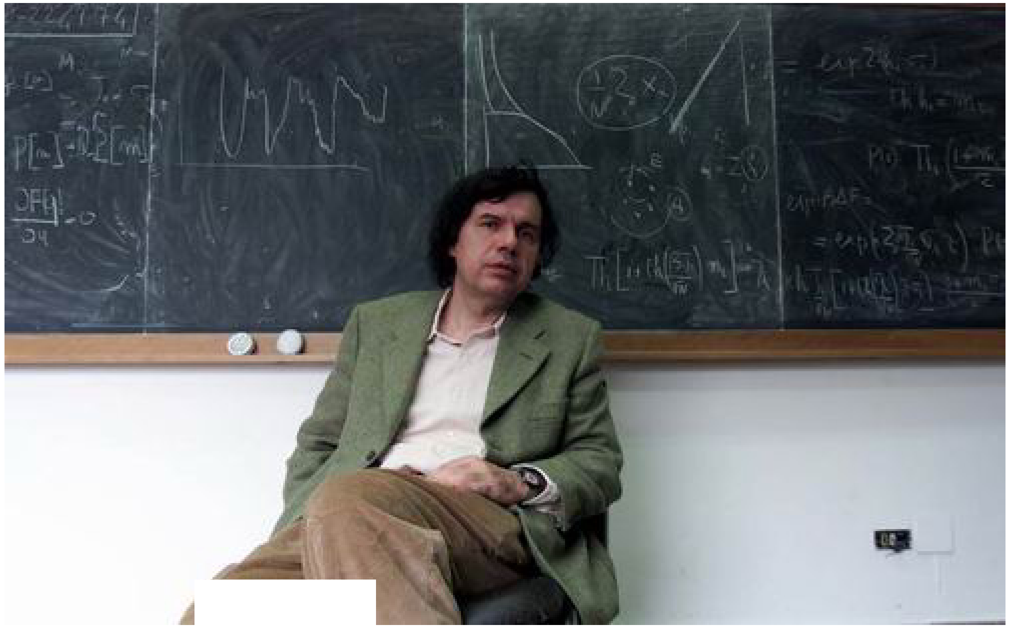
Real spin glasses slowly relax in the shade of hierarchical trees

M. Alba, F. Bert, J.-P. Bouchaud, V. Dupuis, J. Hammann, D. Hérisson, F. Ladieu, M. Ocio and E. Vincent…

Service de Physique de l'Etat Condensé
(IRAMIS / SPEC, CNRS URA 2464)
CEA Saclay (France)



Giorgio Parisi's 60th birthday

1. A few experimental facts…
at the light of the MF spin glass

2. Length scales and temperature microscope

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at the light of the MF spin glass

2. Length scales and temperature microscope

What is a spin glass ?

Theory : **H** $= -\sum J_{ij} S_i . S_j$

random bonds

$\{J_{ij}\}$ gaussian, or $\pm J$

a disordered *and* frustrated

magnetic system

***"Real"* spin glasses :**

Random dilution of magnetic ions

Same generic behaviour in all samples

(Tc≠0 in 3d, slow dynamics, aging...)

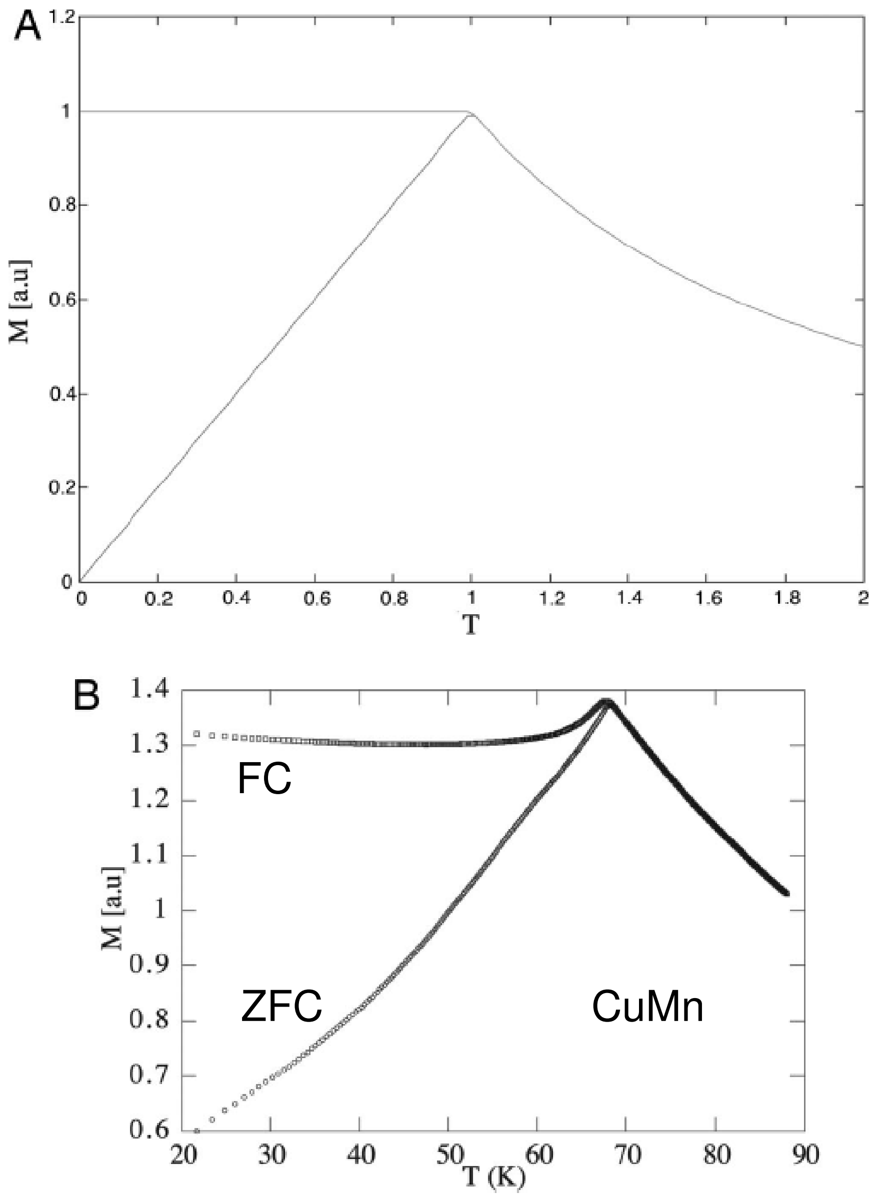


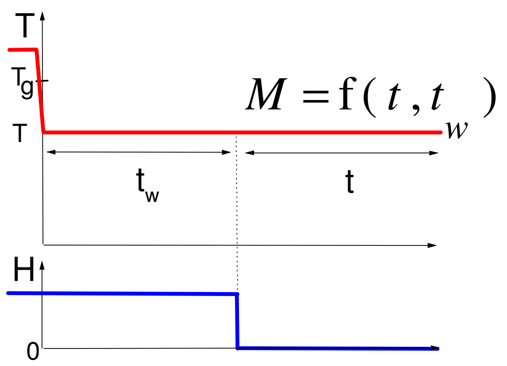
Fig. 3. The two susceptibilities ($\chi_{eq} \geq \chi_{LR}$). (*A*) The analytic results in the mean field approximation (2). (*B*) The experimental results for a metallic spin glass (38).

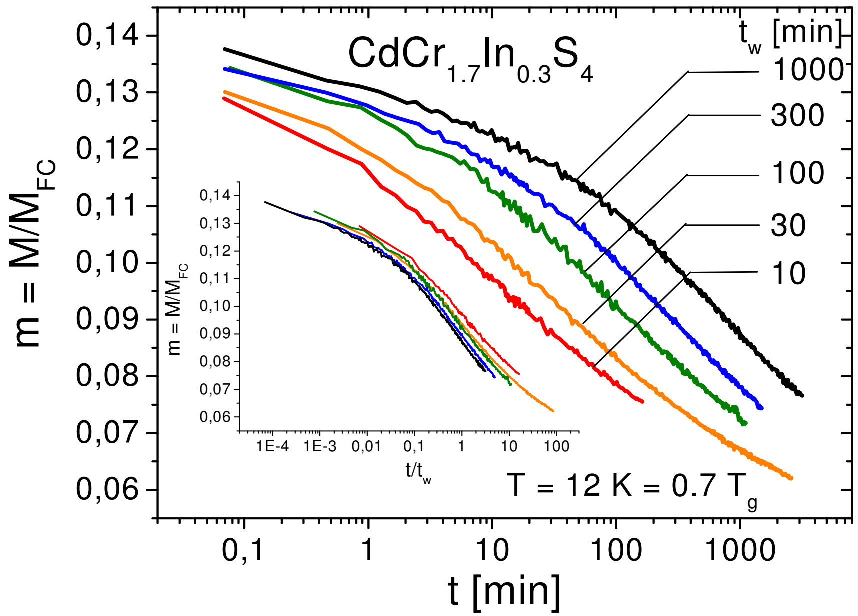
Mézard, Parisi, Virasoro 1987 – CuMn, Uppsala 1999

Spin glass : slow dynamics + aging
non-stationary dynamics

Relaxation of the Thermo-Remanent Magnetization (TRM)

80' Uppsala (Lundgren, Nordblad)
Saclay (Hammann, Ocio, Alba, Vincent)





t_w : waiting time
t : observation time

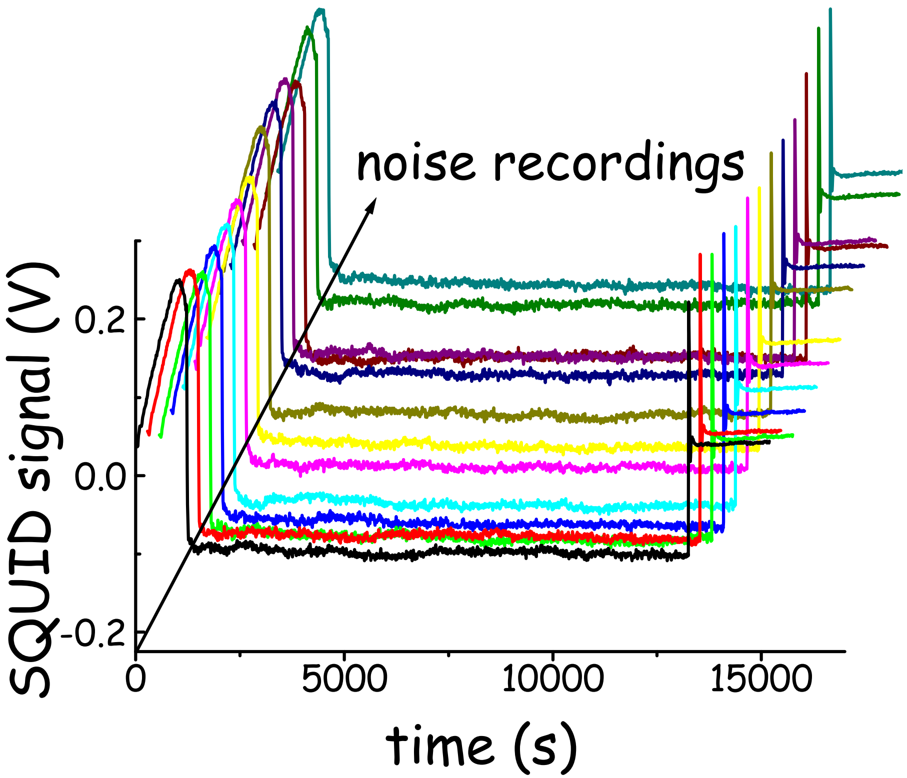
The relaxation curves depend on the waiting time t_w (aging)

