Investigations of the Antiferromagnetic Order Parameter in Nano-Sized YBCO Particles

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Abstract

YBCO ($YBa_2Cu_3O_{6+x}$) is maybe the best known high-temperature superconductor (HTSC), and is as the other cuprate HTSC's antiferromagnetically ordered at low doping, and a superconductor at high doping.
The superconductivity of YBCO is a 2D phenomenon, existing even in materials only one unit cell high. However, it is well known that a reduction of the system size affects the magnetic order in a material [3].

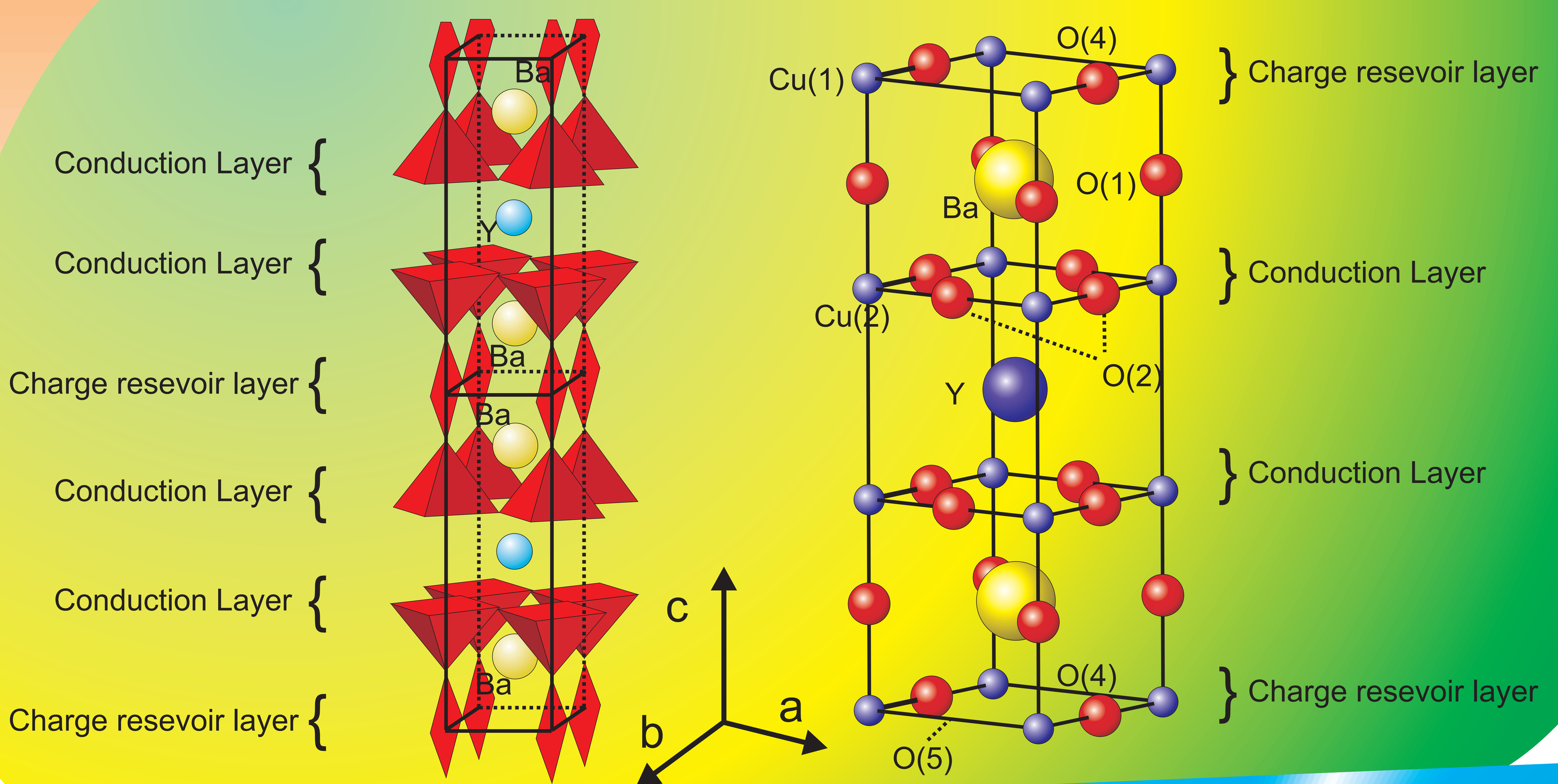
We have manufactured disc-shaped YBCO particles with a diameter of 30nm and a height of 4nm, and utilizing the advantages of both neutron diffraction and Muon Spin Rotation (μSR) techniques we have mapped out the staggered magnetization of these particles as a function of temperature as well as oxygen-doping.
A significant reduction of the Néel temperature is found, strongest at lowest hole doping. Neutron scattering measurements also show a more linearly-shaped magnetic order parameter behavior compared to bulk. These observations are attributed to the confined dimensionality of the disc-shaped system. Our findings agree with a similar study of NiO nanoparticles for which the reported reduction of the Néel temperature was found to stem from finite-size effects [3].

