Quantum Algorithmic Breakeven: on scaling up with noisy qubits

ICQSIM2017 : International Conference on Quantum Simulation

Paris
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Daniel Lidar, USC

To scale up indefinitely we must break even first

break even

phrase of break

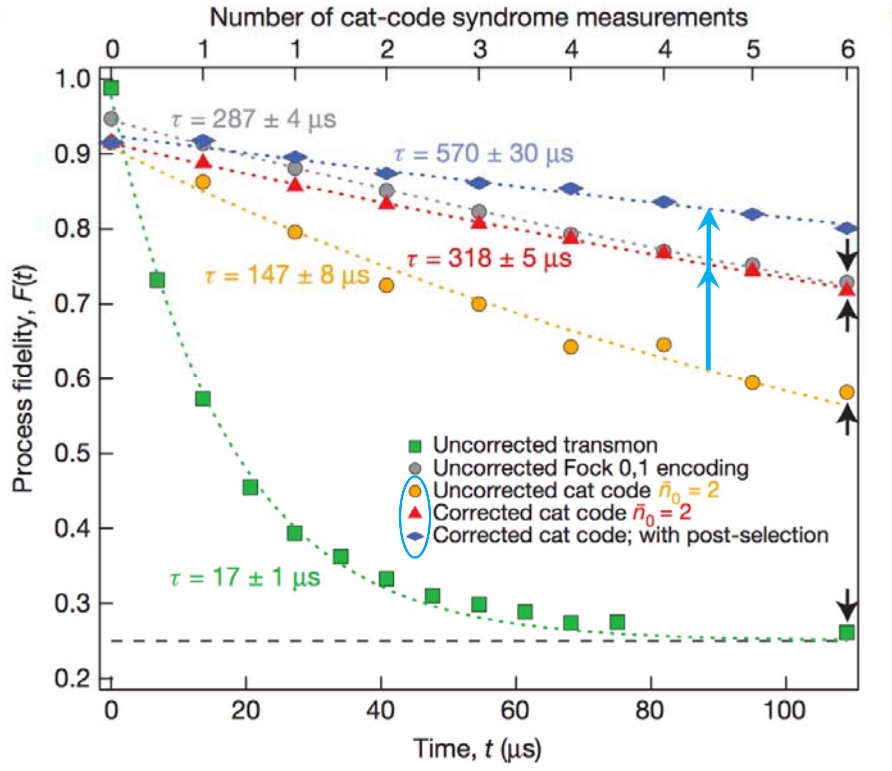
1. reach a point in a business venture when the profits are equal to the costs.
   "the firm will break even at the operating level this year"

What is quantum breakeven?

- Achieving the accuracy threshold for fault tolerant quantum computation
  - Performance guarantee is highly model-dependent:
    threshold = x means different things for different models (e.g., Markovian vs non-Markovian noise)

- A logical qubit with higher coherence than the constituent physical qubits
- A logical gate with higher fidelity than the constituent physical gates
  - No guarantee this will continue to hold at larger scales (more qubits & gates): unanticipated errors may appear

- Can we replace with a breakeven notion that
  - is model-independent?
  - holds at large scales?



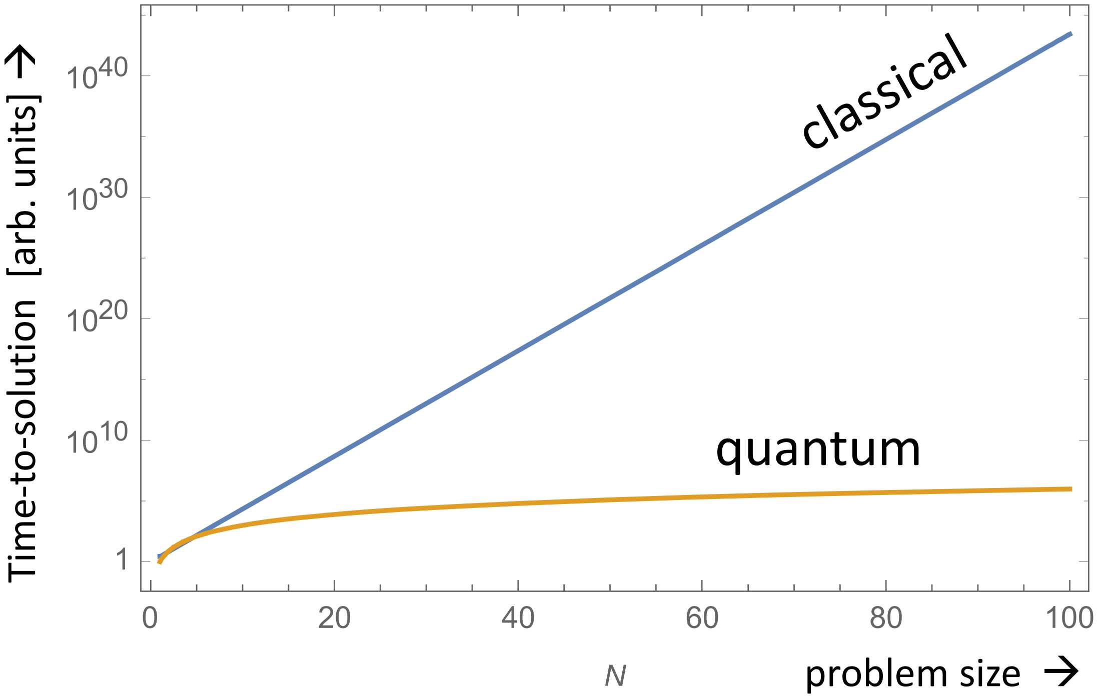
Ofek et al. (Yale group), Nature 536, 441 (2016)

