量子シミュレーションとは何か？

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What’s quantum simulation/computation?

Simulating Physics with Computers

R. Feynman, Int. J. Theo. Phys. **21**, 467 (1982)

Can (quantum) physics be simulated by a (locally interconnected) universal computer?

普通は局所的、共振器を使うと非局所的相互作用も可能

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.

計算機が自然と厳密に同じことをするシミュレーションの可能性について議論

Full description of quantum mechanics

R. Feynman, Int. J. Theo. Phys. **21**, 467 (1982)

M: space-time points, *N*: a *large* number of particles

Because the system has too many variables, it cannot be simulated with a normal computer with a number of elements proportional to *M* or *N*.

ヒルベルト空間は粒子数と時空点が増えると指数関数的に増加する
→古典計算では、計算時間が指数関数的に増大するので、実行できなくなる

時空点についての考察は現在の量子計算の議論から抜け落ちている
→場の理論のシミュレーション可能性と関係？

There are two ways that we can go about it

R. Feynman, Int. J. Theo. Phys. **21**, 467 (1982)

Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws. → quantum simulator

Let the computer still be the same kind that we thought of before – a logical, universal automaton. → quantum computer

Quantum simulator/annealer – 問題設定と実装に個別の工夫が要求
quantum supremacy が問われる

Quantum computer – universal quantum simulator 難易度が格段と高い

Can quantum systems be probabilistically simulated by a classical (universal) computer?

R. Feynman, Int. J. Theo. Phys. **21**, 467 (1982)

Quantum mechanics can’t seem to be imitable by a local classical computer. ← no hidden variable theorem

エンタングルメントが本質的に関与する、あるいは、ベルの不等式を破らないとできないような計算は古典計算機ではまねできない？

Shor’s algorithm はそうなっている

他方、シュレーディンガー方程式は偏微分方程式で書かれているので、古典計算機でできないはずはない？

Three clues for quantum supremacy?

Should aim at classically hard but quantum-mechanically easy problems

1. Superposition – no analog of classical bits

2. Entanglement
   Classically, if the total system is known, its subsystem is also known.
   This is not the case in the quantum world. → quantum thermalization

3. Quantum measurement
   state reduction, post selection, creation of entanglement, etc.
   offers a rich variety of tools that are absent in classical systems.

Global trend and New Moore’s (Gambetta’s) law

Global trend on quantum science and technology

USA	National Quantum Initiative ACT	1450憶円/5年
	Private sectors (Google, IBM, Microsoft, Rigetti, etc.) similar budgets	
Europe	Quantum Technology Flagship	1250憶円/10年
China	量子情報科学国家実験室	1200憶円/5年
Germany	量子技術ー基本から市場へ	860億円/4年
UK	National Quantum Technologies Programme	450憶円/5年
Japan	Q-Leap, SIP, CREST, さきがけ 量子技術イノベーション戦略	50億円/1年 →？

Why such huge investments now?

Hight expectations for the Quantum Leap that

-- could transform society as it happened when transistors replaced vacuum tubes;

-- motivates questions about unknown unknowns.
(L. S. Sapochak, NSF)

量子科学技術のブレークスルーが起こるという強い予感

Quantum technologies

Current

- atomic clocks (GPS)
- MRI (medicine)
- quantum key distribution (security)
- semiconductors/lasers, telecom, classical computation
- quantum-limited devices (LIGO, QHE, Josphson junctions)

