Intra unitcell nematic in the pseudogap states?

Eun-Ah Kim

Cornell University

Michael J. Lawler

Binghamton University,
Cornell University

M.J. Lawler et al, 2009

Lessons from Ruthenates

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Nematic is strong
correlation physics

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Nematic is strong
correlation physics

Nematic is sensitive to
local disorder

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Symmetry breaking field?

Lessons from Ruthenates

Nematic is strong
correlation physics

Nematic is sensitive to
local disorder

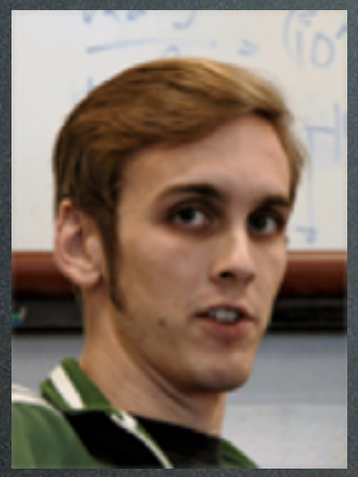
Symmetry breaking field?

Scanning local probes?

Acknowledgements

Dr. Kazuhiro Fujita

Cornell



Dr. Andy Schmit

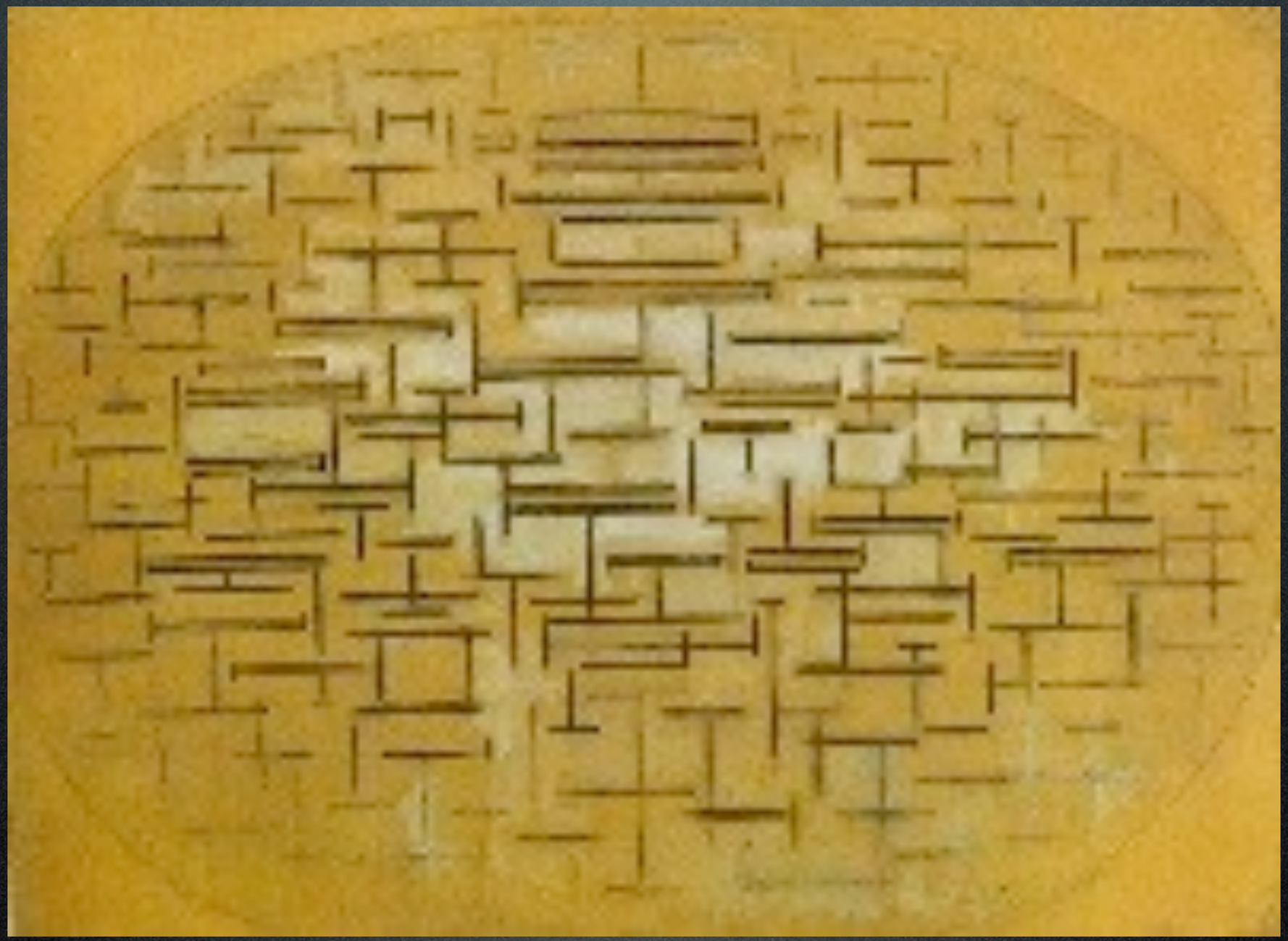
Cornell

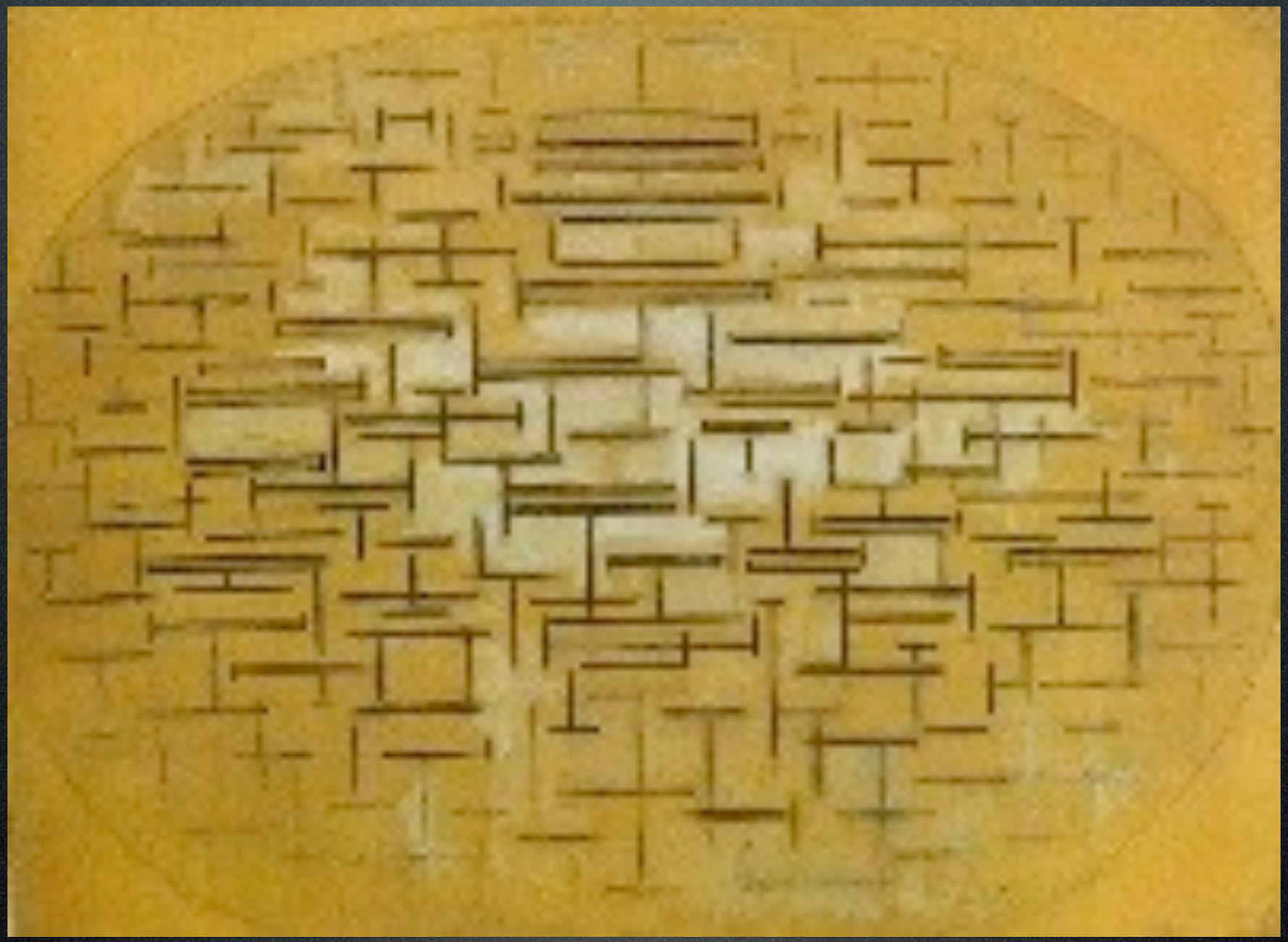
Prof. Seamus Davis

Cornell, BNL,
St. Andrews, UBC

Prof. James Sethna

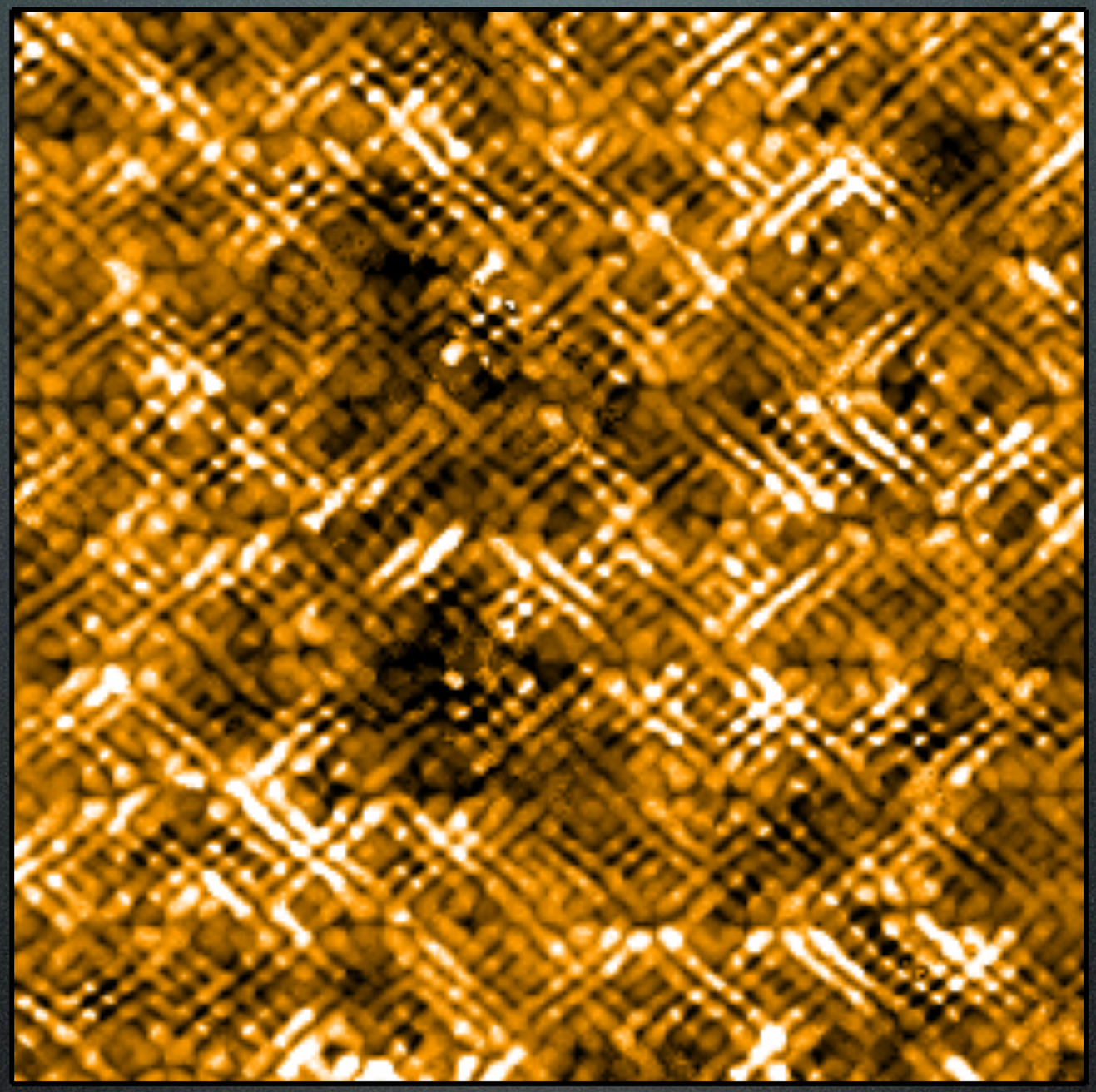
Cornell



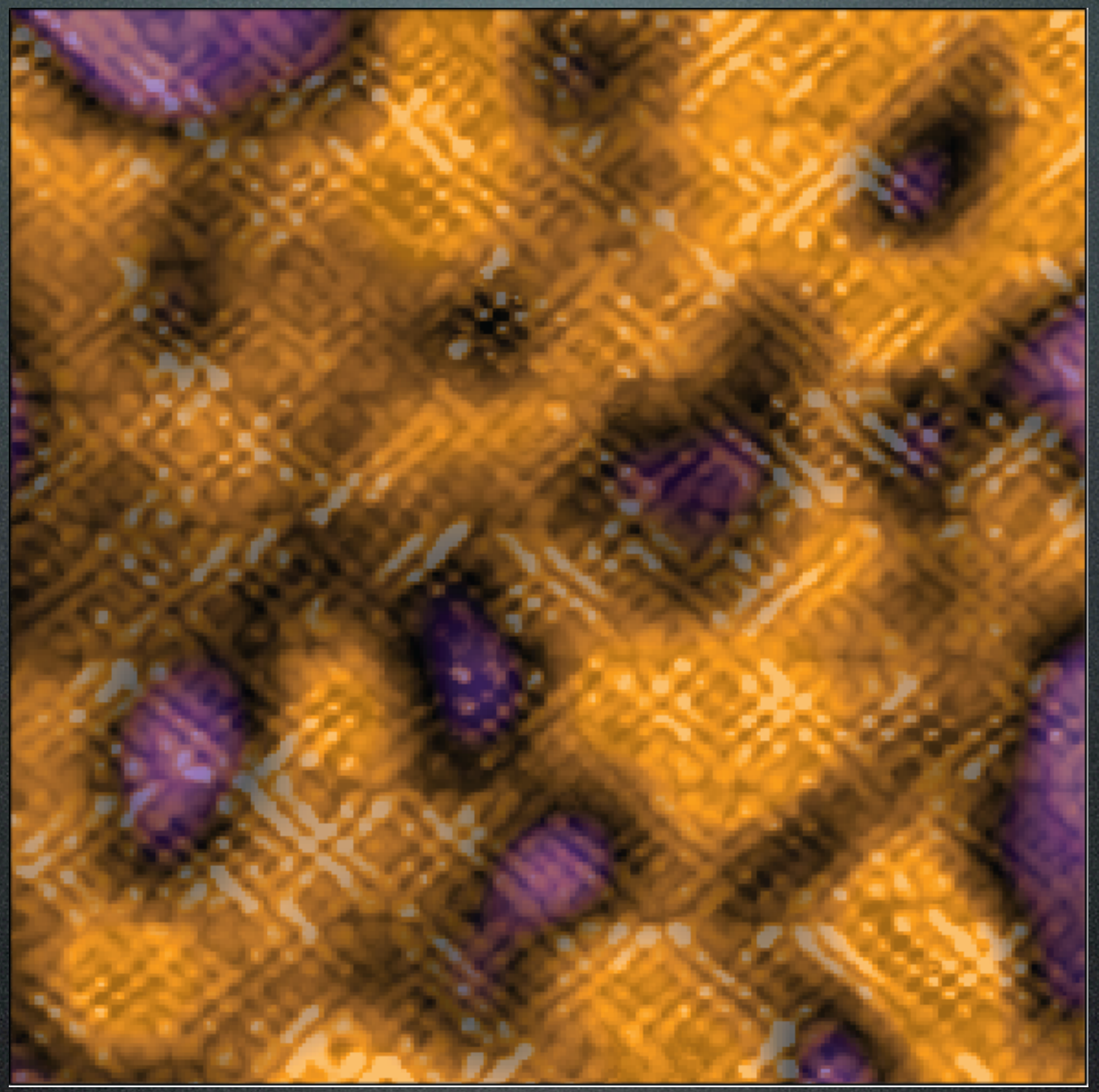


Piet Mondrian, 1915. Says he is searching for hidden order in nature...

Ocean 5, Guggenheim collection, Venice



Dy-Bi2212 UD45K

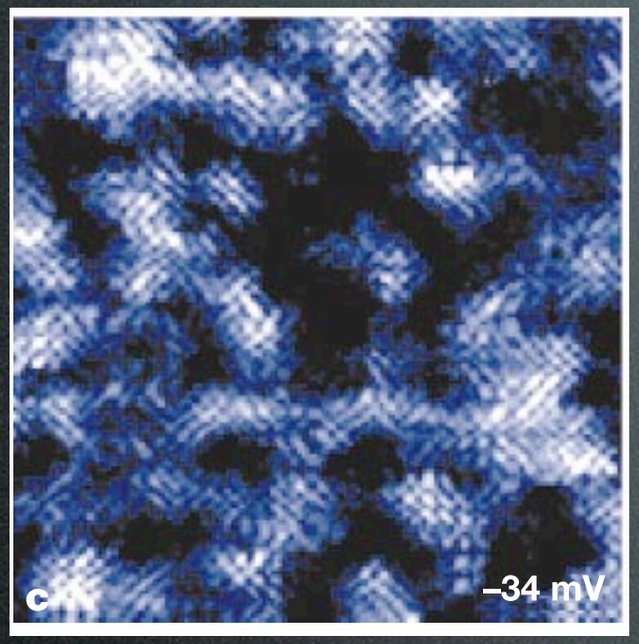


Lawler et al 2009, identified hidden order in the pseudogap state of underdoped Bi2212

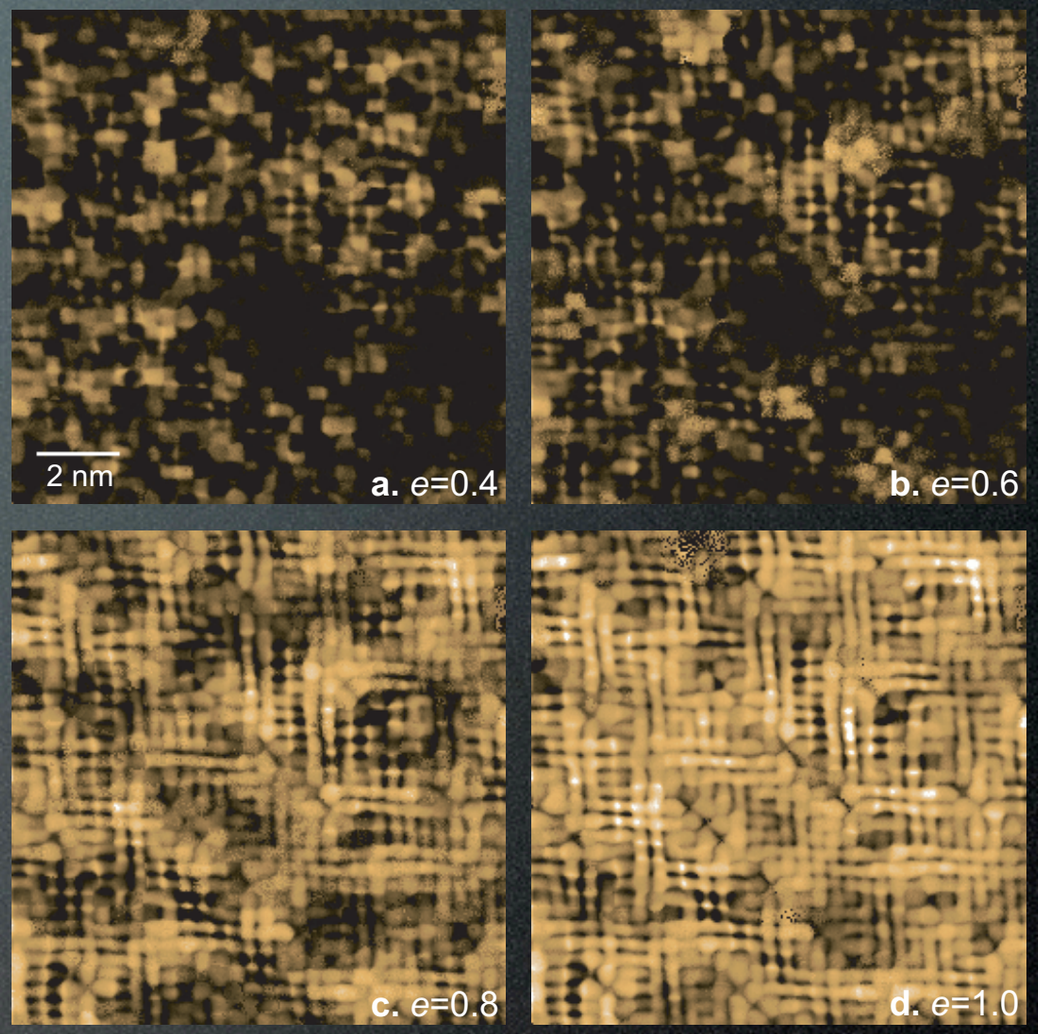
Intra unitcell nematic in the pseudogap states?

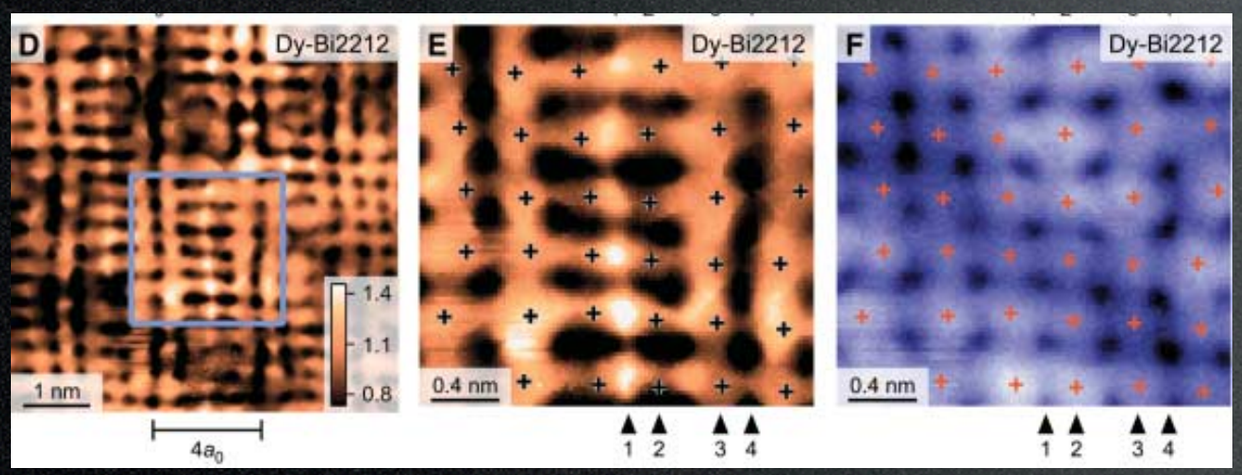
- Where we started
- BSCCO: **got nematic?**
  - -Definition
  - -Analysis
- Meaning?

Local measure of broken symmetry?



dI/dV(ω)-map
McElroy et al, Nature 422, 592 (2003)
OD T_c=86K





R-map
Kohsaka et al, Science 315, 1380 (2007)
UD T_c=45K (p=0.08)

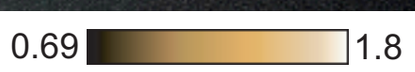
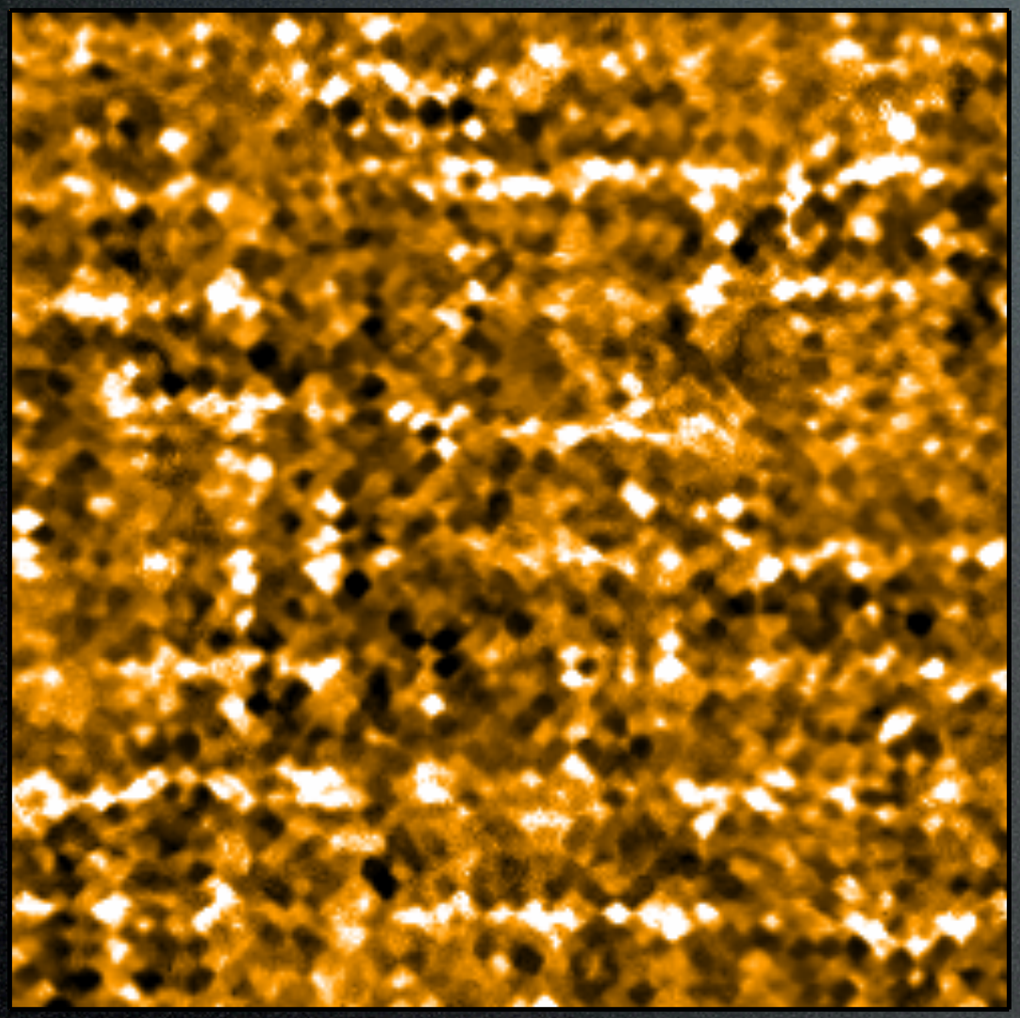


Figure S7 a-f. A series of images displaying the real space conductance ratio Z as a function of energy rescaled to the local psuedogap value, $e = E/\Delta_1(\mathbf{r})$. Each pixel location was rescaled independently of the others. The common color scale illustrates that the bond centered pattern appears strongest in Z exactly at $E = \Delta_1(\mathbf{r})$.

Z-map(ω)
Kohsaka et al, Nature 454, 1072 (2008)
UD T_c=45K

Local measure of broken symmetry?



