# Critical Phenomena in Spin Glasses and Other Magnetic Glasses

## Per Nordblad

# Villa San Michele – Axel Munthe

Axel Munthe (31/10-1857 – 11/2-1949) – Swedish medical doctor

"The Story of San Michele"

# Spin Glass Characteristics

1. Critical slowing down from $\chi(\omega,T)$

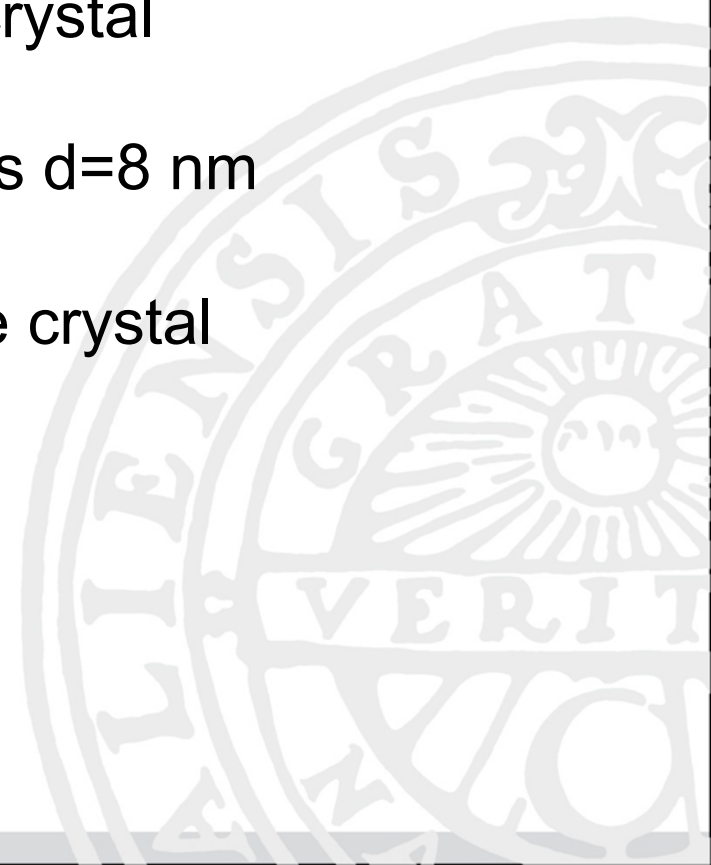2. Field dependence from $M(T)/H$

3. Non-equilibrium dynamics

# Experiments Model Systems

FMTO - $Fe_{0.5}Mn_{0.5}TiO_3$; single crystal

RCP – Maghemite nanoparticles d=8 nm

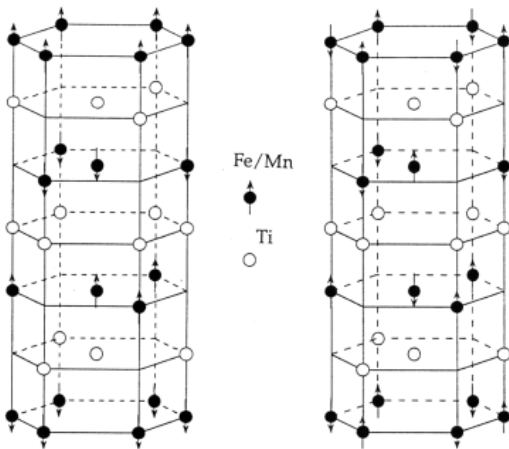LSCO – $La_{0.85}Sr_{0.15}CoO_3$; single crystal

# FMTO

Fe/Mn ●

Ti ○



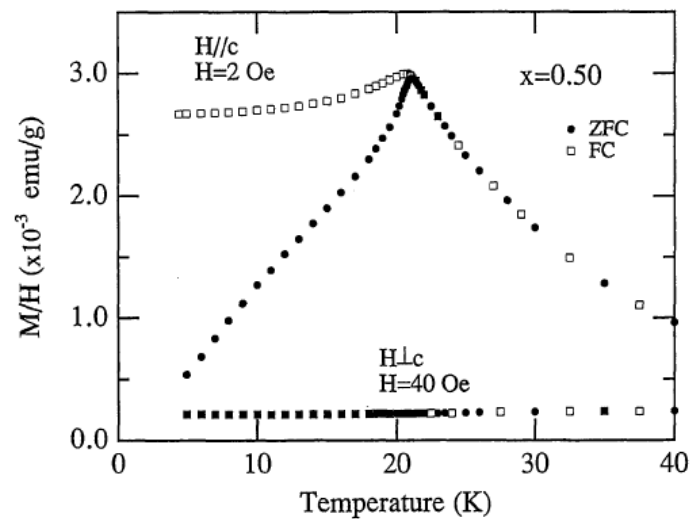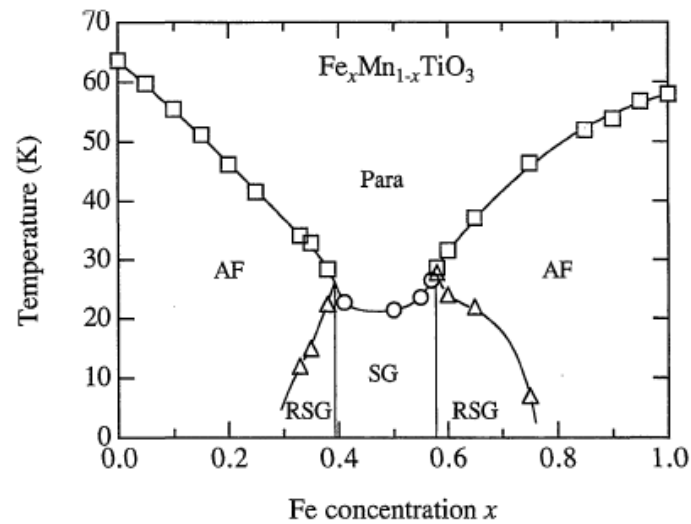$Fe_xMn_{1-x}TiO_3$

Para

AF

AF

SG

RSG

RSG

Fe concentration $x$

Temperature (K)



H//c
H=2 Oe

x=0.50

● ZFC
□ FC

H⊥c
H=40 Oe

M/H ($\times 10^{-3}$ emu/g)

Temperature (K)