Near term

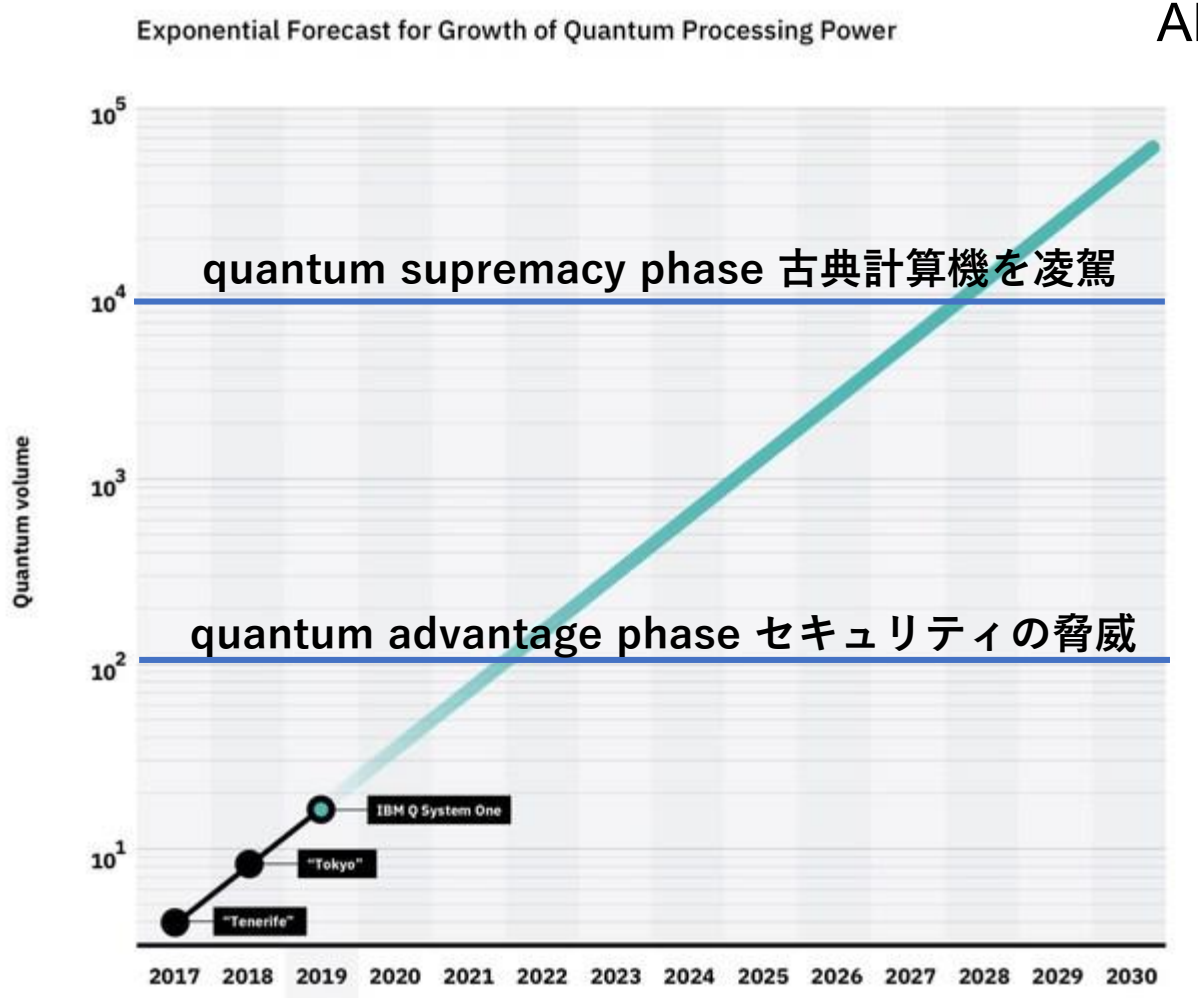
- quantum simulators/annealer (quantum supremacy/acceleration)
- quantum sensors (gravitational gyroscopes/accelerators)
- computational approach to materials, chemistry

Long term

- programmable quantum computation
- uncovering unknown unknowns (completely new)

New Moore's law for quantum computers?

