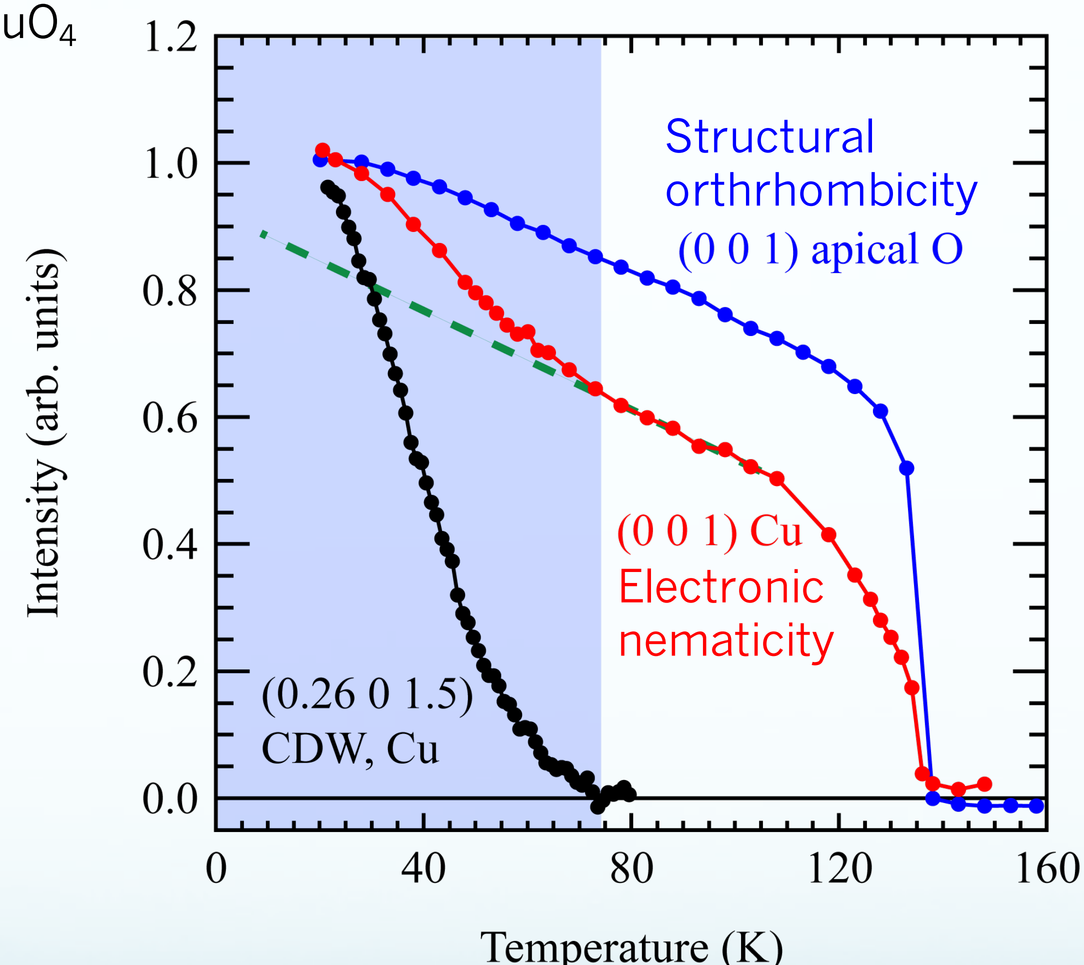
Achkar Science 2016



Distinct order parameters

$La_{1.65}Eu_{0.2}Sr_{0.15}CuO_4$

Achkar Science 2016



Distinct order parameters:

Electronic nematicity of the CuO_2 planes is coupled to, but distinct from the structural distortion of the $(La,X)_2O_2$ spacer layer

Landau Theory

Achkar Science 2016

Electronic Nematic order parameter

Structural C_4 symmetry breaking

CDW along *x*

CDW along *y*

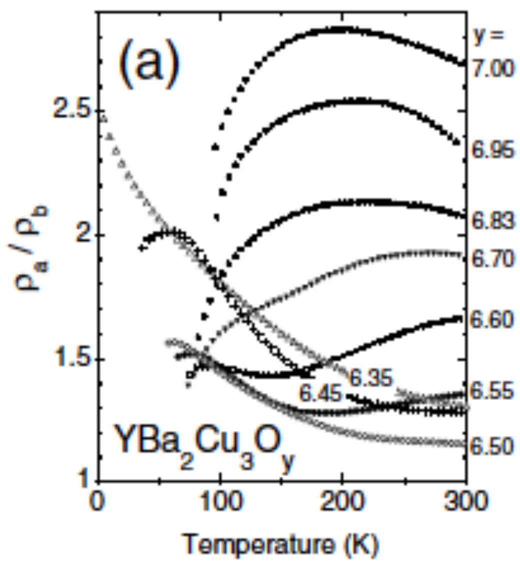
$$F = a_0 n^2 - a_1 n\tilde{n} + b_0 \left(|\Psi_x|^2 + |\Psi_y|^2\right) +$$
$$b_1 n \left(|\Psi_x|^2 - |\Psi_y|^2\right) + b_2 \left(|\Psi_x|^2 + |\Psi_y|^2\right)^2$$
$$+ b_3 \left(|\Psi_x|^4 + |\Psi_y|^4\right).$$

Different materials/dopings can be represented by differences in coupling parameters

Electronic Nematicity is generic?

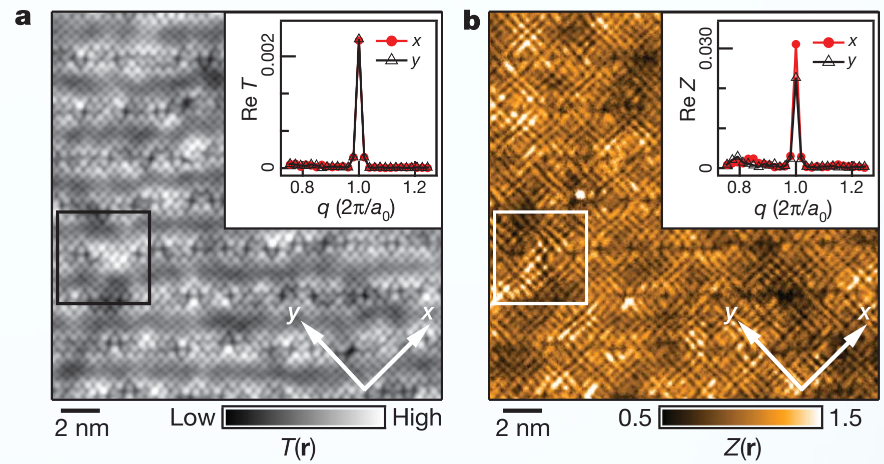
Electronic nematicity is generic to underdoped cuprates??

YBCO

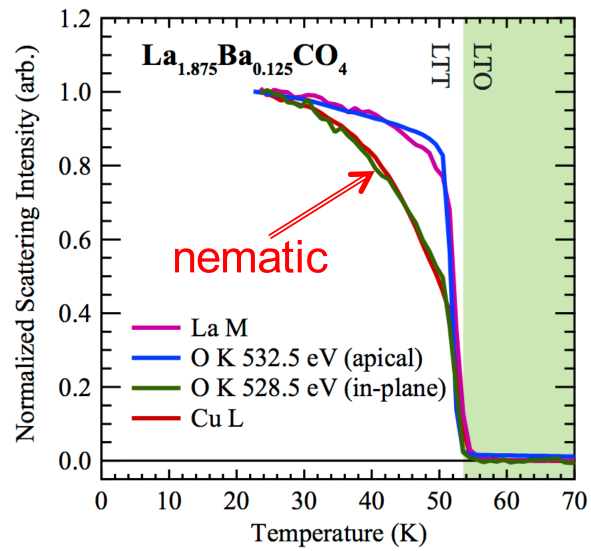


Ando PRL 2002

Bi2212



Lawler, Fujita, et al. Nature 2010



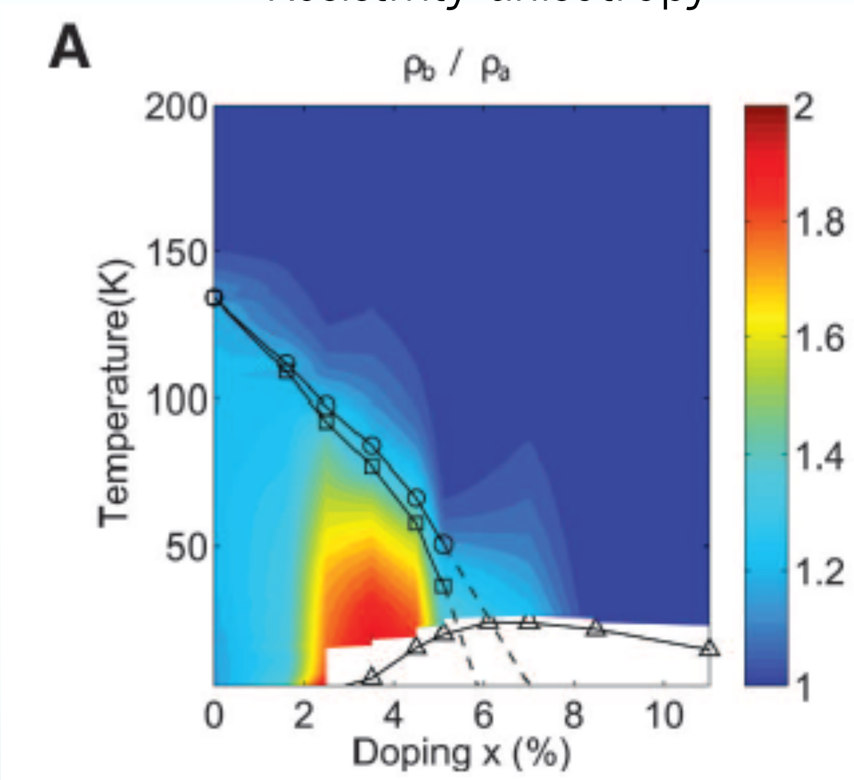
Next step: Unifying the cuprate phase diagrams

