ETH zürich

D-Wave: real quantum computer ?

M. Johnson et al., "*Quantum annealing with manufactured spins*", Nature 473, 194-198 (2011)

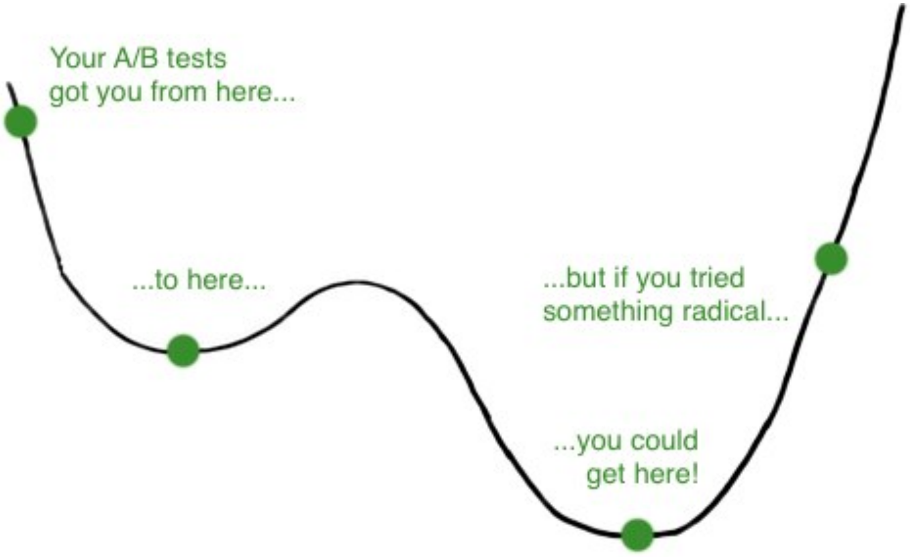
S. Boixo et al., "*Evidence for quantum annealing wiht more than one hundred qubits*", Nature Physics 10, 218-224 (2014)

Marc Serra, Gustavo Villares

Solving optimization problems

Goal of optimization problems:

- A general optimization problem is defined by **cost function**, seen as the **energy** of a **physical system**
- The goal is to find the **global energy minimum**, while avoiding local minima



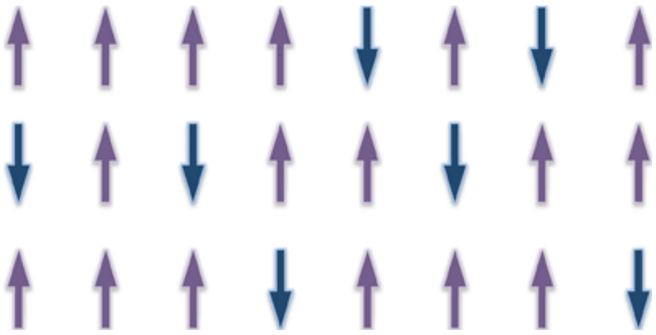
Ising spin glass model

$$\mathcal{H}_P = \sum_{i=1}^{N} h_i \sigma_i^z + \sum_{i,j=1}^{N} J_{ij} \sigma_i^z \sigma_j^z$$

Local fields

couplings

Ex.: magnetism



Characteristics:
- NP-hard problem
- No efficient algorithm exists to find it ground state

Is there a way to find the ground state of the Ising Hamiltonian efficiently ?

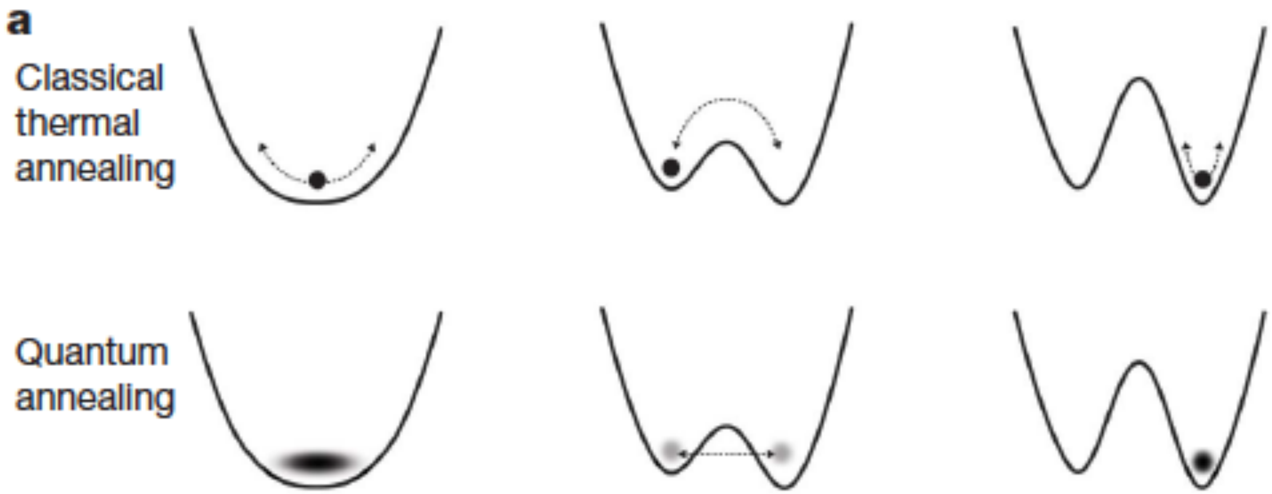
Annealing: way to find Ising‘s model ground state

