united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

SMR.1572 - 6

Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

Vortices, phase coherence and Nernst effect in cuprate superconductors

Nai Phuan ONG
Princeton University
Department of Physics
Jadwin Hall
P.O. Box 708
Princeton NJ 08544
U.S.A.

Vorticies, Phase coherence and Nernst Effect in Cuprate Superconductors

1. Vortex Nernst effect

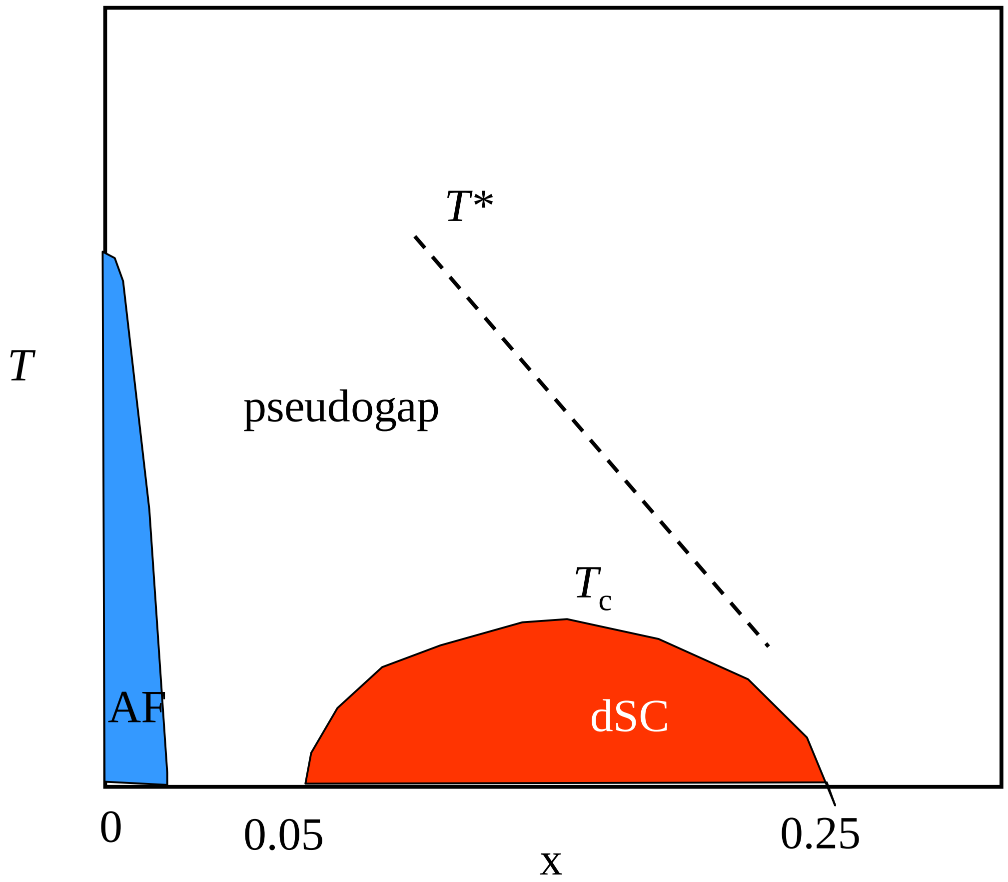
2. The phase diagram in cuprates

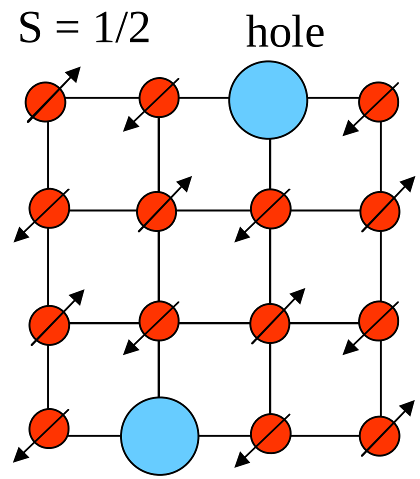
3. The upper critical field problem

4. Pairing, superfluid rigidity and theory

ICTP Trieste 2004

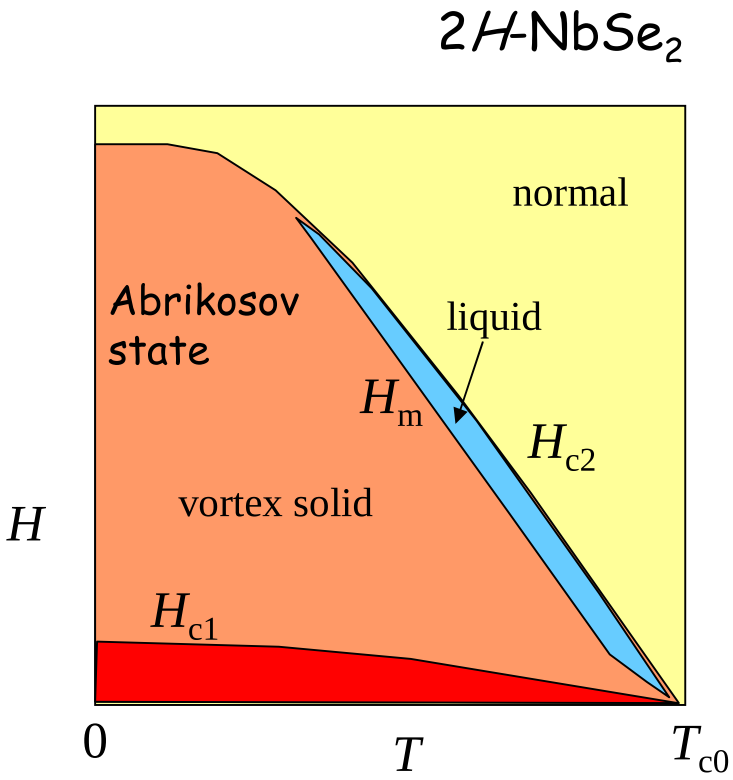
Vorticies, Phase coherence and Nernst Effect in Cuprate Superconductors

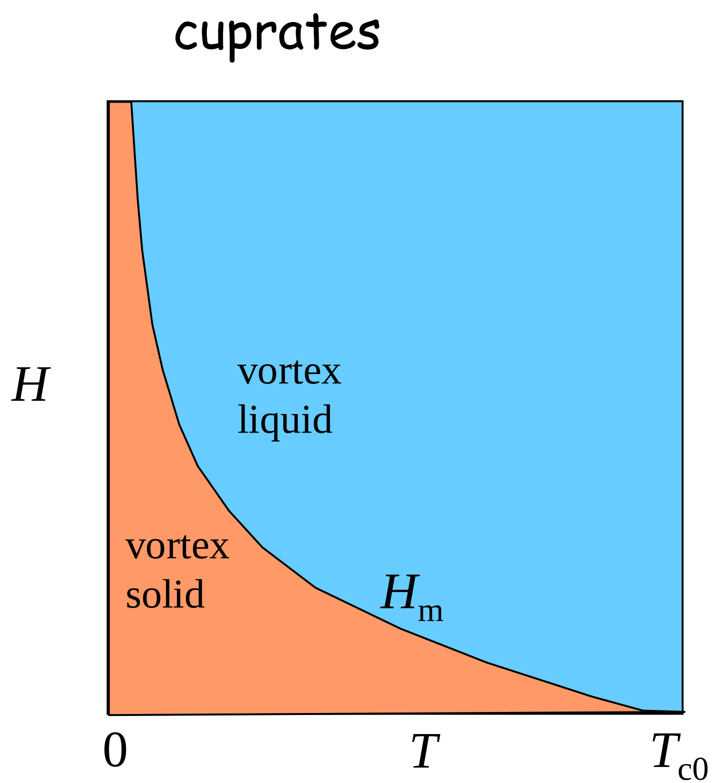




Pairing strength *vs.* x?

Type II superconductor

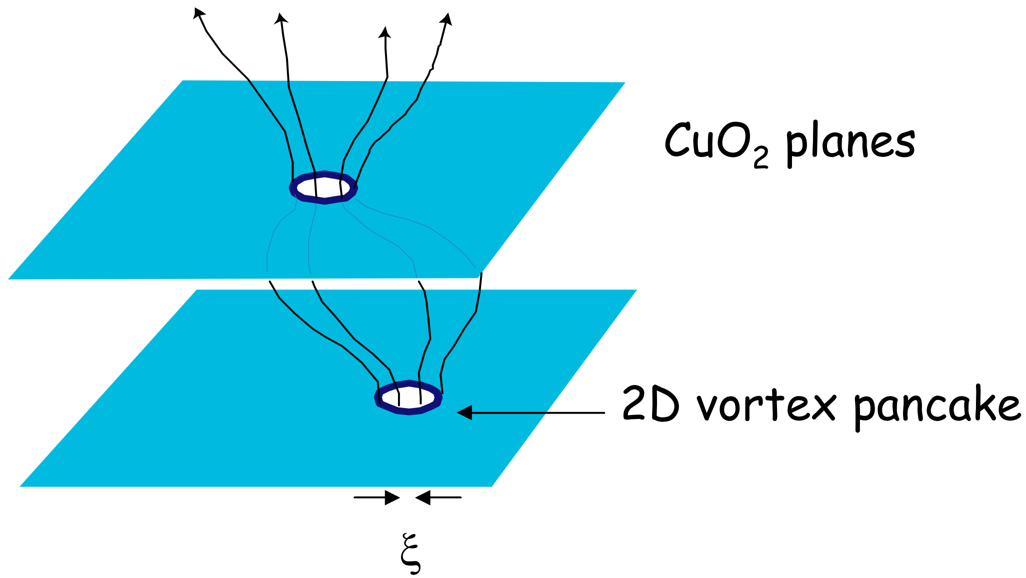


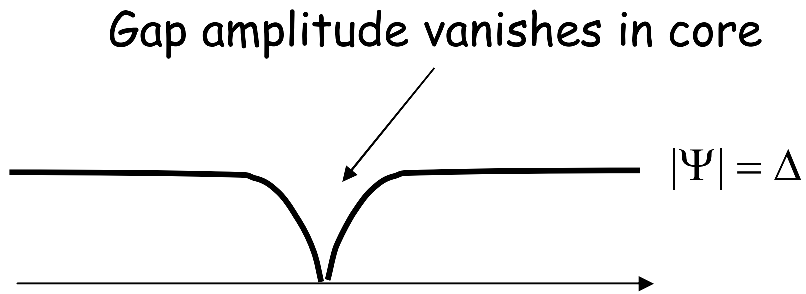


Upper critical field $H_{c2} = \phi_0/2\pi\xi_0^2$

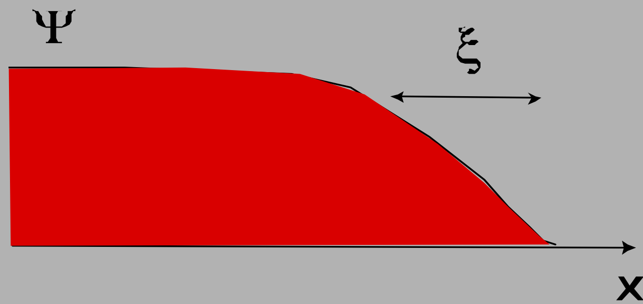
Where is the H_{c2} line in cuprates?

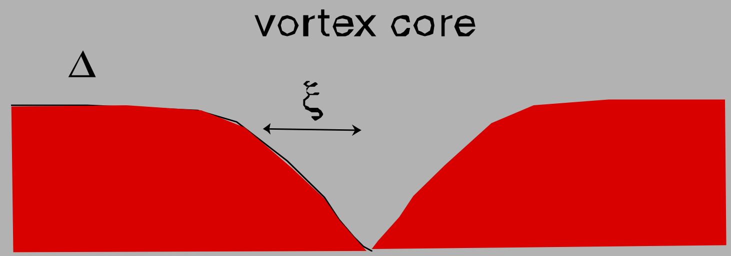
Vortices in cuprates





Coherence Length ξ

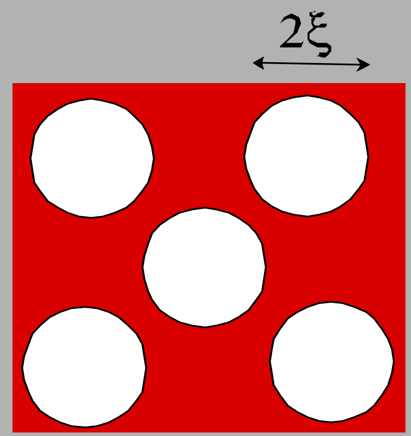




What is ξ in cuprates?