$Fe_{0.5}Mn_{0.5}TiO_3$

Spin moment: ~ 1 $\mu_B$

A. Ito and H. Aruga-Katori

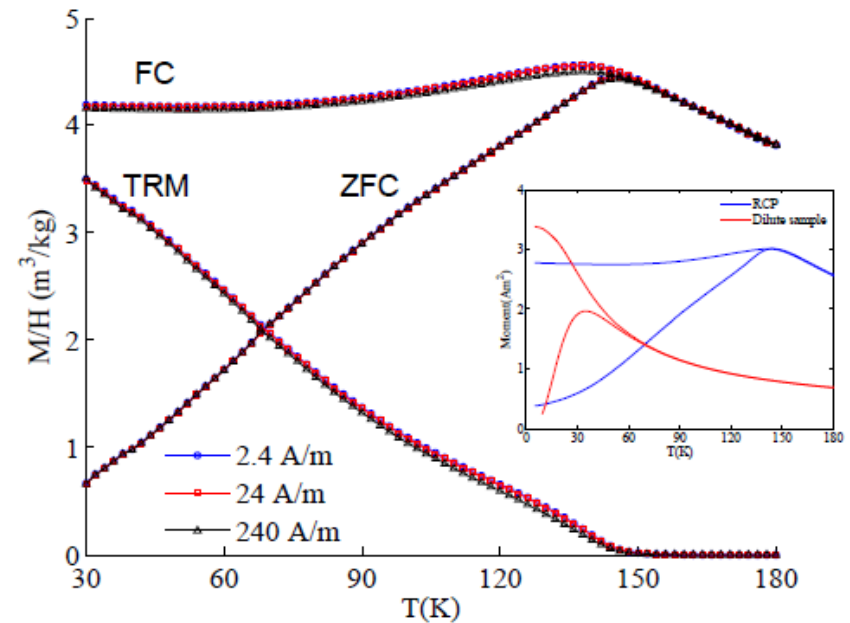# RCP
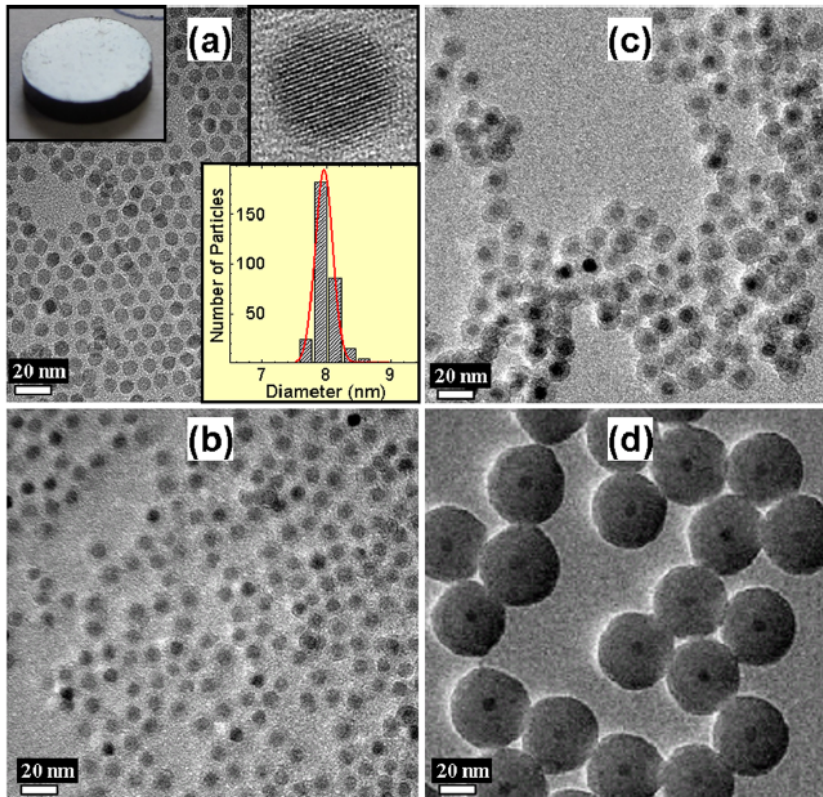


Maghemite-8nm
γ-Fe$_2$O$_3$
Particle moment: ~$10^4$ μ$_B$
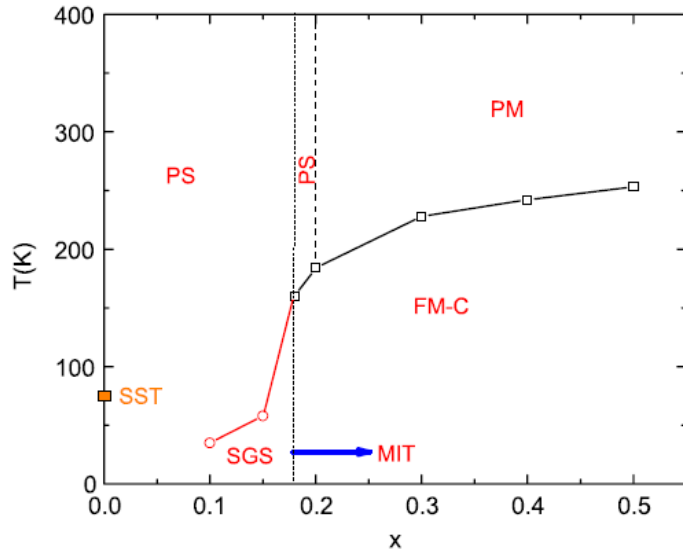
De Toro J.A. et al. APL 102, 183104 (2013), and J. Phys. Chem. C 117, 10213 (2013)

# LSCO



S. Yamaguchi et al.
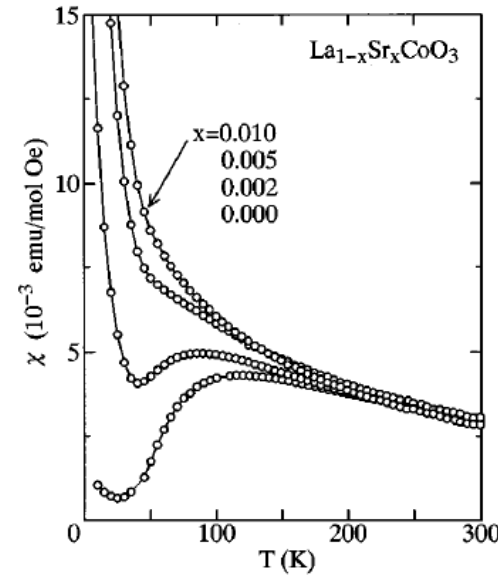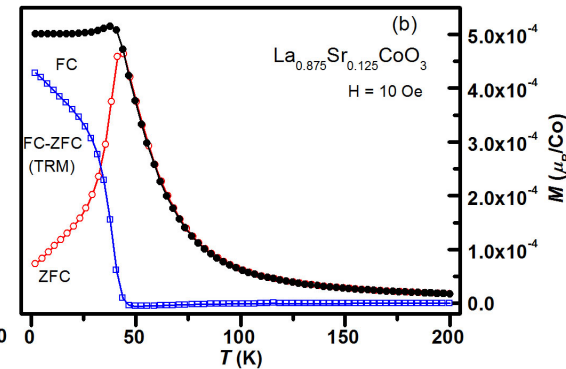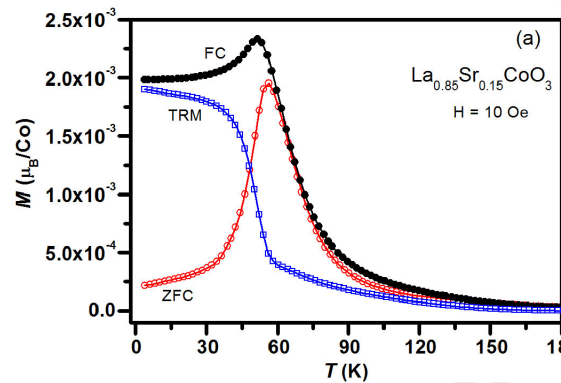Phys. Rev. B 52, R2926 (1996)

