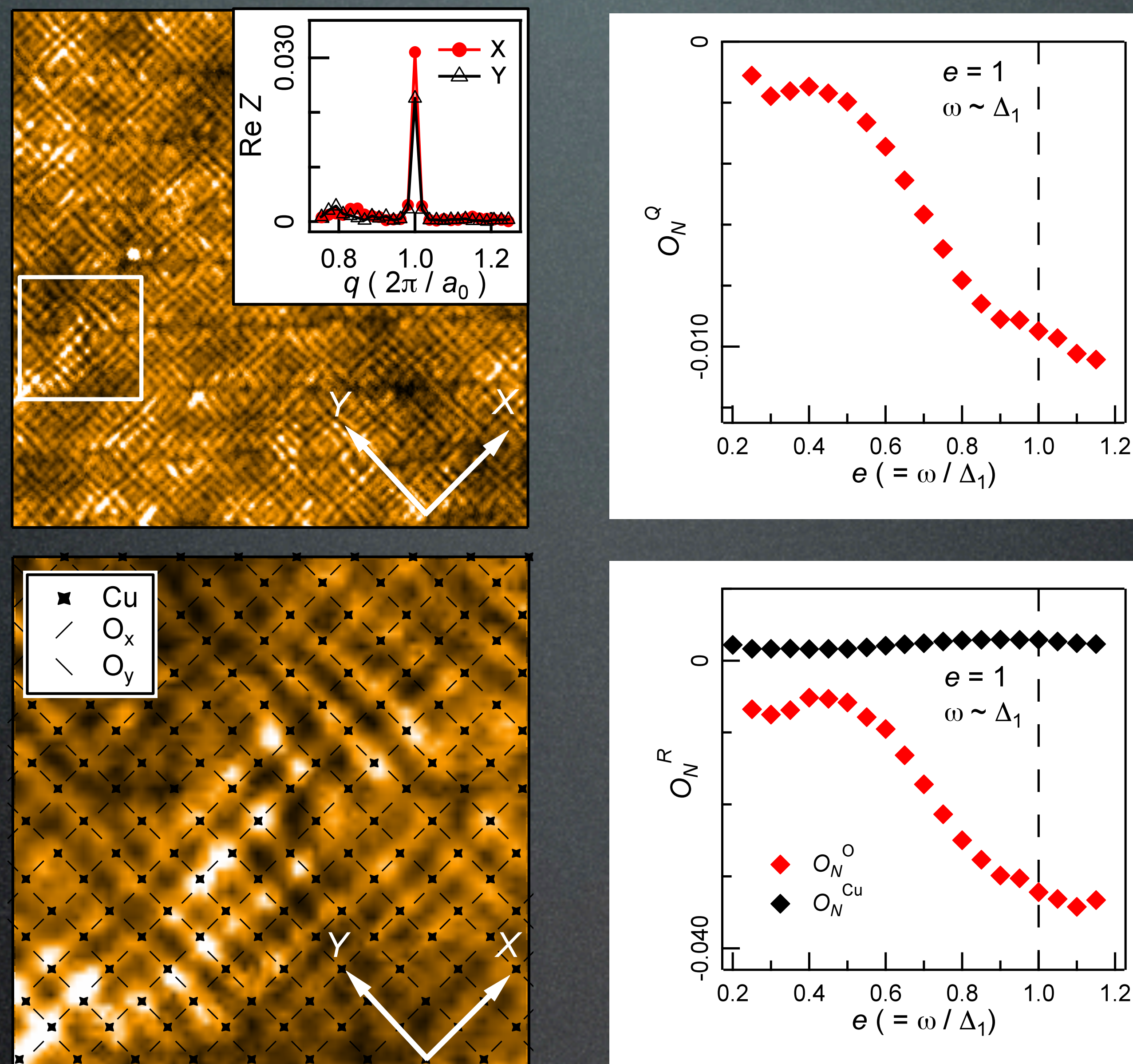
Phenomenology of electronic liquid crystals in high Tc superconductors

Michael J. Lawler / Binghamton, Cornell



Lawler, Fujita, et. al., Nature **466**, 347 (2010)
Mesaros, Fujita, et. al. (2010), unpublished.

Acknowledgments

In collaboration with ...

Experimentalists

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Theorists

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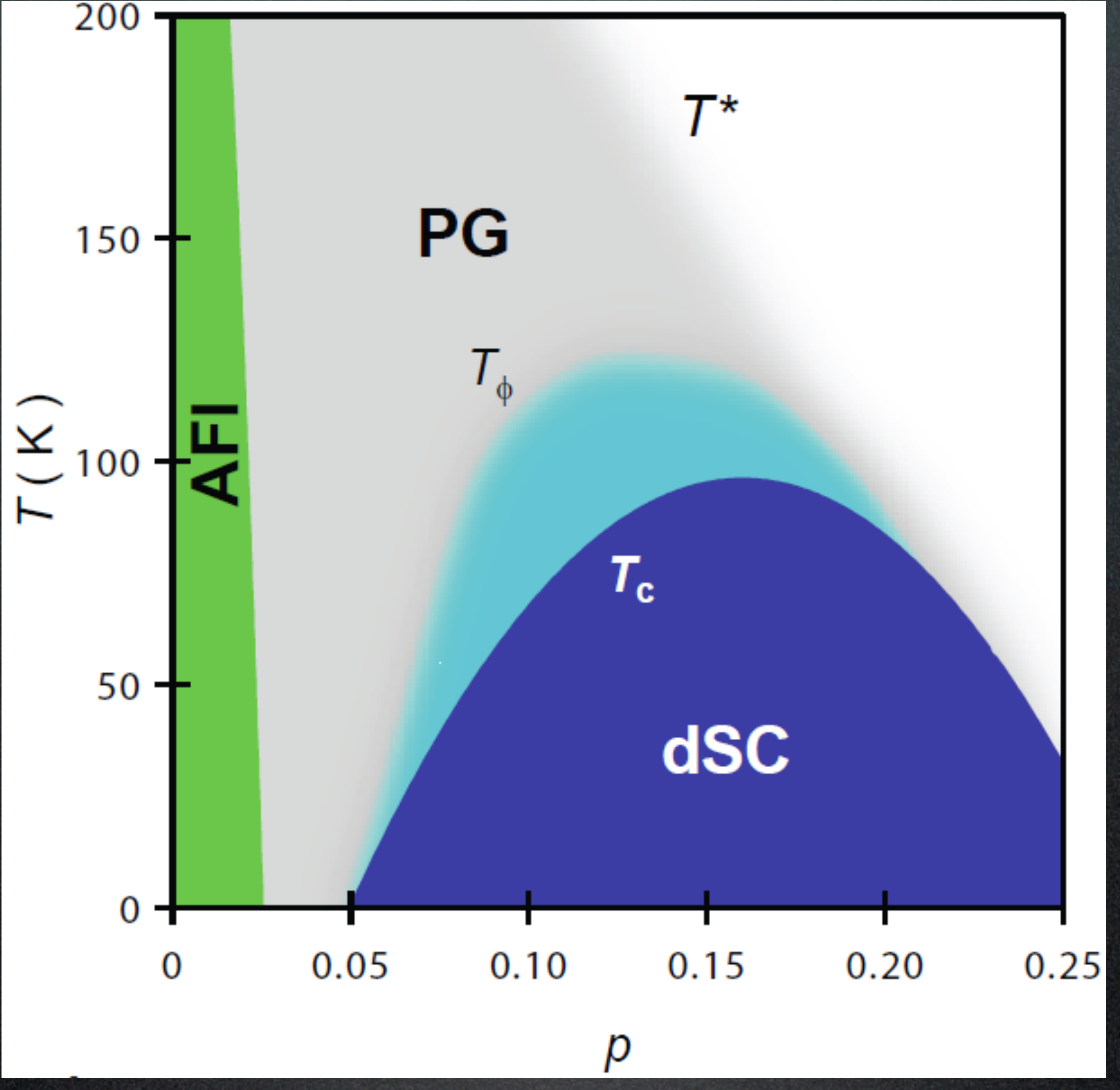
Jan Zaanan / Leiden
Subir Sachdev / Harvard
James P. Sethna / Cornell
Eun-Ah Kim / Cornell

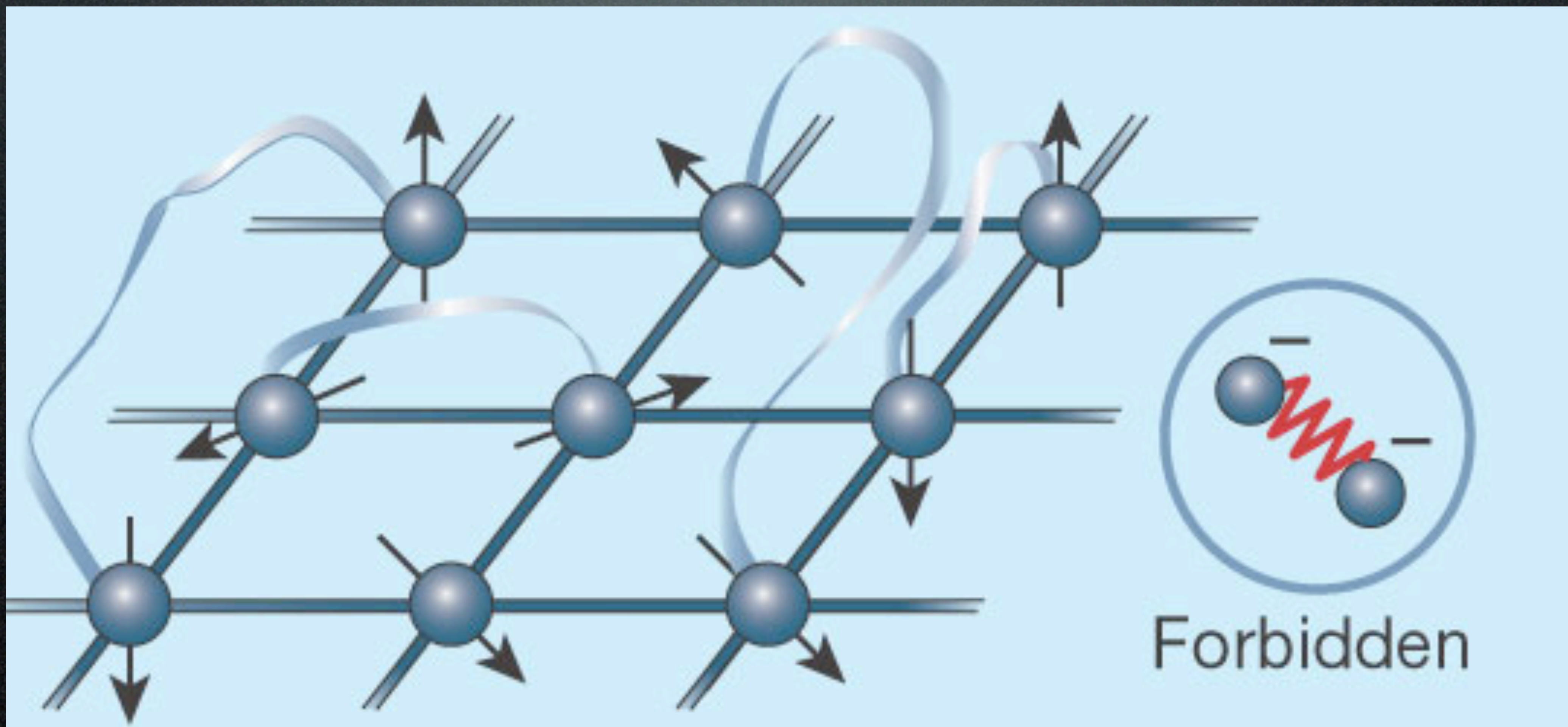
Do electronic liquid crystal phases arise near a Mott insulator?

Effect of doping in cuprates



Mott insulators: a kind of electronic crystal?

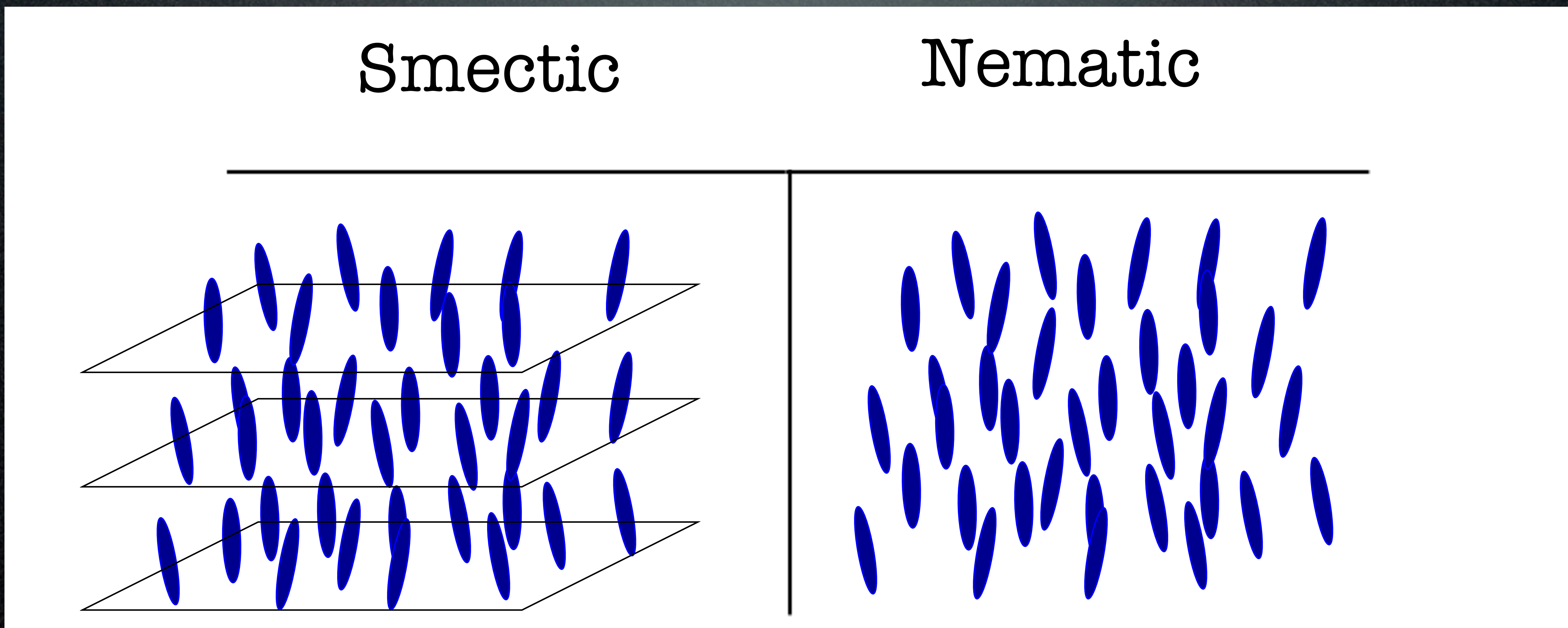
Hopping prohibited by local Coulomb Interactions



K.E. << P.E.

