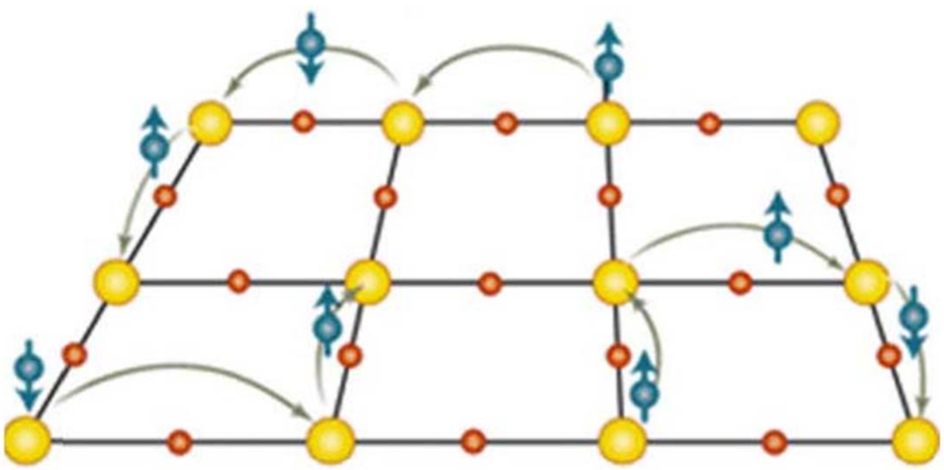
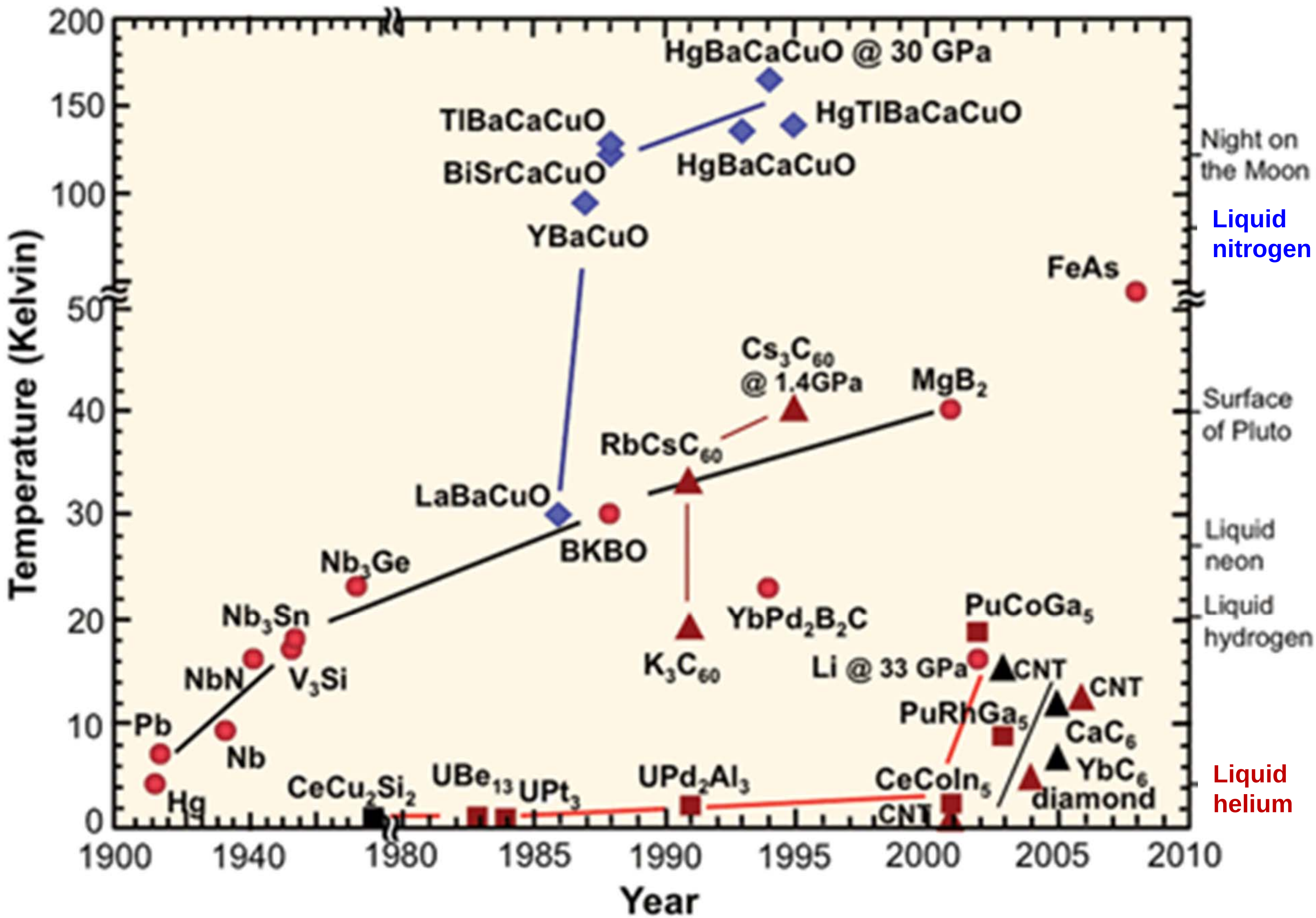
Superconductivity II
(Unconventional Superconductors)

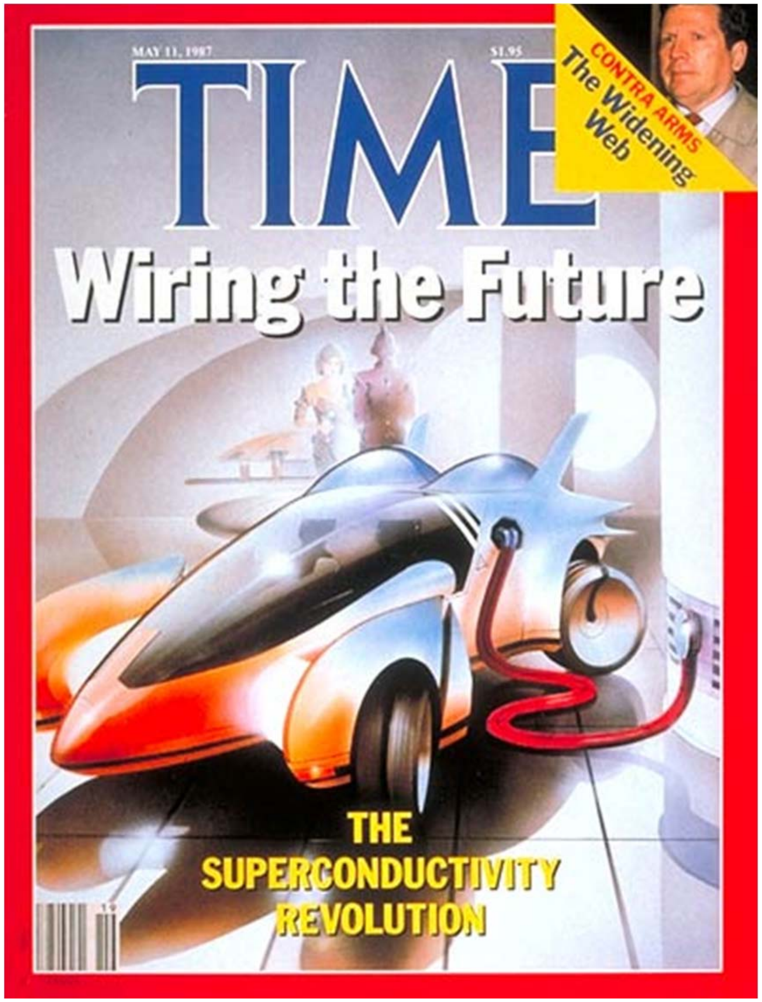
Jeff Sonier
Simon Fraser University



History of Superconductivity



Discovery of High-T_c Superconductivity



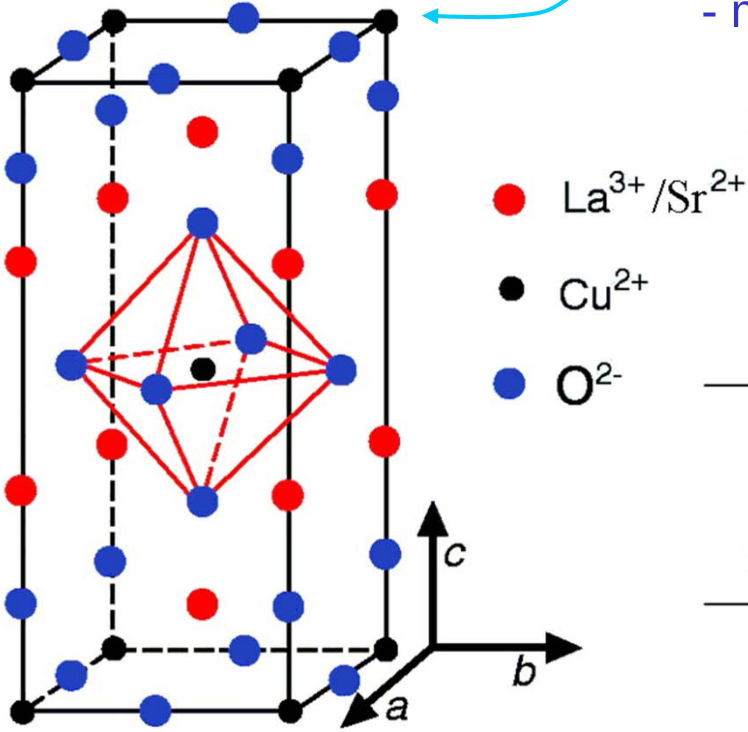
Time Magazine May 11, 1987

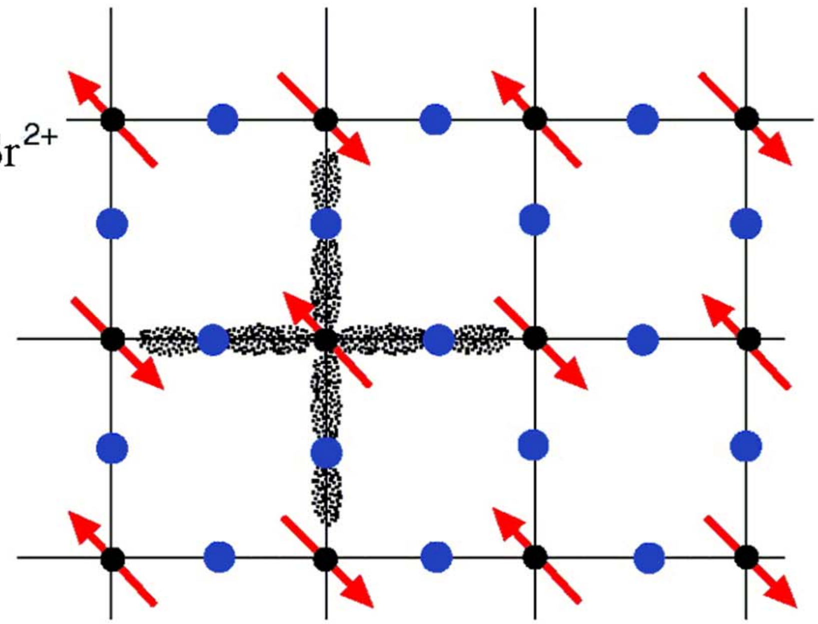
GM advertisement April, 2009

High-T_c Cuprates

$La_{2-x}Sr_xCuO_4$

CuO_2 planes are generic ingredient
- superconductivity is quasi-2D
- magnetism associated with Cu spins



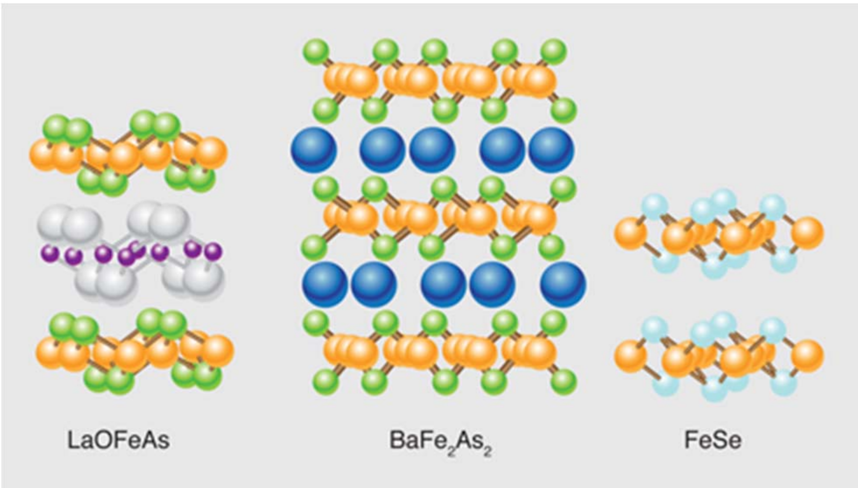


Antiferromagnet → **Superconductor**

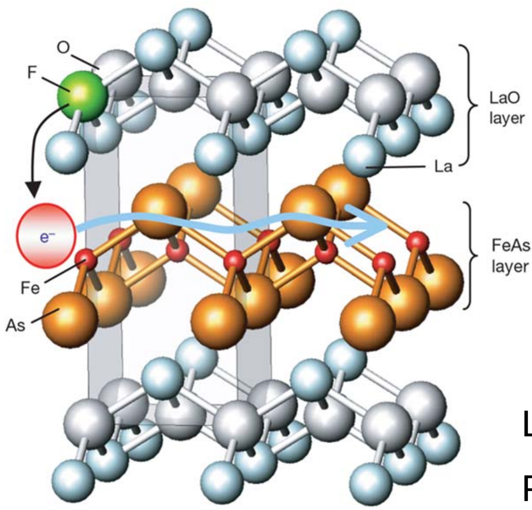
Hole doping by cation substitution or oxygen doping

2008: Beginning of the Iron Age

Science **Top 10 Breakthroughs of the Year**
Discovery of iron–based high-T_c superconductors
Y. Kamihara *et al.*, J. Am. Chem. Soc. **130**, 3296 (2008)



Many chemical substitutions are possible.

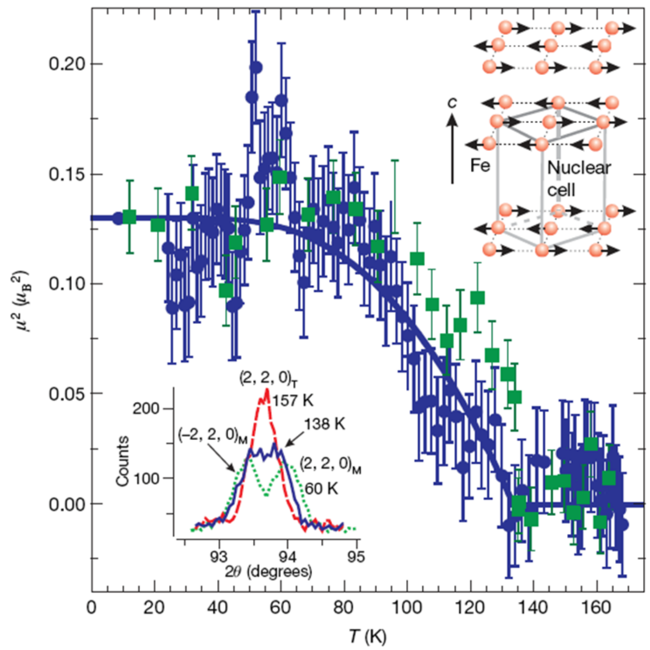


$LaO_{1-x}F_xFeAs$ T_c = 26 K

$PrO_{1-x}F_xFeAs$ T_c = 55 K

They have **layered** structures & exhibit **antiferromagnetic order** like high-T_c cuprates.

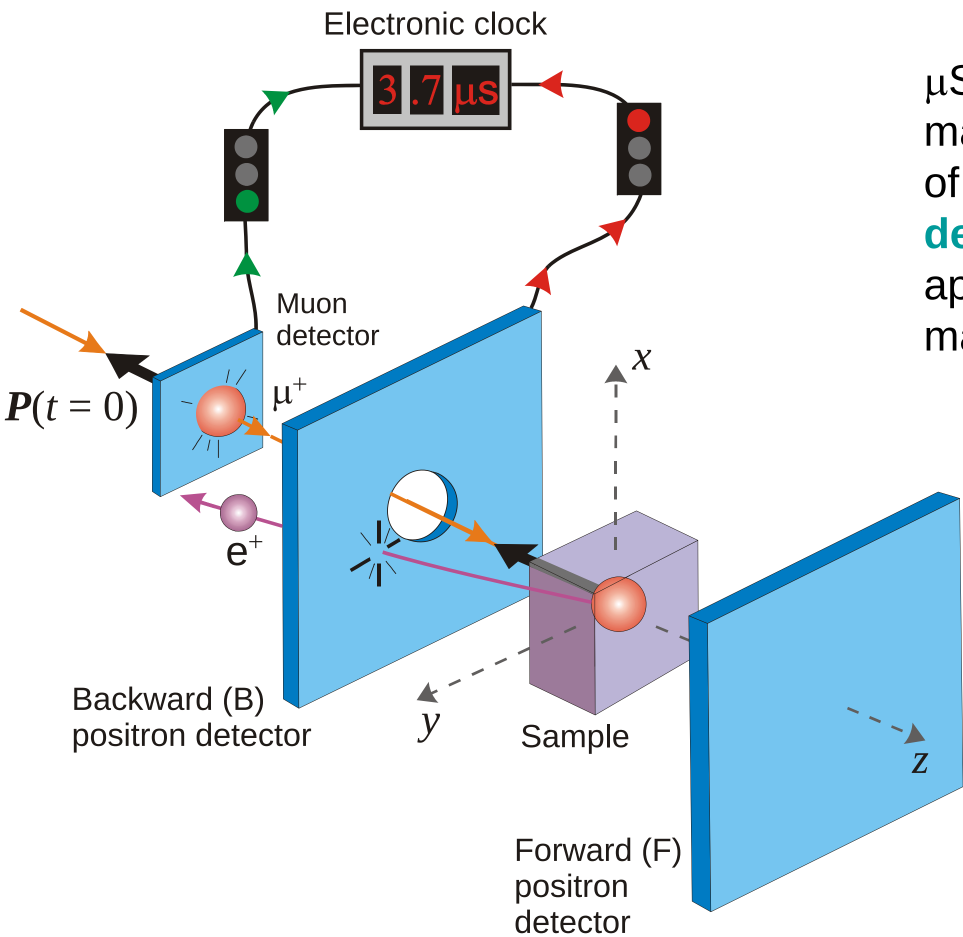
Long-range SDW order in LaOFeAs



de la Cruz *et al.* Nature **453**, 899 (2008)

Structural transition (from tetragonal to orthorhombic or monoclinic) at T_c~150K and a magnetic transition at T_c~134K
Fe moment = 0.36 μ_B : VERY SMALL!

Zero-Field μSR



μSR is an **extremely sensitive** probe of internal magnetism due to the large **gyromagnetic ratio** of the μ^+ (*Note:* γ_μ **= 3.17** γ_H), the method for **detecting** the muon spin polarization, and its applicability in the **absence** of an external magnetic field.

