Title: Nematicity and charge density wave order in stripe ordered cuprates probed via resonant x-ray scattering

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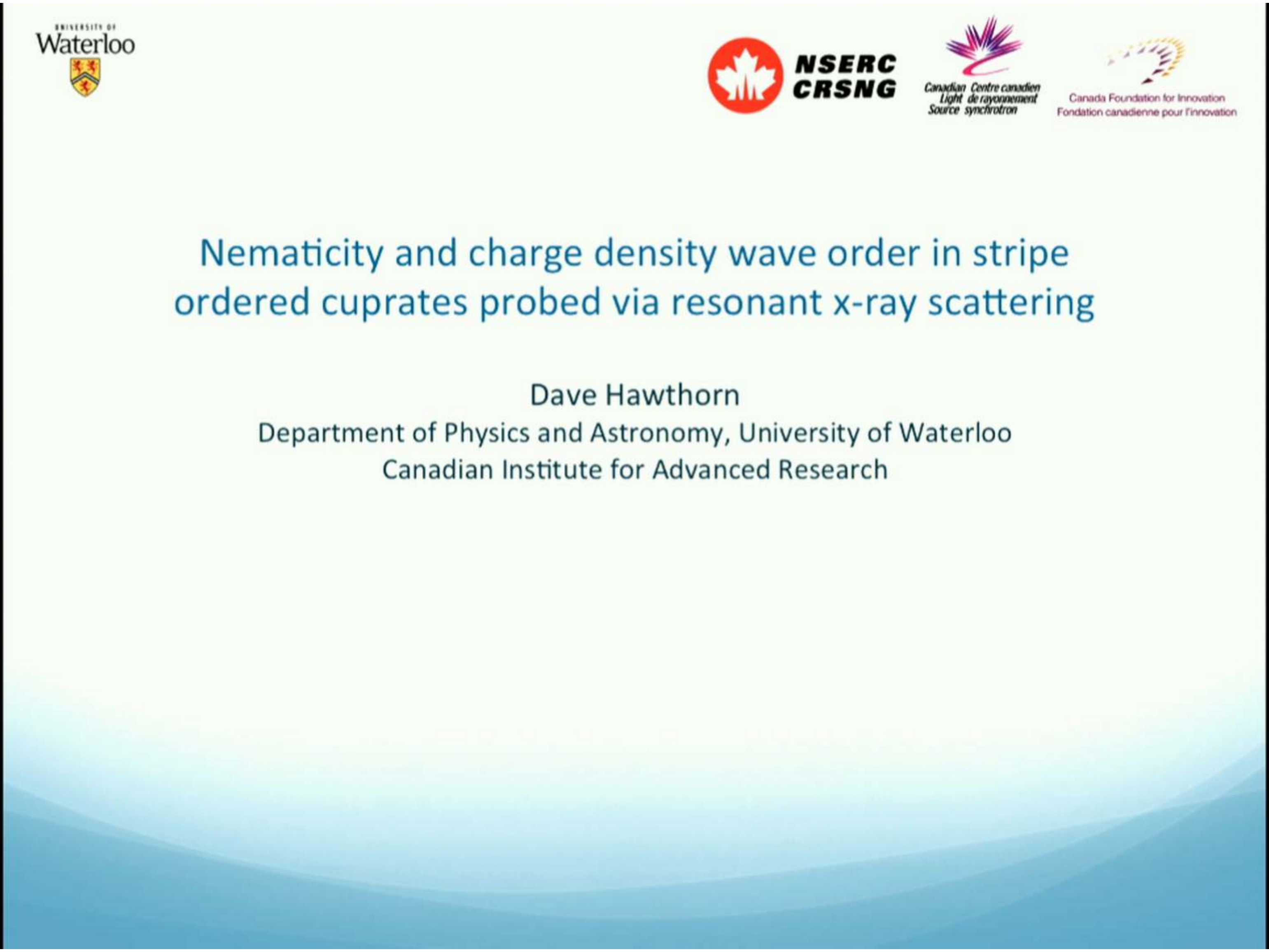
Abstract: Akin to liquid crystals, electronic nematic phases have been theorized and observed in several correlated materials, including cuprate and pnictide superconductors. I will discuss how electronic nematicity is observed in stripe-ordered cuprates using resonant x-ray scattering and how it relates to structural distortions and charge-density wave order.



Nematicity and charge density wave order in stripe ordered cuprates probed via resonant x-ray scattering

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Canadian Light Source
Centre canadien de rayonnement synchrotron

NSERC
CRSNG

Canada Foundation for Innovation
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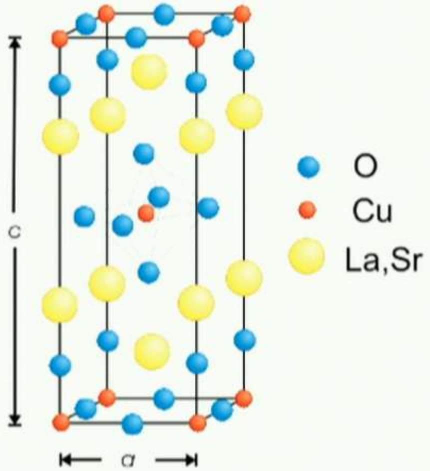
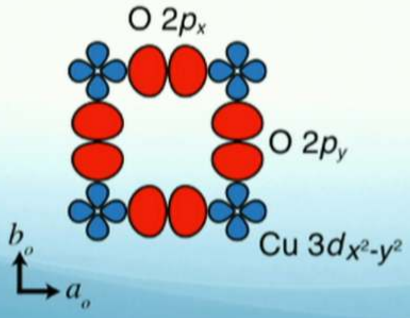
Cuprate high-temperature superconductors

$La_{2-x}Sr_xCuO_4$



Low energy physics is dominated by the CuO_2 planes



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Cuprate high-temperature superconductors

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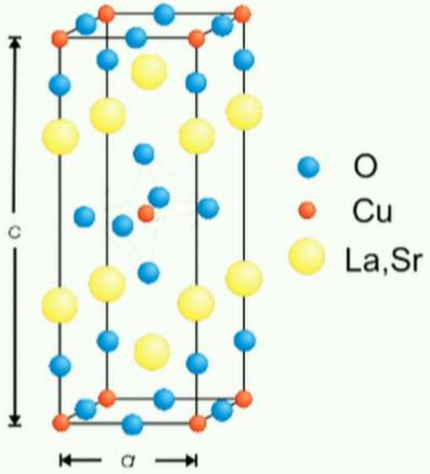

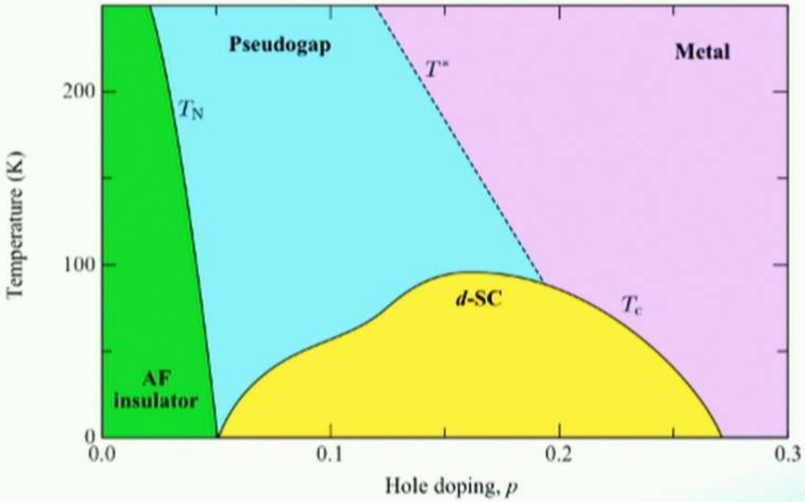

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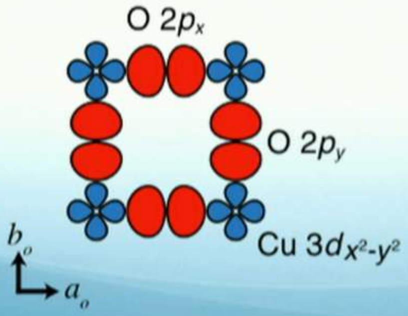

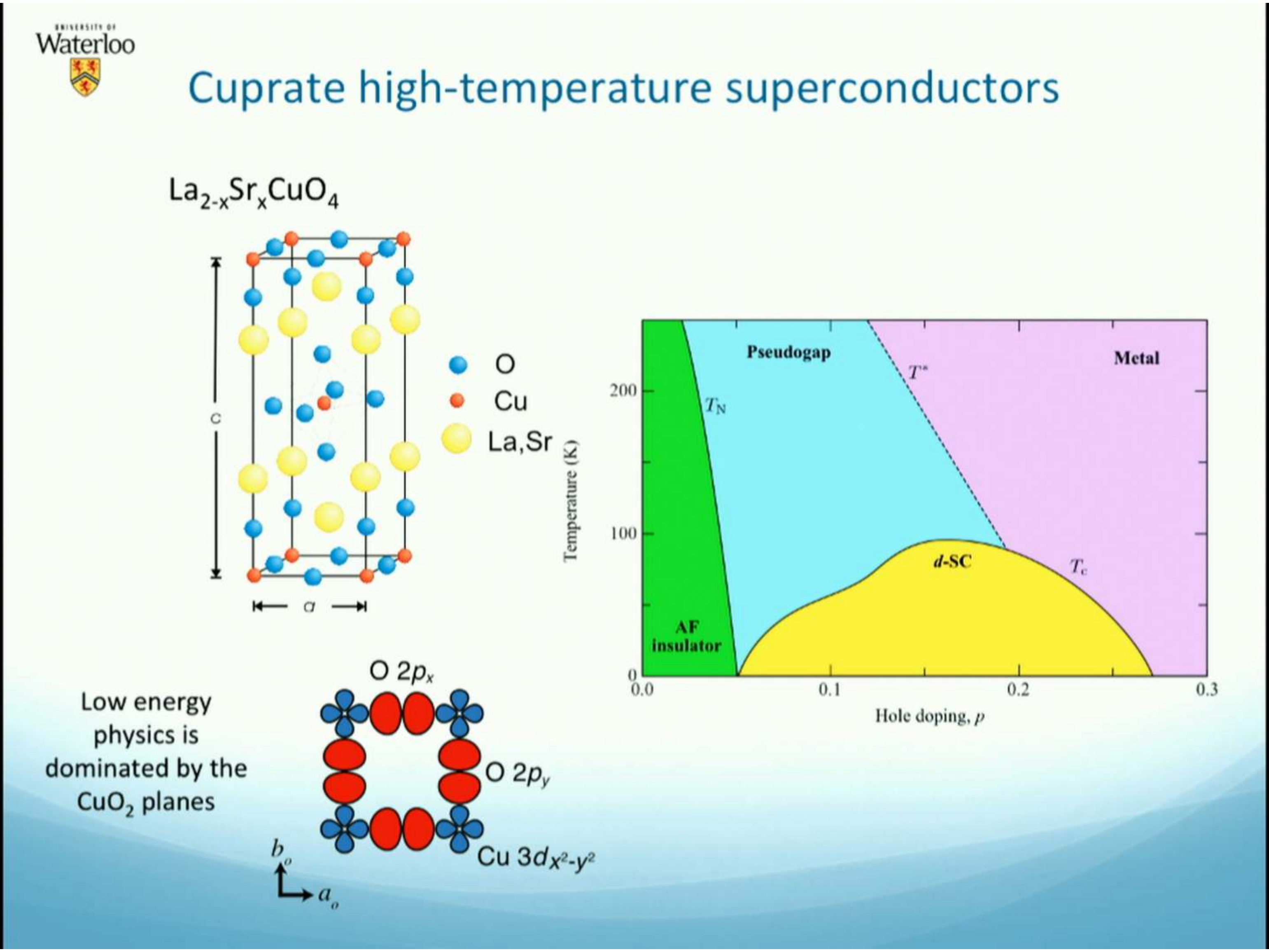

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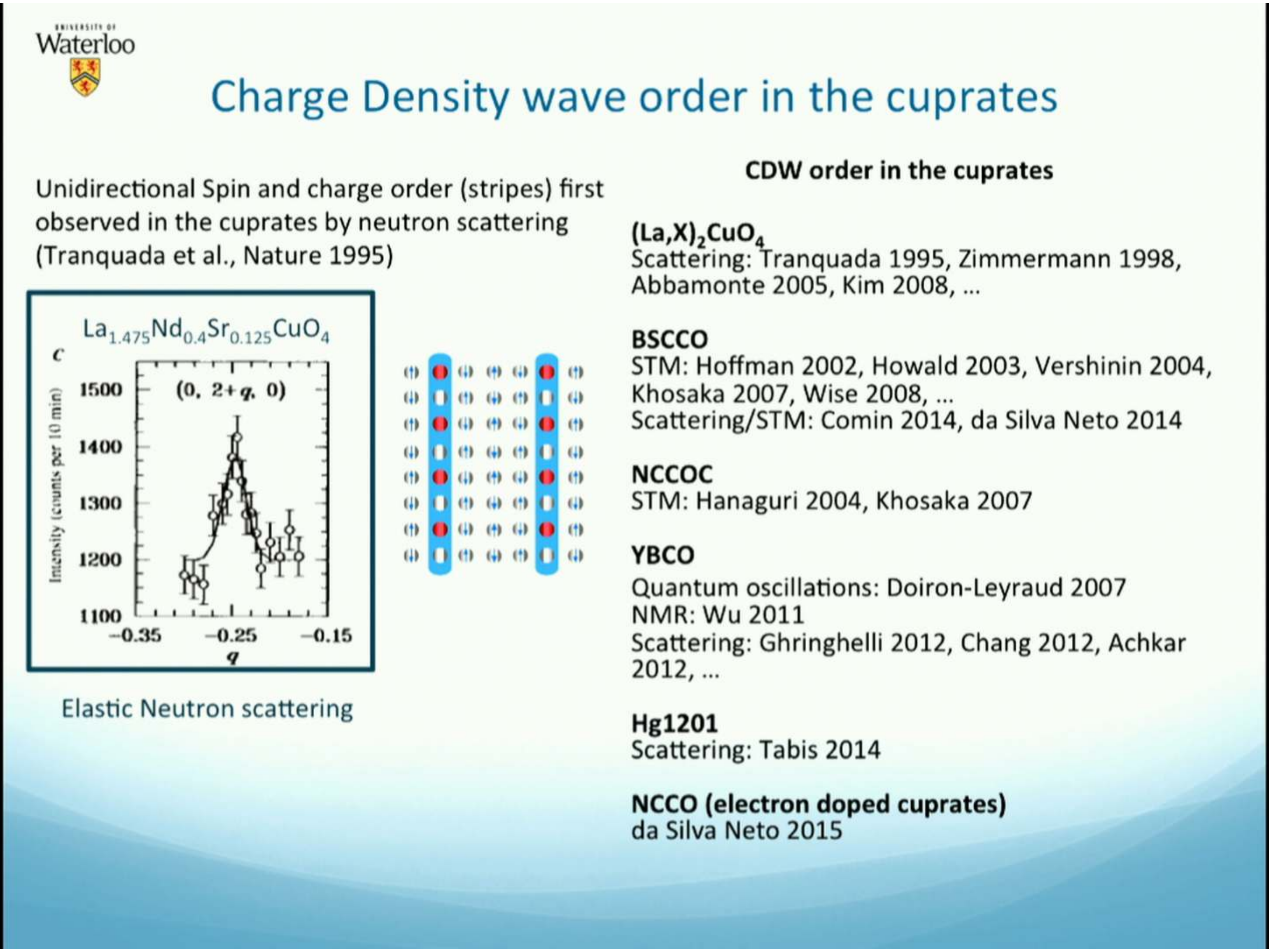