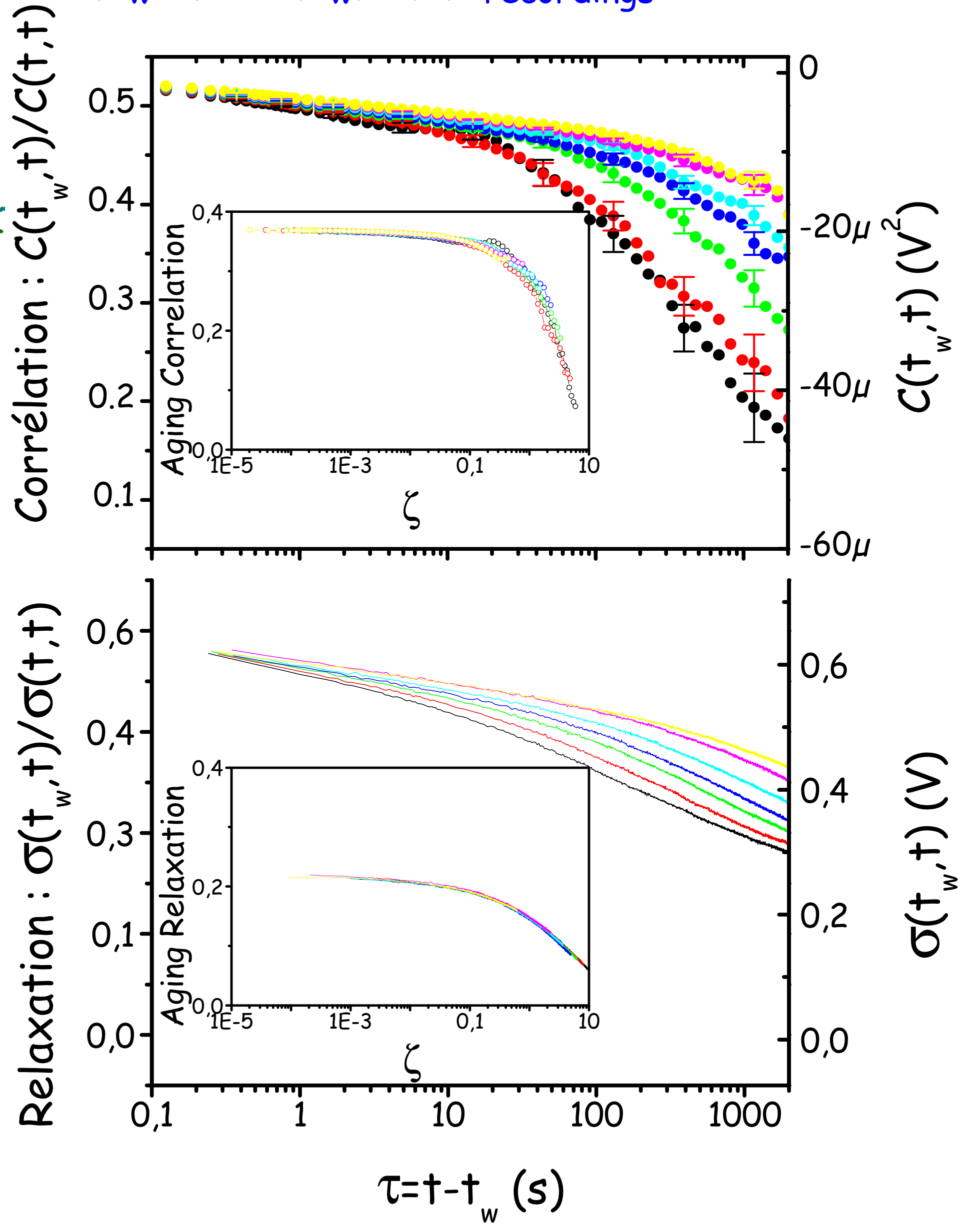
Inflection point at log t ~ log t_w *(figure insert : plot vs t/t_w)*

Given a relaxation curve, one can guess t_w

Noise measurements and Fluctuation-Dissipation ratio

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

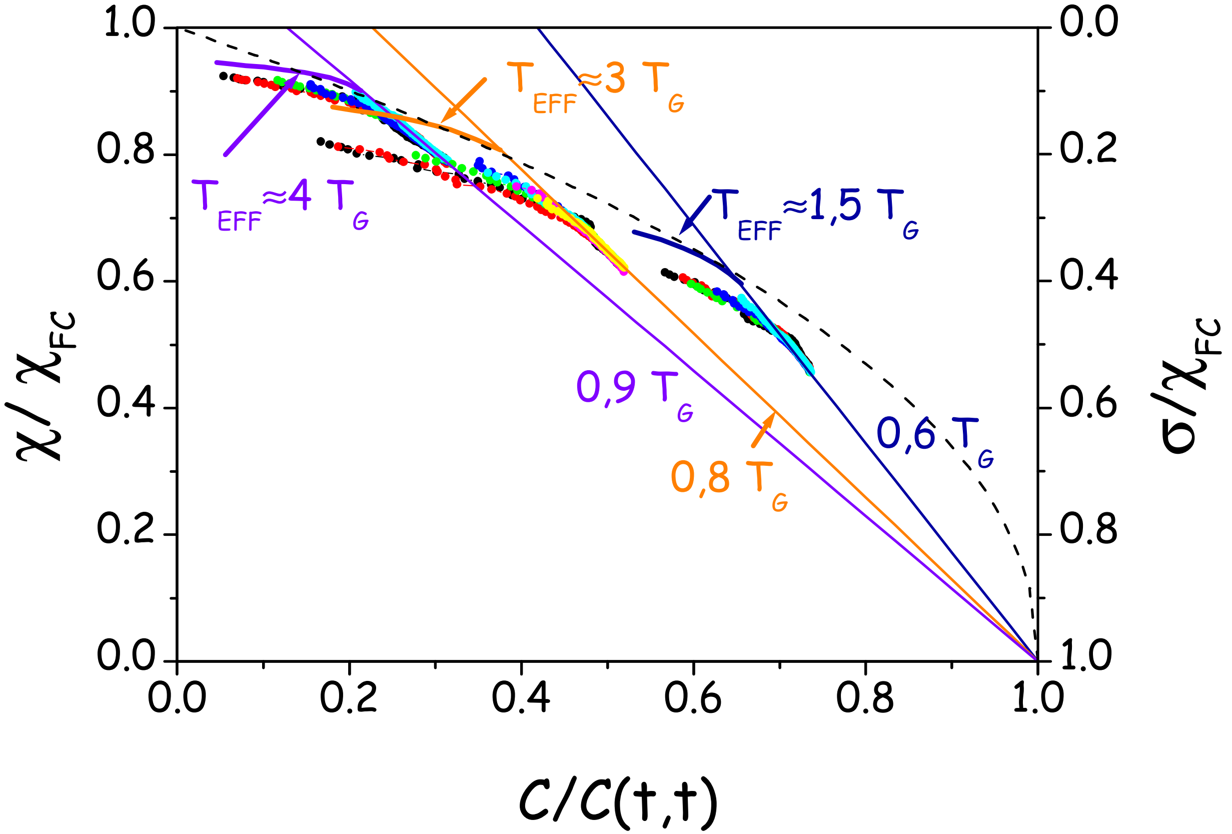




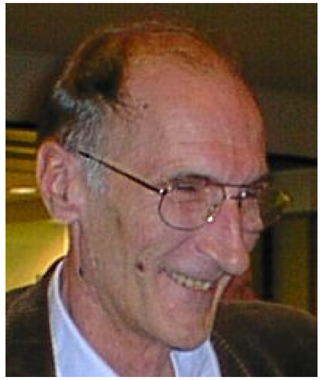
→ Comparison of autocorrelation and response, fluctuation-dissipation relations *in the aging regime*

$CdCr_{1.7}In_{0.3}S_4$ spin glass

FD relation 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' $\rightarrow T_{eff} = f(C)$

Extension of FDR to non-equilibrium situations:

X **= C. F(C)/kT** *(for large t_w)* **T / F(C)** $\equiv$ *effective temperature*

Cugliandolo & Kurchan, *J. Phys. A* **27**, 5749 (1994),
Franz & Mézard, *Europhys. Lett.* **26**, 209 (1994)

P(q) vs S(C) : a relation between statics and dynamics

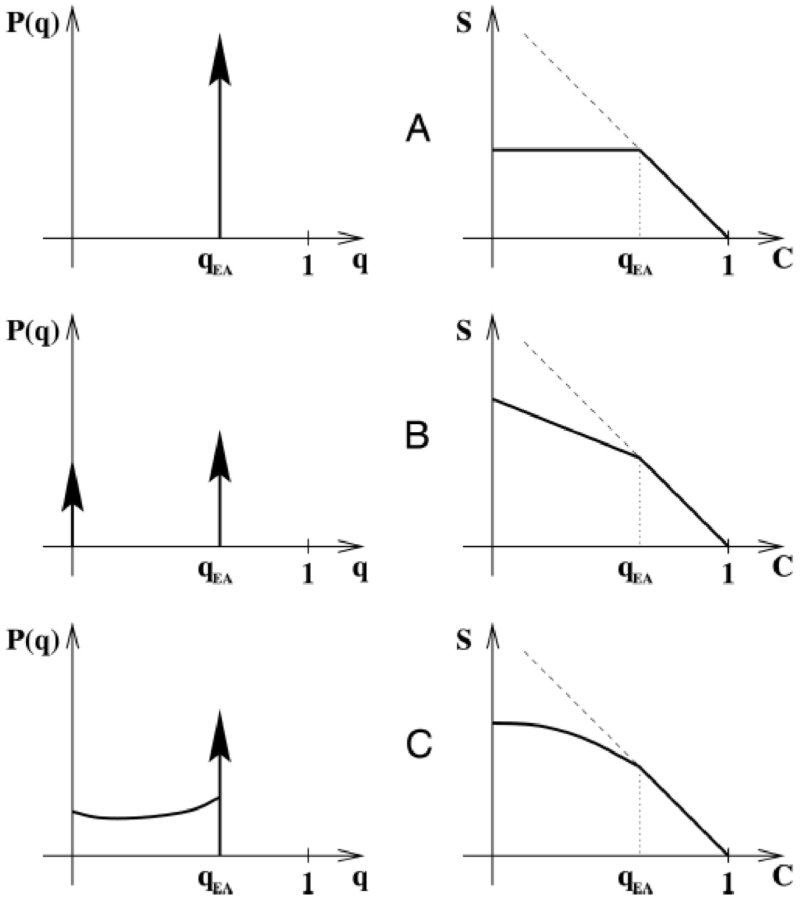
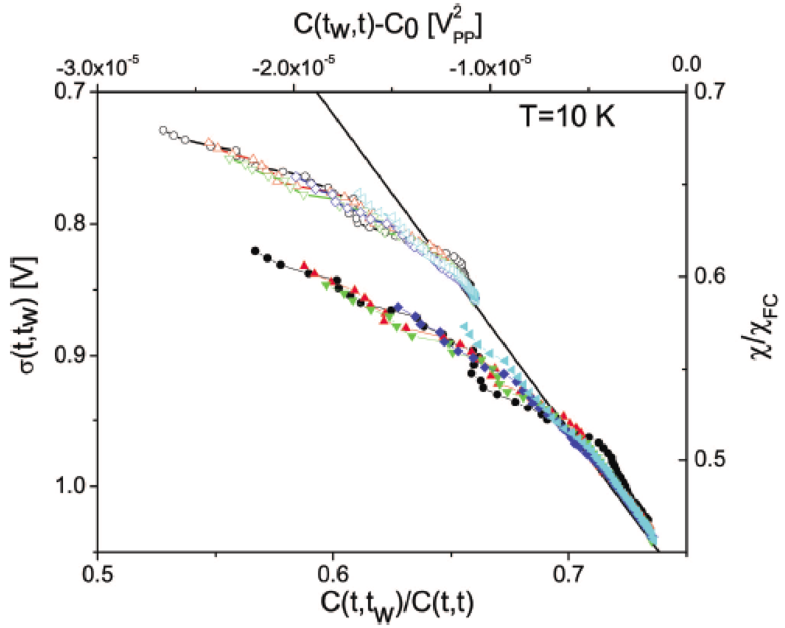