The results show that the magnetic order parameter in YBCO is a 3D phenomenon, in opposition to the superconducting order parameter, and the weak coupling between the pairs of neighboring conduction layers in YBCO indeed is significant.

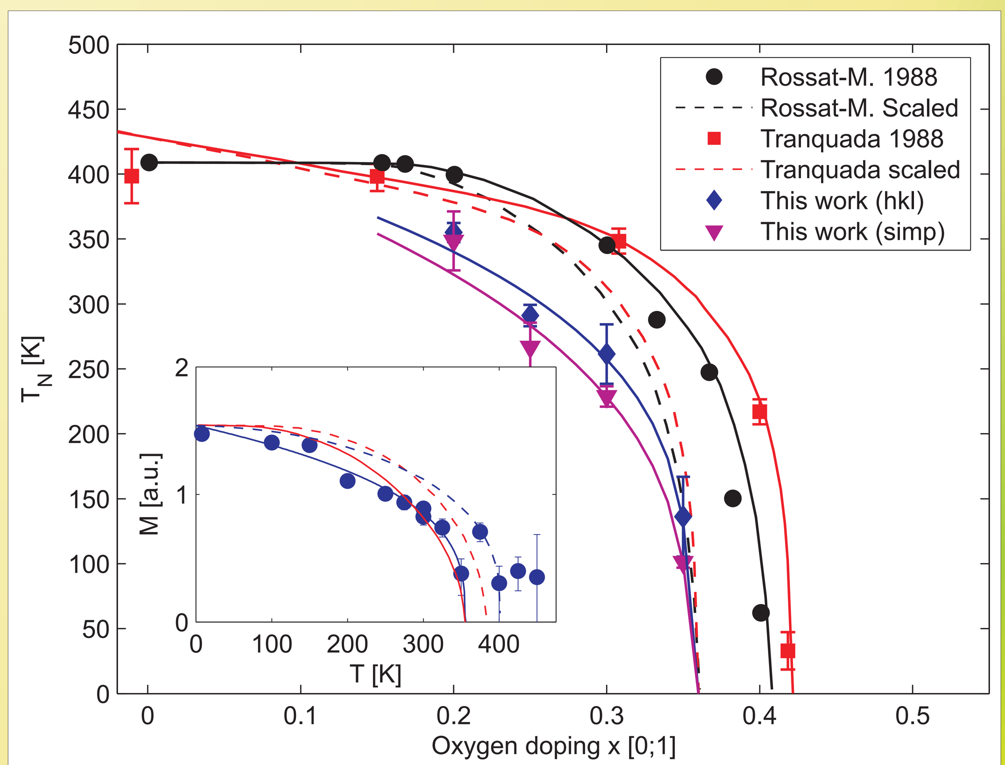
The μSR results reveal a distribution of Néel temperatures, seen as an increasing number of non-ordered spins, coexisting with a bulk-like behavior of the magnetic order parameter vs. temperature. This exotic finite-size effect could be due to superparamagnetic relaxation, surface spin melting or a combination of these, all of which are phenomena exclusively observed in nanoparticles. The finding of these phenomena is supported by the neutron diffraction results, especially in relation to different natures and time scales of the two techniques.

