Finite-size scaling study of pseudocritical temperatures in spin glasses

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Outline

1. The thermodynamic limit and the ‘experimental limit’
2. Pseudocritical temperatures
3. Results for Edwards-Anderson
4. Results for Sherrington-Kirkpatrick

The experimental scale (I)

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- Even for experimental waiting times (t_w) of several hours, the spatial size of the glassy domains is of $\xi(t_\mathrm{w}) \sim \mathcal{O}(10^2)$ lattice spacings.
- In a sense, the non-equilibrium infinite system behaves as if composed of many equilibrium systems of size $\xi(t_\mathrm{w})^D$.
- This statement can be made quantitative through a time-length dictionary.

The experimental scale (II)

Time-length dictionary (Janus Collaboration)

Equilibrium: finite size at infinite t_w
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Quantitative: at $T = 0.64T_\mathrm{c}$, choose t_w such that $L = 3.7\xi(t_\mathrm{w})$

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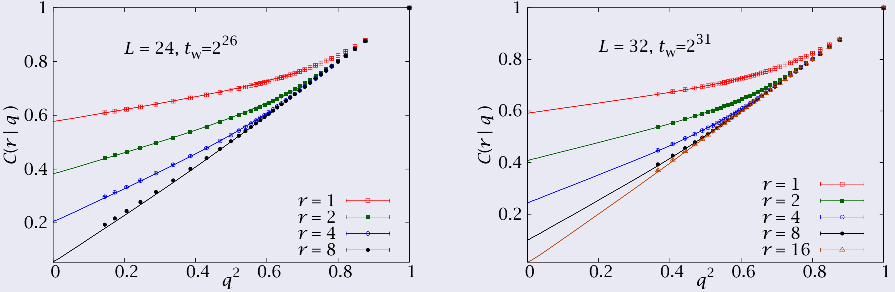

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- Experimental time scale: 1 hour $\sim 4 \times 10^{15}$ MC steps.
- $\xi(t_w) \sim t_w^{1/z(T)}$: relevant equilibrium size $L = 110$

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- These fluctuations typically decrease with system size, but if we want to understand their possible experimental relevance we need to know how their distribution evolves with system size.
- In particular, the finite-system pseudocritical temperature is a relevant (but elusive) quantity.
- We want to characterise the statistical properties of this quantity for three-dimensional (Edwards-Anderson) and mean-field (Sherrington-Kirkpatrick) spin glasses.

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- $\chi_{SG} \sim N$ for all $T < T_c$ (actually, a strictly decreasing function of T), so we need a more sophisticated approach.
- We will consider dimensionless single-sample observables O^J, which scale as

$$O^J(T, L) \simeq G\big((T - T_c^J(L))L^{1/\nu}\big)$$

Observables for the Edwards-Anderson model (I)

The EA model

$$\mathcal{H} = -\sum_{\langle x,y \rangle} S_x J_{xy} S_y , \qquad S_x = \pm 1,\ J_{xy} = \pm 1.$$

Simulations from the Janus Collaboration (up to $L = 32$ down to $T = 0.64\,T_\mathrm{c}$).

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Propagator

- We consider the overlap field q_x and its Fourier transform, $\phi(\boldsymbol{k})$.

$$\phi(\boldsymbol{k}) = \sum_x S_x^{(a)} S_x^{(b)} \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}} = \sum_x q_x \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}}$$

- The two-point propagator is $G^J(\boldsymbol{k}) = \langle \phi(\boldsymbol{k})\phi(-\boldsymbol{k})\rangle$.
- The smallest momentum with periodic boundaries is $k = 2\pi/L$: $\boldsymbol{k}_1^{(1)} = (2\pi/L, 0, 0)$, $\boldsymbol{k}_1^{(2)} = (0, 2\pi/L, 0)$, $\boldsymbol{k}_1^{(3)} = (0, 0, 2\pi/L)$.
- We define $G^J(\boldsymbol{k}_1) = \frac{1}{3}\sum_i G^J(\boldsymbol{k}_1^{(i)})$.

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Dimensionless ratios

- We are going to use several dimensionless ratios to search for T_c^J:

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$$R_{12}^J = \frac{G^J(\boldsymbol{k}_1)}{G^J(\boldsymbol{k}_2)}.$$

Definition of T_c^J for the spin glass (I)

- Let us take the sample-averaged version O of any of the O^J.
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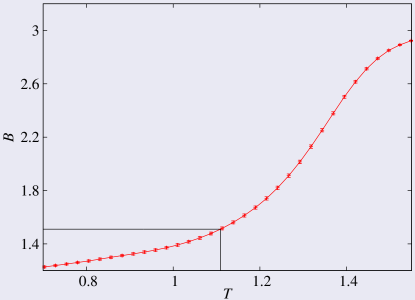
- Of course, different choices of O and y give different $T_{O,y}^J$, but we expect the scaling to be the same.

