Aging, rejuvenation and memory: the example of spin glasses

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Osaka University, Kawamura's group, Nov. 24th 2006

1. Introduction

2. Slow dynamics and aging

3. Rejuvenation and memory

1. Introduction

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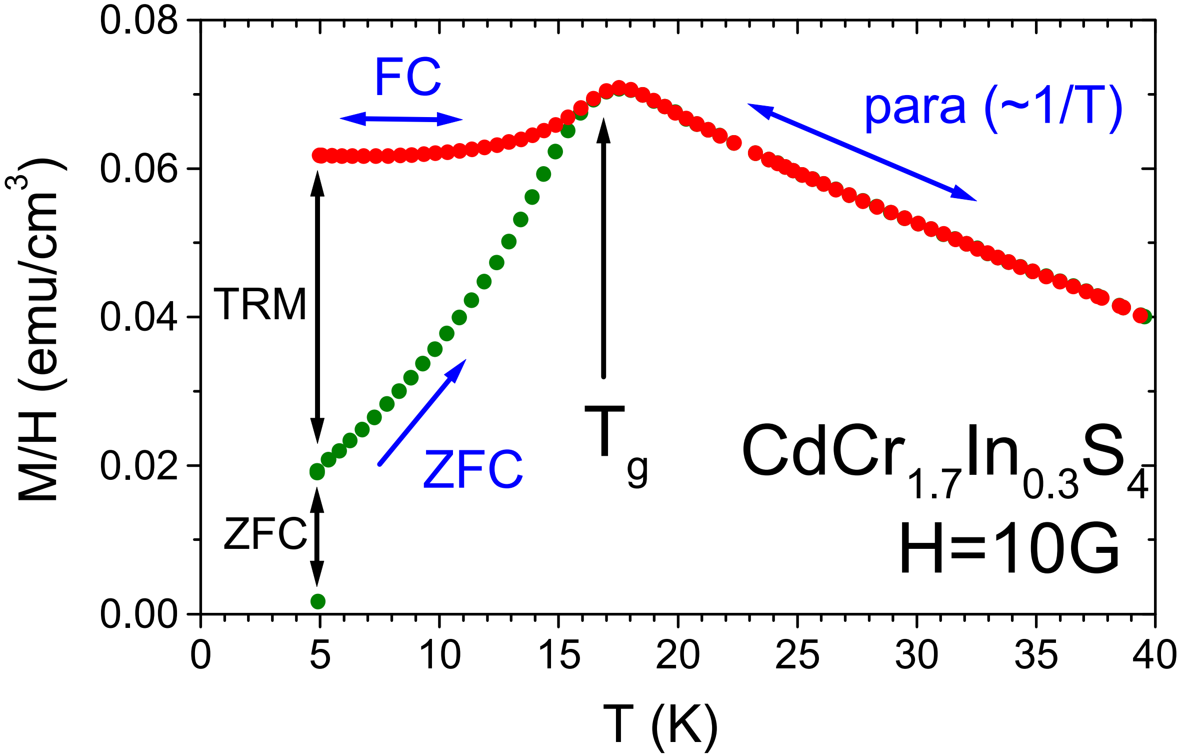
SPIN GLASS: TYPICAL BEHAVIOUR



FC ≡ **F**ield-**C**ooled magnetization

ZFC ≡ **Z**ero-**F**ield **C**ooled magnetization

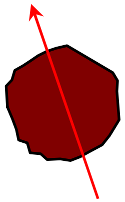
TRM ≡ **T**hermo-**R**emanent **M**agnetization

ZFC(t)+TRM(t) = FC(t)

Nordblad et al, JMMM 54, 185 (1986)

Superspin Glass

- Small enough ferromagnetic nanoparticle→ single domain magnetism
- $T \ll T_c$: response of single nanoparticle ~ response of single spin
  → a 'superspin'



- Varying concentration of nanoparticles in a liquid dispersion changes dipole-dipole interparticle interaction

Dilute nanoparticle system → superparamagnet (non-interacting superspins)

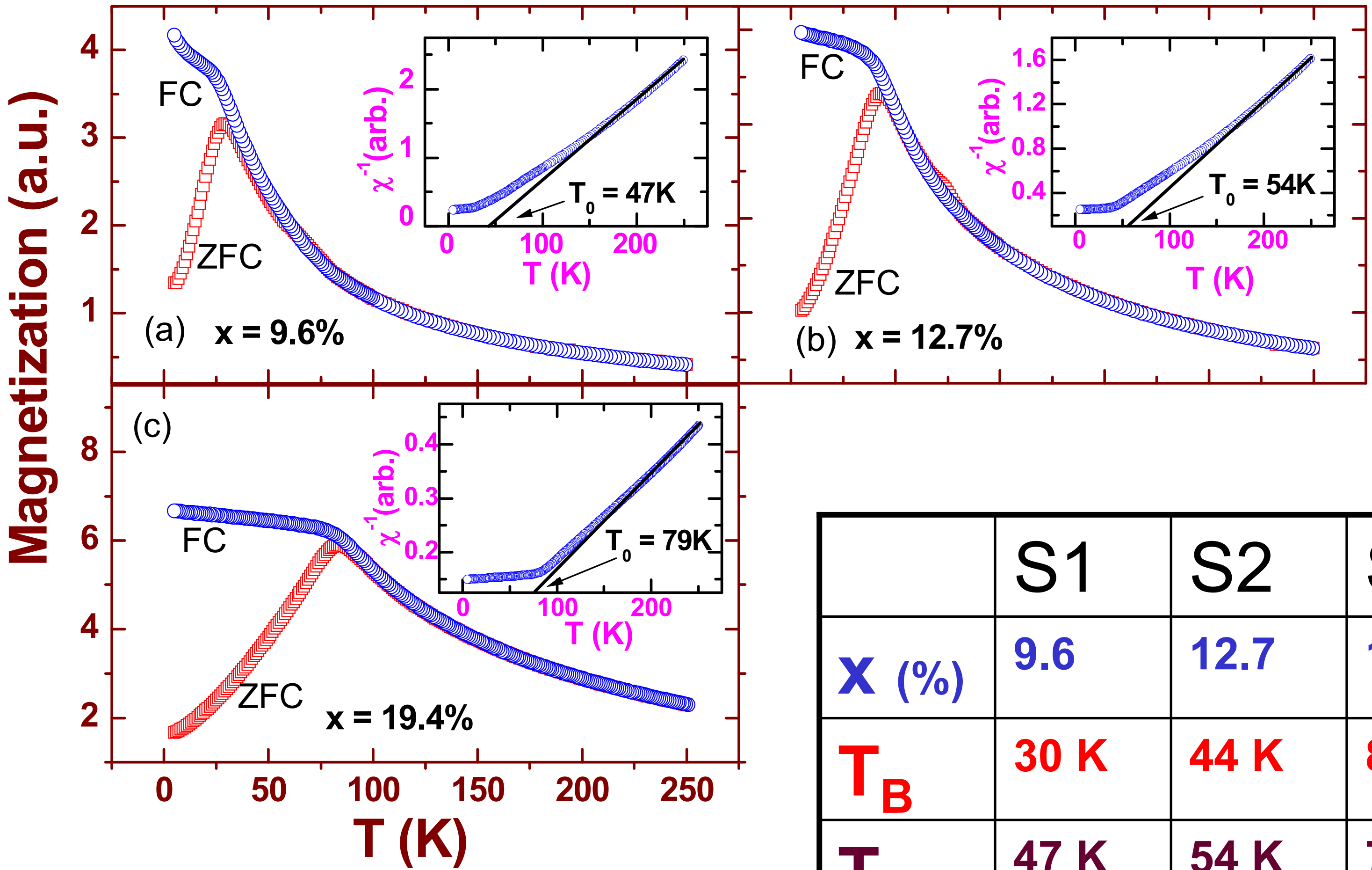
Concentrated nanoparticle system → Superspin glass (interacting superspins)

- To what extent do superspin glasses behave like atomic spin glasses?