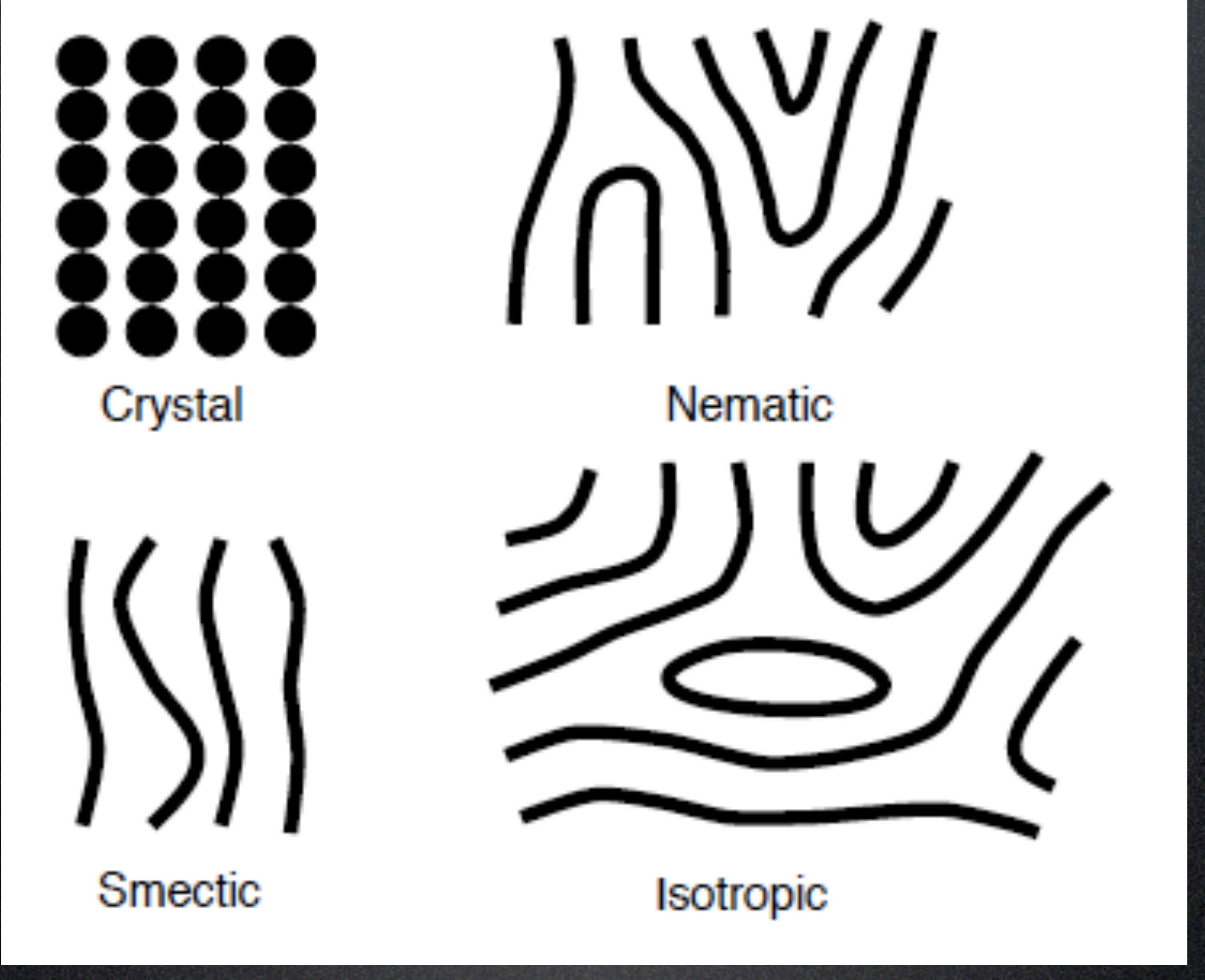
Liquid crystal phases of Rod-like polymers

En-route to a crystal at low temperatures ...



Low T ← High T

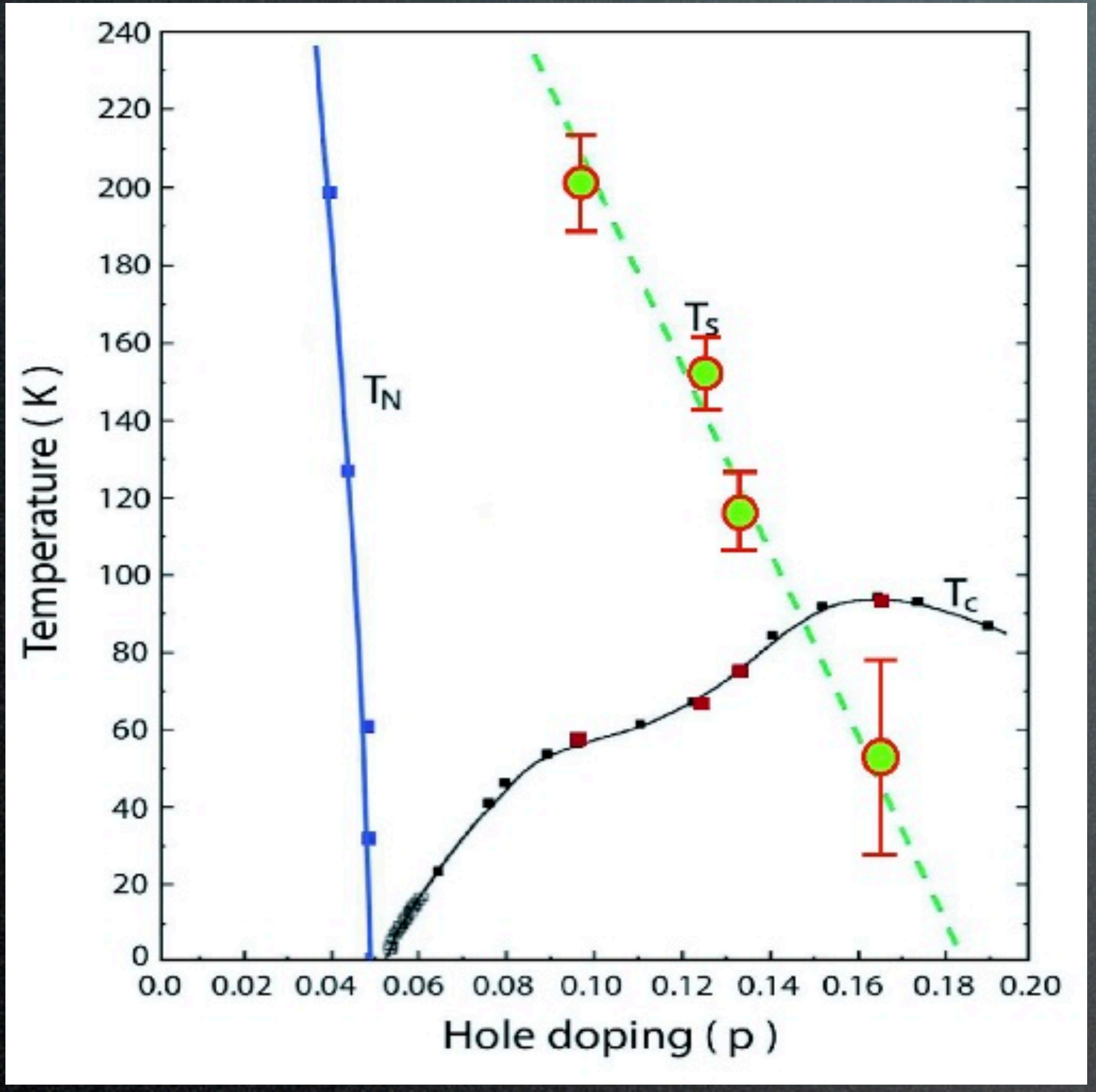
Liquid crystal phases of electrons



Kivelson, Fradkin, Emery Nature (1998)

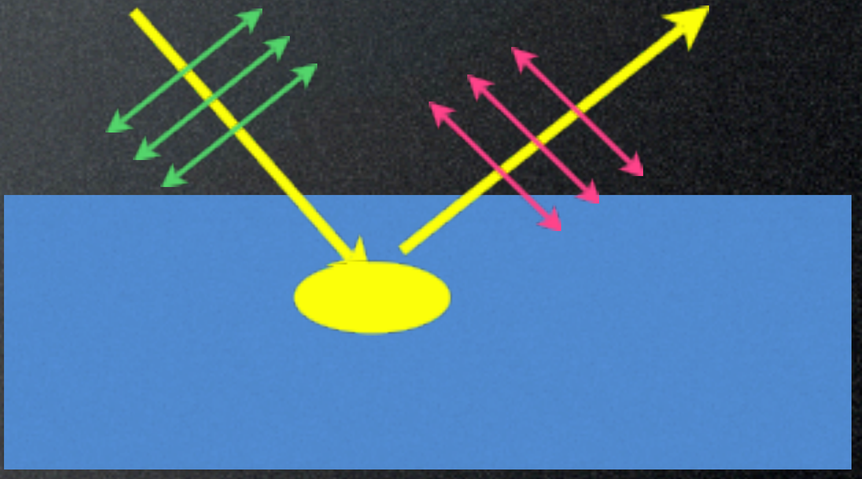
Symmetry of the Pseudogap phase

Pseudogap phase is not Time reversal symmetric



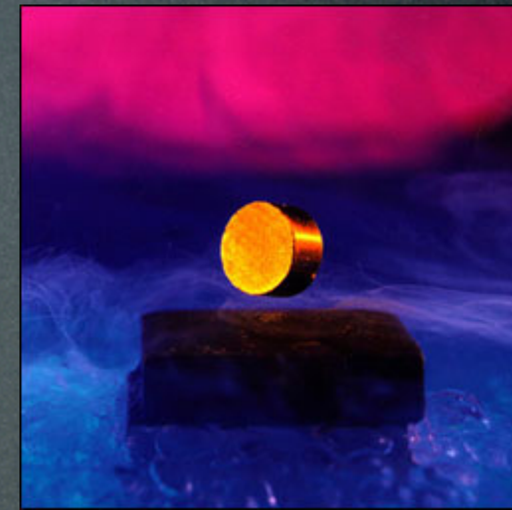
Xia et. al. Phys. Rev. Lett. **100**, 127002 (2008)

Sense ferromagnetism by change in polarization



Spot size ≈ 3 μm

But superconductors repel magnets!



Xia et. al. Explain this with two comments:

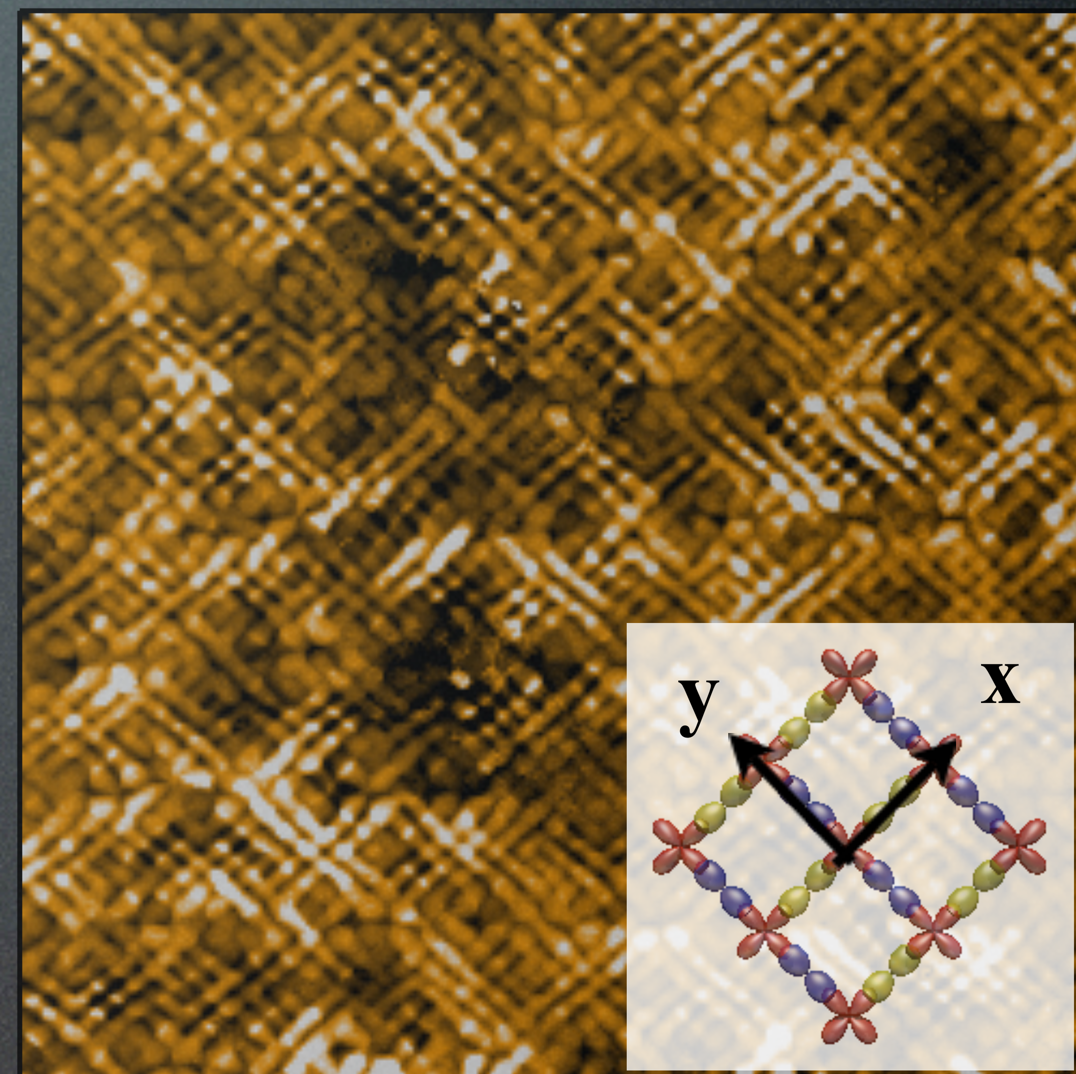
- “The magnitude of the Kerr rotation in $YBa_2Cu_3O_{6+x}$ (YBCO) is smaller by 4 orders of magnitude than that observed in other itinerant ferromagnetic oxides…”
- “… either we are not directly measuring the principal order parameter that characterizes the pseudogap phase in YBCO or we measure its very small “ferromagneticlike” component.”

