Quantum Simulation on the Quantum Hardware

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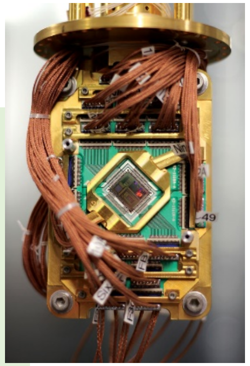
Quantum simulation

Richard Feynman (1981)

"I want to talk about the possibility that there is to be an ***exact*** simulation, that the computer will do ***exactly*** the same as nature."



- **(my) Definition of quantum simulation**
  To reproduce the behavior of a quantum-mechanical system on an artificial quantum device.
- **Advantage over real experiment**
  Precise control microscopic parameters. E.g. interactions between spins
- **Disadvantage**
  Difficult to build large systems without noise.
- **Today's topic**
  Successfully mitigated the difficulty in a (relatively) large system with up to several thousand qubits.

Qubits (quantum bits) in quantum device

Tiny superconducting ring at low T

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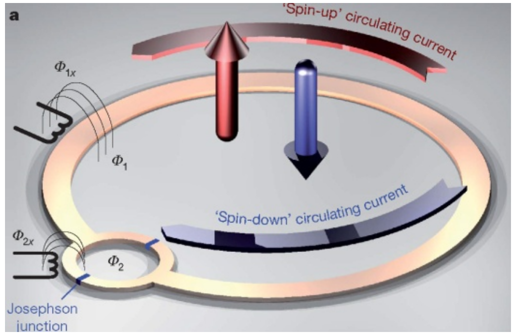

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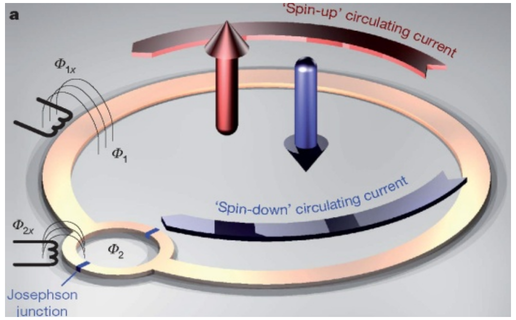

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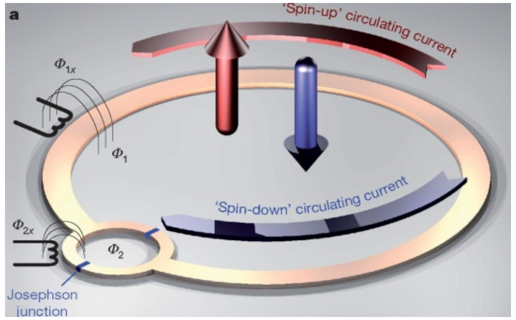
100, 101, 110, 111



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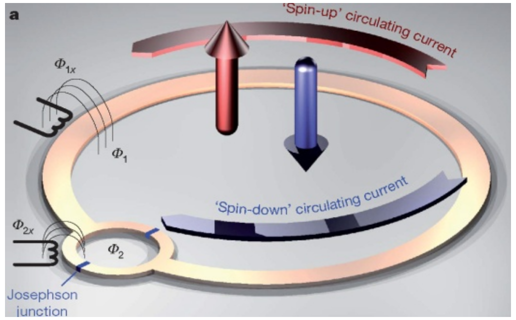

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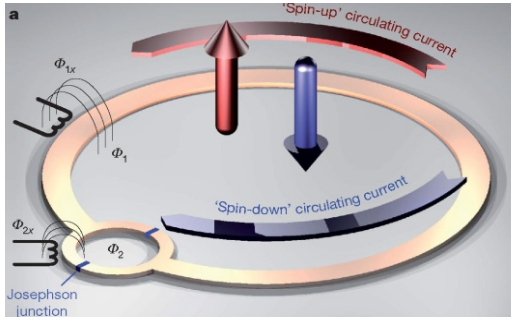

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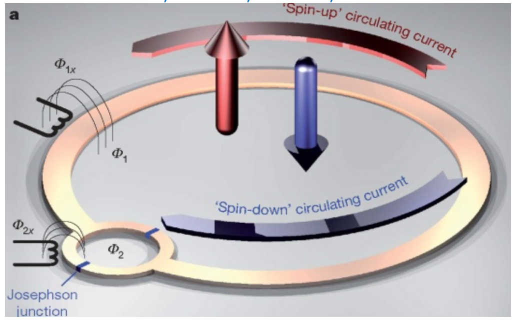

Superposition of very many states

Types of hardware for quantum simulation

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- **Large-scale fault-tolerant quantum computer (FTQC)**

  The “ideal” quantum computer to be realized in the (far) future.

  Theoretically known to be effective for solving some hard problems efficiently.

  Challenge : To build a device of sufficient scale to realize the “ideal” goal.

