Quantum versus Thermal annealing, the role of Temperature Chaos

Víctor Martín-Mayor

Dep. Física Teórica I, Universidad Complutense de Madrid
Janus Collaboration

In collaboration with Itay Hen (Information Sciences Institute, USC).

CPRCS 2014, Capri, September 10 2014.

Foreword

Monte Carlo is an extremely bad *method; it should be used only when all alternative methods are worse.*
(Alan Sokal, 1989).

Foreword

> *Monte Carlo is an extremely* bad *method; it should be used only when all alternative methods are worse.*
> (Alan Sokal, 1989).

Such desperate problems are common in Theoretical Physics.

Foreword

> *Monte Carlo is an extremely* bad *method; it should be used only when all alternative methods are worse.*
> (Alan Sokal, 1989).

Such desperate problems are common in Theoretical Physics.

SG simulations are extremely computer *intensive* but *simple*: the Janus collaboration has dared to produce dedicated hardware.

Foreword

> *Monte Carlo is an extremely* bad *method; it should be used only when all alternative methods are worse.*
> (Alan Sokal, 1989).

Such desperate problems are common in Theoretical Physics.

SG simulations are extremely computer *intensive* but *simple*: the Janus collaboration has dared to produce dedicated hardware.

Janus is a great success, but classical Monte Carlo is hitting an algorithmic wall (temperature chaos).

Foreword

> *Monte Carlo is an extremely* bad *method; it should be used only when all alternative methods are worse.*
> (Alan Sokal, 1989).

Such desperate problems are common in Theoretical Physics.

SG simulations are extremely computer *intensive* but *simple*: the Janus collaboration has dared to produce dedicated hardware.

Janus is a great success, but classical Monte Carlo is hitting an algorithmic wall (temperature chaos).

Is quantum computing our breakthrough?

Plan of the presentation

1. Desperate problem, desperate solutions: the Janus computer.
2. The temperature chaos algorithmic wall.
3. A more conventional approach to temperature chaos.
4. D-wave, the chimera lattice and temperature chaos.

The Janus Collaboration

Team from 5 universities in Spain and Italy:

- Universidad Complutense de Madrid:
  M. Baity-Jesi, L.A. Fernandez, V. Martin-Mayor, A. Muñoz Sudupe
- Universidad de Extremadura:
  A. Gordillo-Guerrero, J.J. Ruiz-Lorenzo
- Università di Ferrara:
  M. Pivanti, S.F. Schifano, R. Tripiccione
- La Sapienza Università di Roma:
  A. Maiorano, E. Marinari, G. Parisi, F. Ricci-Tersenghi, D. Yllanes, B. Seoane
- Universidad de Zaragoza:
  R.A. Baños, A. Cruz, J.M. Gil-Narvión, M. Guidetti, D. Iñiguez, J. Monforte-Garcia, D. Navarro, S. Perez-Gaviro, A. Tarancon, P. Tellez.

Physicists and engineers dedicated to the design and exploitation of special-purpose computers, optimised for Monte Carlo simulations in condensed matter physics.

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.
2. Single instance simulation **very long.**

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.
2. Single instance simulation **very long.**
   For modest system sizes (i.e. $N = 32^3 = 32768$ spins):
   - Typical instance: 4.5 standard-CPU years (i.e. 1.4×10^{17} updates).

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.
2. Single instance simulation **very long.**
   For modest system sizes (i.e. $N = 32^3 = 32768$ spins):
   - Typical instance: 4.5 standard-CPU years (i.e. 1.4×10^{17} updates).
   - Worst in 10^3 instances: 800 standard-CPU years (i.e. 2.7×10^{19} updates).

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.
2. Single instance simulation **very long.**
   For modest system sizes (i.e. $N = 32^3 = 32768$ spins):
   - Typical instance: 4.5 standard-CPU years (i.e. 1.4×10^{17} updates).
   - Worst in 10^3 instances: 800 standard-CPU years (i.e. 2.7×10^{19} updates).

Fortunately, the spin update (the core algorithm) is very simple and (in principle) trivial to parallelize. But…

Desperate problems, desperate solutions: Janus (I)

Even with binary spins, simulation of spin-glasses is heavy in two respects:

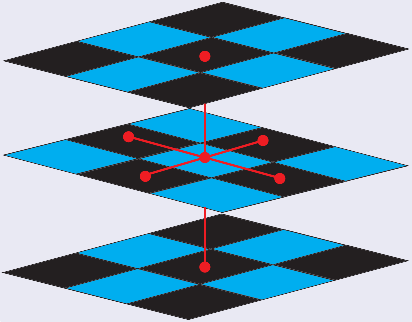
1. Many ($\sim 10^3$) problem instances $\rightarrow$ embarrassingly parallel.
2. Single instance simulation **very long.**
   For modest system sizes (i.e. $N = 32^3 = 32768$ spins):
   - Typical instance: 4.5 standard-CPU years (i.e. 1.4×10^{17} updates).
   - Worst in 10^3 instances: 800 standard-CPU years (i.e. 2.7×10^{19} updates).

Fortunately, the spin update (the core algorithm) is very simple and (in principle) trivial to parallelize. But...

Modern architectures (GPU, Xeon, Xeon-ϕ) efficient only for larger N $\longrightarrow$ astronomical number of updates ($\sim \mathrm{e}^{cN}$, probably).