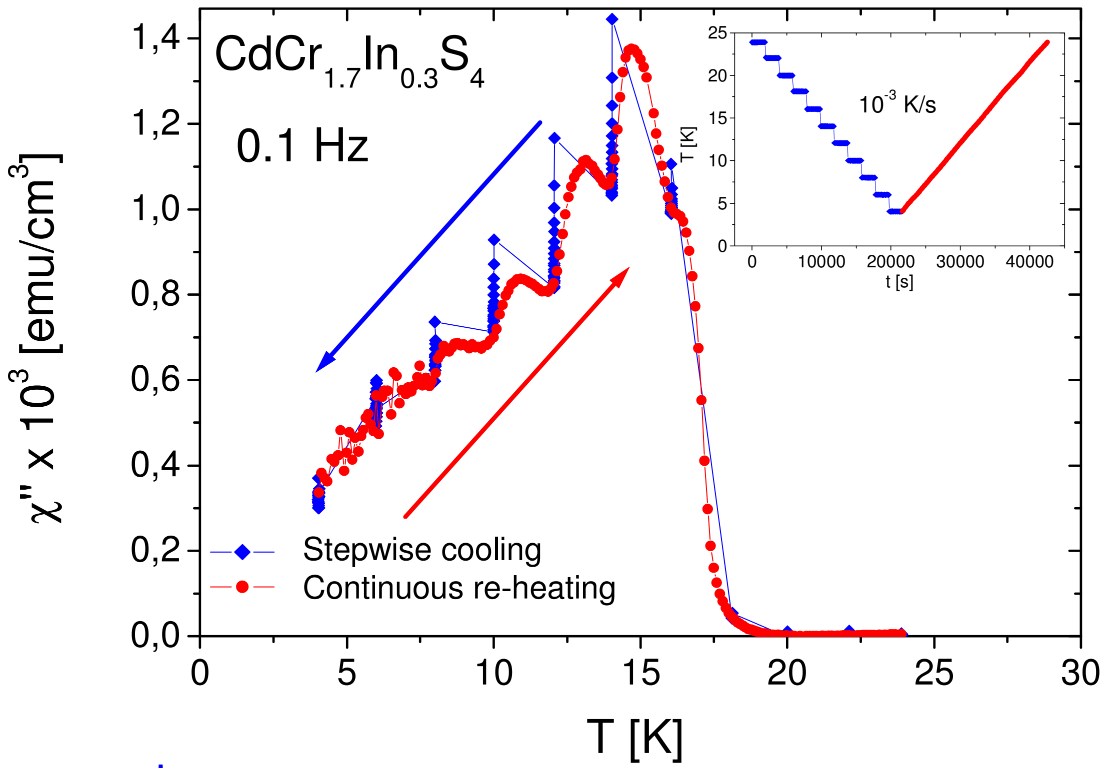
Fig. 6. Three different forms (A, B, and C) of the function *P*(*q*) (*Left*) and the related function *S*(*q*) (*Right*). Delta functions are represented as a vertical arrow (taken from ref. 46).



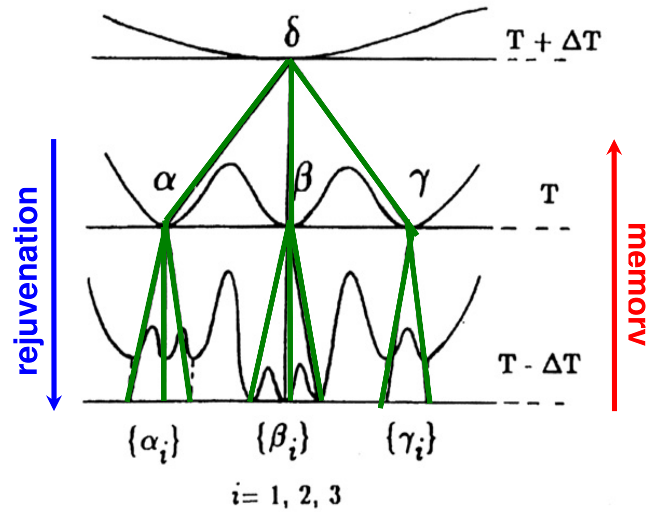
- **A ?** (domain growth-like,$1/T_{eff}=0$, horizontal line) - **NO**
- **B ?** (1-step RSB type models: straight lines of slope $1/T_{eff}$) - ***compatible***
- **C ?** (continuous RSB models : SK, mean-field spin glass) – ***compatible ?***

Franz Mézard Parisi Peliti PRL 81, 1758 (1998) - G. Parisi, PNAS 103, 7948 (2006)

Rejuvenation and memory effects *(ac susceptibility)*



Hierarchical organisation of the metastable states as a function of T



T↓ : rejuvenation

T↑ : memory

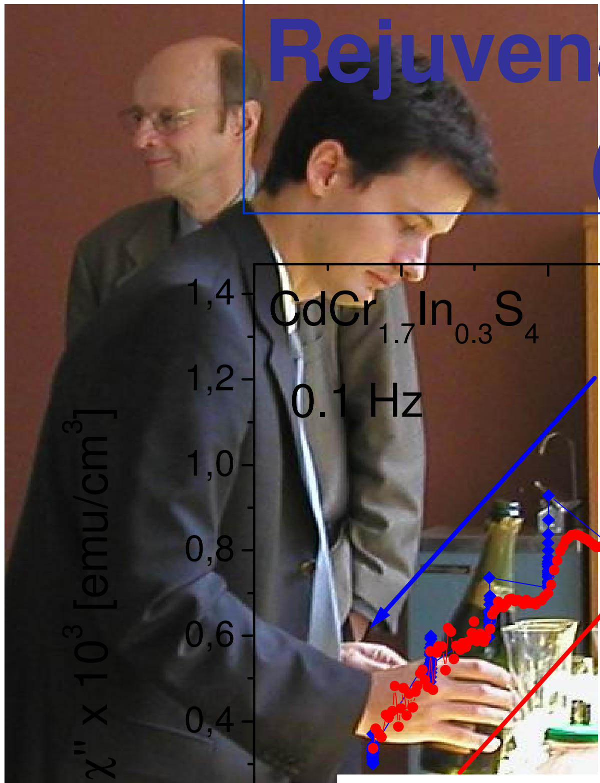
« memory dips » experiments:
Uppsala / Saclay *PRL* **81**, 3243 (1998)

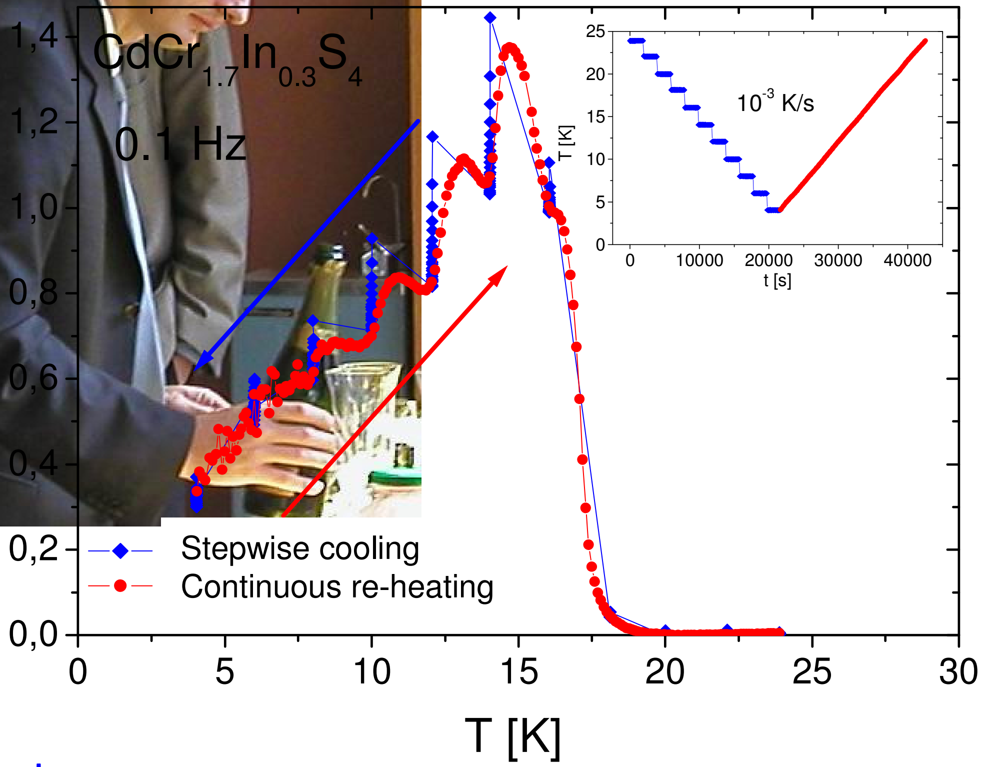
<u>Quantitatively:</u>
Derrida 1981 1986 *(REM, GREM)*
Bouchaud and Dean 1995 *(trap model)*
Sasaki and Nemoto 2000
Sasaki et al, *EPJ B* **29**, 469 (2002)

