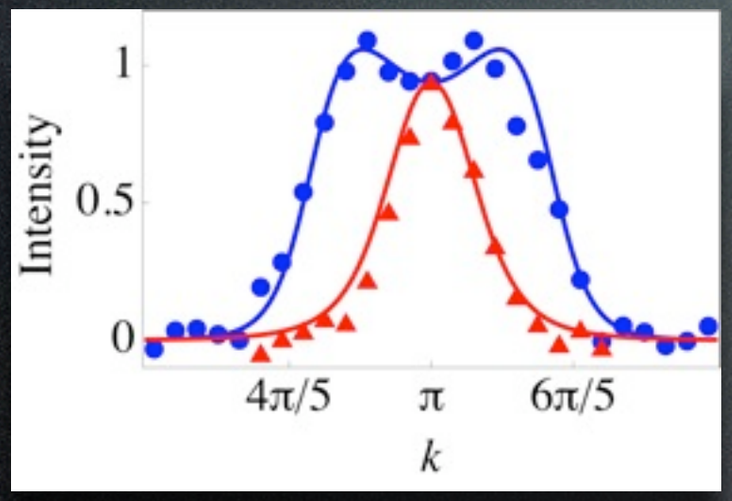
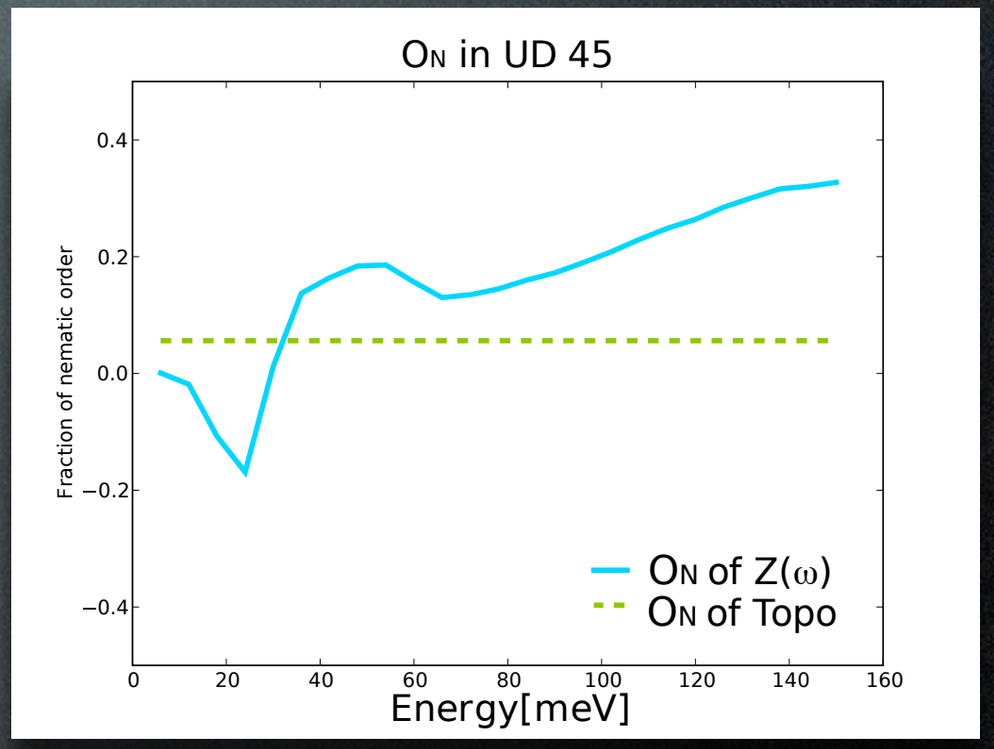
Electronic Nematic in Cuprates?





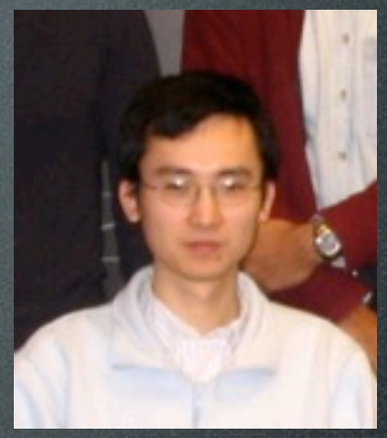
Eun-Ah Kim

Cornell University

Acknowledgements

Prof. Michael Lawler

Binghamton, Cornell

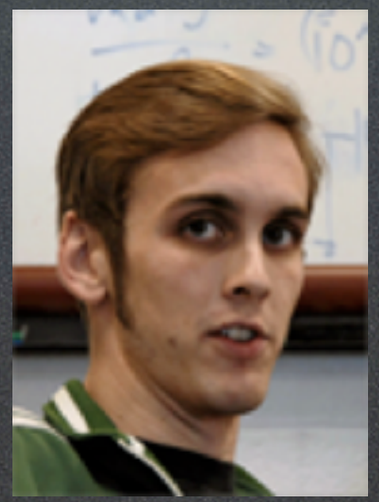


Dr. Kai Sun

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

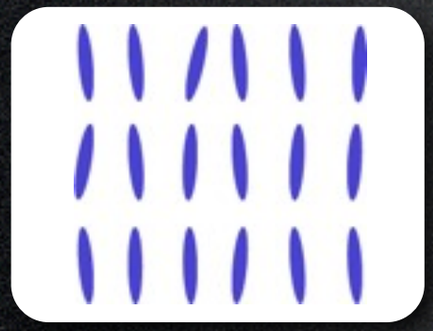
Reinitzer(1888)

Liquid Crystal

Liquid

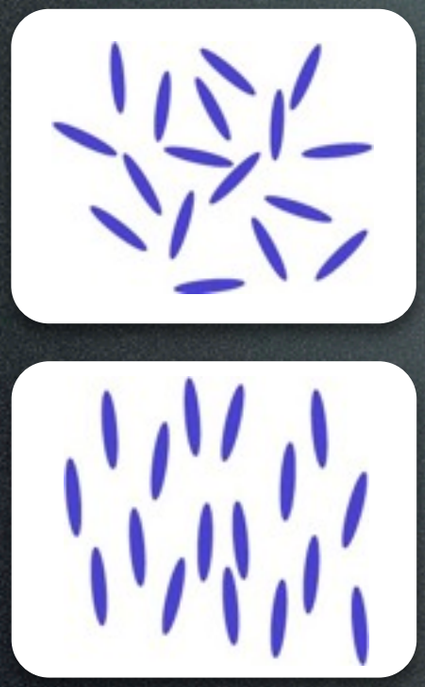
T

Crystal



Reinitzer(1888)

Liquid Crystal



Liquid

Nematic

T

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Reinitzer(1888)

Liquid Crystal

Reinitzer(1888)

T

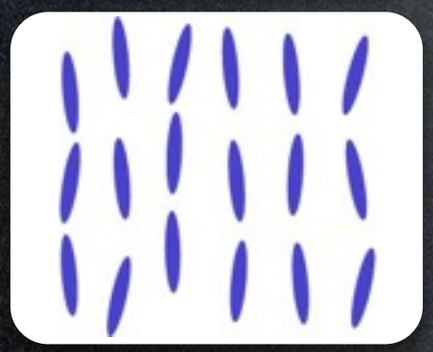
Liquid

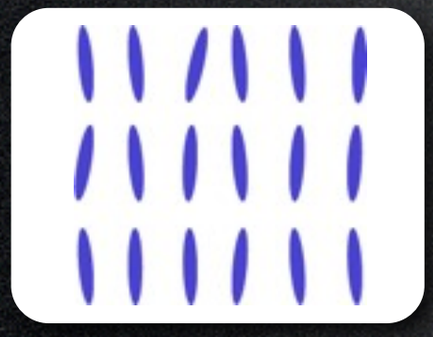
Nematic

Smectic

Crystal

Electronic Liquid Crystal





Liquid

Nematic

Smectic

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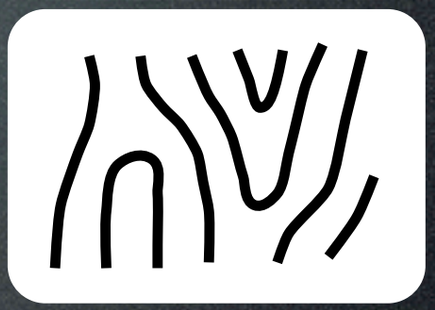
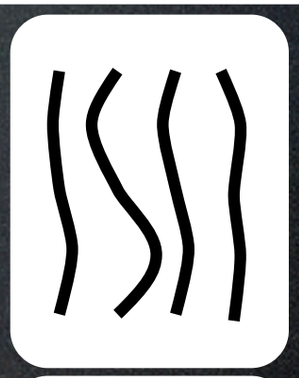
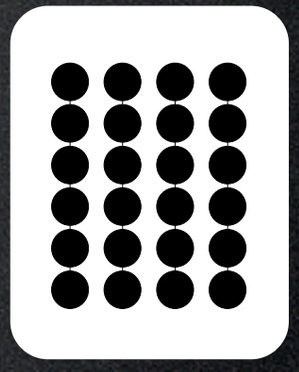
Crystal



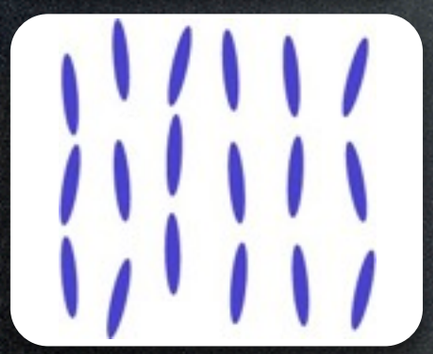


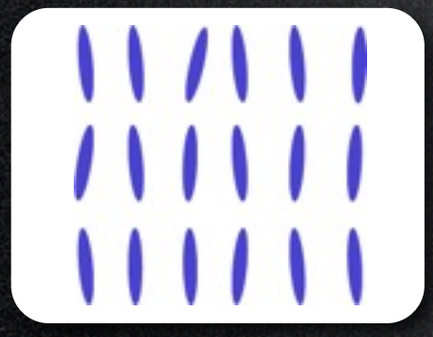


Reinitzer(1888)

Kivelson, Fradkin, Emery, Nature (1998)

Electronic Liquid Crystal





Reinitzer(1888)

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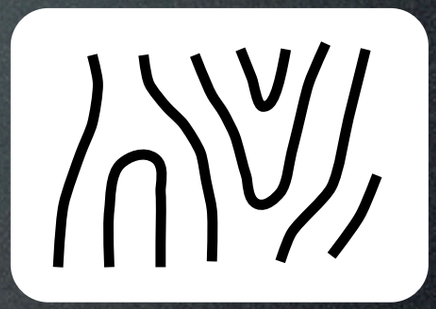
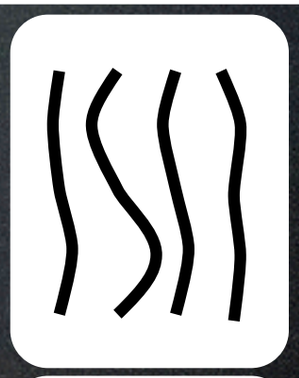
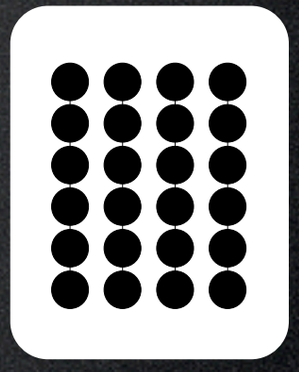
$\hbar,\ g^{-1}$







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Electronic Liquid Crystal

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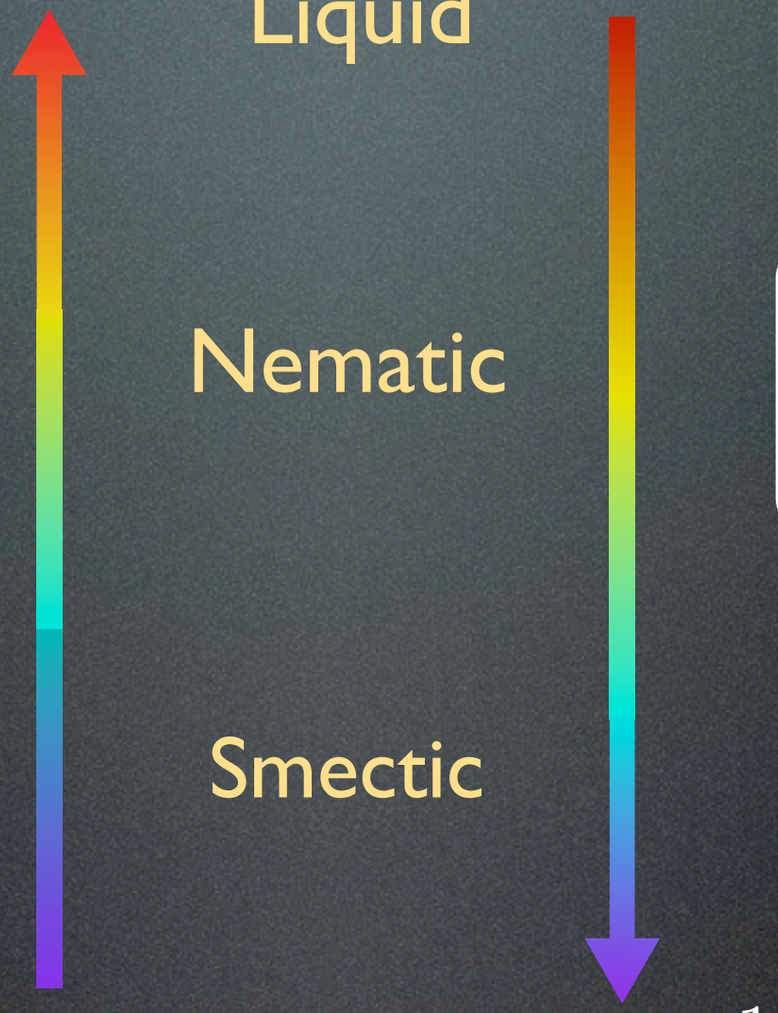

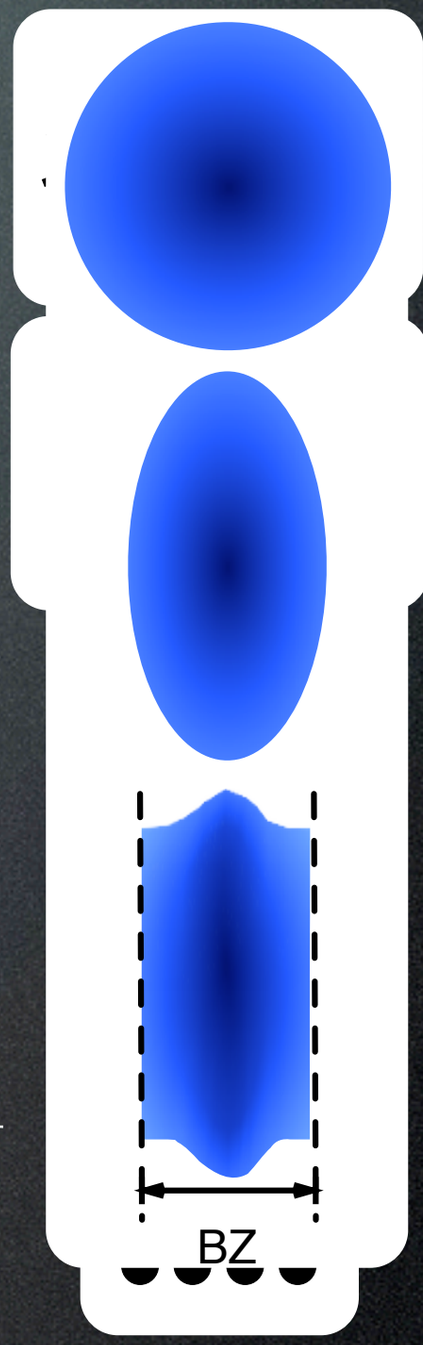

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Electronic Liquid Crystal

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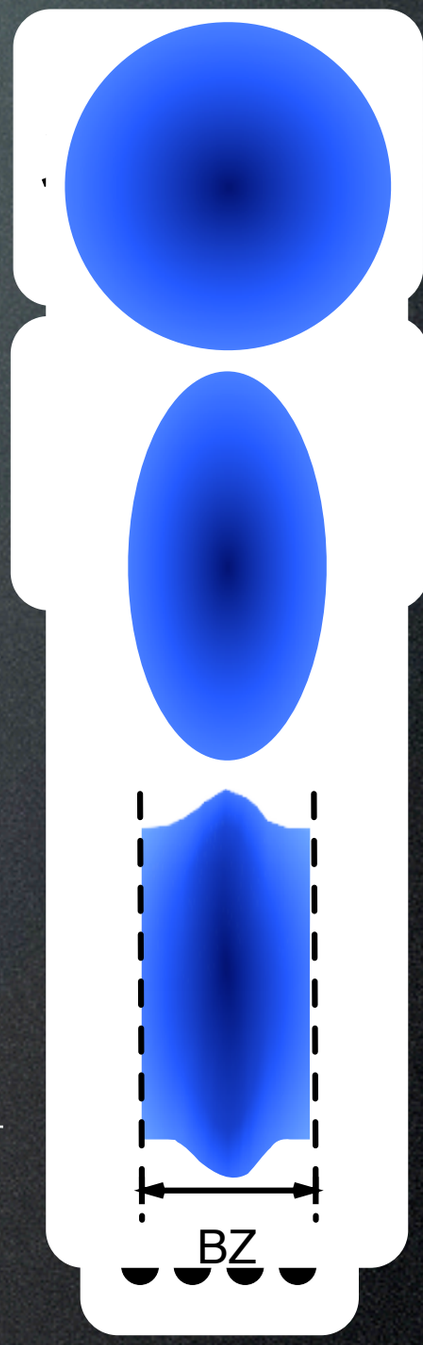

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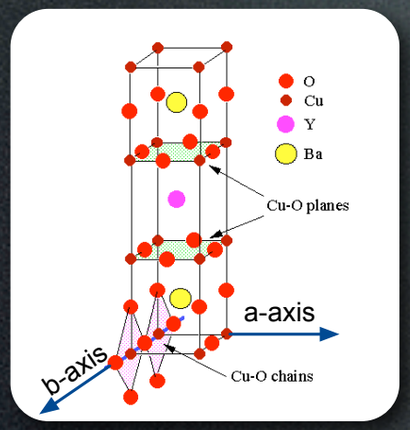
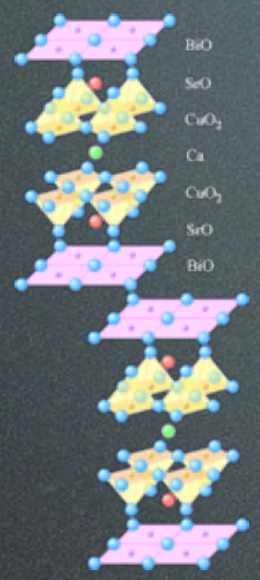
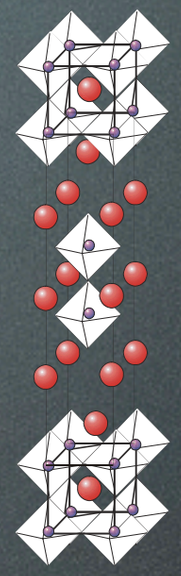
Sufficiently correlated systems

Cuprates

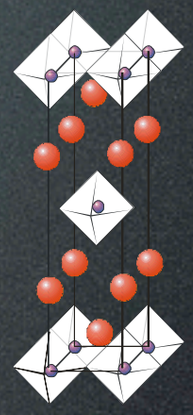




Ruthenates



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



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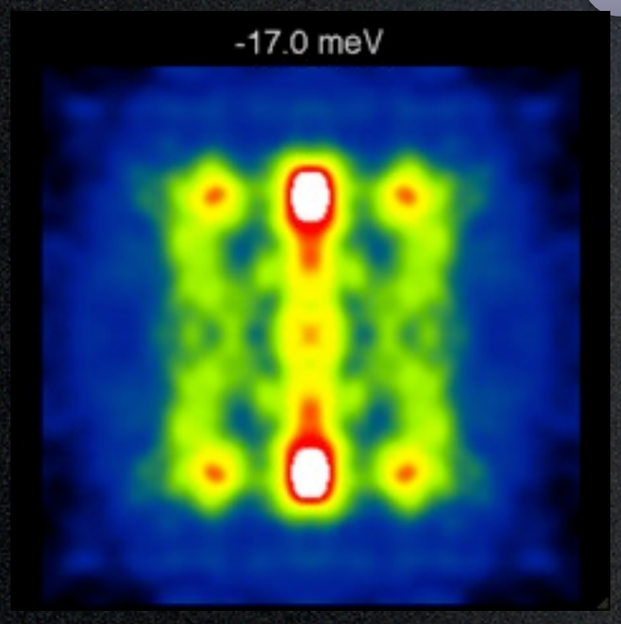
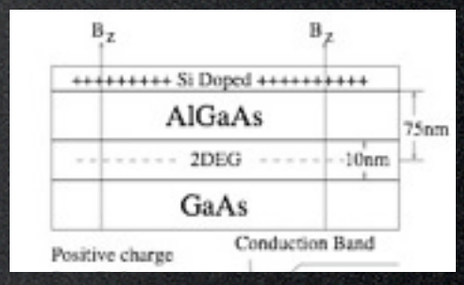
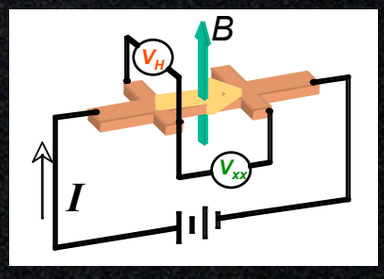


Pnictides

2DEG under $\vec{B}$





Electronic Nematic in UD Cuprates?

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- Quantifying broken symmetry
- License to exist?

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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

Nematic QCP, license to exist?