Parker et al, *J. Appl. Phys.* **97**, 10A502 (2005)

ZFC-FC curves of Co nanoparticles

(Co_xAg_{1-x} , with varying concentration x)



from X.X. Zhang, Hong Kong UST

	S1	S2	S3
x (%)	9.6	12.7	19.4
T_B	30 K	44 K	84 K
T_0	47 K	54 K	79 K

The increase of T_0 indicates an enhancement of interactions

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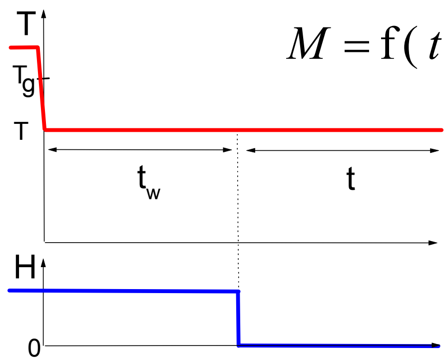
Spin glasses: slow dynamics + aging

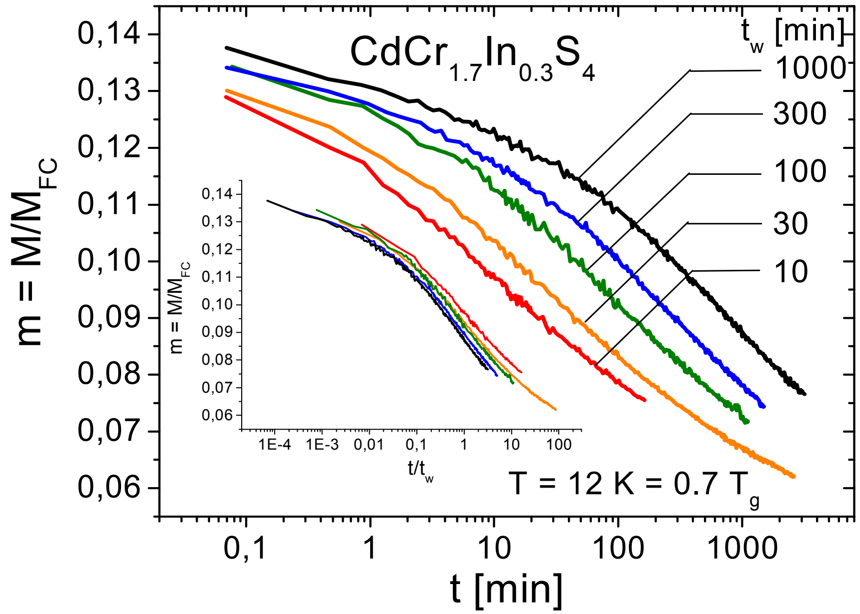
1. dc : Thermo-Remanent Magnetization (TRM)

80' *Uppsala, Sweden (Lundgren, Nordblad…)*
Saclay, France (Hammann, Ocio, Alba, Vincent…)



$$M = f(t, t_w)$$

t_w : waiting time
t : observation time

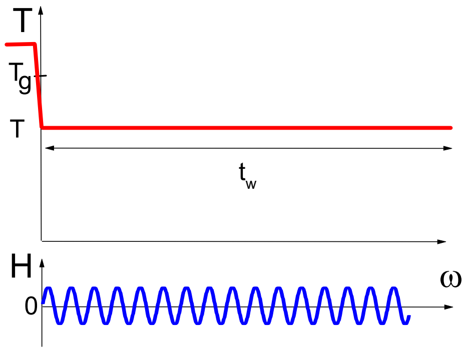


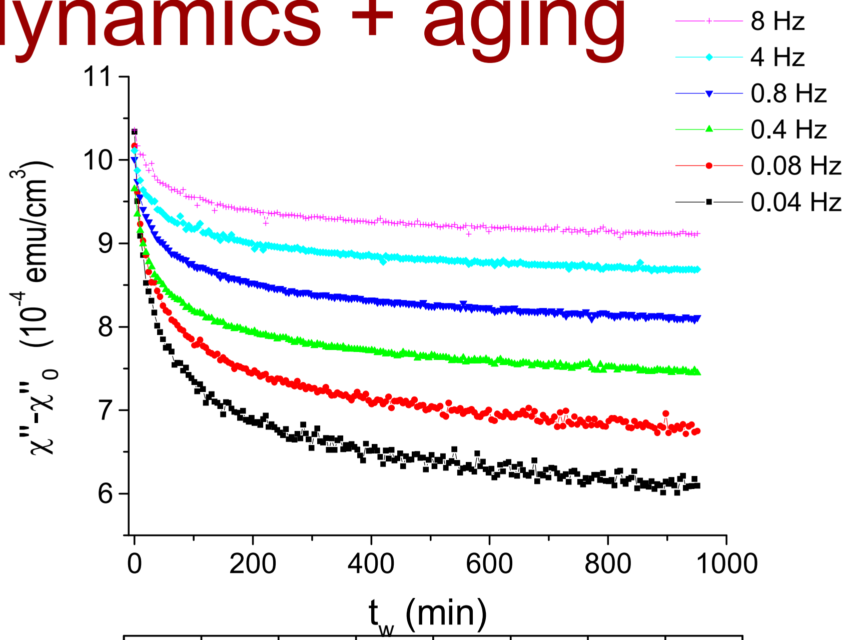
Non-stationary dynamics : $(t\ ,\ t_w)$ *(dc)*
Scaling variable : $\sim t\ /\ t_w$ *(dc)*

Spin glasses: slow dynamics + aging

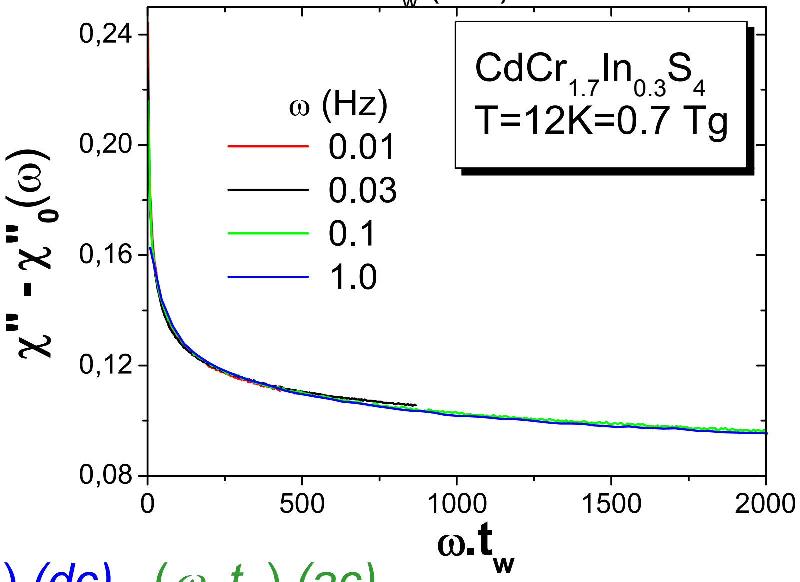
2. ac susceptibility

80' *Uppsala, Sweden (Lundgren, Nordblad…)*
Saclay, France (Hammann, Ocio, Alba, Vincent…)





$$\chi = f(\omega, t_w)$$
$$= \chi_{eq}(\omega) + (\omega . t_w)^{-\alpha}$$
$$(\alpha \approx 0.2)$$

