Rejuvenation and memory effects in spin glasses
temperature as a microscope

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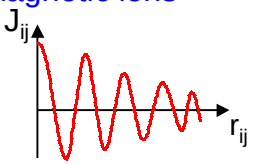
KITP, May 7th 2003

1. Aging, stress-induced rejuvenation
2. Rejuvenation and memory (*effect of temperature*)
3. Spin glasses : Ising ↔ Heisenberg ?
4. Length scales in aging

spin glass ≡ disordered *and* frustrated magnetic system

Theory : random bonds $\mathcal{H} = -\sum J_{ij} S_i S_j$ $\{J_{ij}\}$ gaussian, or $\pm J$

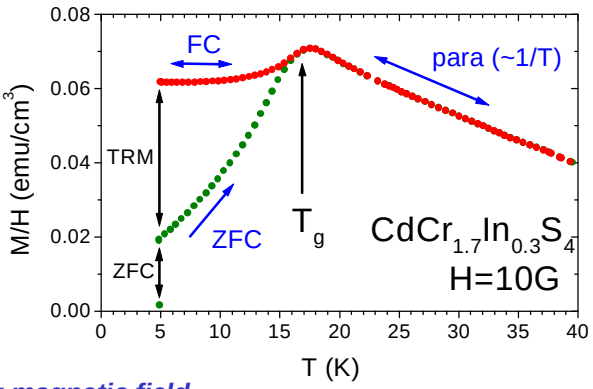
***"Real"* spin glasses :** random dilution of magnetic ions



- metallic alloys : e.g. Cu:Mn 3%
  RKKY interactions
- insulators : $CdCr_{1.7}In_{0.3}S_4$, $Eu_{0.3}Sr_{0.7}S$
  superexchange interactions

F nearest neighbour, AF next-nearest neighbour

same generic behaviour in all samples
(Tc≠0 in 3d, slow dynamics, aging...)
if only frustration, without disorder ?
→ *"topological spin glass phase"* ?
different from the *conventional* spin glass?



weak magnetic field

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)

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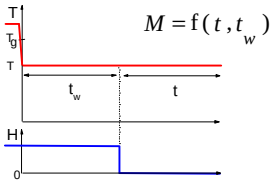
Spin glasses: slow dynamics + aging

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

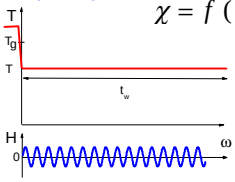
Thermo-Remanent Magnetization (TRM)