Samal D. and Kumar PSA,
J. Phys. Cond. Mater. 23, 016001 (2011)

$La_{1-x}Sr_xCoO_3$

Phase separation magnetic-nonmagnetic – magnetic polarons
Cluster moment: ~ 400 $\mu_B$, Kumar A.P. et al. to appear

# Non-linear Susceptibility: M(T)/H
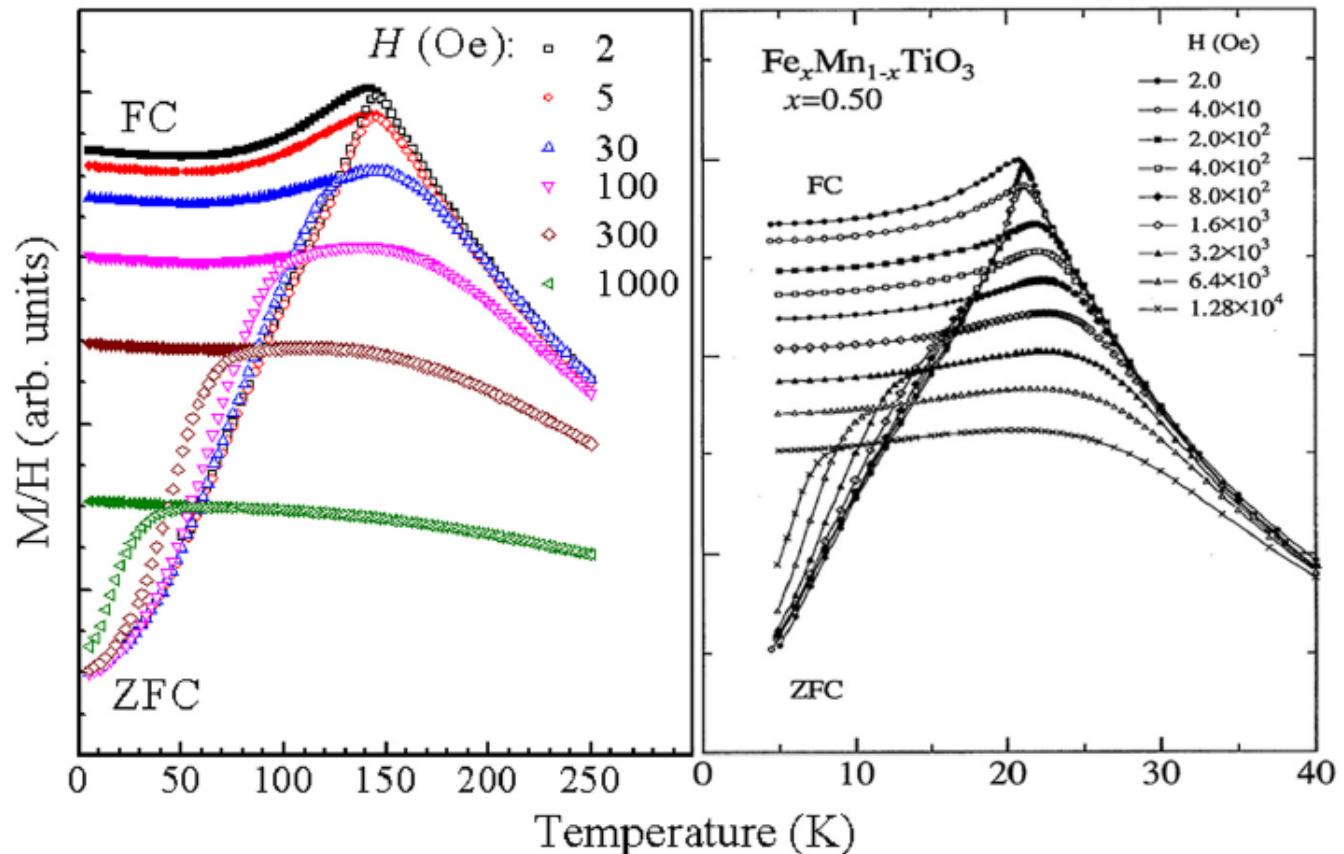


RCP                                    FMTO

# Critical slowing down



Coherence length

Activated dynamics

Paramagnetic behaviour

Critical dynamics

$T_g$

Temperature
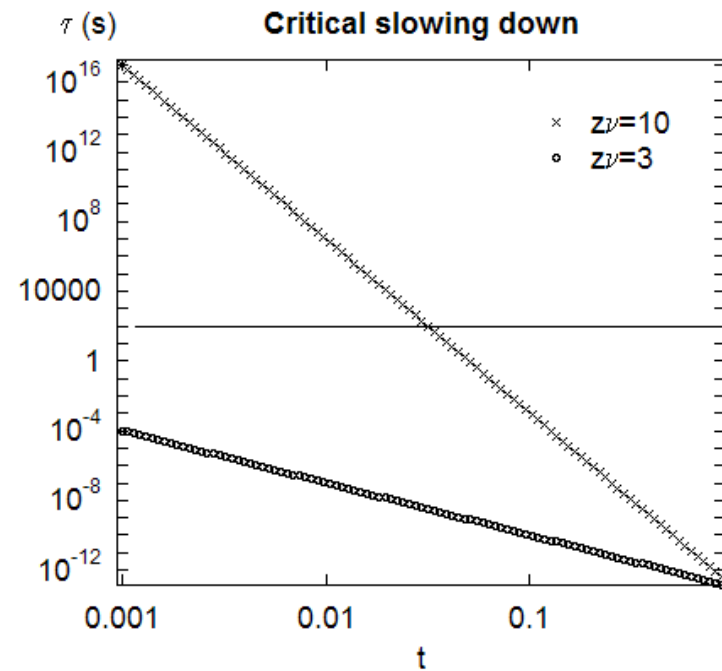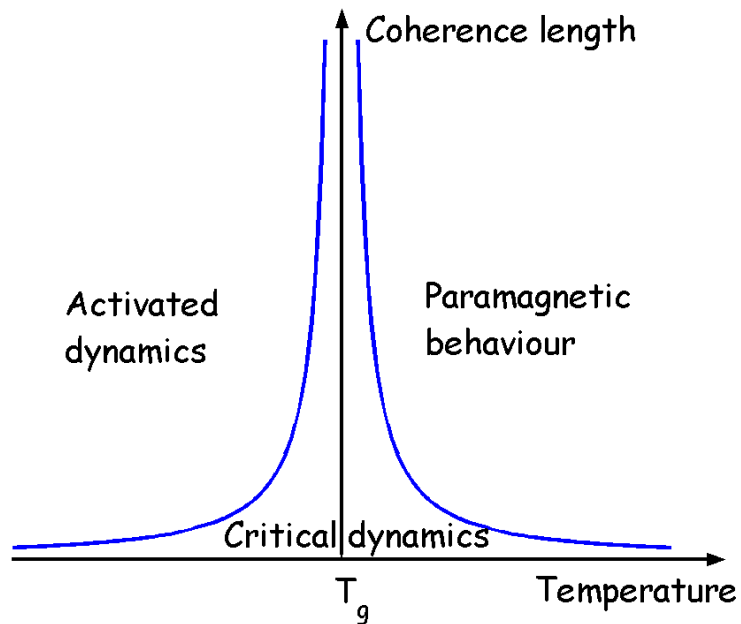


