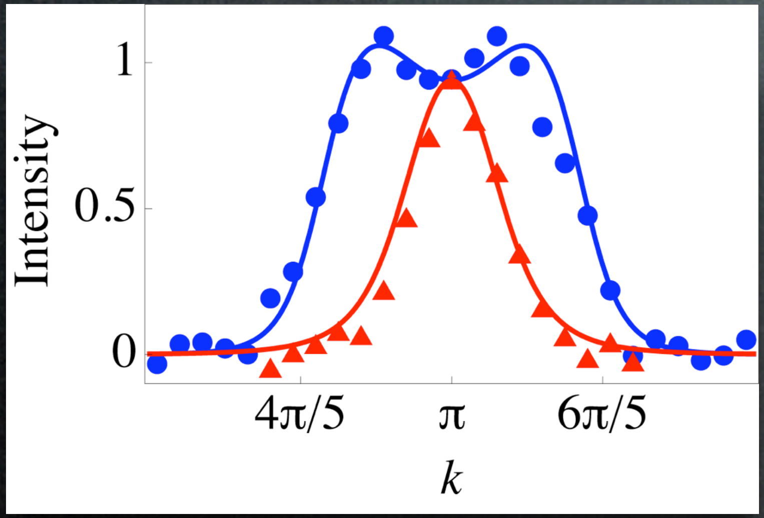
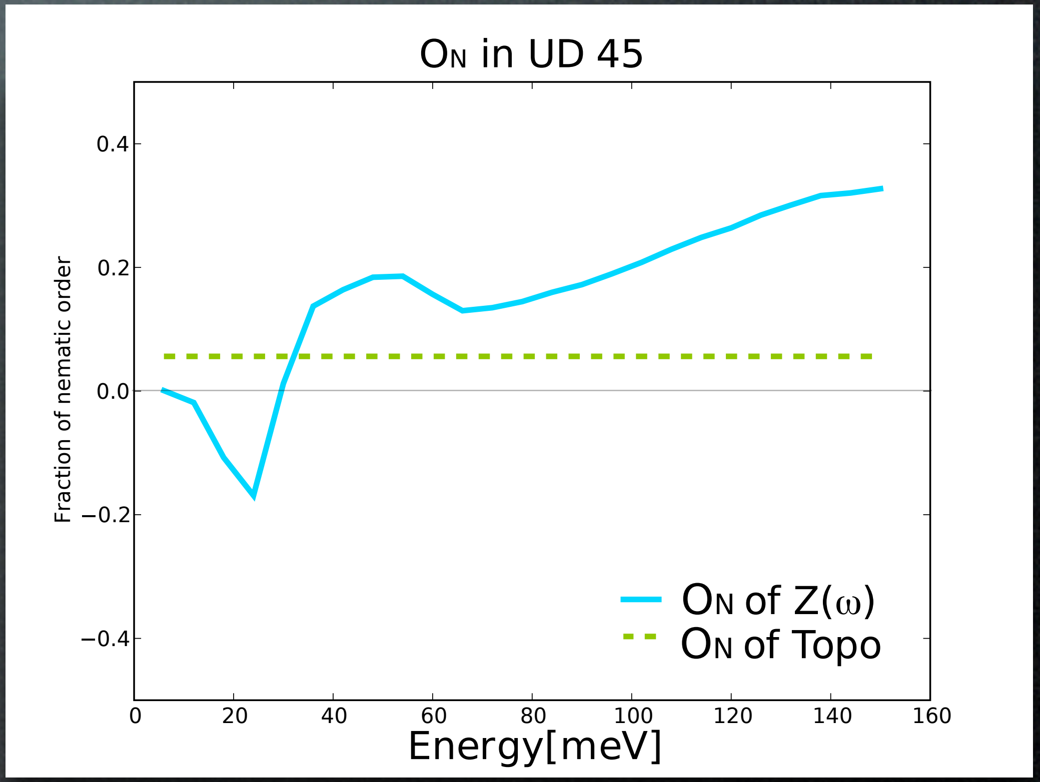
# Electronic Nematic in Cuprates?





Eun-Ah Kim

Cornell University

# Acknowledgements

Prof. Michael Lawler

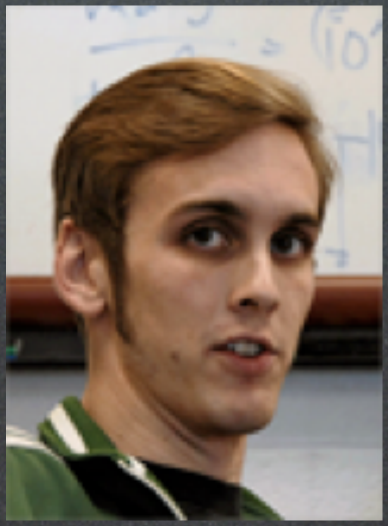
Binghamton, Cornell

Dr. Kai Sun

UIUC ➔UMD

Prof. James Sethna

Cornell



Dr. Andy Schmit

Cornell

Prof. Seamus Davis

Cornell, BNL

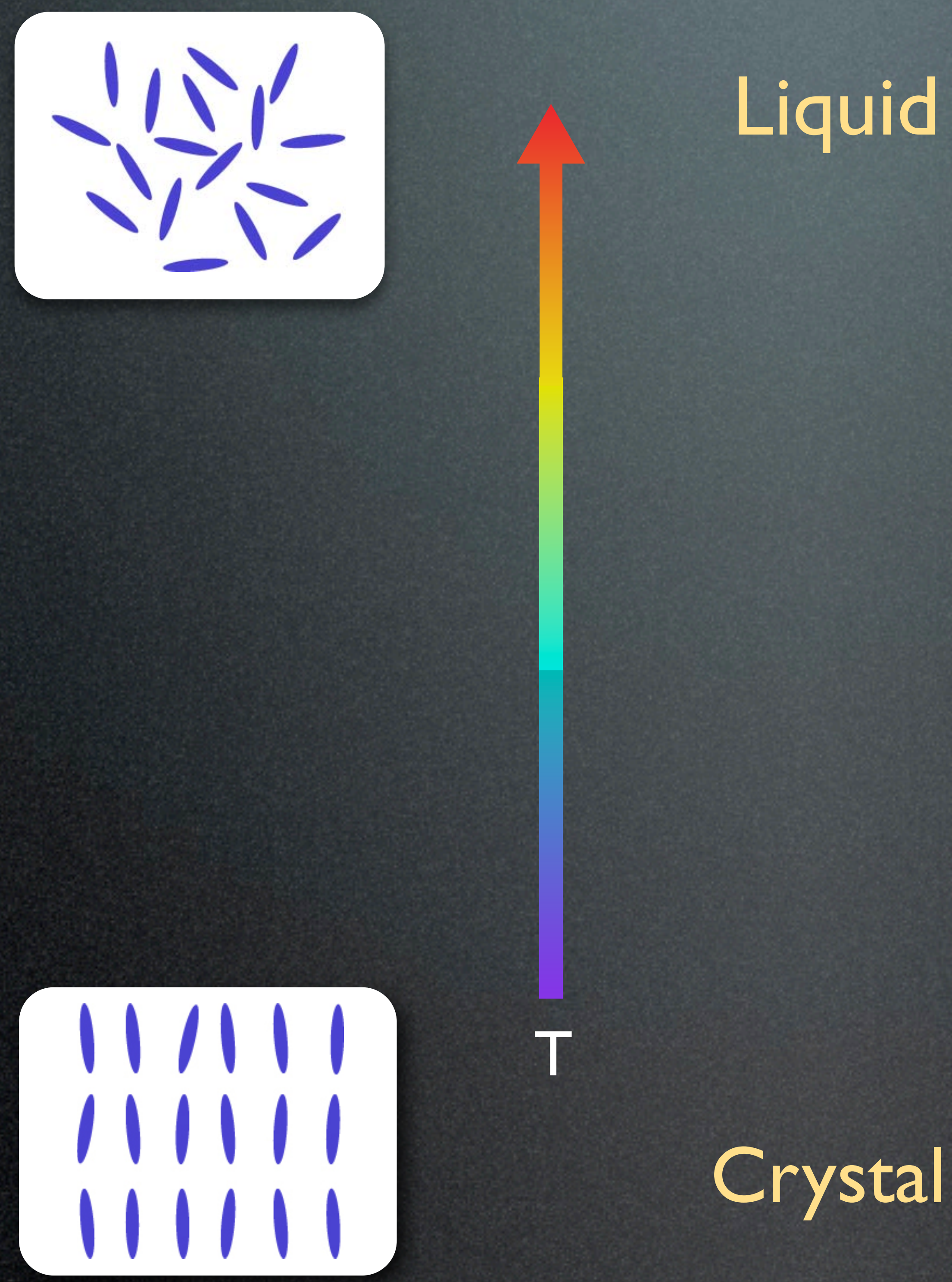
# Electronic Nematic in Cuprates?

- Introduction
- YBCO: spin and charge
- BSCCO: got nematic?
- Look out

# Liquid Crystal

Reinitzer(1888)

# Liquid Crystal

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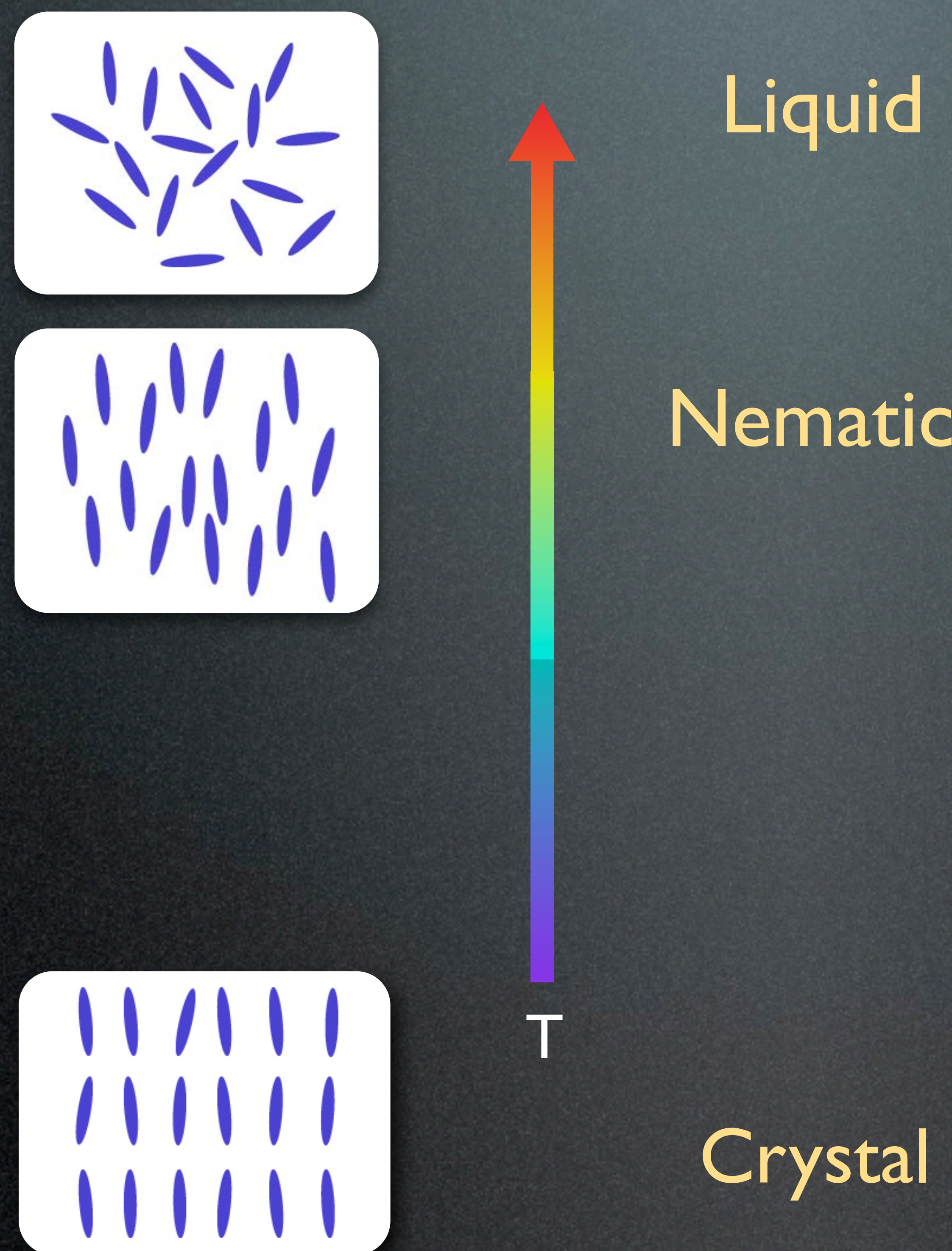


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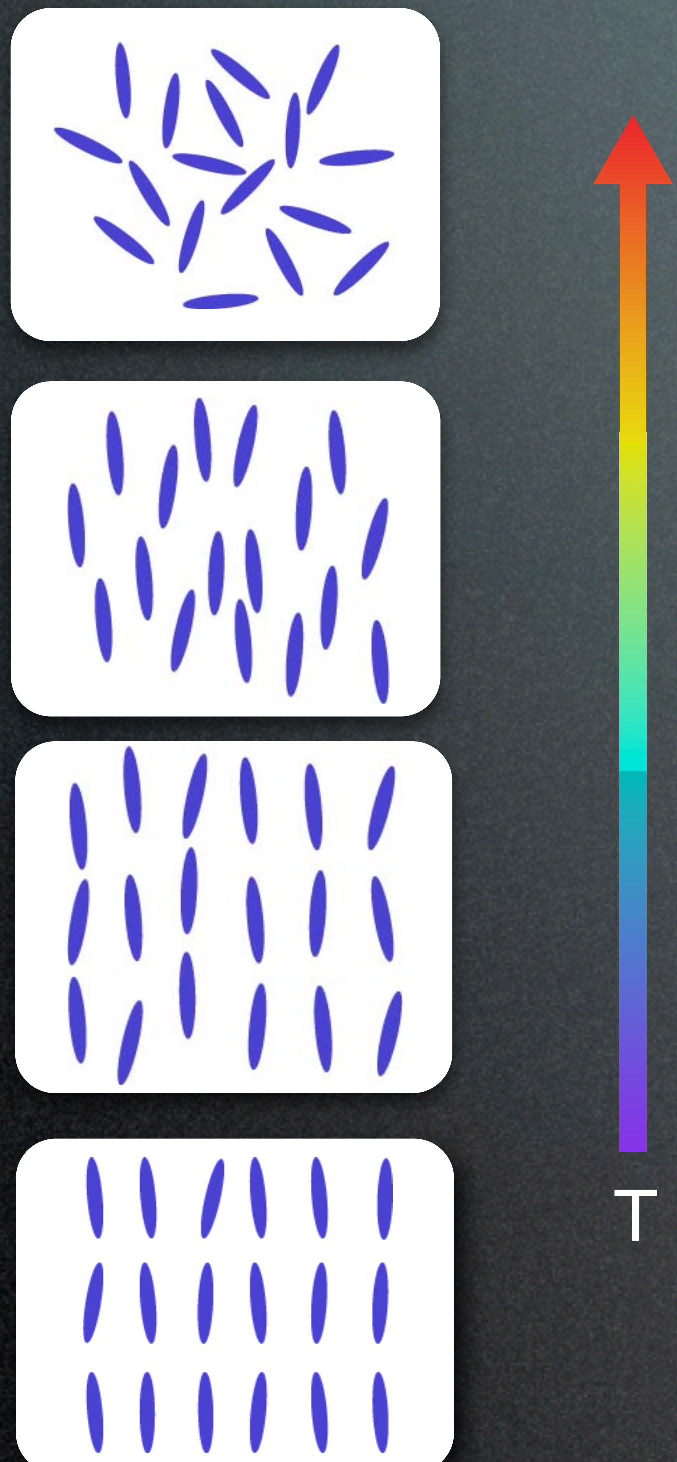



Liquid

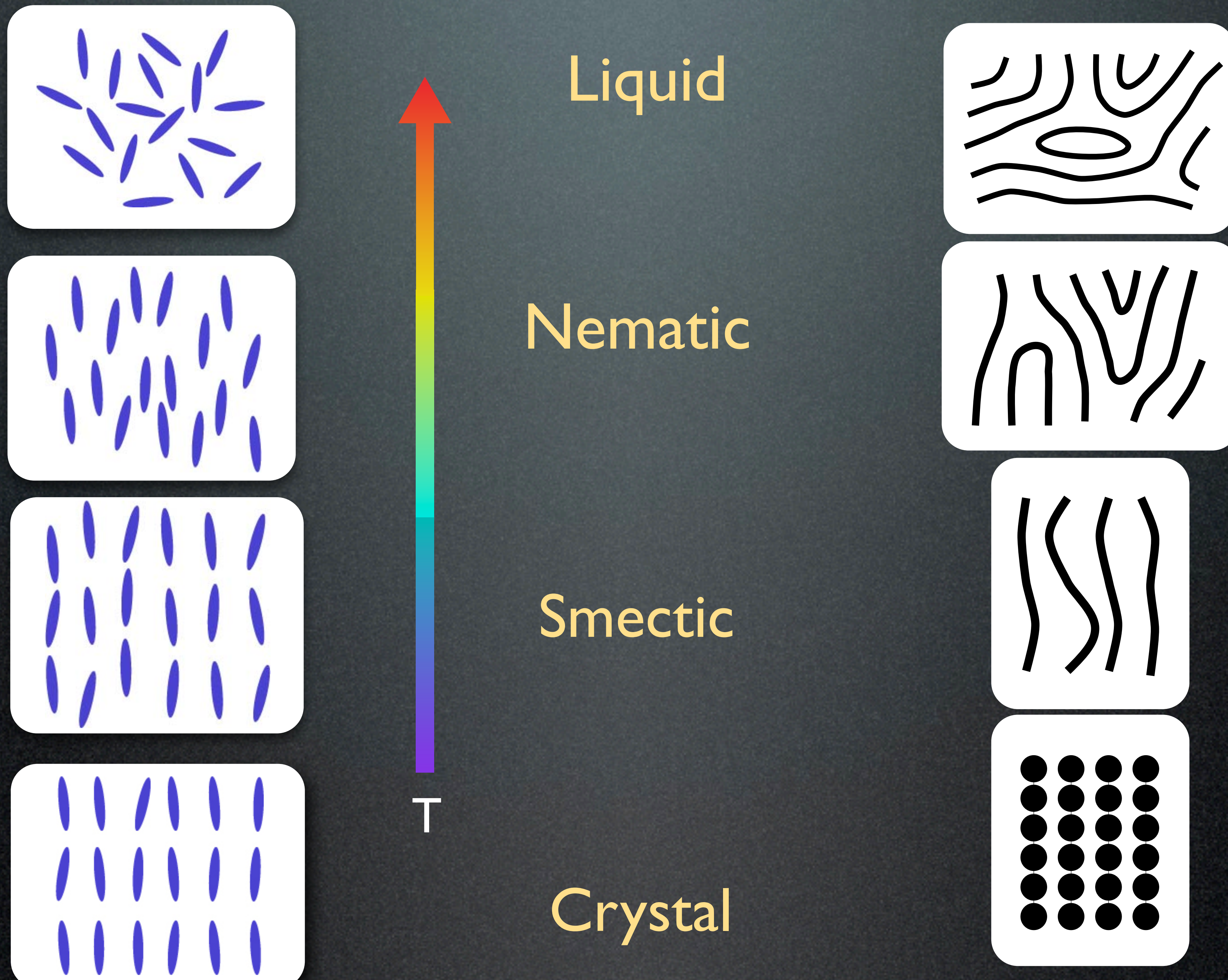
Nematic

Smectic

Crystal

Reinitzer(1888)

# Electronic Liquid Crystal

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Kivelson, Fradkin, Emery, Nature (1998)

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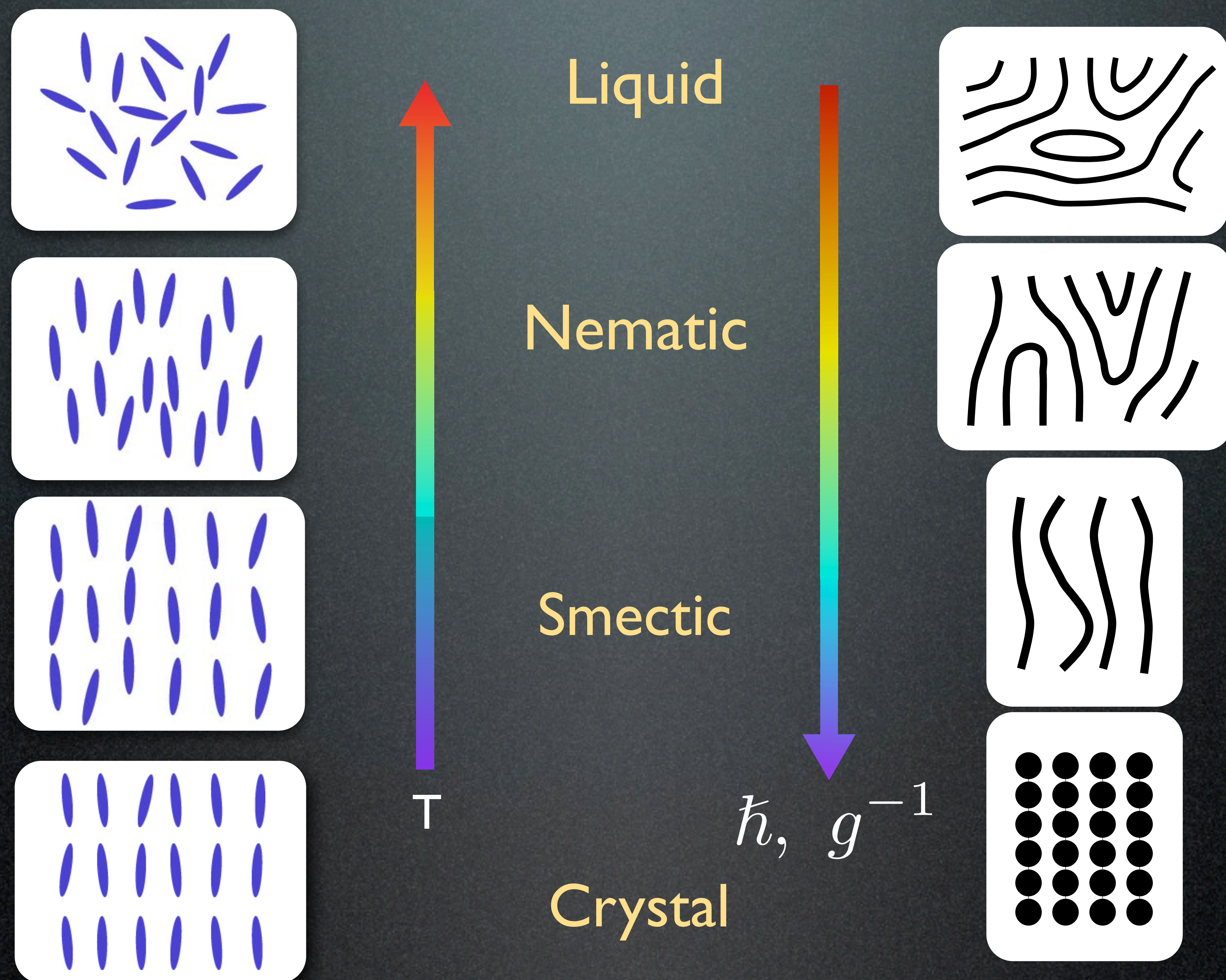


