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# Quantum annealing

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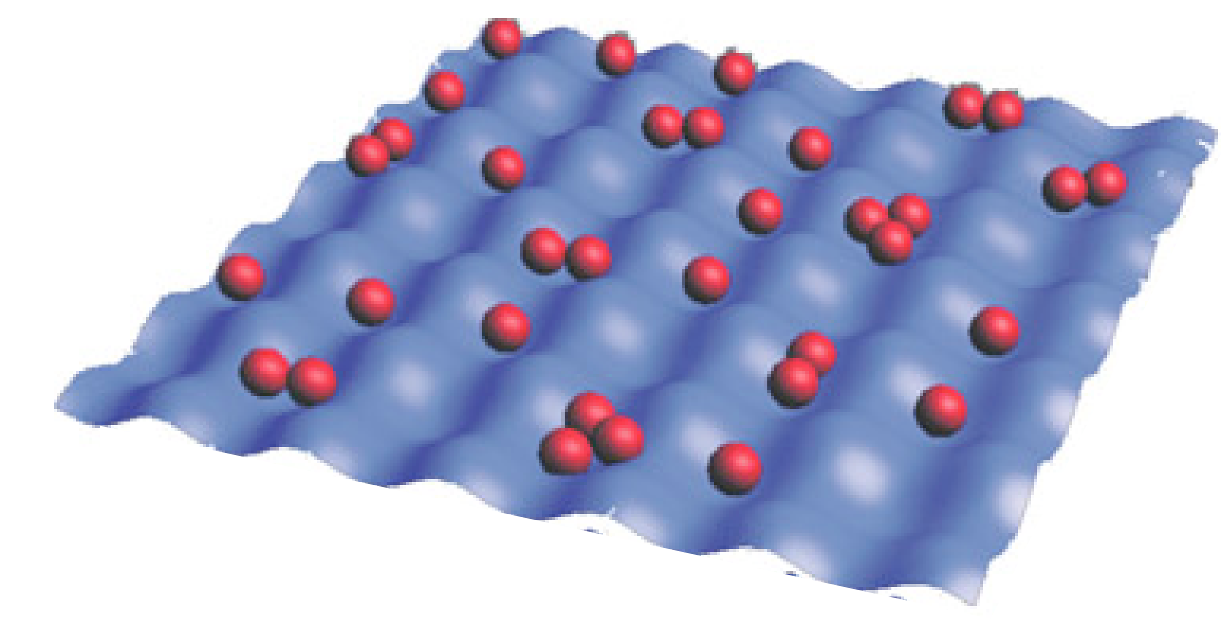
# Beyond Moore's law: quantum devices

Disruptive technology change: use quantum mechanics for computing!


Quantum random
number generators



Quantum simulators

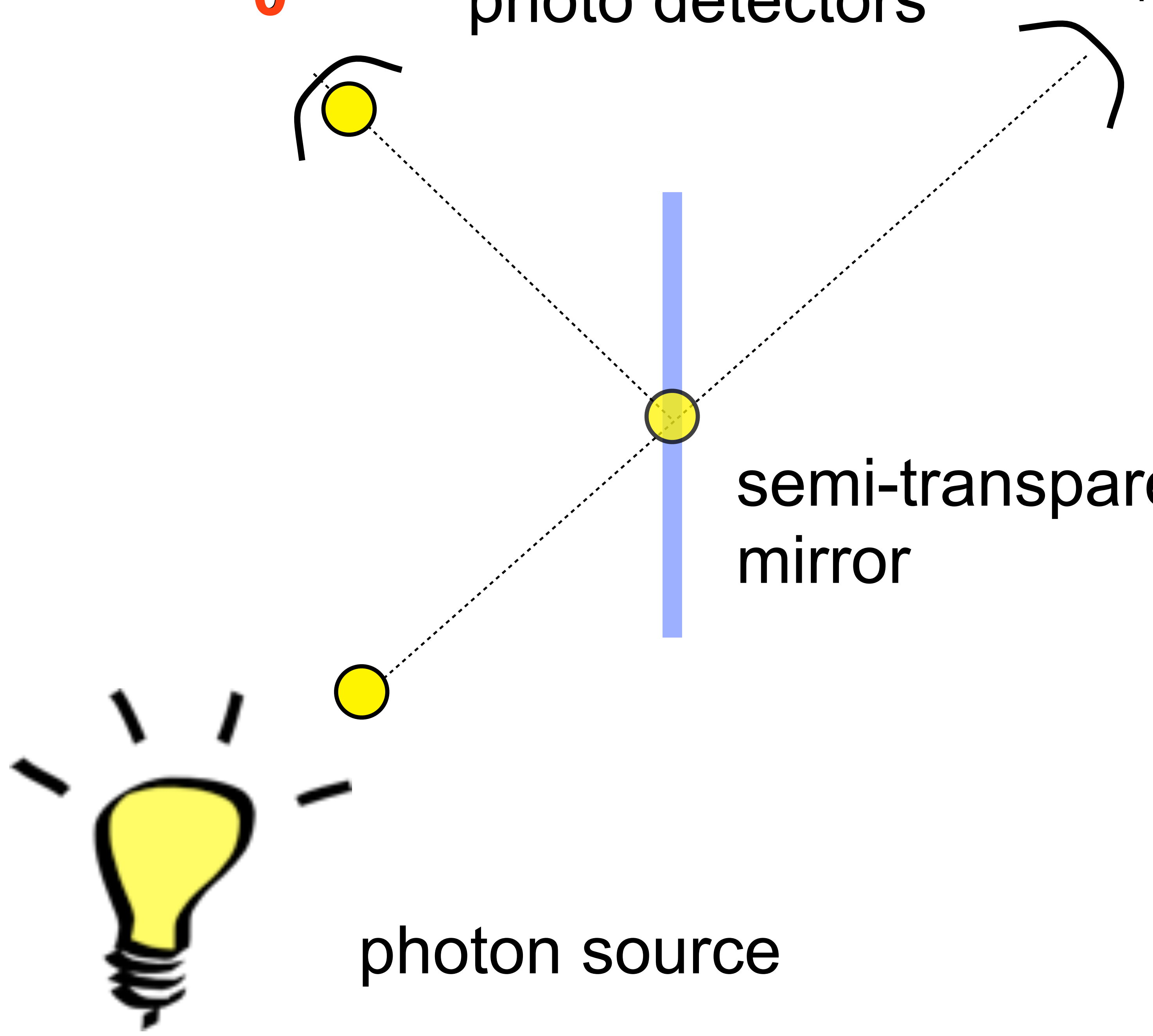
?

**Windows Q**

Quantum computer

# Quantum random number generators

Create true random numbers using the laws of quantum mechanics


1. Photon source emits a photon

2. Photon hits semitransparent mirror

3. Photon follows both paths

4. The photo detectors see the photon only in one place: **random selection**

# When will we have a quantum computer?

?

**Windows Q**

# May 2011:


D:WAVE
Yes, you can
have one.
No, you're not dreaming. D-Wave offer
the first commercial quantum computing system
on the market. We believe in building great things
that are as inspiring as they are powerful.
If you're passionate and curious about the future of
computation, and you'd like to take a different approach
to solving problems, then take a look at our products.
D-Wave One™
information

