Quantum annealing with more than one hundred qubits

Sergio Boixo,[1] Troels F. Rønnow,[2] Sergei V. Isakov,[2] Zhihui Wang,[3] David Wecker,[4] Daniel A. Lidar,[5] John M. Martinis,[6] and Matthias Troyer*[2]

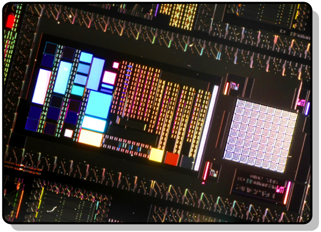
arXiv:1304.4595

Journal Club

Daniel Becker

Central Claims of Paper

- **D-Wave One** device successfully used to solve NP hard optimization problems



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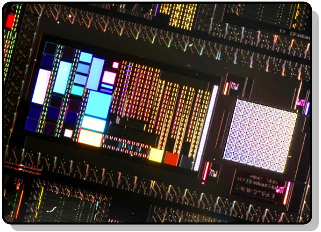

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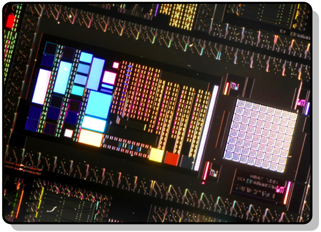

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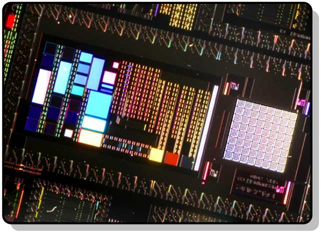
- large-scale entanglement of annealed state after times much longer than coherence time of device
- promising prospects to see "quantum speedup" in larger systems (**D-Wave Two** with 512 qubits)



Adiabatic Quantum Computing

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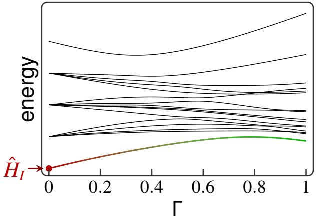

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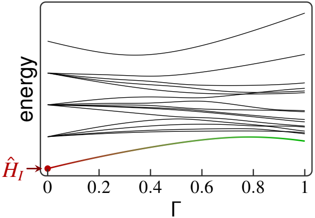

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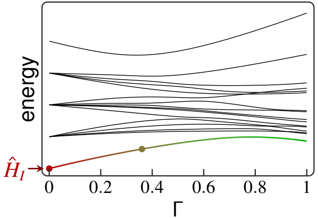

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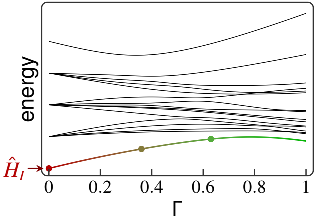

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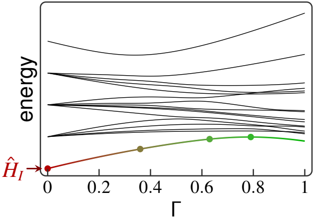

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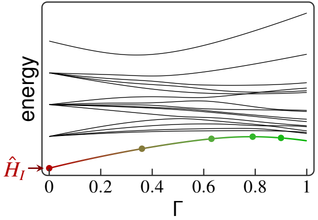

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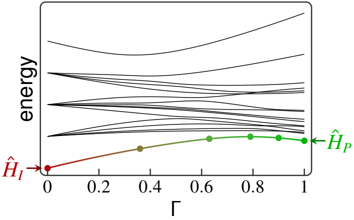

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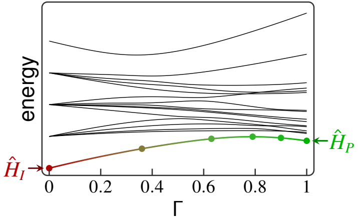

