Relaxation and noise experiments in spin glasses and other glassy stuff

J. Hammann, M. Ocio, E. Vincent
F. Ladieu, D. L'Hôte, S. Nakamae

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

Thanks to J.P. Bouchaud, V. Dupuis, K. Komatsu, …

Mini-Workshop on Glasses, recent experimental results and perspectives
Lyon, April 12-13 2011
with the support of the ANR project Mesoglass

OUTLINE

1. Slow relaxations, aging, noise
   1.a Spin glasses
   1.b Other glassy stuff: recent results, perspectives

2. T-variation experimental protocols in spin glasses :
   rejuvenation, memory
   domain growth ? length scales ?
   (more about « hierarchy »)

3. New paths, conclusions

OUTLINE

1. Slow relaxations, aging, noise
   1.a Spin glasses
   1.b Other glassy stuff: recent results, perspectives

2. T-variation experimental protocols in spin glasses :
   rejuvenation, memory
   domain growth ? length scales ?
   (more about « hierarchy »)

3. New paths, conclusions

What is a spin glass ?

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

random bonds

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

Mean-field spin glass:

χ_{LR} = *Linear Response susceptibility, (within a state)*

χ_{eq} = *Equilibrium susc., (averaged over different states)*

$\chi_{LR} \neq \chi_{eq}$: *"hallmark of RSB" (G.Parisi)*

"*Real*" spin glasses :

Random dilution of magnetic ions

$$\chi_{ZFC} \neq \chi_{FC}$$

Flat χ_{FC} curve : no sign of droplet super-paramagnetism

Same generic behaviour in all samples

(Tc≠0 in 3d, slow dynamics, aging...)

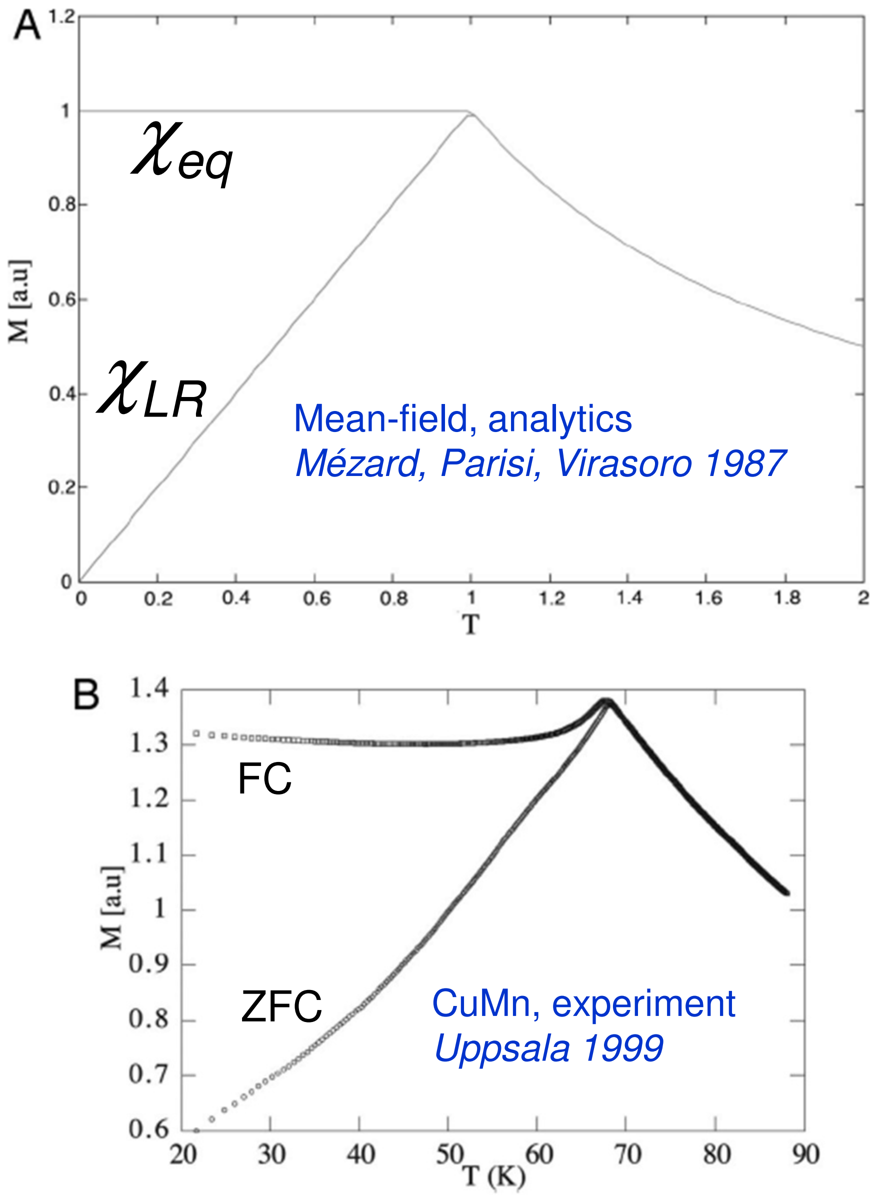
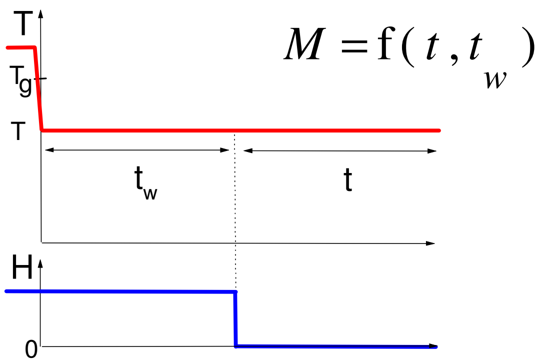


Fig. 3. The two susceptibilities ($\chi_{eq} \geq \chi_{LR}$). (*A*) The analytic results in the mean field approximation (2). (*B*) The experimental results for a metallic spin glass (38).

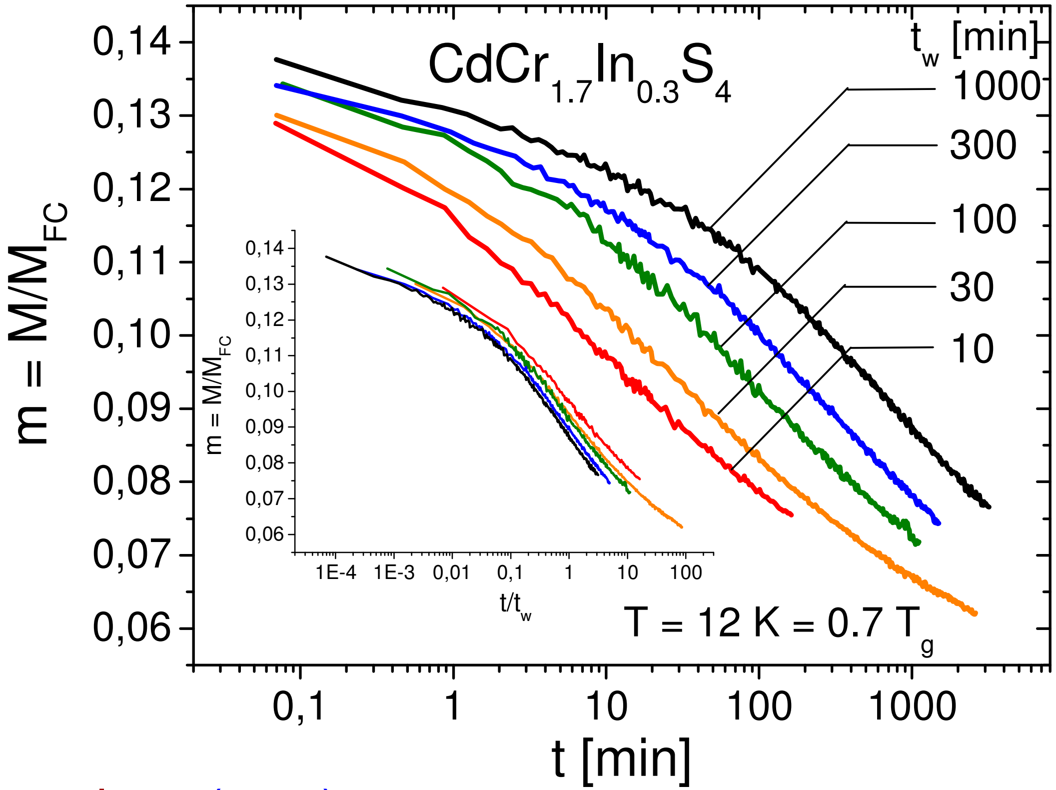
Spin glasses: slow dynamics + aging

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

relaxation of theThermo-Remanent Magnetization (TRM)



t_w : waiting time
t : observation time
t_w+t : « age »
H : weak magnetic field



→ Non-stationary dynamics : $(t\ ,\ t_w)$
Approximate scaling variable : $t\,/\,t_w$ (or $t\,/\,t_w{}^{\mu}$ with $\mu<1$)

THE JOURNAL OF CHEMICAL PHYSICS **123**, 174507 (2005)

Shear stress relaxation and physical aging study on simple glass-forming materials

X. Shi, A. Mandanici, G.B. McKenna, Texas Tech University

Shear relaxation response at different aging times at 6K below *Tg*

m-toluidine (fragile glass-former)
T_g = 187K

Master curve as a function of $t/a(t_w)$ (offset by one decade for clarity).

Insert: shift factors $a(t_w)$ used for master curve
log a vs *log tw : slope 0.61 (~μ* for SG*)*

"The leveling off of shift factors at longer aging times indicates that the sample has aged into equilibrium."

