SUNY at Buffalo

Perspectives for Finding Superconductivity in Conducting Polymers:

Effects of Strong Correlations in Low Dimensions

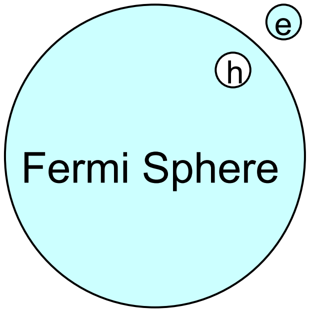
Andrei Sergeev

- **HTS cuprates and polymers have a lot of common features:**
  correlated AF insulators without doping,
  conductivity in real space is realized via 1D channels;
  [Correlated insulator is an insulator due to interaction effects]
- **The mean field superconducting transition temperature of high-Tc cuprates is in fact close to the room temperature;**
- **Superconductivity in cuprates is not directly formed by electrons;**
- **Quasi-one dimensional channels (Stripes) are very favorable for high-Tc superconductivituy.**
- **The key problem is not to get conditions for HTS (strong repulsion, retardation, ets.), but to suppress competing orders (CDW and SDW).**

* Many electron coherent transport = Superconductivity

BCS

BCS is based on the Landau Fermi-liquid theory:
Fermi gas + Interaction = Fermi liquid of electron-like & hole-like excitations, they are fermions (Pauli exclusion principle)



$$\varepsilon_p = v_F \,| p - p_F |$$

In principle, BCS allows various (not only phonon's) mechanisms of pairing.
It assumes weak attraction between "electrons" → Cooper pairs and strong overlapping of the Cooper pairs (*L*>>*d*).
Because of this overlapping the pairs form the phase coherent condensate, i.e. all pairs have the same wavefunction *Ψ*= |*Ψ*| exp (i*φ*): $\delta N \cdot \delta\phi \sim \hbar$

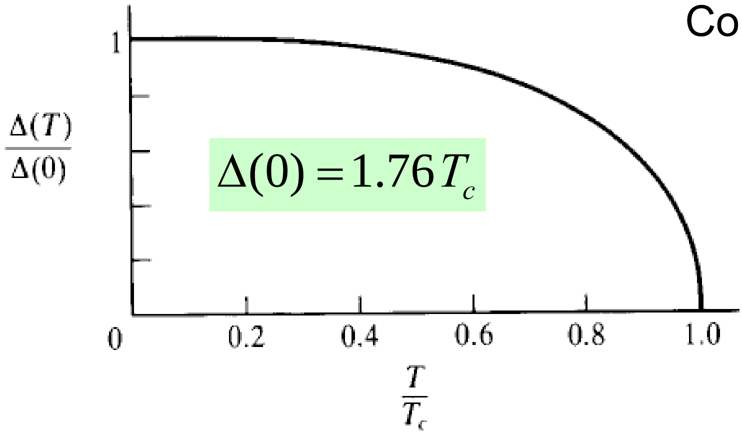
BCS relations:

Quasiparticle spectrum

$$\varepsilon_p = \sqrt{\xi_p^2 + \Delta^2}$$

Condensation energy

$$U_n(0) - U_s(0) = \frac{1}{2}\nu_0 \Delta^2(0) = \frac{H_c^2(0)}{8\pi}$$



$$\Delta(0) = 1.76\, T_c$$

Coherence length

$$\xi_0 = \frac{\hbar v_F}{\pi \Delta(0)}$$

Depairing velocity

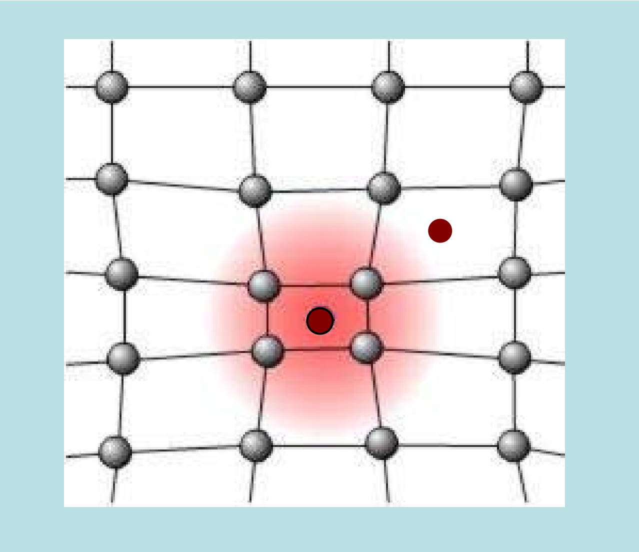
$$v_s = \frac{\Delta(0)}{p_F} = \frac{\hbar}{\pi\, m\, \xi_0}$$

Critical current

$$j_c \propto H_c \propto T_c$$

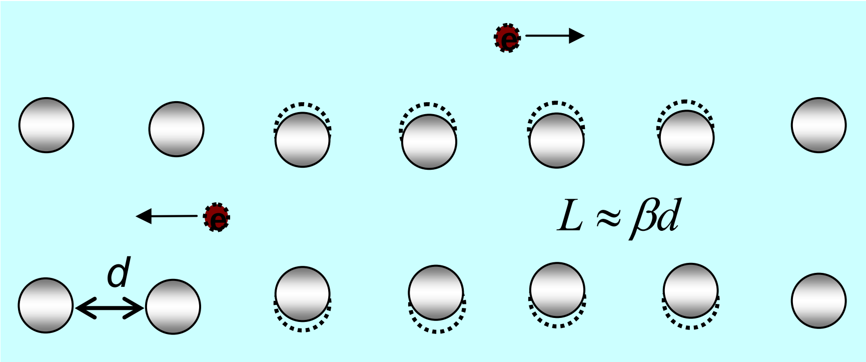
In ordinary superconductors, BCS describes well relations between all experimentally measured parameters: T_c, *Δ*, H_c, j_c …..
but the current theory cannot predict T_c from the first principles.

