Quantum advantages

of analog quantum simulators probing strongly correlated systems and of near-term quantum computers

Jens Eisert, Freie Universität Berlin
CEA/Saclay workshop, June 2019

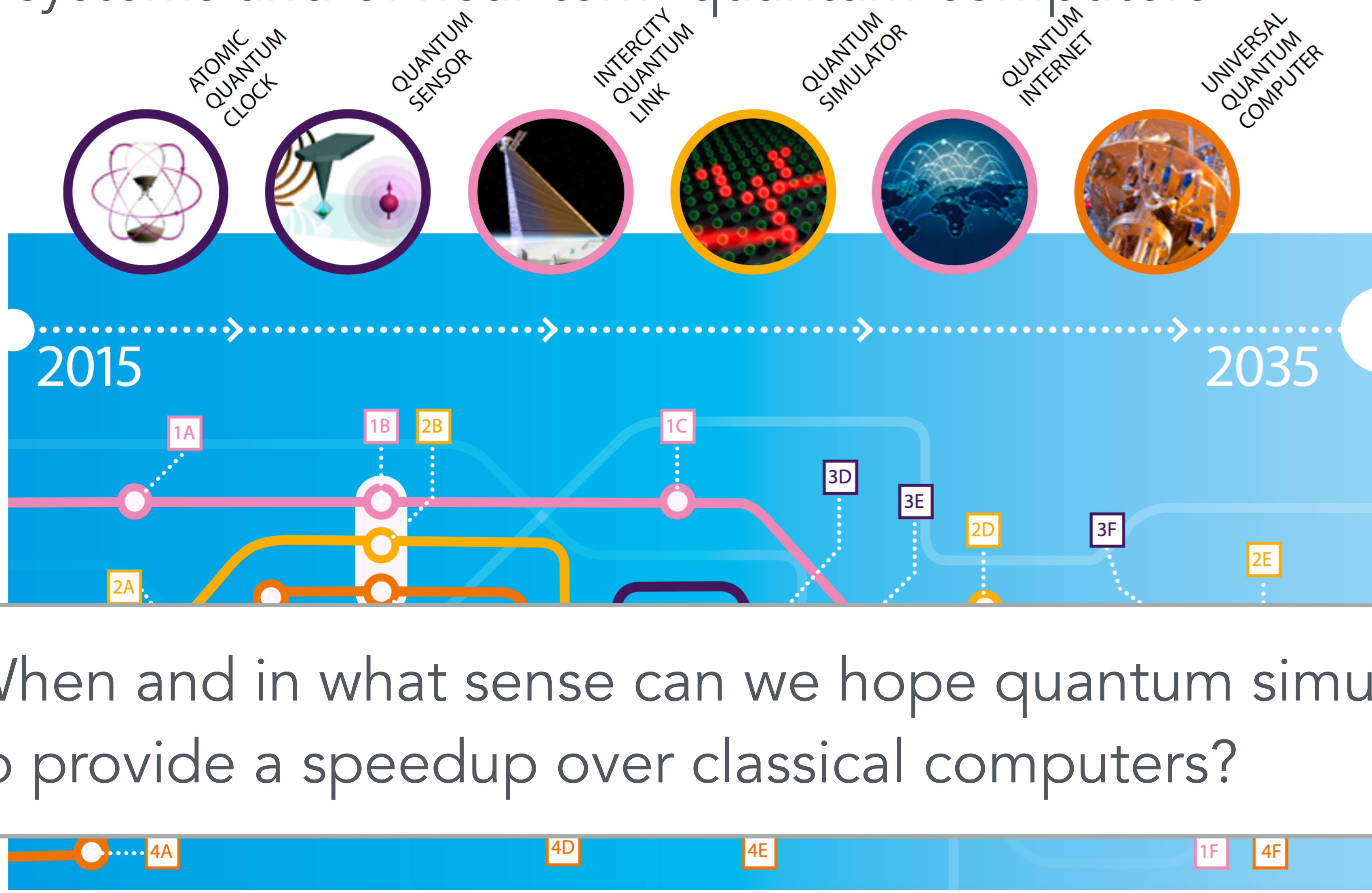
Quantum advantages

of analog quantum simulators probing strongly correlated systems and of near-term quantum computers

- What is an analog quantum simulator? What are relevant problems?

Quantum advantages

of analog quantum simulators probing strongly correlated systems and of near-term quantum computers

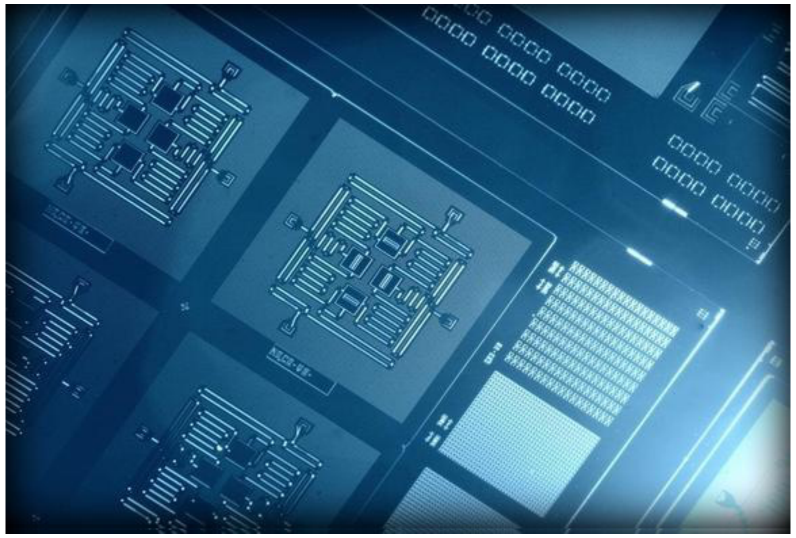


- When and in what sense can we hope quantum simulators to provide a speedup over classical computers?

IBM Research

Google

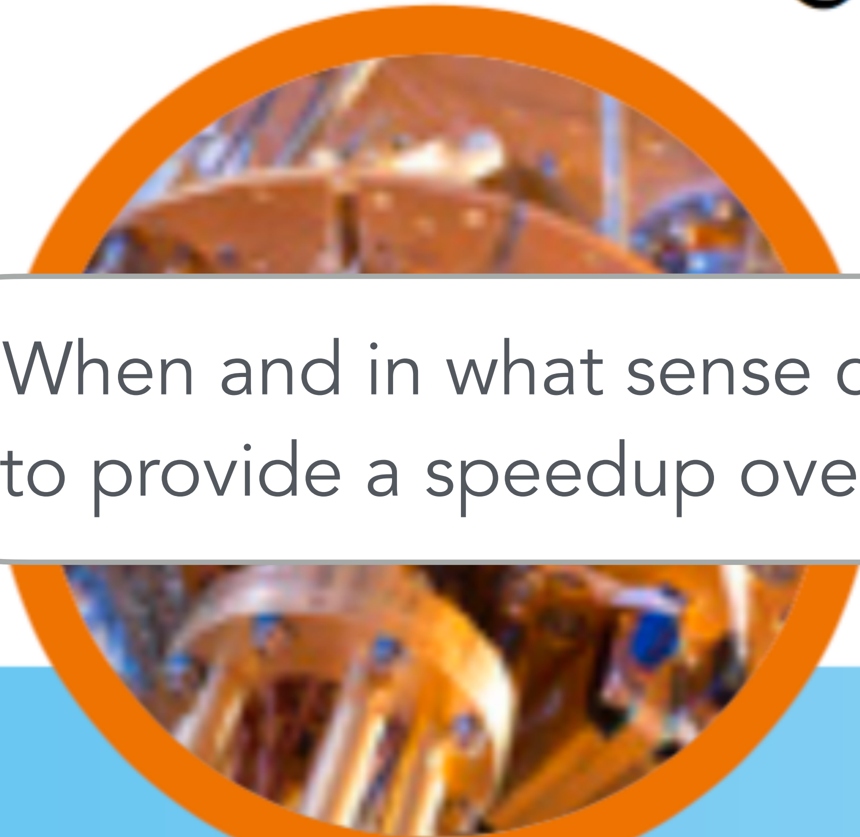
Microsoft Research



- 50-128 qubit quantum devices
- Noisy intermediate scale quantum computers

QUANTUM INTERNET

UNIVERSAL QUANTUM COMPUTER



- When and in what sense can we hope quantum simulators to provide a speedup over classical computers