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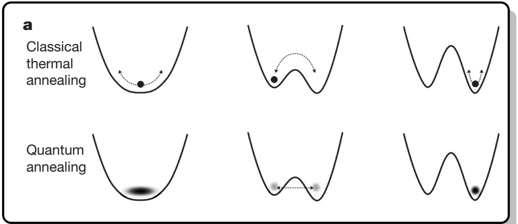
- equivalent to quantum circuit model
- D-Wave: “no error-correction needed”

Classical VS Quantum Annealing

general principle

slowly increase ratio of:

1. size of energy barrier between system states
2. thermal (classical) and quantum fluctuations

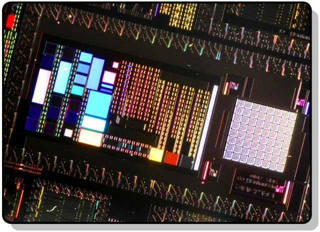


classical:
keep Hamiltonian constant and adiabatically cool the system

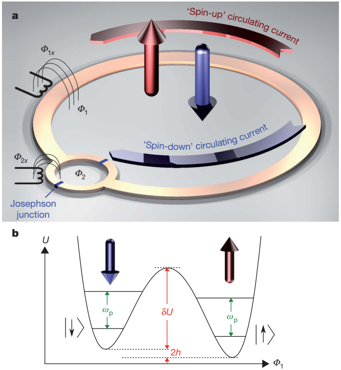
quantum:
keep temperature constant (at zero) and adiabatically switch Hamiltonian

D-Wave's Quantum Annealing Device

a "special purpose optimization engine"



photograph of 512 qubit D-Wave chip



flux qubit

design parameters:

- quadratic lattice of 8 flux qubits per unit cell (temp. $\sim 20mK$)
- flux qubit pairs inductively coupled
- interaction tunable in size and sign
- coherence time: tens of nano-seconds

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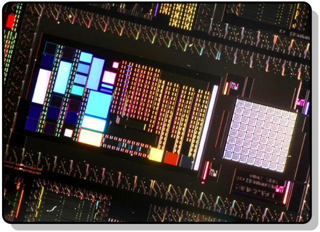

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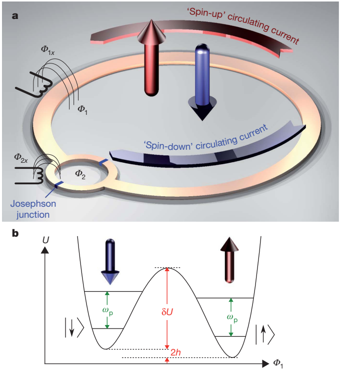

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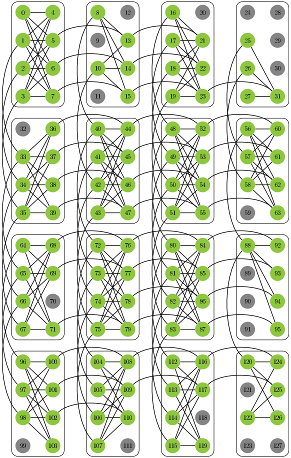
The D-Wave Optimization Problem

the promise

solve (NP hard?) optimization problem encoded into “Chimera” graph



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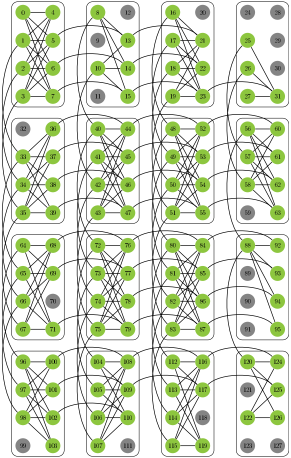

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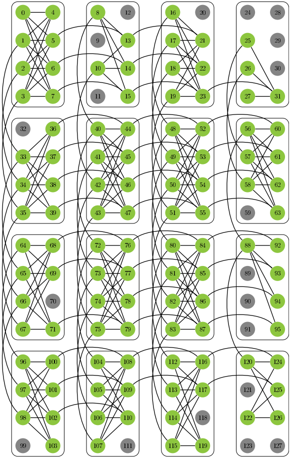