Phonon mechanisms of superconductivity



- In the BCS theory the superconducting state is formed by Cooper pairs.
- The Cooper pair is based on weak attraction between electrons via e-ph interaction: the lattice polarization by the first electron attracts the second one.

How weak e-ph attraction overweights strong e-e repulsion?



Retardation effects:

electrons are fast and ions are slow

$$\beta = \frac{v_F}{u_s} \cong \sqrt{\frac{M}{m_e}} \sim 300$$

$$\frac{\varepsilon_F}{\hbar\omega_D} \approx \frac{100{,}000\,K}{300\,K} \sim \beta$$

Retardation provides a weak residual attraction, even for $\mu >> \lambda_{e\text{-}ph.}$

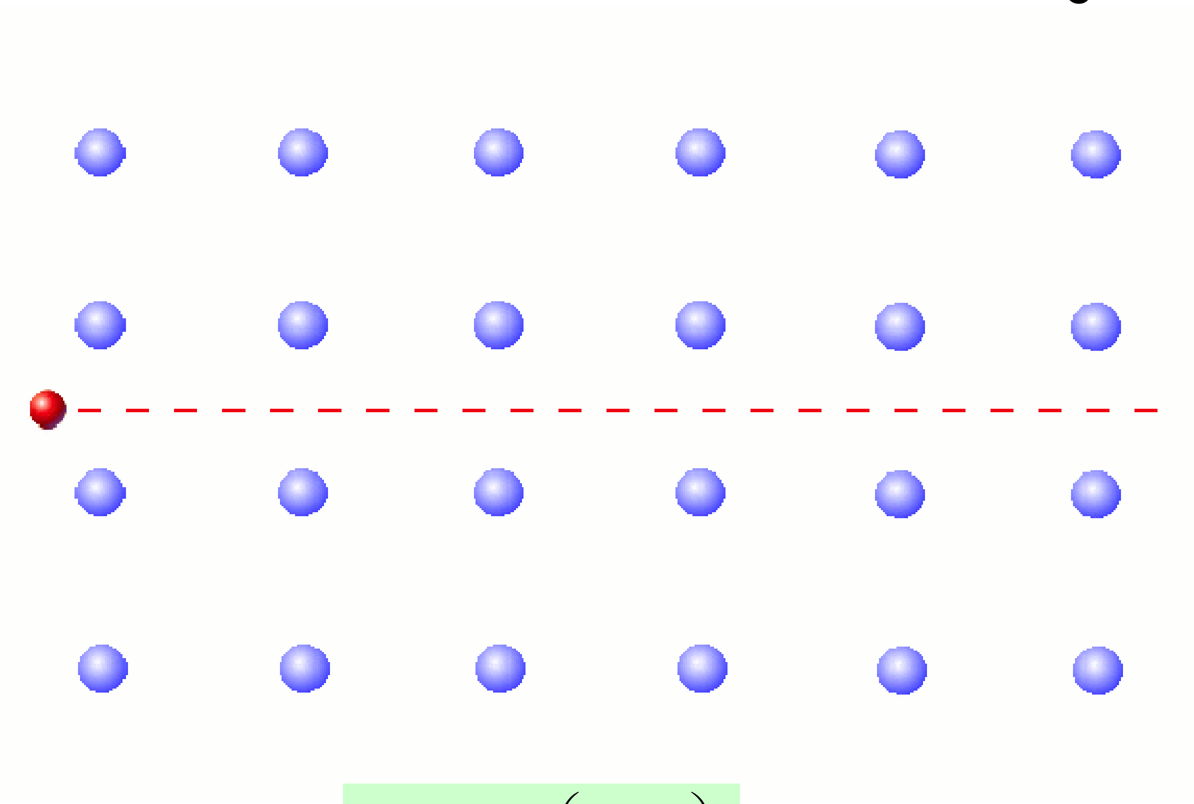
BSC-Eliashberg theory:

$$T_c \sim T_D \exp\left(-\frac{1}{\lambda_{eff}}\right);\lambda_{eff} = \frac{\lambda_{e-ph} - \mu^*}{1+\lambda_{e-ph}}$$

$$\mu^* = \frac{\mu}{1+\mu\log(\varepsilon_F/\omega_D)}$$

For ordinary metals these or more general equations lead to bounds on T_c as 30-50 K.

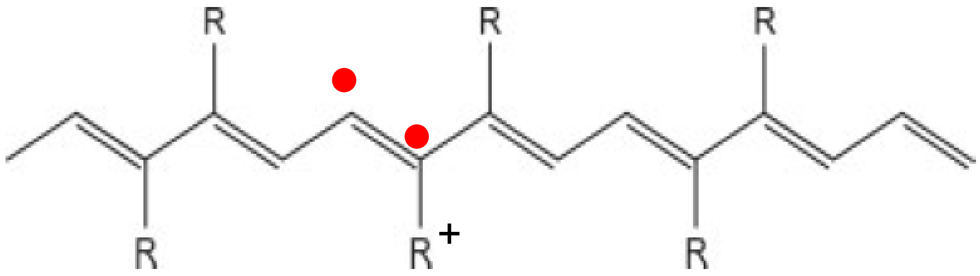
Retardation Effects and T_c



$$T_c \sim T_D \exp\left(-\frac{1}{\lambda_{eff}}\right)$$

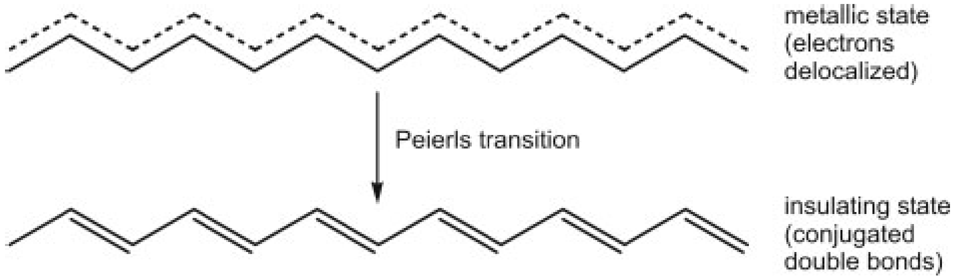
If the Debye temperature (the prefactor) is increased,
the interaction becomes faster, $\hbar\omega_D = k_B T_D$,
in other words, less retarded, and T_c decreases.