V. Dupuis, PhD thesis

Details and references in cond-mat/0603583

Rejuvenation and memory effects *(ac susceptibility)*





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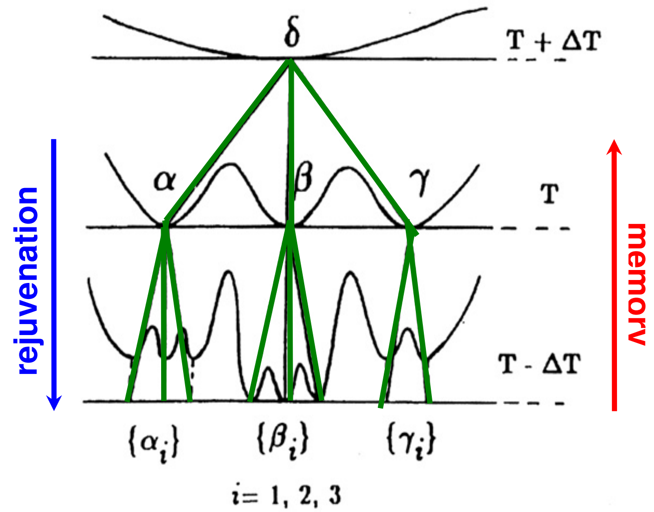

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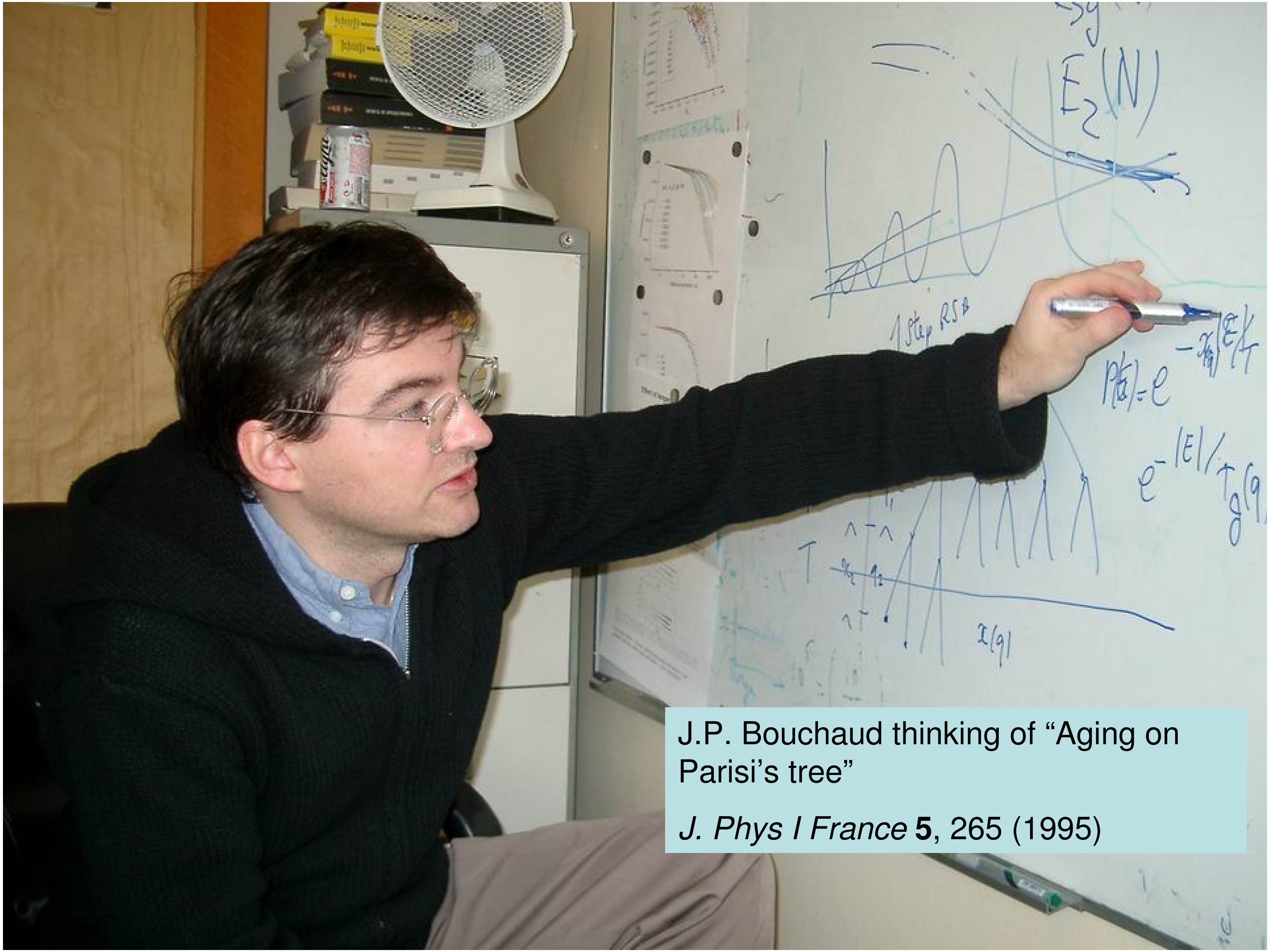
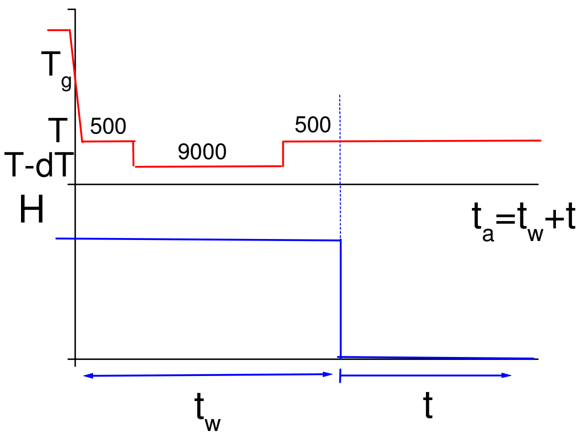


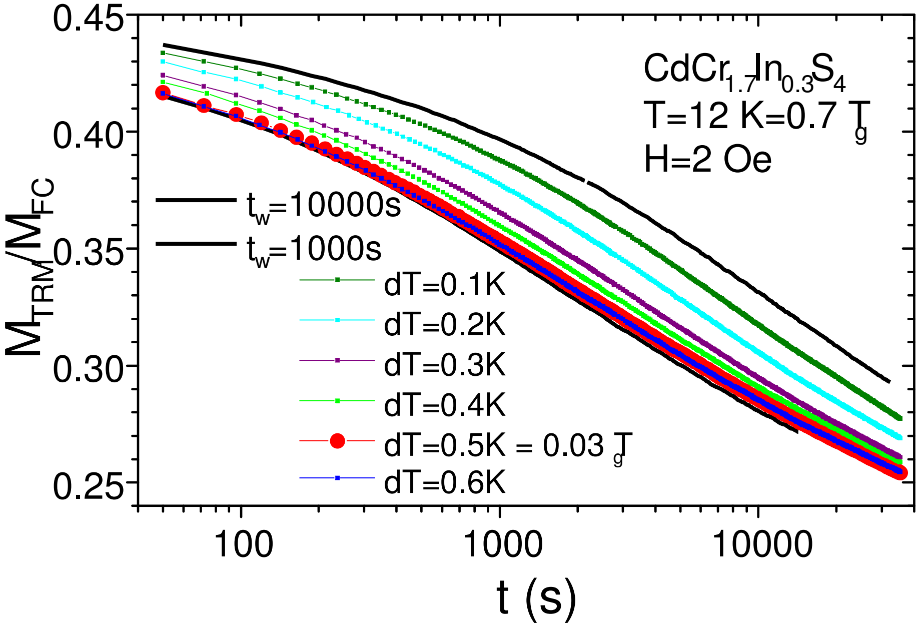
J.P. Bouchaud thinking of “Aging on Parisi’s tree”

J. Phys I France **5**, 265 (1995)

Hierarchical picture : quantitatively ?
→ *measure the T-dependence of the free-energy barriers*

TRM-relaxation with *temperature cycling* to T-dT during t_w → curve with inflection point at t_w^{eff}





dT=0.5-0.6K → no effect at T of aging 9000s at T-dT (memory)
smaller dT : curve with inflection point at $t_w^{eff} \in$ [1000 , 10000]

inflection point at ~ t_W = maximum relaxation rate : defines a typical energy barrier Δ

$t_W = \exp(\Delta / k_B T) \rightarrow \Delta(T) = k_B T . \mathrm{Ln}\ t_W \qquad \Delta(T-dT) = k_B (T-dT) . \mathrm{Ln}\ t_W^{eff}$

→ *Temperature dependence of Δ*

And the result:

•$d\Delta/dT<0$ *the barriers increases when T decreases*
•all data collapse on a unique curve (dashed): $d\Delta/dT$ only depends on Δ

Dashed curve: $-d\Delta/dT = a\,\Delta^6$
Integration: $\Delta \sim (T-T^*)^{-1/5}$, T^* *= free integration constant = characteristic of a barrier which diverges at* T^*

There are barriers diverging at all temperatures below T_g *, starting at* T_g

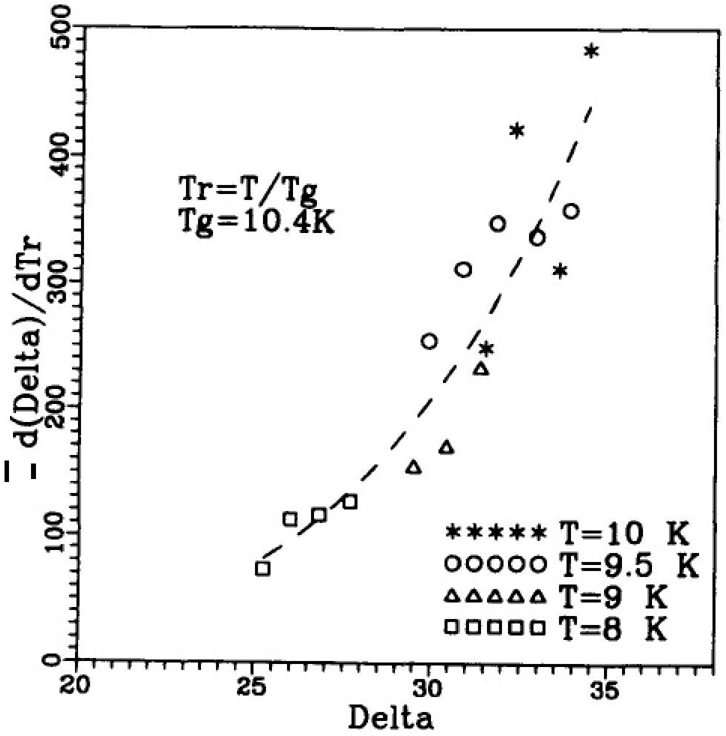
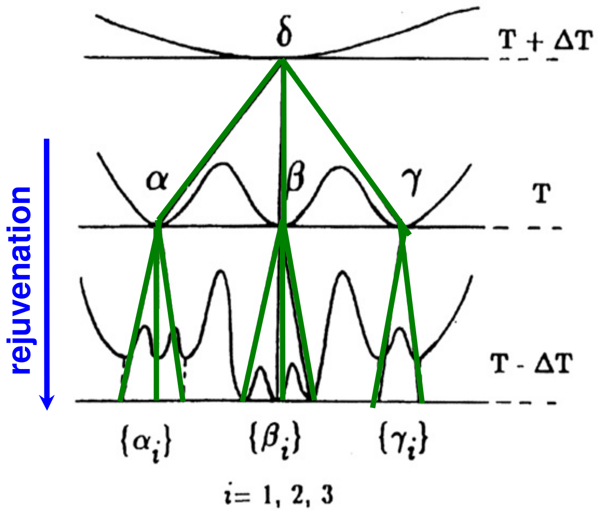


Figure 10 : Rate of thermal variation of free-energy barriers[15] as a function of their height "Delta", as deduced from the effect of temperature variations on the TRM relaxation of an $AgMn_{2.6\%}$ sample. The barrier heights have been normalized to T_g. The dashed line is a fit to Eq. 11. Se

As T ↓, more barriers diverge:
metastable states become pure states !