Consider Algorithmic Scaling

Algorithmic Scaling

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

ideal case: no decoherence

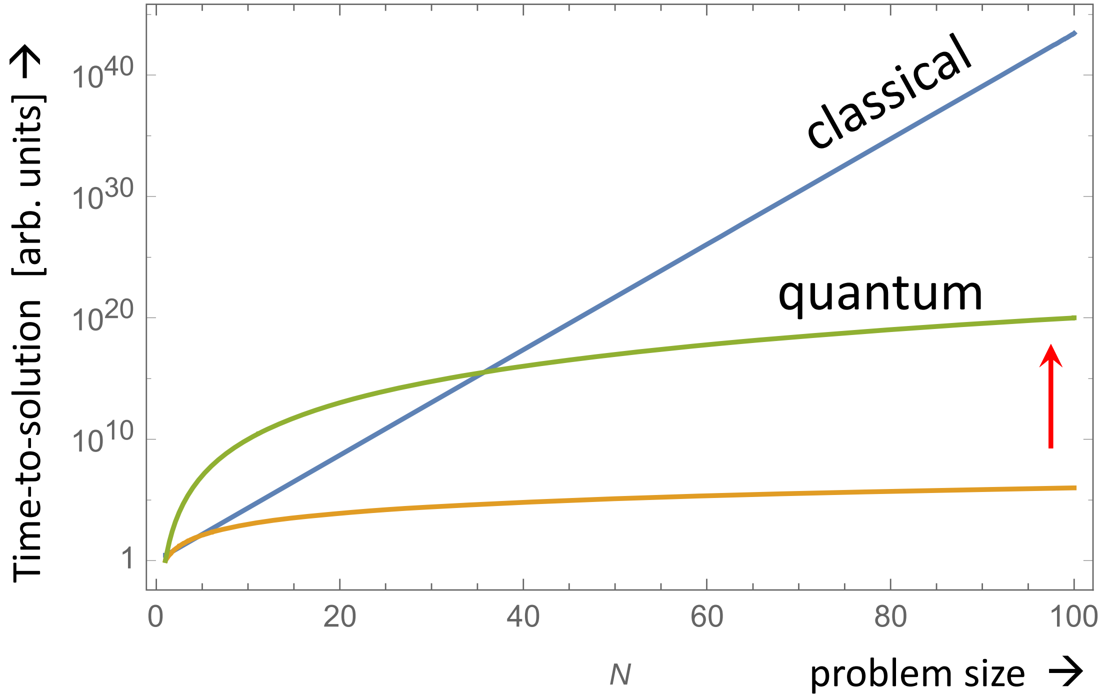


quantum scaling advantage clear for all N

Algorithmic Scaling

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with decoherence

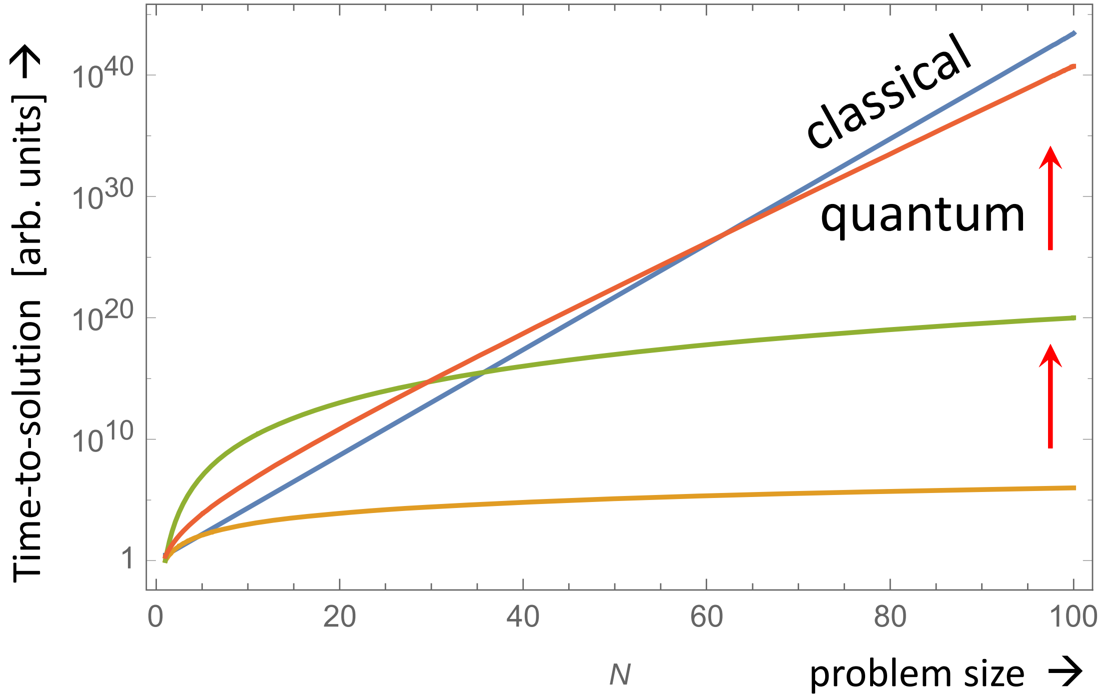


quantum scaling advantage only clear for large *N*

Algorithmic Scaling

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with more decoherence

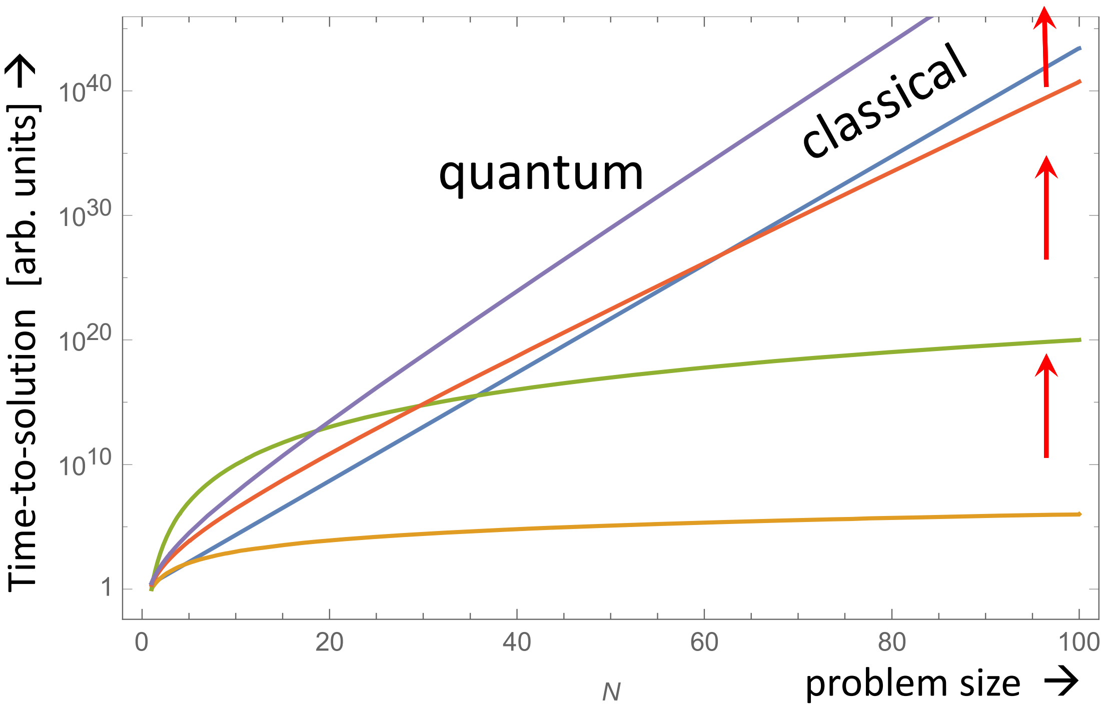


quantum scaling advantage only clear for even larger N

Algorithmic Scaling

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with too much decoherence



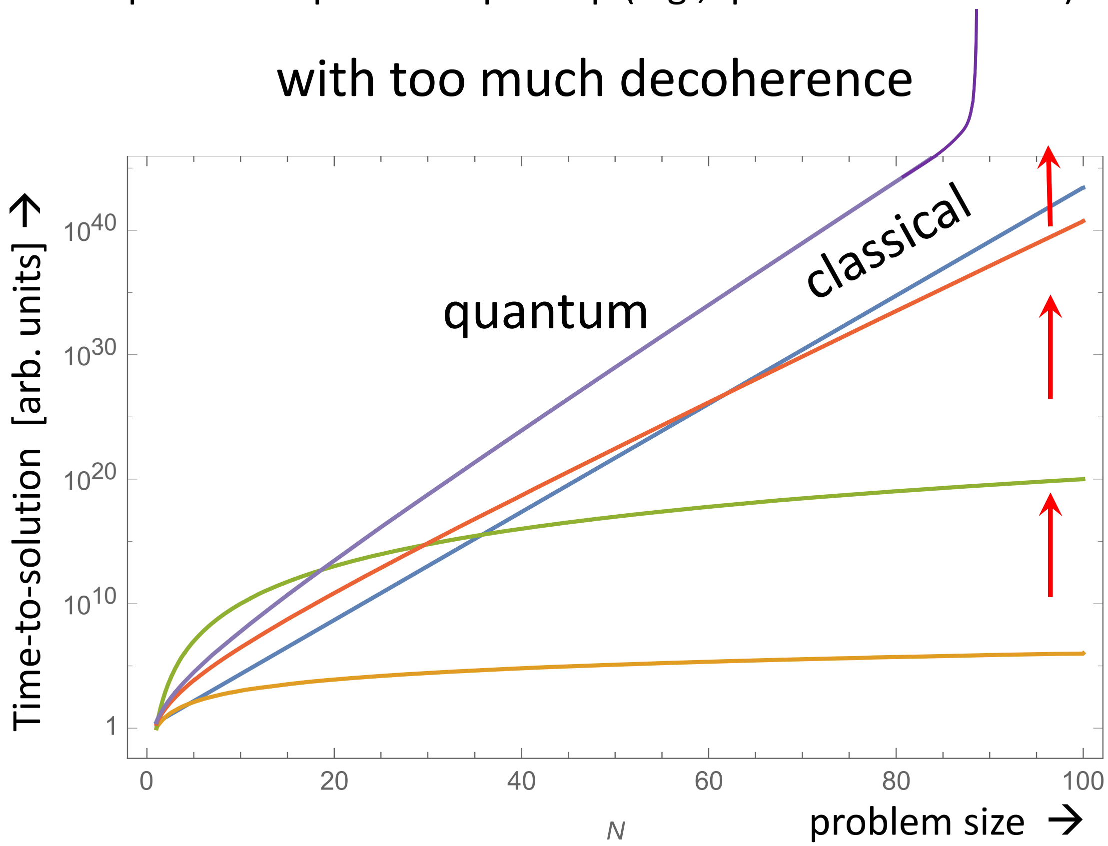
quantum scaling disadvantage

Algorithmic Scaling

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with too much decoherence

quantum blowup



Enter QEC

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with decoherence + QEC

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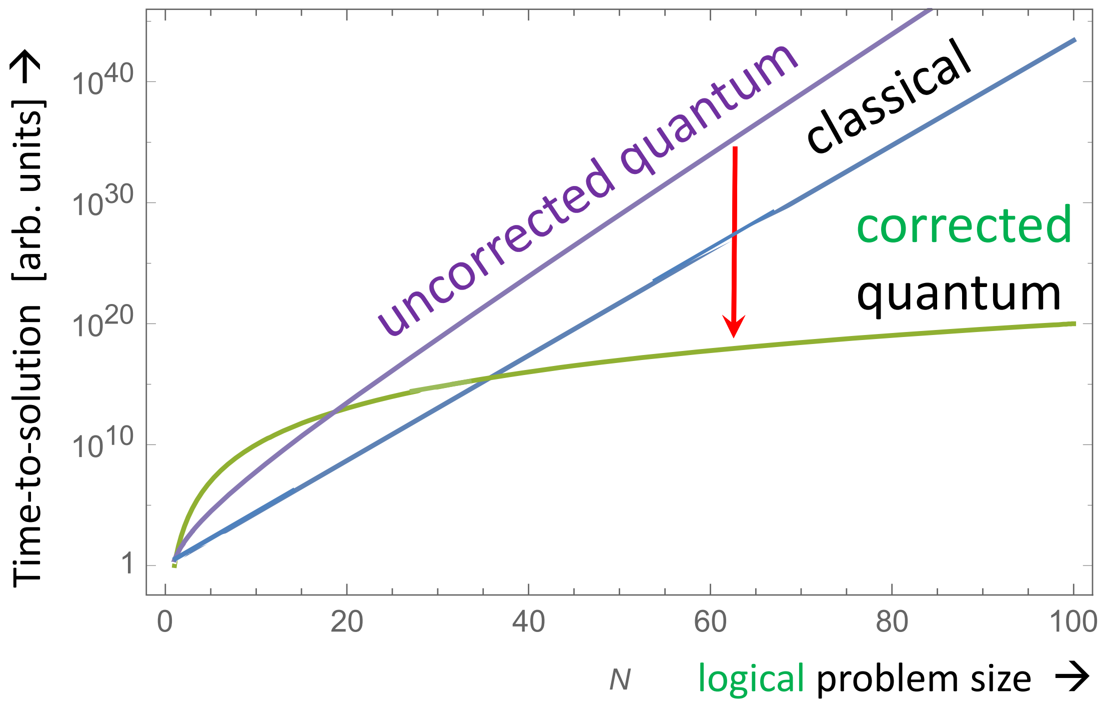


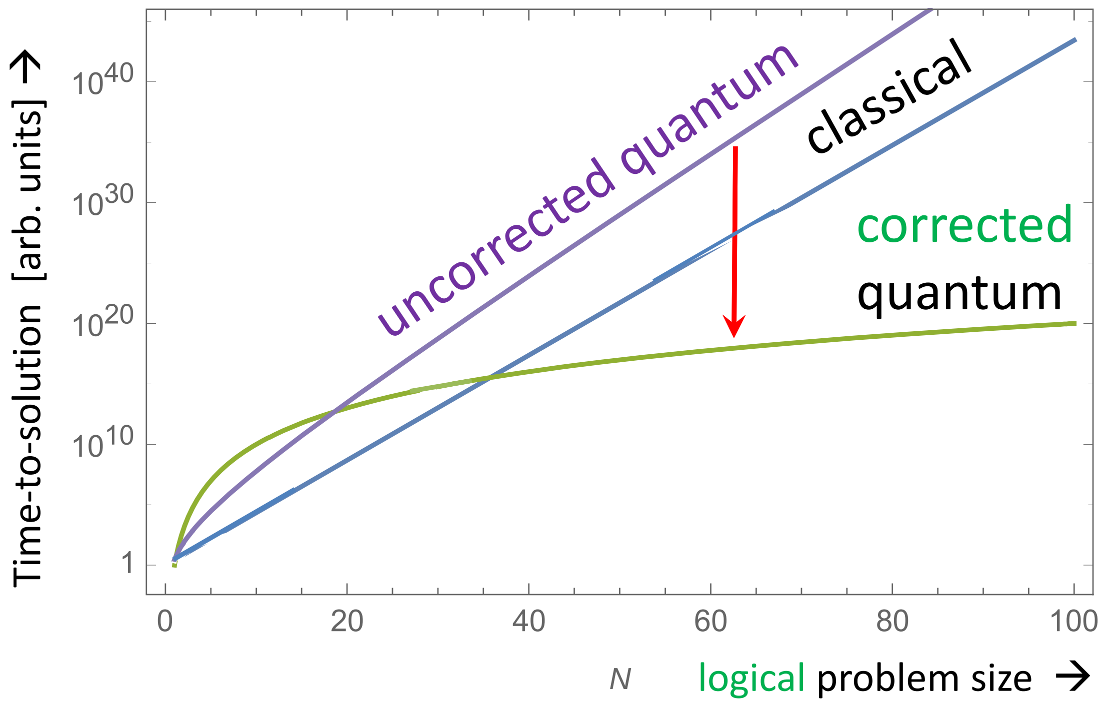
quantum scaling advantage returns

Algorithmic success with QEC: corrected quantum scaling is better than classical & uncorrected quantum

Algorithmic Success with QEC

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with decoherence + QEC



achieving this with quantum hardware =

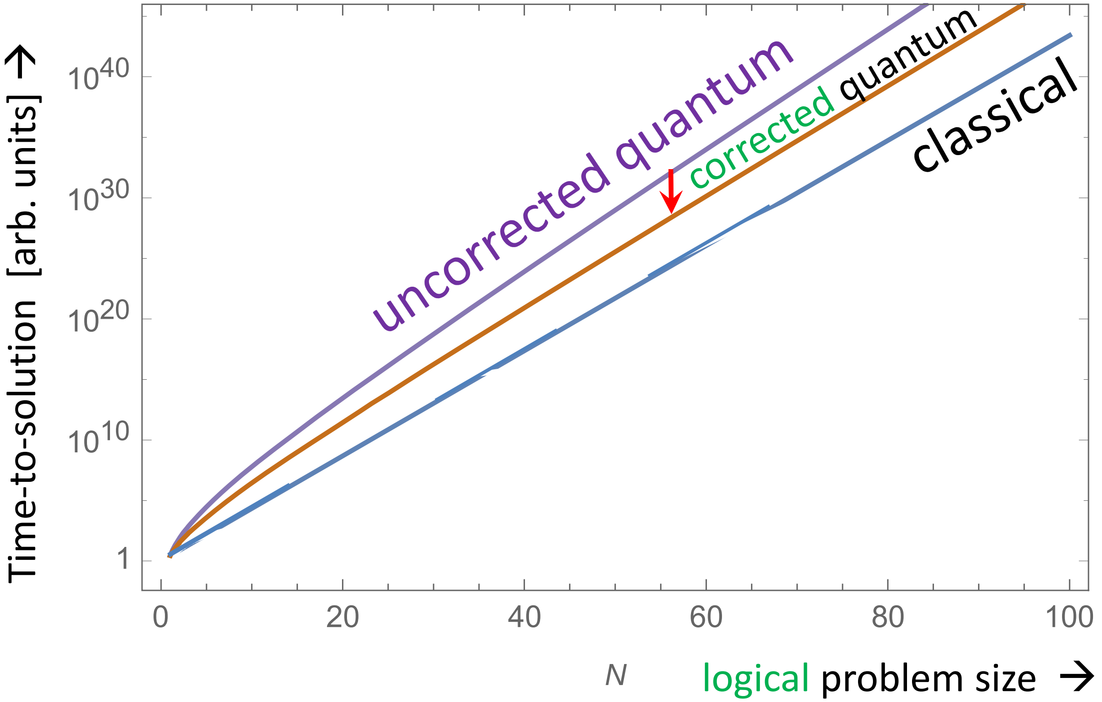
Algorithmic success with QEC: corrected quantum scaling is better than classical & uncorrected quantum

Algorithmic Breakeven with QEC

Run an algorithm with exponential quantum speedup (e.g., quantum simulation) on quantum hardware

with decoherence + QEC

More modest:



model-independent

holds at large scales

Can **this** be achieved with existing quantum hardware?

Algorithmic breakeven with QEC: **corrected quantum scaling is no worse than uncorrected quantum, but not necessarily better than classical**

Algorithmic breakeven with quantum annealing

K. Pudenz, T. Albash, DL, Nature Comm. 5, 3243 (2014); PRA 91, 042302 (2015)

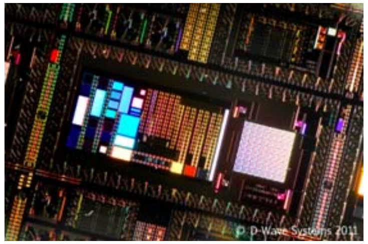
Algorithmic breakeven with quantum annealing

Problem:
find ground state energy of

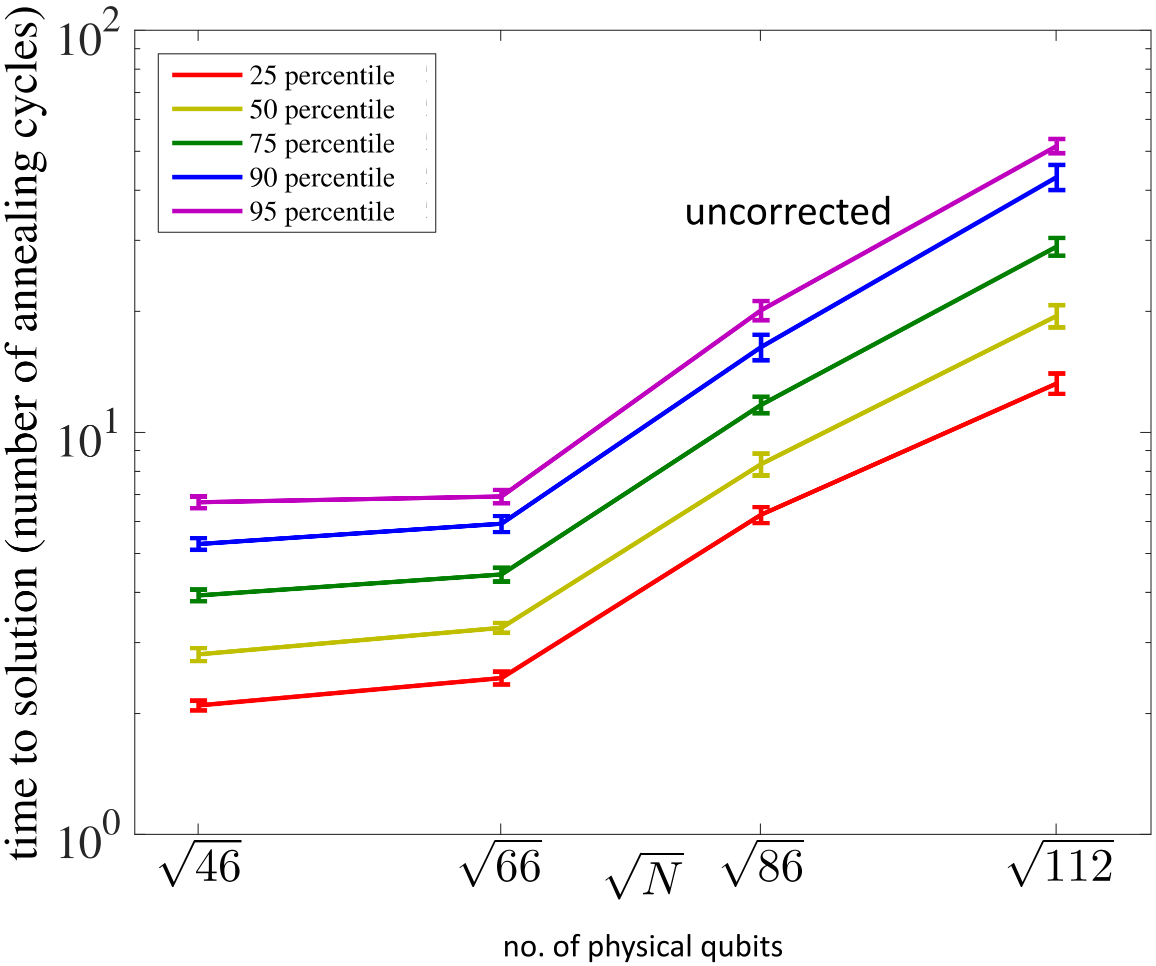
$$H_{\text{Ising}} = \sum J_{ij}\sigma_i^z\sigma_j^z$$

with random

$$J_{ij} \in \left\{\pm\frac{1}{6}, \cdots, \pm\frac{5}{6}, \pm 1\right\}$$



Run on a D-Wave 2
(503 qubits)



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Algorithmic breakeven with quantum annealing ✔

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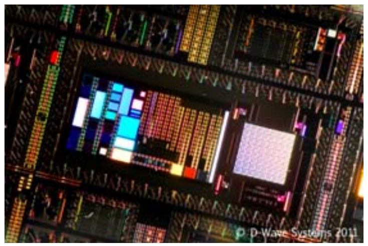

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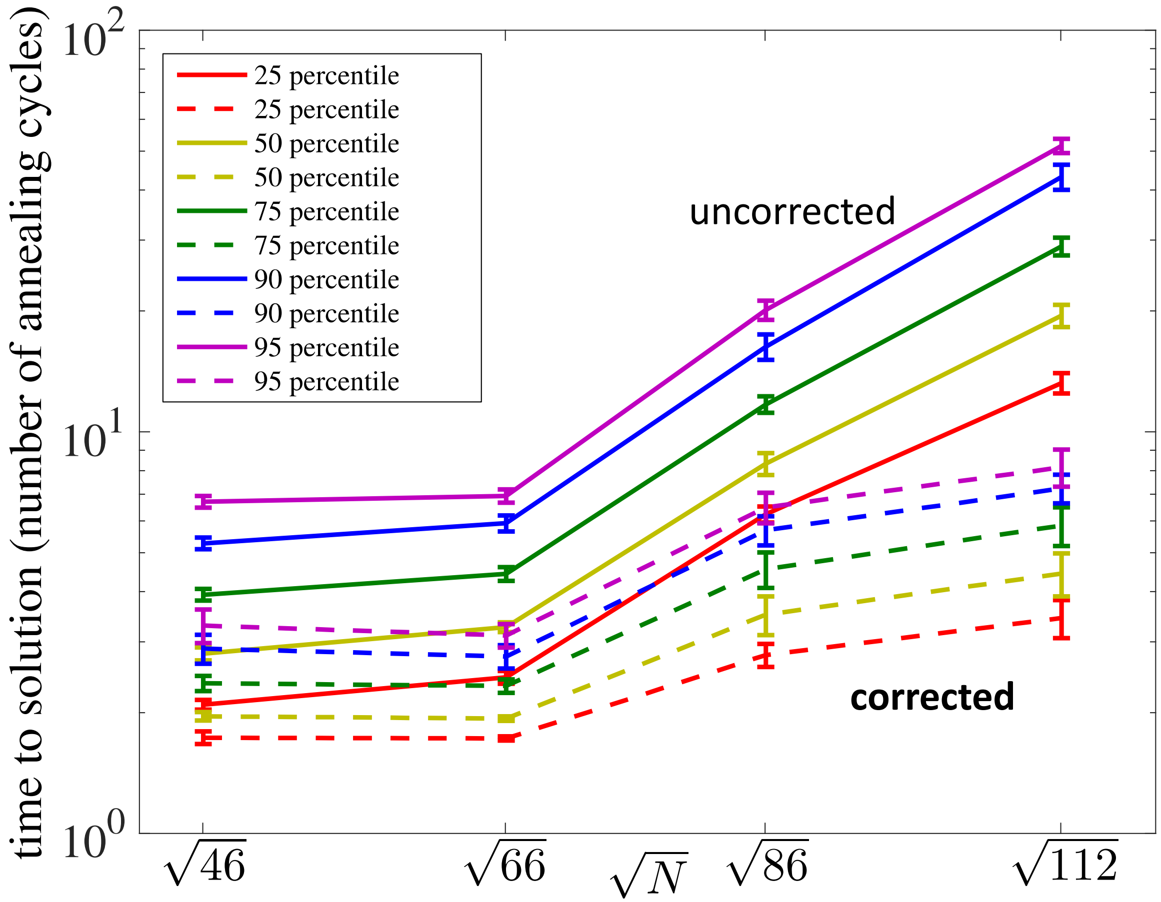
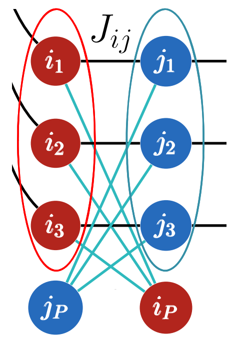


no. of physical/logical qubits

QAC



no claim of q. speedup!

