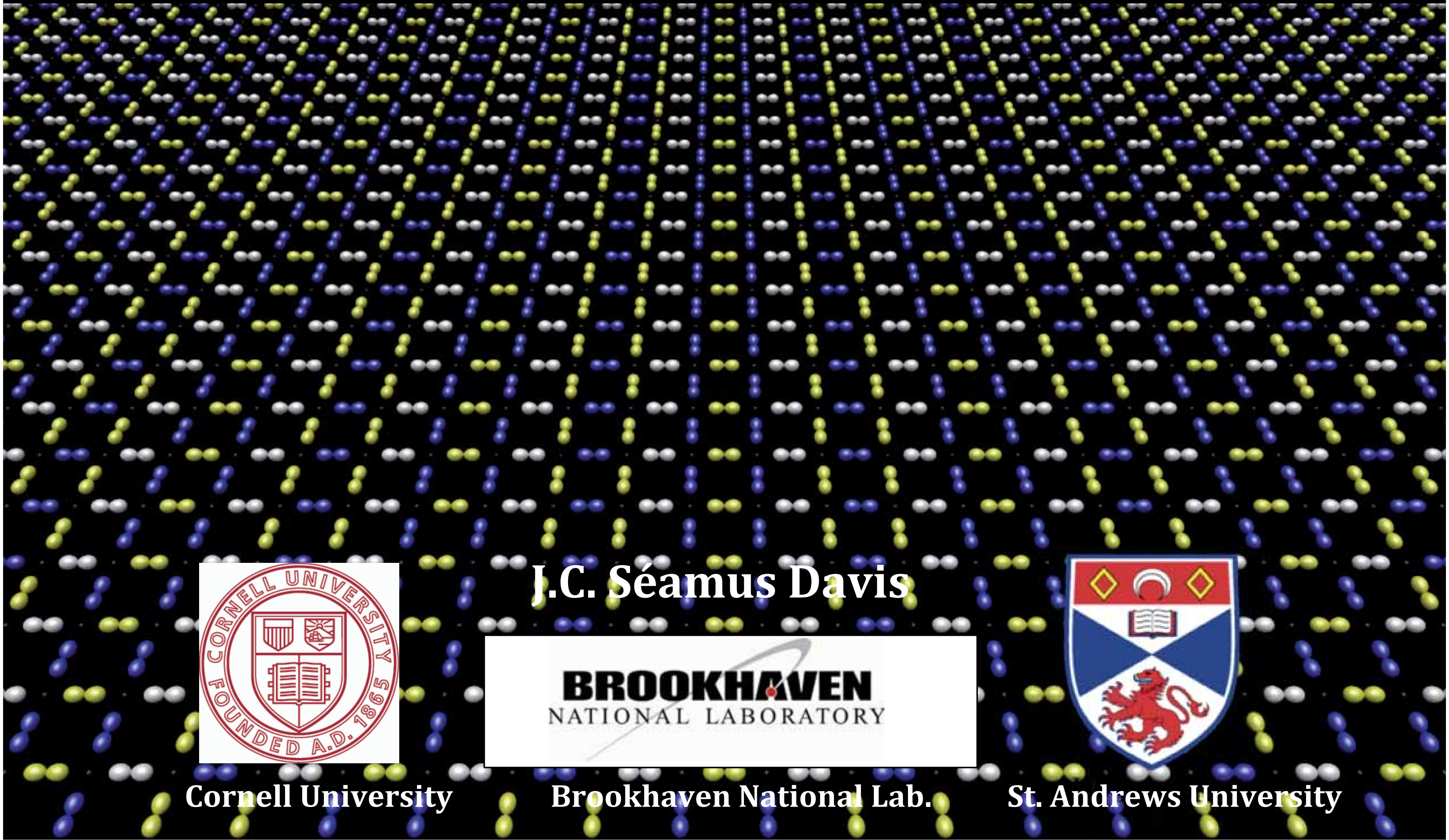
Atomic-scale Antagonism between d-Symmetry Cooper Pairs and d-Symmetry Density Waves in Underdoped Cuprates



J.C. Séamus Davis

Cornell University　Brookhaven National Lab.　St. Andrews University

Atomic-scale Antagonism between d-Symmetry Cooper Pairs and d-Symmetry Density Waves in Underdoped Cuprates


Kazuhiro Fujita
BNL


Mohammad Hamidian
Cornell


Stephen Edkins
St Andrews

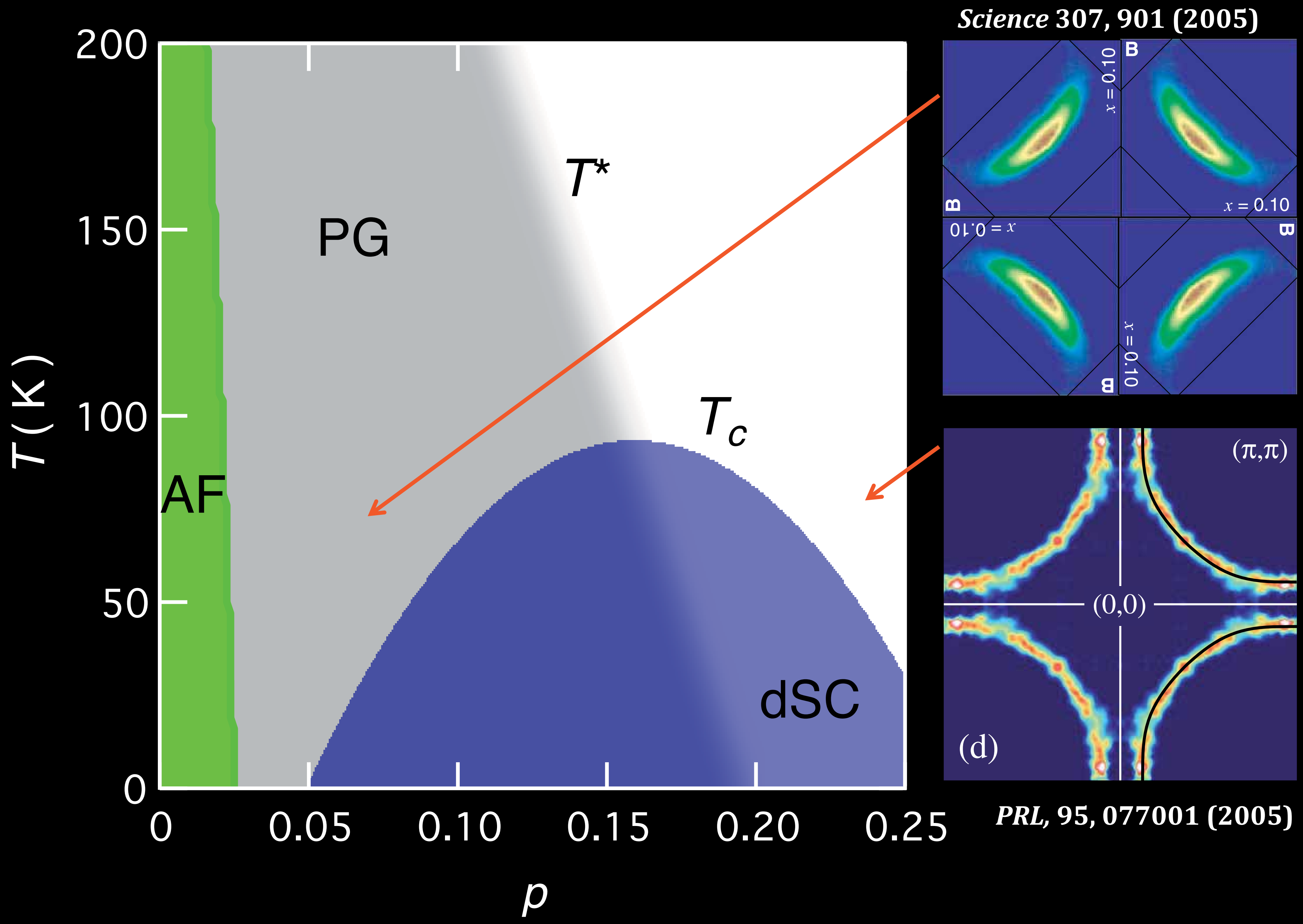

Michael Lawler
Cornell / Binghamton


Eun-Ah Kim
Cornell


Subir Sachdev
Harvard

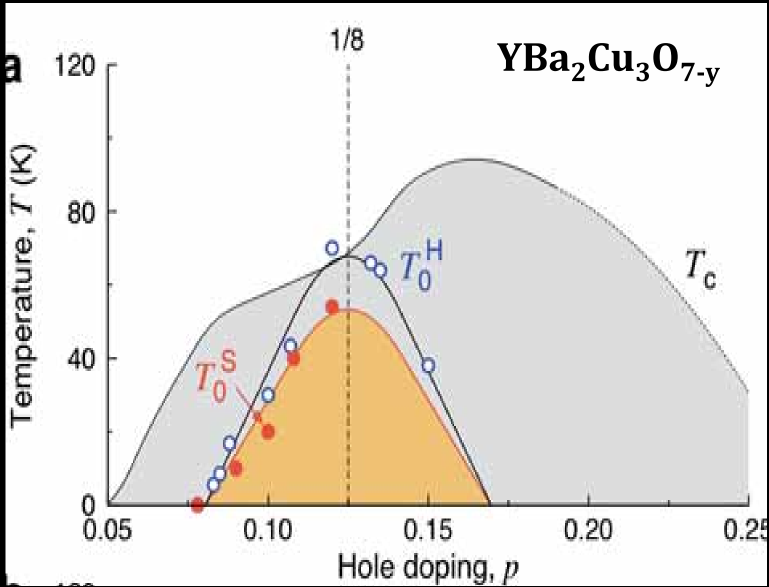
Electronic Structure of High-T_c Cuprates

k-Space Topology (B=0)

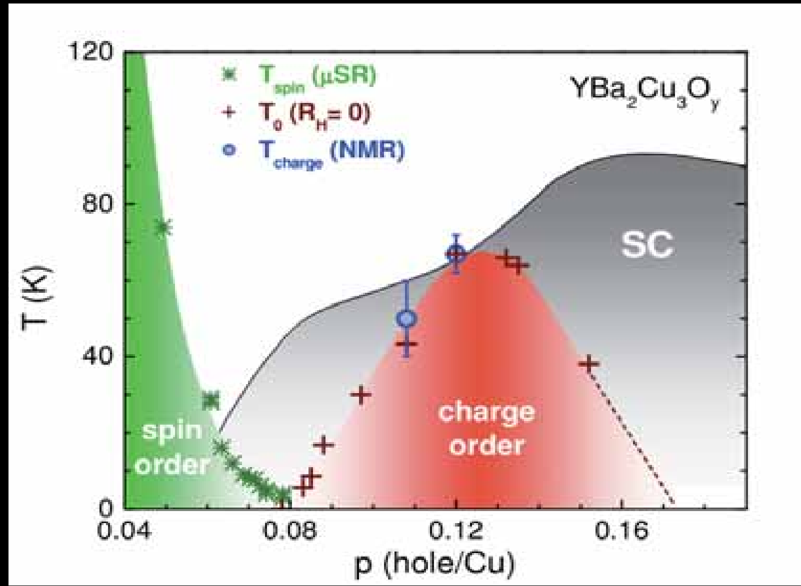


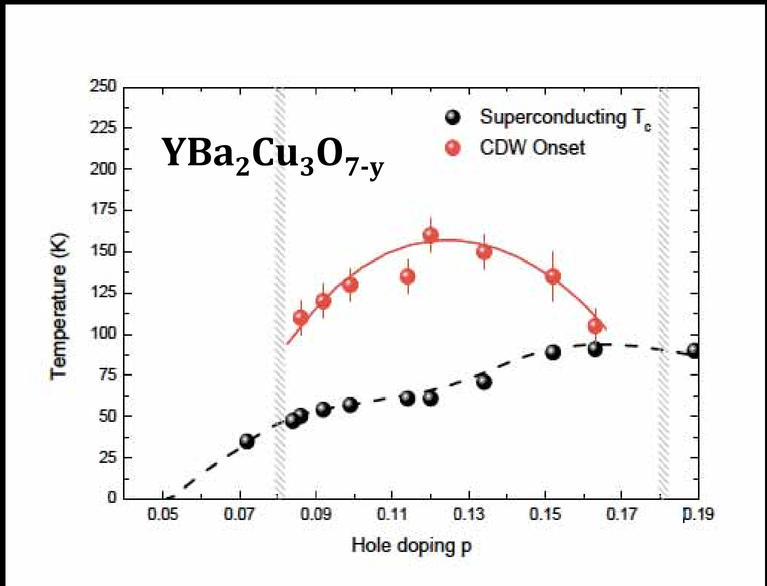
Symmetry Breaking

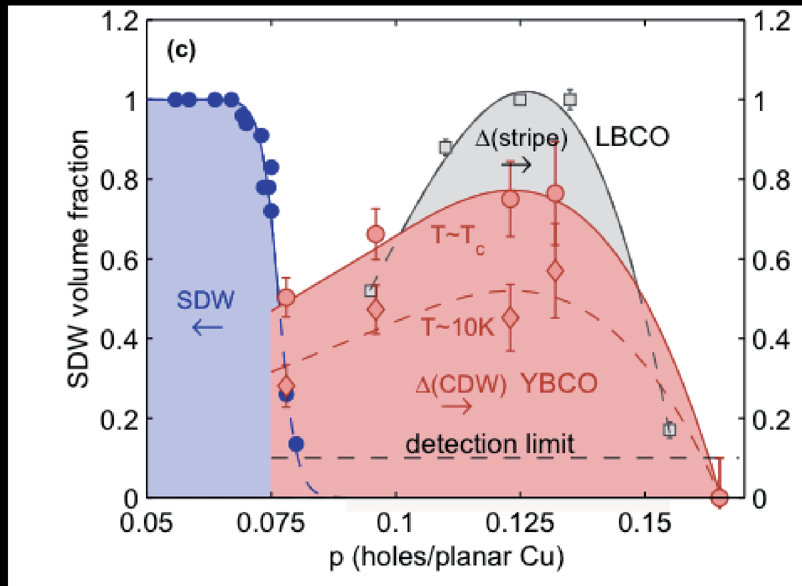
Laliberte *et al,* Nat. Comm. 2 432 (2011)



Wu *et al,* Nature 477, 191 (2011)



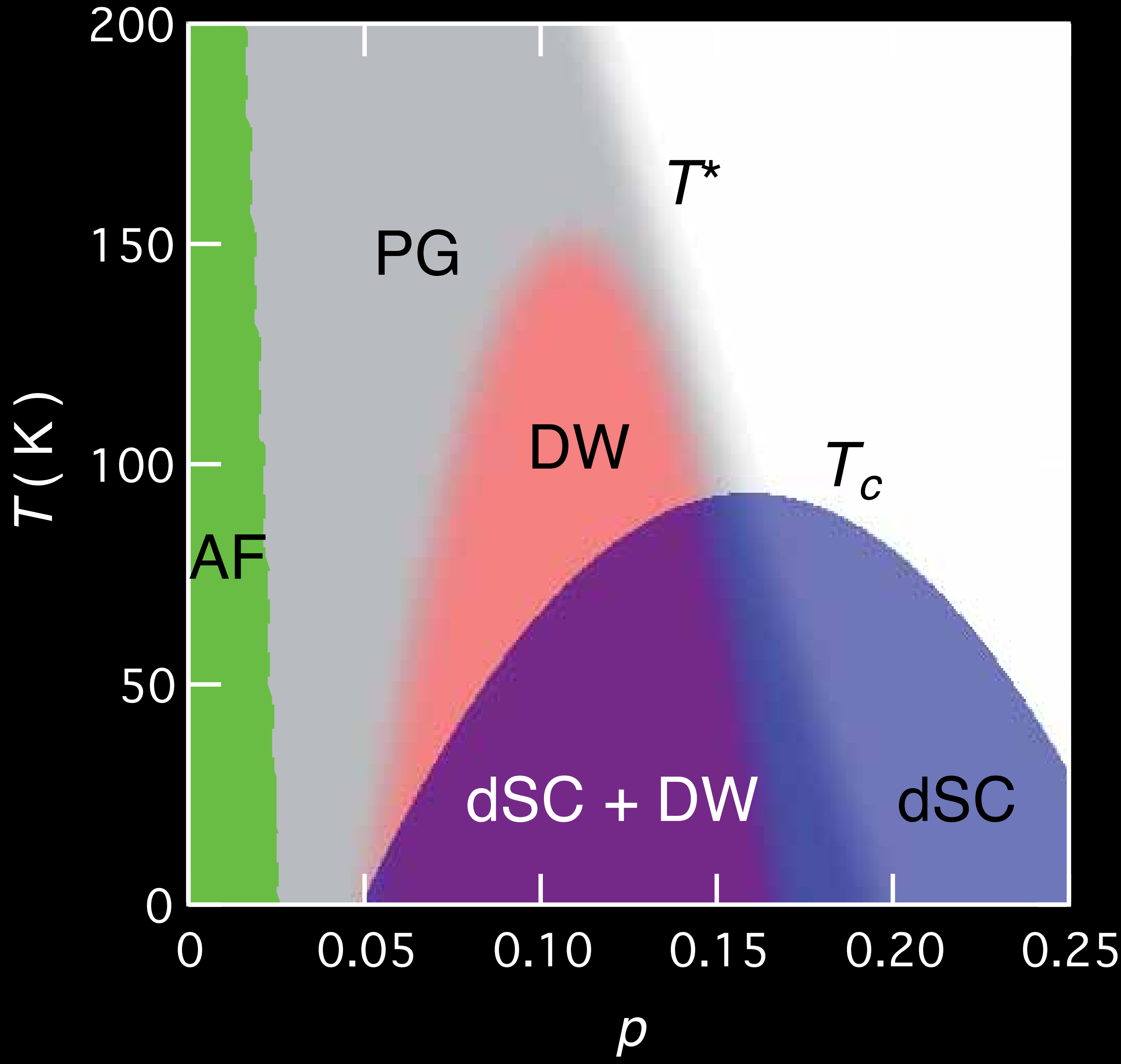




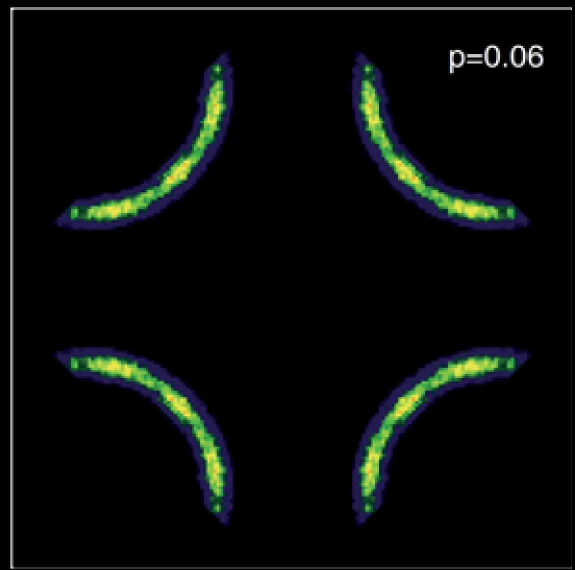
Blanco-Canosa *et al,*
***Phys Rev B* 90:054513-1 (2014).**

Hucker *et al,*
***Phys Rev B* 90:054514-1 (2014)**

Interplay Pseudogap, Density Wave & Superconductivity?

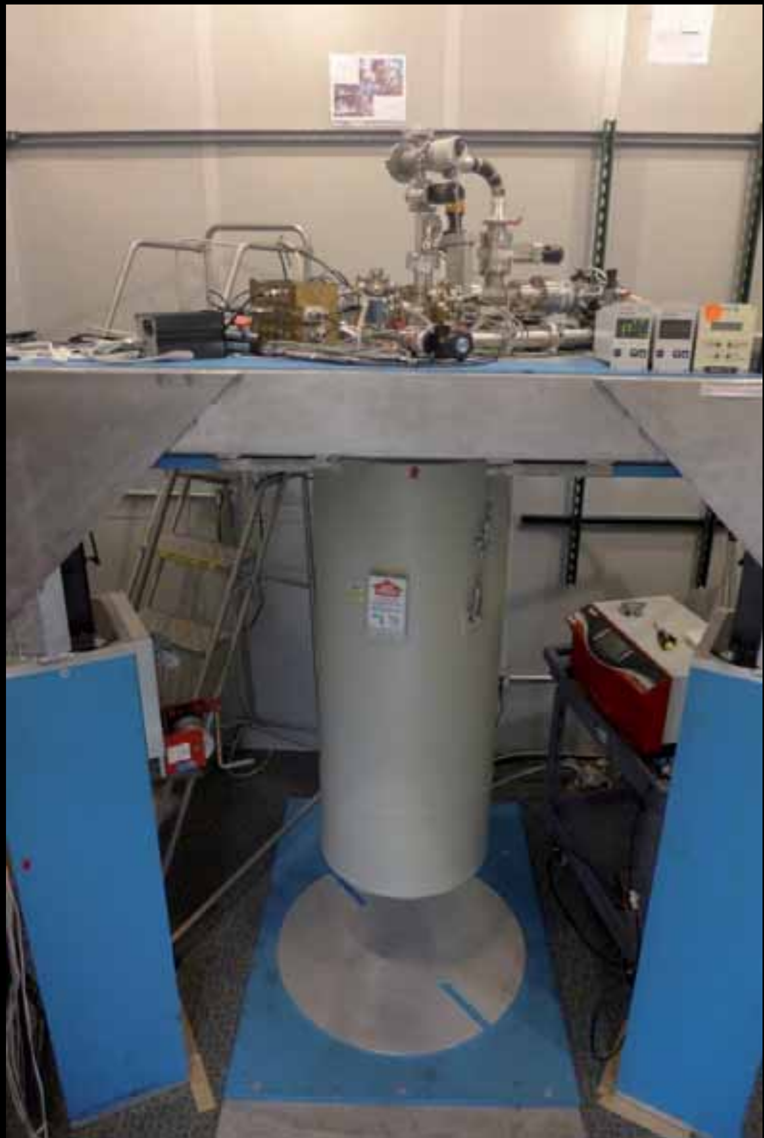


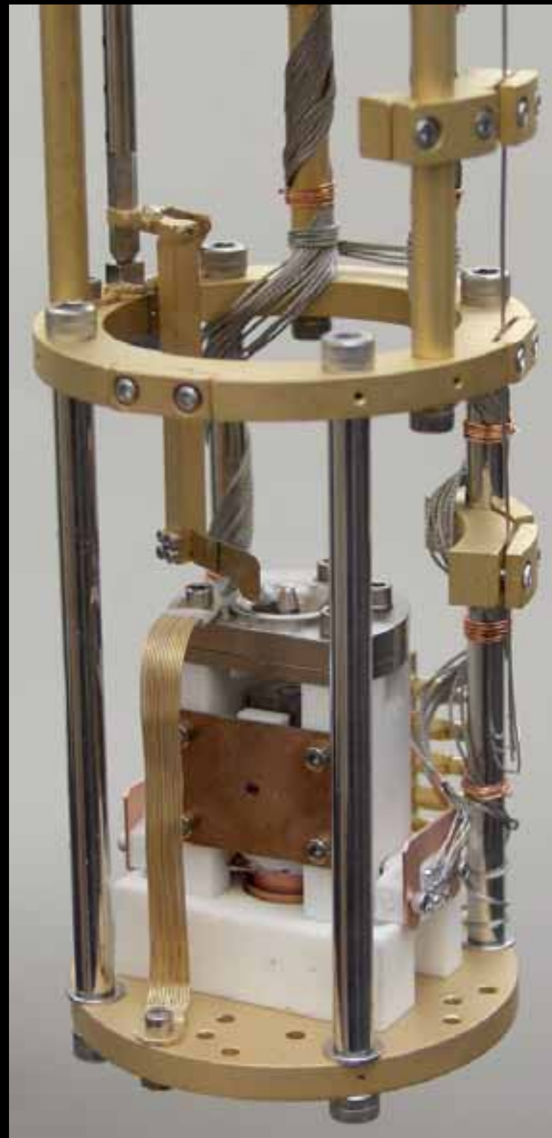
- DW is not the cause of pseudogap regime.
- DW likely an instability of pseudogap regime.
- B=0 DW is not cause of quantum oscillations.



Visualizing Cuprate Symmetry Breaking

SPECTROSCOPIC IMAGING STM

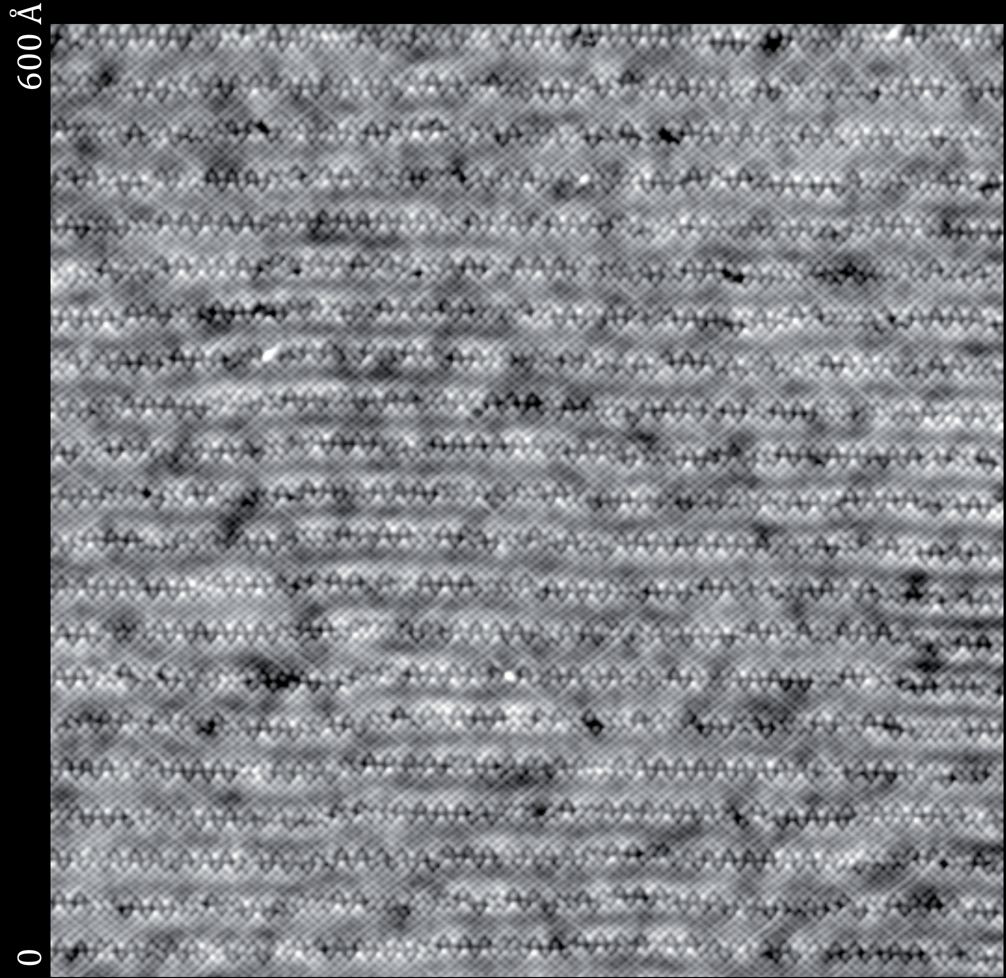




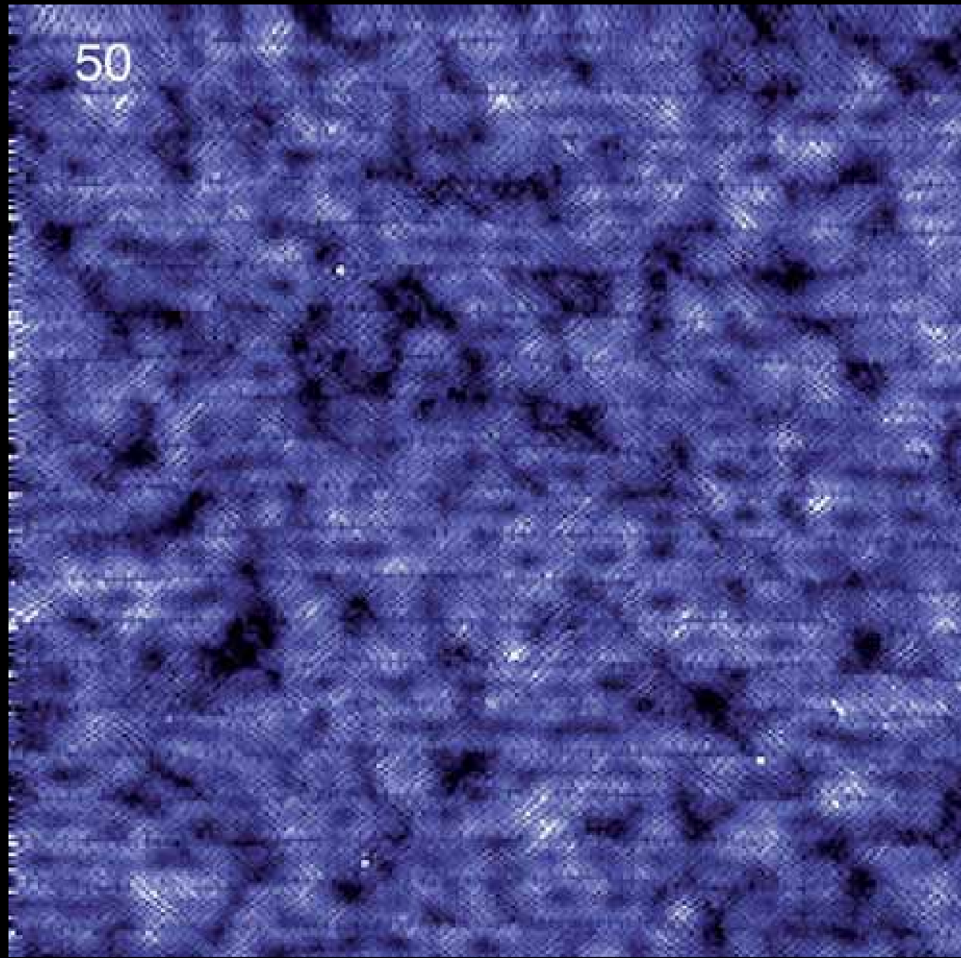
***Rev. Sci. Inst.* 70**, 1459 (1999).

