Are Stripes the Key to the Puzzles of Thermal and Electrical Transport in Underdoped Cuprates?

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50/50 Talk/Discussion. KITP, Sep 8, 2009

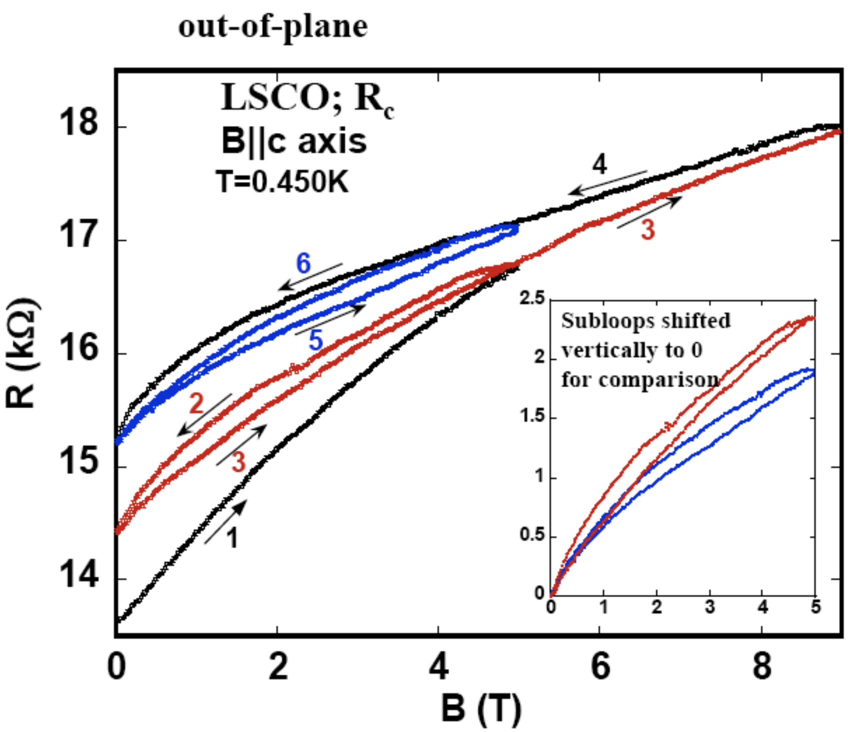
European
Excellence Grants

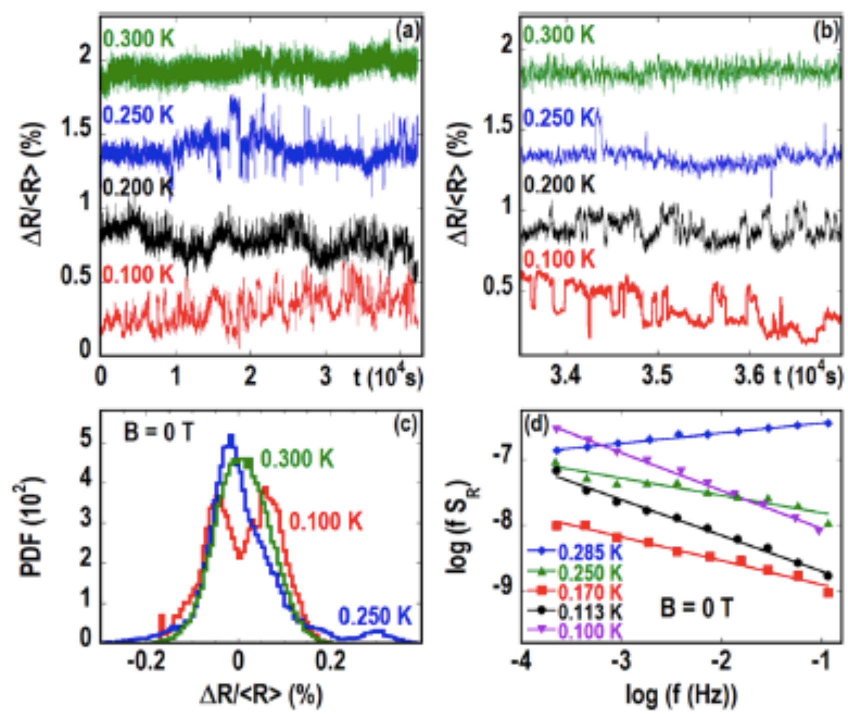
Puzzles

- Normal state transport
  - magnetoresistance and hysteresis in M(B) and R(B) (Panagopoulos et al.)
- Superconducting response above Tc
  - Nernst
  - Diamagnetism
  - ac conductivity

Strange normal behavior

LSCO 3% doped, MR and noise



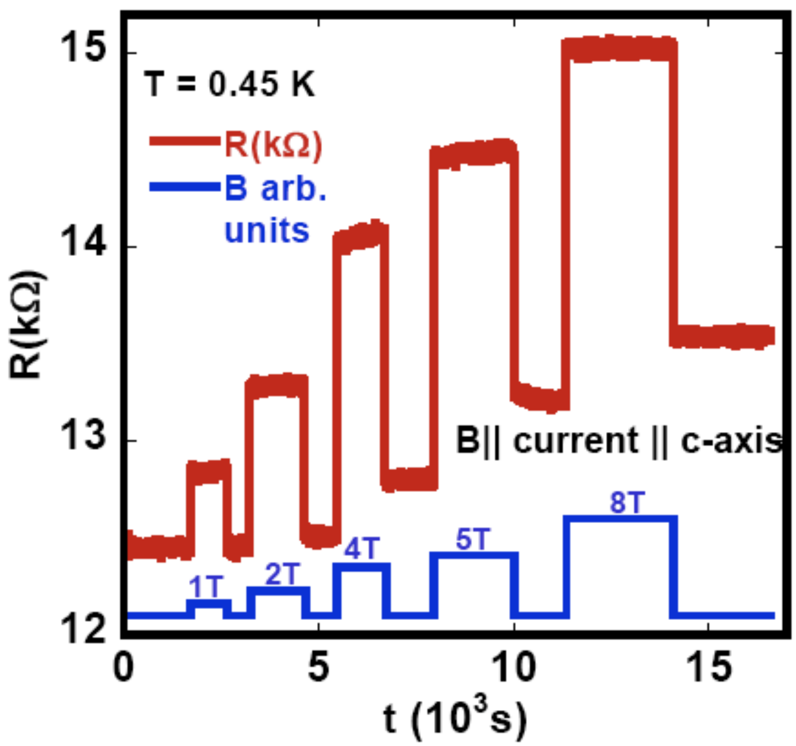


I. Raicˇevic et al, PRL 101, 177004 (2008)

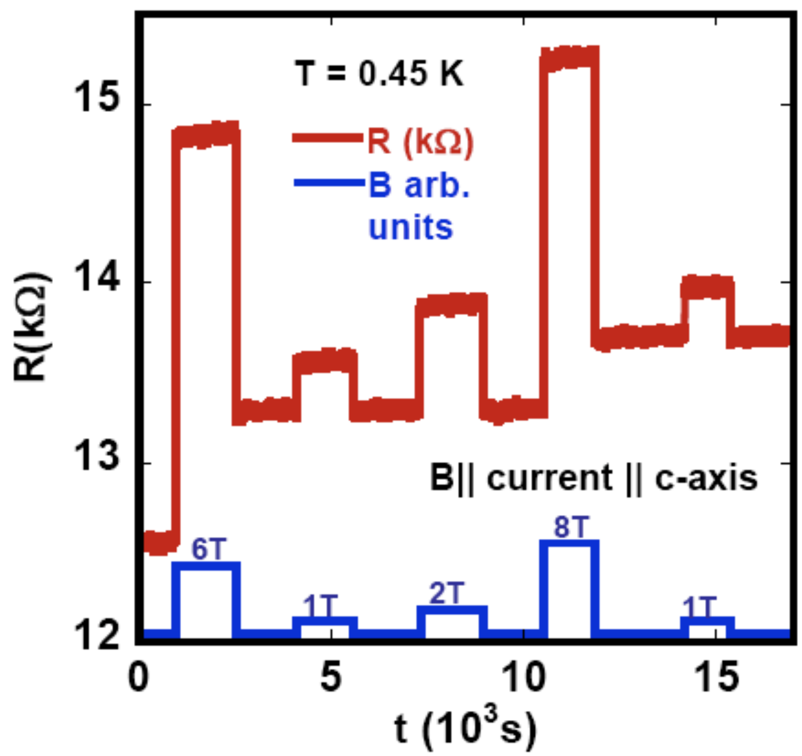
Memory effects

(observed in both R_{ab} and R_c, for both B||c and B||ab)