Even more exciting, our μSR data show that reemergence of the native-like Néel state [2] at low temperature also exists in YBCO nanoparticles. The reemergence is seen as a distinct rise of the staggered magnetization at low temperature in a doped sample and is caused by changes in the internal field distribution due to the localization of holes. This removes the frustration on most spins, allowing these to form a Néel-like state with a staggered magnetization approaching that of the undoped system [1]. This observation along with previous observations in bulk YBCO [5], $Y_{1-x}Ca_xBa_2Cu_3O_6$ [4] and LSCO [2], strongly supports the view that the reemergence of the native-like Néel state is an intrinsic property of cuprate systems.

Structure of YBCO

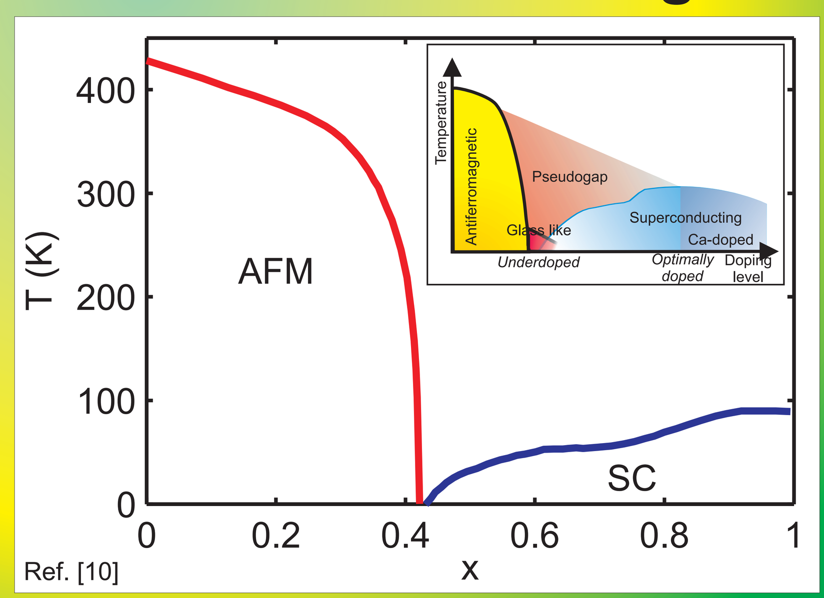


Reduction of the Néel temperature

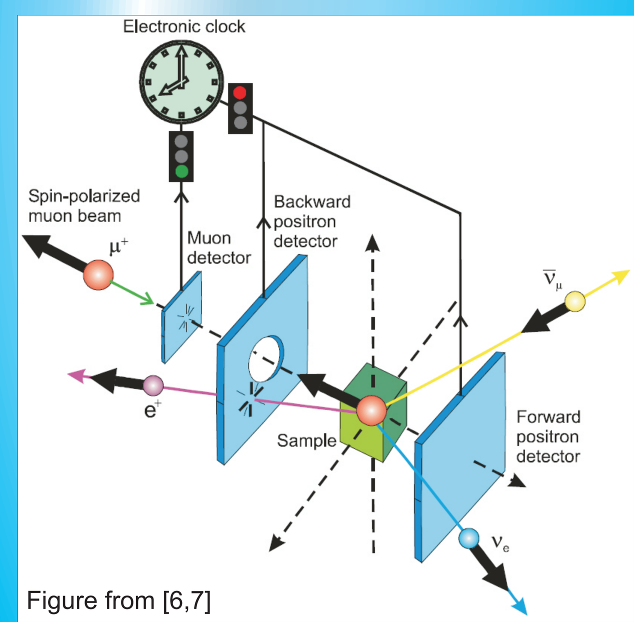


Neutron measurements show:
- A more linearly-shaped magnetic order parameter behavior compared to bulk. This is attributed to the confined dimensionality of the disc-shaped system.
- Our findings agree with a similar study of NiO nanoparticles for which the reported reduction of the Néel temperature was found to stem from finite-size effects [3].

