Talk 3

Magnetization in Vortex-Liquid State in Cuprates

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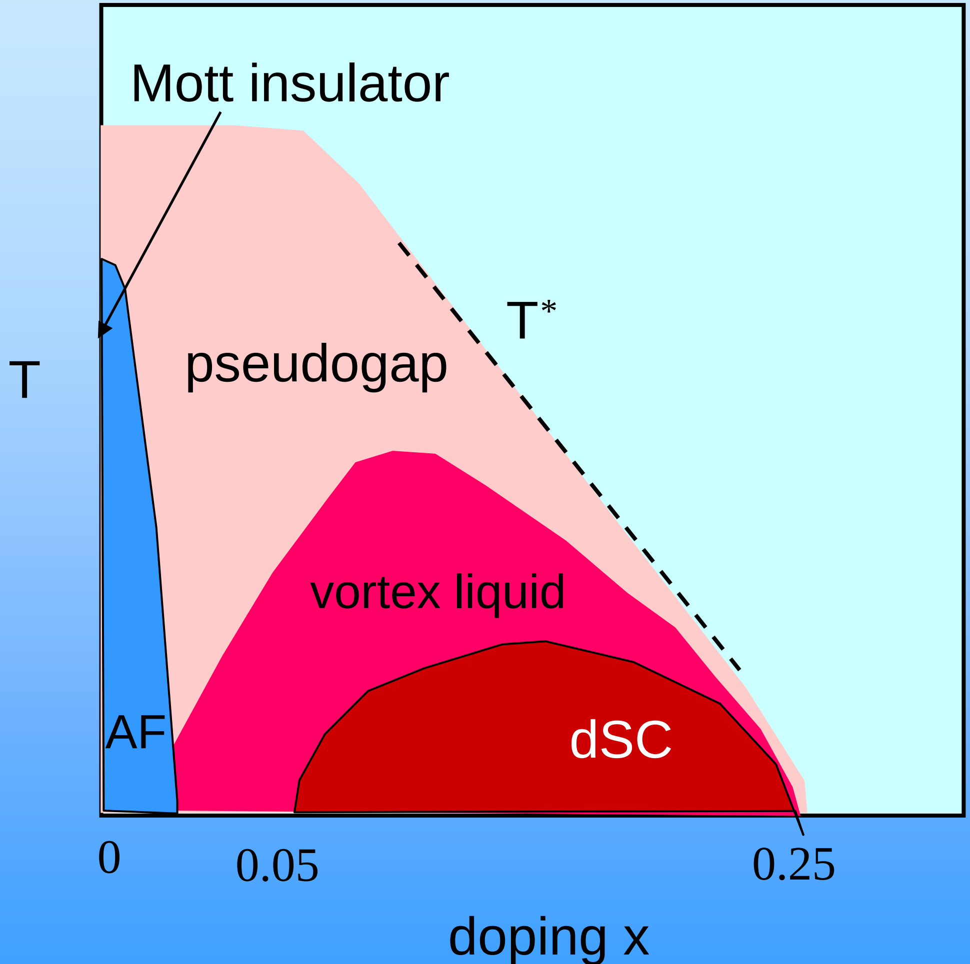
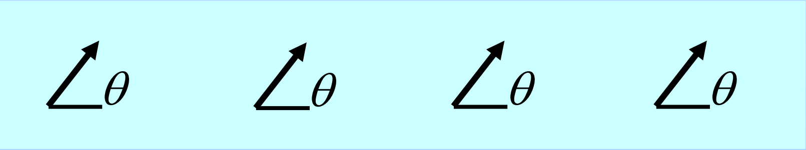
1. Vortex Nernst effect
2. Diamagnetism
3. Phase diagram
4. Low-temp. Vortex Liquid State

Supported by NSF-MRSEC, ONR

Pseudogap state in hole-doped cuprates



Phase rigidity



$$|\Psi| = e^{i\theta(\mathbf{r})}$$

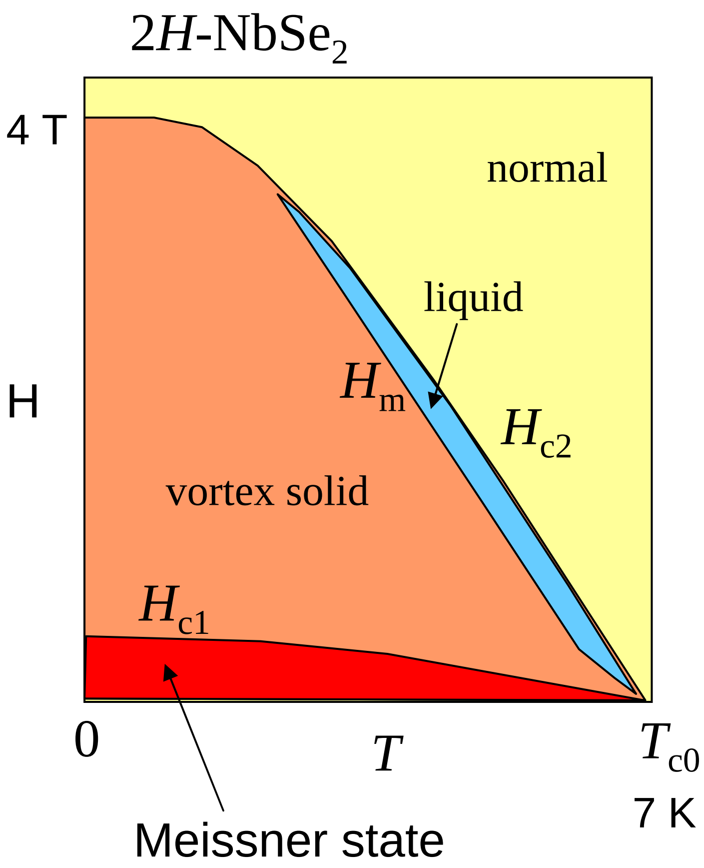
Pairing anomalously strong

Phase rigidity soft

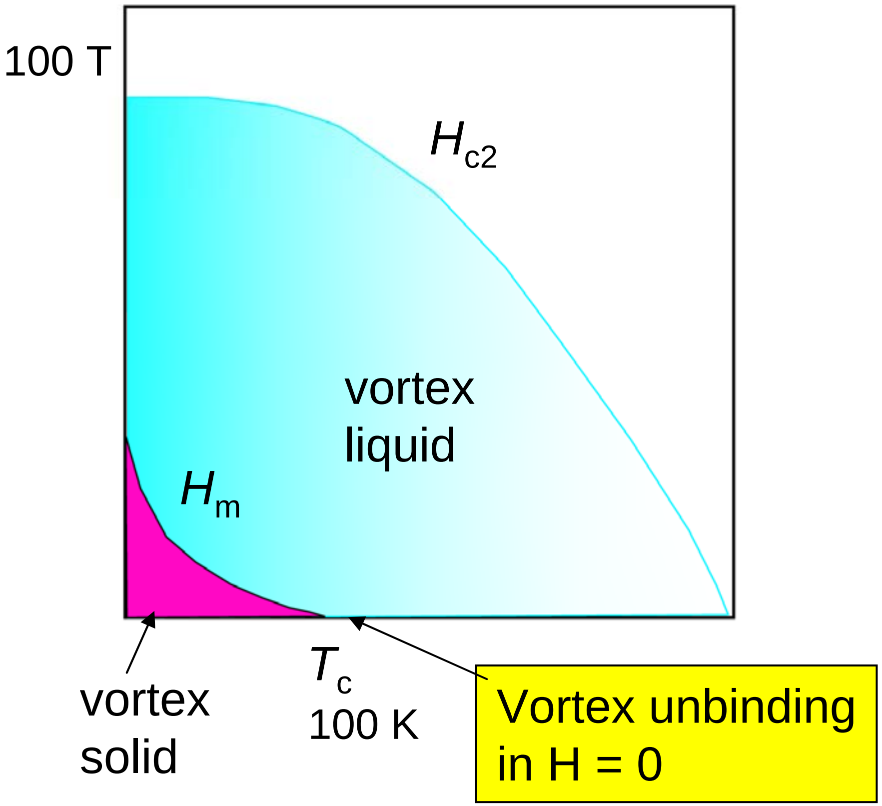
Spontaneous vorticity destroys rigidity and Meissner state

Phase diagram in *H-T* plane

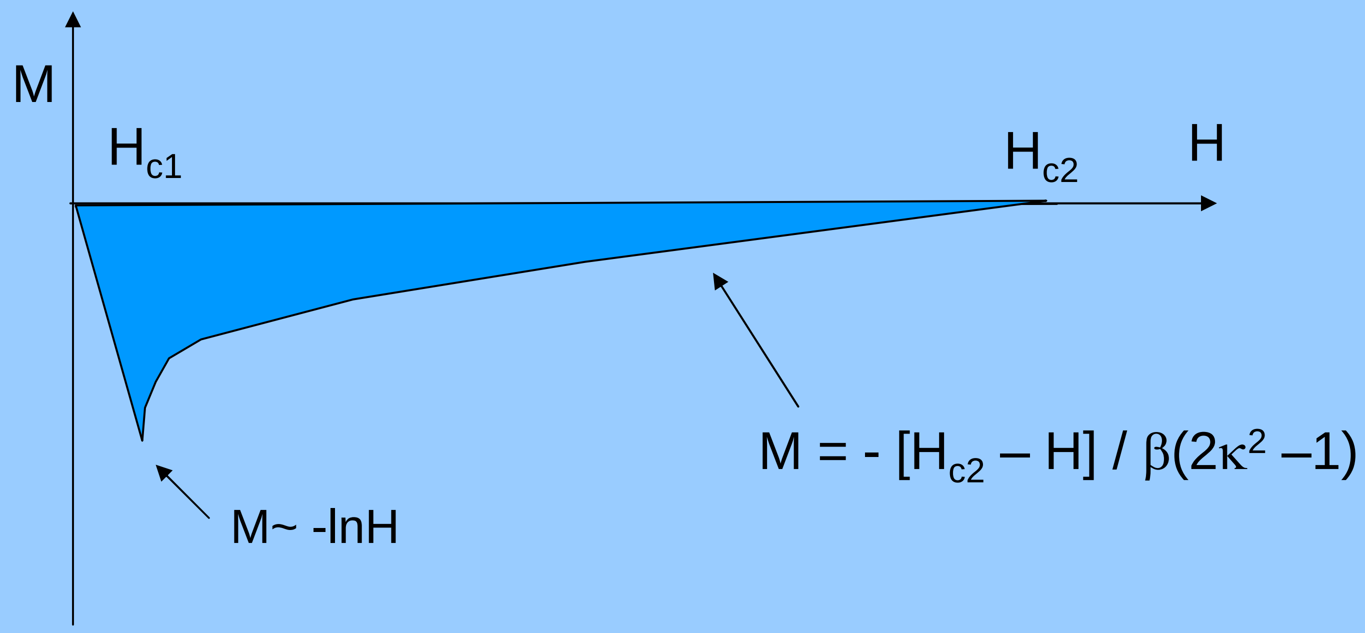
Mean-field phase diagram



Cuprate phase diagram



Magnetization in Abrikosov state



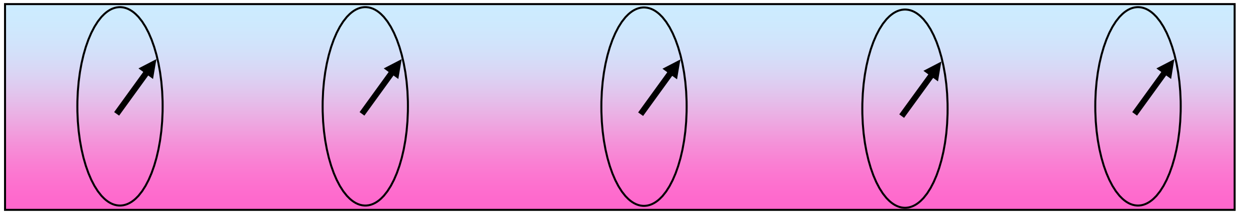
In cuprates, κ = 100-150, H_{c2} ~ 50-150 T

M < 1000 A/m (10 G)

Area = Condensation energy U

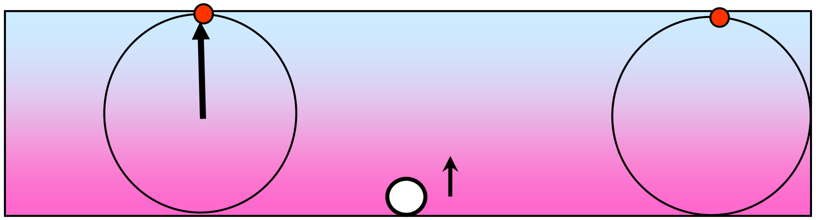
P.W. Anderson Phys. Rev. 1959, RMP 1966

Phase rigidity → uniform phase θ $|\Psi|\ e^{i\theta(\mathbf{r})}$



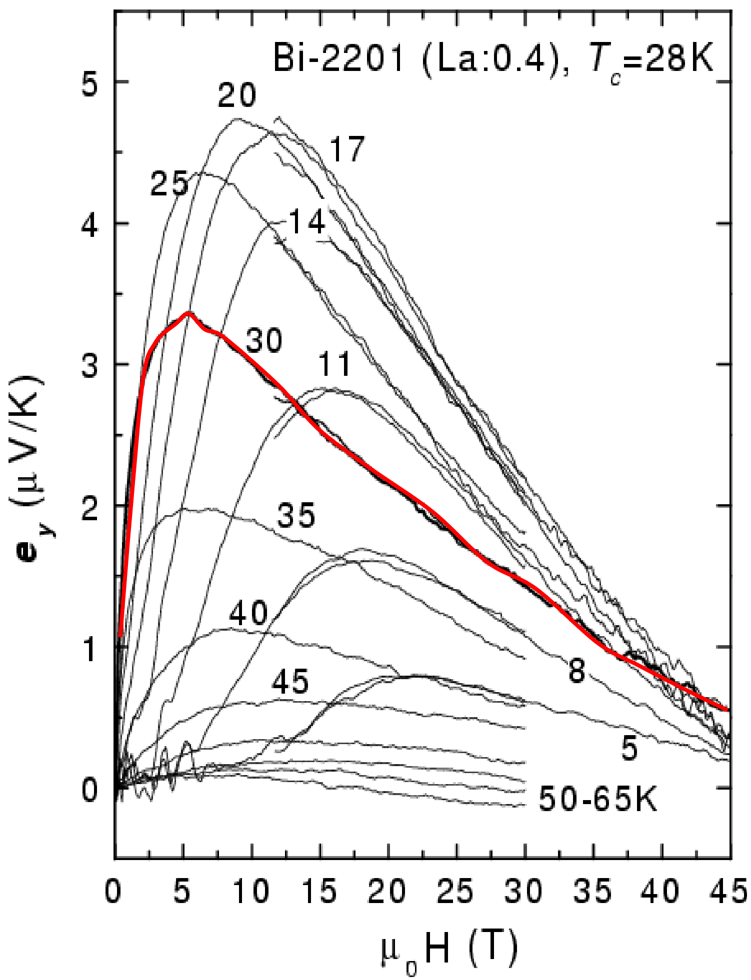
$$H_\rho = \tfrac{1}{2}\int d^3r\ \rho_S\left(\nabla\theta\right)^2$$ phase rigidity measured by ρ_s

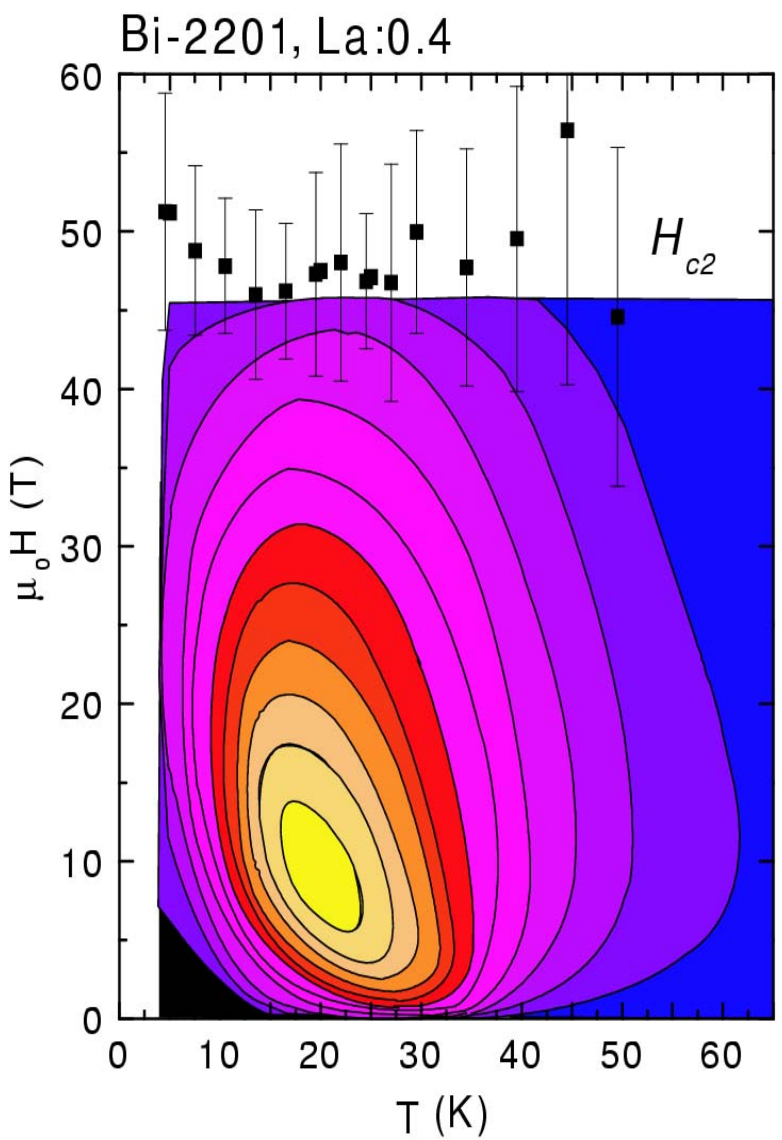
But phase coherence destroyed by mobile vortices

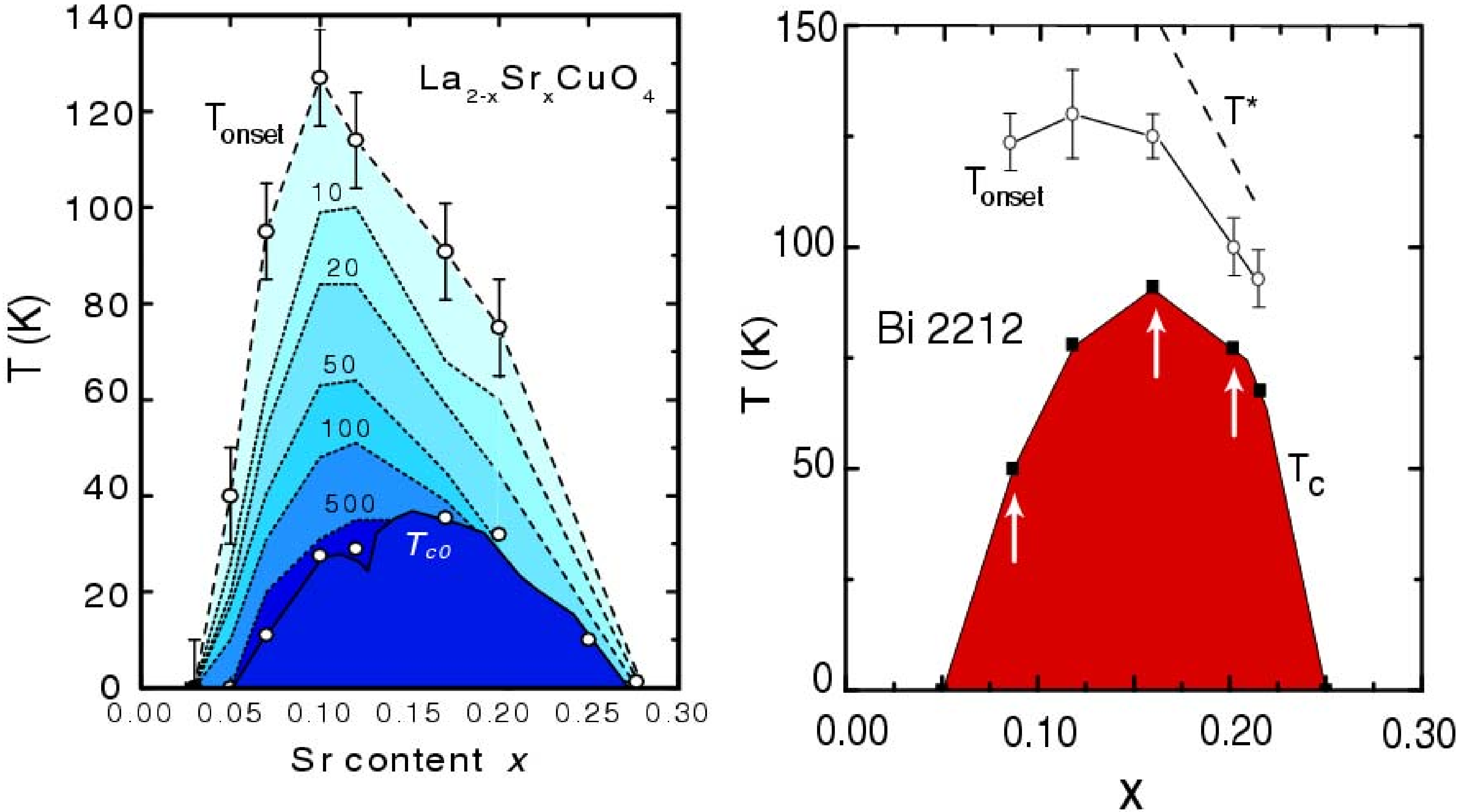


$\Delta\theta = 2\pi$

Contour Map of Nernst Signal in Bi 2201







- Condensate amplitude persists to $T_{onset} > T_c$
- Nernst signal confined to SC dome
- Vorticity defines Nernst region

Implications of Nernst signal

1. **Vorticity persists high above T_c**

2. **Confined to SC "dome"**

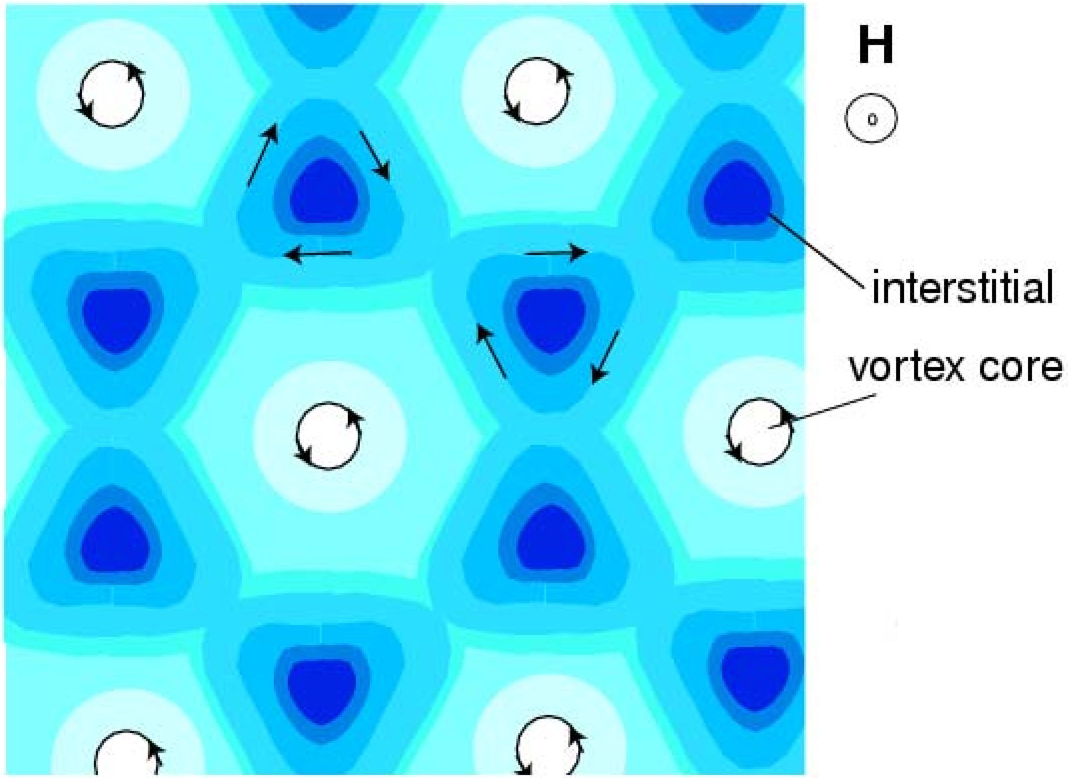
3. **Loss of long-range phase coherence at T_c by spontaneous vortex creation (not gap closing)**

