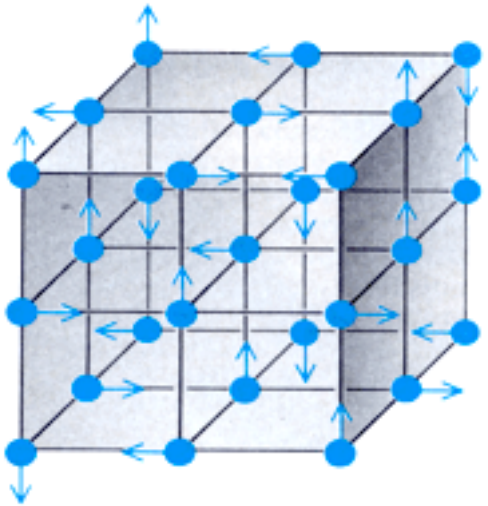
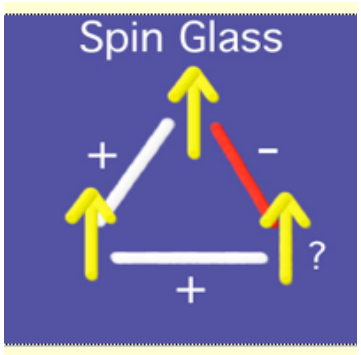
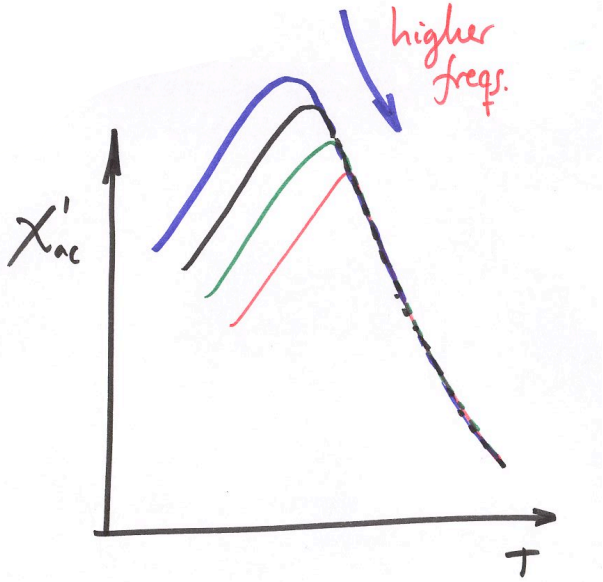
Spin Glass