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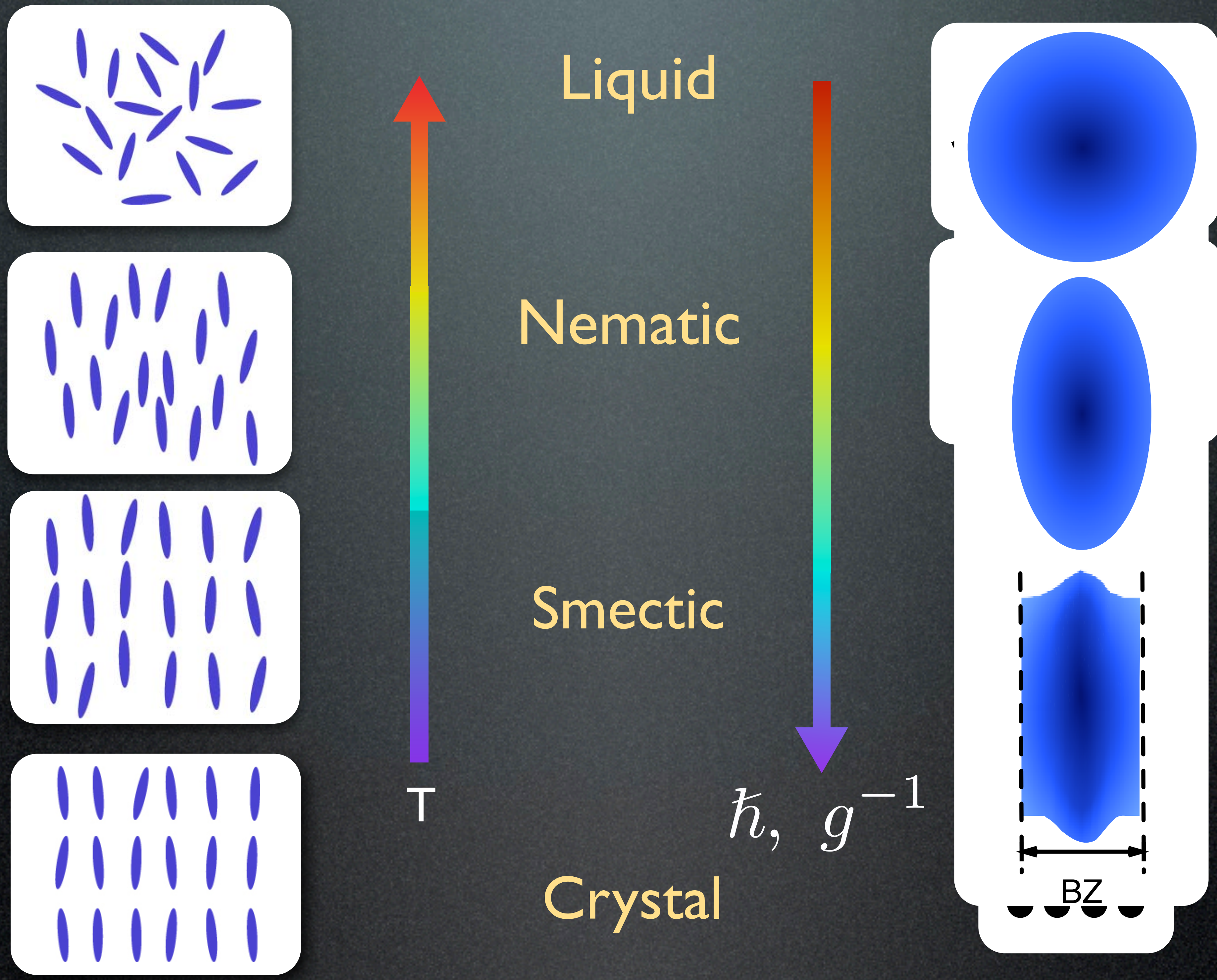


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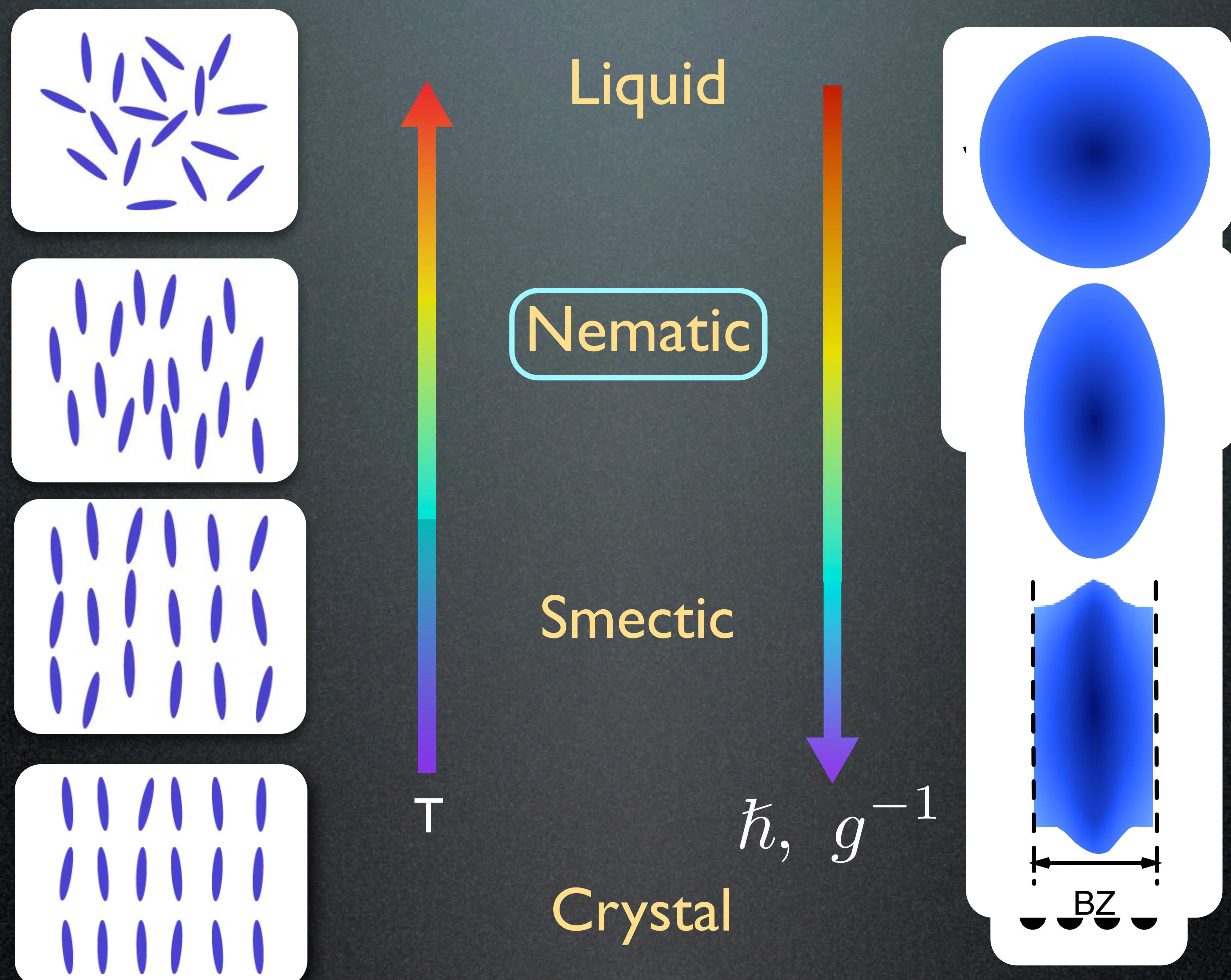


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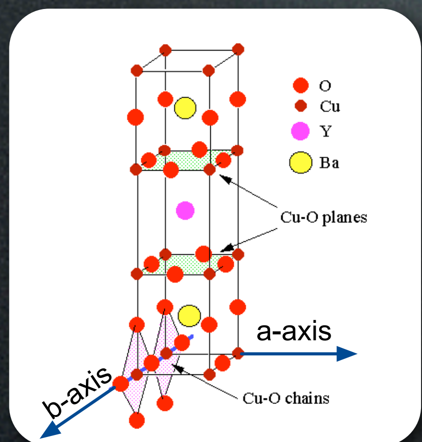
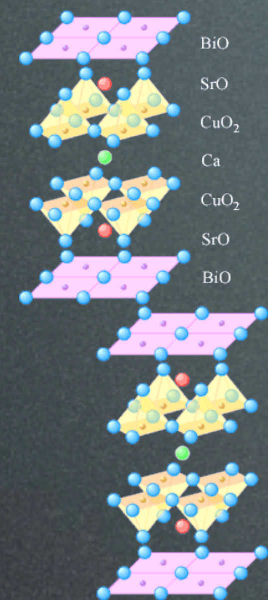
# Sufficiently correlated systems

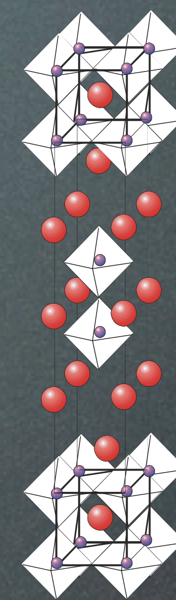
## Cuprates

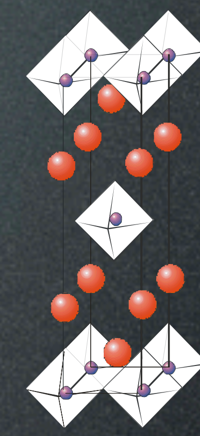


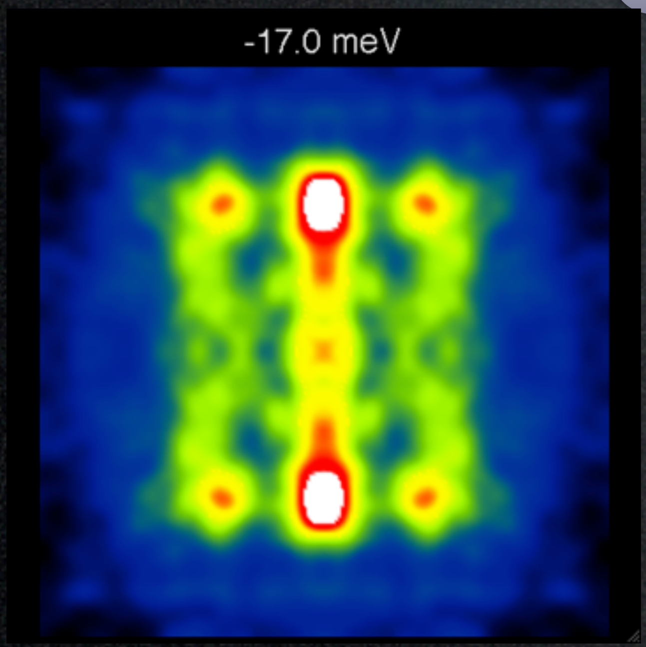

## Ruthenates

Ru: $4d^4$ $U<t$



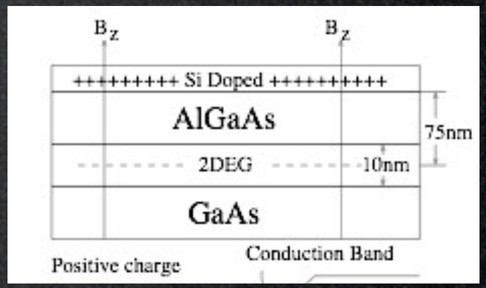


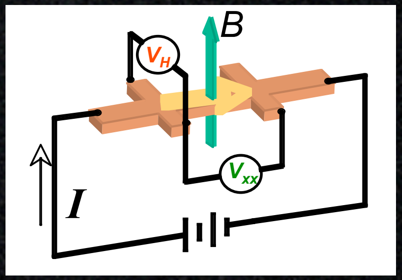
**Electronic Liquid Crystal**




## Pnictides

## 2DEG under $\vec{B}$



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- Quantifying broken symmetry

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# 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

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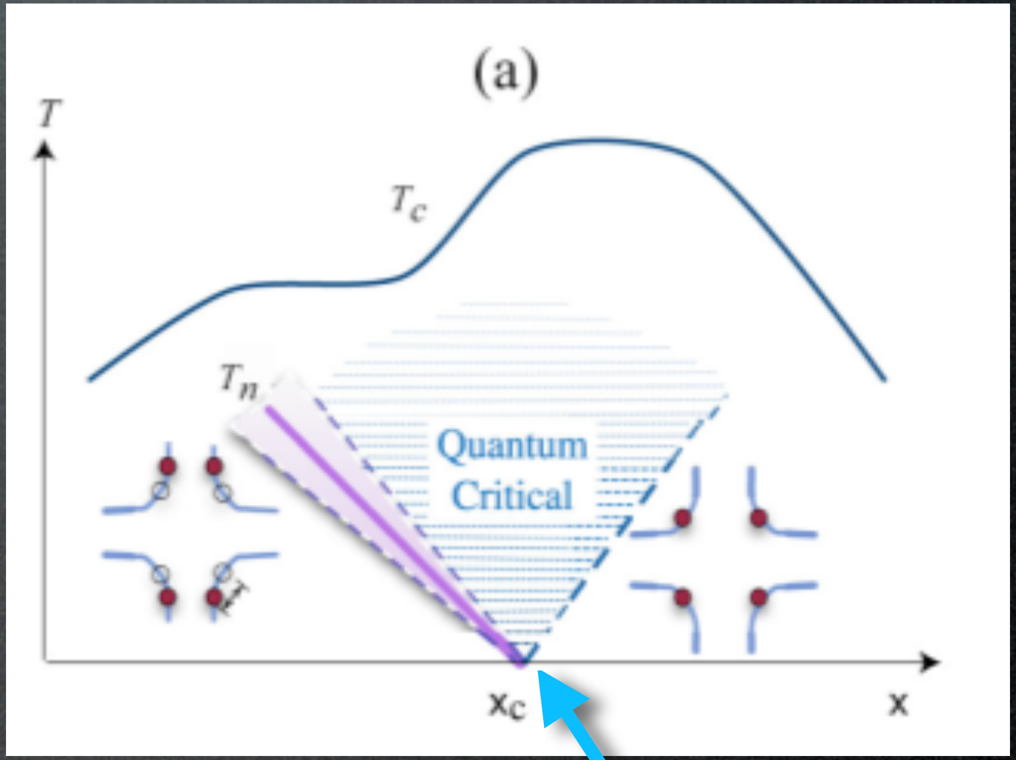


nematic QCP inside SC phase?

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- Nodal nematic QCP
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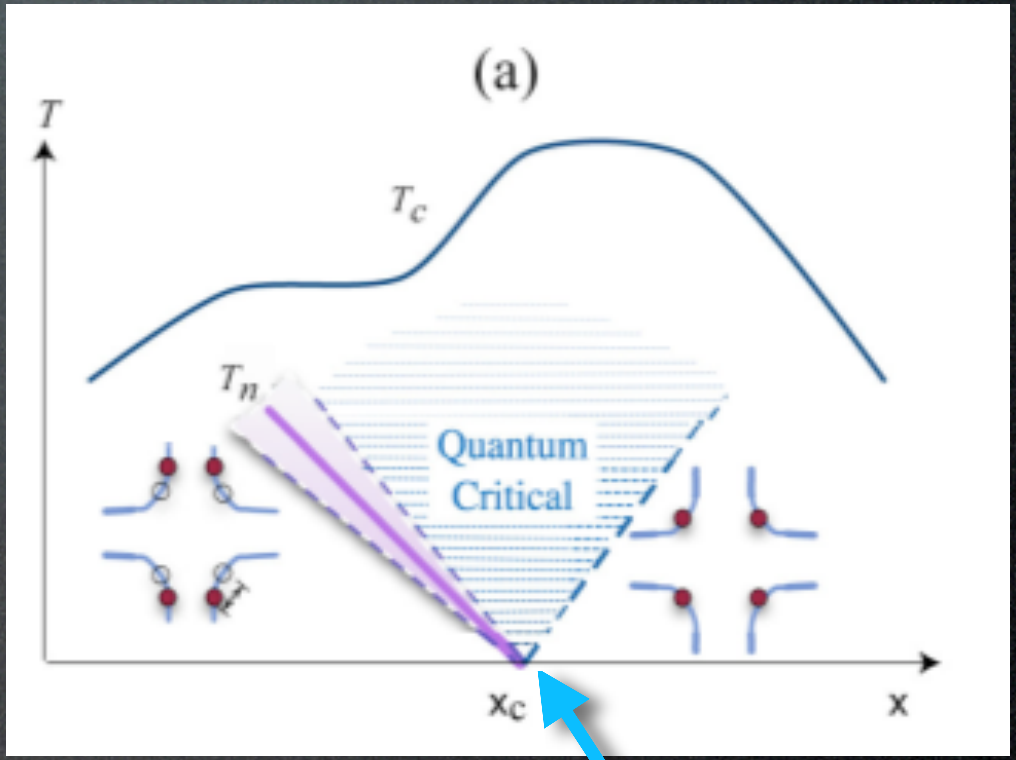
- Nematic d-SC:
  d-SC + small s-component

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

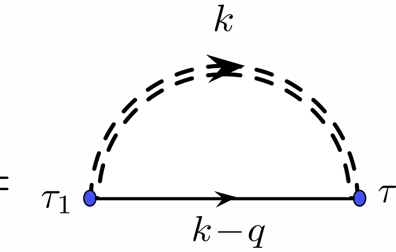



nematic QCP inside SC phase?

# Looking for nematic critical fluctuations

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

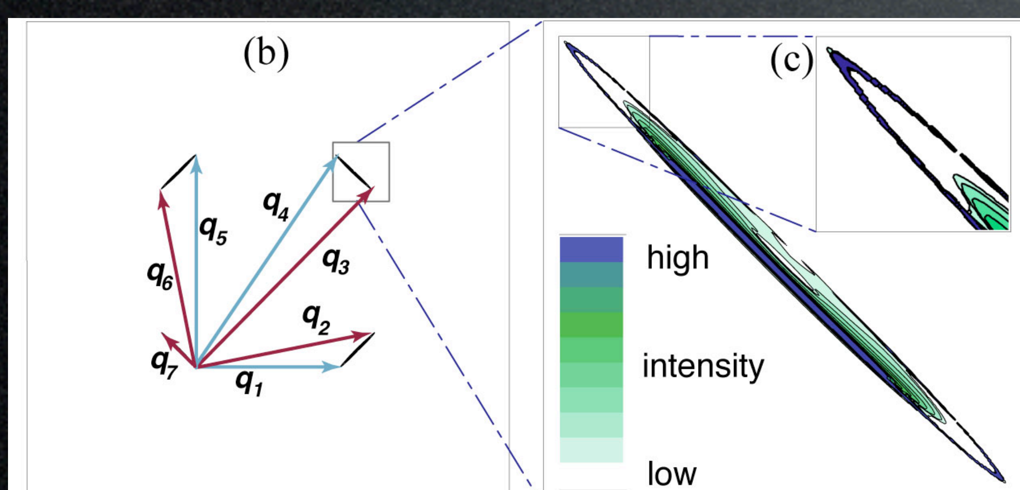
  :k-selective decoherence

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

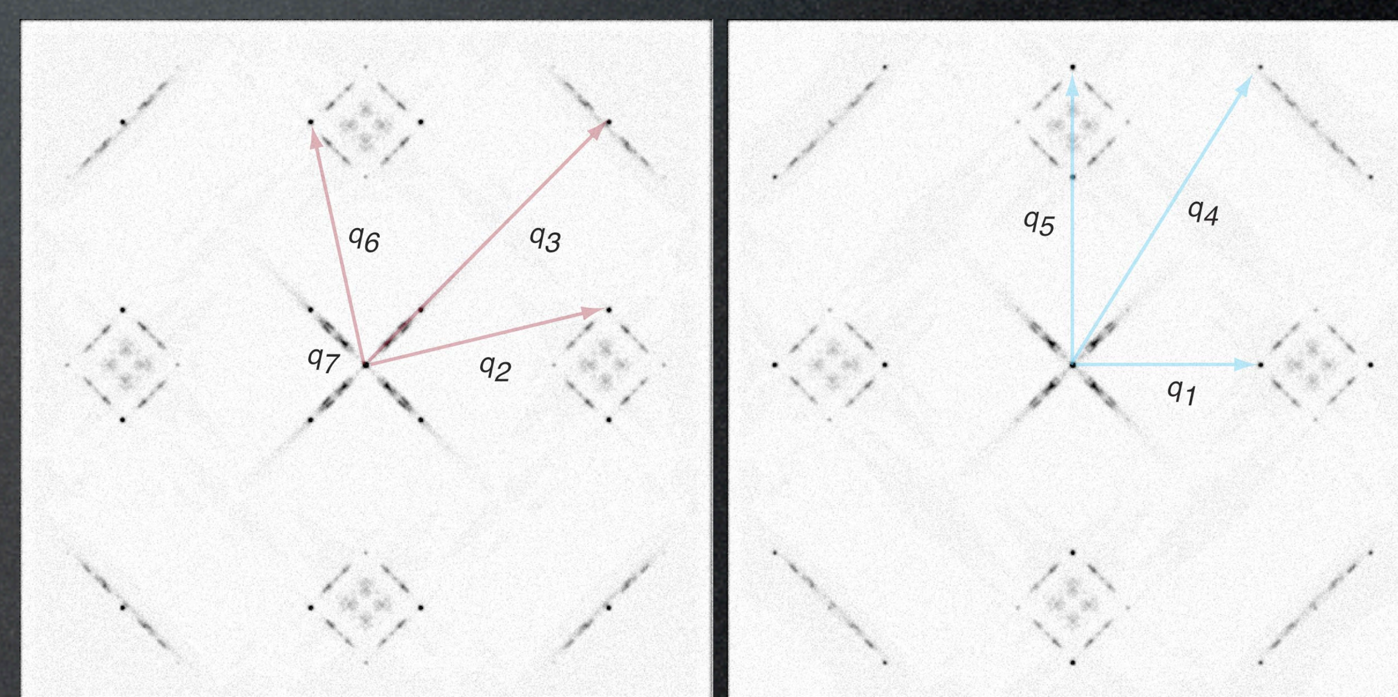

**Interference of nematic quantum critical quasiparticles: a route to the octet model**

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



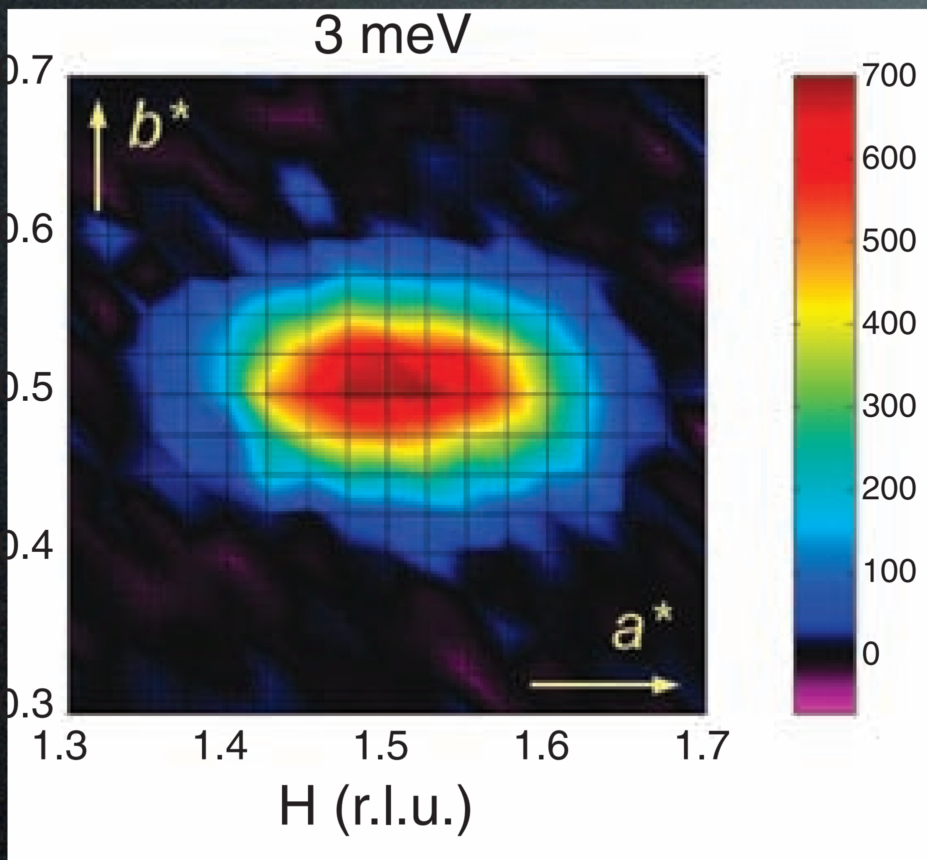

→ QPI peaks

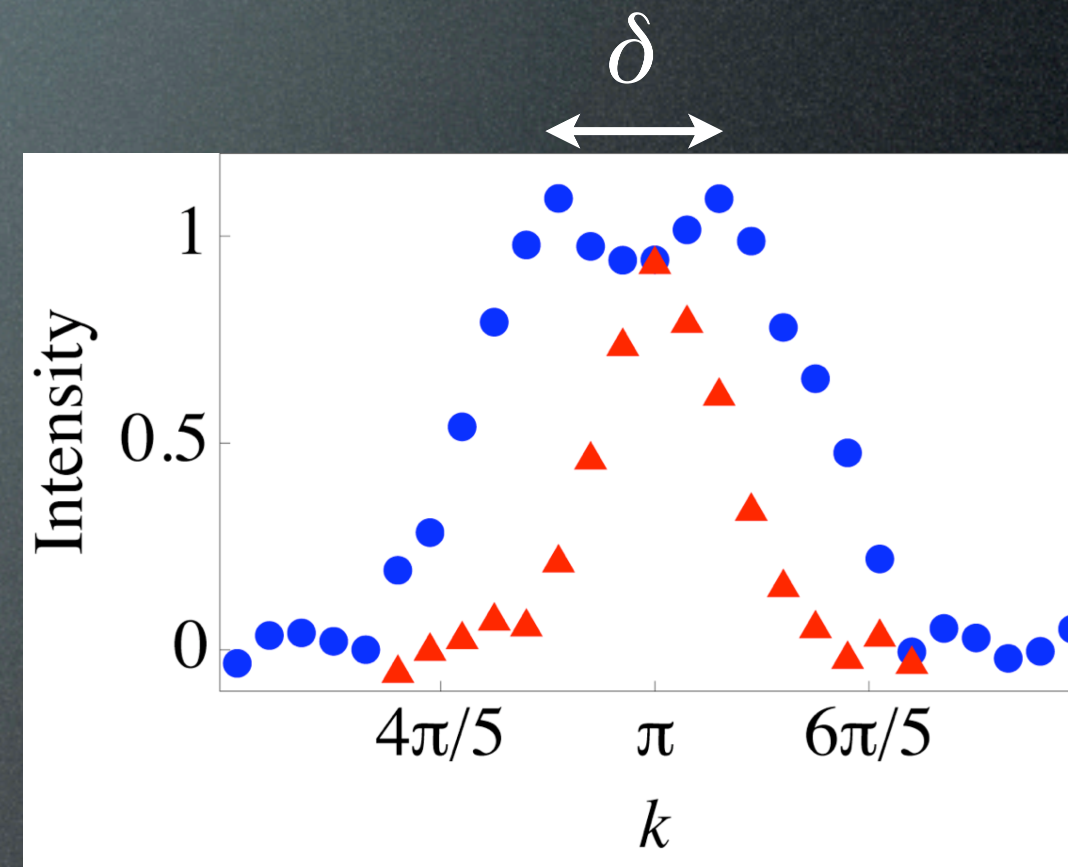



(b) (c)