Charge Density wave order in the cuprates

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

Elastic Neutron scattering

CDW order in the cuprates

$(La,X)_2CuO_4$
Scattering: Tranquada 1995, Zimmermann 1998, Abbamonte 2005, Kim 2008, …

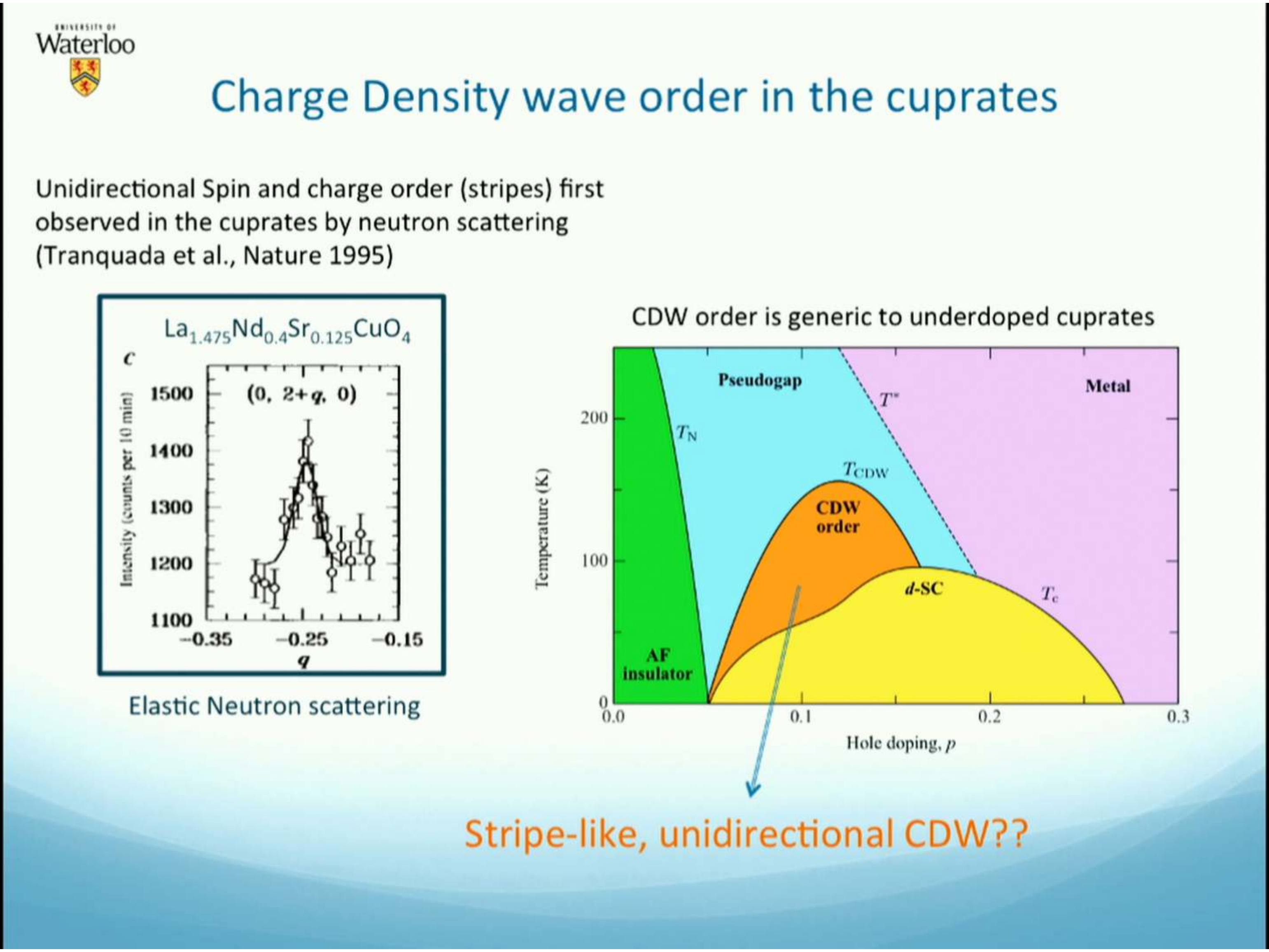
BSCCO
STM: Hoffman 2002, Howald 2003, Vershinin 2004, Khosaka 2007, Wise 2008, …
Scattering/STM: Comin 2014, da Silva Neto 2014

NCCOC
STM: Hanaguri 2004, Khosaka 2007

YBCO
Quantum oscillations: Doiron-Leyraud 2007
NMR: Wu 2011
Scattering: Ghringhelli 2012, Chang 2012, Achkar 2012, …

Hg1201
Scattering: Tabis 2014

NCCO (electron doped cuprates)
da Silva Neto 2015



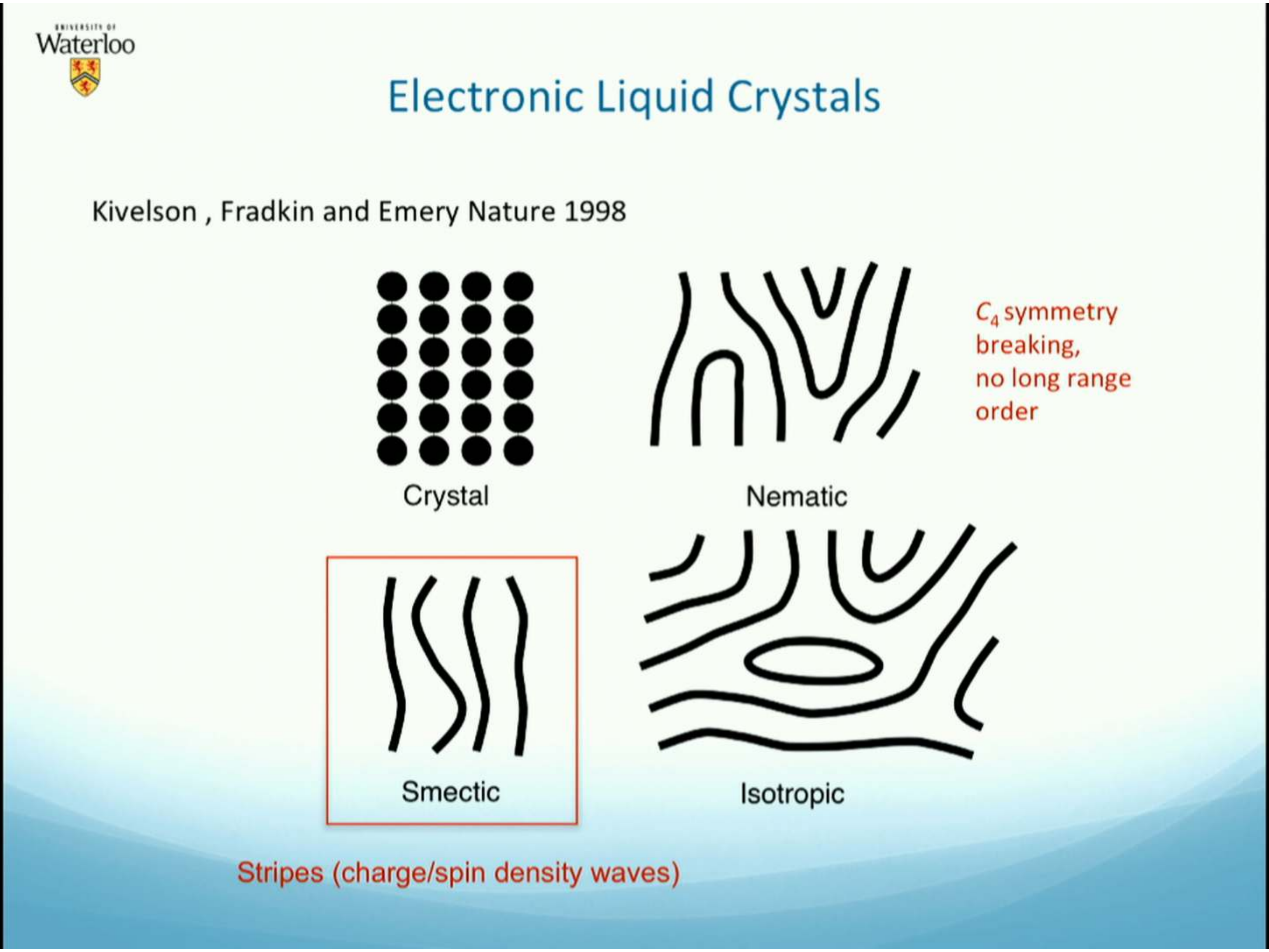
Charge Density wave order in the cuprates

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

Elastic Neutron scattering

CDW order is generic to underdoped cuprates

Stripe-like, unidirectional CDW??



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Electronic Liquid Crystals

Kivelson , Fradkin and Emery Nature 1998

Crystal

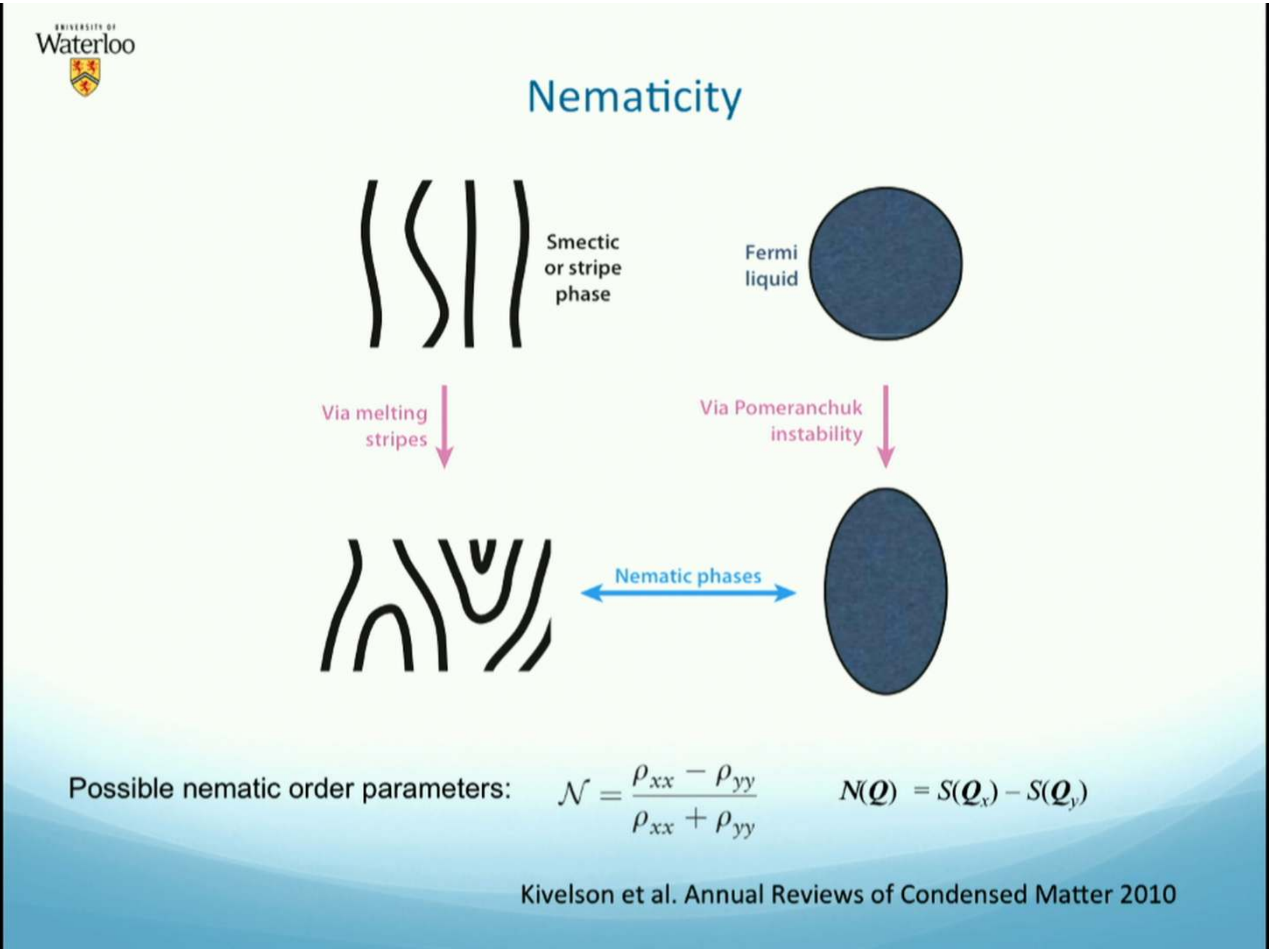
Nematic

C_4 symmetry breaking, no long range order

Smectic

Isotropic

Stripes (charge/spin density waves)



Nematicity

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

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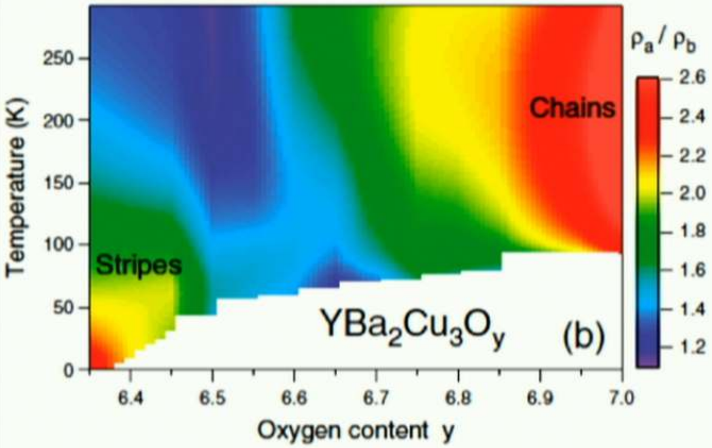
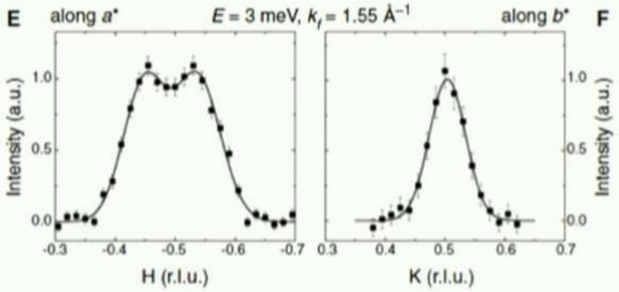
Evidence for Electronic Nematicity in the cuprates

