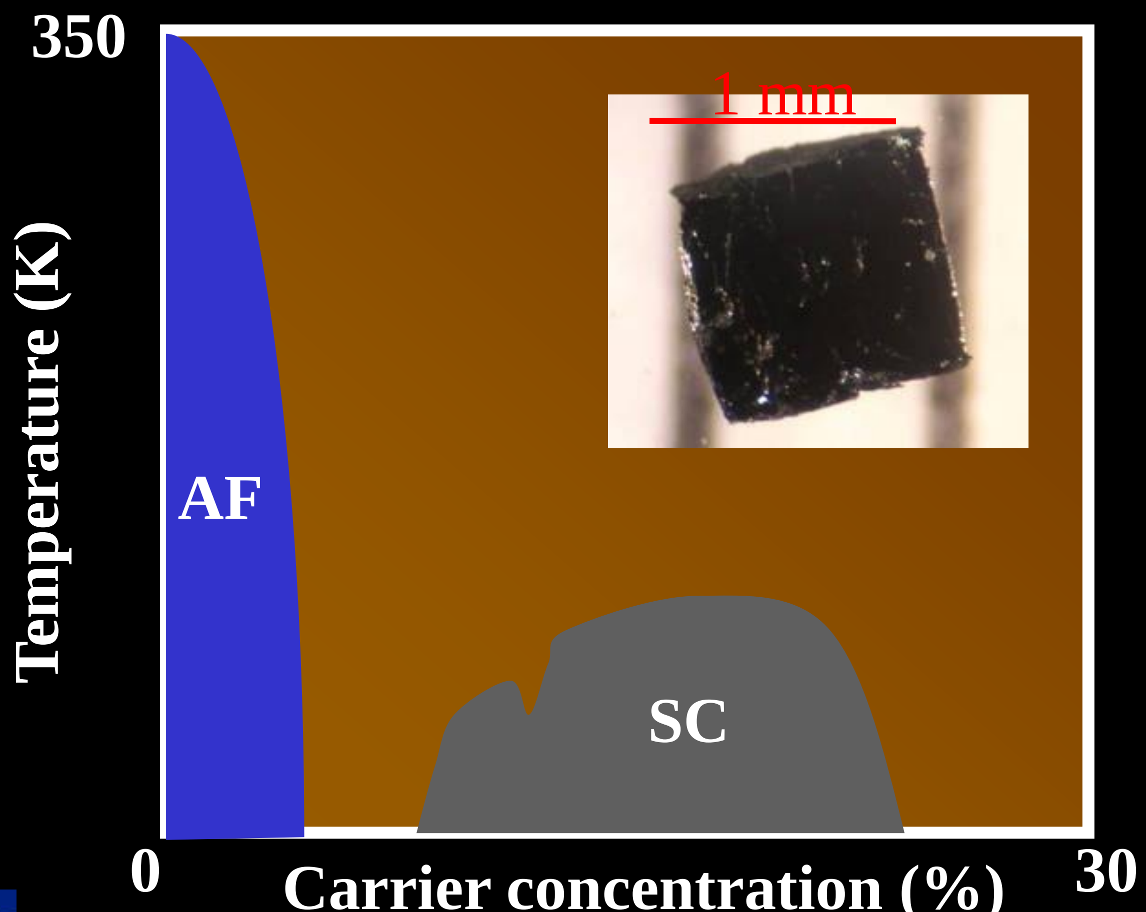
High-T_c from a doped antiferromagnet

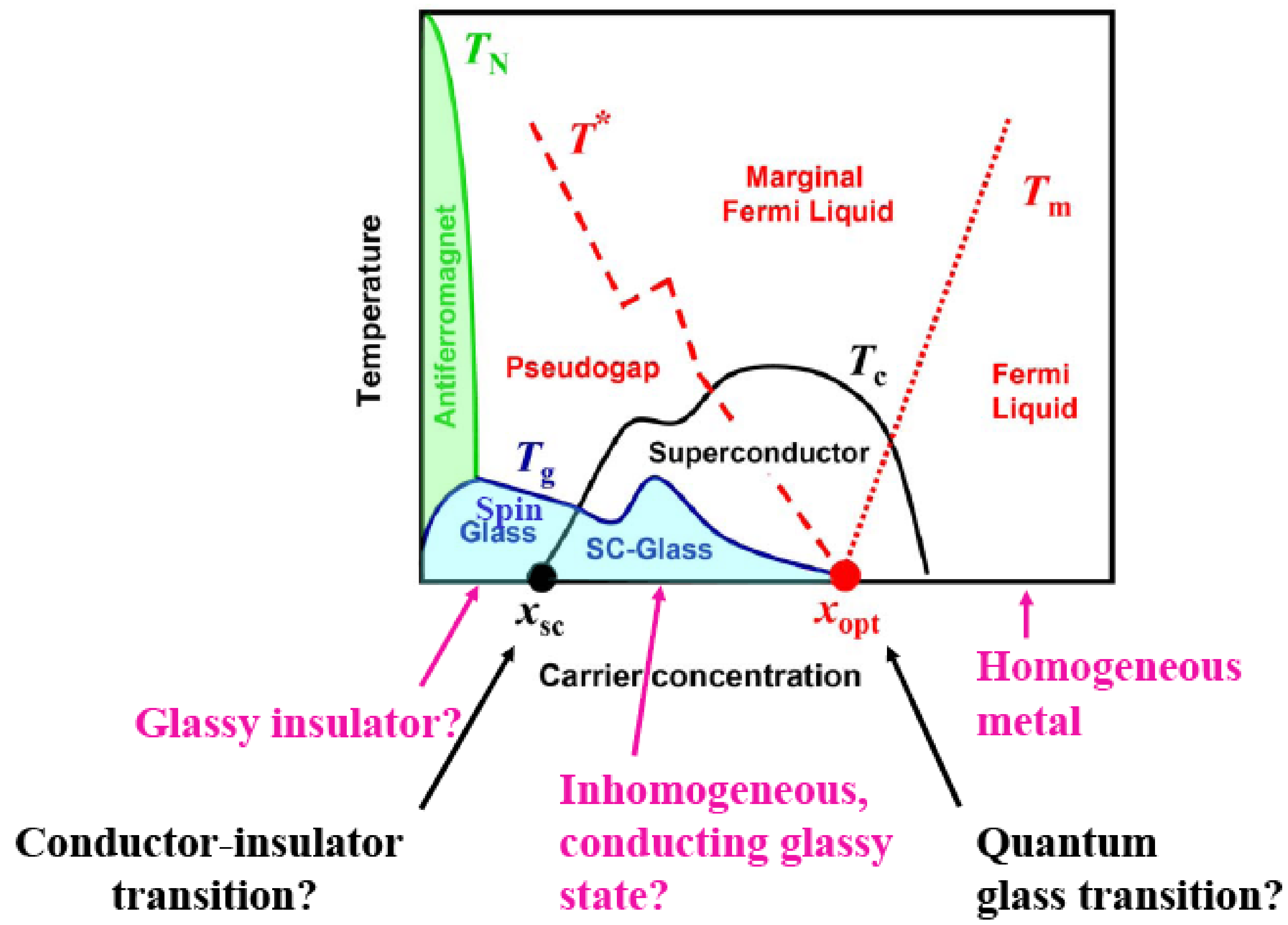
Christos Panagopoulos



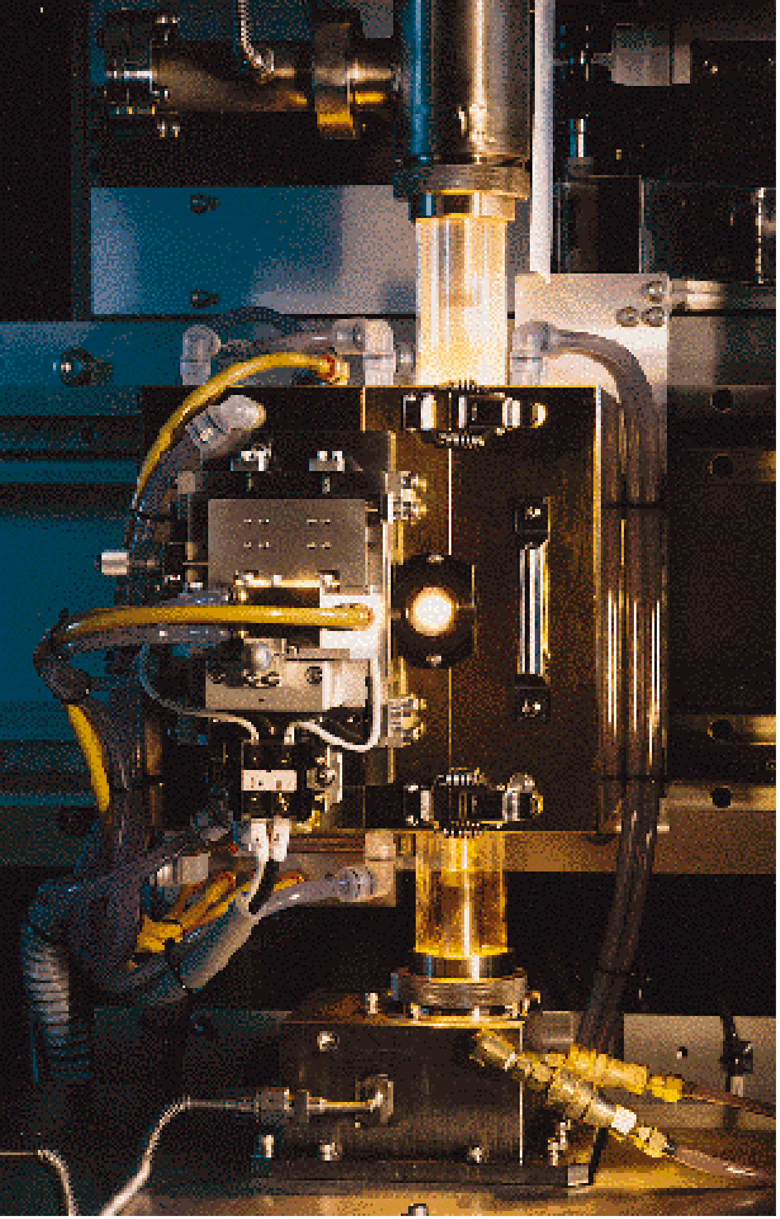
(Quantum tuning parameter)

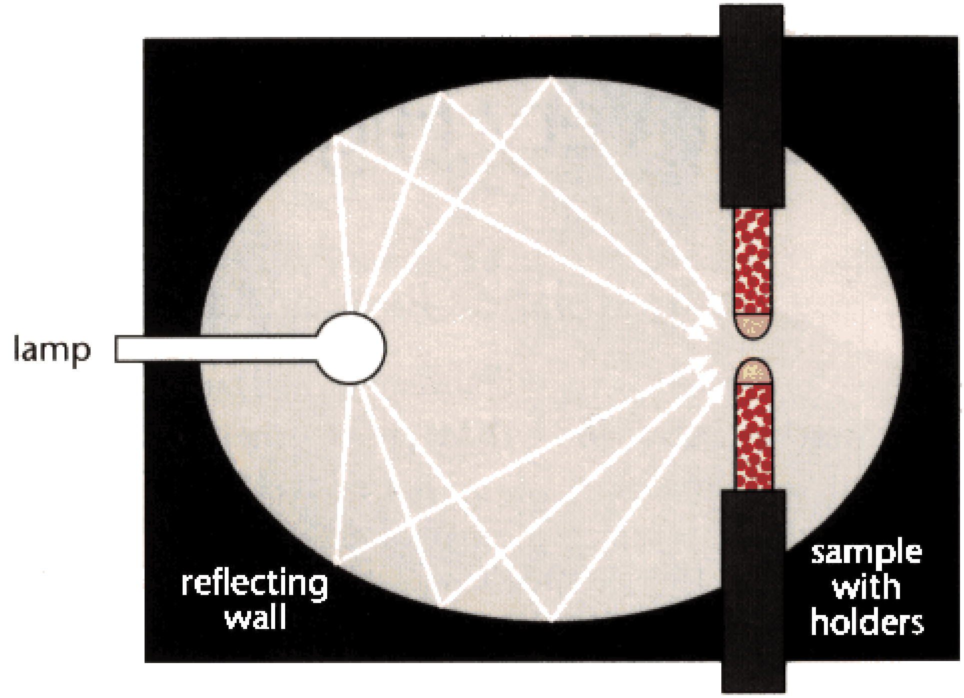
EUROPEAN SCIENCE FOUNDATION

- G. Jelbert (Cambridge)
- A. Petrovic (Cambridge / *Geneva*)
- M. Majoros (Cambridge / *Ohio State*)
- D. Popović (*NHMFL – Florida*)
- I. Raicevic (*NHMFL-Florida*)
- T. Nishizaki (*Tohoku Uni*)
- T. Sasagawa (*Tokyo Inst Tech*)
- I. Martin (*LANL*)



T_N
T^*
Marginal Fermi Liquid
T_m
Antiferromagnet
Temperature
Pseudogap
T_c
Fermi Liquid
T_g
Superconductor
Spin Glass
SC-Glass
x_{sc}
x_{opt}
Carrier concentration
Homogeneous metal
Glassy insulator?
Inhomogeneous, conducting glassy state?
Conductor-insulator transition?
Quantum glass transition?





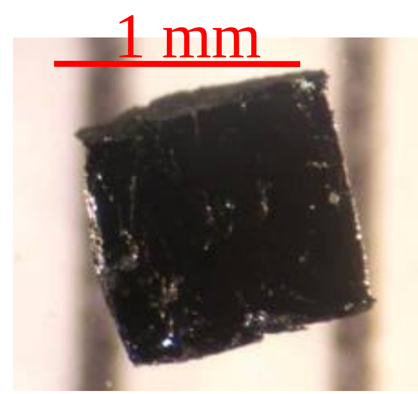
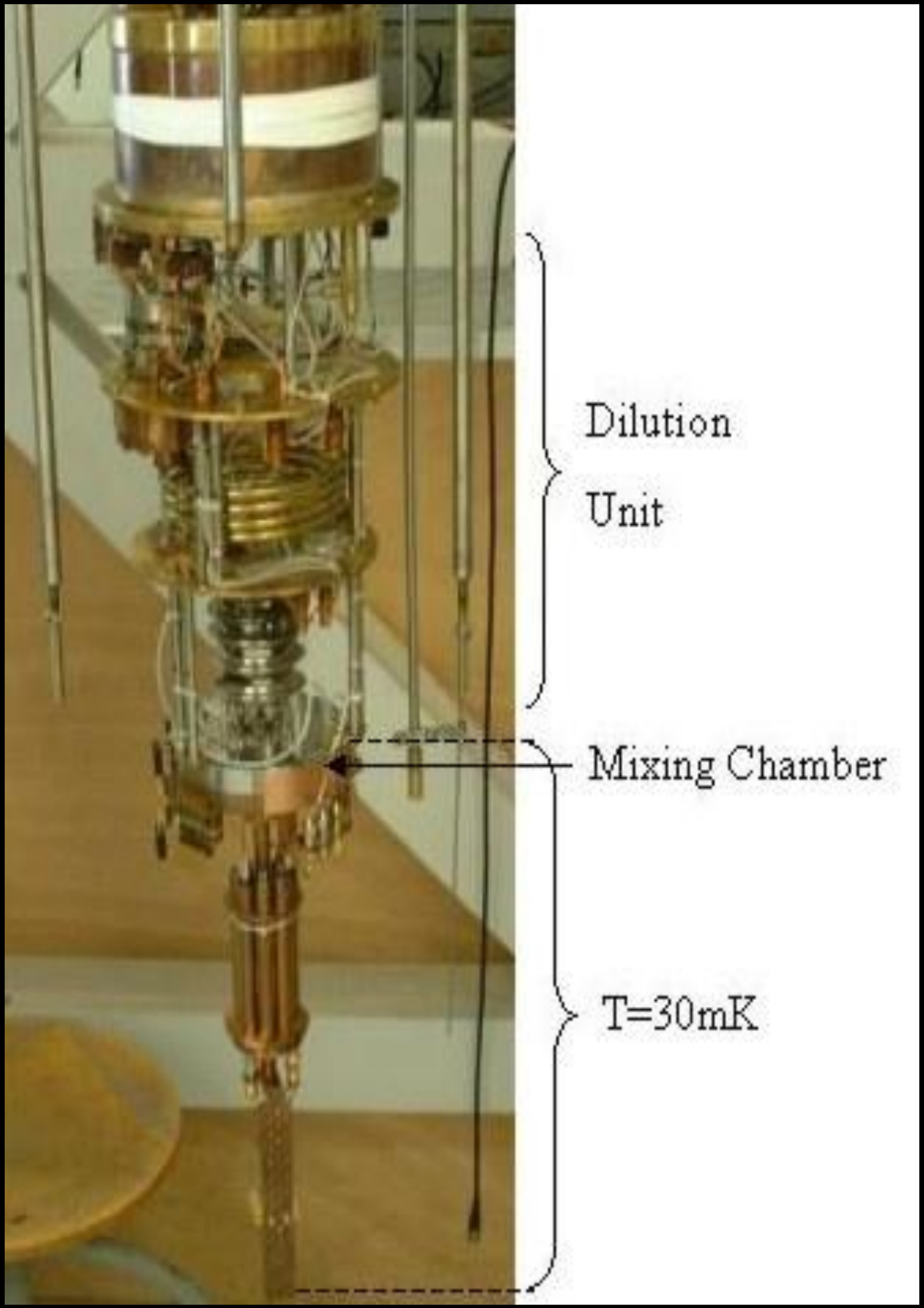


Image Furnace -- Operates in the range of 1000 C to 2800 C in controlled atmospheres. Heating is provided by either a halogen lamp (1.5 or 3.5 kW) or a xenon lamp (5.4 kW).

