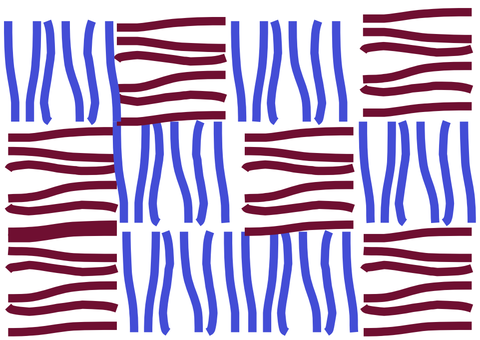
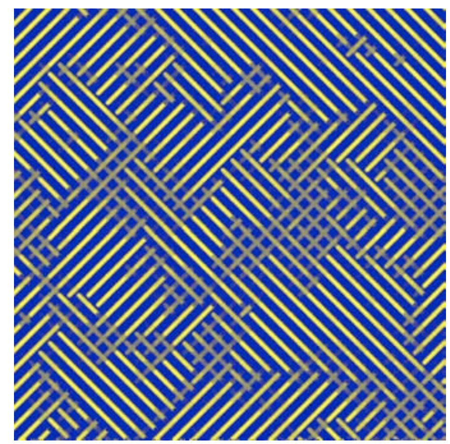
Electronic Noise Due to Thermal Stripe Switching



E. W. Carlson

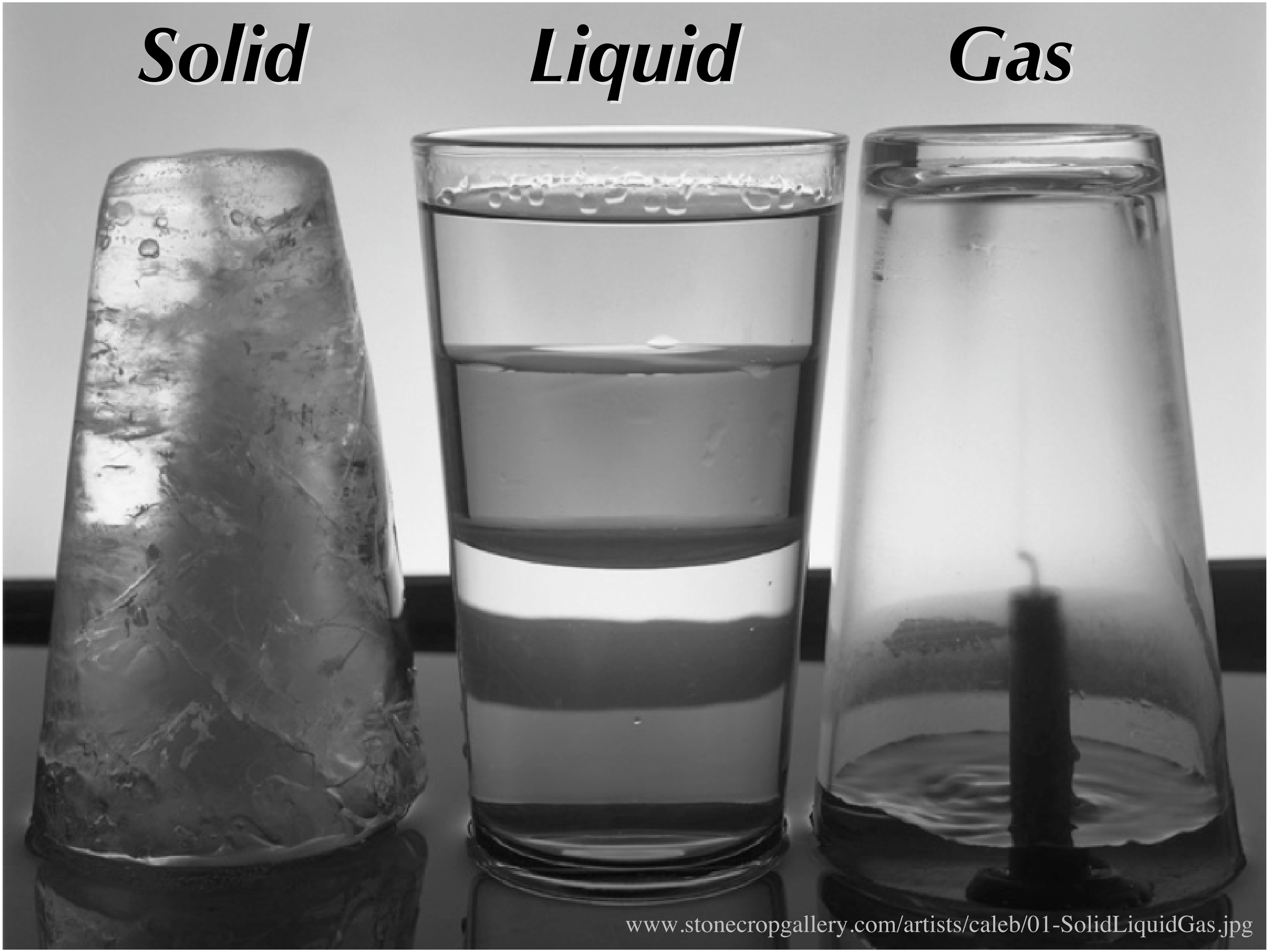
B. Phillabaum
Y. L. Loh
D. X. Yao



PURDUE UNIVERSITY

NSF

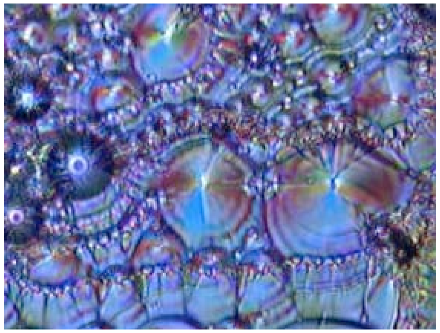
Research Corporation

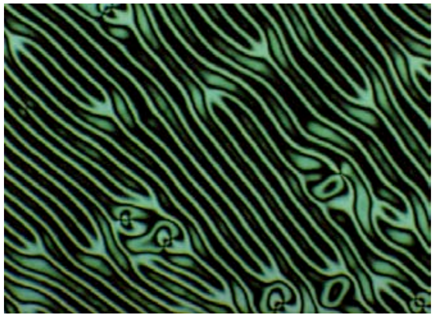

Solid
Liquid
Gas
www.stonecropgallery.com/artists/caleb/01-SolidLiquidGas.jpg

Crystals
Fluids

Crystals
Fluids

Liquid Crystals

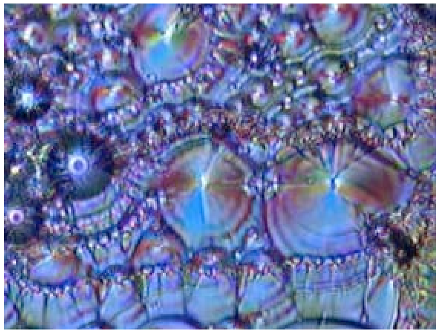


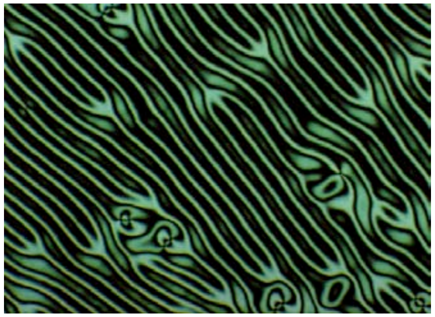


Smectic
Nematic
Hexatic
Cholesteric…

Crystals
Fluids

Liquid Crystals





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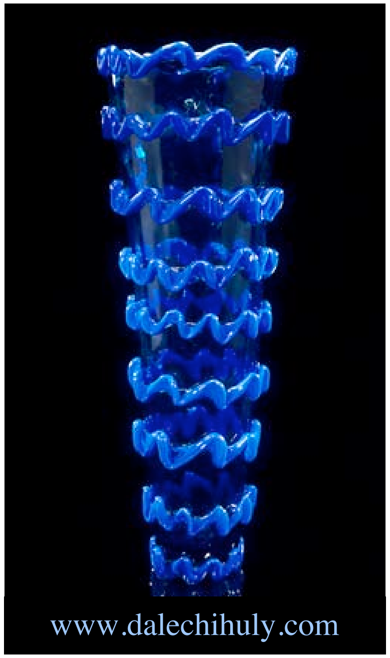
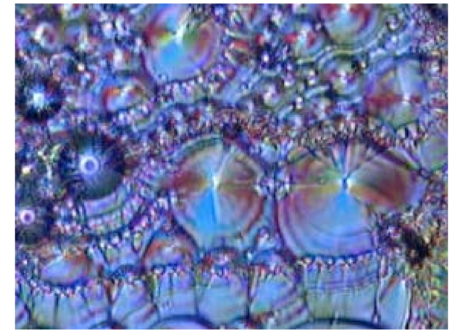
Nematic
Hexatic
Cholesteric…

