ELECTRONIC LIQUID CRYSTAL CORRELATIONS IN THE PSEUDOGAP PHASE OF HIGH T_C SUPERCONDUCTORS

Michael J. Lawler

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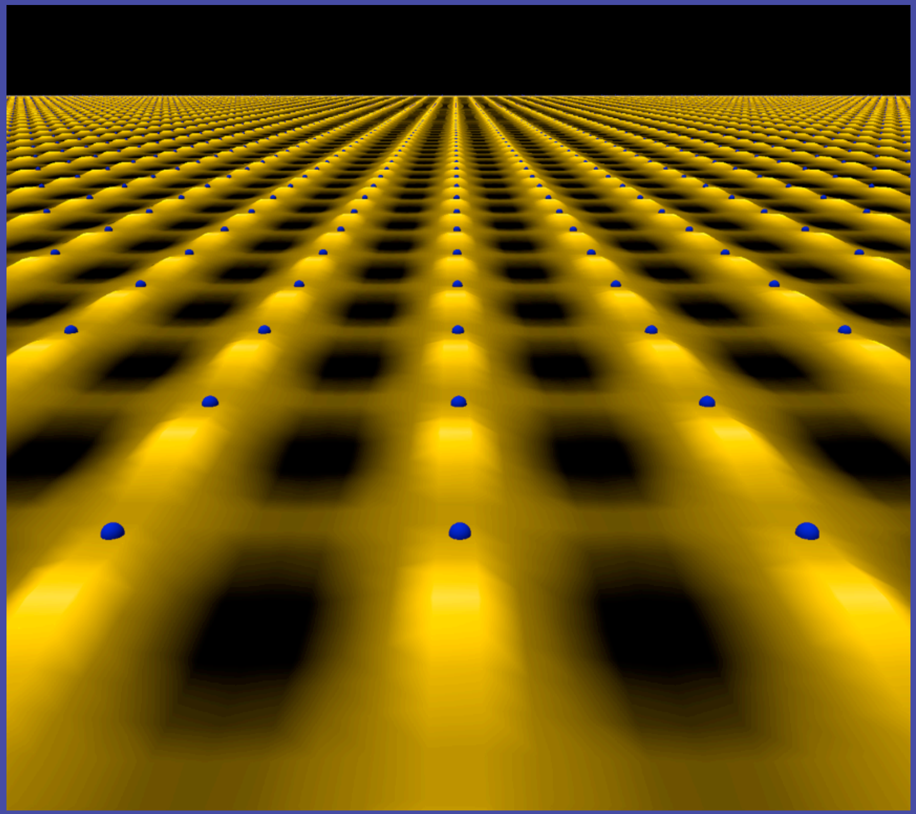

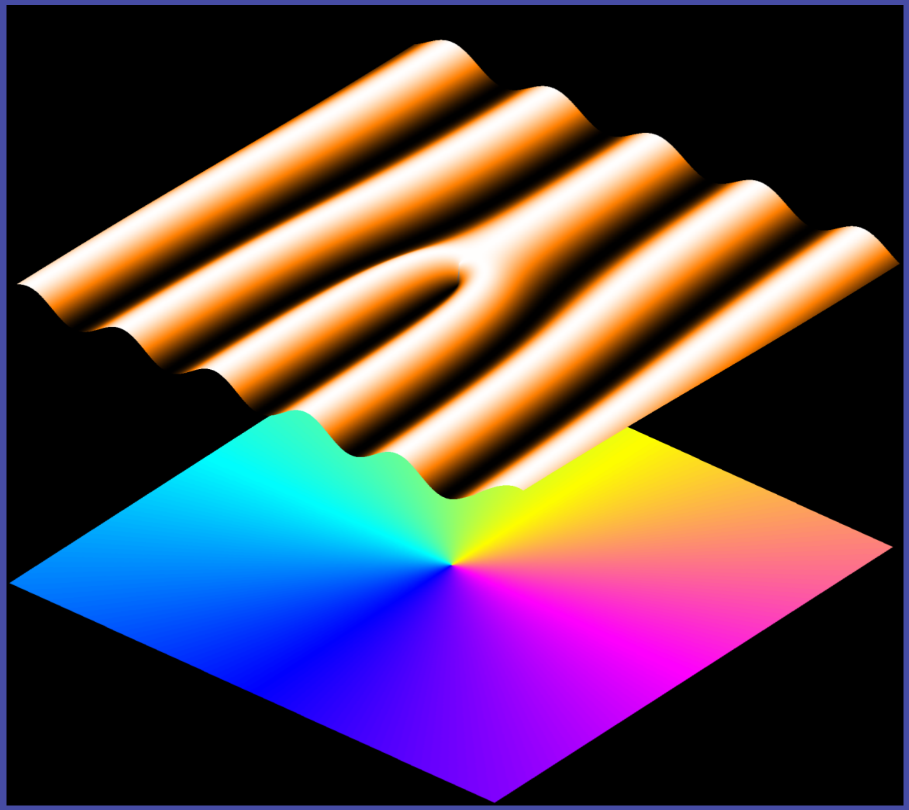

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In collaboration with ...

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Eun-Ah Kim / Cornell

CONTENTS

- Problem: what is the identity of the pseudogap phase?

- Nematic liquid crystal order in the pseudogap phase

- Coupling beween nematic and smectic electronic liquid crystal orders

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News

Superconductors come of age

A South Korean company has placed by far the biggest commercial order for superconducting wires.

Joseph Milton

Almost 100 years after Dutch physicist Heike Kamerlingh Onnes found that mercury has an electrical resistance of zero when cooled in liquid helium, superconductors are finally being rolled out for use in national electricity grids.

Superconducting wires could soon help to light up Seoul.

iStockphoto.com / Min-Gyu Seong

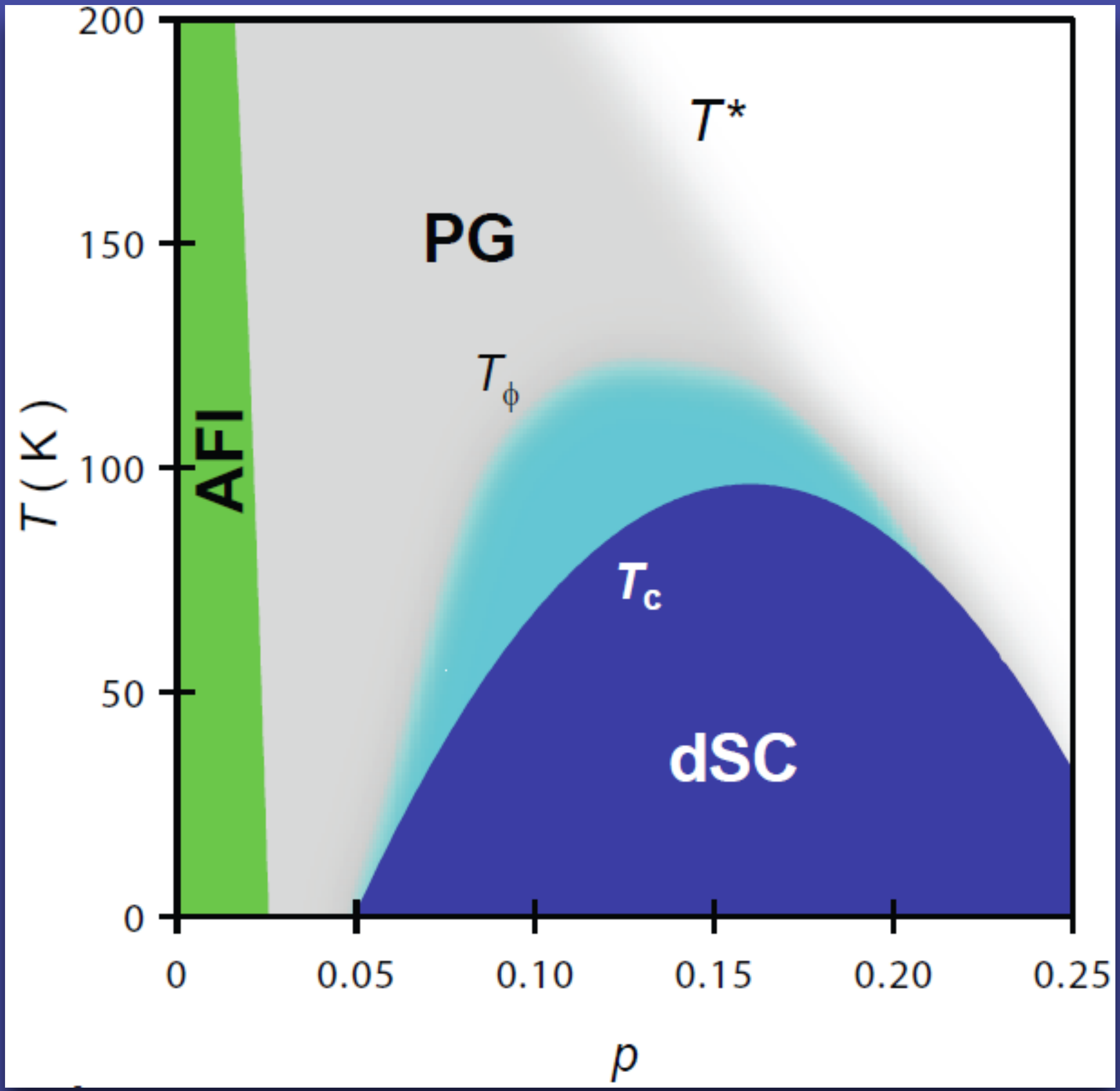
Superconductive wiring carries about ten times as much power as the same volume of conventional copper wiring. Although some of that power is lost and liquid

20 km of YBCO wire!

Part of South Korea's "Green growth" plan

WHAT IS THE IDENTITY OF THE PSEUDOGAP PHASE?