Creating Low Temperatures

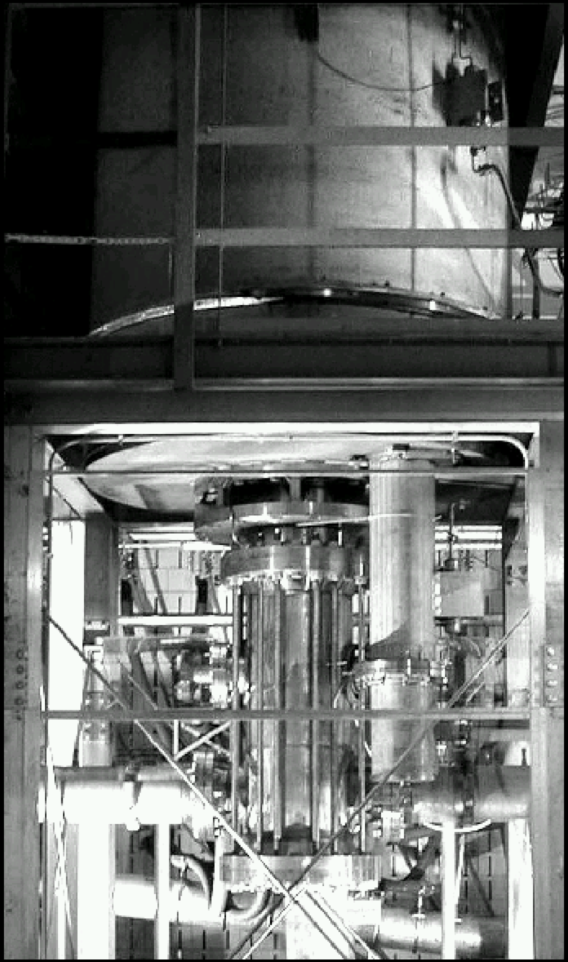
Outer space:
3000 mK



High Magnetic Fields

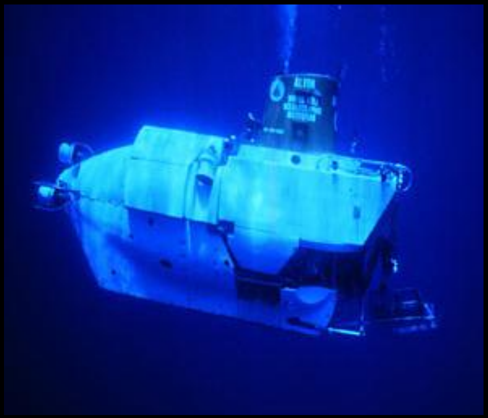
Earth's magnetic field:
0.0001 T

Superconducting solenoids:
up to 21 T

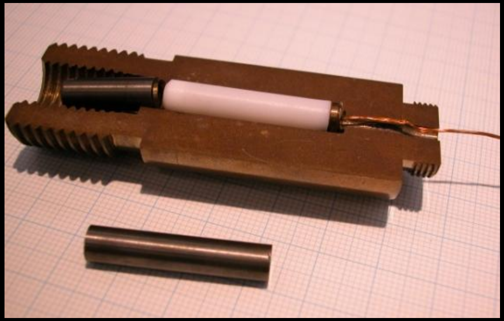


NHMFL hybrid:
45 T

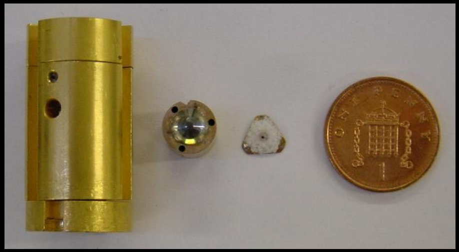
Creating High Pressures



Ocean floor:
1 kbar



Clamp cell:
30 kbar

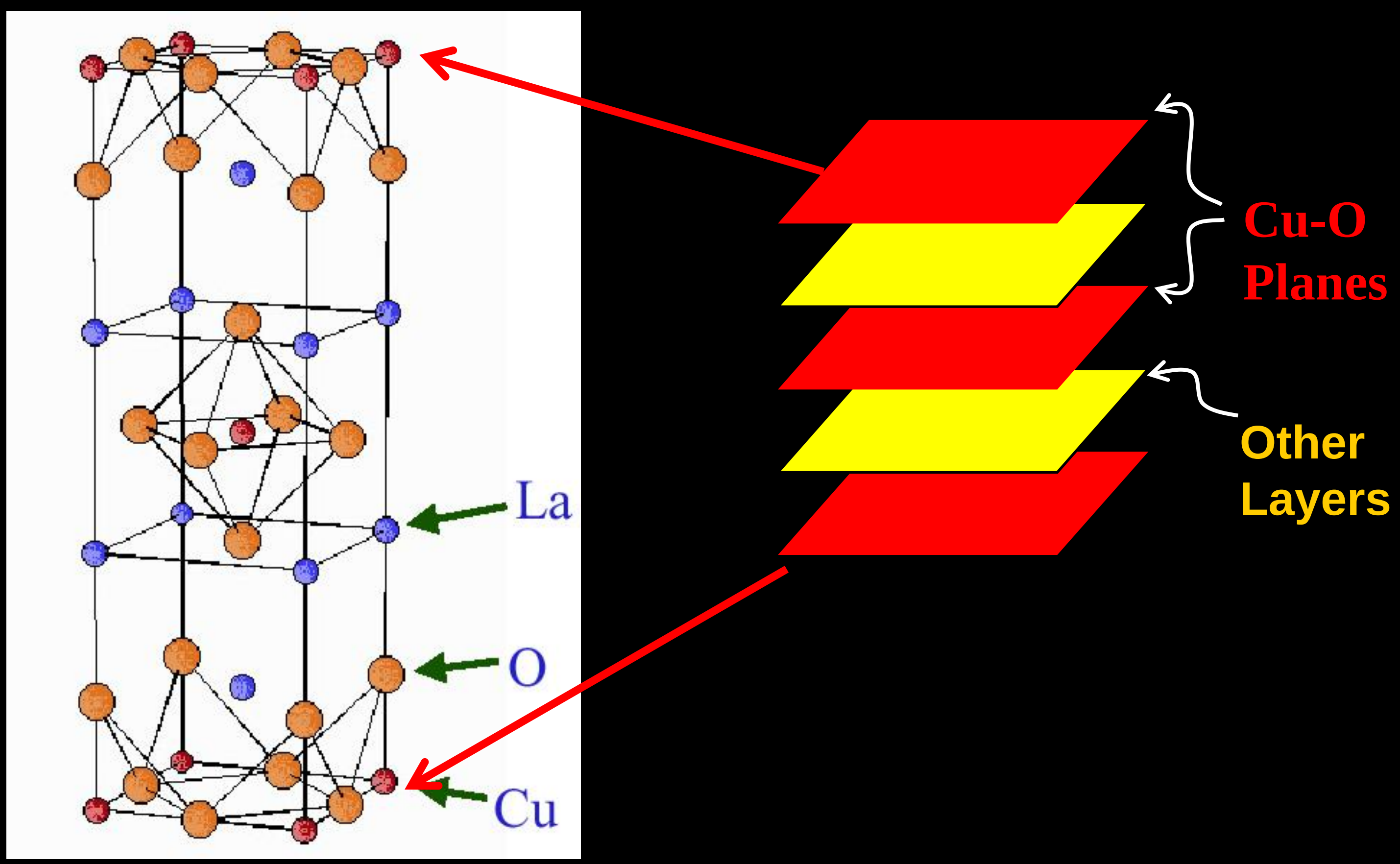


Anvil cell:
150 kbar

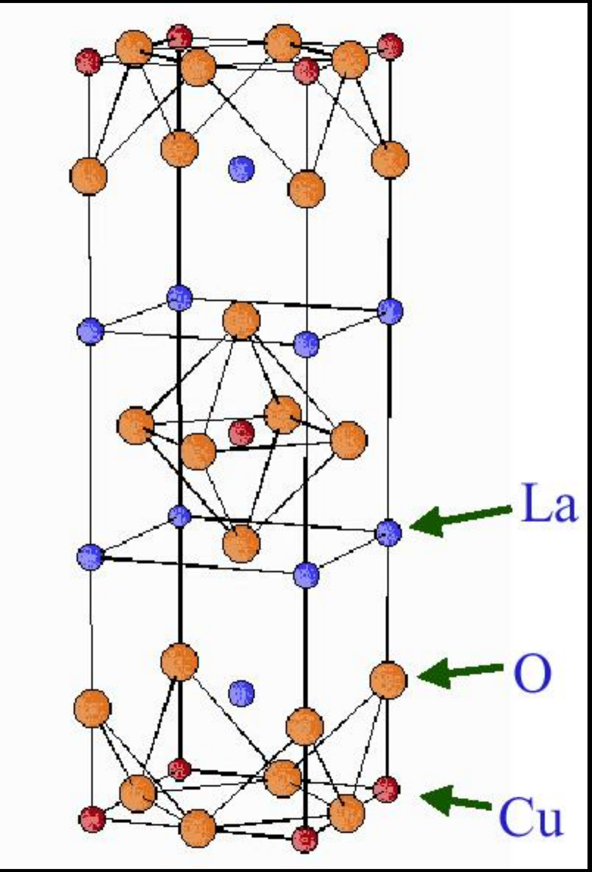
Volume compression of order <u>10%</u>

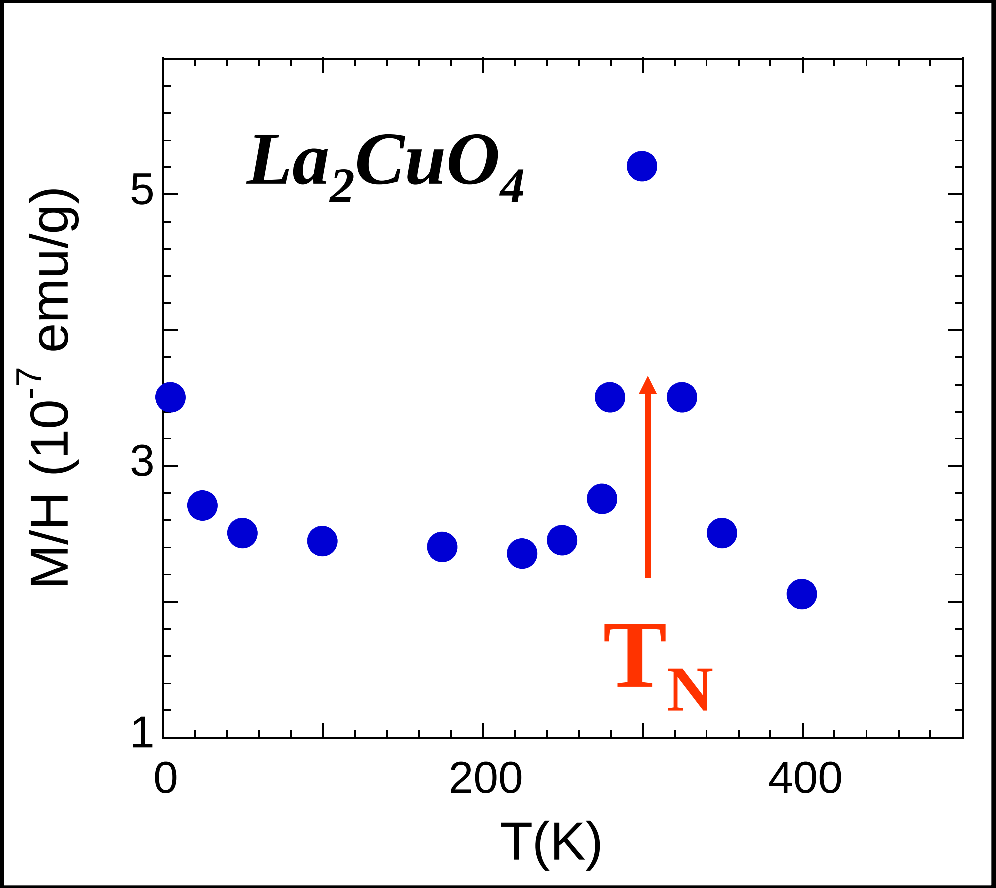
Parent antiferromagnet

La_2CuO_4



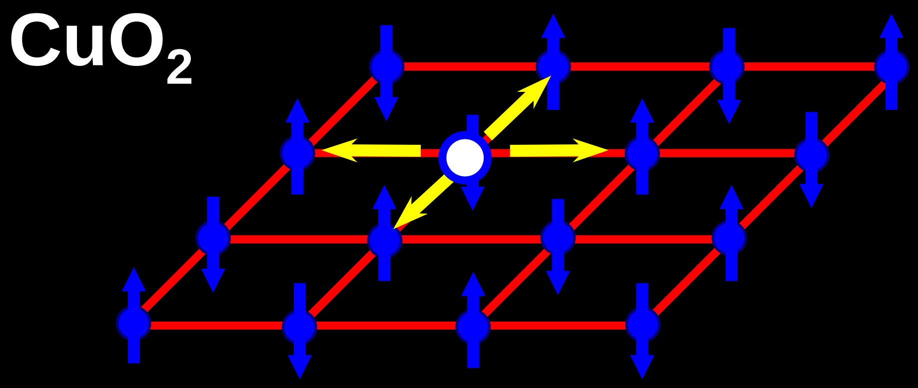
Parent antiferromagnet