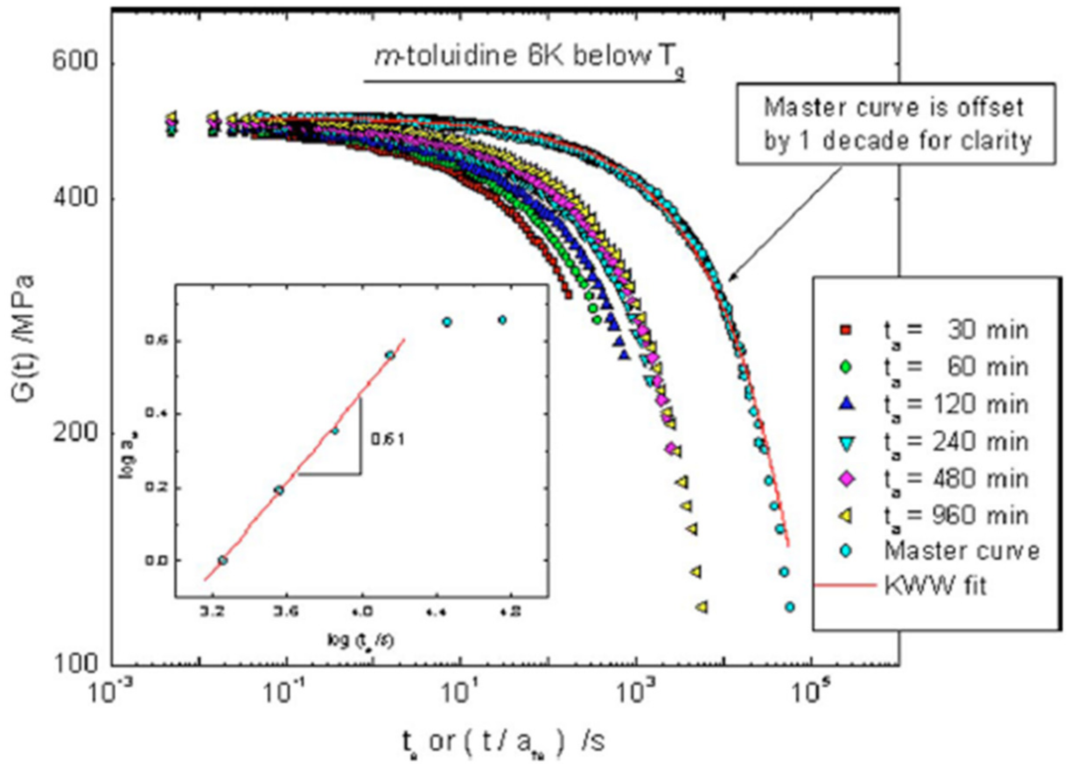
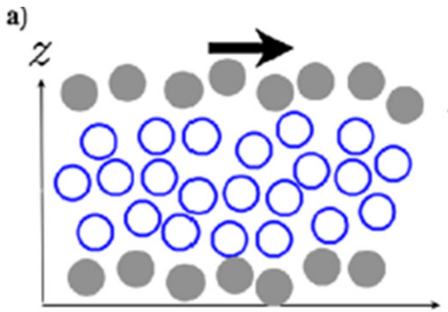


FIG. 7. Shear relaxation response at different aging times for *m*-toluidine at 181 K, which is 6 K below the nominal T_g. The time-aging time master curve was constructed and is offset by one decade for clarity. The curve represents the KWW function fit to the master curve. The insert shows the shift factors used. The leveling off at longer aging times indicates that the sample has aged into equilibrium.

Stress relaxation: Monte Carlo simulations

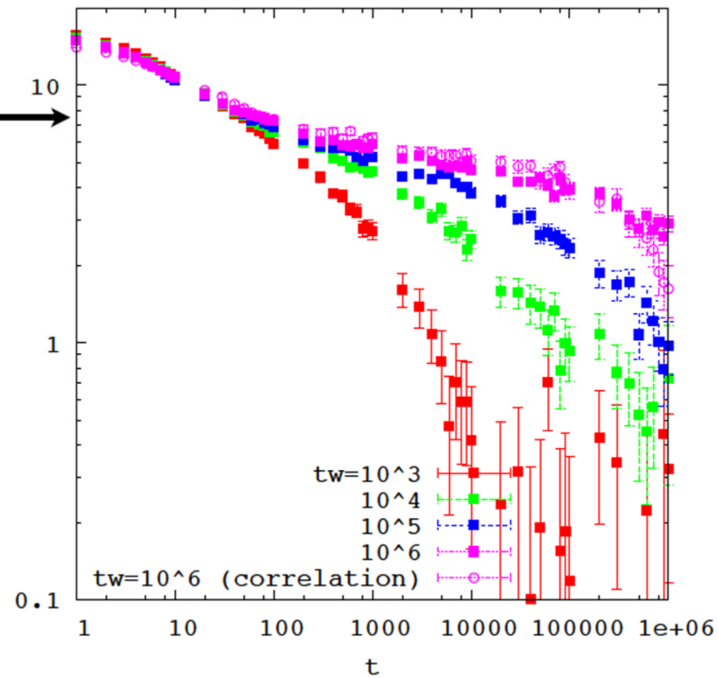
H. Yoshino and M. Mézard, paper in progress – see also PRL 105, 015504 (2010)