Desperate problems, desperate solutions: Janus (II)

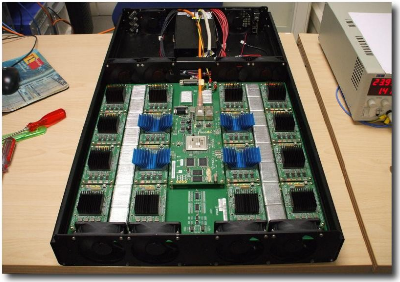
Parallelizable problem



- Parallelise within each instance
- We divide the lattice in a checkerboard scheme,
  all sites of the same colour can be updated simultaneously
- Memory bandwith: 13 bits to update one bit! Only solution: Memory “local to the processor”.

Desperate problems, desperate solutions: Janus (II)

Parallelizable problem



FPGA opportunity window:

- Large on-chip memory (several Mbits).
- Huge bandwidth on-chip “distributed “ memory ($\sim$ 10000 bits in and out per clock cycle).
- Large amount of logic $\rightarrow$ 1024 Spin-Update Engines.

Janus 1 (2008): $\times$1000 boost in spin-glasses simulations.

Green computer: $\times$0.001 energy consumption per update.

Janus 2: Fall 2014

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)
- Clustering correlation functions in equilibrium.

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)
- Clustering correlation functions in equilibrium.
- Quantitative correspondence:
  equilibrium, finite size $\leftrightarrow$ non-equilibrium, finite time.

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)
- Clustering correlation functions in equilibrium.
- Quantitative correspondence:
  equilibrium, finite size $\leftrightarrow$ non-equilibrium, finite time.
- Precision estimates of critical exponents.

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)
- Clustering correlation functions in equilibrium.
- Quantitative correspondence:
  equilibrium, finite size $\leftrightarrow$ non-equilibrium, finite time.
- Precision estimates of critical exponents.
- Ultrametricity in the spin-glass phase.

  ...

Desperate problems, desperate solutions: Janus (III)

Main problems tackled with Janus (2008–2014)

- Spin-glasses in a magnetic field (Juan's talk, tomorrow).
- Isothermal aging (from 1 picosecond to 0.1 seconds)
- Clustering correlation functions in equilibrium.
- Quantitative correspondence:
  equilibrium, finite size $\leftrightarrow$ non-equilibrium, finite time.
- Precision estimates of critical exponents.
- Ultrametricity in the spin-glass phase.

  ...
- Temperature chaos

Temperature chaos: the showstopper (I)

Increasing computing speed *x*1000, not such a big deal

- Pre-Janus era: up to $N = 16^3$ spins.
- Janus era: up to $N = 32^3$ spins.

Why?

Temperature chaos: the showstopper (I)

Increasing computing speed $x1000$, not such a big deal

- Pre-Janus era: up to $N = 16^3$ spins.
- Janus era: up to $N = 32^3$ spins.

Why?

We need to talk a bit about algorithms:

- Simulating at fixed temperature, simply not enough.

Temperature chaos: the showstopper (I)

Increasing computing speed *x*1000, not such a big deal

- Pre-Janus era: up to $N = 16^3$ spins.
- Janus era: up to $N = 32^3$ spins.

Why?

We need to talk a bit about algorithms:

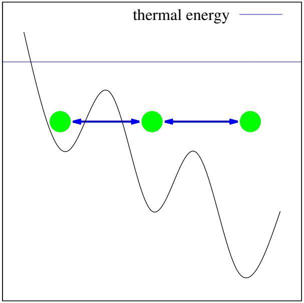
- Simulating at fixed temperature, simply not enough.
- Temperature needs to become dynamic.

Temperature chaos: the showstopper (II)

Simulated Annealing

Simplest protocol:

1. High T: easy exploration

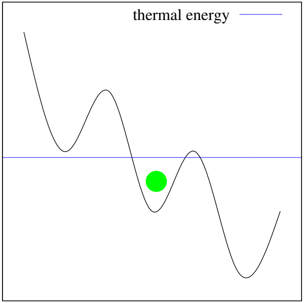


Temperature chaos: the showstopper (II)

Simulated Annealing

Simplest protocol:

1. High T: easy exploration
2. T-lowering protocol: Trapped at nearby local minimum.



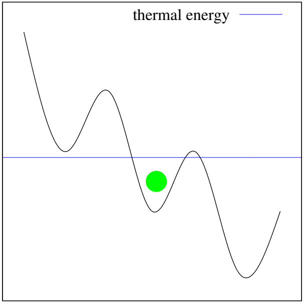
Temperature chaos: the showstopper (II)

Simulated Annealing

Simplest protocol:

1. High T: easy exploration
2. T-lowering protocol: Trapped at nearby local minimum.

Outdated algorithm.