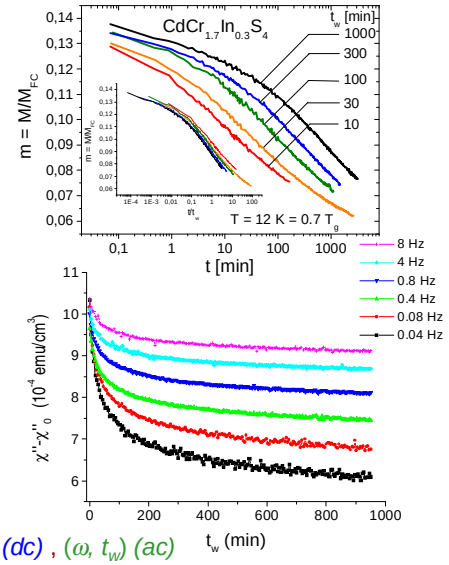
$M = f(t, t_w)$

t_w : waiting time
t : observation time

ac susceptibility

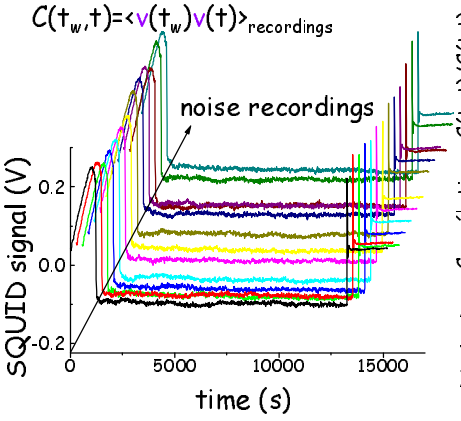


$\chi = f(\omega, t_w)$



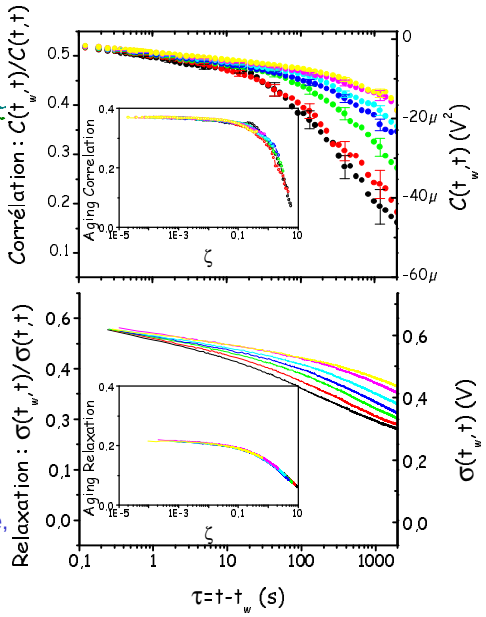
Non-stationary dynamics : (t, t_w) *(dc)* , (ω, t_w) *(ac)*
Scaling variables *:* $\sim t / t_w$ *(dc)* , $\omega\, t_w$ *(ac)*

Noise measurements: determination of the autocorrelation



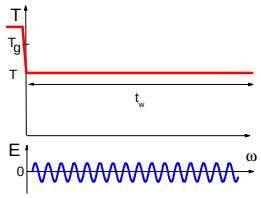
D. Hérisson and M. Ocio,
Phys. Rev. Lett. **88**, 257202 (2002)

comparison of autocorrelation and response, fluctuation-dissipation relations (FDT)
in the aging regime

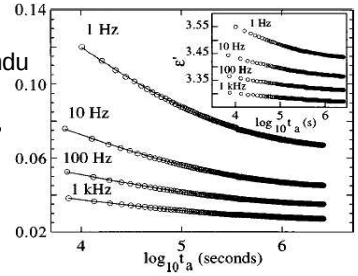


Vieillissement des verres

Réponse diélectrique d'un liquide surfondu

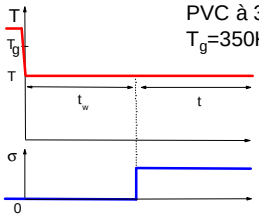


glycérol
à 178K
T_g=190K

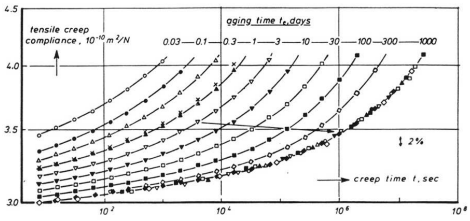


glycérol
Leheny et al. (1998)

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

REJUVENATION BY A STRESS

Volume recovery for an epoxy glass sample after a quench

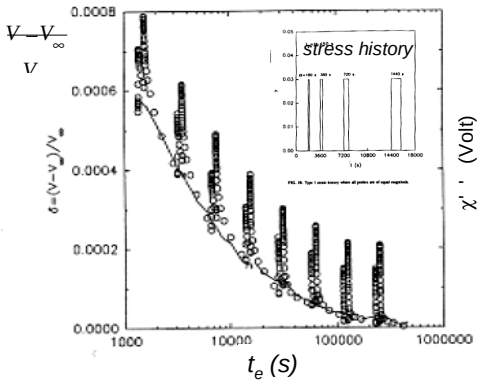
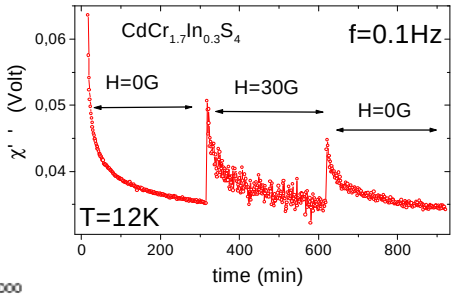


FIG. 9. Volume recovery for DGEBA/D400 epoxy glass (sample #5) after a quench from 44 °C to 33.5 °C and a type 1 history with $\gamma = 0.03$. Curve is the same except $\gamma = 0.0025$.