The muon is sensitive to the **vector sum** of the local magnetic fields at its stopping site:

- from **nuclear** dipole fields (~ 0.1 G)
- from **electronic** moments (100-1000 times larger than from nuclear moments)
- from **external** magnetic fields

The **count rates** for opposing e^+ detectors:

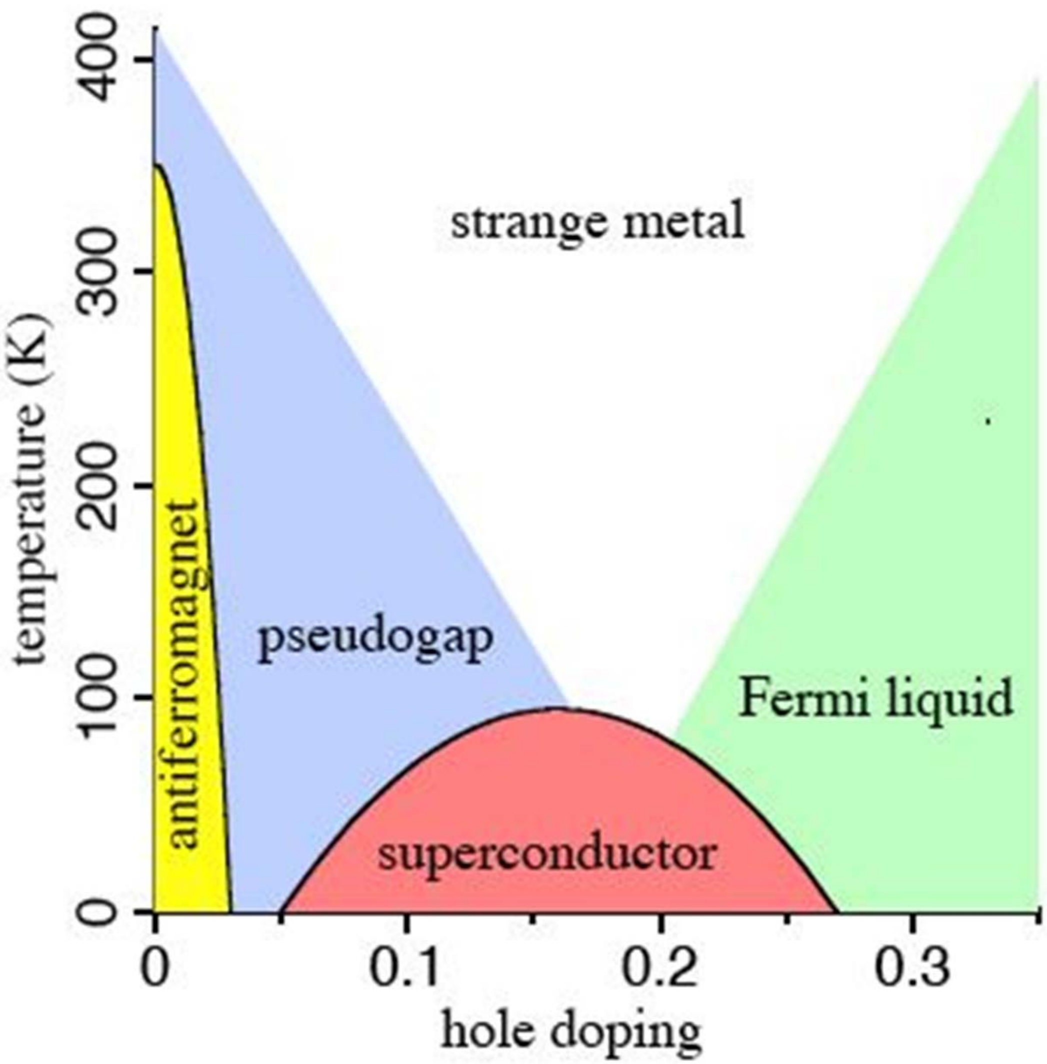
$$N_B(t) = N_0 e^{-t/\tau_\mu}\left[1 + a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

$$N_F(t) = N_0 e^{-t/\tau_\mu}\left[1 - a_0 G(t)\cos(\gamma_\mu B_\mu t + \Phi)\right]$$

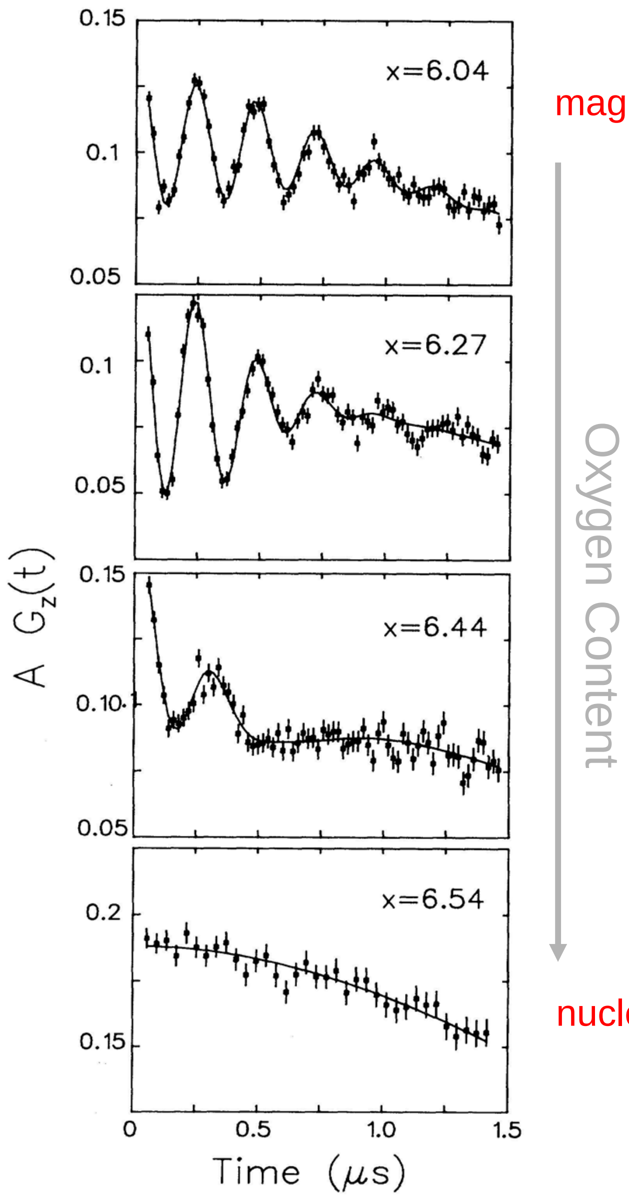
I. Magnetism in Zero External Field

(underdoped cuprates/iron arsenics)

Generic Cuprate Phase Diagram

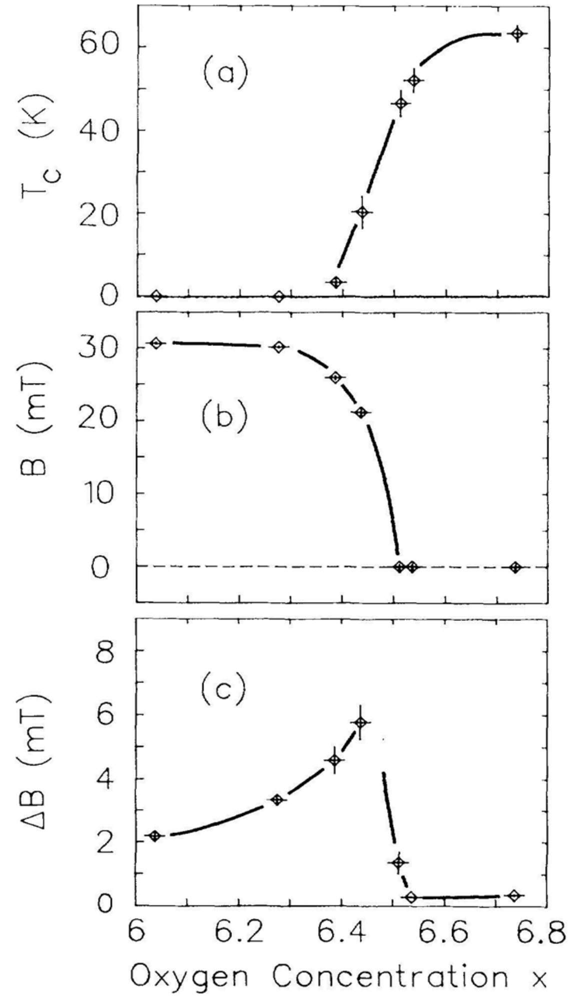


ZF-μSR on underdoped $YBa_2Cu_3O_{6+x}$



magnetic order

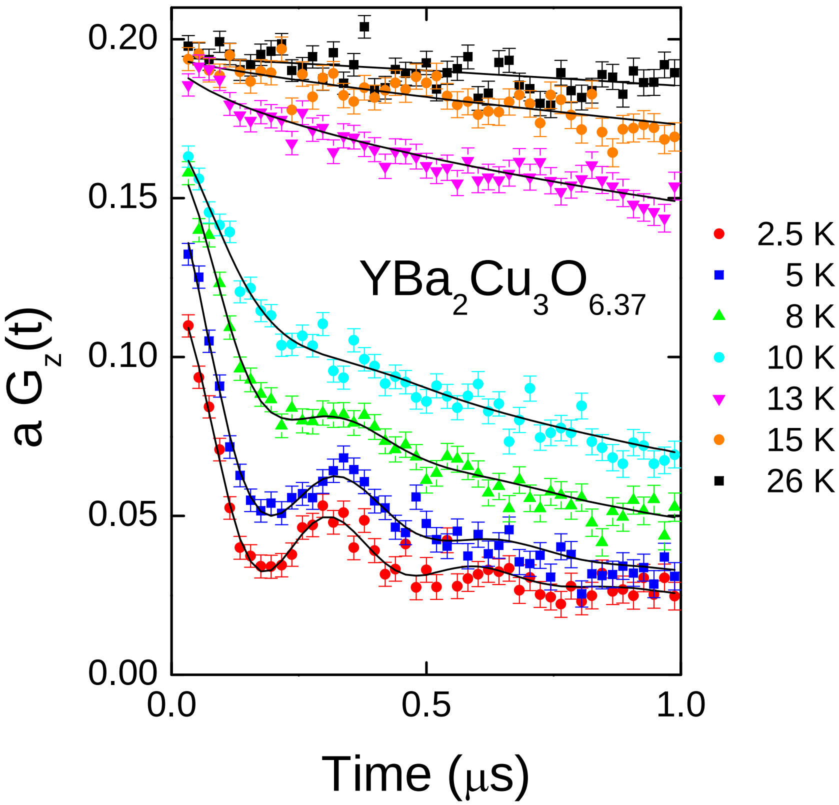
nuclear dipoles

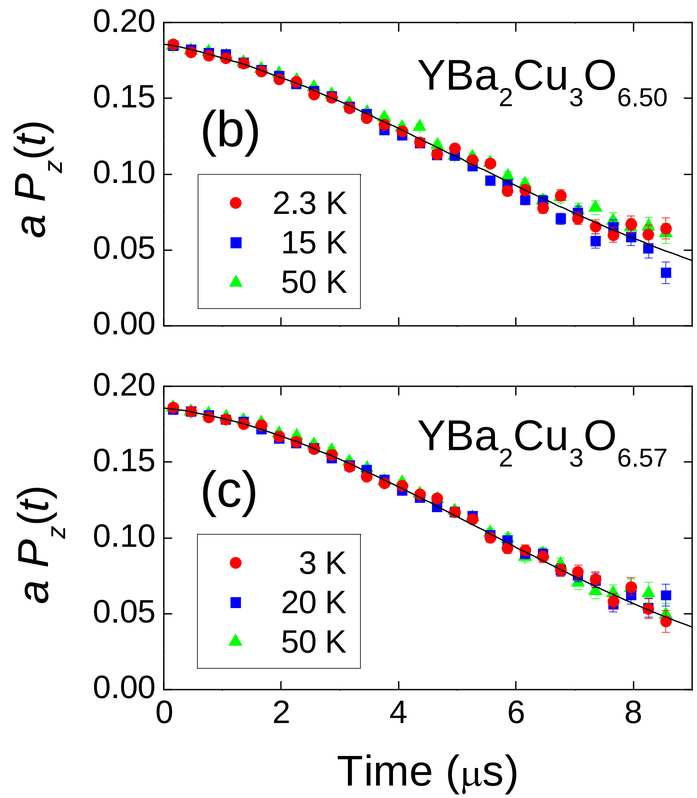


R.F. Kiefl *et al.*, Phys. Rev. Lett. **63**, 2136 (1989)

$$G_z(t) = \frac{1}{3} + \frac{2}{3}\exp[-\frac{1}{2}(\gamma_\mu \Delta B t)^2]\cos(\gamma_\mu B t)$$

lightly doped ⟷ higher doped





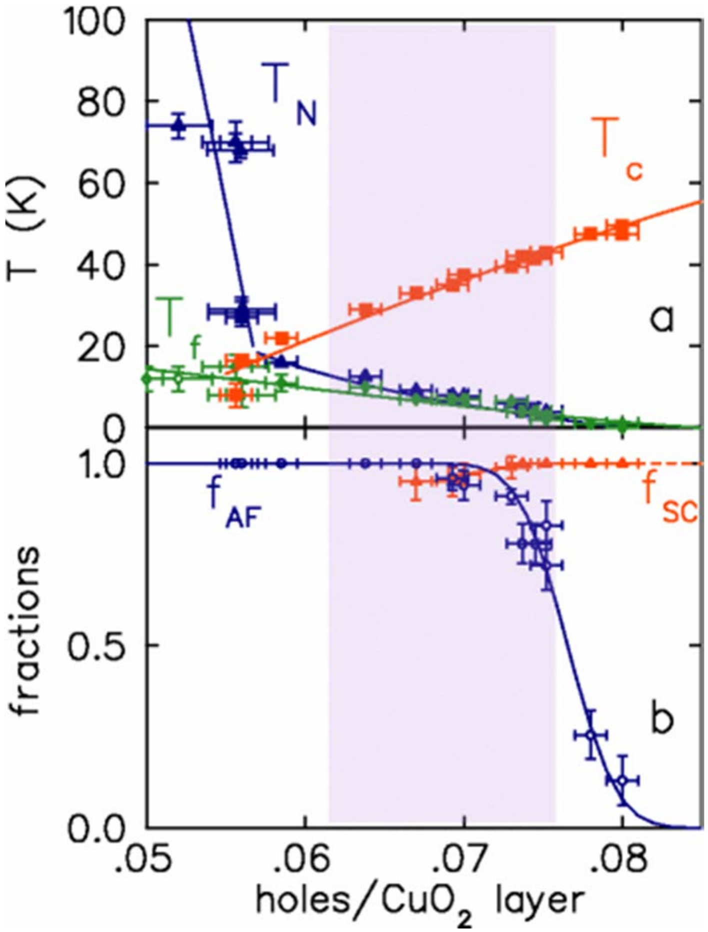
Short-range static AFM correlations

- 100% of the muons experience both spin freezing and superconductivity

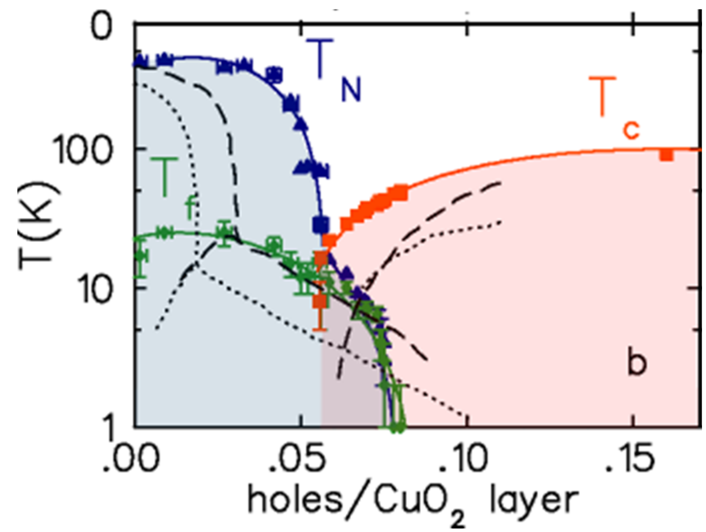
⇒ **nanoscale coexistence**

Nuclear dipoles only

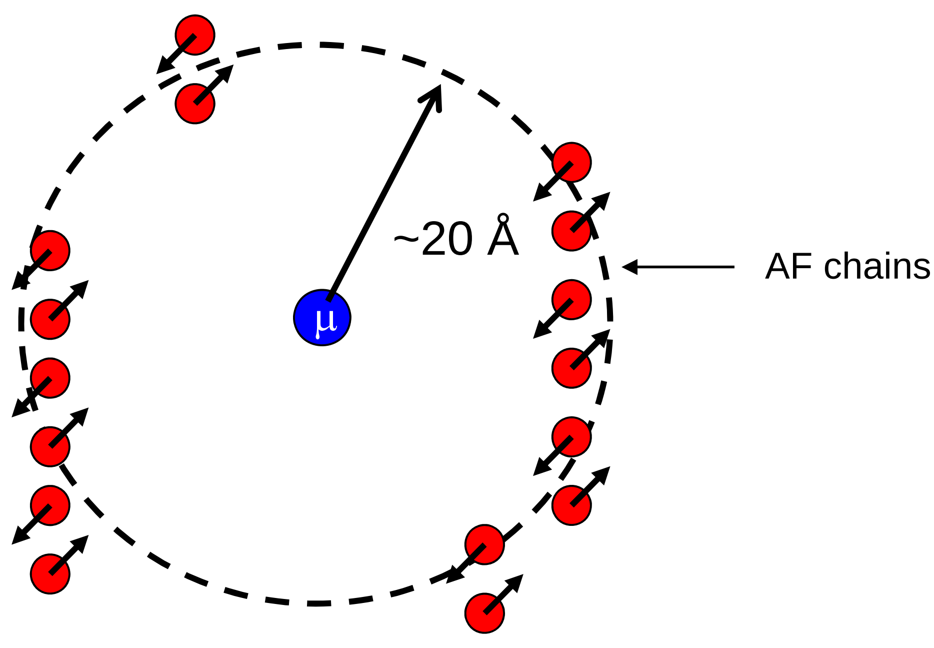
- dynamic AFM correlations too fast on μSR time scale



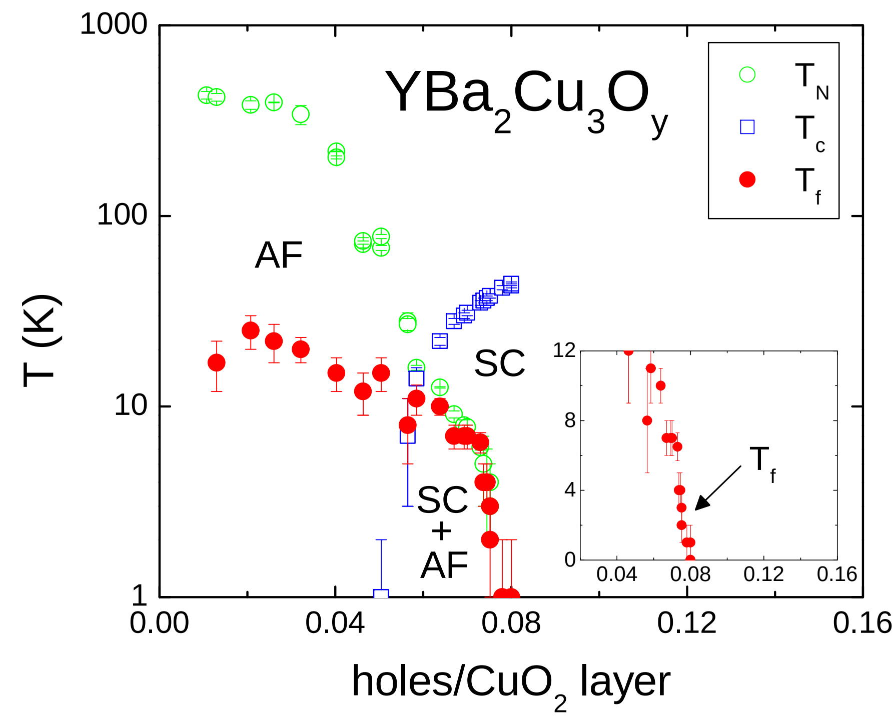
S. Sanna *et al*. PRL **93**, 207001 (2004)

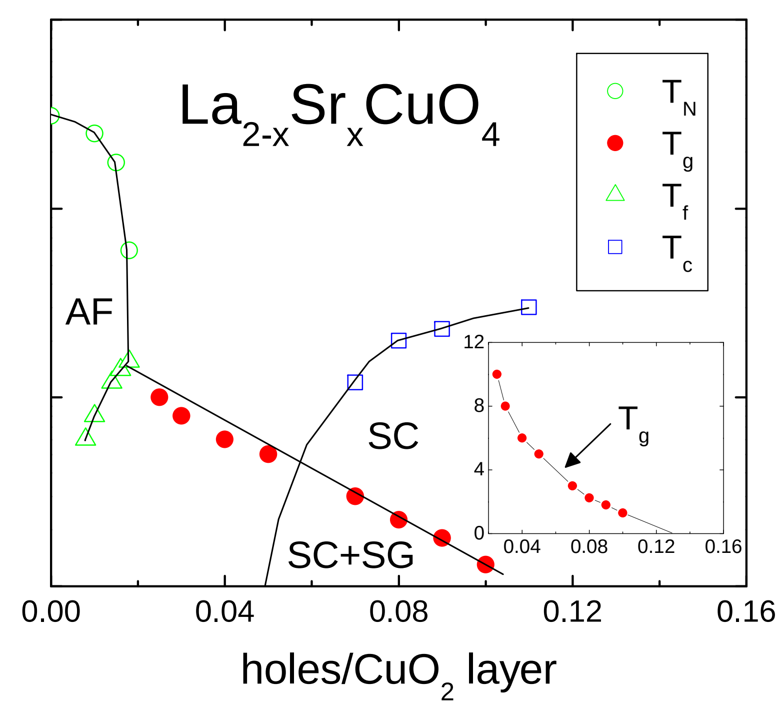


Coexistence of AF and SC on a nanometer scale



ZF-μSR measurements on different families of cuprates show that static Cu moments **coexist** with superconductivity in highly underdoped samples.