From http://www.dwavesys.com

# From http://www.dwavesys.com

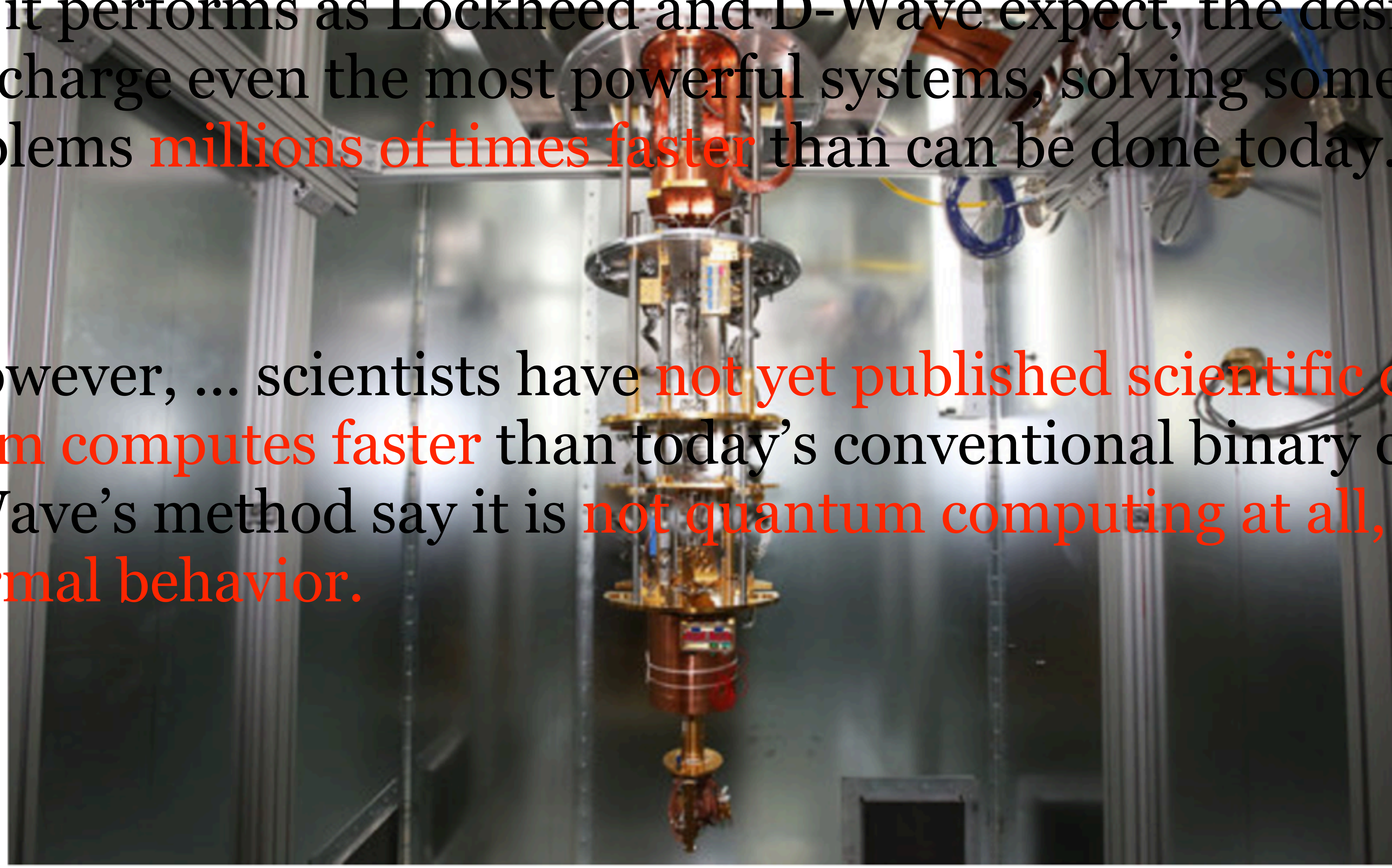
# The New York Times

Friday, March 22, 2013

## A Strange Computer Promises Great Speed

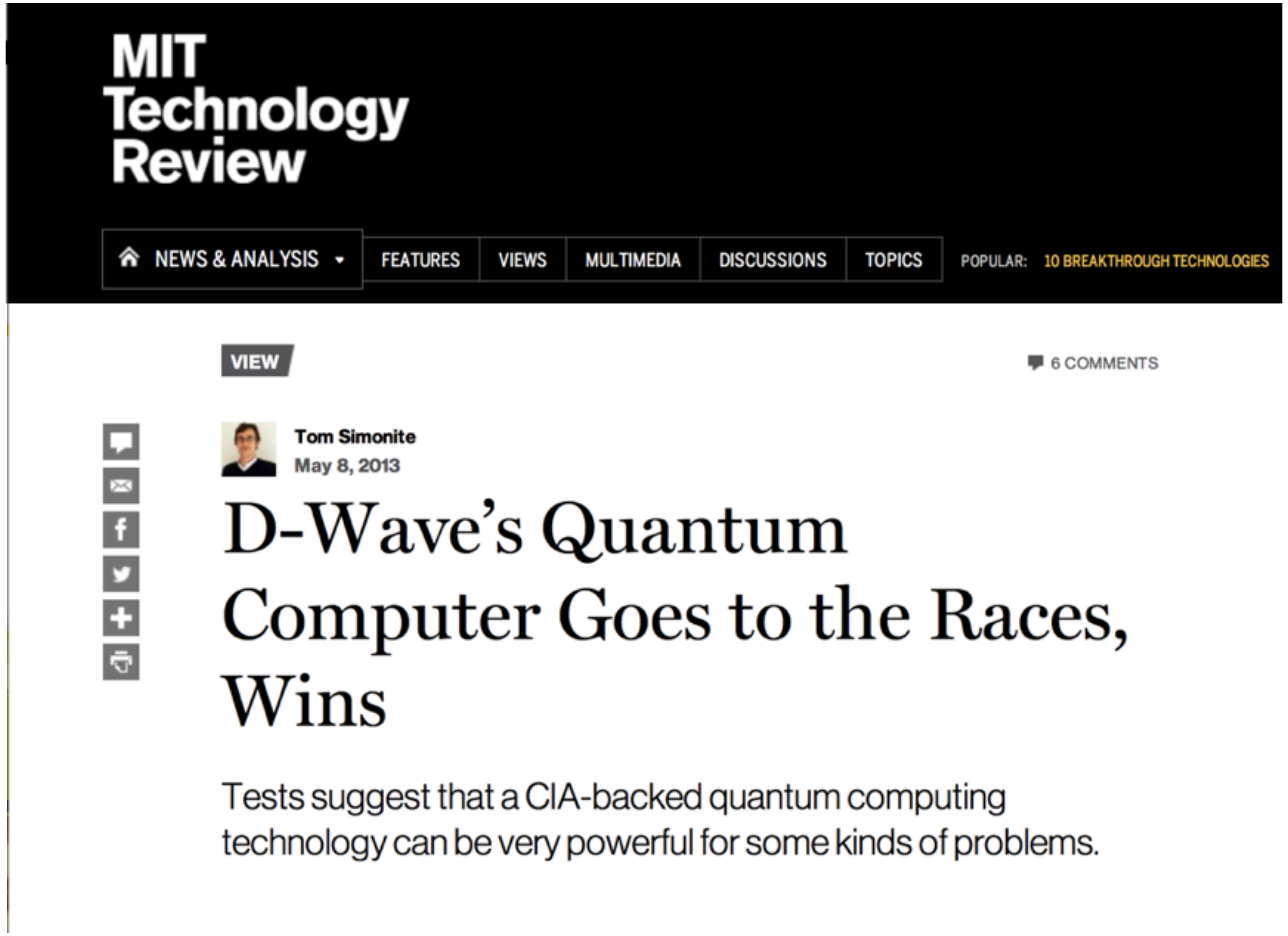
(*page 1*) .... if it performs as Lockheed and D-Wave expect, the design could be used to supercharge even the most powerful systems, solving some science and business problems millions of times faster than can be done today.

(*page 2*) However, ... scientists have not yet published scientific data showing that the system computes faster than today's conventional binary computers. ... critics of D-Wave's method say it is not quantum computing at all, but a form of standard thermal behavior.



Kim Stallknecht for The New York Times

# May 2013: D-Wave is 3600x faster than classical computers!?


MIT Technology Review

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VIEW

6 COMMENTS

Tom Simonite
May 8, 2013

## D-Wave's Quantum Computer Goes to the Races, Wins

Tests suggest that a CIA-backed quantum computing technology can be very powerful for some kinds of problems.

**Experimental Evaluation of an Adiabatic Quantum System for Combinatorial Optimization**

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***Special purpose heuristic device*** (D-Wave)
needs 0.491s

***General purpose exact solver*** (CPLEX)
needs 30 minutes on one CPU core

*"It would of course be interesting to see if highly tuned implementations could compete ..."*

# Some magazines investigate deeper ...
# ... but isn't it business success that counts in the end?

The Economist

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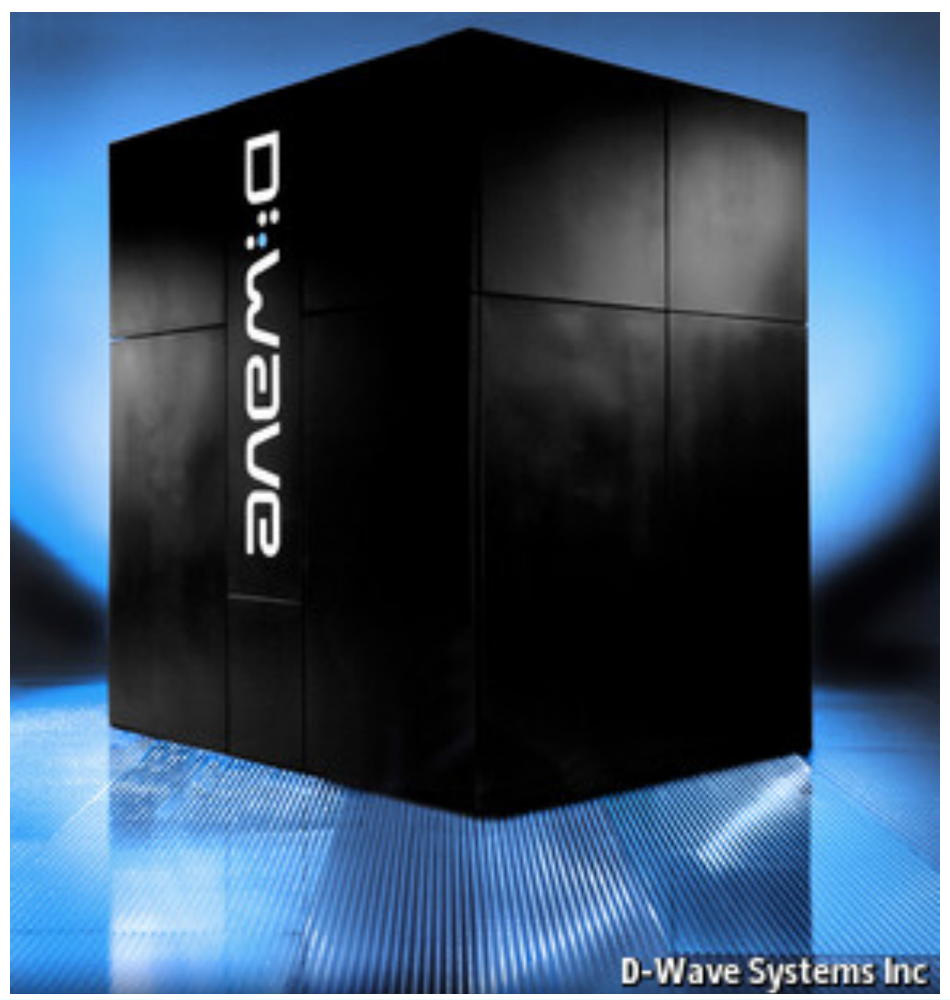
**Quantum computing**