Ando PRL 2002

Resistivity anisotropy



Inelastic neutron scattering $YBa_2Cu_3O_{6.45}$



Hinkov Science 2008

Also:

- Anisotropy in Nernst signal in underdoped YBCO: Daou et al. Nature 2010
- Resistivity Anisotropy: Cyr-Choiniere arXiv 2015

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Evidence for Electronic Nematicity in the cuprates

Ando PRL 2002

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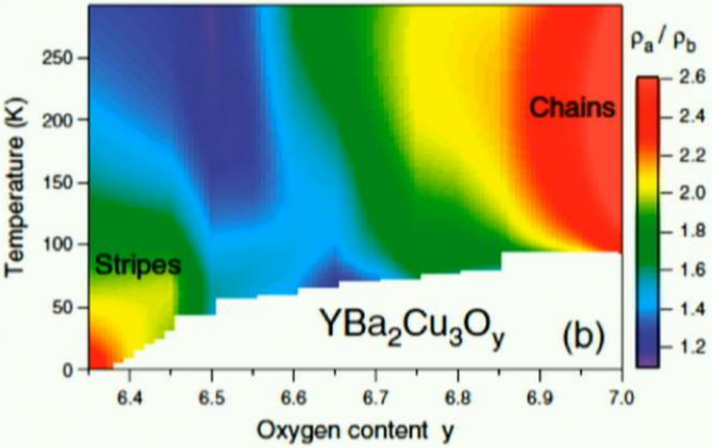

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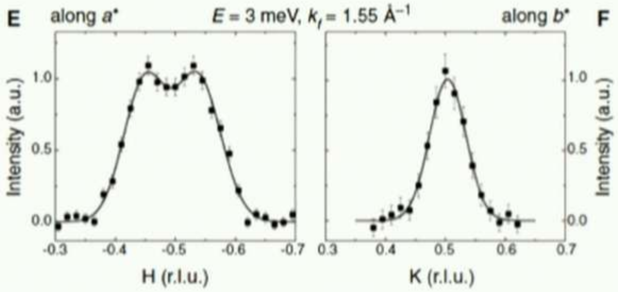

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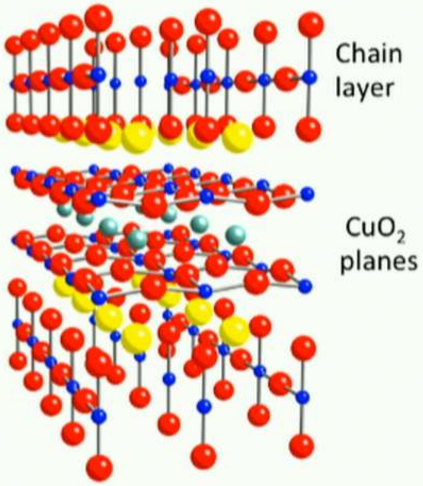
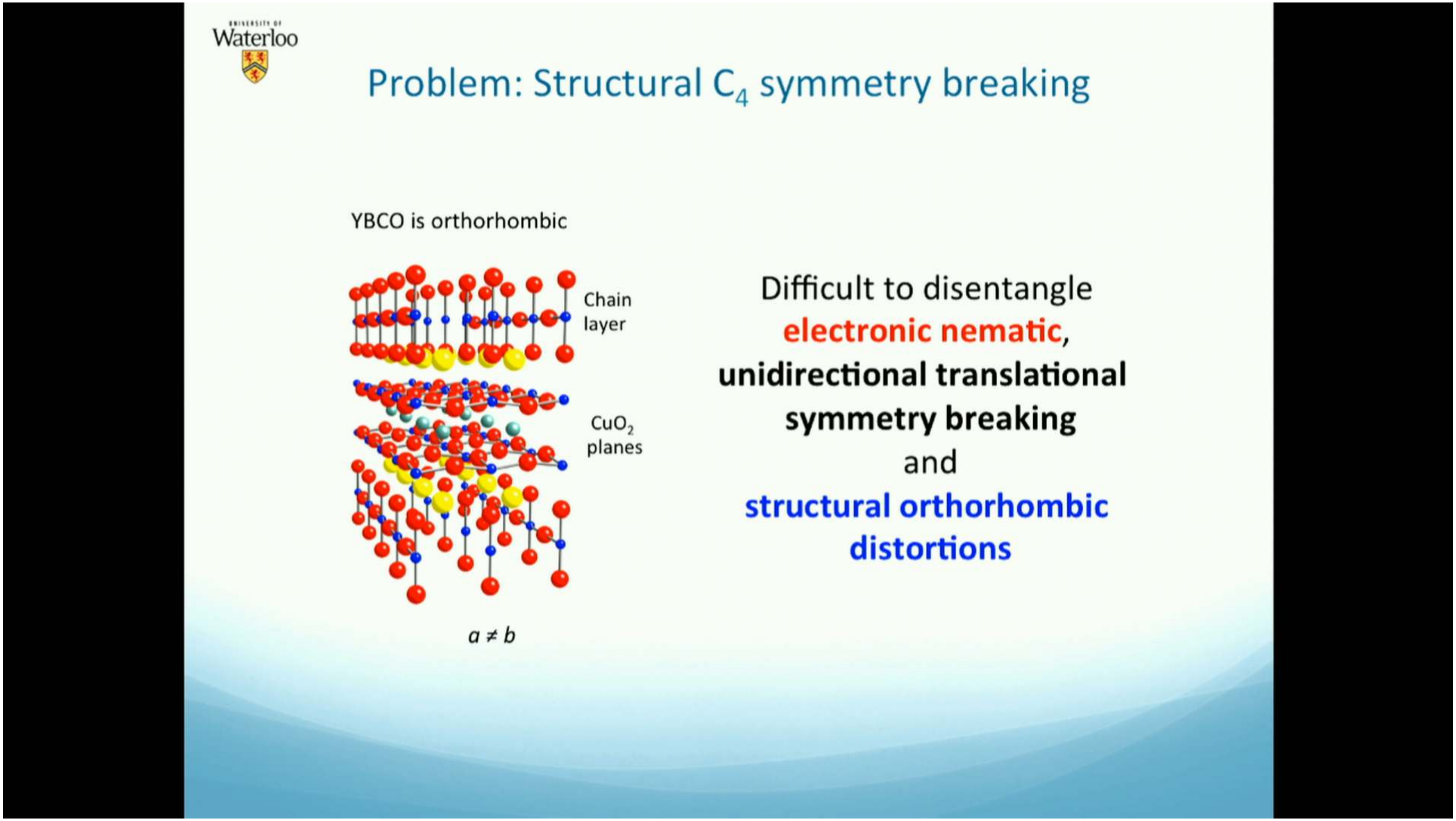
Problem: Structural C_4 symmetry breaking

YBCO is orthorhombic



$a \neq b$

Difficult to disentangle
electronic nematic,
unidirectional translational symmetry breaking
and
structural orthorhombic distortions



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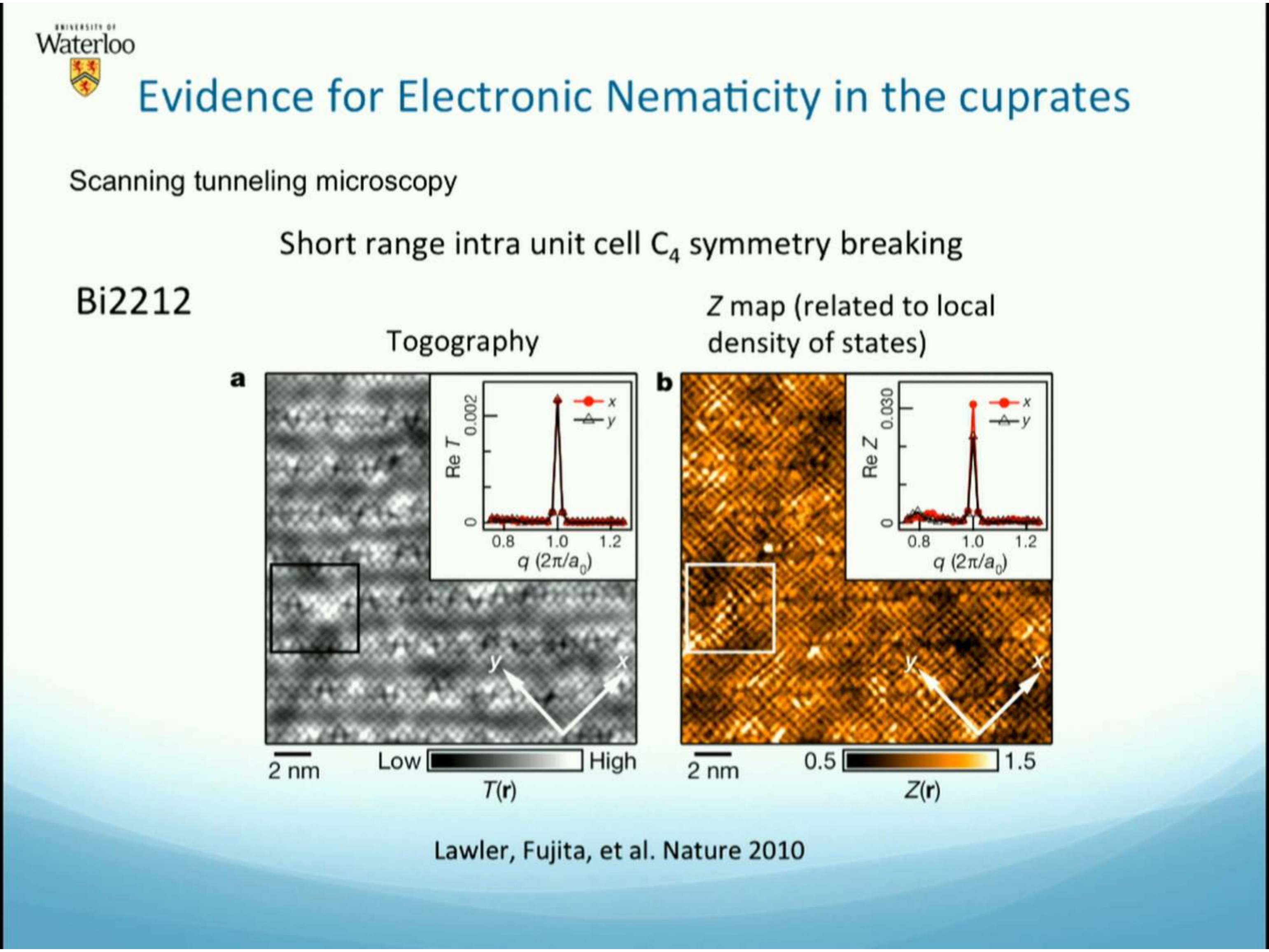


Evidence for Electronic Nematicity in the cuprates

Scanning tunneling microscopy

Short range intra unit cell C_4 symmetry breaking

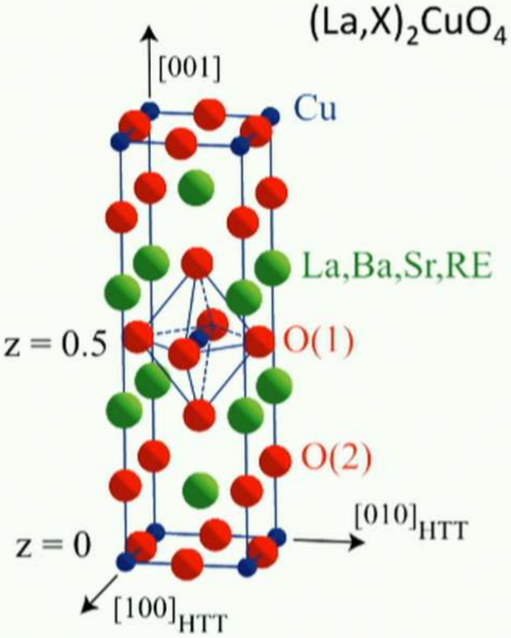
Bi2212

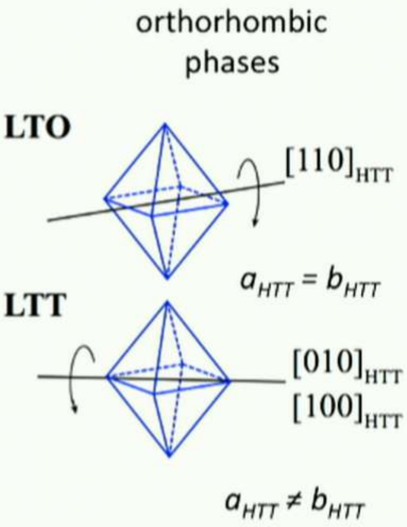
Togography

Z map (related to local density of states)

Lawler, Fujita, et al. Nature 2010

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





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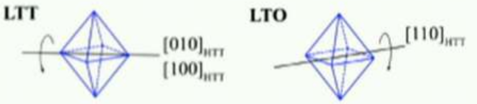
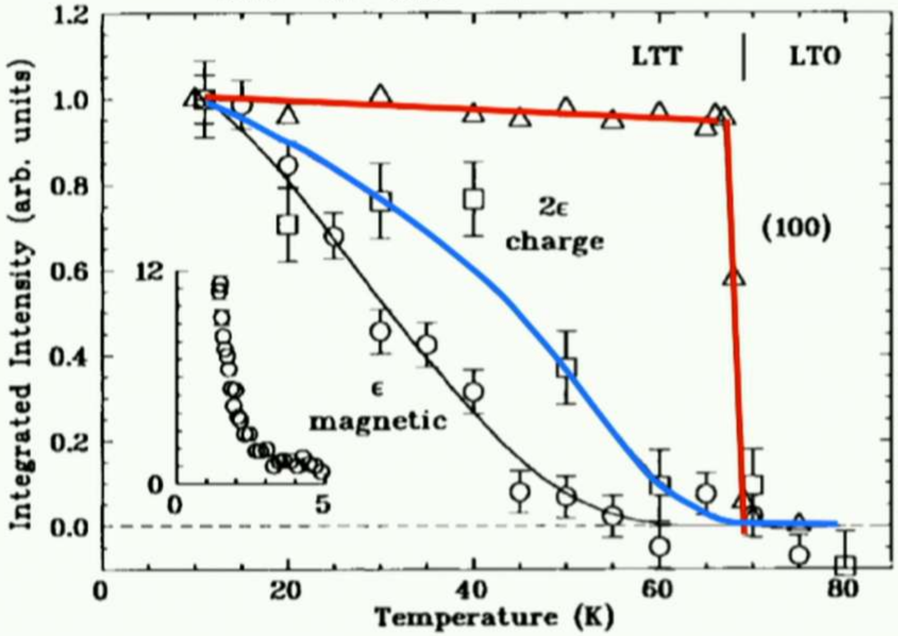
Coupling of structural distortions to CDW order