-- understanding influence of structure on nematicity and CDW order in different cuprates

Electronic Nematicity in pnictide superconductors

$Ba(Fe_{1-x}Co_x)_2As_2$

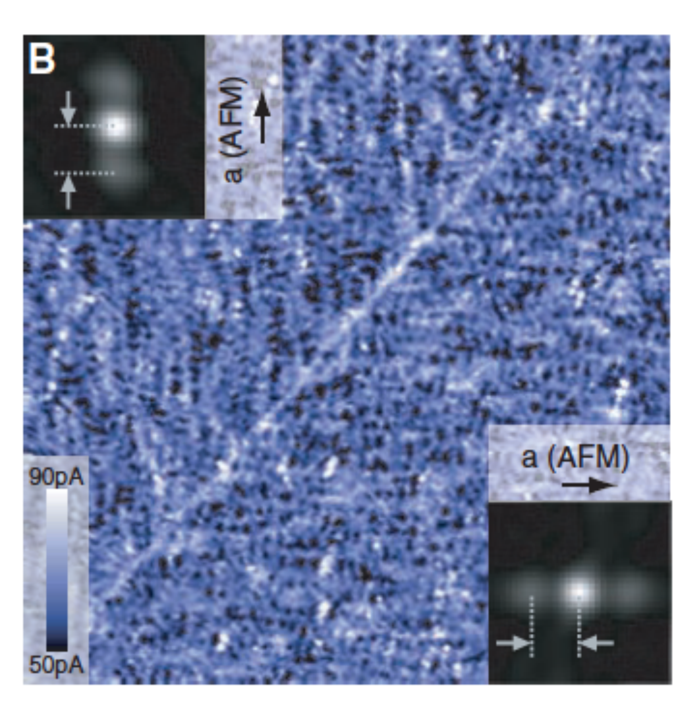
Resistivity anisotropy



Chu Science 2010

$Ca(Fe_{1-x}Co_x)_2As_2$

Fourier transform STM

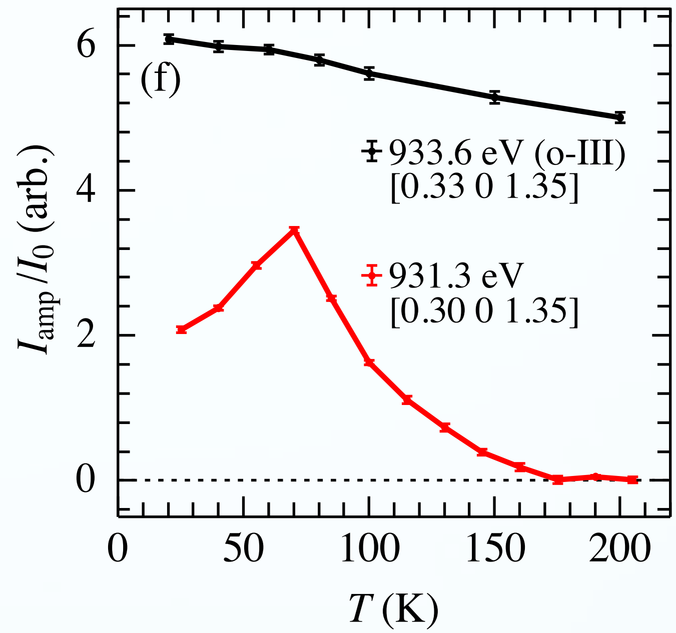


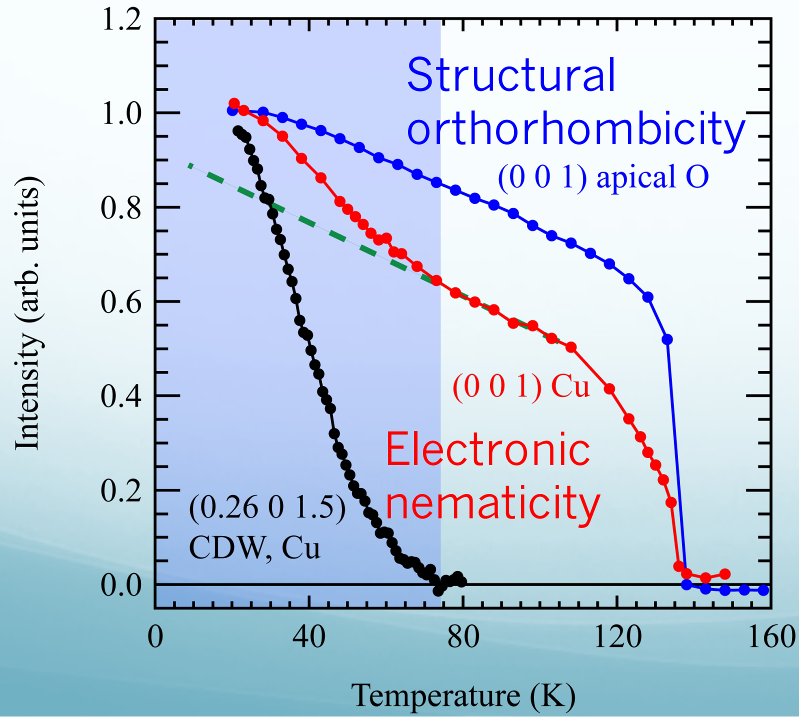
Chuang Science 2010

Iron based superconductors exhibit a similar phenomena of electronic nematicity

Conclusions

1. CDW observed in the cuprates is generic and competes with superconductivity





2.Electonic nematicity distinct from structural distortions may also be a generic feature of the cuprate superconductors

UNIVERSITY OF Waterloo

Orbital Symmetry of Charge Density Wave Order in $La_{7/8}Ba_{1/8}CuO_4$

A. J. Achkar Christopher McMahon, F. He, M. Zwiebler, X. Mao, R. Sutarto, M. Hucker, G. D. Gu, Ruixing Liang, D. A. Bonn, W. N. Hardy, J. Geck, and D. G. Hawthorn. Nature Materials 2016

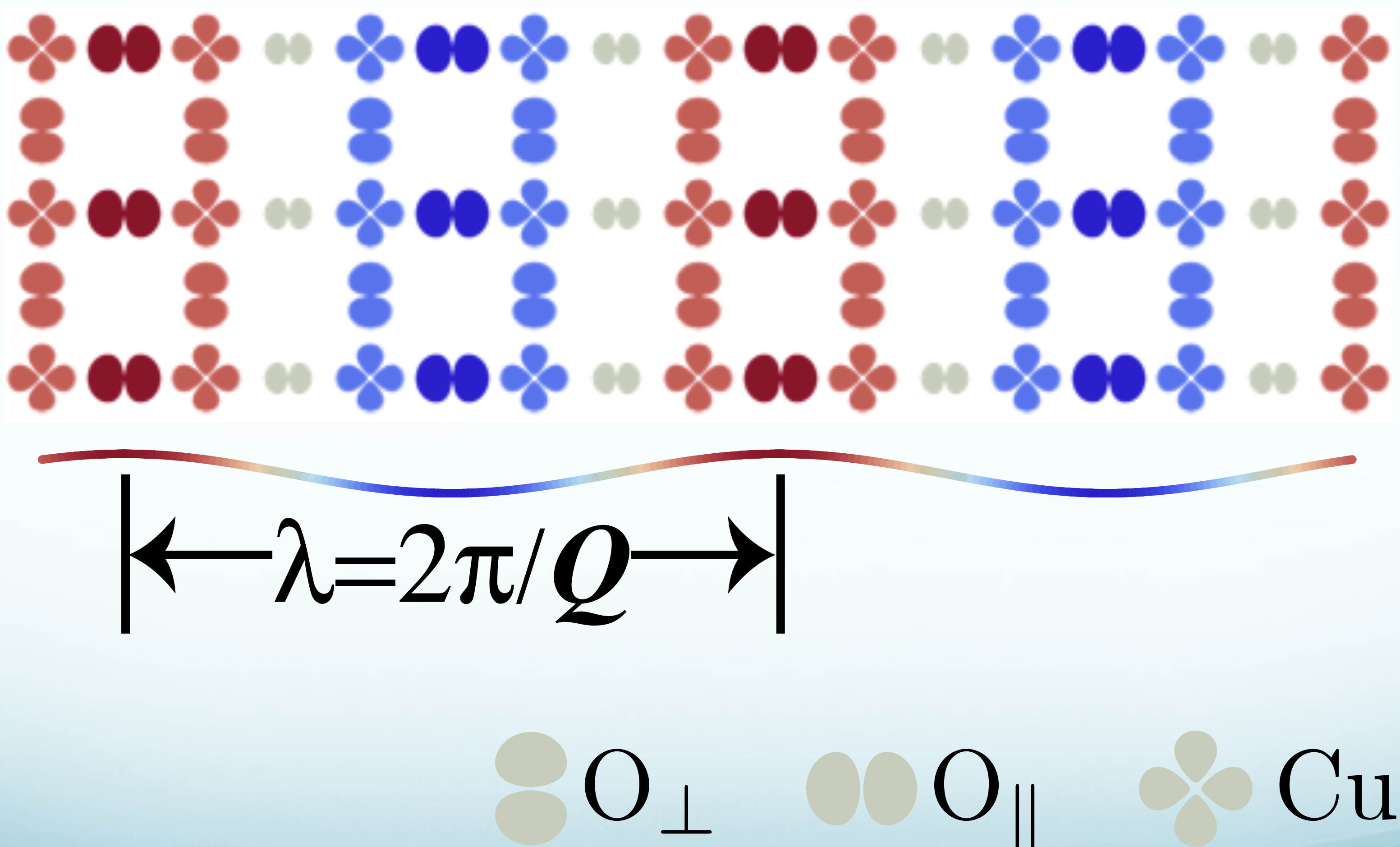
Canadian Light Source Centre canadien de rayonnement synchrotron