Energy-resolved Visualization Real-Space Electronic Structure

Topograph

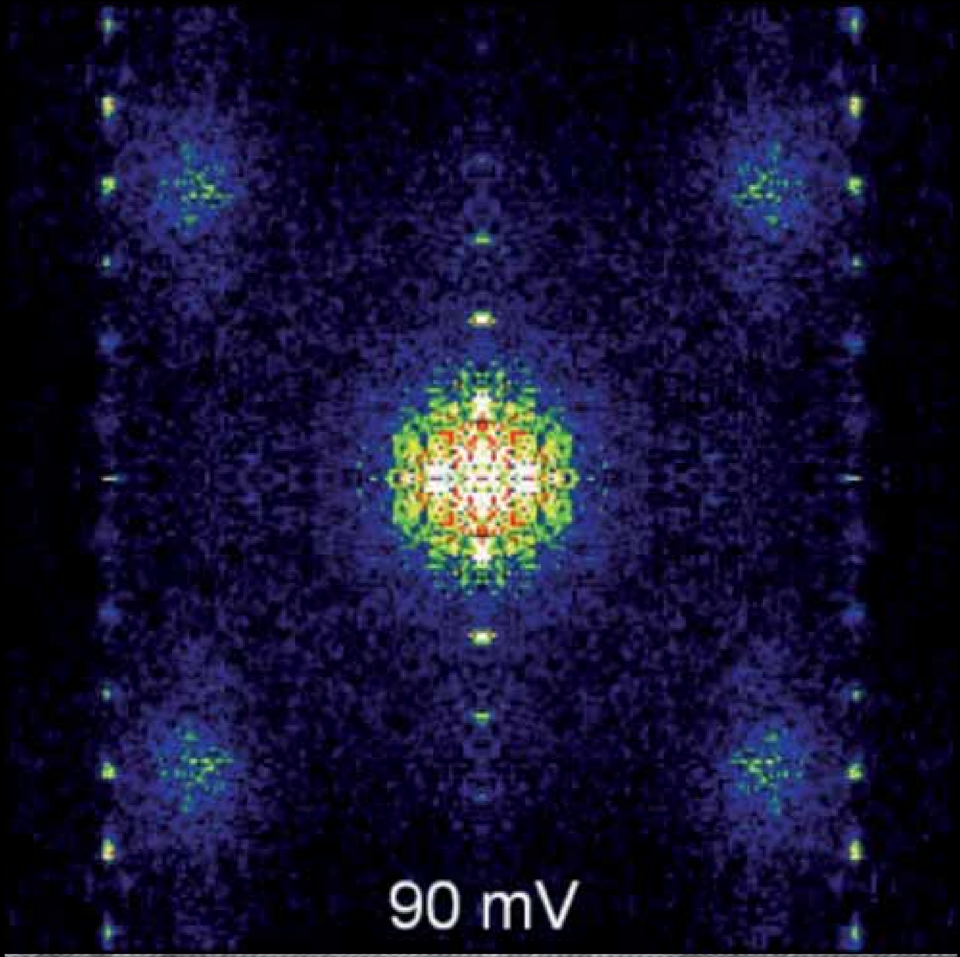


g (r,V)

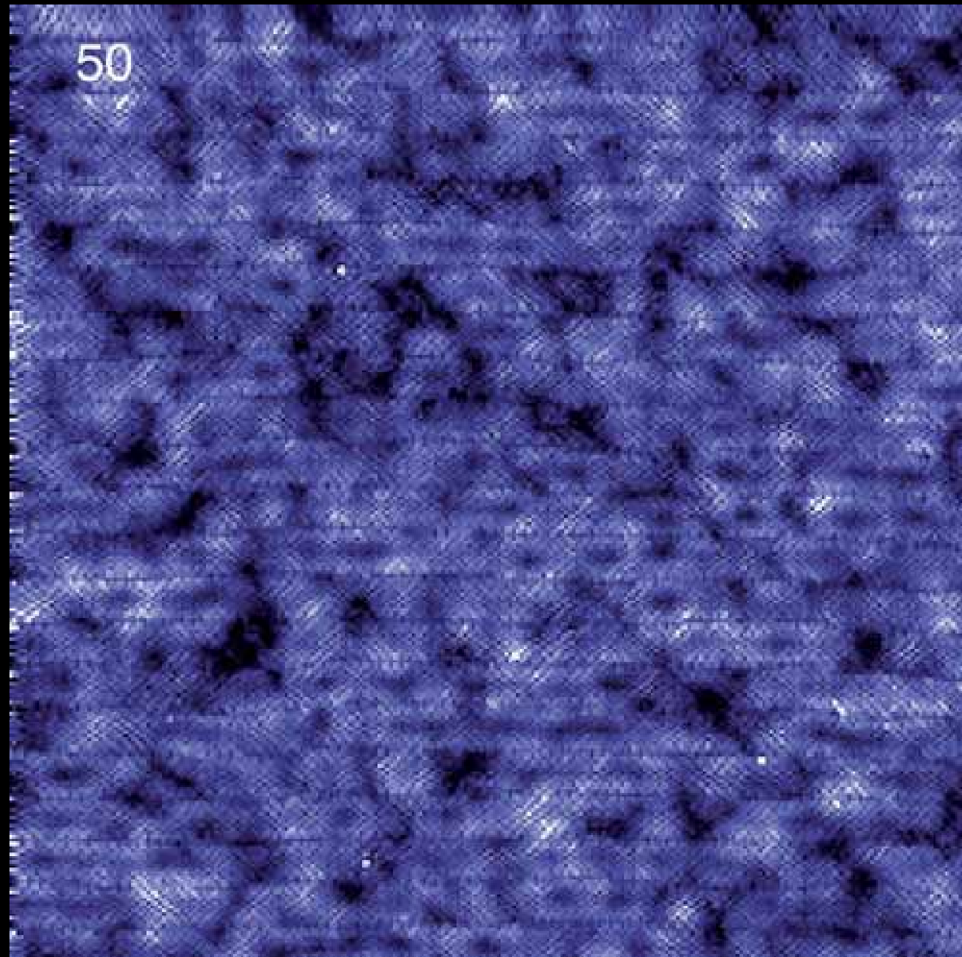


Energy-resolved *k*-Space Electronic Structure

g (q, **E)**

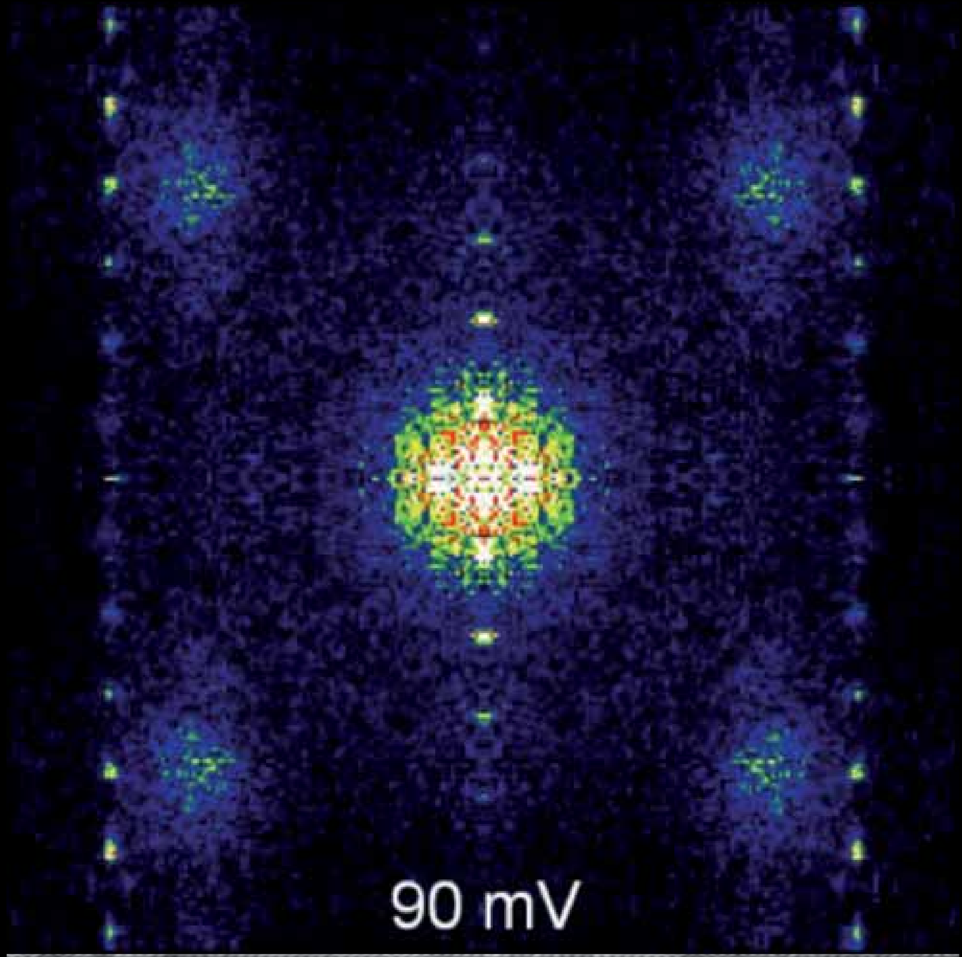


g (r,V)

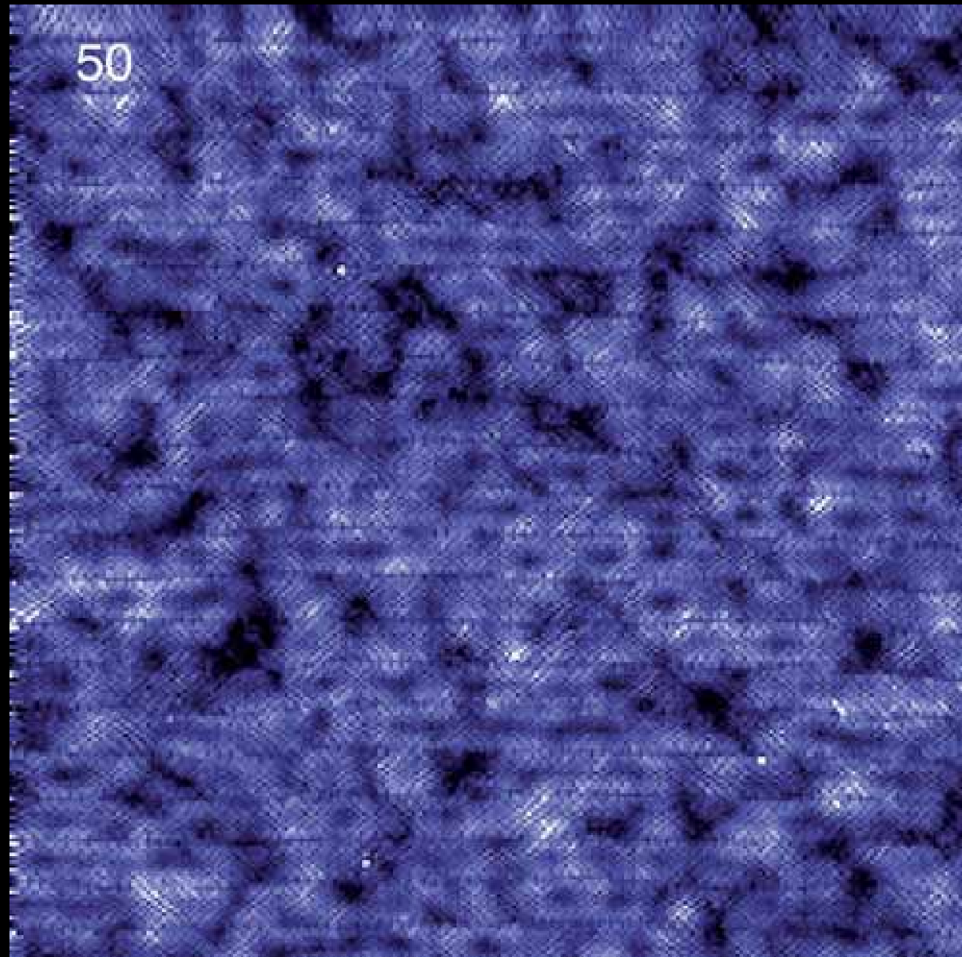


Features of SI-STM Technique

g (q, **E)**

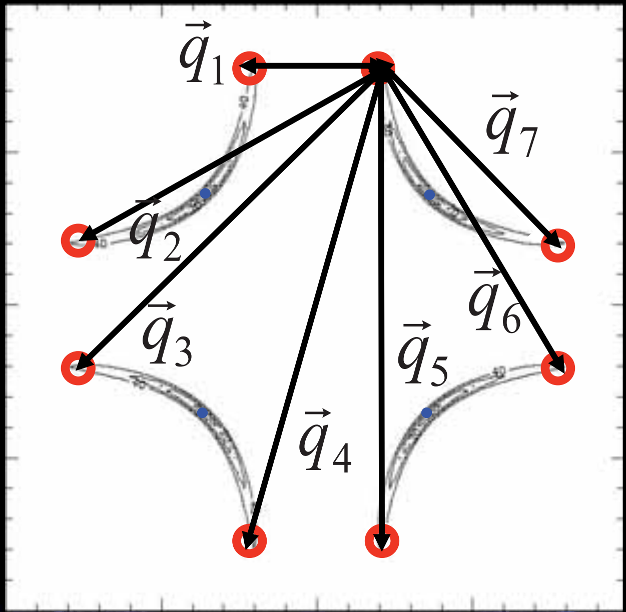


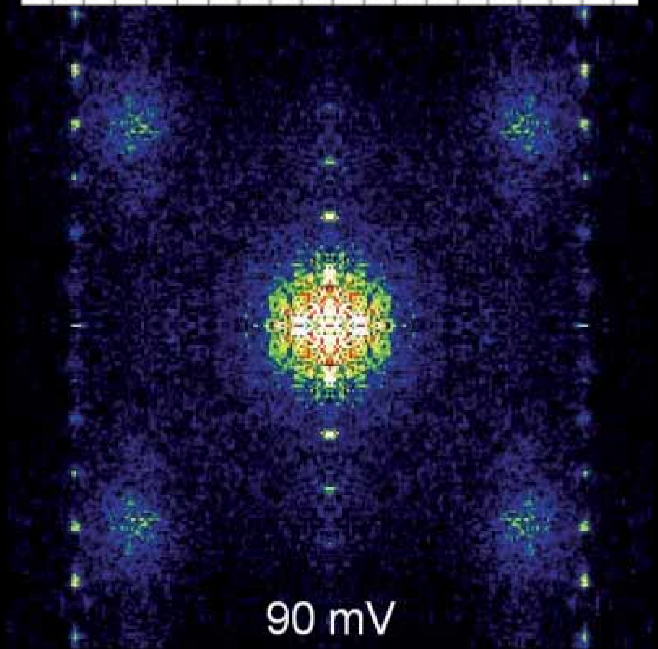
g (r,V)

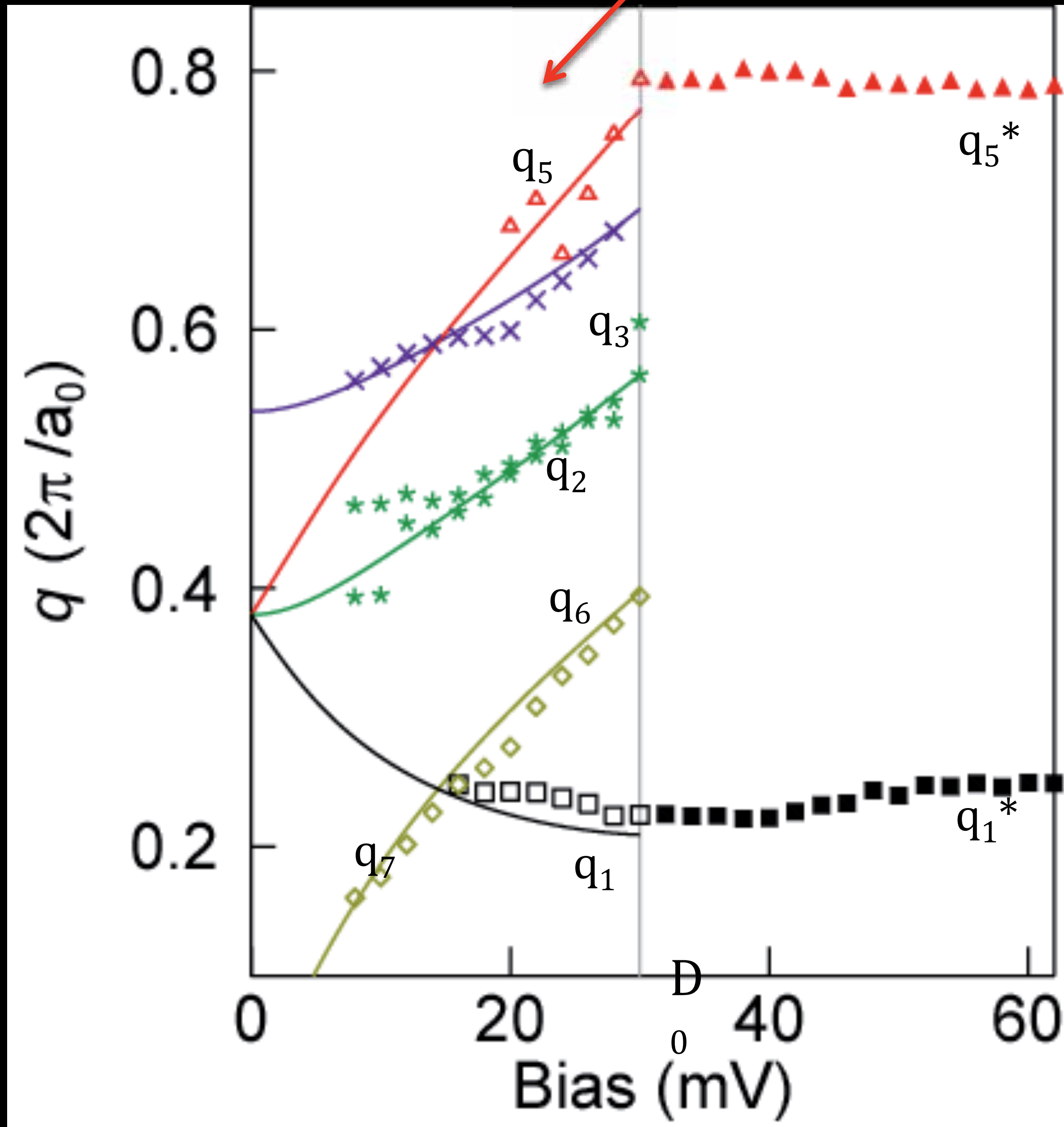


- ➢ k-space & r-space simultaneously
- ➢ energy resolution ~ 30 μV
- ➢ access both filled & empty states
- ➢ functions in high magnetic field

Low Energy: Bogoliubov signature of d-wave Cooper pairing

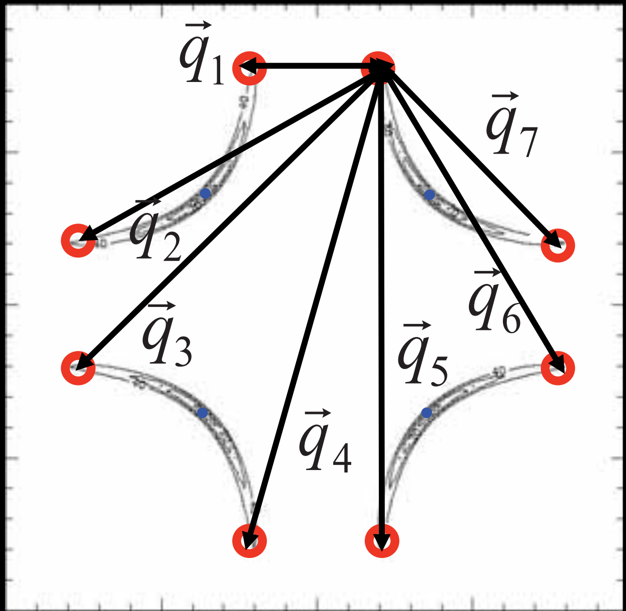


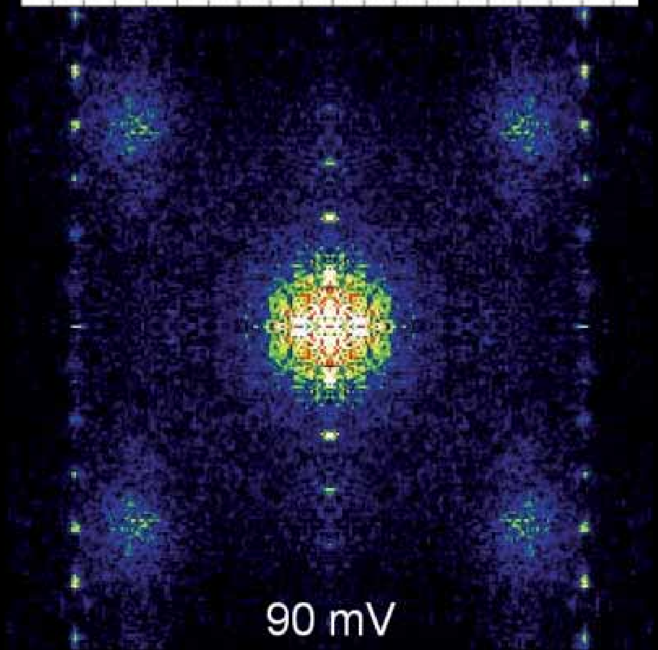


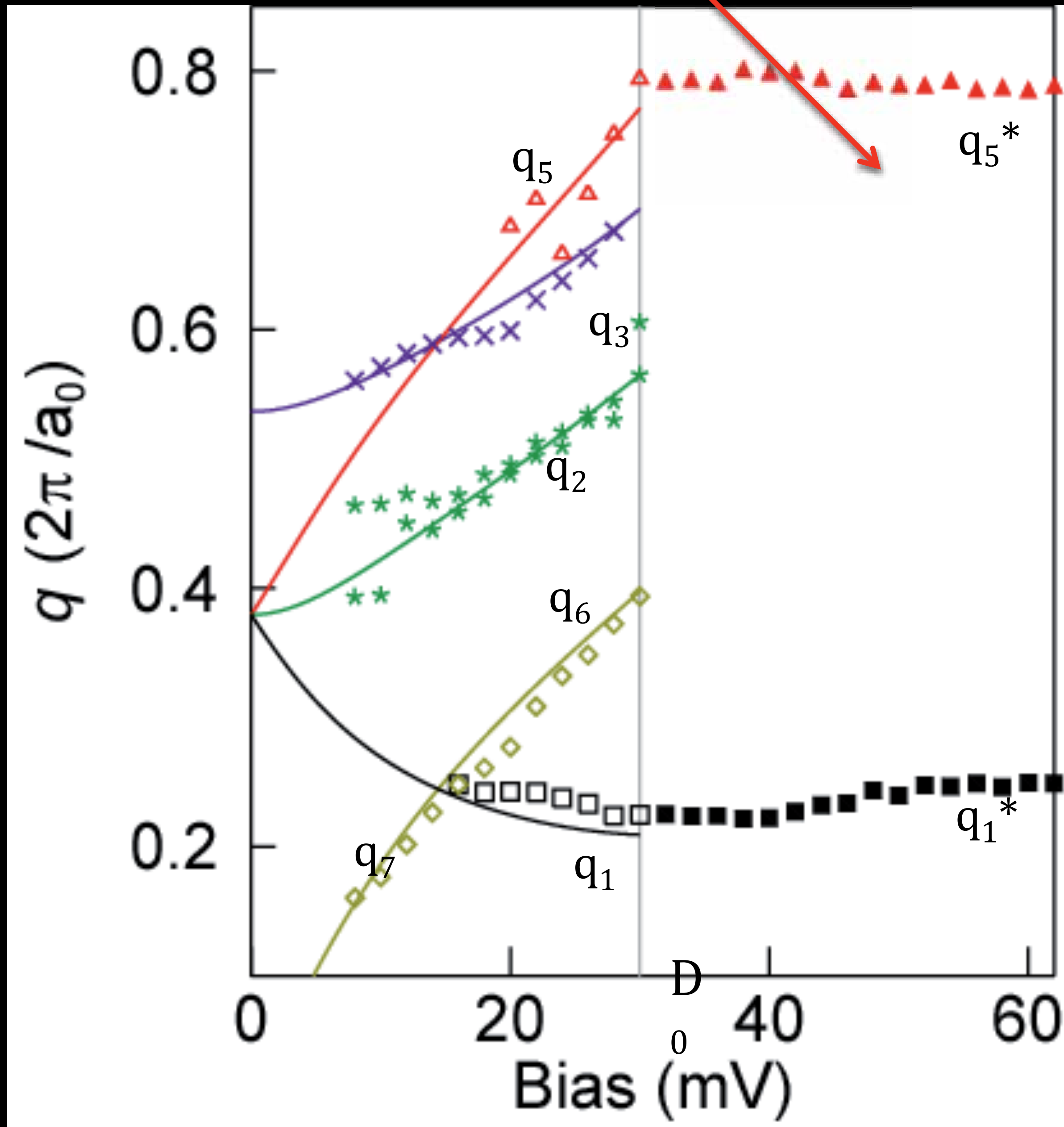


PRL 94, 197005 (2005) ***Science 454,*** 1072 (2007) ***JPSJ 82***, 011005 (2011) ***Science 344,*** 612(2014)