Definition of T_c^J for the spin glass (II)

Example: Binder ratio



The sample-averaged Binder ratio. We take $y = 1.51 \approx B(T_c)$

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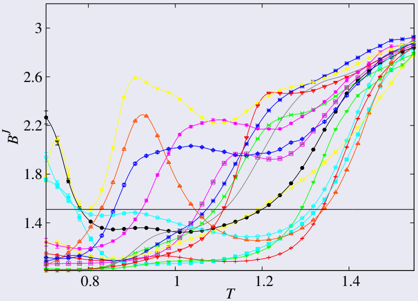

Several samples, wildly fluctuating behaviour

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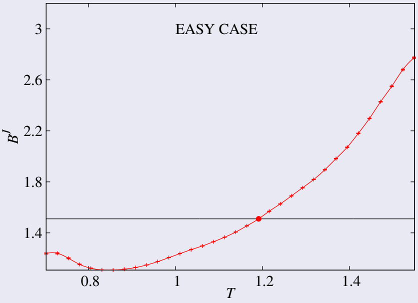

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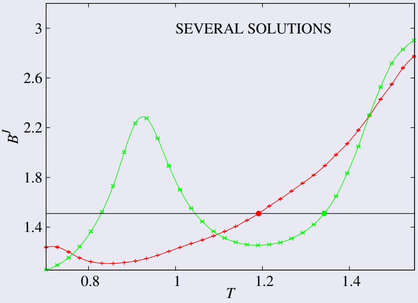

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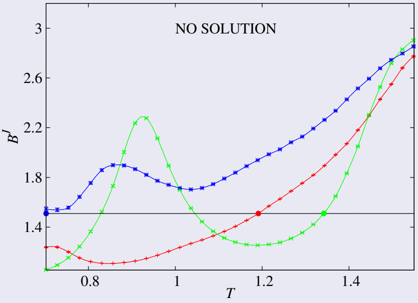

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- No solution (blue): only upper bound (less than 1% of samples).

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- Instead, we analyse the median $\tilde{T}_{O,y}^J$ of the distribution, unaffected by the few samples without a solution.
- Finally, we can also consider the pseudocritical temperature of the susceptibility, given by

$$\chi_{\mathrm{SG}}^J(T_{\chi,y}^J) = \chi_{\mathrm{SG}}(T_\mathrm{c})y,$$

with $y \simeq 1$.

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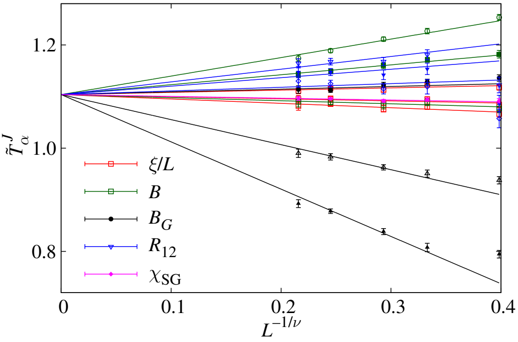
- We consider all the O^J and several y at the same time in a joint fit.
- For the same L the different $\tilde{T}^J_{O,y}$ are correlated, so we consider the full covariance matrix:
$$\chi^2 = \sum_{\alpha,\beta=1}^{n} \sum_{a,b=1}^{\mathcal{L}} \left[\tilde{T}^J_\alpha(L_a) - T_c - A_\alpha L_a^{-1/\nu}\right] \sigma^{-1}_{(ia)(jb)} \left[\tilde{T}^J_\beta(L_b) - T_c - A_\beta L_b^{-1/\nu}\right]$$
(here α, β label both the O^J and the y).
- The fit parameters are $\{T_c, \nu, A_{y_1}, A_{y_2}, \ldots\}$.