N particles interacting via 2-body potentials



Theory

$\hat{\mu} = 7.73$



σ / γ

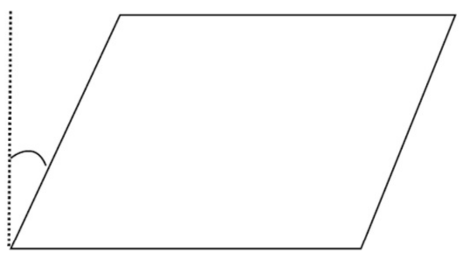
t

$N = 512$

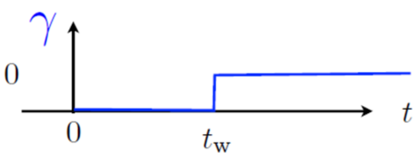
$T = 0.1$

$\gamma = 0.025$

Strain γ

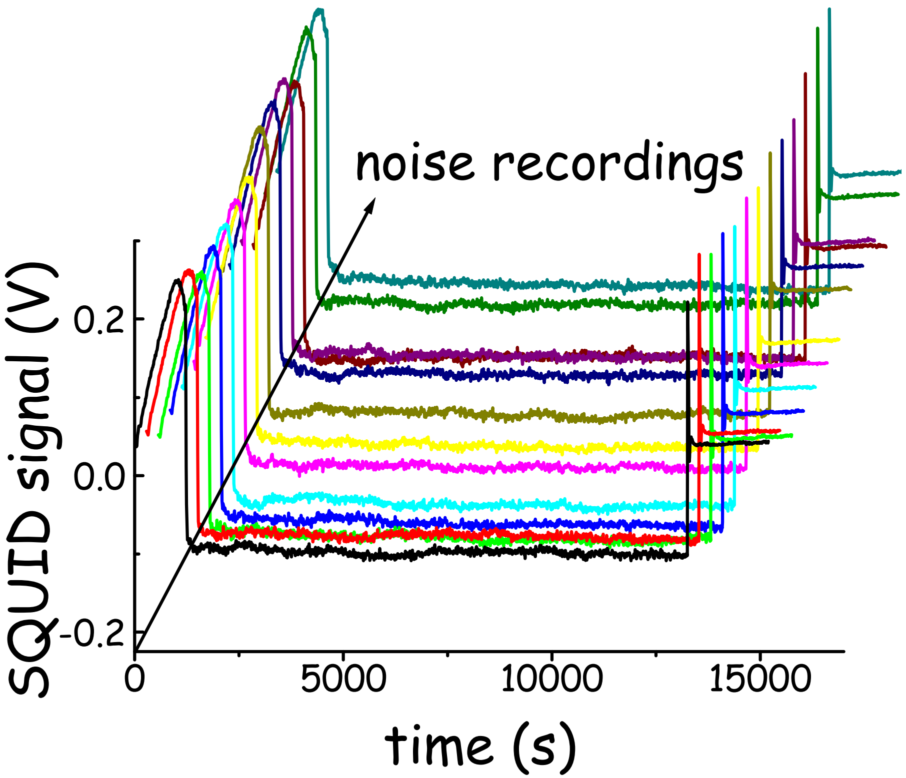


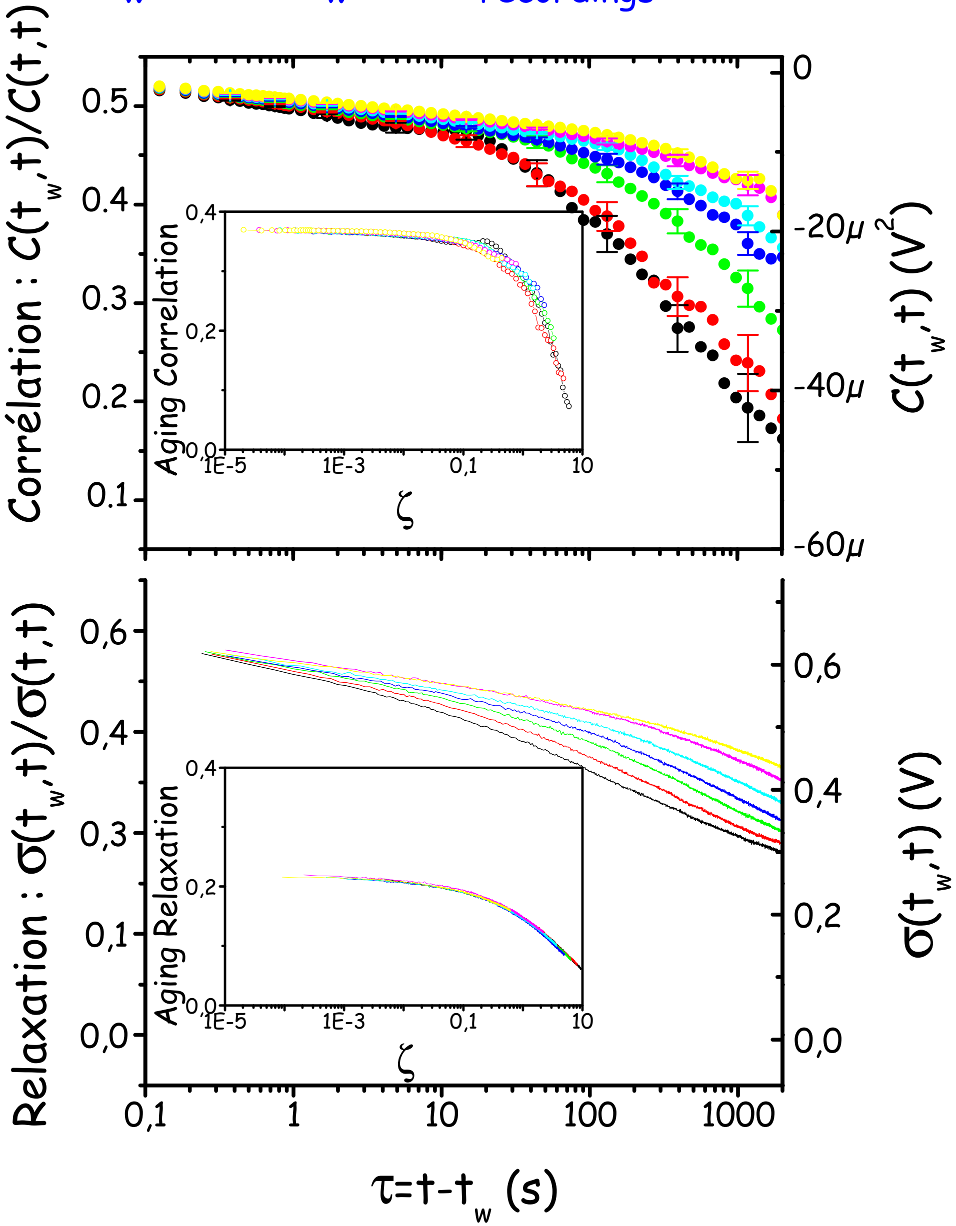
quench at $t = 0$



Noise measurements and Fluctuation-Dissipation ratio

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

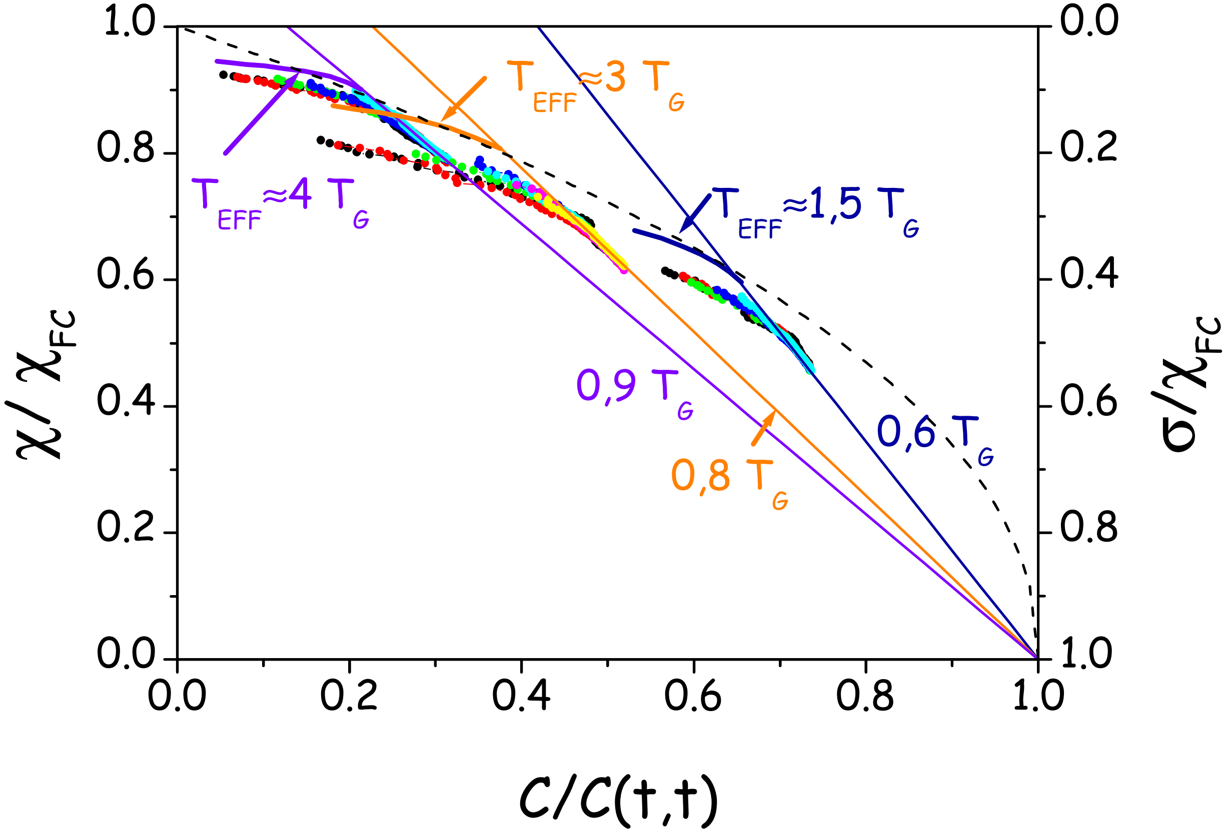




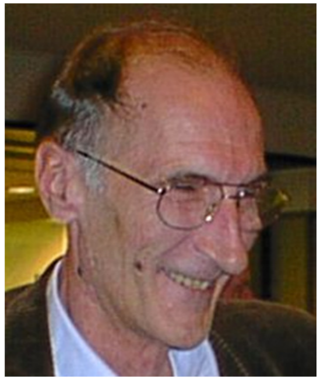
→ Comparison of autocorrelation and response, fluctuation-dissipation relations *in the aging regime*

$CdCr_{1.7}In_{0.3}S_4$ 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' → $T_{eff} = f(C)$

Extension of FDR to non-equilibrium situations:

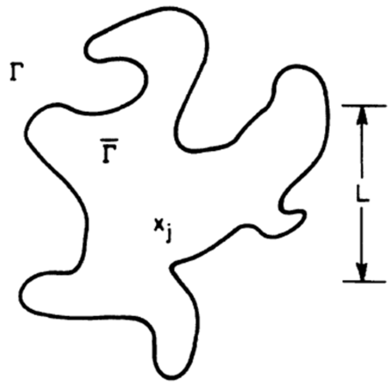
X **= C. F(C)/kT** *(for large t_w)* **T / F(C)** ≡ *effective temperature*

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

Spin-glass dynamics : domain growth-like ?

How far is the spin glass a "disguised ferromagnet" ?

Fisher Huse droplet model idea (1988)



Unique ground state Γ, degenerated with its symmetric

Creation of a droplet : energy cost

$$F_L \propto \Upsilon(T) L^{\theta}$$

characteristic relaxation time $\tau_L \sim \tau_0 \; e^{\;\beta B_L}$

$$B_L \sim B_0(T) L^{\psi}$$

$$L_t \propto [T/B_0 \ln (t/\tau_0)]^{1/\psi}$$

Classes of spin glass models : distribution of pure state overlaps
P(q) vs S(C) : a profound relation between statics and dynamics

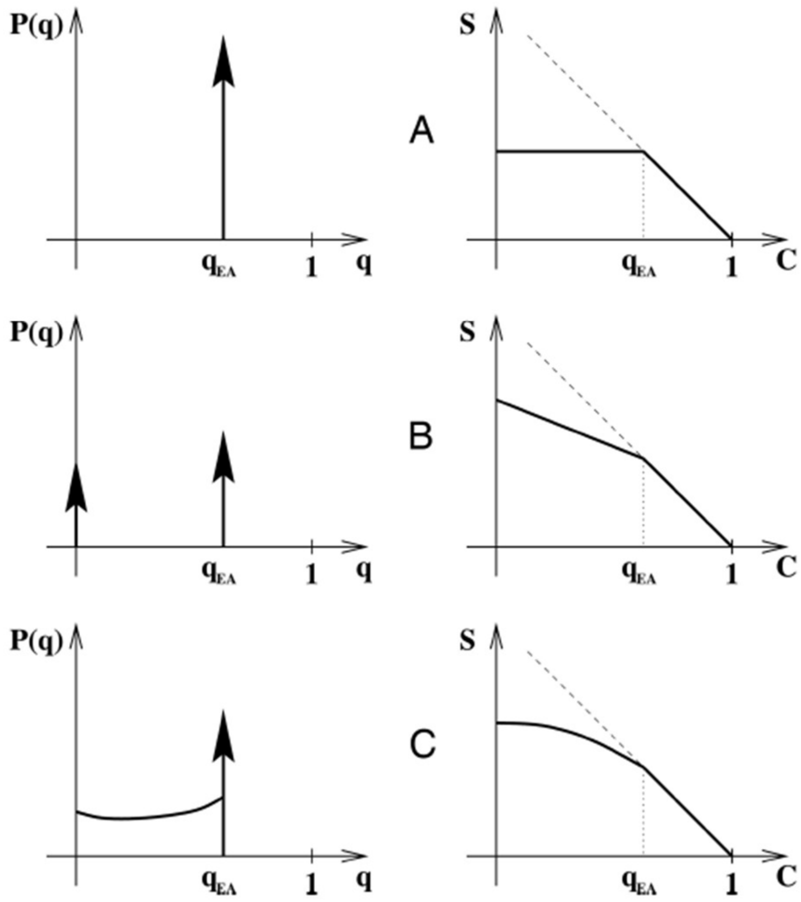
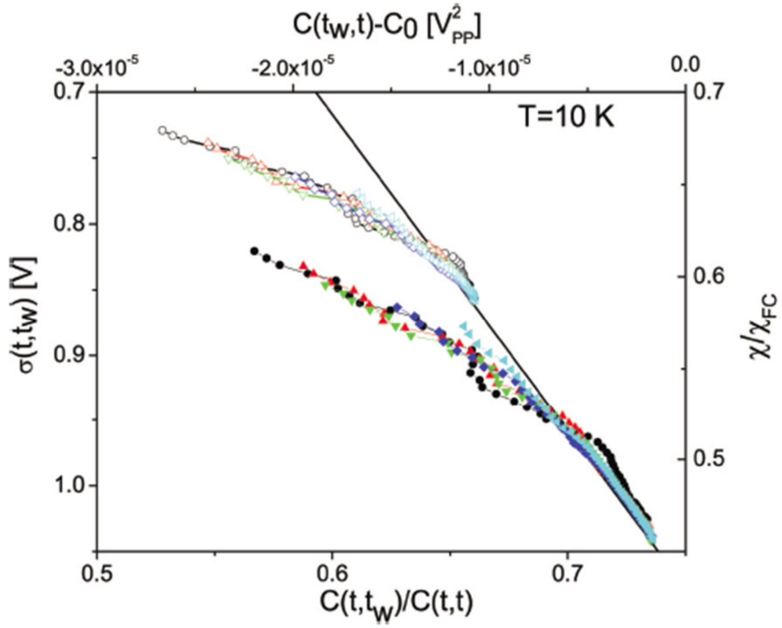


Fig. 6. Three different forms (A, B, and C) of the function *P*(*q*) (*Left*) and the related function *S*(*q*) (*Right*). Delta functions are represented as a vertical arrow (taken from ref. 46).