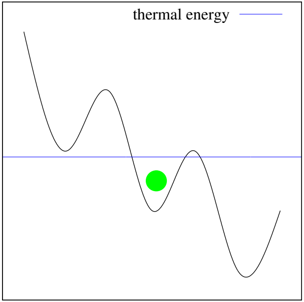


Temperature chaos: the showstopper (III)

Parallel Tempering

T raised or lowered:

1. Low T: local exploration

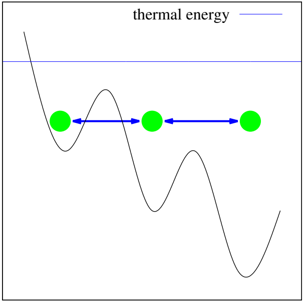


Temperature chaos: the showstopper (III)

Parallel Tempering

T raised or lowered:

1. Low *T*: local exploration
2. High *T*: global exploration

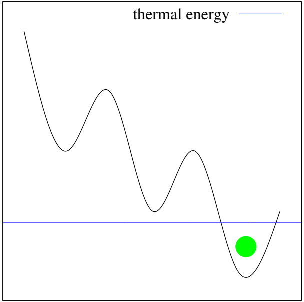


Temperature chaos: the showstopper (III)

Parallel Tempering

T raised or lowered:

1. Low T: local exploration
2. High T: global exploration
3. No trapping $\rightarrow$ better solution.

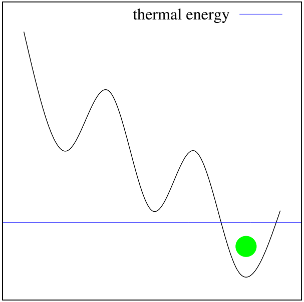


Temperature chaos: the showstopper (III)

Parallel Tempering

T raised or lowered:

1. Low T: local exploration
2. High T: global exploration
3. No trapping $\rightarrow$ better solution.



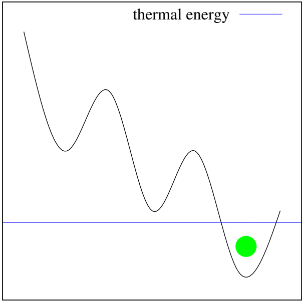
- N_T temperatures: simultaneous simulation of N_T clones (one at each temperature).

Temperature chaos: the showstopper (III)

Parallel Tempering

T raised or lowered:

1. Low T: local exploration
2. High T: global exploration
3. No trapping $\to$ better solution.



- N_T temperatures: simultaneous simulation of N_T clones (one at each temperature).
- Periodically, clones attempt to exchange their temperature. The rule preserves detailed balance.

Temperature chaos: the showstopper (IV)

It looks perfect! What can go wrong?

Temperature chaos: the showstopper (IV)

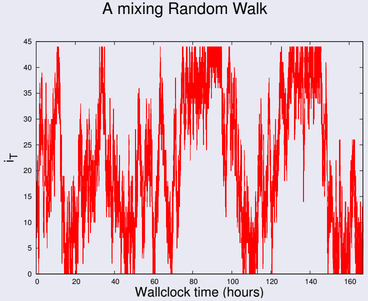
It looks perfect! What can go wrong?
Each clone performs a temperature Random Walk.

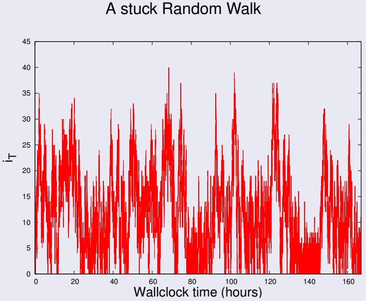
Temperature chaos: the showstopper (IV)

It looks perfect! What can go wrong?
Each clone performs a temperature Random Walk.

The simulation is *long enough* if all the clones visited all the temperatures several times. Mixing time: τ.

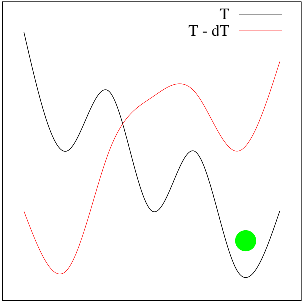
Random Walk in temperatures of a clone





Temperature chaos: the showstopper (V)

Temperature chaos: Relevant minima, completely different at nearby temperatures. T-random walk refuses to go across.



Temperature chaos: the showstopper (VI)

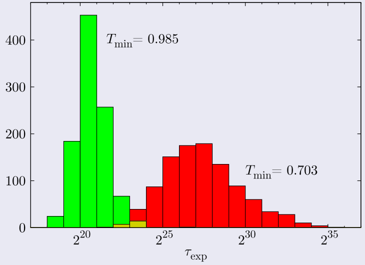
$\mathcal{T}$: Operational definition of Temperature chaos.

Temperature chaos: the showstopper (VI)

τ: Operational definition of Temperature chaos.

τ-pdf

$L = 32$, $T_c \approx 1.1$



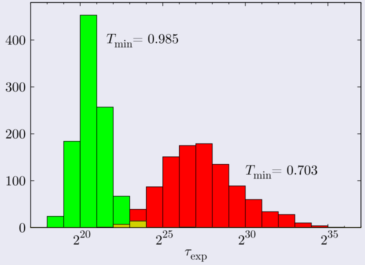
- Extreme sample-to-sample fluctuations.

Temperature chaos: the showstopper (VI)

τ: Operational definition of Temperature chaos.

τ-pdf

$L = 32,\ T_c \approx 1.1$



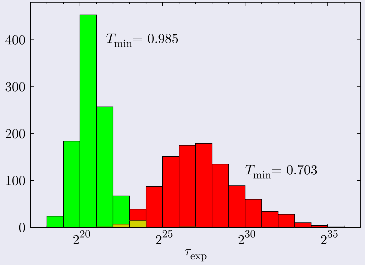
- Extreme sample-to-sample fluctuations.
- L and T sensitivity.

Temperature chaos: the showstopper (VI)

τ: Operational definition of Temperature chaos.