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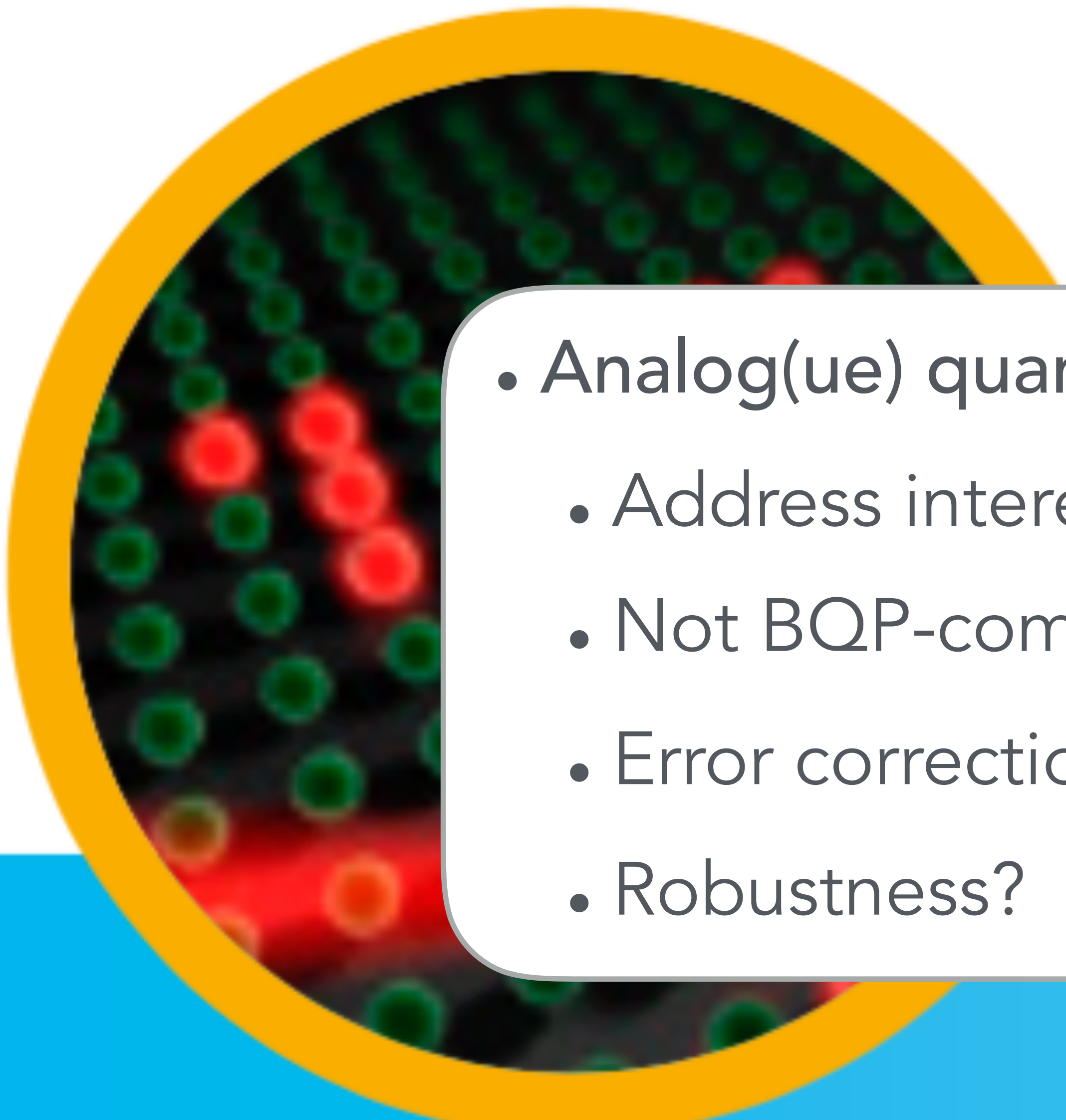
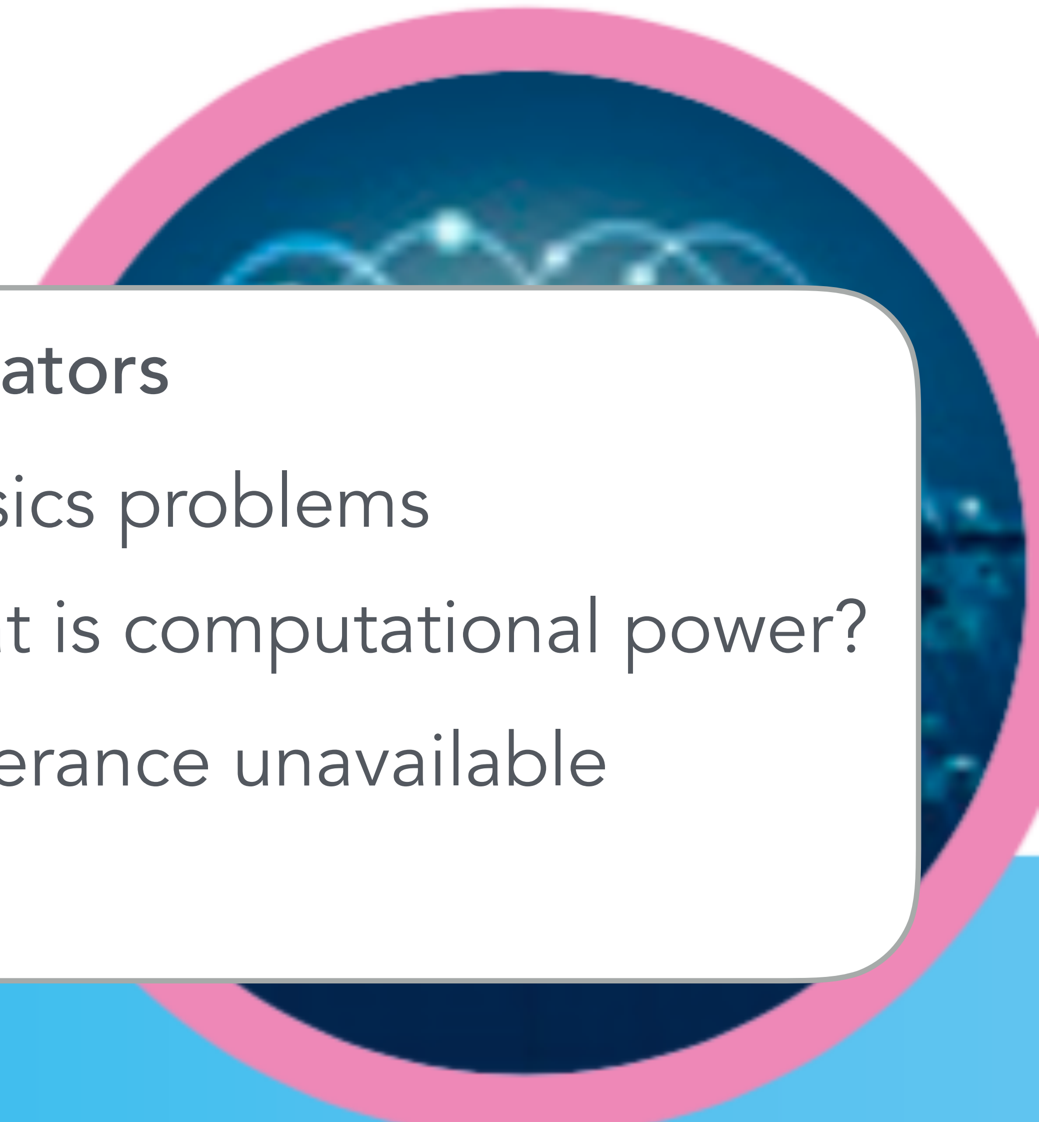


- **Analog(ue) quantum simulators**
  - Address interesting physics problems
  - Not BQP-complete, what is computational power?
  - Error correction/fault tolerance unavailable
  - Robustness?



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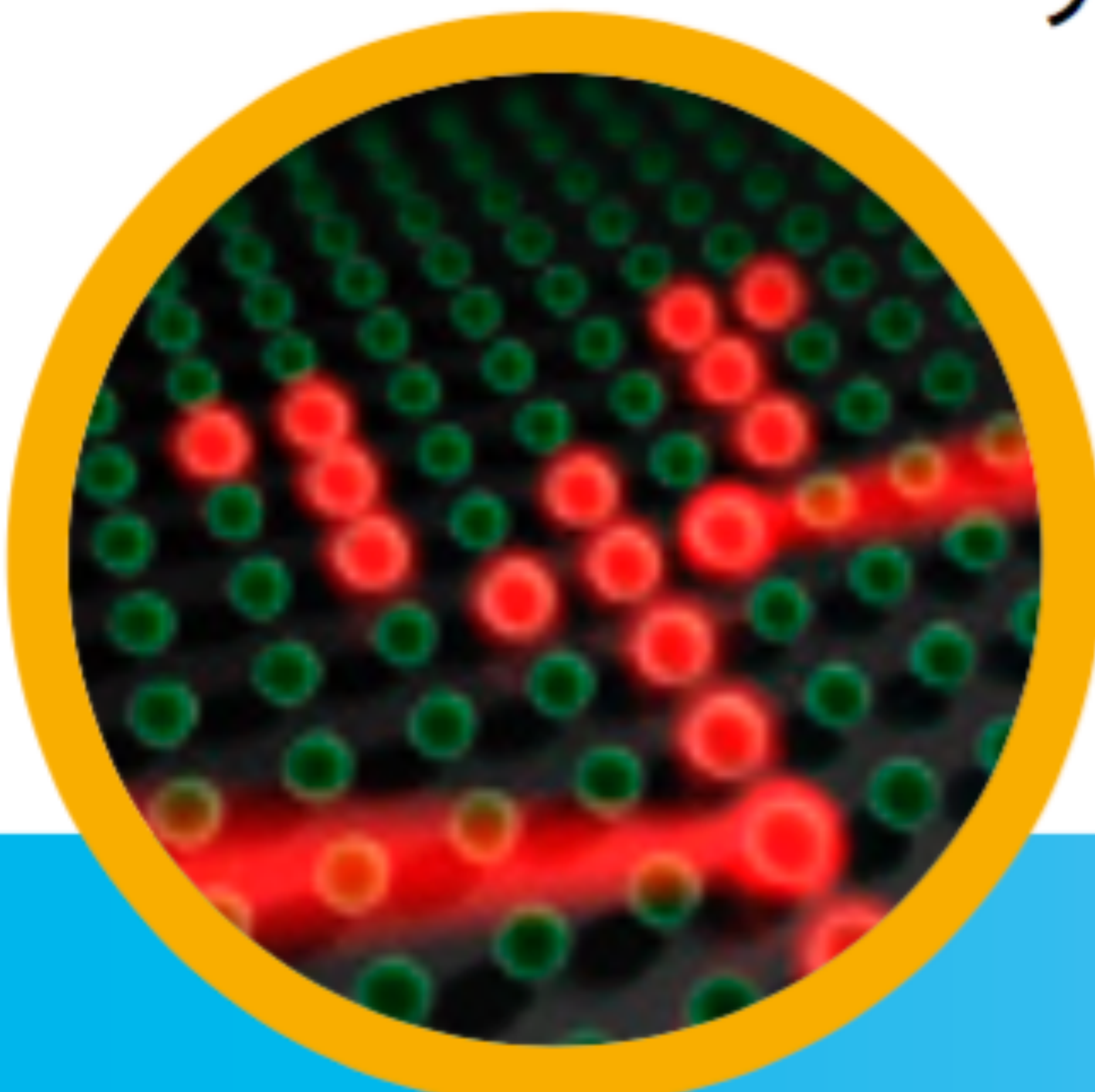

