Andrea Damascelli

Charge order in cuprates: From hole to electron doping

Max Planck – UBC
Quantum Matter Institute

A "few" acknowledgments

Quantum Matter Institute

UBC - ARPES group

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E.H. da Silva Neto
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Jenny Hoffman

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Mathieu Le Tacon
Bernhard Keimer

UBC/CLS – RXS

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Eugen Weschke

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University of Minnesota

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Guichuan Yu
Martin Greven

Unified Charge-Order Phenomenology?

REPORTS

Science **340**, 390 (2014)

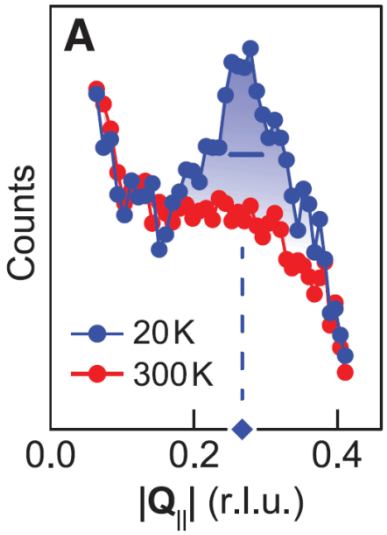
Charge Order Driven by Fermi-Arc Instability in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

R. Comin,[1] A. Frano,[2,3] M. M. Yee,[4] Y. Yoshida,[5] H. Eisaki,[5] E. Schierle,[3] E. Weschke,[3] R. Sutarto,[6] F. He,[6] A. Soumyanarayanan,[4] Yang He,[4] M. Le Tacon,[2] I. S. Elfimov,[1,7] Jennifer E. Hoffman,[4] G. A. Sawatzky,[1,7] B. Keimer,[2] A. Damascelli[1,7]*

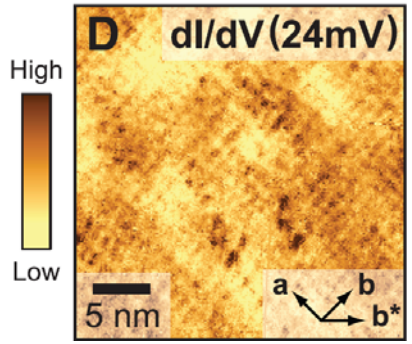
RXS-ARPES-STM on same compound

Connect charge order to Fermiology

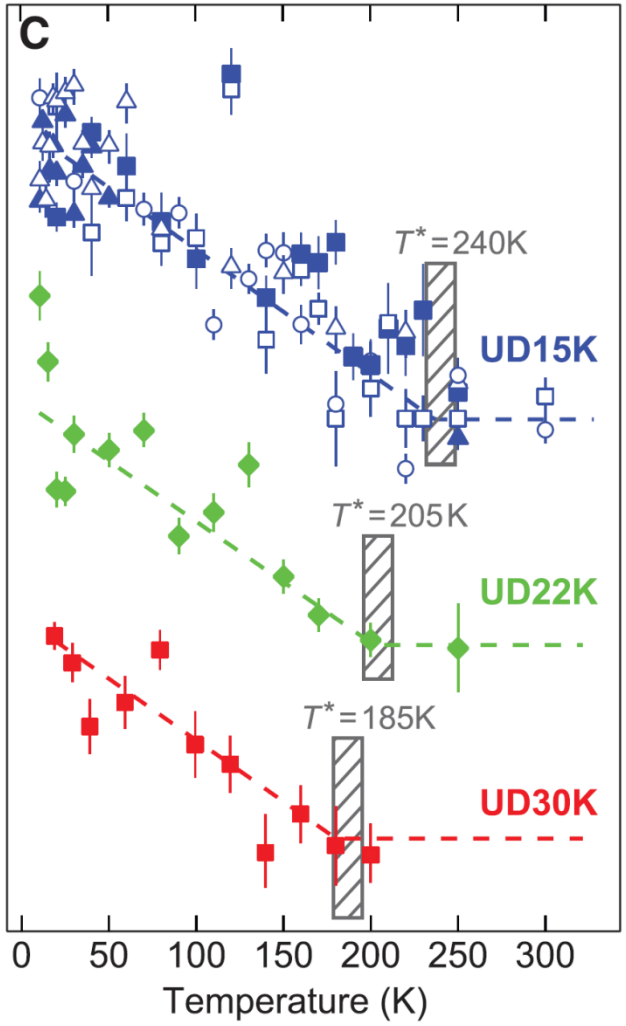
Electronic charge ordering in Bi2201 – RXS/STM



Resonant X-ray Scattering



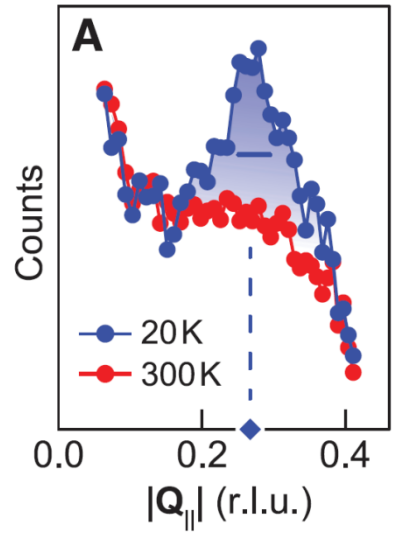
Scanning Tunneling Microscopy



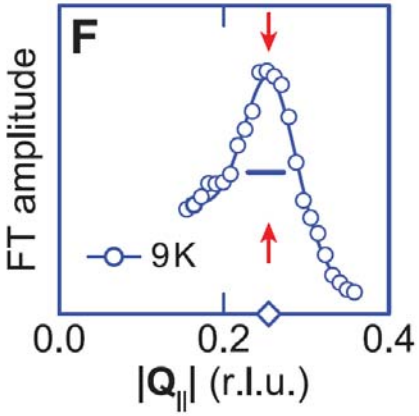
CO in both RXS & STM, with onset $T_{CO} \sim T^*$

Comin *et al*, Science **340**, 390-392 (2014)

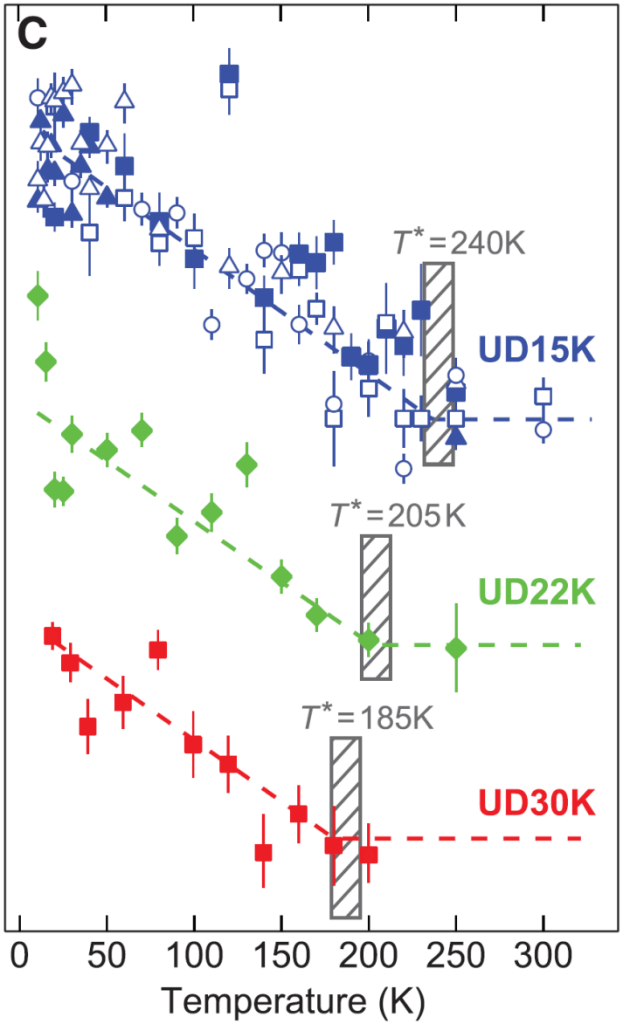
Electronic charge ordering in Bi2201 – RXS/STM



Resonant X-ray Scattering



Scanning Tunneling Microscopy

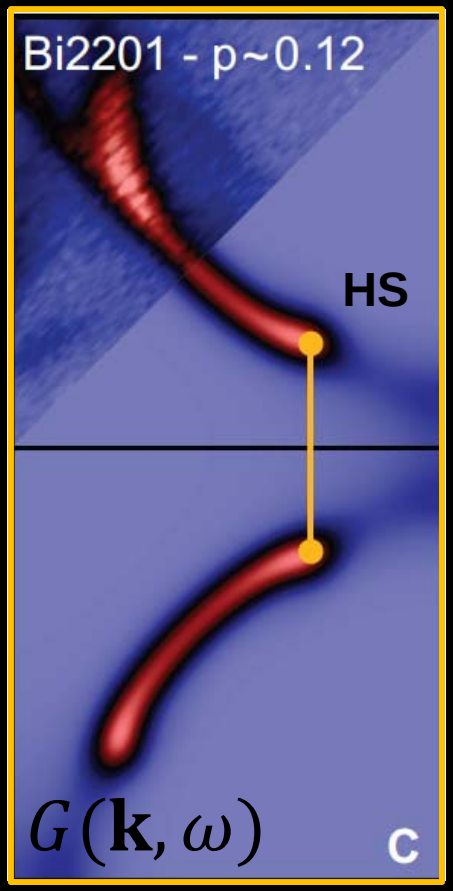


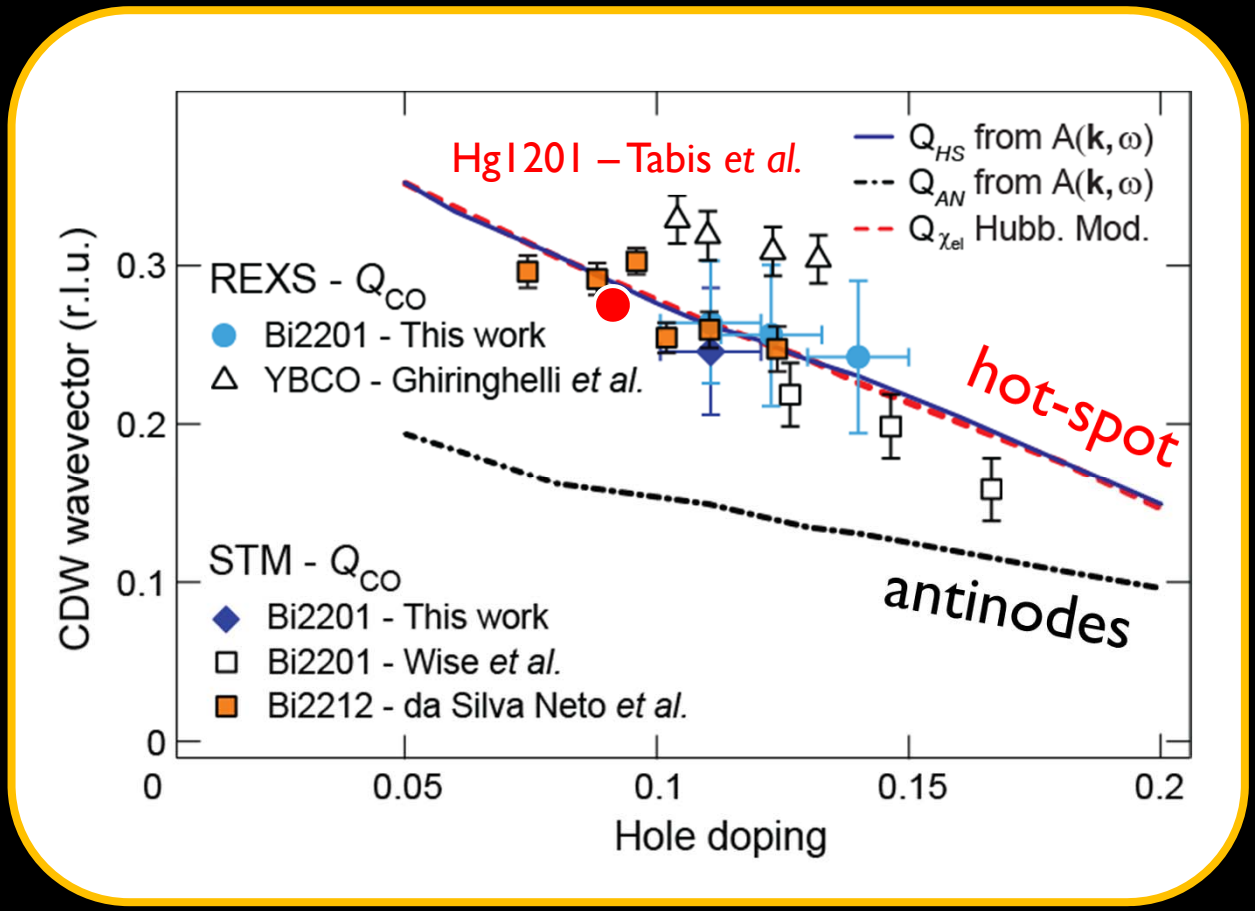
CO in both RXS & STM, with onset $T_{CO} \sim T^*$

Comin *et al*, Science **340**, 390-392 (2014)

Charge ordering in Bi2201 – Link to pseudogap fermiology

No antinodal Fermi surface nesting





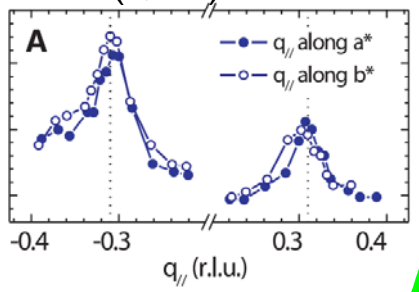
CDW driven by end-of-Fermi-arc (hot spots) instability

Comin *et al*, Science **340**, 390-392 (2014)

