Spin glasses : experimental signatures and some salient outcomes

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NIMS, Tsukuba, November 17th, 2022

CENTRE NATIONAL
DE LA RECHERCHE
SCIENTIFIQUE

1. What is a spin glass ?

2. Aging, rejuvenation and memory effects

3. Correlation length of the « spin-glass order »

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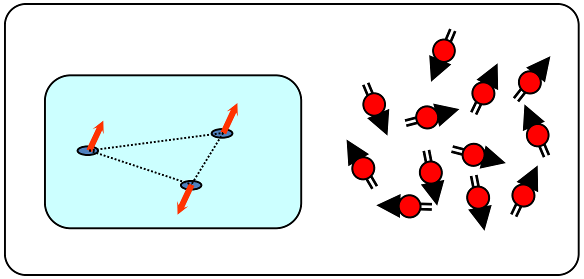
What is a spin glass ?

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

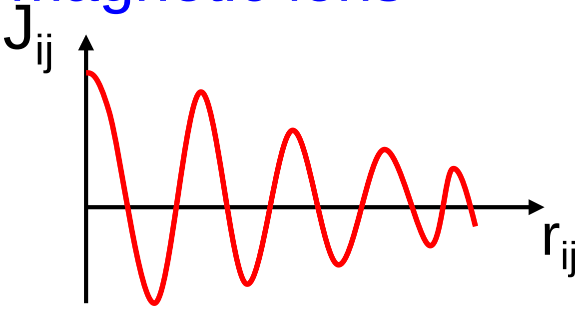


a disordered *and* frustrated magnetic system

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

example: metallic alloys, Cu:Mn 3%

RKKY interactions



same generic behaviour in all samples
(Tc≠0 in 3d, slow dynamics, aging...)

→ « model » disordered systems

Spin glass and cluster glass : the Au:Fe alloy

Magnetic phase diagram of Au:Fe,
from the 1993 book of J.A. Mydosh

Comparison with strain glass and electric relaxor ?

Xiaobing Ren :
In the spin glass literature, spin glass is subdivided into two subsets: a “**dilute spin glass**” with nearly isolated and disordered spins being frozen, and a “**cluster spin glass**” with frozen nano-sized ferromagnetic domains or clusters. In the present article, we shall confine our discussion to cluster spin glass when mentioning spin glass, **as it is physically parallel to strain glass and relaxor**, both being cluster glasses.

J.A. Mydosh :
…Hereby we can avoid, for the sake of simplicity, the mostly unnecessary distinction of having three or more spin-glass regimes…

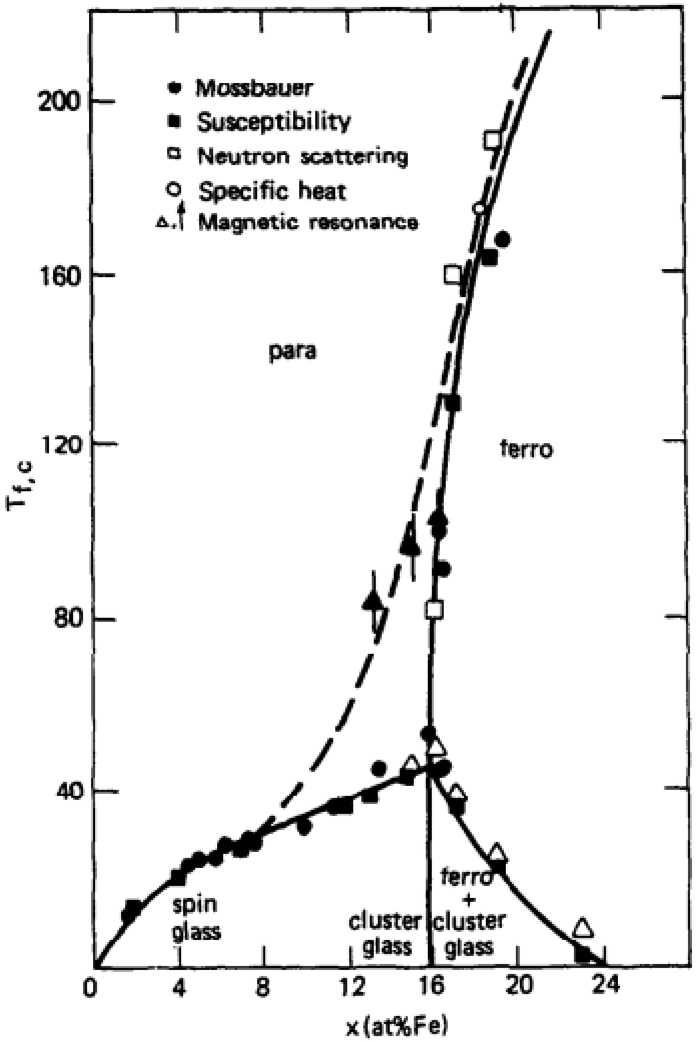


Fig. 2.11 Magnetic phase diagram of *Au*Fe constructed from the anomalies observed in various experiments according to symbol; from Coles *et al.* (1978).