APS March meeting 2019, Jay Gambetta, Lev Bishop

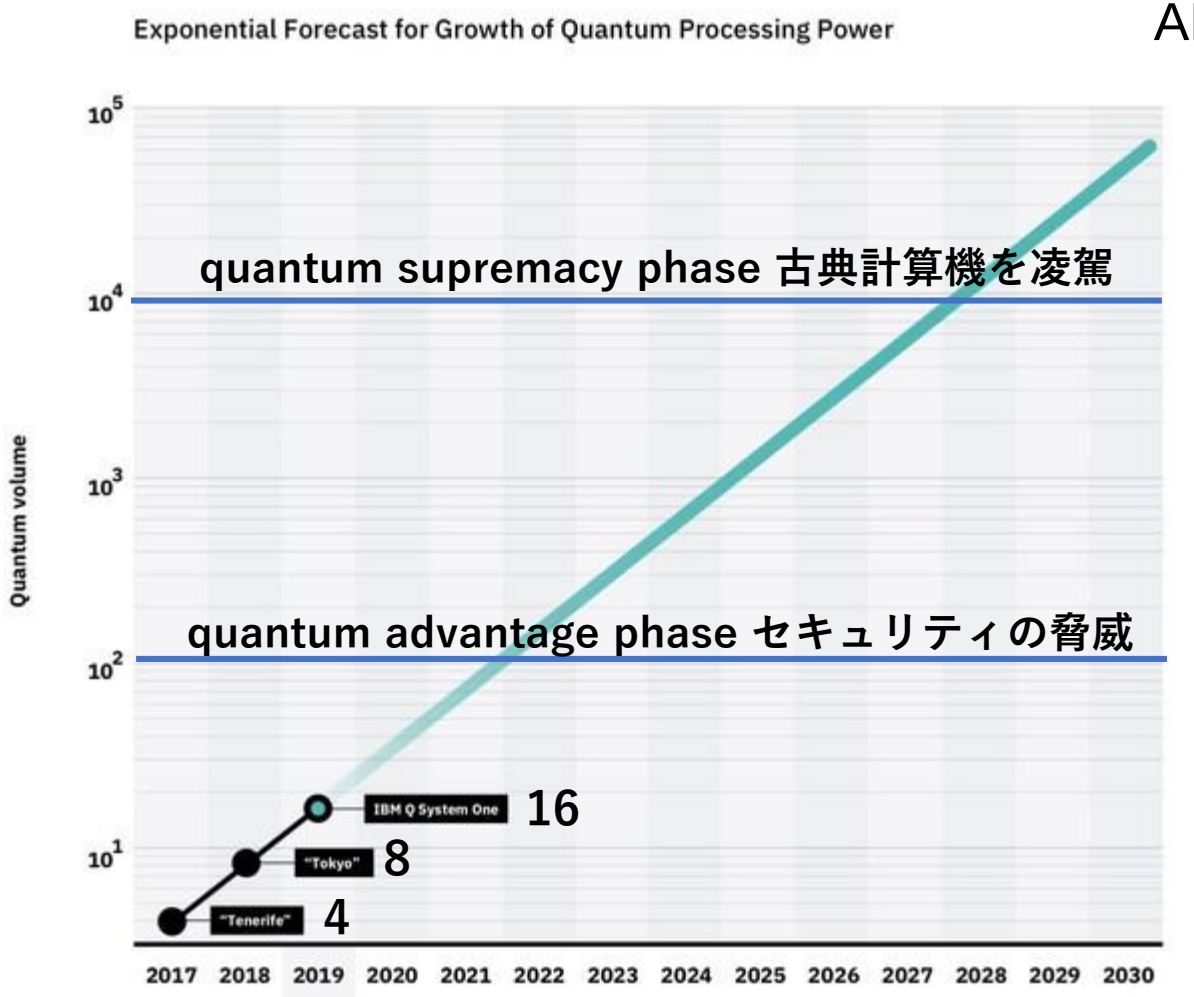


Double quantum computer performance annually as measured by quantum volume – quantum solvability measure (arXiv: 1811.1292):

gate number
measurement & feedback error
cross talk
device connectivity
circuit compiler efficiency
+
thermodynamic constraints

Quantum volume

APS March meeting 2019, Jay Gambetta, Lev Bishop



The higher the quantum volume, the more complex problems one can potentially solve such as

- simulating chemistry,
- modeling financial risk,
- supply chain optimization.

IMB Q System One
Average 2-qubit gate error < 2 %

NISQ – Noisy Intermediate Scale Quantum Computer

Noisy 50-100 qubit quantum computing is coming soon. NISQ devices cannot be simulated by brute force using the most powerful currently existing technology. (John Preskill, APS March Meeting 2019)

ハイブリッド技術、ソフォトウェアー、機械学習が鍵

Hybrid quantum/classical optimizers needed.
Such combinatorial optimization will best be implemented by machine learning.