Classical thermal annealing:

- Progressively weaker **thermal fluctuations** ➔ lowest energy configuration

Quantum annealing:

- Progressively weaker **quantum fluctuations (tunneling)** ➔ lowest energy configuration

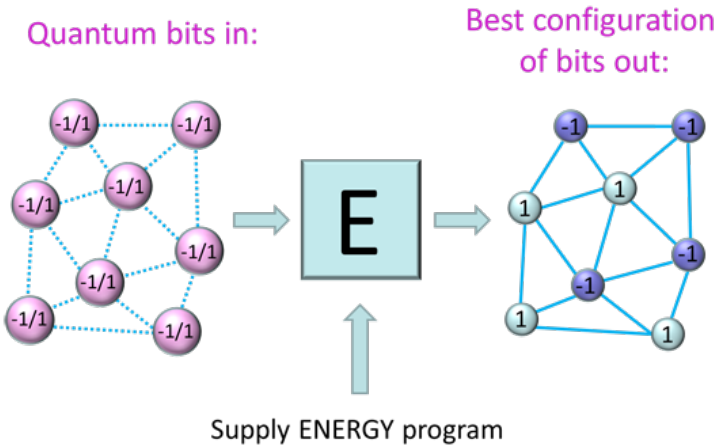


Quantum annealing could in theory **efficiently** find the ground state of an Ising spin model

Ising spin system and quantum computing

Implementation of a processor using quantum annealing:

- Programmable quantum spin system
- Control individual spins and the couplings
- Perform quantum annealing
- Reading the value of each state



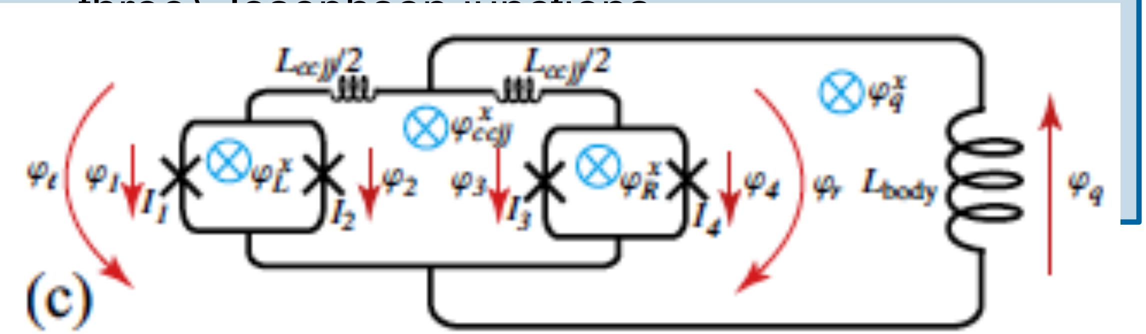
$$\mathcal{H}_{\mathrm{P}} = \sum_{i=1}^{N} h_i \sigma_i^z + \sum_{i,j=1}^{N} J_{ij} \sigma_i^z \sigma_j^z$$