# YBCO, spin and charge

# Anisotropic phase in superconducting ($T_c$=35K) underdoped $YBa_2Cu_3O_{6.45}$




Anisotropy in inelastic ($\pi/a,\pi/b$) neutron scattering peak

Hinkov et al, Science, Jan 2008

Spin channel

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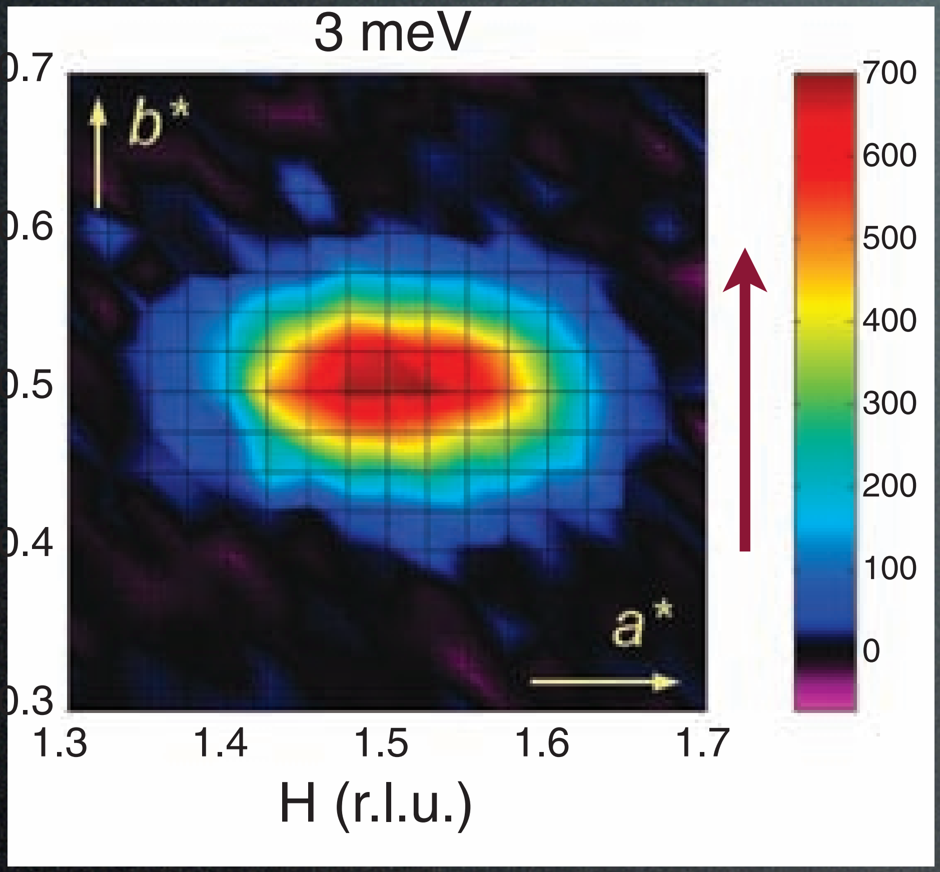


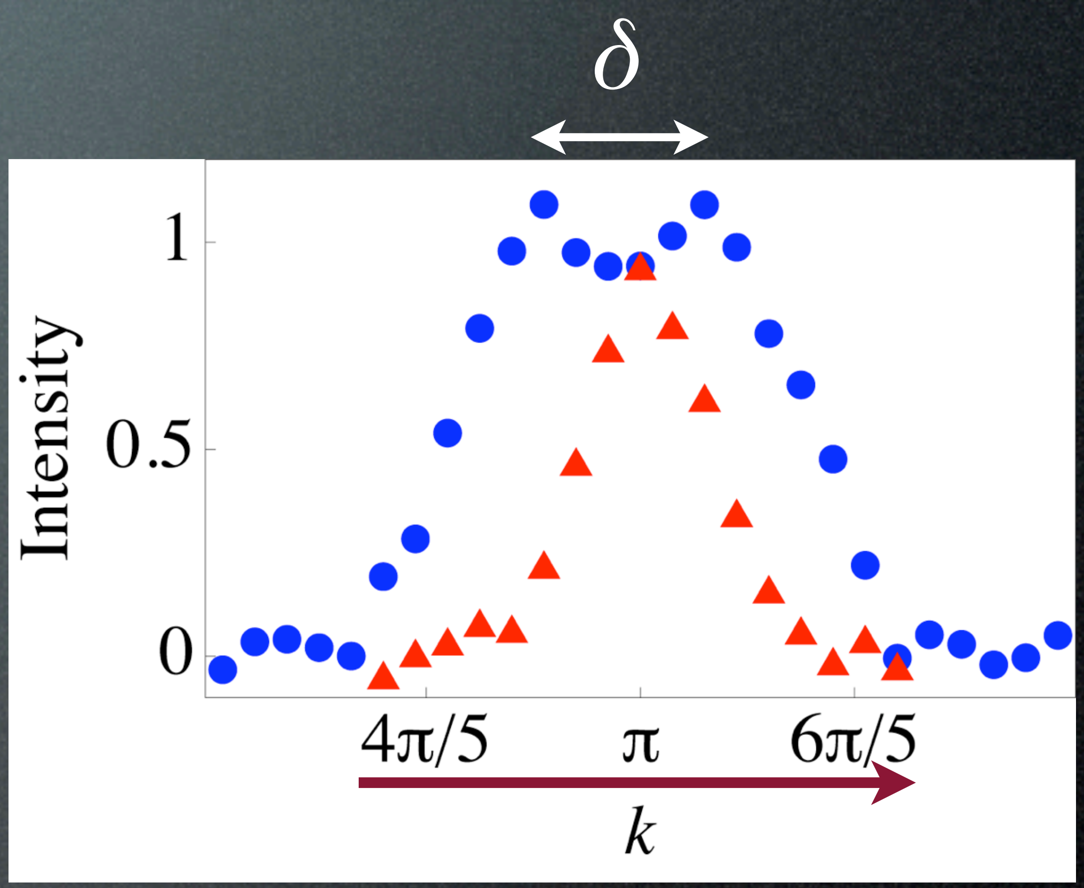


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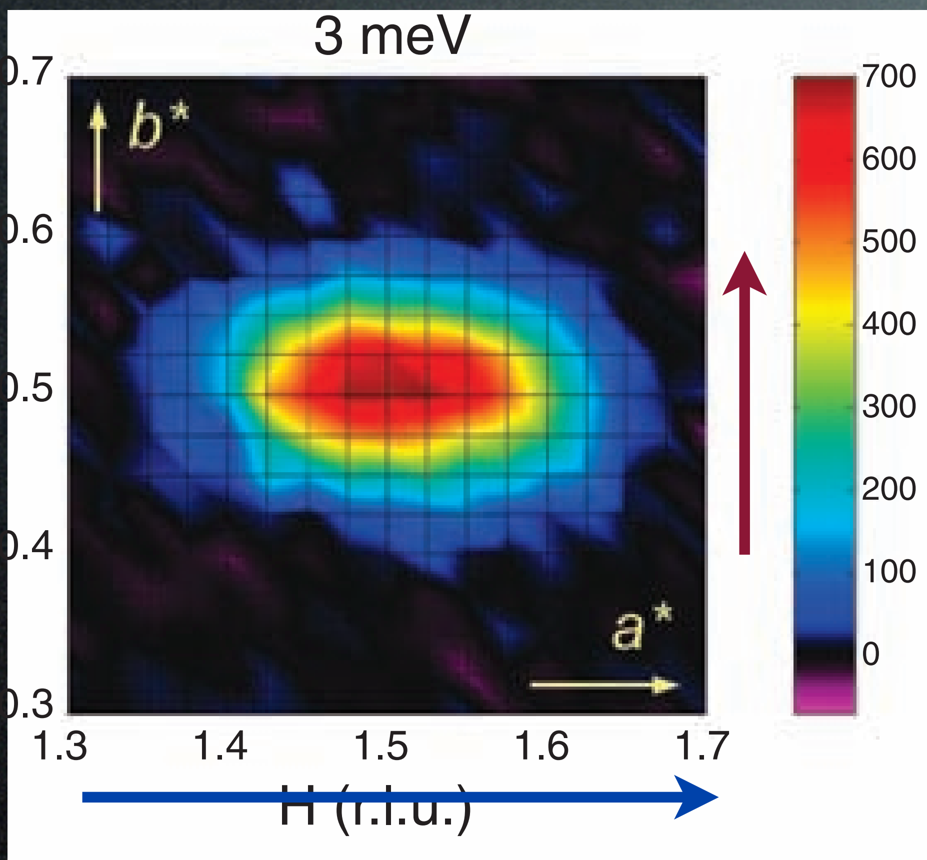


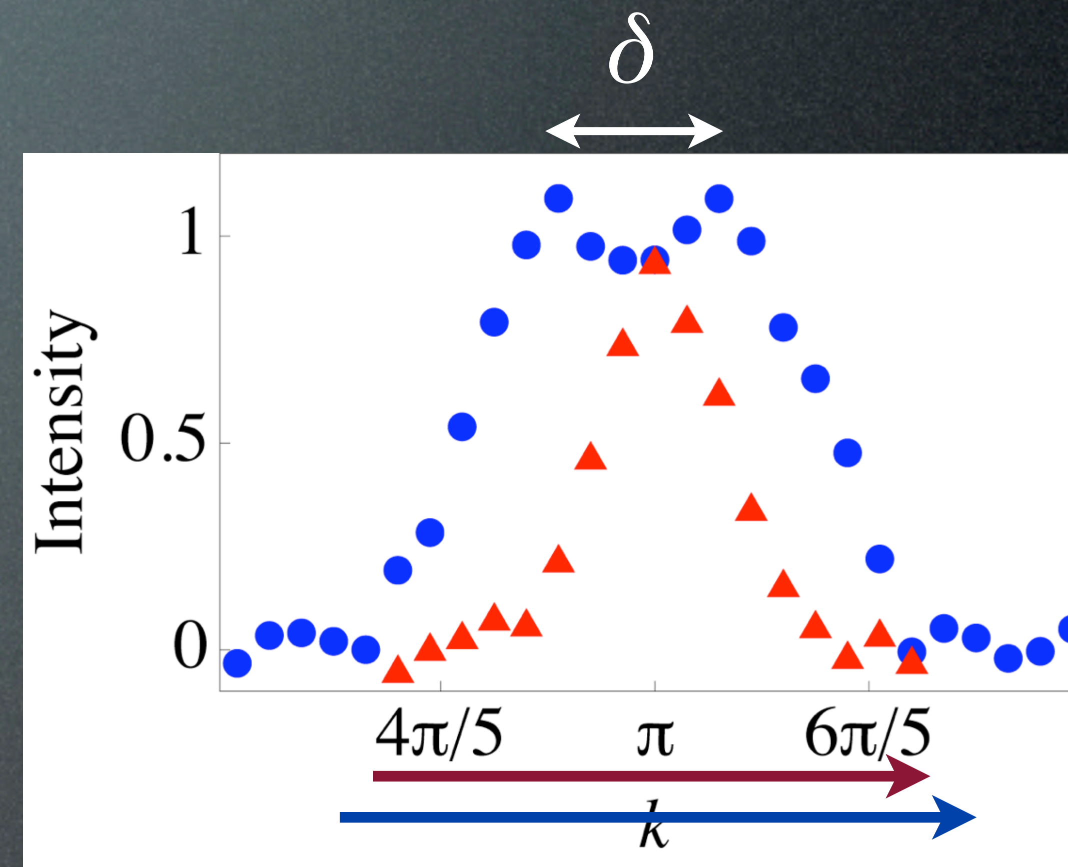


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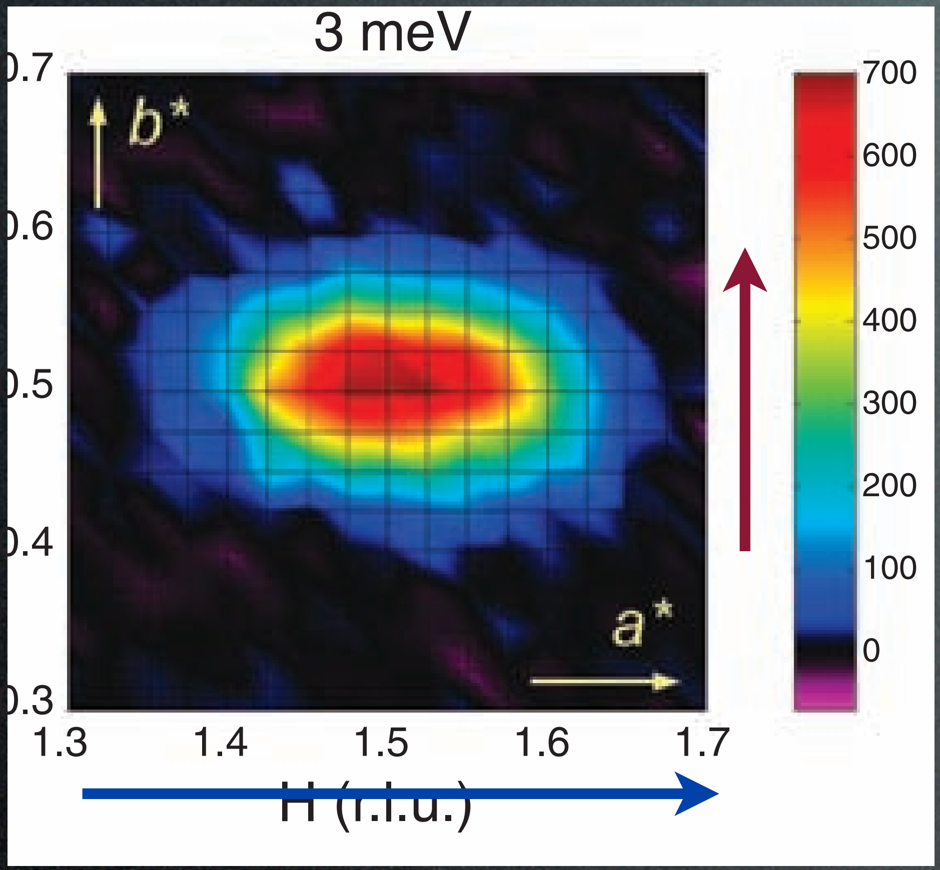



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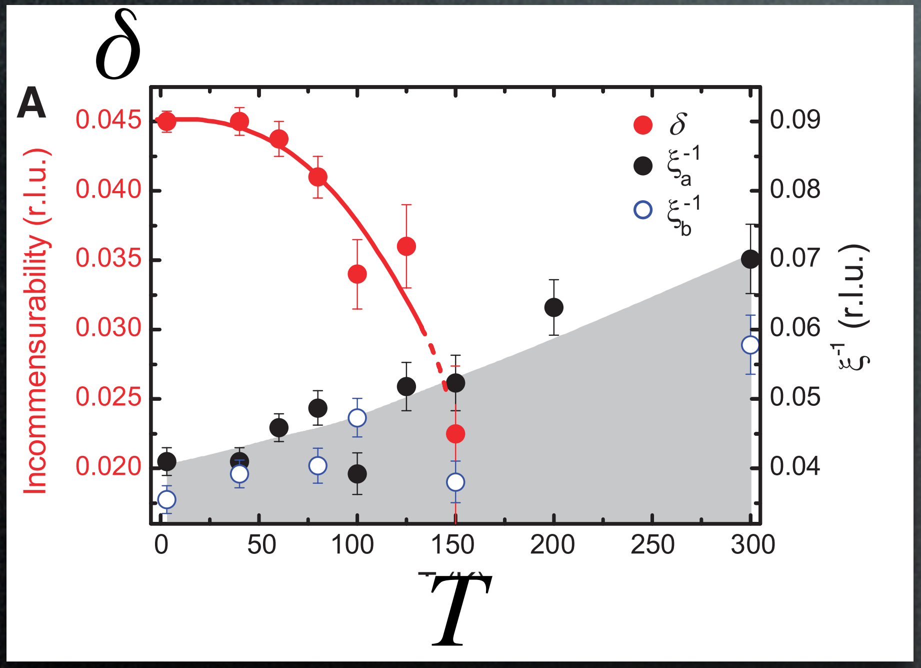
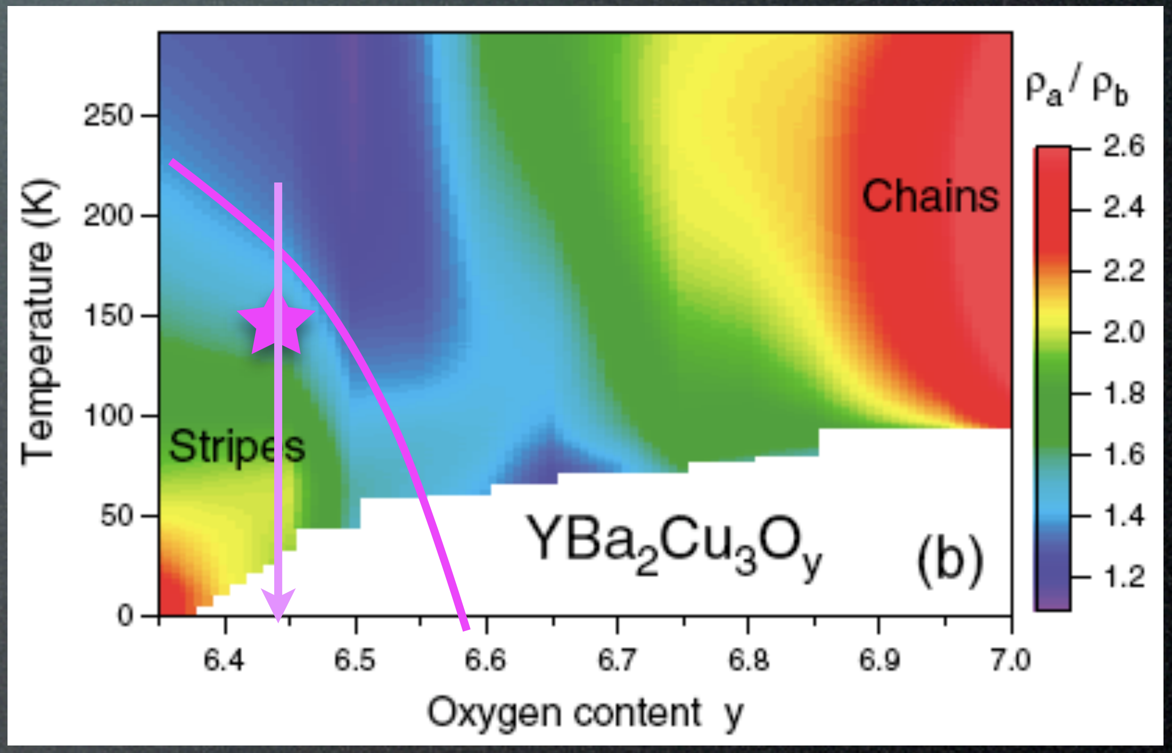
Hinkov et al, Science, Jan 2008

Spin channel

# Incommensurability as Order parameter?

$$\delta \propto \sqrt{T - T^*}$$




Spin channel

Charge channel

**Spin-charge interplay in electronic liquid crystals: fluctuating spin stripe driven by charge nematic**

Kai Sun,[1,2] Michael J. Lawler,[3,4] and Eun-Ah Kim[4]

arXiv:0906.3460

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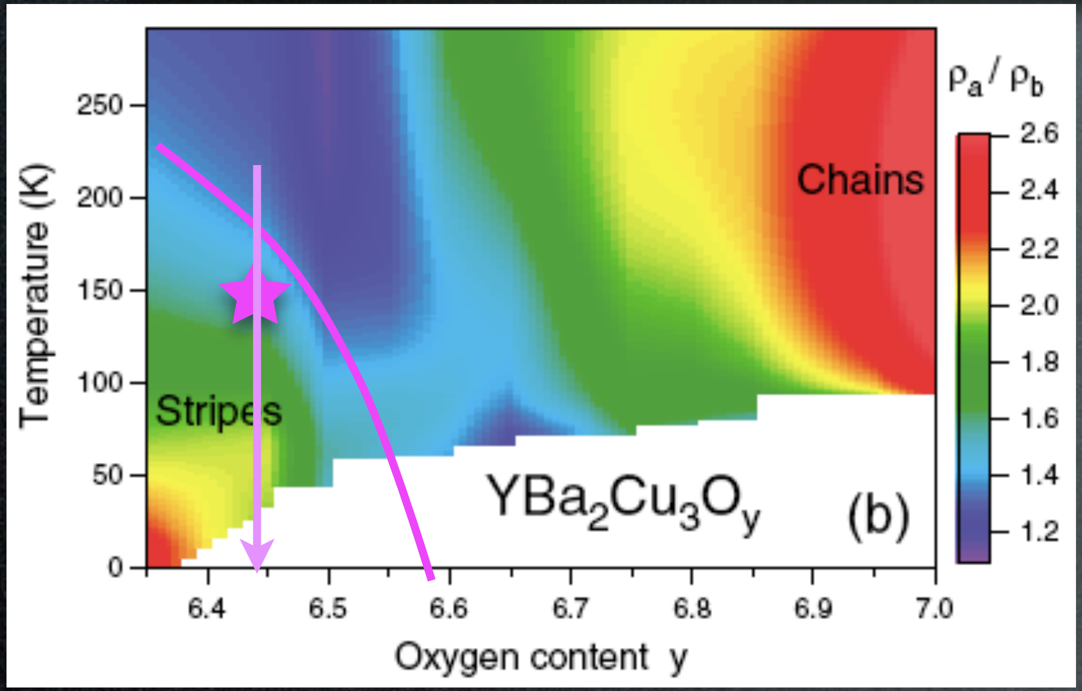


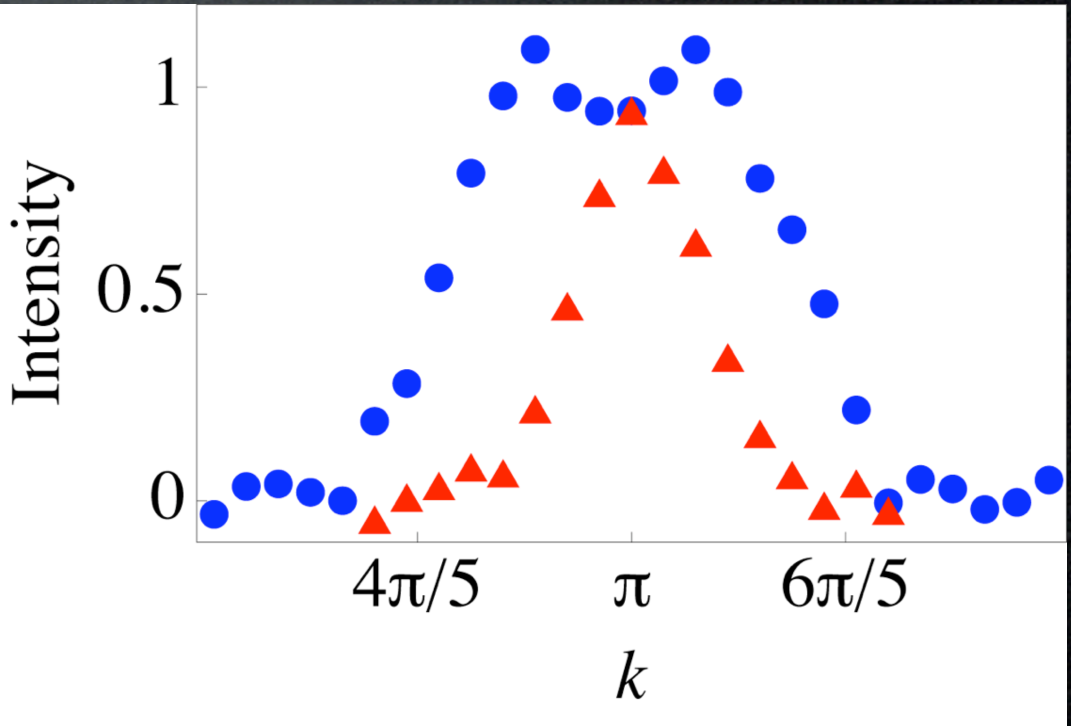

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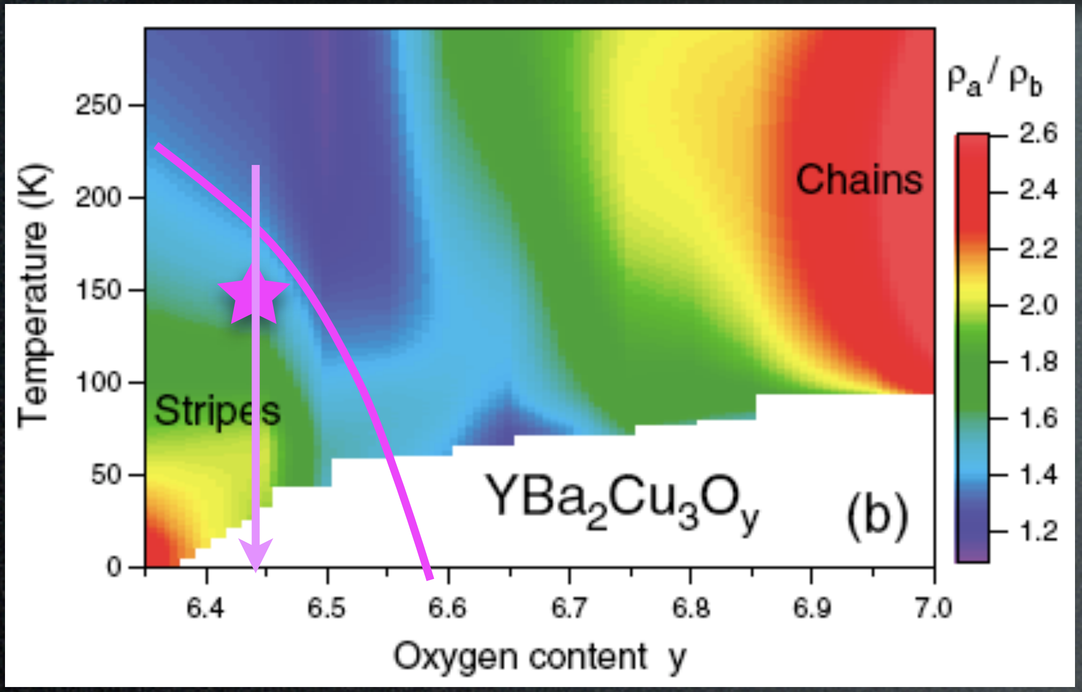


