Using Disorder to Detect Order: Hysteresis and Noise of Nematic Stripe Domains in High Temperature Superconductors

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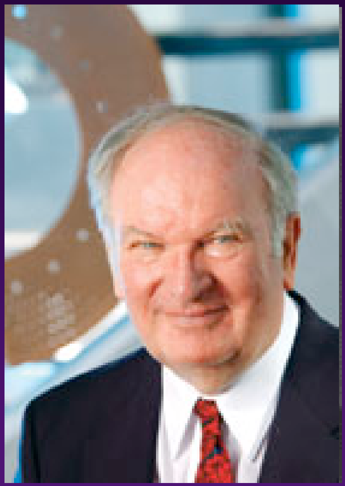
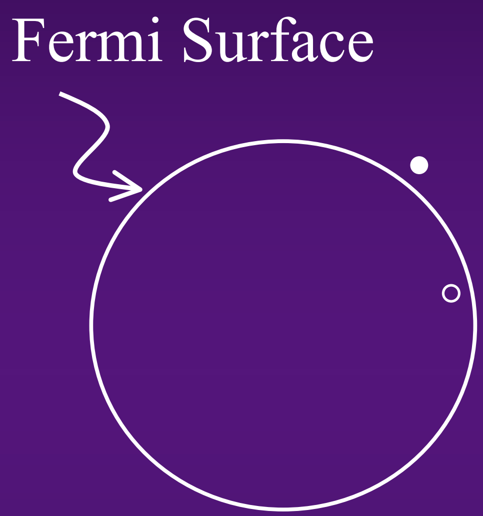


Bob Schrieffer

Conventional Superconductivity

- BCS Theory
- *Instability* of the metallic state

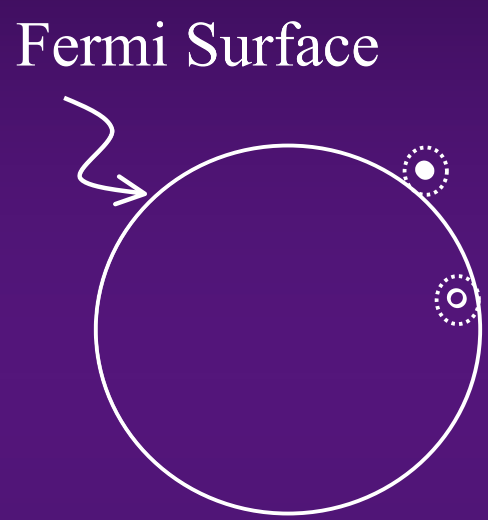
Simple Metals: The Fermi Gas



- Free Electrons $E \sim k^2$
- Pauli exclusion principle
- Fill to Fermi level

Adiabatically turn on temperature, most states unaffected
Very dilute gas of excitations: quasiparticles

Simple Metals: The Fermi Liquid



- Pauli exclusion principle
- Fill to Fermi level

Adiabatically turn on temperature, most states unaffected
Very dilute gas of excitations: quasiparticles

Fermi Gas + Interactions → Fermi Liquid

Quasiparticles = Dressed Electrons

Kinetic Energy Dominant

Cooper Pairing

- Fermi Liquid Unstable to Pairing
- Pair electrons near Fermi Surface
- Phonon mediated

Retardation is Essential
to overcome
Coulomb repulsion

$$\frac{E_F}{\omega_D} \approx 10^3$$

BCS Haiku:

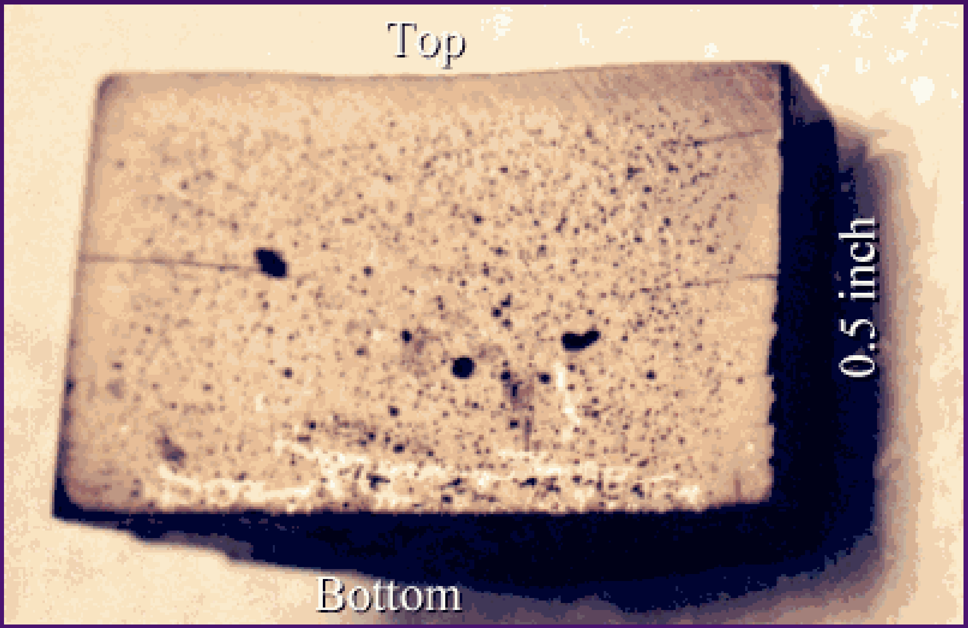
Instability

Of A Tranquil Fermi Sea—

Broken Symmetry

A Ceramic Superconductor?

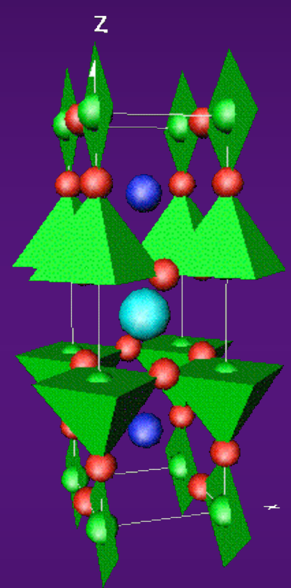
- Brittle
- Ceramic
- Not Shiny
- Not metallic



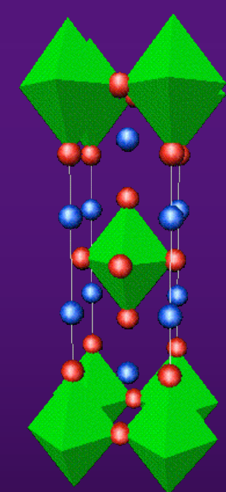
http://www.superconductivecomp.com/

- Why do they conduct at all?