D-wave solution: array of internconnected superconductings flux qubits

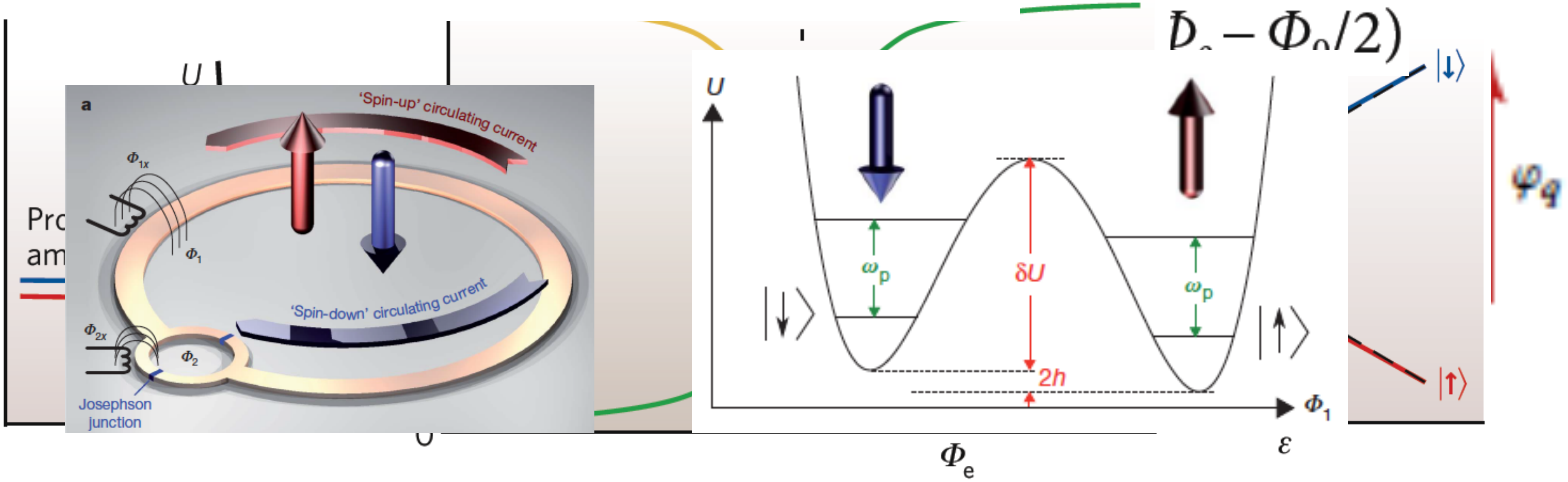
Superconduction flux qubits

- **Adapted for quantum annealing**
- **optimized for high scale production**

Superconducting loop interrupted by one (or

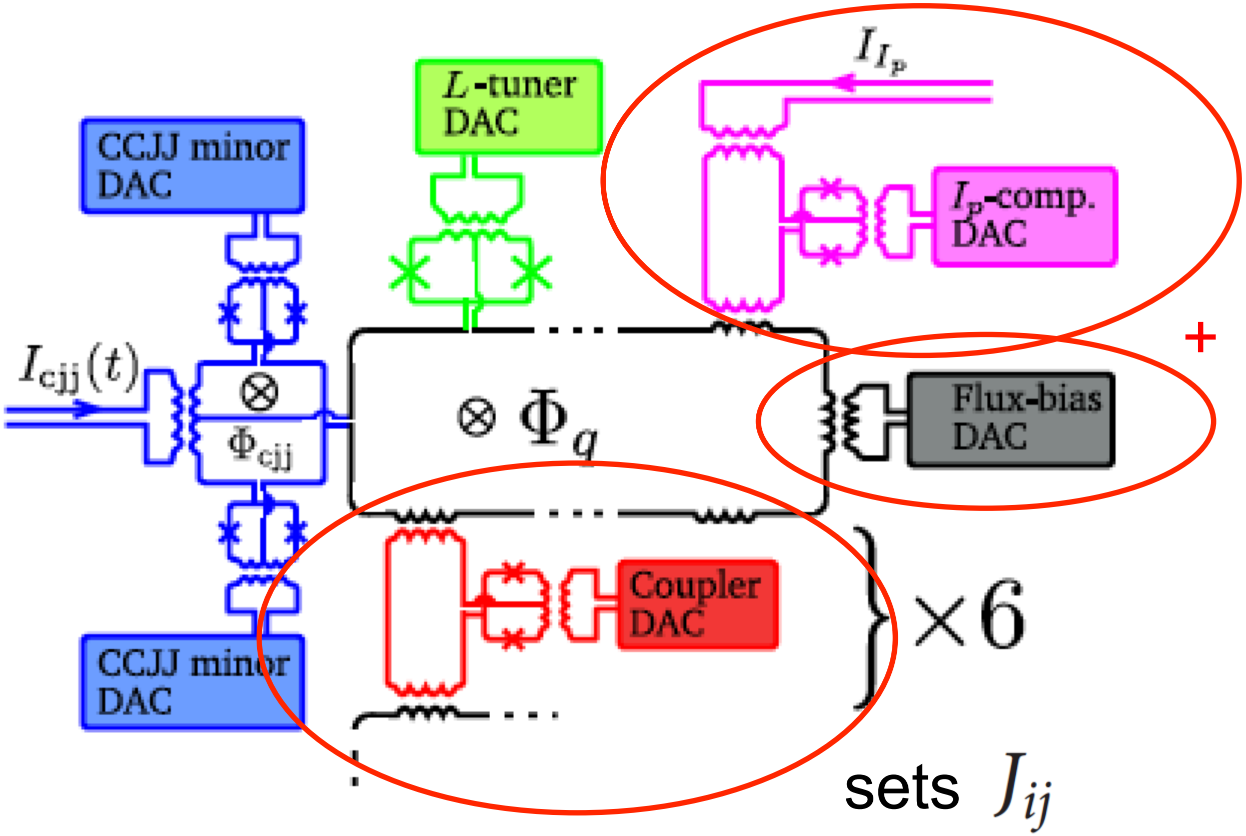


$$\nu = (\Delta^2 + \varepsilon^2)^{1/2}$$



Coupling between flux qubits

- Device only composed of **superconducting wires** and **Josephson jonctions**
- 5 main parts

