Vieillissement, rajeunissement et mémoire: des échelles de longueur dans les verres de spin ?

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1. Vieillissement : dans les verres de spin, et ailleurs
2. Rajeunissement et mémoire
3. Verres de spin : Ising $\leftrightarrow$ Heisenberg ?
4. Échelles de longueur pour le vieillissement

verre de spin ≡ système magnétique <u>désordonné</u> *et* <u>frustré</u>

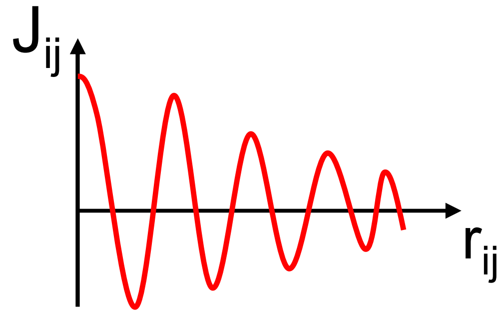
Théorie : interactions magnétiques aléatoires

$H = -\sum J_{ij} S_i.S_j$ $\{J_{ij}\}$ distribués en gaussienne (ou en $\pm$ J)

Verres de spin *"réels"* : dilution aléatoire d'ions magnétiques

- alliages métalliques : e.g. Cu:Mn 3%

  interactions RKKY



- isolants : $CdCr_{1.7}In_{0.3}S_4$, $Eu_{0.3}Sr_{0.7}S$

interactions de super-échange

F (↑↑) proches voisins, AF (↑↓) voisins d'ordre supérieur

même comportement ("générique") dans tous les échantillons

(Tc≠0 en 3d, dynamique lente, vieillissement...)

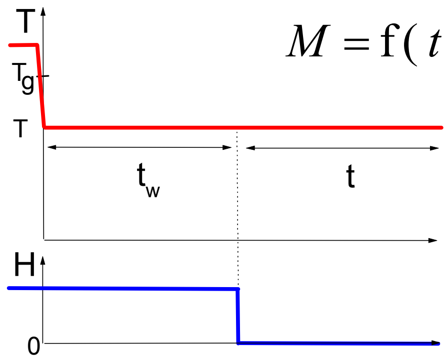
→ *systèmes désordonnés "modèles"*

Verres de spin: dynamique lente + vieillissement

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

Aimantation thermo-rémanente (TRM) *(dc)*

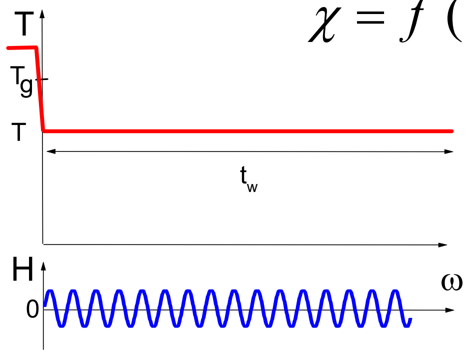
$$M = f(t, t_w)$$

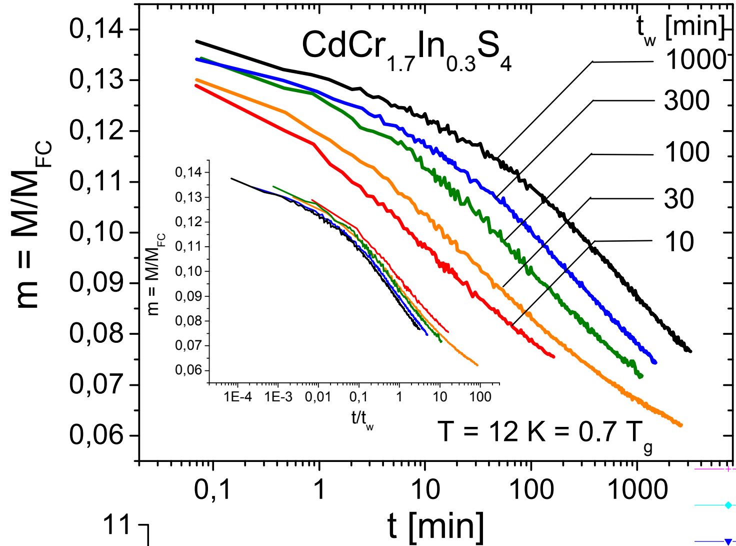


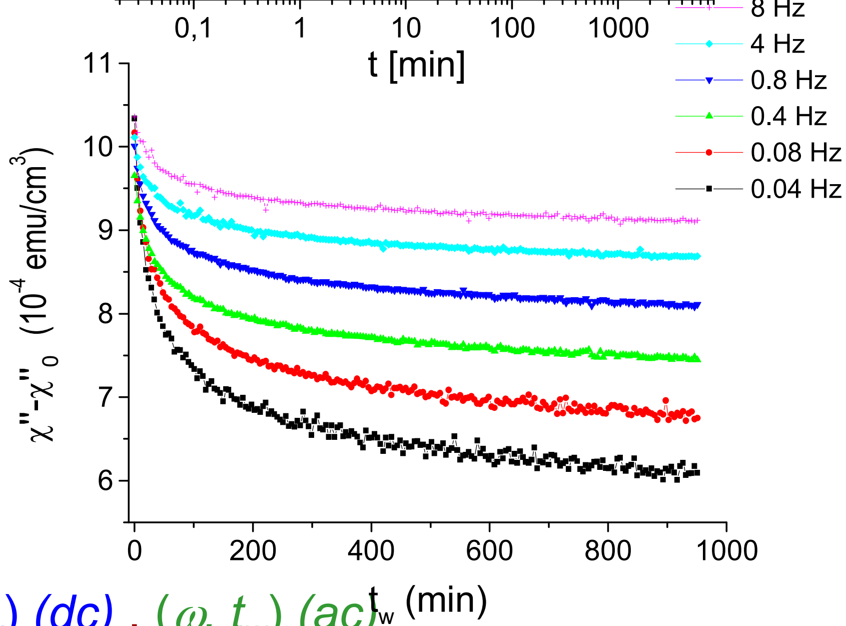
t_w : waiting time
t : observation time

Susceptibilité alternative *(ac)*

$$\chi = f(\omega, t_w)$$



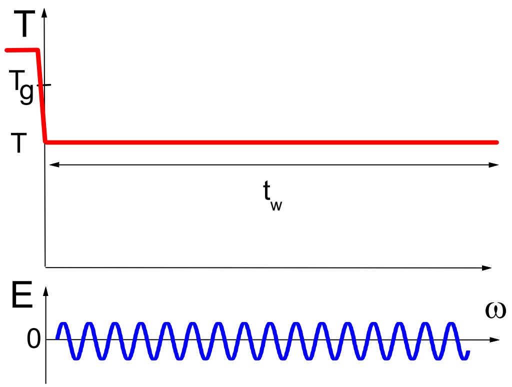




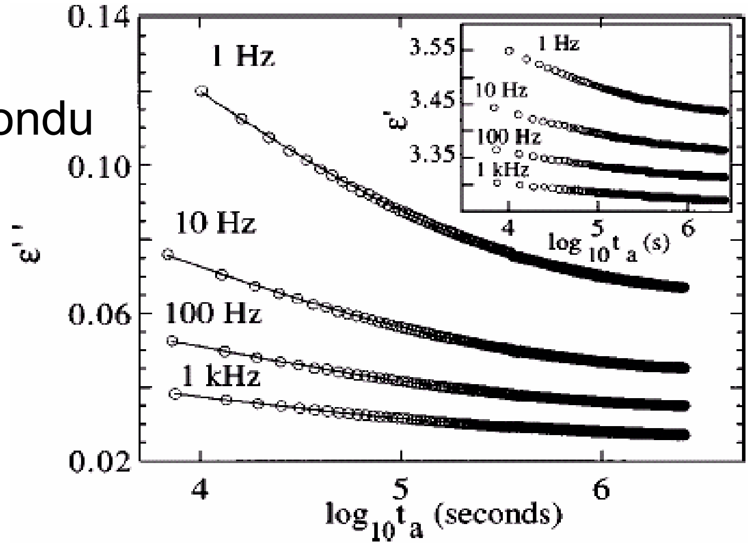
→ Dynamique non-stationnaire : (t, t_w) *(dc)* , (ω, t_w) *(ac)*
Lois d'échelle (1ère approx.) : $\sim t / t_w$ *(dc)* , $\omega\, t_w$ *(ac)*