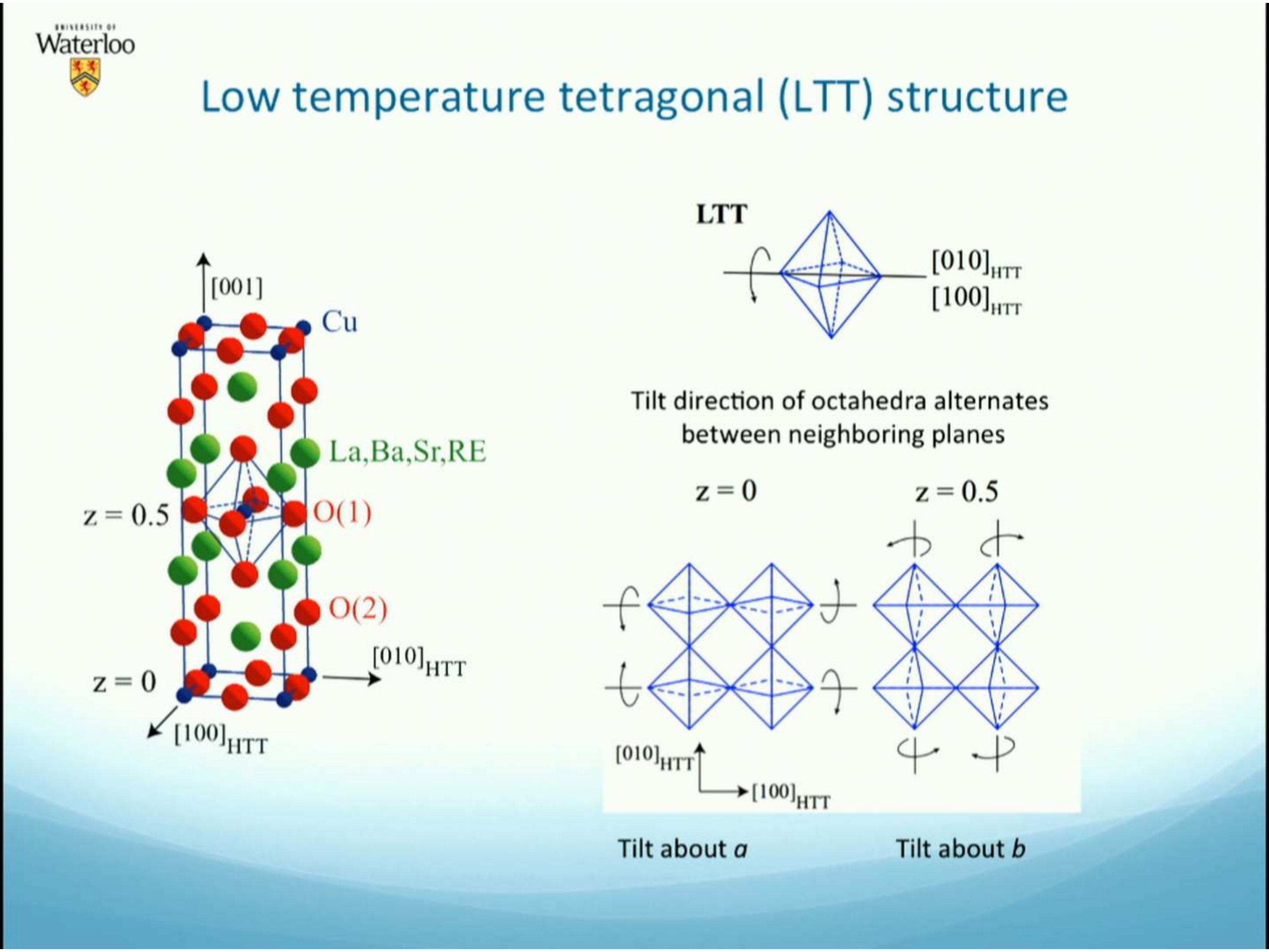
Neutron scattering

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



Charge density wave order onsets below 1st order LTT phase transition

Tranquada Nature (1995)



Low temperature tetragonal (LTT) structure

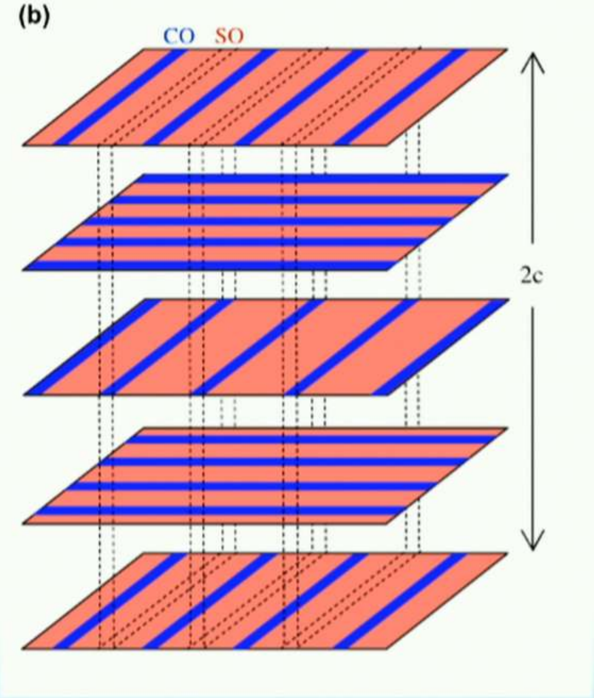
Tilt direction of octahedra alternates between neighboring planes

Tilt about *a*

Tilt about *b*

Unidirectional CDW order: stripes

La-based cuprates



LTT tilts and stripes

Tranquada 1995
Tranquada 1996

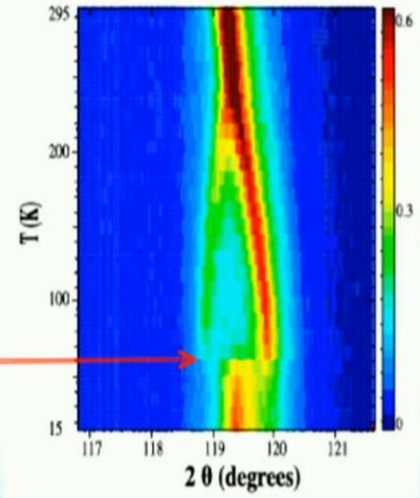
Measuring LTO to LTT phase transition

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

Ex. $La_{1.875}Ba_{0.125}CuO_4$

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

Splitting of $(330)_{HTT}$ peak



HTT

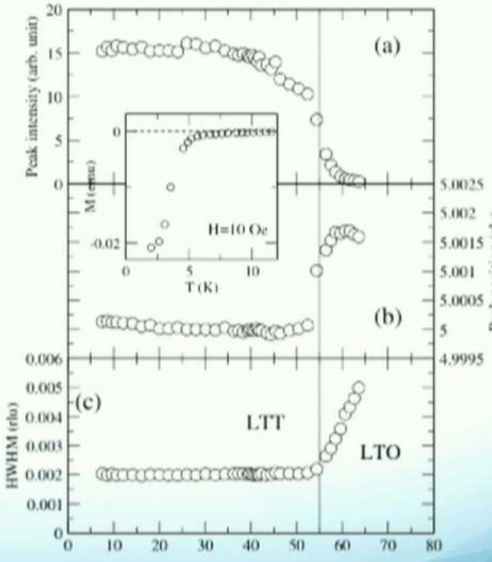
LTO

LTT

1st order

Zhao et al. PRB 2007

$(500)_{HTT}$ peak

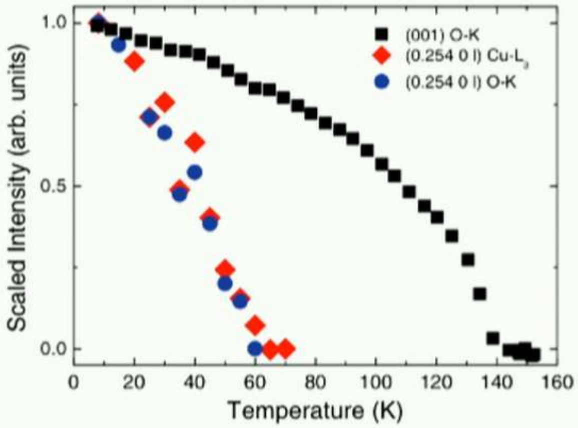


Temperature (K)

Y.-J. Kim PRB 2008

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

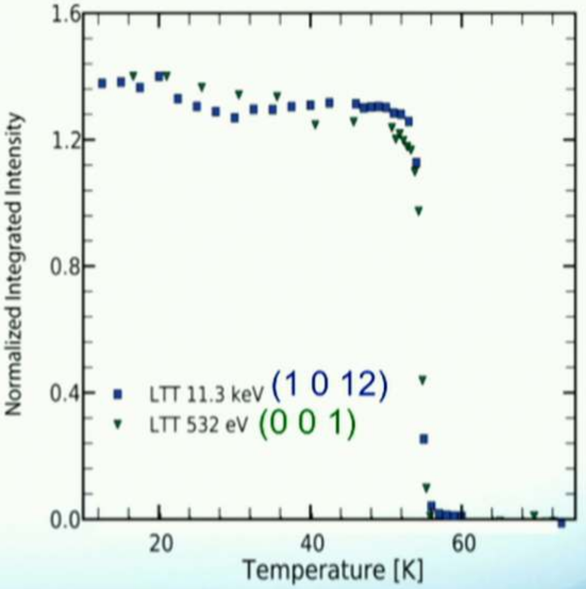
$La_{1.65}Eu_{0.2}Sr_{0.15}CuO_4$



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)

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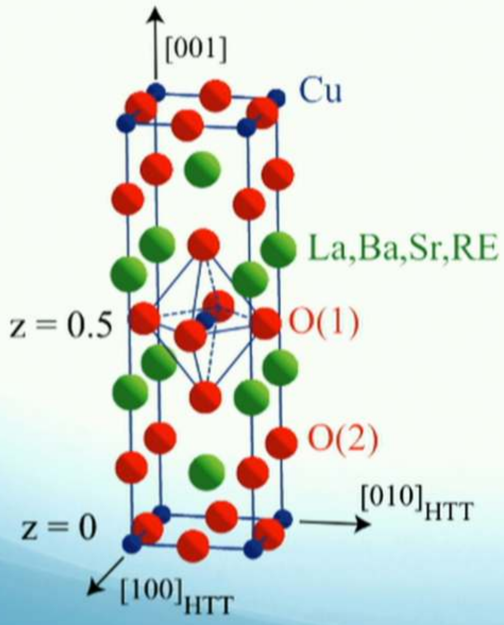
(0 0 1) peak at different photon energies

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



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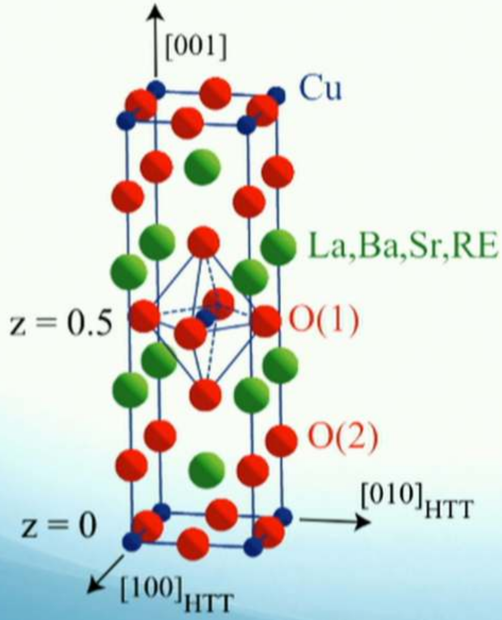

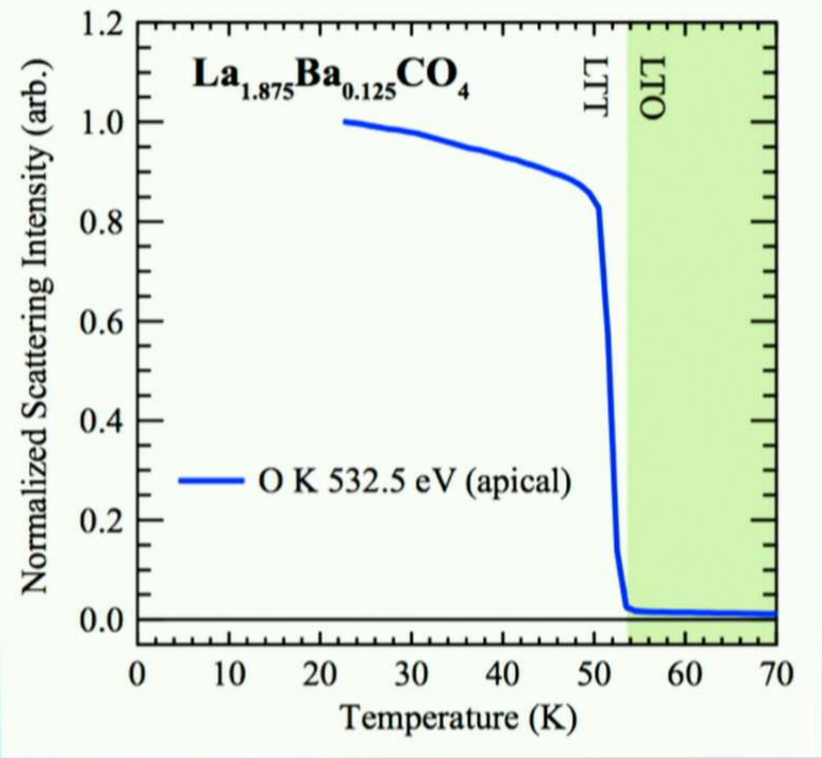

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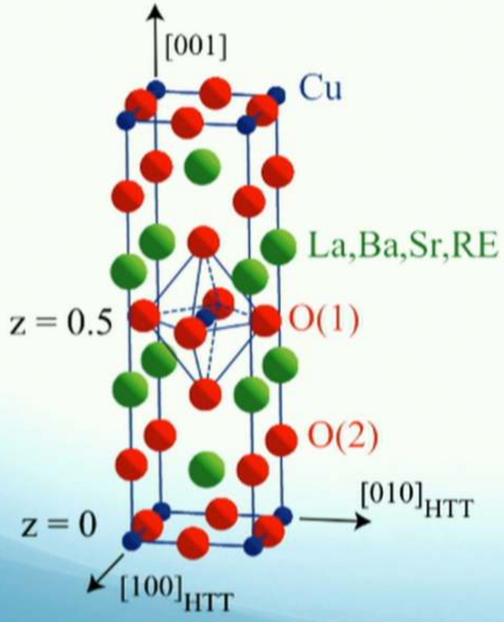