LOCATION OF THE PG PHASE IN THE CUPRATE PHASE DIAGRAM



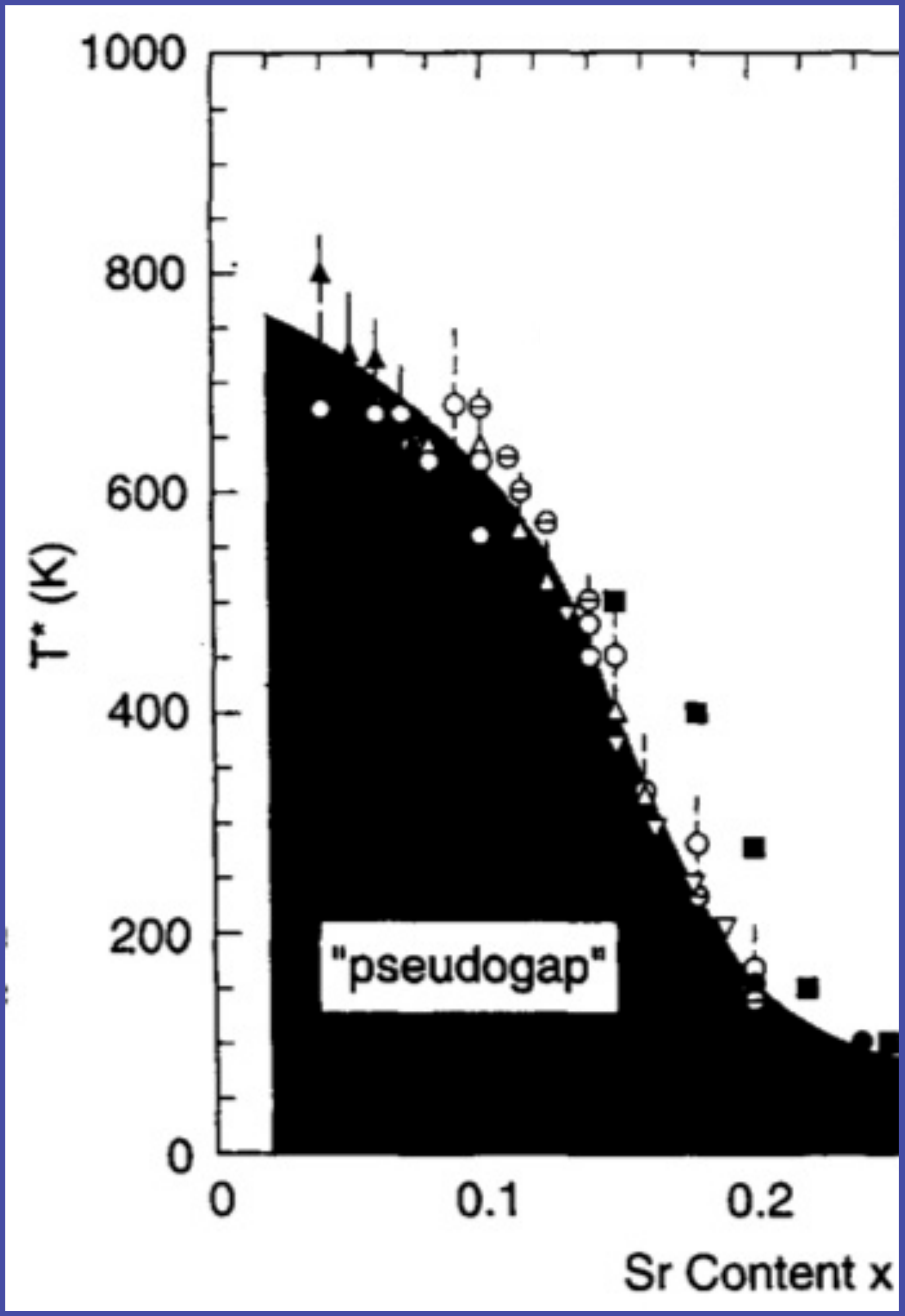
AFI: Antiferromagnetic insulator

PG: Pseudogap phase

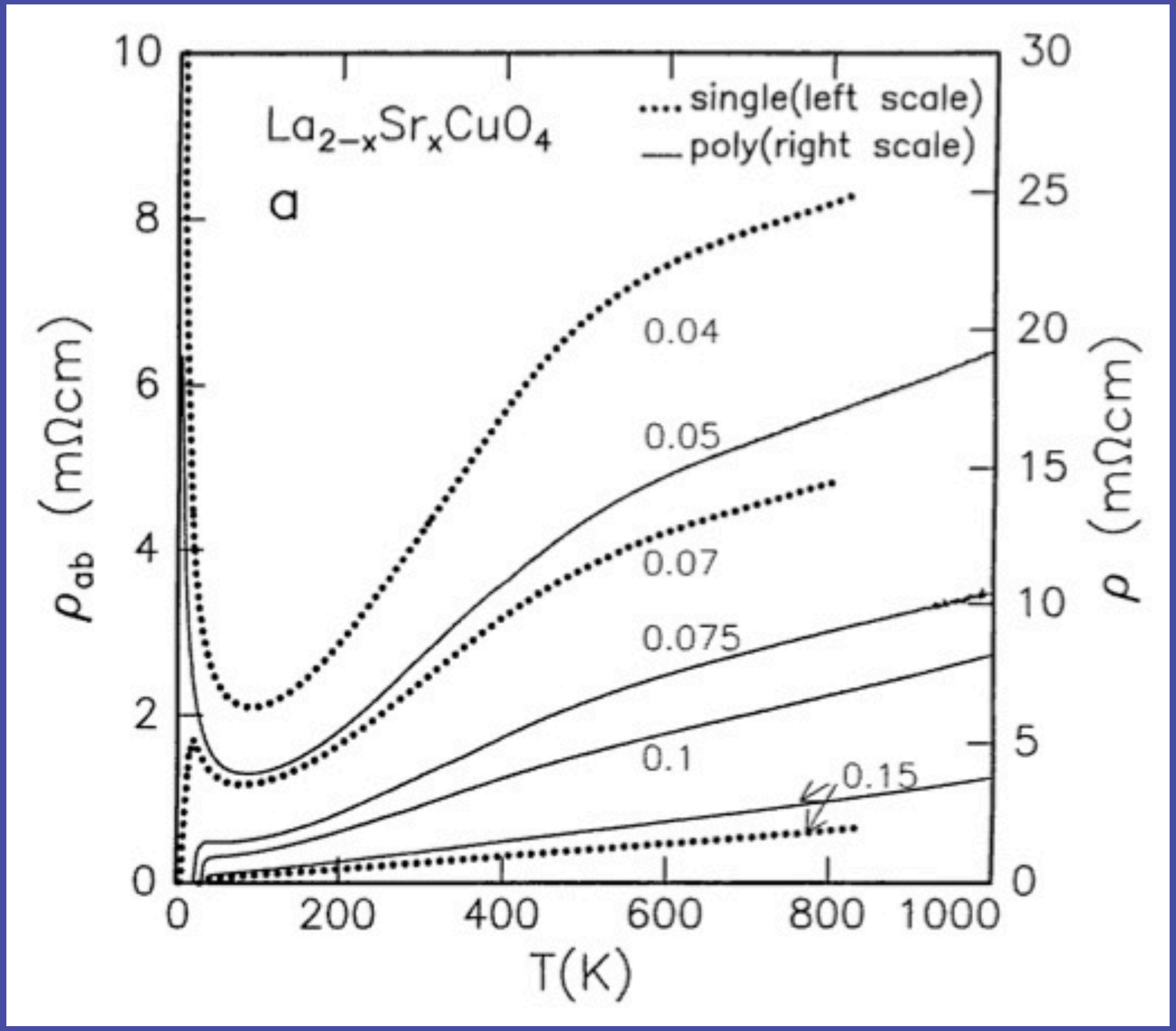
dSC: d-wave superconductor

Electronic phase diagram of cuprate superconductors

RESISTIVITY IN PSEUDOGAP PHASE



Batlogg et. al., Physica C 235-240, 130 (1994)

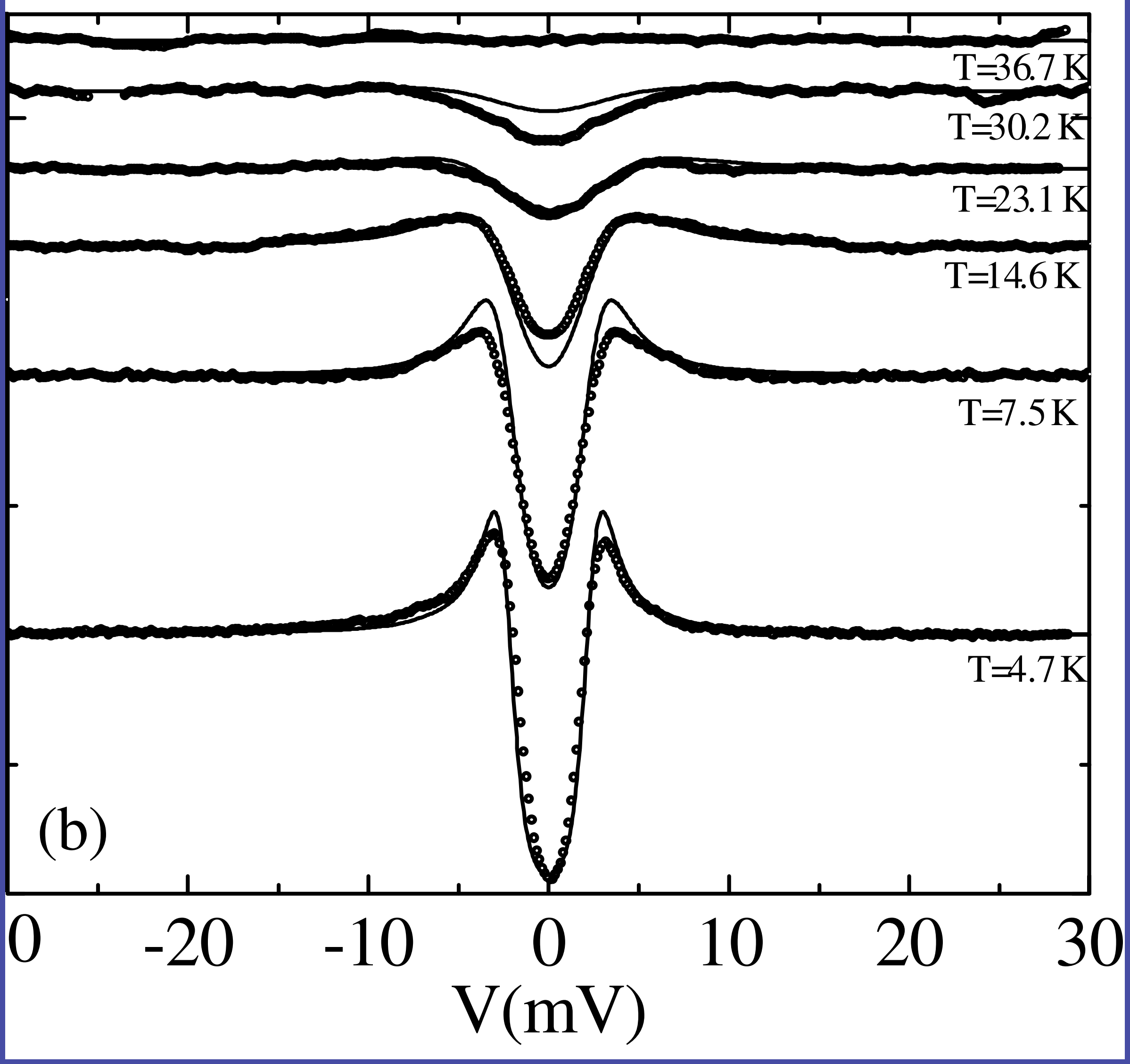


Takagi et. al., Phys. Rev. Lett. **69**, 2975 (1992)

Resistance of copper: 1.68 μΩcm

WHAT GAP IS THE PSEUDOGAP?

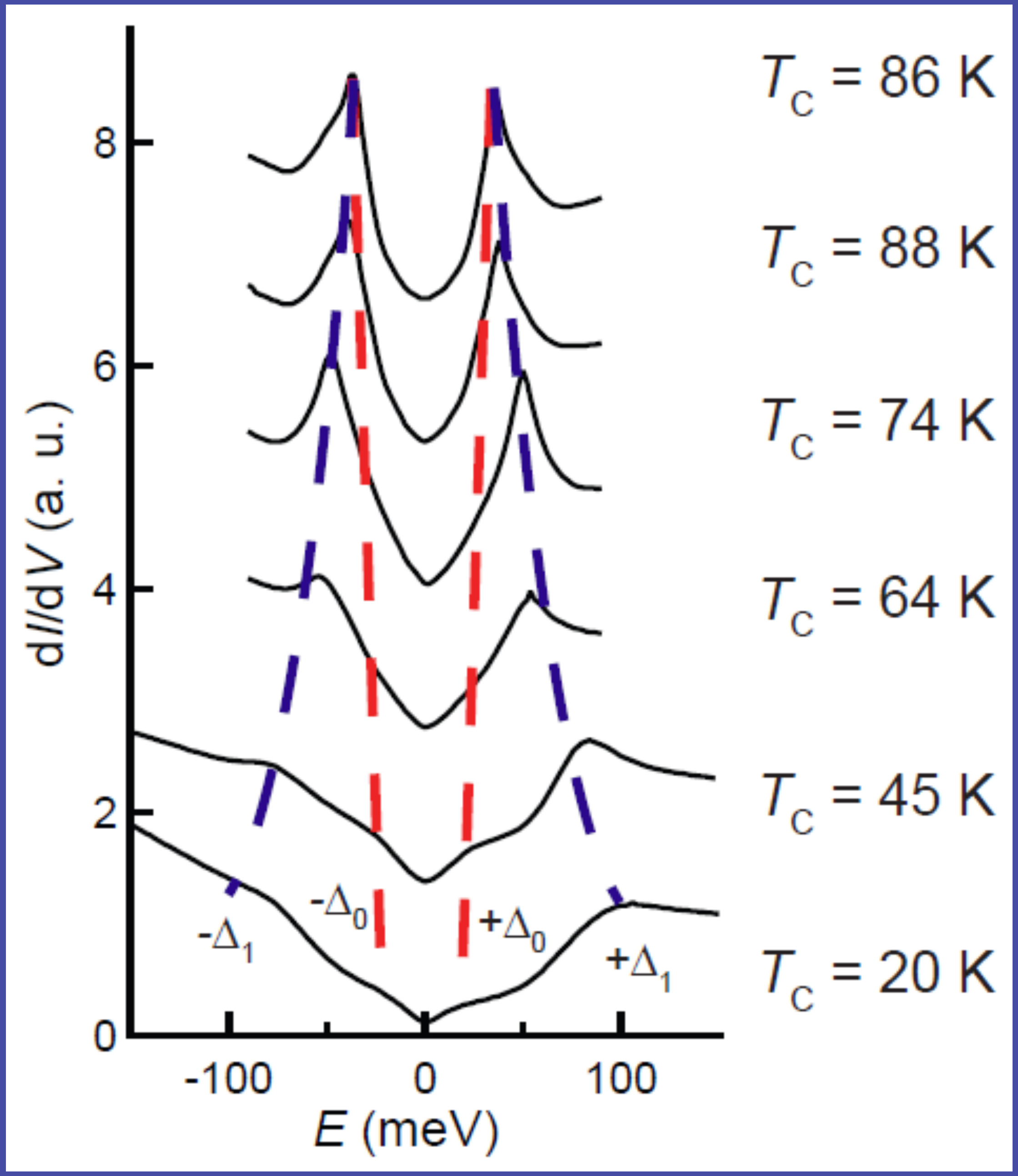
Consider the density of states of MgB_2:

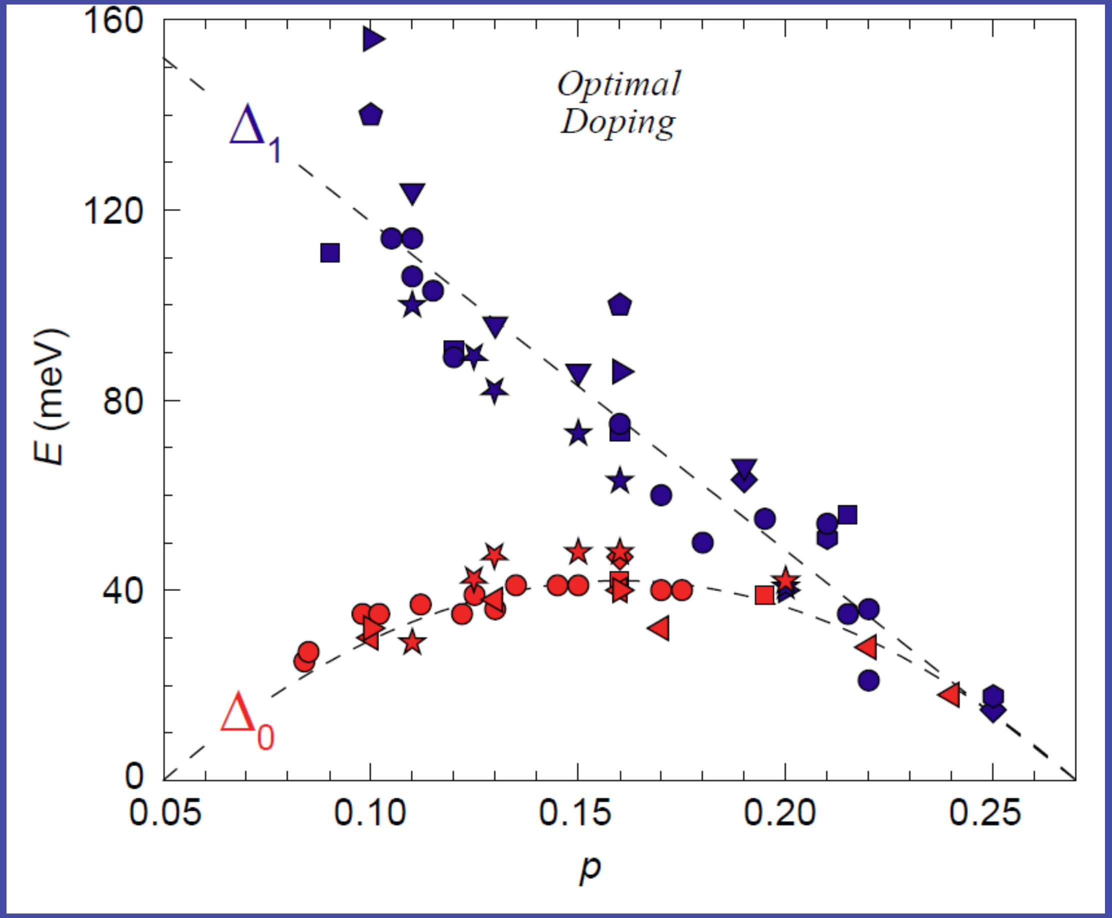


DOS of MgB_2
Tc = 39 K

Iavarone et. al., PRL 2002

WHAT GAP IS THE PSEUDOGAP?