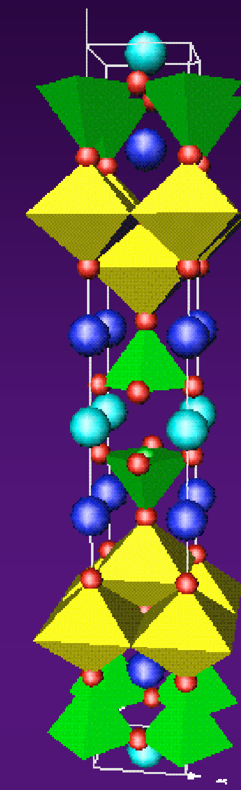
High Temperature Superconductors



$YBCO_7$

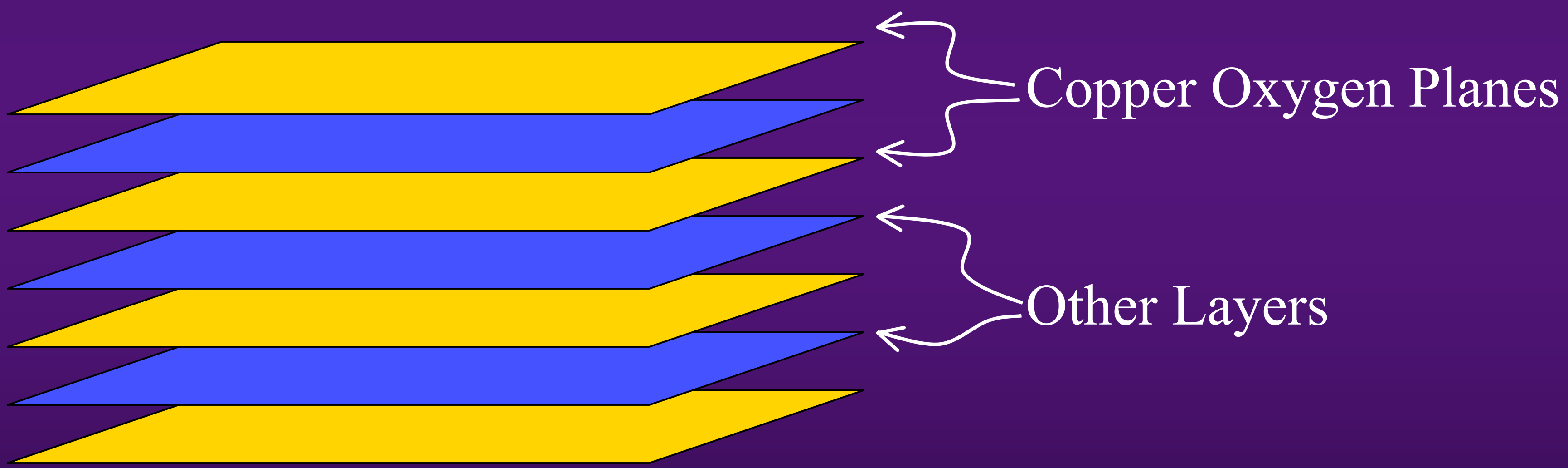


LSCO



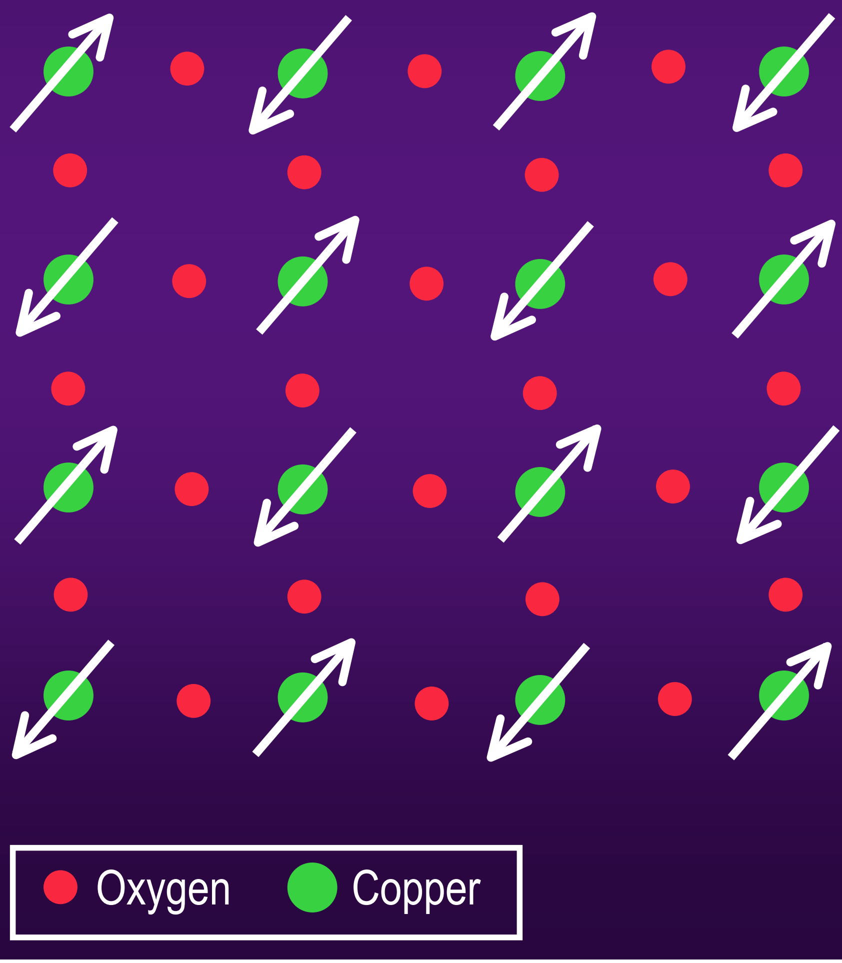
HgCuO

High Temperature Superconductors



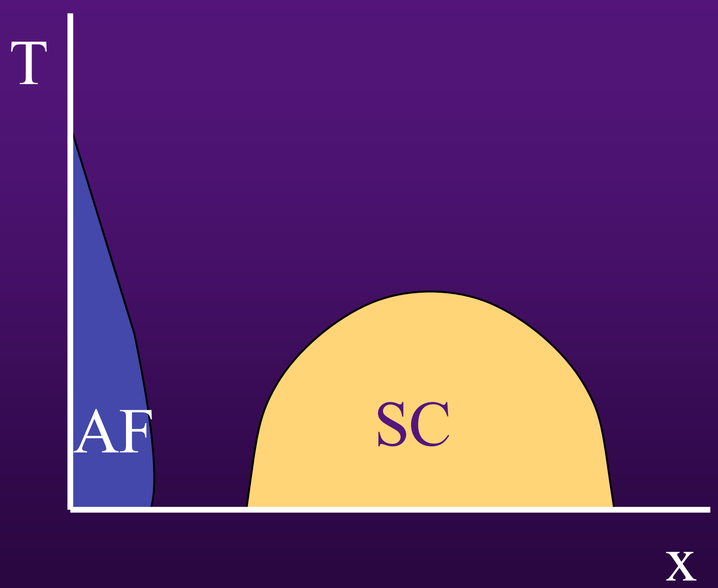
Layered structure → quasi-2D system

High Temperature Superconductors



Dope with holes

Superconducts at certain dopings



Mysteries of High Temperature Superconductivity

- Ceramic! (Brittle)
- “Non-Fermi liquid” normal state
- Magnetism nearby (antiferromagnetism)
- Make your own   (robust)
  http://www.ornl.gov/reports/m/ornlm3063r1/pt7.html
- Pseudogap
- Phase ordering transition

