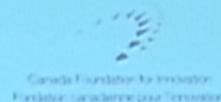
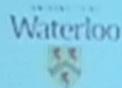


Title: Nematicity and charge density wave order in stripe ordered cuprates probed via resonant x-ray scattering

Date: Jul 08, 2015 10:00 AM

URL: <http://pirsa.org/15070069>

Abstract: In underdoped cuprate superconductors, a rich competition occurs between superconductivity and charge density wave order (CDW). Under debate, however, is whether rotational symmetry breaking (nematicity) also plays a central role -- whether it occurs intrinsically and generically or merely as a consequence of other orders. Here we employ resonant x-ray scattering in stripe-ordered  $(\text{La},\text{X})_2\text{CuO}_4$  to probe the relationship between electronic nematicity of the Cu 3d orbitals, structural orthorhombicity of the  $(\text{La},\text{X})_2\text{O}_4$  layers and CDW order. We find distinct temperature dependences of the structural orthorhombicity and the electronic nematicity, with the electronic nematicity, but no structural orthorhombicity enhancement below the onset of CDW order. These results indicate electronic nematicity is an order parameter that is distinct from a purely structural order parameter in underdoped cuprates.



**Andrew Achkar**  
 Xiaopan Mao  
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Feizhou He  
 Ronny Sutarto  
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Giacomo Ghiringhelli  
 Matteo Minola  
 Claudio Mazzoli  
 Lucio Braicovich  
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Ruixing Liang  
 Doug Bonn  
 Walter Hardy  
 George Sawatzky  
 Riccardo Comin  
 Andrea Damascelli  
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Subir Sachdev  
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Mathieu Le Tacon  
 Alex Frano  
 Santiago Blanco-Canosa  
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 State Research

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 European Synchrotron  
 Radiation Facility

Young-June Kim  
 Harry Zhang  
 University of Toronto

Markus Hücker  
 Genda Gu  
 Brookhaven National Lab

Jochen Geck  
 Martin Zweibler  
 IFW Dresden

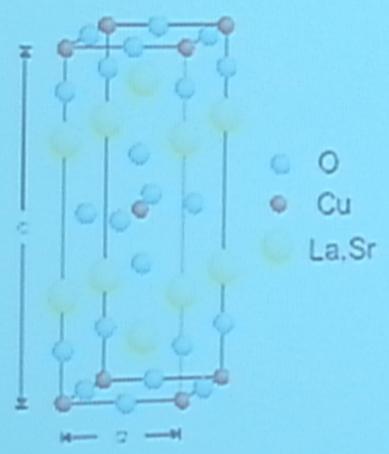
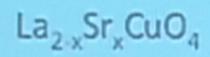
## Outline

- Charge density wave (CDW) order in the cuprates
- Comparison between CDW order in YBCO and La-based cuprates
- Symmetry of CDW order in the cuprates
- Nematicity in stripe ordered cuprates

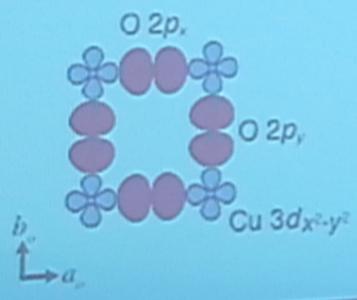
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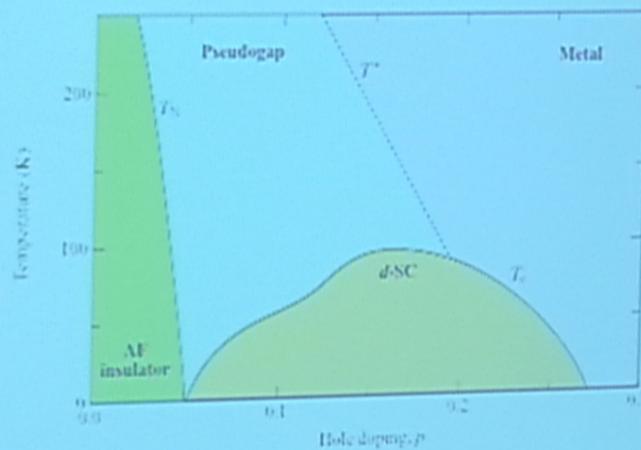
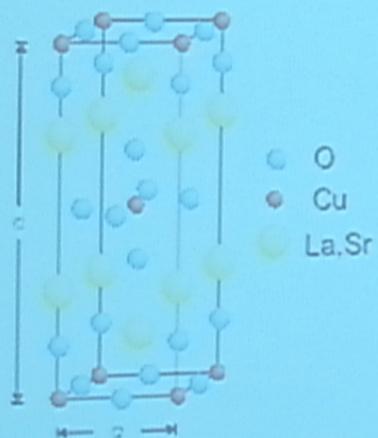
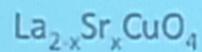
# Cuprate high-temperature superconductors



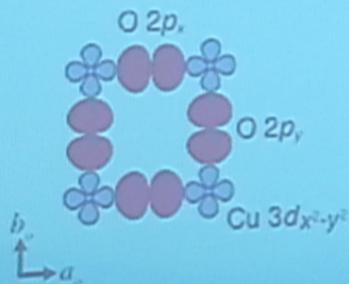
Low energy physics is dominated by the  $\text{CuO}_2$  planes



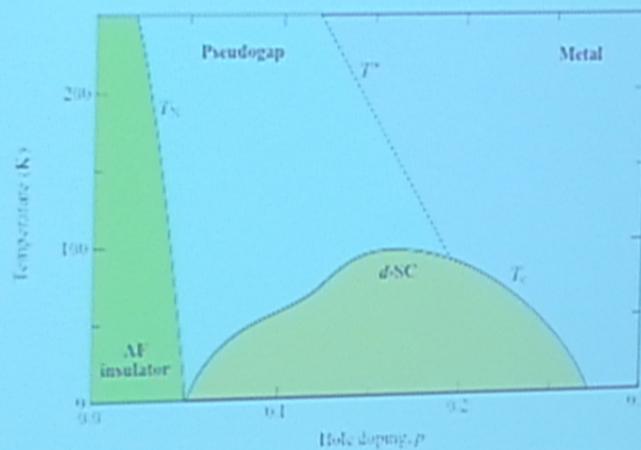
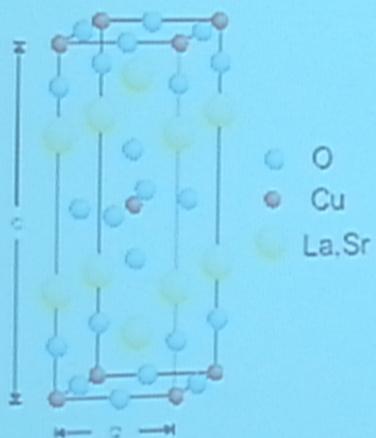
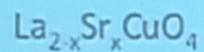
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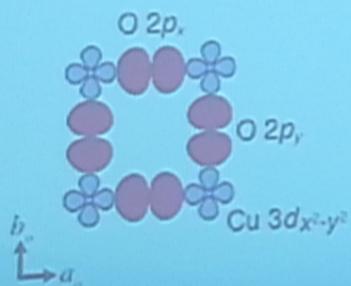
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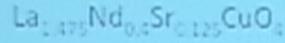
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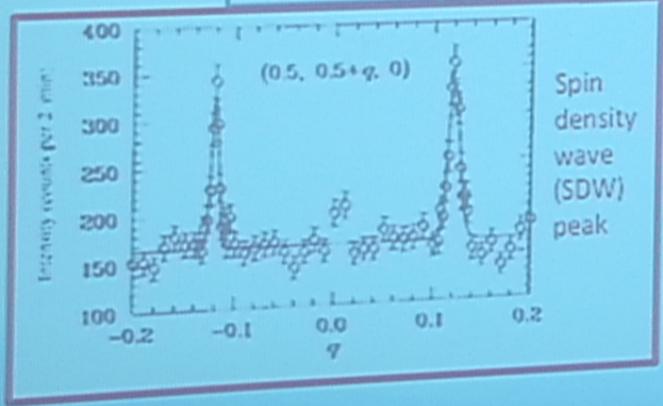
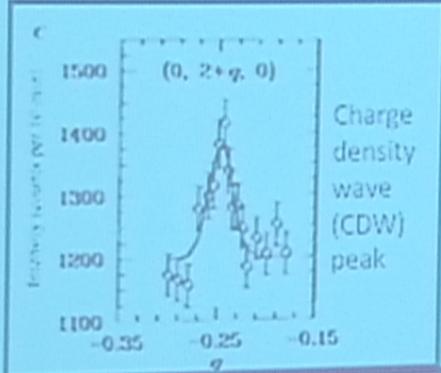
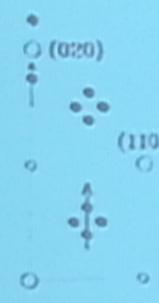


# Density wave order in the cuprates



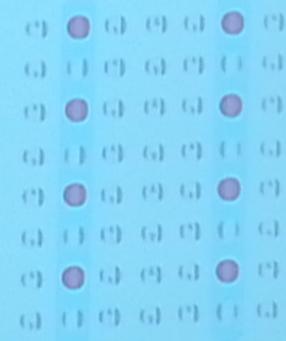
Elastic Neutron scattering

$a$



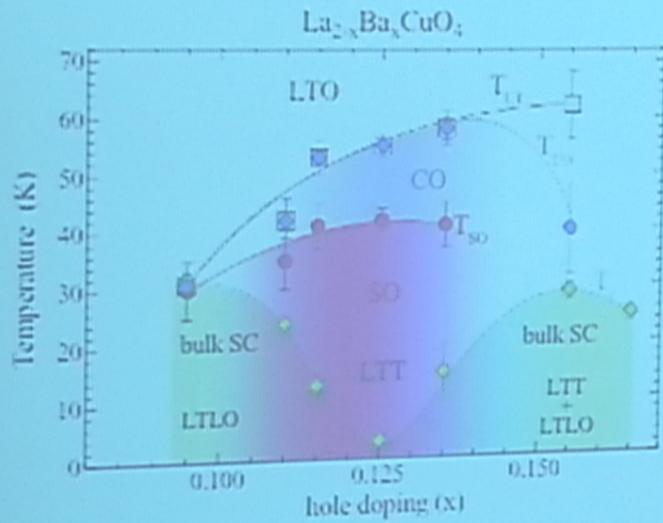
Unidirectional Spin and charge order (stripes) first observed in the cuprates by neutron scattering (Tranquada et al., Nature 1995)

Half-filled charge stripe



Undoped AF regions

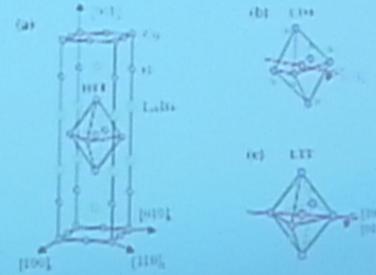
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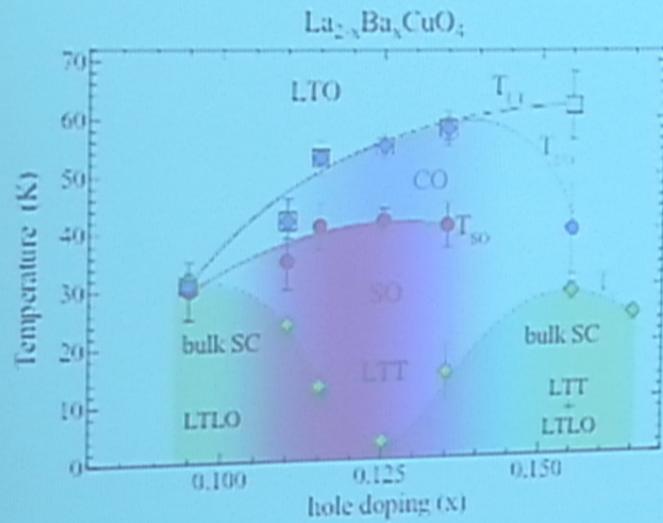
Some characteristic features of "stripes" in La-based cuprates

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

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



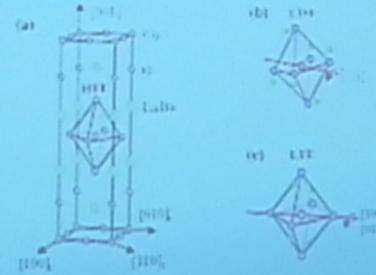
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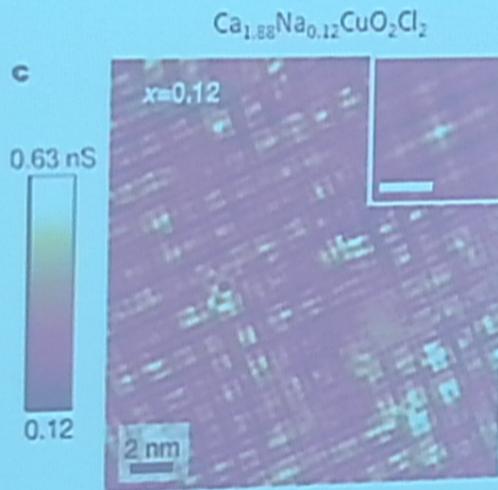
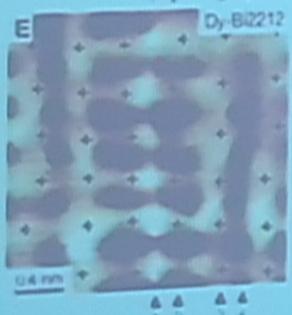
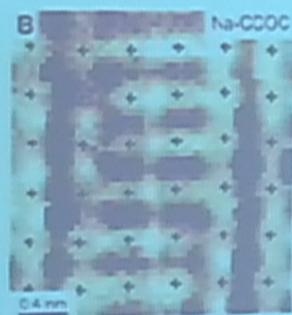
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# Charge order is generic to the cuprates