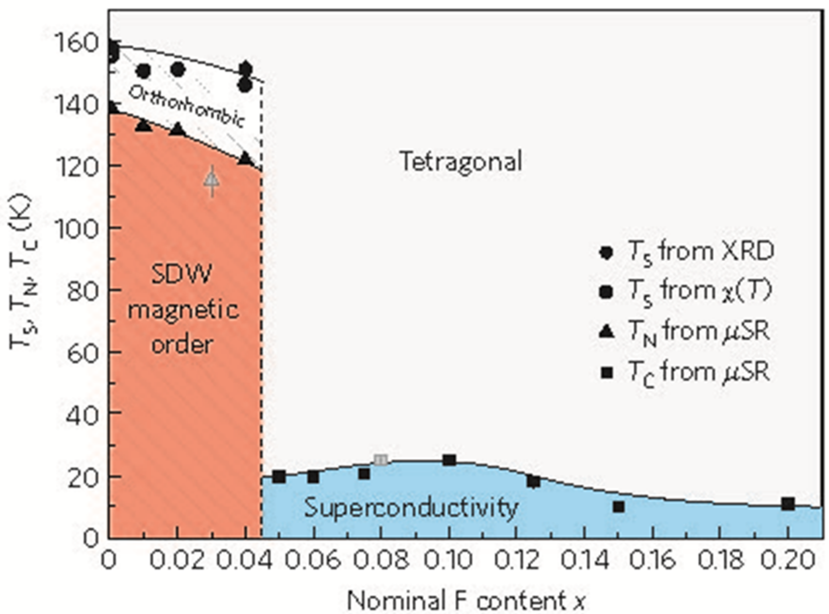


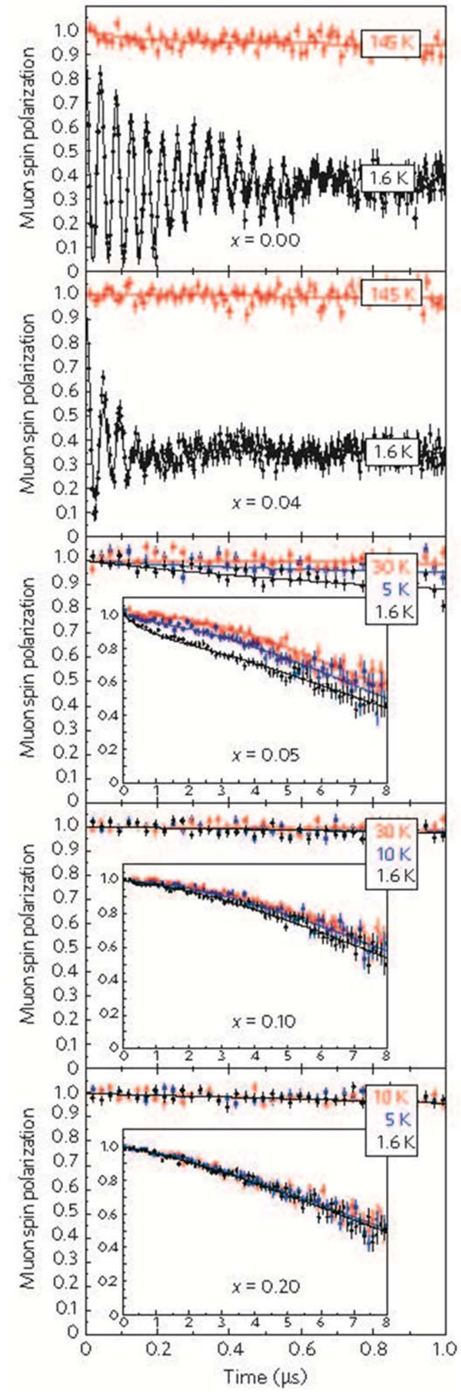
S. Sanna *et al*. PRL **93**, 207001 (2004)

Ch. Niedermayer *et al*. PRL **80**, 3843 (1998)

ZF-μSR on $LaO_{1-x}F_xFeAs$

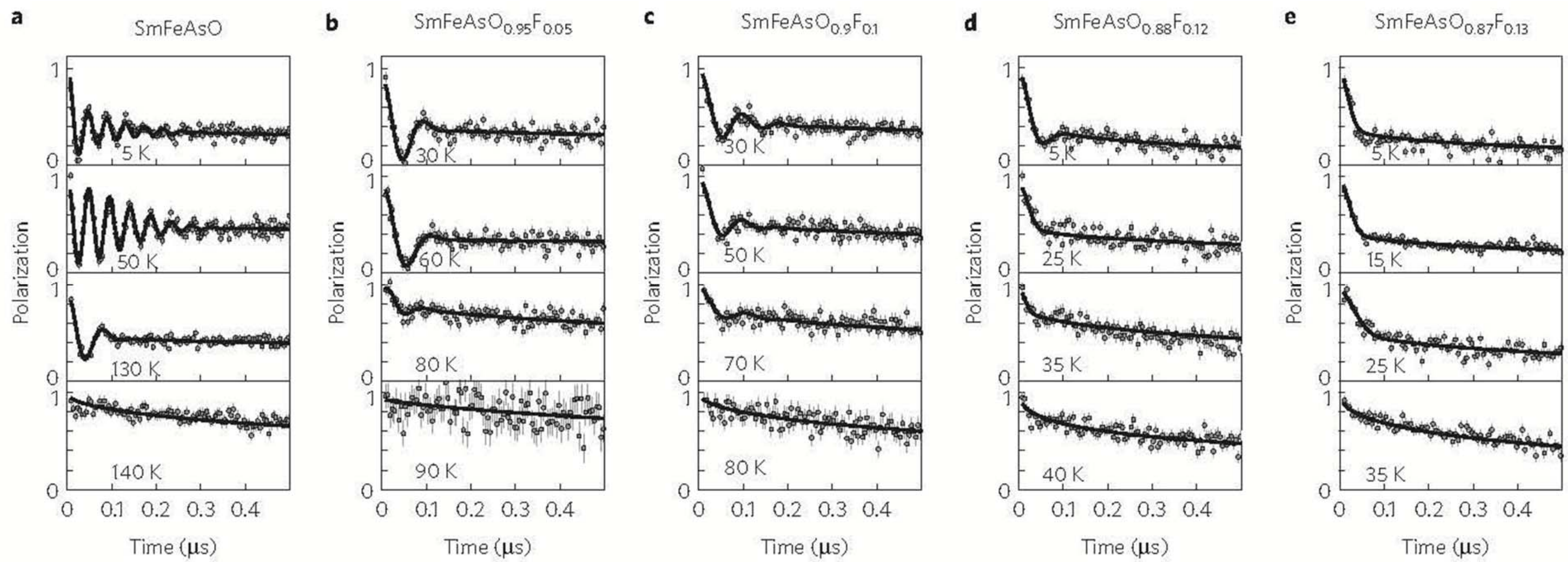
Static magnetism in close
proximity to superconductivity

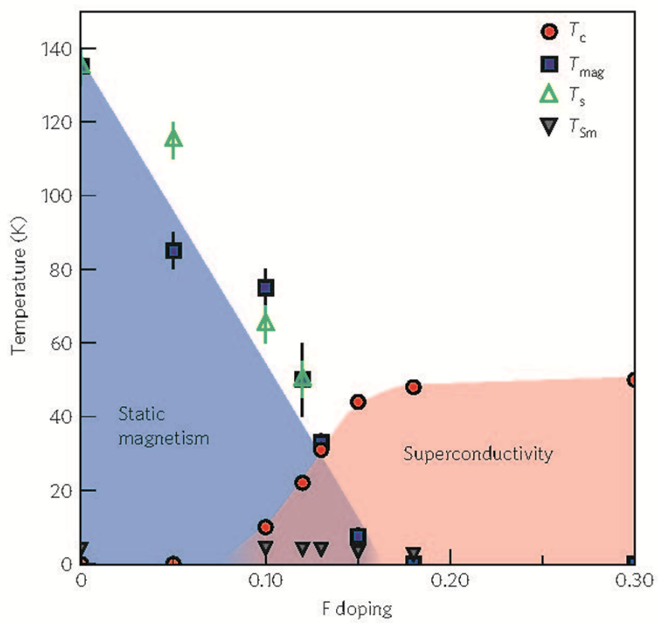




H. Luetkens *et al.*, Nature Materials **8**, 305 (2009)

ZF-μSR on $SmFeAsO_{1-x}F_x$



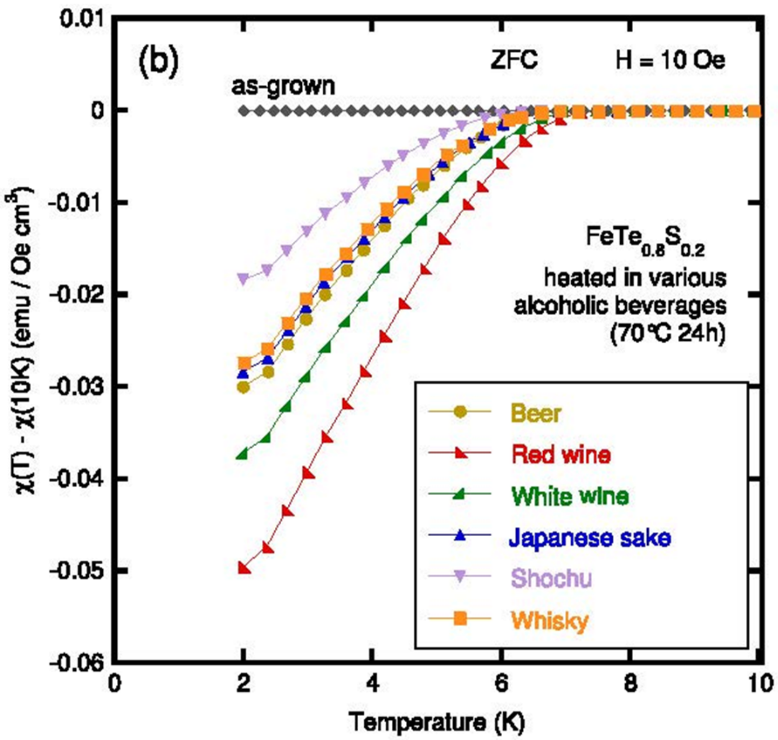


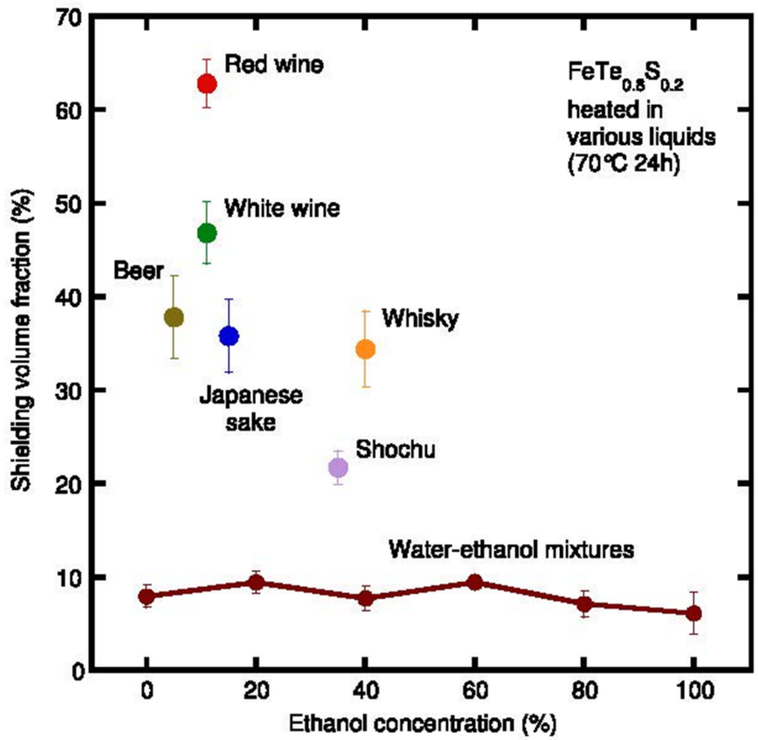
Coexistence of static magnetism and superconductivity

A. Drew *et al.*, Nature Materials **8**, 310 (2009)

Alcoholic beverages induce superconductivity in $FeTe_{1-x}S_x$

K. Deguchi *et al.*, Supercond. Sci. Technol. **24**, 05008 (2011)



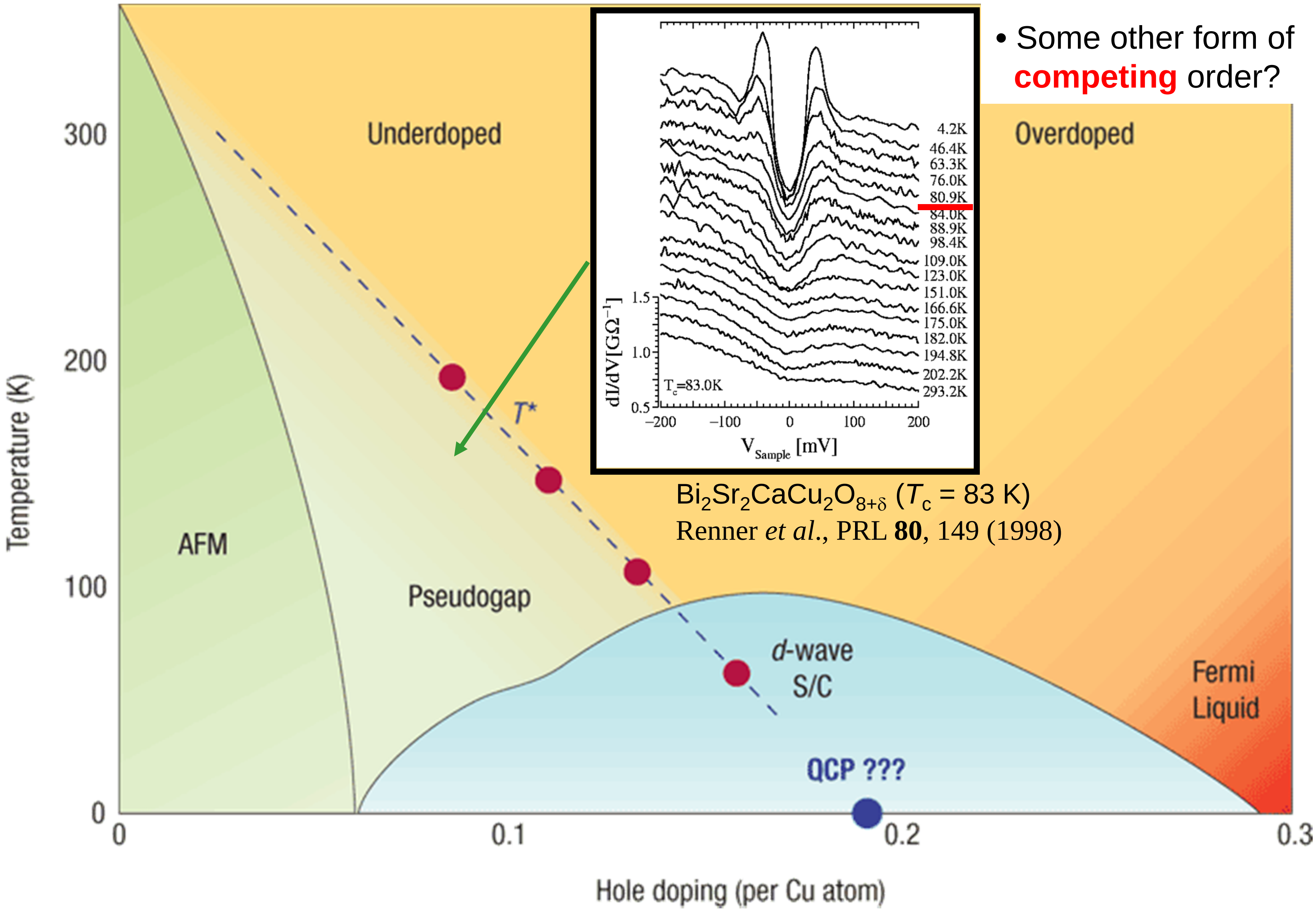


II. Loop Current Order in Pseudogap Phase

(underdoped cuprates)

Origin of Pseudogap?

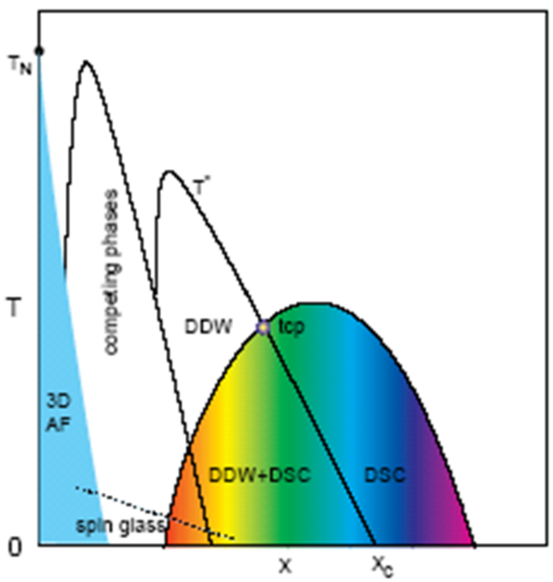
- **Precursor** of SC gap?
- Some other form of **competing** order?