Two Energy Scales in a Superconductor

Two component order parameter

$$\psi = \Delta e^{i\theta}$$

Amplitude	Phase
Pairing	Phase Coherence
Gap	Superfluid Density

BCS is a mean field theory in which pairing precipitates order

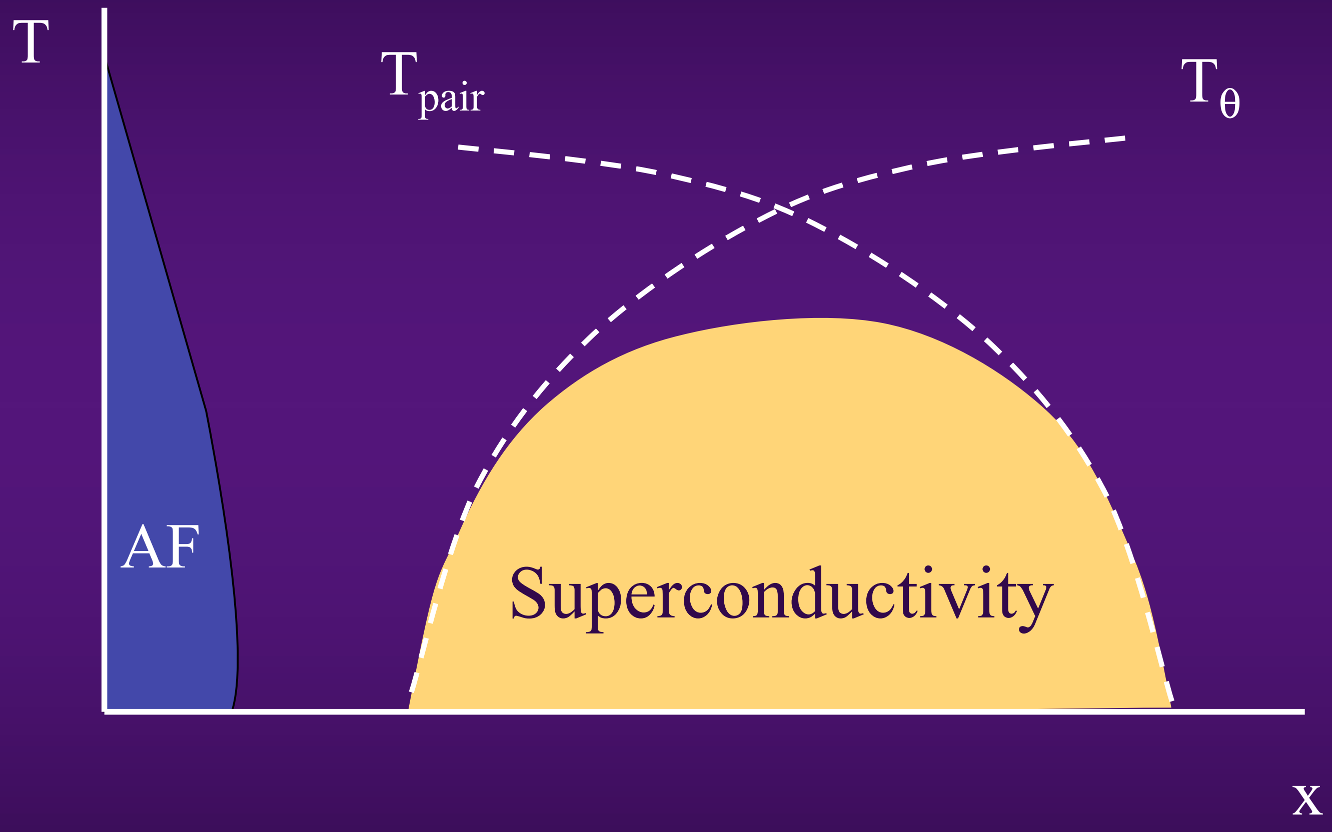
Material	T_{pair}[K]	T_c[K]	T_θ[K]
Pb	7.9	7.2	$6X10^5$
Nb_3Sn	18.7	17.8	$2X10^4$
UBe_{13}	0.8	0.9	10^2
BaKBiO	17.4	26	$5X10^2$
K_3C_{60}	26	20	10^2
MgB_2	15	39	$1.4X10^3$

Phase Fluctuations Important in Cuprates →

Material	T_{pair}[K]	T_c[K]	T_θ[K]
LSCO (ud)	75	30	47
LSCO (op)	58	38	54
LSCO (od)		20	100
Hg-1201 (op)	192	96	180
Hg-1212 (op)	290	108	130
Hg-1223 (op)	435	133	130
Tl-2201 (op)	122	91	
Tl-2201 (od)		80	160
Tl-2201 (od)	26	25	
Bi-2212 (ud)	275	83	
Bi-2212 (op)	220	95	60
Bi-2212 (od)	104	62	
Y-123 (ud)		38	42
Y-123 (op)	116	90	140
Y-123 (od)	55	140	

Emery, Kivelson, Nature, **374**, 434 (1995)
EC, Kivelson, Emery, Manousakis, PRL **83**, 612 (1999)
EC, Emery, Kivelson, Orgad, in The Physics of Superconductors (2004)

T_c and the Energy Scales

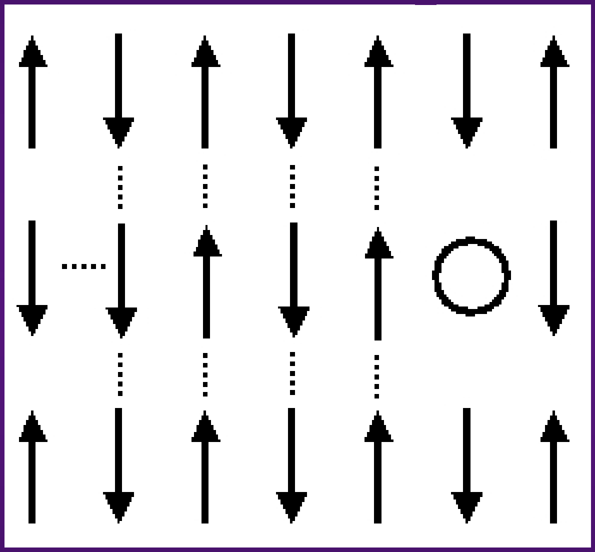


BCS: $T_\theta \sim 1000\ T_c$

HTSC: $T_\theta \sim T_c$ underdoped

Very different from BCS.

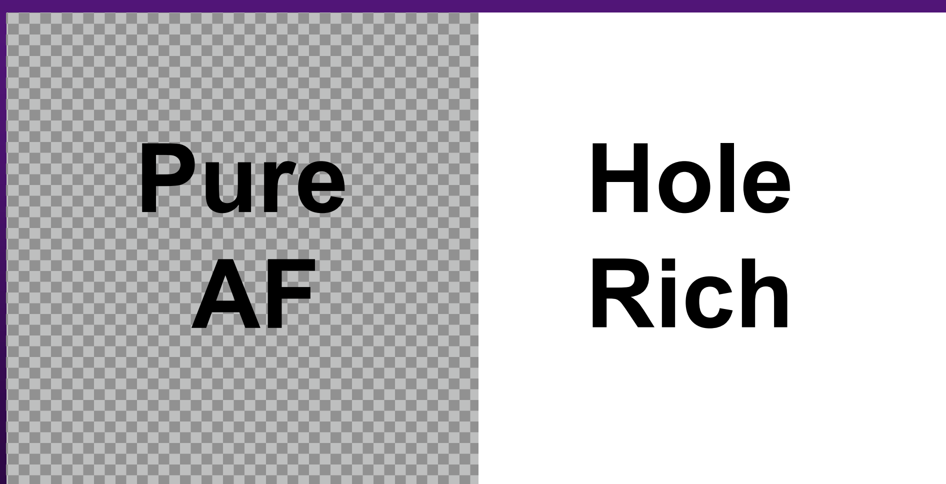
Doped Antiferromagnets



Hole Motion is Frustrated

Doped Antiferromagnets

- Compromise # 1: Phase Separation
- Relieves some KE frustration



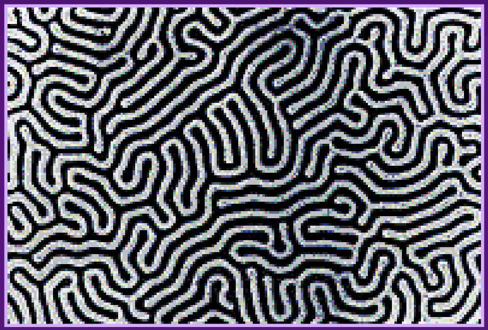
Like Salt Crystallizing
From Salt Water,
The Precipitate (AF) is Pure

Coulomb Frustrated Phase Separation

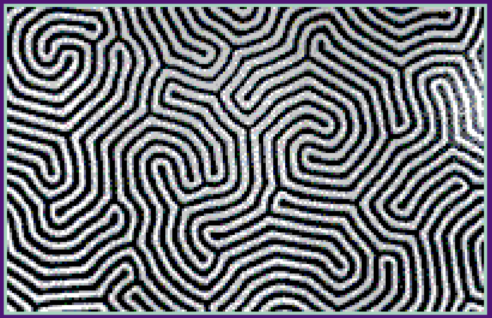
- Long range homogeneity
- Short range phase separation
- Compromise # 2: *mesoscale structure*
- Patches interleave
- quasi-1D structure – stripes ?