- **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)

OUTLINE

1. Slow relaxations, aging, noise
   - 1.a Spin glasses
   - 1.b Other glassy stuff: recent results, perspectives

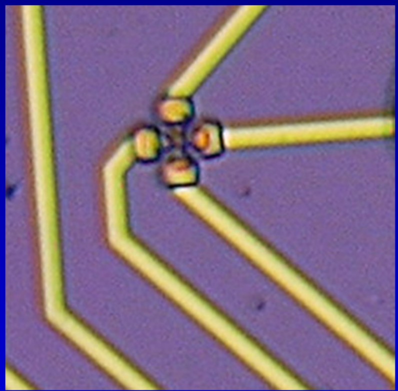
2. T-variation experimental protocols in spin glasses :
   rejuvenation, memory
   domain growth ? length scales ?
   (more about « hierarchy »)

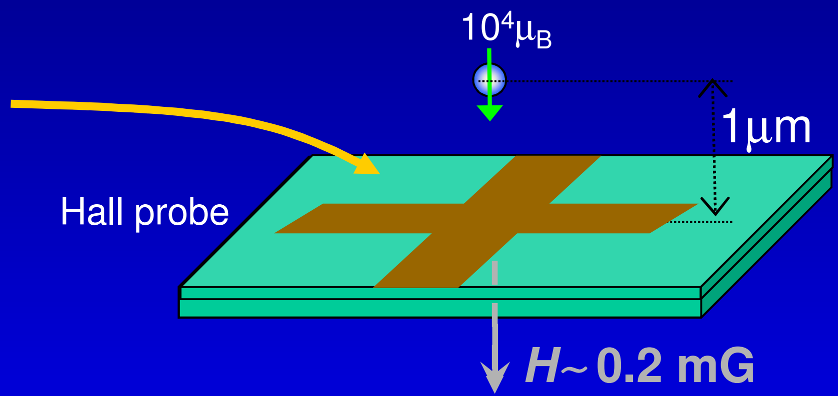
3. New paths, conclusions

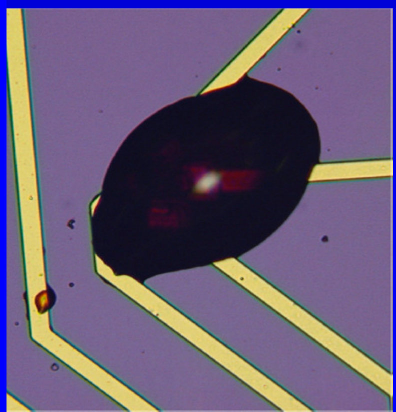
Noise measurements of interacting magnetic particles with high resolution Hall microprobes

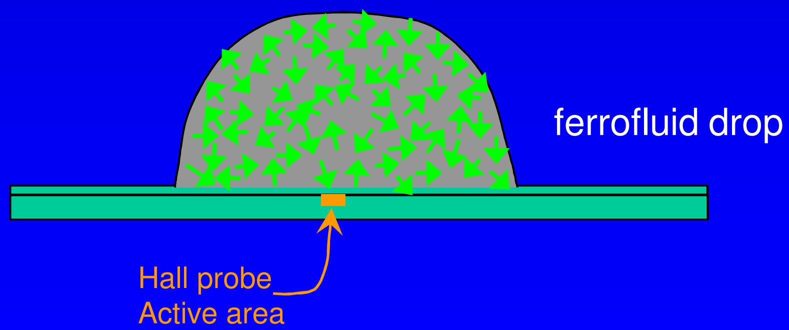
Hall probes: 2DEG in AlGaAs/InGaAs/GaAs heterojunction. Size of active area ~ 1-10 μm^2

From 4 to 300K, from low to high fields, good resolution (2mG/$Hz^{1/2}$)





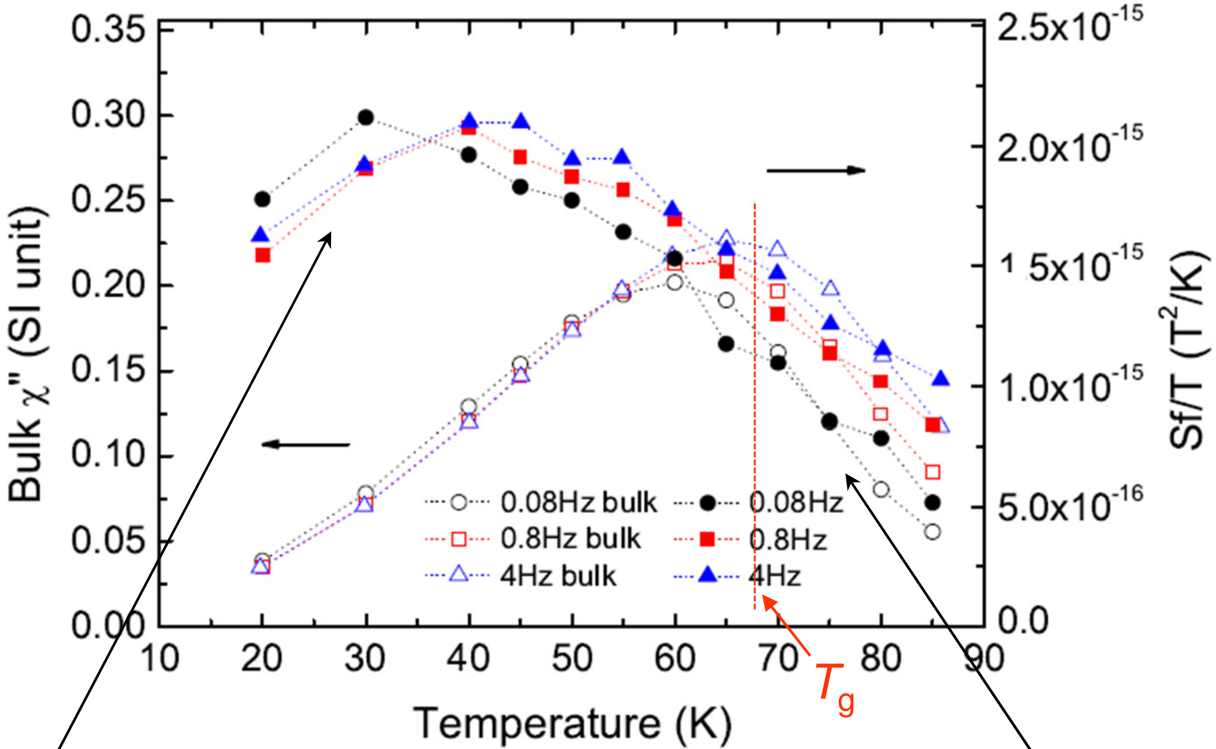




L'Hôte, Nakamae, Ladieu, Mosser, Kerlain, Konczykowski, J. Stat. Mech. P01027 (2009)

First results

γ-Fe_2O_3 nanoparticles
d=8nm,
15% volume fraction



FDT is violated below T_g

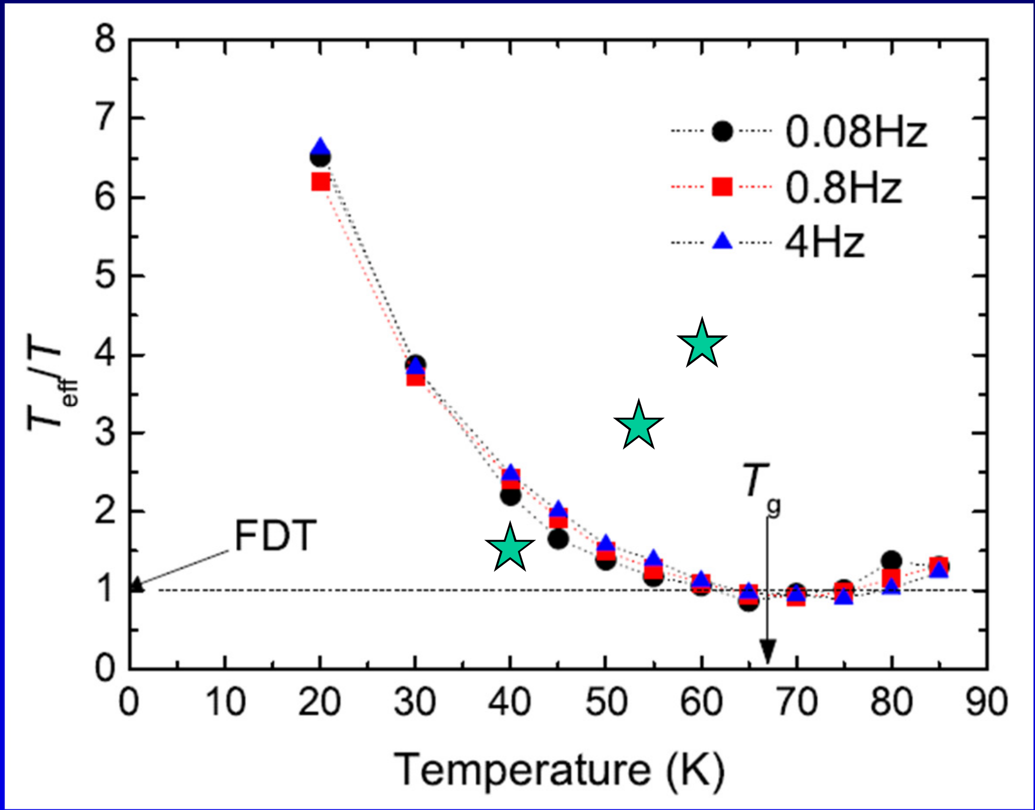
FDT is confirmed at high temperatures above T_g

χ'': Imaginary part of susceptibility

S_m: magn. noise power, f: frequency, T: temperature

$$\chi'' \propto \frac{S_m f}{T}$$

First results



In $CdCr_{1.7}In_{0.3}S_4$ spin glass:
★
Opposite T-dependence of
T_{eff}/T_g ?