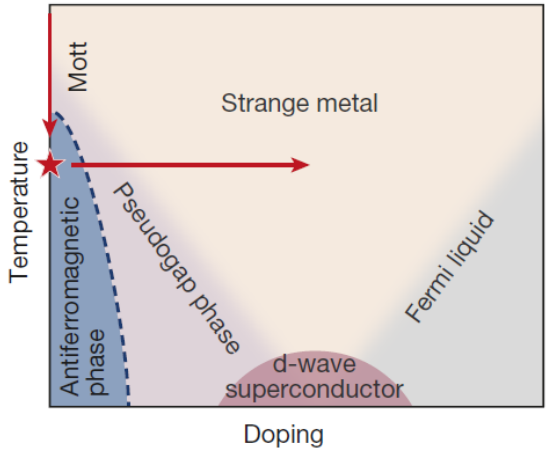
NISQ softwares/algorithms

Examples of quantum simulation

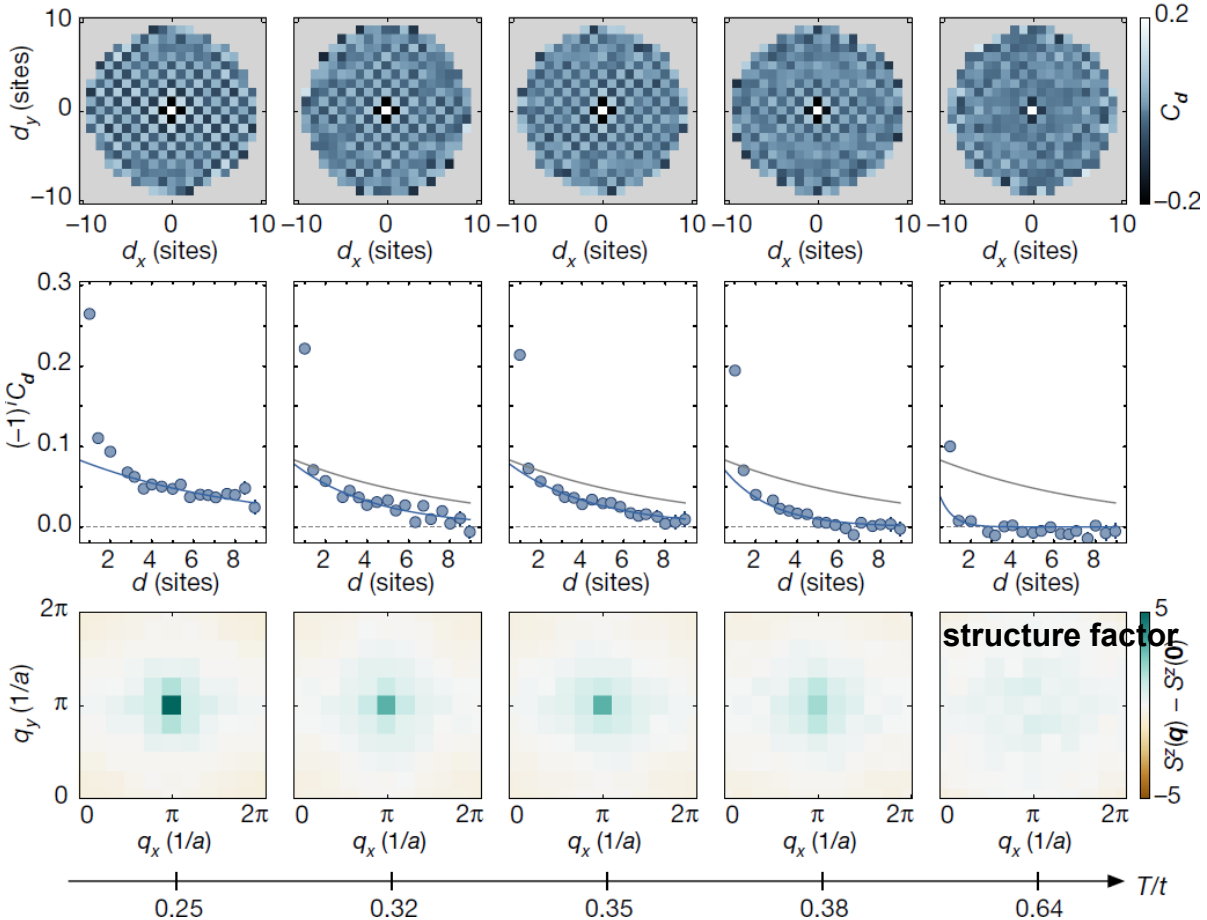
Hole-doped 2D Fermi Hubbard model

- Among the most fundamental CMP models like the Ising model.
- Relevant to high-T_c superconductors and quantum magnetism.
- Difficult to simulate on a classical computer, let alone analytically.
- Can be simulated ideally in an optical lattice (analog QC).