- **NISQ** (**N**oisy **I**ntermediate-**S**cale **Q**uantum computer)

  Already realized in small scales.

  Small-scale experiments have been conducted. Still within the reach of classical computers.

  Challenge: Significant reduction of noise is needed for meaningful results.

- **Quantum annealing and quantum simulator**

  Already realized in intermediate scales.

  Simulations have already been realized with significant scale (to be shown later).

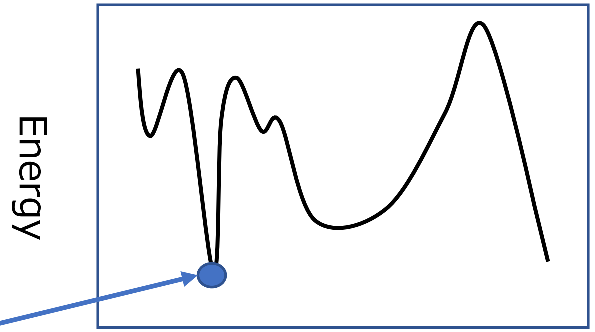
  Challenge: Limited in the type of systems to be simulated, e.g. the transverse-field Ising model.

Quantum annealing

T. Kadowaki and H. Nishimori (1998)

Generic quantum algorithm for combinatorial-optimization problems

- To find the ground (lowest energy) state of the Ising model with complex interactions (spin glass)



To find the state with the lowest energy in a very rugged energy landscape.

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2^N states

Quantum annealing

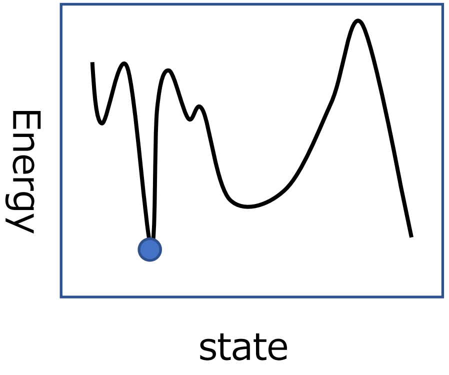
T. Kadowaki and H. Nishimori (1998)

Generic quantum algorithm for combinatorial-optimization problems

- To find the ground state of Ising model with complex interactions (spin glass)
- Many problems of practical importance are formulated this way.
- Example: optimal vehicle routing, job scheduling, portfolio optimization, fault detection

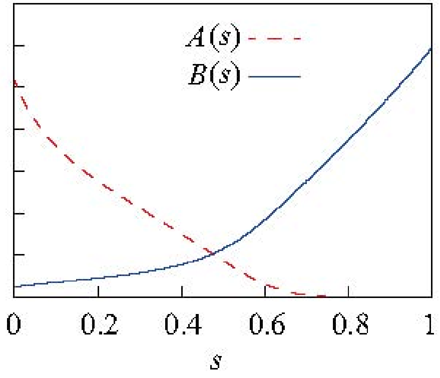
Method

Appropriate control of coefficients of the transverse-field Ising model



$$\boxed{H(s) = -\frac{A(s)}{2}\sum_i \sigma_i^x - \frac{B(s)}{2}\sum_{i,j} J_{ij}\sigma_i^z\sigma_j^z}$$

Time evolution $H(0) = -\frac{A(0)}{2}\sum_i \sigma_i^x \longrightarrow H(1) = -\frac{B(1)}{2}\sum_{i,j} J_{ij}\sigma_i^z\sigma_j^z$



Superposition of all states (trivial)