Spatial Symmetry of Pseudogap phase

Kohsaka et. al. (2007)

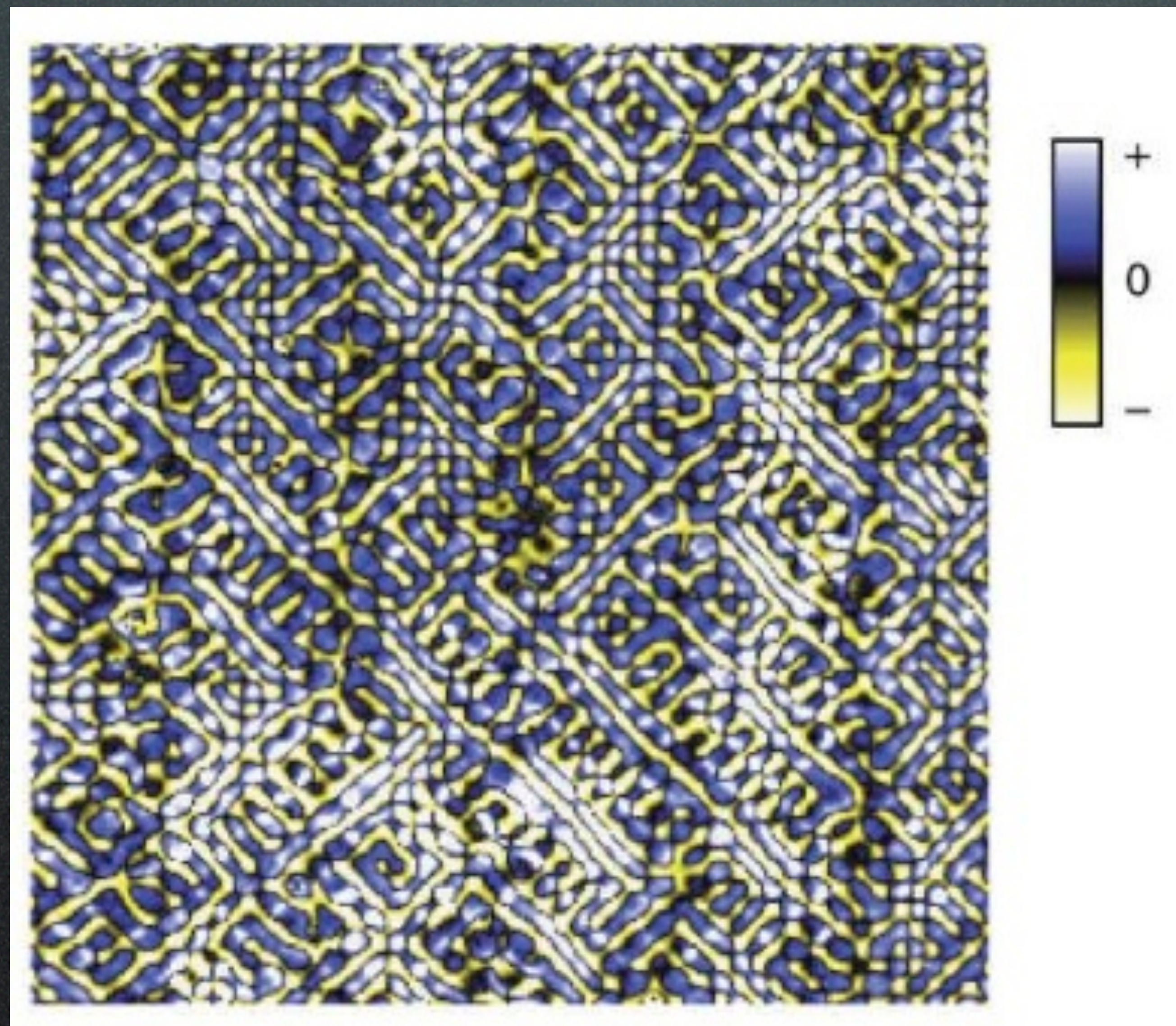
Why look at low temperatures?

- Symmetry breaking at T = T* can influence all properties for T<T*.
- Low temperatures improves signal to noise effects



Patterns observed above T_C

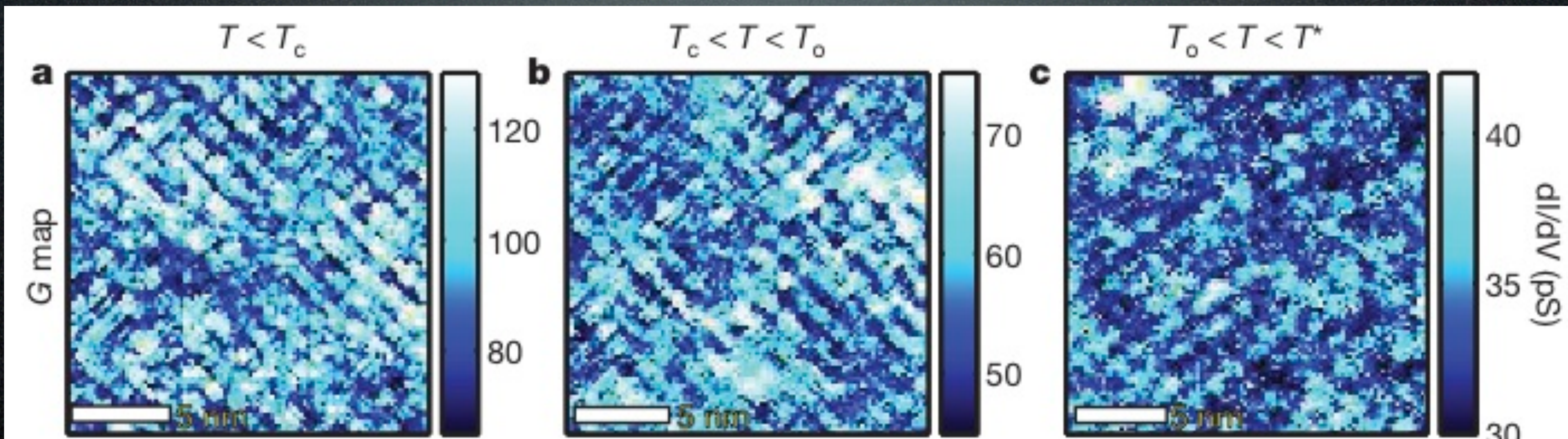
T = 45K, Tc = 37K



Jhinhwan Lee, et. al., Science **325**, 1099 (2009)
(see Fig. S7 of supplementarymaterials)

Persistance of patters for T > T_C

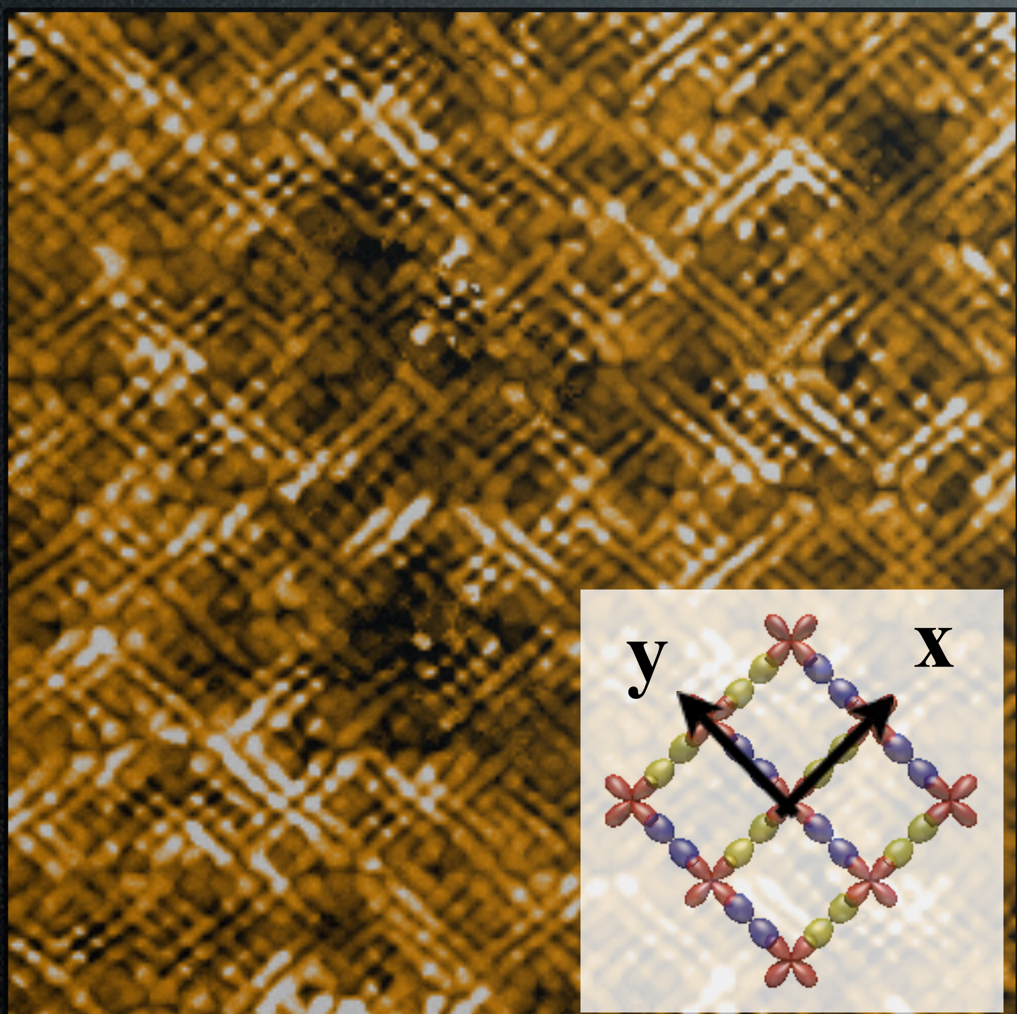
T = 45K, Tc = 35K



Patterns persist up to T*

Colin T. Parker, et. al., Nature **468**, 677 (Dec. 1st 2010)
(Yazdani group at Princeton University)

Can we quantify these patterns?



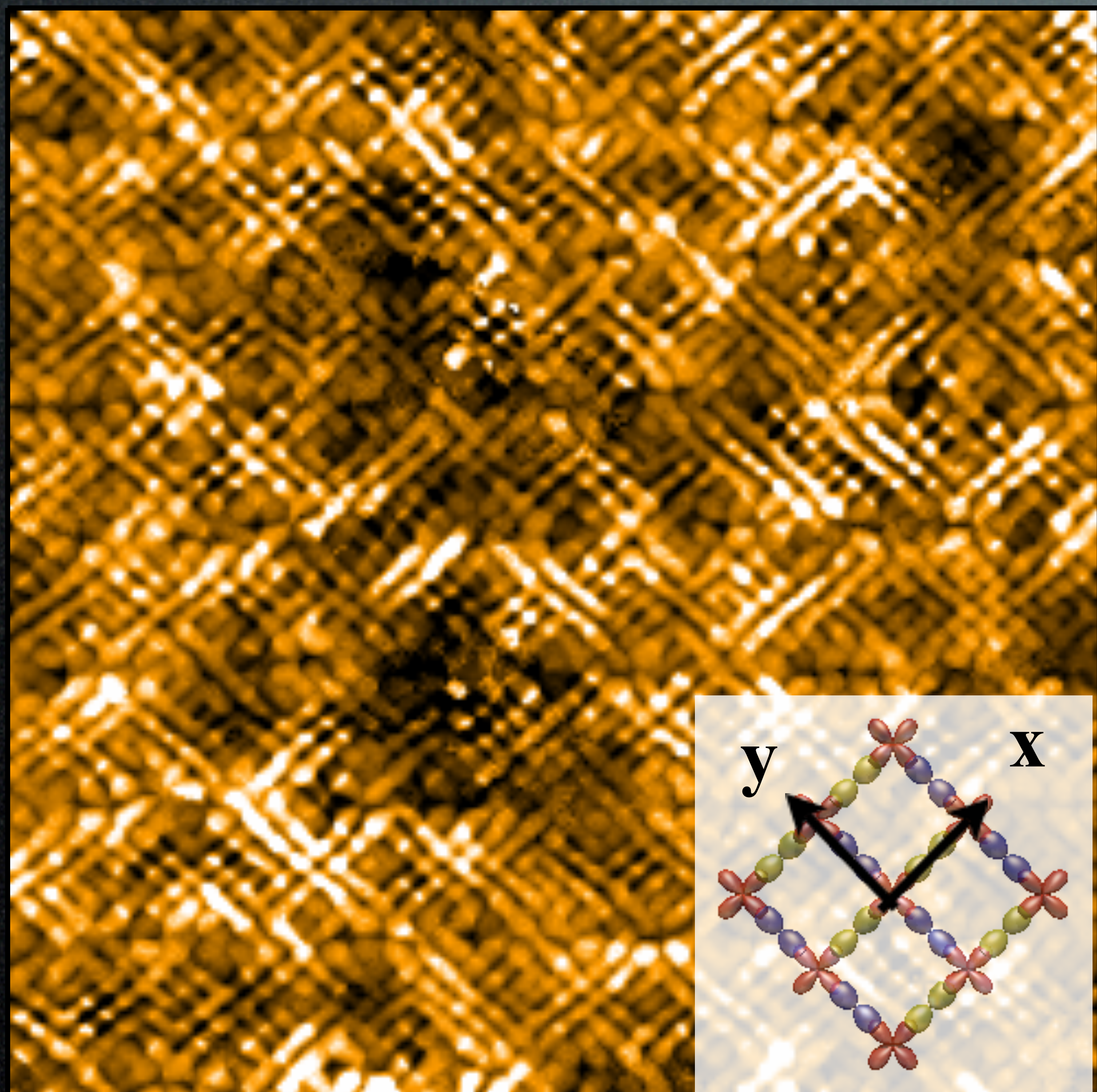
Measure patterns at different length scales?

Measure separately:

- Rotational symmetry
- Translational symmetry

Local measure of broken symmetry?