NSERC CRSNG

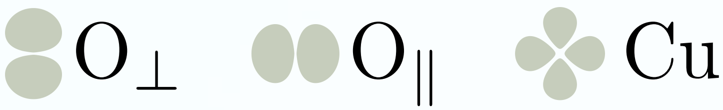
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Orbital Symmetry of CDW order

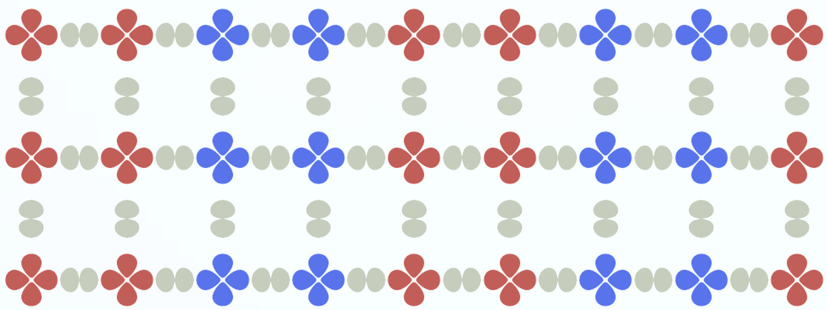
CuO_2 plane



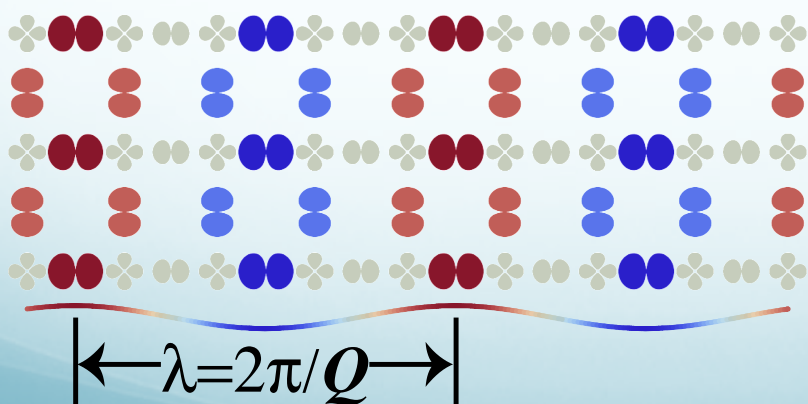
Symmetry of CDW order



Cu sublattice   *s* symmetry CDW

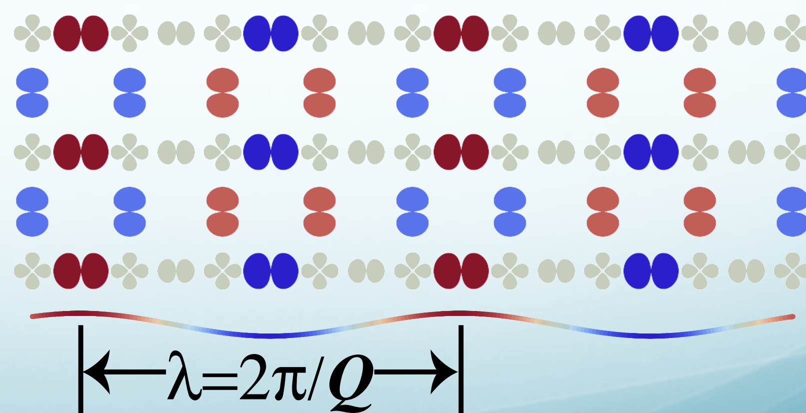


O sublattice   *s'* symmetry CDW



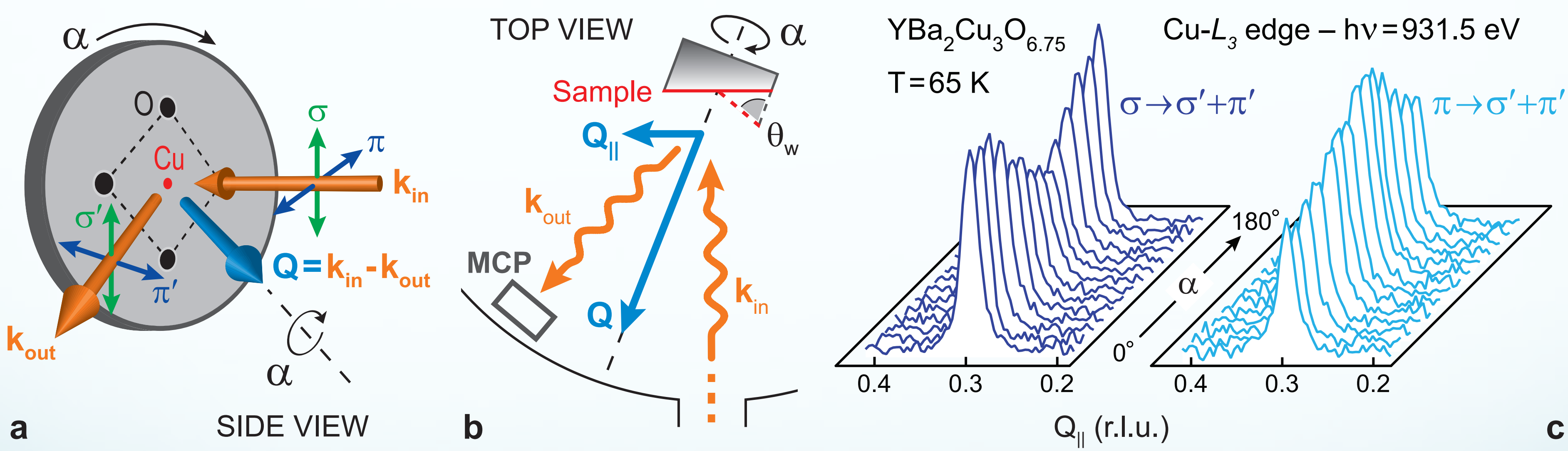
Sachdev and La Placa, PRL 2013
Efetov, Meier and Pepin, Nat. Phys. 2013
Metlitski and Sachdev, PRB 2010
Vojta and Rosch PRL 2008
Atkinson, Kampf and Bulut NJP 2015
Wang and Chubukov PRB 2014
Keo, Chen and Hu PRB 2007
Li, Wu and Lee PRB 2006
Chowdhury and Sachdev PRL 2014
Thomson and Sachdev PRB 2015
...

d symmetry CDW



d symmetry charge order from resonant x-ray scattering

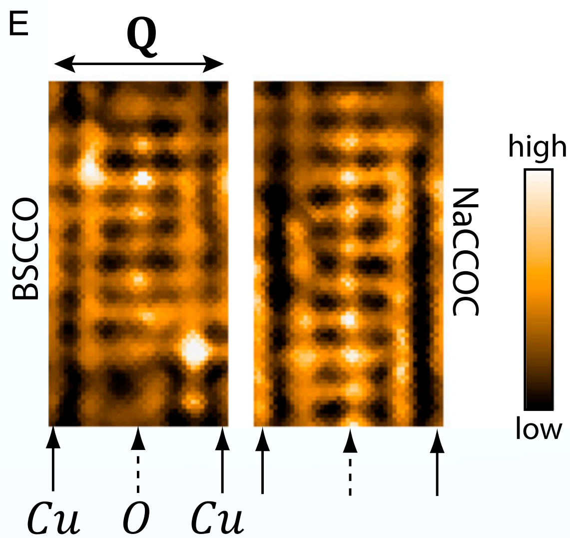
Report of d-symmetry CDW in YBCO from azimuthal angle dependent resonant x-ray scattering