$\tau$ (s)

**Critical slowing down**

$\times$   $z\nu=10$

$\circ$   $z\nu=3$
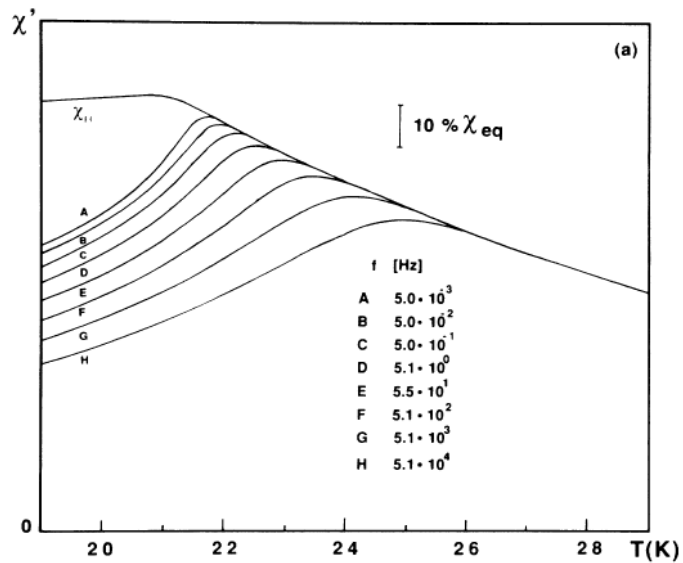
t

$$\tau=\tau_0 t^{-z\nu}$$

# Critical exponents

TABLE I: Critical exponents for the three-dimensional Heisenberg-like Ag(Mn) and Ising-like (Fe,Mn)TiO$_3$ spin glasses (from Refs. 7, 21, 20), and Eu$_{0.5}$Sr$_{1.5}$MnO$_4$.

| | Heisenberg | Eu$_{0.5}$Sr$_{1.5}$MnO$_4$ | Ising |
|---|---|---|---|
| $\gamma$ | 2.3 | 3 | 4 |
| $\beta$ | 0.9 | 0.5 | 0.54 |
| $\alpha$ | -2.1 | -2 | -3 |
| $\nu$ | 1.3 | 1.3 | 1.7 |
| $\delta$ | 3.3 | 7 | 8.4 |
| $\eta$ | 0.4 | -0.25 | -0.35 |
| $z\nu$ | 6-8 | 11 | 10-12 |