LSCO; R_c



LSCO; R_c

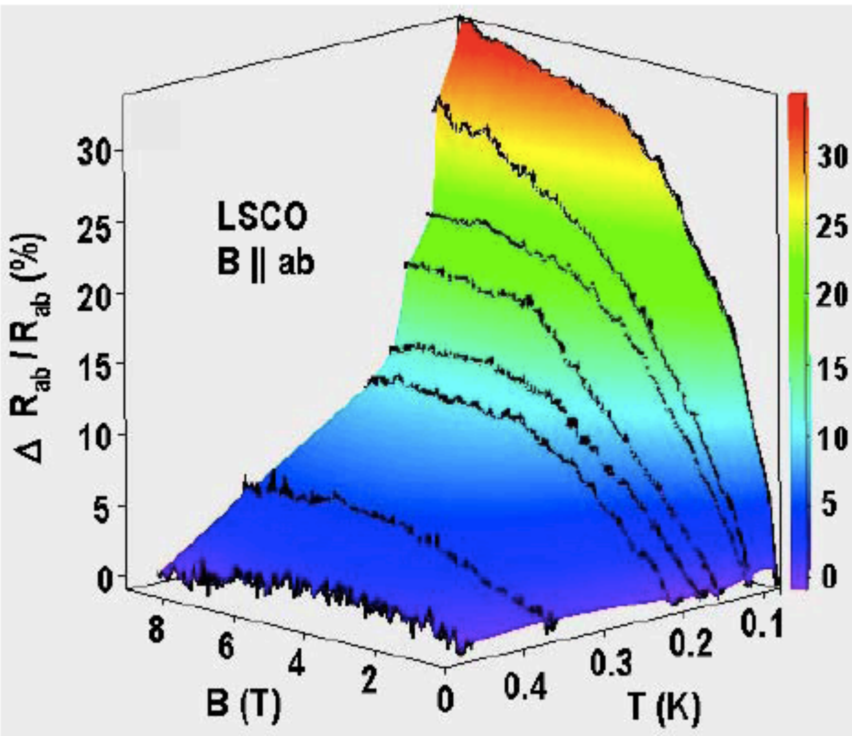


- higher B enable overcoming higher energy barriers

- R(B=0) determined by the highest B previously applied - memory of magnetic history

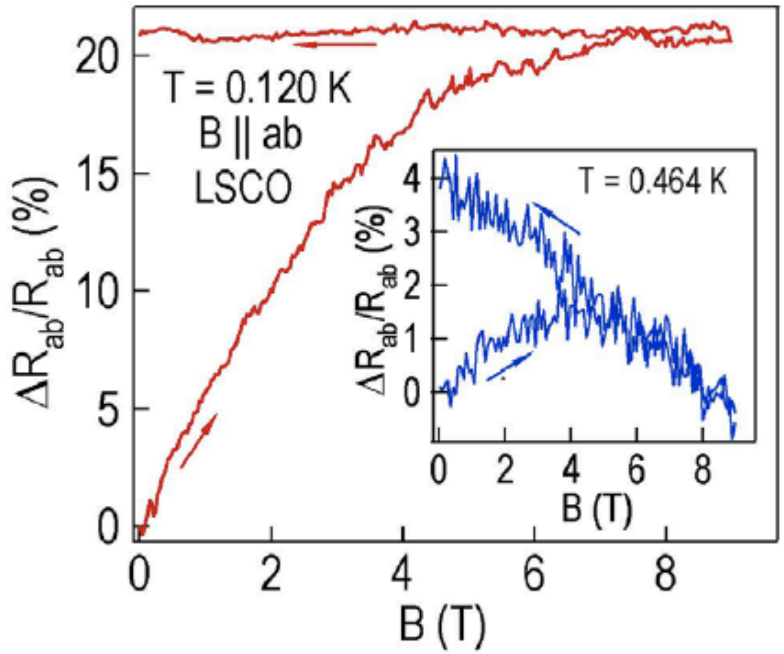
Also, manganites: Levy et al., PRL 89, 137001 (2002); YBCO: Ando et al., PRL 83, 2813 (1999)

In-plane MR – LSCO, low T



Strong positive MR at low T
(below 0.5 K)

Only positive MR exhibits hysteresis



Low-T positive MR coincides with the onset of charge glassiness

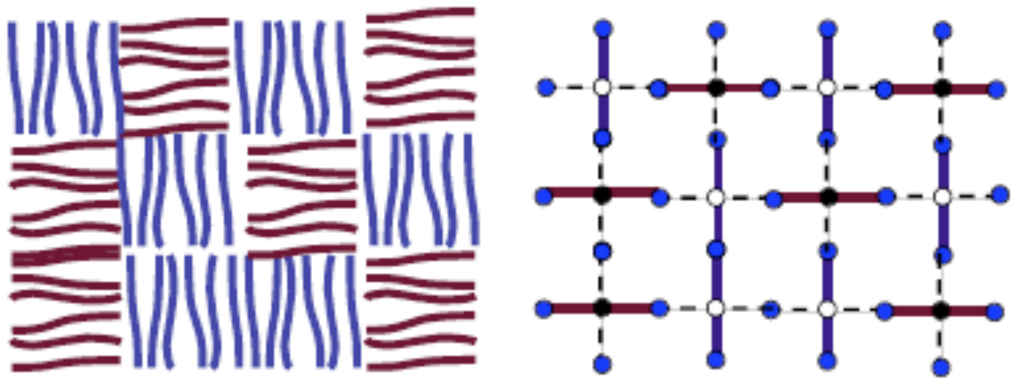
Positive MR - glassy features:

- History dependence
- Memory
- Hysteresis

In the same regime:

- Noise – glassy dynamics as T → 0

Interpretation – stripe *domain* fluctuations



(a) Nematic patches (b) Resistor Network

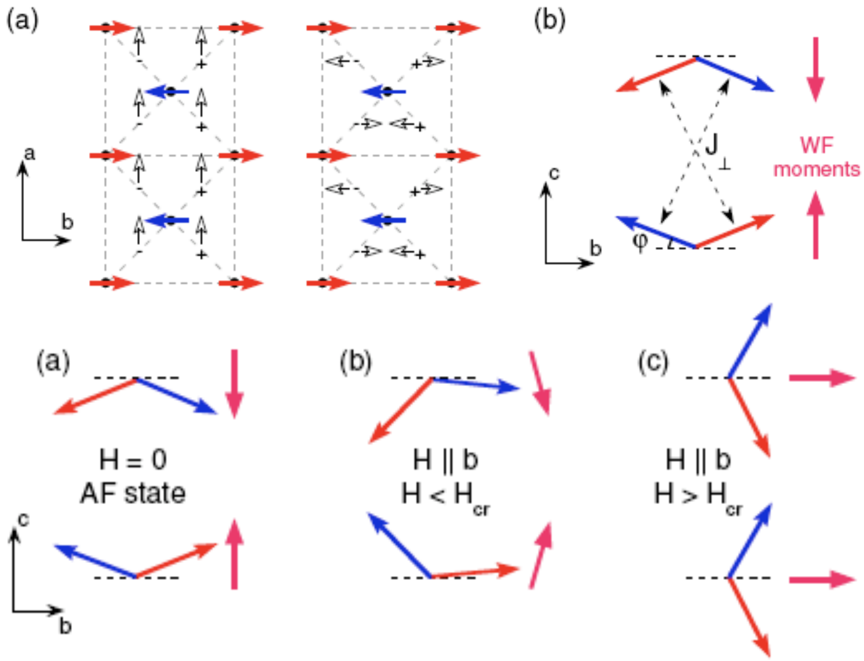
E. W. Carlson, K. A. Dahmen, E. Fradkin, and S. A. Kivelson: **Phys. Rev. Lett. 96, 097003 (2006)**

Issues:

1) Nature of coupling to magnetic field?
2) Flipping large domains has large potential barrier
3) Canonical Stripes cannot have loose ends

Weak Ferromagnetism in LSCO

Coupling AF to B in LSCO:



Gozar, et al, Frontiers in Magnetic Materials (Ed. A.V. Narlikar), Spinger-Verlag Berlin Heidelberg, pp. 755-789 (2005)

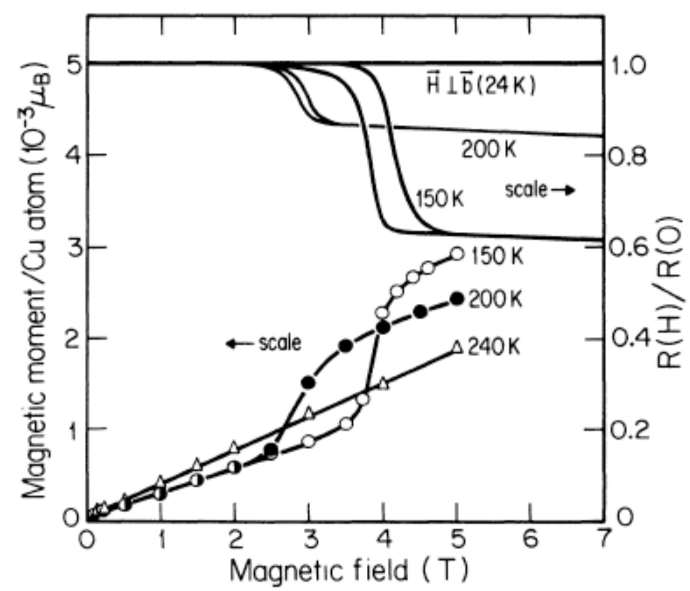
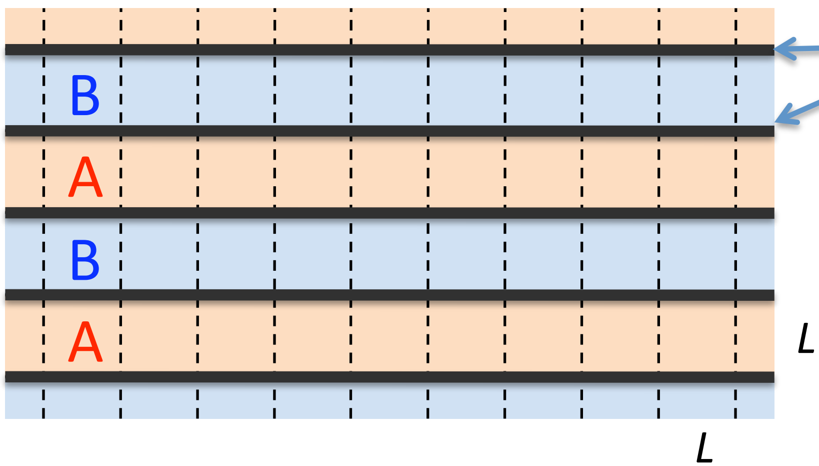


FIG. 1. Resistance and magnetic moment vs magnetic field in the c direction (except as noted).

Thio et al, PRB 1988

Sign of AF ⇔ sign of weak FM!

Coupling stripes to magnetic field



Charge stripes

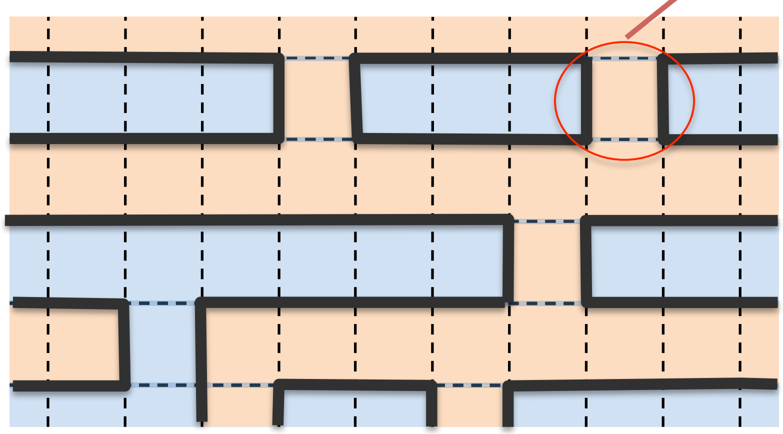
+ AF <-> + M_z

- AF <-> - M_z

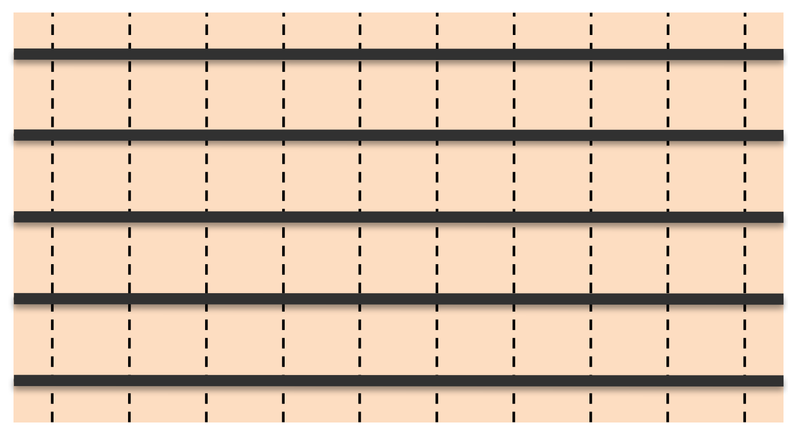
$M_0 \sim 2 .10^3\, L^2 \mu_B$
$L \sim 1/(2x)$
e.g. $L = 4$ @ x = 12.5%