4. **Vortex-liquid state persists deep into pseudogap State**

5. **Pseudogap state distinct from phase fluc in Lightly-doped regime.**

Thermodynamic evidence from diamagnetic response

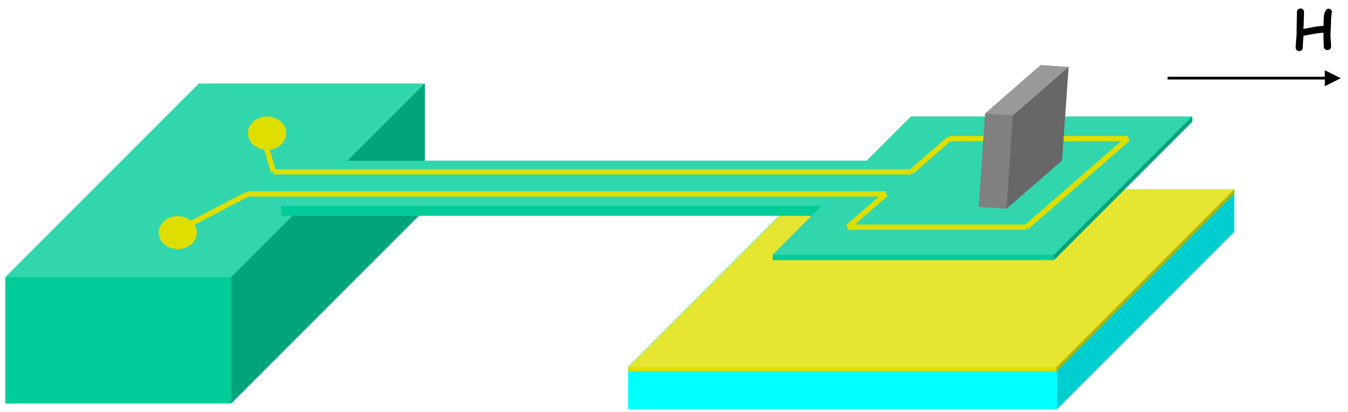
Diamagnetic currents in vortex liquid



Supercurrents follow contours of condensate

$$\mathbf{J}_s = -(e\hbar/m)\nabla \times |\Psi|^2\,\hat{\mathbf{z}}$$

Micro-fabricated single crystal silicon cantilever magnetometer

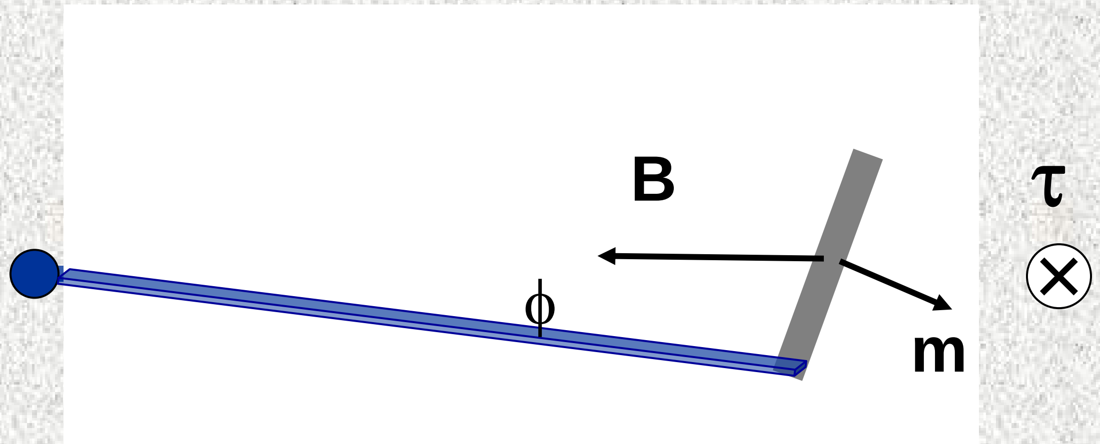


- Si single-crystal cantilever
- Capacitive detection of deflection
- Sensitivity: ~ 5 × 10^{-9} emu at 10 tesla
  ~100 times more sensitive than commercial SQUID

Torque magnetometry

Mike Naughton
(Boston College)

Torque on moment: $\tau = \mathbf{m} \times \mathbf{B}$



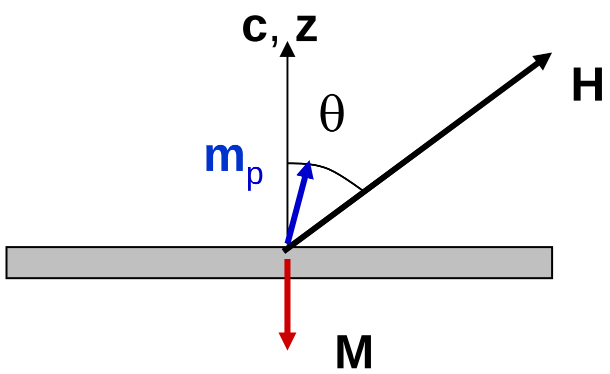
Deflection of cantilever: $\tau = k\,\phi$

Torque magnetometry

Spin moment $\mathbf{m}_p$

$$\tau = \mathbf{m}_p \times \mathbf{B} + \mathbf{M}V \times \mathbf{B}$$

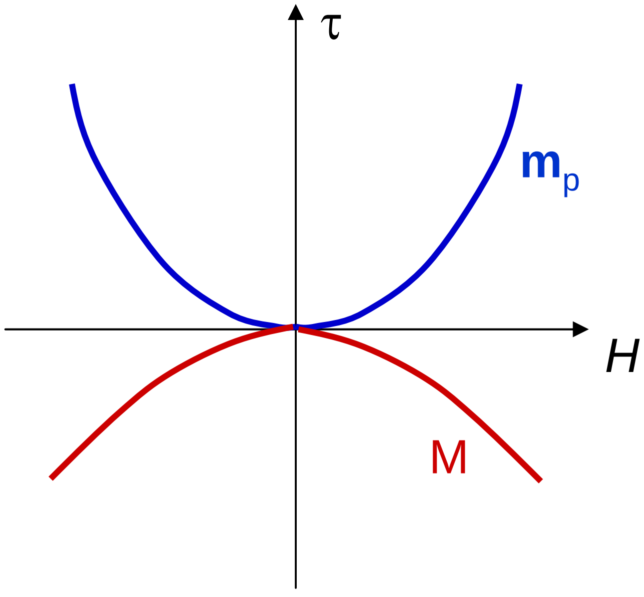
2D supercurrent

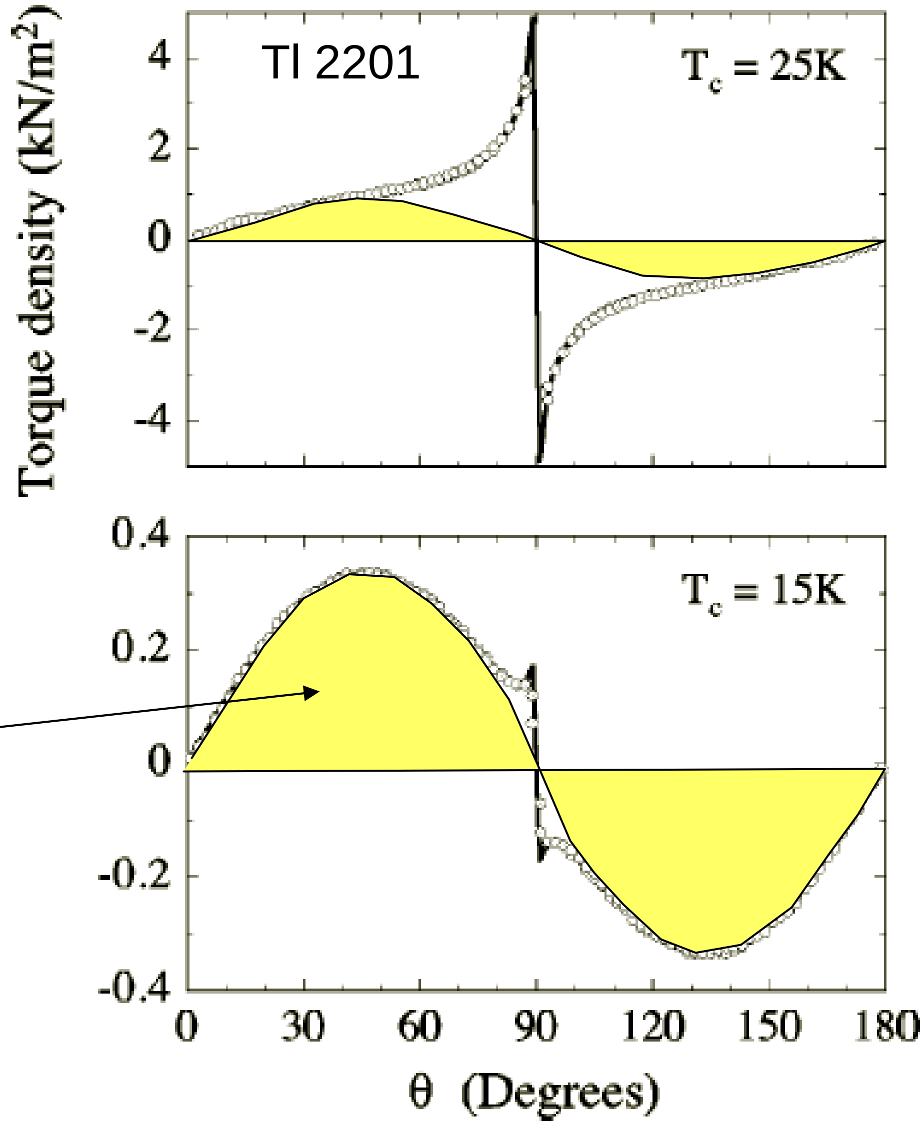


$$\tau/V = \chi_c H_x B_z - \chi_a H_z B_x + M B_x$$

$$M_{eff} = \tau / V B_x = \Delta\chi_p H_z + M(H_z)$$

Exquisite sensitivity to 2D supercurrents

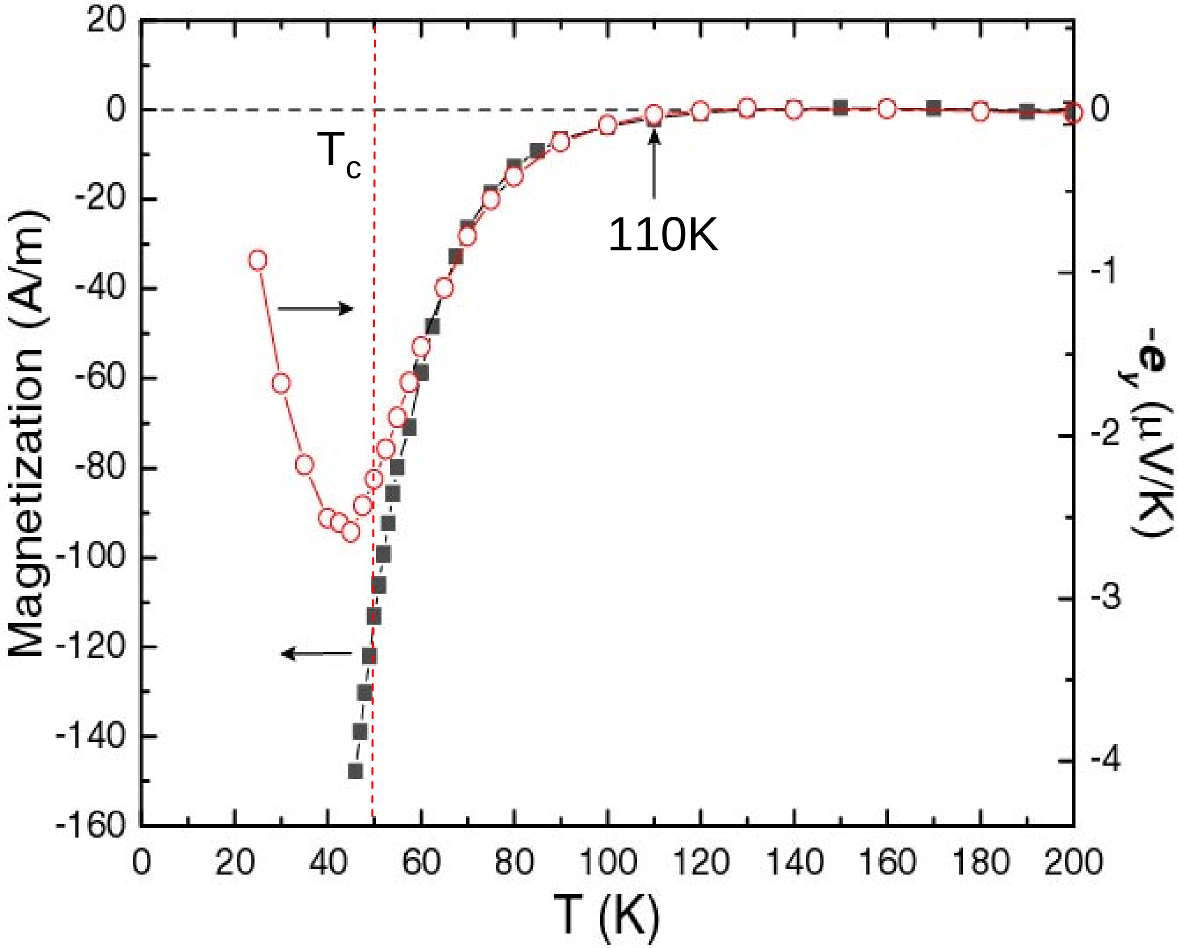




Bergemann, Mackenzie et al. PRB 1998

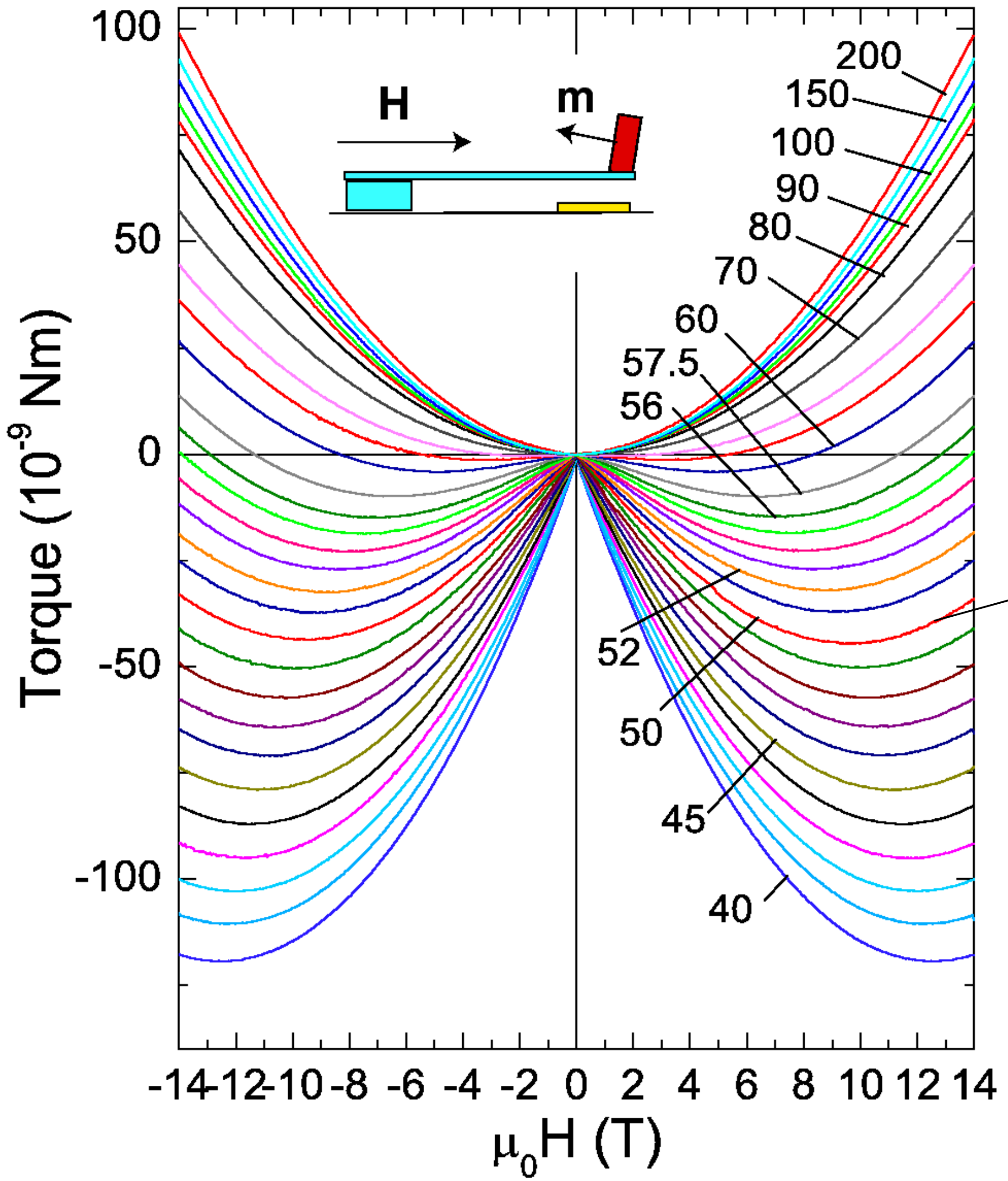
Mysterious $A_1 \sin 2\theta$ term !

FIG. 4. Typical angular dependence of the torque density for the crystals investigated in this work. In all cases, $T/T_c \simeq 0.85$ and $H = 5$ T. The solid curves are the fits according to Eq. (3).



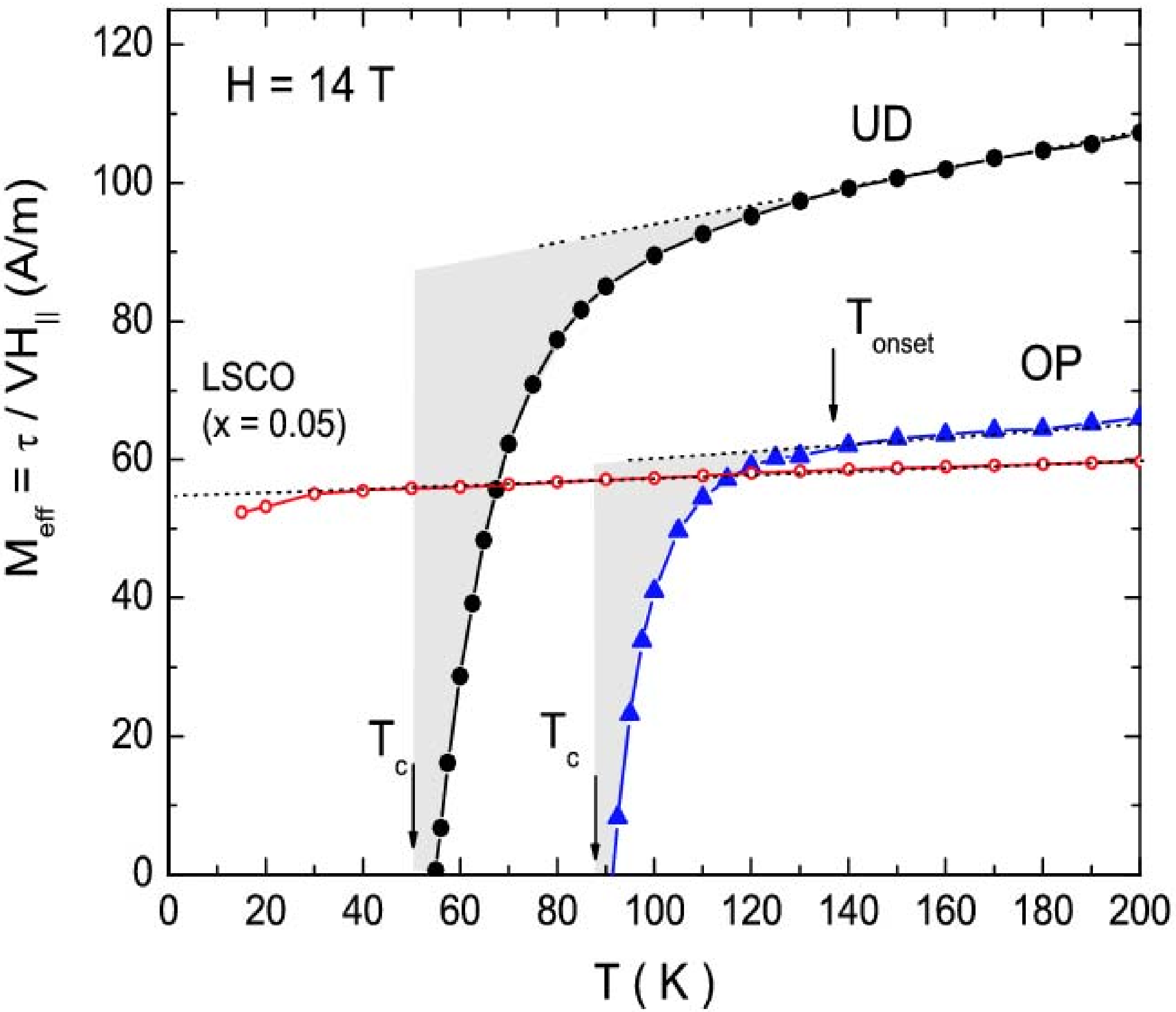
- In underdoped Bi-2212, onset of diamagnetic fluctuations at 110 K
- diamagnetic signal closely tracks the Nernst effect