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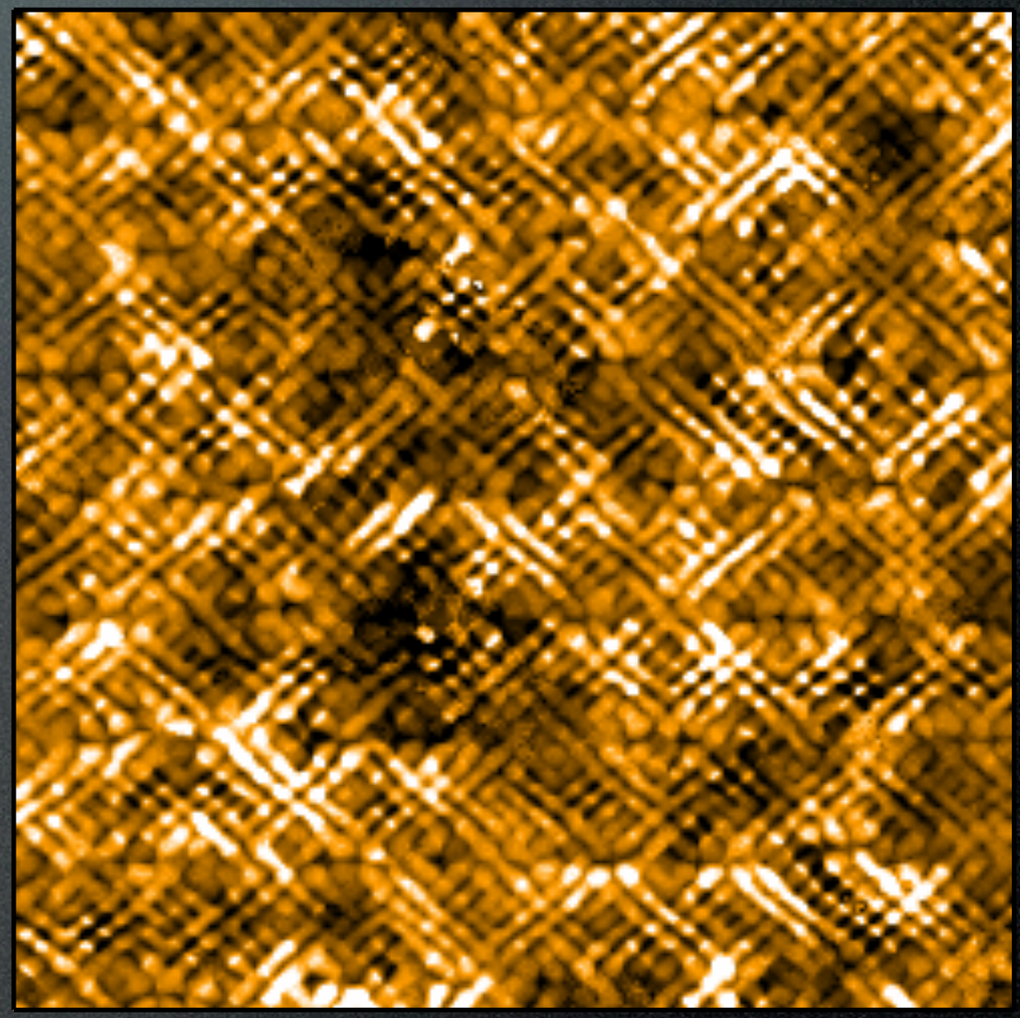
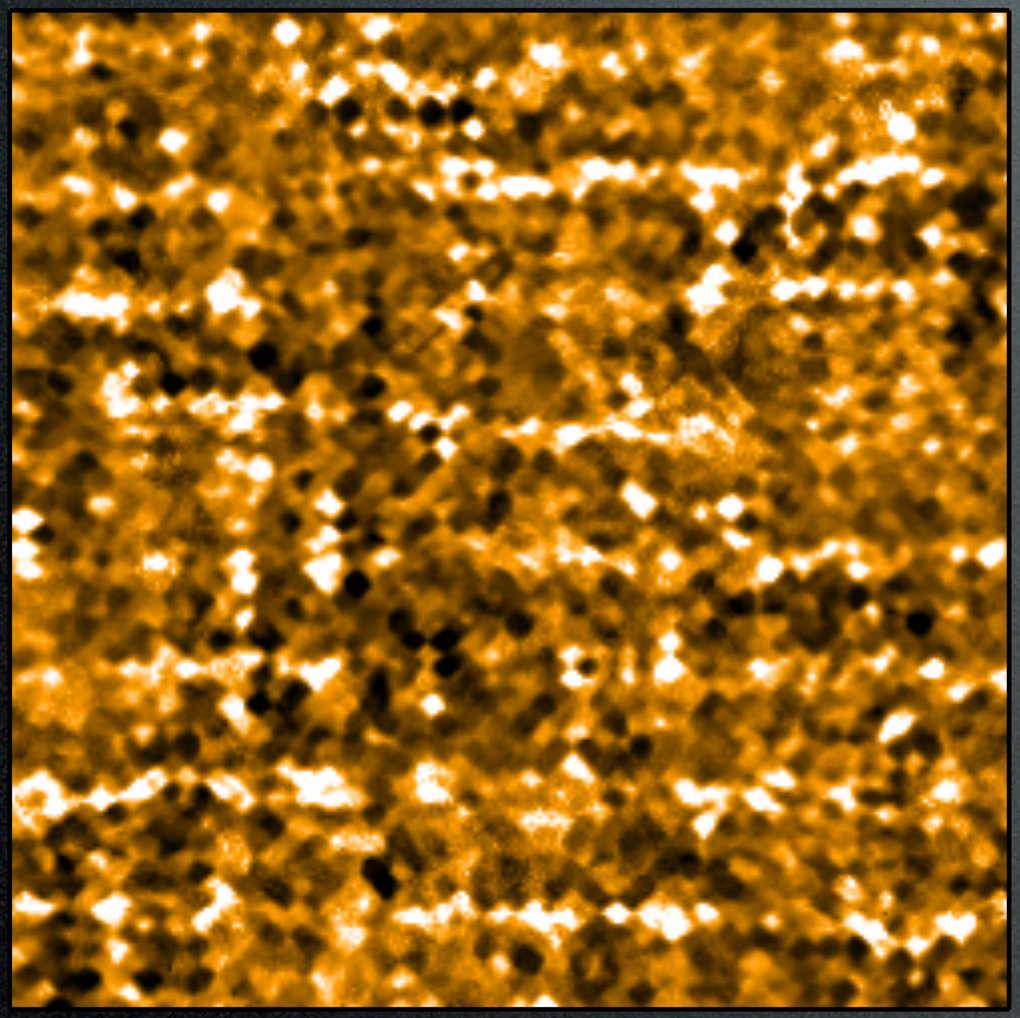


Kohsaka et al, Nature 454, 1072 (2008)

Local measure of broken symmetry?

HAMLET: Do you see yonder cloud that's almost in shape of a camel?
POLONIUS: By th'mass, and 'tis like a camel indeed.
HAMLET: Methinks it is like a weasel.
POLONIUS: It is backed like a weasel.

--W. Shakespeare



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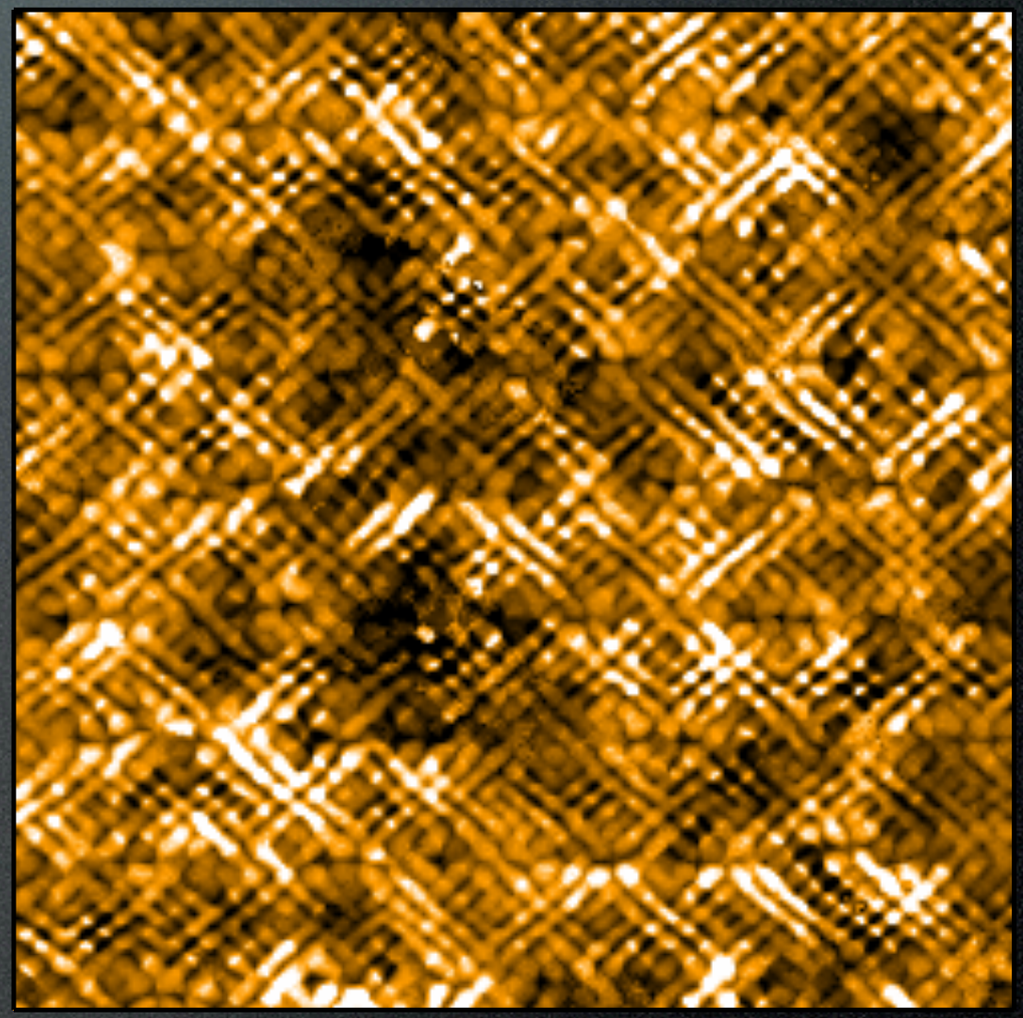

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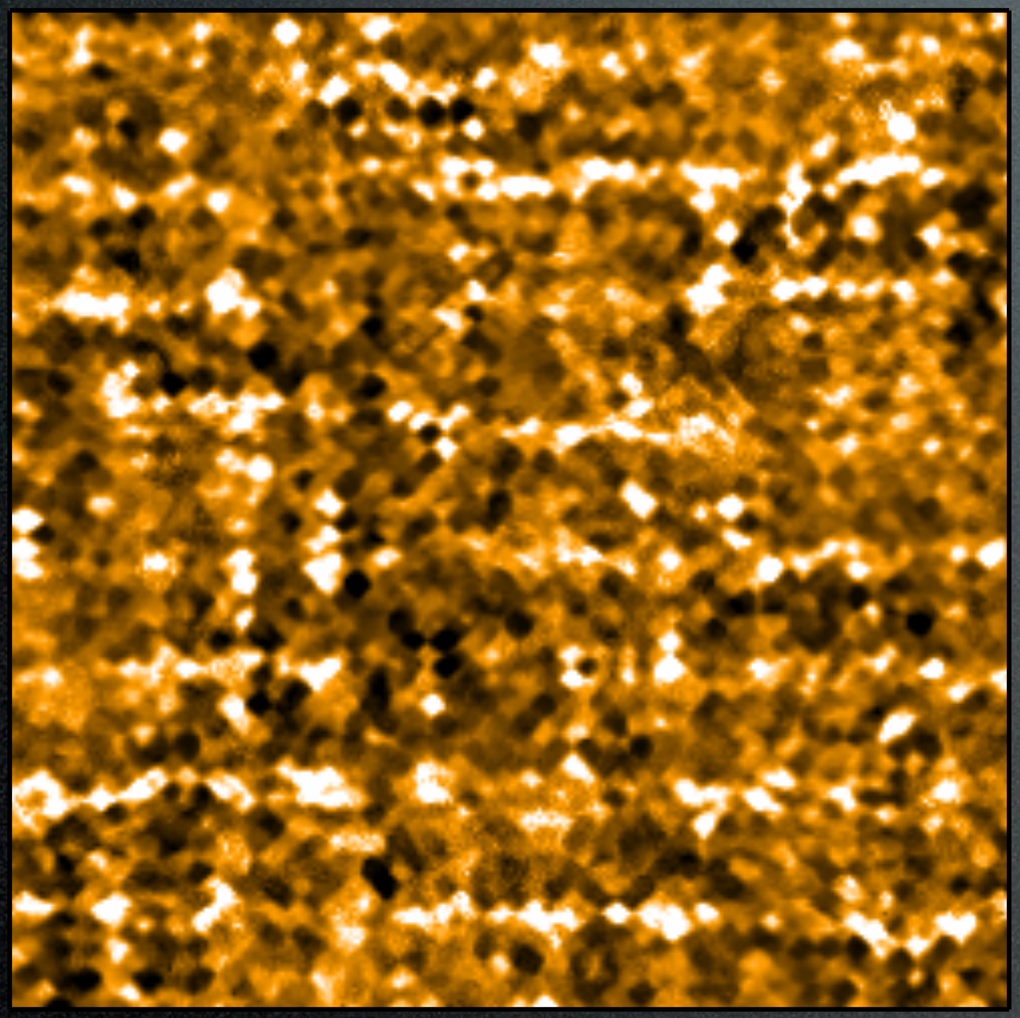

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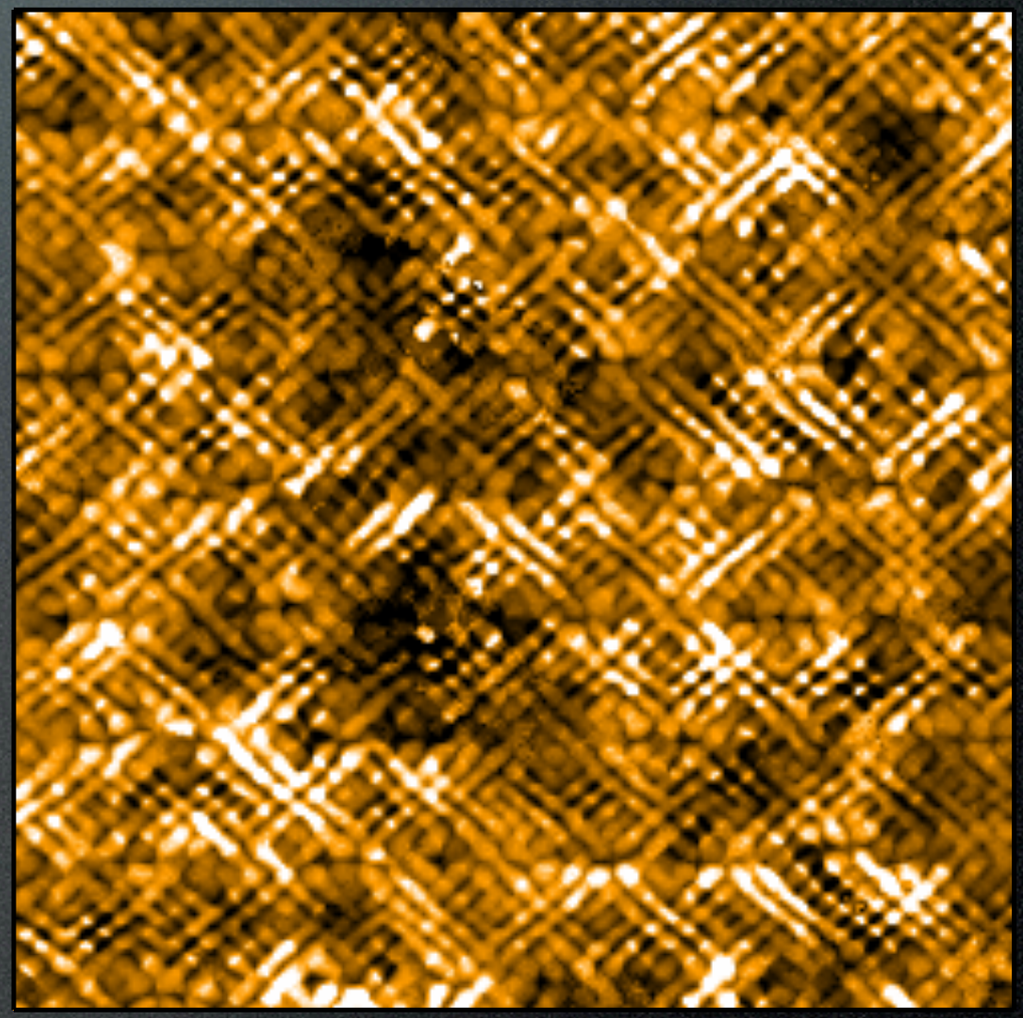


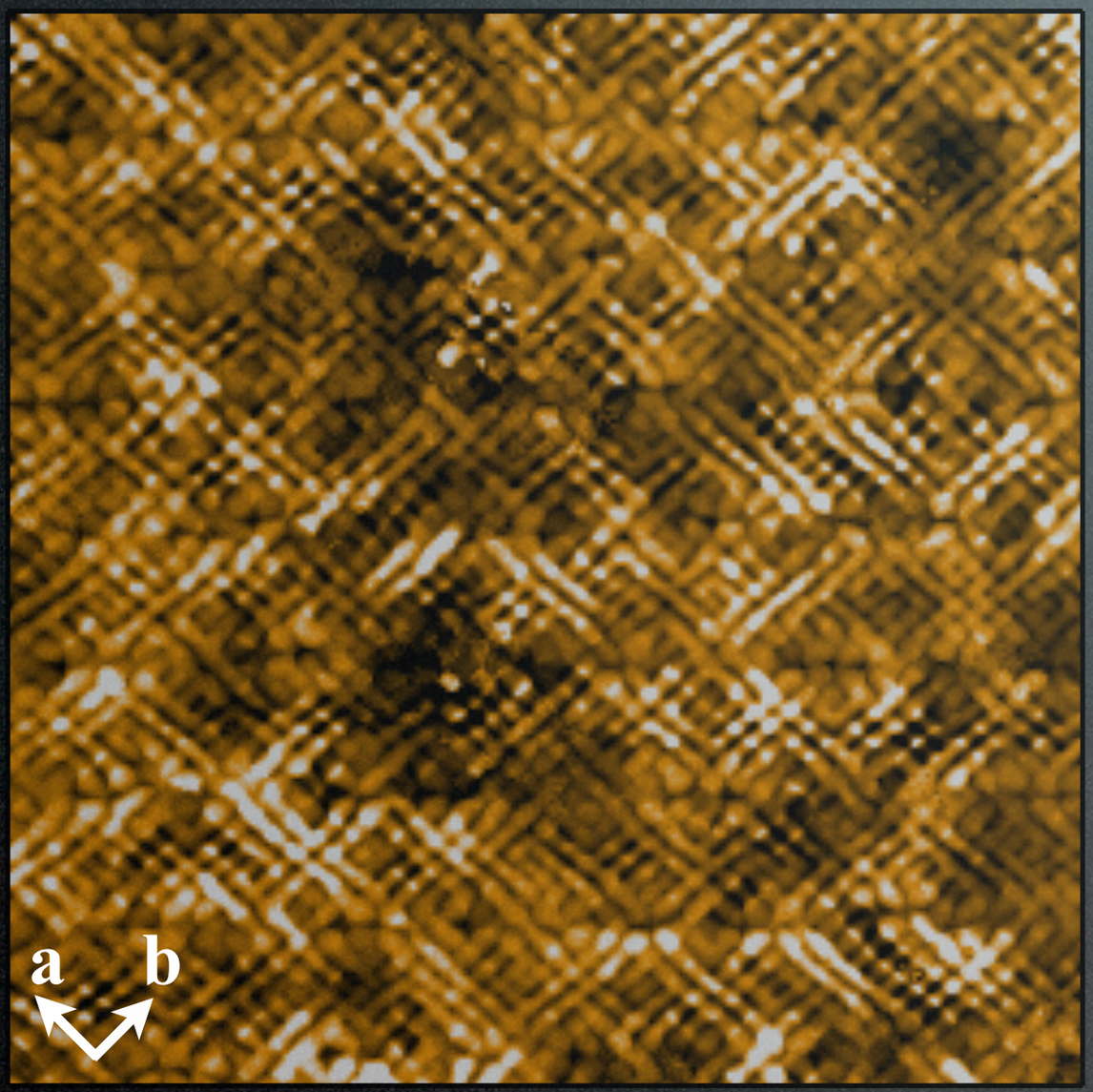
Kohsaka et al, Nature 454, 1072 (2008)

Challenge: An objective measure

BSCCO, got nematic?

Defining the local order parameters

Candidate broken symmetries

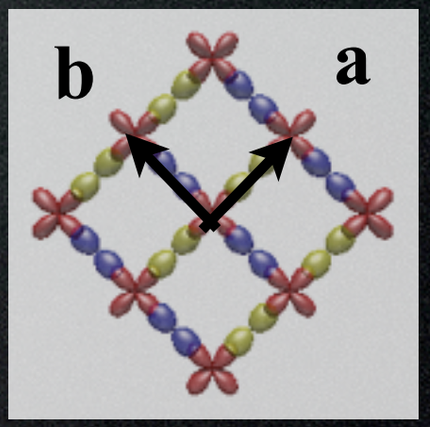


- Translational symmetry

$$\hat{T}_a, \hat{T}_b$$

- Rotational symmetry

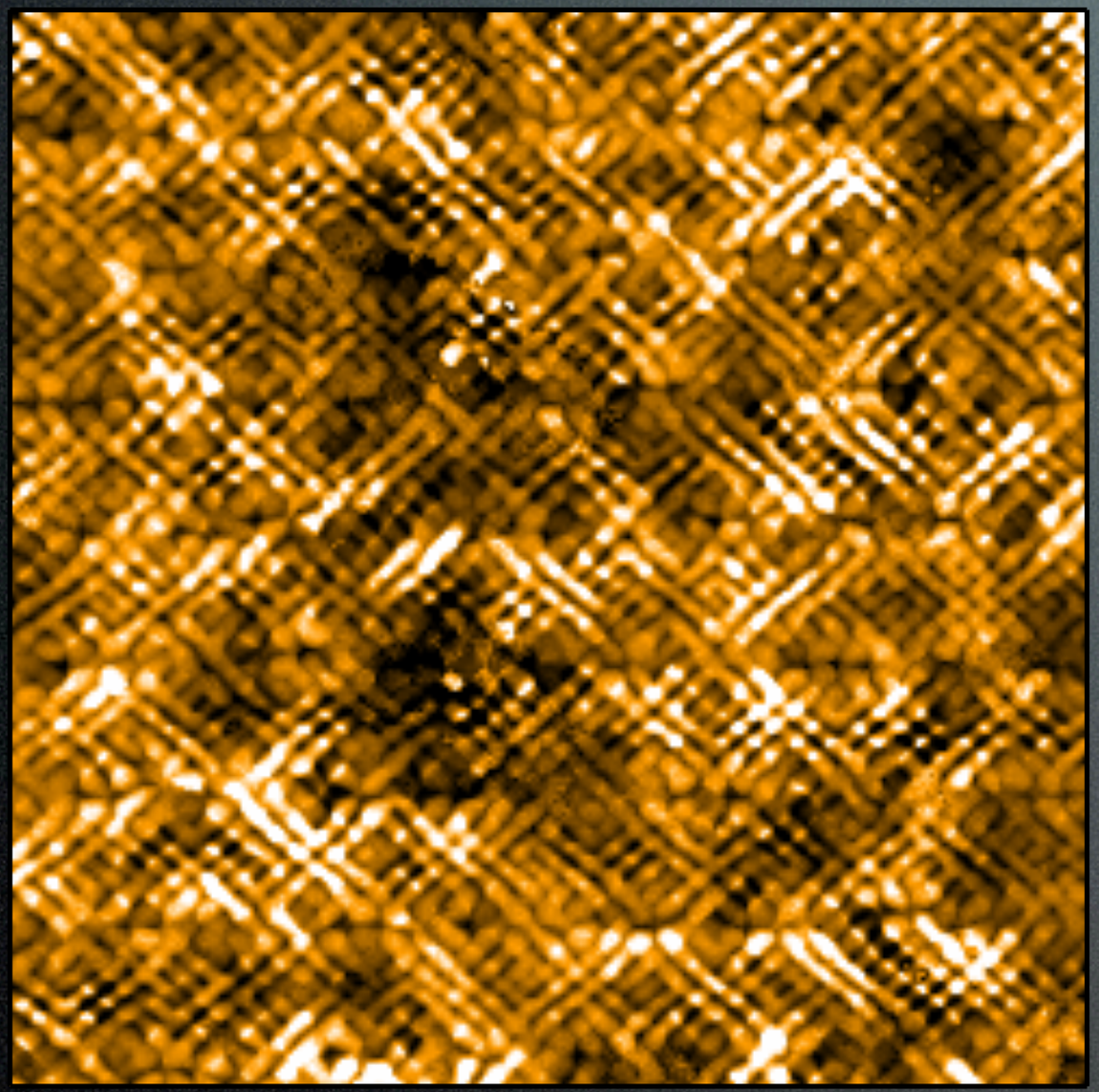
$$\hat{R}_{\pi/2}$$



Can we separately measure?

Need a $\hat{T}_a, \hat{T}_b$ preserving order parameter

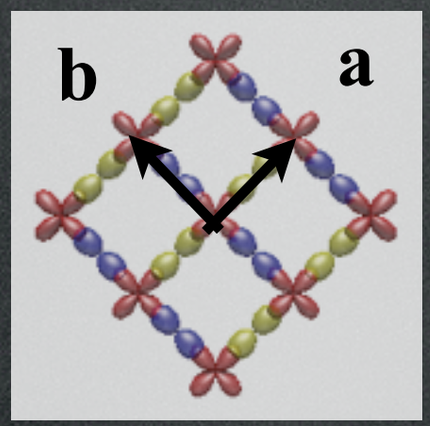
Local measure of broken symmetry?



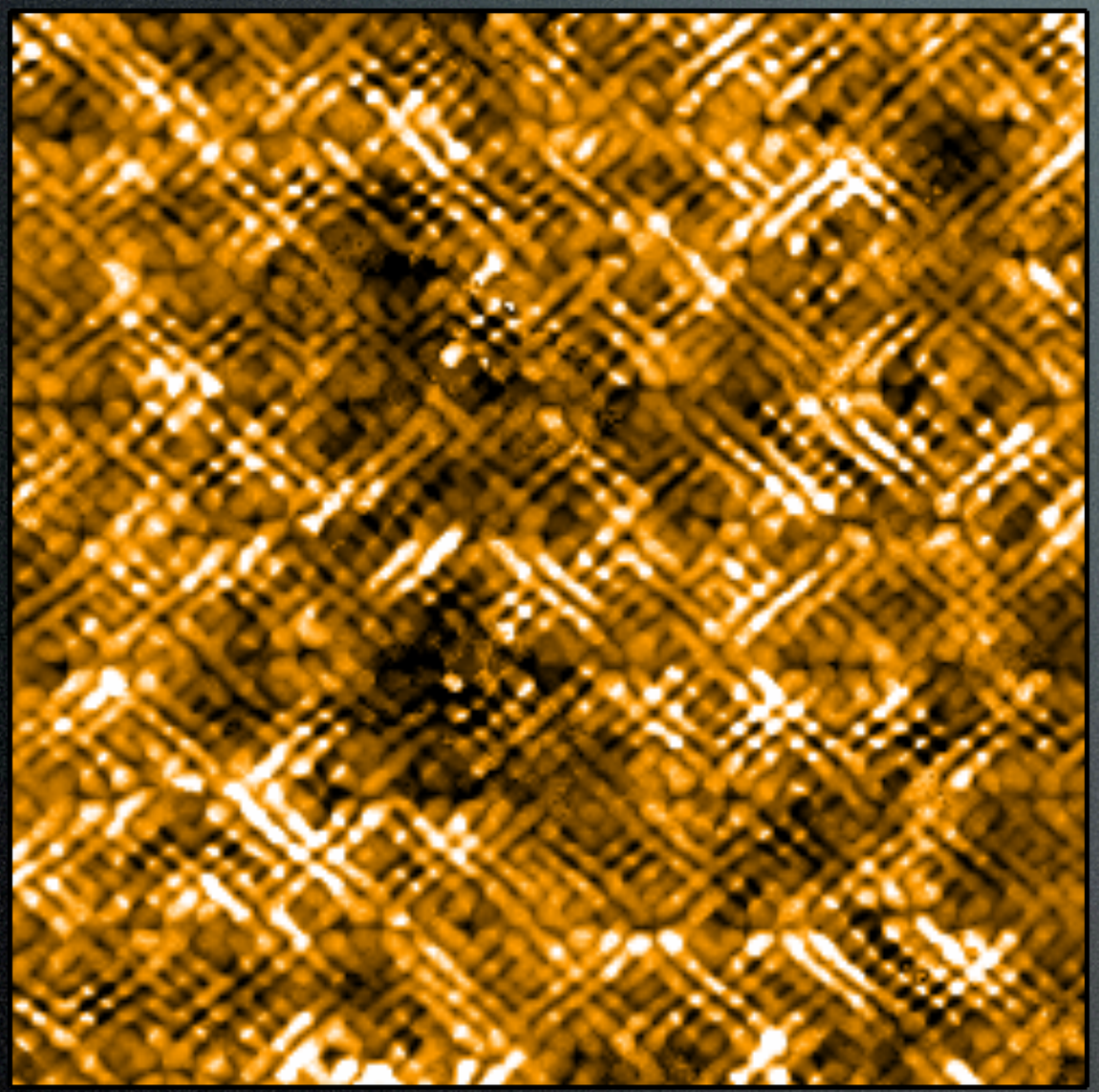
2nm

Z(**r**,*e*=1)

Position space



Local measure of broken symmetry?