Komatsu, L'Hôte, Nakamae, Mosser, Konczykowski, Dubois, Dupuis, Perzynski (2010)
arXiv:1010.4012v2,
PRL 2011 in press

Ongoing experiments: t_w dependence

nature physics
LETTERS
PUBLISHED ONLINE: 20 DECEMBER 2009 | DOI: 10.1038/NPHYS1482

Nanoscale non-equilibrium dynamics and the fluctuation–dissipation relation in an ageing polymer glass

(Boston group)

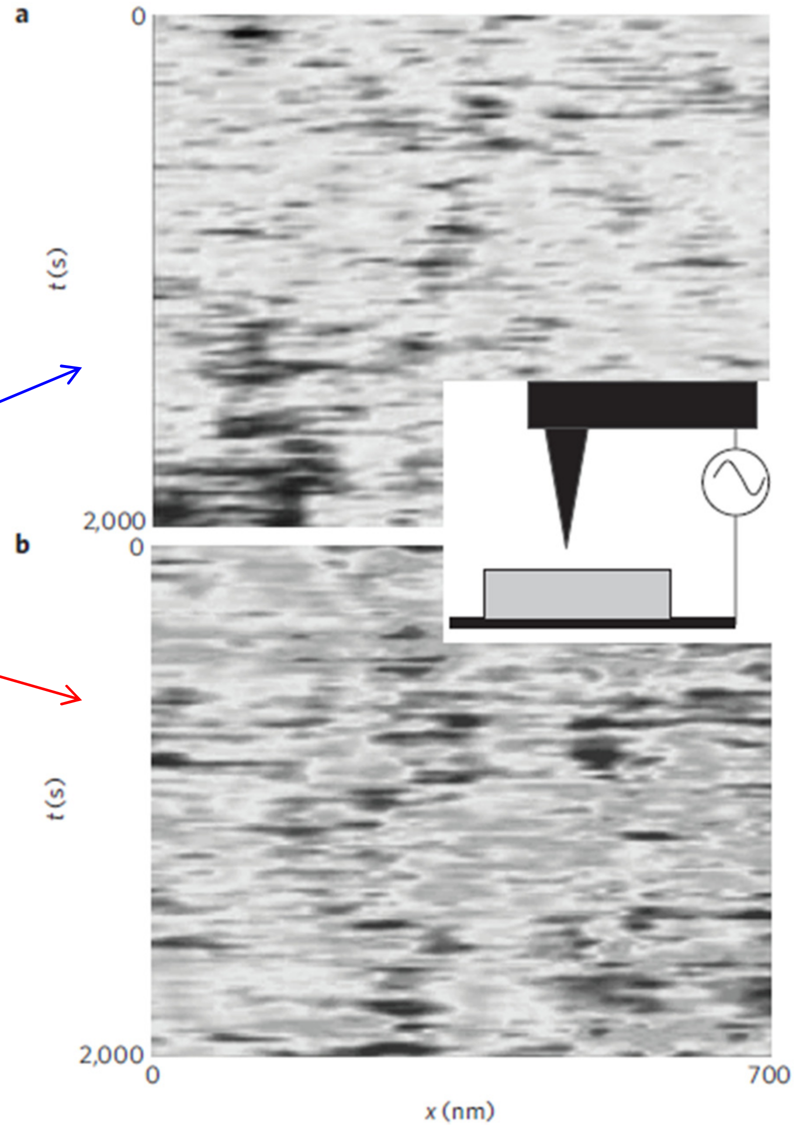
Hassan Oukris and N. E. Israeloff*

Electric Force Microscopy on PVAc film T_g=304K
Measurement of time dependent polarization $V_p(t)$

Space/time fluctuations:
Long-lasting correlations at 301.5K
In contrast with image at 305.5K

local measurement (~100nm)
→ large polarization fluctuations

but average on sample surface (32 regions) to improve statistics
(⇔ 32 samples in parallel)



nature physics
LETTERS
PUBLISHED ONLINE: 20 DECEMBER 2009 | DOI: 10.1038/NPHYS1482

Nanoscale non-equilibrium dynamics and the fluctuation–dissipation relation in an ageing polymer glass

(Boston group)

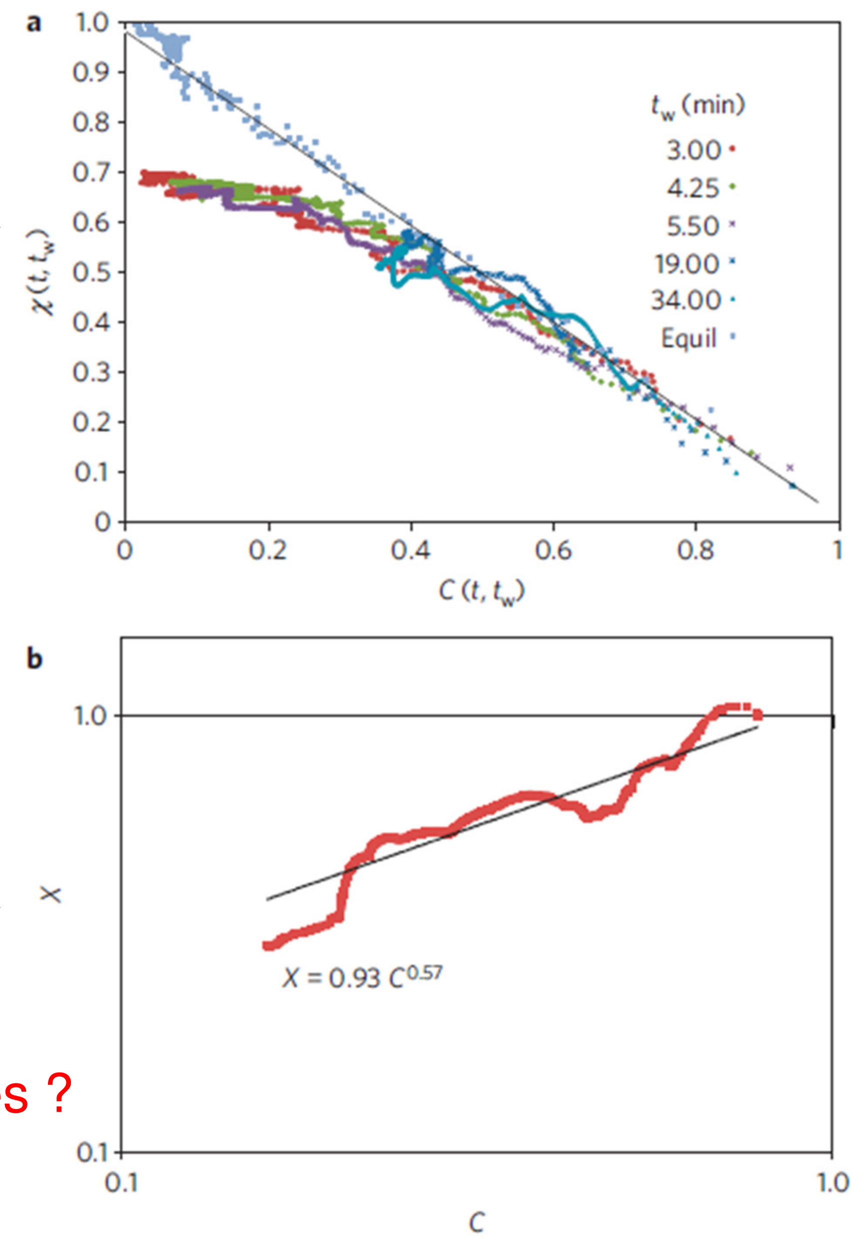
Hassan Oukris and N. E. Israeloff*

FDR graph :

The susceptibility χ is a function of only C in the aging regime
shape similar to SK class of mean-field spin-glass models

FDR-violation factor :
$X = T/T_{eff} \propto -d\chi/dC$
($X=1$ at equilibrium)

SK spin-glass: a model for polymer glasses ?

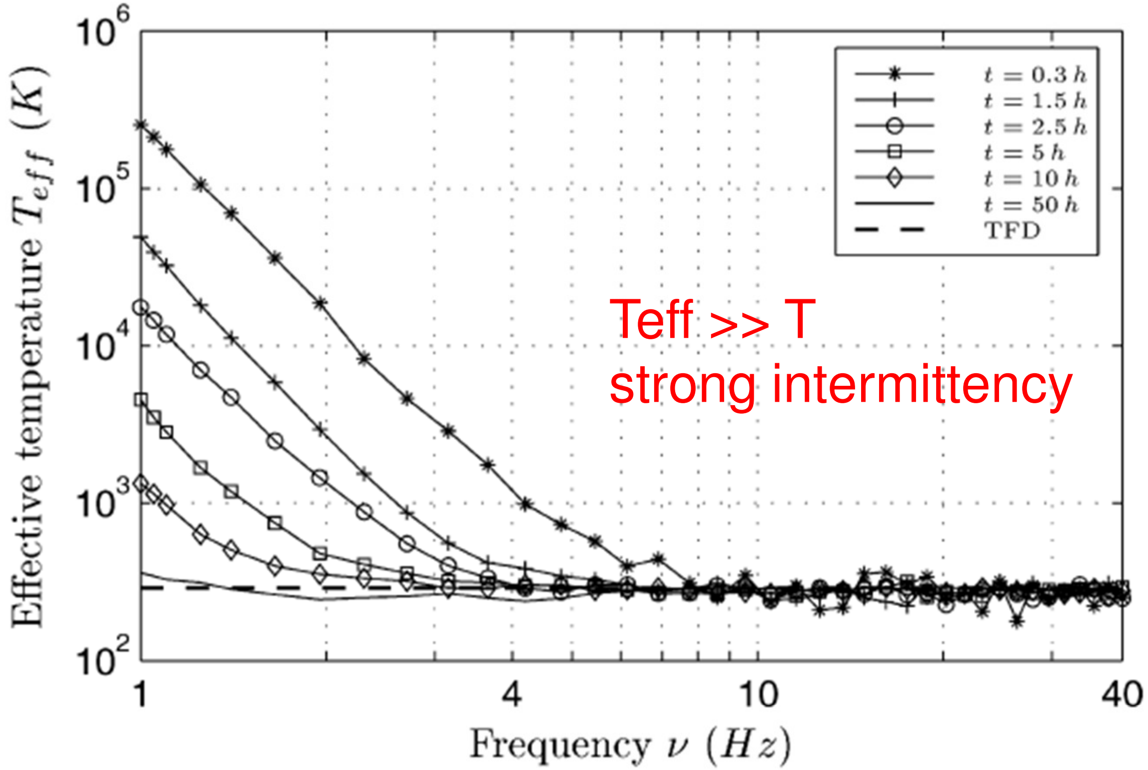


FDR in colloidal glasses: intriguing results on Laponite

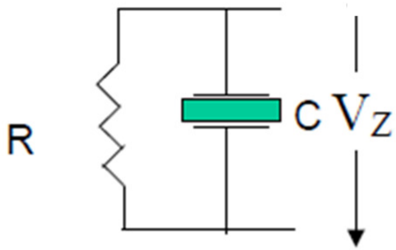
Laponite: a synthetic clay
suspension of electro-charged discs 25nmx1nm

