Lect2. New probes and new reality

Eun-Ah Kim

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probing possible QPT in the presence of disorder

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probing possible QPT in the presence of disorder

with scanning probes

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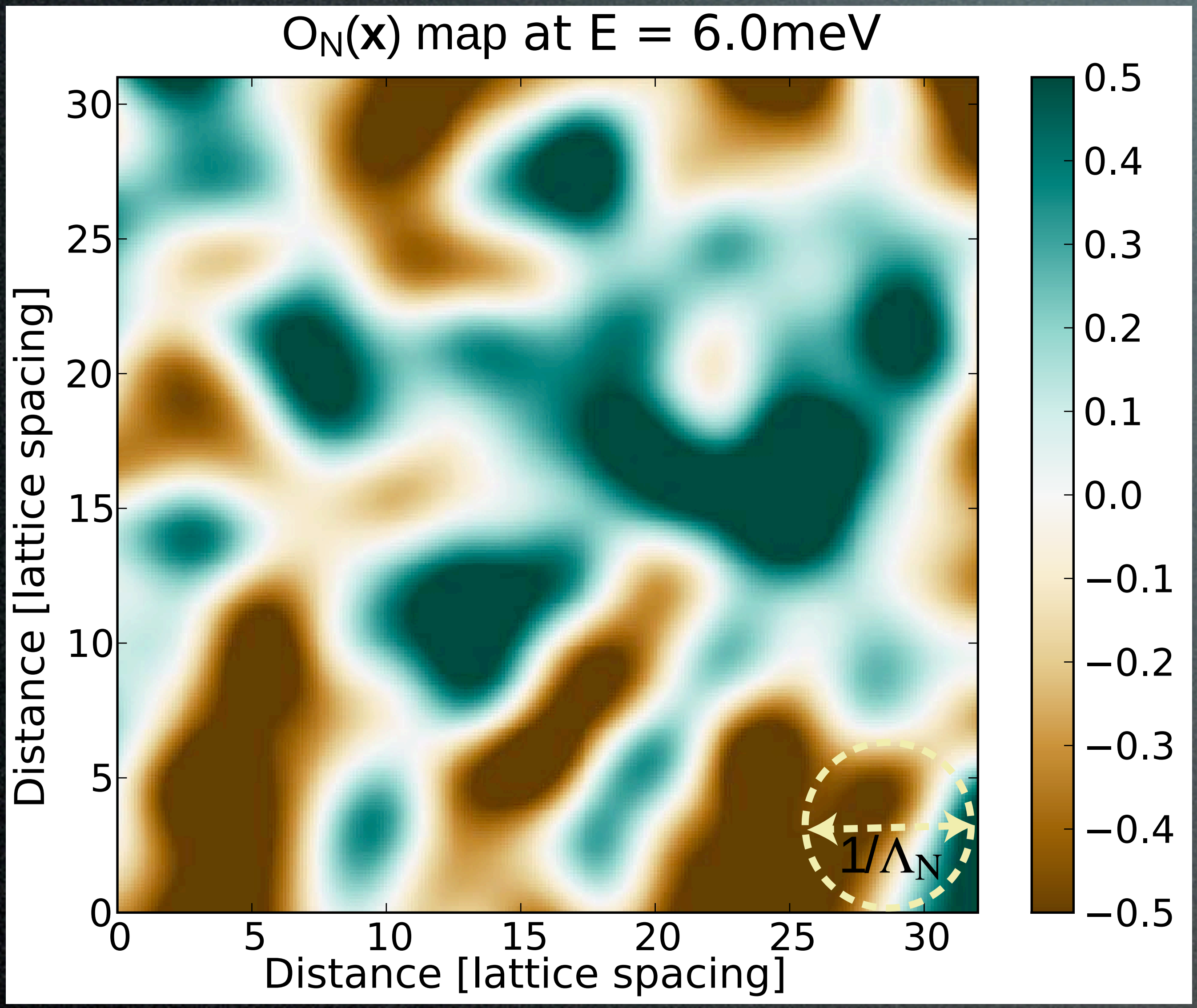
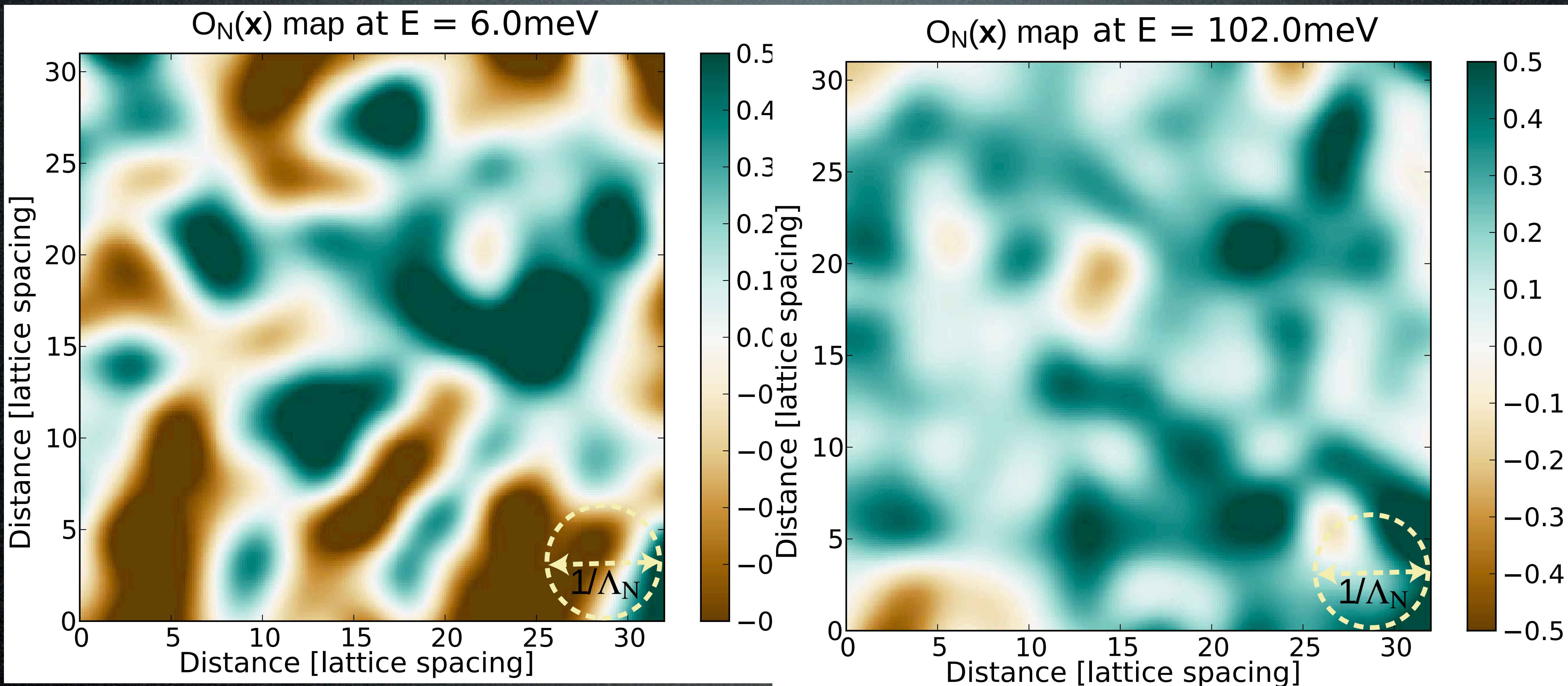

$O_N(\mathbf{x})$ map at E = 6.0meV
Distance [lattice spacing]
Distance [lattice spacing]
$1/\Lambda_N$
0 5 10 15 20 25 30
0 5 10 15 20 25 30
0.5 0.4 0.3 0.2 0.1 0.0 −0.1 −0.2 −0.3 −0.4 −0.5



$O_N(\mathbf{x})$ map at E = 6.0meV
$O_N(\mathbf{x})$ map at E = 102.0meV
Distance [lattice spacing]
Distance [lattice spacing]
Distance [lattice spacing]
Distance [lattice spacing]
$1/\Lambda_N$
$1/\Lambda_N$

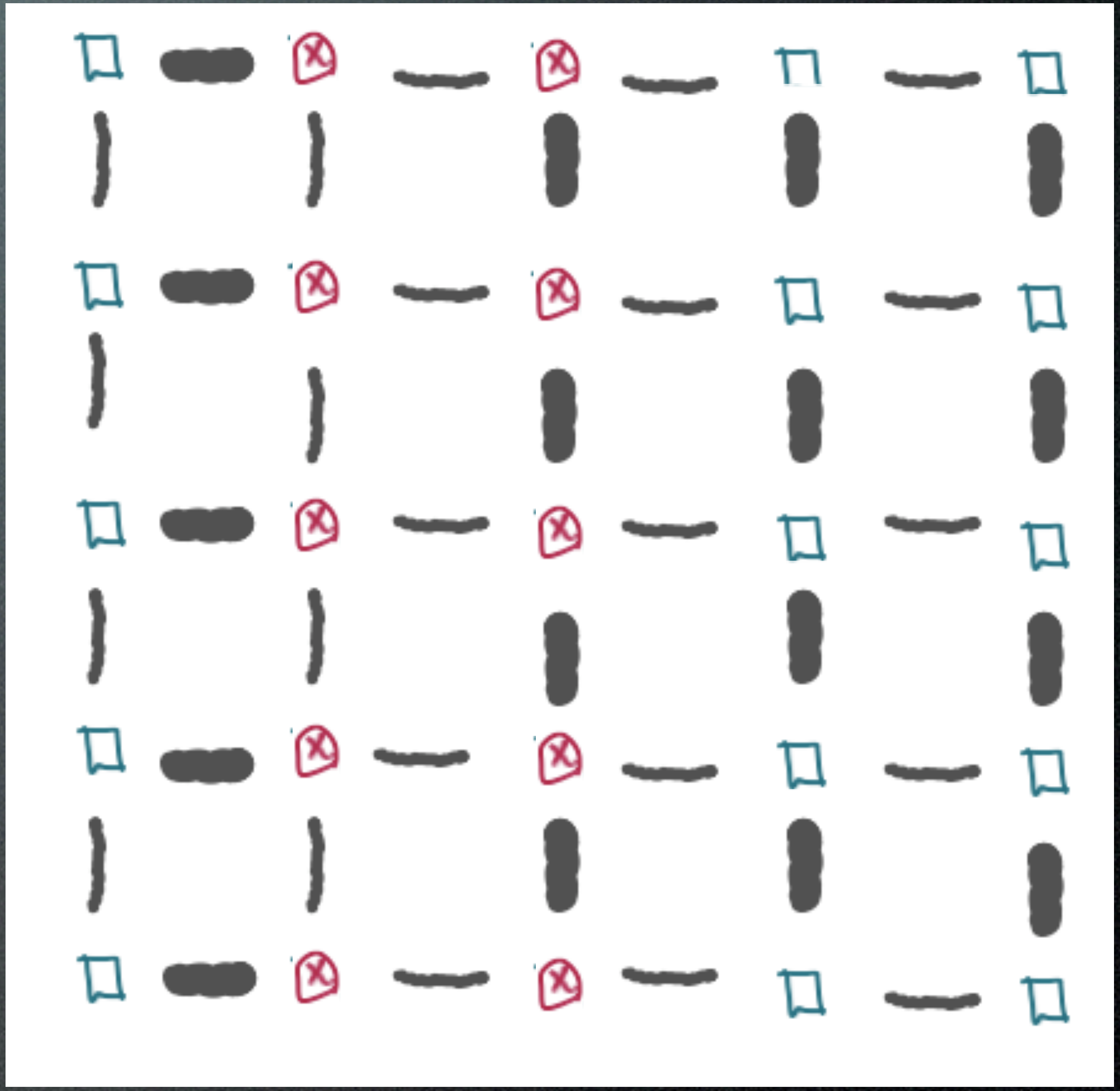
New probes and new reality

- Effect of disorder on QPT’s
- Cuprates, a case study: **got nematic?**
- Look out

Effects of disorder on QPT's

- Disorder is quenched

-perfectly correlated along the τ direction
-correlations increase the disorder effect (harder to average out fluctuation)

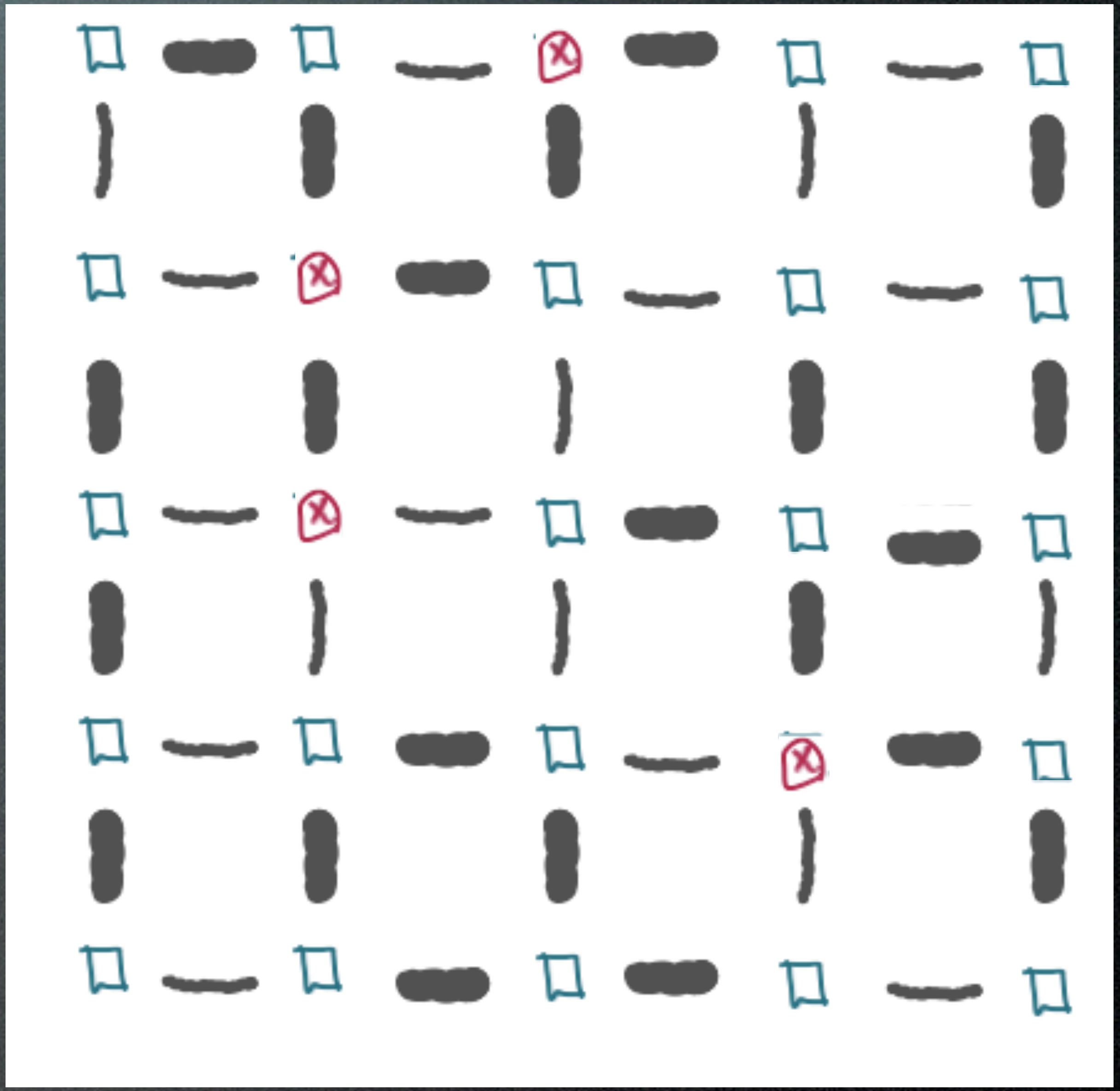


Disorder generically has stronger effects on QPT's than on classical transitions

Ref: T. Vojta, Journal of Phys. A, **39**, 143

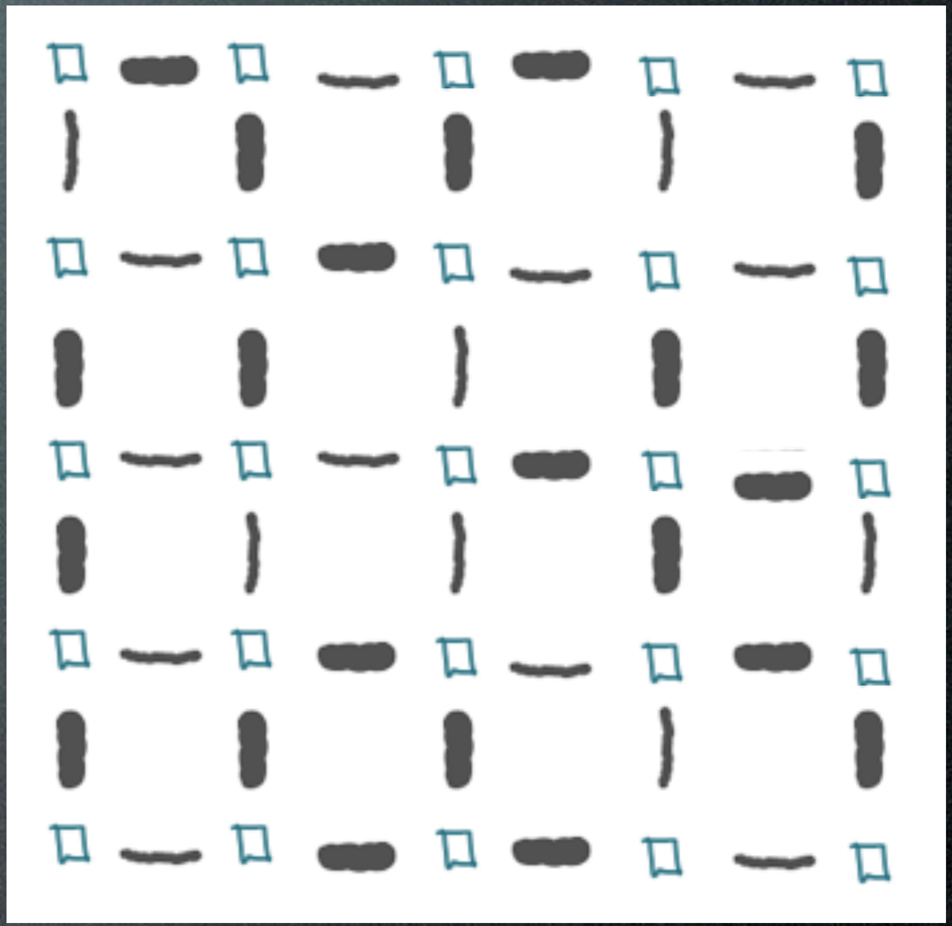
Effects of disorder on Phase Transitions