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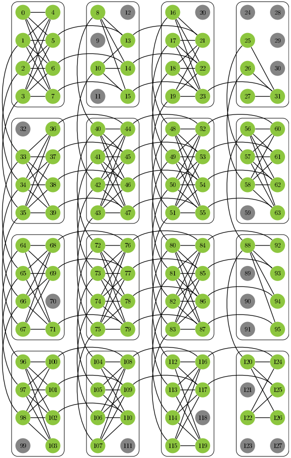

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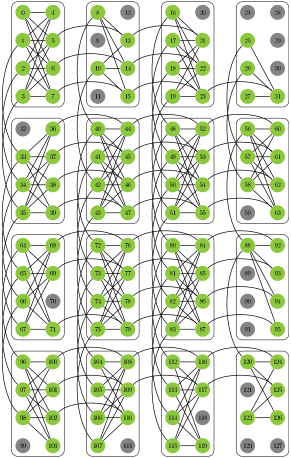

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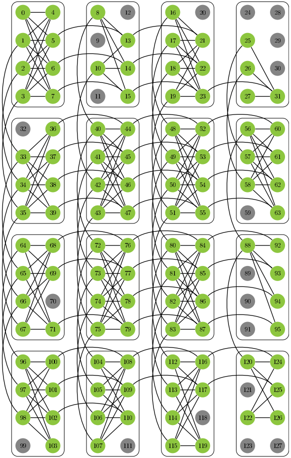


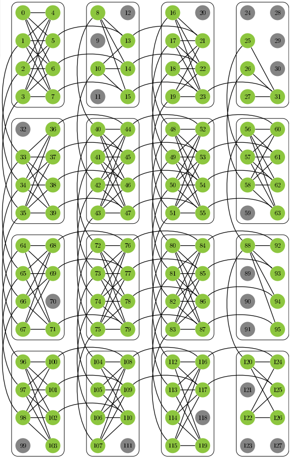
the ultimate goal

solve NP hard problems faster than classical computers (not in polynomial time)

What was Measured/Computed?

the “D-Wave One” device

128 flux qubits in a lattice of 4×4 unit cells



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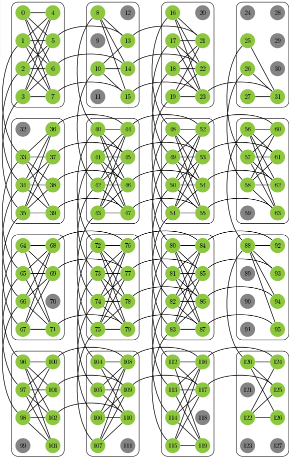

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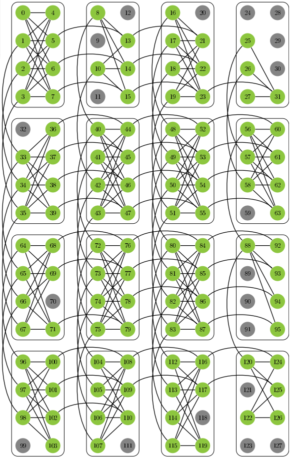

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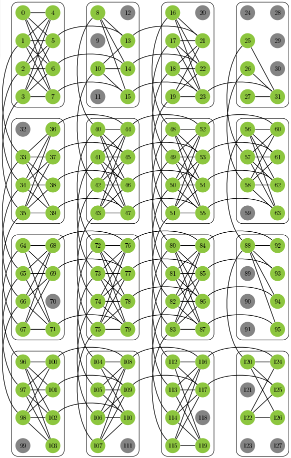

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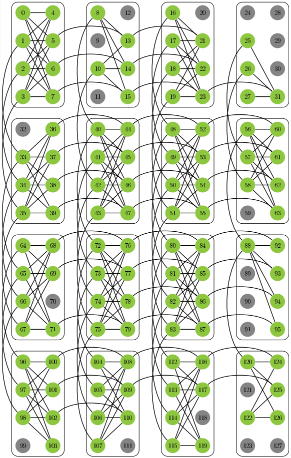