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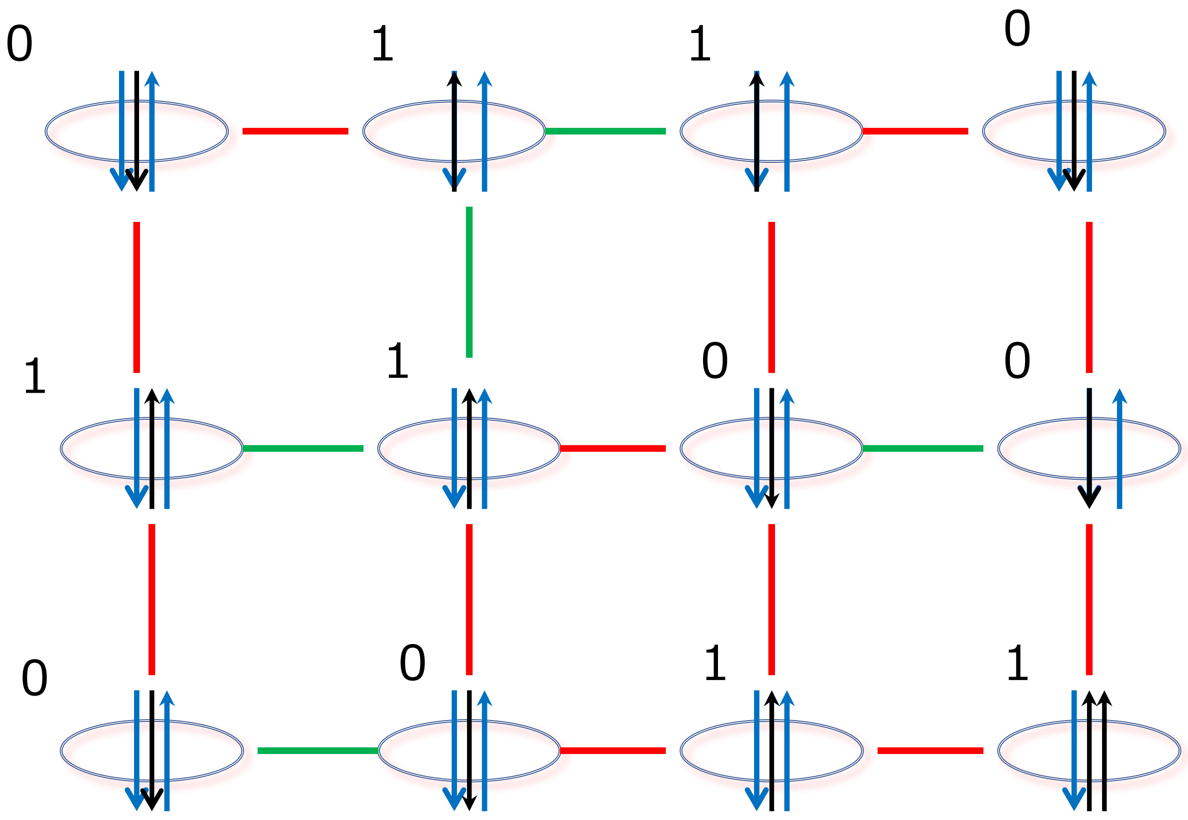
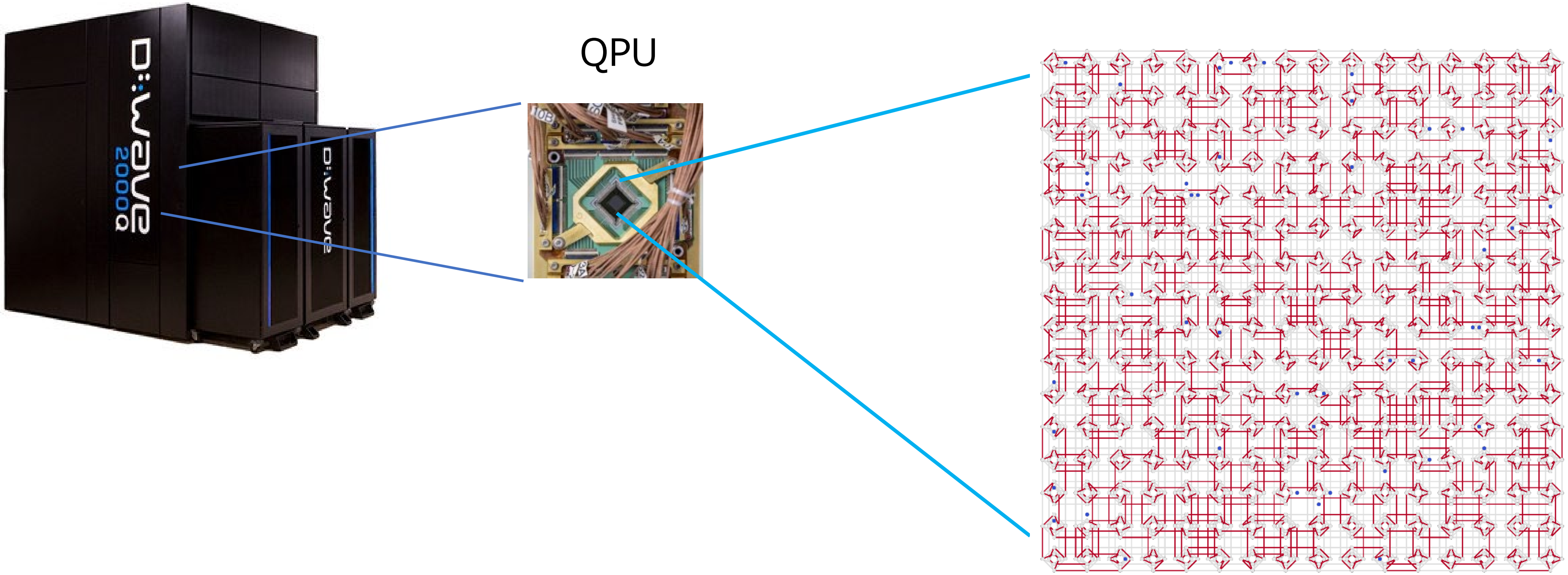
→ 10110 Solution (non-trivial)



Choose the optimal state out of 2^{12}=4096 states

Representation of the Ising model on the device



- The Ising model representing the problem can be implemented on the chip.
- The size is limited to 5300 qubits on the current model.