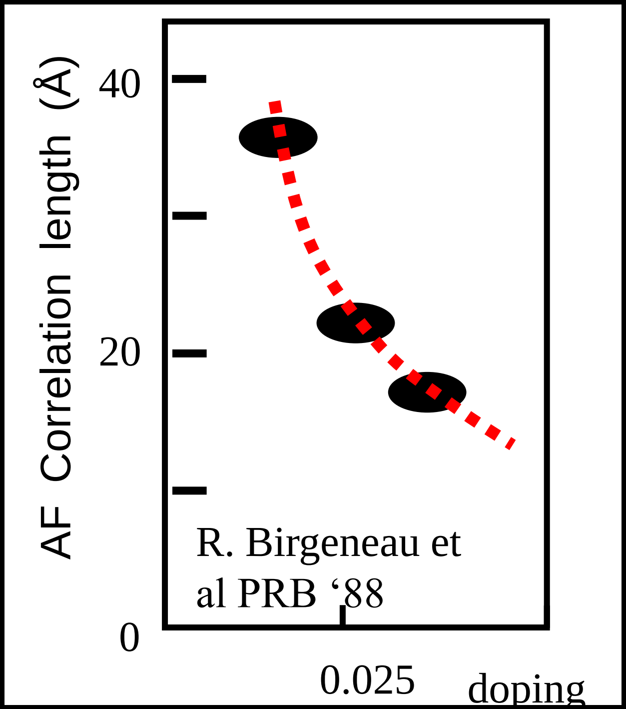




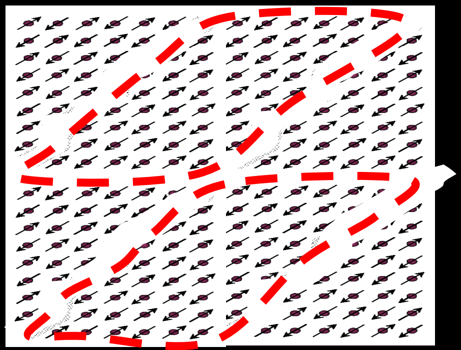
Doping the parent antiferromagnet

$La_{2-x}Sr^{2+}_xCuO_4$

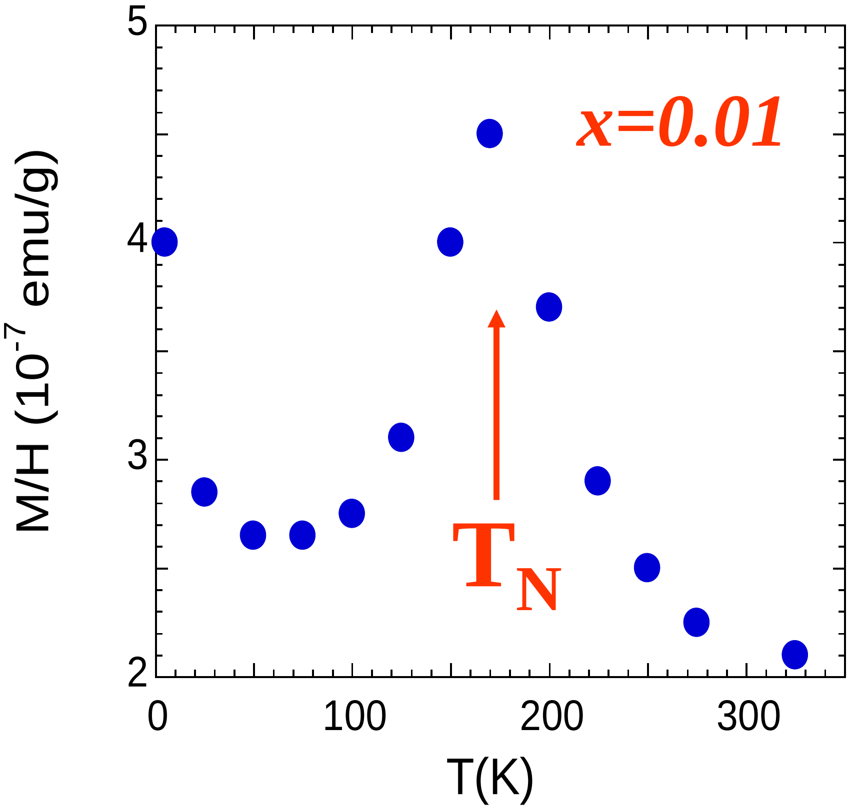




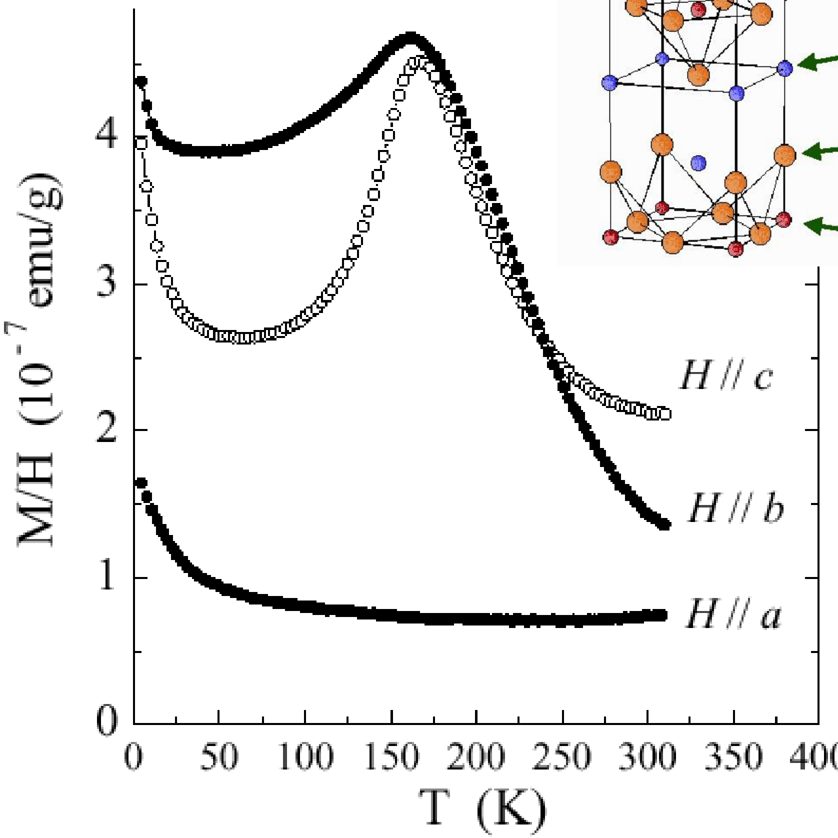
hole motion is frustrated and low energy dynamics come into play

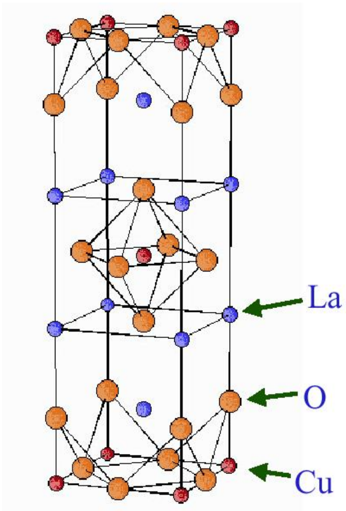


$La_{2-x}Sr^{2+}_{x}CuO_4$



PRB 72, 014536 (2005)



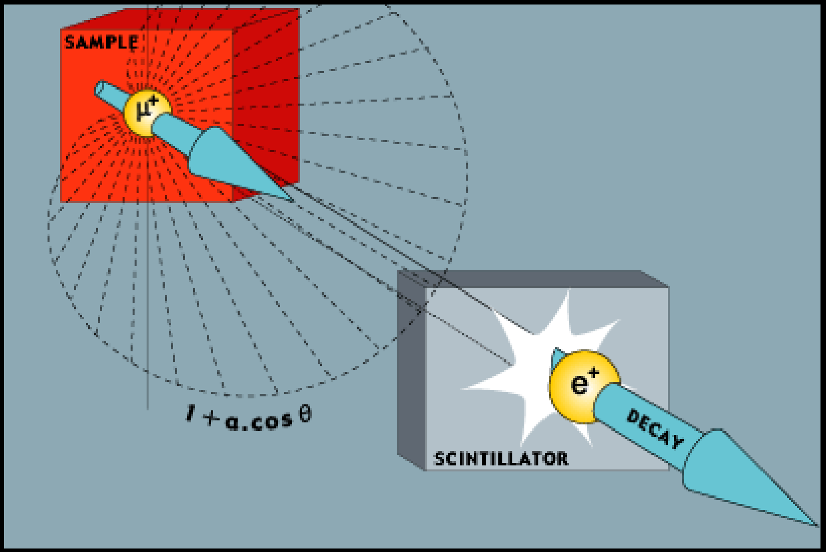


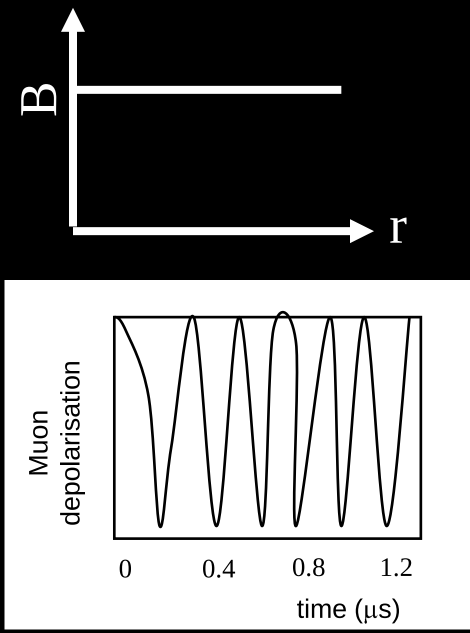
A.N. Lavrov *et al*., PRL 87, 017007 ‘01

In these doped AF hole motion is expected to be frustrated and low energy dynamics come into play

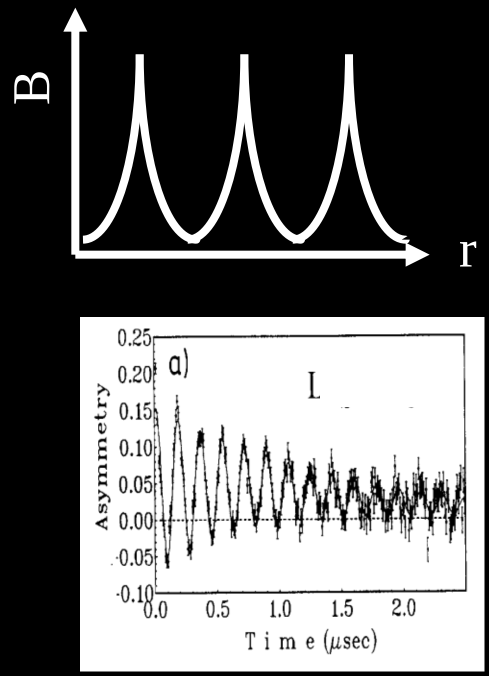
Muon Spin Relaxation (> 10^6 Hz)