Magnetic properties of the $CdCr_{2x}In_{2-2x}S_4$ compound

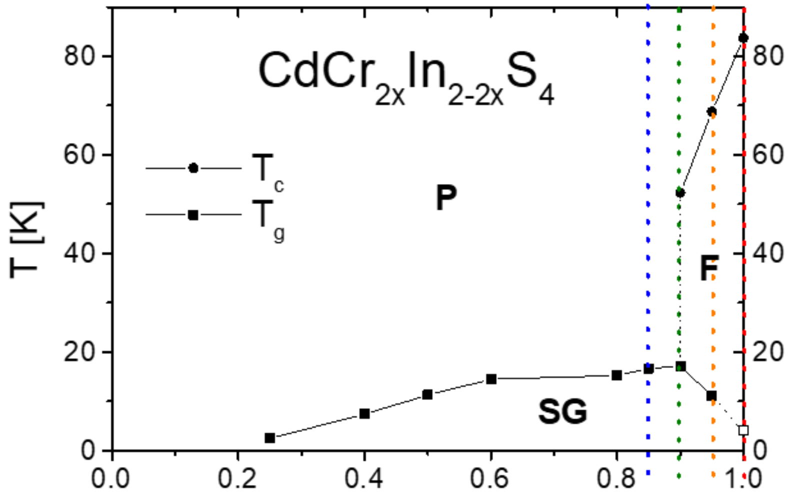
Conflicting interactions between the Cr^{3+}
Nearest neighbours : Ferro
Next-nearest neighbours : Anti-Ferro

Samples with various dilutions
: (Marc Noguès)
x = 0.85, 0.90, 0.95 et 1.00

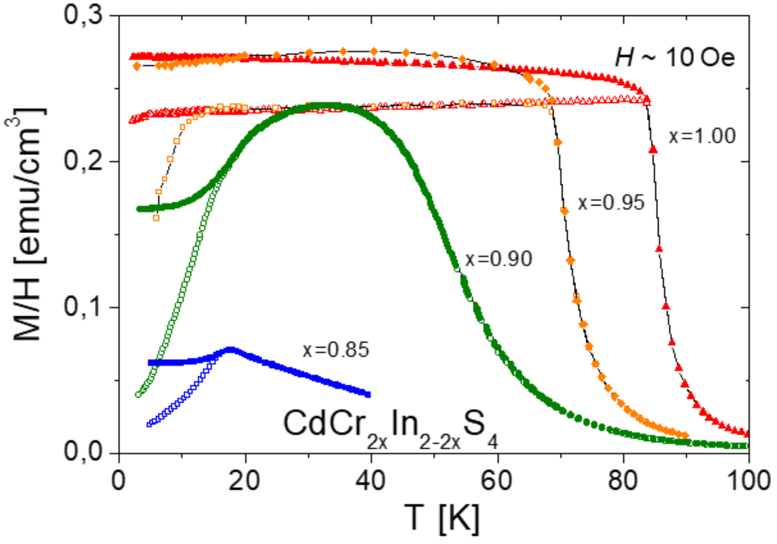
x=1.00-0.95 : Frustrated ferromagnet
x=0.90 : Cluster glass
x=0.85 : Spin glass

Magnetization measurement procedures :
ZFC = Zero-Field Cooling (open symbols)
FC = Field Cooling (full symbols)

Dupuis et al, EPJ B **29**, 19 (2002)



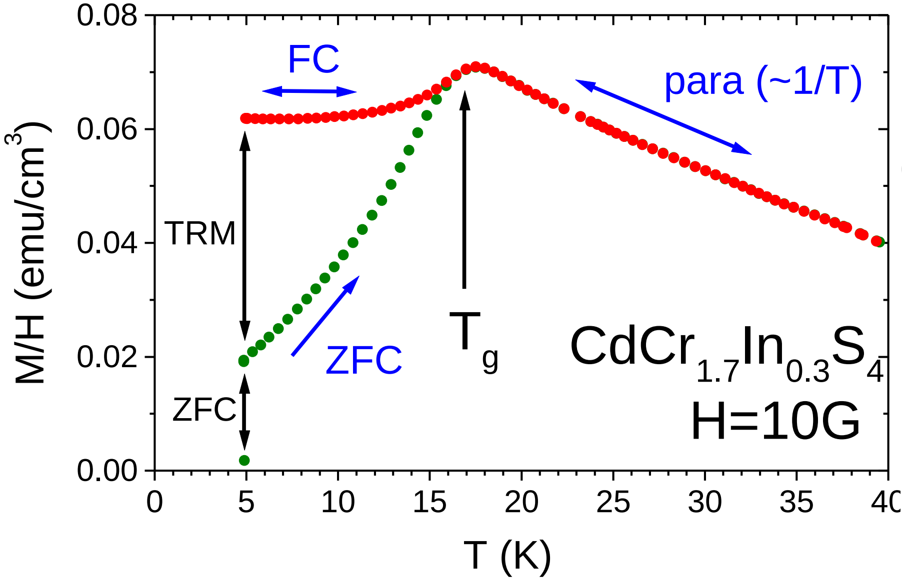
Phase diagram



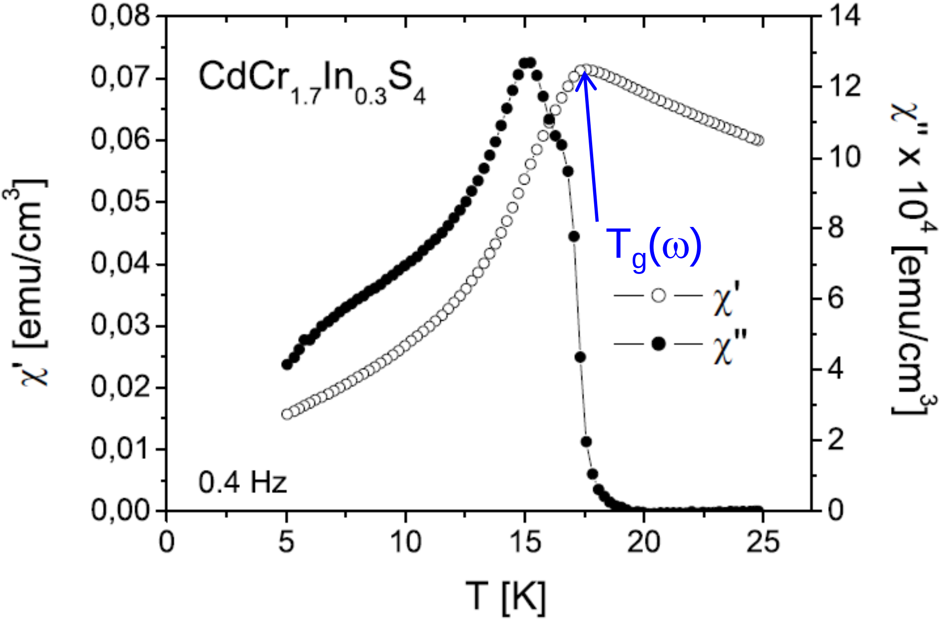
FC and ZFC magnetization

Spin glass: general magnetic features

dc magnetization



ac susceptibility (frequency ω)