$Bi_2Sr_2CaCu_2O_{8+\delta}$ (T_c = 83 K)
Renner *et al.*, PRL **80**, 149 (1998)

D. M. Broun Nature Phys. **4**, 170 (2008)

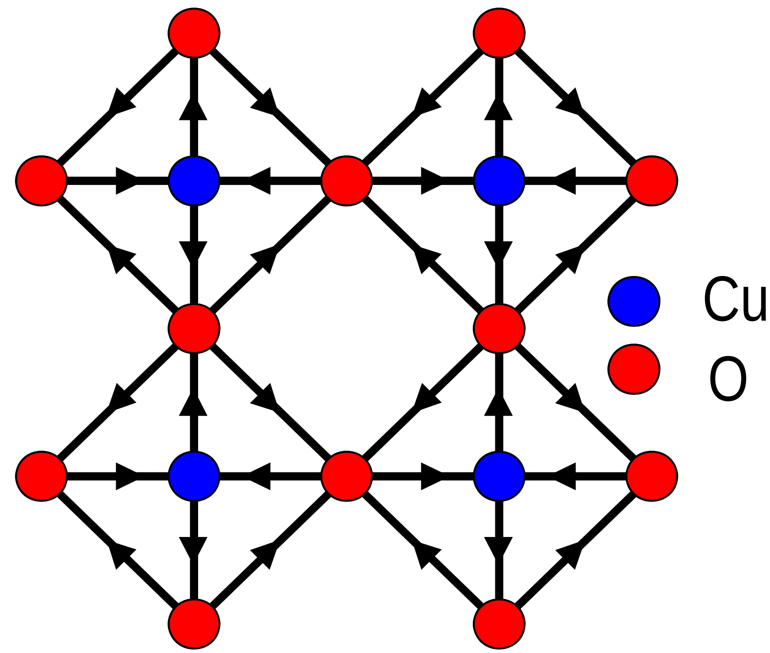
Proposals for pseudogap phase involving orbital currents



I. Chakravarty, Laughlin, Morr, Nayak (2001)
Pseudogap is broken-symmetry phase with d-density wave (DDW) order

Broken symmetries:
- Time reversal
- Rotation
- Translation

II. Lee, Wen *et al.*
Pseudogap region has staggered-flux (DDW) fluctuations, not order

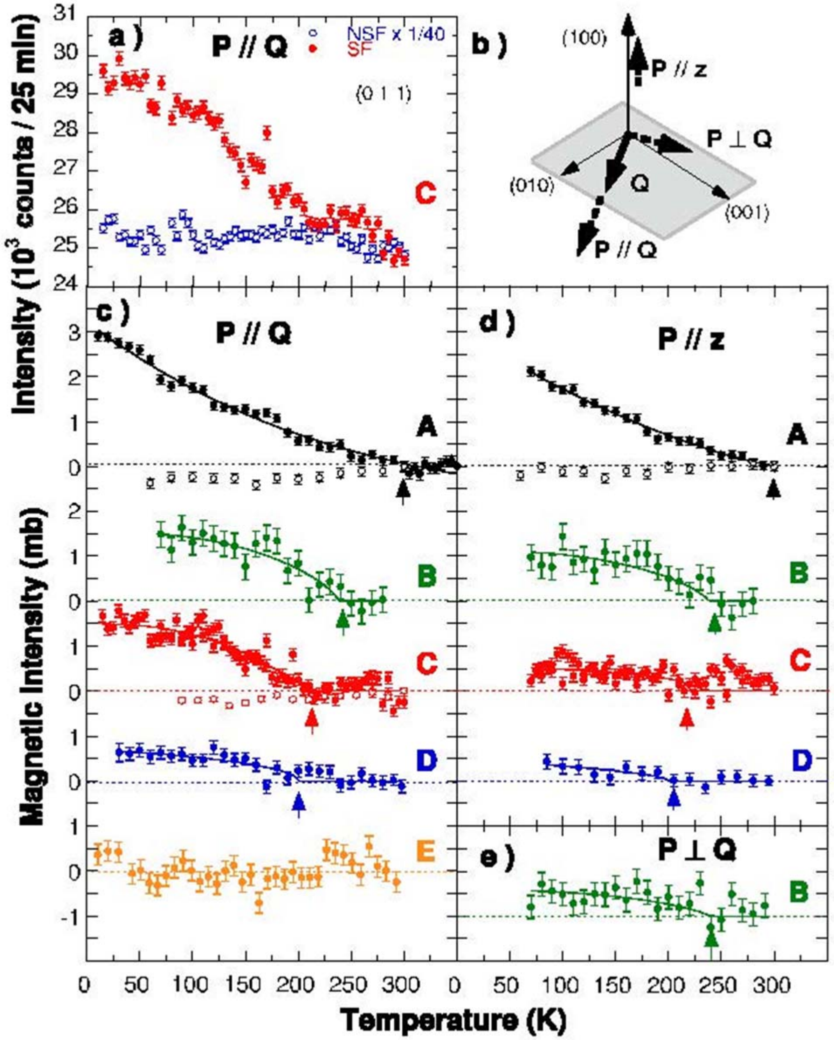


III. Varma (1997)
Pseudogap is broken-symmetry phase with circulating current (CC) order

Broken symmetries:
- Time reversal
- Rotation

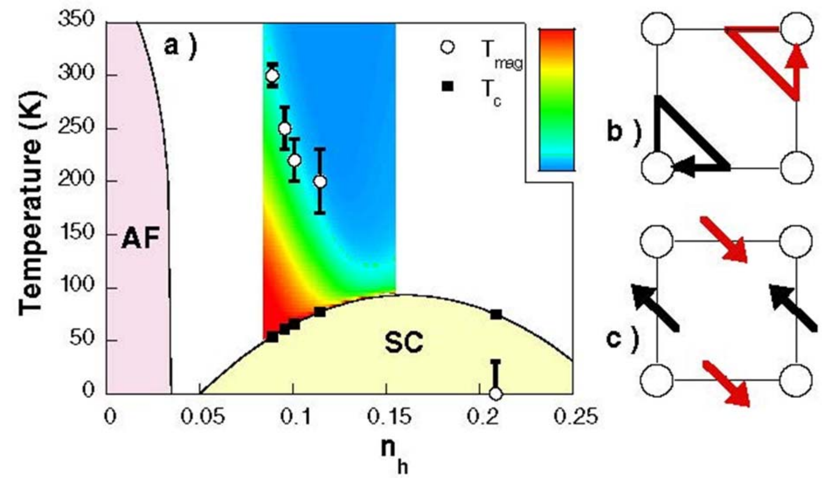
In contrast to the DDW phase, the CC phase does not break translational symmetry

Polarized Neutron-Scattering: $YBa_2Cu_3O_{6+x}$



Onset of long-range magnetic order below T_{mag} (0.05-0.1 μ_B per unit cell)

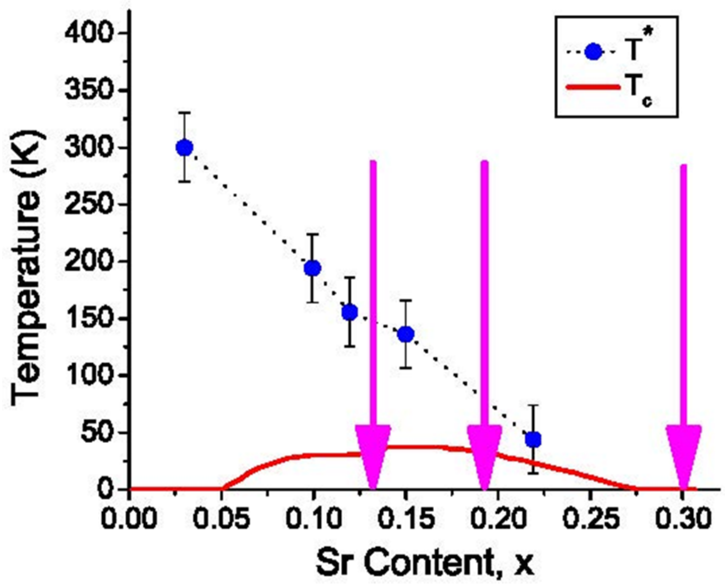
$YBa_2Cu_3O_{6+x}$

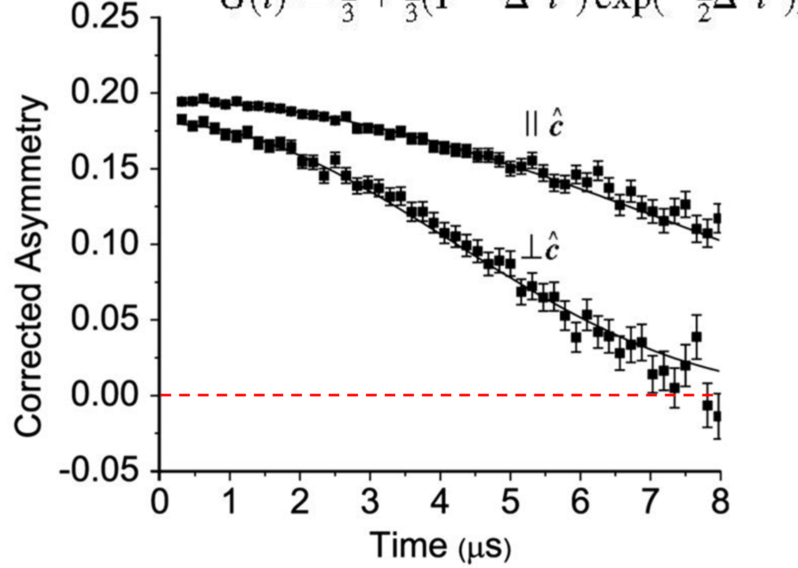


B. Fauque *et al.* Phys. Rev. Lett. **96**, 197001 (2006)

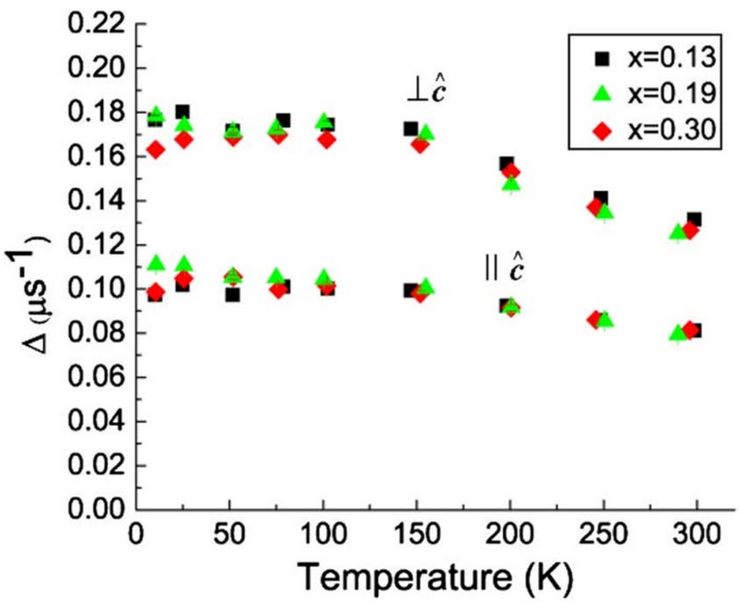
ZF-μSR on $La_{2-x}Sr_xCuO_4$ single crystals

$$G(t) = \frac{1}{3} + \frac{2}{3}(1 - \Delta^2 t^2)\exp(-\tfrac{1}{2}\Delta^2 t^2),$$





G.J. Macdougall *et al*. Phys. Rev. Lett. **101**, 017001 (2008)

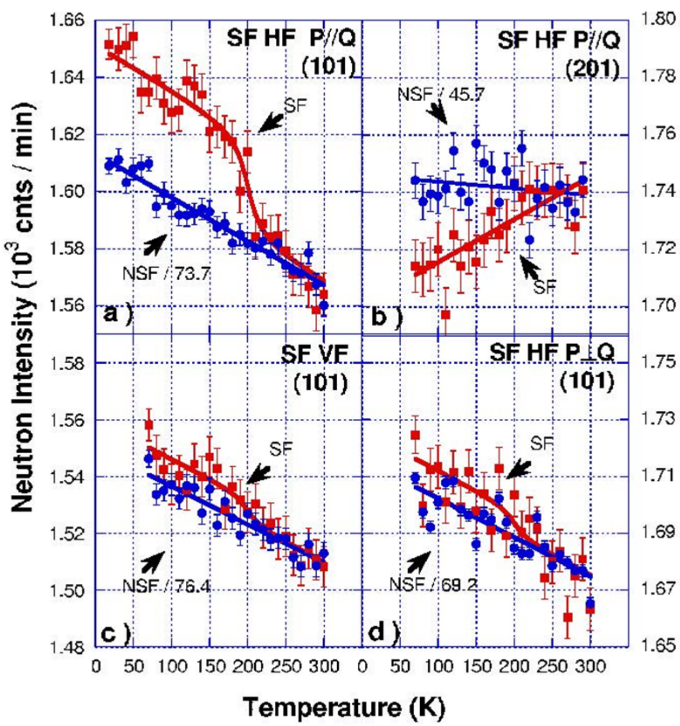


No evidence from ZF-μSR for magnetism in the pseudogap regime associated with loop-current order!

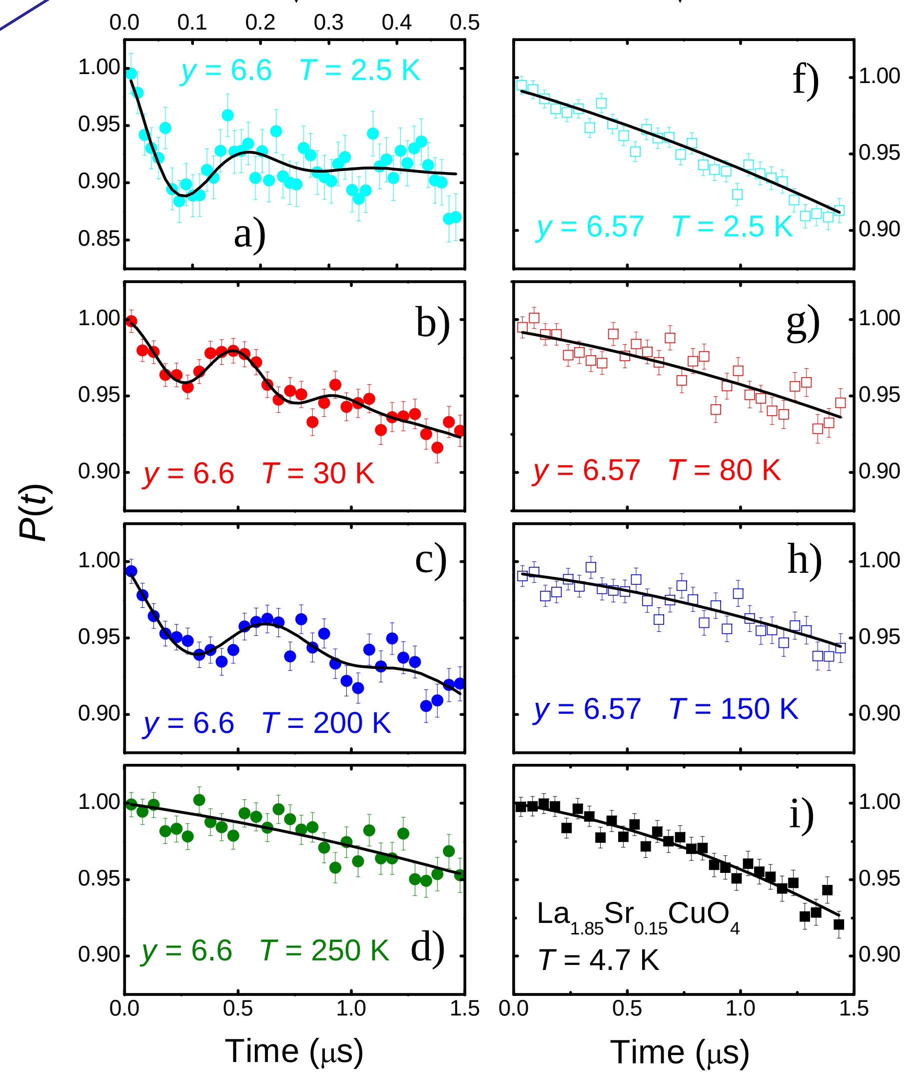
Comparison of ZF-μSR spectra at early times:

Large $YBa_2Cu_3O_{6.6}$ single crystal (studied by polarized neutrons)

Smaller high-quality $YBa_2Cu_3O_{6+x}$ single crystals (UBC)

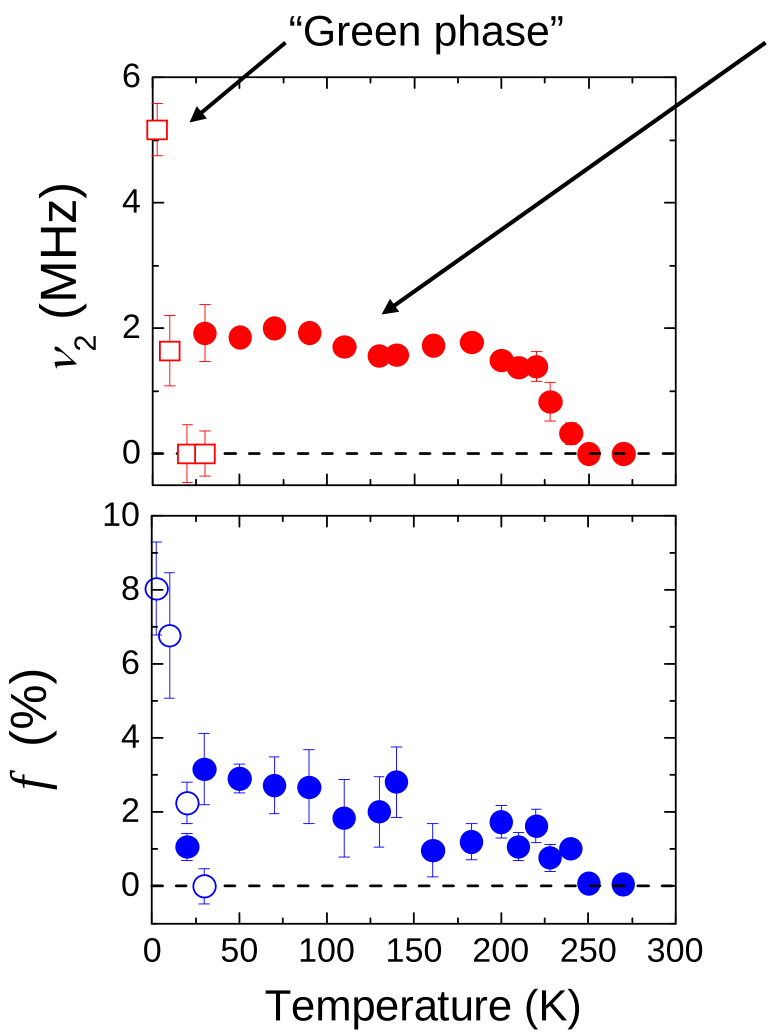


H.A. Mook *et al.* Phys. Rev. B **78**, 020506(R) (2008)



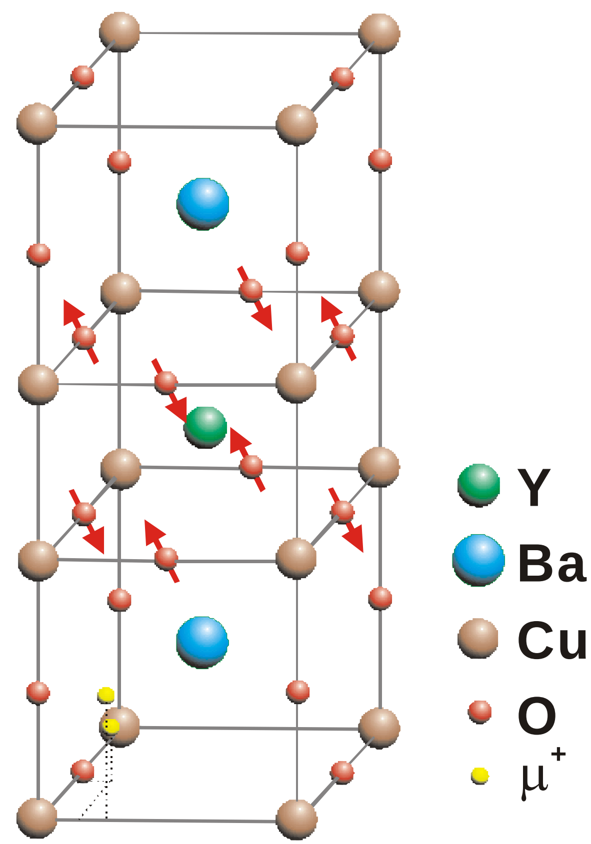
JES *et al.* Phys. Rev. Lett. **103**, 167002 (2009)

Additional magnetic orders in $YBa_2Cu_3O_{6.6}$ neutron crystal



Magnetic order that agrees with neutrons

But only in ~ 3 % of sample!



JES *et al.* Phys. Rev. Lett. **103**, 167002 (2009)

III. Time Reversal Symmetry Breaking

The superconducting order parameter of conventional superconductors only breaks gauge symmetry, but **unconventional** superconductors break additional symmetries.

Some unconventional superconductors **break time reversal symmetry** (TRS) associated with the spin or orbital component of the Cooper pair wave function having nonzero angular momentum.

TRS may be signified by the occurrence of weak **spontaneous internal magnetic fields** below T_c.