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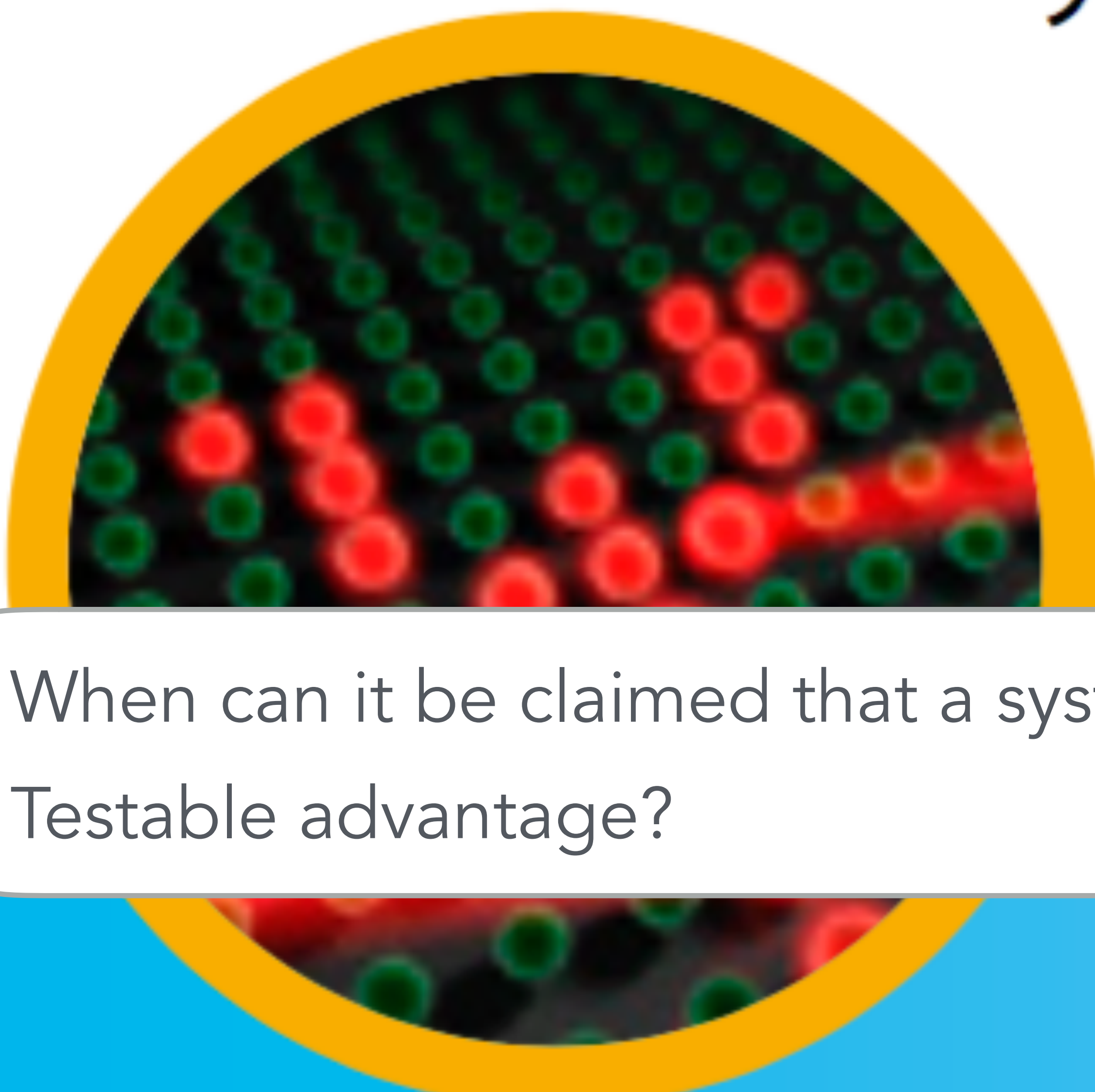
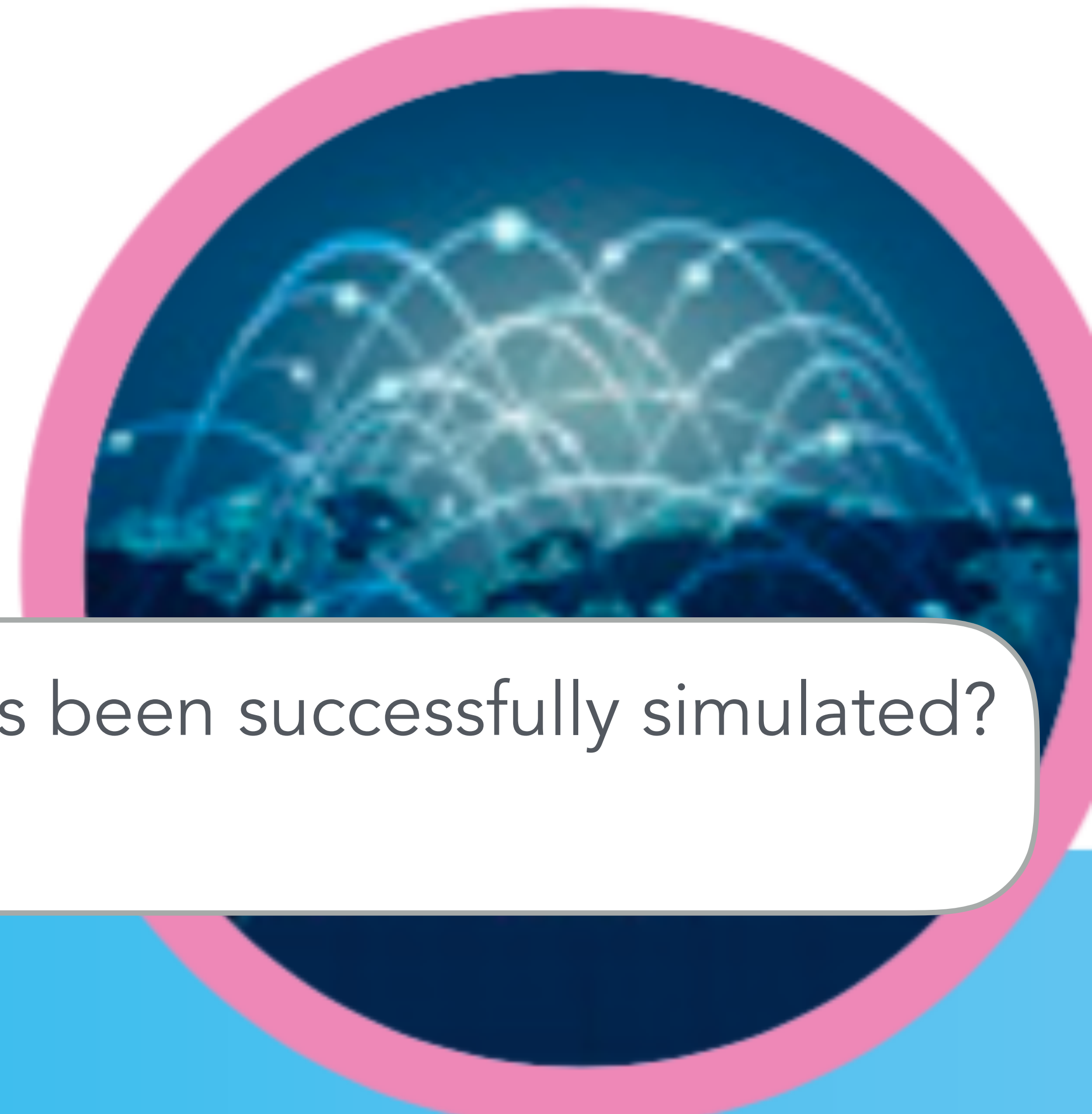
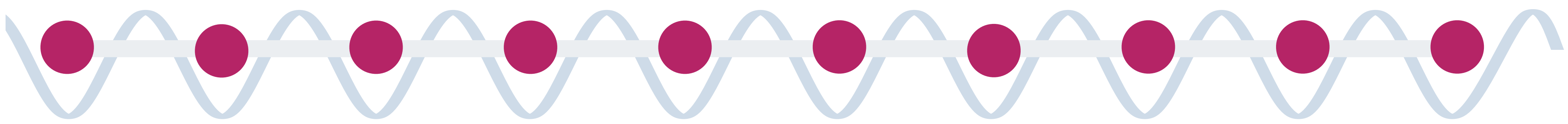




- When can it be claimed that a system has been successfully simulated?
- Testable advantage?

Analog quantum simulators

Analog quantum simulators

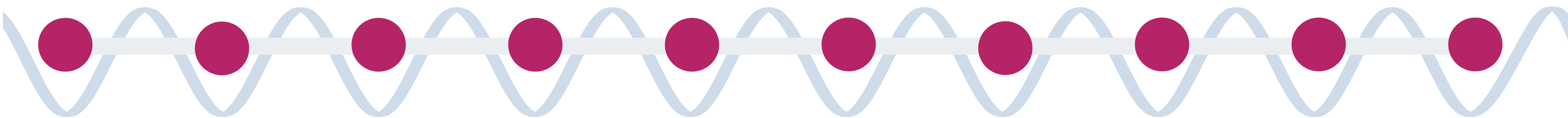


- "Analog", rather than discrete
- Probing questions in physics (including nuclear physics)

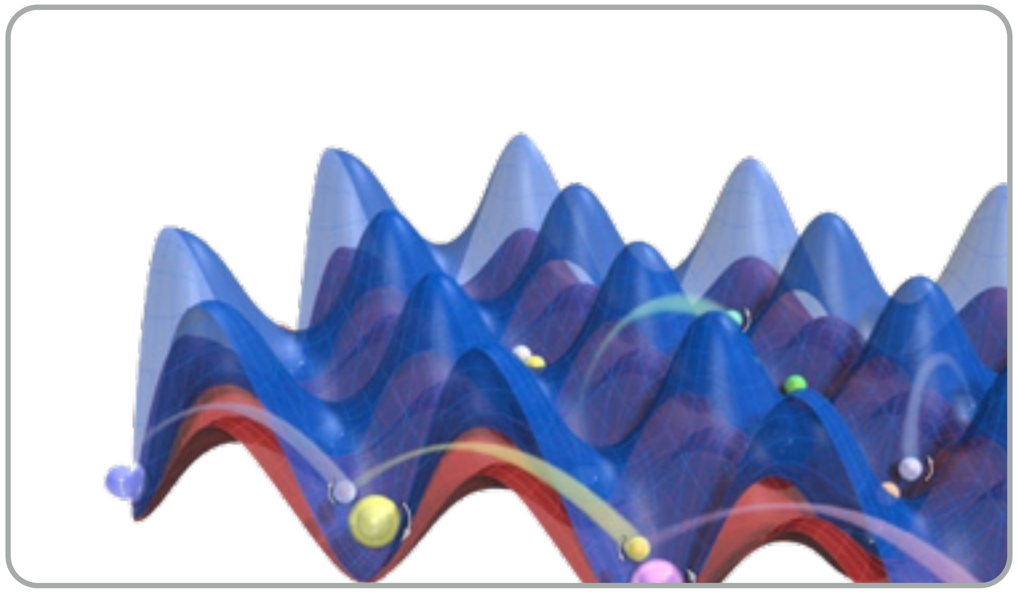
- **System size** n
- Local **Hamiltonians** with some levels of control
- **Noise** levels
- Classes of **preparations** and **measurements**

Cirac, Zoller, Nature Physics 8, 264 (2012)

Analog quantum simulators



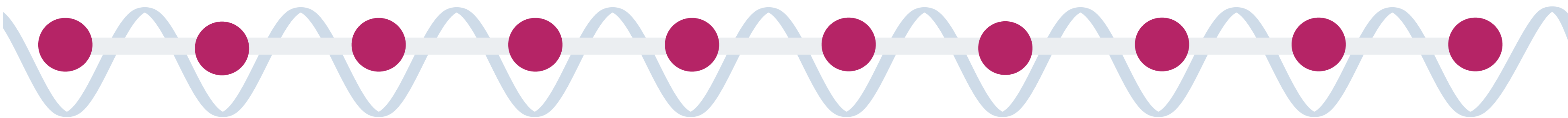
- **Cold atoms in optical lattices** most advanced



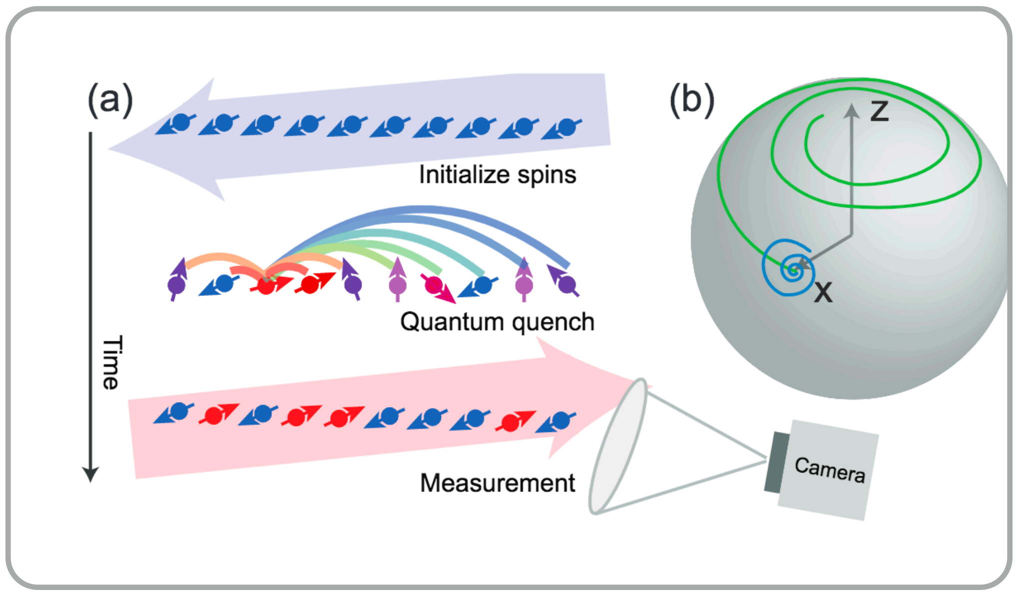
Bloch, Dalibard, Nascimbene, Nature Physics 8, 267 (2012)
Parsons, Mazurenko, Chiu, Ji, Greif, Greiner, Science, 353, 1253 (2016)

  - Global control over $n \sim 10^5$ sites (1D-3D)
  - Bosons and fermions
  - Some tuneability
  - Time-of-flight and in-situ measurements

- Towards programmable potentials



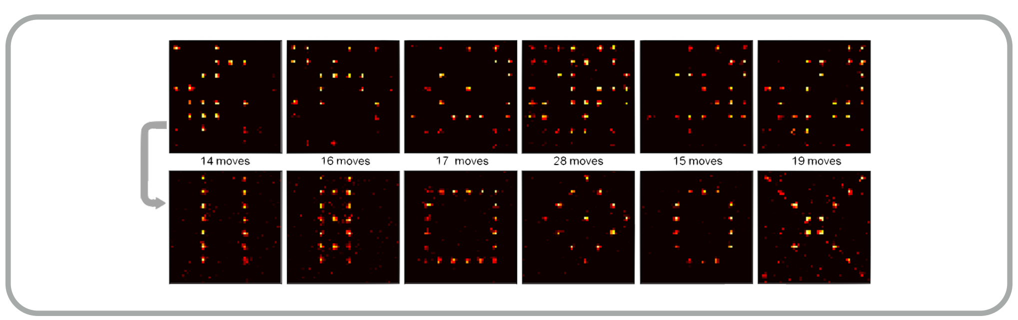
- Trapped ions



Zhang, Pagano, Hess, Kyprianidis, Becker, Kaplan, Gorshkov, Gong, Monroe 551, 601 (2017)
Blatt, Roos, Nature Phys 8, 277 (2012)