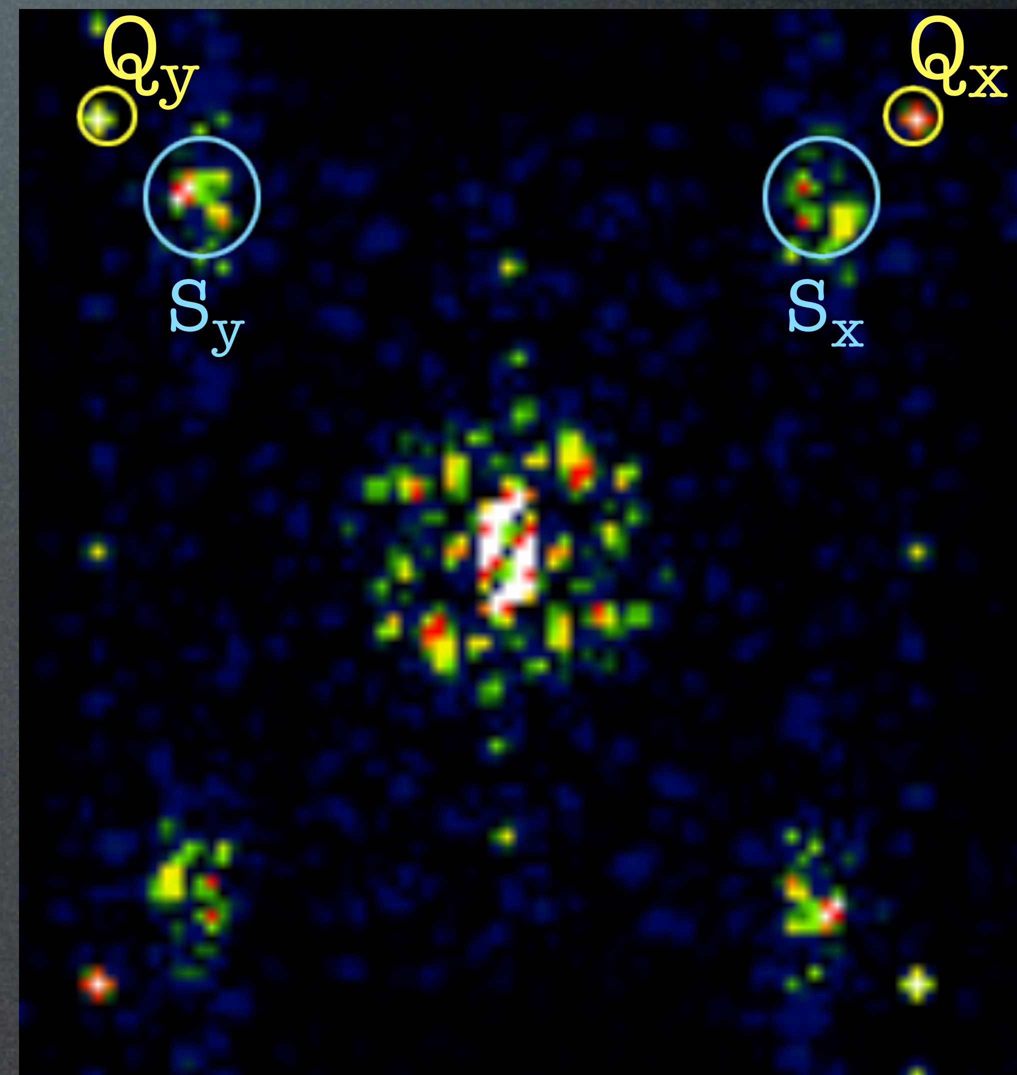
Position space



2nm

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

Fourier space



Q_x vs Q_y?

S_x vs S_y?

Lawler, Fujita et al, Nature 2010

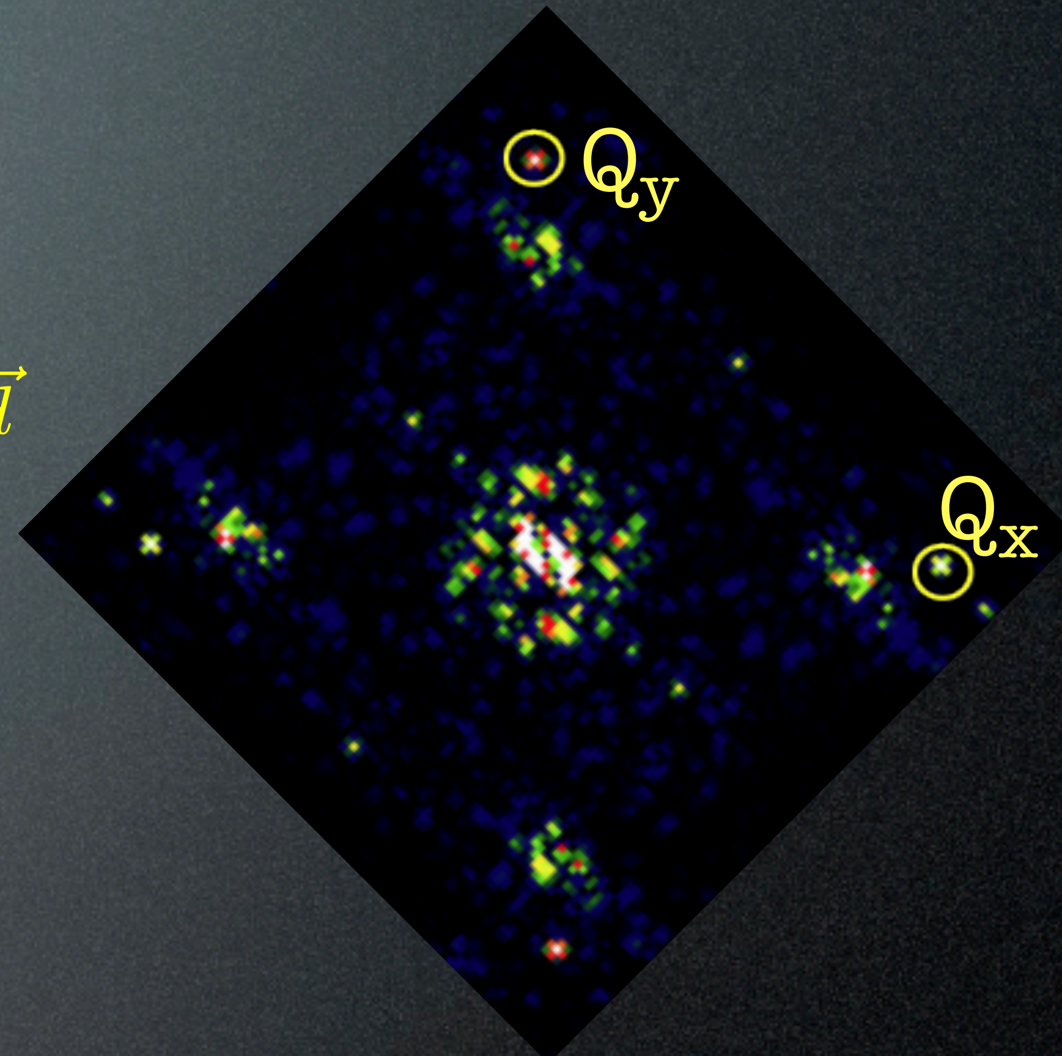
Nematic order

Q_x vs Q_y

- For any local map $M(\vec{r})$
- Bragg peak

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

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



- Nematic OP

$$\begin{aligned} \mathcal{O}_N[M] &= \tfrac{1}{2}\left[\tilde{M}(\vec{Q}_y) - \tilde{M}(\vec{Q}_x) + \tilde{M}(-\vec{Q}_y) - \tilde{M}(-\vec{Q}_x)\right] \\ &= \mathrm{Re}\tilde{M}(\vec{Q}_y) - \mathrm{Re}\tilde{M}(\vec{Q}_x) \end{aligned}$$

➡Measures C_4 breaking

➡Preserves lattice translation

Lawler, Fujita et al, Nature 2010

Additional requirements

- Sub-unitcell resolution

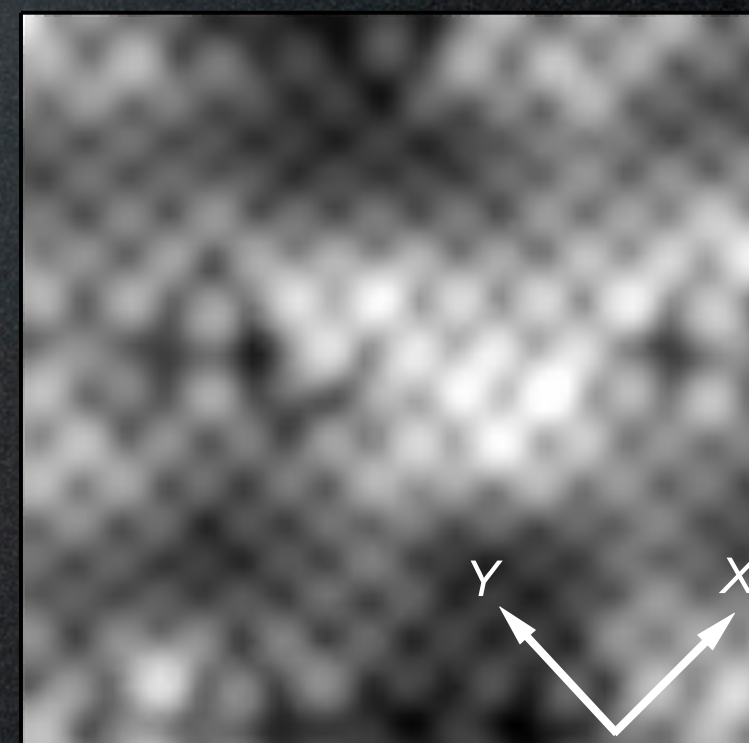
  $\mathcal{O}_N[M]$ sensitive to intra-unit cell structure

- Registry of the Cu location

  $\mathcal{O}_N[M]$ sensitive to phase of FT

  ➡ Set the FT phase from topo-map

  ➡ Use topo-map to correct small distortions

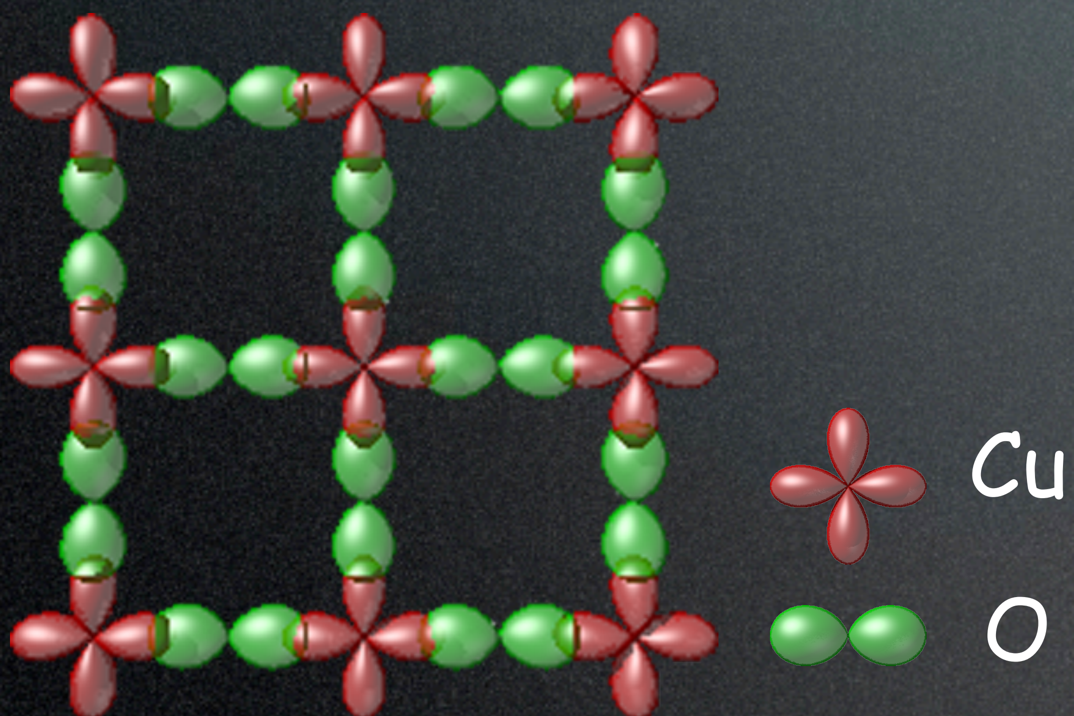


Nematic OP $\mathcal{O}_N$ and Microscopics

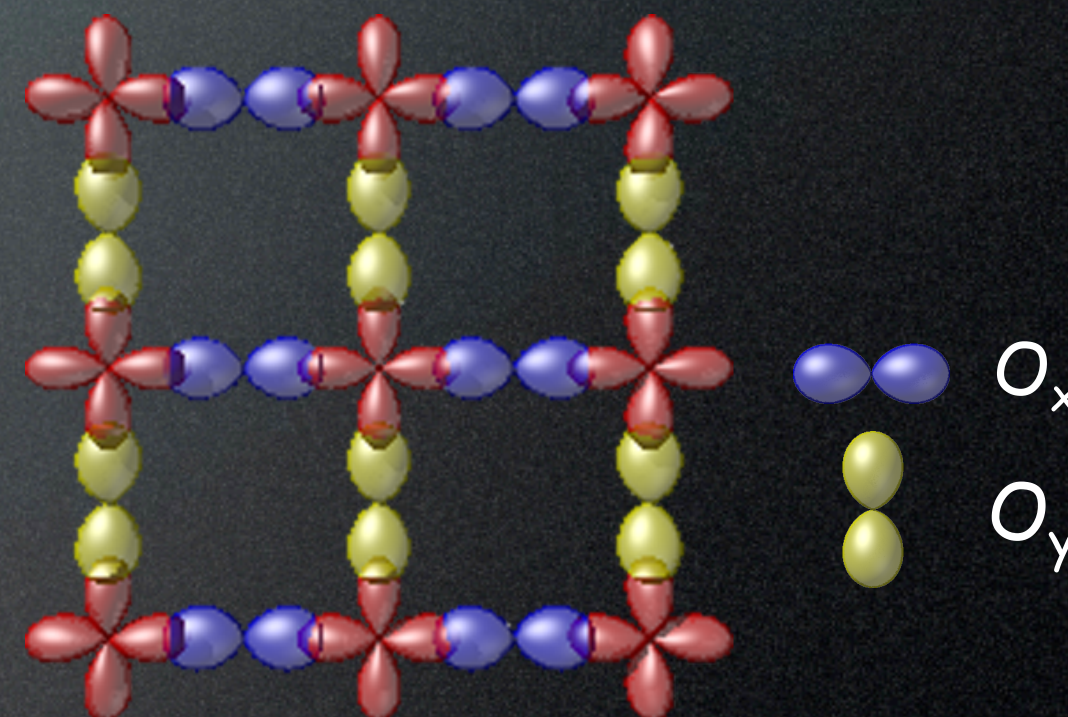
M.J. Lawler, K. Fujita et al, 2010

$$\tilde{M}(\vec{Q}_x) = \bar{M}_{Cu} - \bar{M}_{O_x} + \bar{M}_{O_y},$$
$$\tilde{M}(\vec{Q}_y) = \bar{M}_{Cu} + \bar{M}_{O_x} - \bar{M}_{O_y}$$