The pseudocritical temperature for EA



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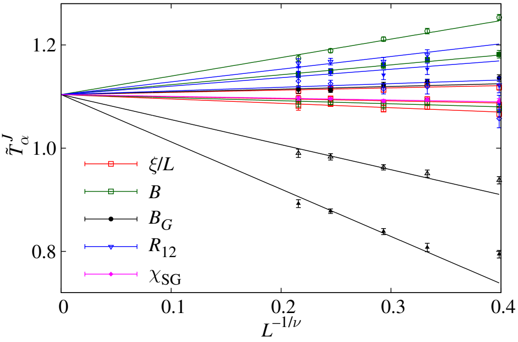

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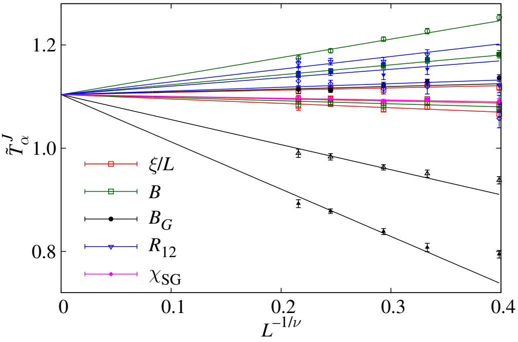

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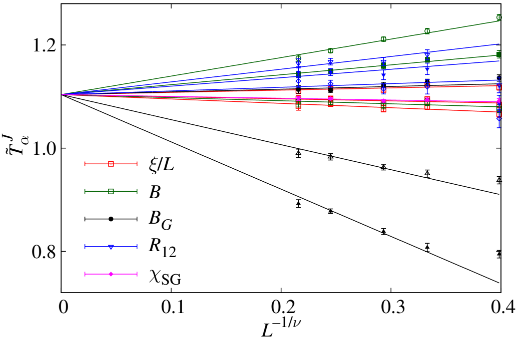

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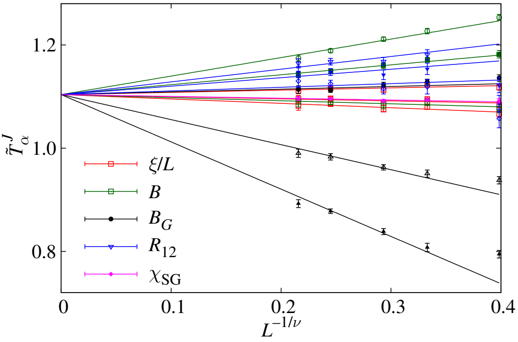

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- Hasenbusch et al. consider corrections to scaling ($\omega = 1$).
- We do not have enough data for small L to fit for ω and ν simultaneously.
- We fix ω, ν to the value of Hasenbusch et al. and fit for T_c, $L \geq 8$:

$$T_c = 1.105(8), \quad \chi^2/\text{d.o.f.} = 40.9/38$$

The width of the distribution

- These results make us confident that our definition of T_α^J makes sense.
- We want to study the fluctuations.
- Define T_α^+ and T_α^-: $P(T_\alpha^J > T_\alpha^+) = 0.16$, $P(T_\alpha^J < T_\alpha^-) = 0.16$.
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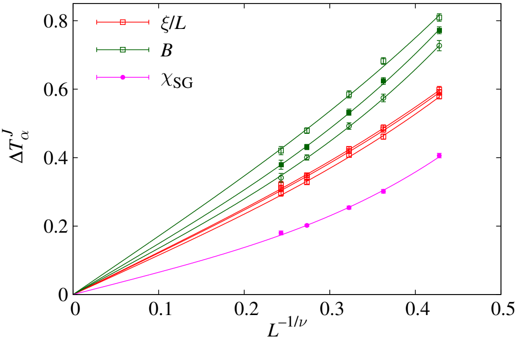

- We consider

$$\Delta T^J_\alpha \simeq A_\alpha L^{-1/\nu}(1 + B_\alpha L^{-\omega}).$$

- Again, we take ν and ω from Hasenbusch et al.
- $\chi^2/\text{d.o.f.} = 19.1/21$.

The Sherrington-Kirkpatrick model

The SK model

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- This scaling can be justified studying the stability of the TAP states.

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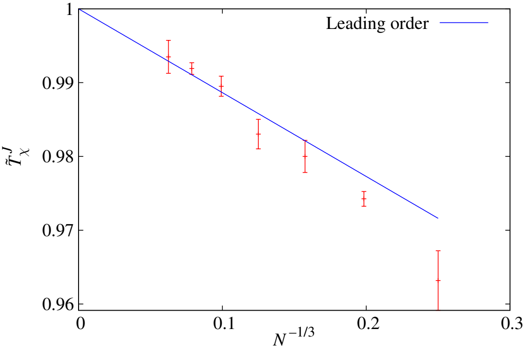

- This time, we know exactly $T_c = 1$ and $1/(\nu D_{up}) = -1/3$.