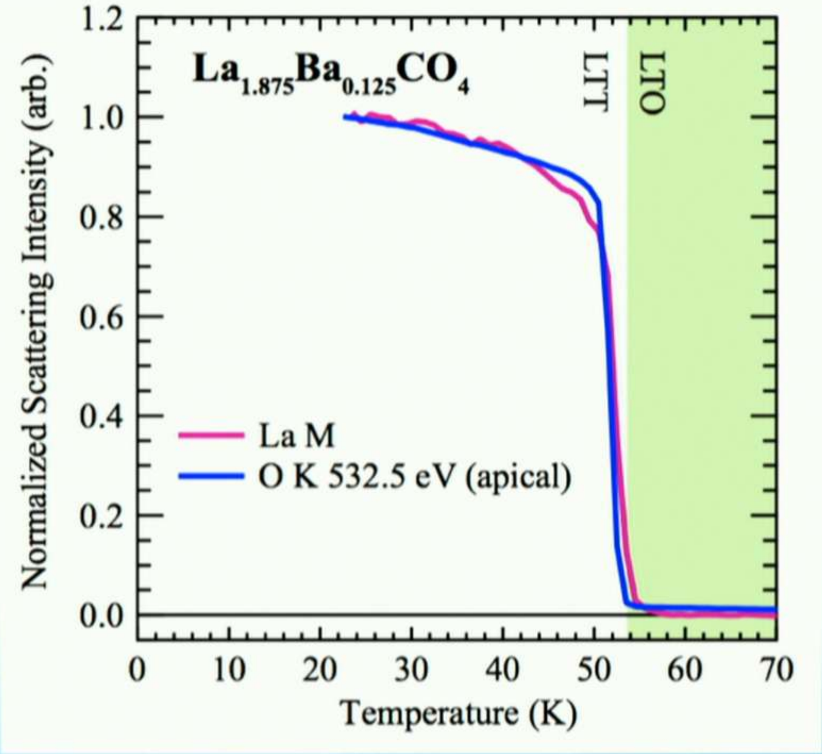

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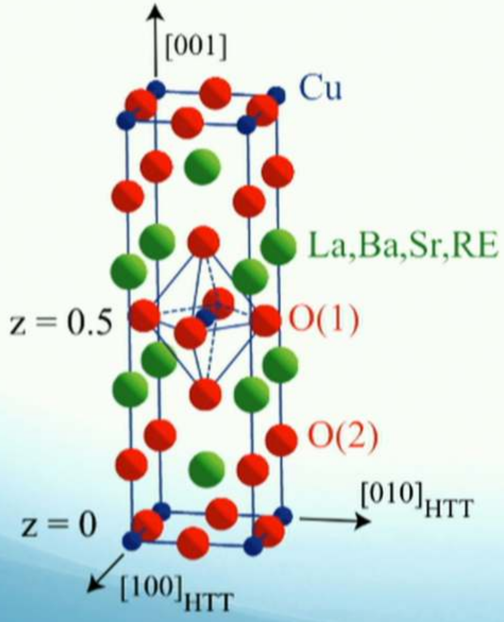

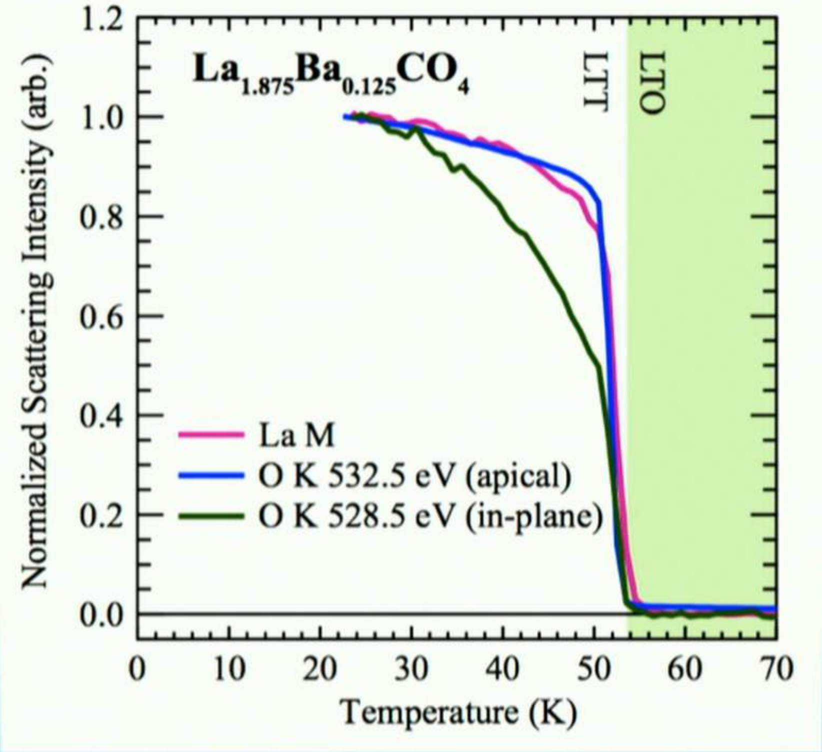

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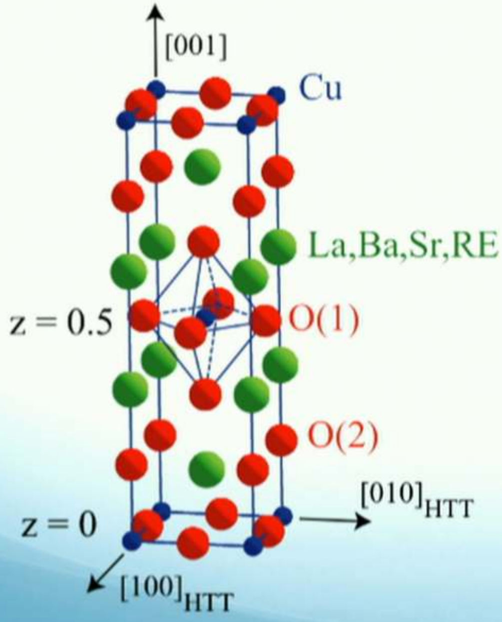
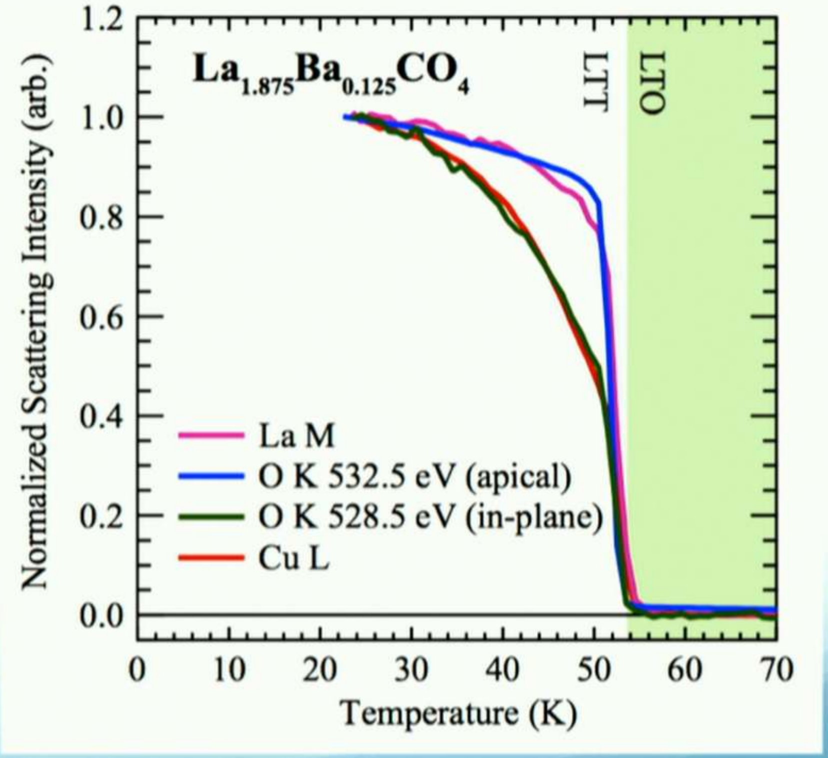
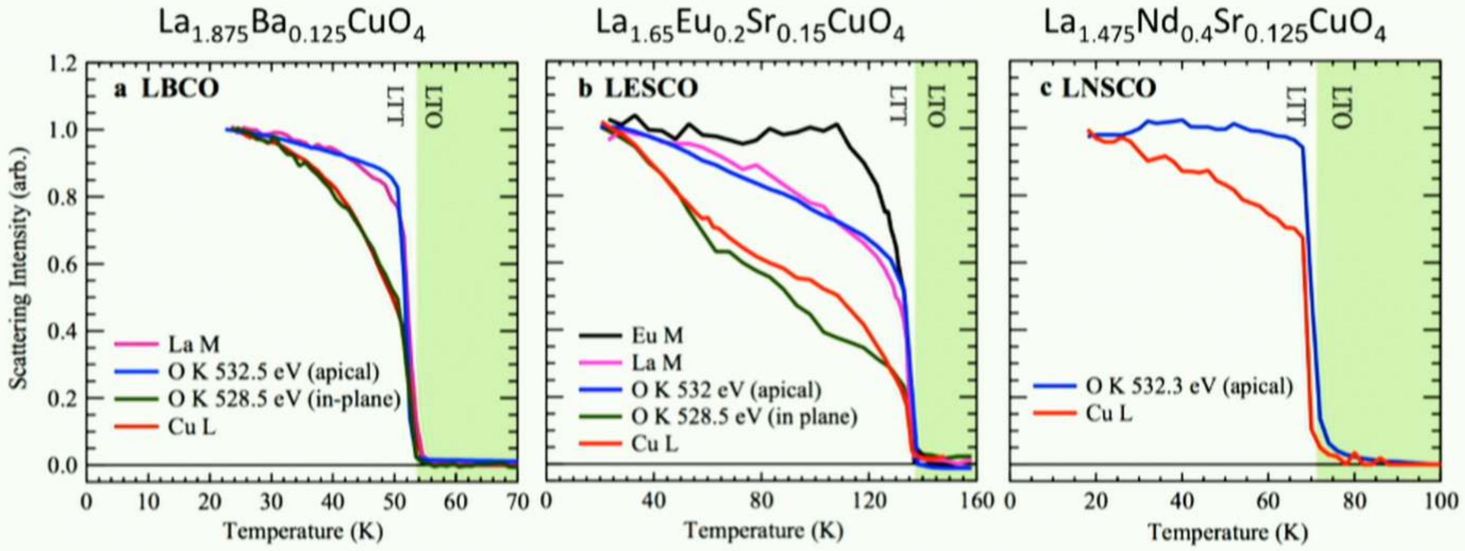




(0 0 1) at different photon energies


$La_{1.875}Ba_{0.125}CuO_4$ $La_{1.65}Eu_{0.2}Sr_{0.15}CuO_4$ $La_{1.475}Nd_{0.4}Sr_{0.125}CuO_4$

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

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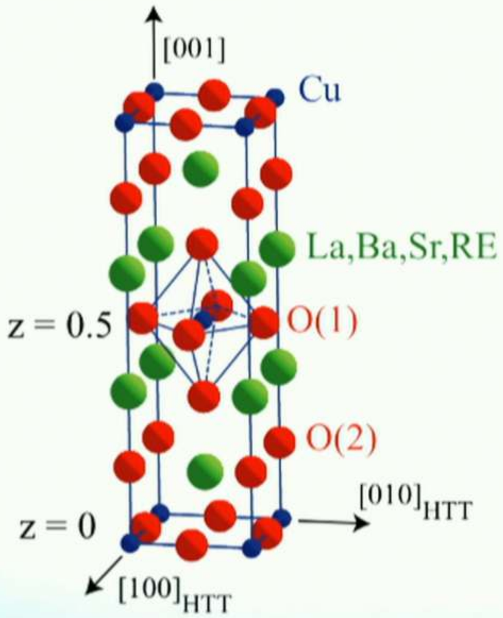
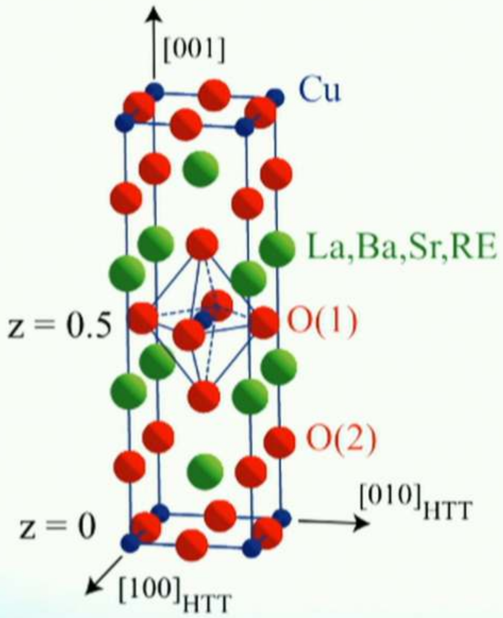
Sensitivity of (0 0 1) peak at Cu *L* edge



The Cu position within the unit cell **does not** change between the LTO and LTT phases.

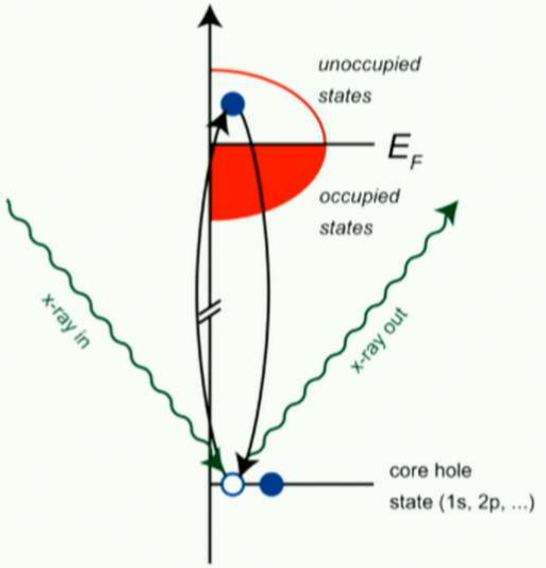
Sensitivity of (0 0 1) peak at Cu *L* edge



The Cu position within the unit cell **does not** change between the LTO and LTT phases.