- Defects, impurities are always present
- Random field v.s T_c: different effects on the classical Ising PT. (Imry-Ma, v.s. Harris)



Harris Criterion (random T_c)

- Variation of average local T_c in volume ξ^d



If true, inhomogeneity vanish at large length scales

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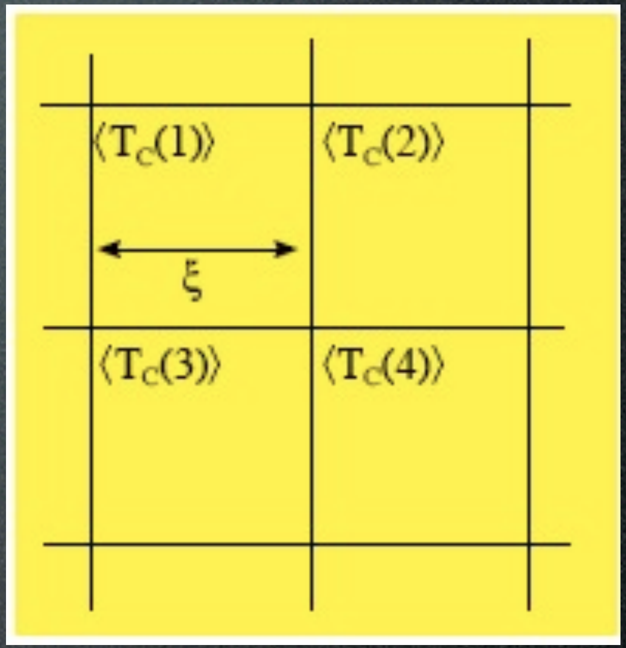

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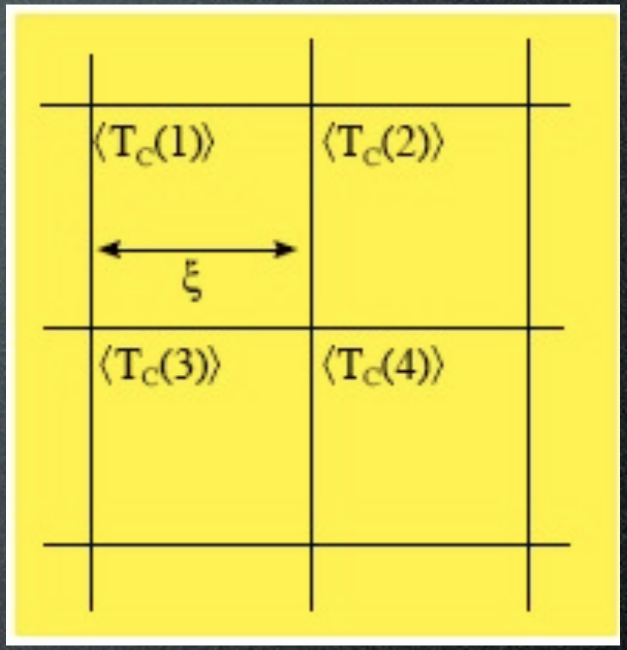
$$\Delta\langle T_c(x)\rangle \sim \xi^{-d/2}$$



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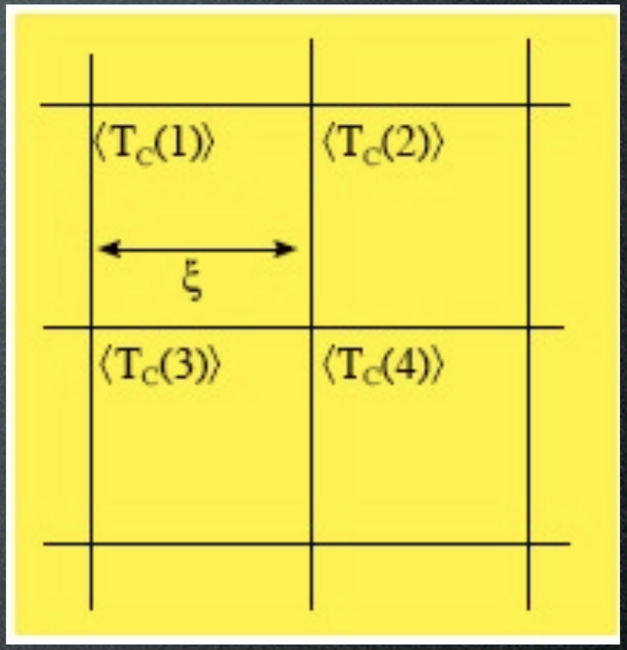
- "Distance" from global T_c in volume ξ^d

$$t \sim \xi^{-1/\nu}$$



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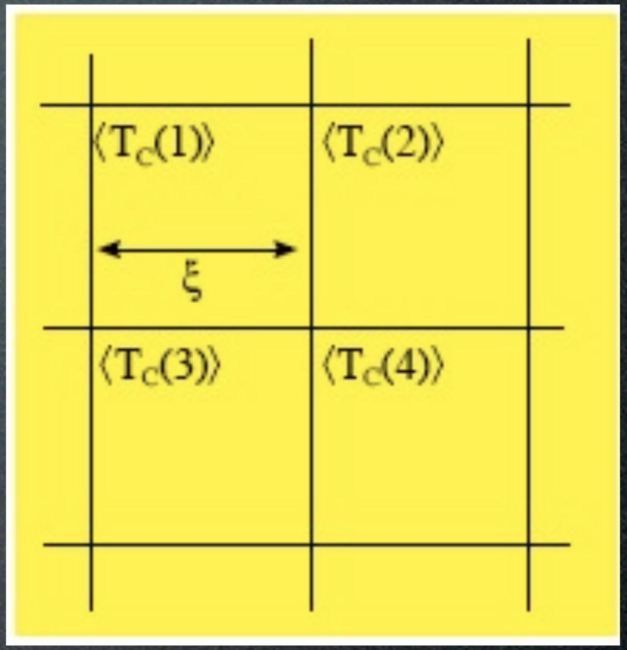
$$t \sim \xi^{-1/\nu}$$

- Harris criterion

$$\Delta \langle T_c(x) \rangle < t \quad \Leftrightarrow \quad d\nu > 2$$

If true, inhomogeneity vanish at large length scales



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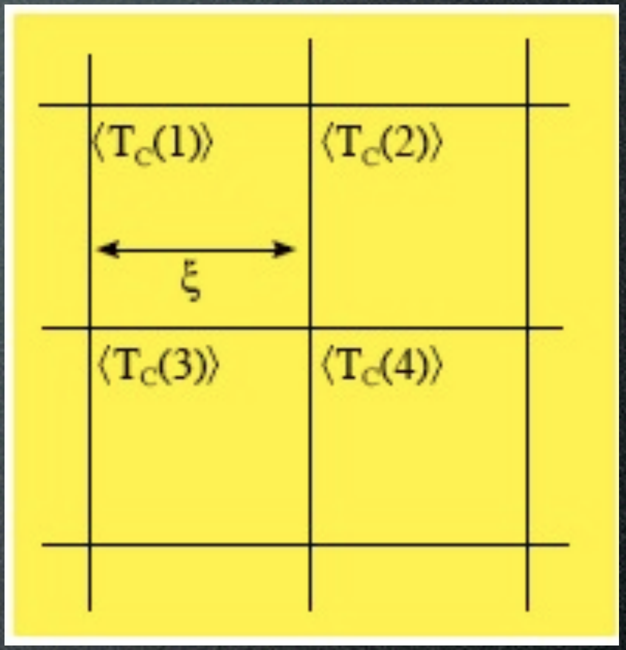


- "Distance" from global T_c in volume ξ^d

$$t \sim \xi^{-1/\nu}$$

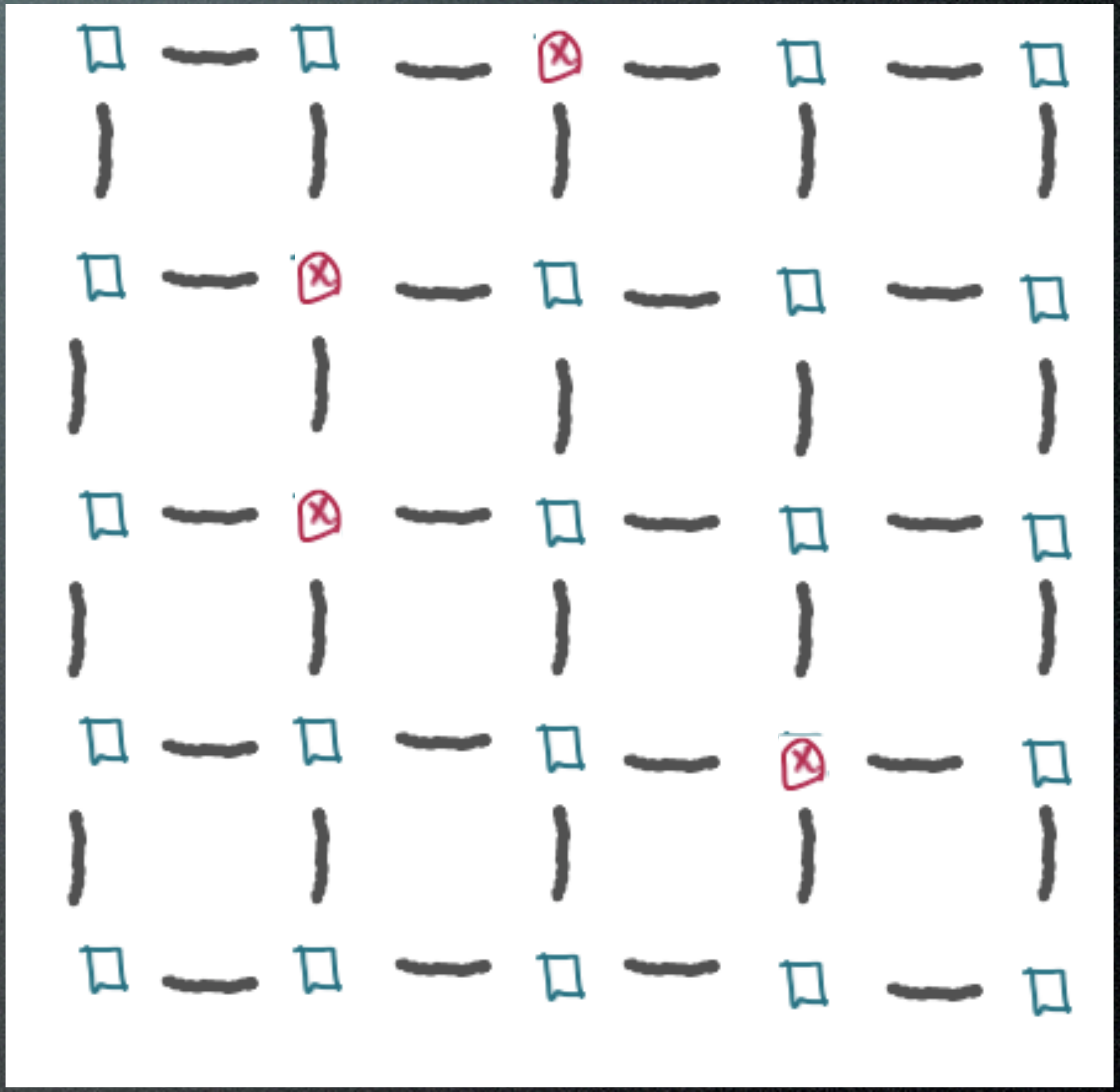
- Harris criterion

$$\Delta\langle T_c(x)\rangle < t \iff d\nu > 2$$ about clean CP.

If true, inhomogeneity vanish at large length scales

Imry-Ma argument (random field)

- Random field breaks the order parameter symmetry
- Domains are pinned by the local fields
- Transition is rounded for $d \leqslant 2$
- At $d=2$ (lower critical dimension), domains are exponentially large



Know your OP and the types of disorder

Nematic QPT in cuprates?

Nematic QCP, license to exist?

PHYSICAL REVIEW B **77**, 184514 (2008)

Theory of the nodal nematic quantum phase transition in superconductors

Eun-Ah Kim,[1] Michael J. Lawler,[2] Paul Oreto,[1] Subir Sachdev,[3] Eduardo Fradkin,[3] and Steven A. Kivelson[1]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[3]*Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801-3080, USA*
(Received 15 February 2008; published 22 May 2008)

- Nodal nematic QCP
  deep inside d-wave SC

Nematic QCP, license to exist?

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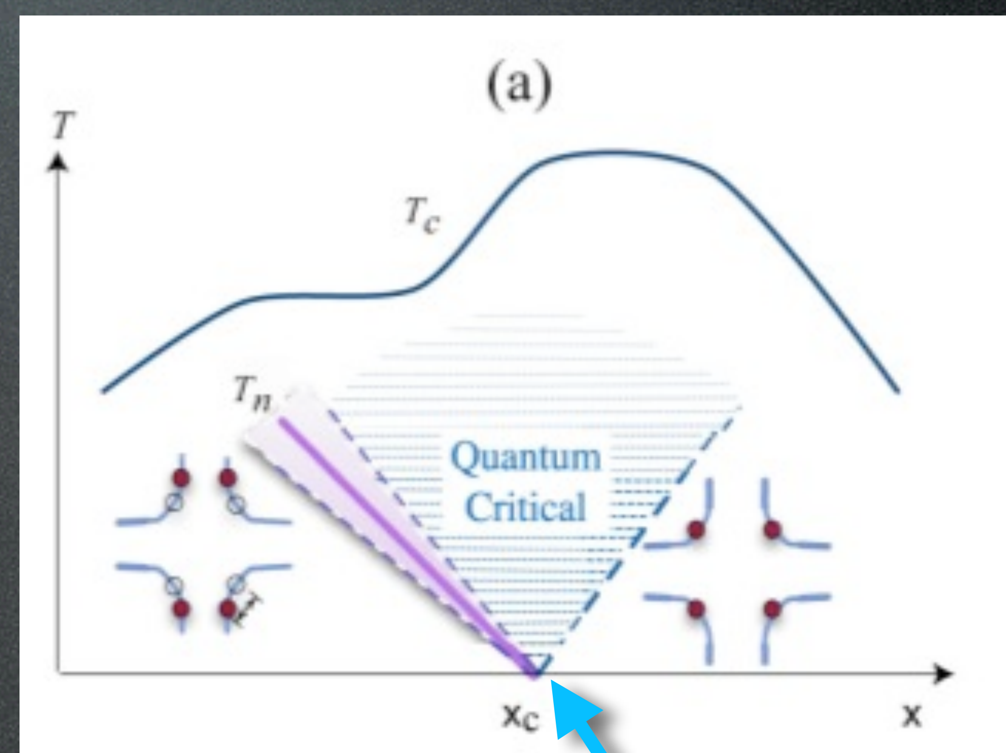

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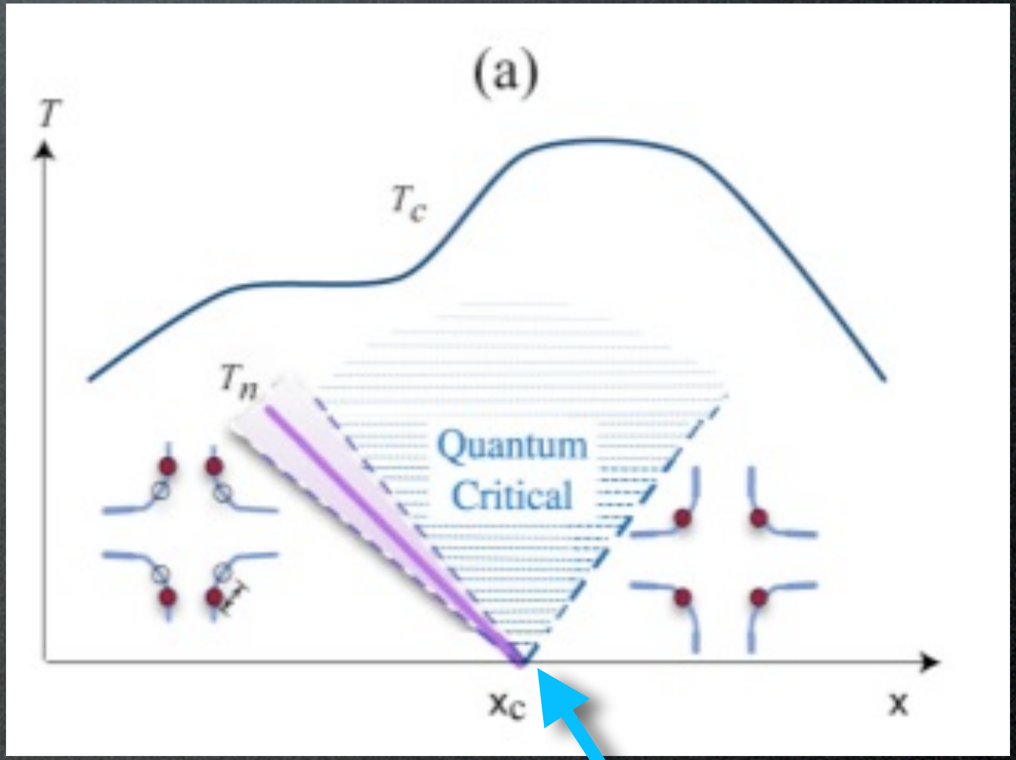
- Nodal nematic QCP
  deep inside d-wave SC

- Nematic d-SC:
  d-SC + small s-component

  $\Delta_d(\cos k_x - \cos k_y) + \lambda\phi$



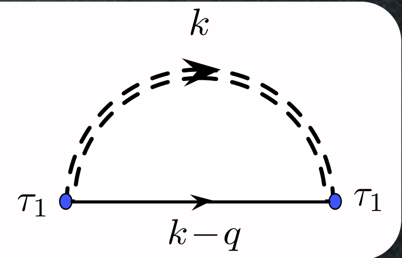
nematic QCP inside SC phase?