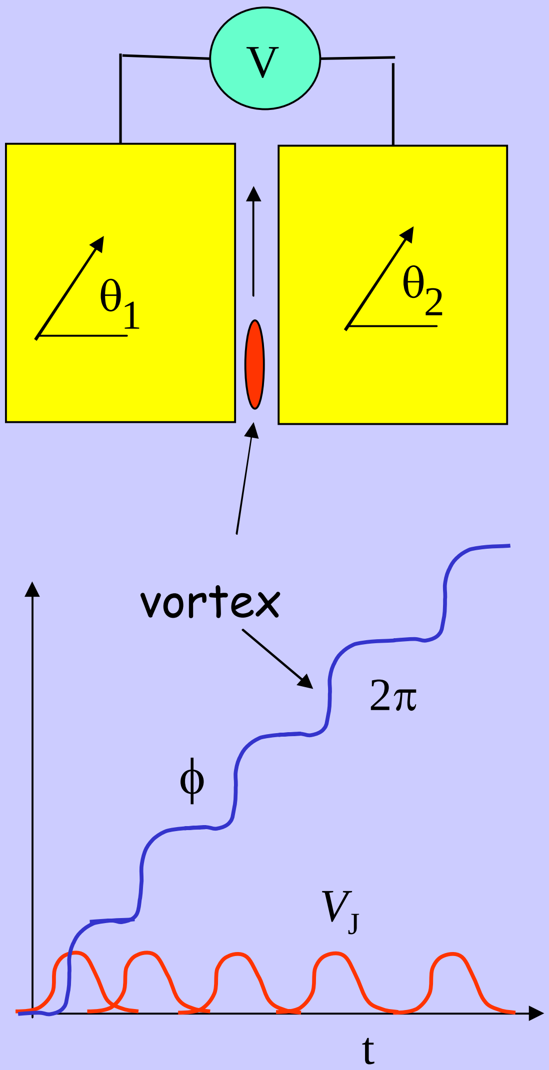
Length scale to bend wave function

$\xi_P = \hbar v_F / \pi \Delta$ (Pippard)