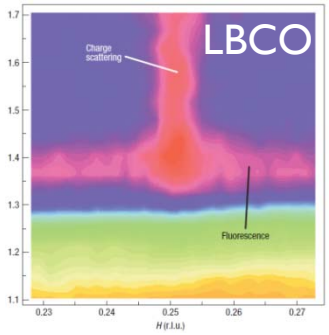
Charge ordering in Bi2201 – RXS and STM

SCATTERING
BULK

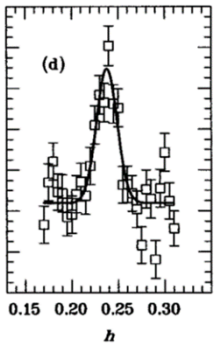
(Y,Nd)BCO



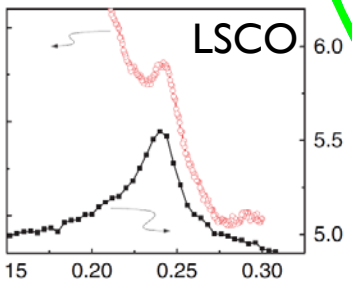
LBCO



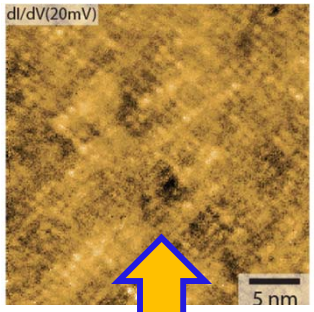
LNSCO-LESCO

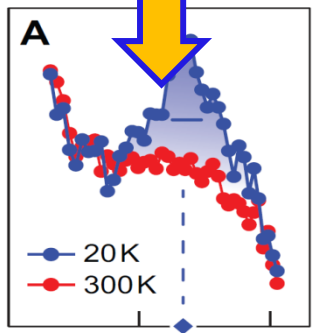


LSCO

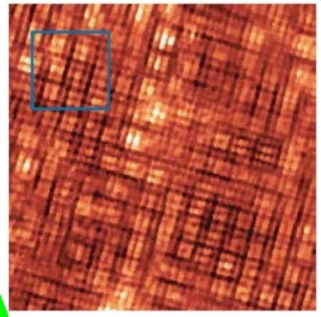


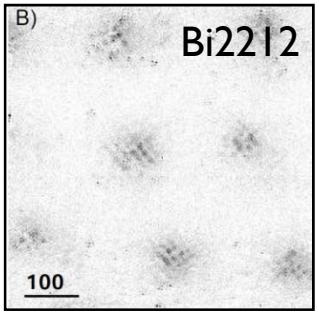
La-Bi2201



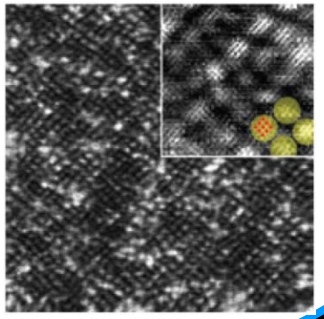


Na-CCOC





(Pb,La)Bi2201

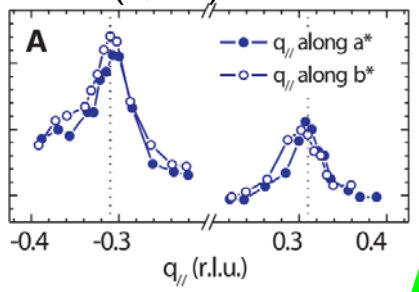


STM
SURFACE

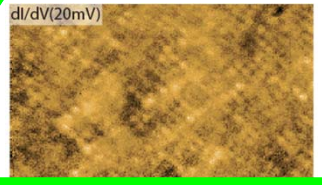
Charge ordering in Bi2201 – RXS and STM

SCATTERING
BULK

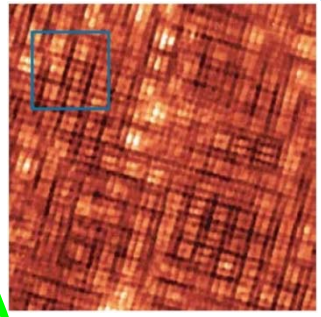
(Y,Nd)BCO

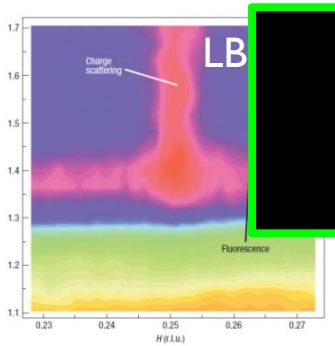


La-Bi2201

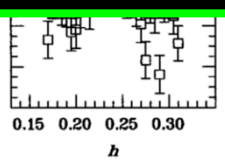


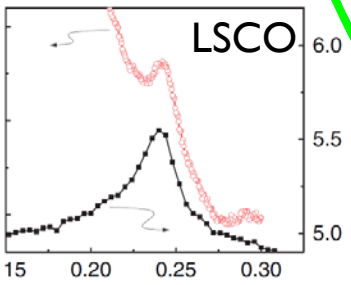
Na-CCOC

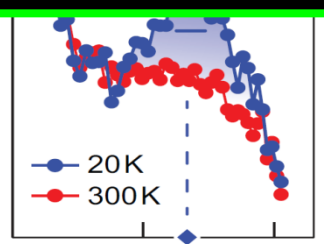




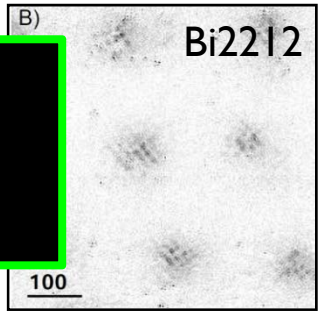
LB



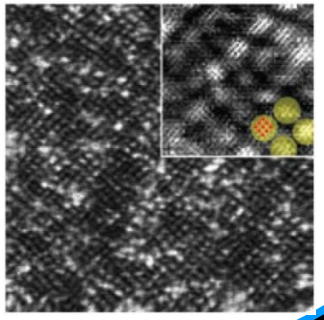




Charge order is a universal phenomenon in the cuprates

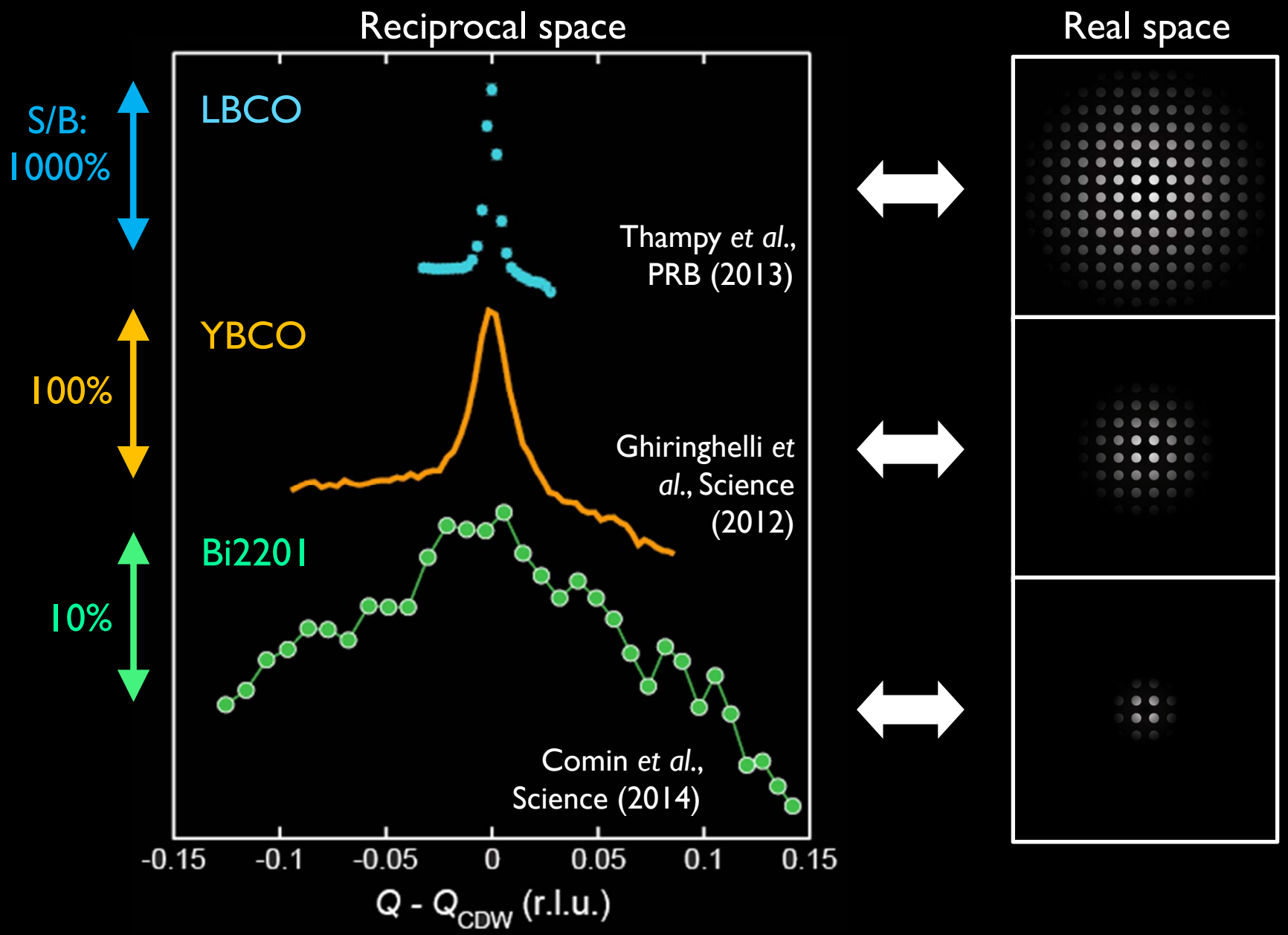


(Pb,La)Bi2201



STM
SURFACE

What do we call a CDW peak?



What else can we learn from RXS?

Inner structure of charge order

- Zooming onto CDW peaks -

1D vs 2D / d-wave vs s-wave

1D vs 2D Charge-order instability in YBCO?

SUPERCONDUCTIVITY

Science **347**, 1335 (2015)

Broken translational and rotational symmetry via charge stripe order in underdoped $YBa_2Cu_3O_{6+y}$

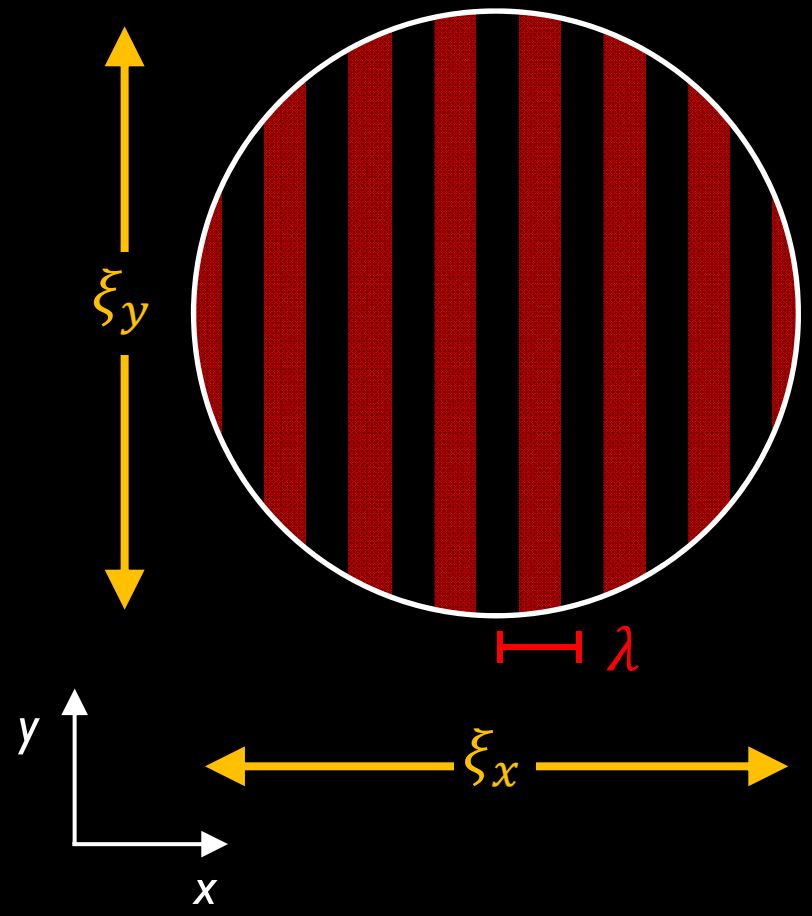
R. Comin,[1,2]* R. Sutarto,[3] E. H. da Silva Neto,[1,2,4,5] L. Chauviere,[1,2,5] R. Liang,[1,2] W. N. Hardy,[1,2] D. A. Bonn,[1,2] F. He,[3] G. A. Sawatzky,[1,2] A. Damascelli[1,2]*

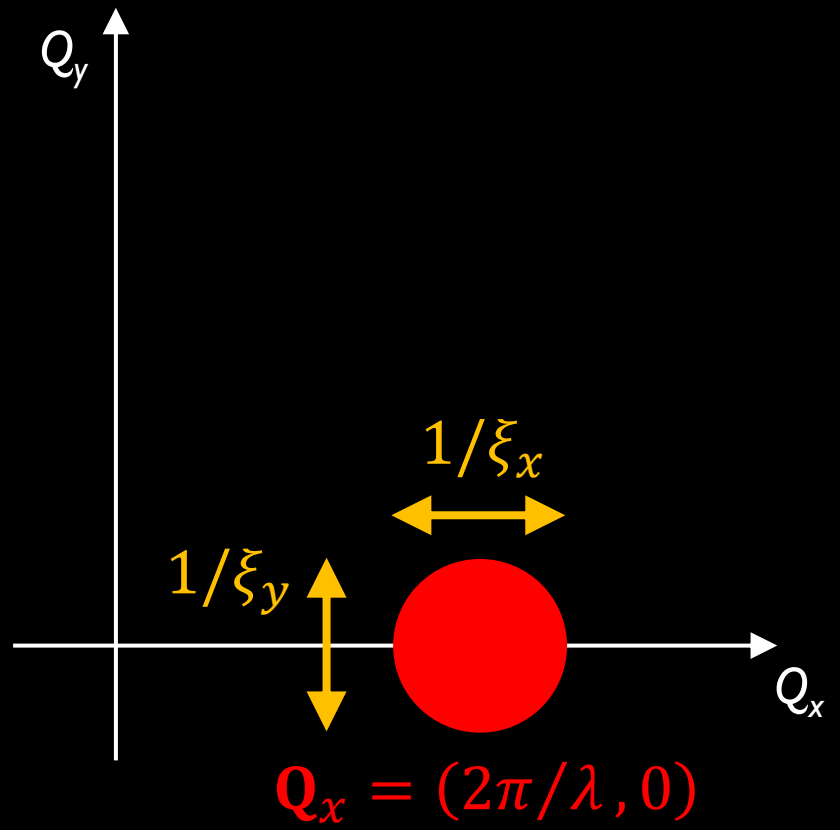
After the discovery of stripelike order in lanthanum-based copper oxide superconductors, charge-ordering instabilities were observed in all cuprate families. However, it has proven difficult to distinguish between unidirectional (stripes) and bidirectional (checkerboard) charge order in yttrium- and bismuth-based materials. We used resonant x-ray scattering to measure the two-dimensional structure factor in the superconductor $YBa_2Cu_3O_{6+y}$ in reciprocal space. Our data reveal the presence of charge stripe order (i.e., locally unidirectional density waves), which may represent the true microscopic nature of charge modulation in cuprates. At the same time, we find that the well-established competition between charge order and superconductivity is stronger for charge correlations across the stripes than along them, which provides additional evidence for the intrinsic unidirectional nature of the charge order.