Looking for nematic critical fluctuations

- Self energy $\hat{\Sigma}(\vec{q},\omega)$ due to fluctuation

:k-selective decoherence

$$\Sigma_{\Psi_i}(\vec{q},\omega) =$$



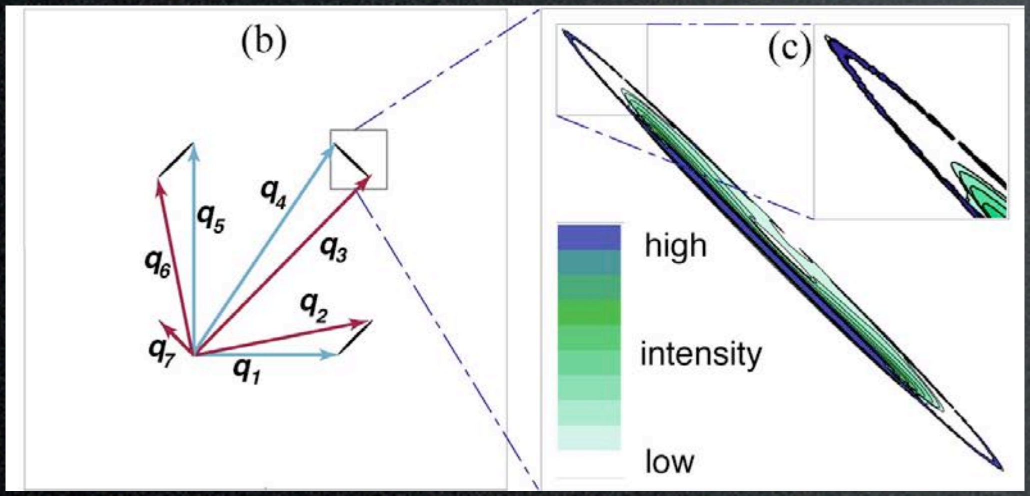
Interference of nematic quantum critical quasiparticles: a route to the octet model

Eun-Ah Kim[1] and Michael J. Lawler[2,1]

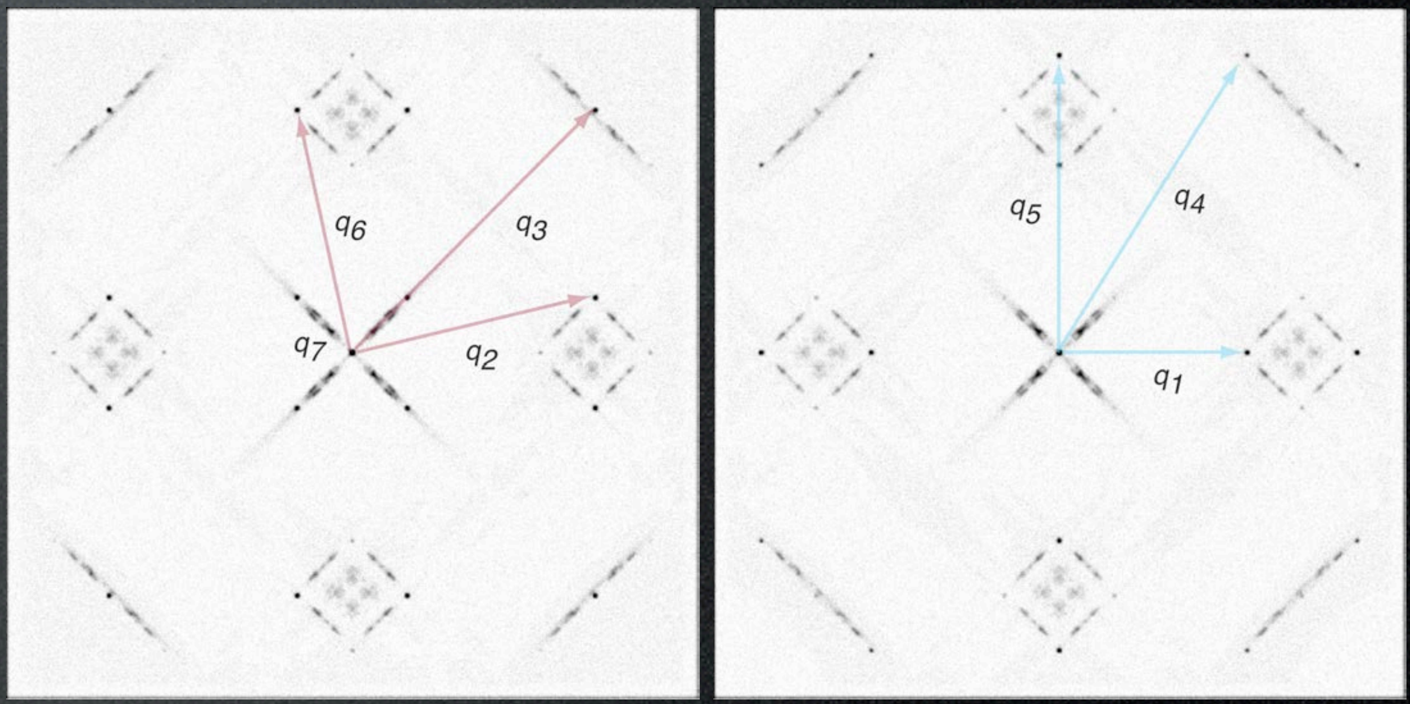
[1]*Department of Physics, Cornell University, Ithaca, NY 14853*
[2]*Department of Physics, Binghamton University, Binghamton NY 13902*

(Dated: November 13, 2008)

arXiv:0811.2242



→ QPI peaks



(b) (c)

BSCCO, got nematic?

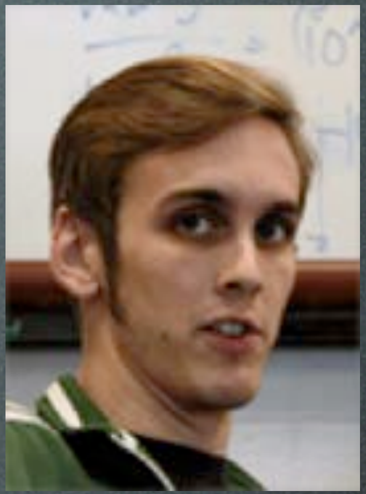
Acknowledgements

Prof. Michael Lawler

Binghamton, Cornell

Prof. James Sethna

Cornell



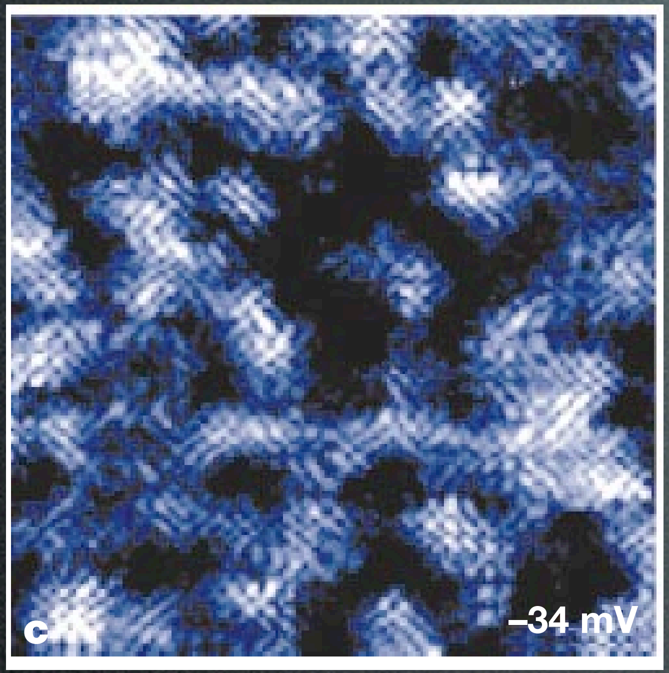
Dr. Andy Schmit

Cornell

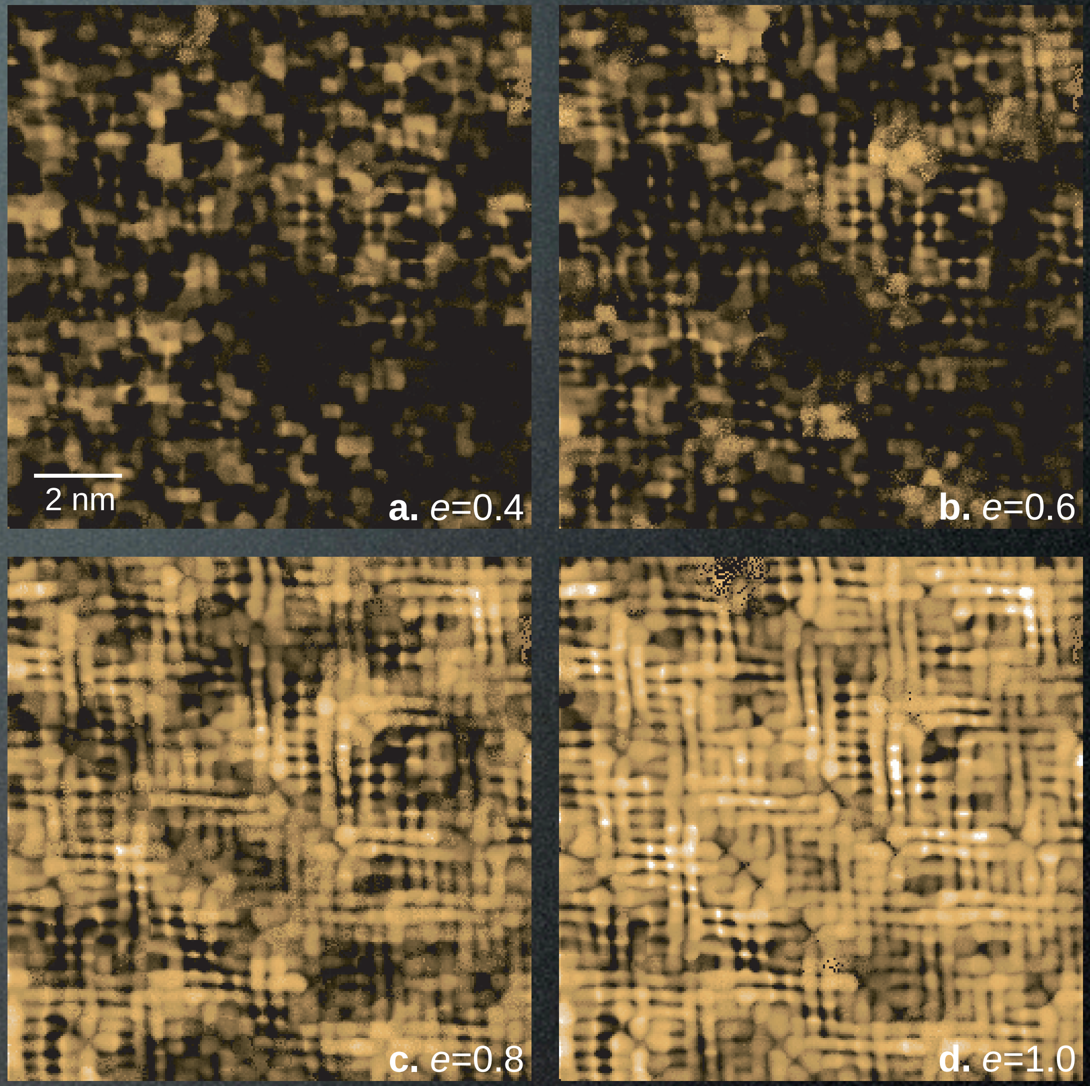
Prof. Seamus Davis

Cornell, BNL

Local measure of broken symmetry?



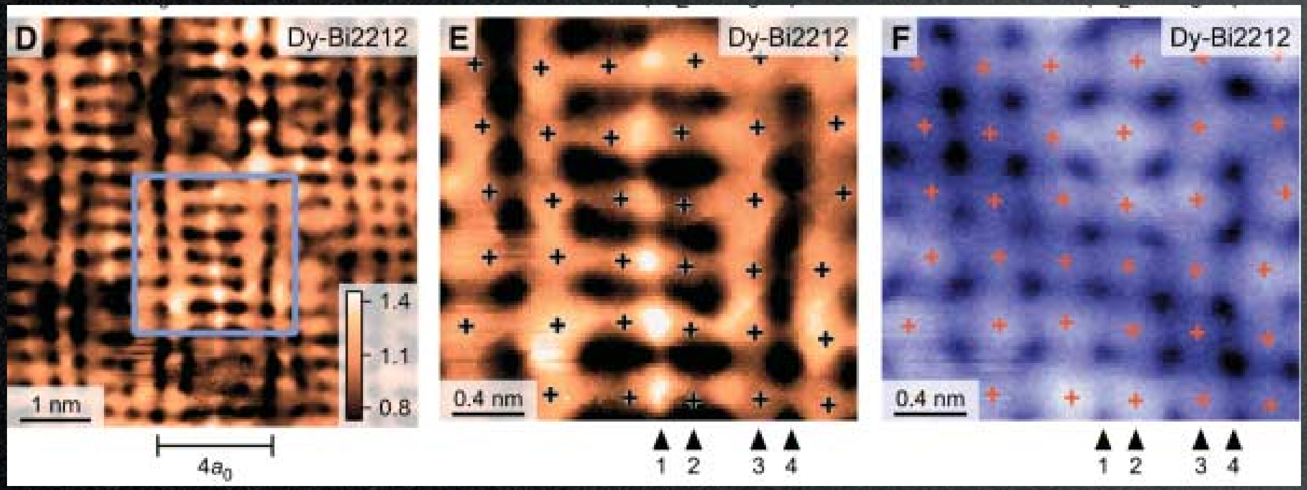
dI/dV(ω)-map
McElroy et al, Nature 422, 592 (2003)
OD T_c=86K (p=)