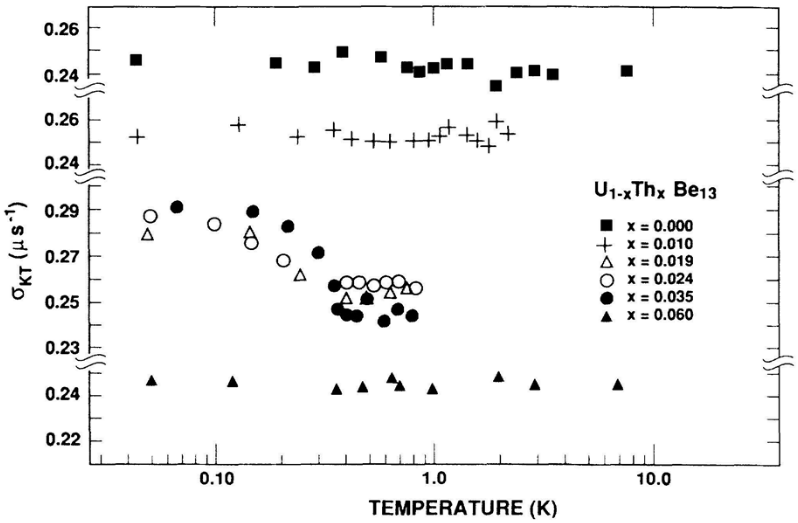
• **nonzero spin and orbital moments**: spontaneous supercurrents near impurities, surface and/or domain walls (*i.e.* where the superconducting order parameter spatially varies)

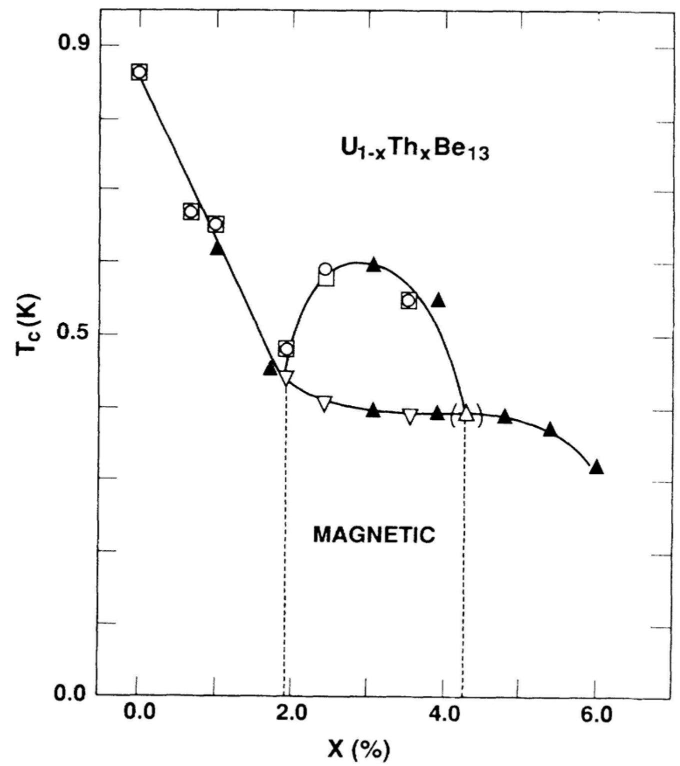
• **nonzero spin moment**: hyperfine field induced at μ^+ sites

ZF-μSR is ideally suited for detecting such fields.

ZF-μSR on the heavy-fermion superconductor $U_{1-x}Th_xBe_{13}$

$$G_{KT}(t) = \frac{1}{3} + \frac{2}{3}(1 - \sigma_{KT}^2 t^2)\exp(-\frac{1}{2}\sigma_{KT}^2 t^2)$$

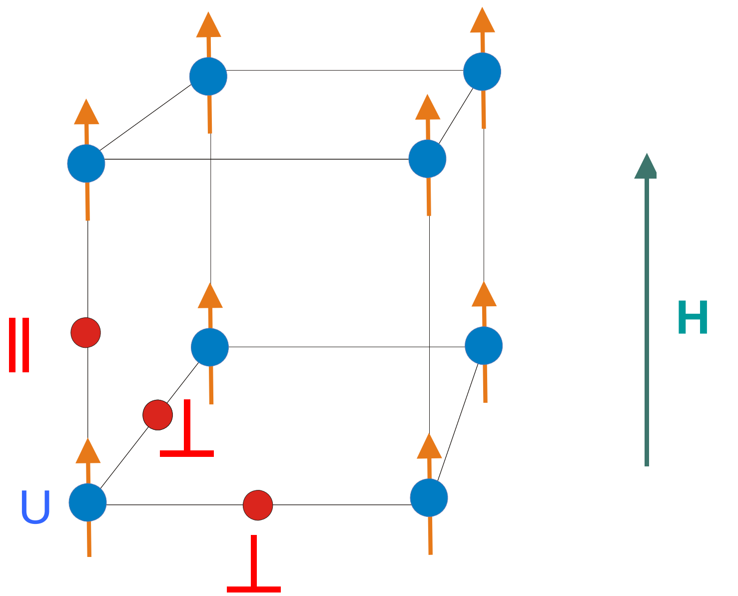


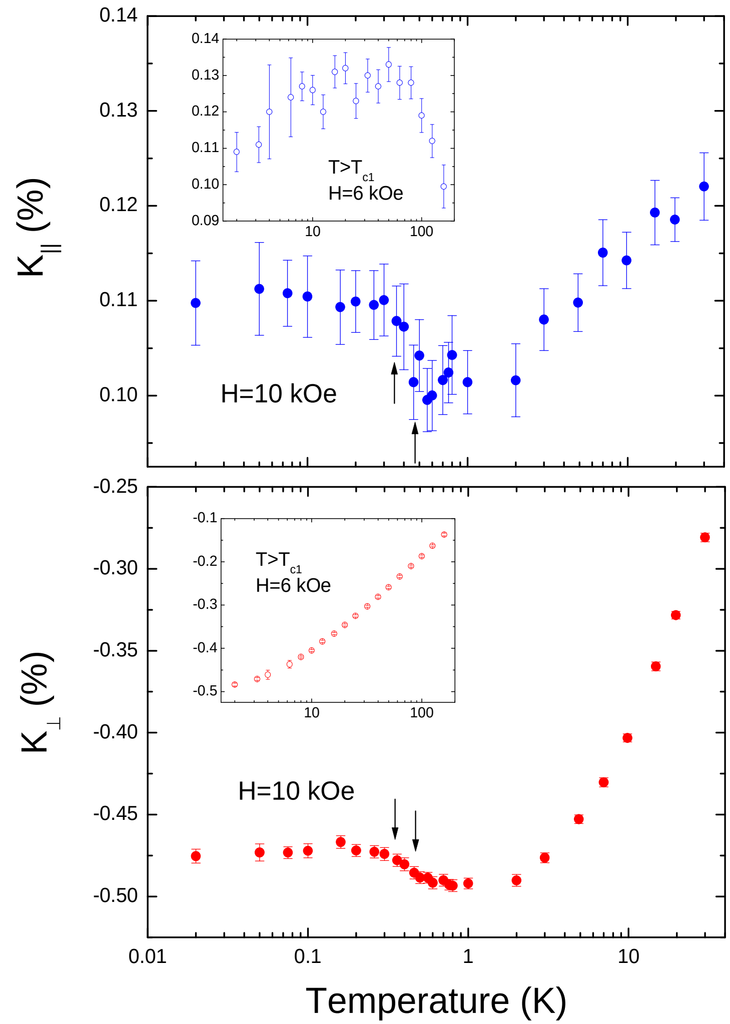


TRS or coexisting magnetic and SC phase?

R.H. Heffner et al. Phys. Rev. Lett. **65**, 2816 (1990)

μ^+-Knight shift in $U_{0.965}Th_{0.035}Be_{13}$



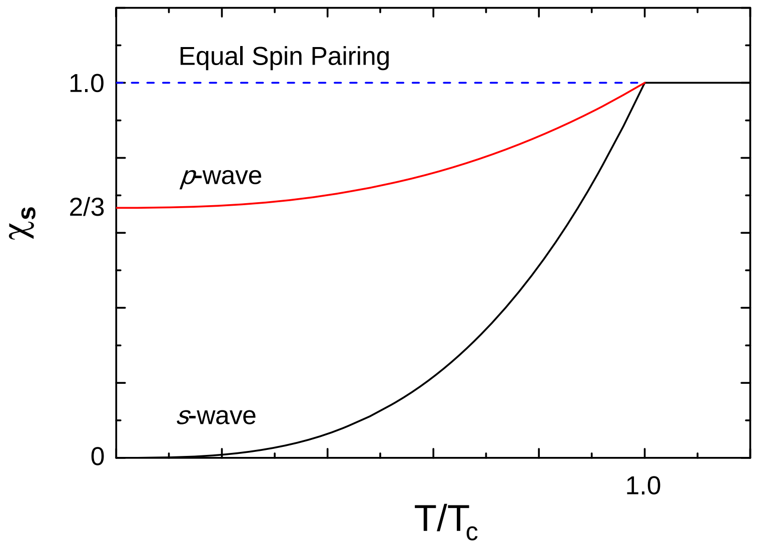


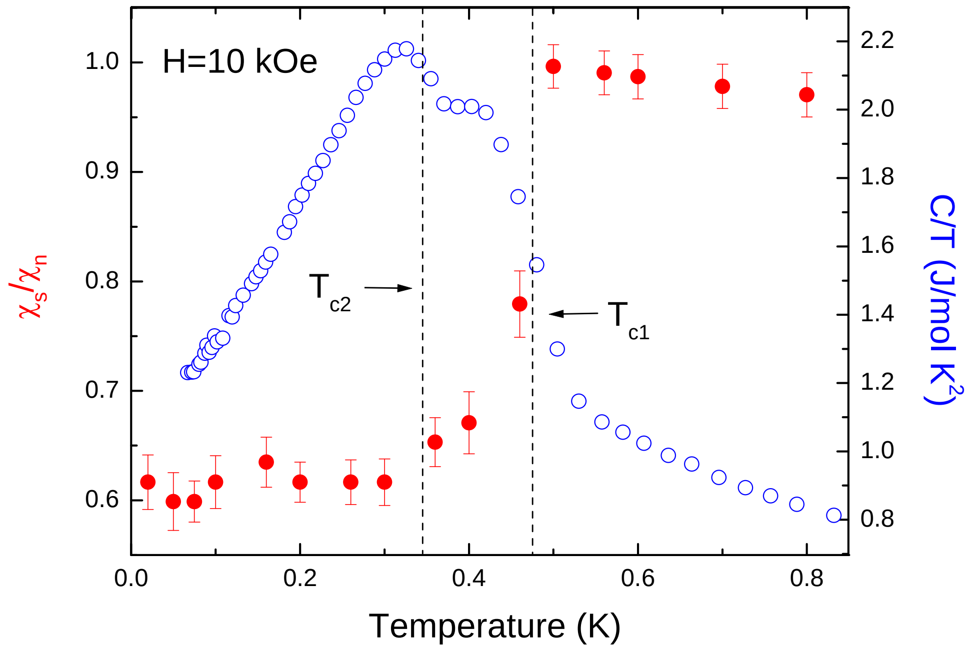
Two magnetically inequivalent muon stopping sites in single crystals

$$K_{||} = (A_c^{||} + A_{dip}^{zz})\chi_{5f} + K_{dem,L} + K_0 + K_{dia}$$

$$K_{\perp} = (A_c^{\perp} - 1/2\, A_{dip}^{zz})\chi_{5f} + K_{dem,L} + K_0 + K_{dia}$$

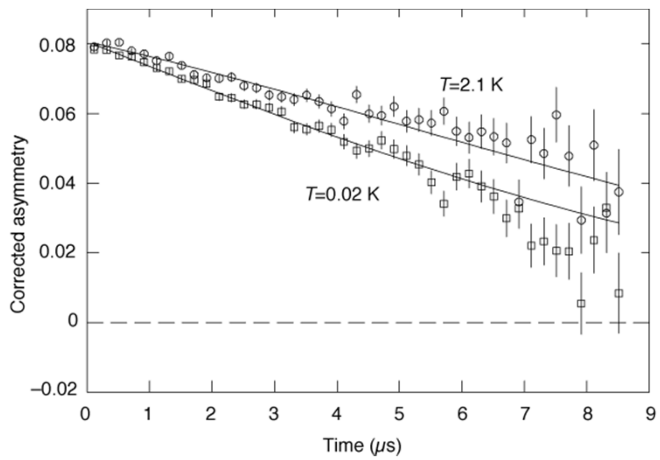
Static spin susceptibility χ_s in the superconducting state of $U_{0.965}Th_{0.035}Be_{13}$

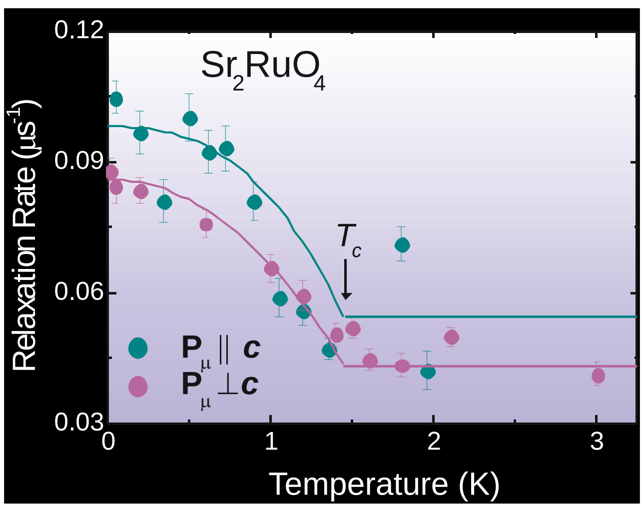




J.E. Sonier *et al.*, Phys. Rev. Lett. **85**, 2821 (2000)

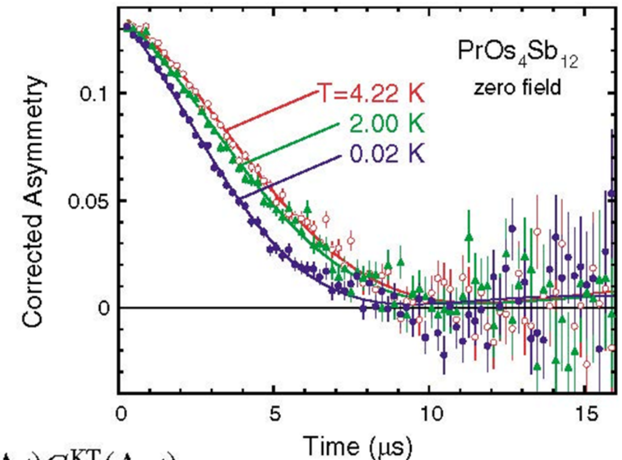
Sr_2RuO_4: rare example of a spin-triplet (p-wave) superconductor





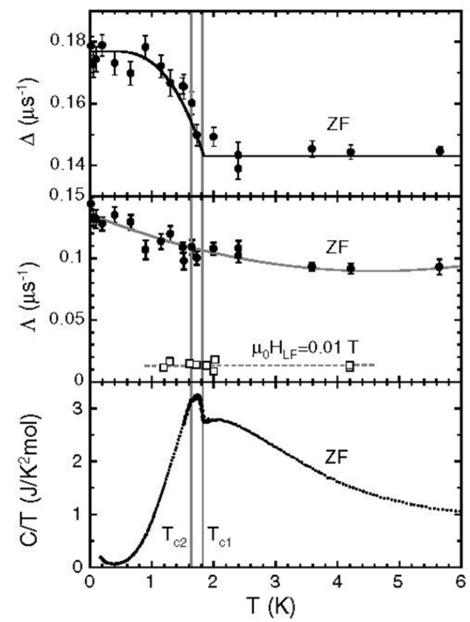
G.M. Luke *et al.*, Nature **394**, 558 (1998)

$PrOs_4Sb_{12}$: heavy fermion superconductor



$$P_\mu = \exp(-\Lambda t) G_z^{\mathrm{KT}}(\Delta, t),$$

$$G_z^{\mathrm{KT}}(\Delta, t) = \tfrac{1}{3} + \tfrac{2}{3}(1 - \Delta^2 t^2)\exp(-\tfrac{1}{2}\Delta^2 t^2)$$



Y. Aoki *et al.*, Phys. Rev. Lett. **91**, 067003 (2003)

IV. Magnetic Penetration Depth

(cuprates)

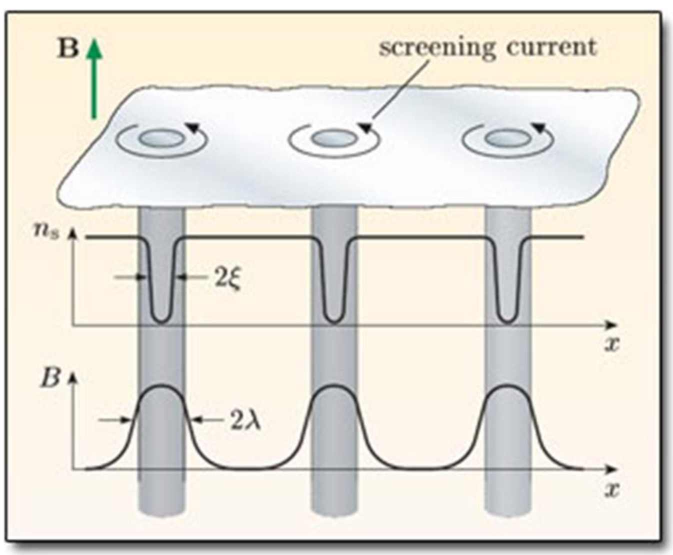
Fit of Single Crystal TF-μSR Spectra to Phenomenological Model

GL-model of spatial field profile:

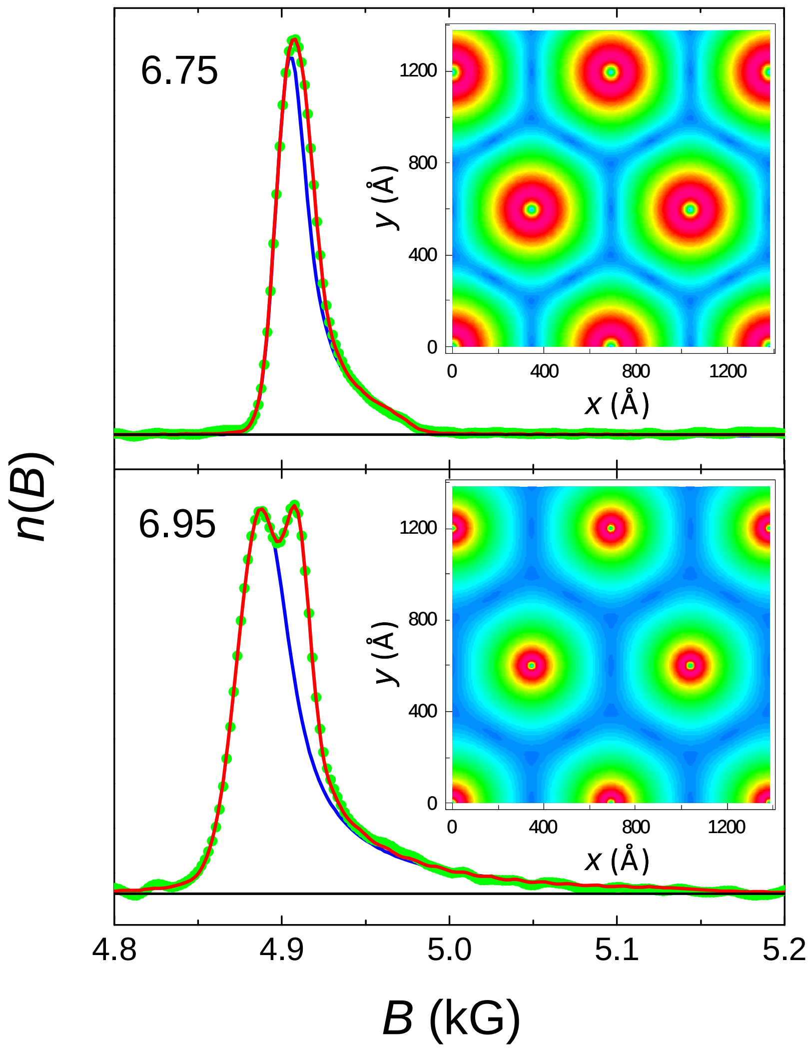
$$B(\vec{r}) = B_0(1-b^4)\sum_{\vec{G}} \frac{uK_1(u)e^{-i\vec{G}\cdot\vec{r}}}{\lambda_{ab}{}^2 G^2}$$

$$b = \frac{B}{B_{c2}} \qquad u^2 = 2\xi_{ab} G^2 (1+b^4)[1-2b(1-b)^2]$$

$\lambda_{ab} \equiv$ <u>effective</u> penetration depth
$\xi_{ab} \equiv$ <u>effective</u> vortex core size