Competition often produces stripes

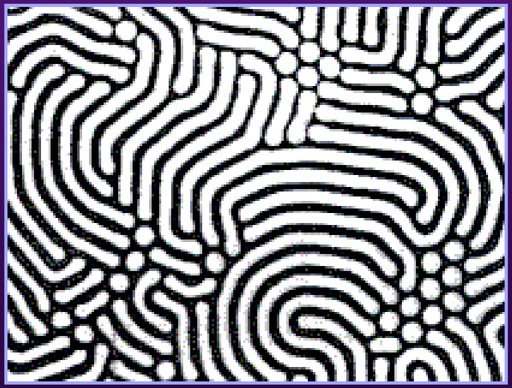
Holes want to phase separate (run away), but Coulomb repulsion prevents it. Competition produces local inhomogeneity.



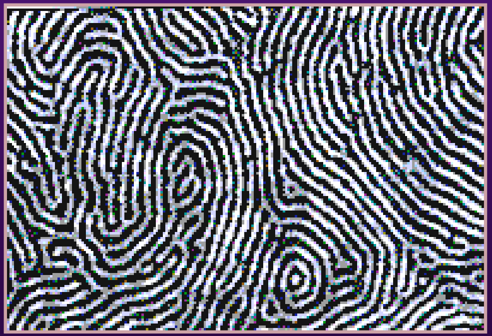
Ferrofluid confined between two glass plates Period ~ 1cm



Ferromagnetic garnet film Faraday effect Period ~ 10^{-5} m

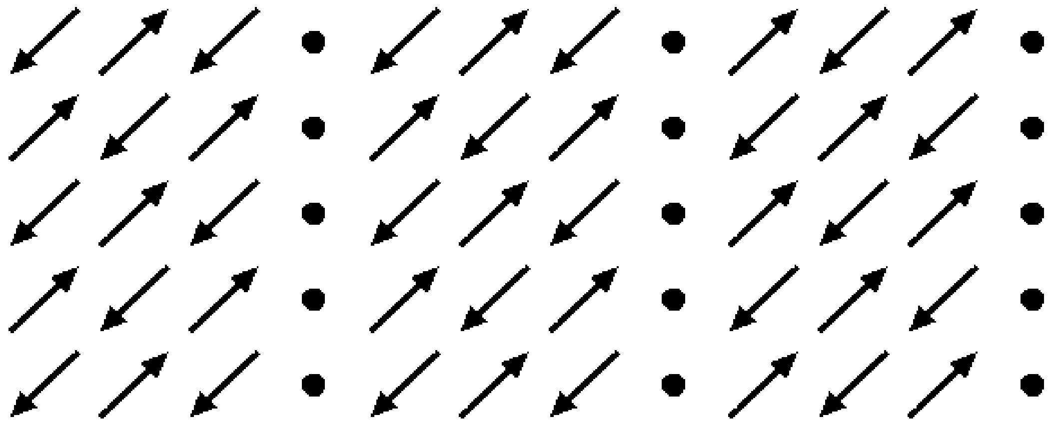


Ferromagnetic garnet film Period ~ 10^{-5} m



Block copolymers Period ~ $4\text{X}10^{-8}$ m

What's so special about 1D?



Liquid-like electrons here have new behavior due to 1D

Two types of solitons:

Charge Solitons

Spin Solitons

The electron is no longer a stable many-body excitation

Pair spins directly, no Coulomb repulsion = Pairs at high temperature!

Stripe Issues

Why do we care?

- Novel electronic phases: liquid crystals
- May shed light on High Tc (route to pairing mechanism)

Issues about stripes in HTSC:

- Are they there?
- Are they ubiquitous?
- What constitutes evidence of them?

Hard to detect!

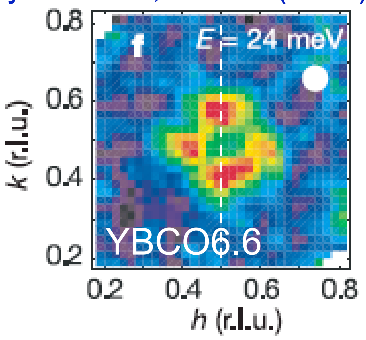
Disorder (chemical dopants)

- Rounds transitions
- Destroys order!

> How do we define and detect “order”
> in the presence of severe disorder effects?

Stripes in what probes?

Hayden *et al.*, Nature (2004)

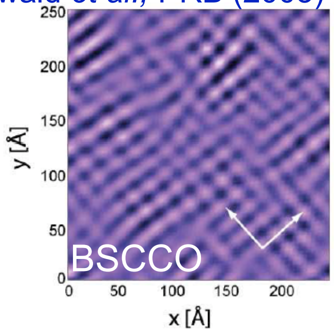


Neutron Scattering

(bulk probe)

LaSrCuO, LaCuO, YBaCuO (not BiSrCaCuO)

Howald *et al.*, PRB (2003)

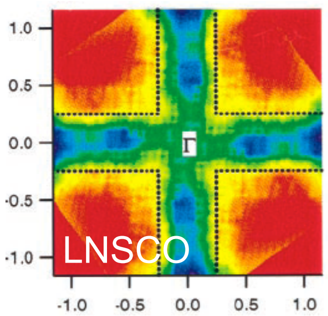


Scanning Tunneling Microscopy

(surface probe)

BiSrCaCuO

Zhou *et al.*, Science (1999)



Angle-Resolved Photoemission Spectroscopy

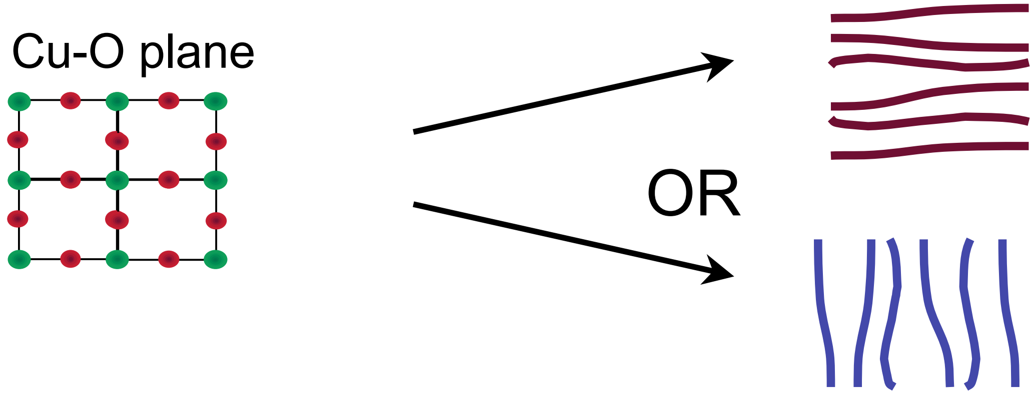
(surface probe)

BiSrCaCuO, YBaCuO

Data not clear cut. Different probes for different materials.
We propose new ways to look for stripes.

Finding Electronic Stripes: Ising Symmetry

<u>Stripes lock to a crystal direction</u>



Horizontal
or
Vertical

$$H = -J \sum_{<i,j>} \sigma_i \sigma_j$$

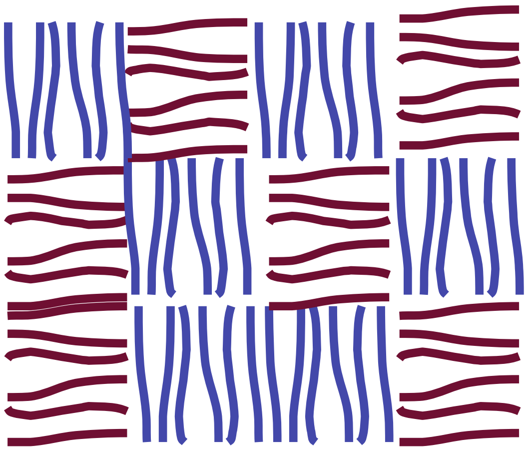
"Ising Model"

σ = 1 for horizontal stripe patch

σ = -1 for vertical stripe patch

Finding Electronic Stripes: Disorder is a Random Field

Disorder favors one direction locally



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

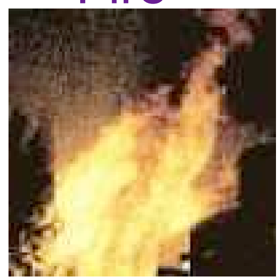
RANDOM FIELD ISING MODEL

Random Field Ising Model in 3D

Pencil

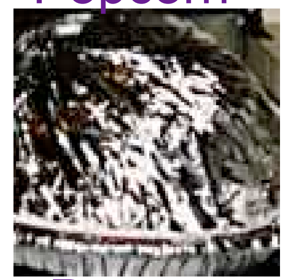
Snap

Fire



Crackle

Popcorn



Pop

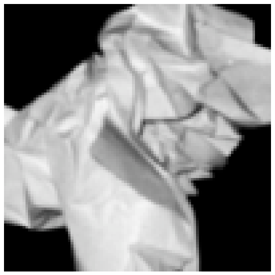
Increasing Disorder

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

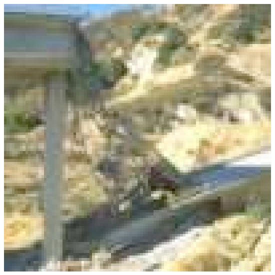
3D RFIM has phase transition
from "Snap" to "Pop" with "Crackle" at criticality.