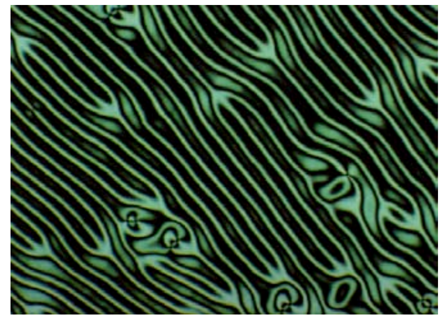


Glass and
Amorphous solids

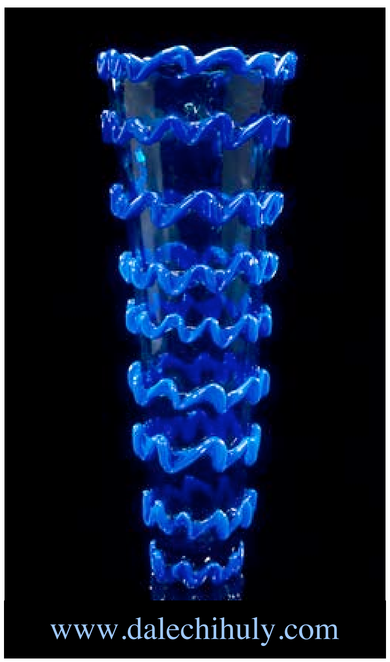
Crystals
Fluids

Liquid Crystals

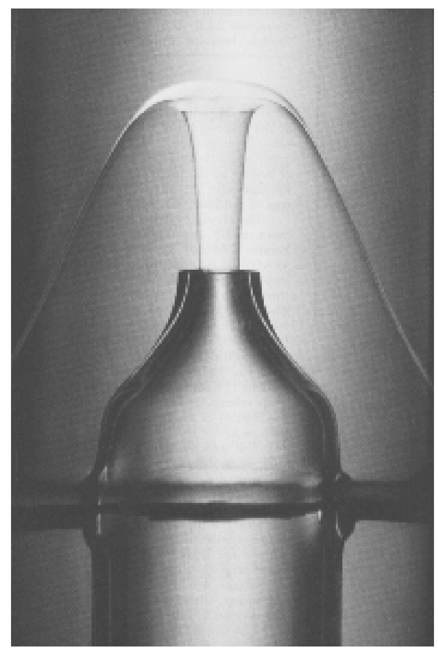




Smectic
Nematic
Hexatic
Cholesteric…



Glass and
Amorphous solids



Superfluid

Metals

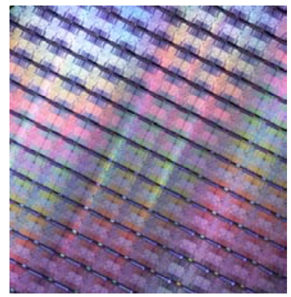
Metals

Band
Insulators

Metals

Band Insulators

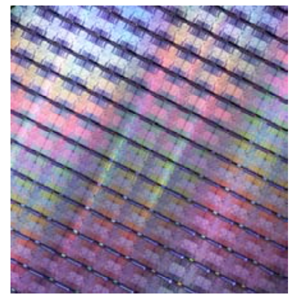
Semi-conductors



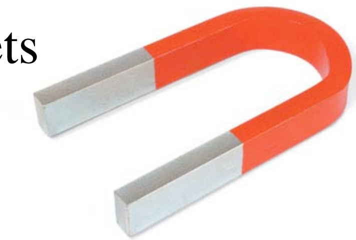
Metals

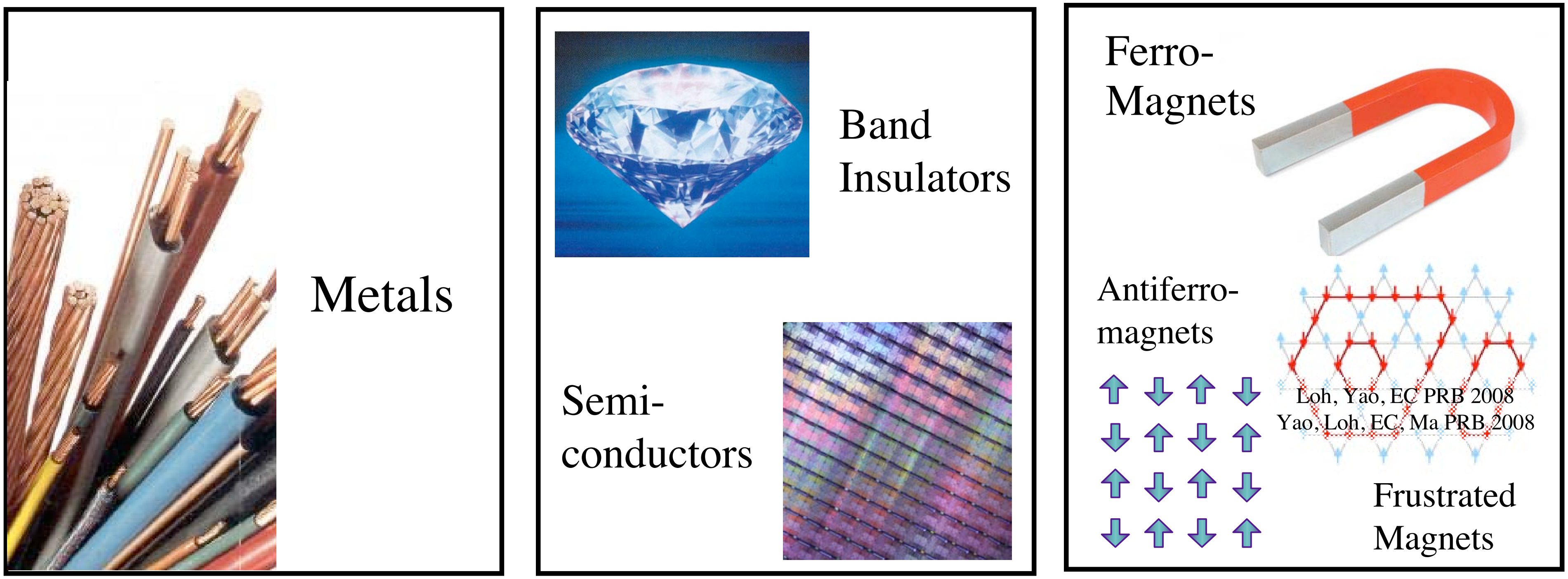
Band
Insulators

Semi-
conductors



Magnets

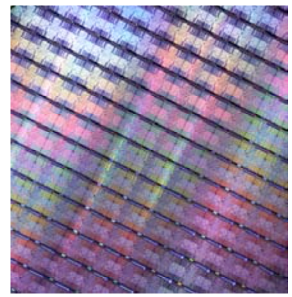



Metals
Band Insulators
Semi-conductors
Ferro-Magnets
Antiferro-magnets
Loh, Yao, EC PRB 2008
Yao, Loh, EC, Ma PRB 2008
Frustrated Magnets

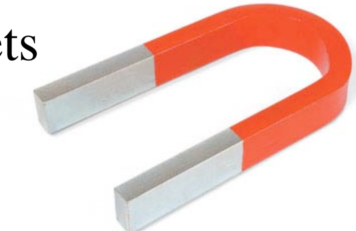
Metals

Band Insulators

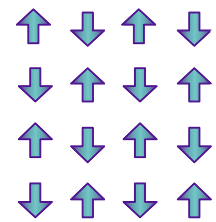
Semi-conductors

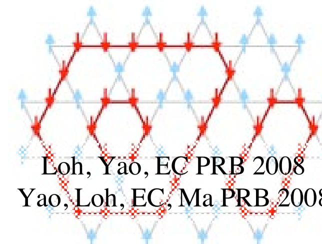


Ferro-Magnets

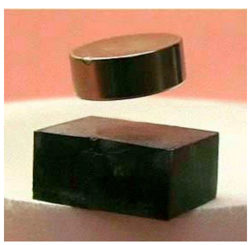


Antiferro-magnets

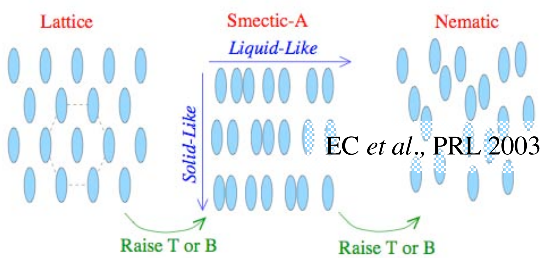




Frustrated Magnets



Super-conductors

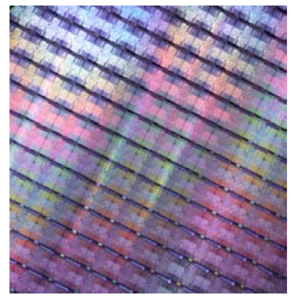


Vortices

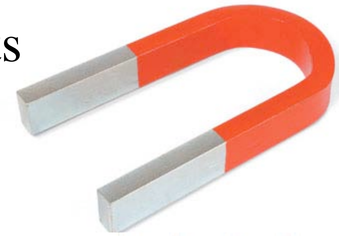
Metals

Band Insulators

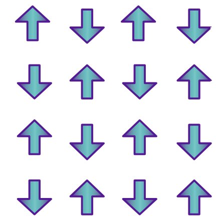
Semi-conductors

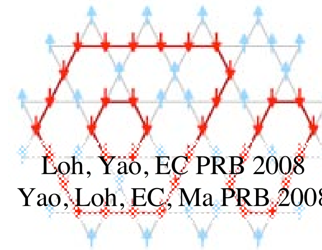


Ferro-Magnets

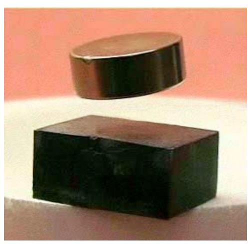


Antiferro-magnets

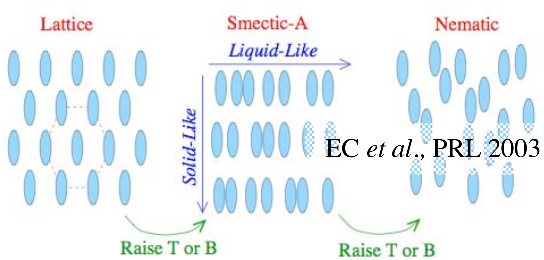




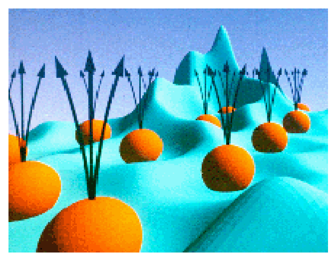
Frustrated Magnets



Super-conductors



Vortices

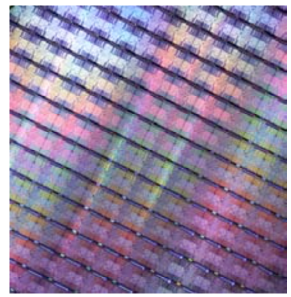


Quantum Hall Phases

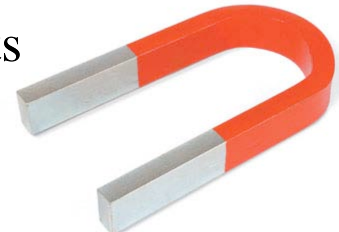
Metals

Band Insulators

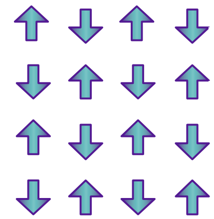
Semi-conductors

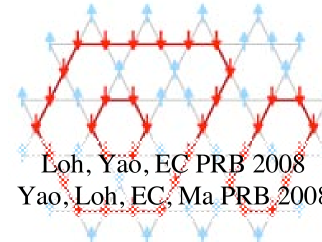


Ferro-Magnets

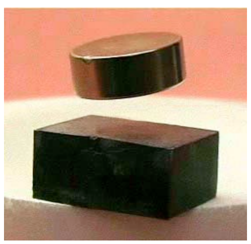


Antiferro-magnets

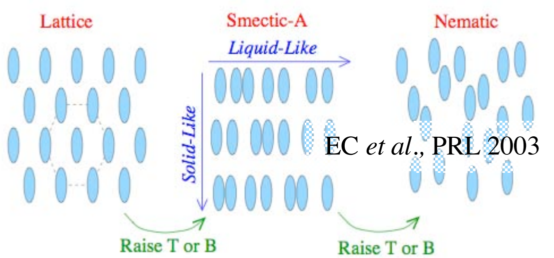




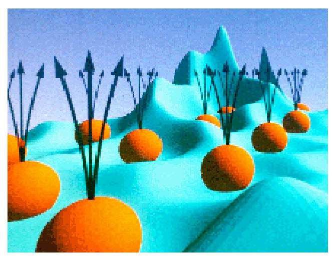
Frustrated Magnets



Super-conductors

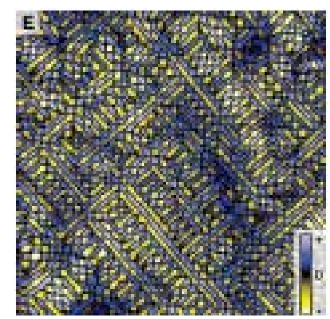


Vortices



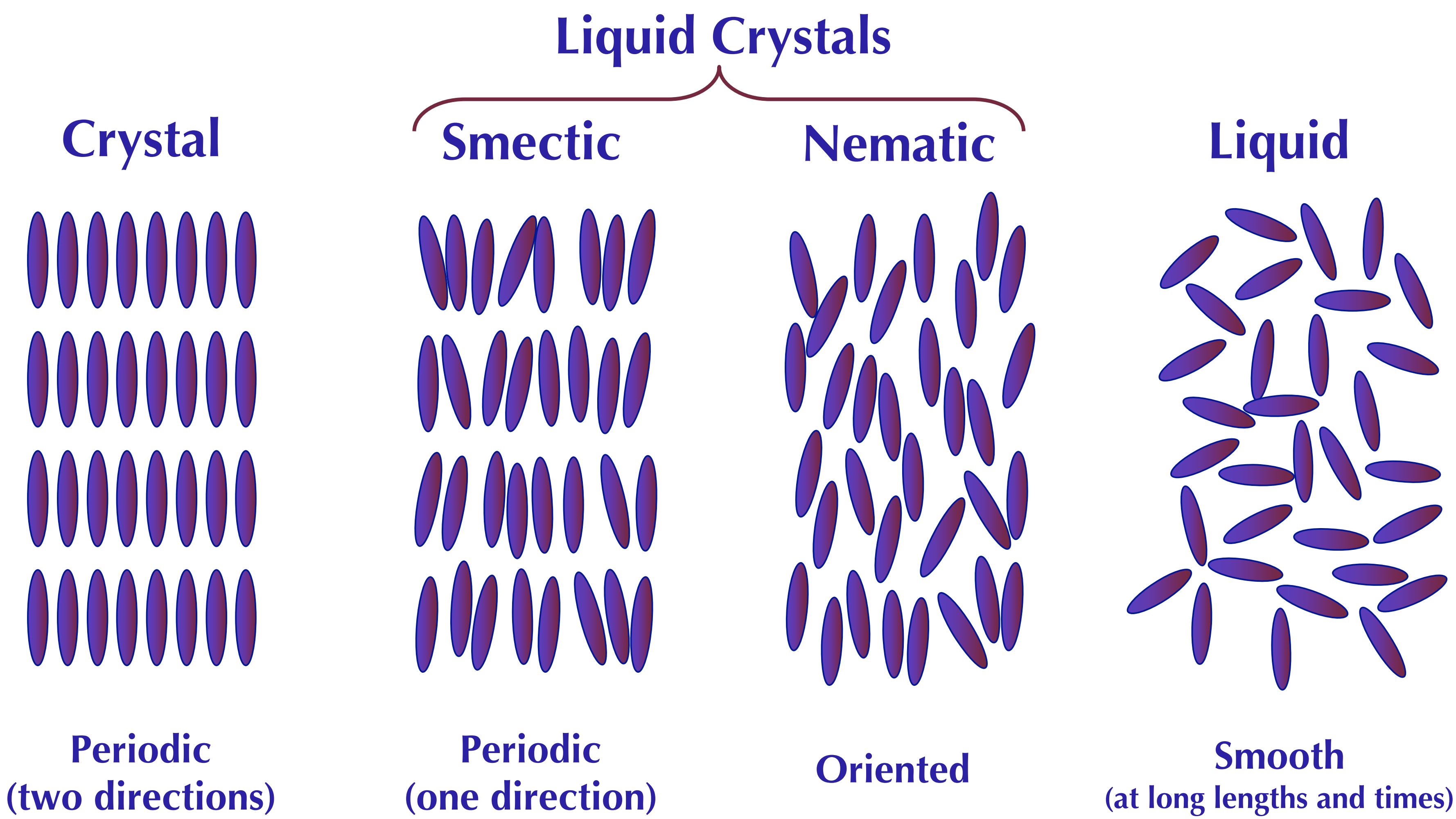
Quantum Hall Phases

Electronic Liquid Crystals

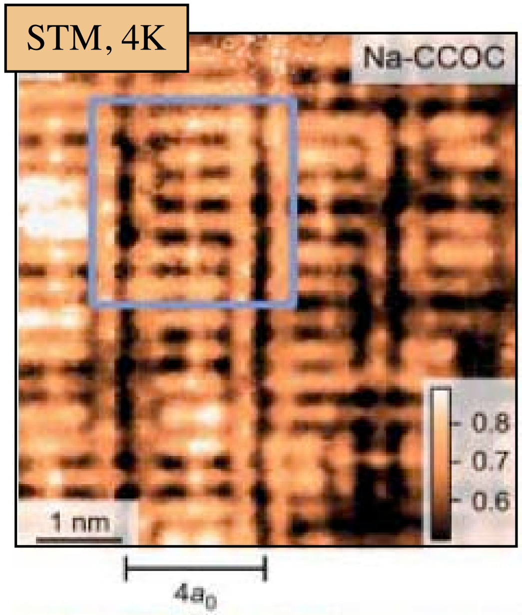


How we classify phases

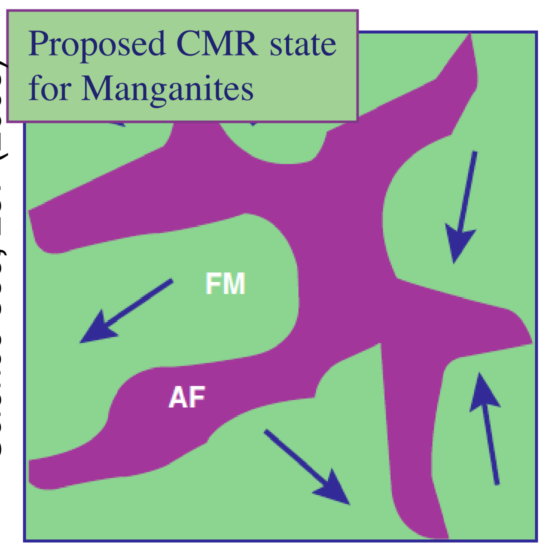
By the symmetry of long distance and long time properties



Strong Correlations and Disorder



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



Dagotto,
Science **309**, 257 (2005)

Many degrees of freedom

- Spin
- Charge
- Orbital
- Lattice

Strong Correlation + Many DOF

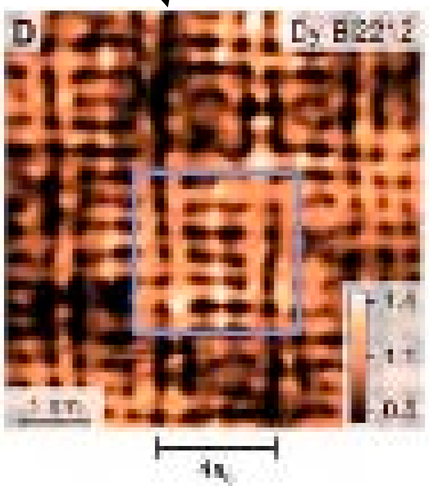
- Many Phases Possible
- Different Phases Compete

Competing Phases + Disorder

- Nanoscale pattern formation
- Complexity

A Way Forward

Important nanoscale structure missed by the definiton of a phase!