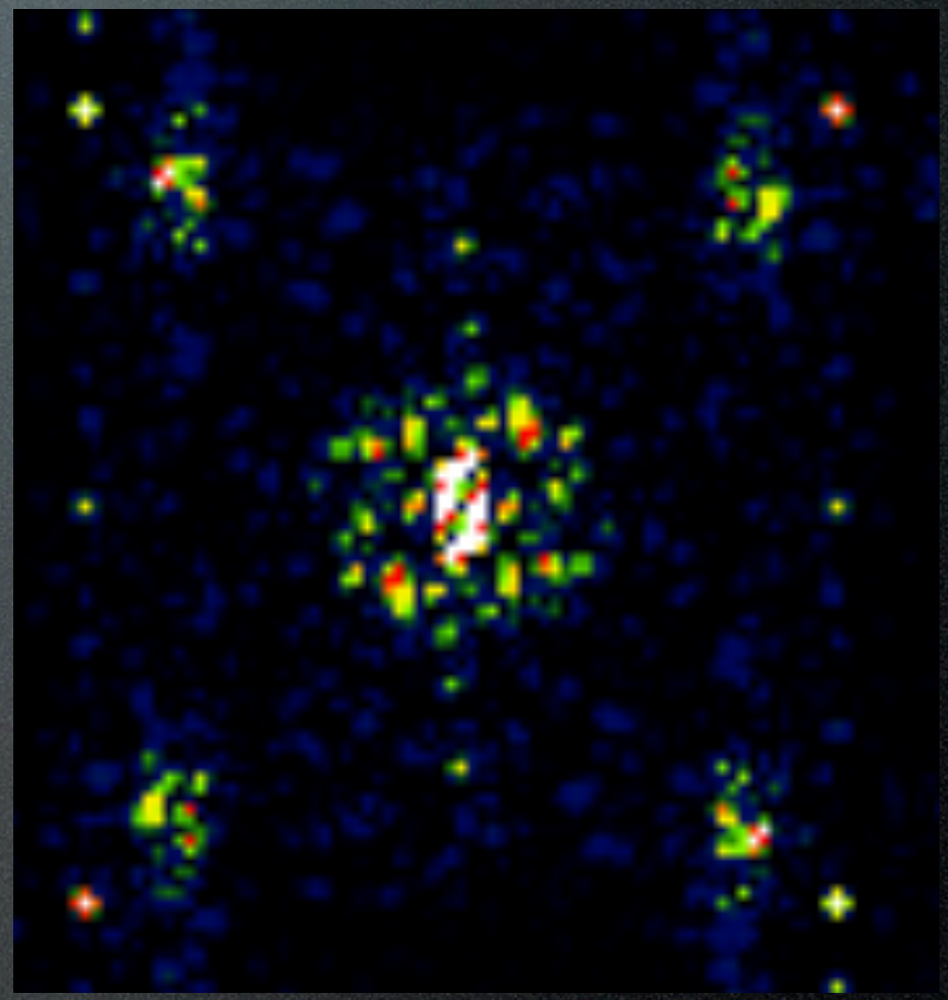


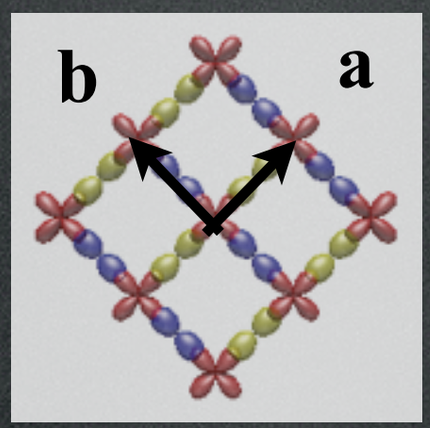
2nm

Z(**r**,*e*=1)

Position space

Fourier space





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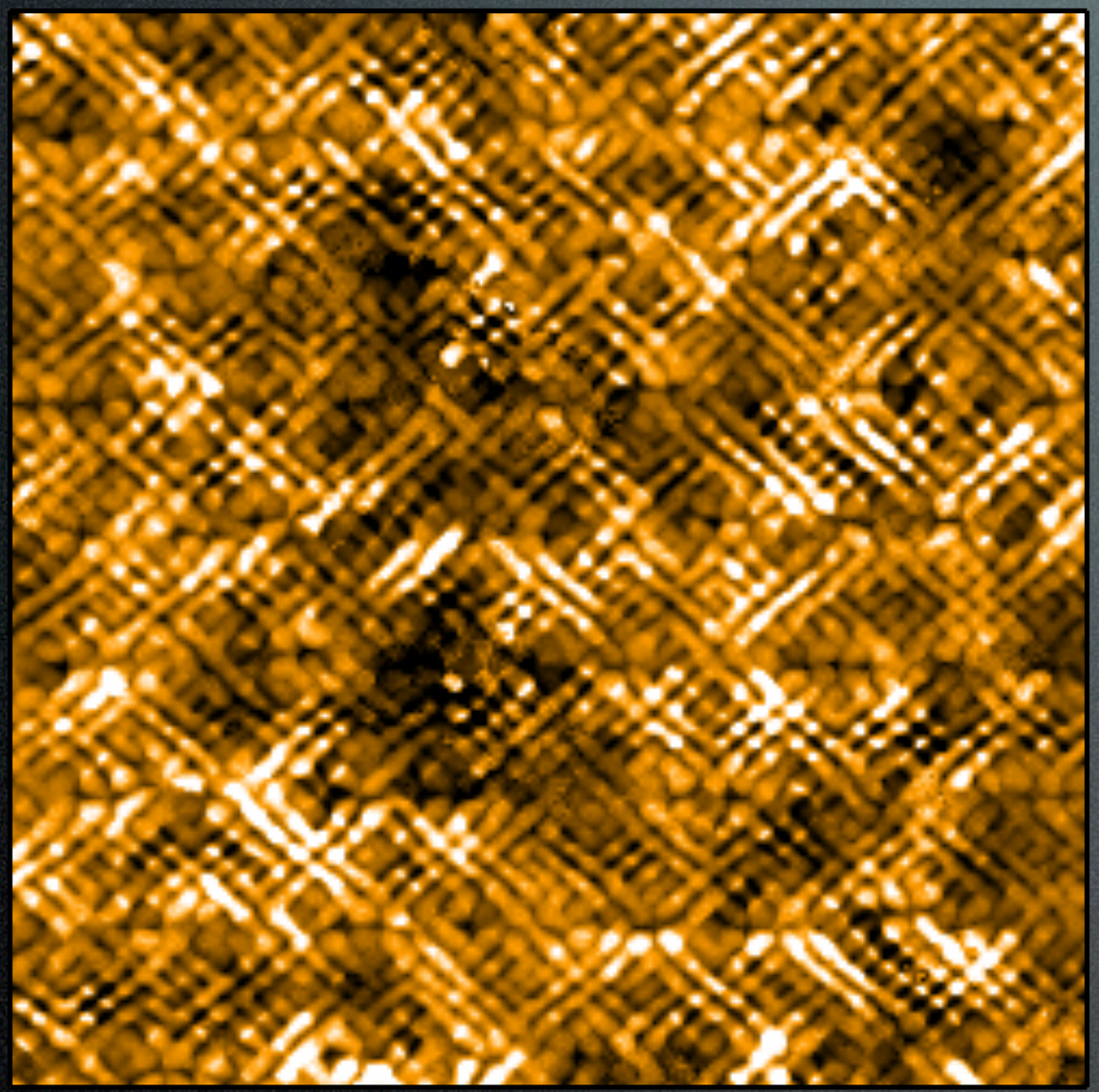
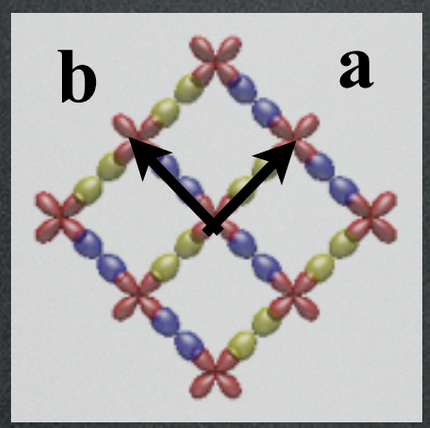


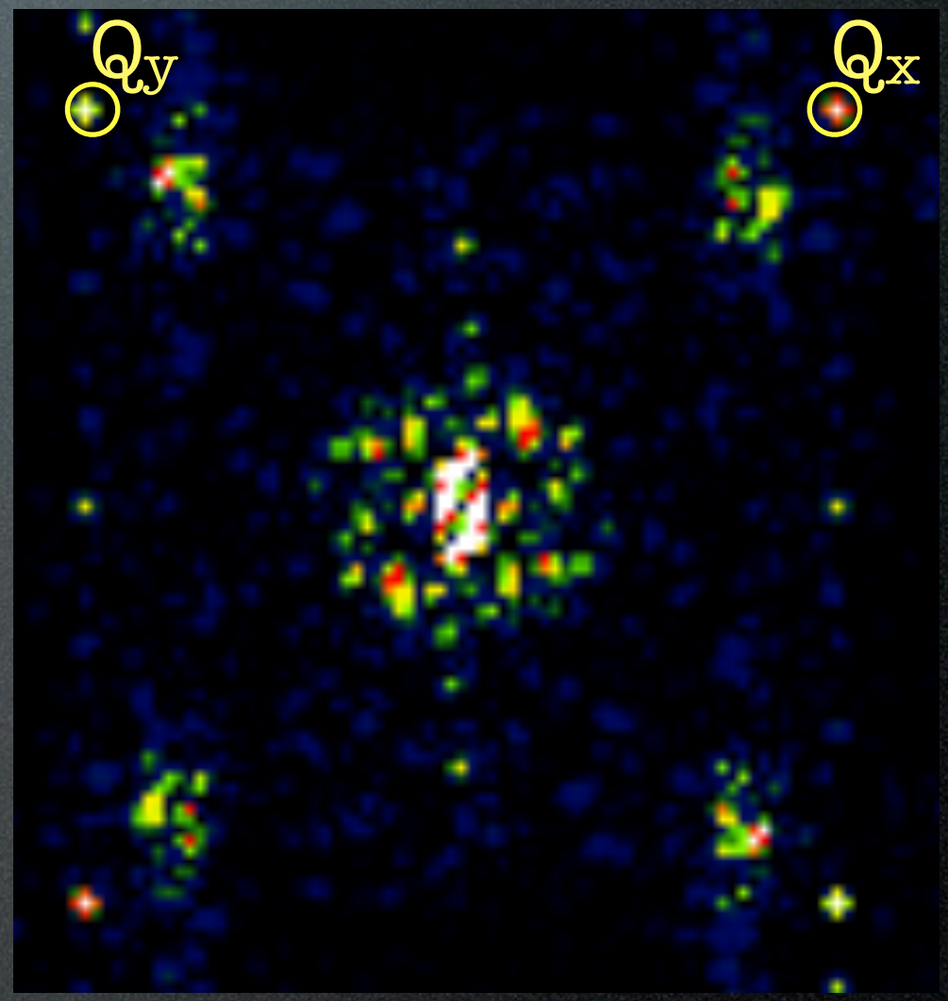
2nm

Z(**r**,e=1)

Position space

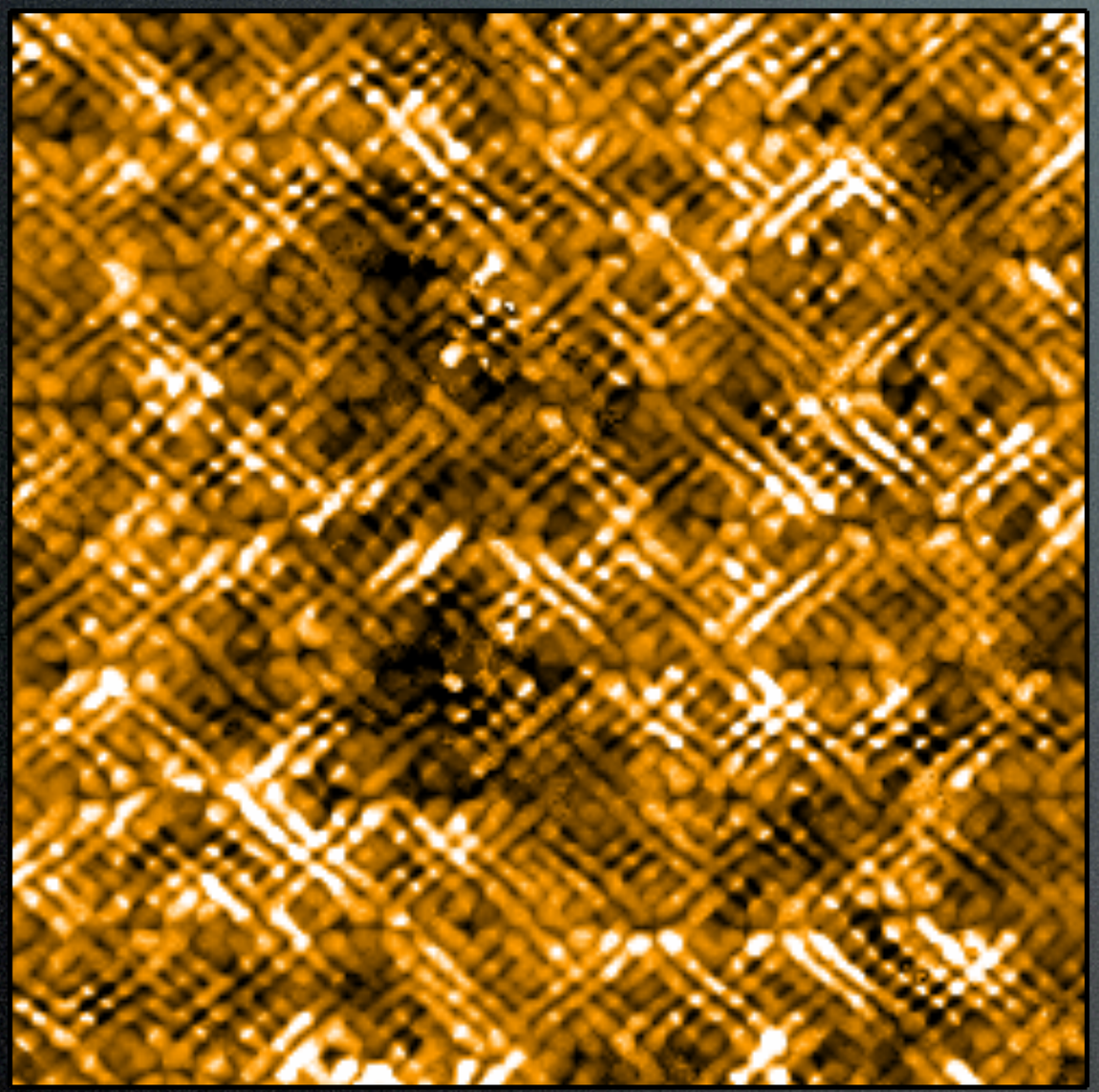


Fourier space



Q_x vs Q_y?

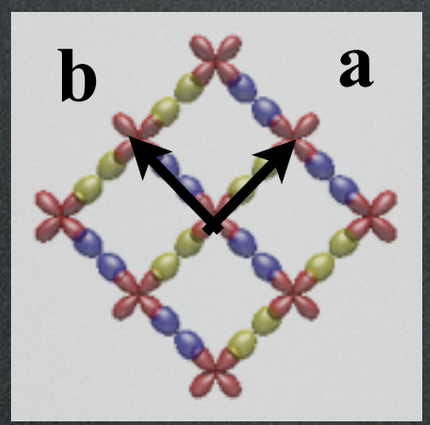
Local measure of broken symmetry?



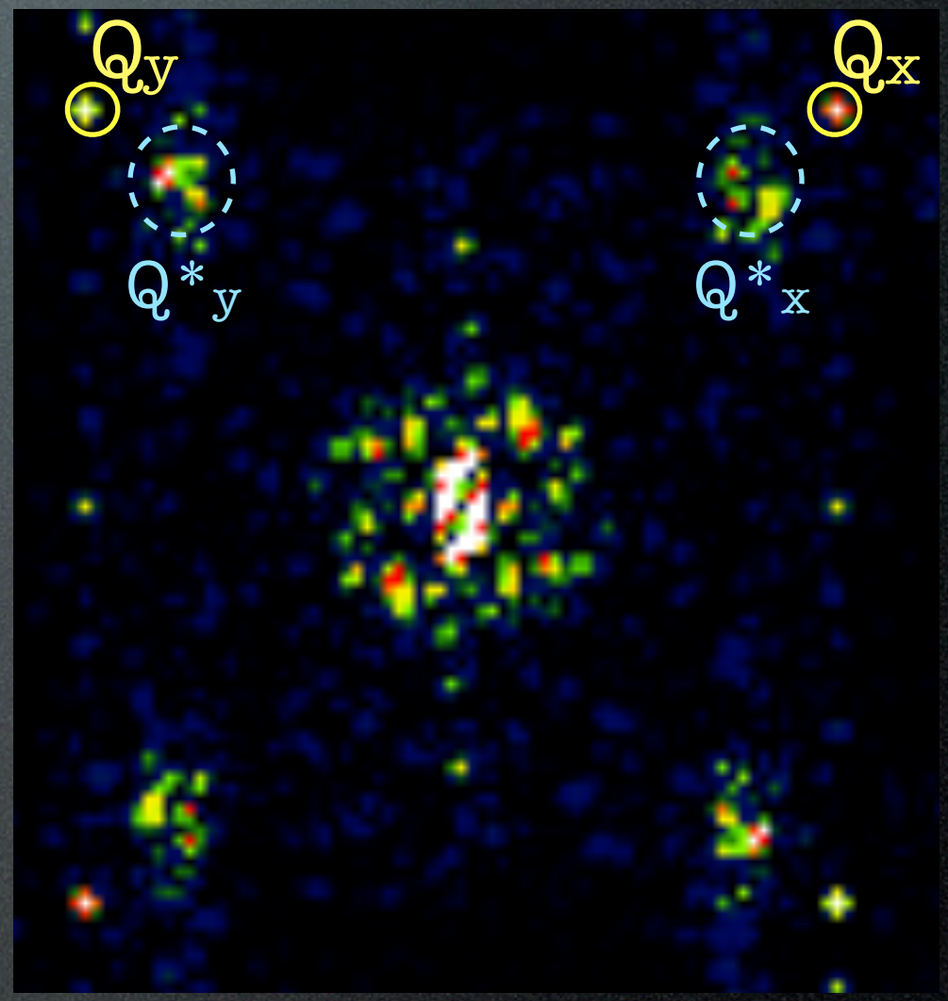
2nm

Z(r,e=1)

Position space



Fourier space



Q_x vs Q_y?

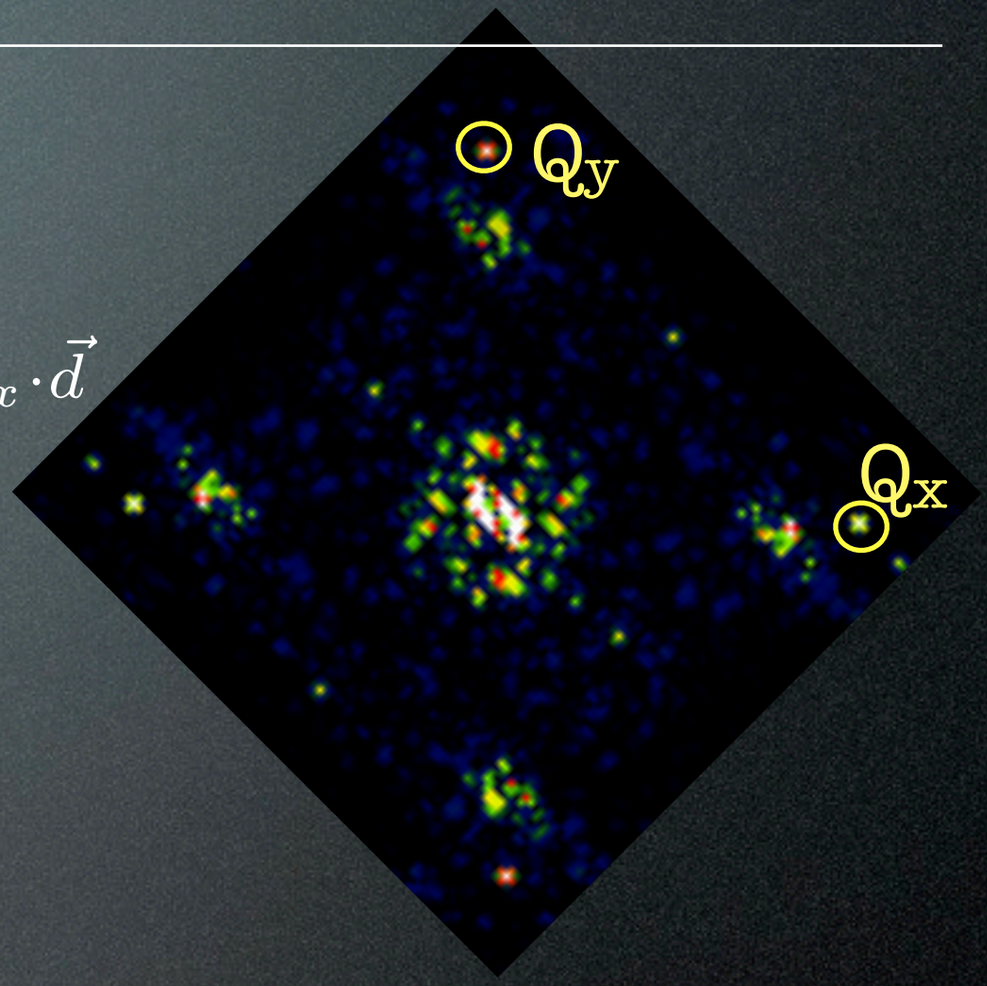
Q^*_x vs Q^*_y?

Q_x vs Q_y

- Bragg peak

$$\tilde{Z}(\vec{Q}_x) = \frac{1}{\sqrt{N}} \sum_{\vec{R}+\vec{d}} Z(\vec{R}+\vec{d}) e^{-i\vec{Q}_x \cdot \vec{d}}$$

$$\vec{Q}_x = (2\pi/a, 0)$$



- Nematic OP

$$\mathcal{O}_N \equiv \tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(-\vec{Q}_x) - \tilde{Z}(-\vec{Q}_y)$$

➡Preserves lattice translation

M.J. Lawler et al, 2009

Q_x vs Q_y

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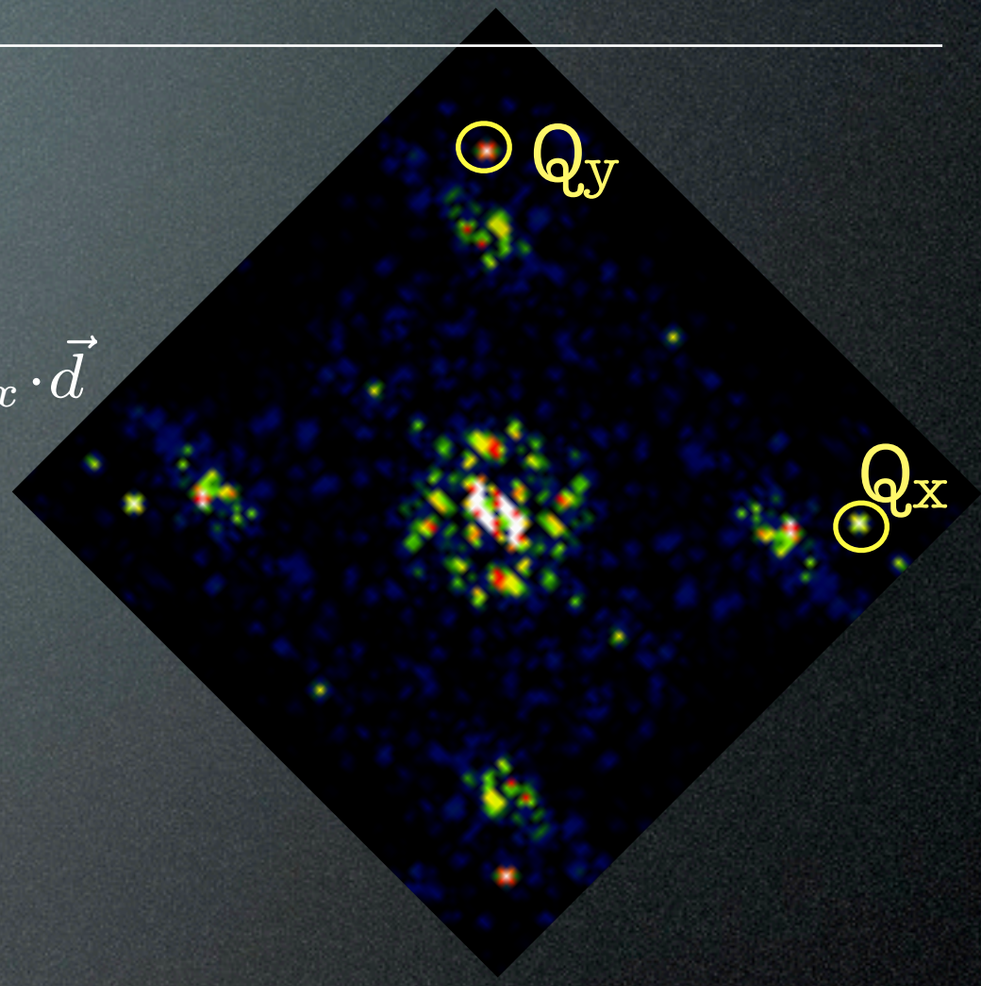

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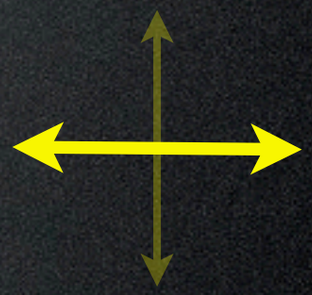
➡Measures C_4 breaking



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M.J. Lawler et al, 2009

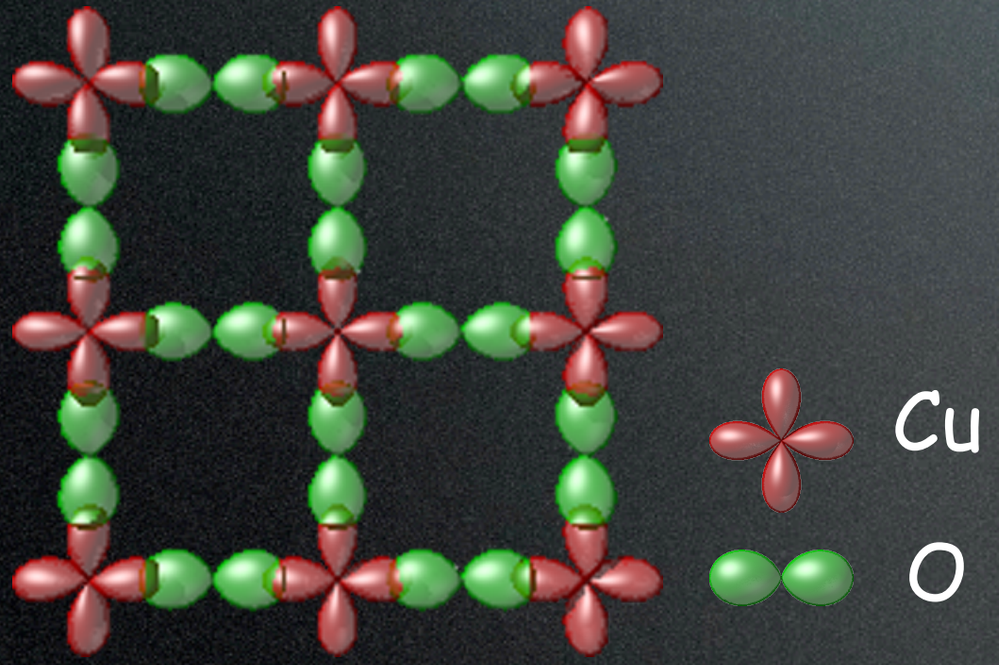
Nematic OP $\mathcal{O}_N$ and microscopics

$$\tilde{Z}(\vec{Q}_x) = \bar{Z}_{\mathrm{Cu}} - \bar{Z}_{\mathrm{O}_x} + \bar{Z}_{\mathrm{O}_y}, \tilde{Z}(\vec{Q}_y) = \bar{Z}_{\mathrm{Cu}} + \bar{Z}_{\mathrm{O}_x} - \bar{Z}_{\mathrm{O}_y}$$

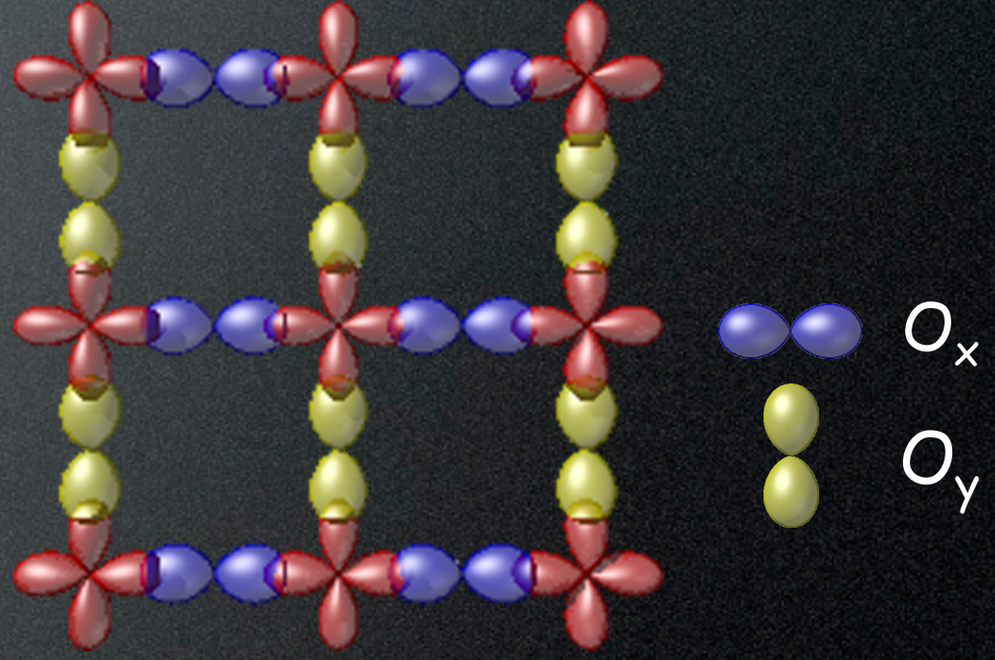
$$\mathcal{O}_N \propto (\bar{Z}_{O_x} - \bar{Z}_{O_y})$$

M.J. Lawler et al, 2009

➡ Need O sites



CuO_2 plane



Intra unitcell Nematic:
C_4 ➠ C_2

Local version of Nematic OP $\mathcal{O}_N(\mathbf{r})$

- What real space information leads to a given momentum space peak?