YBCO Phase Diagram



The SR Technique



- **SR** - what is a muon?
  - Elementary particle (+) S=1/2.
  - Magnetic moment $m_m \approx 3\ m_p$ *very sensitive local magnetic probe.*
  - *Probes magnetic fields in the interstitial regions between the atoms*
- The muon decays in to a positron and two neutrinos.
- A ultra-relativistic positron tends to be emitted in the spin-direction of the muon.

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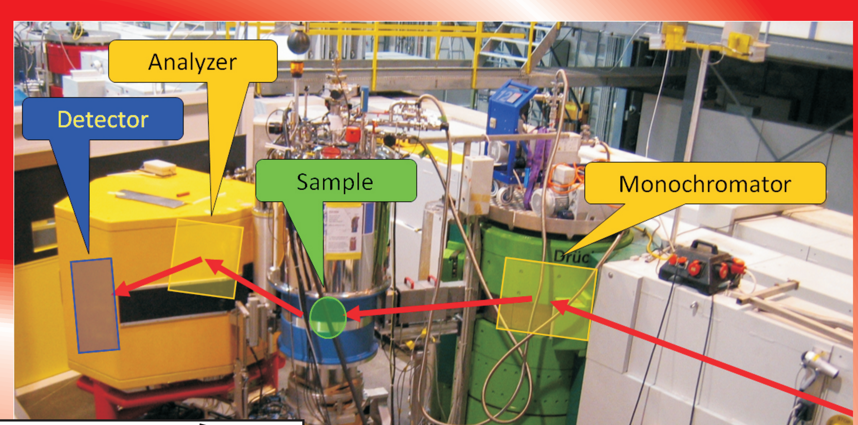
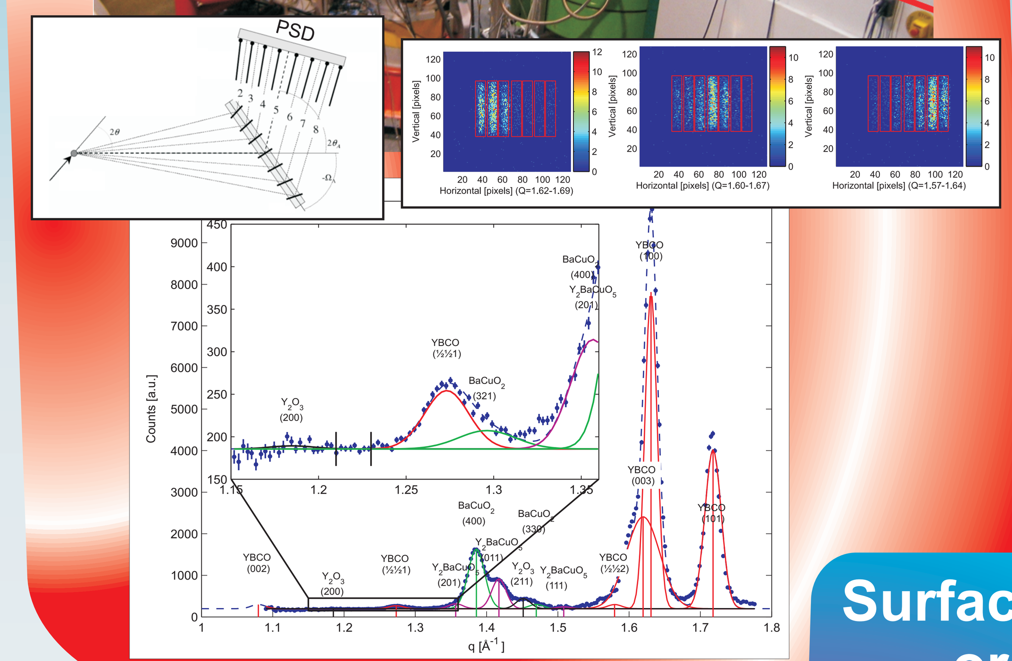
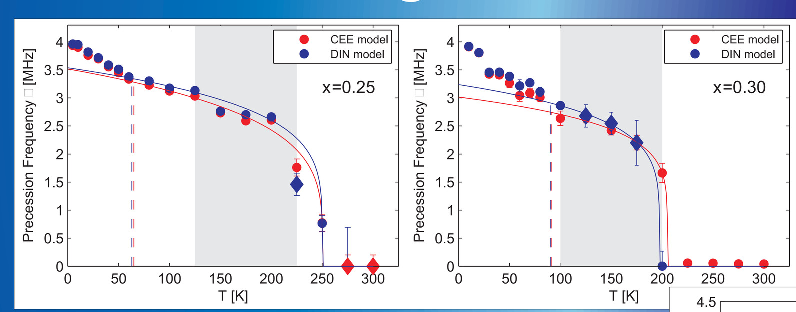