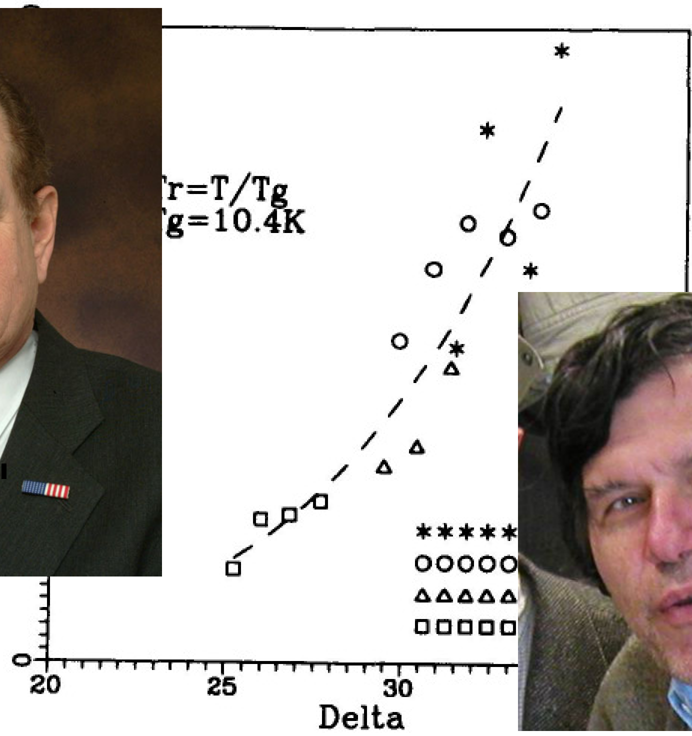
Saclay / UCLA collaboration
R. Orbach, M. Lederman
Physica A 185, 278 (1992)

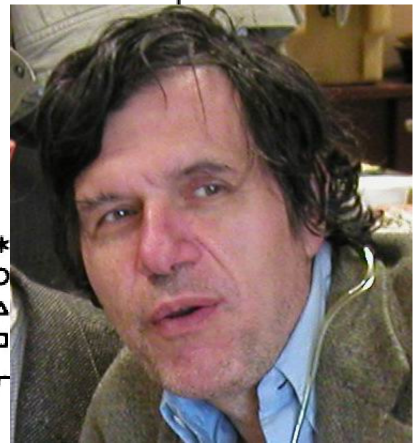
And the result:

- $d\Delta/dT<0$ *the barriers increases*
decreases
- all data collapse on a unique c
(dashed): $d\Delta/dT$ only depends c

Dashed curve: $-d\Delta/dT = a\,\Delta^6$
Integration: $\Delta \sim (T-T^*)^{-1/5}$, T^* = *fr*
integration constant = characte
barrier which diverges at T^*

There are barriers diverging at all temperatures below T_g *, starting at* T_g





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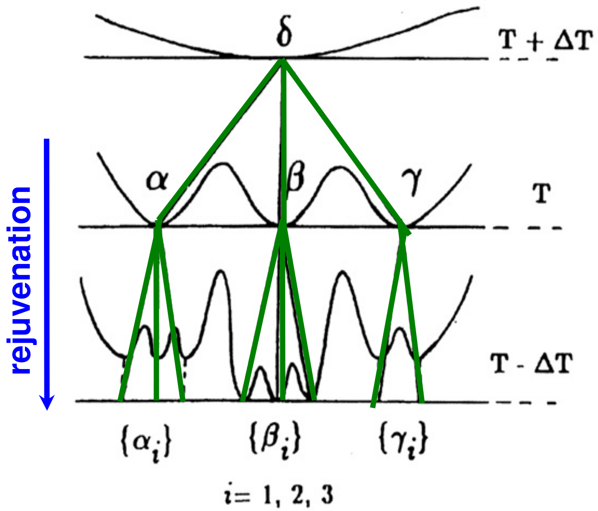

1. A few experimental facts…
at the light of the MF spin glass

2. Length scales and temperature microscope

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2.a Spin glass

2.b Superspin glass

Aging ≡ growth of a local random ordering ?

Fisher Huse droplet model idea (1988)

PHYSICAL REVIEW B **69**, 184423 (2004)

Aging dynamics of the Heisenberg spin glass

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Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, United Kingdom
and Laboratoire des Verres UMR 5587, Université Montpellier II and CNRS, 34095 Montpellier, France

A. P. Young†
Department of Physics, University of California, Santa Cruz, California 95064, USA
(Received 12 December 2003; published 28 May 2004)

FIG. 5. The relative orientation of the spins in two copies of the system, Eq. (9), is encoded on a gray scale in a 60×60×60 simulation box at three different waiting times $t_w = 2$, 27, and 57 797 (from top to bottom) at temperature $T = 0.04$. The growth of a local random ordering of the spins is evident.

t_w=2

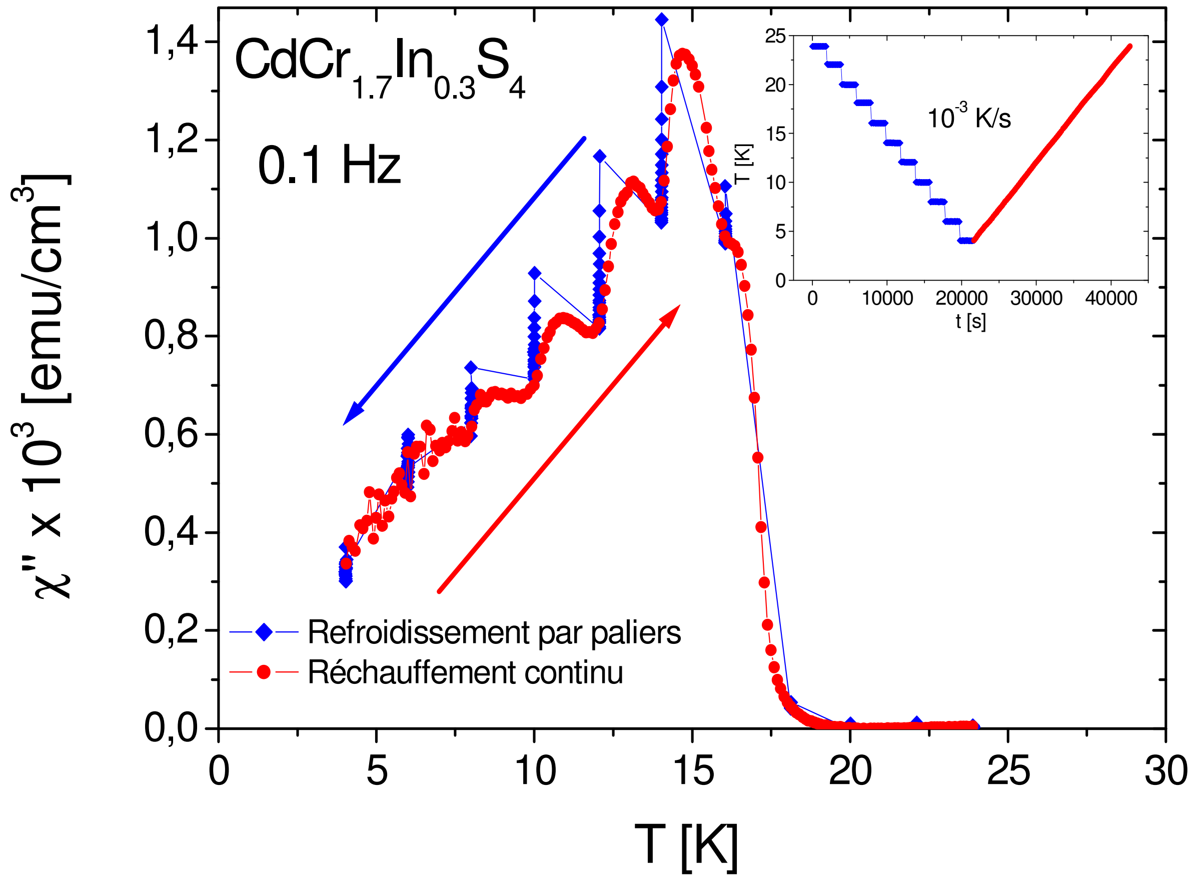
t_w=27

t_w= 57797

grey scale = $\cos\theta_i(t_w) = \boldsymbol{S}_i^a(t_w) . \boldsymbol{S}_i^b(t_w)$

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 ⇒

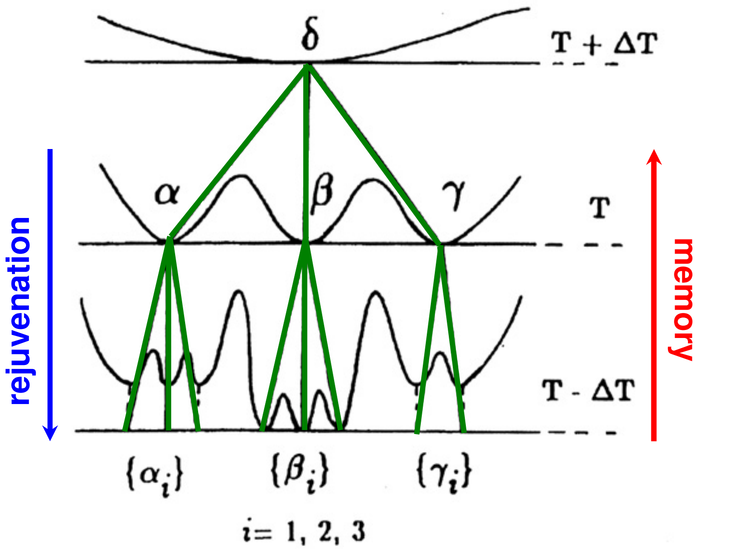
$L^*_n << \ldots.. << L^*_2 << L^*_1$

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

(« T-microscope » effect)