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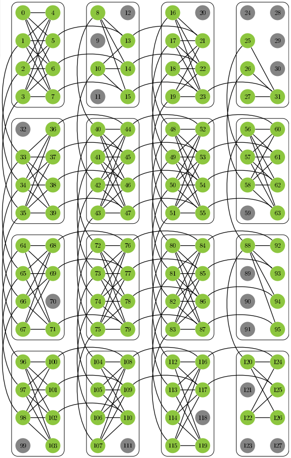

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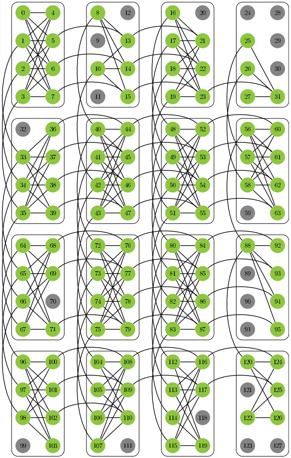

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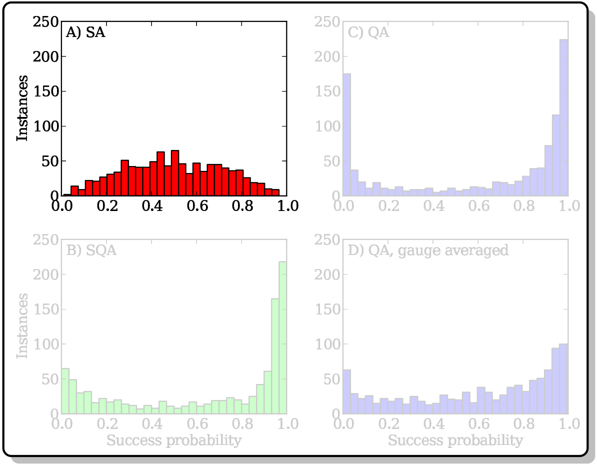
Comparing Success Probability Histograms

classical simulated annealing: monomodal distribution



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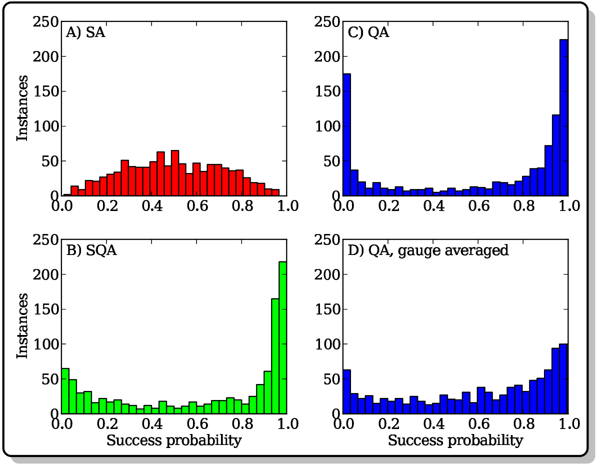
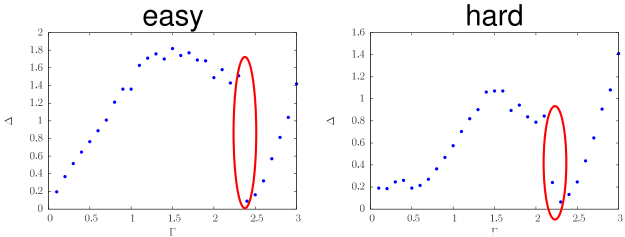


quantum annealing: bimodal distribution

Easy and Hard Instances



- trivial gap closing for all instances around $\Gamma \approx 2.3$

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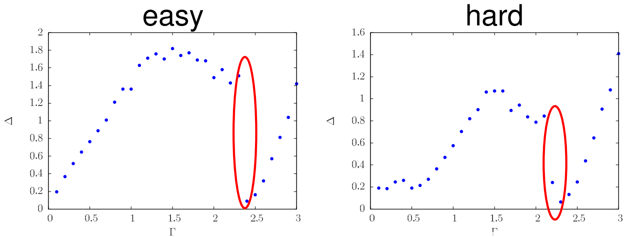