Excitonic mechanism & Superconductivity in quasi-1D systems



Quasi-1D superconductor suggested by W.A. Little (1964):

- Spine is a polymer with conjugated double bonds (functionalized polyacetylene);
- Arms (R) are chain molecules with low-lying excited states;
- An electron excites the molecule when passing by;
- The next electron reabsorbs this exciton.

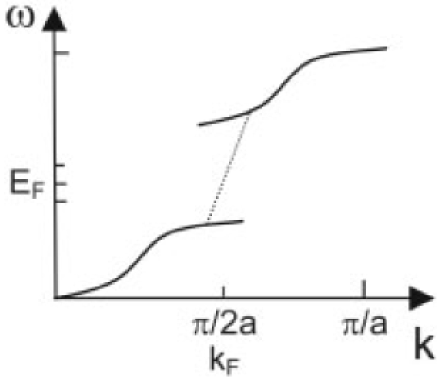


Tight-Binding Model Investigations:

Hirch&Scalapino (1985) : in1D - CDW dominates over SC;

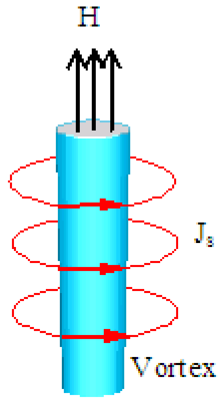
Cheng&Su (2003): in 2D – substantial room for SC

Mermin-Wagner-Hohenberg Theorem:
In 1D conductors, at finite temperature,
the long-range superconducting order
is destroyed by
fluctuations (collective modes).



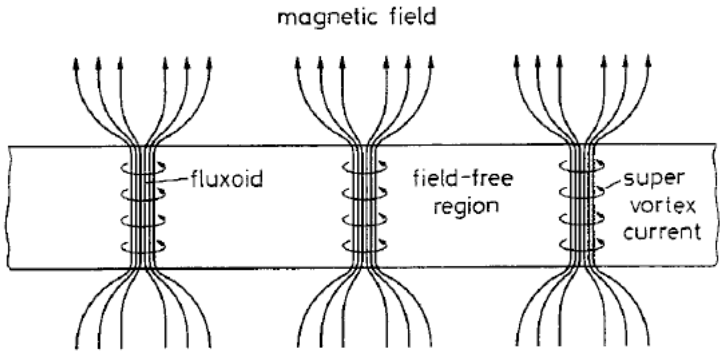
In real, quasi-1D materials,
the superconducting order is possible,
but T_c is low,
because of charge density waves.

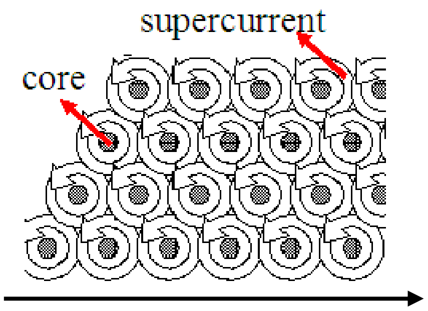
Resistivity of 3D superconductor: Vortices in type II superconductors

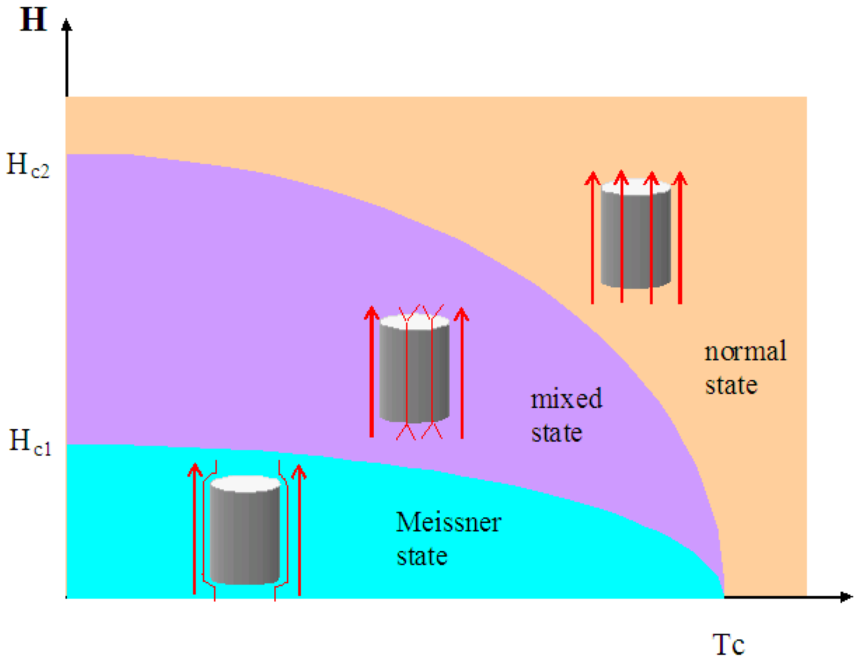


One Vortex

- Normal core is ~ coherent length;
- Supercurrents are concentrated in the area of ~ magnetic field penetration length