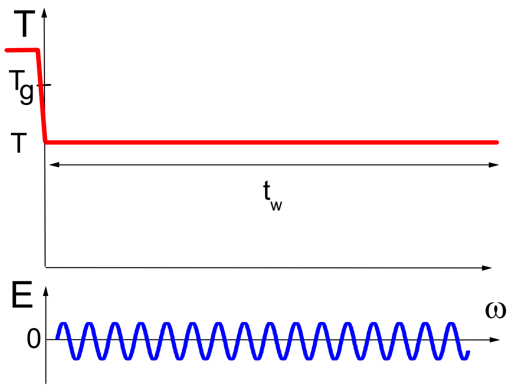


Non-stationary dynamics : (t, t_w) (dc) , (ω, t_w) (ac)
Scaling variables : $\sim t / t_w$ (dc) , $\omega\, t_w$ (ac)

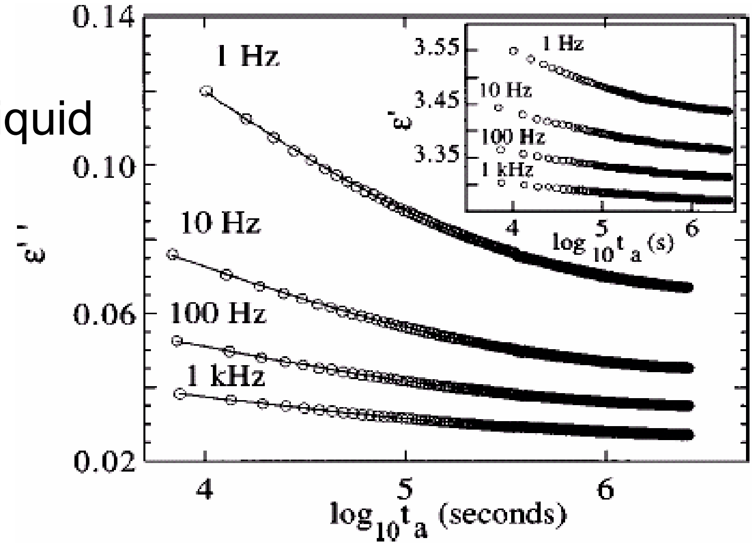
Structural and polymer glasses

Dielectric response of a supercooled liquid

(ac)



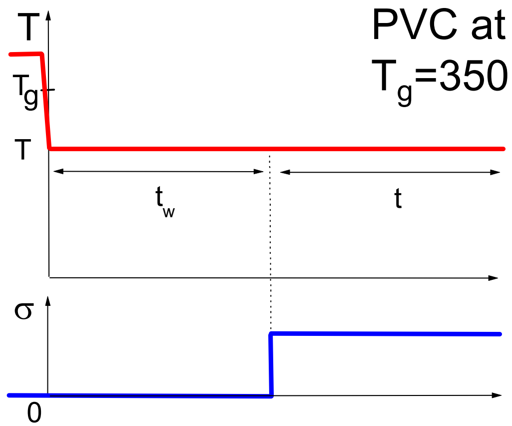
glycerol
at 178K
T_g=190K



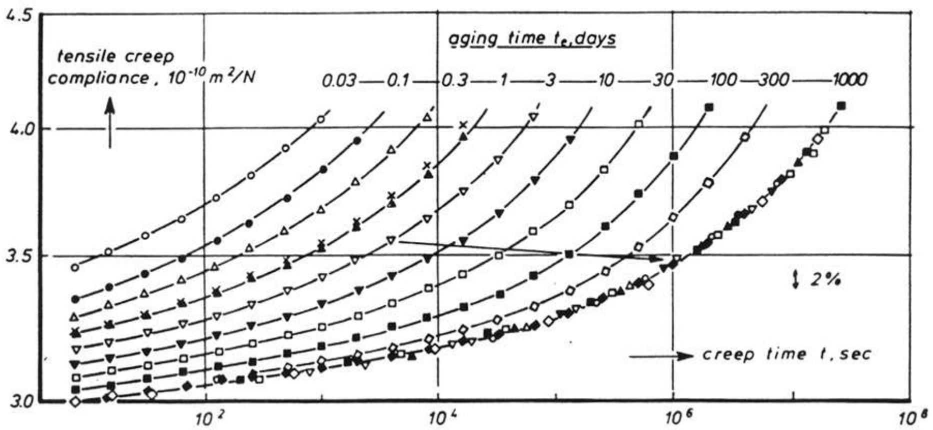
glycerol
Leheny et al. (1998)

Mechanical response of a polymer

(dc)