Charting out the full reciprocal space

Real space ⟺ Reciprocal space

Stripes + isotropic correlations

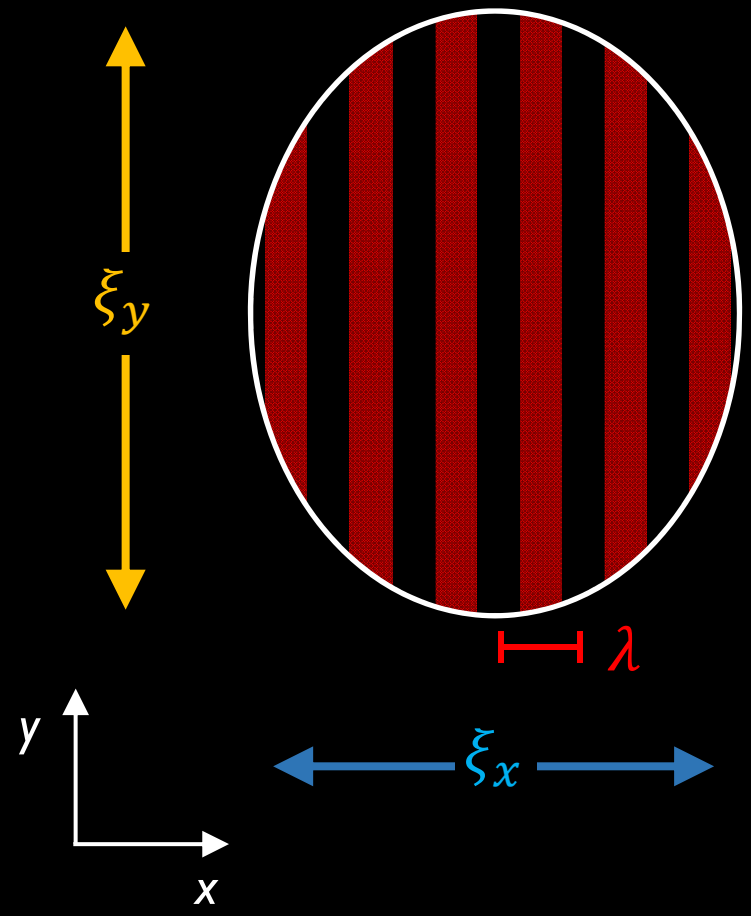


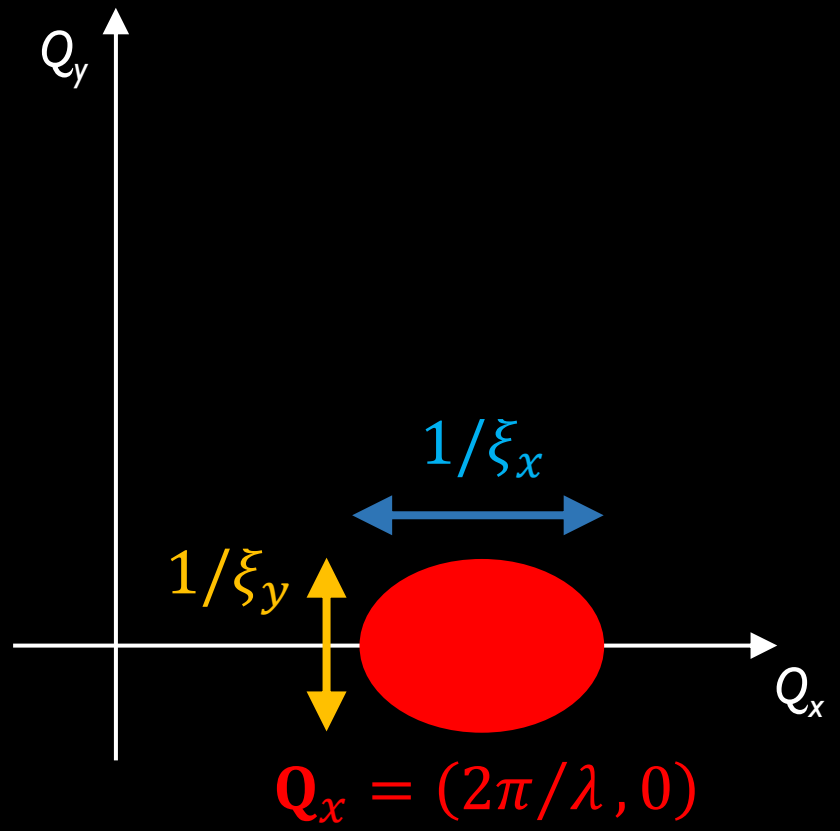


Charting out the full reciprocal space

Real space ⟺ Reciprocal space

Stripes + anisotropic correlations

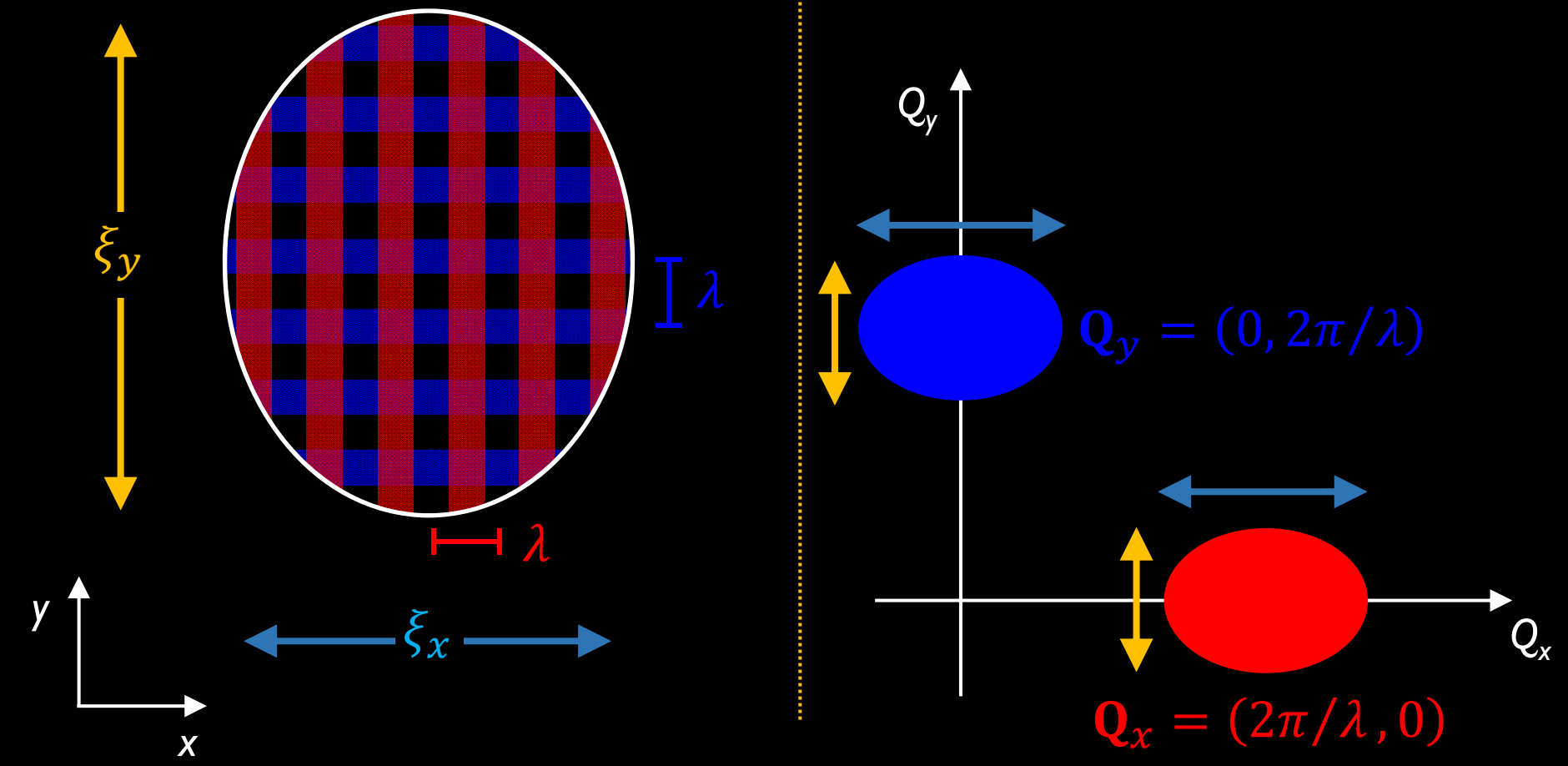




Charting out the full reciprocal space

Real space ⟺ Reciprocal space

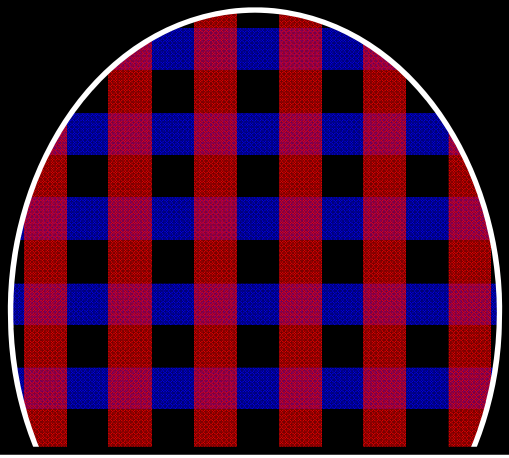
Checkerboard + anisotropic correlations



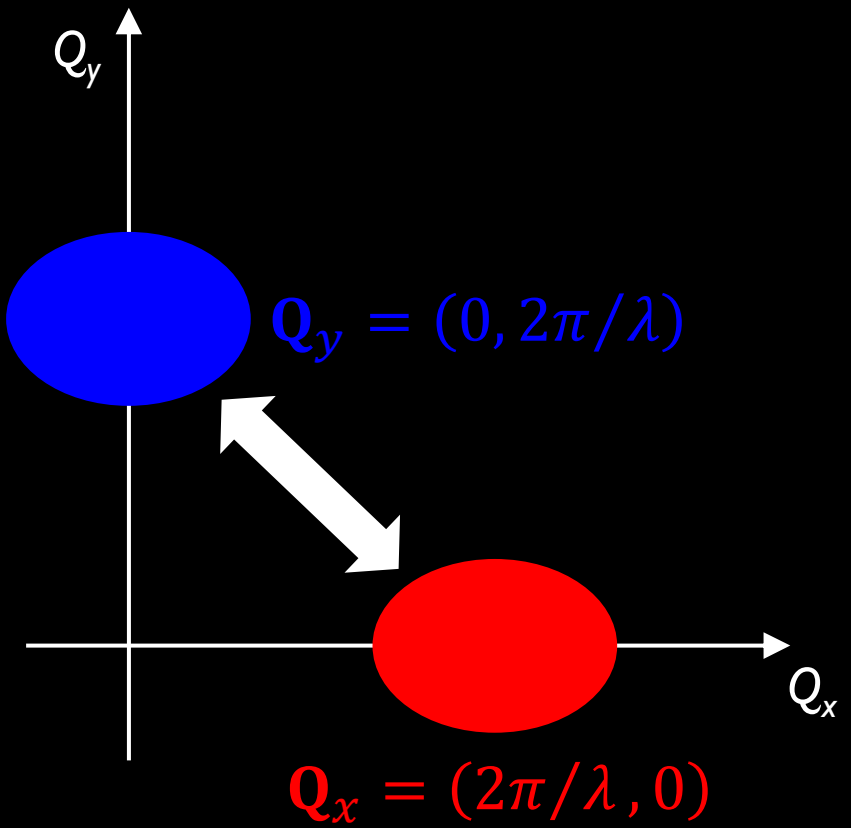
Charting out the full reciprocal space

Real space ⇔ Reciprocal space

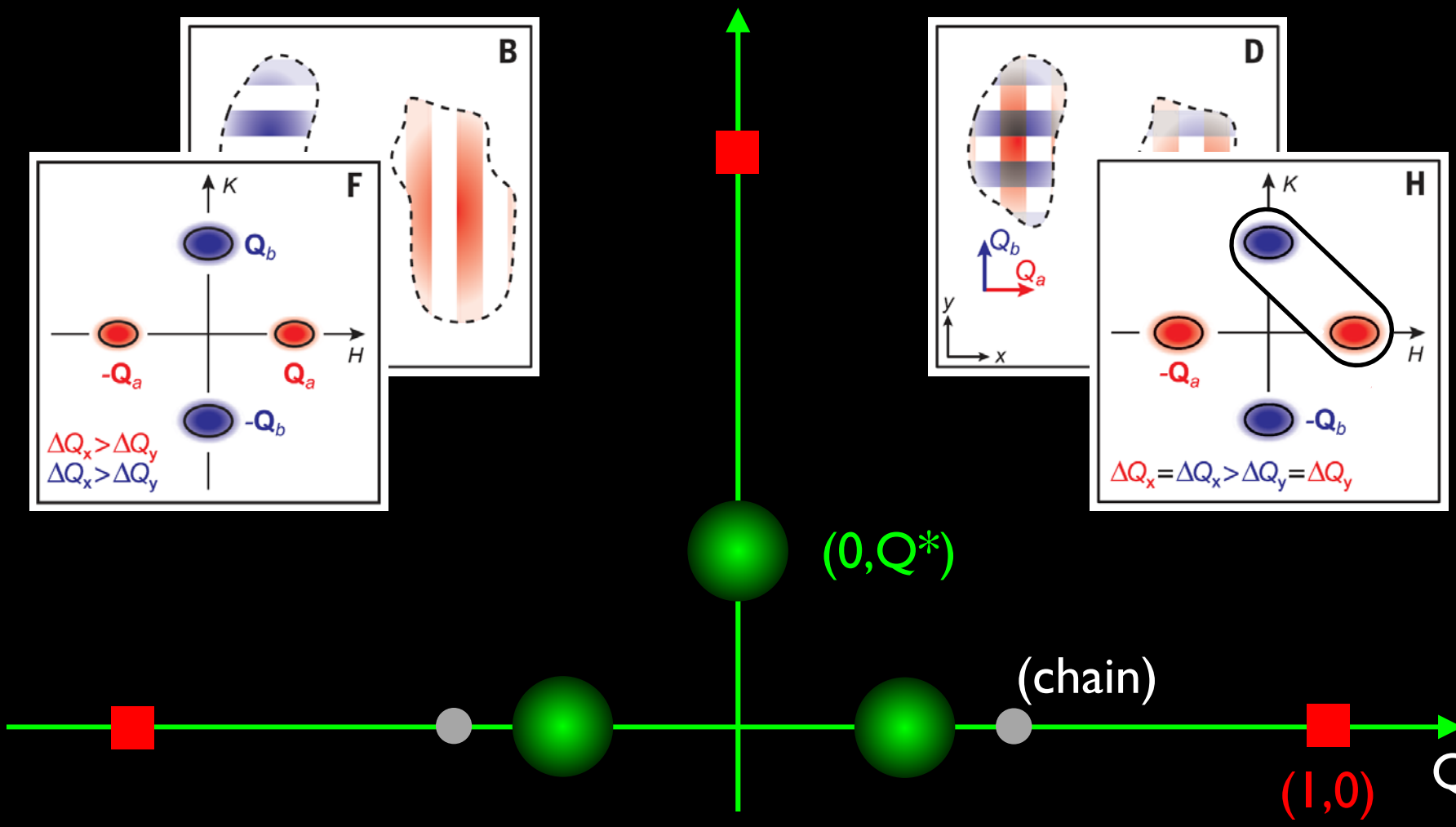