Vieillissement des verres

Réponse diélectrique d'un liquide surfondu

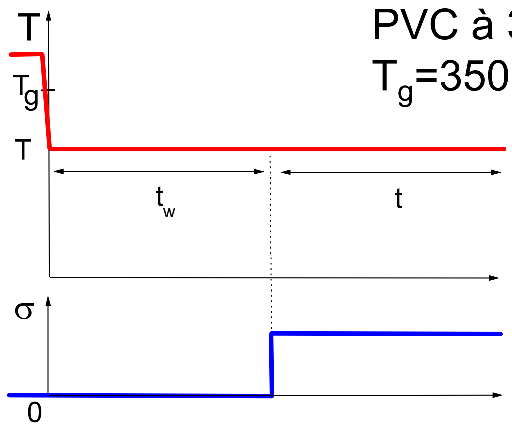


glycérol
à 178K
T_g=190K

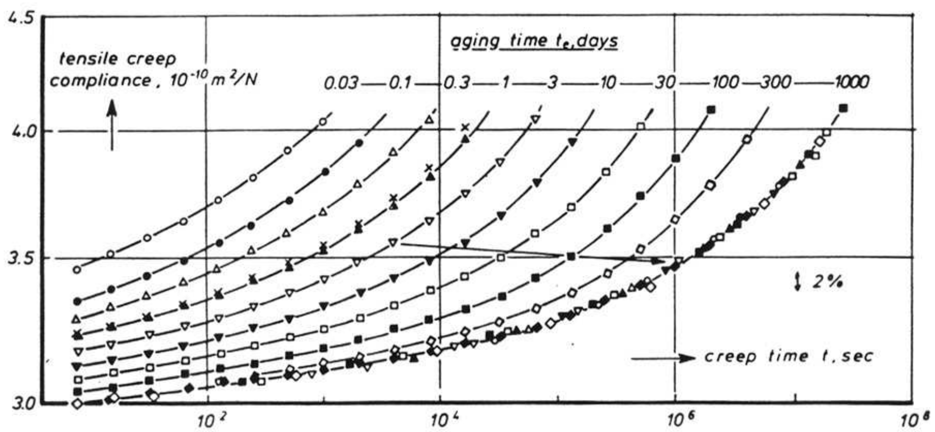


glycérol
Leheny et al. (1998)

Réponse mécanique d'un polymère



PVC à 310K
T_g=350K



PVC
Struik (1978)

→ ~ mêmes lois d'échelle que dans les verres de spin : ωt , t / t_w

Aging ≡ growth of a local random ordering ?

Fisher Huse droplet model idea (1988)

is the spin glass a “disguised ferromagnet” ?

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

Aging dynamics of the Heisenberg spin glass

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

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GLASS-FORMING LIQUIDS

slower cooling rate → closer to equilibrium

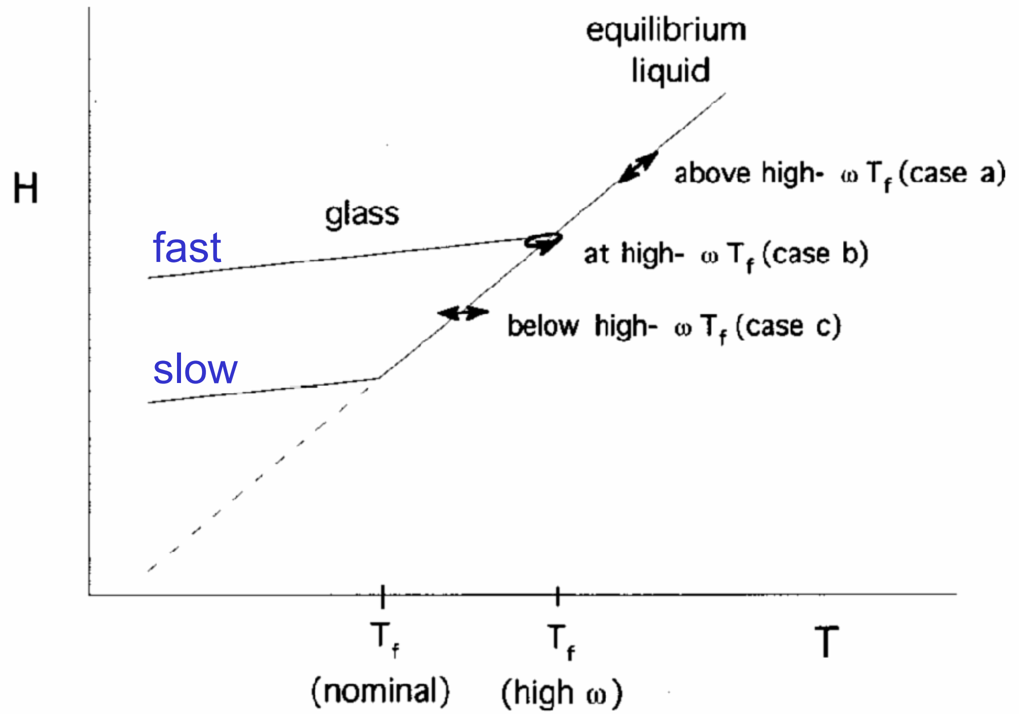


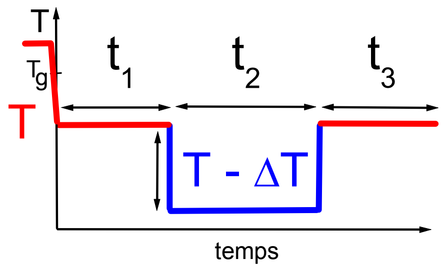
FIG. 2. Enthalpy versus temperature schematic showing two glasses, one obtained at a conventional cooling rate and the other at a higher rate. Situations (a)–(c) are described in the text.

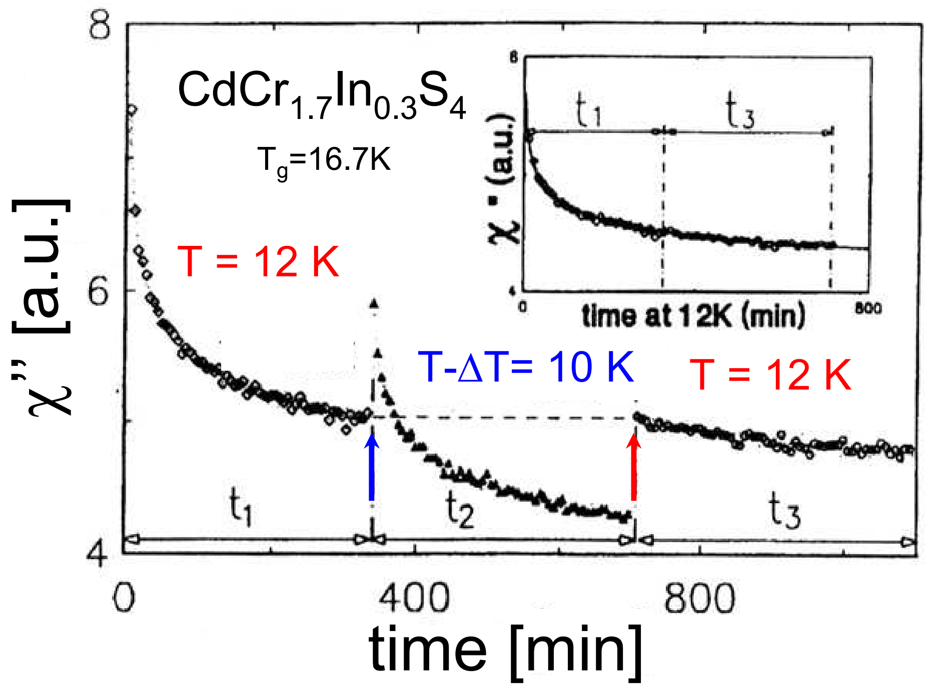
Kovacs 1964

Simon & McKenna
J. Chem. Phys. **107**
(1997) 8678

Aging, rejuvenation and memory

"negative cycling" of a spin-glass (old results!)