Examples of quantum simulation by quantum annealing

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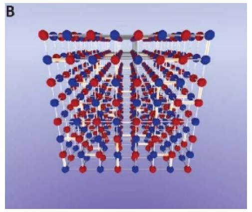
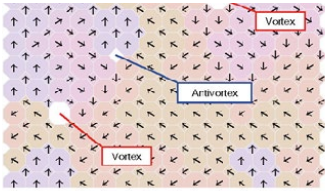
Static properties

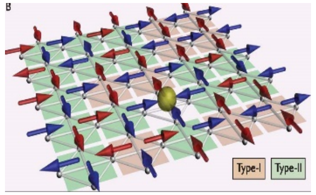
- Spin glass — *Harris et al, Science (2018)*
- Kosterlitz-Thouless transition — *King et al, Nature (2018)*
- Spin ice — *King et al, Science (2021)*
- Shastry-Sutherland model — *Kairys et al, PRX Quantum (2020)*
- Scalar field theory — *Abel et al, PRX Quantum (2021)*
- Griffiths-McCoy singularity — *Nishimura et al, Phys. Rev. A (2020)*

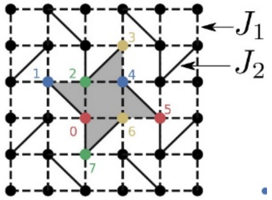
Dynamical properties

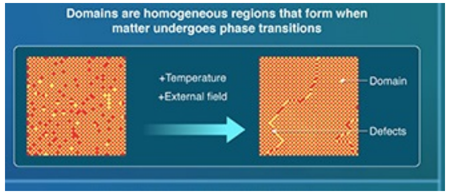
- Kibble-Zurek mechanism — *Gardas et al, Sci. Rep. (2018)*
  Weinberg et al, Phys. Rev. Lett. (2020)
  Bando et al, Phys. Rev. Res. (2020)
  King et al, Nature Phys. (2022)
- Frustrated spin chain — *King et al, PRX Quantum (2021)*

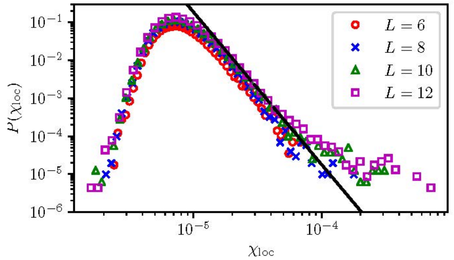


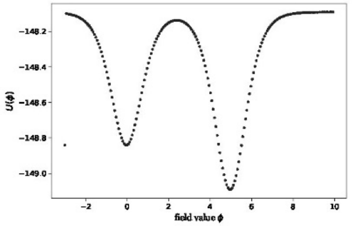












Quantum simulation of the Kibble-Zurek mechanism

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PHYSICAL REVIEW RESEARCH **2**, 033369 (2020)

Probing the universality of topological defect formation in a quantum annealer: Kibble-Zurek mechanism and beyond

Yuki Bando,[1,*] Yuki Susa,[2,†] Hiroki Oshiyama,[3] Naokazu Shibata,[3] Masayuki Ohzeki,[4,1,5] Fernando Javier Gómez-Ruiz,[6] Daniel A. Lidar,[7,8] Sei Suzuki,[9] Adolfo del Campo,[6,10,11] and Hidetoshi Nishimori[1,4,12]

Phys. Rev. Res. **2**, 033369 (2020)