Powder in water: → visco-elastic glass (in a few hours)

L. Bellon, S. Ciliberto / Physica D 168–169 (2002) 325–335



Dielectric measurements:
electric noise ↔ impedance measurement
Out of equilibrium FDR = generalized Nyquist relation:



$$Z(t_w,\omega) = \frac{R}{(1 + i\omega\ R\ C)}$$

$$S_Z(t_w,f) = 4\ K_B\ T_{eff}(\omega,t_w)\ Real[Z(t_w,\omega)]$$

FDR in colloidal glasses: intriguing results on Laponite

Micro-rheological measurements : confirmation of $T_{eff} = T$

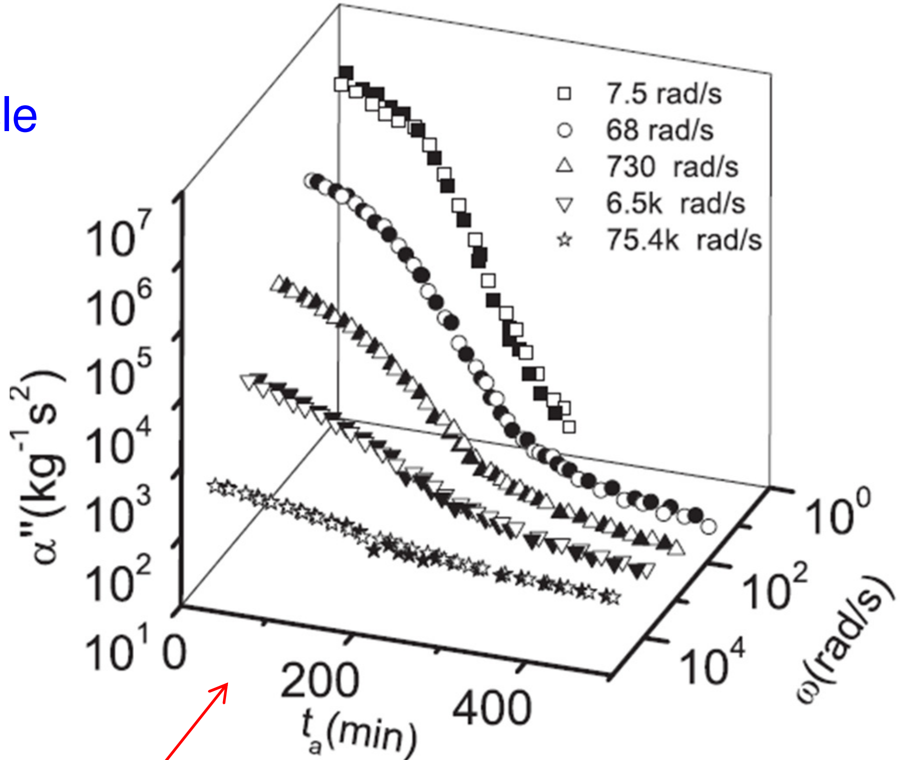
Measurement of the position (resolution 0.1nm !) of a silica bead trapped in Laponite by optical tweezers (2 lasers focused to 'diffraction-limited spots')

Active micro-rheology:
another laser drives oscillations of the particle in the optical trap → α''

Passive micro-rheology:
recording of the spontaneous fluctuations of the particle position → $<|x|>^2$

FDR :

$$\langle |x(\omega)|^2 \rangle = \int_0^\infty \langle x(t)x(0)\rangle e^{i\omega t}\, dt = \frac{2k_B T}{\omega}\alpha''(\omega)$$



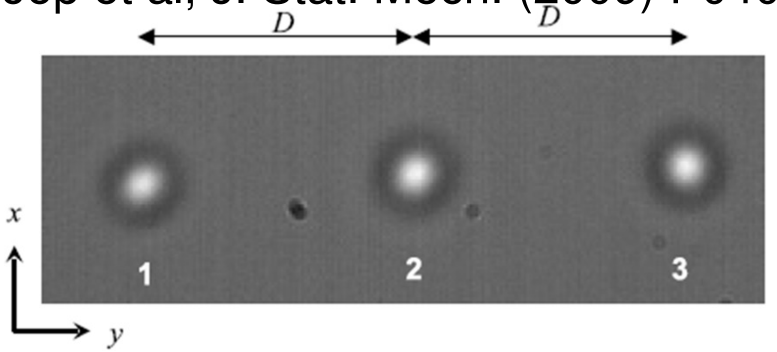
α'' from passive (open symbols) and active (solid) is identical: $T_{eff} = T$ for rheological measurements

Jabbari-Farouji et al, PRL 98, 108302 (2007) *Amsterdam and ENS Paris groups*

FDR in colloidal glasses: intriguing results on Laponite

New micro-rheological results :
simultaneous measurements of three beads in Laponite !

Jop et al, J. Stat. Mech. (2009) P04012 *ENS Lyon group*



simultaneous active and passive measurements

confirms :
(by 4 techniques)
no FDR violation
$T_{eff} = T$

Figure 2. Configuration of three optical traps separated by a distance $D = 9.3 \times 10^{-6}$ m. The bright spots in the image correspond to three probe particles of 2 μm diameter trapped by them.

Abou et al PRL 2004: observation of time varying T_{eff} (up to 1.8T) in microrheology of Laponite, explained by Jop et al by the difference in optical trap strengths in active and passive measurements

but $T_{eff} >> T$ in dielectric measurements ?

Not fully understood. Dissolution of aggregated particles → ions in the solution, effect on dielectric properties and not on rheology

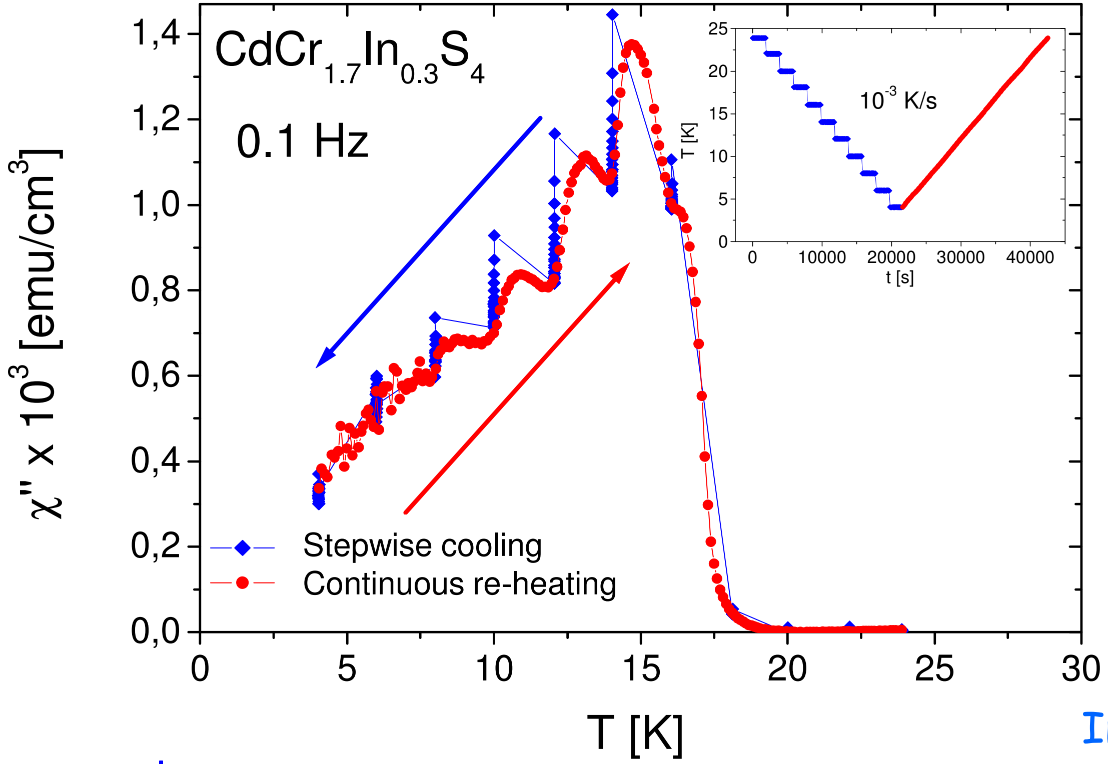
OUTLINE

1. Slow relaxations, aging, noise
   1.a Spin glasses
   1.b Other glassy stuff: recent results, perspectives

2. T-variation experimental protocols in spin glasses :
   rejuvenation, memory
   domain growth ? length scales ?
   (more about « hierarchy »)

3. New paths, conclusions

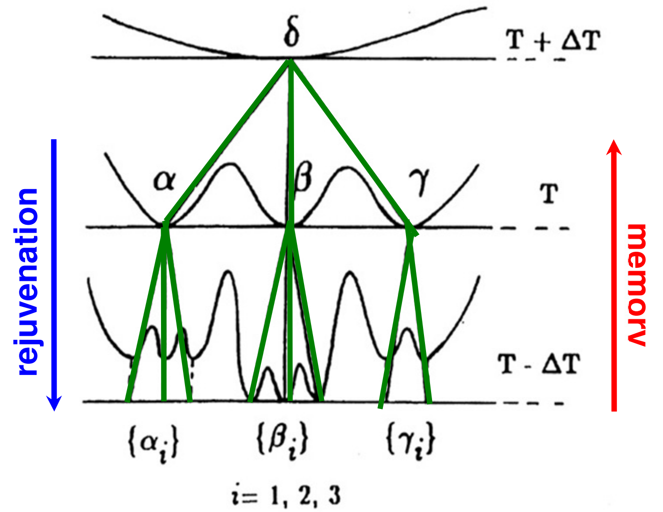
Rejuvenation and memory effects
(ac susceptibility)



T↓ : rejuvenation
T↑ : memory

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

Hierarchical organisation of the metastable states as a function of T



In connection with the hierarchy of *pure states* in the Parisi solution ?