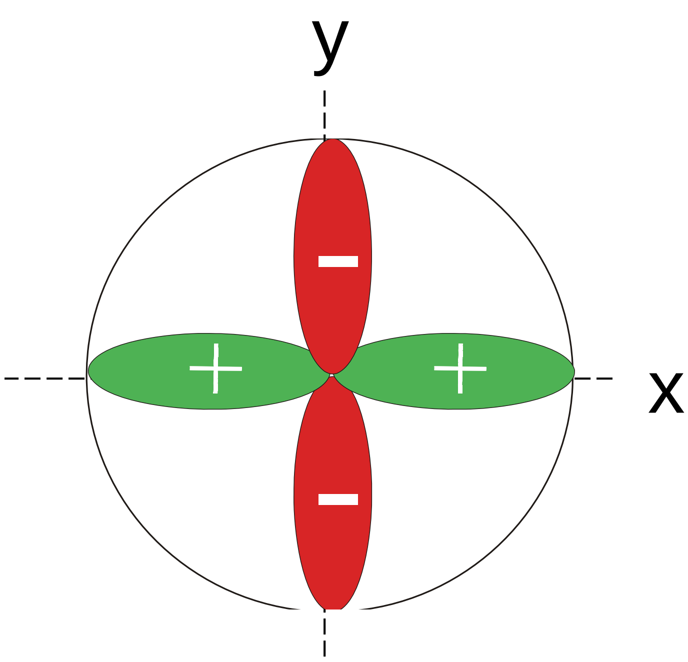


$YBa_2Cu_3O_y$

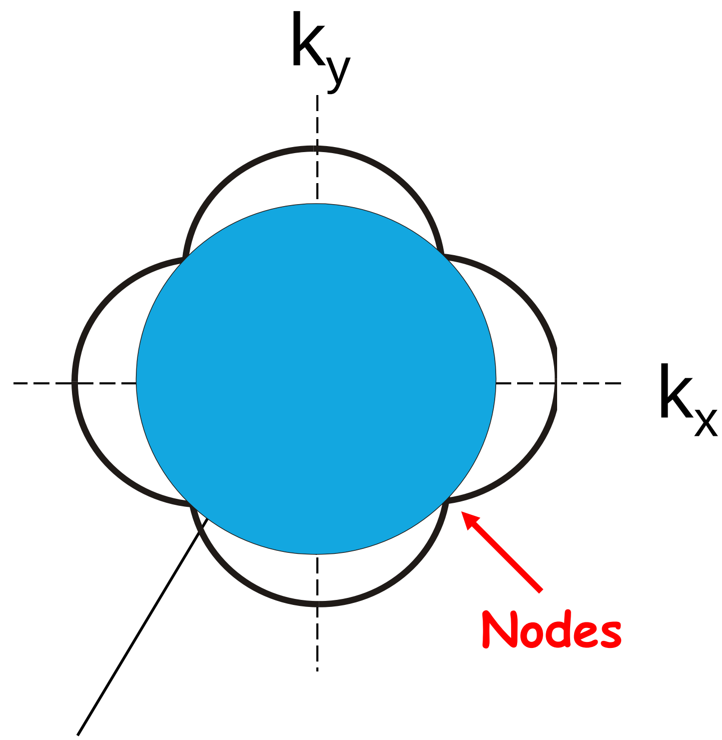


JES *et al.*, *Phys. Rev. B* **76**, 134518 (2007)

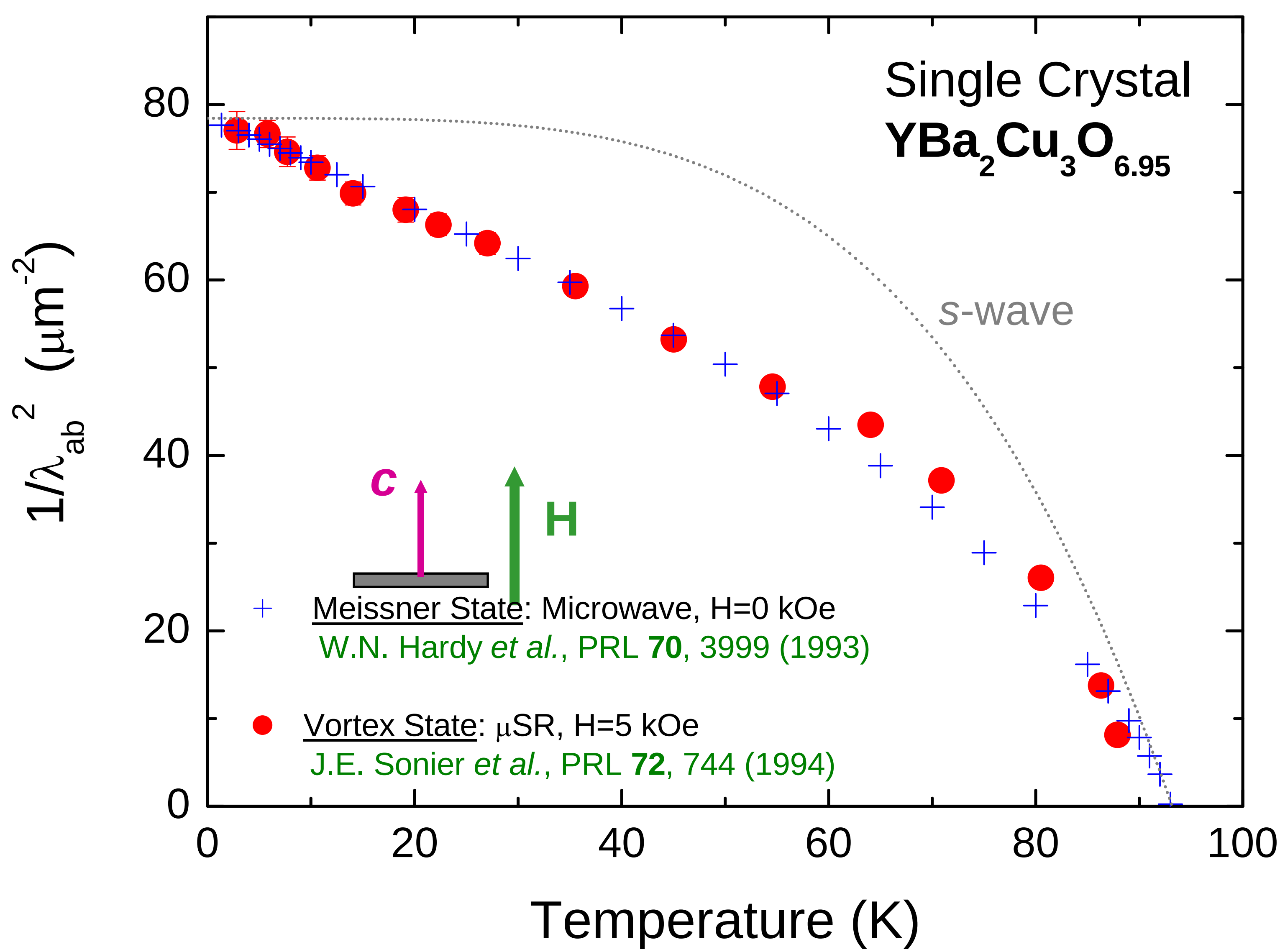
d-wave Pairing Symmetry



$d_{x^2-y^2}$-wave pairing symmetry

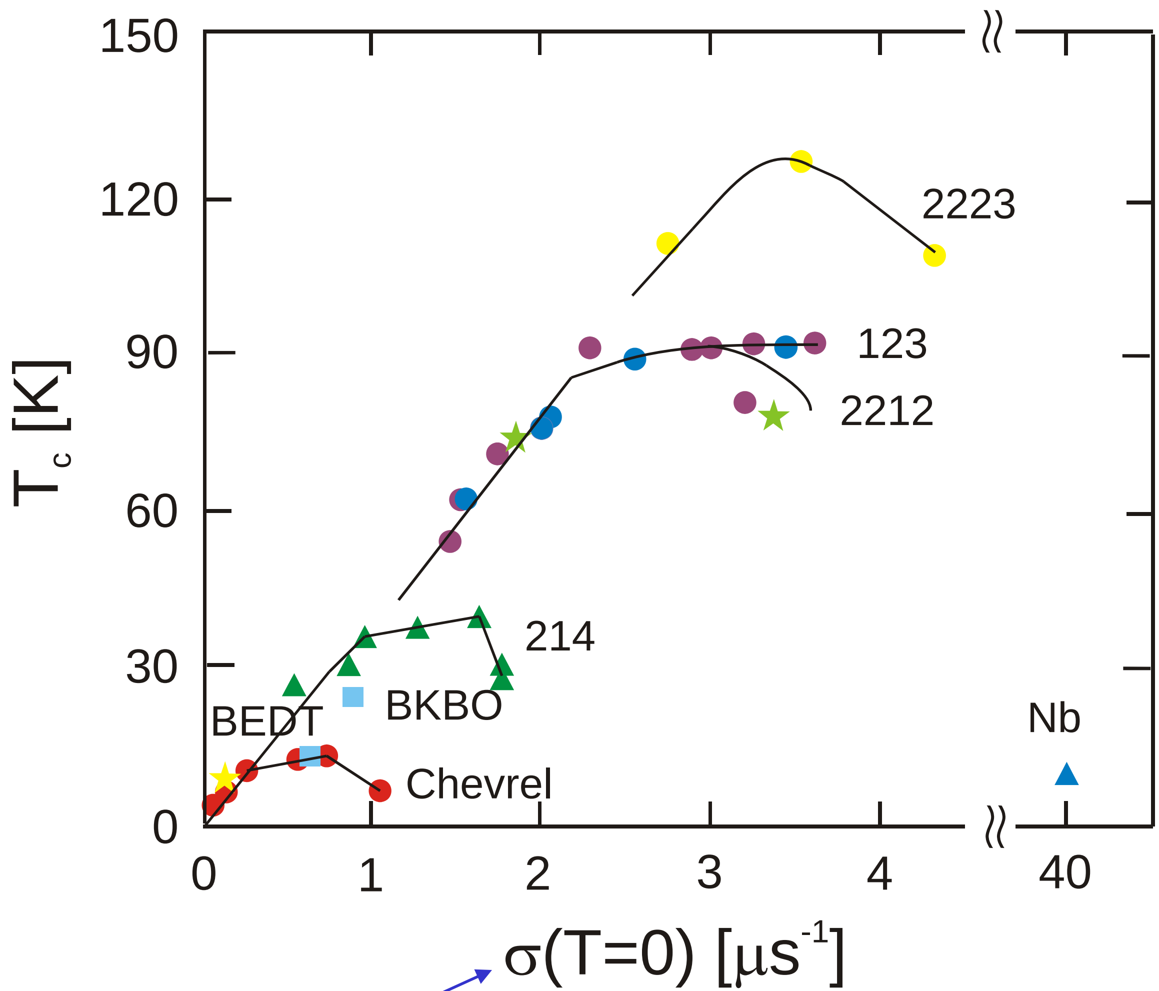


Fermi surface



Single Crystal
YBa2Cu3O6.95
s-wave
c
H
Meissner State: Microwave, H=0 kOe
W.N. Hardy et al., PRL 70, 3999 (1993)
Vortex State: μSR, H=5 kOe
J.E. Sonier et al., PRL 72, 744 (1994)
1/λab2 (μm-2)
Temperature (K)
0
20
40
60
80
100

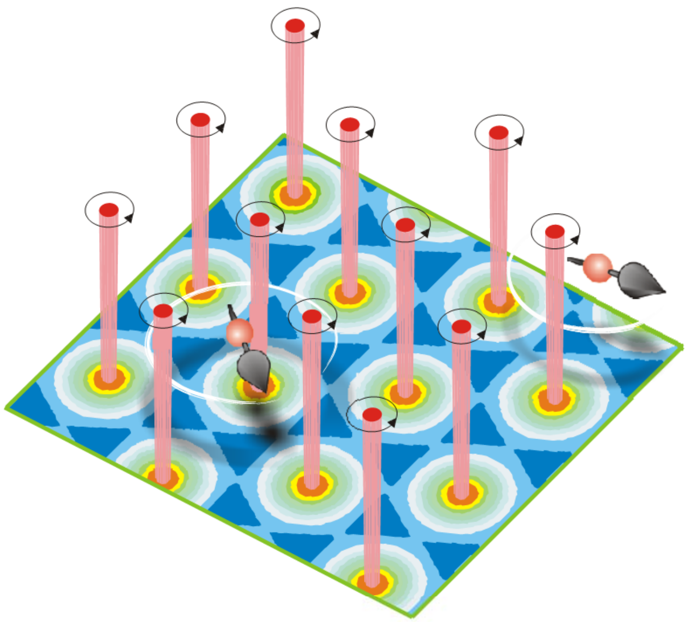
Universal Behavior

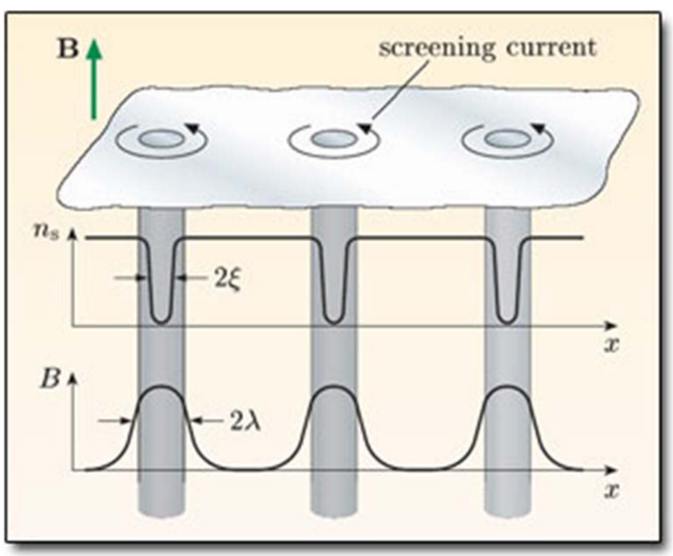


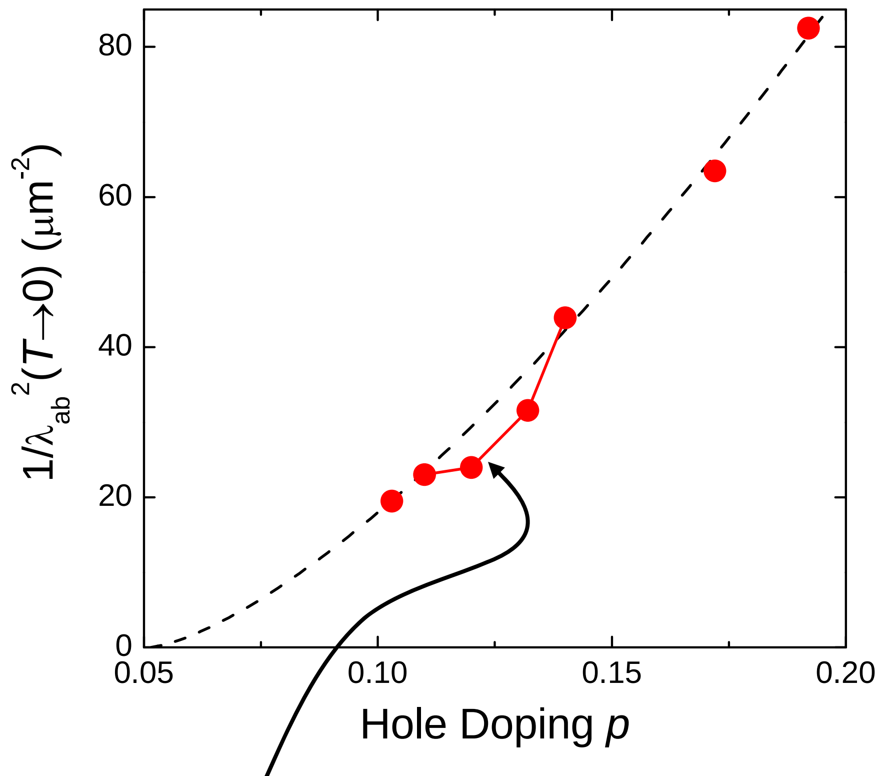
$\sigma \sim 1/\lambda^2$

Y.J. Uemura *et al.*, Phys. Rev. Lett. **66**, 2665 (1991)

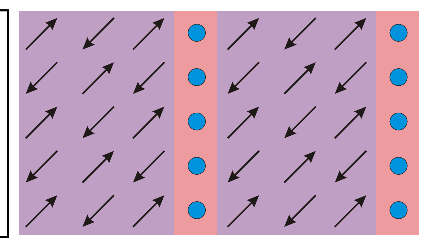
Hole-doping dependence of the ***superfluid density*** $n_s \propto \dfrac{1}{\lambda_{ab}^{\;2}}$ in $YBa_2Cu_3O_y$





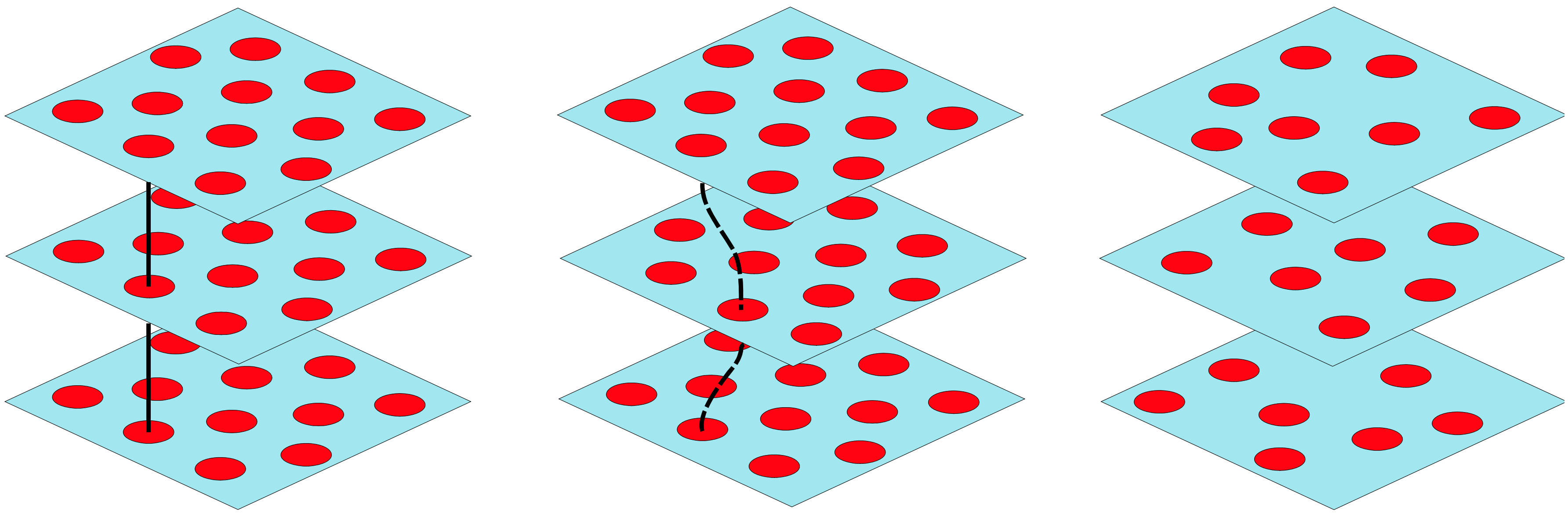


Suppression of superconductivity near **1/8 hole doping**, likely due to dynamic spin/charge "stripe" correlations.