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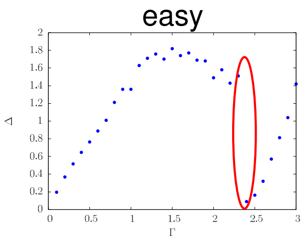

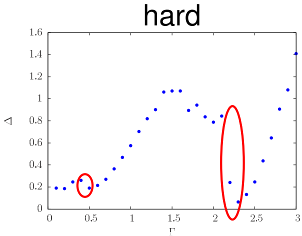

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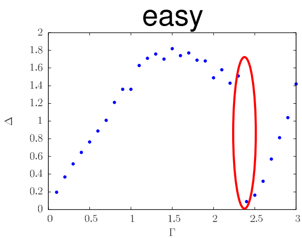

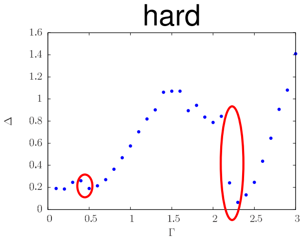

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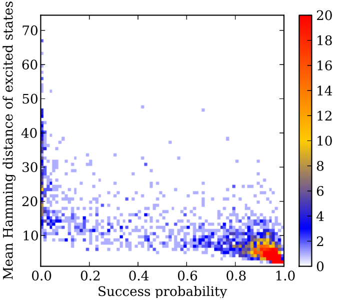
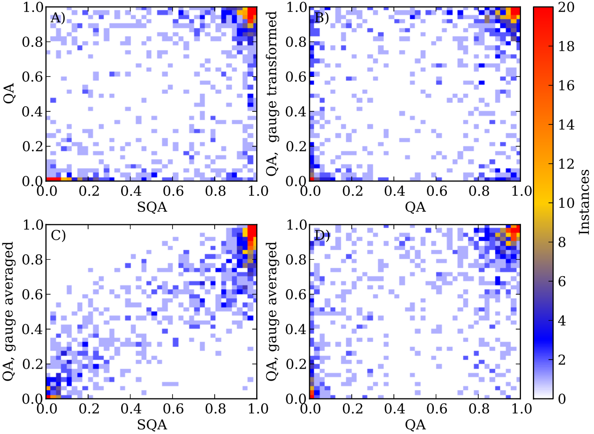
- “easy” instances: no further avoided level crossings
- “hard” instances: small gap avoided level crossings for small Γ
- Hamming distance between ground and excited state larger for hard instances



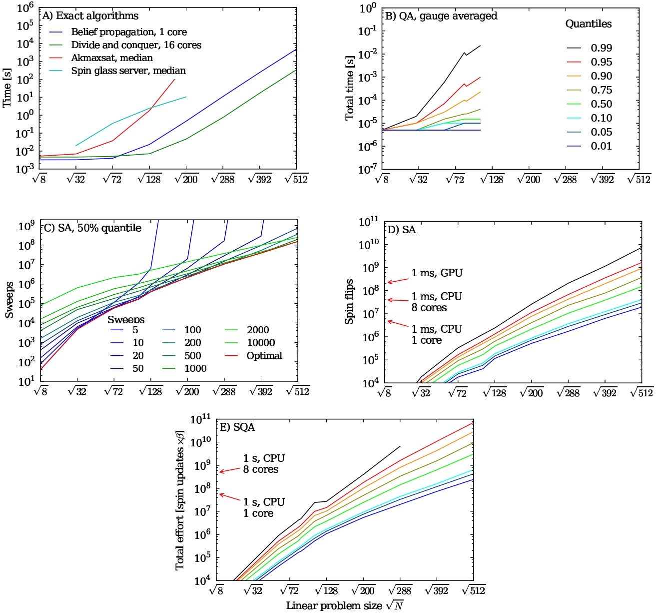
Correlations Between QA and SQA

- gauge averaging to compensate calibration errors



- uncorrelated measurement and simulation results explained by calibration errors