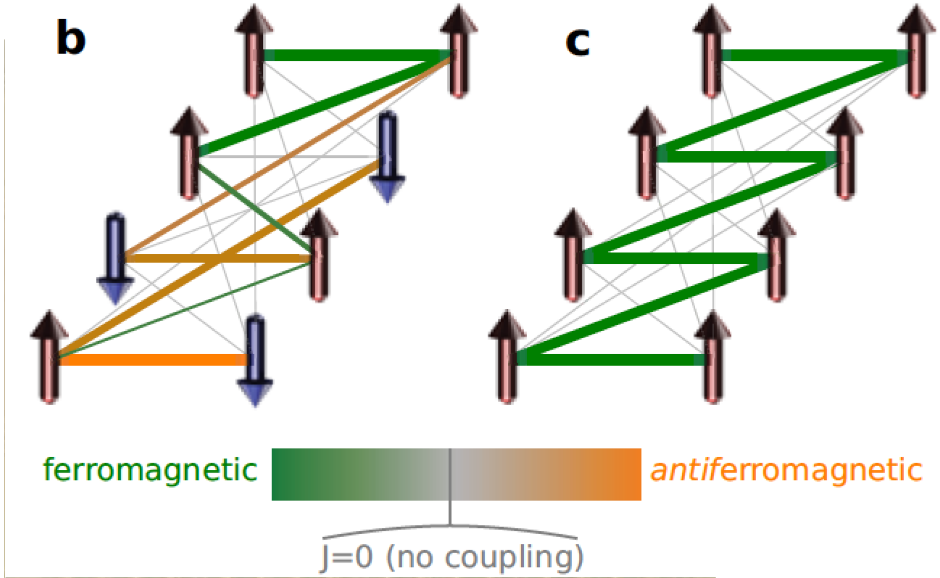


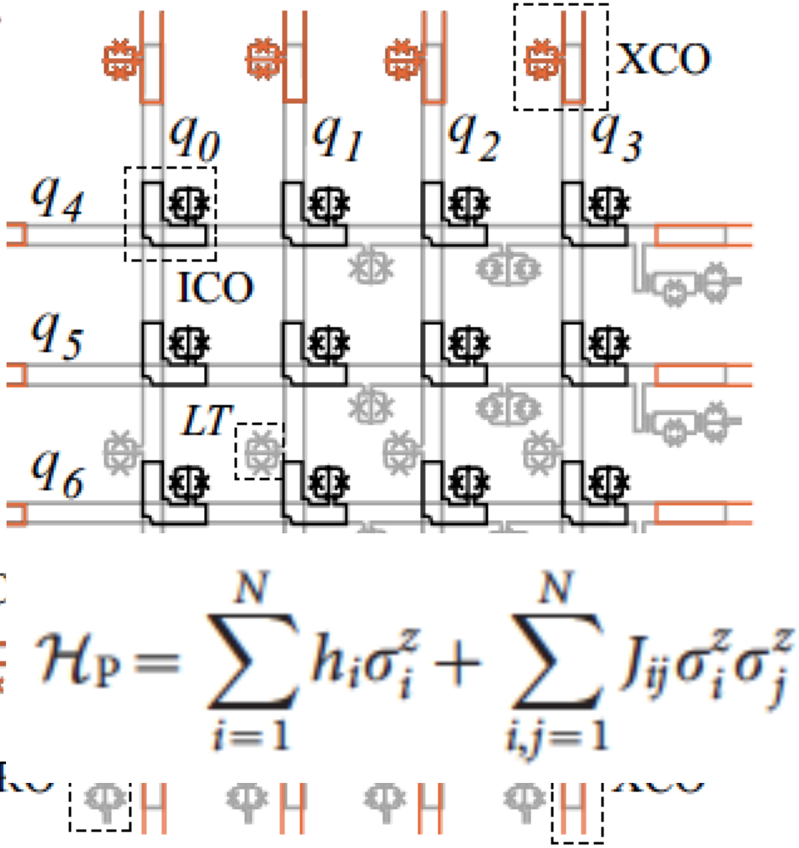
+ sets h_i

sets J_{ij}

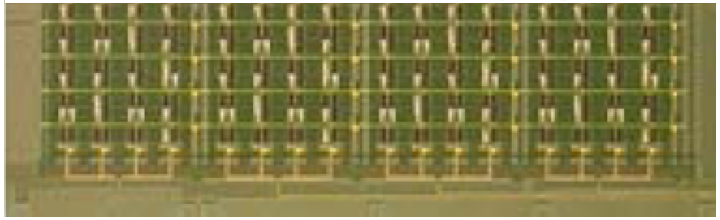
Final chip architecture

- Total of 128 qubits (8 qubits per main block)
- Connected in a **complete bipartite graph** and **interacting** via couples