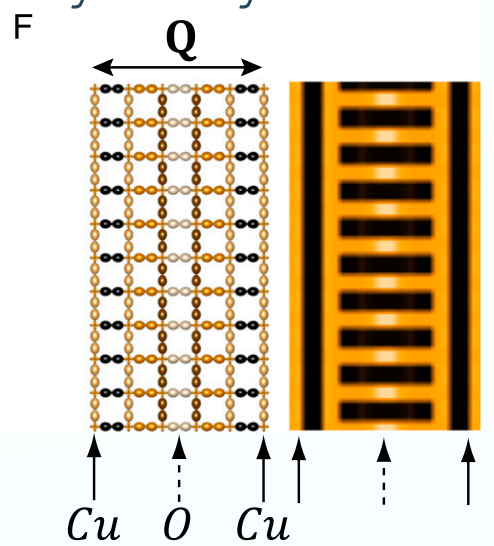
R. Comin, F. He, E.da Silva Neto, L. Chauviere, A. Frano, R. Liang, W. N. Hardy, D. A. Bonn, Y. Yoshida, H. Eisaki, J. E. Hoffman, B. Keimer, G. A. Sawatzky and A. Damascelli. Nature Materials 2015

d symmetry charge order from STM

STM

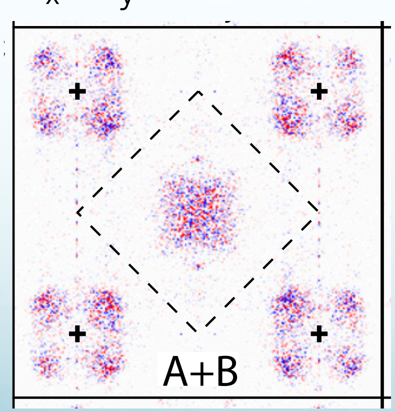


d symmetry calculation

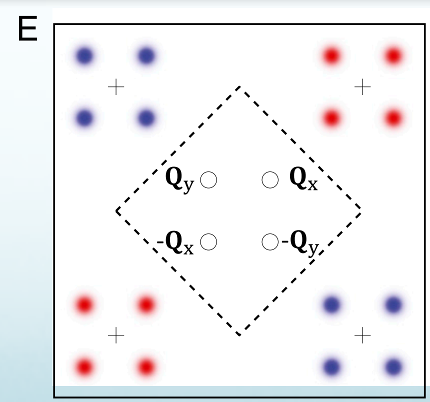


Real space

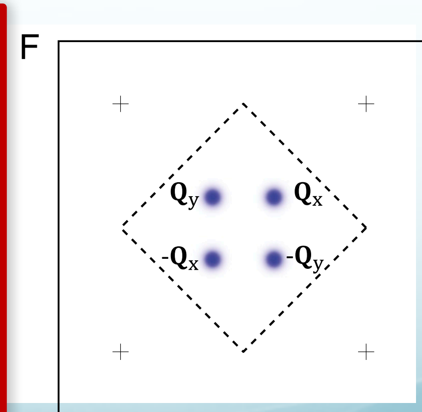
O_x+O_y sublattices



BSCCO



d symmetry



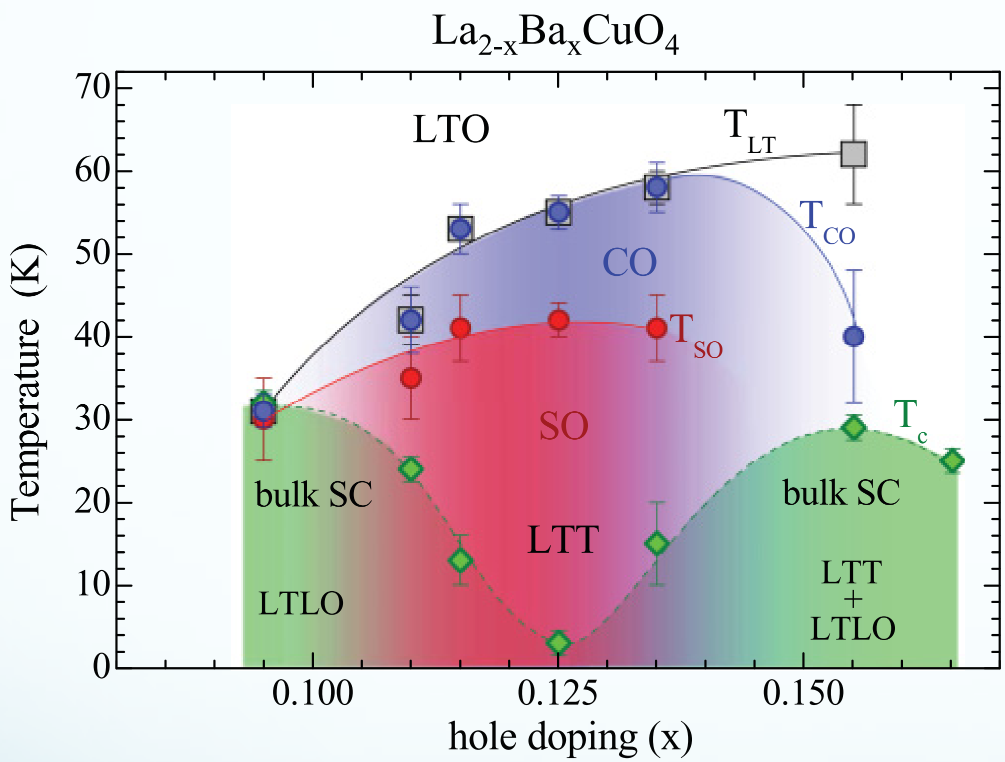
s′ symmetry

Fourier Transforms (Q space)

Fujita et al. PNAS 2014

UNIVERSITY OF Waterloo

Symmetry of density wave order in La-based cuprates



M. Hücker. PHYSICAL REVIEW B **83**, 104506 (2011)

Is CDW different in La-based cuprates?

- Unidirectional spin (SO) and charge (CO)
- More dramatic suppression of superconductivity at $x = 1/8$
- Different doping dependence to CDW incommensurability
- Orbital symmetry of CDW order?

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Resonant X-ray Scattering

Tune photon energy to an x-ray resonance

On resonance, the atomic scattering form factor, f, is sensitive to orbital symmetry

$$I_{sc}(\vec{Q}) \propto \left| \sum_j f_j e^{-i2\pi \vec{Q}\cdot\vec{r_j}} \right|^2$$

$$I_{sc}(\vec{Q}, \omega, \vec{\epsilon}) \propto \left| \sum_j (\vec{\epsilon}^{\,*} F_j(\omega) \vec{\epsilon}) e^{-i2\pi \vec{Q}\cdot\vec{r_j}} \right|^2$$

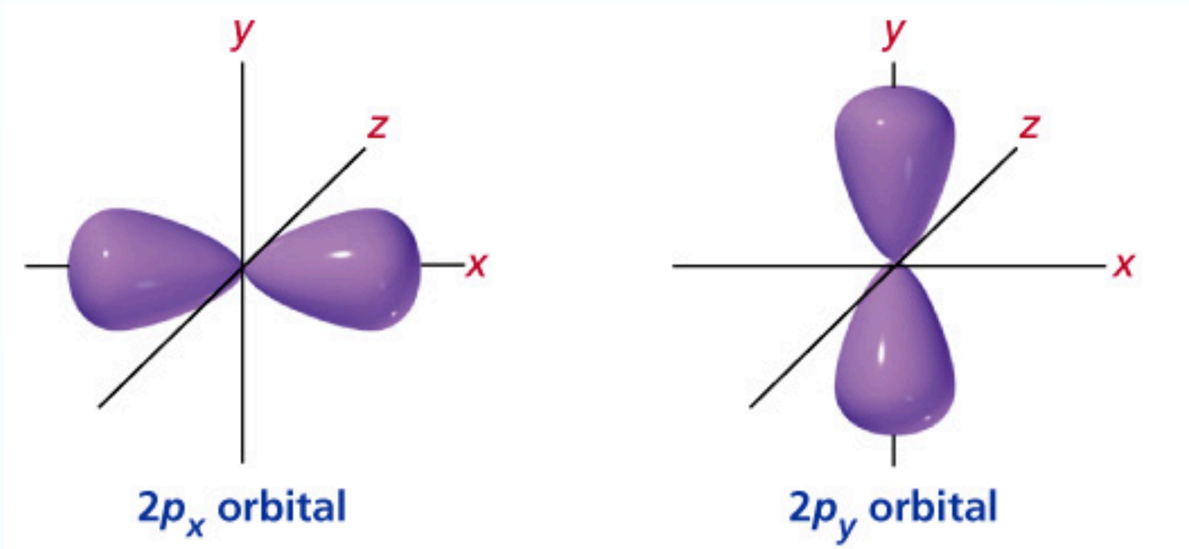
Scattered photon polarization

Incident photon polarization

$$F = \begin{bmatrix} f_{xx} & f_{xy} & f_{xz} \\ f_{yx} & f_{yy} & f_{yz} \\ f_{zx} & f_{zy} & f_{zz} \end{bmatrix}$$