Torque Signal in underdoped Bi 2212



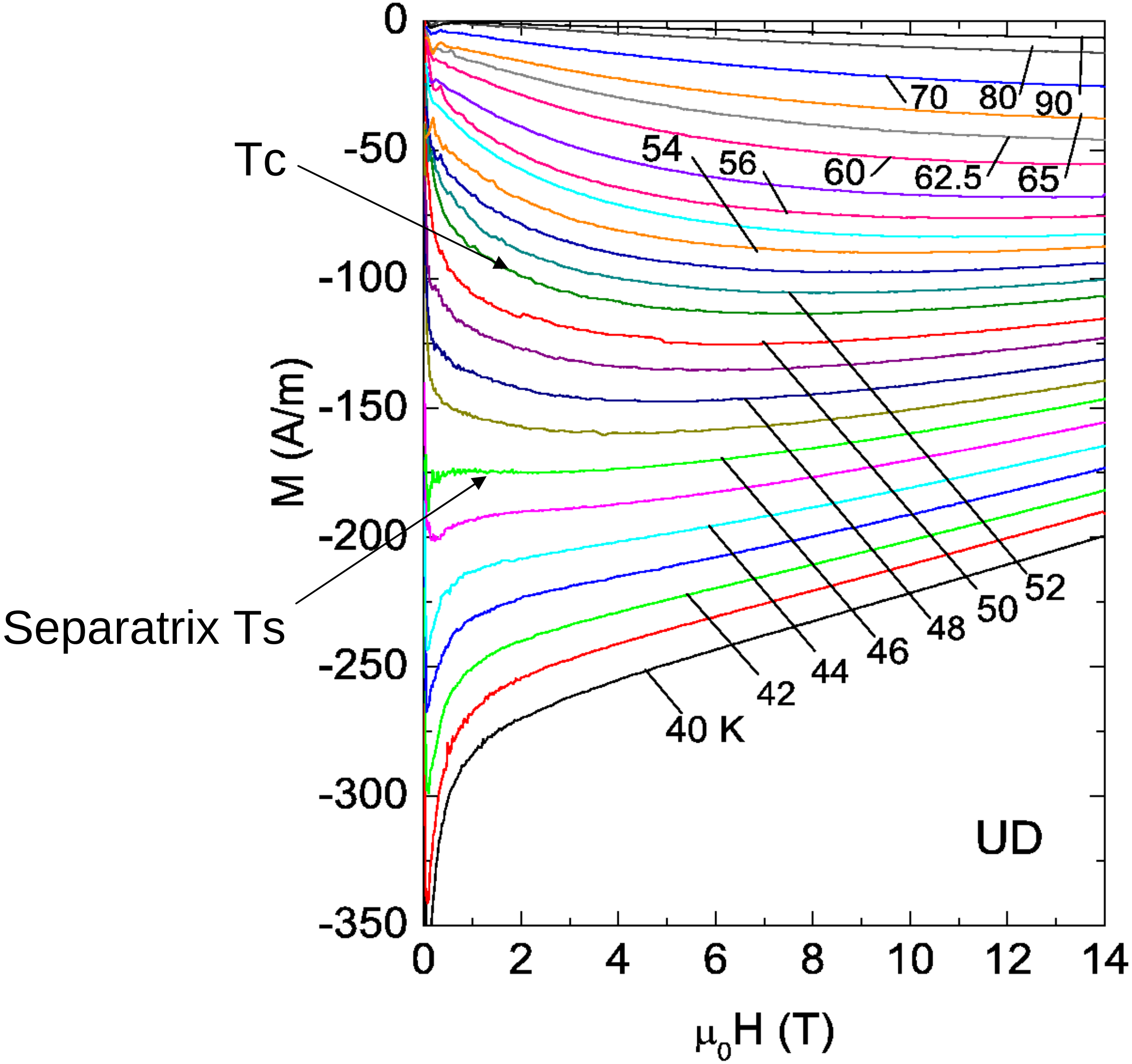
Wang et al.
PRL 2005

Paramagnetic van-Vleck background in Bi 2212 and LSCO

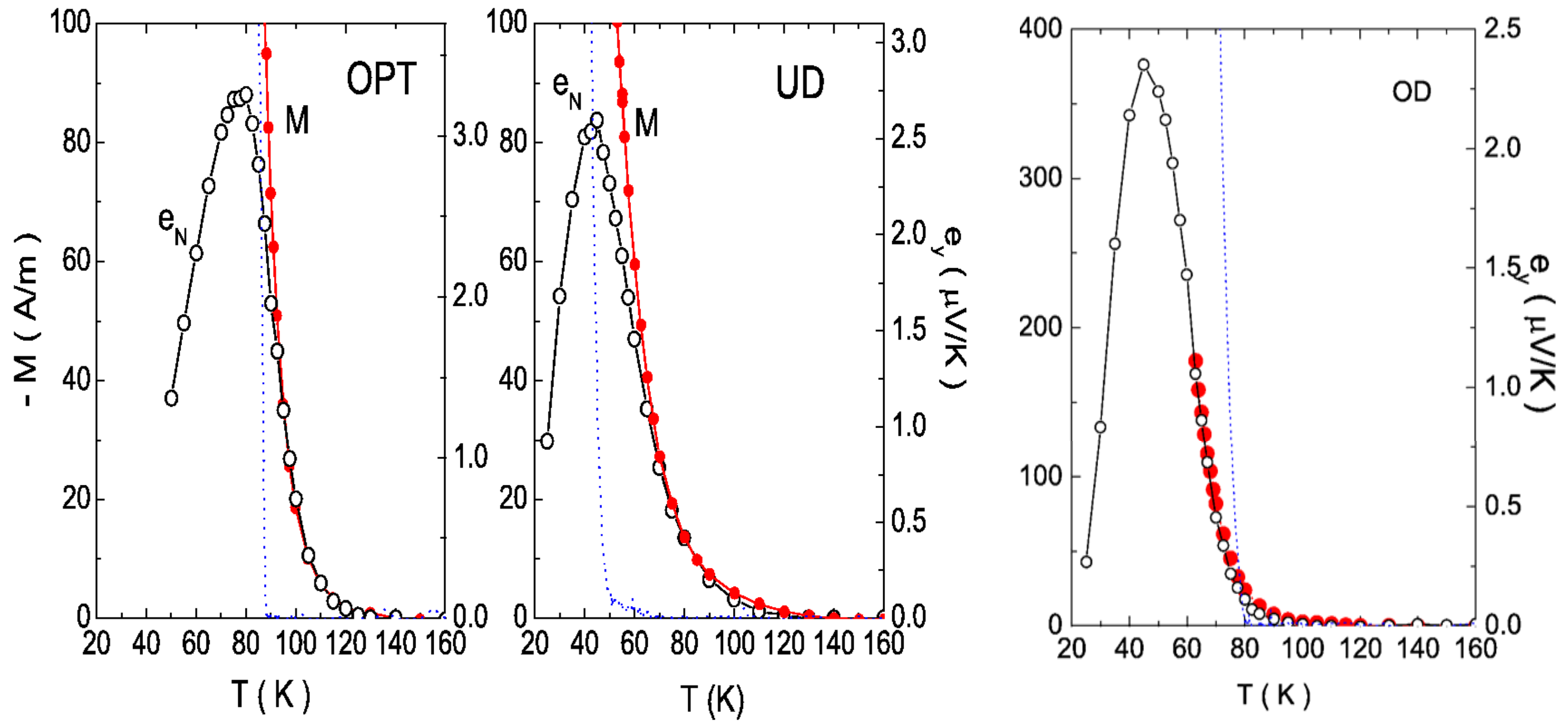


Magnetization curves in underdoped Bi 2212

Wang et al.
PRL 2005



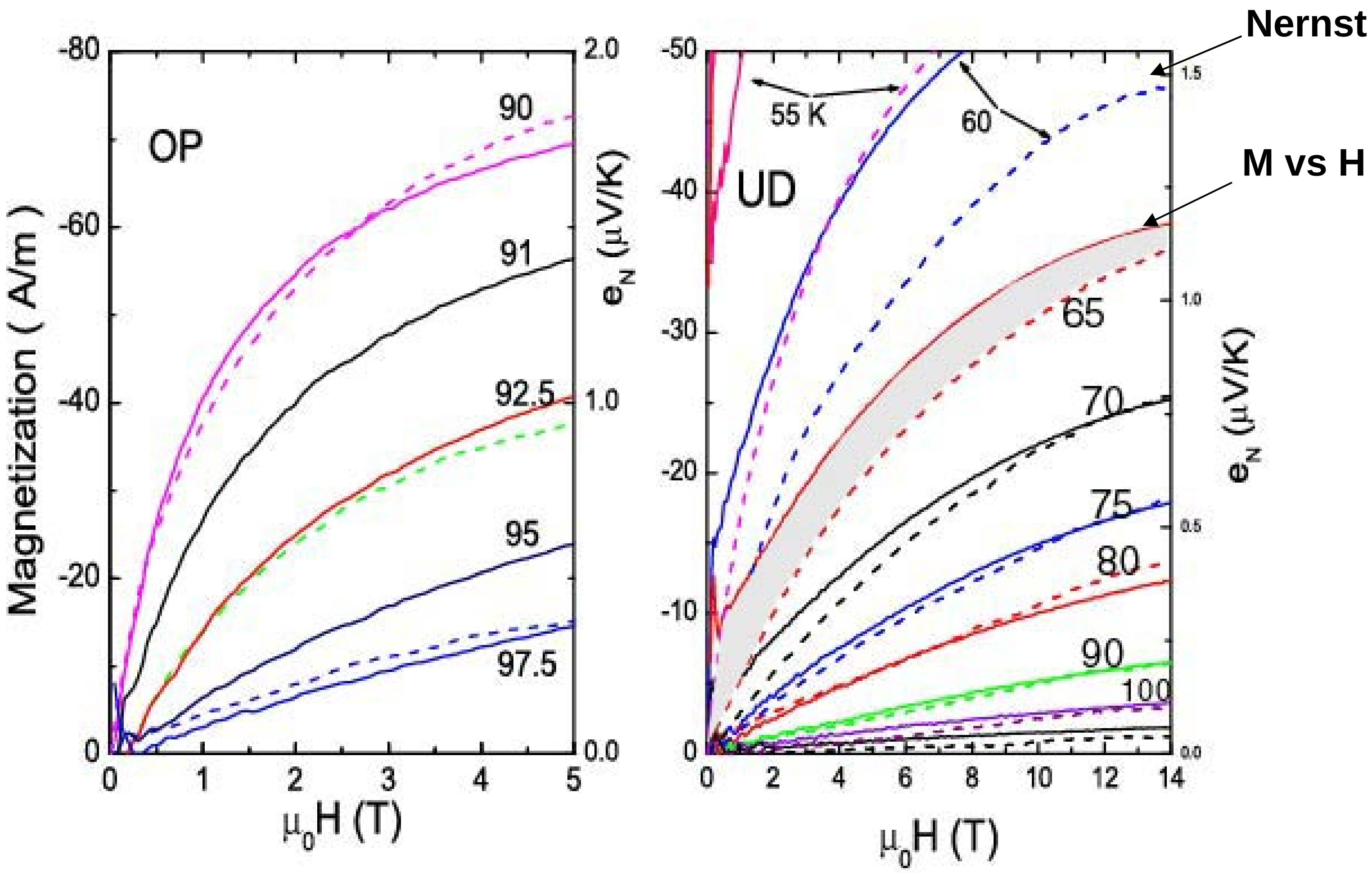
Scaling of Magnetization curves to Nernst in Bi 2212



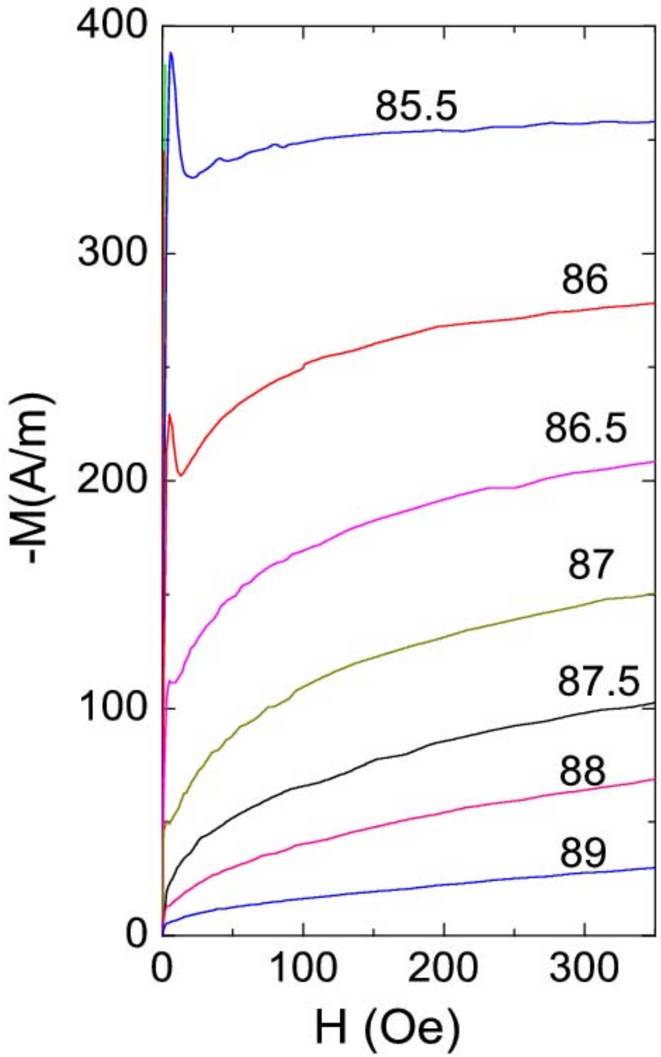
At high T, M scales with Nernst signal e_N

Confirms vortex origin of Nernst signal

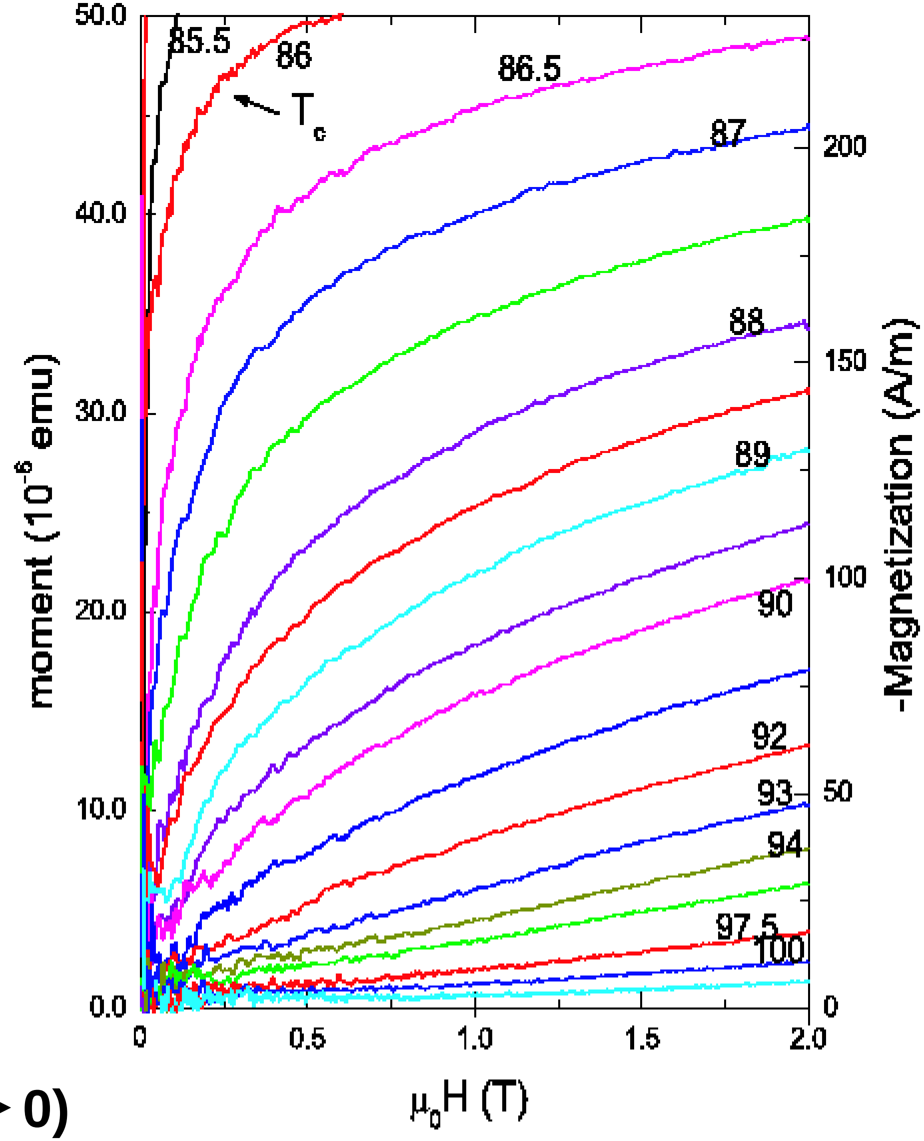
Comparison of M vs H with Nernst signal in OP and UD Bi 2212



“Fragile” London rigidity above Tc



Lu Li et al. EPL ‘05

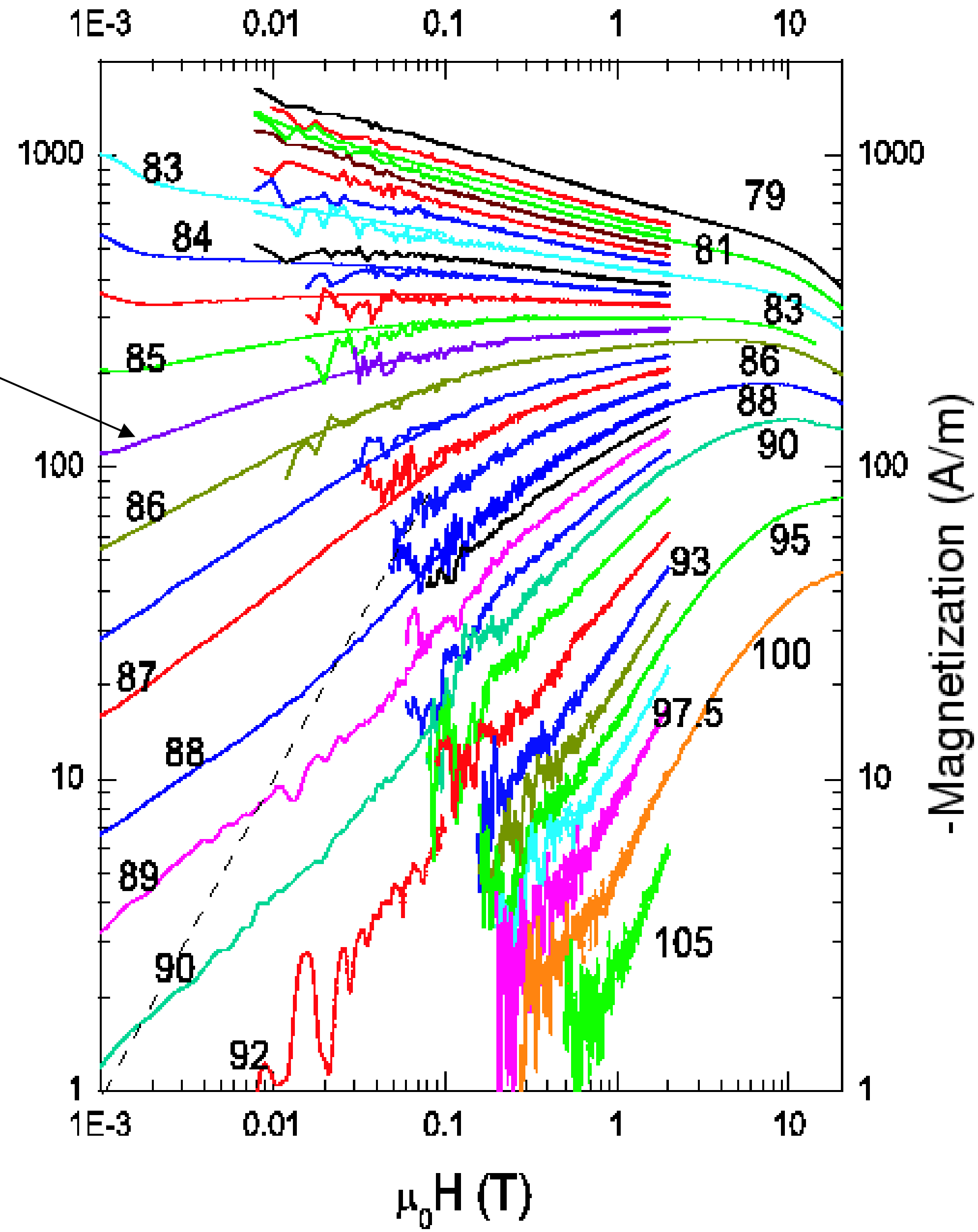


Above T_c, M/H is singular

$M \sim -H^{1/\delta}$ (χ divergent as $H \to 0$)

M non-analytic in weak field

$M \sim H^{1/\delta}$

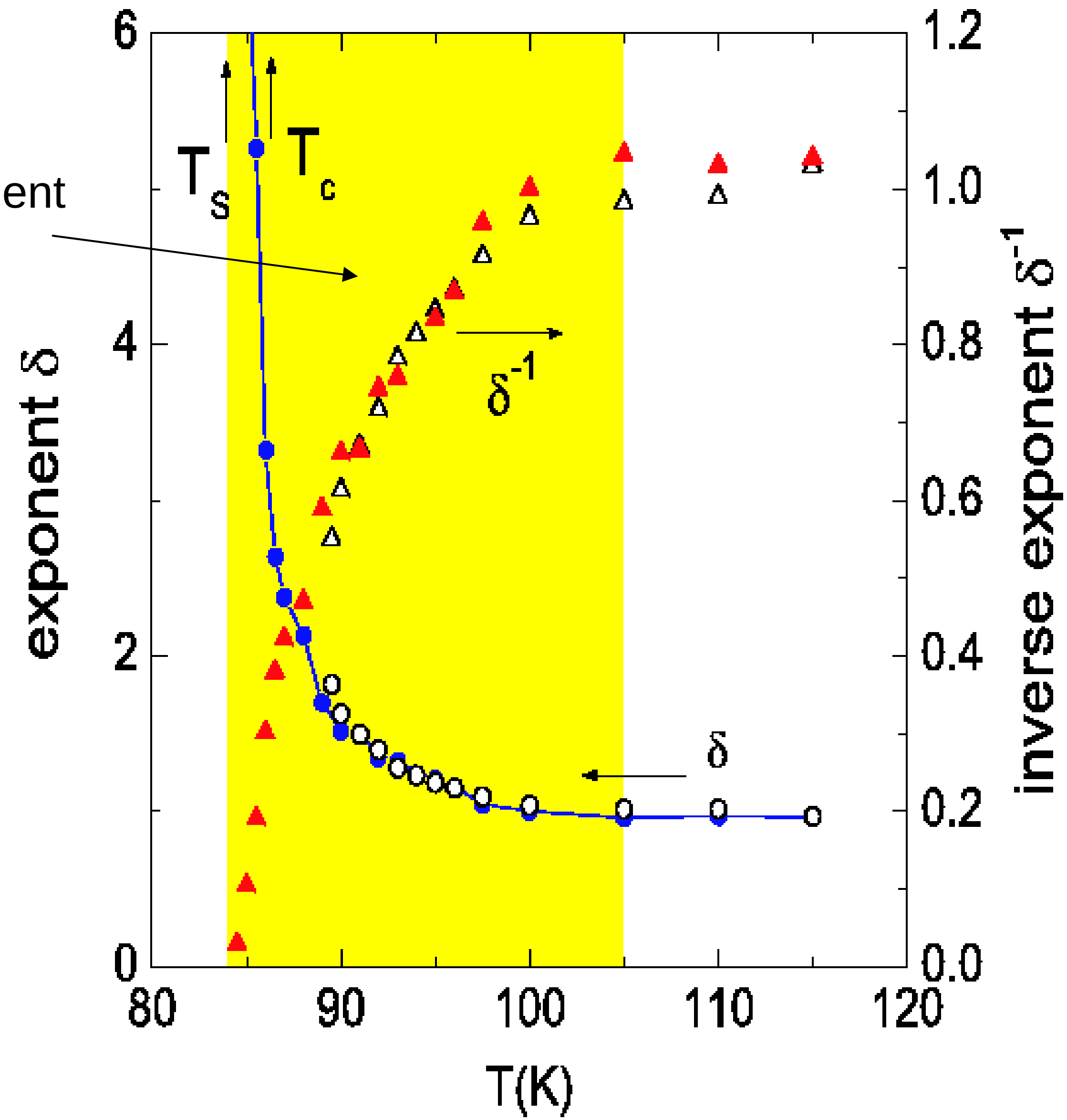


Non-analytic magnetization above Tc

LuLi et al. EuroPhys 2005

$M \sim H^{1/\delta}$

Fractional-exponent region



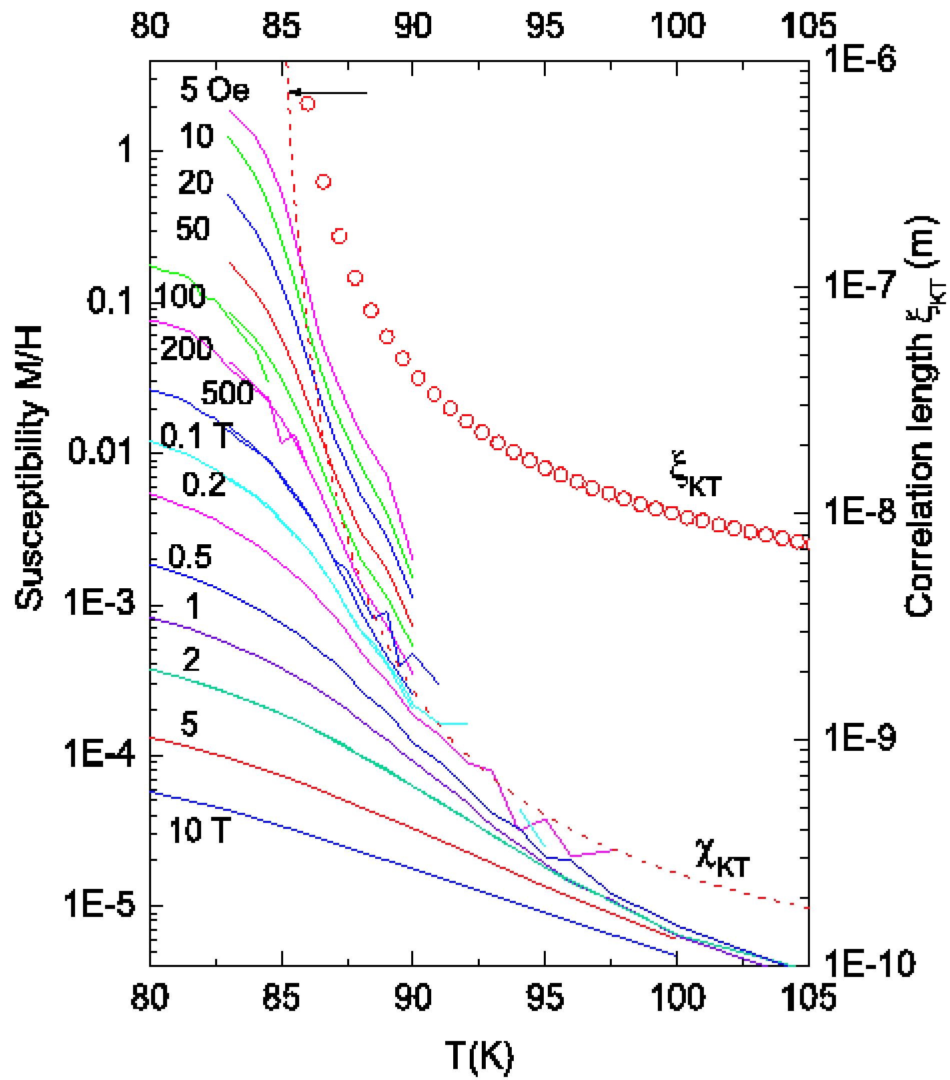
Susceptibility and Correlation Length

Strongly H-dependent
Susceptibility χ = M/H

Fit to
Kosterlitz Thouless theory

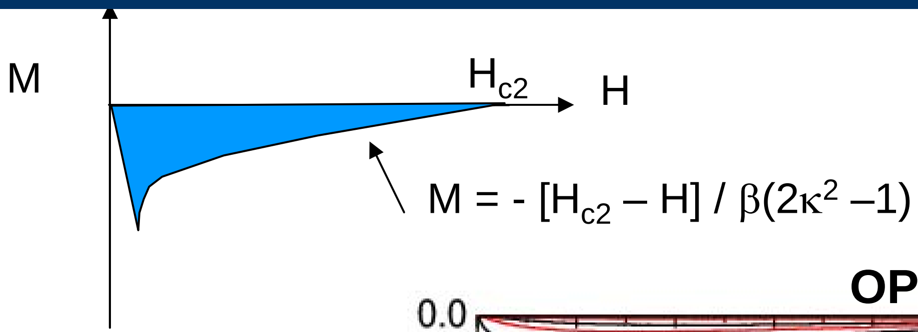
$$\chi = -(k_B T/2d\phi_0^2)\,\xi_{KT}^2$$