- $n \leq 53$
- Universal control
- Some global gates easier than others
- Tomographically complete measurements

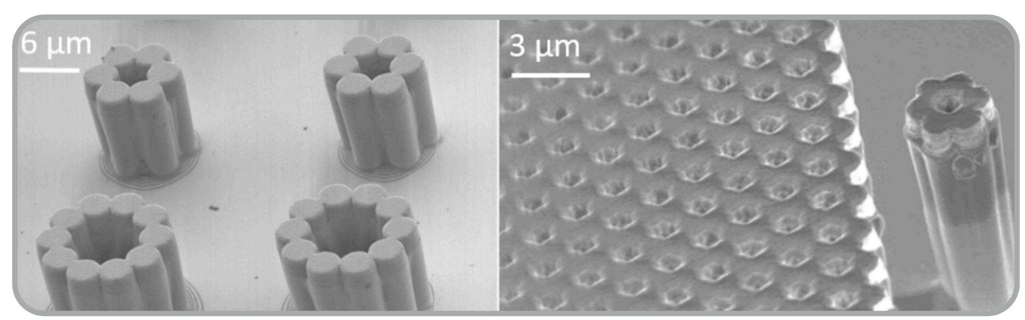
- Optical microtraps



Labuhn, Barredo, Ravets, Léséleuc, Macrì, Lahaye, Browaeys, Nature 534, 667 (2016)

- $n \sim 50 \times 50$, long-ranged Ising

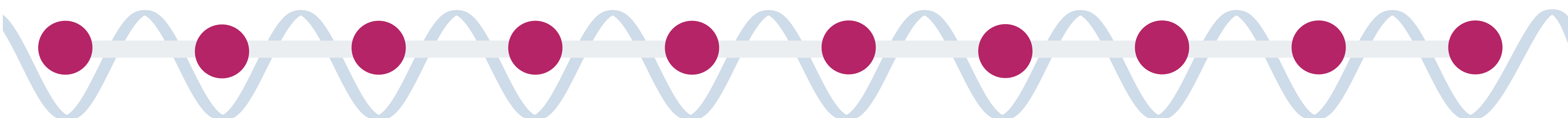
- Polaritonic/photonic architectures



Wertz, Ferrier, Solnyshkov, Johne, Sanvitto, Lemaitre, Sagnes, Grousson, Kavokin, Senellart, Malpuech, Bloch, Nature Phys 6, 860 (2010)

- Large, but intrisically open and noisy

Analog quantum simulators



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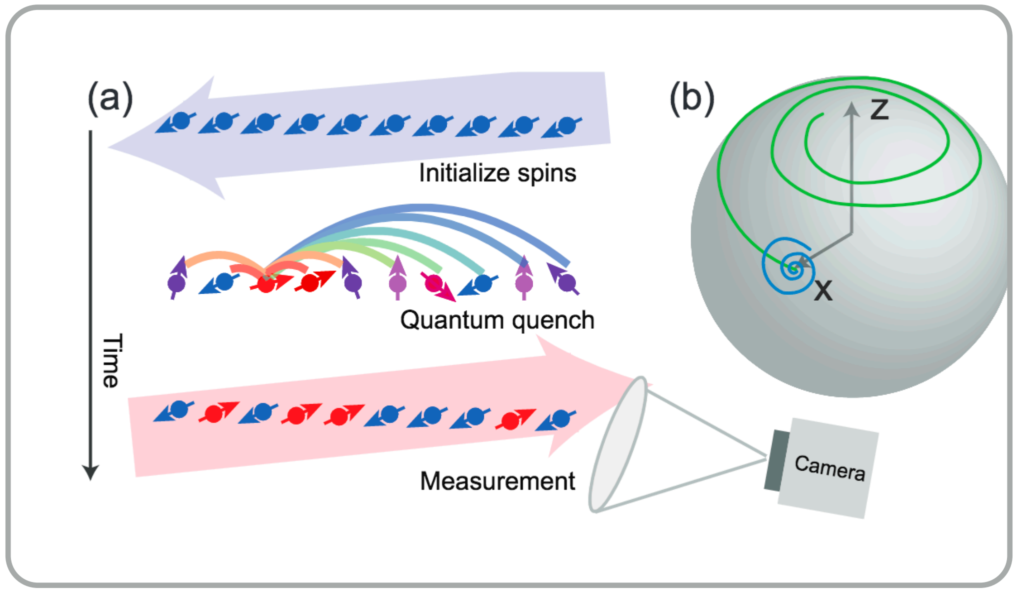

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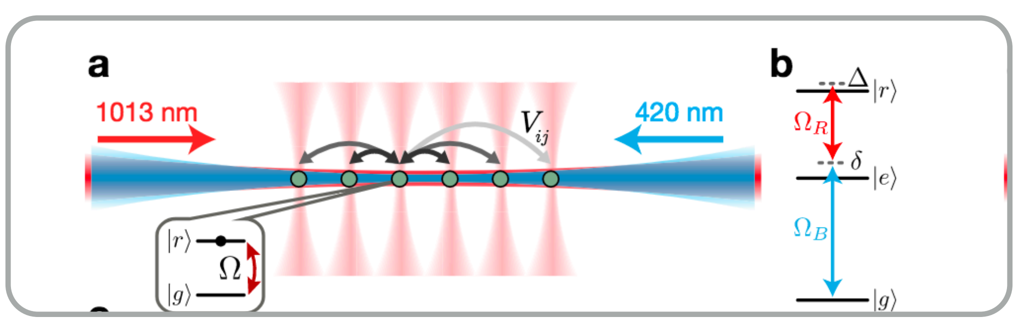
- $n \leq 53$
- Universal control
- Some global gates easier than others
- Tomographically complete measurements

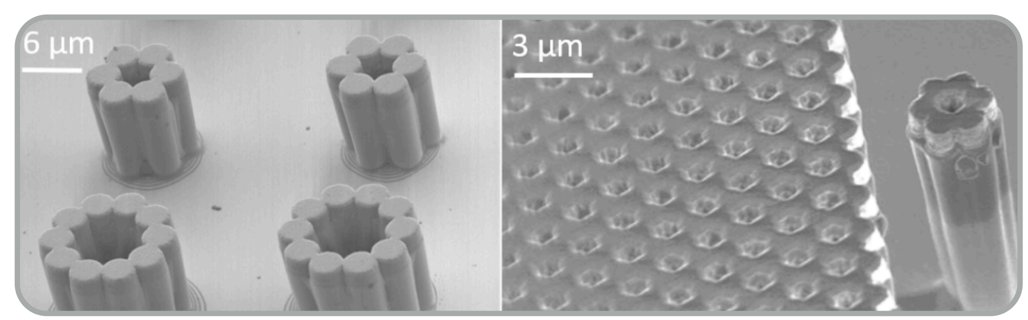
- Cold atoms in Rydberg states



Bernien, Schwartz, Keesling, Levine, Omran, Pichler, Choi, Zibrov, Endres, Greiner, Vuletic, Lukin, Nature 551, 579 (2017)

- Programmable

- Polaritonic/photonic architectures



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What can they probe?

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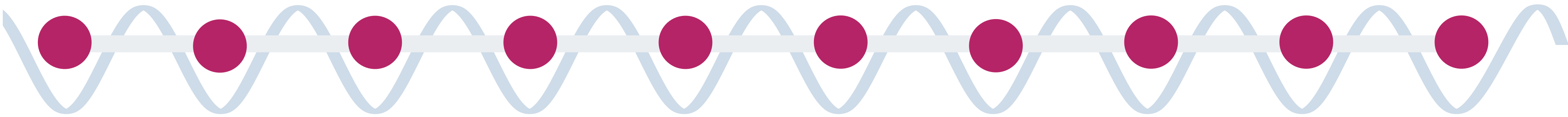


- **Time-dependent** problems ("quenches")

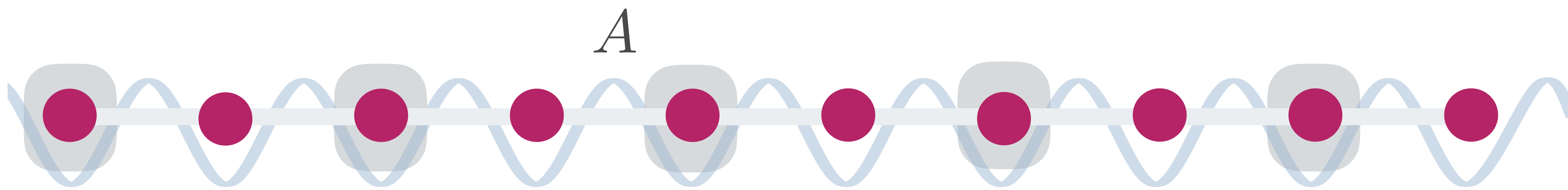
$$\rho(t) = e^{-itH} \rho e^{itH}$$

- E.g. probe **equilibration** and **thermalisation**

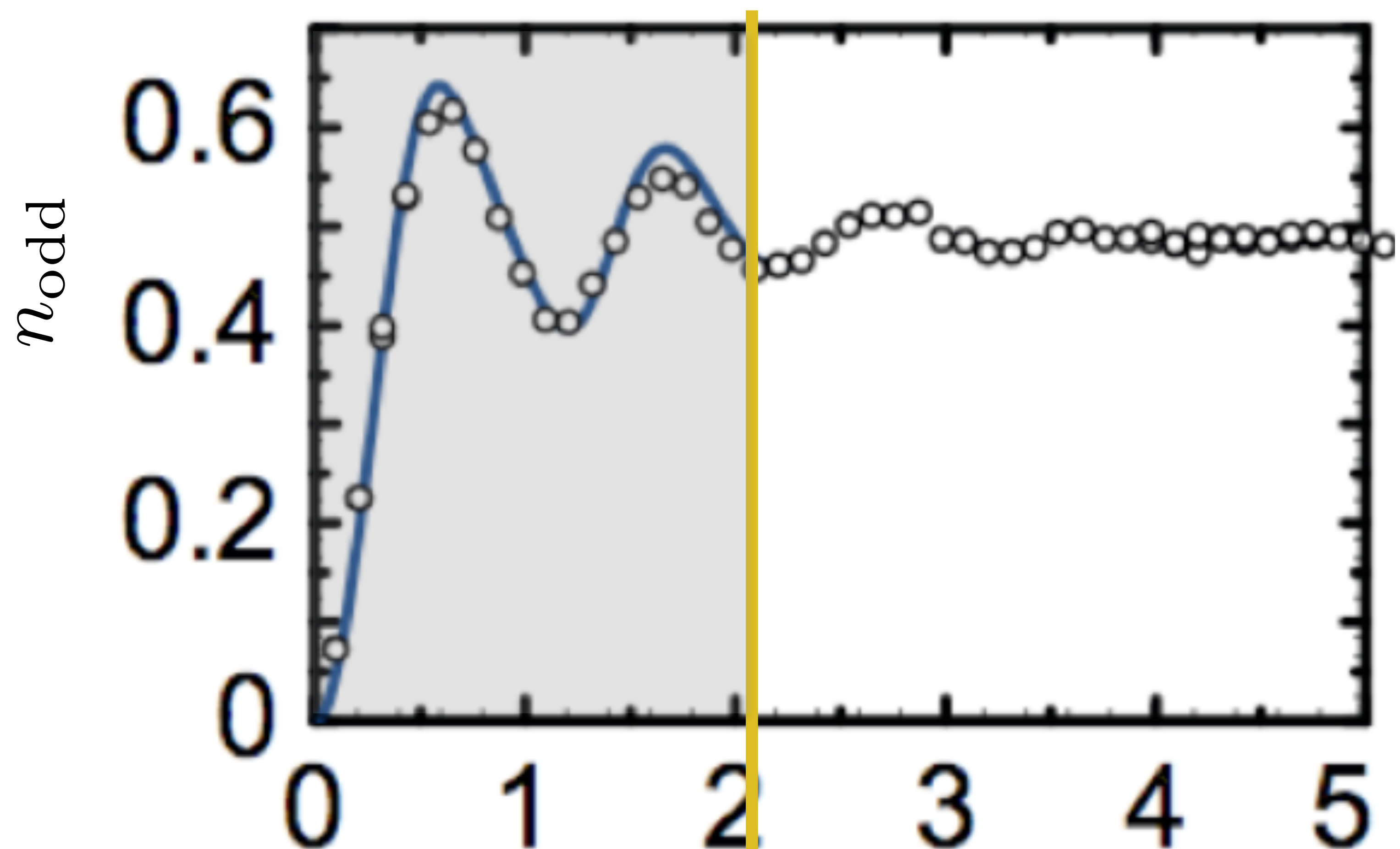
Eisert, Friesdorf, Gogolin, Nature Phys 11, 124 (2015)