## Scanning tunneling microscopy



Observations of  
density wave order  
by STM

Davis group  
Kapitulnik group  
Yazdani group  
Hoffmann group  
Hudson group

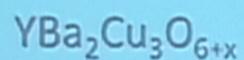
...

differential tunneling conductance

Hanaguri Nature 2004

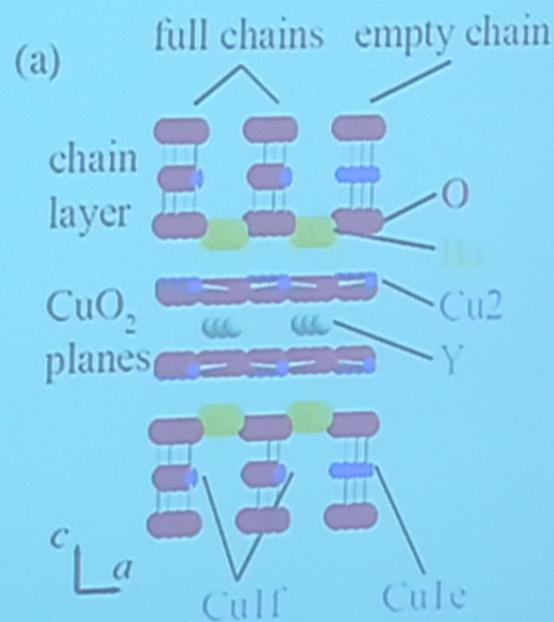
Khosaka Science 2008

## Charge density wave order in YBCO??

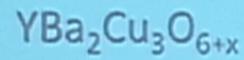


- Bilayer cuprate
- Orthorhombic structure ( $a \neq b \neq c$ )
- Doped by O atoms intercalated into "chain" layer far from the  $\text{CuO}_2$  planes
- Low levels of disorder
- High  $T_{c,max} = 94.2 \text{ K}$
- Oxygen orders in the chain layer

Ex: Ortho III ordered  $\text{YBa}_2\text{Cu}_3\text{O}_{6.75}$

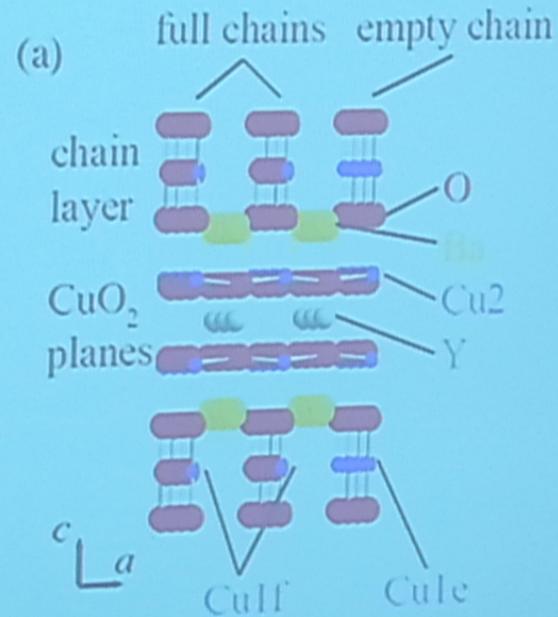


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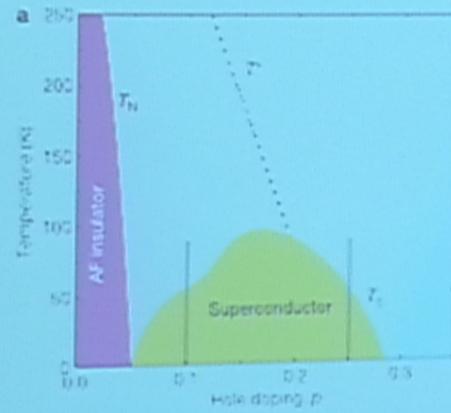


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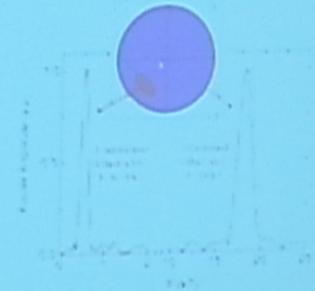
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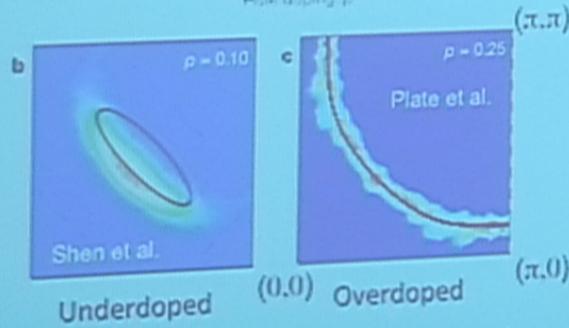
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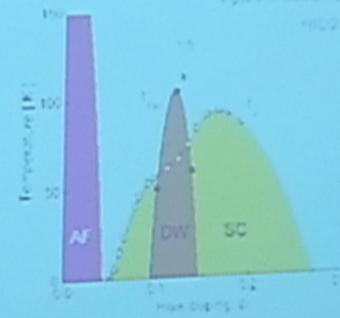
Electron pocket from quantum oscillations in low doped YBCO



Fermi surface (ARPES)

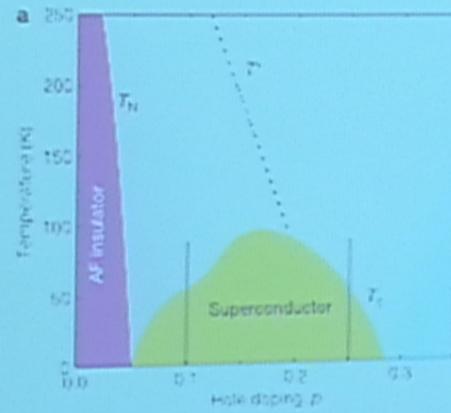


Hole like Fermi surface measured in cuprates by angle resolved photoemission

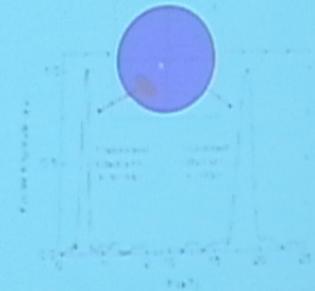


Doiron-Leyraud et al. Nature 2007

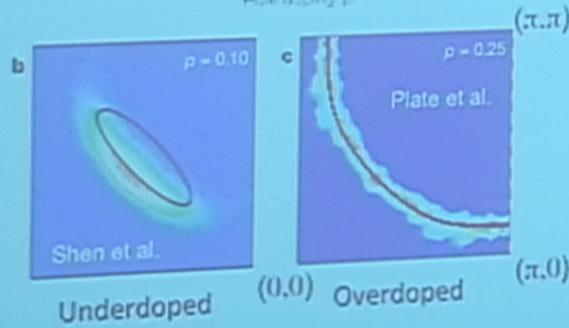
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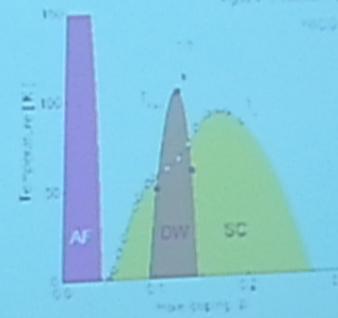
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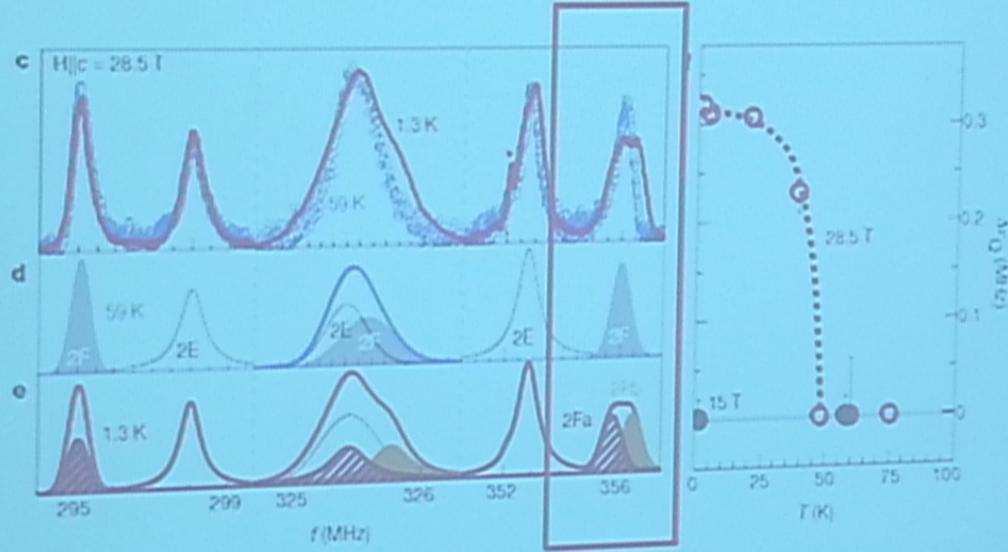
Hole like Fermi surface measured in cuprates by angle resolved photoemission



Doiron-Leyraud et al. Nature 2007

# Evidence of density wave order in $\text{YBa}_2\text{Cu}_3\text{O}_{6+\delta}$

High field NMR in YBCO interpreted as evidence for charge order



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

- weak charge order ( $\delta p = 0.03$ )
- Only observed in high magnetic field (28.5T)

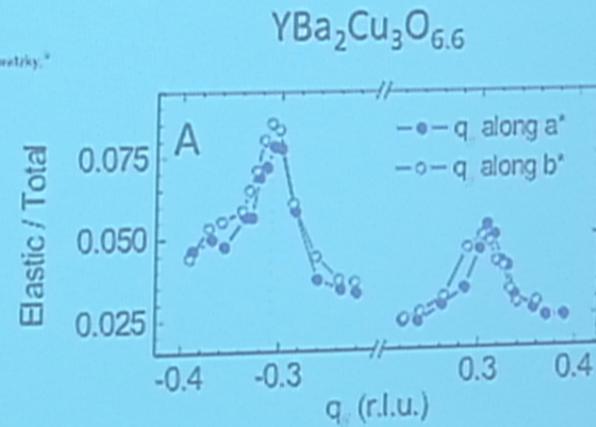
Tao Wu et al., Nature 2011

## CDW order in YBCO

### Long-Range Incommensurate Charge Fluctuations in (Y,Nd)Ba<sub>2</sub>Cu<sub>3</sub>O<sub>6+x</sub>

G. Ghiringhelli,<sup>1\*</sup> M. Le Taron,<sup>2</sup> M. Minola,<sup>3</sup> S. Blanco-Cano,<sup>4</sup> C. Mazzoli,<sup>5</sup> N. B. Brookes,<sup>6</sup> G. M. De Luca,<sup>7</sup> A. Frano,<sup>8,9</sup> D. G. Hawthorn,<sup>10</sup> F. He,<sup>11</sup> I. Lerch,<sup>12</sup> M. Moretti Sala,<sup>13</sup> D. C. Peets,<sup>14</sup> M. Salluzzo,<sup>15</sup> E. Schierle,<sup>16</sup> R. Sutarto,<sup>17</sup> G. A. Sawatzky,<sup>18</sup> F. Weichke,<sup>19</sup> B. Keimer,<sup>20\*</sup> L. Braicovich<sup>1</sup>

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



- 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)