## Faster, slower—or both at once?

**The first real-world contests between quantum computers and standard ones**

May 18th 2013 | From the print edition    Like 268    Tweet 25

CHIPMAKERS dislike quantum mechanics. Half a century of Moore's law means their products have shrunk to the point where they are subject to the famous weirdness of the quantum world. That makes designing them difficult. Happily, those same quantum oddities can be turned into features rather than bugs. For many years researchers have been working on computers that would rely on the strange laws of quantum mechanics to do useful calculations. They would do this by using binary digits which, instead of having a value of either "one" or "zero", had both at

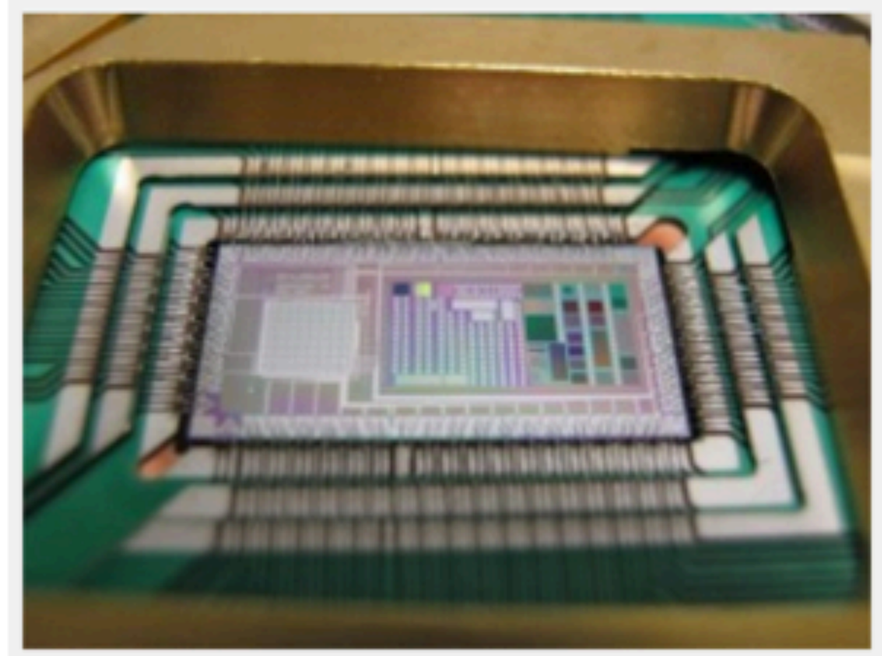



Forbes    New Posts +11 posts this hour    Most Popular Tumblr CEO: Not A Billionaire    Lists Most Powerful Women

## NASA And Google Partner To Work With A D-Wave Quantum Computer

3 comments, 3 called-out    + Comment Now    + Follow Comments

D-Wave, the Canadian-based company that is the first to offer a commercial quantum computer, announced today that it's sold its second $10 million D-Wave Two system. The contract is between the Universities Space Research Association and D-Wave. Google GOOG +0.91%, USRA, and NASA will be collaborating on the use of the machine.



D-Wave 512-Qubit Bonded Processor - Recent Generation (Credit: D-Wave)

627 Share    748 Tweet    82 Share    2.3k Submit    111

The system will be installed at a new lab, which will be located at

# What is behind this?

D-Wave is not a universal quantum computer but a special purpose quantum optimizer

Does it work?

Is it quantum or classical?

Is it thousands of times faster than anything classical?

We performed experiments on D-Wave devices to answer these questions

# Binary quadratic optimization: an NP-hard problem

Find the values $x_i$ (=0 or 1) which minimize the quadratic cost function

$$\sum_{ij} a_{ij} x_i x_j + \sum_i b_i x_i \qquad \text{where} \qquad x_i \in \{0,1\}$$

Finding the solution is exponentially hard (unless P=NP)

# The Ising spin glass: an NP-hard problem

Find the values $x_i$ (= -1 or +1) which minimize the quadratic cost function

$$\sum_{ij} J_{ij} x_i x_j + \sum_i h_i x_i \qquad \text{where} \qquad x_i \in \{-1,+1\}$$

Finding the solution is exponentially hard (unless P=NP)

Many important problems can be expressed as binary quadratic optimization problems (or Ising spin glasses) with only polynomial overhead

- factoring integers: 15 = 3 x 5
- traveling salesman problem
- portfolio optimization
- graph isomorphism
- ...

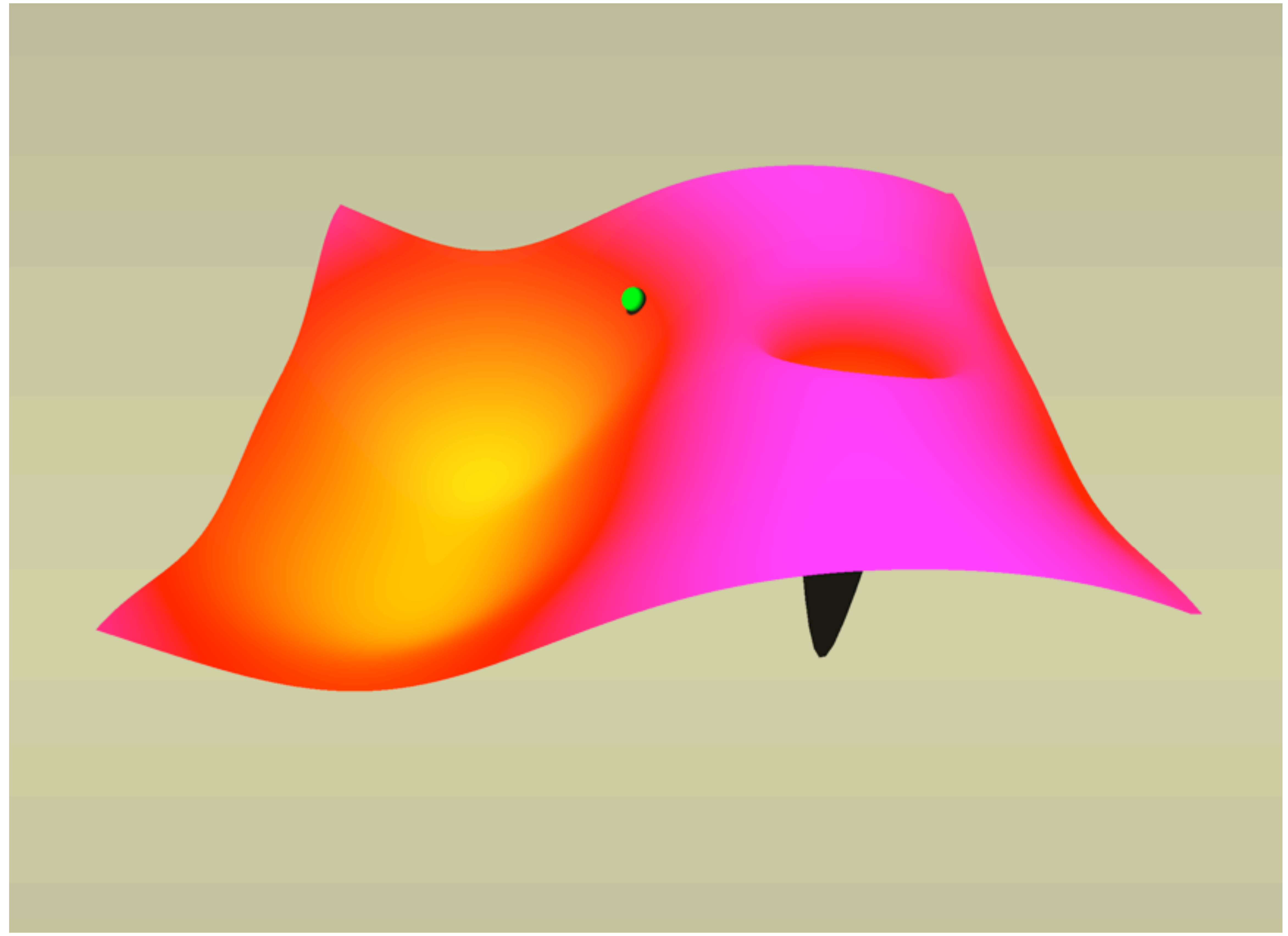
Can a quantum device solve these problems faster than a classical one?