τ-pdf

$L = 32$, $T_c \approx 1.1$



- Extreme sample-to-sample fluctuations.
- L and T sensitivity.
- At variance with standard T-chaos studies, it is easy to observe the effect.

Contacting with conventional approach (I)

Defining T-chaos through a Markov MC dynamics is:

- Mathematically clear.

Contacting with conventional approach (I)

Defining T-chaos through a Markov MC dynamics is:

- Mathematically clear.
- Cumbersome (analytical computations??).

Contacting with conventional approach (I)

Defining T-chaos through a Markov MC dynamics is:

- Mathematically clear.
- Cumbersome (analytical computations??).
- Unsatisfying: T-chaos is supposed to be a static effect!

Contacting with conventional approach (I)

Defining T-chaos through a Markov MC dynamics is:

- Mathematically clear.
- Cumbersome (analytical computations??).
- Unsatisfying: T-chaos is supposed to be a static effect!

However, it provides a useful definition. Instead, the static approach:

- Hard for some analytically tractable models.
  Sherrington-Kirkpatrick: Rizzo-Crisanti (2003)

  Migdal-Kadanoff: McKay, Nihat-Berker, Kirkpatrick, (1982).
- Numerically, very hard to identify. Scaling laws barely known (Katzgraber& Krzakala, 2007).
- We still lack predictions relevant for experiments.

Contacting with conventional approach (II)

Our main ingredients (Fernandez, V.M.-M,Parisi,Seoane, 2013)

- Janus data base (2010): $\mathcal{O}(10^3)$ samples, $L \leq 32$, well thermalized at low temperatures.
- Wash-out thermal fluctuations (Ney-Nifle and Young, 1997)
- Look at whole distribution (not only average!)
- Large-deviation functional (the successful analytical approach for SK)

Contacting with conventional approach (II)

Our main ingredients (Fernandez, V.M.-M,Parisi,Seoane, 2013)

- Janus data base (2010): $\mathcal{O}(10^3)$ samples, $L \leq 32$, well thermalized at low temperatures.
- Wash-out thermal fluctuations (Ney-Nifle and Young, 1997)
- Look at whole distribution (not only average!)
- Large-deviation functional (the successful analytical approach for SK)

Consistency checks:

- Must correlate with dynamic approach
- Previously *subtle* effects should become visible.

Contacting with conventional approach (III)

Washing-out thermal fluctuations

Useful technicality: the chaotic parameter

$$X^J_{T_1,T_2} = \frac{\langle q^2_{T_1,T_2}\rangle_J}{\sqrt{\langle q^2_{T_1,T_1}\rangle_J \langle q^2_{T_2,T_2}\rangle_J}}$$

$X^J = 1 \longrightarrow$ no chaos; $X^J = 0 \longrightarrow$ strong chaos.

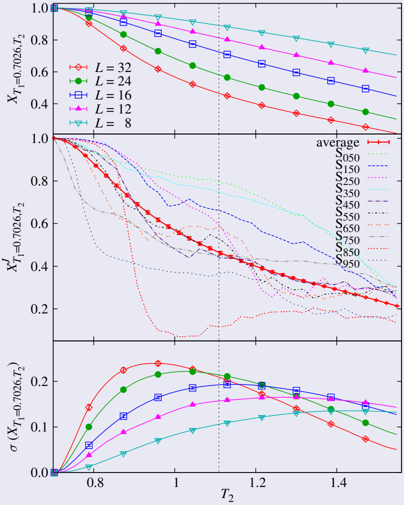
Mind that, for T_1, $T_2 < T_\mathrm{c}$ and large L, one expects

$$X^J_{T_1,T_2} \sim \langle q^2_{T_1,T_2}\rangle_J$$

$$\langle q^2_{T_1,T_1}\rangle_J \sim \langle q^2_{T_2,T_2}\rangle_J \sim 1\,.$$

Contacting with conventional approach (IV)

Average or full distribution?



- Expectations:

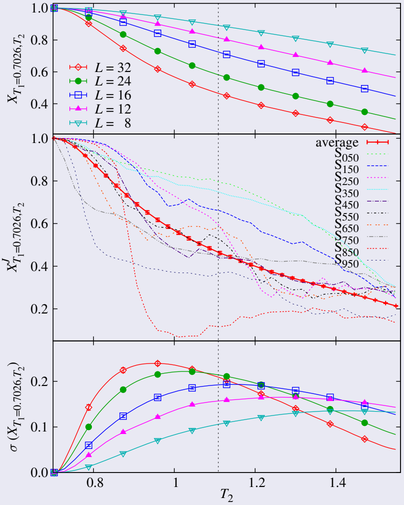
  $E_J(X^J_{T_1,T_2}) = 0$ if $T_1 \neq T_2$

  - We are far from that.
  - $T_2 > T_\mathrm{c}$: nothing happens.

$$X^J_{T_1,T_2} = \frac{\langle q^2_{T_1,T_2}\rangle_J}{\sqrt{\langle q^2_{T_1,T_1}\rangle_J \langle q^2_{T_2,T_2}\rangle_J}}$$

Contacting with conventional approach (IV)

Average or full distribution?