Checkerboard + anisotropic correlations



Bi-directional order (checkerboard) imposes the same CDW structure at (Q,0) and (0,Q)



Tomographic Resonant Elastic X-ray Scattering



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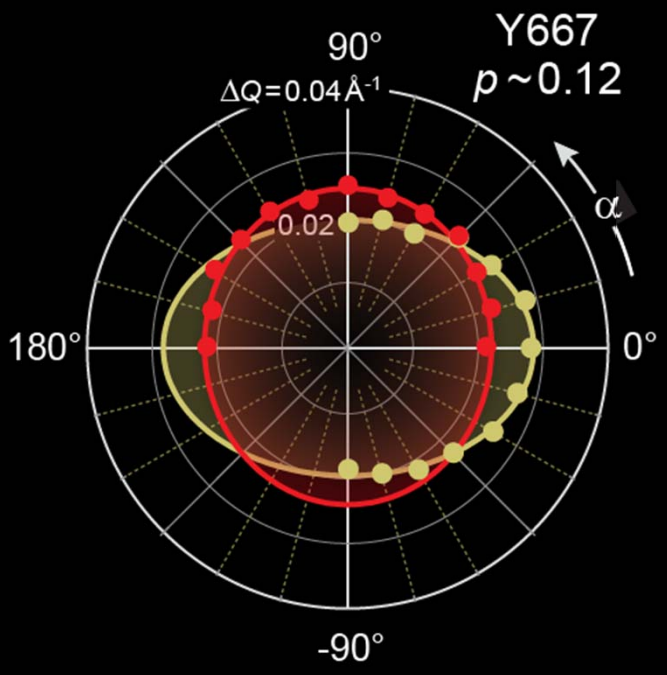
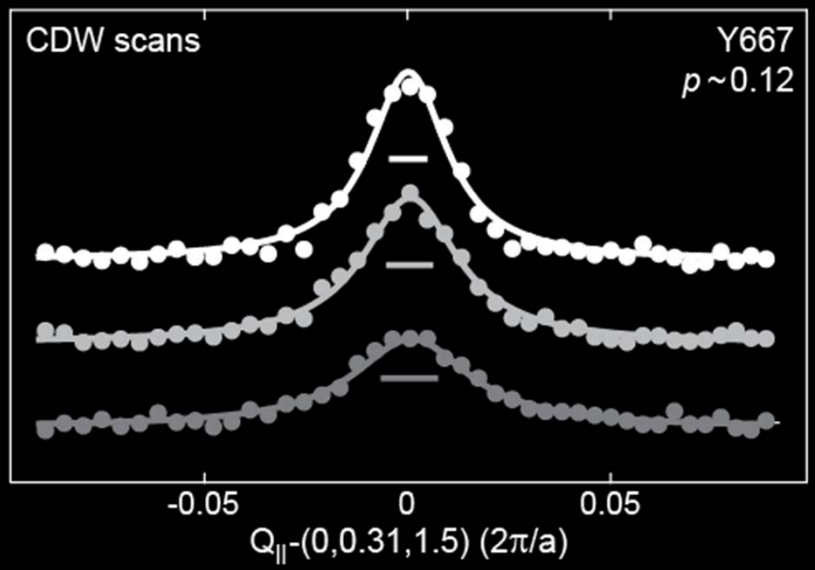
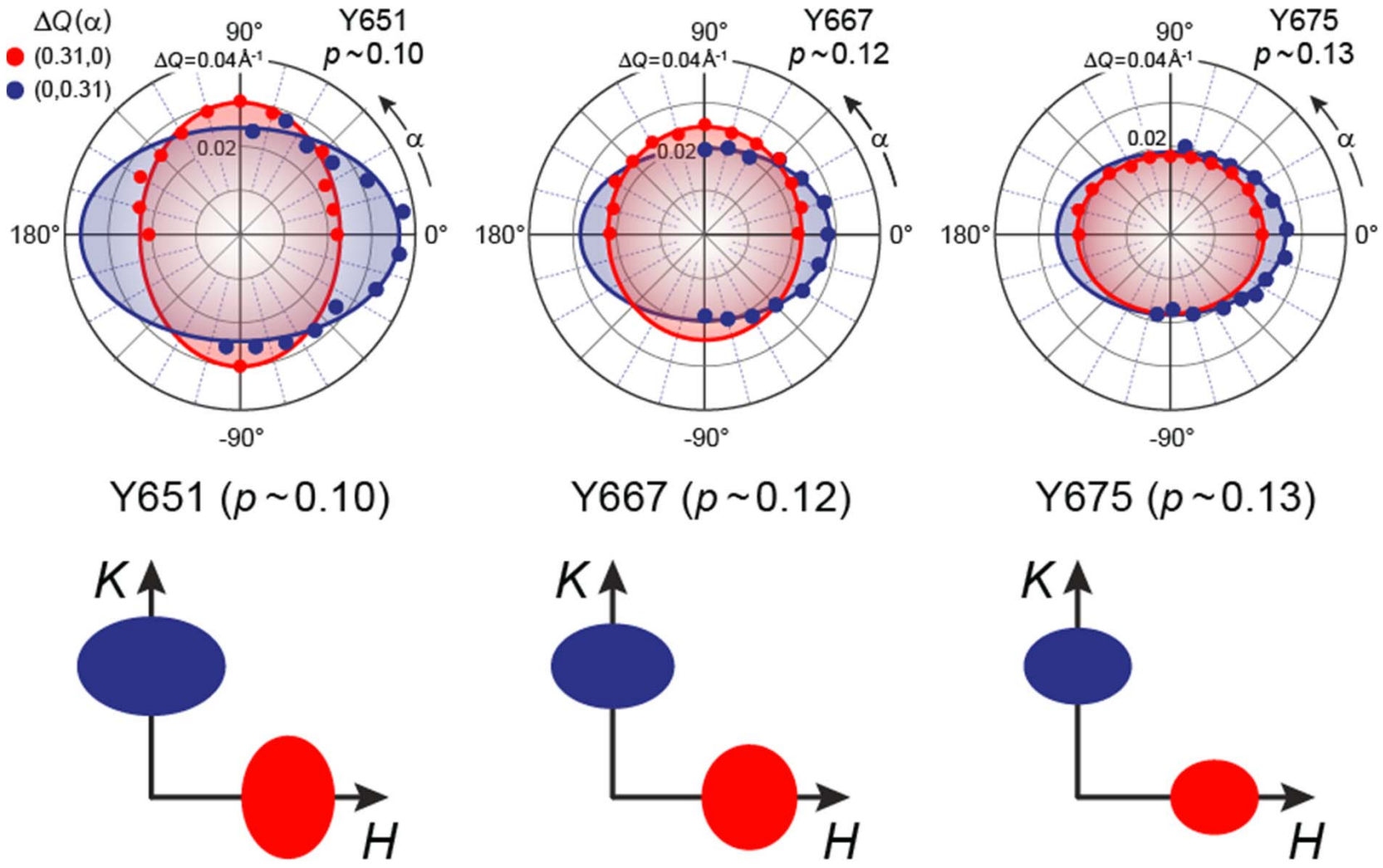
Tomographic Resonant Elastic X-ray Scattering





Tomographic Resonant Elastic X-ray Scattering



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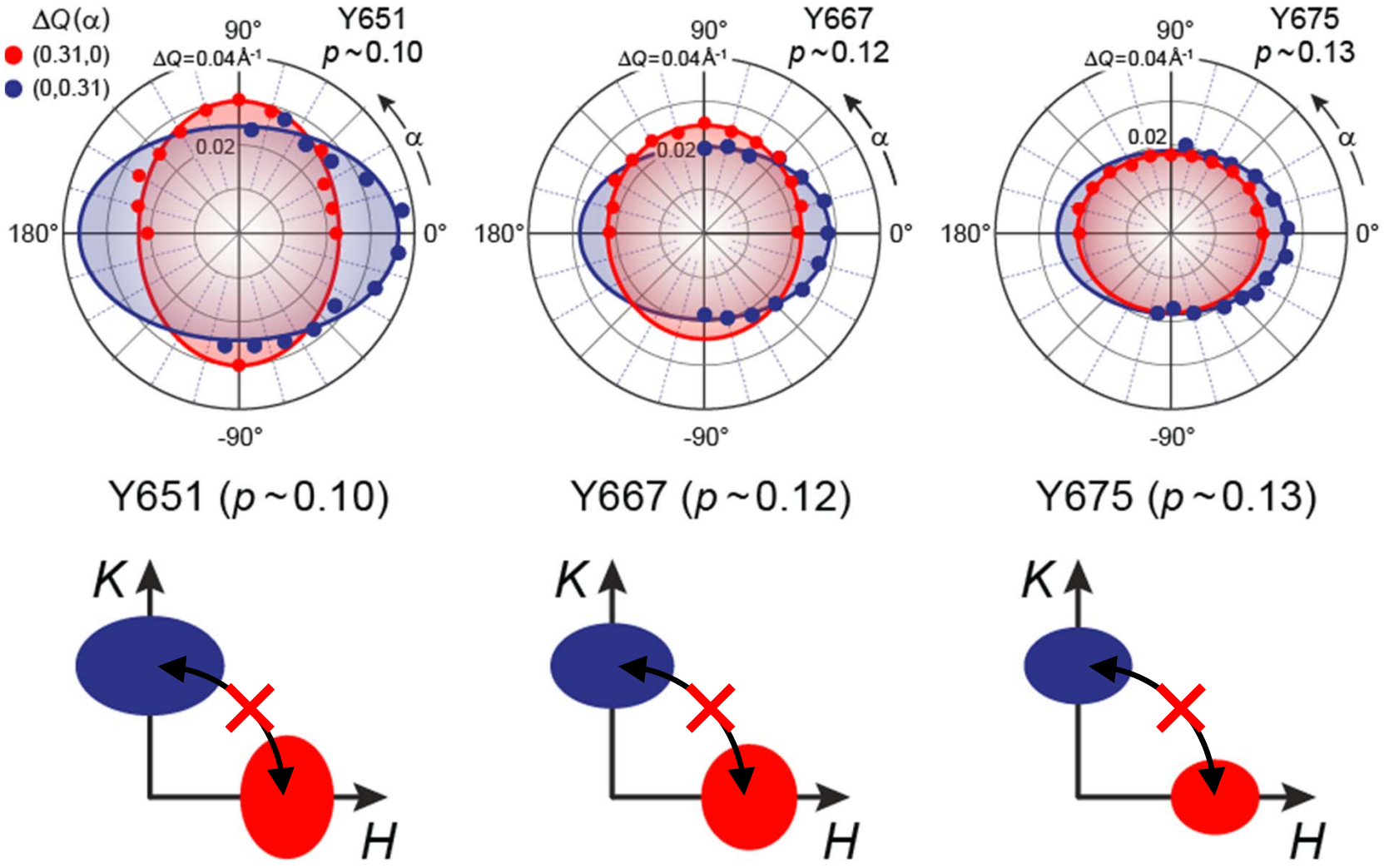
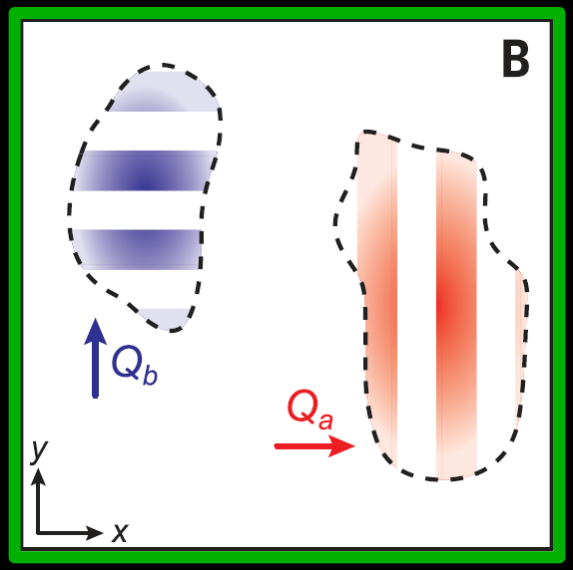
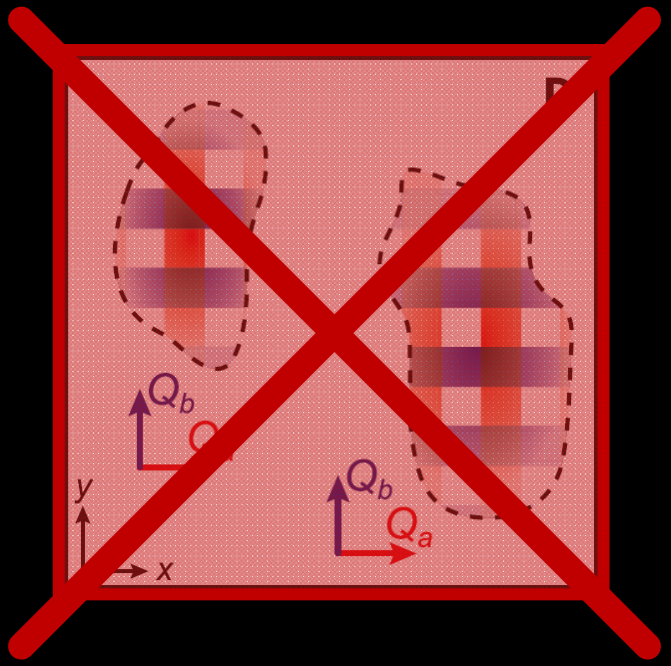


C_4 symmetry breaking NOT sufficient for a stripe state!