JES *et al.*, Phys. Rev. B **76**, 134518 (2007)

Vortex Phases in Layered Superconductors



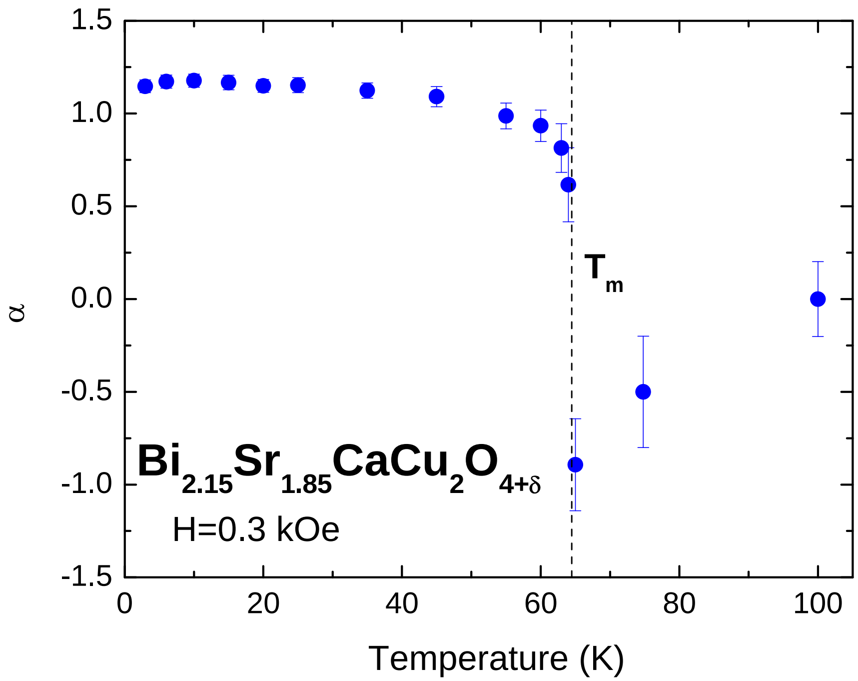
3D Vortex Solid

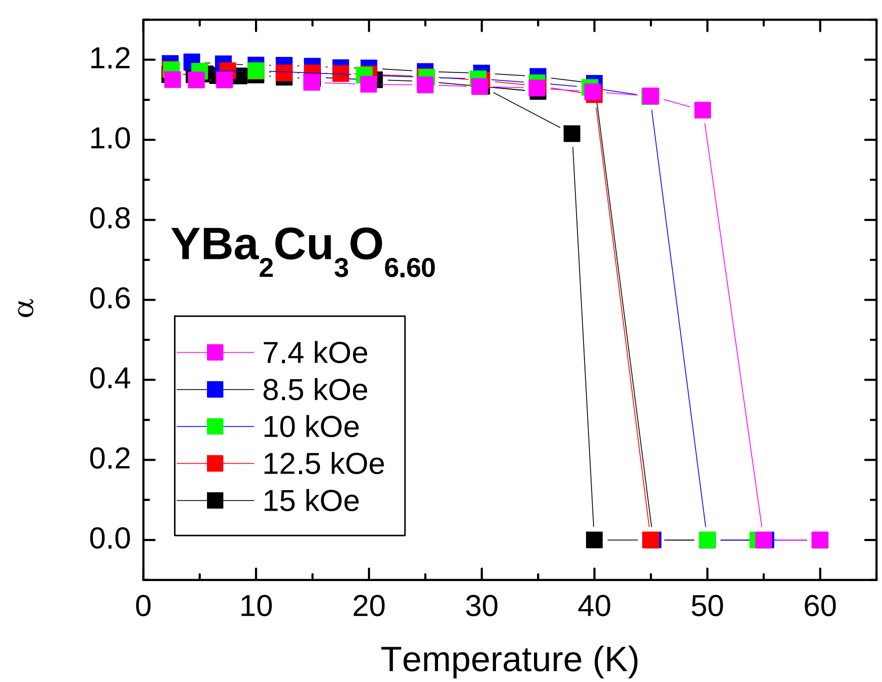
Decoupled Pancake Vortices

Vortex Liquid

Vortex Lattice Melting in High-T_c Superconductors

Skewness Parameter: $\alpha = \langle(\Delta B)^3\rangle\langle(\Delta B)^2\rangle^{1/2}$, $\langle(\Delta B)^n\rangle = \langle(B - \langle B\rangle)^n\rangle$

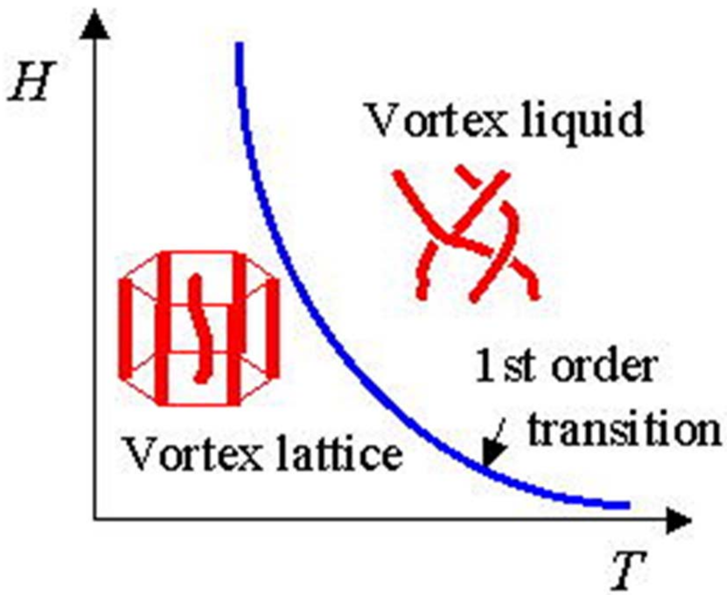




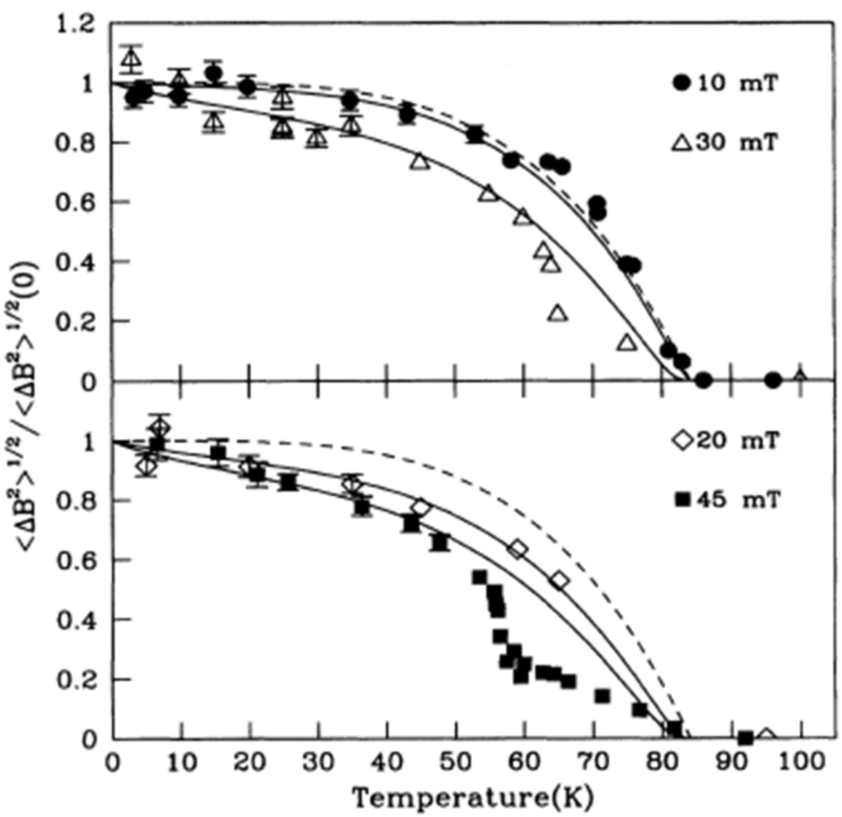
S.L. Lee *et al.*, Phys. Rev. B **55**, 5666 (1997)

J.E. Sonier *et al.*, Phys. Rev. B **61**, R890 (2000)

μSR measurements of ***vortex solid-to-liquid*** transition



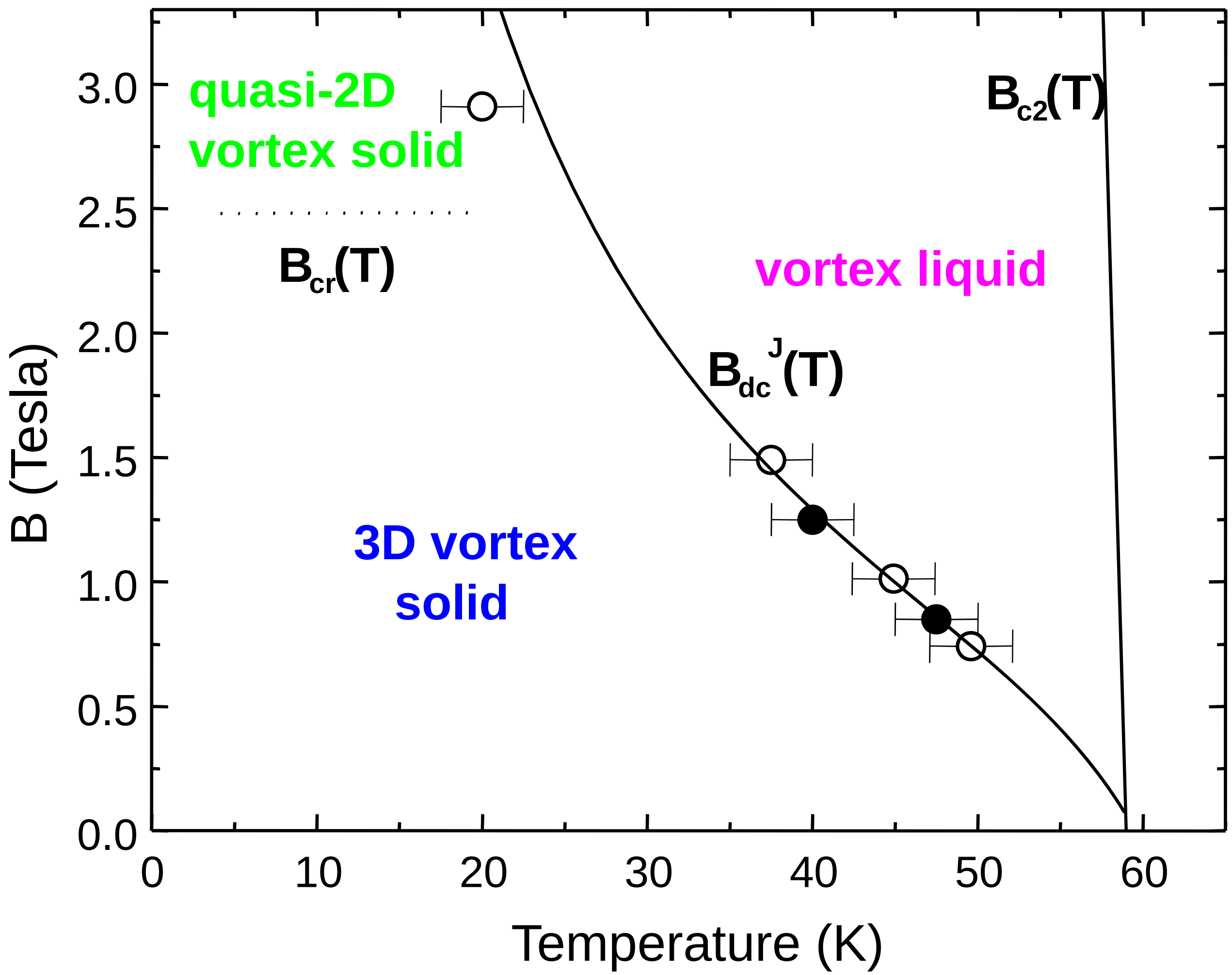
BSCCO (T_c = 84 K)



Lee *et al*. Phys. Rev. Lett. **75**, 922 (1995)

- Collapse of μSR line width at $T_m < T_c$
- μSR line width in vortex liquid phase ***decreases*** with increased *H*

Vortex Phase Diagram of a $YBa_2Cu_3O_{6.60}$ Single Crystal



J.E. Sonier *et al.*, Phys. Rev. B **61**, R890 (2000)

V. Superconductivity above T_c
(cuprates)

$$\Psi(\vec{r}) = \left|\Psi_0\right| e^{i\theta(\vec{r})}$$

BCS wave function describing the superconducting state

In the superconducting state, both the pairing amplitude $\left|\Psi_0\right|$ and the phase $\theta(\vec{r})$ are ***rigid***.

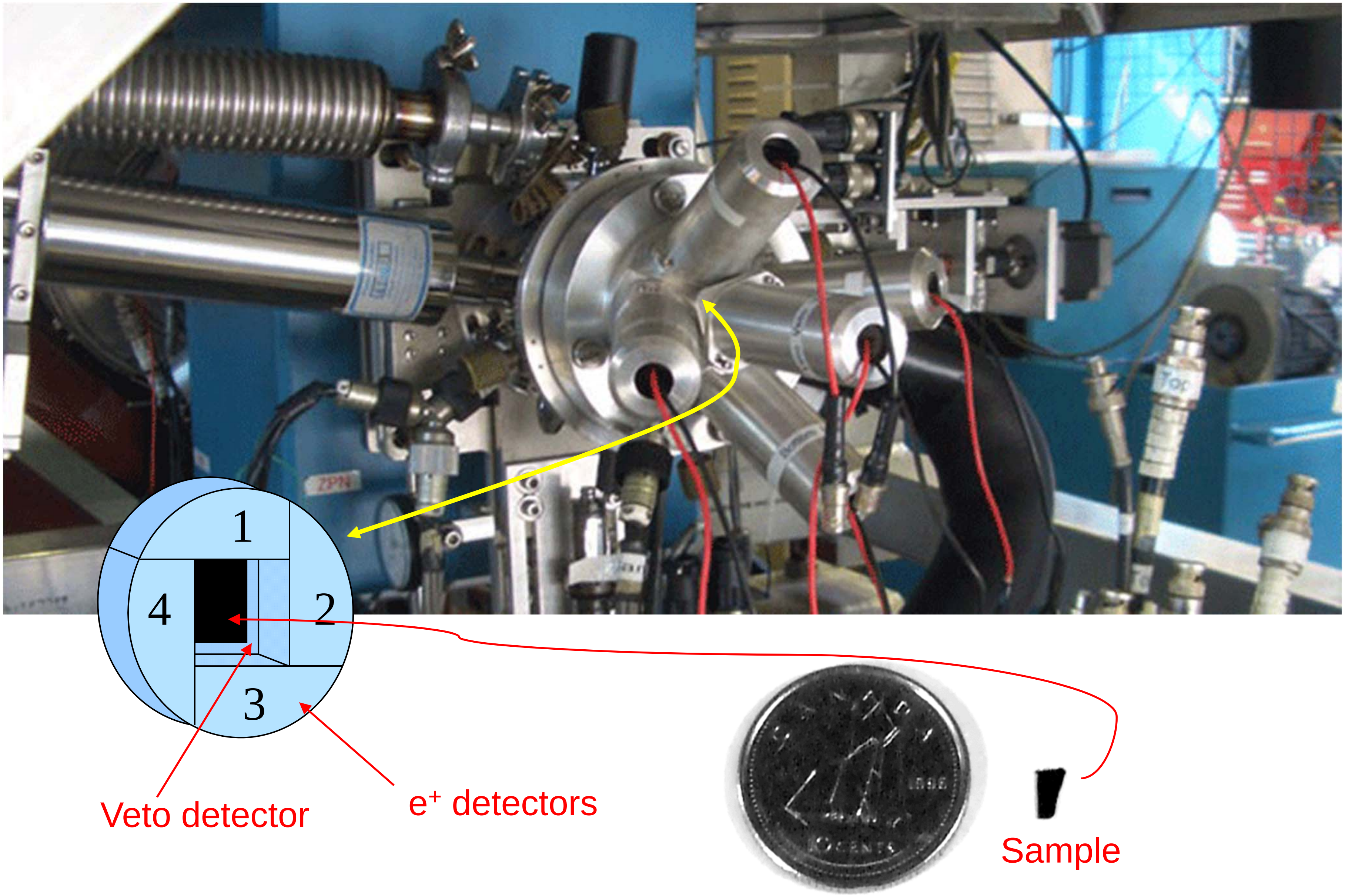
The superconducting state can be destroyed by ***fluctuations*** of the amplitude, phase, or both.

- **Low-Temperature Superconductor**
  Superconductivity destroyed by ***amplitude*** fluctuations
  i.e. destruction of Cooper pairs

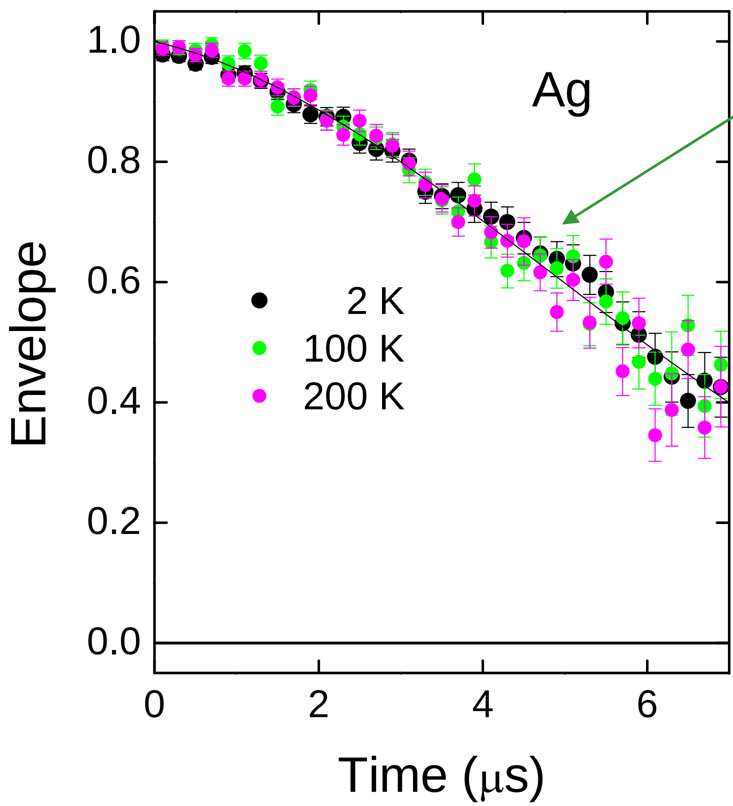
- **High-Temperature Superconductor**
  Superconductivity destroyed by ***phase*** fluctuations
  i.e. destruction of long-range phase coherence of Cooper pairs

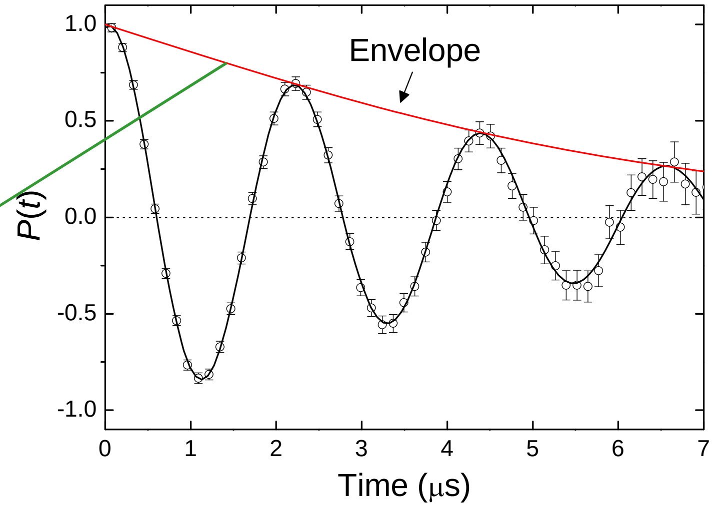
Consequently the simple binding of electrons into Cooper pairs and short-range phase coherence may occur at temperatures well ***above*** T_c!