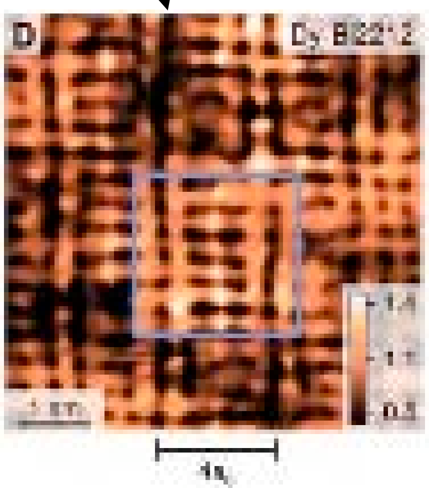


Kohsaka *et al.*,
Science **315,** 1380 (2007)

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

A Way Forward

Important nanoscale structure missed by the definiton of a phase!



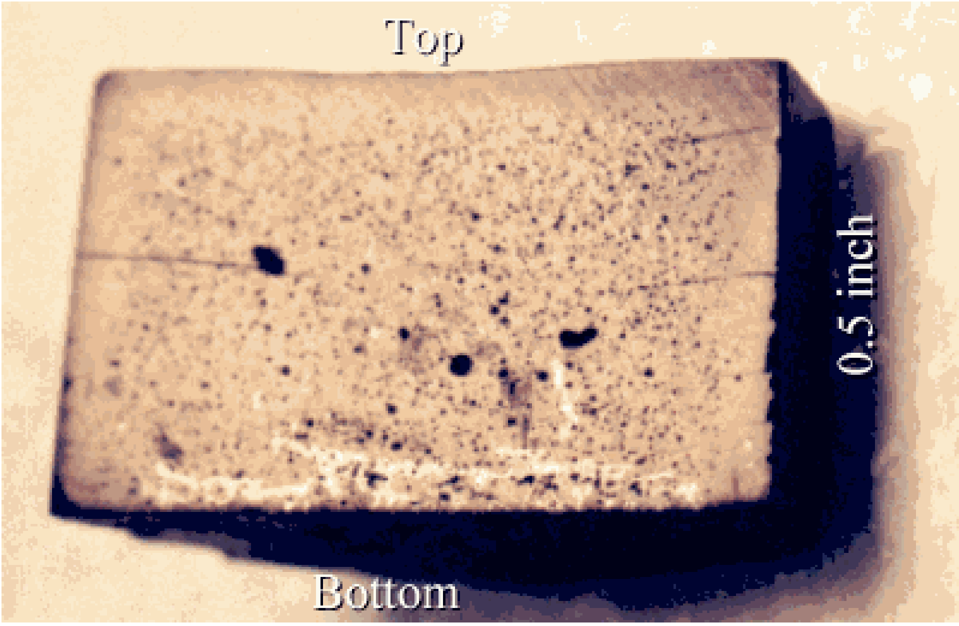
Kohsaka *et al.*,
Science **315,** 1380 (2007)

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

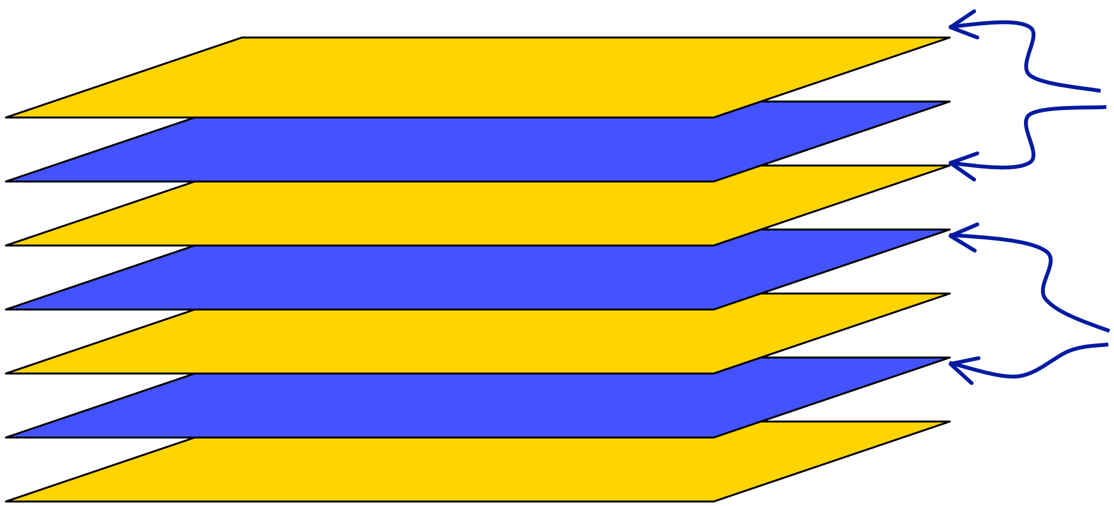
Cuprate Superconductors

Brittle
Ceramic
Not Shiny
Not Metallic



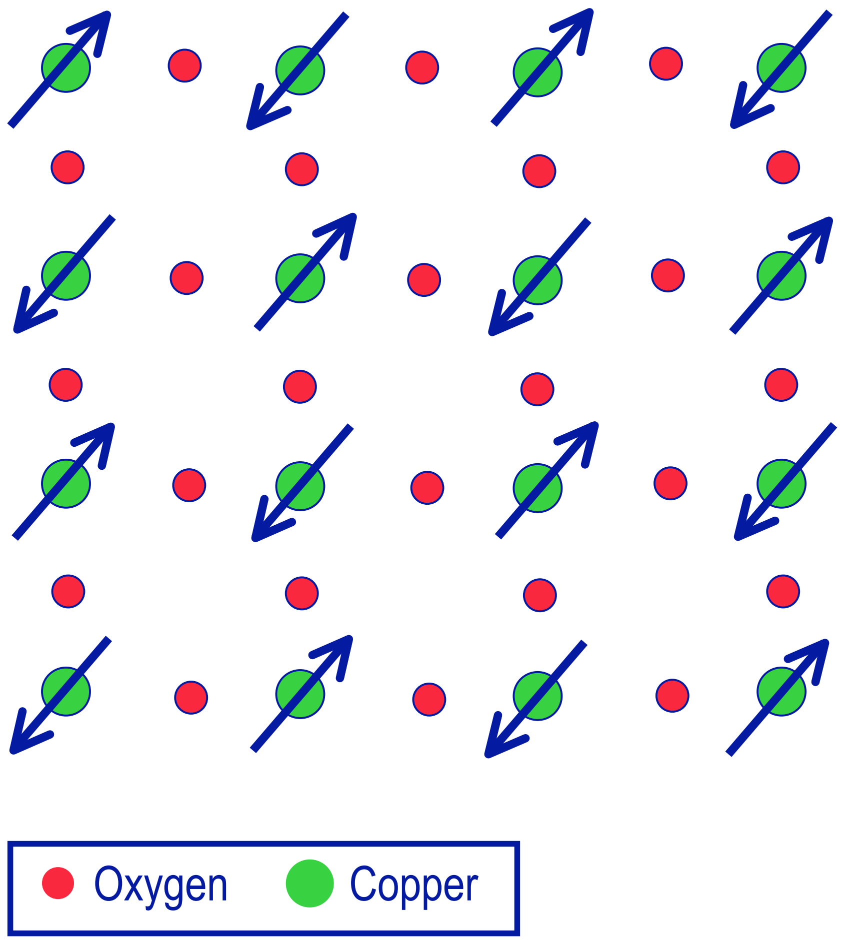
Discovered in 1986 and still unexplained
There is still no consensus on the phase diagram
Is our outdated definition of a phase hindering progress?

Cuprate Superconductors



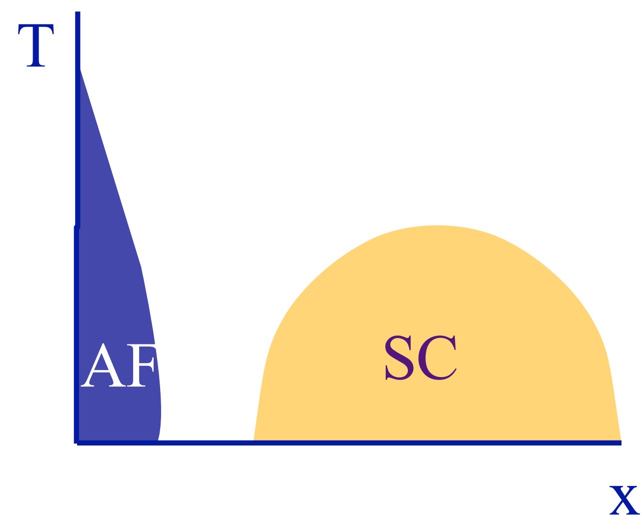
Layered structure → quasi-2D system

Cuprate Superconductors



Dope with holes

Superconducts at certain dopings

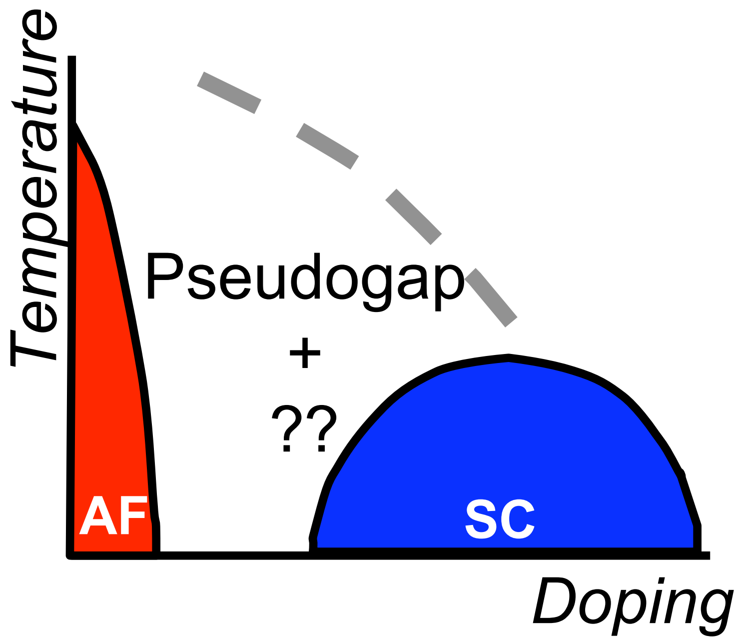


Cuprate Superconductors

High pairing scale ⇒ 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

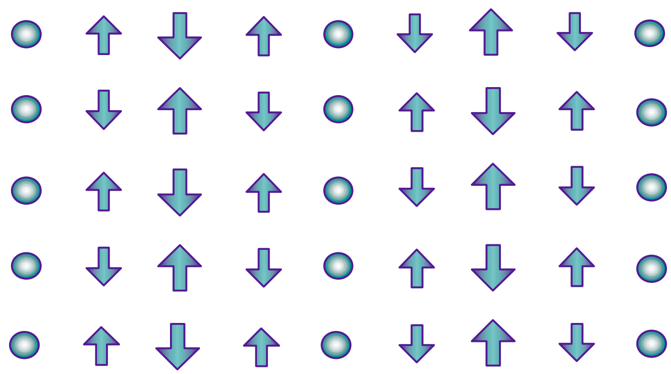
Hard to detect!
Disorder (chemical dopants)
- Rounds transitions
- Can destroy order!



How do we define and detect phases with nanoscale pattern formation?

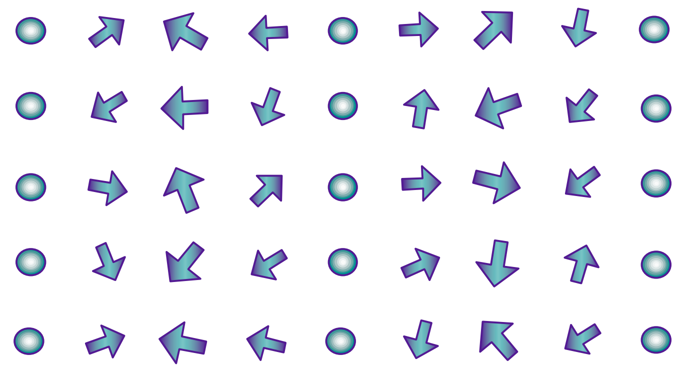
What's a Stripe?