Scaling of Computation Time



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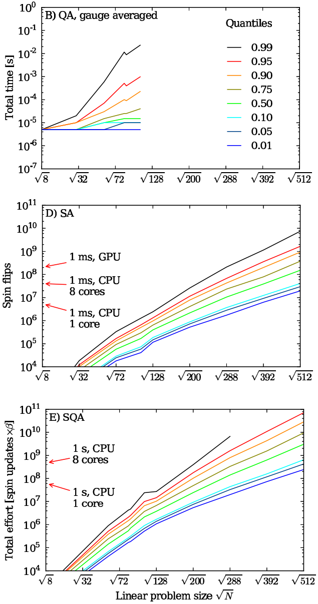

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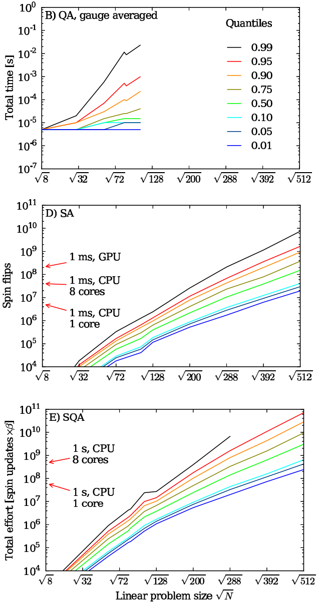
- better scaling than $\exp[O(\sqrt{N})]$ for annealing curves



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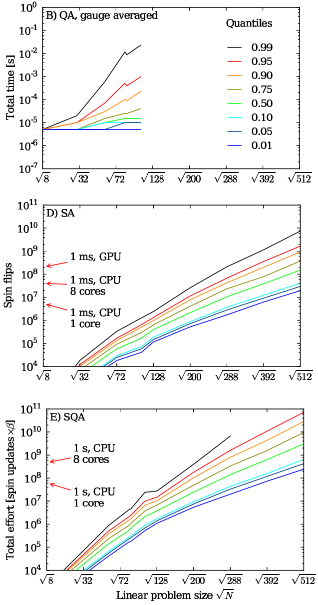

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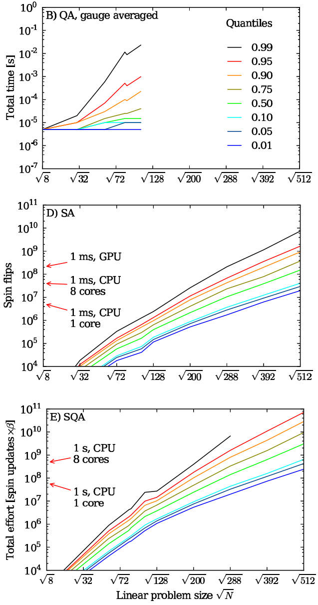

Scaling of Computation Time

- for D-Wave device (QA) only upper limit $\longrightarrow$ scaling curves too flat
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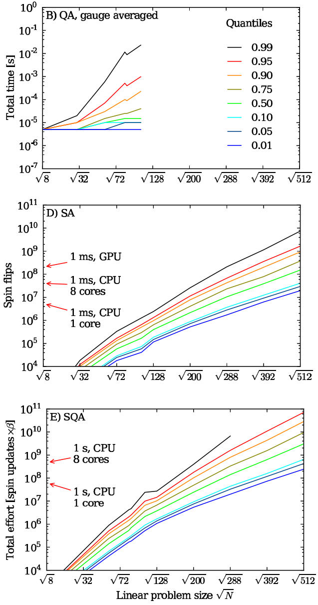
- future work: quantum speedup of QA for larger systems?