m_μ=200m_e
K.E.=***4 MeV***
1mm depth in 1g/cm3
Spin J=1/2,
Sensitivity: 0.01μB

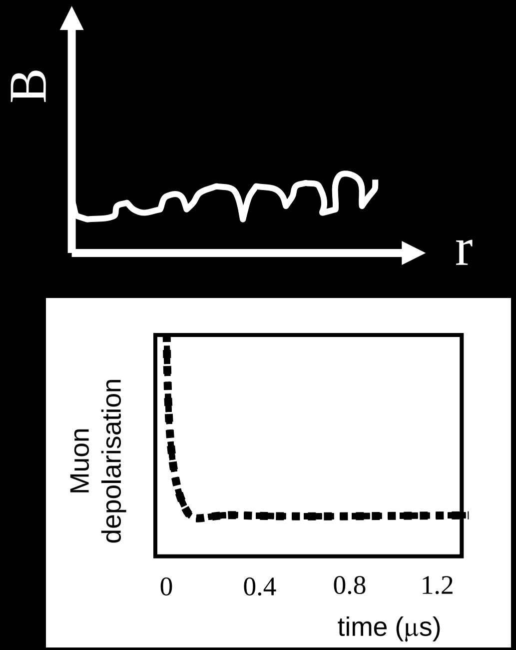




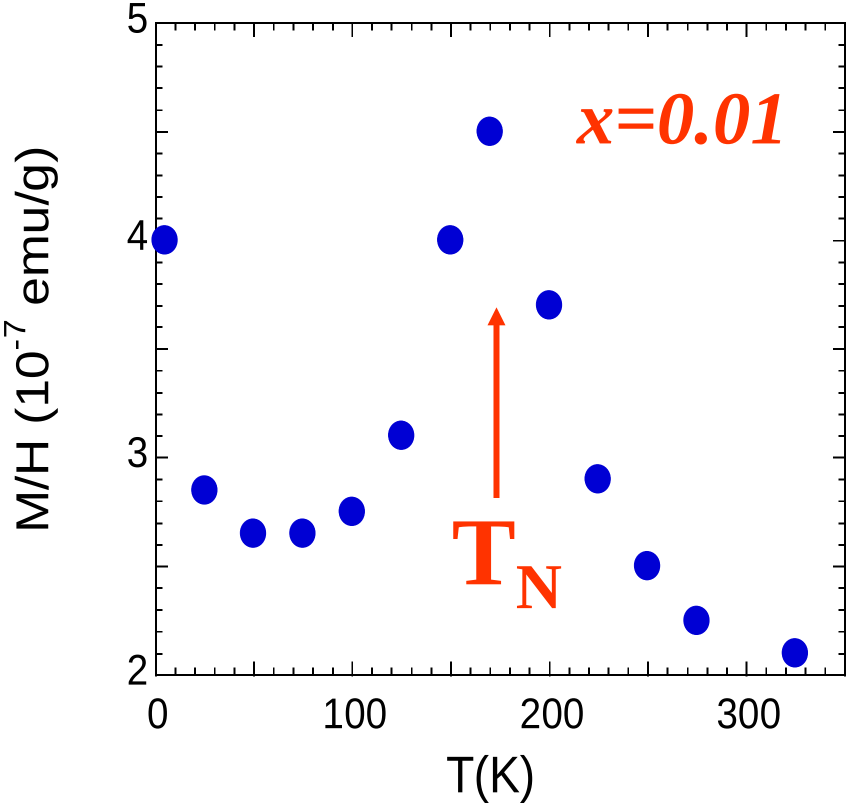
Uniform long range ordered magnet

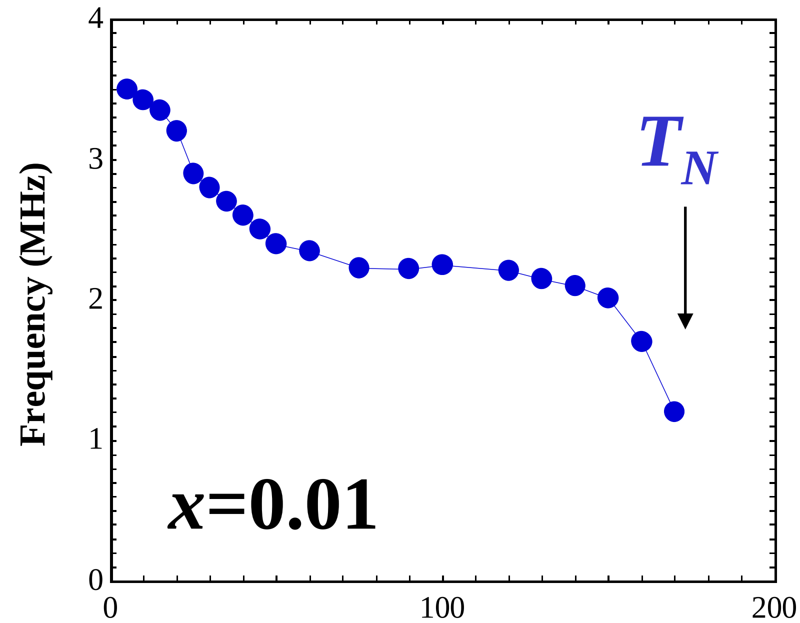


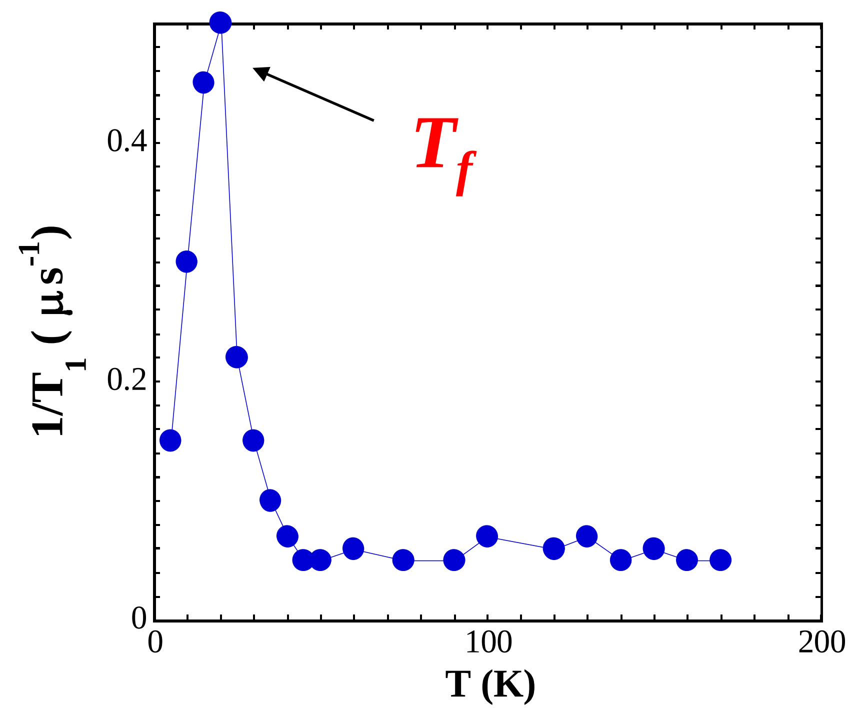
In-homogeneously ordered magnet



Fast fluctuating moments

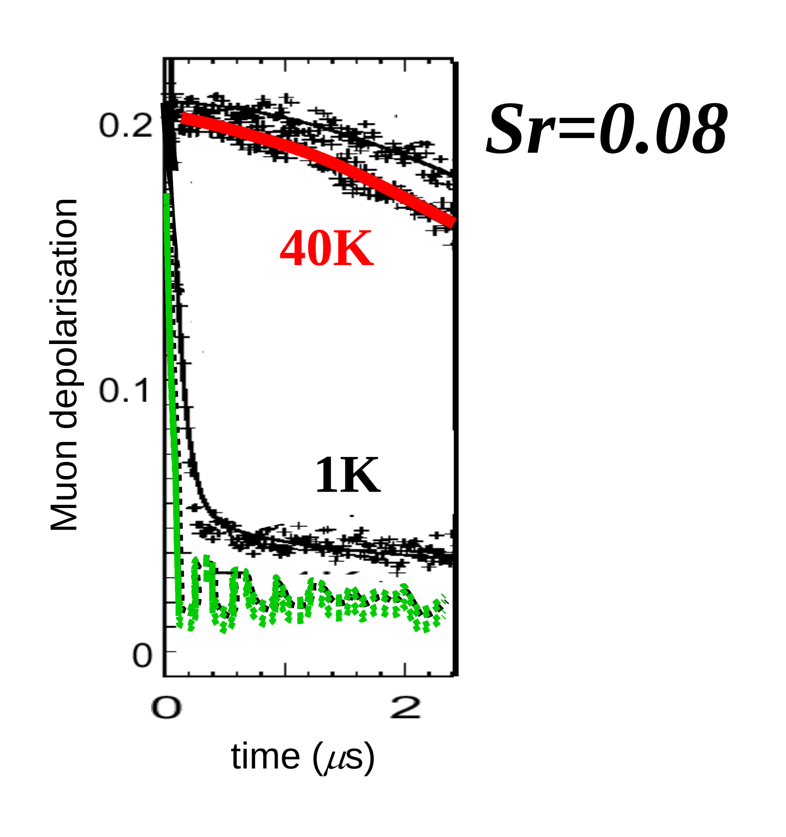


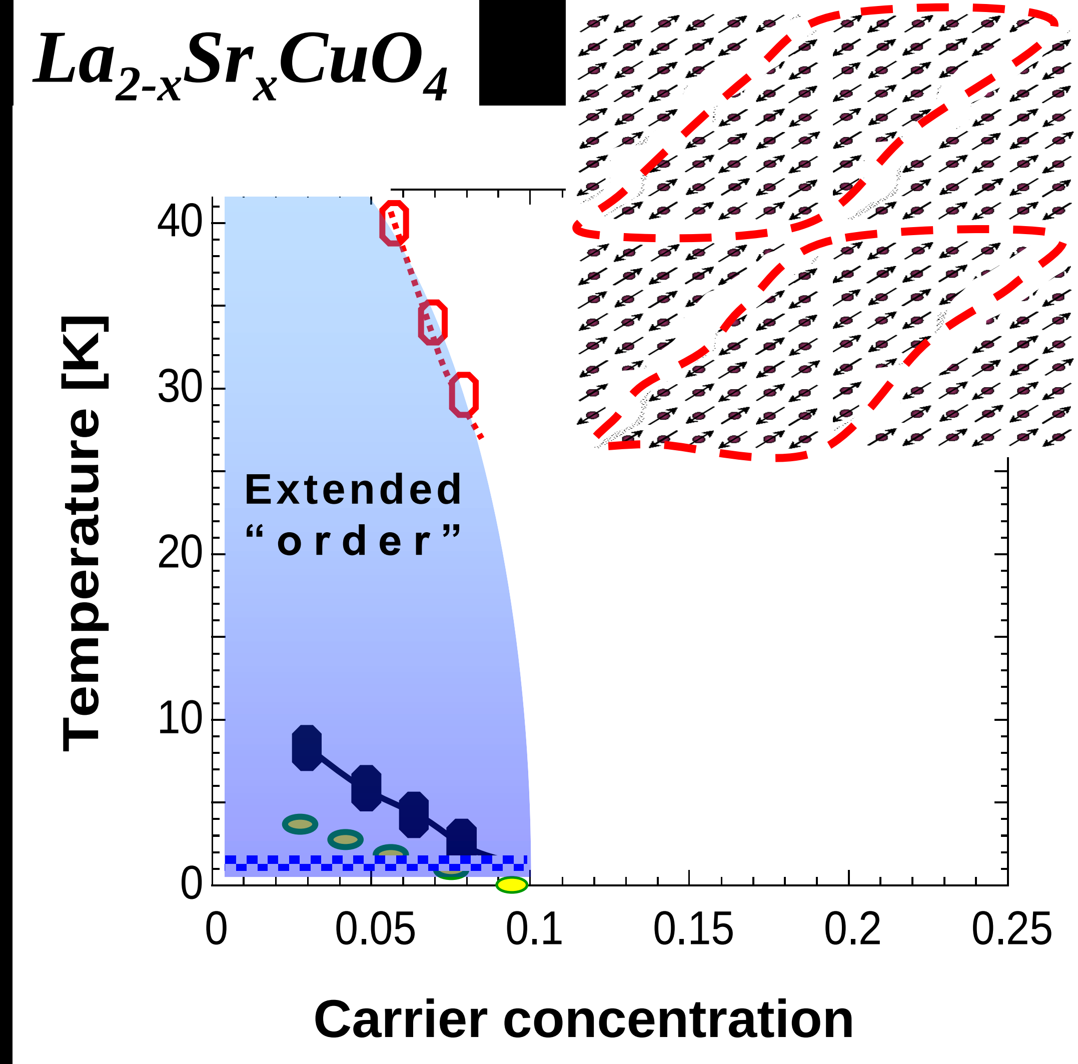


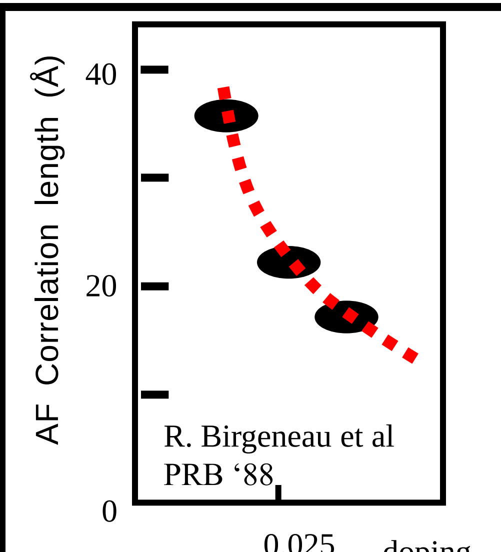


C. P. Solid State Comm. <u>126</u>, 47 ‘03

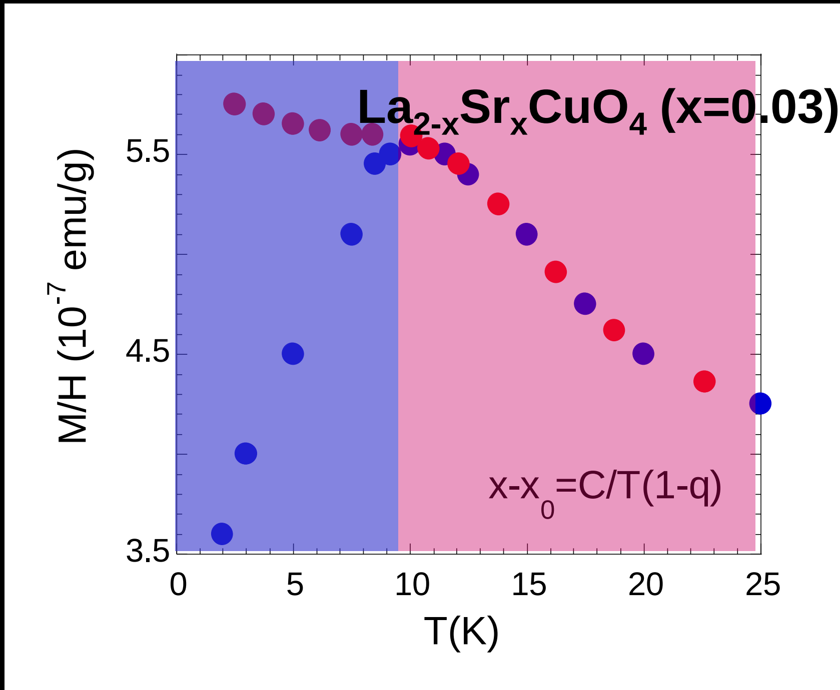
Eds Y.J. Uemura & A.J. Millis

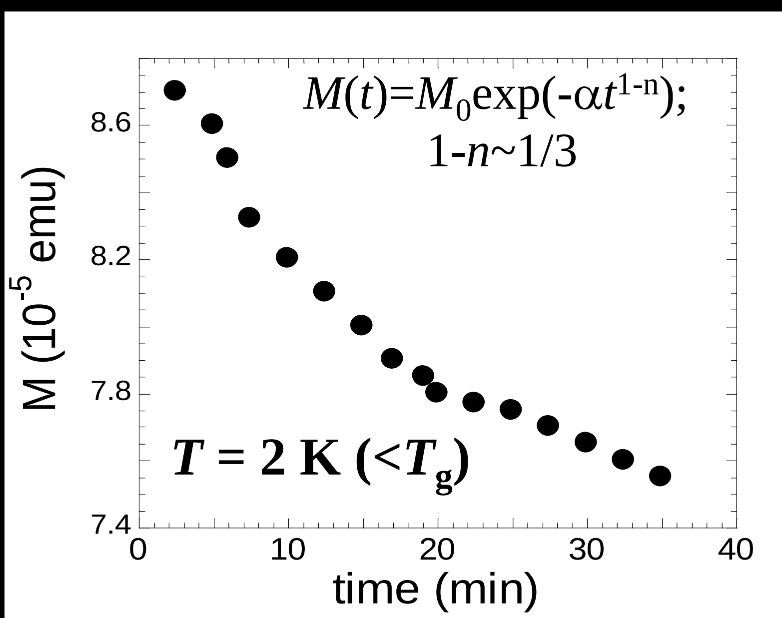


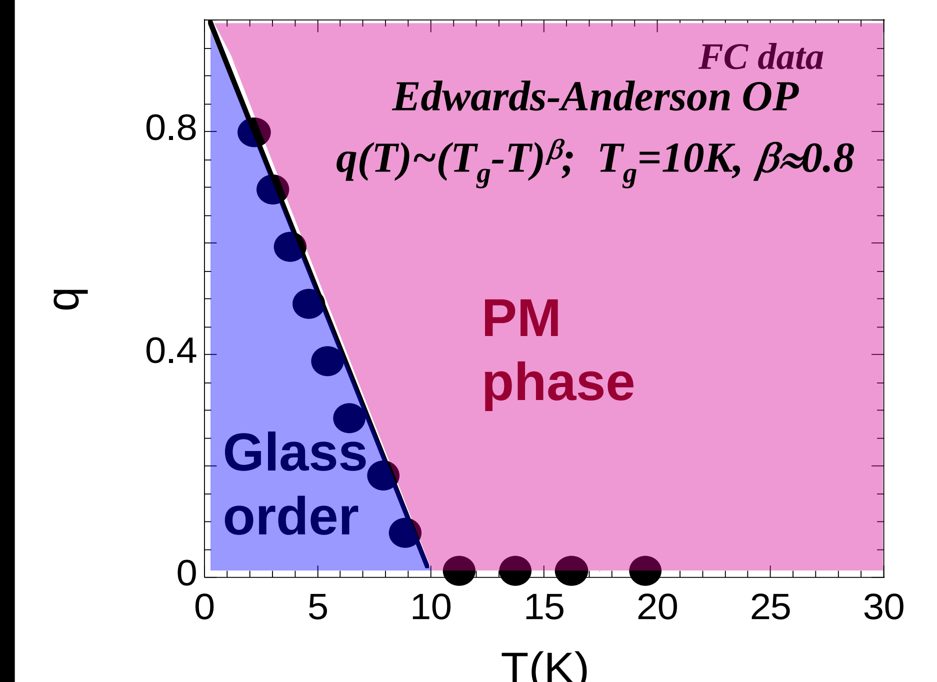




A set of dynamic phase transitions occurring over a wide time window

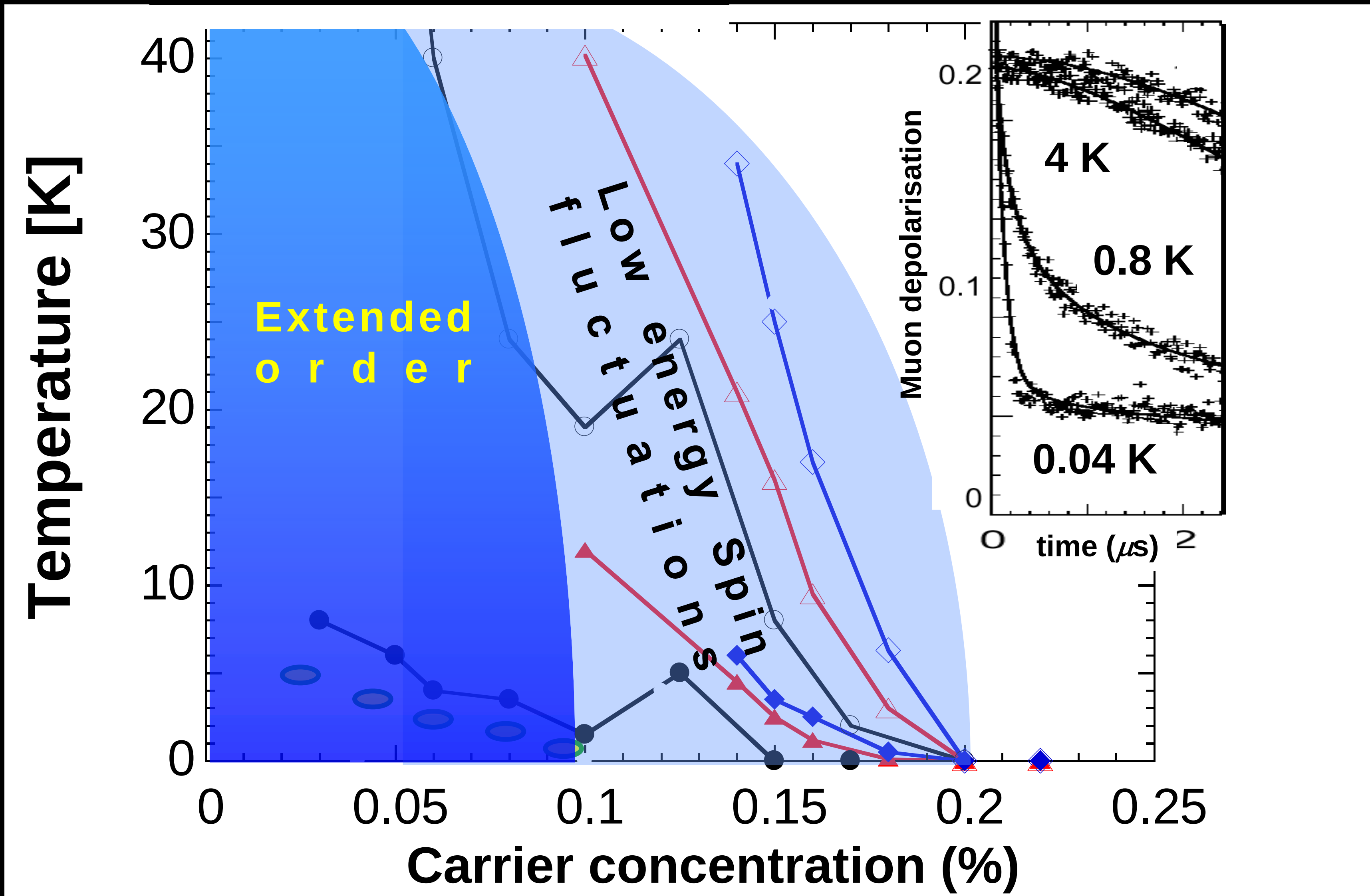






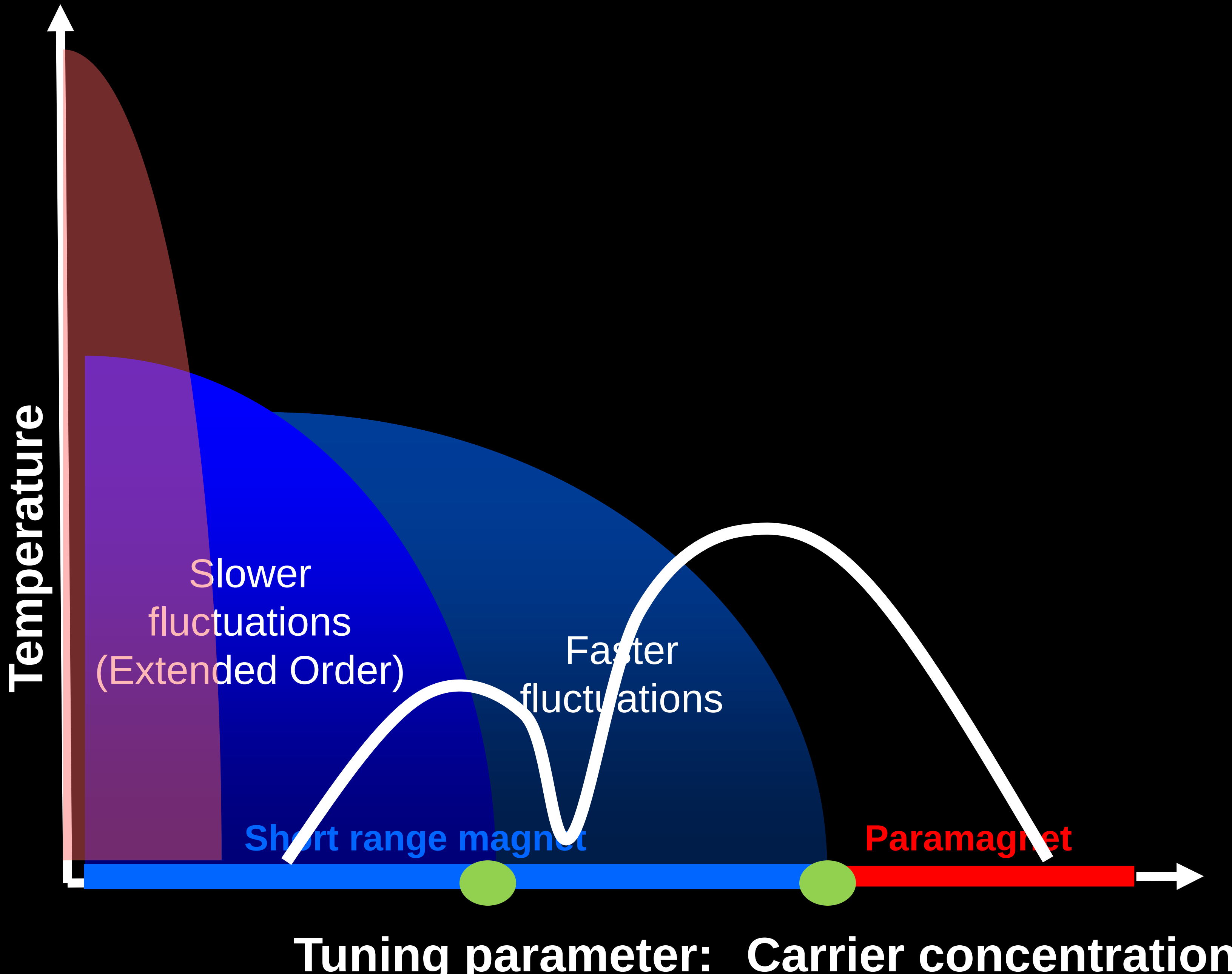