@ x = 3%: $M_0 = 0.5\ \mu_B$

B = 0: $S_A = S_B$

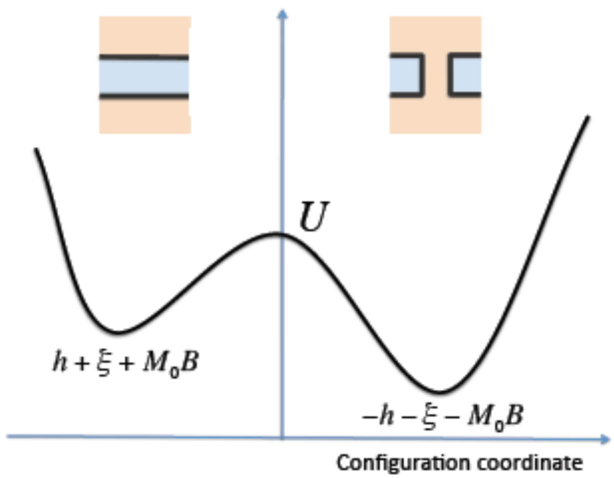


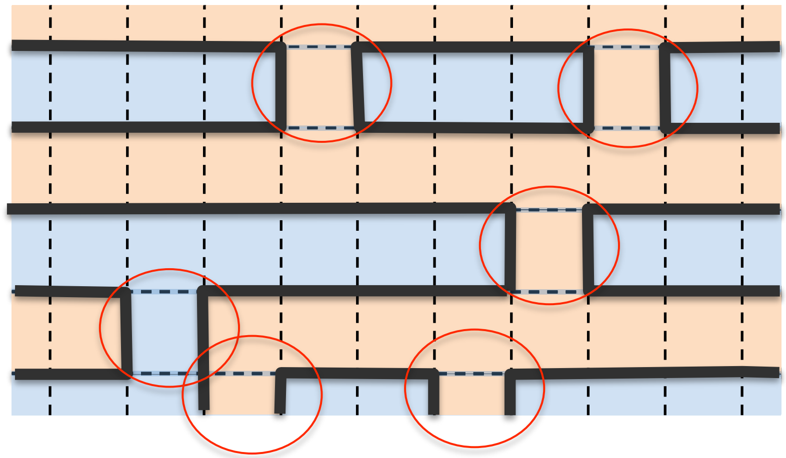
B > 0: $S_A > S_B$



B large: $S_B = 0$

Fluctuator model

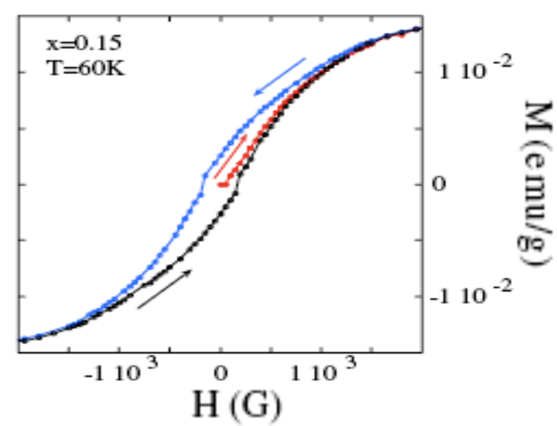




h - "bias", e.g. tetragonal distortion
ξ – random potential (atomic and configuration)

For T < typical barrier height U, and **no interaction** between fluctuators (Preisach model)

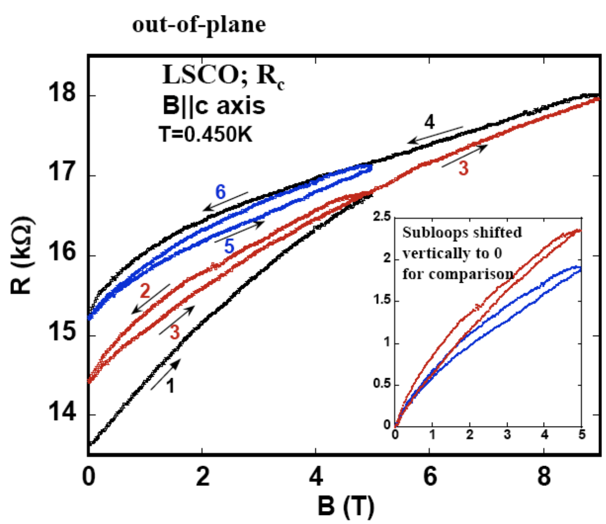
$$M(B) = M_0 \int d\xi \mathcal{P}_\xi(\xi) \tanh \frac{\pm h - \xi - M_0 B}{k_B T}$$
$$\approx 4\mathcal{P}_\xi(h) M_0^2 B$$

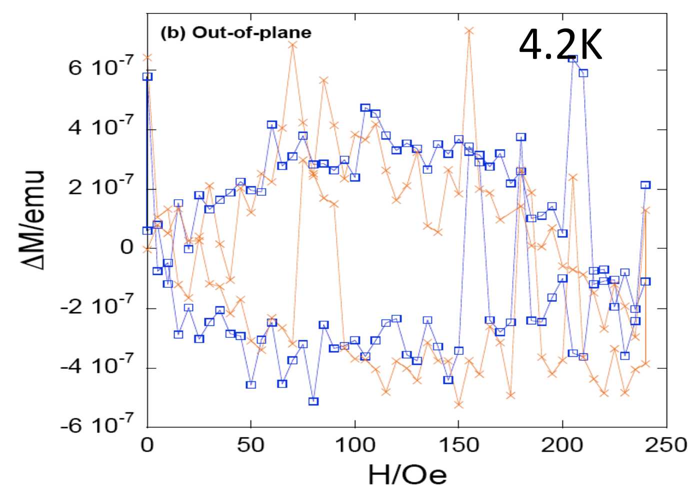


C. Panagopoulos, PRL **96, 047002 (2006)**

Consequences of fluctuator model

- Hysteretic behavior for M_0 B > k_B T in magnetization and resistivity
- 1/f noise (Dutta-Horn)
- The strength interaction between fluctuators can be determined from deviations from Preisach model (loop congruency)

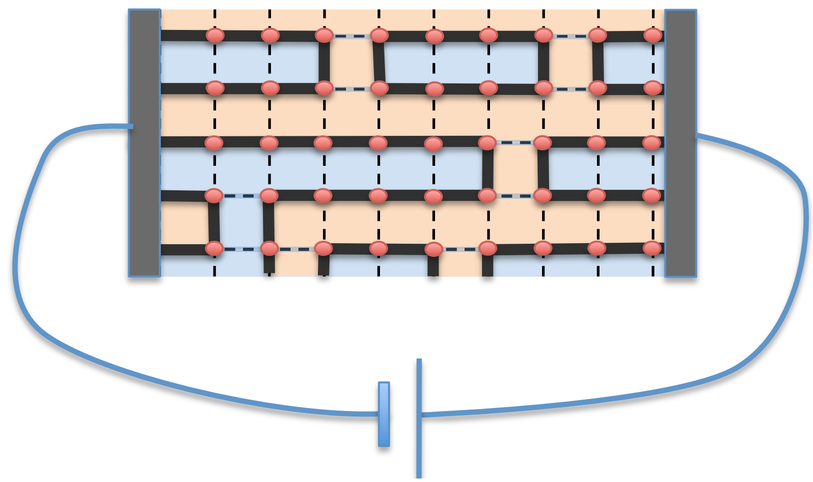




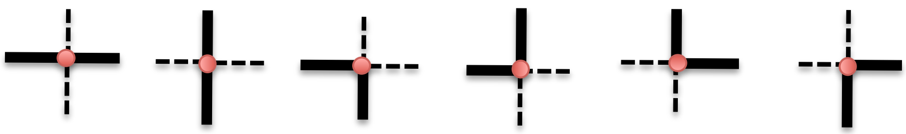
3% LSCO: Magnetoresistance loops are not congruent (-> interaction!), but magnetization ones are (almost, -> no interaction!)

Contributions of fluctuators are additive in M, but not in R!