# Annealing and simulated annealing

## Annealing

A 7000 year old neolithic technology

Slowly cool a metal to improve its properties



## Simulated annealing

Kirkpatrick, Gelatt and Vecchi, Science (1983)

A 30 year old optimization technique

Slowly cool a model in a Monte Carlo simulation to find the solution to an optimization problem

We don't always find the global minimum and have to try many times

# Quantum annealing

## Advantages of quantum mechanics

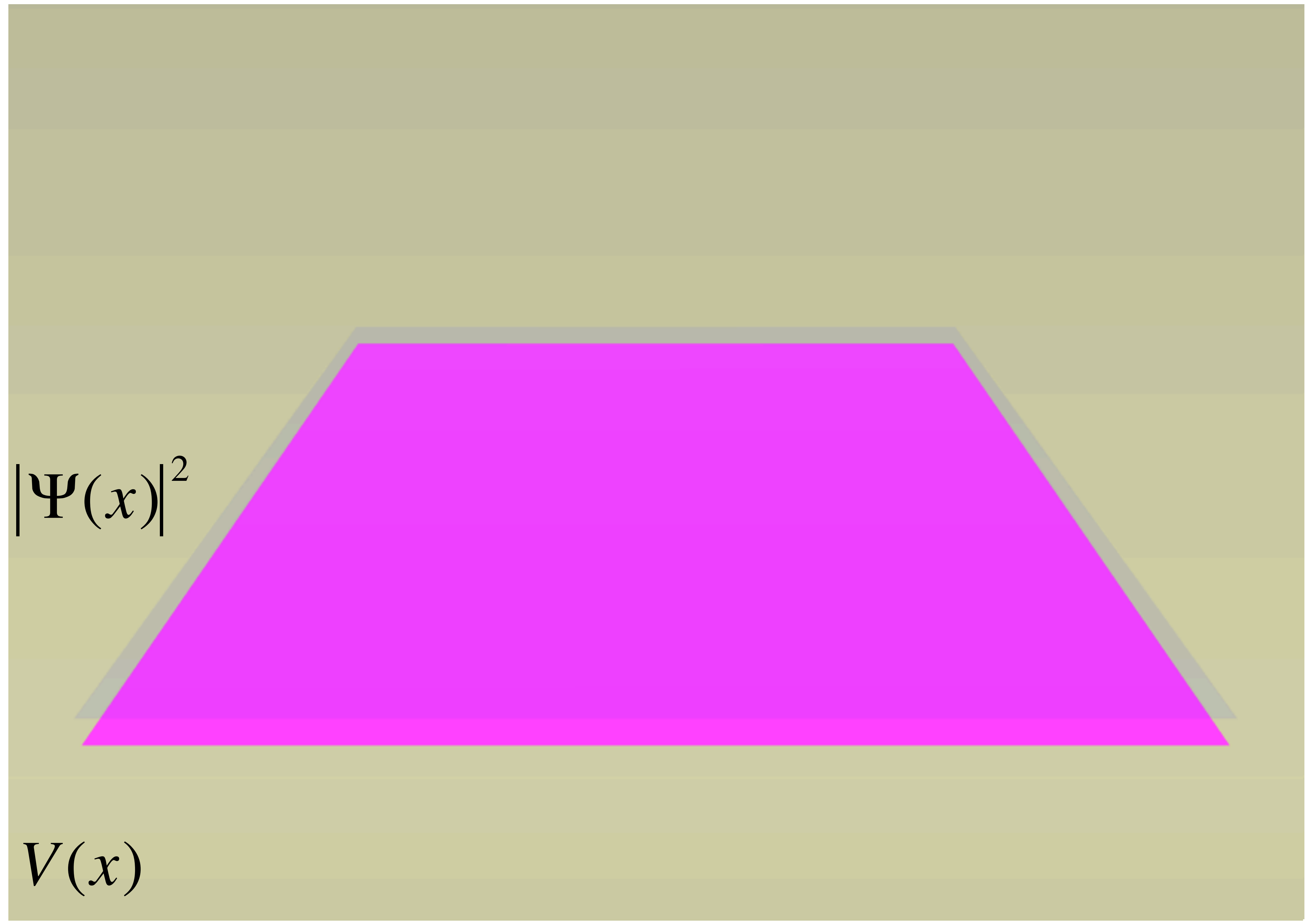
A quantum particle can be everywhere at once and explore all of the configuration space

## Quantum annealing schedule

Start with a constant potential $V(x)$

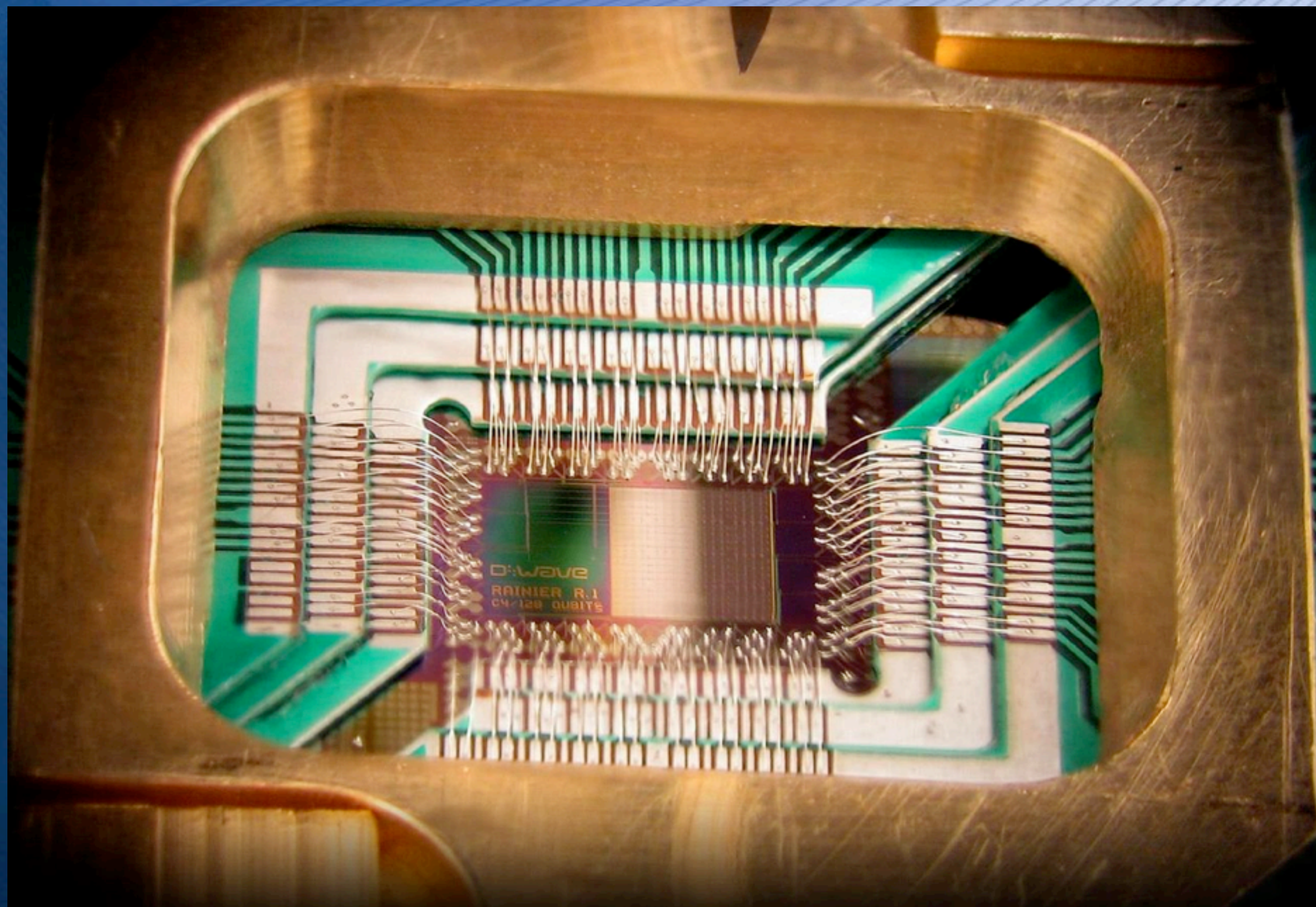
The particle is everywhere with equal probability given by the square of the wave function $|\Psi(x)|^2$

Turning on the potential the wave function concentrates around the minima of the potential




We have to anneal very slowly for the hard problems to let the particle "tunnel" to the global minimum