"The nonlinear viscoelastic response and apparent rejuvenation of an epoxy glass",

Waldron, McKenna, Santore, *J. Rheol.* **39**, 471 (1995)

Spin glass:
rejuvenation by a field variation



E. Vincent, J.P. Bouchaud, D.S. Dean and J. Hammann, *Phys. Rev. B* **52**, 1050 (1995).

good agreement with spin-glass simulations
(Takayama group, *cond-mat/0304556*)

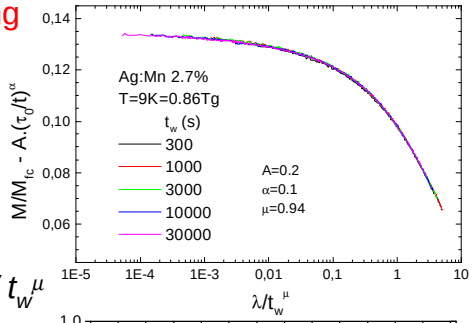
TRM decay : scaling of aging

age dependence of response times

$\tau \sim (t_w+t)^{\mu}$

$\mu \sim 0.9$ $\mu < 1$: « sub-aging »

(J. Appl. Phys. 61, 3683 (1987))



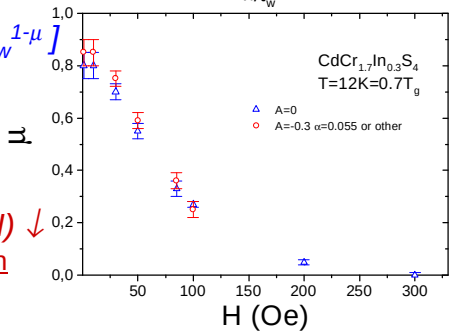
$dm/m = dt/\tau = dt / (t_w+t)^{\mu} = d\lambda / t_w^{\mu}$

$\rightarrow \lambda / t_w^{\mu} = [1/(1-\mu)] [(t_w+t)^{1-\mu} - t_w^{1-\mu}]$

good scaling variable

$(\lambda \sim t$ for $t << t_w)$

from glassy polymers, Struik 1978



$H \uparrow, \mu(H) \downarrow$

aging can be erased by a field variation (rejuvenation)

VOLUME 85, NUMBER 22 PHYSICAL REVIEW LETTERS 27 NOVEMBER 2000

Rheological Aging and Rejuvenation in Microgel Pastes

Michel Cloitre,* Régis Borrega,† and Ludwik Leibler
Laboratoire CNRS-ATOFINA, 95, rue Danton, 92303 Levallois-Perret, France
(Received 3 April 2000)

Controlling the flow properties of soft concentrated dispersions such as emulsions, foams, and colloidal pastes is a key to success in many applications. Yet, several peculiar features of the rheology of these materials remain poorly understood. For example, at low stresses, they behave like weak elastic solids, whereas they flow like viscous liquids above the so-called yield stress. A day-to-day illustration of this interesting behavior is toothpaste which spreads out only when the tube is pressed strongly. The

tw=0 : "quench" by a stress

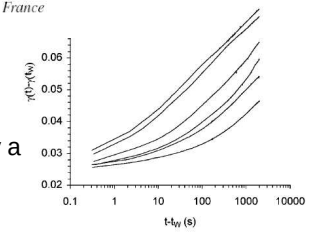


FIG. 3. Creep curves measured at different waiting times when the probe stress σ_m is larger than σ_C ($\sigma_C = 4$ Pa, $\sigma_m = 10$ Pa, $\sigma_y = 20$ Pa). From top to bottom: $t_W = 15$ s, $t_W = 30$ s, $t_W = 300$ s, $t_W = 1000$ s, $t_W = 2000$ s, $t_W = 10\,000$ s.

In conclusion, time-dependent phenomena in paste rheology exhibit all the main features of aging in glassy systems. Rheological aging is closely associated with frustration and cooperative relaxation of steric constraints between interlocked neighboring particles.

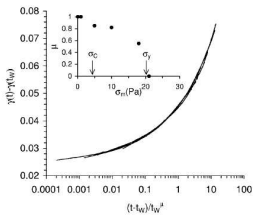


FIG. 5. Same curves as in Fig. 3 plotted as a function of $(t - t_W)/t_W^{\mu}$ ($\mu = 0.80$). The inset gives the values of μ obtained for different σ_m.