Upper Critical field $H_{c2} = \phi_0 / 2\pi\xi^2$

The Josephson Effect and phase-slip



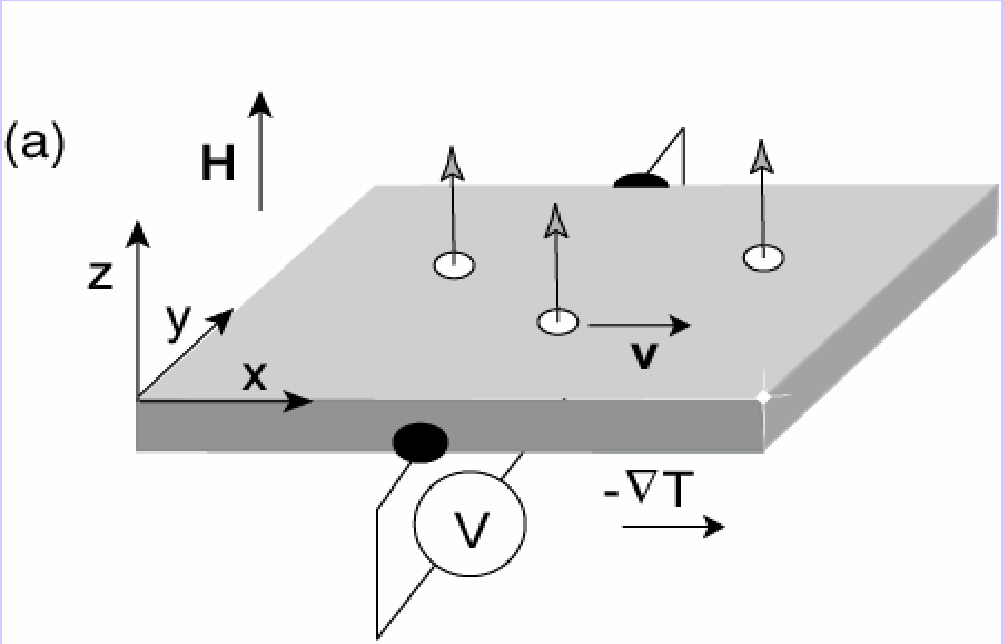
2nd Josephson Equation

$$2eV_J = \hbar\dot{\phi}, \qquad \phi = \theta_2 - \theta_1$$

$$2eV_J = 2\pi\hbar\dot{n}_V$$

dc Josephson voltage proportnal to phase-slip rate

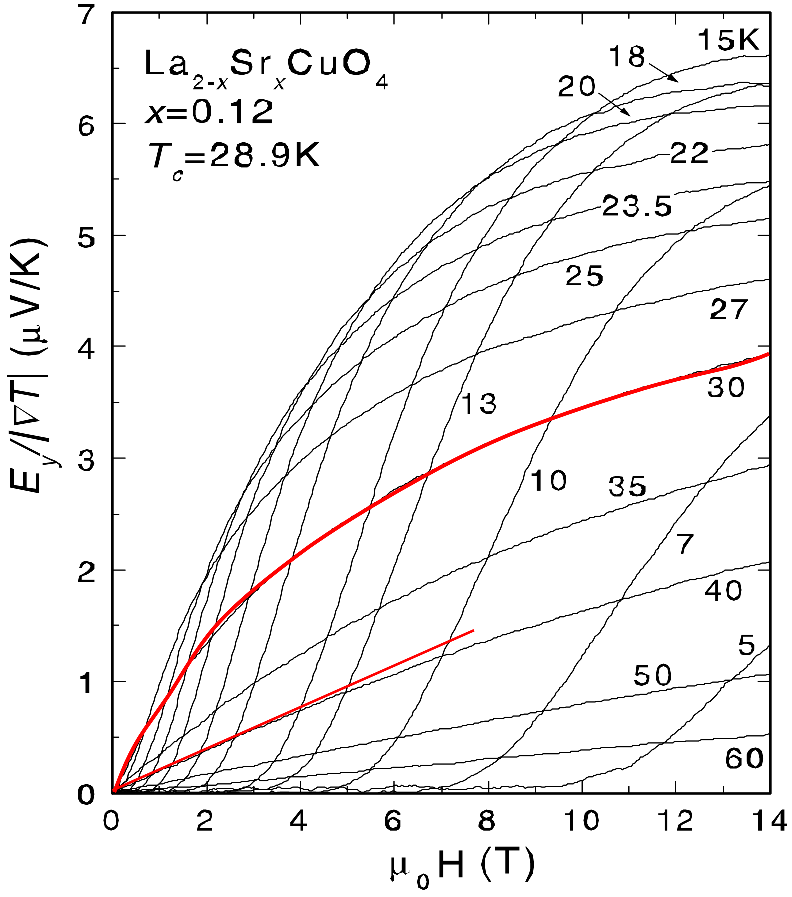
Nernst experiment



Walter Nernst

Vortices move in a temperature gradient
Phase slip generates Josephson voltage

$$2eV_J = 2\pi\hbar\,\dot{n}_V$$
$$\mathbf{E}_J = \mathbf{B} \times \mathbf{v}$$



Nernst signal

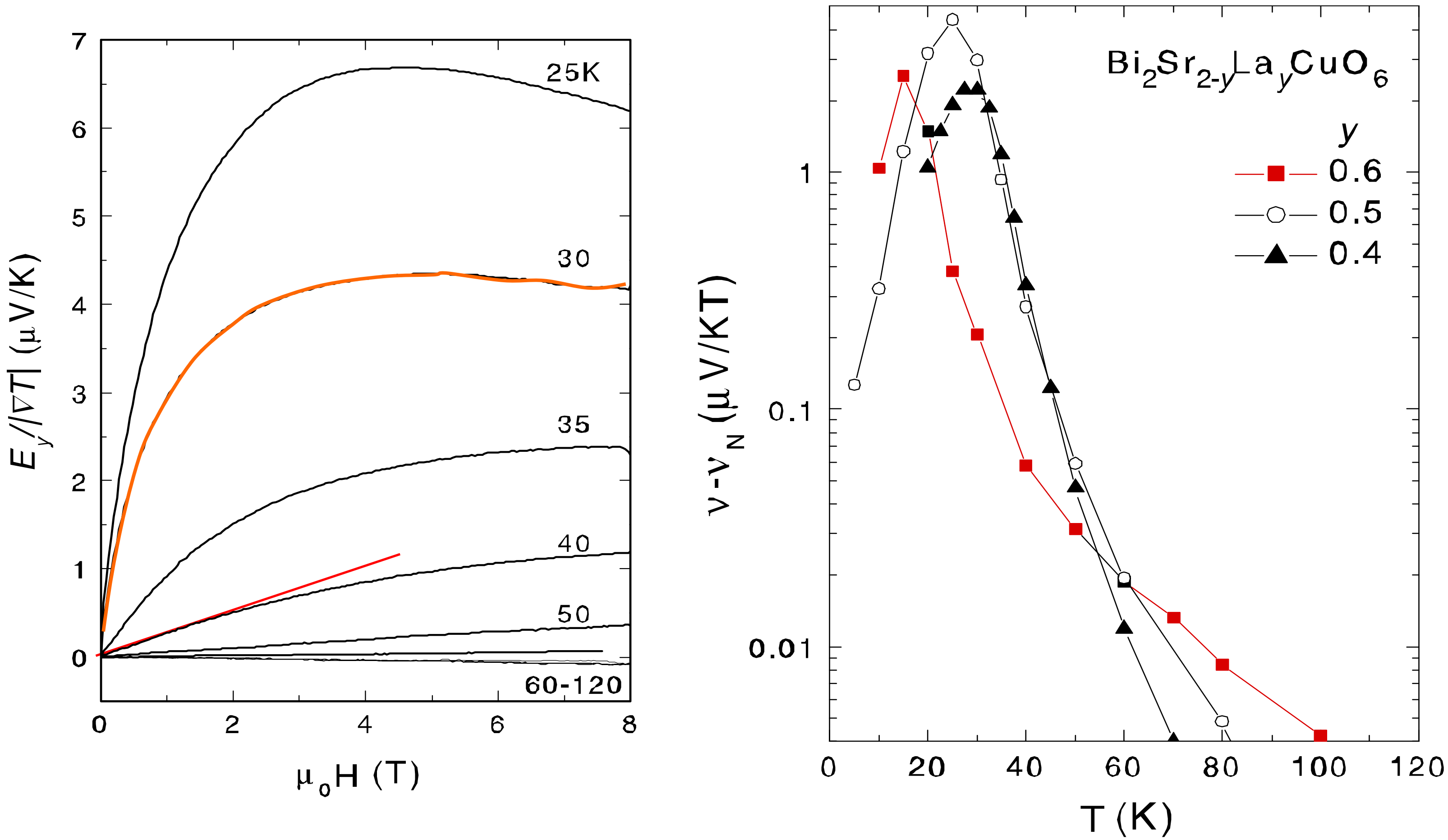
$e_y = E_y / | \nabla T |$

Nernst coefficient

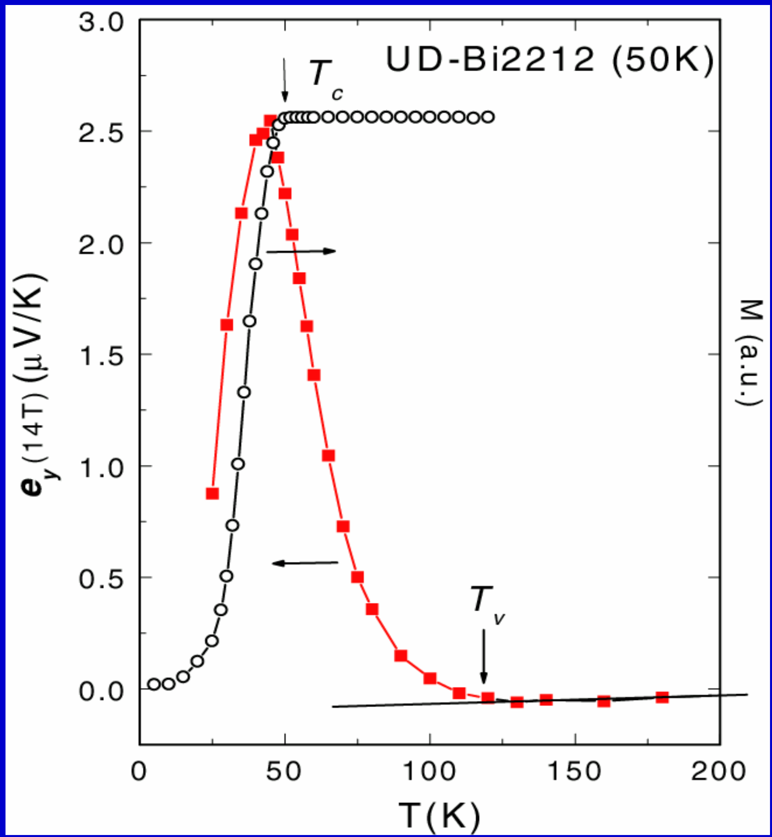
$\nu = e_y / B$

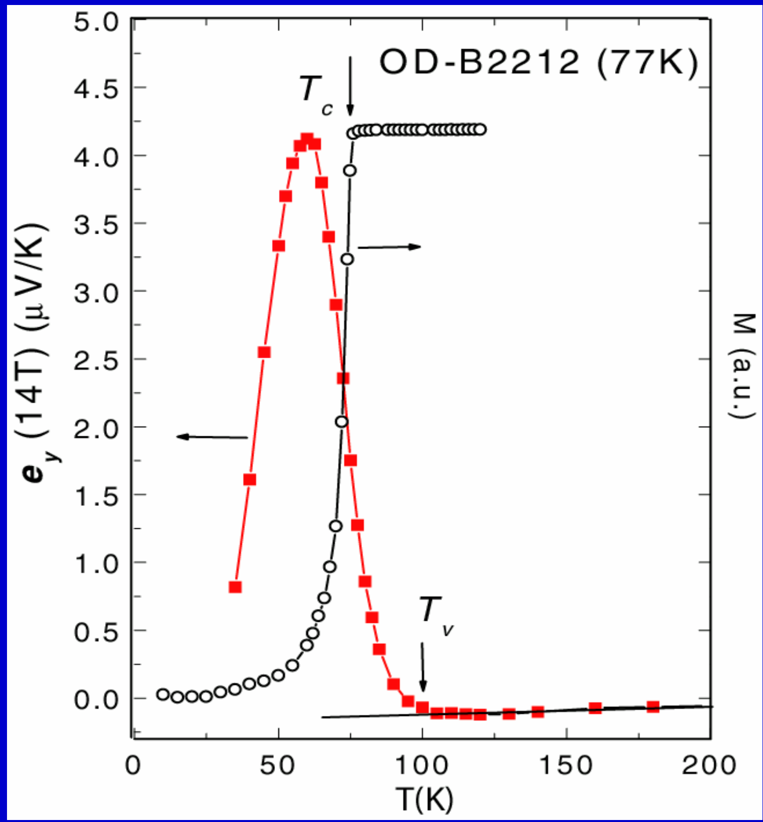
Nernst signal versus field at fixed T in LaSrCuO (x = 0.12)

$Bi_2Sr_{2-y}La_yCu_2O_6$ T_c = 28 K
Nernst signal survives up to 80 K

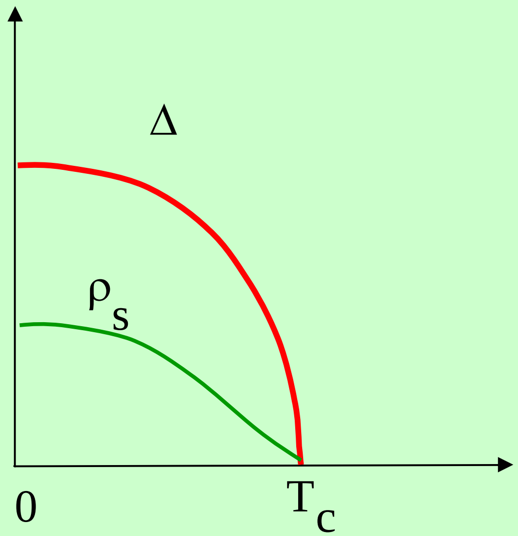


Vortex signal above T_{c0} in under- and over-doped Bi 2212





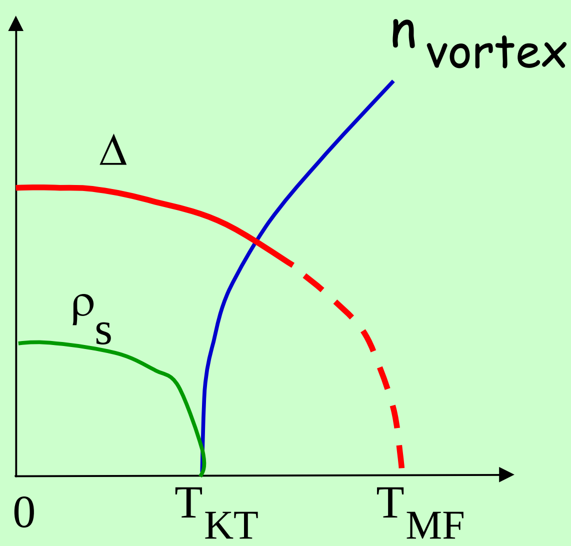
BCS transition



$$H = \tfrac{1}{2}\rho_s \int d^3r\, (\nabla\phi)^2$$

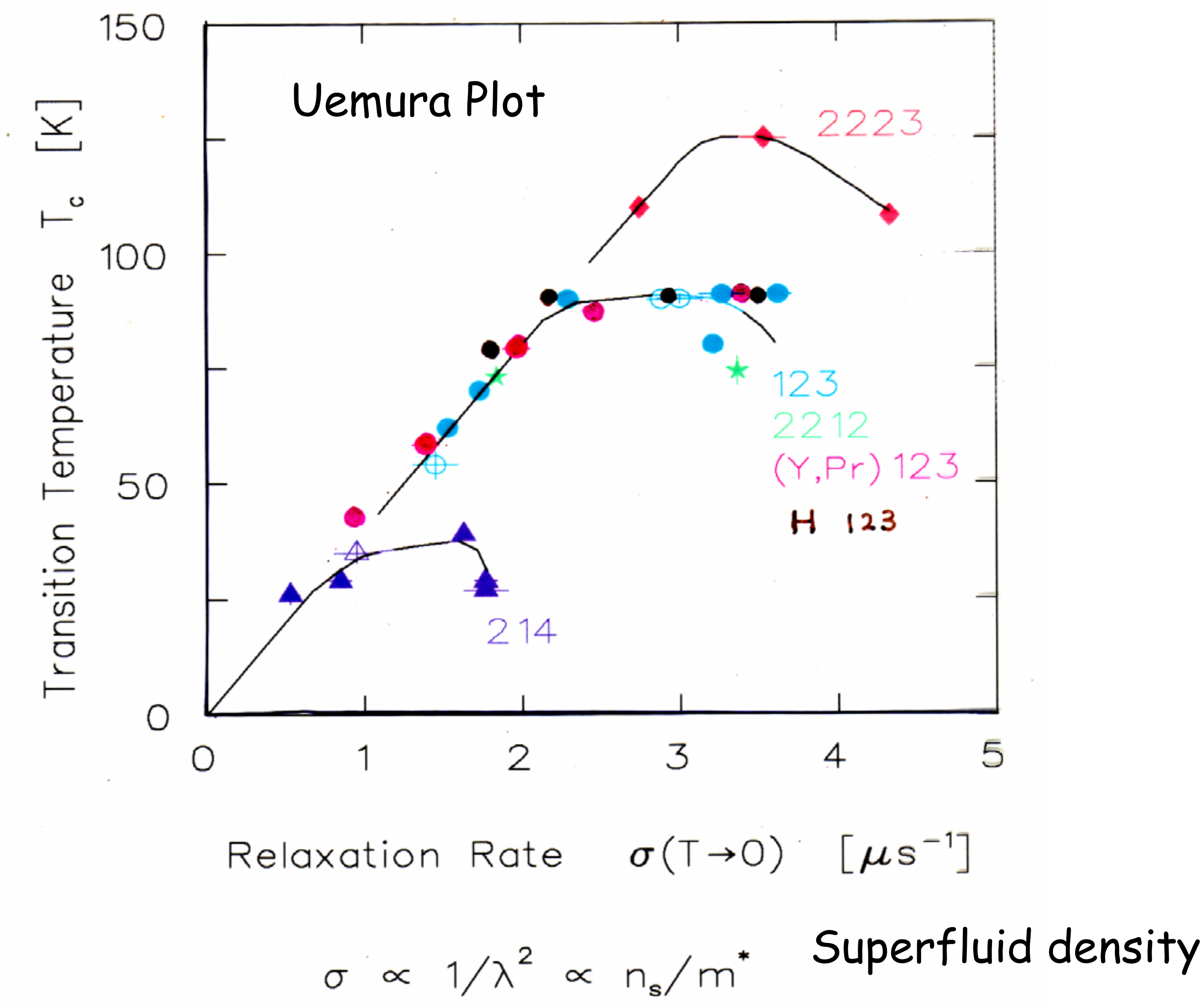
ρ_s measures phase rigidity

2D Kosterlitz Thouless transition



Phase coherence destroyed at T_{KT}
by proliferation of vortices

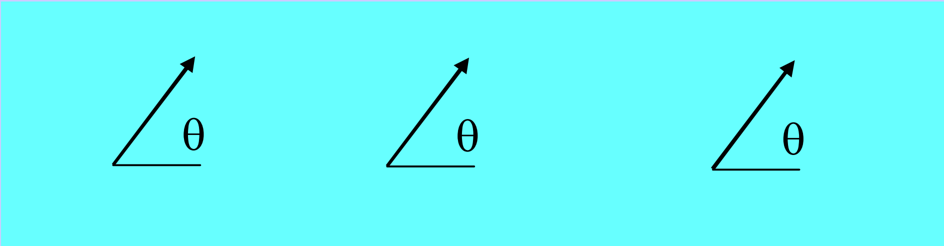
High temperature superconductors?


Uemura Plot
Transition Temperature T_c [K]
150
100
50
0
0
1
2
3
4
5
2223
123
2212
(Y,Pr) 123
H 123
214
Relaxation Rate $\sigma(T \to 0)$ [μs^{-1}]
$\sigma \propto 1/\lambda^2 \propto n_s/m^*$
Superfluid density

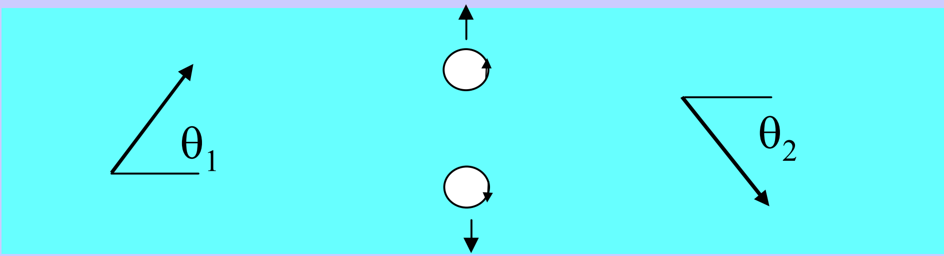
Phase rigidity

Complex wave function $\Psi(\mathbf{r})\, e^{i\theta(\mathbf{r})}$

$\theta(\mathbf{r})$ has long-range coherence in Meissner state

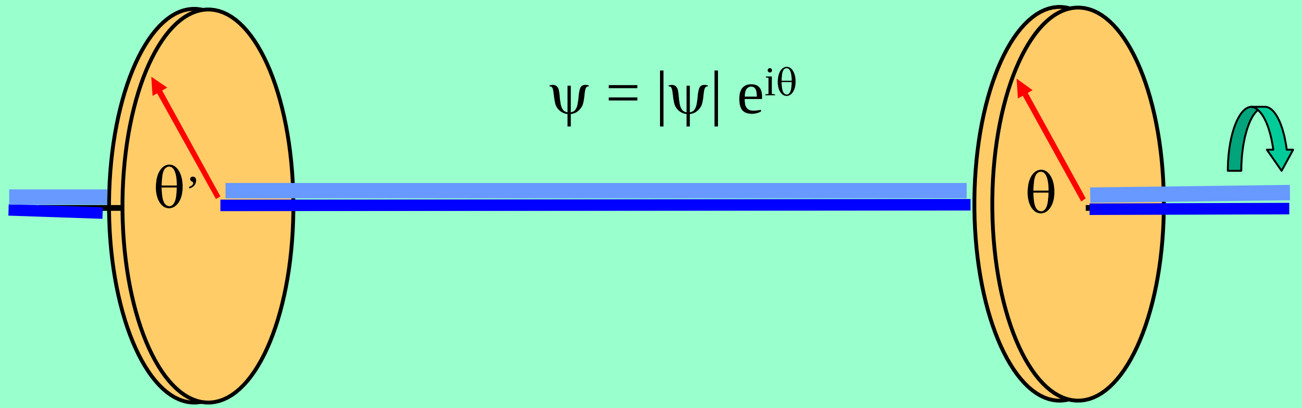


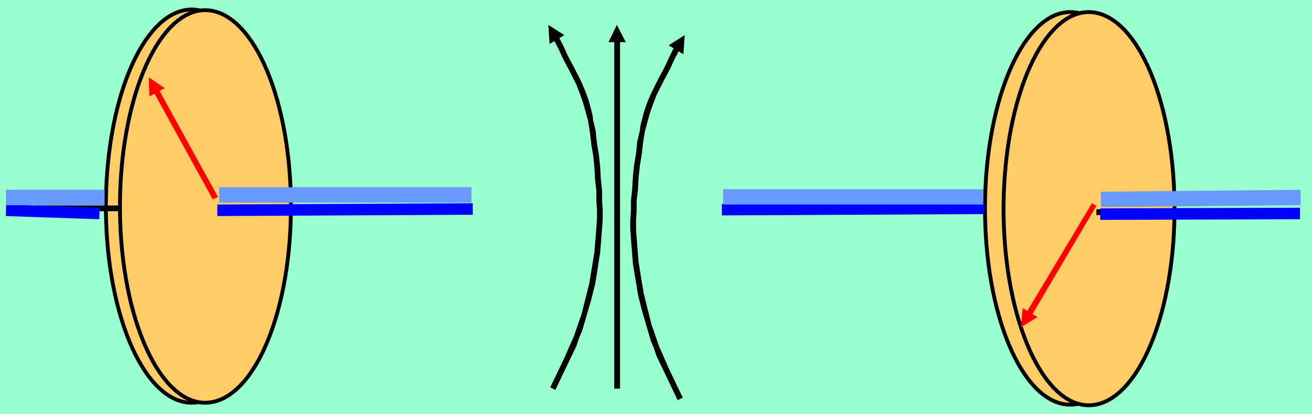
Phase coherence destroyed by vortex motion