Microscopic symmetry of charge order



1D Charge Stripe



2D Checkerboard

Need to resolve 2D CDW peaks to detect the unidirectional charge stripe nature of the order

d-wave vs s-wave / site vs bond order?

The symmetry of charge order in cuprates

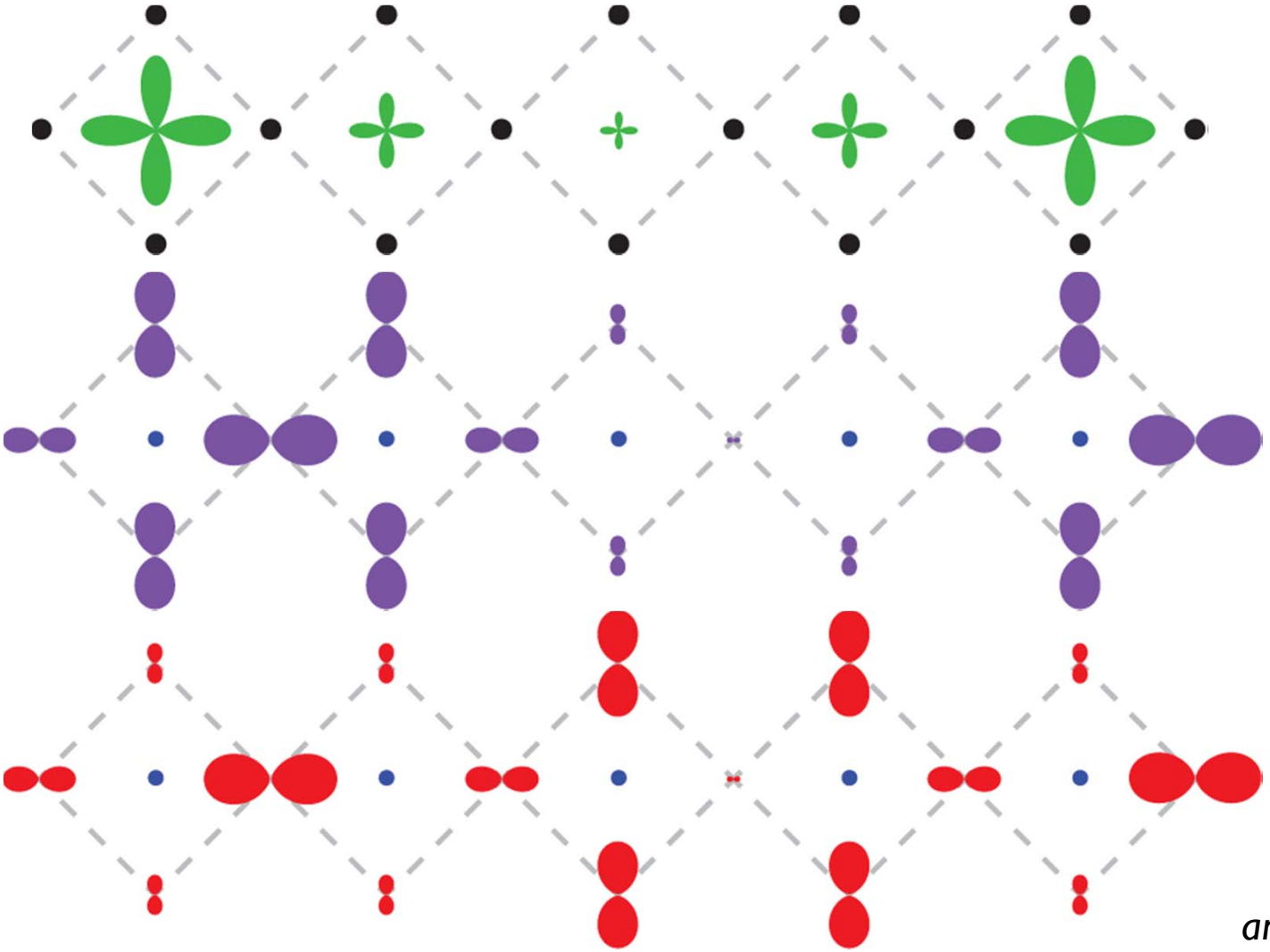
R. Comin,[1,2,*] R. Sutarto,[3] F. He,[3] E. H. da Silva Neto,[1,2,4,5] L. Chauviere,[1,2,4] A. Frano,[4,6] R. Liang,[1,2] W.N. Hardy,[1,2] D.A. Bonn,[1,2] Y. Yoshida,[7] H. Eisaki,[7] A.J. Achkar,[8] D.G. Hawthorn,[8] B. Keimer,[4] G.A. Sawatzky,[1,2] and A. Damascelli[1,2,†]

arXiv:1402.5415 (2014)
Nature Materials in press

The inner symmetry of charge order

S. Sachdev and R. La Placa, *PRL* 111, 027202 (2013)

$$\Delta_{CDW}(\boldsymbol{k}, \boldsymbol{Q}) = \delta(\boldsymbol{Q} - \boldsymbol{Q}^*)$$



Site (*s*)

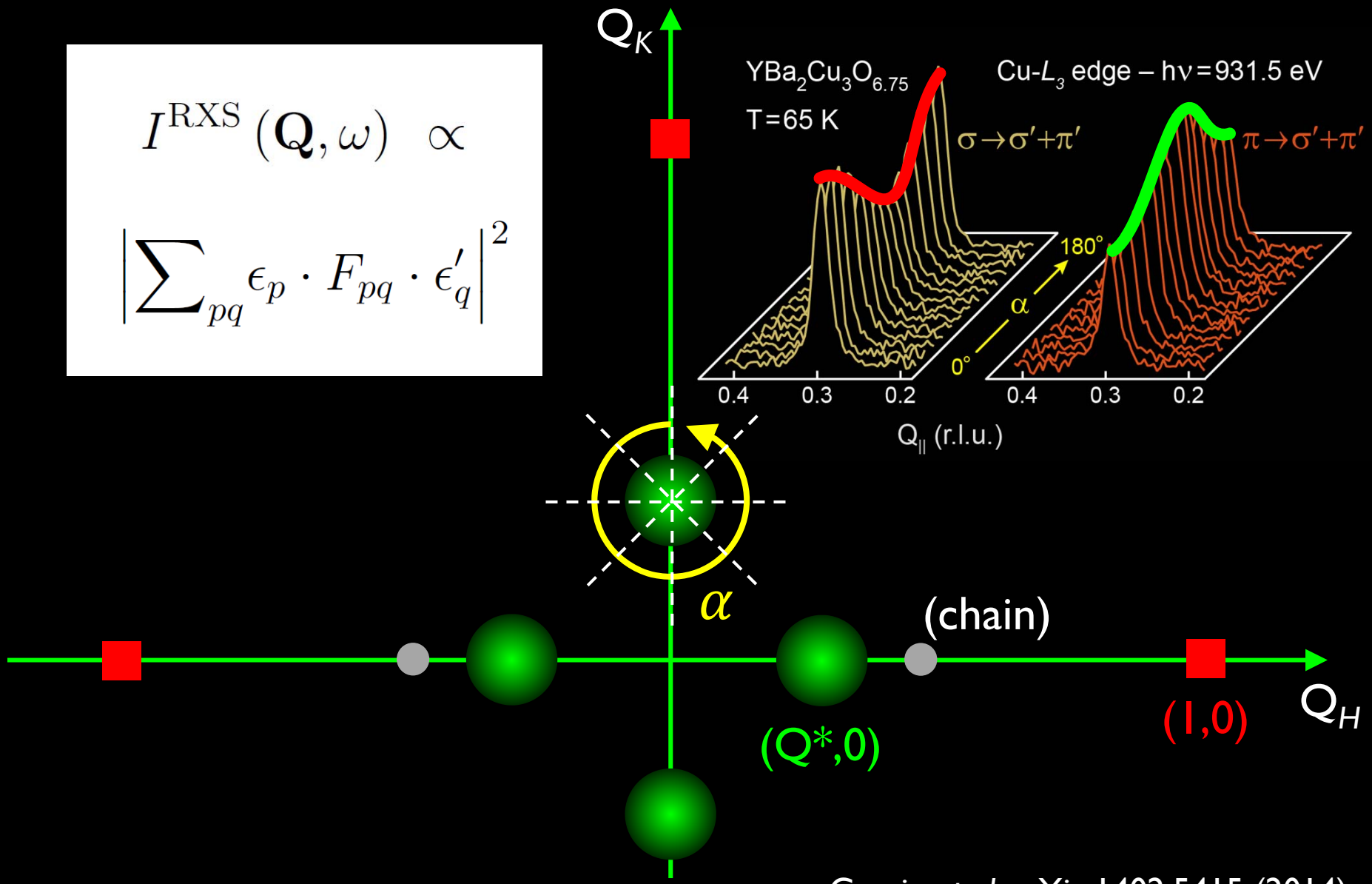
Bond (*s'*)

Bond (*d*)

Comin *et al*, *arXiv:1402.5415* (2014)

Probing the symmetry of charge order in YBCO

$$I^{\mathrm{RXS}}(\mathbf{Q},\omega) \propto \left|\sum_{pq} \epsilon_p \cdot F_{pq} \cdot \epsilon'_q\right|^2$$



Comin *et al*, arXiv:1402.5415 (2014)

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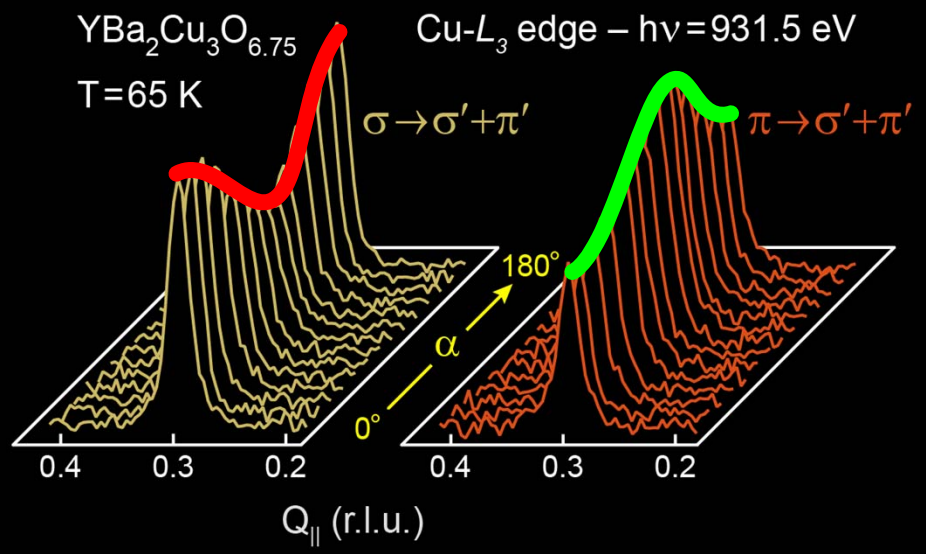
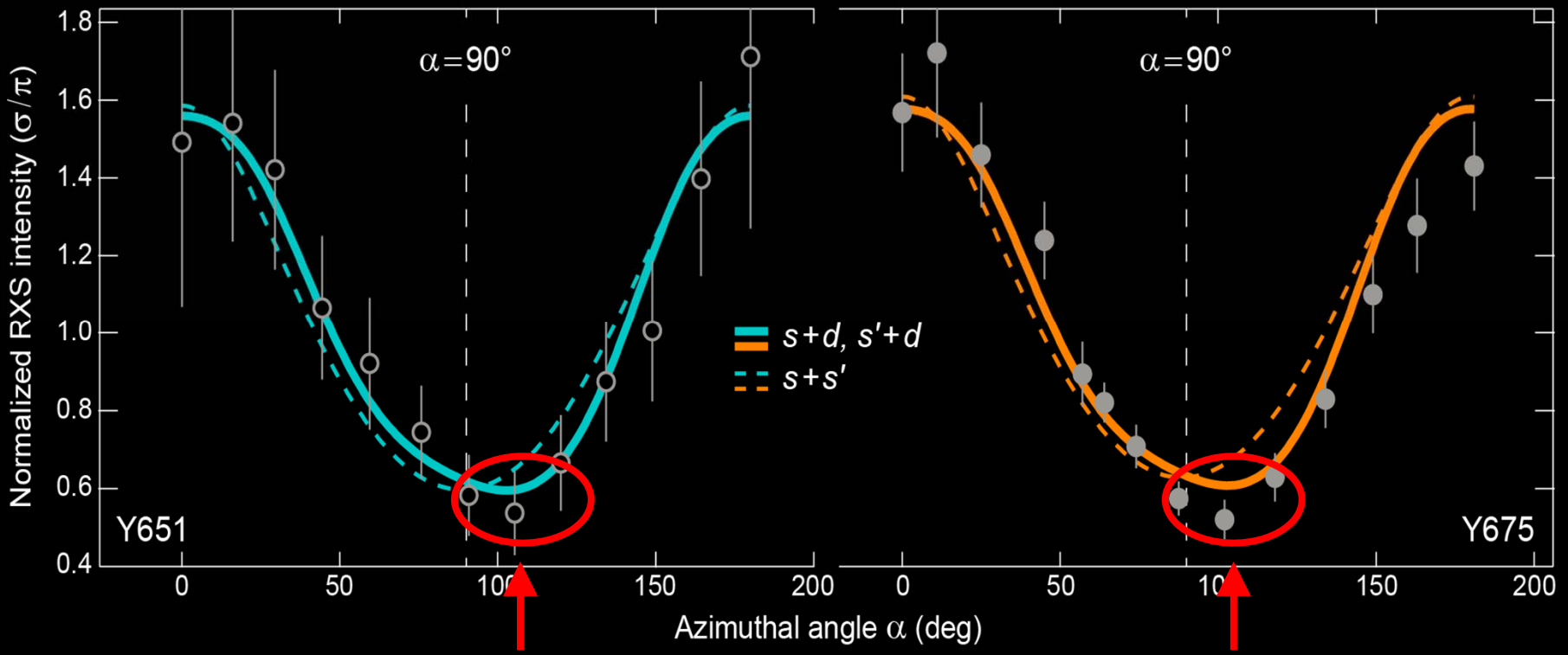
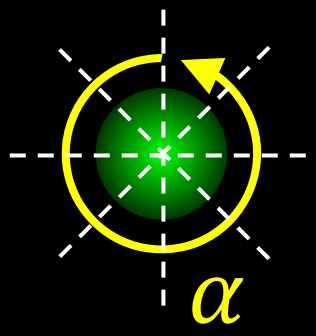


$$F_{pq}(\pm\mathbf{Q}_{\mathrm{CO}}) = \begin{vmatrix} \delta_s + (\delta_{s'} + \delta_d)\cos\phi & 0 & 0 \\ 0 & \delta_s + \delta_{s'} - \delta_d & 0 \\ 0 & 0 & \gamma\delta_s \end{vmatrix}$$