# Dynamics - FMTO



$T_g = 21.0$ K

$zv = 10.0$

$\tau_0 = 10^{-13}$ s
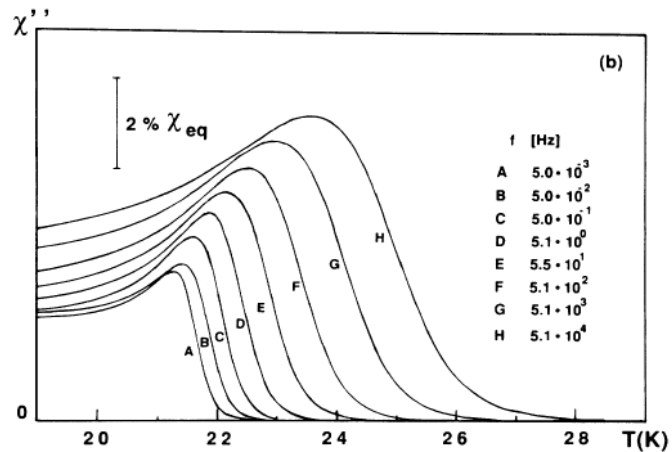
K. Gunnarsson et al. PRL 61, 754 (1988)
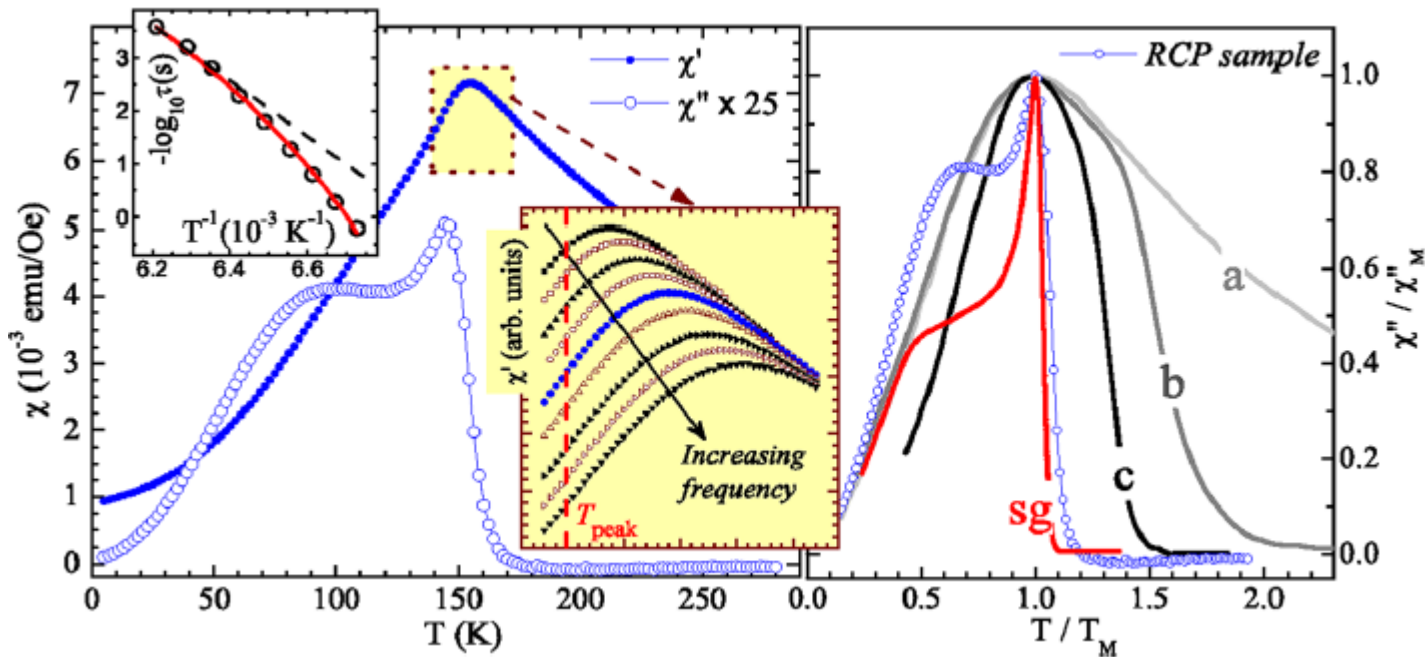
$T_g$ = 140 K
zv = 9.5
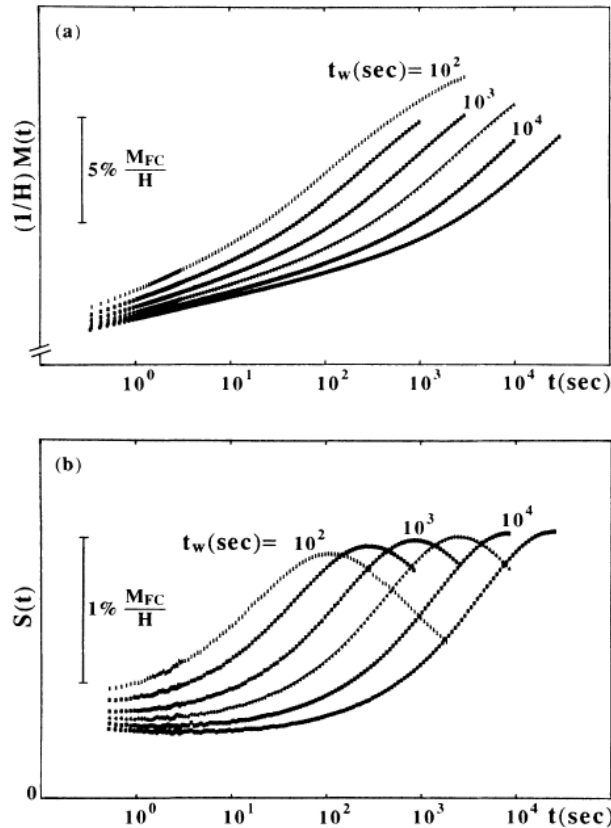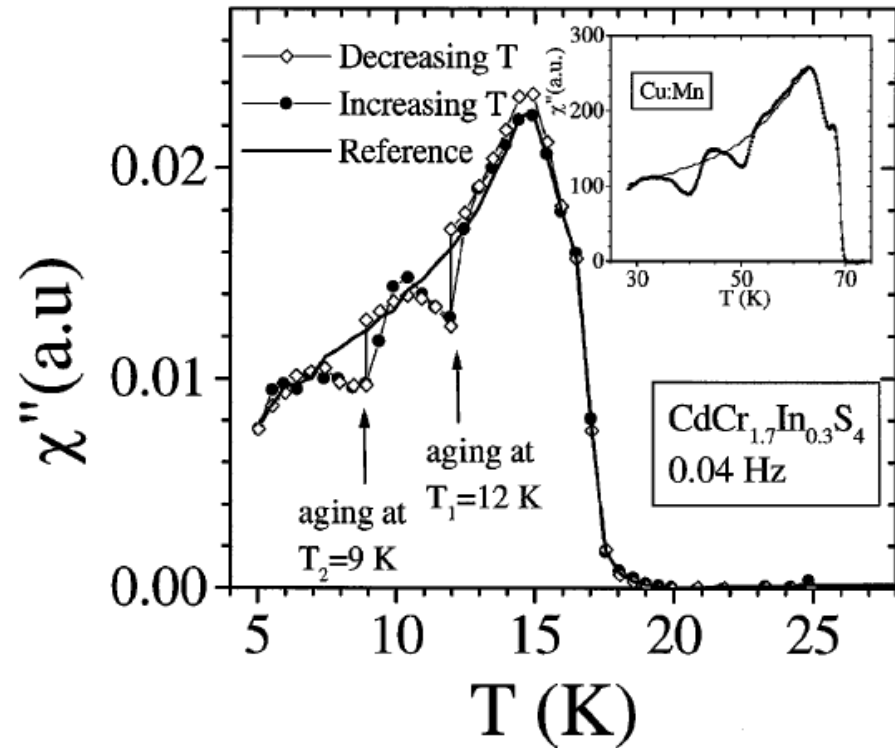$\tau_0$ = $10^{-11}$ s

