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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Bart Ludbrook
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Alessandro Nicolaou
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Andrea Damascelli

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Yang He
A. Soumyanarayanan
Jenny Hoffman

MPI Stuttgart – RXS

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Mathieu Le Tacon
Bernhard Keimer

UBC/CLS – RXS

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UBC – Supercond.

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Doug Bonn
Walter Hardy

BESSY – RXS

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Eugen Weschke

ELETTRA

Luca Petaccia

Groningen -- XRD

Graeme Blake
Thomas Palstra

AIST – Japan

Yoshiyuki Yoshida
Hiroshi Eisaki

University of Maryland

Yeping Jiang
Rick Greene

Charge order in high-T_c cuprates

Spontaneous segregation of charge carriers (holes) in the very lightly doped square CuO_2 plane

D. Poilblanc, T. M. Rice, PRB **39**, 9749 (1989)

J. Zaanen, O. Gunnarsson, PRB **40**, 7391 (1989)

K. Machida, Physica C: Supercond. **158**, 192 (1989)

V. J. Emery, S. A. Kivelson, H. Q. Lin, PRL **64**, 475 (1990)

Evidence for stripe correlations of spins and holes in copper oxide superconductors

J. M. Tranquada*, B. J. Sternlieb†, J. D. Axe*, Y. Nakamura† & S. Uchida†

1995

2002

REPORTS

A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$

J. E. Hoffman,[1] E. W. Hudson,[1,2]* K. M. Lang,[1] V. Madhavan,[1] H. Eisaki,[3]† S. Uchida,[3] J. C. Davis[1,2]‡

Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor

2007

Nicolas Doiron-Leyraud[1], Cyril Proust[2], David LeBoeuf[1], Julien Levallois[2], Jean-Baptiste Bonnemaison[1], Ruixing Liang[3,4], D. A. Bonn[3,4], W. N. Hardy[3,4] & Louis Taillefer[1,4]

Magnetic-field-induced charge-stripe order in the high-temperature superconductor $YBa_2Cu_3O_y$

2011

Tao Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Mladen Horvatić[1], Claude Berthier[1], W. N. Hardy[2,3], Ruixing Liang[2,3], D. A. Bonn[2,3] & Marc-Henri Julien[1]

2012

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

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

2012

Direct observation of competition between superconductivity and charge density wave order in $YBa_2Cu_3O_{6.67}$

J. Chang[1,2]*, E. Blackburn[3], A. T. Holmes[3], N. B. Christensen[4], J. Larsen[4,5], J. Mesot[1,2], Ruixing Liang[6,7], D. A. Bonn[6,7], W. N. Hardy[6,7], A. Watenphul[8], M. v. Zimmermann[8], E. M. Forgan[3] and S. M. Hayden[9]

D. Poilblanc, T. M. Rice, PRB **39**, 9749 (1989)
J. Zaanen, O. Gunnarsson, PRB **40**, 7391 (1989)
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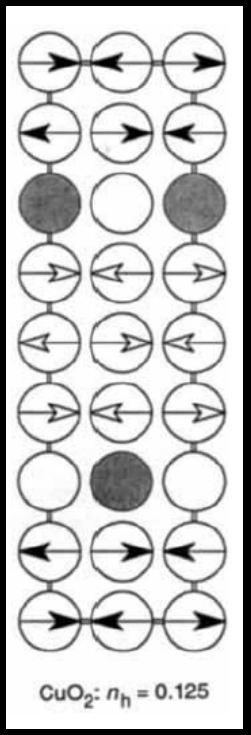
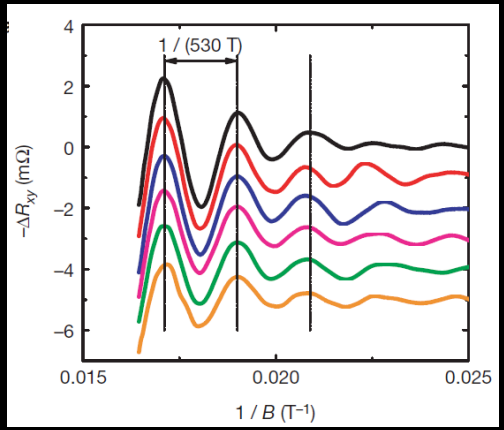


Evidence for stripe correlations of spins and holes in copper oxide superconductors

J. M. Tranquada*, B. J. Sternlieb†, J. D. Axe*, Y. Nakamura† & S. Uchida†

1995



Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor

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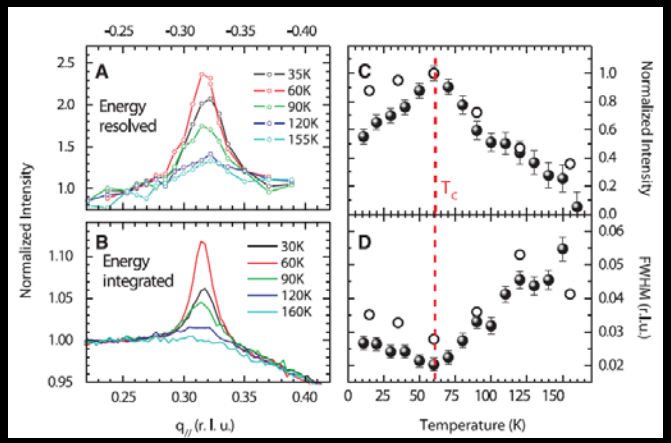
Nicolas Doiron-Leyraud[1], Cyril Proust[2], David LeBoeuf[1], Julien Levallois[2], Jean-Baptiste Bonnemaison[1], Ruixing Liang[3,4], D. A. Bonn[3,4], W. N. Hardy[3,4] & Louis Taillefer[1,4]

2012

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

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



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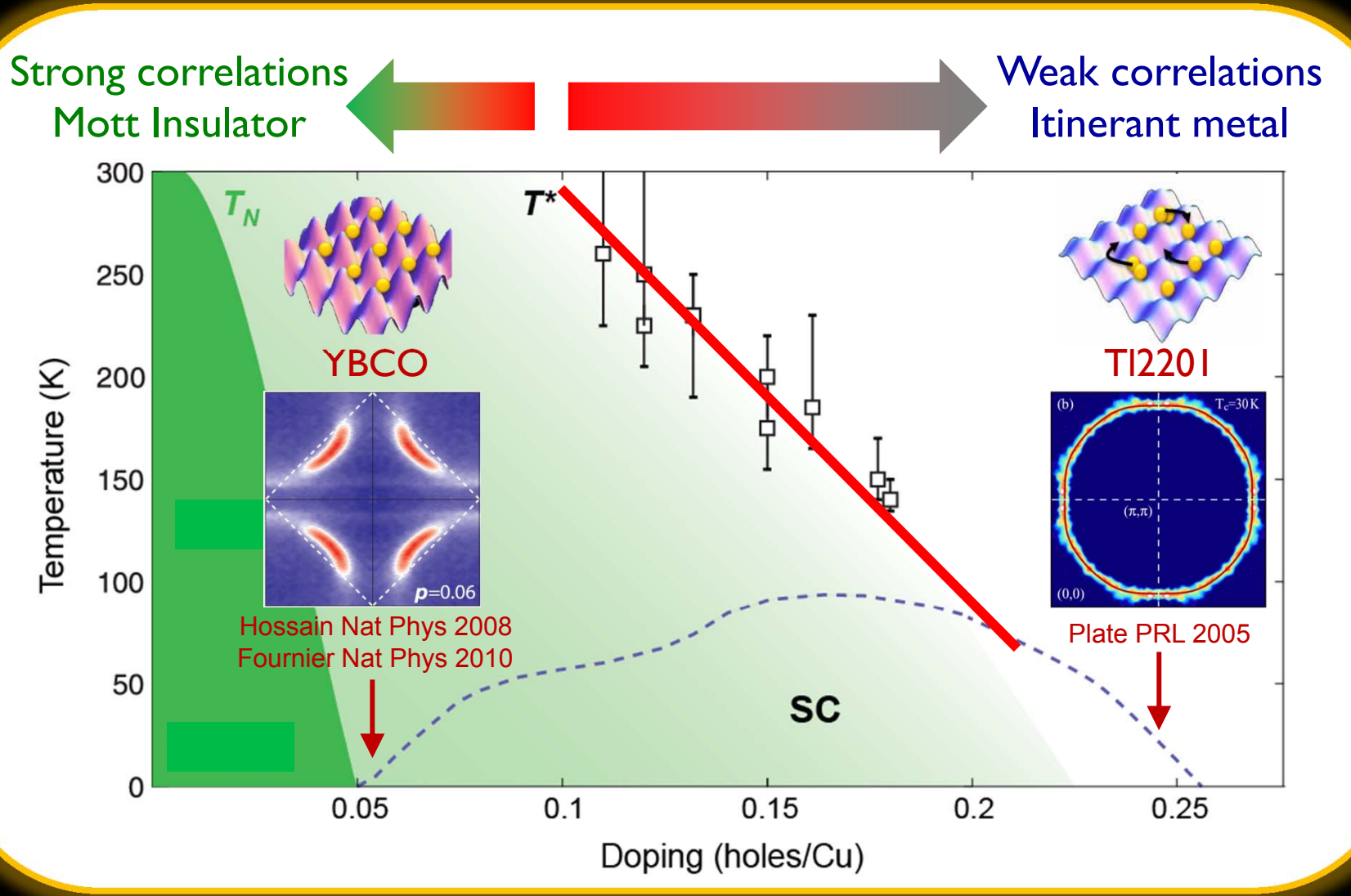
J. Zaanen, O. Gunnarsson, PRB **40**, 7391 (1989)

K. Machida, Physica C: Supercond. **158**, 192 (1989)
V. J. Emery, S. A. Kivelson, H. Q. Lin, PRL **64**, 475 (1990)

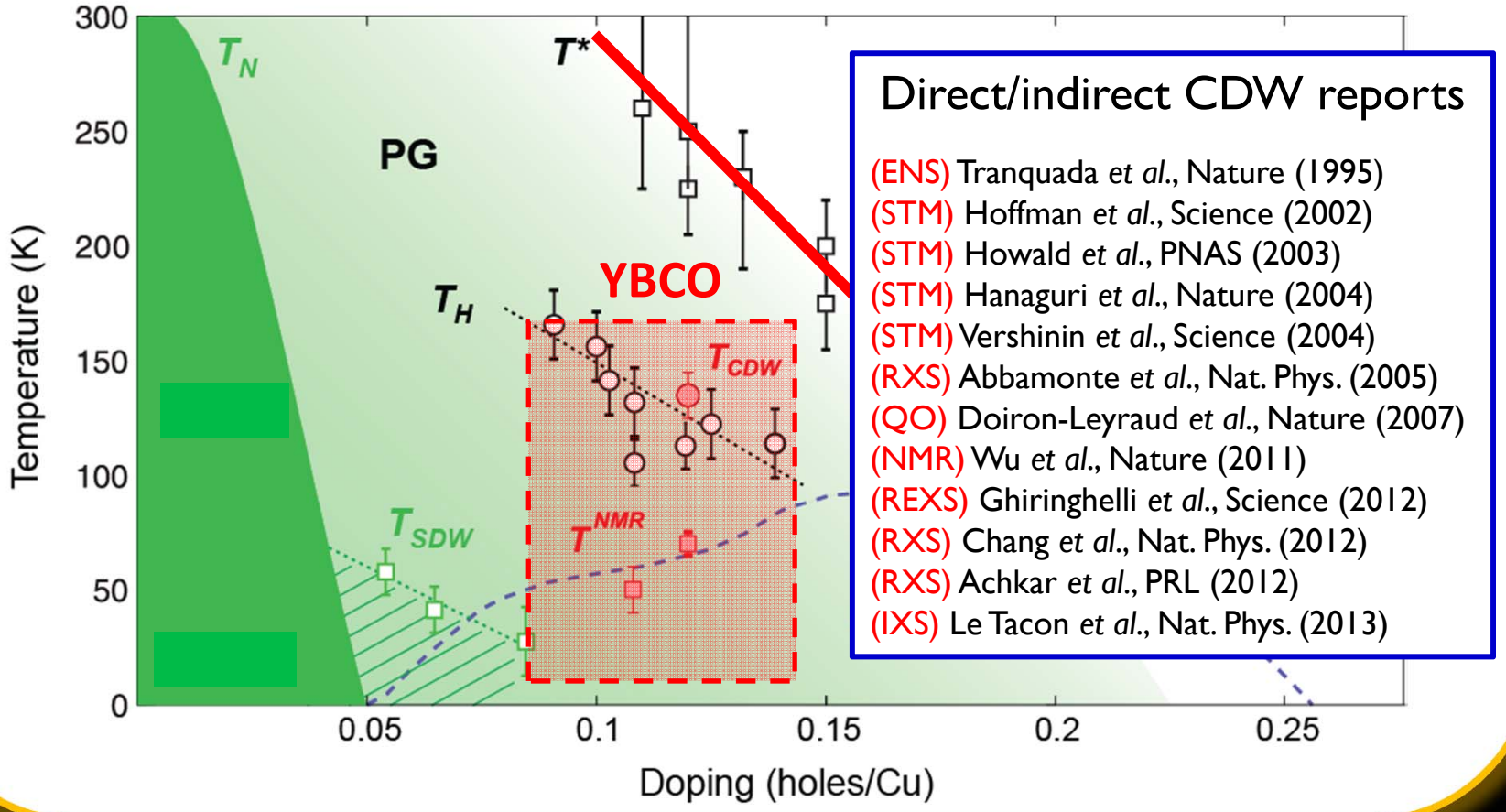
Cuprates: a favourite physicist's playground