$\mathcal{O}_N[M] \propto \bar{M}_{O_x} - \bar{M}_{O_y}$ ➡ Need O sites



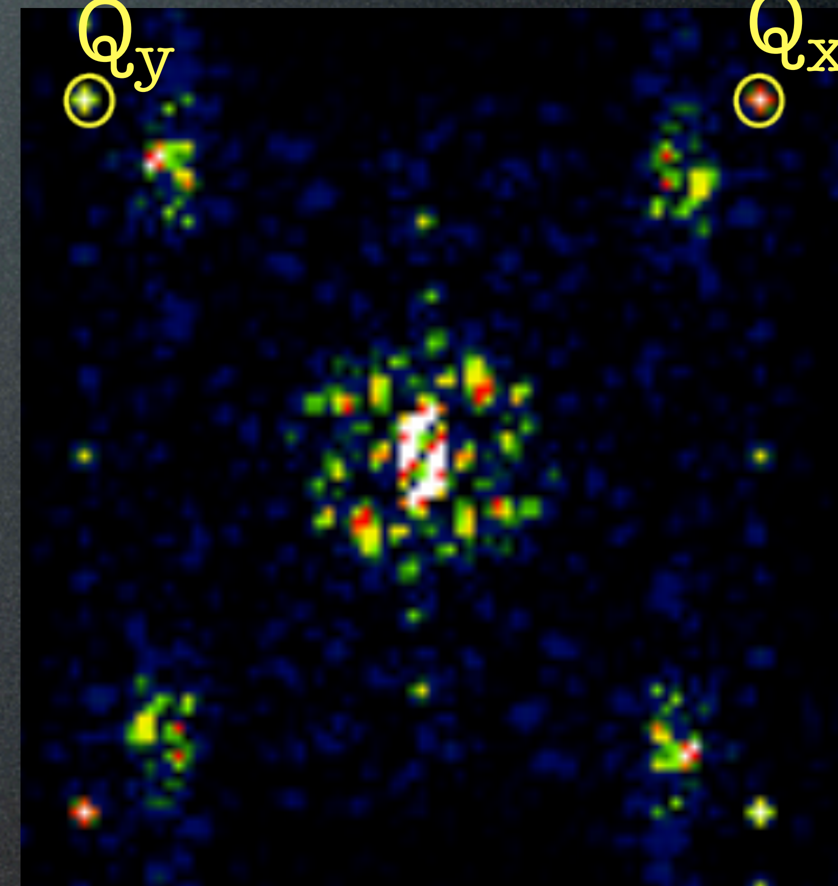
CuO_2 plane



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?



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

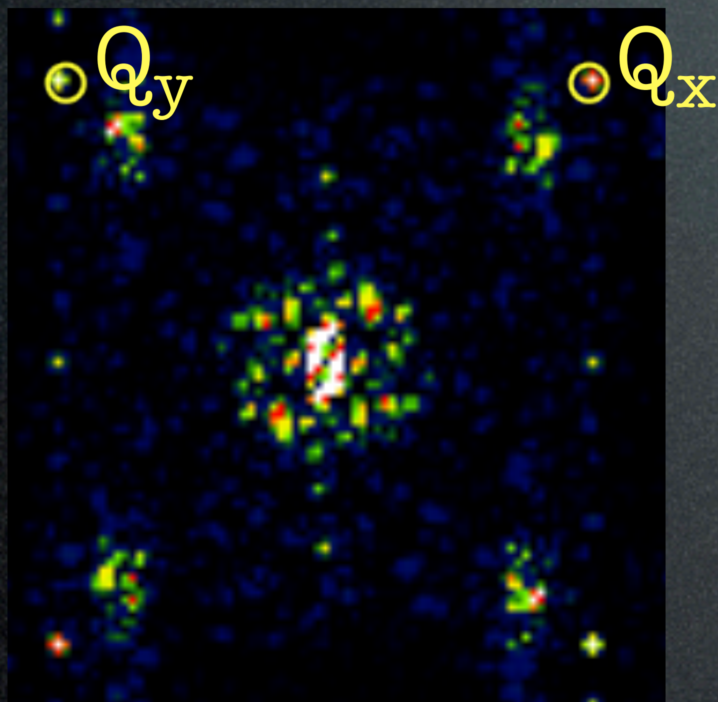
- Local order parameter:

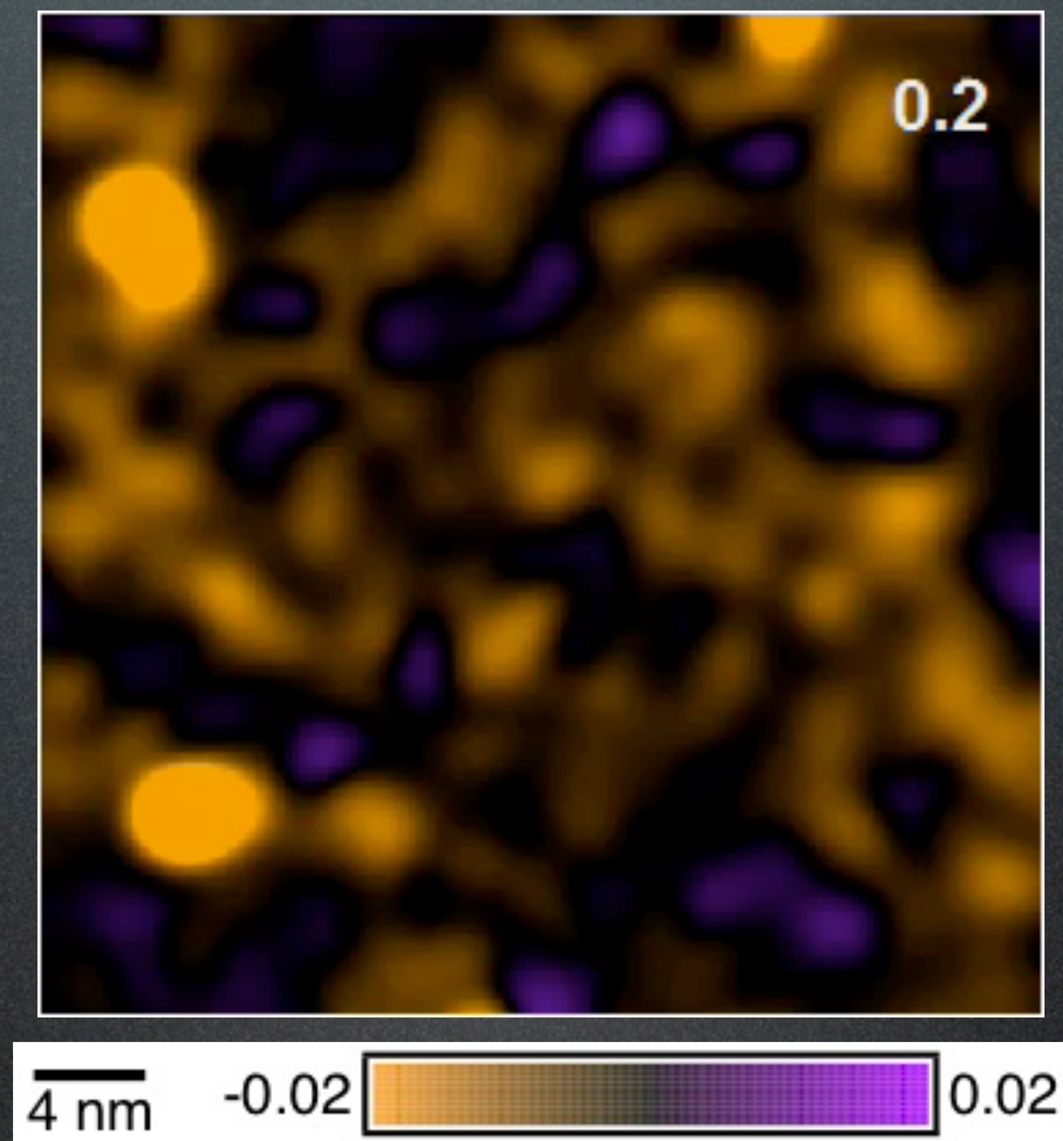
$$\mathcal{O}_N[M](\vec{x}) = \frac{1}{2}\left[\tilde{M}(\vec{Q}_y,\vec{y}) - \tilde{M}(\vec{Q}_x,\vec{x}) + \tilde{M}(-\vec{Q}_y,\vec{x}) - \tilde{M}(-\vec{Q}_x,\vec{x})\right]$$