$$\mathcal{H}_P = \sum_{i=1}^{N} h_i \sigma_i^z + \sum_{i,j=1}^{N} J_{ij} \sigma_i^z \sigma_j^z$$



Performing annealing with D-wave

- Main steps:
  1. Initialization
  2. Annealing
  3. Read-out

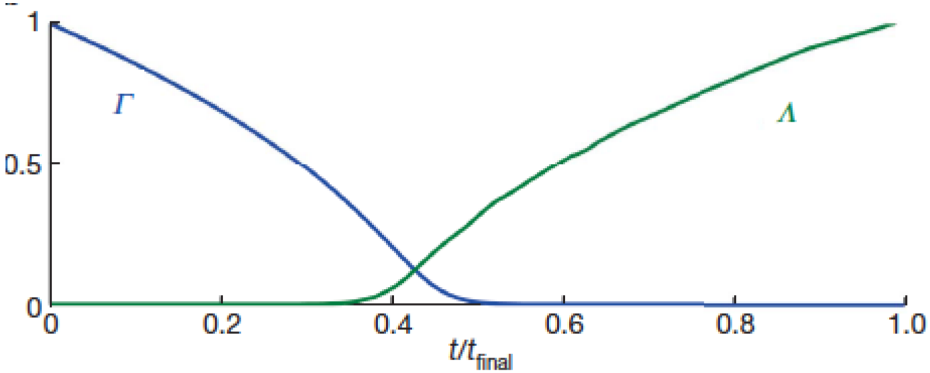
$$\mathcal{H}(t) = \Gamma(t)\sum_{i=1}^{N} \Delta_i \sigma_i^x + \Lambda(t)\mathcal{H}_\mathrm{P}$$

1. Initialization $\Gamma = 1, \Lambda = 0$

$$\sum_{i=1}^{N} \Delta_i \sigma_i^x .$$

Ground state: superposition of all states in the basis

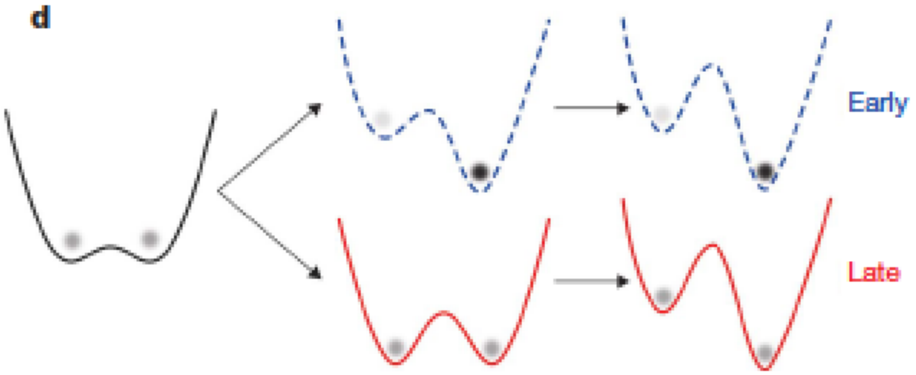
2. Annealing: slow change of the Hamiltonian



3. Read out: measures the **magnetisation of the qubit,** not its quantum state

Proof of quantum annealing: T-dependence (1/2)

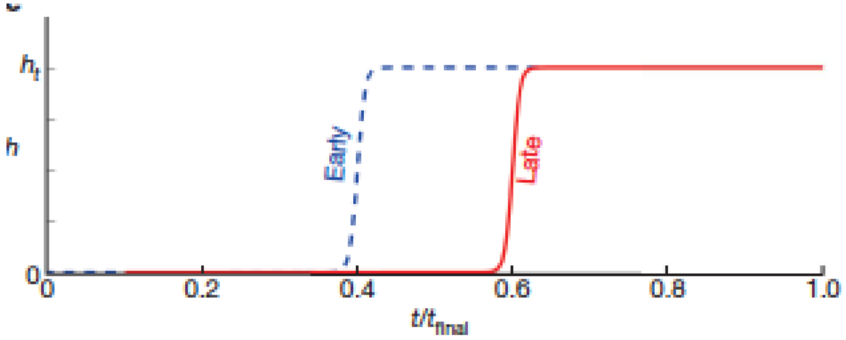
- Measure **freeze time** (time at which the system can no longer respond to changes in its energy landscape):
  - Thermal annealing - > t_{freeze} has a linear dependence on temperature
  - Quantum annealing ->t_{freeze} is independent of temperature