Cuprates: a favourite physicist's playground

Strong correlations
Mott Insulator

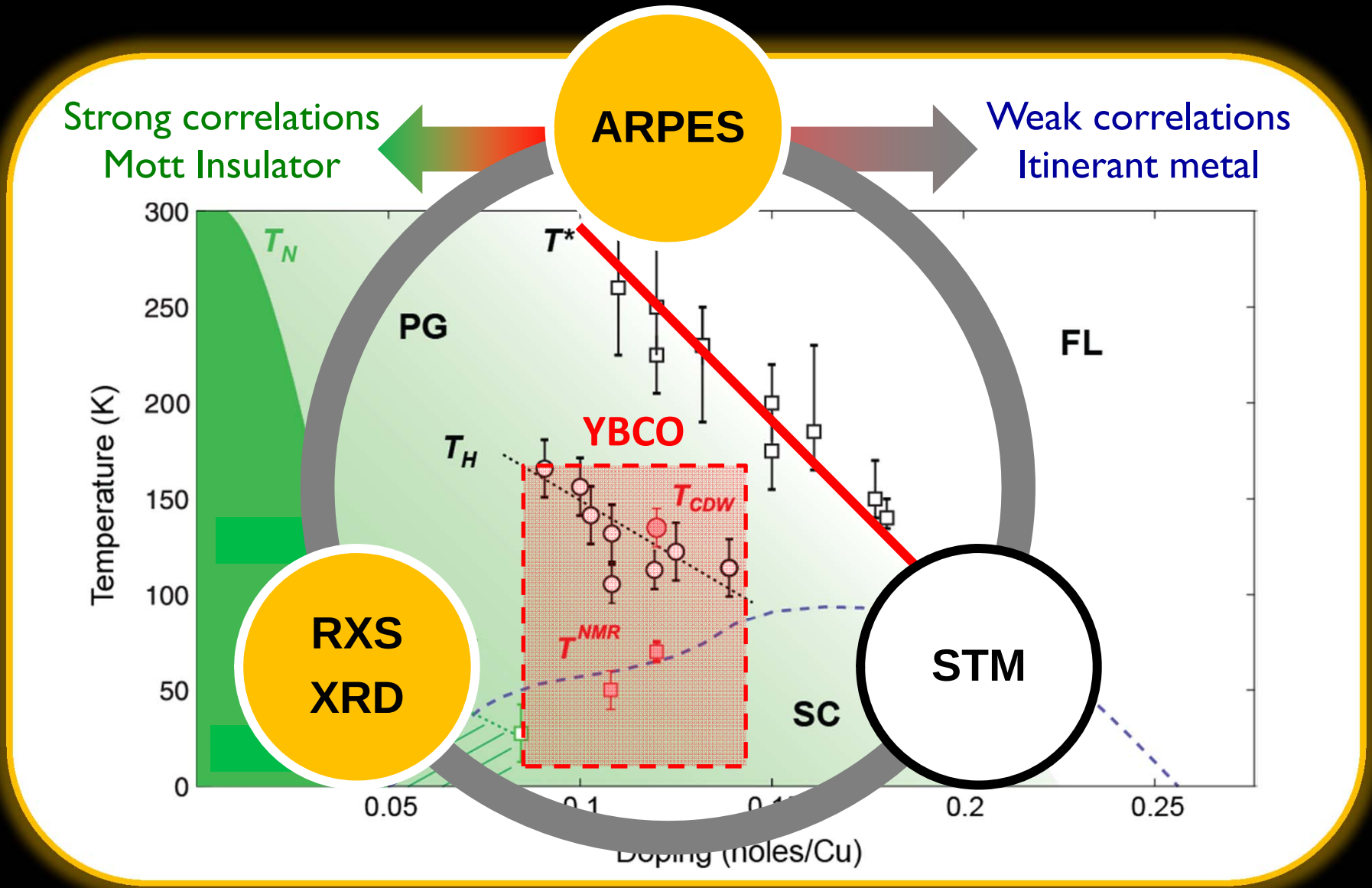
Weak correlations
Itinerant metal



Direct/indirect CDW reports

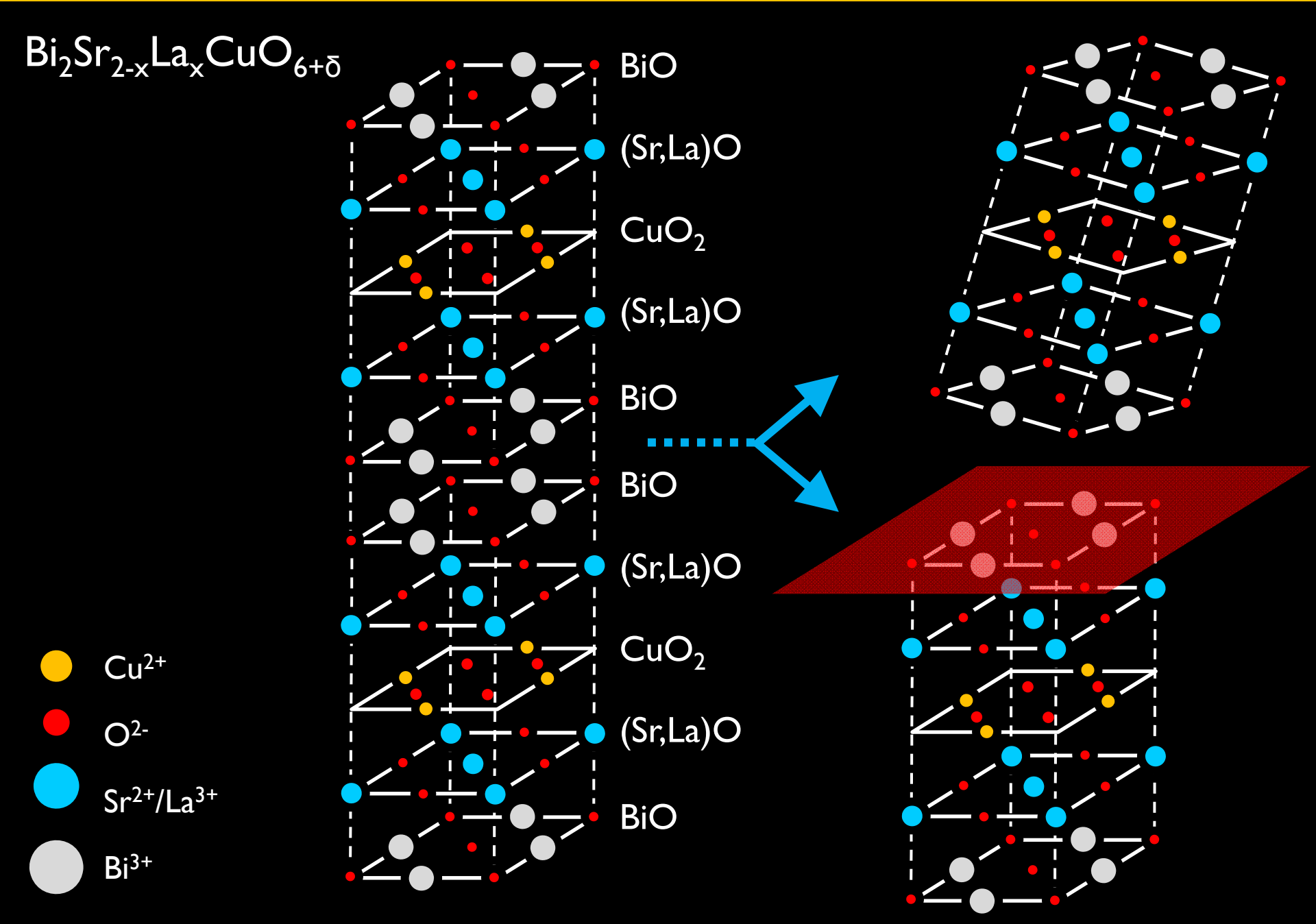
(ENS) Tranquada *et al.*, Nature (1995)
(STM) Hoffman *et al.*, Science (2002)
(STM) Howald *et al.*, PNAS (2003)
(STM) Hanaguri *et al.*, Nature (2004)
(STM) Vershinin *et al.*, Science (2004)
(RXS) Abbamonte *et al.*, Nat. Phys. (2005)
(QO) Doiron-Leyraud *et al.*, Nature (2007)
(NMR) Wu *et al.*, Nature (2011)
(REXS) Ghiringhelli *et al.*, Science (2012)
(RXS) Chang *et al.*, Nat. Phys. (2012)
(RXS) Achkar *et al.*, PRL (2012)
(IXS) Le Tacon *et al.*, Nat. Phys. (2013)

Cuprates: a favourite physicist's playground



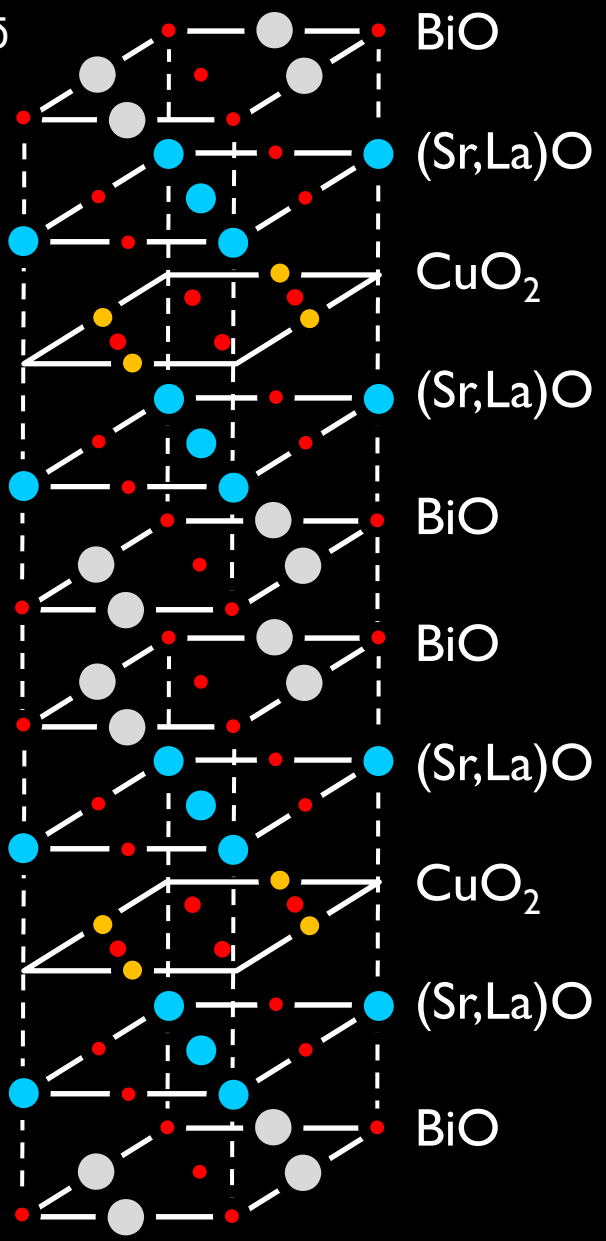
Comin *et al*, Science **340**, 390-392 (2014)