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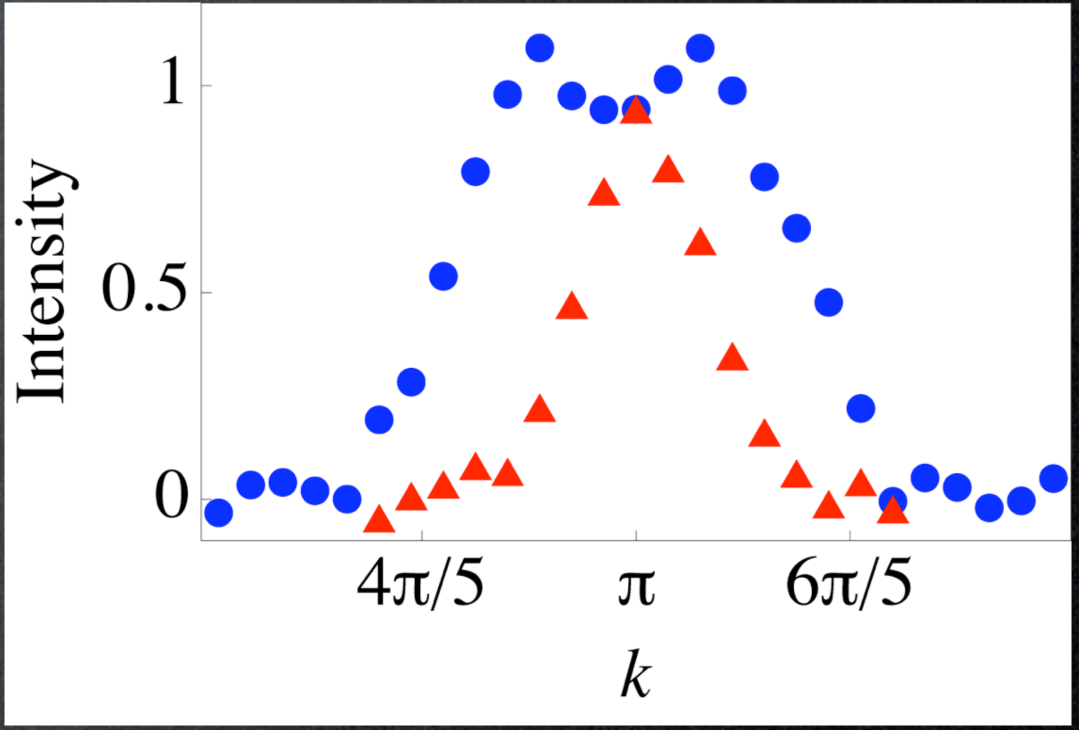

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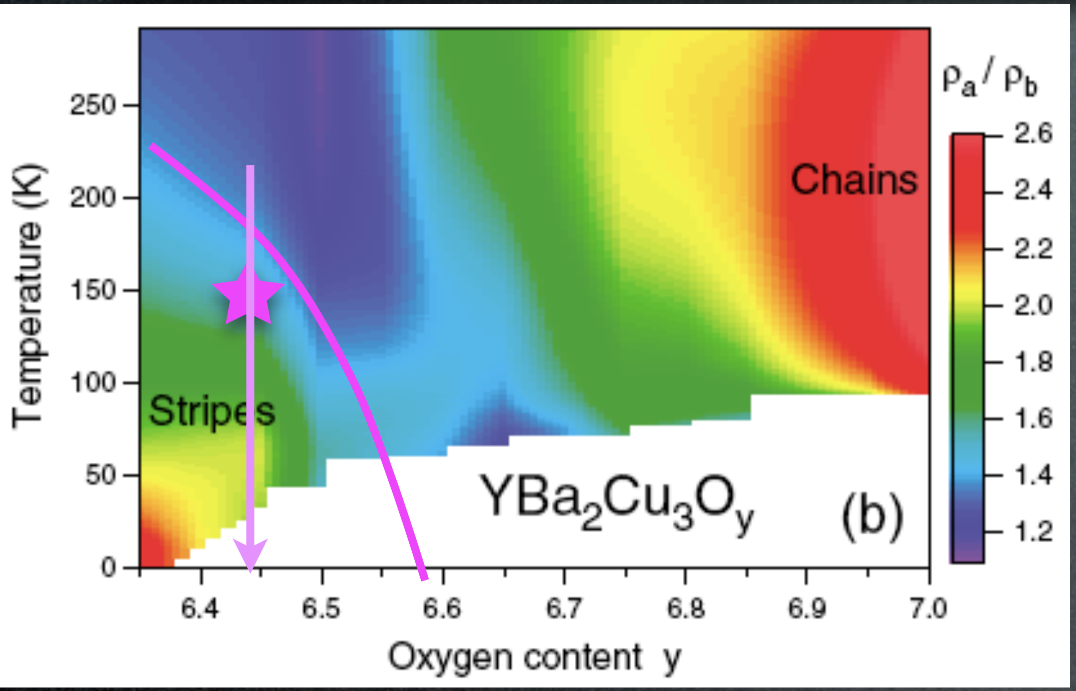


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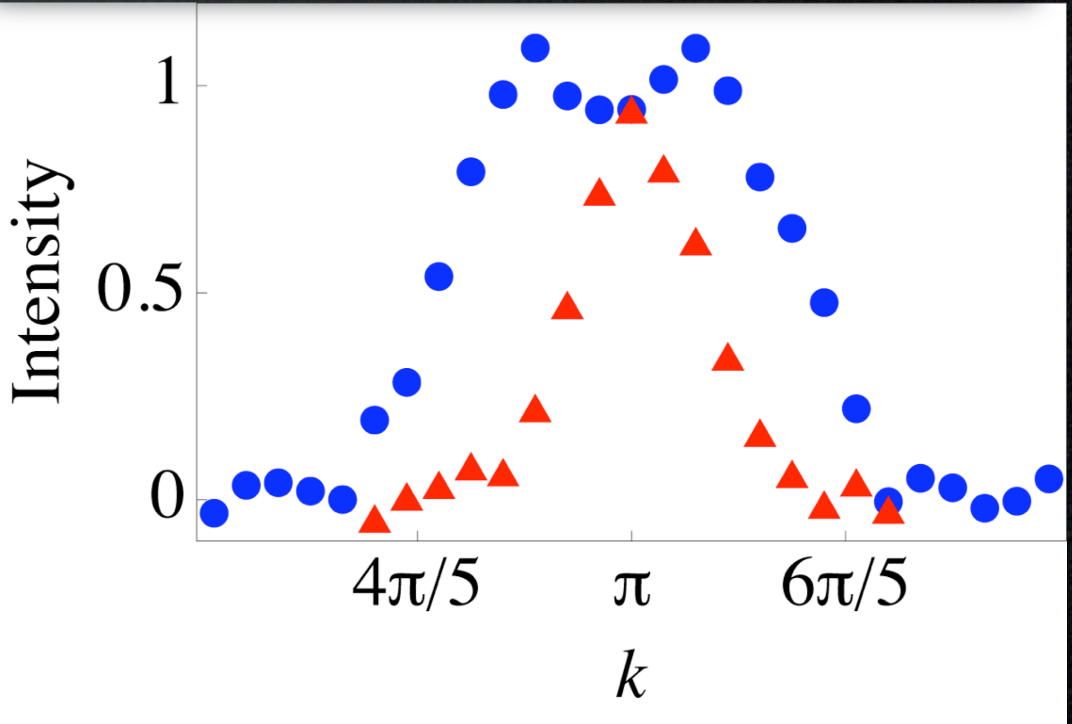

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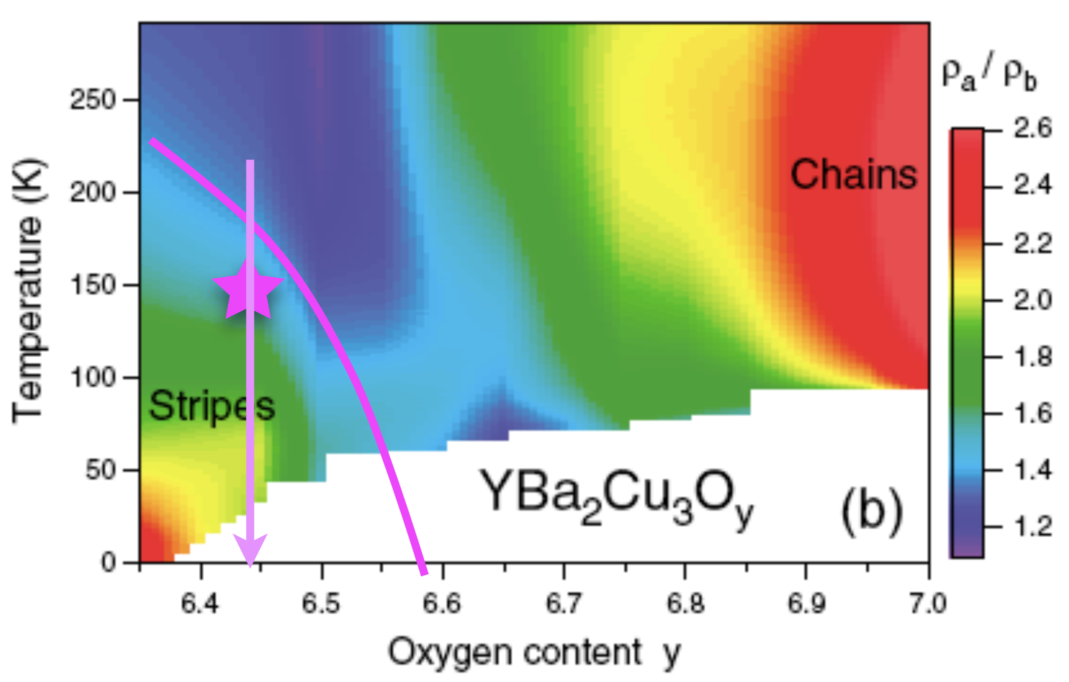


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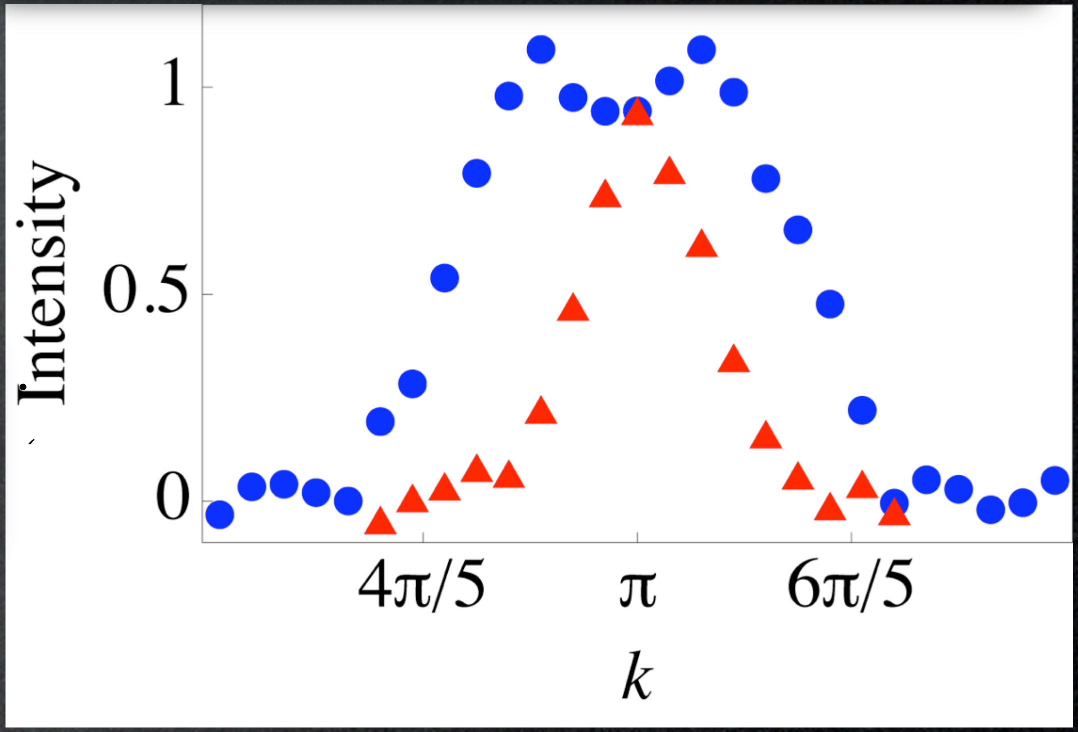

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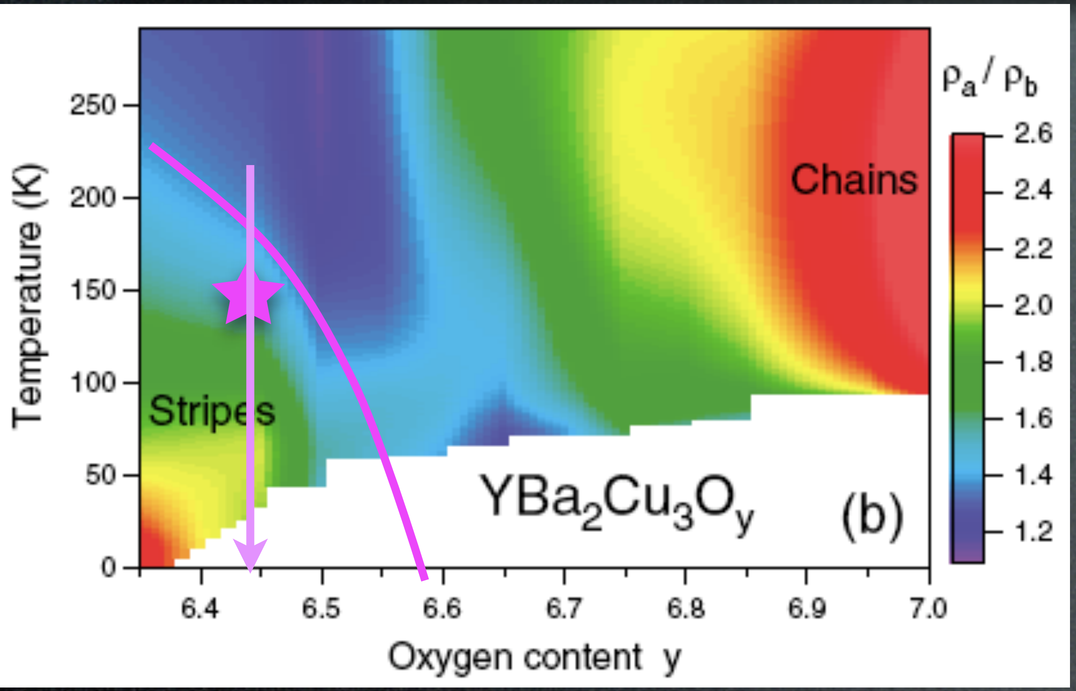


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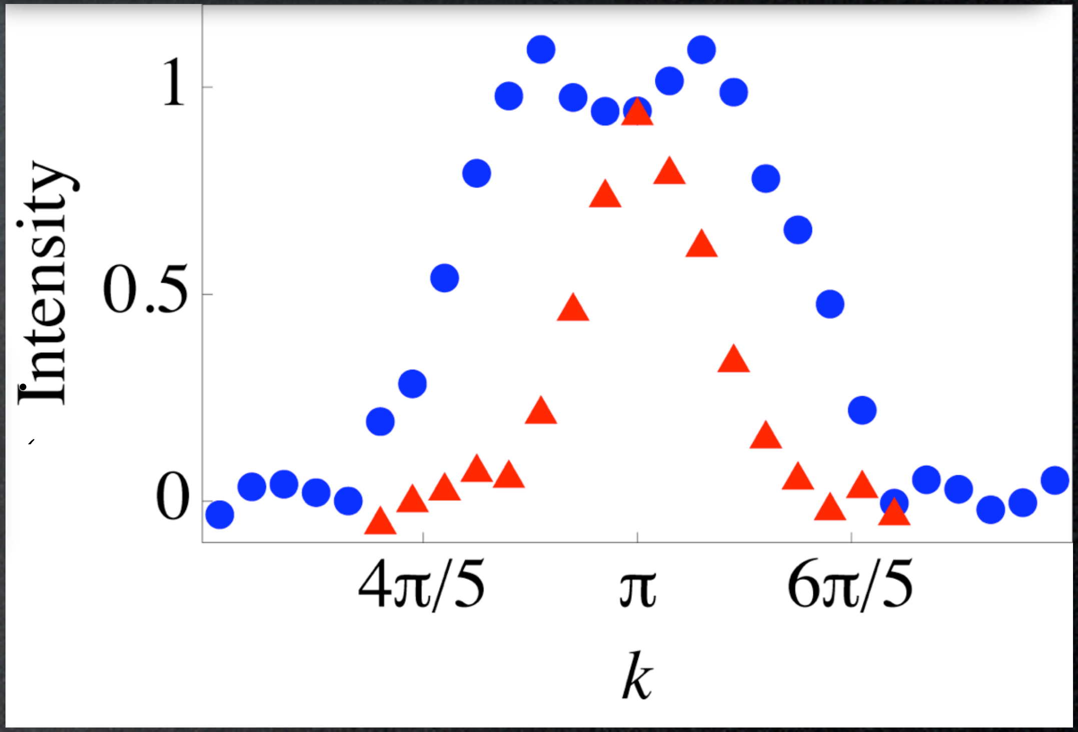

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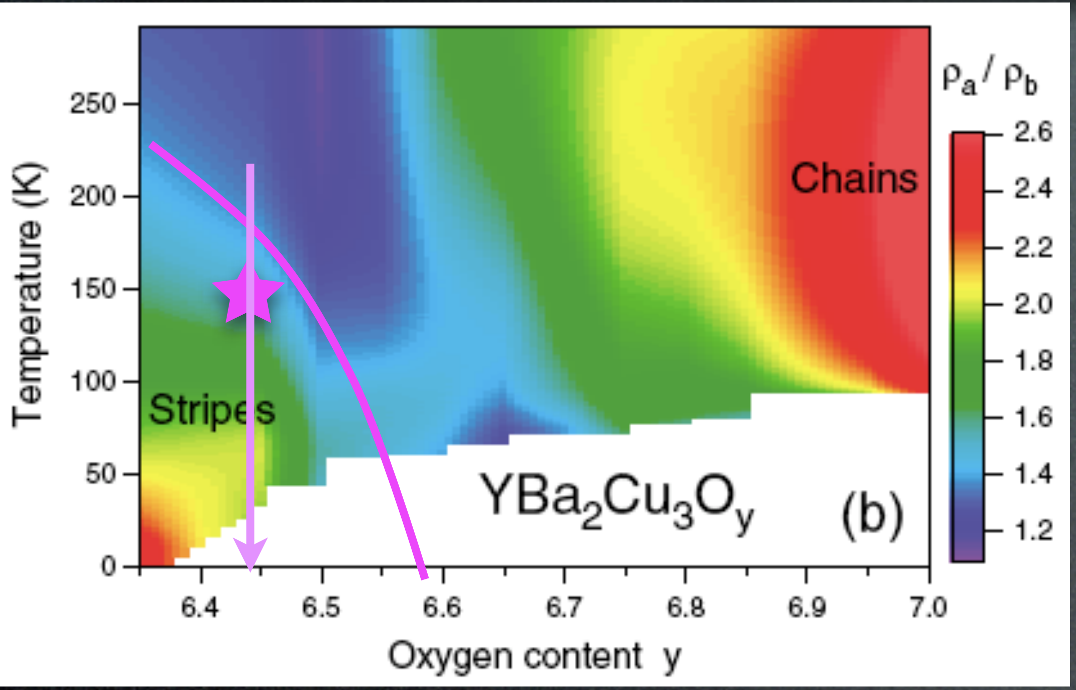


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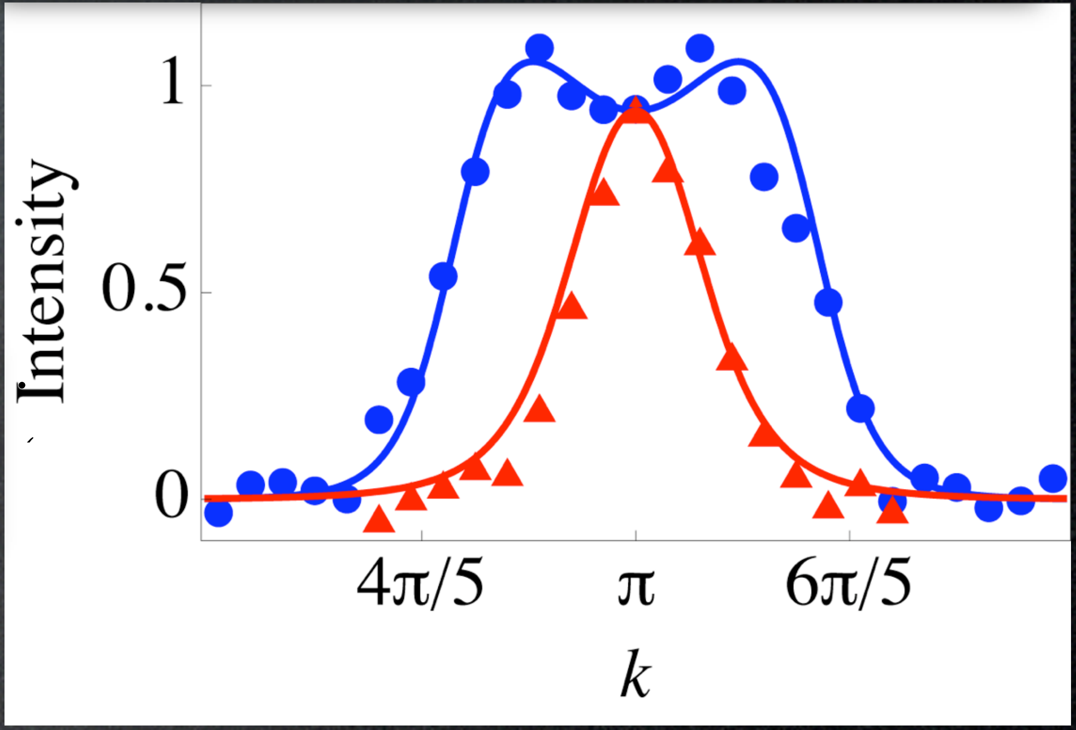

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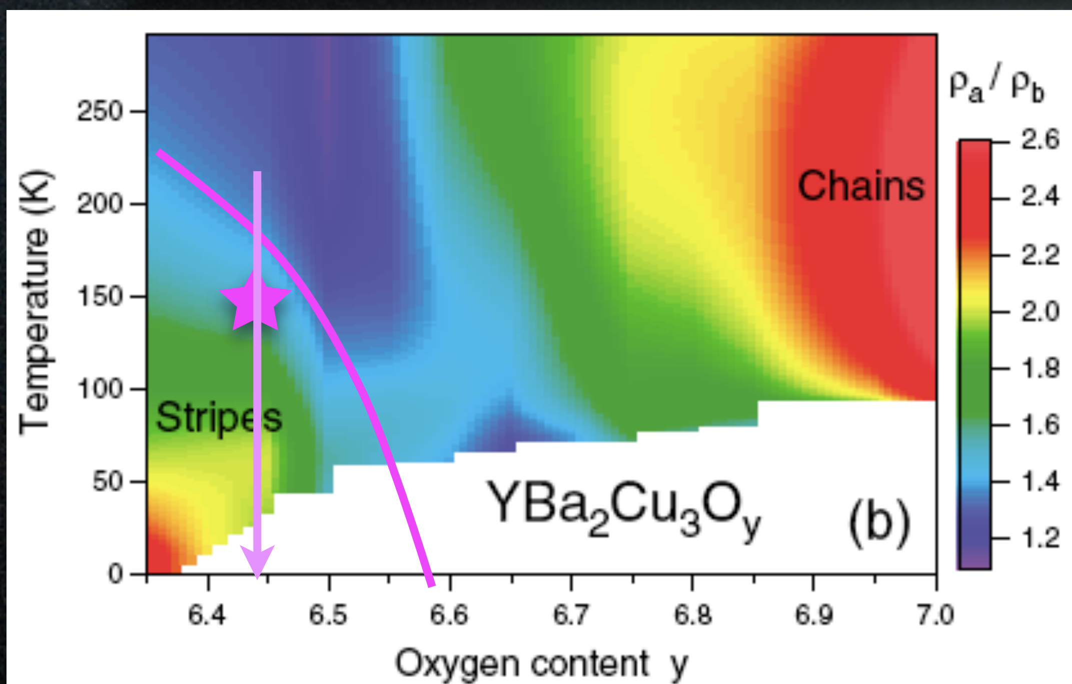