Most Ordered



Unidirectional Spin and Charge Density Wave

Less Ordered



Unidirectional Charge Density Wave

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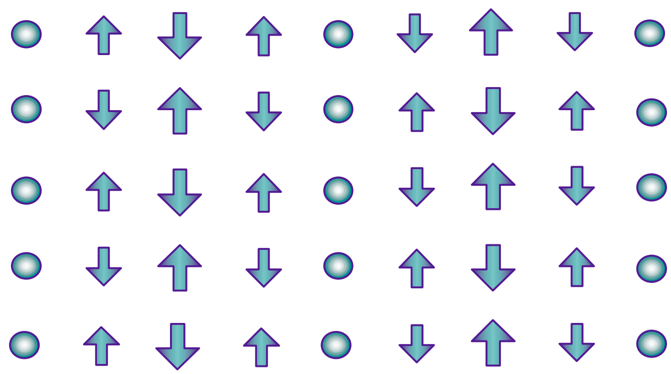

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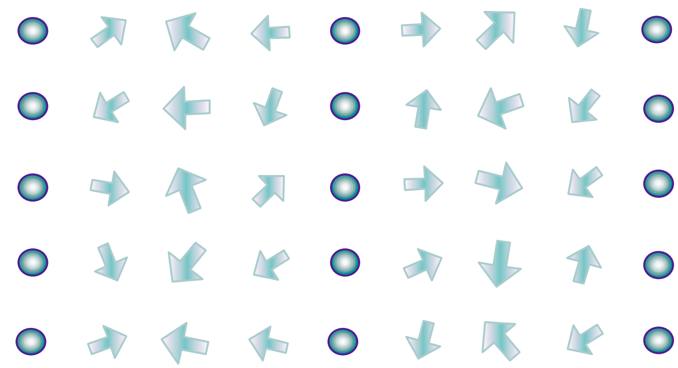

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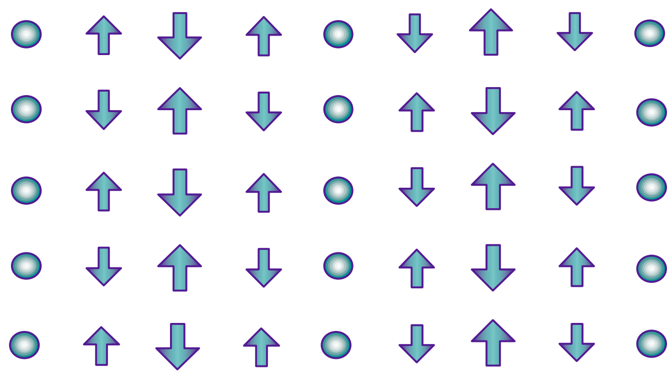

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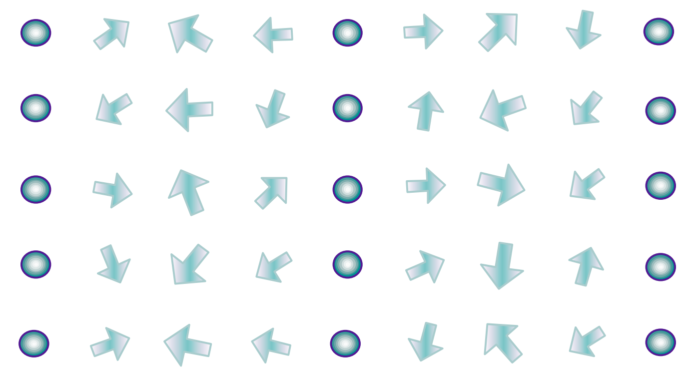
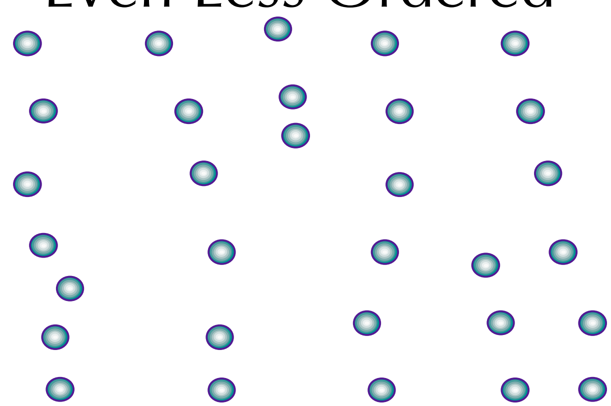


Unidirectional Charge Density Wave

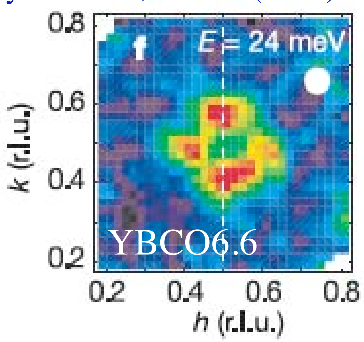
Even Less Ordered



Oriented Charge (nematic)

Stripes in what probes?

Hayden *et al*., Nature (2004)

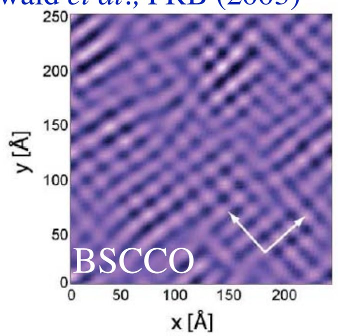


Neutron Scattering

(bulk probe)

LaSrCuO, LaCuO, YBaCuO (not BiSrCaCuO)

Howald *et al*., PRB (2003)

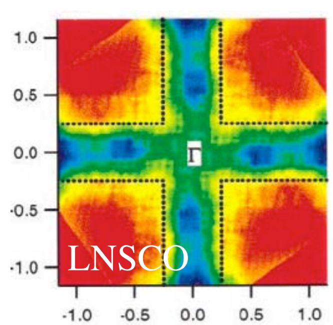


Scanning Tunneling Microscopy

(surface probe)

BiSrCaCuO

Zhou *et al*., Science (1999)



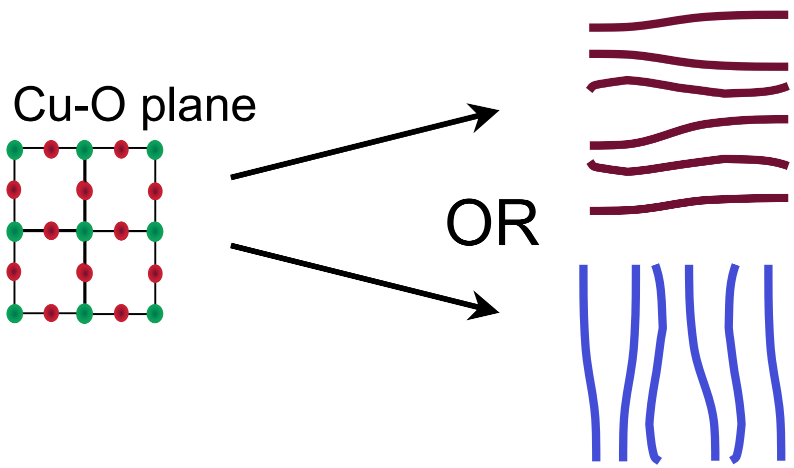
Angle-Resolved Photoemission Spectroscopy

(surface probe)