Materials and techniques



Materials and techniques

$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$



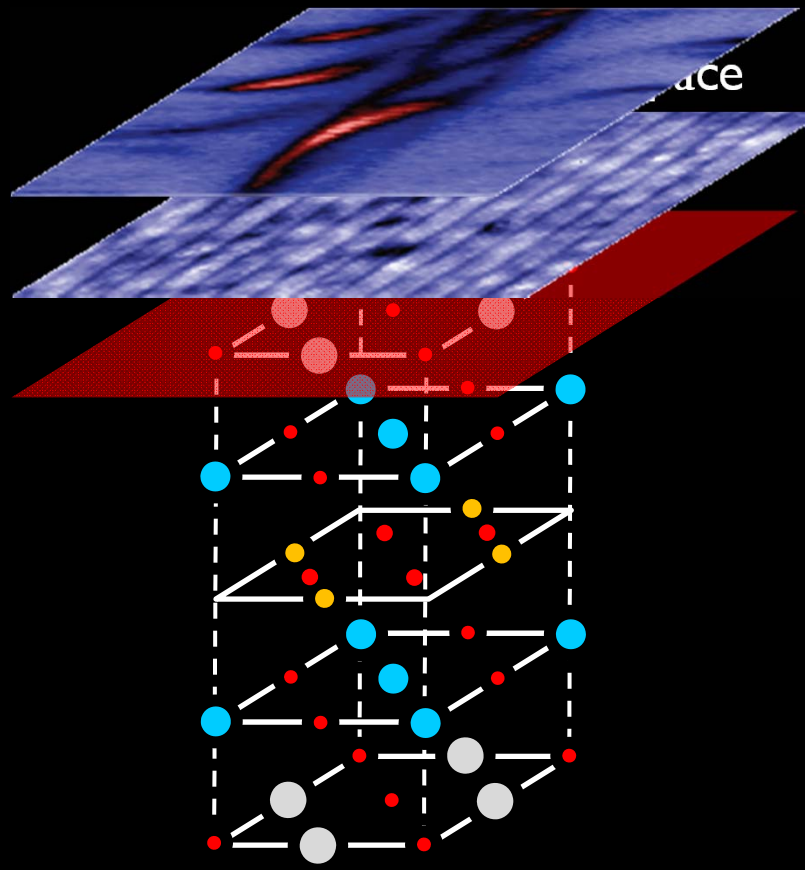
Cu^{2+}

O^{2-}

Sr^{2+}/La^{3+}

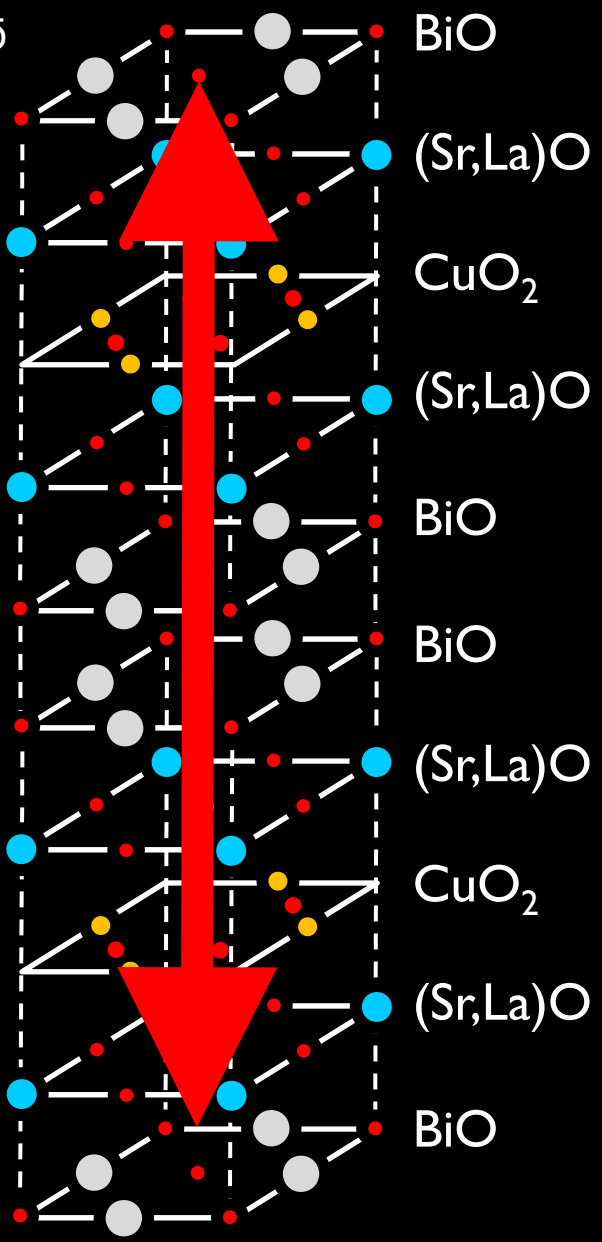
Bi^{3+}

ARPES
Momentum space



Materials and techniques

$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$



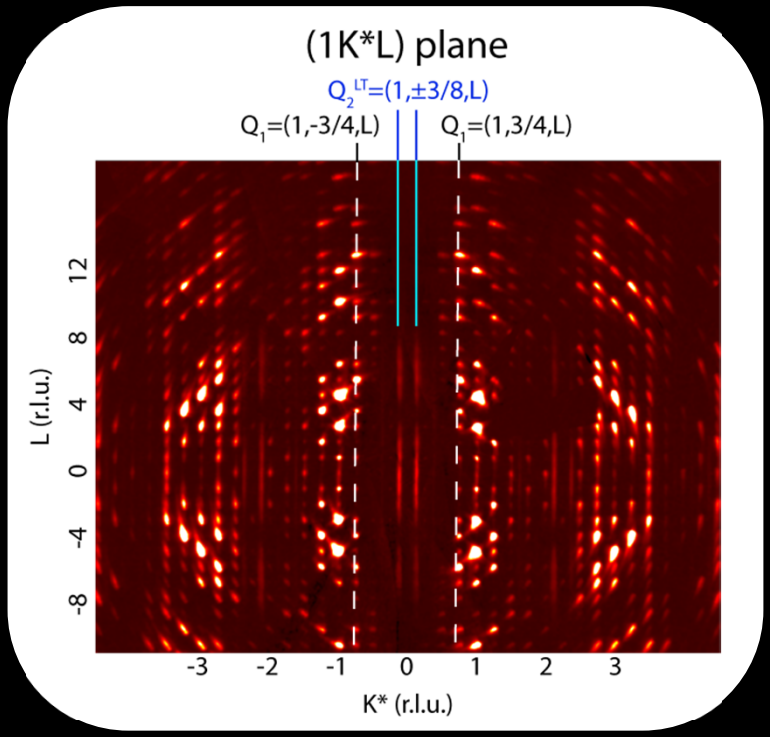
Cu^{2+}

O^{2-}

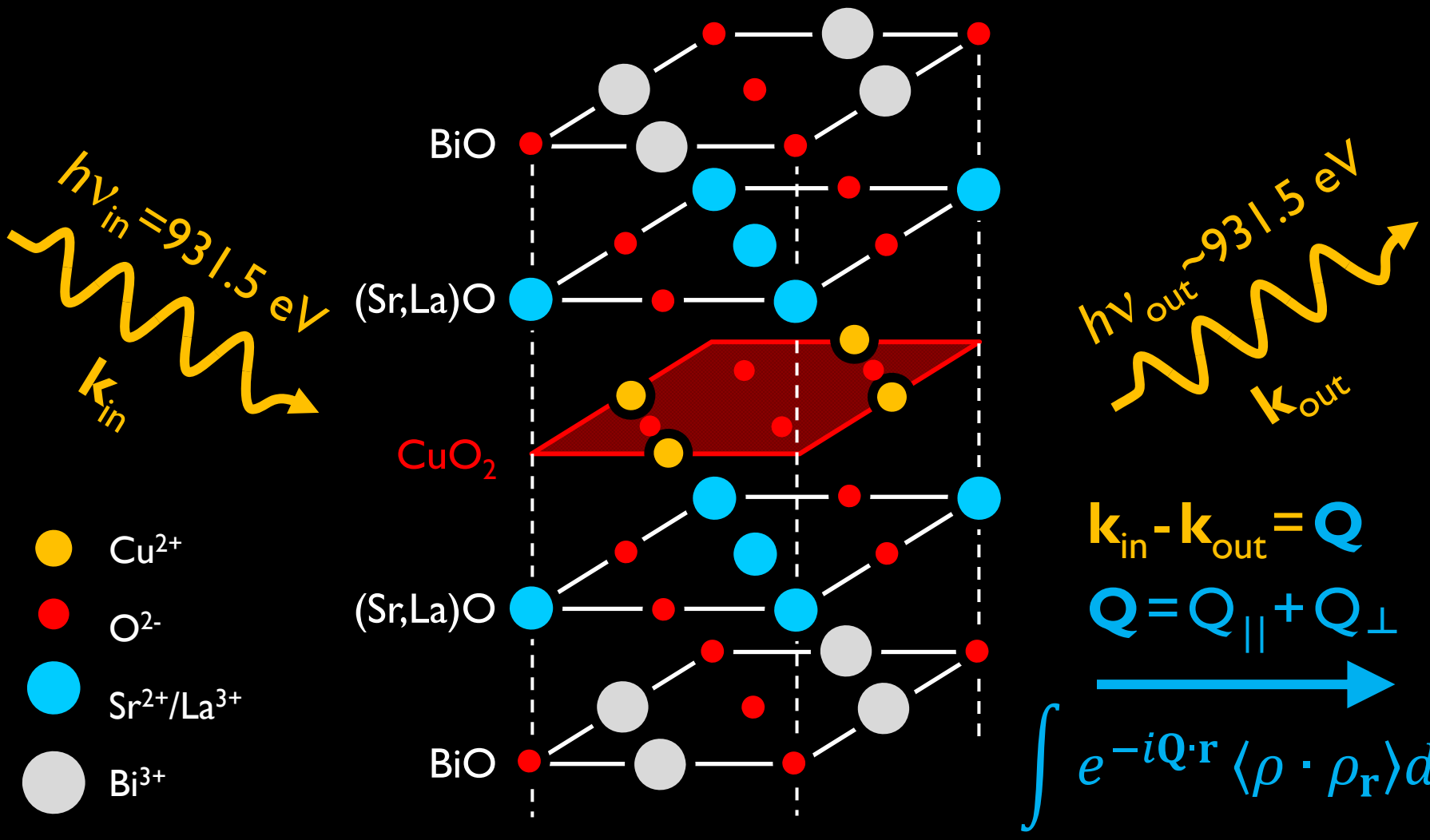
Sr^{2+}/La^{3+}

Bi^{3+}

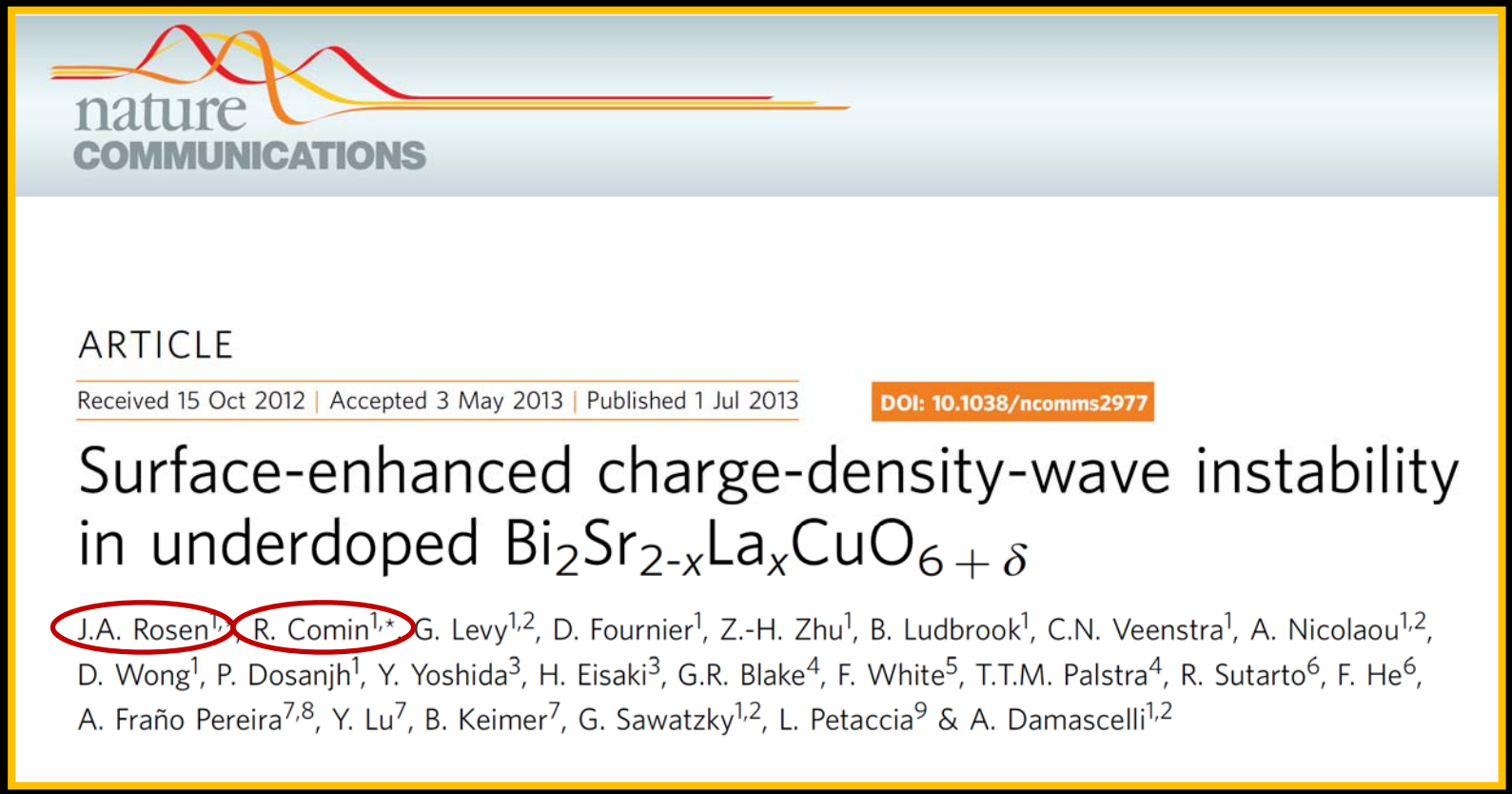
Reciprocal Space Diffraction (bulk)



RXS – Resonant X-ray Scattering



ARPES-XRD-RXS on same compound



nature COMMUNICATIONS

ARTICLE

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DOI: 10.1038/ncomms2977

Surface-enhanced charge-density-wave instability in underdoped $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

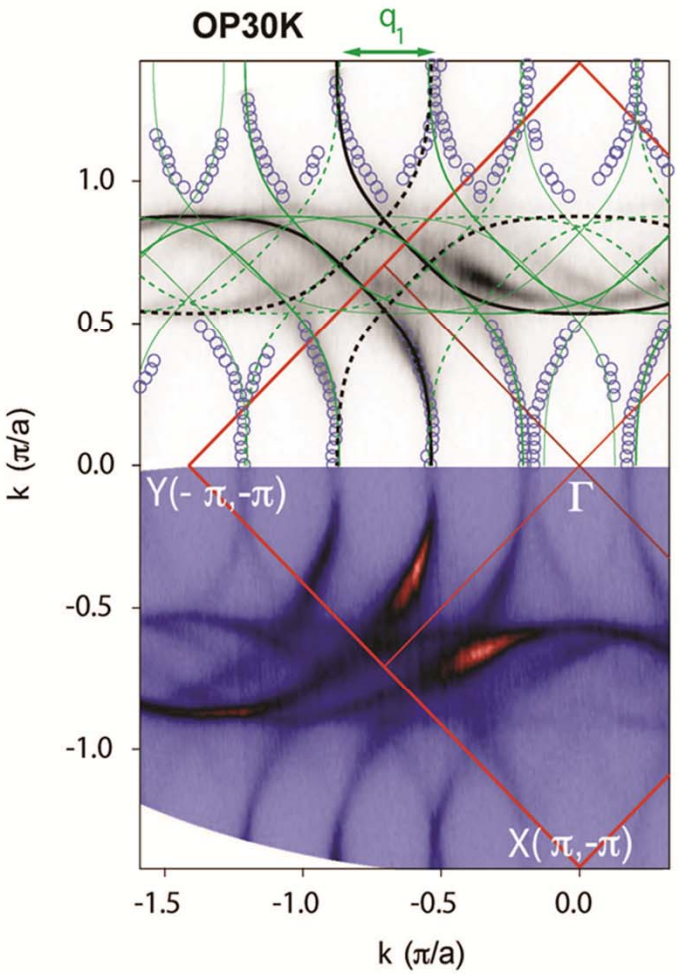
J.A. Rosen[1], R. Comin[1,*], G. Levy[1,2], D. Fournier[1], Z.-H. Zhu[1], B. Ludbrook[1], C.N. Veenstra[1], A. Nicolaou[1,2], D. Wong[1], P. Dosanjh[1], Y. Yoshida[3], H. Eisaki[3], G.R. Blake[4], F. White[5], T.T.M. Palstra[4], R. Sutarto[6], F. He[6], A. Fraño Pereira[7,8], Y. Lu[7], B. Keimer[7], G. Sawatzky[1,2], L. Petaccia[9] & A. Damascelli[1,2]

Connect charge order to Fermiology?

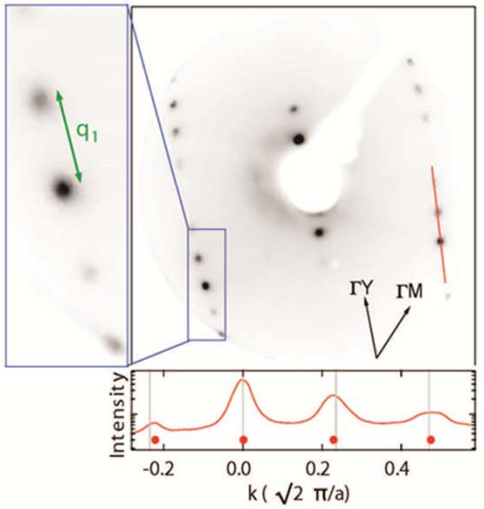
PRL 106, 127005 (2011) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2011

Structural Origin of Apparent Fermi Surface Pockets in Angle-Resolved Photoemission of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

P. D. C. King,[1] J. A. Rosen,[2] W. Meevasana,[1,3] A. Tamai,[1] E. Rozbicki,[1] R. Comin,[2] G. Levy,[2] D. Fournier,[2] Y. Yoshida,[4] H. Eisaki,[4] K. M. Shen,[5] N. J. C. Ingle,[6] A. Damascelli,[2,7] and F. Baumberger[1,*]



LEED picks up a crystalline modulation with Q_1 as reciprocal lattice vector



Optimal Doping

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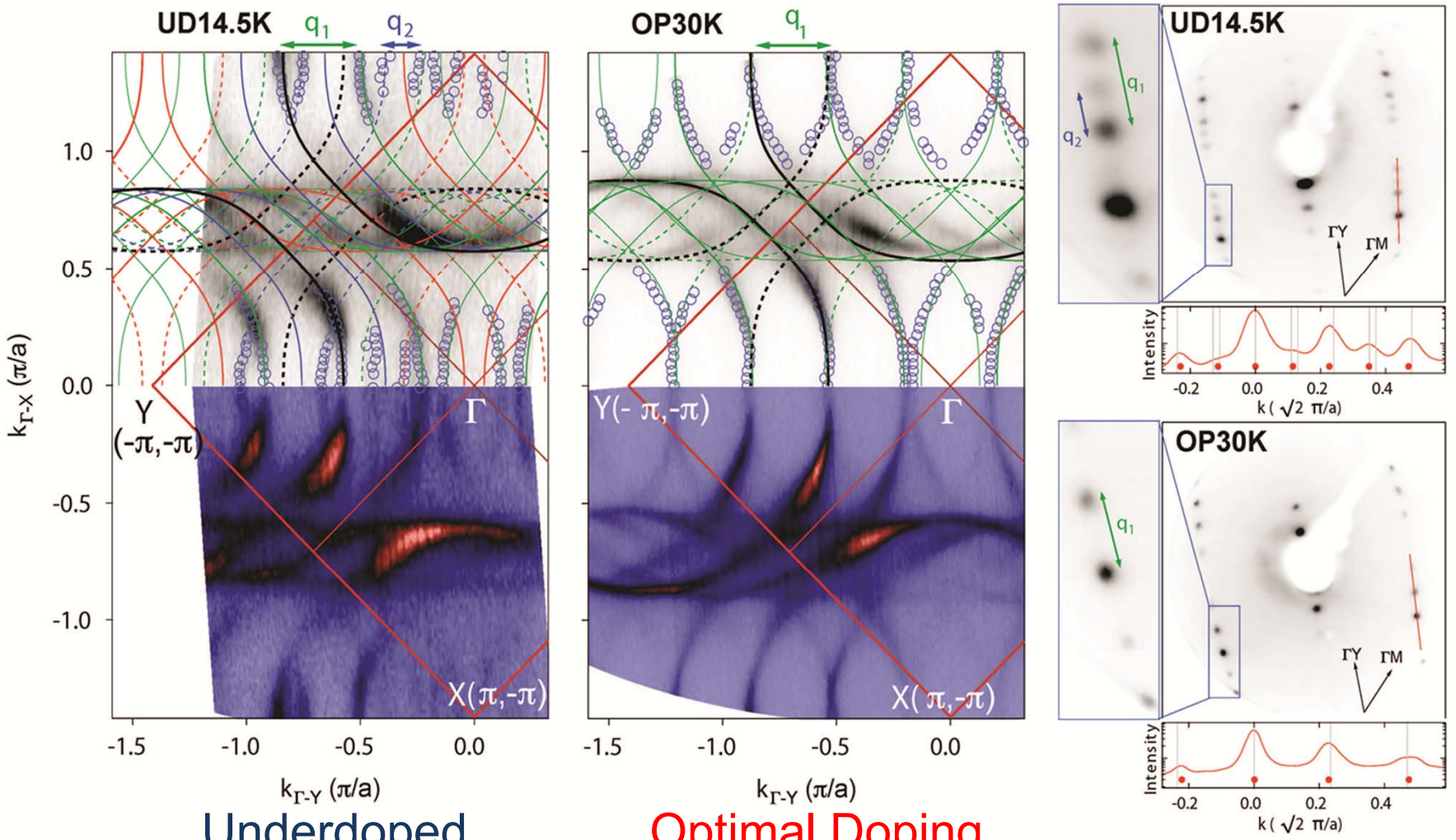
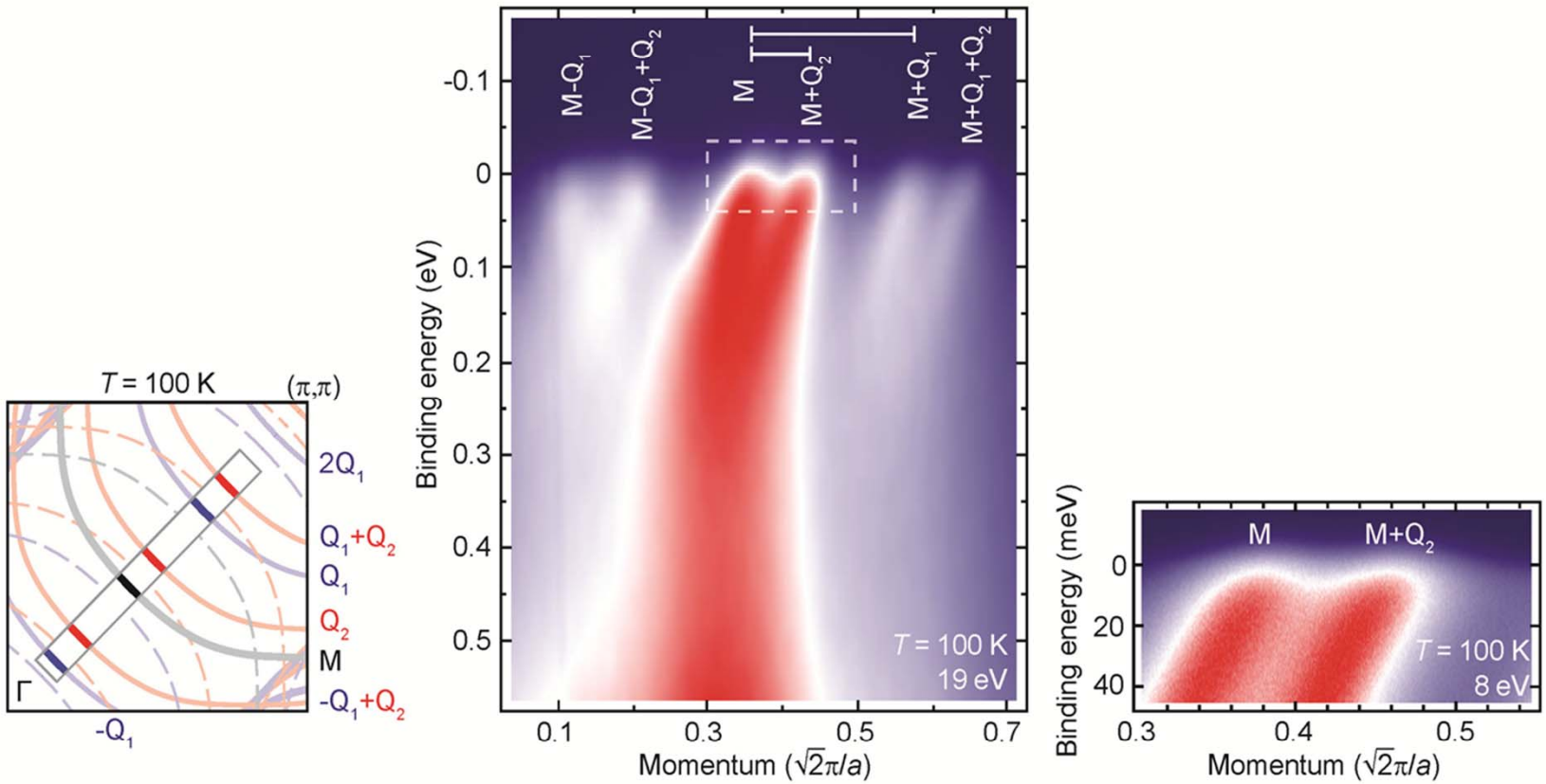