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)

Peak of χ' : T$_g$(ω)

Spin freezing at time scale $\tau \sim 1/\omega$

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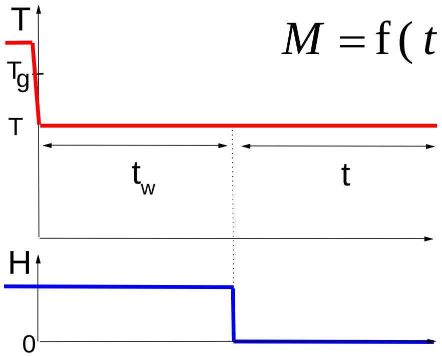
Spin glasses: slow dynamics + aging

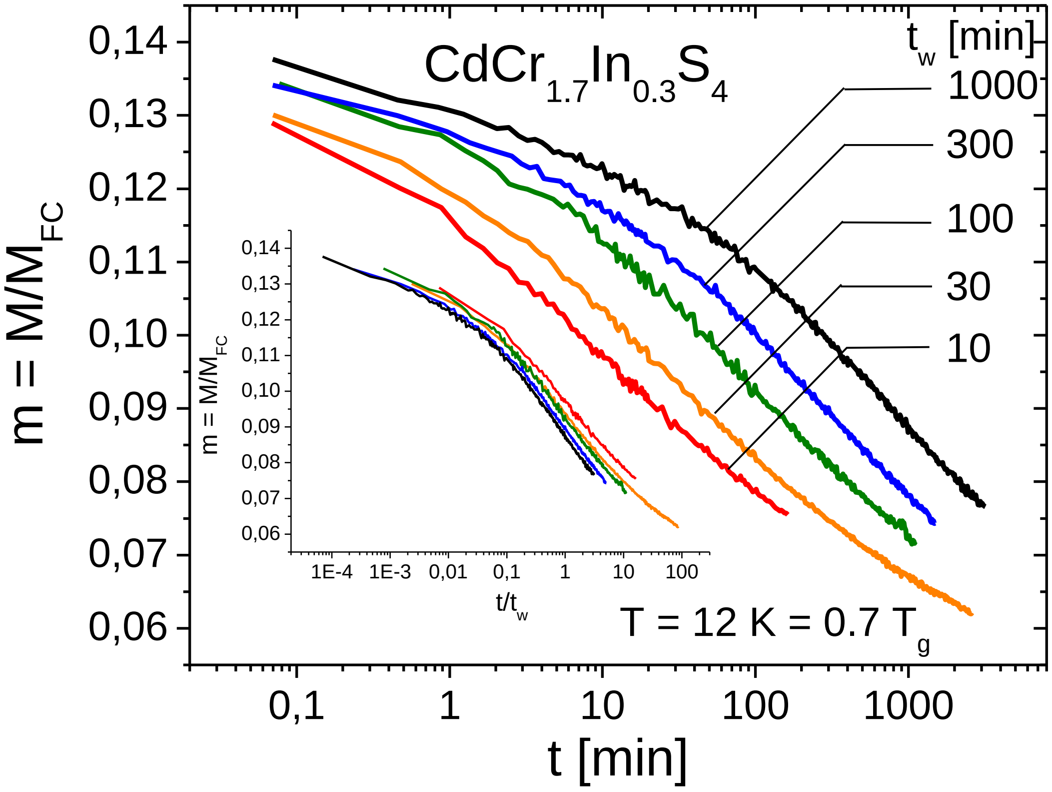
80’ Uppsala (Lundgren, Nordblad)
Saclay (Hammann, Ocio, Alba, Vincent)

Relaxation of theThermo-Remanent Magnetization (TRM)