- Expectations:

  $$E_J(X^J_{T_1,T_2}) = 0 \text{ if } T_1 \neq T_2$$

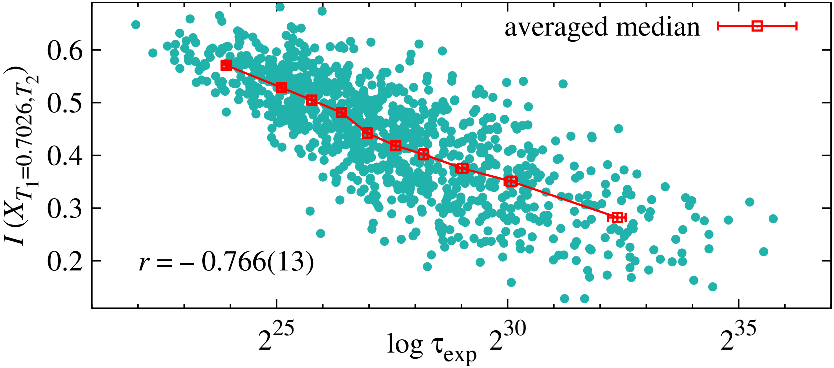
  - We are far from that.
  - $T_2 > T_c$: nothing happens.

- In the slowest samples we identify chaotic events ($\sim$ level-crossings in Quantum Mechanics).

$$I_J = \int_{T_{\min}}^{T_{\max}} \mathrm{d}T_2\, X^J_{T_{\min},T_2}$$

Contacting with conventional approach (V)

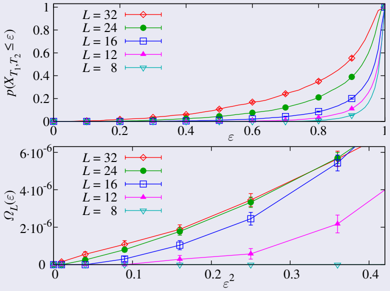
I_J correlates with τ! We are on the right track...



Contacting with conventional approach (VI)

Large deviations functional

3D, $T_1 = 0.7$, $T_2 = 0.84$, ($T_c = 1.1$).



$\Omega_L(\epsilon, T_1, T_2)$

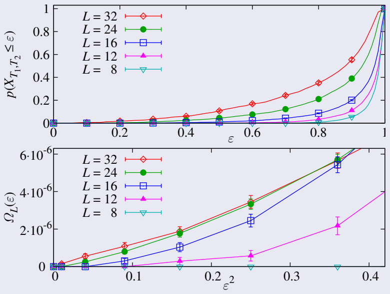
Probability$[X^J_{T_1,T_2} > \epsilon] = \mathrm{e}^{-L^D \Omega_L(\epsilon)}$

- $\Omega > 0 \rightarrow$ chaos!

Contacting with conventional approach (VI)

Large deviations functional

3D, $T_1 = 0.7$, $T_2 = 0.84$, ($T_c = 1.1$).



$\Omega_L(\epsilon, T_1, T_2)$

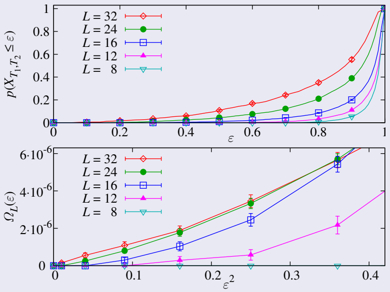
Probability$[X^J_{T_1,T_2} > \epsilon] = \mathrm{e}^{-L^D \Omega_L(\epsilon)}$

- $\Omega > 0 \rightarrow$ chaos!
- Ω_L approaches convergence within Janus' L-range.

Contacting with conventional approach (VI)

Large deviations functional

3D, $T_1 = 0.7$, $T_2 = 0.84$, ($T_c = 1.1$).



$\Omega_L(\epsilon, T_1, T_2)$

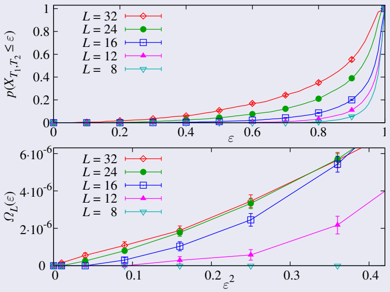
$\text{Probability}[X^J_{T_1,T_2} > \epsilon] = e^{-L^D \Omega_L(\epsilon)}$

- $\Omega > 0 \rightarrow$ chaos!
- Ω_L approaches convergence within Janus' L-range. $L = 8, 12$ chaos is extremely rare.

Contacting with conventional approach (VI)

Large deviations functional

3D, $T_1 = 0.7$, $T_2 = 0.84$, ($T_c = 1.1$).



$\Omega_L(\epsilon, T_1, T_2)$

Probability$[X^J_{T_1,T_2} > \epsilon] = \mathrm{e}^{-L^D \Omega_L(\epsilon)}$

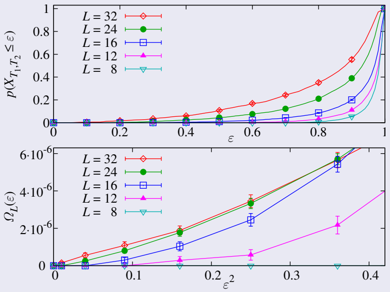
- $\Omega > 0 \to$ chaos!
- Ω_L approaches convergence within Janus' L-range. $L = 8, 12$ chaos is extremely rare.
- Crude parameterization

$$\Omega_{T_1,T_2}(\epsilon) \propto |T_1 - T_2|^b \epsilon^\beta$$

Contacting with conventional approach (VI)

Large deviations functional

3D, $T_1 = 0.7$, $T_2 = 0.84$, ($T_c = 1.1$).