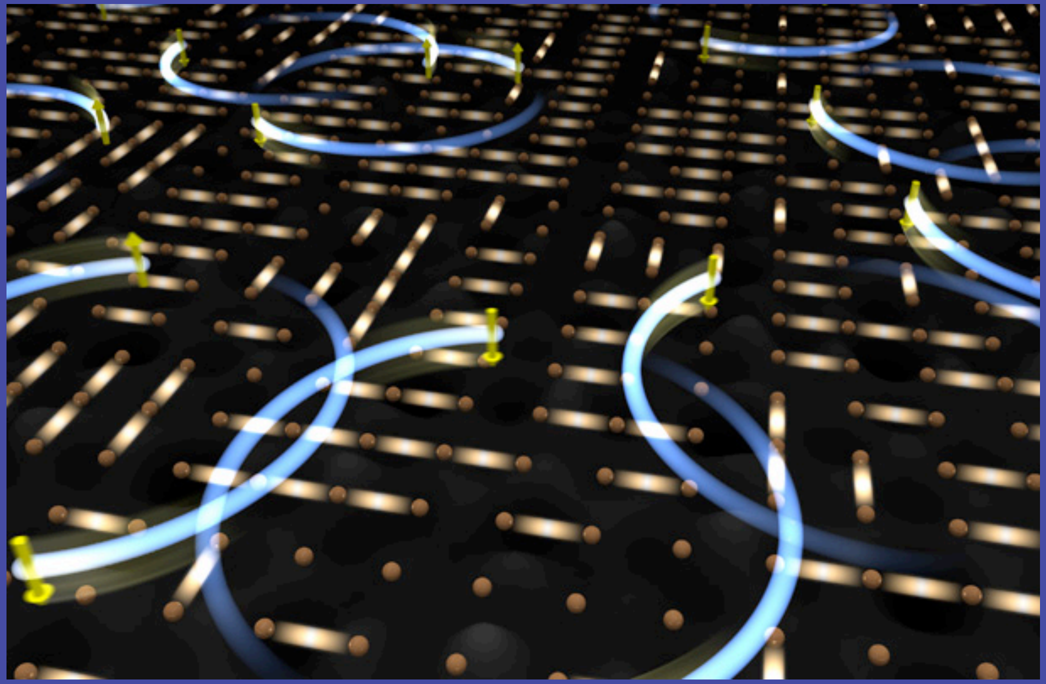


Pseudogap states

$$E \sim \Delta_1$$

S. Hüfner et al., Rep. Prog. Phys. **71**, 062501 (2008)

LIKE AN INCOHERENT SUPERCONDUCTOR

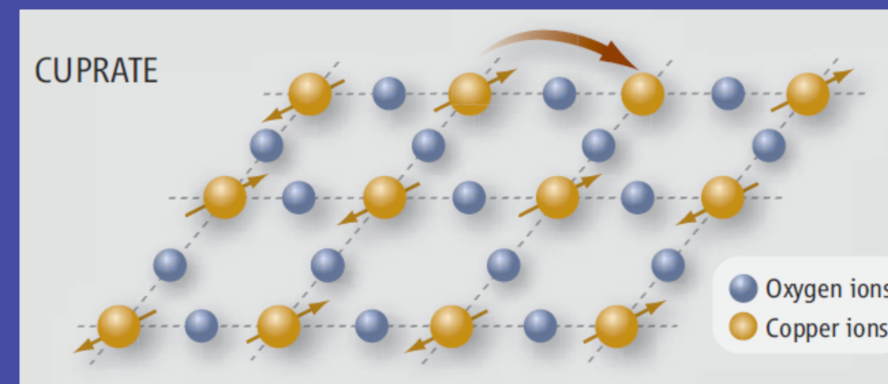


(c) Kohsaka

- It has a lower resistivity and a gap in the electronic spectrum
- This hints at how a bad metal becomes the worlds greatest superconductor.
- But the full identity of the PG phase is still unknown

A MIDDLE DOWN/UP STRATEGY

Top-down:



Middle-down/up: Symmetry Principles

Bottom-up: Neutron Scattering ↔ STM ↔ ARPES

This strategy needs lots of information

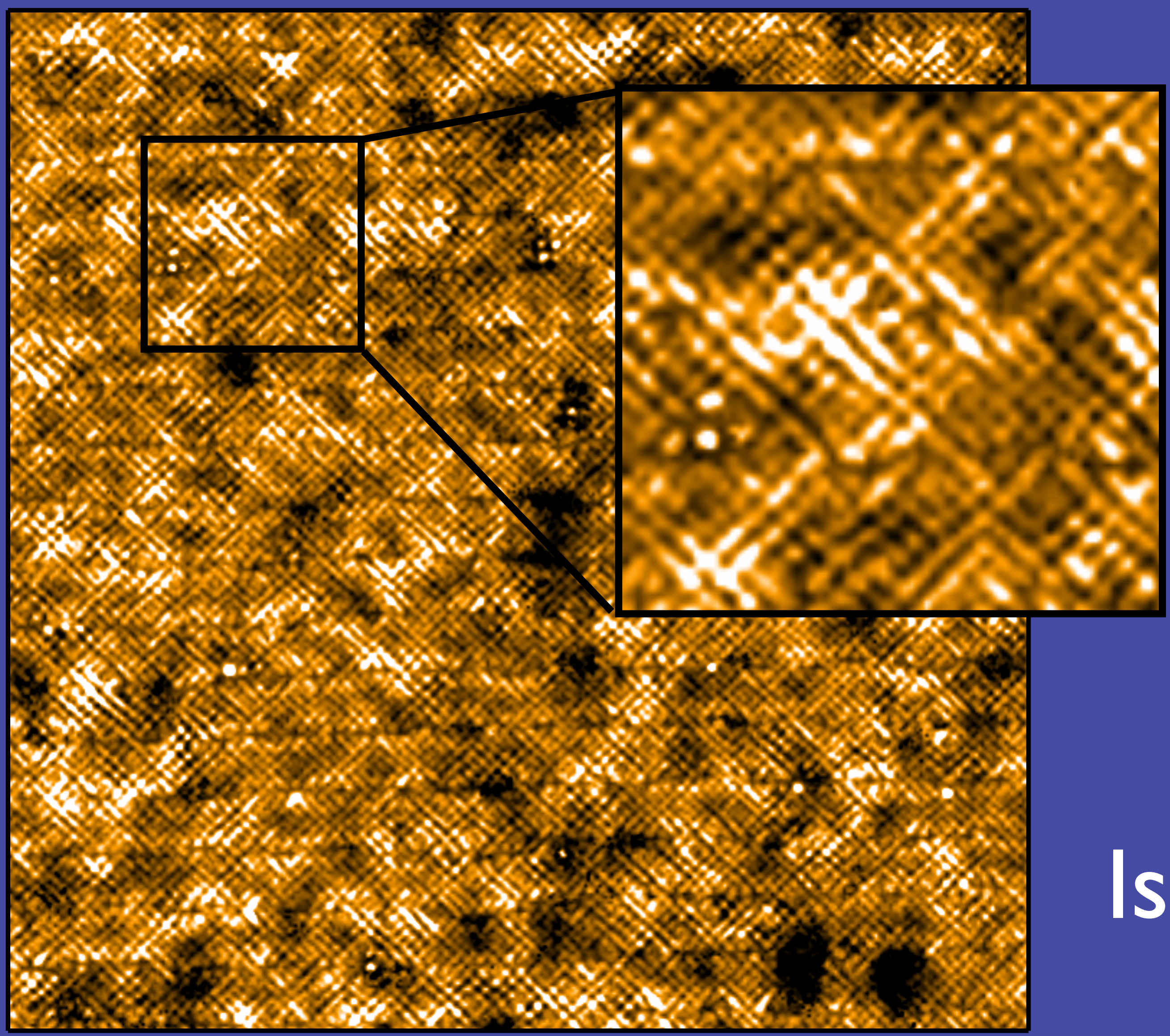
NEMATIC ORDER IN BSCCO

Lawler, Fujita et. al., Nature 2010

PSEUDOGAP PATTERNS

Kohsaka et. al. Science 2007

LDOS($x,y,E=\Delta_1$)



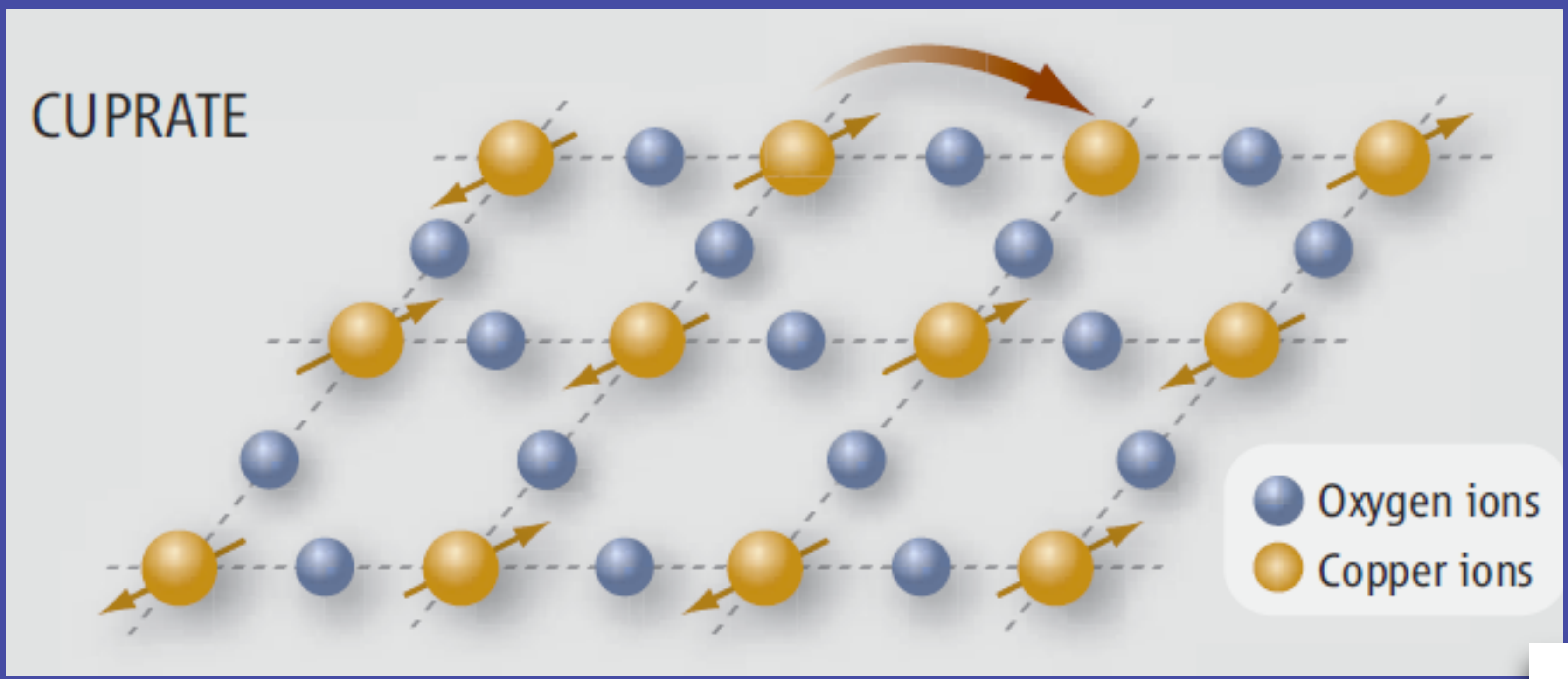
Pseudogap state is very inhomogeneous

Pattern breaks many lattice symmetries

Is the PG phase is a kind of electronic liquid crystal?

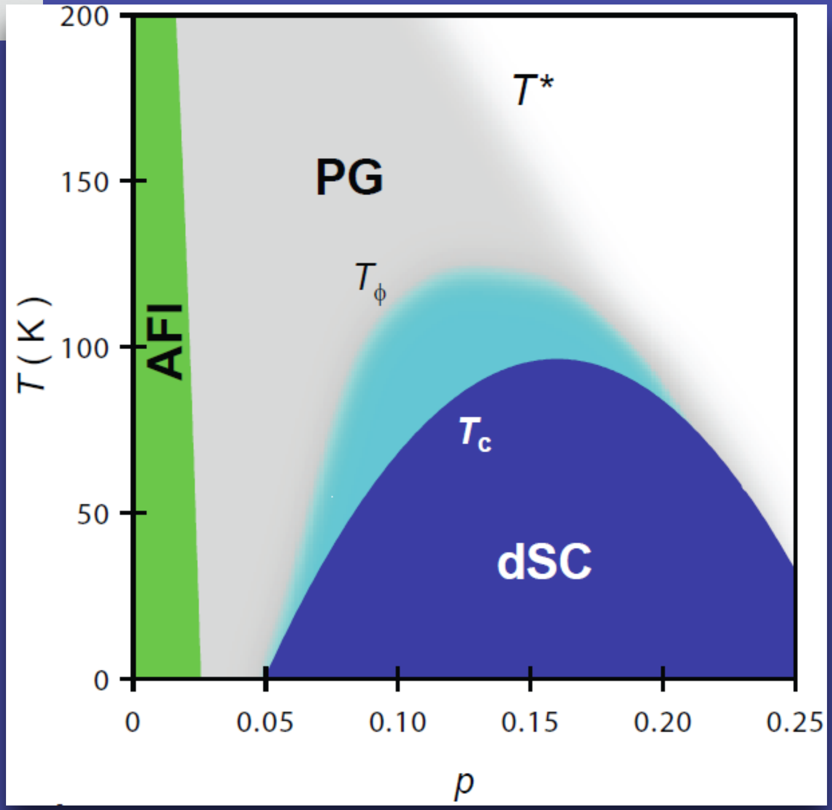
Lawler, Fujita et. al., Nature 2010

DESIRE TO CRYSTALIZE?



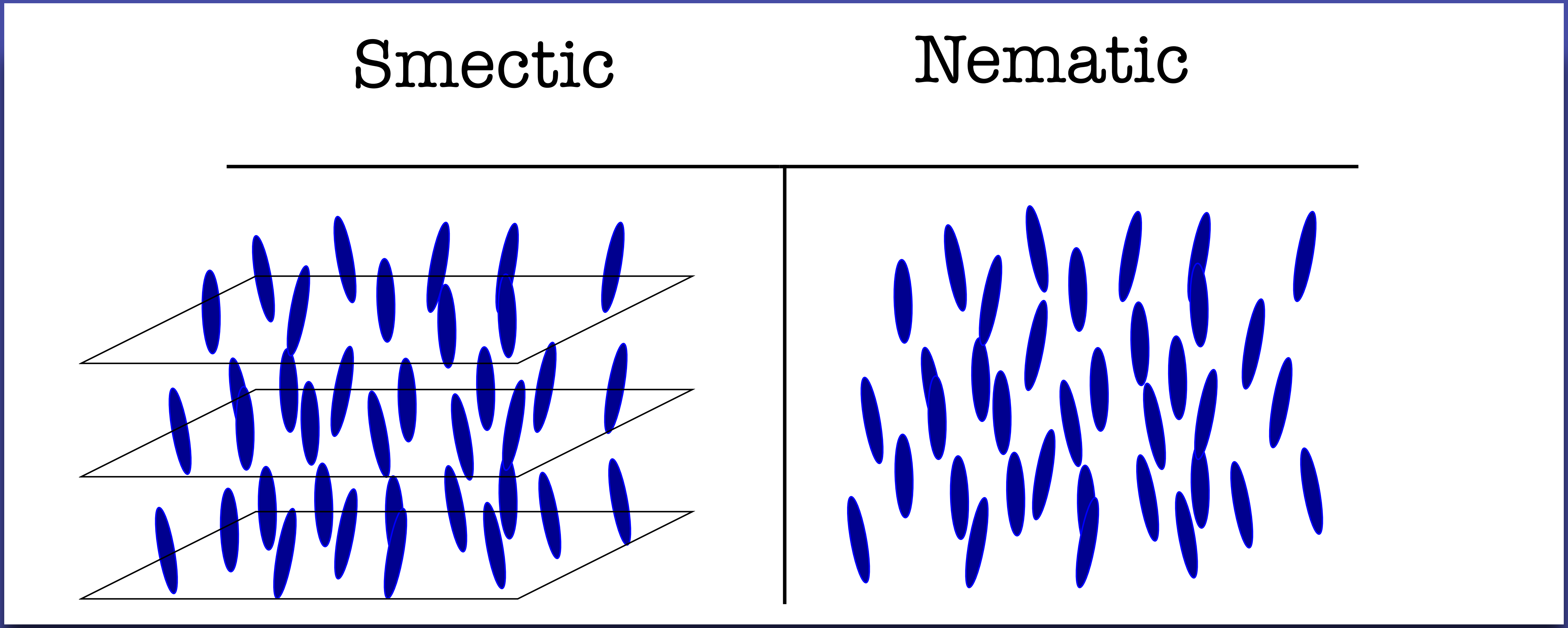
Can we consider a Mott insulator a kind of electron crystal?