SG

- randomness
- interacciones magnéticas
- anisotropía
- frustración







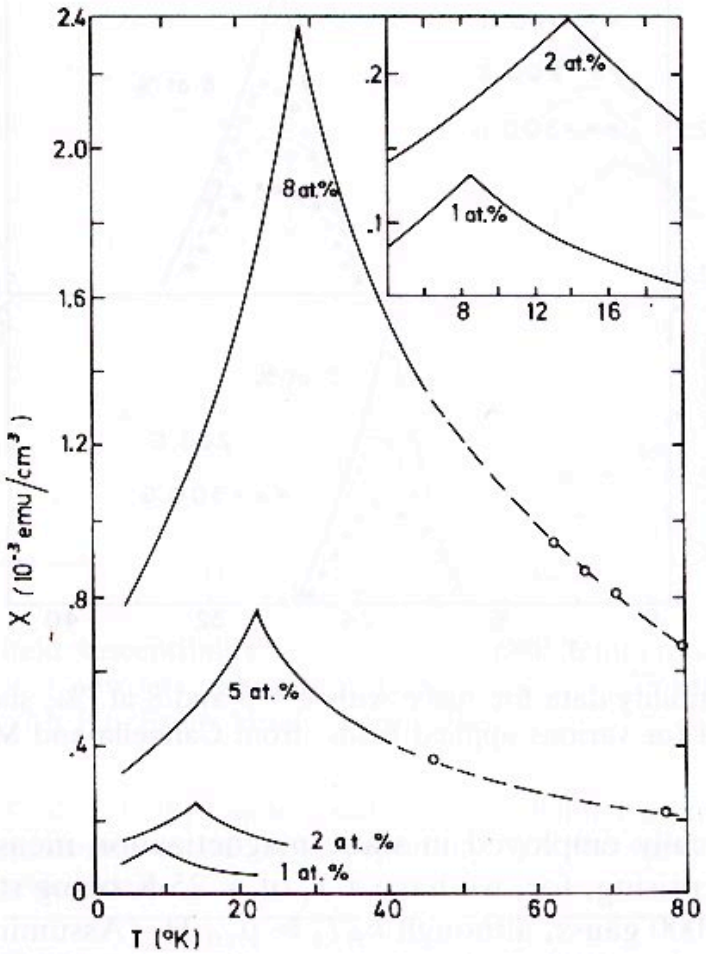


Fig. 3.12 Low-field susceptibility $\chi(T)$ of *Au*Fe for $1 \leq x \leq 8$ at. %. The data were taken every $\frac{1}{4}$ K in the region of the peak, and every $\frac{1}{2}$ or 1 K elsewhere. The scatter is of the order of the thickness of the lines. The open circles indicate isolated points taken at higher temperatures. From Cannella and Mydosh (1972).

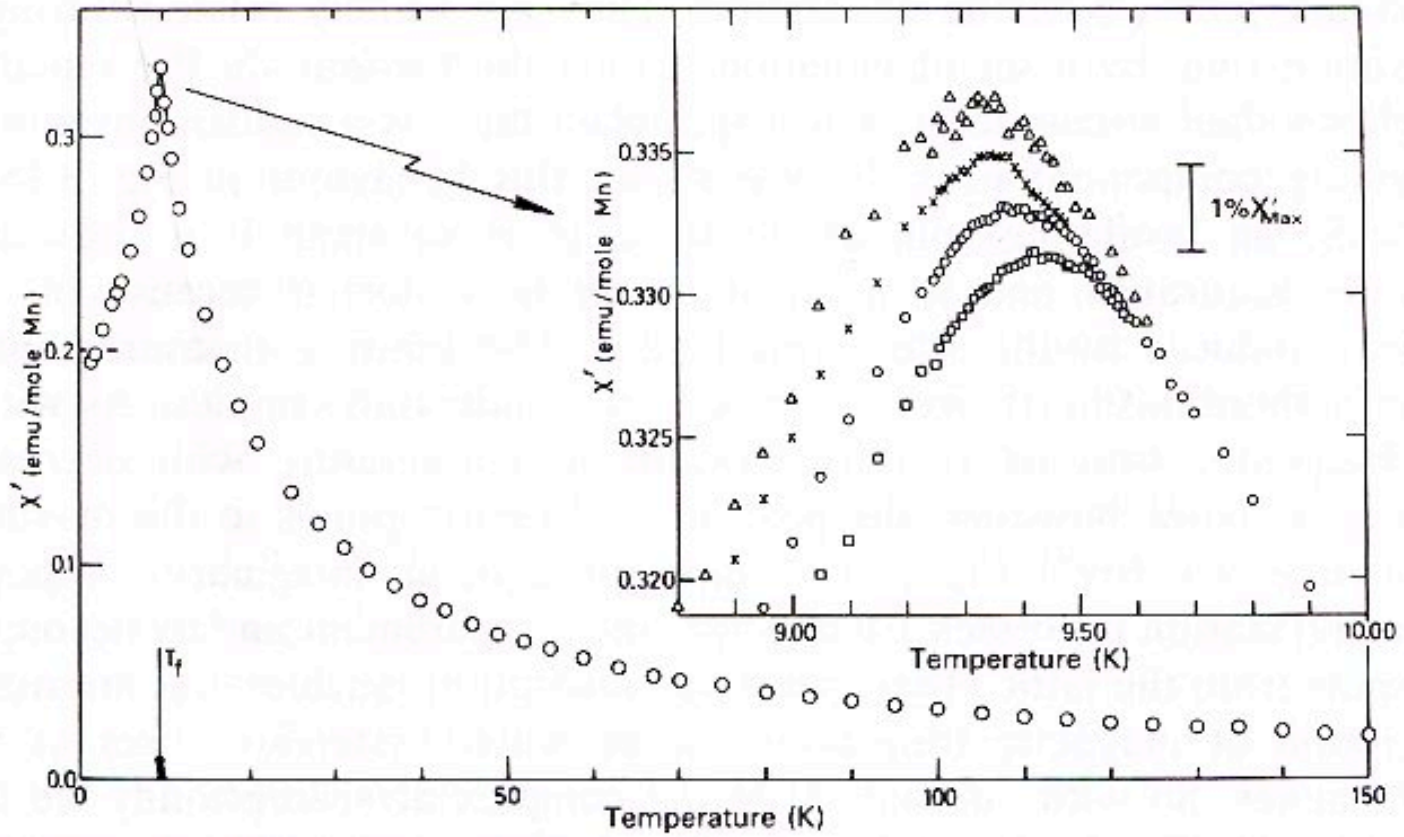


Fig. 3.14 Zero-field susceptibility χ' as a function of temperature for sample IIc (*Cu*Mn (0.94 at. %) powder), measuring frequencies: □, 1.33 kHz; ○, 234 Hz; ×, 10.4 Hz; and △, 2.6 Hz. From Mulder *et al.* (1981).