Lawler, Fujita et al, Nature 2010

Nematic Order

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



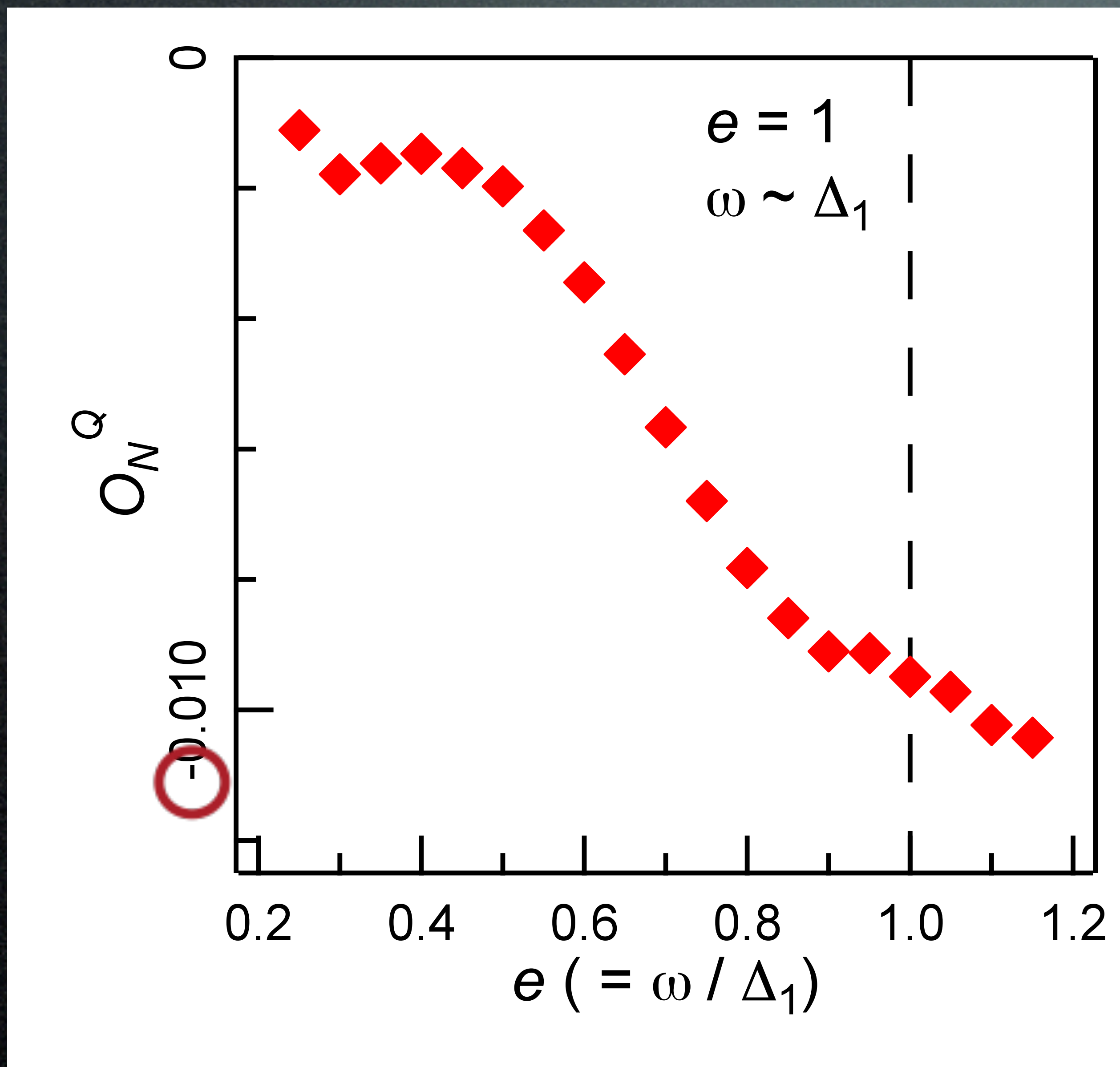


Orders near pseudogap energy scale

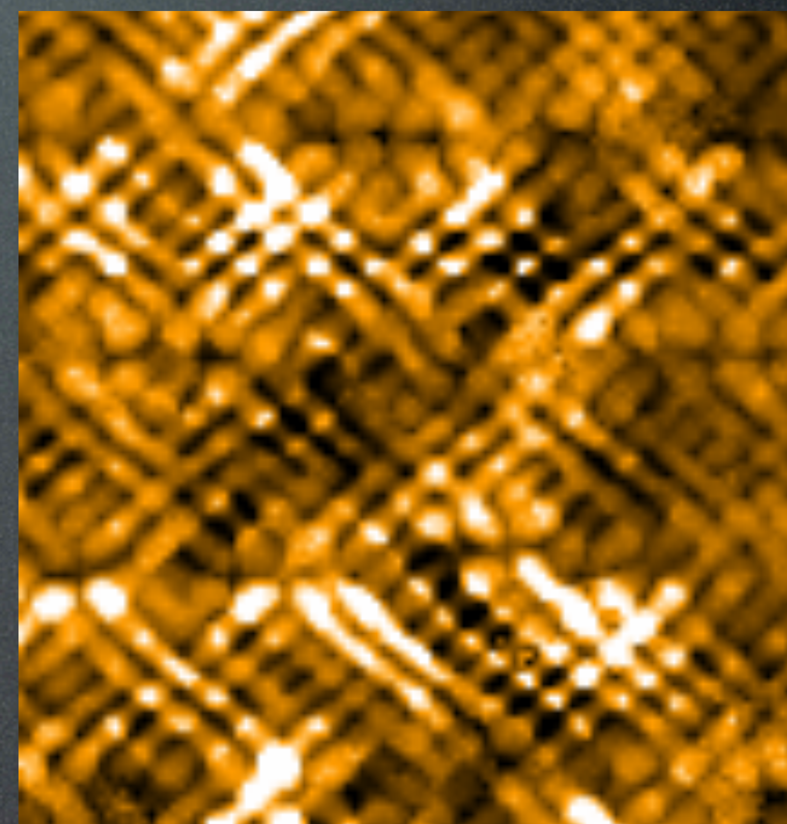
Lawler, Fujita et al, Nature 2010

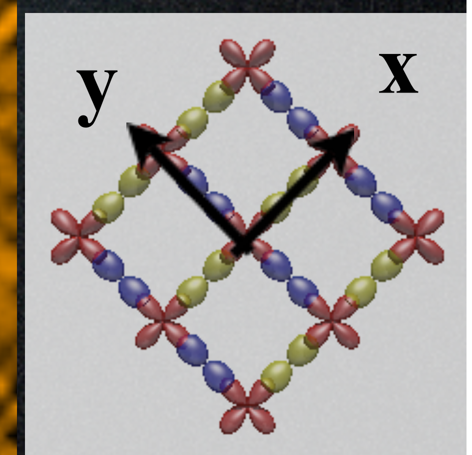
Nematic ordering at Pseudogap energy

Energy dependence of average $\mathcal{O}_N[Z(e)]$



$$\mathcal{O}_N[M] \propto \bar{M}_{O_x} - \bar{M}_{O_y}$$

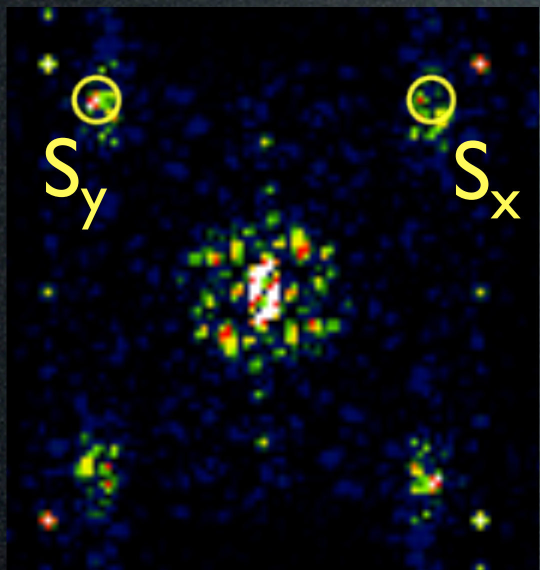




Lawler, Fujita et al, Nature 2010

Smectic order

Stripe OP



Breaks translational symmetry

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

Define smectic fields:

$$\psi_i = \text{low pass}_\Lambda \left[M(\vec{x}) e^{i\vec{S}_i \cdot \vec{x}} \right]$$

Can also study orientational ordering of stripes

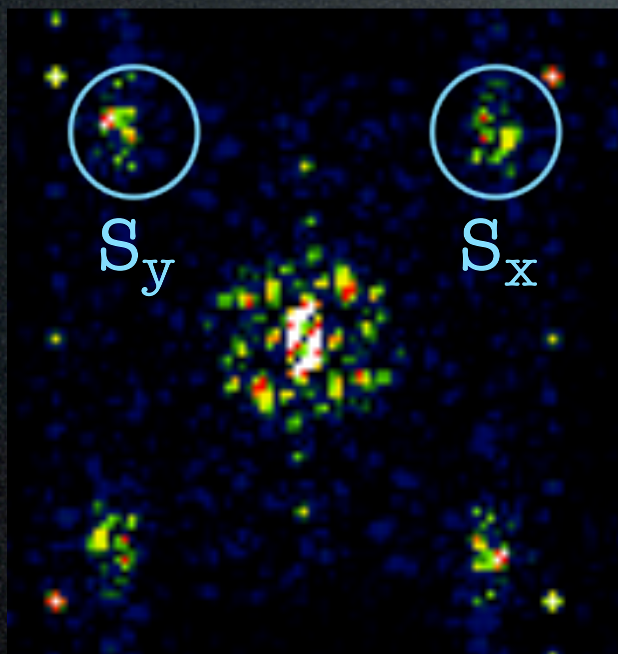
$$\mathcal{O}_S[M](\vec{x}) = \frac{1}{2}\left[\tilde{M}(\vec{S}_y,\vec{x}) - \tilde{M}(\vec{S}_x,\vec{x}) + \tilde{M}(-\vec{S}_y,\vec{x}) - \tilde{M}(-\vec{S}_x,\vec{x})\right]$$

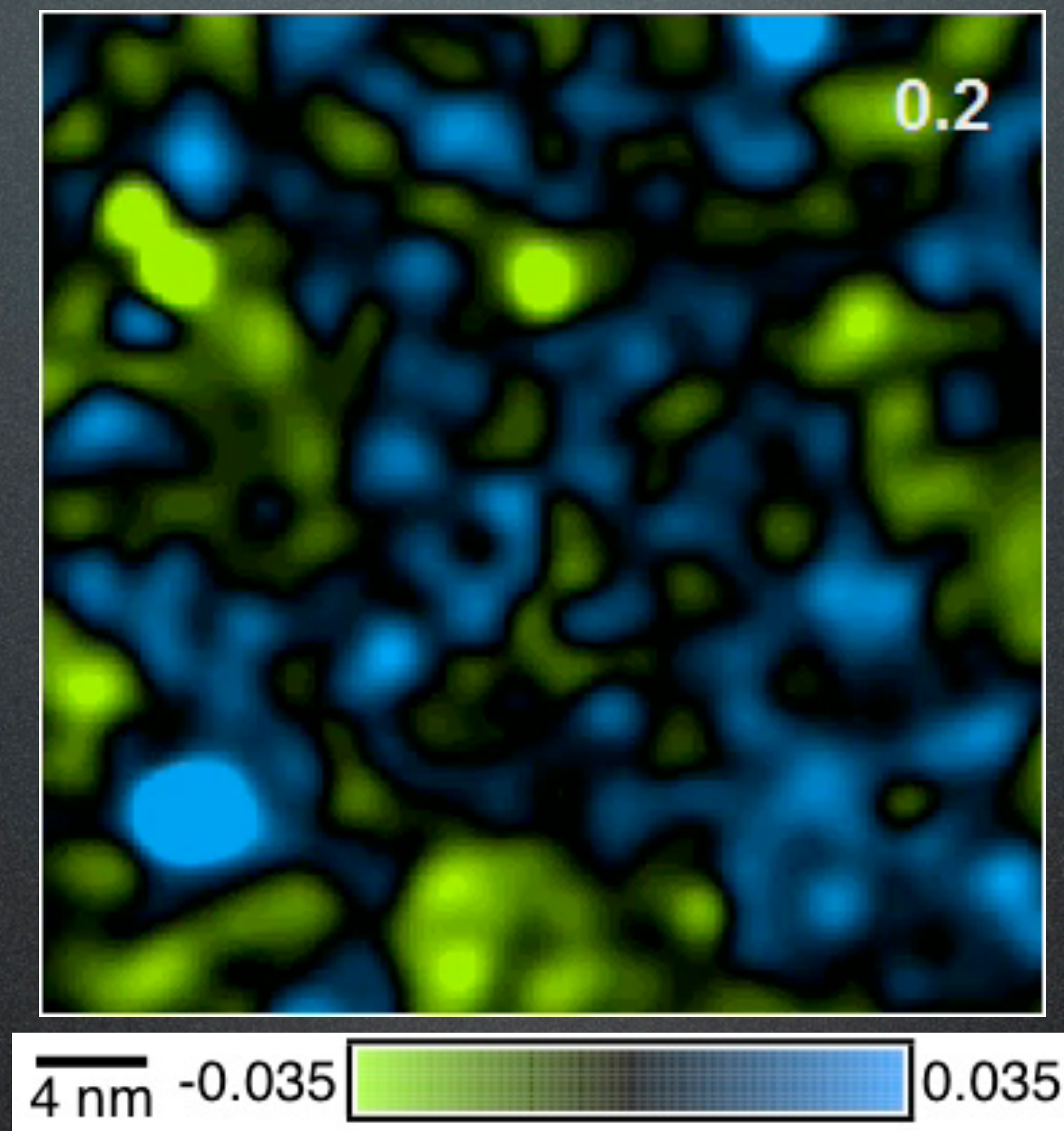
Lawler, Fujita et al, Nature 2010

Smectic domains

- Shift S_x, S_y to origin ("tune to the channel")

- Low pass filter (long distance physics)





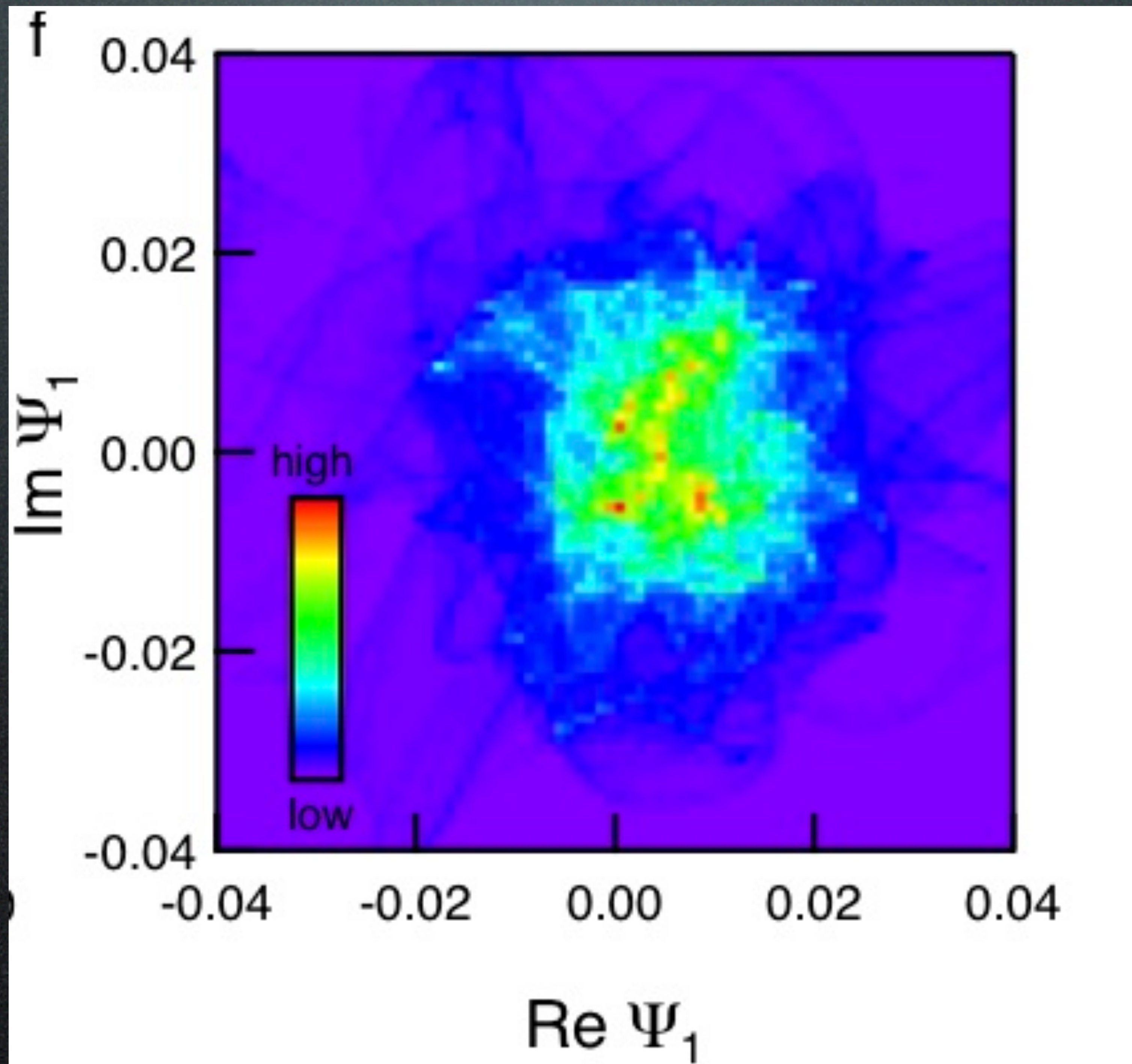
Lawler, Fujita et al, Nature 2010

Severely fluctuating in space at all energies

:Consistent with previous studies

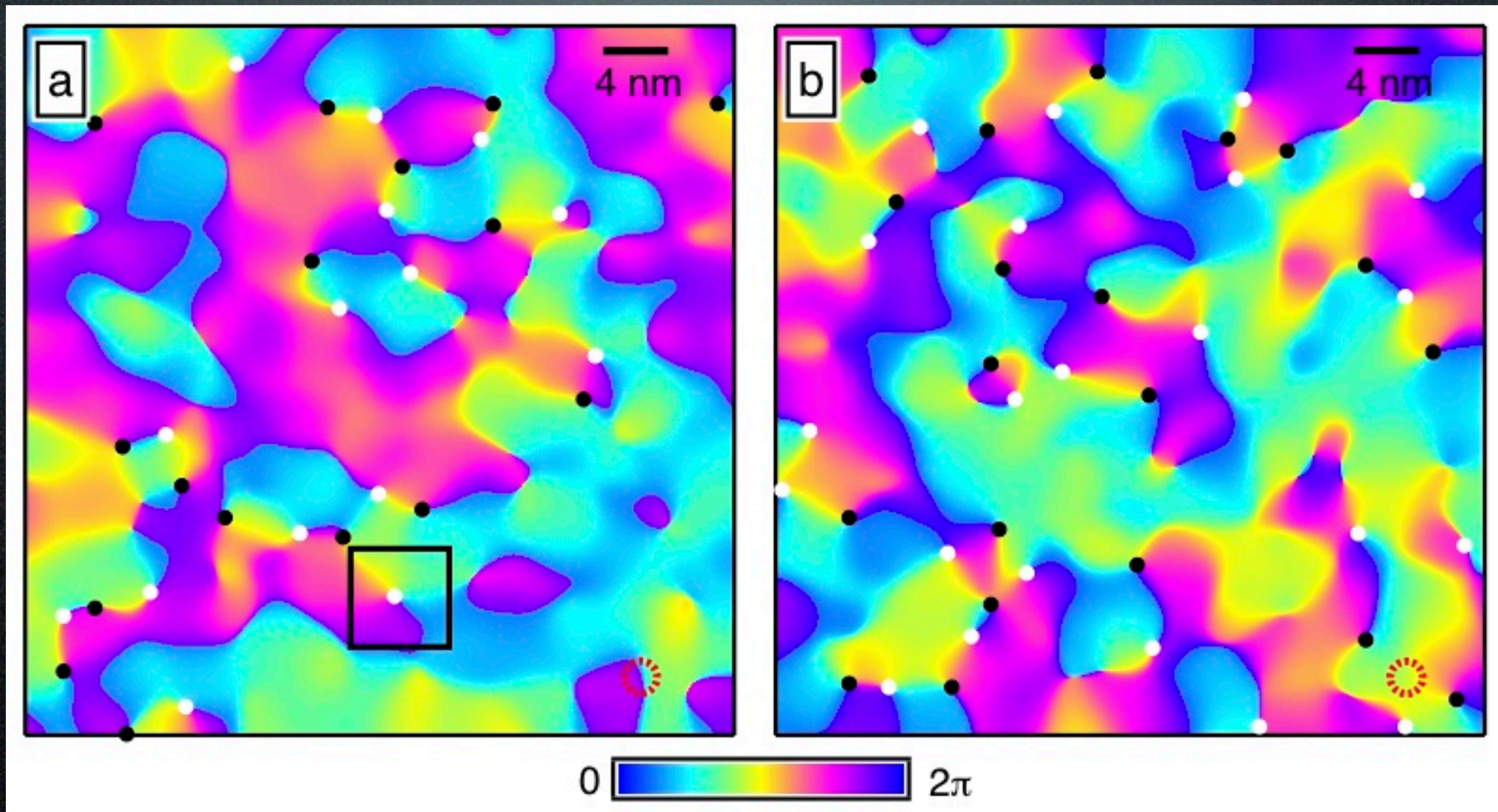
Howald et al (2003) Kohsaka et al (2008) Robertson et. al. (2006) Del Meastro et. al.