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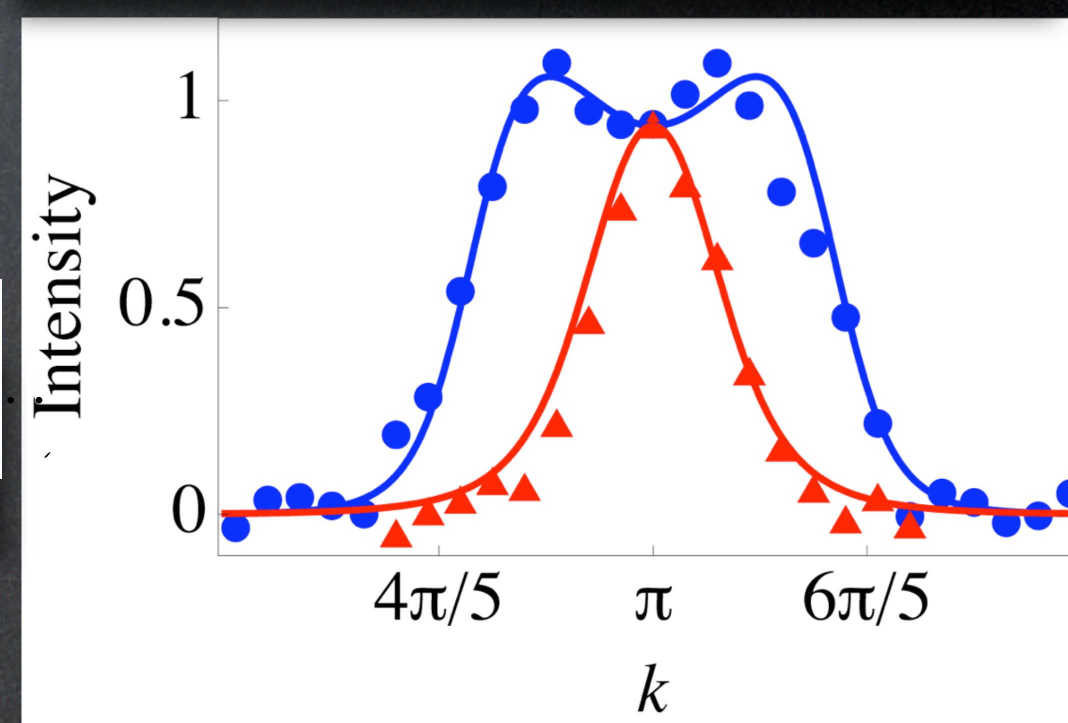


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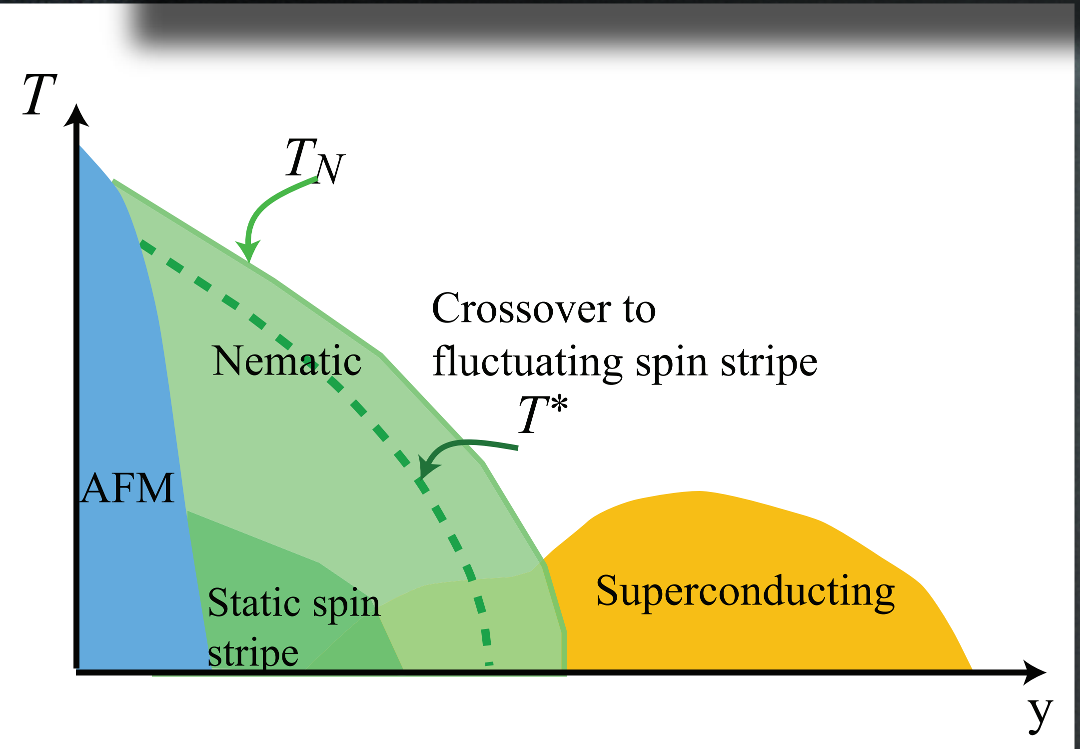
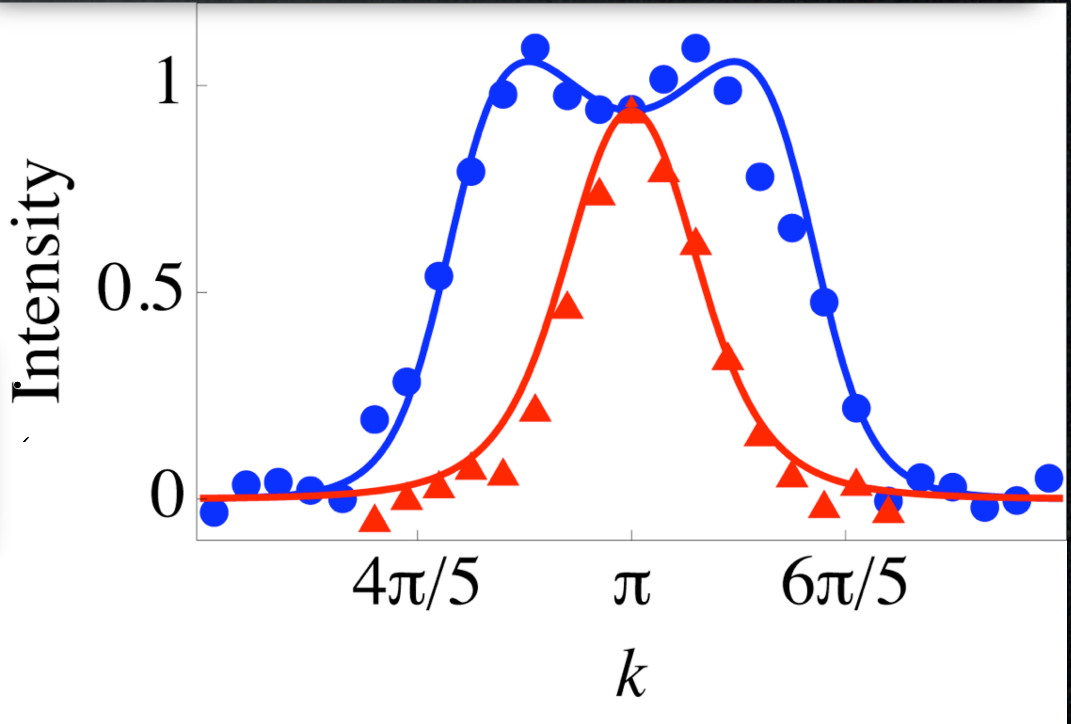



$$S[\vec{\phi}] = \frac{1}{g}\int \frac{d^2\mathbf{q}d\omega}{(2\pi)^3}\left(i\Gamma|\omega| + \omega^2 - \Delta^2(\mathbf{q})\right)|\vec{\phi}(\mathbf{q},\omega)|^2.$$

$$\chi''(\omega,\mathbf{q}) = g\frac{\Gamma\omega}{(\Gamma\omega)^2 + (\omega^2 - \Delta(\mathbf{q})^2)^2}.$$

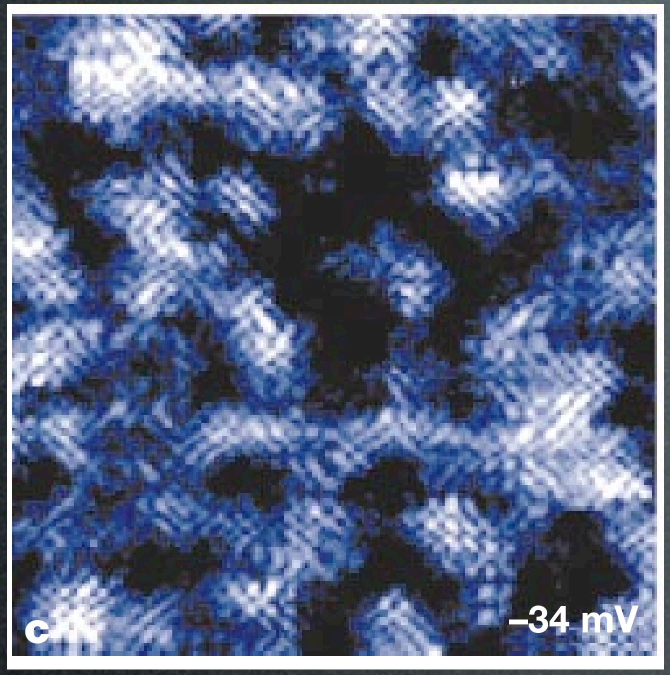
$$\Delta^2(\mathbf{q};N) = \Delta_0^2(N) + c_0^2(N)q^2 - c_2^2(N)N(q_x^2 - q_y^2) + \cdots$$

$$\boxed{\delta \propto \sqrt{T - T^*}}$$

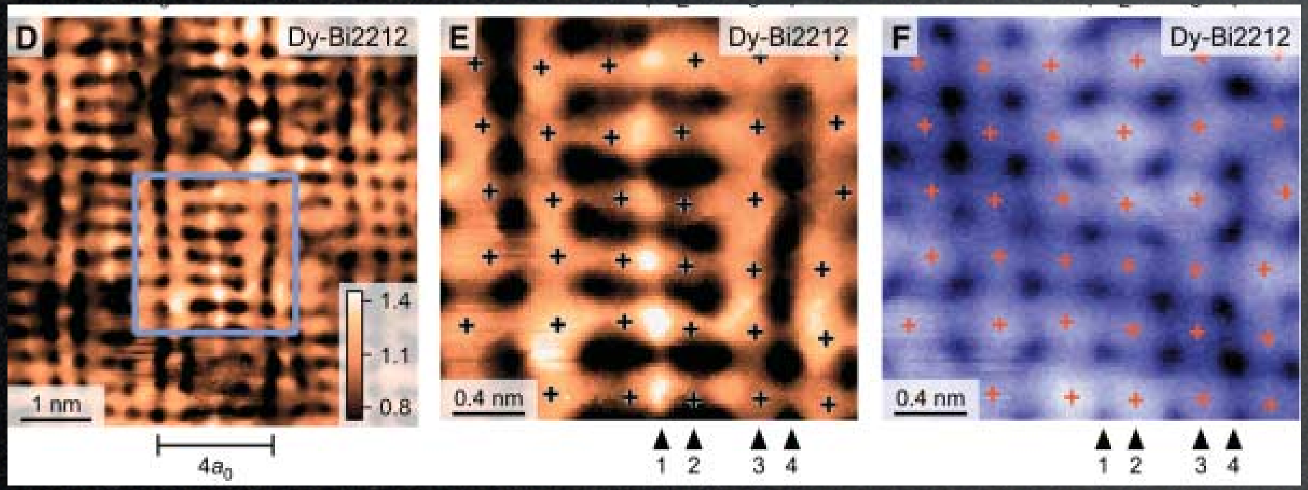


# BSCCO, got nematic?

# Local measure of broken symmetry?




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




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

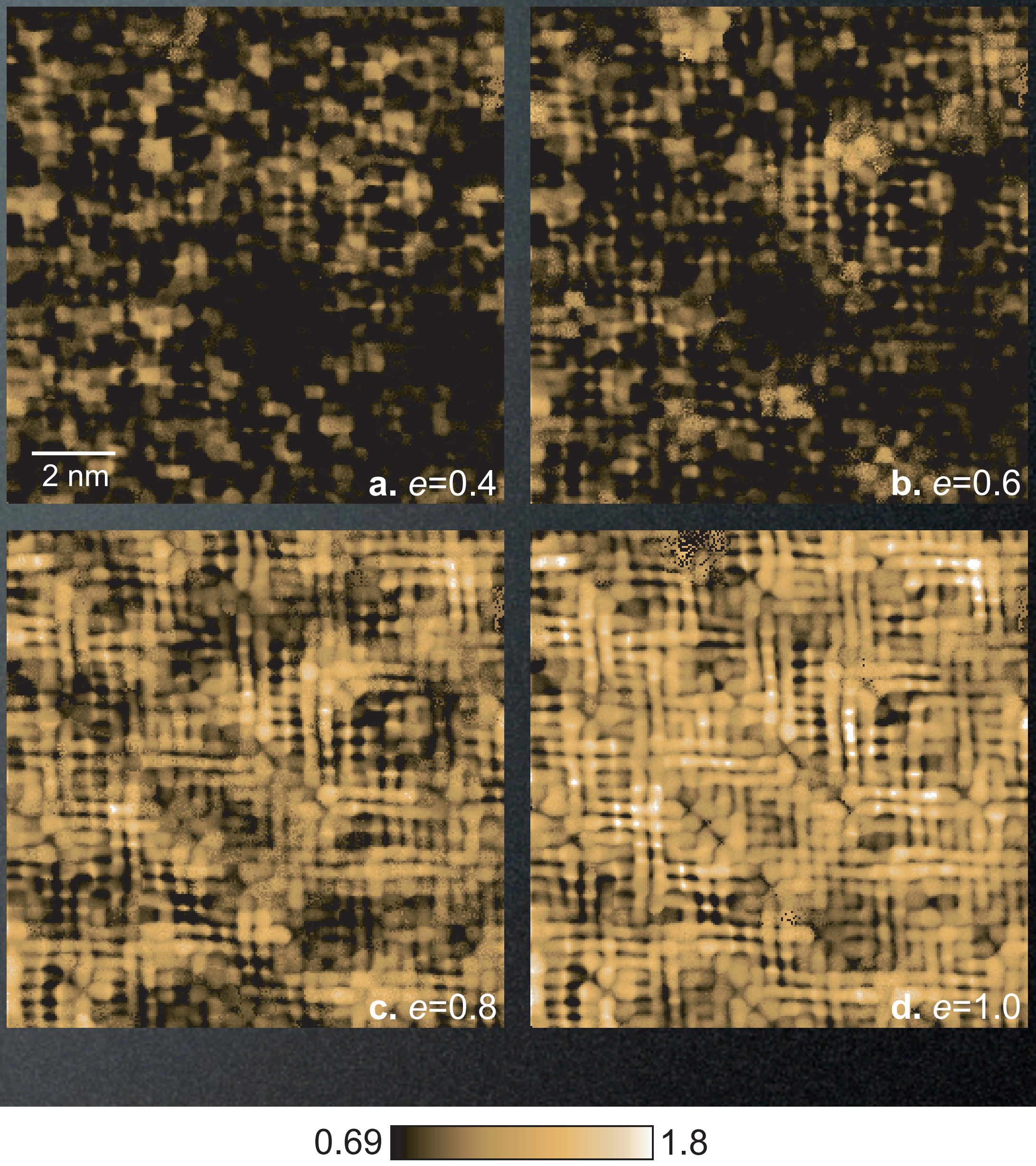
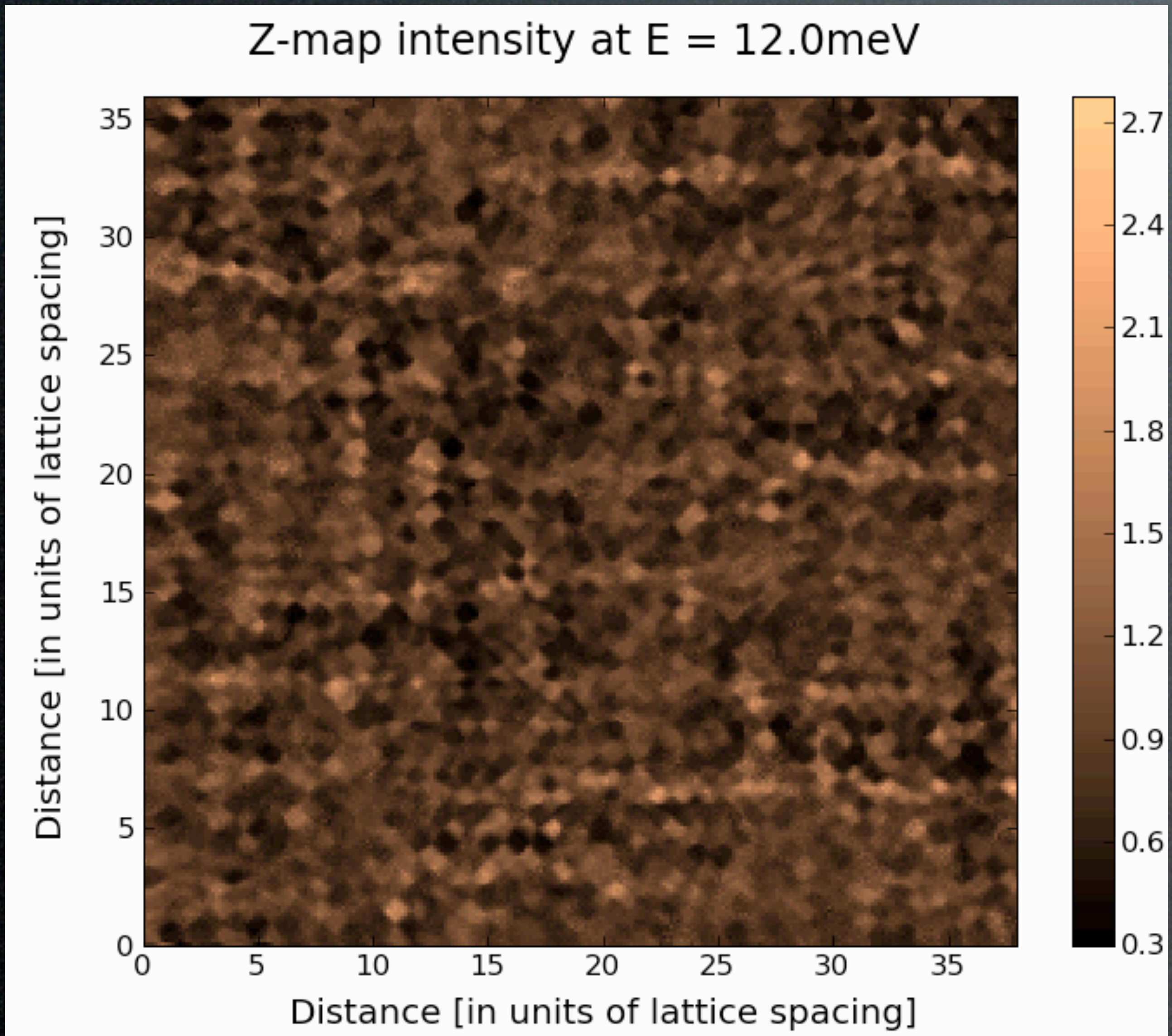


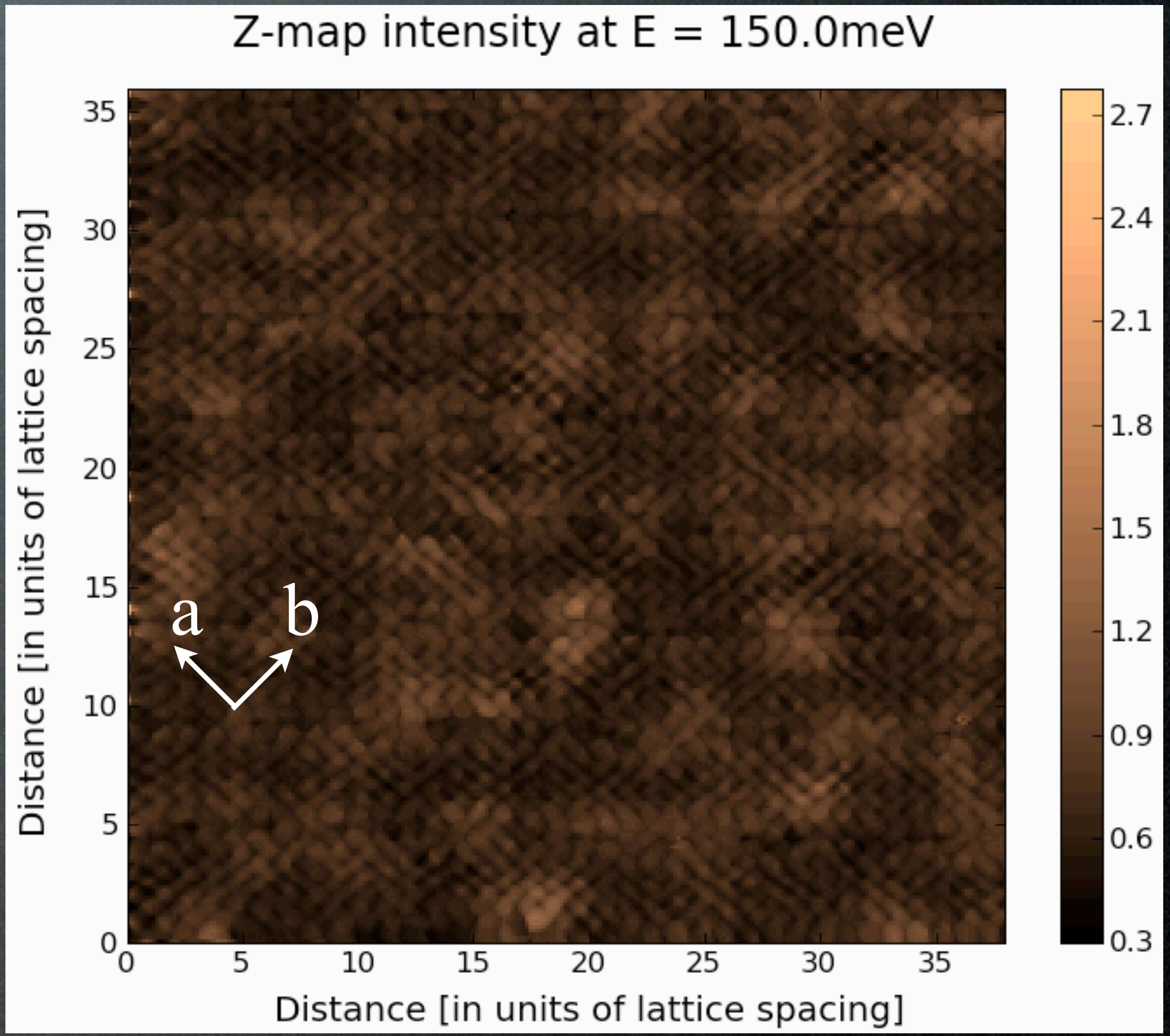

**Figure S7 a-f.** A series of images displaying the real space conductance ratio $Z$ as a function of energy rescaled to the local psuedogap value, $e = E/\Delta_1(\mathbf{r})$. Each pixel location was rescaled independently of the others. The common color scale illustrates that the bond centered pattern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