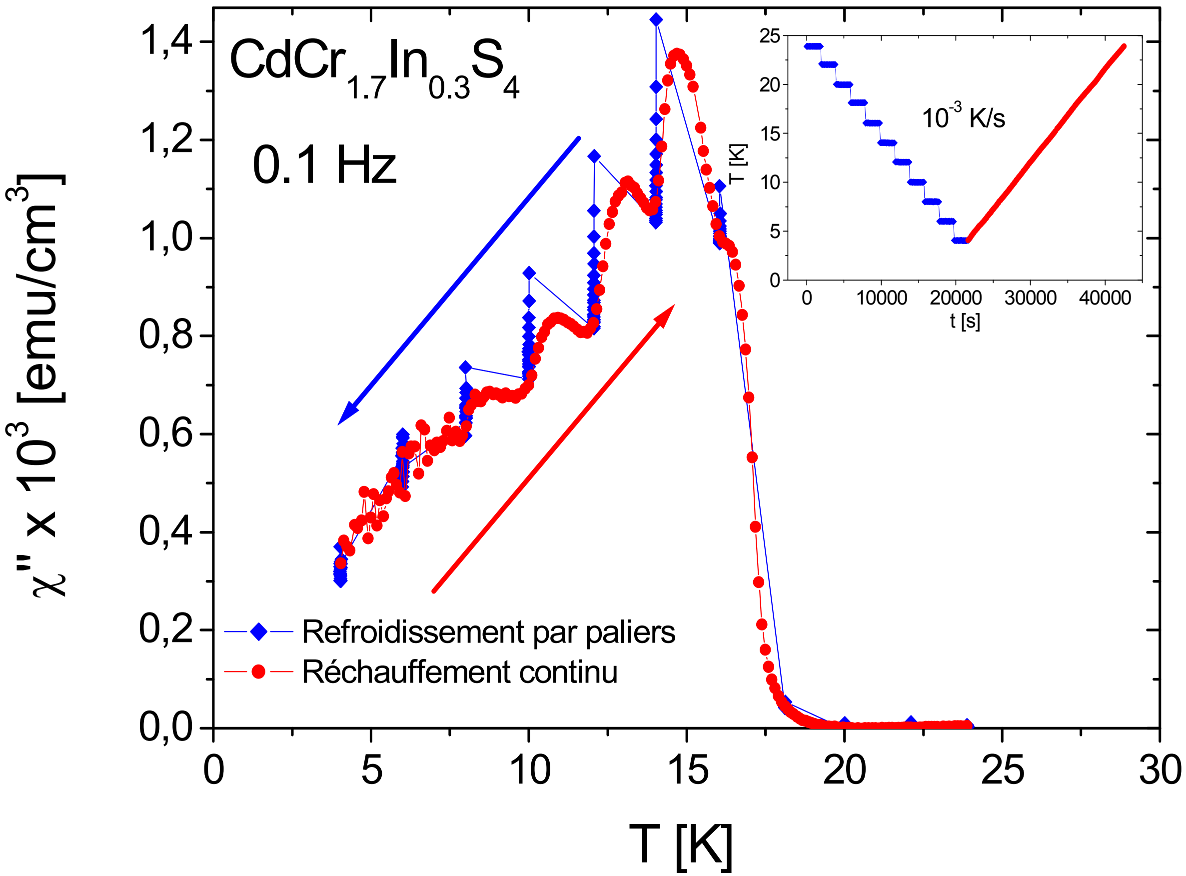




T↓ : rejuvenation, *restart of the relaxation*

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

Rejuvenation and memory effects : *not simply domain growth-like*



T↓ : rejuvenation

T↑ : memory

At each T step

T → T-ΔT , $L^*_{T-\Delta T} << L^*_T$

Rejuvenation ⇒
different equilibrium correlations at different T's

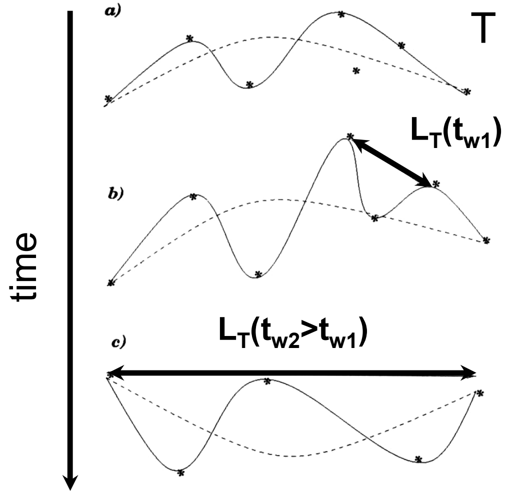
Memory ⇒
$L^*_n << \ldots << L^*_2 << L^*_1$
strong T-separation of the aging length scales
(« T-microscope » effect)

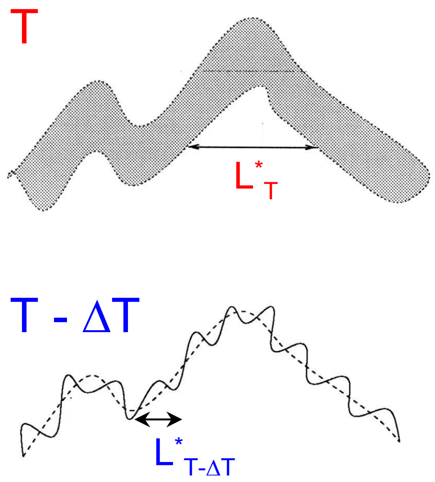
V. Dupuis et al, cond-mat/0406721

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

Aging as a growing correlation length

model system:
elastic line in pinning disorder
hierarchy of reconformation length scales



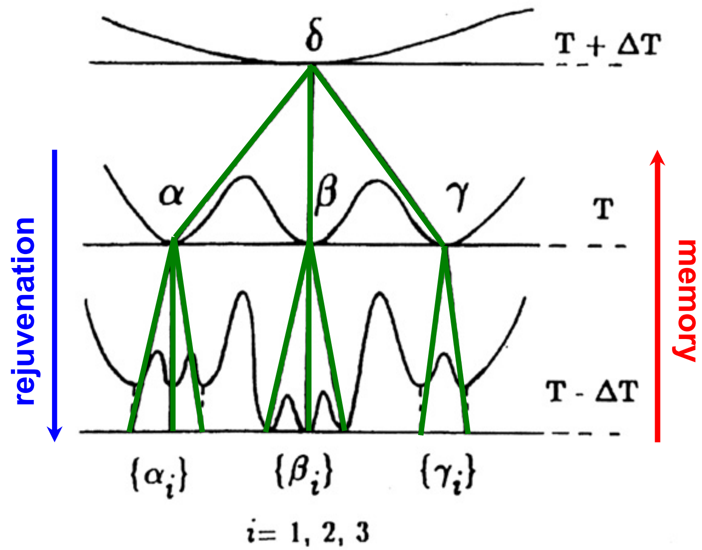


Bouchaud (2000)