Stripe-based resistivity model
random resistor network

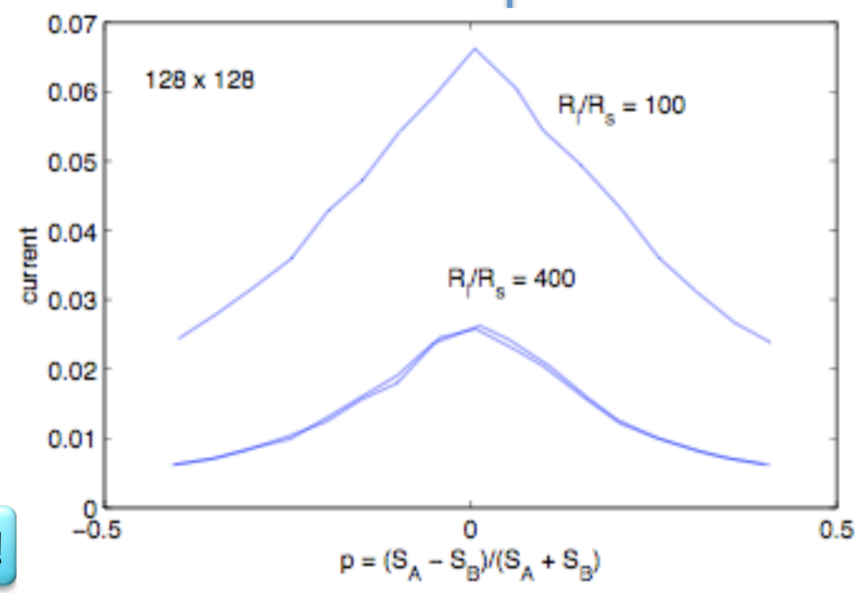


4 resistors attached to every node ● :
Two small (▬, R_s) and two large (---, R_l)
("Six-vertex model")



Lowest resistivity is achieved for $S_A = S_B$
Percolation.
If approach by disordering smectic,

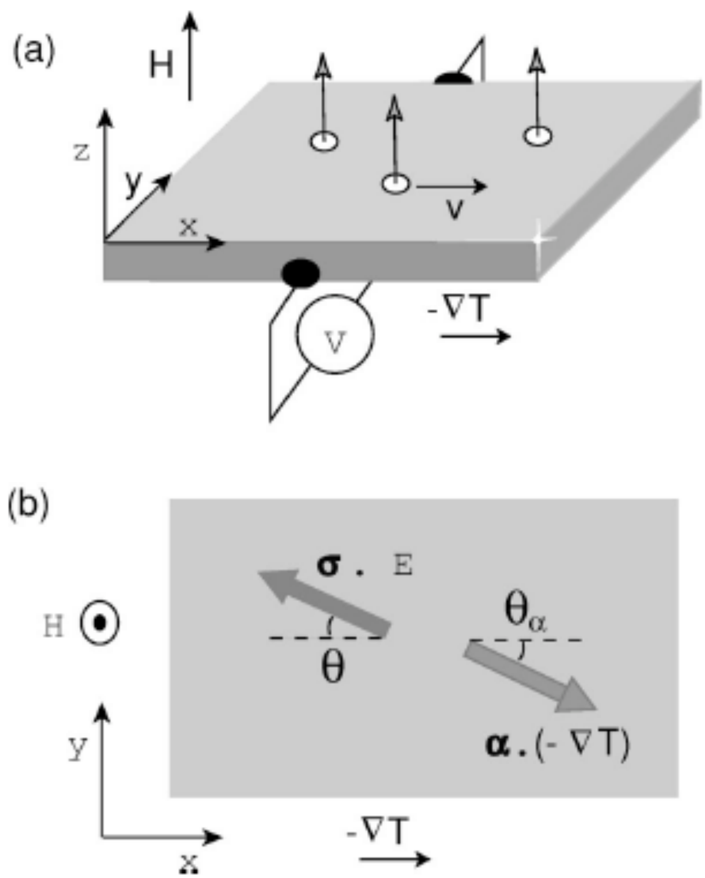
$$R_{\square} = [N(1-|p|)R_s + N|p|R_l]/N$$
$$= R_s + |p|(R_l - R_s)$$
$$p \sim (S_A - S_b)/(S_A + S_b)$$

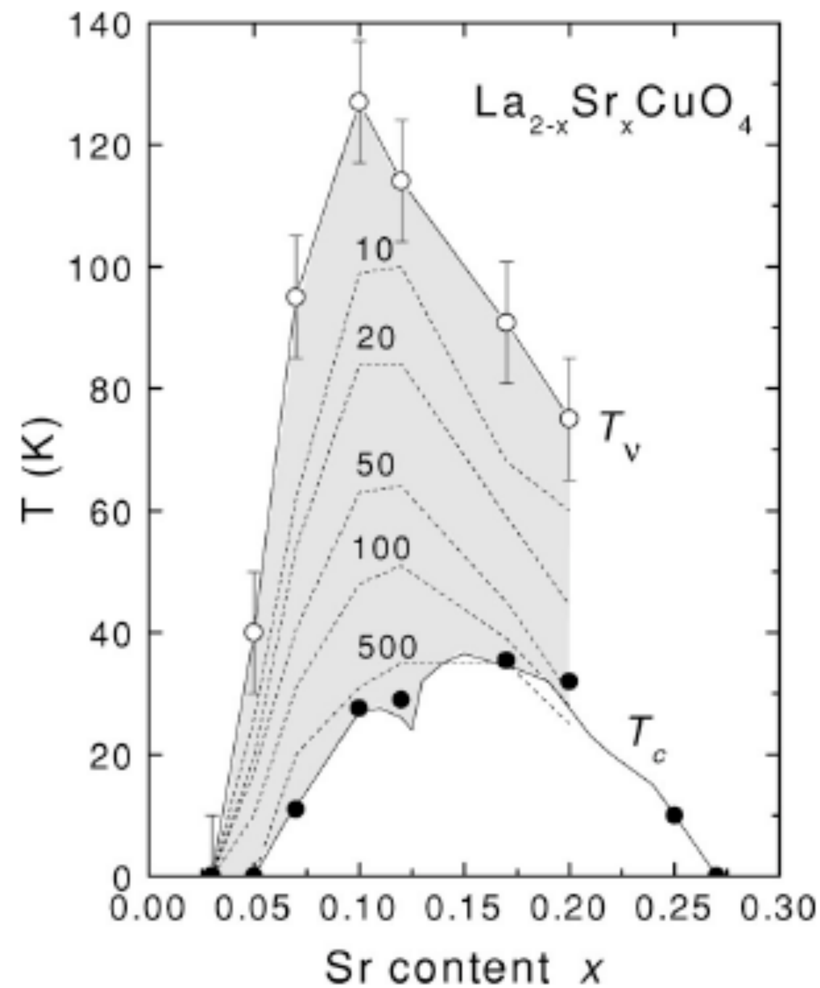


Recall $p \propto M \propto B$ -> positive linear MR!