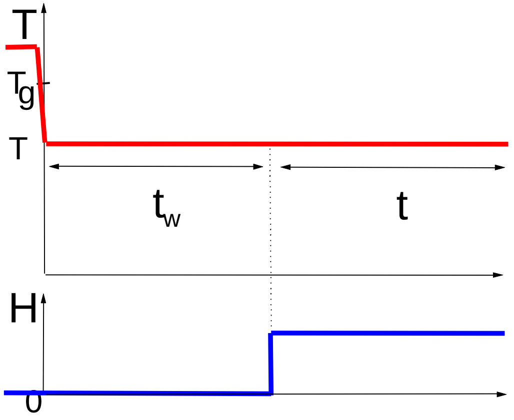
$$M = f(t, t_w)$$

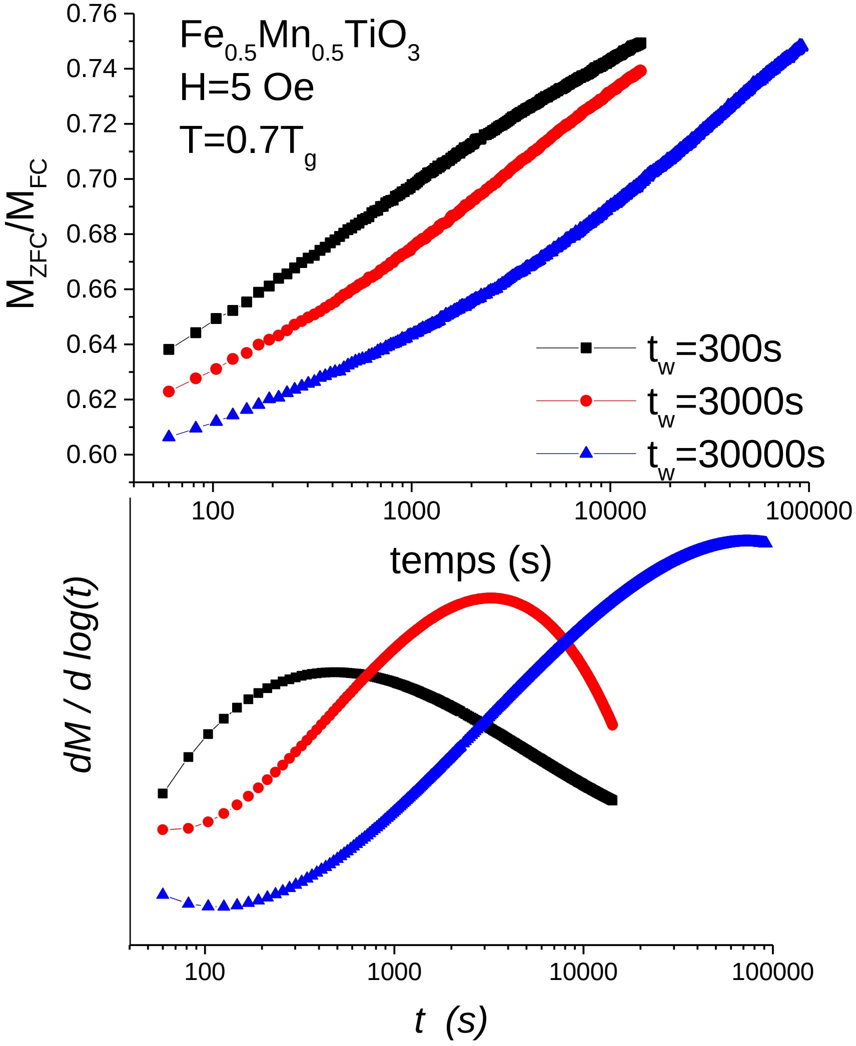
t_w : waiting time
t : observation time
H : weak magnetic field



→ Non-stationary dynamics : *(t , t_w)*
Scaling variable *:* ~ *t / tw* (or *t / t_w^{μ} with $\mu \leq \sim 1$)*

Relaxation of the ZFC magnetization : aging effects





For longer tw, slower relaxation : aging

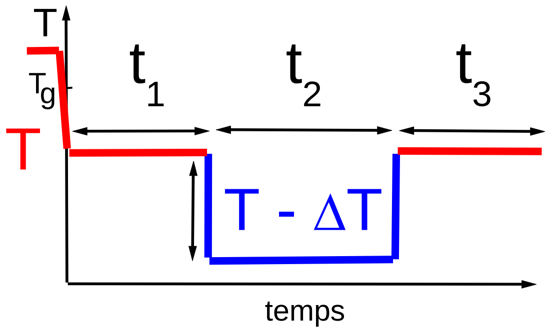
The relaxing magnetization depends on both *t* and t_w

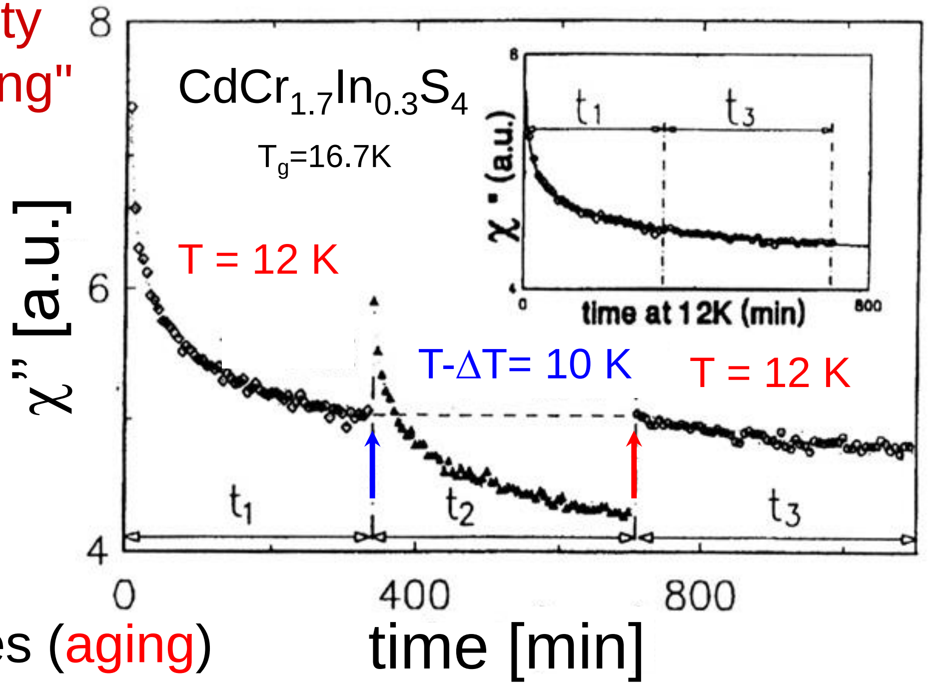
The relaxation rate $dM_{tw} / d \log t$ peaks around $t_i \sim t_w$, defining a characteristic time t_i in the relaxation process.