Comin *et al*, arXiv:1402.5415 (2014)

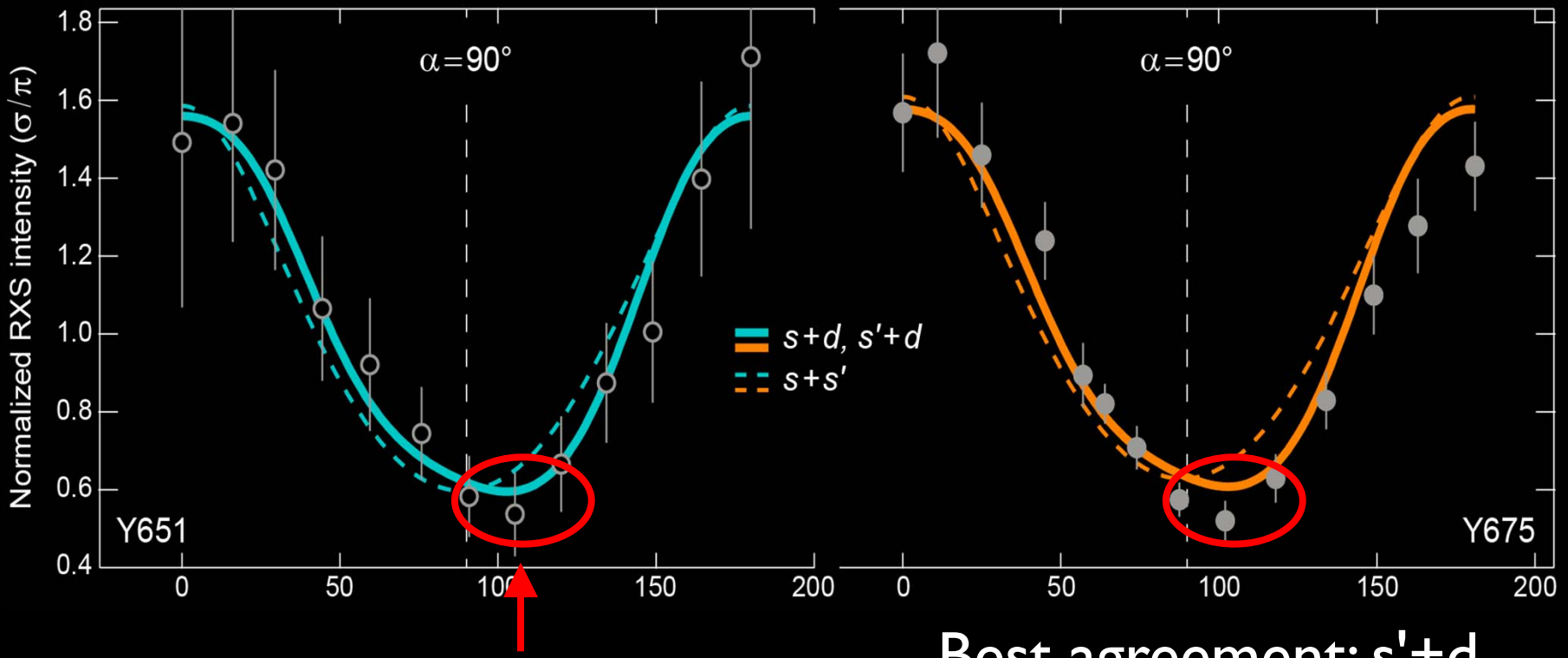
Probing the symmetry of charge order in YBCO

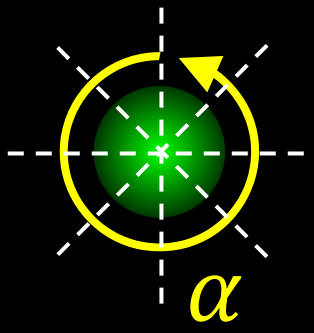




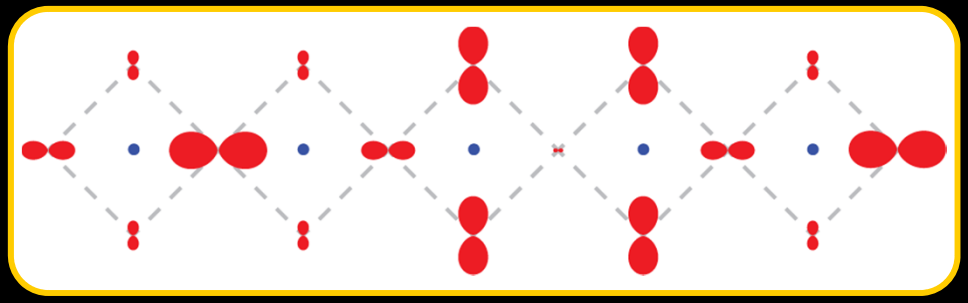
Comin *et al*, arXiv:1402.5415 (2014)

Probing the symmetry of charge order in YBCO





Best agreement: s'+d,
with 70% d- and 30% s'-wave



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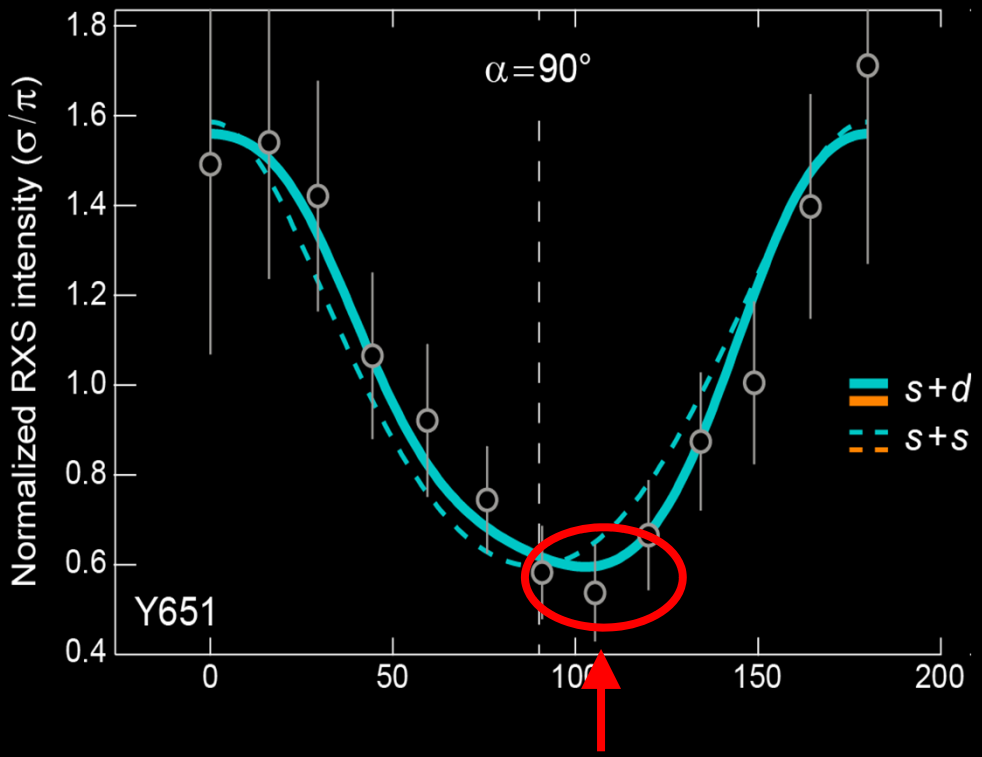
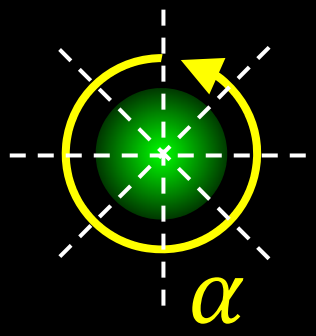
Probing the symmetry of charge order in YBCO





RXS (this work)

YBCO: prominent d symmetry

Bi2201: inconclusive

STM

(Fujita et al, PNAS 2014)

Bi2212, Na-CCOC:

dominant d-wave form factor

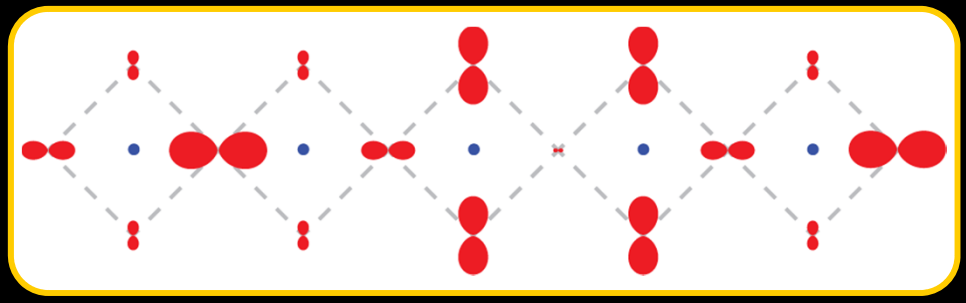
RXS

(Achkar et al, arXiv:1409.6787)

LBCO: dominant s' symmetry

Best agreement: s'+d,

with 70% d- and 30% s'-wave



Comin *et al*, arXiv:1402.5415 (2014)

Charge Ordering in electron-doped cuprates ?

SUPERCONDUCTIVITY

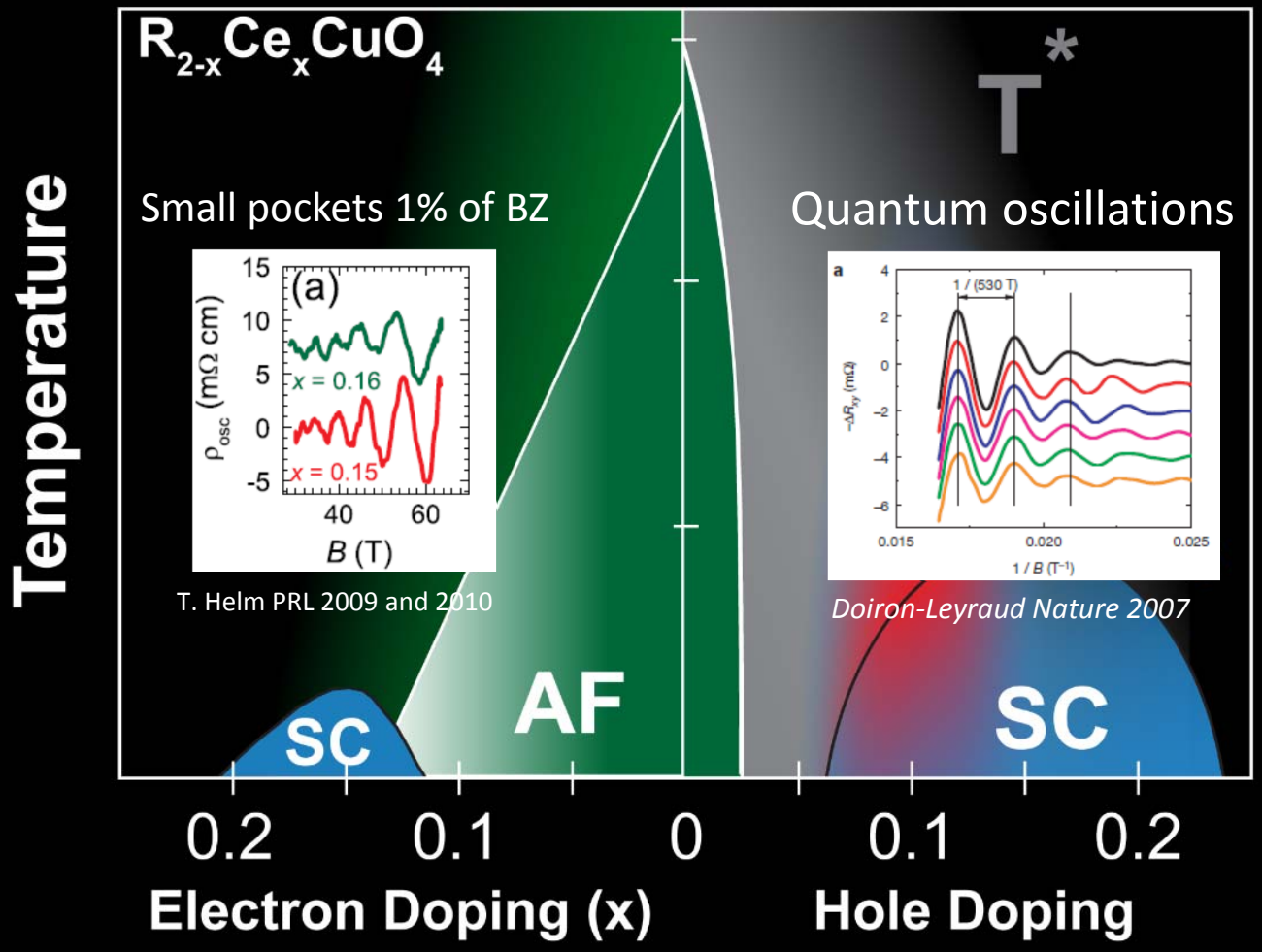
Science **347**, 282 (2015)