Many Things Crackle

Paper

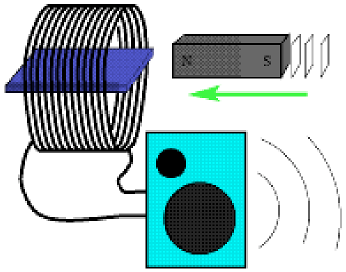


Earthquakes

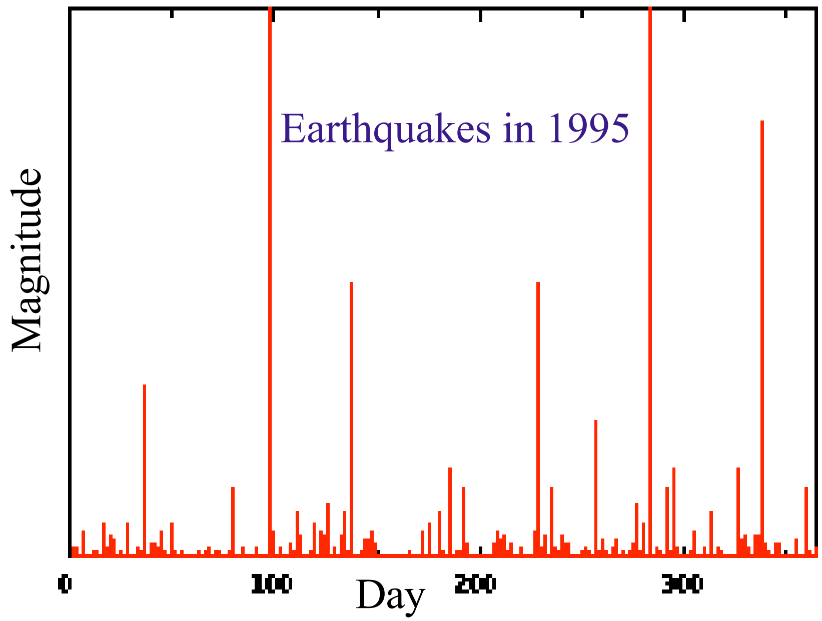


Rice Crispies

Magnets



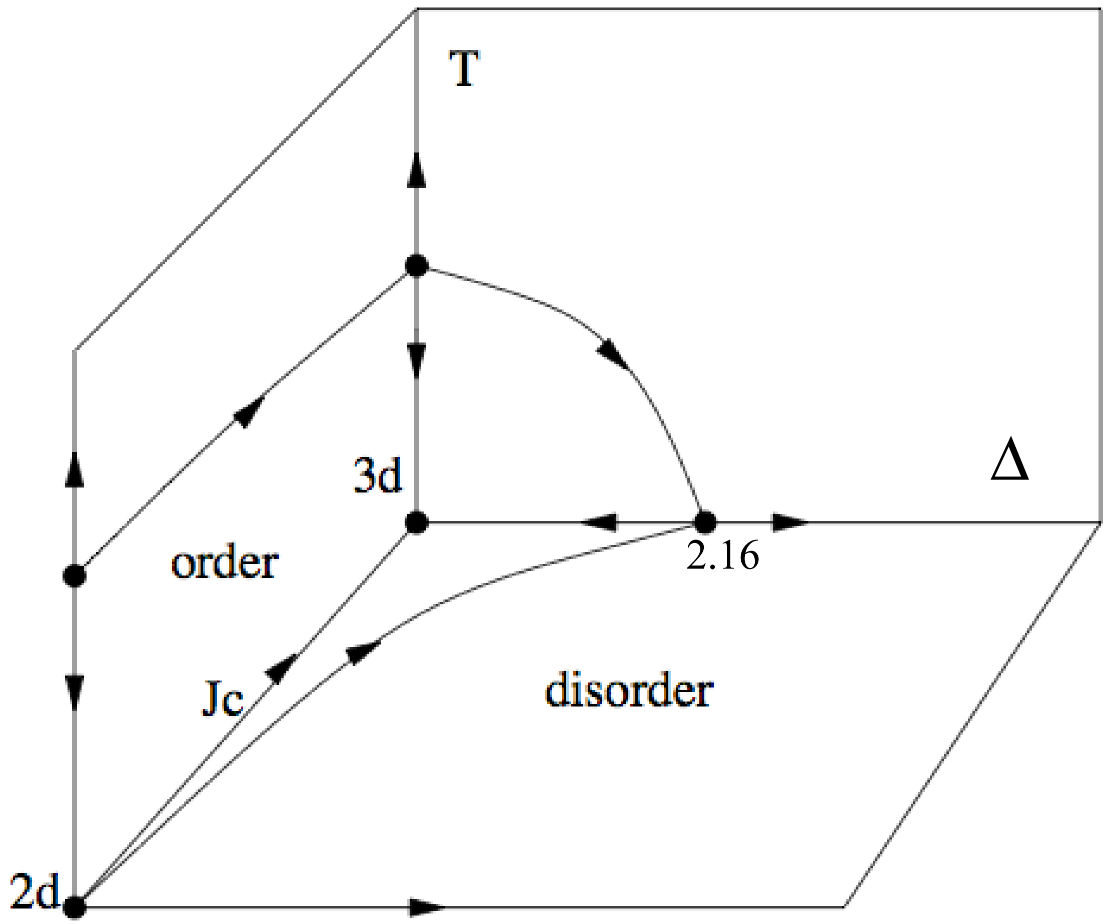
Crackling: Random times, random sizes.



Large critical region in 3D RFIM

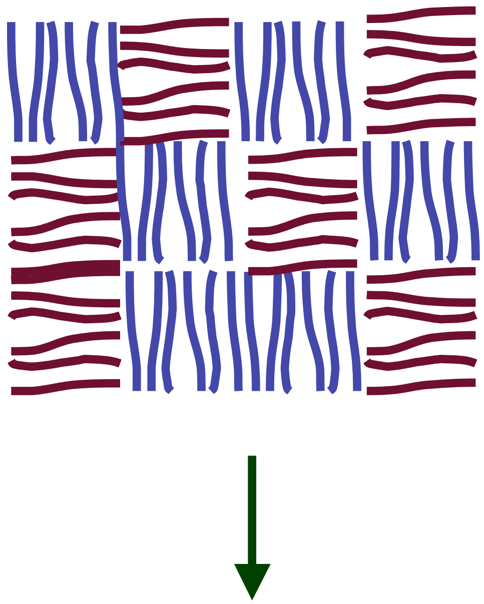
(Perkovic, Dahmen, and Sethna, PRL 1995)