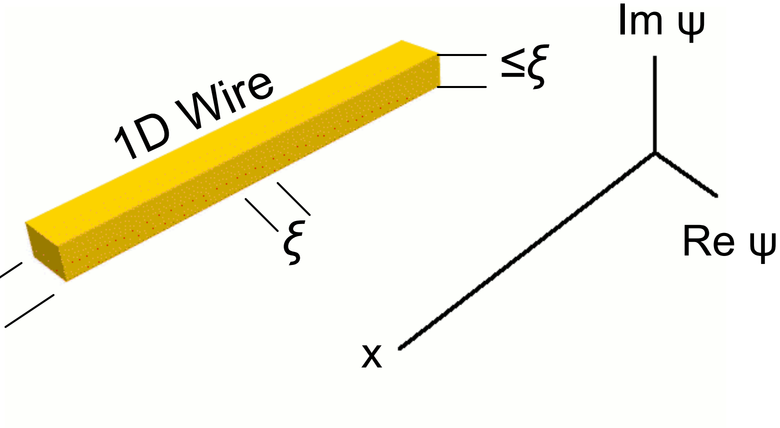


- Electric current applies the Lorentz force to vortices;
- If this force exceeds the pinning forces vortices start moving → Dissipation & Resistivity

Resistivity of low-dimensional superconductor

One Dimensional Resistive Transition

- Langer, Ambegaokar, McCumber, and Halperin (LAMH) theory of thermally activated phase slip centers



LAMH at low currents

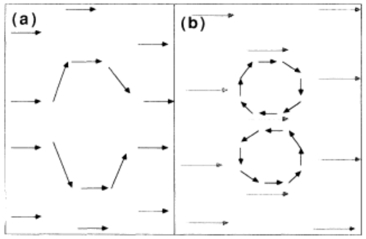
$$R_{LAMH}(T) = \frac{\pi\hbar^2\Omega}{2e^2 k_B T} e^{-\Delta F / k_B T}$$

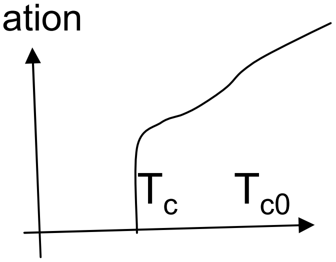
$$\Omega = L/\xi(T)\sqrt{\Delta F/k_B T}\,1/\tau_{GL}$$

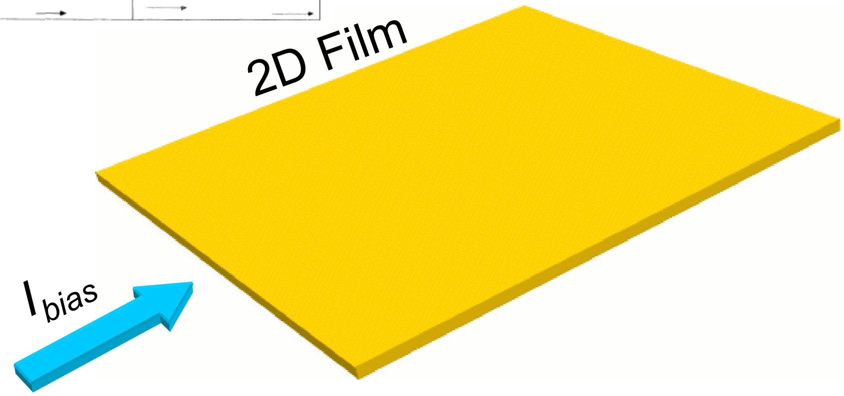
$$\Delta F = (8\sqrt{2}/3)(H_c^2/8\pi)A\xi_0$$

Two Dimensional Resistive transition

- Berezinskii-Kosterlitz-Thouless (BKT) theory of vortex-antivortex dissociation







Above BKT transition temperature T_C

$$R_{HN} = 10.8 b R_N \exp\left(-2\sqrt{b\left(T_{C0}-T_C\right)/\left(T-T_C\right)}\right)$$

Below T_C

$$R_{VAP} = 4R_N \frac{T_C - T}{T_{CO} - T_C}\cdot\left(\frac{I}{I_0}\right)^{2\frac{T_{CO}-T}{T_{CO}-T_C}}$$