Rejuvenation and memory in « phase space » :

hierarchical organization of the metastable states as a function of T

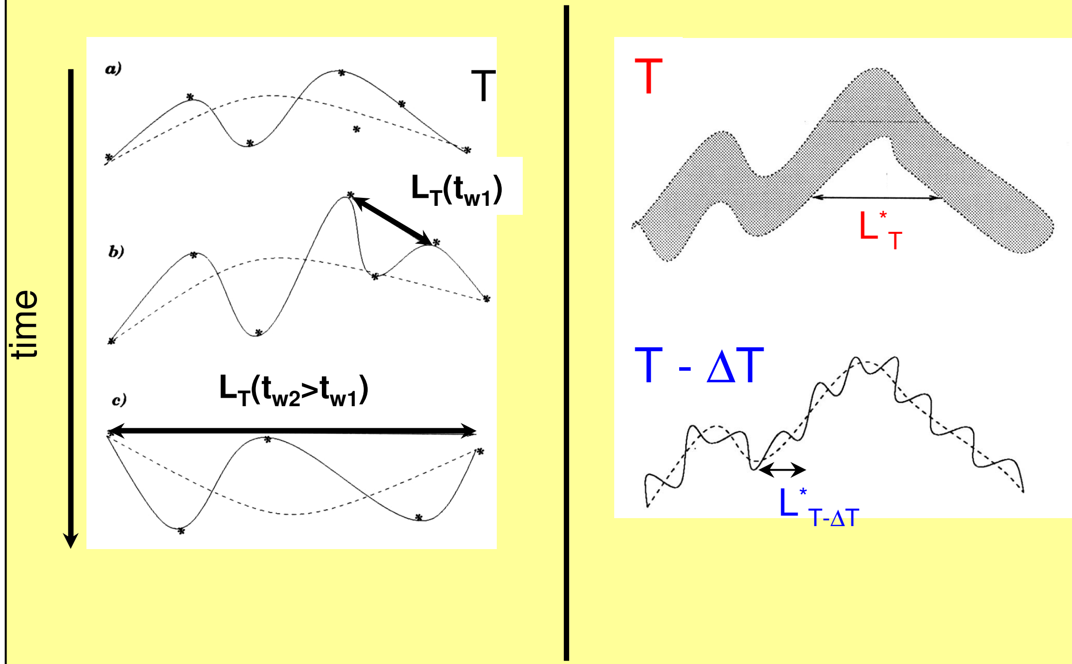


Rejuvenation and memory: a hierarchy of coherence lengths

model system:

elastic line in pinning disorder

hierarchy of reconformation length scales



$T \rightarrow T\text{-}\Delta T \quad L^*_{T-\Delta T} << L^*_T$

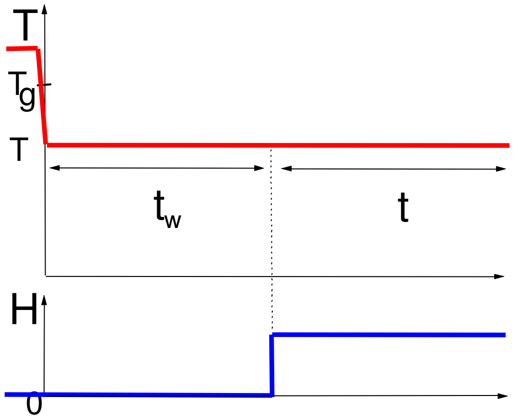
Bouchaud et al, *Phys. Rev. B* **65**, 024439 (2001)

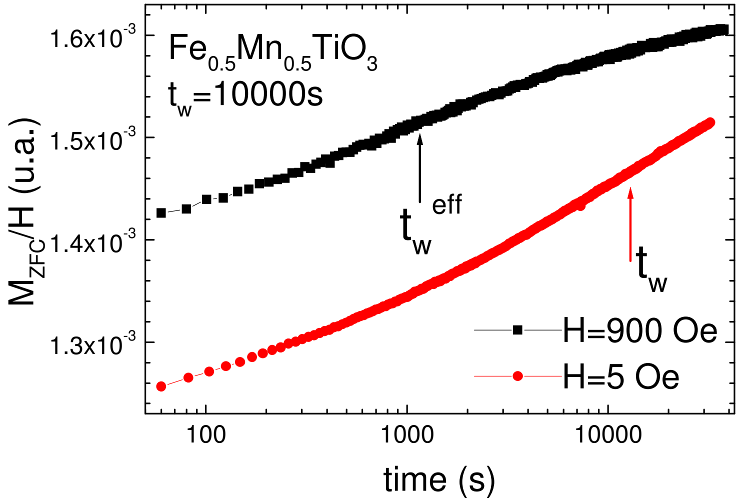
Growing number of correlated spins (from field effect experiments)

Field amplitude influence on the *dc*-magnetization relaxation (TRM or ZFC)

Relaxation becomes faster with H (inflection point $t_W \rightarrow t_W^{eff}$)

(Ising SG example)





Inflection at ~ t_W = maximum relaxation rate : typical energy barrier Δ

$$t_w = \exp(\Delta / k_B T) \rightarrow \Delta = k_B T \ln(t_w) \qquad \Delta - E_Z(H) = k_B T \ln(t_w^{eff}(H))$$

$$E_Z = k_B T \ln\left(t_w / t_w^{eff}\right)$$ Zeeman Energy : $H \leftrightarrow N_s(t_W)$ coupling after t_w

Y.G. Joh et al, PRL 82, 438 (1999), R.Orbach's group in UCR + Saclay

F. Bert et al, Phys. Rev. Lett. 92, 167203 (2004)

What is the dependence of $E_Z = k_B T \ln(t_w / t_w^{eff})$ on $N_S(t_w)$?

<u>Hyp. 1:</u> $M(N_s) \propto \sqrt{N_s}$ *(Ising spins)*

then $E_Z(H,t_w) = \sqrt{N_s}\, m\, H$ *(m = moment of 1 spin)*

<u>Hyp. 2:</u> $M(N_s) \propto N_s$ *(Heisenberg-like spins)*

then $E_Z(H,t_w) = N_s\, \chi\, H^2$ *(χ = susceptibility of 1 spin)*

Measure at various H & t_w to construct $t_w^{eff}(H, t_w) \rightarrow E_Z(H,t_w)$

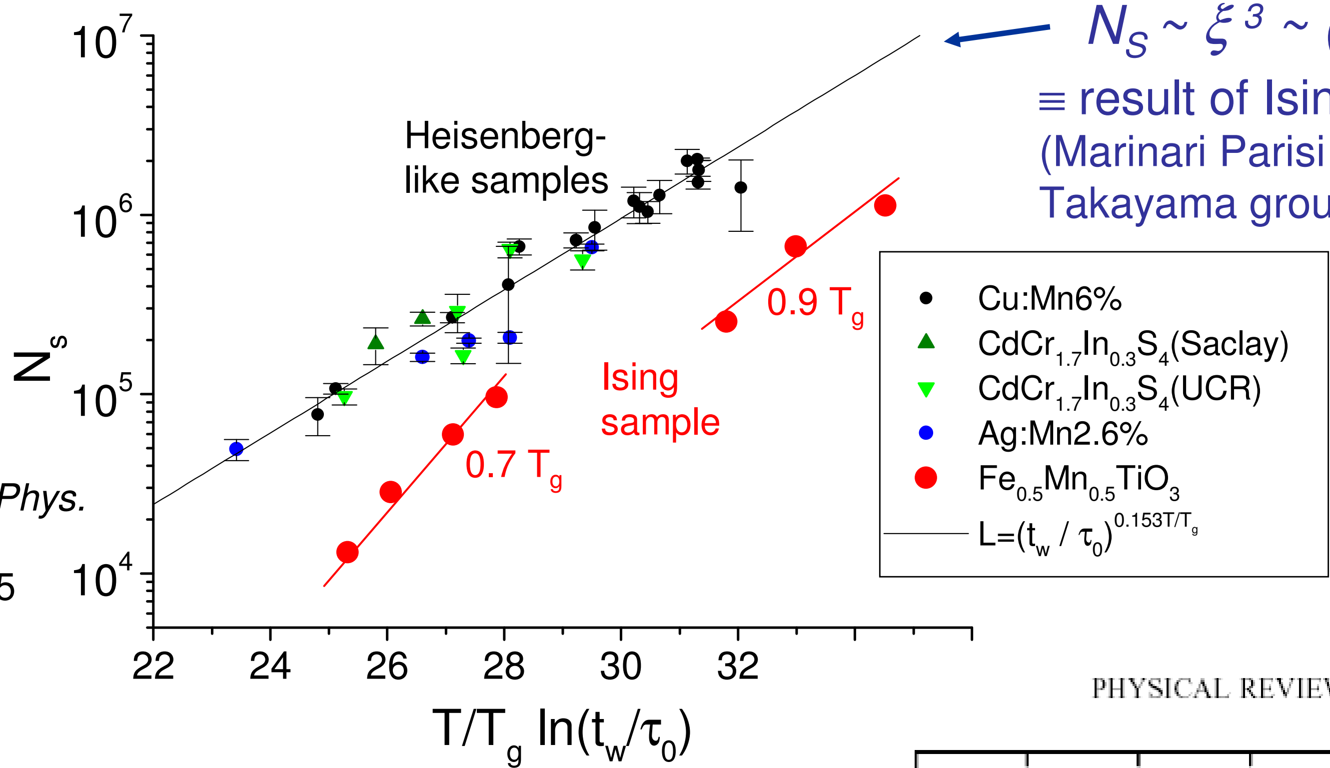
$\rightarrow$ <u>number of correlated spins</u> $N_s(t_w)$ *and* $L = N_s^{1/d-\alpha}$

$(2 < d\text{-}\alpha < 3)$

Increase of $N_s(t_w)$ with t_w $\rightarrow$ slow growth of a "spin glass order"

$N_S \sim \xi^3 \sim (t_w/\tau_0)^{0.45\, T/T_g}$

≡ result of Ising simulations!
(Marinari Parisi group,
Takayama group, Rieger et al...)



Joh et al, *J. Phys. Soc. Jpn.* **69** Suppl. A, 215 (2000)

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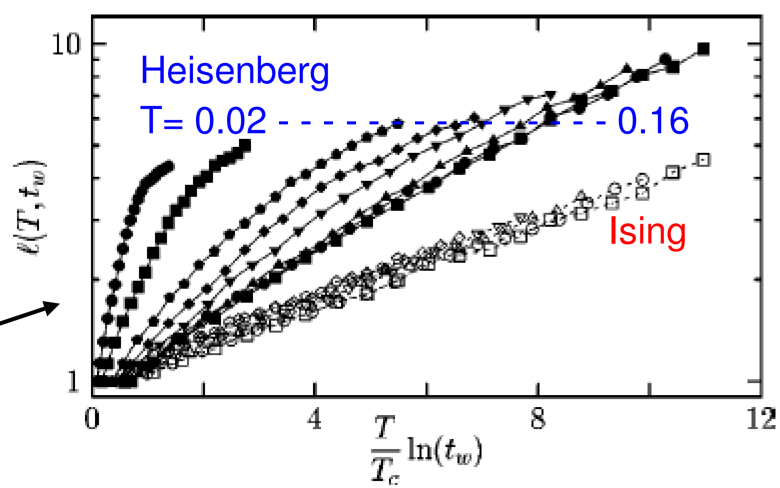


<u>Ising spin glass:</u> smaller N_S, although growing faster

Ising + Heisenberg simulations by Berthier and Young (PRB 04)
(at long times, same trend as exp. ?)