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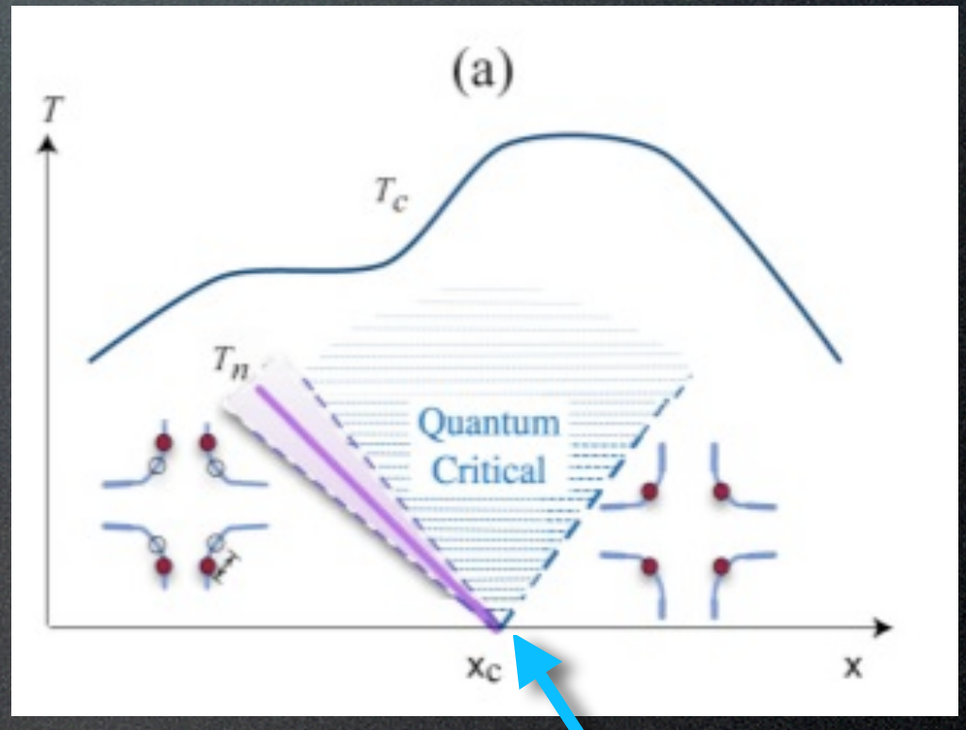

nematic QCP inside SC phase?

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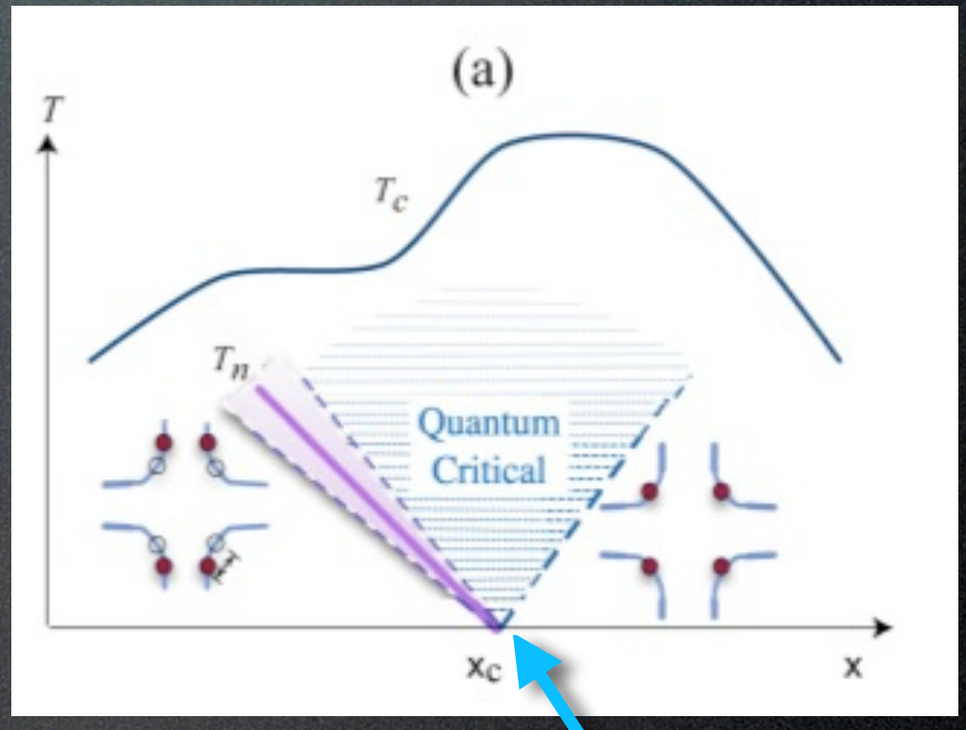
- Nodal nematic QCP
  deep inside d-wave SC

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

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

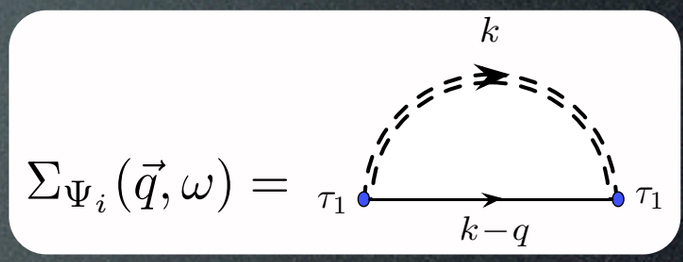


nematic QCP inside SC phase?

Looking for nematic critical fluctuations

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

:k-selective decoherence



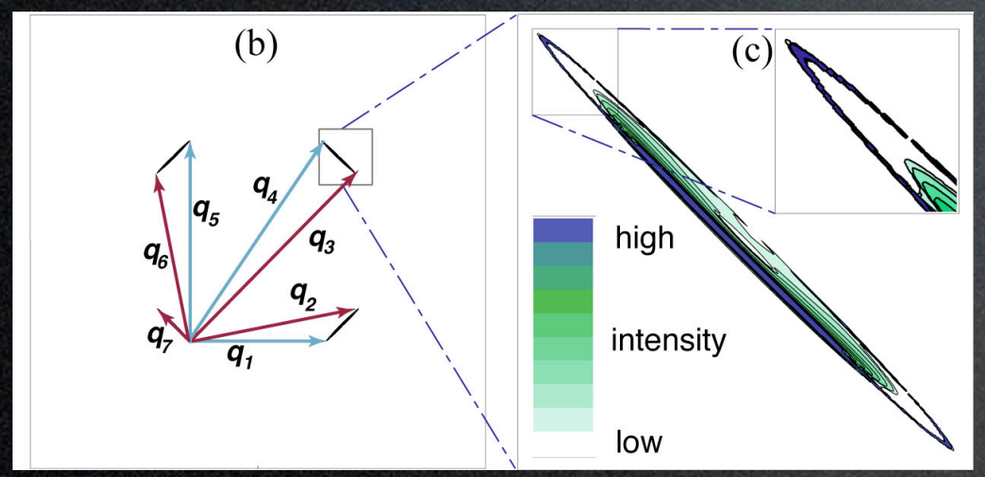
Interference of nematic quantum critical quasiparticles: a route to the octet model

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

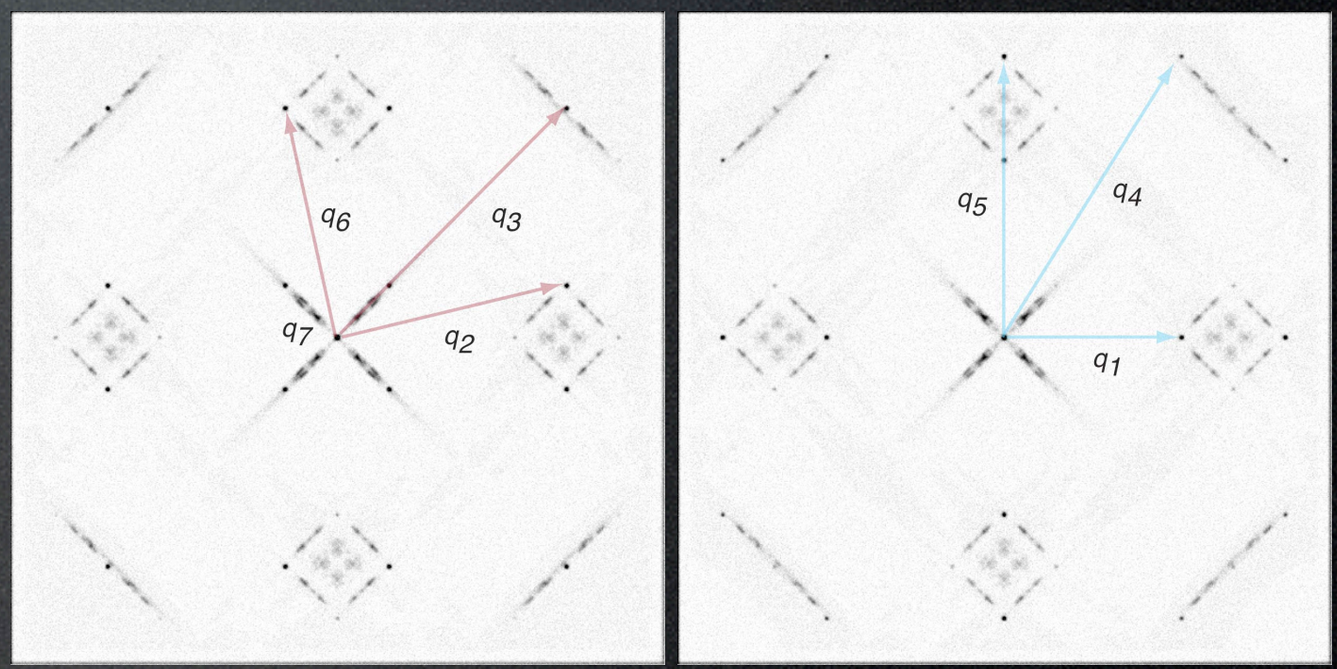
[1] *Department of Physics, Cornell University, Ithaca, NY 14853*
[2] *Department of Physics, Binghamton University, Binghamton NY 13902*

(Dated: November 13, 2008)

arXiv:0811.2242



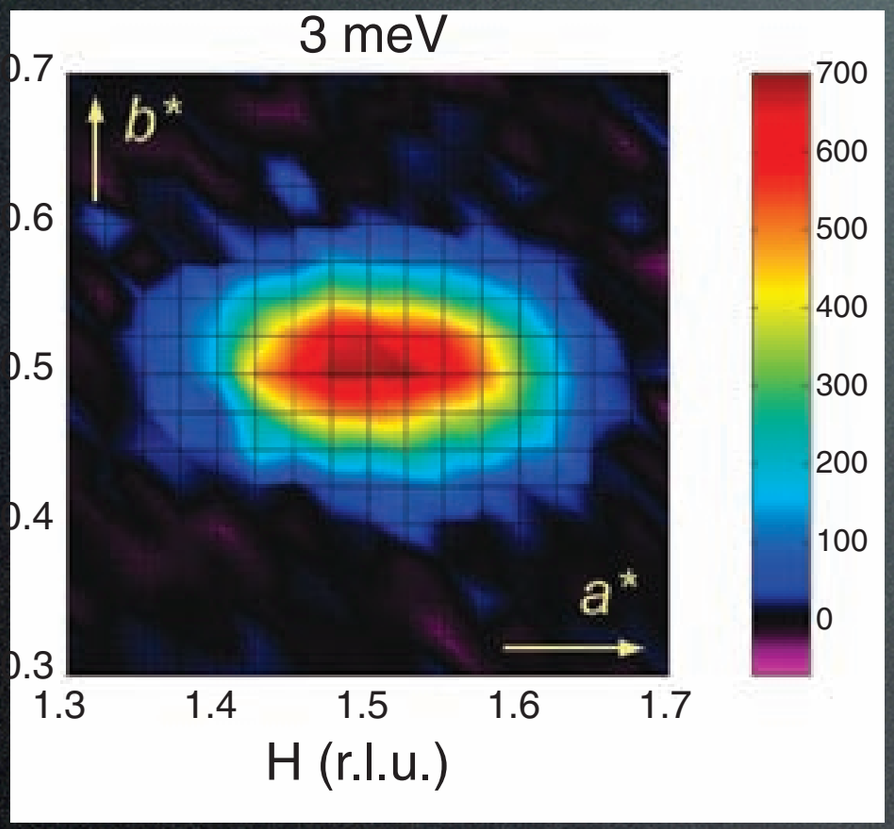
→ QPI peaks

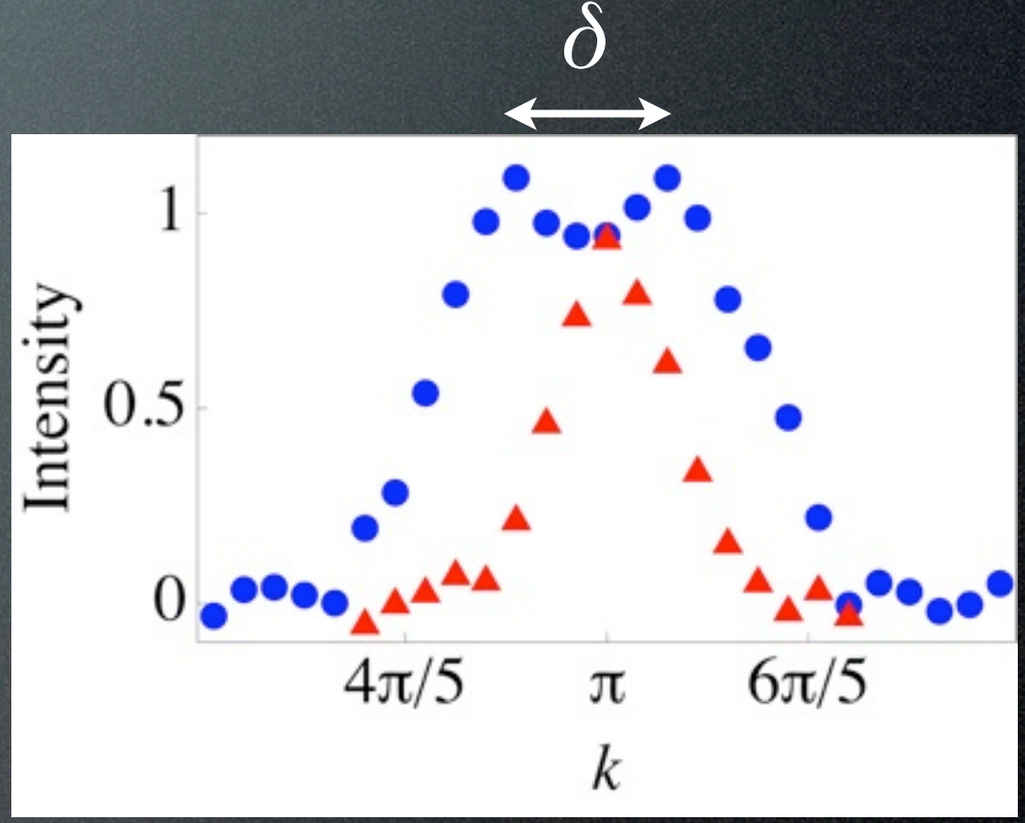


(b) (c)

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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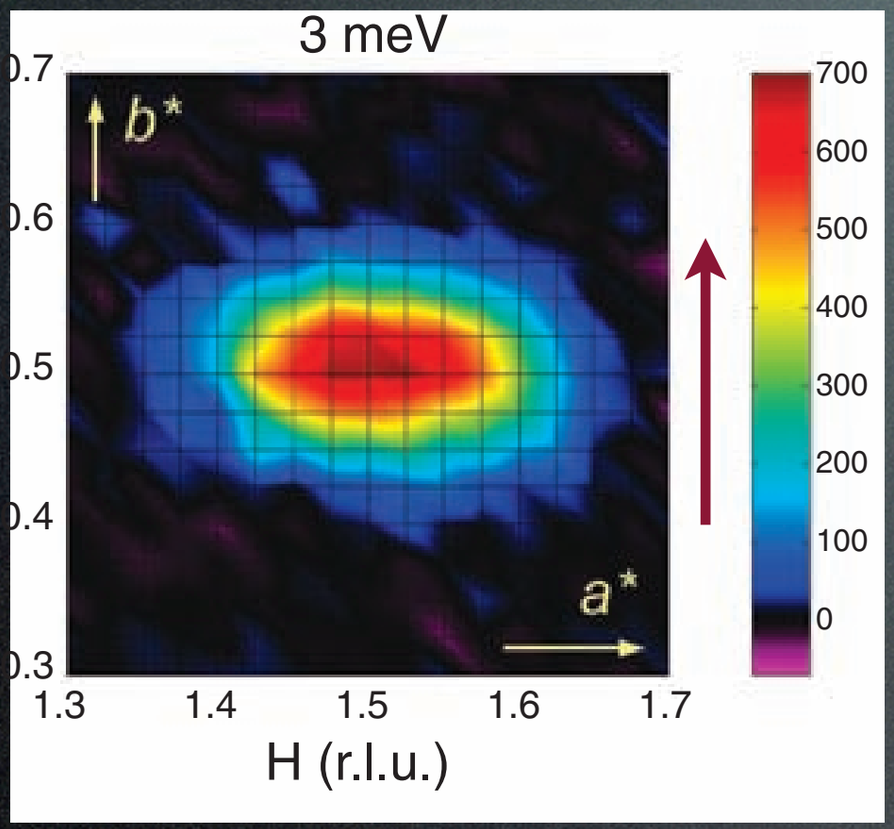

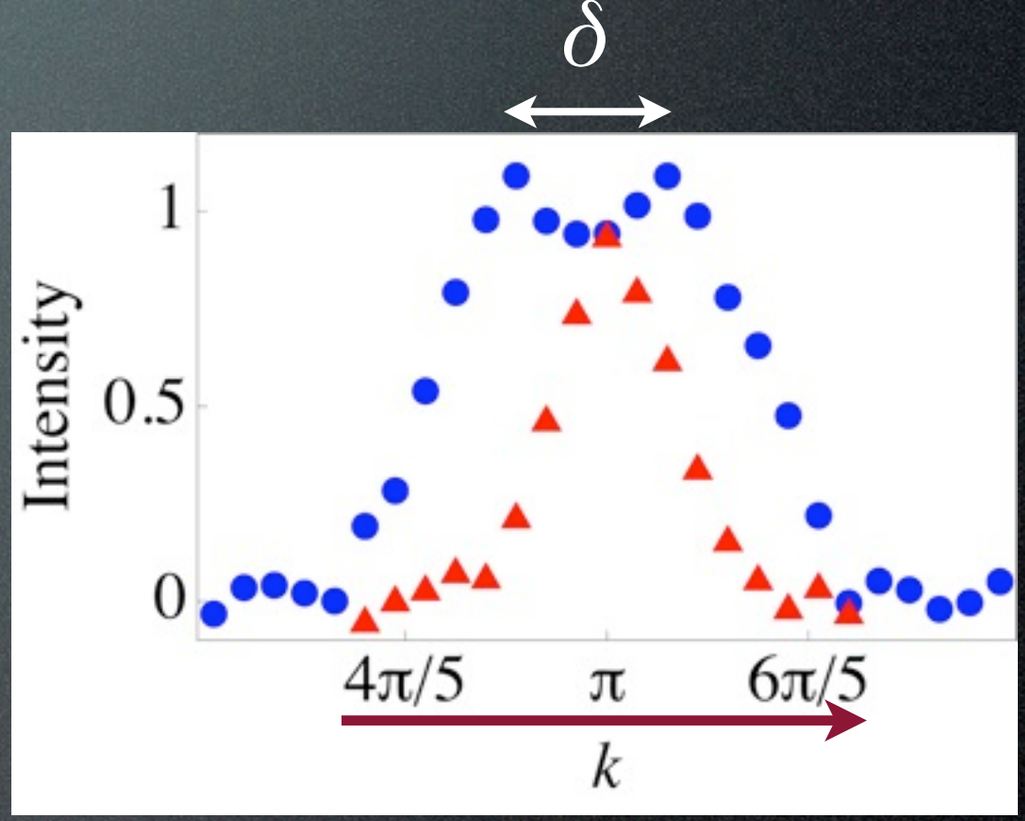

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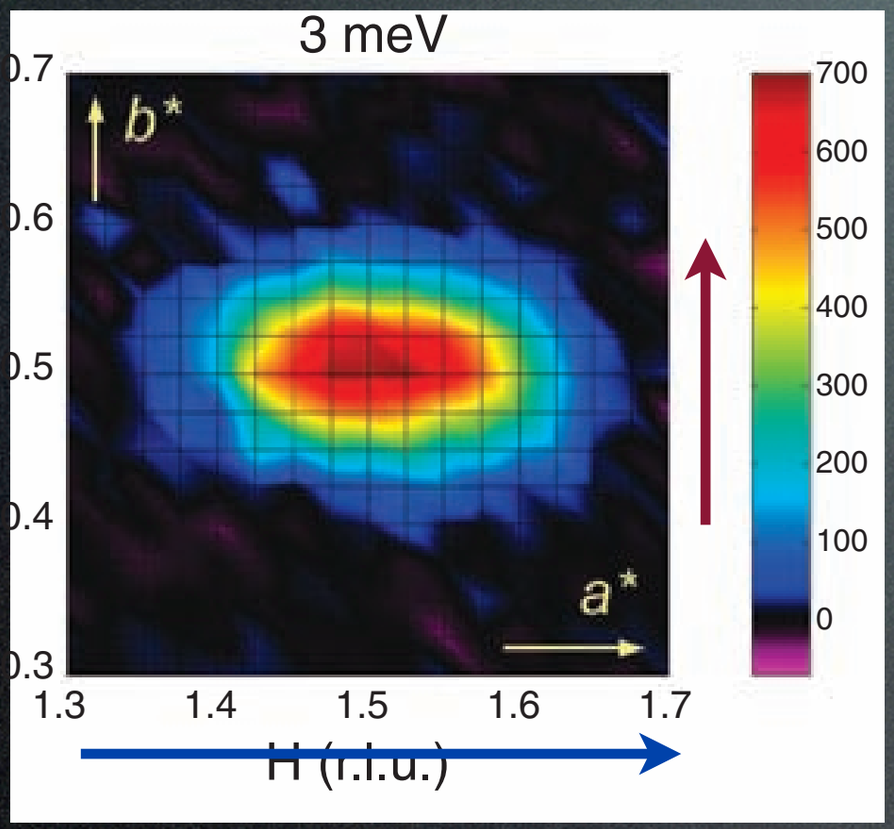