# The D-Wave device



# Superconducting flux qubits

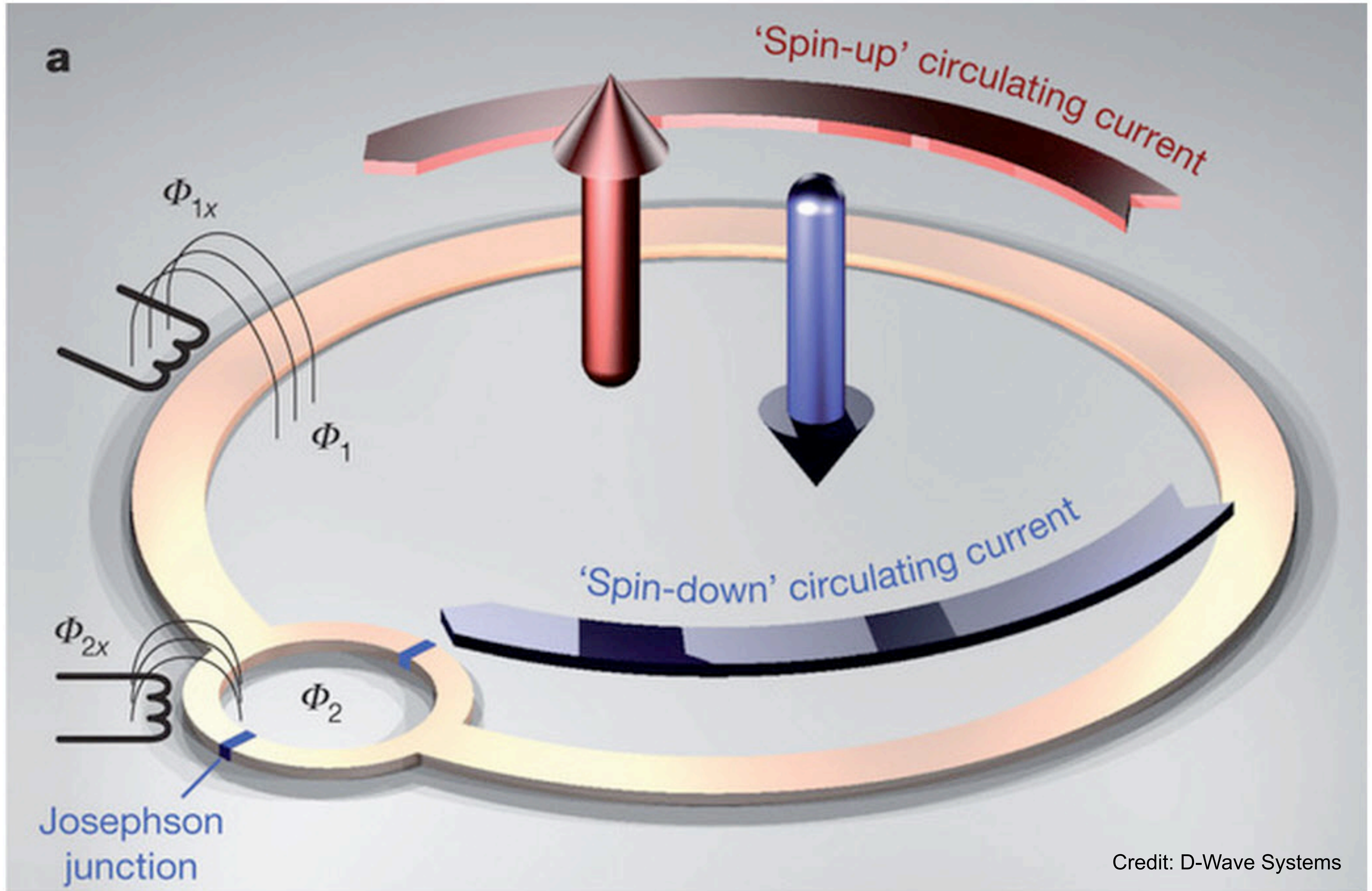
The qubit is implemented by magnetic fluxes caused by circulating superconducting currents