BiSrCaCuO, YBaCuO

Stripes + Disorder → Random Field Ising Model

Stripes lock to a crystal direction



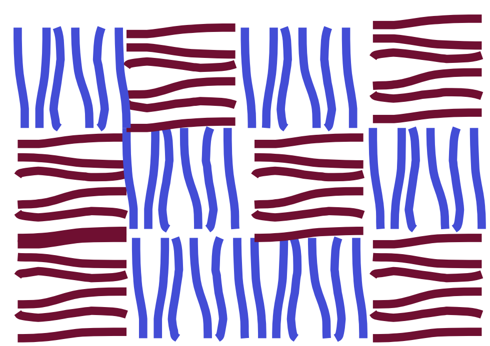
Ising Nematic

σ = 1 for horizontal stripe patch

σ = -1 for vertical stripe patch

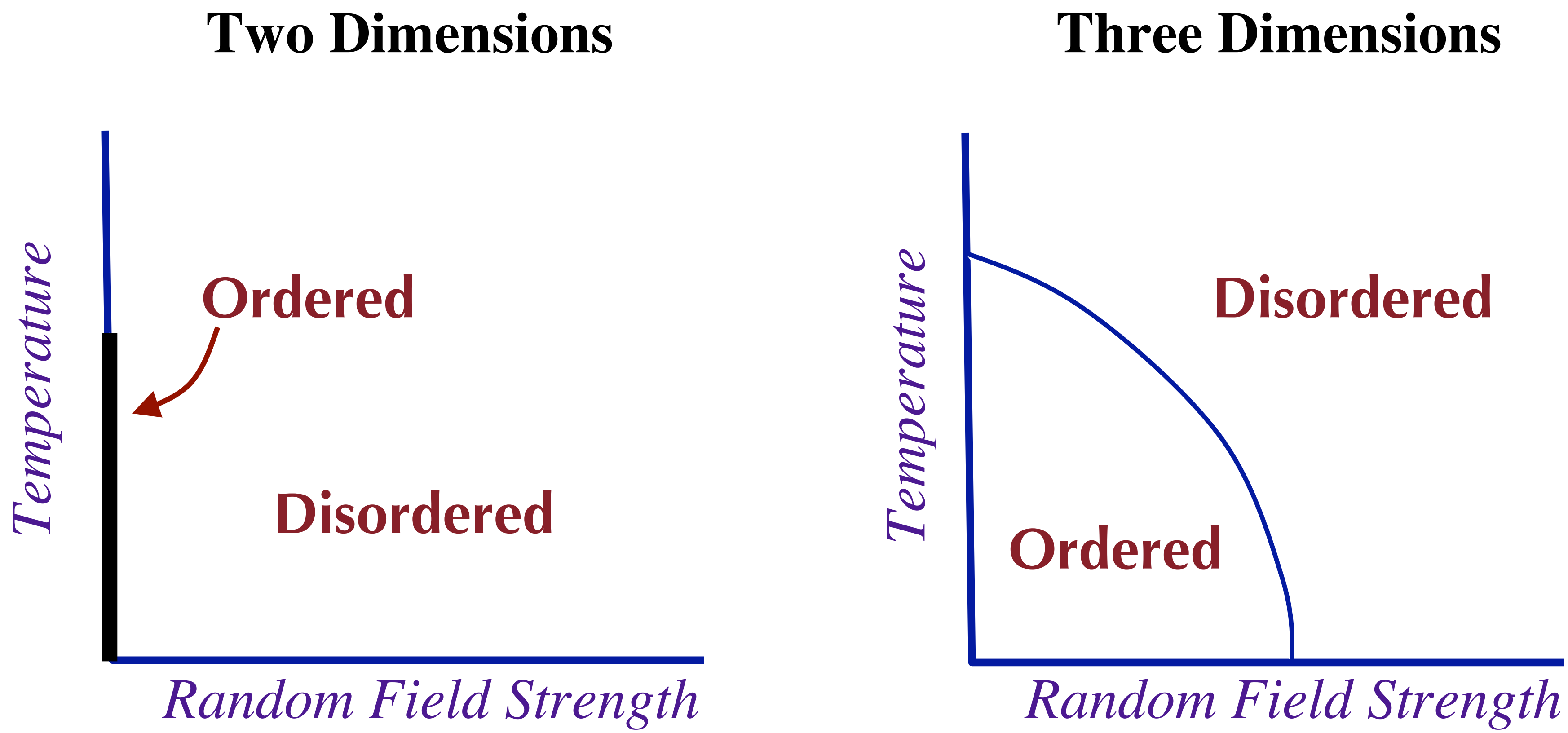
Disorder favors one direction locally

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



RANDOM FIELD ISING MODEL

Random Field Ising Model



$$H = -J \sum_{\langle i,j \rangle} \sigma_i \sigma_j - \sum_i h_i \sigma_i$$

Noise: Snap, Crackle, Pop

Pencil

Snap

Fire

Crackle

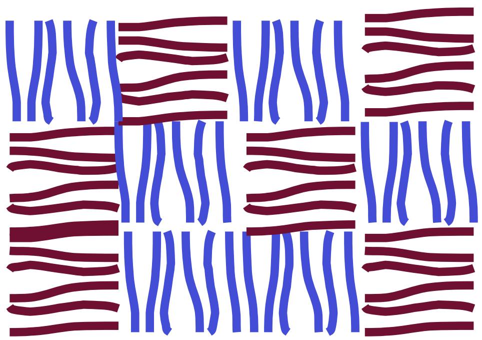
Popcorn

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

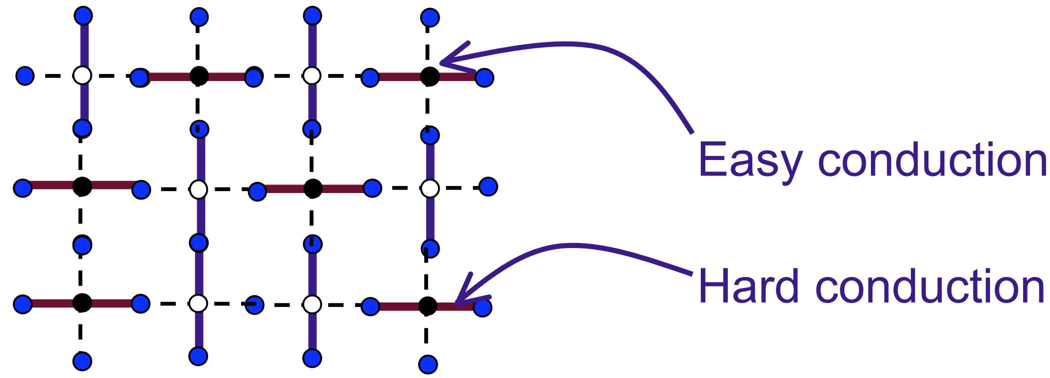
Transport

Stripe Patches



Maps To

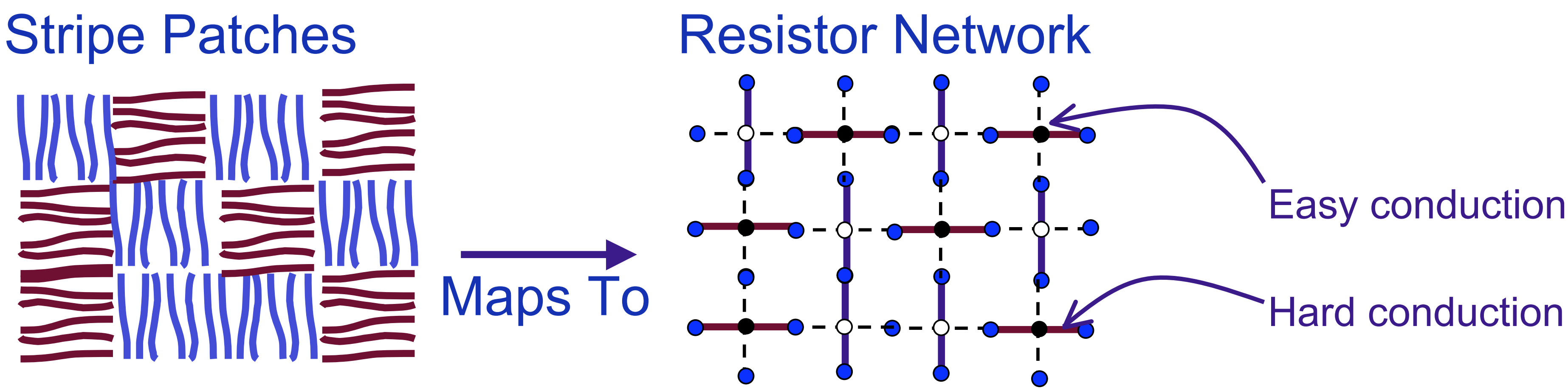
Resistor Network



Calculations:

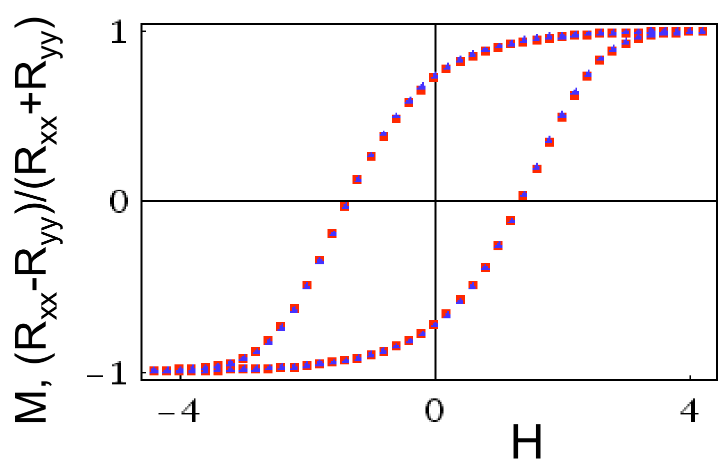
Monte Carlo Simulation of random field Ising Model
Each configuration maps to a resistor network
R_{xx} and R_{yy} calculated via
bond propagation algorithm (Frank *et al.*, PRB 1988)
(Generalized to planar Ising models: Loh, EC, PRL 2006)

Transport



Resistance Anisotropy and RFIM Magnetization exhibit hysteresis

"Magnetization" = orientational order



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

LXL = 300X300

T=0; Δ = 2.8 J; R_{large}/R_{small} = 2

Confined Geometries: Telegraph Noise

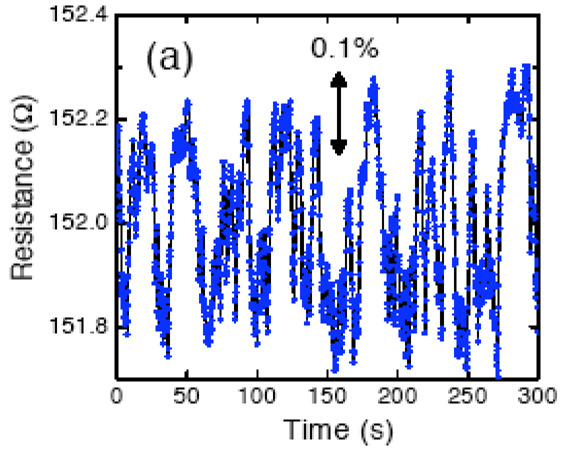
Experiment

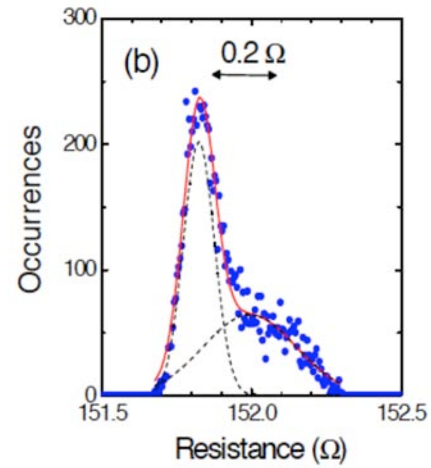
Bonetti *et al.*, PRL 93, 087002 (2004).

YBCO nanowire
(underdoped)

T=100K
500nmX250nm

Large switch ≈ 5 patches





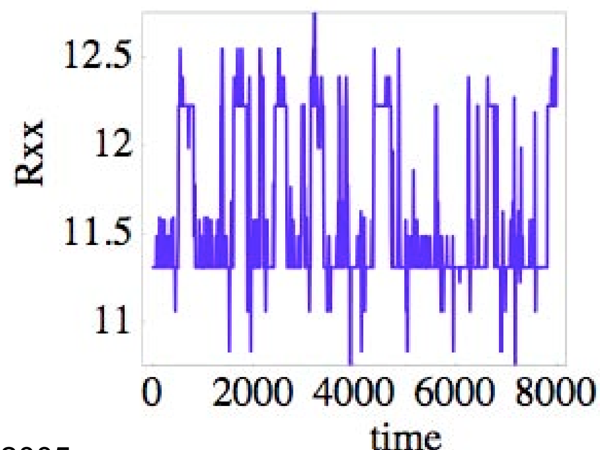
Theory

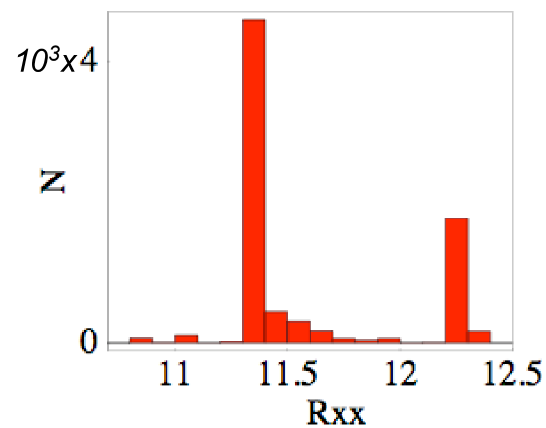
EC *et al.*, PRL 96, 097003 (2006).

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

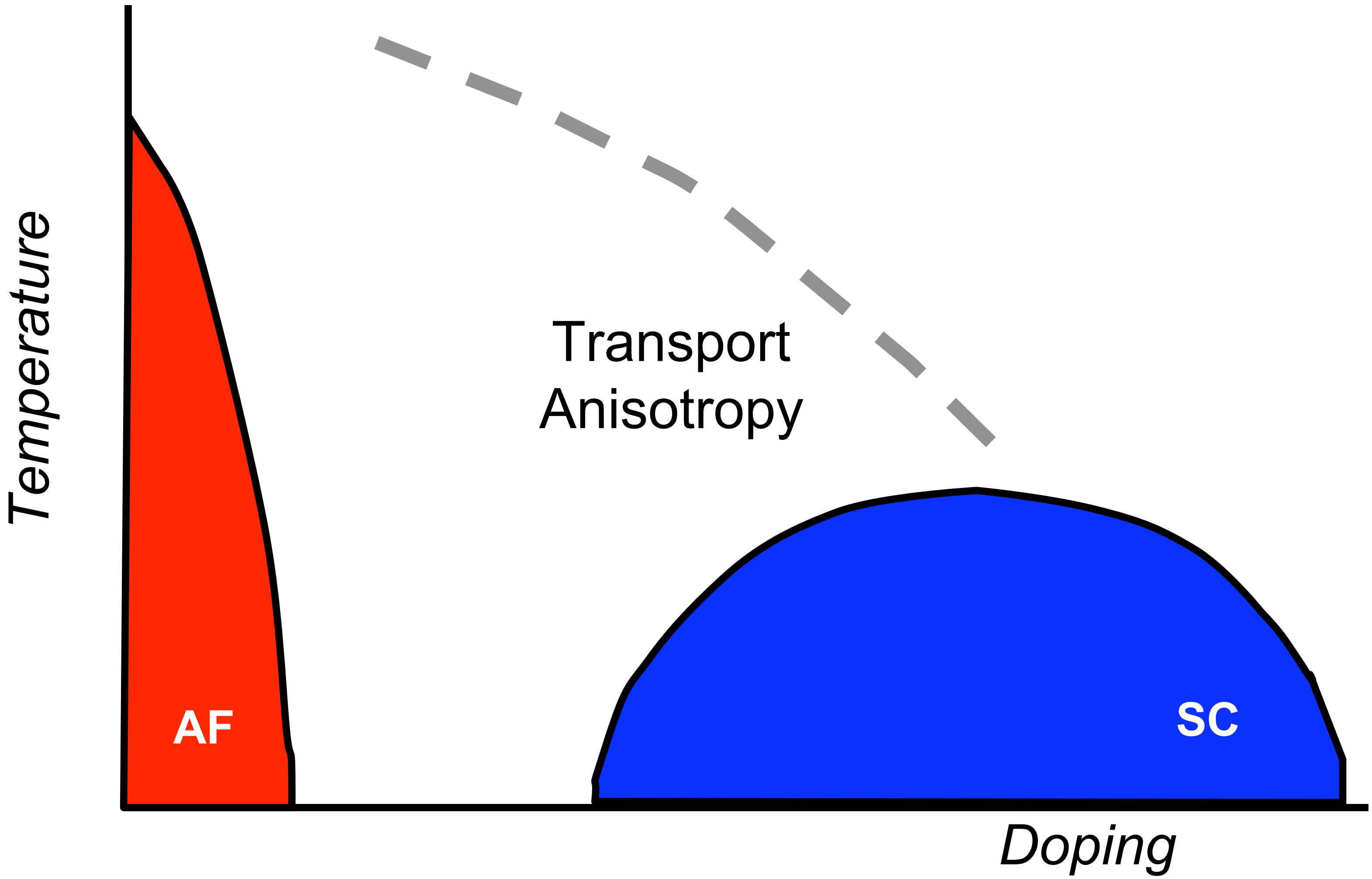
- Stripe correlation length
  ~ 40nm(from neutron data)

see also Reichhardt et al, Europhys. Lett. 2005

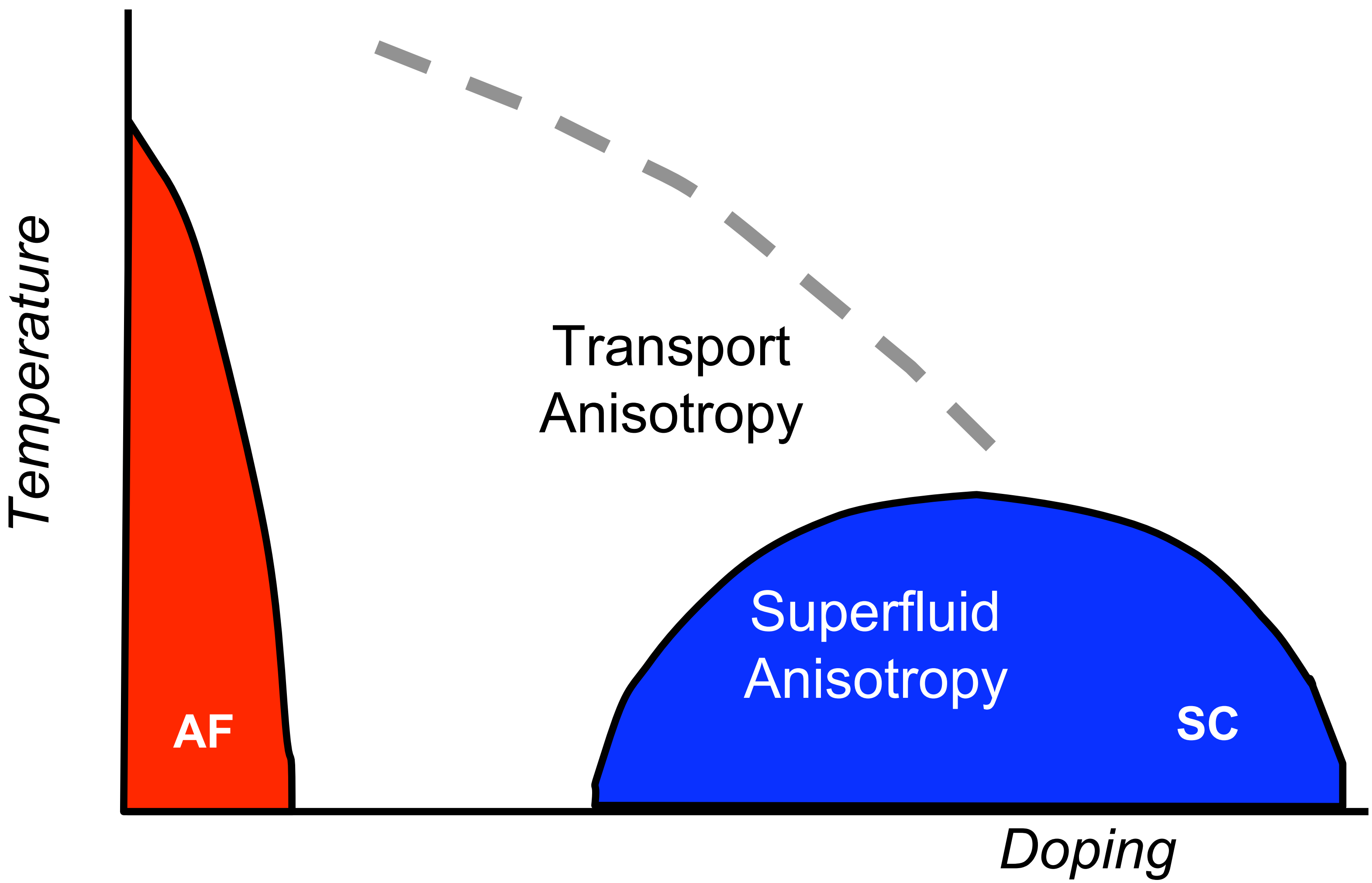




That was for the normal state...