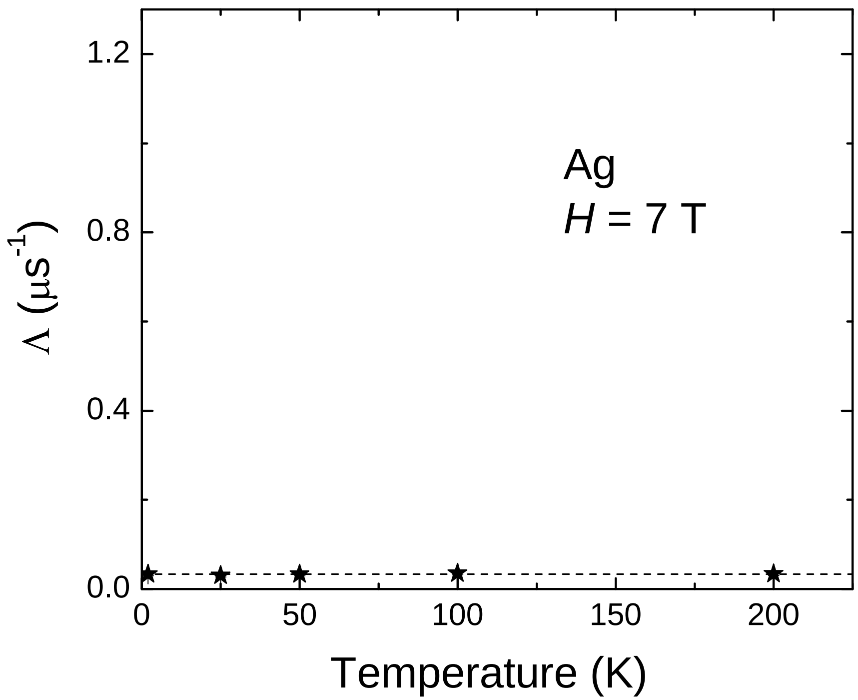
HiTime: High transverse-field (7 T) μSR spectrometer



Relaxation of TF-μSR Signal in Pure Ag at *H* = 7T







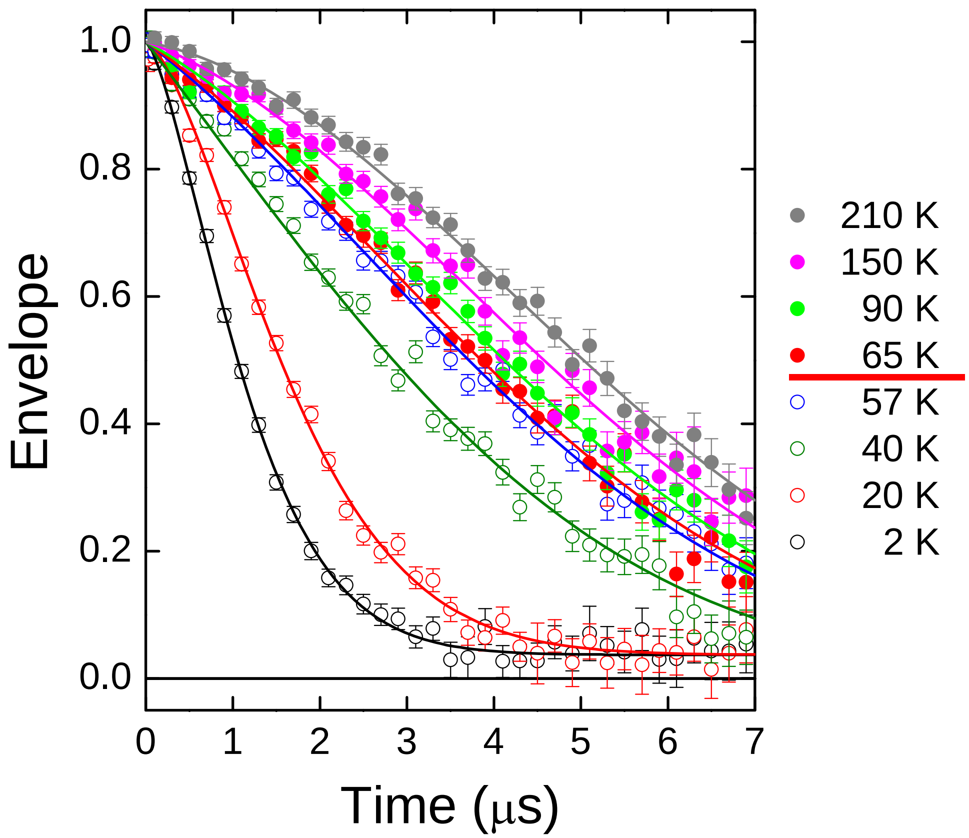
nuclear dipoles

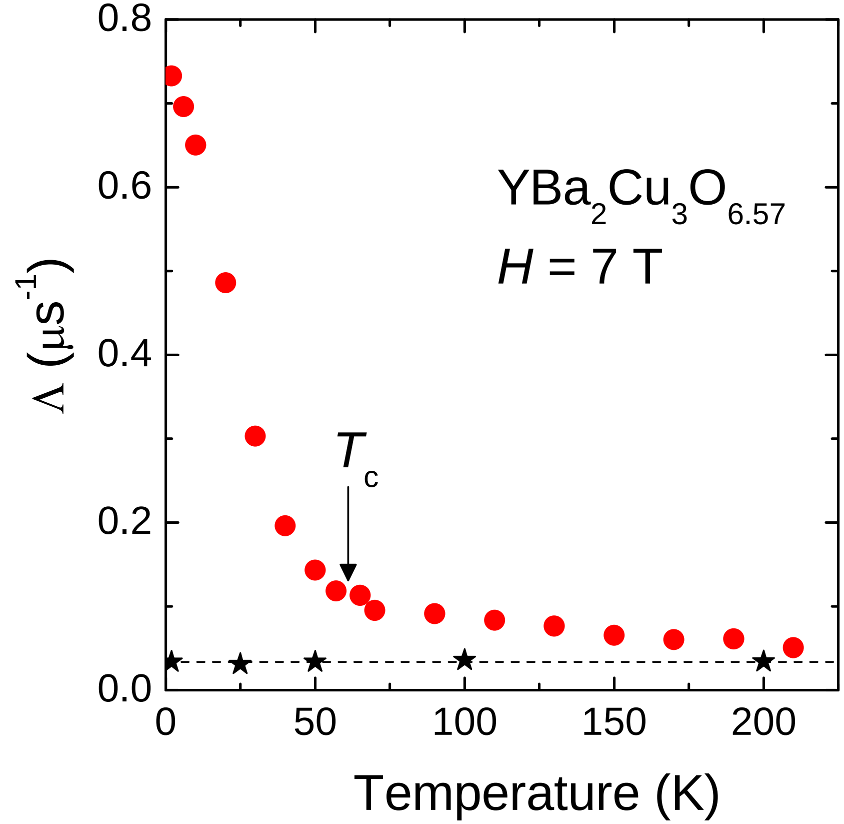
$$G_x(t) = \exp(-\Lambda t)\exp(-\Delta^2 t^2)$$

inhomogeneity of spectrometer magnet

(<u>no</u> <u>electronic</u> magnetic moments in Ag)

Relaxation of TF-μSR Signal in $YBa_2Cu_3O_{6.57}$ (T_c = 62.5 K) at H = 7T





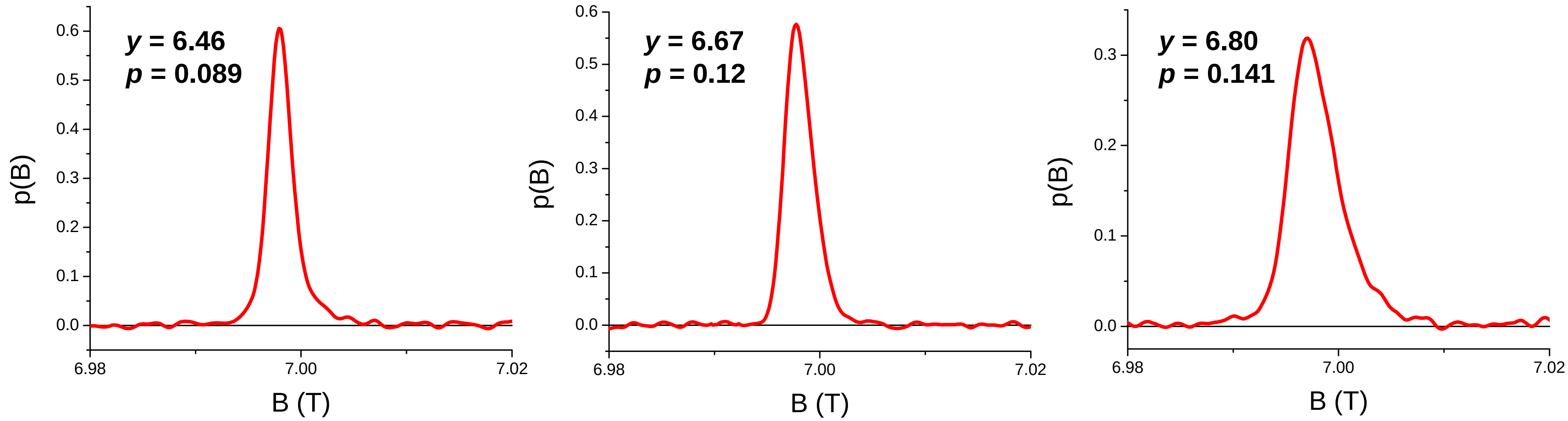
nuclear dipoles

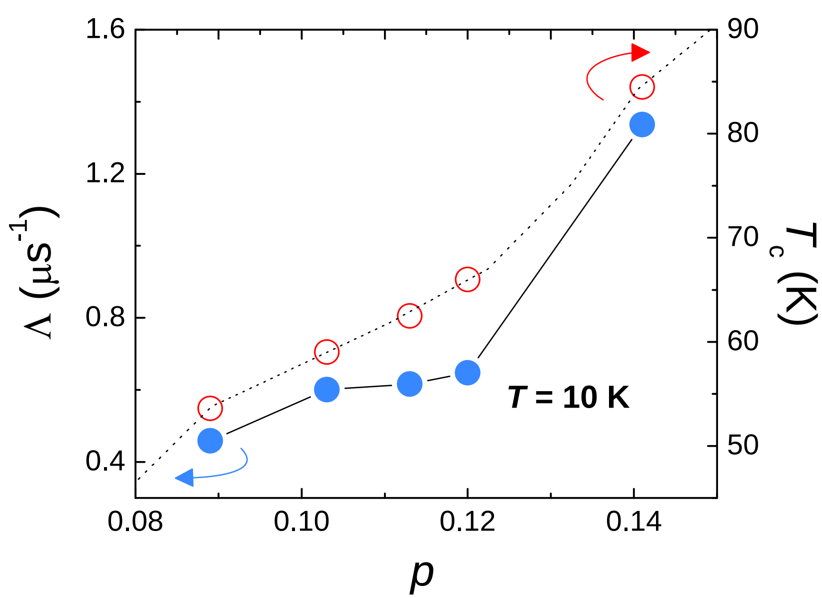
$$G(t) = \exp[(-\Lambda t)^{\beta}]\exp(-\Delta^2 t^2)$$

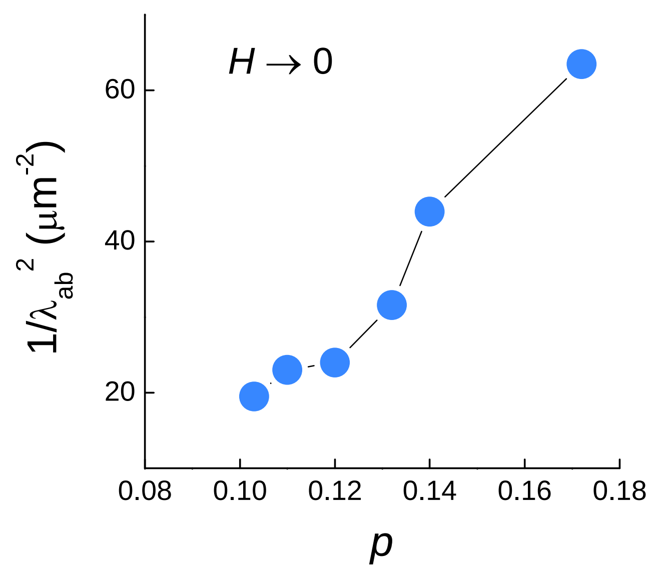
spatial field inhomogeneity **(β = 1 at $T \geq$ 40 K)**

$T < T_c$: $YBa_2Cu_3O_y$ @ $H = 7$ T

$T = 2.3$ K



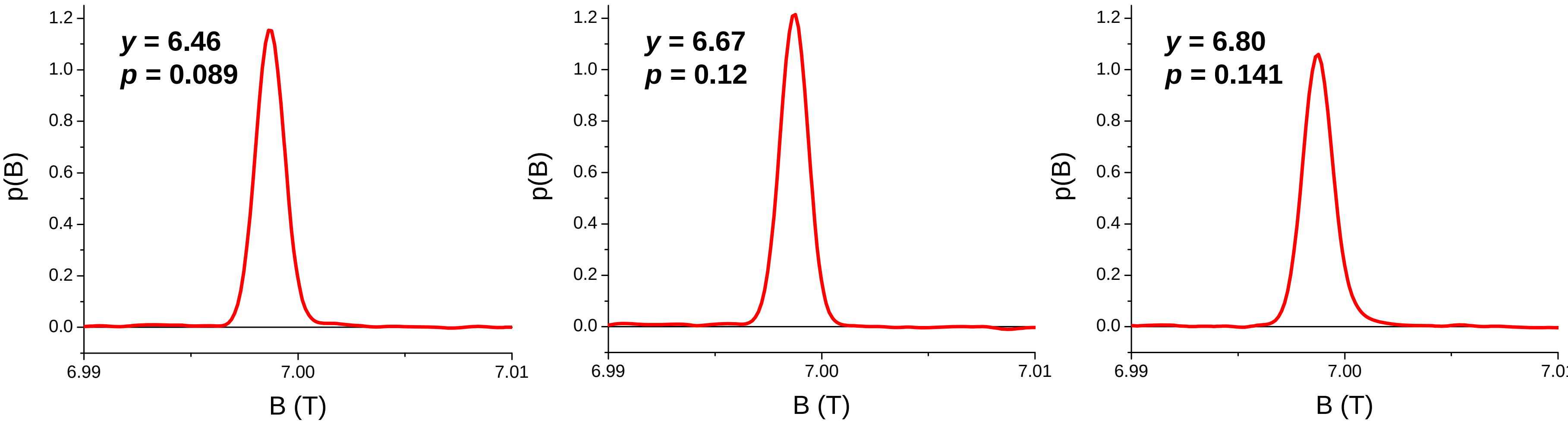


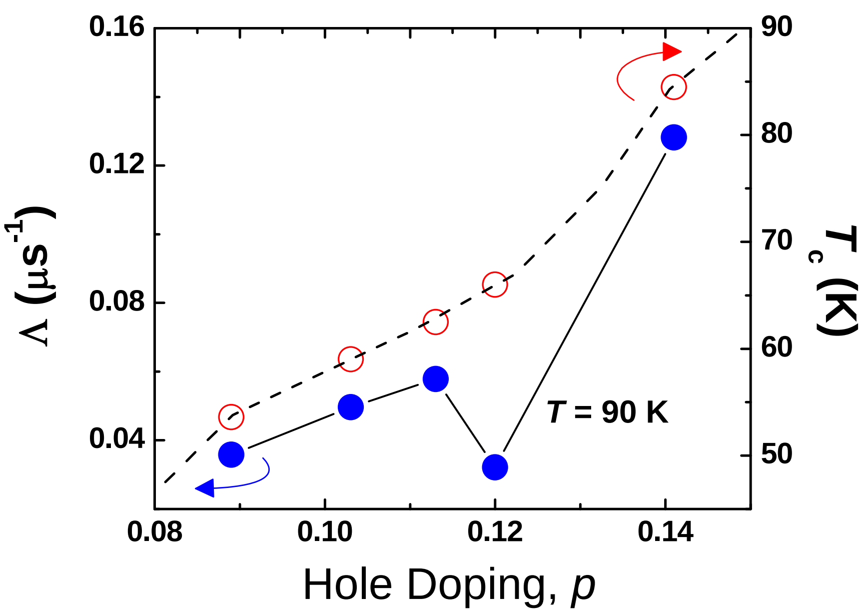


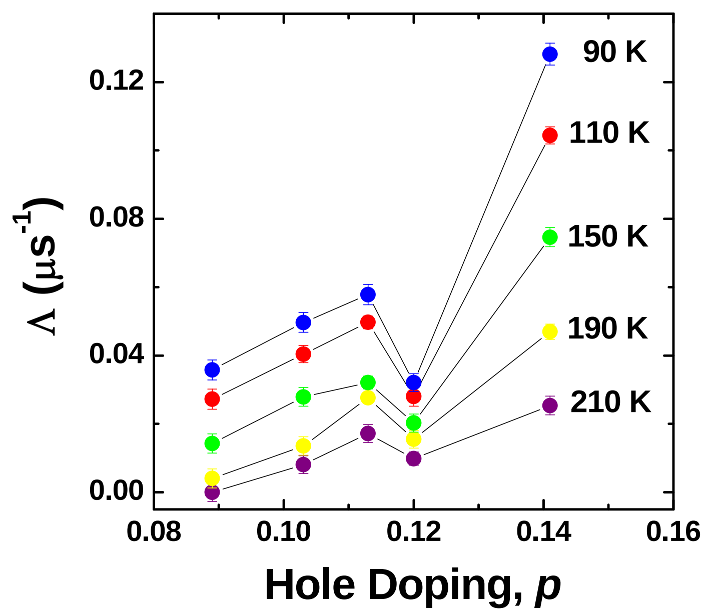
JES *et al.* PRB **76**, 134518 (2007)

$T > T_c$: $YBa_2Cu_3O_y$ @ $H = 7$ T

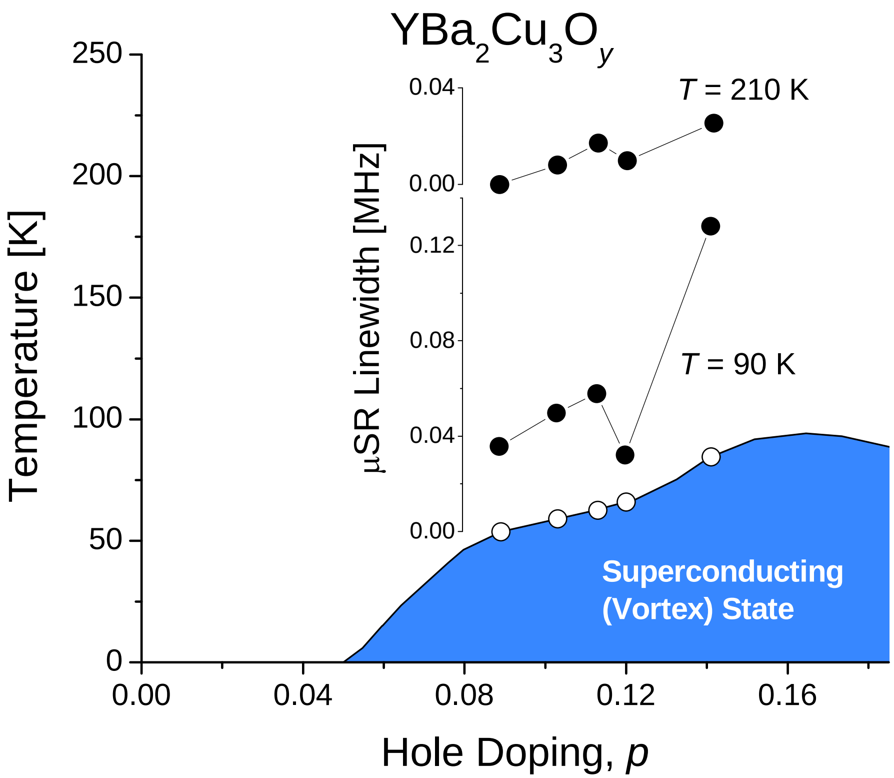
$T = 90$ K



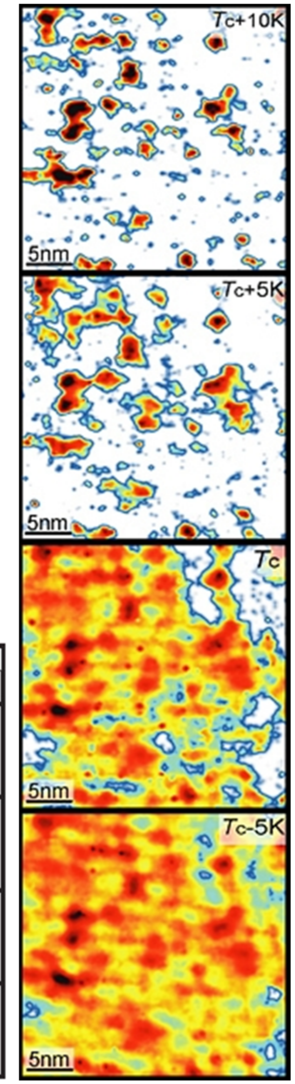




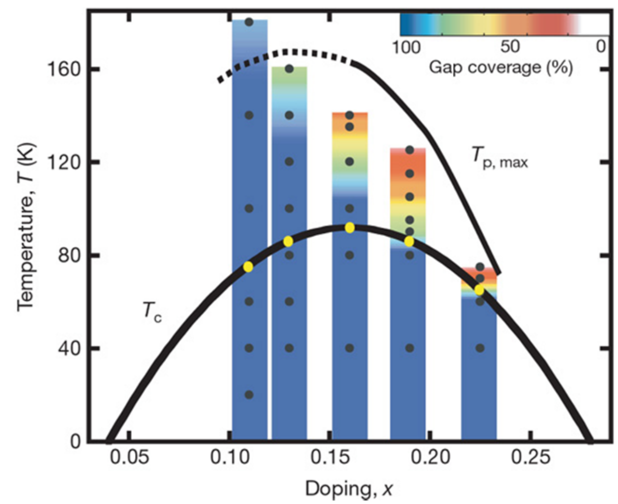
JES *et al.* PRL **101**, 117001 (2008)



Spatially-resolved STM Measurements of Gap Formation



Tiny, isolated patches of superconductivity only a few nanometers wide exist above *Tc* in $Bi_2Sr_2CaCu_2O_{8+\delta}$.



Gomes *et al.* Nature **447**, 569 (2007)