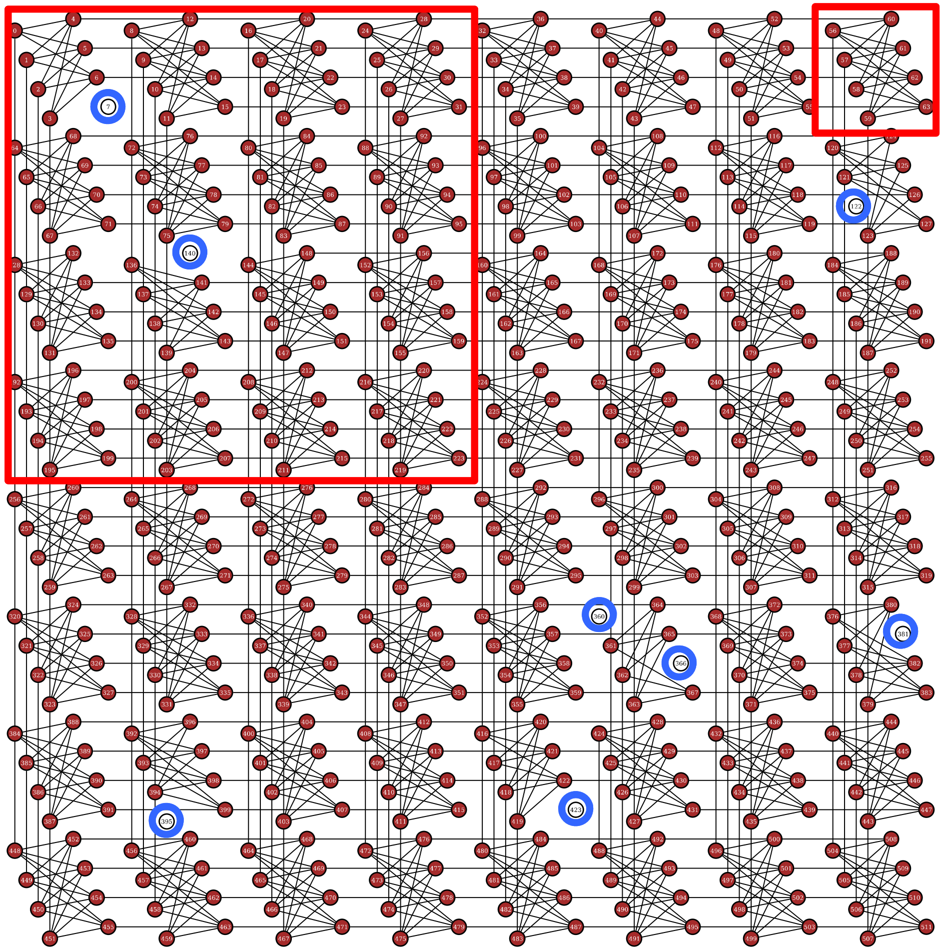
K. Pudenz, T. Albash, DL, Nature Comm. 5, 3243 (2014); PRA 91, 042302 (2015)

Brief interlude on D-Wave processors

They are a type of quantum (& classical thermodynamics) simulator

D-Wave 2 Connectivity Graph

512 qubits with "Chimera graph" couplings



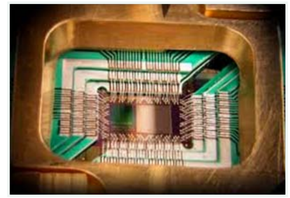
$K_{4,4}$ unit cell

8 × 8 unit cells

Most "natural" problems defined over complete graphs; must be (minor-)embedded

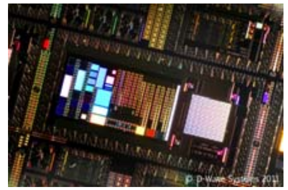
Largest complete graph embeddable in $L \times L$ Chimera graph of L unit cells, each $K_{c,c}$ is K_{cL+1}

All D-Wave chips to date: $c = 4$
Graph degree = $c + 2 = 6$



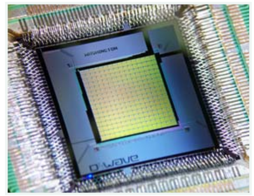
Oct 2011

D-Wave 1:
$L = 4, N$=128 (USC yield: 108)
K_{17} for ideal
K_{14} for actual



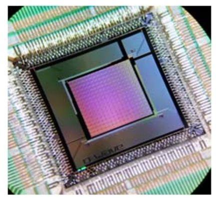
March 2013

D-Wave 2:
$L = 8, N$=512 (USC yield: 504)
K_{33} for ideal
K_{32} for actual



March 2016

D-Wave 2X:
$L = 12, N$=1152 (USC yield: 1098)
K_{49} for ideal
K_{44} for actual

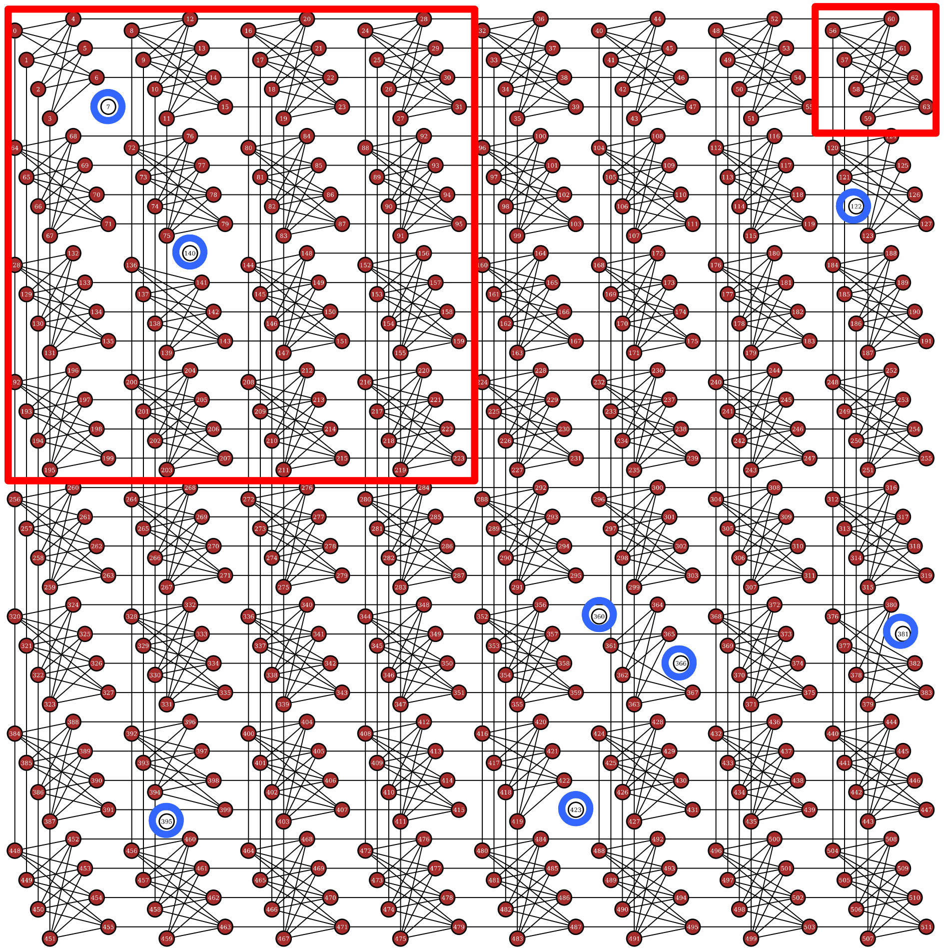


Sep 2017

D-Wave 2000Q
$L = 16, N$=2048 (NASA yield: 2031)
K_{65} for ideal

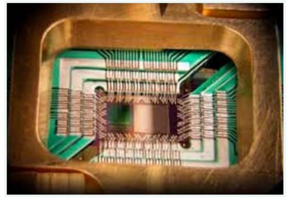
D-Wave 2 Connectivity Graph

512 qubits with "Chimera graph" couplings



$K_{4,4}$ unit cell

8×8 unit cells



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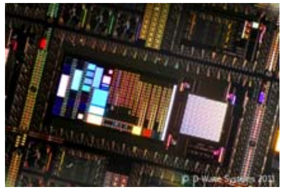

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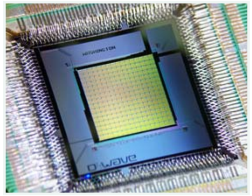

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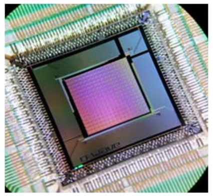


Sep 2017

D-Wave 2000Q

$L = 16, N$=2048 (NASA yield: 2031)

K_{65} for ideal

Designed to solve/sample Ising model problems

Ideally, evolve adiabatically according to $H(t) = A(t)H_X + B(t)H_P$

$\downarrow$ $$H_X = H_{\text{transverse}} = \sum_{j\in V} \sigma_j^x$$

programmable

$\uparrow$ $$H_P = H_{\text{Ising}} = \sum_{j\in V} \boxed{h_j}\,\sigma_j^z + \sum_{(i,j)\in E} \boxed{J_{ij}}\,\sigma_i^z \sigma_j^z$$

finds the ground state energy

$$\min_{\{\sigma_i^z\}} H_{\text{Ising}}$$

NP hard (Barahona 1982)

Samples from Gibbs dist.

$$\frac{1}{Z} e^{-\beta H_{\text{Ising}}}$$

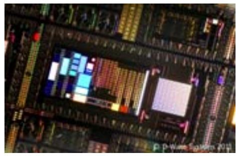
#P-hard (=counting)

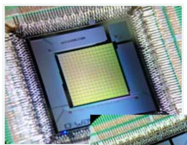
ideal, adiabatic quantum annealer

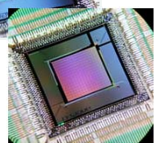
In reality: “control error”
H implemented $\neq$ H intended

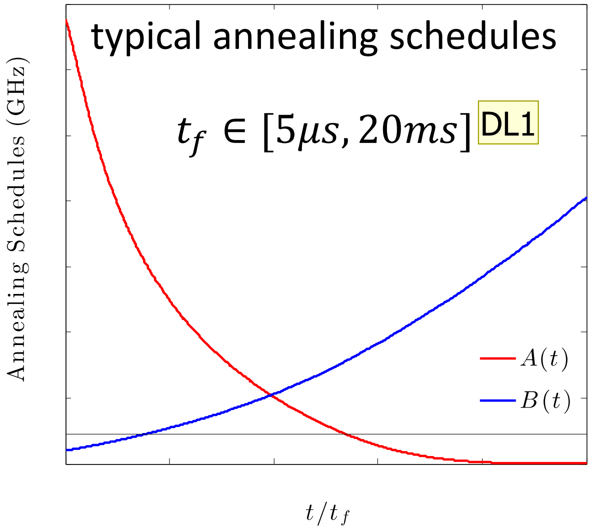
D-Wave 2 precision:
$\delta h \sim N(0,0.05 h_{\max})$,
$\delta J \sim N(0,0.04 J_{\max})$
$\Longrightarrow$ 3 bits
… 4 bits on D-Wave 2X

… 5 bits on D-Wave 2000Q









$\leftarrow$ ~10mK

Diapositive 20

DL1 Note colors are flipped!
Daniel Lidar; 06/09/2017

Beyond control errors: How quantum?