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

# 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

# Local measure of broken symmetry?

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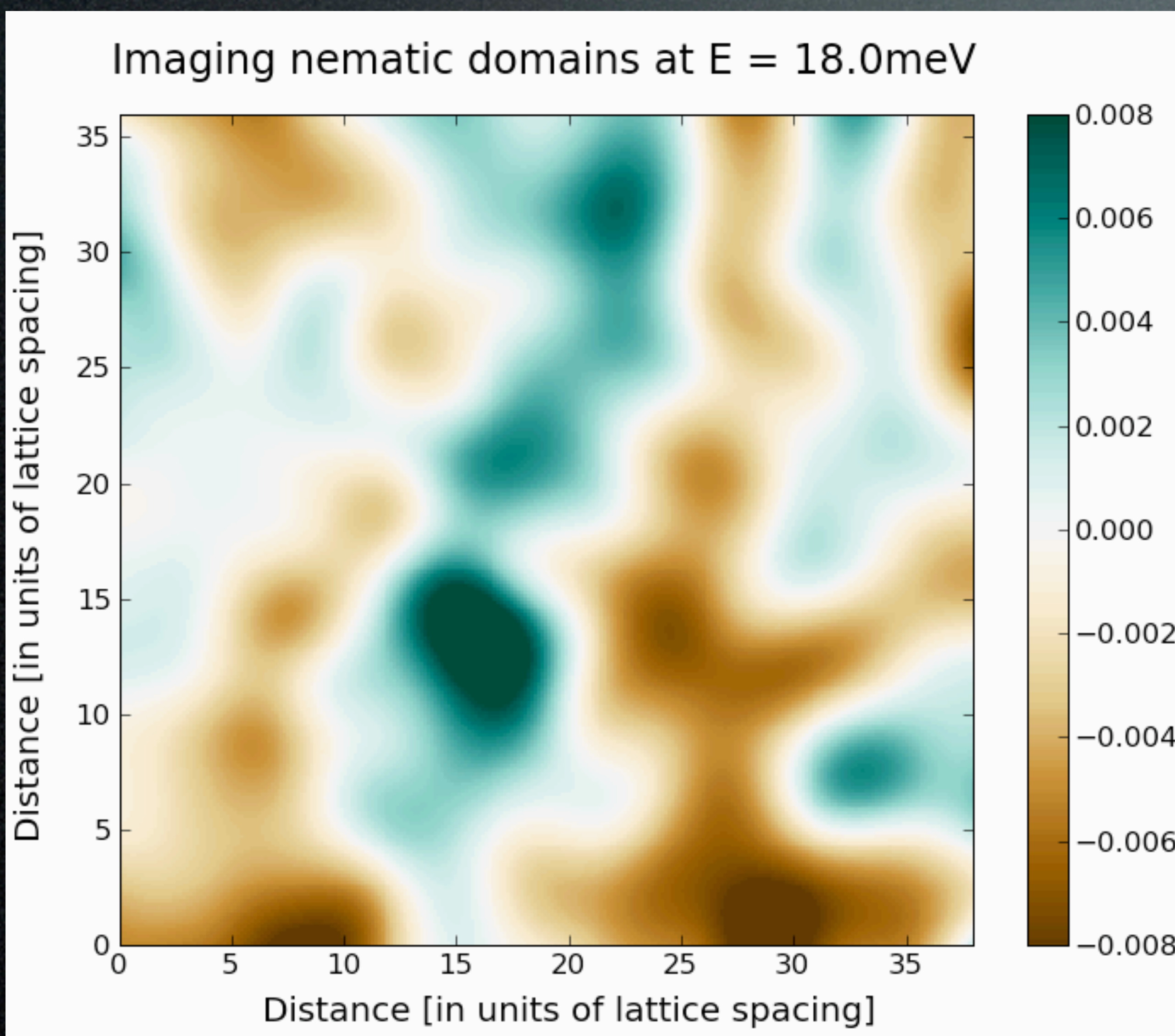
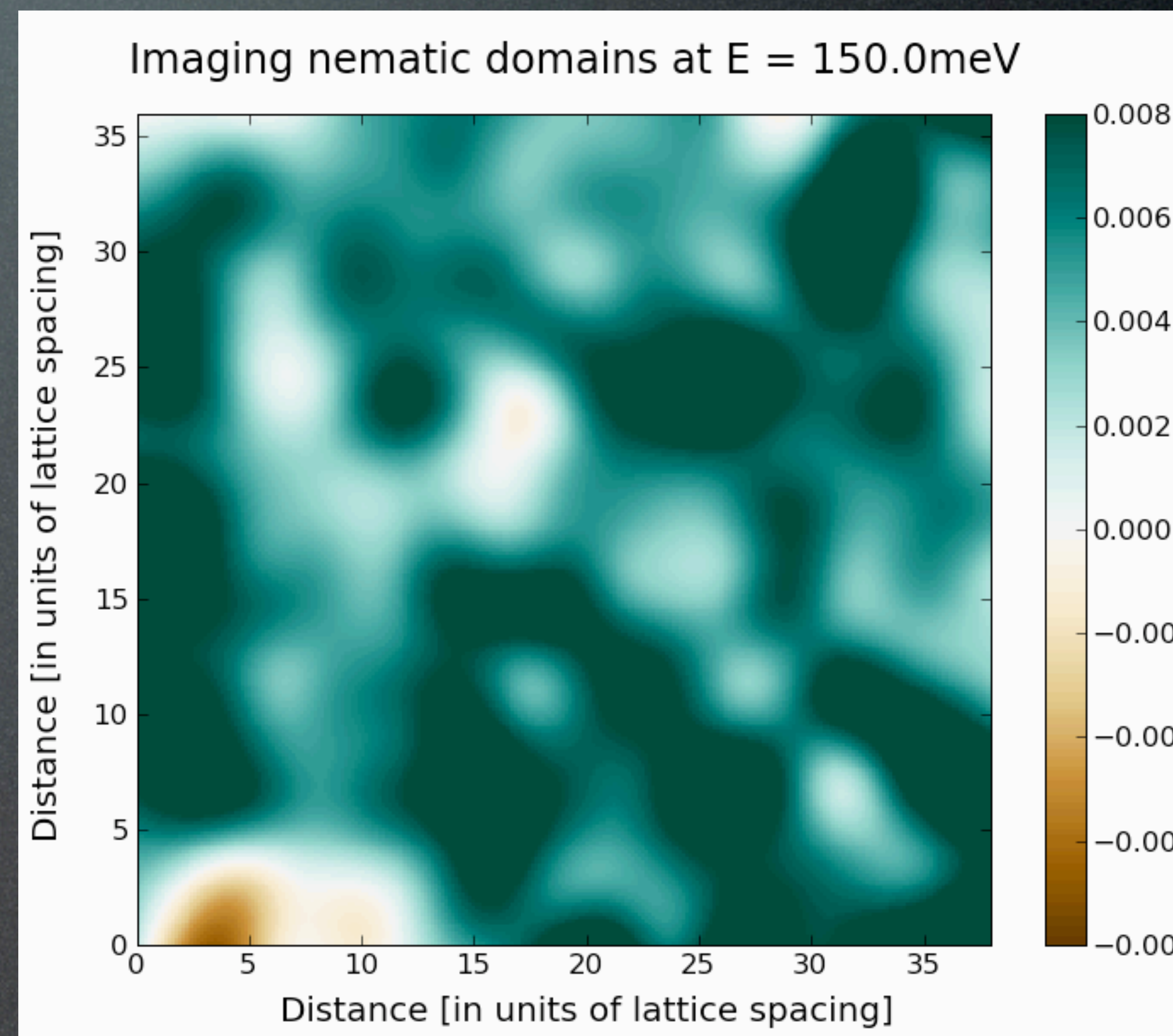
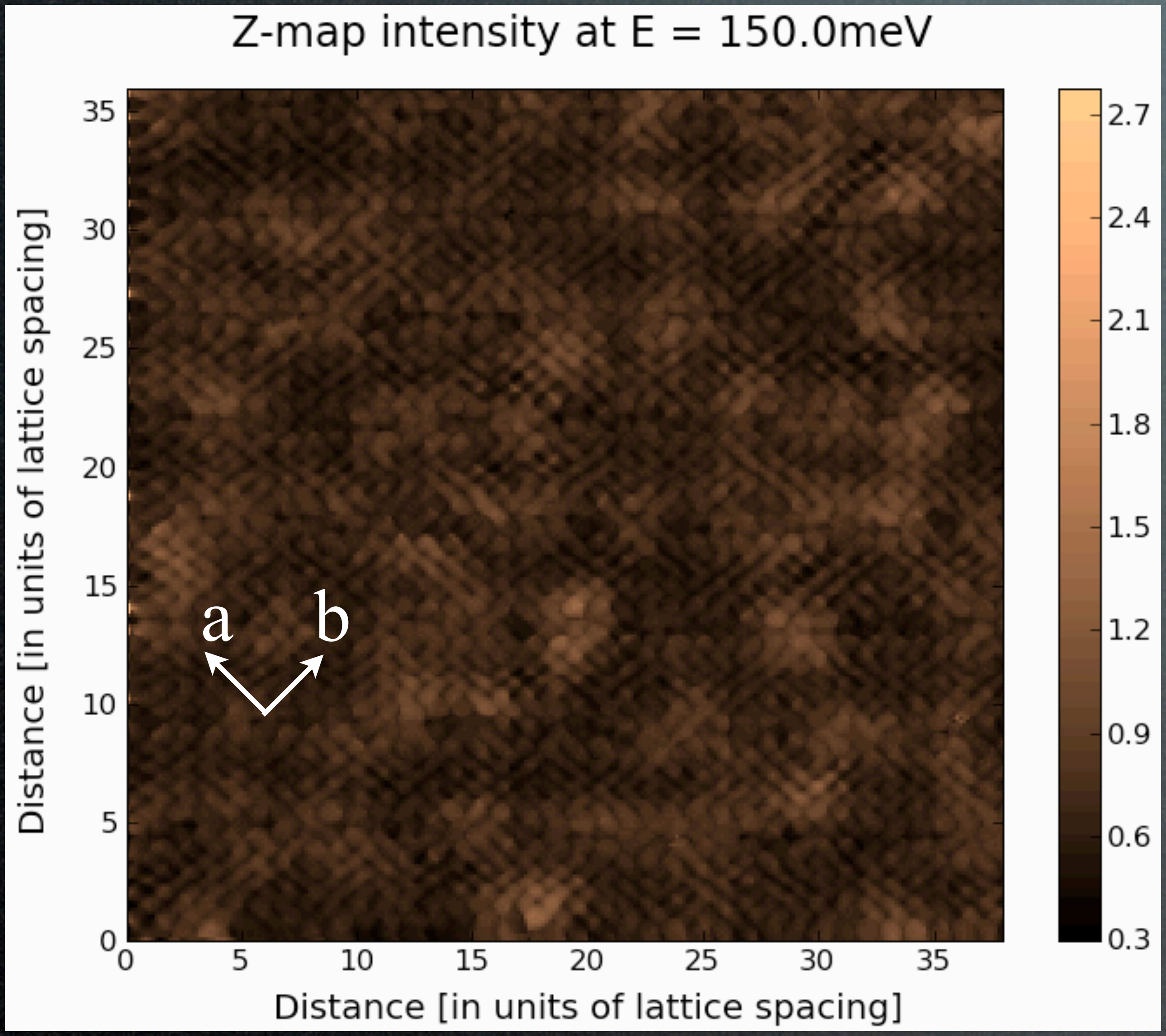



M. Lawler et al, in prep.

## 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

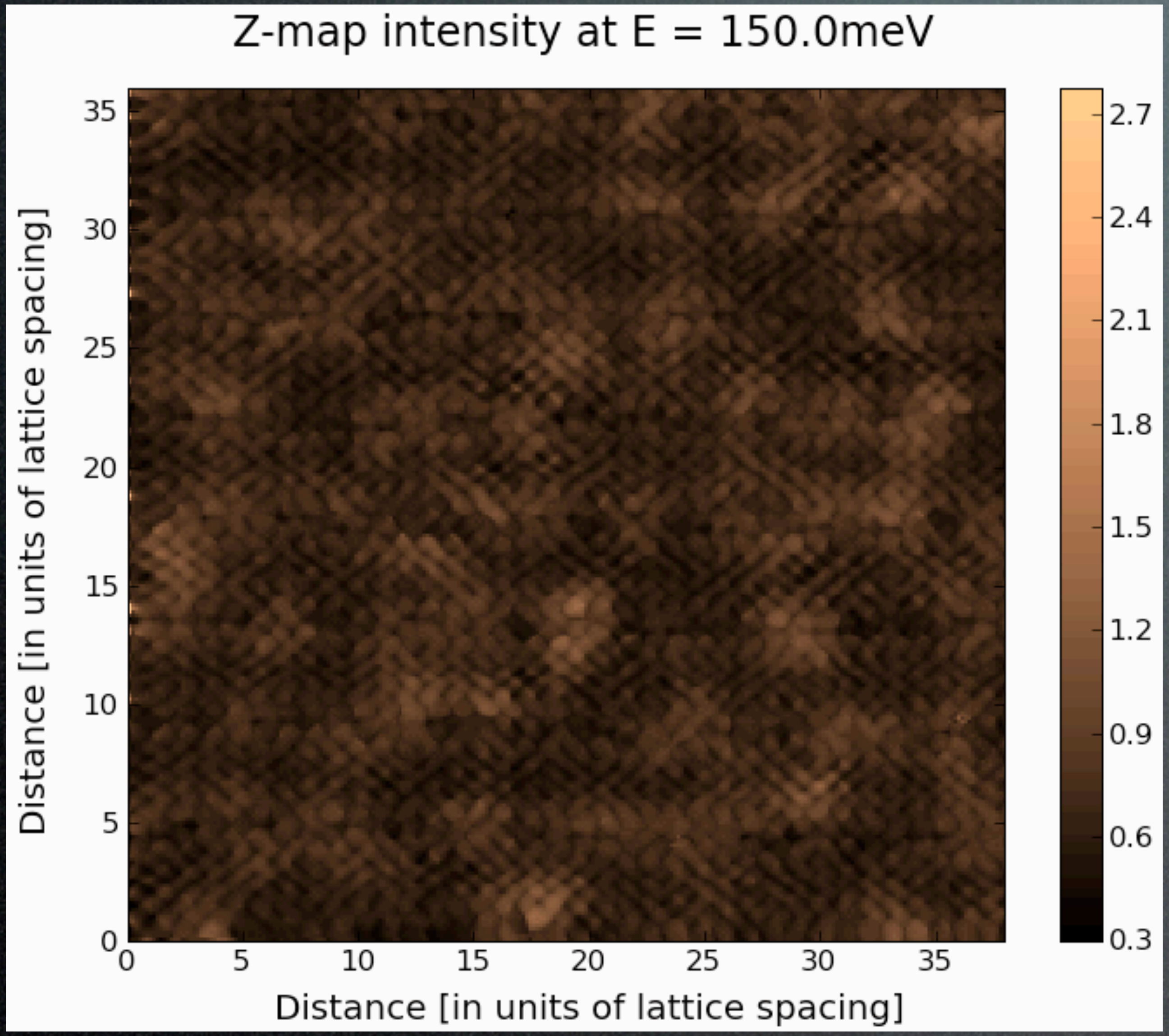
$$N_f(\mathbf{r},E)=\int d\mathbf{r}' f(\mathbf{r}-\mathbf{r}')N(\mathbf{r}',E),$$

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

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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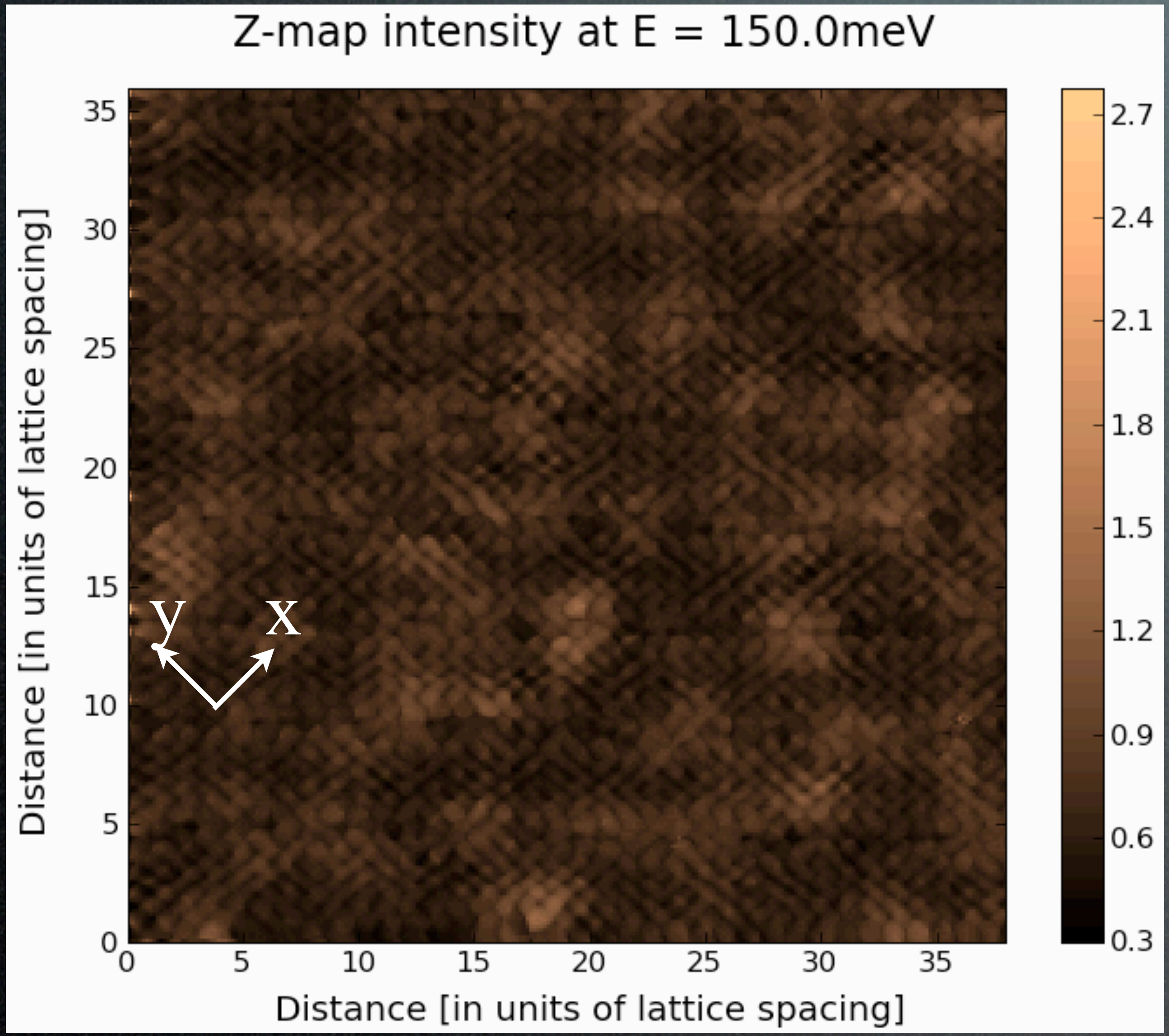

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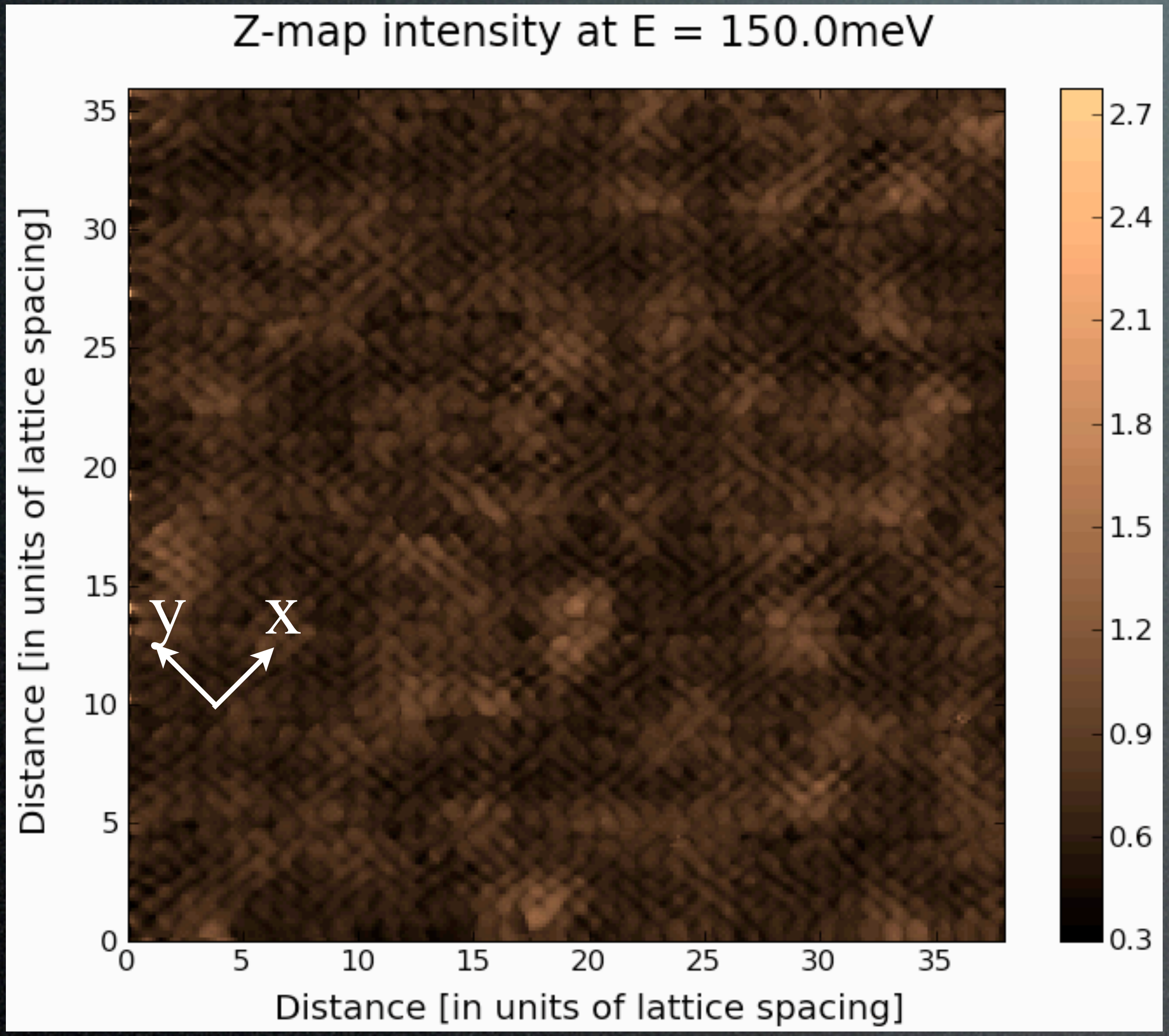


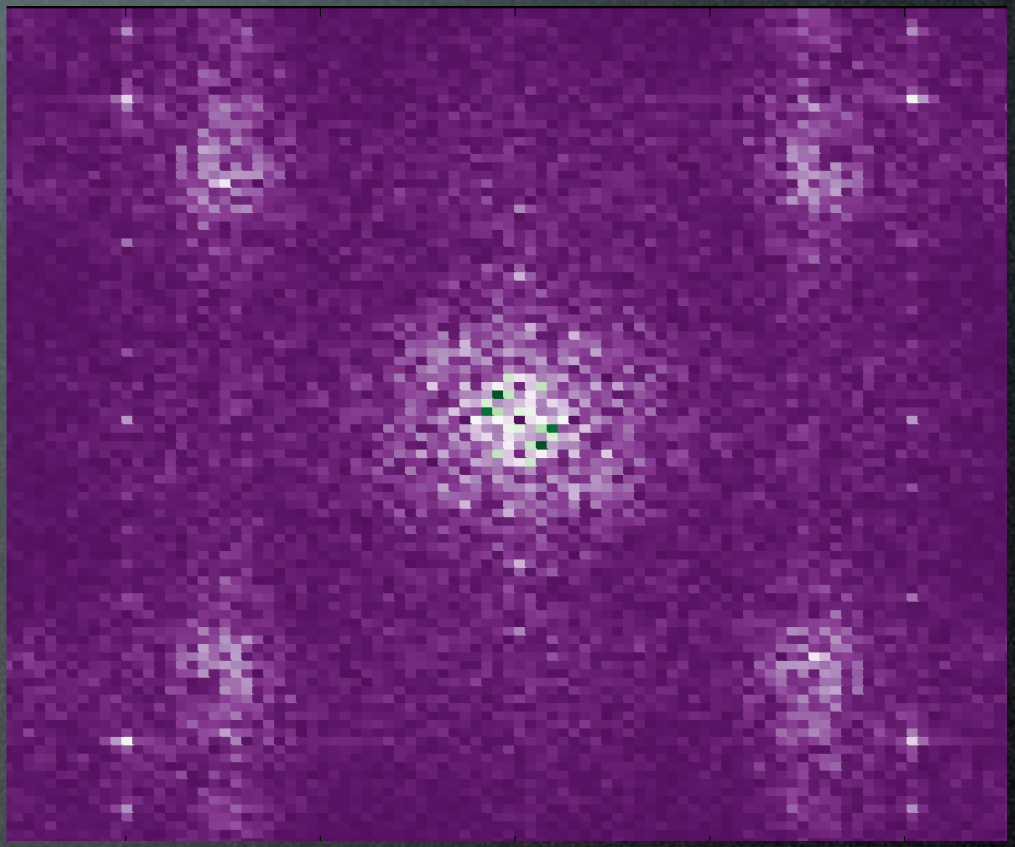

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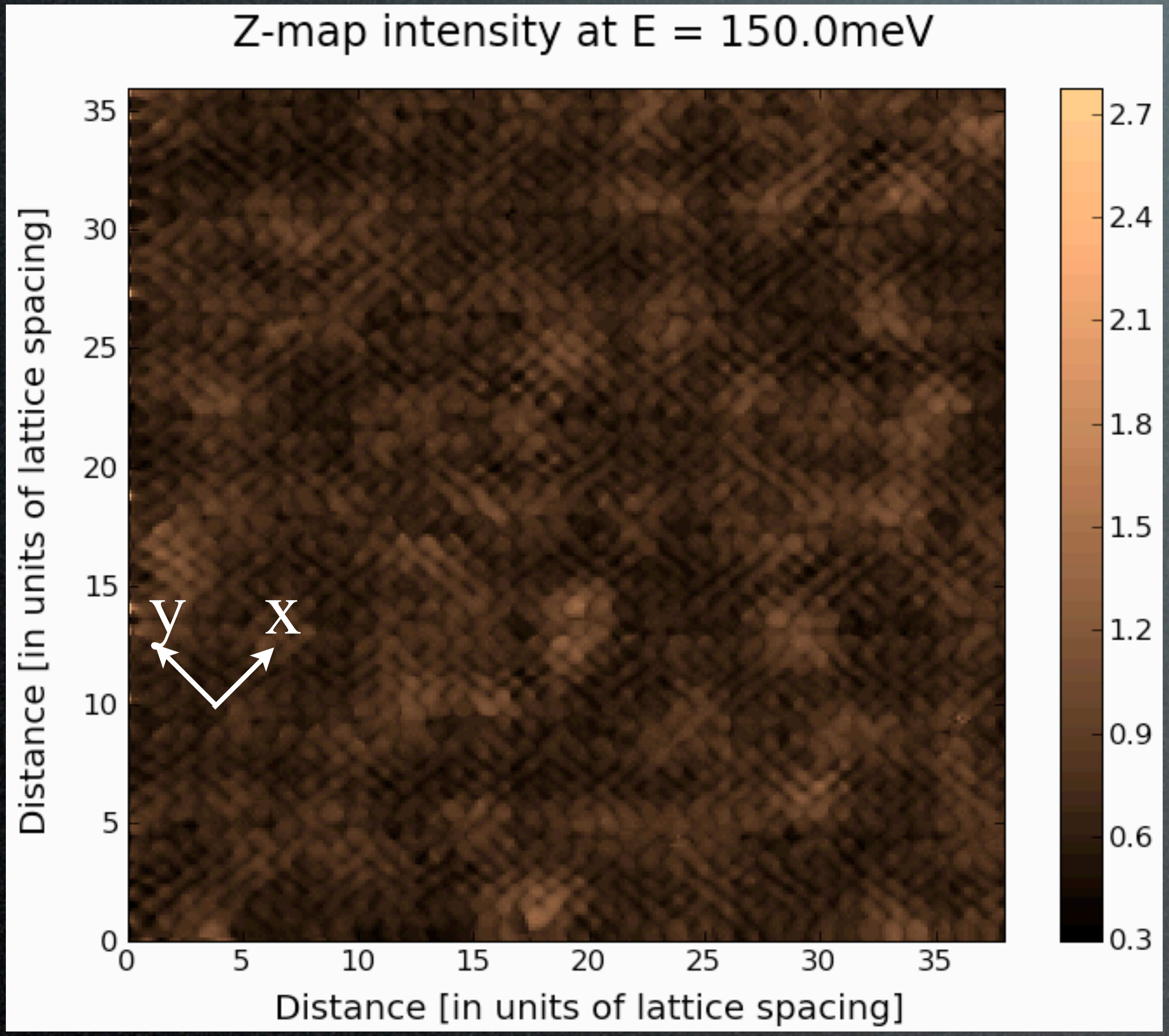


