Electronic Noise
Due to Thermal Stripe Switching

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Crystals
Fluids
Crystals
Fluids

Liquid Crystals

Smectic
Nematic
Hexatic
Cholesteric...
Crystals
Fluids

Liquid Crystals
Smectic
Nematic
Hexatic
Cholesteric...

Glass and
Amorphous solids

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Crystals
Fluids

Liquid Crystals
Smectic
Nematic
Hexatic
Cholesteric...

Glass and
Amorphous solids

Superfluid
Metals
Metals

Band Insulators
Metals

Band Insulators

Semi-conductors
Metals

Insulators

Semi-conductors

Magnets
Metals

Semi-conductors

Band Insulators

Ferromagnets

Antiferromagnets

Frustrated Magnets

Loh, Yao, EC PRB 2008
Yao; Loh, EC; Ma PRB 2008
Metals

Band Insulators

Semi-conductors

Ferro-Magnets

Antiferromagnets

Frustrated Magnets

Superconductors

Vortices
Metals

Semi-conductors

Band Insulators

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Super-conductors

Quantum Hall Phases

Vortices

Loh, Yao, EC PRB 2008

Yao, Loh, EC, Ma PRB 2008
Metals

Band Insulators

Semi-conductors

Ferro-Magnets

Antiferromagnets

Frustrated Magnets

Superconductors

Quantum Hall Phases

Electronic Liquid Crystals
How we classify phases

By the symmetry of long distance and long time properties

**Crystal**
- Periodic (two directions)

**Smectic**
- Periodic (one direction)

**Nematic**
- Oriented

**Liquid**
- Smooth (at long lengths and times)
Strong Correlations and Disorder

Many degrees of freedom
Spin
Charge
Orbital
Lattice

Strong Correlation + Many DOF
Many Phases Possible
Different Phases Compete

Competing Phases + Disorder
Nanoscale pattern formation
Complexity

Kohsaka et al., Science 315, 1380 (2007)

A Way Forward

Important nanoscale structure missed by the definition of a phase!

PROBLEM: Most theoretical and experimental tools are designed to characterize and detect long distance behavior.

Kohsaka et al., Science 315, 1380 (2007)
A Way Forward

**Important nanoscale structure missed by the definition of a phase!**

**PROBLEM:**
Most theoretical and experimental tools are designed to characterize and detect long distance behavior


**One Solution:**
Exploit Disorder, Using Noise and Nonequilibrium Effects to Characterize and Detect Nanoscale Pattern Formation
Cuprate Superconductors

Brittle
Ceramic
Not Shiny
Not Metallic

Discovered in 1986 and still unexplained
There is still no consensus on the phase diagram
Is our outdated definition of a phase hindering progress?
Cuprate Superconductors

Layered structure \(\rightarrow\) quasi-2D system

Copper Oxygen Planes

Other Layers
Cuprate Superconductors

Dope with holes

Superconducts at certain dopings
Cuprate Superconductors

High pairing scale $\Rightarrow$ Short range order may be key

_Pseudogap:_ Many possible phases. Which one(s) is(are) happening?
_Disorder only compounds the problem!_

Stripes in cuprates?
So far, detected in only a subset of materials
Are they ubiquitous?
Even short stripes can generate pairing

Hard to detect!
Disorder (chemical dopants)
Rounds transitions
Can destroy order!

How do we define and detect phases with nanoscale pattern formation?
What's a Stripe?

Most Ordered

Unidirectional Spin and Charge Density Wave

Less Ordered

Unidirectional Charge Density Wave
What's a Stripe?

Most Ordered

Unidirectional Spin and Charge Density Wave

Less Ordered

Unidirectional Charge Density Wave
What's a Stripe?

Most Ordered

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Unidirectional Spin and Charge Density Wave

Less Ordered

\[
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Unidirectional Charge Density Wave

Even Less Ordered

\[
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Oriented Charge (nematic)
Stripes in what probes?

**Neutron Scattering**
*(bulk probe)*
LaSrCuO, LaCuO, YBaCuO (not BiSrCaCuO)

**Scanning Tunneling Microscopy**
*(surface probe)*
BiSrCaCuO

**Angle-Resolved Photoemission Spectroscopy**
*(surface probe)*
BiSrCaCuO, YBaCuO
Stripes lock to a crystal direction

OR

Cu-O plane

Ising Nematic

\[ \sigma = 1 \text{ for horizontal stripe patch} \]
\[ \sigma = -1 \text{ for vertical stripe patch} \]

Disorder favors one direction locally

\[ H = -J \sum_{<i,j>} \sigma_i \sigma_j - \sum_i (H + h_i) \sigma_i \]

Random Field Ising Model
Random Field Ising Model

Two Dimensions

Ordered

Disordered

Random Field Strength

Three Dimensions

Disordered

Ordered

Random Field Strength

Temperature

\[ H = -J \sum_{\langle i,j \rangle} \sigma_i \sigma_j - \sum_i h_i \sigma_i \]
Noise: Snap, Crackle, Pop

Snap: One large, system-size event
Crackle: Many events at random times, of random sizes.
Pop: Many small, same-sized events at random times
Transport

Stripe Patches

Resistor Network

Maps To

Easy conduction

Hard conduction

Calculations:

Monte Carlo Simulation of random field Ising Model
Each configuration maps to a resistor network
$R_{xx}$ and $R_{yy}$ calculated via
bond propagation algorithm (Frank et al., PRB 1988)
(Generalized to planar Ising models: Loh, EC, PRL 2006)
Transport