- Charge/lattice displacements make no direct contribution to the Cu (001) peak
- Cu sites make no contribution to hard x-ray or neutron scattering (100) peaks, which are dominated by the $(La,X)_2O_2$ layer

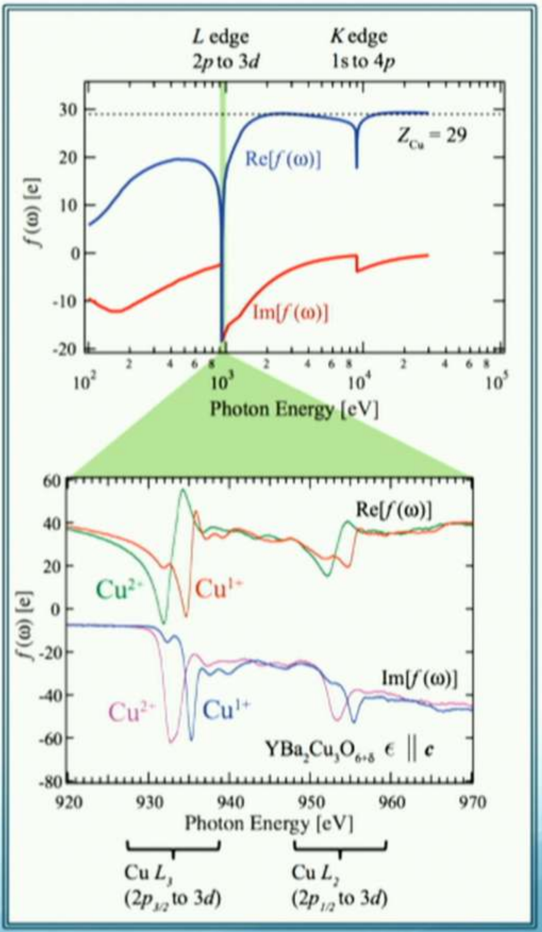
Resonant elastic x-ray scattering



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

$$\downarrow$$

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

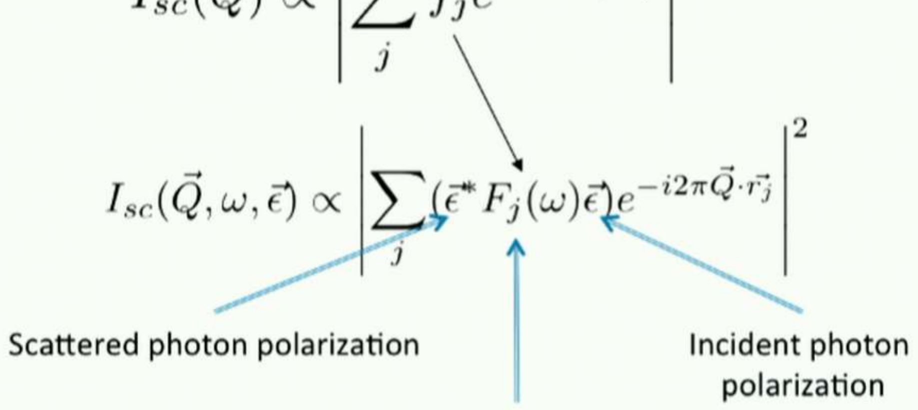


Resonant X-ray Scattering

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

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

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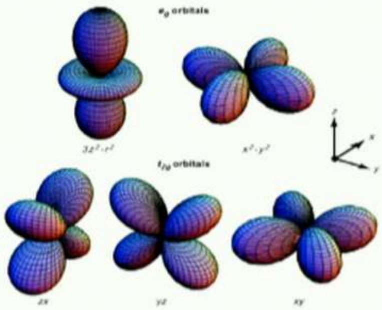
Form factor: polarization dependence

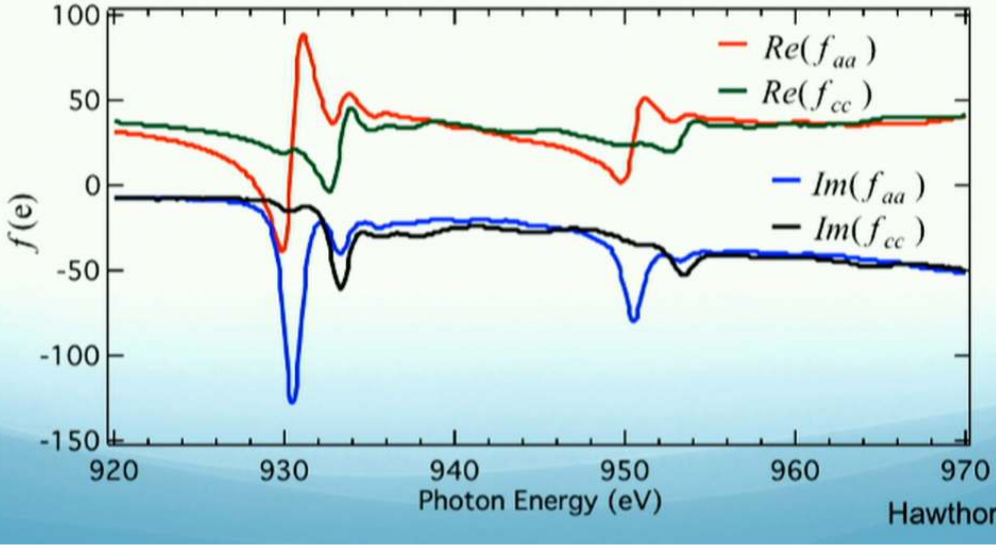
depending on symmetry

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



Cu *L* edge

$YBa_2Cu_3O_6$



Hawthorn et al PRB 2011

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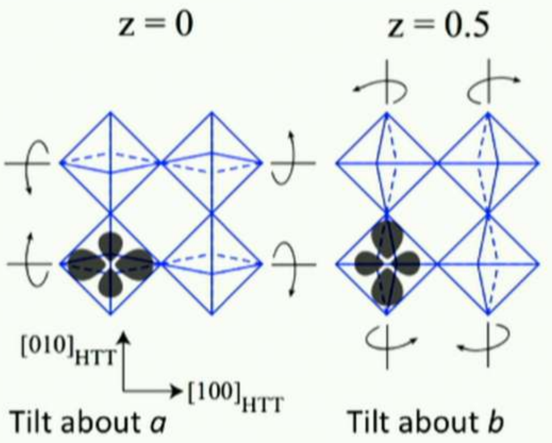
Low temperature tetragonal (LTT) structure



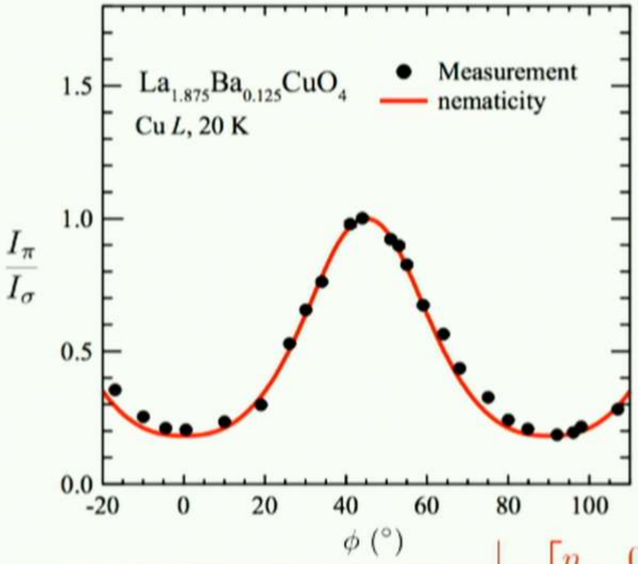
Tilt direction of octahedra alternates between neighboring planes

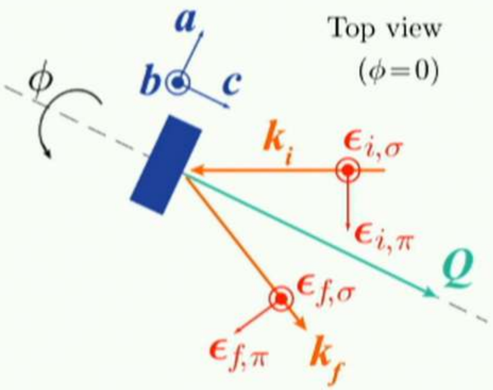
C_4 symmetry of Cu *d* states is broken within each plane and alternates between neighbouring planes

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

Azimuthal angle dependence

Azimuthal dependence of scattering intensity:
verifies the Cu (0 0 1) is measuring electronic nematicity of the CuO_2 planes





$$I(001) \propto \left| \vec{\epsilon}^{*} \begin{bmatrix} \eta & 0 & 0 \\ 0 & -\eta & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{\epsilon} \right|^2$$

Azimuthal angle dependence

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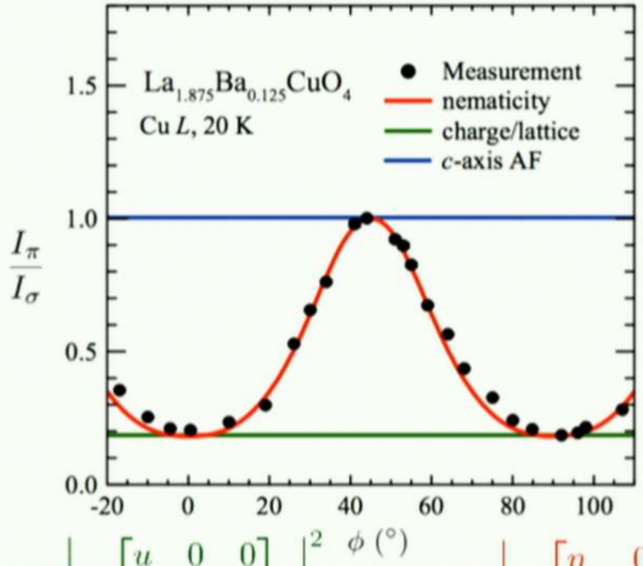
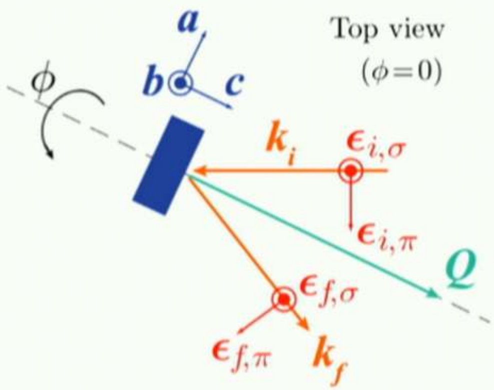
the CuO_2 planes





$$I(001) \propto \left| \vec{\epsilon}^{\,*} \begin{bmatrix} u & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{\epsilon} \right|^2 \quad I(001) \propto \left| \vec{\epsilon}^{\,*} \begin{bmatrix} \eta & 0 & 0 \\ 0 & -\eta & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{\epsilon} \right|^2 \quad I(001) \propto \left| \vec{\epsilon}^{\,*} \begin{bmatrix} 0 & m & 0 \\ -m & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \vec{\epsilon} \right|^2$$

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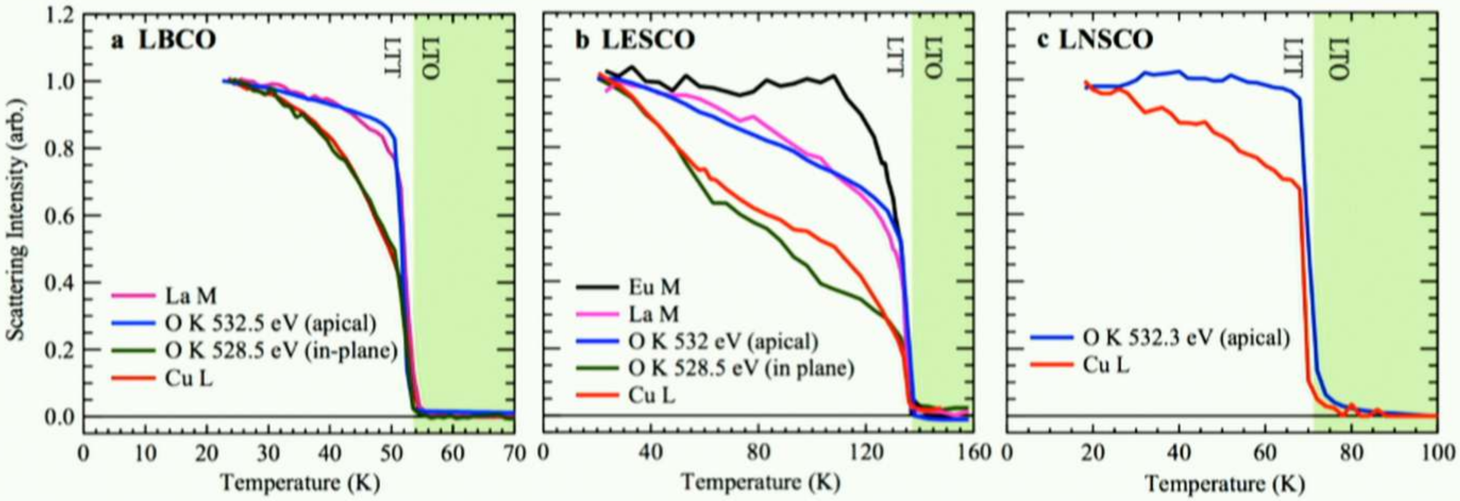
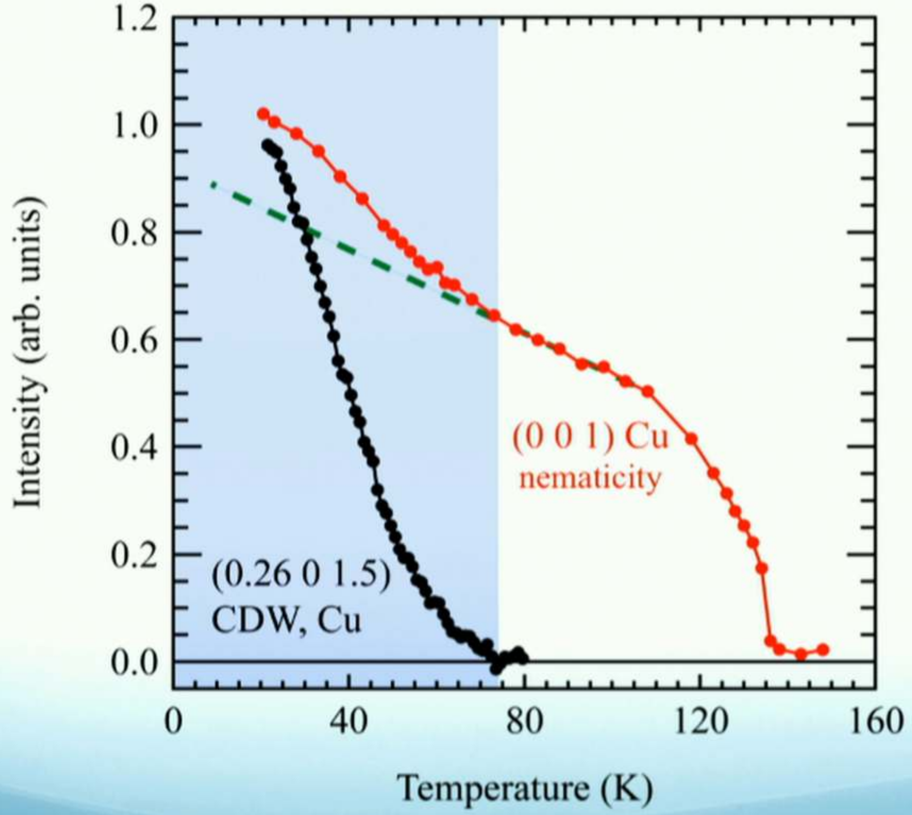
(0 0 1) at different photon energies