Underdoped

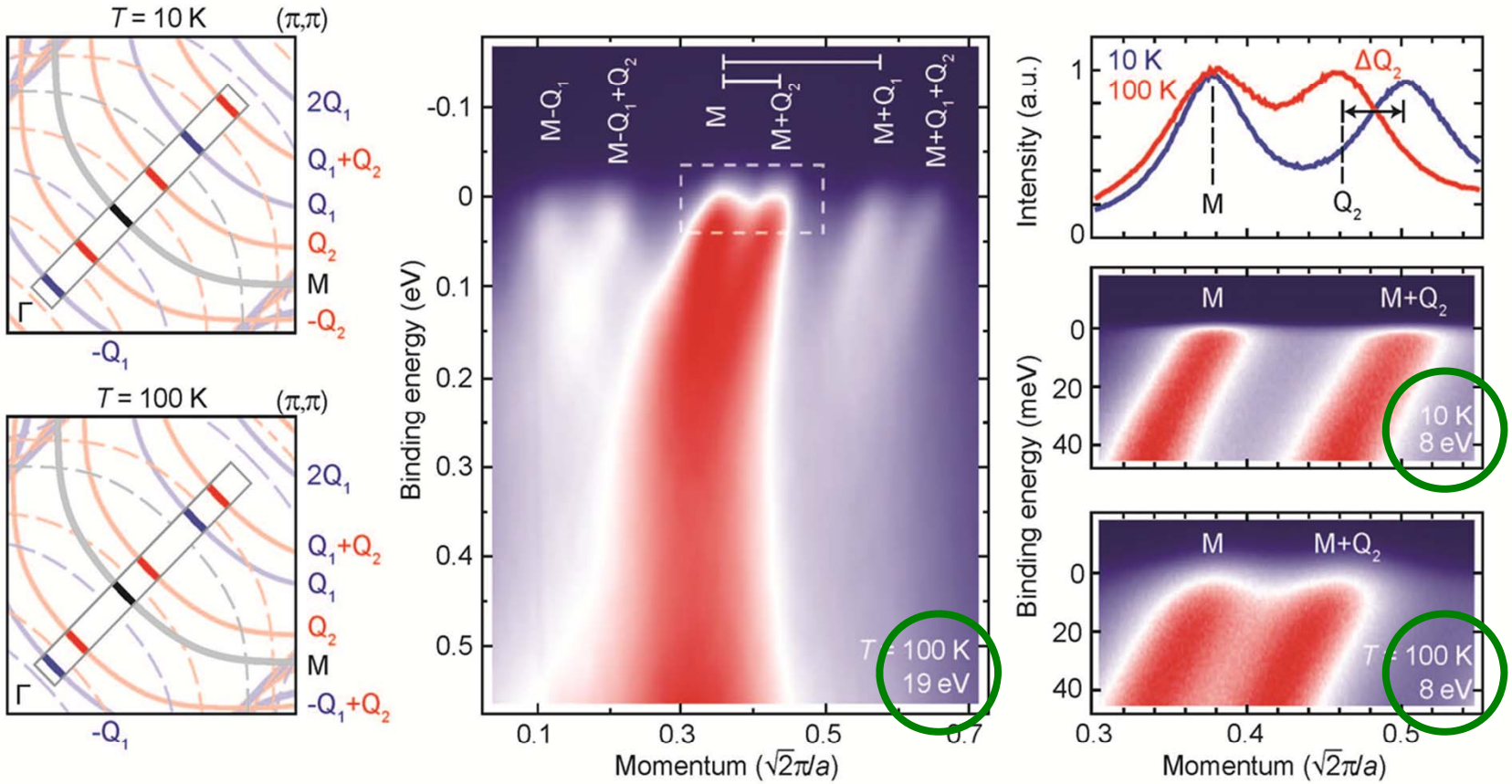
Optimal Doping

ARPES at 100K along Nodal Direction - Underdoped



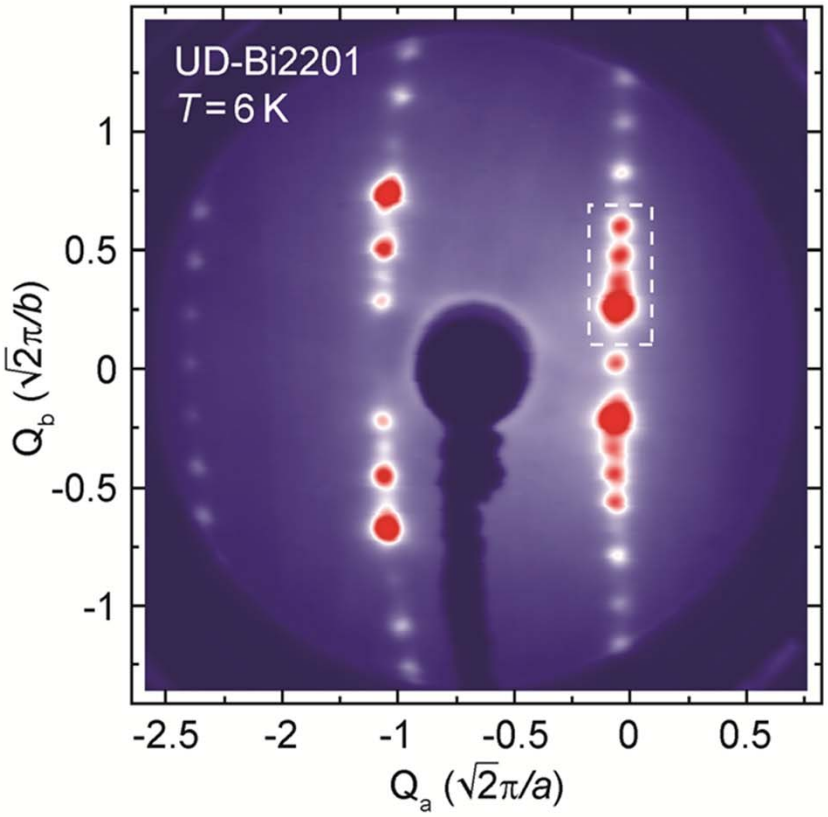
Rosen, Comin, et al.,
Nat. Comm. 4, 1977 (2013)

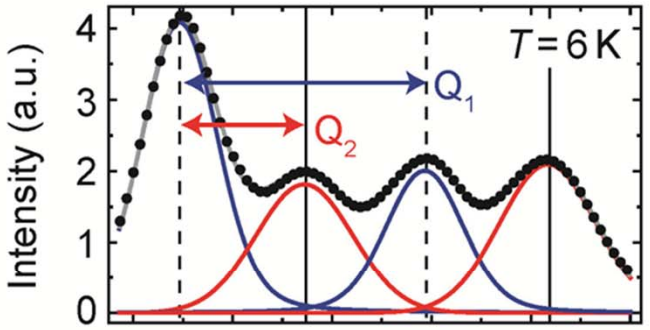
ARPES at 100K along Nodal Direction - Underdoped



Rosen, Comin, et al.,
Nat. Comm. 4, 1977 (2013)

Careful Temperature Dependence in LEED





Rosen, Comin, et al.,
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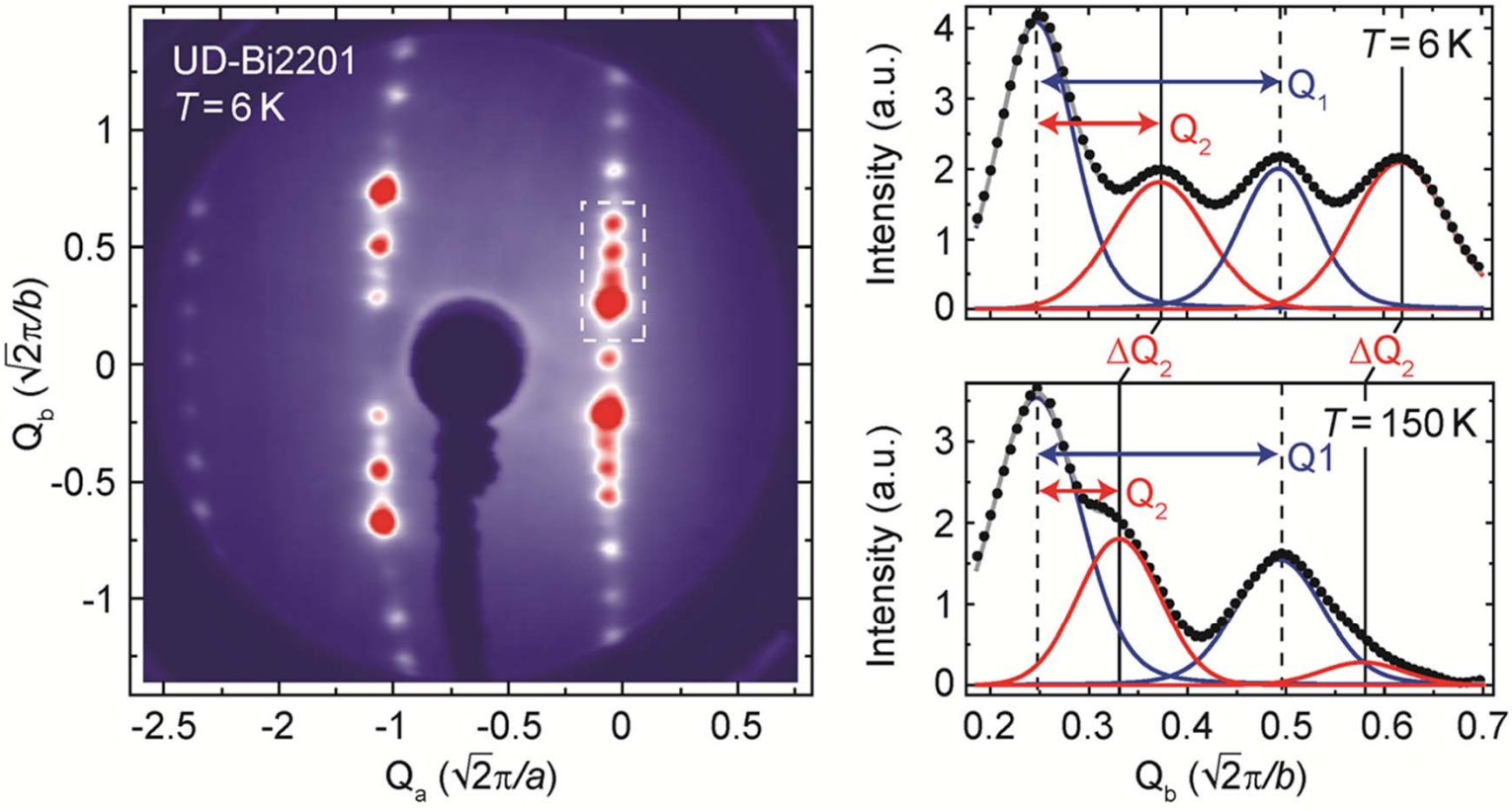

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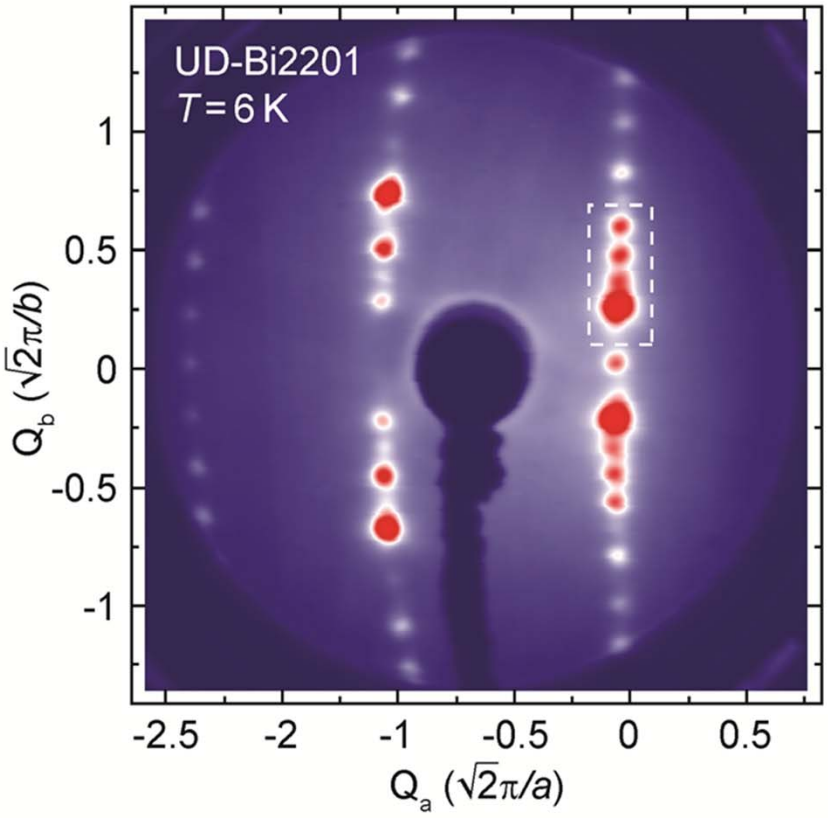
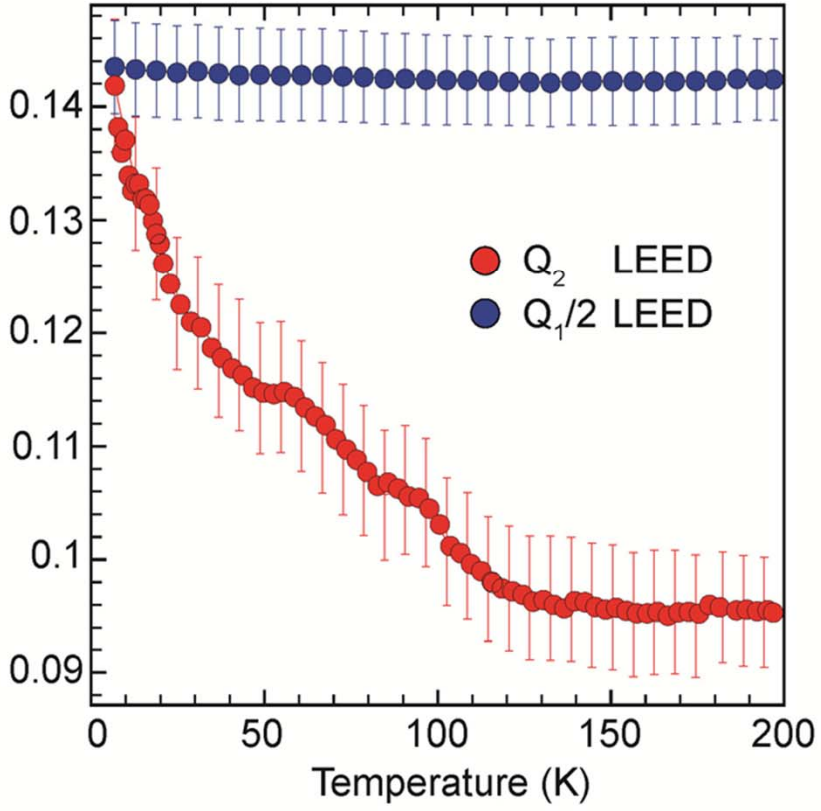
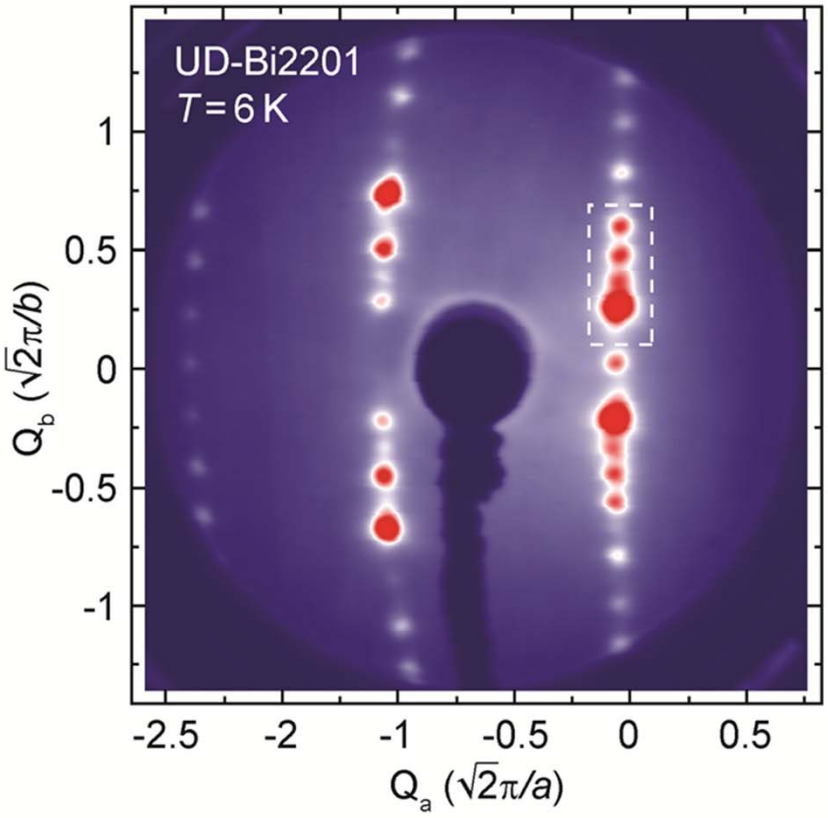