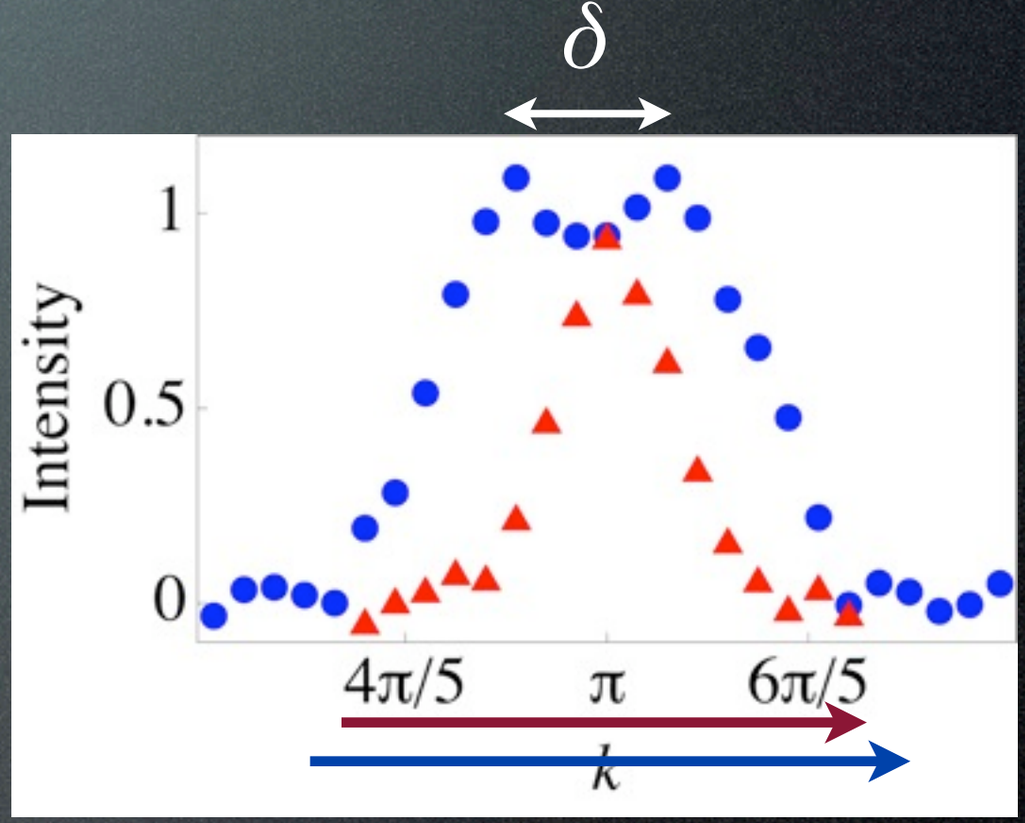

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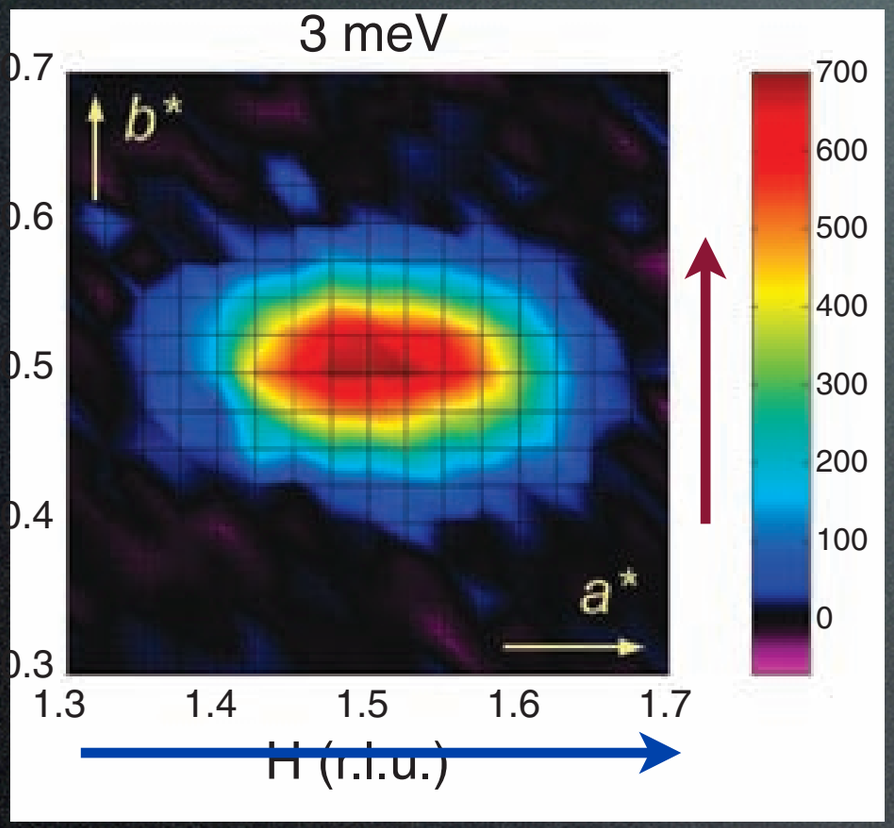

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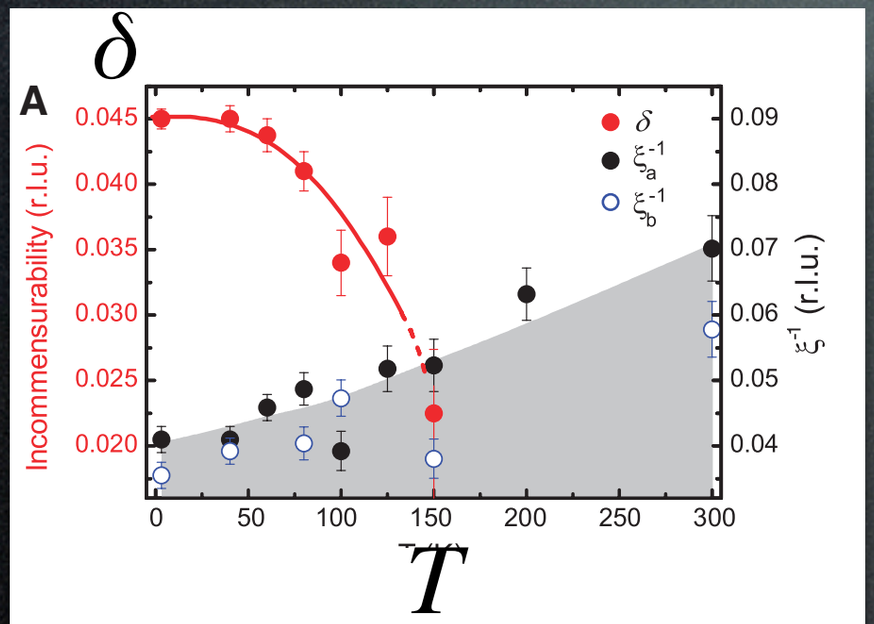
Hinkov et al, Science, Jan 2008

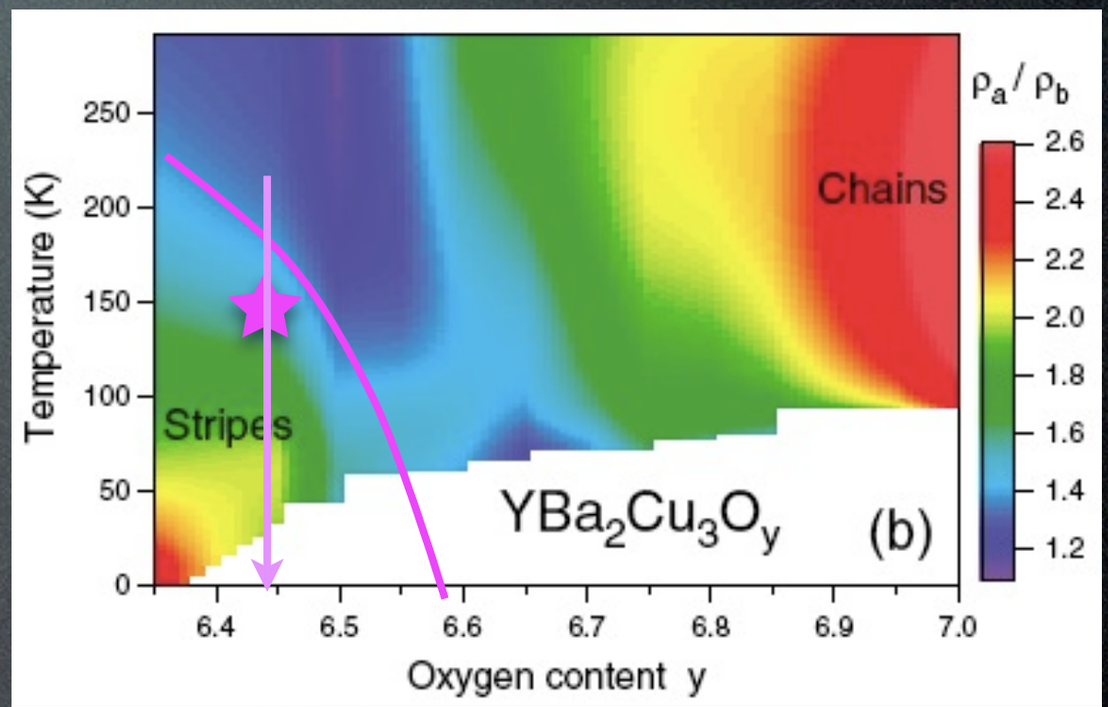
Spin channel

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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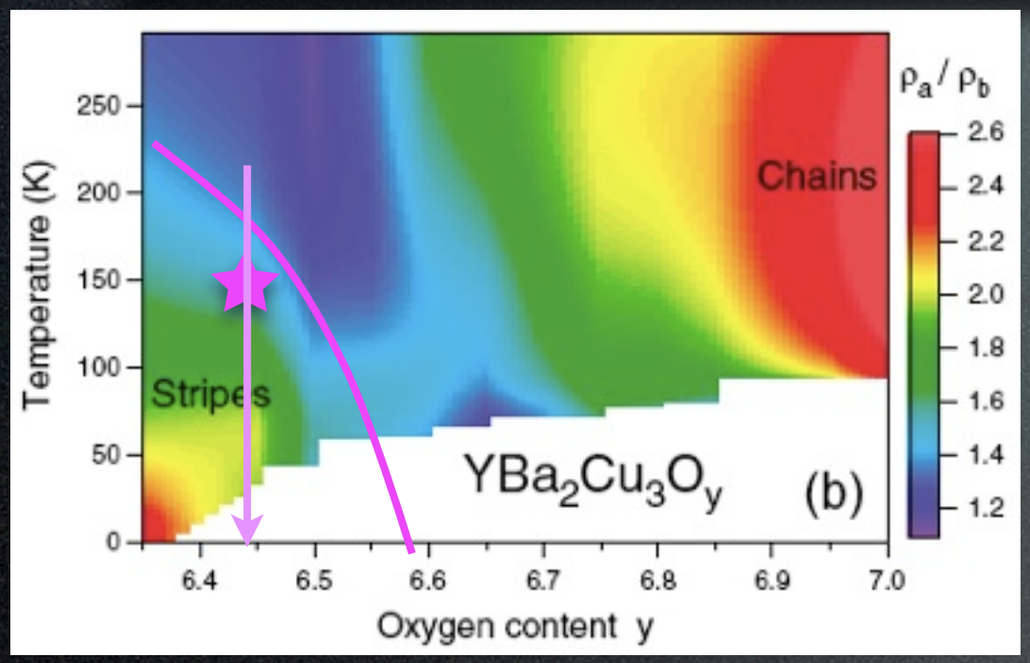

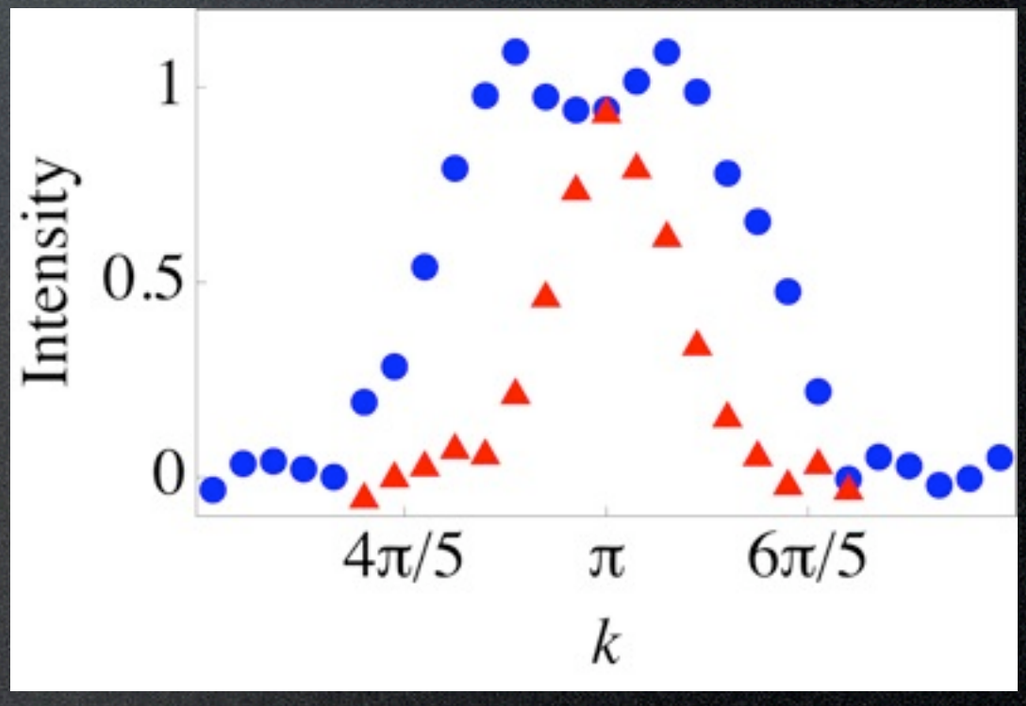

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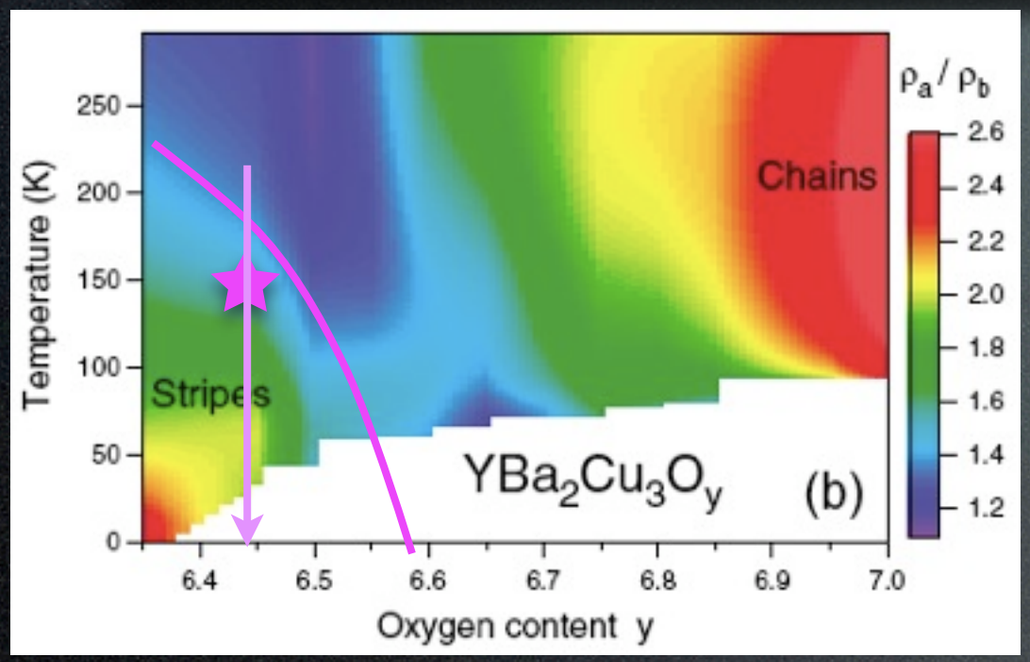
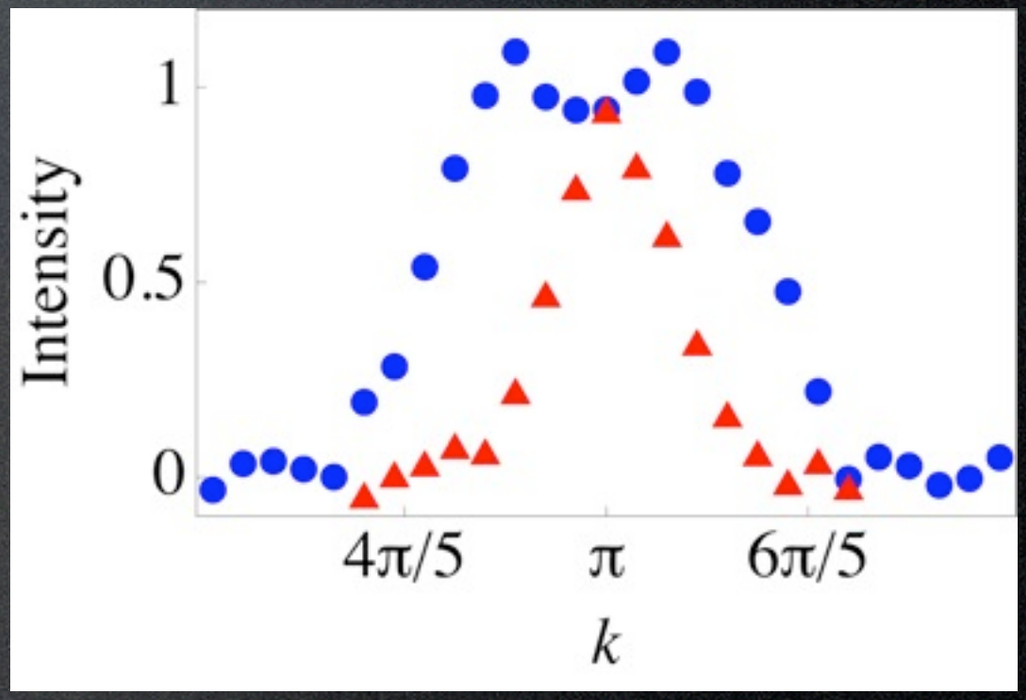


$$S[\vec{\phi}] = \frac{1}{g}\int \frac{d^2\mathbf{q}d\omega}{(2\pi)^3}\left(i\Gamma|\omega| + \omega^2 - \Delta^2(\mathbf{q})\right)|\vec{\phi}(\mathbf{q},\omega)|^2.$$



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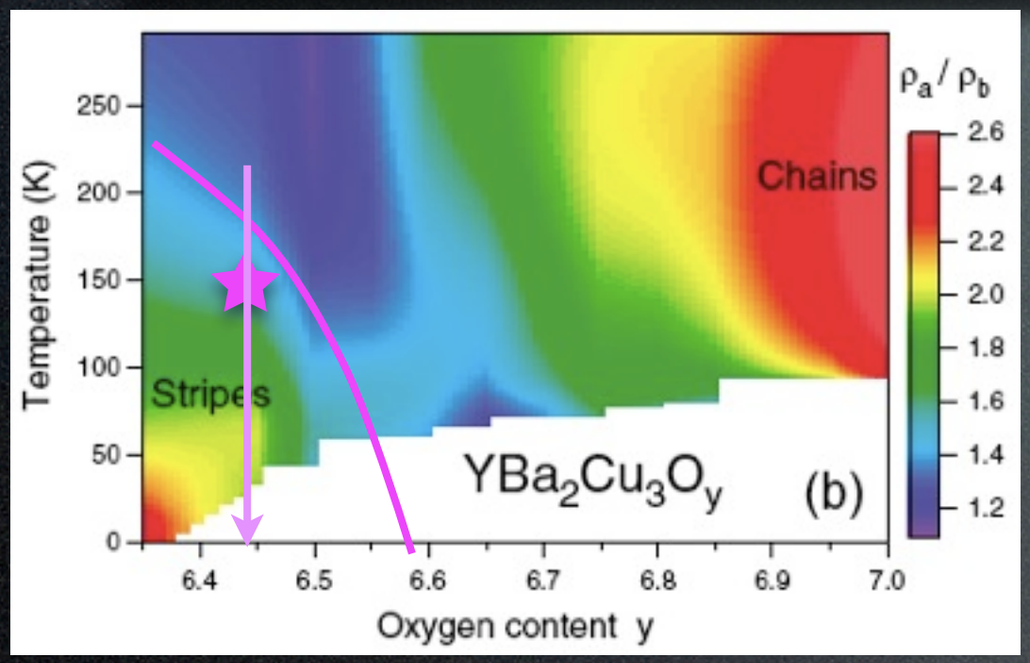