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GLASS-FORMING LIQUIDS

slower cooling rate $\rightarrow$ closer to equilibrium

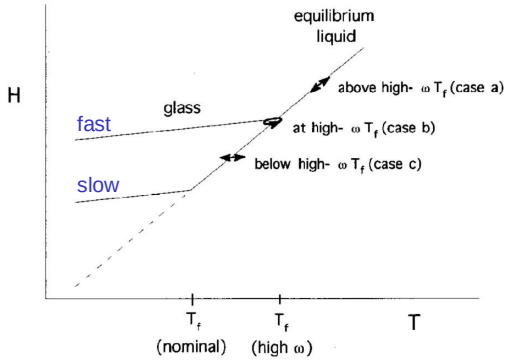


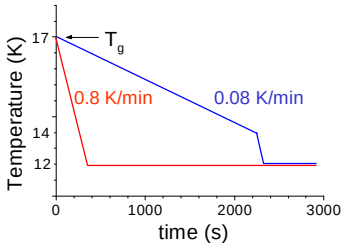
FIG. 2. Enthalpy versus temperature schematic showing two glasses, one obtained at a conventional cooling rate and the other at a higher rate. Situations (a)–(c) are described in the text.

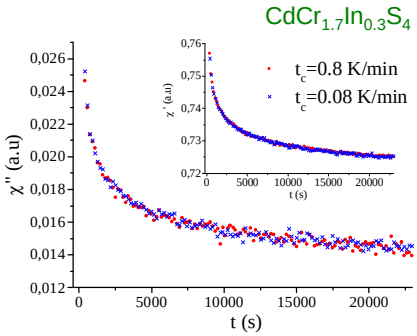
Kovacs 1964

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

Spin glass: no cooling rate effects ?

« slower cooling does not help »

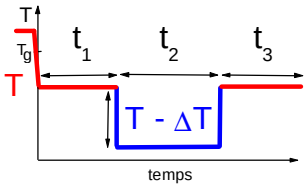


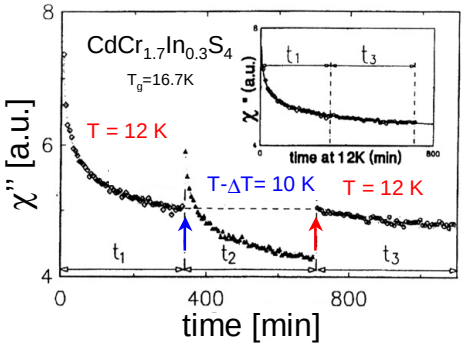


Phys. Rev. Lett. **81**, 3243 (1998)
(Uppsala-Saclay)

Effect on aging of temperature variations

Negative temperature cycle
(case of a large enough ΔT)

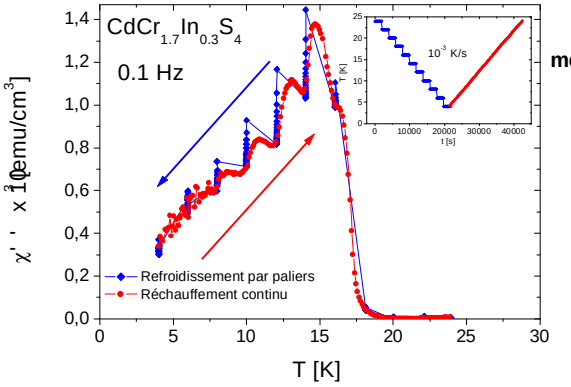




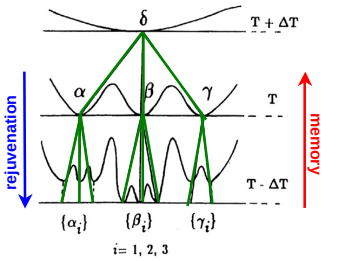
Lefloch et al., *EPL* **18**, 647 (1992)

T↓ : rejuvenation, *restart of the relaxation*
T↑ : memory, *no effect of the time spent at T-ΔT*