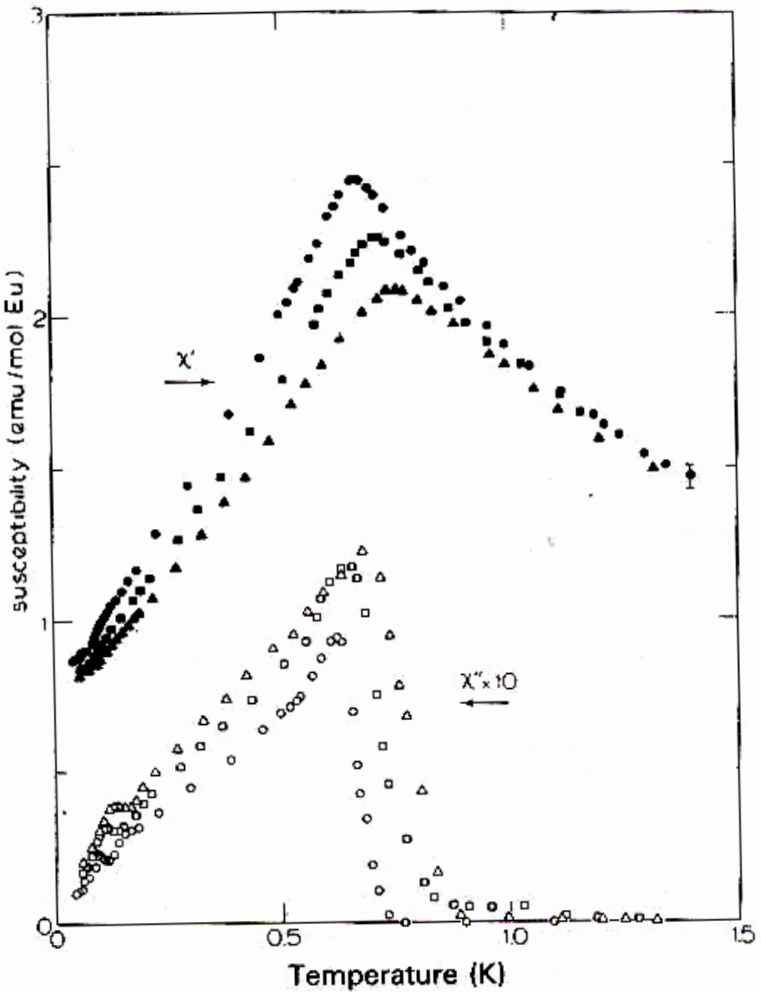


Fig. 3.15 Temperature dependence of the dispersion χ' (solid symbols) and absorption χ'' (open symbols) for $Eu_{0.2}Sr_{0.8}S$: ●○, 10.9 Hz; ■□, 261 Hz; ▲△, 1969 Hz (applied ac field $h \approx 0.1$ Oe); from Hüser *et al.* (1983).