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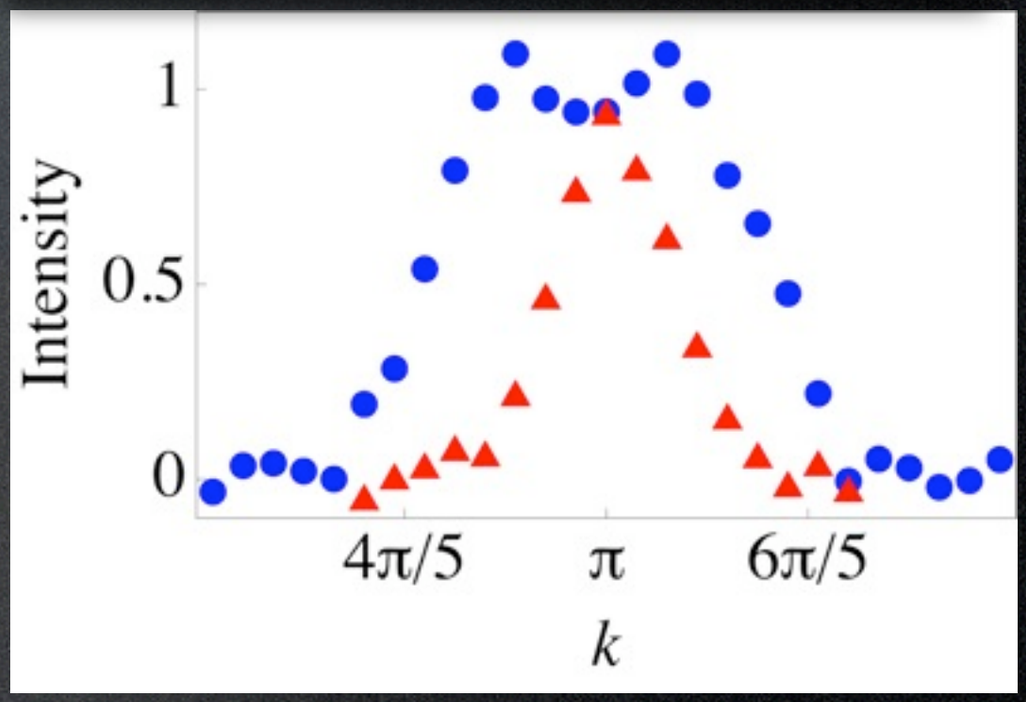
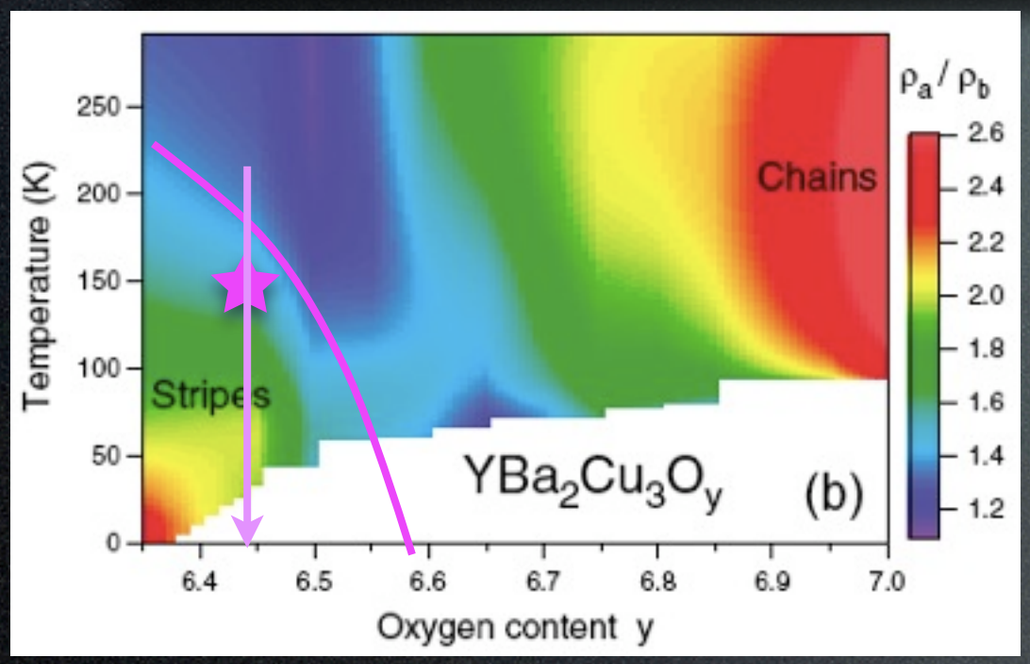


Spin-charge interplay in electronic liquid crystals: fluctuating spin stripe driven by charge nematic

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

arXiv:0906.3460



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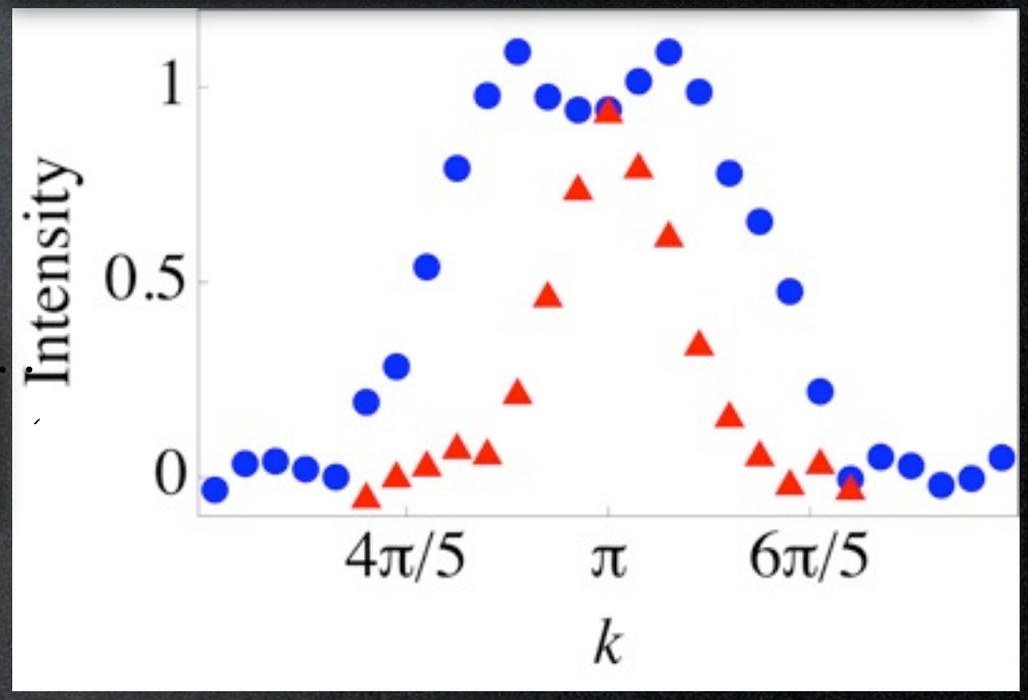

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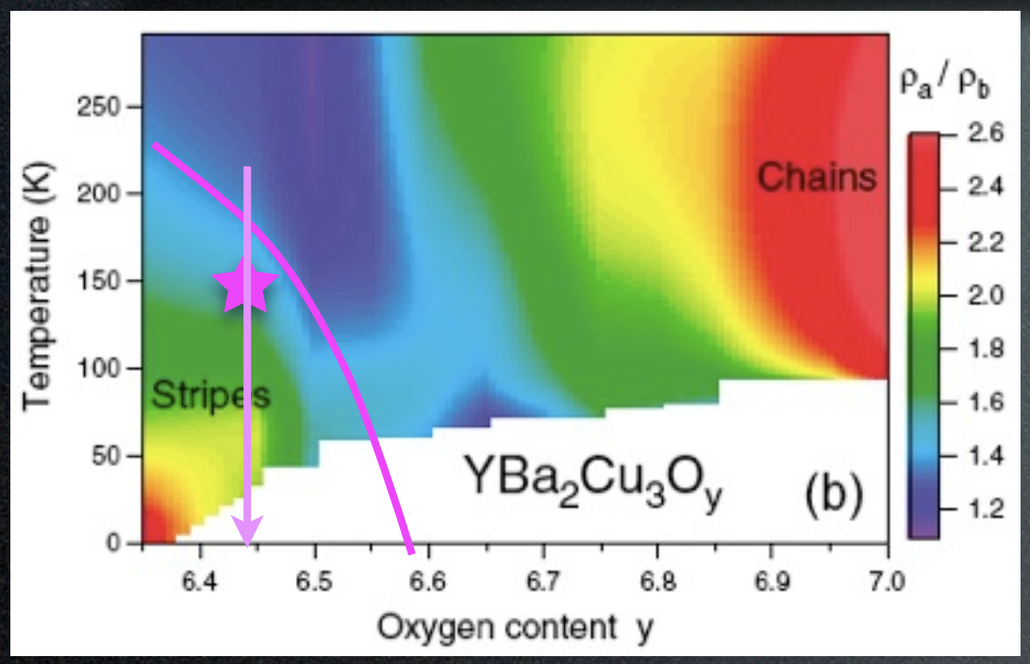

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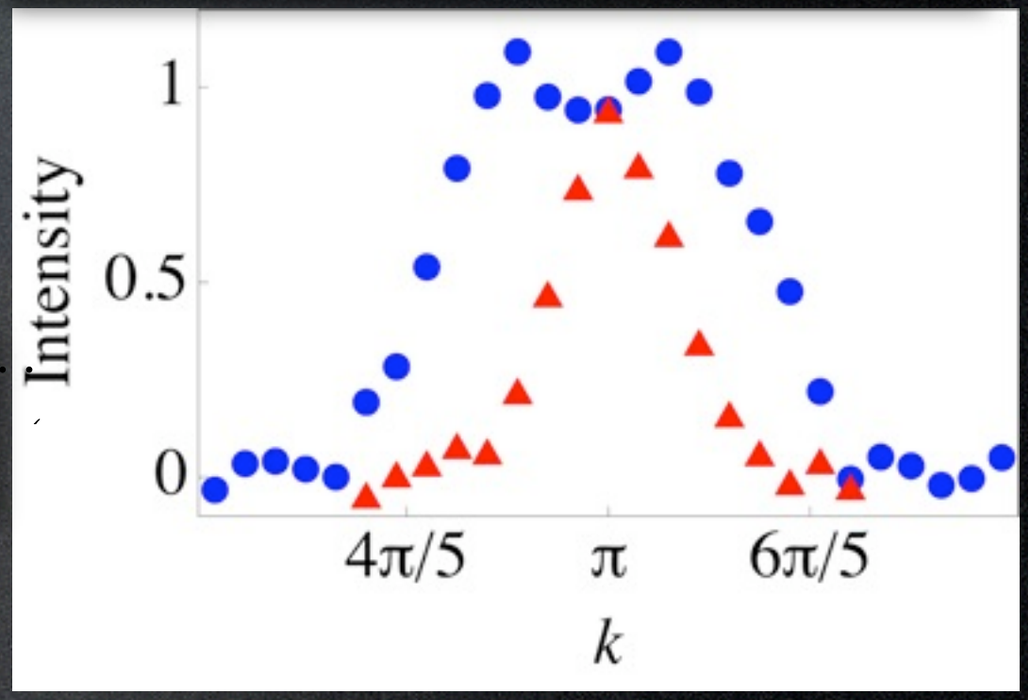

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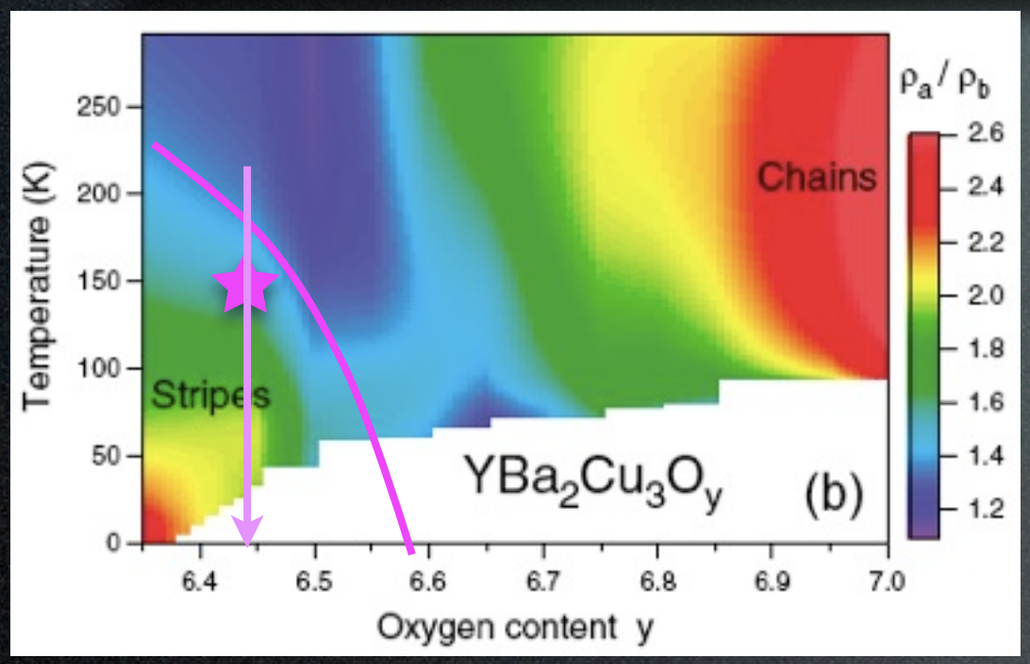

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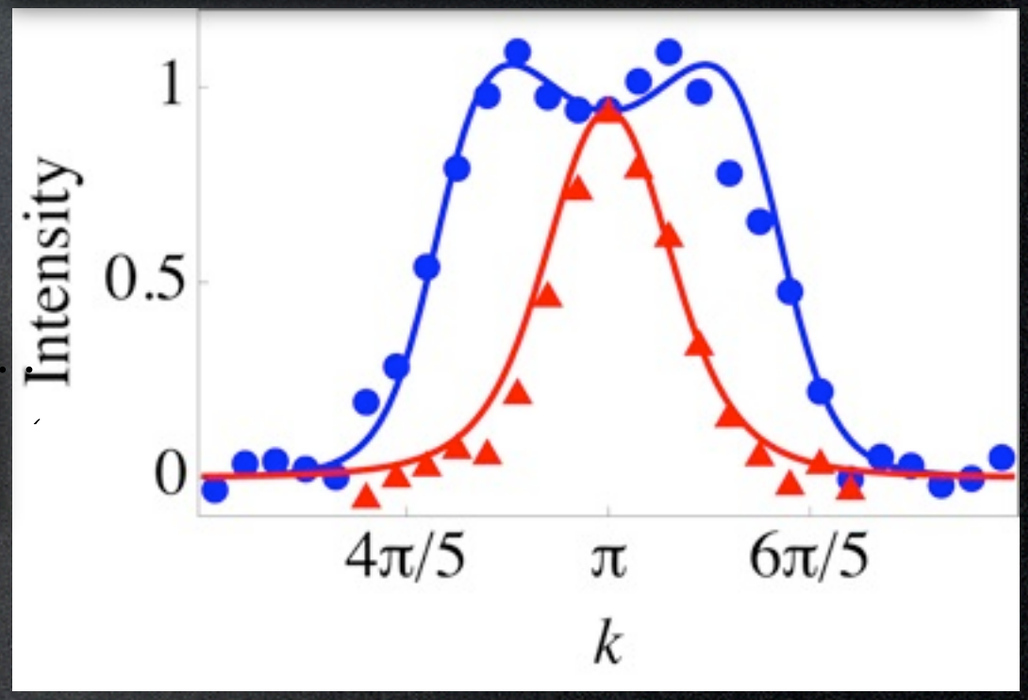

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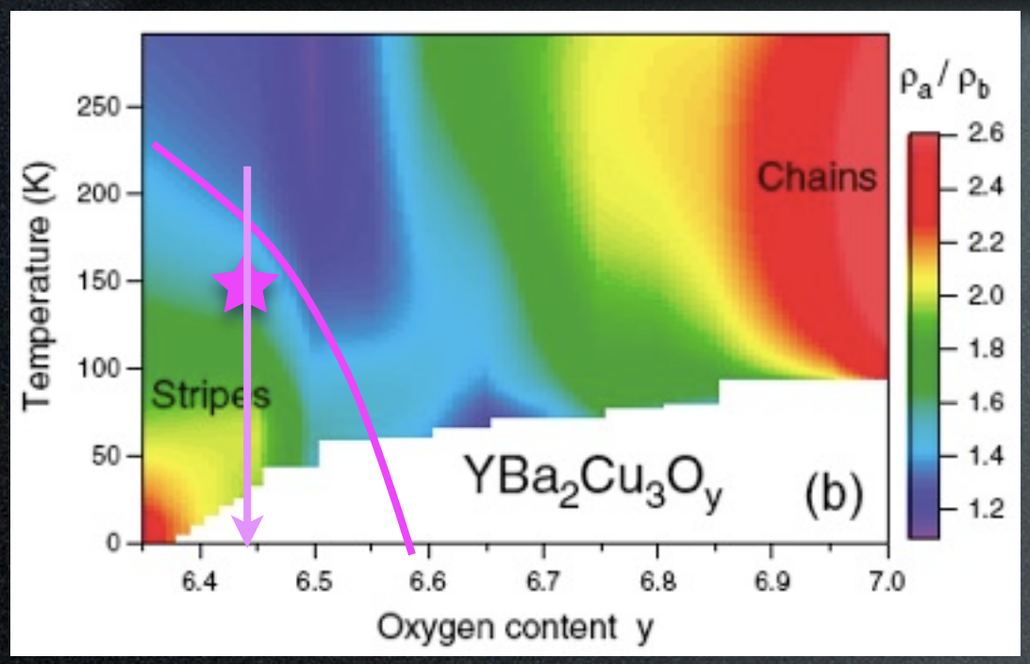

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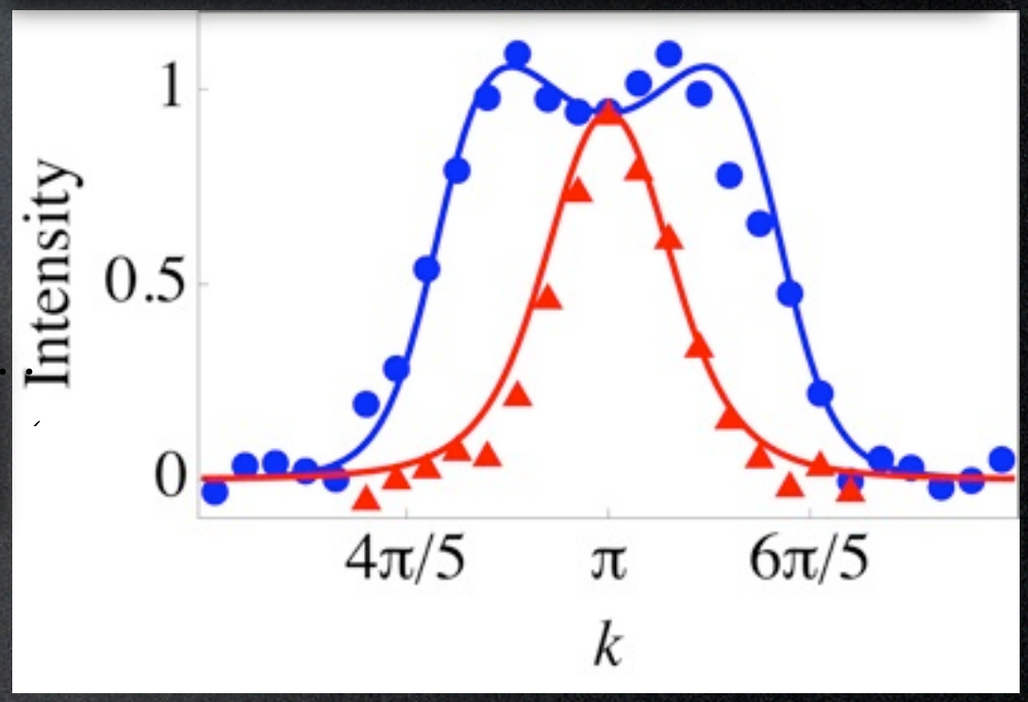

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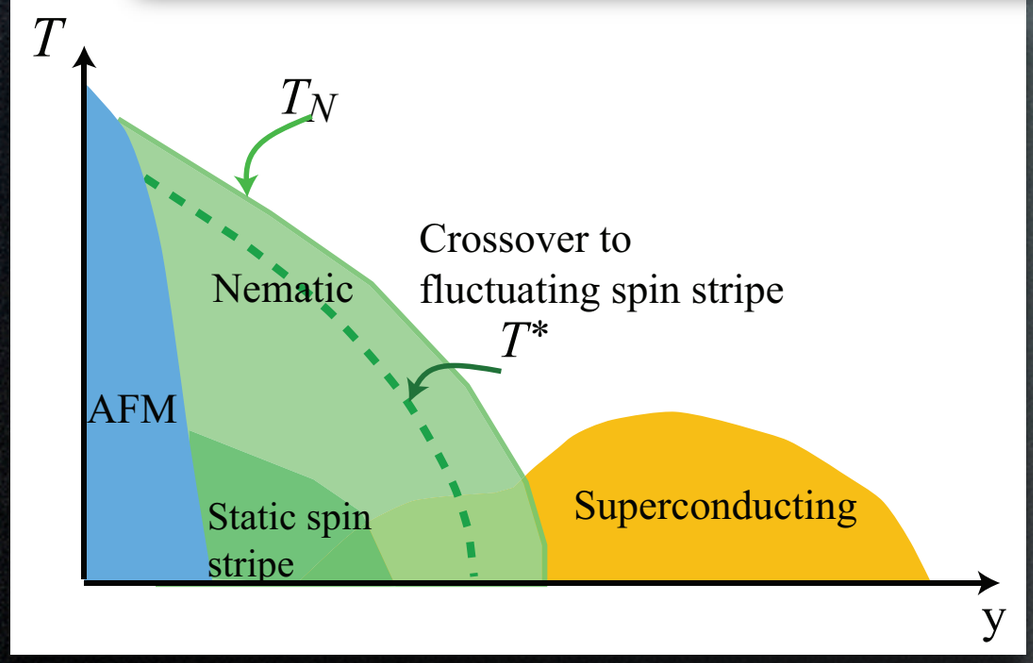