$$\xi_{KT} = a\,\exp(b/t^{1/2})$$

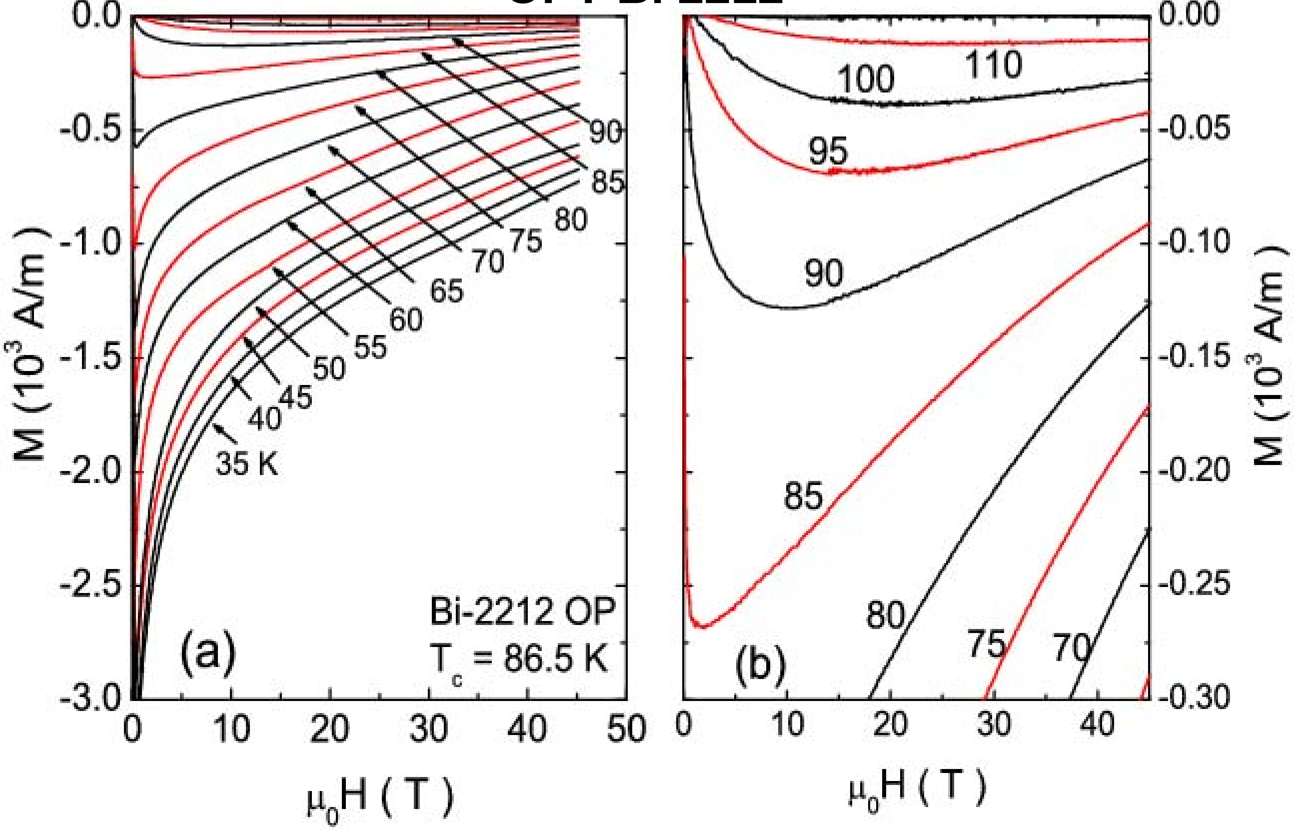


High-field Magnetization Curves in Bi 2212

Lu Li et al., JMMM 2007



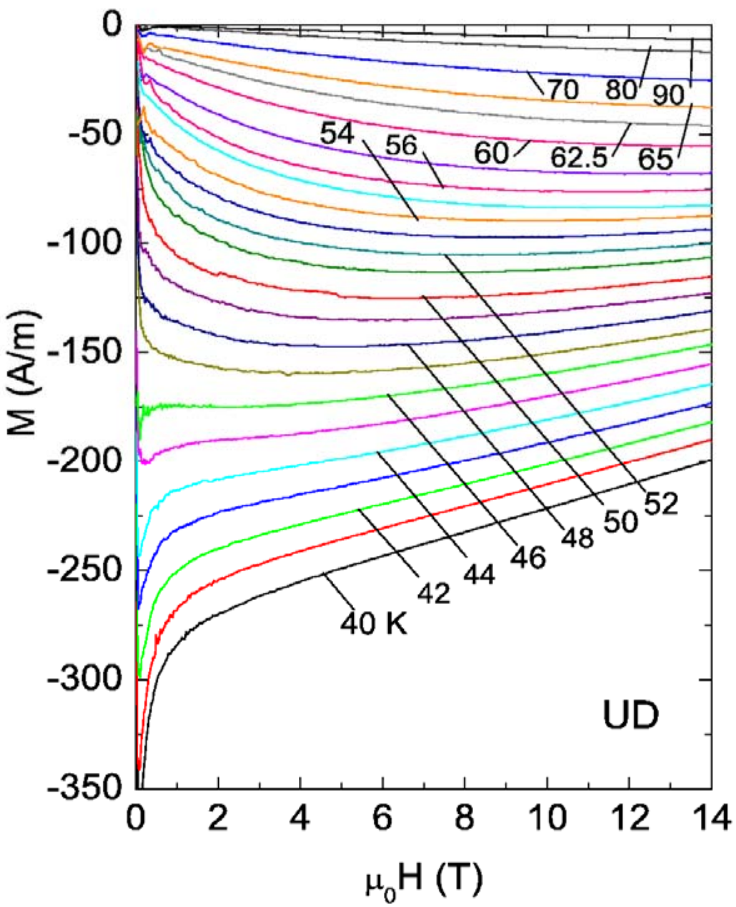
OPT Bi 2212



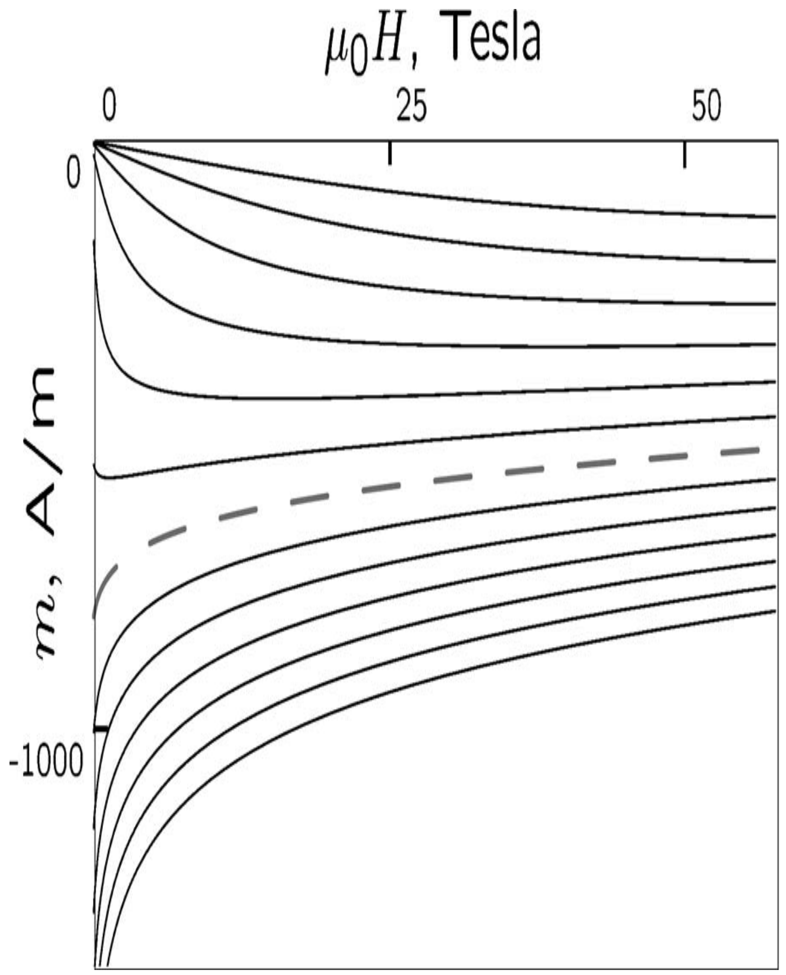
***H_{c2}* is not linear in (1-t), not BCS scenario**

Oganesyan, Sondhi, Huse, PRB (2006)

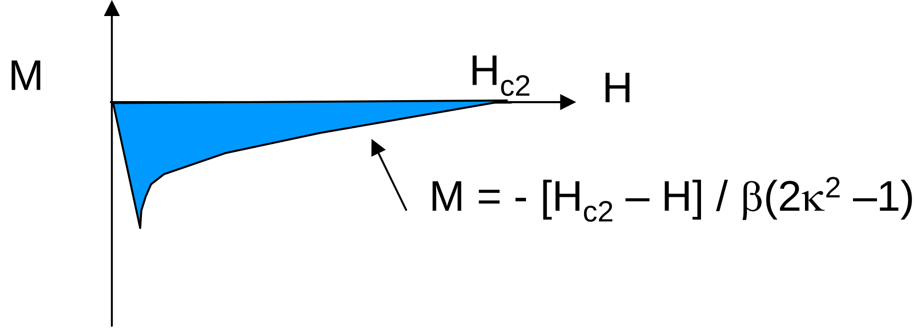
Calculated diamagnetic response of Kosterlitz-Thouless superconductor

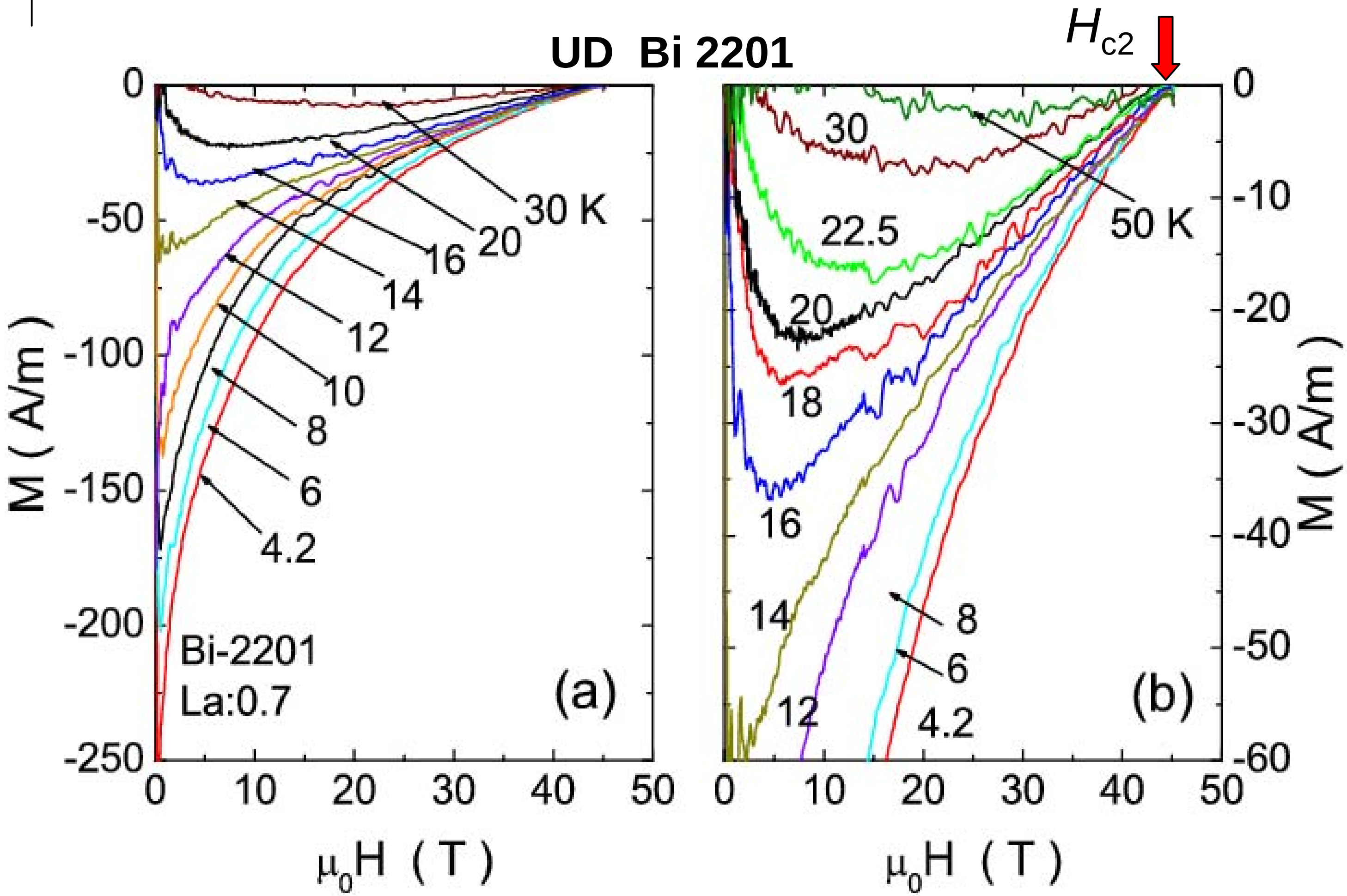


Wang et al., PRL '05

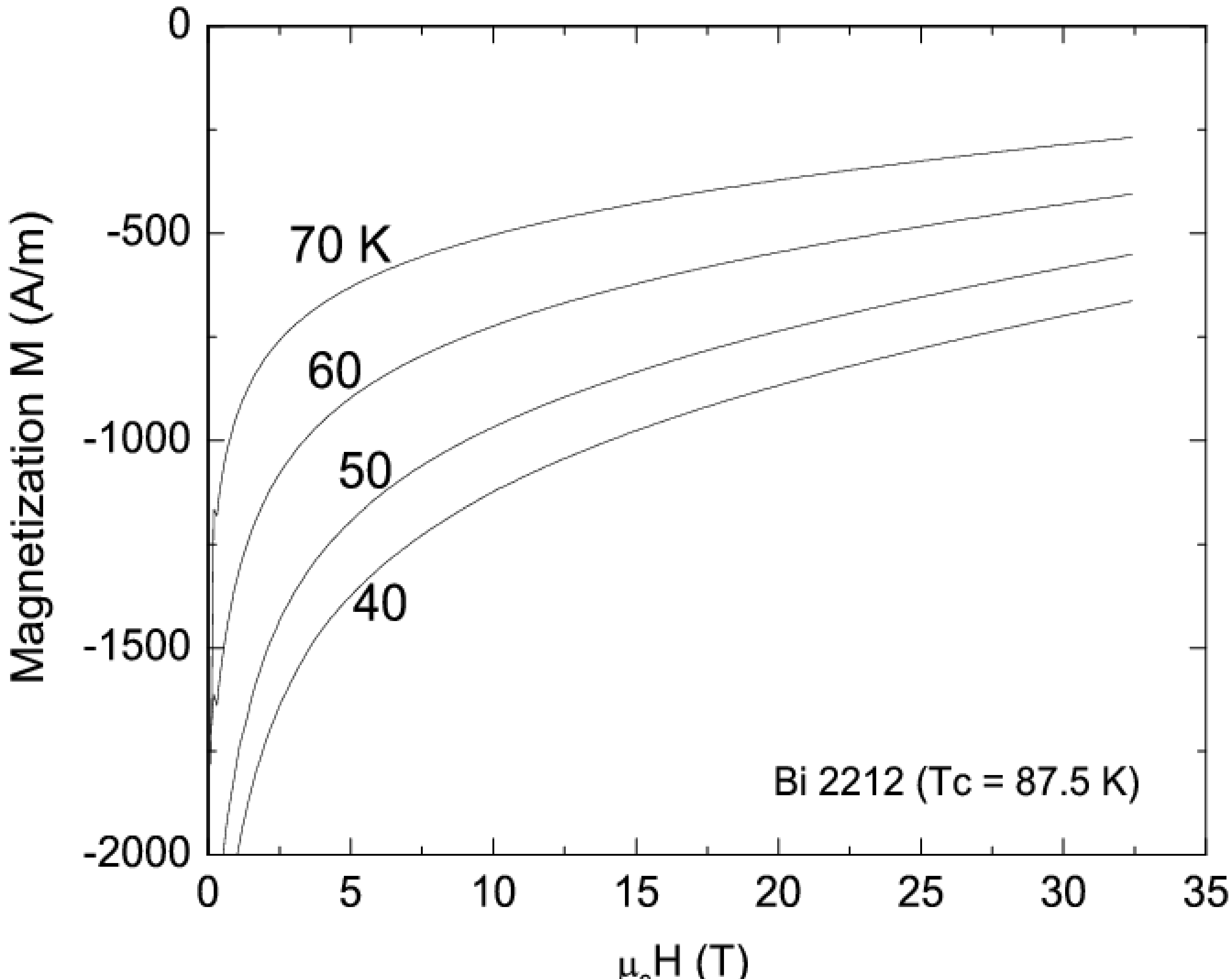


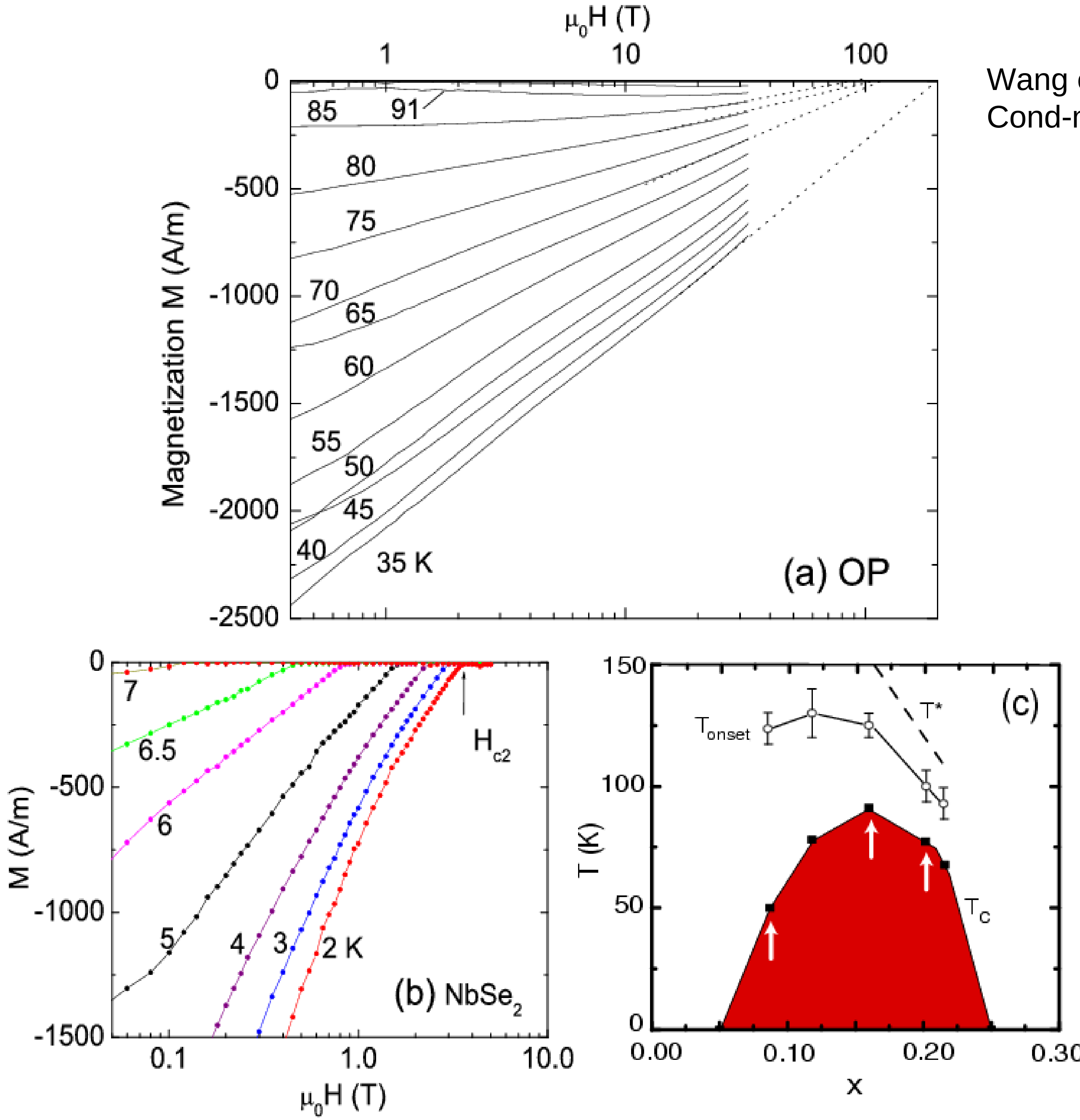
Lu Li et al., unpubl.





***H_{c2}* nearly *T* independent**

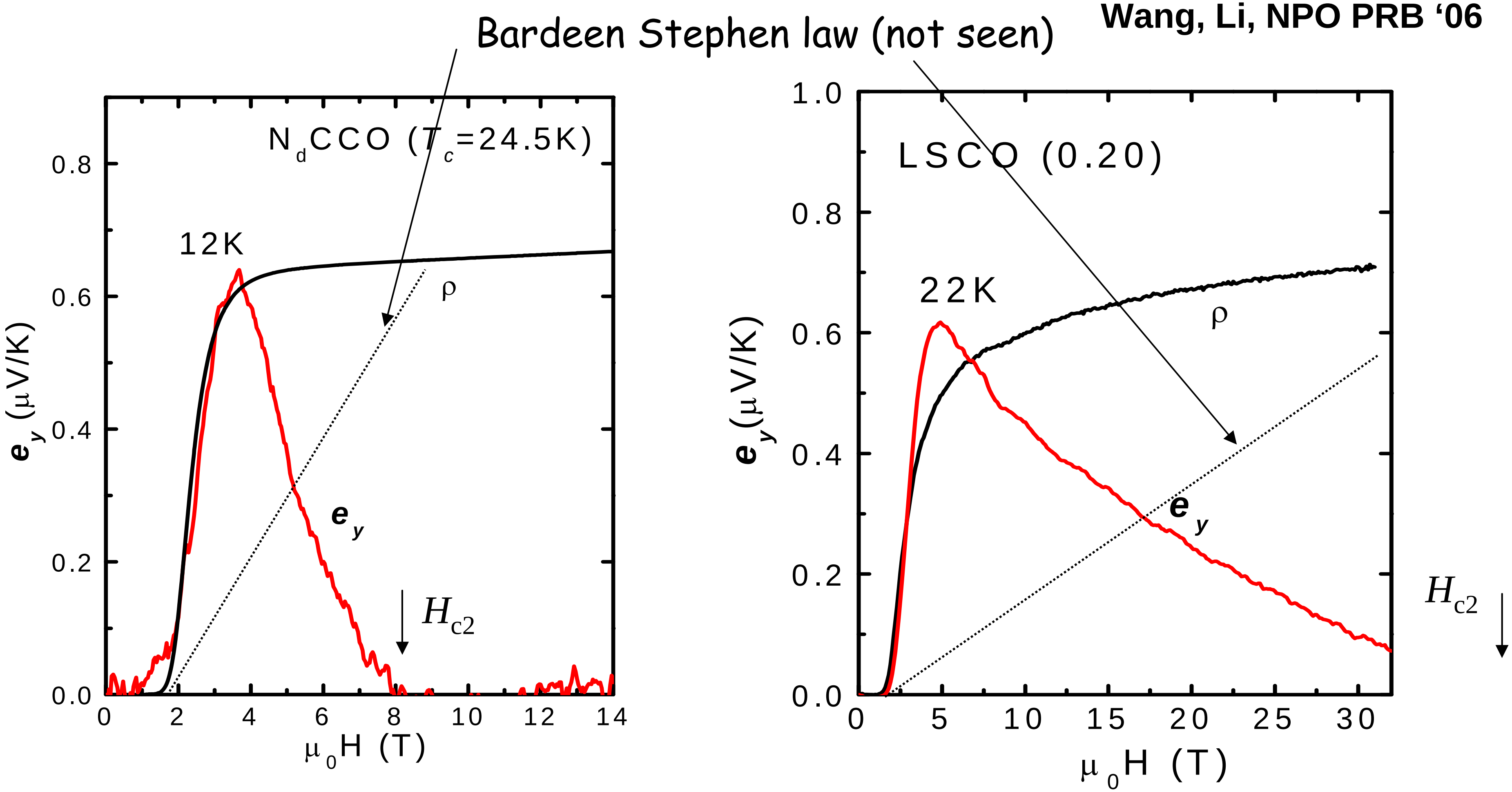

0
-500
-1000
-1500
-2000
Magnetization M (A/m)
0
5
10
15
20
25
30
35
μ0H (T)
70 K
60
50
40
Bi 2212 (Tc = 87.5 K)



Wang et al.
Cond-mat/05

Problems with Flux-flow Resistivity

Wang, Li, NPO PRB '06



Resistivity does not distinguish vortex liquid and normal state

H_{c2} vs T_{onset} in single-layer cuprates

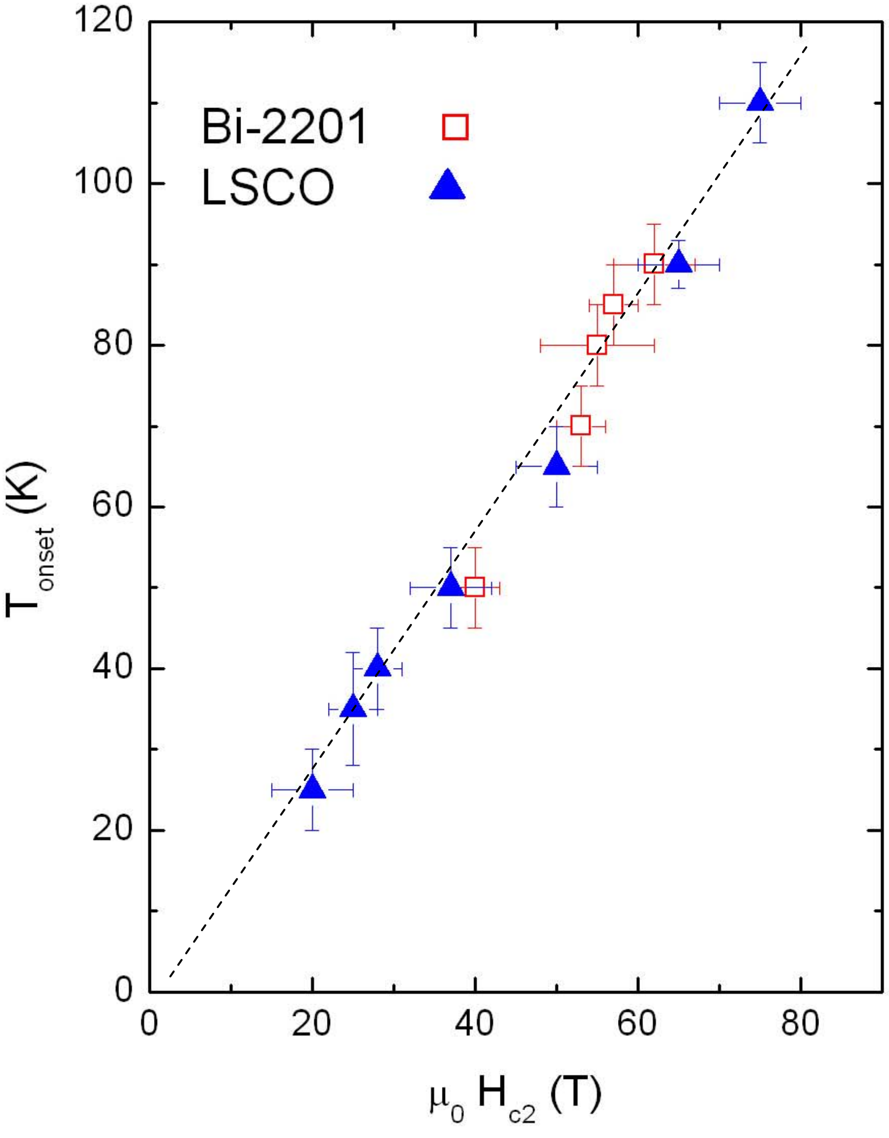
H_{c2} torgue magnetization scales linearly with T_{onset}

Fit to

$$2\left(\frac{g}{2}\right)\mu_B H_{c2} = k_B T_{onset}$$

gives $g = 2.2$

Clogston limit determines H_{c2}



Lu Li et al., unpubl.