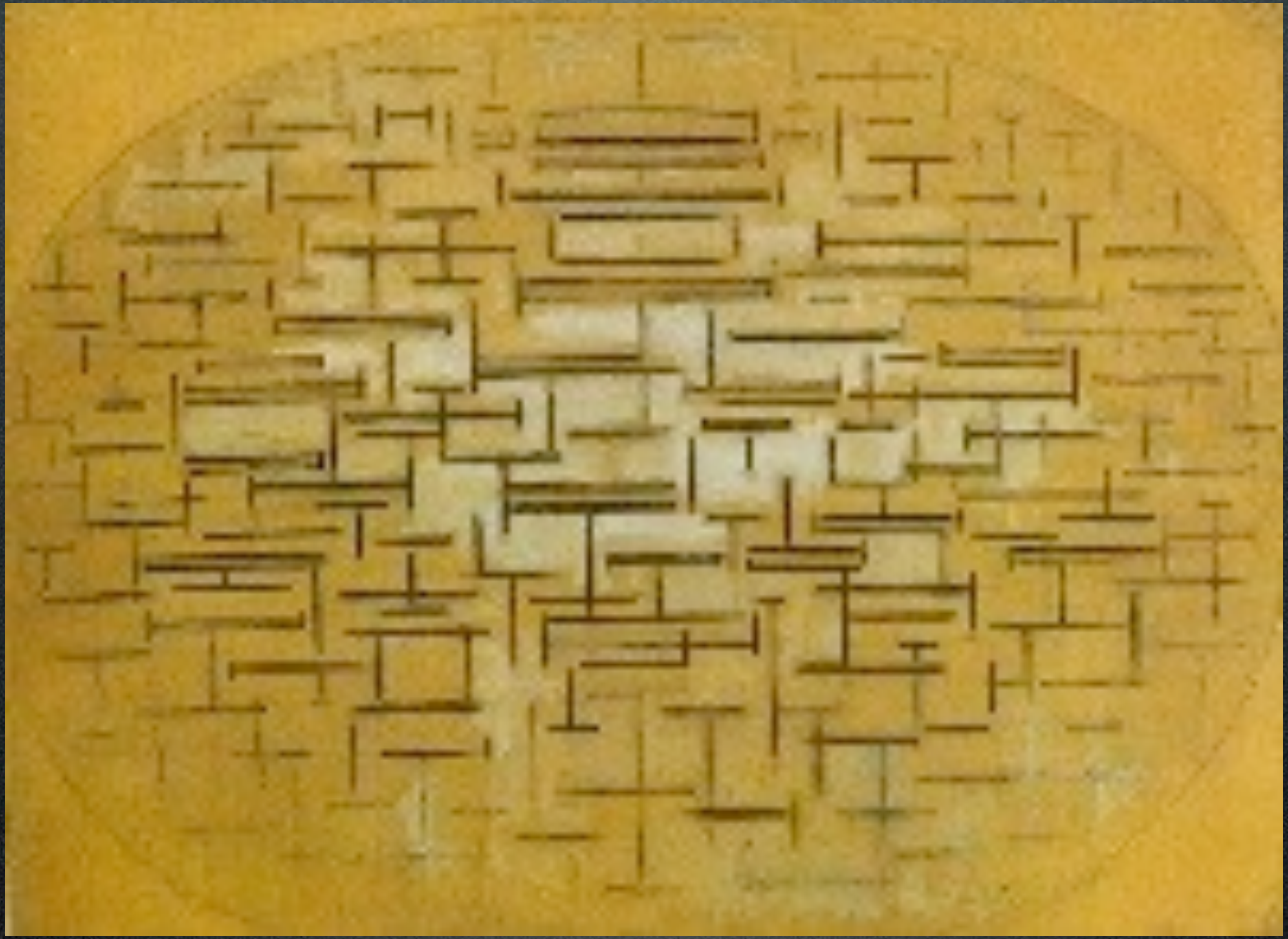
0.69 1.8

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



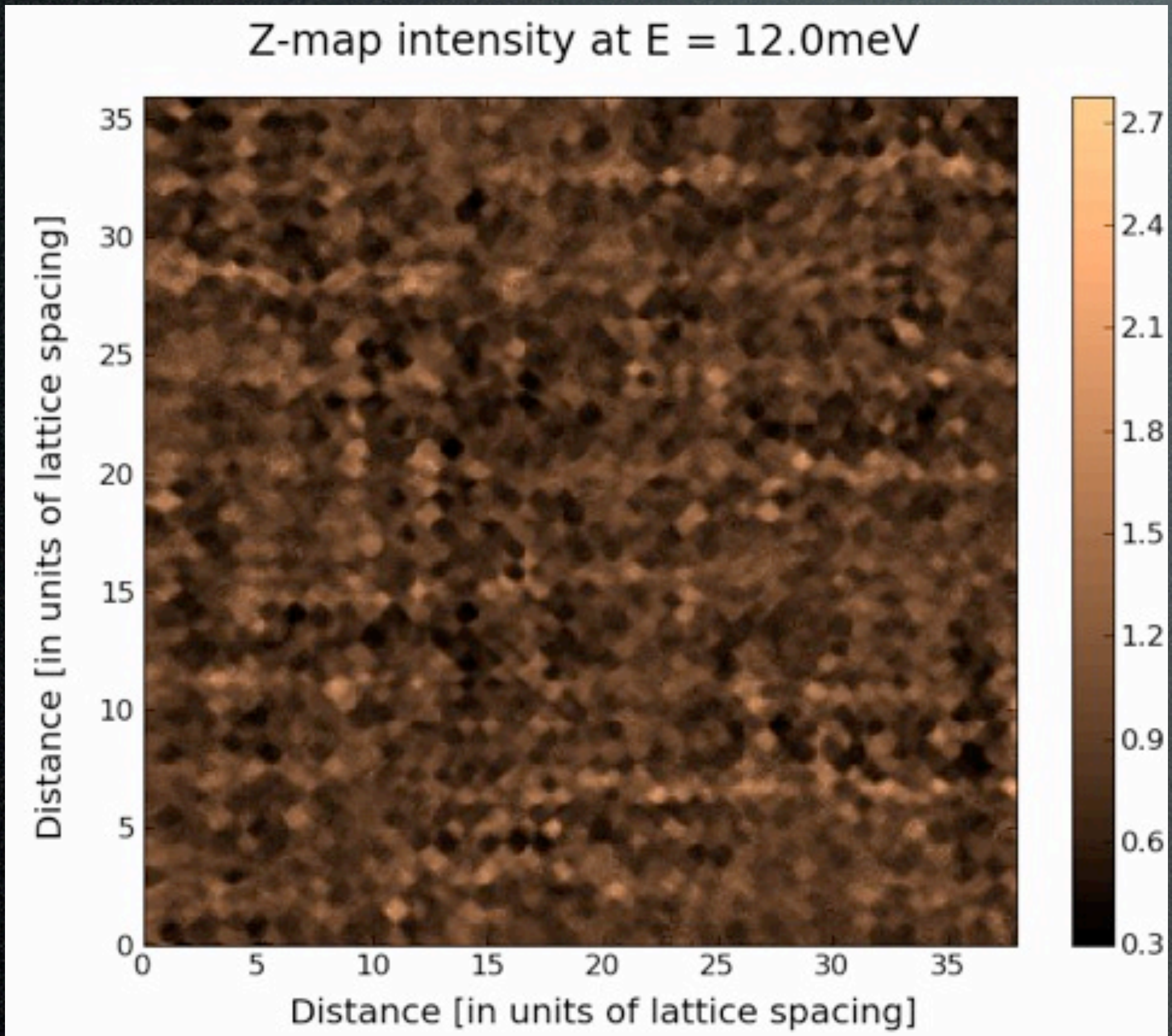
R-map
Kohsaka et al, Science 315, 1380 (2007)
UD T_c=45K (p=0.08)

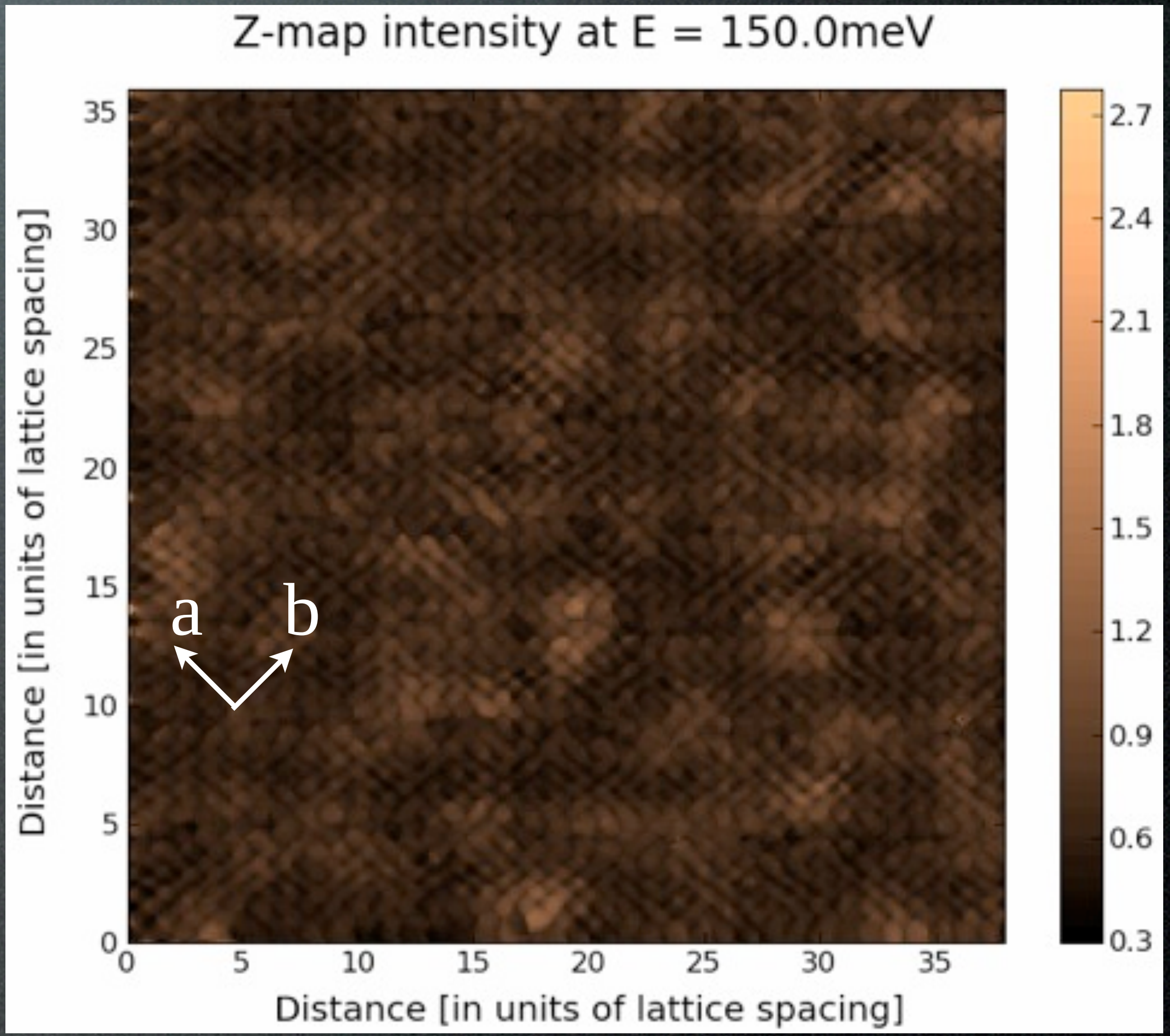


Piet Mondrian, 1915. Says he is searching for hidden order in nature...

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 (S. Chakravarty's perspectives Science 08)





UD T_c=45K (p=0.08) Kohsaka et al, Nature 454, 1072 (2008)

Challenge: An objective measure

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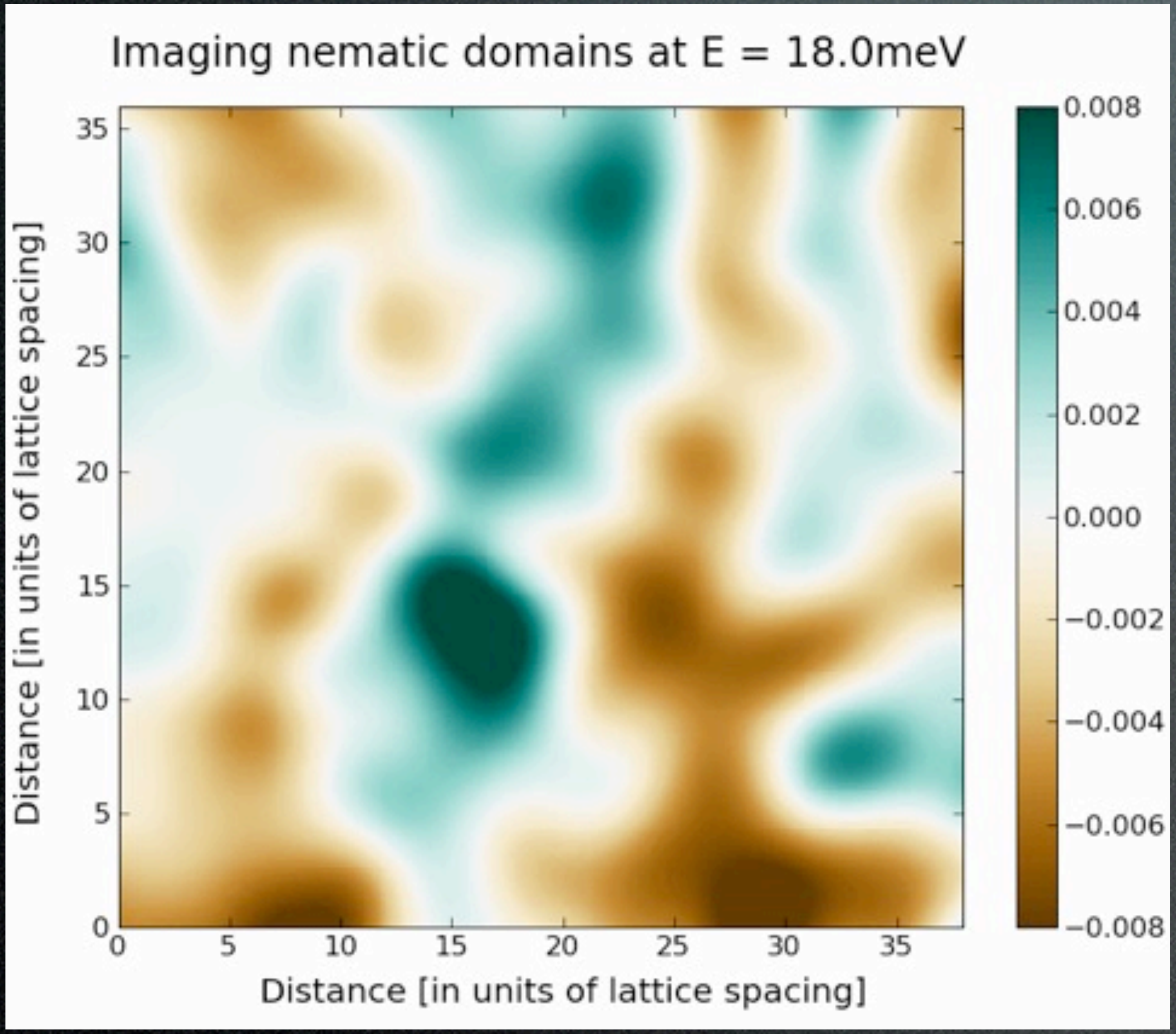
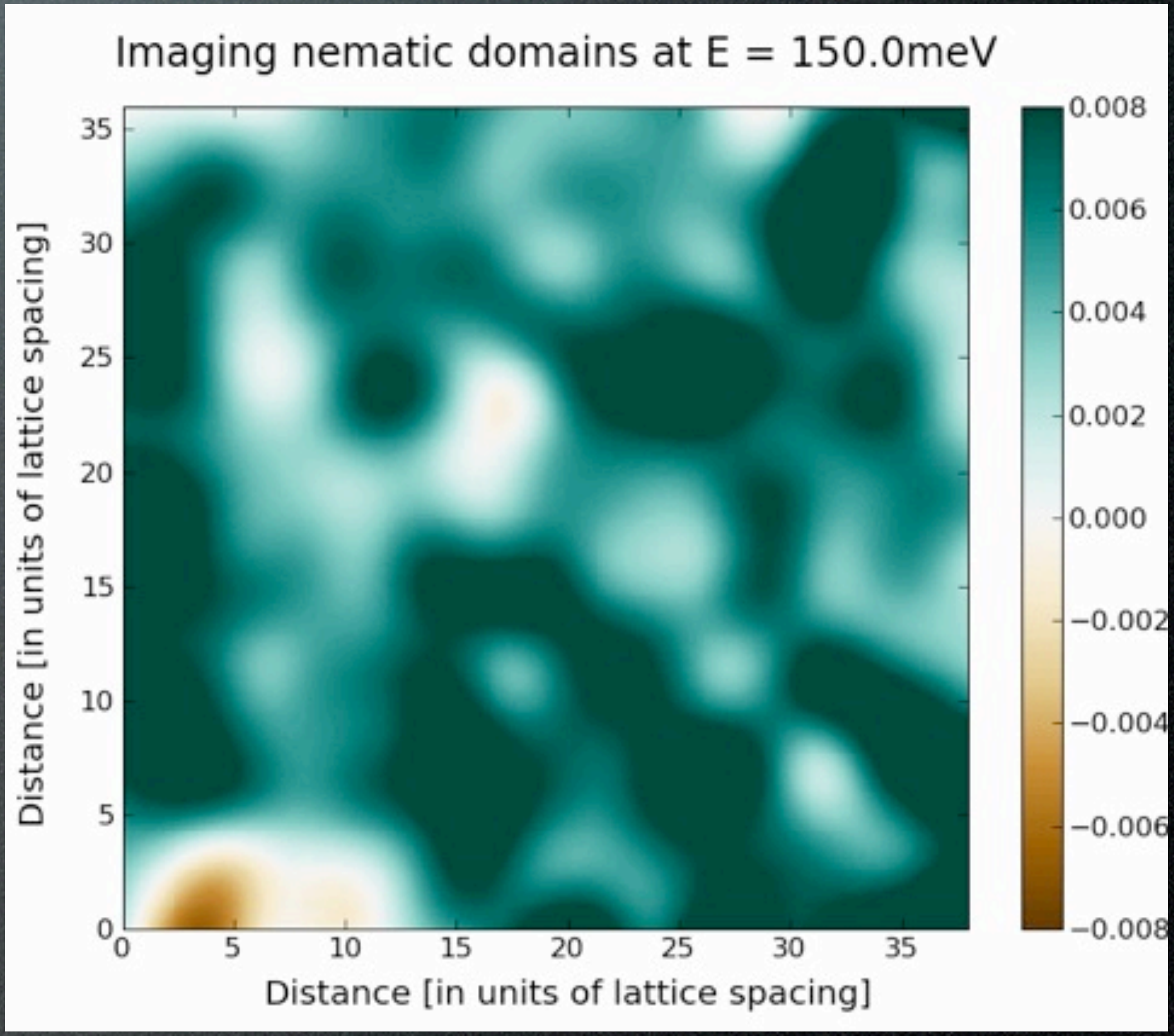
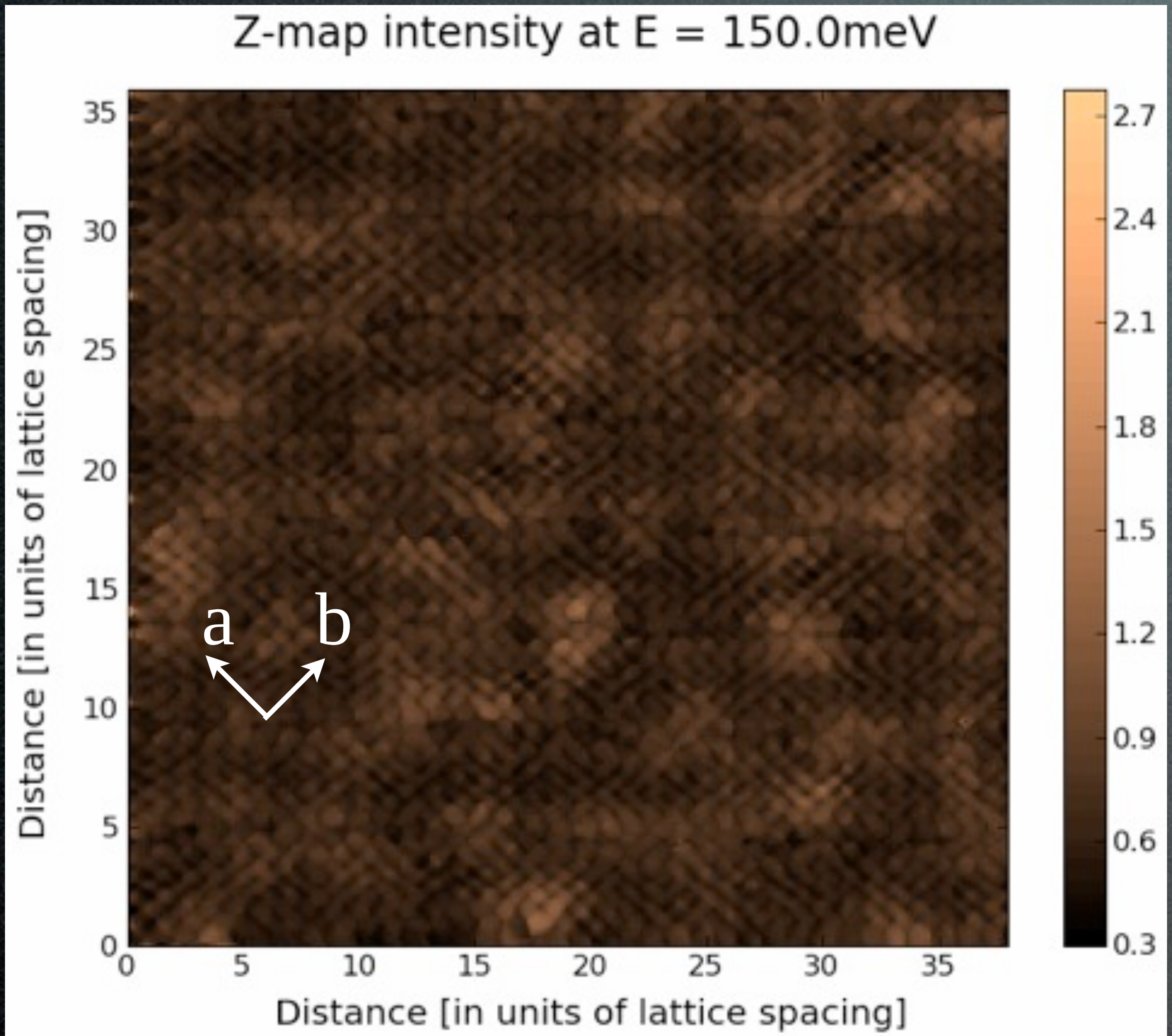