Aging corresponds to the shift of t_i with t_w

Aging, rejuvenation and memory: the simplest experiment

Aging can also be observed in *ac* measurements :
Relaxation of the *ac* susceptibility
in a "negative temperature cycling"





- At constant *T*, χ relaxes (aging)
- *T* ↘: rejuvenation, *restart of the relaxation*
- *T* ↗: memory, *no effect of the time spent at T-ΔT*

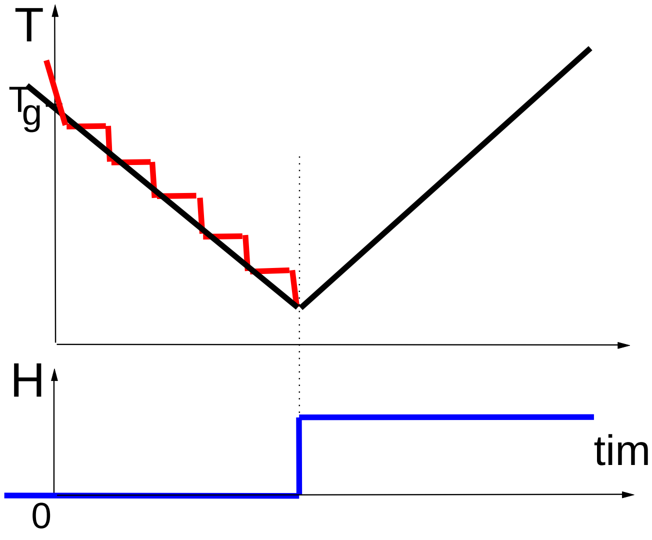
Lefloch et al, Europhys. Lett. **18**, 647 (1992)

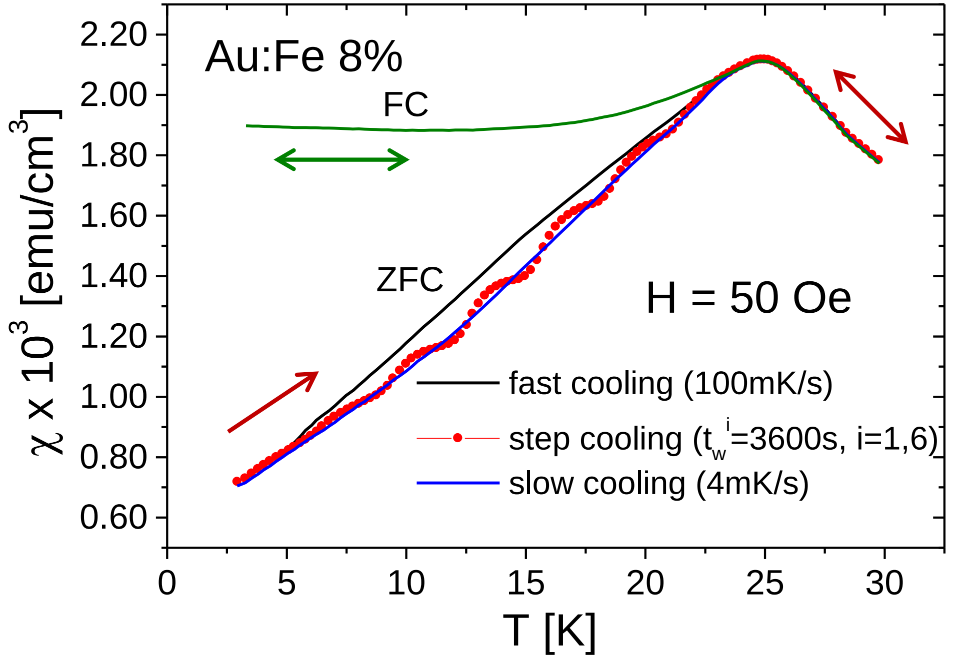
see references in arXiv:2208.00981

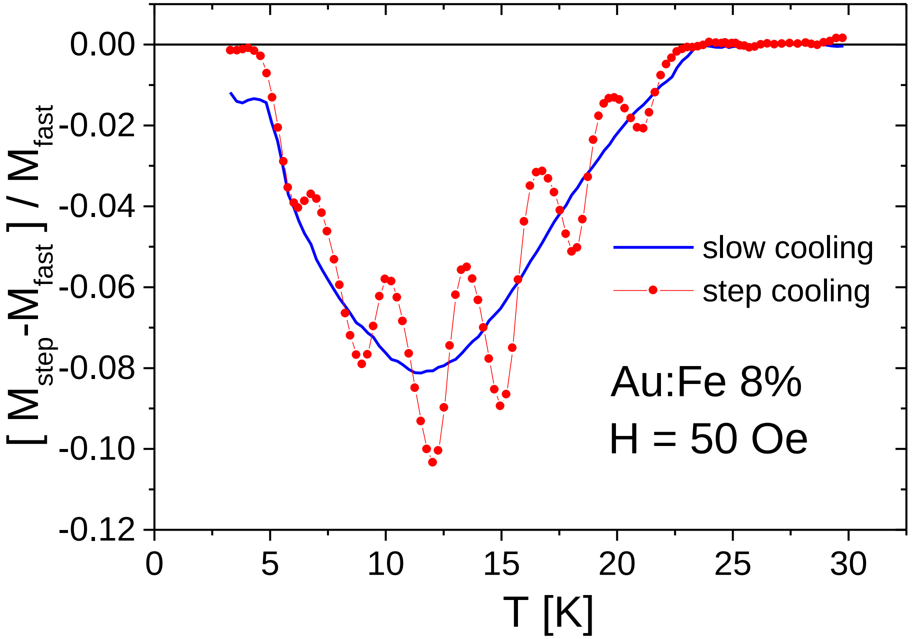
Rejuvenation and memory effects in the ZFC relaxation

ZFC procedure with stops

(Uppsala 2001)







Multiple memories can be stored

Rejuvenation and memory effects now seen in numerical simulations !
Baity-Jesi et al (Janus collaboration), arXiv:2207.06207v2