LETTERS
https://doi.org/10.1038/s41567-022-01741-6

nature physics

Check for updates

Coherent quantum annealing in a programmable 2,000 qubit Ising chain

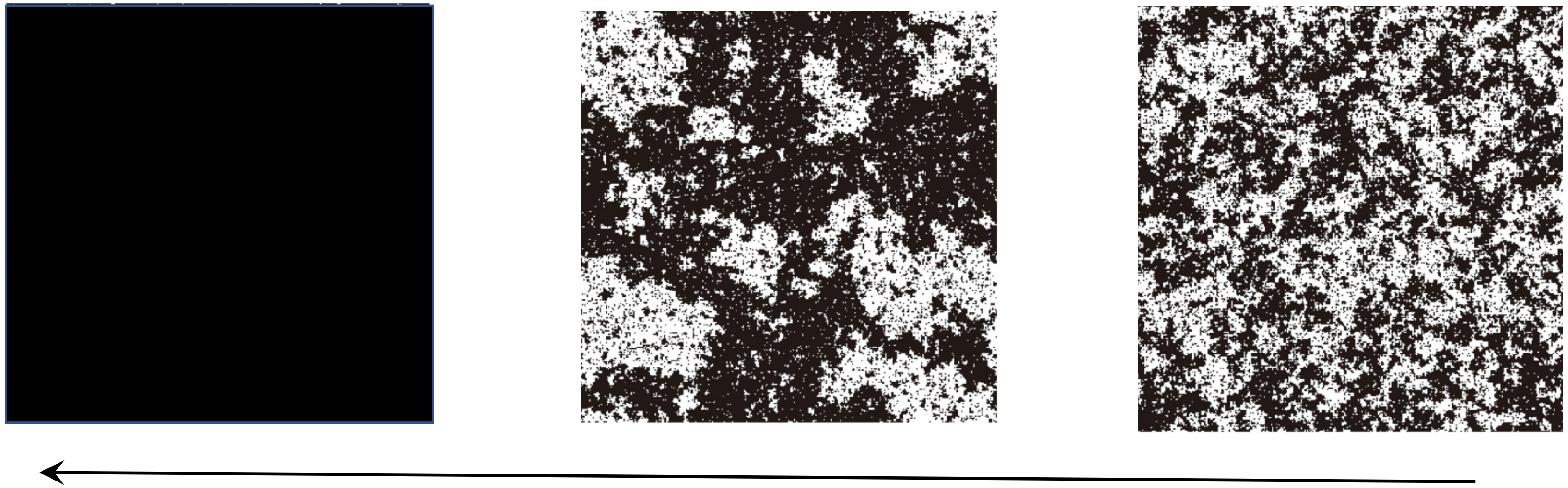
Andrew D. King[1], Sei Suzuki[2], Jack Raymond[1], Alex Zucca[1], Trevor Lanting[1], Fabio Altomare[1], Andrew J. Berkley[1], Sara Ejtemaee[1], Emile Hoskinson[1], Shuiyuan Huang[1], Eric Ladizinsky[1], Allison J. R. MacDonald[1], Gaelen Marsden[1], Travis Oh[1], Gabriel Poulin-Lamarre[1], Mauricio Reis[1], Chris Rich[1], Yuki Sato[1], Jed D. Whittaker[1], Jason Yao[1], Richard Harris[1], Daniel A. Lidar[3,4], Hidetoshi Nishimori[5,6,7] and Mohammad H. Amin[1,8]

Nature Phys. **18**, 1324 (2022)

Phase transition (classical)

2d Ising model

Low temperature (ordered) | Critical temperature | High temperature (disordered)



Temperature decrease

Slow decrease of temperature: System traces equilibrium.

Fast decrease of temperature : Falls out of equilibrium. Defects are created at T=0.

Problem: Relation of the density of defects ρ and the time scale t_a of temperature decrease $\rho = f(t_a)$

1d quantum Ising model

$$H = -J \sum_{i=1}^{L} \sigma_i^z \sigma_{i+1}^z - \Gamma \sum_{i=1}^{L} \sigma_i^x \quad (J > 0)$$

Solution

$|\uparrow_1\uparrow_2\uparrow_3 \cdots \uparrow_{L-1}\uparrow_L\rangle$

$+ |\downarrow_1\downarrow_2\downarrow_3 \cdots \downarrow_{L-1}\downarrow_L\rangle$

111111

0   1 Γ/J

Critical point

Slow change

Superposition of all states

$|\uparrow_1\uparrow_2\uparrow_3 \cdots \uparrow_L\rangle + |\uparrow_1\uparrow_2\uparrow_3 \cdots \downarrow_L\rangle + \cdots + |\downarrow_1\downarrow_2\downarrow_3 \cdots \downarrow_L\rangle$

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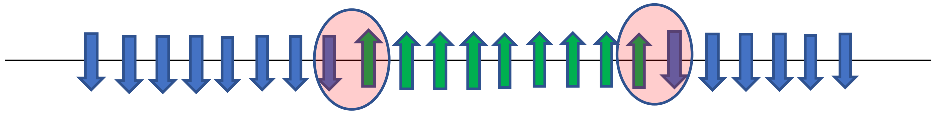
Defect (Kink)



By decreasing Γ/J at a finite rate, defects are created at Γ/J=0.

What is the number (density) of defects ρ as a function of annealing time t_a? $\rho = f(t_a)$