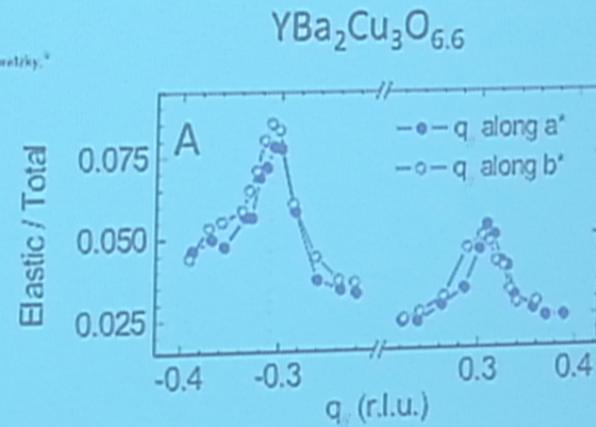
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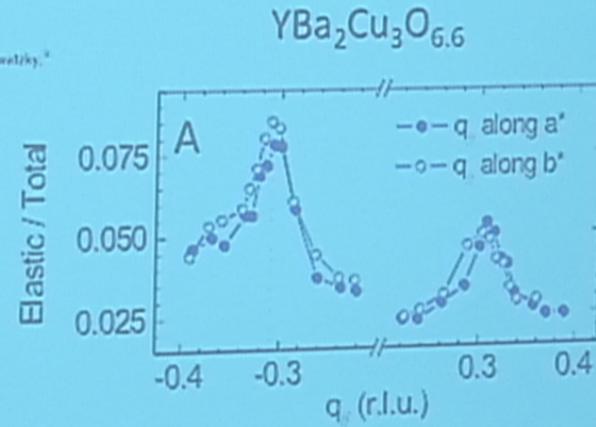
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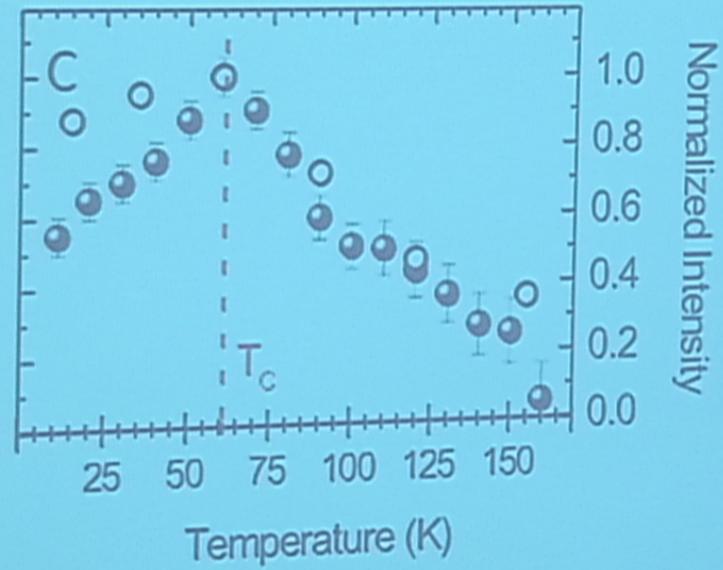
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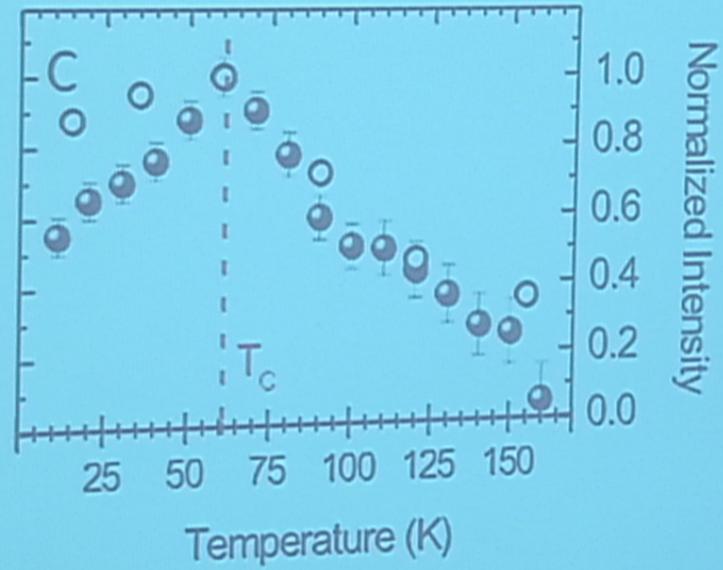
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CDW order onsets at  $\sim 150$  K and peaks in intensity at  $T_c$ , the superconducting transition temperature

Ghiringhelli et al. Science (2012).

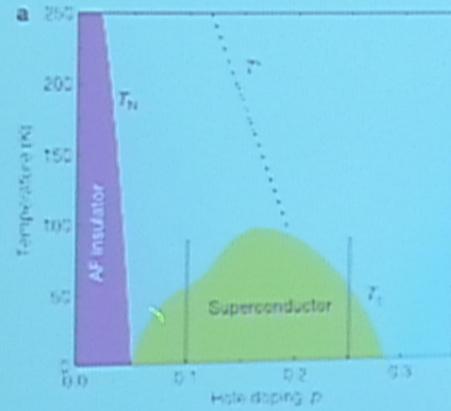
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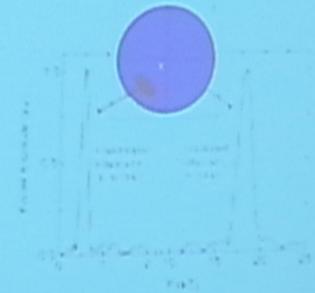
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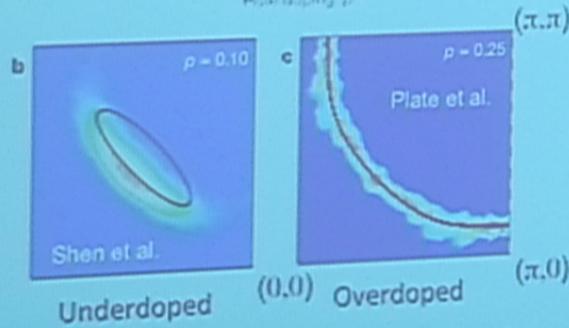
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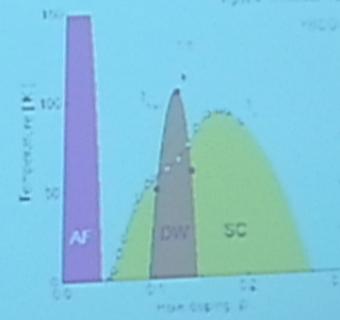
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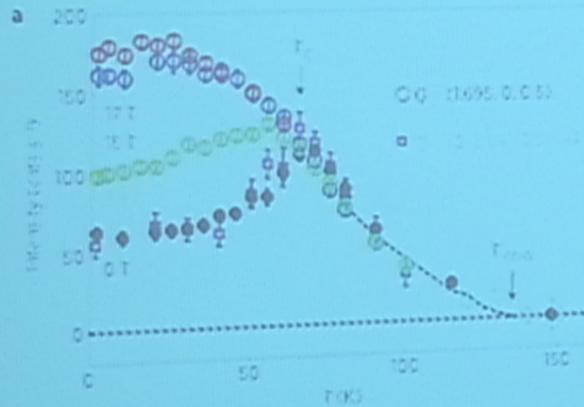
Doiron-Leyraud et al. Nature 2007

## CDW order in YBCO in magnetic field

### Hard x-ray scattering

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

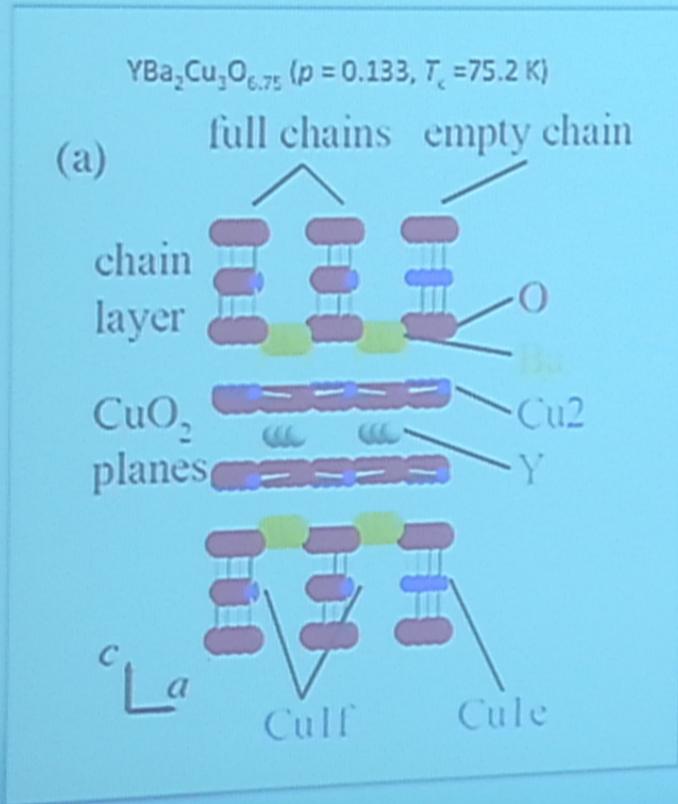
#### Ortho VIII ordered YBCO



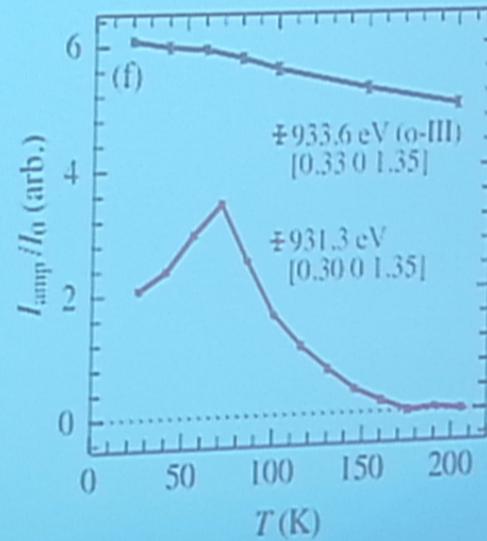
Competition between SC and CDW orders:

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

## Density wave order in the planes of Ortho III YBCO



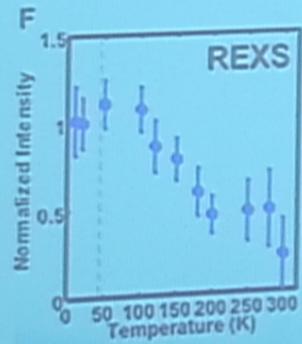
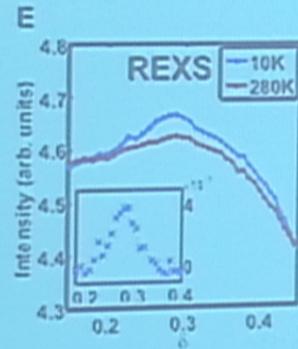
- CDW order in the CuO<sub>2</sub> planes
- CDW order present in high purity, oxygen-ordered samples
- Insight into microscopic character of CDW order



Achkar et al. PRL 109, 167001 (2012)

# CDW order in the other cuprates

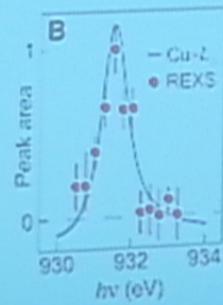
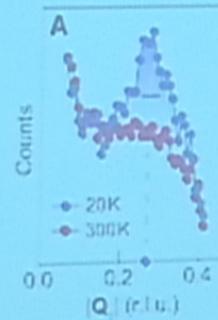
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  (Bi2212)



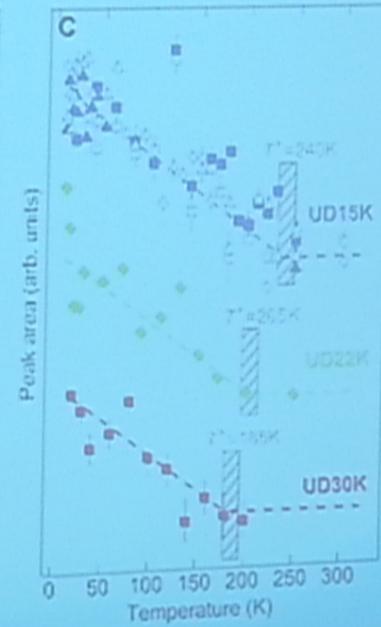
da Silva Neto et al. Science (2014)

$\text{Bi}_2\text{Sr}_{2-x}\text{La}_x\text{CuO}_{6+\delta}$  (Bi2201)

REXS - UD15K



REXS - Doping comparison

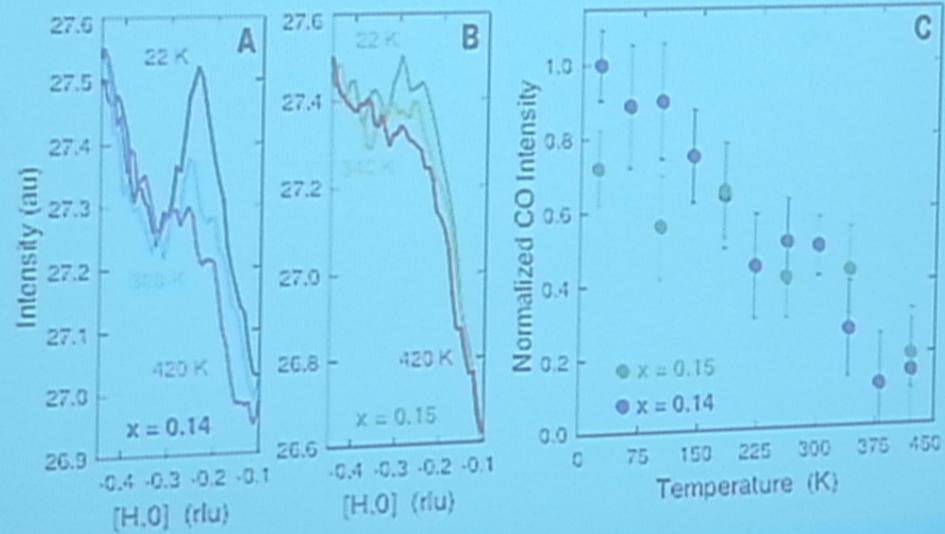


Comin et al. Science (2014)