0: magnetic flux flowing down

1: magnetic flux flowing up

Programmable magnetic coupling allows to define the optimization problem

$$\sum_{ij} J_{ij} x_i x_j + \sum_i h_i x_i$$

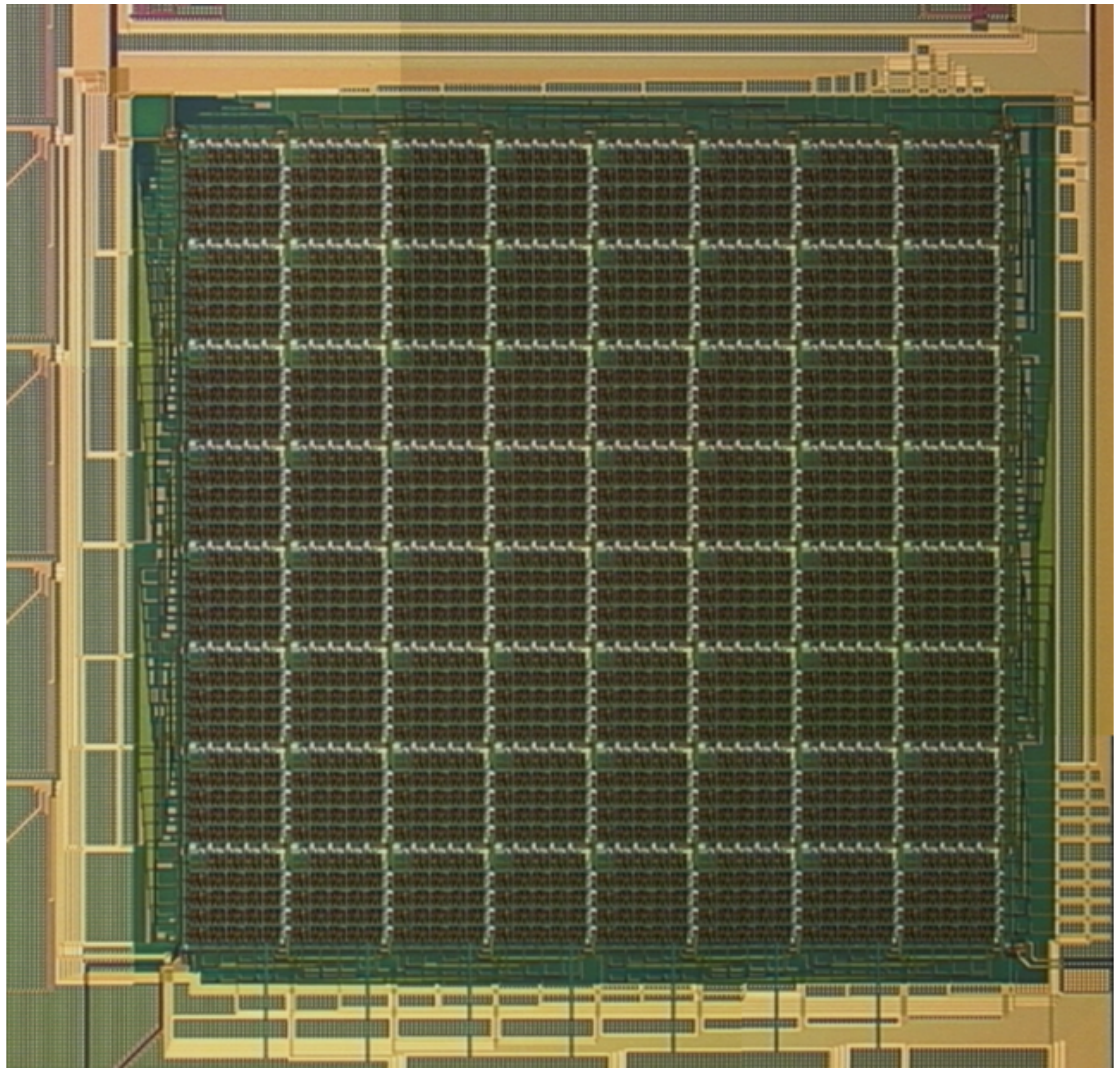


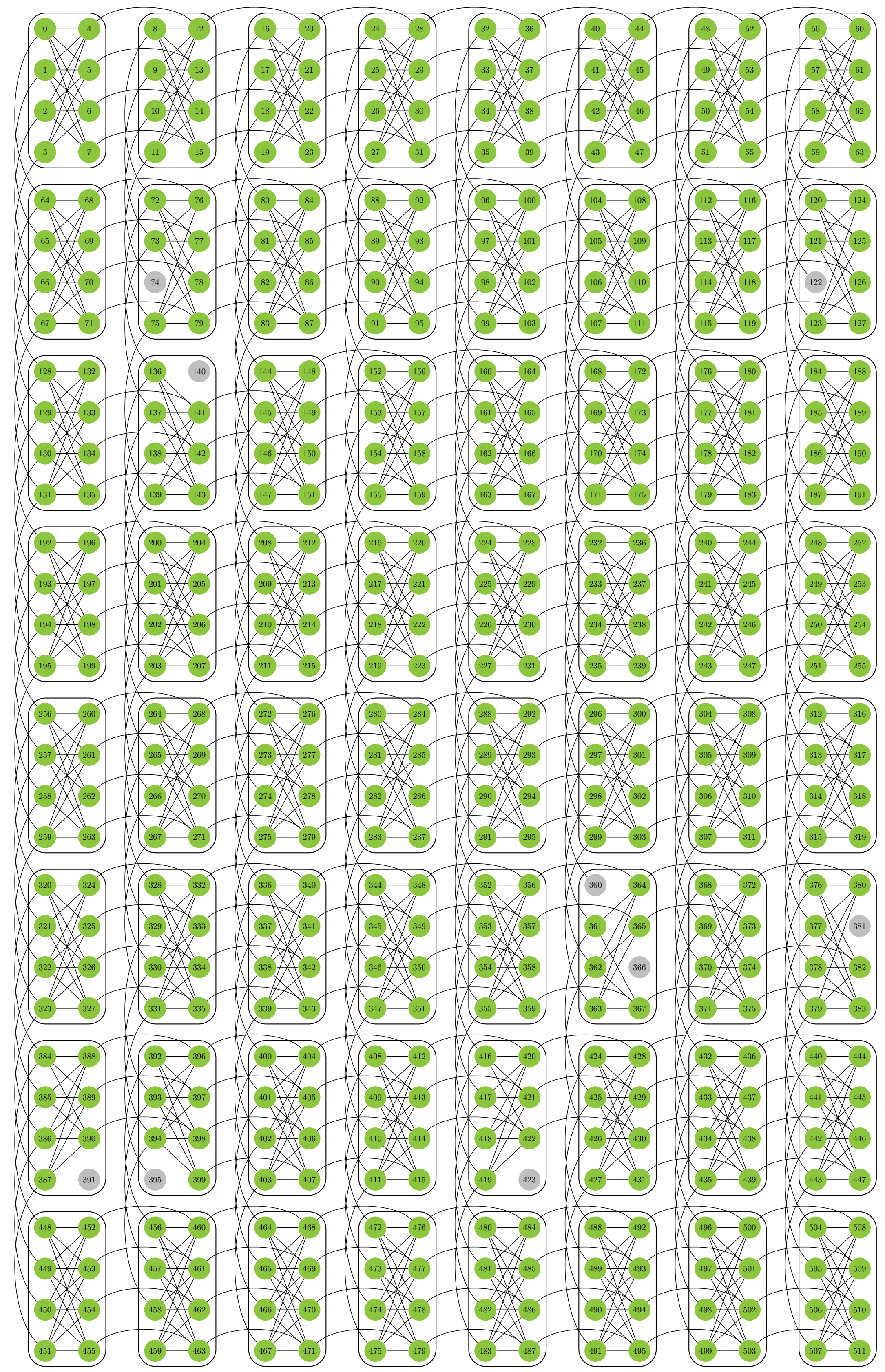

Credit: D-Wave Systems

# Lockheed Martin bought two D-Wave devices

D-Wave One installed at USC in October 2011: 108 of 128 qubits working

D-Wave Two installed at USC in March 2013: 503 of 512 qubits working





Couplings can be defined on edges of the“chimera graph” implemented by the device

$$\sum_{ij} J_{ij} x_i x_j + \sum_i h_i x_i$$

# Is D-Wave a quantum annealer?

Many scientists doubt that D-Wave is a quantum device
since the qubits are imperfect and the device is exposed to lots of thermal noise

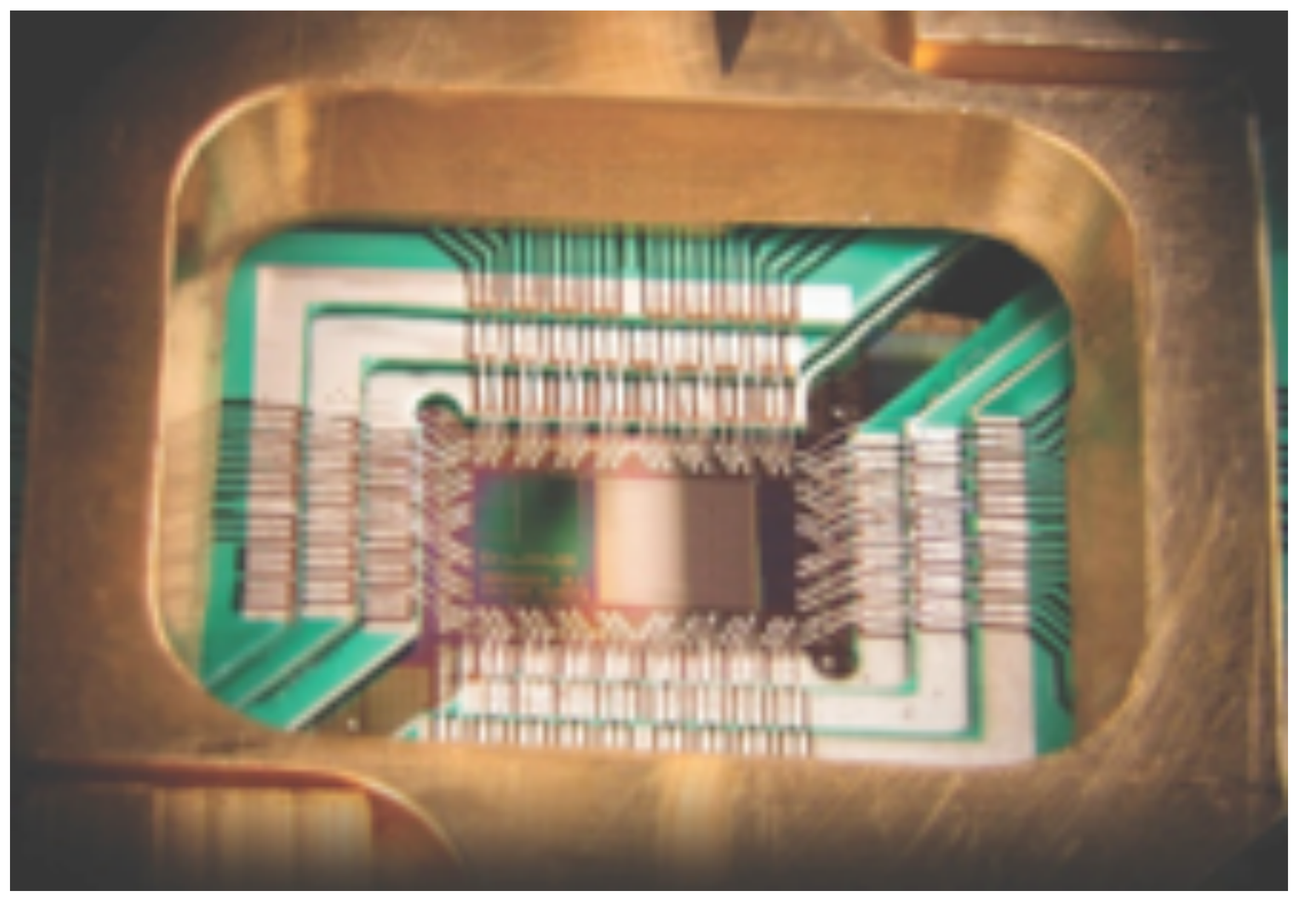
| | |
|---|---|
| **Hypothesis 1:** D-Wave is a not quantum but just a classical annealer | **Experimental test:** compare to a simulated classical annealer (Monte Carlo simulation) |
| **Hypothesis 2:** D-Wave is a quantum annealer | **Experimental test:** compare to a simulated quantum annealer (quantum Monte Carlo) |
| **Hypothesis 3:** D-Wave is a quantum device and shows quantum speedup | **Experimental test:** scaling with problem size is better than that of the classical codes |