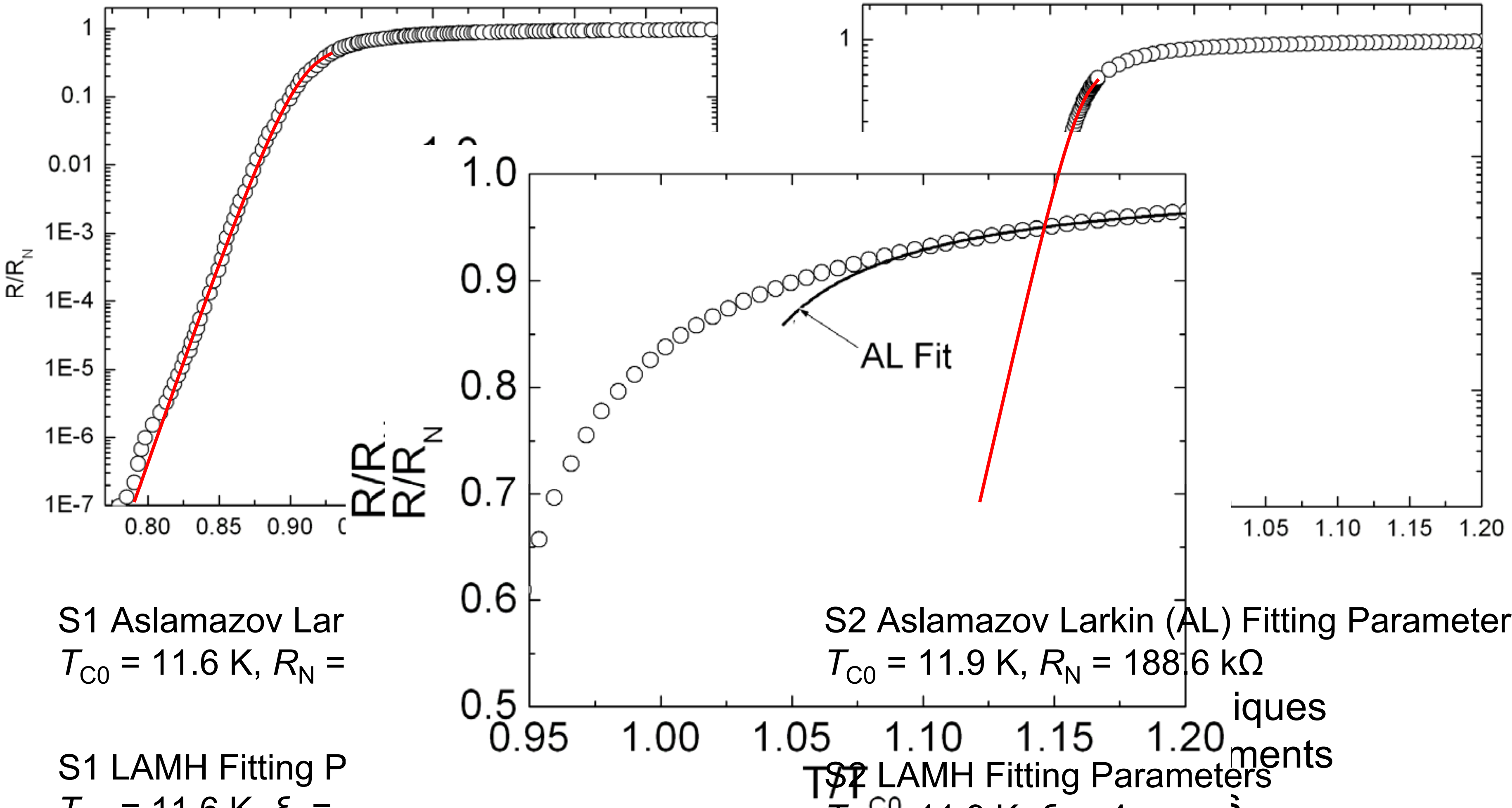
$$I_{th} = \left(1+2\frac{T_{C0}-T}{T_{C0}-T_C}\right)\frac{2ek_B T}{\pi\hbar}$$

What is T_c ?

Resistivity of sub-micron superconducting samples

Sample 1

Sample 2



S1 Aslamazov Lar

T_{C0} = 11.6 K, R_N =

S1 LAMH Fitting P

T_{C0} = 11.6 K, ξ_0 =

S2 Aslamazov Larkin (AL) Fitting Parameters

T_{C0} = 11.9 K, R_N = 188.6 kΩ

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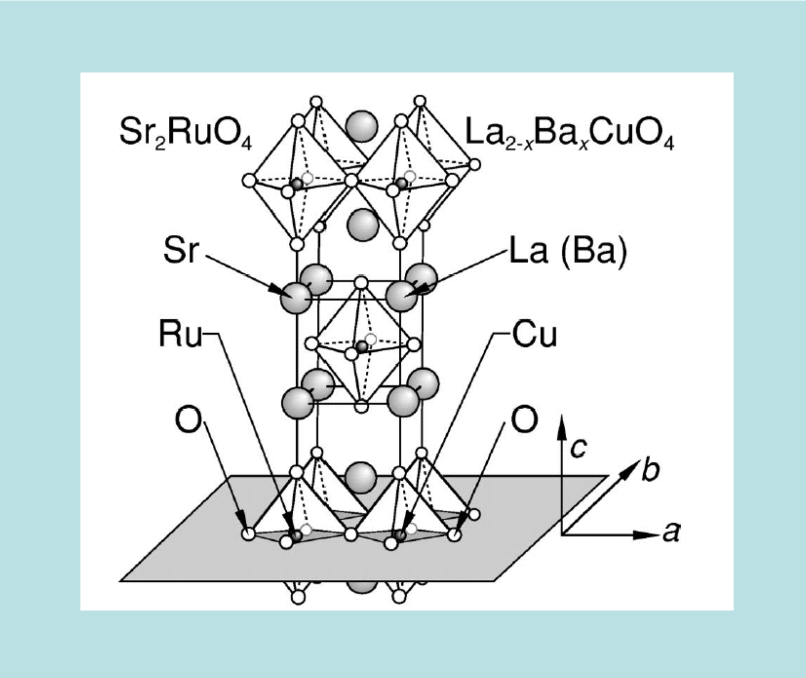
ments

S2 LAMH Fitting Parameters

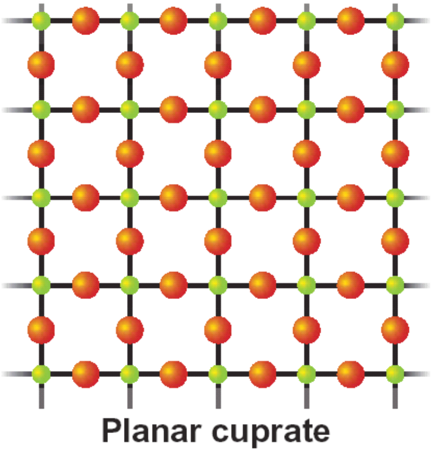
T_{C0} = 11.9 K, ξ_0 = 4 nm

- I_b = 10 nA

Lessons from high-T_c cuprates



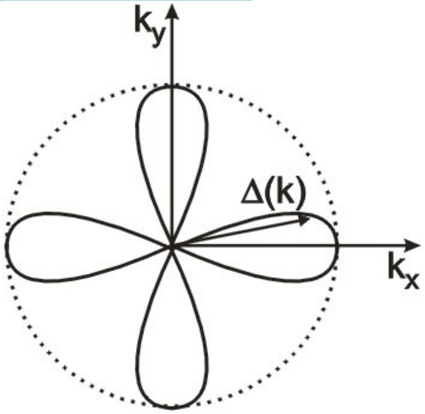
- Electron concentrations are significantly smaller than that in metals;
- The Cu-O planes are mainly responsible for the superconductivity;



Cu-O planes become conducting only after doping

d-wave pairing:
Superconducting gap in the plane is

$$\Delta(k) = \Delta_0(\cos k_x - \cos k_y)$$



Because of d-wave pairing:
(i) There are nodal regions with Δ=0;
(ii) Elastic scattering from impurities and defects drastically affects the superconductivity;
(iii) $\Delta_x = -\Delta_y$; additional phase shift

Again, d-wave pairing provides explanation to relations between various parameters in a superconducting state (not so well as for ordinary superconductors), but origin of high-T_c conductivity is still a puzzle.