Is the PG phase inbetween an electron liquid and an electron crystal?



LIQUID CRYSTAL PHASES OF ROD-LIKE POLYMERS

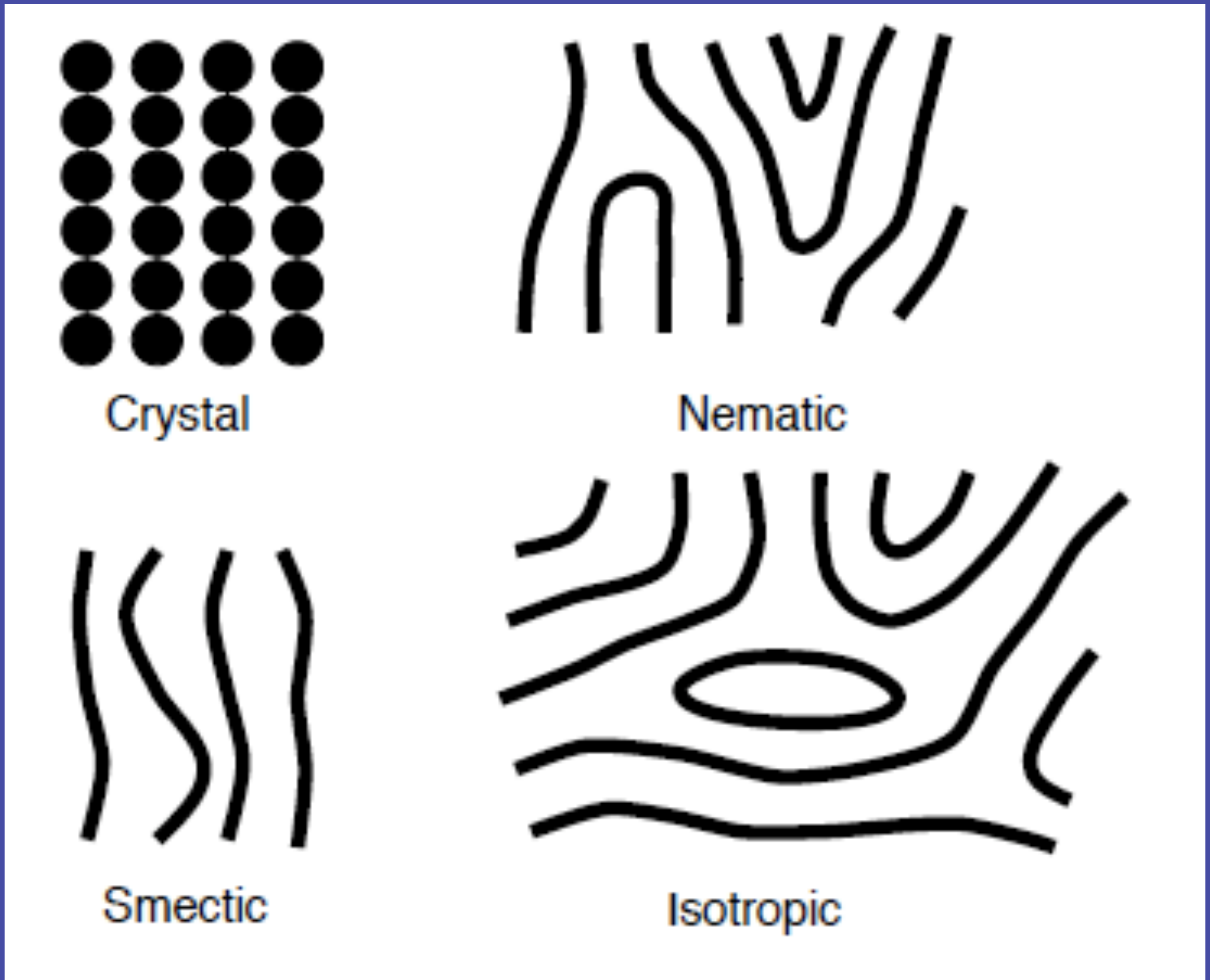
En-route to a crystal at low temperatures ...



Low T ← High T

LIQUID CRYSTAL PHASES OF ELECTRONS

Consider "rivers of charge"

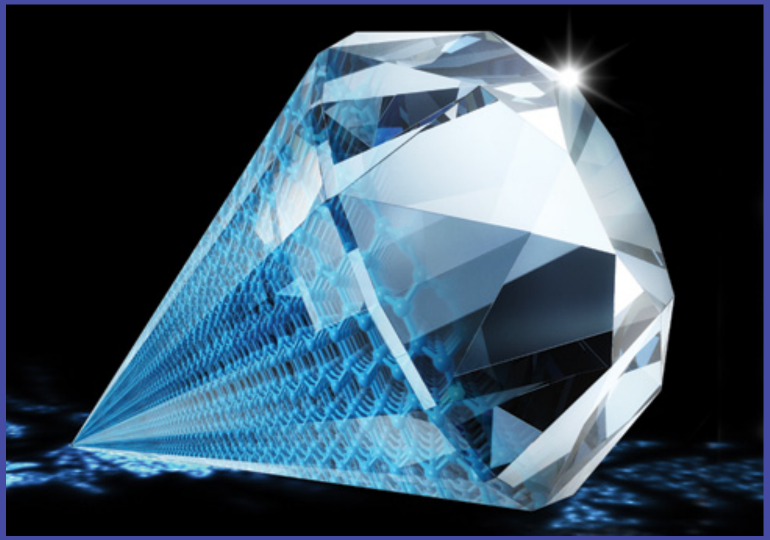


Kivelson, Fradkin, Emery, Nature (1998)

These phases are likely not good metals

CAPTURE SYMMETRY BREAKING

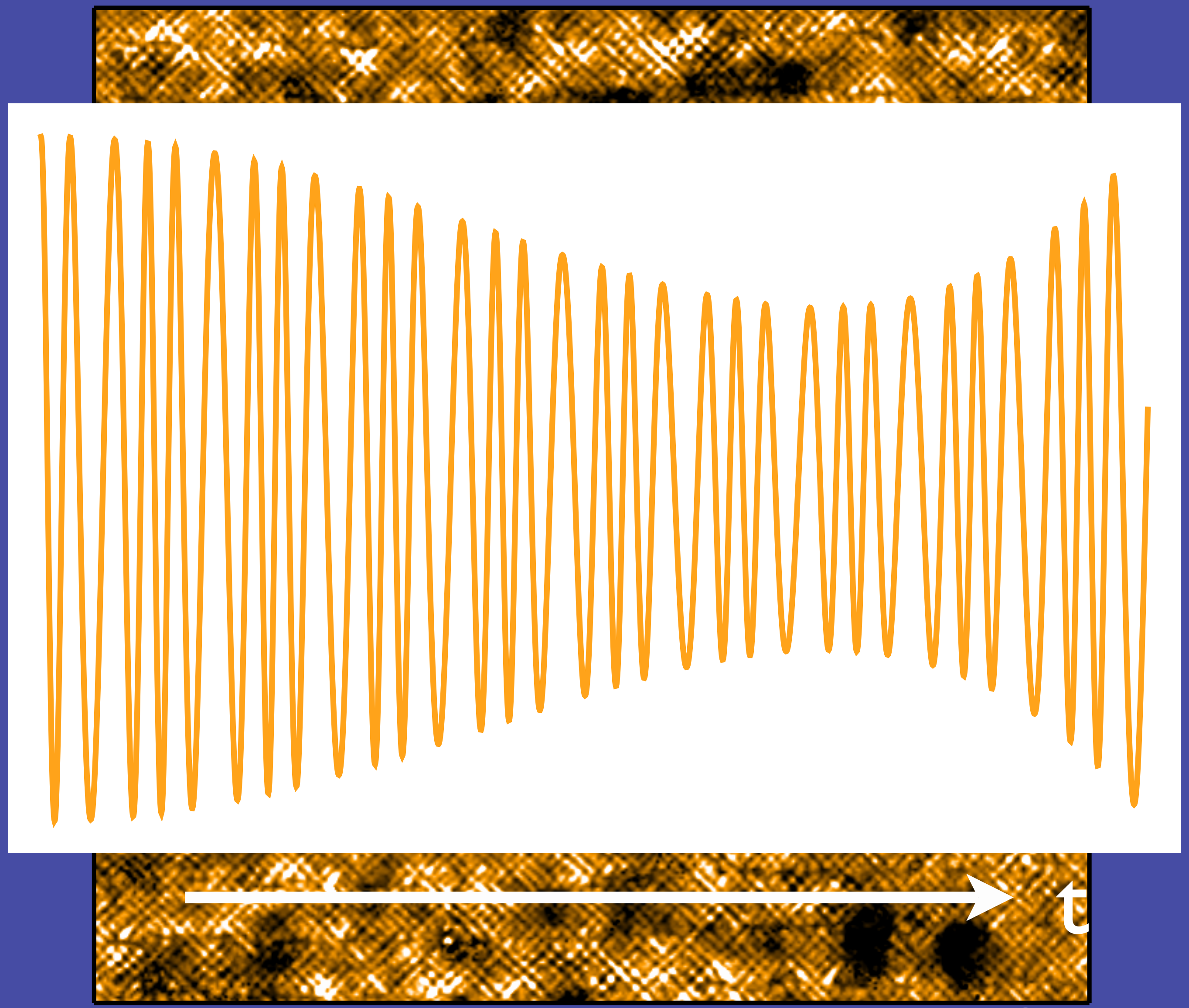
Symmetry breaking in Diamonds is long ranged



From this perspective, farm land does not look very ordered.

CHARACTERISTICS OF PG PATTERNS

- Periodicity with modulated phase and amplitude



$$A(t)\cos\left(\omega_c t + \phi(t)\right)$$

ω_c: carrier frequency

$A(t)$: amplitude modulation

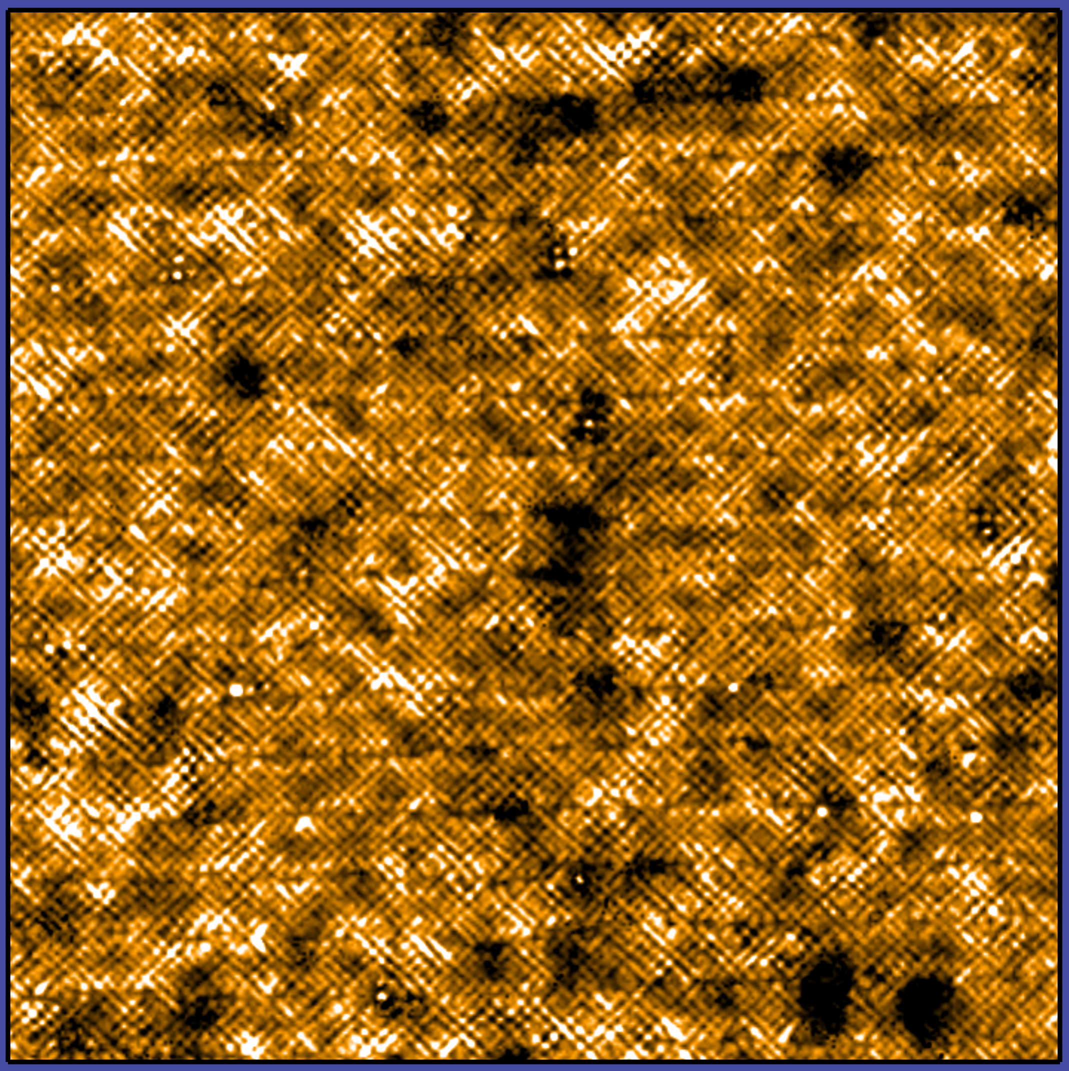
$\phi(t)$: phase or frequency modulation

This is precisely the form of a radio signal!