Stripe Patches

Resistor Network

Maps To

Resistance Anisotropy and RFIM Magnetization exhibit hysteresis

"Magnetization" = orientational order

\[ M, \frac{(R_{xx}-R_{yy})}{(R_{xx}+R_{yy})} \]

- Orientational Order
- \((R_{xx}-R_{yy})/(R_{xx}+R_{yy})\)

LXL = 300X300

T=0; \( \Delta = 2.8 \) J; \( R_{\text{large}}/R_{\text{small}} = 2 \)
Confined Geometries: Telegraph Noise

**Experiment**

- YBCO nanowire (underdoped)
- \( T = 100K \)
- \( 500\text{nm} \times 250\text{nm} \)
- Large switch \( \approx 5 \) patches

\[ \text{Bonetti et al., PRL 93, 087002 (2004).} \]

**Theory**

- \( R_{\text{large}} / R_{\text{small}} = 2 \)
- Size: 6X6 patches
- Disorder \( R = 2.8 \text{ J} \)
- \( T = .5 \text{ J} \)
- Dimension = 2

- Stripe correlation length
  \( \sim 40\text{nm} \) (from neutron data)

\[ \text{see also Reichhardt et al, Europhys. Lett. 2005} \]

\[ \text{EC et al., PRL 96, 097003 (2006).} \]
That was for the normal state...
That was for the normal state...
Superfluid Density Anisotropy

Calculations:

Monte Carlo Simulation of random field Ising Model
Each configuration maps to Josephson Junction Array (JJA)
Monte Carlo simulation for each JJA pattern

\[ \sigma = -1 \rightarrow \sigma = +1 \]

Maps to

\[ J_{\text{eff}} = \frac{J_1 J_2}{J_1 + J_2} \]
Superfluid Density Anisotropy

\[ \sigma = -1 \quad \text{Maps to} \quad \sigma = +1 \]

Josephson Junction Array

\[ J_w \quad J_s \]

\[ J_w \quad J_s \]
Superfluid Density Anisotropy

\[ \sigma = -1 \rightarrow \sigma = +1 \]

Maps to

Josephson Junction Array

\[ J_s = 2 \]
\[ J_w = 1 \]
\[ J = 10 \]

\[ n_x, n_y \]

\[ T_{RFIM} > T_{SC} \]

Temperature vs. Density

- \( T_c(R = 1) \)
- \( J_s = 2 \)
- \( J_w = 1 \)
- \( J_L = 10 \)
Superfluid Density Anisotropy

Josephson Junction Array

Maps to

\[ \sigma = -1 \quad \text{and} \quad \sigma = +1 \]

\[ R = 1 \quad J_s = 2 \quad J_w = 1 \quad J_\perp = 10 \]

\[ T_{c \text{ RFIM}} > T_{c \text{ SC}} \]

\[ T_{c \text{ RFIM}} < T_{c \text{ SC}} \]

\[ n_x \quad \text{and} \quad n_y \]
Hysteretic Superfluid Density Anisotropy

Apply an orienting field, “H”

\[
\Delta = 1 \\
J_s = 2 \\
J_w = 1 \\
L = 8 \\
T = 0, 0.5, 1
\]

Intermediate disorder: Weak disorder within planes, Strong disorder between planes. Planes “snap” individually

with B. Phillabaum, Y. Loh
Comparisons to STM

Low Temperature Electronic Glass with Unidirectional Domains

Experiment

Ca$_{1.88}$Na$_{12}$CuO$_2$Cl$_2$
T=4.2K
Kohsaka et al.,
Science 315, 1380 (2007)

Theory

Layered system
J$_\perp$=J$_\parallel$/10 (Ising couplings)
T=1.5J$_\parallel$
$\Delta$=1.5 (disorder strength)
Prediction: Telegraph Noise in STM

Stripe Glass:
- R = 1.5
- T = 0.5

Active Regions are at Domain Boundaries

Variance

Place STM tip on a line at a stripe boundary

Telegraph Noise
\( R=2.5 \)
\( T=0.5 \)

\( R=2.5 \)
\( T=1.0 \)

\( R=2.5 \)
\( T=1.5 \)
Detecting Correlations

Other possible sources of telegraph noise:

- Bad tip
- Defects hopping on surface

Power Spectrum

- Single uncorrelated switcher: Lorentzian power spectrum
- Interactions cause deviations

Power spectrum is impractical for 25-60 second noise
Spatial and Temporal Correlations in Noise

R = 2.5
T = 0.5
"On-the-fly" Reblocking Algorithm  

(Kent et al., J. Comp. Chem. 2007)

Each block spin is the average of the ones below it.
Accumulate averages and variances for each block size $m$.
Memory requirement = $O(\log_2 N)$, rather than $O(N)$
In-Situ Test for Correlations

Low m deviations from horizontal line indicate correlations
Conclusions

Stripes + Host crystal + Disorder = Random Field Ising Model

Disorder makes stripes hard to detect. Need new ways to probe: *Noise, Hysteresis*

**Transport:** Switching noise in small systems in $R_{xx}$
Orientational Order measured by $R_{xx} - R_{yy}$
Similar for Superfluid Anisotropy

**Scanning Noise Spectroscopy (STM):**
Telegraph Noise at Domain Boundaries
Active regions are at stripe cluster boundaries
More active regions as temperature is raised
Local Noise Maps out Stripe Clusters
Spatial and Temporal Noise Correlations