How unusual the “unusual” cuprates?

Ordinary metals: $\frac{\varepsilon_F}{\hbar\omega_D} \approx 300$

Cuprates: $\frac{\varepsilon_F}{\hbar\omega_D} \approx 5$

There is no retardation in cuprates

Cuprates are
strongly interacting materials:

- Without doping these materials are dielectrics;
- Antiferromagnetic ordering
- Non-Fermi-liquid normal state !!!
- Pseudogap in the “normal” state !

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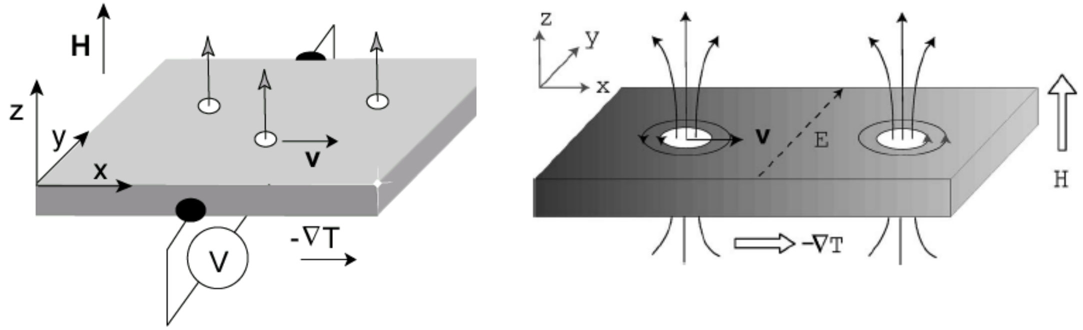
Vortex-like excitations and the onset of superconducting phase fluctuation in underdoped $La_{2-x}Sr_xCuO_4$

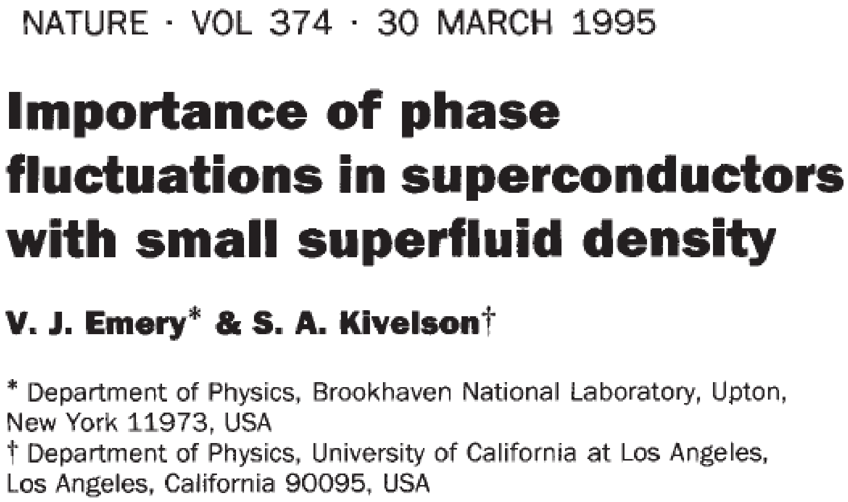
Z. A. Xu[*,†], N. P. Ong[*], Y. Wang[*], T. Kakeshita[‡] & S. Uchida[‡]

Here we report evidence for vortices (or vortex-like excitations) in La2-xSrxCuO4 at temperatures significantly above the critical temperature…
We find that the Nernst signal is anomalously enhanced at temperatures as high as 150 K.



- Very recently we have shown that
  the large Nernst effect = Non-Fermi-liquid state
  Sergeev et al. ArXiv:0708.1003v1 [con-mat.supr-con]

What is T_c in cuprates?



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Importance of phase fluctuations in superconductors with small superfluid density

V. J. Emery[*] & S. A. Kivelson[†]

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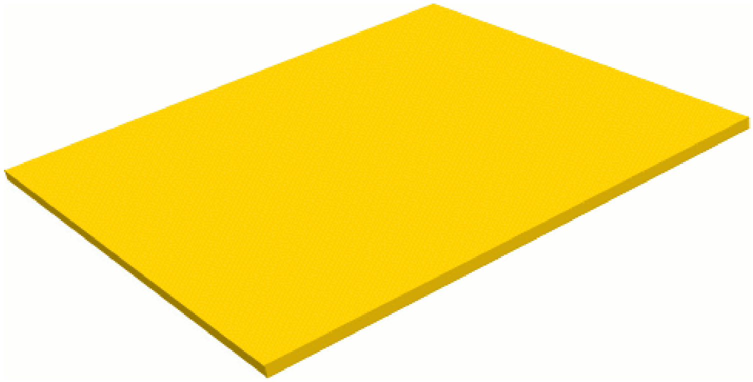
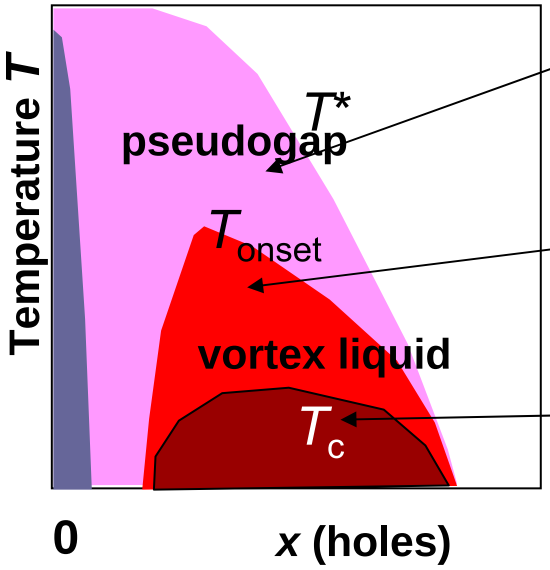
Summary of current results and ideas:

- Large region in phase diagram above Tc with enhanced Nernst signal;
- It is associated with vortex excitations;
- It is confirmed by torque magnetometry;

- Transition at Tc is 3D version of KT transition (loss of phase coherence)

- Upper critical field behavior confirms conclusion





Spin pairing
(NMR relaxation)

Onset of charge pairing
Vortex-Nernst signal
Enhanced diamagnetism

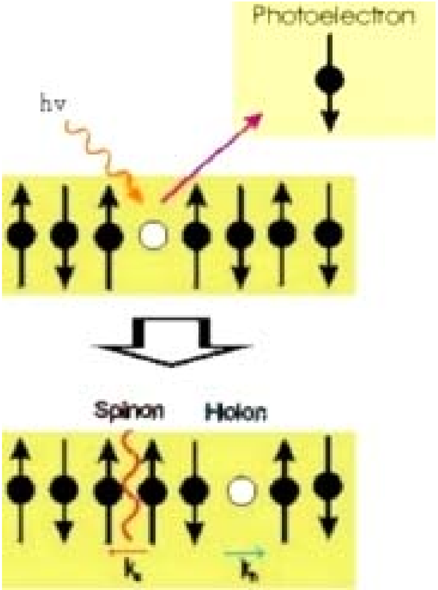
Superconductivity
long-range phase coherence
Meissner effect.

Wang et all.“Vorticity and Phase Coherence in Cuprate Superconductors”

Luttinger liquid

- 1D spin-charge separation
- Pair spins only
- Avoid Coulomb Repulsion!

It is well understood (already in textbooks)
that in this case pair binding can occur from purely
repulsive electron interaction.



Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 8814–8817, August 1999

Perspective

Stripe phases in high-temperature superconductors

V. J. Emery, S. A. Kivelson†‡, and J. M. Tranquada**

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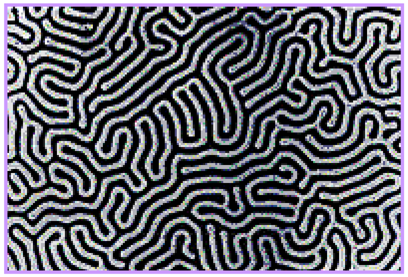
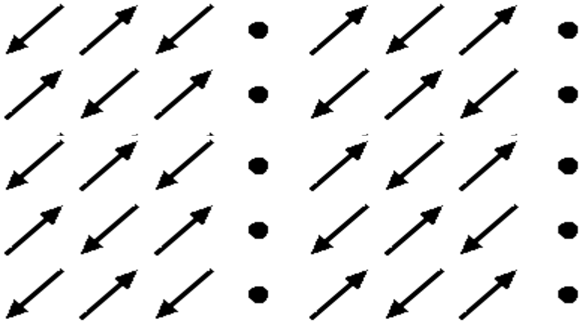
Stripe phases are predicted and observed to occur in a class of strongly correlated materials describable as doped antiferromagnets, of which the copper-oxide superconductors are the most prominent representatives. The existence of stripe correlations necessitates the development of new principles for describing charge transport and especially superconductivity in these materials.

Stripes

- There are many competing orders in strongly interacting systems;
- Competition always produces stripes:

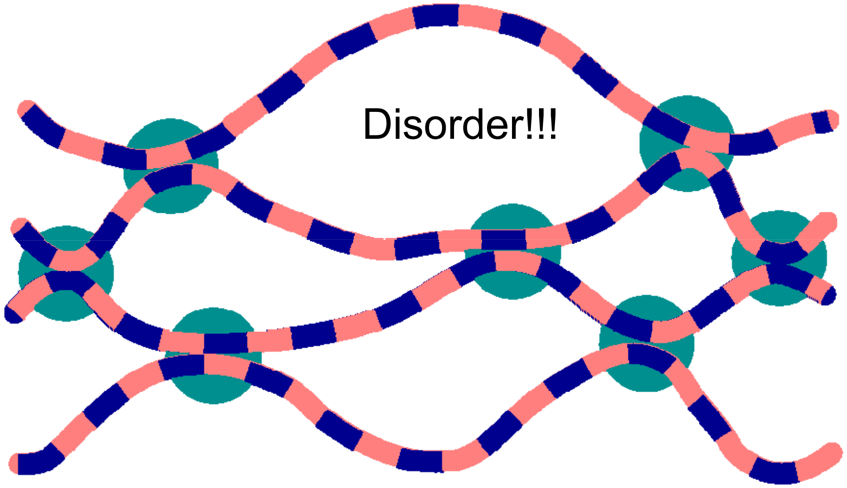


Ferrofluid confined between two glass plates (period ~ 1cm)



Doping in cuprates results in phase separation: (overdoped) rivers of charge between (underdoped) antiferromagnetic strips. Electronic structure becomes effectively 1D.

