SPIN GLASSES WARS

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Plan of the Talk

- What are spin glasses?

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- Different Theories and Models.

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  - The overlaps: spin and link overlap (D. Yllanes' talk).
  - Equilibrium Studies (D. Yllanes' talk).

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  - Equilibrium Studies (D. Yllanes' talk).
- Some Open (in field) Problems.

What are Spin glasses

- Materials with disorder and fustration.
- Quenched disorder (similar to the Born-Oppenheimer in Molecular Physics).
- Canonical Spin Glass: Metallic host (Cu) with magnetic impurities (Mn).
- RKKY interaction between magnetic moments: $J(r) \sim \frac{\cos(2k_F r)}{r^3}$.
- Role of anisotropy: Ag:Mn at 2.5% (Heisenberg like), $CdCr_{1.7}IN_{0.3}S_4$ (also Heisenberg like) and $Fe_{0.5}Mn_{0.5}TiO_3$ (Ising like).

Some equations

- Edwards-Anderson Hamiltonian:

$$\mathcal{H} = -\sum_{<ij>} J_{ij}\sigma_i\sigma_j$$

J_{ij} are random quenched variables with zero mean and unit variance, $\sigma = \pm 1$ are Ising spins.

- The order parameter is:

$$q_{\mathrm{EA}} = \overline{\langle \sigma_i \rangle^2}$$

Using two real replicas:

$$\mathcal{H} = -\sum_{<ij>} J_{ij}\left(\sigma_i\sigma_j + \tau_i\tau_j\right)$$

Let $q_i = \sigma_i\tau_i$ be the normal overlap, then: $q_{\mathrm{EA}} = \overline{\langle \sigma_i\tau_i \rangle}$.
We also define the link overlap: $q^l_{i,\mu} = q_i q_{i+\mu}$.

Dedicated Computers: Janus.

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Some figures

- Dedicated computer optimized to simulate a wide variety of spin models.
- 16 boards of 16 FPGA's each.
- Performance. For Ising models: Janus is equivalent to 10000 PC.
- Previous numerical simulations simulated the 10^{-5} sec region (SSUE).
- Janus allows us to simulate in the 0.1 second time region. Note: Experimental times range from 1 sec to 3000 sec.

Different Theories and Models.

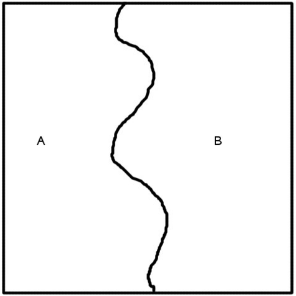
The Droplet Model.

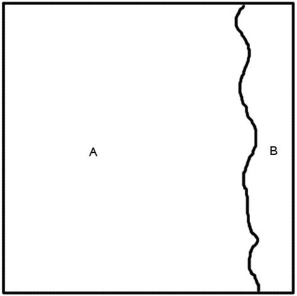
- Based on the Migdal-Kadanoff implementation (approximate) of the Renormalization Group (exact in $D = 1$).
- *Disguished Ferromagnet*: Only two pure states with order parameter $\pm q_{\rm EA}$ (related by spin flip).
- Compact Excitations of fractal dimension d_f. The energy of a excitation of linear size L grows as L^θ. The free energy barriers (in the dynamics) grow as L^ψ. $\psi < \theta < (D-1)/2 < D-1 < d_f < D$.
- Any amount of magnetic field destroys the spin glass phase (even for Heisenberg spin glasses).
- Trivial probability distributions of the overlaps (both normal overlap and link one).

Different Theories and Models.

The Trivial Non Trivial (TNT) Model.

- *Disguished Ferromagnet with Anti Periodic Boundary conditions*.
- Trivial probability distributions for the link overlap (the interfase has no effect) but Non Trivial probability distribution for the normal one (induced by the interface).





Different Theories and Models.

Replica Symmetry Breaking (RSB) Theory.

- Exact in $D = \infty$.
- Infinite number of phases (pure states) not related by any kind of symmetry.
- These (pure) states are organized in a ultrametric fashion.
- The spin glass phase is stable under (small) magnetic field. Phase transition in field: the de Almeida-Thouless line.
- The excitations of the ground state are space filling: e.g. the interfase between two pure states is space filling.
- Overlap equivalence: All the definitions of the overlap are equivalent.

Note: In a pure state, α, the clustering property holds: $\langle S_i S_j \rangle_\alpha - \langle S_i \rangle_\alpha \langle S_j \rangle_\alpha \to 0$ as $|i-j| \to \infty$.

Different Theories and Models (III cont.).