$$\mathcal{H}_{\mathcal{J},N} = -\frac{1}{\sqrt{N}} \sum_{1\le i<j\le N} J_{ij}\sigma_i\sigma_j$$

Phys Rev B 72, 014536 (2005)

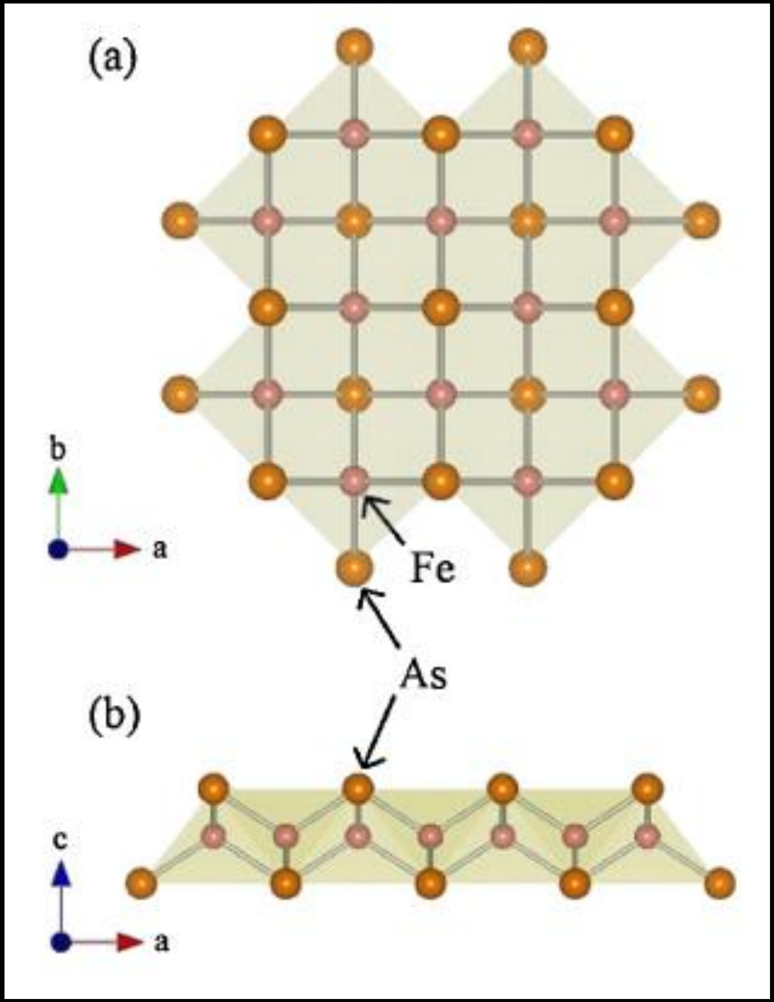


Phys Rev B 66, 064501 (2002)

Phys Rev B 69, 144510 (2004)


Temperature
Slower
fluctuations
(Extended Order)
Faster
fluctuations
Short range magnet
Paramagnet
Tuning parameter: Carrier concentration

Seems to be common among doped AF's

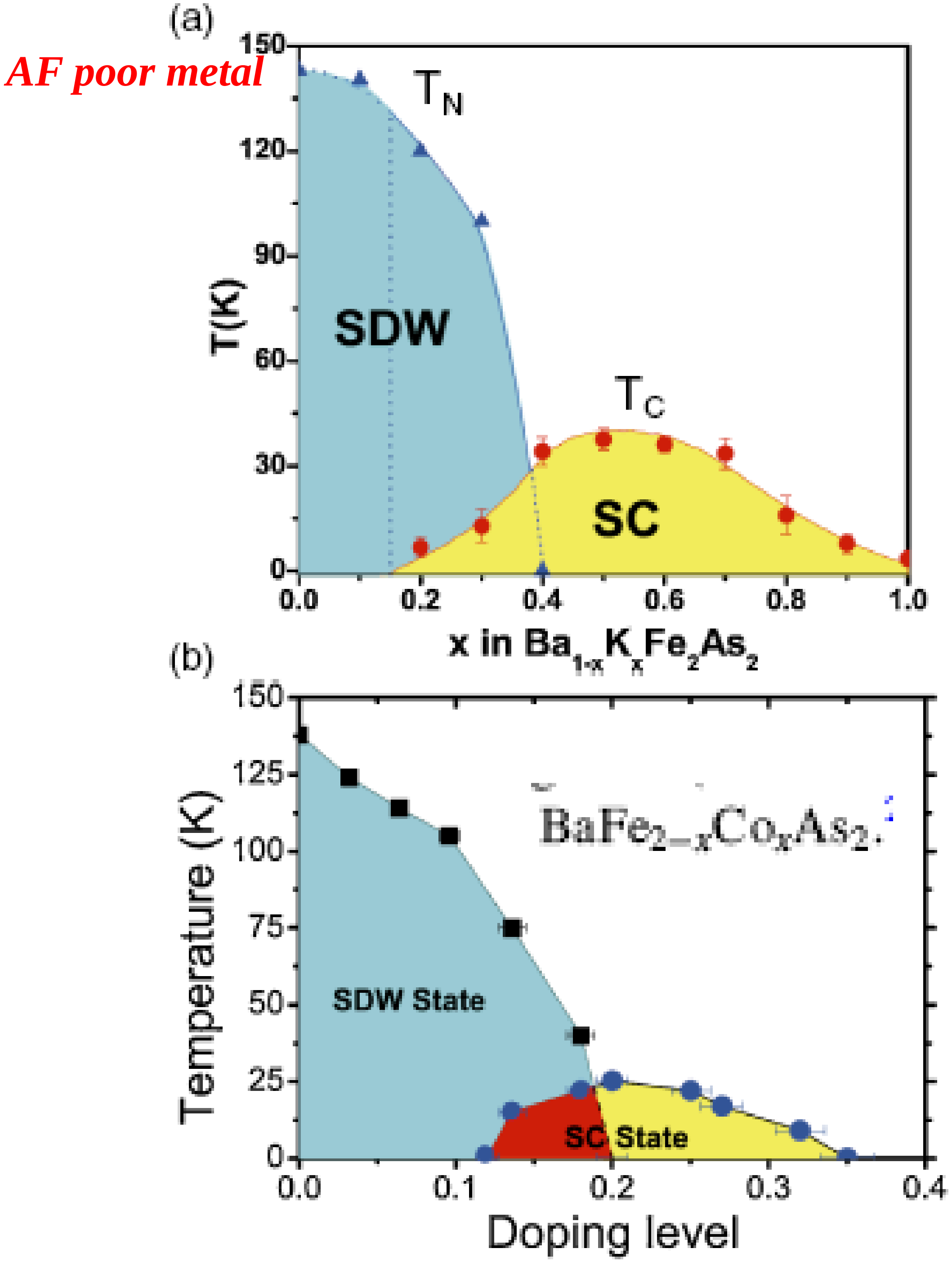


2D-like Fe-based high-T_c SC's

(a) Top (c-axis)

(b) b-axis

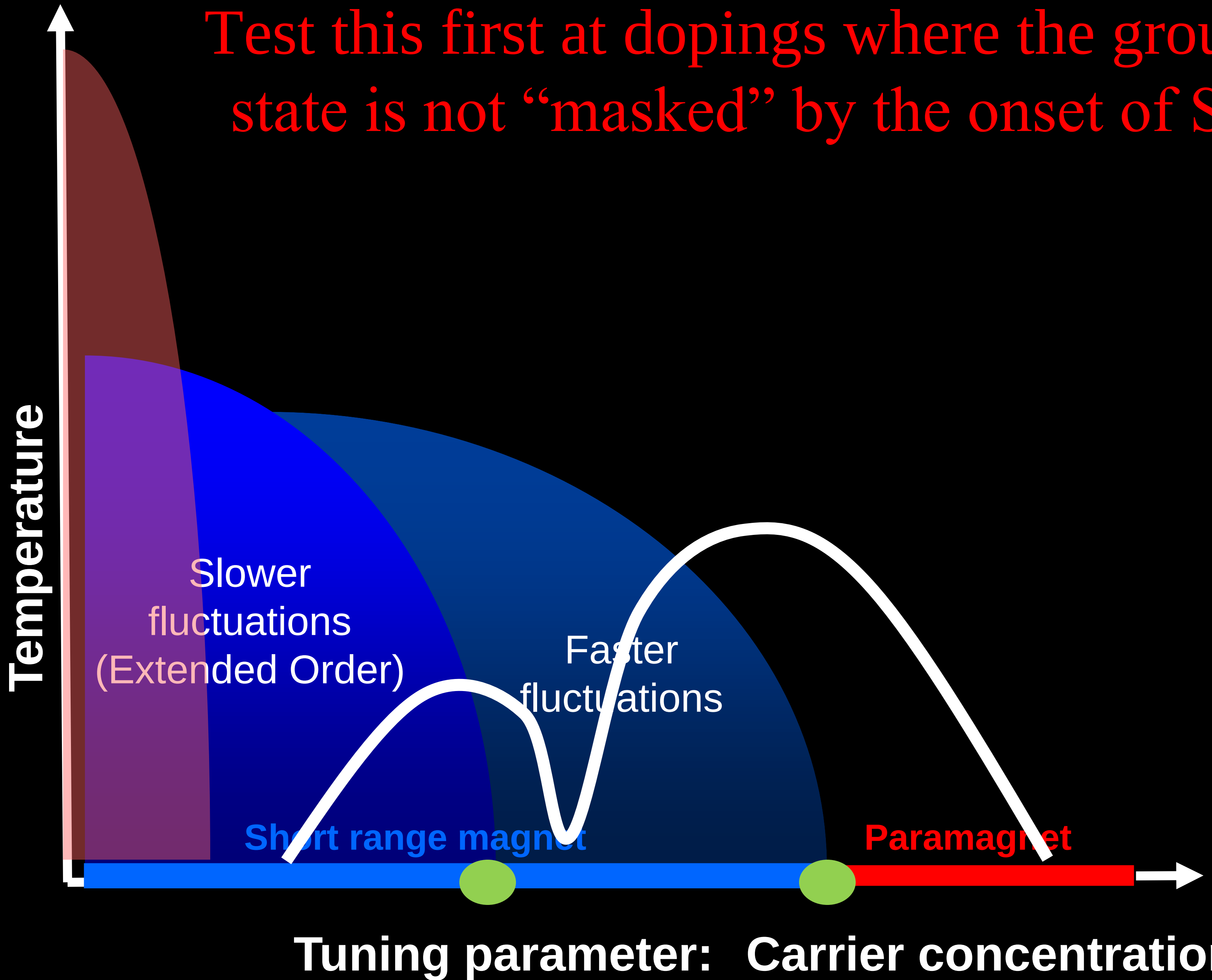
views of the FeAs layer.


AF poor metal
(a)
T_N
SDW
T_C
SC
T(K)
x in Ba1-xKxFe2As2
(b)
BaFe2-xCoxAs2
SDW State
SC State
Temperature (K)
Doping level

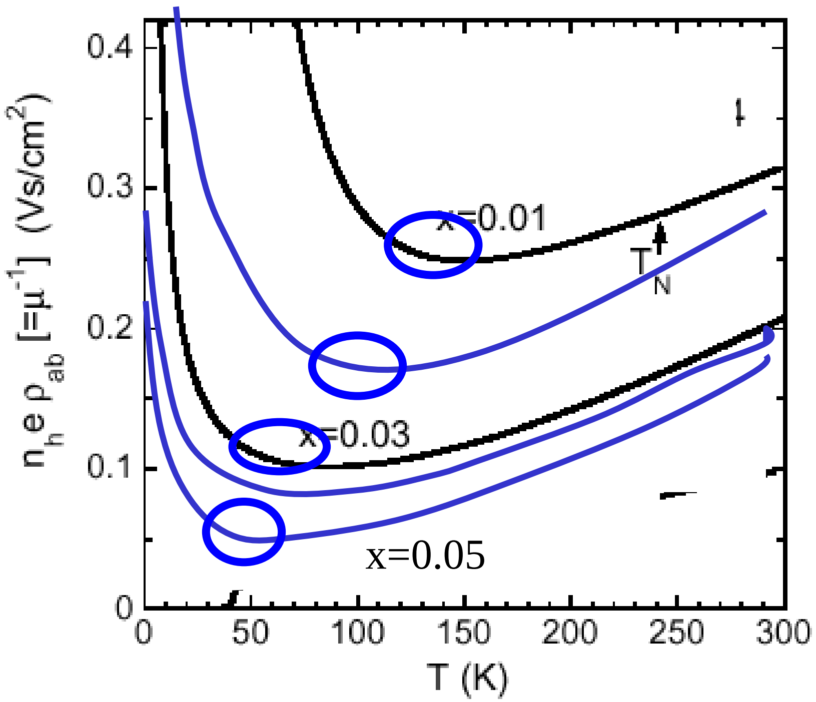
Are the doped carriers affected by the induced spin fluctuations?

Is there a correlation with SC?