# Dynamics-LSCO
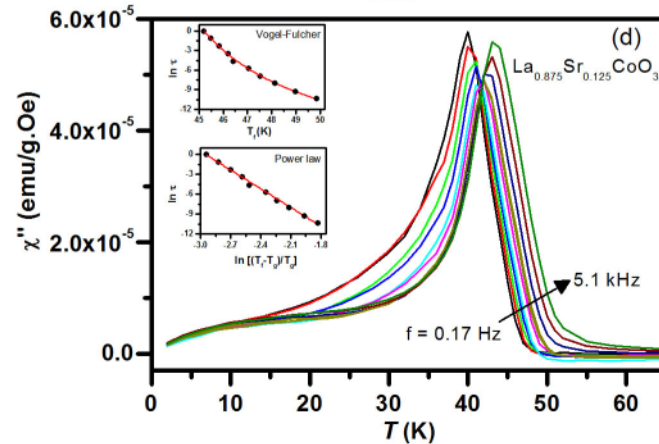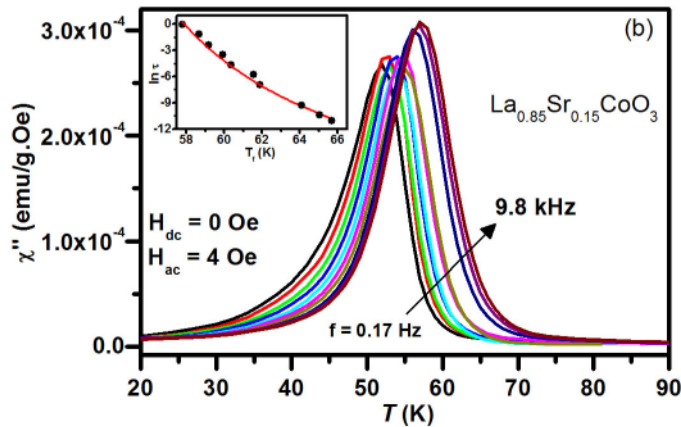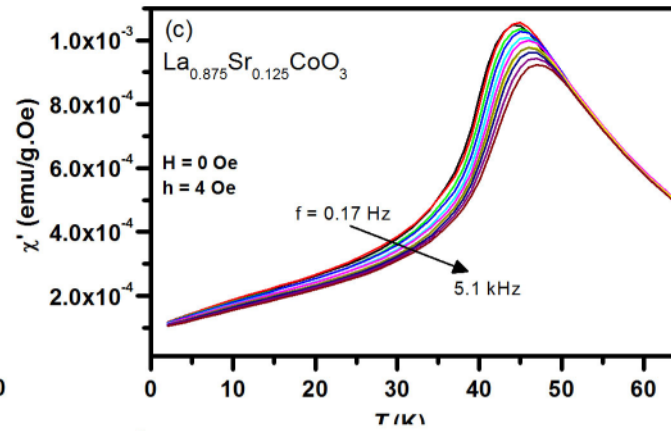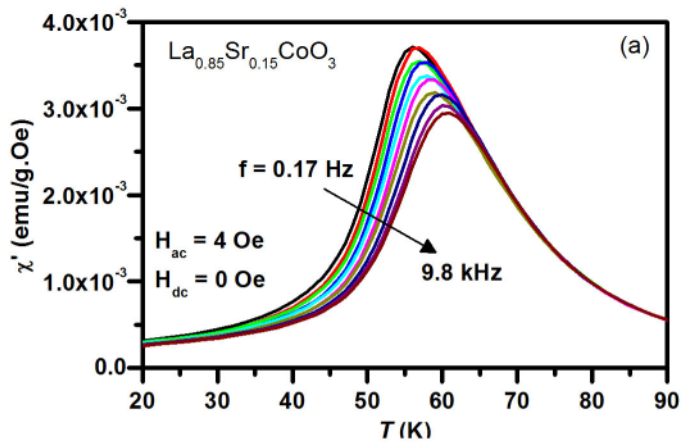


$T_g$ = 50 K
zv = 16.0
$\tau_0$ = $10^{-13}$ s

# Non-equilibrium dynamics



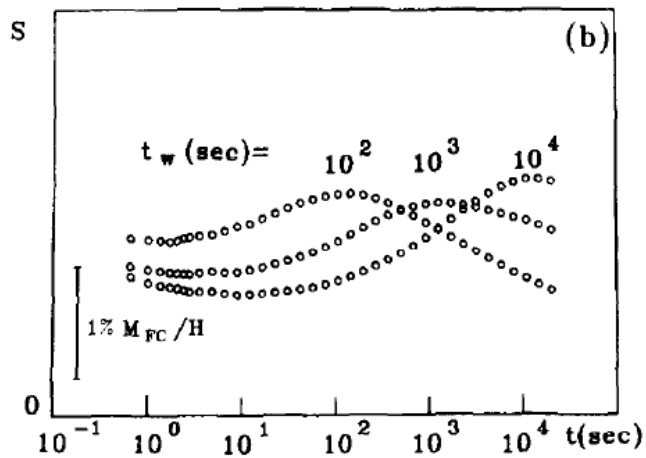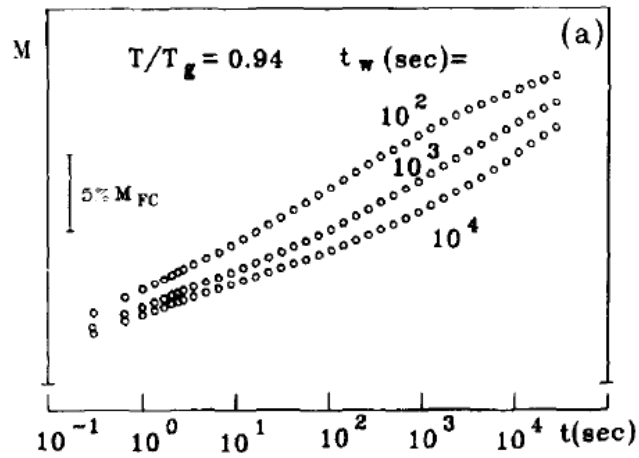Ageing, Cu(10%Mn)
Granberg et al. PRB (1988)



Memory, CdC1.7rIn0.3S4
Jonason et al. PRL (1998)