Facts:

- DW Ni flux qubits have $T_2 \sim 100ns$, annealing time $t_f \geq 5\mu s$
- gap(H) can be $\ll T \sim 10mK$

Properly described as an open quantum system

Governed by Markovian adiabatic master equation[1]

- Dynamics (probably) not efficiently classically simulatable
- As an optimizer: so far no evidence of a q. speedup

A playground for testing algorithmic scaling with noisy qubits and error correction

[1] T. Albash, S. Boixo, DL, P. Zanardi, New J. of Phys. **14**, 123016 (2012); T. Albash, DL, PRA **91**, 062320 (2015)

Error Correction for Quantum Annealing

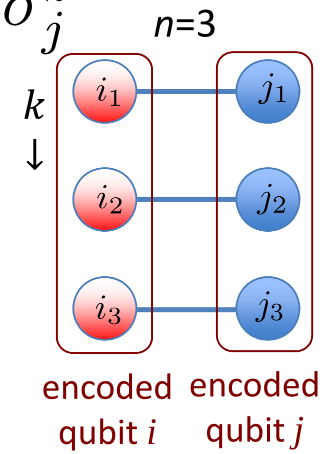

K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

Error Correction for Quantum Annealing

1. Encode into $[n,1,n]$ repetition code:

$$\overline{H}_{\text{Ising}} = \sum_{i=1}^{N} h_i \overline{\sigma_i^z} + \sum_{i<j}^{N} J_{ij} \overline{\sigma_i^z \sigma_j^z}$$

$$\overline{\sigma_i^z} = \sum_{k=1}^{n} \sigma_{i_k}^z \qquad \overline{\sigma_i^z \sigma_j^z} = \sum_{k=1}^{n} \sigma_{i_k}^z \sigma_{j_k}^z$$



Nice features of this code:

Implementable: Logical *Z* and *ZZ* operators are 1 and 2-local

Energy Boost: Logical operators stronger than physical by factor of *n*


K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

Error Correction for Quantum Annealing

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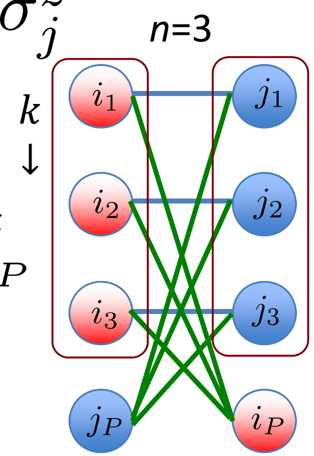
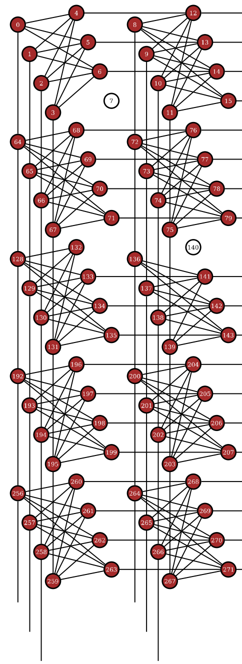
2. Add FM energy penalty:

$$H_P = -\sum_{i=1}^{N} \left(\sigma_{i_1}^z + \cdots + \sigma_{i_n}^z\right) \sigma_{i_P}^z$$



enforced by DW "Chimera" graph unit cell structure: tiling of $K_{4,4}$'s



Also implementable: *ZZ* operators are 2-local (stabilizers of the bit-flip repetition code)

K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

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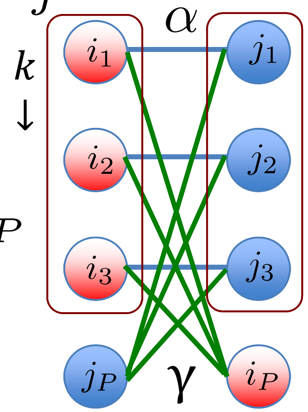

3. Combine:

$$\overline{H}_{\text{Ising},P}(\alpha,\gamma) := \alpha \overline{H}_{\text{Ising}} + \gamma H_P$$

"problem scale" (controllable)

"penalty scale" (optimized)


K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

Error Correction for Quantum Annealing

Quantum Annealing Correction (QAC)

1. Encode into $[n, 1, n]$ repetition code: $\overline{H}_{\text{Ising}} = \sum_{i=1}^{N} h_i \overline{\sigma_i^z} + \sum_{i<j}^{N} J_{ij} \overline{\sigma_i^z \sigma_j^z}$

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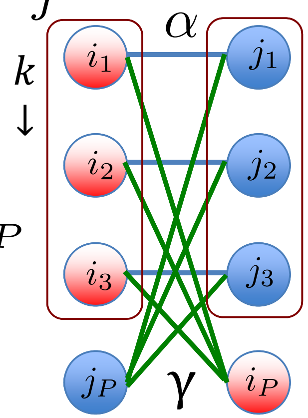

3. Combine: $\overline{H}_{\text{Ising},P}(\alpha, \gamma) := \alpha \overline{H}_{\text{Ising}} + \gamma H_P$

"problem scale" (controllable) — α

"penalty scale" (optimized) — γ

4. Run QA: $\overline{H}(t) = A(t) H_X + B(t) \overline{H}_{\text{Ising},P}(\alpha, \gamma)$

5. Decode at end by majority vote

K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

Error Correction for Quantum Annealing

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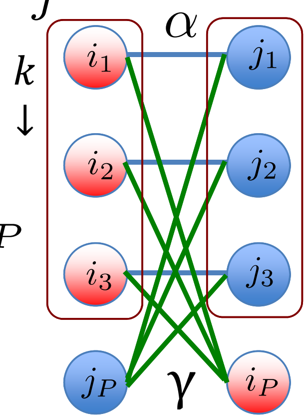

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α: "problem scale" (controllable)

γ: "penalty scale" (optimized)

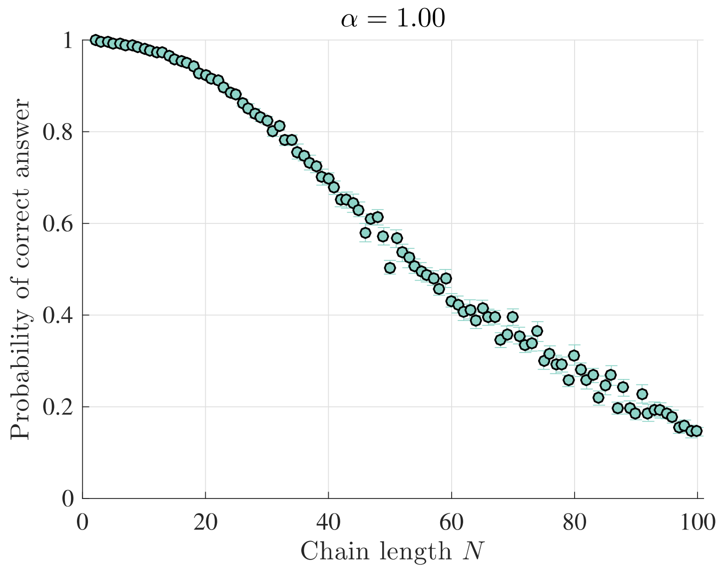
4. Run QA: $$\overline{H}(t) = A(t) H_X + B(t) \overline{H}_{\text{Ising},P}(\alpha,\gamma)$$

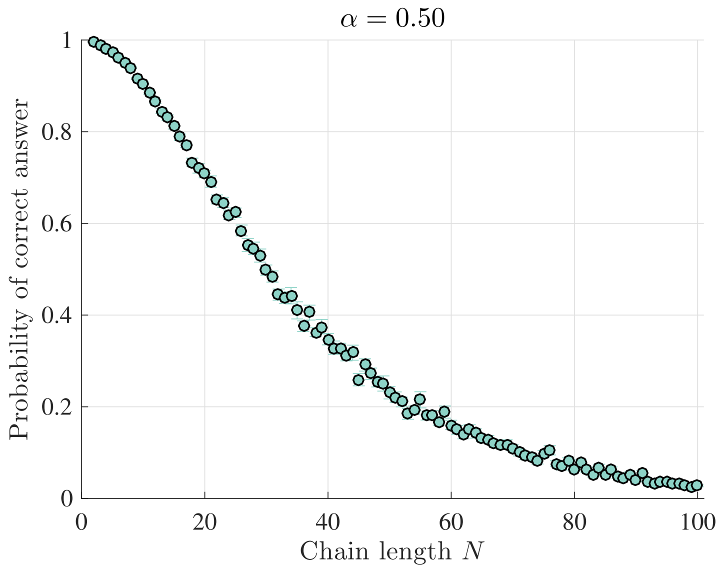
H_X: unencoded $[\overline{\sigma^x} = (\sigma^x)^{\otimes n}]$

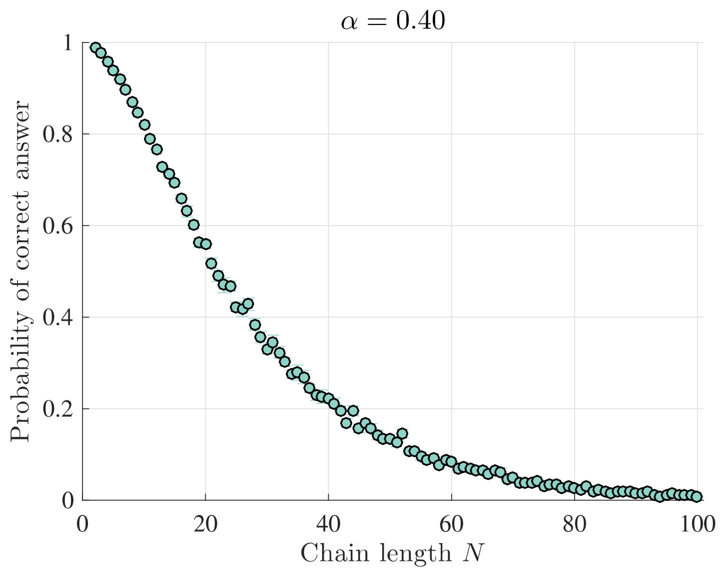
5. Decode at end by majority vote

K. Pudenz, T. Albash & DL, Nature Comm. 5, 3243 (2014)

test on AFM chains



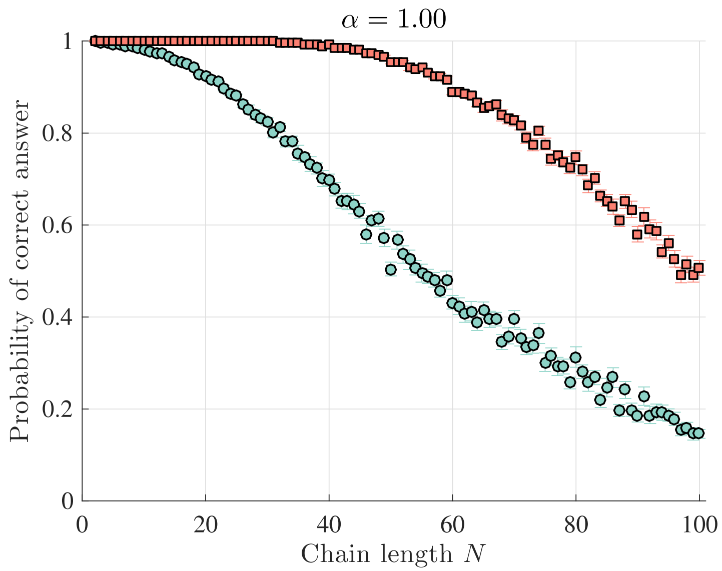


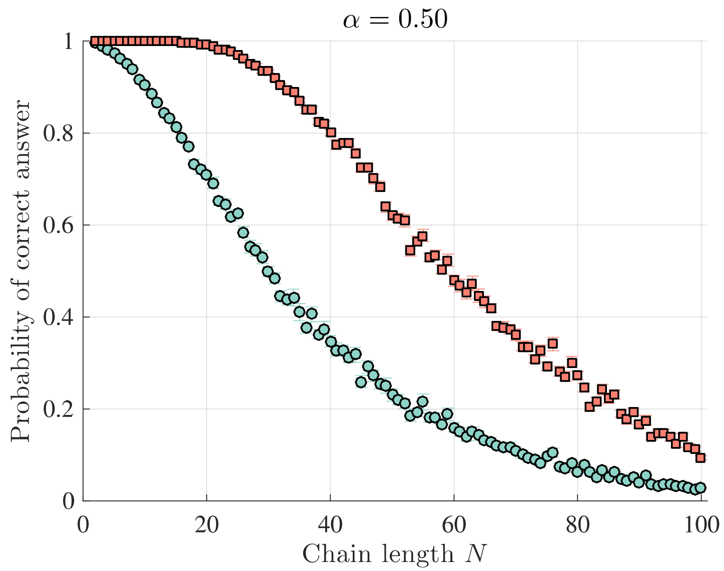


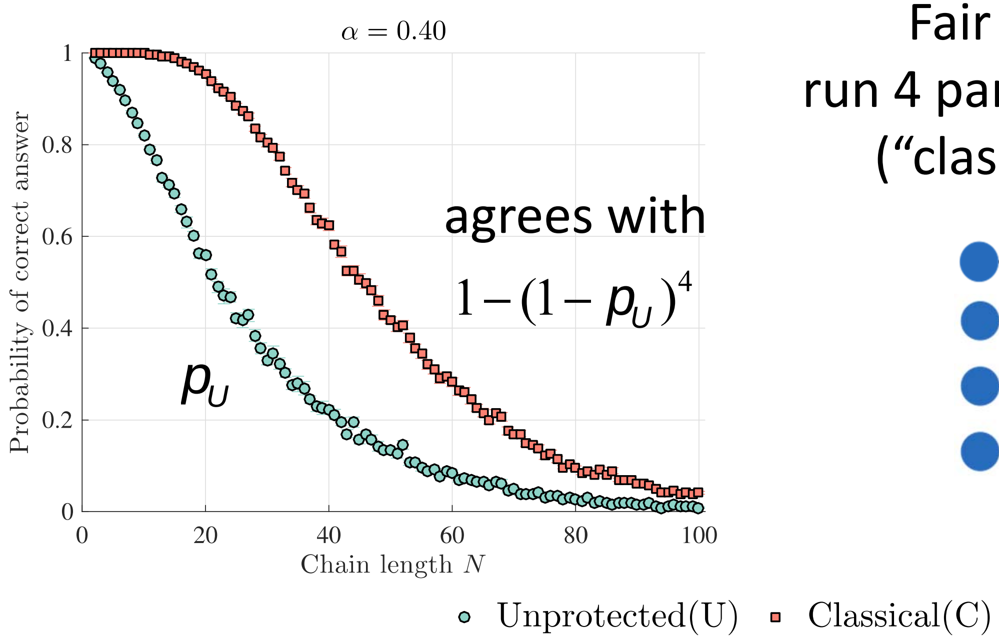
Unprotected(U)

"unprotected"
(unencoded,
no energy penalty)

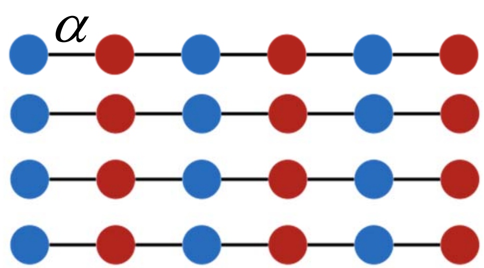
A. Mishra, T. Albash & DL, Q. Info. Proc. (2016)
K. Pudenz, T. Albash & DL, Nat. Comm. (2014)







Fair comparison for QAC:
run 4 parallel chains, take the best
("classical" error correction)