- Dynamical phase transitions

Zhang, Pagano, Hess, Kyprianidis, Becker, Kaplan, Gorshkov, Gong, Monroe, Nature 551, 601 (2017)



- **Time-dependent** problems ("quenches")
  - Imbalance as function of time for $|\psi(0)\rangle = |0, 1, \ldots, 0, 1\rangle$ under Bose-Hubbard Hamiltonian (MPQ)



Trotzky, Chen, Flesch, McCulloch, Schollwoeck, Eisert, Bloch, Nature Phys 8, 325 (2012)

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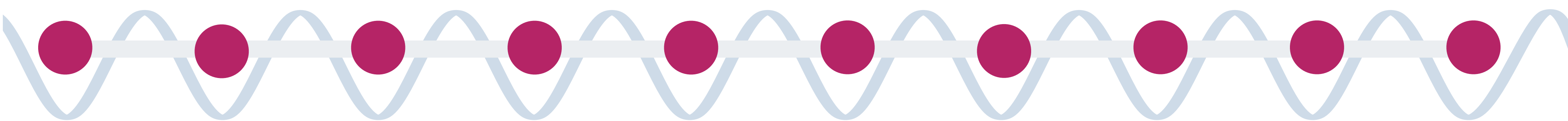
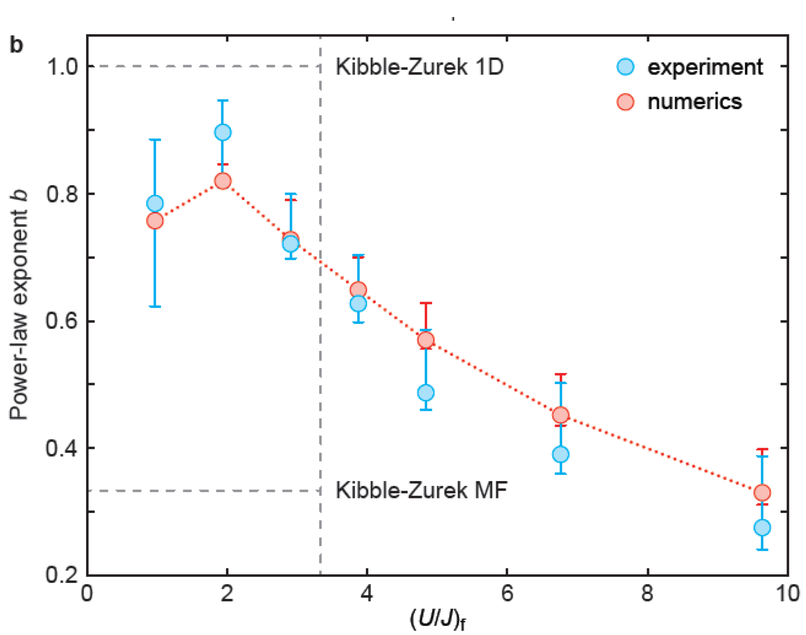


- **Slow parameter variations** (reminiscent of adiabatic quantum algorithms)
  - E.g., Kibble-Zurek dynamics (1D-2D)

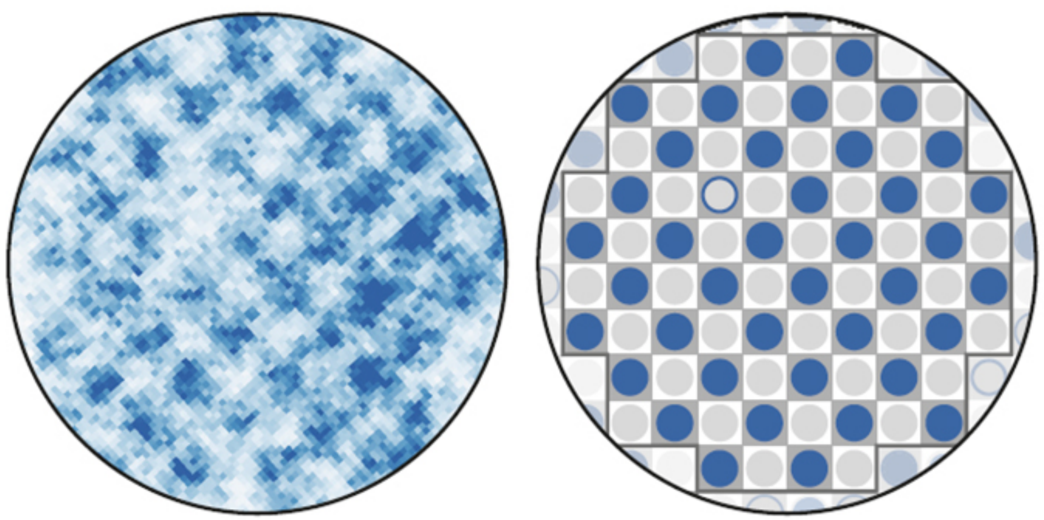


  - Probing scaling laws of correlations

Braun, Friesdorf, Hodgman, Schreiber, Ronzheimer, Riera, del Rey, Bloch, Eisert, Schneider, Proc Natl Acad Sci 112, 3641 (2015)

What can they probe?

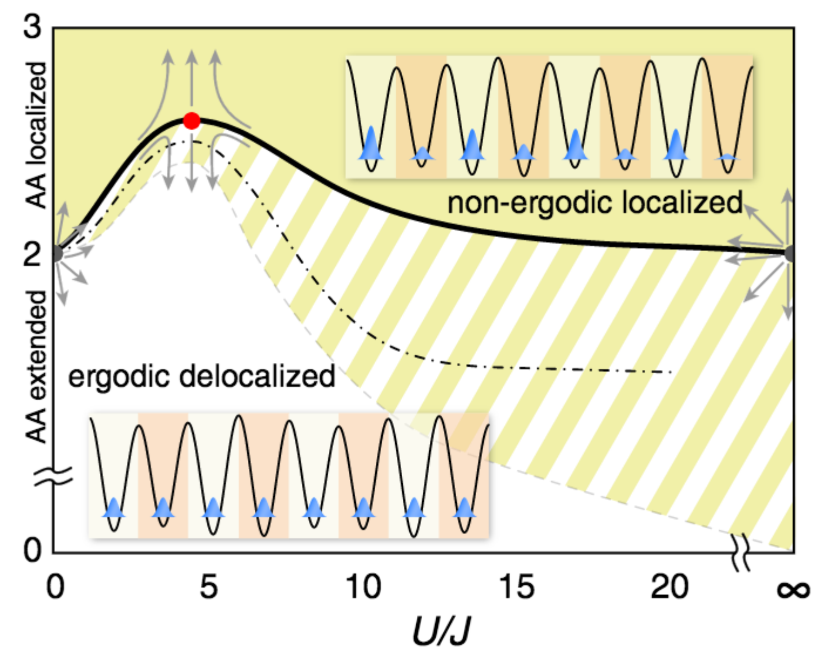
- **Ground state** and static problems
  - Hubbard model, probing high-Tc superconductivity



  - Cooled to create a magnetic state with long-range order

Mazurenko, Chiu, Ji, Parsons, Kanász-Nagy, Schmidt, Grusdt, Demler, Greif, Greiner, Nature 545, 462 (2017)
Esslinger, Ann Rev Cond Mat Phys 1, 129 2010

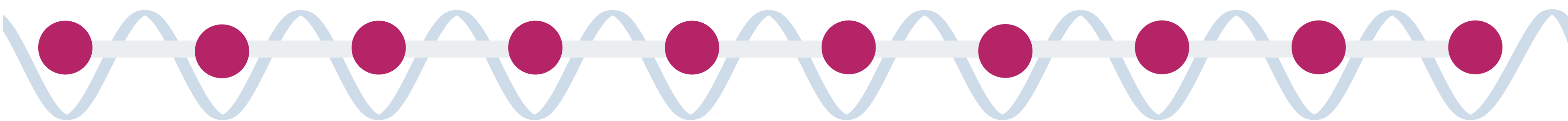
  - Many-body localization (1D-2D)



  - Debated in 2D

Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk, Altman, Schneider, Bloch, Science 349, 842 (2015)

What can they probe?



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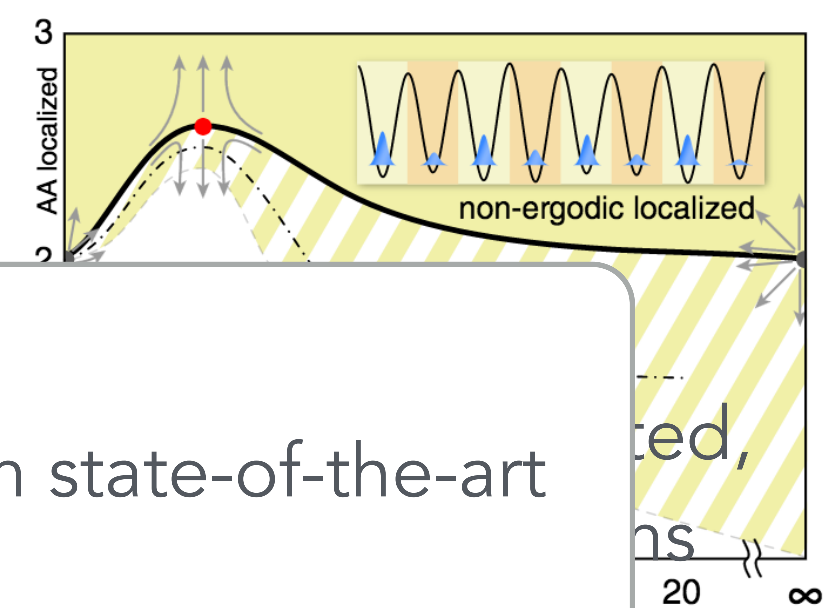

- Debated in 2D

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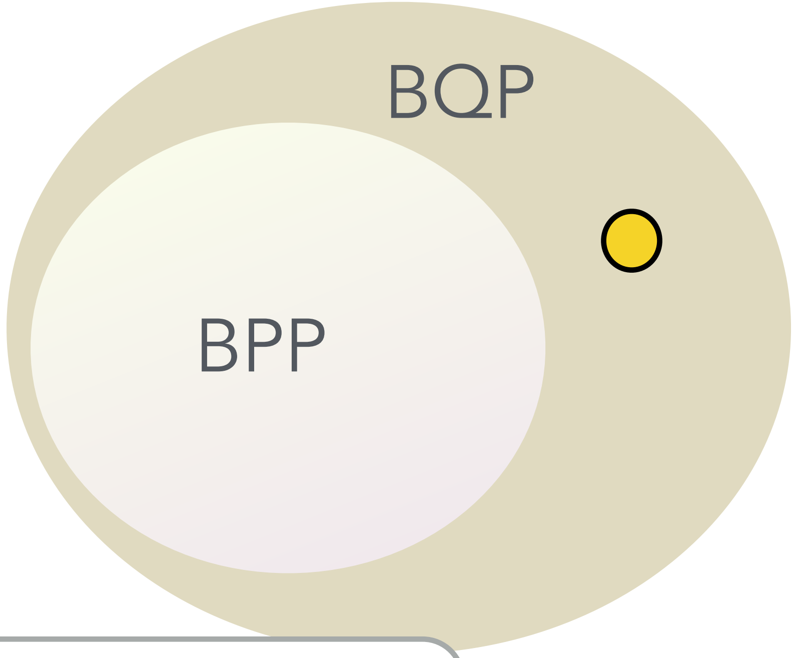
- **Quantum simulators**

Existing quantum simulators outperform state-of-the-art algorithms on classical supercomputers

- Cleverer simulation method?