In hole-doped cuprates

1. **Large region in phase diagram above Tc dome with enhanced Nernst signal**

2. **Associated with vortex excitations (not Gaussian)**

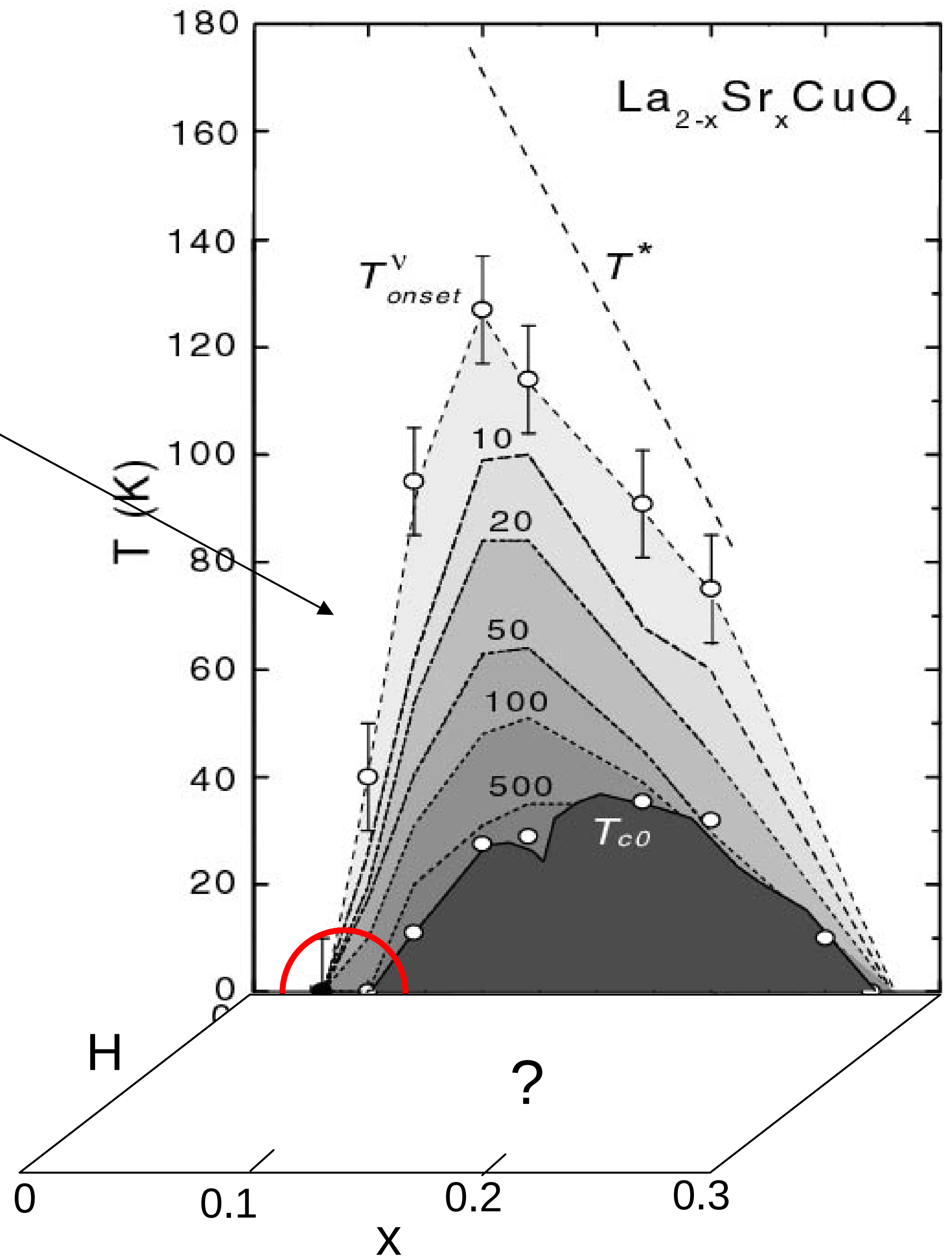
3. **Confirmed by torque magnetometry**

4. **Transition at T_c is 3D version of KT transition (loss of phase coherence)**

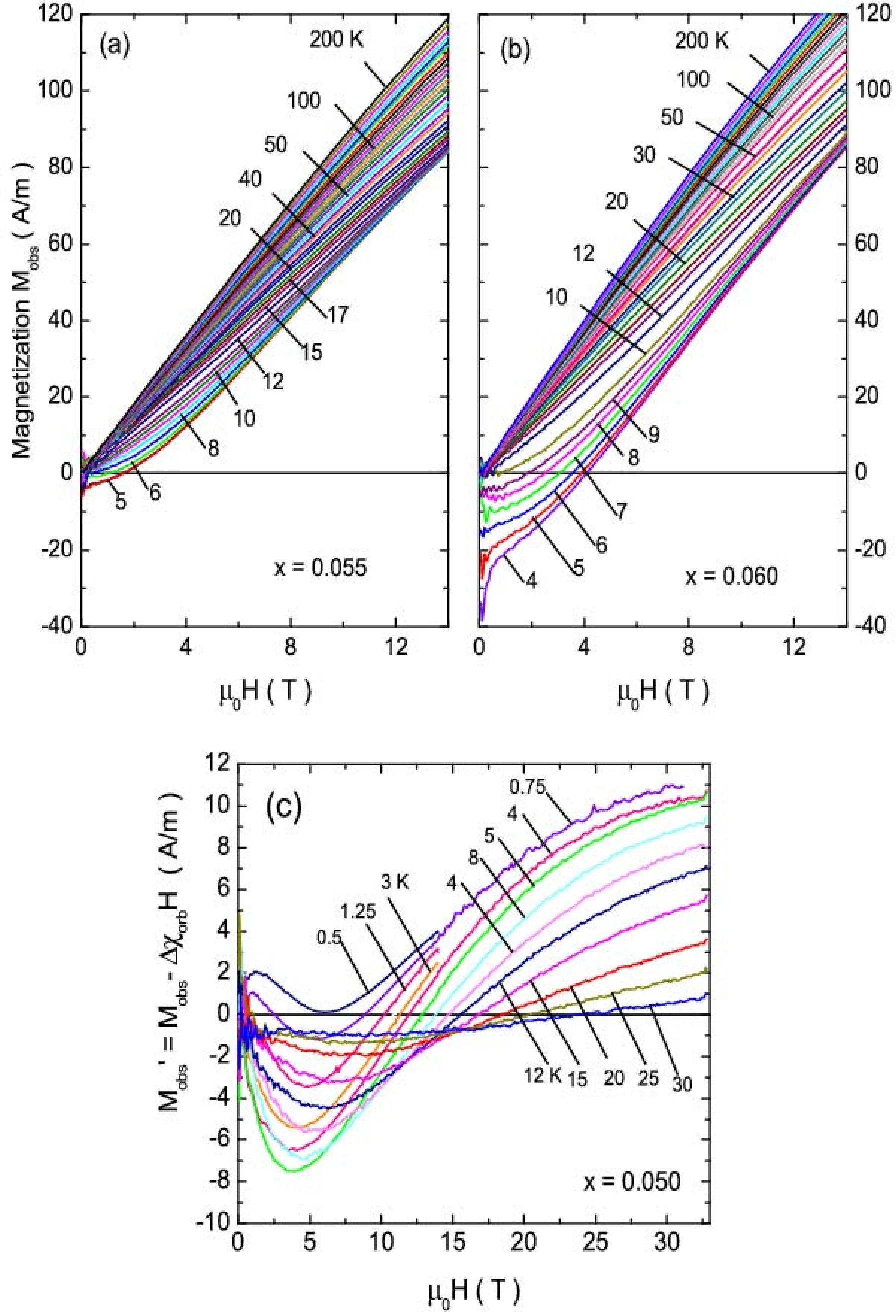
5. **Depairing field Hc2 anomalous in T dependence,**
6. **Scales linearly with T_{onset}**

Very lightly doped limit in LSCO

Nernst region

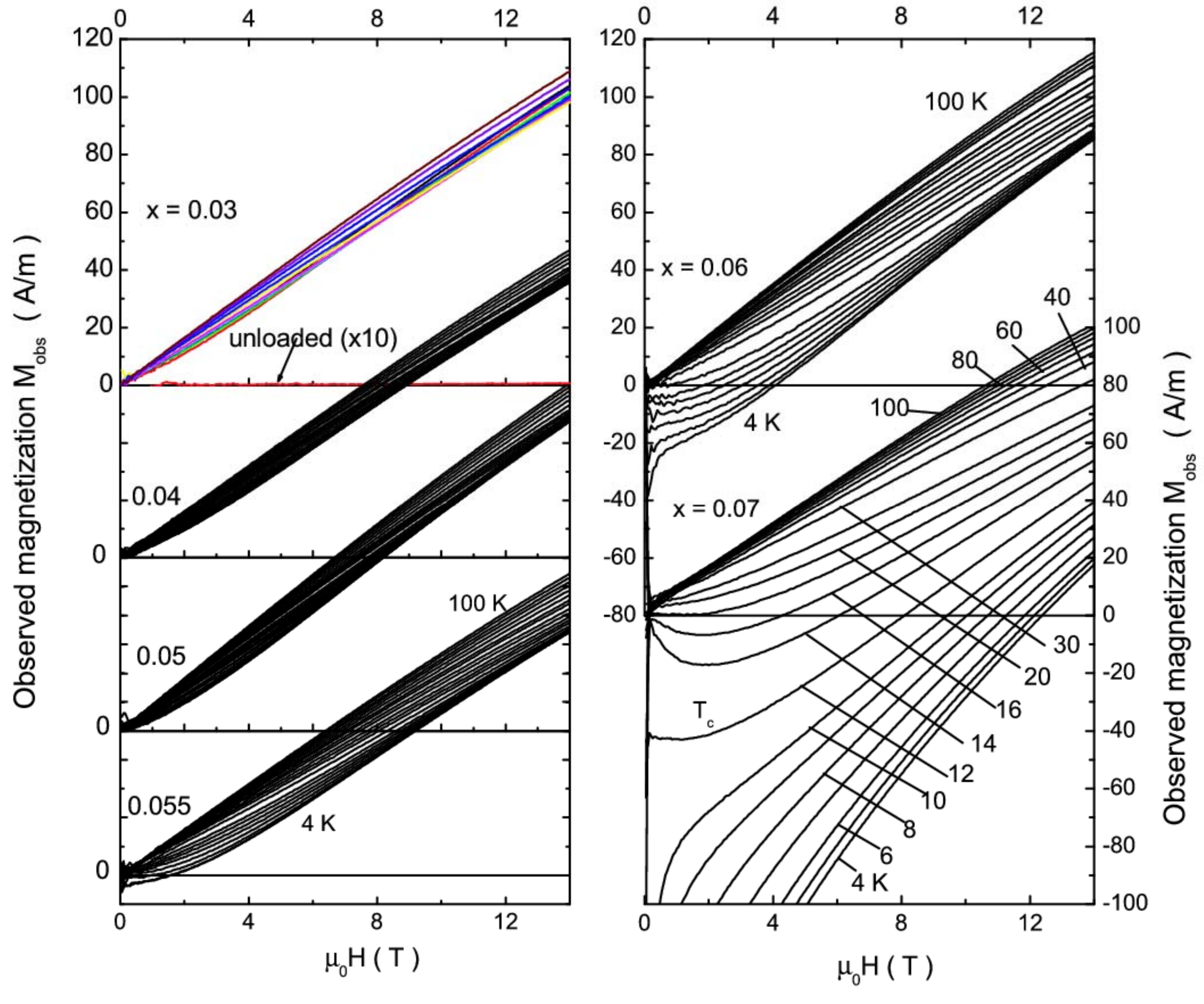


The phase diagram
in x-H plane at low T?



(a)
(b)
(c)
Magnetization M_{obs} (A/m)
μ_0H (T)
$M_{obs}' = M_{obs} - \Delta\chi_{orb}H$ (A/m)
x = 0.055
x = 0.060
x = 0.050
200 K
100
50
40
20
17
15
12
10
8
6
5
30
9
7
4
0.75
3 K
1.25
0.5
12 K
25

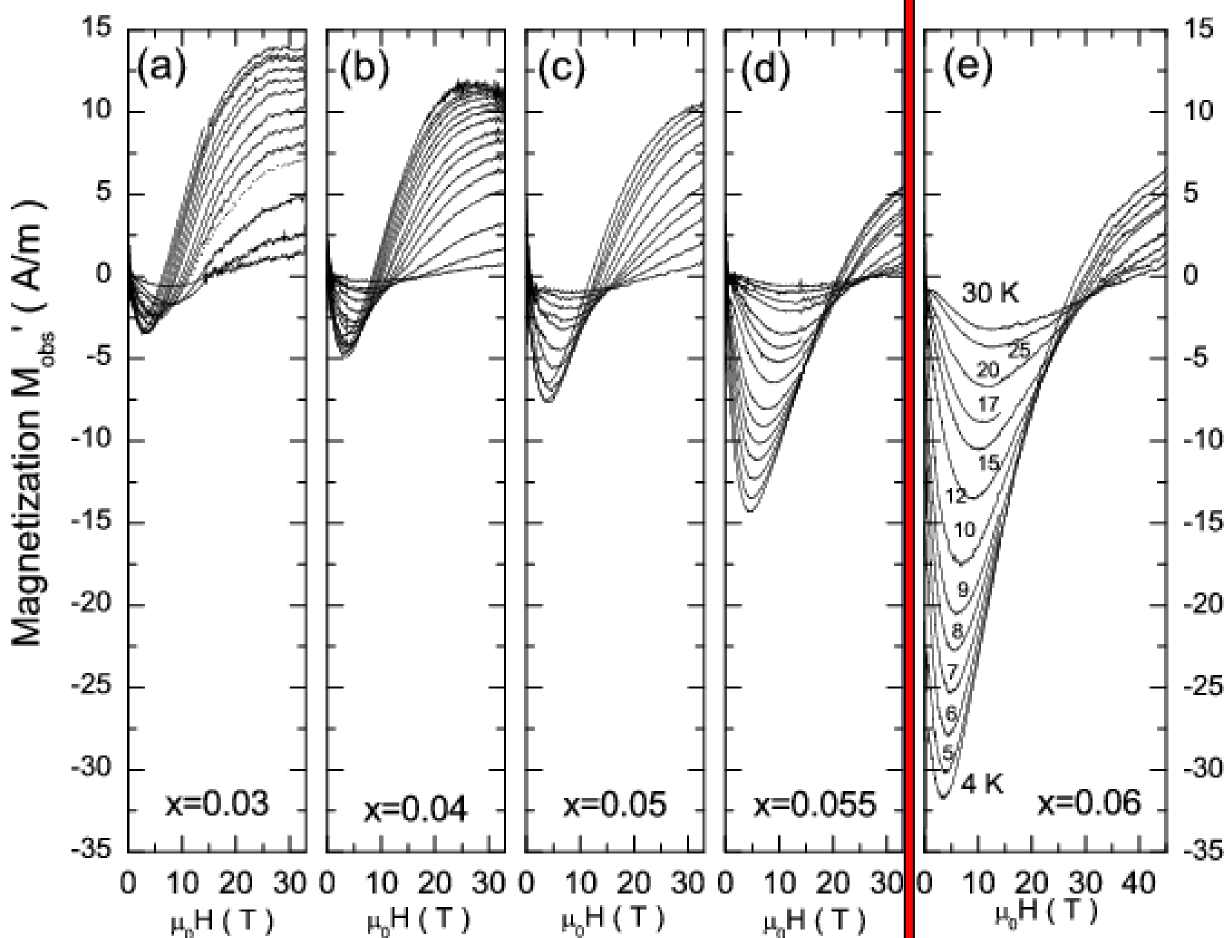
As-observed torque magnetization results in 6 LSCO xtals



Lu Li et al., unpubl.

Magnetization in lightly doped $La_{2-x}Sr_xCuO_4$

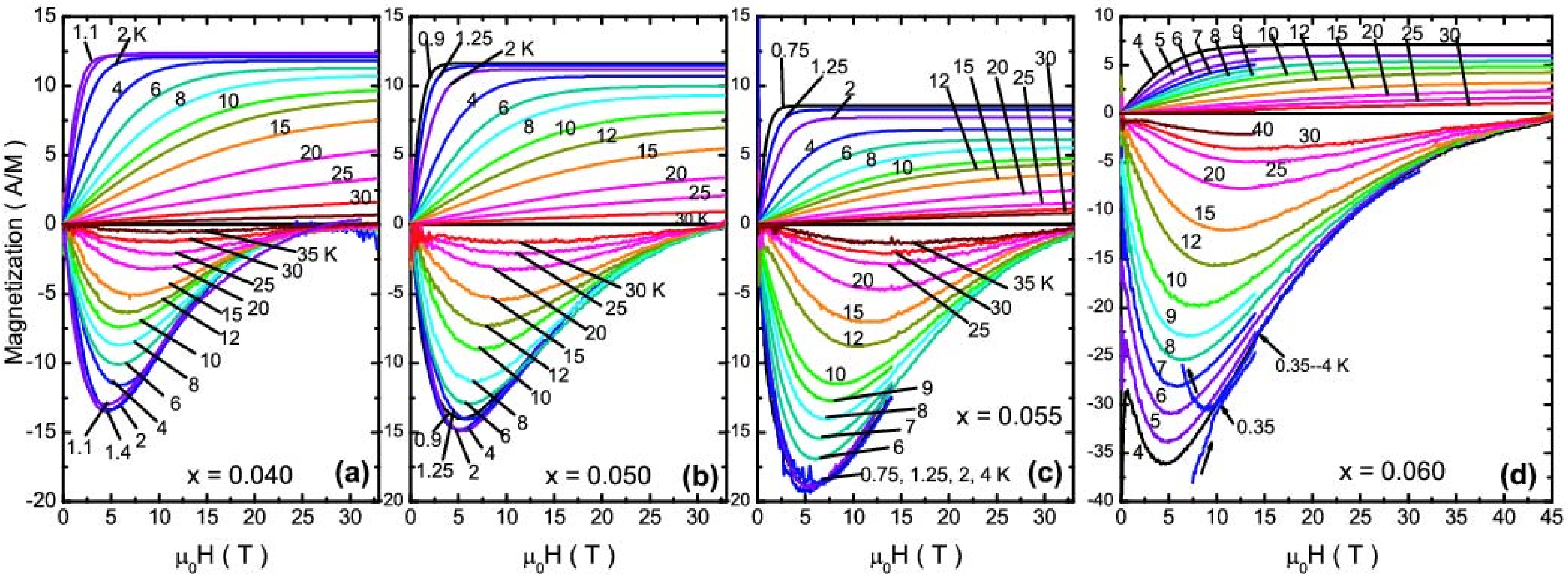
Lu Li et al., Nature Phys



Evidence for robust diagmagnetism for $x < x_c$

Magnetization curves in very lightly-doped LSCO

Lu Li et al., Nature Physics ‘07

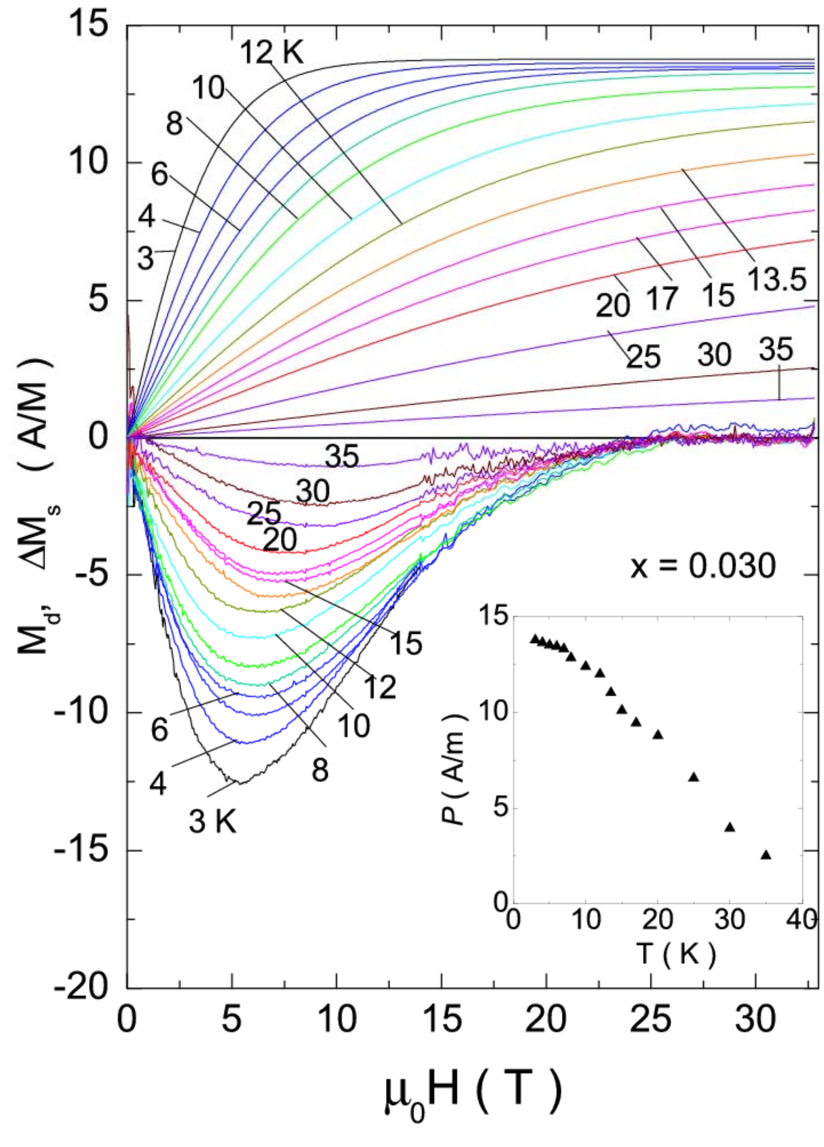


Doping x

Diamagnetism persists to 3 percent doping
Vortex liquid stable at 0.3 K
Cooper pair competes with local moment formation

M_{obs}' is comprised of diamagnetic and paramagnetic terms

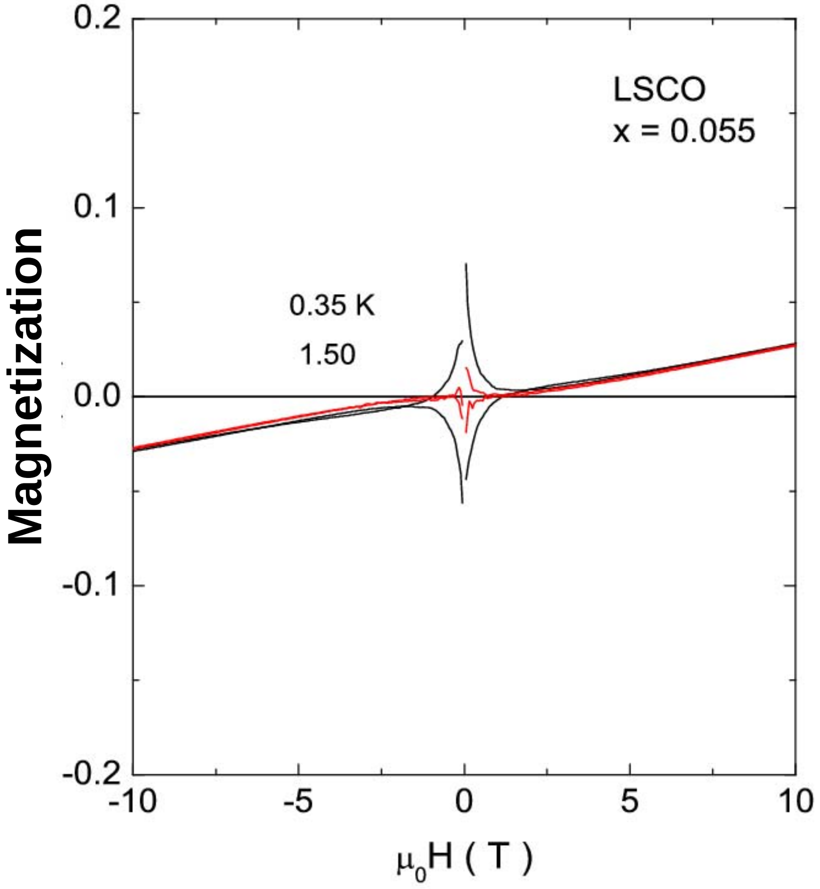
Lu Li et al., unpubl.