## CDW order in electron doped

### Charge ordering in the electron-doped superconductor $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$

Eduardo H. da Silva Neto,<sup>1,2,3,4,\*</sup> Ricardo Comin,<sup>1,2,3</sup> Feilou He,<sup>2</sup> Romay Sutarso,<sup>2</sup> Yeping Jiang,<sup>2</sup> Richard L. Greene,<sup>2</sup> George A. Sawatzky,<sup>1,2</sup> Andrea Damascelli<sup>1,2,3</sup>



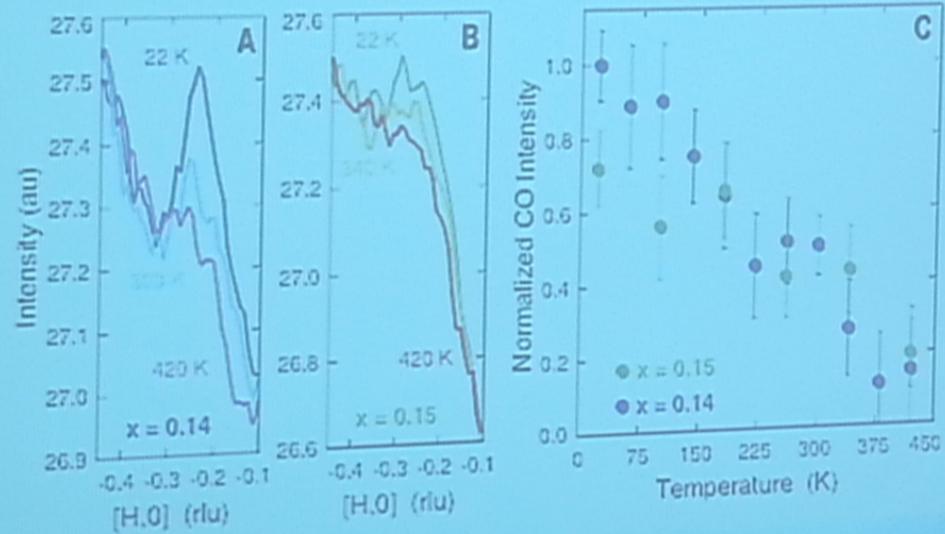
da Silva Neto et al. Science (2015)



## CDW order in electron doped

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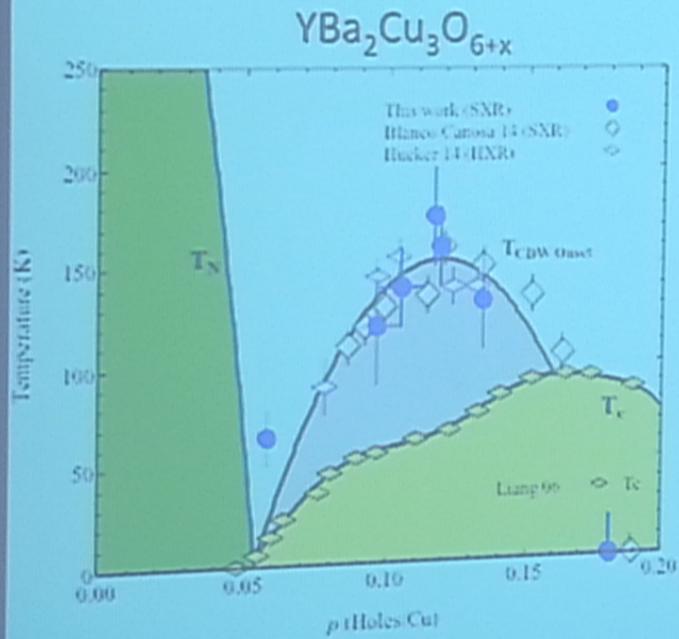
da Silva Neto et al. Science (2015)



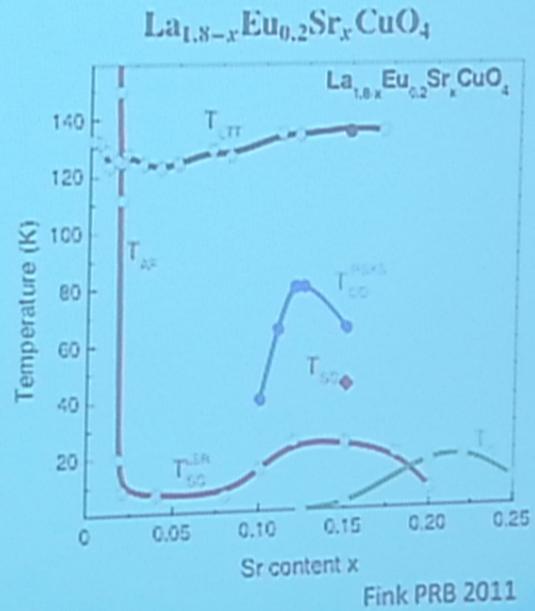
## Characteristics of CDW order in the cuprates

What is common or different about the CDW order observed in different cuprate families?

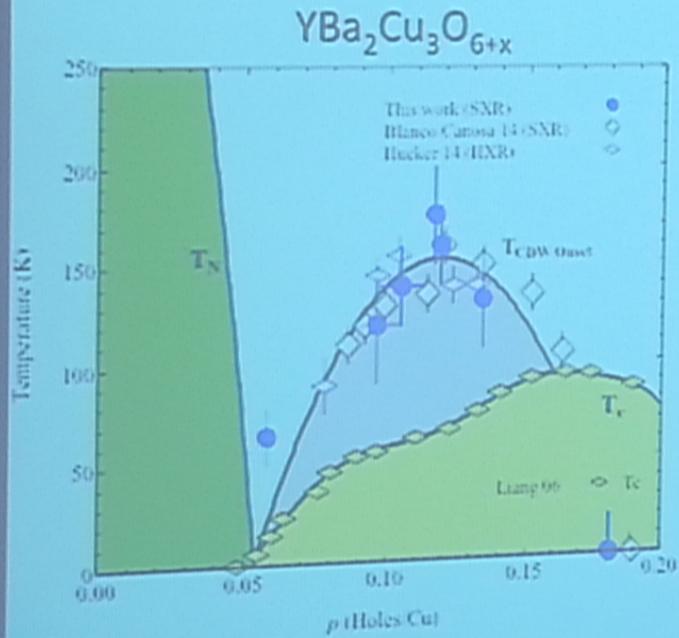
# CDW onset temperature peaked near $p = 1/8$



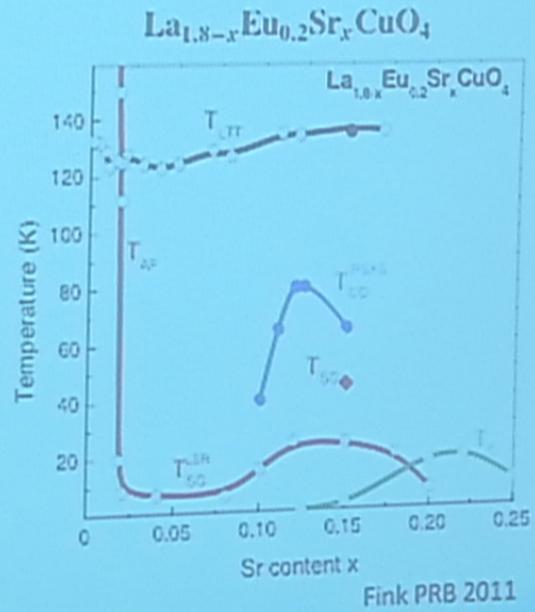
Achkar et al. unpublished  
 Banco-Canosa PRB 14  
 Hucker PRB 14



CDW onset temperature peaked near  $p = 1/8$



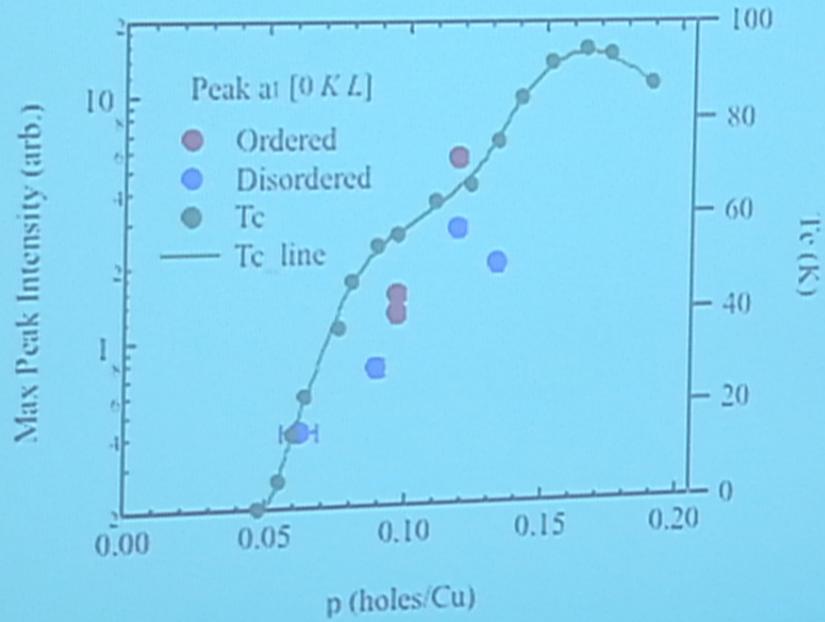
Achkar et al. unpublished  
 Banco-Canosa PRB 14  
 Hucker PRB 14



# CDW intensity peaked near $p = 1/8$

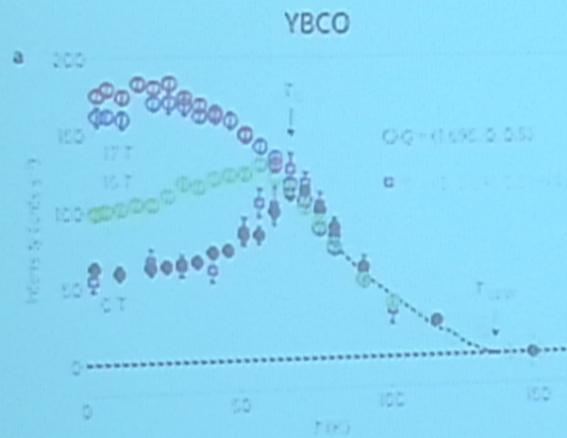
YBCO

CDW intensity peaked near  $p = 1/8$ , coincident with a suppression of  $T_c$

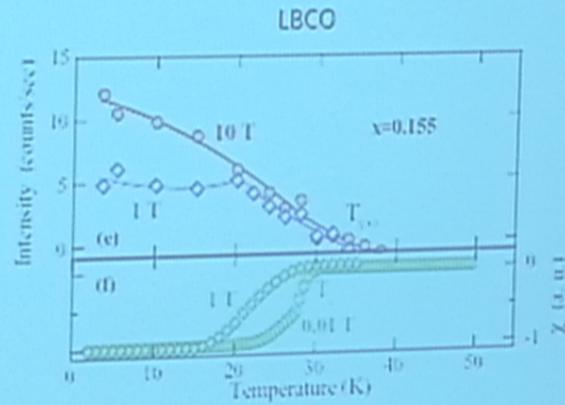


Achkar et al. unpublished

# Competition between CDW order and superconductivity: Magnetic field dependence



Chang Nat. Phys. 2012

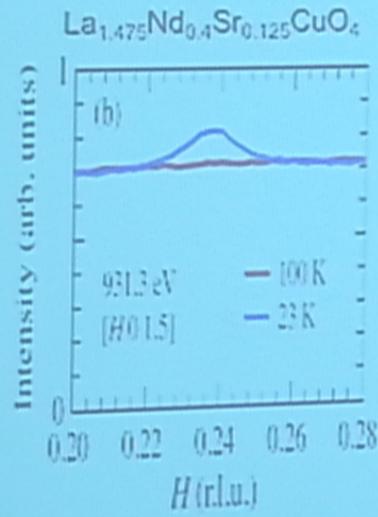


Hucker PRB 2013

Similar enhancement of CDW order in YBCO and LBCO observed by suppressing SC with an applied magnetic field

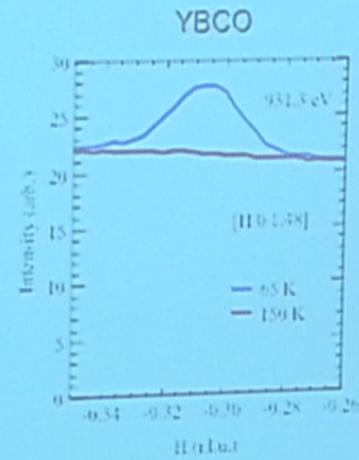
## Short range order

Correlation length of CDW order is short and similar in magnitude (~20 – 200 Å) in different cuprates