Spin glass:
(multiple) rejuvenation and memory effects



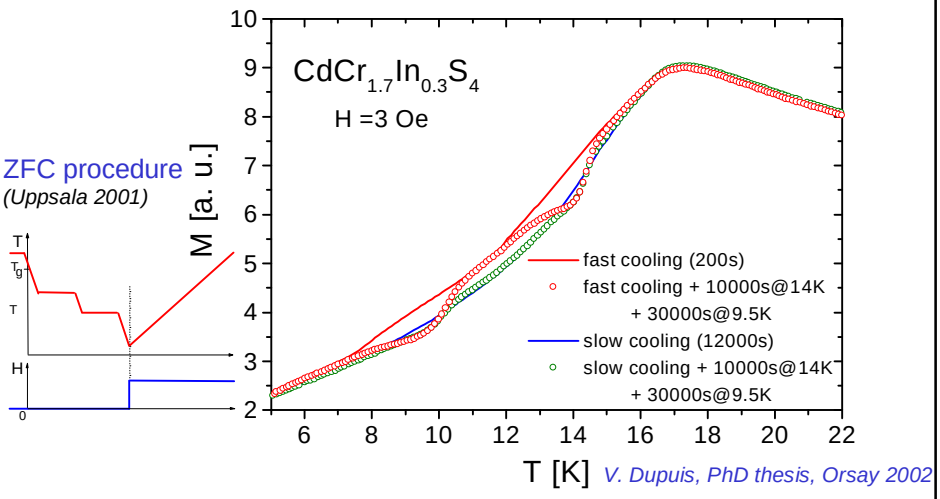
hierarchical organization of the metastable states as a function of T



T↓ : rejuvenation
T↑ : memory

Quantitatively:
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 ?



V. Dupuis, PhD thesis, Orsay 2002

aging ≡ combination of { **cooling rate effects** *T-cumulative*
rejuvenation and memory effects *T-specific*

EUROPHYSICS LETTERS

Europhys. Lett., **51** (5), pp. 551–556 (2000)

Memory in the aging of a polymer glass

L. BELLON, S. CILIBERTO and C. LAROCHE

Ecole Normale Supérieure de Lyon, Laboratoire de Physique CNRS UMR5672, 46 Allée d'Italie, 69364 Lyon Cedex 07, Fr

PMMA Tg=388K

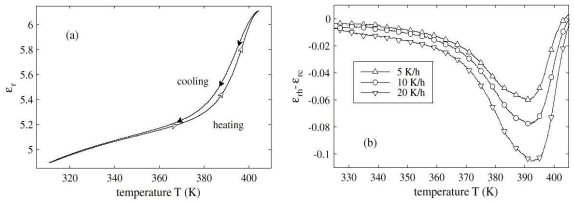


Fig. 1 – (a) Evolution of ϵ_r at $\nu = 0.1\,\mathrm{Hz}$ as a function of T. Reference curve obtained with $|R| = 20\,\mathrm{K/h}$. (b) Hysteresis of the reference curve (difference between the heating and cooling curves $\epsilon_{rh} - \epsilon_{rc}$) for 3 different $|R|$: 5 K/h (△), 10 K/h (○) and 20 K/h (▽).

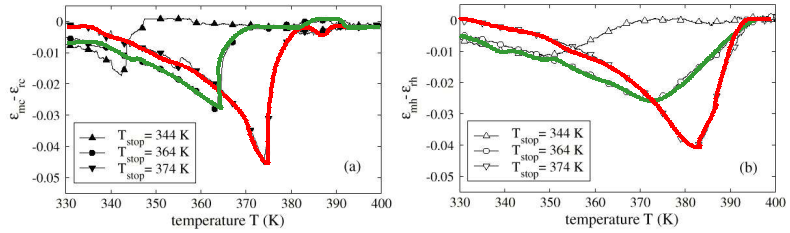


Fig. 3 – Dependence on T_{stop}. Difference between ϵ_r and ϵ_m for three different cooling stops at $\nu = 0.1\,\mathrm{Hz}$, $|R| = 10\,\mathrm{K/h}$ and $t_{stop} = 10\,\mathrm{h}$. (a) Writing memory (cooling): $\epsilon_{mc} - \epsilon_{rc}$ with $T_{stop} = 344\,\mathrm{K}$ (▲), $T_{stop} = 364\,\mathrm{K}$ (●) and $T_{stop} = 374\,\mathrm{K}$ (▼). (b) Reading memory (heating): $\epsilon_{mh} - \epsilon_{rh}$ of $T_{stop} = 344\,\mathrm{K}$ (△), $T_{stop} = 364\,\mathrm{K}$ (○) and $T_{stop} = 374\,\mathrm{K}$ (▽).