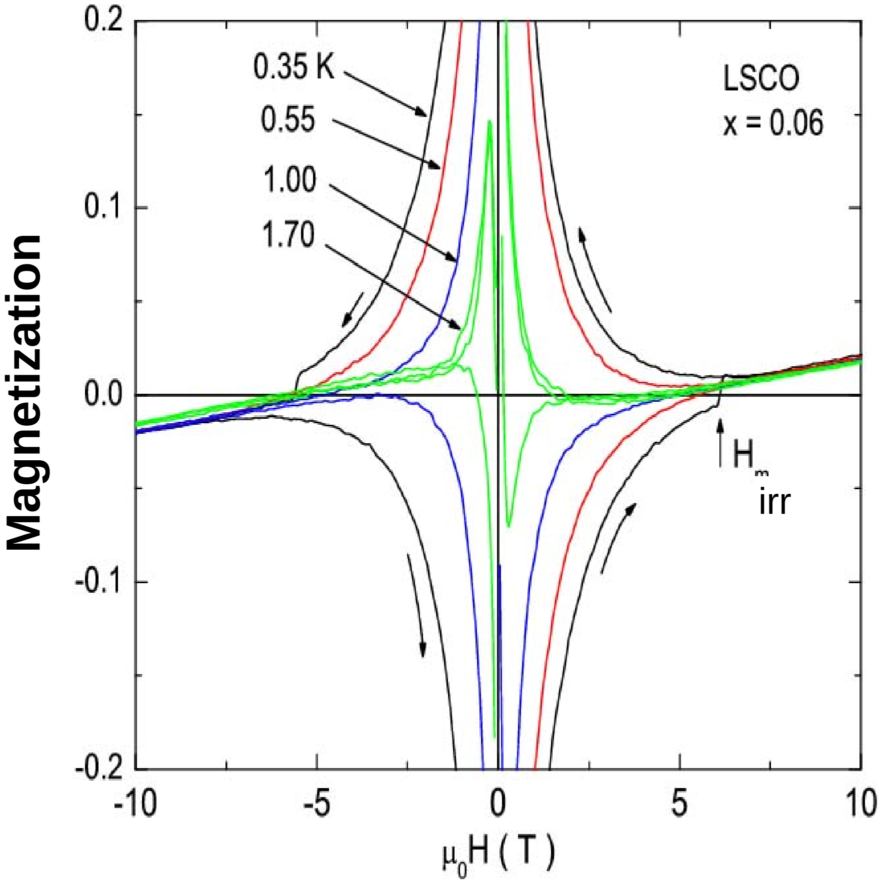


Ground state

Lu Li et al., Nature Physics ‘07

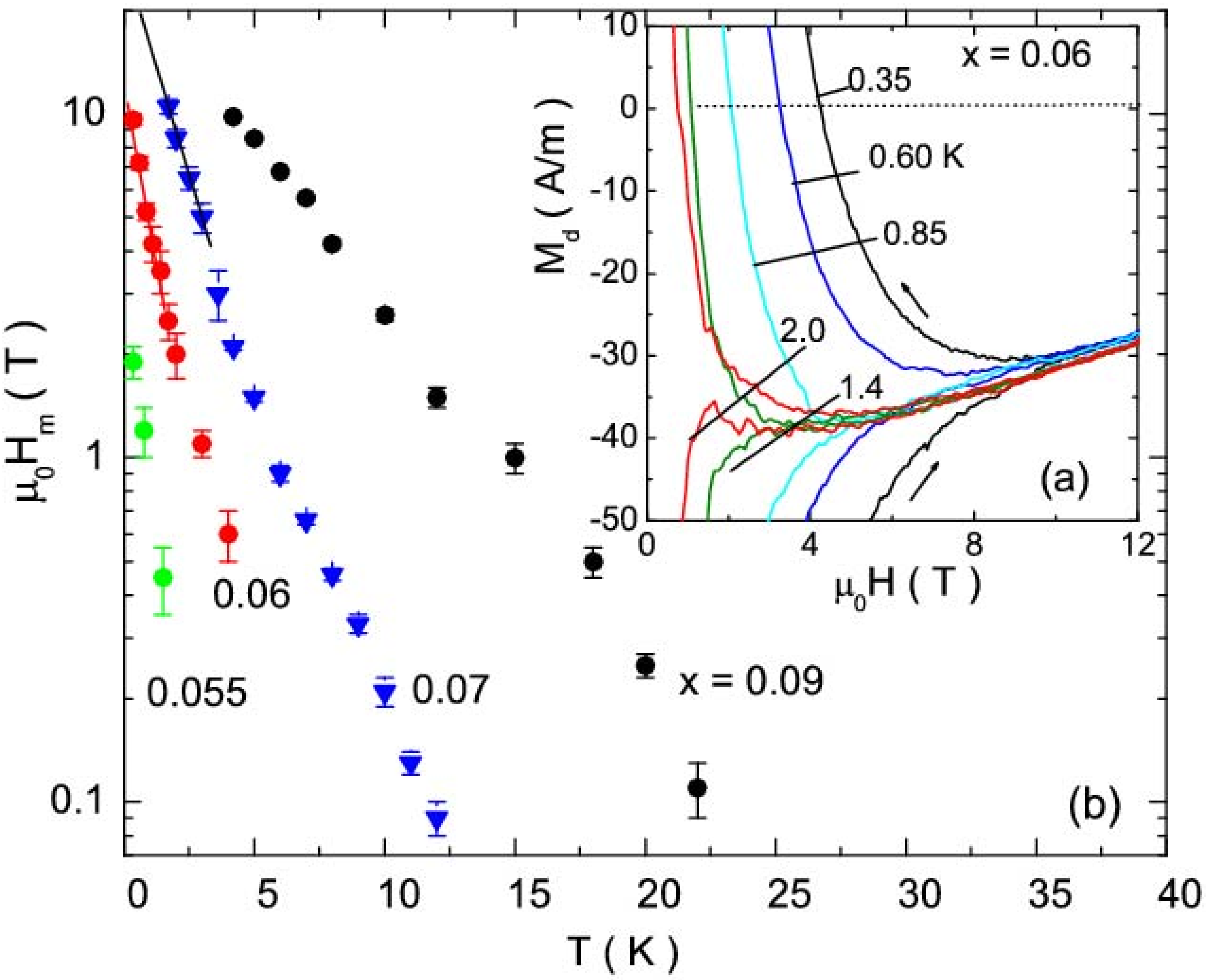
Comparison between x = 0.055 and 0.060





Pinning current reduced by a factor of ~100 in ground state

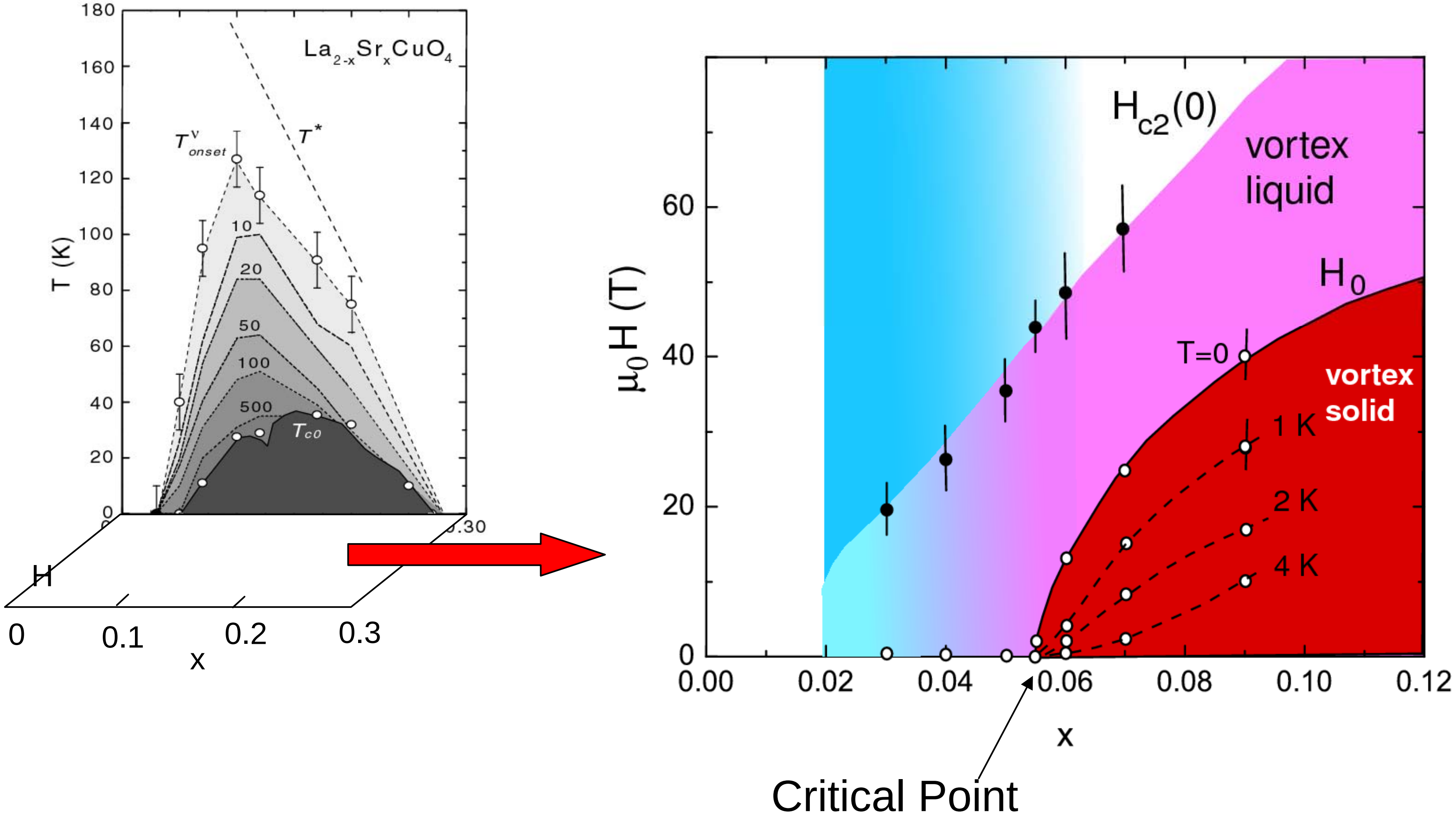
Vortex solid-to-liquid transition for $x < x_c$ Lu Li et al., unpubl.



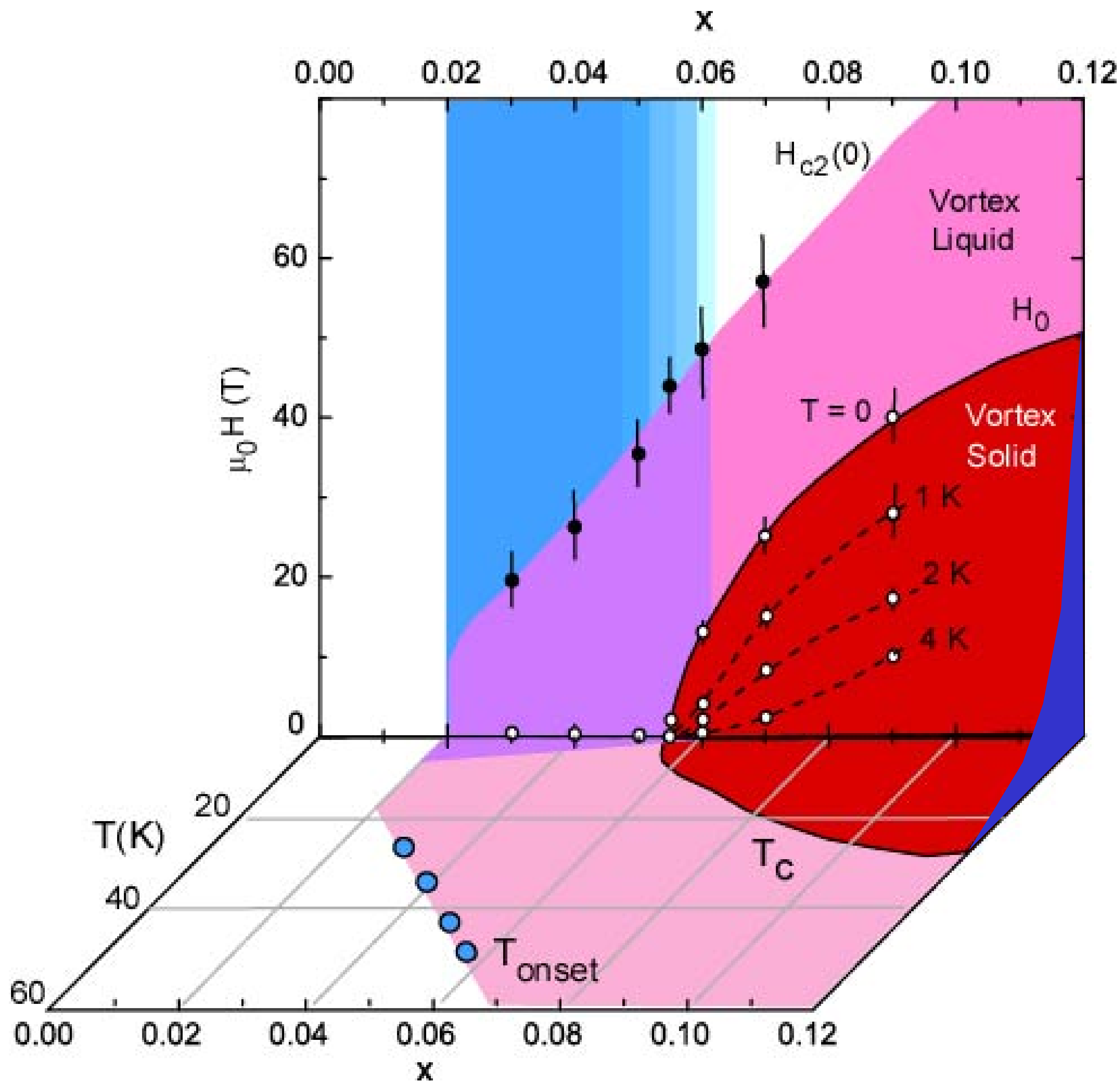
Debye Waller dependence $H_m(T) = H_0 \exp(-T/T_0)$

Low-Temperature *H-x* Phase Diagram

Lu Li et al., Nature Physics ‘07

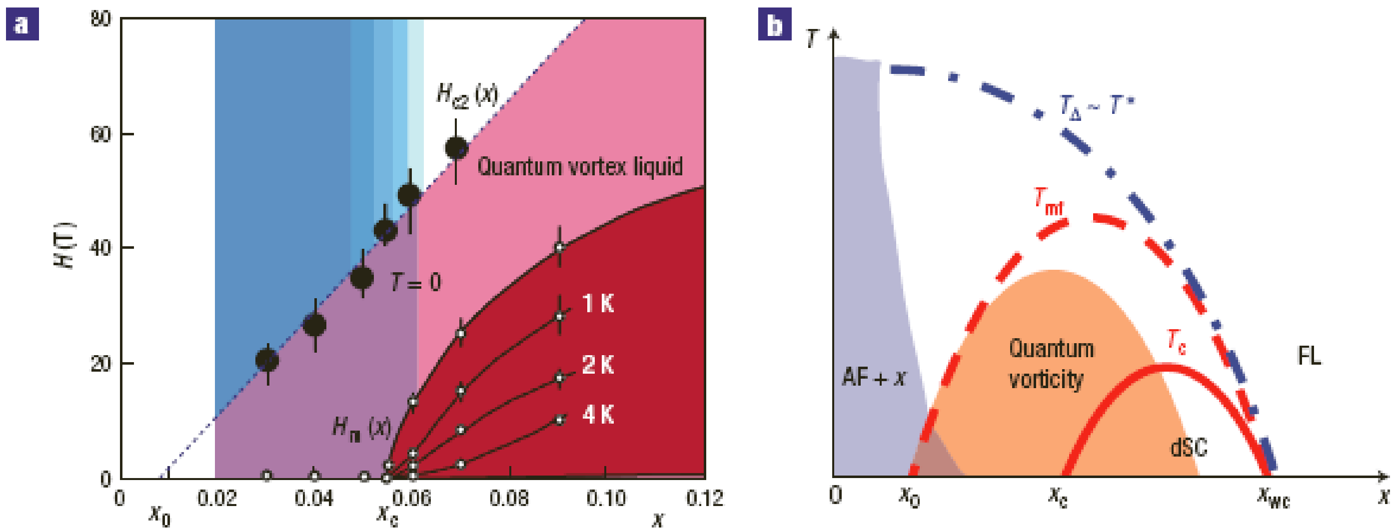


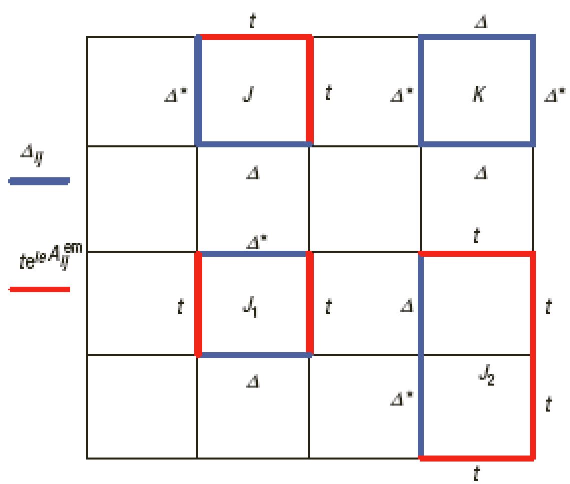
T-H-x phase diagram of LaSrCuO in UD regime



d-wave duality near Mott limit

Z. Tesanovic, Nature Phys. 2008





$$L^d_{\mathrm{QGL}} = \gamma_\tau |\dot{\Psi}|^2 + \gamma |(\nabla - i(2e)\mathrm{A})\Psi|^2 + \alpha |\Psi|^2 + \frac{1}{4}|\Psi|^4,$$

Low-temperature vortex liquid

1. Vortex solid surrounded by vortex liquid at 0.35 K

2. Sharp quantum transition at $x_c = 0.055$. Quantum vortices destroy phase coherence

3. At 0.35 K, pair condensate survives without phase rigidity even for x = 0.03

4. Melting of vortex solid appears to be classical at 0.35 K (Debye-Waller like).

Other Experimental Techniques

1. Kinetic inductance at THz freq in Bi 2212 (Orenstein, Nature ‘99)

2. Thermal expansion YBCO (Meingast, PRL ‘00)

3. Magnetization Bi 2212, LSCO, Bi 2201 (Wang, Li, PRL, EPL ‘05)

4. STM above Tc Bi 2212 (Yazdani, Nature ‘07)

5. ARPES?

Other Superconductors

1. $CeCoIn_5$ (Matsuda-Behnia, PRL ‘05),
   corrected (Onose, NPO, Petrovic EPL ‘07)
   Large Nernst signal 13 K above Tc (2.3 K)

2. Organic superconductor κ-$(BEDT\text{-}TTF)_2$-X
   (Nam, Ardavan, Blundell, Schlueter preprint ‘07)
   Nernst signal 6 K above Tc (12 K) near Mott trans.

3. $Nb_{1-x}Si_x$ (Behnia et al, NaturePhys 06), 2D Gaussian fluct.?

References (Talk 3)

1. Yayu Wang, Lu Li, M. J. Naughton, G. Gu, S. Uchida and N. P. Ong, Phys. Rev. Lett. 95, 247002 (2005).

2. Lu Li, Yayu Wang, M. J. Naughton, S. Ono, Yoichi Ando, and N. P. Ong, Eurpophys. Lett. 72, 451-457 (2005).

3. Vadim Oganesyan, David A. Huse, and S. L. Sondhi, Phys. Rev. B 73, 094503 (2006).

4. N. P. Ong, Lu Li, Yayu Wang and M. J. Naughton, Phys. Rev. Lett. 78, 119702 (2007).

5. Lu Li, Yayu Wang, M. J. Naughton, Seiki Komiya, Shimpei Ono, Yoichi Ando and N. P. Ong, J. Magn. Magn. Mater. 310, 460-466 (2007).

6. Lu Li, J. G. Checkelsky, Seiki Komiya, Shimpei Ono, Yoichi Ando and N. P. Ong, Nature Physics 3, 311-314 (2007).

7. L. Benfatto, C. Castellani, and T. Giamarchi, Phys. Rev. Lett. 99, 207002 (2007); Phys. Rev. Lett. 98, 117008 (2007).

8. Z. Tesanovic, Nature Physics 4, 408 (2008).

Summary

1. **Nernst region is suffused with vorticity, enhanced diamagnetism and finite pairing amplitude**

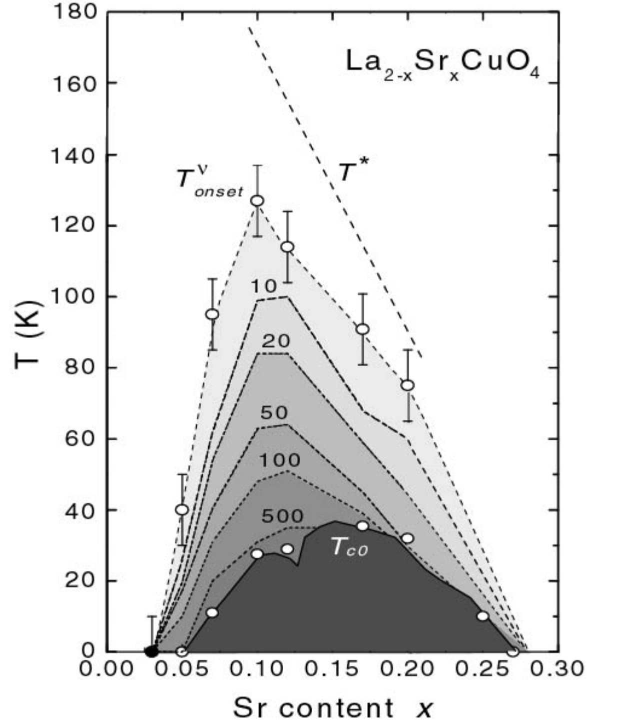
2. **Extends from T_c to $T_{onset} < T^*$**

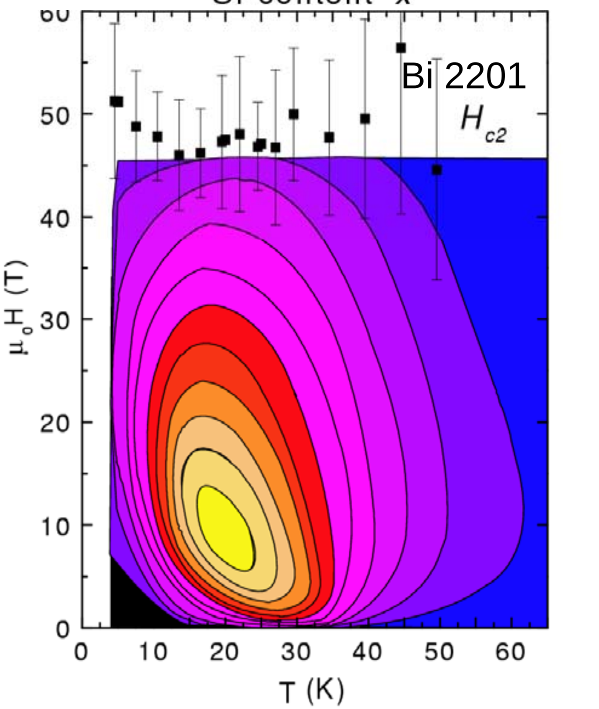
3. **Nernst region *dominates* lower temp part of Pseudogap state**

4. **Depairing field H_{c2} and binding energy are very large**

   Pairing (diamagnetism) persists to 0.03

5. **Vortex-liquid state is ground state below x_c**





Pre- and Post-amble

- Baskaran, Zou, Anderson (Sol. St. Comm. 1987)
- Doniach, Inui (PRB 1989)
- Uemura plot (Nature 1989)

- Emery, Kivelson (Nature 1995)
  low hole density and high Tc
  cuprates highly suscep. to phase fluctuations

- Corson, Orenstein (Nature 1999)
  Kinetic inductance meas. at THz freq extends above Tc
  KT physics in ultra-thin film BSCCO

- M. Franz and Z. Tesanovic (1999)
  Vortex-charge duality, QED3 model
- A. Vishawanath, Raghu (2006) *Simulation 2DXY*
- Sachdev (2007) *AdS-CFT duality technique*
- Tesanovic (2007) *Quantum vortices*