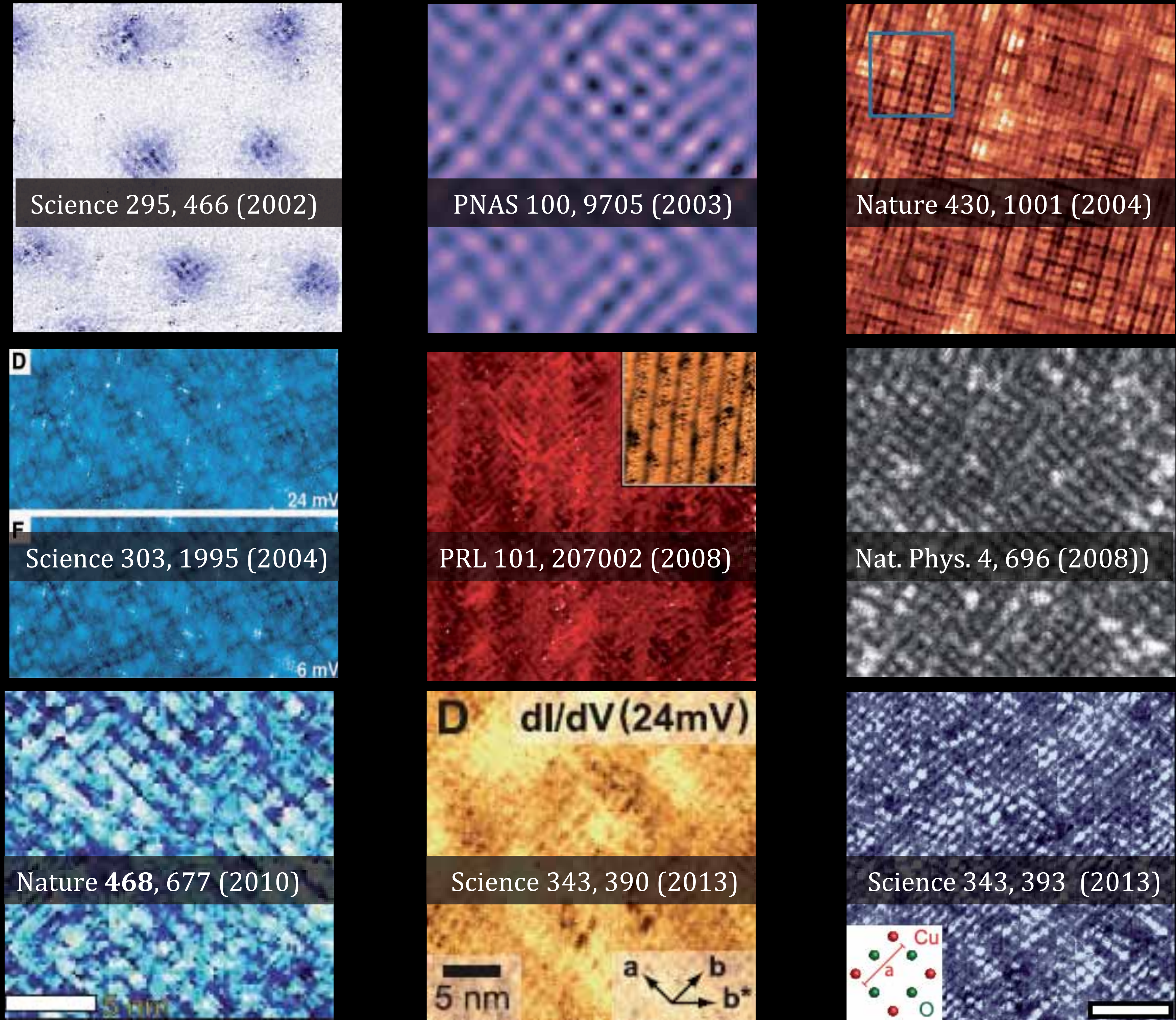
High Energy: Quasi-static Broken Symmetry States



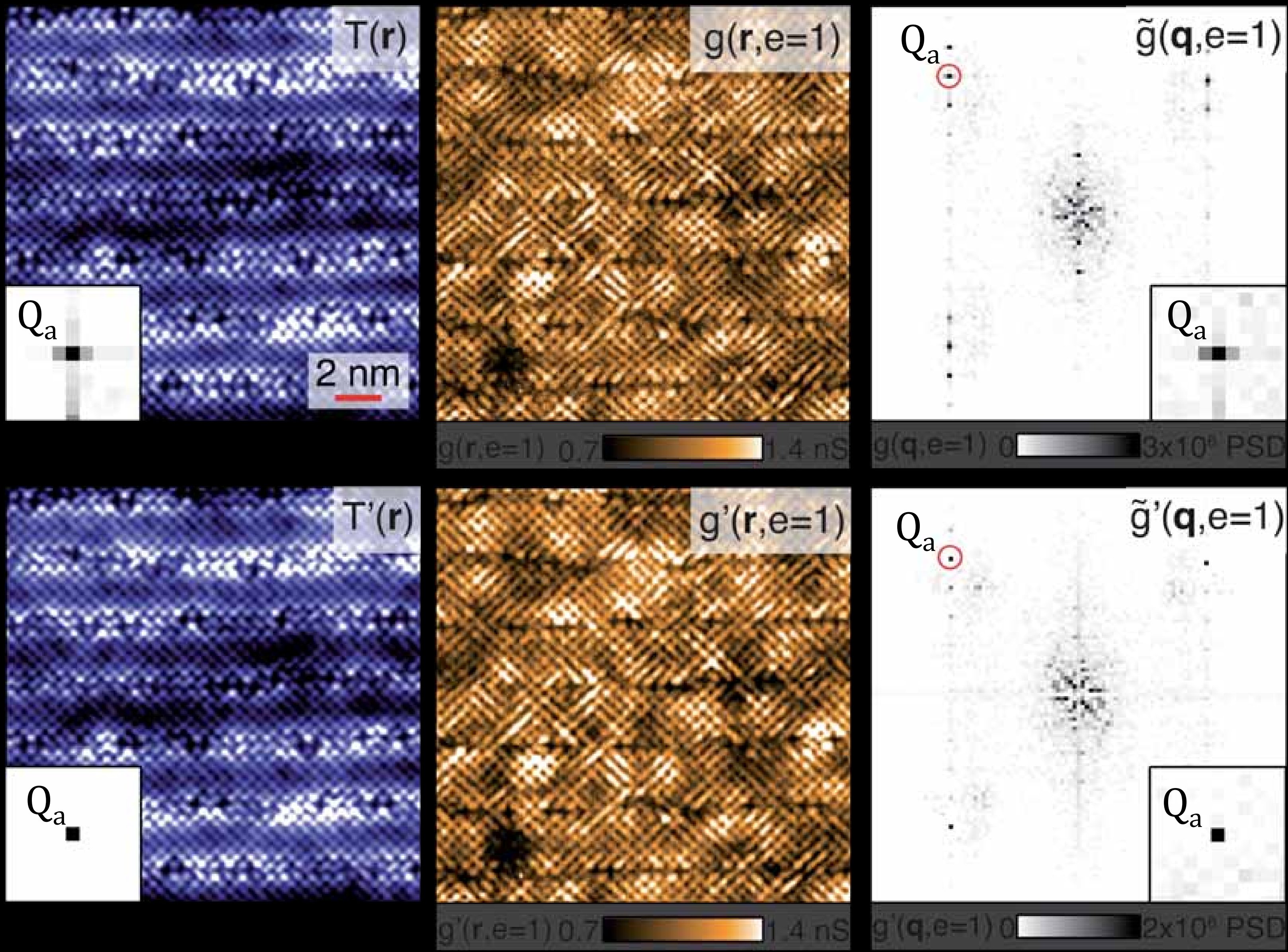




PRL 94, 197005 (2005) ***Science 454,*** 1072 (2007) ***JPSJ 82***, 011005 (2011) ***Science 344,*** 612(2014)

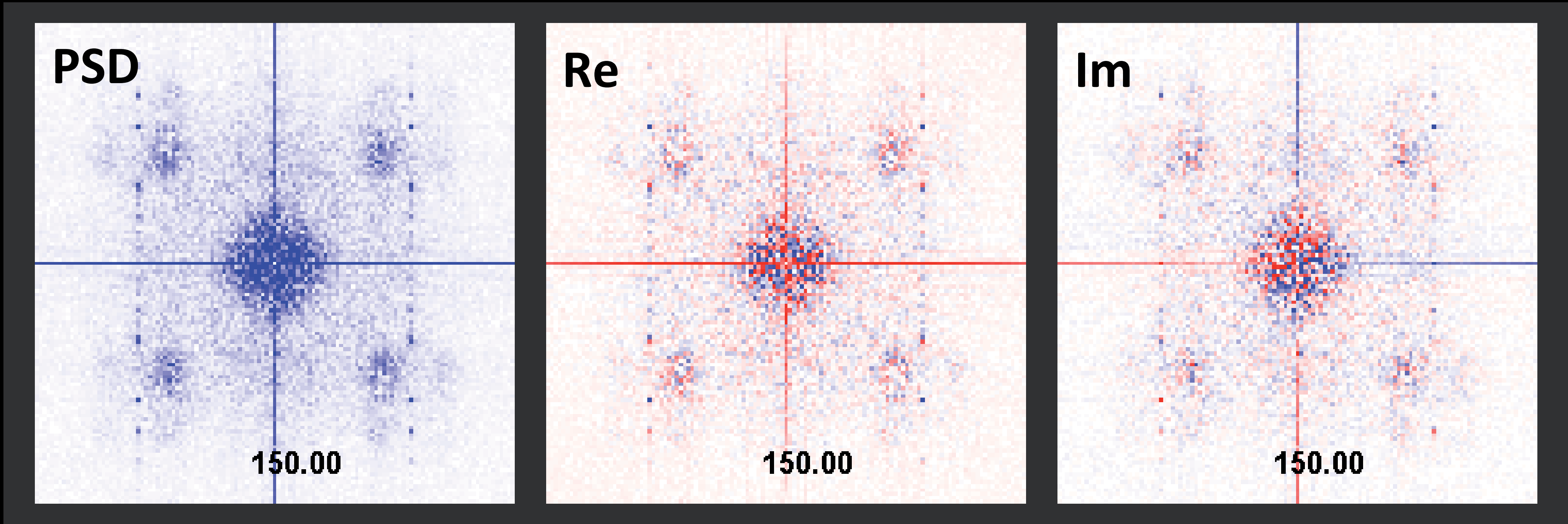

Science 295, 466 (2002)
PNAS 100, 9705 (2003)
Nature 430, 1001 (2004)
D
24 mV
F
Science 303, 1995 (2004)
6 mV
PRL 101, 207002 (2008)
Nat. Phys. 4, 696 (2008))
Nature **468**, 677 (2010)
D
dI/dV(24mV)
Science 343, 390 (2013)
5 nm
a
b
b*
Science 343, 393 (2013)
Cu
a
O

New SI-STM Modality: Phase Resolved Intra-unit-cell Imaging



***Nature* 466**, 374 (2010); ***NJP* 14**, 053017 (2012); ***J. Phys. Soc. Jpn* 82**, 011005 (2011); ***PNAS* 111**, E3026 (2014)

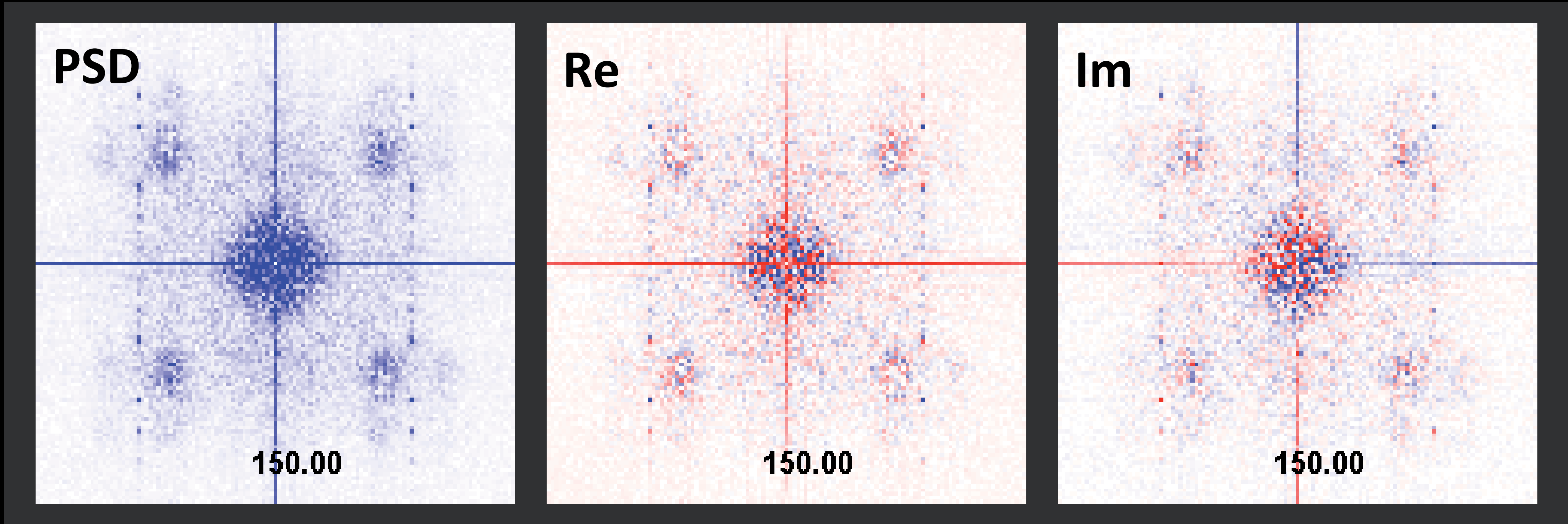
New SI-STM Modality: Phase Resolved Intra-unit-cell Imaging



Information not possible from scattering probes

Nature 466, 374 (2010); ***NJP 14***, 053017 (2012); ***J. Phys. Soc. Jpn 82***, 011005 (2011); ***PNAS* 111**, E3026 (2014)

New SI-STM Modality: Phase Resolved Intra-unit-cell Imaging



$C_{4v} \rightarrow C_{2v}$ (Nematic) : Re $g(\boldsymbol{Q}_A)$-Re $g(\boldsymbol{Q}_B)$

Inversion Breaking : $|\mathrm{Im}\ g(\boldsymbol{Q}_A)| + |\mathrm{Im}\ g(\boldsymbol{Q}_B)|$

Density Wave FF Symmetry : To be described in this talk

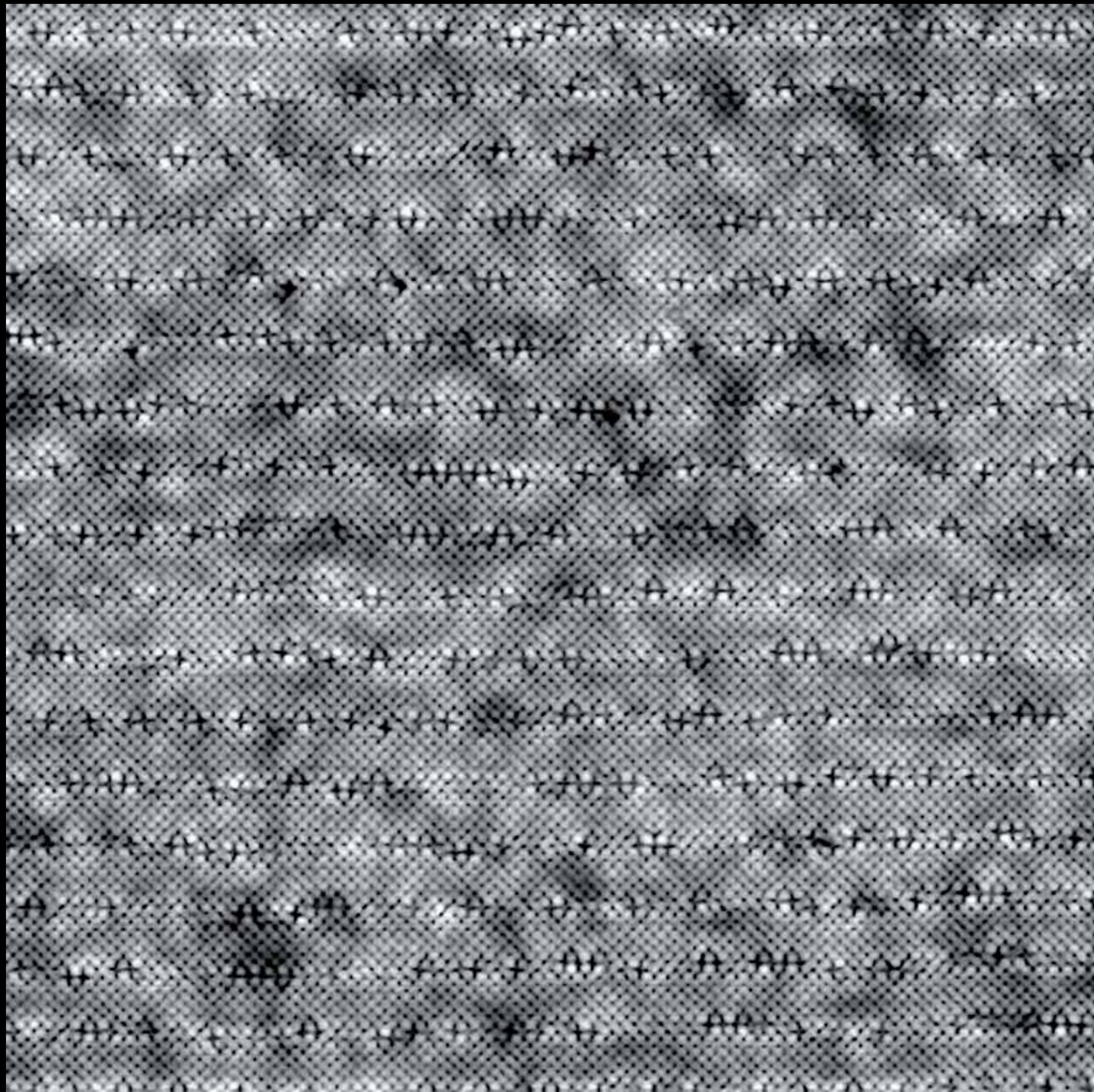
Nature 466, 374 (2010); ***NJP 14***, 053017 (2012); ***J. Phys. Soc. Jpn 82***, 011005 (2011); ***PNAS 111***, E3026 (2014)

[redacted]

FF Symmetry of Cuprate Density Wave State

Topograph

$T(\boldsymbol{r})$



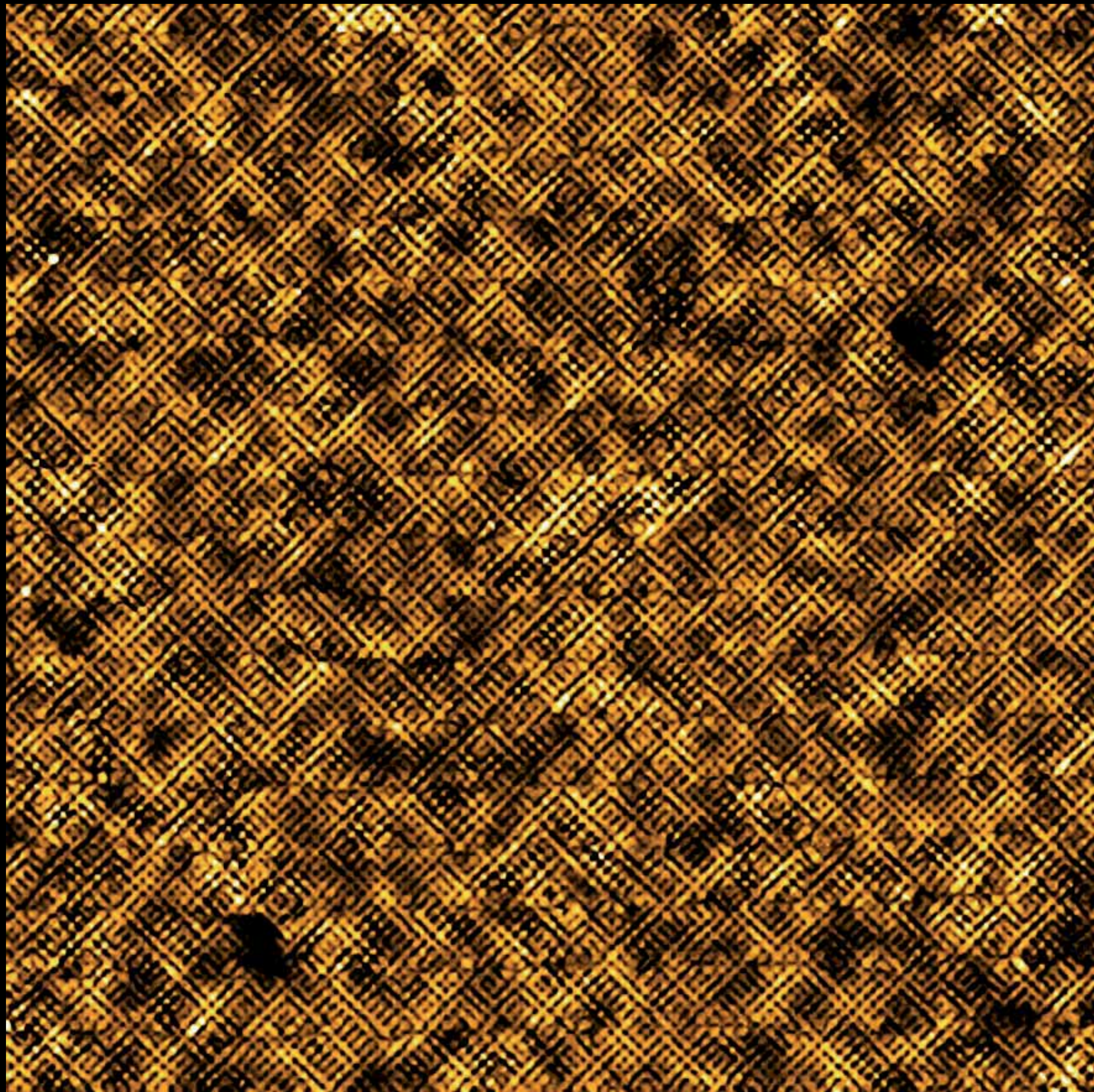
45 nm

Nature 430, 1001 (2004) ***Science 315,*** 1380 (2007) *Nature* **466,** 374 (2010) ***Science 344, 612*** (2014)

Electronic Structure

R($\boldsymbol{r}$)

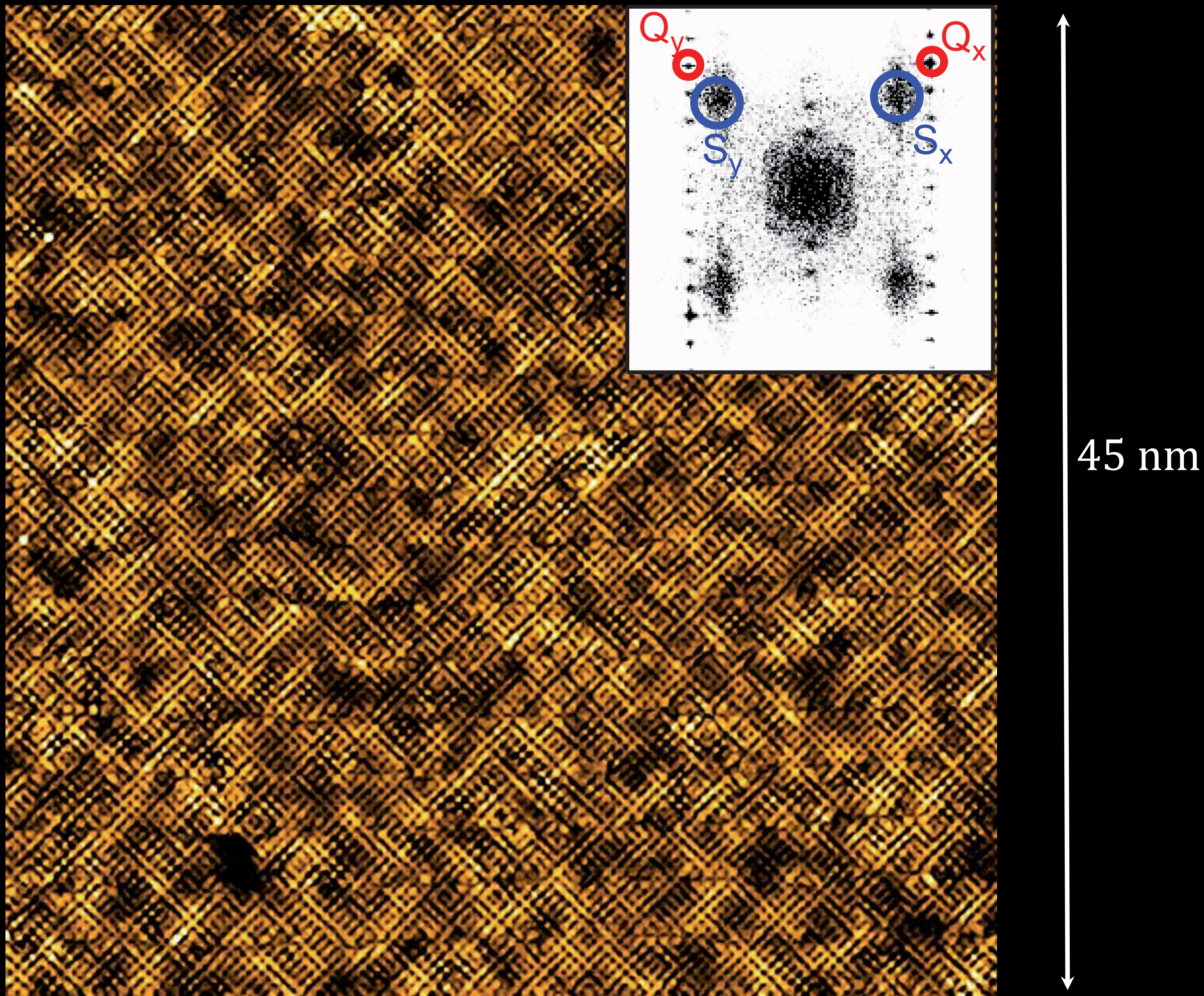
$p \sim 10\%$



45 nm

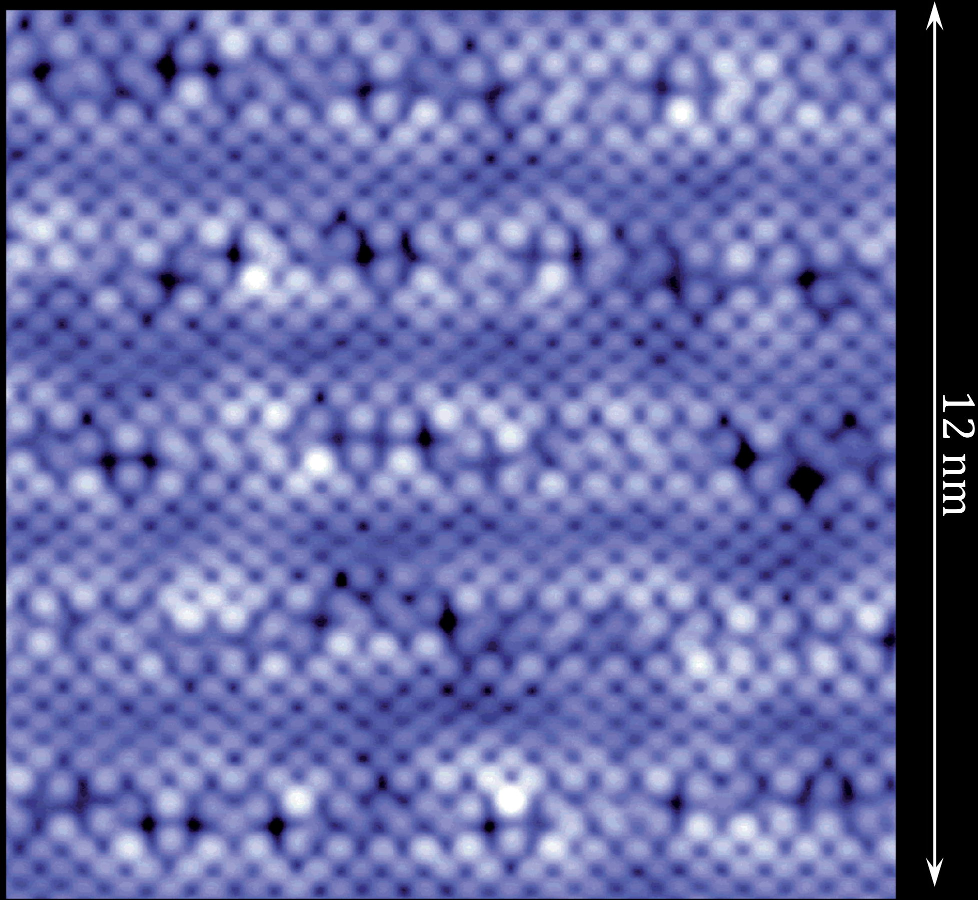
***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