PVC at 310K
T_g=350K

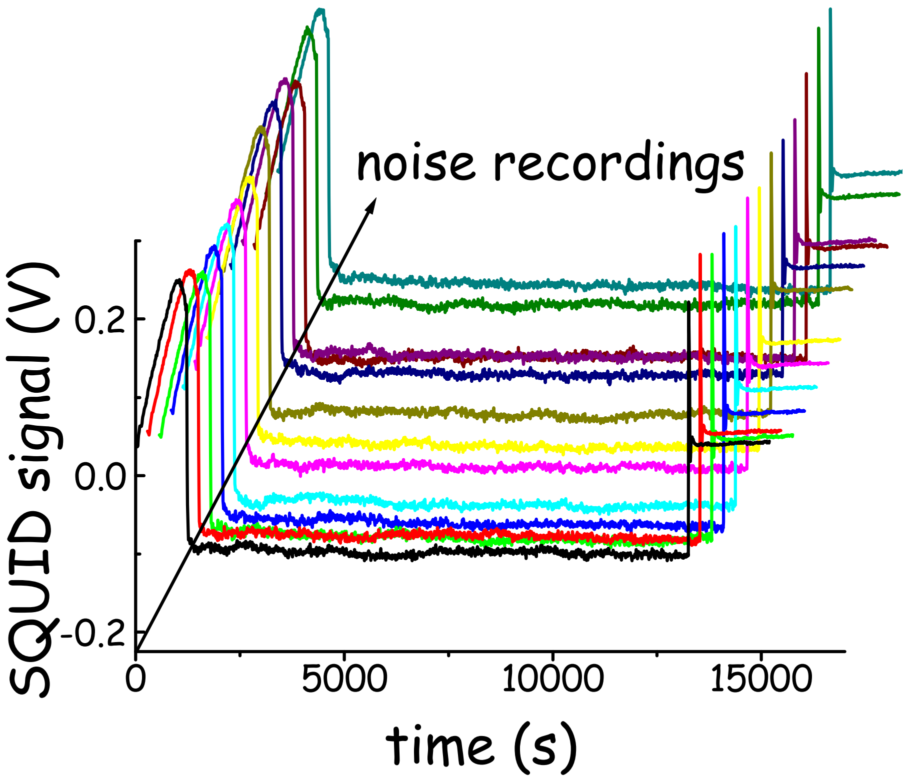


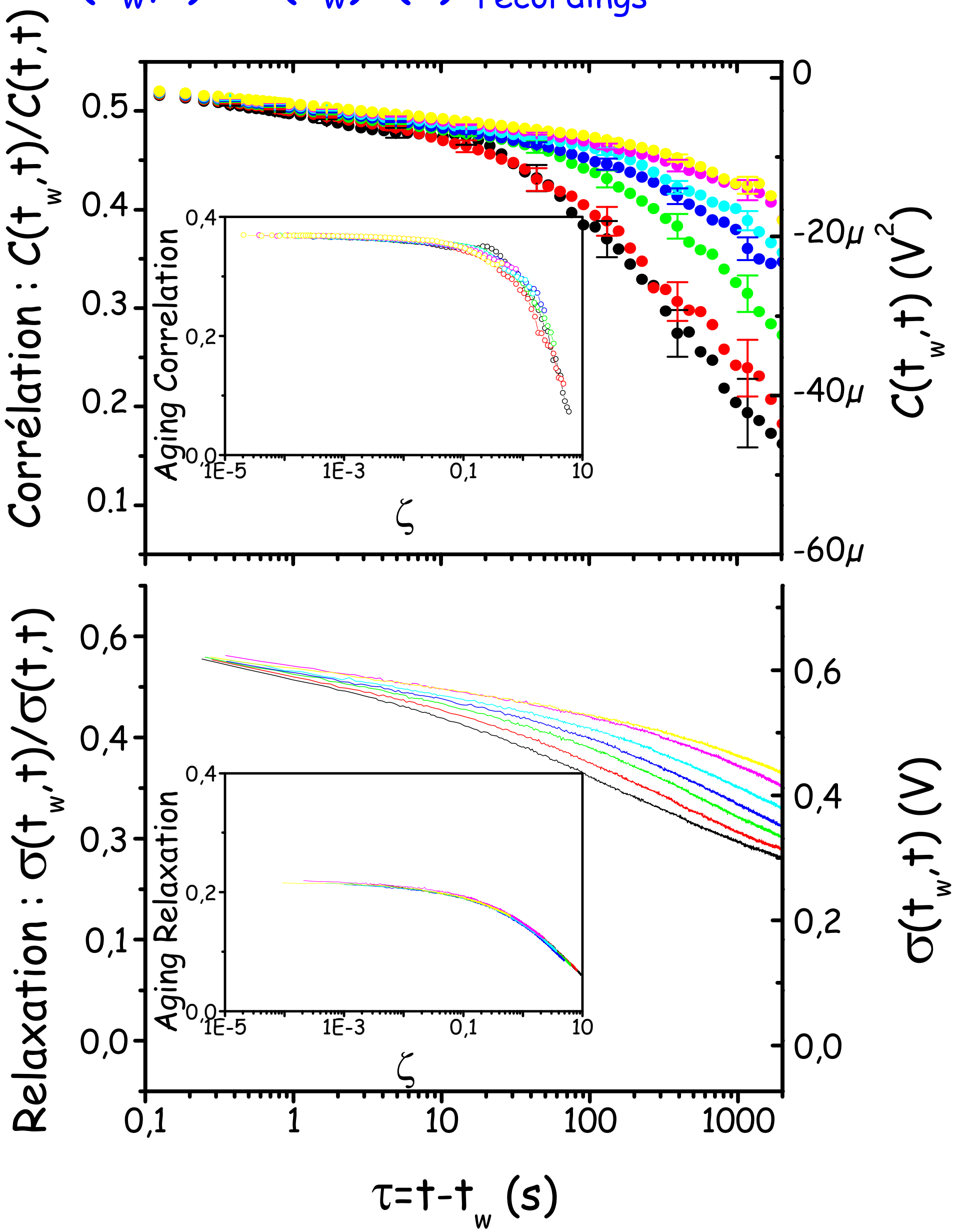
PVC
Struik (1978)

→ ~ same scaling laws as in spin glasses : ωt , t / t_w

3. Spin glasses: noise measurements

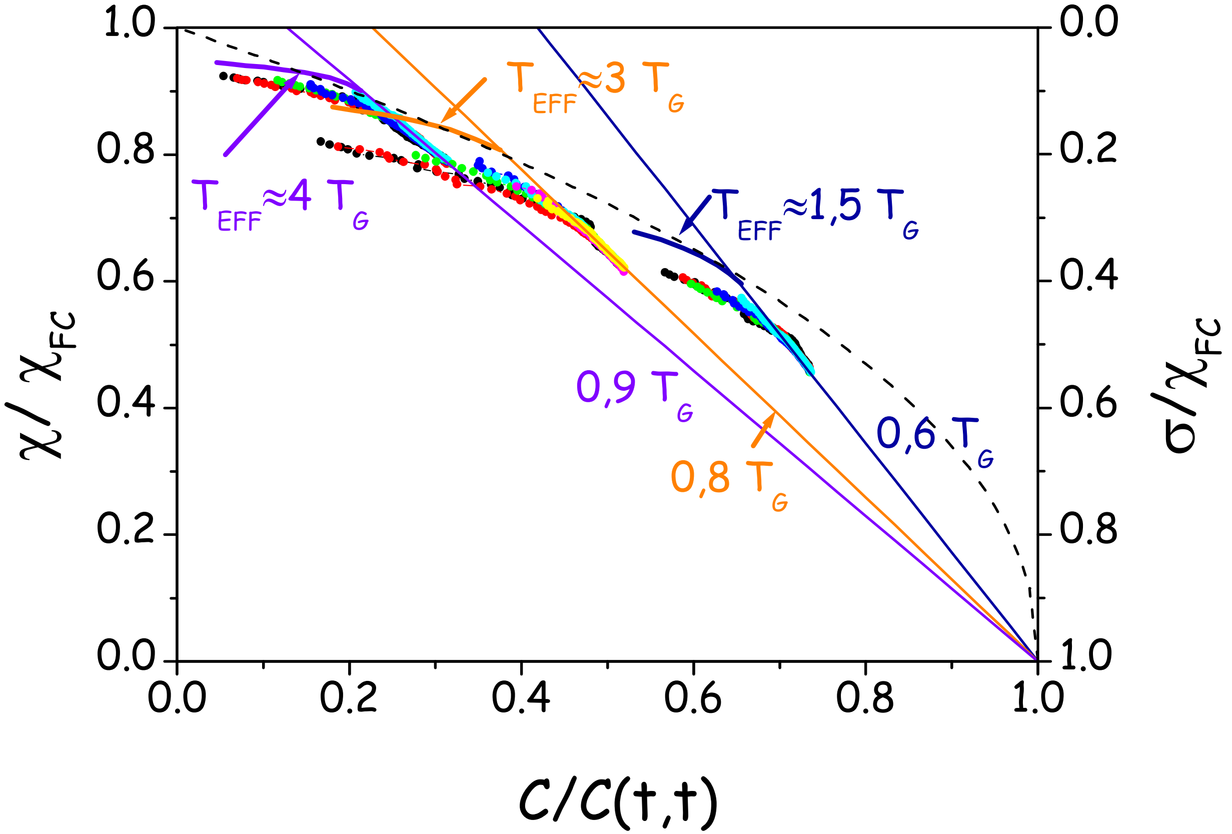
determination of the autocorrelation $C(t_w,t)=\langle v(t_w)v(t)\rangle_{recordings}$





→ Comparison of autocorrelation and response, fluctuation-dissipation relations *in the aging regime*

FD relation graph (« *CuKu graph* »)