V. Dupuis, PhD thesis, Orsay 2002
E.V., Lect. Notes Phys. ***716****, 7 (2007), or*
cond-mat/0603583

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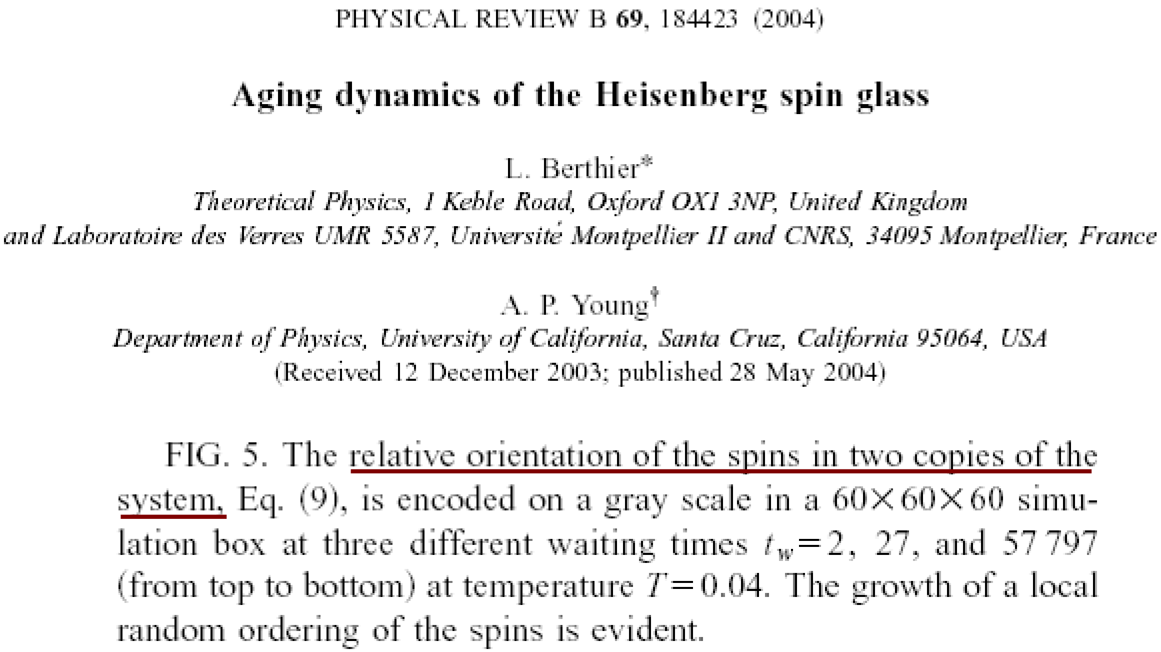
Aging ≡ growth of a local « random order »

Fisher Huse droplet model idea (1988)

Starting from a ***random*** *state,* ***aging*** *can be viewed as the* ***expansion*** *of* ***cooperative*** *regions whose size ξ defines a "****glassy coherence length****".*

Can we see such domains ?

(Of how many types are they ?)



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

Aging dynamics of the Heisenberg spin glass

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(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 $60\times60\times60$ 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 = $\cos\theta_i(t_w) = \mathbf{S}_i^a(t_w).\,\mathbf{S}_i^b(t_w)$

Measuring the growth of the “spin-glass order” with time during aging

In a ZFC relaxation curve : inflection point at ~ t_W = characteristic time

This time defines a typical free-energy barrier $\Delta = k_B T.Ln\ t_W$

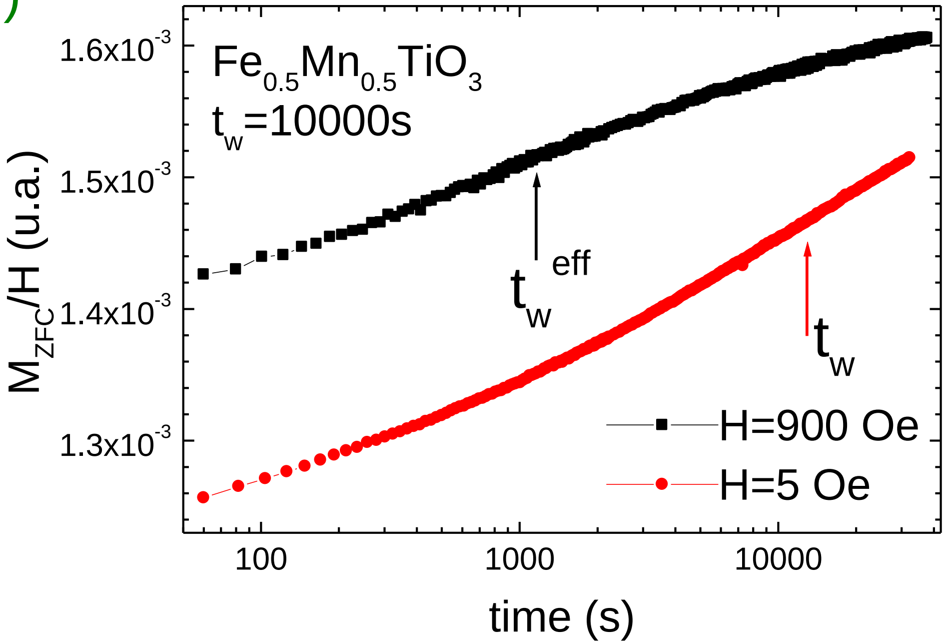
(Thermal activation : $t_W = exp(\Delta / k_B T)$)

Relaxation measurements for *increasing* field amplitudes :

As H ↑, the measured relaxations become faster

Inflection point at $t_W \rightarrow t_W^{eff}$ *(H)*

→ The typical barrier is reduced to $k_B T.Ln\ t_W^{eff}(H)$



- After t_w, cooperative regions have grown up to a size $N_s(t_W)$
- Idea (R. Orbach) : There is a Zeeman energy of coupling of H to the $N_s(t_W)$

correlated spins, $E_z(H) = \chi_{1spin}.N_s(t_w).H^2$,

which lowers the barrier to $k_B T.Ln\ t_W^{eff}(H) = \Delta - E_Z(H)$.