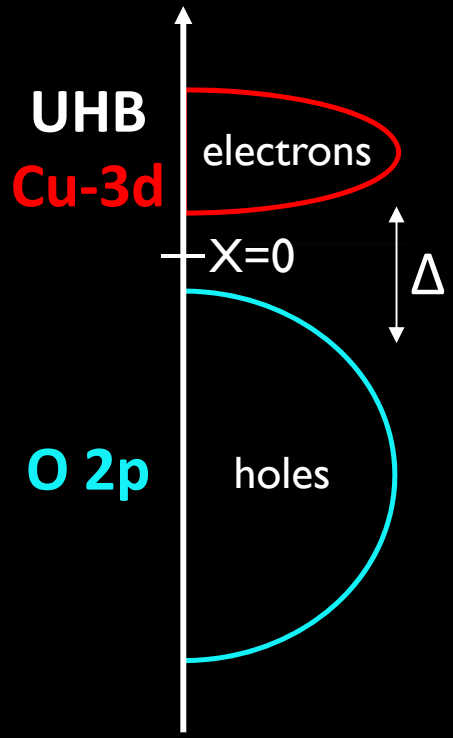
Charge ordering in the electron-doped superconductor $Nd_{2-x}Ce_xCuO_4$

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

In cuprate high-temperature superconductors, an antiferromagnetic Mott insulating state can be destabilized toward unconventional superconductivity by either hole or electron doping. In hole-doped (p-type) cuprates, a charge ordering (CO) instability competes with superconductivity inside the pseudogap state. We report resonant x-ray scattering measurements that demonstrate the presence of charge ordering in the n-type cuprate $Nd_{2-x}Ce_xCuO_4$ near optimal doping. We find that the CO in $Nd_{2-x}Ce_xCuO_4$ occurs with similar periodicity, and along the same direction, as in p-type cuprates. However, in contrast to the latter, the CO onset in $Nd_{2-x}Ce_xCuO_4$ is higher than the pseudogap temperature, and is in the temperature range where antiferromagnetic fluctuations are first detected. Our discovery opens a parallel path to the study of CO and its relationship to antiferromagnetism and superconductivity.

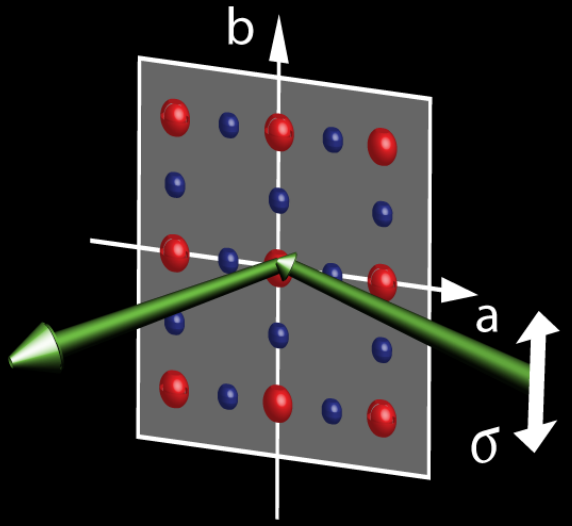
Electron vs. hole-doping asymmetry in Cuprates

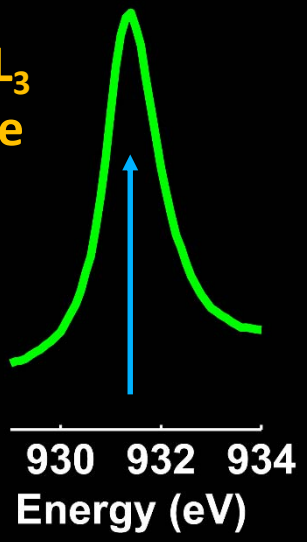




Charge Ordering in $Nd_{2-x}Ce_xCuO_4$!

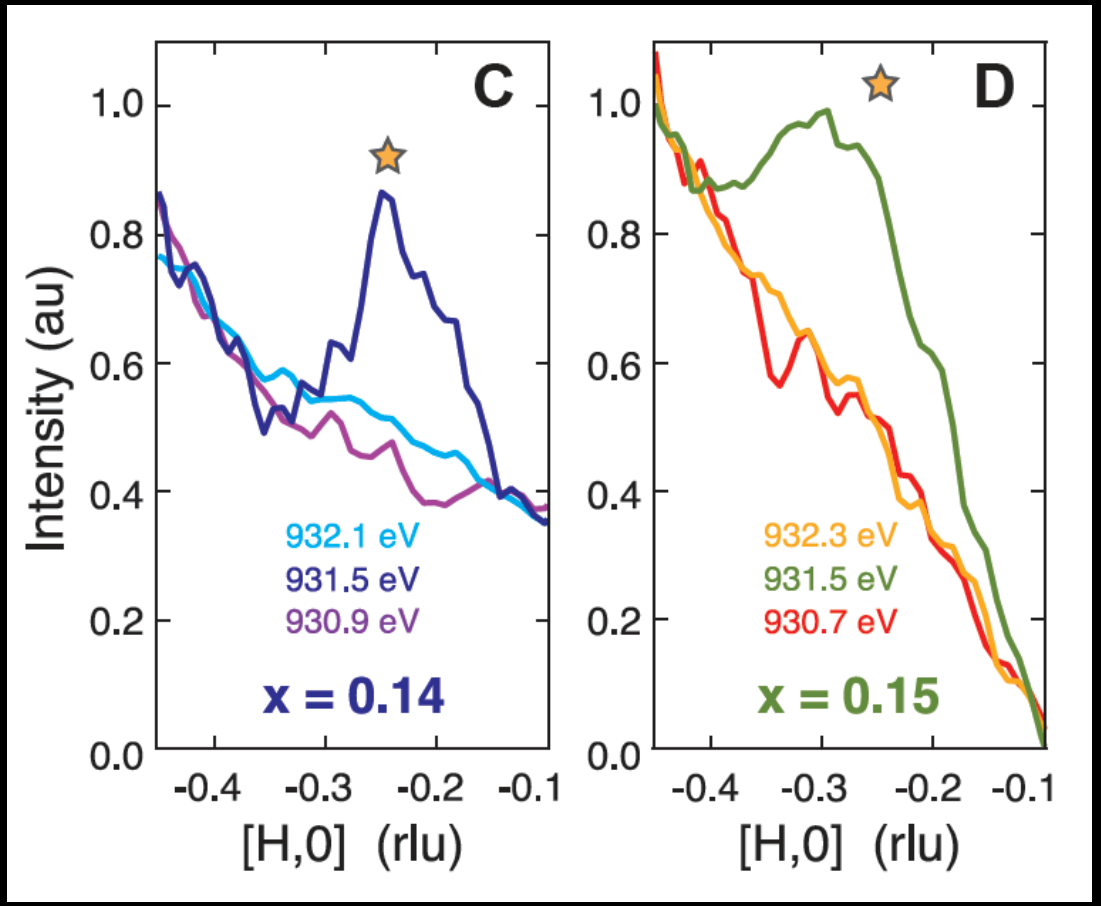
RXS





Resonance

Electronic origin of CO (CuO_2 plane)

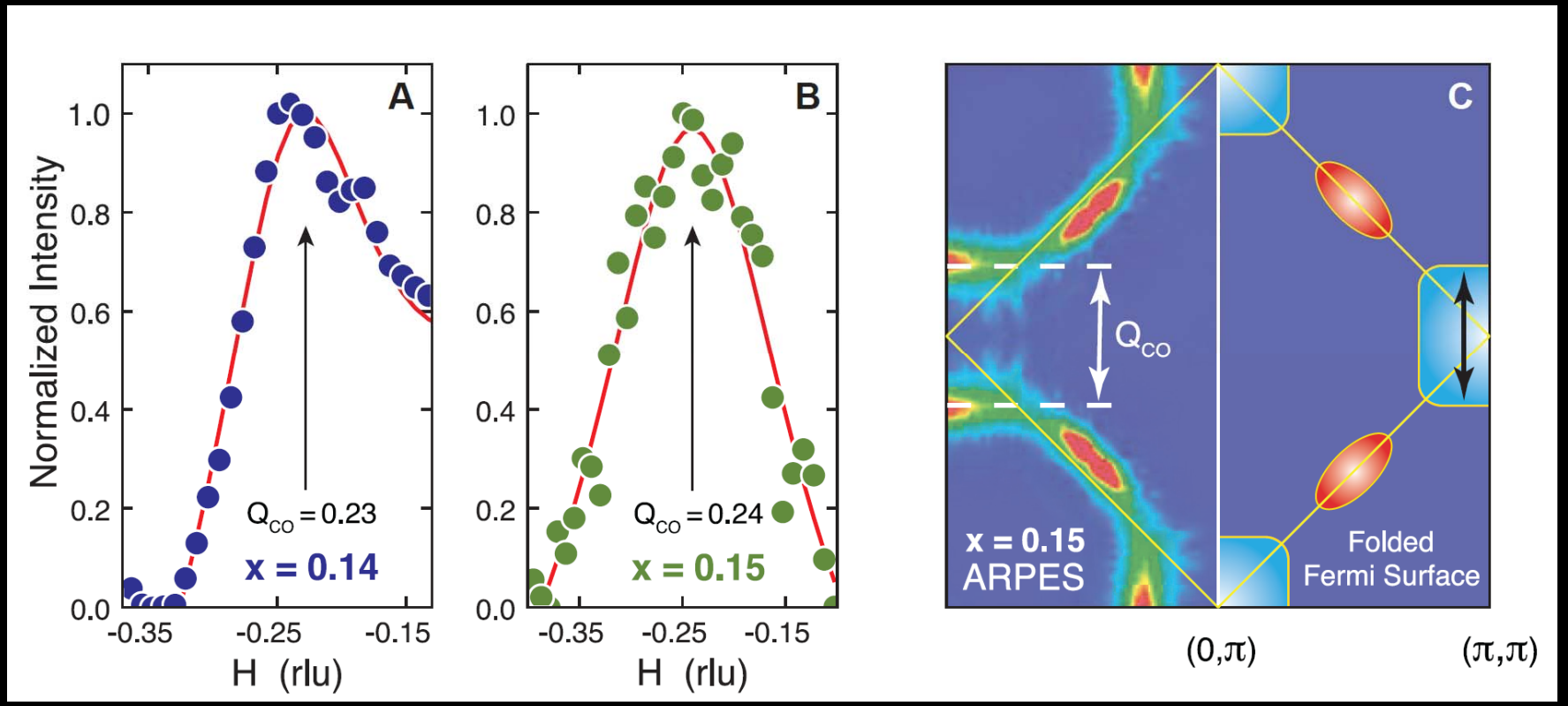


Similar to RXS signal on Bi-based cuprates

Connection Between CO and Fermiology

No gap near (π,0) => Incompatible with conventional nesting

Connects the AF zone boundary ?



Q_{CO} similar to hole-doped systems (ξ = 25 - 35 Angstroms)

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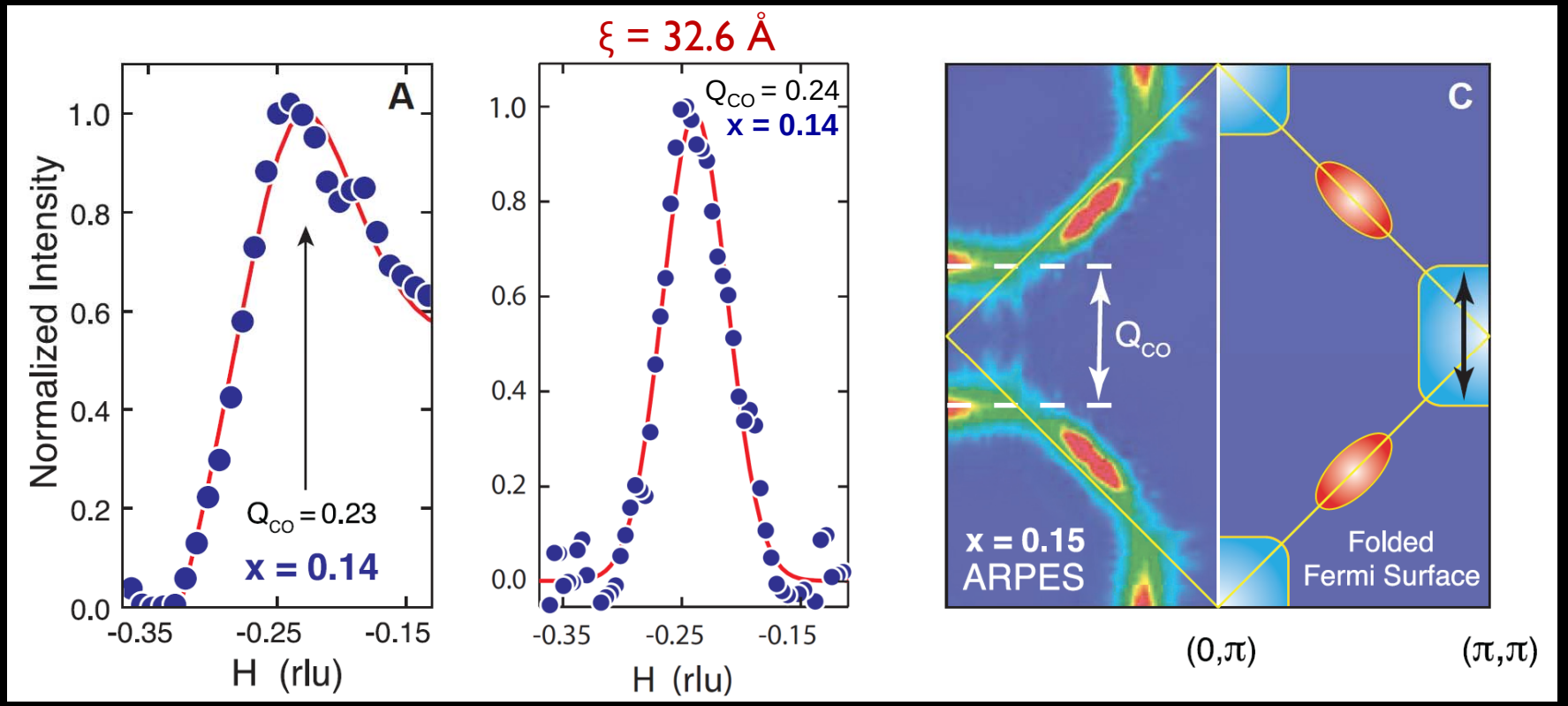
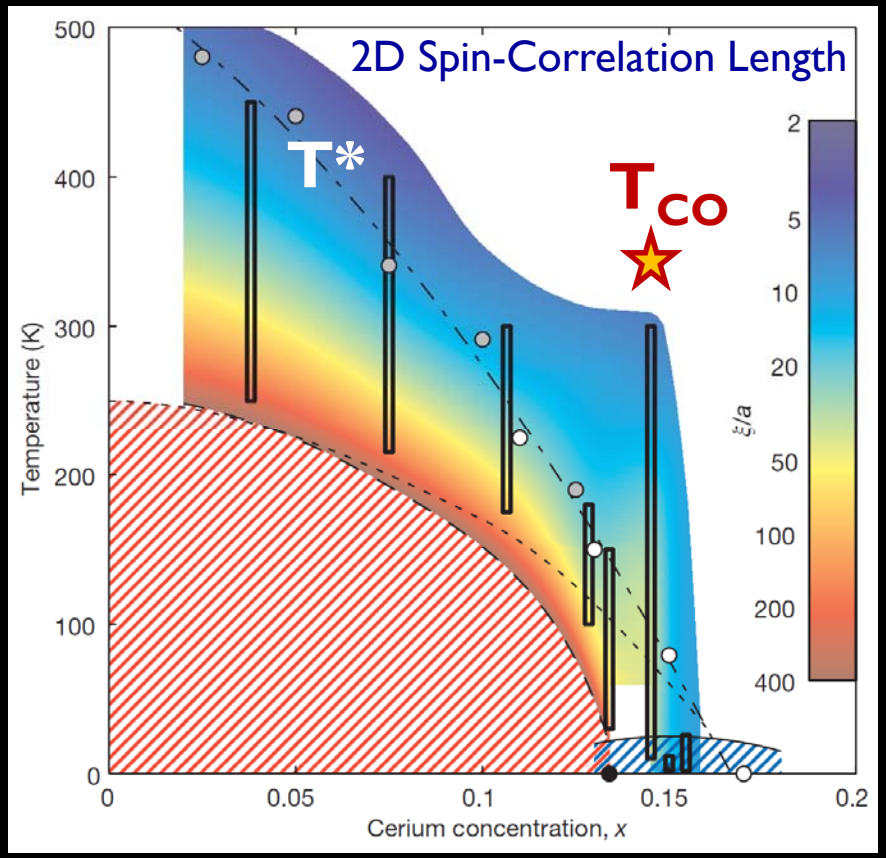