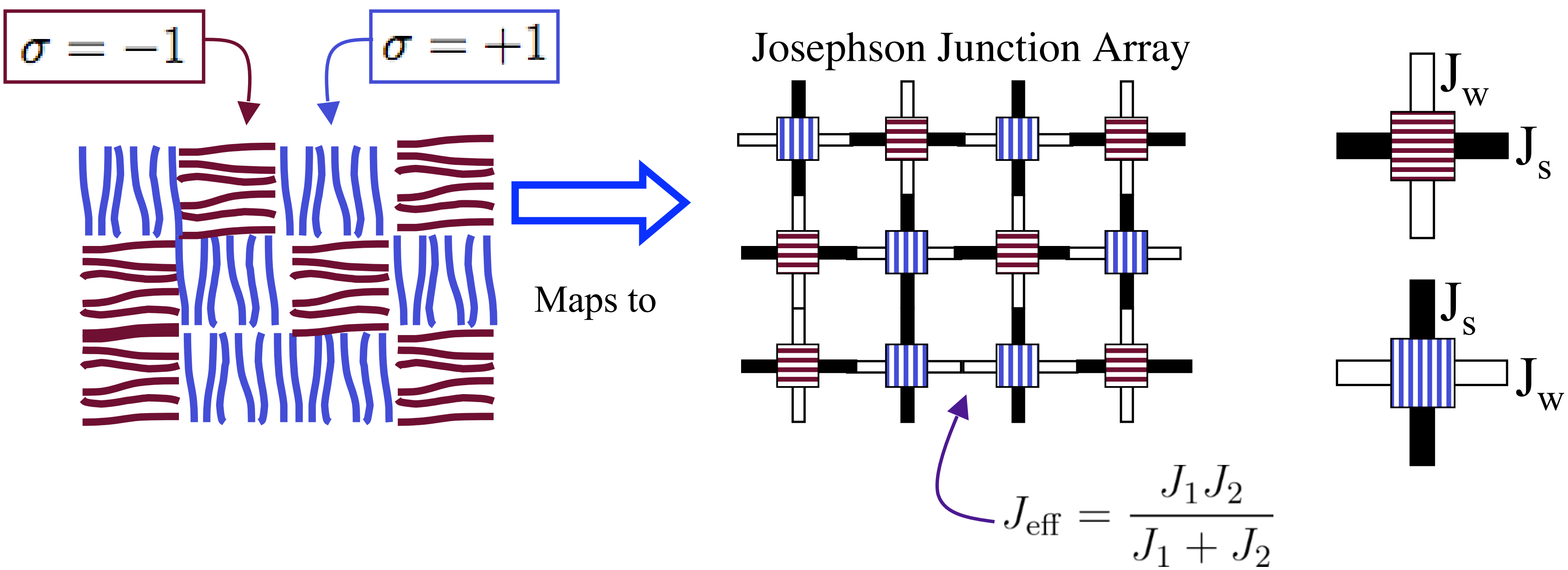
That was for the normal state...



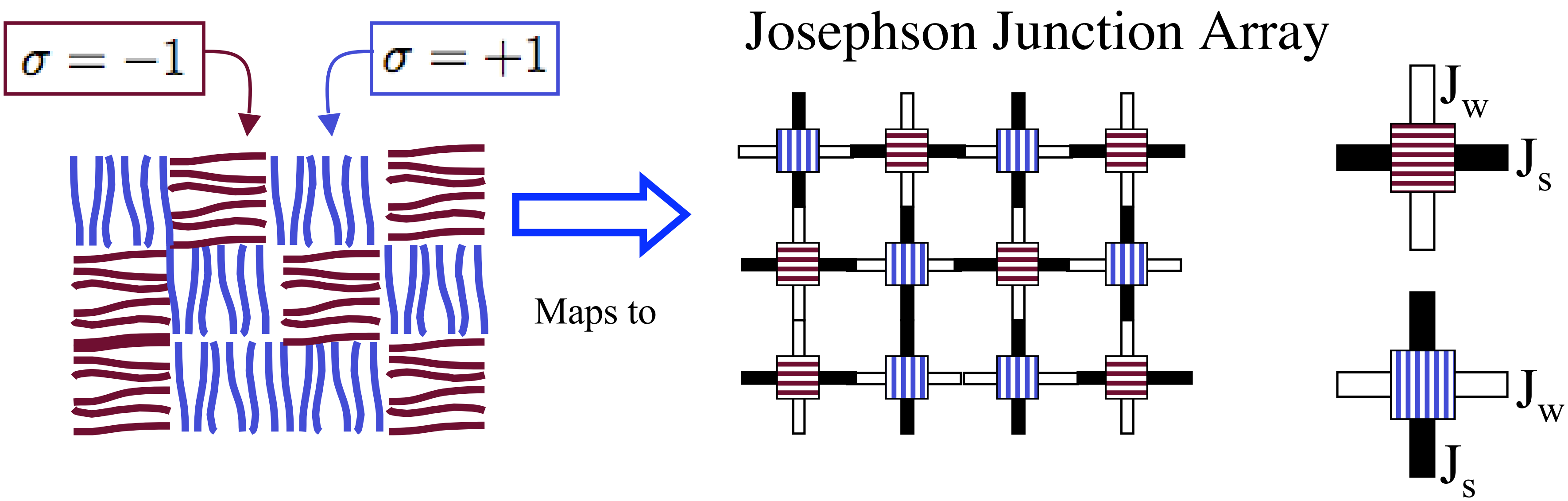
Superfluid Density Anisotropy

Calculations:

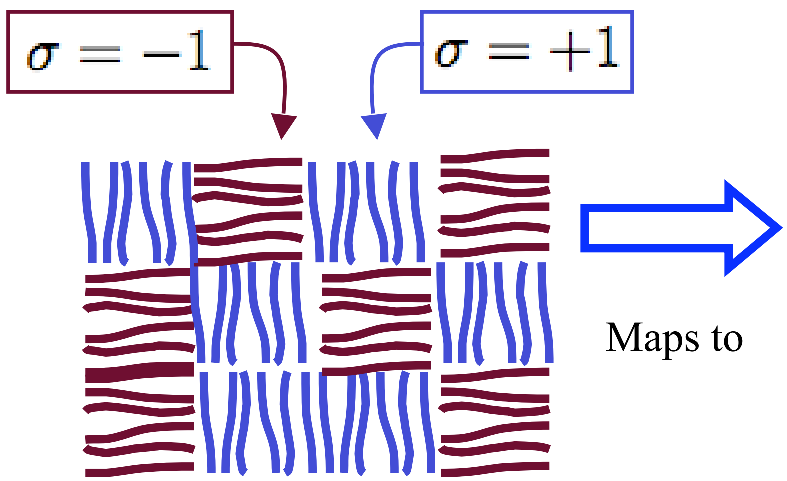
Monte Carlo Simulation of random field Ising Model
Each configuration maps to Josephson Junction Array (JJA)
Monte Carlo simulation for each JJA pattern