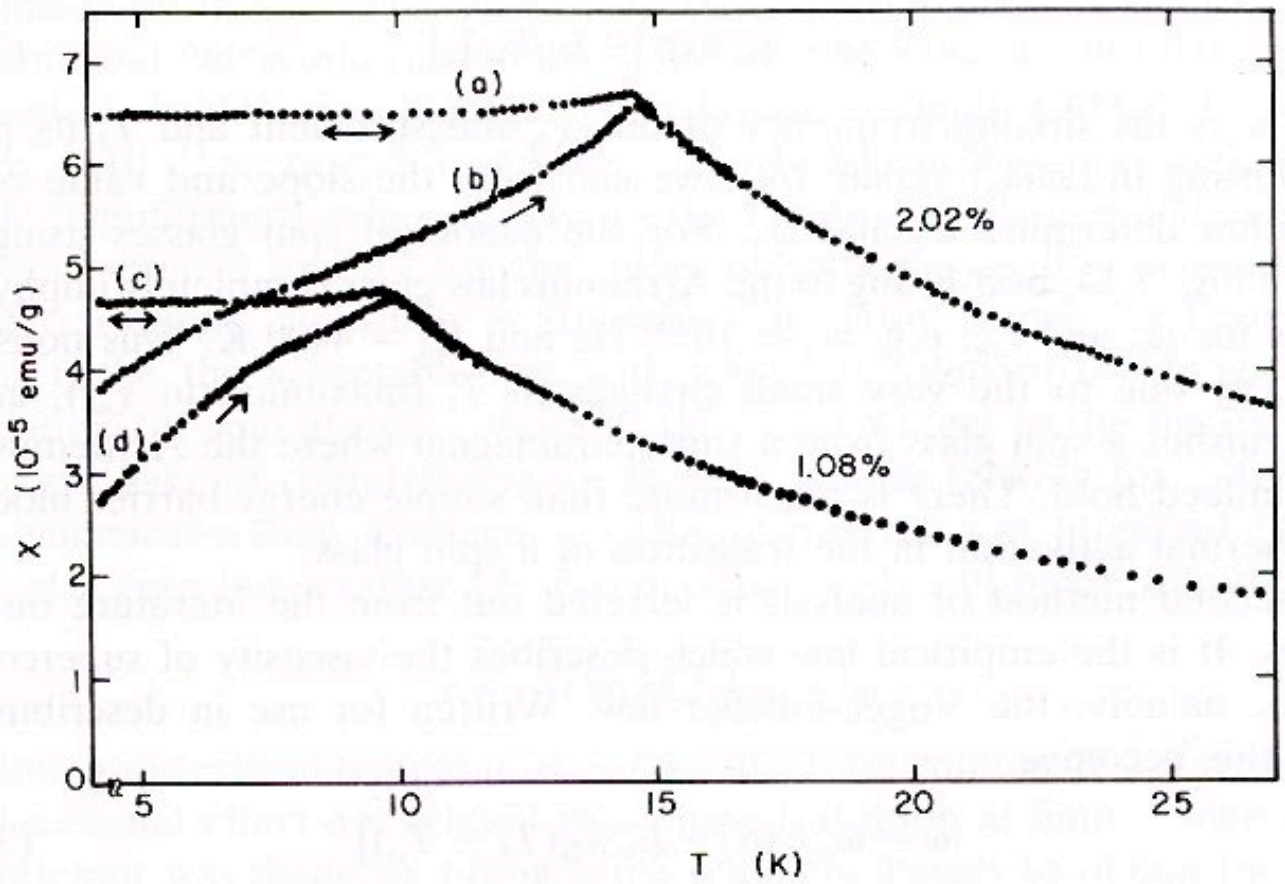


Fig. 3.16 Field cooled [(a), (c)] and zero-field cooled [(b), (d)] magnetizations ($\chi \equiv M/6$ gauss) for *Cu*Mn (1 and 2 at. %) as a function of temperature; from Nagata *et al.* (1979).

How can we better analyse and interpret the data near T_f? Let us begin with the frequency shift of T_f. First of all we could try the Arrhenius law for thermal activation already used for a superparamagnet

$$\tau = \tau_o \exp\left[E_a/k_B T\right] \tag{3.29}$$

which we can rewrite as

$$\omega = \omega_o \exp\left[-E_a/k_B T_f\right] \tag{3.30}$$

Here ω is the driving frequency of our χ_{ac}-measurement and T_f its peak. By plotting ln (ω/ω_o) versus $1/T_f$, we can from the slope and value of the logarithm determine E_a and ω_o. For the canonical spin glasses using the data in Fig. 3.14, best-fitting to the Arrhenius law gives completely unphysical values for ω_o and E_a, e.g. $\omega_o \approx 10^{200}$ Hz and $E_a = 4400$ K. This nonsense is clearly due to the very small changes in T_f (maximum in χ_{ac}), and it distinguishes a spin glass from a superparamagnet where the Arrhenius law does indeed hold. There is much more than simple energy-barrier blocking and thermal activation in the transition of a spin glass.