Scattering form factor: orbital symmetry dependence

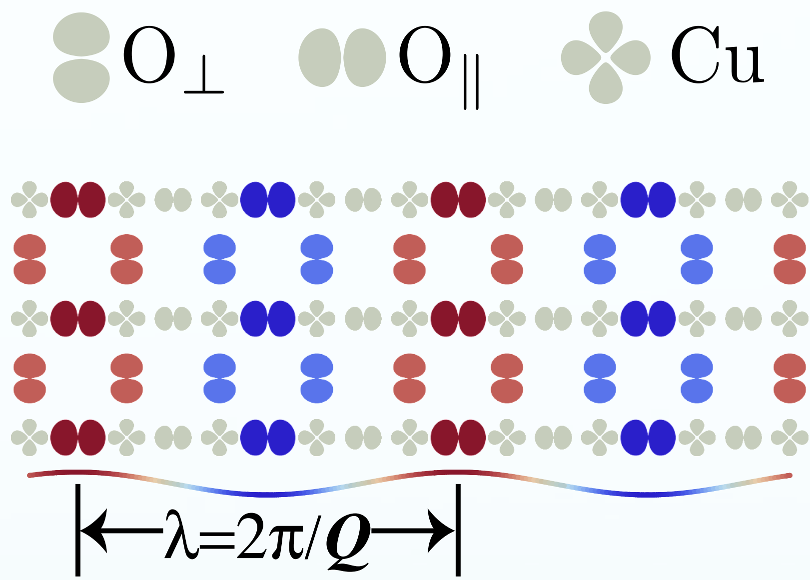
O *K* edge (1s → 2p transition): sensitive to orbital symmetry of O 2*p* holes



$$F = \begin{bmatrix} f_{xx} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad F = \begin{bmatrix} 0 & 0 & 0 \\ 0 & f_{yy} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

CDW symmetry

Holes in O $2p_x$ or $2p_y$ states form two sublattices



$\mathrm{O}_\perp$ sublattice $\mathrm{O}_\parallel$ sublattice

Measureable parameters

$$t_\perp = \sum_j f_{\perp,j} e^{-i2\pi\vec{Q}\cdot\vec{r_j}} \qquad t_\parallel = \sum_j f_{\parallel,j} e^{-i2\pi\vec{Q}\cdot\vec{r_j}}$$

Components of a tensor equivalent of the structure factor

Map scattering intensity to CDW symmetry

Measuring the magnitude and sign of $t_{//}/t_{\perp}$ provides a measure of CDW symmetry

$\mathrm{O}_{\perp}$ $$t_{\perp} = \sum_j f_{\perp,j} e^{-i2\pi\vec{Q}\cdot\vec{r_j}}$$

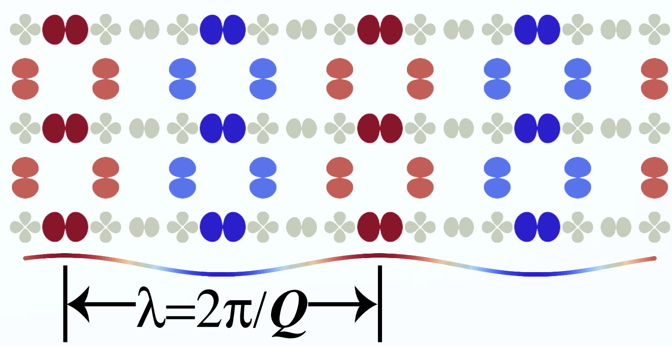
$\mathrm{O}_{\parallel}$ $$t_{\parallel} = \sum_j f_{\parallel,j} e^{-i2\pi\vec{Q}\cdot\vec{r_j}}$$

Admixture of d and s'

$$\frac{\Delta_d}{\Delta_{s'}} = \frac{t_{\parallel}/t_{\perp} - 1}{t_{\parallel}/t_{\perp} + 1}.$$

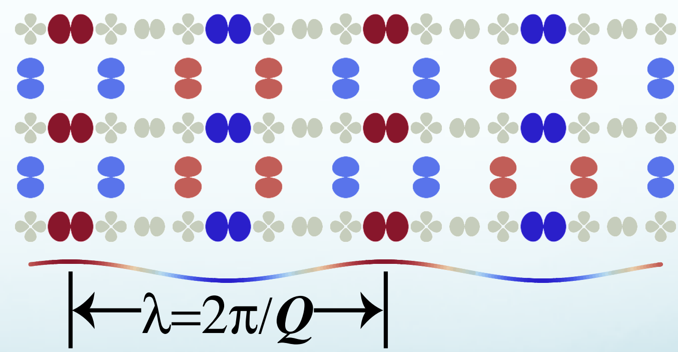
$\mathrm{O}_{\perp}$ $\mathrm{O}_{\parallel}$ Cu

s' symmetry CDW



$t_{\perp}$ and $t_{\parallel}$ in phase

d symmetry CDW

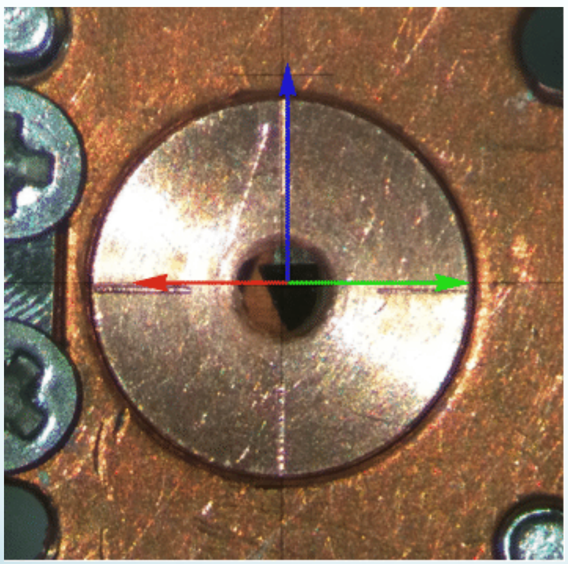


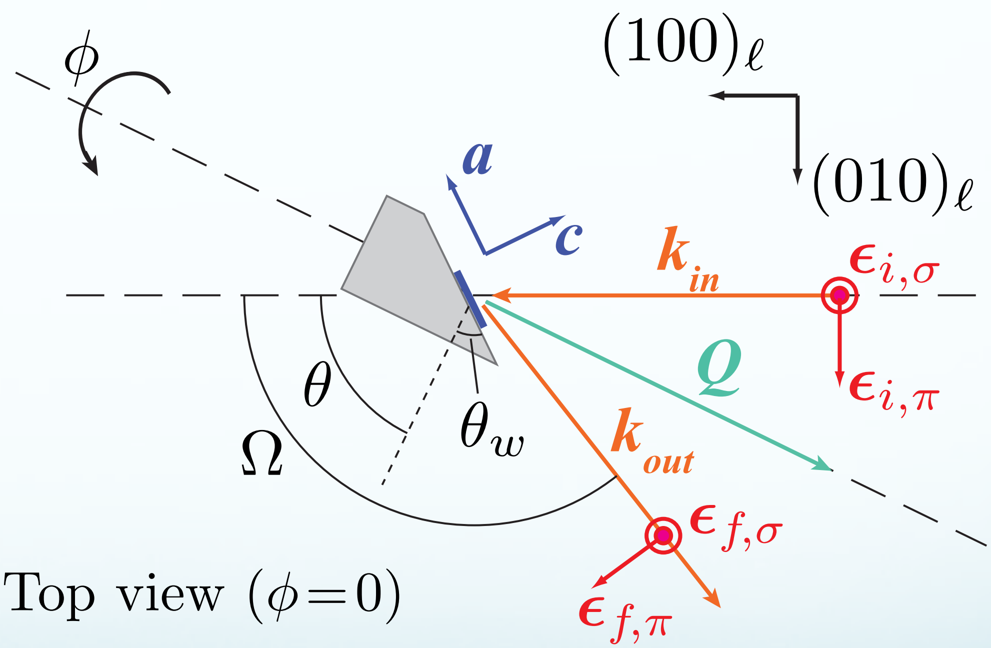
$t_{\perp}$ and $t_{\parallel}$ out of phase

Experimental scheme

Rotate the sample geometry and photon polarization relative to the *a*, *b* and *c* axes

Side view





Top view ($\phi=0$)

REIXS beamline at the Canadian Light Source
Hawthorn *et al.* Rev. Sci. Instrum. 2011