Strange fluctuating SC behavior

Nernst at T >Tc





Wang et al, Phys. Rev. B 64, 224519 (2001)

Finite frequency superfluid stiffness
In in BSCCO

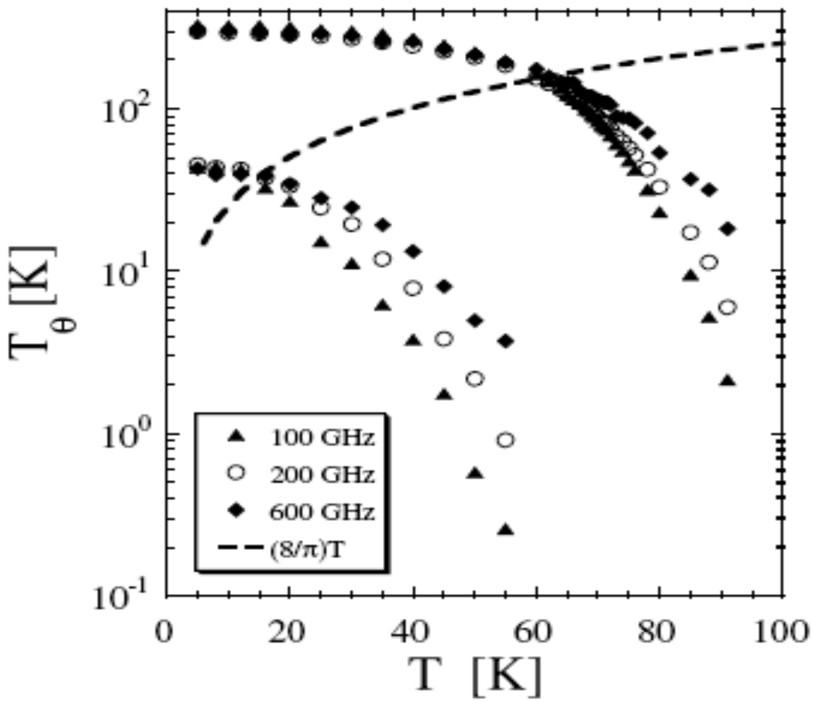


Fig. 2 The dynamic (frequency dependent) phase-stiffness temperature, $T_\Theta(\omega) \equiv \omega\sigma_2(\omega)/\sigma_Q$ as a function of temperature T. Data are shown for two samples, one with T_c=33 K (left side) and the other with T_c=71 K (right side). The dashed line corresponds to the KTB condition for 2D melting, i.e., phase stiffness and temperature related by $T_\Theta = (8/\pi)T$.

J. Orensein e al, Ann. Phys. (Leipzig), **15, No. 7 – 8, 596 – 605 (2006)**

Also, P. Armitage (JHU), UNPUBLISHED on LSCO

Phase diagram for BSCCO

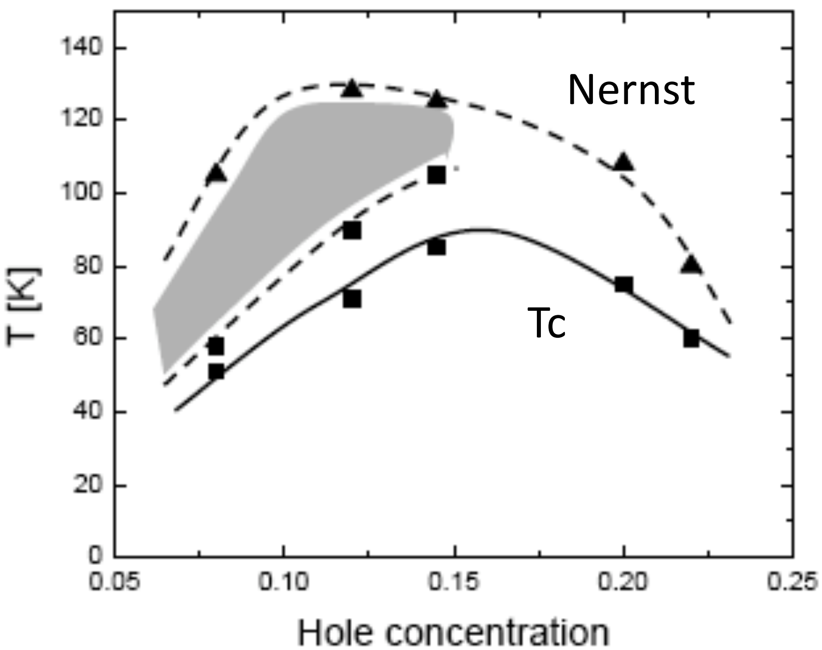
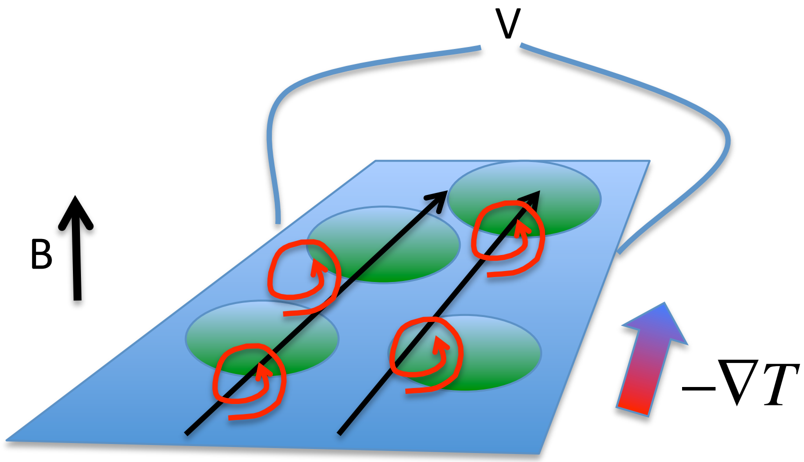
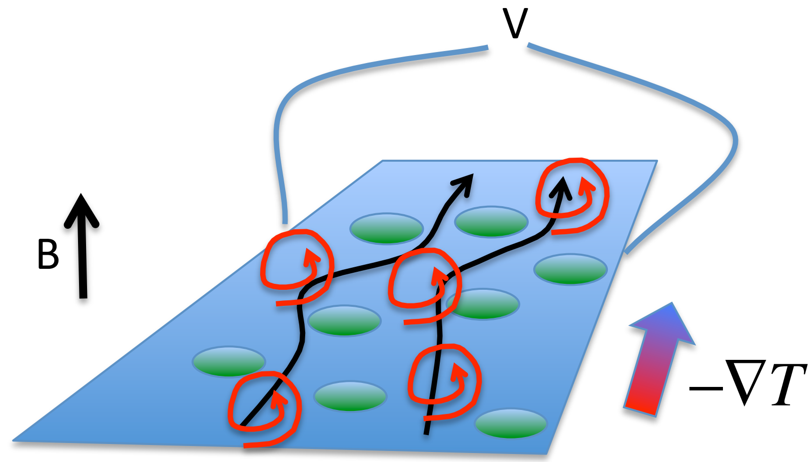


Fig. 10 Comparison of onset temperatures of superconductivity, fluctuation conductivity, and Nernst effect in the BSCCO system. Nernst onset T's (triangles) are from [14]. Shading illustrates the region in which the conductivity is essentially normal yet the Nernst signal is nonzero.

J. Orensein e al, Ann. Phys. (Leipzig) **15, No. 7 – 8, 596 – 605 (2006)**

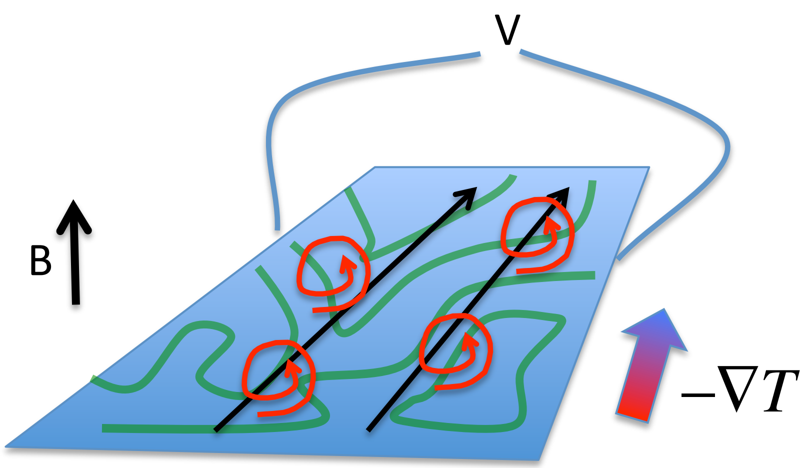
Similar trends in LSCO, P. Armitage (JHU), UNPUBLISHED





T slightly higher than Tc – Nernst

T significantly higher than Tc – No Nernst!
(heat current can avoid SC regions)



If SC regions have large aspect ratio (stripes!) heat current cannot avoid them
-> *Phase slips*

Evidence for 2D SC (pi-SC stirpes?)