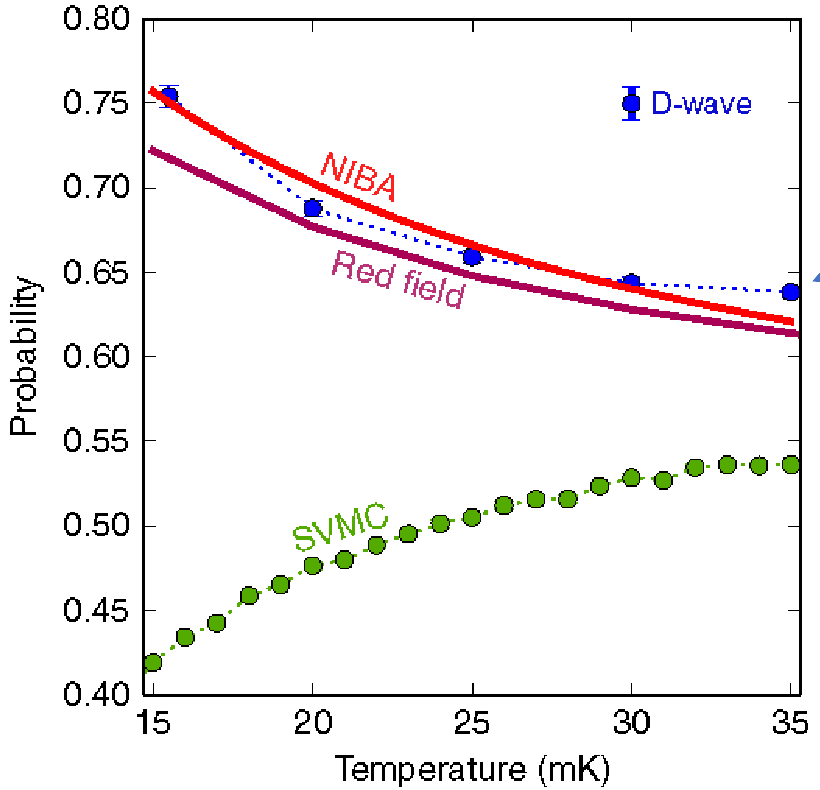
Kibble-Zurek mechanism

1d (chain) problem
Number (density) of defects is known exactly by quantum mechanics (noise-free).

$$\rho = \frac{1}{2\pi}\sqrt{\frac{\hbar}{2J}}\; t_a^{-1/2}$$

Goal: To verify this formula on the D-Wave quantum annealer.

Evidence of thermal noise on the device



● : Output from D-Wave

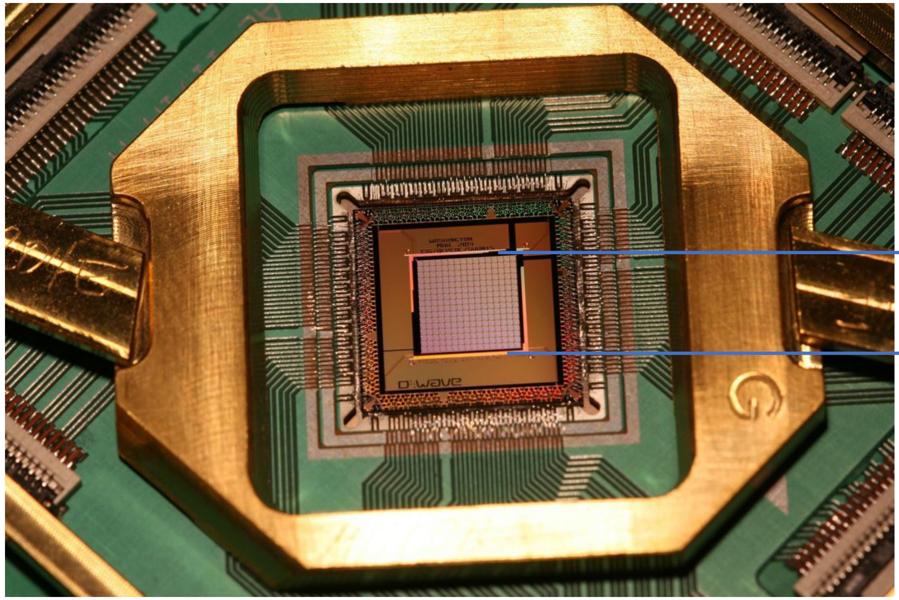
Bold lines: Quantum theory for finite temperature

● : Classical theory

Agrees with the finite-temperature quantum theory.