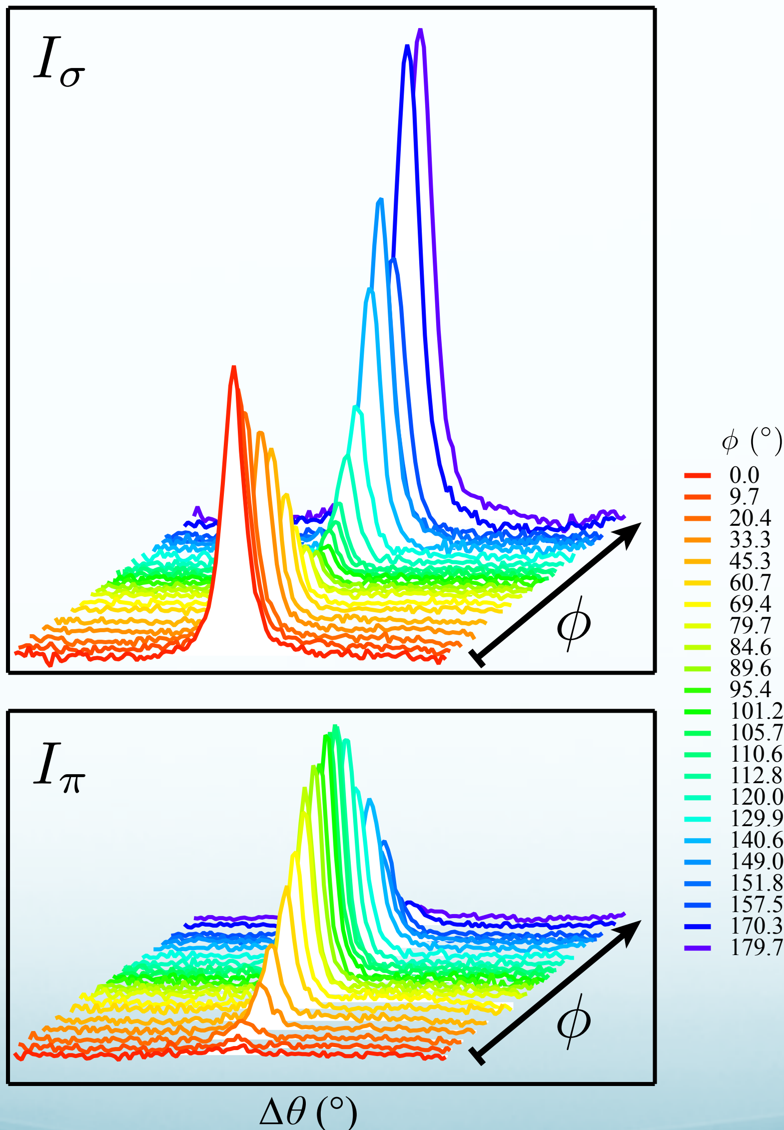
Comin Nature Materials 2015
Achkar Nature Materials 2016

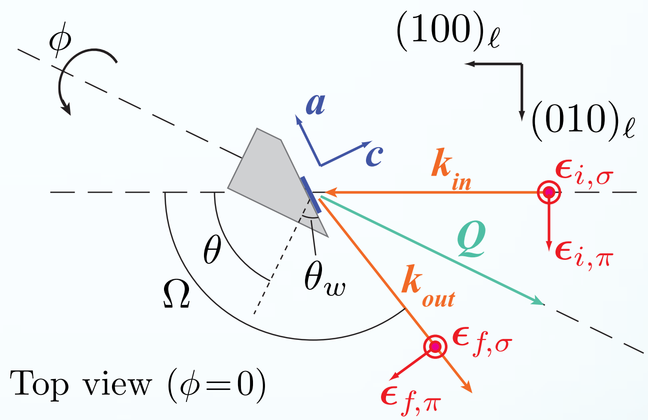
LBCO: O K edge

CDW peak at $\boldsymbol{Q} = (0.232\ 0\ 0.611)$

σ
Incident photon polarization perpendicular to scattering plane

π
Incident photon polarization parallel to scattering plane





Achkar et al. Nature Materials (2016)

LBCO: O K edge

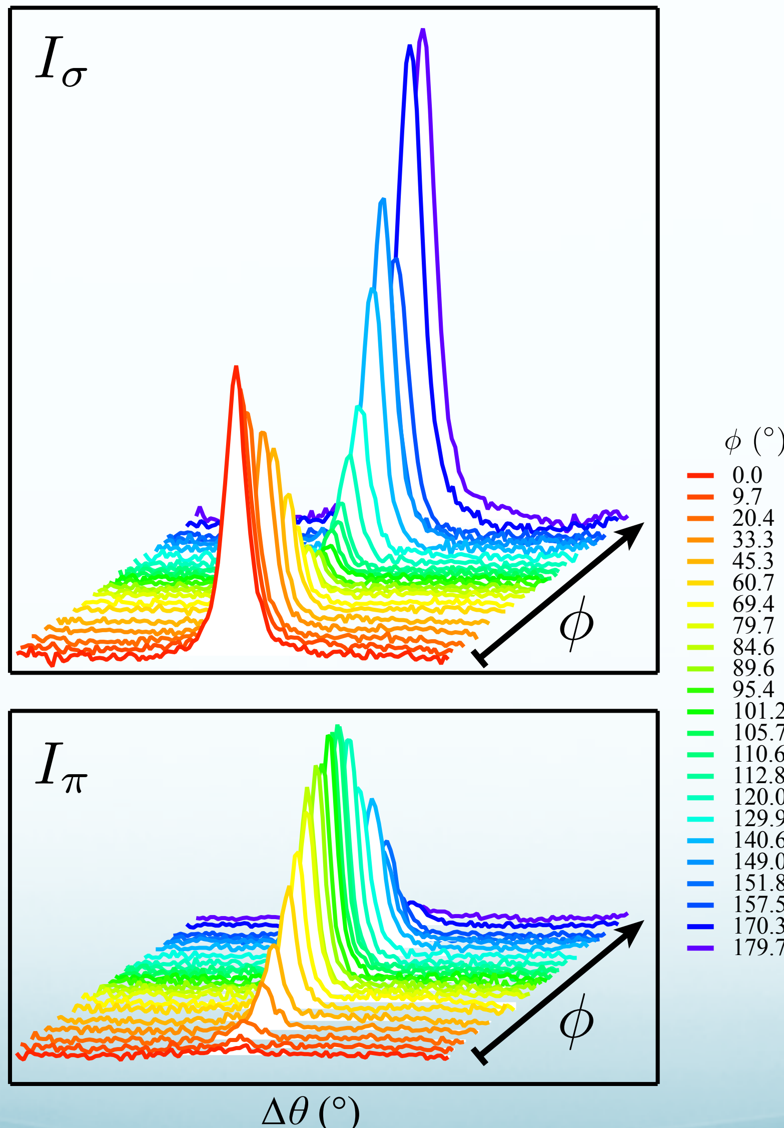
σ

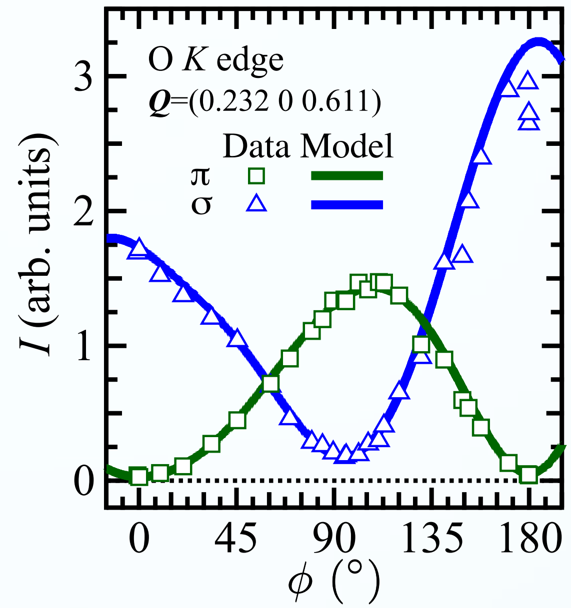
Incident photon polarization perpendicular to scattering plane

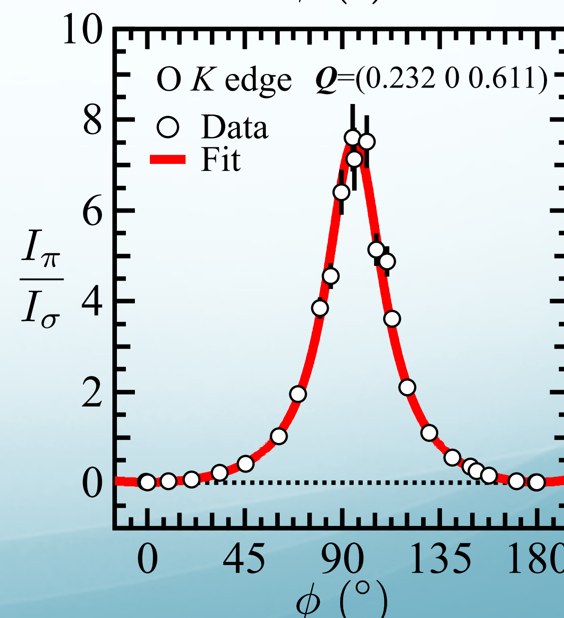
π

Incident photon polarization parallel to scattering plane

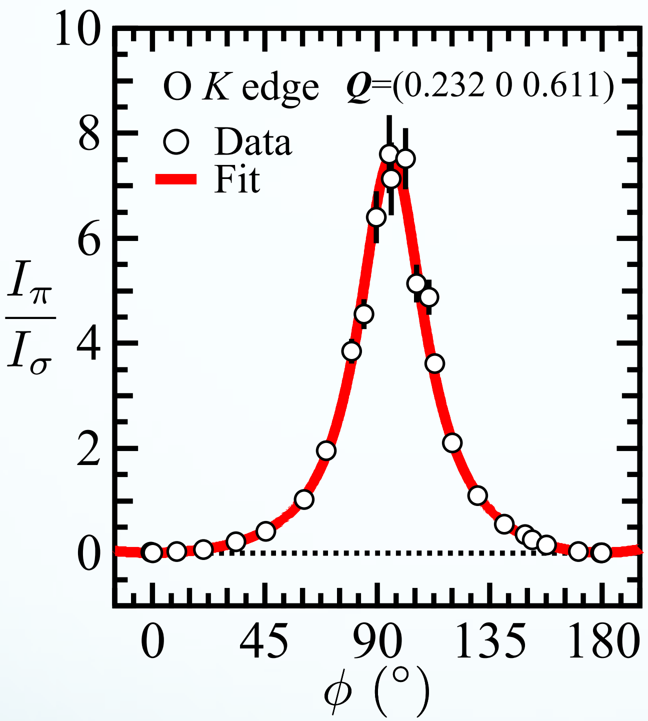
CDW peak at $\boldsymbol{Q} = (0.232\ 0\ 0.611)$