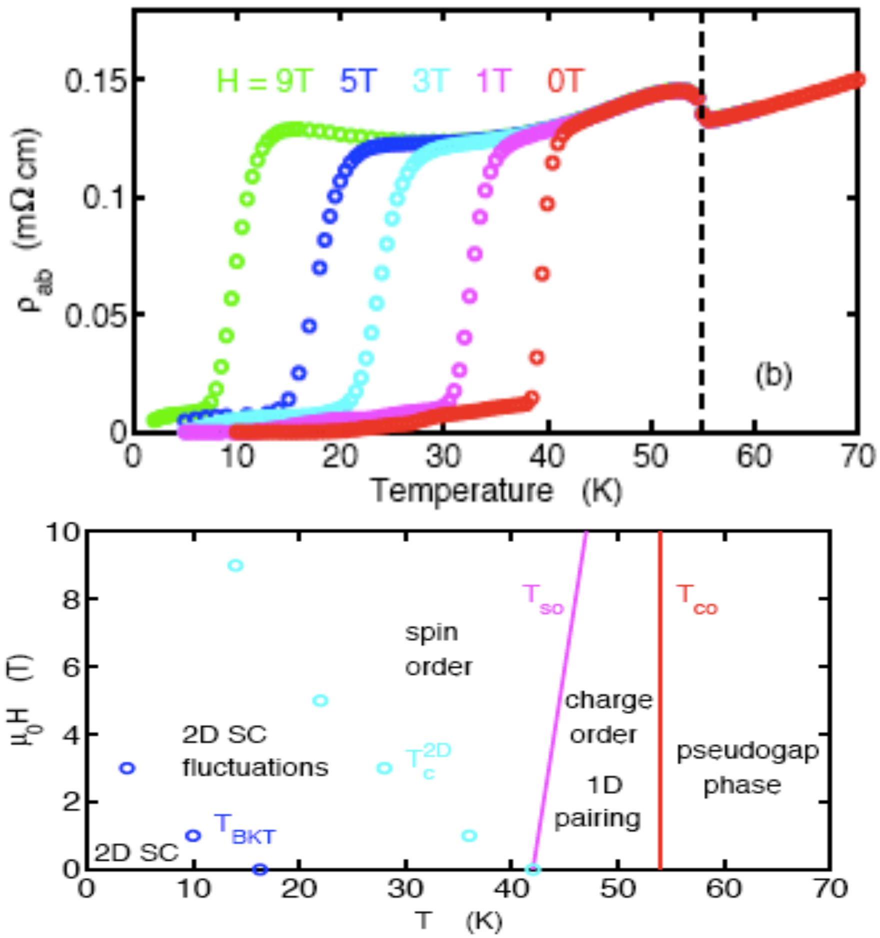


FIG. 1: (color online) Experimental phase diagram for $La_{1.875}Ba_{0.125}CuO_4$. The transition lines for charge order and spin order are from [6]. The boundaries labeled T_c^{2D} and T_{BKT} are described in the text.

Q. Li et al, Phys. Rev. Lett. 99, 067001 (2007)

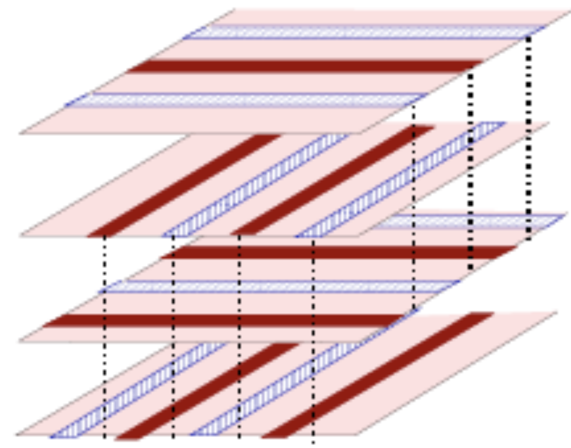
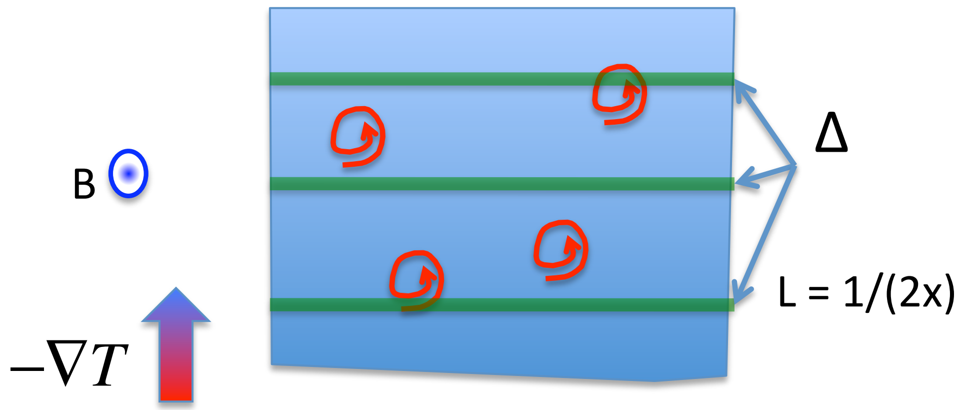


FIG. 3: Stacking of stripe planes.

E. Berg et al, PRL 99, 127003 (2007)

Stripe model for Nernst

Vortex density B/ϕ_0



Energy of phase slip

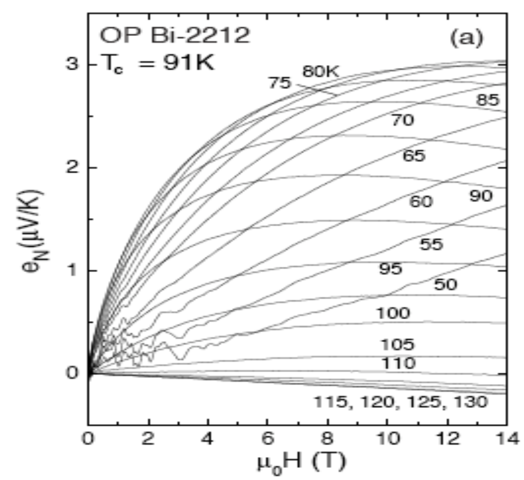
$$\Delta F \sim N_0 \Delta^2 \xi a c$$
$$\sim 25(\xi/a)\ \mathrm{K}$$

Tunneling rate

$$\Gamma \sim T_c^* \exp(-\Delta F/T)$$

Transverse voltage due to phase slips (LAMH)

$$\bar{V}_\xi = \phi_0[\Gamma(T+\Delta T) - \Gamma(T)](\ell \xi B/\phi_0)$$
$$\Delta T = \nabla T \ell$$