M.J. Lawler et al, 2009

$$\tilde{Z}(\vec{Q},\vec{x}) = \text{low pass}_\Lambda \left[Z(\vec{x},e) e^{i\vec{Q}\cdot\vec{x}} \right]$$
$$= \sum_{\vec{x}'} Z(\vec{x}',e) e^{i\vec{Q}\cdot\vec{x}'} f_\Lambda(\vec{x}'-\vec{x})$$

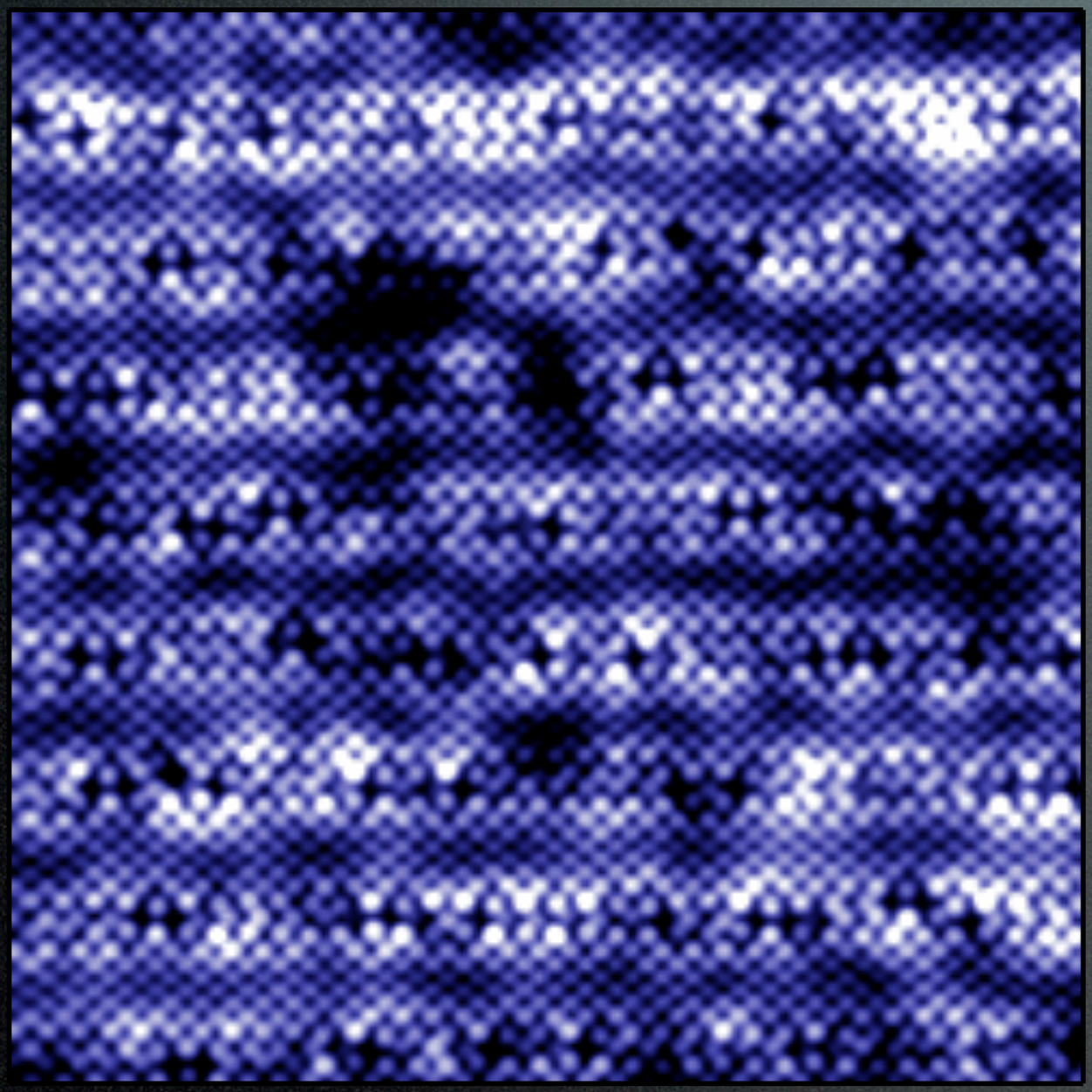
- Local order parameter:

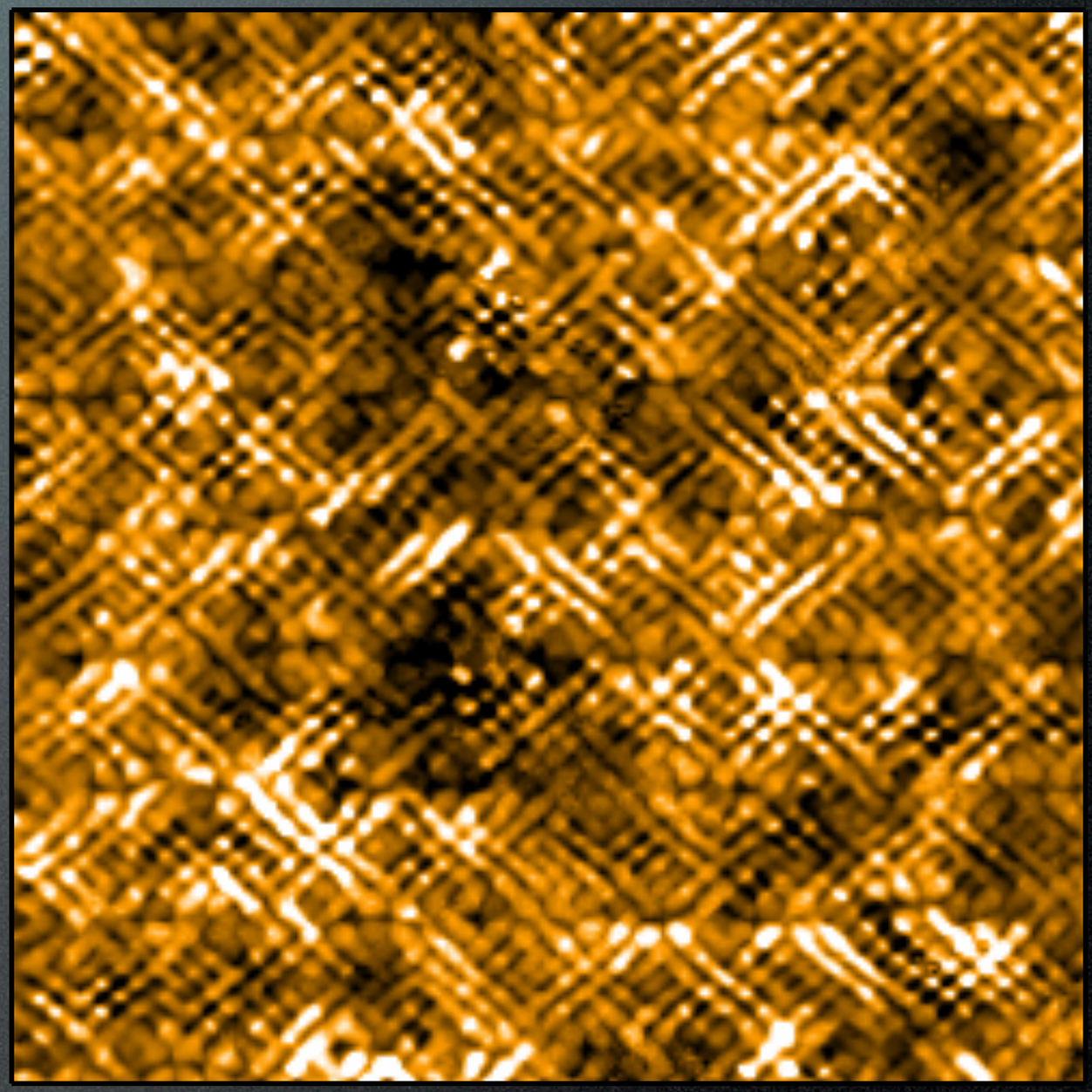
$$\mathcal{O}_N(\vec{x}) = \tilde{Z}(\vec{Q}_x,\vec{x}) - \tilde{Z}(\vec{Q}_y,\vec{y}) + \tilde{Z}(-\vec{Q}_x,\vec{x}) - \tilde{Z}(-\vec{Q}_y,\vec{y})$$

BSCCO, got nematic?

Piezo Drift

Key: Atomic registry with the lattice





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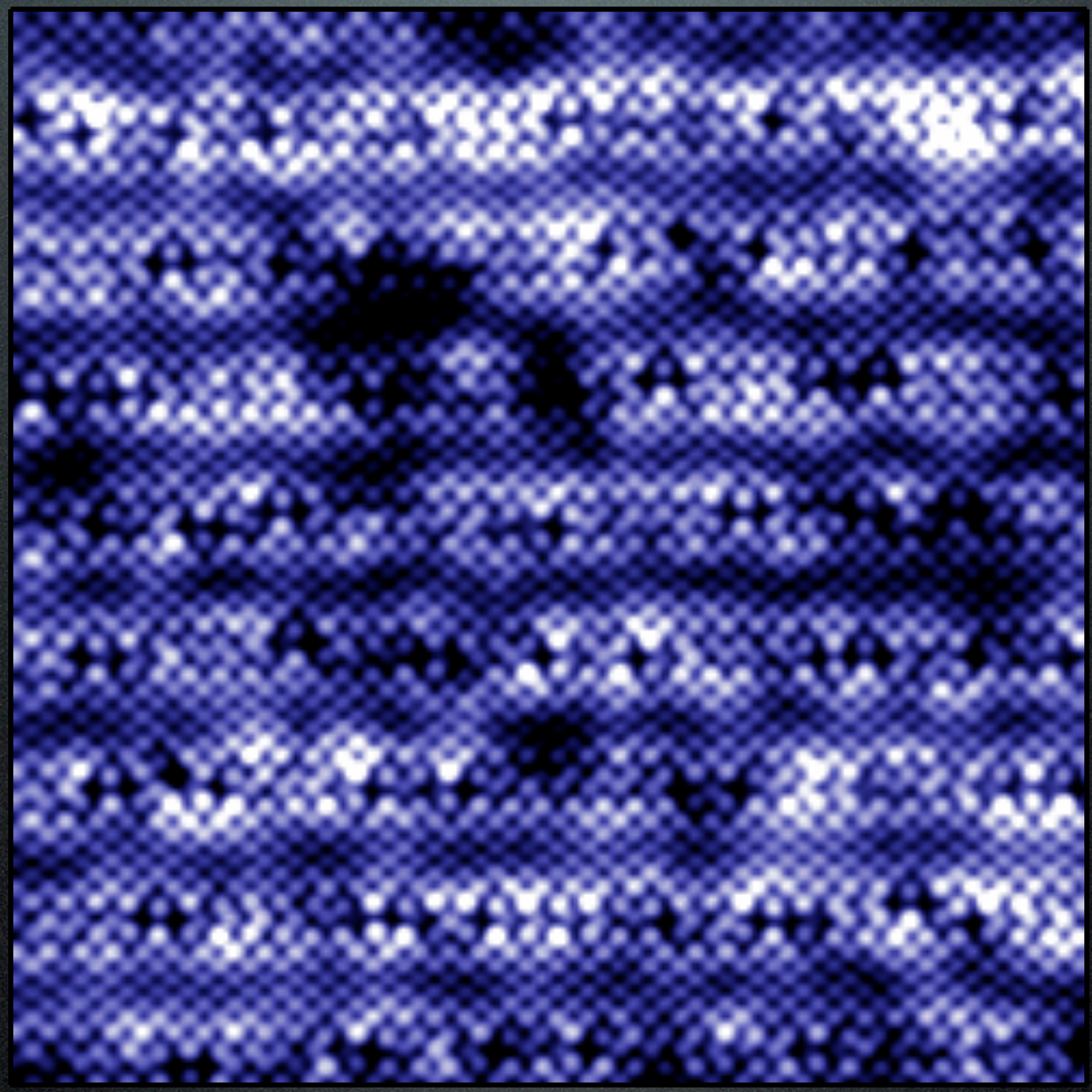

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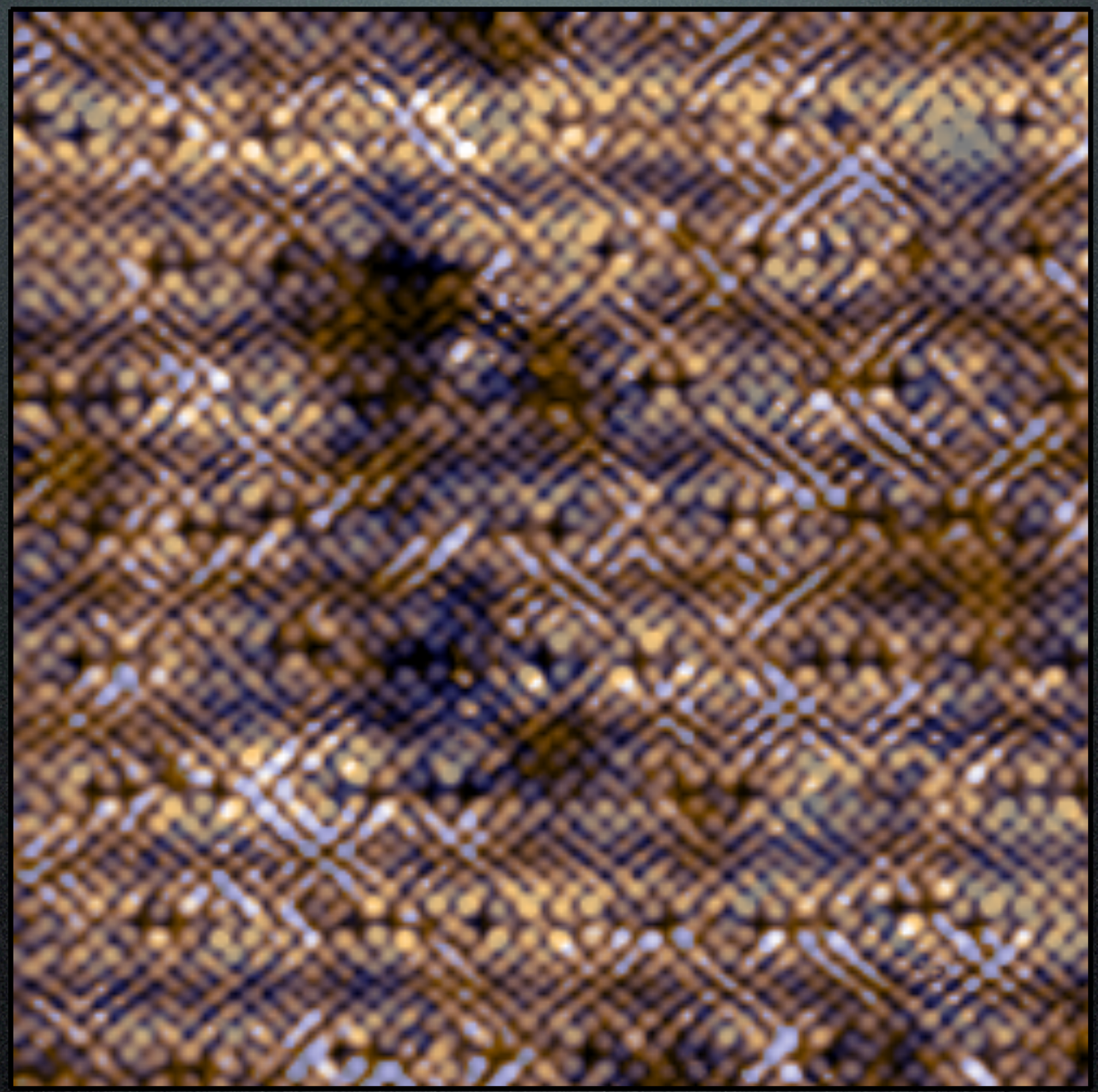
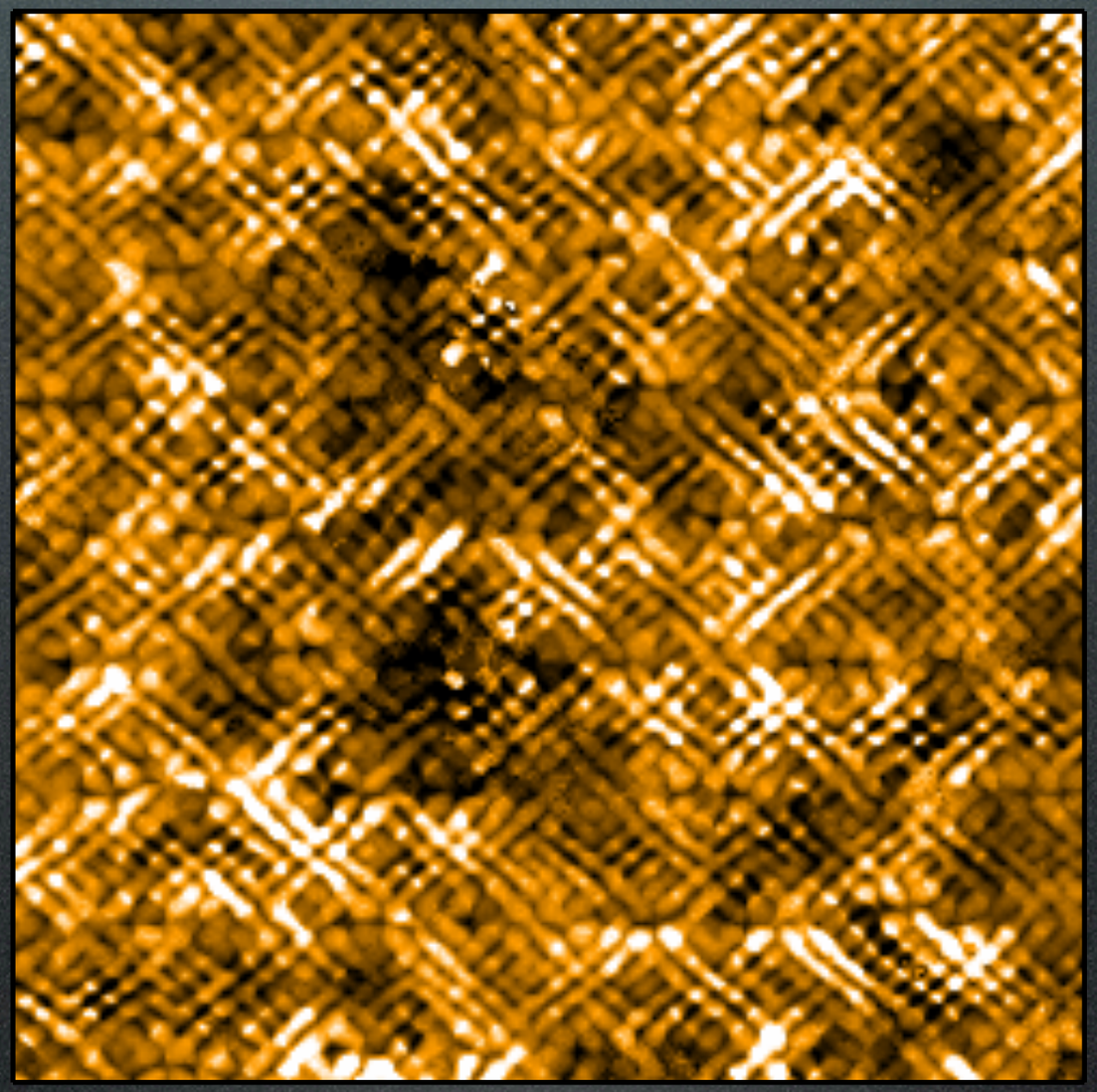
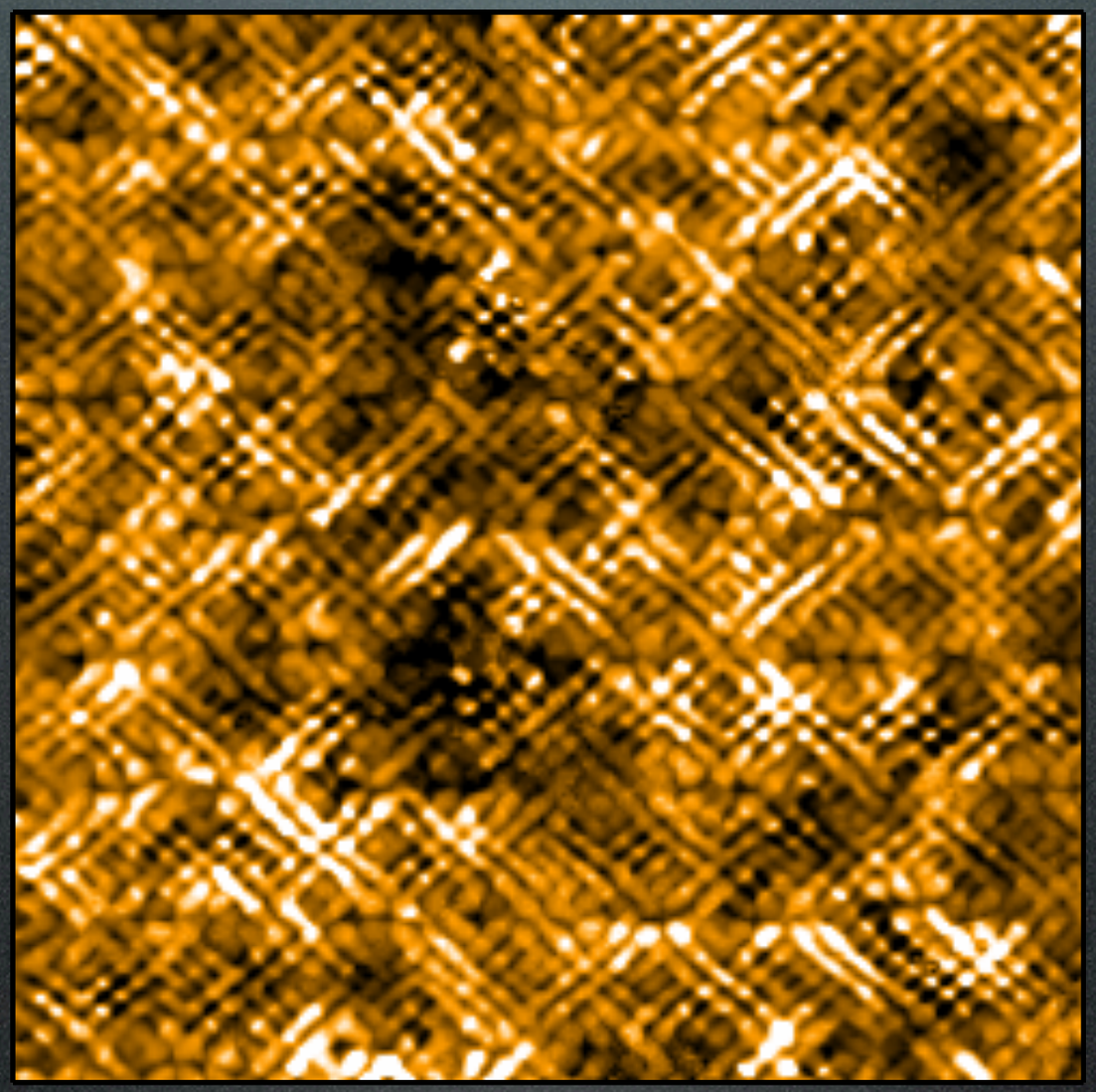


Correct Piezo drift



Undistorts and fixes phase of Bragg peaks

Correct Piezo drift

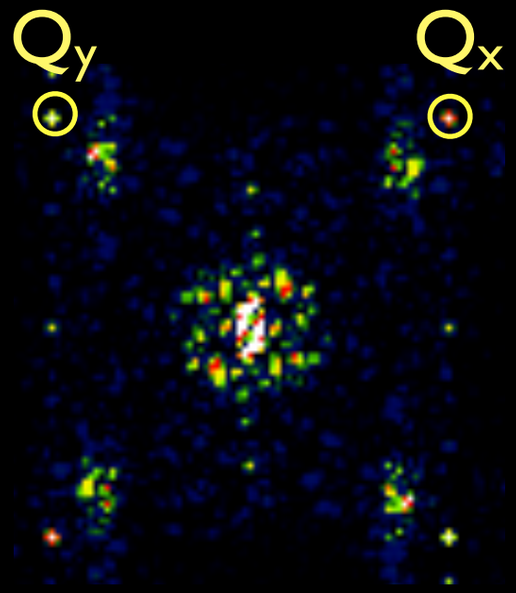


Undistorts and fixes phase of Bragg peaks

BSCCO, got nematic?