Test this first at dopings where the ground state is not "masked" by the onset of SC



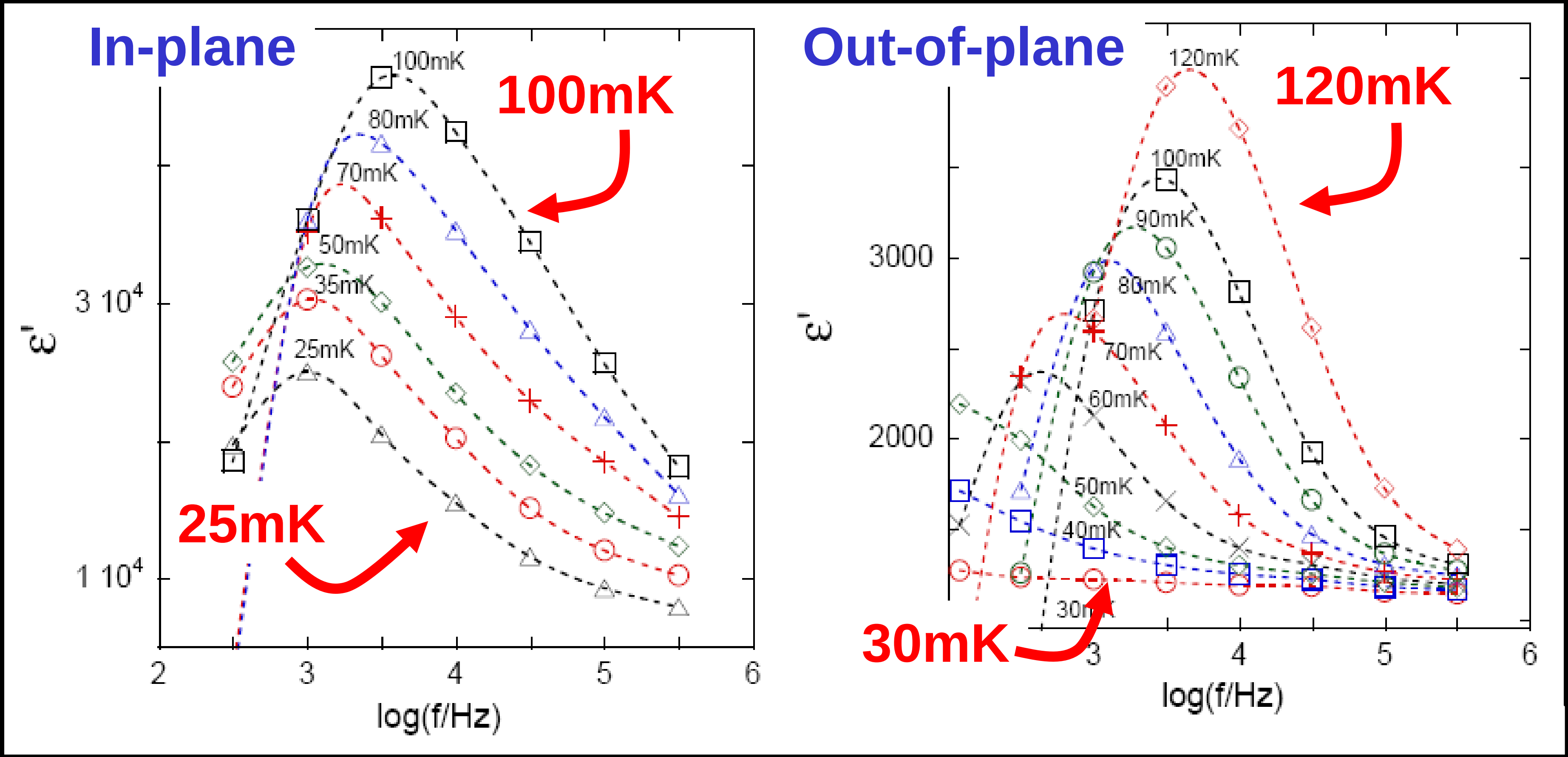
Inverse mobility



There is a correlation between the frustration caused by the added holes and the charge transport.

Y. Ando *et al.*, *Phys. Rev. Lett. '03*

C. Panagopoulos *et al.*, ***unpublished***

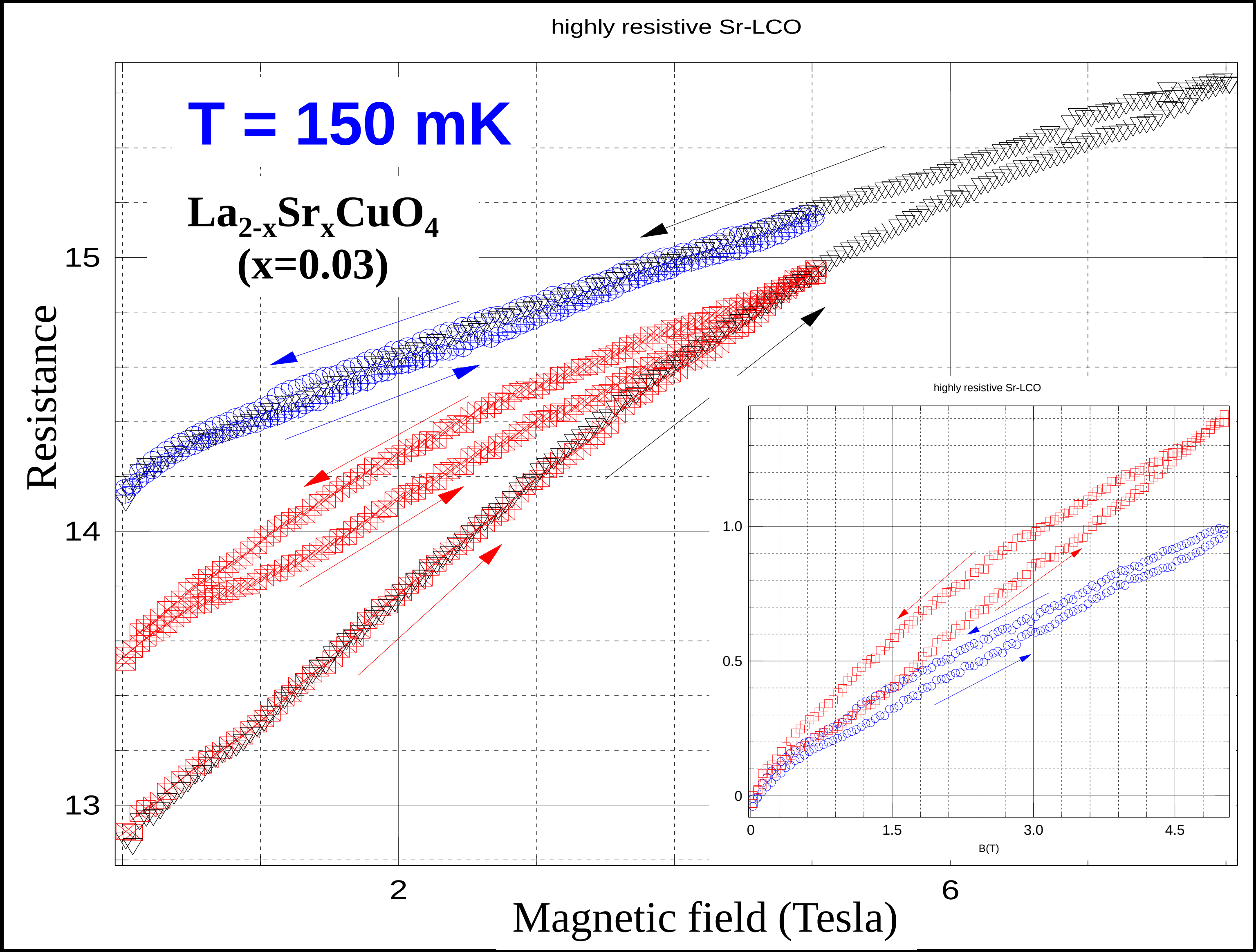


- **Dielectric dispersion:** Broadening of the distribution of relaxation frequencies → Distribution of sizes of electronic domains.

Phys. Rev. Lett. 101, 177004 (2008)

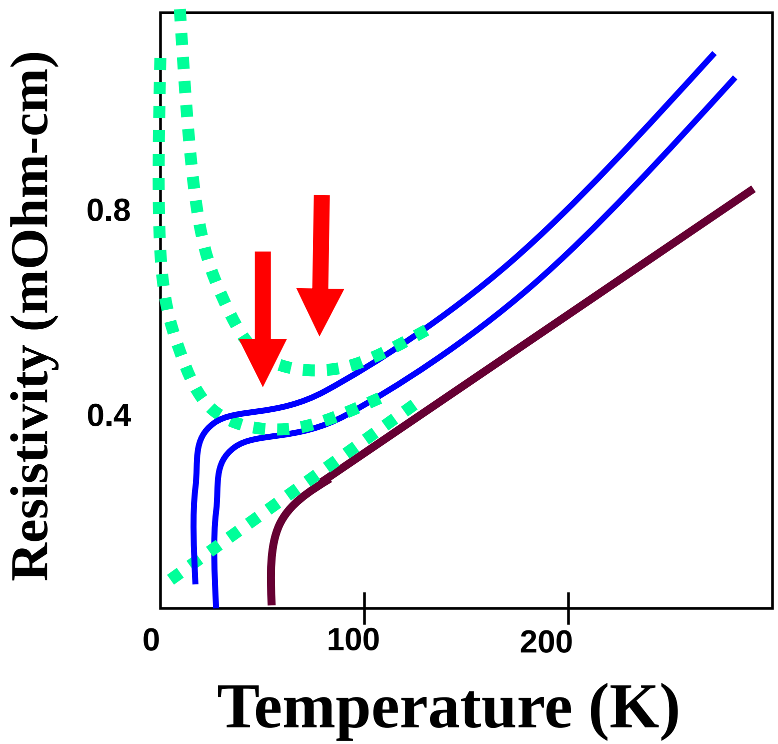
Phys. Rev. B 78, 132513 (2008)

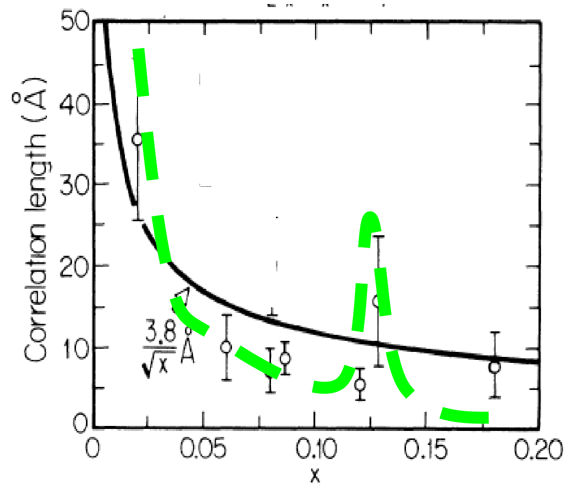
Charge Driven Return Point Memory (c-axis); but also in ab.

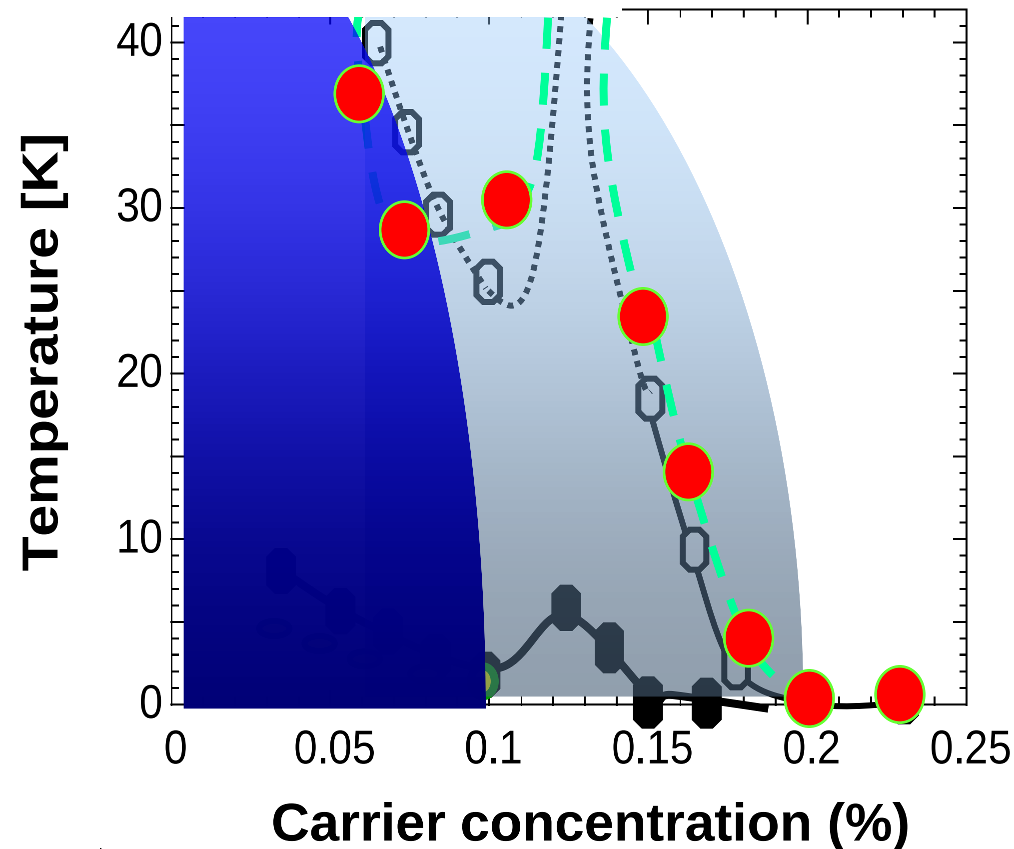


Phys. Rev. Lett. 101, 177004 (2008)

G. Boebinger et al. PRL ’96

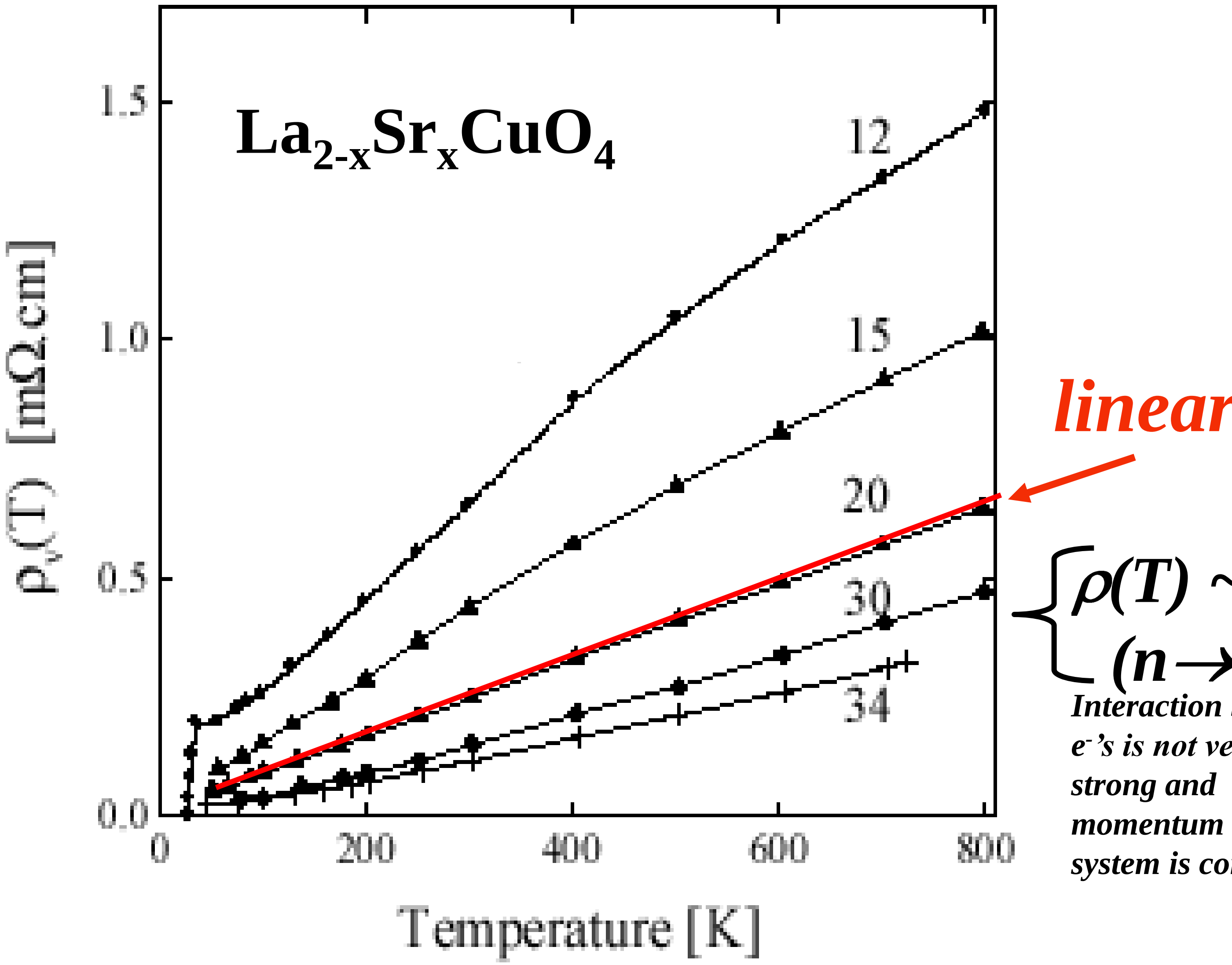






C.P. *et al.*, Phys Rev B 72, 014536 (2005)