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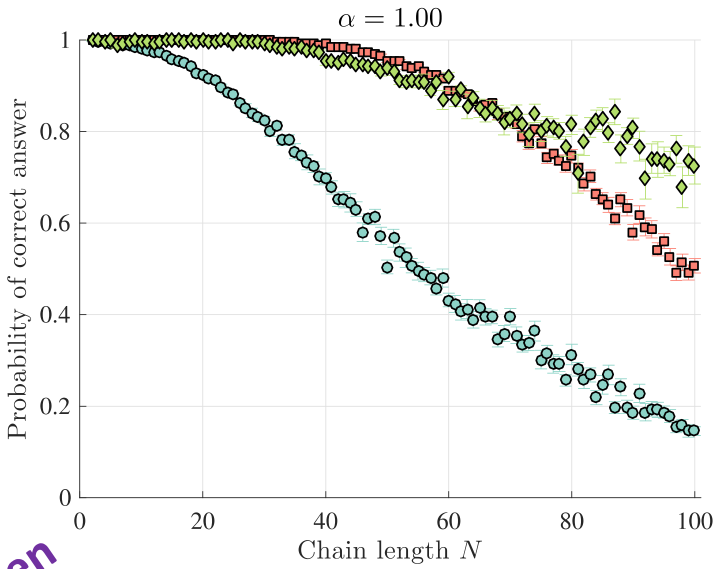
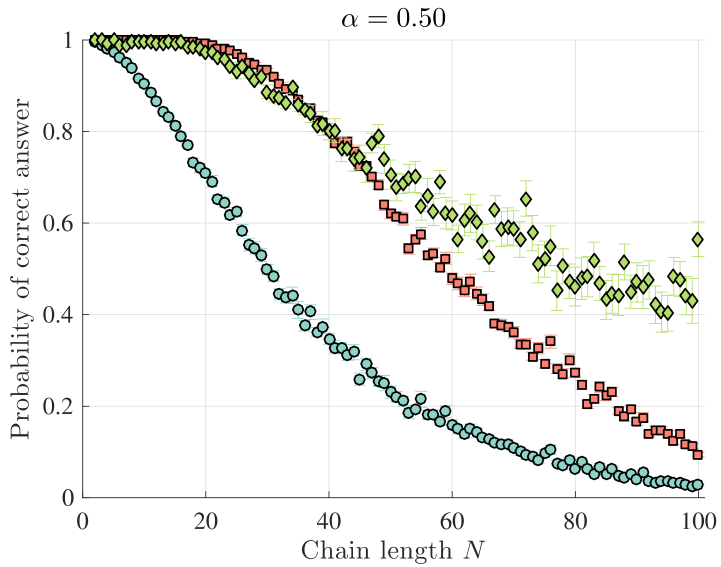
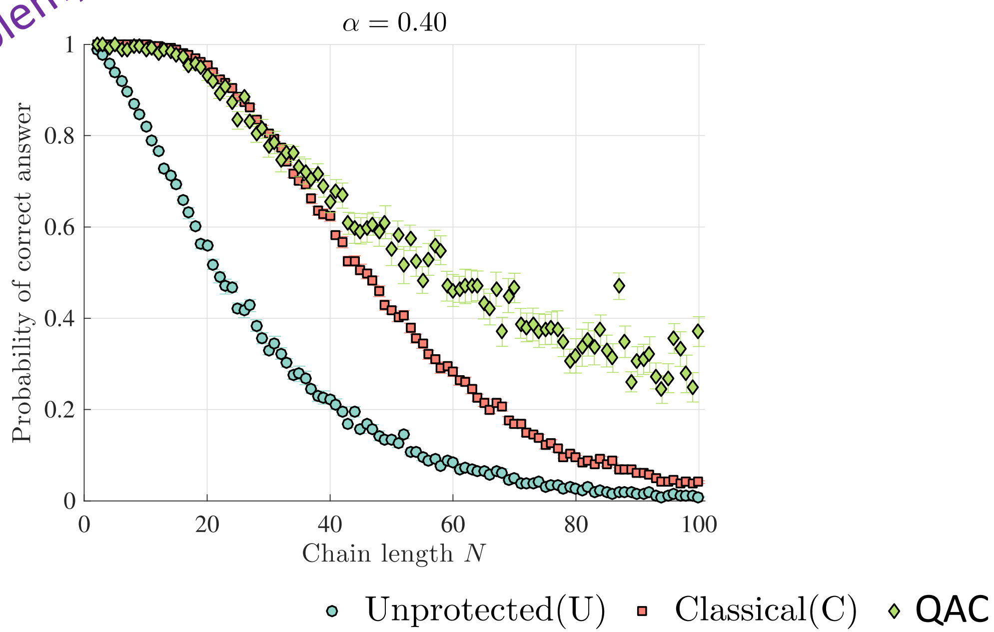
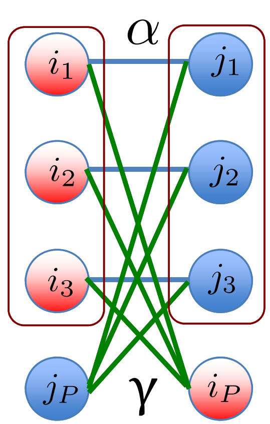




algorithmic breakeven
(for a trivial problem)

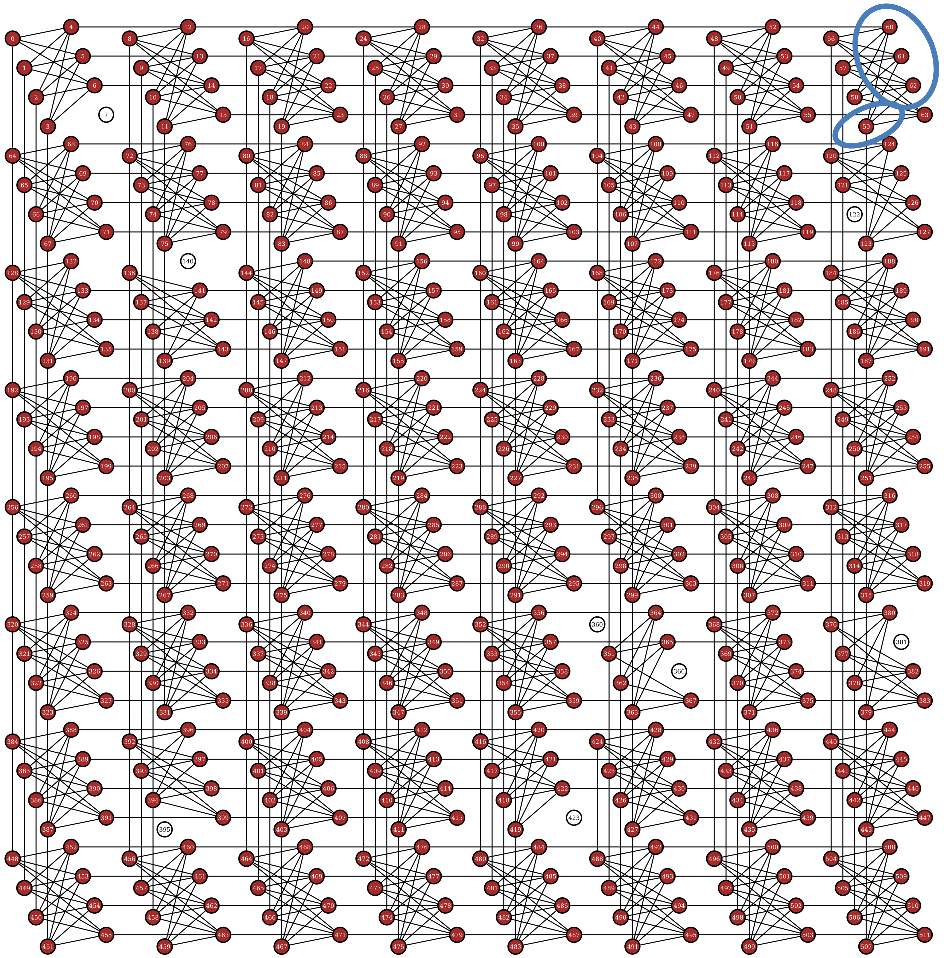


QAC



A. Mishra, T. Albash & DL, Q. Info. Proc. (2016)
K. Pudenz, T. Albash & DL, Nat. Comm. (2014)

From chains to random non-planar Ising …

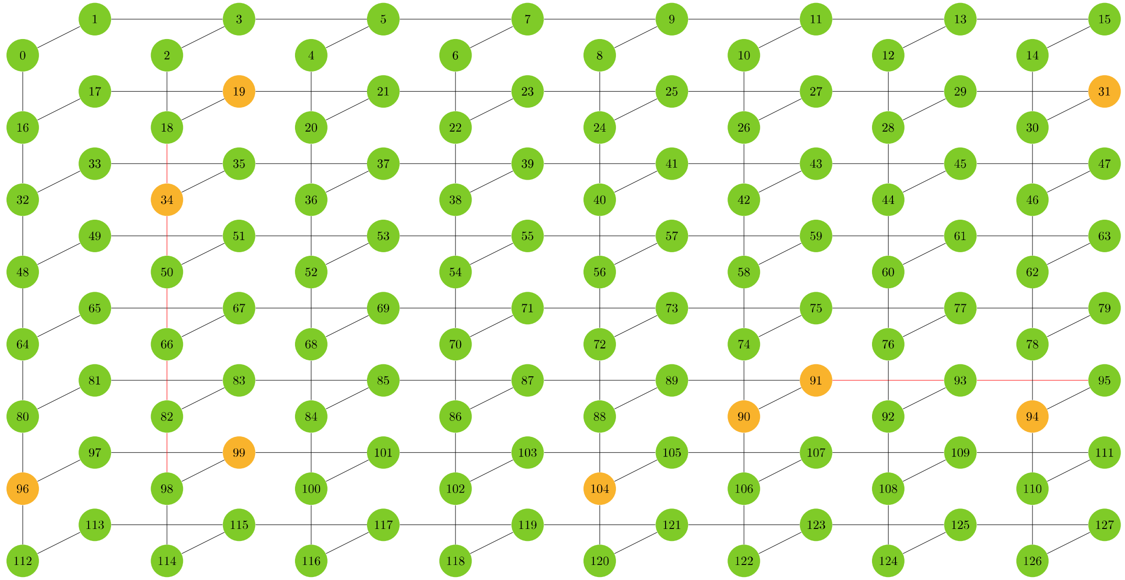


Chimera(DW2); degree 6; 503 functional qubits

QAC encoding

degree 3; still non-planar

119 functional logical qubits

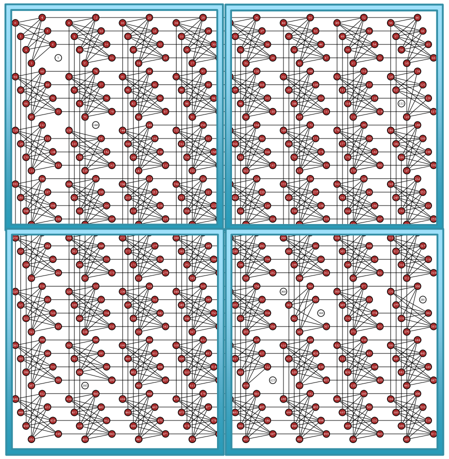


$$H_{\text{Ising}} = \sum_{(i,j)\in E(G)} J_{ij}\overline{\sigma_i^z\sigma_j^z}$$

random $J_{ij} \in \left\{\pm\frac{1}{6}, \cdots, \pm\frac{5}{6}, \pm 1\right\}$

Algorithmic breakeven with quantum annealing correction

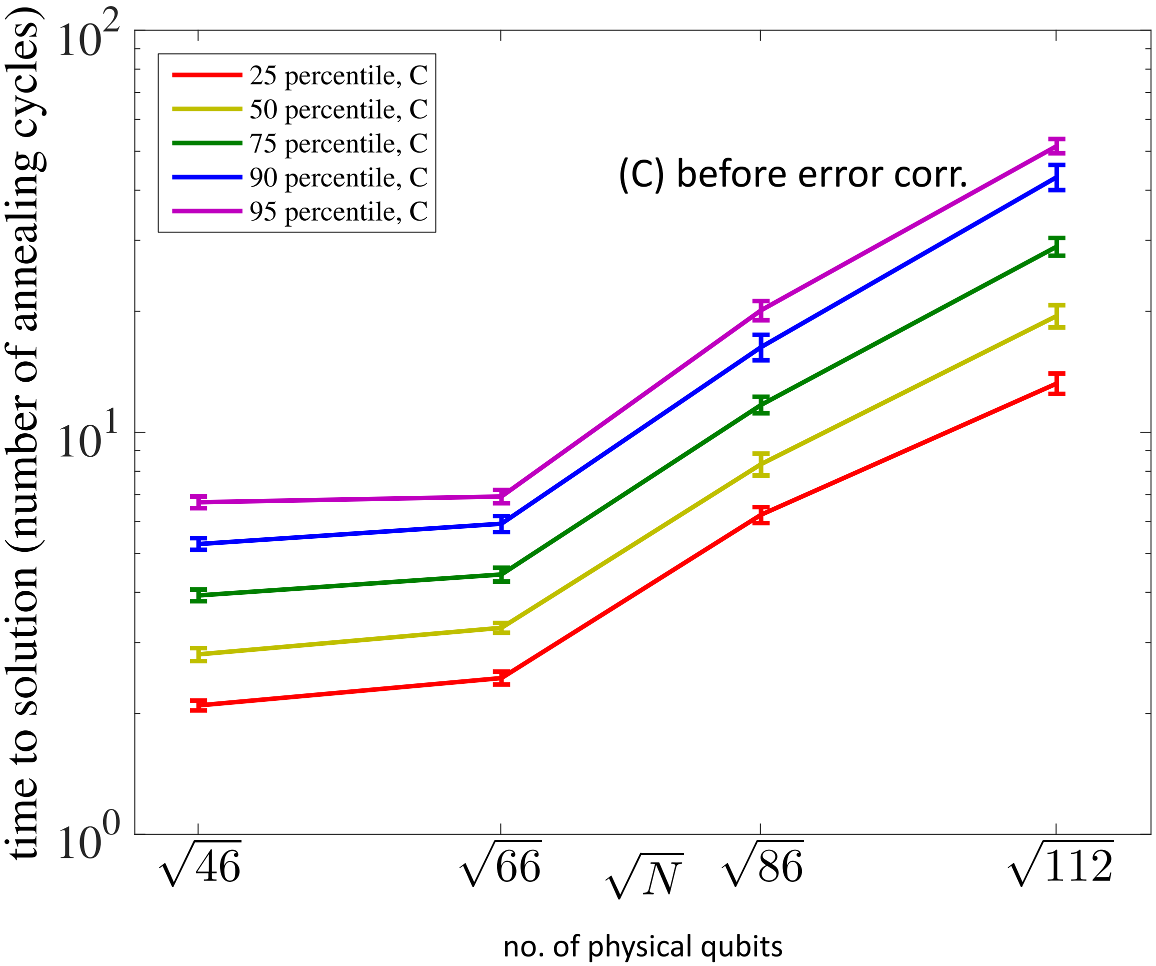
"classical" (C)



best of 4 copies

$$H_{\text{Ising}} = \sum_{(i,j)\in E(G)} J_{ij}\sigma_i^z\sigma_j^z$$

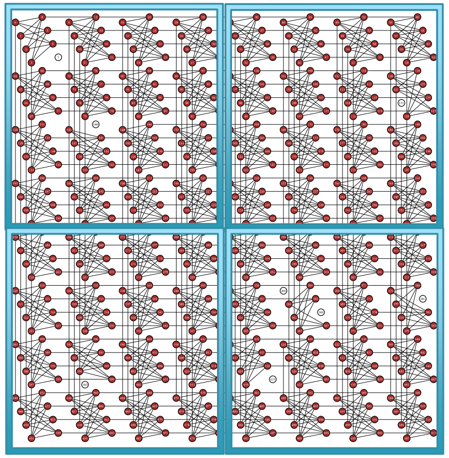
$$J_{ij} \in \left\{\pm\frac{1}{6}, \cdots, \pm\frac{5}{6}, \pm 1\right\}$$