2D square lattice (80 sites, a=569nm)
U/t=7.2(2), T = 12nK~t/4
precise control of uniform density



A. Mazurenko, et al., Nature **545**, 462 (2017)

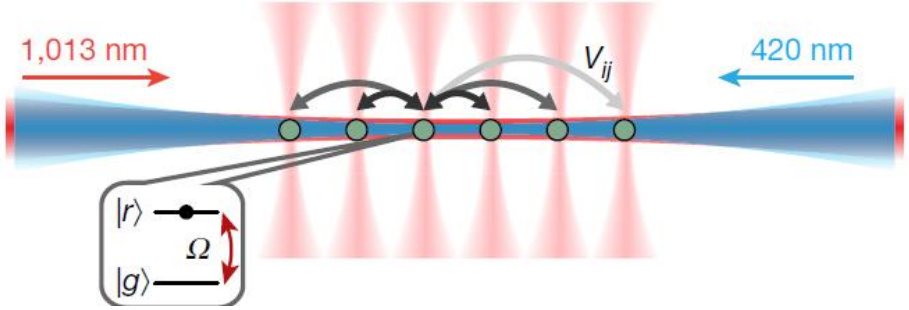


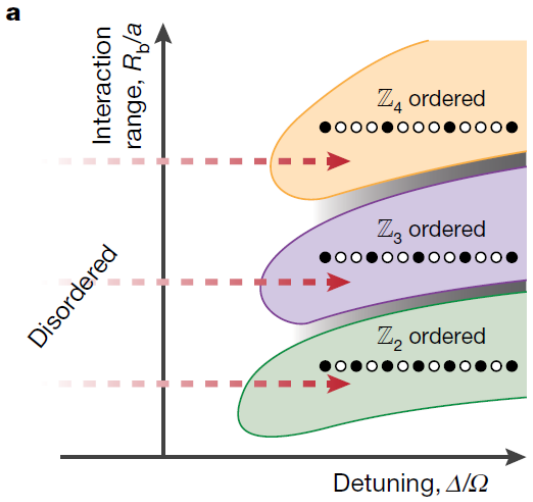
51-Rydberg-atom quantum simulator

H. Bernien, et al., Nature **551**, 579 (2017)

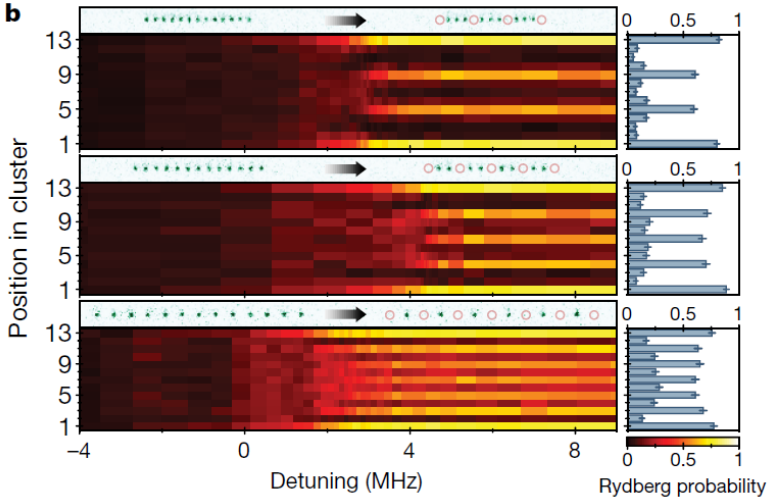
- Realize a “programmable” Ising-type quantum spin model with tunable int.
- Verify the high-fidelity preparation of 51 qubits in a Rydberg state ($70S_{1/2}$) by eliminating the entropy via measurement and feedback
- Investigate dynamics across the phase transition

$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j \qquad V_{ij} = C/R_{ij}^6$$





Rydberg crystals (13 atoms)