Incommensurate Q≠0: Density Wave



***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

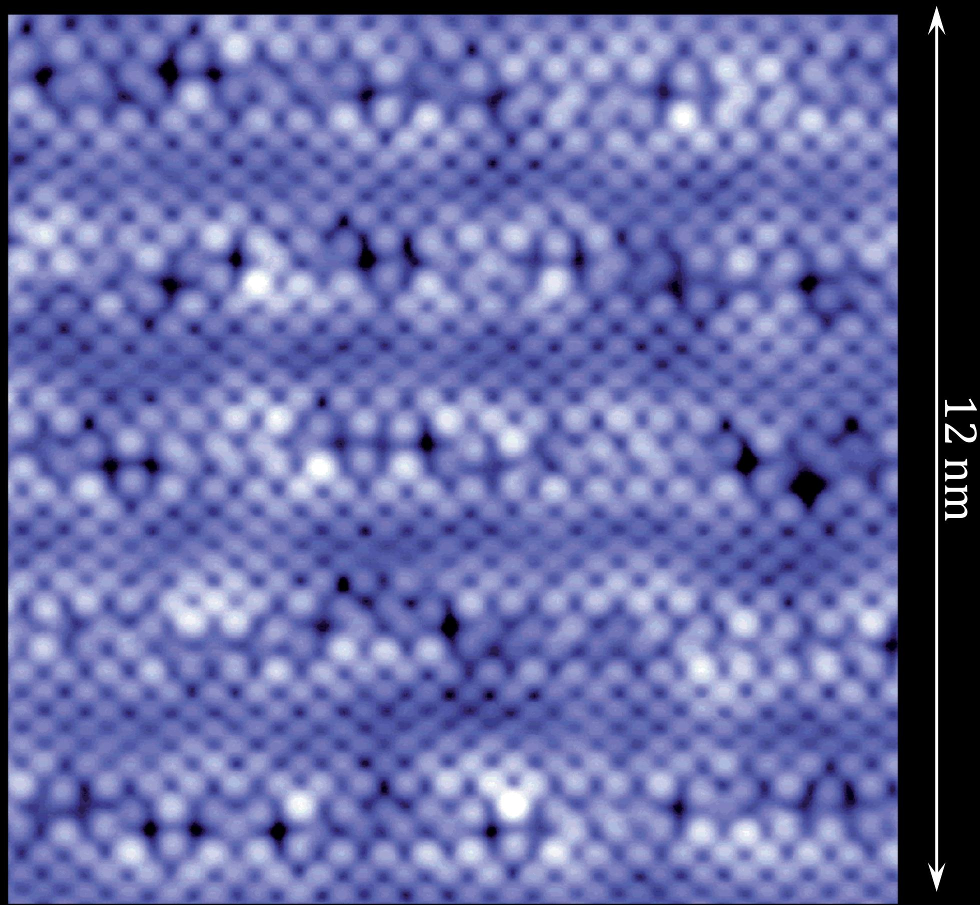
High-resolution Imaging Cuprate Broken-Symmetry States



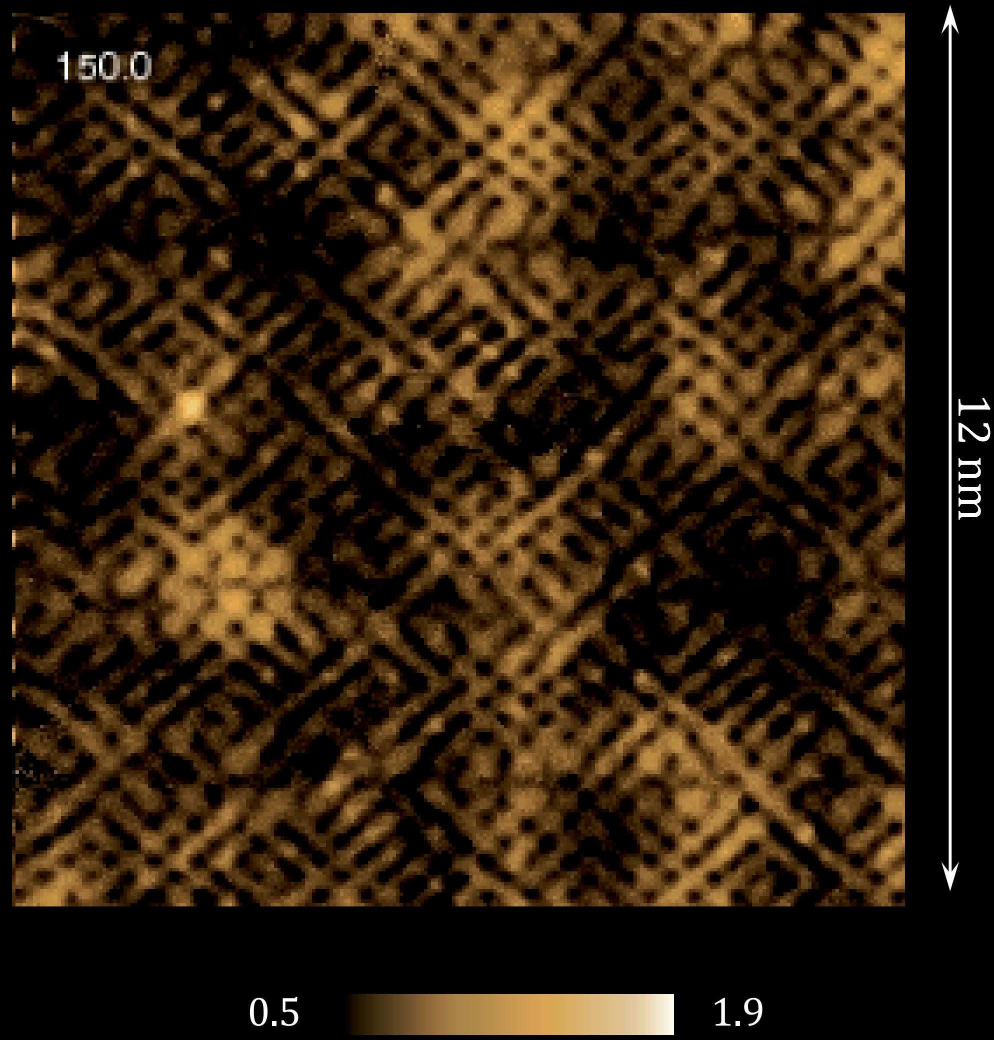
$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

Nature 430, 1001 (2004) ***Science 315,*** 1380 (2007) *Nature* **466,** 374 (2010) ***Science 344, 612*** (2014)

High-resolution Imaging Cuprate Broken-Symmetry States

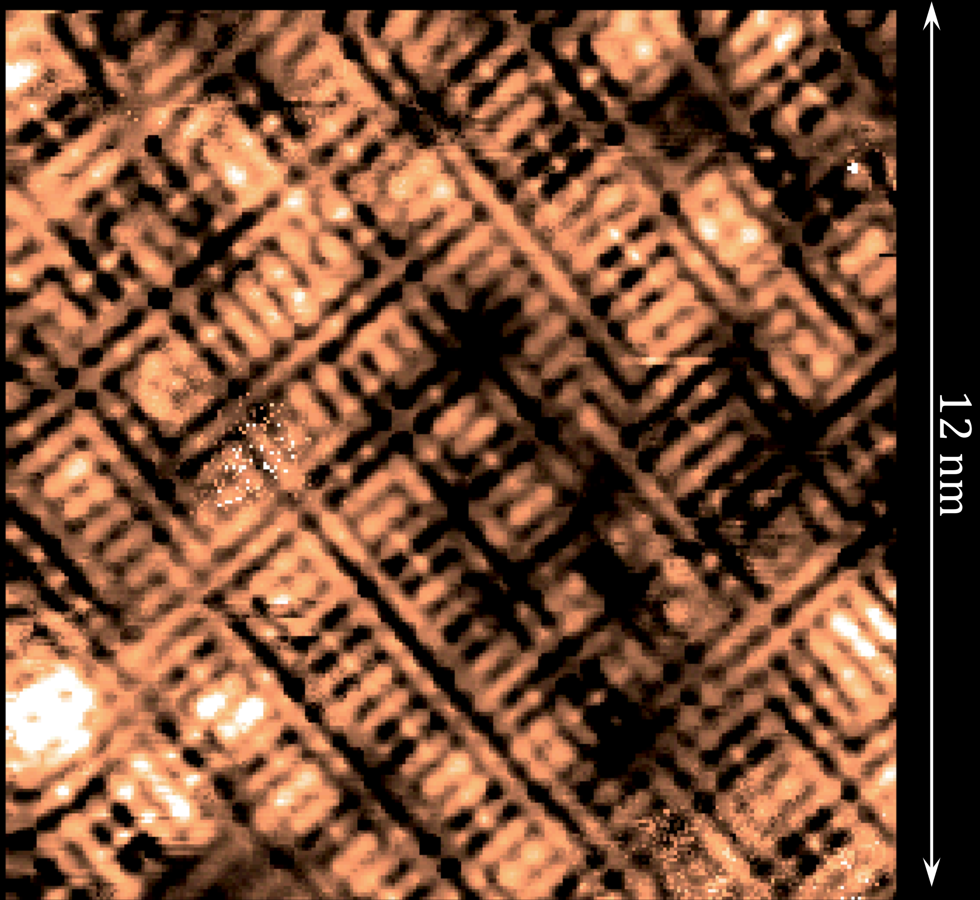


$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$

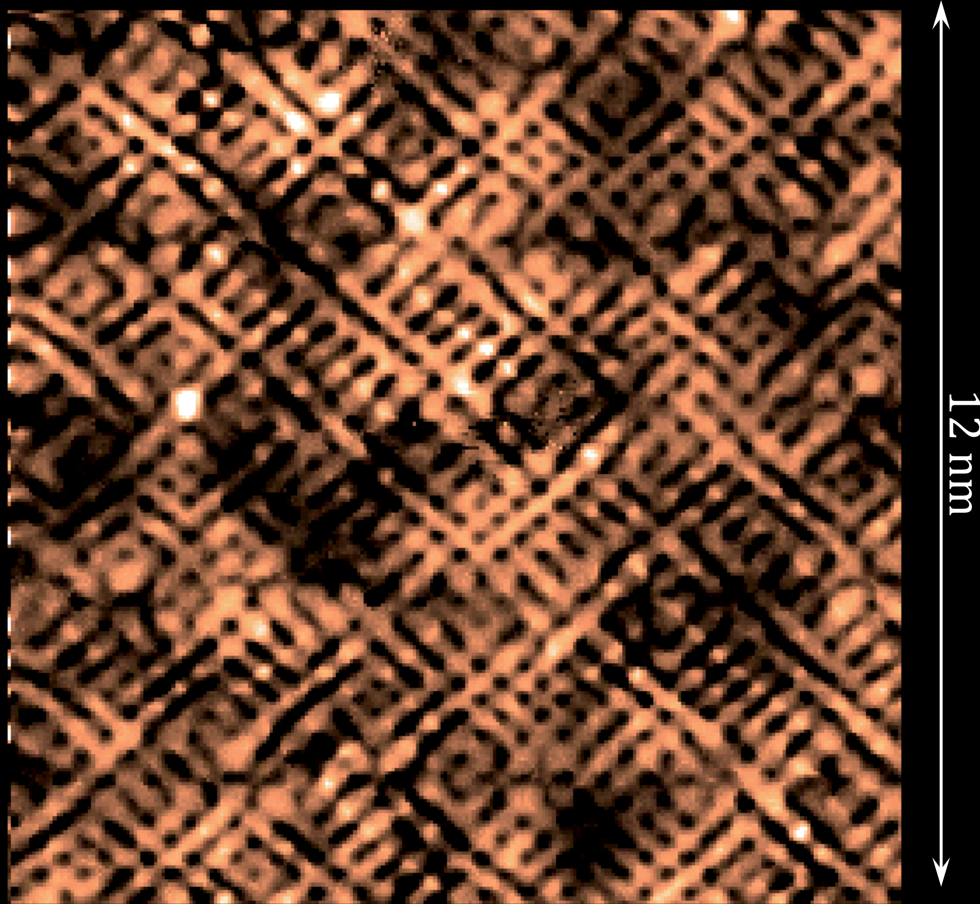


Nature 430, 1001 (2004)   ***Science 315,*** 1380 (2007)   *Nature* **466,** 374 (2010)   ***Science 344, 612*** (2014)

Q≠0 Trans. & Rot. Symmetry Breaking



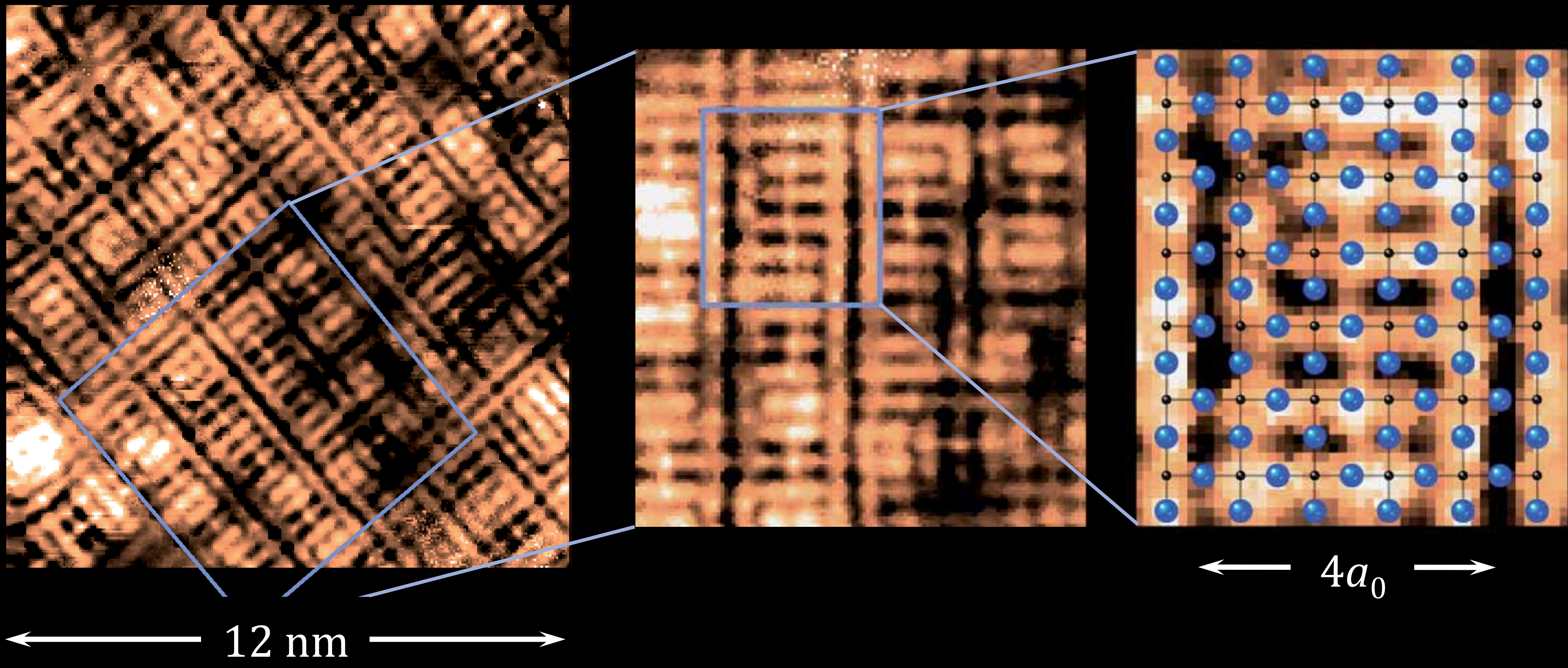
$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

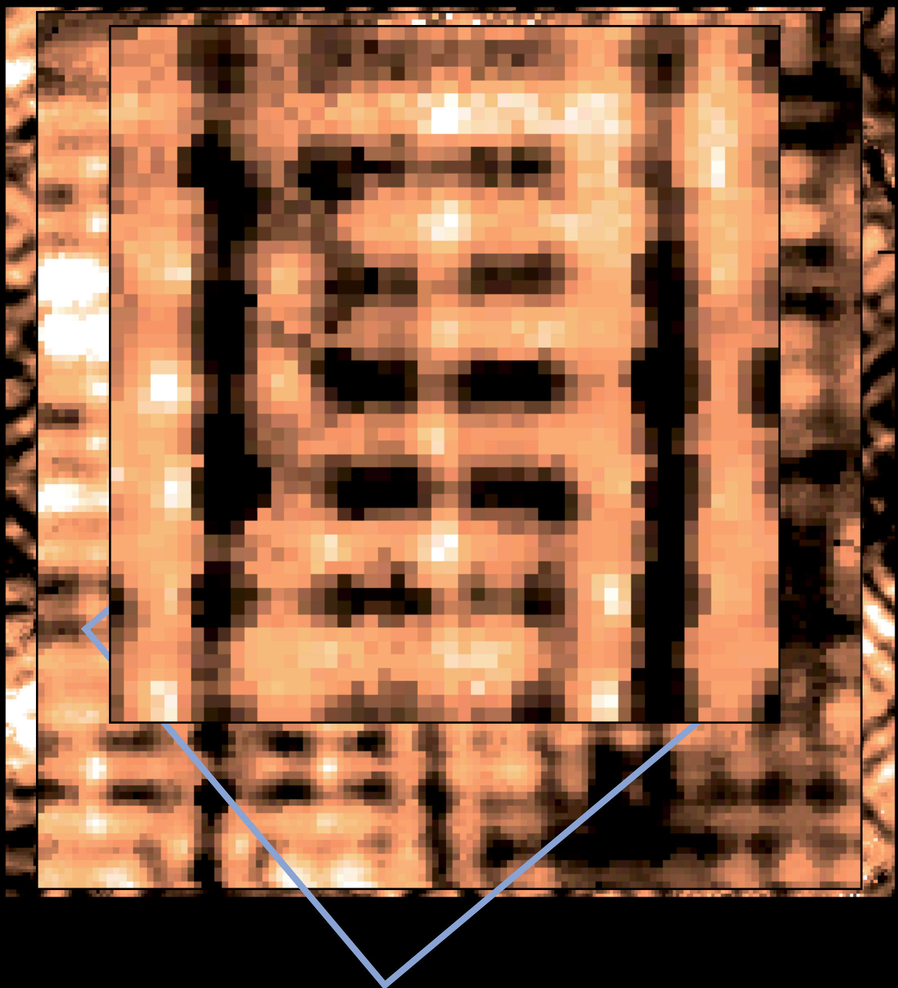
Electronically Inequivalent Oxygen-sites within CuO_2 Unit Cell



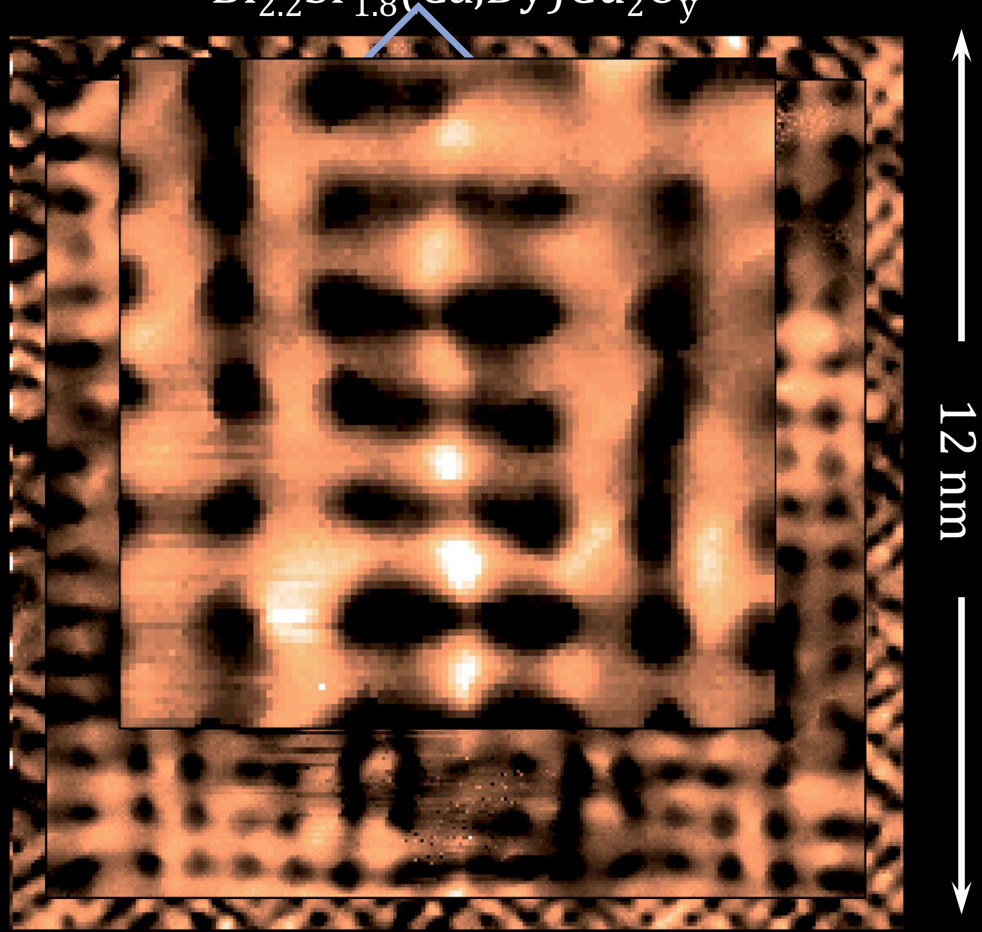
Nature* *430, 1001 (2004) ***Science 315,*** 1380 (2007) *Nature* **466,** 374 (2010) ***Science 344, 612*** (2014)