K. Pudenz, T. Albash, DL, PRA 91, 042302 (2015)

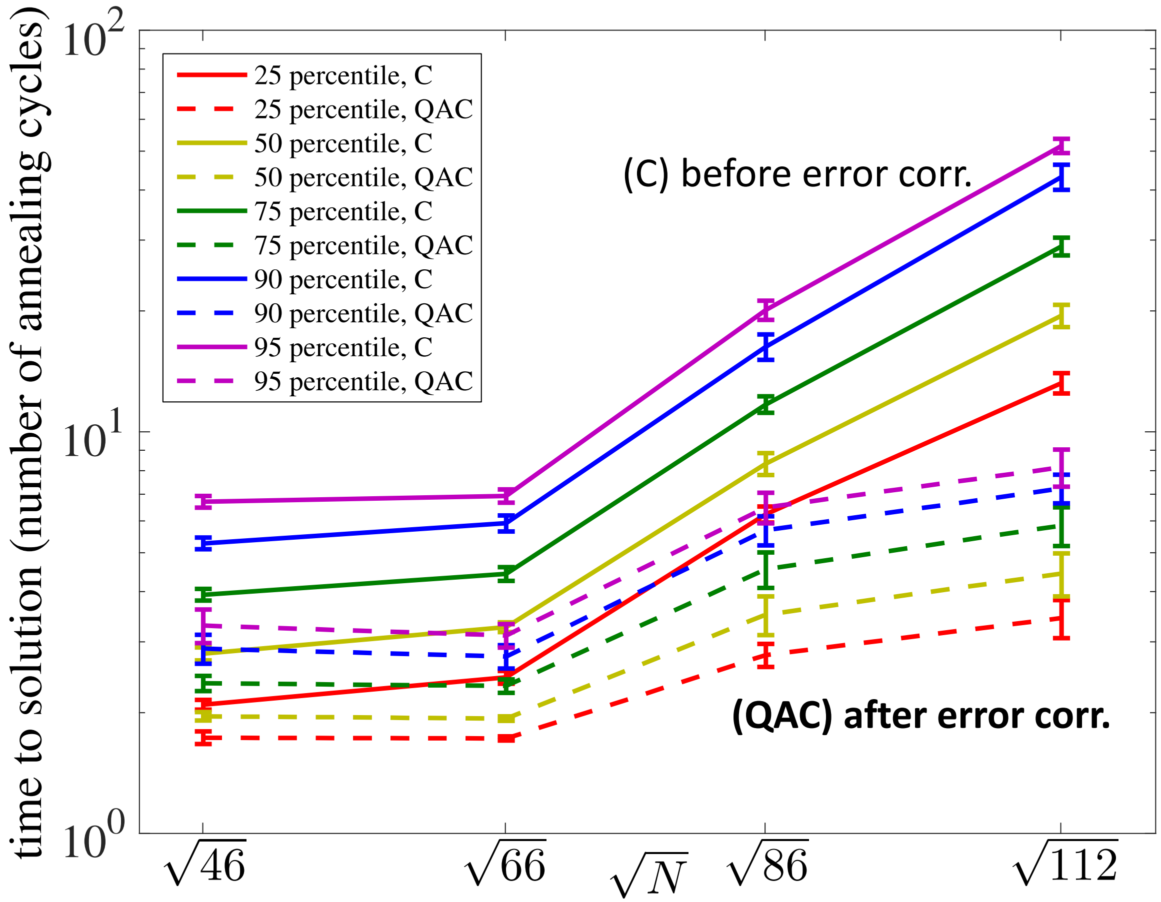
Algorithmic breakeven with quantum annealing correction

“classical” (C)



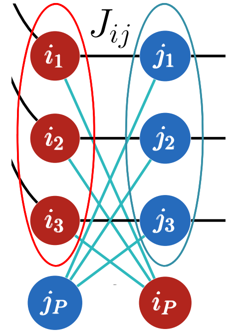
best of 4 copies

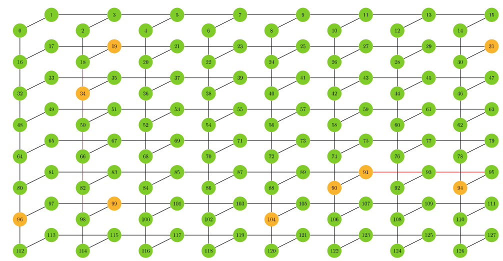
$$H_{\text{Ising}} = \sum_{(i,j)\in E(G)} J_{ij}\sigma_i^z\sigma_j^z$$



QAC

3-qubit repetition code + energy penalty





$$H_{\text{Ising}} = \sum_{(i,j)\in E(G)} J_{ij}\overline{\sigma_i^z\sigma_j^z}$$

$$J_{ij} \in \left\{\pm\frac{1}{6}, \cdots, \pm\frac{5}{6}, \pm 1\right\}$$

K. Pudenz, T. Albash, DL, PRA 91, 042302 (2015)

Why does QAC work?

Main mechanism:

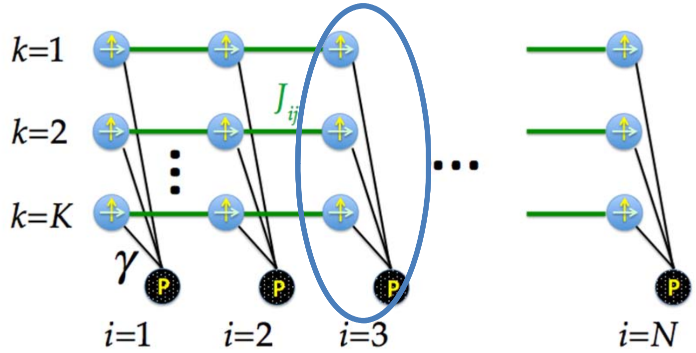
avoidance or modification of a quantum phase transition
due to penalty term

S. Matsuura, H. Nishimori, W. Vinci, T. Albash, DL. Phys. Rev. A 95, 022308 (2017)
S. Matsuura, H. Nishimori, T. Albash. DL., Phys. Rev. Lett. 116, 220501 (2016)

Why does QAC work?

Mean-field analysis of *p*-body ferromagnet

N logical qubits
each in $[K, 1, K]$
repetition code
($K = n$ in earlier notation)



Model Hamiltonian $H = H_x + H_z$

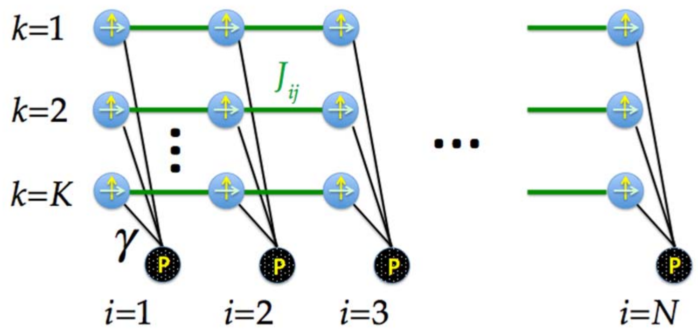
$$H_z = \underbrace{-N\sum_{k=1}^{K}\left(\frac{1}{N}\sum_{i=1}^{N}\sigma_{iz}^{k}\right)^{p}}_{\substack{\text{problem Hamiltonian}\\ \text{fully-connected logical qubits}}} - \boxed{\gamma\sum_{k=1}^{K}\sum_{i=1}^{N}\sigma_{iz}^{k}\sigma_{iz}^{0}}$$

penalty

Why does QAC work?

Mean-field analysis of *p*-body ferromagnet

N logical qubits
each in $[K, 1, K]$
repetition code
($K = n$ in earlier notation)



Model Hamiltonian $H = H_x + H_z$

$$H_z = -N \sum_{k=1}^{K} \left(\frac{1}{N} \sum_{i=1}^{N} \sigma_{iz}^k \right)^p \underbrace{- \gamma \sum_{k=1}^{K} \sum_{i=1}^{N} \sigma_{iz}^k \sigma_{iz}^0}_{\text{penalty}}$$

$$H_x = \underbrace{-\underbrace{\Gamma}_{\text{annealing schedule}} \sum_{k=1}^{K} \sum_{i=1}^{N} \sigma_{ix}^k}_{\text{transverse Hamiltonian}}$$

penalty

annealing schedule

transverse Hamiltonian

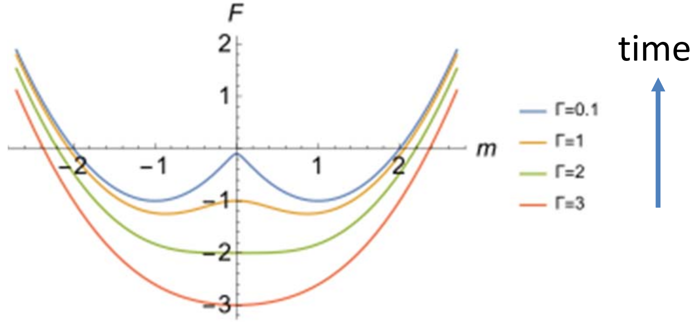
use stat. mech. tricks to
compute partition function

$$Z = \operatorname{Tr} e^{-\beta(H_z + H_x)}$$

then free energy etc.

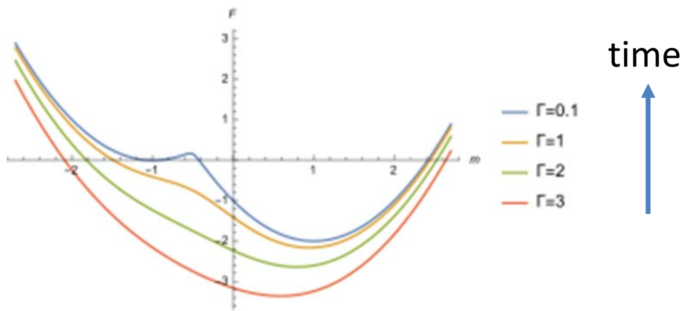
Free energy and magnetization for *p*=2

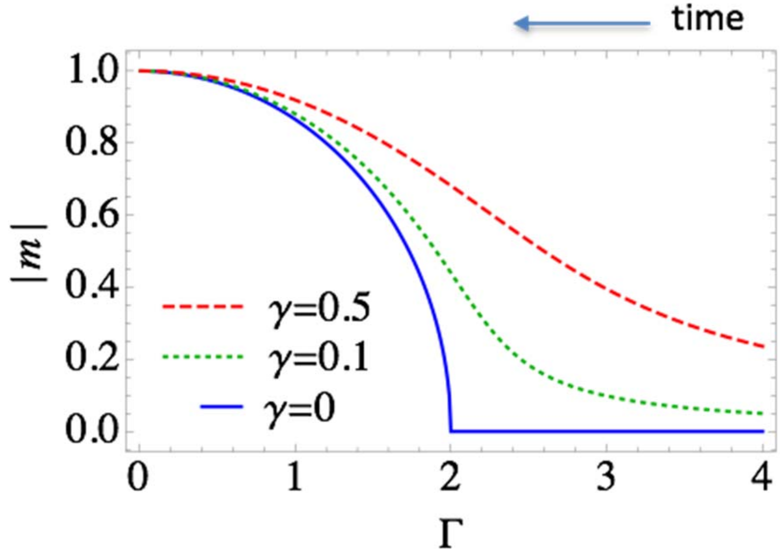
$\gamma = 0$



no penalty:
2nd order phase transition

$\gamma = 1$

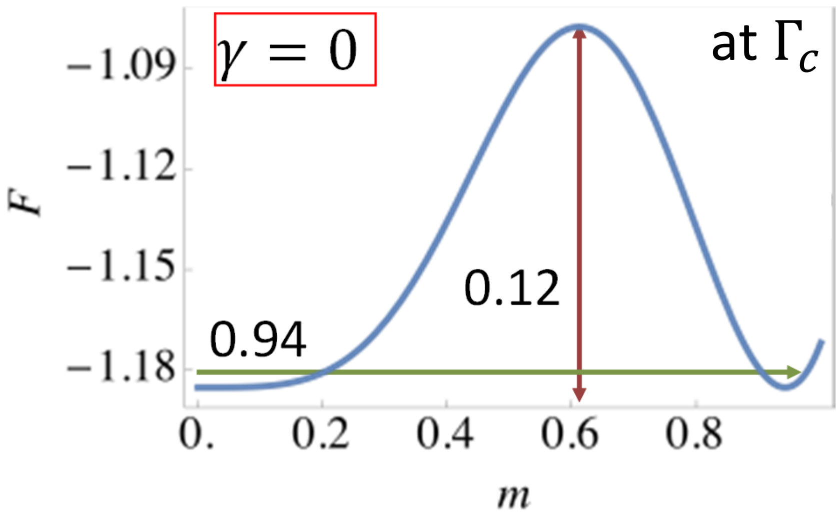


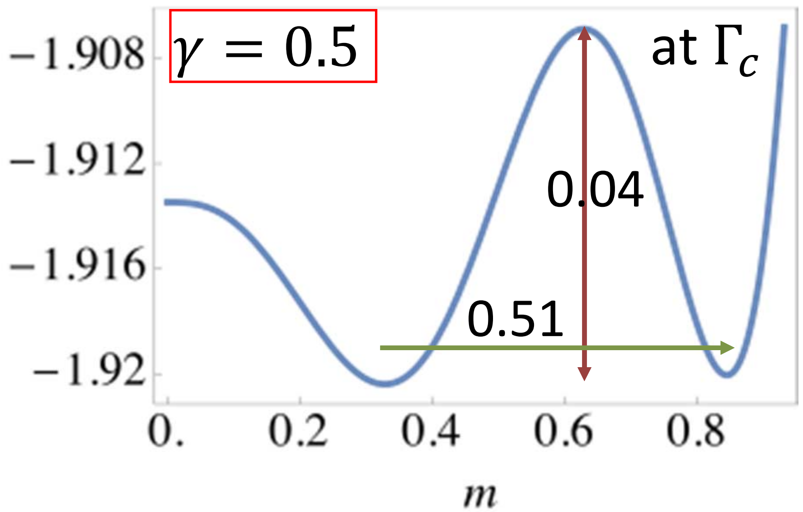


Turning the penalty on *avoids* the phase transition

1st order transition for $p \geq 3$

$p = 4$



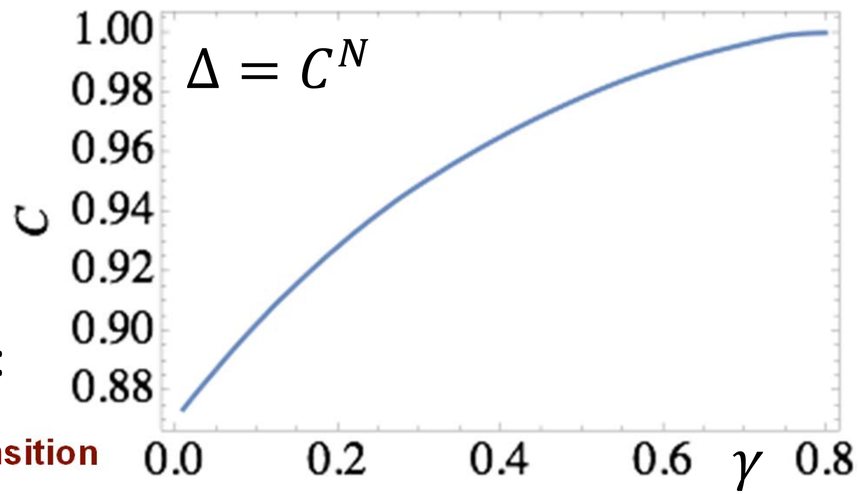


discontinuous transition from *m*=0 to *m*=0.94
(wide and tall tunneling barrier)

discontinuous transition from *m*=0.33 to *m*=0.84

Increasing penalty γ
lowers and narrows
the tunneling barrier

also increases the minimum gap Δ:



Turning the penalty on *softens* the phase transition

Why does QAC work?