Layered RFIM

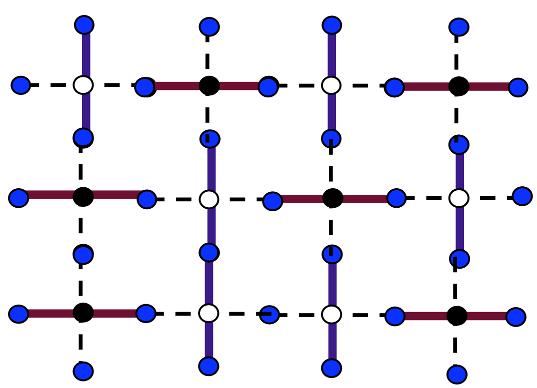


Zachar and Zaliznyak, PRL 2003

Mapping to Random Resistor Network



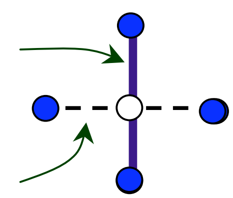
Stripe Patches



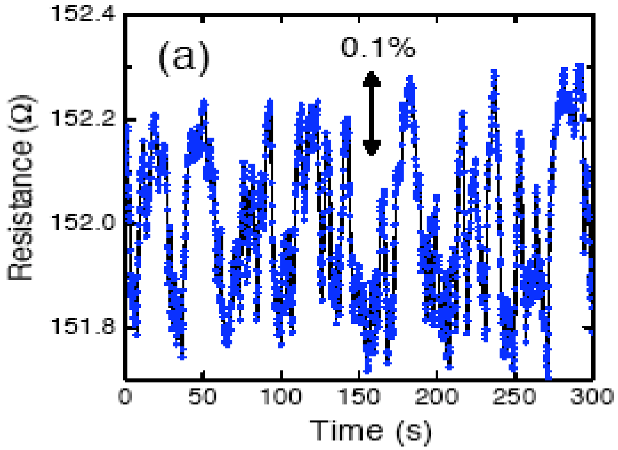
Resistor Network

Easy conduction

Hard conduction



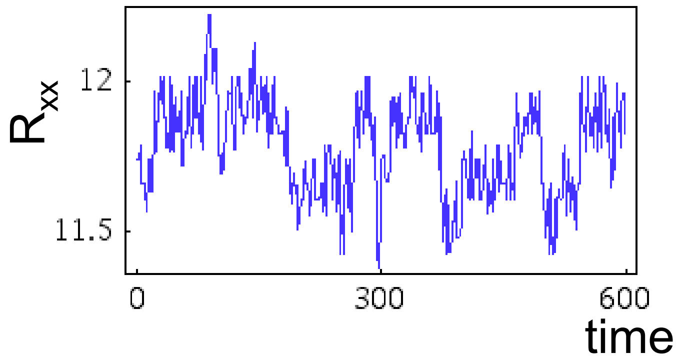
Noise in Resistance



Experiment

YBCO nanowire (underdoped)
T=100K 500nmX250nm

Bonetti, Caplan, Van Harlingen, Weissman.,Phys. Rev. Lett. 2004

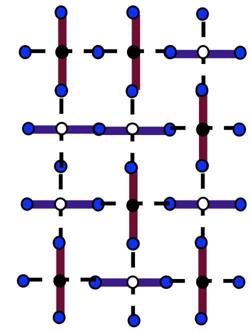


Theory

- Local patch anisotropy: 2
- Size: 10X10 patches
- Disorder R=2.8 J
- T = .5 J
- Dimension = 2

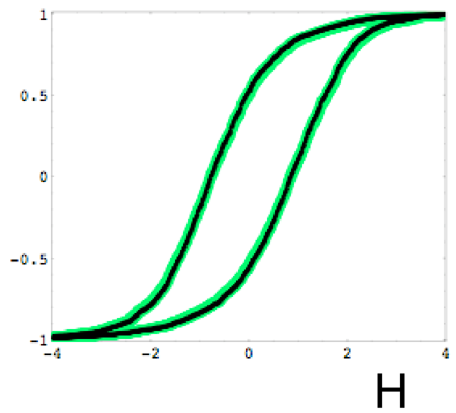
- Stripe correlation length
  ~ 40nm (from neutron data)

Macroscopic Resistance Anisotropy



Resistance Anisotropy and RFIM Magnetization exhibit hysteresis

“Magnetization” = orientational order

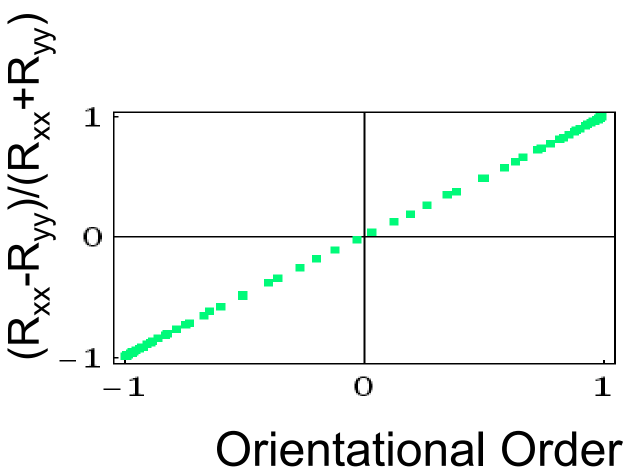


■ Orientational Order

■ $(R_{xx}-R_{yy})/(R_{xx}+R_{yy})$

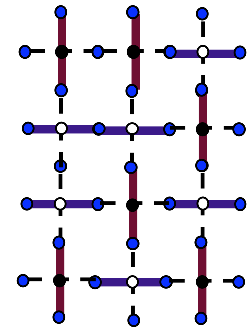
LXL = 100X100 $R_{large}/R_{small} = 2$

T=0; R = 3 J; Dimension = 2



Resistance Anisotropy
≈ Orientational Order

Macroscopic Resistance Anisotropy



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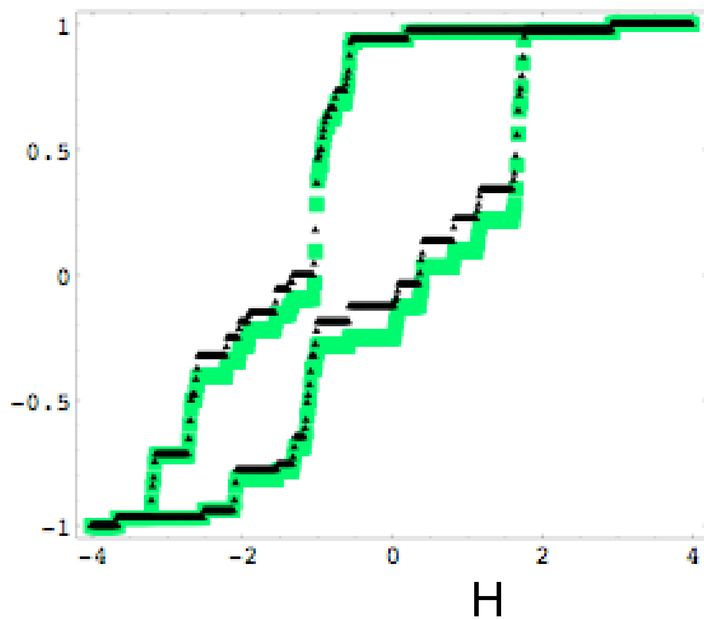


■ Orientational Order

■ $(R_{xx}-R_{yy})/(R_{xx}+R_{yy})$

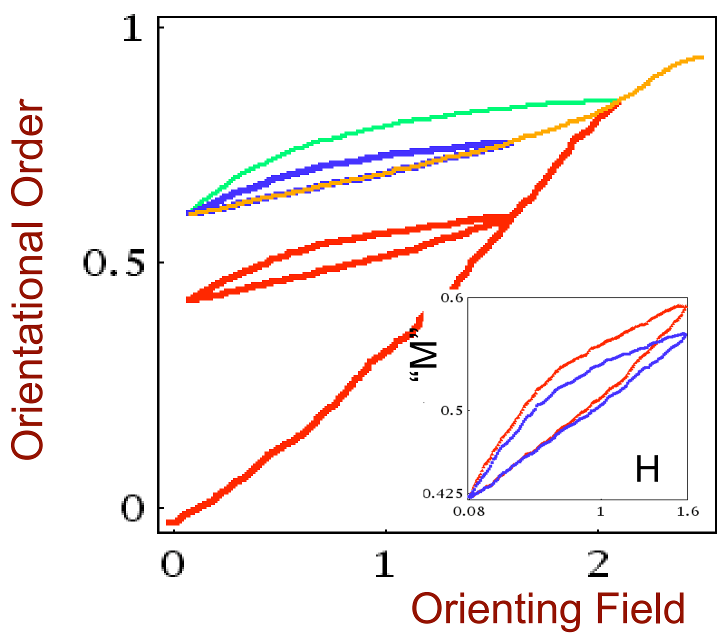
LXL = 8X8

T=0; R = 3 J;

$R_{large}/R_{small} = 2$

Smaller system -- more fluctuations.