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

In « phase space » :

hierarchical organization of the metastable states as a function of T

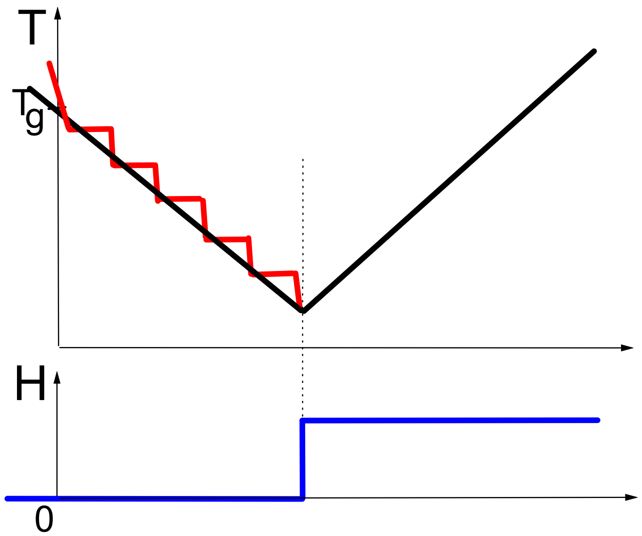


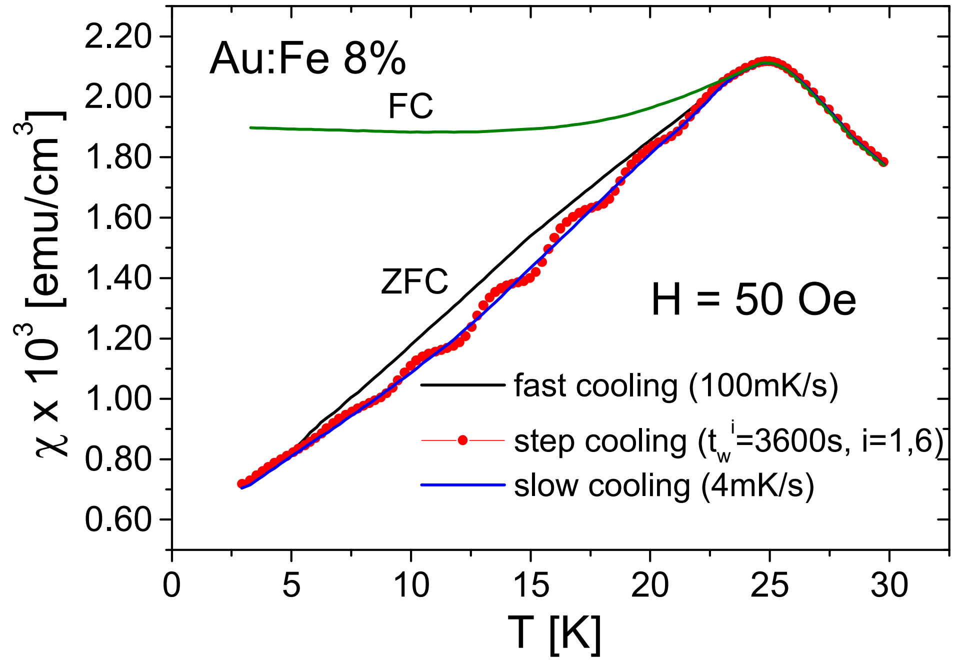
<u>Quantitatively:</u>
Derrida 1981 1986 *(REM, GREM)*
Bouchaud and Dean 1995 *(trap model)*
Sasaki and Nemoto 2000
Sasaki et al, *EPJ B* **29**, 469 (2002)

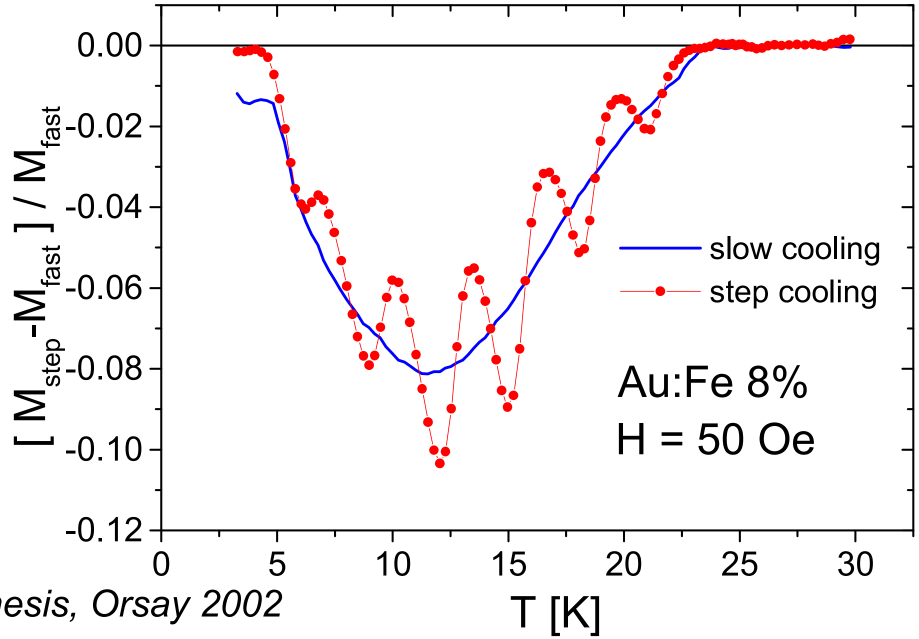
Spin glass : no cooling rate effects at all ?

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

The spin glass dynamics of gelatine gels

Alan Parker and Valéry Normand

Research Division, Firmenich SA (Geneva , Switzerland)

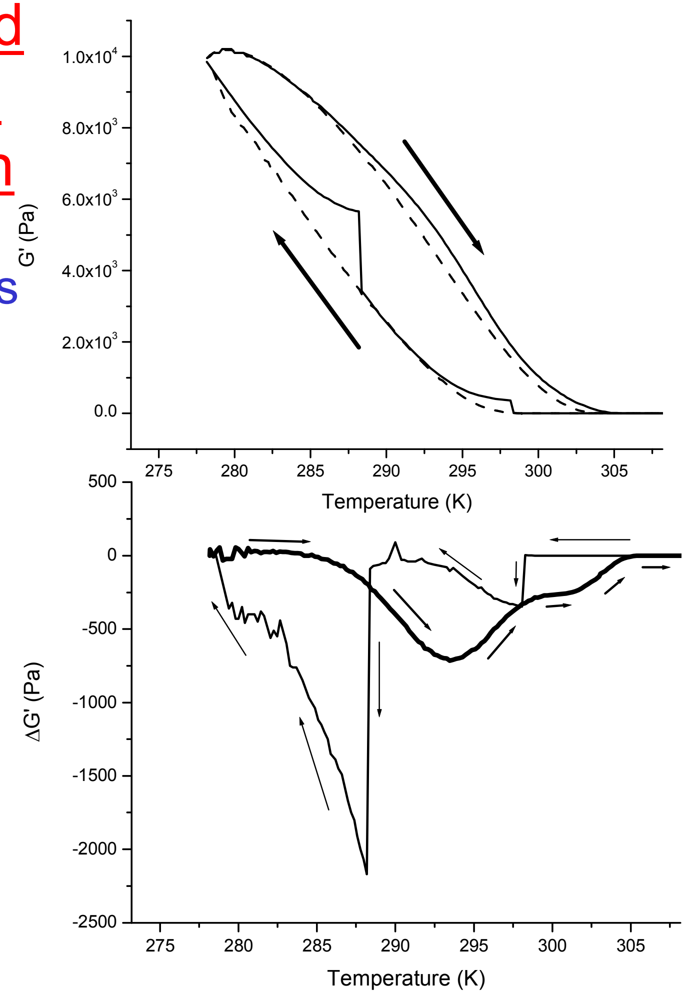
cond-mat/0306056

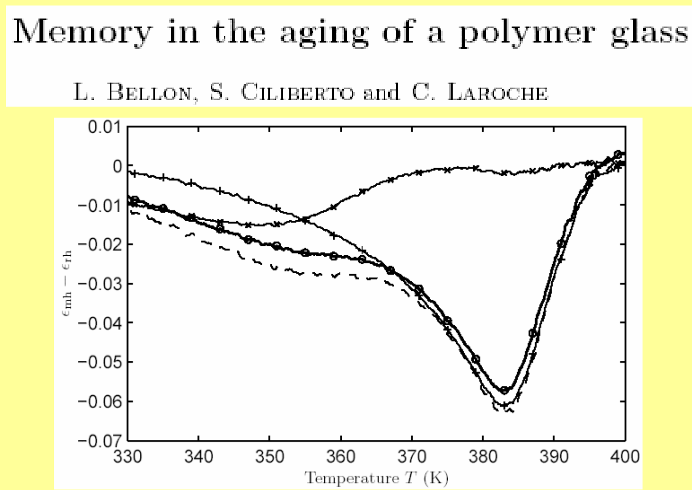
Elasticity measured during heating and cooling at 0.2K/min

dashed line: continuous heating and cooling

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

Bottom figure : difference plot





double memory reading in PMMA (dielectric measurement)