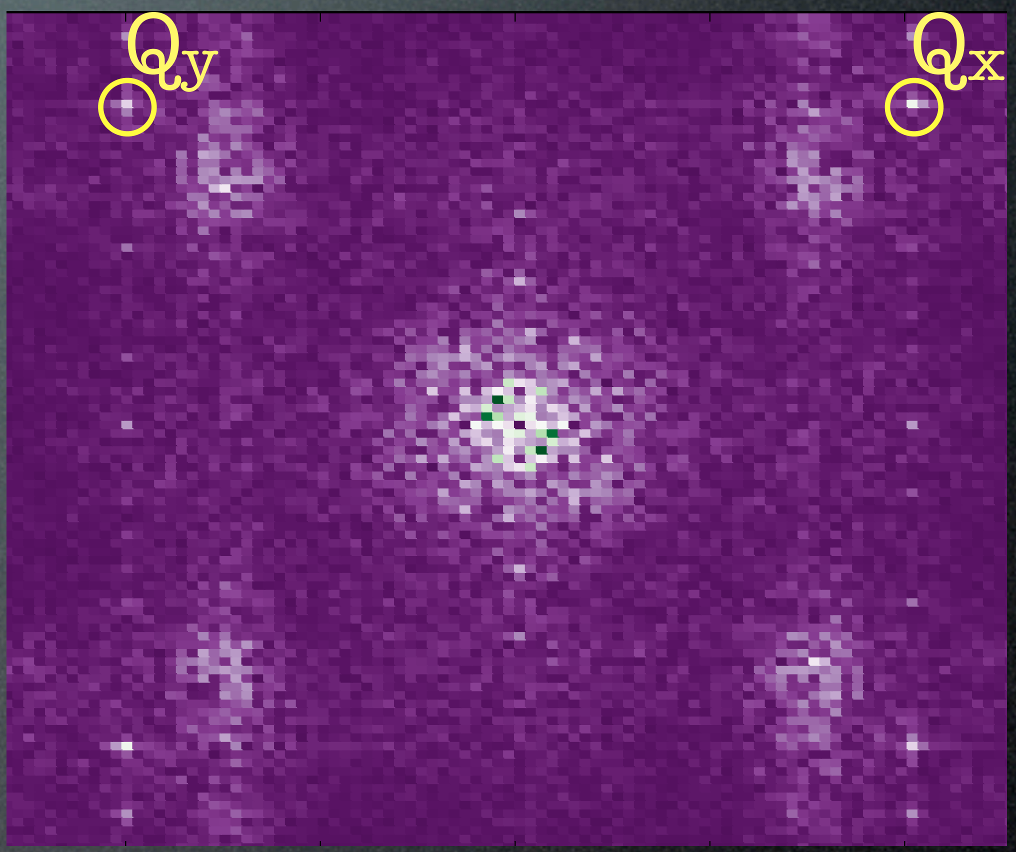

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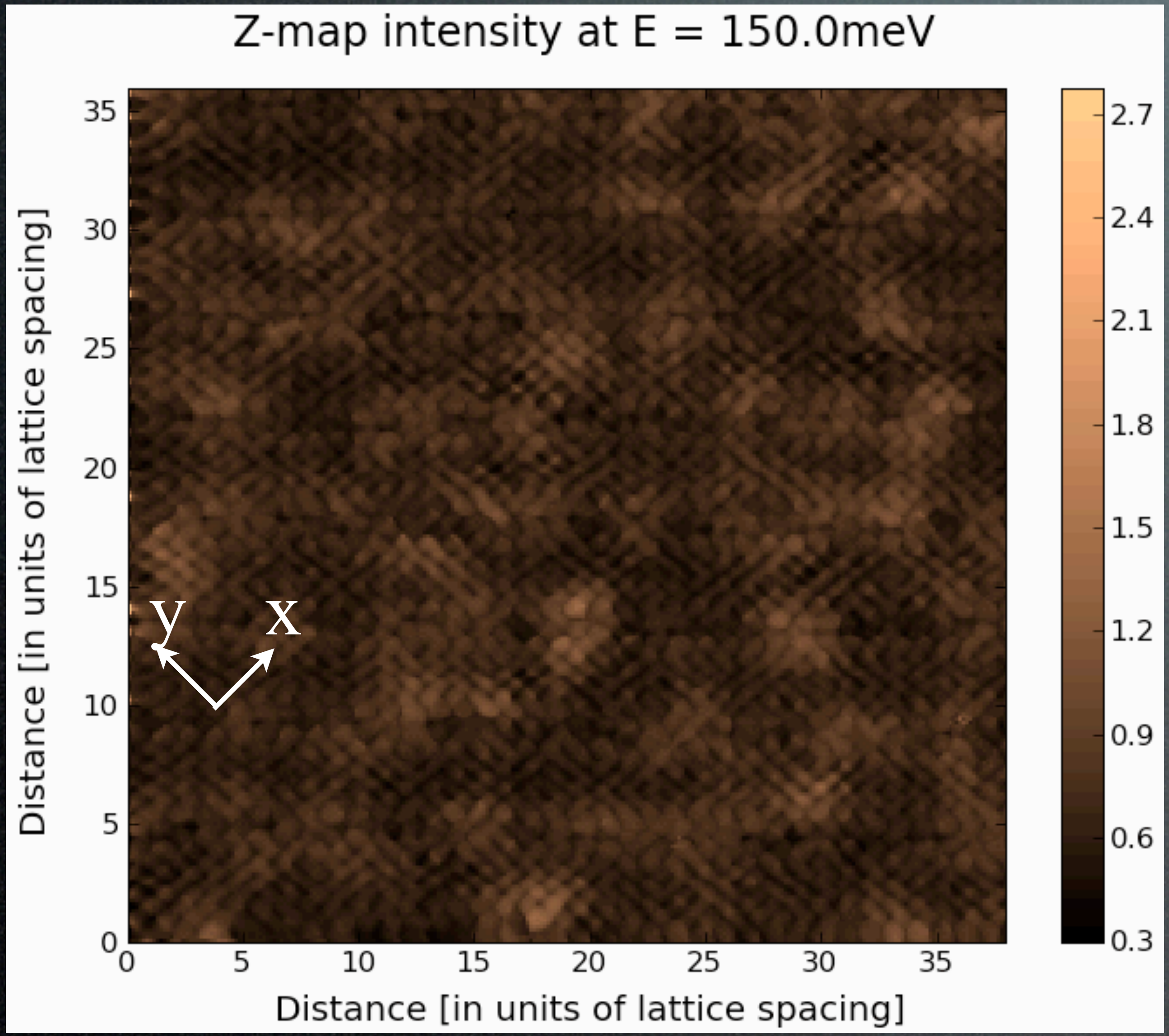


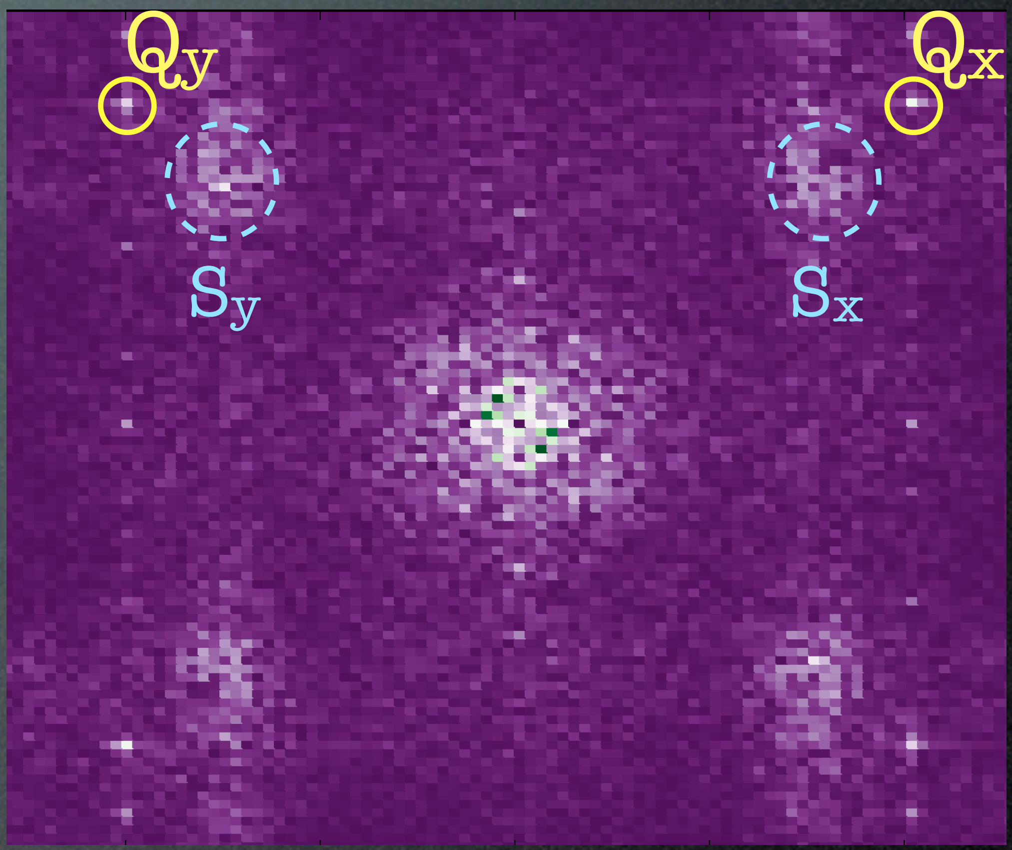

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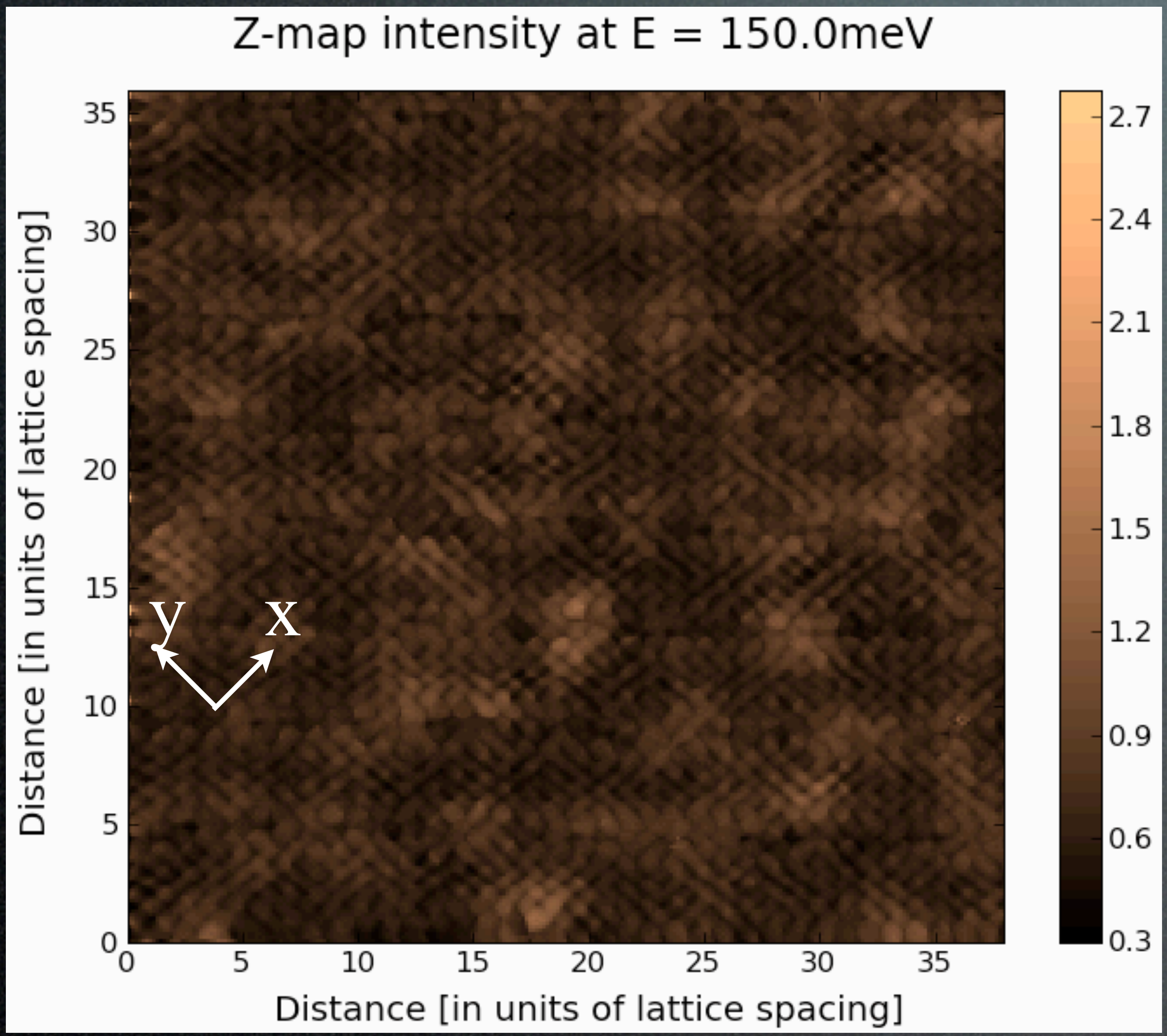


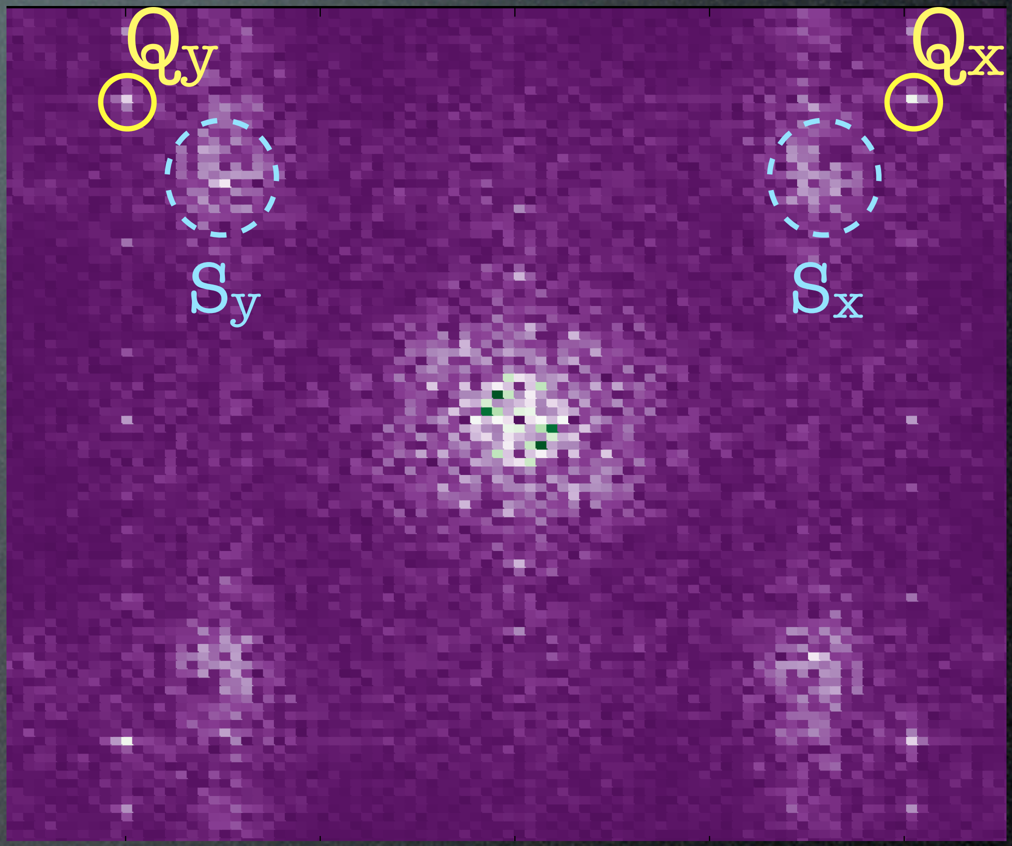


$Q_x$ vs $Q_y$?
$S_x$ vs $S_y$

# 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

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

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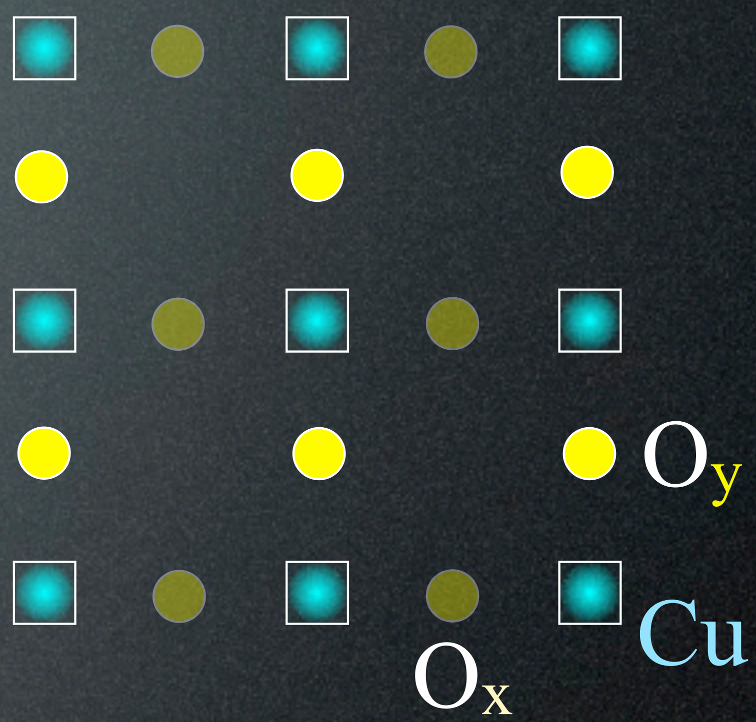


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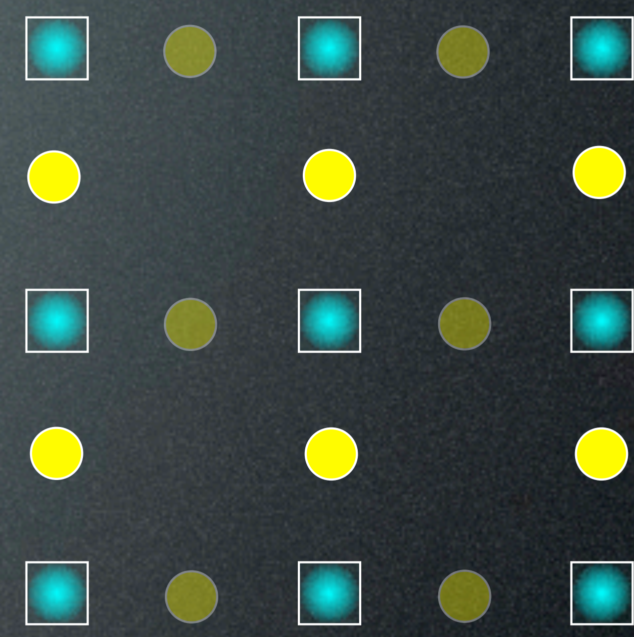


- Nematic OP

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

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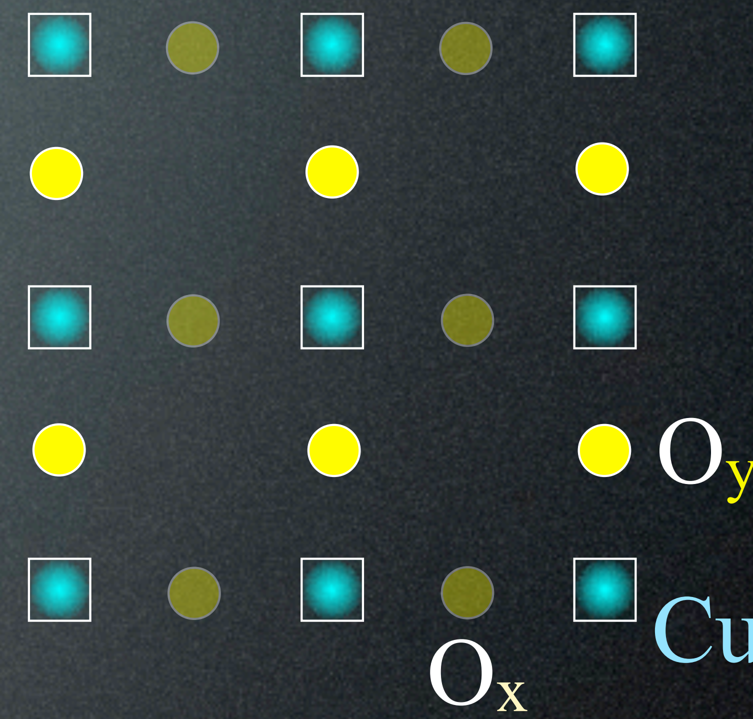


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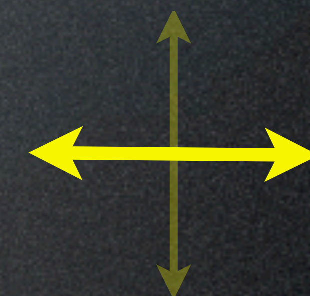
➡Measure C$_4$ breaking



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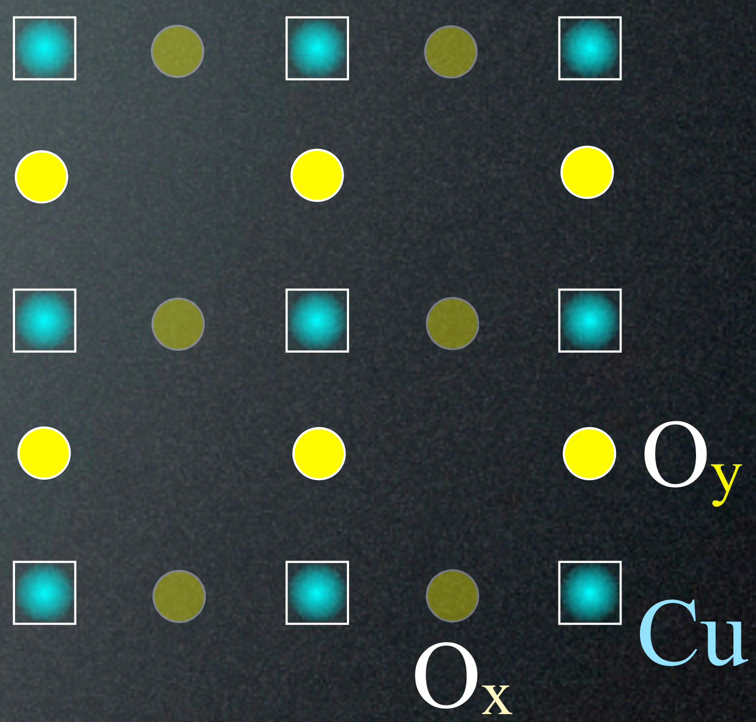