A second method of analysis is ferreted out from the literature on real glasses. It is the empirical law which describes the viscosity of supercooled liquids, namely, the Vogel–Fulcher law. Written for use in describing T_f shifts this becomes

$$\omega = \omega_o \exp\left[-E_a/k_B(T_f - T_o)\right] \tag{3.31}$$

where T_o is a new parameter (for real glasses it is called the 'ideal glass' temperature). With three fitting parameters (ω_o, E_a and T_o) the agreement is naturally much better, except perhaps at low frequencies, using a more physical set of parameter values. Typically for *Cu*Mn (4.6 at. %) $\omega_o = 1.6 \times 10^8$ Hz, $E_a = 11.8$ K and $T_o (< T_f = 27.5\ \text{K}) = 26.9$ K. The problem here is the precise physical meaning of the large T_o. Some attempts have been made to relate it to the interaction strengths between the clusters in a spin glass. Since a spin glass is *not* a non-interacting collection of clusters something must be added to take into account the inter-cluster couplings. T_o might also be related to the true critical temperature of an underlying phase transition for which T_f is only a dynamic manifestation. Thus far, a deeper understanding of T_o and its connection to the longer-range interactions is lacking.

SG - MODELOS

Edwards - Anderson (EA) 1975

- Cada S_i se bloquea en una dirección preferida, random en i
- SG $\Rightarrow$ NO LONG-RANGE ORDER

  y entonces ... ¿QUÉ PARAMETRO de ORDEN?

No se pueden usar las CORRELACIONES ESPACIALES $\longrightarrow$ EA proponen la AUTOCORRELACIÓN EN EL TIEMPO

$$q = \lim_{t\to\infty} \langle\langle \vec{S}_i(0) \cdot \vec{S}_i(t) \rangle_T \rangle_c$$

$\{ q \to 0 \text{ as } T \to T_f \}$

$\{ q = 1 \text{ @ } T = 0 \}$

EA "compara fotos" del sistema tomadas a varios "t"

Si "no se parece en nada a sí mismo" ⟶ PARA

Si "se parece a sí mismo" ⟶ FROZEN

en sistemas ergódicos: $q = \langle\langle \vec{S}_i \rangle_T^2 \rangle_C$ ← Parámetro de orden EA

NOTA: en SG's $\langle\langle S_i \rangle_T \rangle_C = 0$

(el sistema no es ferro ni antiferro)

Ahora... MODELO ≡ CÁLCULO de E. en f. de q

↓ Mecánica Estadística ...

EA Hamiltonian

$$\mathcal{H} = -\sum_{ij} J_{ij}\,\vec{S}_i\vec{S}_j - \sum_i \vec{H}_i S_i$$

J_{ij}: random bond

$$P(J_{ij}) = \frac{\exp\left(-\frac{J_{ij}^2}{2\Delta^2}\right)}{(2\pi\Delta^2)^{1/2}}$$

gaussian
($\Delta \equiv$ varianza)

$$F = -K_B T \ln Z = -K_B T\, Tr\left(\exp\frac{-\mathcal{H}}{K_B T}\right)$$

es 'difícil' promediar $\ln Z$ en $P(J_{ij})$

↳ "replica-trick"

$$\ln Z = \lim_{n\to 0}\left[\frac{1}{n}(Z^n - 1)\right]$$

(n entero)

por T≤ fluctuación - disipación

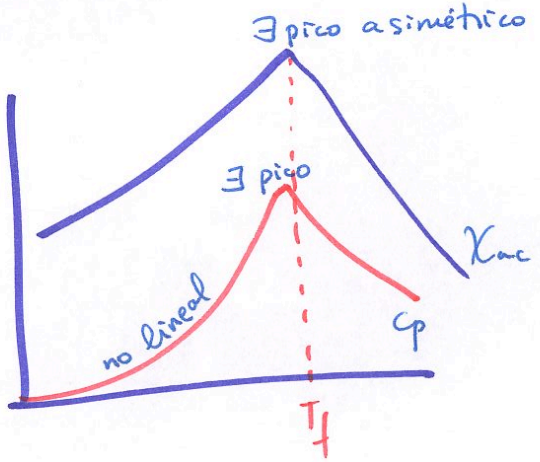
$$\chi(T, H=0) = \frac{(g\mu_B)^2}{3k_BT} \sum_{ij} \left[\underbrace{\langle\langle S_i^2 \rangle_T \rangle_c}_{1} - \underbrace{\langle\langle S_i \rangle_T^2 \rangle_c}_{q} \right]$$

con $i \neq j = 0$

$$\chi(T, H) = \frac{(g\mu_B)^2}{3KT} (1 - q(T)) \approx \chi_{ac}(T)$$

$\chi_{ac}(T) \sim$ OK

$C_p(T) \longrightarrow$ NO !!