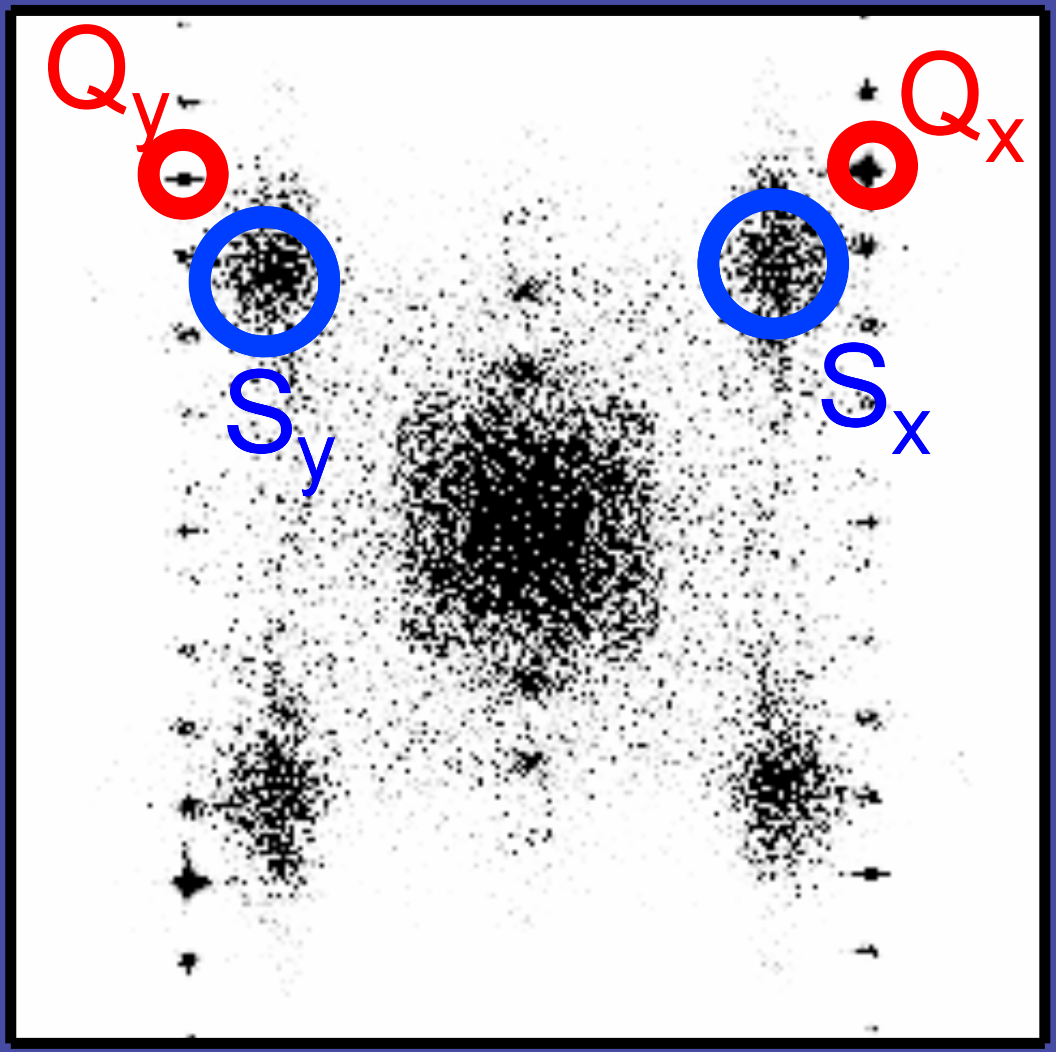
Lawler, Fujita et. al., Nature 2010

"CARRIER FREQUENCIES" OF PG PATTERNS

$M(\vec{r})$



$\tilde{M}(\vec{q})$



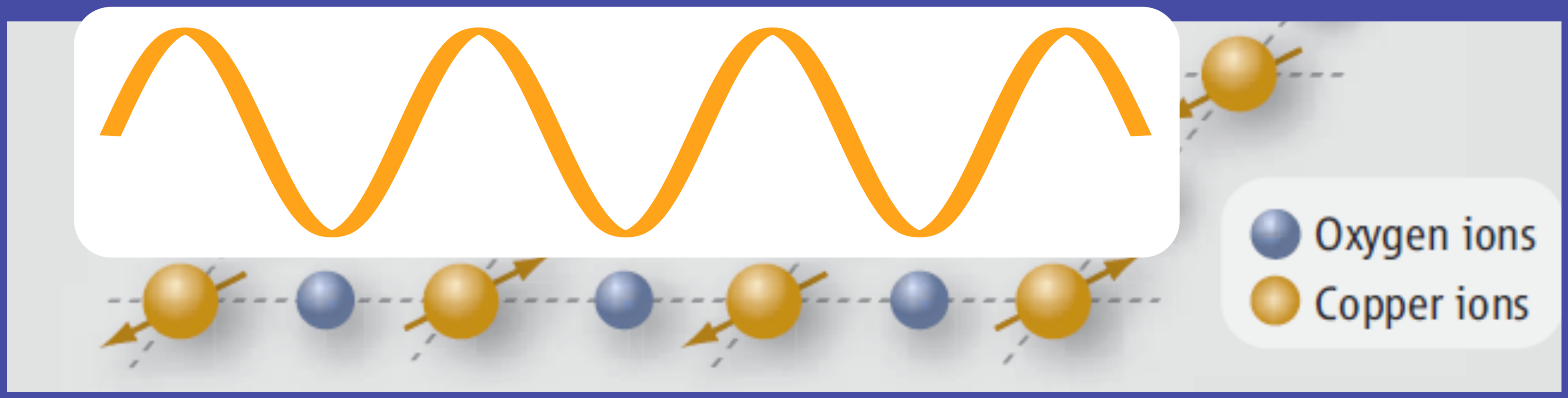
$$M(\vec{r}) = \mathrm{Re}\left\{ \psi_{\vec{Q}_x}(\vec{r})e^{i\vec{Q}_x\cdot\vec{r}} + \psi_{\vec{Q}_y}(\vec{r})e^{i\vec{Q}_y\cdot\vec{r}} + \ldots \right\}$$

Lawler, Fujita et. al., Nature 2010

NEMATIC ORDER

Insight from spatial averages

$$\int d^2r\, \psi_{Q_x}(\vec{r}) = \tilde{M}(\vec{Q}_x) = \bar{M}_{Cu} - \bar{M}_{Ox} + \bar{M}_{Oy}$$



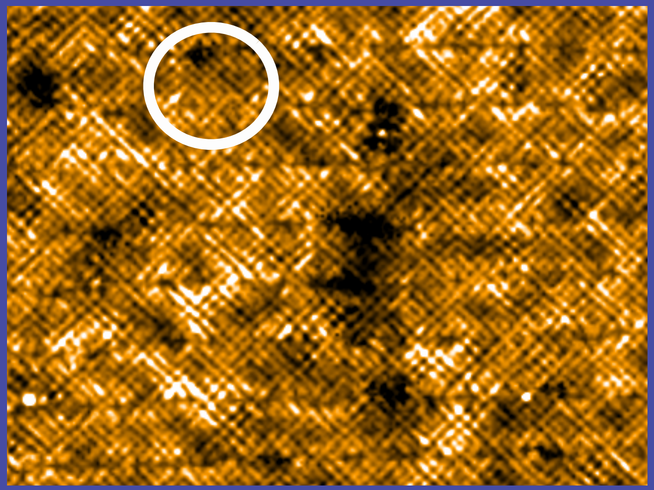
Nematic Order parameter: $\bar{\mathcal{O}}_n = \bar{M}_{O_x} - \bar{M}_{O_y}$

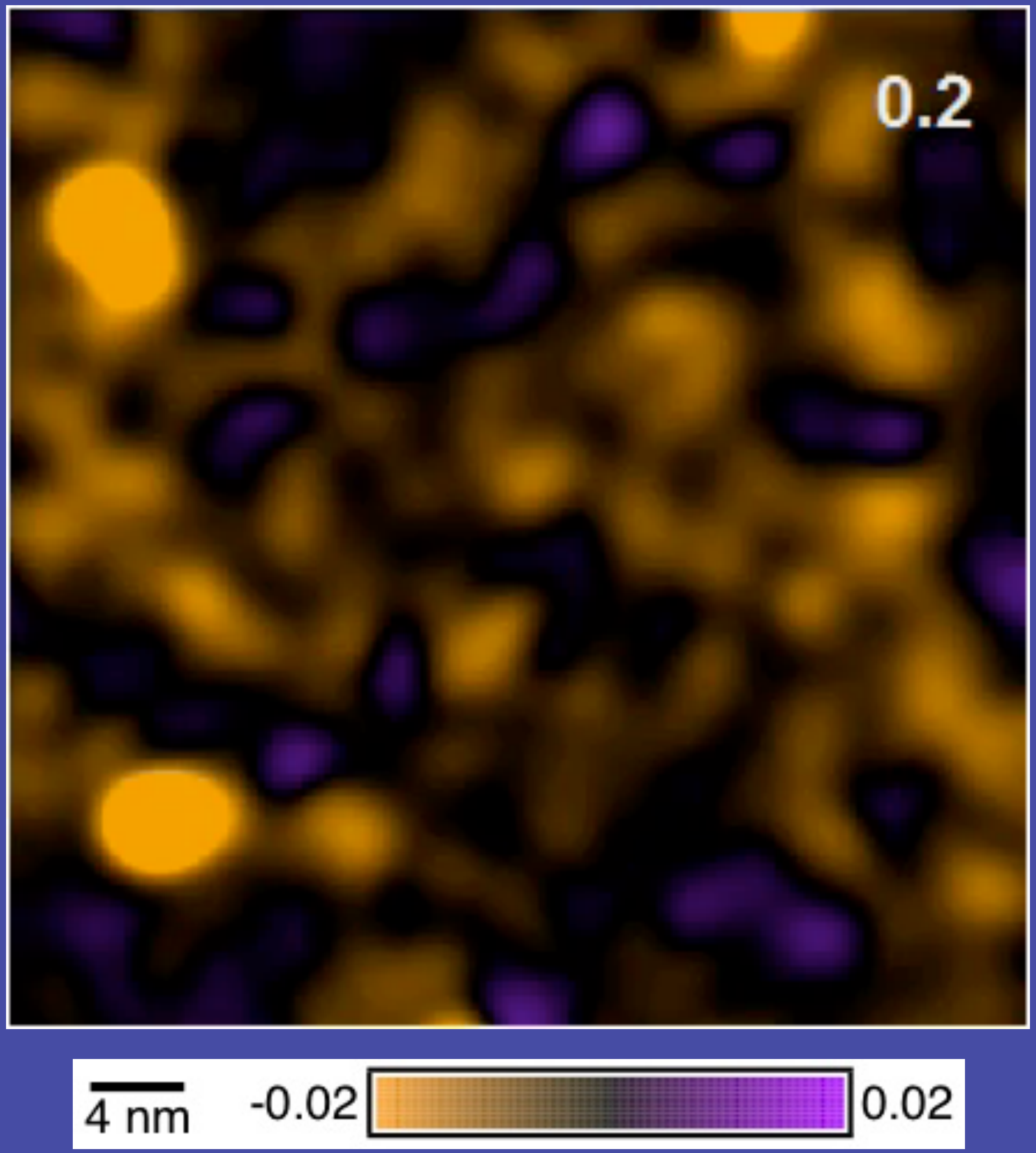
Local Nematic Order: $\mathcal{O}_n(\vec{r}) = \mathrm{Re}\left[\psi_{Q_y}(\vec{r}) - \psi_{Q_x}(\vec{r})\right]$

From Bragg peaks, we obtain a measure of local anisotropy

ENERGY DEPENDENCE

$\mathcal{O}_n(\vec{r})$



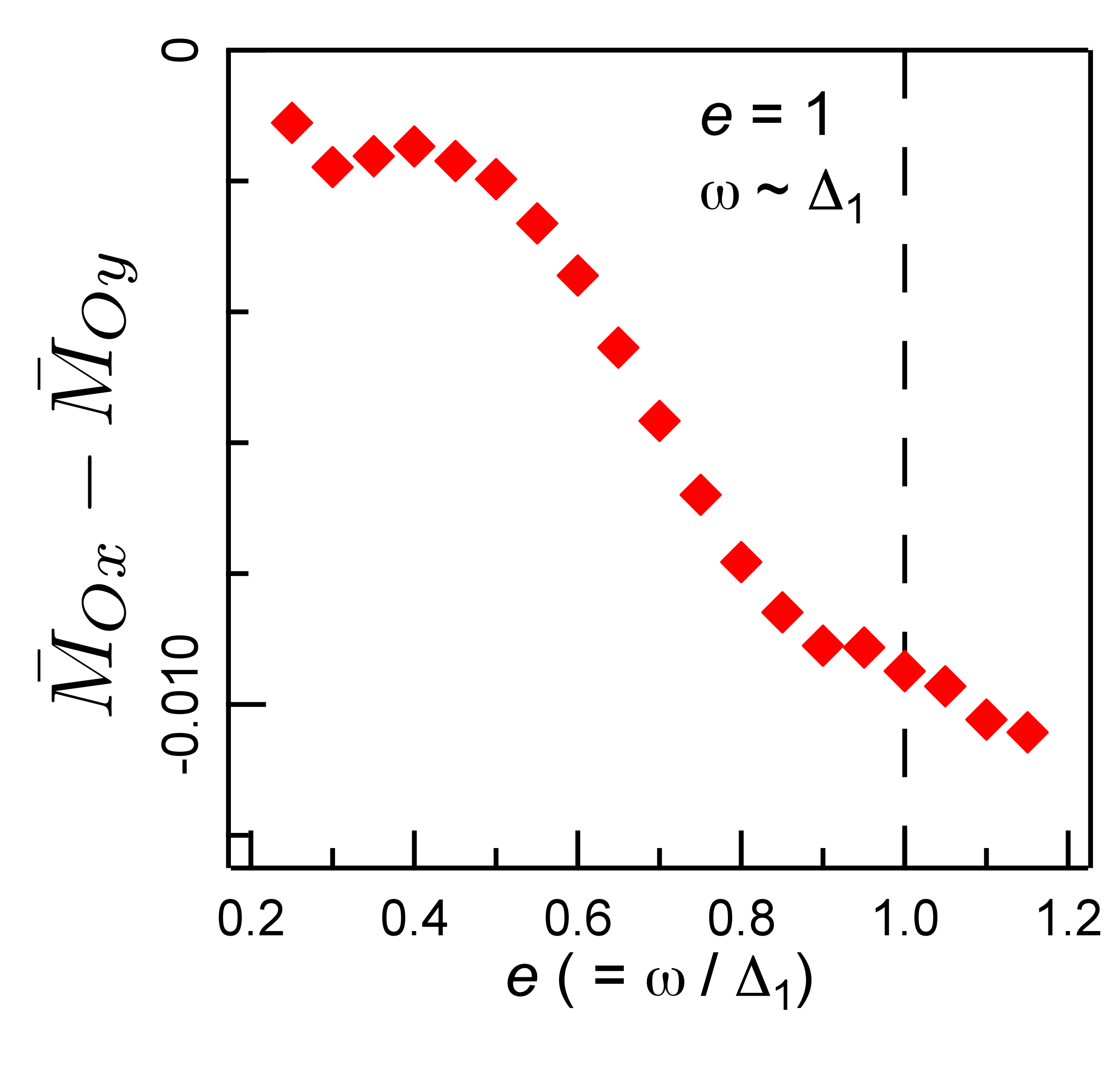


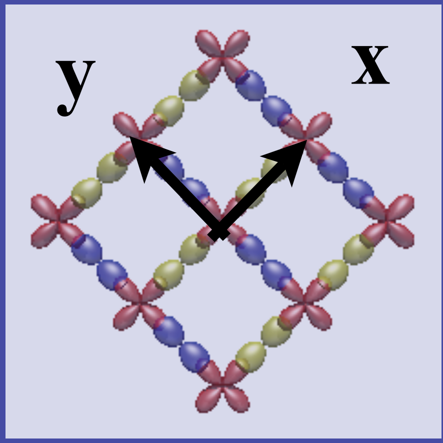
Long range order at the pseudogap energy scale