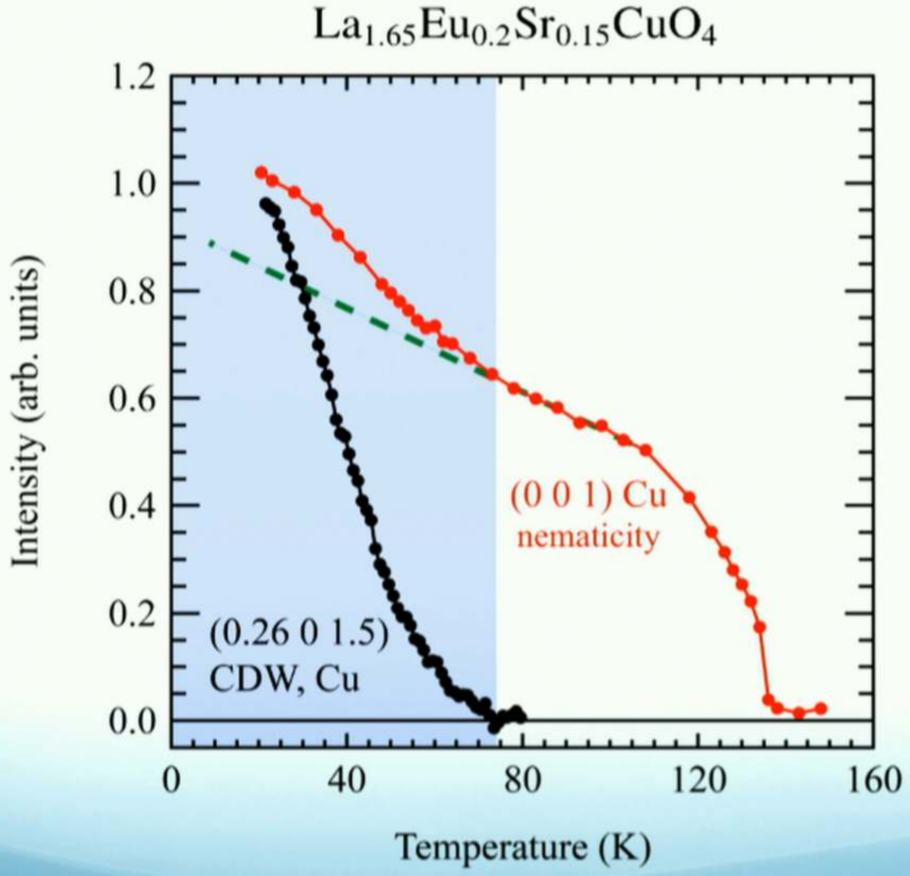
Electronic nematicity of the CuO_2 planes is coupled to, but distinct from the structural distortion of the $(La,X)_2O_2$ spacer layer

CDW order and nematicity



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

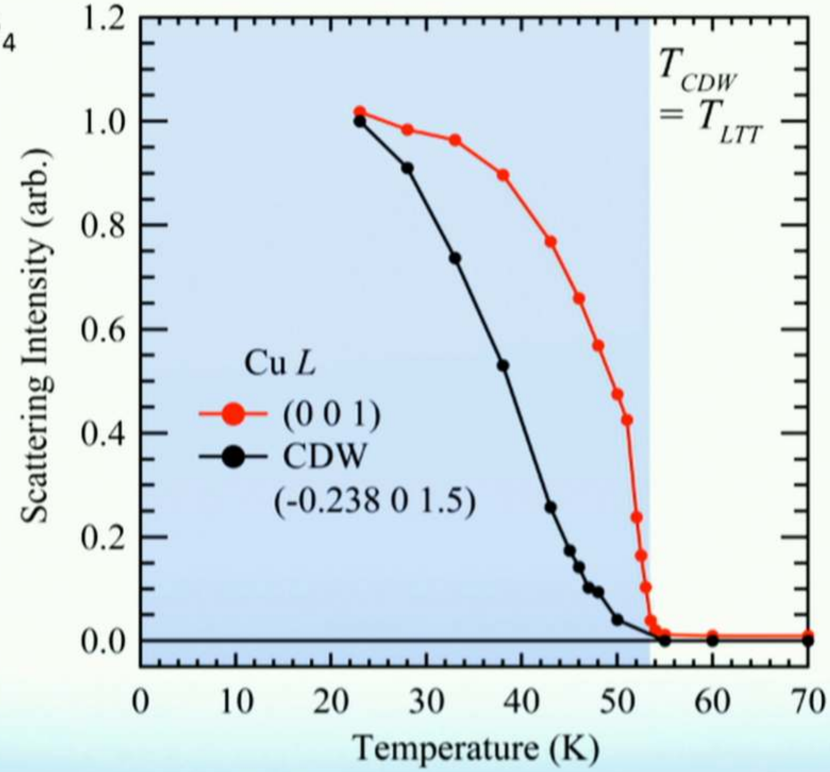
CDW order and nematicity



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

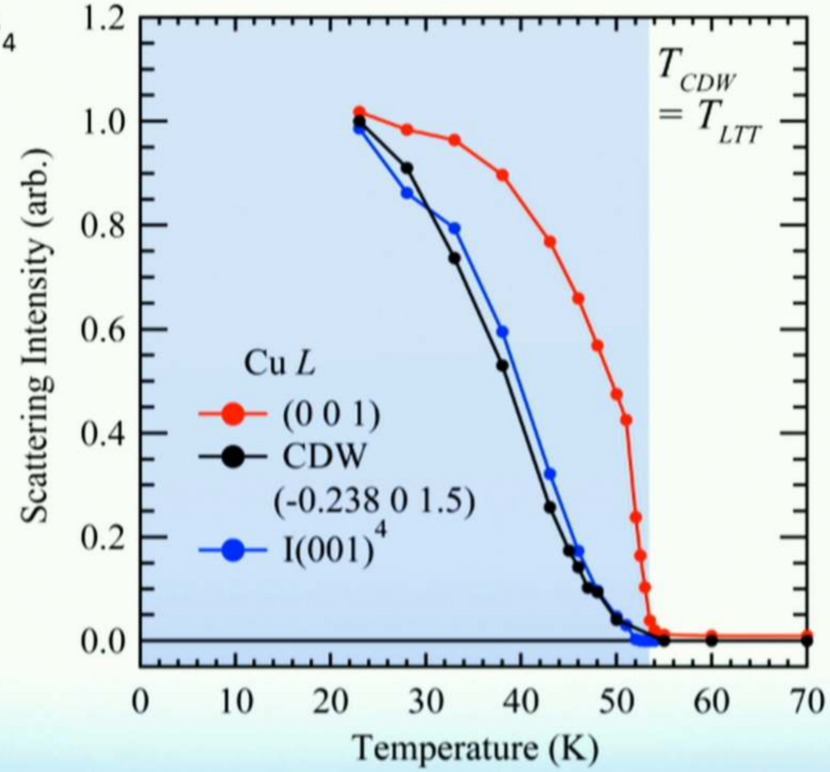
CDW order and nematicity

$La_{1.875}Ba_{0.125}CuO_4$

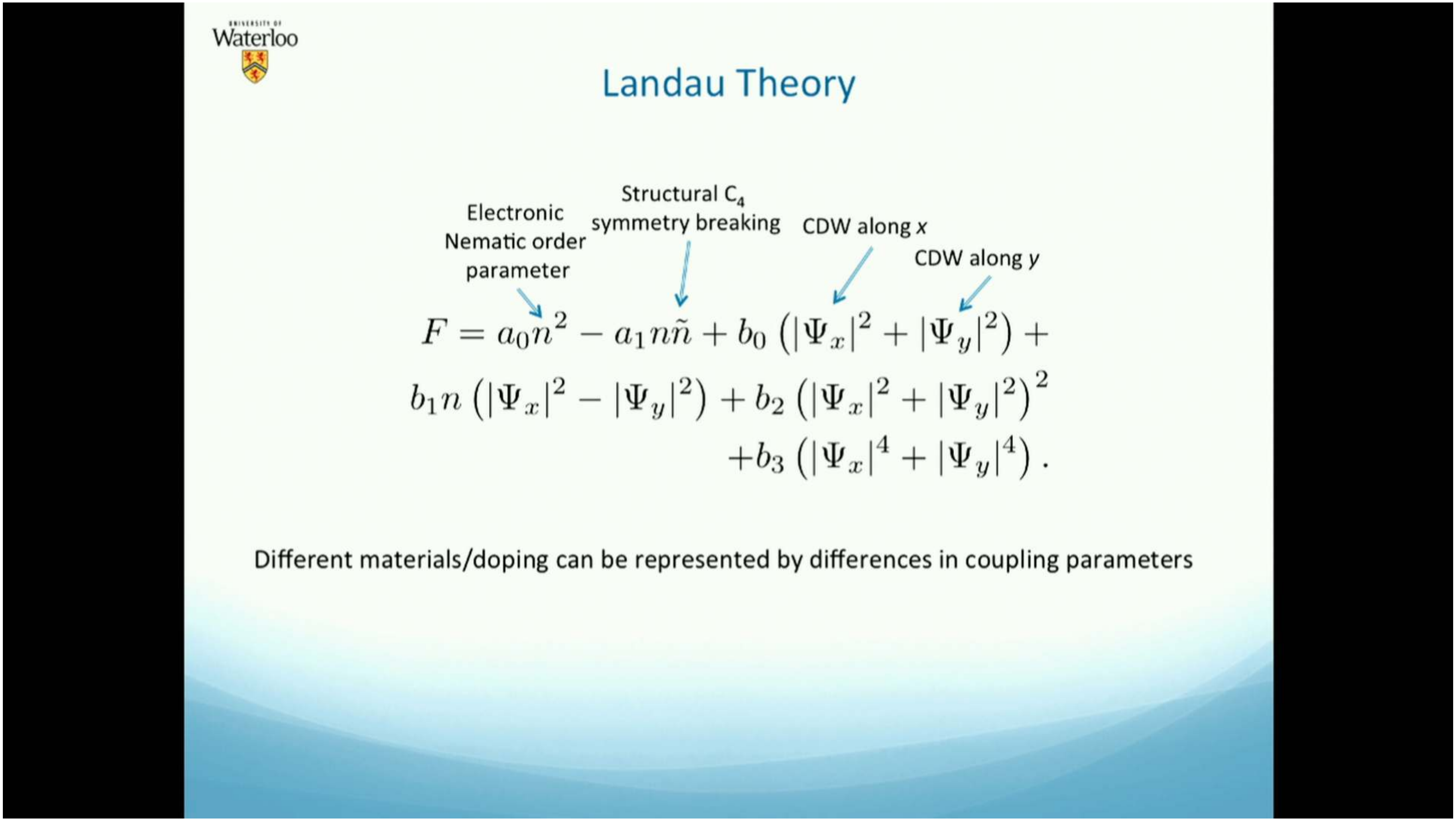


CDW order and nematicity

$La_{1.875}Ba_{0.125}CuO_4$



(0 0 1) peak intensity has quartic relation to CDW peak intensity



Landau Theory

Electronic Nematic order parameter

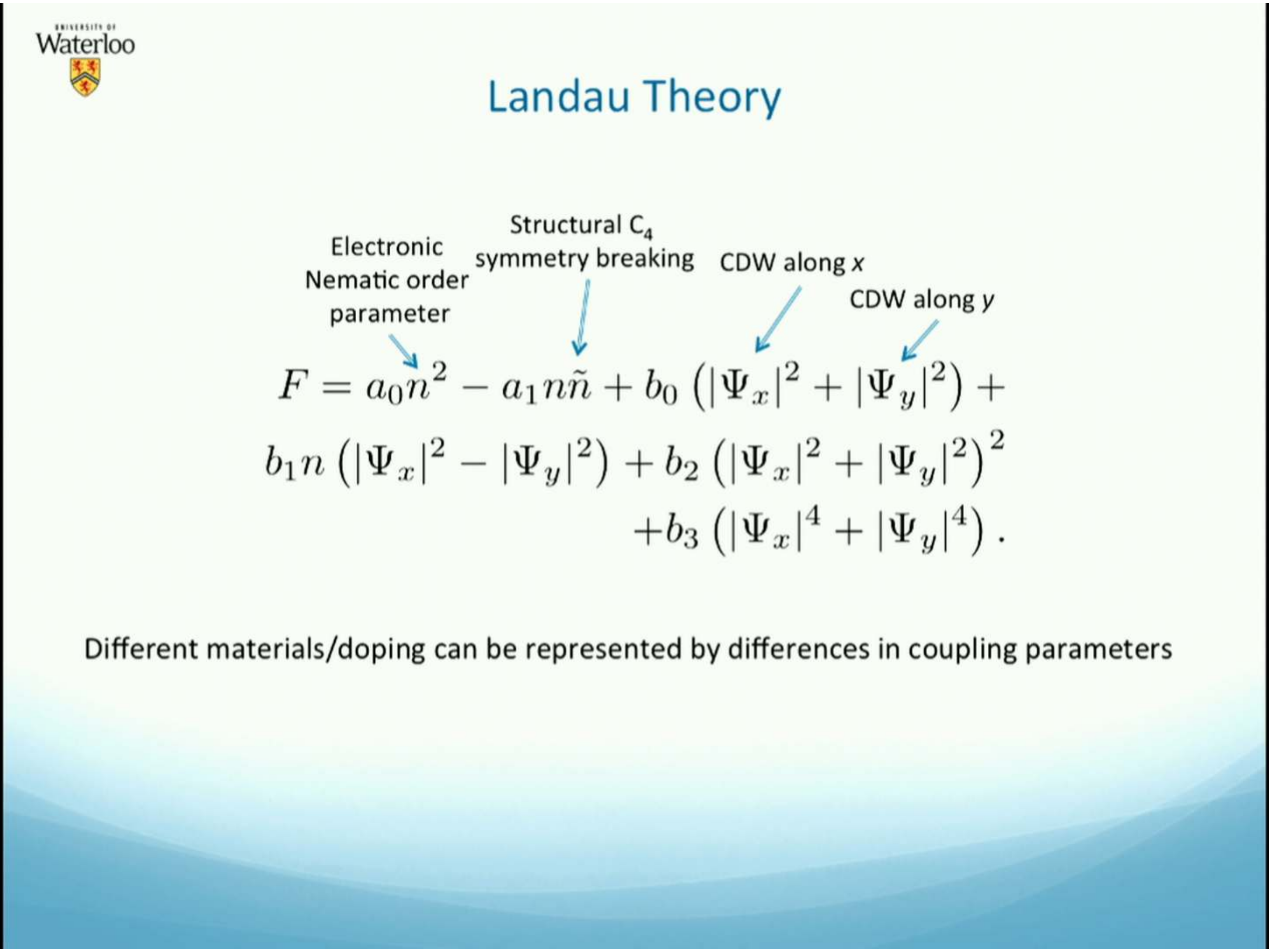
Structural C_4 symmetry breaking

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/doping can be represented by differences in coupling parameters



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Landau Theory

Electronic
Nematic order
parameter

Structural C_4
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CDW along *x*