- For models with a second order quantum phase transition:
  - QAC avoids the phase transition
- For models with a first order quantum phase transition:
  - QAC softens the closing of the gap

S. Matsuura, H. Nishimori, T. Albash. DL., Phys. Rev. Lett. 116, 220501 (2016)
S. Matsuura, H. Nishimori, W. Vinci, T. Albash, DL. Phys. Rev. A 95, 022308 (2017)

- QAC rescales the temperature; rescaling can be made as large as n^2 for $[n, 1, n]$ code (using all-to-all connectivity):
  qubits can be traded for temperature reduction

W. Vinci, T. Albash & DL, Nature Quant. Info. 2, 16017 (2016)

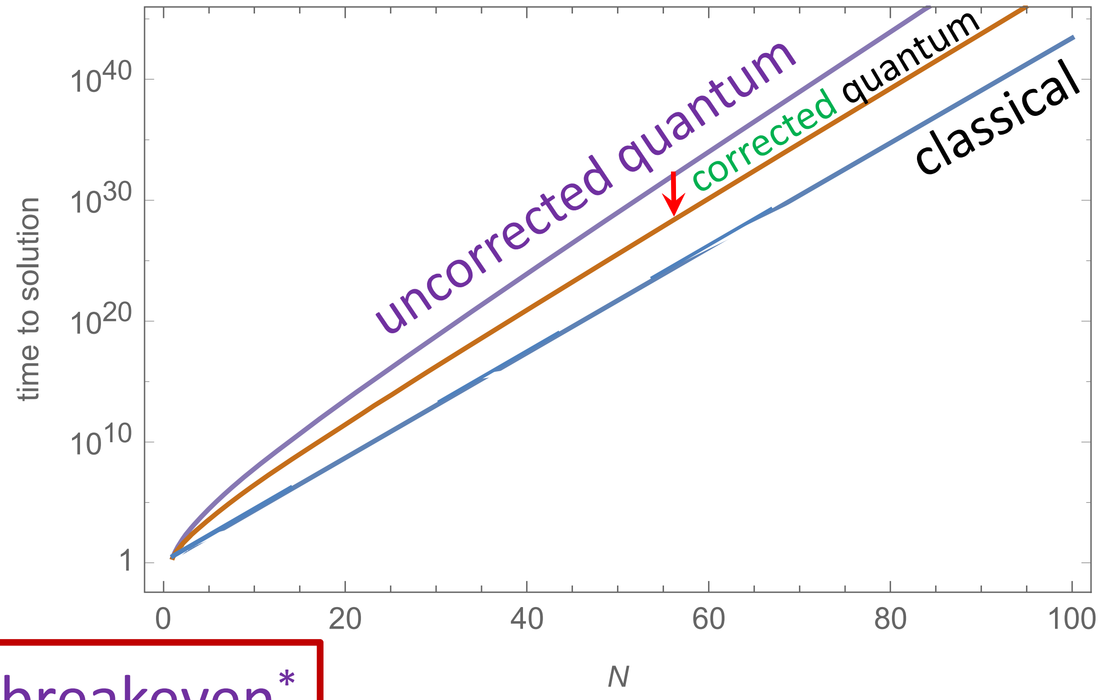
➔ Helps to achieve algorithmic breakeven

∴ Target for Error-Corrected Circuit-Model Quantum Computing

achieve algorithmic breakeven*

*Demonstrate error-corrected scaling that is no worse than uncorrected on a computational problem

∴ Target for Error-Corrected Circuit-Model Quantum Computing



achieve algorithmic breakeven*

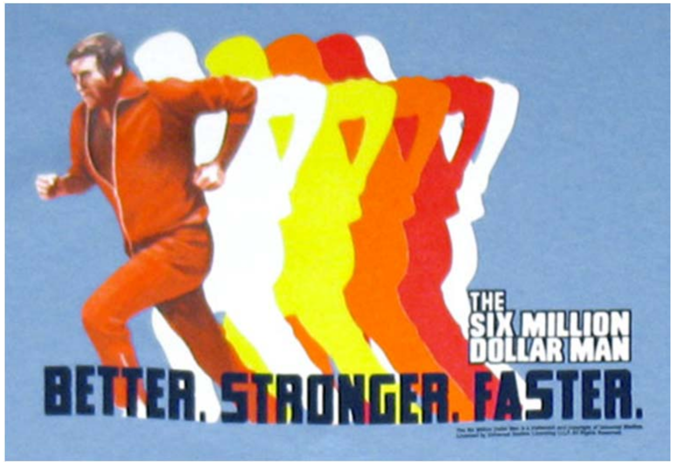
Thanks!

*Demonstrate error-corrected scaling that is no worse than uncorrected on a computational problem

The Future

IARPA

As of June 2017, funded under IARPA''s "**Quantum Enhanced Optimization**" (QEO) Program we will implement all the lessons we've learned studying the D-Wave machines, with a mission to build a 100-qubit quantum annealer in 5 years that is



USC University of Southern California

東京工業大学 Tokyo Institute of Technology

HARVARD UNIVERSITY

MIT

UCL

NORTHROP GRUMMAN

Berkeley UNIVERSITY OF CALIFORNIA

UNIVERSITÄT DES SAARLANDES

UNIVERSITY OF WATERLOO

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

LOCKHEED MARTIN

Additional slides

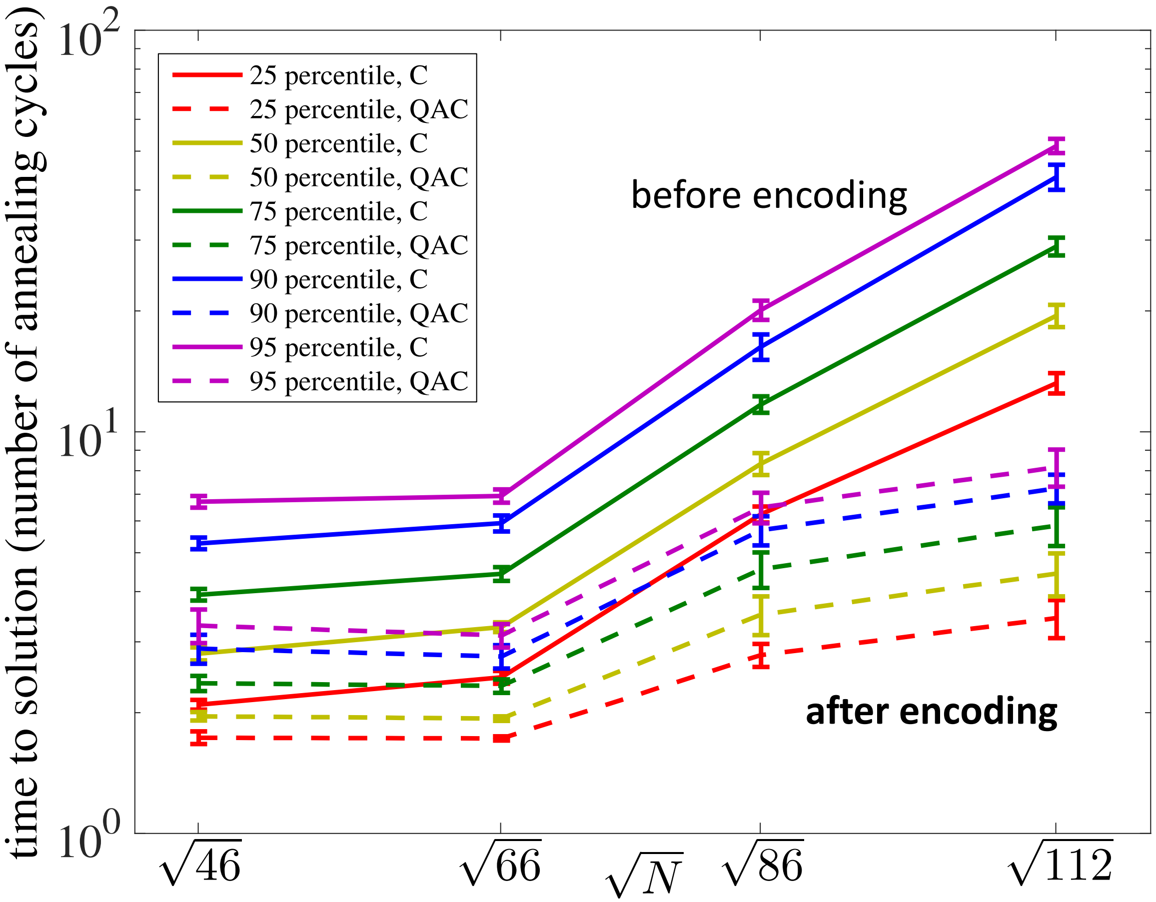
Surpassing breakeven with quantum annealing correction

$$H_{\text{Ising}} = \sum_{j\in V} h_j \sigma_j^z + \sum_{(i,j)\in E} J_{ij}\sigma_i^z \sigma_j^z$$

random Ising

$$h_j = 0$$

$$J_{ij} \in \{\pm\frac{1}{6}, \dots, \pm\frac{5}{6}, \pm 1\}$$



no. of physical/logical qubits

Begs the question:
is this a quantum speedup?

Answer:
We don't know since cannot certify scaling is correct

K. Pudenz, T. Albash, DL, Phys. Rev. A 91, 042302 (2015)

Certifiable speedup requires a proof of optimality

Time-to-solution (TTS):
the time required to find the ground state (GS) at least once
with probability 99%

Run the device with annealing time t_a and measure probability p_{GS} of finding the GS. Then:

$$\mathrm{TTS} = t_a \times (\text{no. of repetitions to get to } 99\%) = t_a \, \frac{\log(1-0.99)}{\log(1-p_{\mathrm{GS}}(t_a))}$$

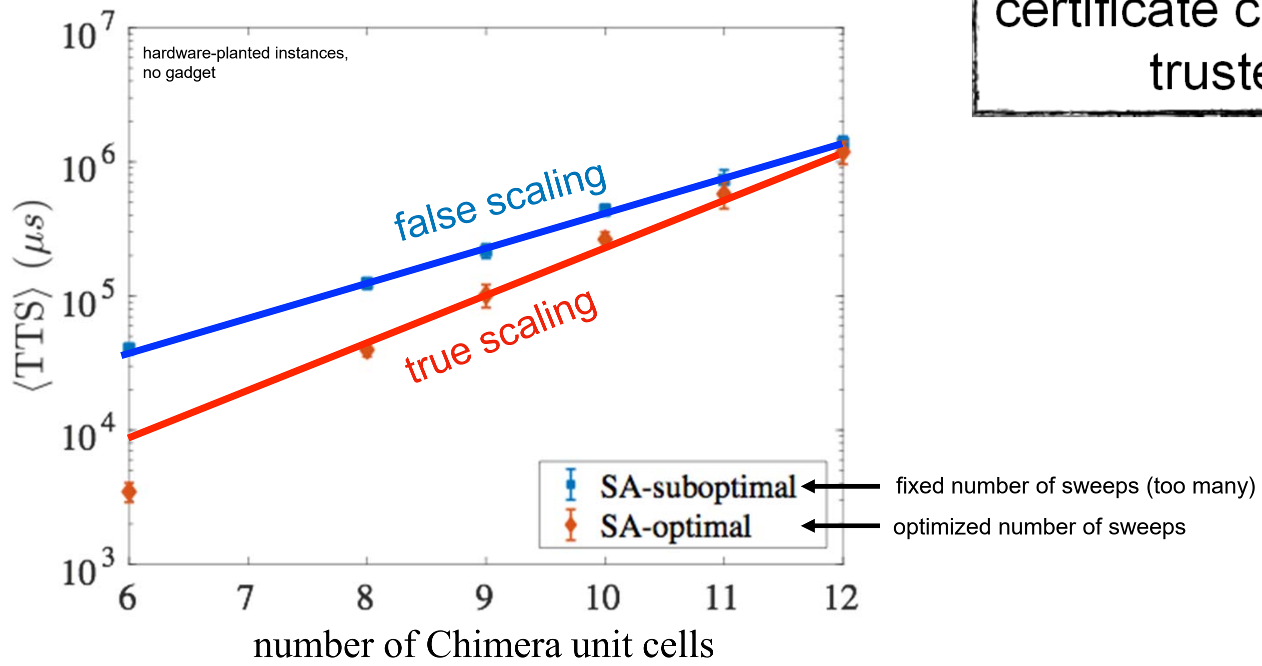
The optimal annealing time t_a is that
which minimizes the TTS for fixed problem size N

Scaling *cannot be trusted* unless optimal t_a has been identified[1,2]

(1) T.F. Rønnow, Z. Wang, J. Job, S. Boixo, S.V. Isakov, D. Wecker, J.M. Martinis, D.A. Lidar, and M. Troyer, Science 345, 420 (2014)
(2) I. Hen, J. Job, T. Albash, T.F. Rønnow, M. Troyer, D.A. Lidar, Phys. Rev. A 92, 042325 (2015)

Certifiable speedup requires a proof of optimality

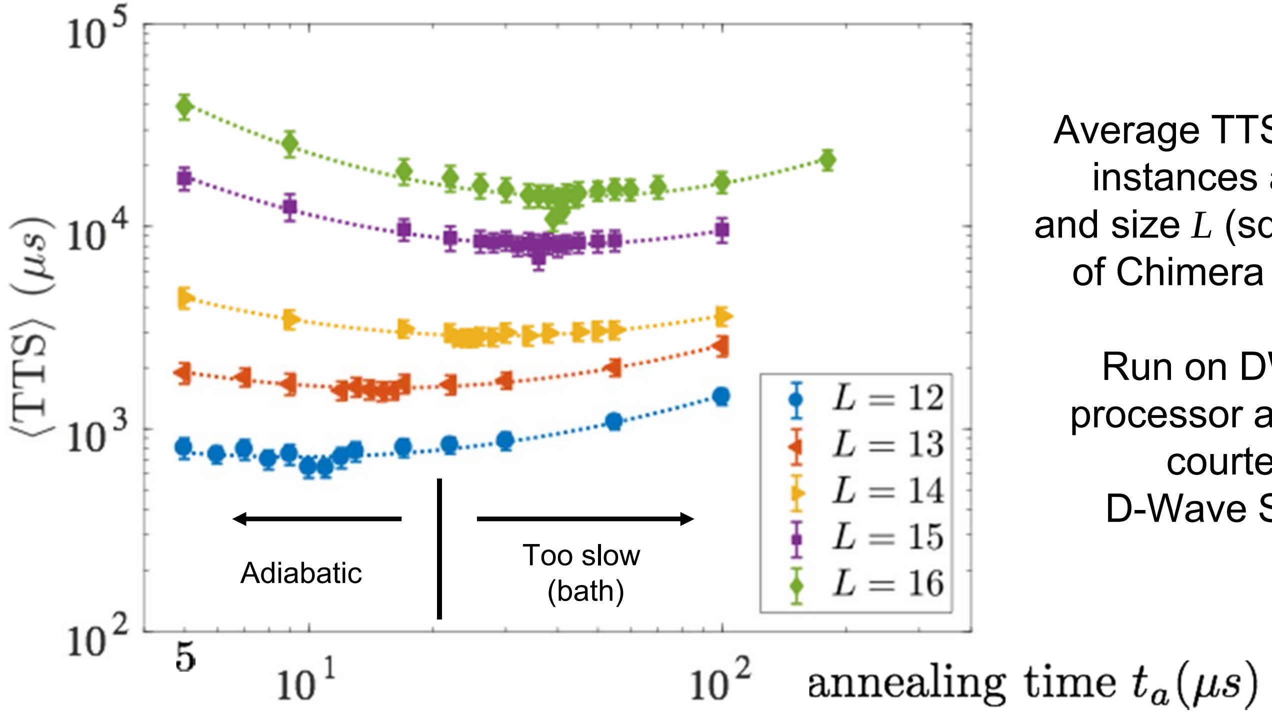
Excessively long annealing time causes **false flat scaling**



Scaling curves without an optimality certificate cannot be trusted

An optimal annealing time certificate

Smoking gun is a minimum in TTS as a function of annealing time …



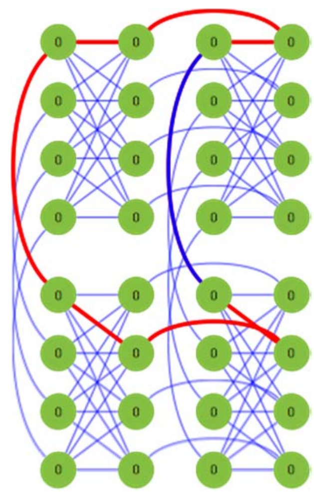
Average TTS over 1000 instances at each t_a and size L (sqrt of number of Chimera unit cells).

Run on DW2000Q processor at Burnaby, courtesy of D-Wave Systems.