If $t_d < t_{freeze}$: $P_{up} > 1/2$
Annealing possible

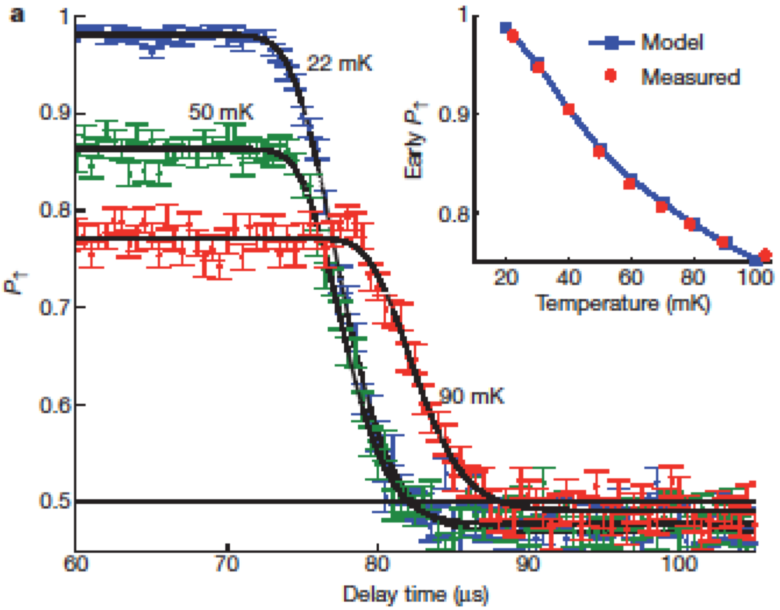
If $t_d > t_{freeze}$: $P_{up} = 1/2$
Too late

- Apply a step response on h_i:

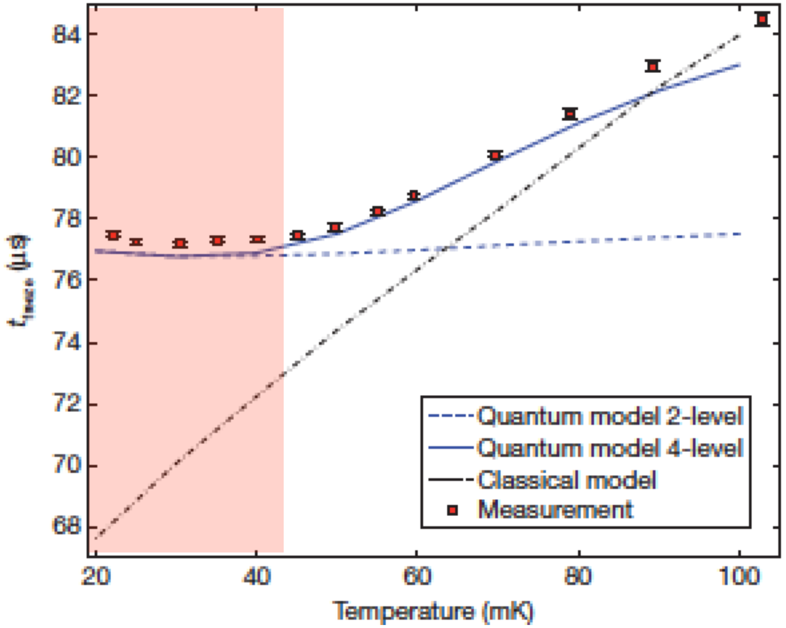


Proof of quantum annealing: T-dependence (2/2)

For a **single qubit**: quantum annealing



Quantum regime



Same observation for 8 coupled qubits

Problem solving performance

Determine the “quantumness” of the D-Wave machine by comparint the difficulty of solving a problem with classical and quantum simulation