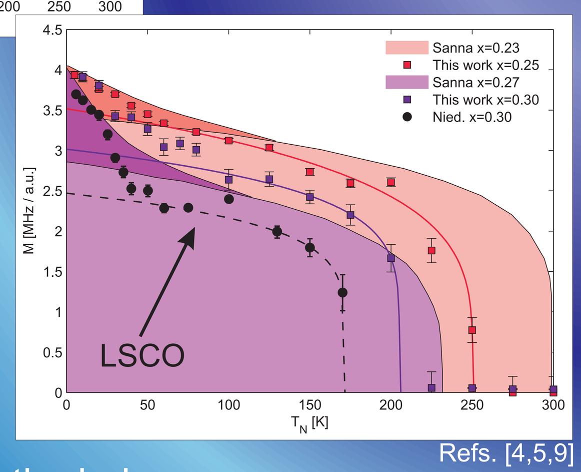


Reemergence of the Néel State



An increase in M at low T?
- Reemergence of native Néel state.

How is the behavior in bulk?
- Similar
- Lower T_N
- Otherwise unchanged



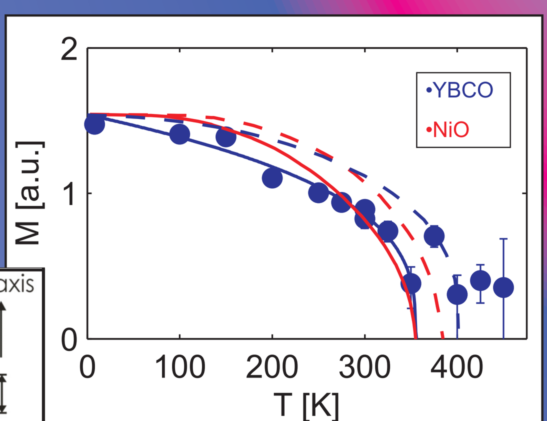
What is the Reemergence?

The holes in YBCO ...
- ... are dynamic
- ... cause frustration of the Cu spins
- ... therefore frustrate all Cu spins

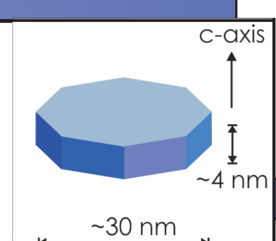
At low T, the holes ...
- ... become localized
- ... only frustrate a few spins
- ... leave most spins in native state

3D magnetic order parameter

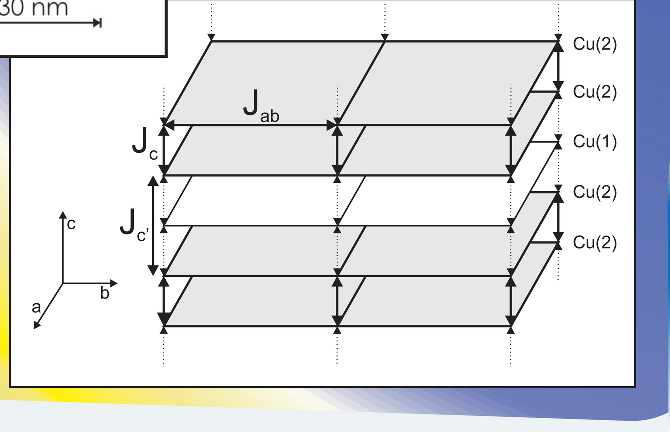
- Lower T
- Changed M curve
- Caused by reduced dimensionality (c-axis)



- *c*-axis dimensions
  3.7 unit cells
  7.5 magn.layers
  (NiO 7)