# The experiments to test the machine

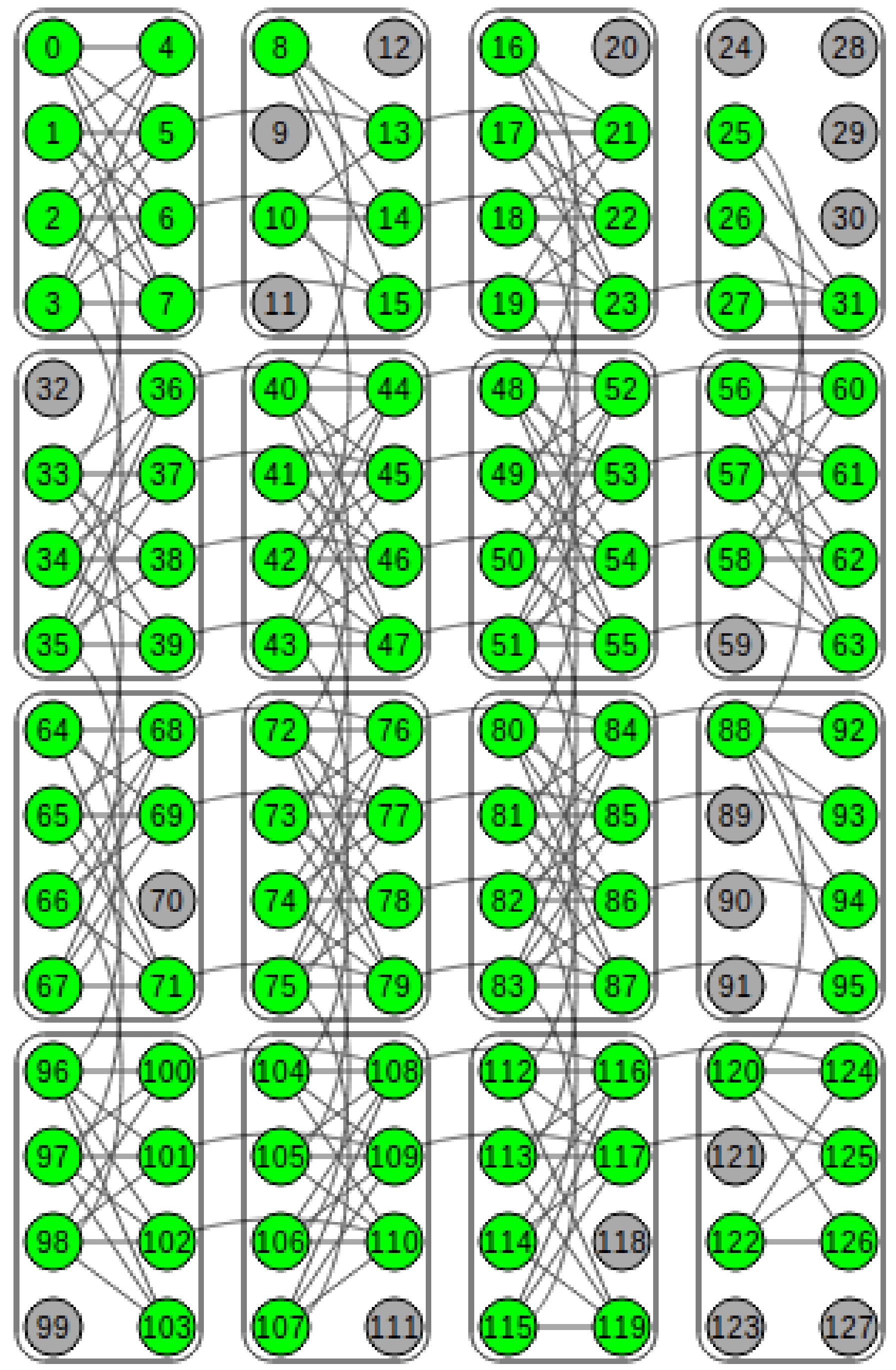
## Find the hardest problems that the machine can solve

Random ±1 couplings on all edges of the chimera graph

1000s of choices of couplings
1000s of repetitions of the annealing
10s of problem sizes
vary the annealing time and schedule



hundred million experiments
on D-Wave One

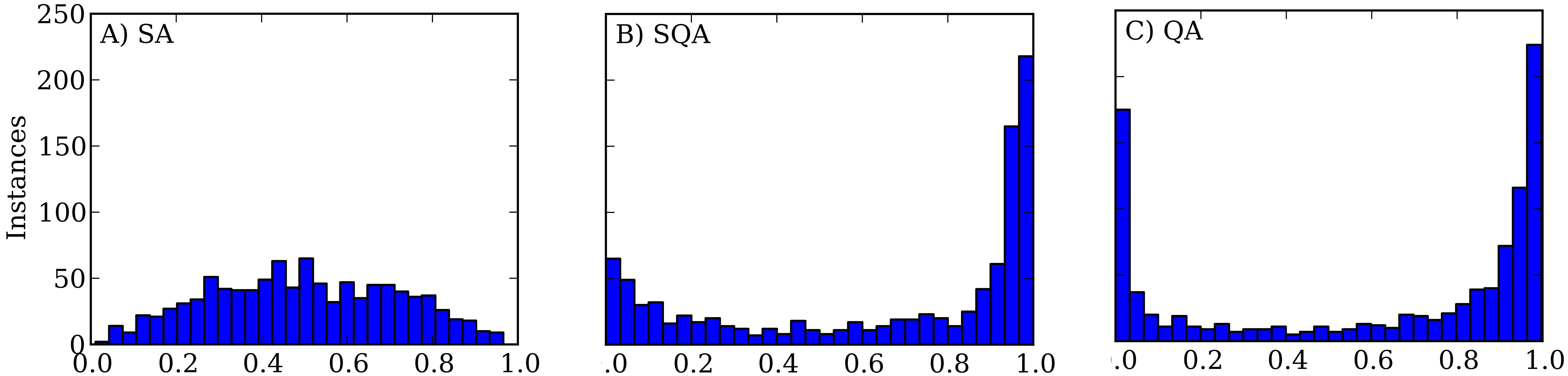



billions of simulations
classical and quantum Monte Carlo

# Success probability histograms

1. Pick 1000 different random problems
2. For each problem run experiments and count how often the global minimum was reached
3. Plot a histogram of the probabilities of finding the global minimum

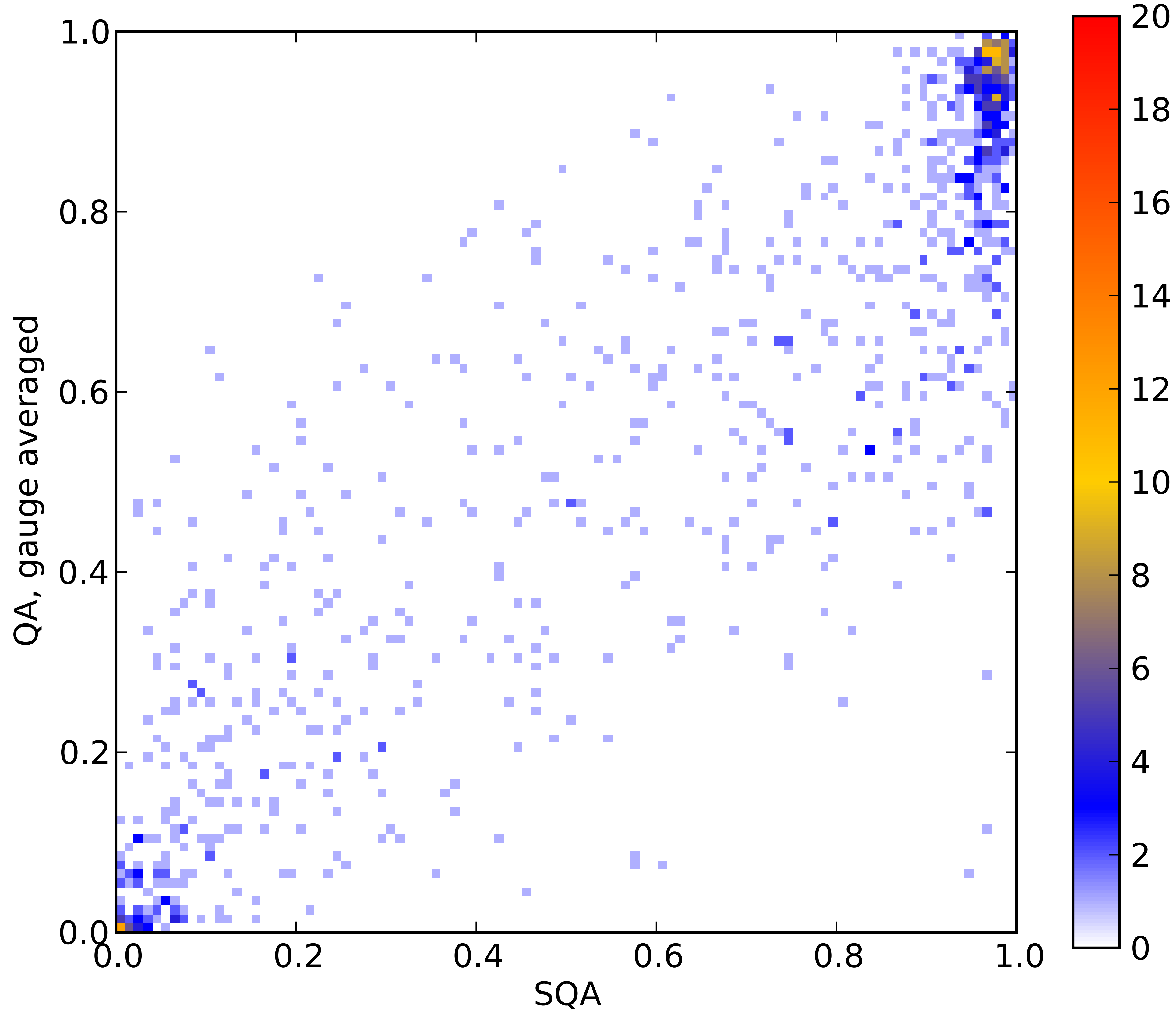
Simulated classical annealer | Simulated quantum annealer | D-Wave One