Destroys superfluidity but not condensate

Phase rigidity of wave function





Phase coherence destroyed by vortex

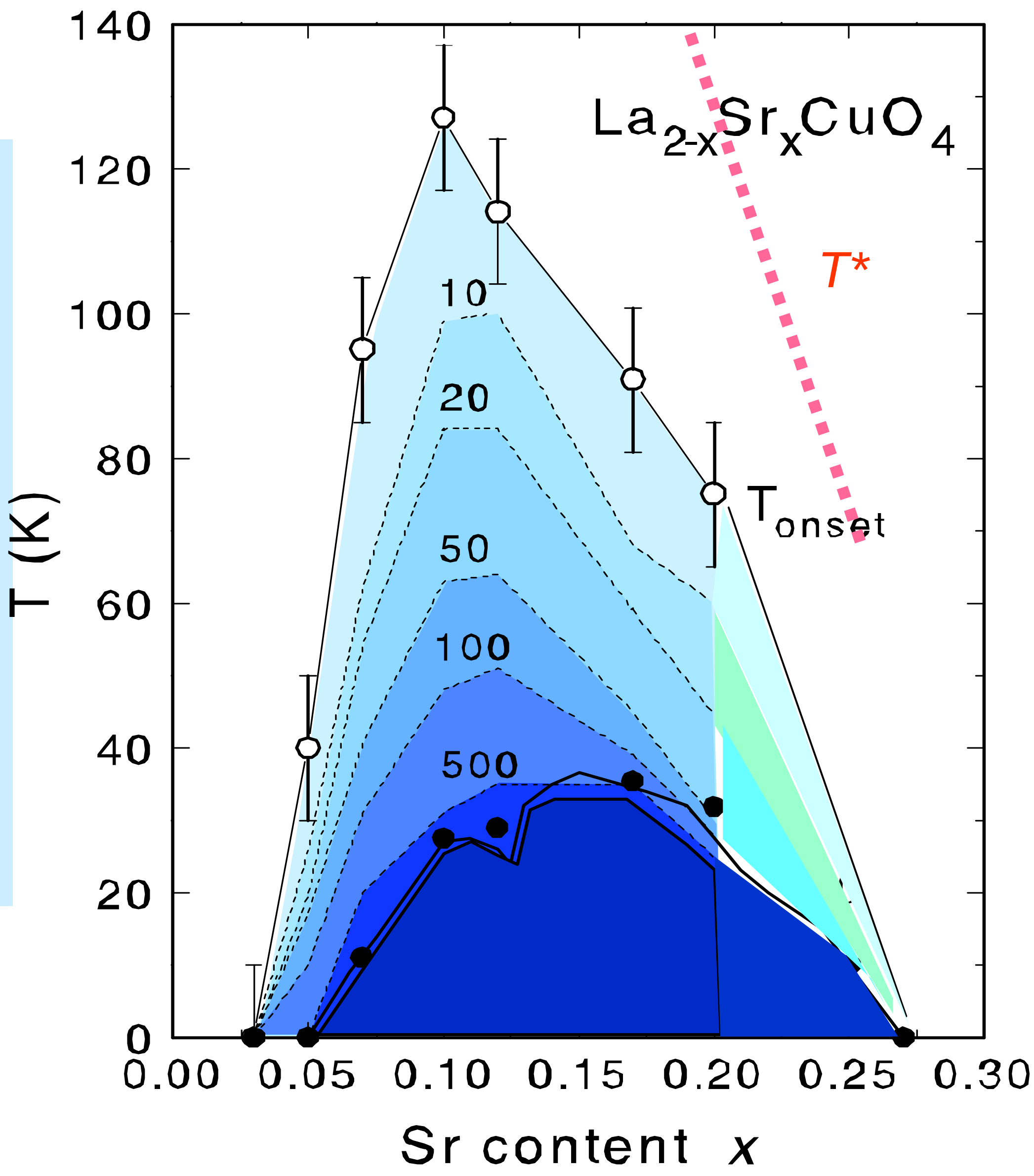
1. Vortex signal extends to T_{onset}, above T_{c0};

2. Vortex fluc. Phase (0.03< x < 0.26)

3. T_{onset} lower than T^*

4. T_{c0} (Meissner) is loss of long-range phase coherence.

5. Strong competition between dSC and pseudogap state.

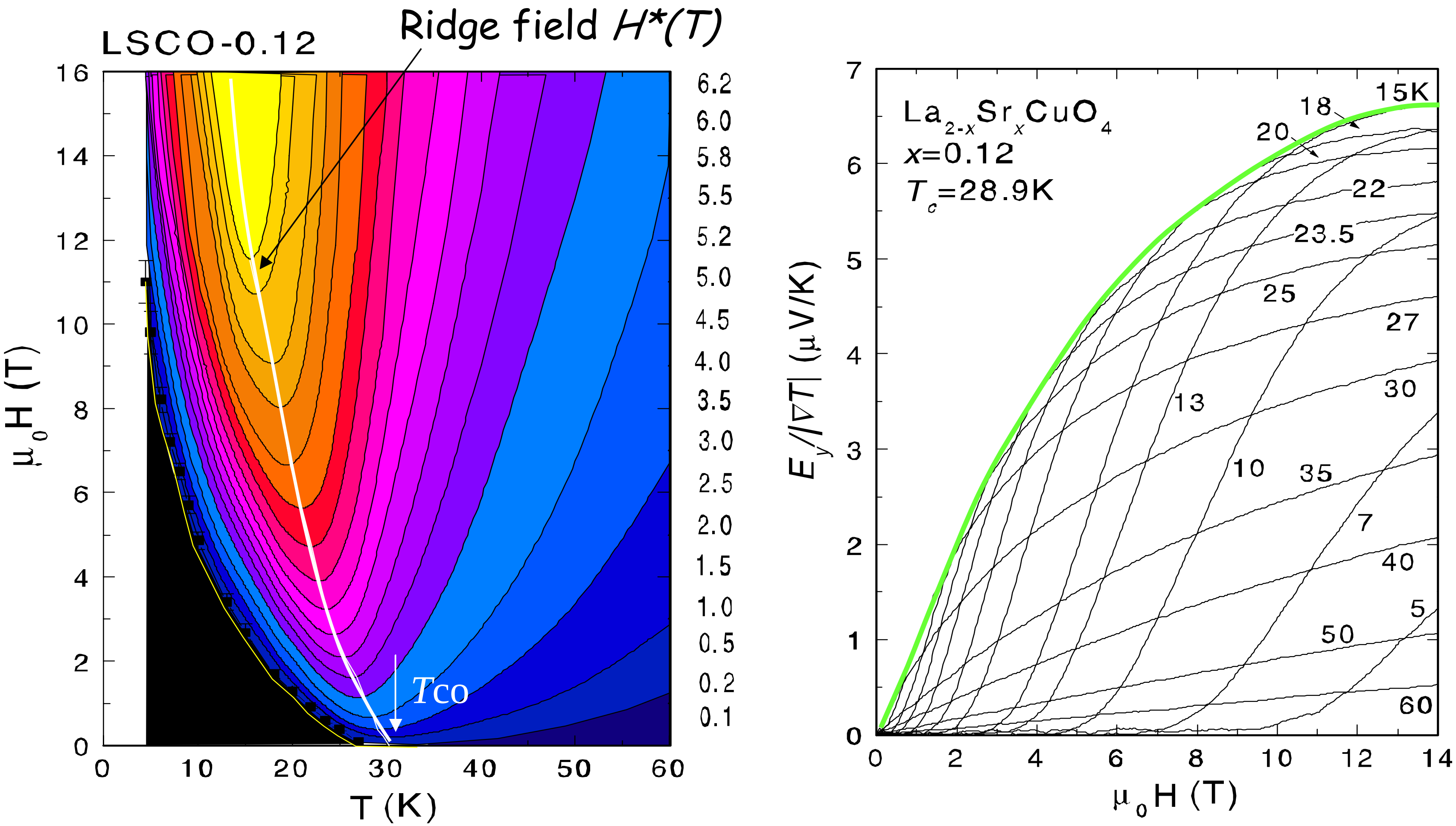


Conclusions (Part I)

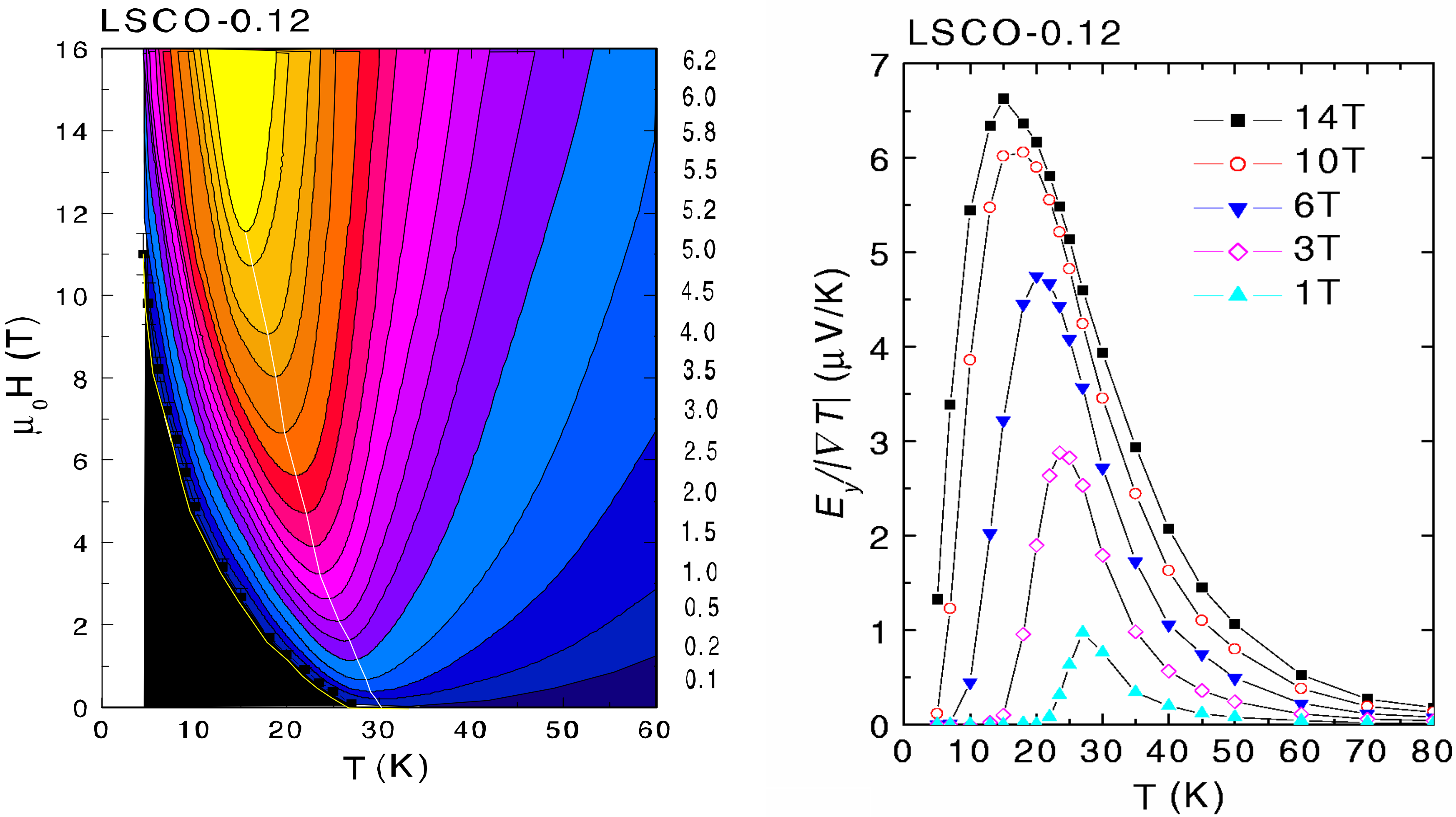
1. Vortex-Nernst signal exists high above T_{c0}.