D. Hérisson and M. Ocio,
Phys. Rev. Lett. **88**, 257202 (2002)
Eur. Phys. J. B **40**, 283 (2004)

Miguel Ocio
(1943-2003)
D. Hérisson
PhD thesis

- clear 1/T regime, and crossover to aging regime $1/T_{eff}$
- vanishing t_w-dependence in the 'extrapolation' → $T_{eff} = f(C)$
- not domain growth-like ($1/T_{eff}=0$, horizontal lines)
- 1-step RSB type models: *straight lines of slope $1/T_{eff}$ - compatible*
- continuous RSB models (SK, mean-field spin glass): $\chi=1-\sigma=(1-C)^{0,47}$ *(dashed line)*

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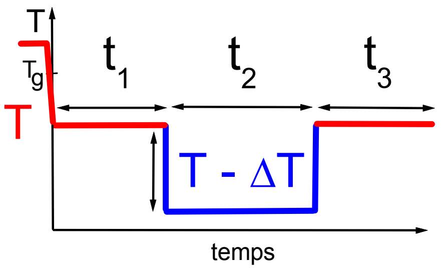
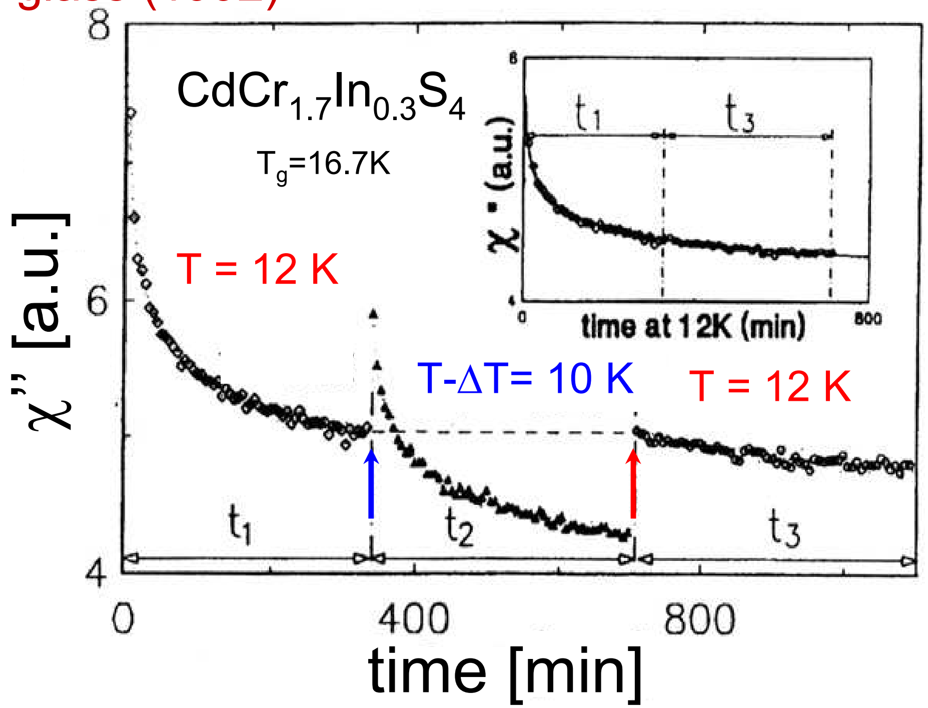
Aging, rejuvenation and memory: basic observation

« Negative temperature cycling » of a spin-glass (1992)





T↓ : rejuvenation, *restart of the relaxation*

T↑ : memory, *no effect of the time spent at T-ΔT*

In simulations:

no rejuvenation and memory effects in the Ising spin glass ?

Tokyo (Takayama group), Roma (Parisi group), …

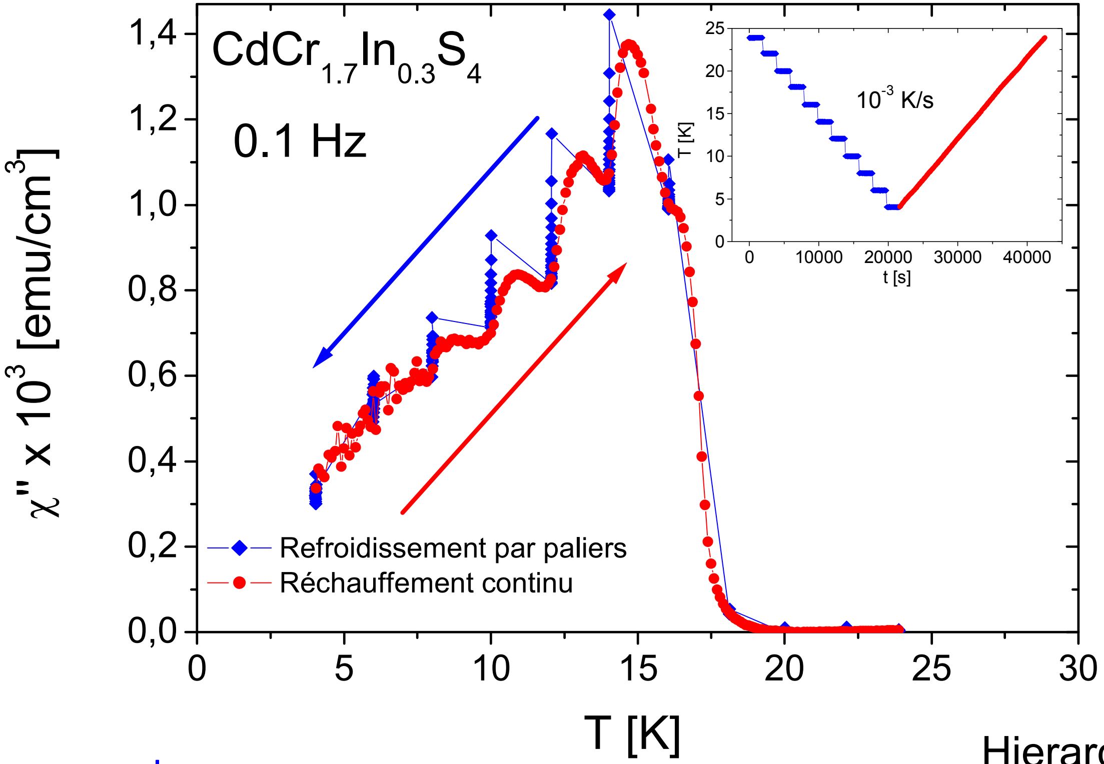
Recently: rejuvenation and memory effects in the Heisenberg spin glass

Berthier & Young (2005)

Experiments on Ising and Heisenberg spin glasses: see *PRL* **92**, 167203 (2004)

(nature of the Heisenberg spin-glass phase ? chiral glass à la Kawamura ?)