- Field Theory of the Replica Symmetry Breaking (RSB) Theory.
- Hamiltonian (Action)

$$S_n = H_n = \int d^D x \left[(\partial_\mu Q_{ab})^2 + \tau \mathrm{Tr} Q^2 + g_3 \mathrm{Tr}(Q^3) + \lambda \sum Q_{ab}^4 \right]$$

$a, b = 1, ..., n$. At the end, $n \to 0$! (The replica trick)

- Propagator ($T > T_c$):

$$G(p) = \frac{1}{p^2 + m^2}$$

- Propagator ($T = T_c$, λ is irrelevat, ϕ^3 theory, upper critical dimensions $D = 6$):

$$G(p) = \frac{1}{p^{2-\eta}}$$

Different Theories and Models (III cont.).

- Propagators (Parisi Matrix) ($T < T_c$ and λ is relevant):

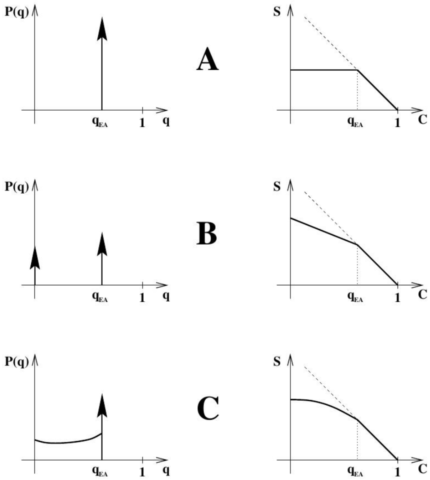
$$G_q(r) \simeq q^2 + A(q) r^{-\theta(q)}$$

where

  - $\theta(q_M) = D - 2$. This result may be exact (some kind of Goldstone theorem).
  - $\theta(q_M) = D - 3$ for $q_M > q > q_m$. This result should be modified below D=6.
  - $\theta(q_m) = D - 4$ for $q_m = 0$. For $D < 6$ this result should be modified to:

$$\theta(q = 0) = \frac{D - 2 + \eta}{2}$$

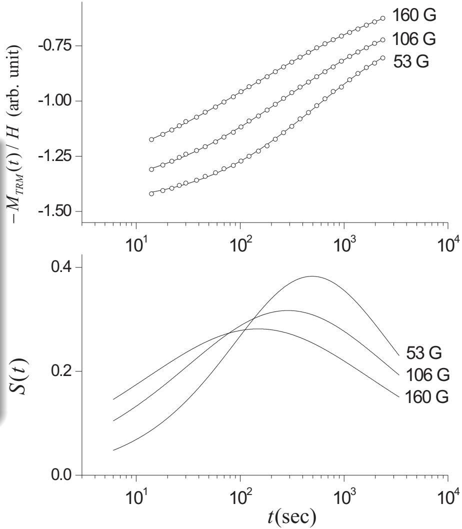
Different Theories and Models (Comparison).



On the dynamical critical exponent z below and at the critical Temperature.

Experimental Approach based in Zeeman Energies (I) (Joh et al.)

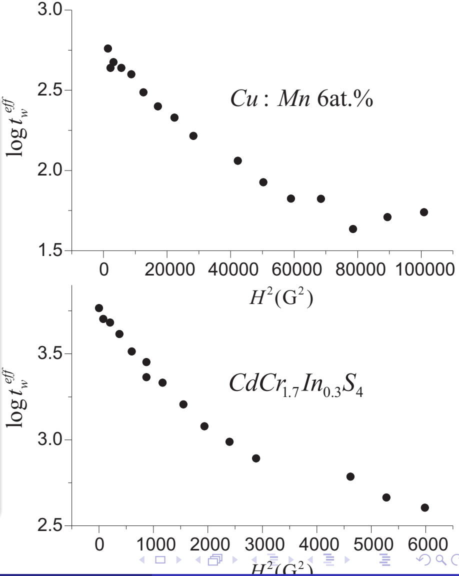
- Measure of the TRM magnetization: $M_{\rm TRM}(t, t_w)$.
- Computation of $S(t)$ defined as: $S(t) = -\frac{dM_{\rm TRM}(t,t_w)}{Hd \log t}$.



On the dynamical critical exponent z below and at the critical Temperature.

Experimental Approach based in Zeeman Energies (II)

- In absence of field, the free energy barriers scales as: $\Delta(t, t_w) = k_B T\,(\log t_w - \log \tau_0)$.
- In presence of field, we obtain: $\Delta(t, t_w) - E_z = k_B T(\log t_w^{\rm eff} - \log \tau_0)$.
- The Zeeman Energy is: $E_z = N_s \chi_{\rm fc} H^2$.