S. Boixo et al, Nature Comm. **7**, 10327 (2016)

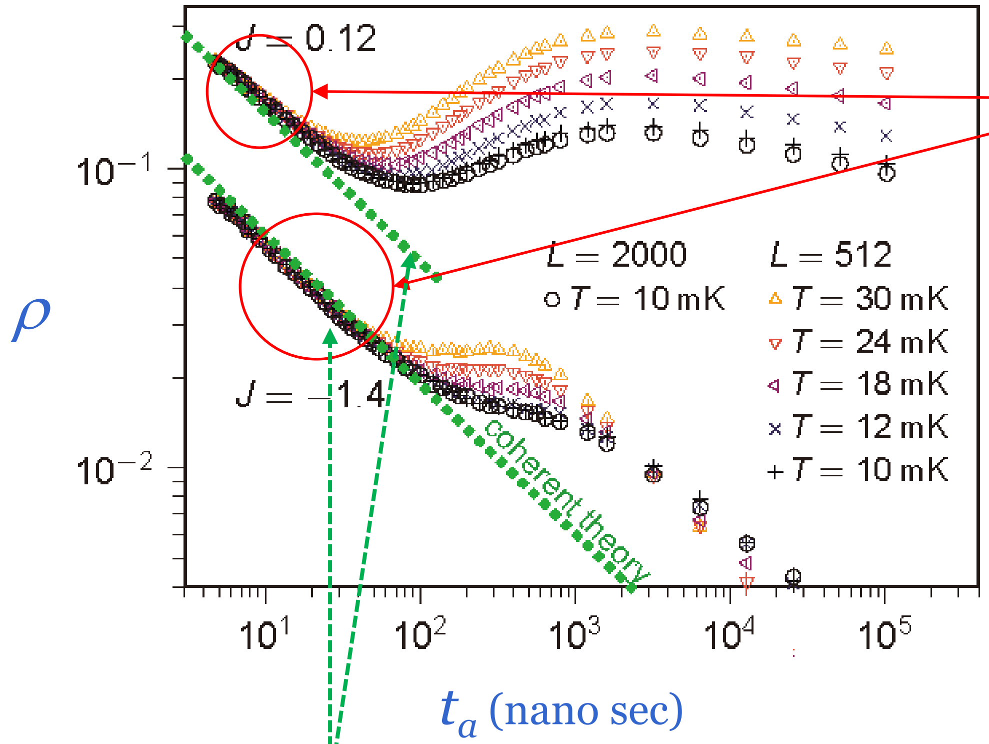
Signal synchronization



Chip size is 1cm.

Light speed is 30cm/ns. Smallest experimental time scale: 2 nano second.
⇒
Signal **synchronization** should be carefully tuned **to reach all qubits simultaneously**.

Result



$$\rho = \frac{1}{2\pi}\sqrt{\frac{\hbar}{2J}}\, t_a^{-1/2}$$

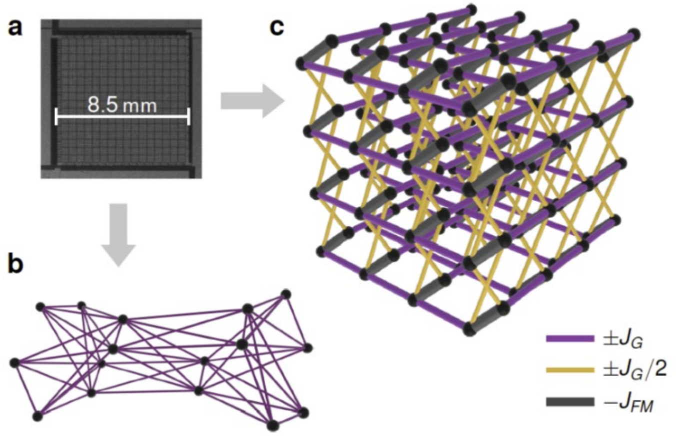
- Data agrees with theory at short time scale up to 50 ns.
- The device runs coherently without noise.
- Kibble-Zurek theory has been confirmed including the coefficient.

Significance

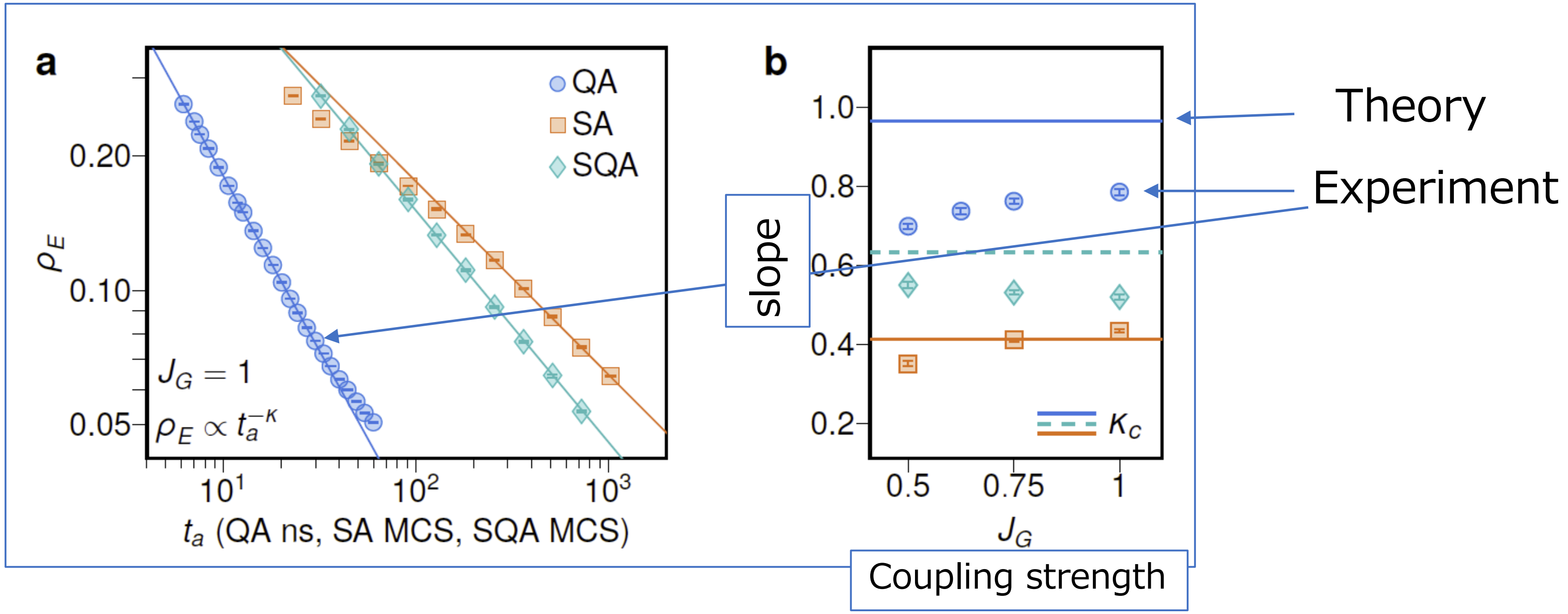
- First case to run a large-scale artificial quantum device with L=**2000 qubits noise-free**.
  (cf. The largest quantum simulation on other platforms is about 200 qubits.)
- Opened a path toward large-scale quantum simulations beyond the capacity of classical computers.