Complex histogram of Smectic order



No clear sign of ordering except for large amplitues

Phase map of smectic order



phase of Ψ_1 phase of Ψ_2

Phase disordered smectic appears incommensurate

Coupling of nematic and smectic orders

Consider the Landau theory of O_N and Ψ_i

Phase coupling:

$$\vec{\alpha}_1 \cdot \delta\mathcal{O}_N \left(\psi_1^* \vec{\nabla} \psi_1 + \mathrm{c.c.}\right)$$

Amplitude coupling:

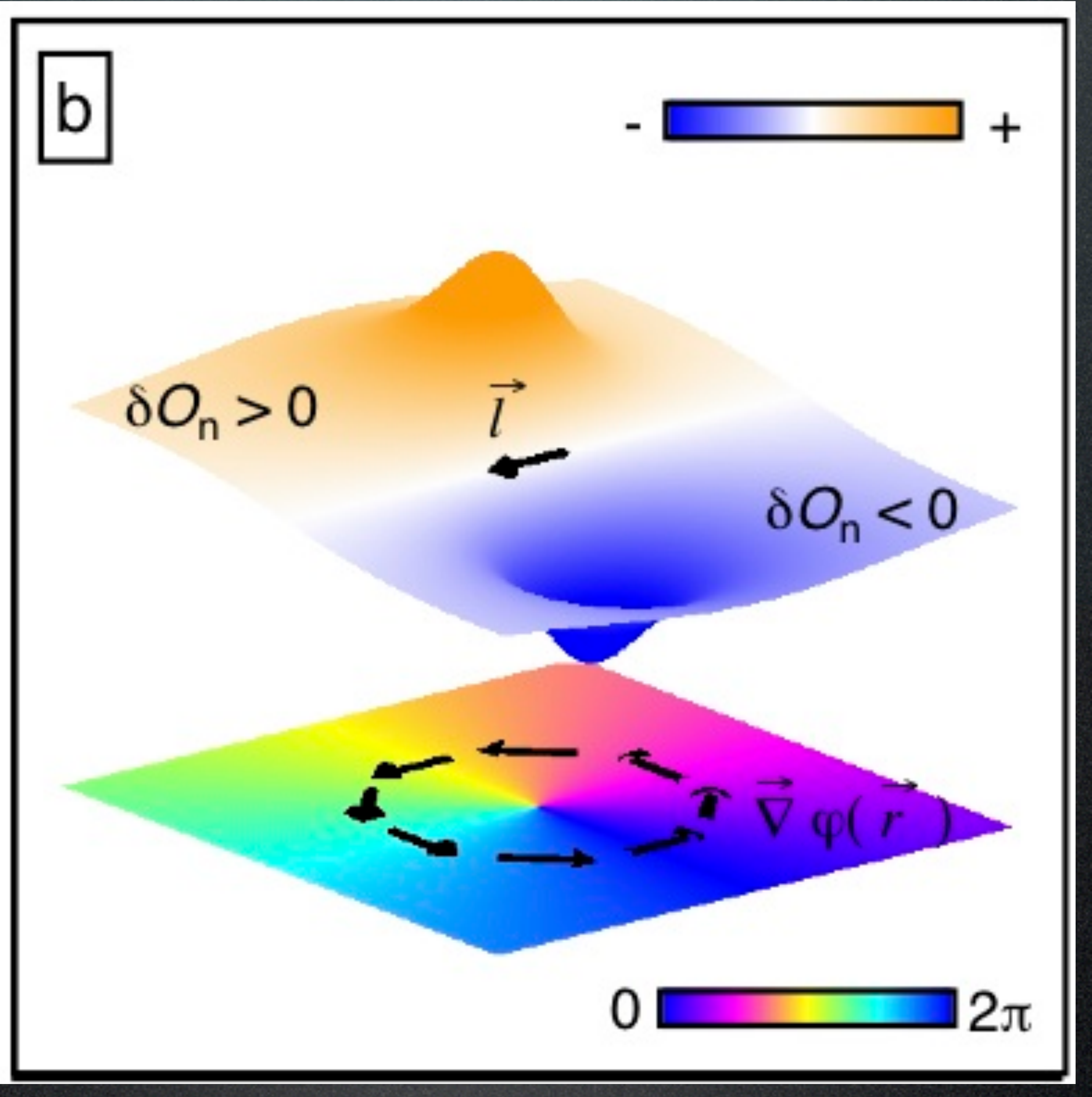
$$\beta \delta O_n \left(|\psi_1|^2 - |\psi_2|^2\right)$$

These are the most import couplings observed by a correlation analysis

Mesaros, Fujita et al, unpublished

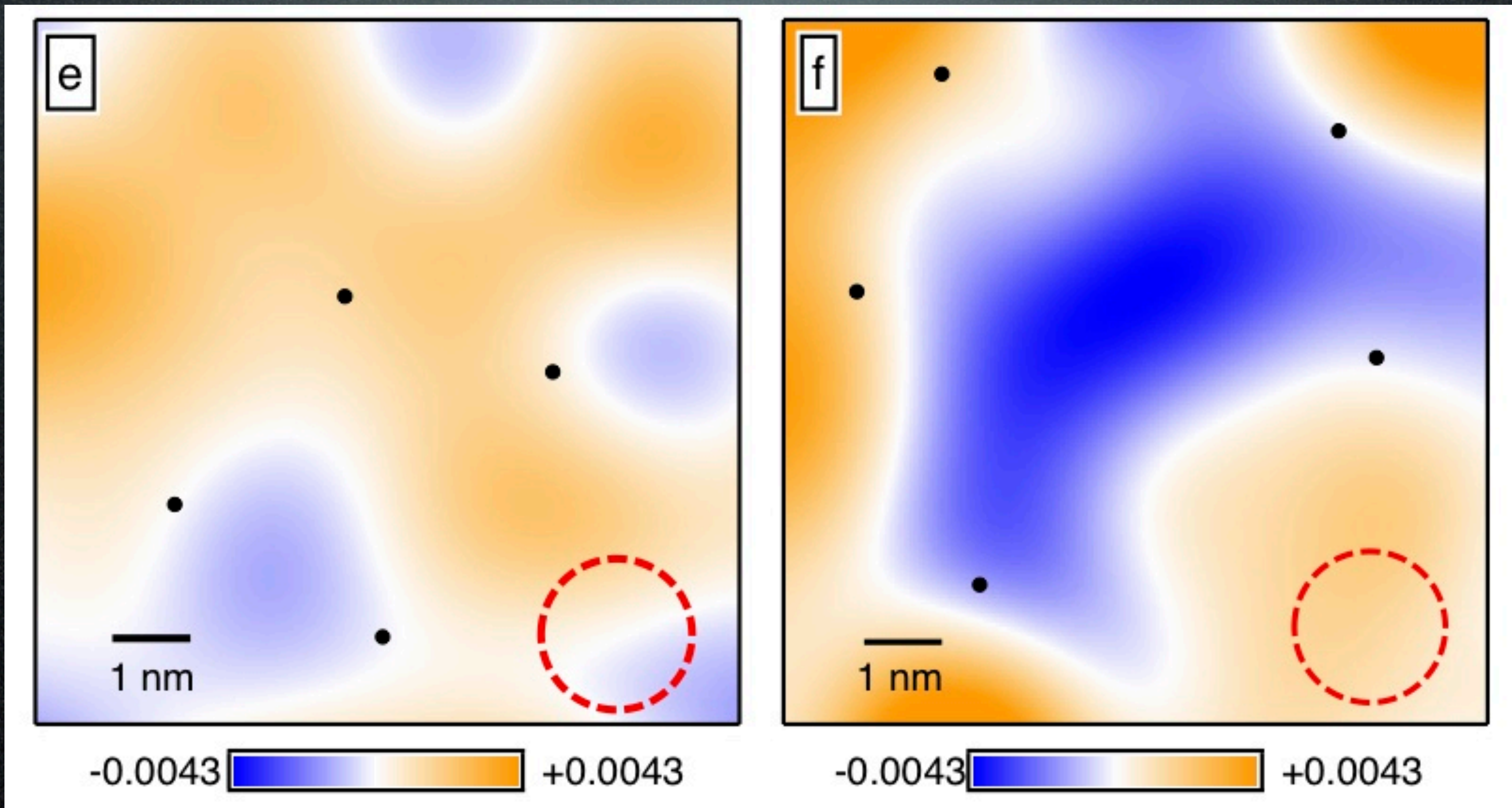
Footprint of smectic dislocations in nematic order

$$\vec{\ell} \propto \vec{\alpha}$$



Mesaros, Fujita et al, unpublished

Observation of coupling between smectic and nematic orders

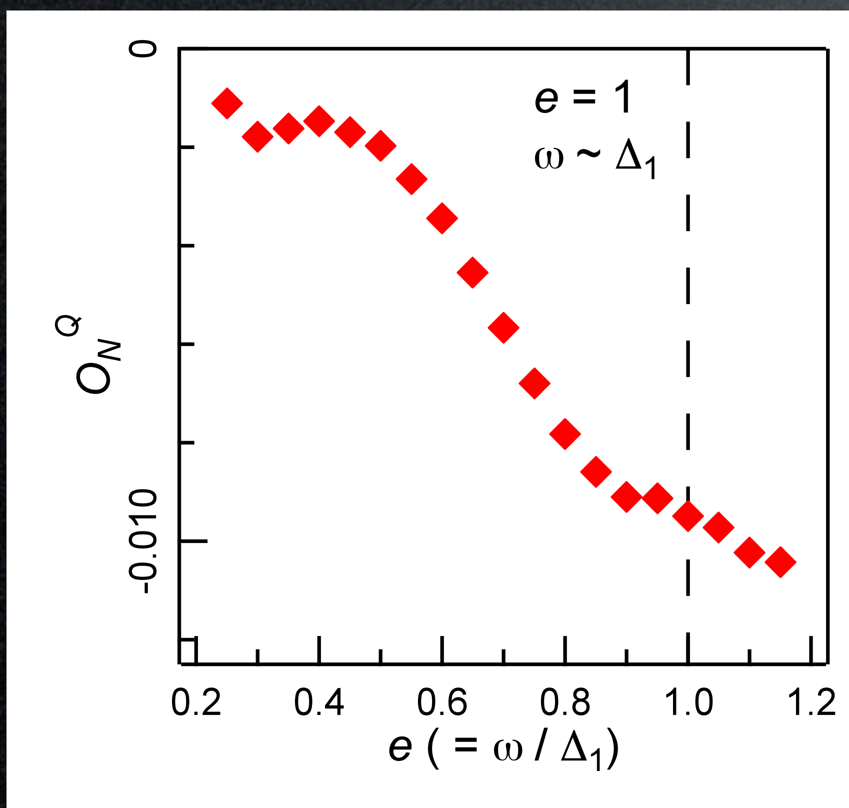


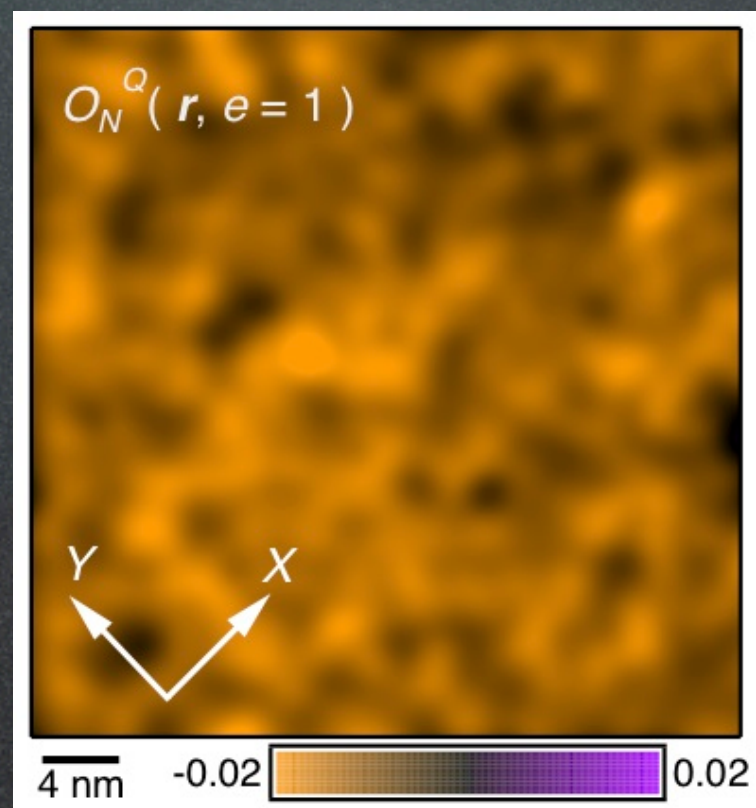
Correlation analysis shows that $|\alpha| \approx 2\beta$