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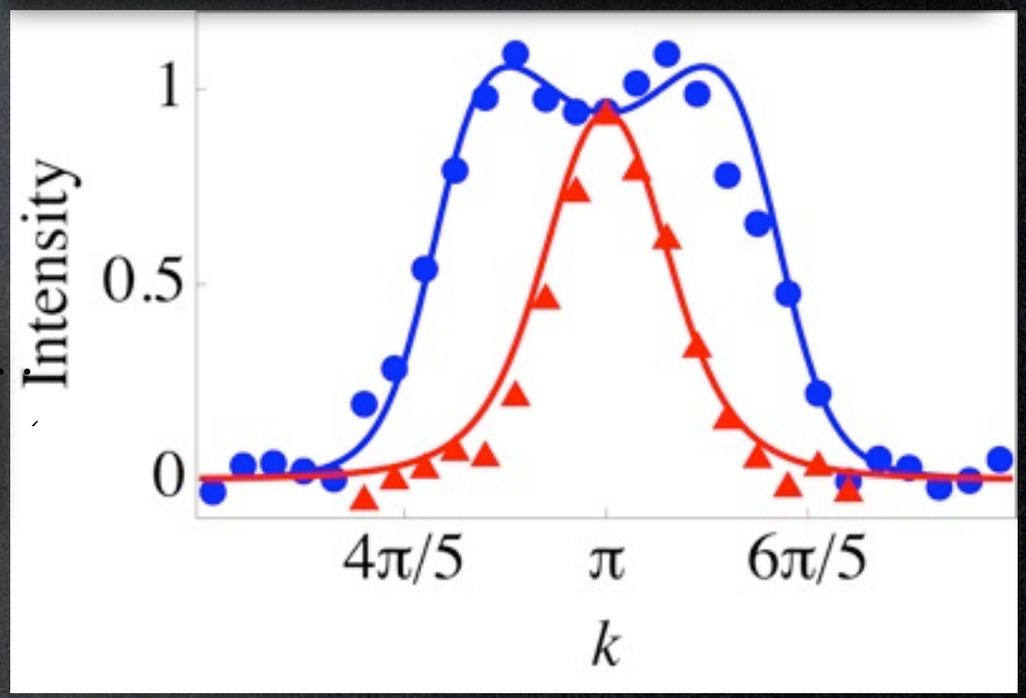
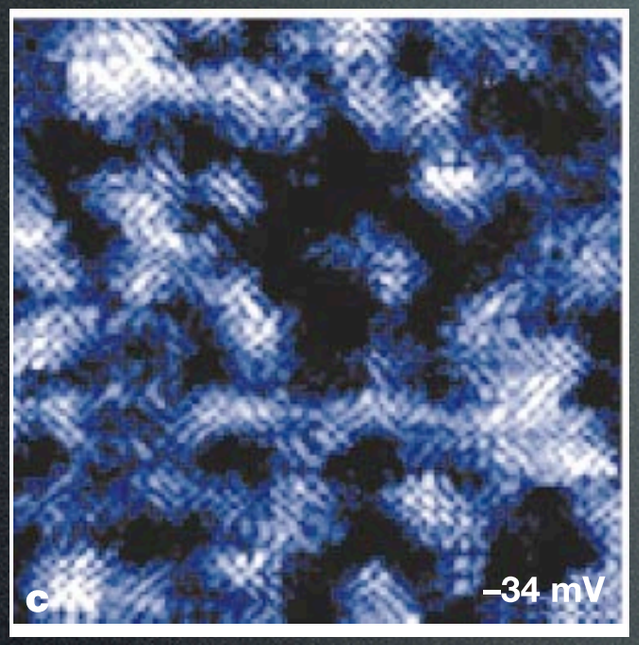
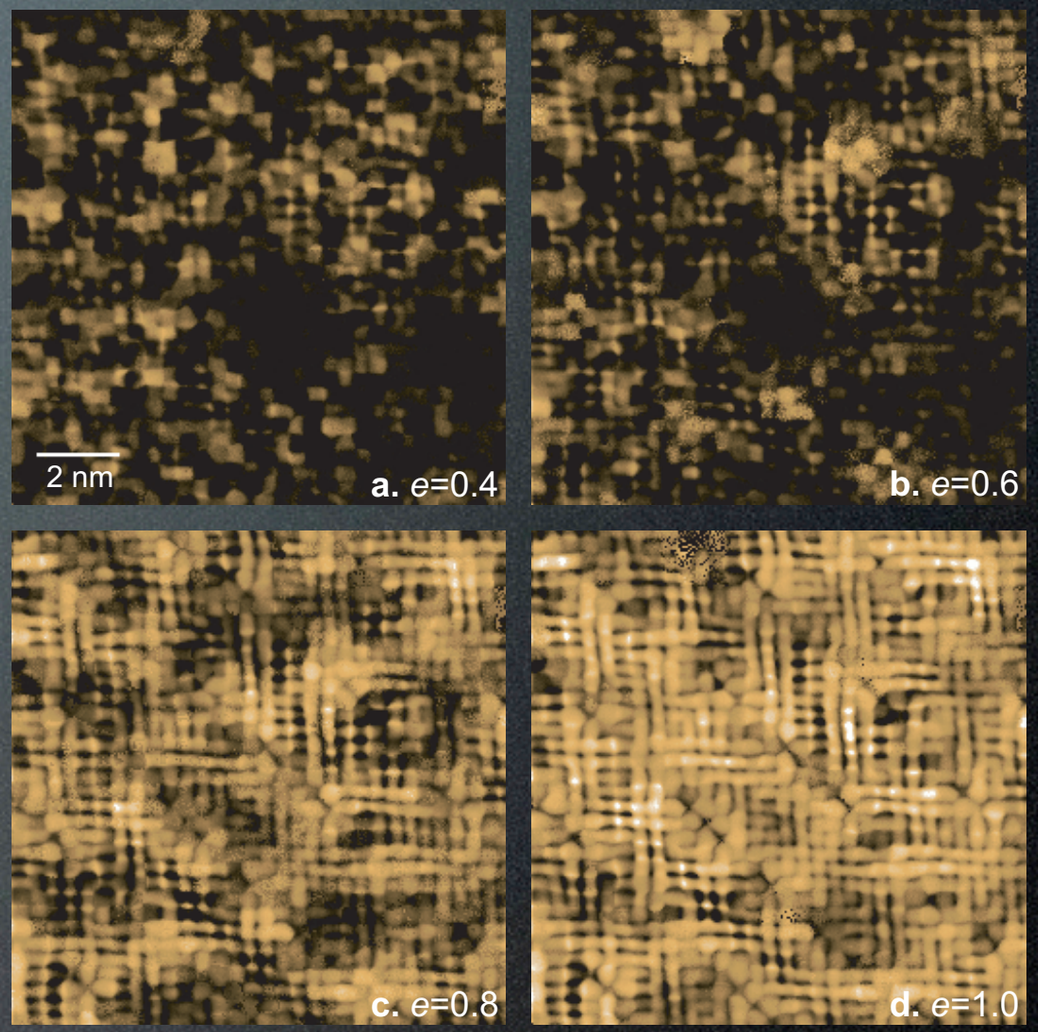


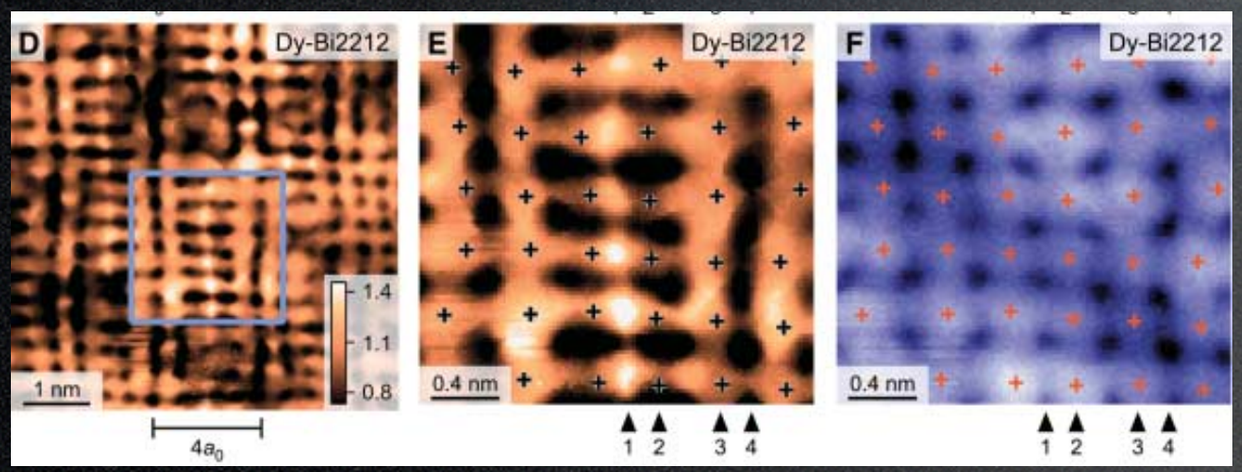
BSCCO, got nematic?

Local measure of broken symmetry?



dI/dV(ω)-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)

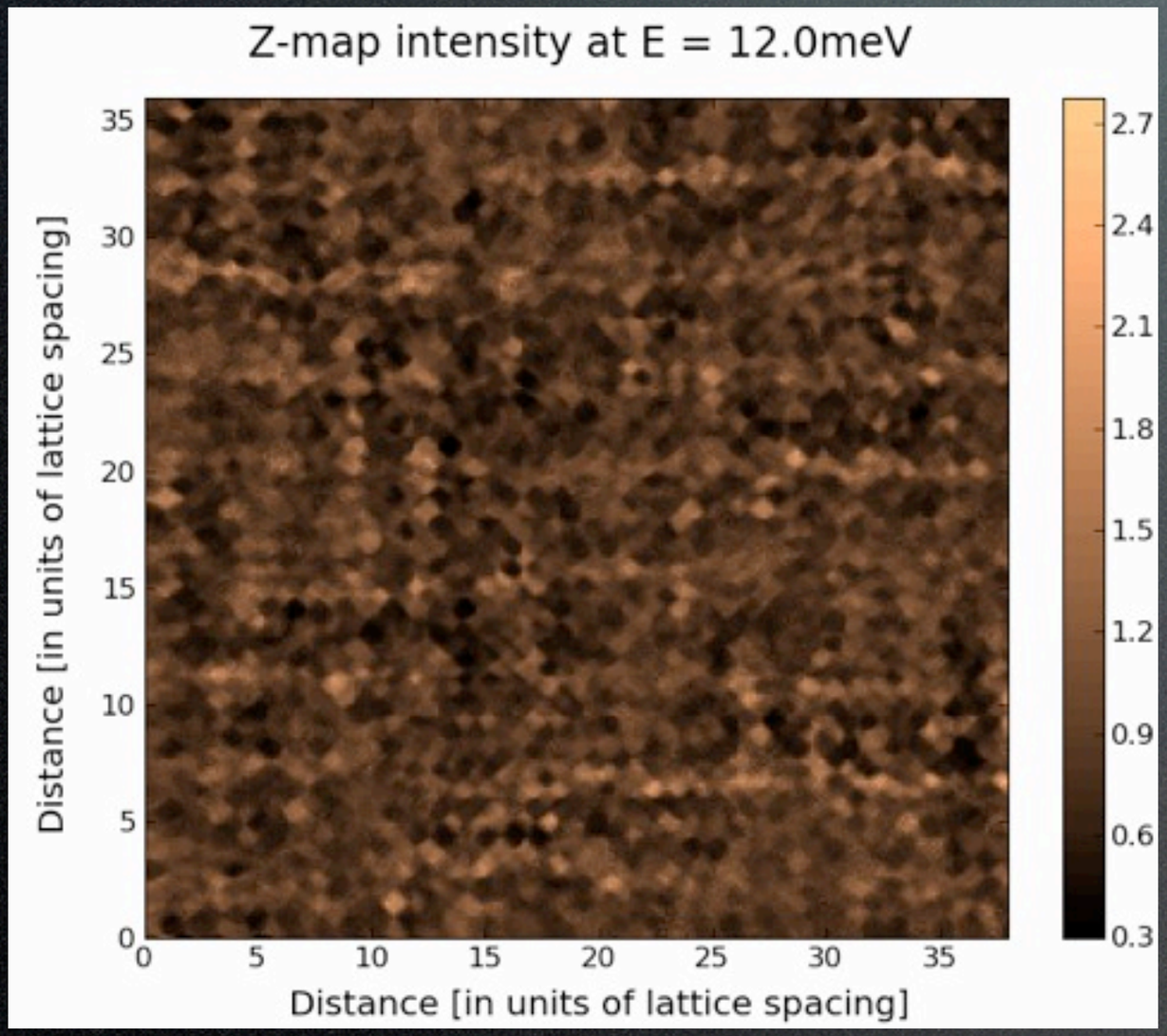
Figure S7 a-f. A series of images displaying the real space conductance ratio *Z* as a function of energy rescaled to the local psuedogap value, $e = E/\Delta_1(\mathbf{r})$. Each pixel location was rescaled independently of the others. The common color scale illustrates that the bond centered pattern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

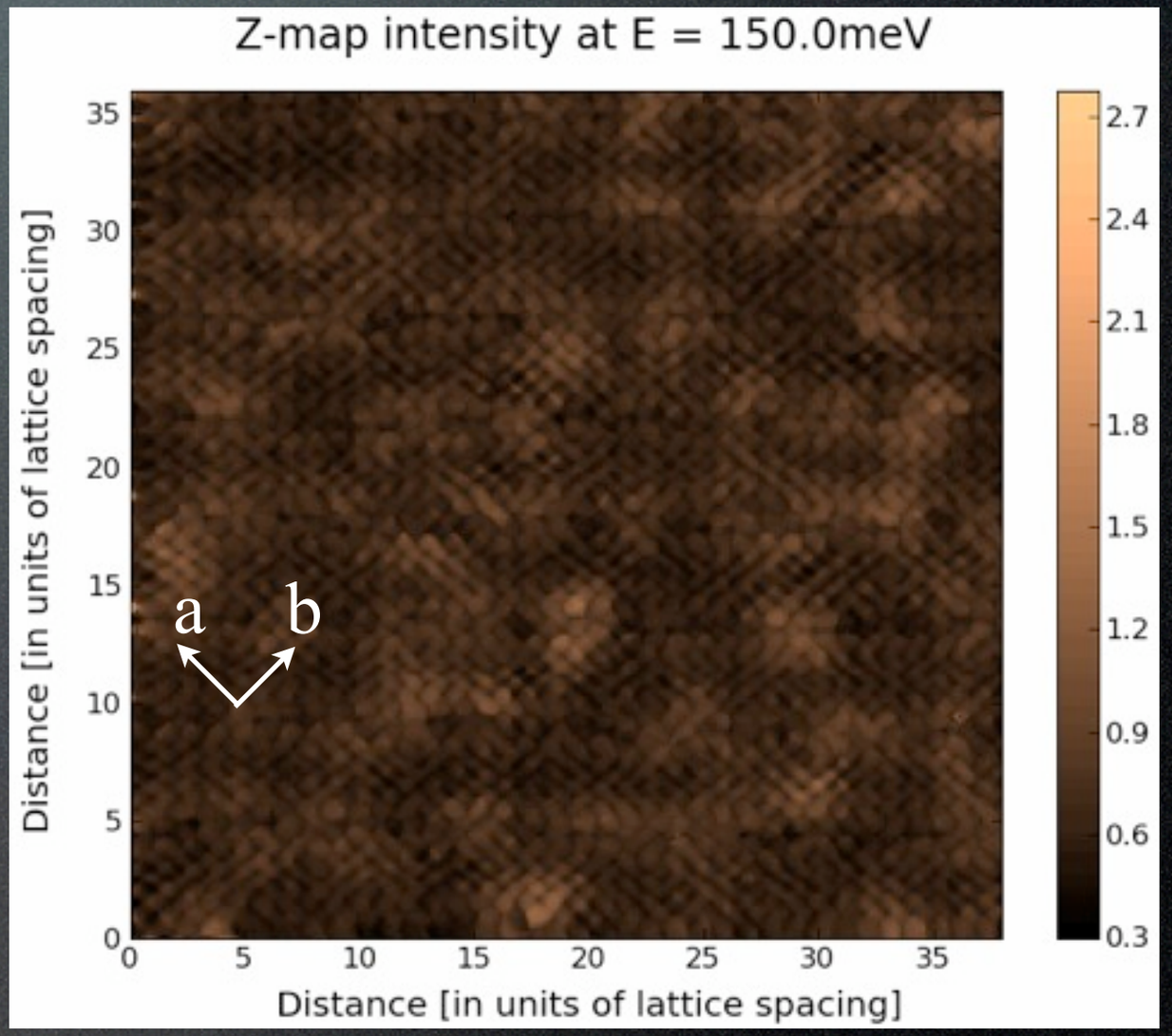
Z-map(ω)
Kohsaka et al, Nature 454, 1072 (2008)
UD T_c=45K

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)





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Challenge: An objective measure

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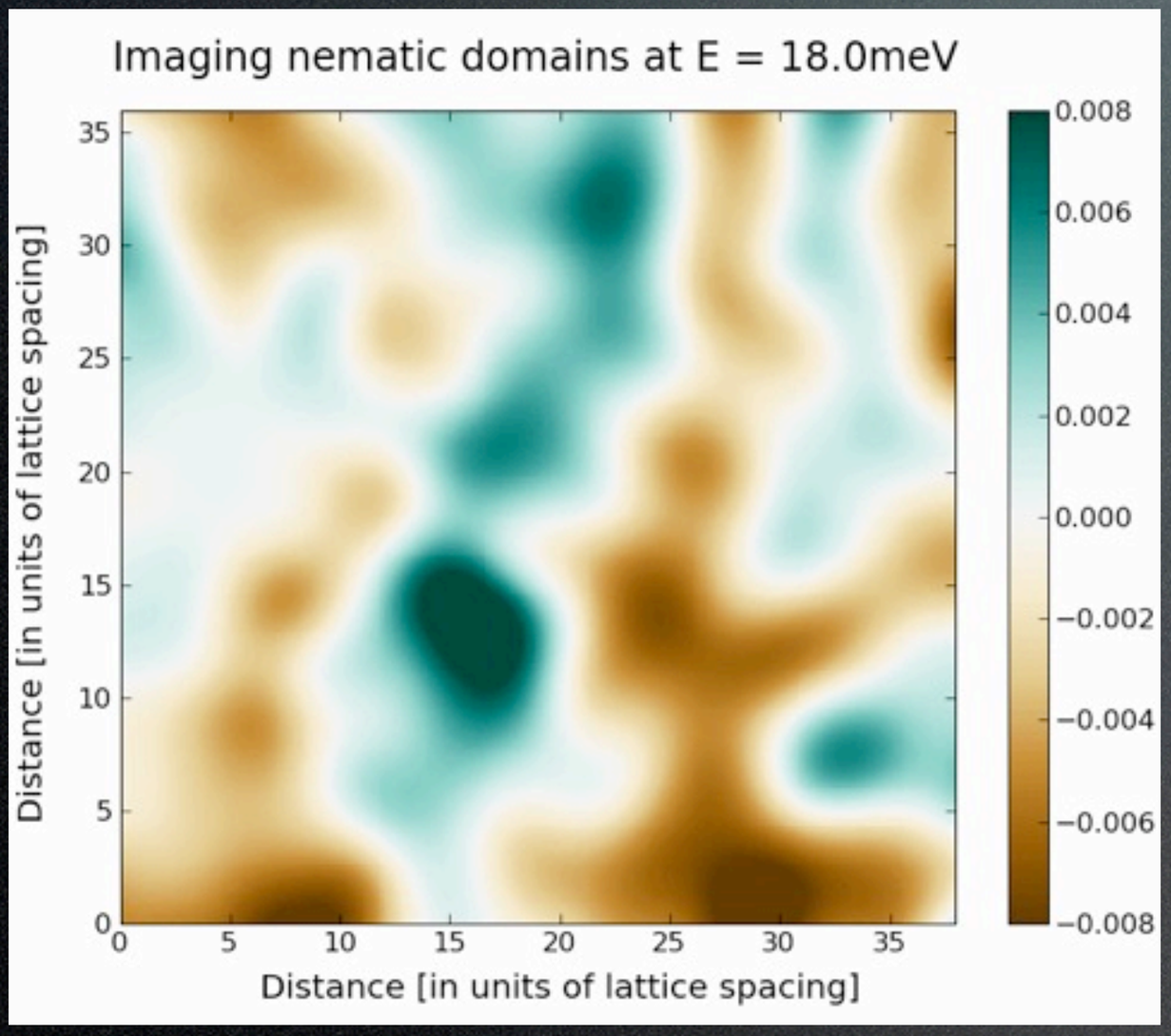
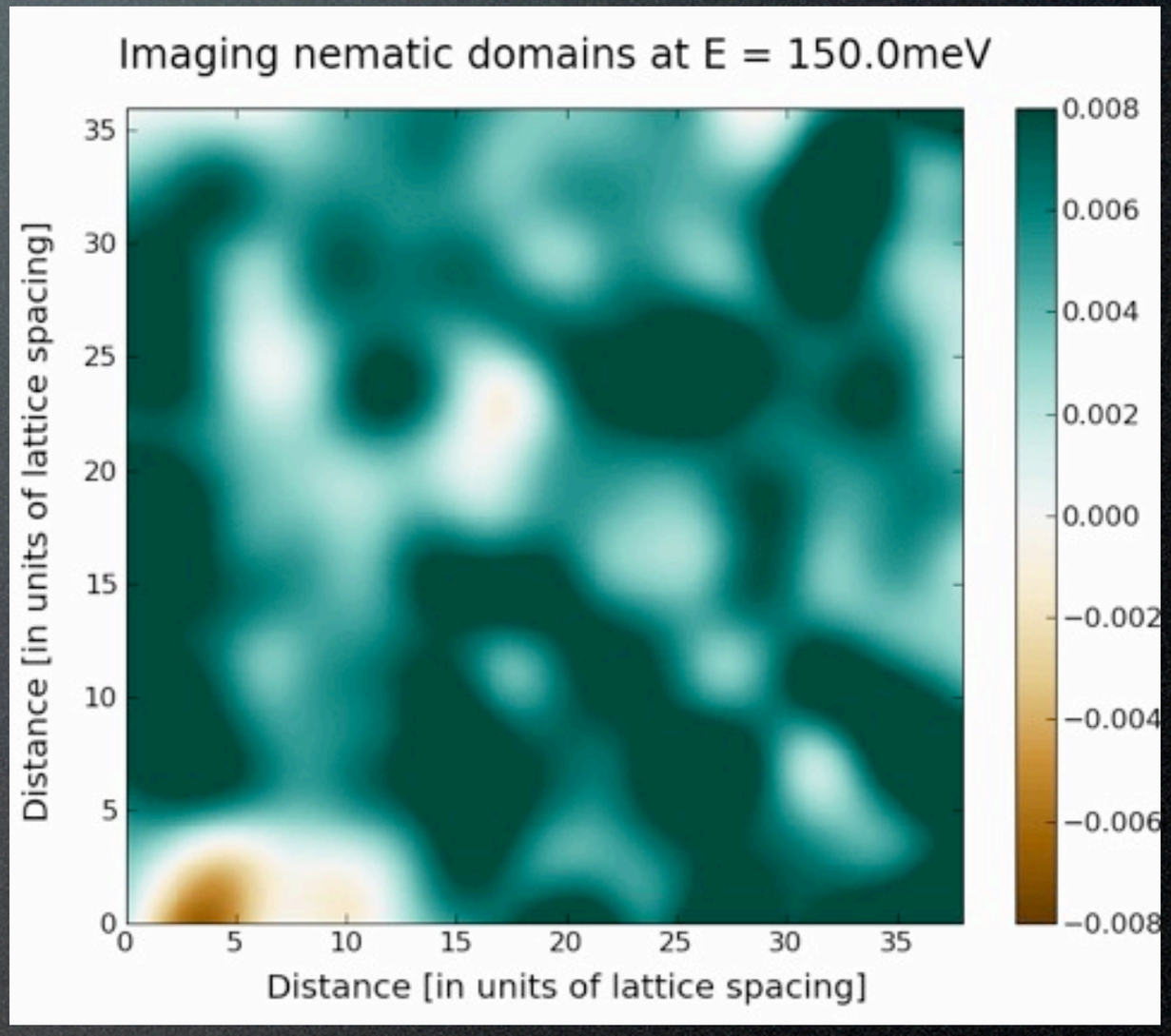
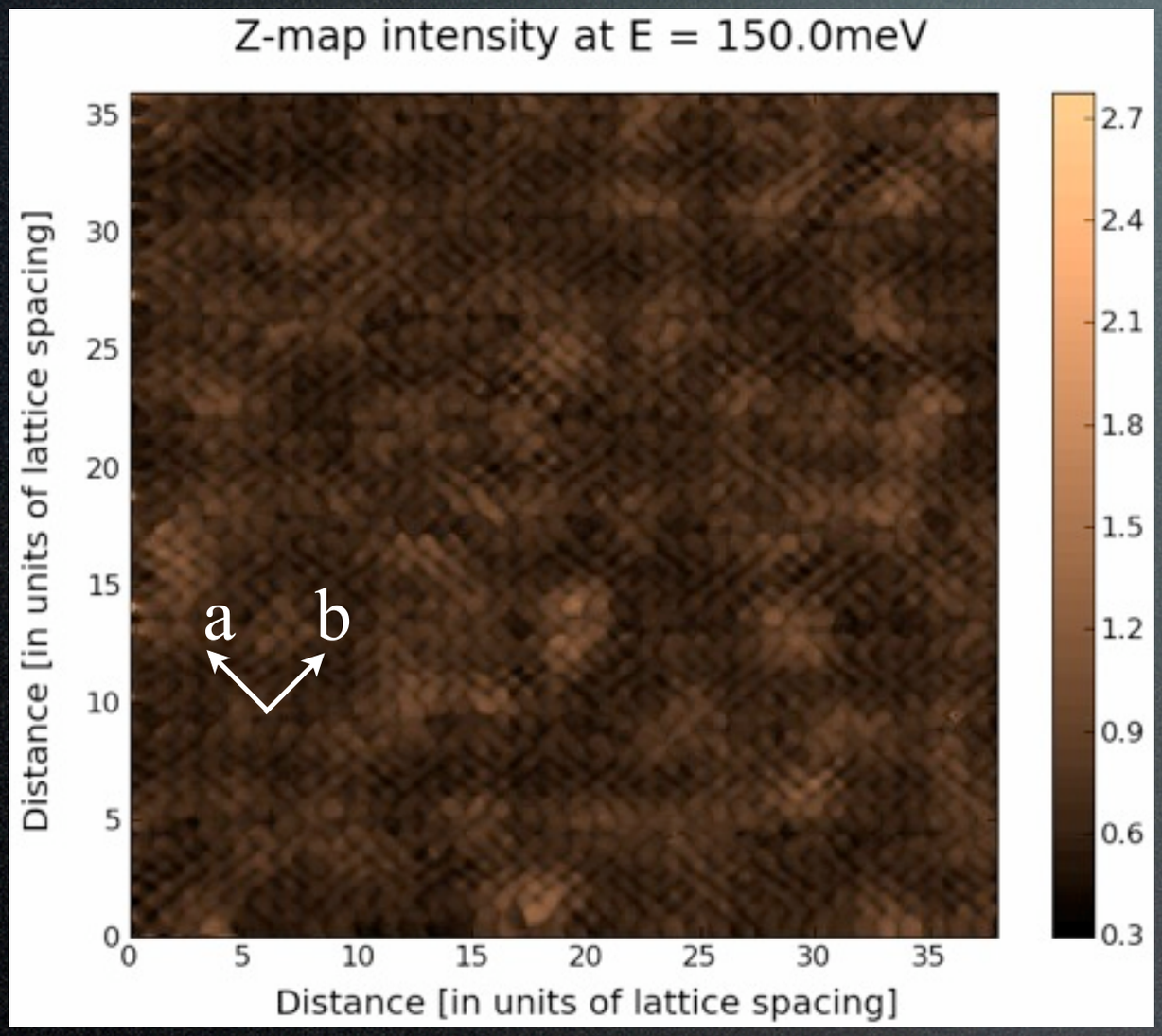