- Stripe fluctuations discourage CDW and encourage SC



Synthetic Metals
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Strategies for finding superconductivity in conducting polymers

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Abstract

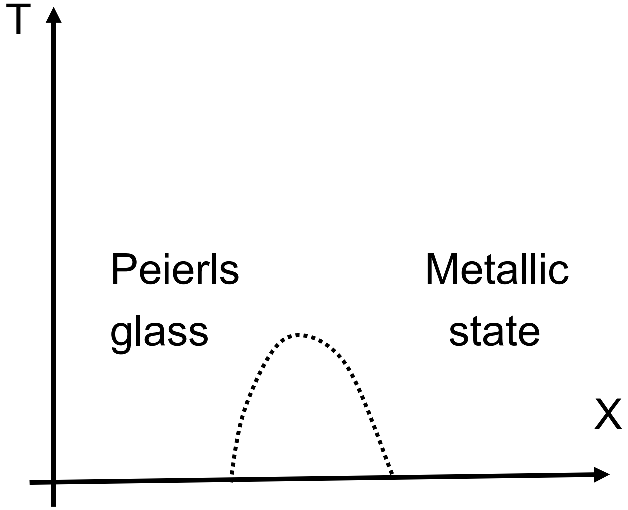
By combining experimental information and some very general aspects of the current theory of highly correlated systems, we develop a set of strategies for searching for high temperature superconductors in ***highly correlated solids***, with particular reference to the ***conducting polymers***.

- **HTS cuprates and polymers have a lot of common features:**

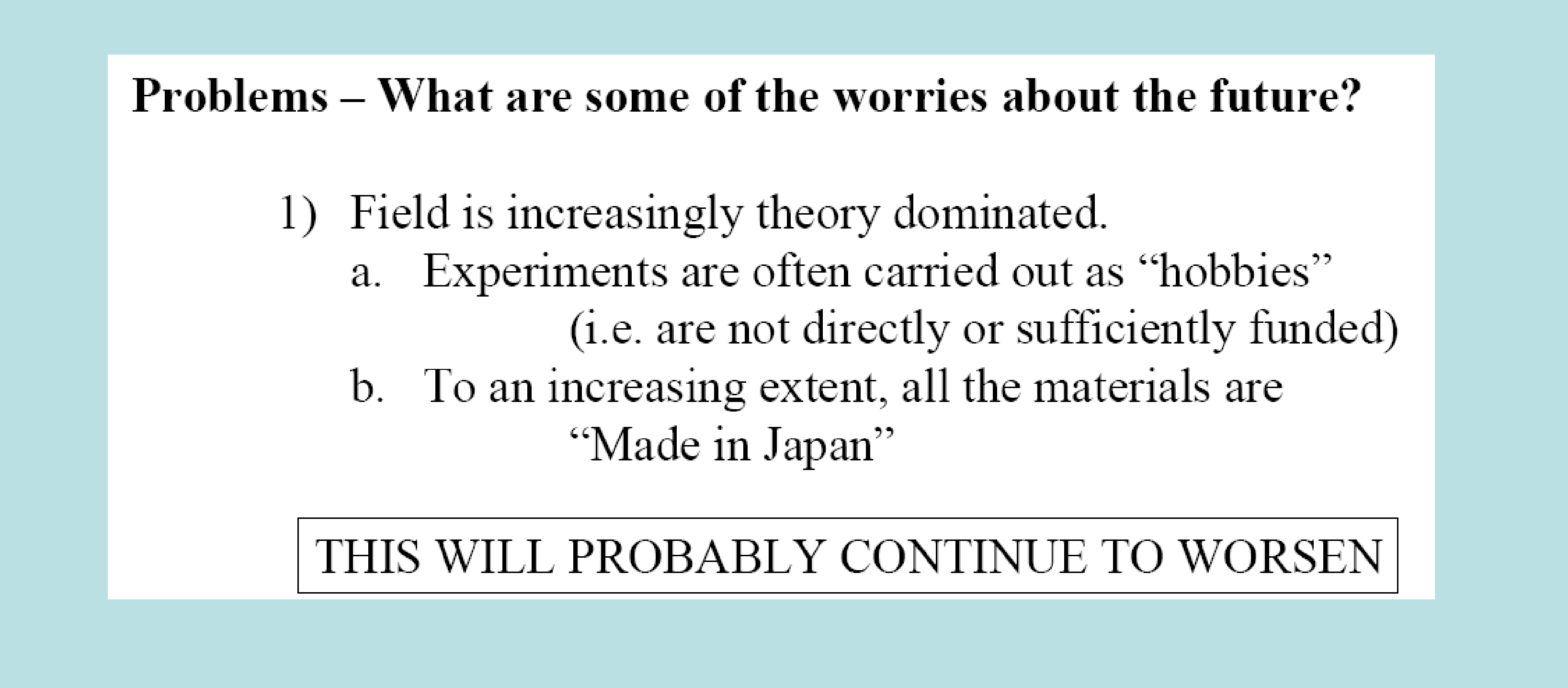
  correlated AF insulators without doping,

  conductivity in real space is realized via 1D channels;

- **The key problem is not to get conditions for HTS (strong repulsion, retardation, ets.), but to suppress competing orders (CDW and SDW).**



From talk by Steven Kivelson,
The Solid State Sciences Committee Meeting, Irvine 2005



Problems – What are some of the worries about the future?

1) Field is increasingly theory dominated.
    a. Experiments are often carried out as “hobbies” (i.e. are not directly or sufficiently funded)
    b. To an increasing extent, all the materials are “Made in Japan”

THIS WILL PROBABLY CONTINUE TO WORSEN

Conclusions

- There are principle limitations on T_c for traditional e-pn mechanism.
- High-T_c cuprates have another, non e-ph, pairing mechanism.
- High-T_c superconductivity in cuprates originates from unusual, non-Fermi-liquid, normal state.
- Superconducting cuprates demonstrate quasi-one-dimensional microstructure (superconducting stripes).
- Quasi-one-dimensional structures are very favorable for superconductivity:
  - (i) Luttinger (non-fermi-liquid) normal state;
  - (ii) Strong correlations;
  - (iii) Uncharged elementary excitations.
- For variety of well-understood reasons quasi-1D systems tend to have transition to CDW or SDW at higher temperatures than a superconducting state.
  Disorder (stripe fluctuations) suppress CDW and encourage superconductivity.
- At high temperatures, fluctuation effects are strong:
  Sharp superconducting transitions are not expected.