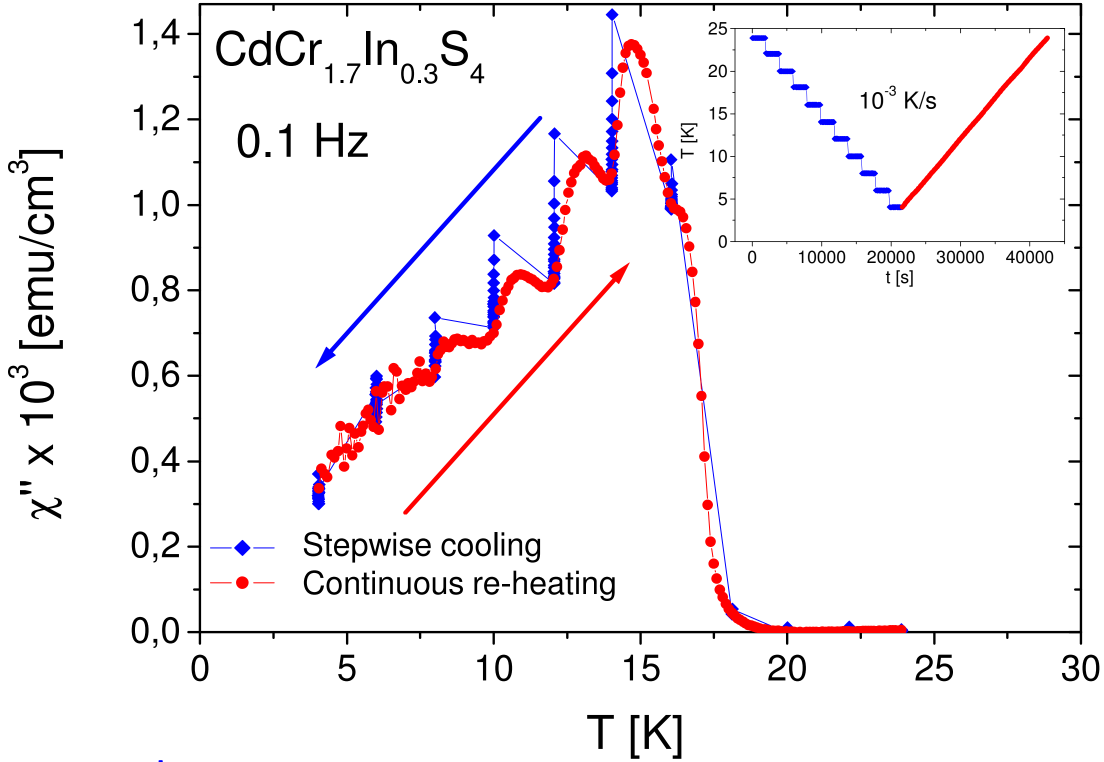
Quantitatively, see:
Derrida 1981 1986 *(REM, GREM)*
Bouchaud and Dean 1995 *(trap model)*
Sasaki and Nemoto 2000
Sasaki et al, *EPJ B* **29**, 469 (2002)

V. Dupuis, PhD thesis

Details and references in cond-mat/0603583

Rejuvenation and memory effects

a hierarchy of embedded length scales



T↓ : rejuvenation

T↑ : memory

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

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

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

Memory ⇒
$L^*_n << \; ..... << L^*_2 << L^*_1$
- *hierarchy of length scales*
- *net separation of* L_i*'s with temperature*

« T-microscope » effect
not a simple domain-growth process

V. Dupuis, PhD thesis

Details and references in cond-mat/0603583

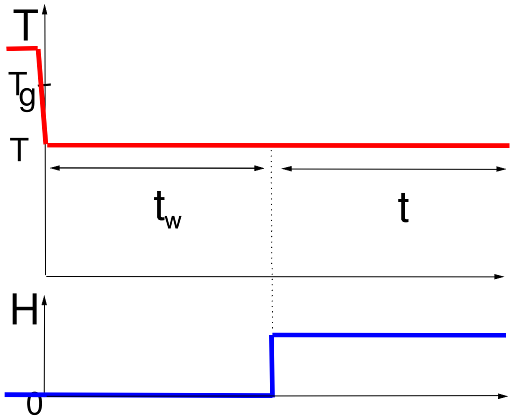
How to measure a number of correlated spins ?

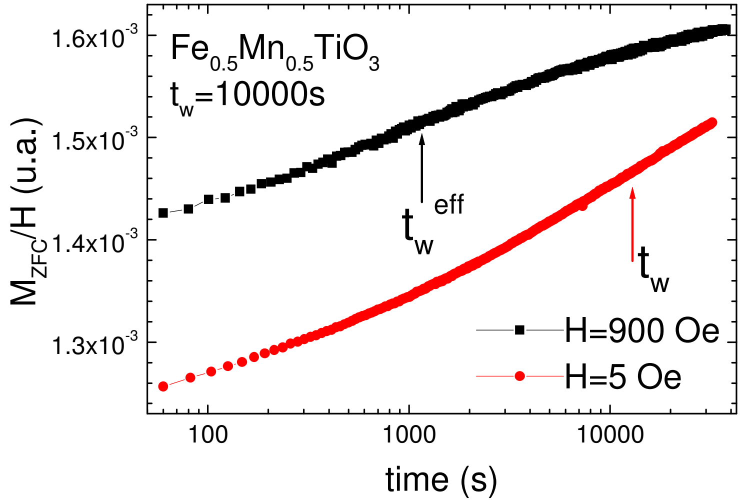
How does it grow with time ? vary with temperature ?

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 $N_S(t_w)$?

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

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

Hyp. 2: $M(N_s) \propto N_s$ *(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 determine $t_w^{eff}(H, t_w) \rightarrow E_Z(H,t_w)$

$\rightarrow$ number of correlated spins $N_s(t_w)$

(and correlation length $L = N_s^{1/d-\alpha}$, $2 < d-\alpha < 3$)

Results *(in very brief !) :*

$N_s(t_w) \sim (t_w / \tau_0)^{0.45T/Tg}$ (SG's: $(t_w / \tau_0) \sim 10^{12} - 10^{17}$)

- ~ *Ising SG simulations, where* $(t_w / \tau_0) \sim 1 - 10^6$
- ~ *superspin glass, where* $(t_w / \tau_0) \sim 10^6 - 10^{12}$ EPL **84**, 37011 (2008)

A hierarchy of length/time scales: Temperature microscope effect

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

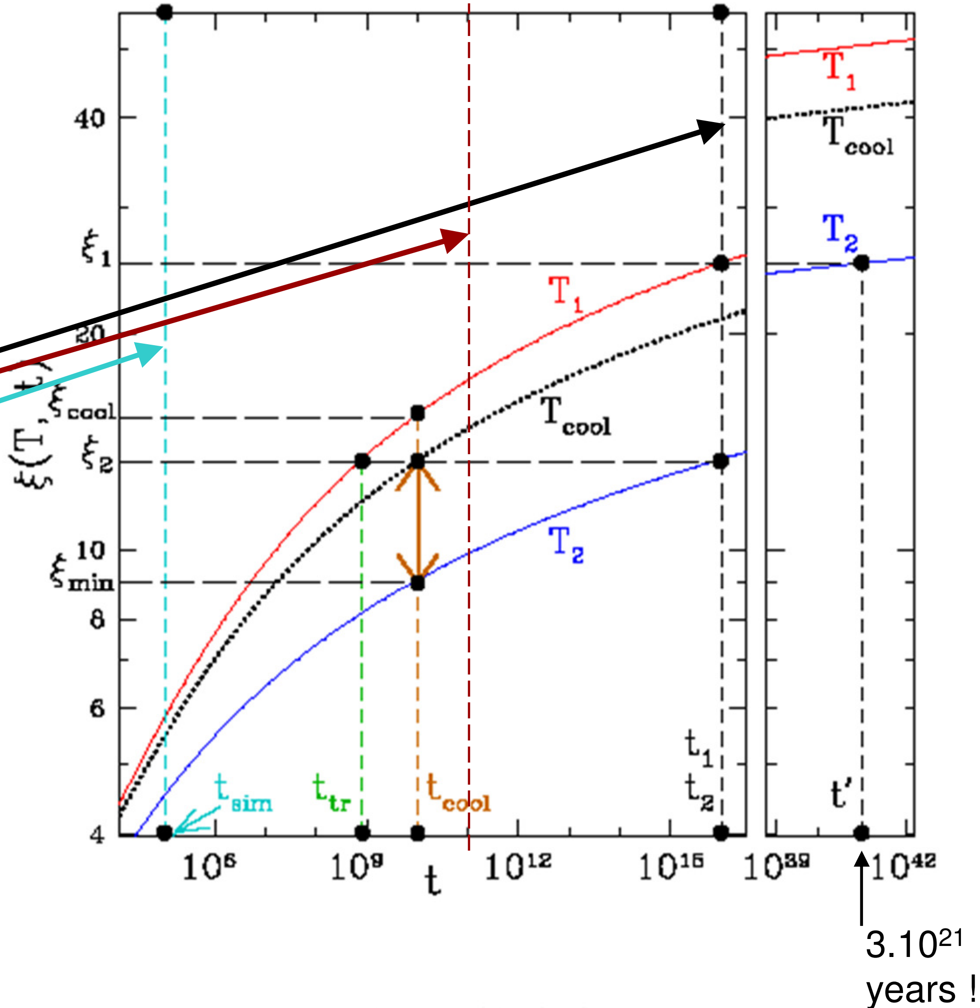
Plot of *L(T,t)* (≡ξ) as obtained from the experiments

(quasi-Heisenberg spins, and $L=N^{1/3}$)

Experimental time scales

Superspin glass

Simulations



Experiments: $L(T_1) \sim 25$, $L(T_2) \sim 15$

Simulations: $L(T_1) \sim 6$, $L(T_2) \sim 4.5$

→ T-separation of time scales rather than length scales

Not a very powerful microscope !