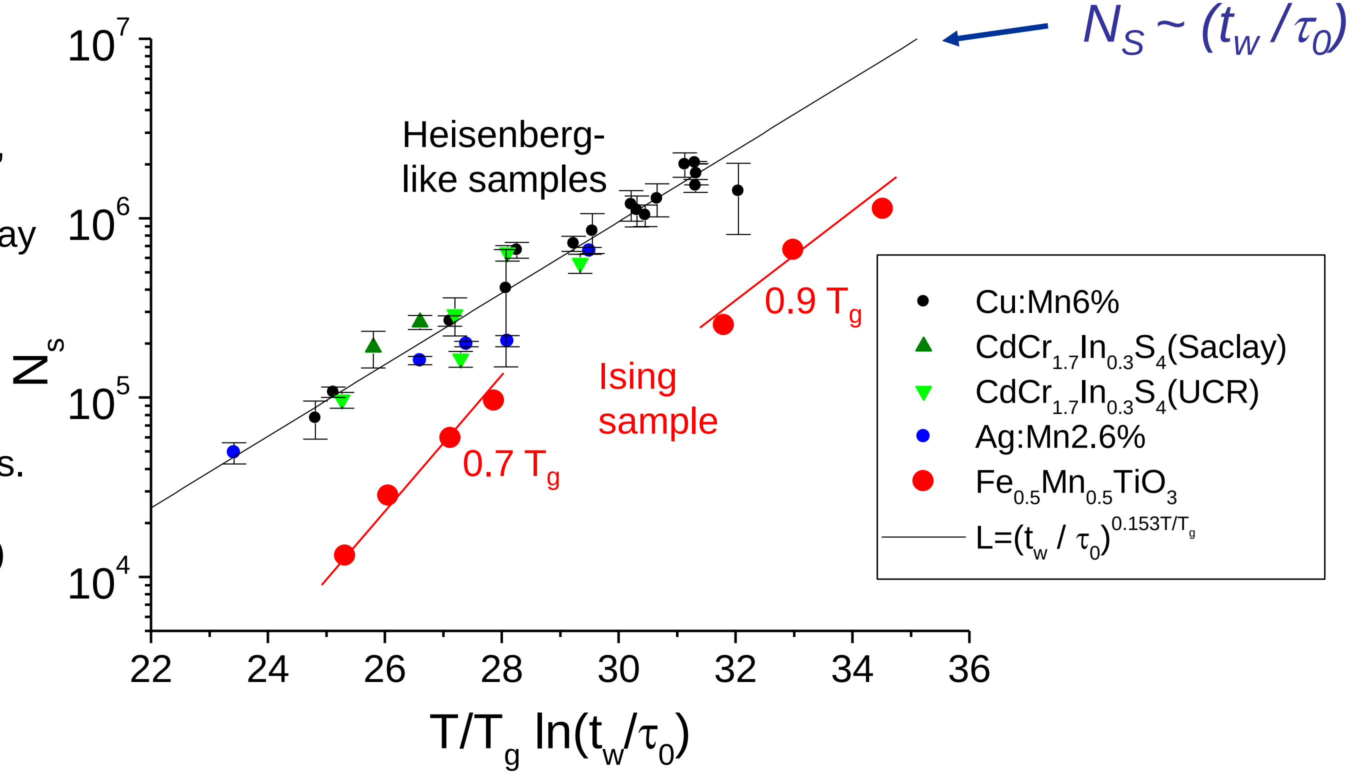
At fixed t_w*, measure* $E_Z(H) = k_B T.Ln\ t_W / t_W^{eff}(H)$ → *obtain* $N_s(t_W)$.

Growth of the number of correlated spins during aging :

$N_S \sim 10^4$-10^6 - from 5 different spin glasses

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

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



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

N_s grows up to ~10^6 spins. If $N_S \sim \xi^3$, correlation length $\xi \sim 100$ lattice units

$N_S \sim (t_w/\tau_0)^{0.45\, T/T_g}$: extrapolation of the simulations – ~overall agreement

But : Ising spins, and ξ computed from microscopic 4-point correlation function

$$C_4(r,t_w) = \frac{1}{N}\sum_i \langle \mathbf{S}_i^a(t_w)\cdot\mathbf{S}_{i+r}^a(t_w)\mathbf{S}_i^b(t_w)\cdot\mathbf{S}_{i+r}^b(t_w)\rangle$$

Experiments and simulations : recent results (1)

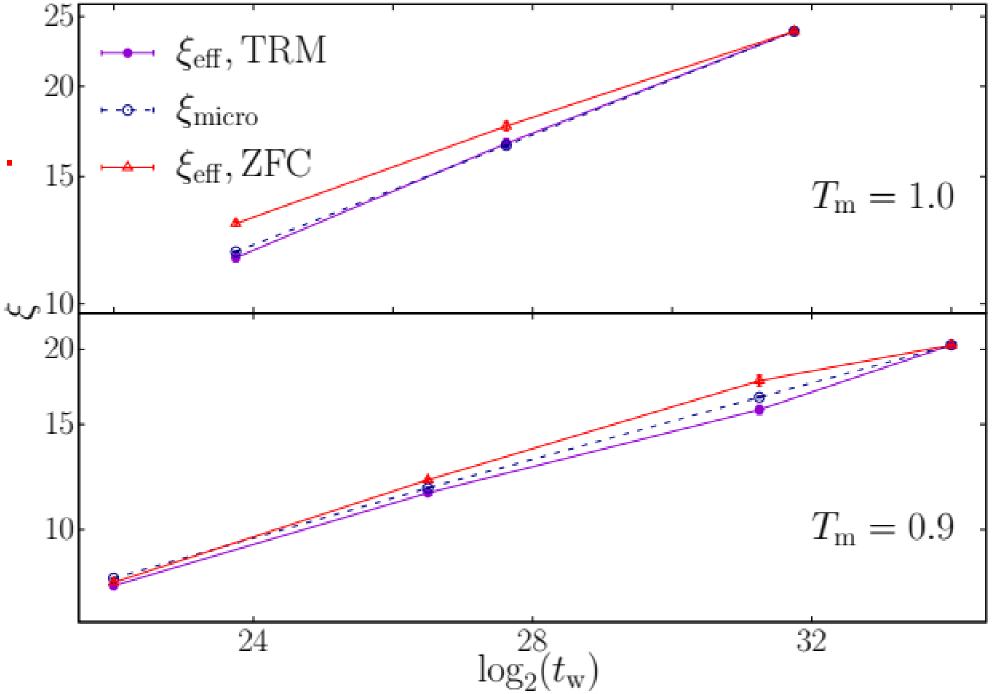
Massive simulations on the Janus II supercomputer (« Janus Collaboration »)
Ising spins on a cubic lattice, size L=160, nearest-neighbour interactions (Edwards-Anderson model) – many results
Time going as far as $2^{34}=10^{10.6}$ MC steps (Experiments : $t/\tau_0=10^5/10^{-12}=10^{17}$)