… for a new problem class: 'logical-planted-solution instances'

T. Albash & DL, arXiv:1705.07452

`logical-planted-solution' instances

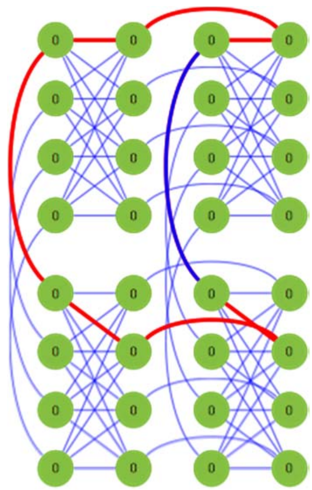


1. Create a spin-glass backbone using
   frustrated loops with planted solutions(1)
   on the logical graph of Chimera unit cells(2)

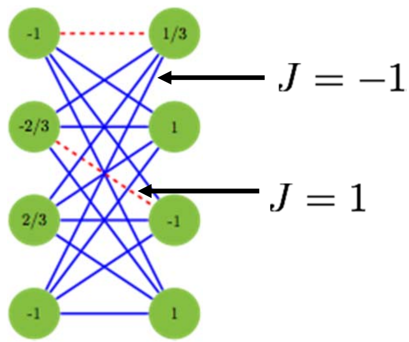
T. Albash & DL, arXiv:1705.07452

`logical-planted-solution' instances

1. Create a spin-glass backbone using
   frustrated loops with planted solutions
   on the logical graph of Chimera unit cells



2. Add 8-qubit 'gadgets' placed randomly in some fraction (10%) of all unit cells



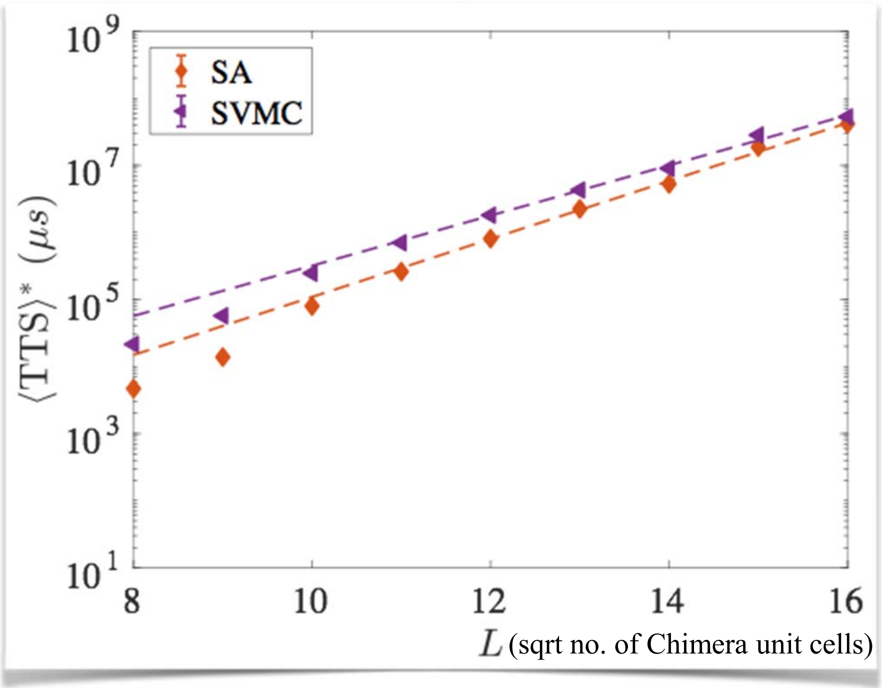
Can now use to demonstrate **limited** quantum speedup

T. Albash & DL, arXiv:1705.07452

Limited quantum speedup: the evidence

Speedup relative to a `relevant' class of classical algorithms

Start with two optimized 'DW-like' classical solvers:
- Simulated Annealing (SA) with single-spin updates
- Spin-vector Monte Carlo[1] (SVMC)



Fit curves to

$$a \exp(bL)$$

Solver	b [95% CI]
SA	1.002 ± 0.066
SVMC	0.867 ± 0.079

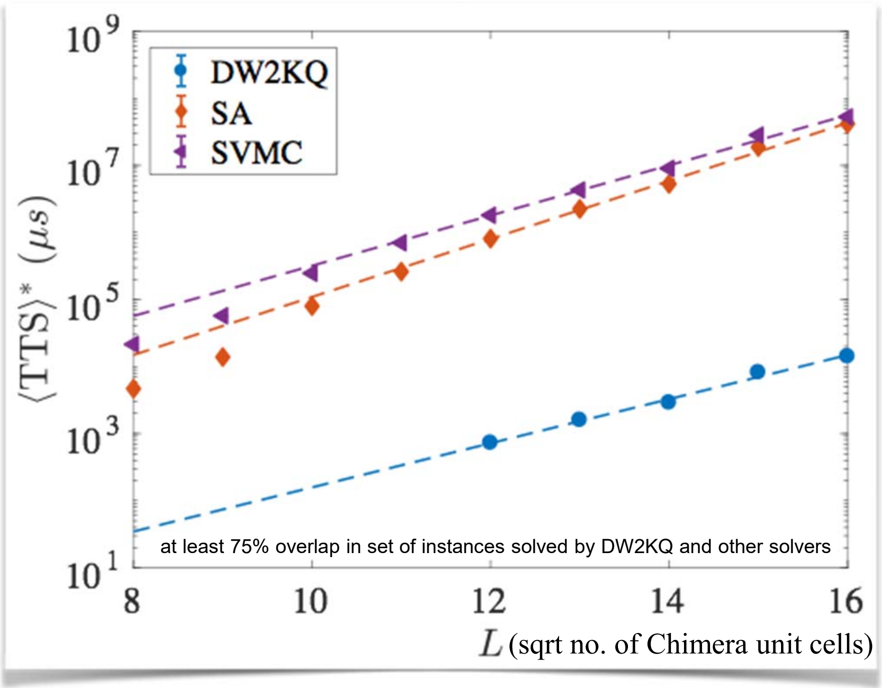
scaling of the median of the instance distribution

(1) S. Shin, G. Smith, J. Smolin, U. Vazirani, arXiv:1401.7087

Limited quantum speedup: the evidence

Speedup relative to a `relevant' class of classical algorithms

DW2000Q unequivocally beats the classical solvers



Fit curves to

$$a \exp(bL)$$

Solver	b [95% CI]
DW2KQ	0.760 ± 0.017
SA	1.002 ± 0.066
SVMC	0.867 ± 0.079

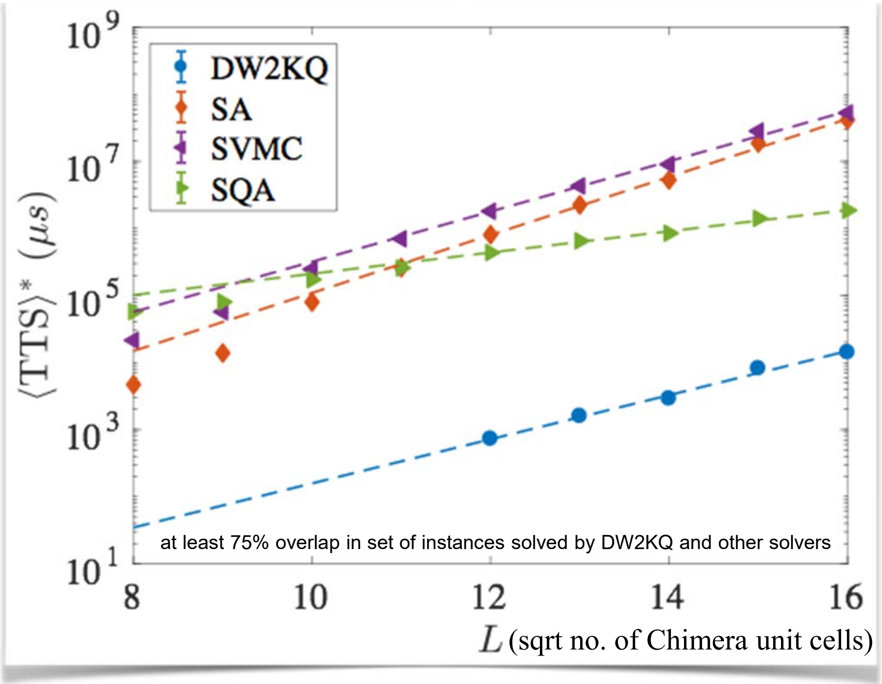
scaling of the median of the instance distribution

T. Albash & DL, arXiv:1705.07452

Limited quantum speedup: the evidence

Speedup relative to a `relevant' class of classical algorithms

Simulated quantum annealing[(1)] dominates



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SQA	0.370 ± 0.052

scaling of the median of the instance distribution

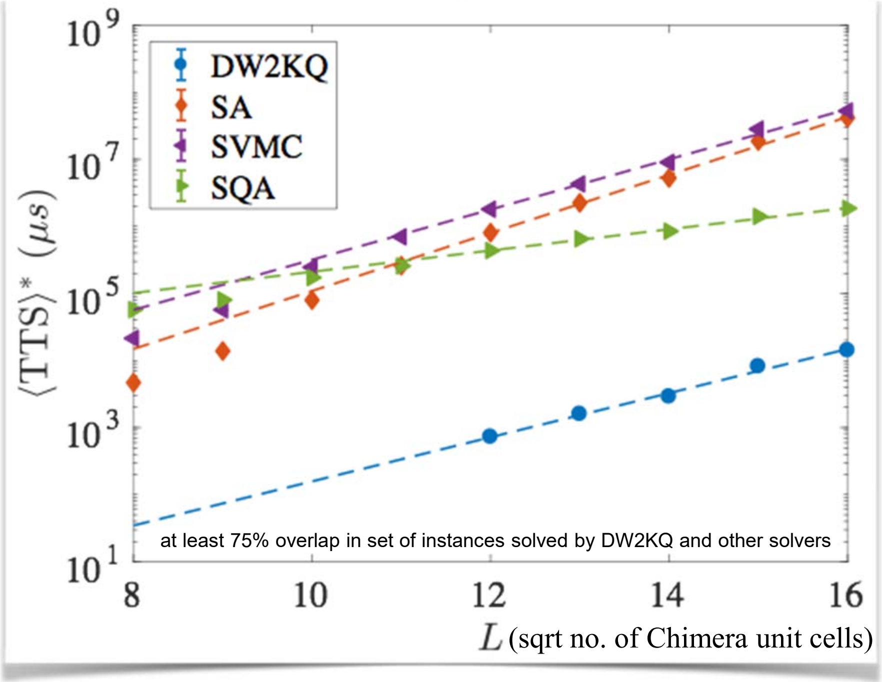
(1) G.E. Santoro, R. Martoňák, E. Tosatti and R. Carr, Science 295, 2427 (2002) [discrete-time path integral Monte Carlo]

Limited quantum speedup: the evidence

Speedup relative to a `relevant' class of classical algorithms

Simulated quantum annealing[1] dominates

Can we reach breakeven (and beyond) through quantum annealing correction?



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scaling of the median of the instance distribution

(1) G.E. Santoro, R. Martoňák, E. Tosatti and R. Carr, Science 295, 2427 (2002)

T. Albash & DL, arXiv:1705.07452

Backup slides

Error/Noise Sources

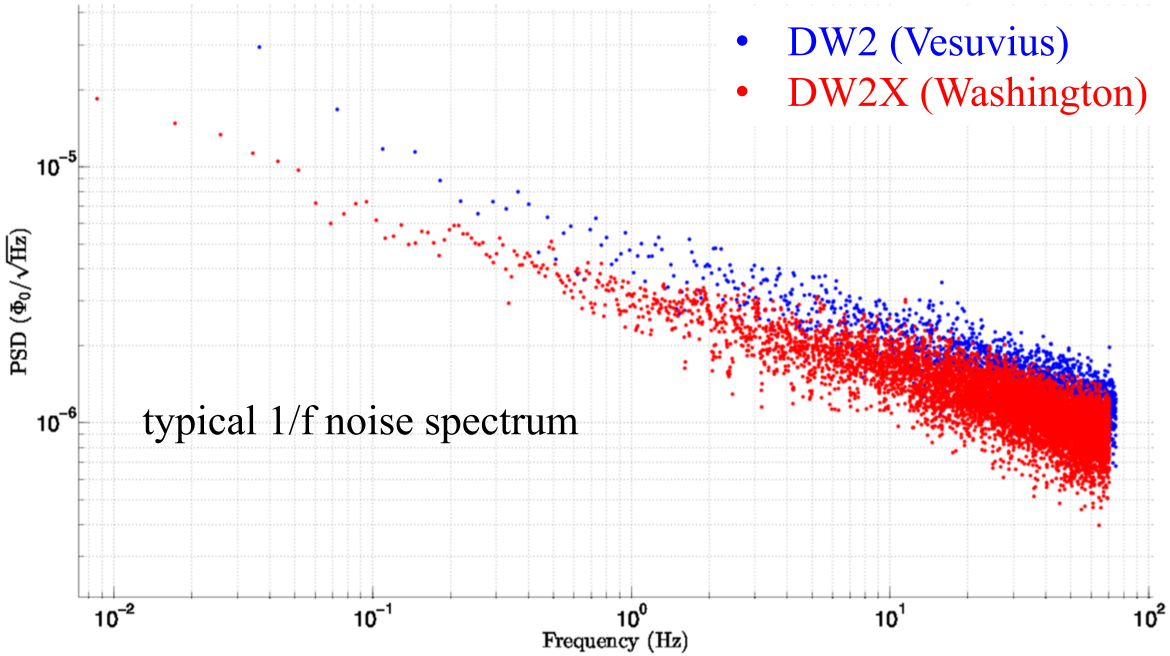
❖ Technical/Engineering:

- Non-ideal spin implementation (not a true 2-level system)
- Finite digital-to-analog conversion (DAC) precision
- Imperfect device characterization & calibration
- Crosstalk
- Low-frequency flux noise

h_i/J_{ij} control:
DW2: 3 bits precision
DW2X: 4 bits precision

❖ Decoherence:

- Thermal excitations (T_1)
- Dephasing in computational basis (T_2; problematic for instances with small gap)
- Dephasing between energy eigenstates



Adiabatic Markovian Master Equation

T. Albash, S. Boixo, DL, P. Zanardi, New J. of Phys. **14**, 123016 (2012); T. Albash, DL, PRA **91**, 062320 (2015)

Weak coupling, work in the instantaneous energy eigenbasis of system Hamiltonian:

$$\frac{d}{dt}\rho_S = -i\left[H_S(t) + H_{LS}(t), \rho_S(t)\right]$$

Unitary evolution with bath-induced Lamb shift

$$+\sum_{\omega}\gamma_{\alpha\beta}(\omega)\left(L_{\omega,\beta}(t)\rho_S L^{\dagger}_{\omega,\alpha}(t) + \frac{1}{2}\left\{L^{\dagger}_{\omega,\alpha}(t)L_{\omega,\beta}(t), \rho_S(t)\right\}\right)$$

Non-unitary dissipative dynamics

Thermal transition rate from GS:

bath spectral density (FT of bath correlation function)

$$\frac{d}{dt}\rho_{00}(t) \approx \sum_{i>0}|\mathcal{O}_i(t)|^2\gamma(\Delta_{i0})\left(\rho_{ii}(t) - e^{-\beta\Delta_{i0}}\rho_{00}(t)\right)$$

excitation

matrix element of the system operator (from the system-bath Hamiltonian) in the instantaneous energy eigenbasis

relaxation

gap suppresses excitations

$T_2 = 1/\gamma(0)$ doesn't appear!