Complex / Repeatable Patterns of IUC C_4 Breaking

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$



$Bi_{2.2}Sr_{1.8}(Ca,Dy)Cu_2O_y$



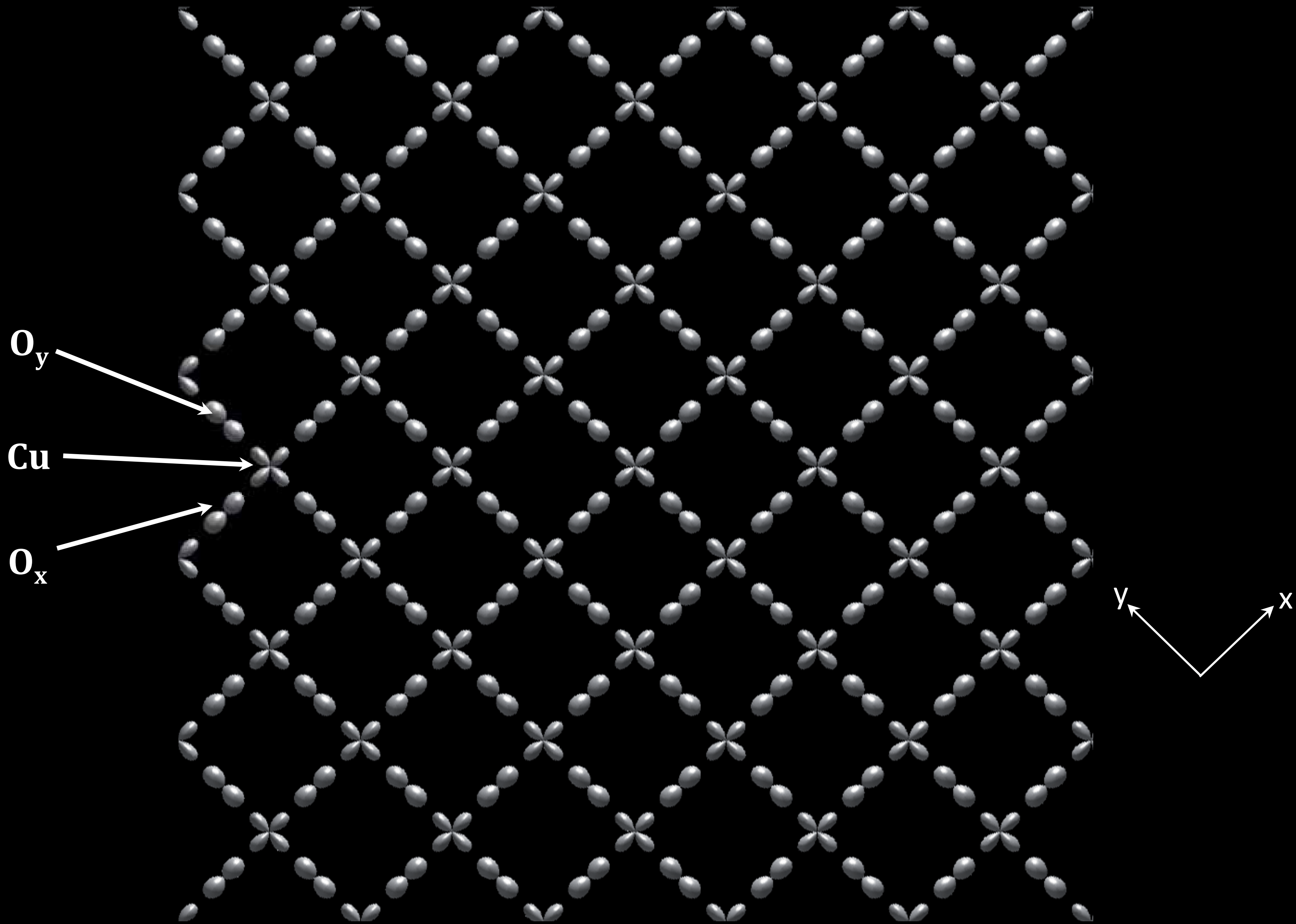
150 mV, 4.2 K

***Nature* 430**, 1001 (2004) ***Science* 315,** 1380 (2007) *Nature* **466,** 374 (2010) ***Science* 344, 612** (2014)

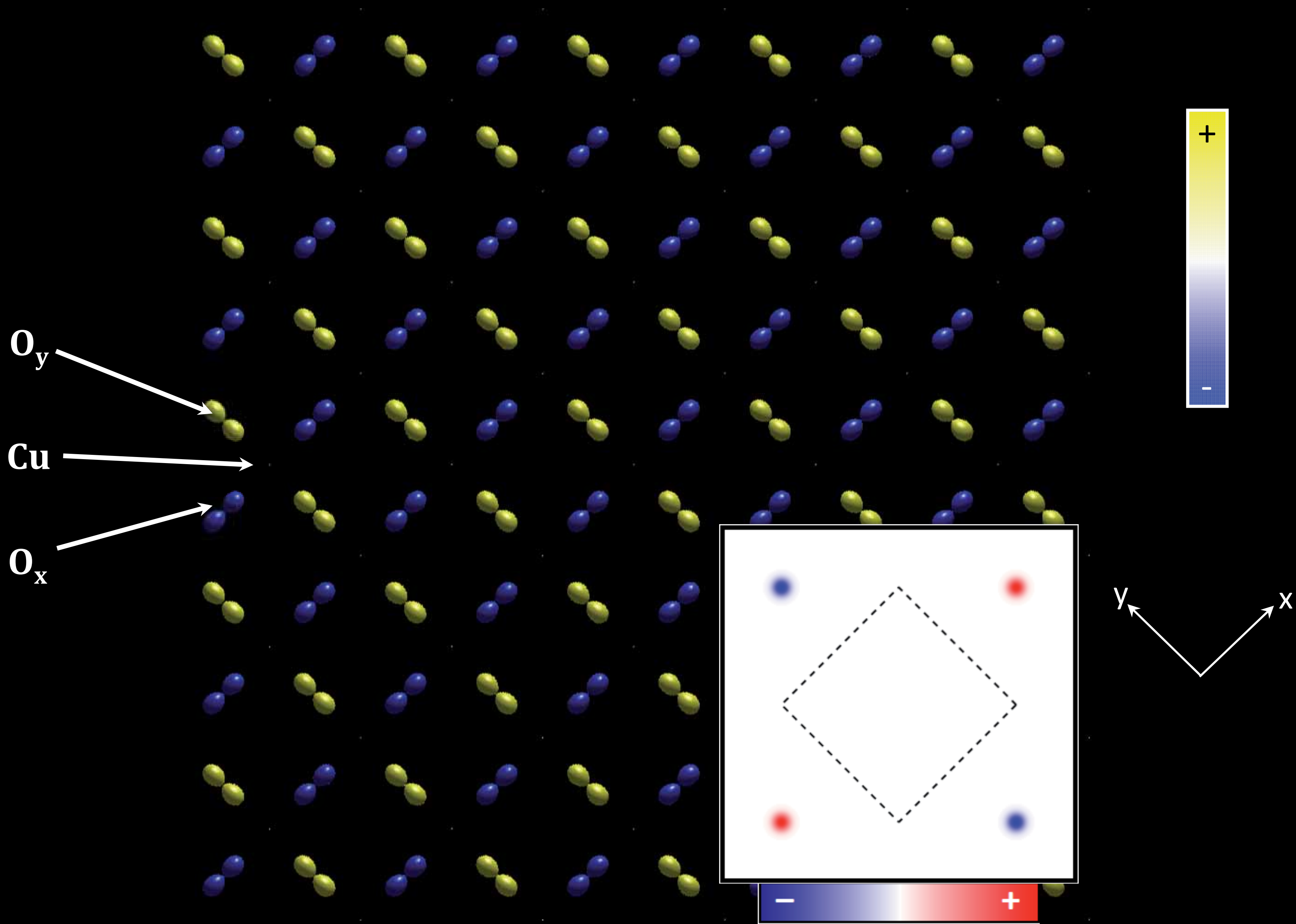
Proposals for Cuprate *d*-Symmetry FF Density Waves

- J.-X. Li, C-Q Qu, and D.-H. Lee, *Phys Rev B* 74 184515 (2006)
- K. Seo, H.-D. Chen, J. Hu, *Phys. Rev. B* 76, 020511 (2007)
- D.M. Newnes & C.C. Tsuei, *Nat. Phys.* 3, 184 (2007)
- C. Honerkamp, H.C. Fu and D.-H. Lee *Phys. Rev. B* 75, 014503 (2007)
- M. Vojta and O. Rosch, *Phys. Rev. B* 77, 094504 (2008)
- M. A. Metlitski and S. Sachdev, *New J. Phys.* 12, 105007 (2010)
- T. Holder and W. Metzner, *Phys. Rev.* B 85, 165130 (2012)
- K. B. Efetov, H. Meier, and C. Pépin, *Nat. Phys. 9*, 442 (2013)
- S. Bulut, W. A. Atkinson, A. P. Kampf, *Phys. Rev. B* 88, 155132 (2013)
- S. Sachdev and R. La Placa, *Phys. Rev. Lett.* 111, 027202 (2013)
- D.-H. Lee & J.C. Davis *Proc. Nat. Acad. Sci*. 101, 17623 (2013)