The correlation length ξ can now be determined following the experimental procedure (effect of increasing field values on the ZFC relaxation)

This ξ agrees with the one determined microscopically, validating the experimental protocol.

Some differences are pointed out regarding the development of spin-glass order in a field, also found now in experiments.

T_g=1.10



Several recent papers in common between experimentalists and numericians :

See e.g. Paga et al arXiv:2207.10640v1, Janus Collaboration + Univ. of Texas + etc.

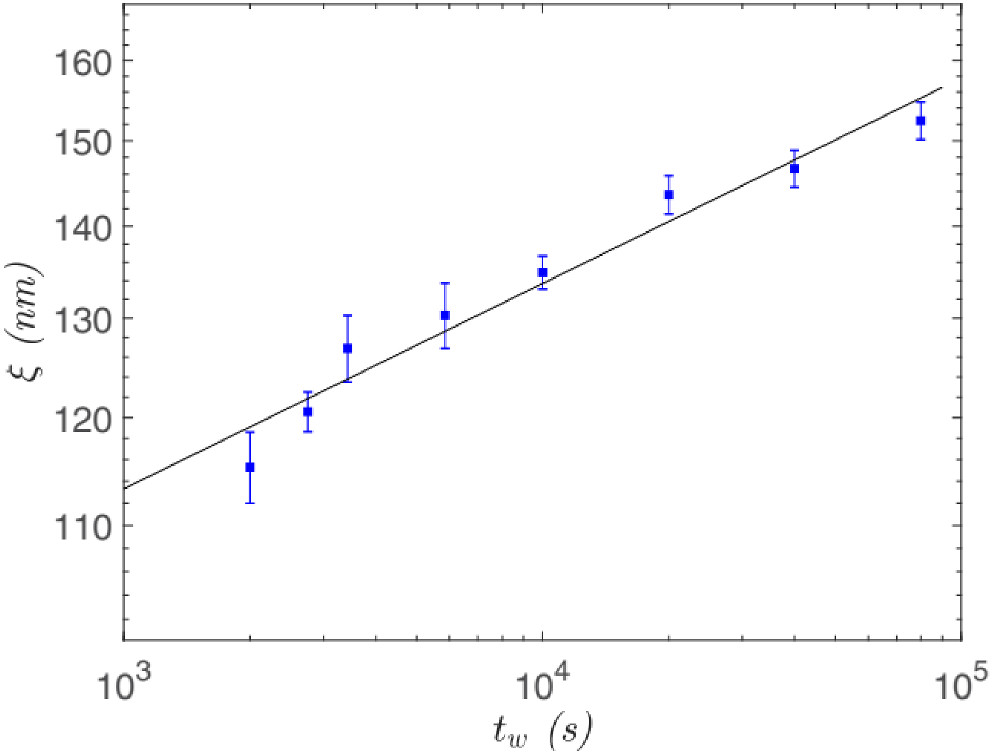
Experiments and simulations : recent results (2)

New experiments on a single crystal of Cu:Mn, very close to T_g

University of Texas at Austin

- The correlation length almost reaches the macroscopic scale (150nm)

- Still in agreement with the numerical simulations



Qiang Zhai,[1] V. Martin-Mayor,[2,3] Deborah L. Schlagel,[4] Gregory G. Kenning,[5] and Raymond L. Orbach[1]

PHYSICAL REVIEW B **100**, 094202 (2019)

Summary

- Spin glasses : random dilution of magnetic atoms (ions) in a non-magnetic matrix, disorder leading to frustration
- At higher concentrations : **« cluster glass » .** Maybe closer to **strain glass** and **relaxor** ? Does it make a big difference ?

- In the glassy phase : slow dynamics + aging effects
- *T* ↘ aging restarts, rejuvenation effect
- *T* ↗ back : memory of the previous state of aging

Multiple rejuvenation and memory processes can be obtained
Rejuvenation and memory now observed in numerical simulations

- Aging can be viewed as the expansion of cooperative regions whose size ξ defines a « glassy coherence length » (« glassy order »).
- During aging, ξ grows up to ~ 100-1000 lattice units (recent : 150nm)
- **Numerical simulations** (Janus Collaboration) now almost reach this scale (~20-25)
- Simulations show that ξ from experimental methods coincides with the microscopic ξ

New open ways

Exploring the « glassy order », in parallel with the present development of numerical simulations :

- Understanding the **microscopic mechanism** at play in **rejuvenation and memory** effects (Janus collaboration)
- Clarifying the **nature of the spin-glass phase in a field** (recent results on the failure of the « superposition principle)
- Observing **when the correlation length reaches the sample size** in mesoscopic samples or thin films (Texas Univ., Orbach et al)

Nature of the spin-glass transition for Heisenberg spins ?

Is it driven the **spin-chirality freezing** ? (Kawamura 1992)

→ measurements of the anomalous Hall effect (Starting : Pureur 2004,Taniguchi 2007… difficult)

Two (ferro-like, droplet model) or many pure states (RSB-like) ?

Measuring the Universal Conductance Fluctuations in mesoscopic samples (Carpentier 2008, Forestier 2020).

Etc.