SHERRINGTON - KIRKPATRICK : SG - MFT

(SK) 1975

SK proponen MFT como solución exacta de EA a rango ∞

MFT ⇒ cada i $(1 \dots N)$ spin, S_i, se acopla igual con todos

$P(J_{ij})$ es igual para todo par i-j

(da igual lo lejos que estén ... no es muy realista)

$$P(J_{ij}) = \frac{1}{\sqrt{2\pi\Delta^2}} \exp\left(-(J_{ij} - J_0')^2 / 2\Delta^2\right)$$

(J_0': media)

de nuevo; replica-trick:

Se calcula $\langle Z^n \rangle_c$ en lugar de $\langle \ln Z \rangle_c$

y después de muchas cuentas [1] (todas las réplicas indistinguibles)

Solución "replica-simétrica"

$$q = q_{\alpha\beta} = \langle\langle \vec{S}^\alpha \vec{S}^\beta \rangle_T \rangle_c$$

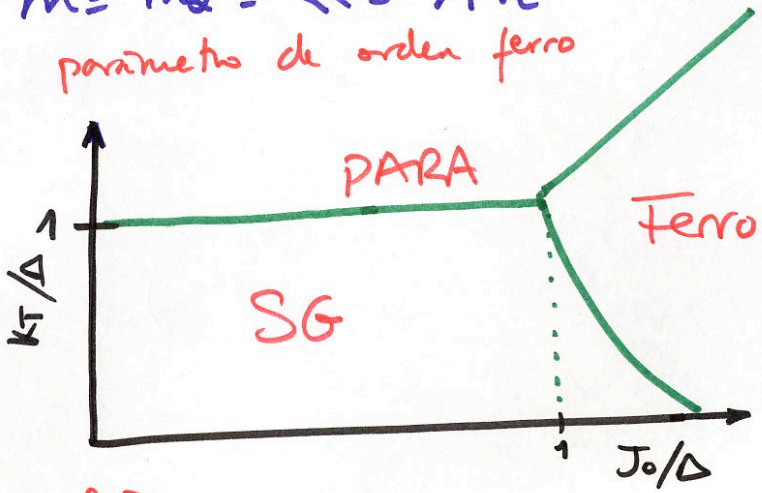
parámetro de orden SG

$$m = m_\alpha = \langle\langle S^\alpha \rangle_T \rangle_c$$

parámetro de orden ferro

$$q = \frac{1}{\sqrt{2\pi}} \int \exp\left(\frac{-z^2}{2}\right) \tanh^2\left[\frac{\Delta q^{1/2}}{k_B T} z + \frac{J_0 m}{k_B T}\right] dz$$

$$m = \frac{1}{\sqrt{2\pi}} \int \exp\left(\frac{-z^2}{2}\right) \tanh\left[\frac{\Delta q^{1/2}}{k_B T} z + \frac{J_0 m}{k_B T}\right] dz$$



[1] J.A. Mydosh, "Spin Glasses" Taylor & Francis 1993

SK predice

1) PARA → SG

2) PARA → FERRO → Re SG

3) PARA → FERRO

$Pd_{1-y-x}Fe_yMn_x$

J_0

mixed interaction : Δ

$$\chi(T) = \frac{[1 - q(T)]}{k_B T - J_0[1 - q(T)]} \longrightarrow \text{CUSP !! } (1)$$

BAJA T

$C \propto T$ (2)

SK predice

1) PARA → SG

2) PARA → FERRO → Re SG

3) PARA → FERRO

$Pd_{1-y-x}\,Fe_y\,Mn_x$

J_0

mixed interaction : Δ

$$\chi(T) = \frac{[1 - q(T)]}{k_B T - J_0[1 - q(T)]}$$

→ CUSP !! (1)

BAJA T

$C \propto T$ (2)

pero, también en q_p

ALTA T:

además ... $q_p \propto \frac{1}{T^2}$ high T

y $S < 0$ @ $T = 0$

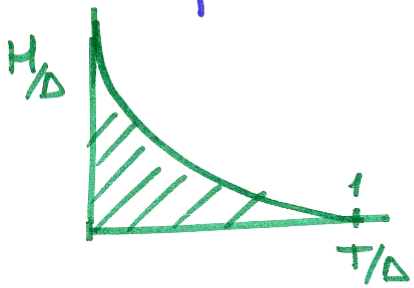
ALMEIDA-THOULESS → SK es inestable a baja T

[Solución q=0 "unphysical"

[S<0 at T=0

[χ<0

[la inestabilidad se debe a que las réplicas no son indistinguibles]



→ RSB scheme → Parisi, 1979

TAP approach

modificación del resultado MPT-ferro con una especie de "random field"