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Landau Theory

Electronic Nematic order parameter

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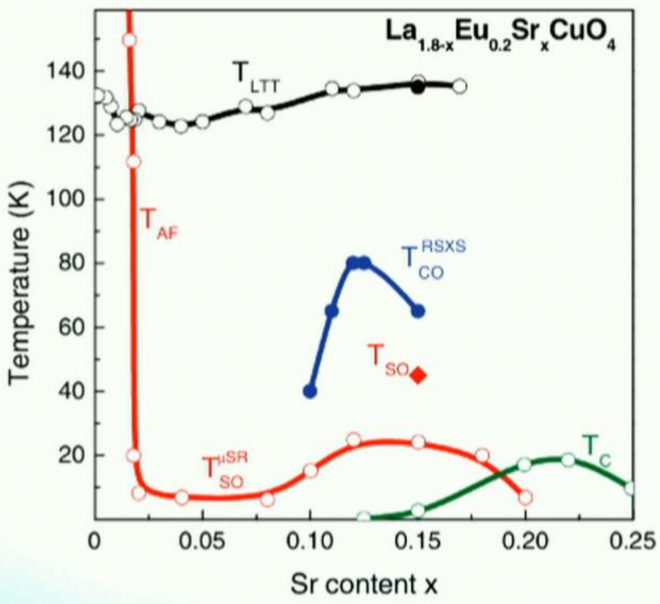
Different materials/doping can be represented by differences in coupling parameters

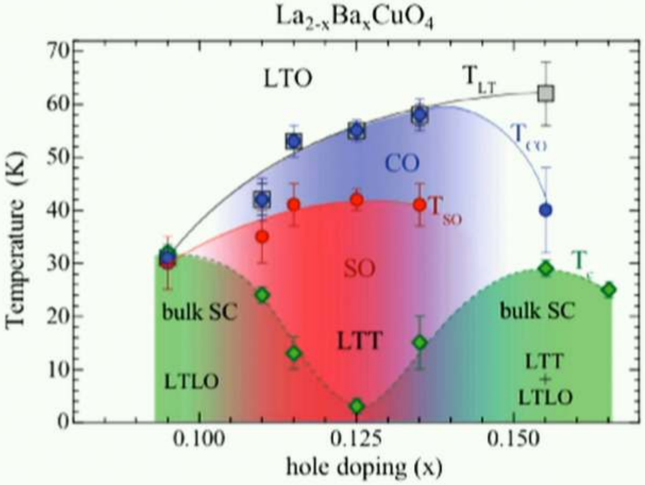
LTT and CDW order phase diagrams

$La_{1.8-x}Eu_{0.2}Sr_xCuO_4$



Fink PRB 2011
Klaus PRL 2000

$T_{CDW} < T_{LTT}$

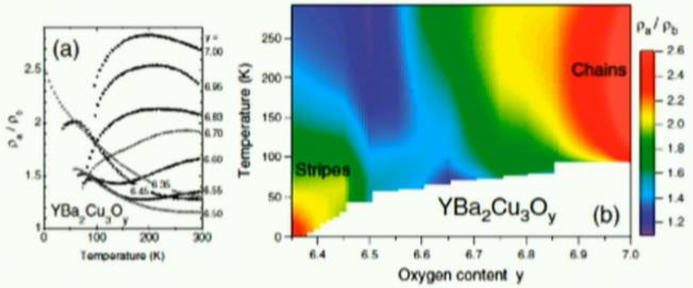


M. Hücker.
PHYSICAL REVIEW B **83**, 104506 (2011)

Generic Nematicity?

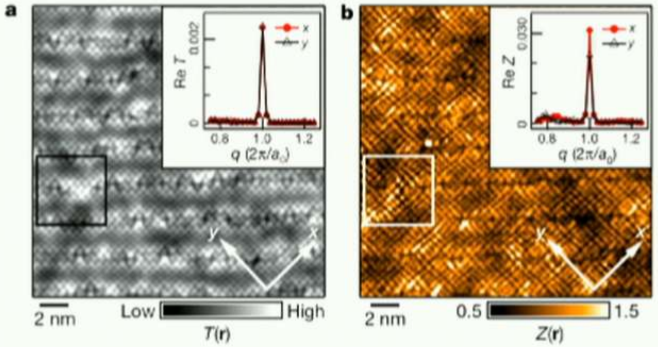
Electronic (not just structural) nematicity is generic to underdoped cuprates

YBCO



Ando PRL 2002

Bi2212



Lawler, Fujita, et al. Nature 2010

Waterloo

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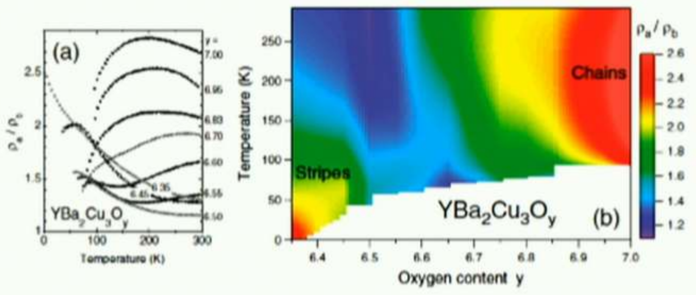

Ando PRL 2002

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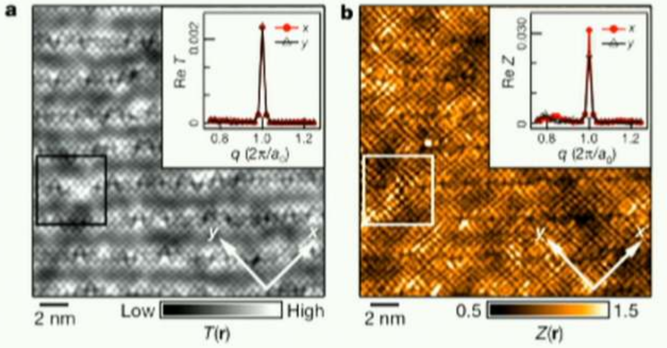

Lawler, Fujita, et al. Nature 2010

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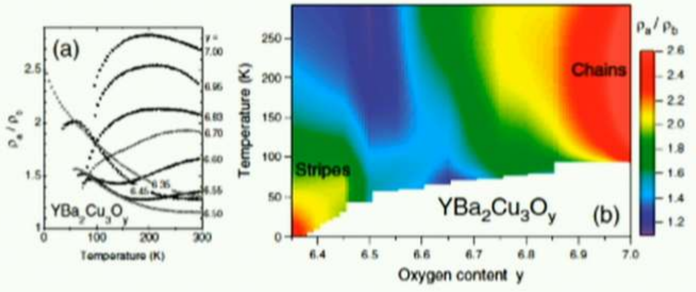
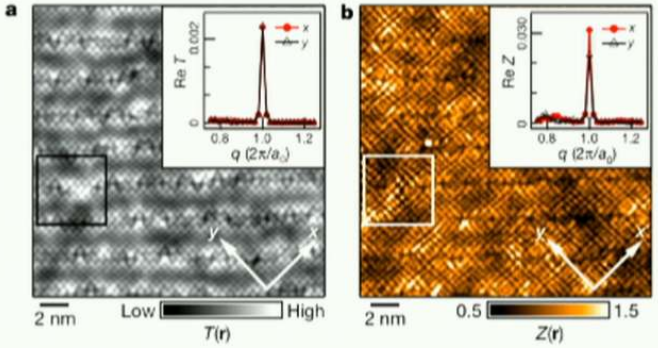
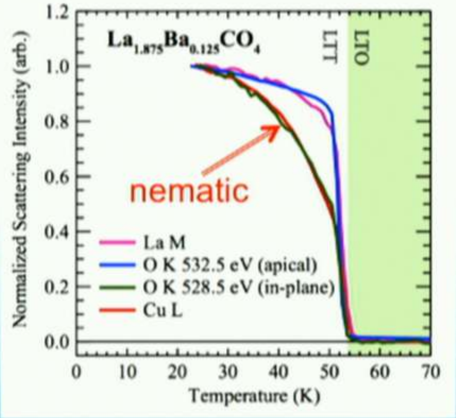


Ando PRL 2002

Bi2212



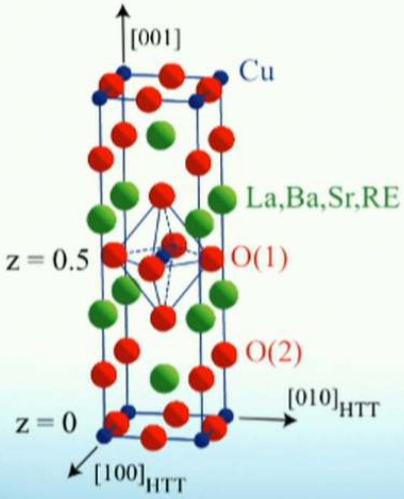
Lawler, Fujita, et al. Nature 2010

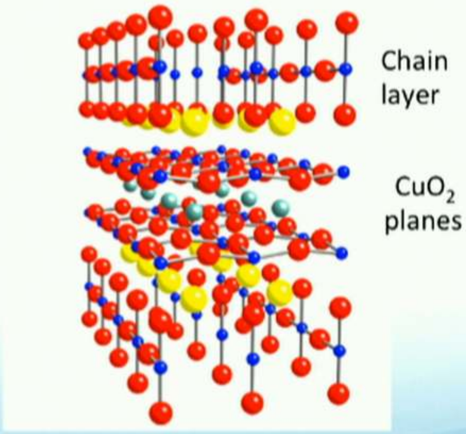


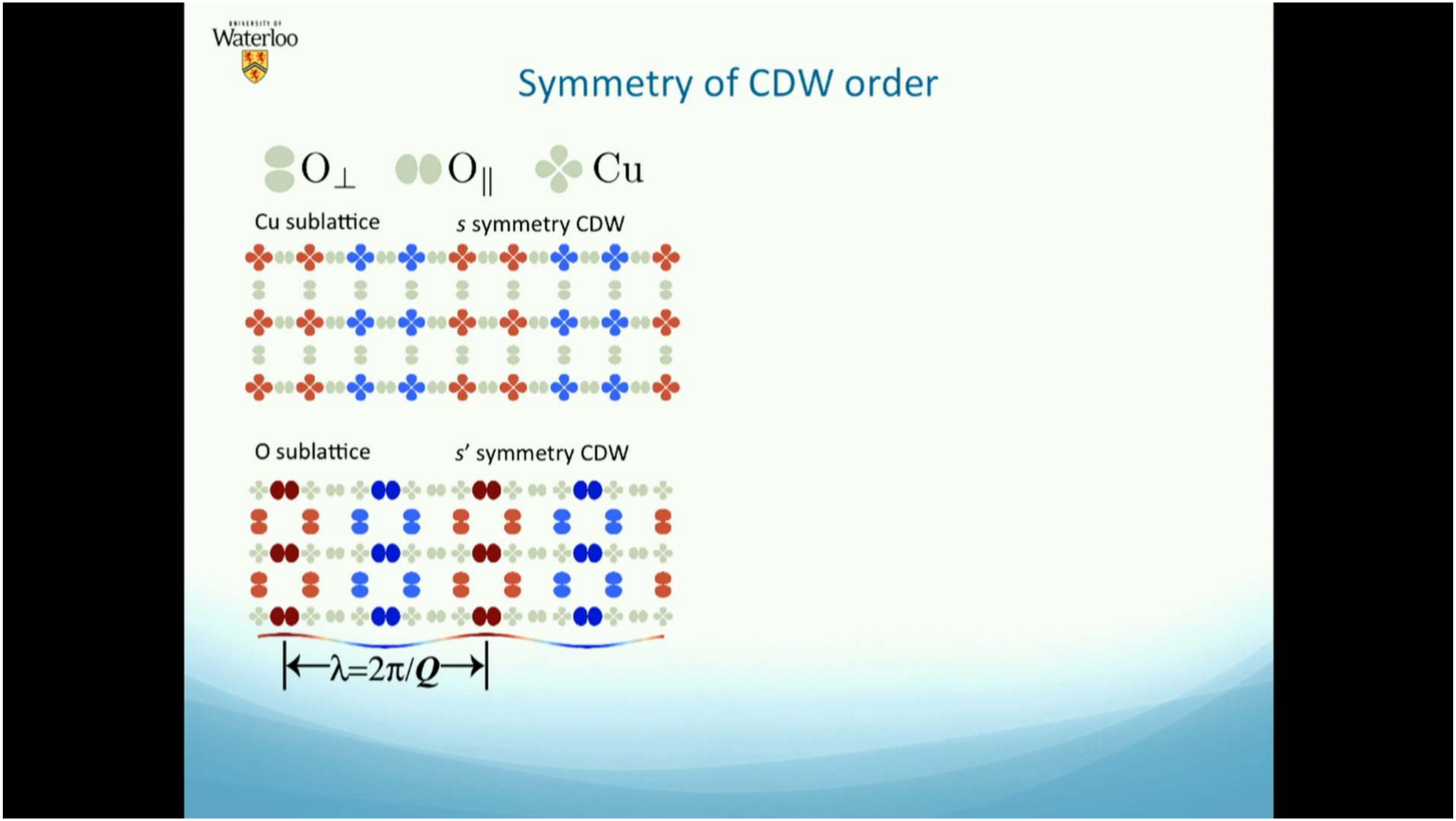
Next step: Unifying the cuprate phase diagrams

Underdoped cuprates exhibit unidirectional CDW order, electronic nematicity and superconductivity

Differences in the coupling of nematicity to the varied structures of the cuprates (and to disorder) is likely important for unifying the cuprate phase diagrams







Symmetry of CDW order

Cu sublattice

s symmetry CDW

O sublattice

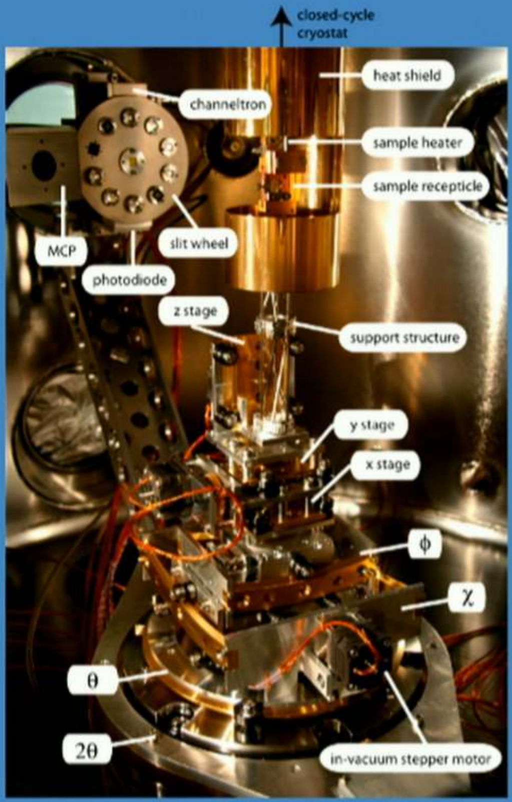
s' symmetry CDW

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)

The Canadian Light Source



- •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)

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