Q_{CO} similar to hole-doped systems (ξ = 25 - 35 Angstroms)

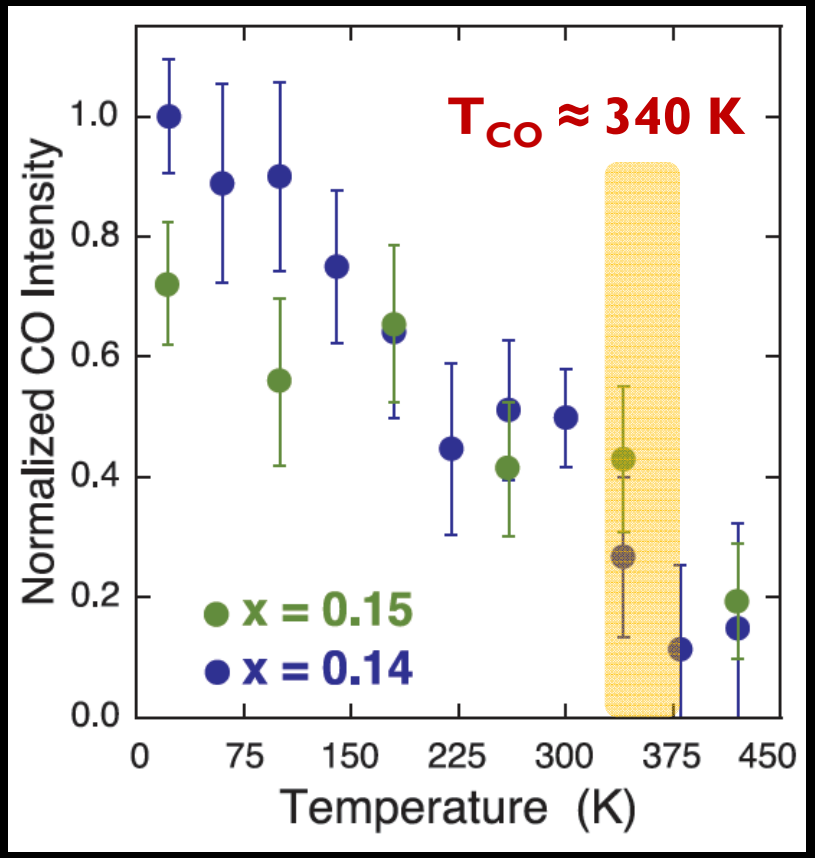
CO Temperature Dependence in NCCO

CO onsets at a higher temperature than pseudogap ($T_{CO} > T^*$)

Charge ordering onsets with AF spin fluctuations?



E.M. Motoyama et al., Nature (2007)



E.H. da Silva Neto et al., Science (2015)

Conclusions

RXS – ARPES – STM

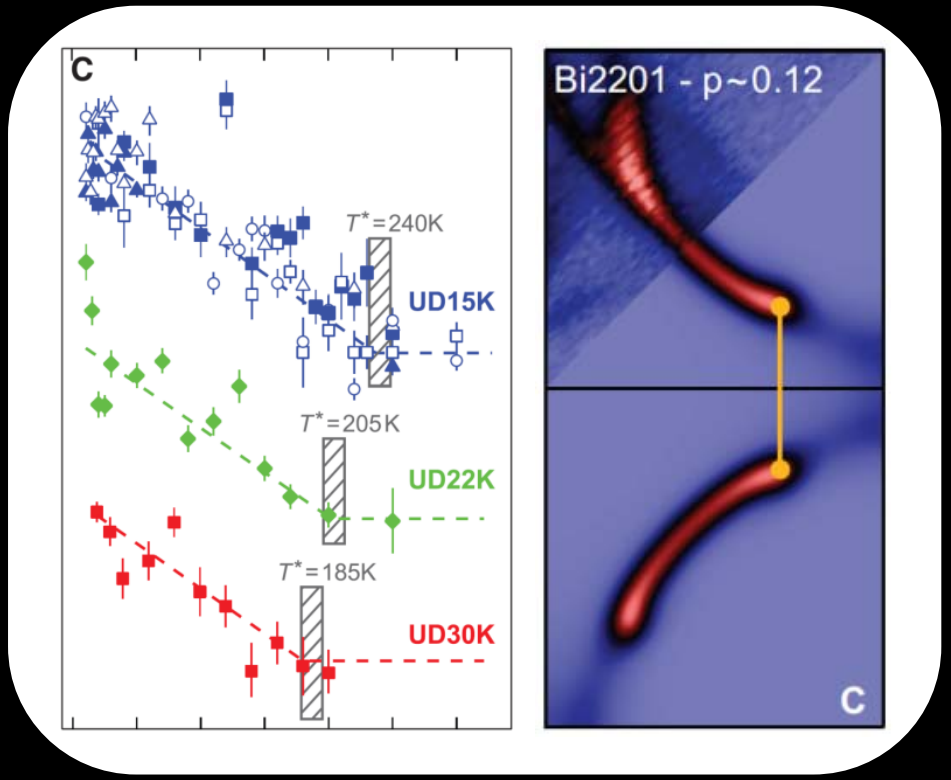
Bulk / surface + real /momentum space

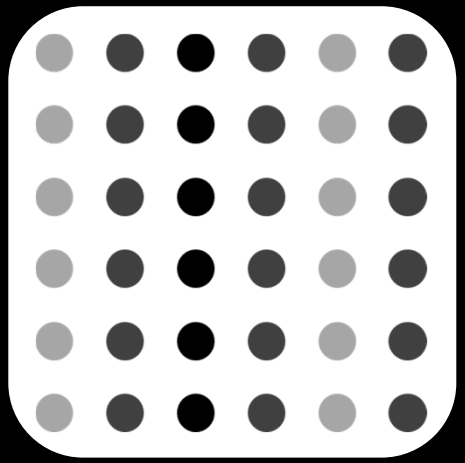
Resonant soft X-ray scattering

Charge order in Bi2201 below T*

Connect CO to fermiology

Fermi-arcs, no AN nesting



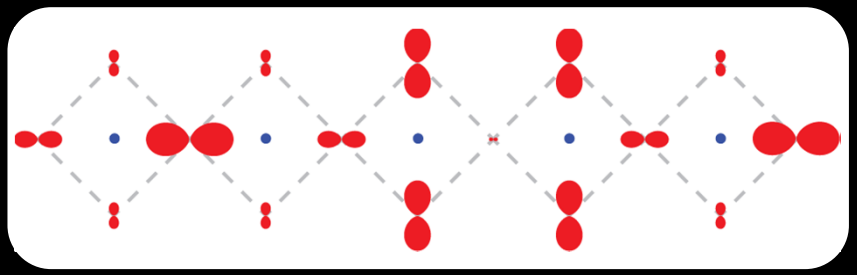


Ubiquitous stripe order in hole-doped cuprates

Longitudinal correlations compete with SC

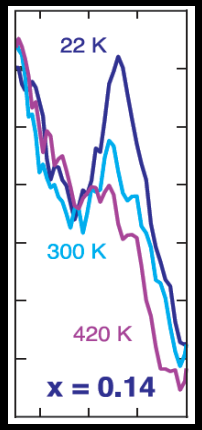
Symmetry of CO:

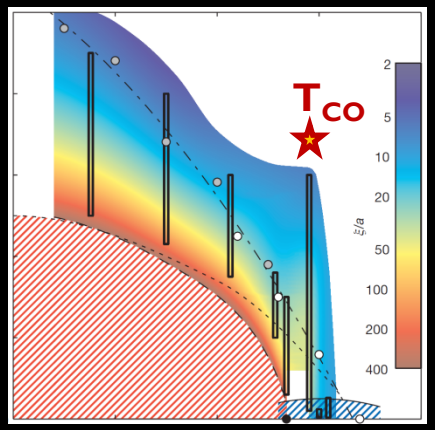
d-wave bond order

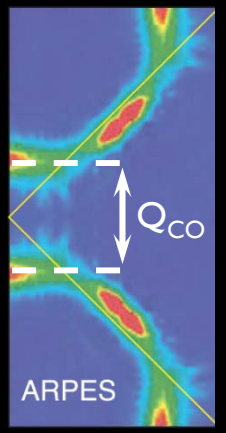


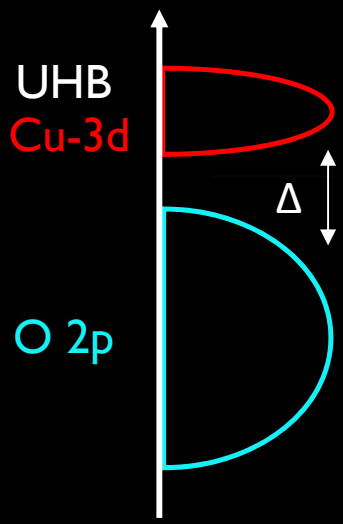
Conclusions

- CO in electron-doped cuprates
- CO onsets with AF fluctuations
- Q_{CO} connects the AF zone boundary in momentum space?



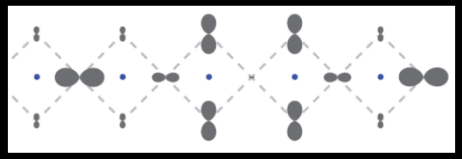






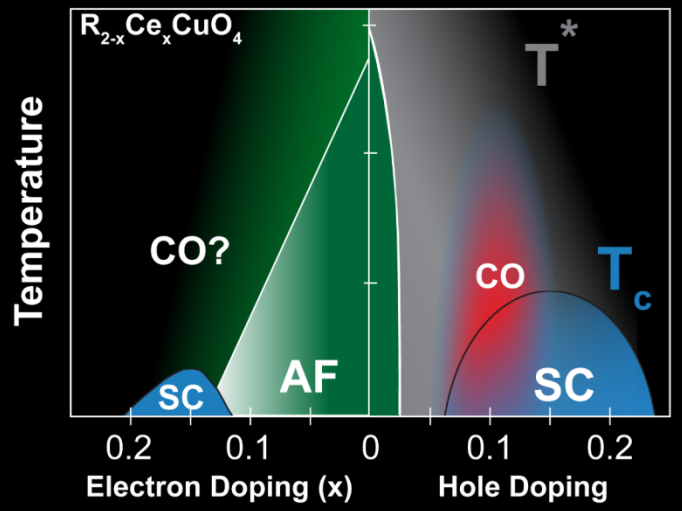
Site-centered ?

Bond-centered !



Comin et al. 1402.5415

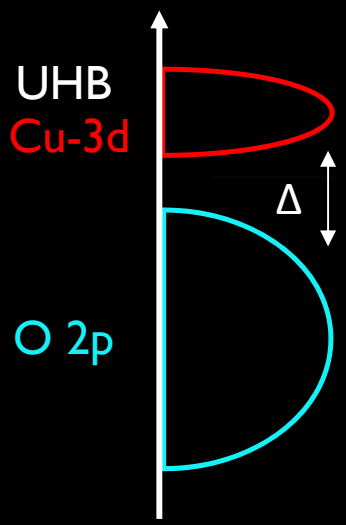
Do specifics of the participating states matter for charge order formation?



Conclusions

CO independent of the electron-hole asymmetry in the electronic structure stemming from the Mott physics?

Is CO a concomitant phenomenon to the emergence of high-Tc superconductivity?



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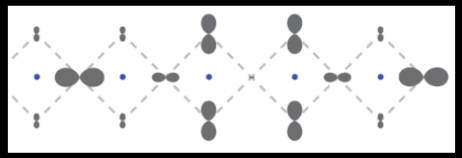

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