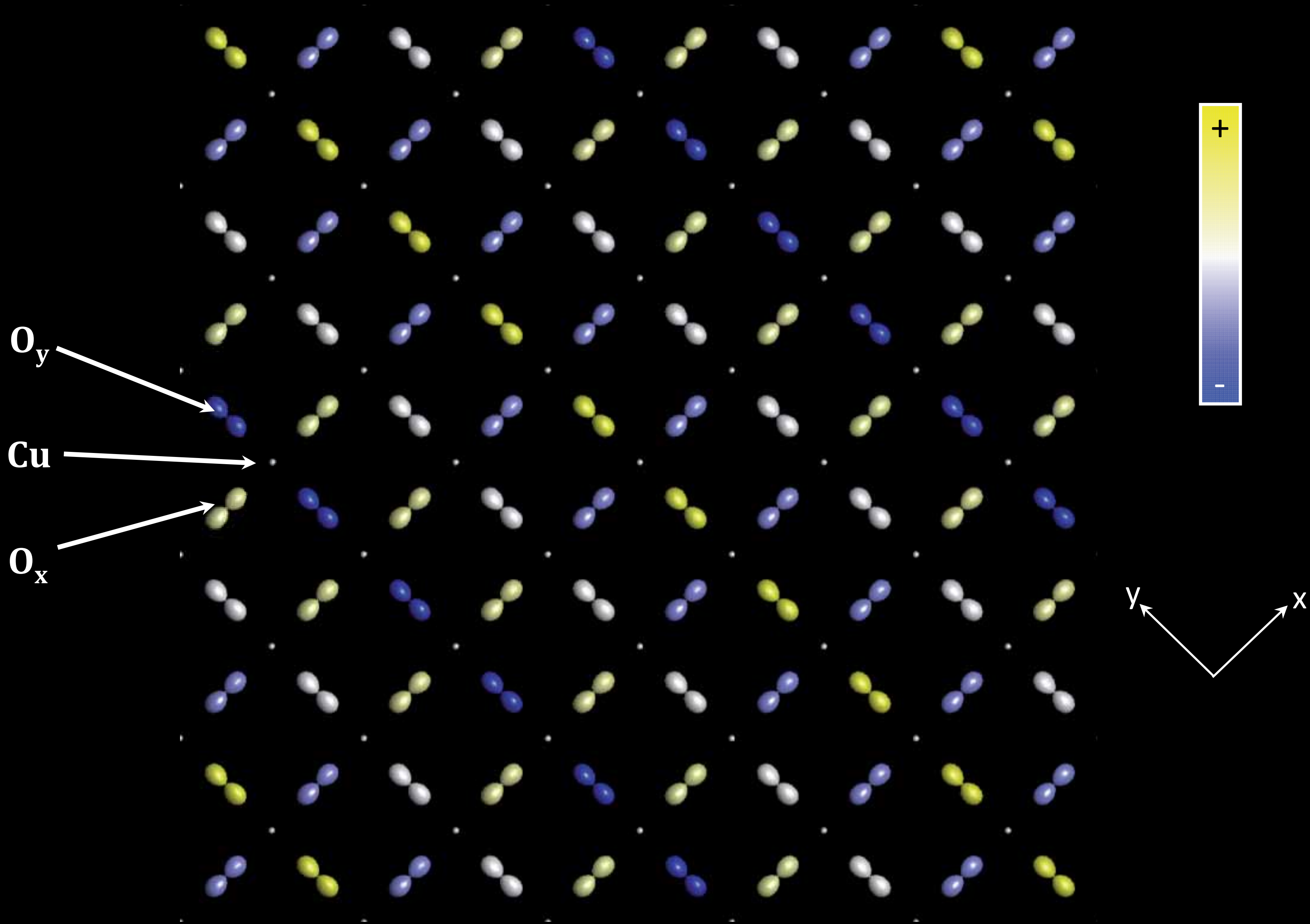
CuO_2 Lattice



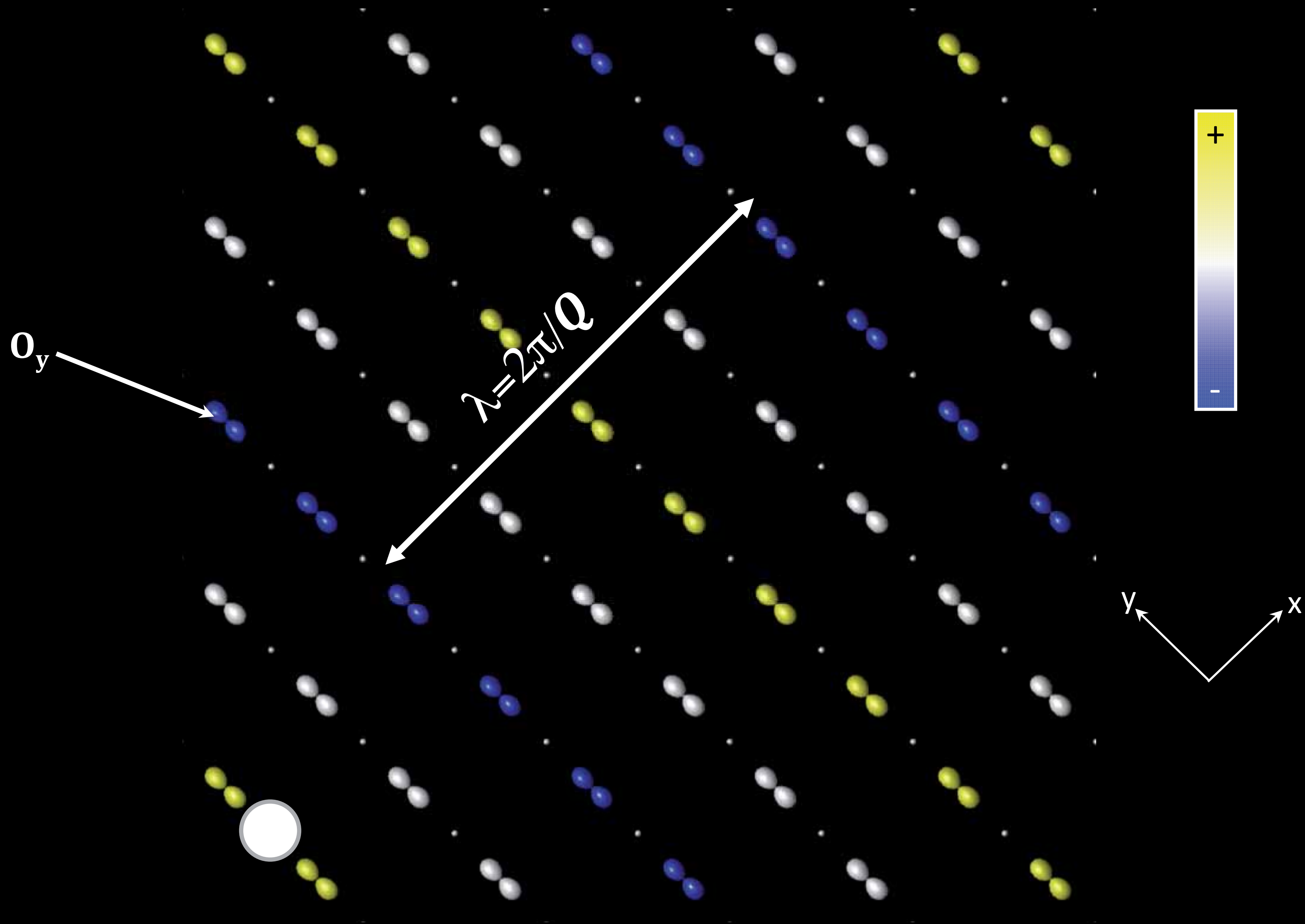
d-Symmetry Form Factor



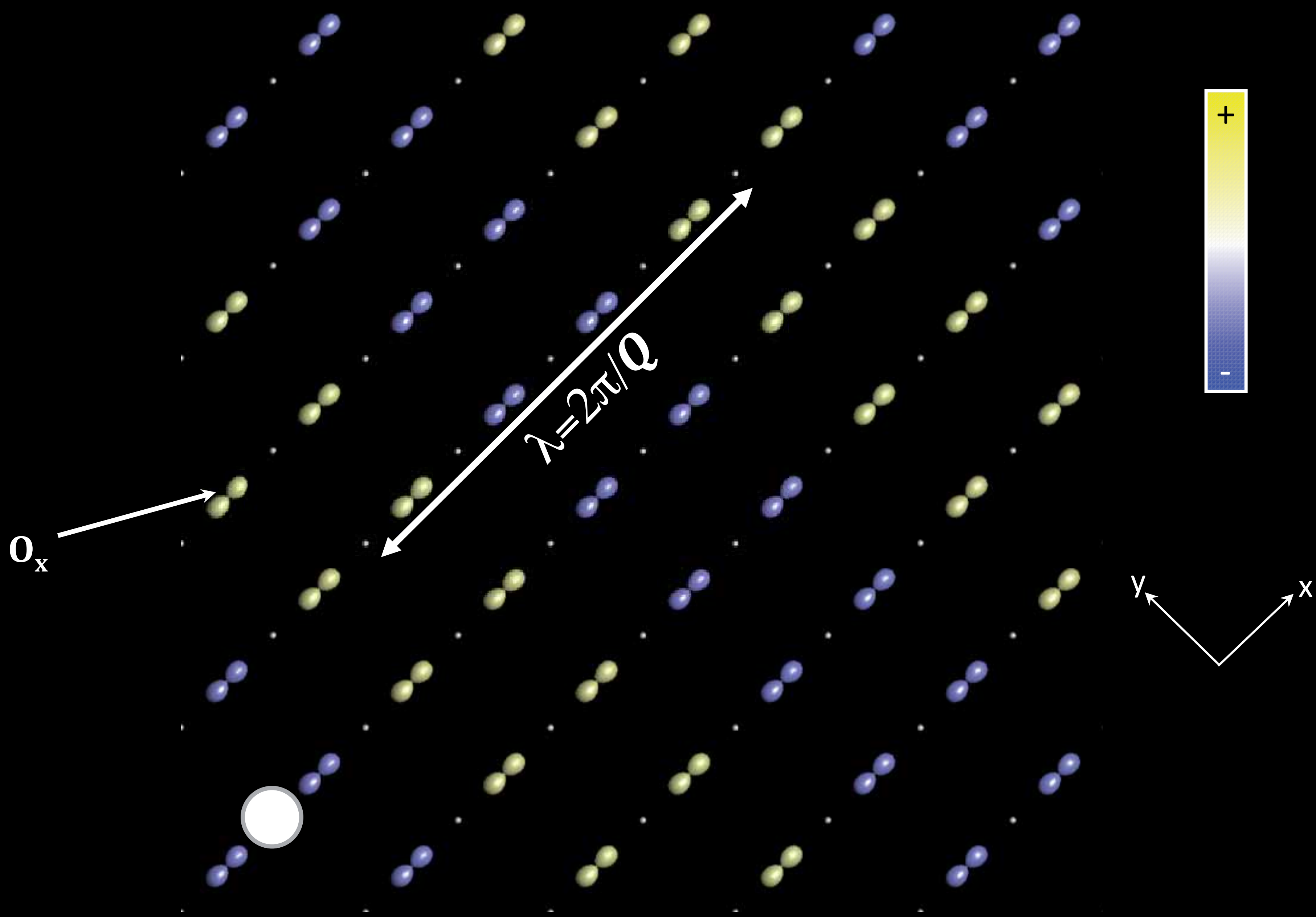
d-Symmetry Form Factor Density Wave

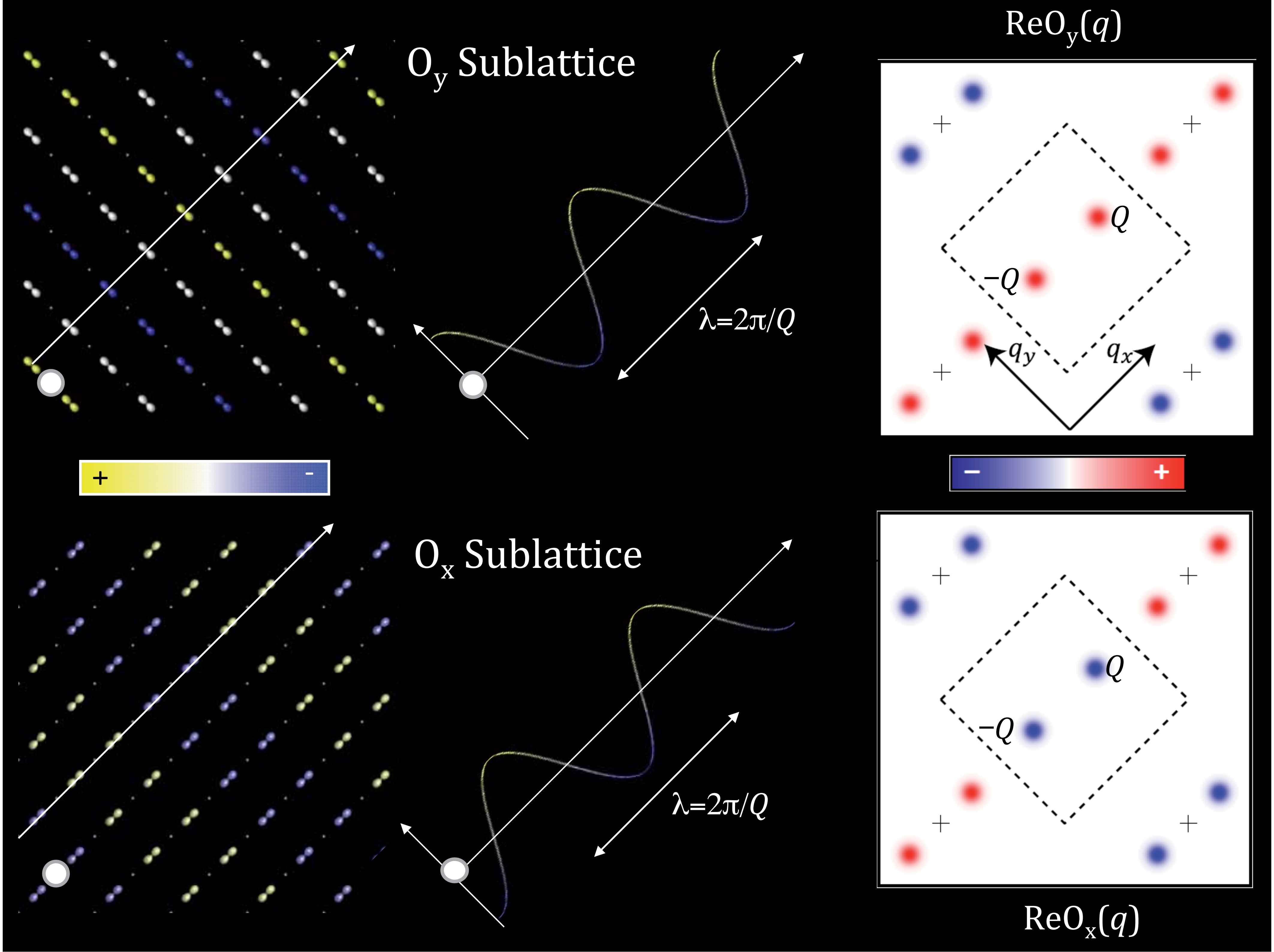


O_y Modulates at $\boldsymbol{Q}_x$

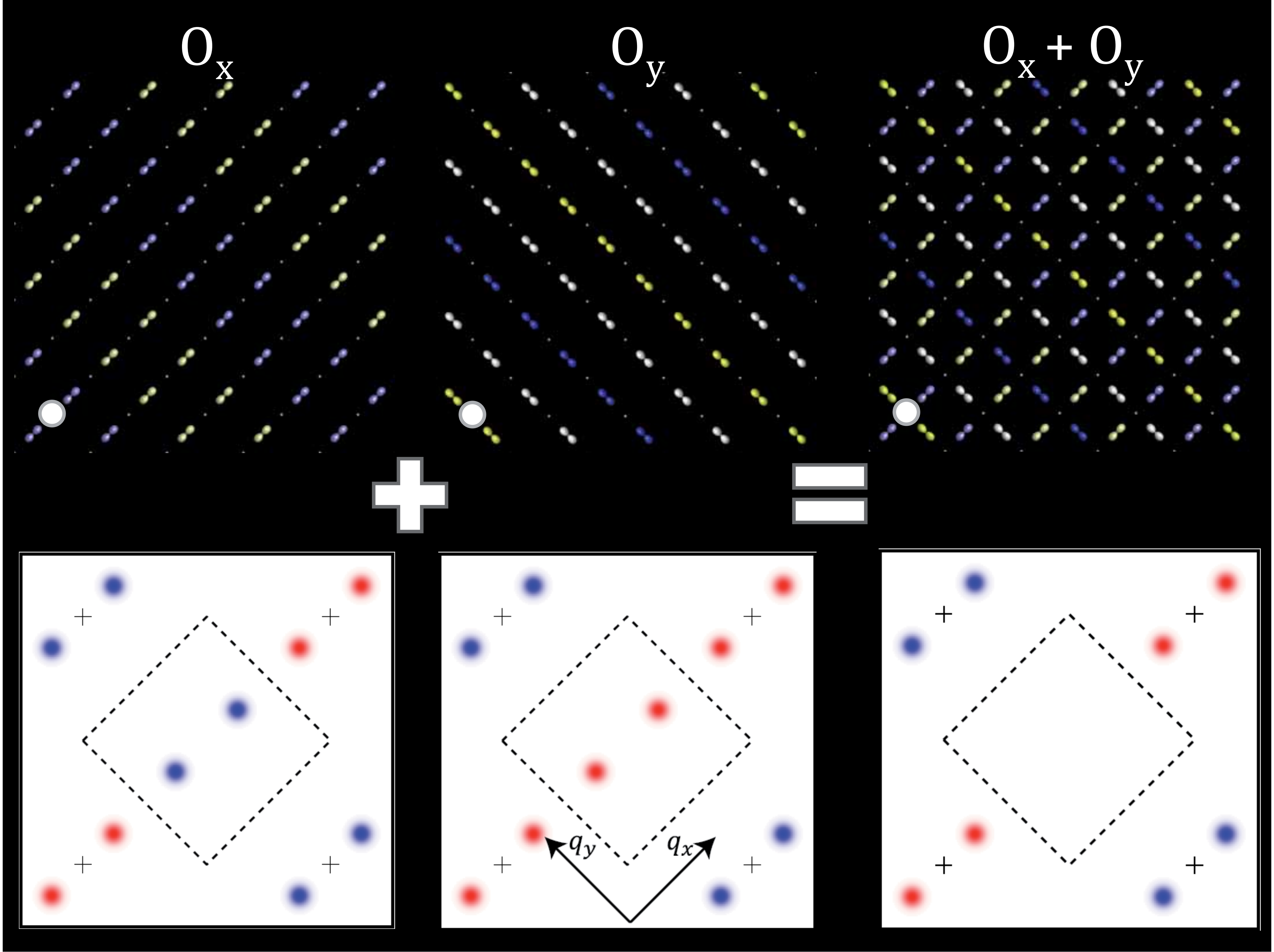


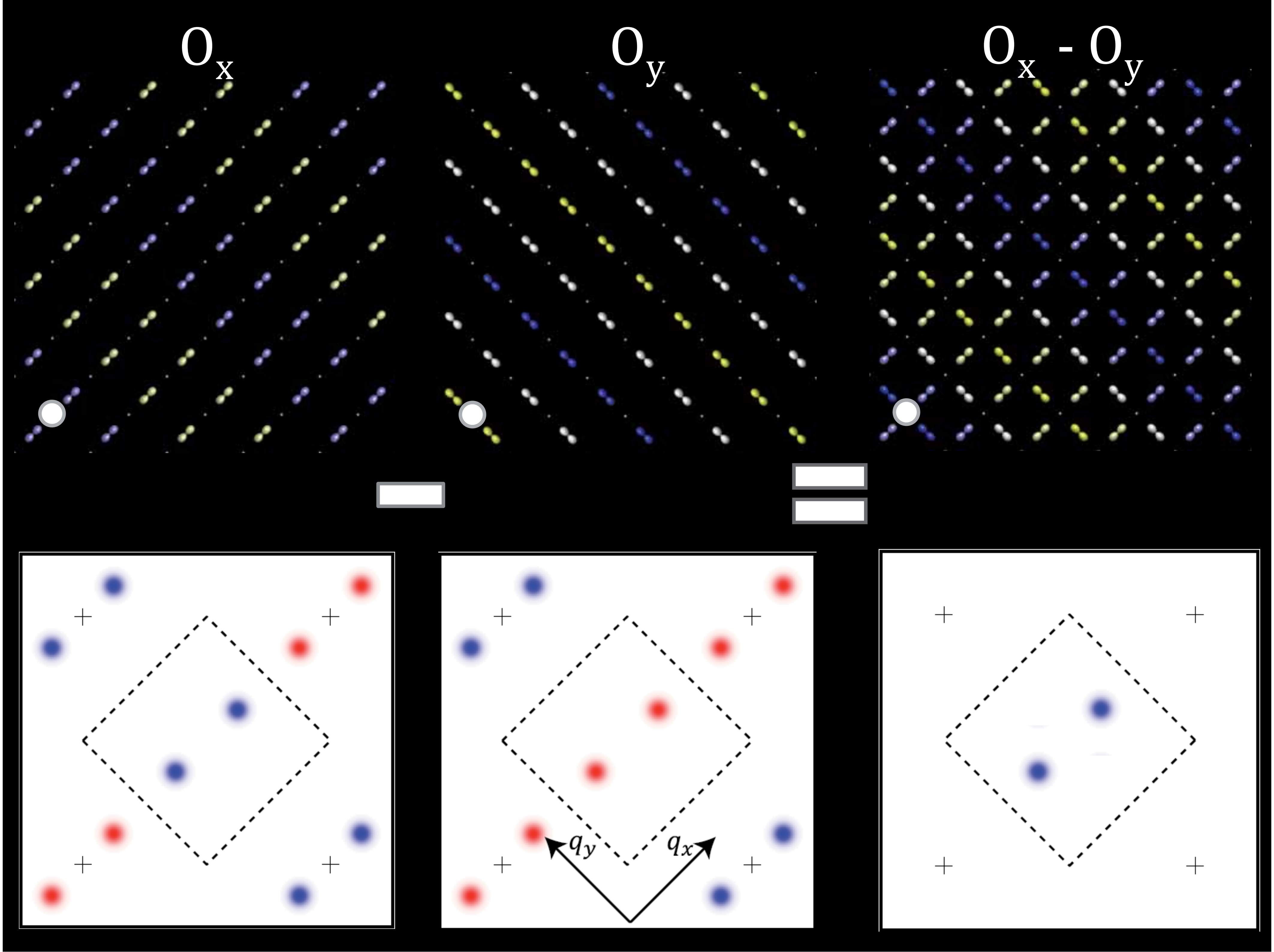
O_x Modulates at $\boldsymbol{Q}_x$





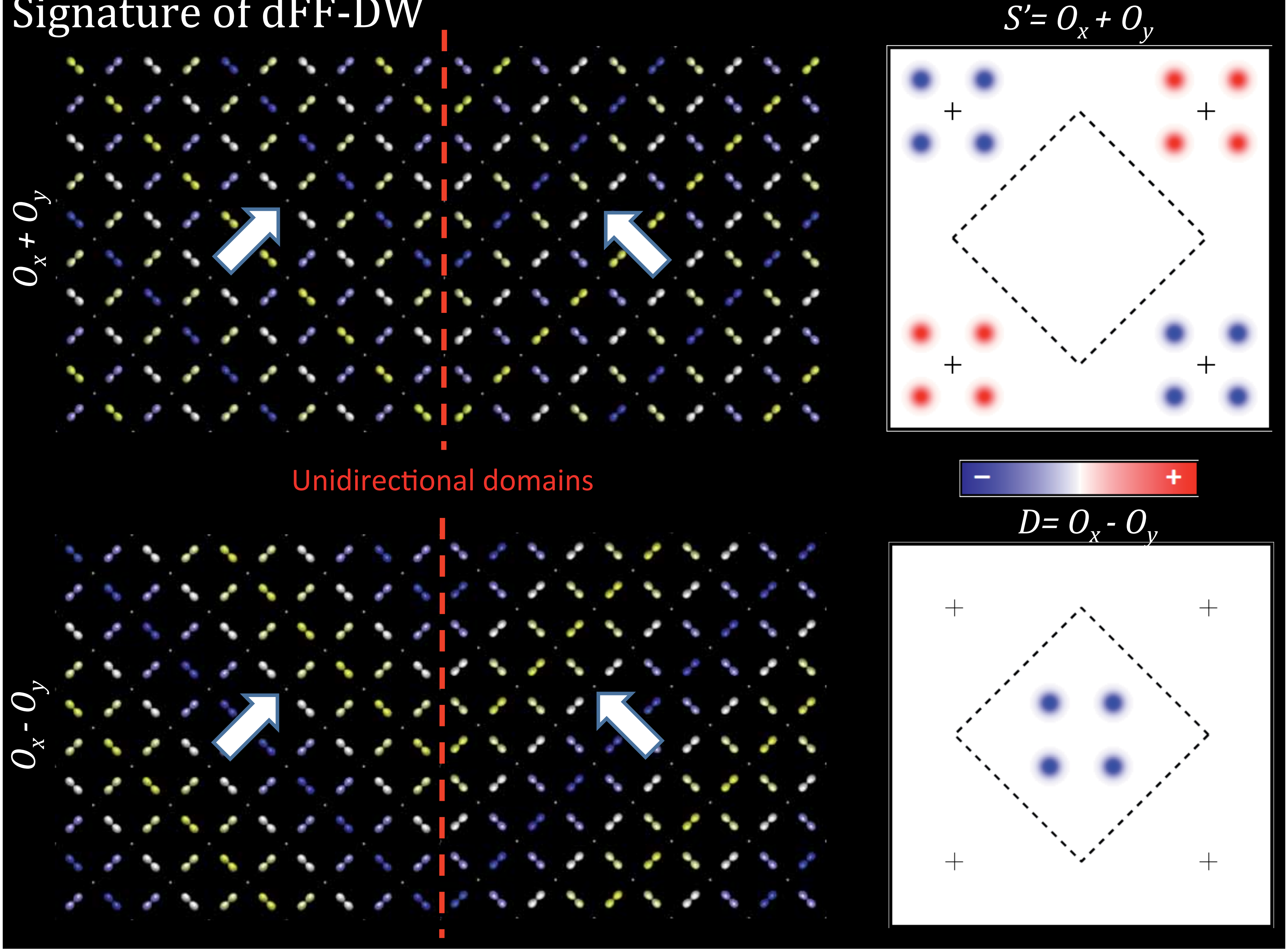
$\mathrm{ReO_y}(q)$
$\mathrm{O_y}$ Sublattice
$\lambda=2\pi/Q$
Q
$-Q$
q_y
q_x
+
−
$\mathrm{O_x}$ Sublattice
$\lambda=2\pi/Q$
Q
$-Q$
$\mathrm{ReO_x}(q)$


O_x
O_y
$O_x + O_y$
q_y
q_x



O_x
O_y
O_x - O_y
q_y
q_x

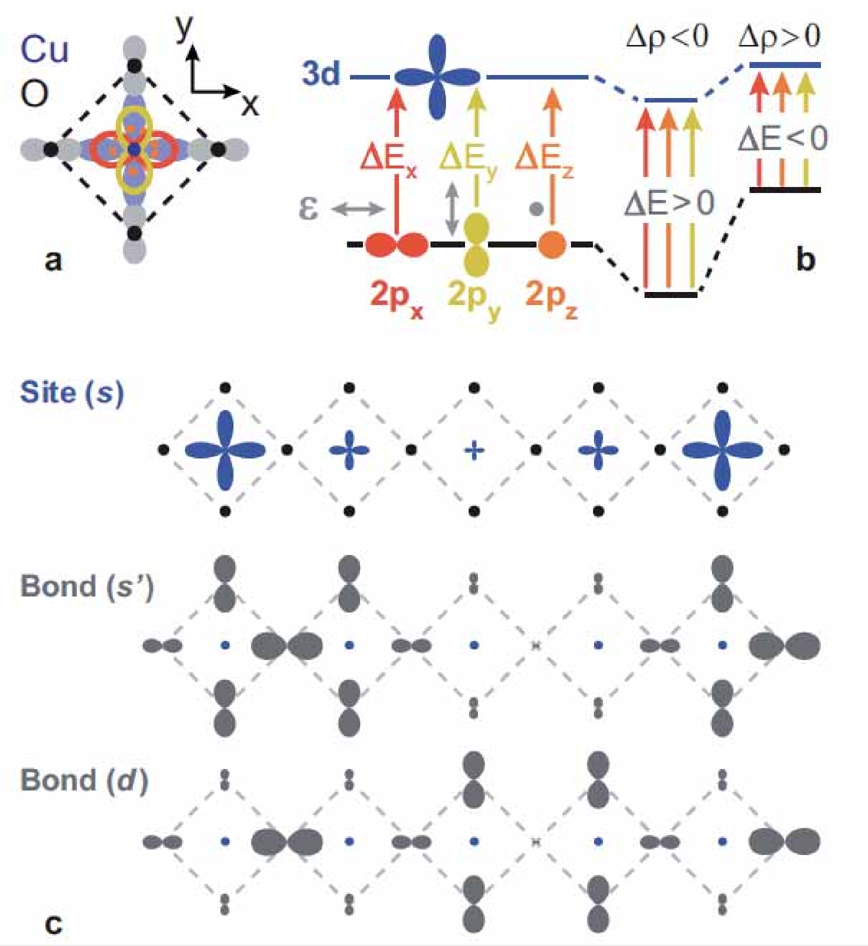
Signature of dFF-DW

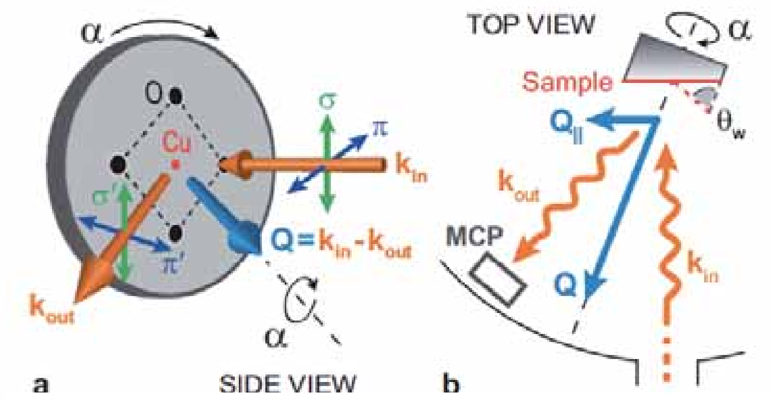


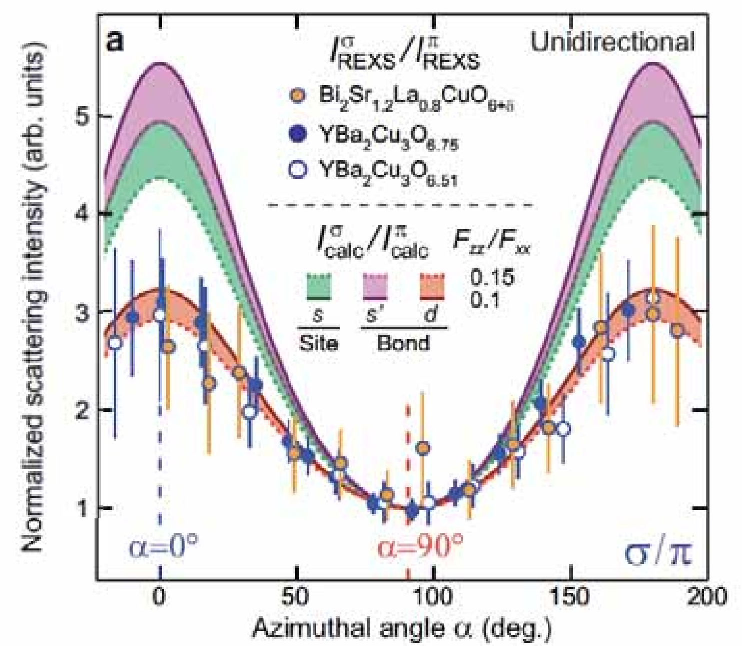
[redacted]

Cuprate *d*-Symmetry FF Density Wave

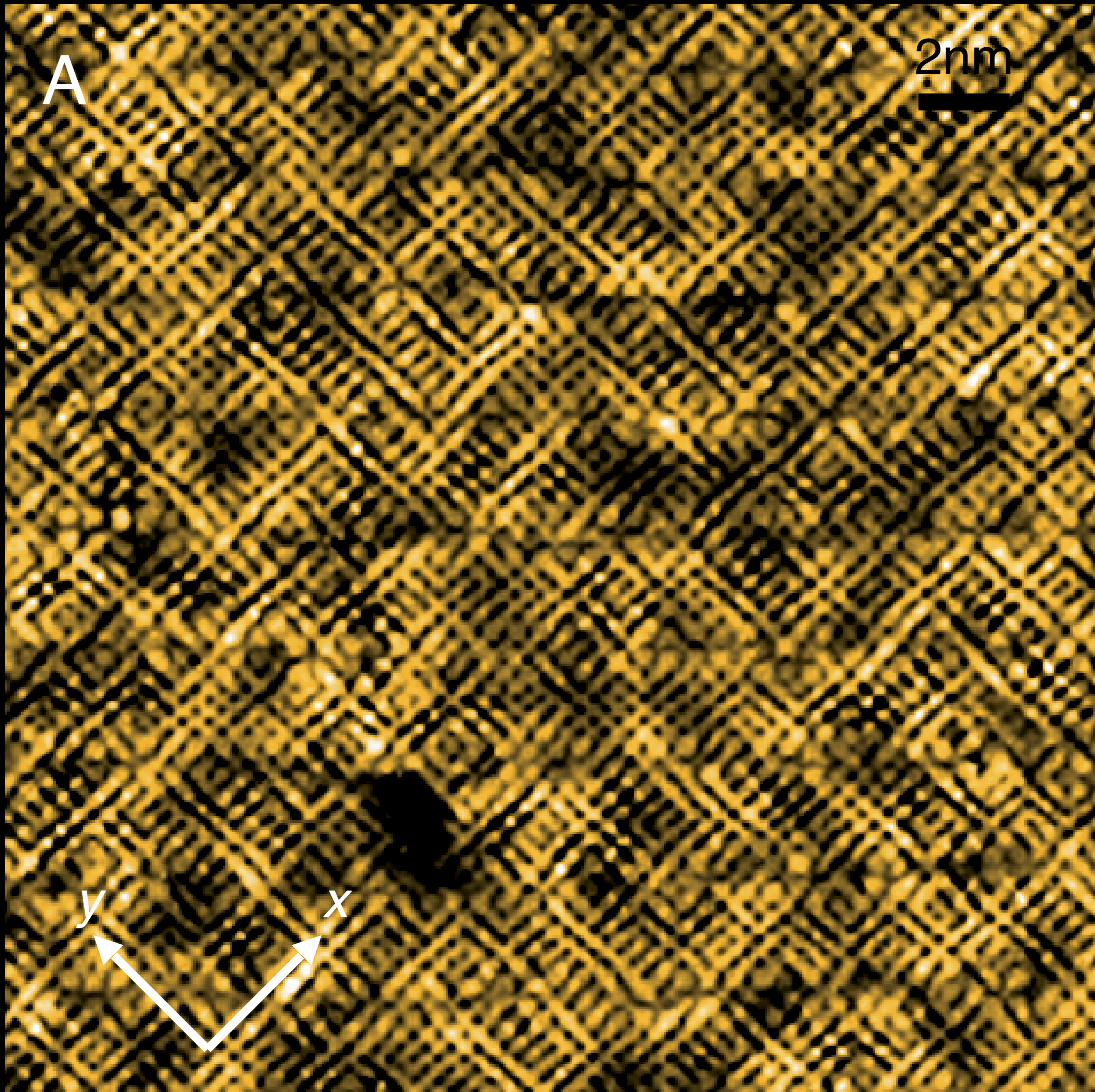
Comin *et al arXiv* 1402.5415







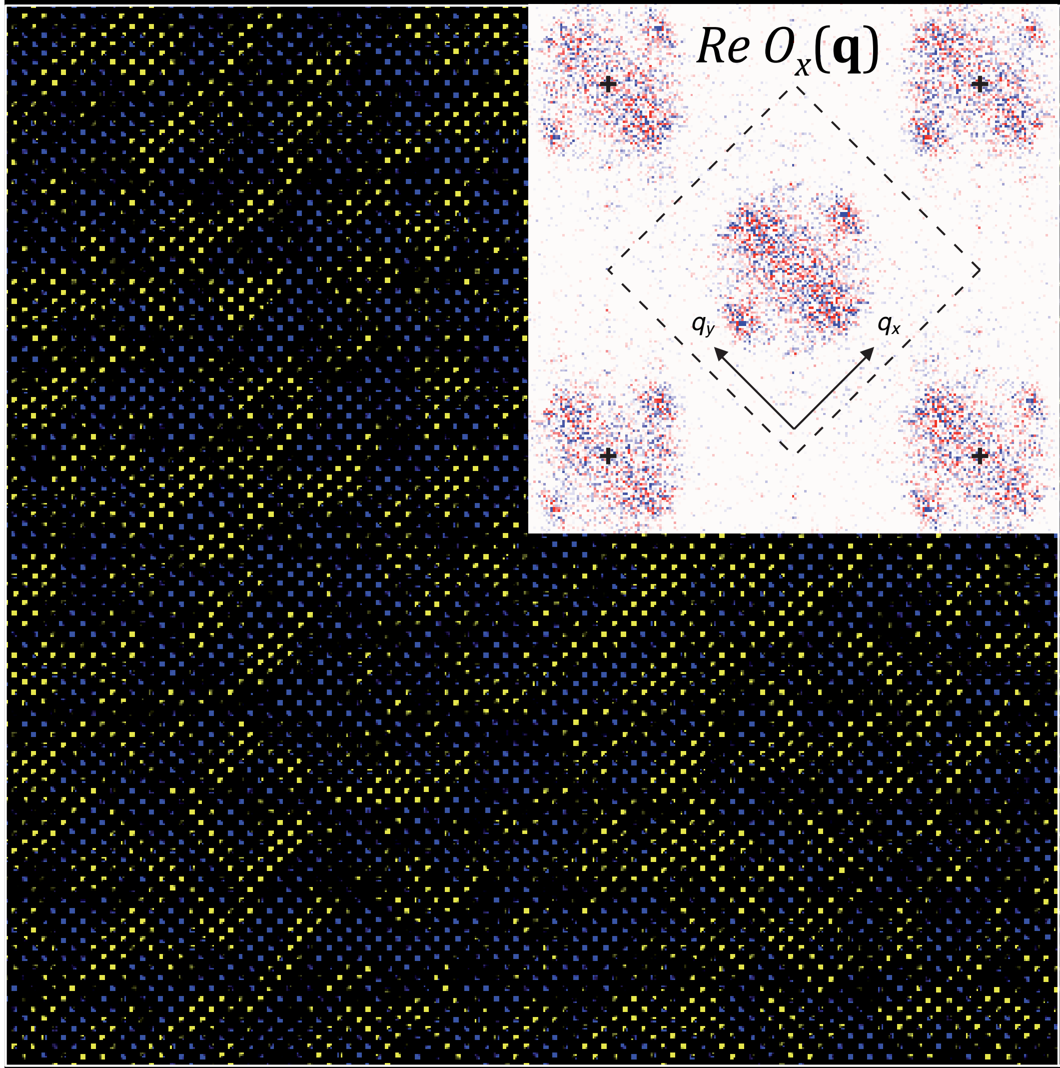
Sublattice Phase-Resolved Electronic Structure



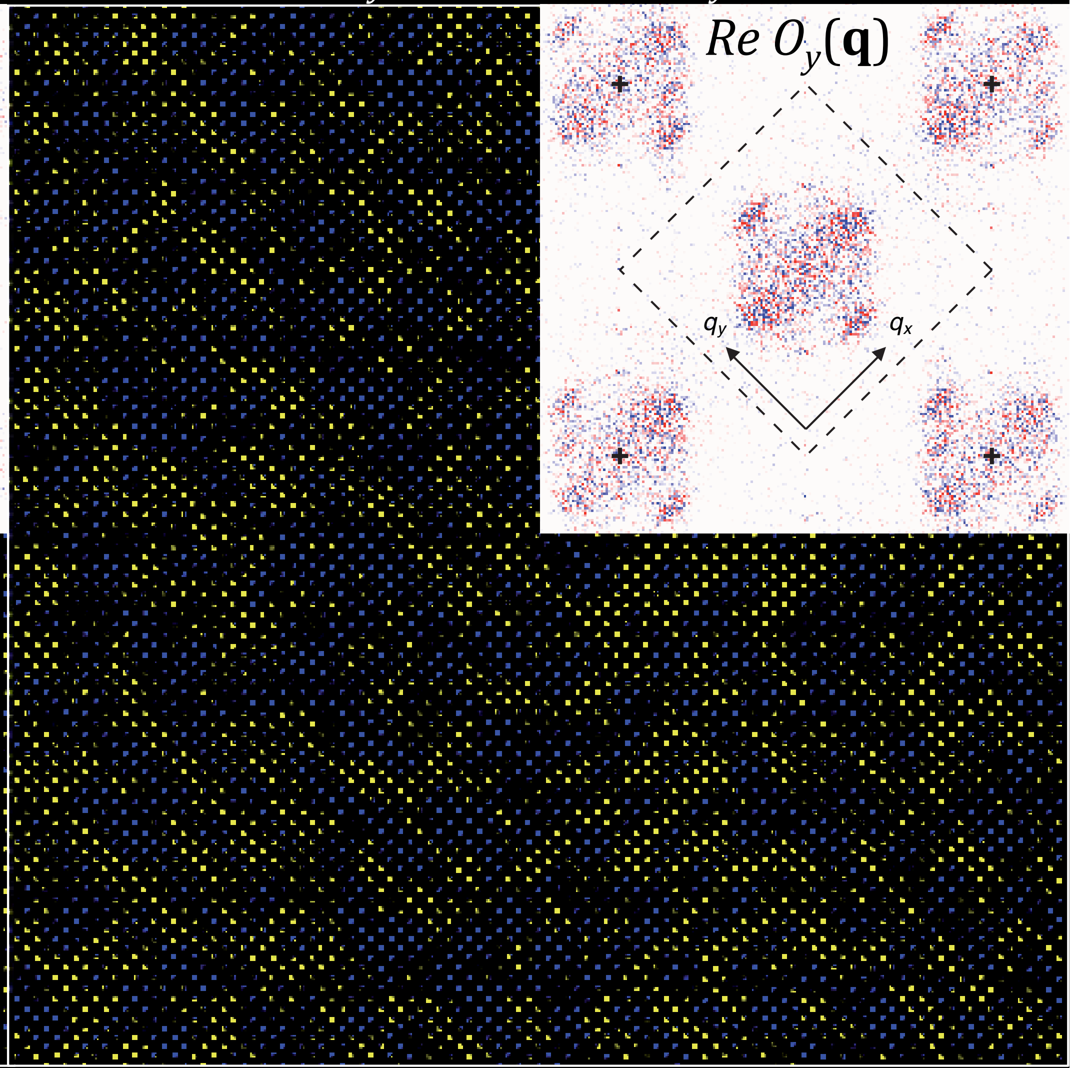
PNAS **111**, E3026 (2014)

O_x / O_y Sublattice Segregation

$O_x(\mathbf{r})=R(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}_{0x})$



$O_y(\mathbf{r})=R(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}_{0y})$

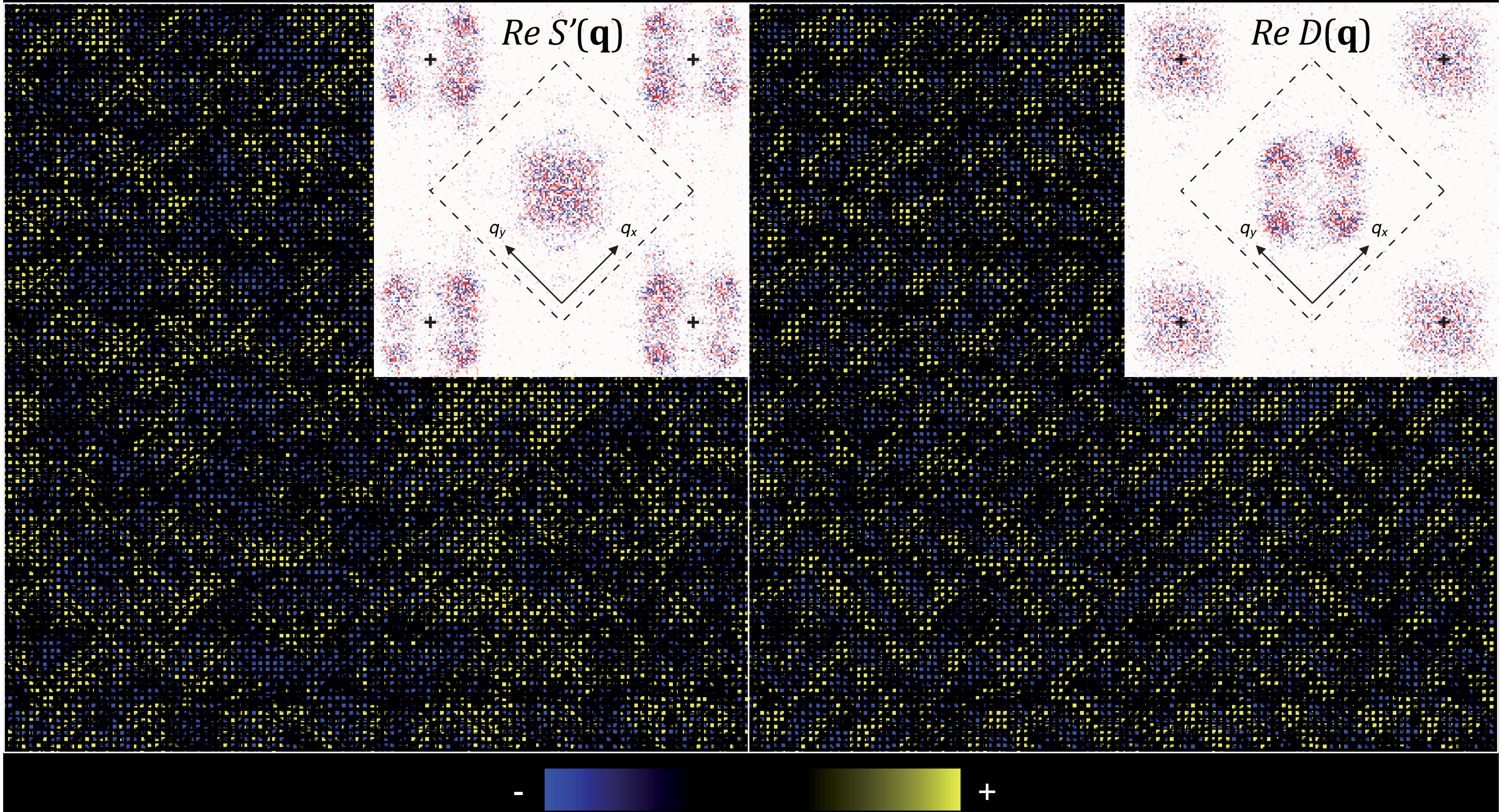


Both $O_x(\mathbf{r})$ and $O_y(\mathbf{r})$ show intense modulation.