51-Rydberg-atom quantum simulator

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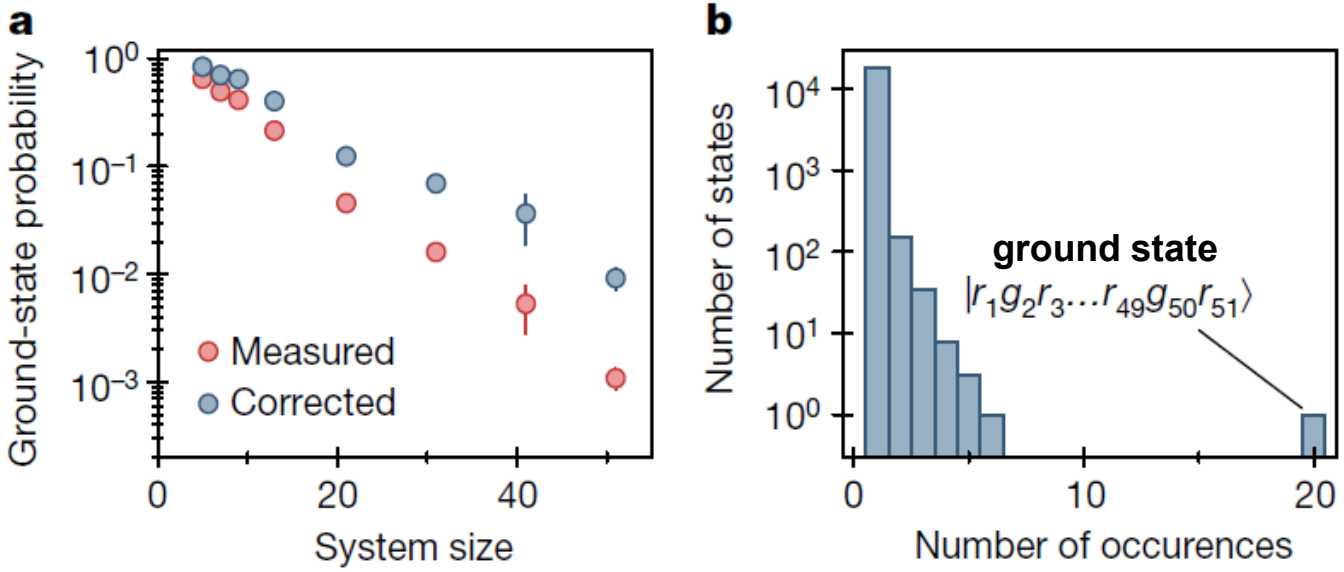
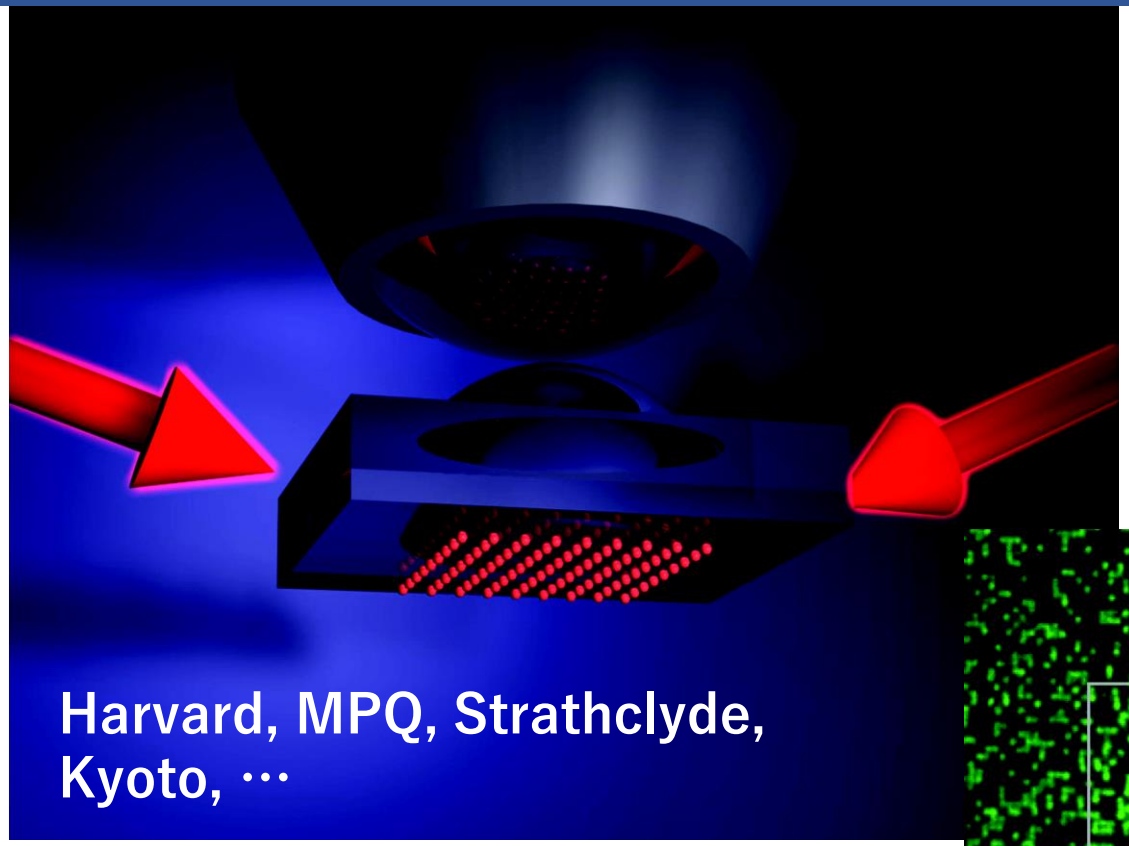