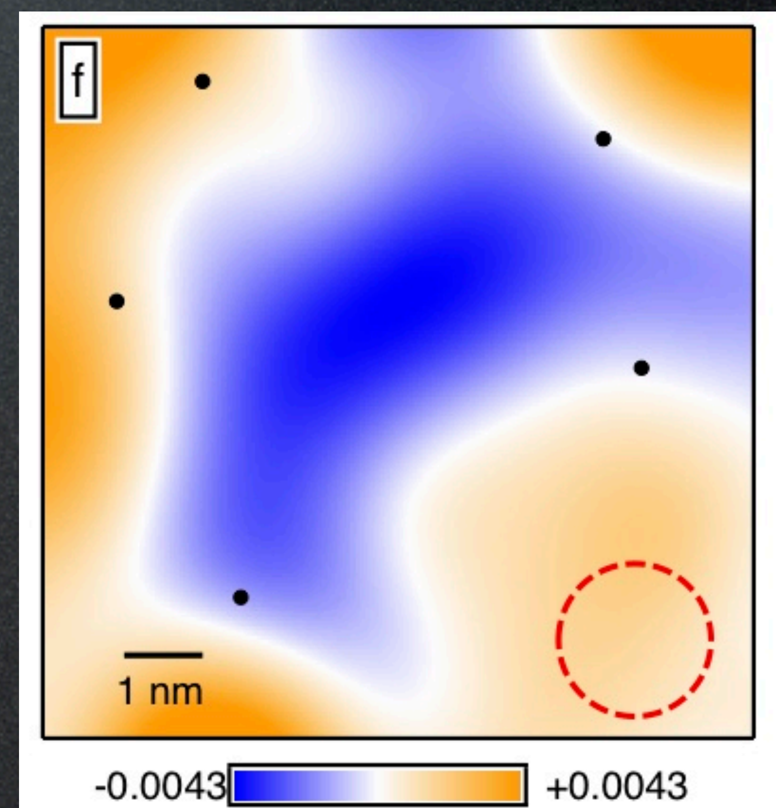
Mesaros, Fujita et al, unpublished

Summary

- Observation of electronic liquid crystals in the pseudogap "states"
- "Long range" nematic order exists in BSCCO
- Nematic order associated with inequivilance of electronic structure at the oxygen sites within the unit-cell.
- Nematic and smectic orders are coupled, shown by footprint signature of smectic dislocations in nematic order.



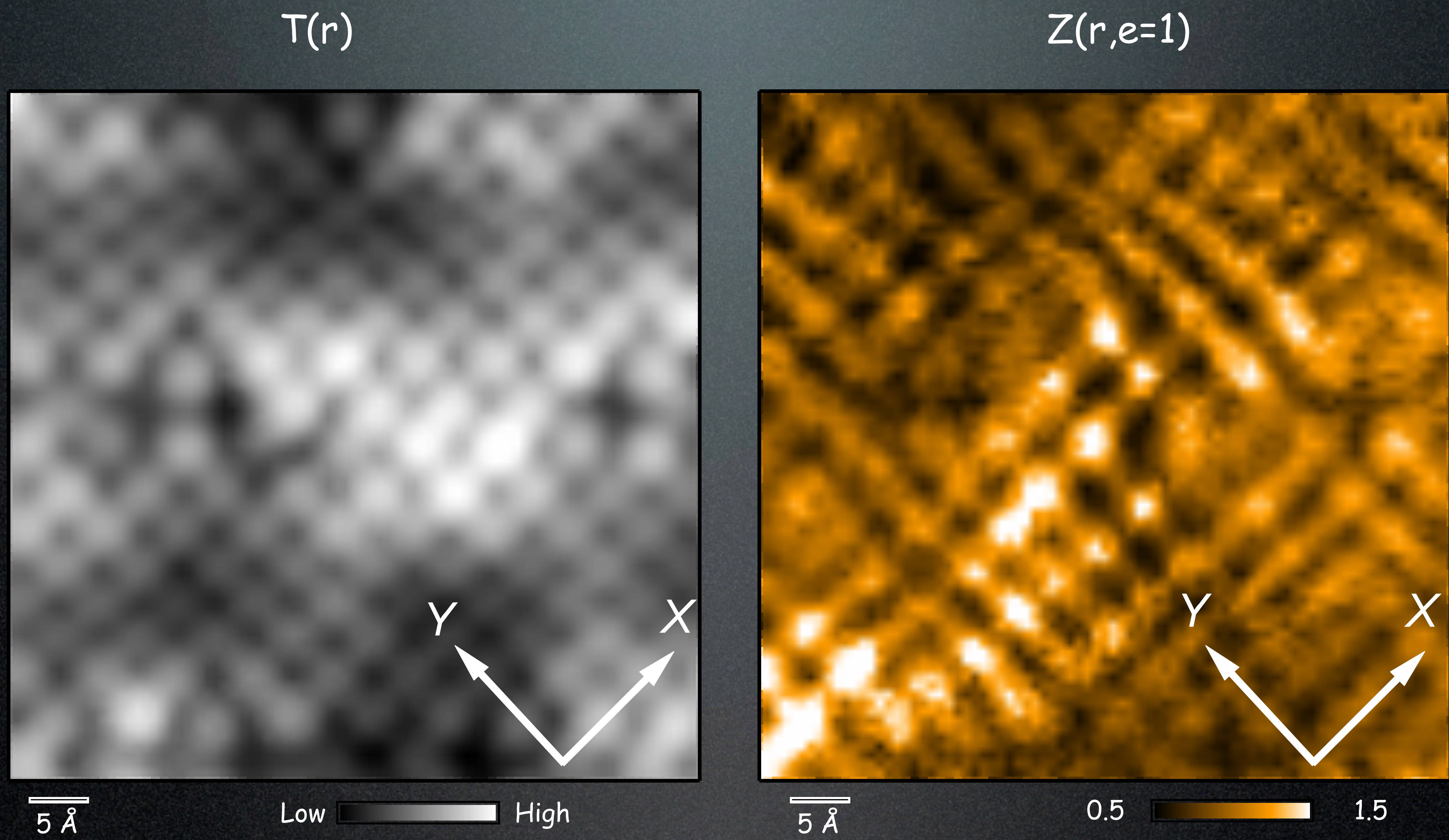




Lawler, Fujita et al, Nature 2010

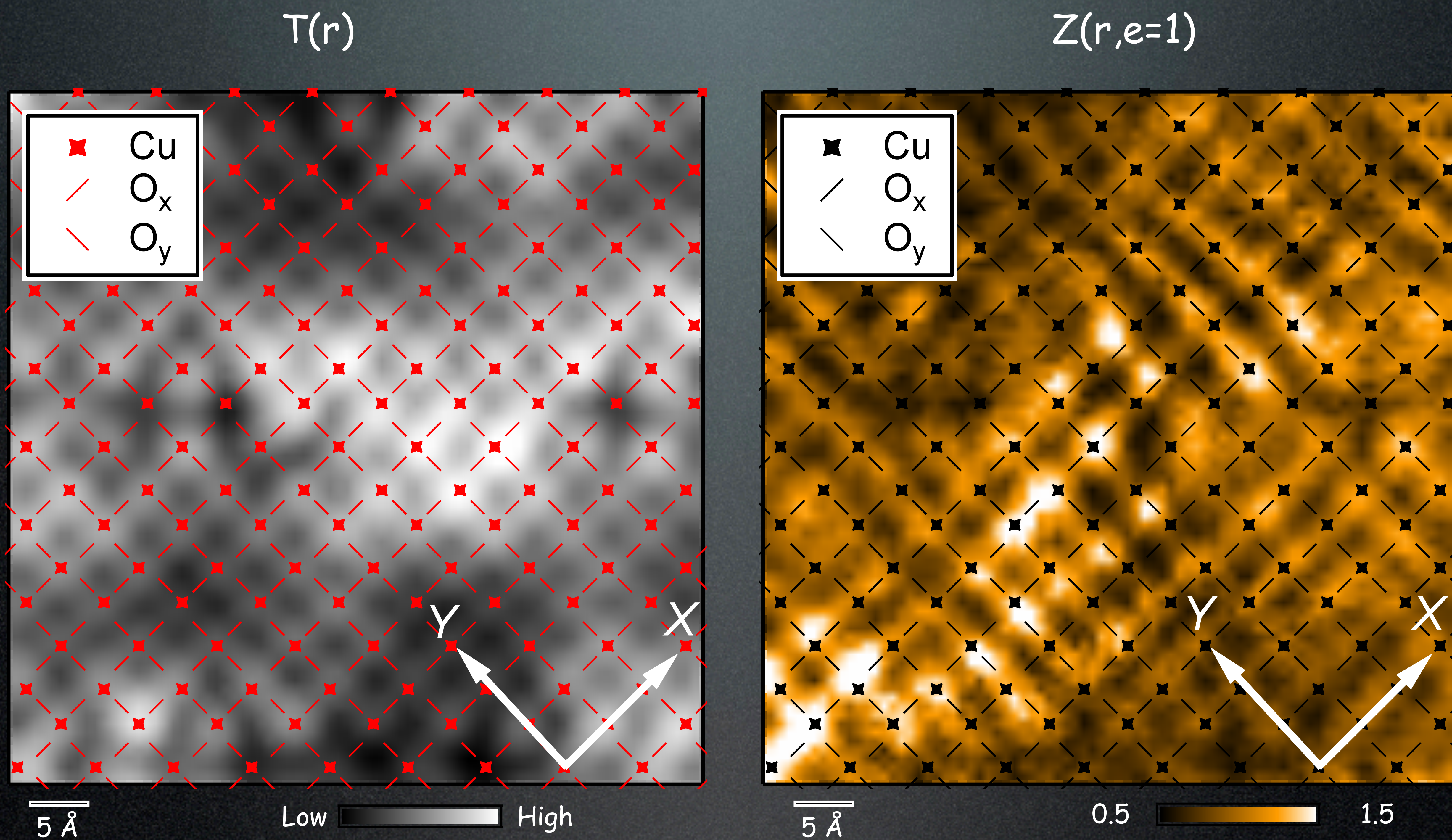
Mesaros, Fujita et al, unpublished

Direct version of nematic order parameter



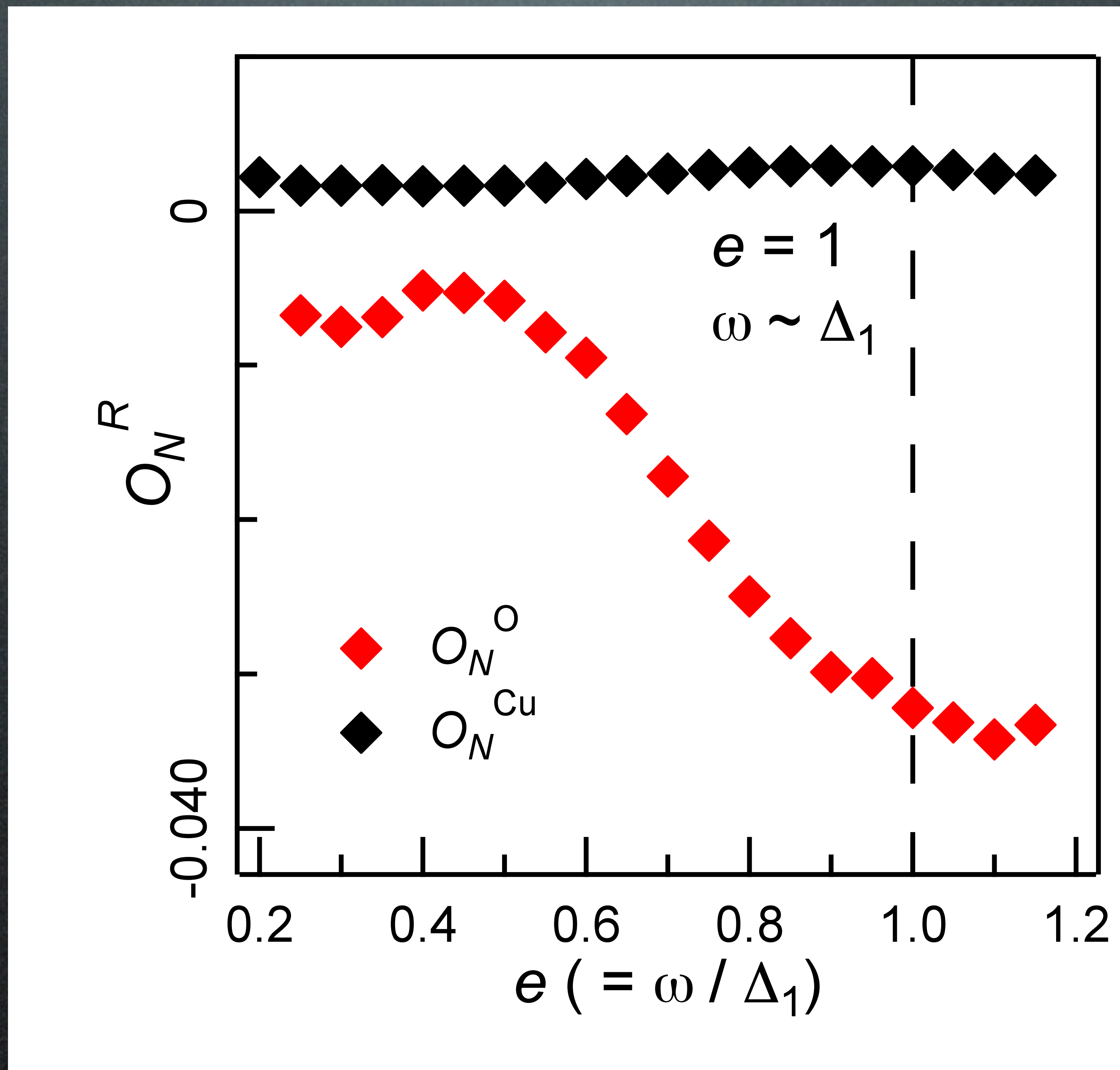
Lawler, Fujita et al, Nature 2010

Direct version of nematic order parameter



Lawler, Fujita et al, Nature 2010

Average of direct order parameter



Lawler, Fujita et al, Nature 2010