$\Omega_L(\epsilon, T_1, T_2)$

$\text{Probability}[X^J_{T_1,T_2} > \epsilon] = \mathrm{e}^{-L^D \Omega_L(\epsilon)}$

- $\Omega > 0 \to$ chaos!
- Ω_L approaches convergence within Janus' L-range. $L = 8, 12$ chaos is extremely rare.
- Crude parameterization

$$\Omega_{T_1,T_2}(\epsilon) \propto |T_1 - T_2|^b \epsilon^\beta$$

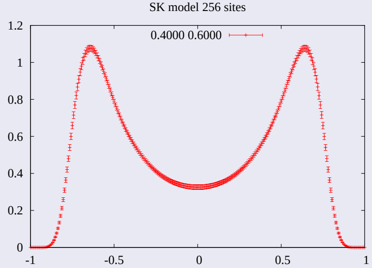
Weak-chaos scaling (Katzgraber& Krzakala, 2007) explained: $\zeta = D/b = 1.07(2)$

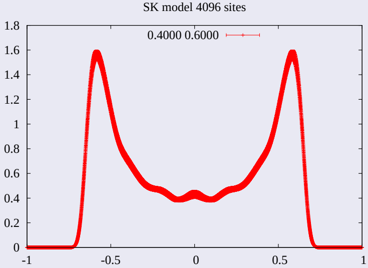
Chaos length: $\xi_C = L^a$ unless $\beta = 1$.

Contacting with conventional approach (VII)

SK finally yields to numerics (Billoire 2014)

Rizzo-Crisanti and Rizzo-Parisi compute $\tilde{\Omega}(q_{T1,T2})\ldots$



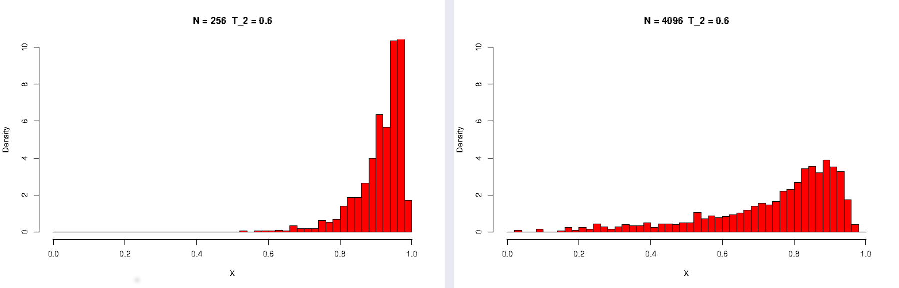


Contacting with conventional approach (VII)

SK finally yields to numerics (Billoire 2014)

Rizzo-Crisanti and Rizzo-Parisi compute $\tilde{\Omega}(q_{T1,T2})\ldots$

But $\Omega(X^J_{T_1,T_2} > \epsilon) \gg \tilde{\Omega}(q_{T1,T2})$ (see also Rizzo 2014)



Contacting with conventional approach (VIII)

Take-home messages

- Dynamic methods might be preferable in real calculations.

Contacting with conventional approach (VIII)

Take-home messages

- Dynamic methods might be preferable in real calculations.
- Three (rather than 2) scaling variables: N, ΔT and ϵ.

Contacting with conventional approach (VIII)

Take-home messages

- Dynamic methods might be preferable in real calculations.
- Three (rather than 2) scaling variables: N, ΔT and ϵ.
- Temperature chaos is generic for large problem size N.

Contacting with conventional approach (VIII)

Take-home messages

- Dynamic methods might be preferable in real calculations.
- Three (rather than 2) scaling variables: N, ΔT and ϵ.
- Temperature chaos is generic for large problem size N.
- In practice, specially for small N:
  1. The large majority of problem instances are *easy* (small τ).
  2. For some of them, though, τ inordinately large.
  3. The larger is N, the more frequently missbehaving instances appear $\longrightarrow$ difficult to assess algorithmic scaling with N.

Is quantum-computing our breakthrough? (I)

From an impressive insight (Richard P. Feynman, 1982)

NP-problems, specially simulation of quantum systems: best solved on quantum computers. . .

Is quantum-computing our breakthrough? (I)

...to (possibly) quantum-computing objects (2014).

D-wave Two

Is quantum-computing our breakthrough? (I)

. . . to (possibly) quantum-computing objects (2014).

A quantum annealer should:

1. Read accurately an instance.
2. Add a strong *transverse* magnetic field.

D-wave Two

Is quantum-computing our breakthrough? (I)

...to (possibly) quantum-computing objects (2014).

A quantum annealer should:

1. Read accurately an instance.
2. Add a strong *transverse* magnetic field.
3. At low enough T...
4. With low noise...
5. Slowly take field $\to 0$.

D-wave Two

Is quantum-computing our breakthrough? (I)

...to (possibly) quantum-computing objects (2014).

A quantum annealer should:

1. Read accurately an instance.
2. Add a strong *transverse* magnetic field.
3. At low enough T...
4. With low noise...
5. Slowly take field $\rightarrow 0$.

All requirements met? $\rightarrow$ global minimum.

D-wave Two

Is quantum-computing our breakthrough? (II)

D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).