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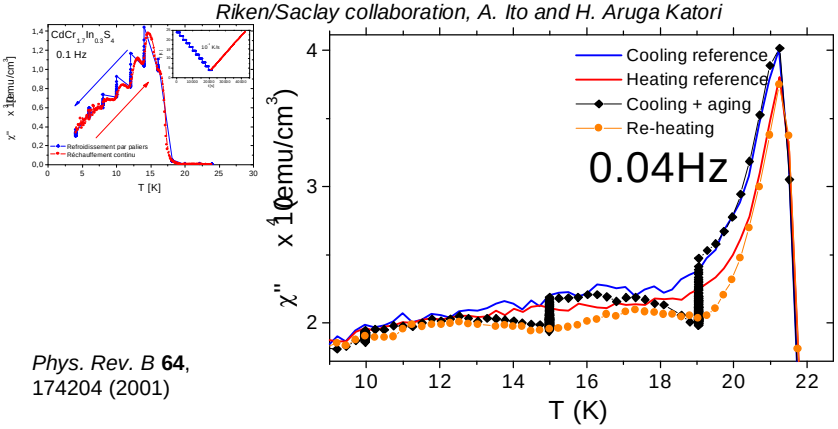
Ising spins (simulations) ↔ **Heisenberg** spins (experiments) **?**

Rejuvenation and memory in an Ising spin glass:

$Fe_{0.5}Mn_{0.5}TiO_3$ single crystal

Riken/Saclay collaboration, A. Ito and H. Aruga Katori



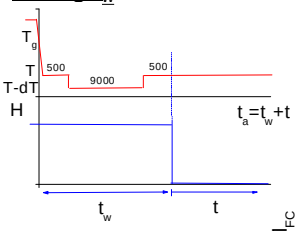
Phys. Rev. B **64**, 174204 (2001)

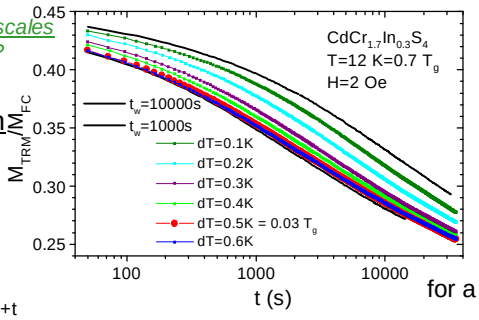
Memory effects are present - but more *spread out* in temperature than in other (~Heisenberg) spin glasses

How does *aging at T-dT* influence *aging at T* ?

how fast do the aging time scales separate with temperature ?

TRM experiments with *temperature cycling* during t_w

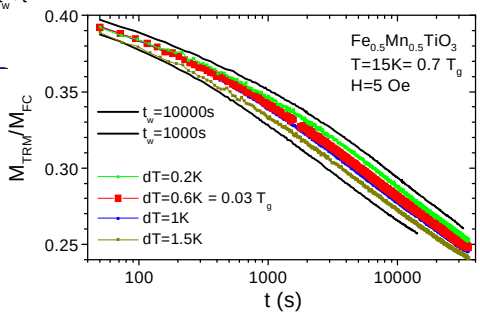




~ Heisenberg

weak contribution of T-dT to T

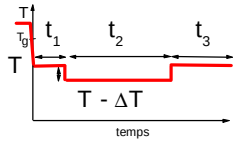
for a given dT=0.03 T_g



strong contribution of T-dT to T

Ising

Temperature cycling experiments: results from spin glasses of different anisotropies



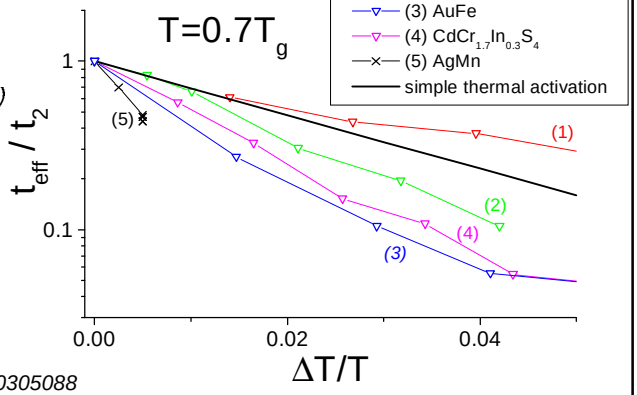
$(t_2$ at T-ΔT) ≡ (t_{eff} at T) → t_{eff} / t_2

Samples :