PNAS **111**, E3026 (2014)

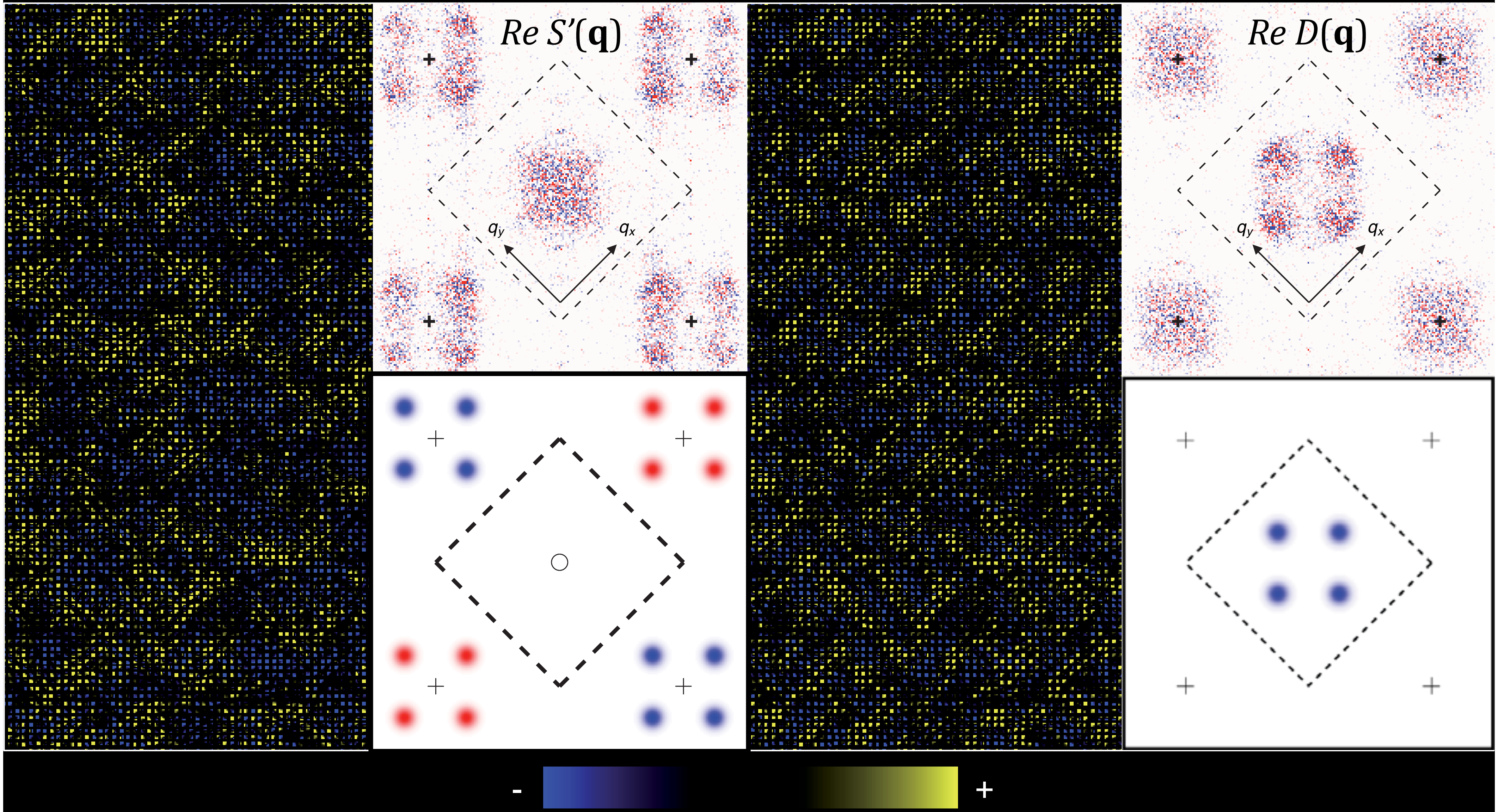
Sublattice Phase-Resolved Symmetry Measurements

S' : $(O_x(\mathbf{r})+O_y(\mathbf{r}))$ $\qquad$ D : $(O_x(\mathbf{r})-O_y(\mathbf{r}))$



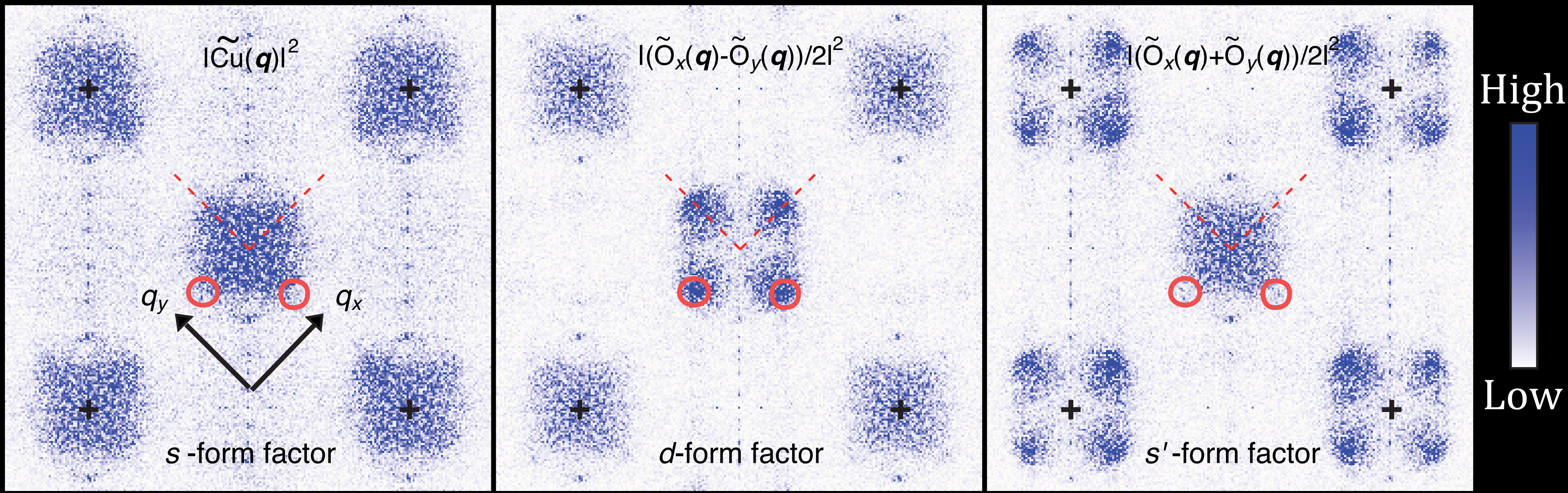
d-Symmetry FF Density Wave

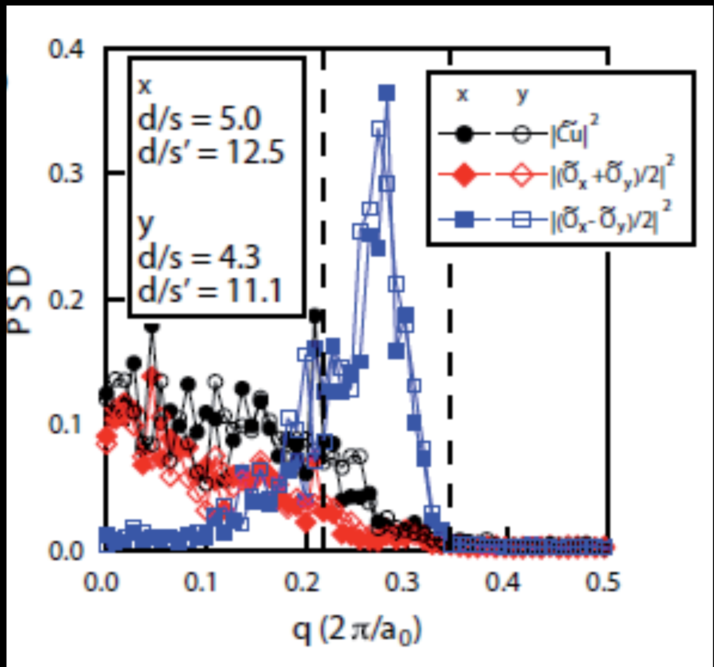
S' : $(O_x(\mathbf{r})+O_y(\mathbf{r}))$ D : $(O_x(\mathbf{r})-O_y(\mathbf{r}))$



PNAS **111**, E3026 (2014)

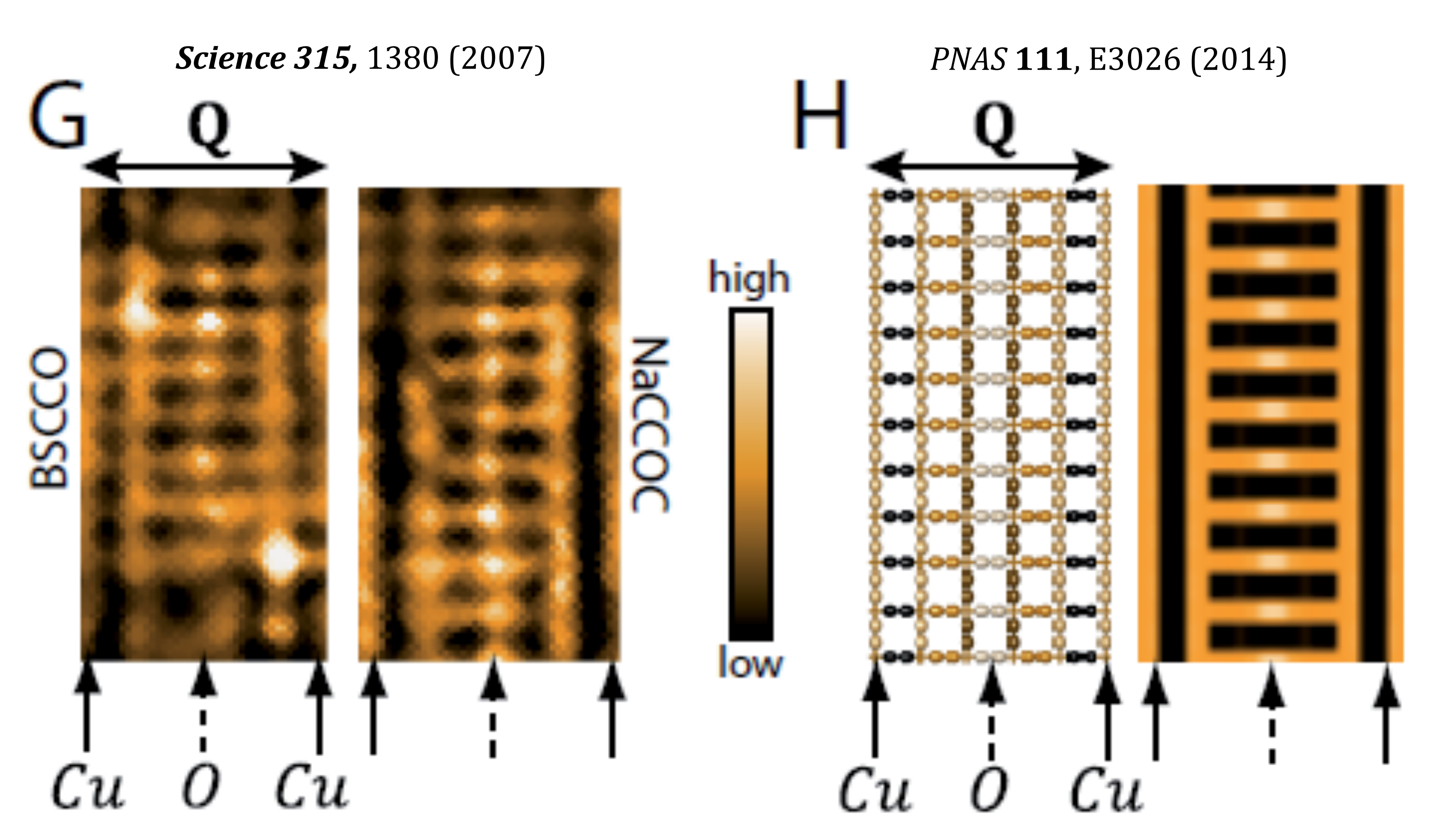
d-Symmetry FF DW Predominates





PNAS **111**, E3026 (2014)

Real-space: Unidirectional *d*-Symmetry FF DW

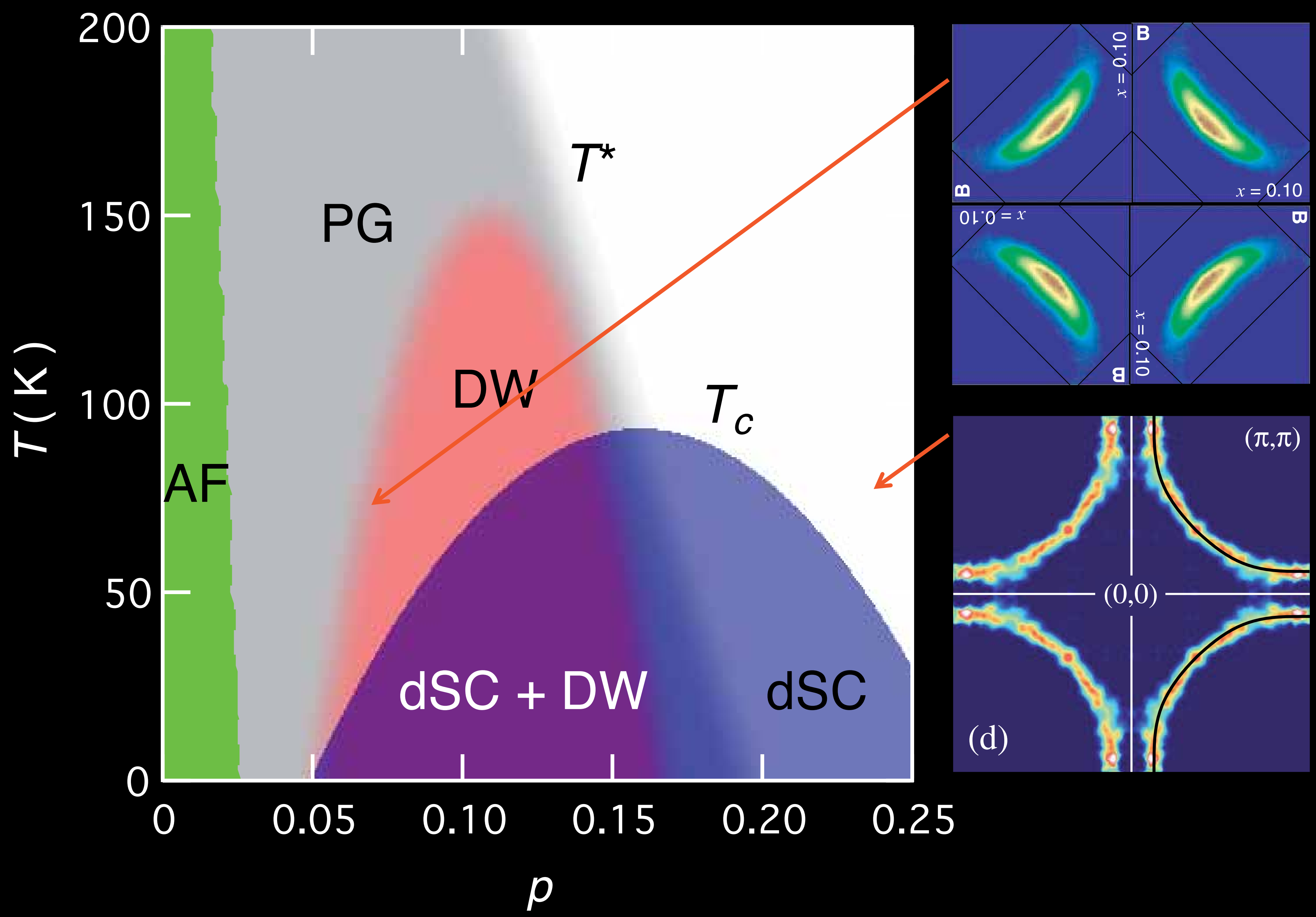


PNAS **111**, E3026 (2014)

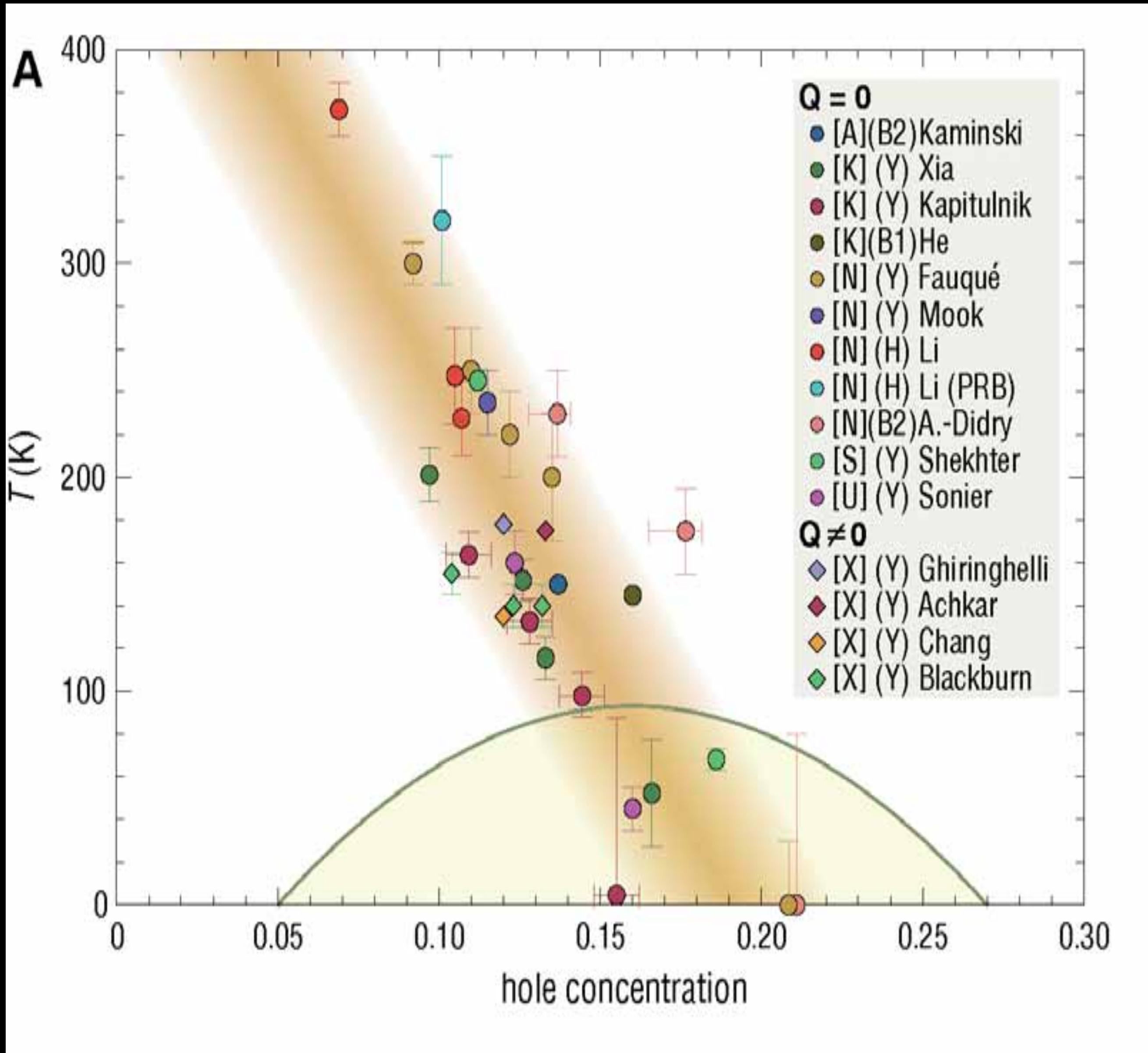
[redacted]

d-Symmetry FF Density Wave
&
k-space Topology of Cuprates

Transition in *k*-space Electronic Structure

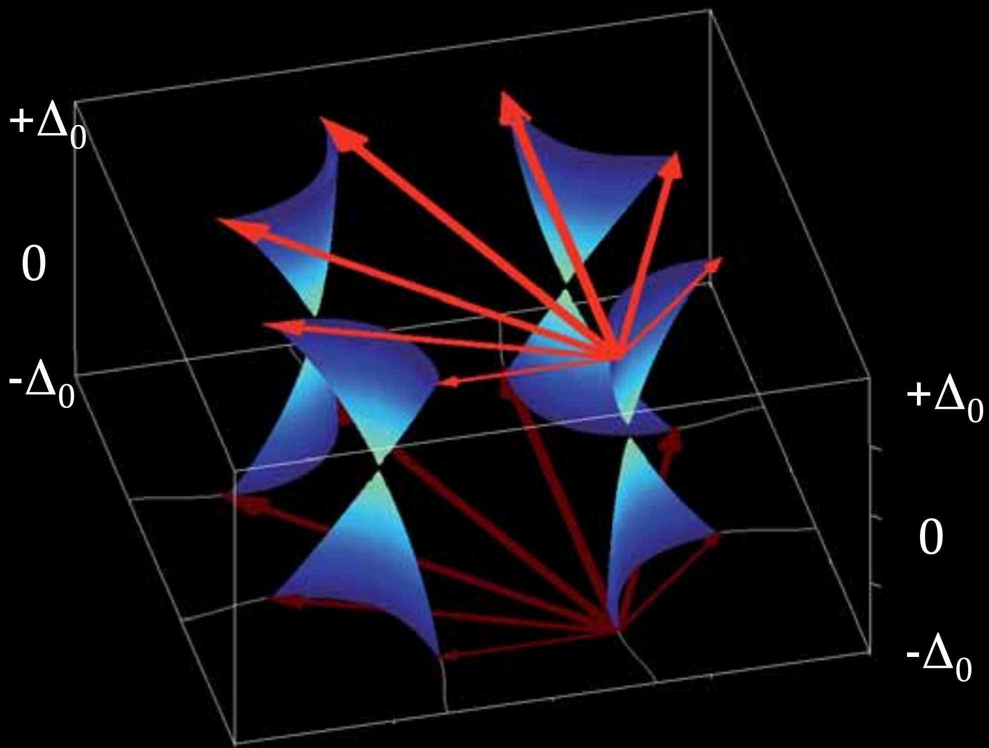


Evolution of Cuprate Broken-Symmetry States

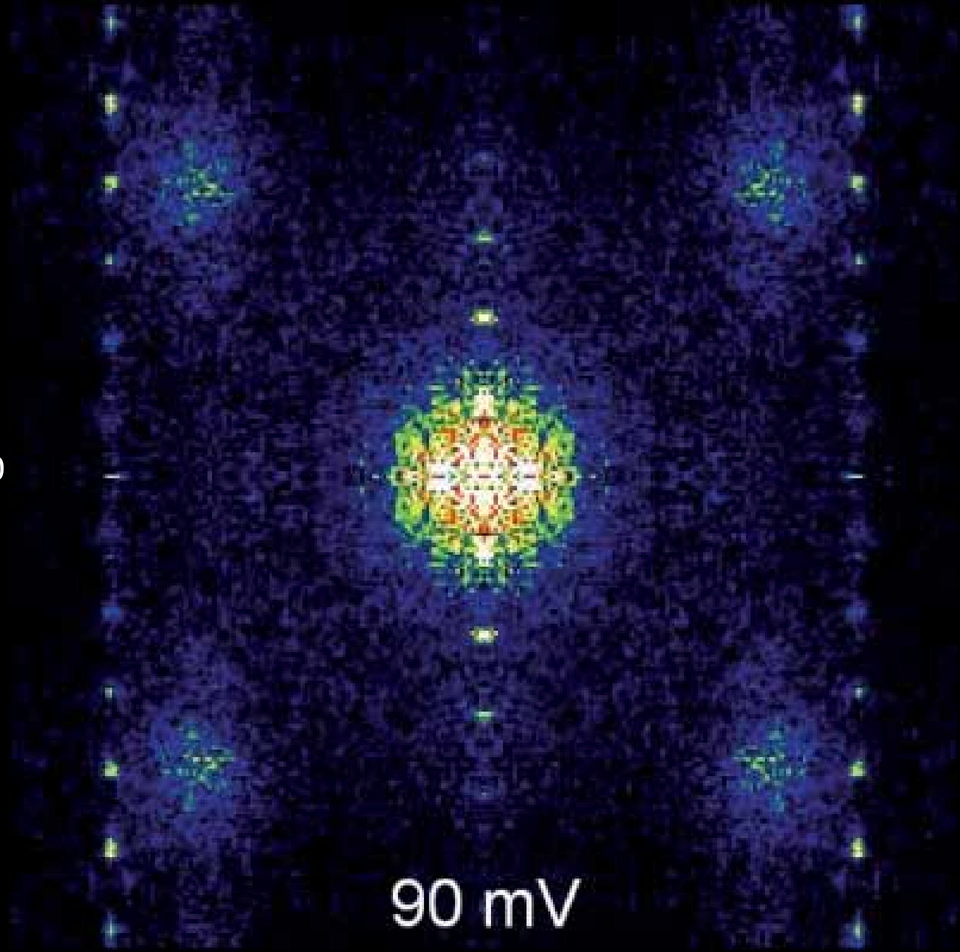


Science 344, 612(2014)

$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



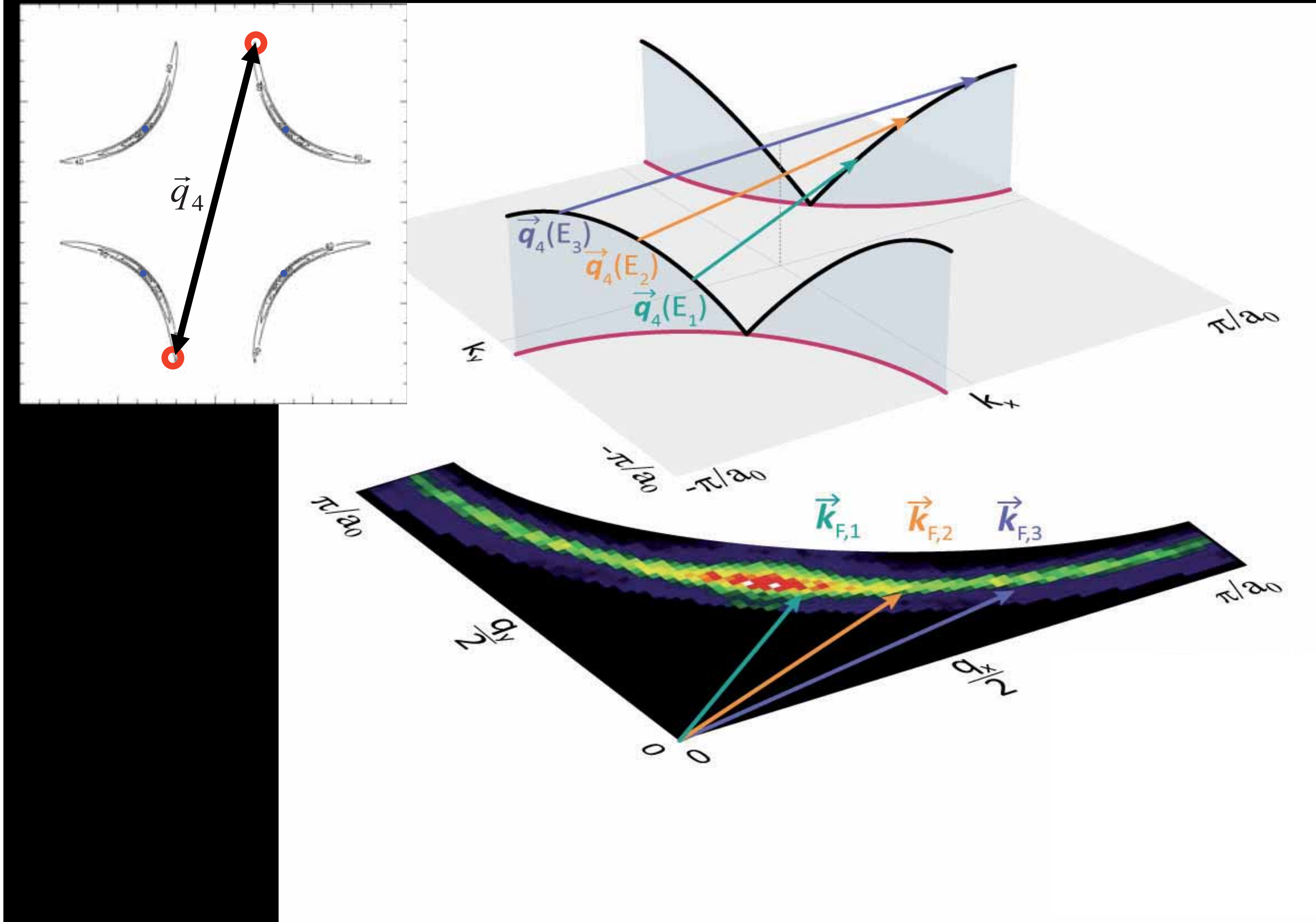
Particle-hole symmetric
i=1,..7 Bogoliubov QPI



g (q, **E)**

Science 344, 612 (2014)