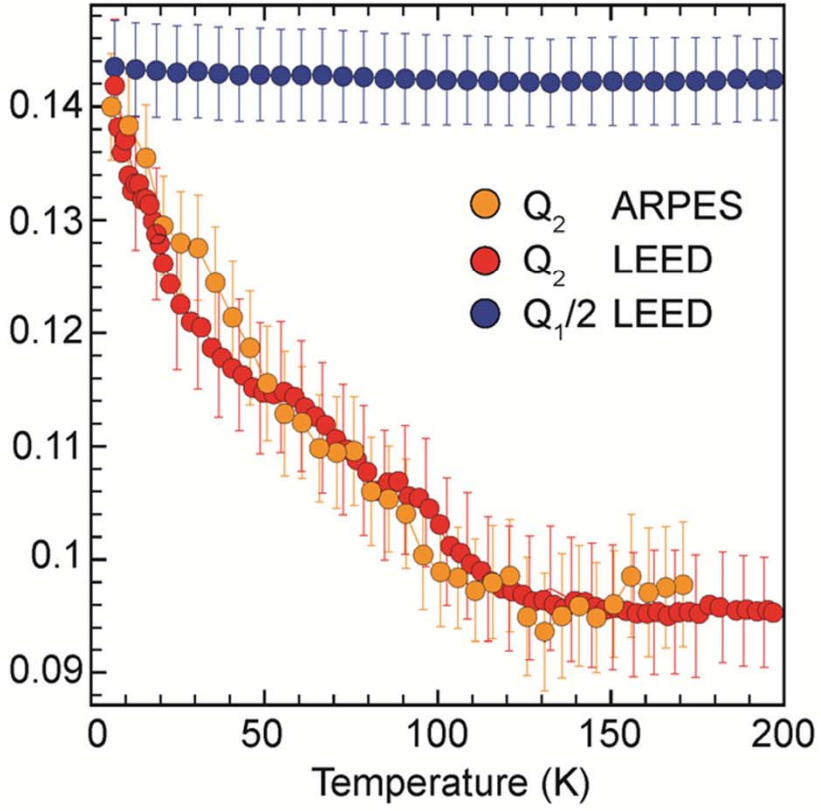


Rosen, Comin, et al.,
Nat. Comm. 4, 1977 (2013)

Q2 evolution agrees in LEED and ARPES

- 30% change in Q_2 over 130K temperature range
- Q_2 wavelength changes from 43-66 Å



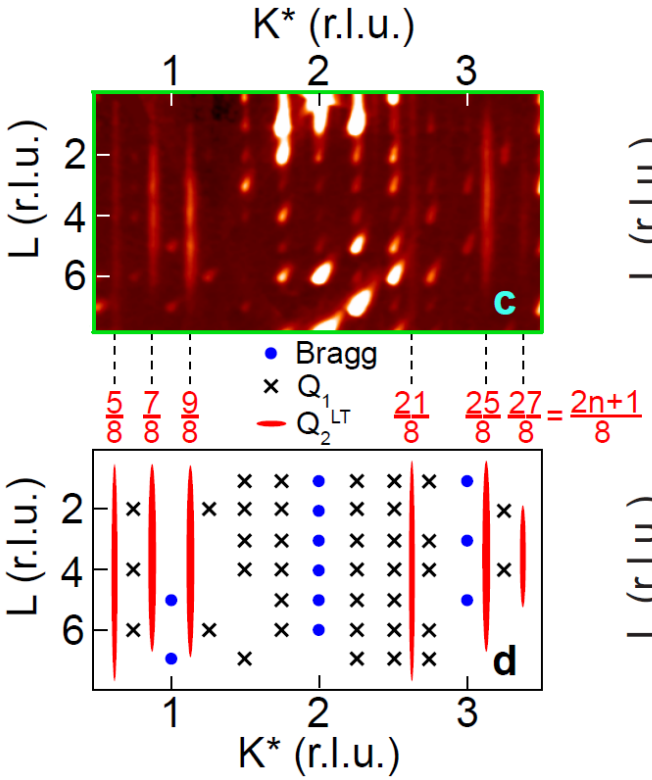


Surface-bulk CDW?

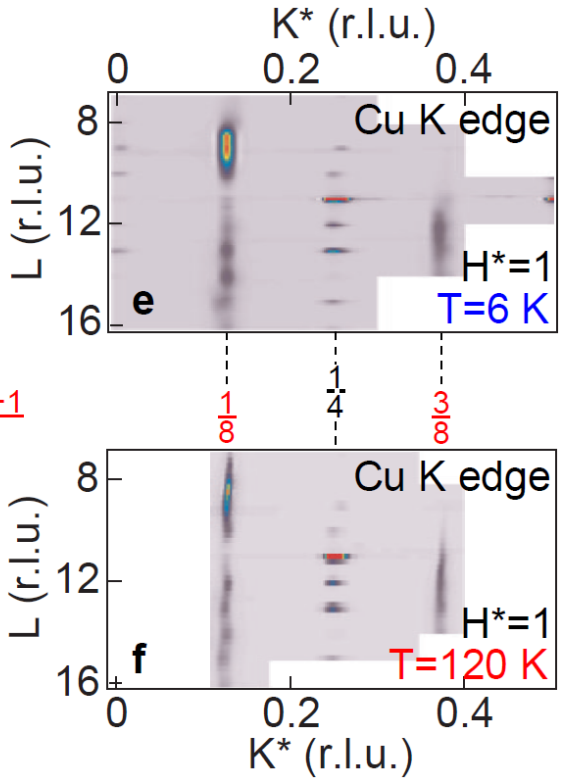
Rosen, Comin, et al., Nat. Comm. 4, 1977 (2013)

Bulk Sensitive XRD and REXS

XRD (17 keV)



RXS (8.9 keV)



Long-range ordered Q1 and Q2 modulations in the bulk.

Rod-like Q2 superstructure, lack of c-axis coherence

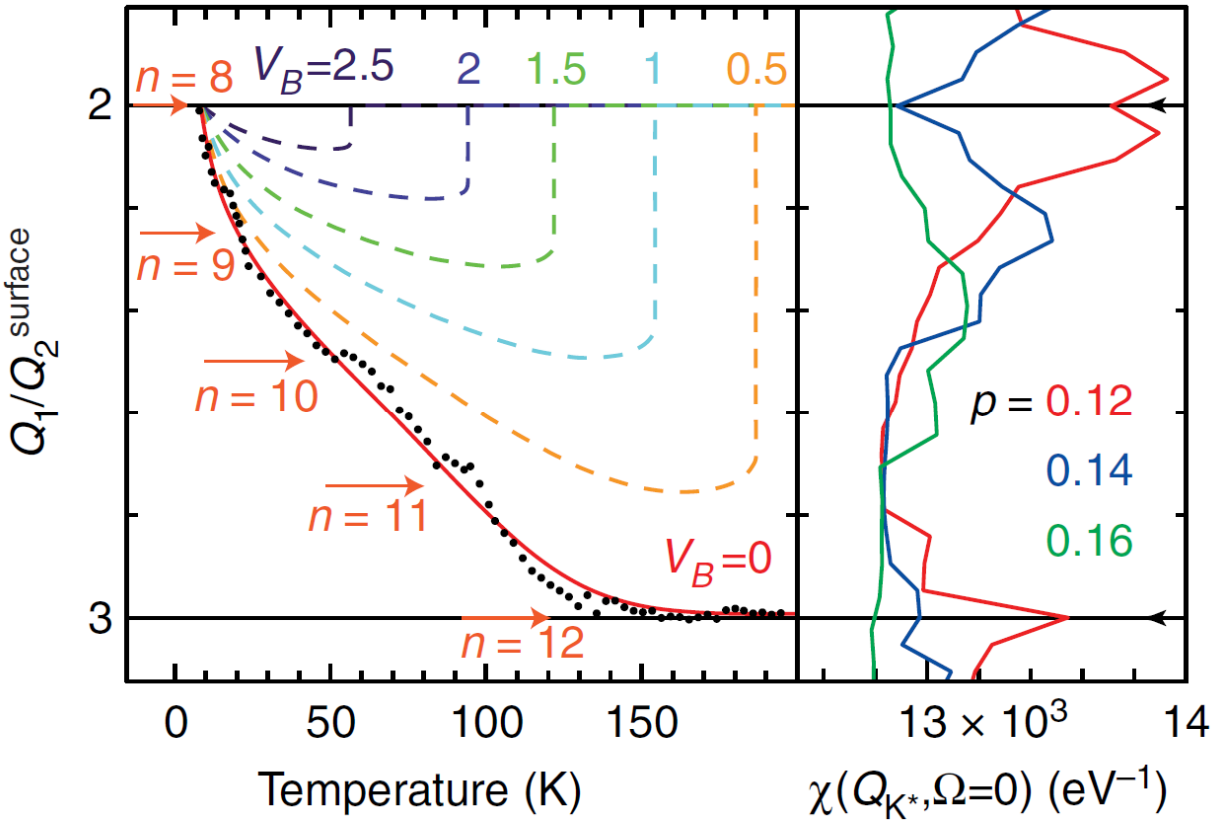
NO temperature dependence in the bulk!

Q_2 XRD/REXS value matches Q_2(5K) in ARPES/LEED

Mean Field Analysis of the Surface CDW

Surface Q_2 CDW coupled to a static bulk Q_1-Q_2 modulation

Minimization of CDW free energy with respect Q and amplitude



The bulk potential V_B pins the surface CDW suppressing its T dependence

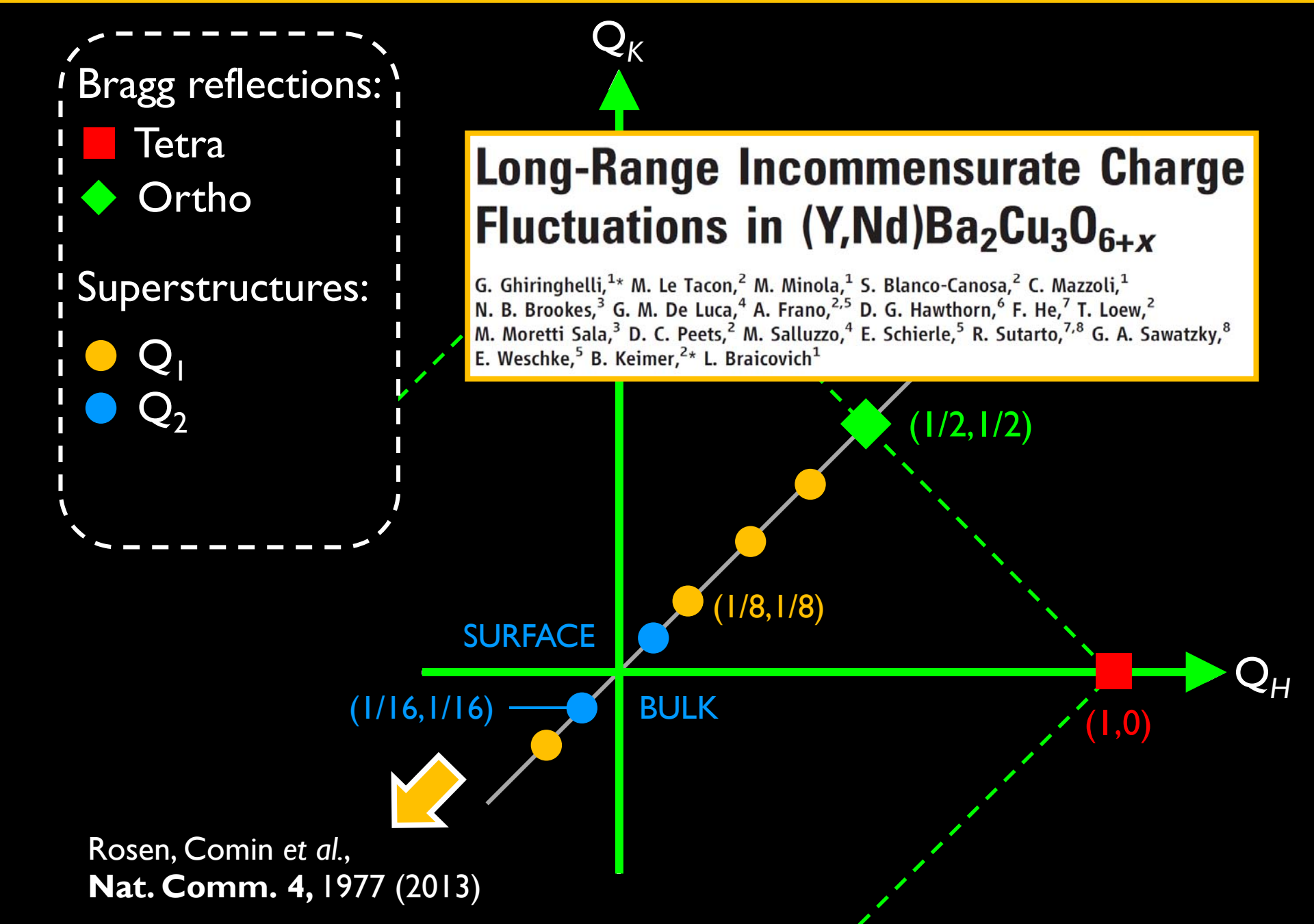
$Q_2=Q_1/2 \rightarrow$ AN nesting

$Q_2=Q_1/3 \rightarrow$ N nesting

$Q_2=Q_1/3$ nesting vanishes with p

Electronically soft phases exist at the surface of Bi2201

Bi2201 Q-space Overview



Rosen, Comin *et al.*,
Nat. Comm. 4, 1977 (2013)

Unified Charge-Order Phenomenology?