M. Lawler et al, in prep.

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

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

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

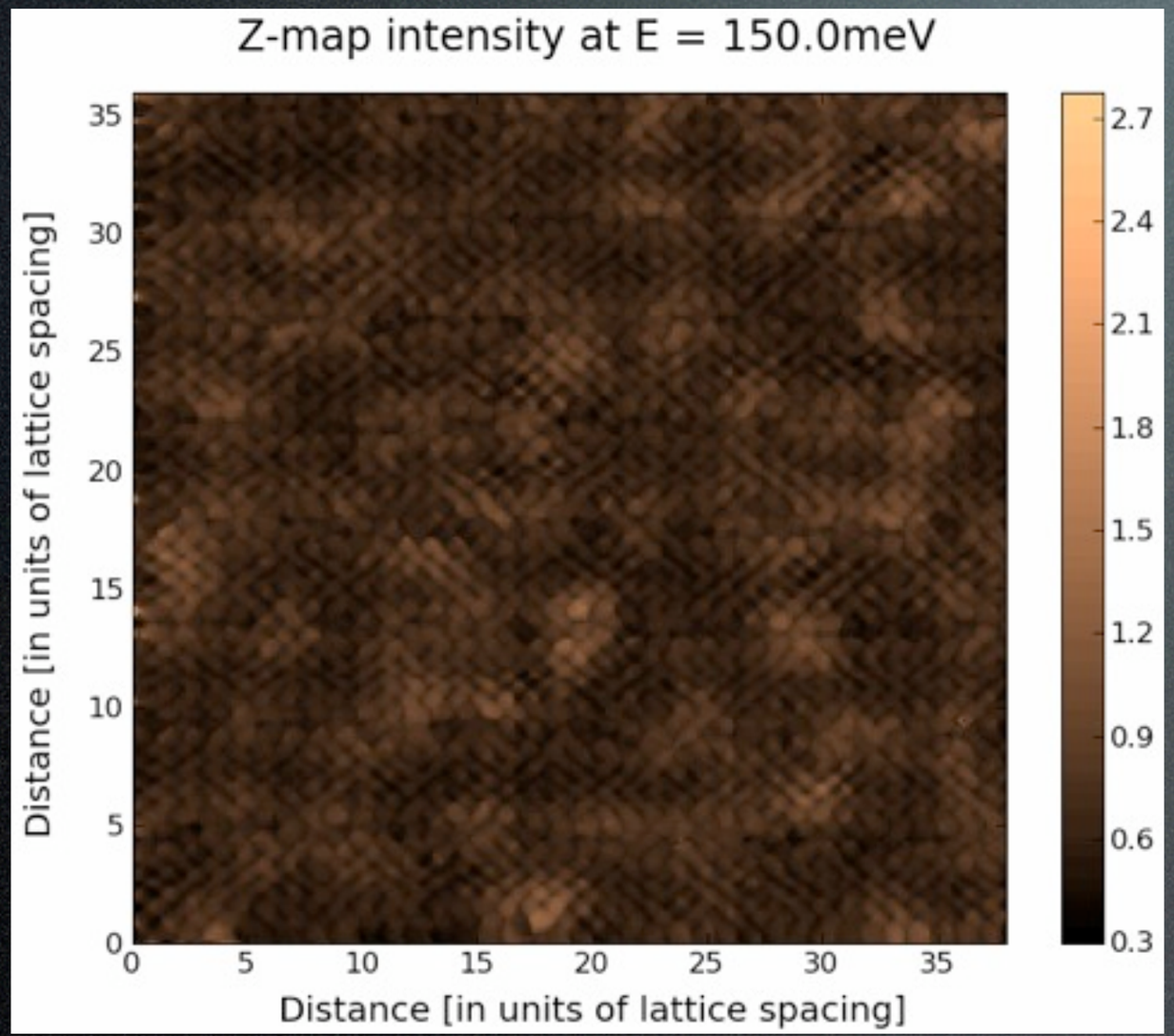
$$N_f(\mathbf{r},E)=\int d\mathbf{r}' f(\mathbf{r}-\mathbf{r}')N(\mathbf{r}',E),$$

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

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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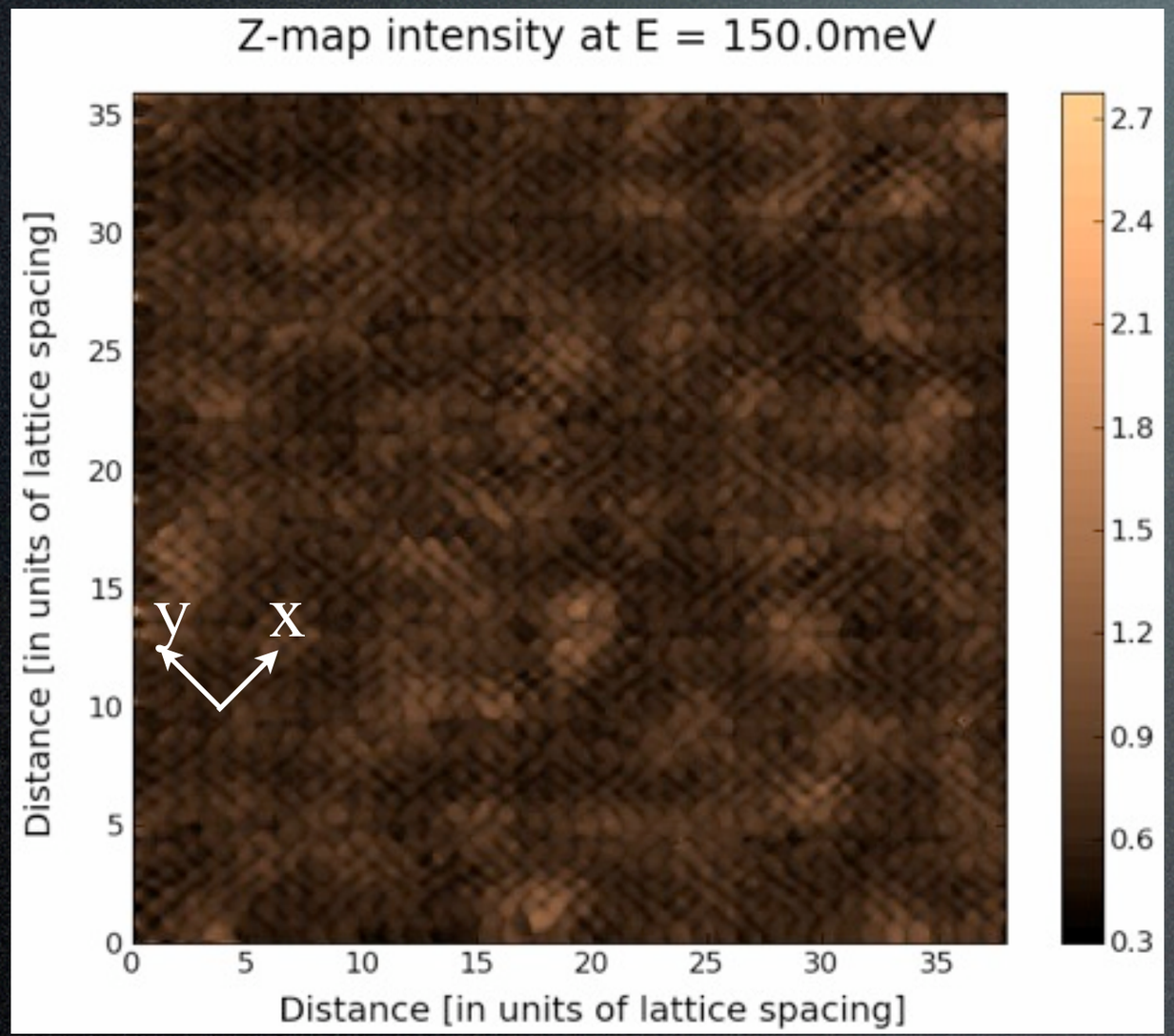

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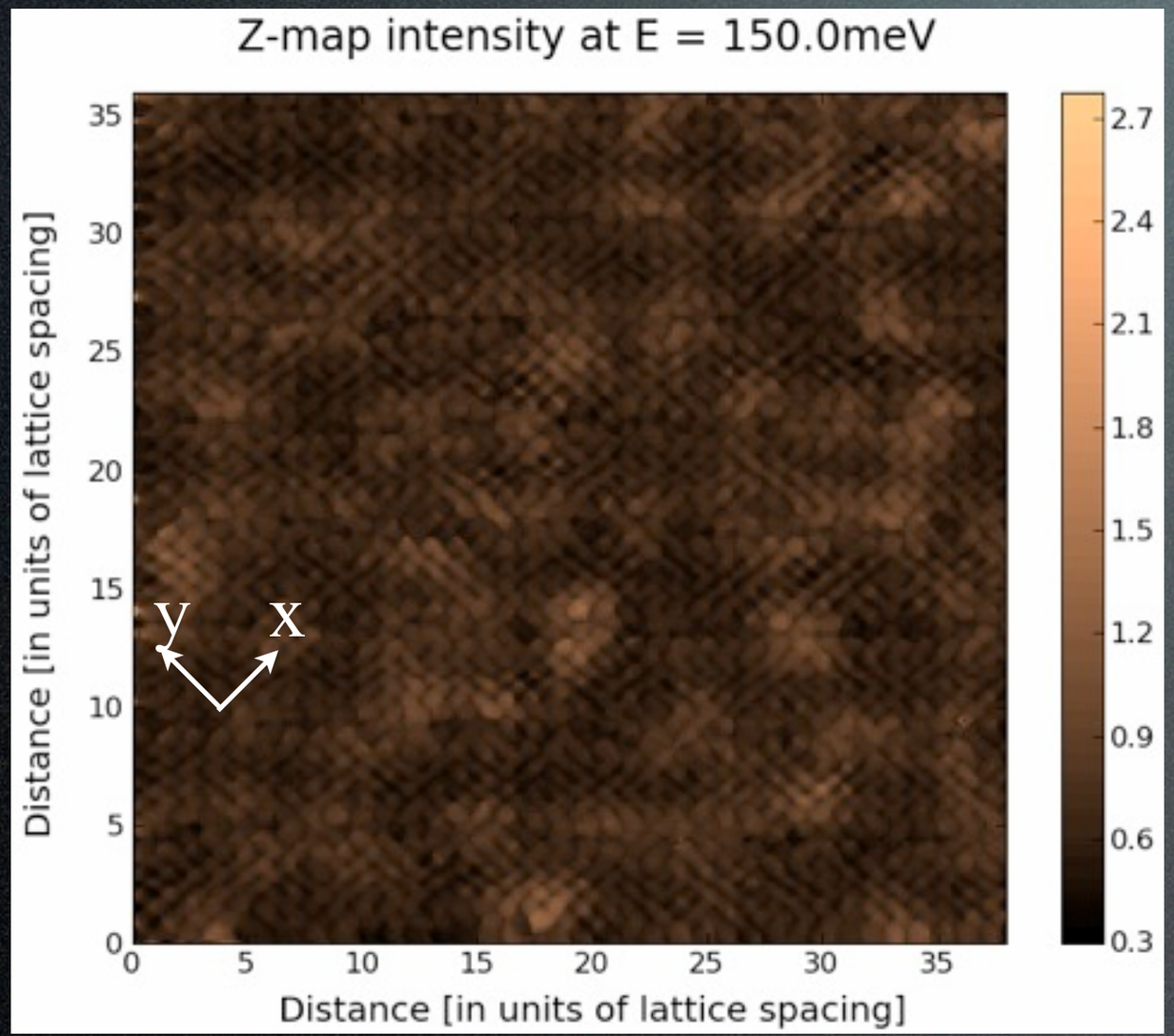

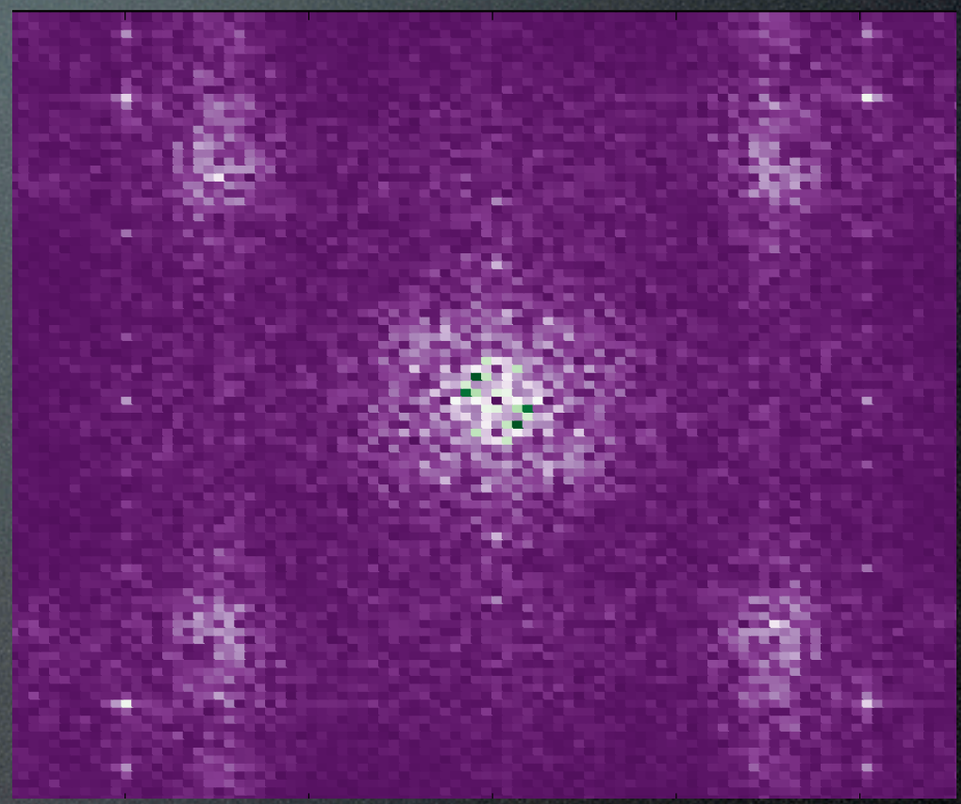

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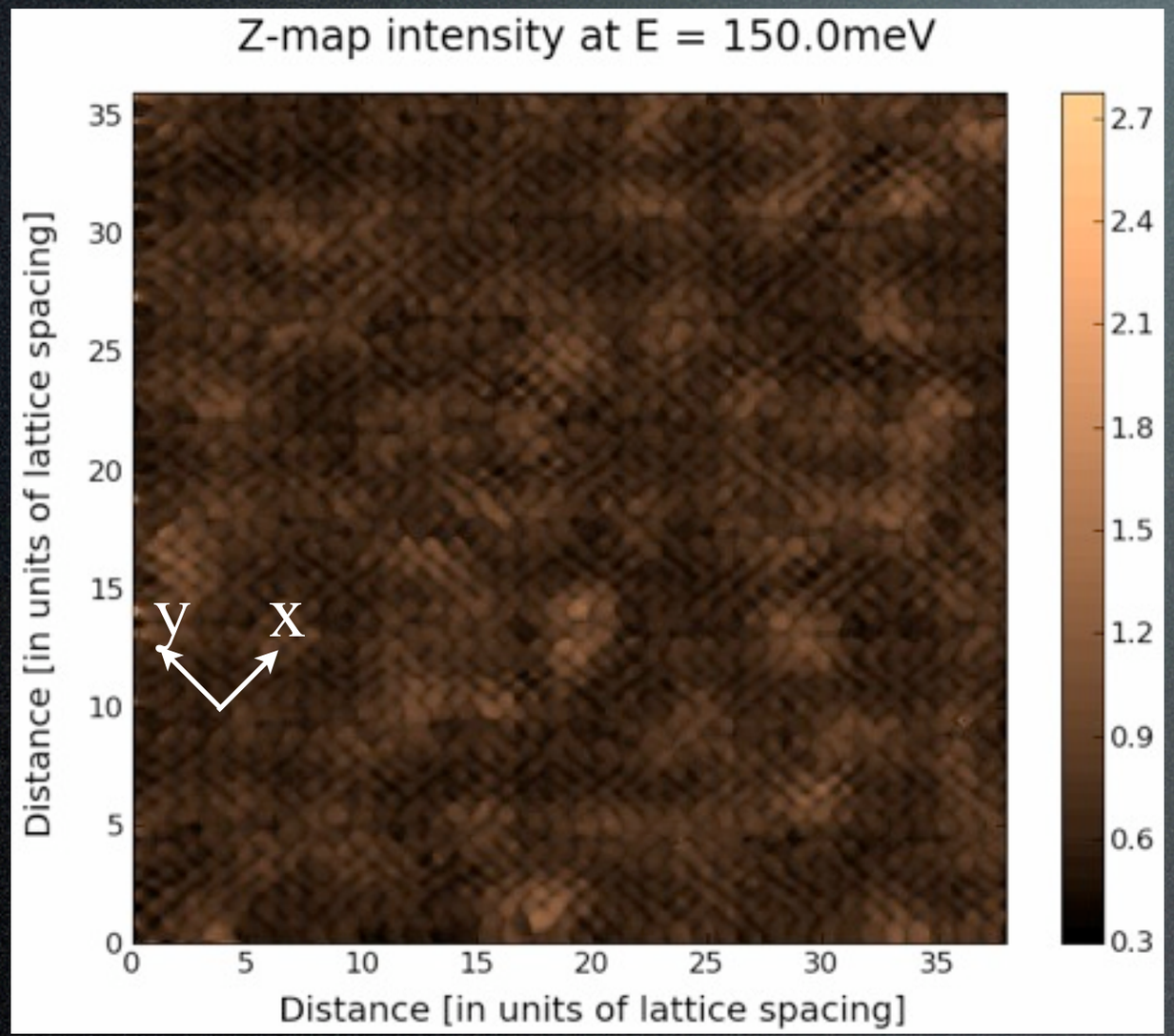