Vortex-liquid state at limit $T \to 0$

1. Large diamagnetism ($0.03 < x < 0.06$)

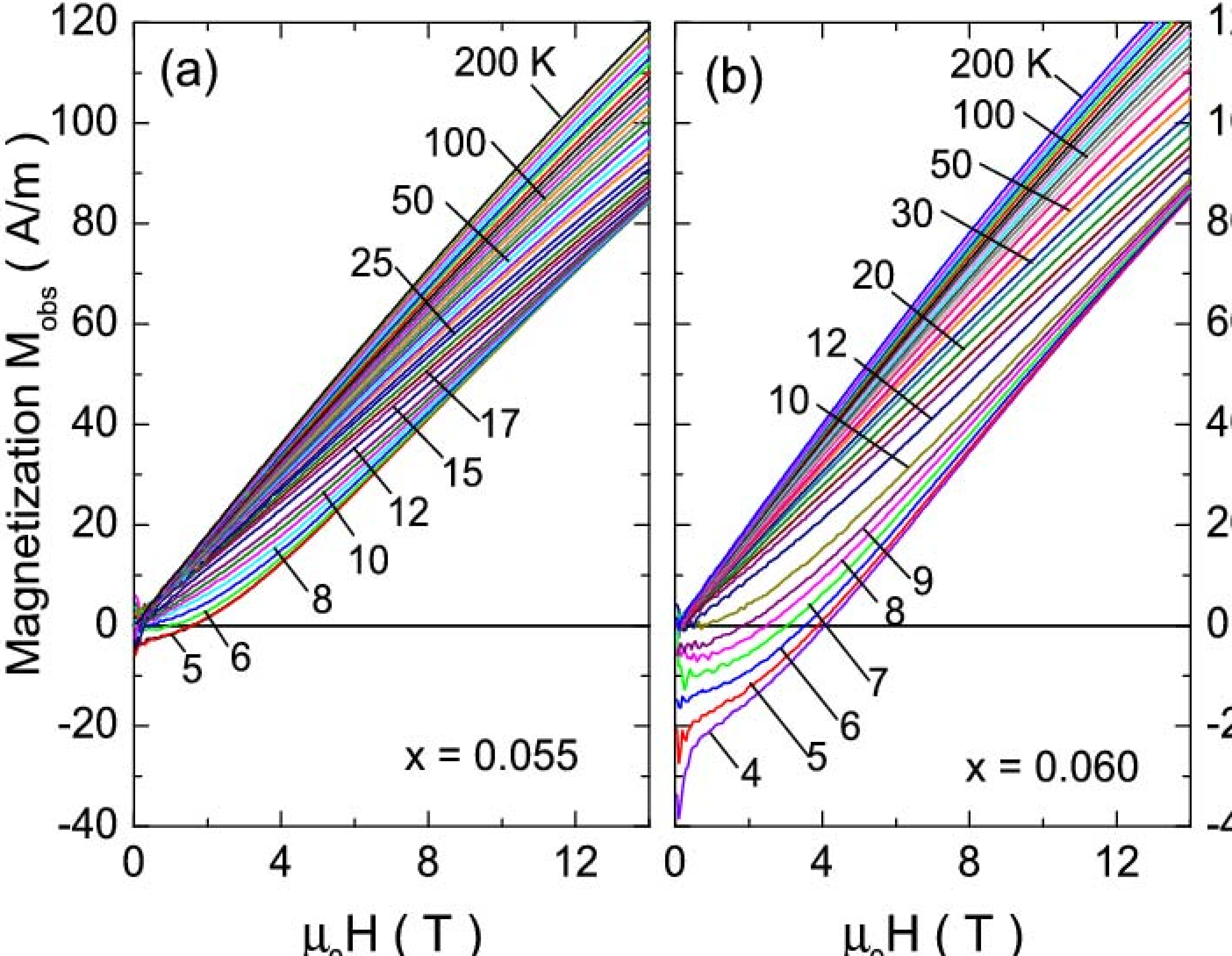
2. Electrically insulating (in LSCO)

3. Pairing energy (Hc2) very large

4. Pairing coexists with
   weak background paramag. moment (0.01 μ_B/cell)

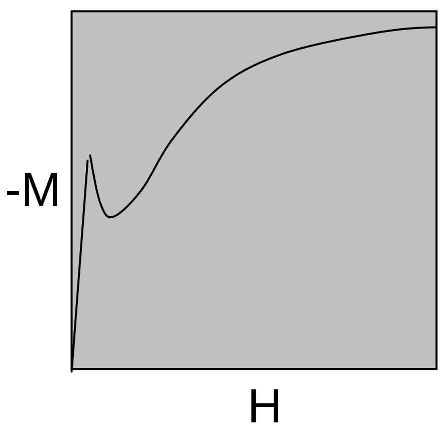
5. Long-range phase coherence transition vs x very sharp

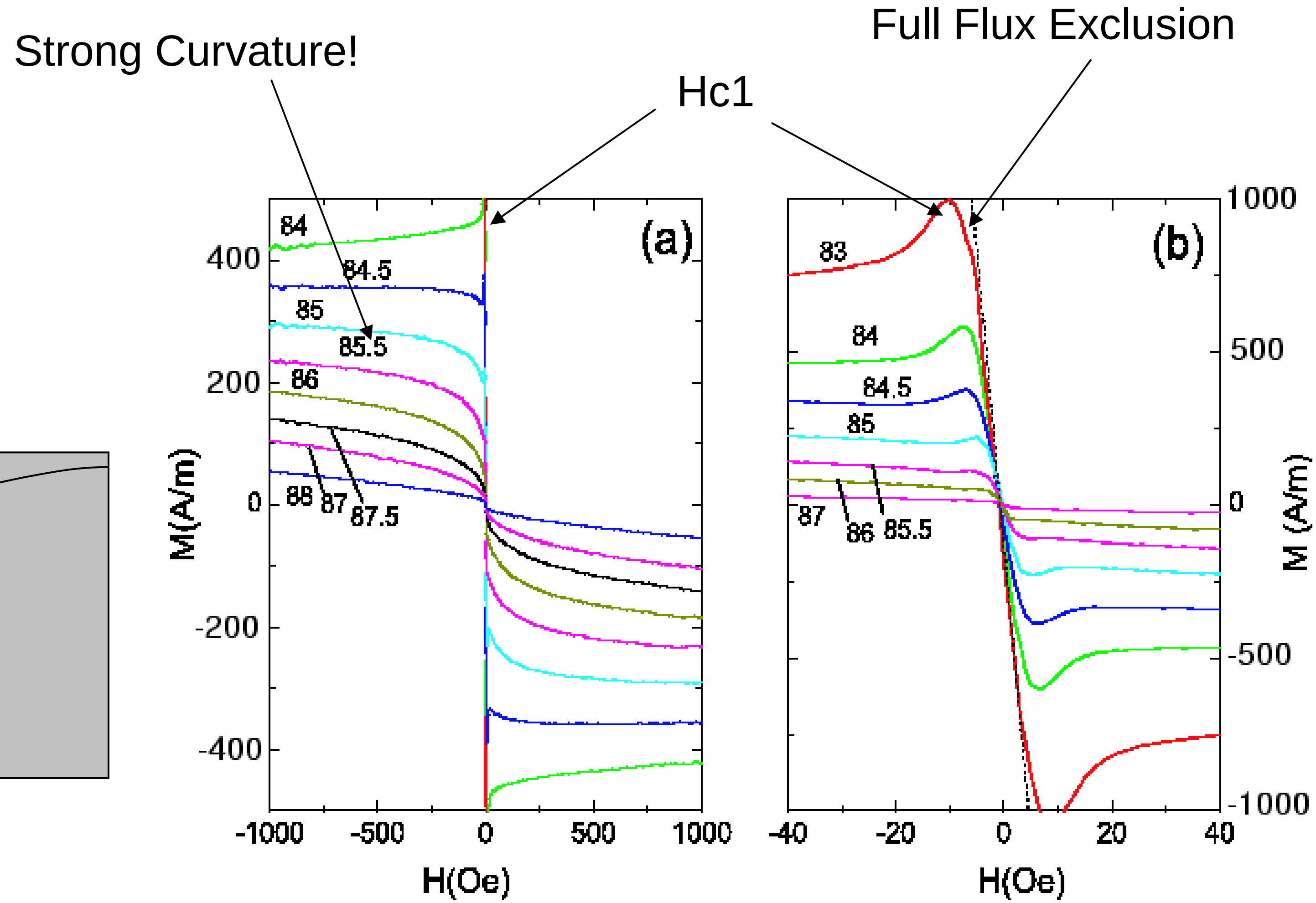
6. Incompatible with cluster of supercond. droplets


(a)
(b)
200 K
100
50
30
25
20
17
15
12
10
9
8
7
6
5
4
x = 0.055
x = 0.060
Magnetization M_obs (A/m)
μ0H (T)
μ0H (T)

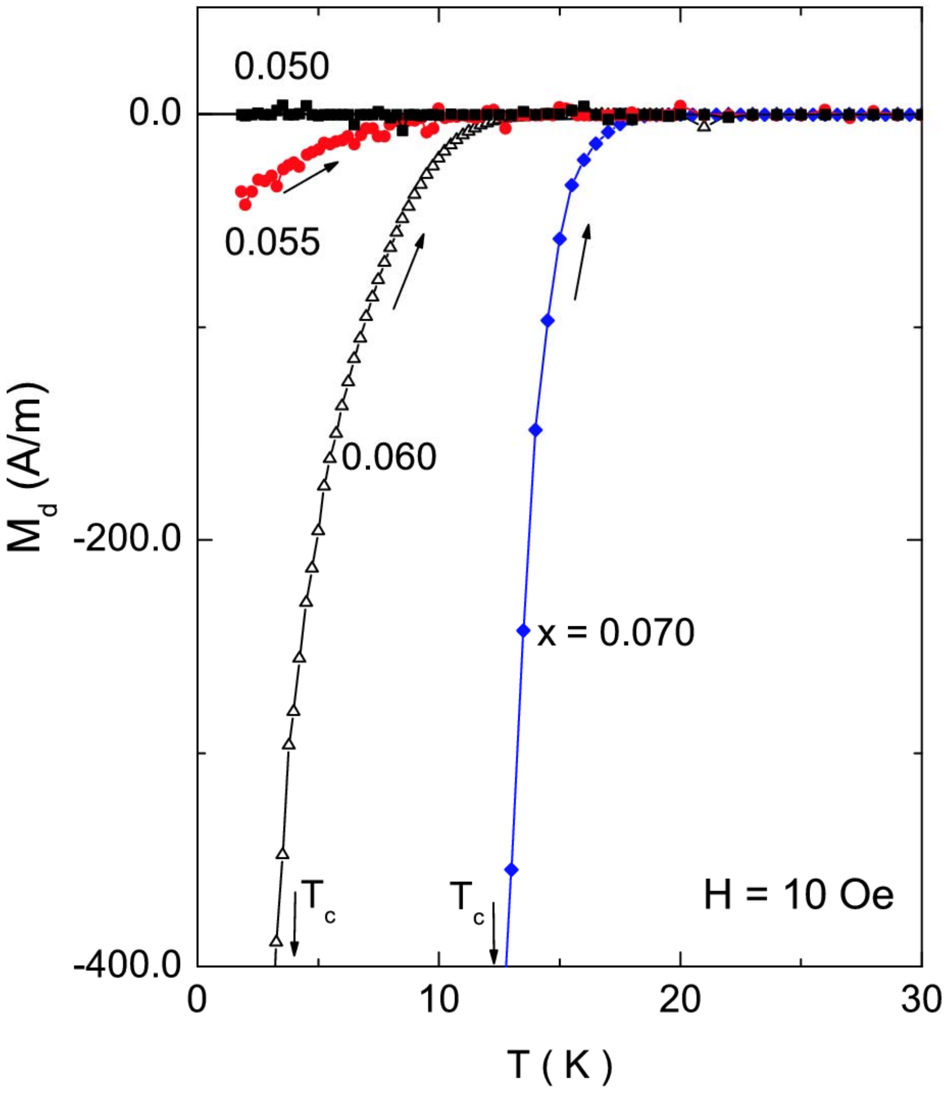
M vs H below Tc

Lu Li et al. Europhys Lett 2005

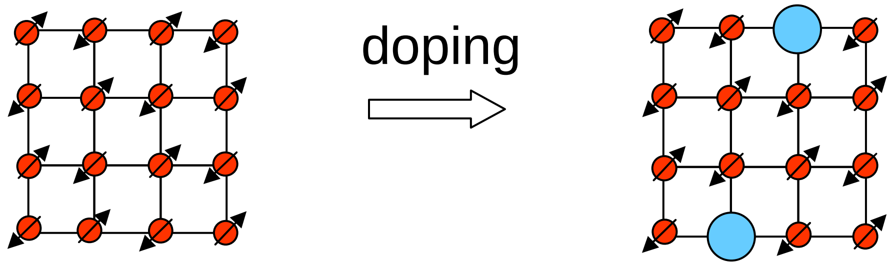




Meissner curves measured after zero-field cooling



Strong correlation in CuO_2 plane

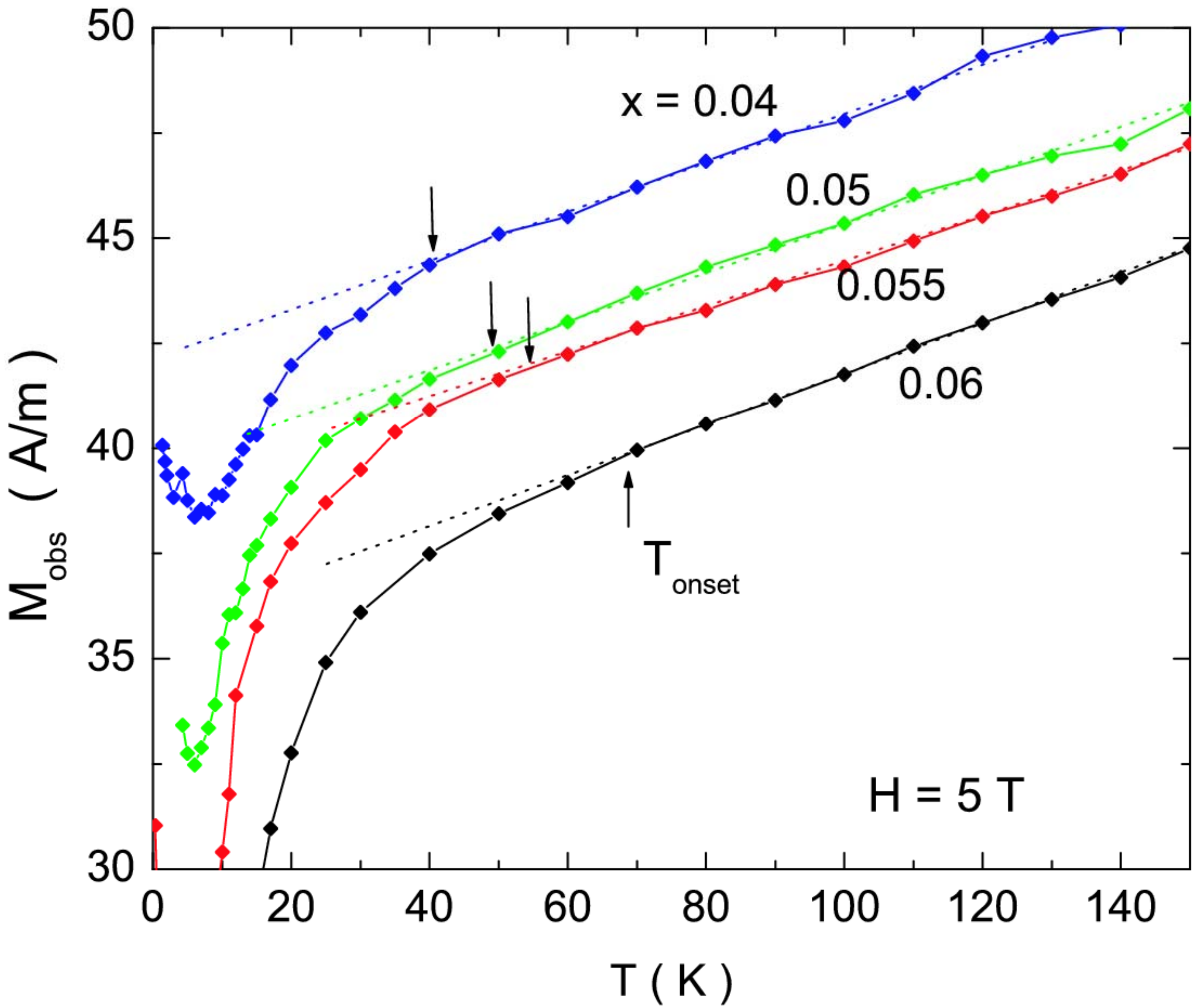


Hubbard

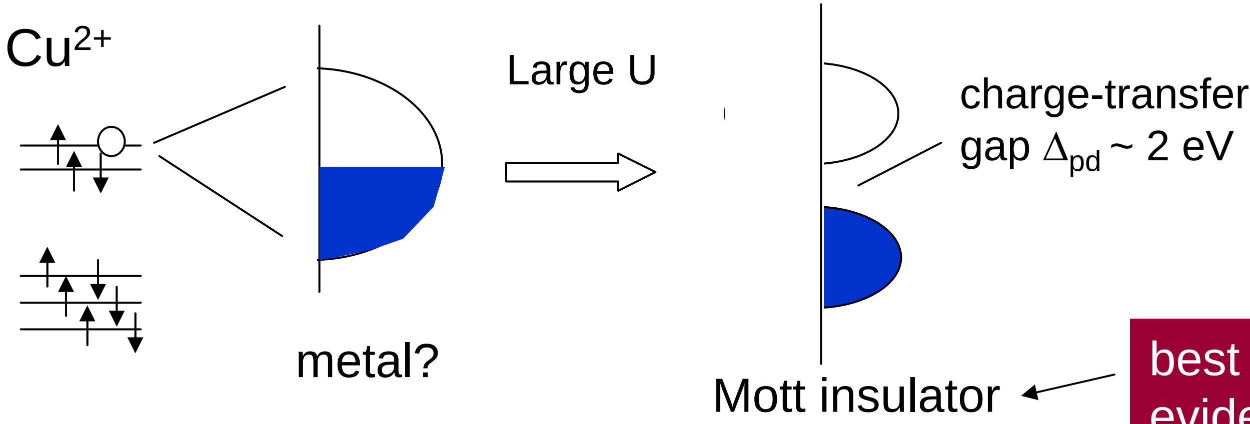
$$H = -t \sum_{i,j,\sigma} c^{+}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

t = 0.3 eV, U = 2 eV, $J = 4t^2/U$ = 0.12 eV

Onset of diamagnetic signal at 5 Tesla

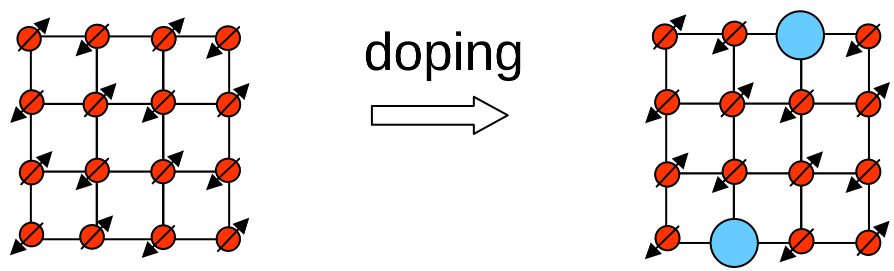


Strong correlation in CuO_2 plane



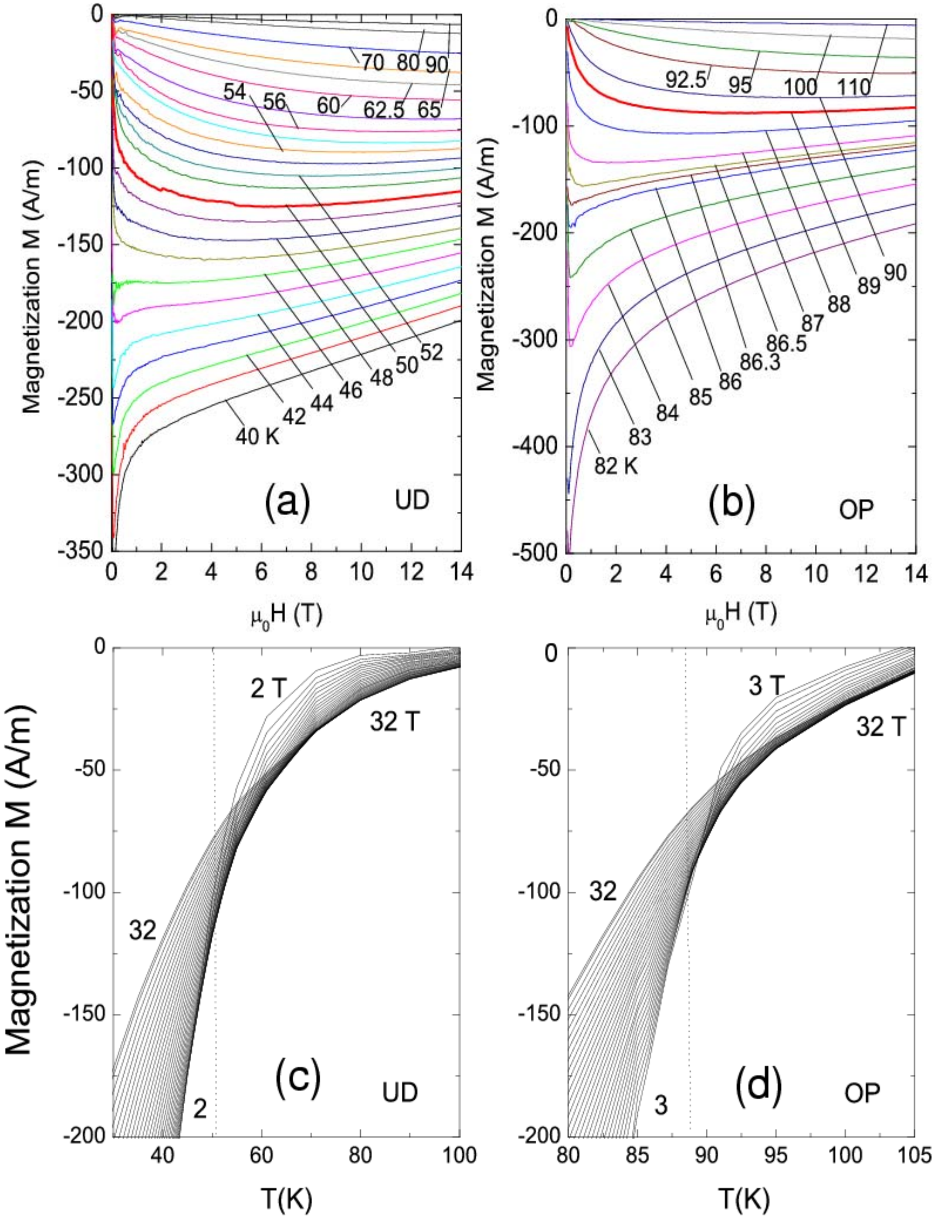
best evidence for large U

antiferromagnet   J~1400 K

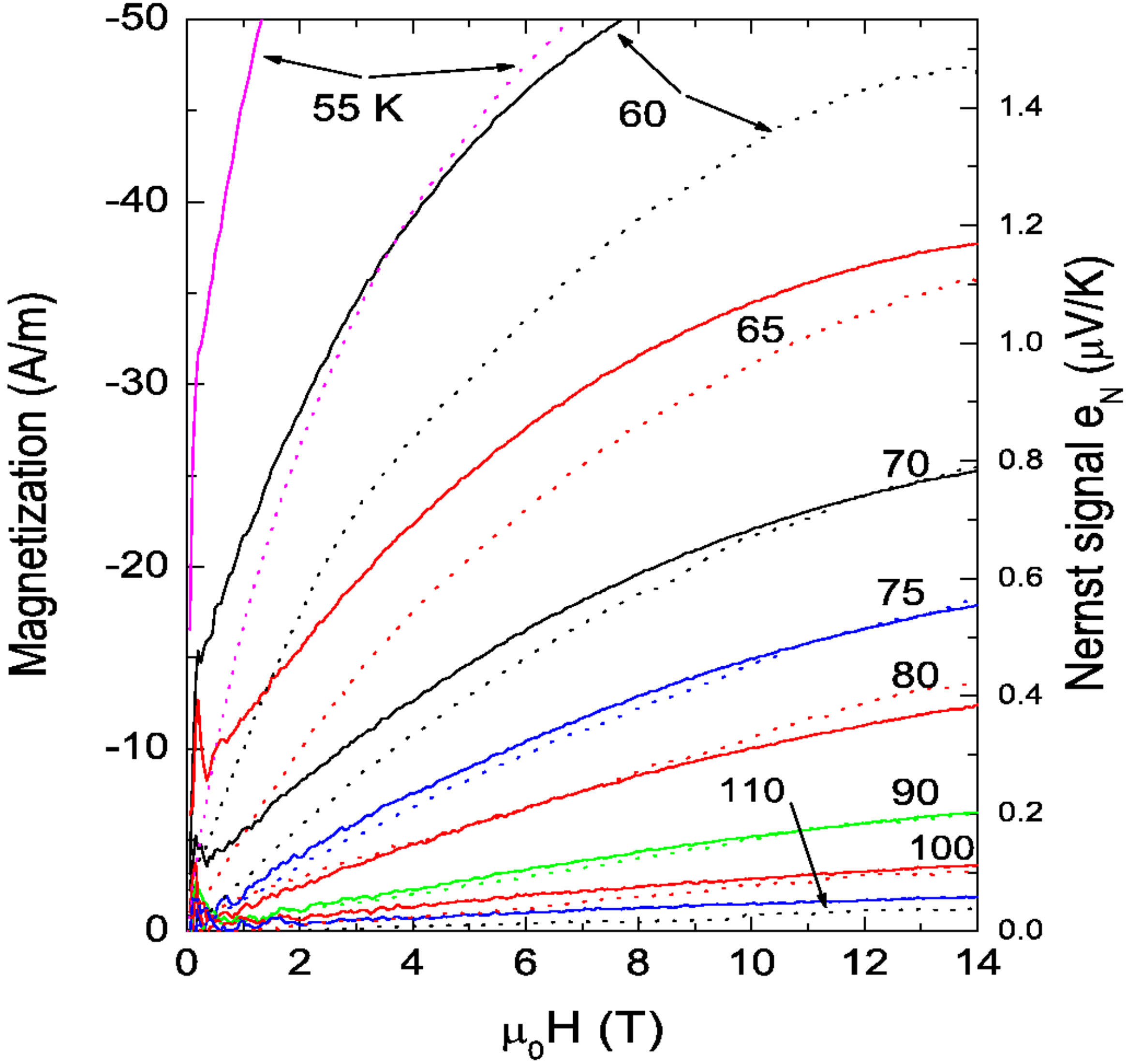


$$H = -t \sum_{i,j,\sigma} c^{+}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ Hubbard