Achkar et al. PRL **110**, 017001 (2013)

Correlation length = 73 Å



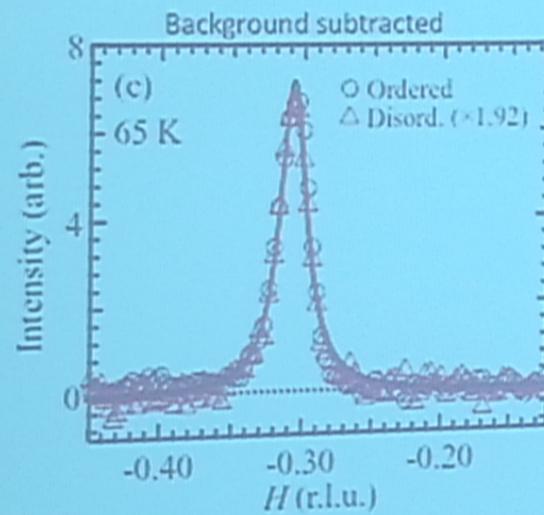
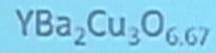
Achkar et al. PRL **113**, 107002 (2014)

Correlation length = 50 Å

Also, similar peak intensities (Thammy PRB 2013)

## Short range order: Effect of disorder in YBCO

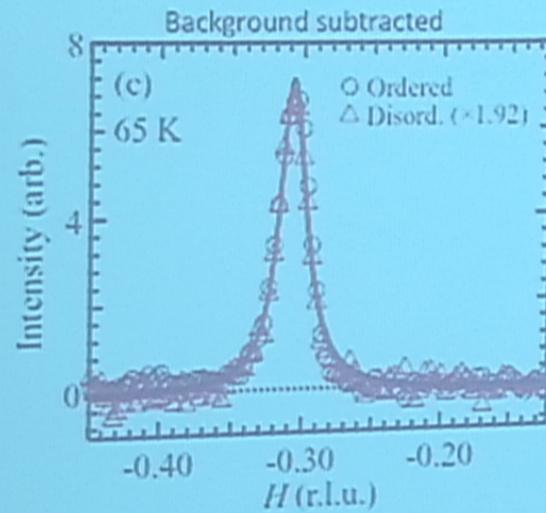
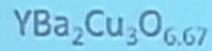
Achkar et al. PRL 113, 107002 (2014)



Changing the degree of disorder (disordering the oxygen ortho order in the chain layer) in YBCO:

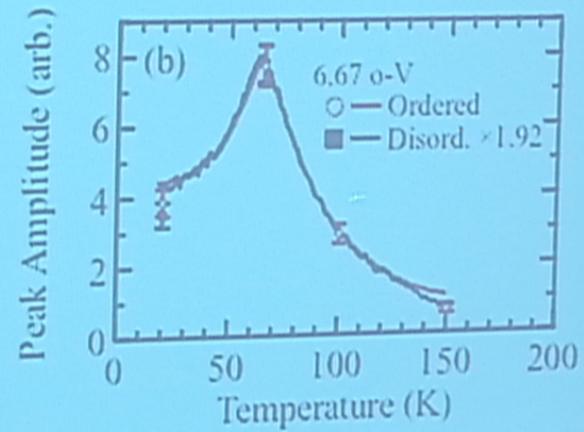
- Reduction in peak intensity
- No effect on the incommensurability
- No effect on correlation length

## Short range order: Effect of disorder in YBCO



Achkar et al. PRL 113, 107002 (2014)

Temperature dependence

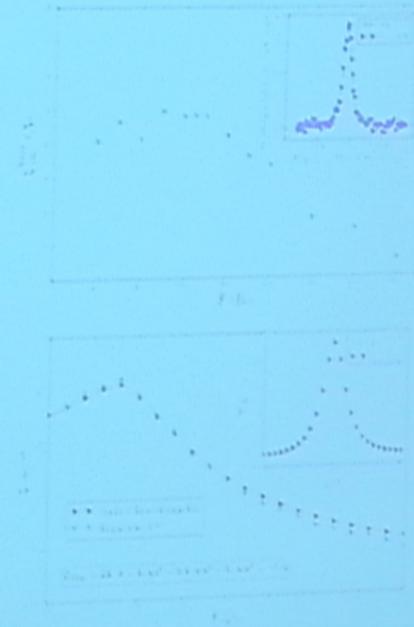
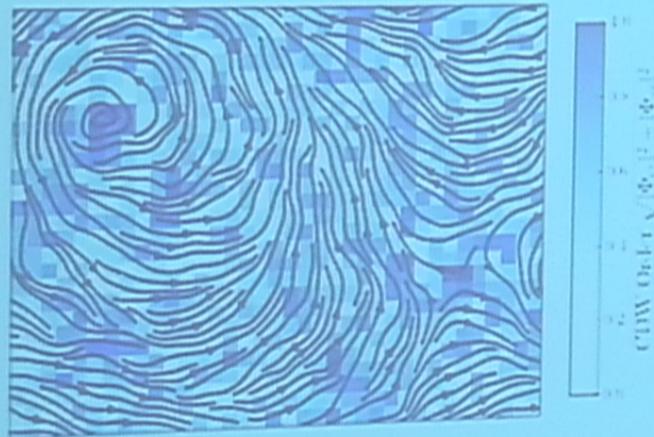


Changing the degree of disorder (disordering the oxygen ortho order in the chain layer) in YBCO:

- ✓ Reduction in peak intensity
- ✓ No effect on the incommensurability
- ✓ No effect on correlation length
- ✓ No effect on temperature dependence

## Short range order: CDW/SC competition

Monte Carlo calculations of non-linear sigma model  
(multi-component order parameter)



CDW order may be intrinsically short-ranged due to competition with superconductivity and/or frustration between unidirectional domains of CDW order

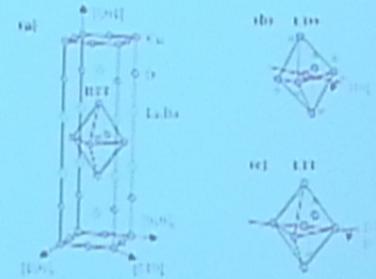
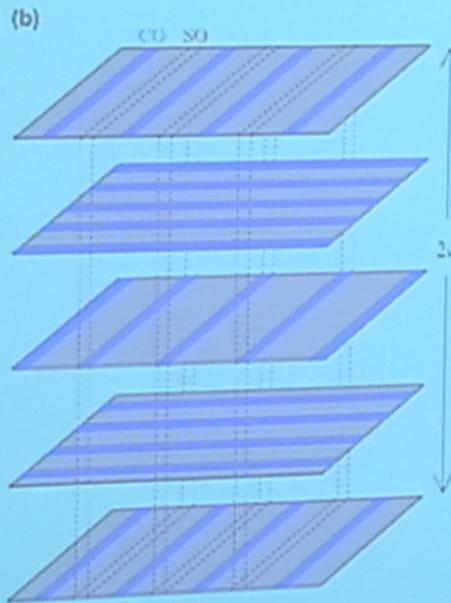
Hayward et al. Science (2014)

Hayward et al. PRB (2014)

Achkar et al. PRL (2014)

# Unidirectional order: stripes

## La-based cuprates

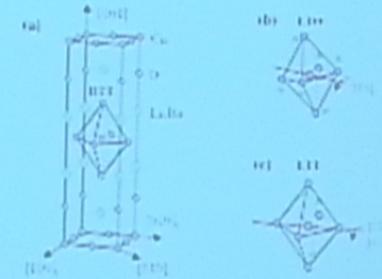
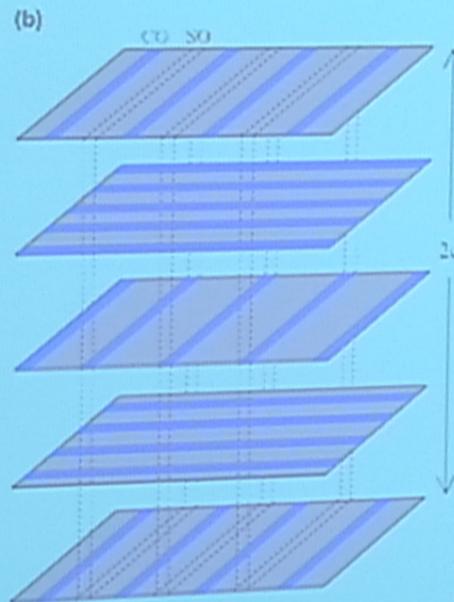


- Tilting of  $\text{CuO}_2$  octahedra along Cu-O bond in the LTT phase breaks  $C_2$  symmetry and is understood to produce stripe-like CDW/SDW order
- Tilt direction alternates between planes

Tranquada 1995  
Tranquada 1996

## Unidirectional order: stripes

### La-based cuprates



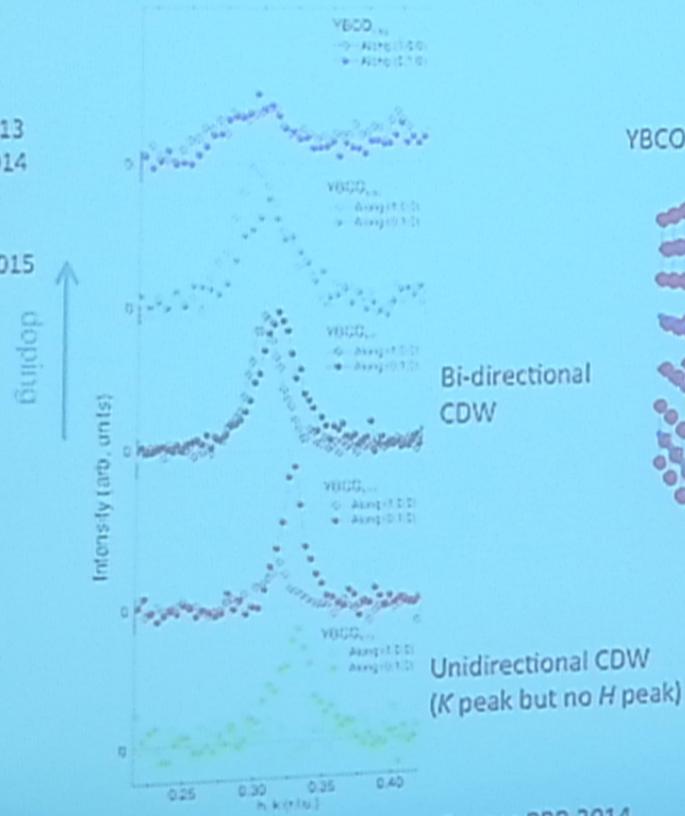
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- Tilt direction alternates between planes

Tranquada 1995  
Tranquada 1996

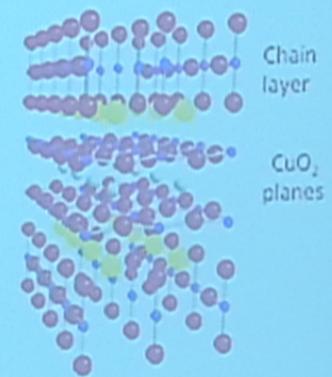
# Unidirectional CDW: YBCO

Blackburn PRL 2013  
Blanco-Canosa PRL 2013  
Blanco-Canosa PRB 2014  
Achkar unpublished

Also: Comin Science 2015  
Achkar arXiv 2014



YBCO is orthorhombic

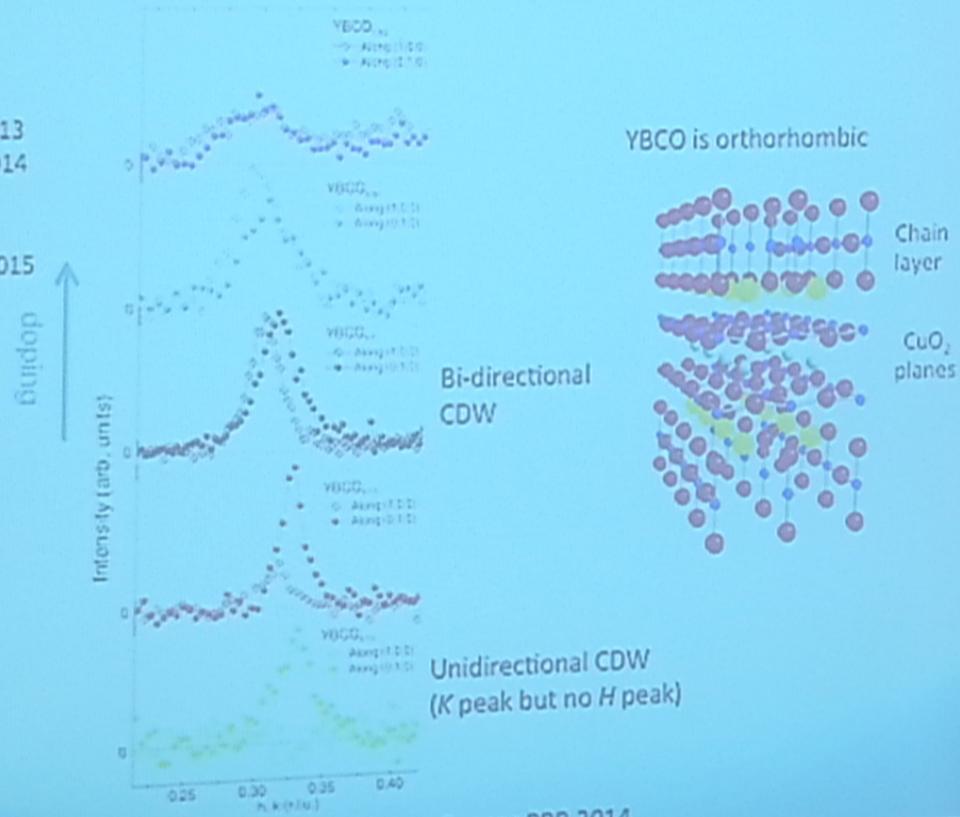


Blanco-Canosa PRB 2014

# Unidirectional CDW: YBCO

Blackburn PRL 2013  
Blanco-Canosa PRL 2013  
Blanco-Canosa PRB 2014  
Achkar unpublished