Lawler, Fujita et al, Nature 2010

NET OXYGEN IMBALANCE

Energy dependence of average



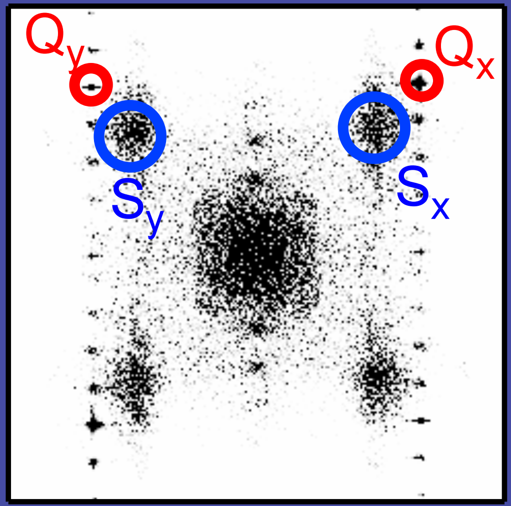


Lawler, Fujita et. al., Nature 2010

COUPLING BETWEEN NEMATIC AND SMECTIC ORDERS

Mesaros, Fujita et. al., submitted to Science

ORDER PARAMETER FIELDS



- Local **Nematic Order** (anisotropy):

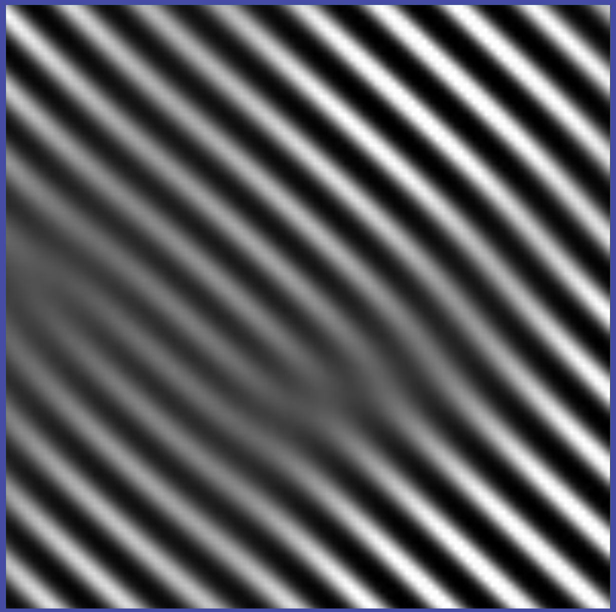
$$\mathcal{O}_n(\vec{r}) = \mathrm{Re}\big(\psi_{Q_y}(\vec{r}) - \psi_{Q_x}(\vec{r})\big)$$

- Local **Inversion** symmetry?

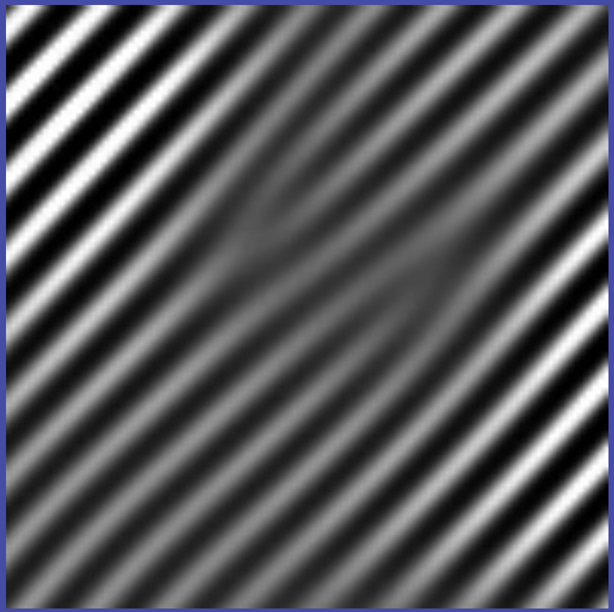
$$\vec{d}(\vec{r}) = (\mathrm{Im}\,\psi_{Qx}(\vec{r}), \mathrm{Im}\,\psi_{Qy}(\vec{r}))$$

- Local **Smectic Order** (S_x, S_y Stripes):

$\psi_{S_x}(\vec{r})$



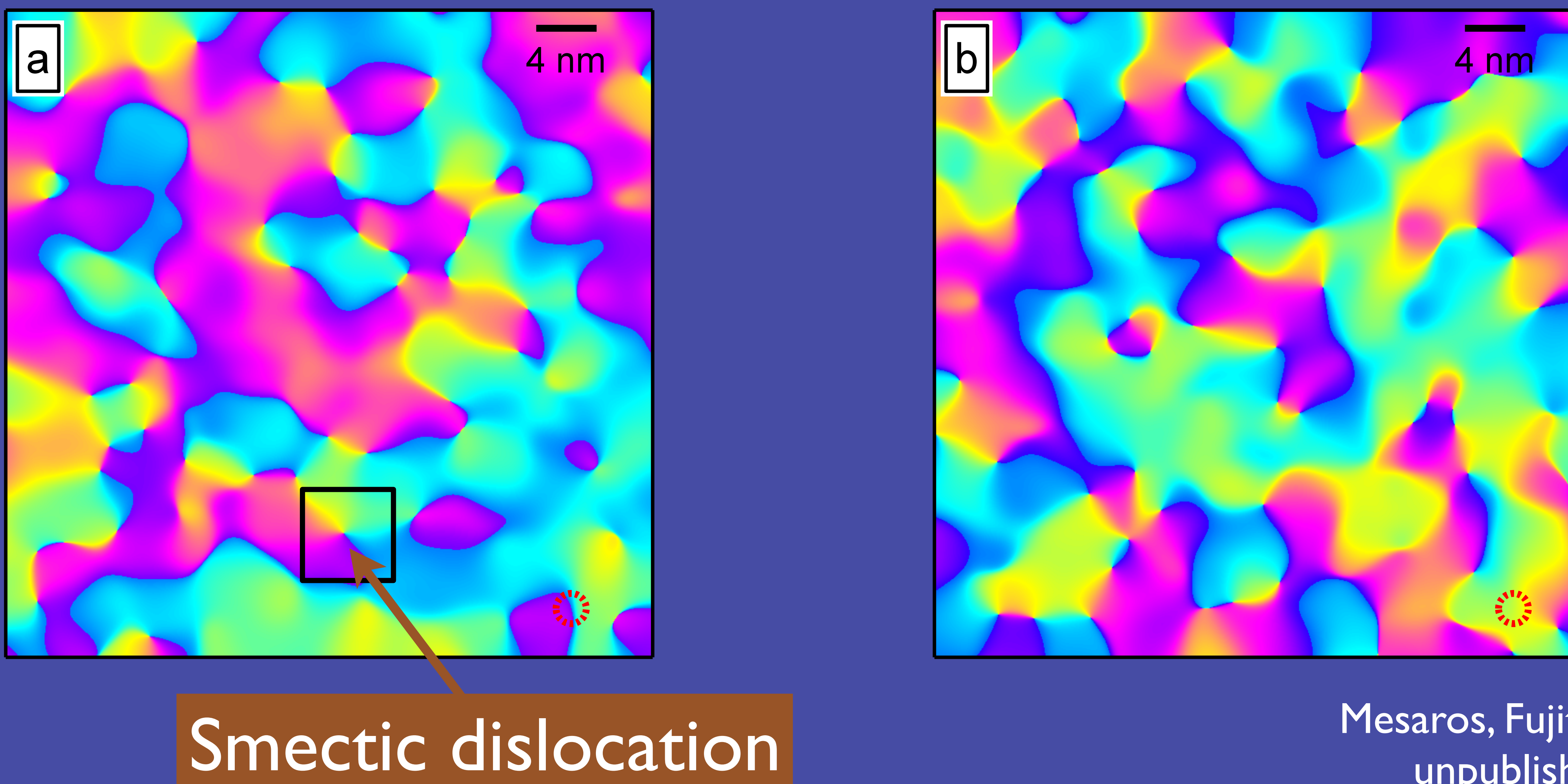
$\psi_{S_y}(\vec{r})$



Mesaros, Fujita et. al
unpublished.

PHASE OF SMECTIC WAVES

$$\varphi_{Sx} = \arg(\psi_{Sx}) \qquad \varphi_{Sy} = \arg(\psi_{Sy})$$



Mesaros, Fujita et. al., unpublished.

These waves do not have long range order

SYMMETRY PRINCIPLES

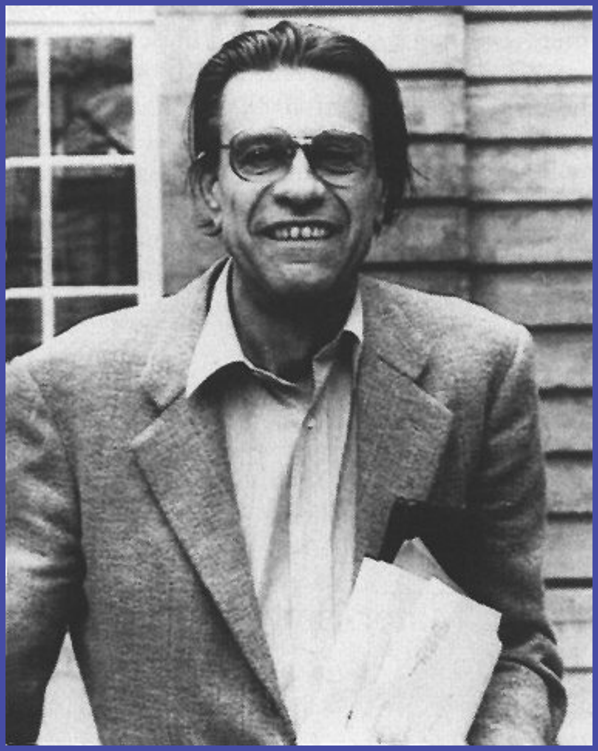
Landau theory of phase transitions suggests

$$F = \int d^2r \left[\left| (\nabla - i\vec{\alpha}\delta\mathcal{O}_n)\psi_{Sx} \right|^2 + r|\psi_{Sx}|^2 + u|\psi_{Sx}|^4 + \ldots \right]$$

Coupling to phase of ψ_{Sx}

$\delta\mathcal{O}_n = \mathcal{O}_n(\vec{r}) - \bar{\mathcal{O}}_n$

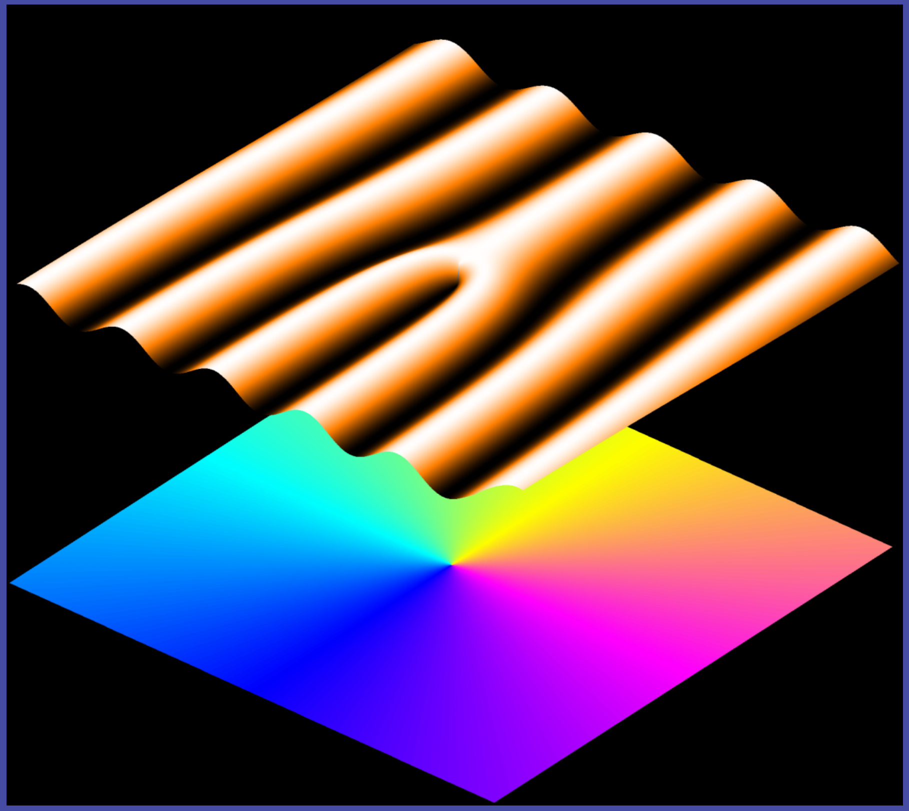
Other couplings

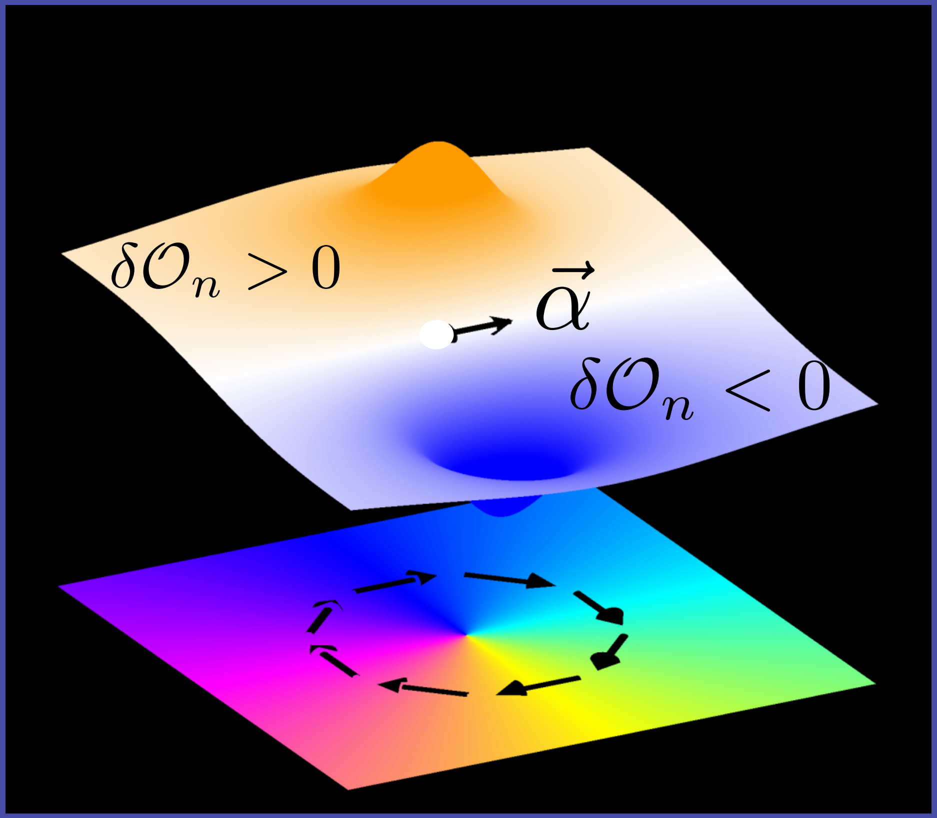


de Gennes suggested this coupling between orientational order and bending of smectic waves