REPORTS

Science **340**, 390-392 (2014)

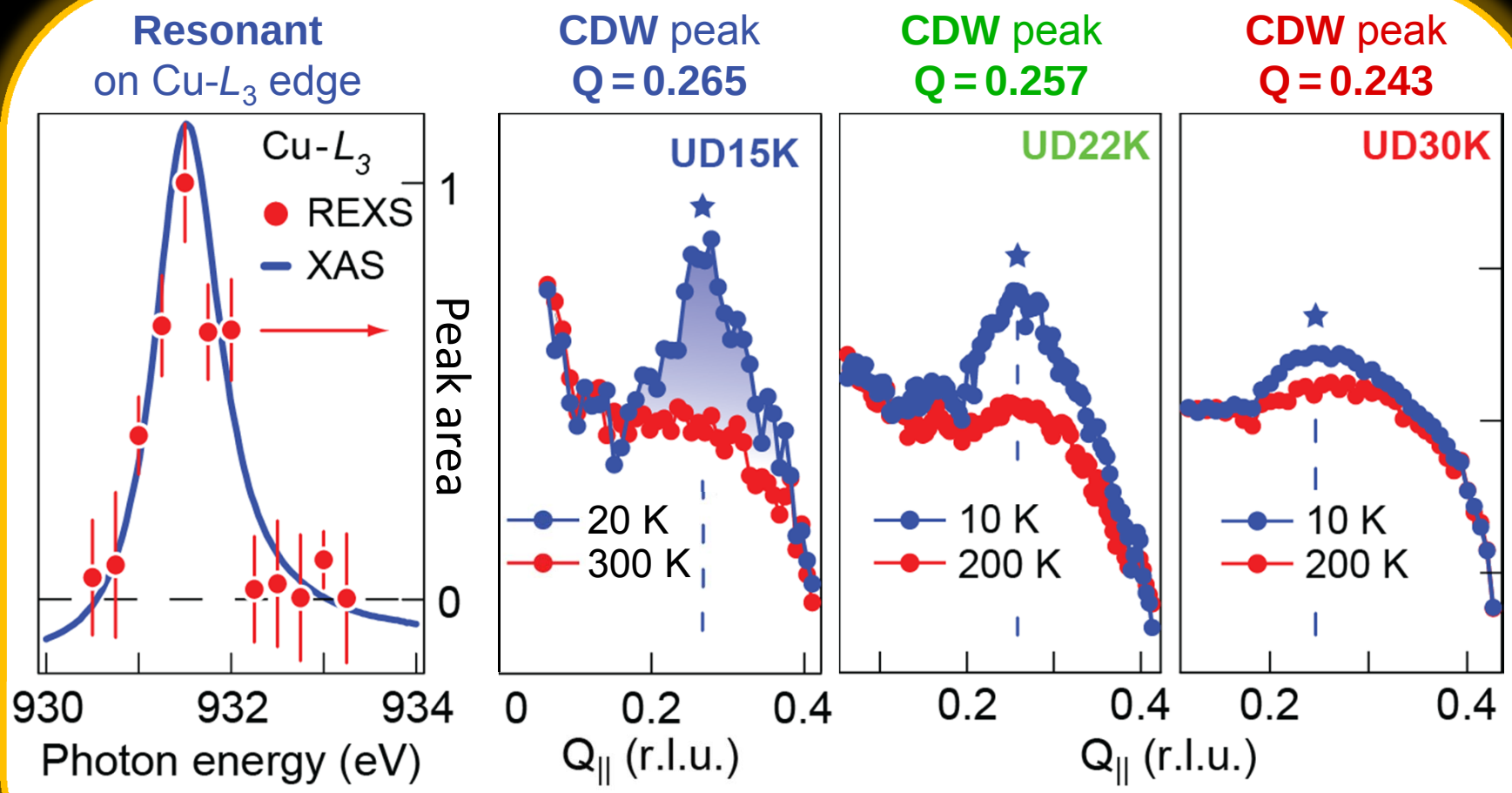
Charge Order Driven by Fermi-Arc Instability in $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

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



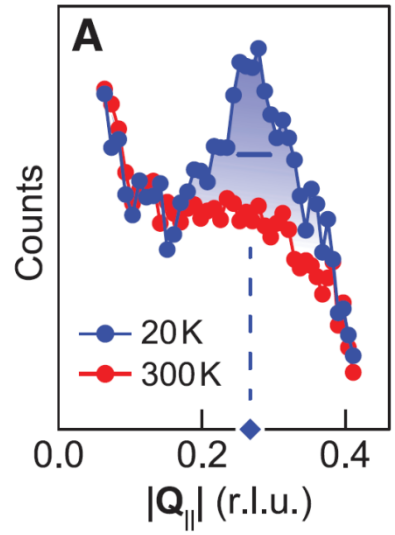
RXS

Persisting although weakening upon doping

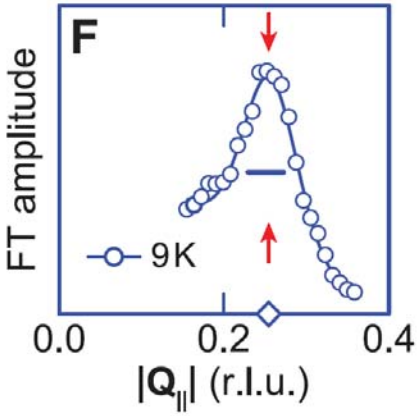
Charge modulation in CuO_2 planes!

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

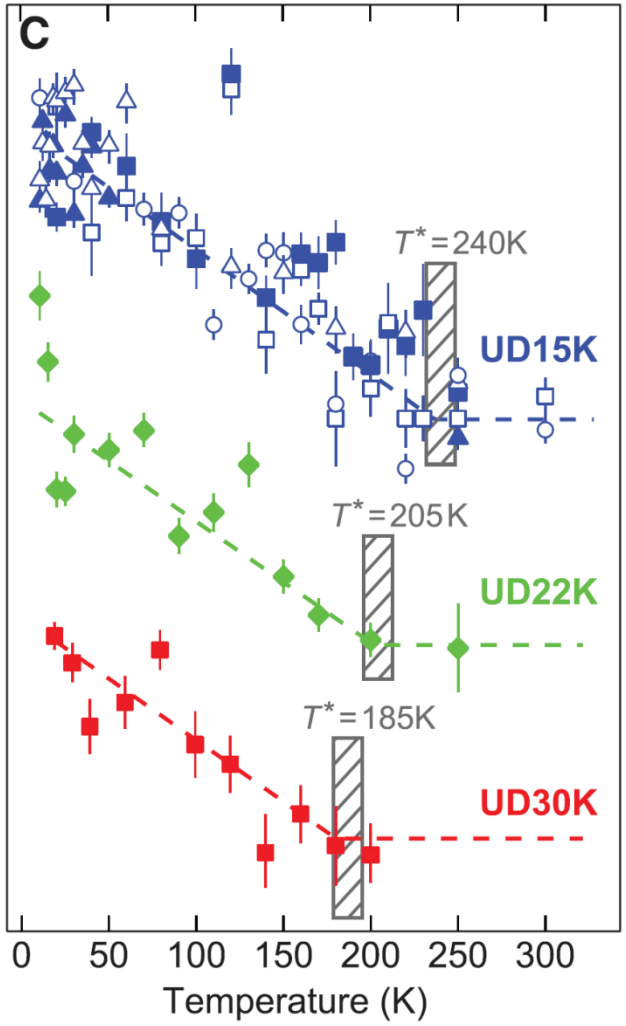
Electronic charge ordering in Bi2201 – RXS/STM



Resonant X-ray Scattering



Scanning Tunneling Microscopy



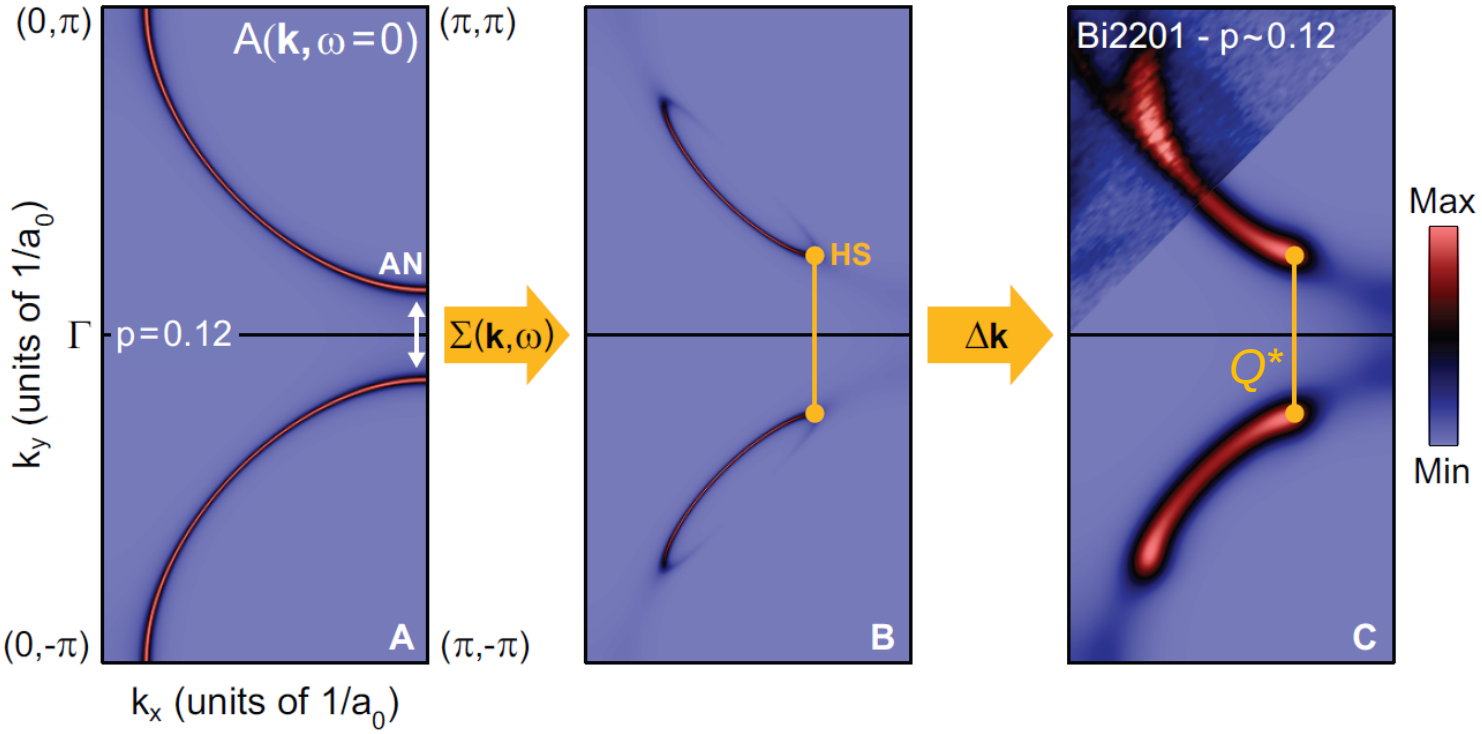
CO in both RXS & STM, with onset $T_{CO} \sim T^*$

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

Connection between charge ordering and Fermiology

Approximation to full susceptibility using particle-hole bubble

$$\chi(\mathbf{Q}, i\Omega_n) = \frac{1}{V} \cdot \frac{1}{\beta} \sum_{\mathbf{k},\, i\omega_m,\, \sigma} G(\mathbf{k}+\mathbf{Q}, i\omega_m + i\Omega_n, \sigma) \cdot G(\mathbf{k}, i\omega_m, \sigma)$$

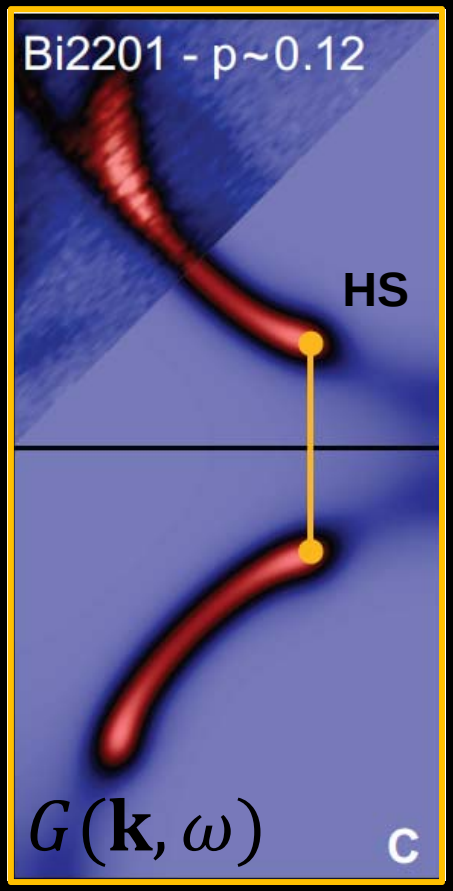


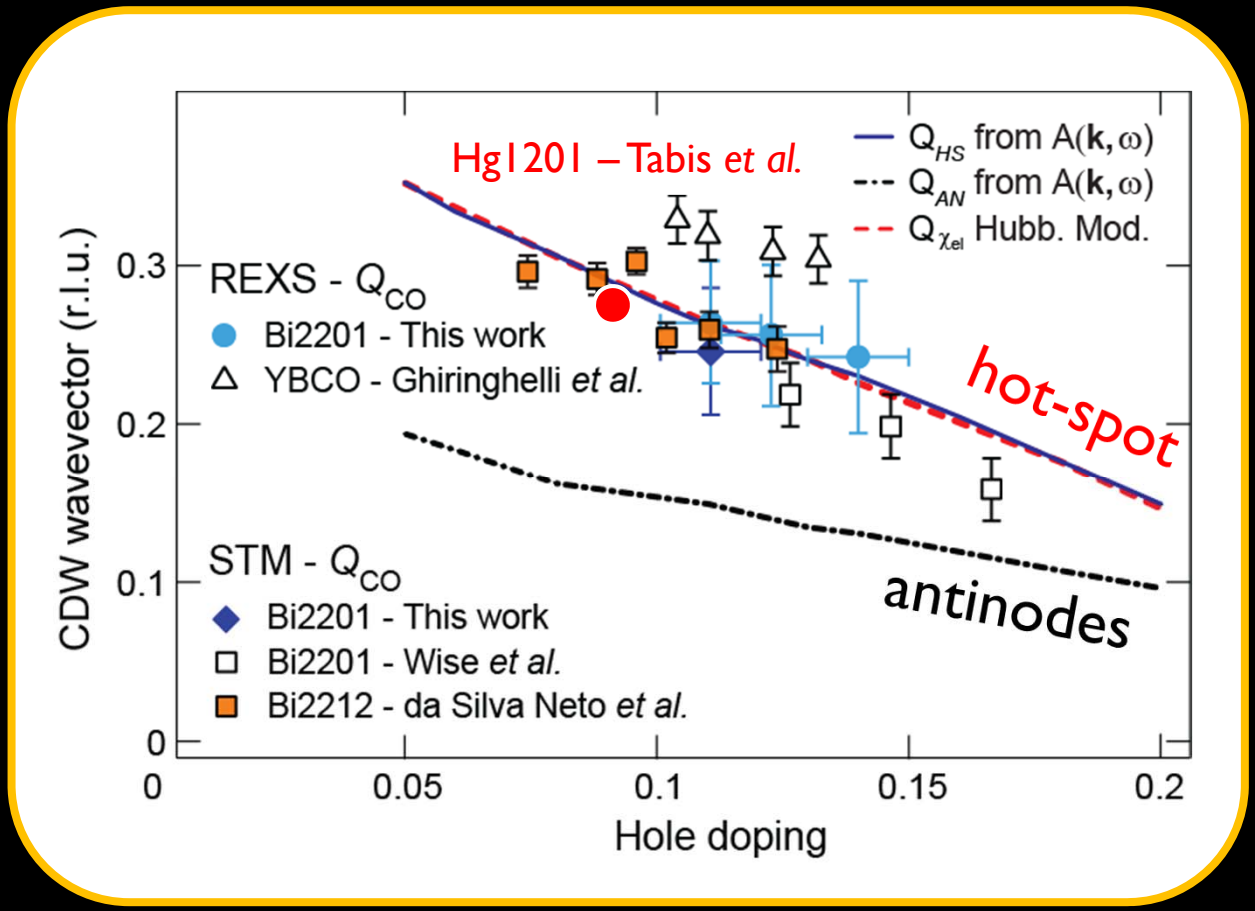
No AN nesting - CO driven by Fermi-arc instability

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)

YBCO: 1D Charge-Order!

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

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

Submitted (2014)

YBCO: d-wave bond order!