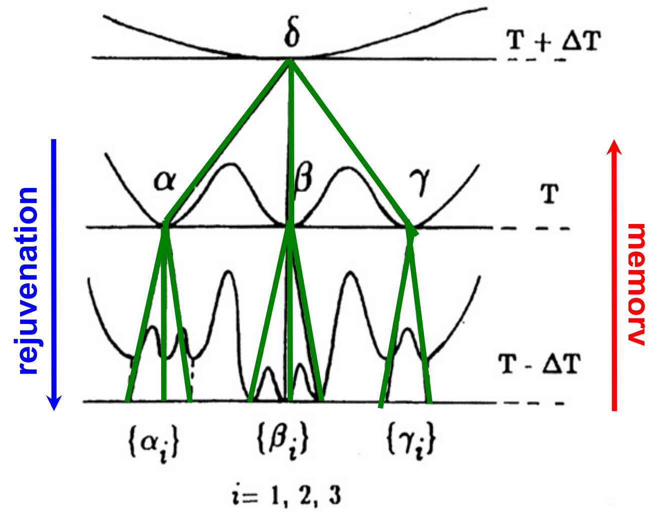
Multiple rejuvenation and memory effects in a spin glass



T↓ : rejuvenation
T↑ : memory

« memory dips » experiments:
Uppsala / Saclay *PRL* **81**, 3243 (1998)

hierarchical organisation of the metastable states as a function of T

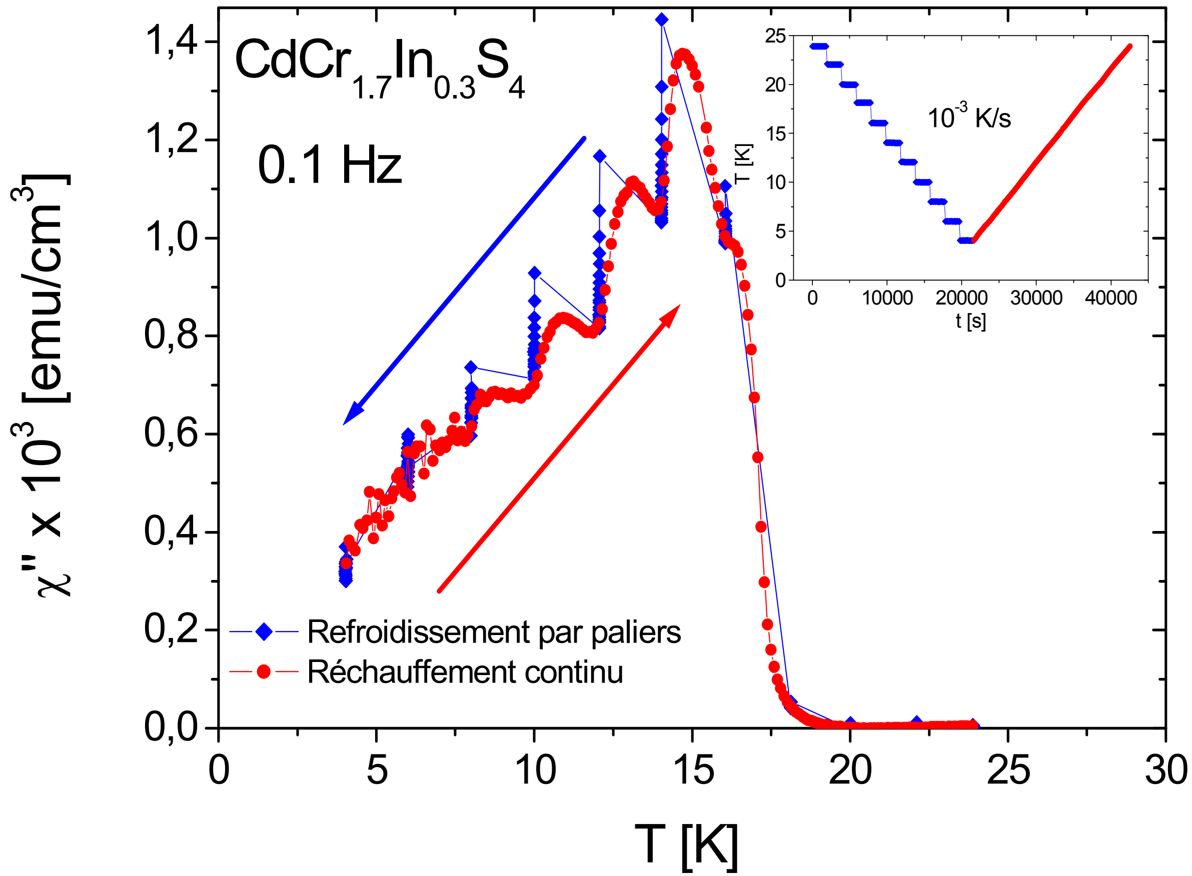


Hierarchical models (REM, GREM, traps):
Bouchaud and Dean (1995)
Sasaki and Nemoto (2000)
Sasaki et al, *EPJ B* **29**, 469 (2002)

more details and references in cond-mat/0603583

Rejuvenation and memory effects in terms of spins ?

not simply domain growth-like



T↓ : rejuvenation

T↑ : memory

Aging at fixed T : *growth of SG-order up to some coherence length L^*_T*

Rejuvenation ⇒
different equilibrium correlations at different T's (chaos-like ?)

Memory ⇒

$L^*_n << \ldots\ldots << L^*_2 << L^*_1$

- *hierarchy of length scales*
- *net separation of L_i's with temperature*

(« T-microscope » effect)

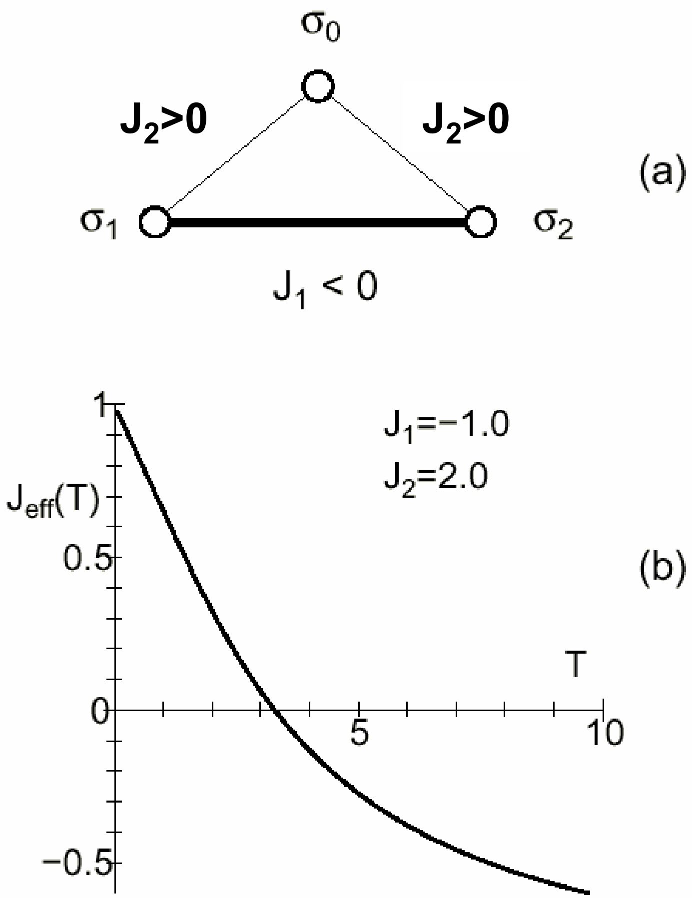
A microscopic mechanism for rejuvenation *and* memory ?

S.Miyashita and E.V., *EPJ B* **22**, 203 (2001)

1) Temperature dependent effective interactions

(due to frustration)

Example :



$J_{eff} \equiv$effective interaction between σ_1 and σ_2

varies with temperature

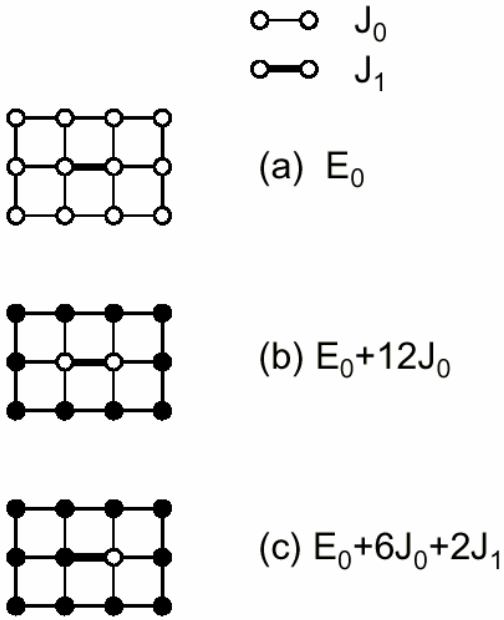
→ rejuvenation

A microscopic mechanism for rejuvenation *and* memory ?