D-Wave One is **inconsistent with a classical** annealer

D-Wave One is **consistent with a simulated quantum** annealer

# Correlations between D-Wave and a simulated quantum annealer




easy for both D-Wave and
the simulated quantum annealer

hard for both D-Wave and
the simulated quantum annealer

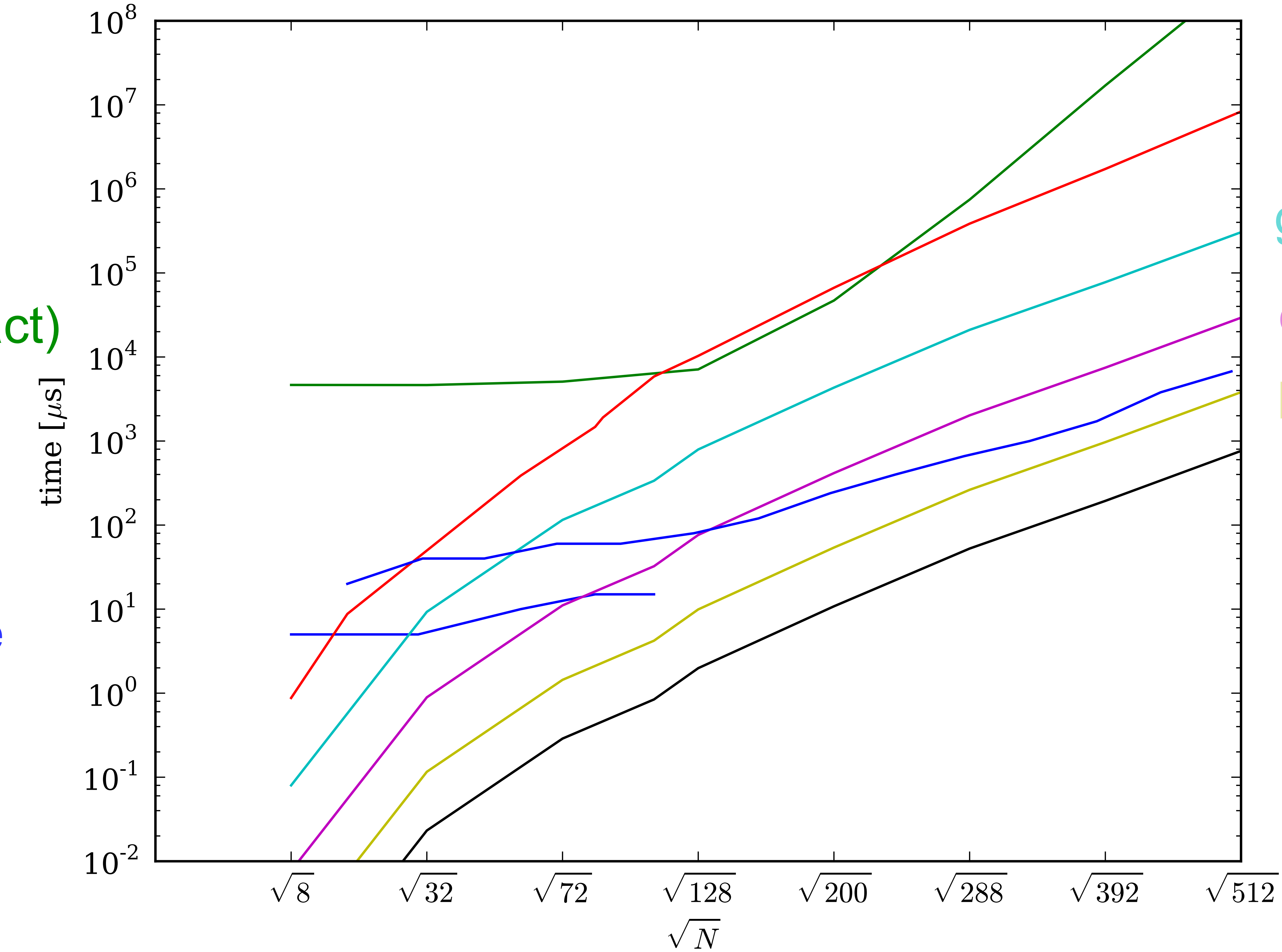
The same instances are hard and easy
on D-Wave and the simulated quantum annealer

# Scaling of the median time to solution with problem size

Belief Propagation (exact)

D-Wave Two

D-Wave One




Simulated Quantum Annealing

generic

optimized

parallelized

GPU

Simulated Annealing

200 Monte Carlo updates per nanosecond

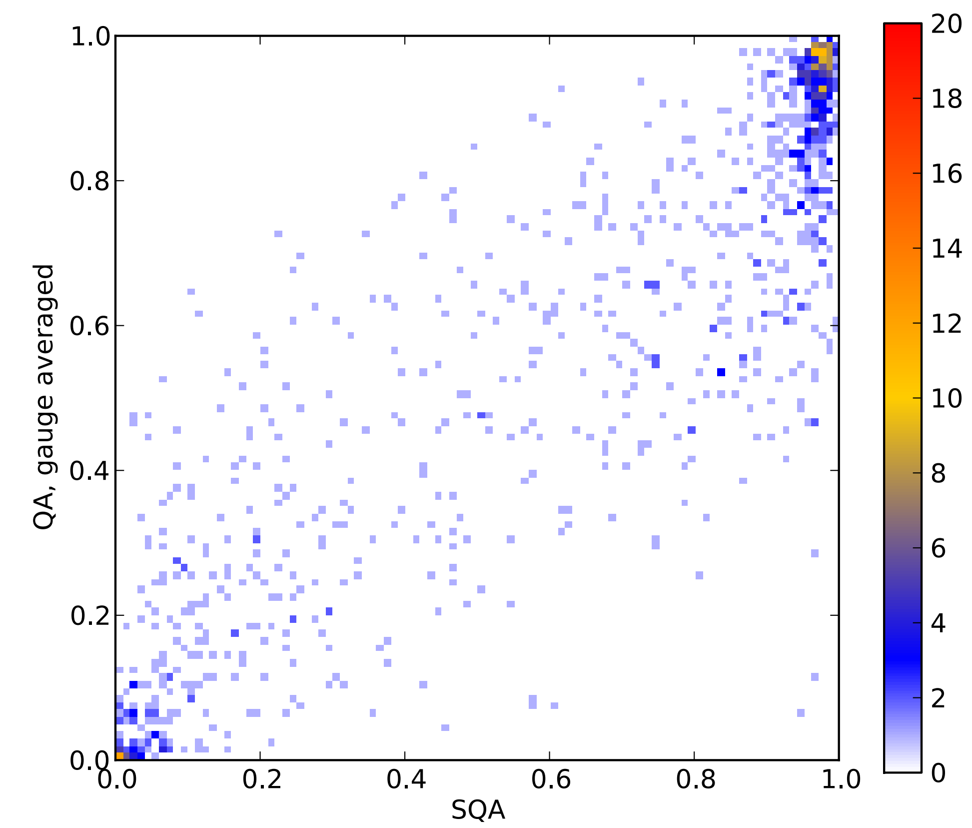
This is for random ±1 couplings and the conclusion may be different for other benchmarks

# We understand the D-Wave "black box" much better

Special purpose device for combinatorial optimization problems

$$\sum_{ij} a_{ij} x_i x_j + \sum_i b_i x_i$$

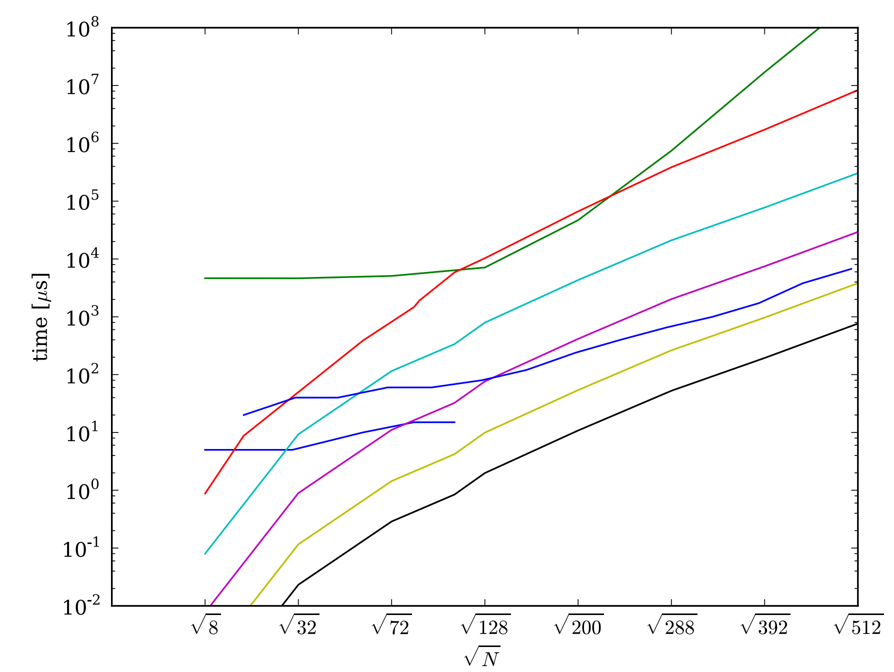
Finds the global optimum out of $2^{503}$ states (non-trivial!)




Evidence for quantum behavior

- Performance correlates well with a simulated quantum annealer but not with a simulated classical annealer

Performance can (so far) be matched by highly optimized classical codes on a single GPU or CPU




Observed scaling is the same as that of classical codes

Can improved calibration change the conclusion?