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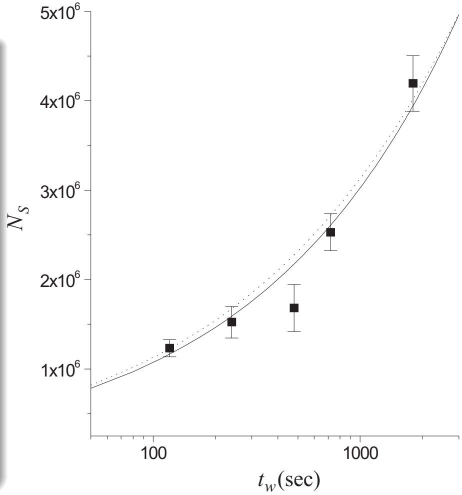
Experimental Approach based in Zeeman Energies (III)

- They extract the dynamical correlation length as: $N_s(t_w^{\mathrm{eff}}) = \xi(t_w^{\mathrm{eff}})^3$.
- $\xi(t_w, T) = 0.653\,(t_w/\tau_0)^{0.169T/T_g}$. $\tau_0^{-1} = 4.1 \times 10^{12}\ \mathrm{s}^{-1}$.
- $\xi(t_w, T) = 10^{-5}\left[\frac{T}{T_g}\log(\frac{t_w}{\tau_0}\right]^{1/0.21}$. Numerically: $\psi = 0.7$!.



Theoretical Basis supporting $z(T)$.

- Assuming the dynamical free energy barriers scales as $\log L$ (i.e. $\psi = 0$) (Rieger).
- In the Sine-Gordon model with phase disorder. Near T_c, $z(T) = 2 + 2e^{\gamma_E}(T - T_c)/T_c + O(\tau^2)$, and in the low T phase: $z(T) \simeq 1/T$. (Rieger and Schehr).
- A particle in a one dimensional disordered potential with logarithmic barriers in the marginal glassy phase ($\theta = 0$) (Le Doussal, Carpertier and Le Doussal).

The Quest for the Replicon.

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The replicon in $D = 6$.

- We assume $z(T) = 4\frac{T_c}{T}$
- χ, computed off equilibrium, should grow following the propagator $p^{-2}(r^{-4})$ for $T = T_c$ and the replicon mode $p^{-4}(r^{-2})$ for $T < T_c$.
- Hence $\chi(t) \simeq t^{h(T)}$ where:
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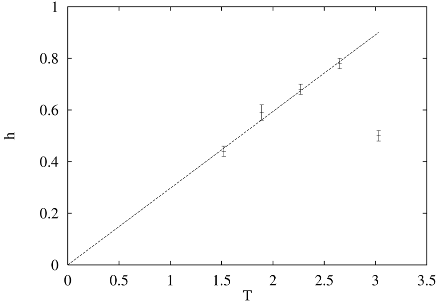

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Replicon/$z(T)$.

- The replica-replica correlation function is:

$$C_4(x, t_w) = \frac{1}{L^3} \overline{\sum_i q_i(t_w) q_{i+x}(t_w)}.$$

$T < T_c$ $C_4(r, t_w) \simeq r^{-a} e^{-[r/\xi(t_w)]^b}$ (Parisi, Marinari and JJRL)

- In equilibrium at the critical point: $a = 1 + \eta = 0.625(10)$. (Hasenbusch et al.)

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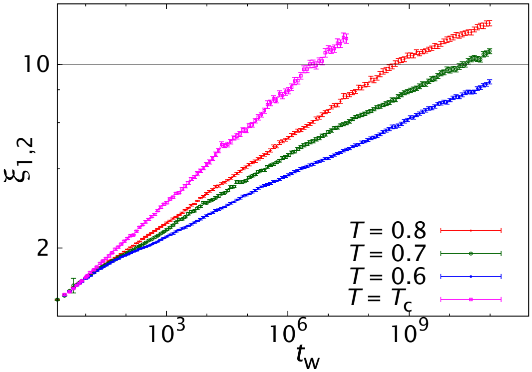
- In equilibrium at the critical point: $a = 1 + \eta = 0.625(10)$. (Hasenbusch et al.)
- We have proposed an Ansatz-independent determination of ξ and a (Janus collaboration):