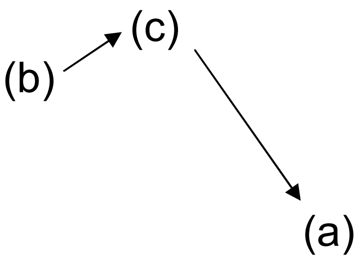
2) Memory spots

(due to inhomogeneity of interactions)

Example:



$J_1 >> 3J_0 > 0$



barrier = $2J_1$-$6J_0$

→ slow relaxation, frozen at low T

→ memory

Is this necessary to memory ?
see Yoshino et al, *EPJ B* **20**, 367 (2001)

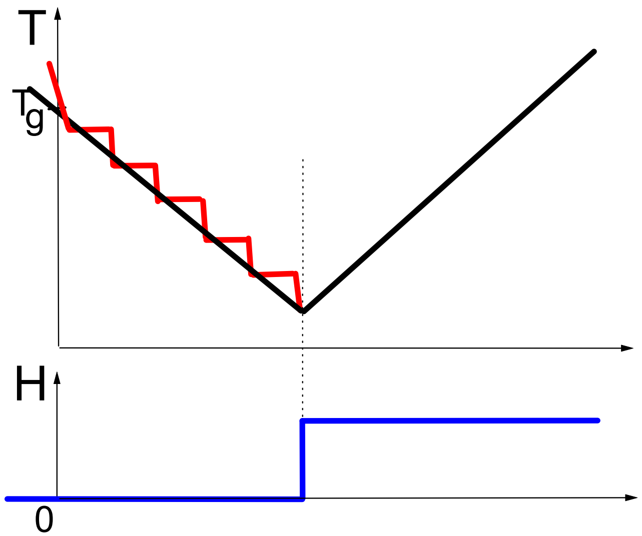
and "**entropy induced slowing down**" by Tanaka and Miyashita, *Progr. Theoret. Phys. Suppl.* **157**, 34 (2005)

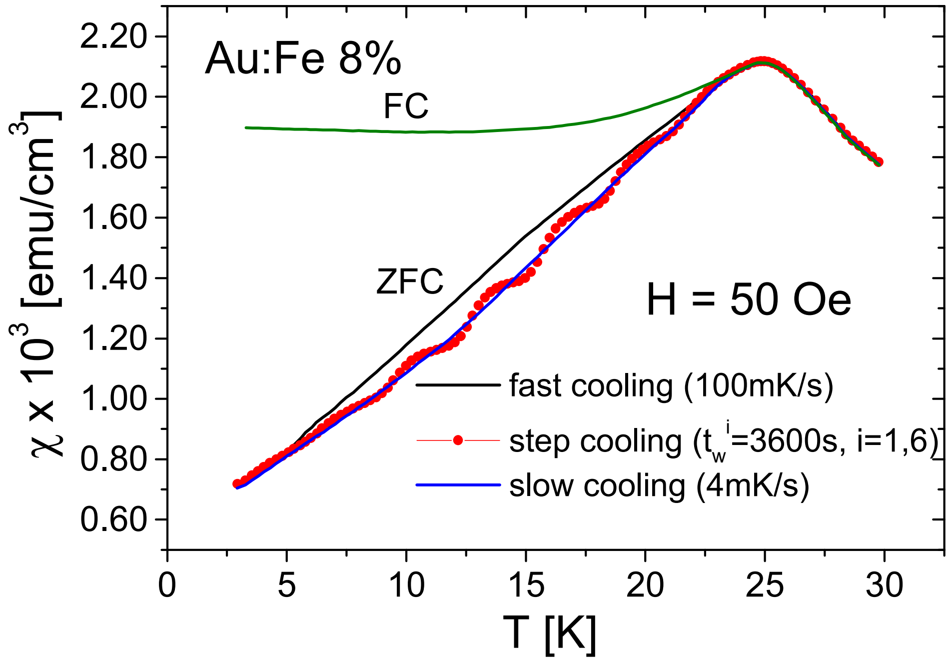
In a real spin glass :
should occur naturally at various length/energy scales

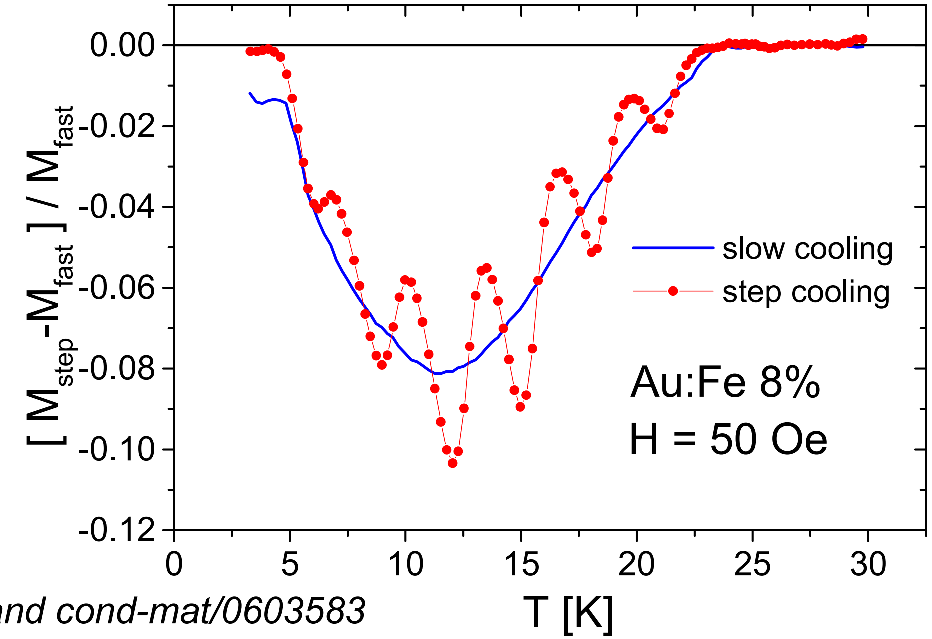
Spin glass : rejuvenation *vs* cooling rate effects

ZFC procedure with stops

(Uppsala 2001)