Hysteresis And Subloops



Theory

- Return Point Memory (subloops close)
- Incongruent Subloops →Interactions important

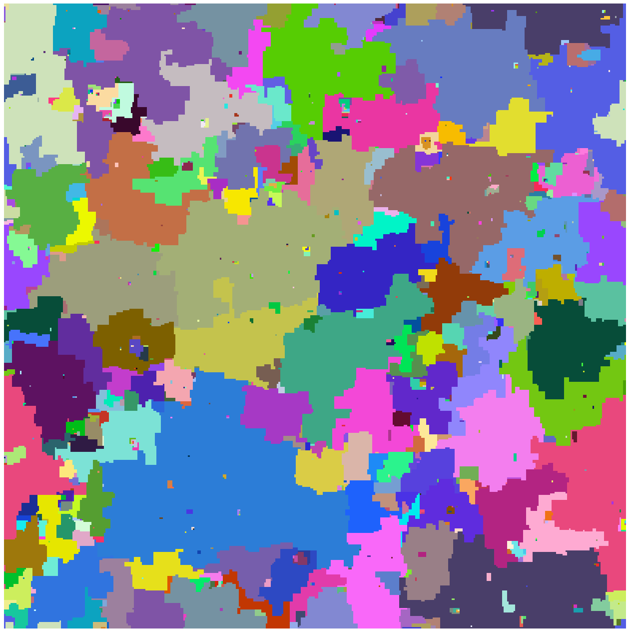
•Disorder R=3J, T=0, Size = 100X100

Orientational Order → Resistance Anisotropy; Superfluid Anisotropy; Ratio of IC peaks in neutron scattering, STM

Orienting Field → Magnetic Field H^2; Uniaxial Strain; High Current

New STM mode: Scanning Noise Spectroscopy

Map of crackling clusters



Sethna, Dahmen, Perkovic, cond-mat/0406320

Each cluster has characteristic dynamics.
Small clusters flip often,
and large clusters flip much less often.

Position-dependent power spectrum can map out the cluster pattern.

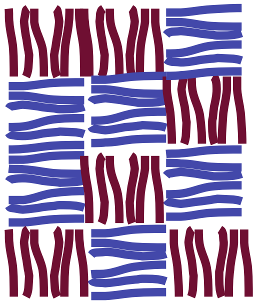
Conclusions

High Temperature Superconductors: Need a fundamentally different mechanism from BCS

Stripes: 1D System has *spin-charge separation*
Pair spins directly to achieve high pairing scale despite large Coulomb repulsion

Stripes + Host crystal + Disorder = Random Field Ising Model

Disorder makes stripes hard to detect -- need new probes. *Noise, Hysteresis*



Transport: Switching noise in small systems in R_{xx}
Orientational Order measured by R_{xx}-R_{yy}
Hysteresis, Return Point Memory at low T
Subloops Incongruent $\Rightarrow$ Interactions important

Scanning Noise Spectroscopy:
Power spectrum of local noise can map out the cluster pattern

Hysteresis:

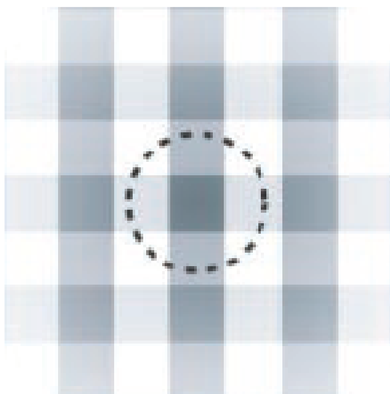
Resistance Anisotropy Superfluid Anisotropy Ratio of IC peaks in neutron scattering, STM	*vs.*	Magnetic Field H^2 Uniaxial Strain High Current

What's so special about 1D?

→ *solitons*

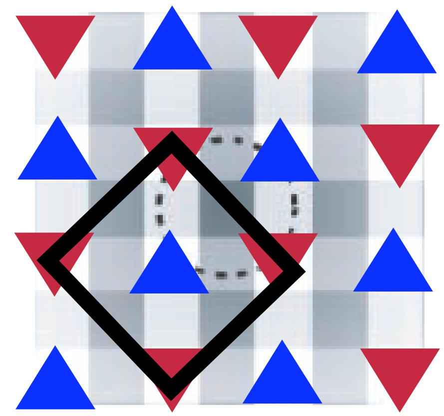
Disturbances in 3D:	dissipate as ~ $1/R^2$	Like the intensity of light
Disturbances in 2D:	dissipate as ~ $1/R$	Like a stone thrown in a pond
Disturbances in 1D:	"dissipate" as ~ 1	Like a wave in a canal

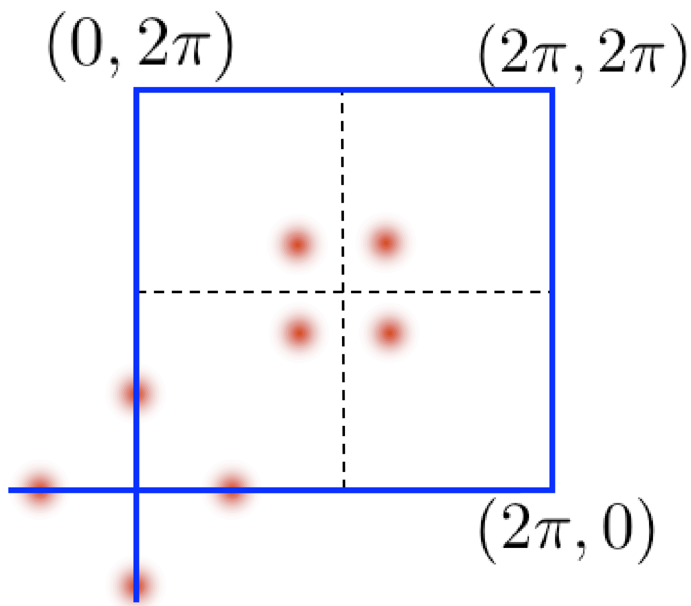
Checkerboards and Plaids?



Hoffman *et al.*, Science (2002)
Vershinin *et al.*, Science (2004)

Antiphase Domain Walls in Antiferromagnetism

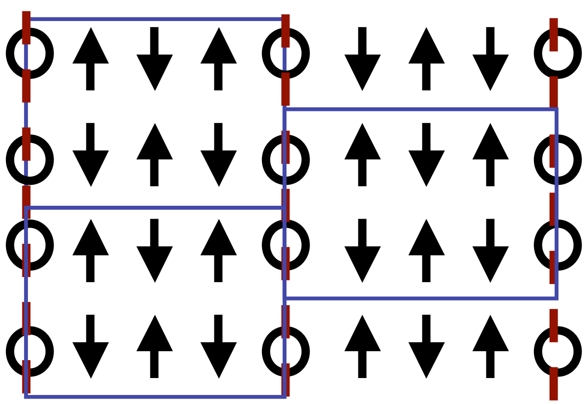


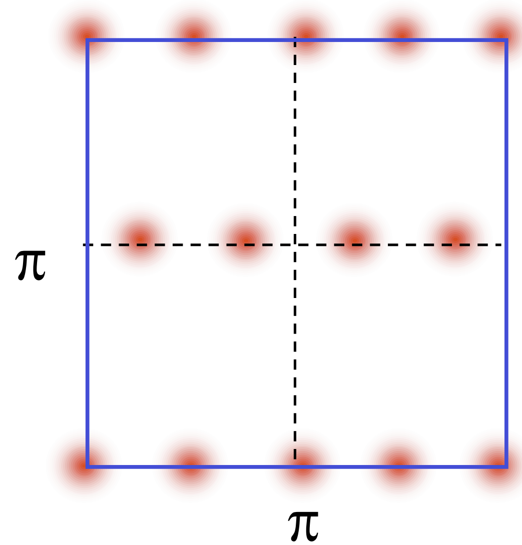


Spin Peaks in Wrong Direction!