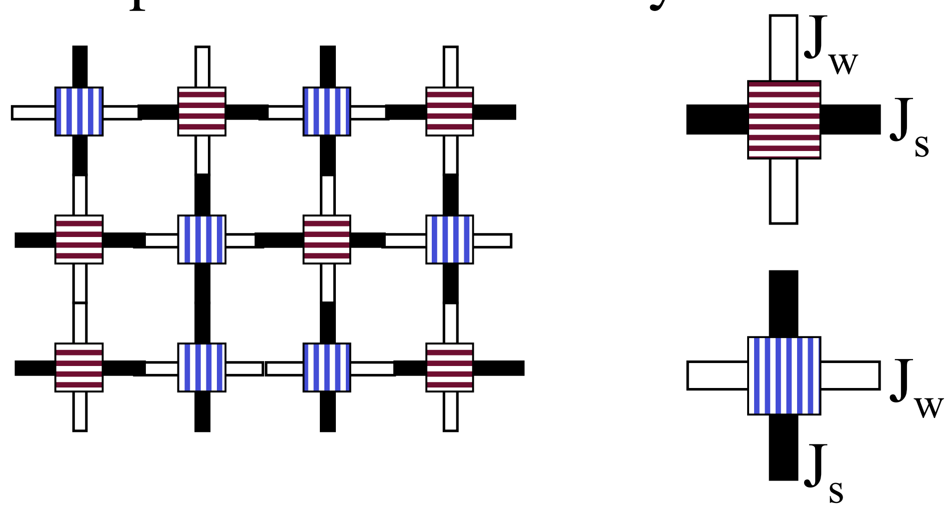
Superfluid Density Anisotropy

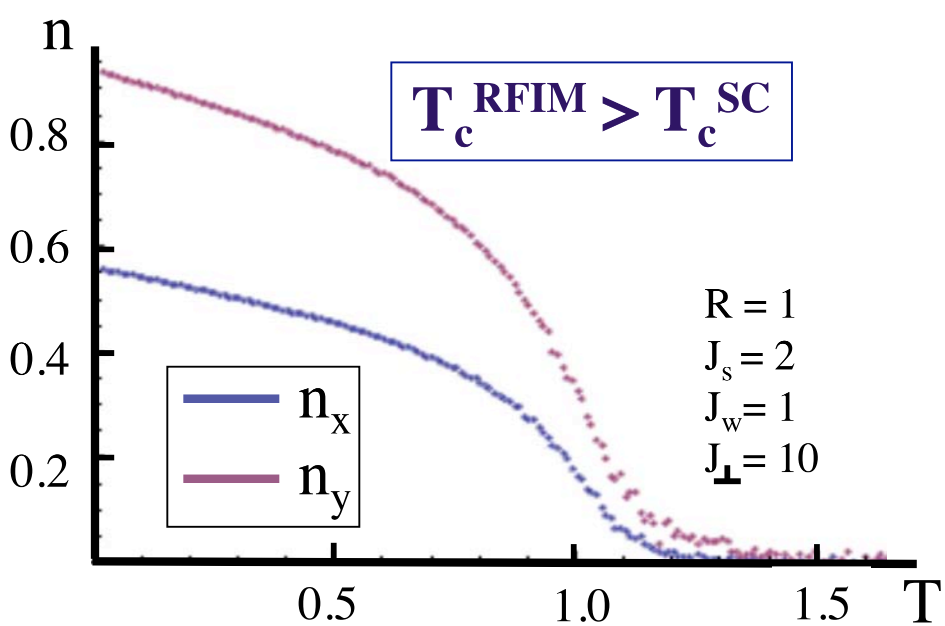


Superfluid Density Anisotropy

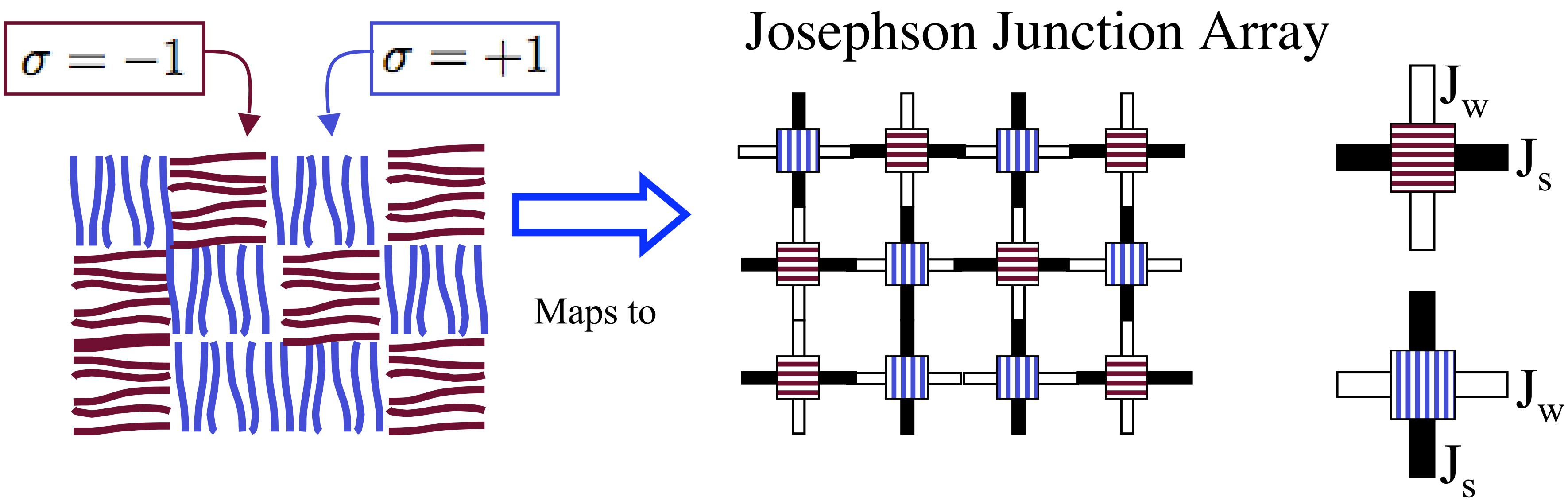


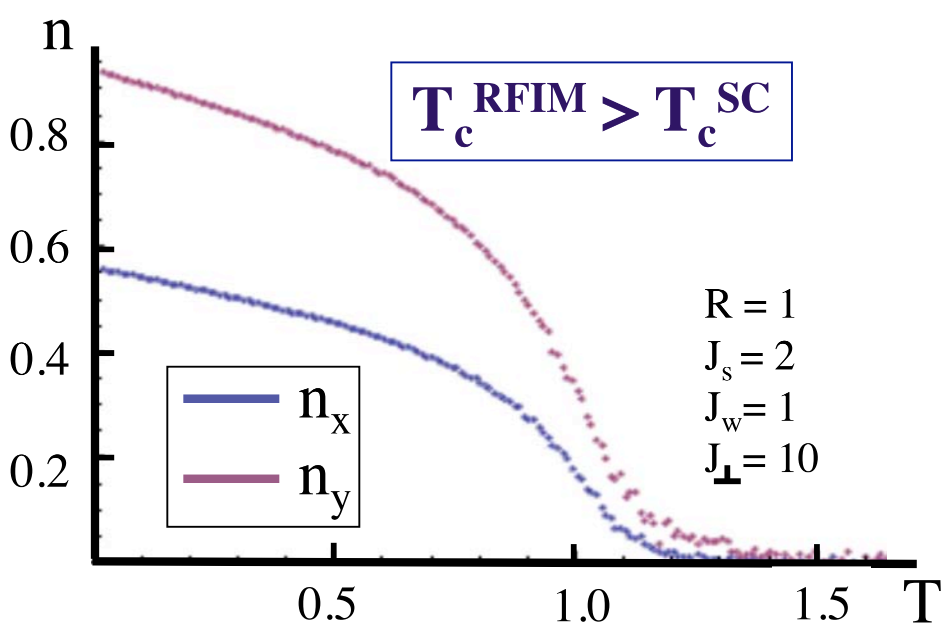
Josephson Junction Array

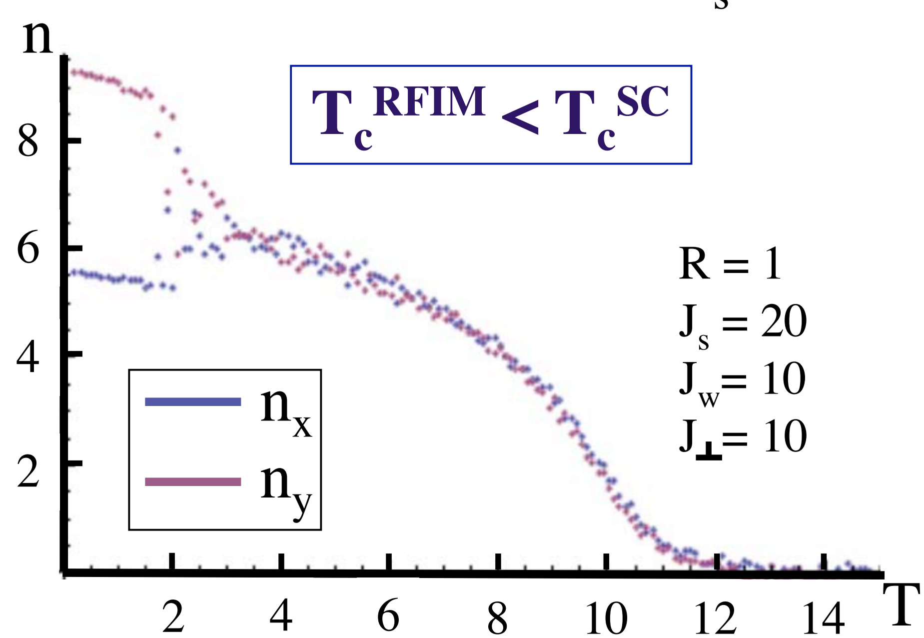




Superfluid Density Anisotropy







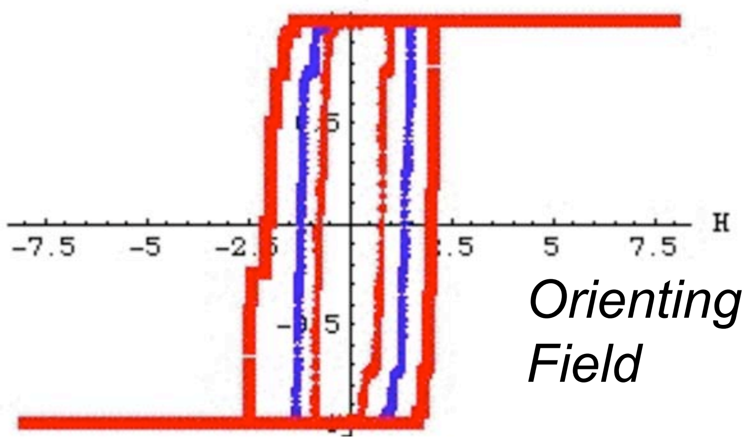
Hysteretic Superfluid Density Anisotropy

Apply an orienting field, "H"

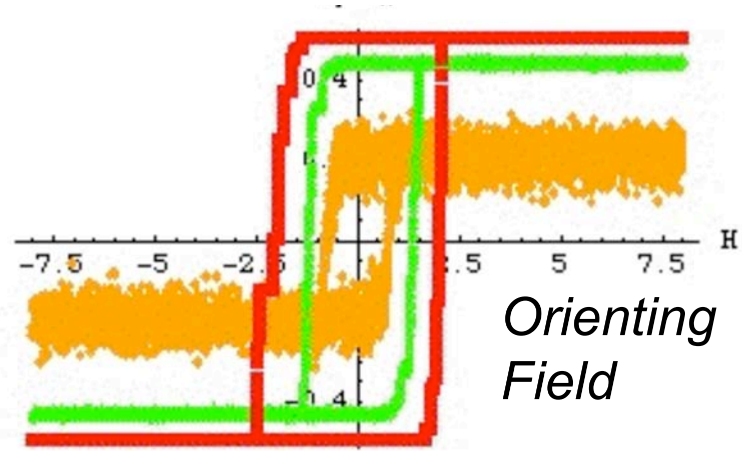
e.g., Uniaxial Strain on a Thin Film

Ordered
$\Delta=1$
Js=2
Jw=1
L = 8
T=0,.5,1

Stripe Orientation



Superfluid Anisotropy



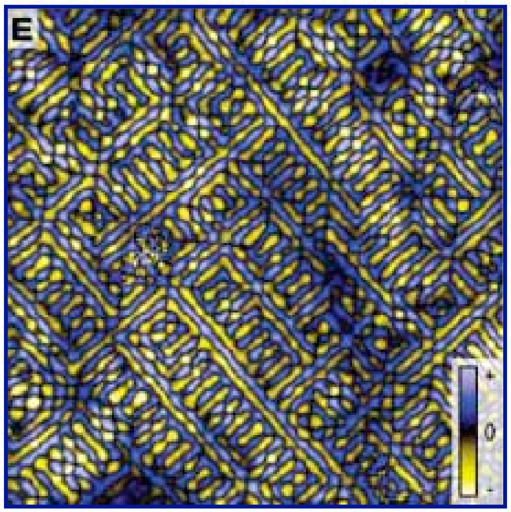
Intermediate disorder: Weak disorder within planes, Strong disorder between planes.
Planes "snap" individually

with B. Phillabaum, Y. Loh

Comparisons to STM

Low Temperature Electronic Glass with Unidirectional Domains

Experiment



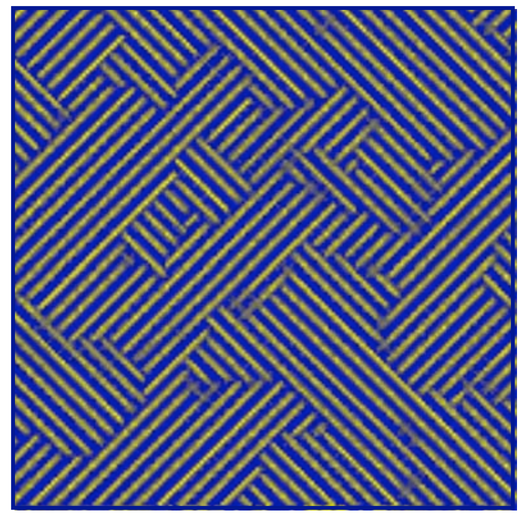
$Ca_{1.88}Na_{.12}CuO_2Cl_2$

T=4.2K

Kohsaka *et al.*,

Science **315**, 1380 (2007)

Theory



Layered system

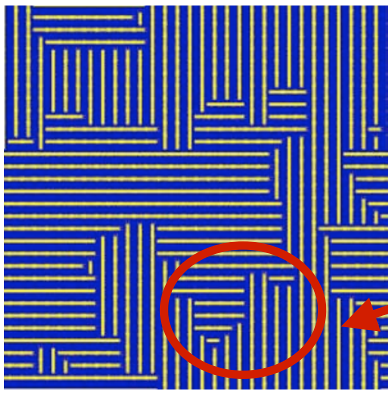
$J_{\perp} = J_{\parallel}/10$ (Ising couplings)

$T = 1.5 J_{\parallel}$

$\Delta = 1.5$ (disorder strength)