Quantum simulation of the 3D spin glass

King et al, arXiv:2207.13800



Realized 3d spin glass of size 15×15×12

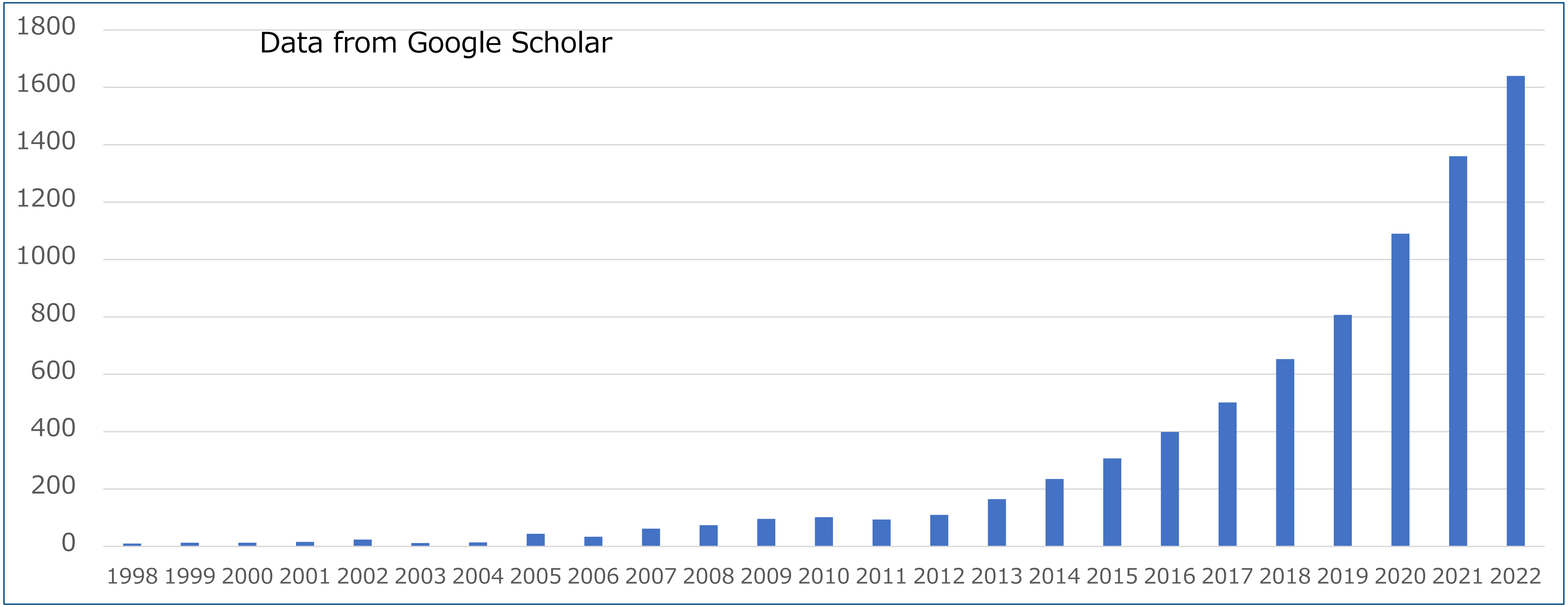


- Quantum simulation of **3d spin glass dynamics with 5300 qubits**.
- Small deviations from the theory.
- **Faster dynamics** toward optimal **by quantum** than classical.

Conclusion

- Large-scale quantum simulations have been conducted on a device with several thousand qubits.
- Confirmed that the device operates coherently (quantum-mechanically without noise) up to about 20-50 nanosecond.
- For optimization:
  Quality of data may be improved by running quantum annealing at short time scales and/or with improved coherence.

Rapidly expanding field of quantum annealing



Number of papers with keyword “quantum annealing”