EFFECT OF SMECTIC DISLOCATIONS

Theory: smectic defects do not suppress nematic order

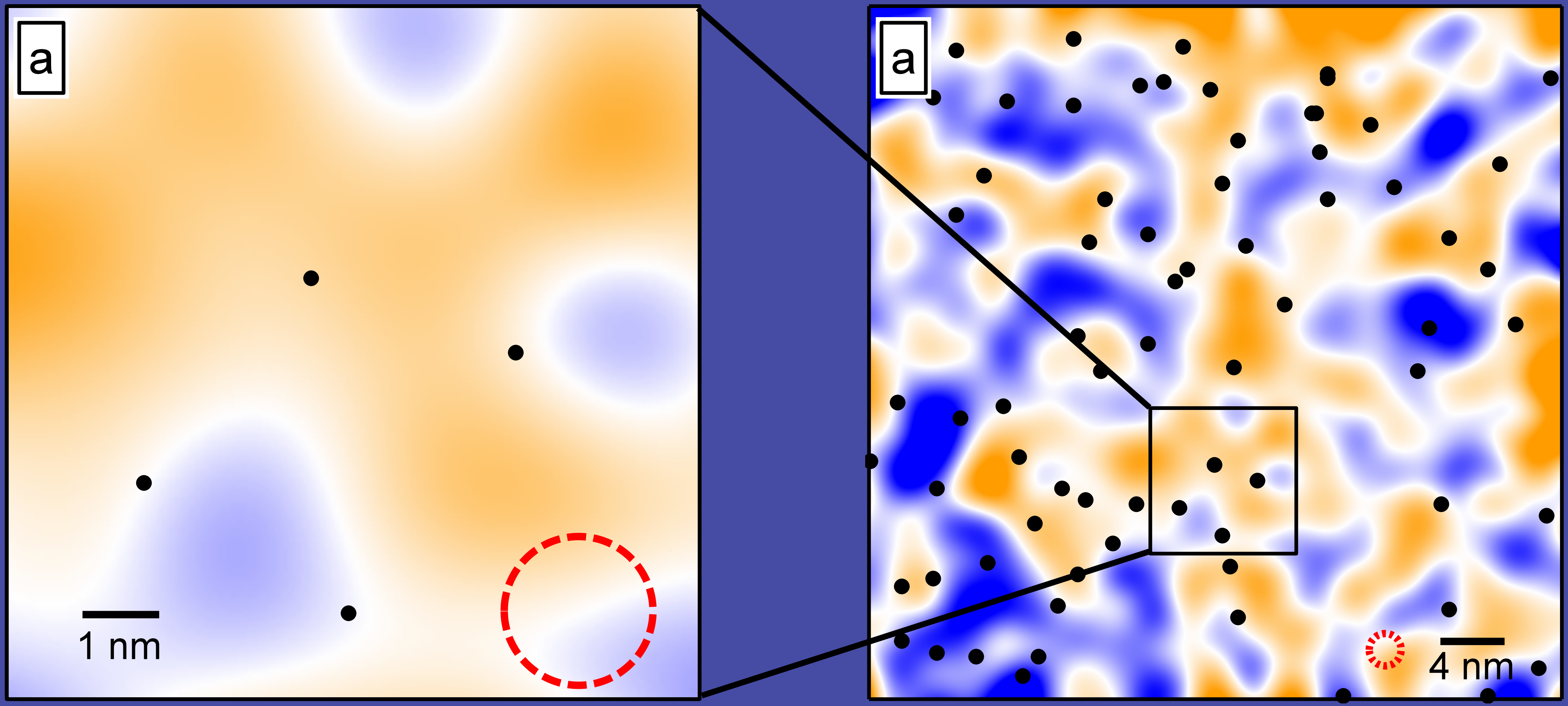




SIMULATE NEMATIC FLUCTUATIONS

Zoomed image

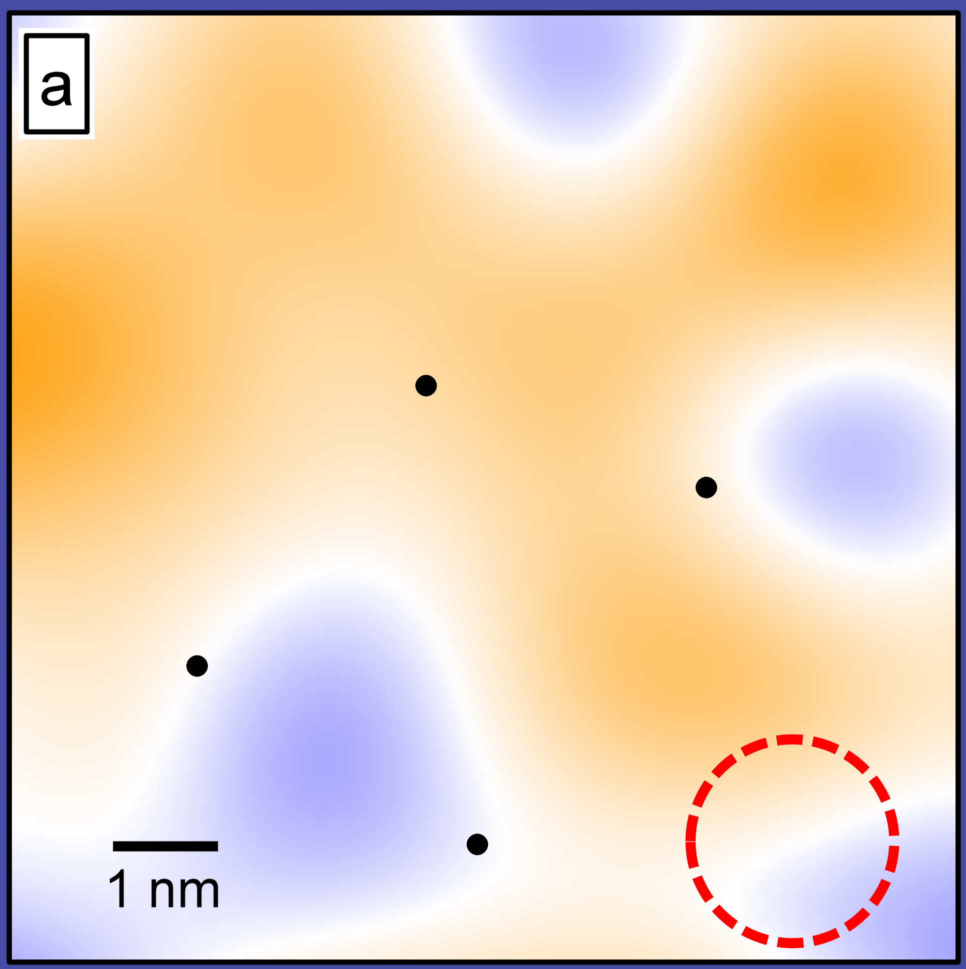
$$\delta\mathcal{O}_n(\vec{r}) = \mathcal{O}_n(\vec{r}) - \bar{\mathcal{O}}_n$$



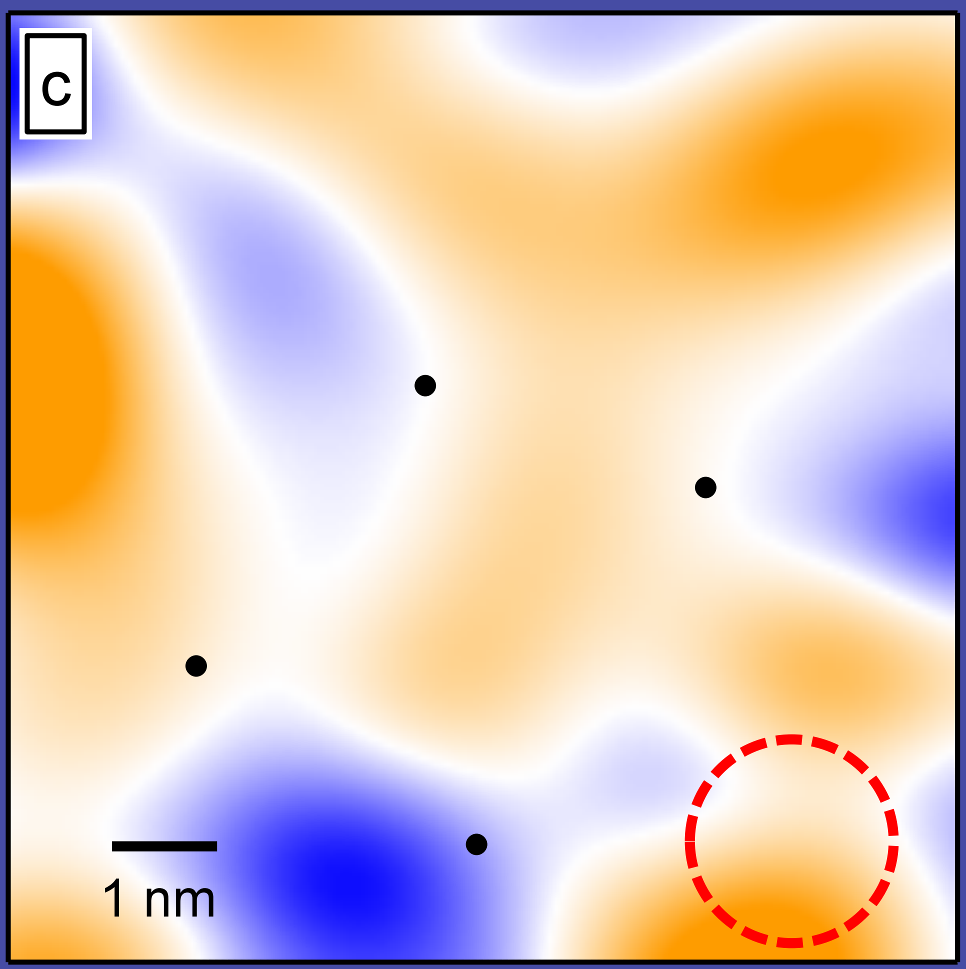
Mesaros, Fujita et. al., unpublished.

SIMULATE NEMATIC FLUCTUATIONS

Experimental Data

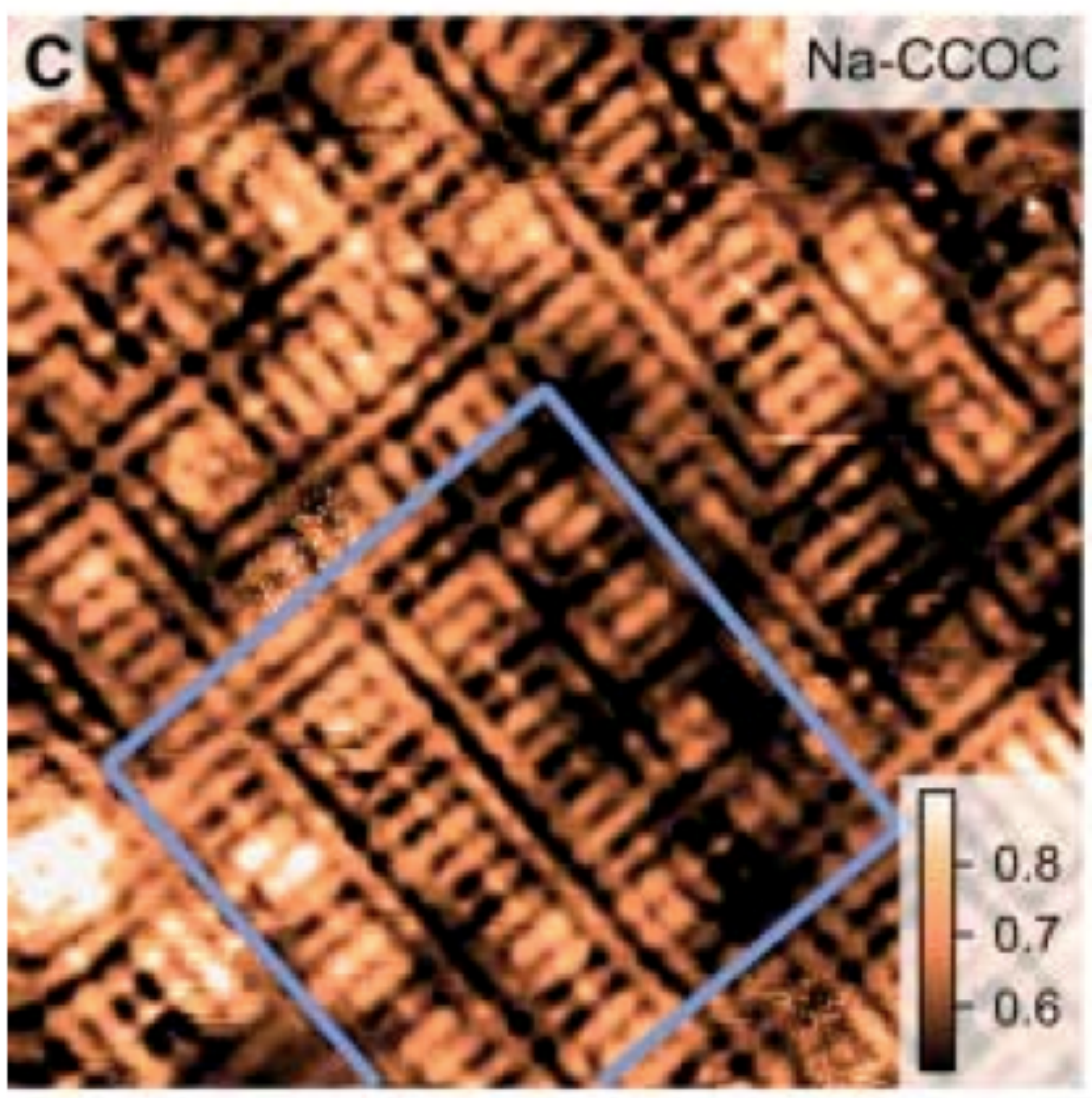


Free energy predictions



Mesaros, Fujita et. al.,
unpublished.