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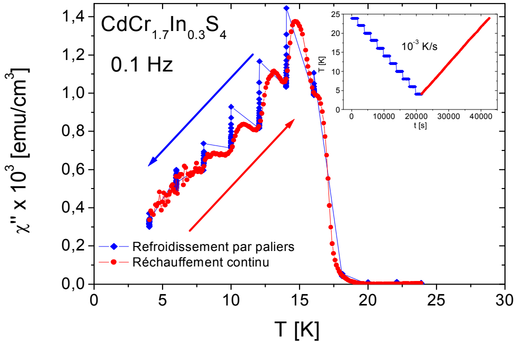
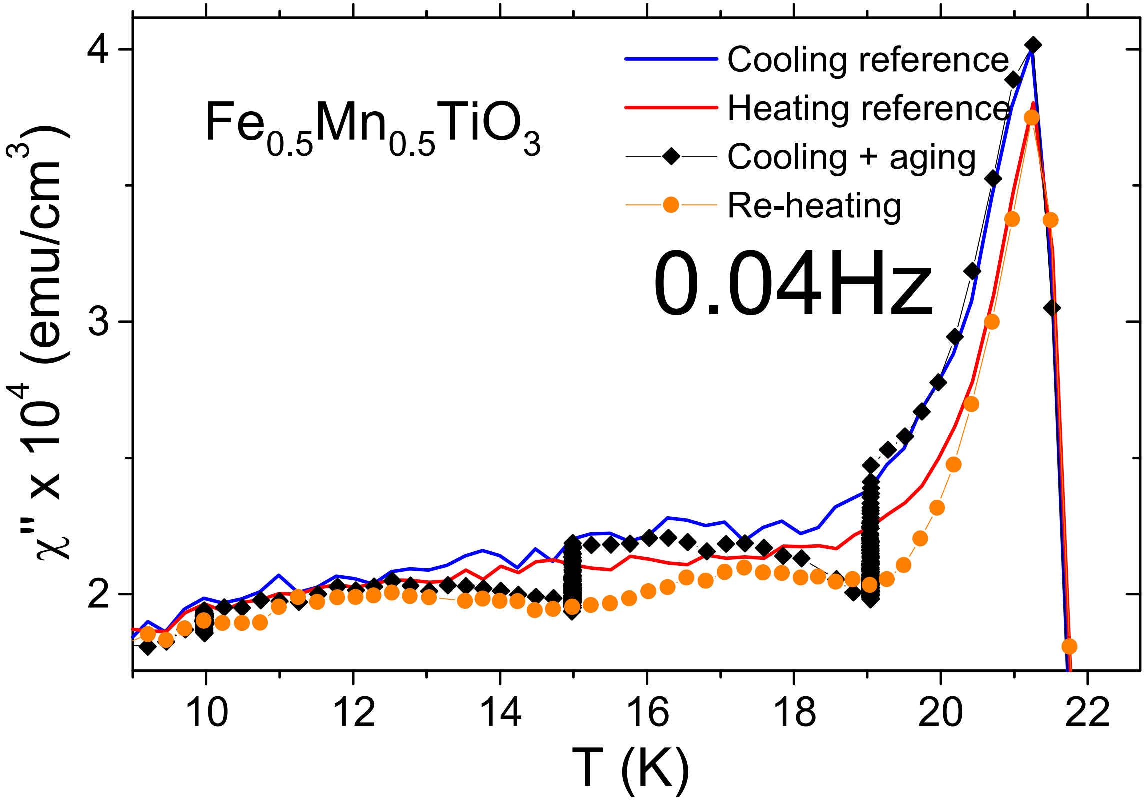
Ising spins (simulations) ↔ **Heisenberg** spins (experiments) **?**

Rejuvenation and memory in an Ising spin glass



*Dupuis et al, Phys. Rev. B **64**, 174204 (2001)*

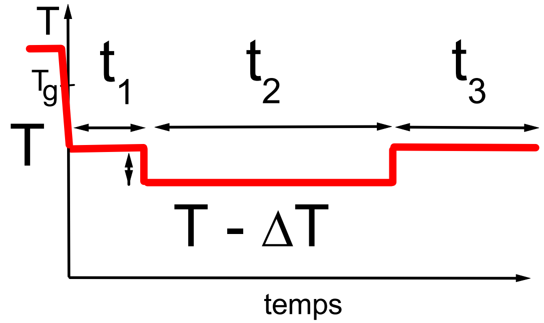


R&M effects are present in the Ising SG – but not so sharp

aging is here more 'cumulative' from one T to the other

Temperature cycling experiments : a quantitative study
(Ising to Heisenberg : 5 spin-glass examples)

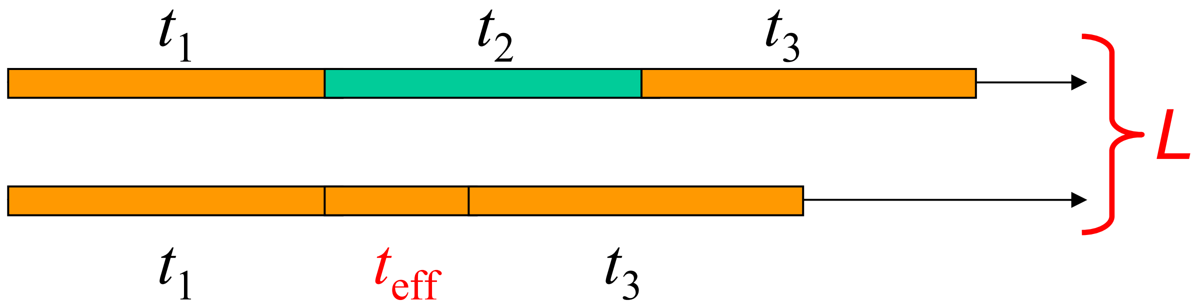
small ΔT → cumulative regime, ~ no rejuvenation



Samples :

	Ising ↑ anisotropy	*K (a.u.)*
(1) $Fe_{0.5}Mn_{0.5}TiO_3$		---
(2) (FeNi)PBAl		*16.5*
(3) Au:$Fe_{8\%}$		*8.25*
(4) $CdCr_{1.7}In_{0.3}S_4$		*5*
(5) Ag:$Mn_{2.7\%}$	Heisenberg	*1*

Perform 2 experiments *(ac* or *dc):*



D.Petit, I. Campbell, *Phys. Rev. Lett.* **88**, 207206 (2002)

with t_{eff} chosen such that both experiments yield the same stage of aging *(here: same TRM relaxation)*

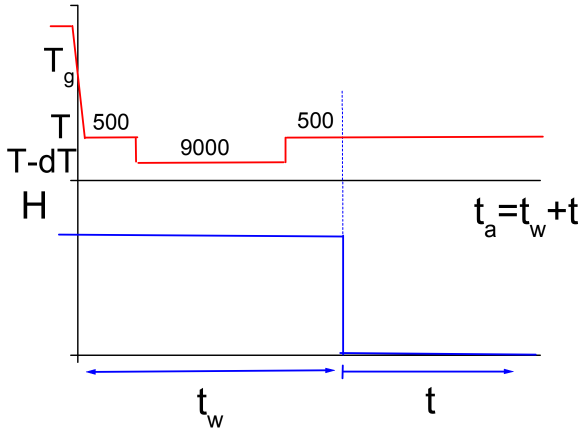
$$L(t_2, T\text{-}\Delta T) = L(t_{eff}, T)$$