M. Lawler et al, in prep.

Challenge: An objective measure

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

On the shoulder of

- Relating asymmetry to a quantitative measure

$$Z(\mathbf{r}, \mathrm{w}) \qquad R(\mathbf{r})$$

P. Anderson, N.P. Ong
J. Phys. Chem. Solids, **67**,1(1993)

M.B.J. Meinders, H. Eskes, G.A. Sawatzky
Phys. Rev. B, **48**, 3916 (1993)

M. Randeria et al,
PRL **95**, 137001 (2005)

- Fourier filtering to look for stripe

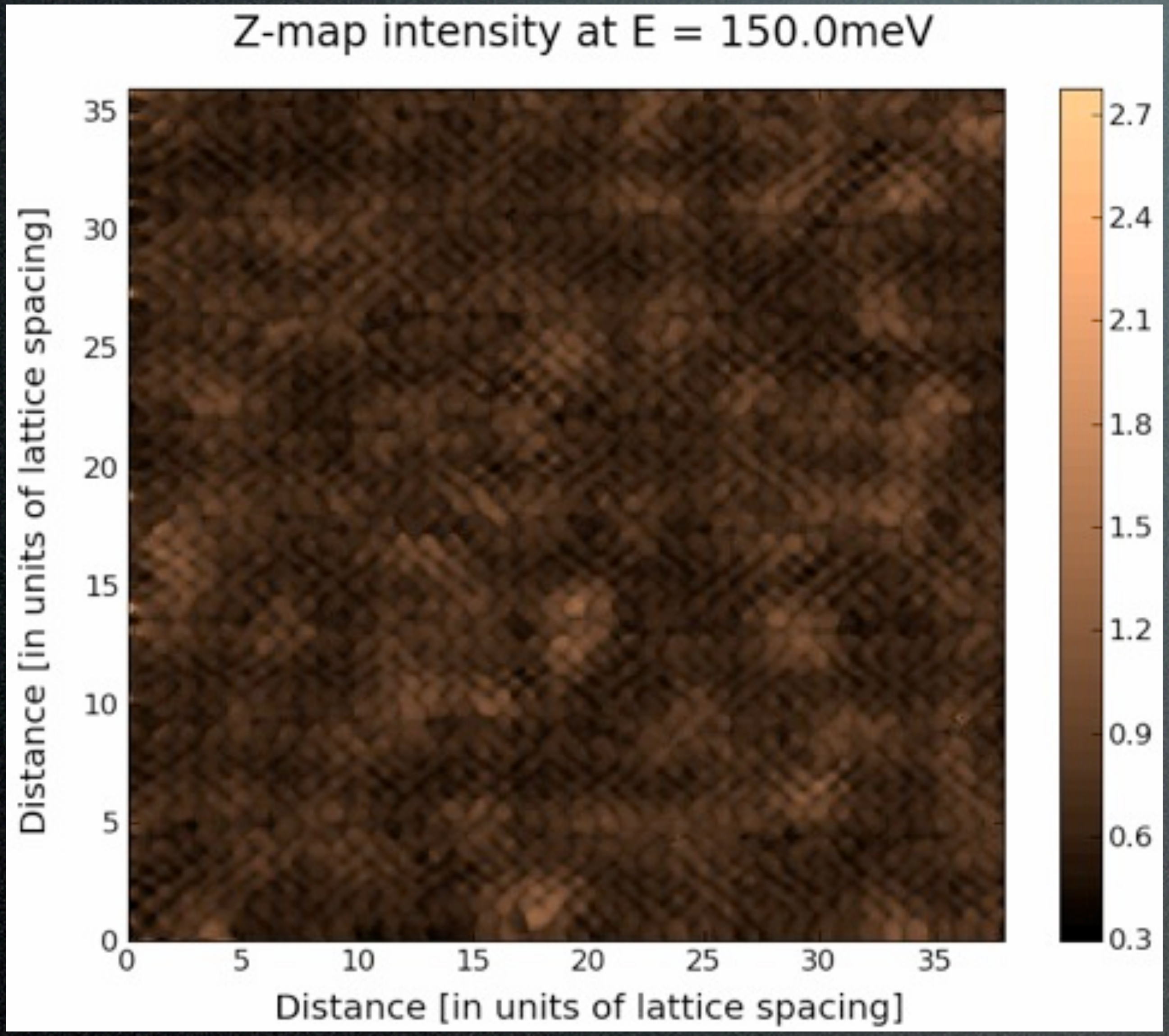
$$N_f(\mathbf{r},E)=\int d\mathbf{r}' f(\mathbf{r}-\mathbf{r}')N(\mathbf{r}',E),$$

$$f(\mathbf{r})\propto \Lambda^2 e^{-r^2\Lambda^2/2}[\cos(\pi x/2a)+\cos(\pi y/2a)].$$

C. Howald et al,
PRB **67**, 014533 (2003)

S. Kivelson et al,
RMP **75**, 1201 (2003)

Local measure of broken symmetry?



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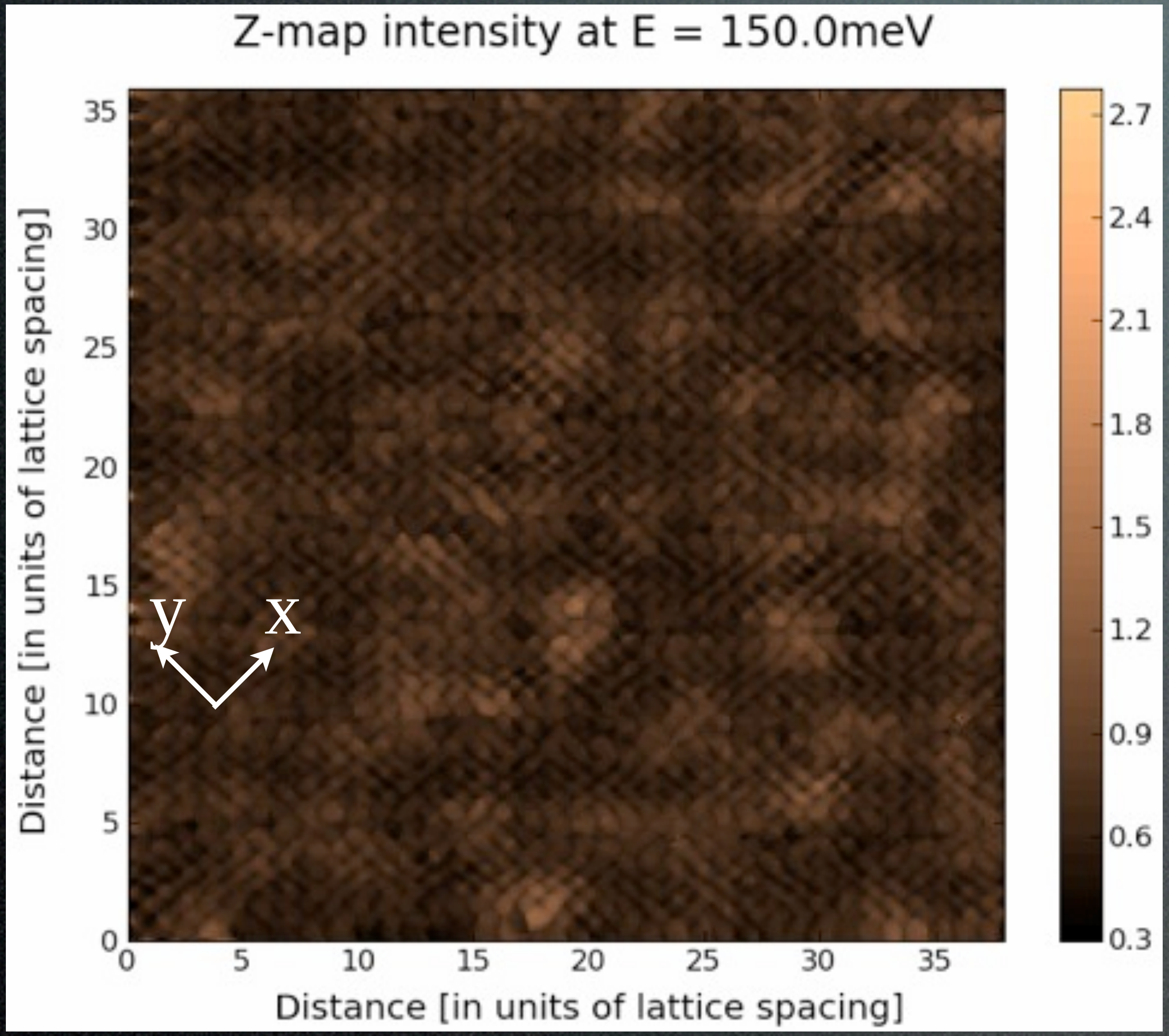

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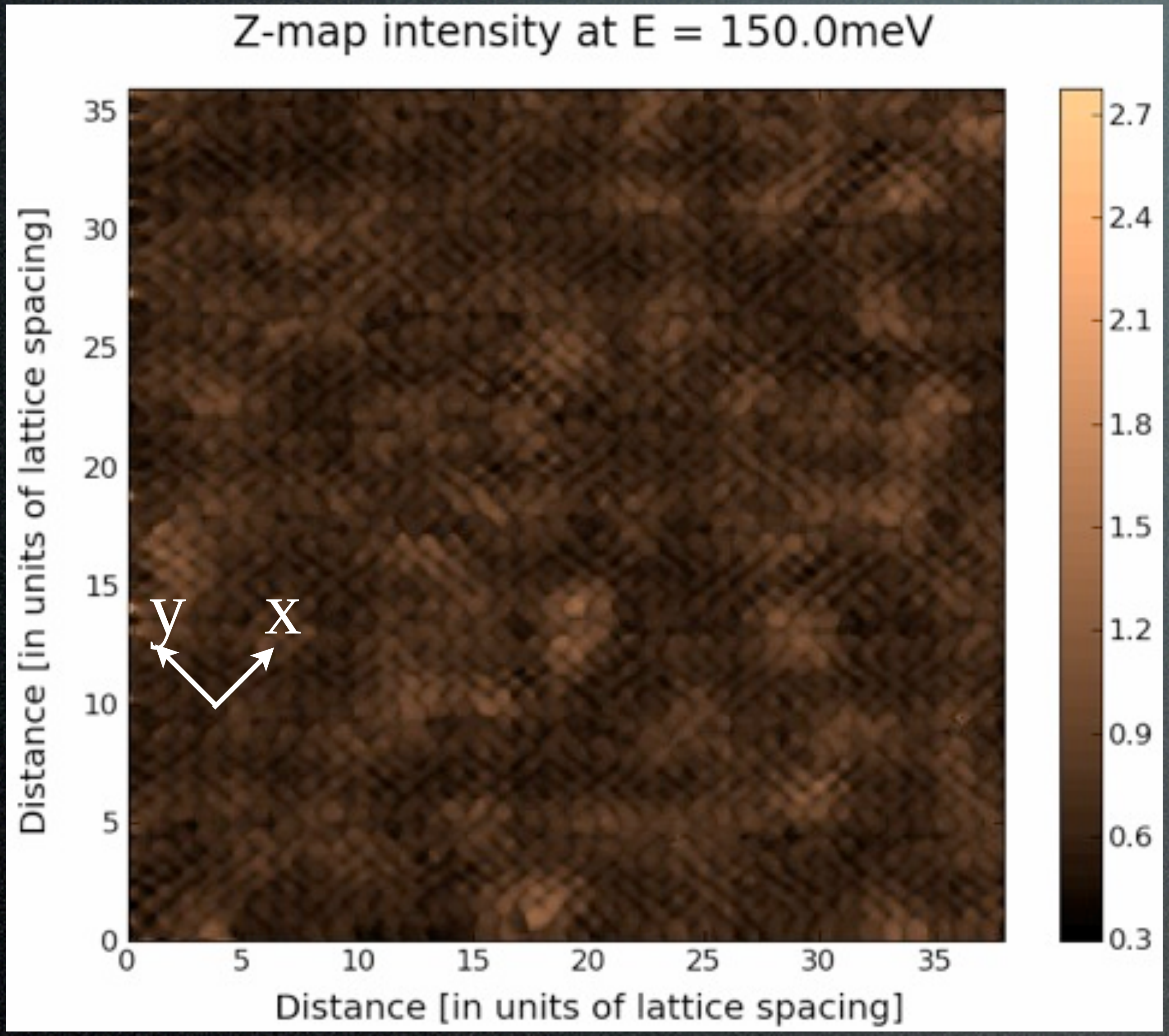