Listening to the Bragg peaks

Nematic ordering in UD 45



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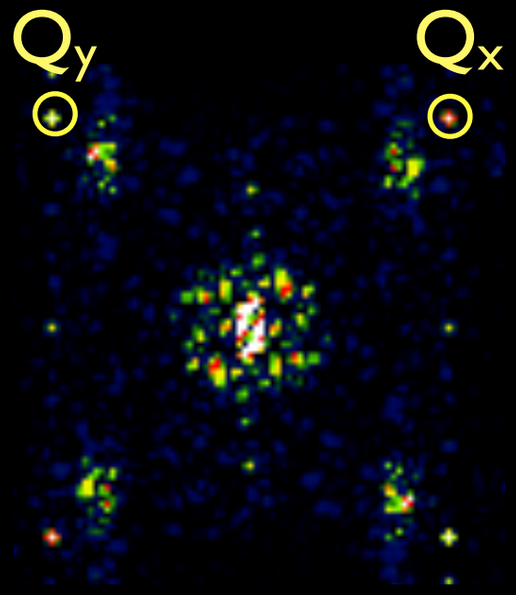
Extracted from published data, T=4K

Kohsaka et al, Nature 454, 1072 (2008)

Nematic ordering in UD 45



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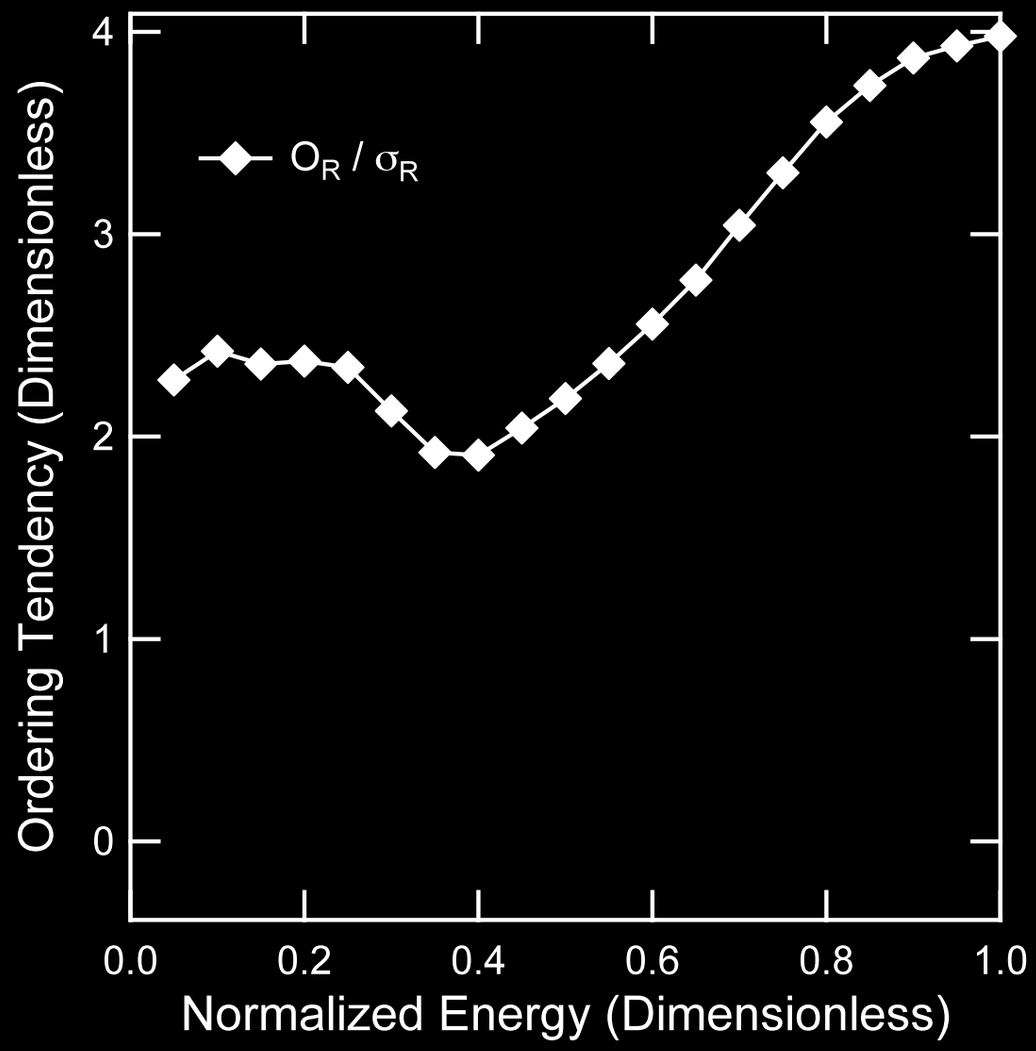

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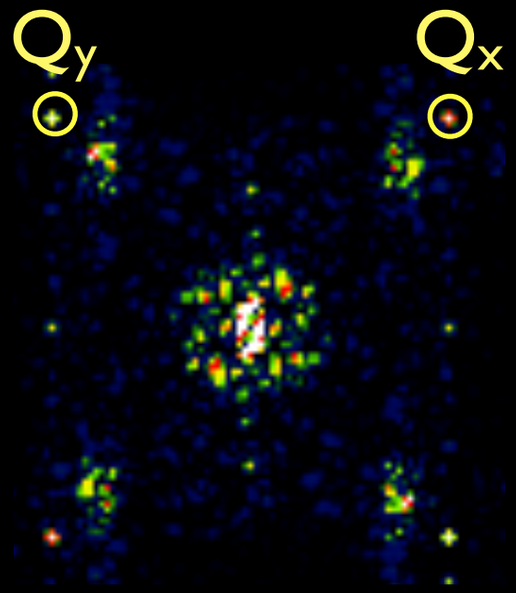

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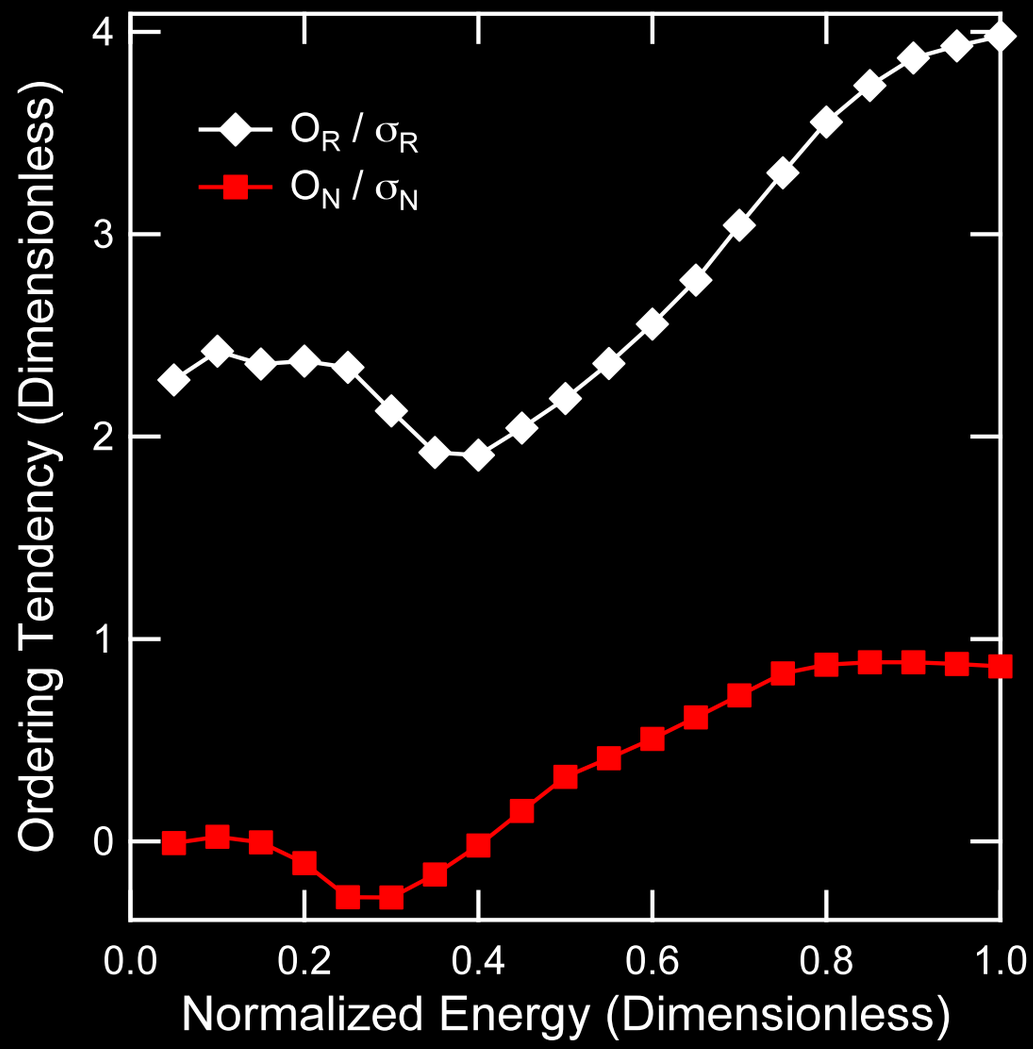

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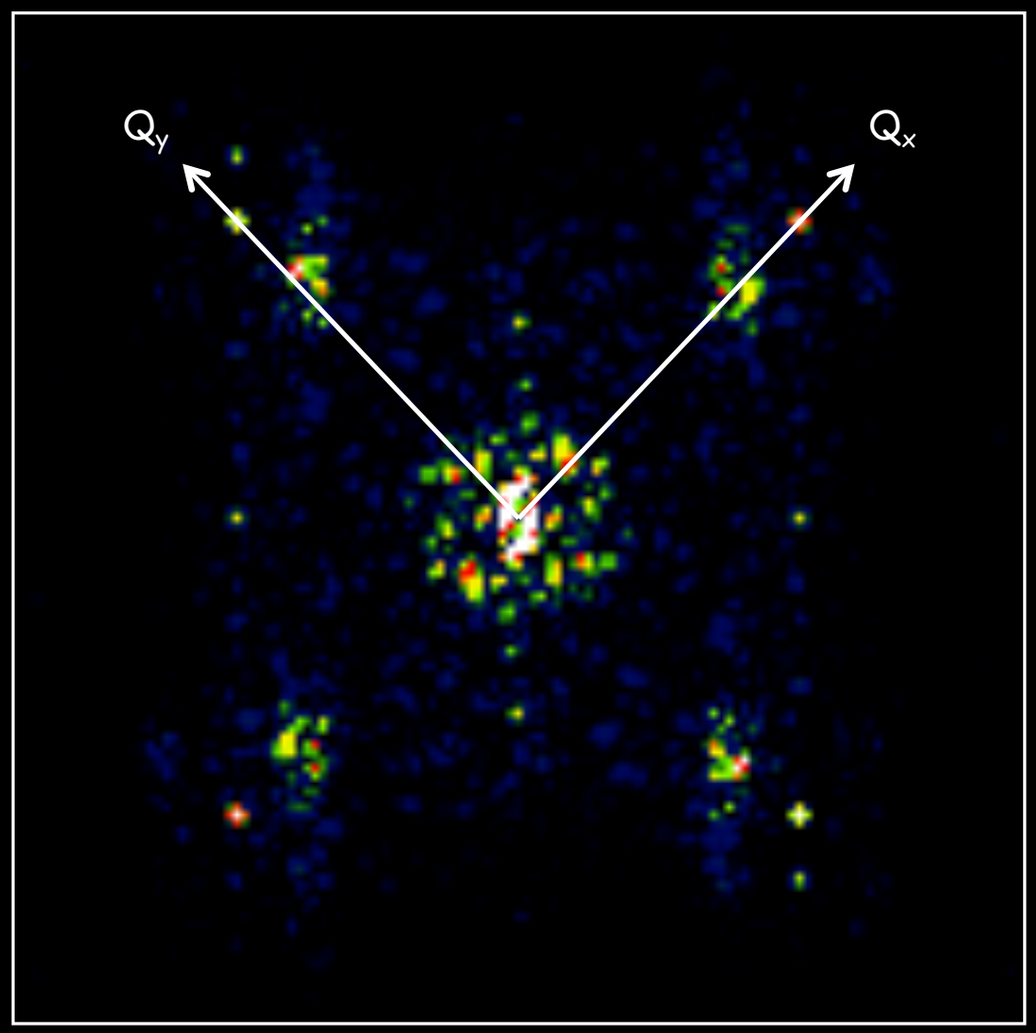
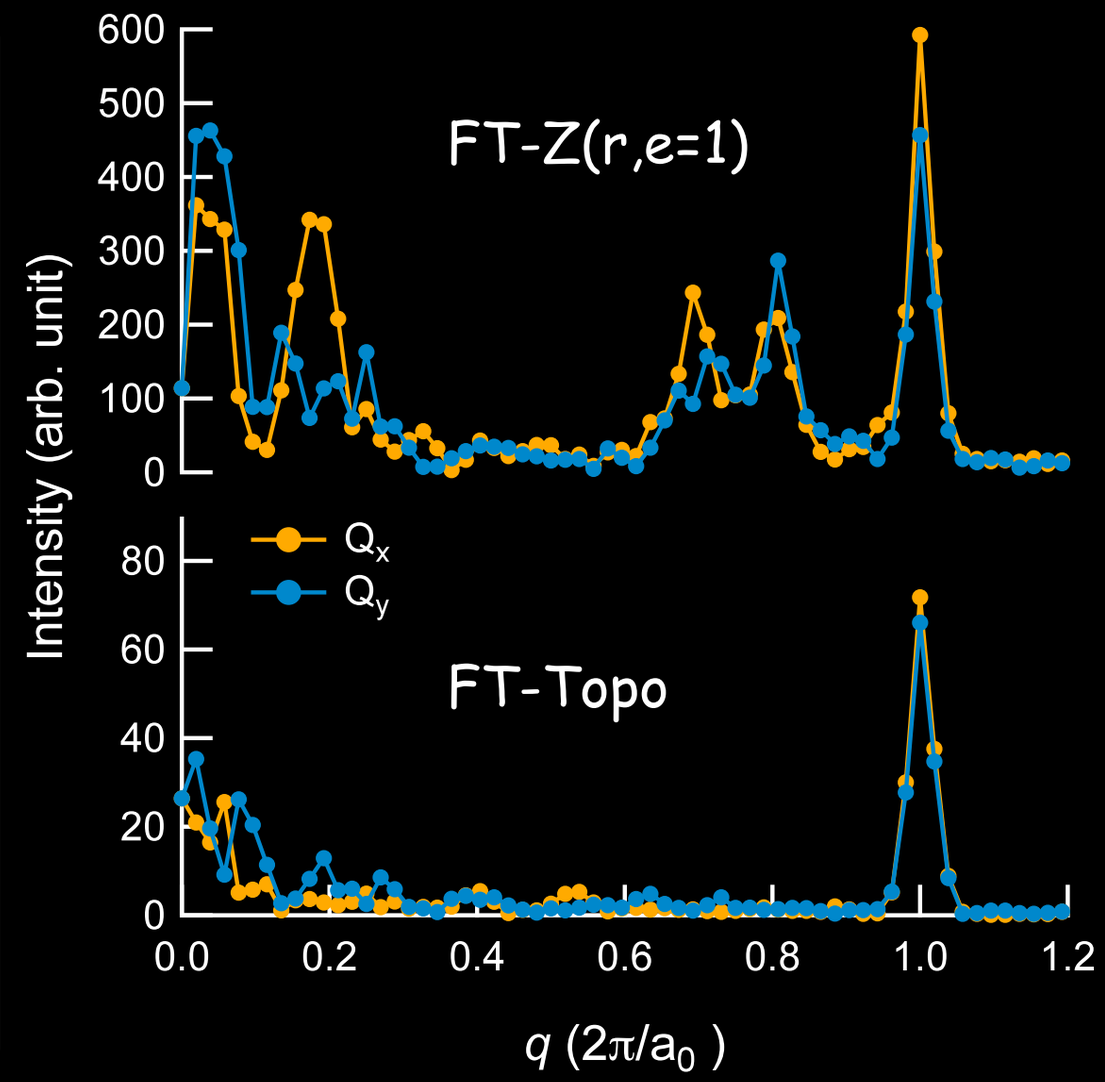
Kohsaka et al, Nature 454, 1072 (2008)

Dy-Bi2212 UD45K

Linecut : FT-Z(r,e=1)

FT-Z(r,e=1)





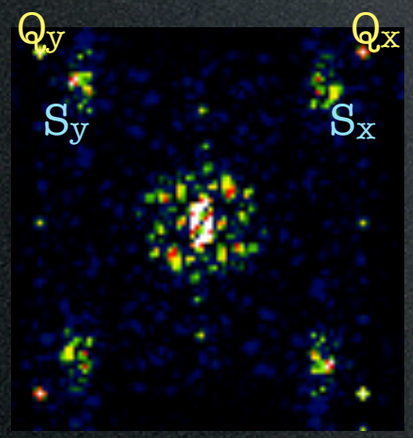
70307

Nematic domains

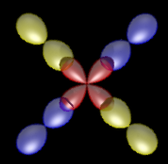
- Shift Q_x, Q_y to origin ("tune to the channel")

$O_N(\mathbf{r},e)$

- Low pass filter (long distance physics)



Purple



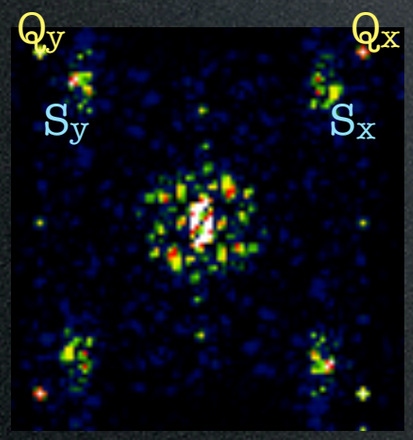
Gold

2nm

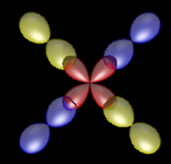
Nematic domains

- Shift Q_x, Q_y to origin ("tune to the channel")
- Low pass filter (long distance physics)

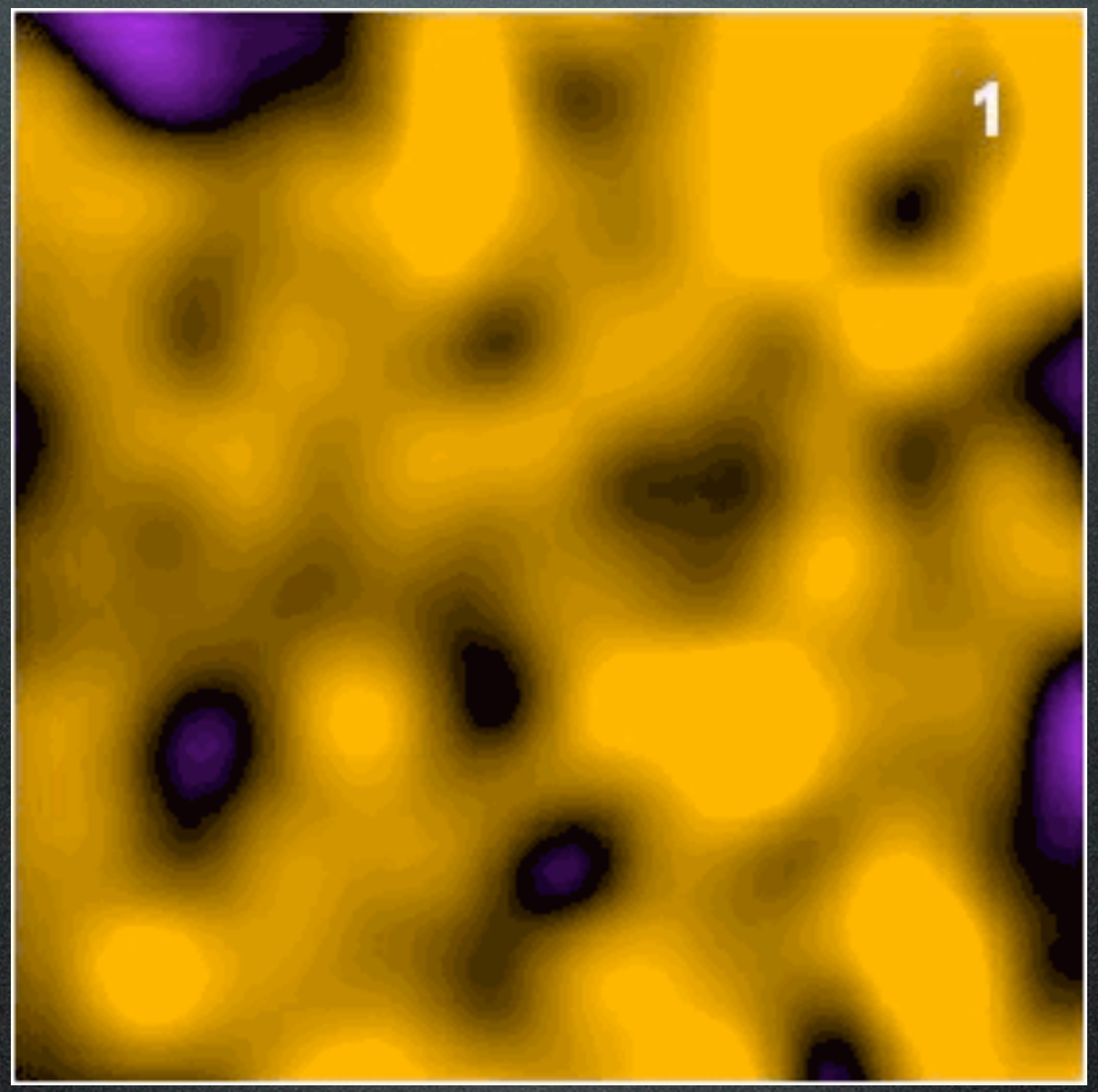
$O_N(\mathbf{r},e)$



Purple



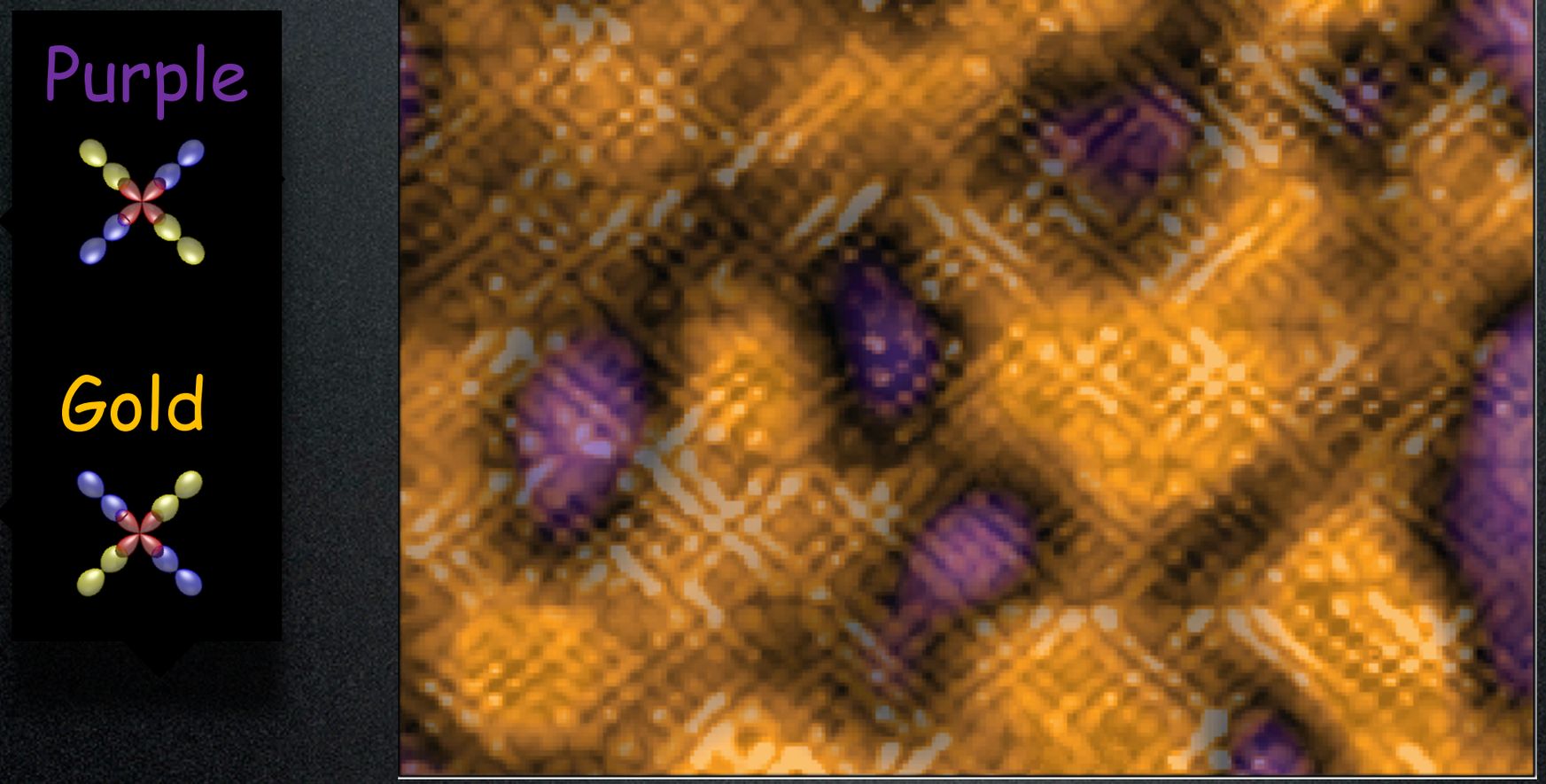
Gold



2nm

Nematic domains

$O_N(\mathbf{r},e=1) + Z(\mathbf{r},e=1)$



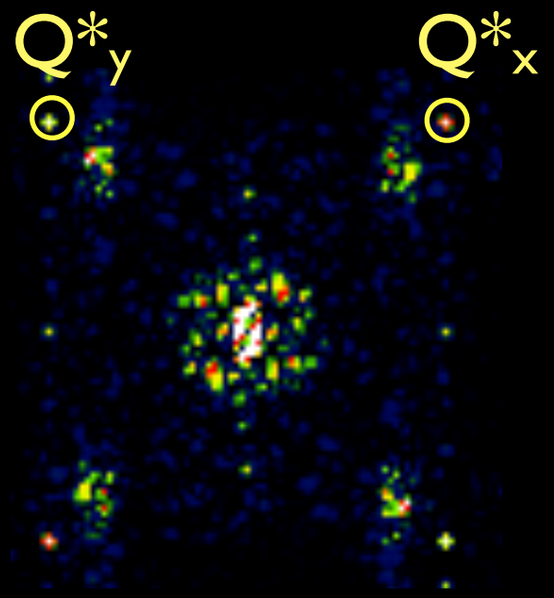
Dy-Bi2212 UD45K

M.J. Lawler et al, 2009

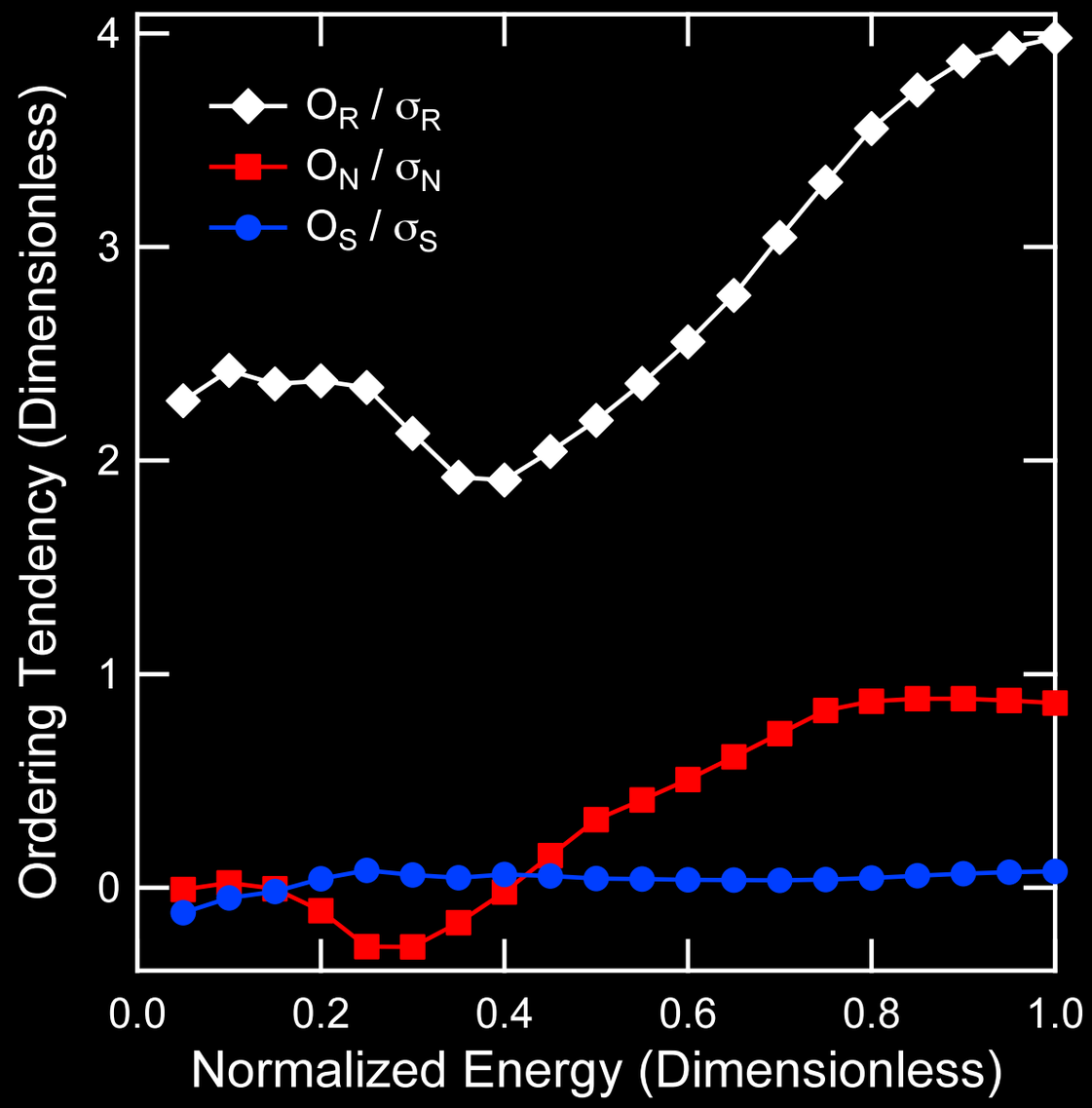
BSCCO, got nematic?