t = 0.3 eV, U = 2 eV, $J = 4t^2/U$ = 0.12 eV

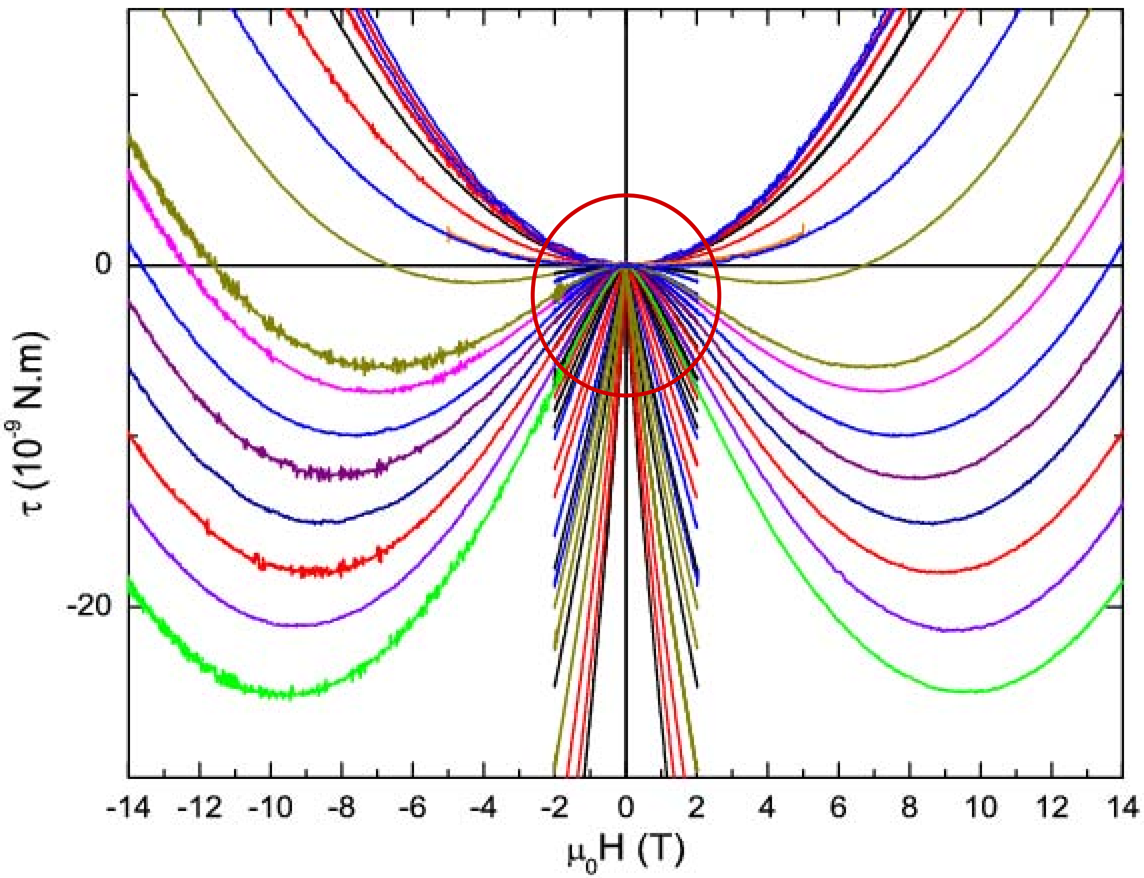


Magnetization M (A/m)
μ0H (T)
70
80
90
92.5
95
100
110
54
56
60
62.5
65
52
50
48
46
44
42
40 K
90
89
88
87
86.5
86.3
86
85
84
83
82 K
(a)
UD
(b)
OP
Magnetization M (A/m)
T(K)
2 T
32 T
32
2
3 T
3
(c)
UD
(d)
OP



M(T,H) matches e_N in both H and T above T_c

Non-analytic magnetization



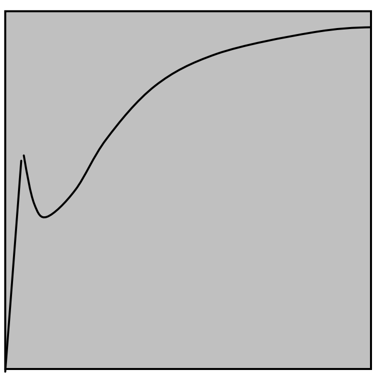
M vs H below Tc

Strong Curvature!

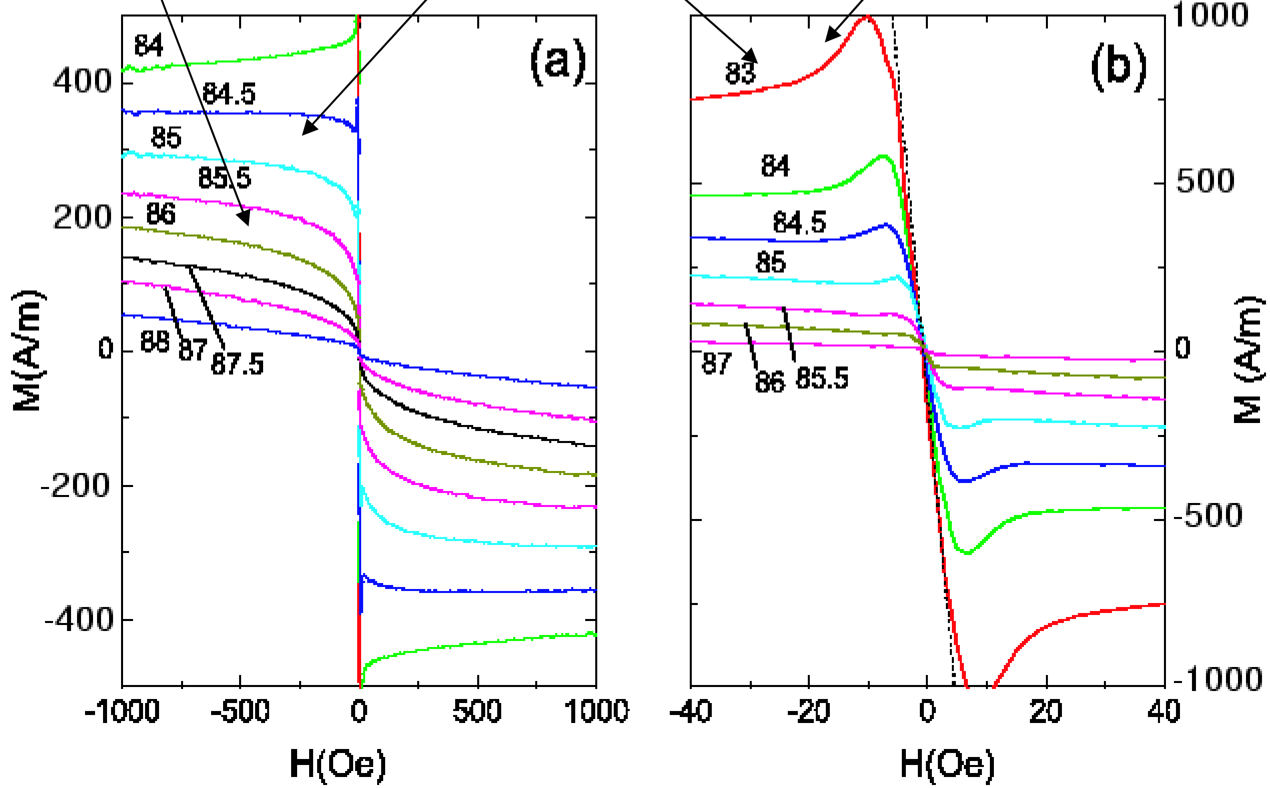
Hc1

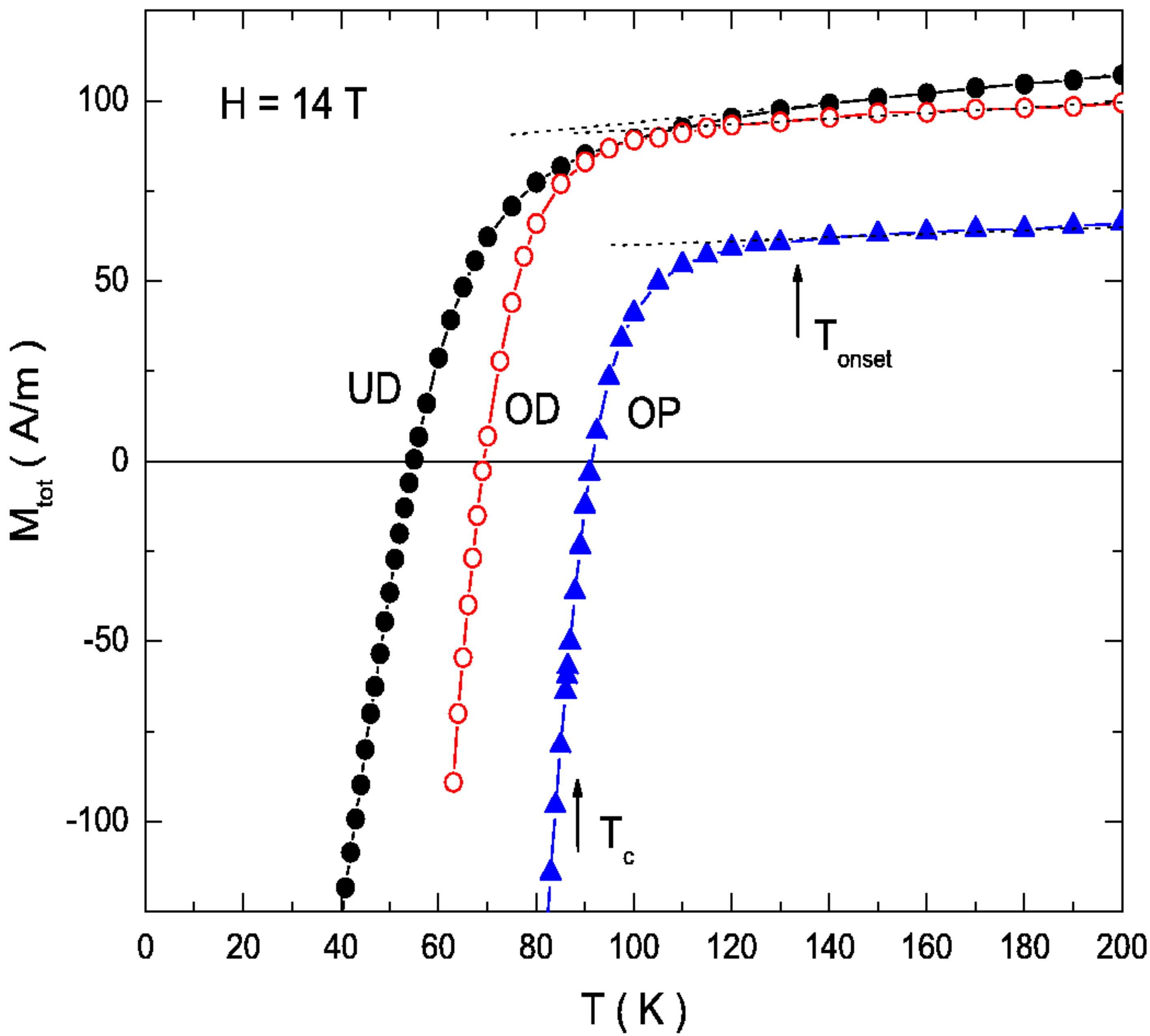
Full Flux Exclusion

-M



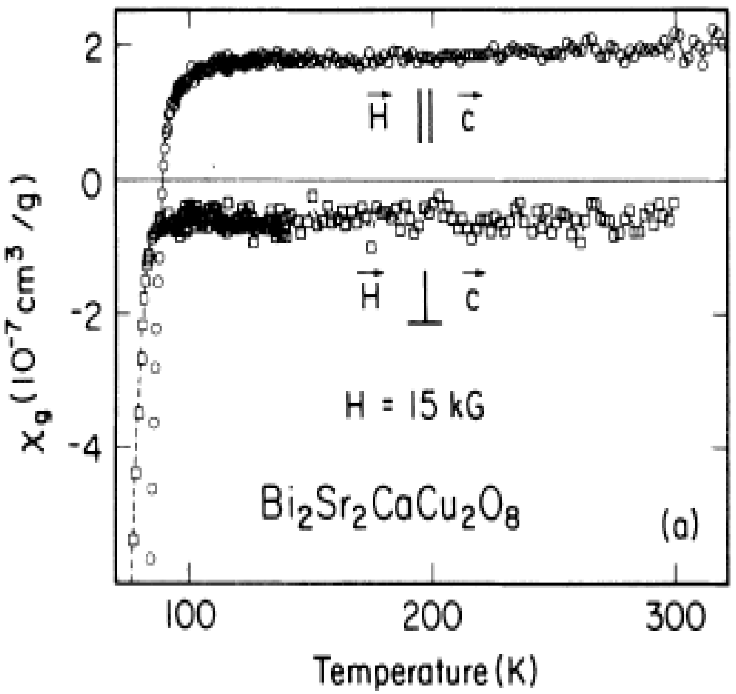
H



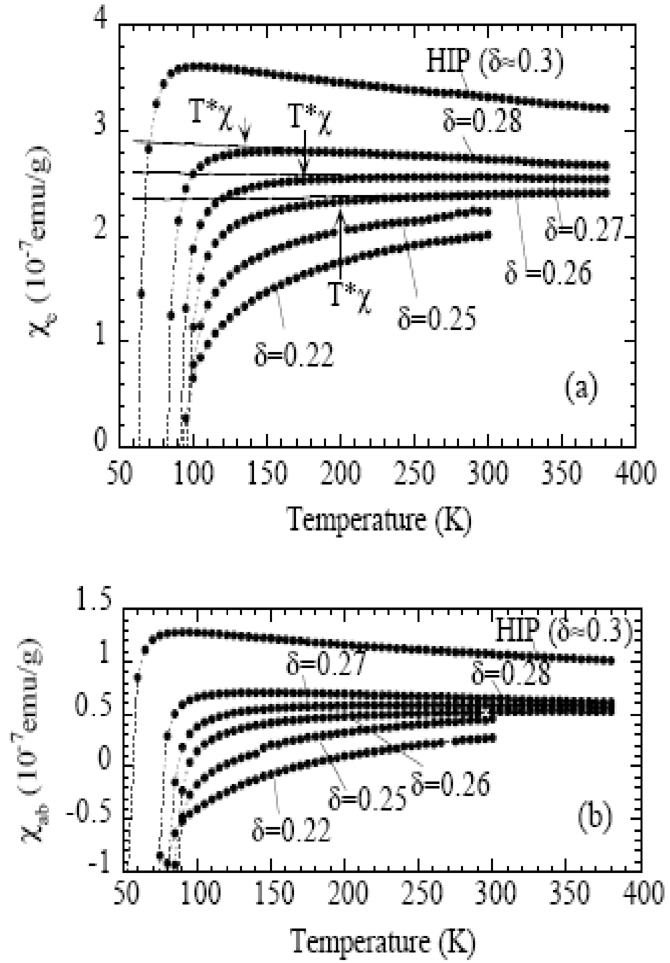


H = 14 T
UD
OD
OP
T onset
T c
M tot (A/m)
T (K)
100
50
0
-50
-100
0
20
40
60
80
100
120
140
160
180
200

Direct measurements of uniform susceptibility χ_c and χ_{ab}

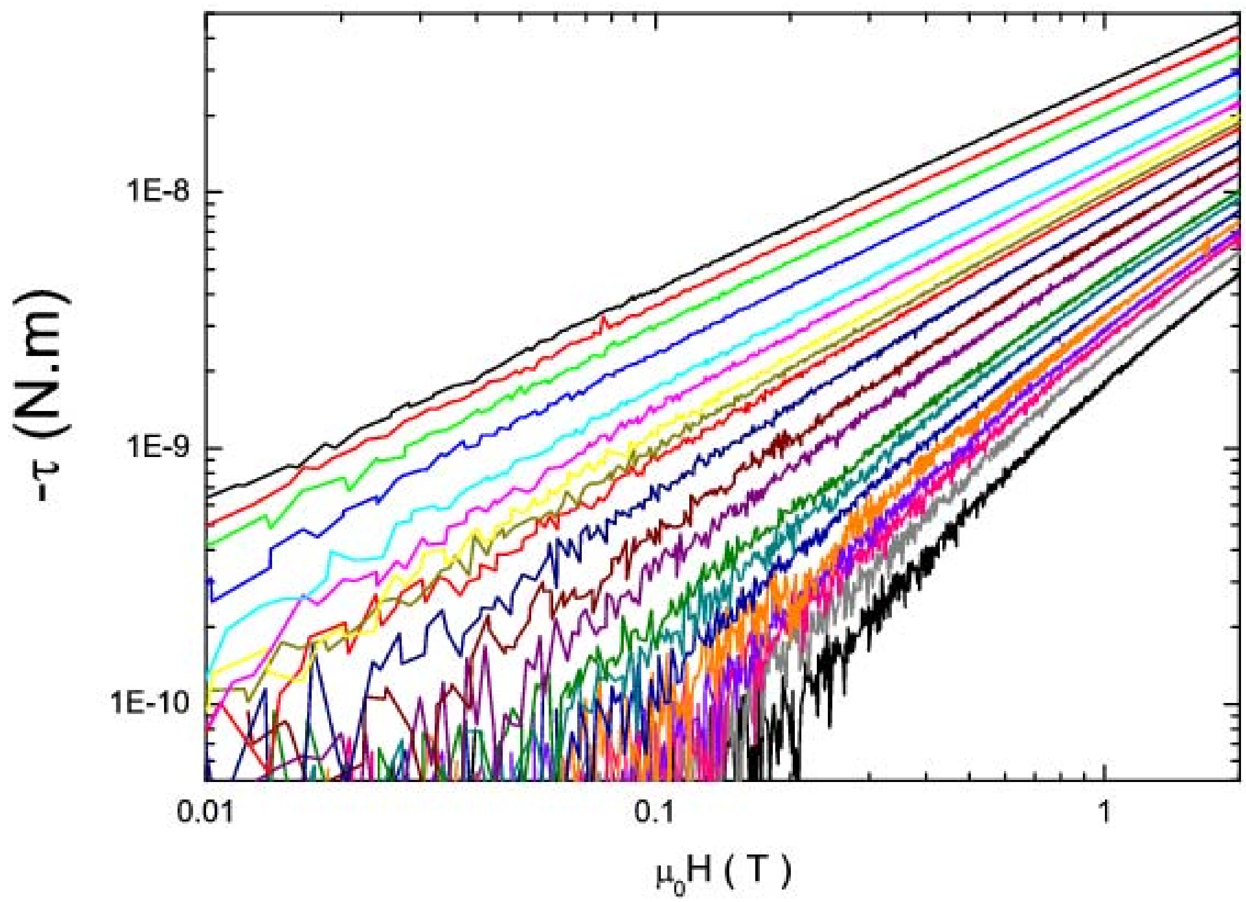


Johnston Cho, Phys Rev. B 1990

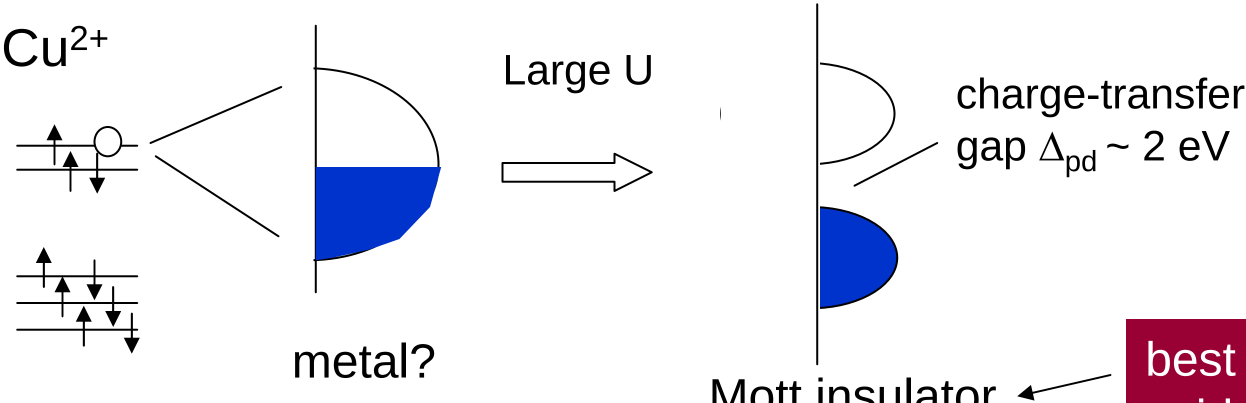


Watanabe, Fujii, Matsuda, PRL 2000

Torque $\tau = A' H^{1+\alpha}, \ (\alpha < 1)$



Strong correlation in CuO_2 plane



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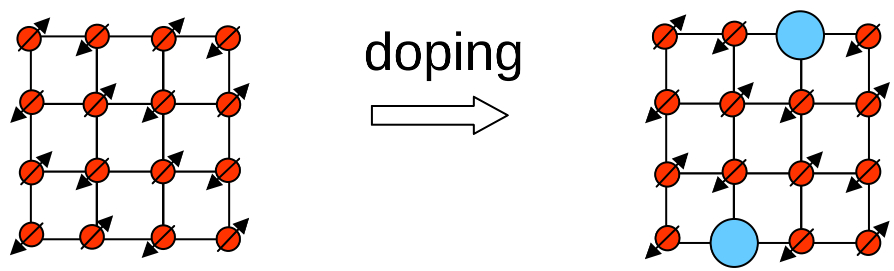

$$H = -t \sum_{i,j,\sigma} c^{+}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ Hubbard

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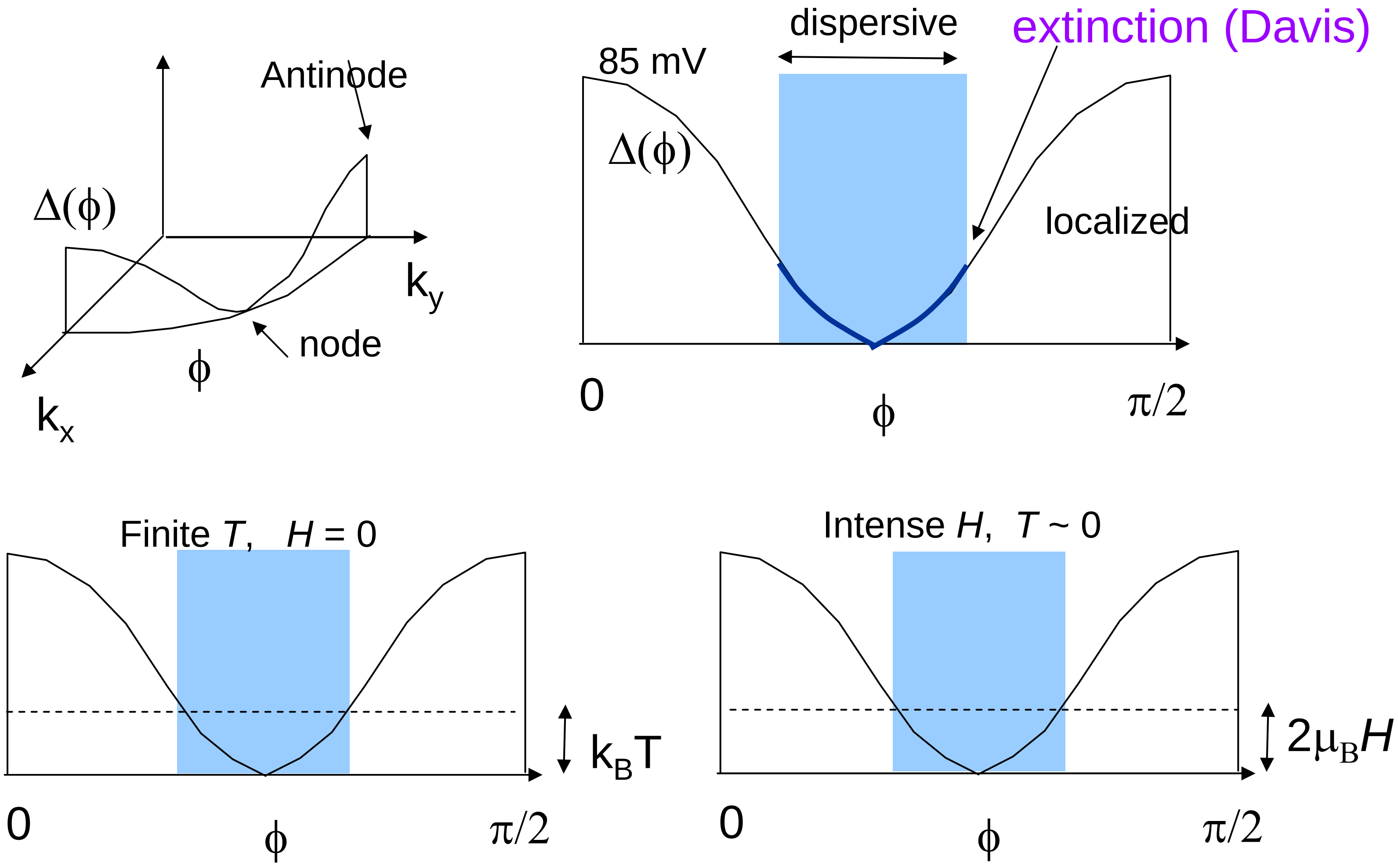
Selective gap suppression in d-wave



At field H_{c2} (or T_{onset}), pairs in dispersive region destroyed. Gap in antinode region survives.