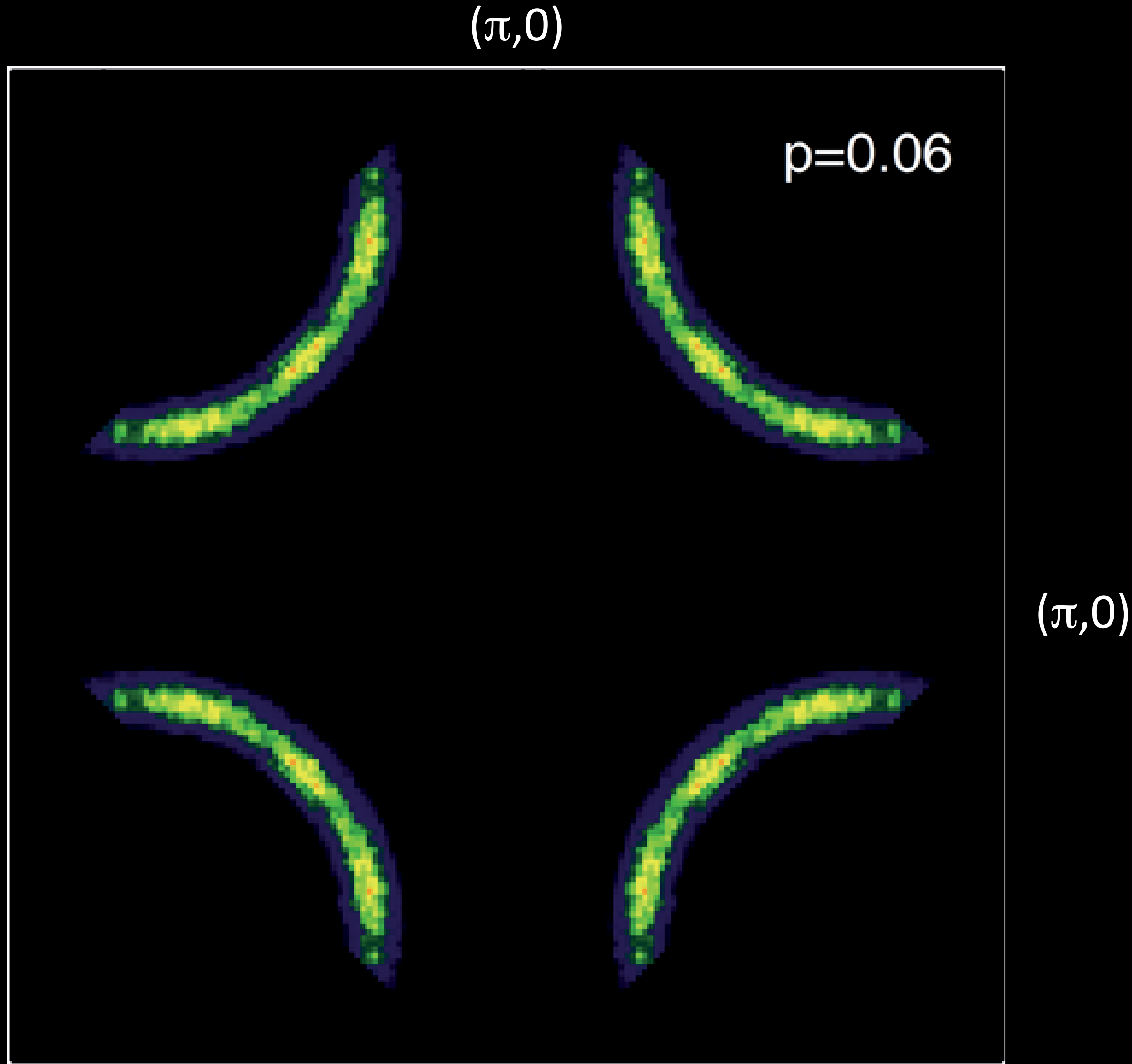
$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



$k_F = q_4/2$

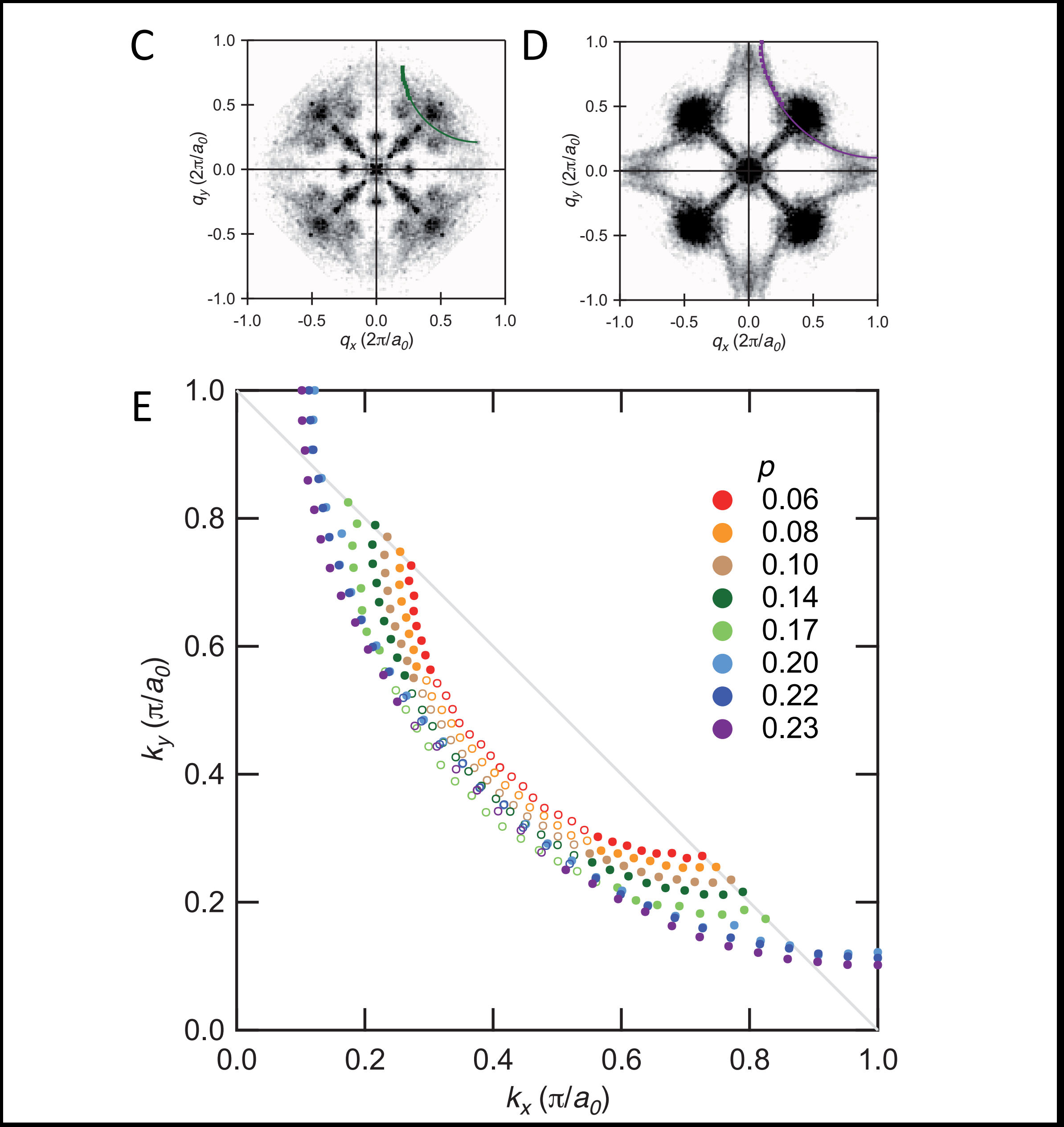
***Science* 344,** 612 (2014)

$Bi_2Sr_2CaCu_2O_8$ *k*-space Topology from q_4



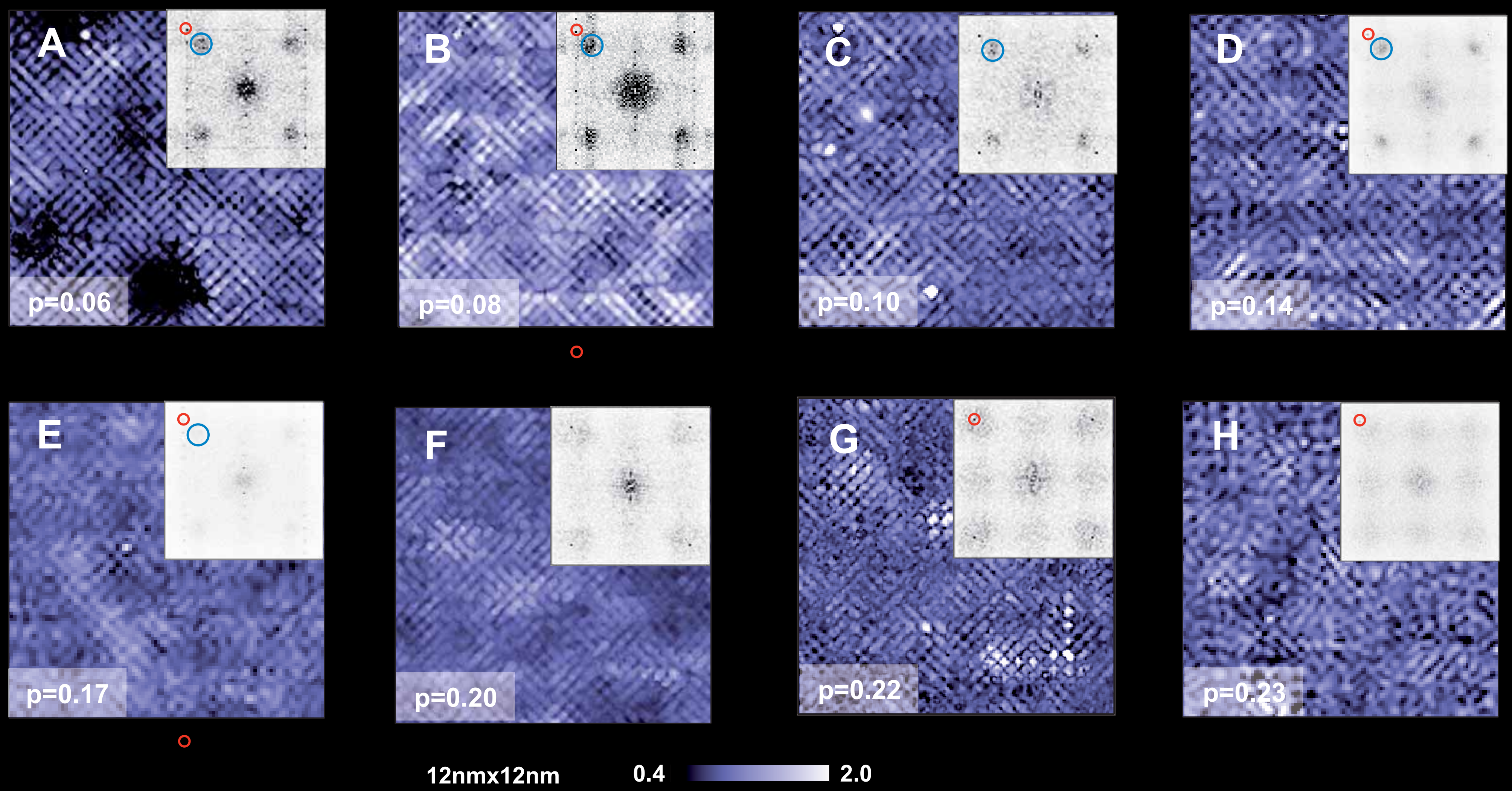
Science 344, 612 (2014)

Abrupt Transition in $Bi_2Sr_2CaCu_2O_8$ *k*-space Topology at p=19±1%



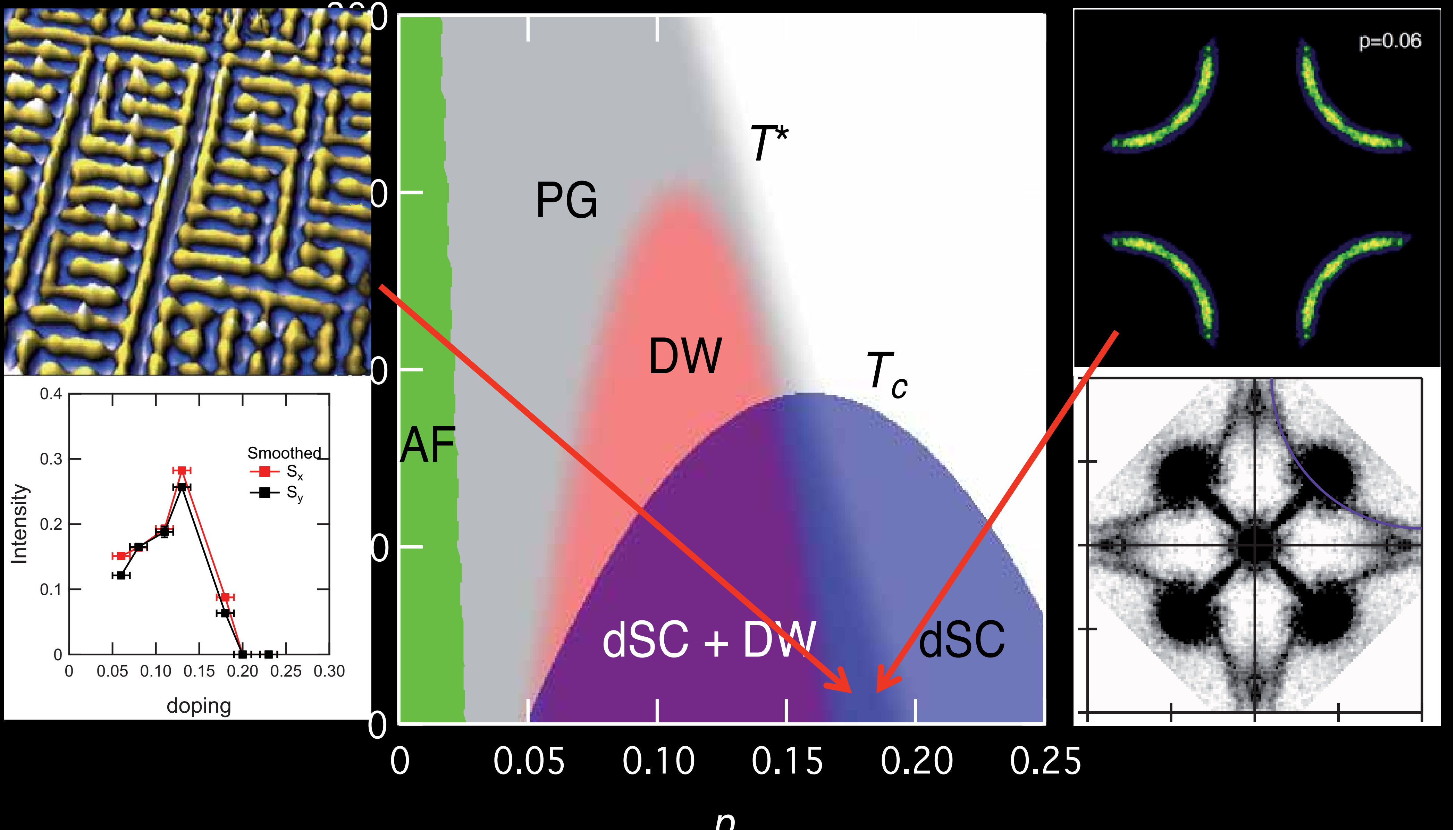
***Science* 344,** 612 (2014)

Coincides with disappearance of d-symmetry FF Effects at ~ 19%



Science ***344,*** 612 (2014)

Simultaneous Symmetry & *k*-space Topology Transitions



***Science* 344**, 612 (2014)

Microscopic Electronic Structure of Cuprate *d*-Symmetry FF Density Wave

Mechanism of Cuprate d-Symmetry FF DW

PHYSICAL REVIEW B 90, 245136 (2014)

Density-wave instabilities of fractionalized Fermi liquids

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Amperean Pairing and the Pseudogap Phase of Cuprate Superconductors

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Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 17 April 2014; published 29 July 2014)

Phys. Rev. B 90, 195207 (2014)

Pseudo-gap, charge order and pairing density wave at the hot spots in cuprate superconductors

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[3] *International Institute of Physics, UFRN, Av. Odilon Gomes de Lima 1722, 59078-400 Natal, Brazil*

NJP 17 , 13025 (2015)

Charge order in the pseudogap phase of cuprate superconductors

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[2] Theoretical Physics III, Center for Electronic Correlations and Magnetism, Institute of Physics, University of Augsburg, D-86135 Augsburg, Germany

Mechanism of Cuprate d-Symmetry FF DW

arxiv 1501.07287

Co-existence of charge-density-wave and pair-density-wave orders in underdoped cuprates

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[3] *William I. Fine Theoretical Physics Institute, and School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

arxiv 1408.6592

Charge Order Instability in Doped Resonating Valence Bond State and Magnetic Orbits from Reconstructed Fermi Surface in Underdoped Cuprates: A Phenomenological Synthesis

Long Zhang[1] and Jia-Wei Mei[2]

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Genesis of charge orders in high temperature superconductors

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(Dated: February 9, 2015)

Experimental Challenges

- Determine if cuprate dFF-DW exhibits a characteristic energy gap ?
- Identify the *k*-space states contributing to dFF-DW spectral weight ?
- Symmetry relating DW modulations above/below Fermi energy ?

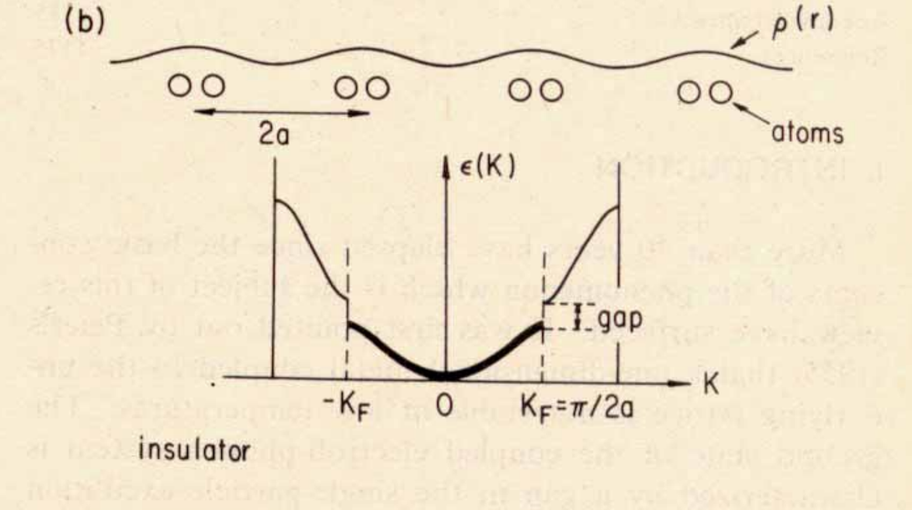


FIG. 1. Peierls distortion in a one-dimensional metal with a half-filled band: (a) undistorted metal; (b) Peierls insulator.

The wavefunctions of the density wave at $\boldsymbol{Q} = \boldsymbol{k_1} - \boldsymbol{k_2}$ that form bonding/anti-bonding states below/above the Fermi level are $e^{i\boldsymbol{k}_1\cdot\boldsymbol{r}} \pm e^{i\boldsymbol{k}_2\cdot\boldsymbol{r}}$

(1) Densities of these states are maximum at E~$\pm\Delta_{CDW}$ edges.

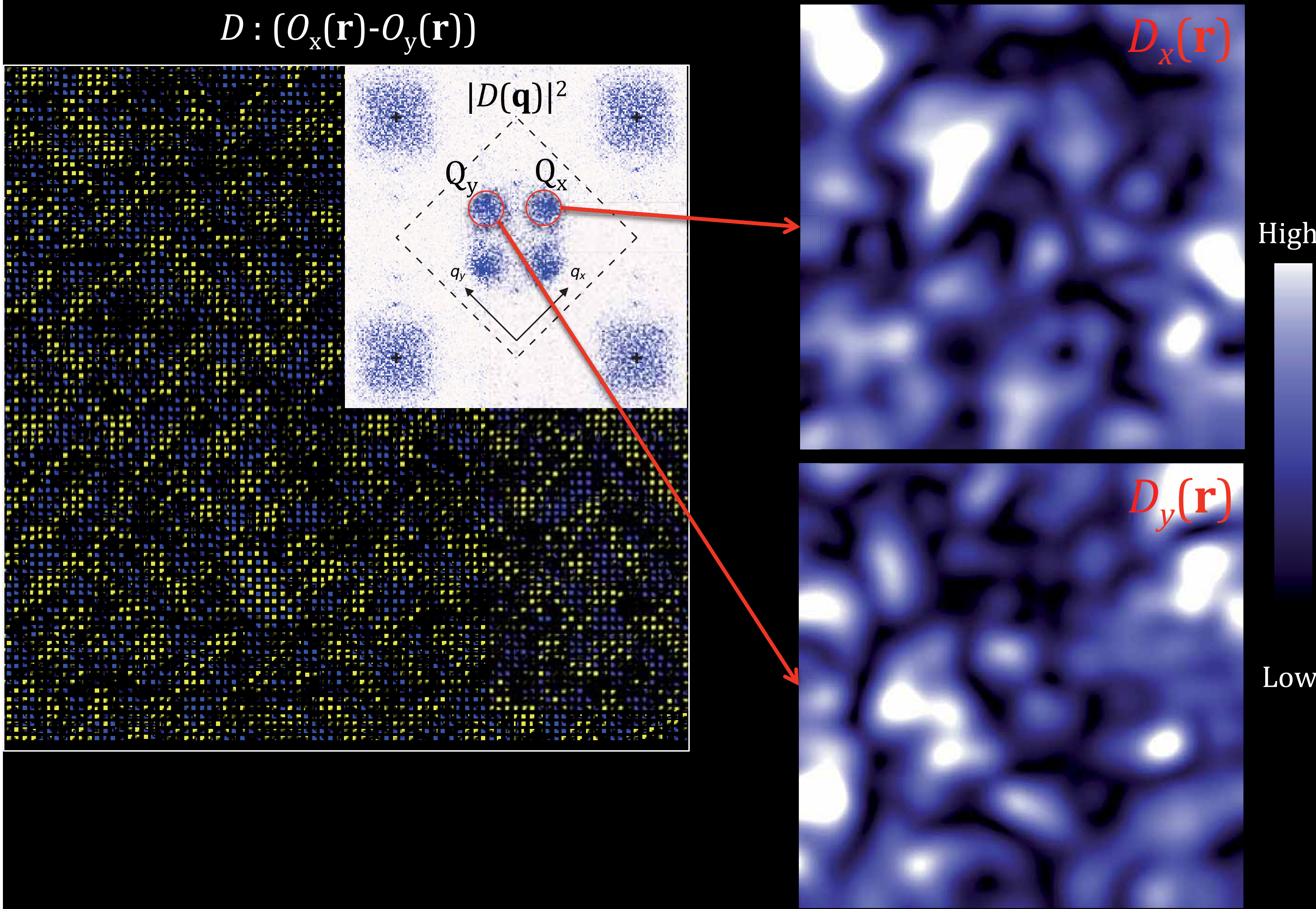
(2) Densities of filled/empty states are π out of phase

$$\left|e^{i\boldsymbol{k}_1\cdot\boldsymbol{r}} \pm e^{i\boldsymbol{k}_2\cdot\boldsymbol{r}}\right|^2 = 2(1 \pm Cos(\boldsymbol{Q}\cdot\boldsymbol{r}))$$

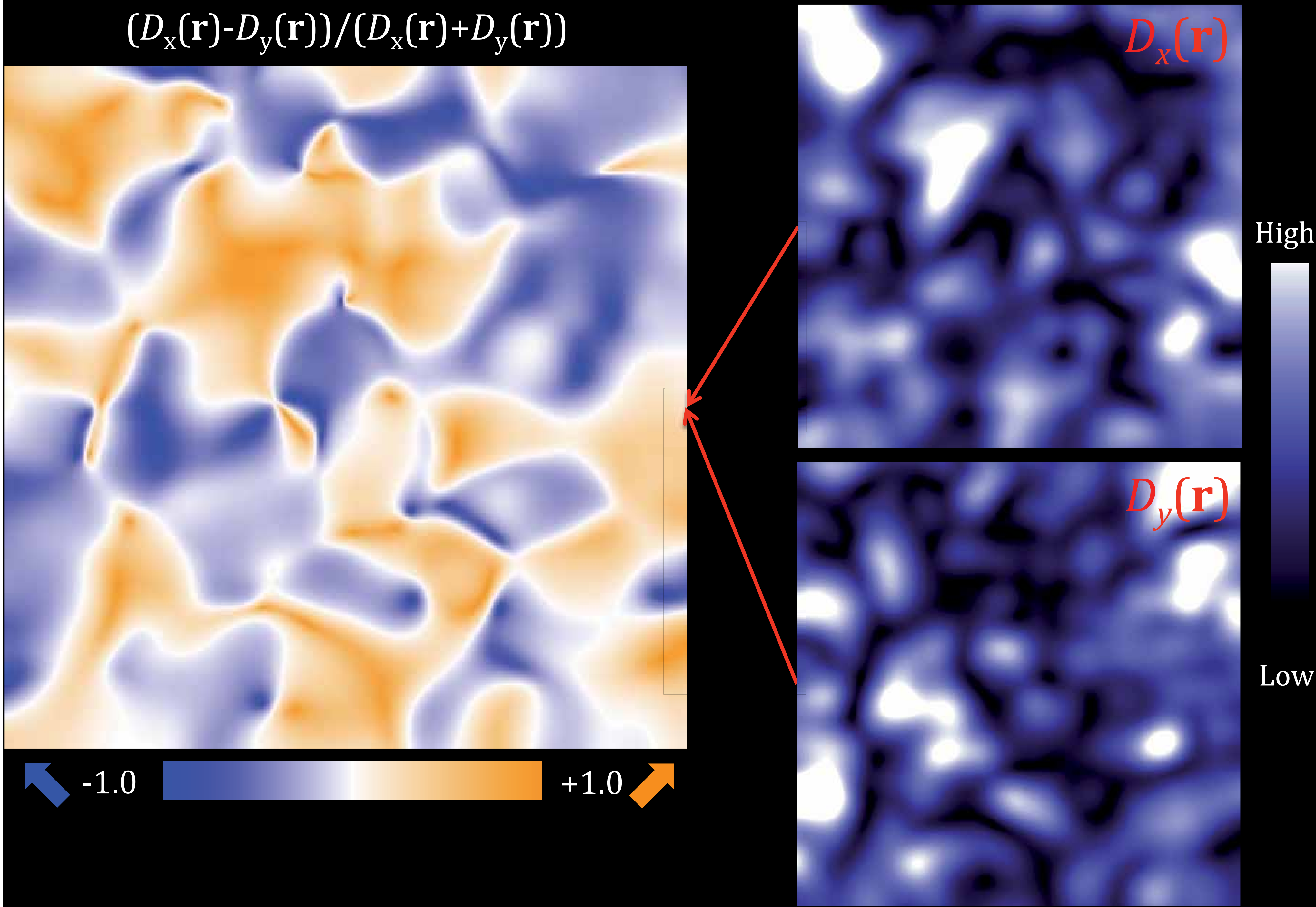
- Checkerboard or domains of unidirectional dFF-DW ?
- Microscopic interplay pseudogap, density wave, superconductivity?

Real Space dFF-DW Domain Structure

$D:(O_x(\mathbf{r})\text{-}O_y(\mathbf{r}))$



Real Space dFF-DW Domain Structure



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