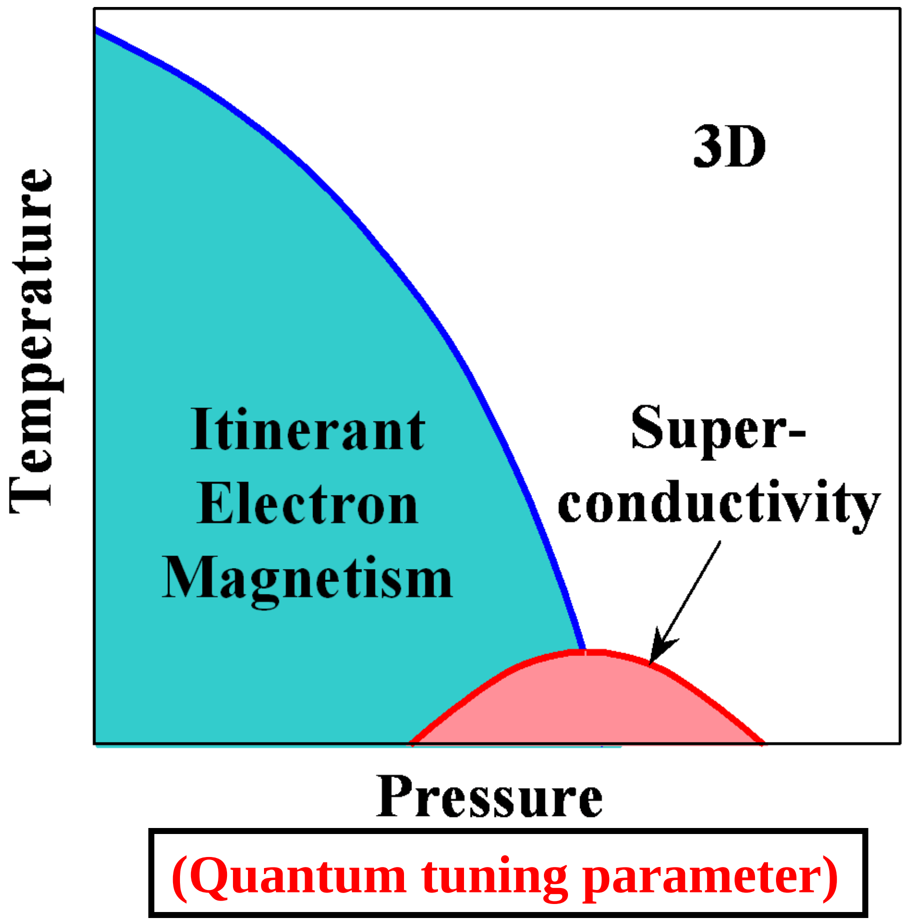
Raw data from T. Takagi *et al.*, PRL '92

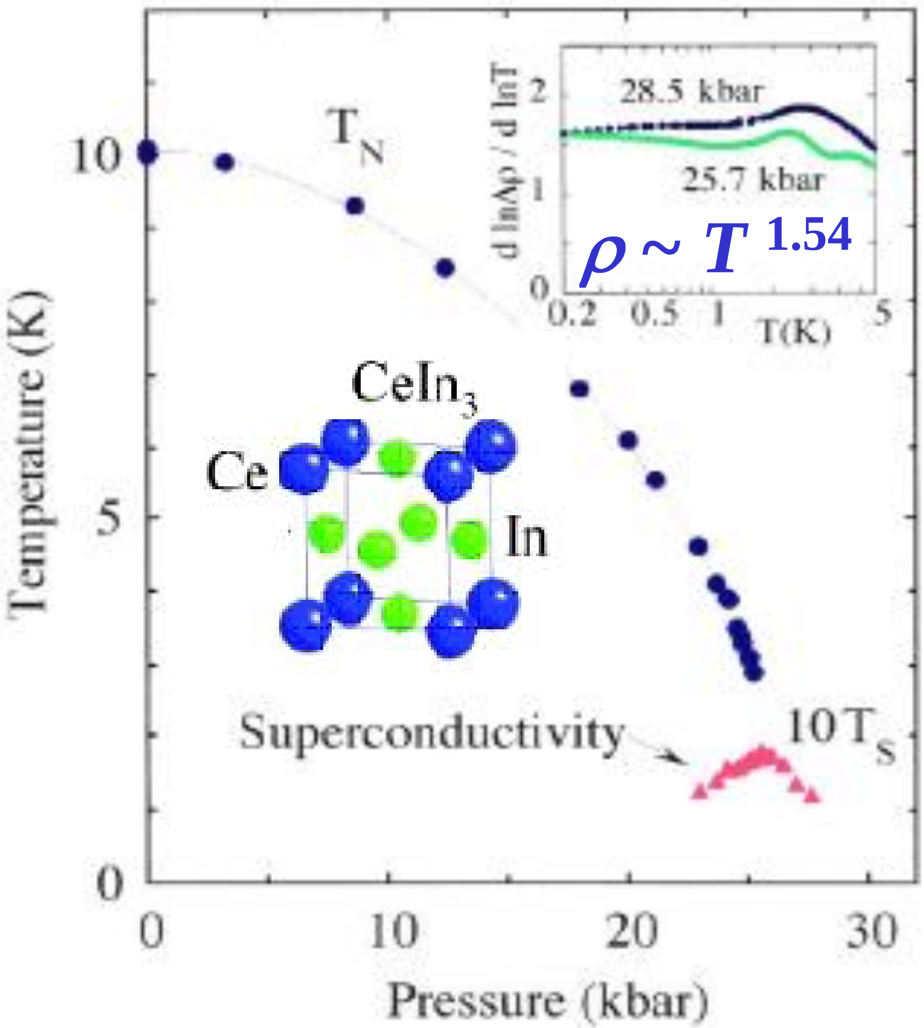


$\rho(T) \sim T^n$ $(n \to 2)$

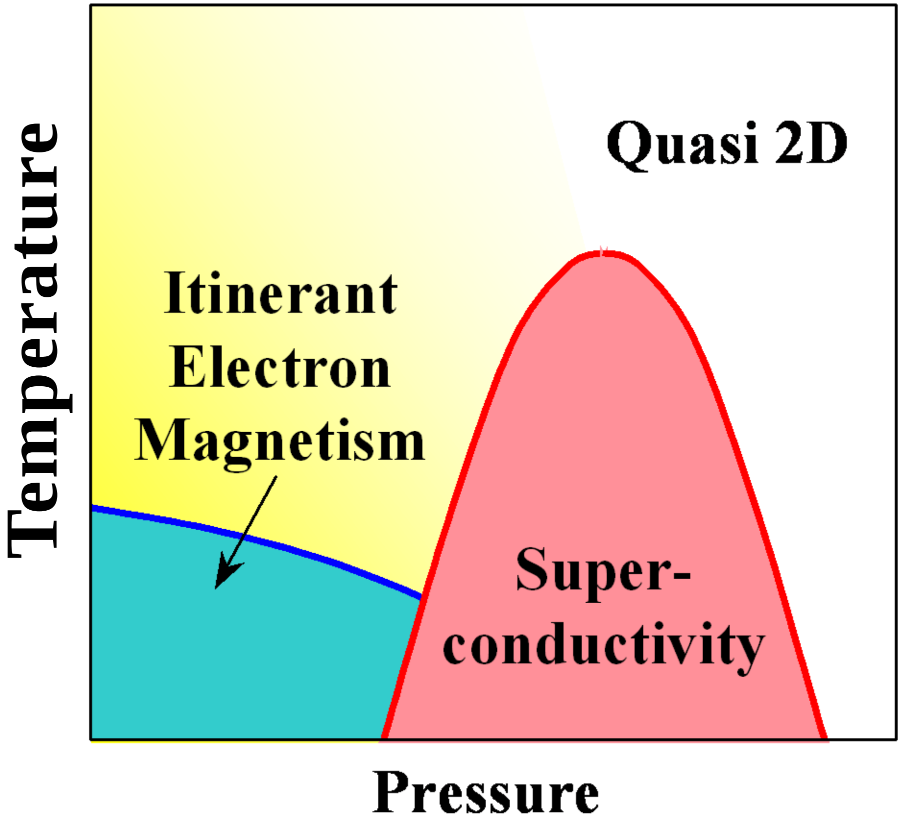
Interaction between e^-'s is not very strong and momentum in the system is conserved.

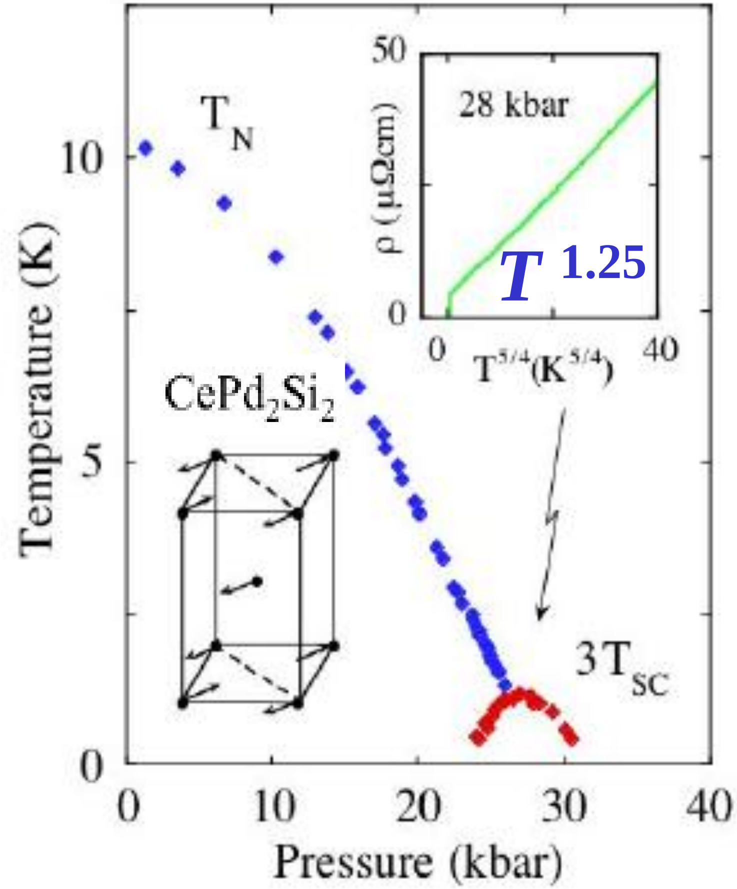
What defines the linear resistivity at the possible QCP?





Mathur ND, *et al.*, *Nature* 394 (1998) 39



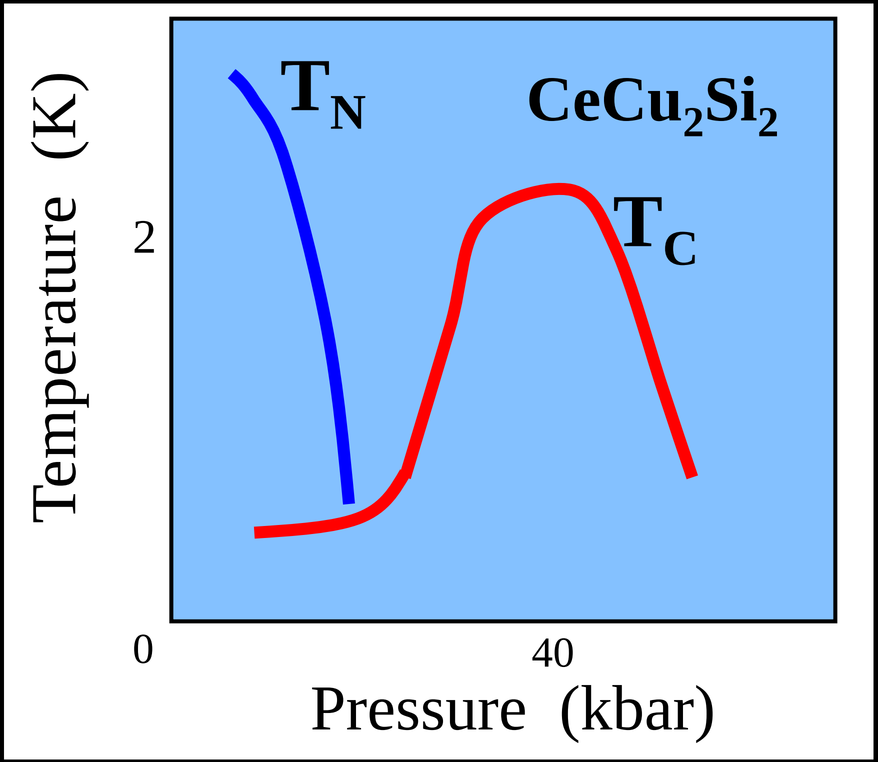


Mathur ND, *et al.*, *Nature* 394 (1998) 39

Mermin-Wagner: Purely 2D systems with a continuous symmetry cannot sustain long-range order in the thermodynamic limit at finite temperature.

Quasi 2D however would have a **reduced magnetic order and associated slow fluctuations**

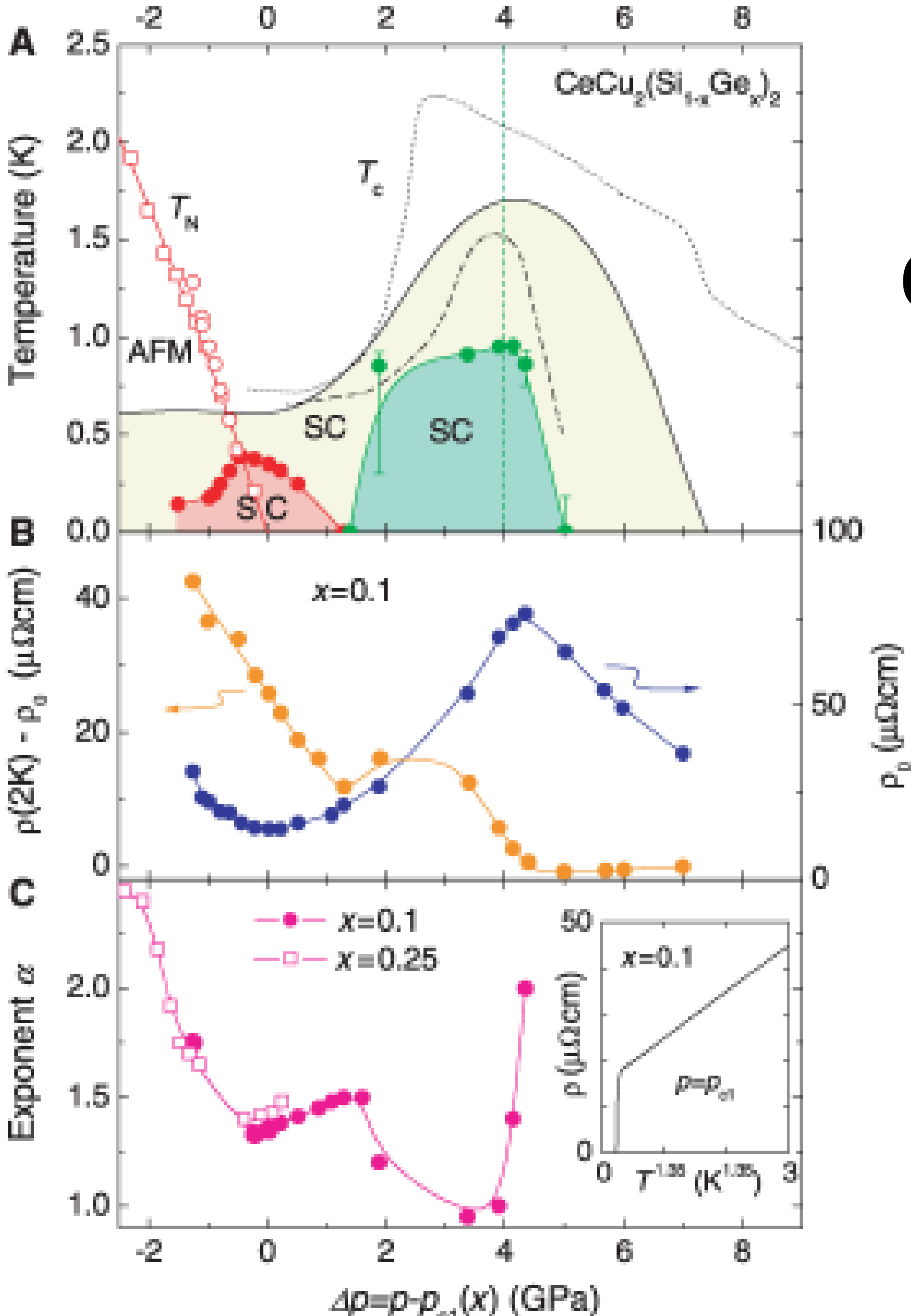
Add disorder and increase anisotropy



++ disorder … reduces T_N further and in SC with a gap anisotropic in k-space will also suppress SC