Ising + Heisenberg samples ⇒ go beyond the simple power law $L \sim t^{aT/Tg}$

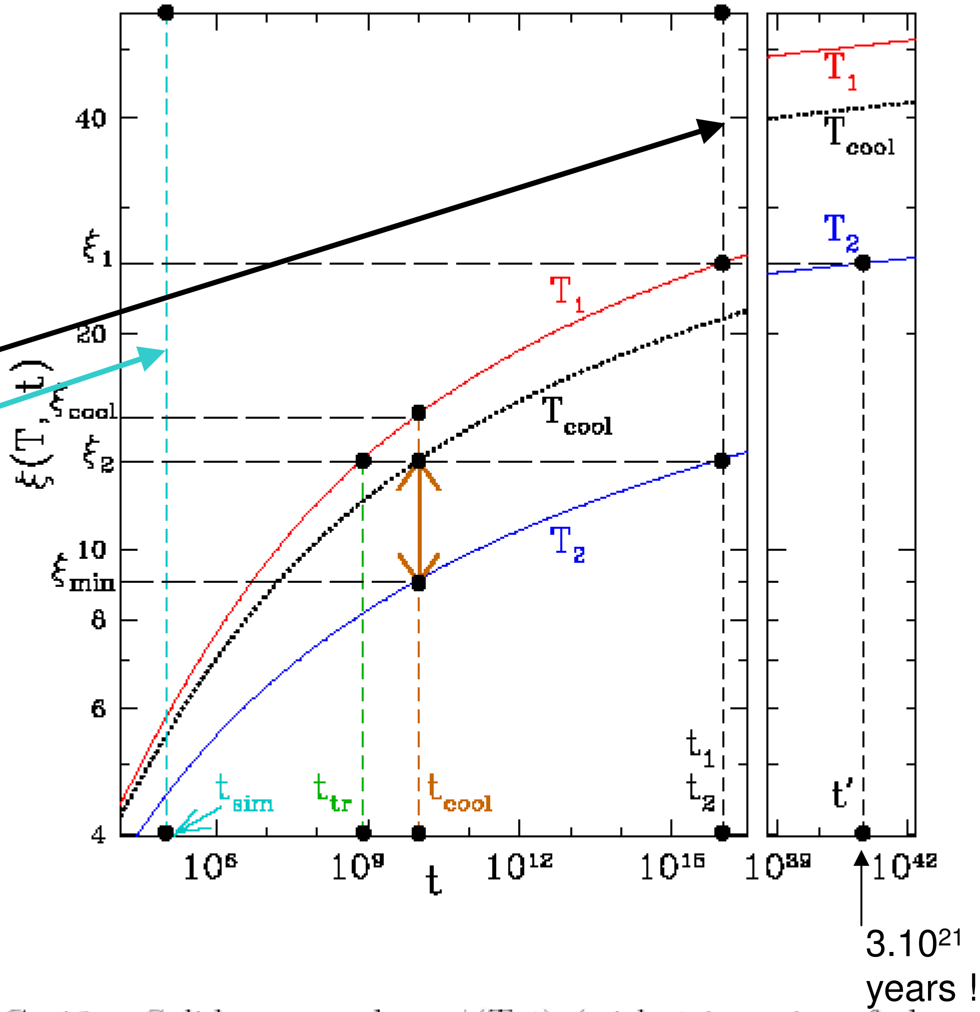
Temperature microscope effect, separation of length scales… how much ?

Plot of *L(T,t)* (≡ξ) as obtained from the experiments (Heisenberg, $L=N^{1/3}$)

Berthier & Young, *Phys. Rev. B* **71**, 314429 (2005)

Experimental time scales

Simulation time scales



Experiments: $L(T_1)$ ~ 25, $L(T_2)$ ~ 15

Simulations: $L(T_1)$ ~6, $L(T_2)$ ~ 4.5

Not a very powerful microscope !
Yet, rejuvenation and memory effects exist, even in simulations

→ T-separation of time scales rather than length scales

FIG. 12: Solid curves show $\xi(T,t)$ (with t in units of the microscopic time $t_0 = 10^{-12}$ s) inferred in Ref. [37] for a Heisenberg spin glass at temperatures $T_1/T_c = 0.825$, and $T_2/T_c = 0.7$. Note the break in the horizontal scale between

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2. Length scales and temperature microscope

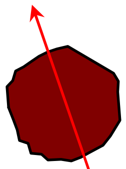
   2.a Spin glass

   2.b Superspin glass

Super-spins, superspin glass

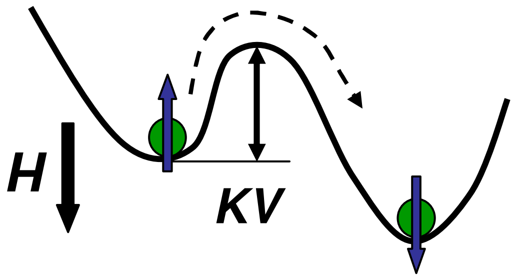
- Small enough ferromagnetic nanoparticle→ single domain
- $T \ll T_c$: response of single nanoparticle ~ response of single spin

  → a ‘superspin’



- Anisotropy → easy axis, barrier ~K.V

  T<<KV → blocking of magnetization



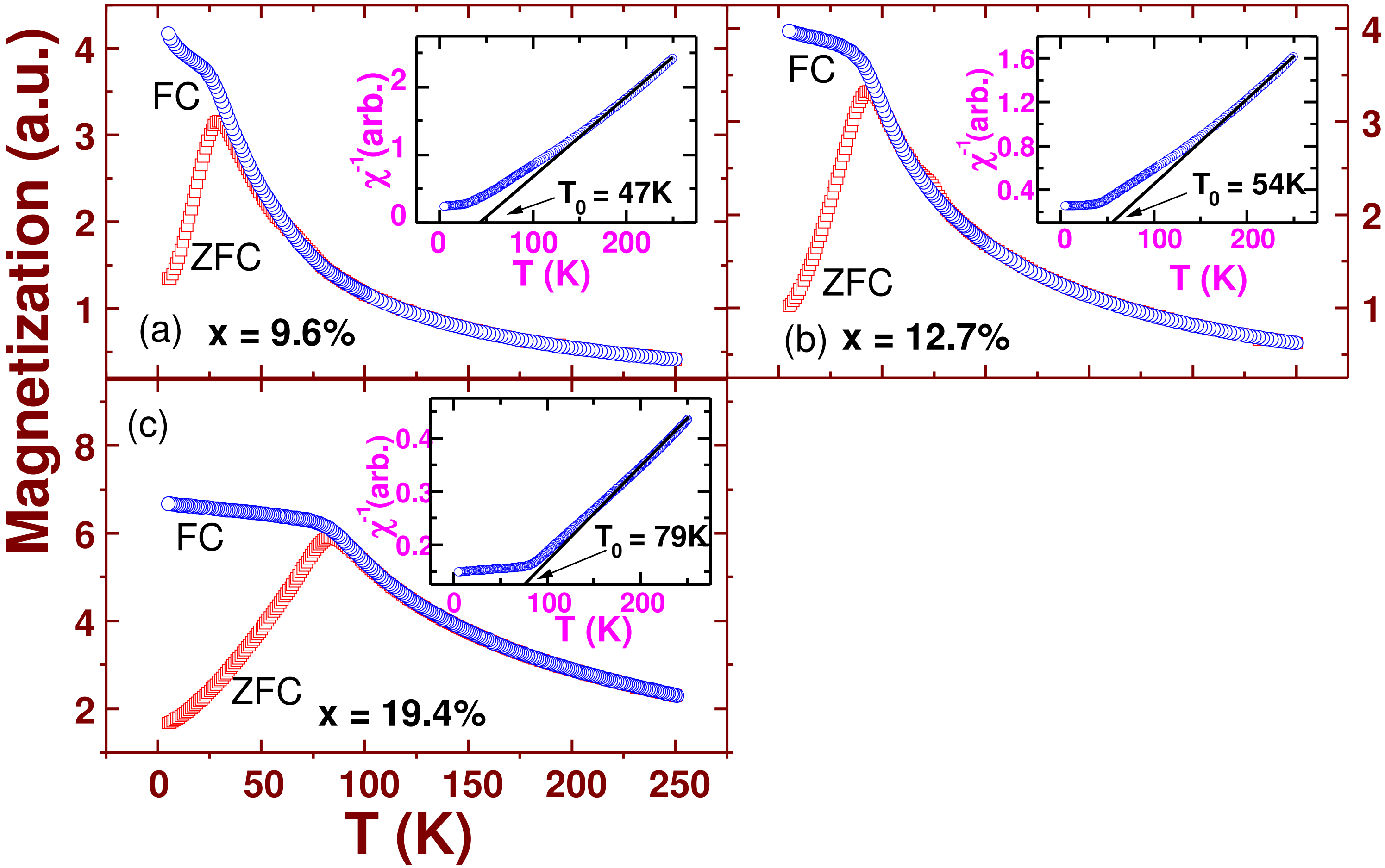
- Varying concentration of nanoparticles in an aqueous dispersion changes dipole-dipole interparticle interaction

Dilute nanoparticle system	Concentrated nanoparticle system
↓	↓
Non-interacting superspins Superparamagnet (dynamical freezing at T_g)	Interacting superspins Superspin glass ? (phase transition at T_g)

Co nanoparticles in Ag matrix

(Co_xAg_{1-x} , metal matrix $\rightarrow$ RKKY interactions)

X.X. Zhang group, Phys. Rev. B75, 014415 (2007)



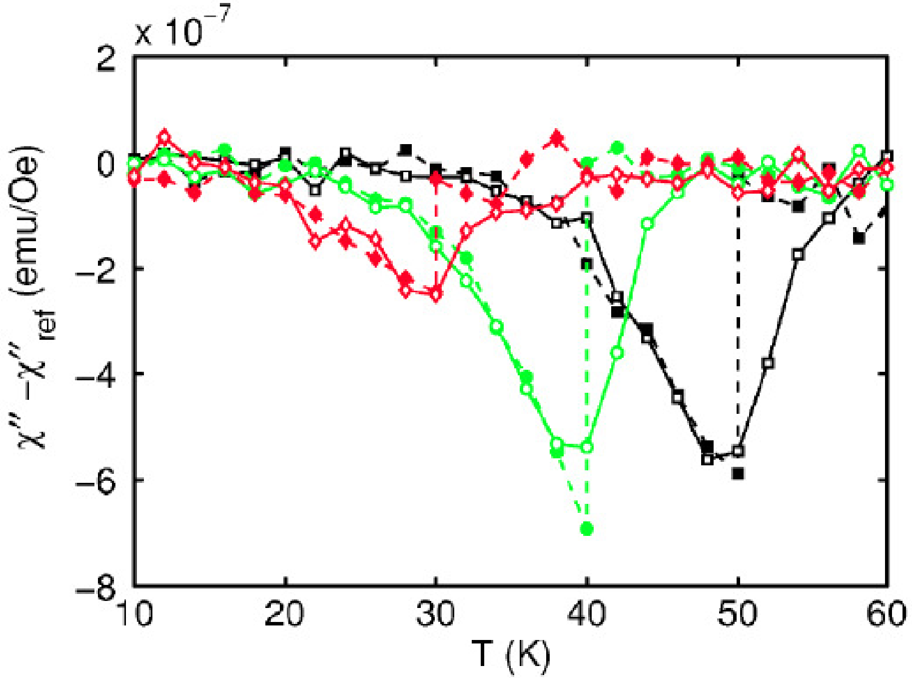
With increasing x : increase of T_B and T_0, flattening of FC curve