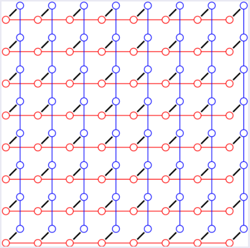
Is quantum-computing our breakthrough? (II)

D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

Two-dimensional penalties:

Chimera



Each blob: 8 q-bits

Is quantum-computing our breakthrough? (II)

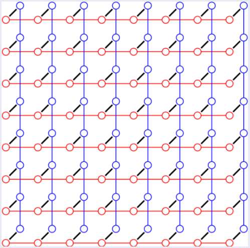
D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

Two-dimensional penalties:

- No SG phase for $T > 0$
  $T_\mathrm{c} = 0 \longrightarrow$ easier problems.

Chimera



Each blob: 8 q-bits

Is quantum-computing our breakthrough? (II)

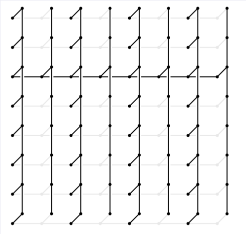
D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

Two-dimensional penalties:

- No SG phase for $T > 0$
  $T_{\mathrm{c}} = 0 \longrightarrow$ easier problems.
- Small decycling set

Chimera



Main graph in Selby heuristics: 78% in a single tree (no loops!)

Is quantum-computing our breakthrough? (II)

D-wave solves a toy problem:

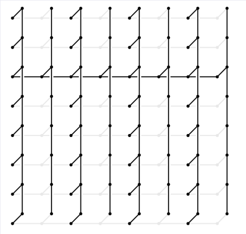
- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

Two-dimensional penalties:

- No SG phase for $T > 0$
  $T_c = 0 \longrightarrow$ easier problems.
- Small decycling set

  $T = 0$ heuristics better than thermal methods (i.e. PT).

Chimera



Main graph in Selby heuristics: 78% in a single tree (no loops!)

Is quantum-computing our breakthrough? (II)

D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

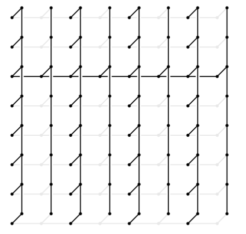
Two-dimensional penalties:

- No SG phase for $T > 0$
  $T_c = 0 \longrightarrow$ easier problems.
- Small decycling set

  $T = 0$ heuristics better than thermal methods (i.e. PT).

  $T > 0$ 2D-methods better than Monte Carlo (Middleton 2011, square lattice: $N = 512^2 \approx 2.6 \times 10^5$).

Chimera



Main graph in Selby heuristics: 78% in a single tree (no loops!)

Is quantum-computing our breakthrough? (II)

D-wave solves a toy problem:

- Small problems $N = 512$ (actually, $N = 503$ in USC).
- Chimera graph: non-planar but 2D-like.

Two-dimensional penalties:

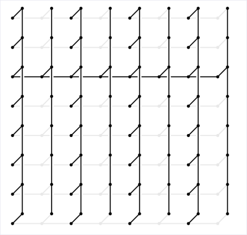
- No SG phase for $T > 0$
  $T_c = 0 \longrightarrow$ easier problems.
- Small decycling set

  $T = 0$ heuristics better than thermal methods (i.e. PT).

  $T > 0$ 2D-methods better than Monte Carlo (Middleton 2011, square lattice: $N = 512^2 \approx 2.6 \times 10^5$).

  Are we learning something?

Chimera



Main graph in Selby heuristics: 78% in a single tree (no loops!)

Is quantum-computing our breakthrough? (III)

In three spatial dimensions only thermal annealing works.
Real question: Is there chaos in the chimera lattice?

Is quantum-computing our breakthrough? (III)

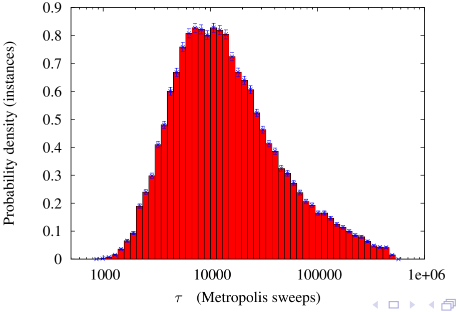
In three spatial dimensions only thermal annealing works.
Real question: Is there chaos in the chimera lattice?

Middleton et al.: chaos in square lattice, but $N = 2.6 \times 10^5$.
Chaos with only $N = 503$ q-bits?

Is quantum-computing our breakthrough? (III)

In three spatial dimensions only thermal annealing works.
Real question: Is there chaos in the chimera lattice?

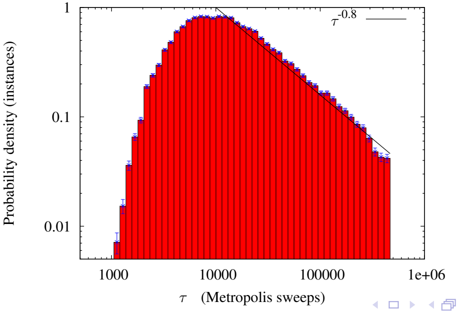
Middleton et al.: chaos in square lattice, but $N = 2.6 \times 10^5$.
Chaos with only $N = 503$ q-bits?
Not at first sight. . .



Is quantum-computing our breakthrough? (III)

In three spatial dimensions only thermal annealing works.
Real question: Is there chaos in the chimera lattice?