2. Pairing amplitude finite above T_{c0}.

3. Transition at T_{c0} is loss of long-range phase coherence.

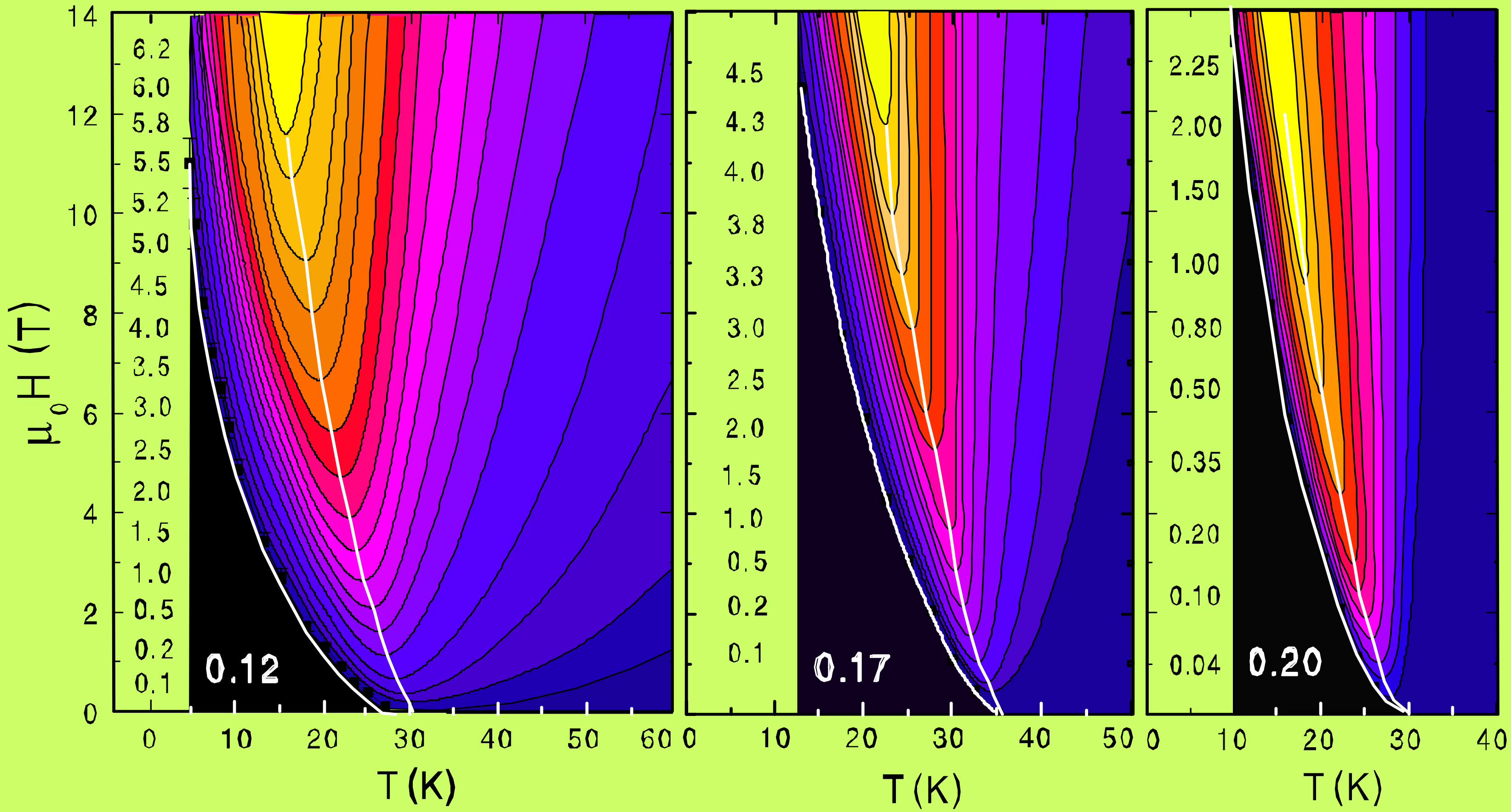


Contour plot of Nernst signal e_y in *T*-*H* plane
Vortex signal extends above T_{c0} continuously



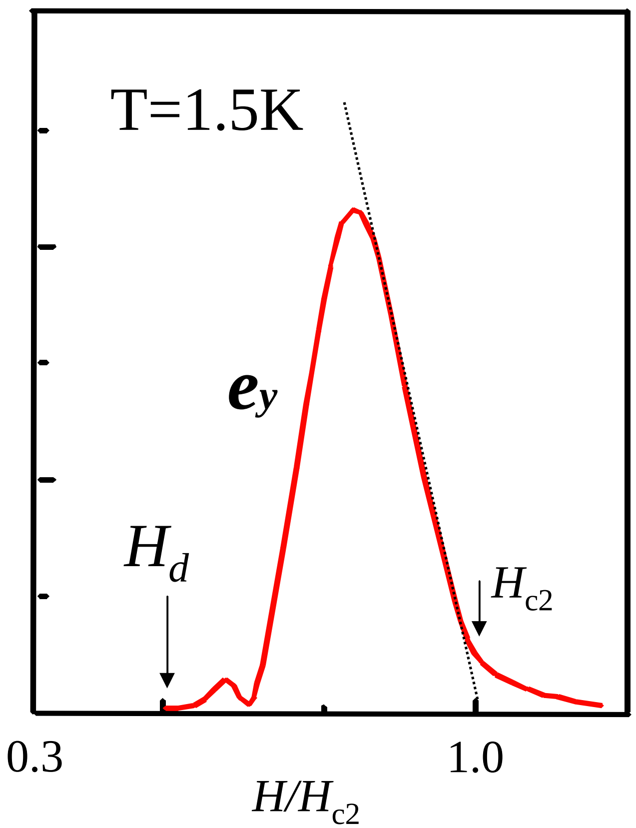
LSCO-0.12
16
14
12
10
8
6
4
2
0
μ0H (T)
0
10
20
30
40
50
60
T (K)
6.2
6.0
5.8
5.5
5.2
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.2
0.1
LSCO-0.12
7
6
5
4
3
2
1
0
Ey/|∇T| (μV/K)
14T
10T
6T
3T
1T
0
10
20
30
40
50
60
70
80
T (K)

Vortex Nernst map in underdoped, optimal and overdoped LSCO

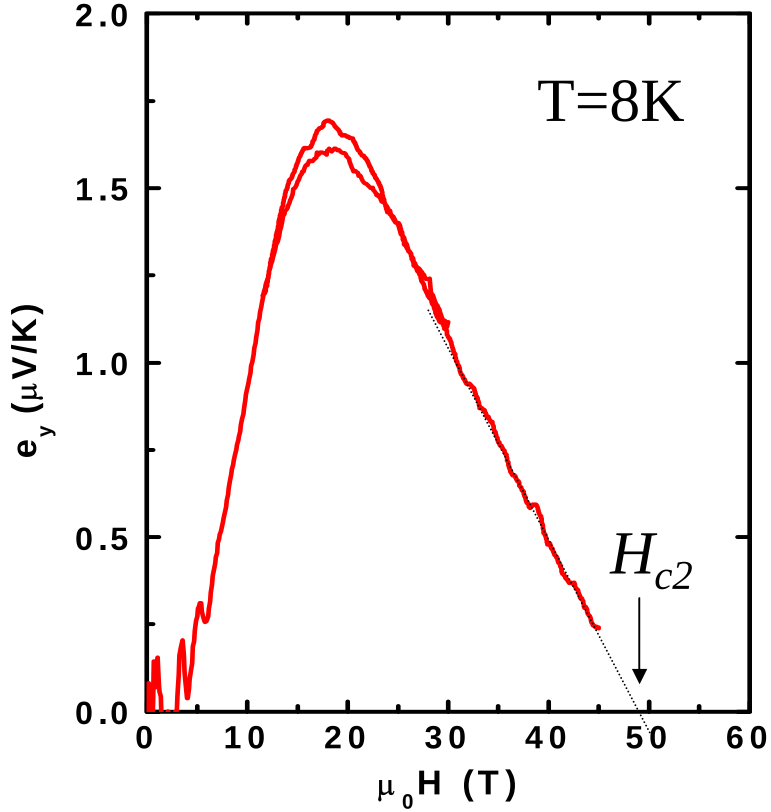


Where is H_{c2} line?

PbIn, T_c = 7.2 K (Vidal, PRB '73)

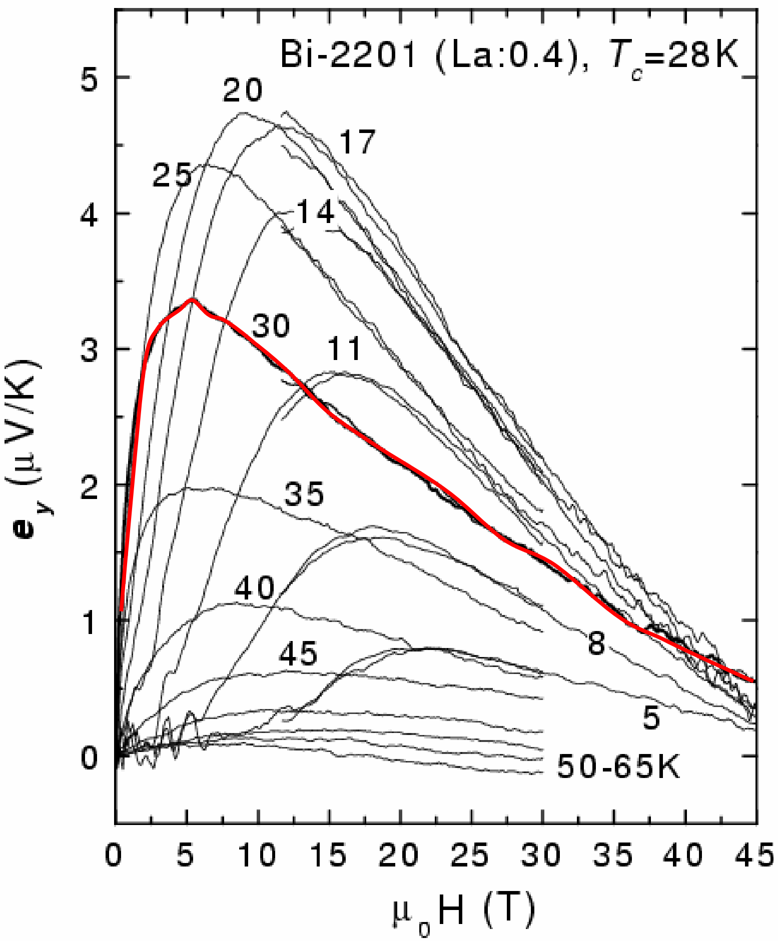


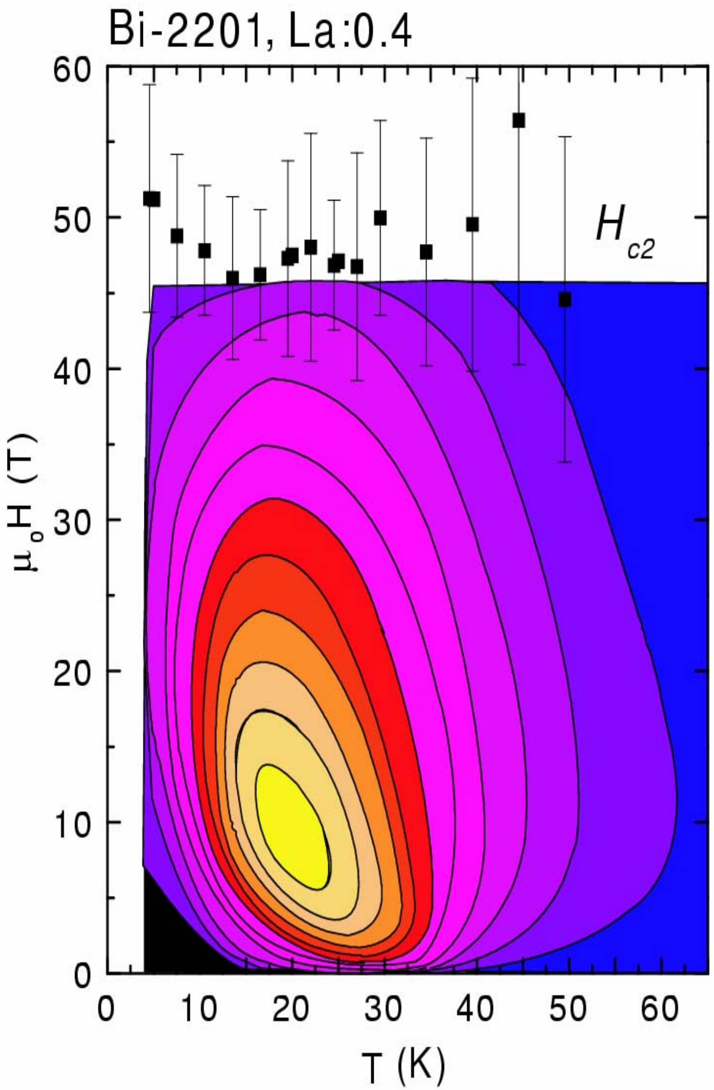
Bi 2201 (T_c = 28 K, H_{c2} ~ 48 T)