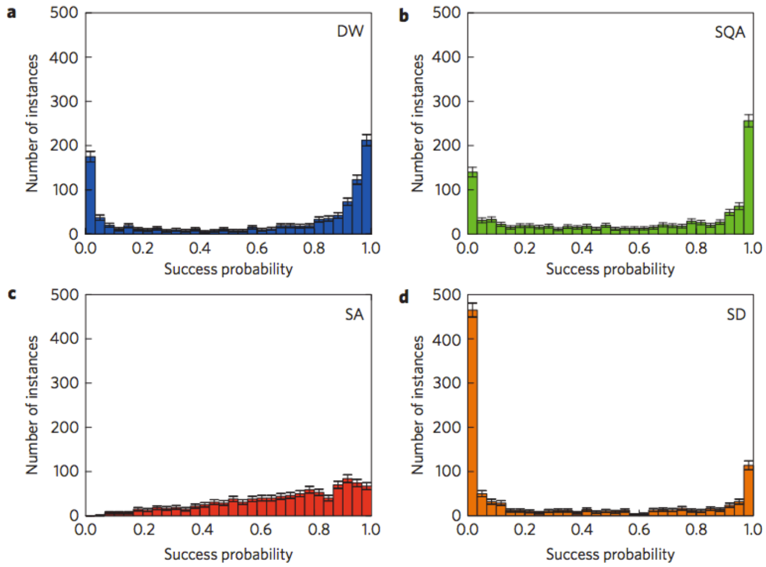
- Pick 1000 random problem instances, run different algorithms 1000 times and compare results each time with the correct solution.
- Determine the probability of getting the correct result.
- Compare the probabilities of getting the correct result for each problem between classical and quantum methods

[1] “Evidence for quantum annealing with more than one hundred qubits”, Seung Woo Shin, Graeme Smith, J
and Umesh Vazirani (Jan 2014)

Problem solving performance

Determine the “quantumness” of the D-Wave machine by comparing the difficulty of solving a problem with classical and quantum simulation

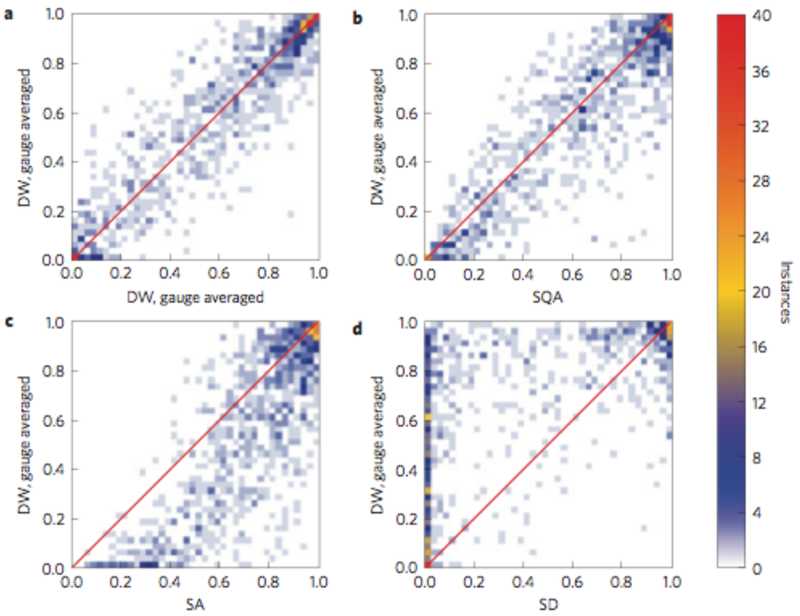
- Results:



- Simulated Quantum annealing and the D-Wave have a bimodal distribution.
- Simulated annealing has an unimodal distribution
- D-Wave seems to correlate better with simulated quantum annealing than with simulated thermal annealing.

Problem solving performance

Compare the difficulty* of solving a problem with classical and quantum simulation



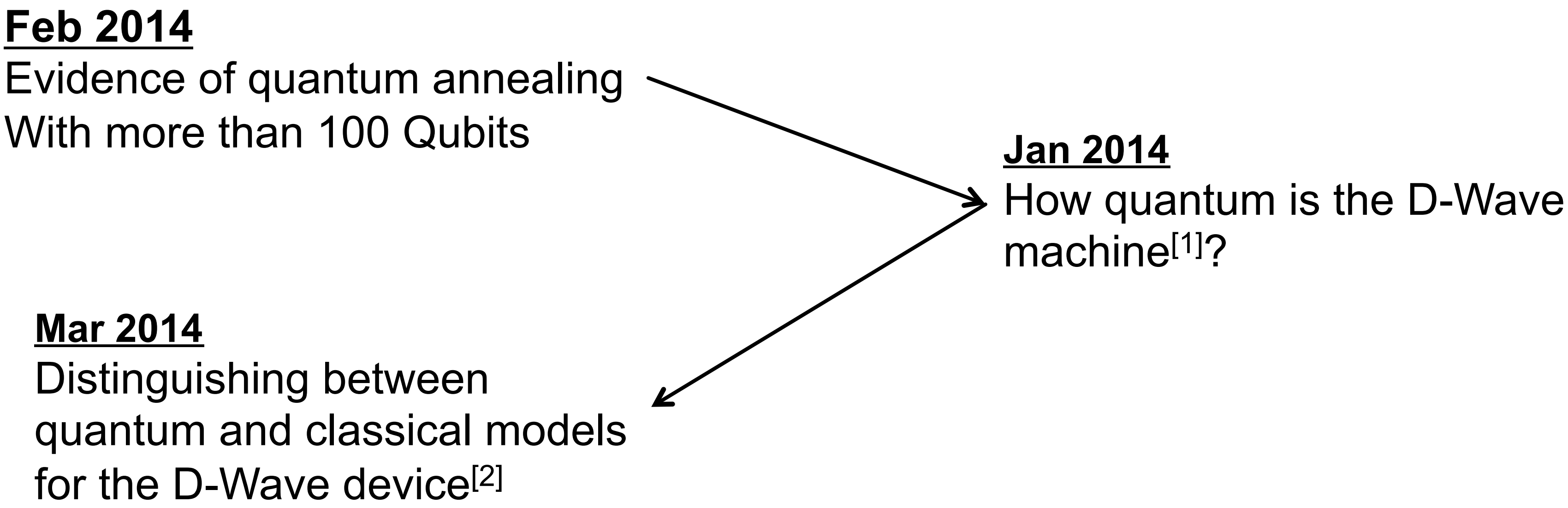
- Problems hard for quantum algorithms are hard for the D-Wave. (High correlation)