But enough for rejuvenation at small scales, while memory is preserved at larger 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

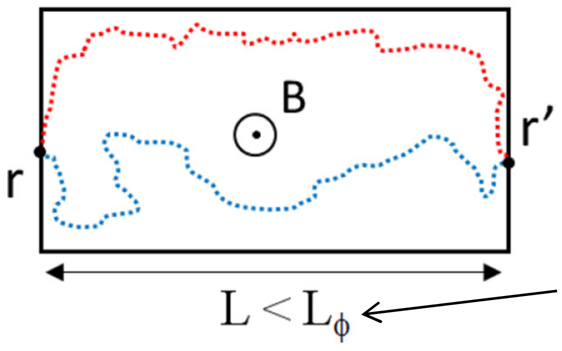
OUTLINE

1. Slow relaxations, aging, noise
   1.a Spin glasses
   1.b Other glassy stuff: recent results, perspectives

2. T-variation experimental protocols in spin glasses :
   rejuvenation, memory
   domain growth ? length scales ?
   (more about « hierarchy »)

3. New paths, conclusions

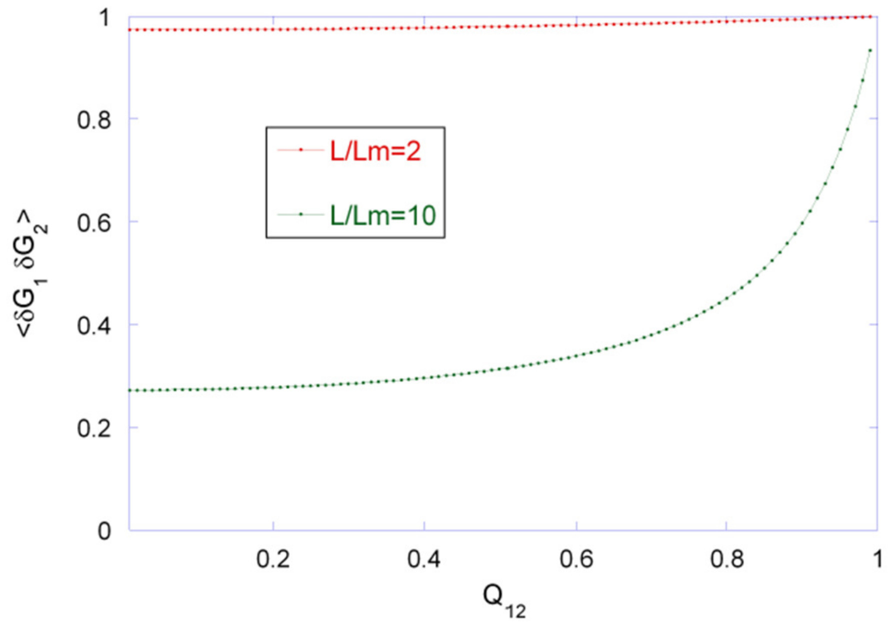
New paths for spin-glass experiments ? Accessing to spin configurations via the Universal Conductance Fluctuations



Interferences between electron trajectories, depending on the microscopic configuration of (magnetic) disorder, create conductance fluctuations as a function of magnetic field

⇒ low T, and mesoscopic size

First « spin-glass fingerprints » obtained on CuMn by de Vegvar, Lévy, Fulton, PRL **66**, 2380 (1991)



Carpentier Orignac PRL **100**, 057207 (2008) :

The correlation of the conductance fluctuations in two spin states is a direct function of their overlap

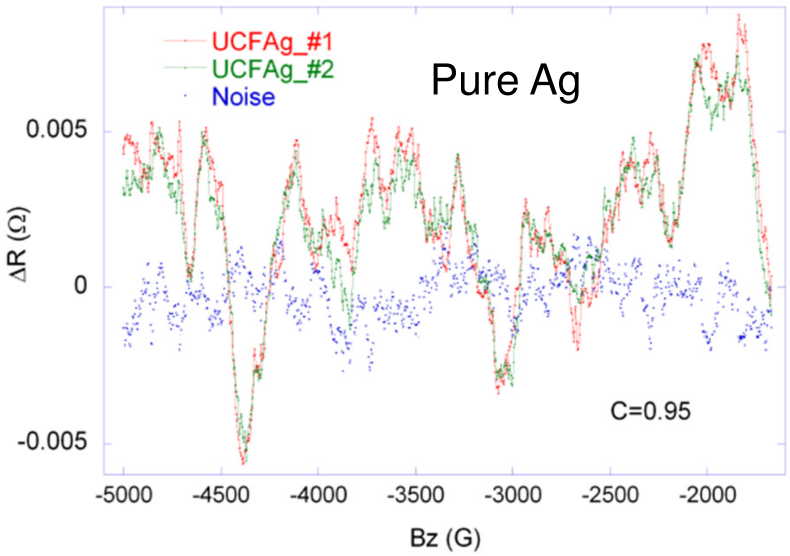
… if L / Lm large enough (while smaller than L_Φ *)*

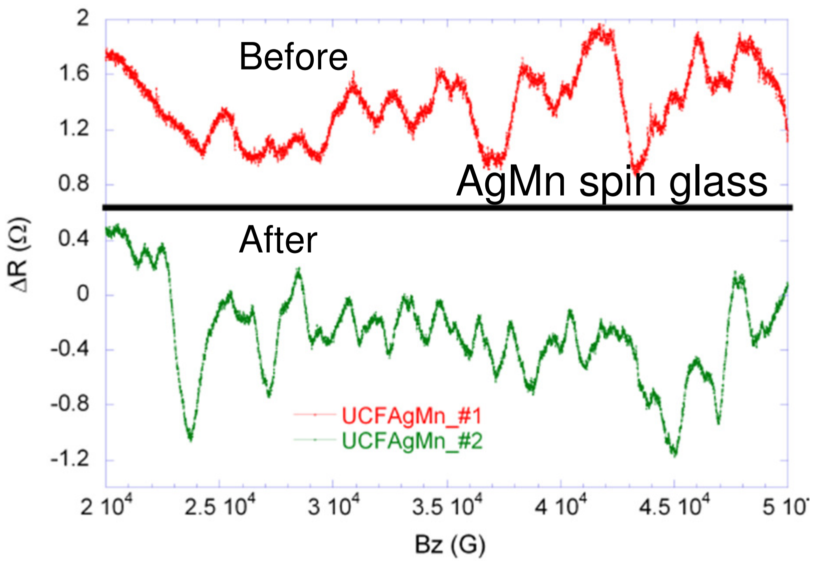
Lm = free path between magnetic atoms

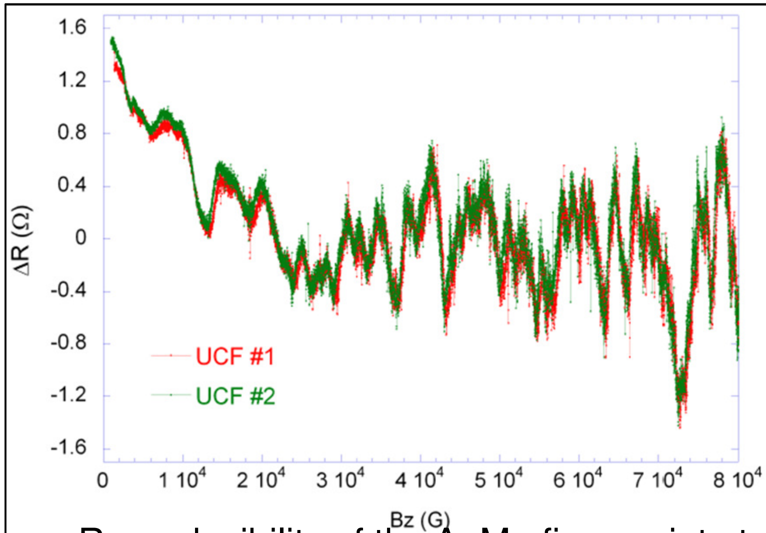
Accessing to spin configurations via UCF

T. Capron (PhD), L. Lévy, L. Saminadayar et al, Lab. Louis Néel (Grenoble)

Magneto-fingerprints before and after annealing







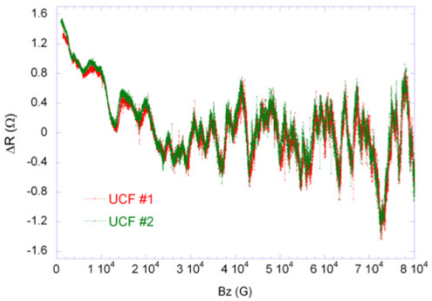
Reproducibility of the AgMn fingerprint at low temperature

Many difficulties

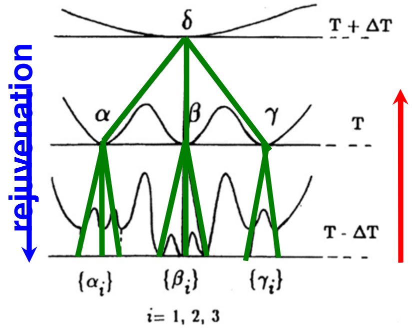
- low T, small sample size
- T_g characterization by susceptibility difficult but necessary
- influence of the high field sweep ? etc.

Exciting challenges

- single or multiple ground state ?
- chaos in temperature ?
- microscopic understanding of rejuvenation and memory effects ? etc.



Conclusions



- Aging in spin glasses : noise measurements → Fluctuation-Dissipation ratio in agreement with a « non-trivial » (RSB) scenario
- Aging and FD ratio in superspin glass, polymers, gels : many experiments in progress with new powerful tools. A generic scenario ?
- T-variation experiments in spin glasses : rejuvenation and memory effects, hierarchy of metastable states (a relation with pure states in MFT ?)
- Hierarchy of correlation lengths *L(T,t)* (T-microscope) : rejuvenation at small scales, memory at large scales. Embedded length scales: not a simple domain growth scenario.
- New paths : Universal Conductance Fluctuations, the spin-glass problem in the light of mesoscopic physics (ANR Mesoglass project). Neither easy nor simple, but exciting !