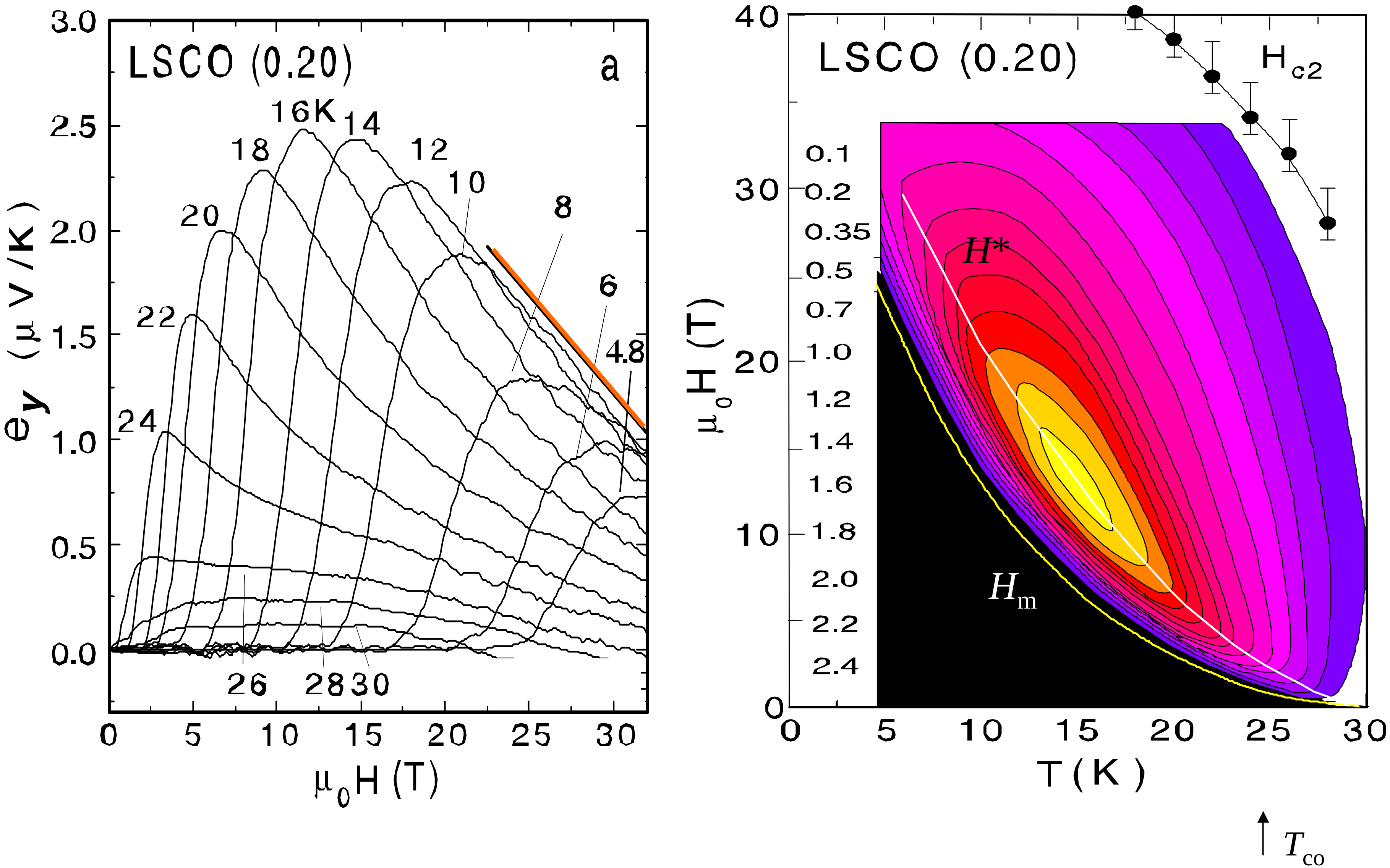
- Upper critical Field H_{c2} given by $e_y \rightarrow 0.$
- Hole cuprates --- Need *intense* fields.

Vortex-Nernst signal in Bi 2201

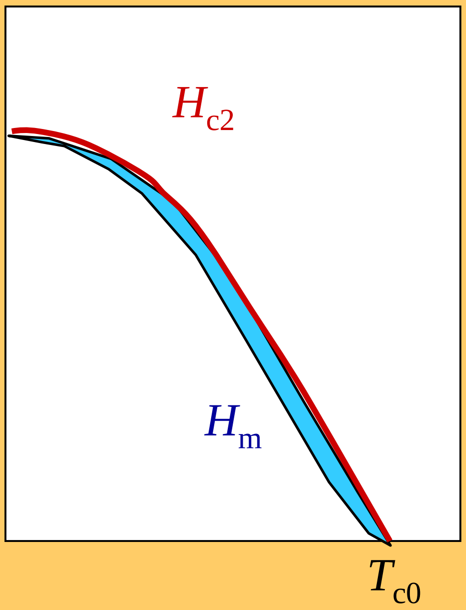




Overdoped LaSrCuO

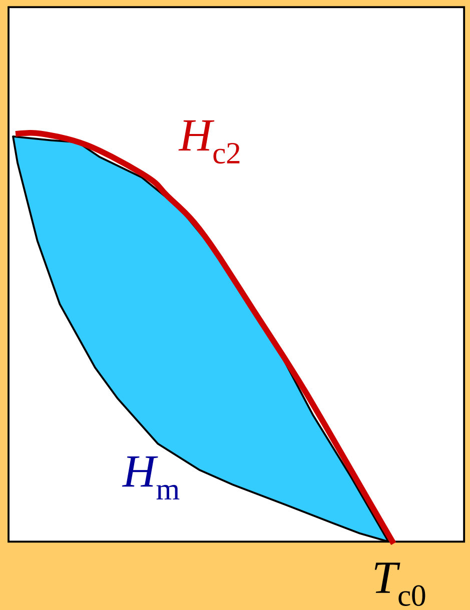


$NbSe_2$



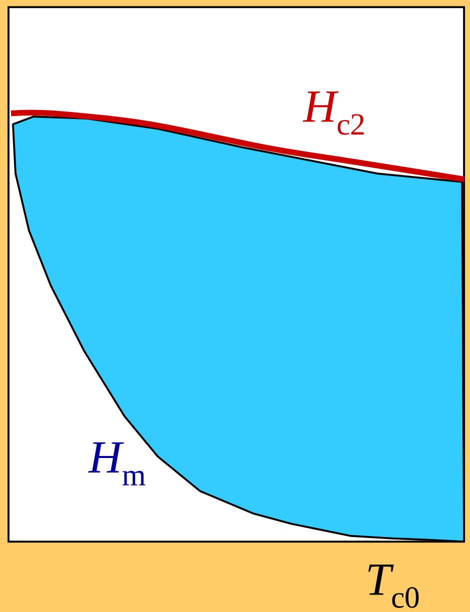
"Conventional"
Amplitude $\longrightarrow$ 0
at T_{c0} (BCS)

NdCeCuO



Expanded vortex liquid
Amplitude trans. at T_{c0}

Hole-doped cuprates



Vortex liquid phase is dominant.
Loss of phase coherence at T_{c0} (zero-field melting)

Closing in on H_{c2} . . . .

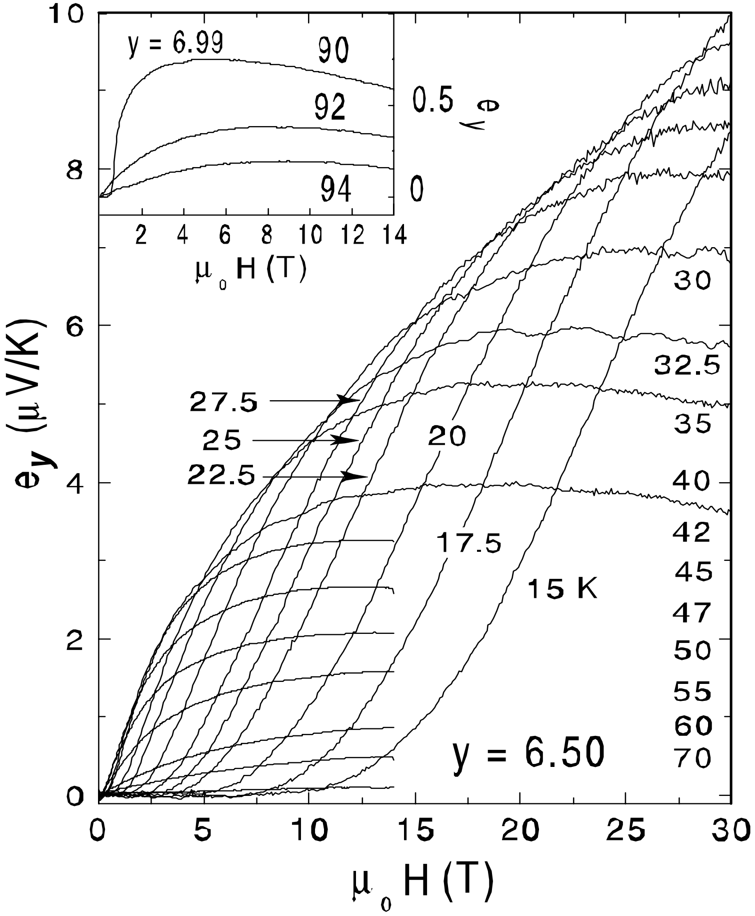
1. With intense fields, can go over the ridge line H^*

2. Above ridge, Nernst signal decreases rapidly.

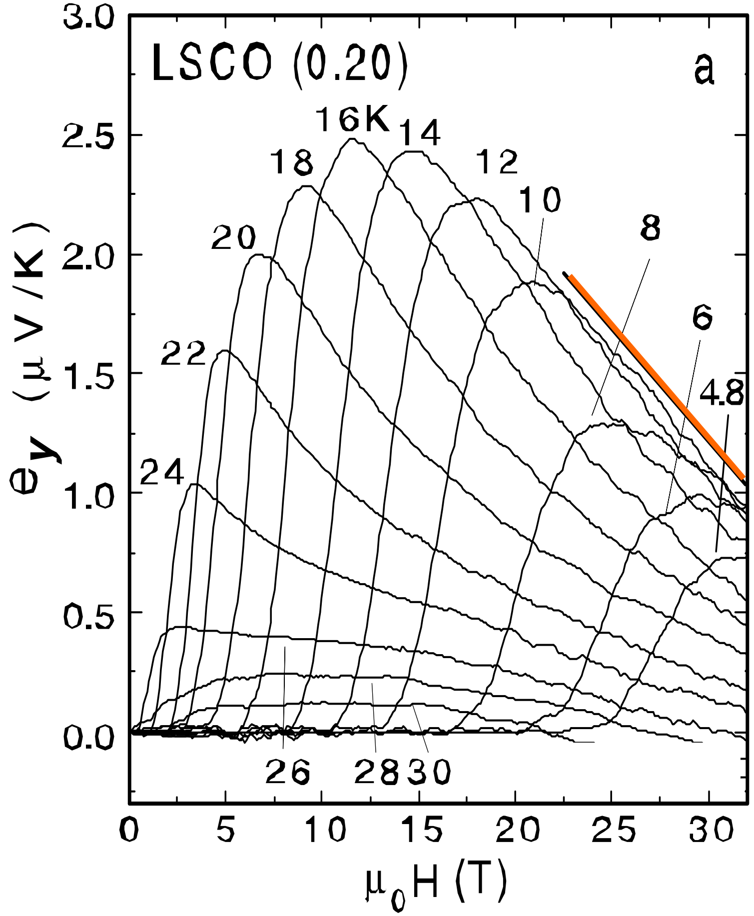
3. H_{c2} is determined when signal approaches zero.