Also: Comin Science 2015  
Achkar arXiv 2014

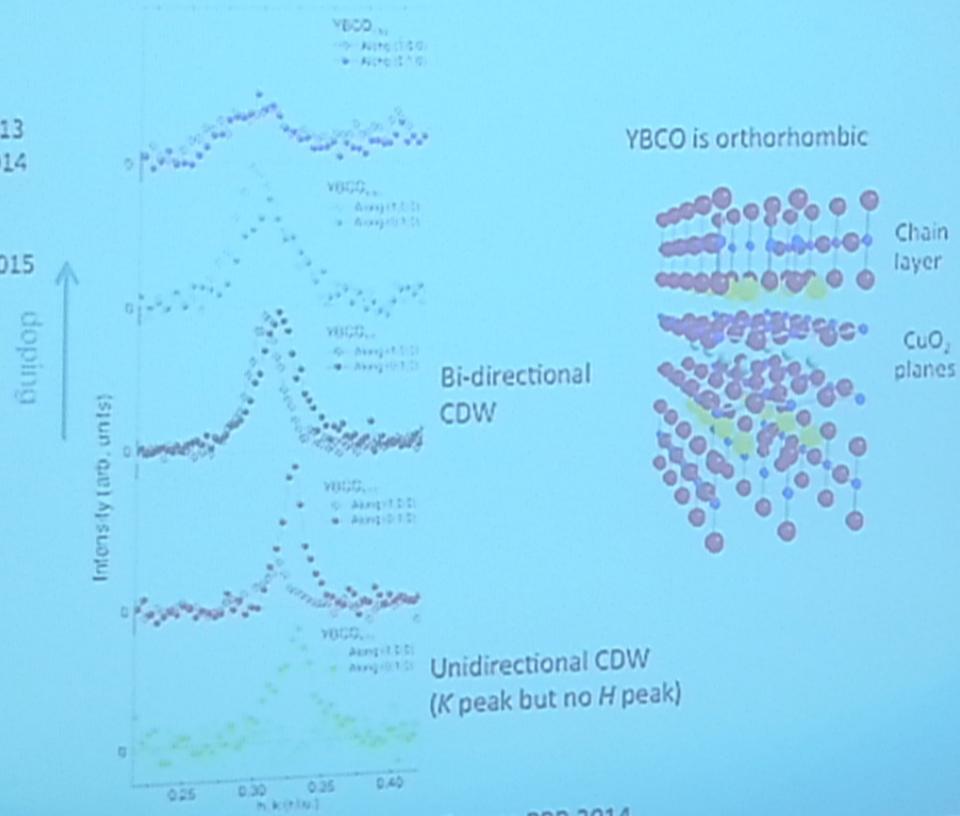


Blanco-Canosa PRB 2014

# Unidirectional CDW: YBCO

Blackburn PRL 2013  
Blanco-Canosa PRL 2013  
Blanco-Canosa PRB 2014  
Achkar unpublished

Also: Comin Science 2015  
Achkar arXiv 2014

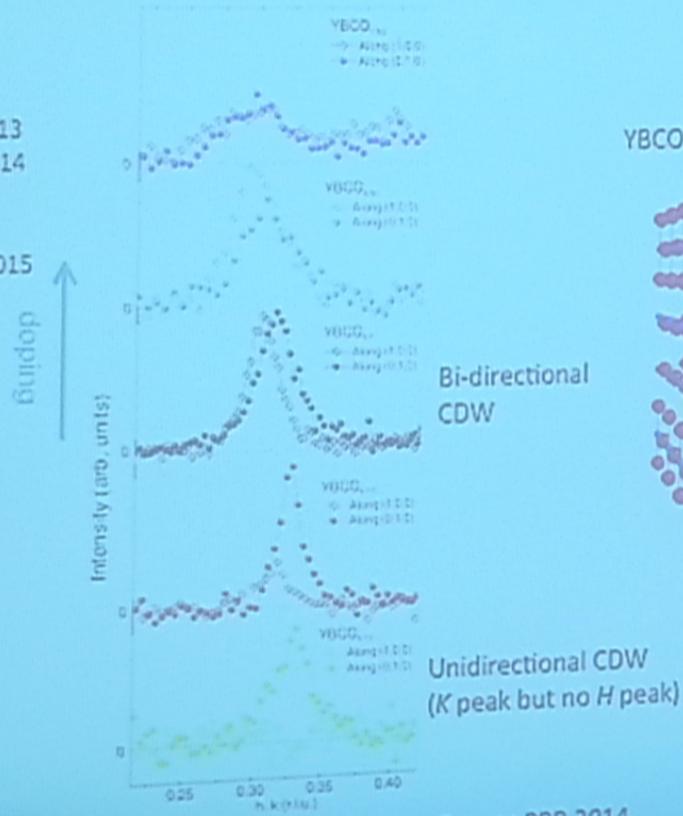


Blanco-Canosa PRB 2014

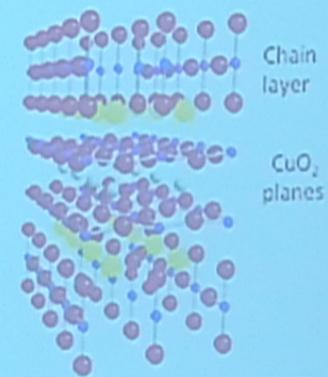
# Unidirectional CDW: YBCO

Blackburn PRL 2013  
Blanco-Canosa PRL 2013  
Blanco-Canosa PRB 2014  
Achkar unpublished

Also: Comin Science 2015  
Achkar arXiv 2014



YBCO is orthorhombic



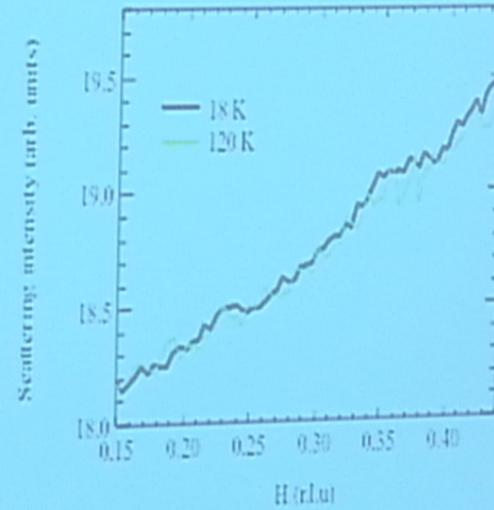
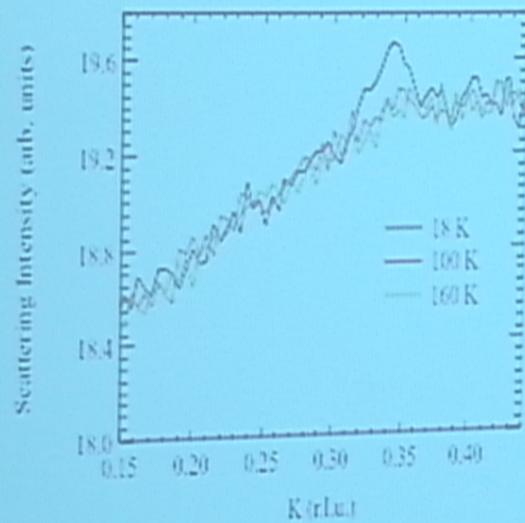
Blanco-Canosa PRB 2014

## CDW doping dependence

$\text{YBa}_2\text{Cu}_3\text{O}_{6.335}$

$\rho \sim 0.06, T_c \sim 12 \text{ K}$

No oxygen order in the chain layer

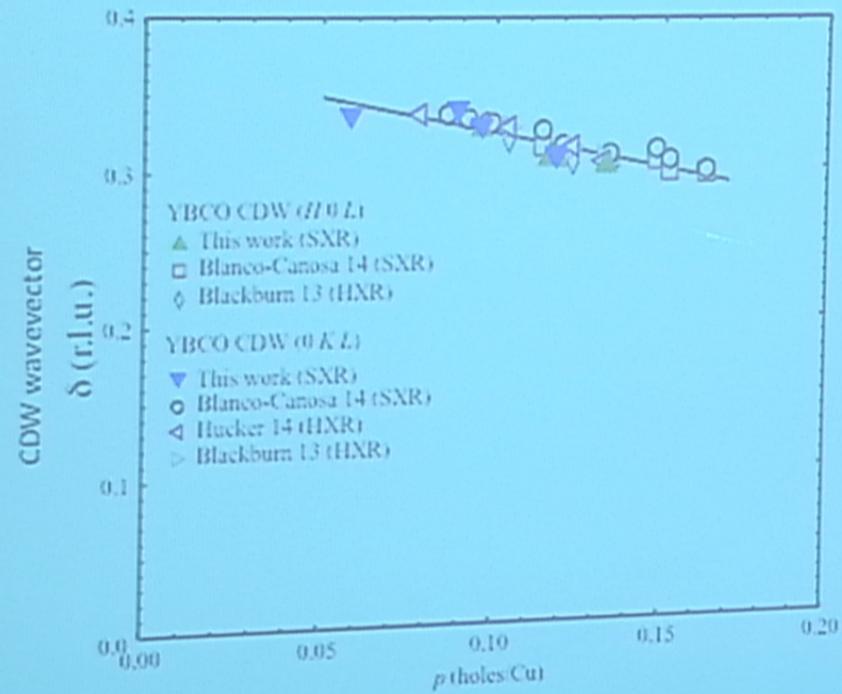


No measurable peak intensity along  $H$

Also, co-existence of CDW order with quasi-static AF order at this doping (although not SDW order that has a 2Q relation to CDW order, like the stripes in La-based cuprates).