# Ageing FMTO

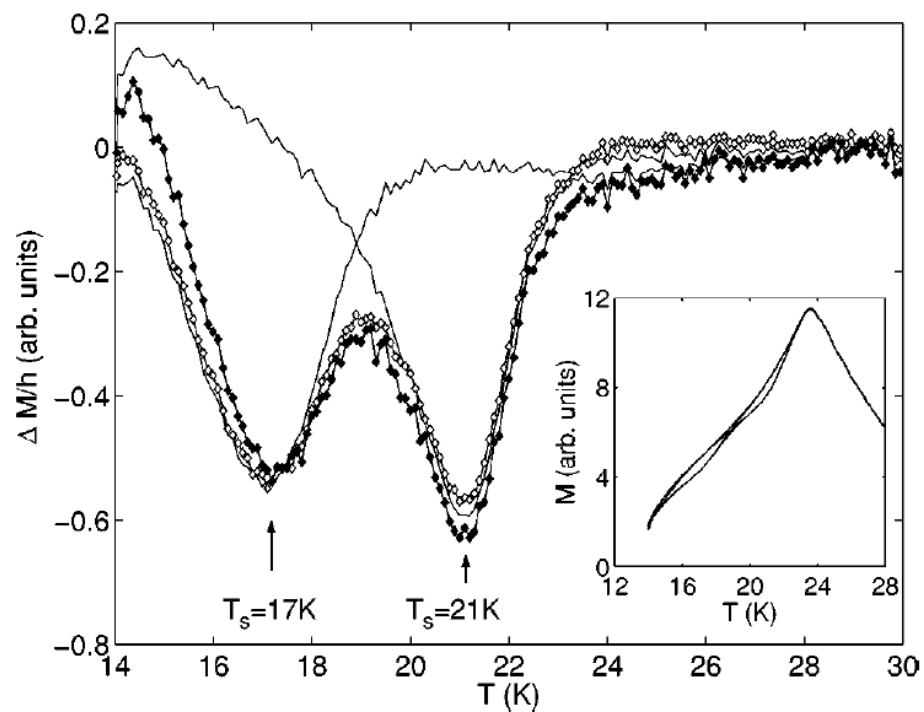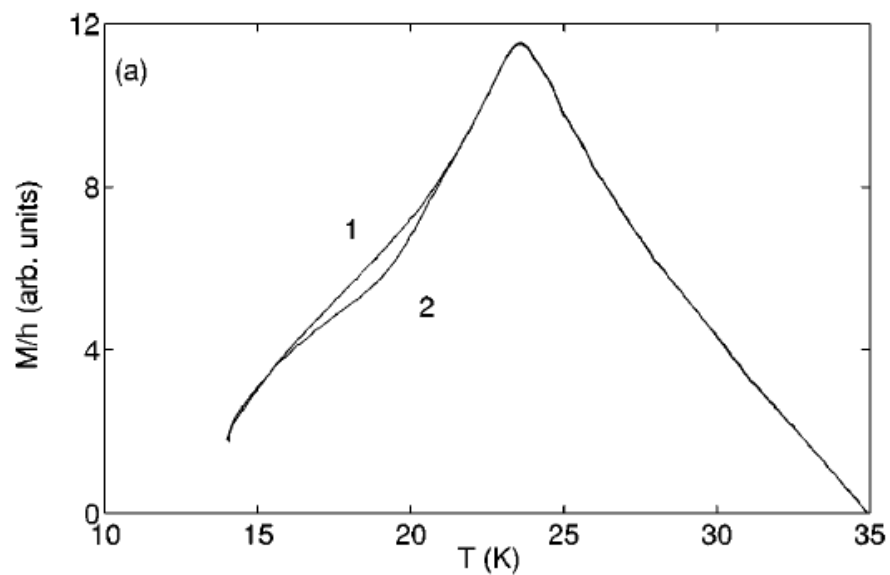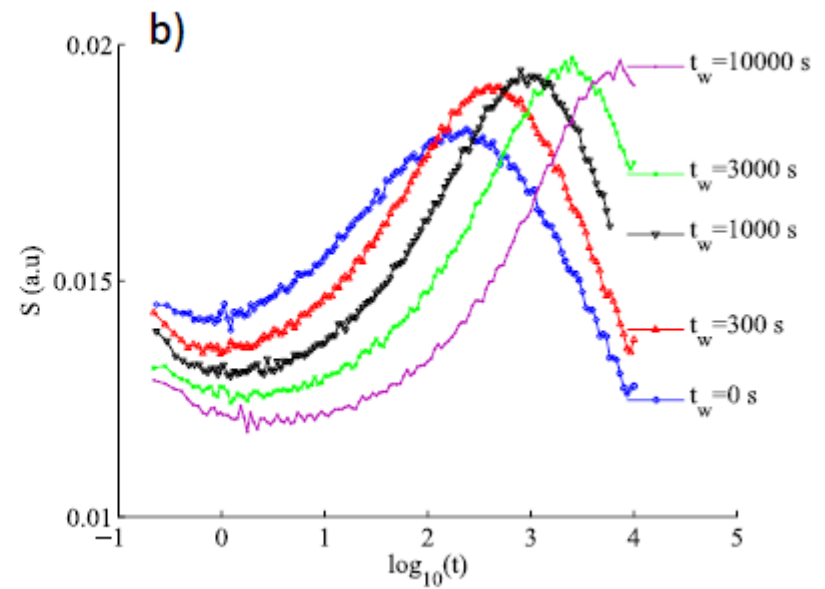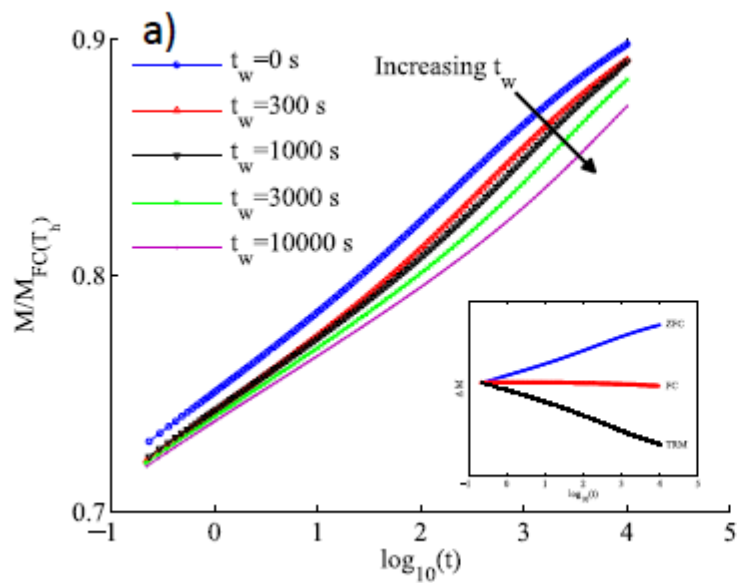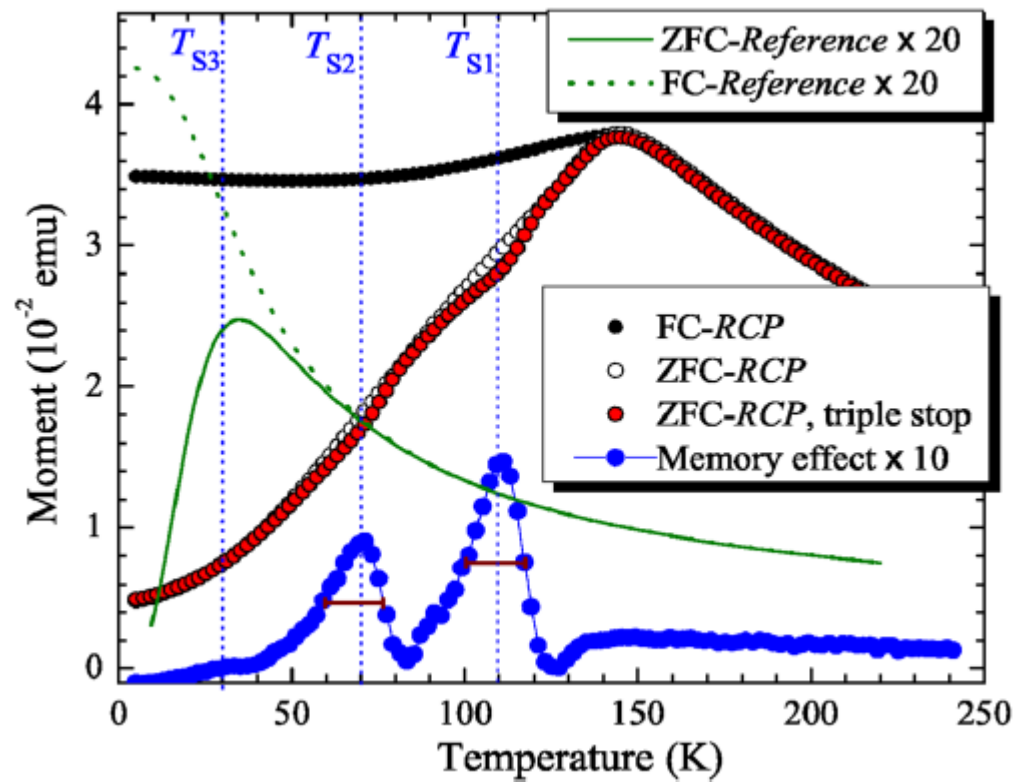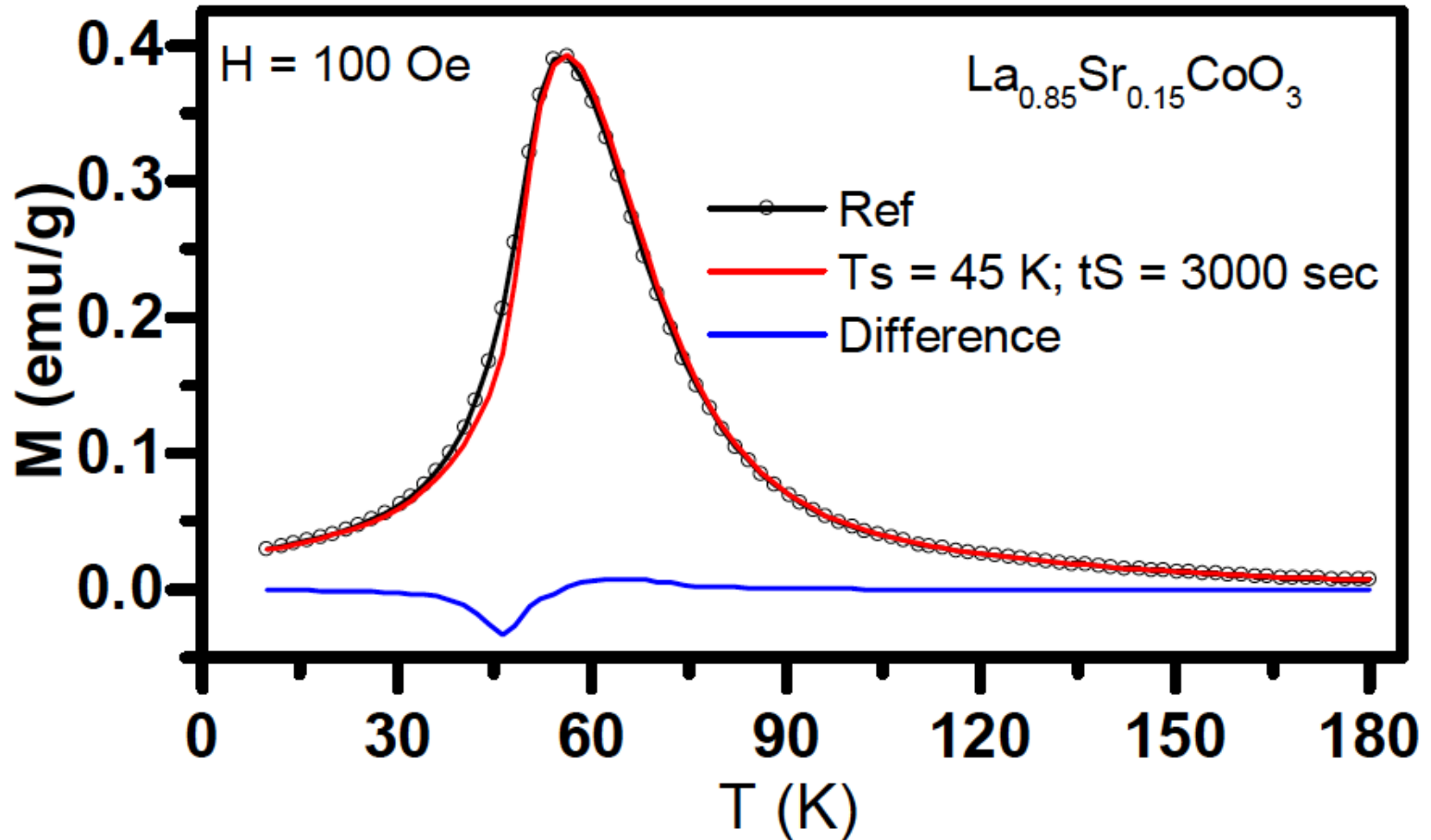# Memory FMTO