4. H_{c2} line does not terminate at T_{c0} in hole cuprates!

Underdoped

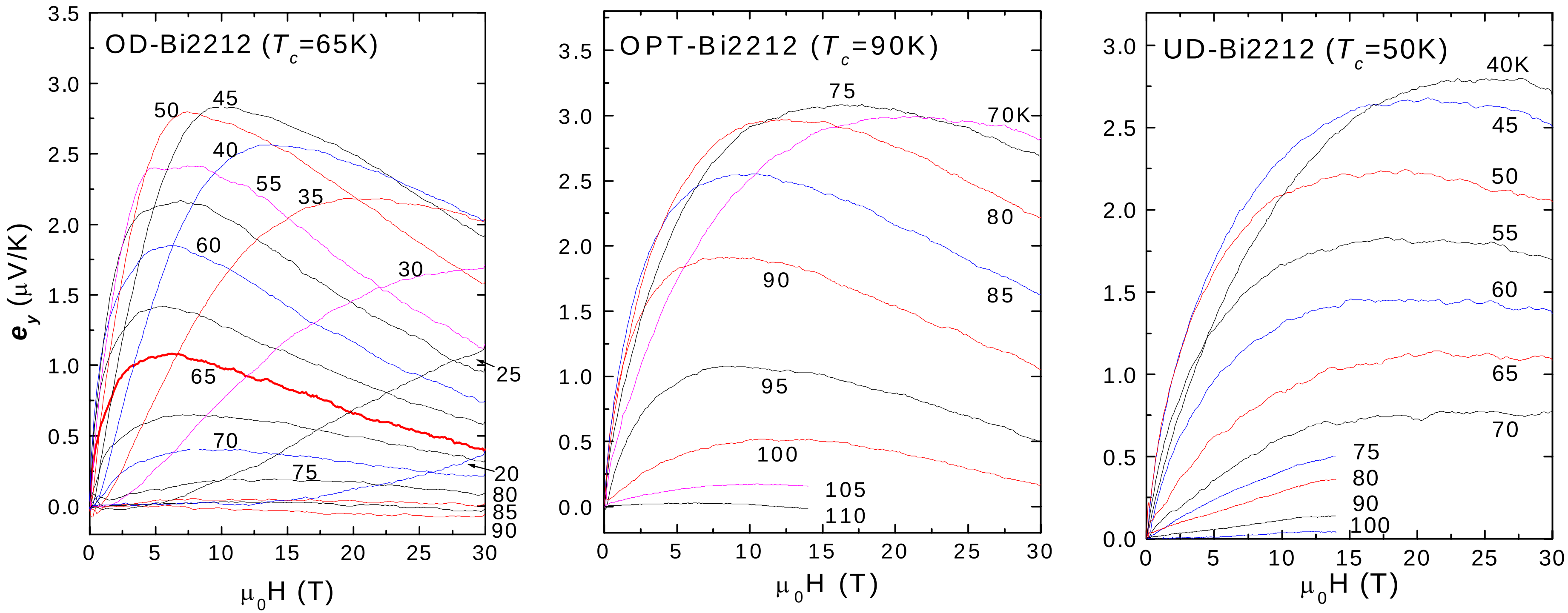


Overdoped



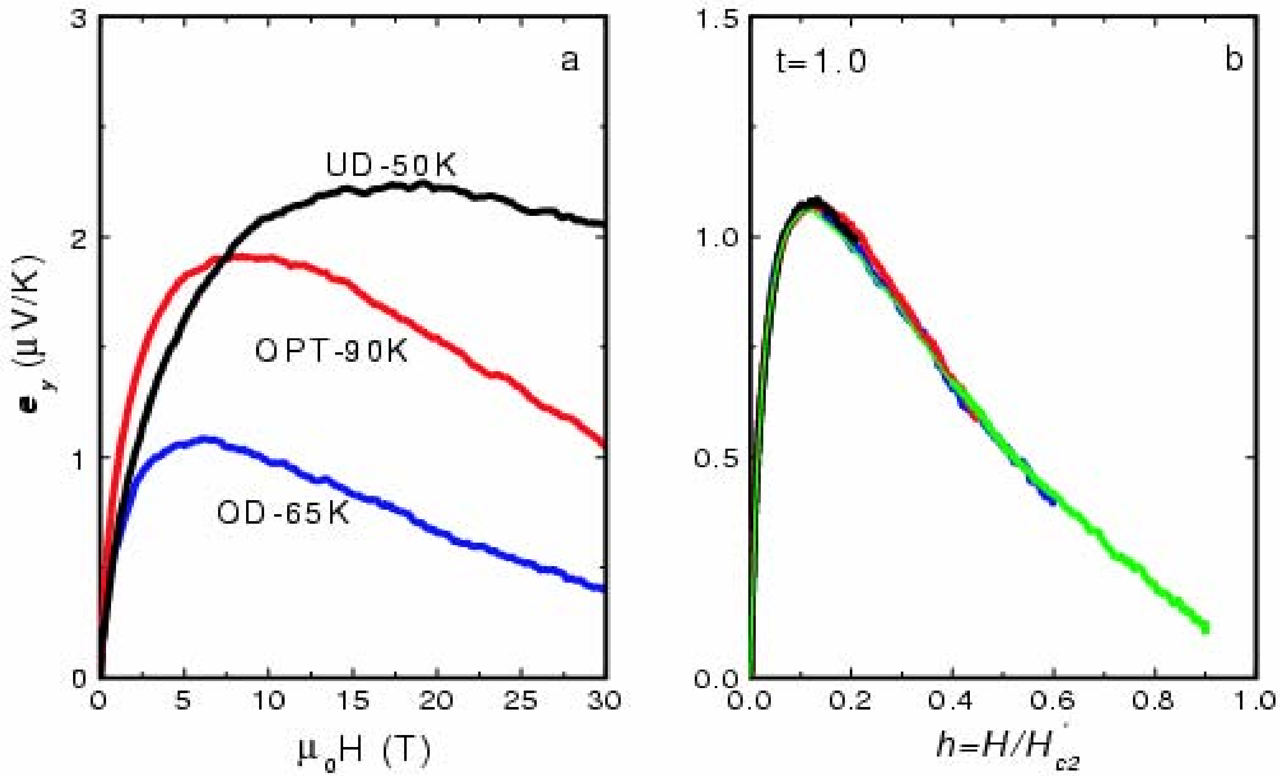
Nernst signal in underdoped YBaCuO (T_c = 50 K)
and overdoped LaSrCuO (T_c = 29 K).
Intrinsic field scale much higher in underdoped YBCO.

overdoped optimum underdoped



Field scale increases as x decreases

Scaling of e_y near T_{c0}



- Curves at T_{c0} obey scaling behavior $e_y/e_y^{max} = F(h)$
- Allows $H_{c2}(T_{c0})$ to be determined.

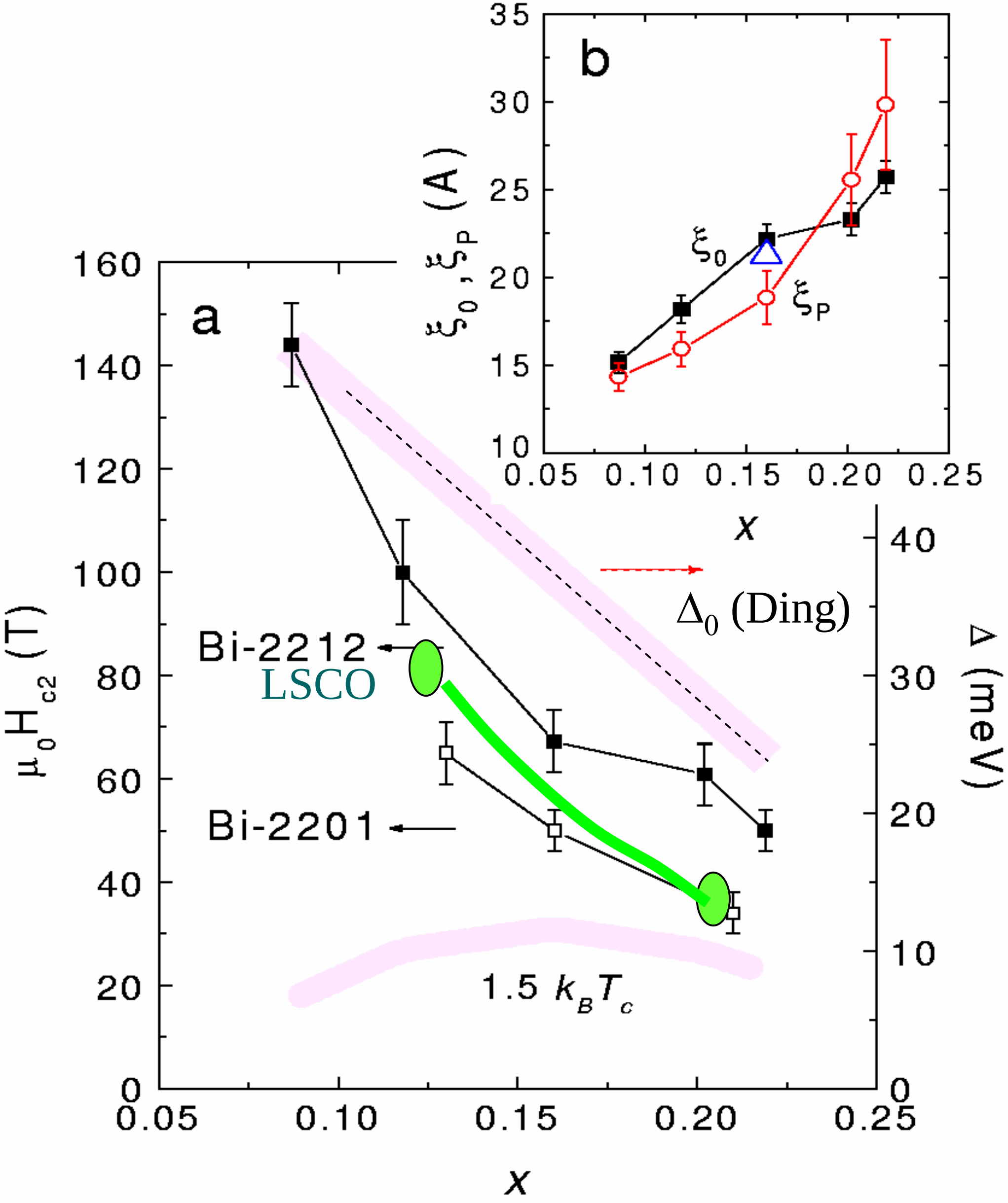
- H_{c2} *increases* as x decreases (like ARPES gap Δ_0)

- Compare ξ_0 (from H_{c2}) with

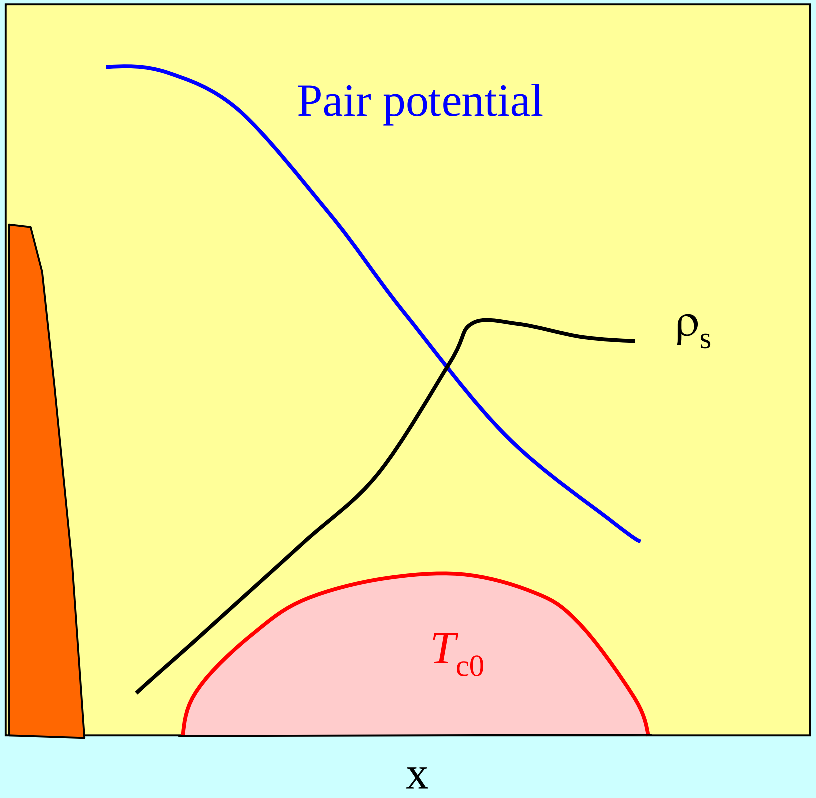
Pippard length
$\xi_P = \hbar v_F / a\Delta_0$ (a = 3/2)

STM vortex core
$\xi_{STM} \sim$ 22 A

Cooper pairing potential largest in underdoped regime



Implications of H_{c2} vs. x



- Pair potential largest in underdoped
  (RVB theory, … Baskaran '87)
- Loss of phase coherence fixes T_{c0}
  (Emery Kivelson 1995)

Conclusions (Part II)

1. H_{c2} line is nearly T independent (like ARPES gap).
2. H_{c2} values higher than suggested by resistivity
3. H_{c2} decreases (x increases) as x increases.
4. Pairing potential is largest at small x.
5. T_{c0} is loss of long-range phase coherence.