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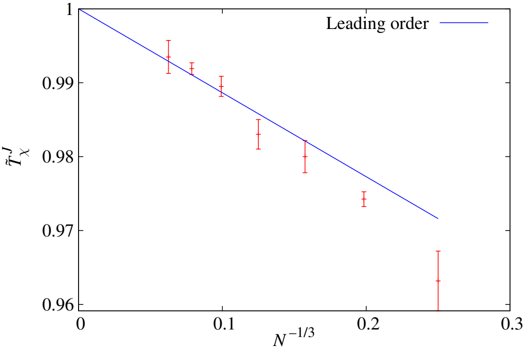

- This time, we know exactly $T_c = 1$ and $1/(\nu D_{\rm up}) = -1/3$.
- We fit only for the amplitude for $N \geq 256$, (χ^2/d.o.f. $= 4.44/4$).

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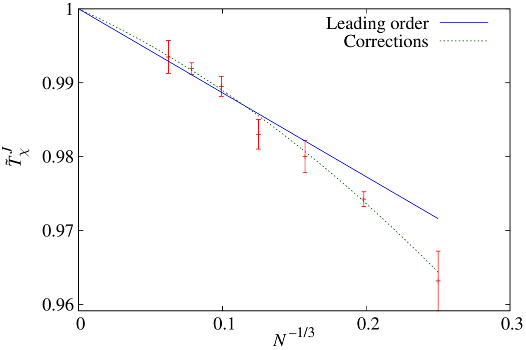
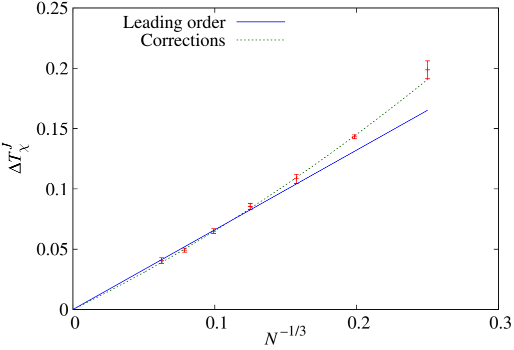


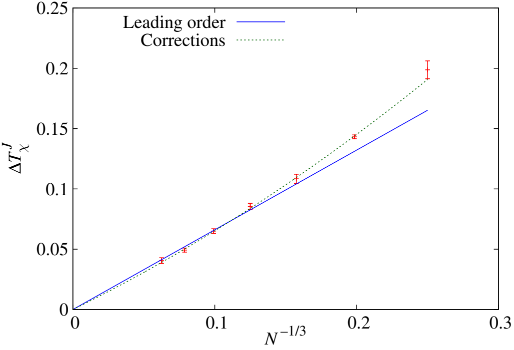
- This time, we know exactly $T_c = 1$ and $1/(\nu D_{up}) = -1/3$.
- We fit only for the amplitude for $N \geq 256$, ($\chi^2/\text{d.o.f.} = 4.44/4$).
- We can include a scaling correction with $N^{-2/3}$. Now all sizes $N \geq 64$ fit, with $\chi^2/\text{d.o.f.} = 2.07/5$.

Results for SK (II)



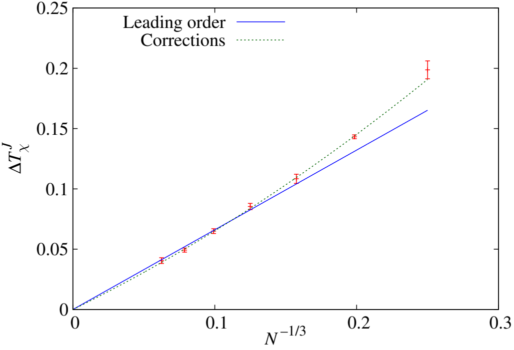
- Same analysis for the width: $\Delta T_\alpha^J = A_\alpha N^{-1/3} + B_\alpha N^{-2/3}$.

Results for SK (II)



- Same analysis for the width: $\Delta T_\alpha^J = A_\alpha N^{-1/3} + B_\alpha N^{-2/3}$.
- Without corrections: $N \geq 256$, $\chi^2/\text{d.o.f.} = 5.36/4$.

Results for SK (II)



- Same analysis for the width: $\Delta T^J_\alpha = A_\alpha N^{-1/3} + B_\alpha N^{-2/3}$.
- Without corrections: $N \geq 256$, $\chi^2/\text{d.o.f.} = 5.36/4$.
- With corrections: $N \geq 64$, $\chi^2/\text{d.o.f.} = 2.57/5$.

Conclusions

Comclusions

- We have presented a simple method to study the probability distribution of the pseudocritical temperatures in spin glasses.
- We have applied it to the Edwards-Anderson and the Sherrington-Kirkpatrick models.
- The T_α^J are shown to follow a straightforward finite-size scaling.
- For EA, our computed values for T_c and ν are compatible with state-of-the-art results and of similar precision.