Listening to the Q* peaks

Smectic ordering in UD 45



$$\mathcal{O}_S \equiv \tilde{Z}(\vec{Q}_x^*) - \tilde{Z}(\vec{Q}_y^*) + \tilde{Z}(-\vec{Q}_x^*) - \tilde{Z}(-\vec{Q}_y^*)$$

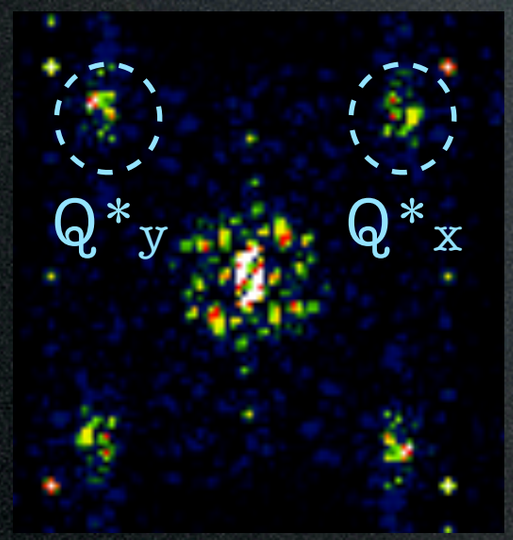


O_S average suppressed through out

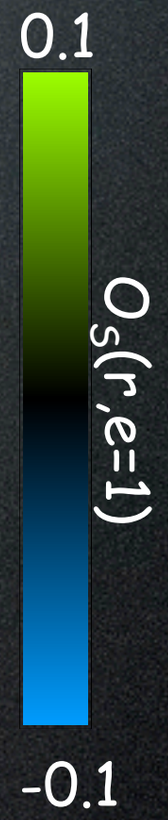
Kohsaka et al, Nature 454, 1072 (2008)

Smectic domains

- Shift Q^*_x, Q^*_y to origin ("tune to the channel")



- Low pass filter (long distance physics)



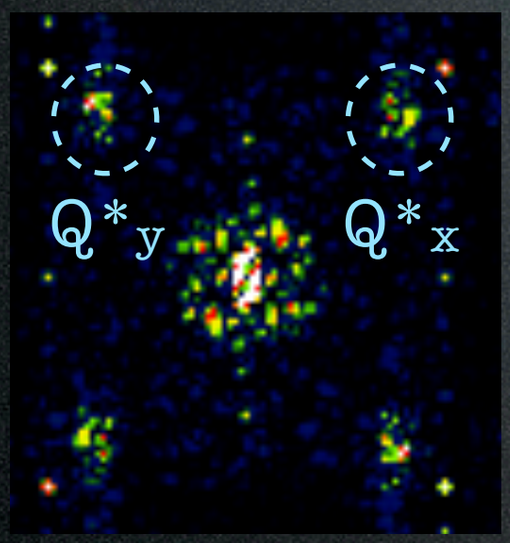
2nm

Severely fluctuating in space through out

Confirm A.Maestro et al, J. Robertson et al (2006)

Smectic domains

- Shift Q^*_x, Q^*_y to origin ("tune to the channel")



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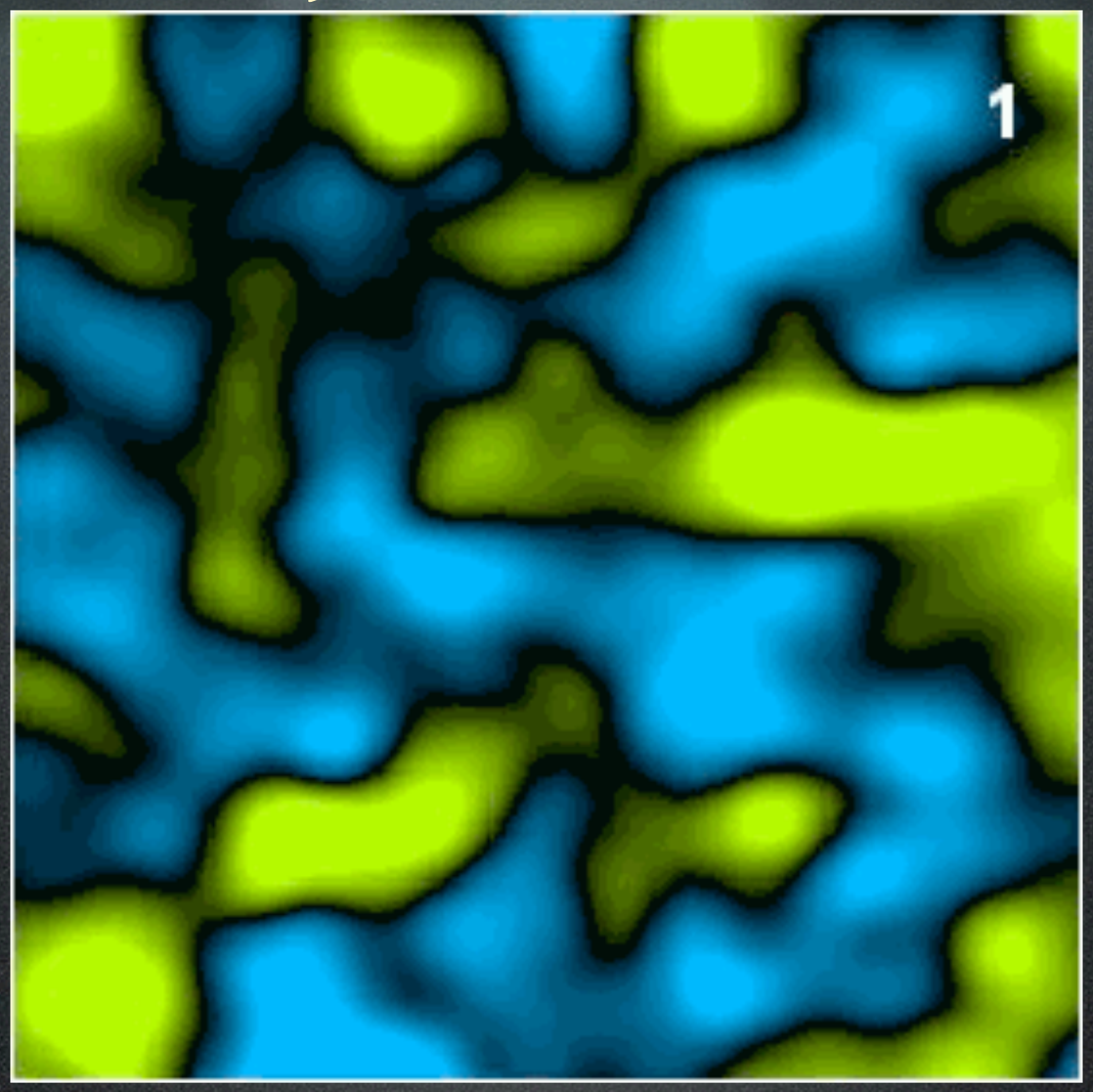

Severely fluctuating in space through out

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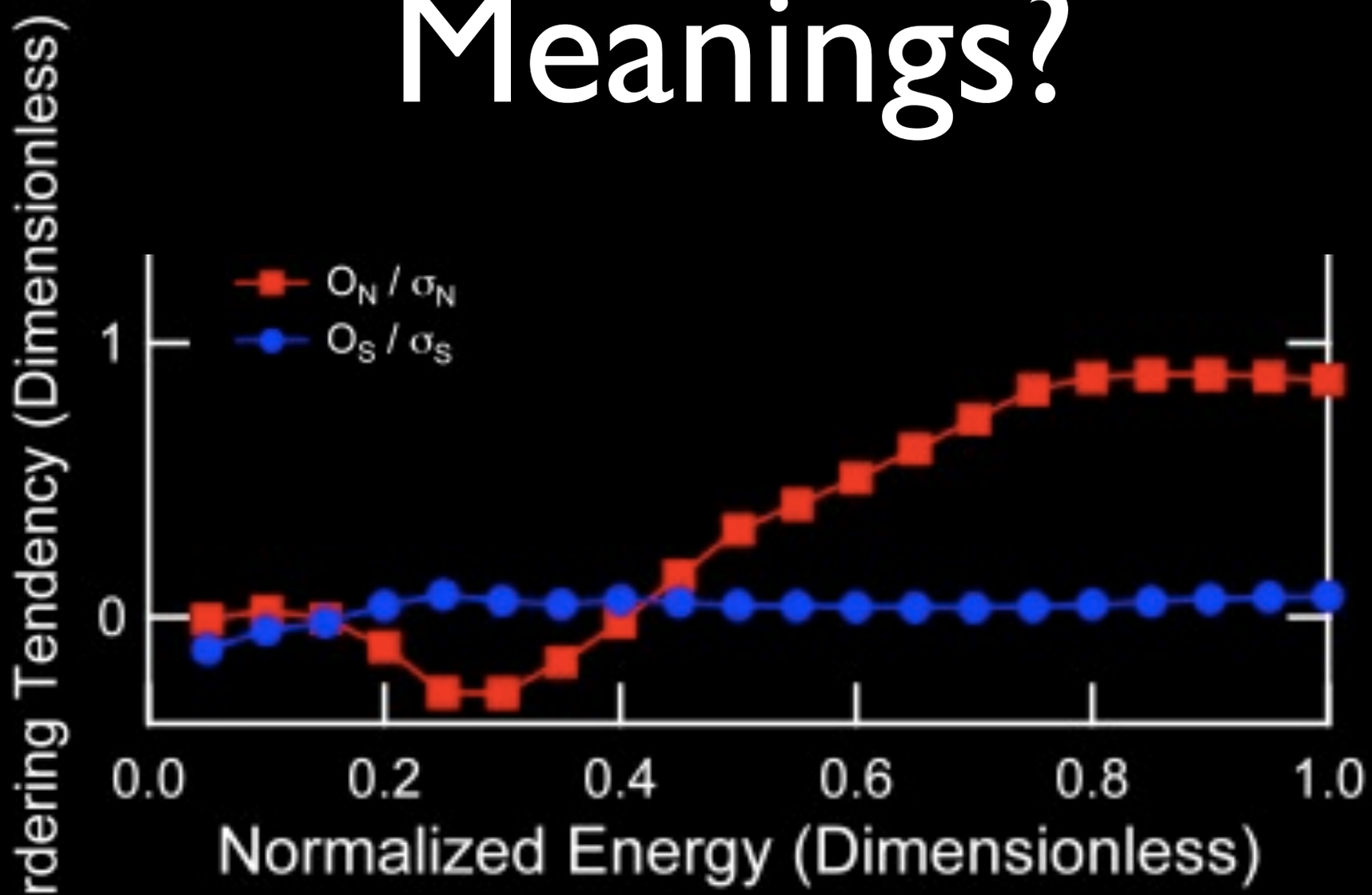
Meanings?


O_N / σ_N
O_S / σ_S
1
0
Ordering Tendency (Dimensionless)
0.0
0.2
0.4
0.6
0.8
1.0
Normalized Energy (Dimensionless)

Hypothesis: longer ranged orientational ordering ?

Hypothesis: longer ranged orientational ordering ?

Example:

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Weak Pinning and Hexatic Order in a Doped Two-Dimensional Charge-Density-Wave System

Hongjie Dai, Huifen Chen, and Charles M. Lieber
Departments of Chemistry and Applied Physics, Columbia University, New York, New York 10027
(Received 11 July 1990; revised manuscript received 25 February 1991)

Scanning-tunneling microscopy has been used to characterize the effects of Nb impurities on the incommensurate charge-density-wave (CDW) phase in 1*T*-TaS_2. Real- and reciprocal-space data indicate that disorder in the CDW is due to dislocations and small random rotations of the CDW. The dislocations destroy translational order; however, calculations show that the orientational order is long range.

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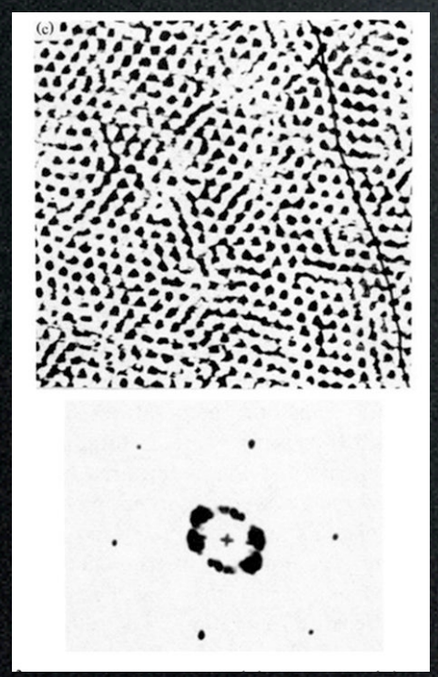

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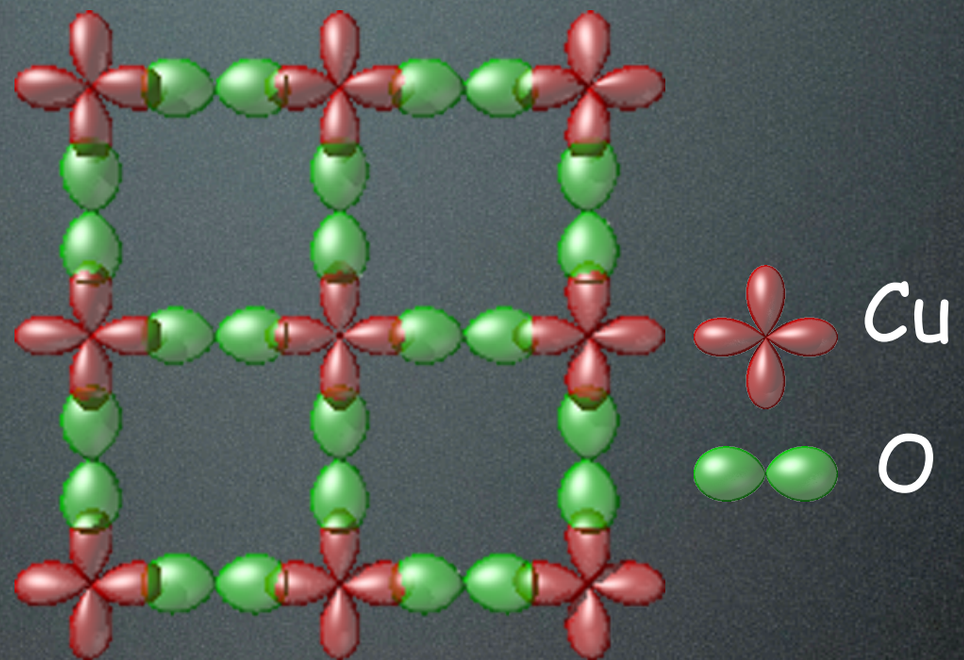
in the Nb-doped samples. These small rotations are readily observed by viewing the images at a glancing angle along the indicated lines. Analyses of atomic-

Microscopic Model

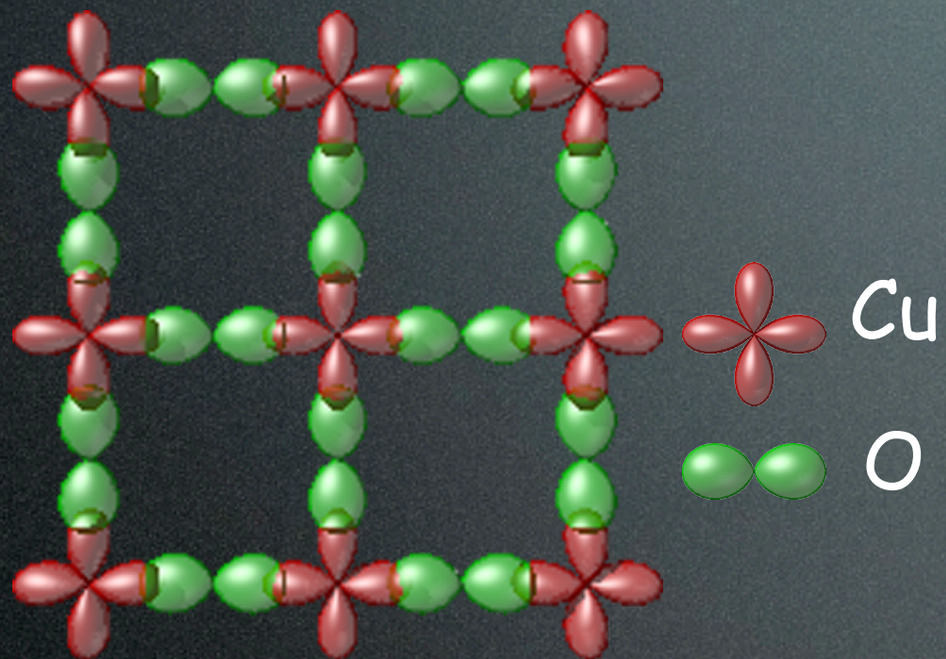


CuO_2 plane

Extended
Hubbard Model

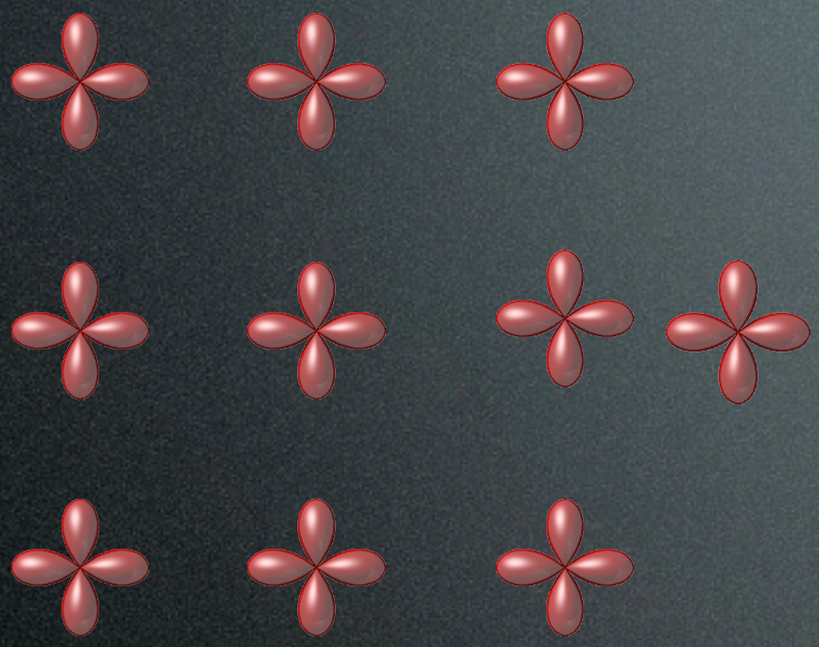
V. Emery, PRL 58, 2974 (1987)
C. Varma et al, PRL 58, 2974 (1987)

Microscopic Model



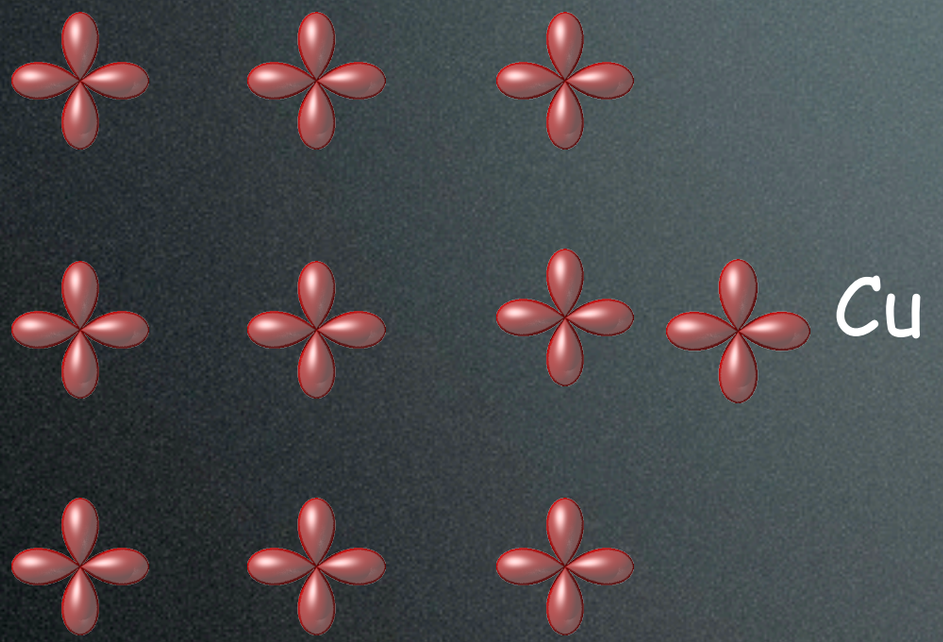
CuO_2 plane

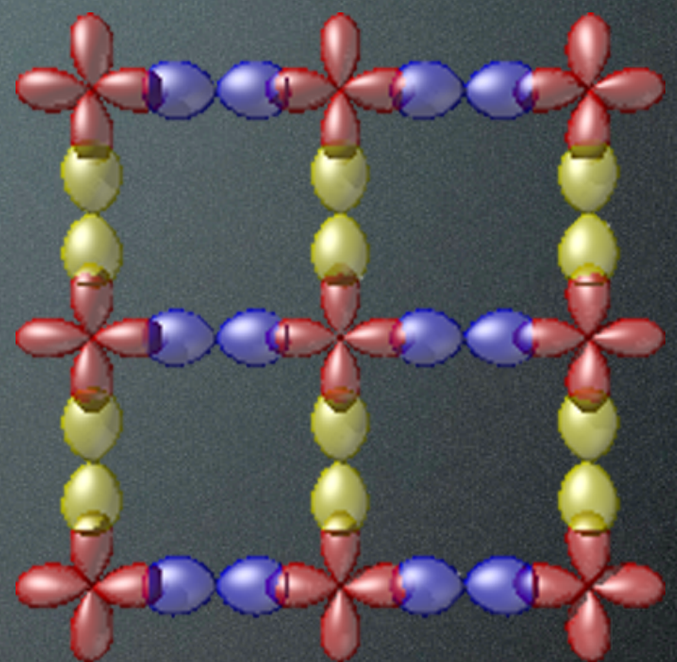
Microscopic Model

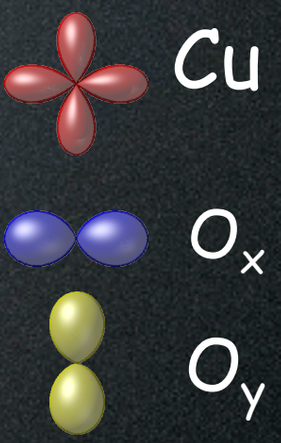


One-band Model
Hubbard or t-J

Microscopic Model





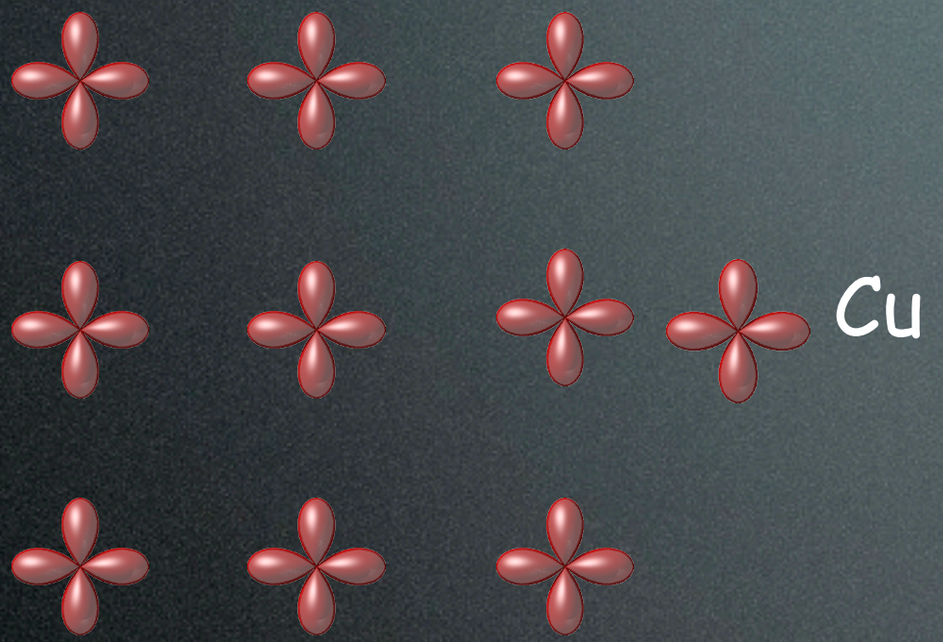


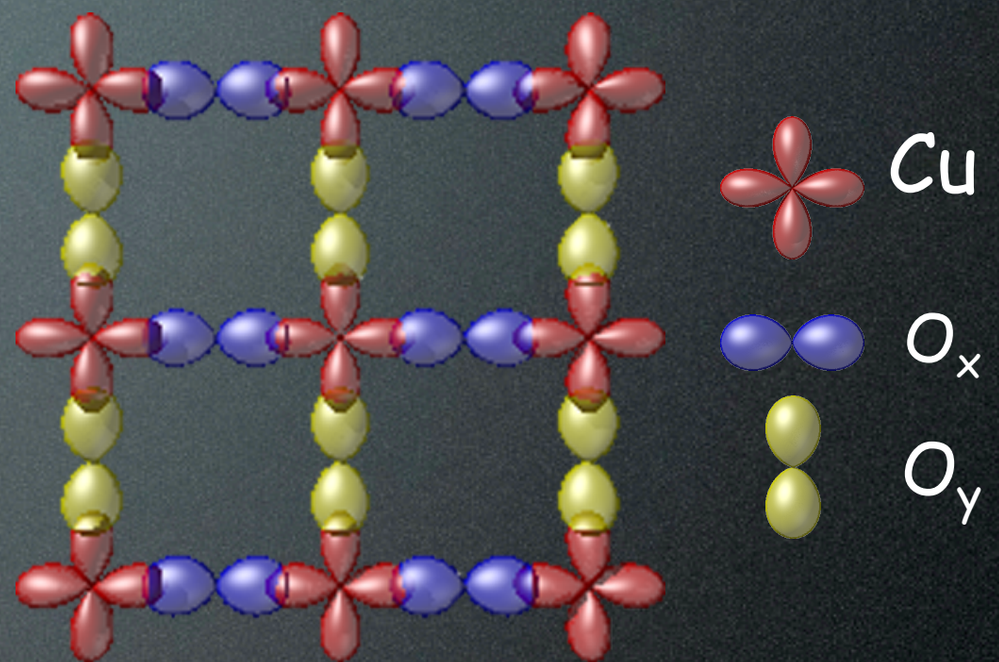
Intra unitcell Nematic in Pseudogap phase

M.J. Lawler et al, 2009

One-band Model
Hubbard or t-J

Microscopic Model





Intra unitcell Nematic in Pseudogap phase

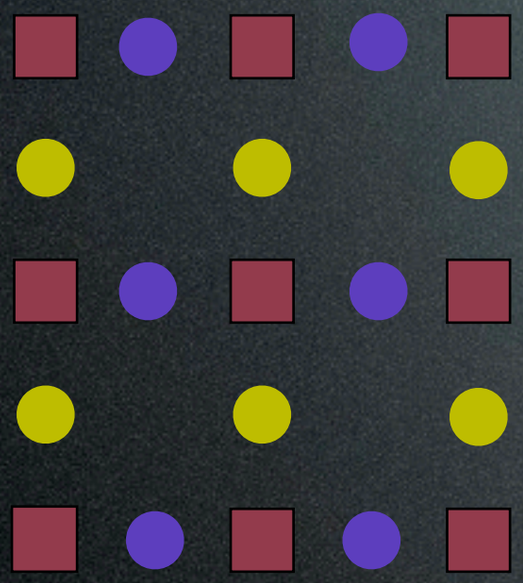
M.J. Lawler et al, 2009

One-band Model
Hubbard or t-J

Extended
Hubbard Model

Kivelson, Fradkin, Geballe, PRB 69, 144505 (2004)

Other competing orders?

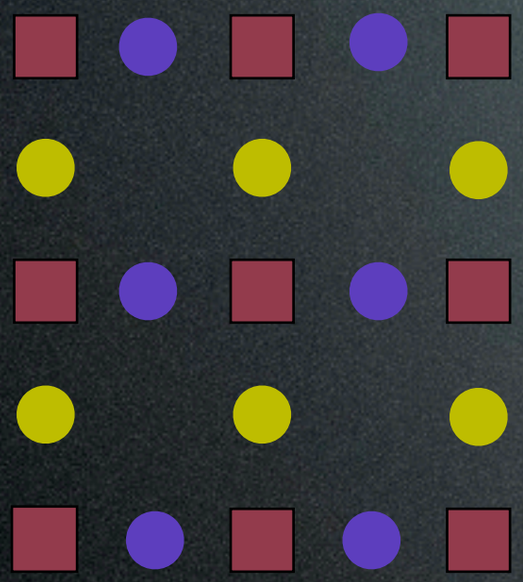


- Congruent with

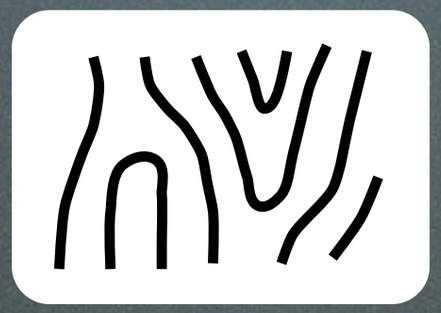
Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al,
2009

Other competing orders?



- Congruent with

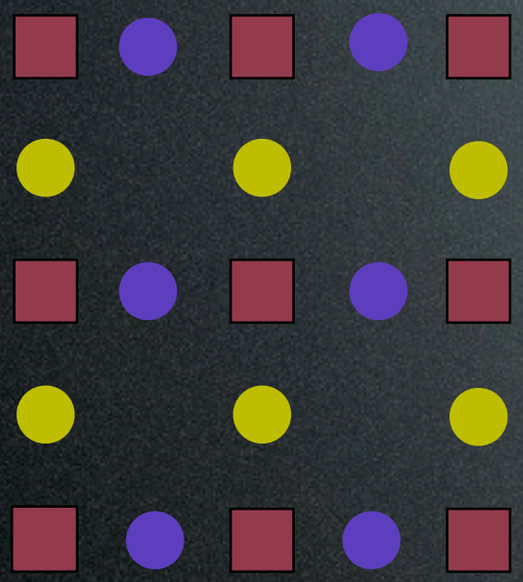


Charge nematic

Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al,
2009

Other competing orders?