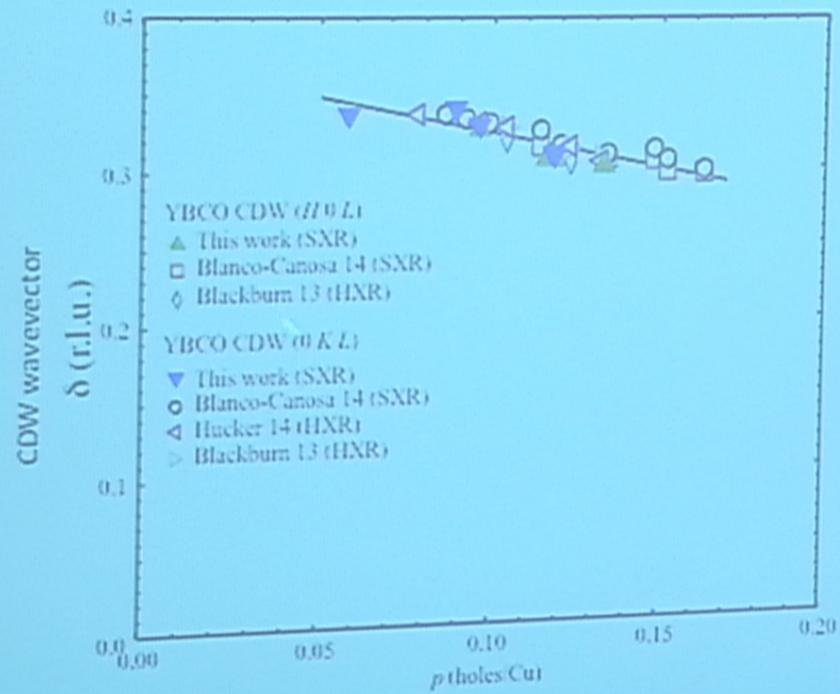
Achkar et al. unpublished

## Incommensurability (Period of CDW order): YBCO



Achkar et. al unpublished

## Incommensurability (Period of CDW order): YBCO

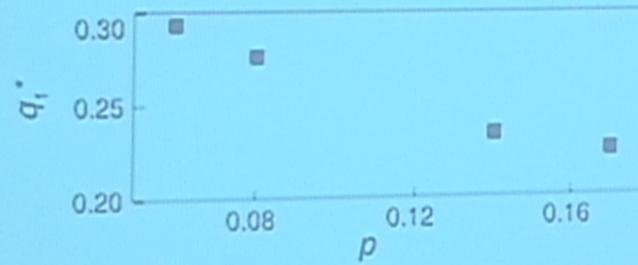


Achkar et. al unpublished

## Bi2212: Incommensurability

STM Bi2212

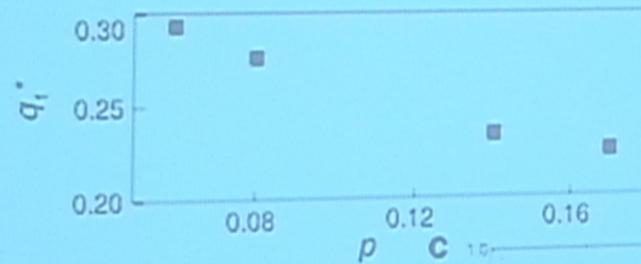
Kohsaka Nature 2008  
Fujita JPSJ 2011



# Bi2212: Incommensurability

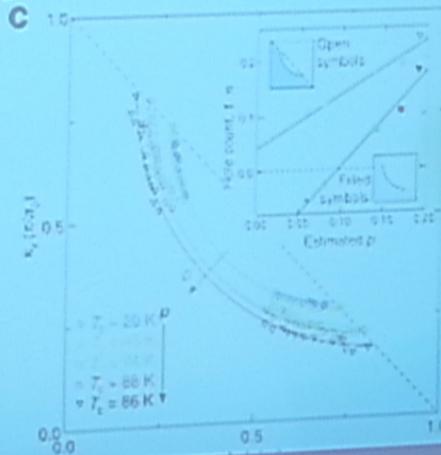
STM Bi2212

Kohsaka Nature 2008  
Fujita JPSJ 2011



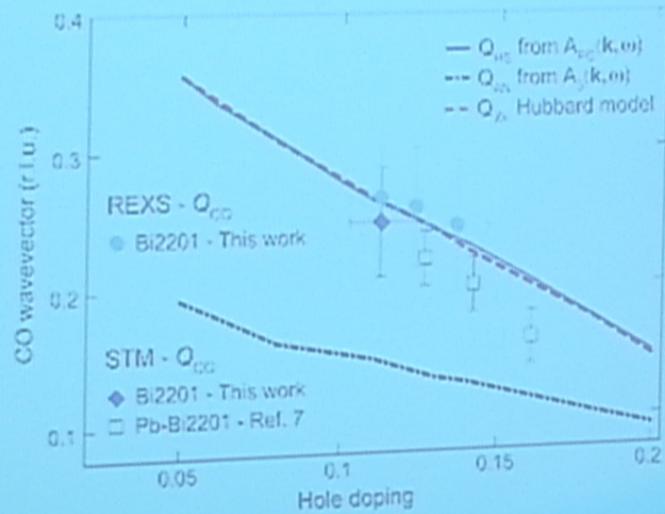
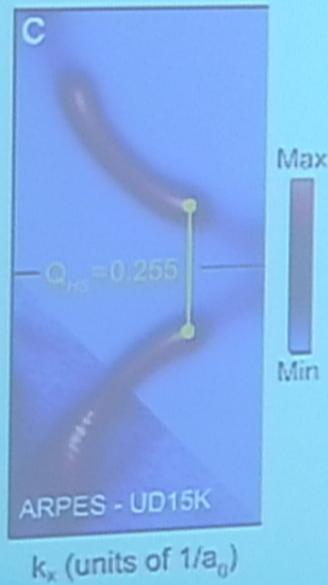
$Q_{CDW}$  connects ends of Fermi-surface arcs (Hot-spots)

Ghiringhelli 2012  
Sachdev PRL 2013  
Efetov Nature Physics 2013  
Dalla Torre arXiv 2014  
Kohsaka Nature 2008  
Fujitya JPSJ 2011  
Comin 2014  
...



# Bi2201: Incommensurability

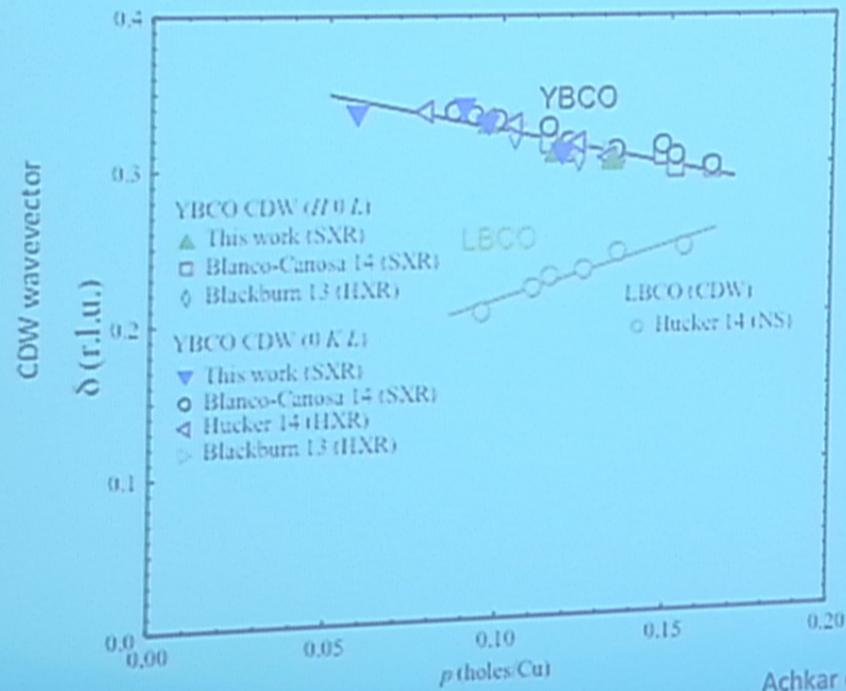
$Q_{CDW}$  connects ends of Fermi-surface arcs (Hot-spots)



RSXS, STM, ARPES: Comin et al. Science (2014)

## Incommensurability: LBCO

Doping dependence of incommensurability is different in La-based cuprates (Yamada plot)



Yamada 1998  
Hucker 2011

Achkar et. al unpublished

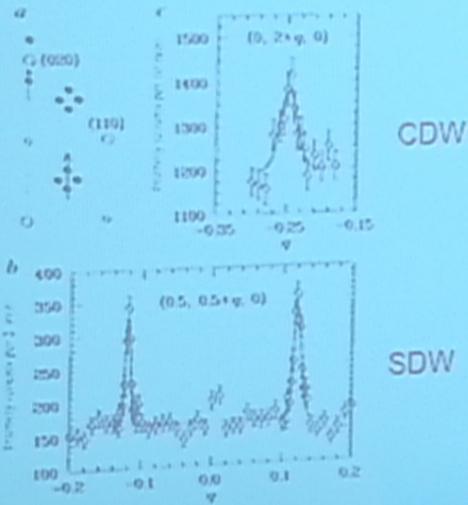
## Static spin density wave (SDW) order

La-based cuprates

Static SDW order with twice  
the period of the charge order

BSCCO, YBCO

Spin gap – No static SDW  
order related to CDW order



Tranquada 1995

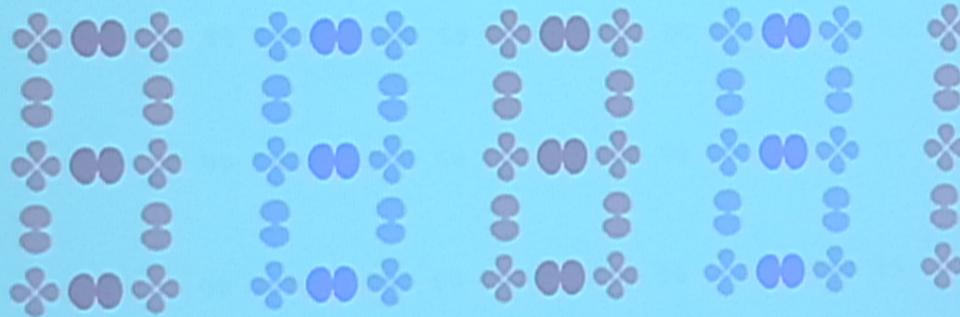
## Orbital Symmetry of CDW order

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. arXiv:1409.6787

R. Comin, R. Sutarto, 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, A. J. Achkar, D. G. Hawthorn, B. Keimer, G. A. Sawatzky and A. Damascelli. Nature Materials 2015

## Orbital Symmetry of CDW order

CuO<sub>2</sub> plane



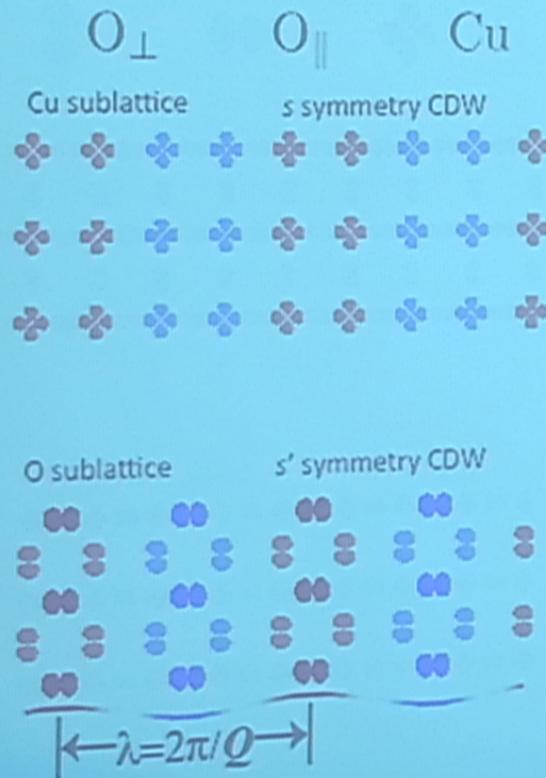
$$\leftarrow \lambda = 2\pi/Q \rightarrow$$

O<sub>⊥</sub>

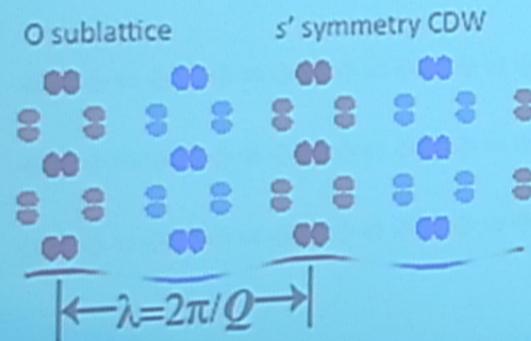
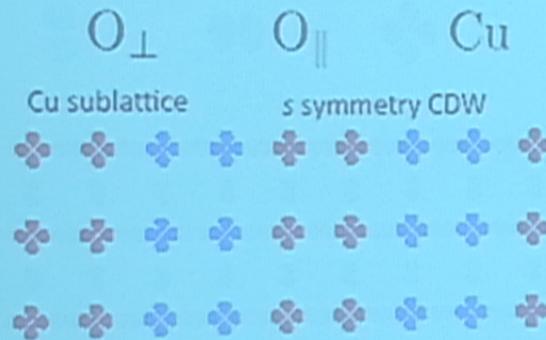
O<sub>∥</sub>

Cu

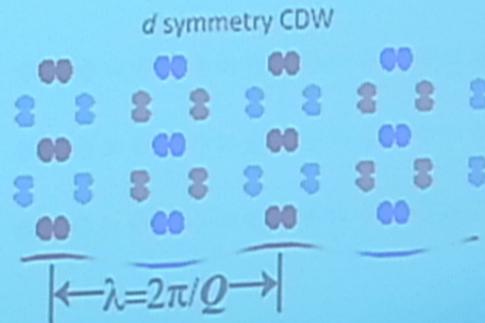
# Symmetry of CDW order



## Symmetry of CDW order

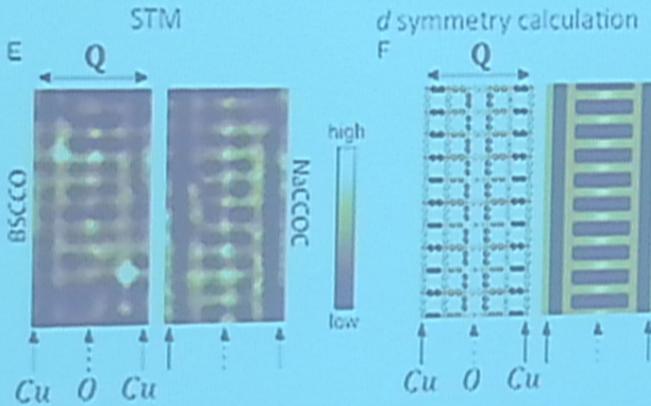


Sachdev and La Placa, PRL 2013  
 Efetov, Meier and Pepin, Nat. Phys. 2013  
 Metlitski and Sachdev, PRB 2010  
 Vojta and Rosch PRL 2008  
 Atkinson, Kampf and Bulut NJP 2015  
 Wang and Chubukov PRB 2014  
 Keo, Chen and Hu PRB 2007  
 Li, Wu and Lee PRB 2006  
 Chowdhury and Sachdev arXiv 2014  
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