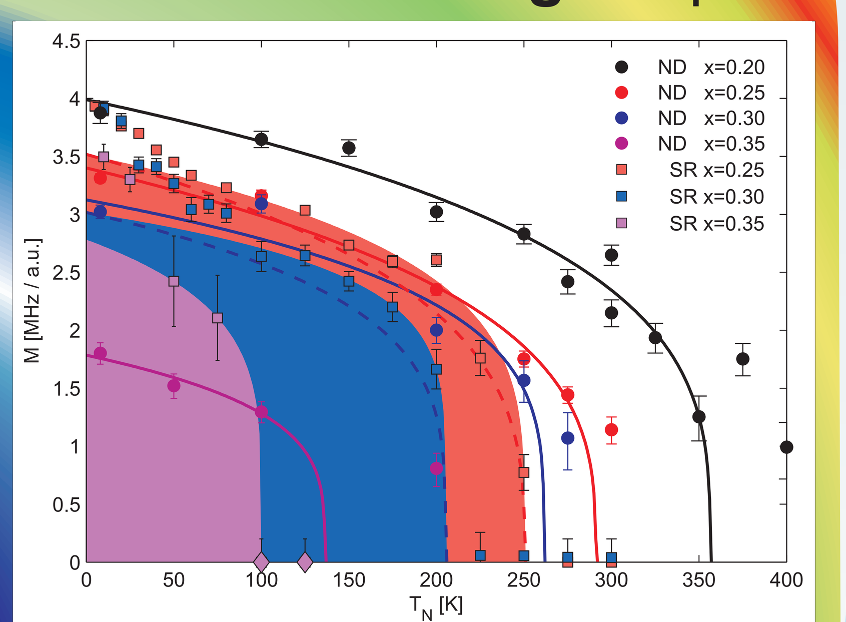


- Quasi-2D AFM structure
  J_{ab} 80(30)meV, J_c 2meV
  Weak: J_c 0.020(5)
- **Interlayer coupling important!**