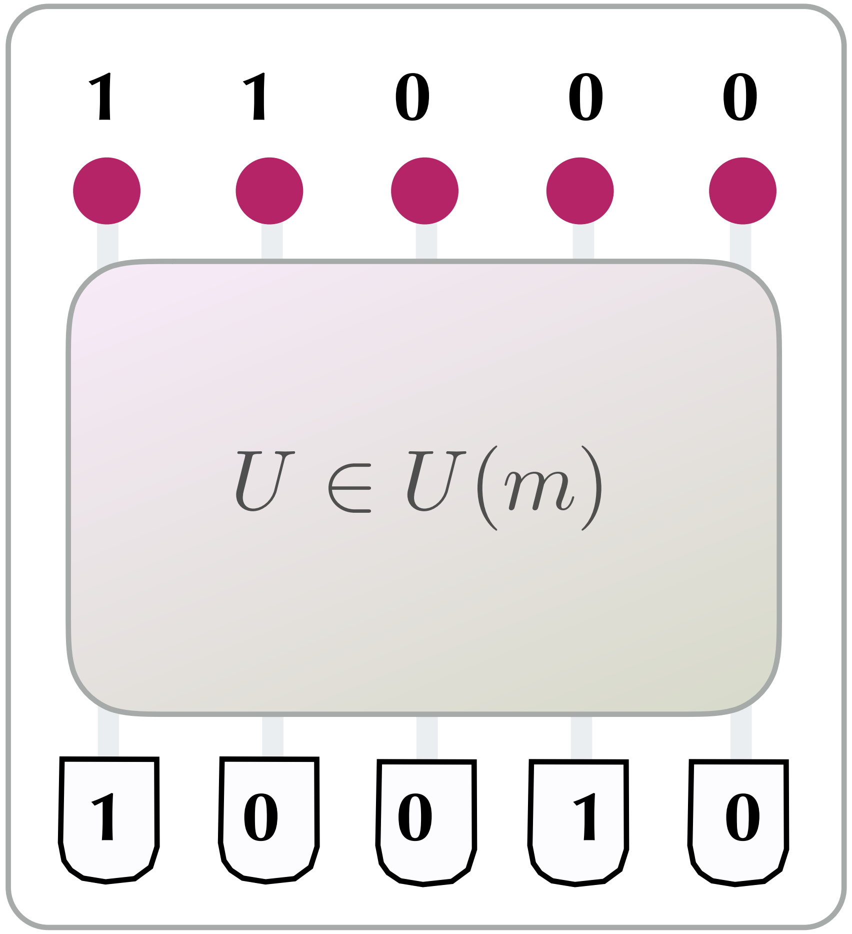
- **Intermediate problems**

To be safe against "lack of imagination", we must prove the hardness of the task in a complexity-theoretic sense

Super-polynomial quantum advantages?

Complexity-theoretic quantum advantages

- **Aim:** Find **some** problem with strong evidence for quantum advantage
- Boson sampling
  Aaronson, Arkhipov, Th Comp 9, 143 (2013)



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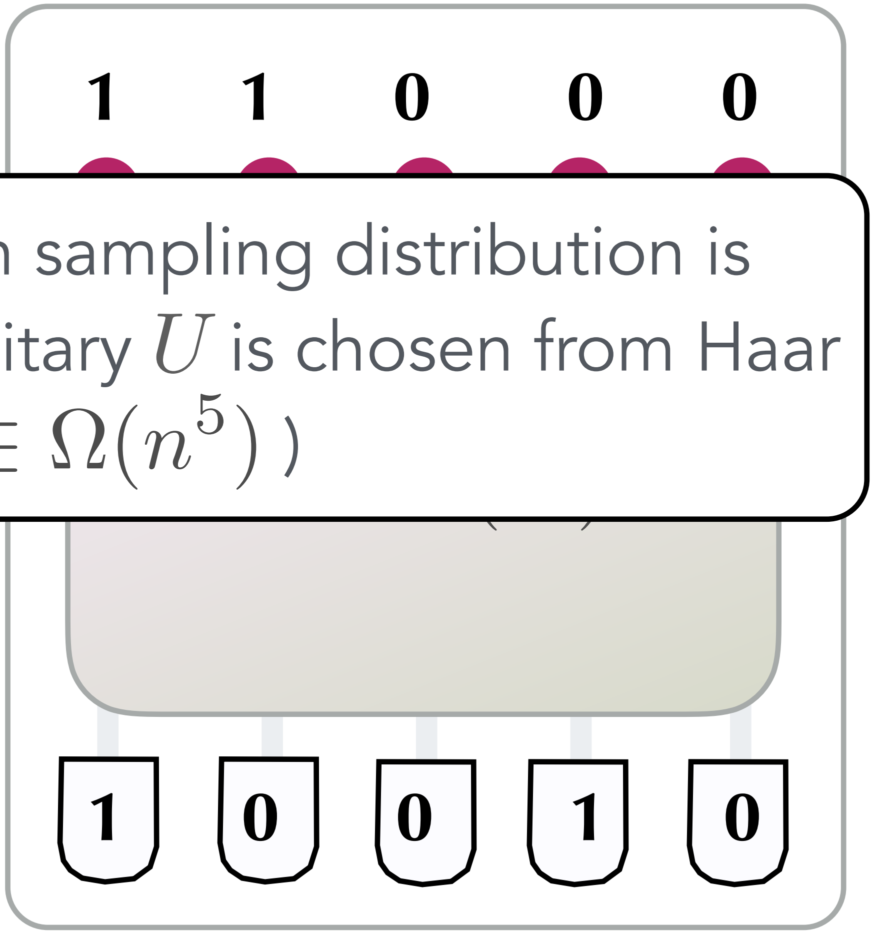


Sampling from a distribution close in l_1 norm to boson sampling distribution is "computationally hard" with high probability if the unitary U is chosen from Haar measure and m increases sufficiently fast with n ($m \in \Omega(n^5)$)

Complexity-theoretic quantum advantages

- **Aim:** Find **some** problem with strong evidence for quantum advantage

- **Verification and testing?** Black-box verification seems out of question

Hamiltonian quantum simulation architectures

- **Aim:** Find **some** problem with strong evidence for quantum advantage

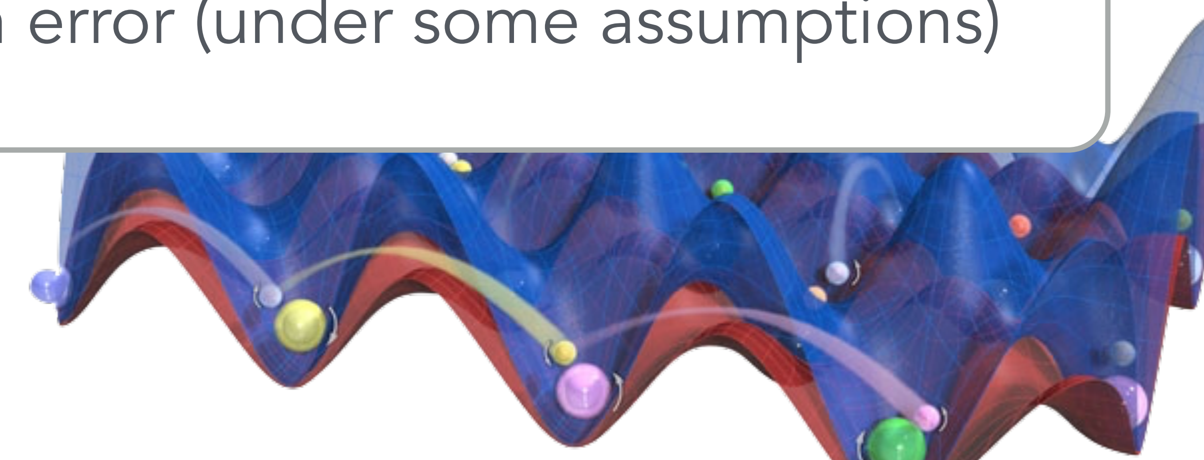
- **Challenging prescription**: It this possible to scale it up to provably hard regimes, in an architecture close to a quantum simulation?

Hamiltonian quantum simulation architectures

- **Aim:** Find **some** problem with strong evidence for quantum advantage

Combine benefits of both worlds

- **Hamiltonian quench architecture**
- **Low periodicity** of the interaction Hamiltonian (NN or NNN)
- **Hardness proofs** with l_1-norm error (under some assumptions)



Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)

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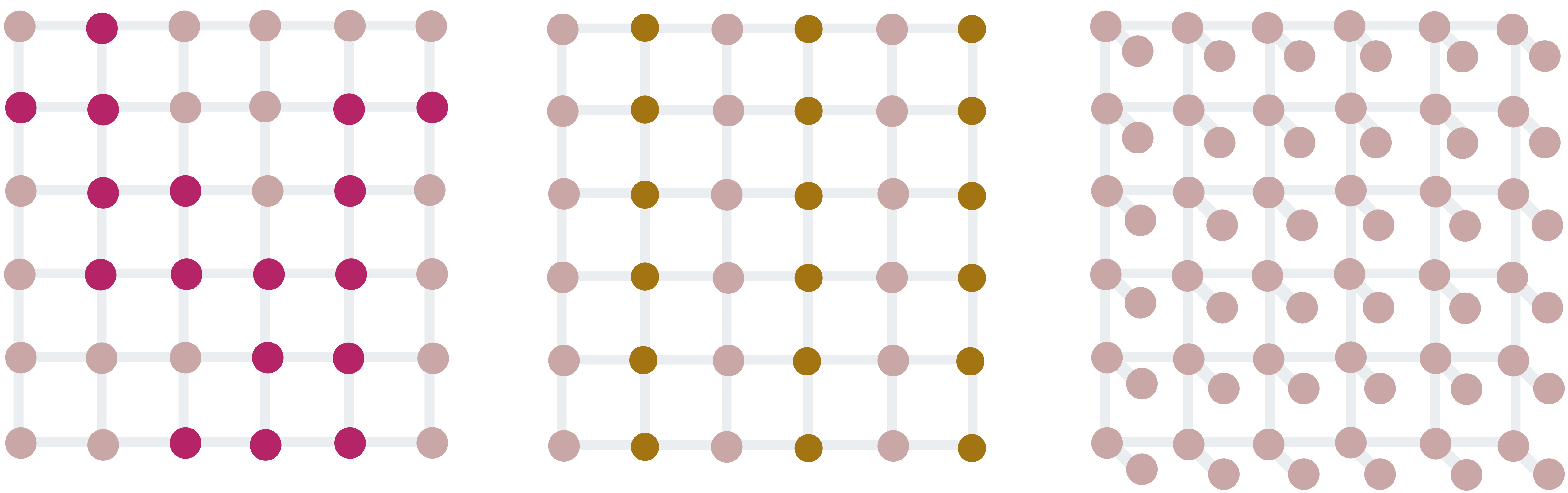