(1) $Fe_{0.5}Mn_{0.5}TiO_3$ — Ising — K (a.u.) = ---
(2) (FeNi)PBAl — 16.5
(3) Au:$Fe_{8\%}$ — 8,25
(4) $CdCr_{1.7}In_{0.3}S_4$ — 5
(5) $Ag:Mn_{2.7\%}$ — 1

anisotropy

Heisenberg

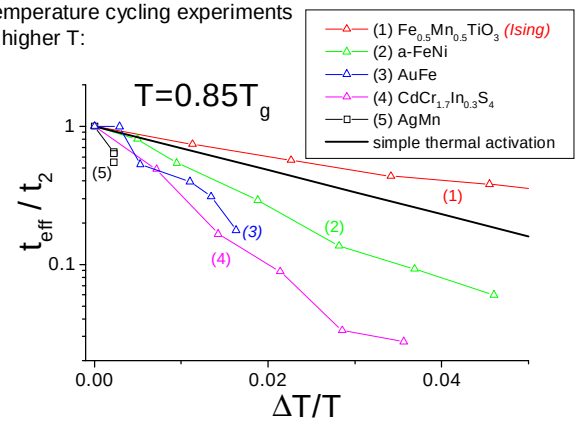


cond-mat/0305088

Heisenberg spins: a different nature of the spin-glass phase ?

Tc≠0 for d=3 Heisenberg spin-glass ? See Lee and Young cond-mat/0302371 !!! (Tc=0.16)

Temperature cycling experiments at higher T:



cond-mat/0305088

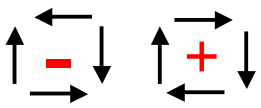
also:

D.Petit, I. Campbell : systematic variation of critical exponents with anisotropy, from Ising to chiral glass values

Phys. Rev. Lett. **88**, 207206 (2002)

In relation with the chirality freezing (Kawamura' s scenario) ?

Kawamura 1987, Phys. Rev. E 61 (2000) R1008



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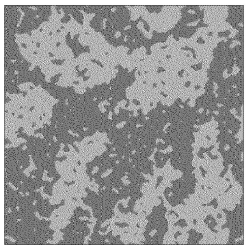
aging ⇔ growth of spin-glass ordered domains ?

droplet model (Fisher Huse 1986-88):
spin glass ≡ "disguised ferromagnet"
aging: growth of $R(t) \sim (T.\ Ln\ t / \Delta(T))^{1/\psi}$
rejuvenation ↔ chaos
memory ↔ typical size of domains

multiple memories at $\neq T \Rightarrow$ *hierarchy of* "domains within domains", *selected by temperature*
«T-microscope effect »
what is the geometry of such domains ?



Yoshino et al, EPJ B ***20****, 367 (2001)*

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

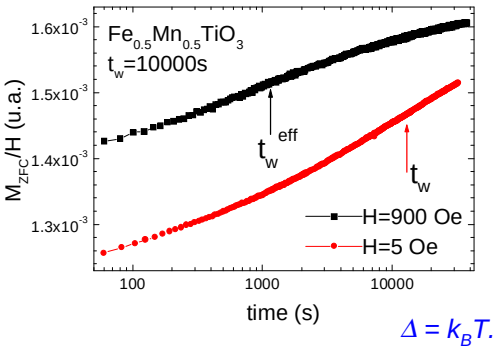
Evidence of a growing length scale in a spin glass during aging ?

- in simulations: YES ! *dynamical correlation length* $\xi(t,T) \sim (t/\tau_0)^{0.15\ T/T_g}$
(Takayama ISSP group, Roma group, Rieger et al...)

- in experiments ? *indirectly, yes*
does it show a difference between Ising and Heisenberg spin glasses ?

Determination of the *time* growth of a characteristic *length* scale for aging

measurements of the influence of the field amplitude on the relaxation of the *dc* magnetization (TRM or ZFC)



as H ↑,

the relaxations become faster

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

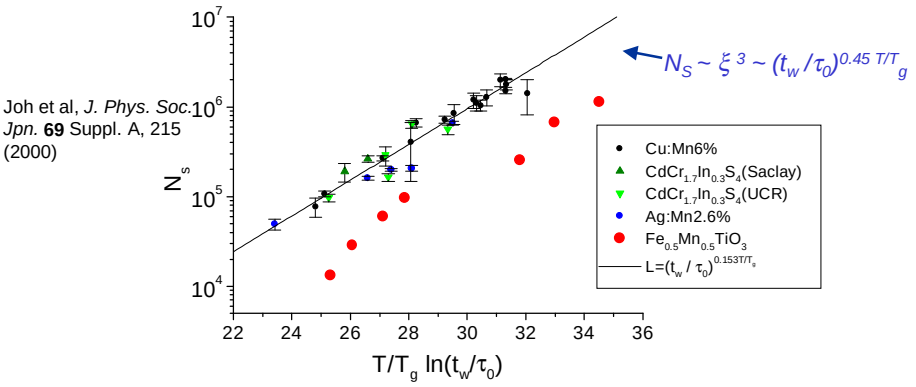
⇔ barrier reduction: $\Delta \rightarrow \Delta - E_Z(H)$