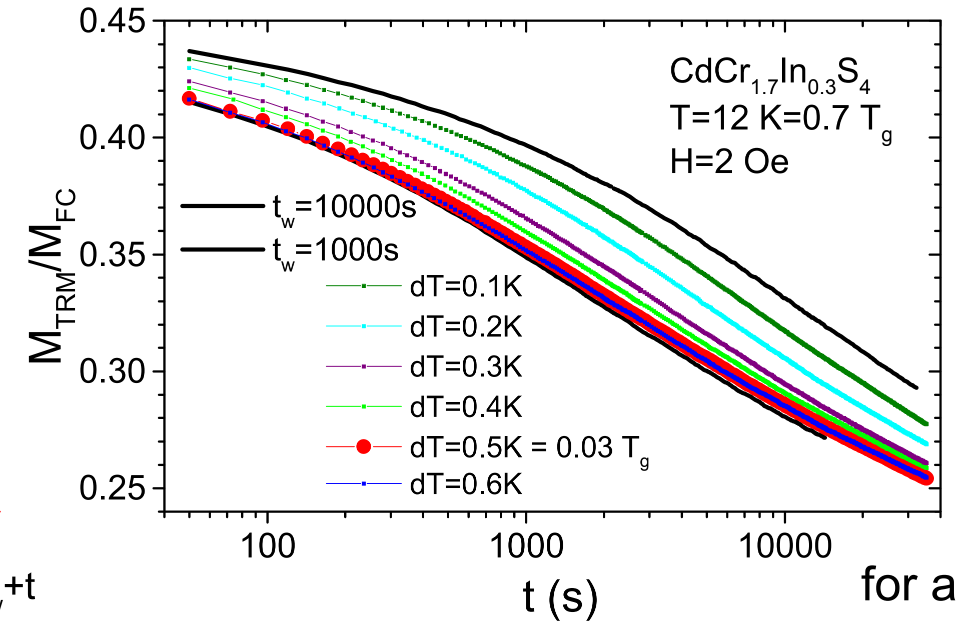
→ $L(t,T)$ from the ΔT-experiments

How far does aging « accumulate » between *T-dT* and *T* ?

(how fast do the <u>aging time/length scales</u> separate *with temperature ?)*

<u>TRM experiments with *temperature cycling* during t_w</u>

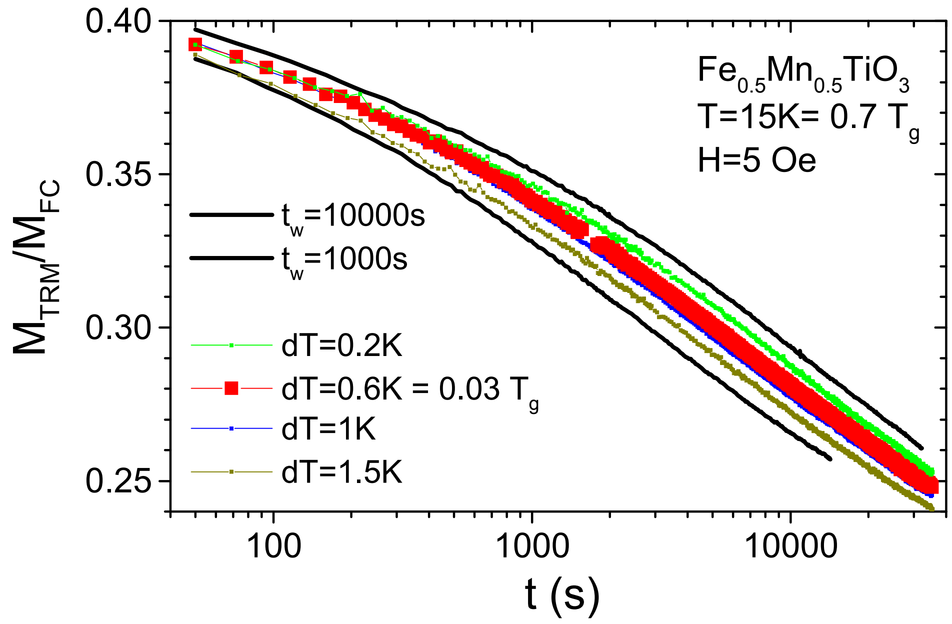




~ Heisenberg

weak contribution of T-dT to T

for a given dT=0.03 T_g



strong contribution of T-dT to T

Ising

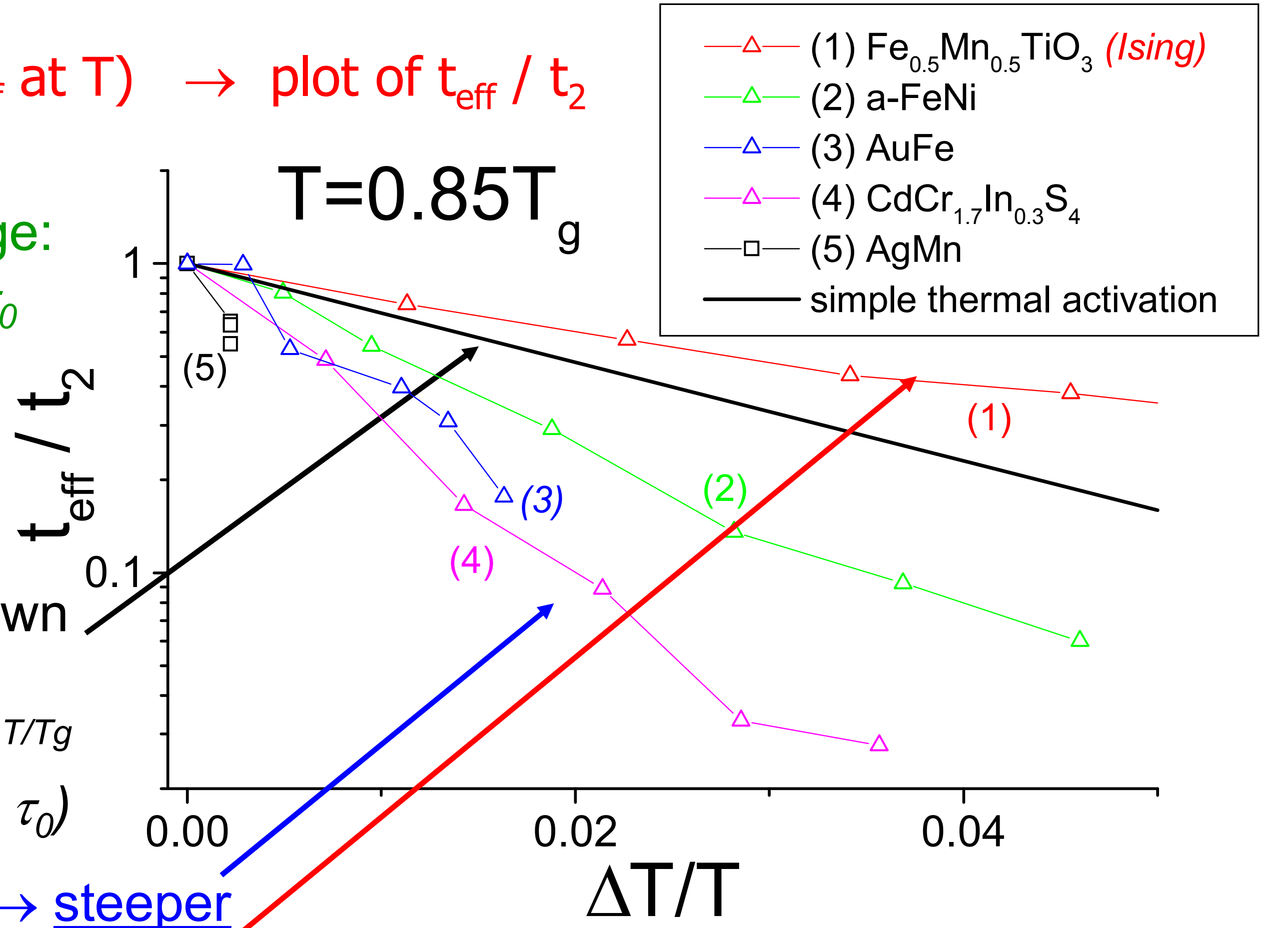
From Ising to Heisenberg: sharper and sharper memory effects

(t_2 at T-ΔT) ≡ (t_{eff} at T) → plot of t_{eff} / t_2

thermal activation language:

$U_L(T-\Delta T)=(T-\Delta T).\ Ln\ t_2/\tau_0$

$U_L(T)=T.\ Ln\ t_{eff}/\tau_0$



simple thermal slowing down

$U_L(T) = U_L(T-\Delta T)$

power law case $L \sim (t/\tau_0)^{aT/Tg}$

(straight line of slope ~log τ_0*)*

Heisenberg-like samples → steeper

$U_L(T) < U_L(T-\Delta T)$

Ising sample → softer

$U_L(T) > U_L(T-\Delta T)$???