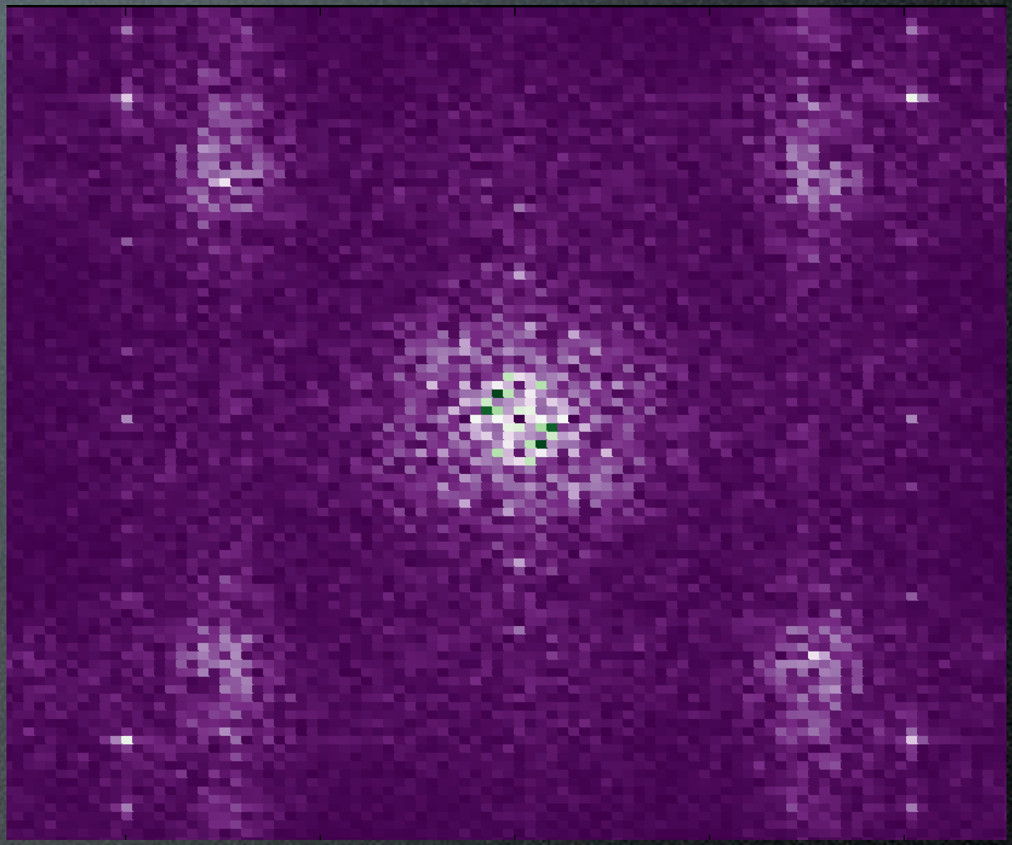

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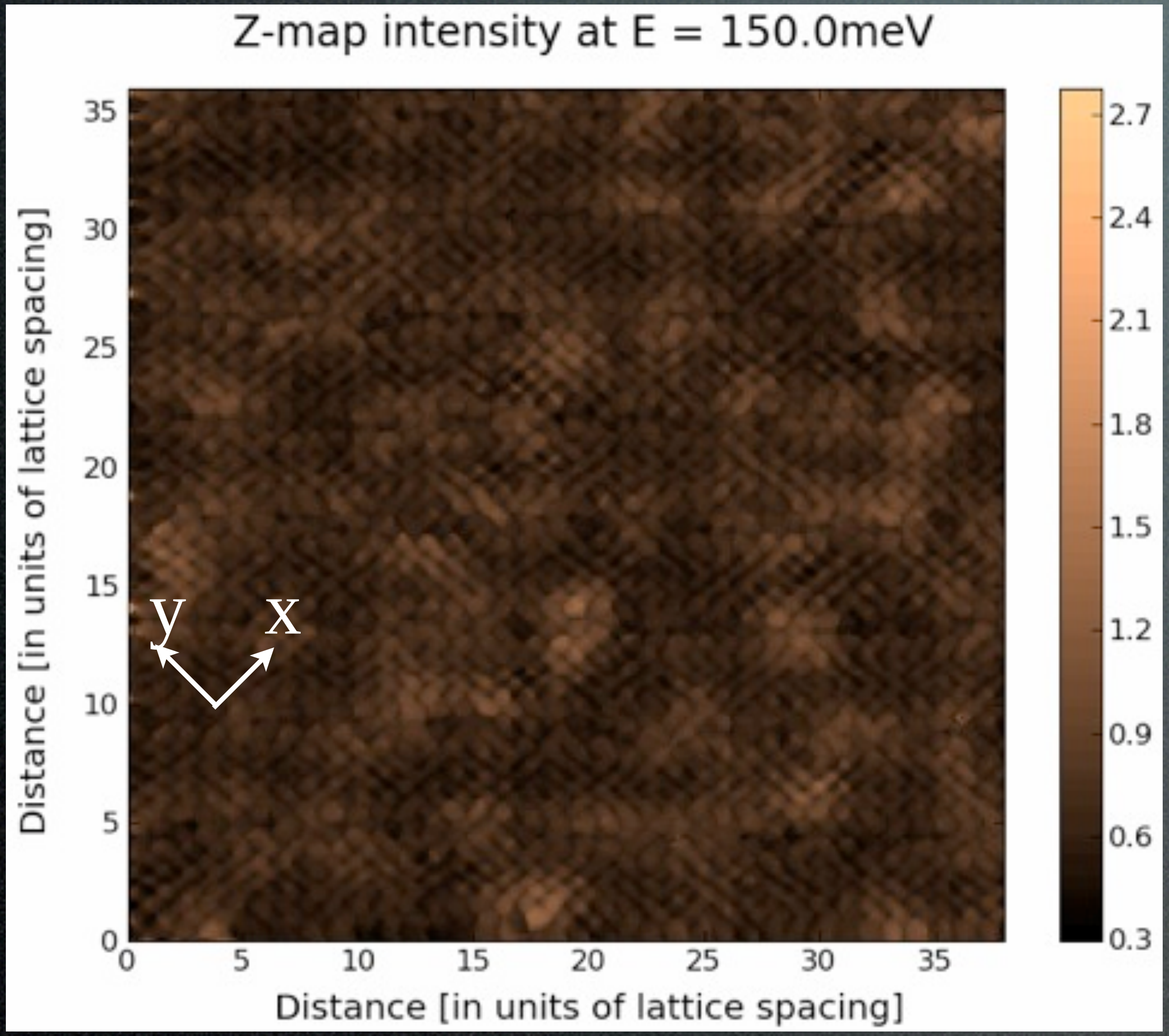

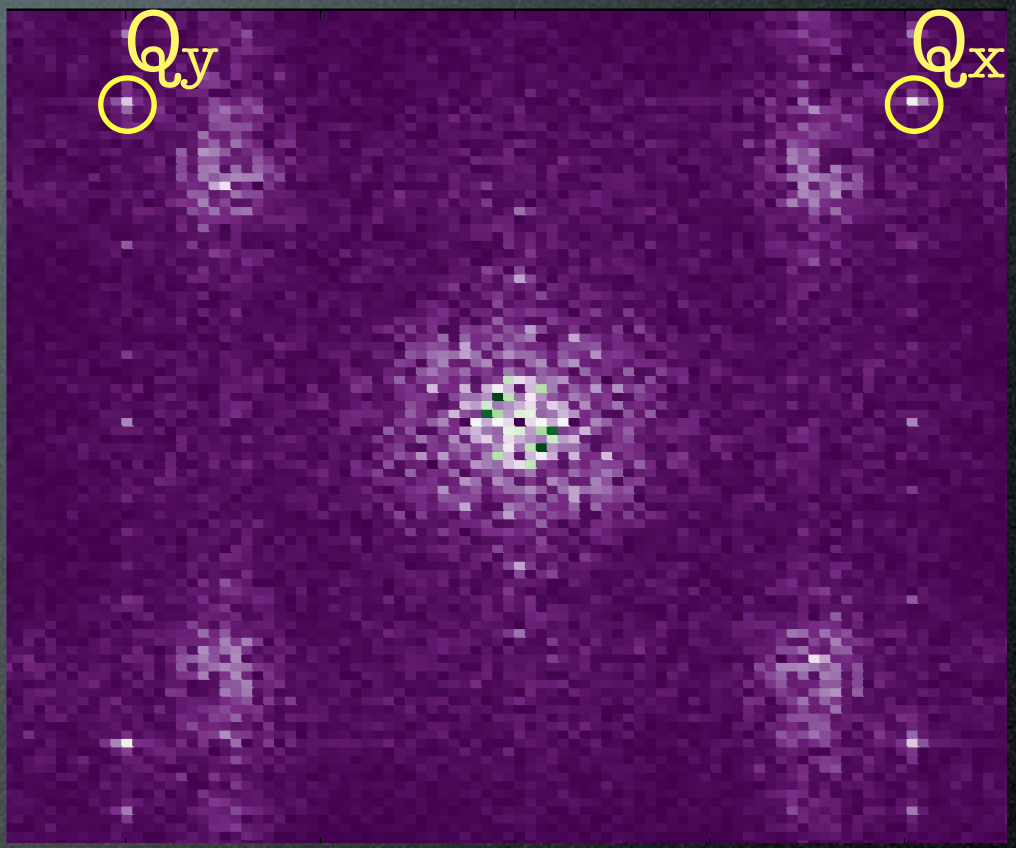

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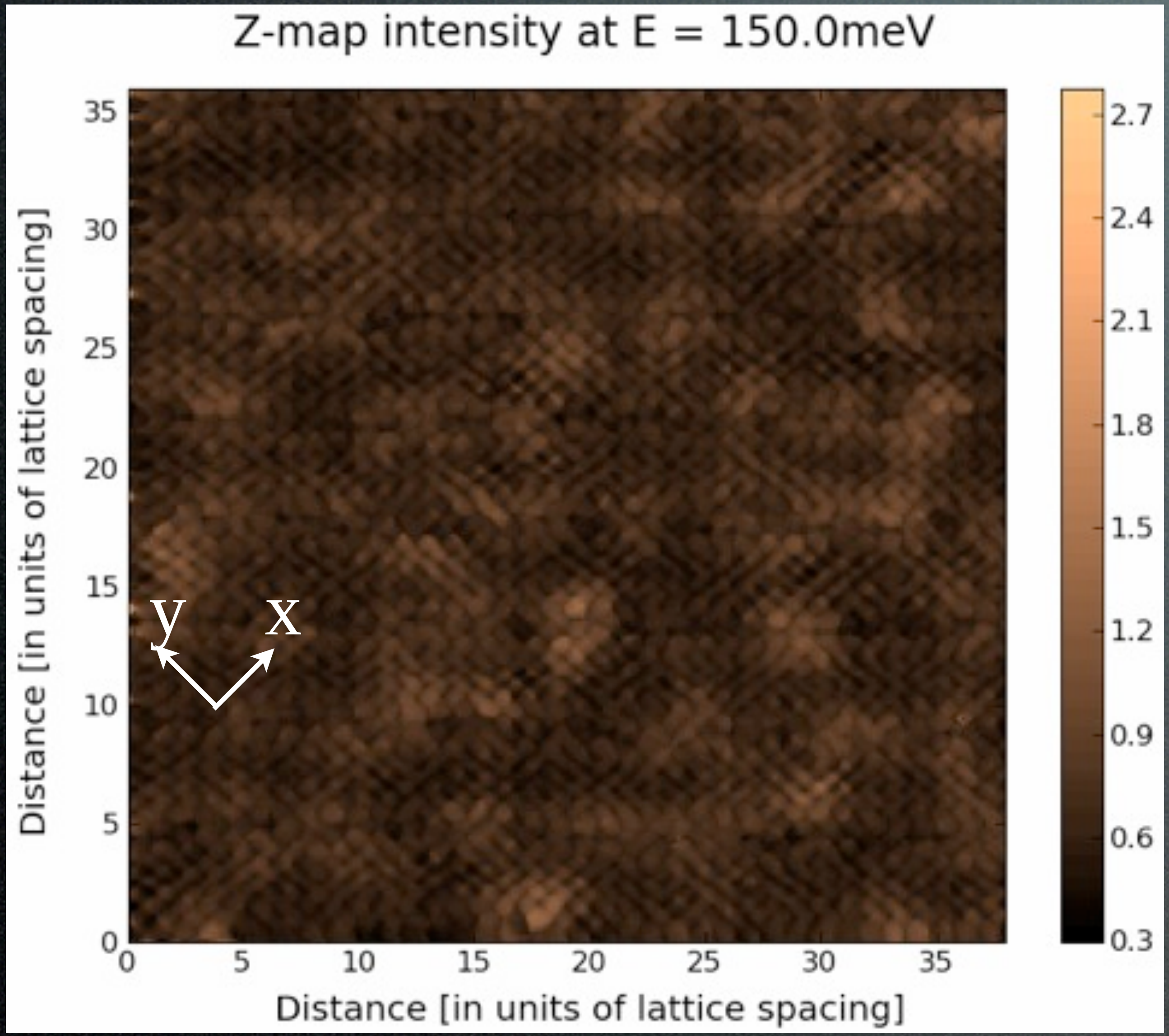

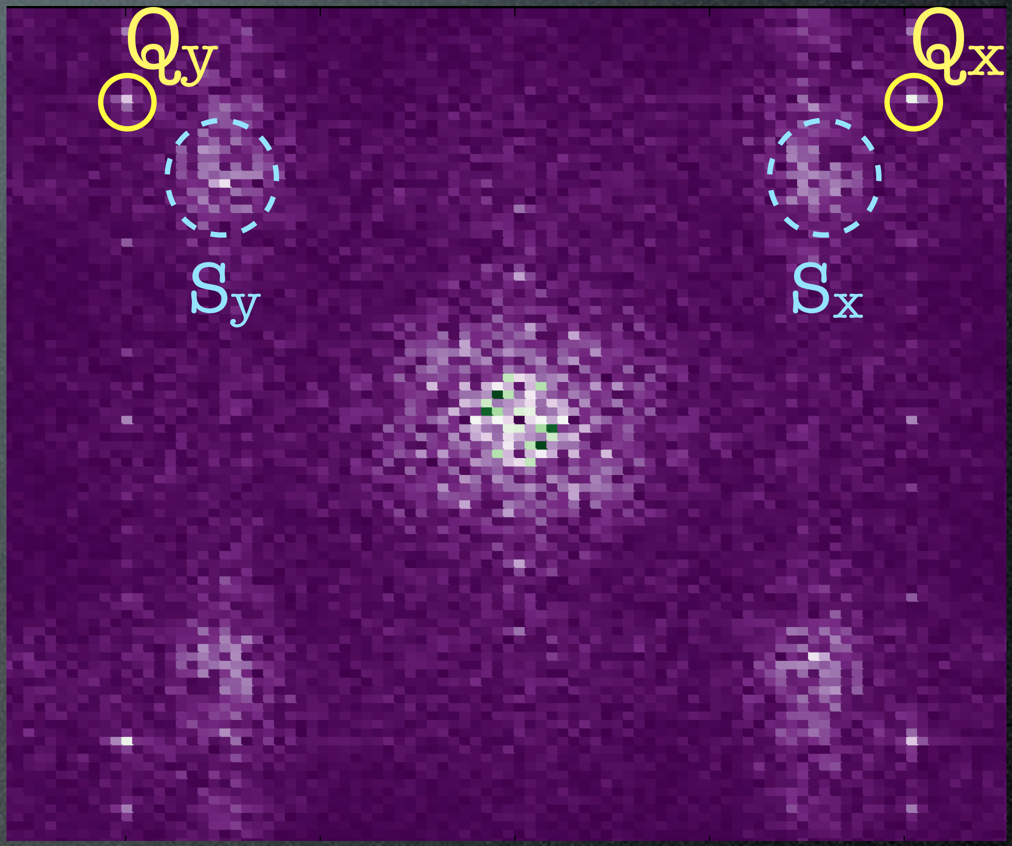

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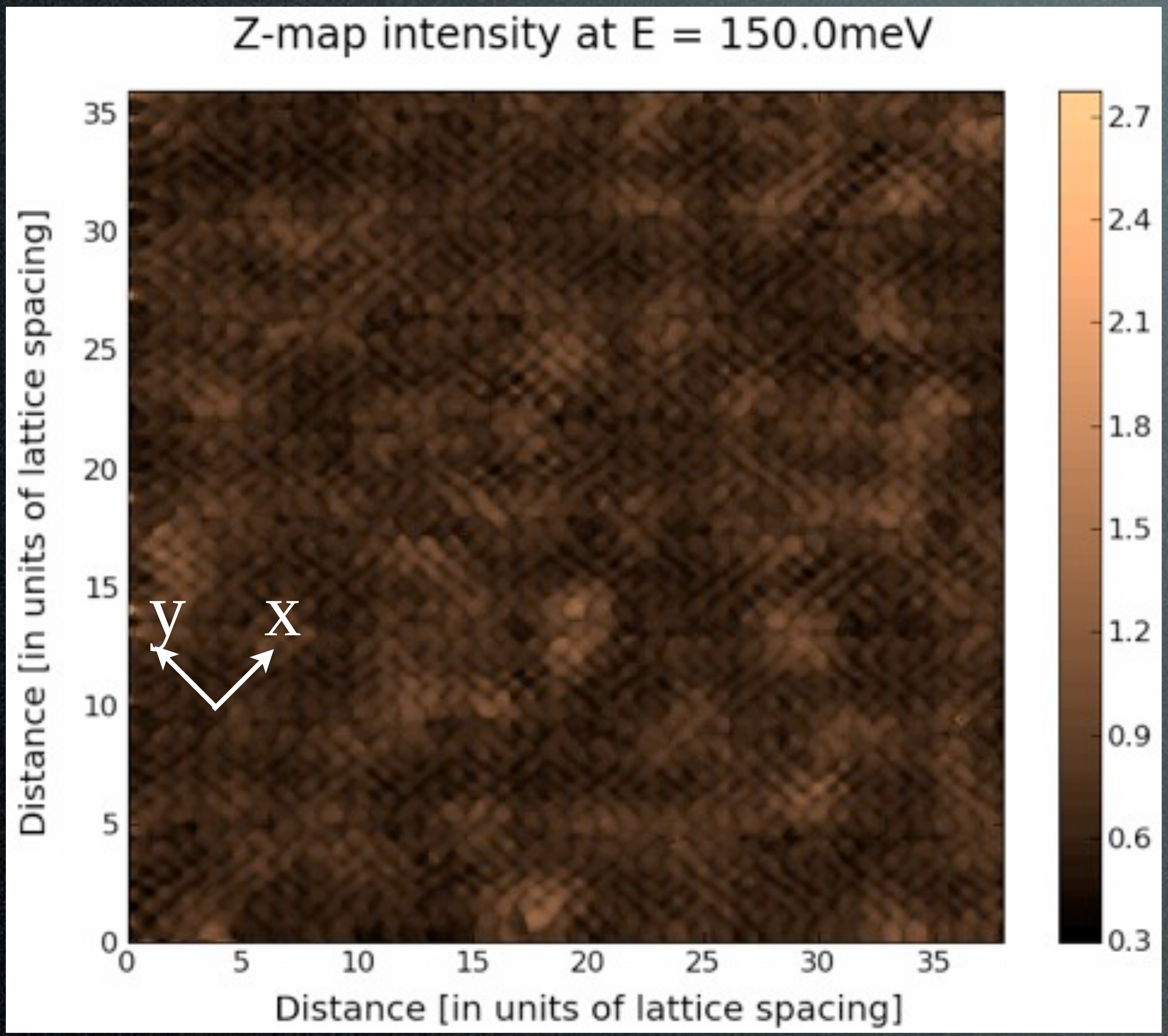

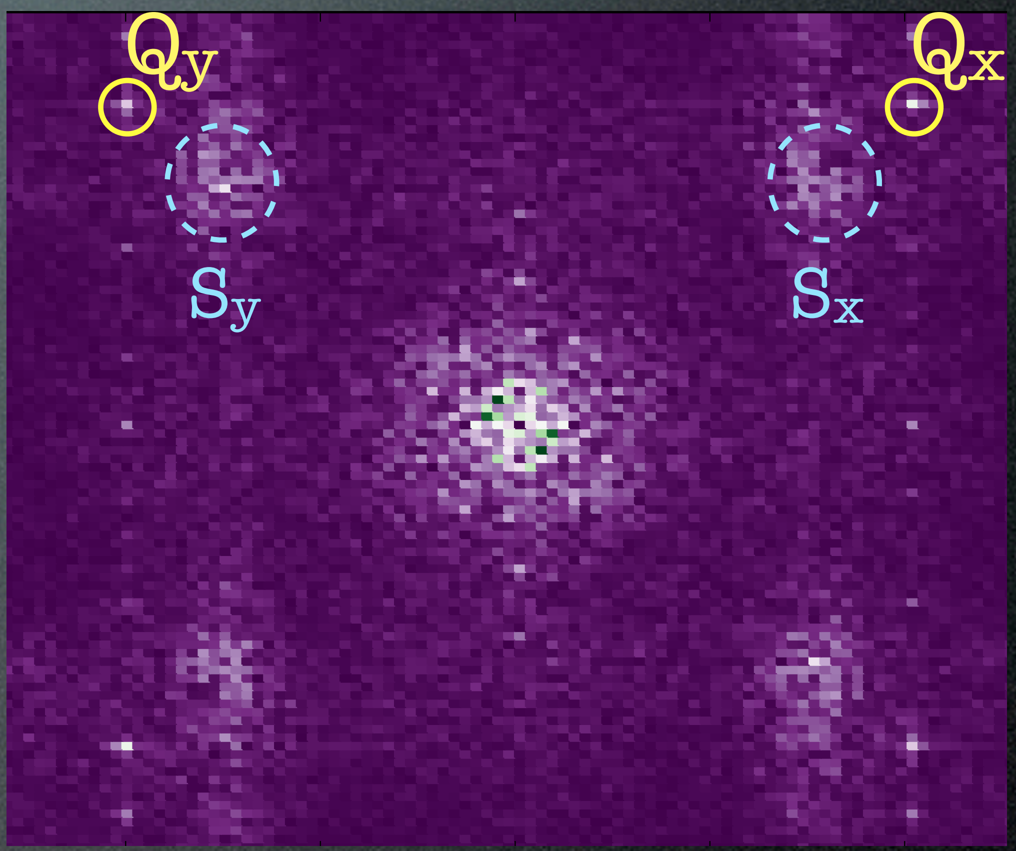

Q_x vs Q_y?