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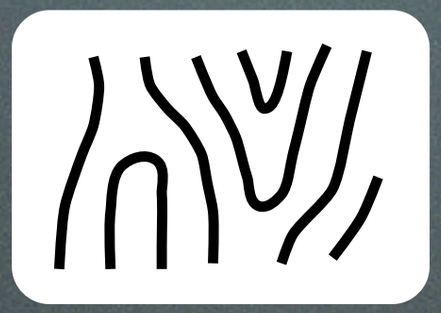
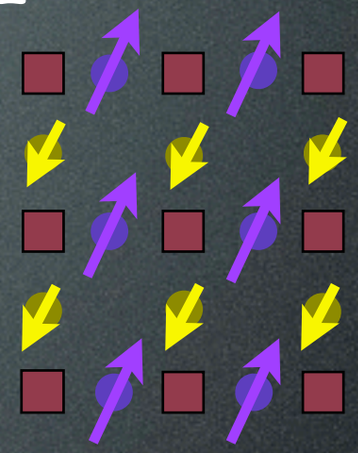


Charge nematic



Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al,
2009

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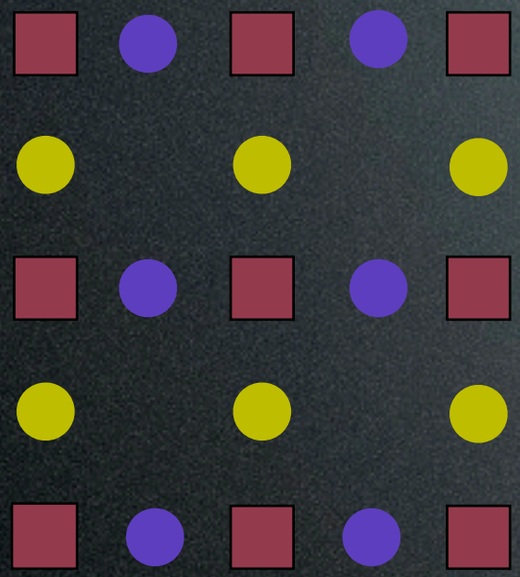

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M.J. Lawler et al,
2009

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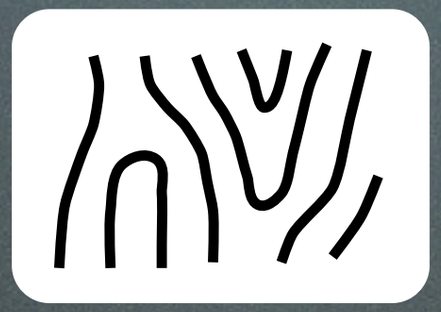
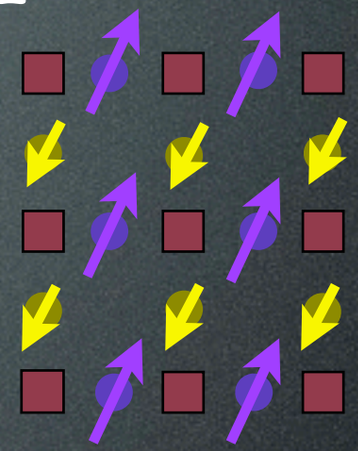
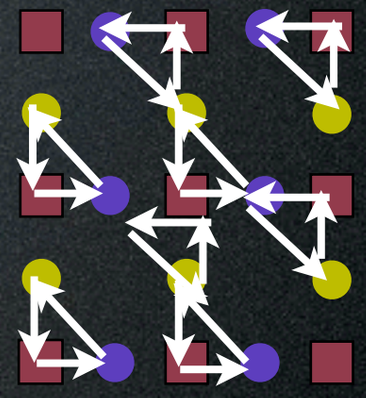


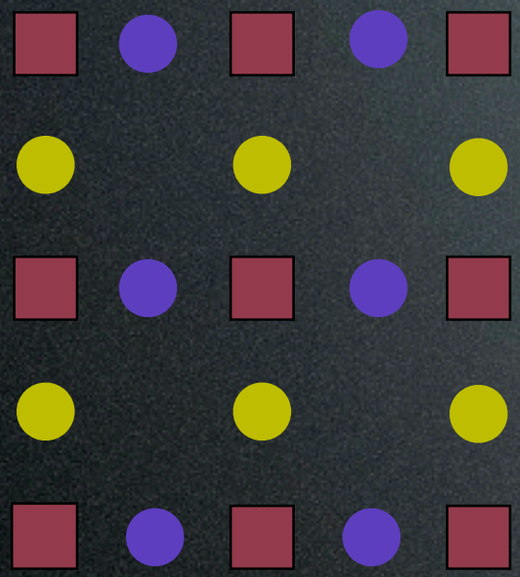
Charge nematic





translation preserving
magnetism

Other competing orders?



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M.J. Lawler et al, 2009

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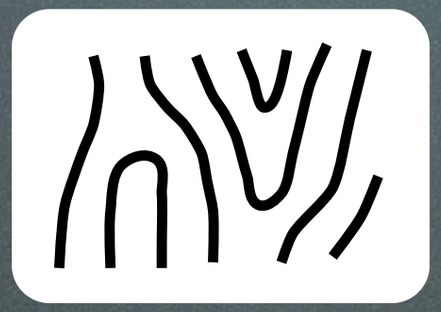
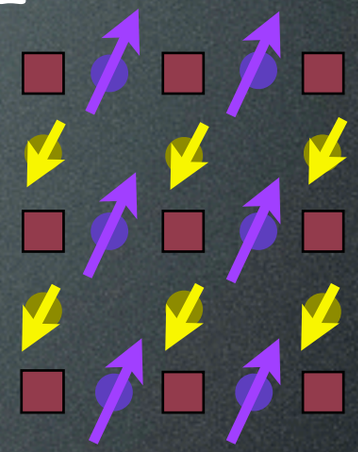
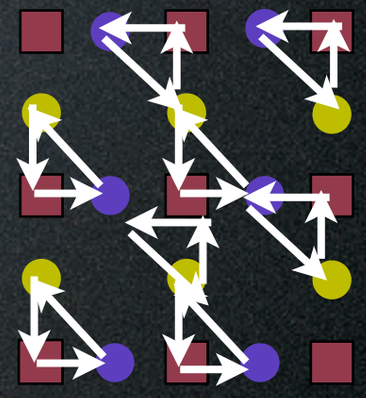


Charge nematic

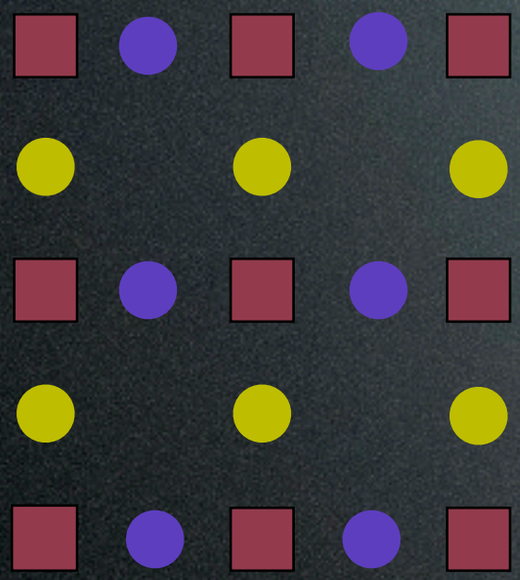




translation preserving magnetism

- Relation unclear yet

Other competing orders?



Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al,
2009

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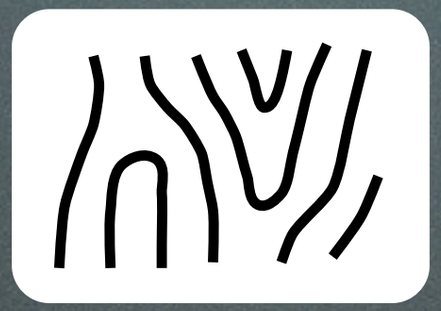

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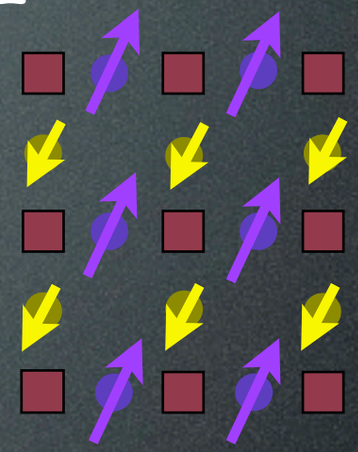
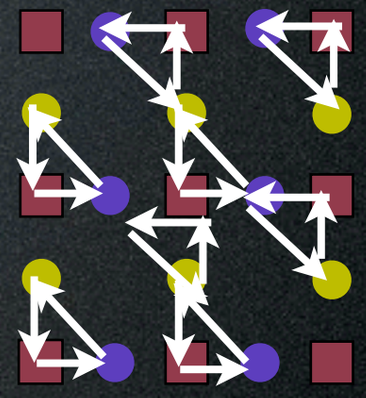
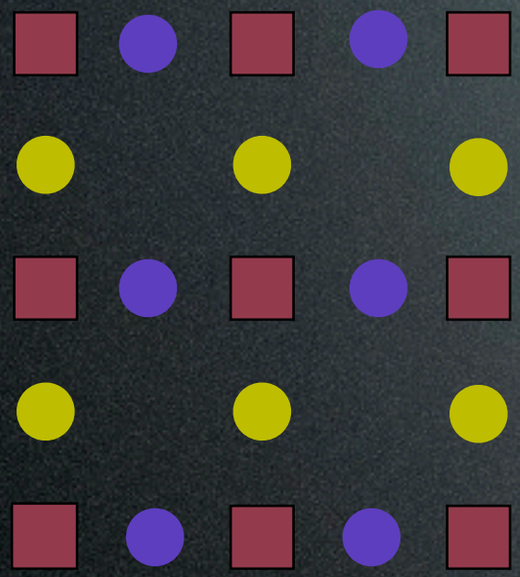




translation preserving
magnetism

- Relation unclear yet
  : various $\hat{T}_a, \hat{T}_b$ breaking orders

Other competing orders?



Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al,
2009

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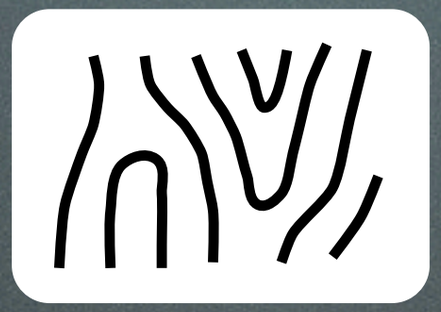

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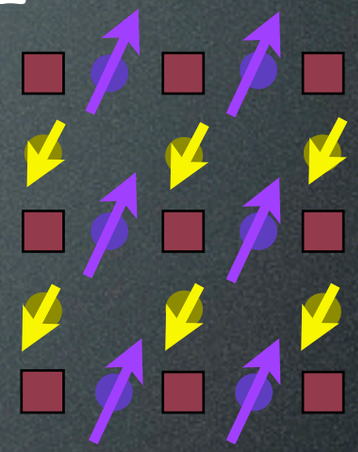

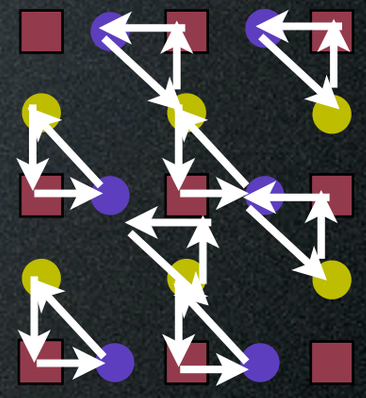

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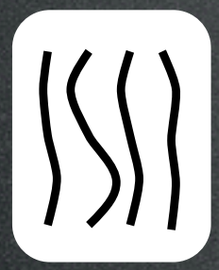
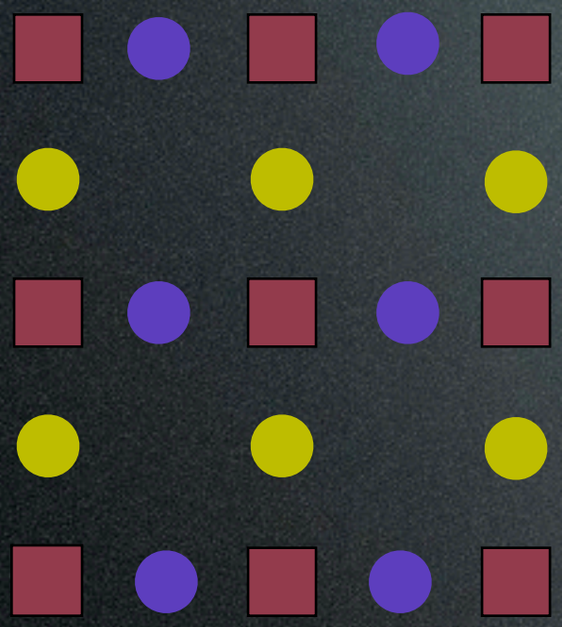


spin/charge
smectic

Flux phase,
DDW,
valence bond solid,
...

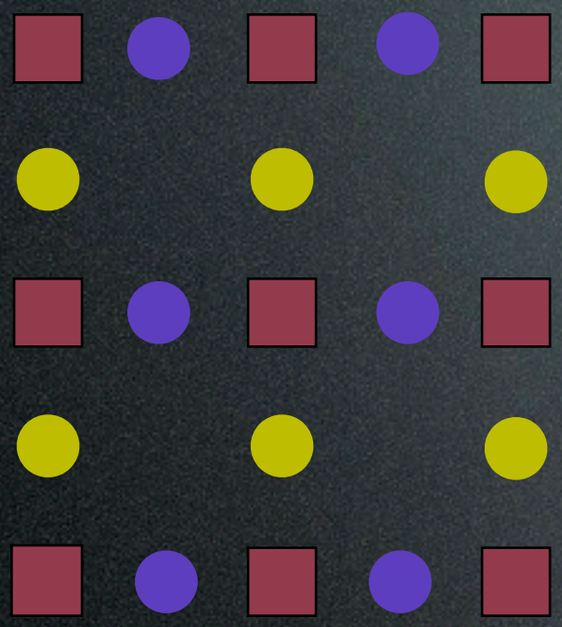
Other systems?



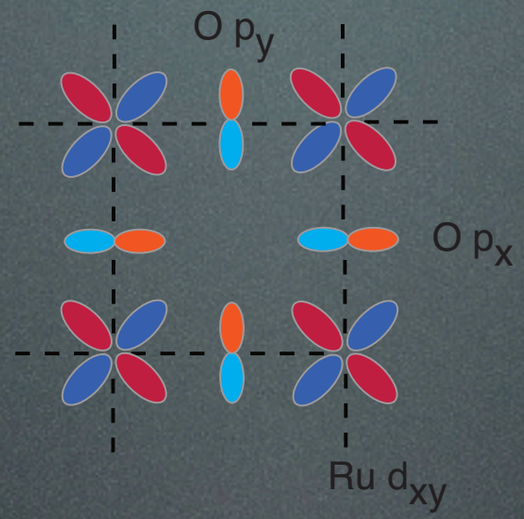
Intra unitcell Nematic
in Pseudogap phase

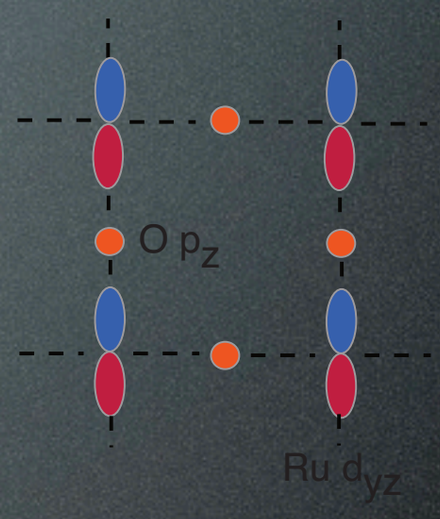
M.J. Lawler et al, 2009

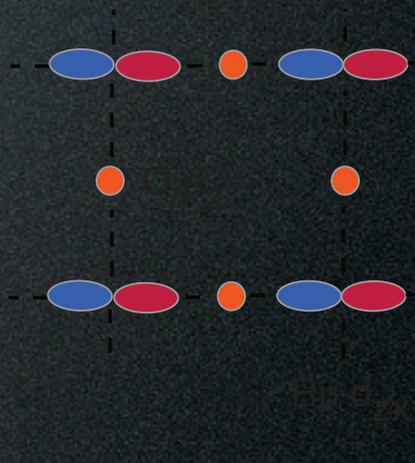
Other systems?



Ruthenates



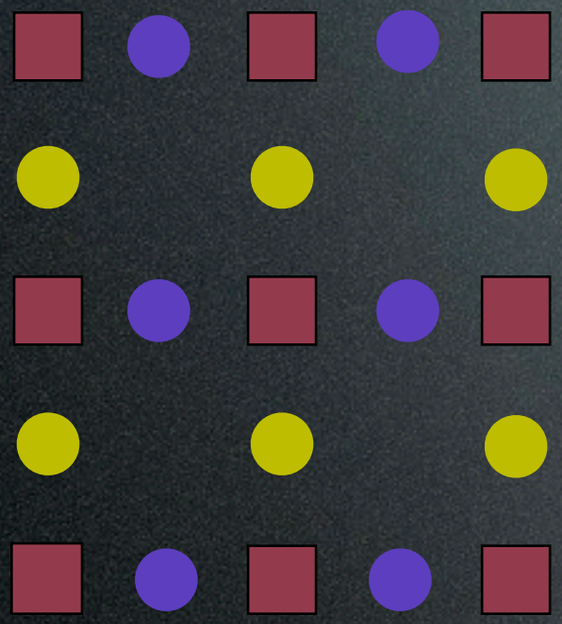




Intra unitcell Nematic
in Pseudogap phase

M.J. Lawler et al, 2009

Other systems?



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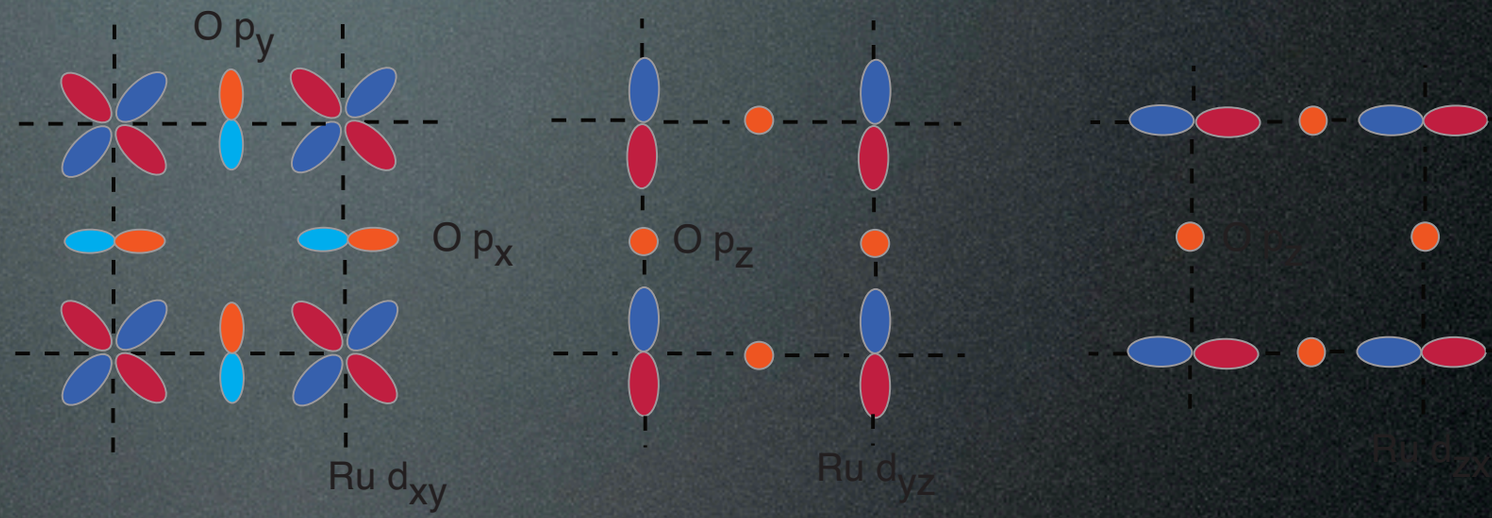

Intra unitcell Nematic
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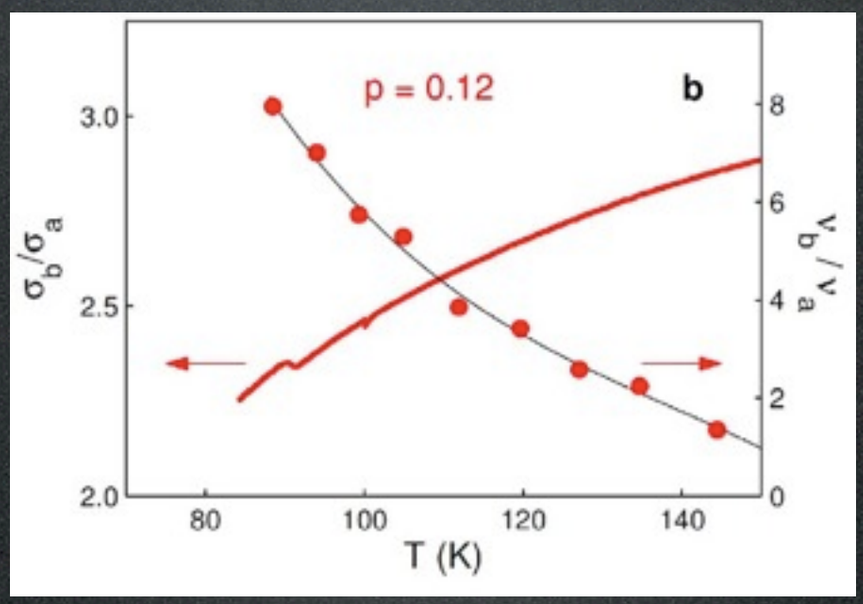
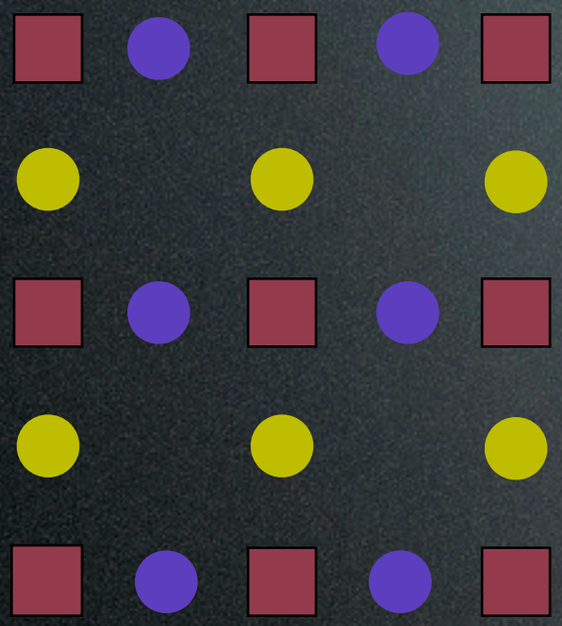
M.J. Lawler et al, 2009

YBCO

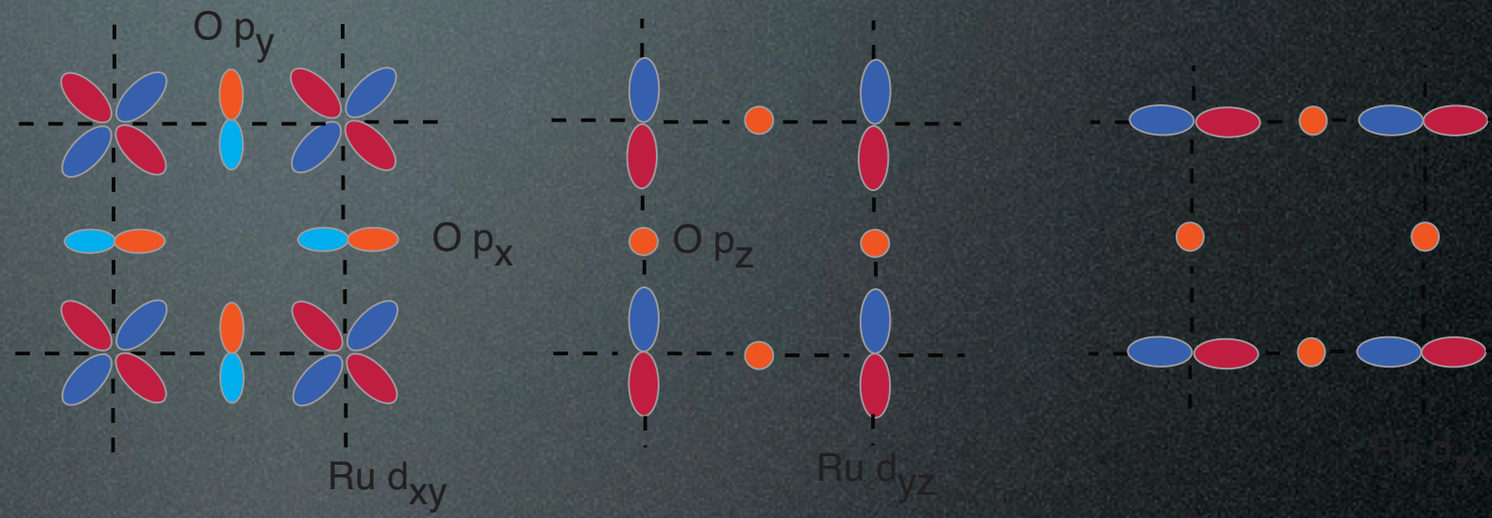


(R.Daou et al)

Other systems?



Ruthenates



Intra unitcell Nematic
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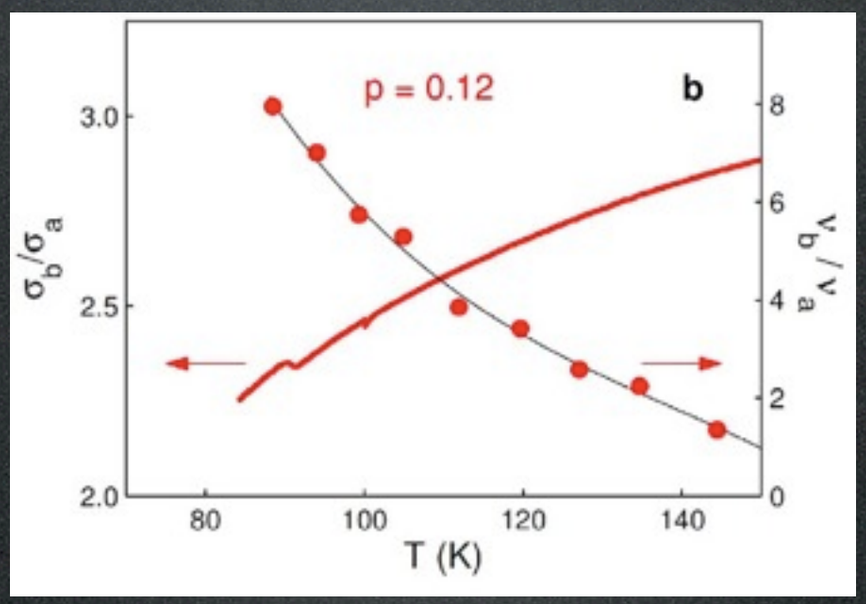
M.J. Lawler et al, 2009

YBCO



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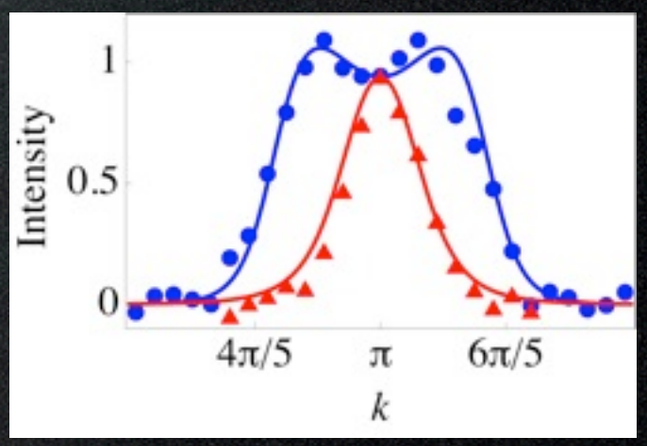
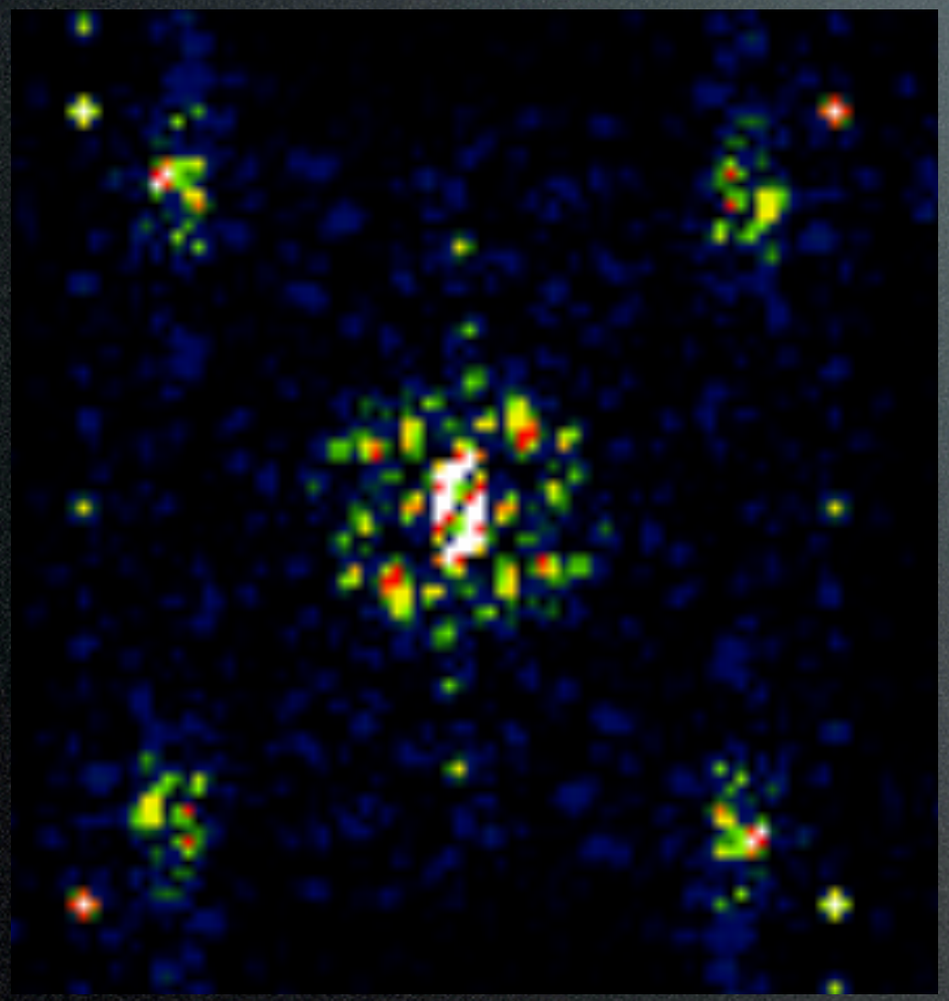


Hinkov et al
+ K. Sun et al

Other probes?