The symmetry of charge order in cuprates

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

arXiv:1402.5415 (2014)

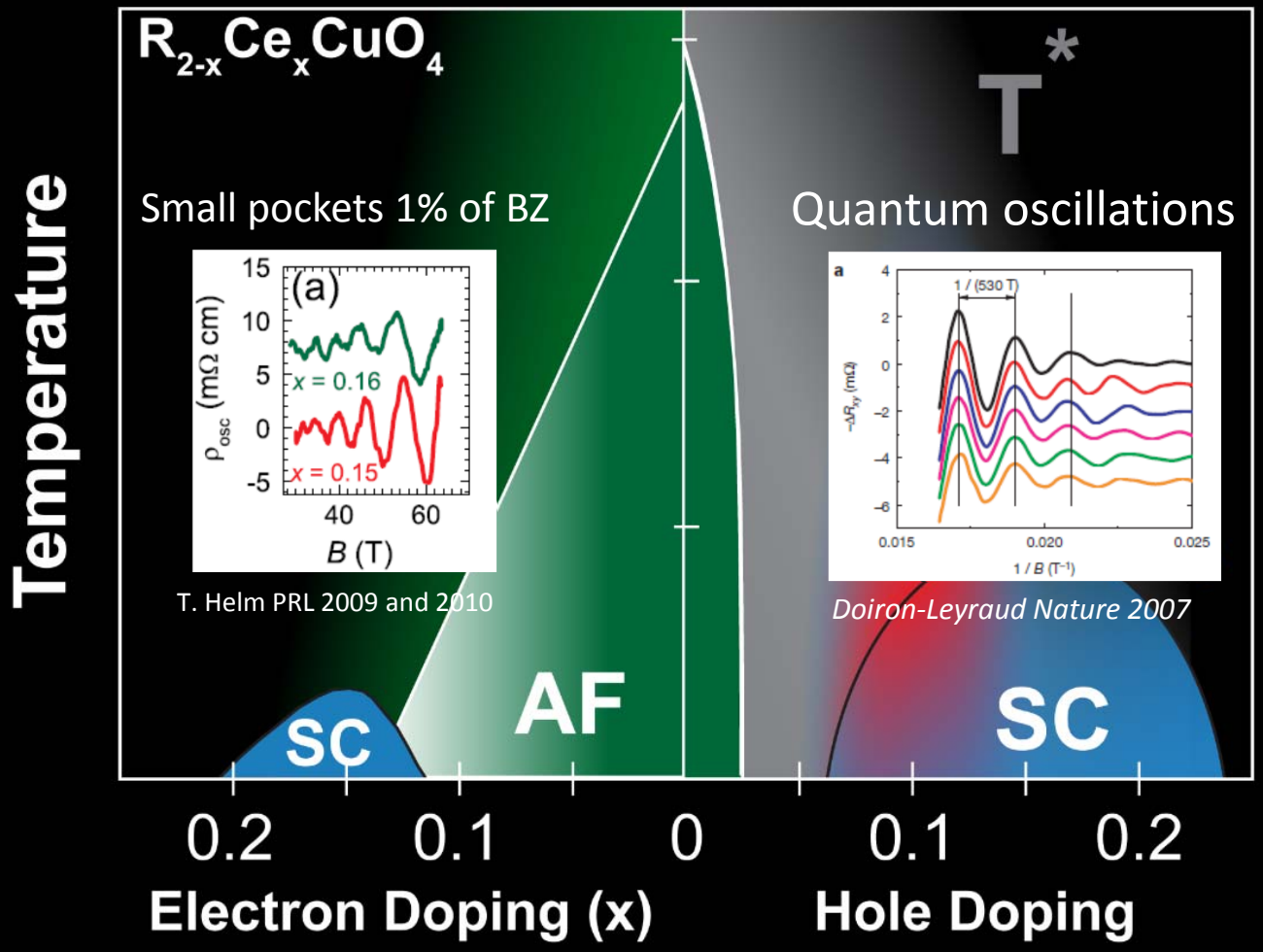
Charge Ordering in electron-doped cuprates ?

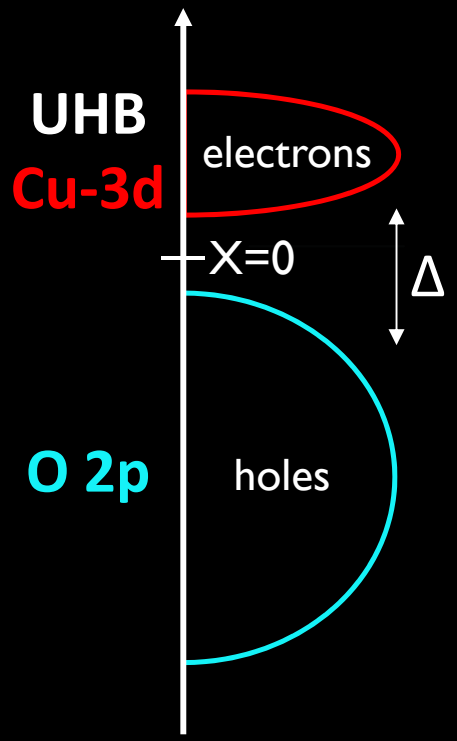
Charge ordering in the electron-doped superconductor $Nd_{2-x}Ce_xCuO_4$

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

Science, in press (2014)

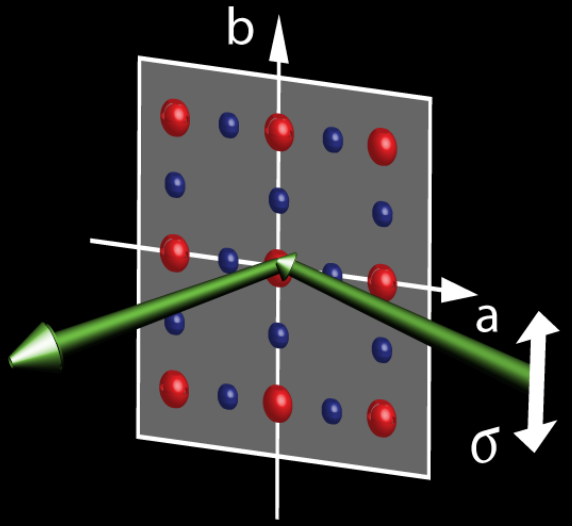
Electron vs. hole-doping asymmetry in Cuprates

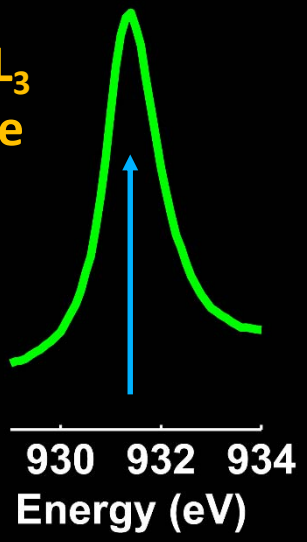




Charge Ordering in $Nd_{2-x}Ce_xCuO_4$!

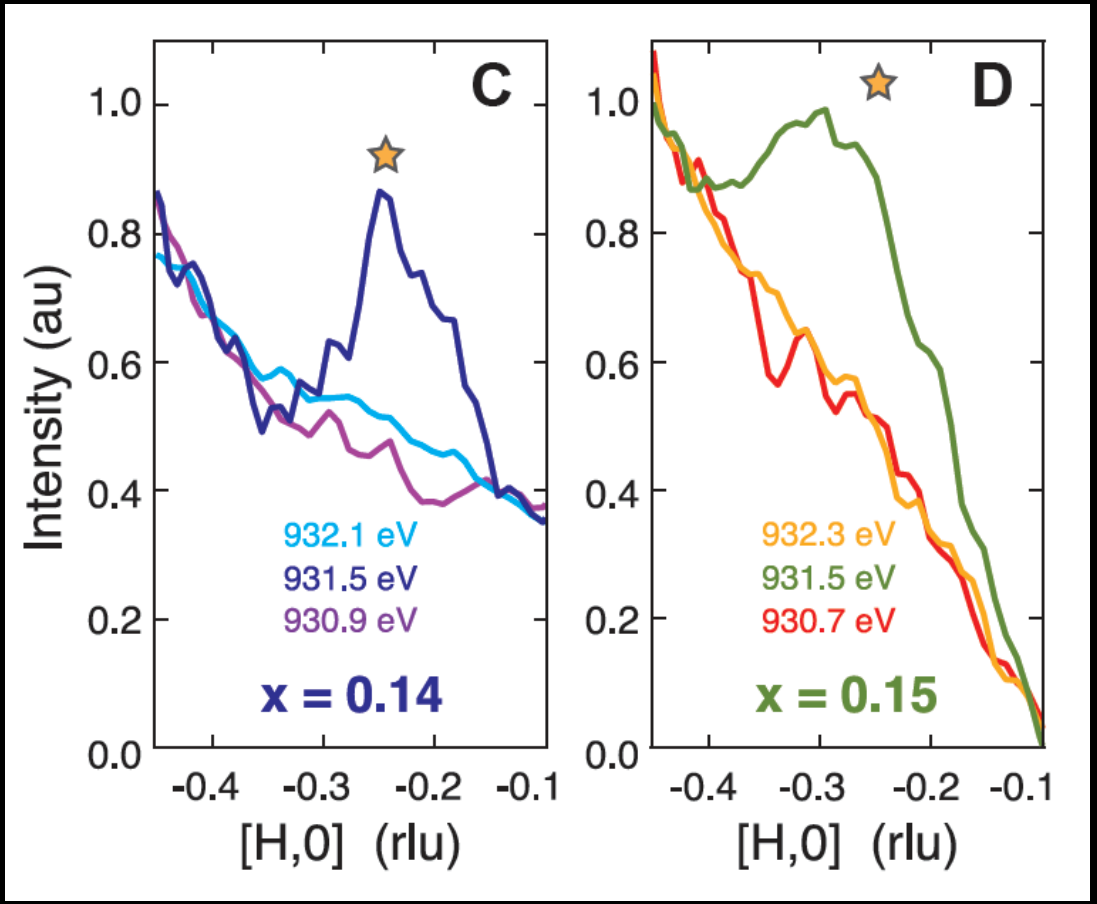
RXS





Resonance

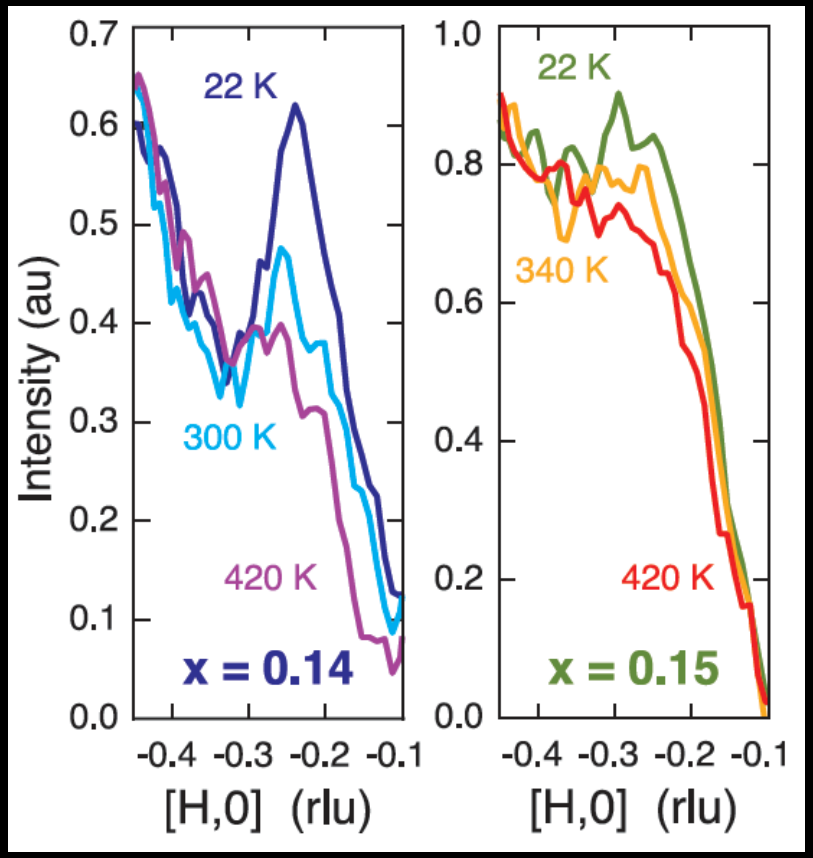
Electronic origin of CO (CuO_2 plane)