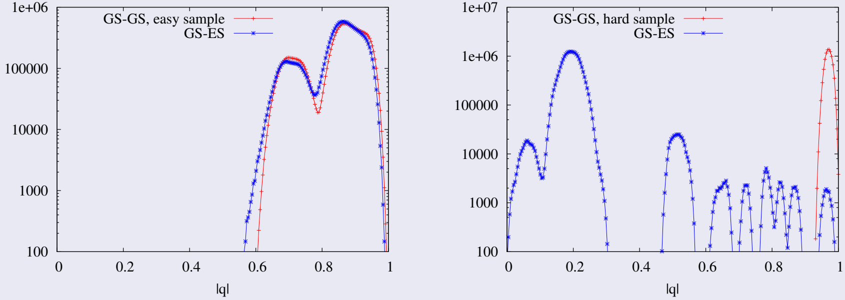
Middleton et al.: chaos in square lattice, but $N = 2.6 \times 10^5$.
Chaos with only $N = 503$ q-bits?
Not at first sight. . . But look at that fat tail!
2 in 10^4 instances: $\tau \gg 10^7$.



Is quantum-computing our breakthrough? (IV)

As usual, τ pinpoints peculiar samples...

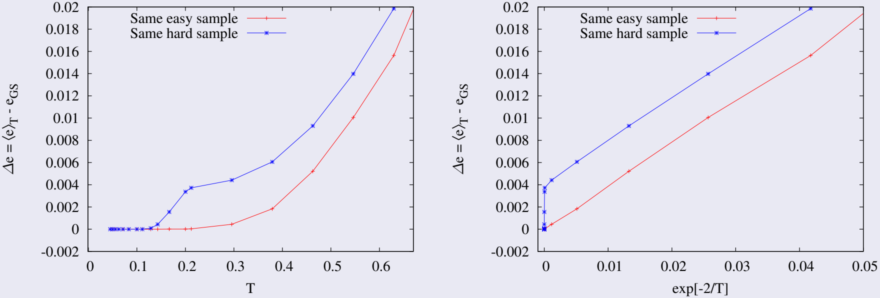
Overlap betwen Ground-State and 1$^{\rm st}$ Excited-State...



Is quantum-computing our breakthrough? (IV)

As usual, τ pinpoints peculiar samples. . .

. . . or energy-dependence with T.



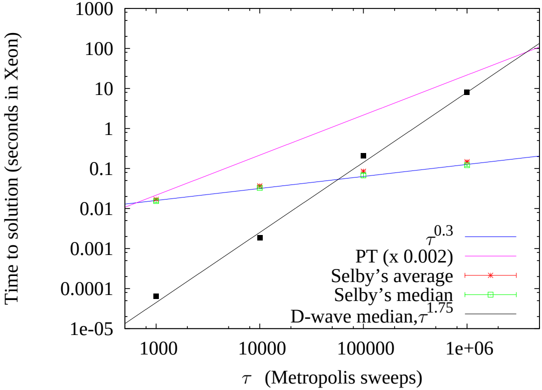
Is quantum-computing our breakthrough? (V)

Meaningful algorithmic classification at fixed N: τ-scaling.

Is quantum-computing our breakthrough? (V)

Meaningful algorithmic classification at fixed N: τ-scaling.

Parallel-Tempering: τ^1, Selby heuristics (2D!): $\tau^{b\approx 0.3}$, D-wave: $\tau^{a\approx 1.75}$.



Conclusions

- The Janus computer: new window for spin-glasses.
  A new generation will soon enter into operation.
- Not everything in Spin-Glasses Physics is self-averaging.
  Temperature chaos is a clear example.
- Sometimes, studying dynamics (τ) might be the easiest way to learn about statics.
- Temperature chaos is a major obstacle. Is quantum annealing an alternative?

Conclusions

- The Janus computer: new window for spin-glasses.
  A new generation will soon enter into operation.
- Not everything in Spin-Glasses Physics is self-averaging.
  Temperature chaos is a clear example.
- Sometimes, studying dynamics (τ) might be the easiest way to learn about statics.
- Temperature chaos is a major obstacle. Is quantum annealing an alternative?
  - D-wave is a candidate quantum-annealer. Object to be experimentally investigated, rather than a finished product.

Conclusions

- The Janus computer: new window for spin-glasses.
  A new generation will soon enter into operation.
- Not everything in Spin-Glasses Physics is self-averaging.
  Temperature chaos is a clear example.
- Sometimes, studying dynamics (τ) might be the easiest way to learn about statics.
- Temperature chaos is a major obstacle. Is quantum annealing an alternative?
  - D-wave is a candidate quantum-annealer. Object to be experimentally investigated, rather than a finished product.
  - Currently, performance not competitive with Parallel Tempering.

Conclusions

- The Janus computer: new window for spin-glasses.
  A new generation will soon enter into operation.
- Not everything in Spin-Glasses Physics is self-averaging.
  Temperature chaos is a clear example.
- Sometimes, studying dynamics (τ) might be the easiest way to learn about statics.
- Temperature chaos is a major obstacle. Is quantum annealing an alternative?
  - D-wave is a candidate quantum-annealer. Object to be experimentally investigated, rather than a finished product.
  - Currently, performance not competitive with Parallel Tempering.
  - Reasons for failure intrinsic? Current investigation.

Many thanks to…

- The Janus collaboration,
- Alain Billoire,
- Itay Hen,
- The meeting organizers,
- …and to you (the audience), for your attention!