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concise summary: http://www.scottaaronson.com/blog/

Mathias Troyer:

- simulated classical annealing on standard PC faster than D-Wave device

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- larger systems (more) volatile against: noise, thermal fluctuations, single-qubit decoherence

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John A. Smolin, Graeme Smith, arXiv:1305.4904

**classical (thermal) annealing NOT
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classical analog to QA:
adiabatic ground state dragging

Classical Adiabatic Ground State Dragging

John A. Smolin, Graeme Smith, arXiv:1305.4904

classical SO(2) spins (compass needles)

potential energy

$$V_{\text{trans}} = -\sum_i \sin(\theta_i) B_x$$
$$V_{\text{Ising}} = \sum_i \cos(\theta_i) h_i + \sum_{i<j} \cos(\theta_i)\cos(\theta_j) J_{ij}$$

adiabatic switching

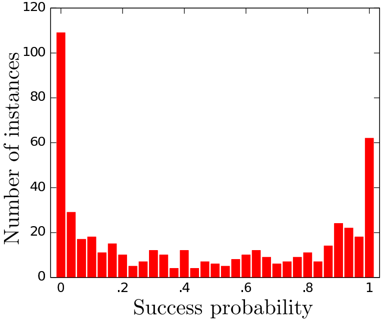
$$V(\Gamma) = (1-\Gamma) V_{\text{trans}} + \Gamma V_{\text{Ising}}$$

equations of motion

$$\frac{d}{dt}\theta_i = \dot{\theta}_i \quad \text{and} \quad \frac{d}{dt}\dot{\theta}_i = \frac{d}{d\theta_i} V(t)$$

initial state

$$|\rightarrow\rightarrow\rightarrow \cdots \rightarrow\rangle$$



Comment from Wang et al.

Wang et al., arXiv:1305.5837

- consider SO(3) model of semi-classical spins described by LLG equation
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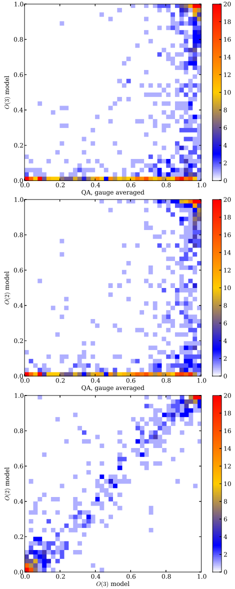
- bimodal distribution in ground state dragging of both classical models



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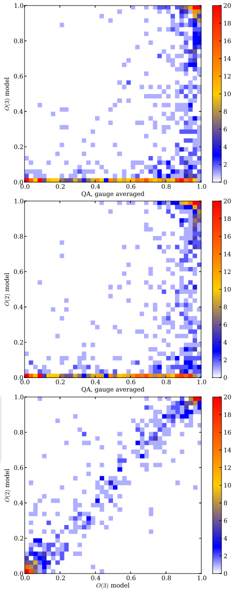
- weak correlations between classical models and quantum system



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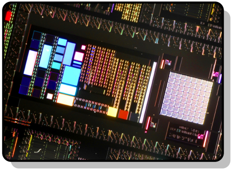

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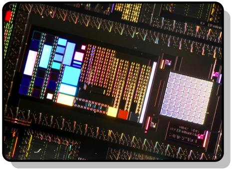

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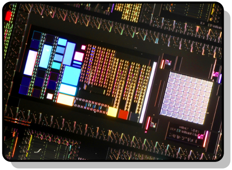

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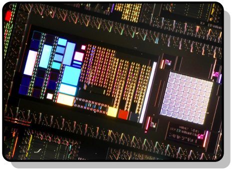

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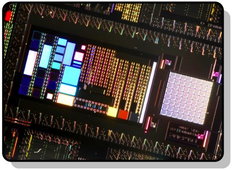

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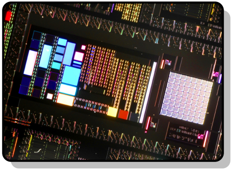

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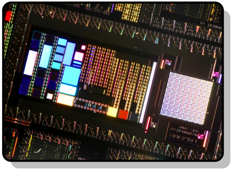

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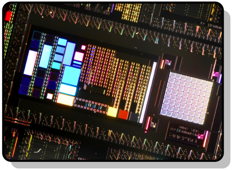

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