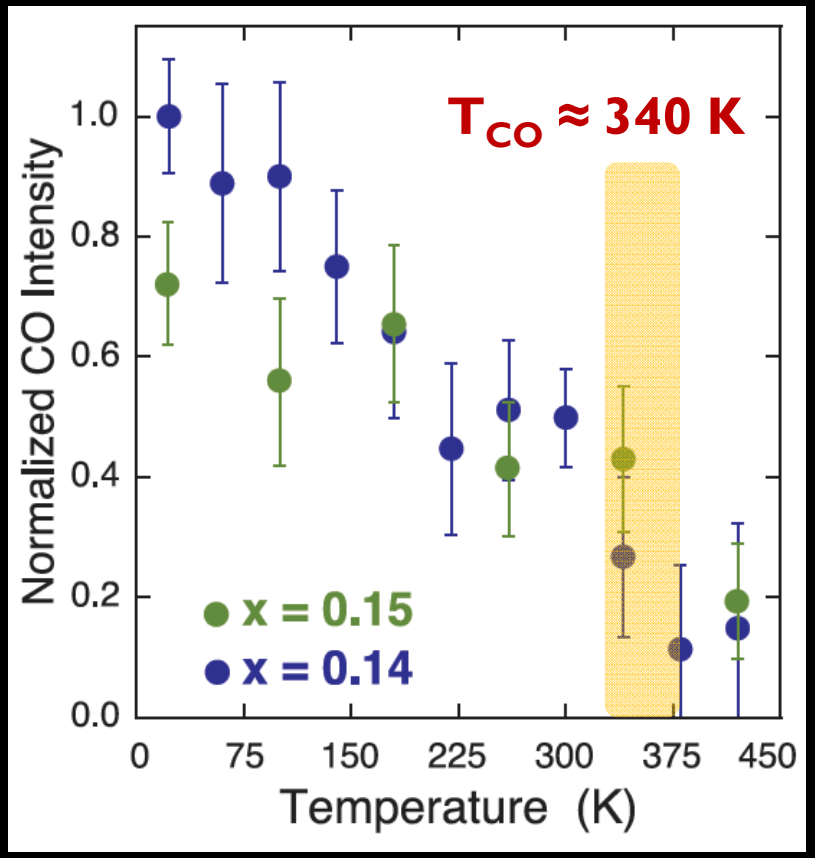


Similar to RXS signal on Bi-based cuprates

CO Temperature Dependence in NCCO

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

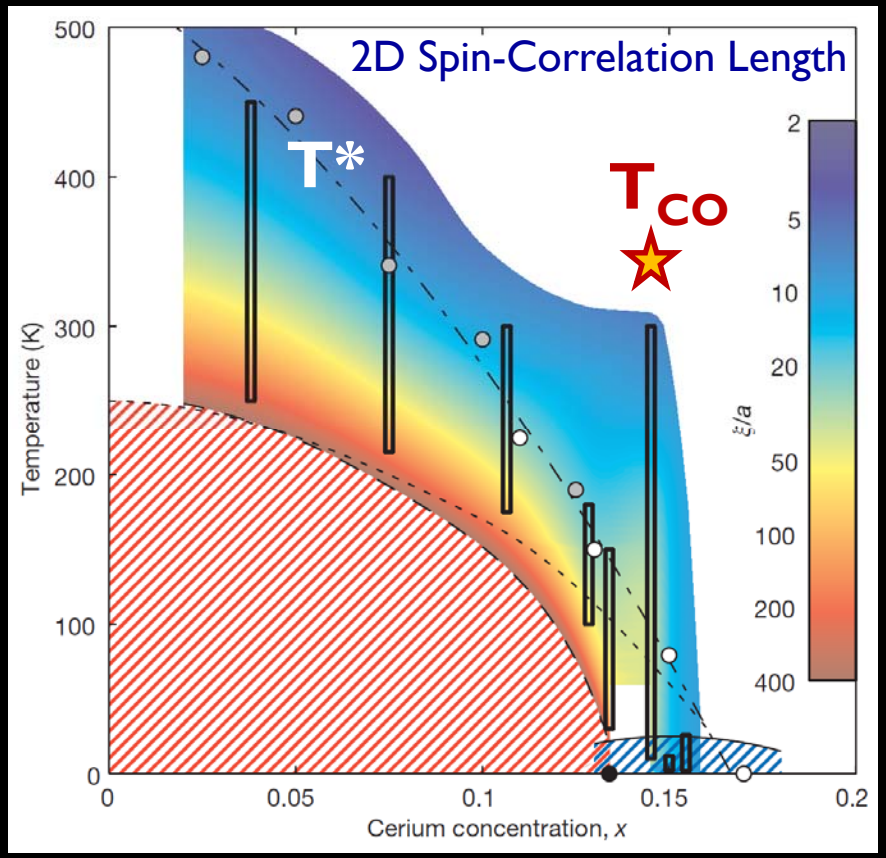


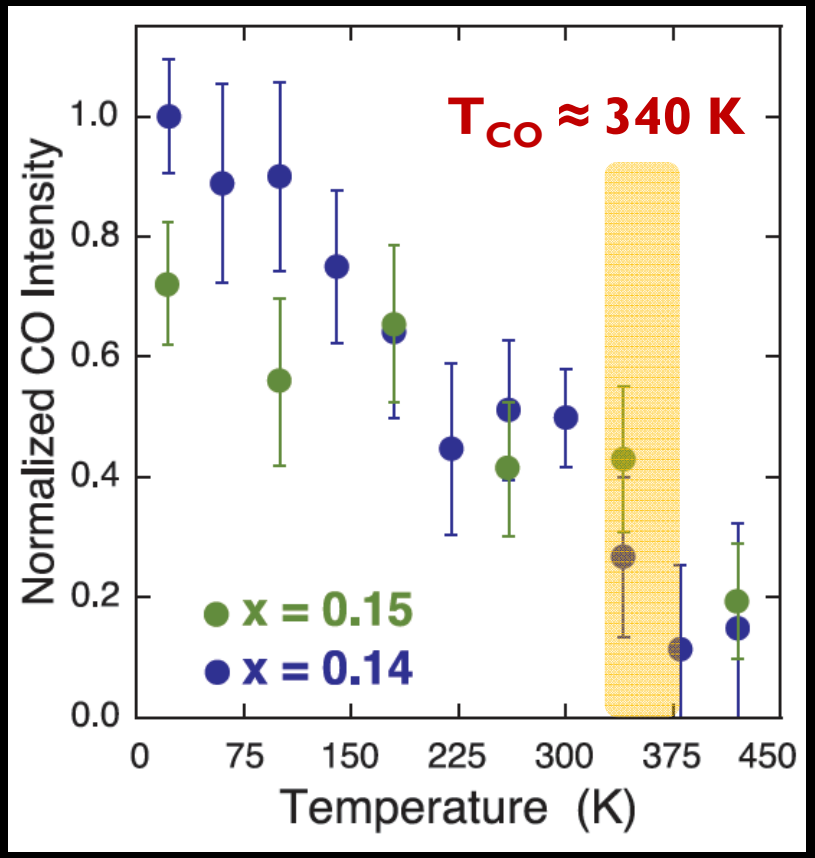


CO Temperature Dependence in NCCO

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

Charge ordering onsets with AF spin fluctuations



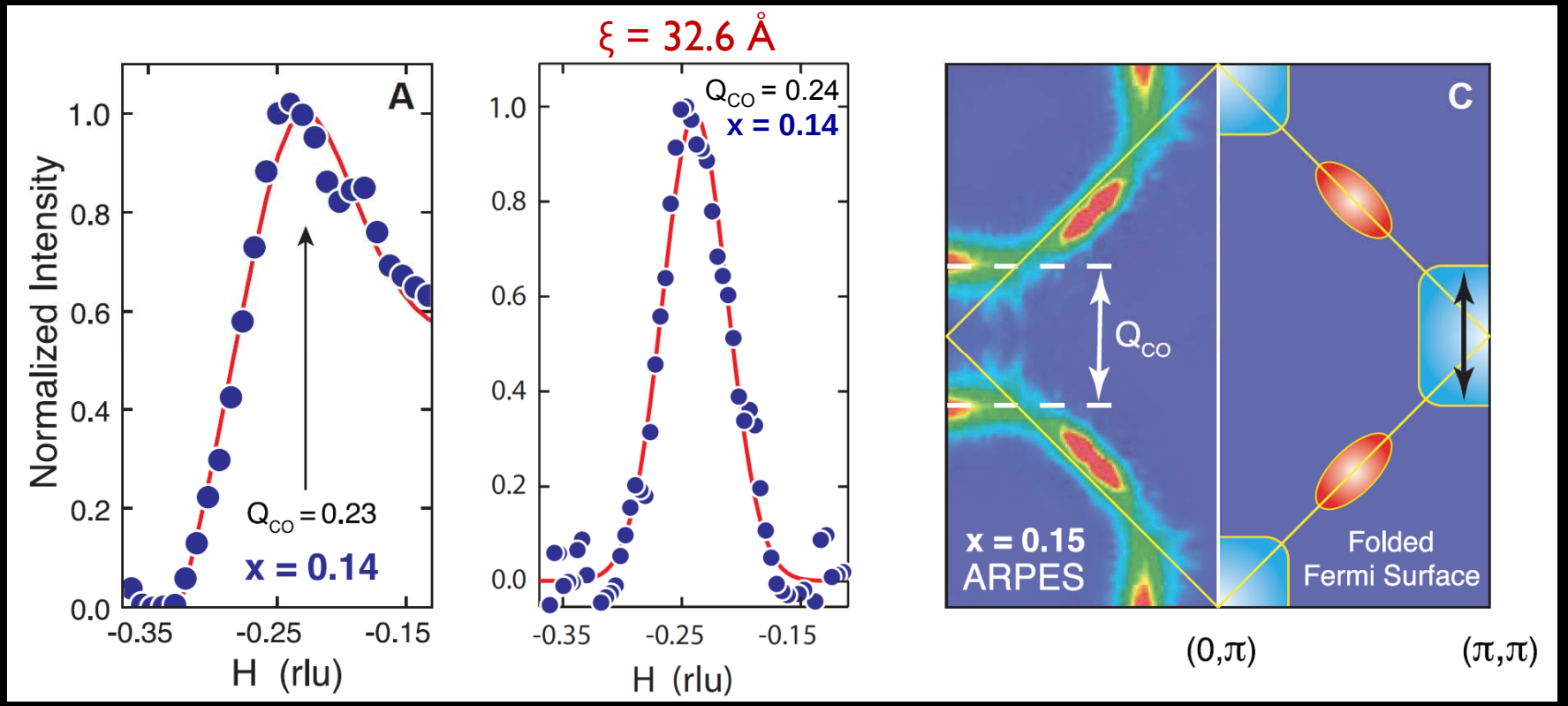


E.M. Motoyama et al. Nature (2007)

Connection Between CO and Fermiology

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

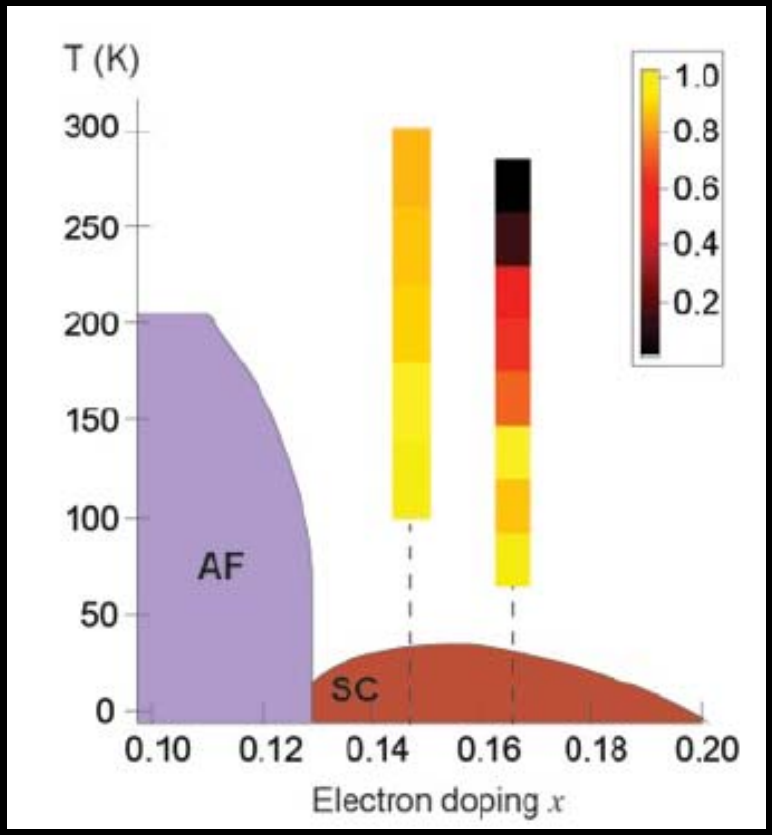
Connects the AF zone boundary ?

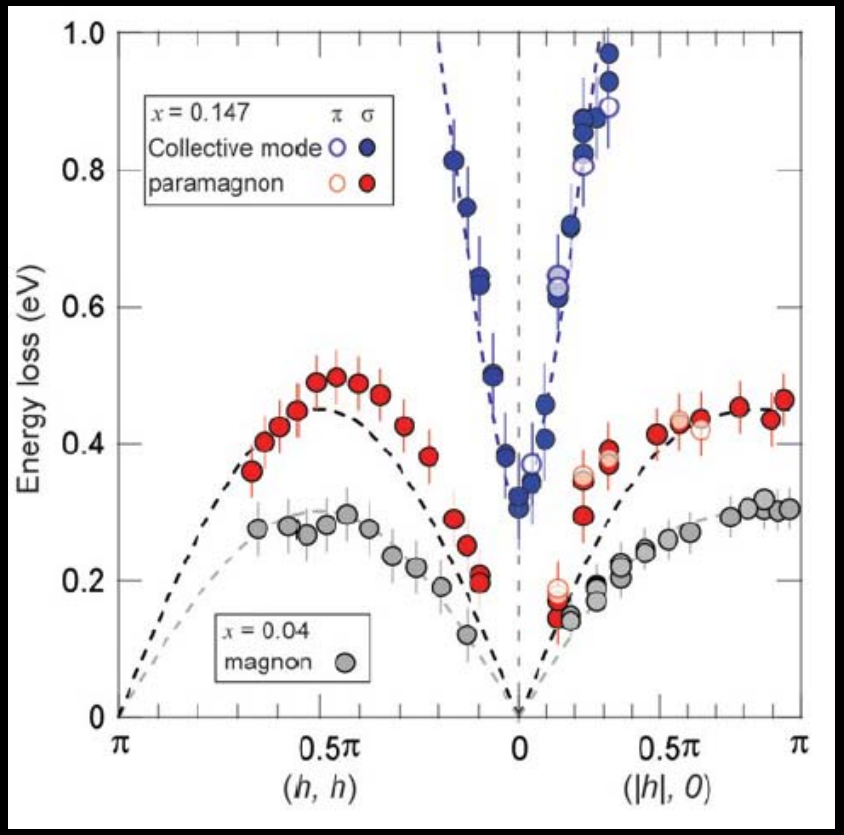


Q_{CO} similar to hole-doped systems (ξ = 25 - 35 Angstroms)

Connection to new collective mode by RIXS

As suggested by the temperature dependence





Lee et al. arXiv 13084740

Also see Ishii et al. Nat Comm 5, 3714 (2014)

Conclusions

RXS – ARPES – STM

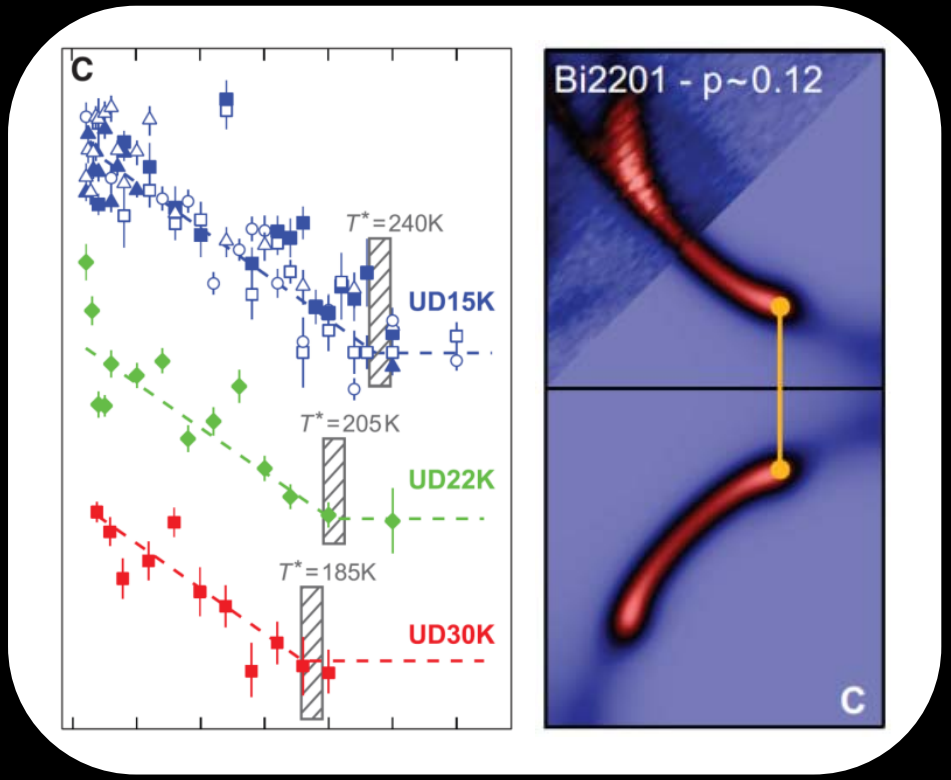
Bulk / surface + real /momentum space

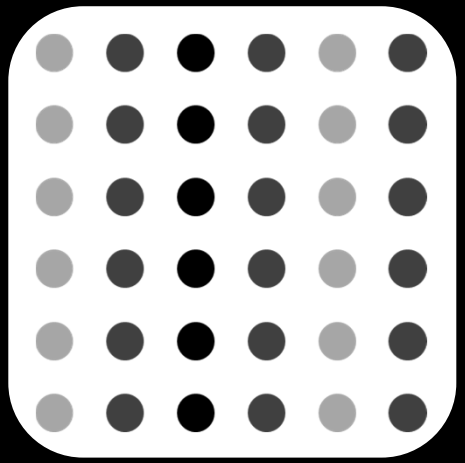
Resonant soft X-ray scattering

Charge order in Bi2201 below T*

Connect CO to fermiology

Fermi-arcs, no AN nesting



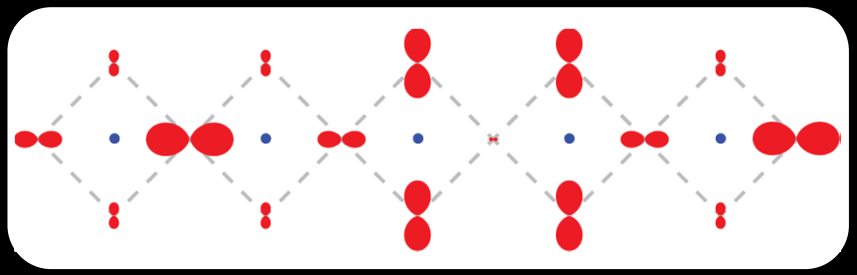


Ubiquitous stripe order in hole-doped cuprates

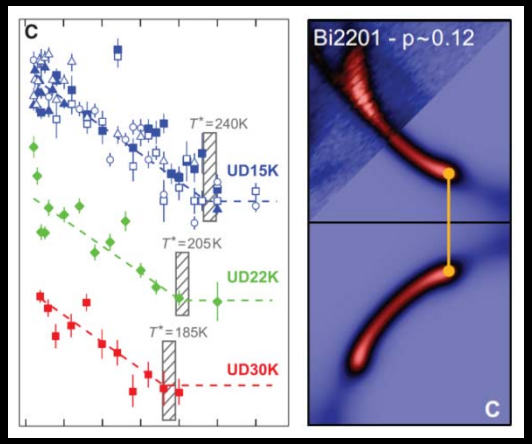
Longitudinal correlations compete with SC

Symmetry of CO:

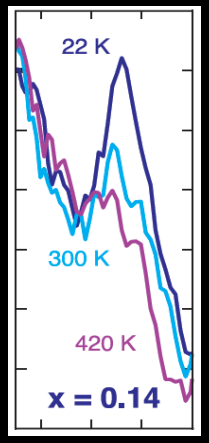
d-wave bond order

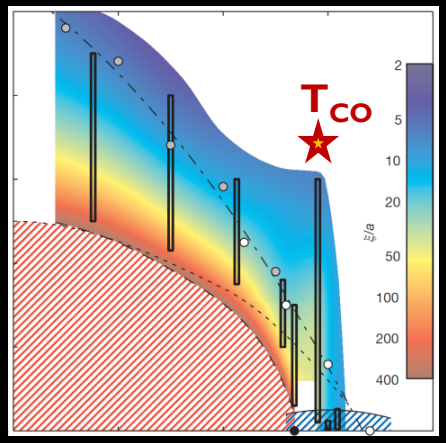


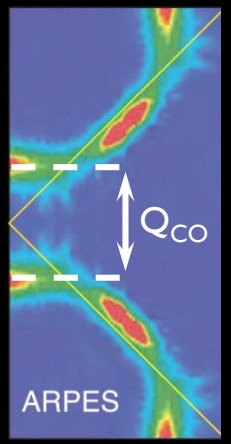
Charge order in cuprates: hole to electron doping



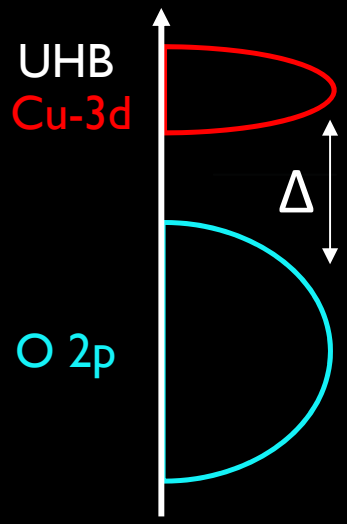
R. Comin et al., Science 340, 390 (2014)







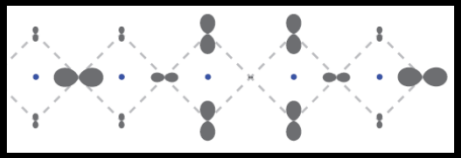
E.H. da Silva Neto et al., arXiv:1410.2253 (2014)



Site-centered ?

da Silva Neto et al.

Bond-centered !



Comin et al.

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