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]

Concentrated Fe_3N nanoparticle system



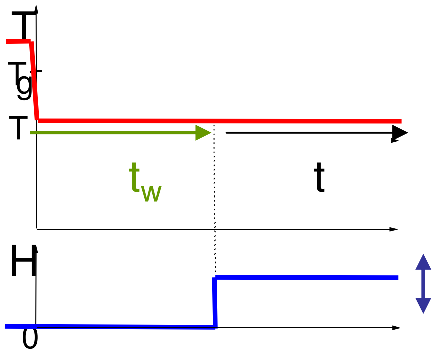
Clear T-specific **memory** effect, although not so well-marked as in atomic SG's

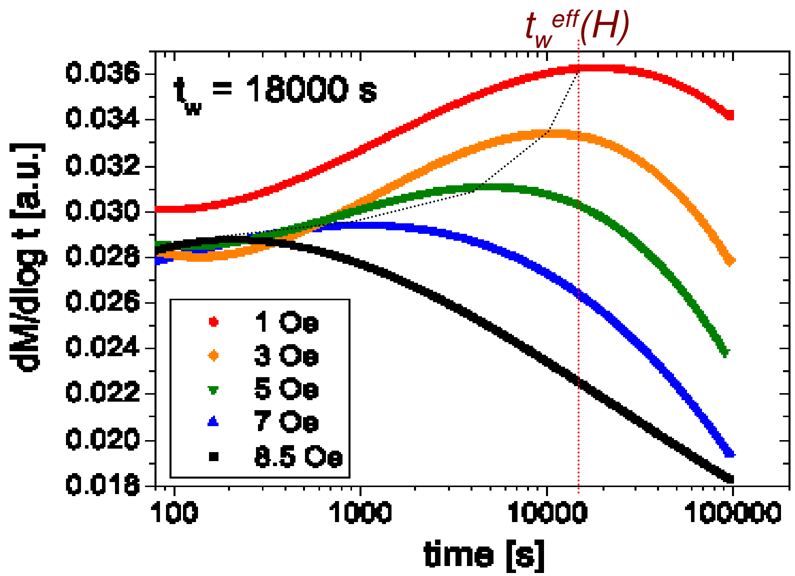
SSG $\tau_0 \approx 10^{-9}$ s (or longer)
SG $\tau_0 \approx 10^{-12}$ s
longer $\tau_0 \rightarrow$ shorter accessible time scale t_{exp}/τ_0

(see below)

FIG. 7. (Color online) $\Delta\chi''$ vs temperature measured on cooling (filled symbols connected by dashed lines) and reheating (open symbols connected by solid lines). A temporary stop is made on cooling at T_s=50, 40, or 30 K for t_s=9000 s. $\omega/2\pi$=510 mHz.

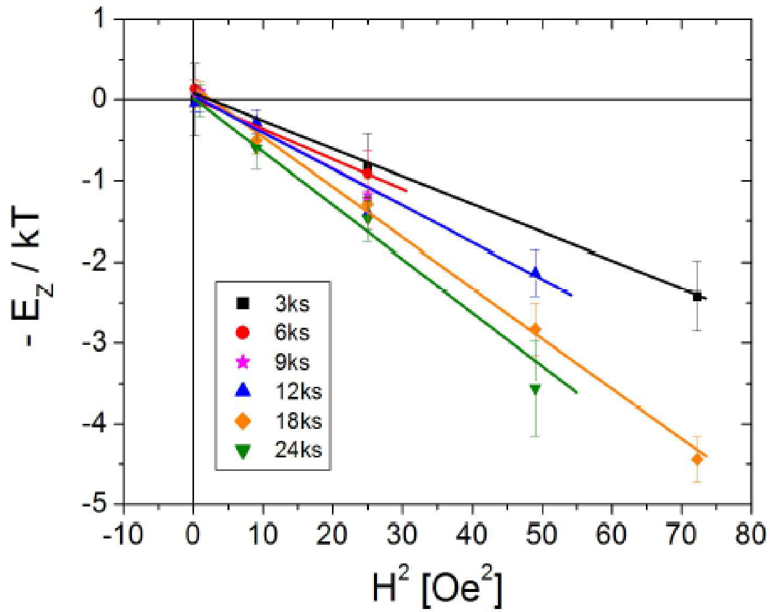
Relaxation of the superspin glass: field effect





- Vary *H* amplitude and t_w
- Find $t_W^{eff}(H)$

$$E_Z = k_B T \ln\left(\frac{t_w}{t_w^{eff}}\right)$$



result: $E_Z \propto N_s H^2$ (Heisenberg-like)

Aging ≡ growing number of correlated (super)spins

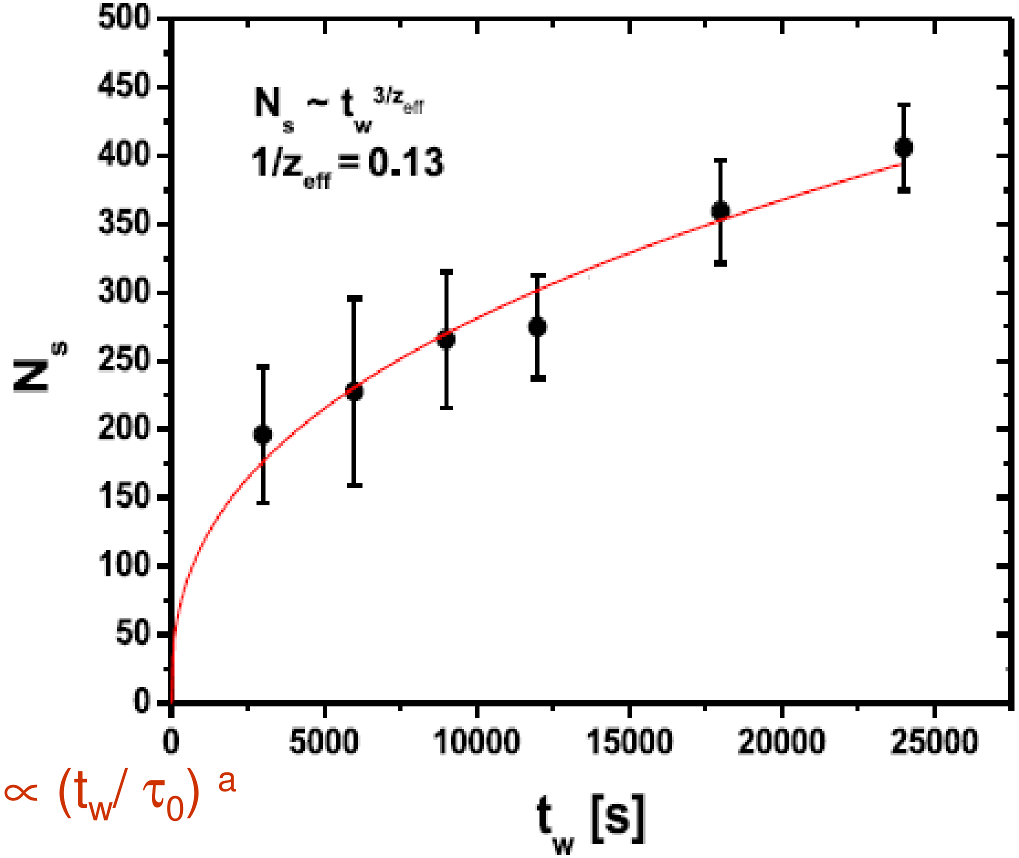
N_s is growing ~ as a power law of t_w (red curve = fit)

$N_s \sim t_w^{3/z\_eff}$ with z_{eff} ~7.7

Similar power law as in Heisenberg-like spin glasses, but N_s smaller here:

N_s~200 - 400 (~10^4 - 10^6 in SG)

L~ $N_s^{1/2-3}$ ~ 5-20 (~10-100-1000? in SG)



N_s grows with t_w in units of τ_0 : $N_s \propto (t_w/\tau_0)^a$

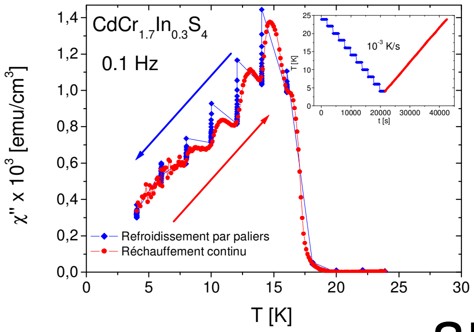
τ_0 in atomic SG ~ 10^{-12} sec

but τ_0 superspin is at least 10^{-8}-10^{-9}s, or even ~ $exp(E_d/k_BT)$, as large as μs →

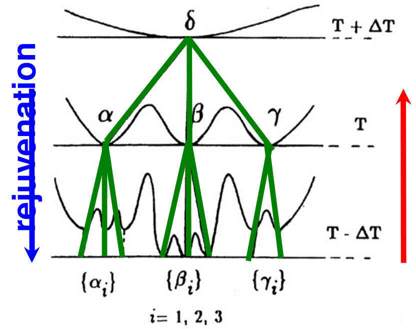
shorter time regime explored in SSG than in SG in units of τ_0

→ N_s smaller *(possible explanation of weaker rejuv. and memory effects…)*

E. Wandersman PhD thesis, cond-mat/0806.0564

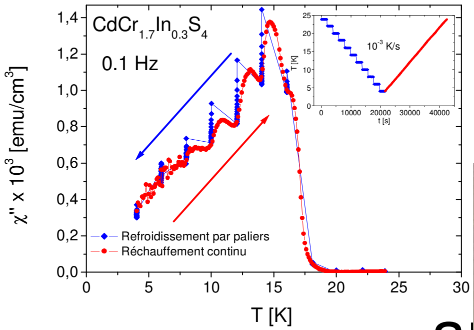


Conclusions

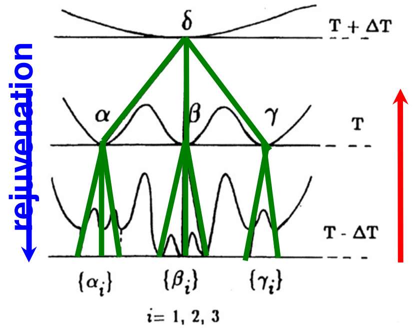


MF spin glass and RSB solution:
any relevance to real spin glasses ?

- Noise measurements → FD ratio in agreement with a « non-trivial » (RSB) scenario
- Rejuvenation and memory effects: hierarchy of metastable states, hierarchy of coherence lengths L(T,t) (T-microscope)
- T-cycle experiments → possible divergence of barrier heights as T↓ … *hierarchy of metastable states → pure states ?*
- Field-effect experiments → determination of L(T,t)
- Superspin glass (nanoparticles) may bridge the gap between numerical (L~5) and real (L~100) spin glasses



Conclusions



ar

- Noise measu … with a « non-trivial » (RSB …
- Rejuvenation … metastable states, hierar … microscope)
- T-cycle expe … barrier heights as T↓ … *hier … states ?*
- Field-effect e … T,t)
- Superspin gl … gap between numerical (L…