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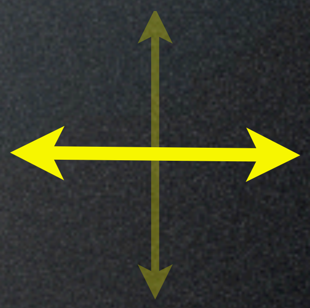

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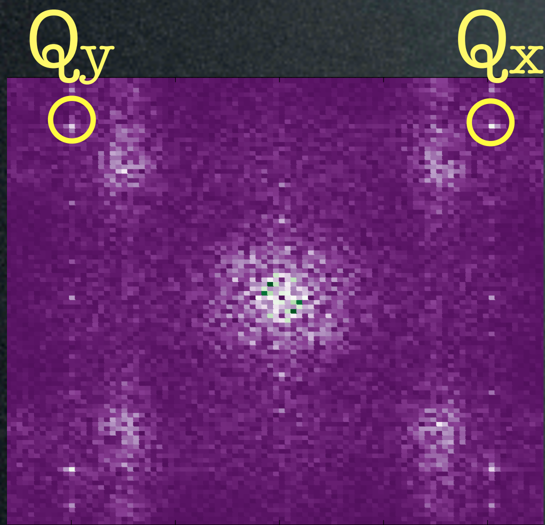
V. Emery, PRL 58, 2974 (1987)

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

# Nematic ordering in UD 45

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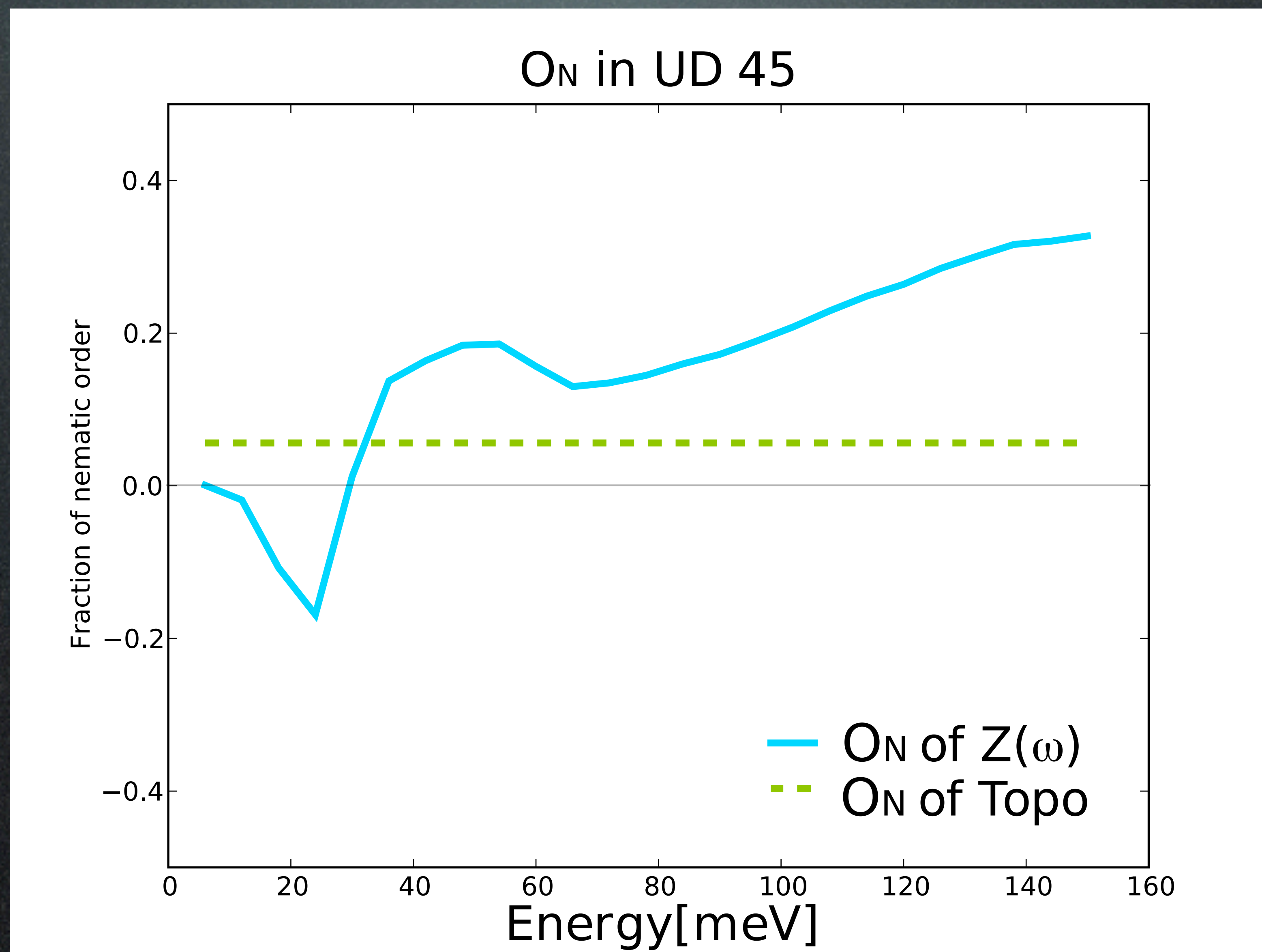


Extracted from published data, T=4K

Kohsaka et al, Nature 454, 1072 (2008)

# Domain size in Z-map

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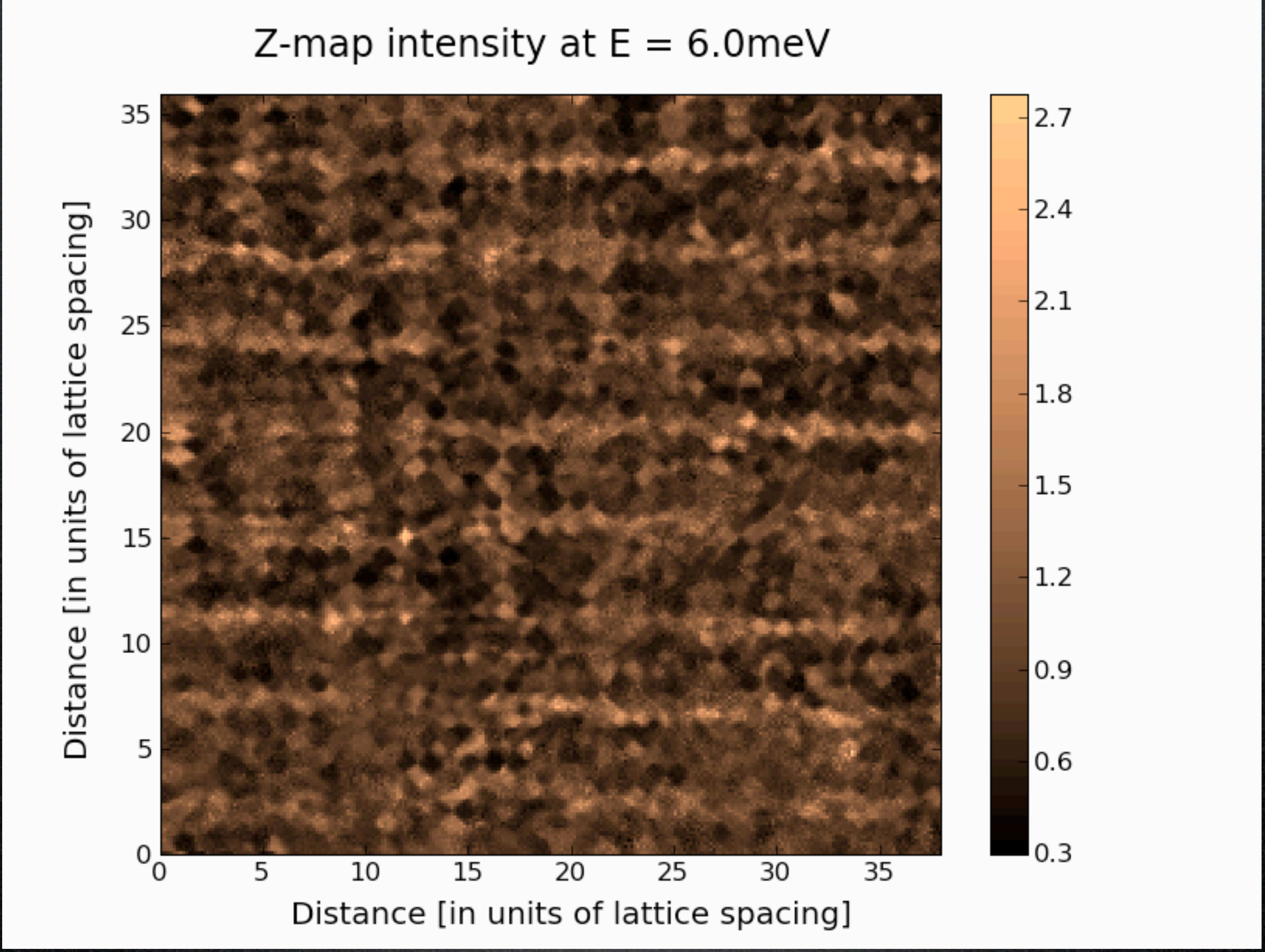
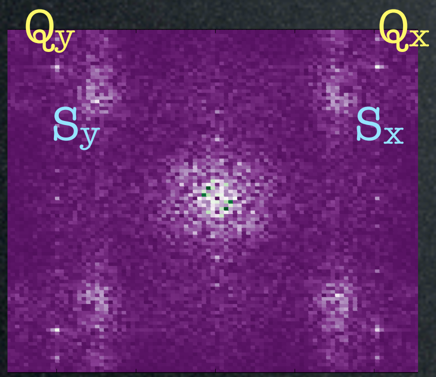


# Nematic domains

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

- Low pass filter (long distance physics)



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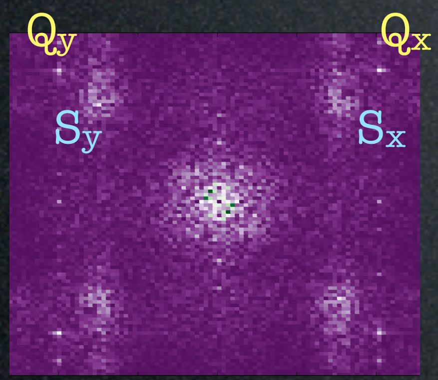
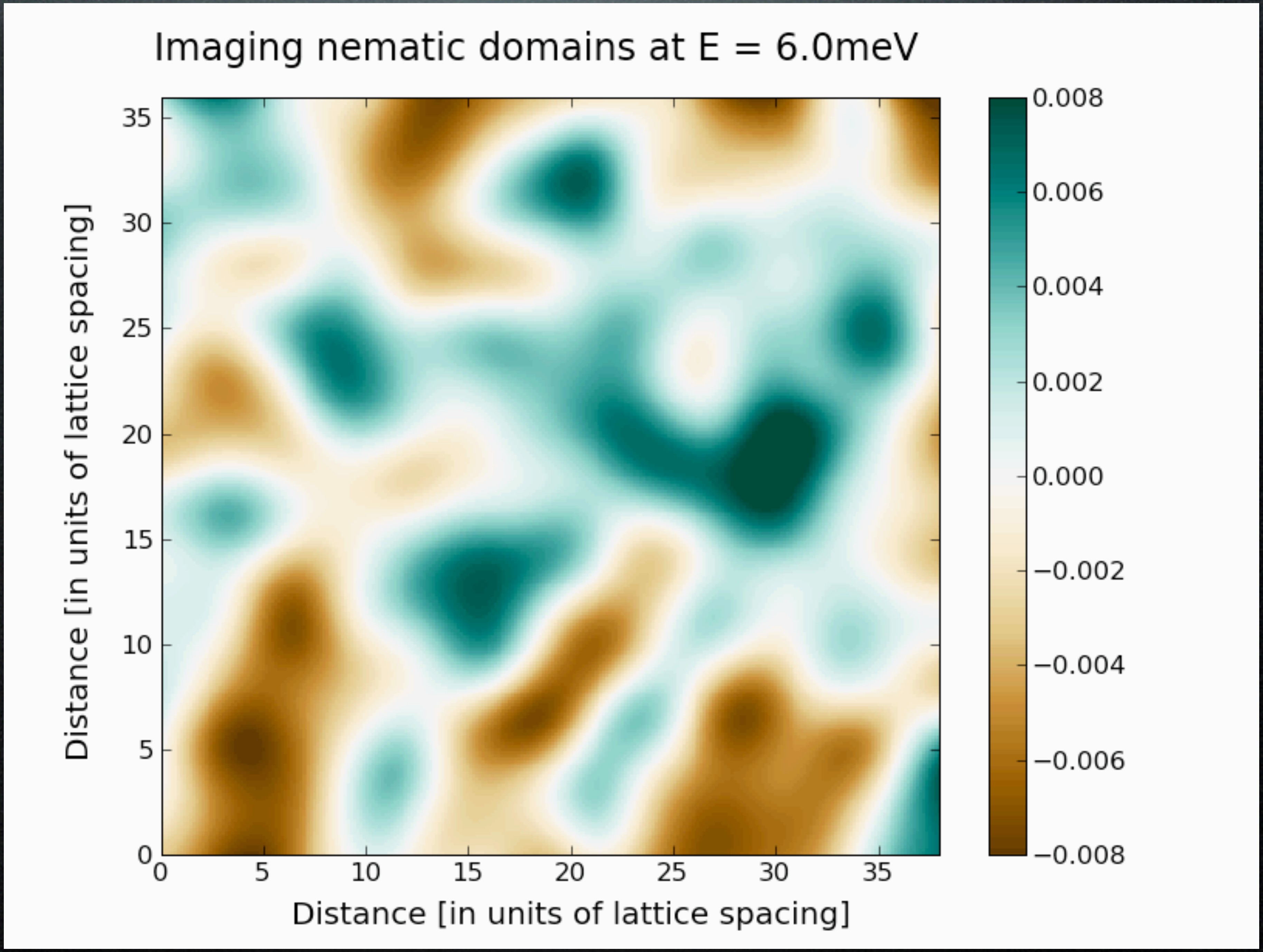
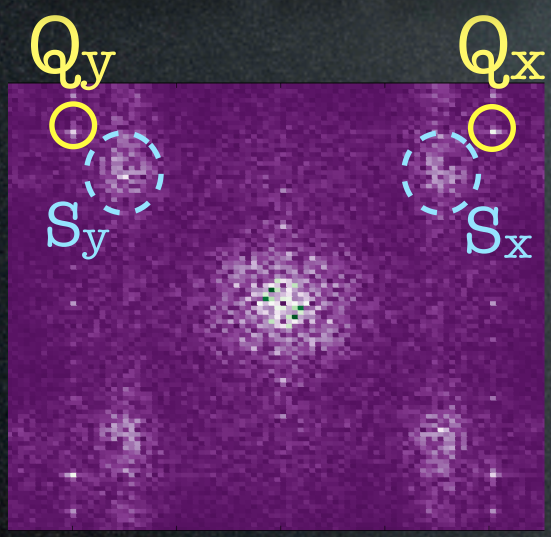


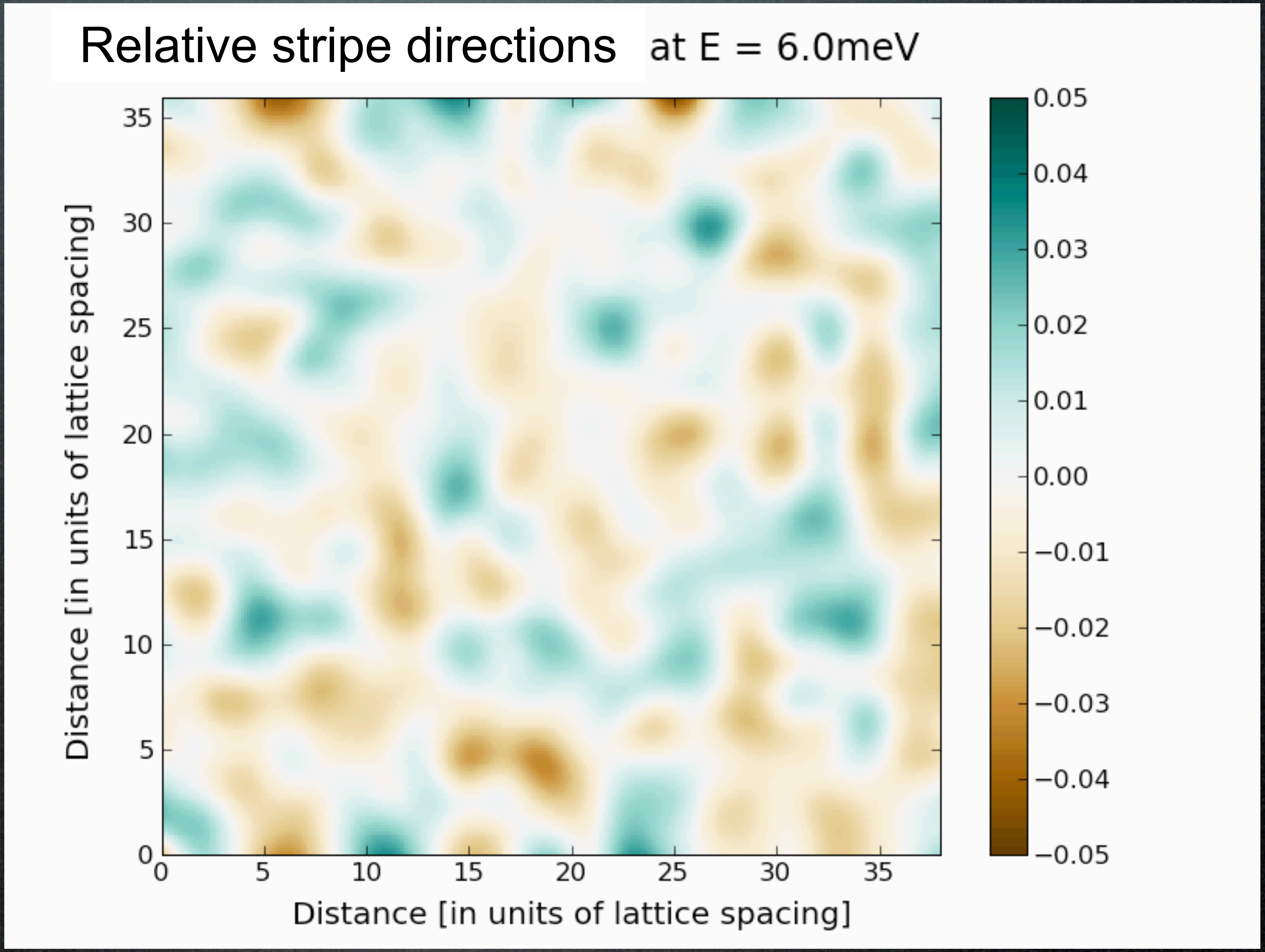



Listen to channel S

# Oriented stripe domains

- Shift $S_x$, $S_y$ to origin ("tune to the channel")
- Low pass filter (long distance physics)



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VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

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

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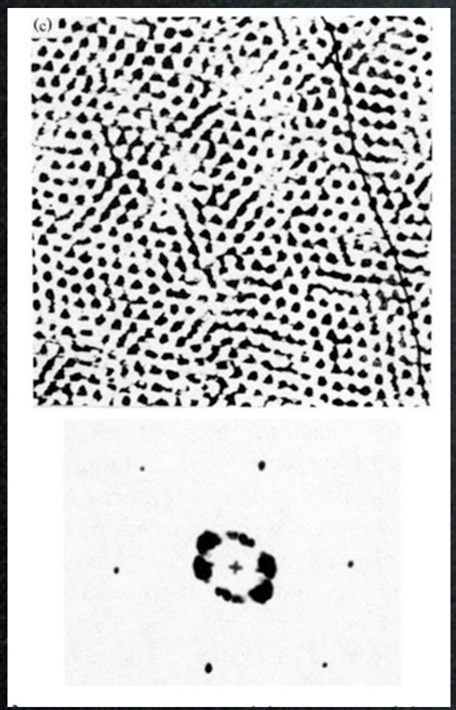

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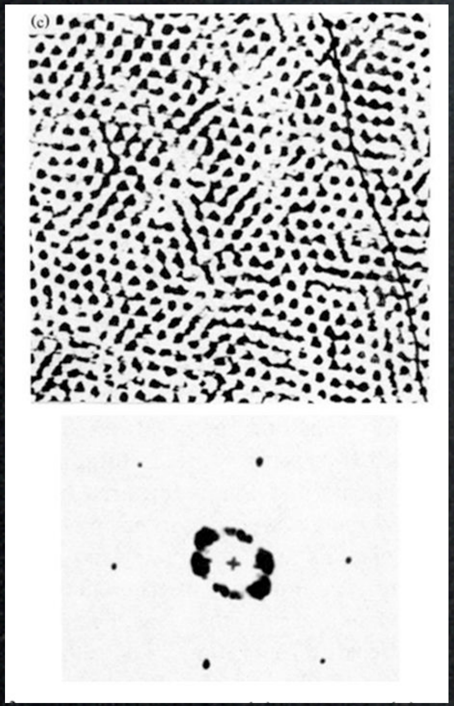

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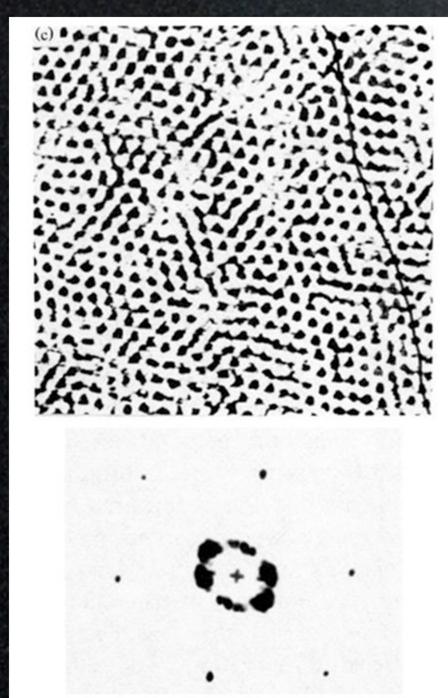

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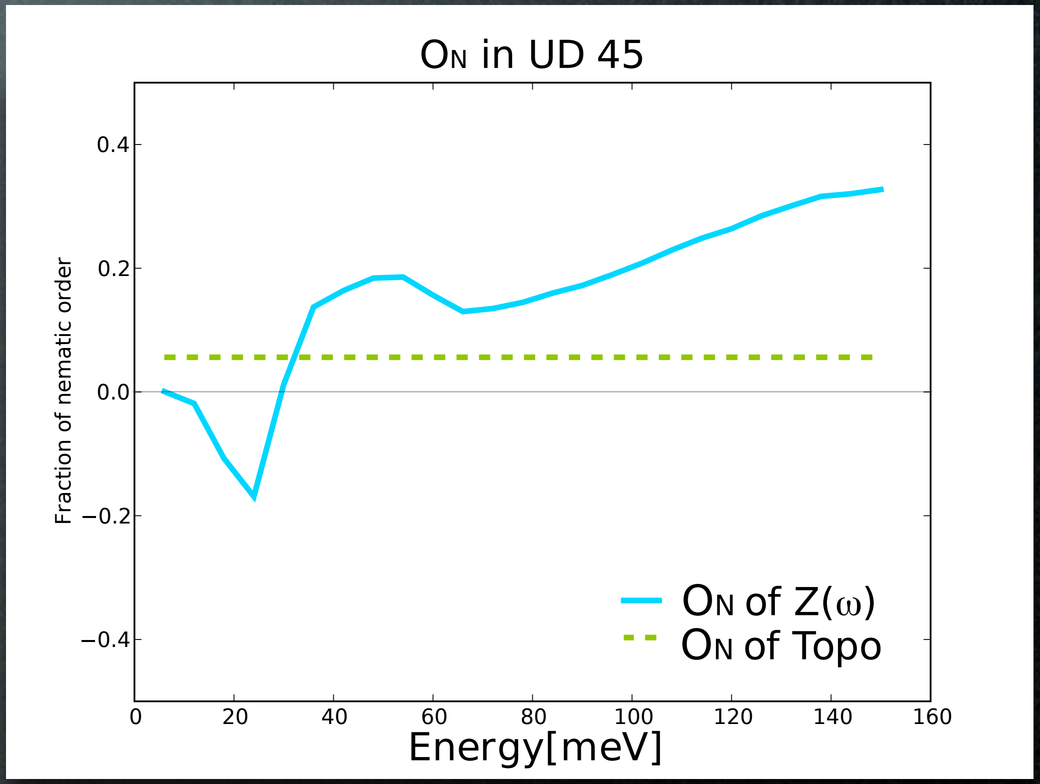
# Electronic Nematic in Cuprates?

## Looking ahead

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




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