Nernst coeff:

$$\frac{e_N}{B_z} = \frac{E_y}{B_z\, \partial_x T} \sim \frac{k_B \Delta F T_c^*}{\hbar T^2} \ell^2\, e^{-\Delta F/T} \sim 100(\ell/a)^2\, e^{-\Delta F/T} \left[\frac{n\mathrm{V}}{\mathrm{K\ Tesla}}\right]$$

Relation between Nernst, diamagnetism and optics

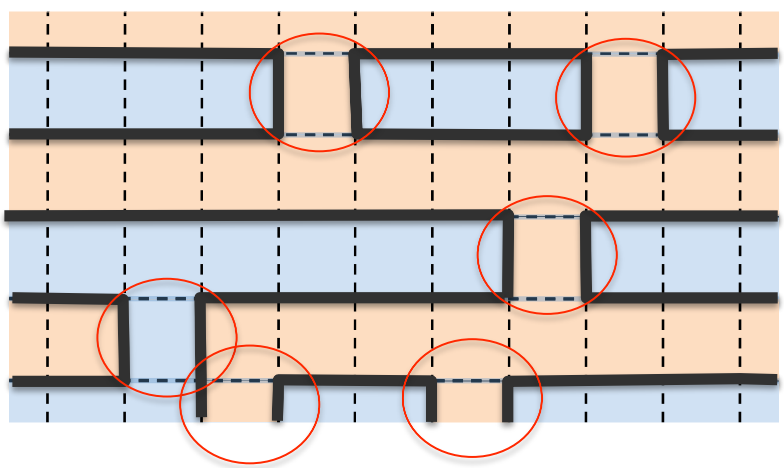
- Diamagnetism:
  - Enough to have disconnected SC grains
- Nernst
  - Need extended superconducting regions to prevent heat (and vortices) flowing around SC regions, but not necessarily globally connected
- Optics ($\sigma(\omega)$, finite superfluid stiffness)
  - "Globally" connected SC regions? ***What is the relevant length scale?***

Extension to higher doping

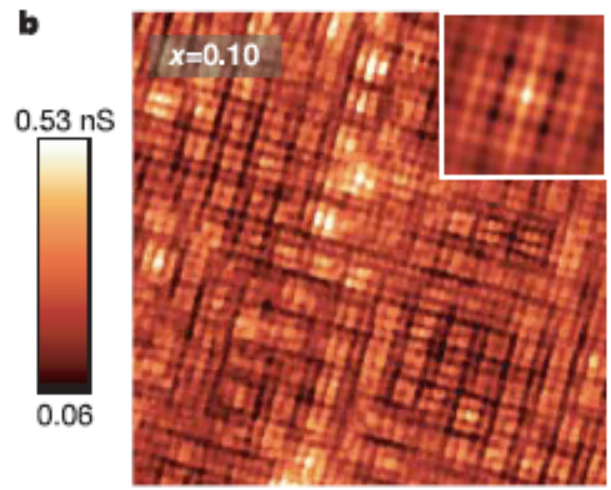
Nernst exists to higher dopings, at least up to optimal. What do stripes do there? Quantum fluctuate?

Model: “six vertex” model *+ quantum fluctuations*

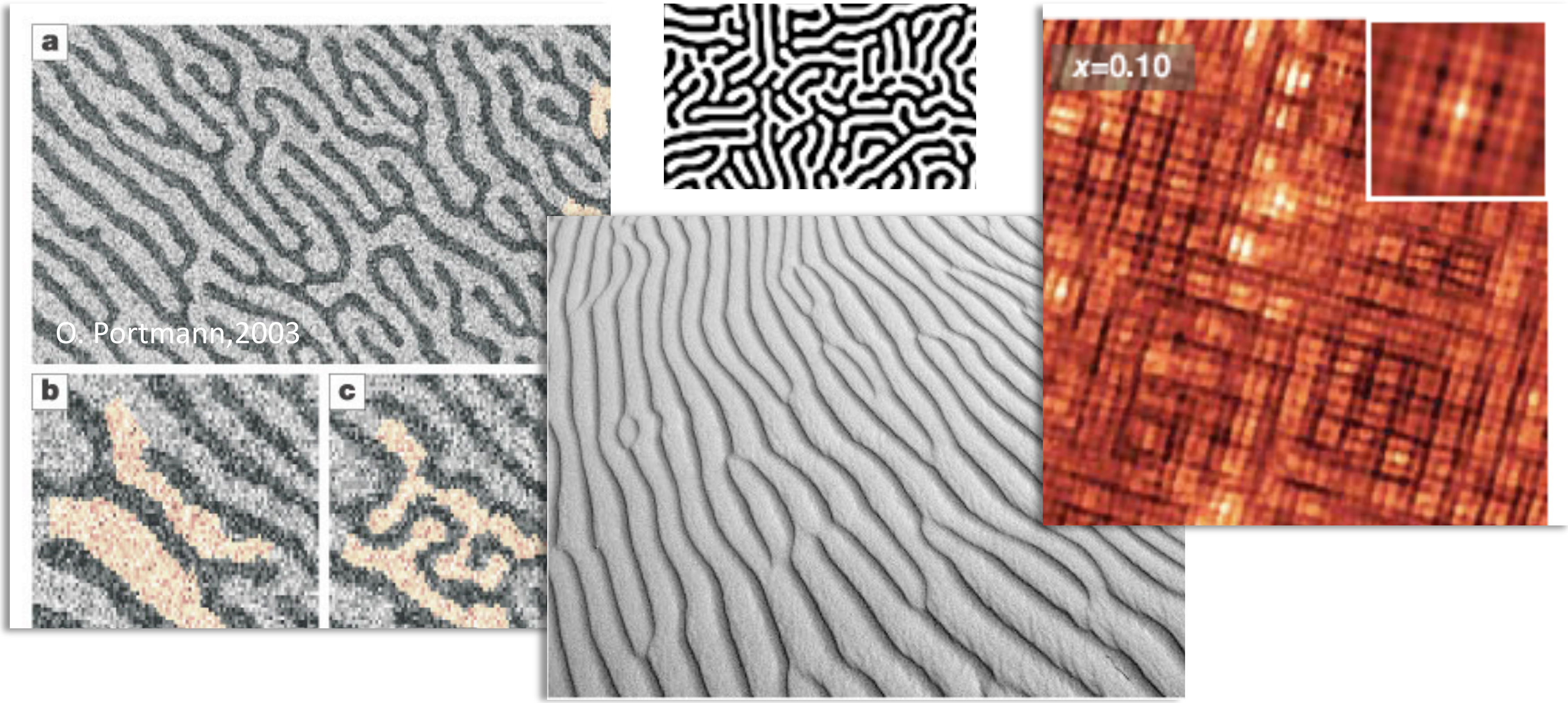
Seen already???

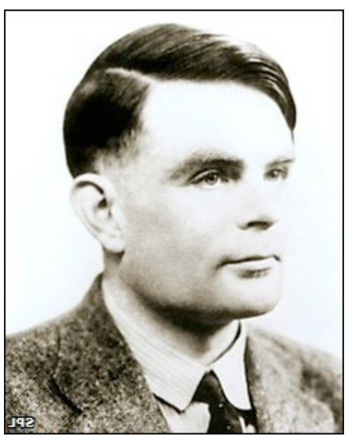


Fluctuating stripes – Fluctuating AF
(spin liquid, “macro-RVB”)



$Ca_{2-x}Na_xCuO_2Cl_2$
T. Hanaguri et al (2004)





Alan Turing

‘Well, the stripes are easy, but what about the horse part?’ – on “Turing patterns” in morphogenesis