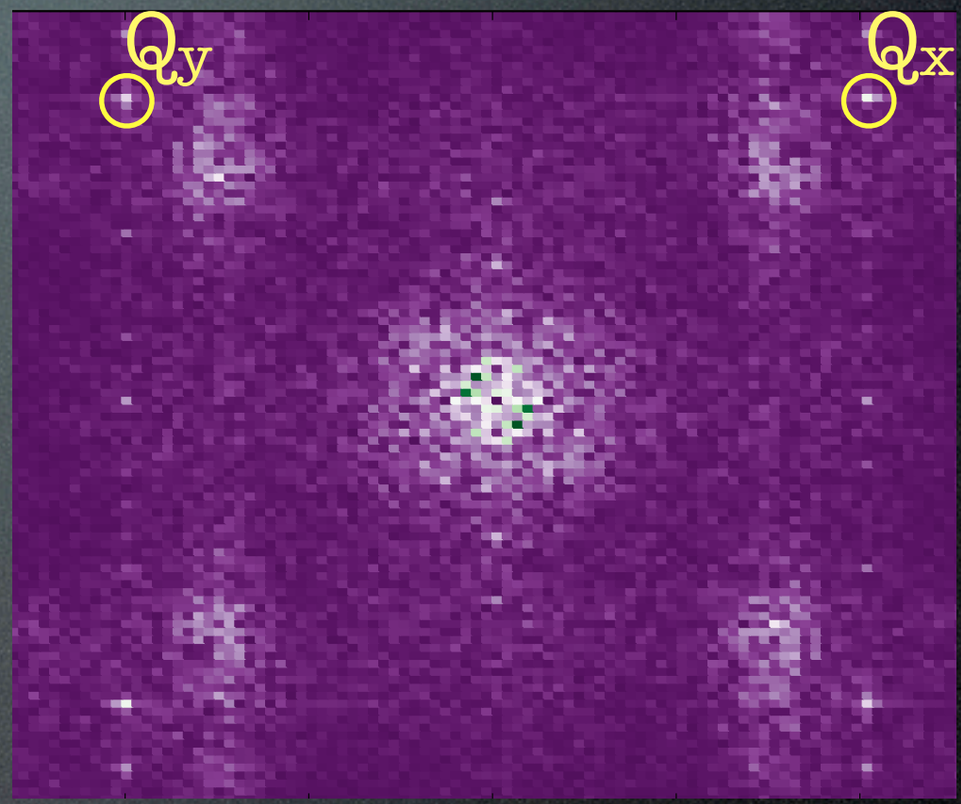

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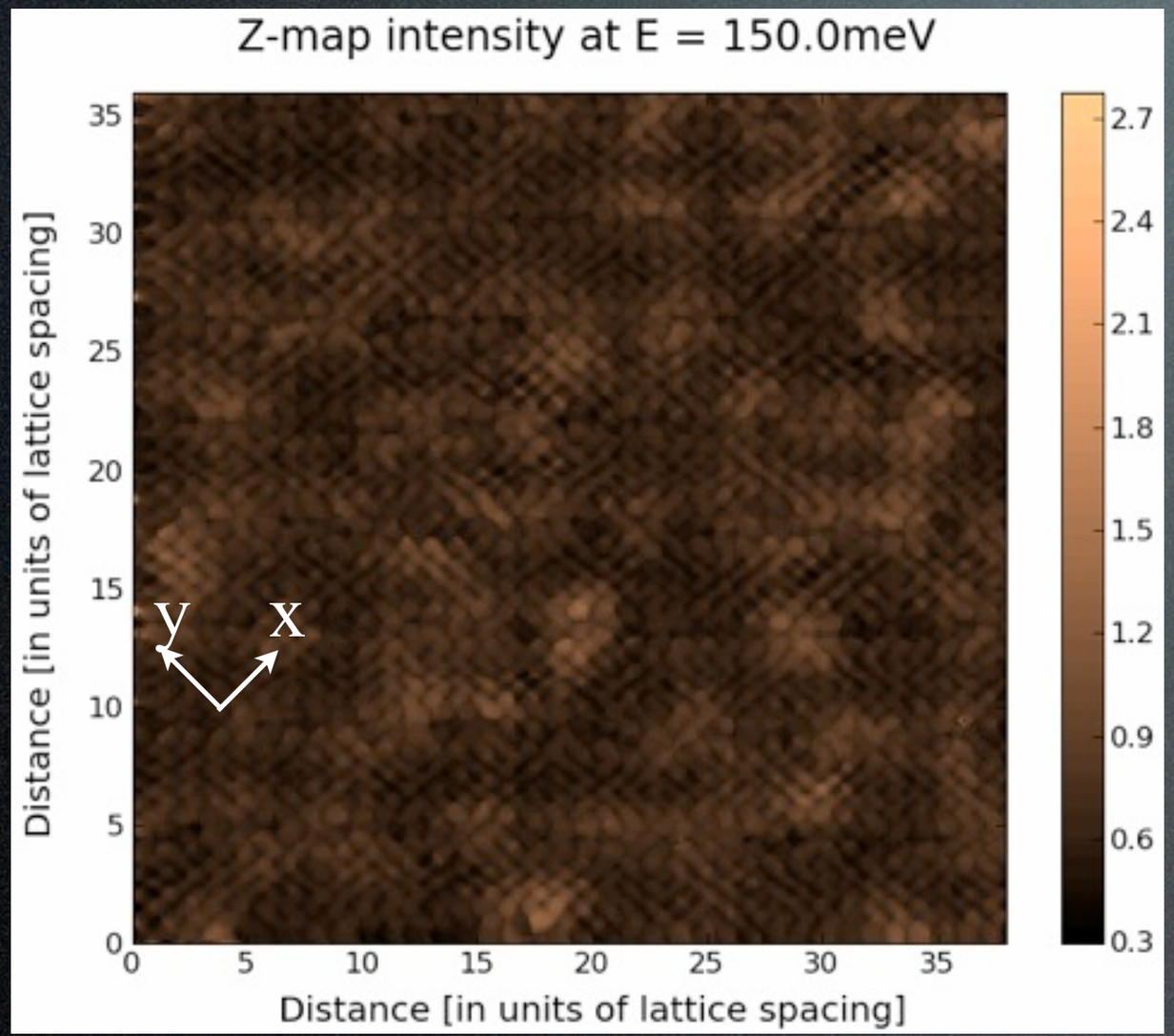

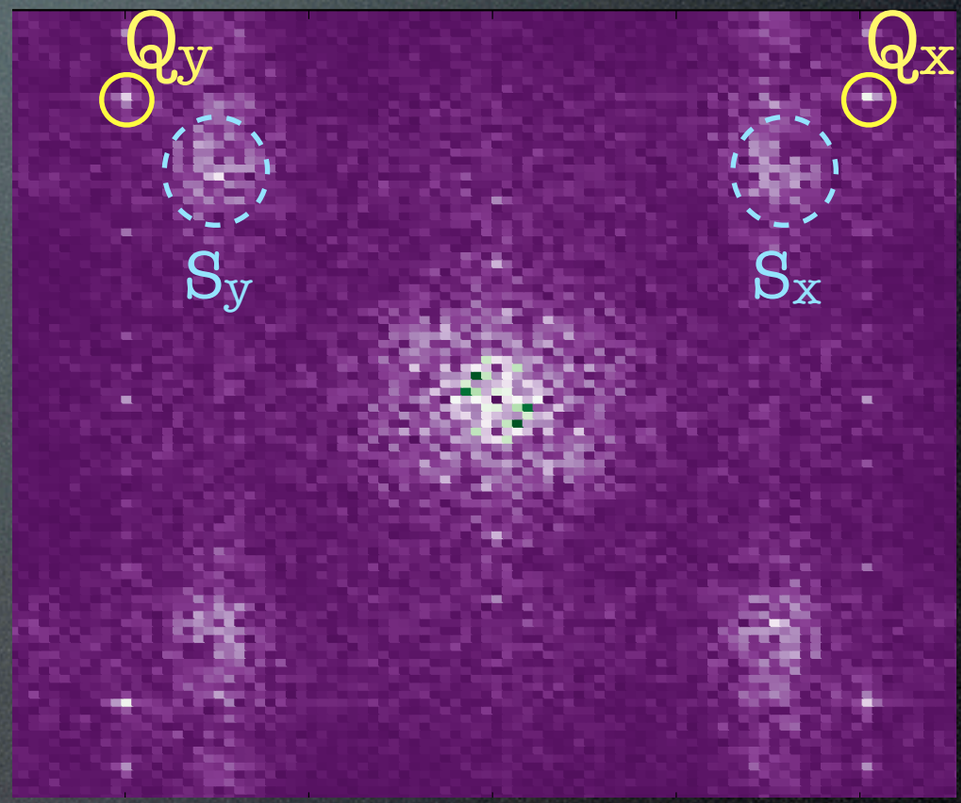

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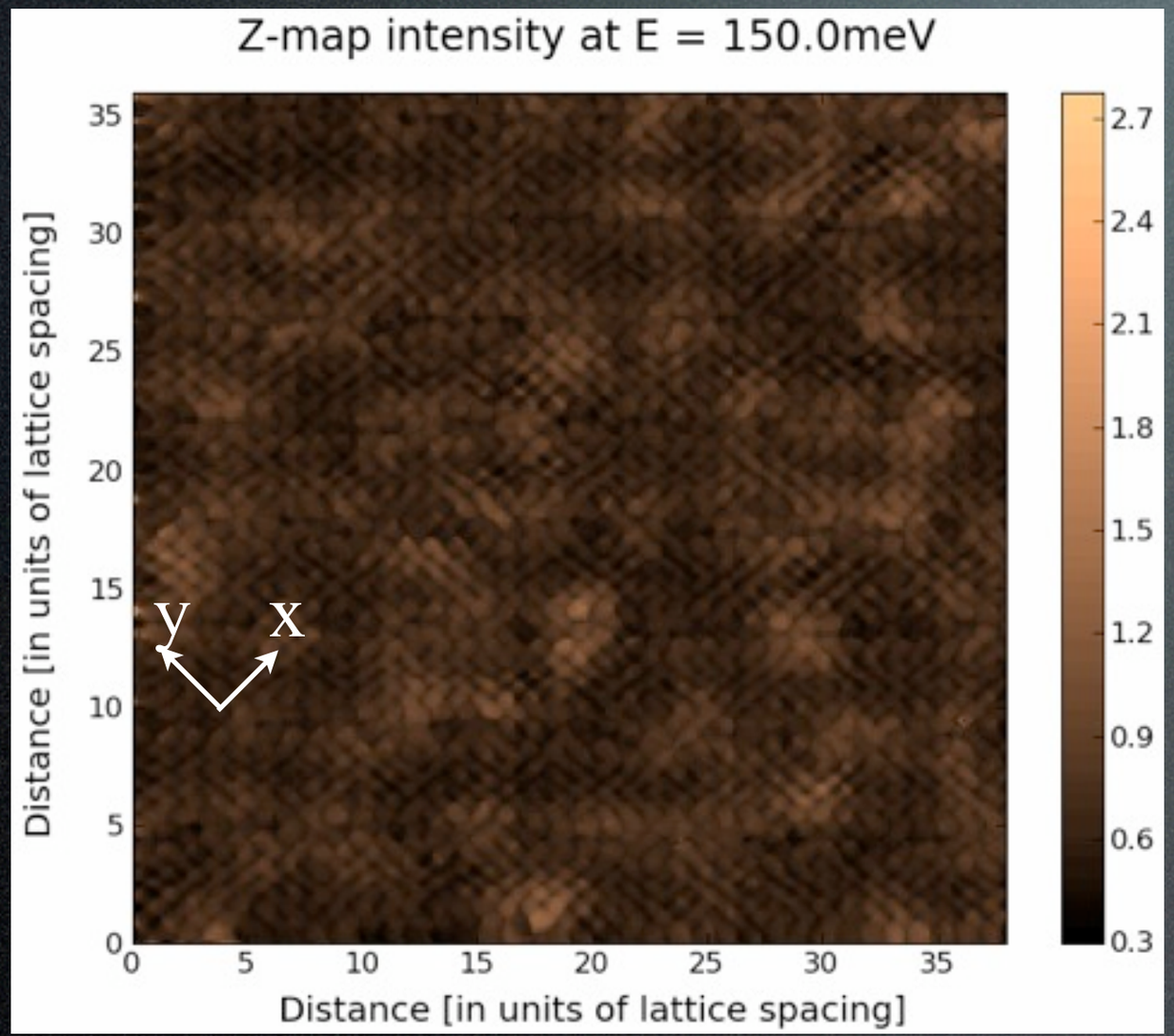

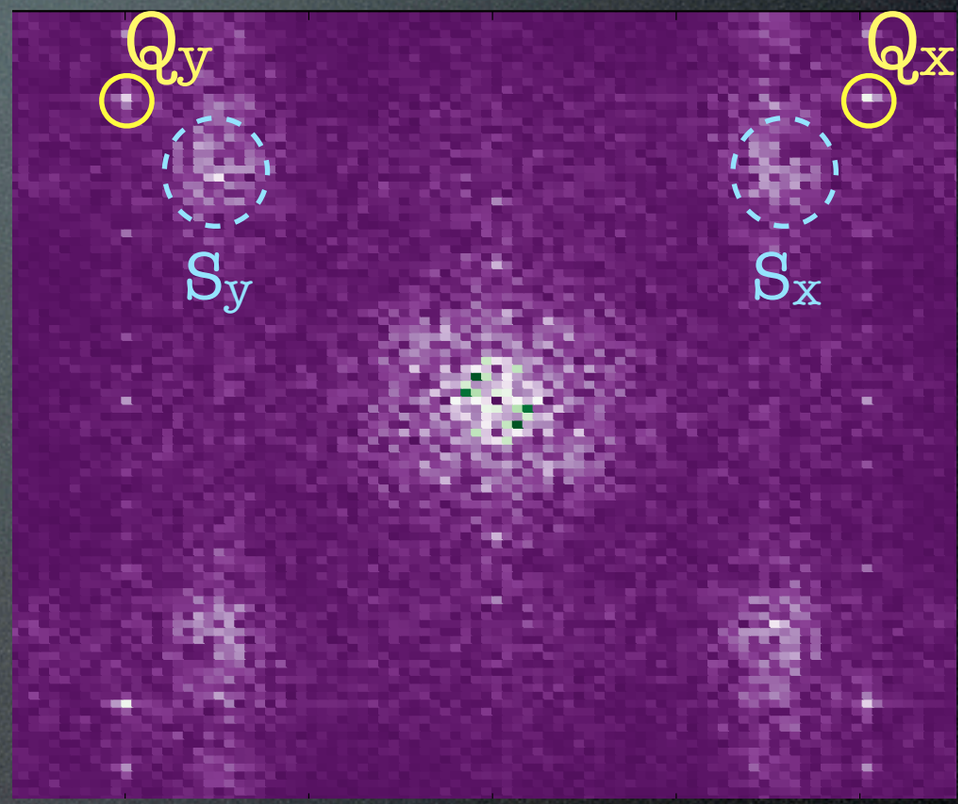

Q_x vs Q_y?

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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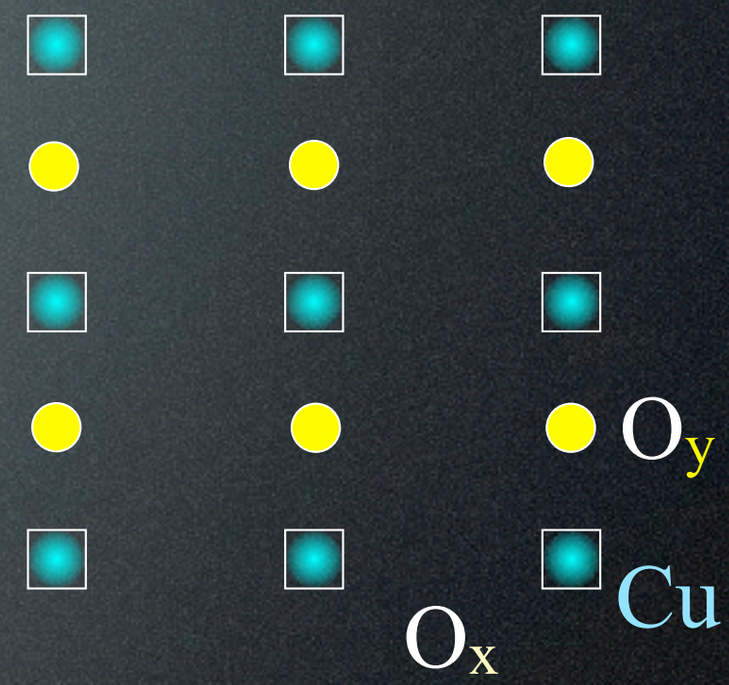

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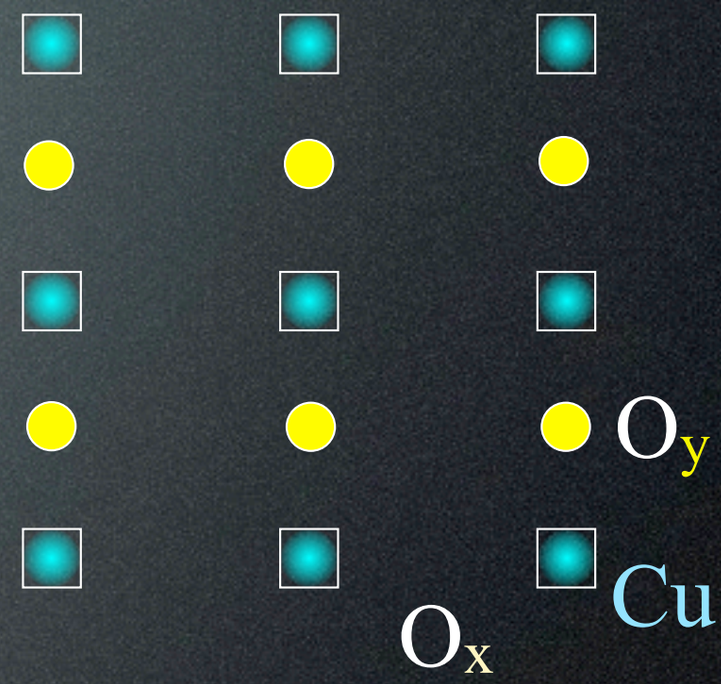

- Nematic OP

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

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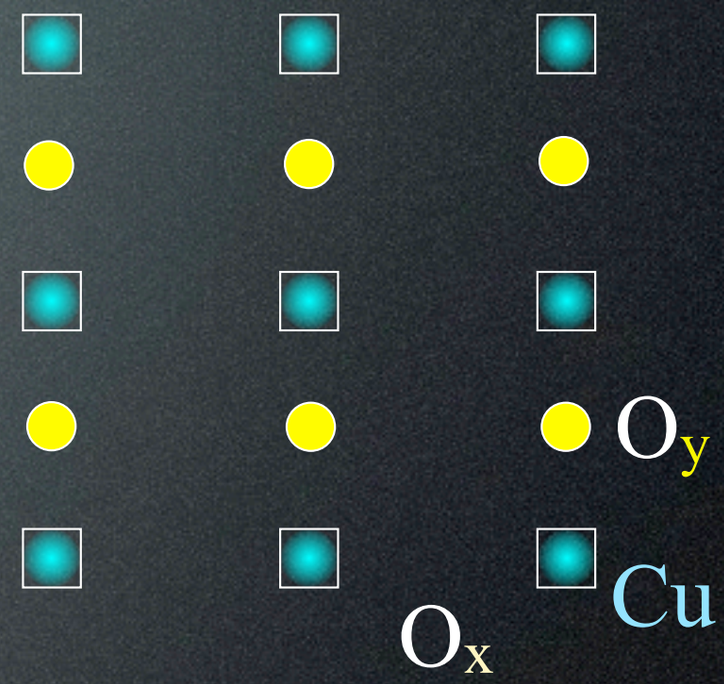

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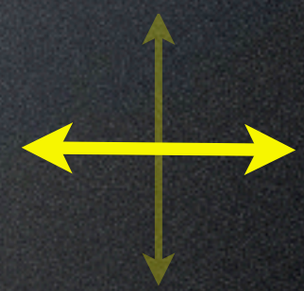
➡Measure C_4 breaking



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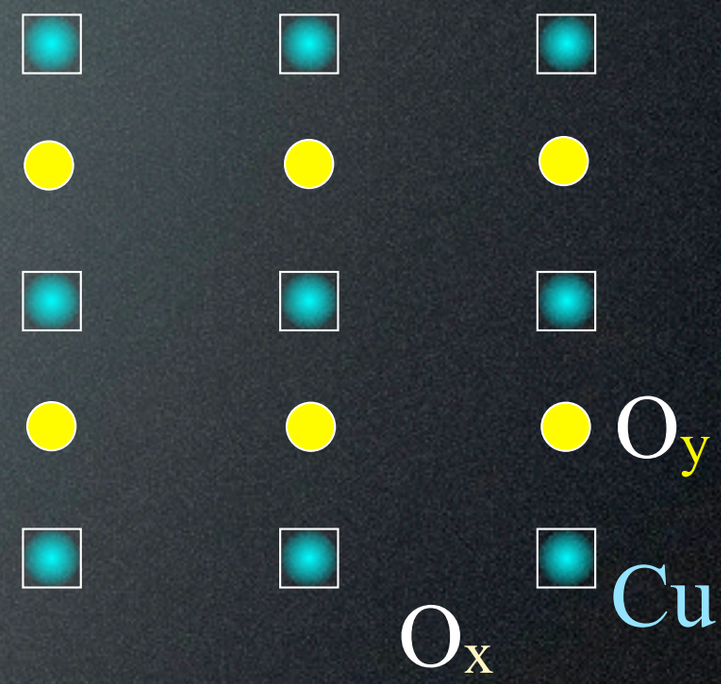

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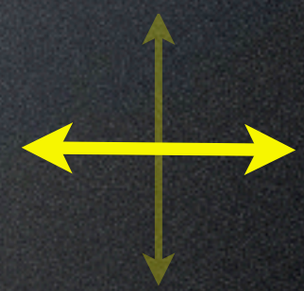


- Need O sites

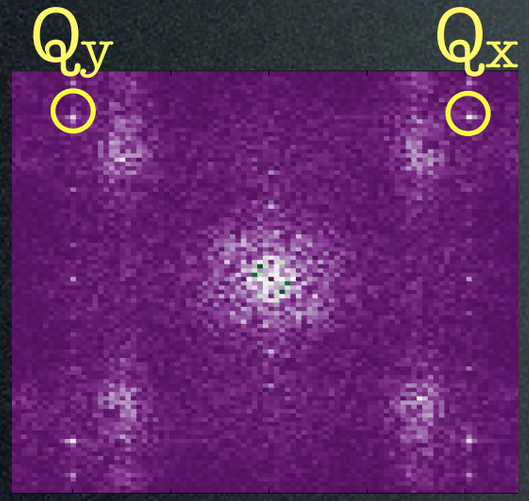
$$\tilde{Z}(\vec{Q}_x) = \bar{Z}_{\mathrm{Cu}} - \bar{Z}_{\mathrm{O}_x} + \bar{Z}_{\mathrm{O}_y}, \quad \tilde{Z}(\vec{Q}_y) = \bar{Z}_{\mathrm{Cu}} + \bar{Z}_{\mathrm{O}_x} - \bar{Z}_{\mathrm{O}_y}$$