S_x vs S_y

Listen to Bragg Peaks

$\overleftrightarrow{Q_1}$ vs $\overleftrightarrow{Q_2}$

- Bragg peak

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

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

- Need O sites

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

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

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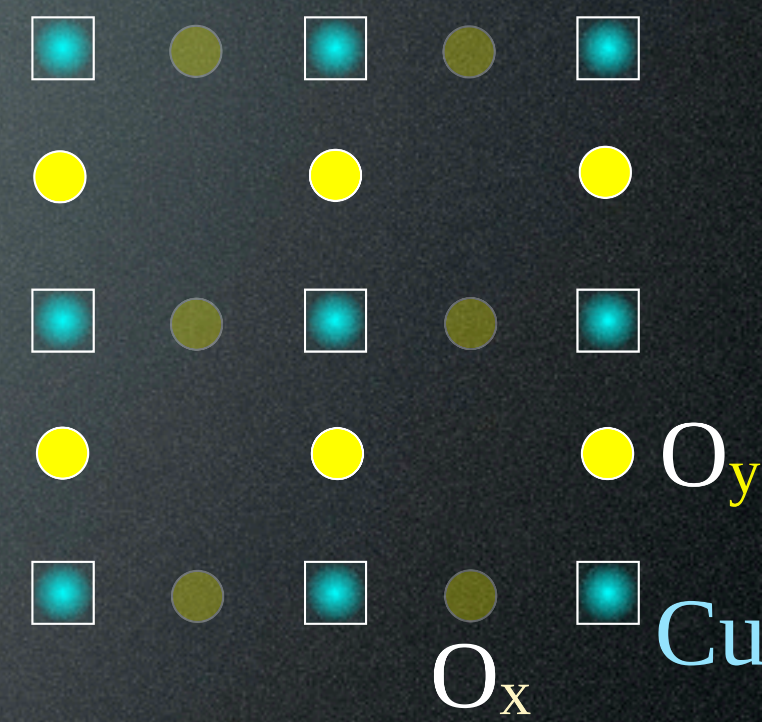

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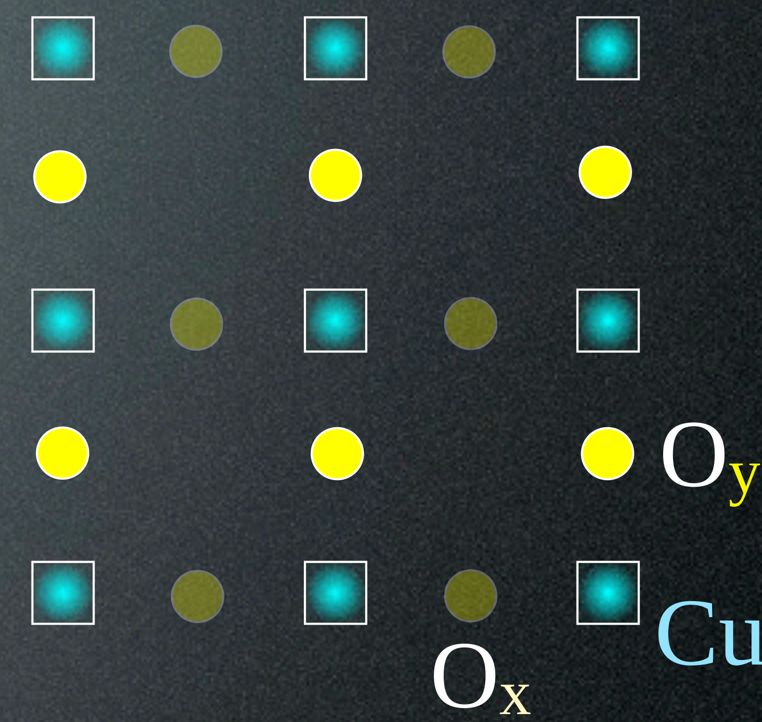

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- Nematic OP

$$\mathcal{O}_N \equiv \frac{[\tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(-\vec{Q}_x) - \tilde{Z}(-\vec{Q}_y)]}{(\text{sum})}$$

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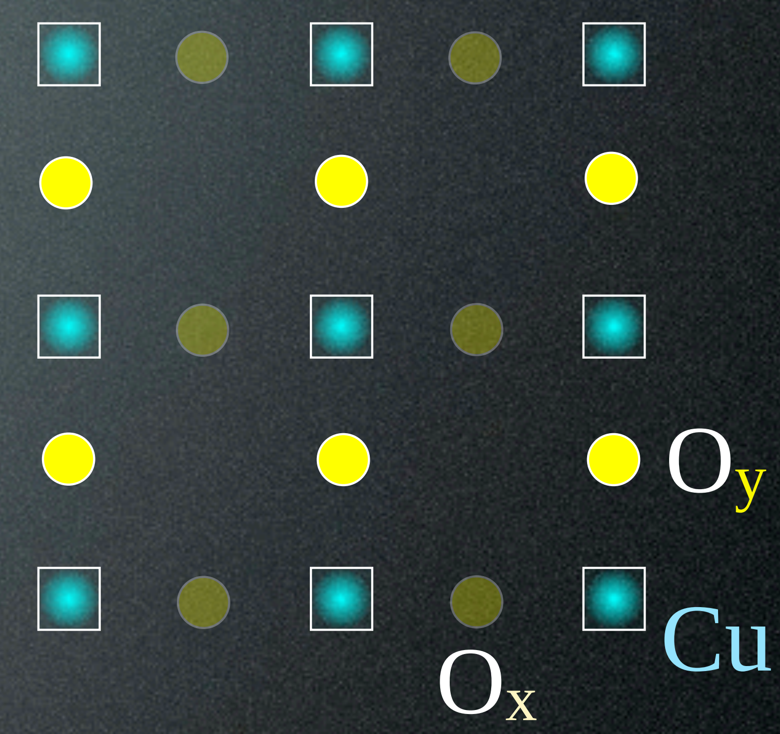

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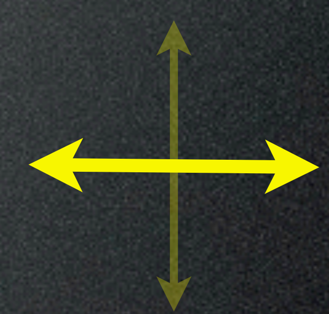
➡Measure C_4 breaking



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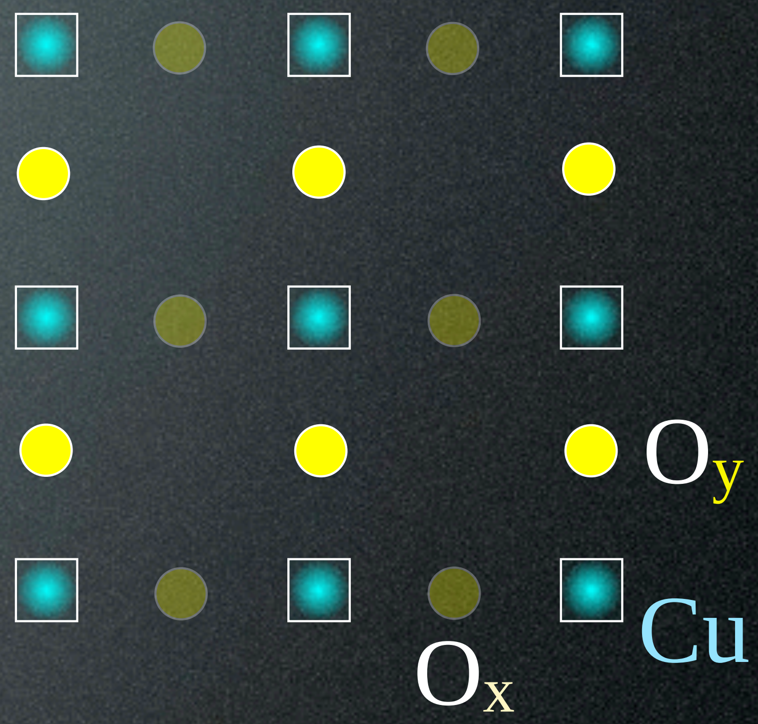
$\overleftrightarrow{Q_1}$ vs $\overleftrightarrow{Q_2}$

- Bragg peak

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

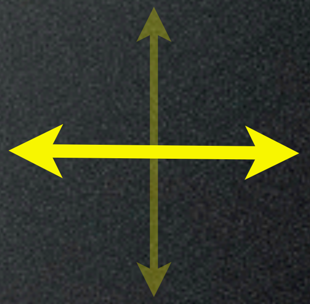
$$\vec{Q}_x = (2\pi/a, 0)$$



- Nematic OP

$$\mathcal{O}_N \equiv \frac{[\tilde{Z}(\vec{Q}_x) - \tilde{Z}(\vec{Q}_y) + \tilde{Z}(-\vec{Q}_x) - \tilde{Z}(-\vec{Q}_y)]}{(\text{sum})}$$

➡Measure C_4 breaking



- Need O sites

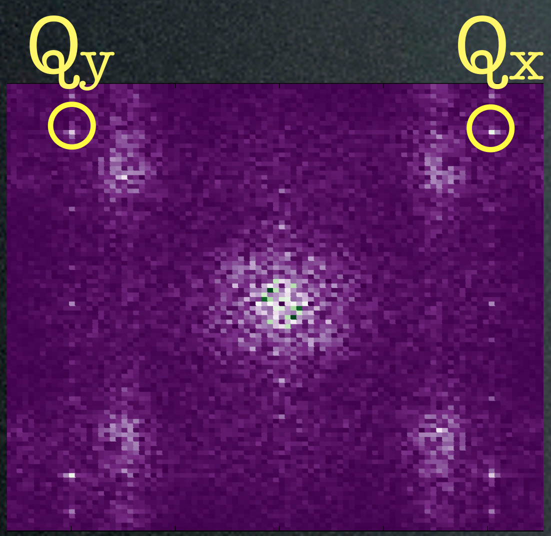
$$\tilde{Z}(\vec{Q}_x) = \bar{Z}_{\mathrm{Cu}} - \bar{Z}_{\mathrm{O}_x} + \bar{Z}_{\mathrm{O}_y}, \quad \tilde{Z}(\vec{Q}_y) = \bar{Z}_{\mathrm{Cu}} + \bar{Z}_{\mathrm{O}_x} - \bar{Z}_{\mathrm{O}_y}$$

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

V. Emery, PRL 58, 2974 (1987)

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

Nematic ordering in UD 45



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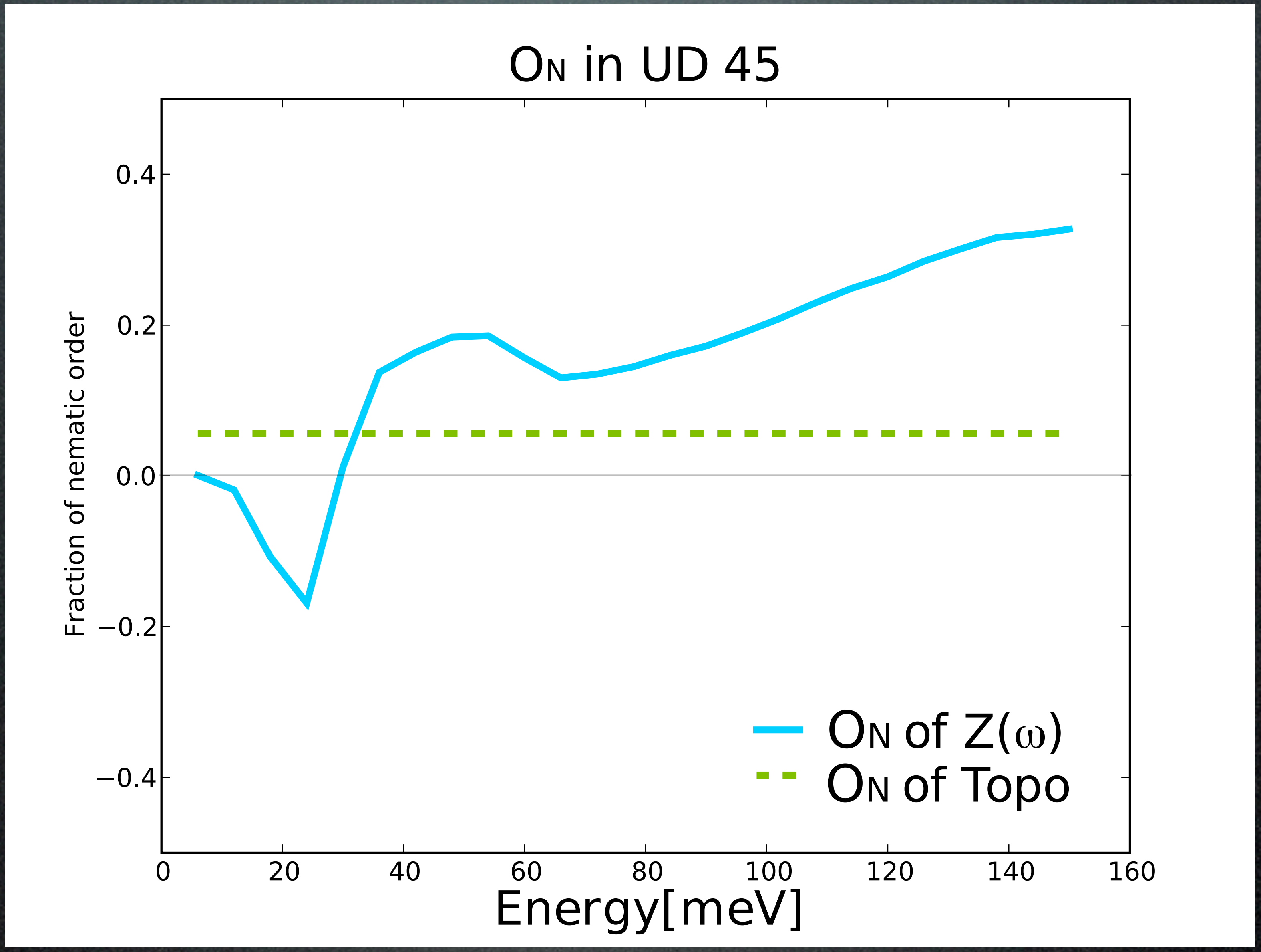

Extracted from published data, T=4K

Kohsaka et al, Nature 454, 1072 (2008)