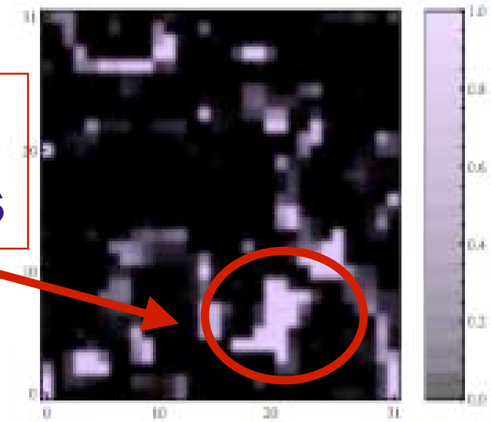
Prediction: Telegraph Noise in STM

Stripe Glass



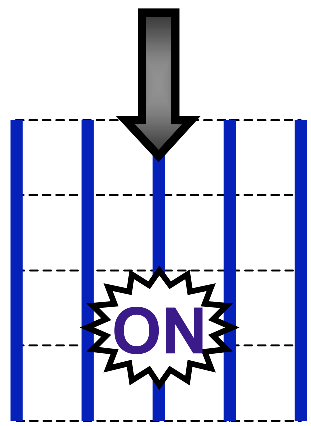
R=1.5
T=0.5

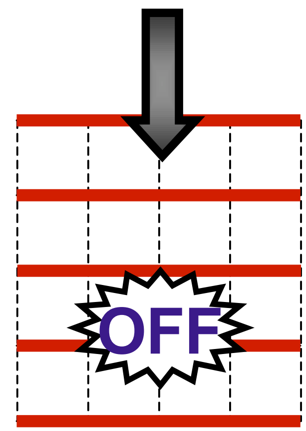
Variance



Active Regions are at Domain Boundaries

Place STM tip on a line at a stripe boundary





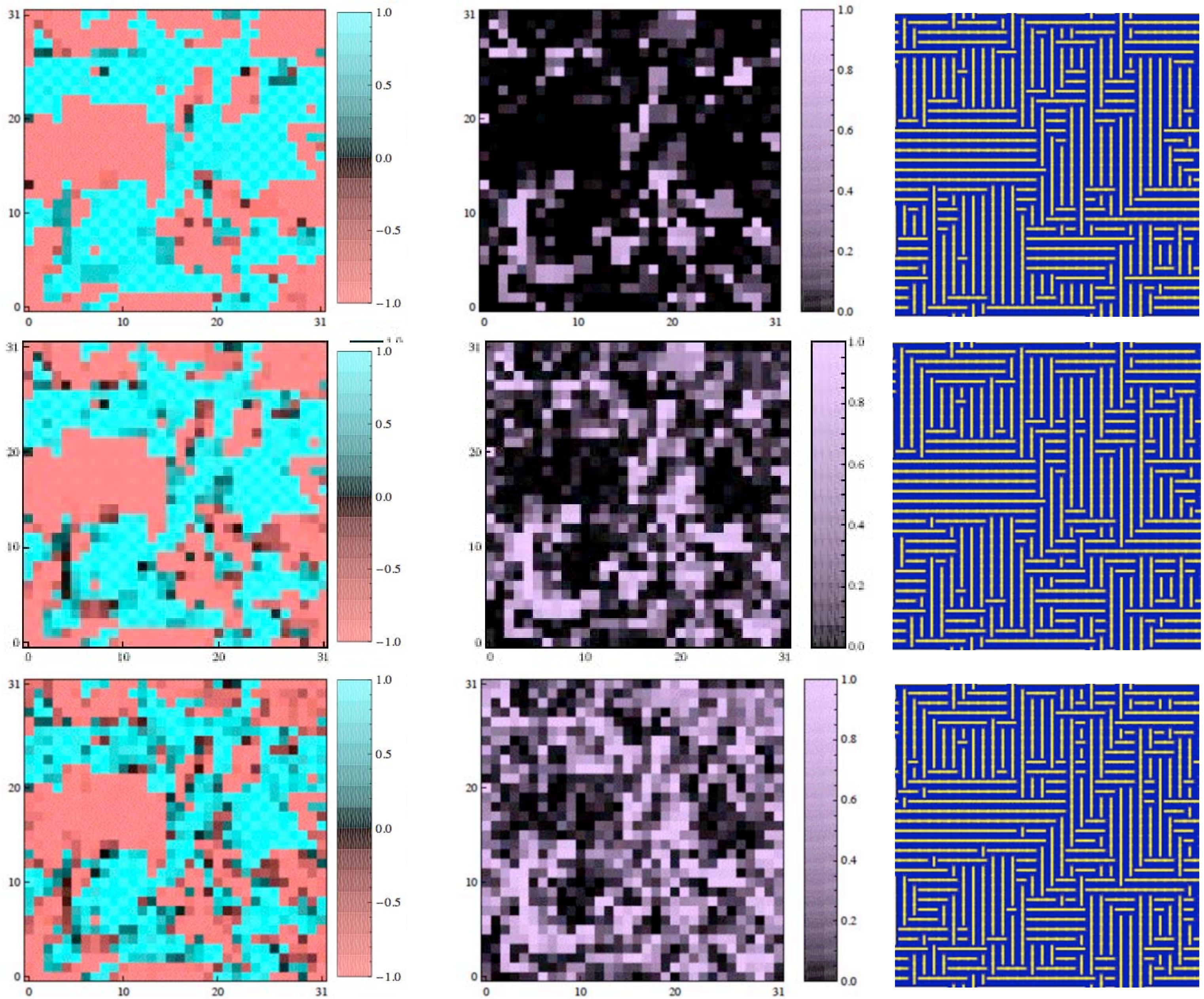
Telegraph Noise

Time Average | Variance | Stripe Glass

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

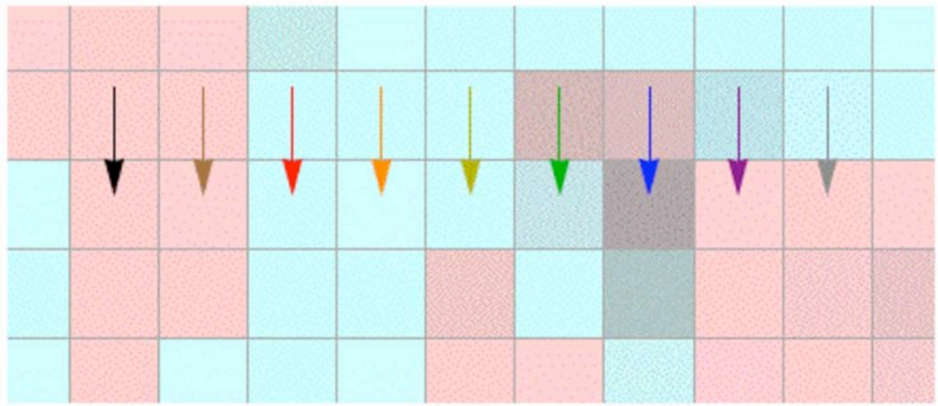
Power Spectrum

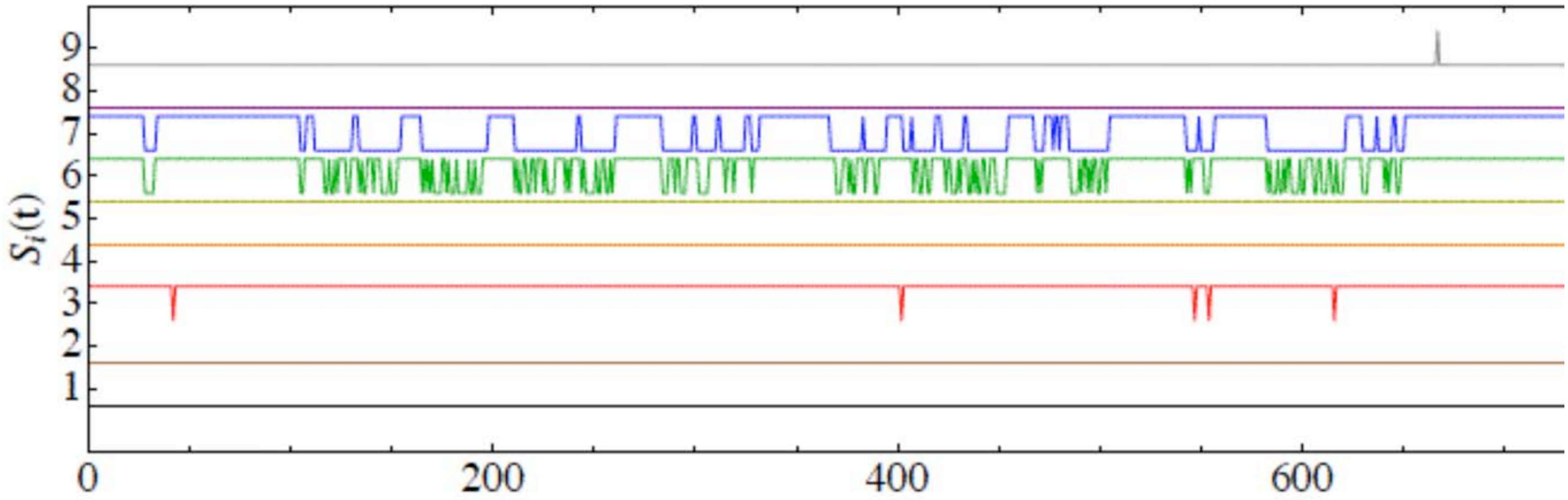
- Single uncorrelated switcher: Lorentzian power spectrum
- Interactions cause deviations

Power spectrum is impractical for 25-60 second noise

Spatial and Temporal Correlations in Noise

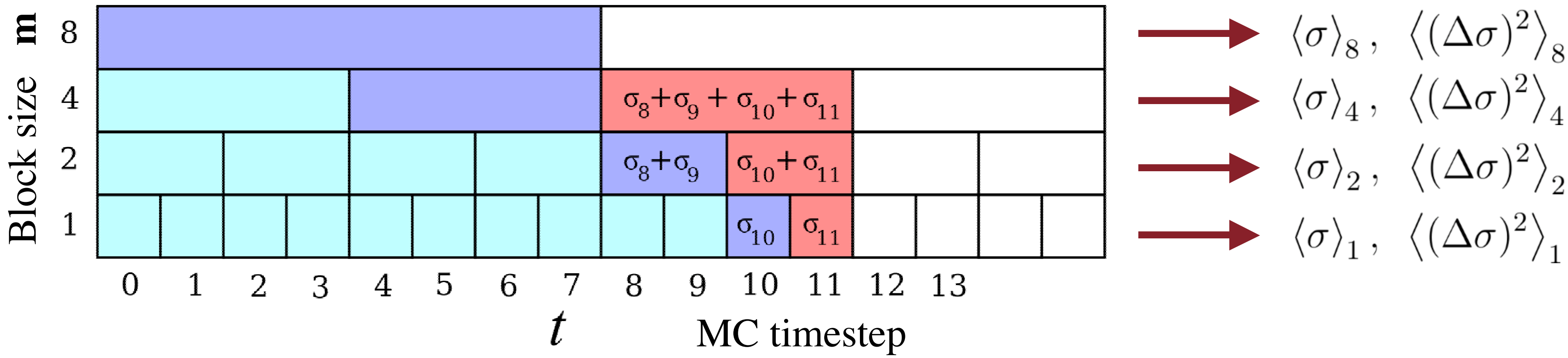
R=2.5
T=0.5





In-Situ Test for Correlations

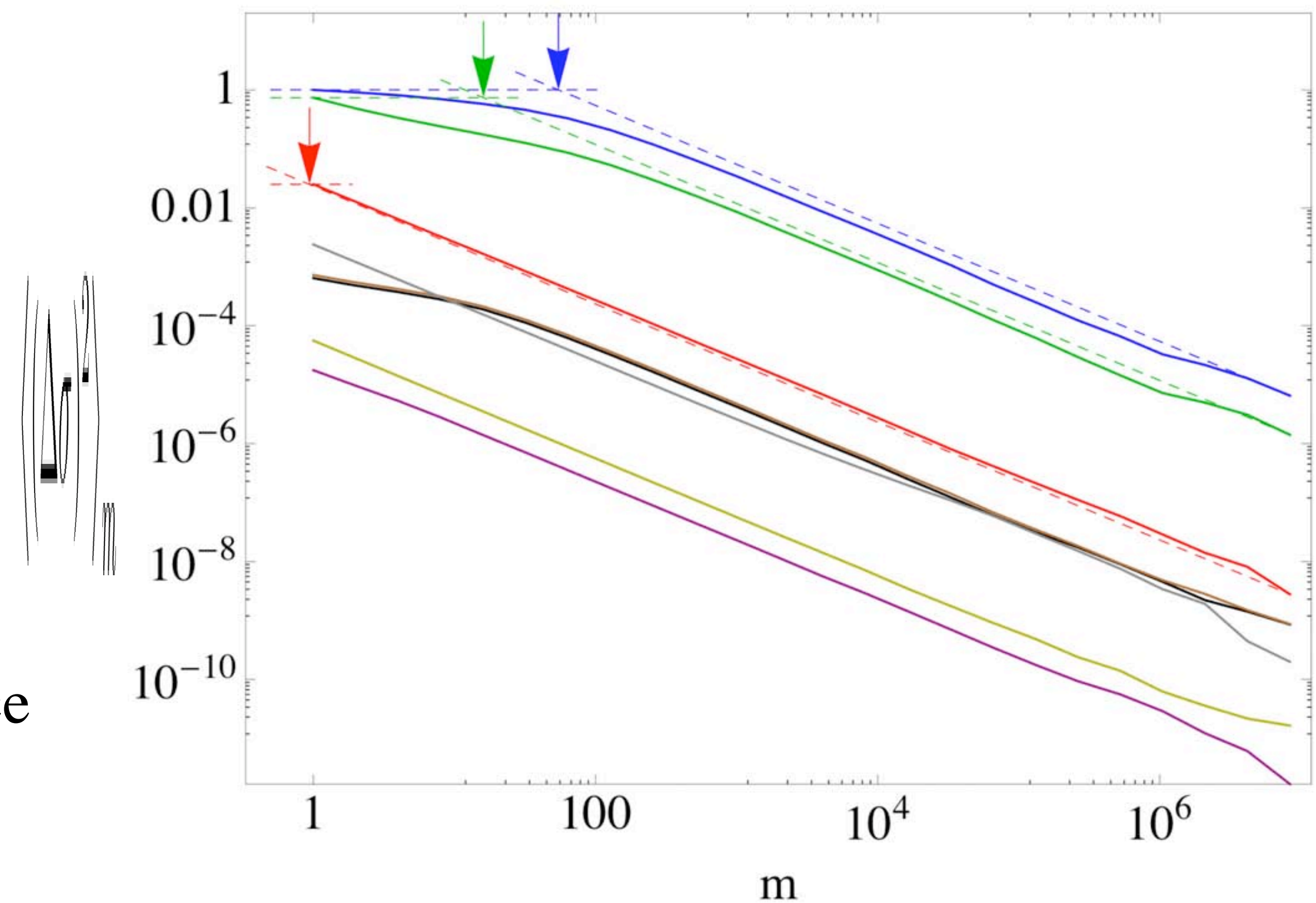
"On-the-fly" Reblocking Algorithm (Kent *et al.*, J. Comp. Chem. 2007)



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

Block
Variance

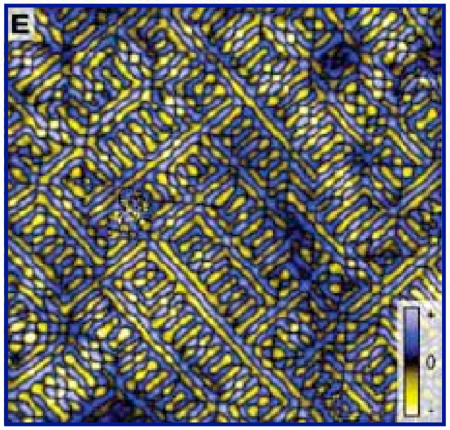


Low m deviations from horizontal line indicate correlations

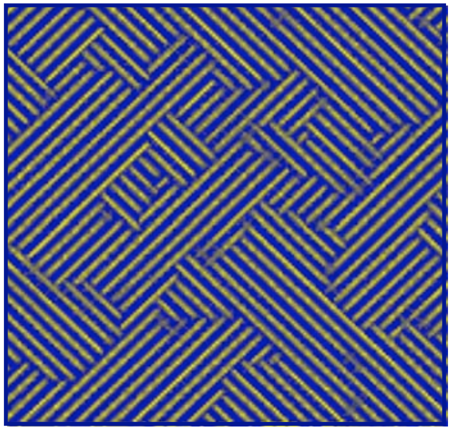
Conclusions

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