Charge Peaks

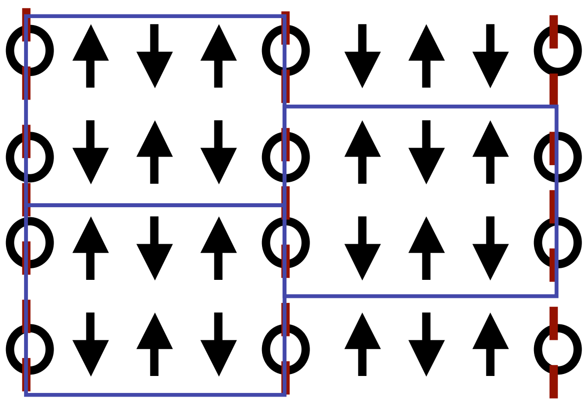
Neutron Scattering

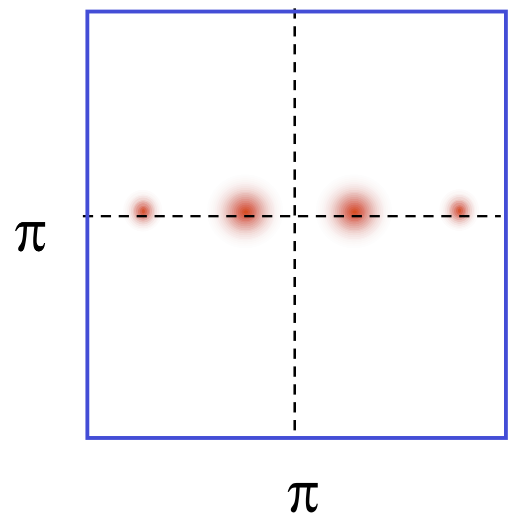




Magnetic Reciprocal Lattice Vectors

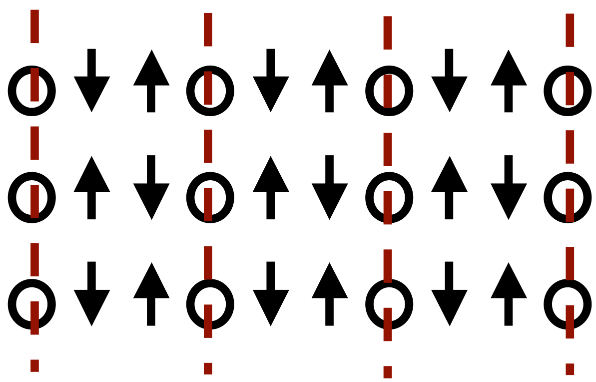
Neutron Scattering

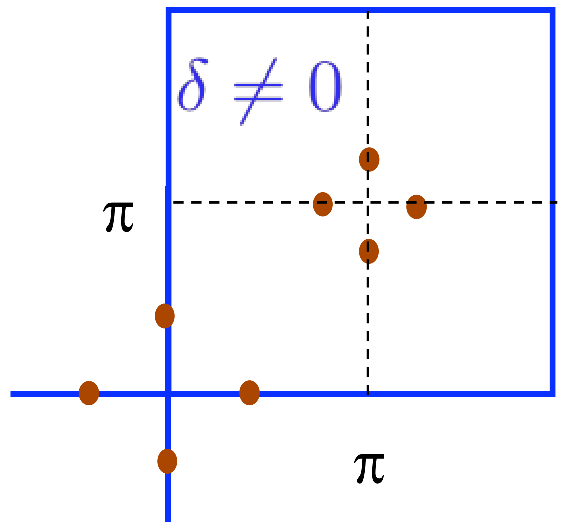




Intensities

Neutron Scattering in Cuprates





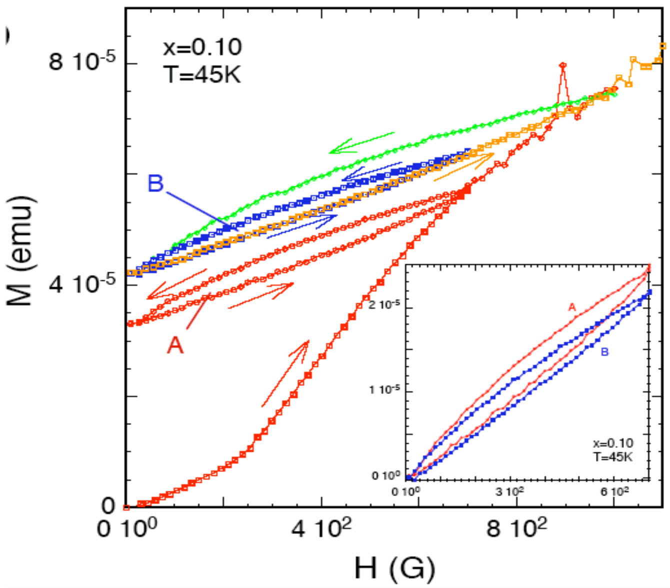
Charge Peaks related by X2

Data is usually twinned due to crystal twinning.

LaSrCuO, LaCuO

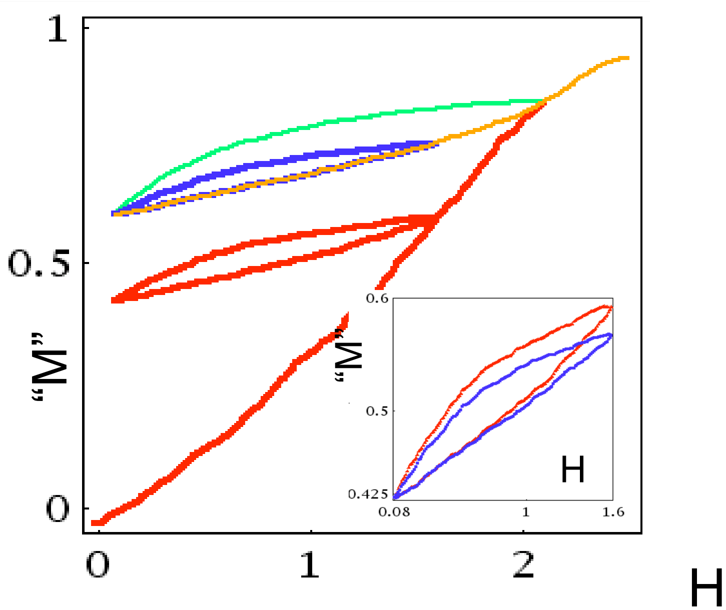
YBaCuO

Hysteresis Subloops



Experiment

LSCO, X=.10
ZFC, ZFW
T=45K
Panagopoulos *et al.*, cond-mat/0412570



Theory

- Return Point Memory (subloops close)
- Incongruent Subloops
→Interactions important

•Disorder R=2.8J, T=0,
Size = 100X100

Definitions

$T_{pair} = \Delta/2$ (Δ=single particle gap)

$$T_\theta = \frac{1}{2} A \frac{\hbar^2 n_s}{m^*} L^{d-2}$$

(n_s= superfluid density)

$$L = \sqrt{\pi}\xi_o$$

3D: $A = 2.2$ $\frac{n_s}{2m^*} = \frac{c^2}{8\pi e^2 \lambda^2}$

2D: $A = 0.9$ $\frac{n_s}{2m^*} = \frac{c^2 L}{8\pi e^2 \lambda^2}$

Back