→ *influence of critical fluctuations*

(attempt time τ_0 *>> microscopic)*

↓

go beyond a simple power law

$L \sim t^{aT/Tg}$

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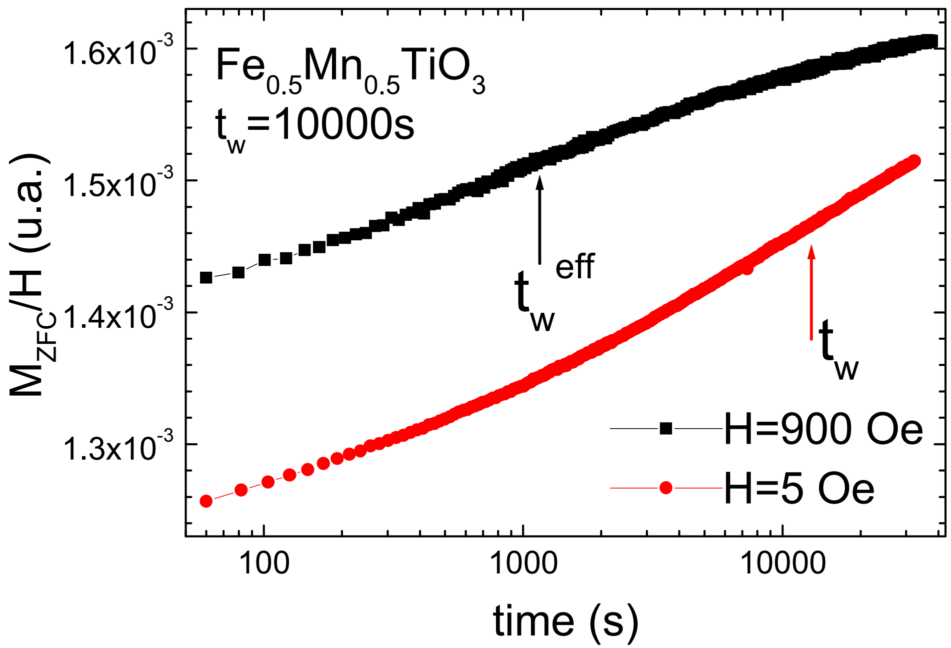
An (indirect) measurement of the growth of the correlation length during aging

influence of the field amplitude on the relaxation of the *dc* magnetization

Y.G. Joh et al, PRL 82, 438 (1999)
+ *Saclay new data*



as H ↑,

the relaxations become faster

inflection point $t_w \rightarrow t_W^{eff}$

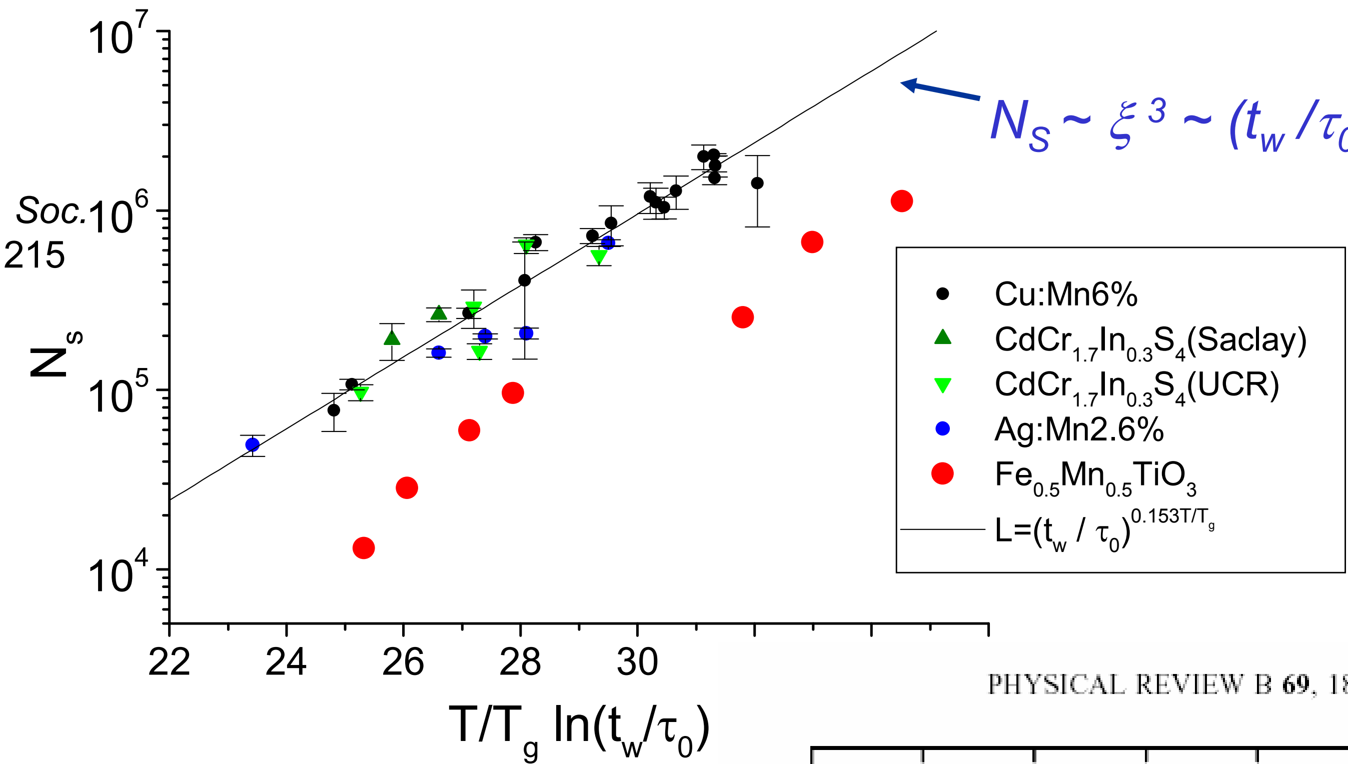
⇔ barrier decrease: $\Delta \rightarrow \Delta - E_Z(H)$
$E_Z(H,t_w) \equiv$ *Zeeman coupling of H to an increasing number of correlated spins* $N_S(t_w)$

$$\Delta = k_B T.Ln\, t_W \rightarrow \Delta - E_Z(H) = k_B T.Ln\, t_W^{eff}(H)$$

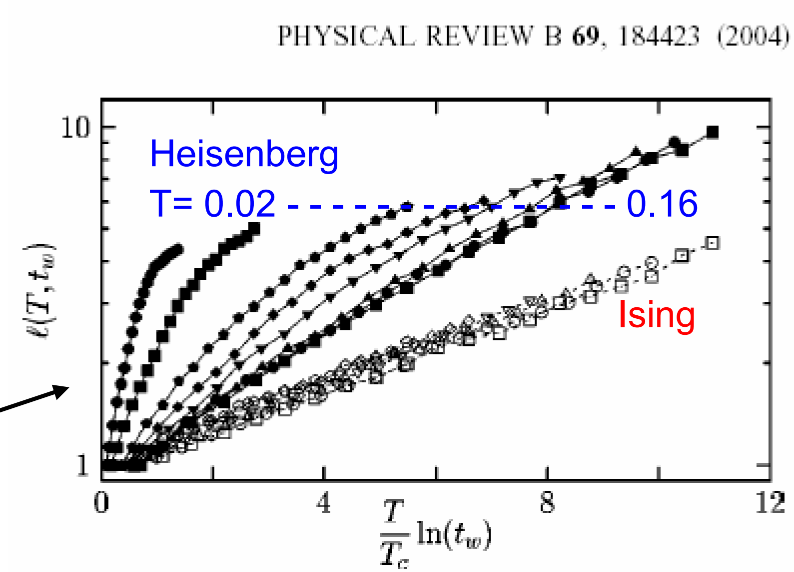
measurement of $t_W^{eff}(H) \rightarrow E_Z(H,t_W) = N_s(t_W).\chi.H^2$

→ number of correlated spins $N_s(t_W) \rightarrow L(t_W) = N_s(t_W)^{1/3}$

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



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



Ising spin glass: smaller N_S, although growing faster

in agreement with T-cycle experiments

same trend as in new large scale simulations by Berthier and Young !