$$I_k(t_w) = \int_0^\infty dr\, r^k C_4(r, t_w)$$

then, if $C_4 \simeq r^{-a} f(r/\xi)$,

$$\xi_{k,k+1}(t_w) = I_{k+1}(t_w)/I_k(t_w) \propto \xi(t_w), \quad (\xi \ll L)$$

Our $z(T)$



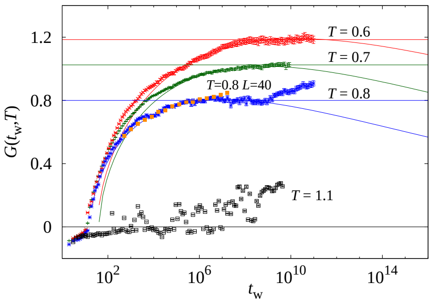
$$\xi(t_w) = A(T) t_w^{1/z(T)}$$

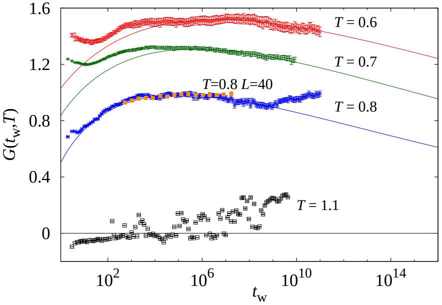
$$z(T_c) = 6.86(16)$$
$$z(0.8) = 9.42(15)$$
$$z(0.7) = 11.84(22)$$
$$z(0.6) = 14.06(25)$$
$$z(T) \simeq z(T_c) T_c / T$$

On the dynamical critical exponent z below T_c. Modified Droplet analysis.

$$t_w \sim \tau_0 \xi^{z_c} \exp\left(\frac{Y(T)\xi^{\psi}}{T}\right)\ , \ \text{(Bouchaud et al.)}$$

$$G(t_w, T) = \left(\frac{\log(t_w/\tau_0) - z_c \log \xi(t_w, T)}{\xi^{\psi} T_c/T}\right)^{\frac{1}{\psi\nu}}\ .$$





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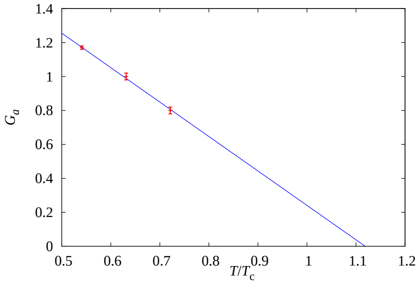

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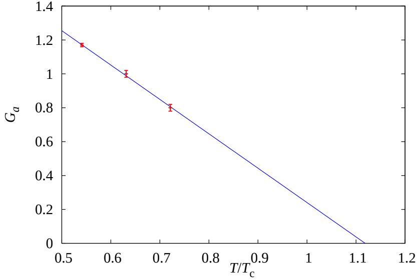

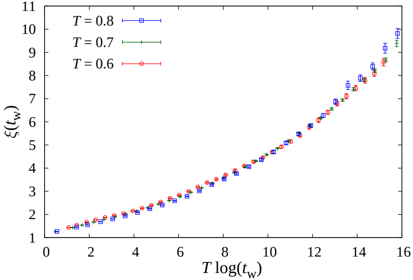

On the replicon.

- $C_4(r, t_w) \sim r^{-a} f\big(t/\xi(t_w)\big) \implies I_1(t_w) \propto \xi_{k,k+1}^{2-a}(t_w)$.

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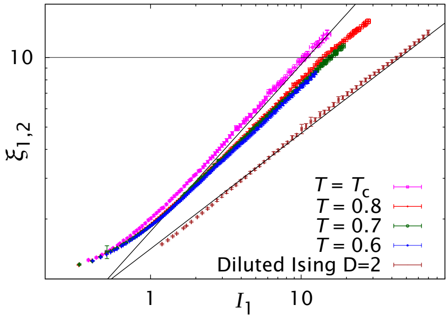
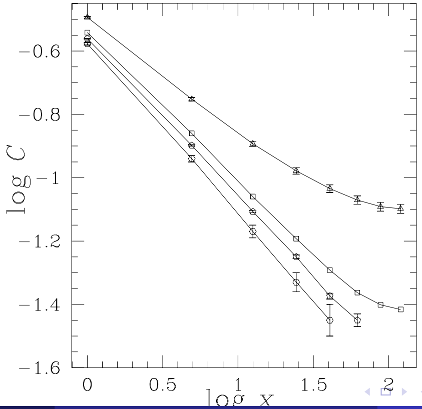


$$a(0.8) = 0.442(11)$$
$$a(0.7) = 0.397(12)$$
$$a(0.6) = 0.359(13)$$
$$a(T_c) = 0.585(12)$$

The Quest for the Replicon.

- Equilibrium and out of equilibrium correlations in $D = 3$ (Marinari, Parisi and JJRL).



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- Lower critical dimensions for the Ising spin glass in a field $D_l > 3$?