PG PATTERNS IN NACCOC

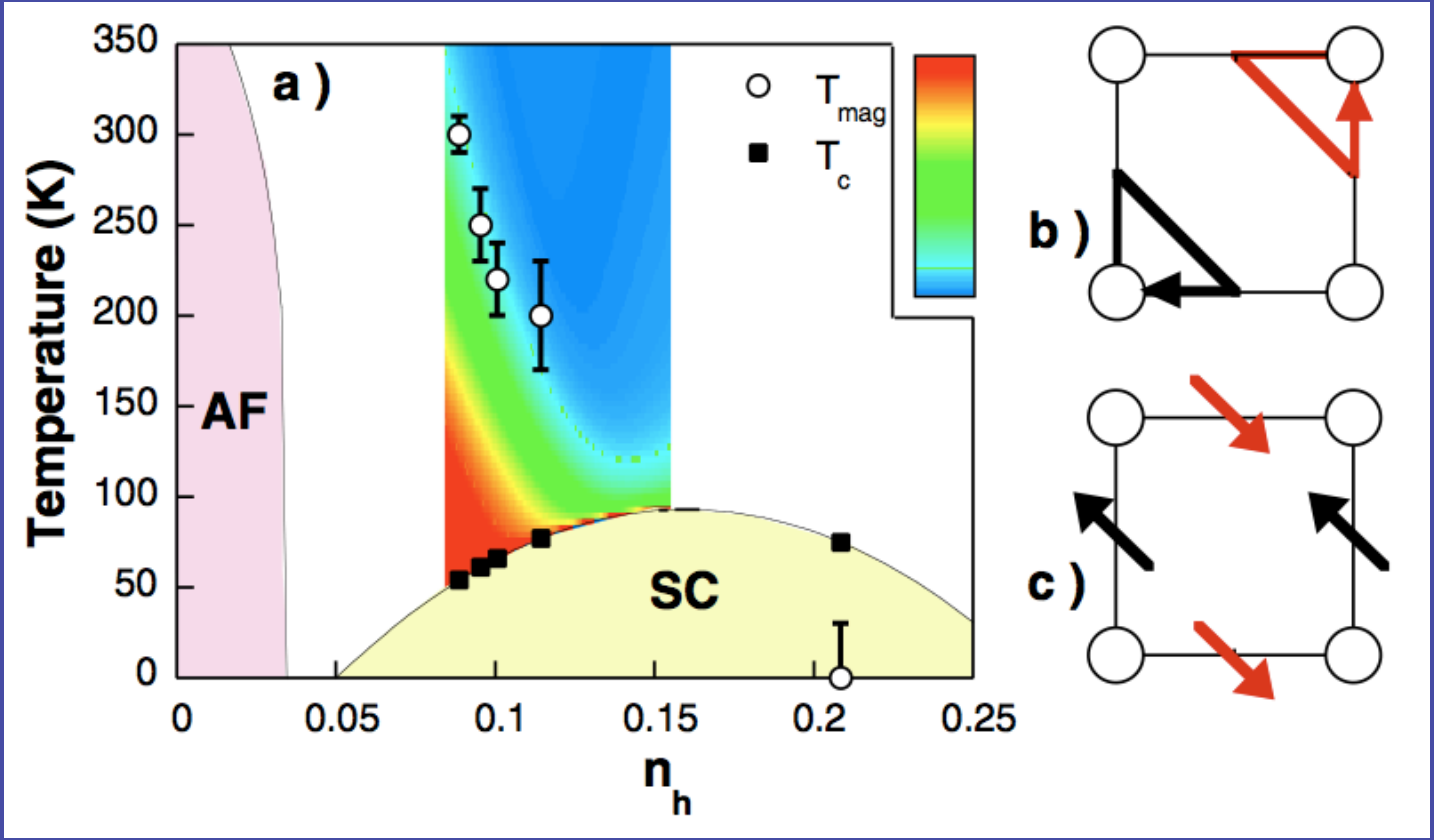


Na-CCOC has a very different surface chemistry

Kohsaka et. al. Science 2007

SPONTANEOUS SYMMETRY BREAKING FROM NEUTRON SCATTERING

By studying Bragg peaks:

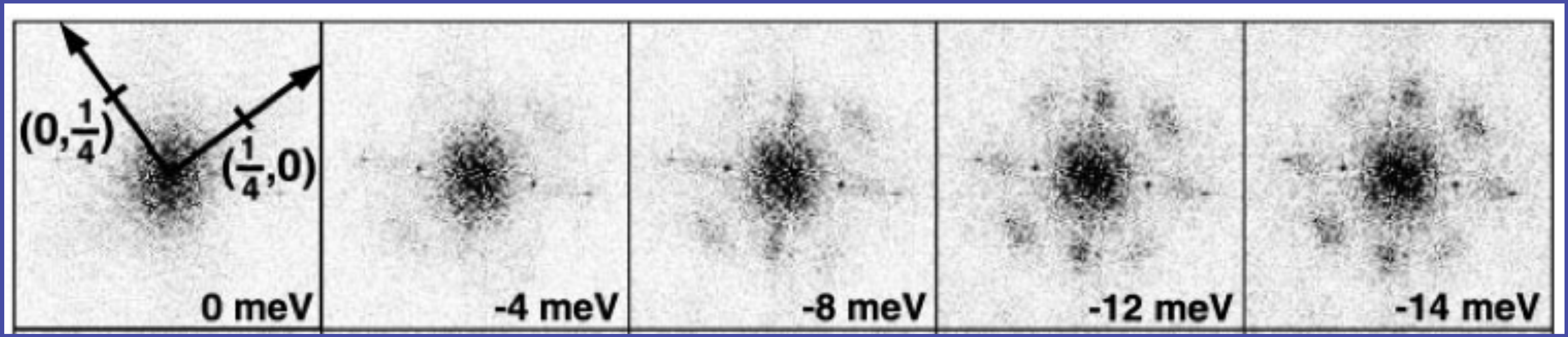


Fauqué et. al., PRL 2006

IMPLICATIONS FOR SUPERCONDUCTIVITY

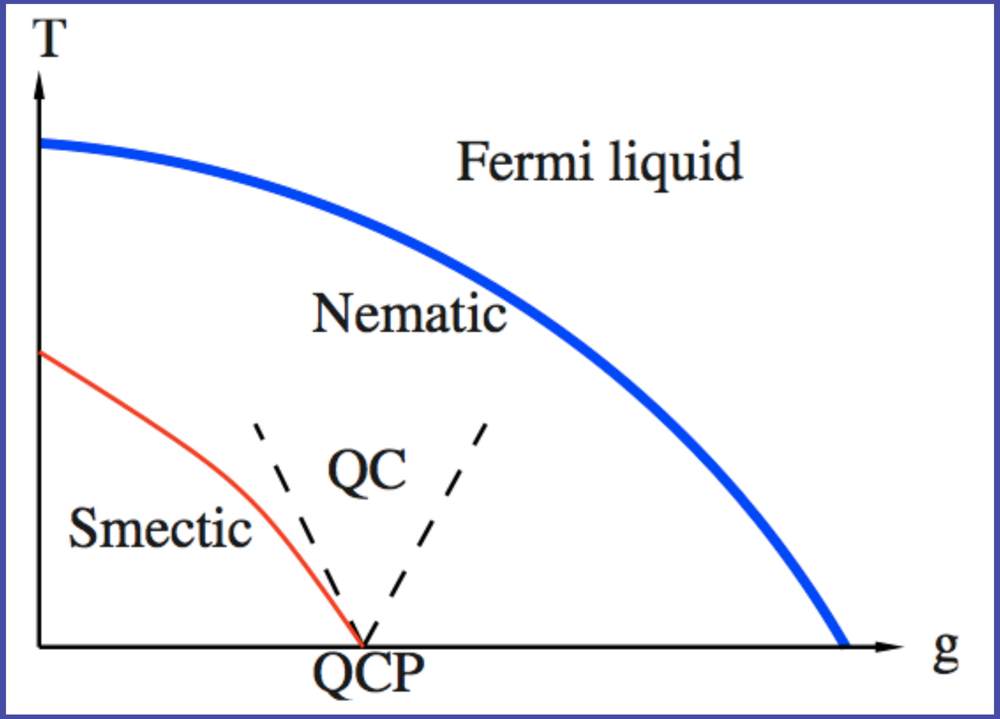
Emperically: do these liquid crystal phenomena help superconductivity?

Low energy peaks



Hoffman et. al., Science 2002

Theoretically: Need to solve Quantum de-Gennes Model:



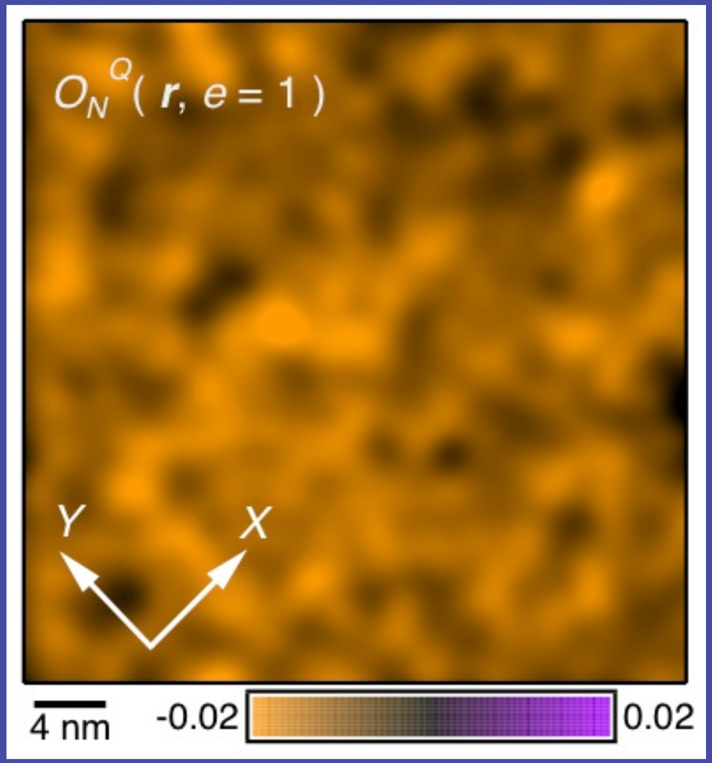
Sun, Fregoso, Lawler and Fradkin, PRB 2008

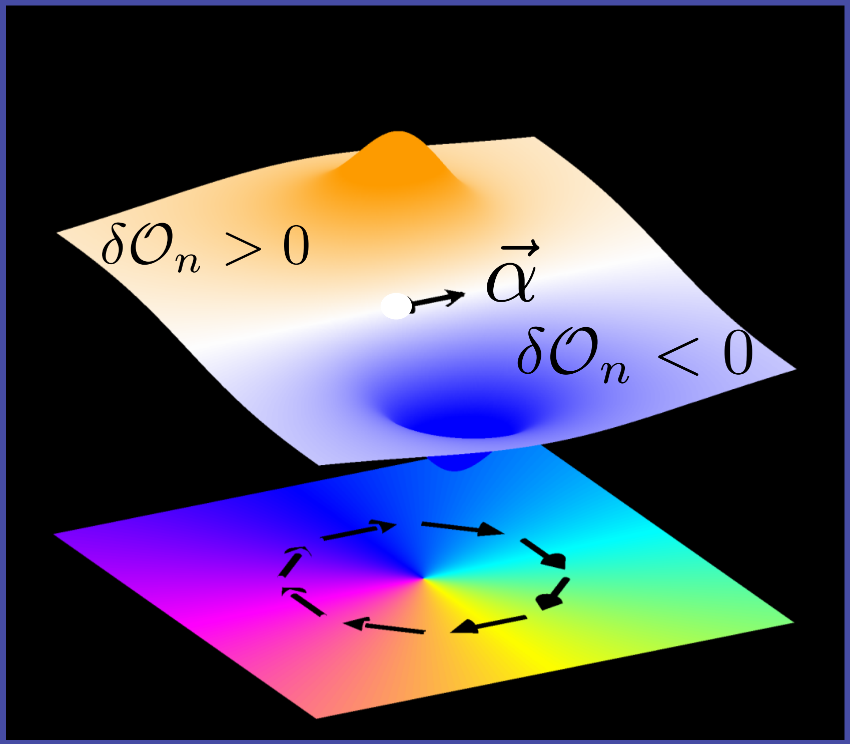
CONCLUSIONS

- Developed powerful data analysis techniques based on similarities with radio spectrums

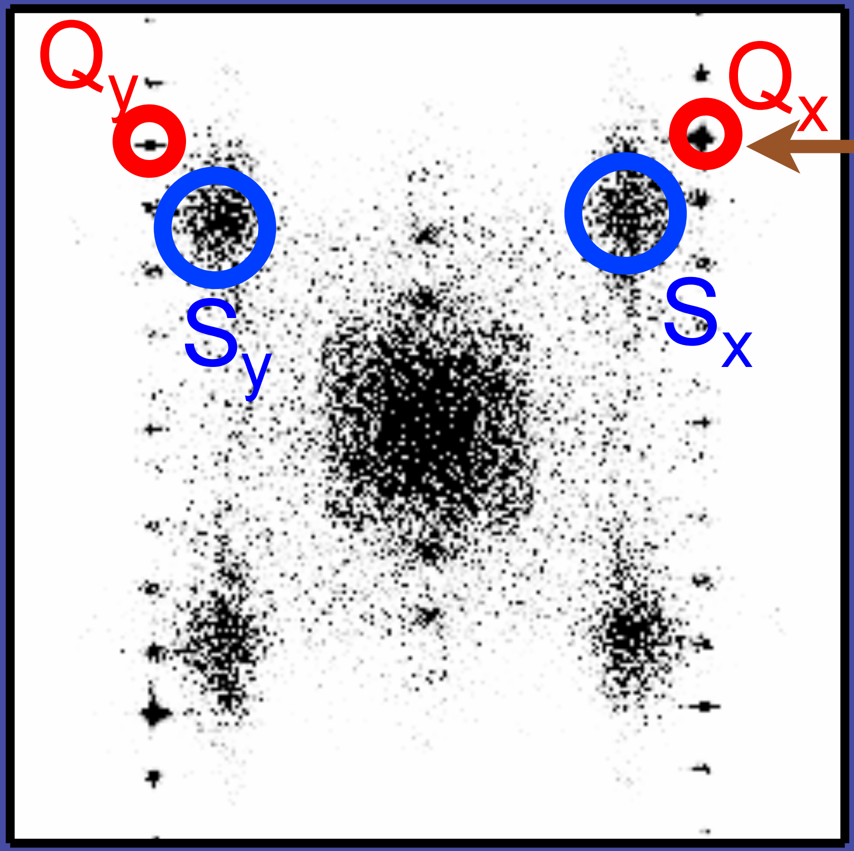
$$M(\vec{r}) = \mathrm{Re}\left\{\psi_{\vec{Q}_x}(\vec{r})e^{i\vec{Q}_x\cdot\vec{r}} + \psi_{\vec{Q}_y}(\vec{r})e^{i\vec{Q}_y\cdot\vec{r}} + \dots\right\}$$

- Discovered nematic order over at least 100 nm in BSCCO
- Found de Gennes-like coupling explains impact of smectic dislocations on nematic order





APPENDIX: FOURIER ANALYSIS



Radius of ring: Λ

$$\psi_{Qx}(\vec{r}) = \mathrm{Blur}_{\Lambda}\left[M(\vec{r})e^{-i\vec{Q}_x\cdot\vec{r}}\right]$$

$$\psi_{Qx}(\vec{r}) = \int d^2r'\left[M(\vec{r}')e^{-i\vec{Q}_x\cdot\vec{r}'}e^{-\Lambda^2|\vec{r}-\vec{r}'|^2}\right]$$