$\Rightarrow$ *go beyond the simple power law $L \sim t^{\,aT/Tg}$*

Time/length relation: a crossover from critical to activated dynamics

$$t_n = t(l_n, T) \sim \tau_0 l_n^{z_c} \exp\left(\frac{\Upsilon(T) l_n^{\psi}}{k_B T}\right), \qquad \Upsilon(T) = \Upsilon_0 [1 - T/T_c]^{\psi\nu}$$

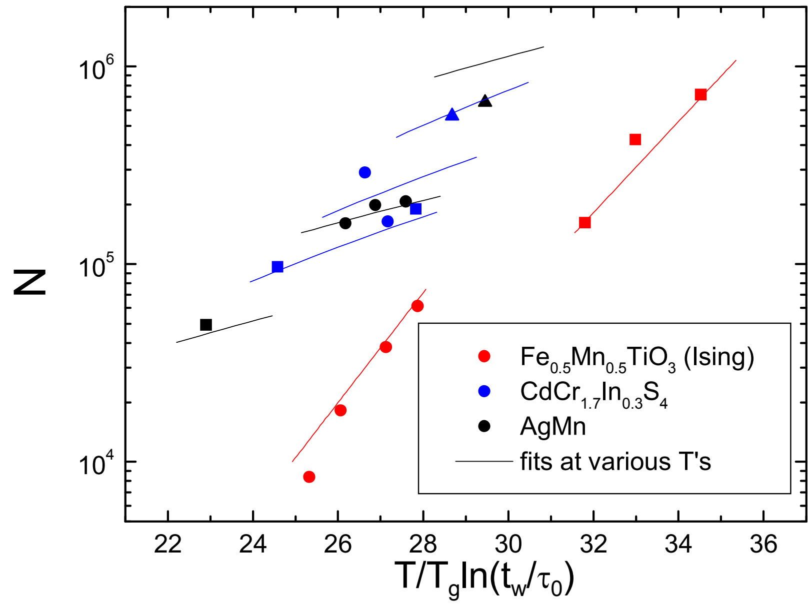
("super"-activated)

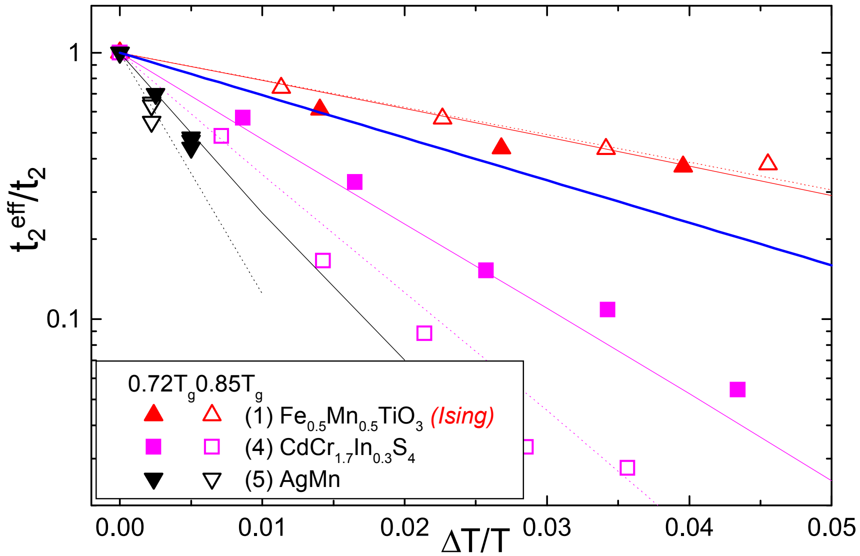
not so far from the power law :

$$\Leftrightarrow t \sim l^{z_{eff}(T)} \quad \text{with} \quad z_{\text{eff}} = \frac{d \log t_n}{d \log l_n} = z_c + \psi \frac{\Upsilon(T) l_n^{\psi}}{k_B T}$$

Bouchaud et al., Phys. Rev. B ***65****, 024439 (2002)*

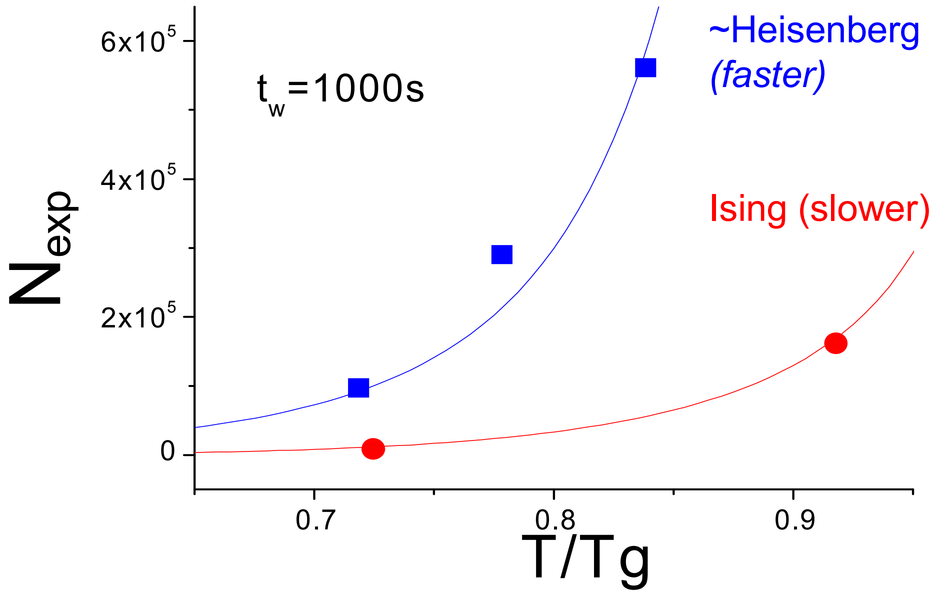
Common analysis of field variation + temperature cycling experiments :





Simultaneous fit of both sets of experiments → $N(T,t_W)$ in different samples

		Y_0	ψ	$z\nu$
Ising				
anisotropy ↑	(1)	14.5	0.03	10.5
	(4)	1.2	1.1	7
	(5)	0.7	1.55	5
Heisenberg				



→ stronger *"T-microscope"* effect for Heisenberg spins

(why ???)

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

Conclusions

- Verres de spin → effets de *rajeunissement et mémoire*

  variation systématique avec l'anisotropie des spins :

  effet mémoire plus piqué en T pour Heisenberg que pour Ising

- effets R&M ⇒ ≠ degrés de liberté peuvent être excités à ≠ T's

↔ *hiérarchie d'échelles de longueurs de corrélation dynamiques, sélectionnées par la température (effet « microscope »)*

- Expériences de cycles en T + effet du champ TRM(H) →

  caractérisation of d'une longueur de corrélation dynamique

  $L(T,t_w)$ ~ *critique* x *(super-)activé*

- Où trouver une hiérarchie d'échelles de longueurs ou de temps ?

  - verre de spin en champ moyen (Cugliandolo Kurchan)
  - « ferromagnétiques spéciaux » (2d XY Berthier Holdsworth, modèle de Potts à 30 couleurs Ricci) – *voir aussi expériences sur ferromagnétiques désordonnés*
  - verres structuraux et polymériques ? probablement oui