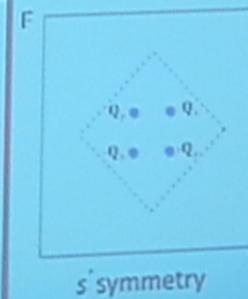
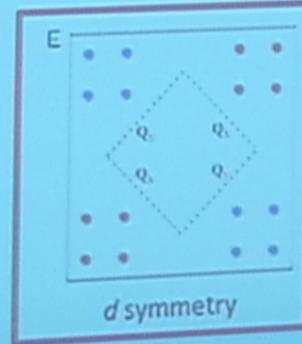
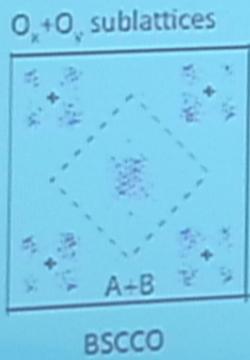


# *d* symmetry charge order from STM

Real space



Fourier Transforms (Q space)

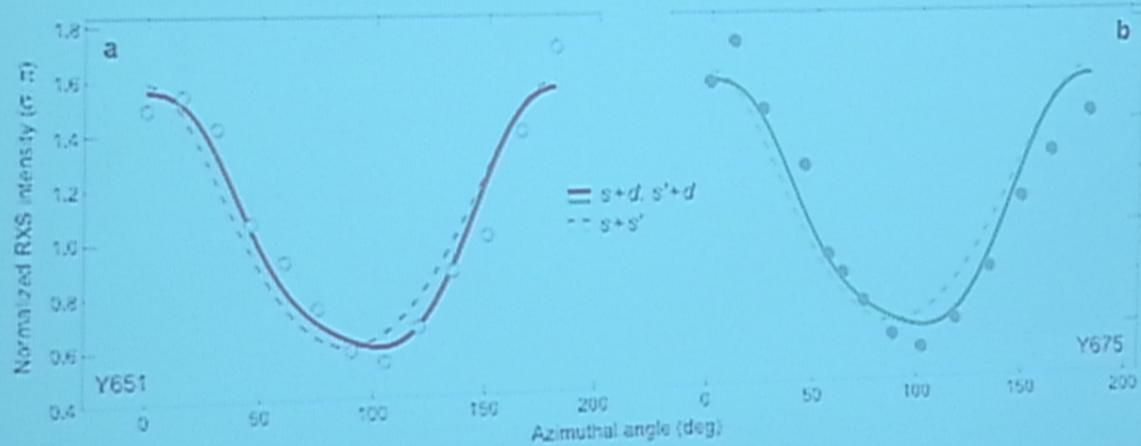


Fujita et al. PNAS 2014

# *d* symmetry charge order from resonant x-ray scattering

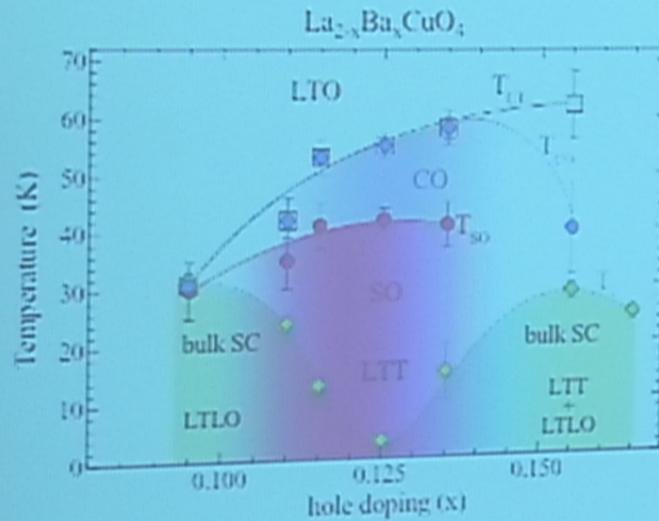
Report of *d*-symmetry CDW in YBCO from azimuthal angle dependent resonant x-ray scattering

Cu *L* edge resonant x-ray scattering



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

## Symmetry of density wave order in La-based cuprates



M. Hucker, PHYSICAL REVIEW B 83, 064506 (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?

## 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

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

$$I_{sc}(\vec{Q}, \omega, \vec{\epsilon}) \propto \left| \sum_j (\vec{\epsilon} \overset{\wedge}{F}_j(\omega) \vec{\epsilon}) e^{-i2\pi\vec{Q}\cdot\vec{r}_j} \right|^2$$

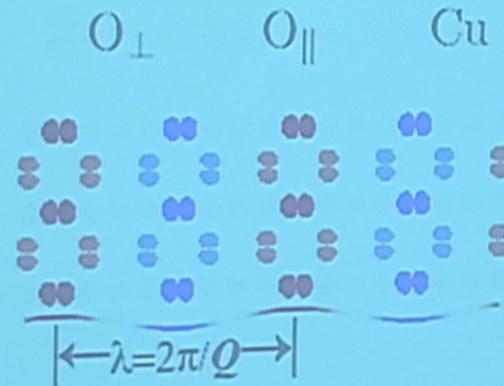
Scattered photon polarization

Incident photon polarization

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

## CDW symmetry

Holes in O  $2p_x$  or  $2p_y$  states form two distinct sublattices relative to the CDW direction ( $Q$ ).

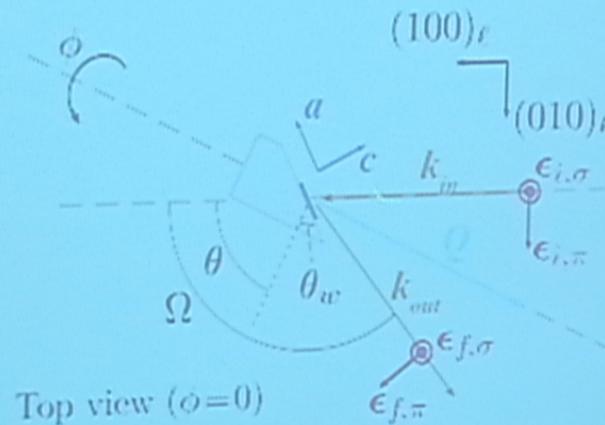
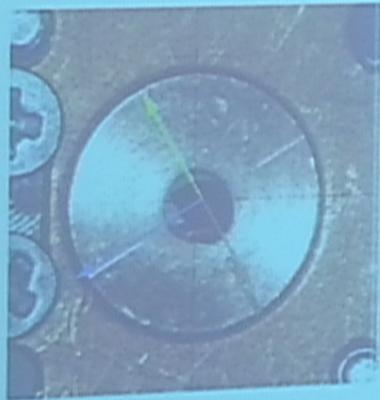


Components of a tensoral equivalent of the structure factor

## Experimental scheme

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

Side view



Top view ( $\phi=0$ )

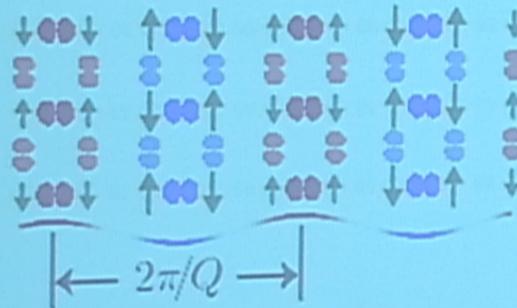
REIXS beamline at the Canadian Light Source Hawthorn *et al.*  
Rev. Sci. Instrum. 2011

Comin 2014  
Achkar 2014

## Why would CDW symmetry be different?

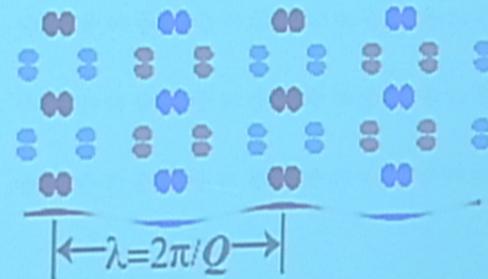
LBCO (La-based cuprates)

$s'$  symmetry CDW+SDW



BSCCO, NCCOC, (YBCO?)

$d$  symmetry CDW



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

## SDW order and CDW symmetry

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

Thomson and Sachdev arXiv:1410.348

- "... 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,  $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$ ."

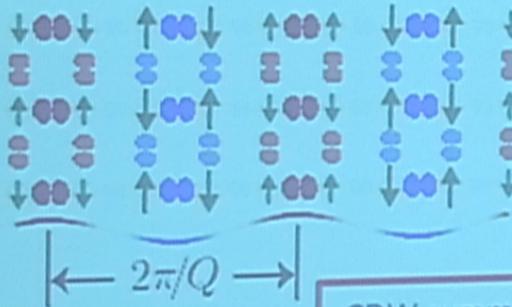
Fischer, Wu, Paramakanti, Lawler, Kim New Journal Physics 2014

- A model with spin and charge stripes exhibits  $d/s' \sim 0.1$

# CDW symmetry and Superconductivity

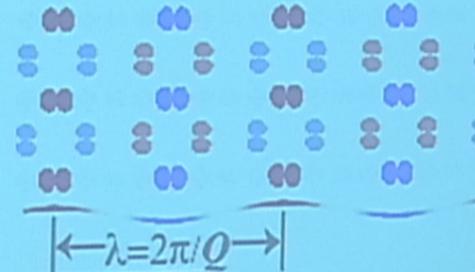
LBCO (La-based cuprates)

$s'$  symmetry CDW+SDW

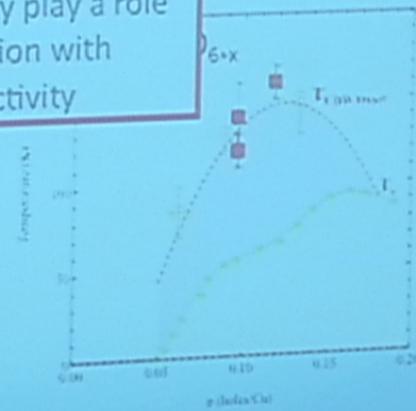
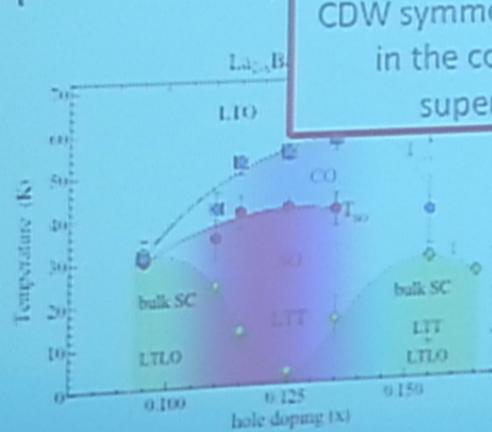


BSCCO, NCCOC, (YBCO?)

$d$  symmetry CDW

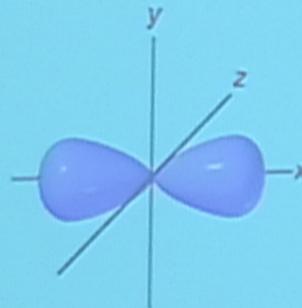


CDW symmetry may play a role in the competition with superconductivity



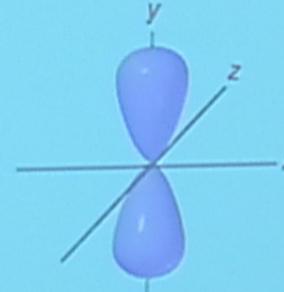
## Scattering form factor: orbital symmetry dependence

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



$2p_x$  orbital

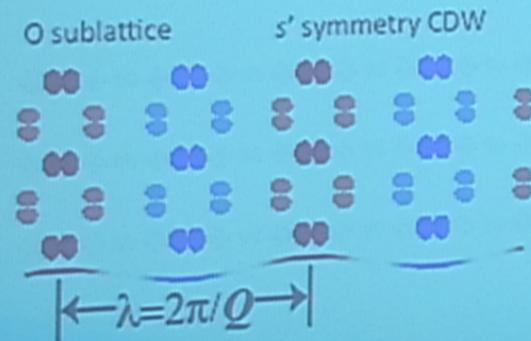
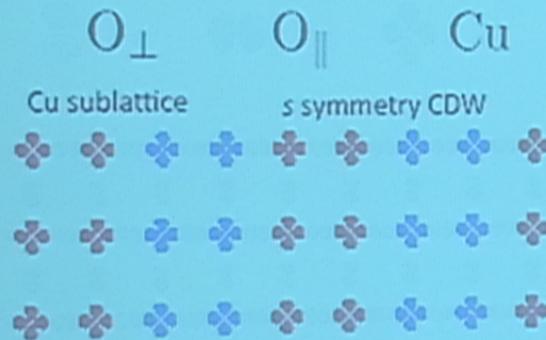
$$F = \begin{bmatrix} f_{xx} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



$2p_y$  orbital

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

## Symmetry of CDW order



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 arXiv 2014  
 Thomson and Sachdev arXiv 2014