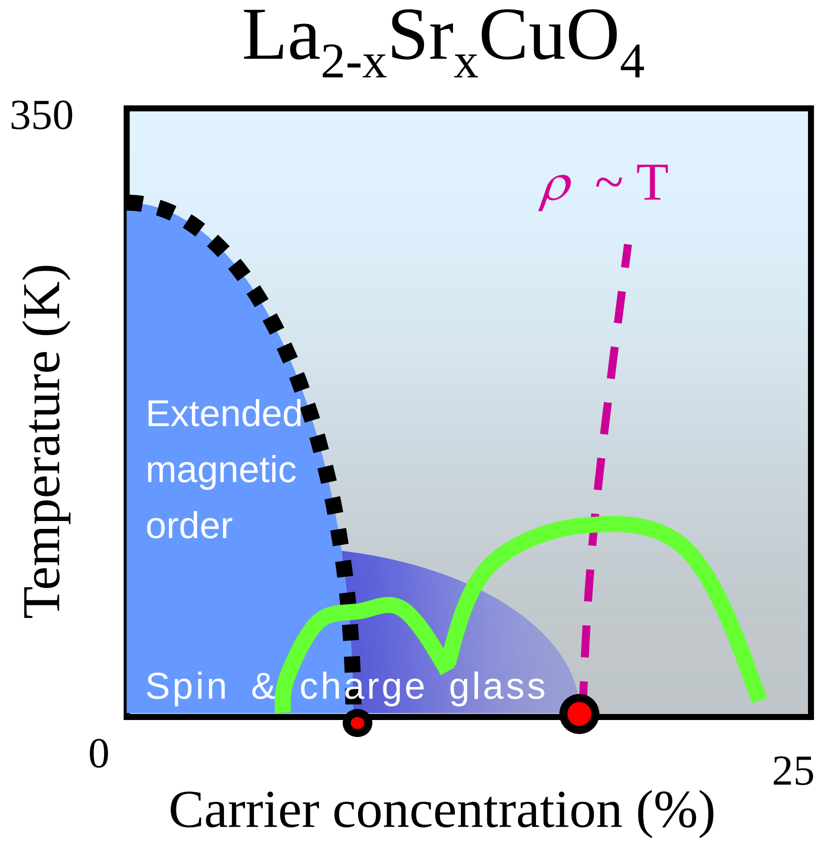
$\rho(@T_c \text{ max}) = \mathbf{10\ \mu\Omega\text{-cm}}$

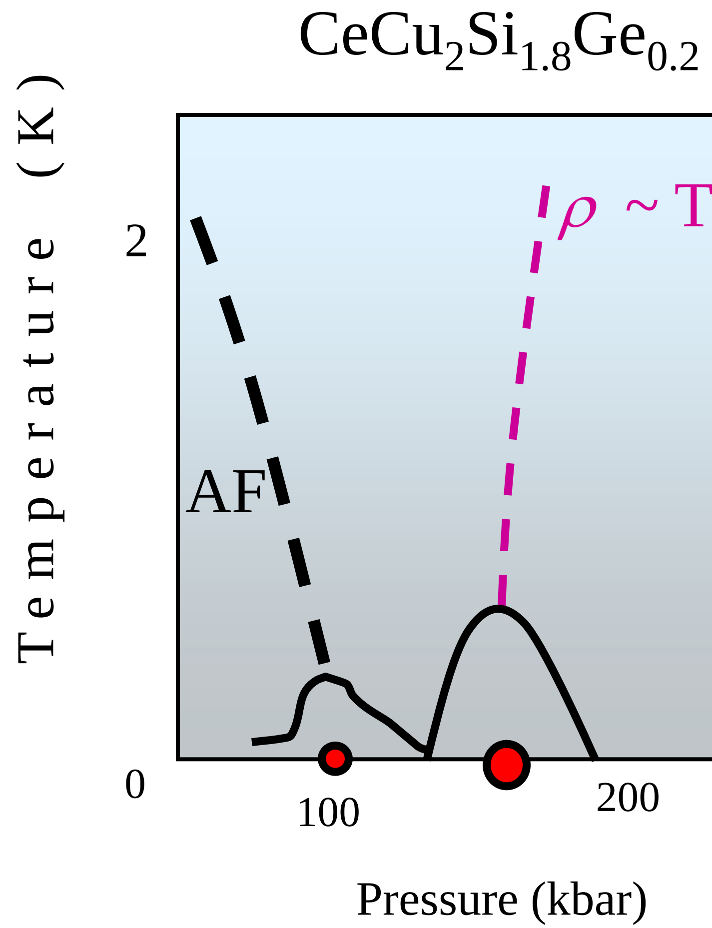
B. Bellarbi et al., PRB 30, 1182 (1984)



$CeCu_2(Si_{1-x}Ge_x)_2$

H. Q. Yuan, *et al.*
Science **302**, 2104 (2003);

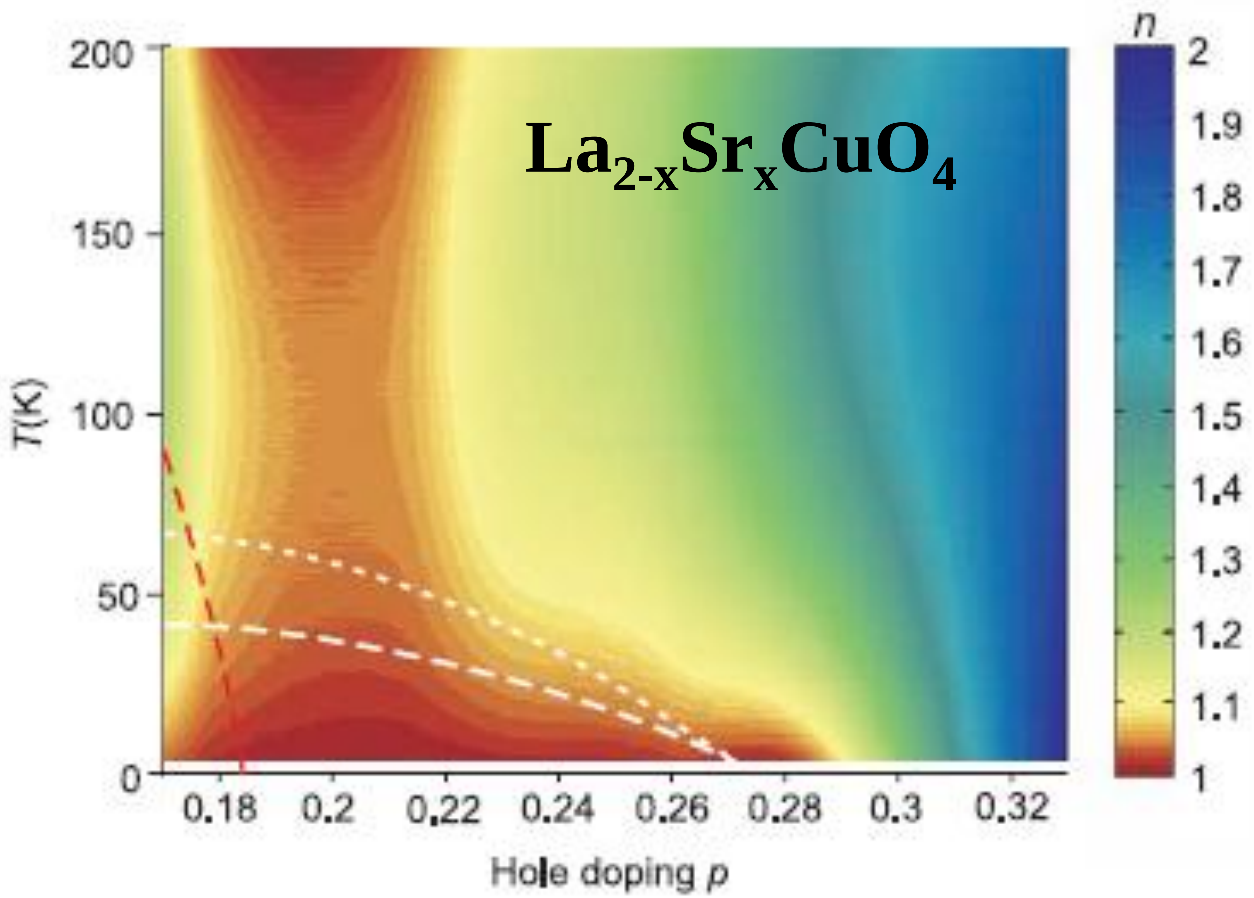




- Reduced magnetic order,
- Low dimensionality,
- Intrinsic disorder
- Associated slow spin and charge fluctuations

For pairing anisotropic in k-space by reducing dimensionality we reduce scattering and Tc is expected to rise.

- Could therefore the spin charge fluctuations discussed here be associated to the linear resitivity and relate the latter to SC?



R. A. Cooper, *et al.*
Science **323**, 603 (2009)

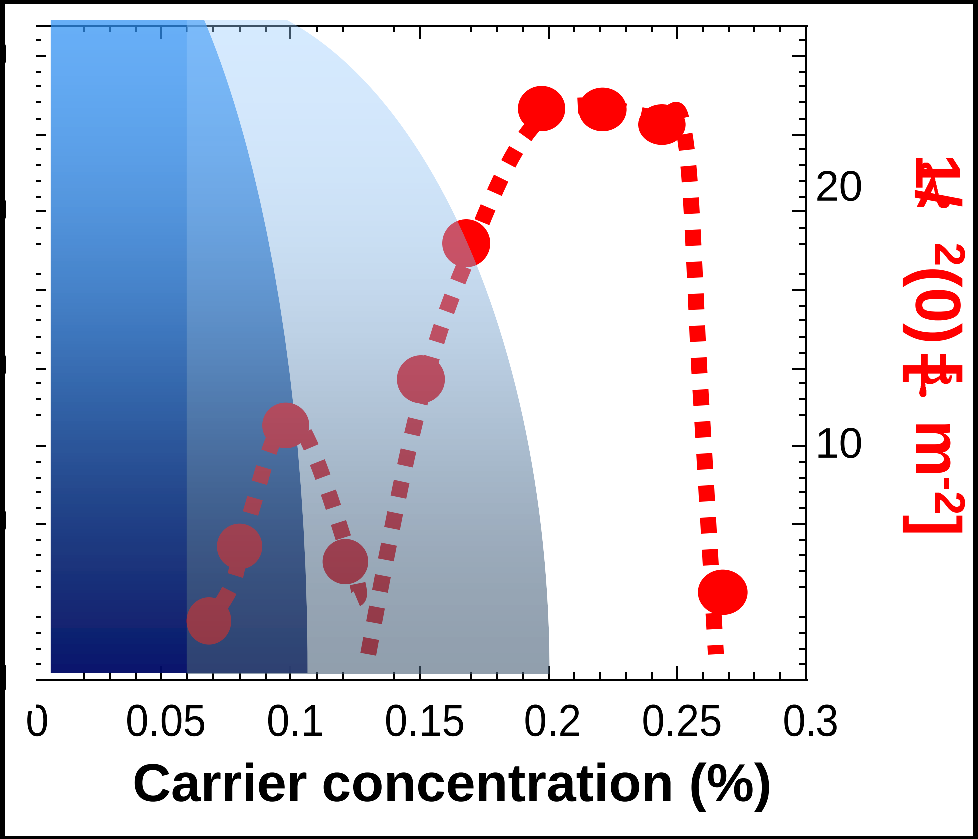
The T-linear regime grows wider with decreasing temperature, coinciding with the SC dome (long dashed white line) and the region where superconducting fluctuations become significant (short dashed white line).

An actual order → 0 as T → 0 ?

Impurities break the translational symmetry associated with CO states, prohibiting an actual QCP associated with CO in the presence of randomness in 2D!

But we may have a QCP intercepted by “disorder”

Transition in the SC ground state



Phys. Rev. Lett. 81, 2336 (1998)

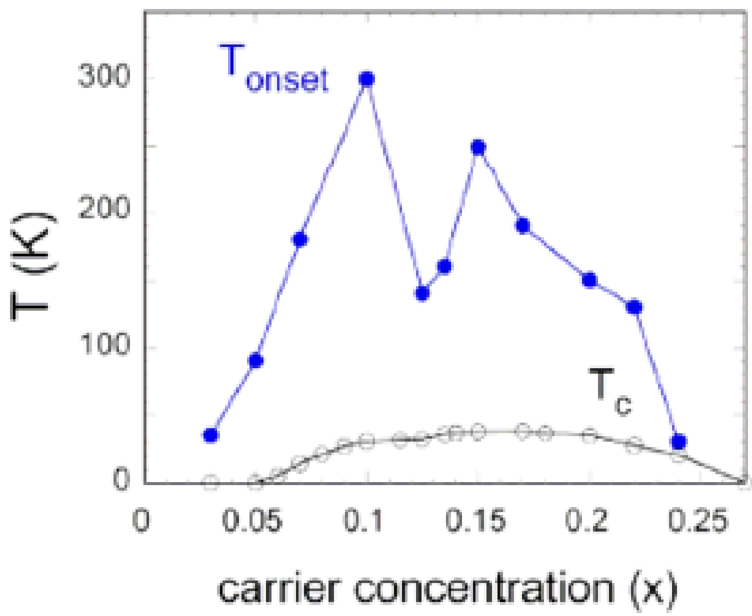
Phys Rev B 60, 14617 (1999)

Phys Rev B 66, 064501 (2002)

Phys Rev B 67, R220502 (2003)

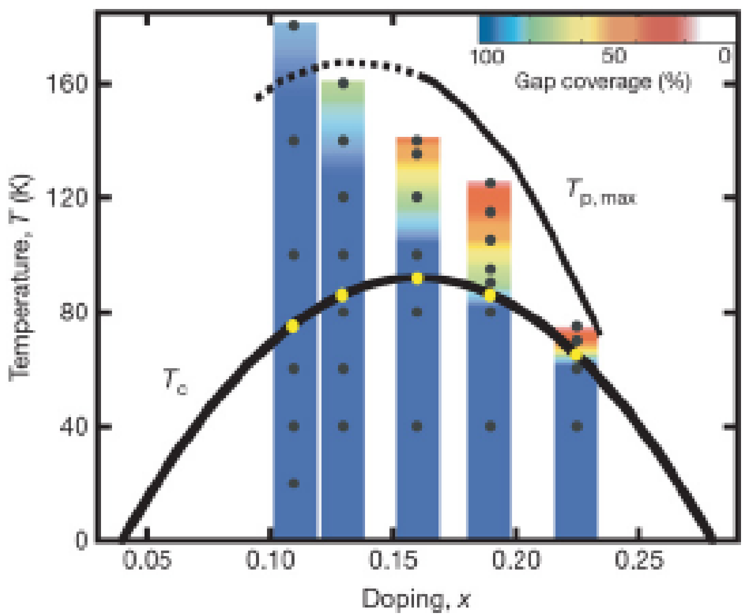
Phys. Rev. B 72, 014536 (2005)

Experimental Signatures of Spatially-Inhomogeneous Pairing Correlations above T_c



Weak magnetic domains of unknown origin in $La_{2-x}Sr_xCuO_4$ above T_c, identified from thermo-magnetic hysteresis.

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



Spatially-inhomogeneous pairing correlations in $Bi_2Sr_2CaCu_2O_{8+\delta}$ above T_c observed by STM.

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

Figure 5 | Schematic phase diagram for $Bi_2Sr_2CaCu_2O_{8+\delta}$. Temperatures and doping levels where large area gap maps were obtained are indicated by points. The colours are the percentage of the sample that is gapped at a given temperature and doping as measured in the gap maps. The $T_{p, max}$ line is the … which <10% of the sample is gapped. The lower solid line … k T_c.

Slide borrowed from Jeff Sonier's talk – Paris '09

Phys Rev B 69, 144508 (2004)

Phys Rev Lett 96, 047002 (2006)