Random | Quasi-periodic | Translationally invariant

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)
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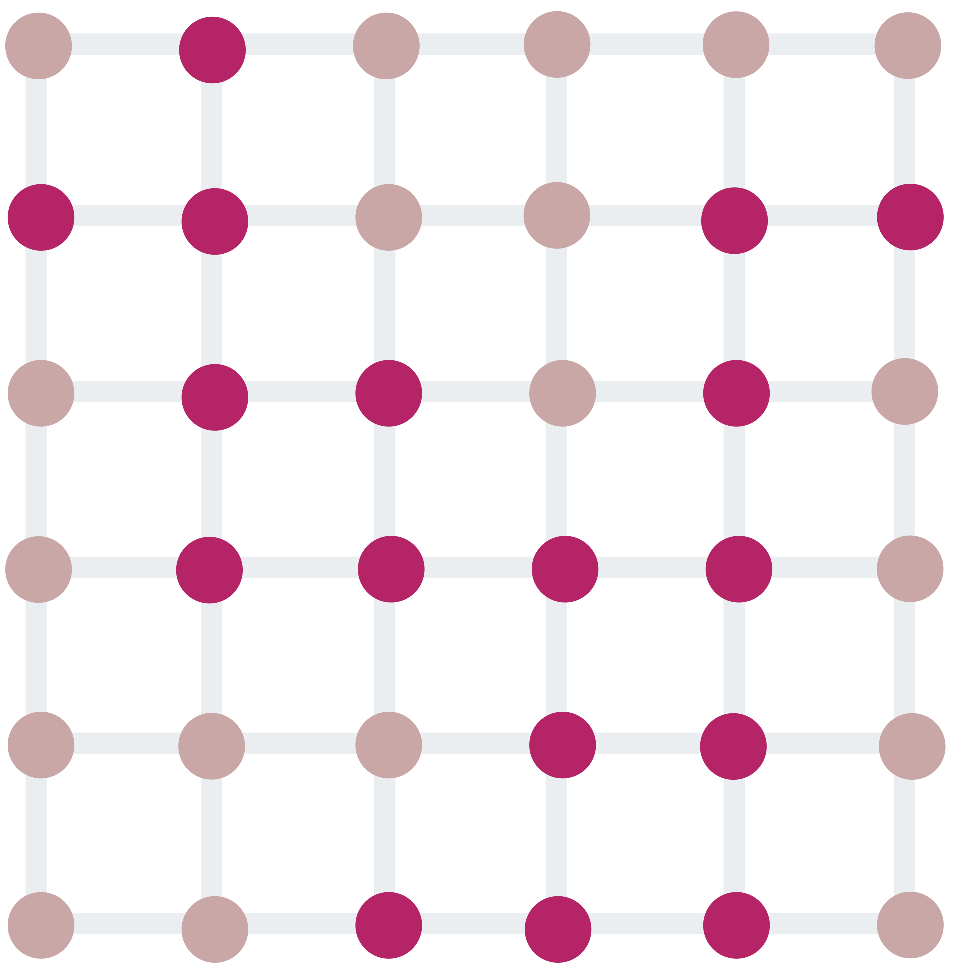
Simple Ising models

- Prepare N qubits in $n \times m$ square lattice in product

$$|\psi_\beta\rangle = \otimes_{i,j=1}^{n,m}(|0\rangle + e^{i\beta_{i,j}}|1\rangle)$$

with $\beta_{i,j} \in \{0, \pi/4\}$, {●,●} i.i.d. randomly



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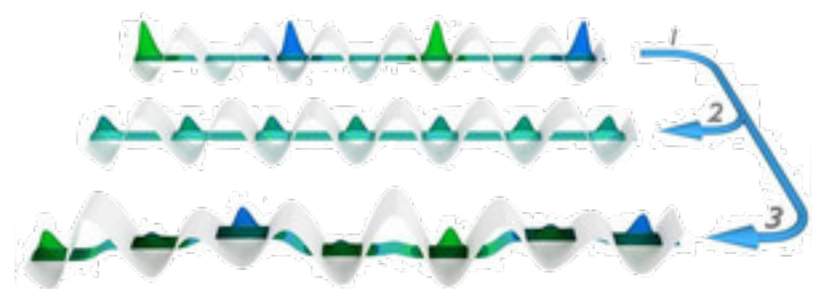
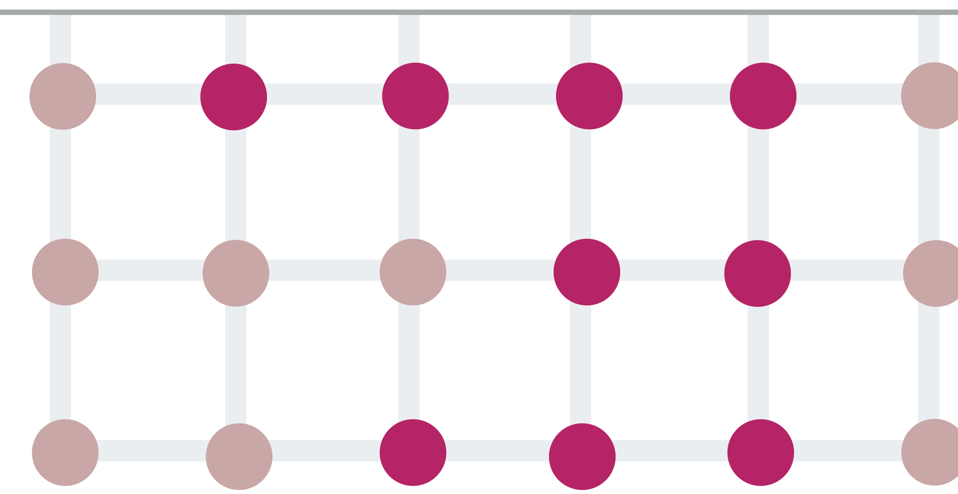
- Reminscient of disordered optical lattices



Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk, Altman, Schneider, Bloch, Science 349, 842 (2015)



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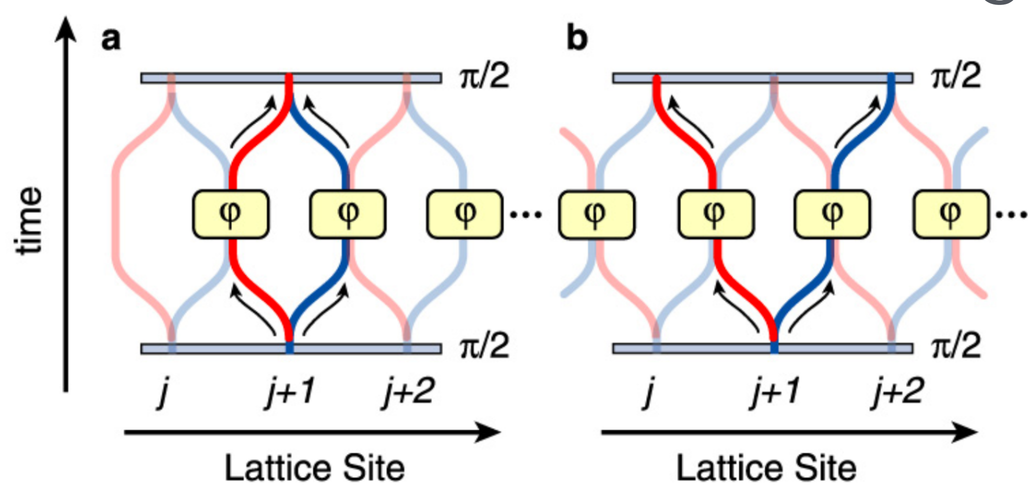
- **Quench** to $H = \sum_{(i,j)\in E} Z_i Z_j + \frac{\pi}{4} \sum_{i \in V} Z_i$ and evolve under $U = e^{iH}$

- Controlled coherent collisions long realized



Mandel, Greiner, Widera, Rom, Hänsch, Bloch, Nature, 425, 937 (2003)

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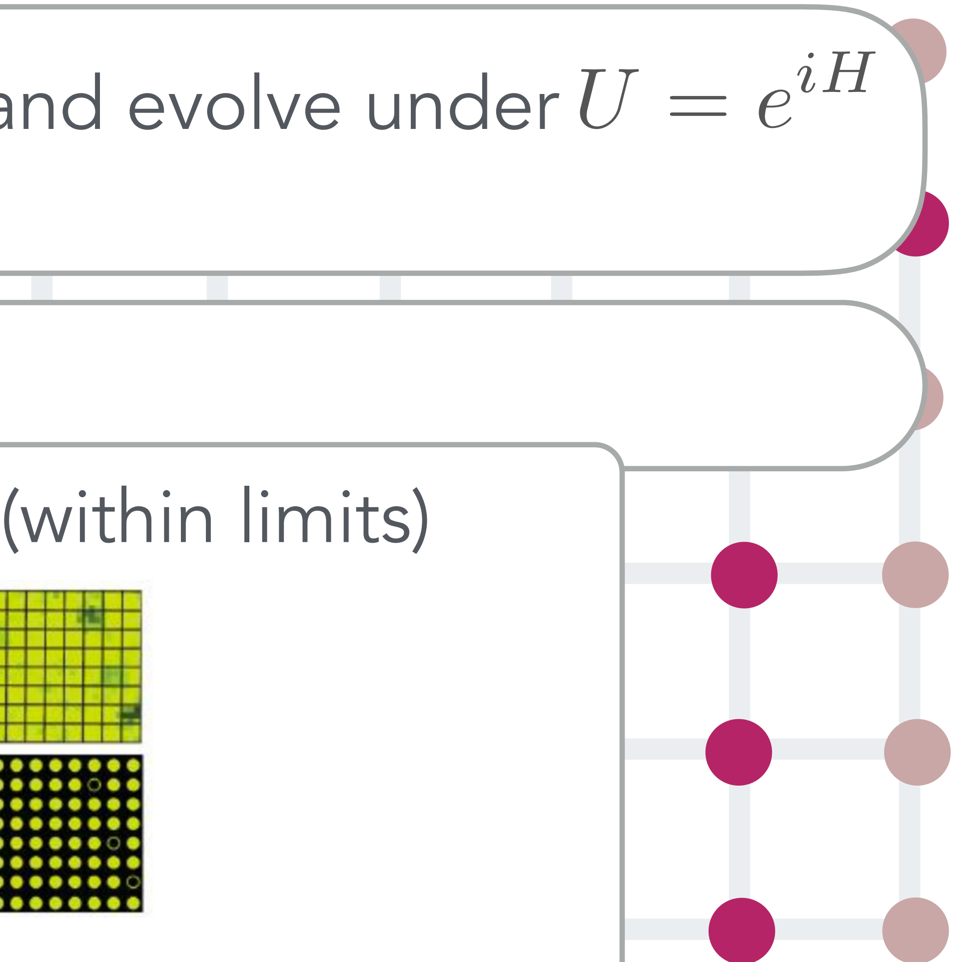
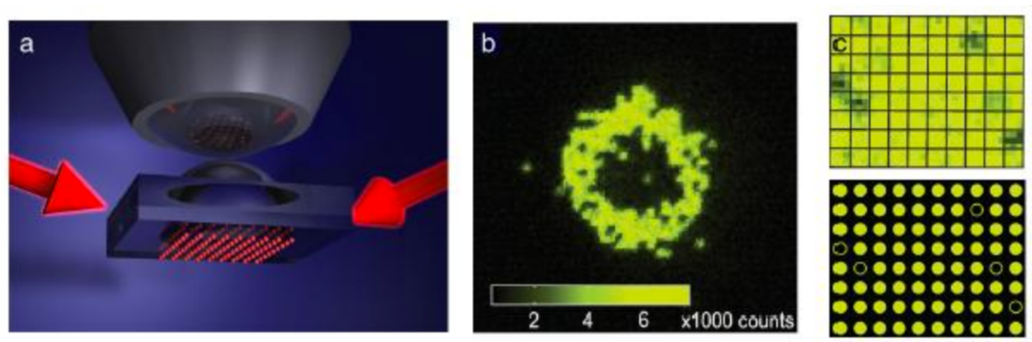
- Measure all qubits in X-basis