Domain size in Z-map

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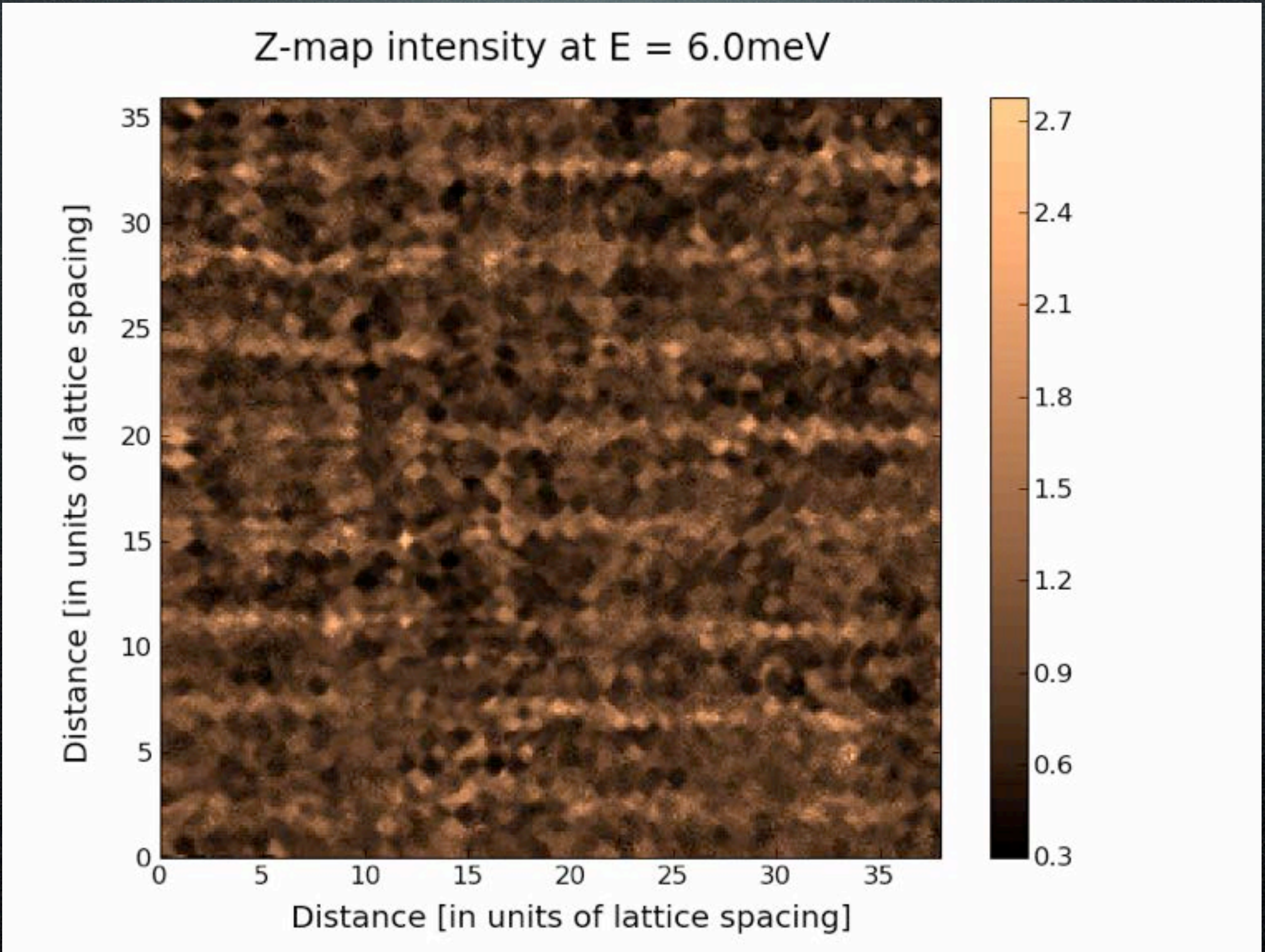
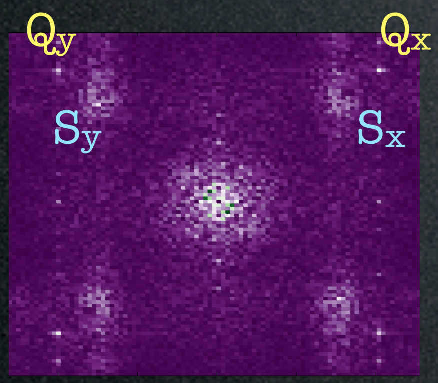


Nematic domains

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

- Low pass filter (long distance physics)



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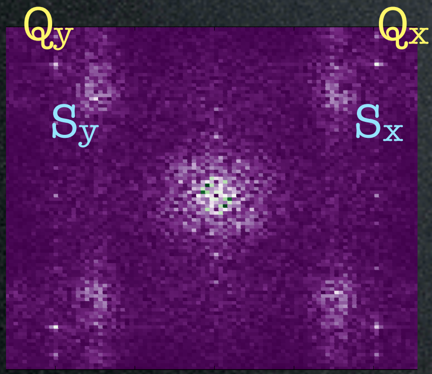
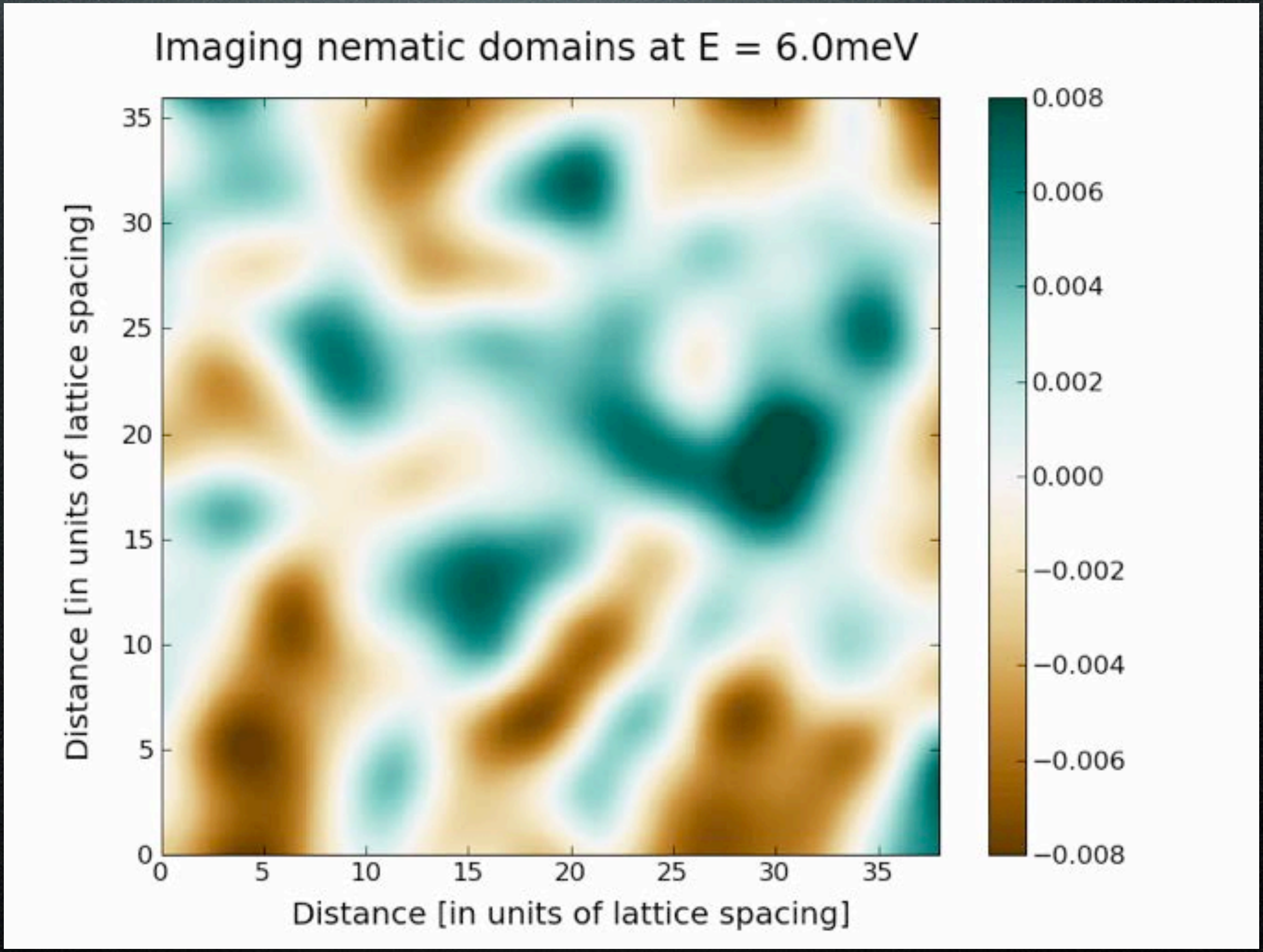


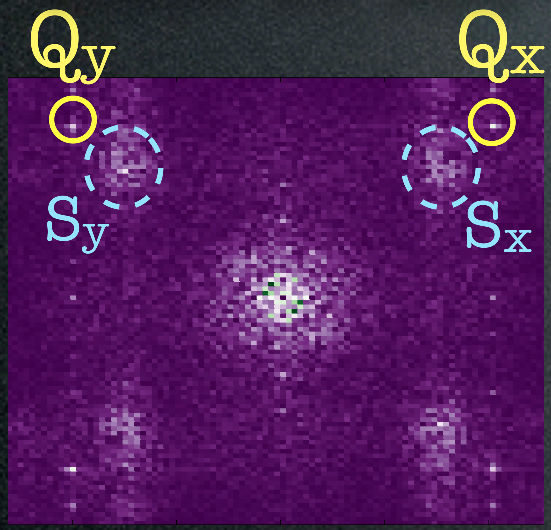


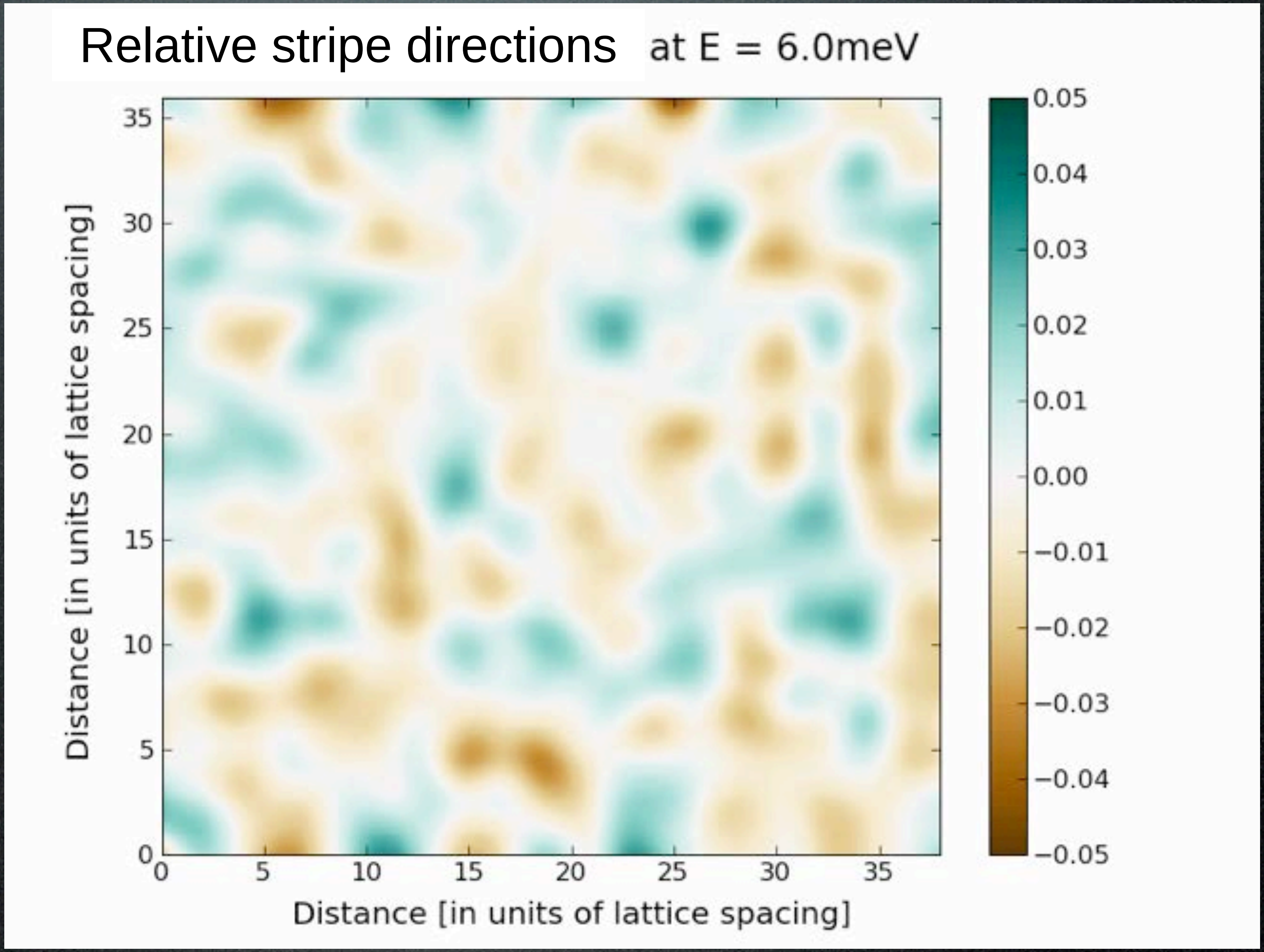
Listen to channel S

Oriented stripe domains

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

- Low pass filter (long distance physics)





Hypothesis: longer ranged orientational ordering than stripe ordering ?

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VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

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

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(Received 11 July 1990; revised manuscript received 25 February 1991)

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Example:

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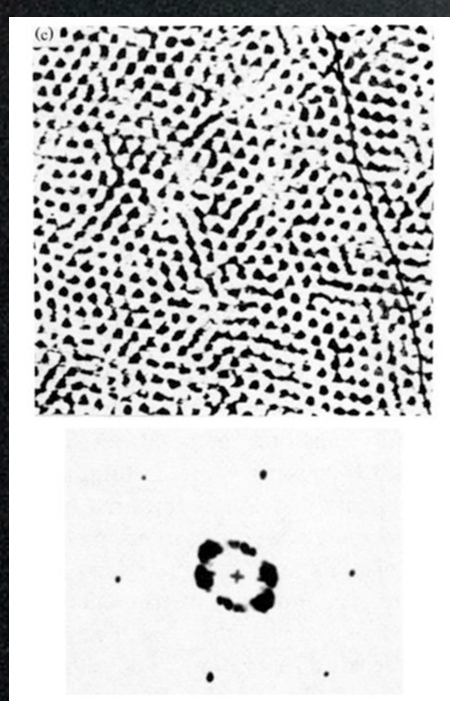

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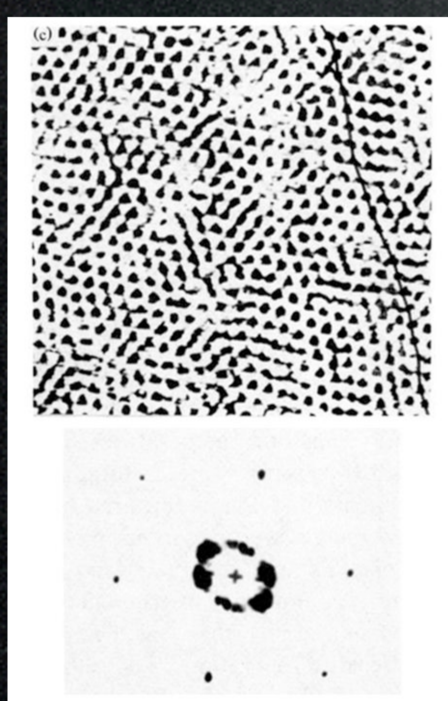

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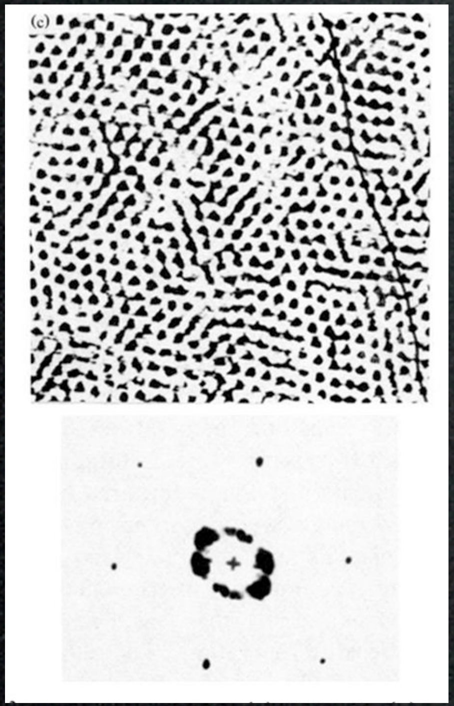

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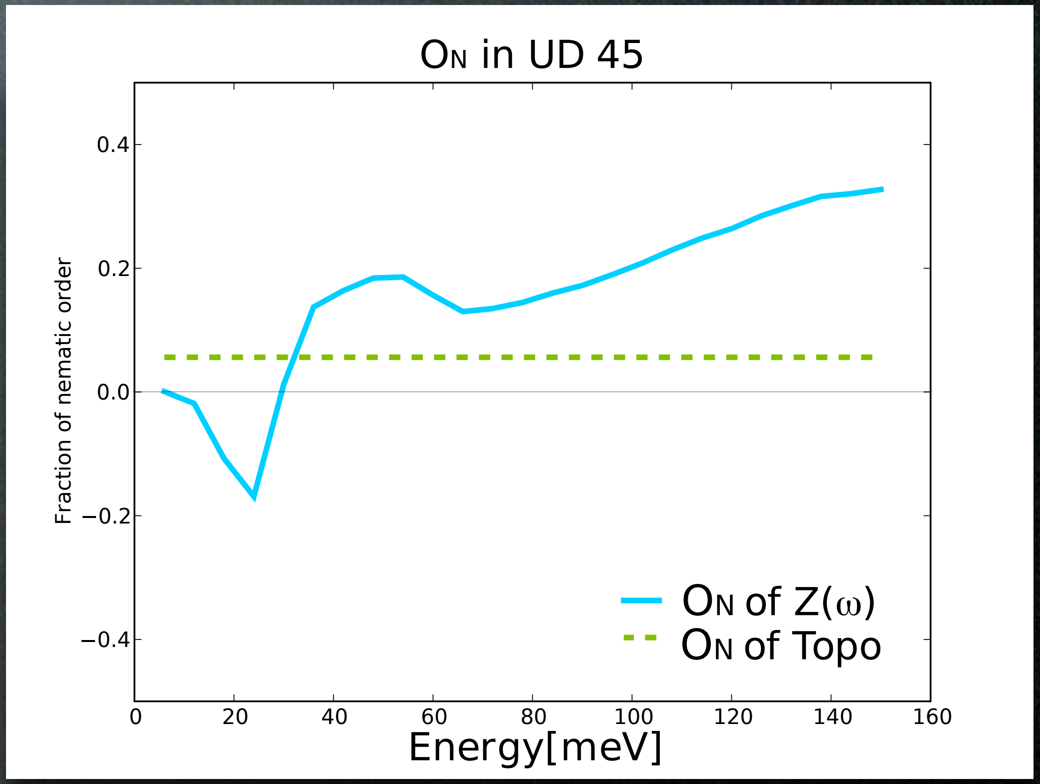
Electronic Nematic in Cuprates?

Looking ahead

- Doping dependence?
- Temperature dependence?
- Diffraction measurements?



- Phenomenological model
- Why would cuprates do that?
- Is it useful for superconductivity?