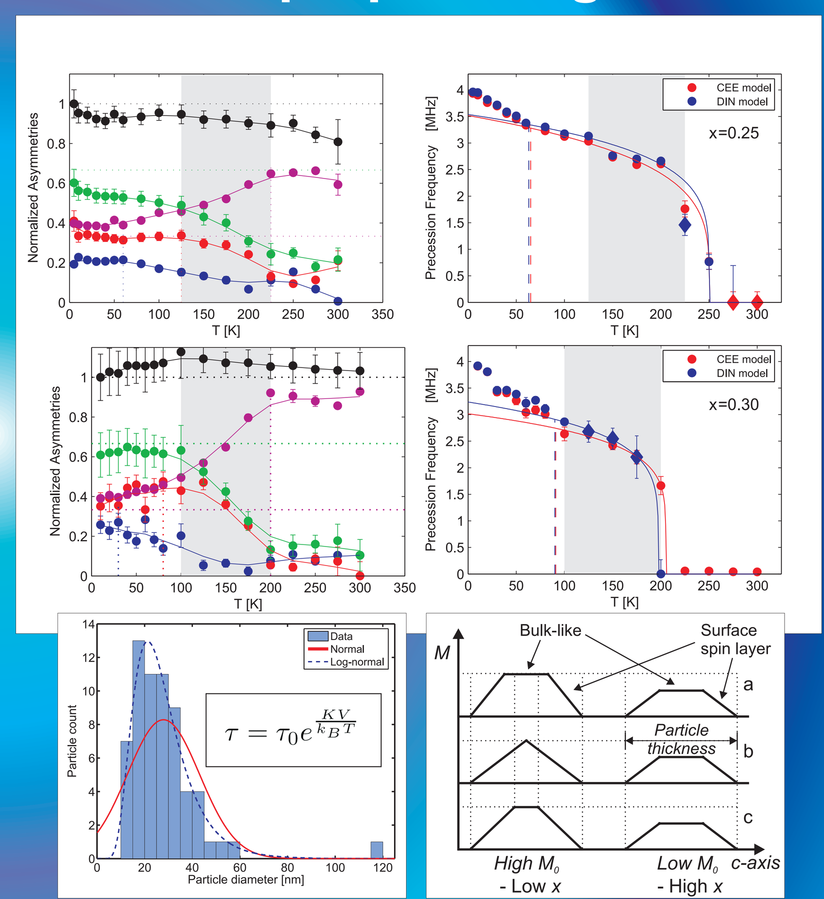
[3] Klausen (2005), [8] Tranquada 1989

Neutron scattering vs. μSR

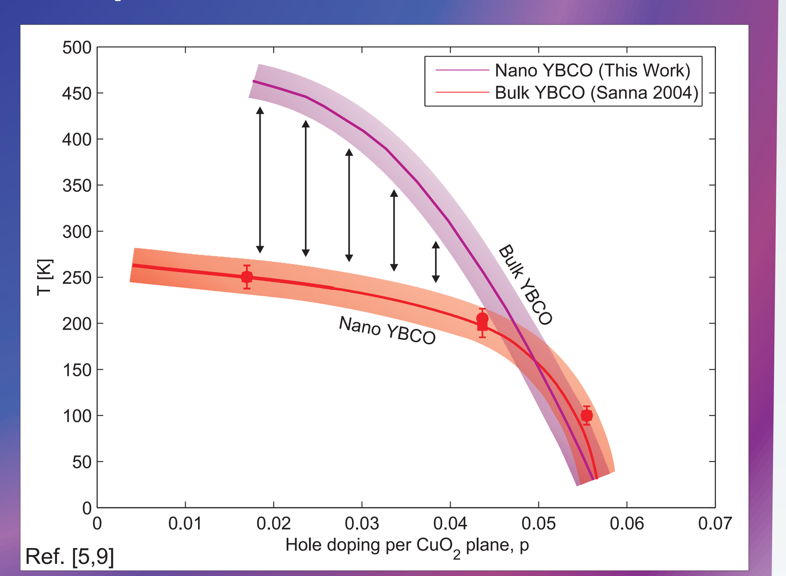


- Different curve shapes.
- Difference in T_N – Time scale related?

Surface Spin Melting or Superparamagnetism?

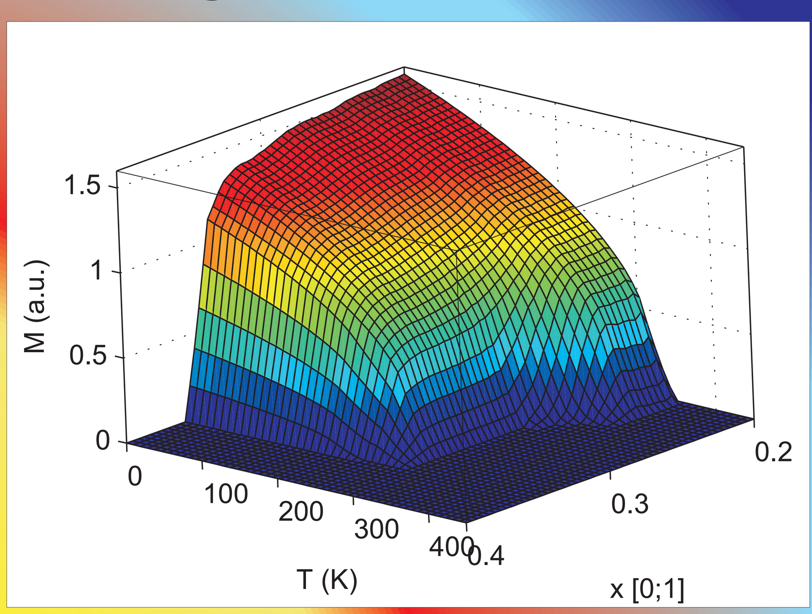


μSR Bulk vs. Nano



- High doping – Similar T_N
- Low doping – Reduced T_N

Map of Magnetic Order Parameter



Conclusion

- Significantly altered T_N – An upper limit.
- Reemergence of native Néel state.
- Local field distribution:
  – superparamagnetism
  or **surface spin melting**
- M is thickness-dependent ...
  – J_c is significant.
  – The magnetism in YBCO is 3D!

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