LBCO: CDW symmetry



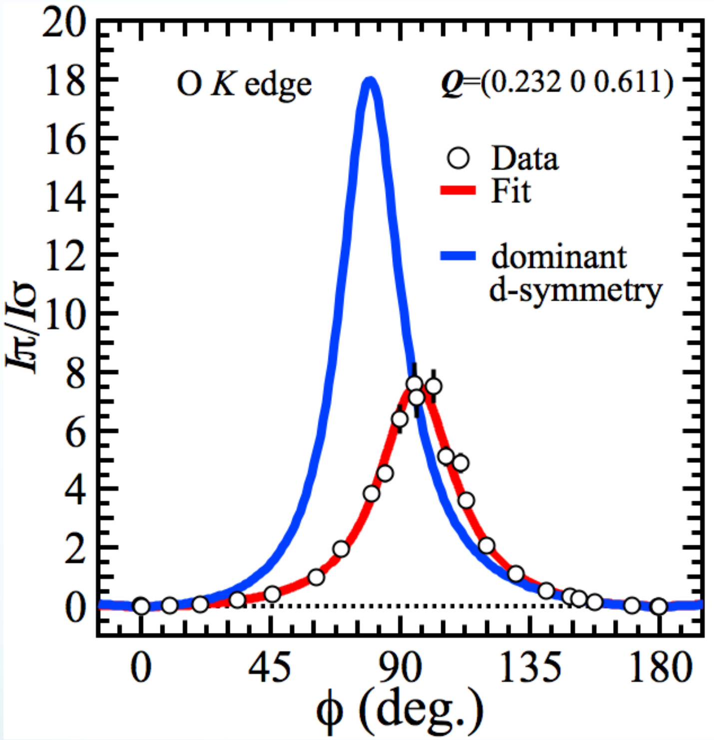
Fit results

$t_{//}/t_{\perp} = +0.612 \pm 0.035$
$t_{cc}/t_{bb} = +0.034 \pm 0.021$

- Scattering is larger for $O_{\perp}$ than for $O_{\|}$
- c-axis component of scattering is small
- $t_{//}/t_{\perp}$ +VE: CDW in LBCO is predominantly s' symmetry

Achkar et al. Nature Materials (2016)

LBCO: CDW symmetry



Fit results

$t_{//}/t_{\perp}$ = +0.612 ± 0.035
t_{cc}/t_{bb} = +0.034 ± 0.021

- Scattering is larger for $O_{\perp}$ than for $O_{\|}$
- c-axis component of scattering is small
- $t_{//}/t_{\perp}$ +VE: CDW in LBCO is predominantly s' symmetry

$$\frac{\Delta_d}{\Delta_{s'}} = \frac{t_{\|}/t_{\perp} - 1}{t_{\|}/t_{\perp} + 1}.$$

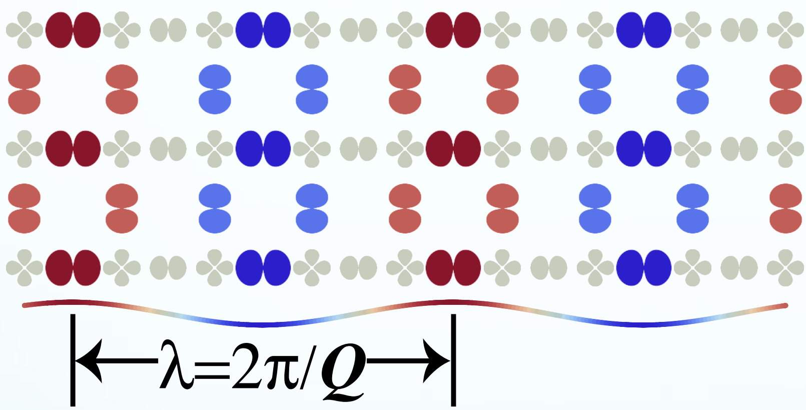
$\Delta_d/\Delta_{s'}$ = −0.241 ± 0.027

Achkar et al. Nature Materials (2016)

Why would CDW symmetry be different?

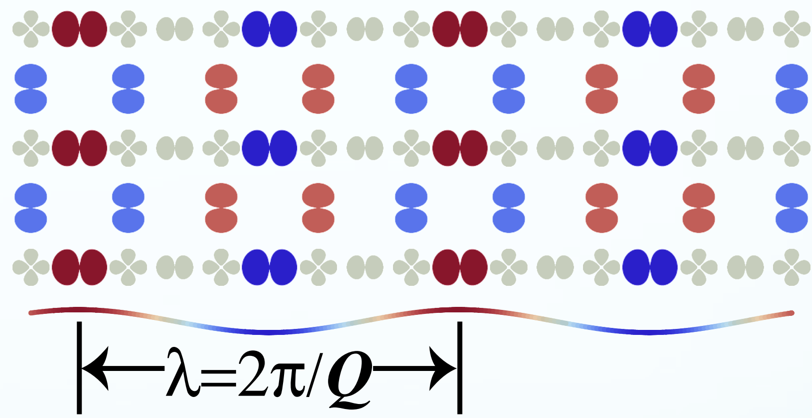
LBCO (La-based cuprates)

s’ symmetry CDW



BSCCO, NCCOC, YBCO

d symmetry CDW

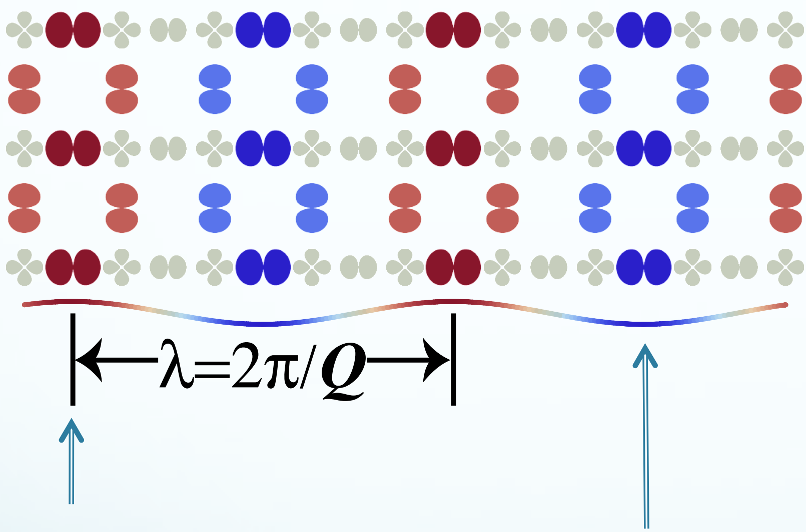


SDW order??

Why would CDW symmetry be different?

LBCO (La-based cuprates)

s' symmetry CDW



High charge density

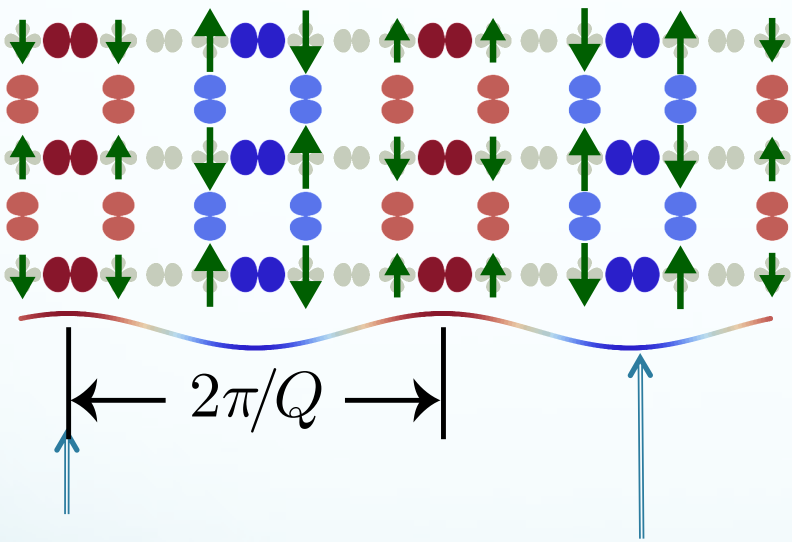
Low charge density

In spin and charge stripes: Correlation between the local charge and local AF order

Why would CDW symmetry be different?