Summary

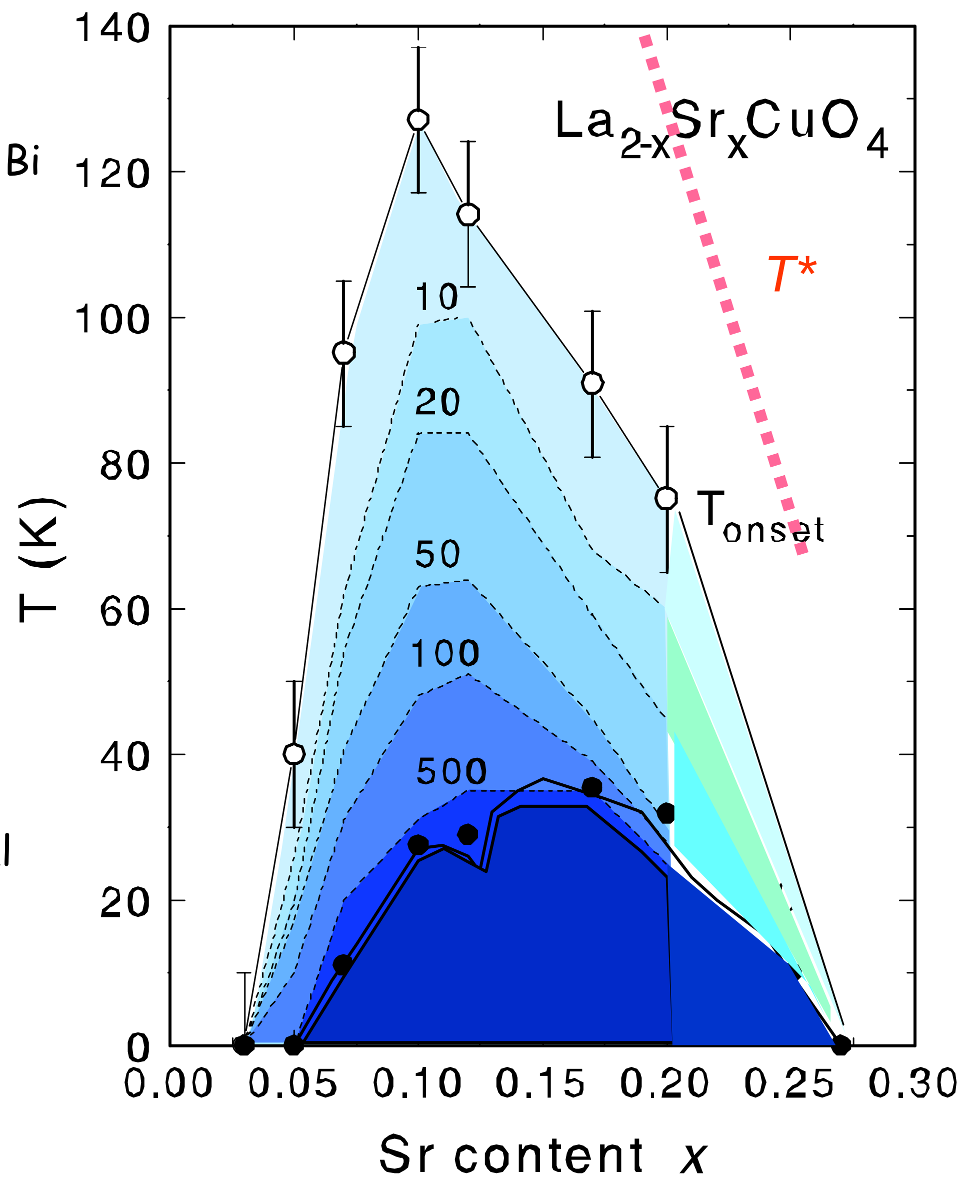
1. Vortex Nernst signal above T_c
 in LaSrCuO, YBaCuO, Bi 2201, Bi 2212, Bi 2223, NdCeCuO….

2. Contour plots of e_y
 Smooth continuity between incoherent vortex regime and vortex liquid

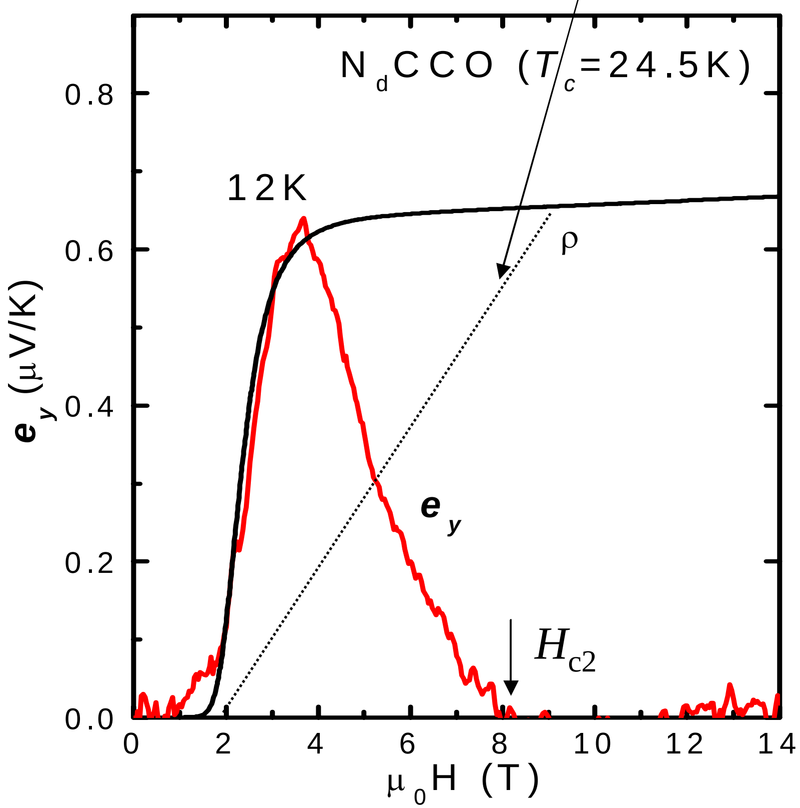
3. H_{c2} determined in overdoped regime
 $H_{c2}(0)$ = 50 T for x = 0.20 in LSCO
 H_{c2} vs. T does not terminate at T_{c0}

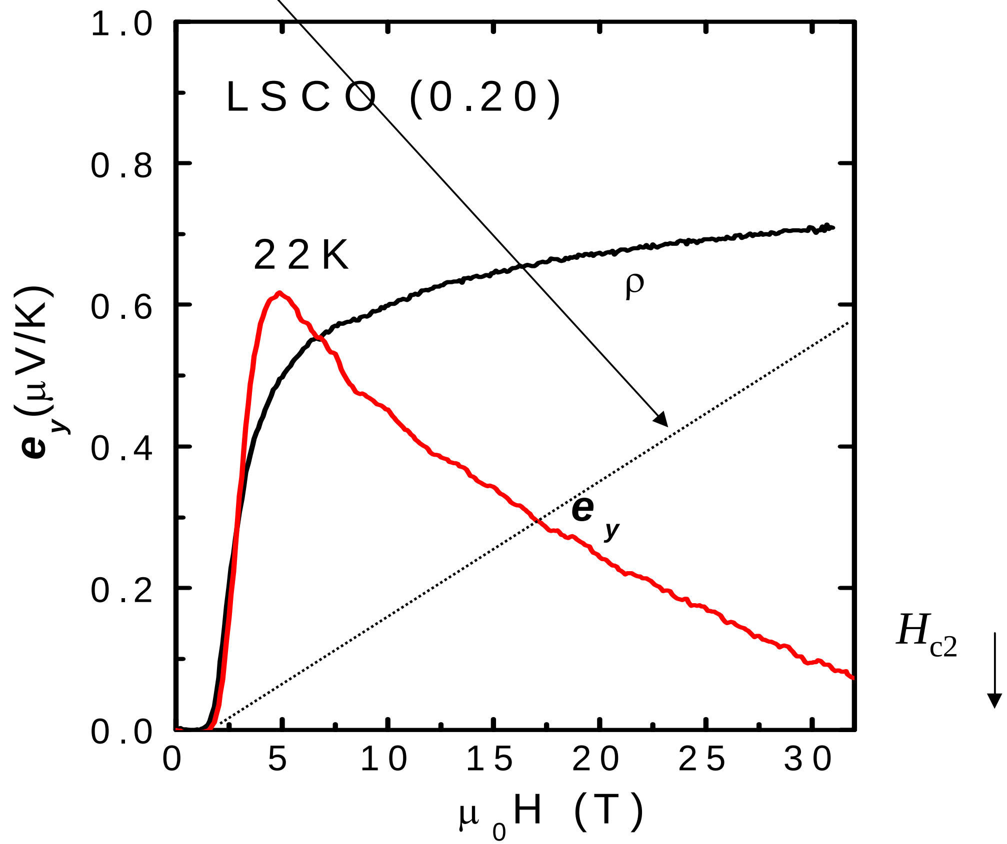
 Phase coherence lost at T_{c0}
 but H_{c2} and Δ are finite

4. H_{c2} vs. x implies H_{c2} and pairing potential largest in underdoped regime



Bardeen Stephen law not seen



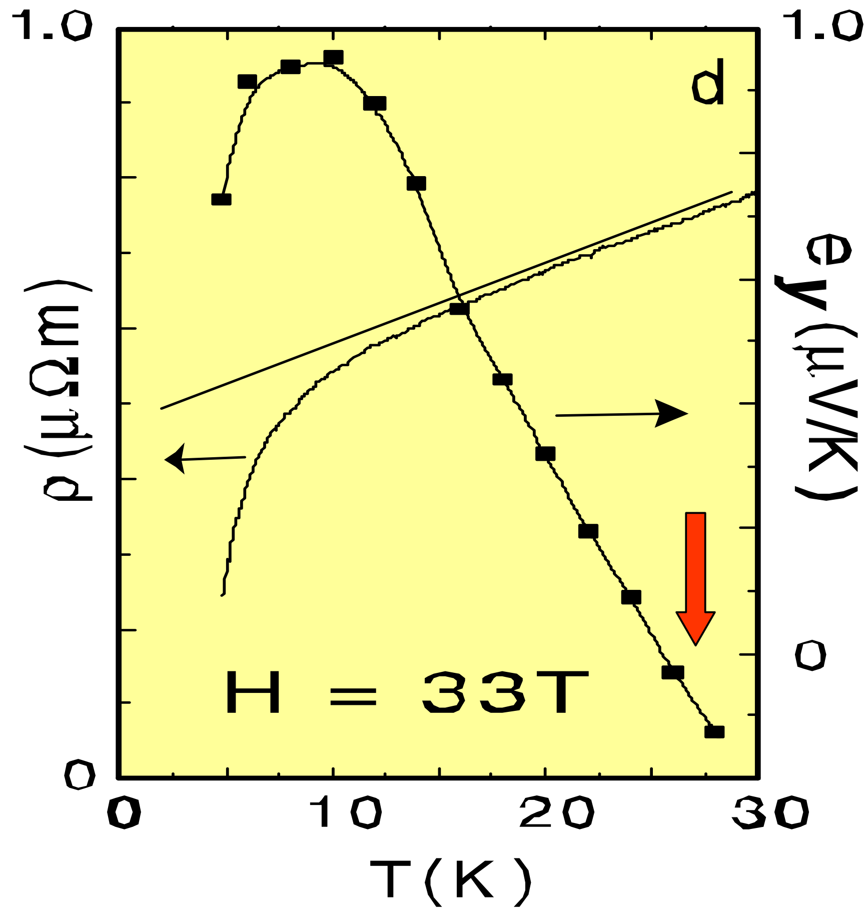


Resistivity does not distinguish vortex liquid and normal state

Resistivity is a *bad diagnostic* for field suppression of pairing amplitude

Plot of ρ and e_y versus *T* at fixed *H* (33 T).

Vortex signal is large for *T* < 26 K, but ρ is close to normal value ρ_N above 15 K.



Yayu Wang,
Z. A. Xu (Princeton)

T. Kakeshita
S. Uchida (U. Tokyo)

S. Ono
Yoichi Ando (CRIEPI, Japan)

Y. Onose
Y. Tokura (U. Tokyo)

High-fields at NHMFL, Tallahassee
Supported by NSF, ONR and NEDO

Appendix