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

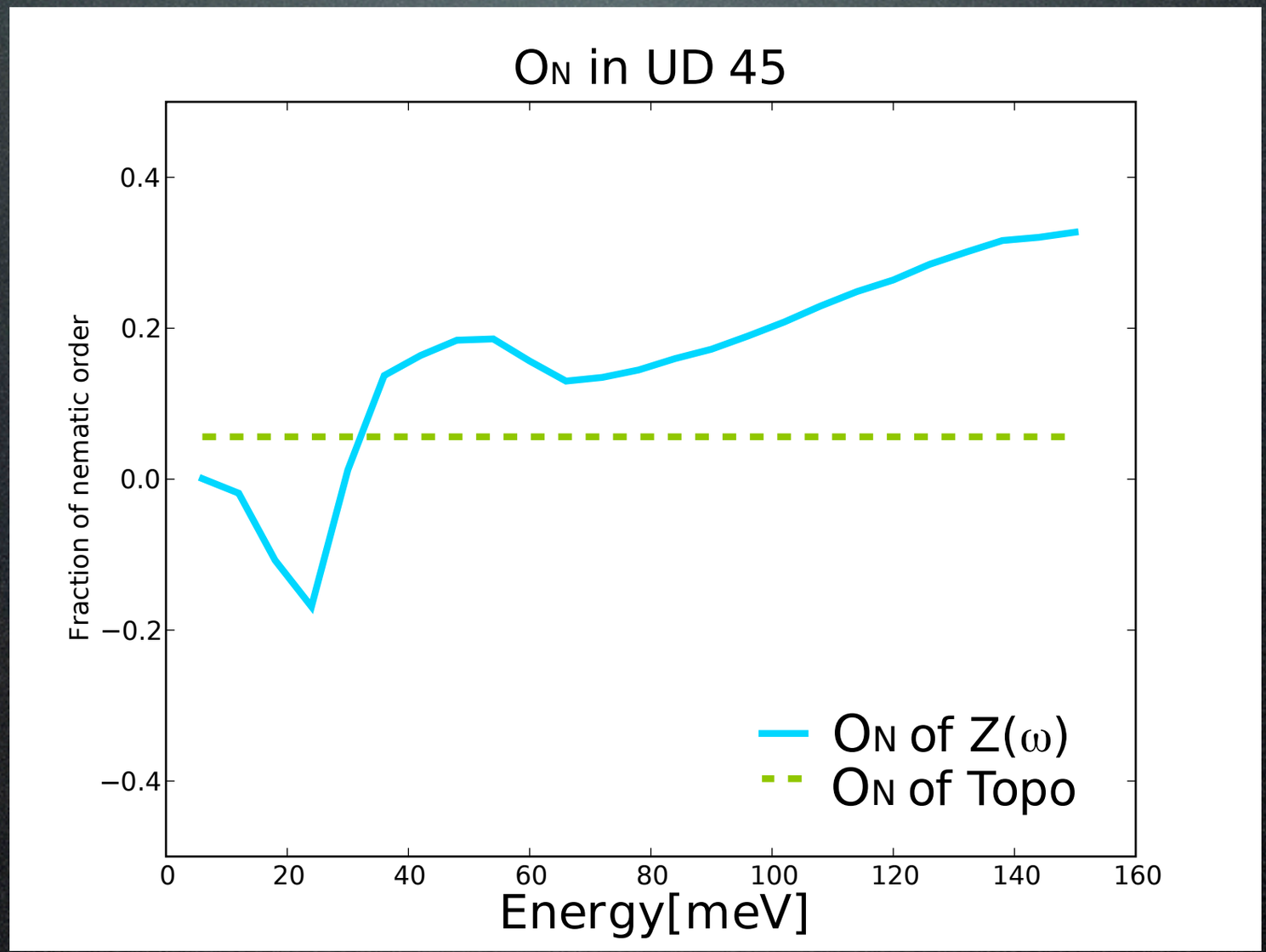
V. Emery, PRL 58, 2974 (1987)

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

Nematic ordering in UD 45



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



Extracted from published data, T=4K

Kohsaka et al, Nature 454, 1072 (2008)

Domain size in Z-map

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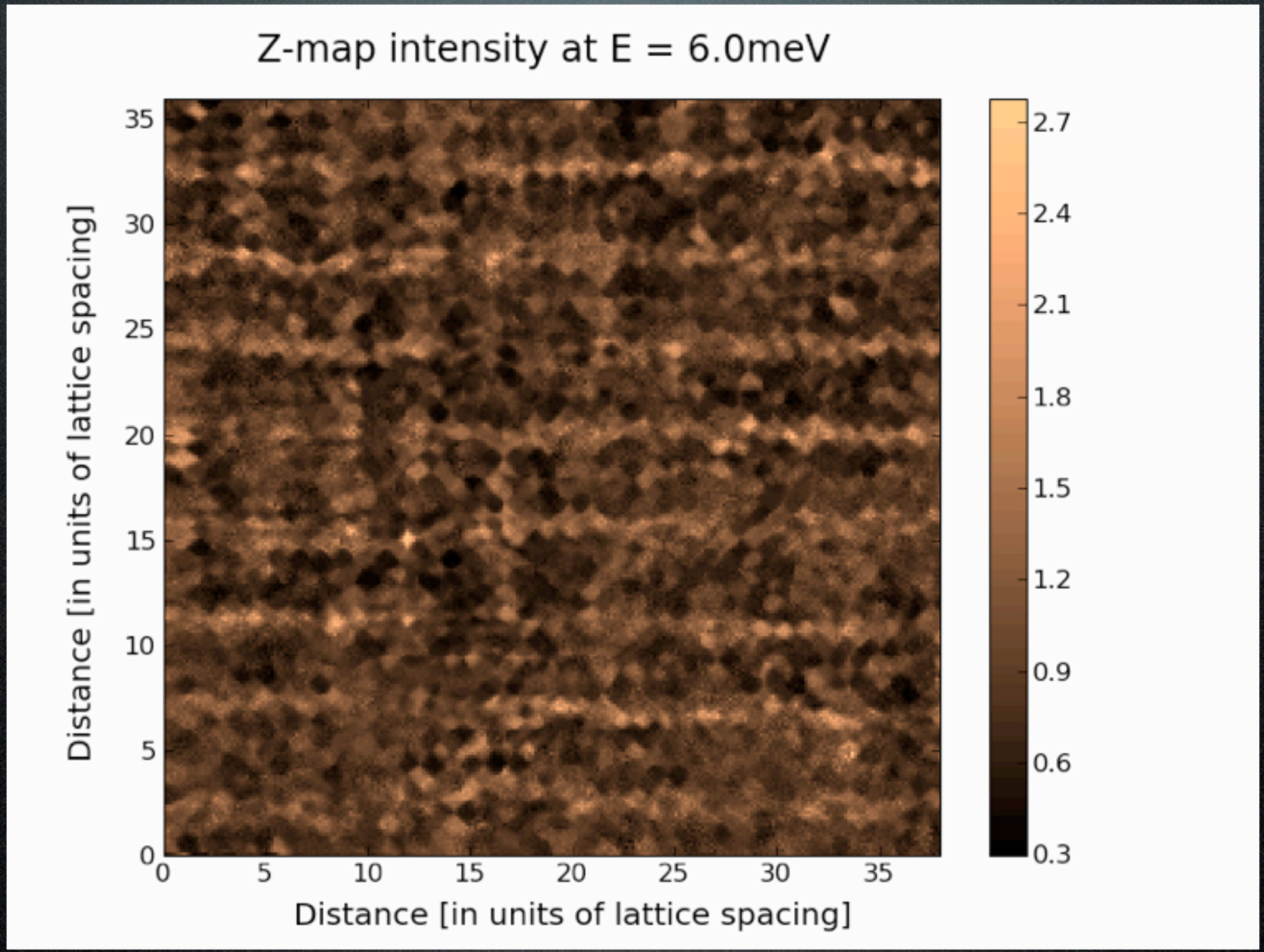
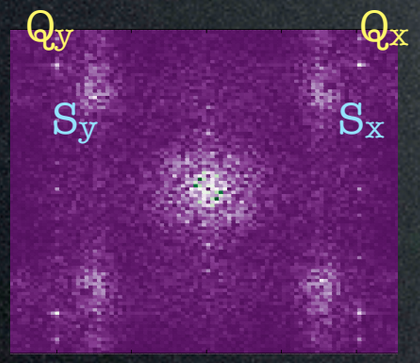


Nematic domains

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



- Low pass filter (long distance physics)

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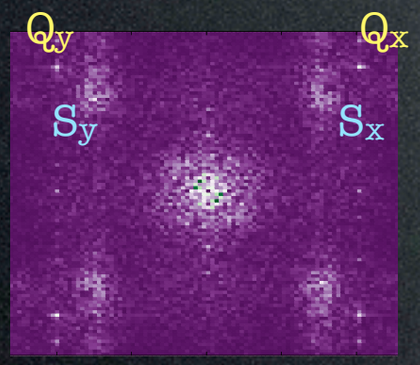

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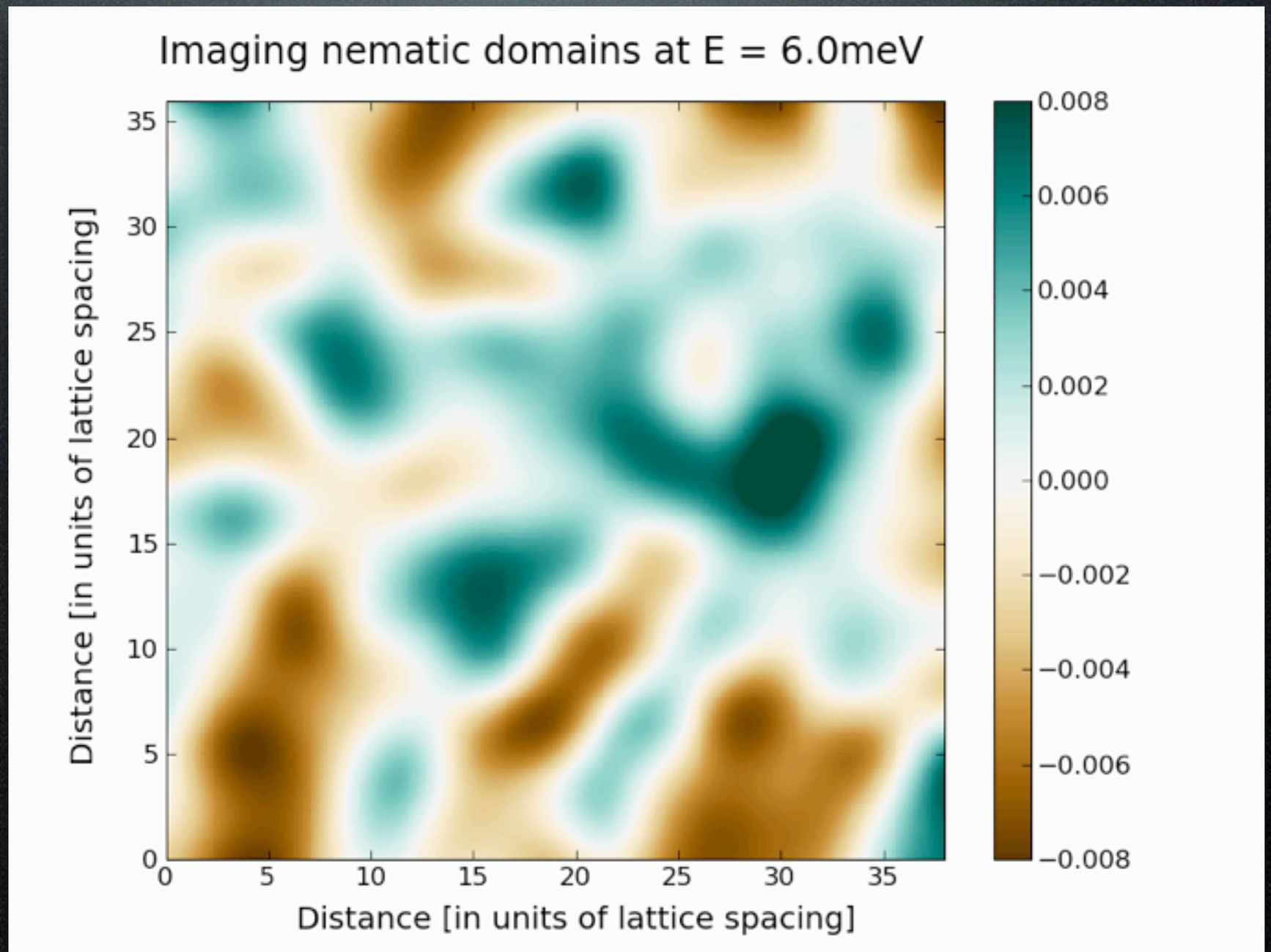
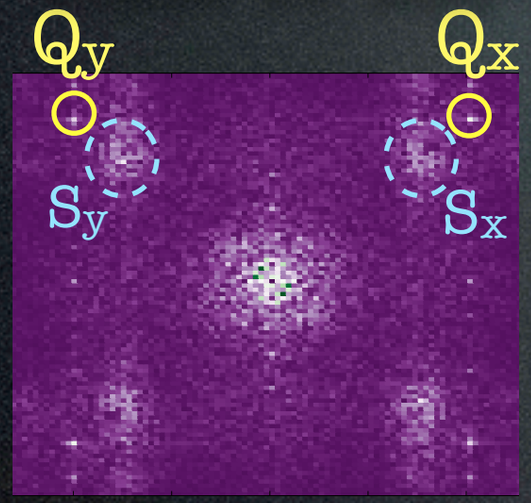


Listen to channel S

Oriented stripe domains

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



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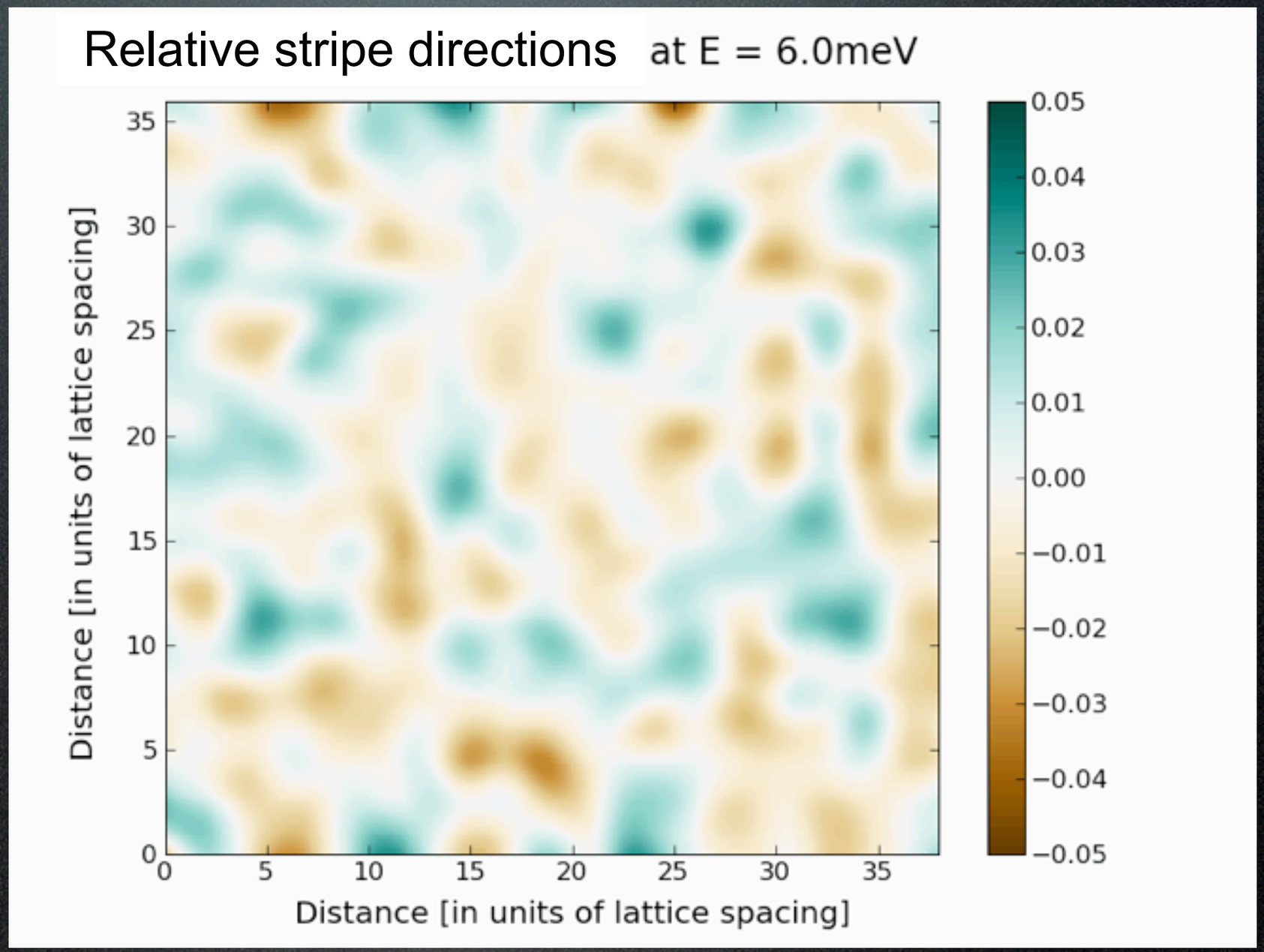

Hypothesis: longer ranged orientational ordering than stripe ordering ?

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

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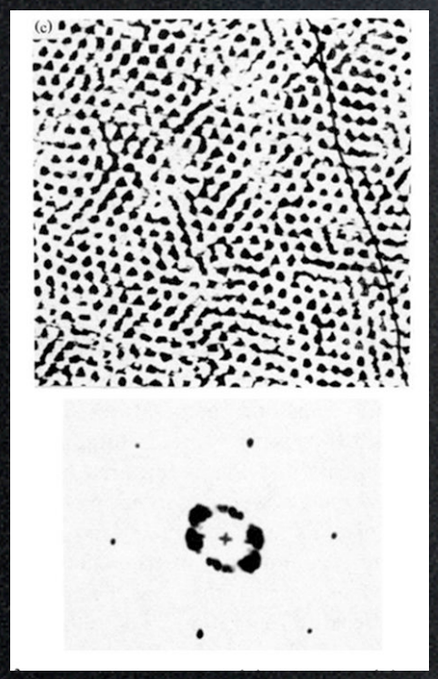

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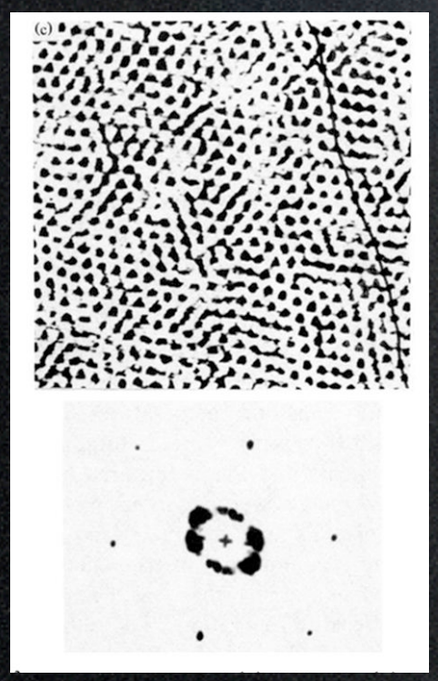

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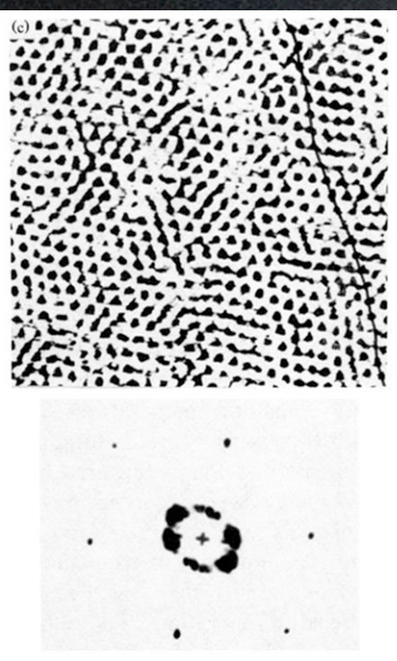

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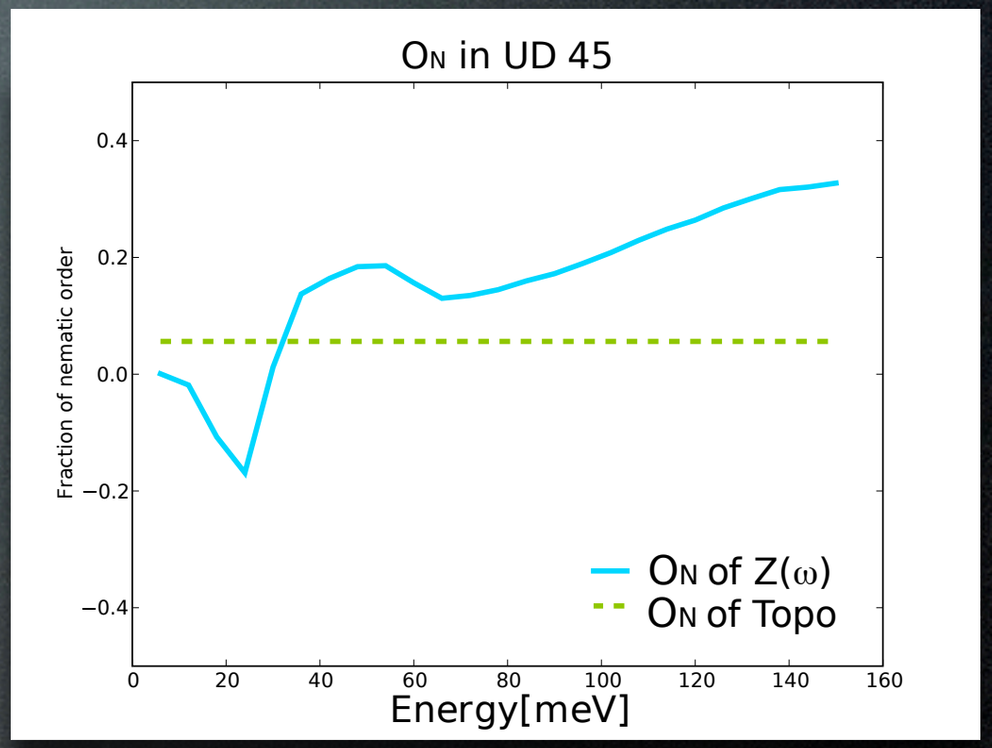
Electronic Nematic in Cuprates?

Looking ahead

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



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