a. **Preparation fidelity of the crystalline GS as a function of cluster size.**
b. **Number of observed MB states per # of occurrences out of 18,439 experimental realizations in a 51 cluster. The most frequently occurring state is the GS of the MB Hamiltonian.**

クエンチ実験を行うと、1回しか起こらない状態がほとんどだが、
基底状態が実現できる回数は有意に大きい

Yet another objective of quantum simulation
– exploring the frontiers of physics –

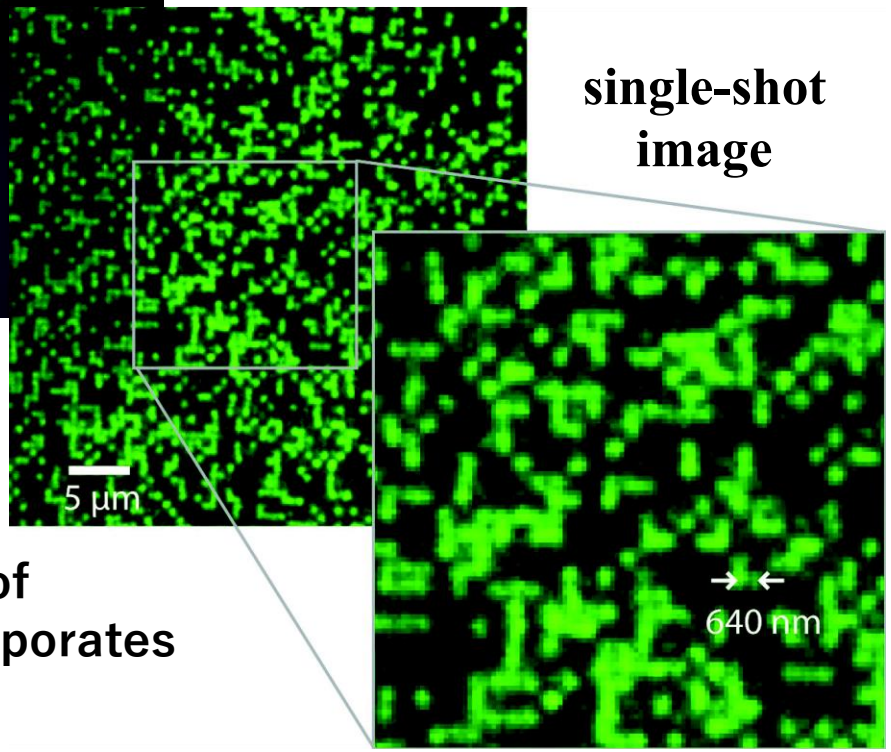
Motivation –Quantum Gas Microscopy –



Enables observation of the many-body wave function at the single-site resolution.

↓ Heisenberg's uncertainty relation

The higher the resolution, the greater the backaction will be.



single-shot image

How are the many-body dynamics and quantum phase transitions altered by the measurement backaction?

Frontier of QGM requires generalization of quantum statistical mechanics that incorporates effects of measurement backaction.

Conclusion

- **Quantum simulation is approaching a critical point beyond which classical computers cannot handle problems efficiently.**

- **Researchers anticipate new Moore's law – quantum volume doubles every year. If this continues to be true, we will reach the quantum advantage phase in just a few years.**

- **NISQ – noisy intermediate scale quantum computer – requires hybrid quantum systems; optimization requires softwares/algorithms, and machine learning.**

- **Quantum simulation involves not just solving hard many-body problems but also can explore the frontiers of physics.**

- **A key to breakthrough: Integration of Physics and AI**