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

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

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

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



New data on the Ising sample :

- not on the same line as the others
- smaller N_S

smaller $N_S \rightarrow$ *more difficult to build independent memories (spin arrangements) at* $\neq T$ ... *confirmation of T-cycle experiments*

QUANTITATIVELY ?

go beyond the simple power law $\xi \sim t^{aT/Tg}$

Time growth of the correlations: a crossover from critical to activated dynamics

("super"-activated)

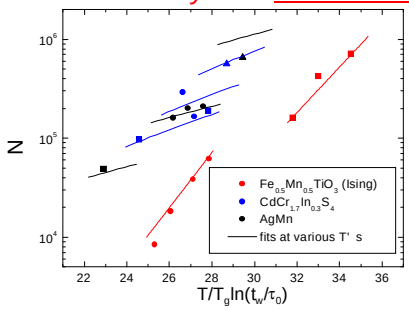
$$t_n = t(l_n, T) \sim \tau_0 l_n^{z_c} \exp\left(\frac{\Upsilon(T) l_n^{\psi}}{k_B T}\right)^{\psi} \qquad \Upsilon(T) = \Upsilon_0 [1 - T/T_c]^{\psi\nu}$$

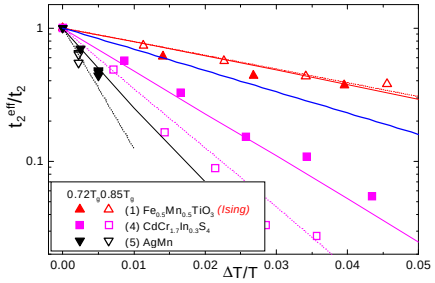
not so far from the power law :

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

Bouchaud et al., Phys. Rev. B ***65****, 024439 (2002)*
Dupuis et al, Phys. Rev. B ***64****, 174204 (2001)*

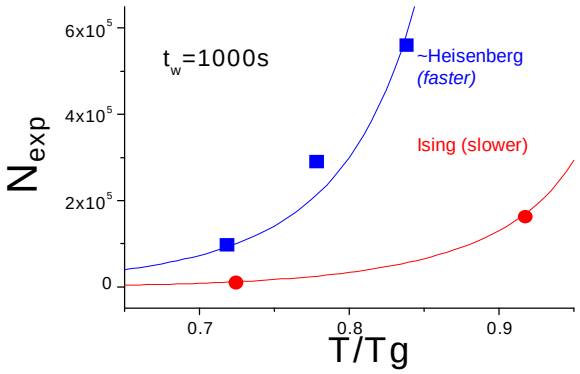
→ *common analysis of* field variation **+** temperature cycling *experiments*





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

	Y_0	ψ	zv
(1)	14.5	0.03	10.5
(4)	1.2	1.1	7
(5)	0.7	1.55	5



cond-mat/0305088

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

(why ???)

Conclusions

1. At constant temperature

- aging ~ same in spin glasses, polymers, colloïds...
- rejuvenation by a field change (spin glasses) or a stress (glasses, colloïds…)

2. Temperature sensitivity

- spin glasses: weakly sensitive to the cooling rate
  rejuvenation and memory as a function of T
- rejuvenation and memory effects possible in some polymers, dielectrics...
  generalization **?** aging = combination of *T- cumulative* and *T- specific effects* **?**
  glasses ↔ spin glasses : same phenomenology with very ≠ building blocks **?**

3. Length scales in aging

- hierarchy of metastable states ⇔ *hierarchy of length scales*
  simulations + ~Heisenberg real samples → $\xi \sim t^{aT/Tg}$
  Ising sample → beyond power law: crossover *critical* x *(super-)activated*
  what are these length scales **?** what are spin-glass *'domains'* **?** (sponge-like ?)
- *sharp memory effects* if *strong separation of length scales with T* ($L_{T-\Delta T} << L_T$)
  why a stronger T-separation for Heisenberg spins **? Ising ≠ Heisenberg SG ?**