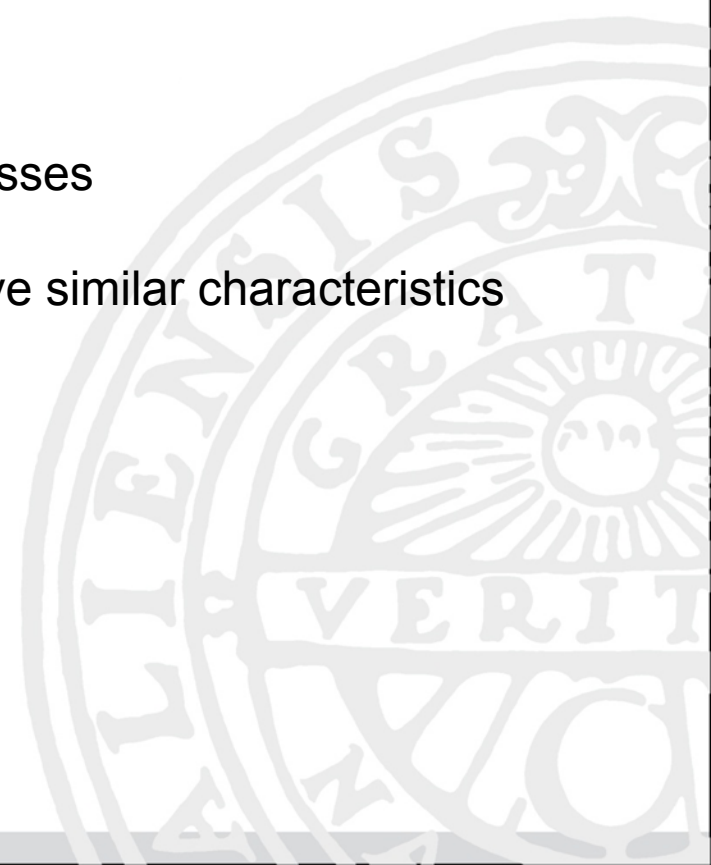# Ageing RCP

# Memory RCP

# Memory LSCO

# Conclusions

Spin Glasses have outstanding dynamic and static properties

There are superspin glasses

There may be phase separated superspin glasses

Spin glassiness and superspin glassiness have similar characteristics

Phoenician Stairs:
943 (or 921) steps – 300 m