LBCO (La-based cuprates)

s’ symmetry CDW



High charge density

Low charge density

In spin and charge stripes: Correlation between the local charge and local AF order

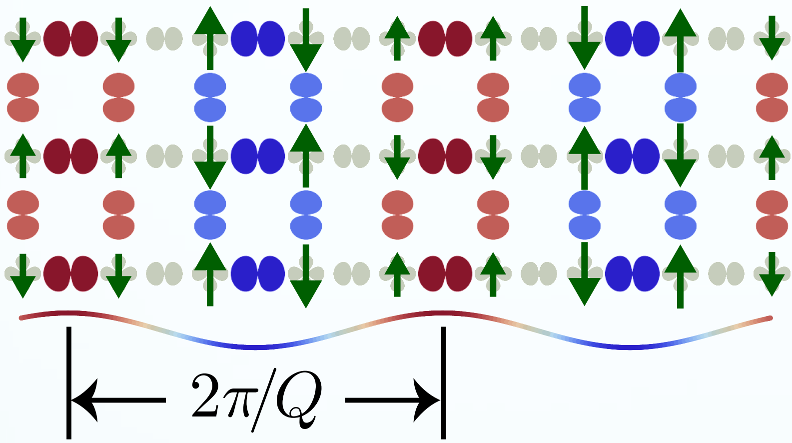
Spin stripes are compatible with s’ symmetry CDW

Achkar et al. Nature Materials (2016)

Why would CDW symmetry be different?

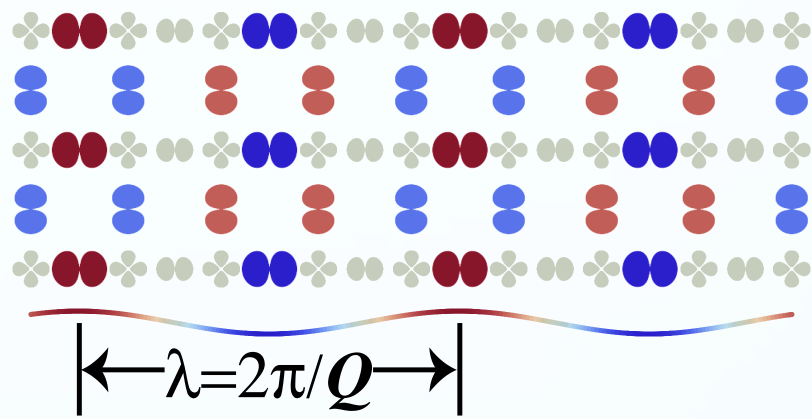
LBCO (La-based cuprates)

s' symmetry CDW+SDW



BSCCO, NCCOC, (YBCO?)

d symmetry CDW



d-symmetry CDW order is unfavorable for static spin density wave order

Achkar et al. Nature Materials (2016)

SDW order and CDW symmetry

Theoretical support for a relation between static SDW order and CDW symmetry

Thomson and Sachdev PRB 2015

- "… the presence of antiferromagnetic order decreases the magnitude of the d-form factor; this trend is consistent with recent observation of a dominant s' form factor in the hole-doped cuprate with magnetic order, $La_{1.875}Ba_{0.125}CuO_4$."

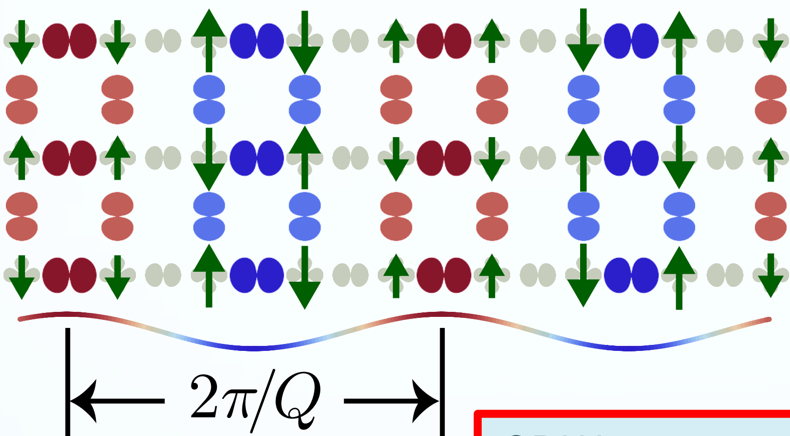
Fischer, Wu, Paramekanti, Lawler, Kim New Journal Physics 2014

- A model with spin and charge stripes exhibits d/s' ~0.1

CDW symmetry and Superconductivity

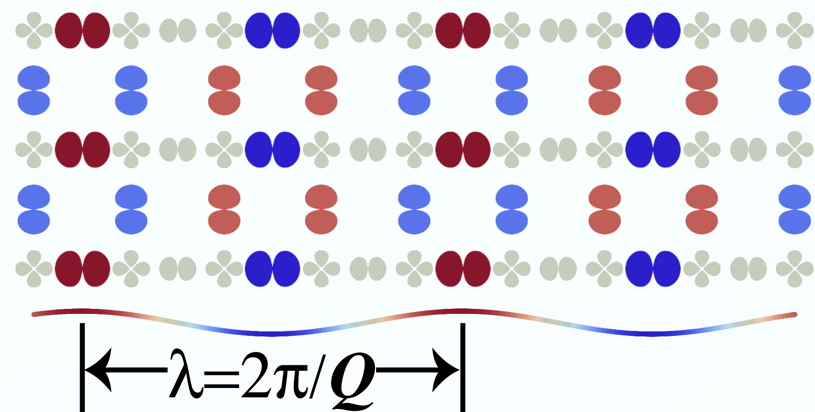
LBCO (La-based cuprates)

s' symmetry CDW+SDW

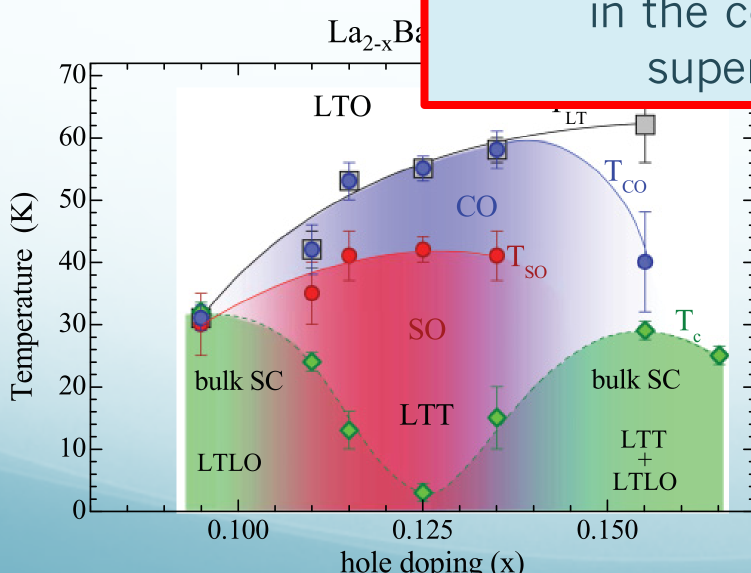


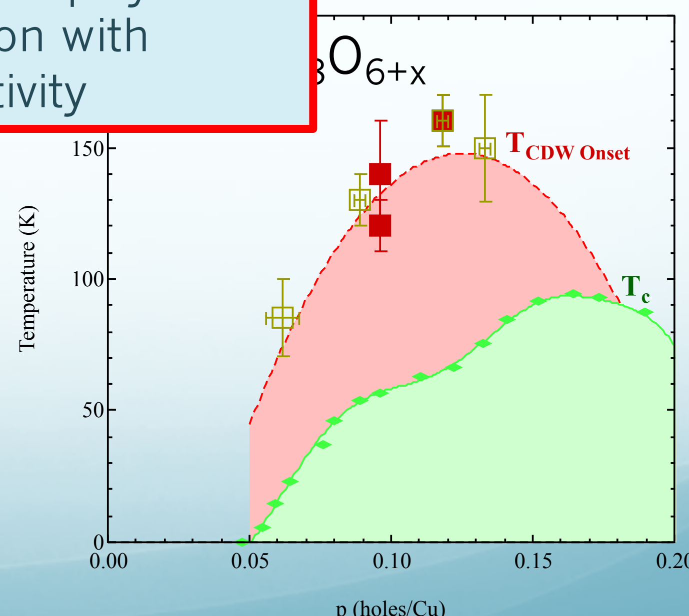
BSCCO, NCCOC, (YBCO?)

d symmetry CDW



CDW symmetry may also play a role in the competition with superconductivity





Conclusions

CDW order may have a different orbital symmetry in different cuprate materials

- $La_{7/8}Ba_{1/8}CuO_4$: dominant *s'* symmetry
- $Ca_{2-x}Na_xCuO_2Cl_2$, $Bi_2Sr_2CaCu_2O_{8+\delta}$: dominant *d* symmetry

- Orbital symmetry of the CDW order may be a key feature related to the presence of static SDW order and strong competition with superconductivity in $La_{7/8}Ba_{1/8}CuO_4$

Achkar et al. Nature Materials (2016)