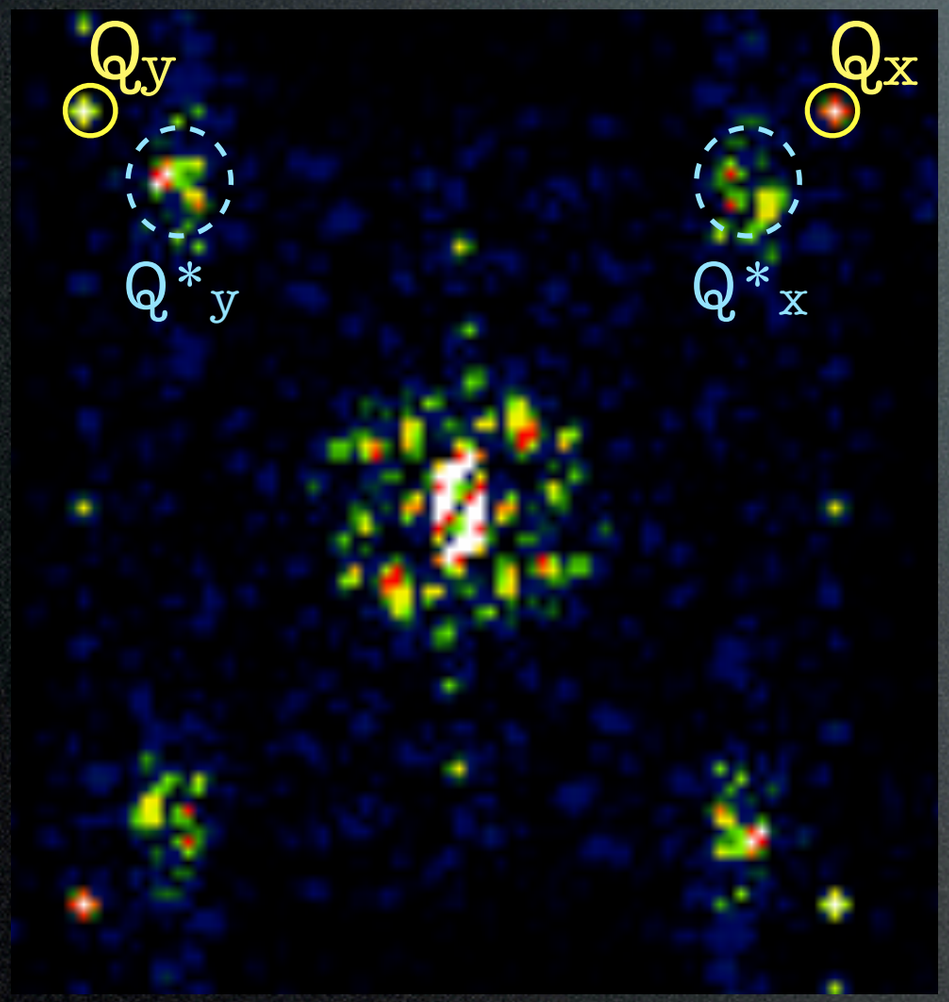
Other probes?

Fourier space



Other probes?

Fourier space

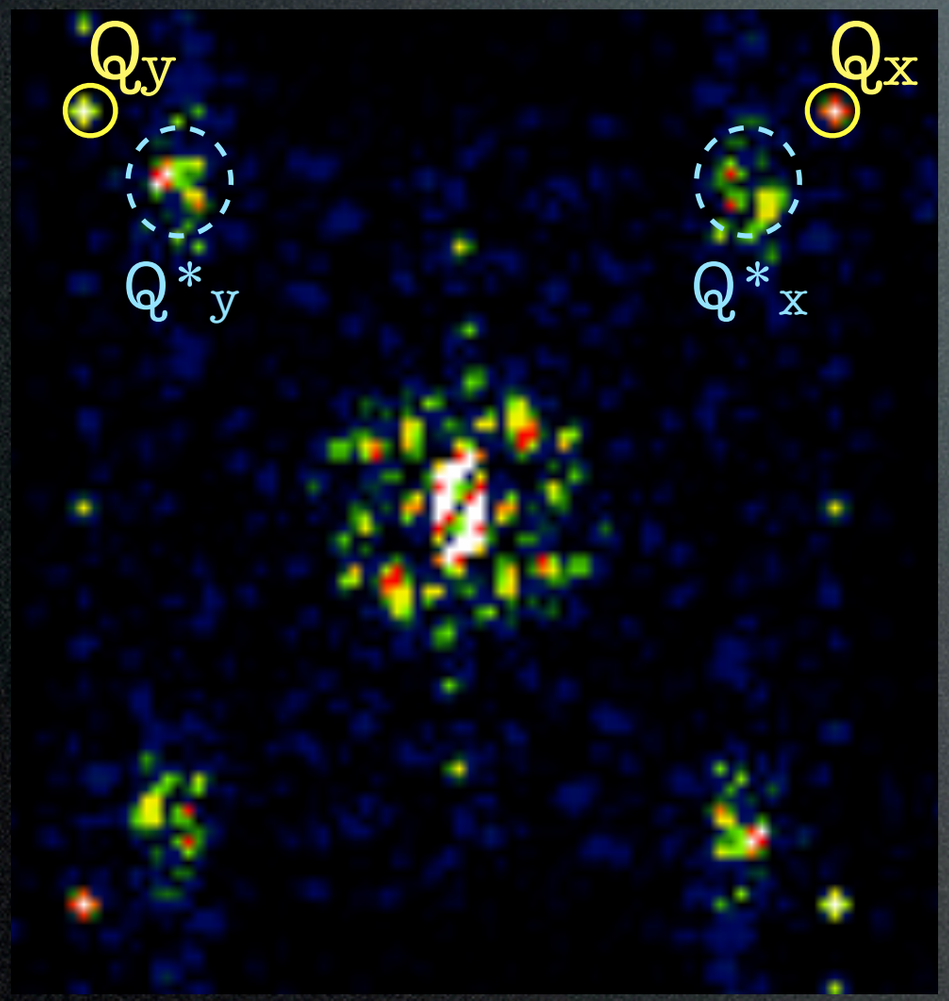


Q_x vs Q_y?

Q^*_x vs Q^*_y?

Other probes?

Fourier space



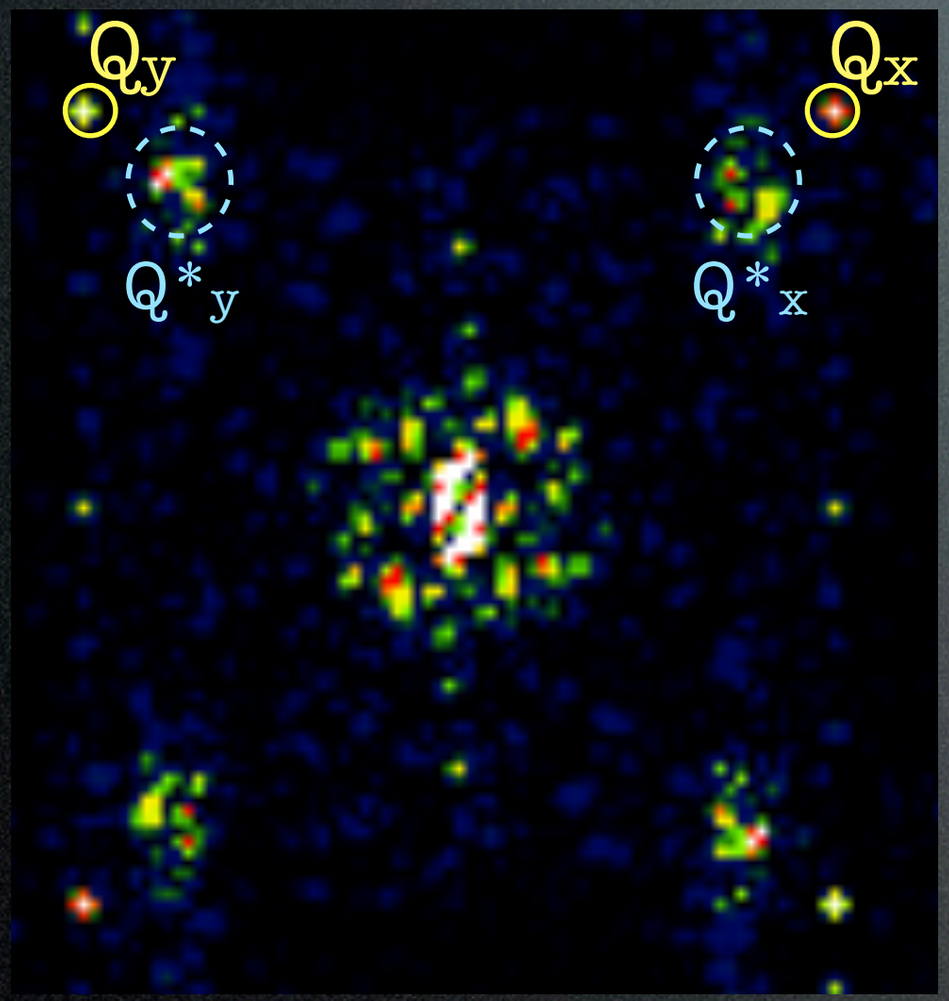
- Diffuse scattering in bulk probe

Q_x vs Q_y?

Q^*_x vs Q^*_y?

Other probes?

Fourier space

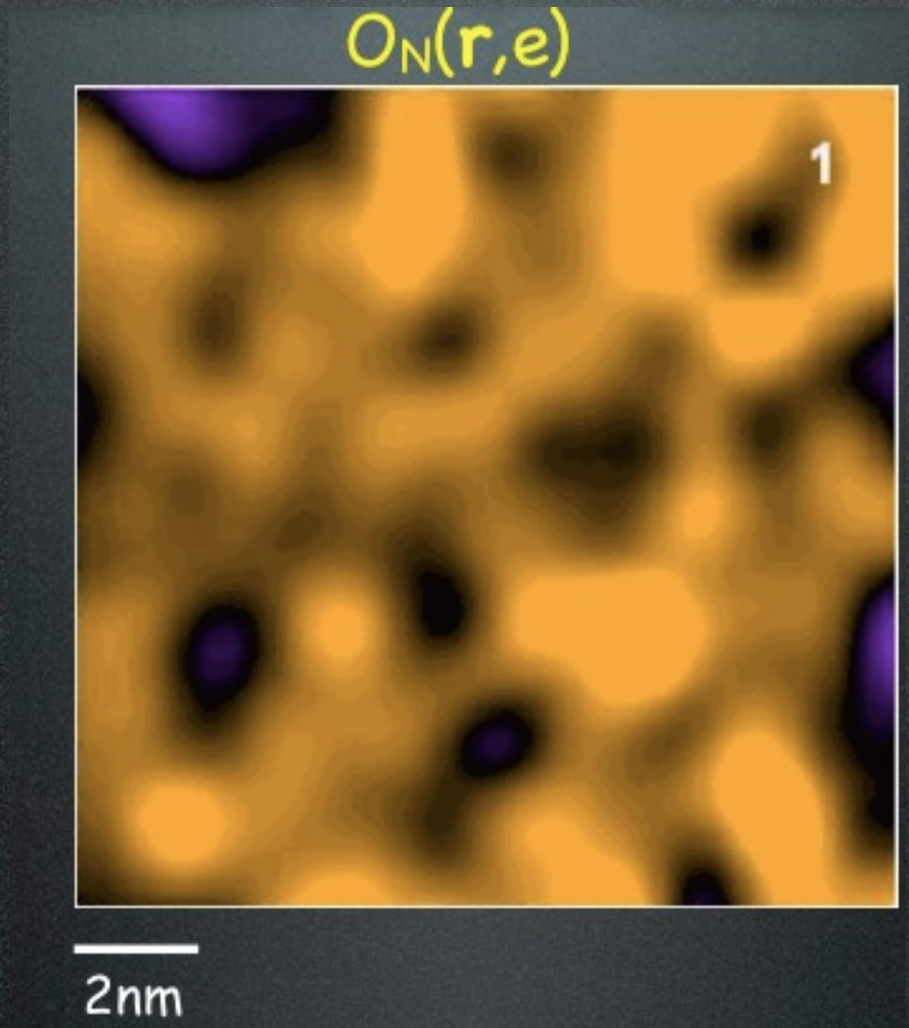


Q_x vs Q_y?

Q^*_x vs Q^*_y?

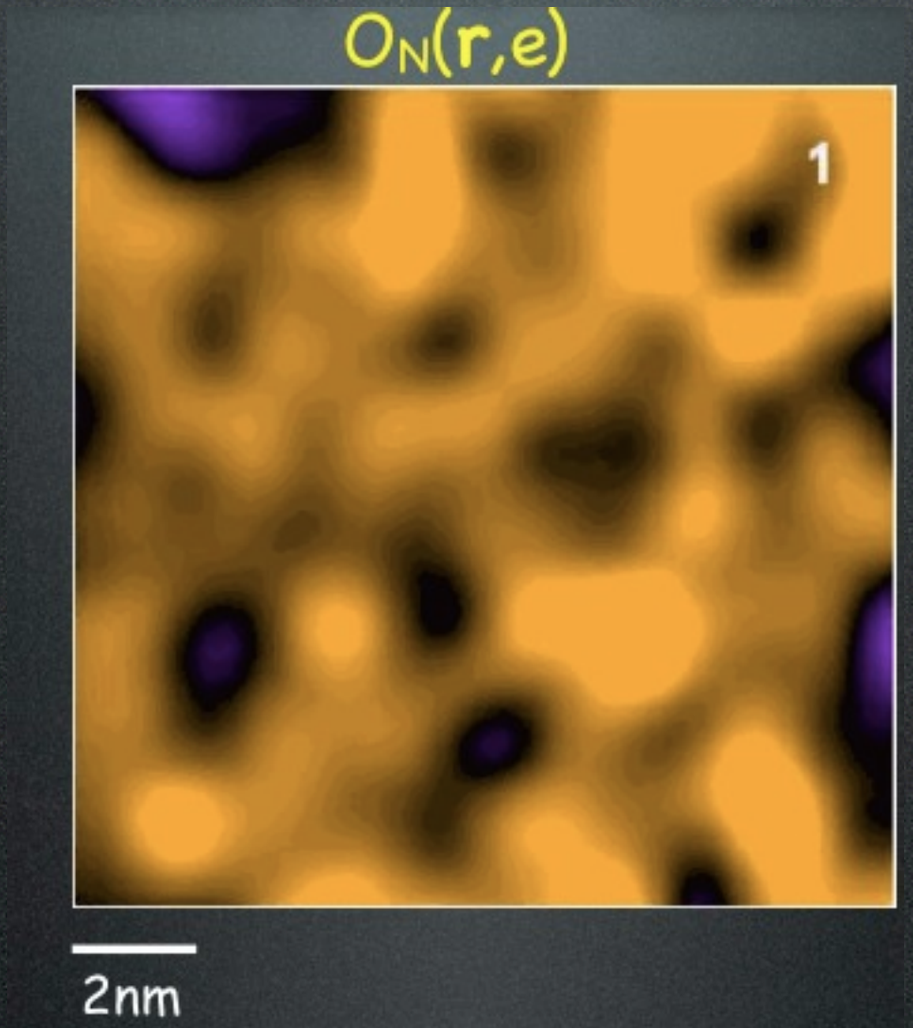
- Diffuse scattering in bulk probe
- Other local probes? Go after oxygens?

Intra unitcell nematic in the pseudogap states?

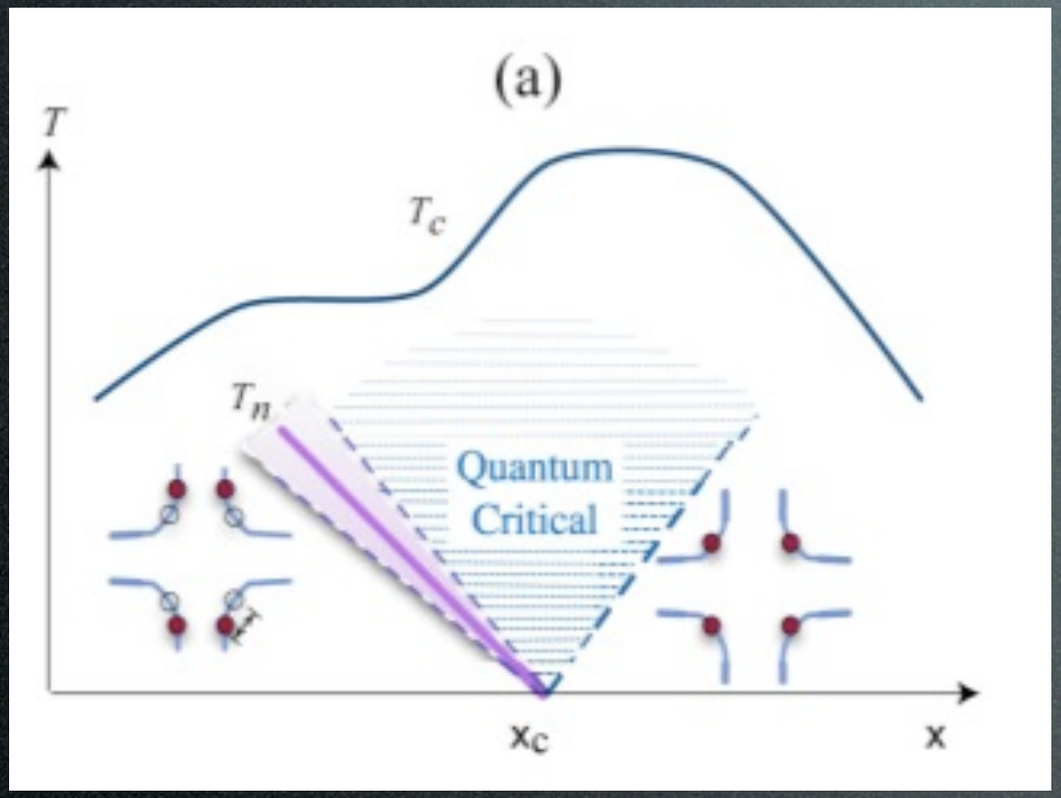


Intra unitcell nematic in the pseudogap states?

Prepared identification



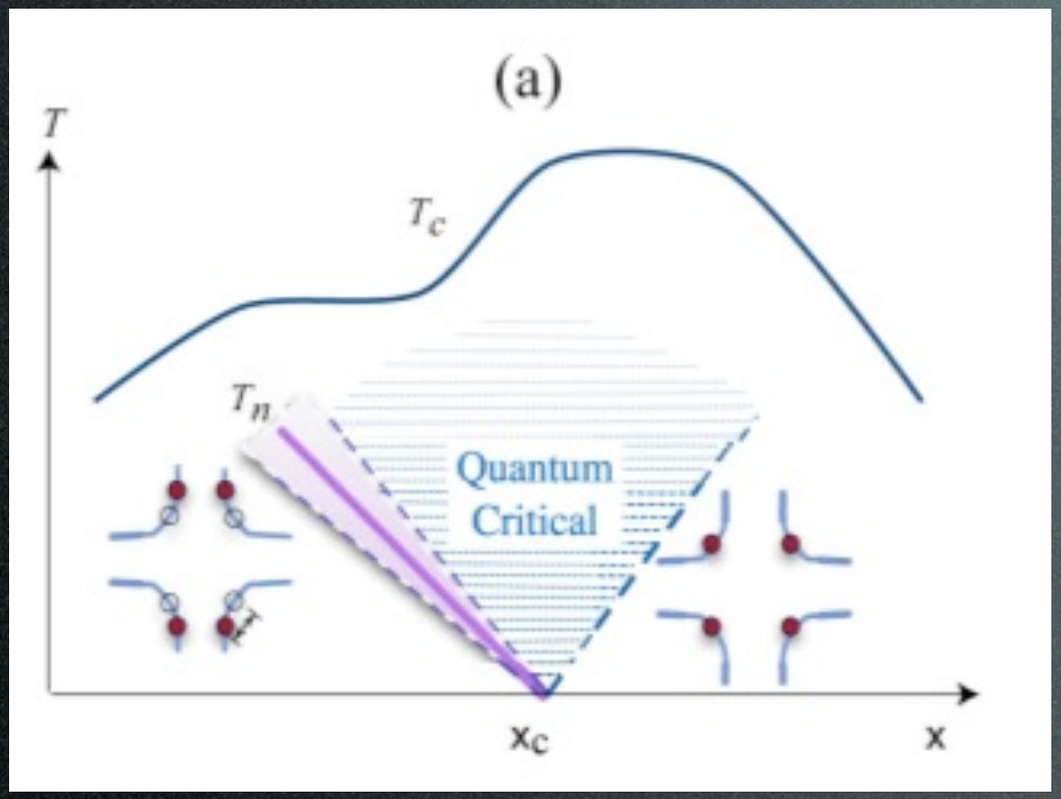
Theory



- Nematic d-wave QPC, license to exist

  Kim et al, (2008)

Theory



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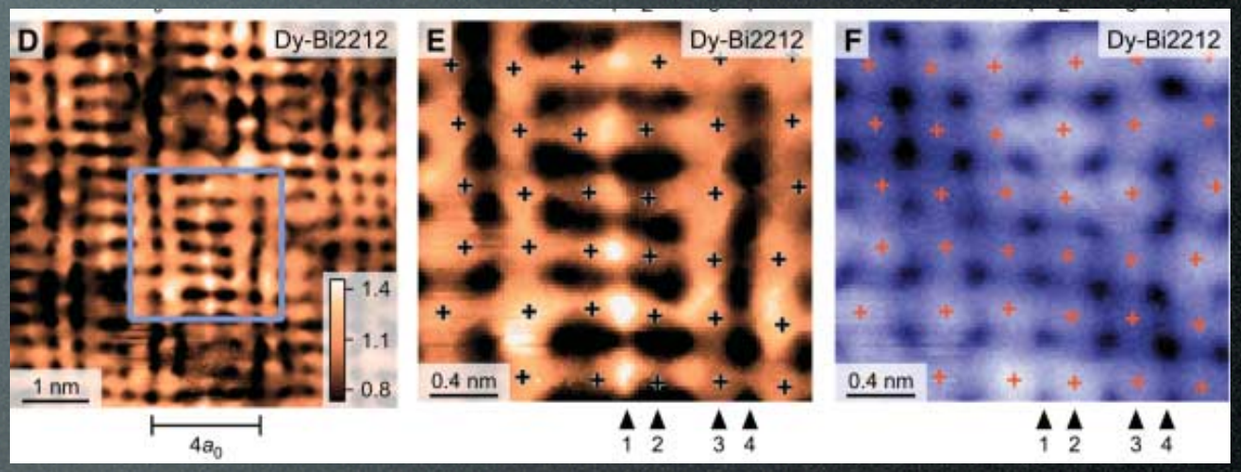
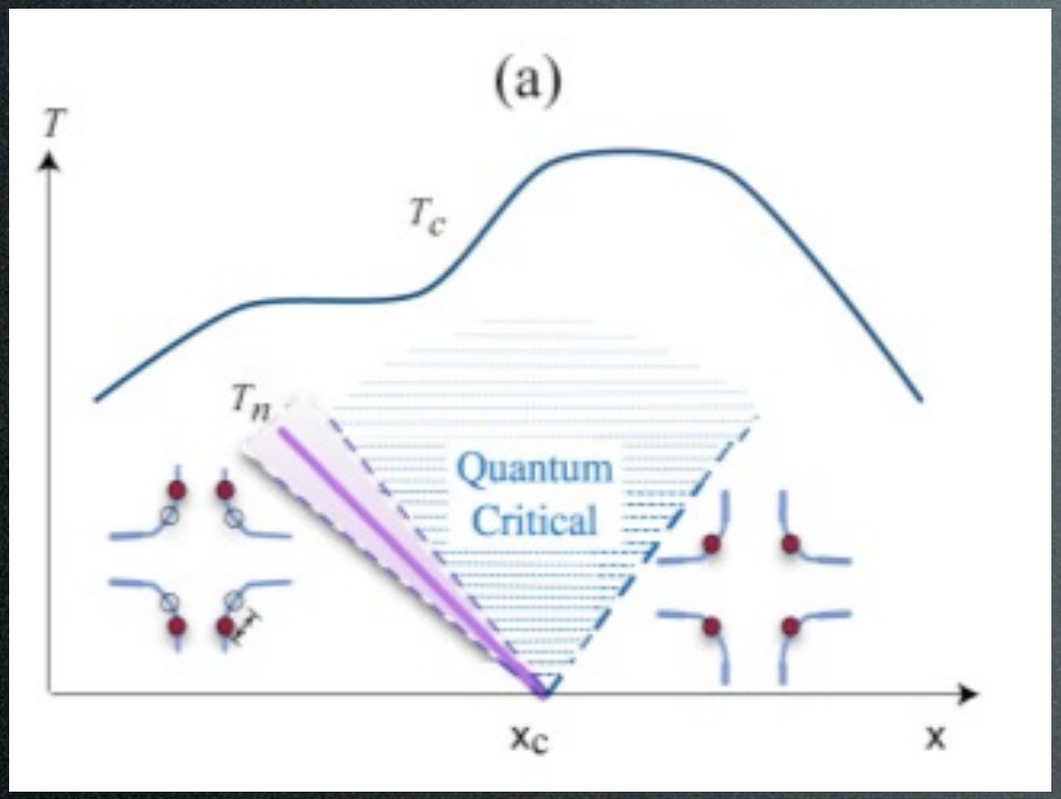
Experiment



- Local broken C4 symmetry
- Importance of Oxygens

Kohsaka et al, Science 315, 1380 (2007)
UD T_c=45K (p=0.08)

Theory



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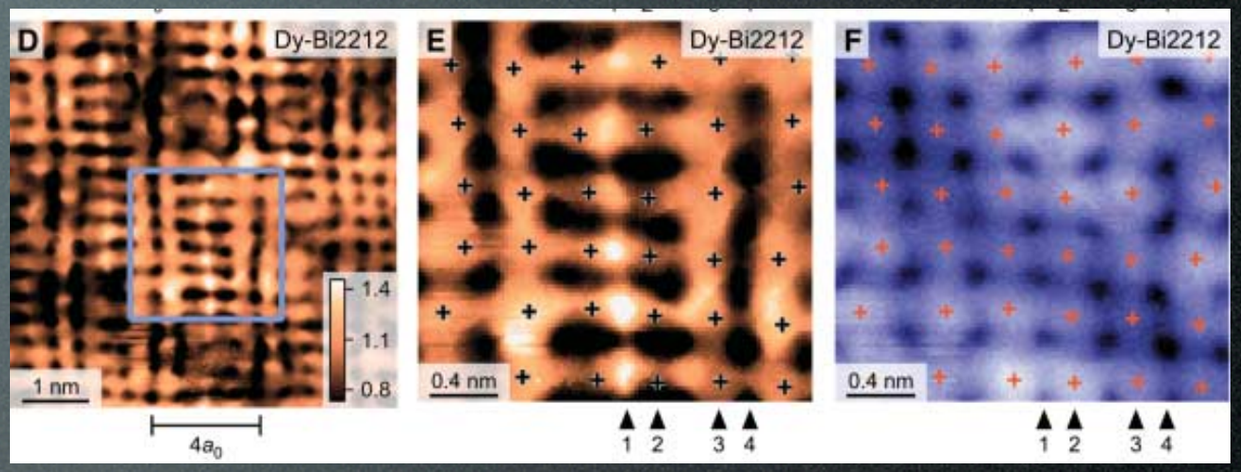

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Domain average ➡ Arc