- Problems hard for a classical algorithm are not necessarily hard for the D-Wave. (Low correlation)

- Simulated quantum algorithm running on a classical computer still faster than D-Wave

***Number of instances that are not solved after 1000 iterations**

Controversy about the results



In favor of D-Wave

Opposed to D-Wave

Feb 2014
Evidence of quantum annealing
With more than 100 Qubits

Jan 2014
How quantum is the D-Wave machine[1]?

Mar 2014
Distinguishing between
quantum and classical models
for the D-Wave device[2]

[1] “How ‘Quantum’ is the D-Wave Machine?”, Seung Woo Shin, Graeme Smith, John A. Smolin, and Umesh Vazirani (Jan 2014)

[2] “Distinguishing quantum and classical models for the D-Wave device”,Vinci, W., Albash, T., Mishra, A., Warburton, P. A. & Lidar, D. A. (Mar 2014)

Scalability of the D-Wave

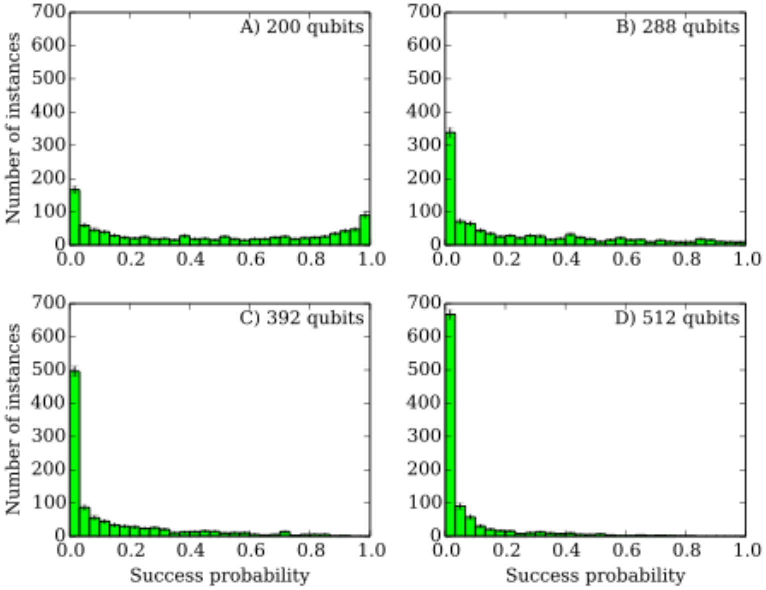
- Hardness of problems is affected by the height of avoided crossings (How energetically-close wrong solutions are). Dictates required “slowness” to ensure the system stays in the ground state.

$$\tau \propto \frac{1}{\Delta^2}$$

- Not all qubits are connected to each other.

- Gap energy Δ decreases exponentially with problem size.

- Does not turn exponential problem into polynomial problem. May still provide speedup.



Summary/Conclusion

- The D-Wave “Quantum Computer” is a device based on superconducting qubits that simulates the Ising spin model.

- The D-Wave computer exhibits physical signatures of quantum behavior
  - Dependence of the freezing time with temperature
  - “Hardness” of problems correlates well with simulated quantum algorithms

- There is an ongoing (As of April 2014) debate on the literature on whether the “Quantumness” of the D-Wave is fine-grained enough for quantum computation or it can be explained by mean field theories.

- Current implementation not faster than a classical computer

Outlook, debate

- Is D-Wave on the right path?
  - Can a machine that is not an universal quantum computer use quantum physics to solve problems faster?
    - Should research focus on technology that can work in the near future, or at least not neglect it?
  - Will D-Wave eventually evolve into such a device?
  - Is the approach by D-Wave scientifically acceptable?