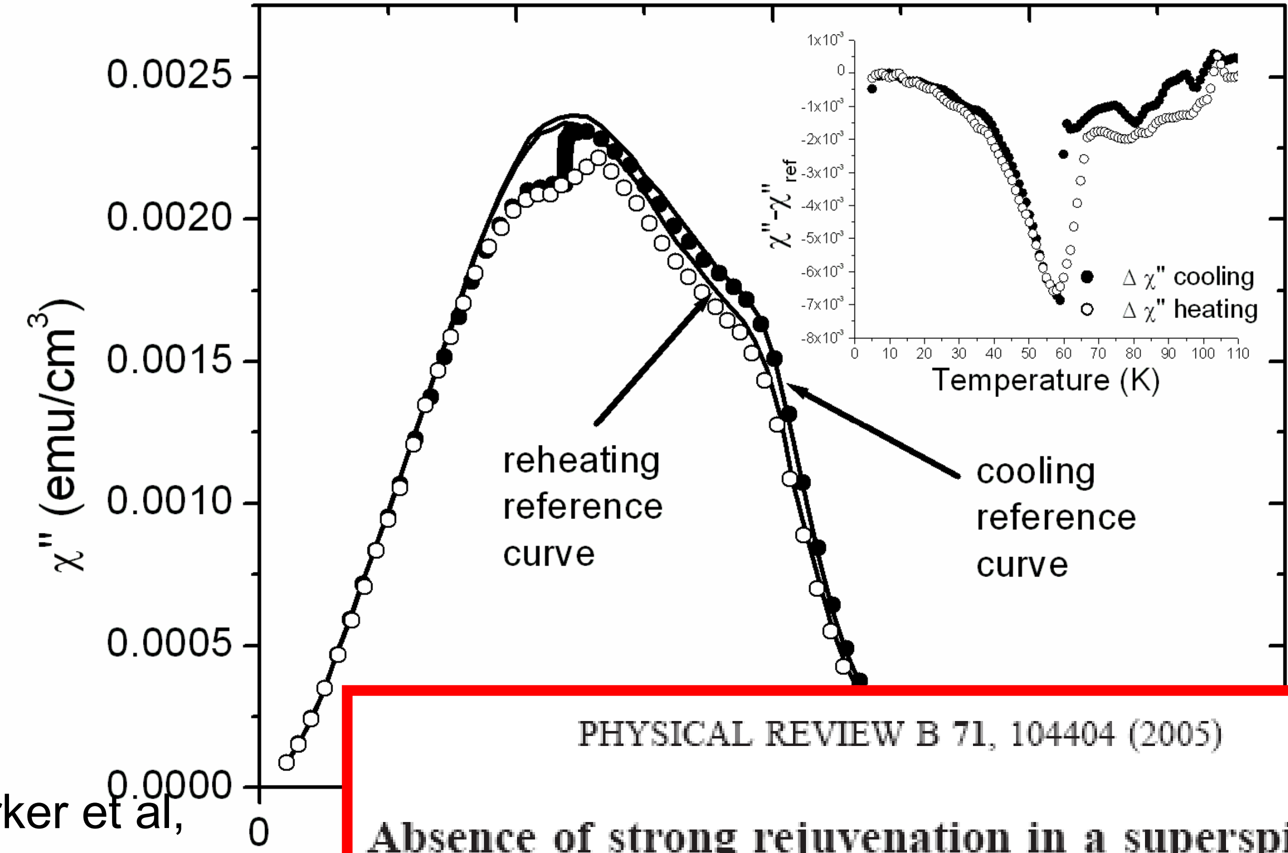
aging ≡ combination of

- **cooling rate effects**
  T-cumulative
- **rejuvenation & memory effects**
  T-specific

V. Dupuis, PhD thesis, Orsay 2002, and cond-mat/0603583

MEMORY EFFECT IN NANOPARTICLES

γ-Fe_2O_3 nanoparticles, d~8.5nm, f_v=35%



V. Dupuis, D. Parker et al,
AIP Conf. Proc.
832, 295 (2006)

PHYSICAL REVIEW B 71, 104404 (2005)

Absence of strong rejuvenation in a superspin glass

P. E. Jönsson,[1] H. Yoshino,[2] H. Mamiya,[3] and H. Takayama[1]

MEMORY EFFECTS IN A GELATINE GEL

"The spin glass dynamics of gelatine gels"

Alan Parker and Valéry Normand

Research Division, Firmenich SA (Geneva , Switzerland)

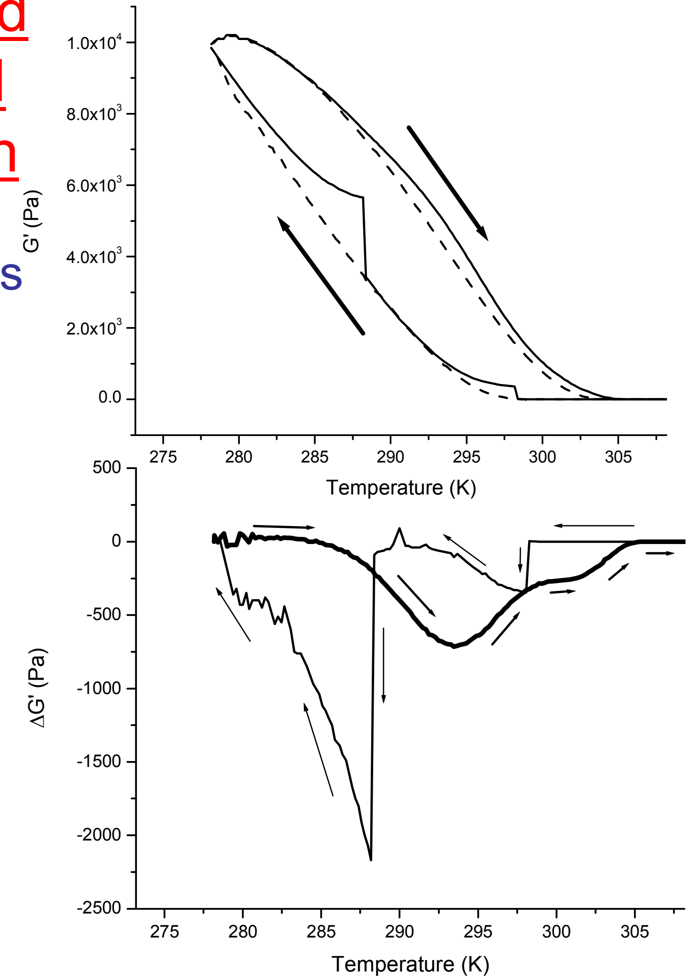
cond-mat/0306056

Elasticity measured during heating and cooling at 0.2K/min

dashed line: continuous heating and cooling

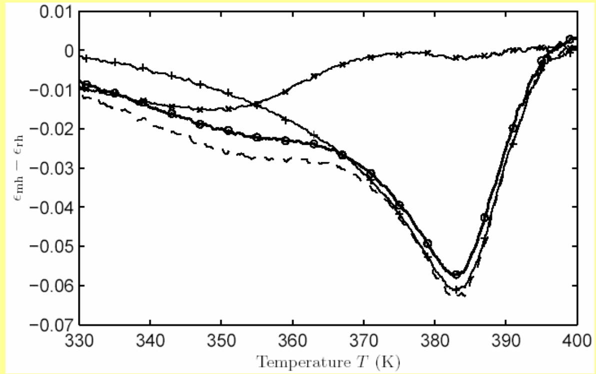
solid line: with 2 stops (2h at 25° and 15°C)

Bottom figure : difference plot



Memory in the aging of a polymer glass

L. Bellon, S. Ciliberto and C. Laroche



double memory reading in PMMA (dielectric measurement)

Conclusions

- Spin glasses : aging effects

  waiting time dependence of ac+dc susceptibility, and in noise

  similar to aging in structural and polymer glasses

- Effect on aging of thermal history:

  rejuvenation and memory phenomena (T-specific)

  \+

  cooling rate effects (T-cumulative)

- Rejuvenation and memory :

  aging at different temperatures can take place

  at well-separated length scales

  ↔*hierarchy of embedded coherence length scales, selected by T*

  (microscope effect)

- Same scenario in other glassy systems ?

  probably yes (R&M in nanoparticles, PMMA, gelatine …)

more details and references in cond-mat/0603583