- Single-site addressing possible (within limits)



Bakr, Gillen, Peng, Foelling, Greiner, Nature 462, 74–77 (2009)
Weitenberg, Endres, Sherson, Cheneau, Schauß, Fukuhara, Bloch, Kuhr, Nature 471, 319 (2011)

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)
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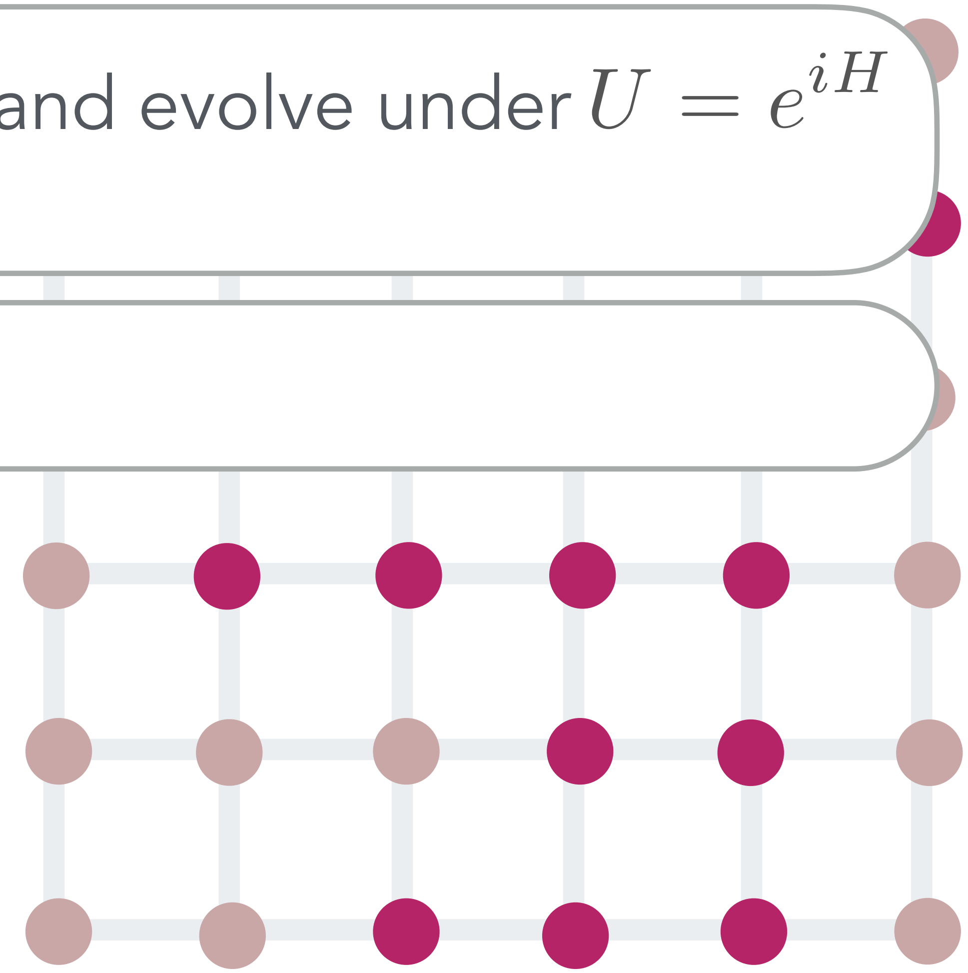

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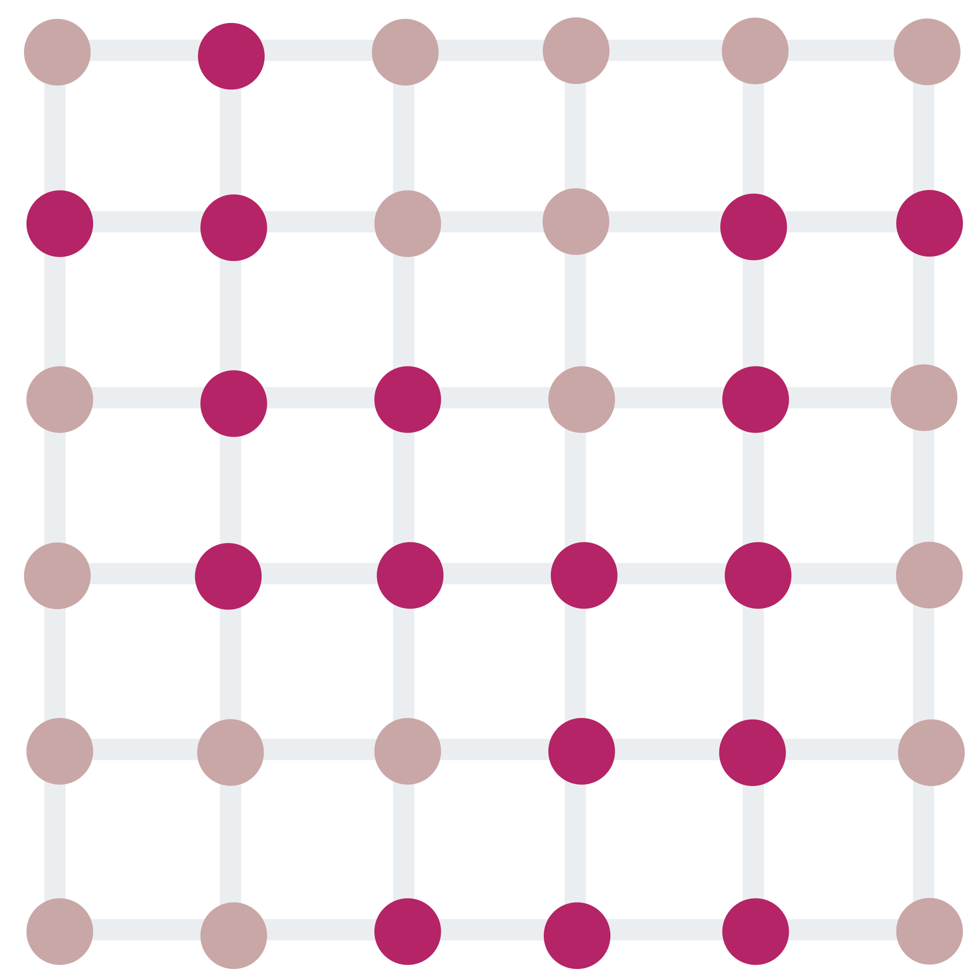
- **Theorem** (Hardness of classical sampling):

Assuming three highly plausible complexity-theoretic conjectures are true a classical computer cannot efficiently sample from the outcome distribution of our scheme up to constant error in l_1 distance



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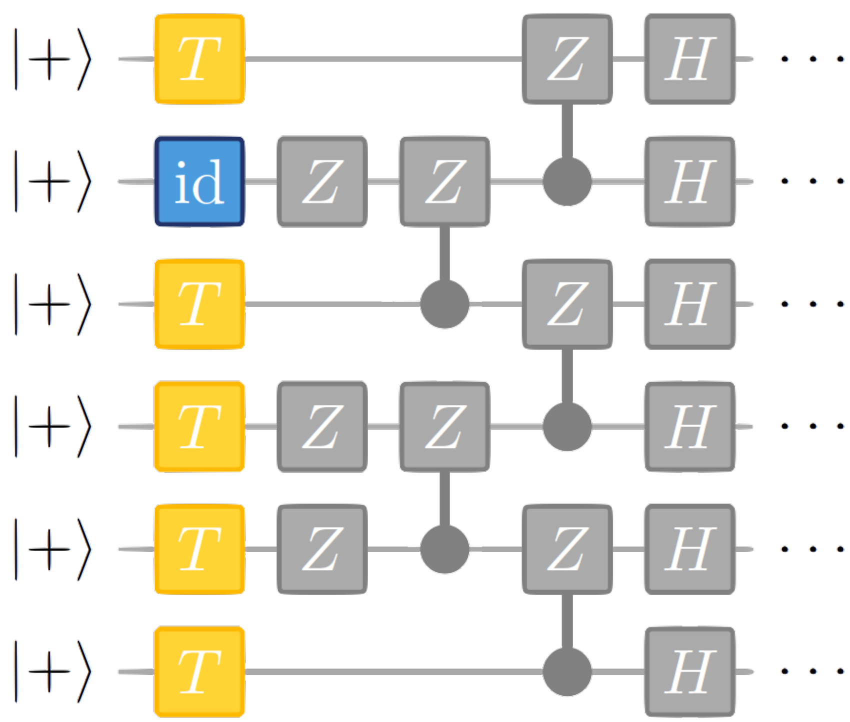
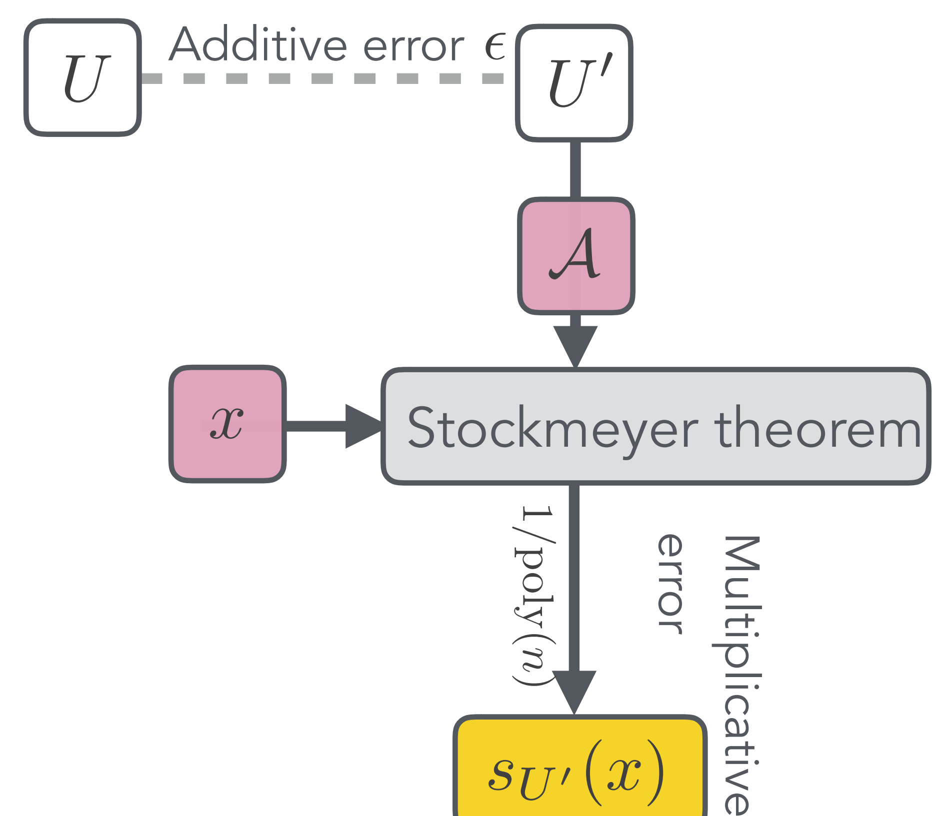
- Relate quench architecture to post-selected measurement-based quantum computing

- Universal quantum circuit for postBQP



- It is #P-hard to approximate the outcome distribution

- Relate hardness of computing probabilities to hardness of sampling with additive errors



- Polynomial hierarchy (similar P≠ NP)
- Average-case complexity

  Bouland, Fefferman, Nirkhe, Vazirani, arXiv:1803.04402
- Anti-concentration

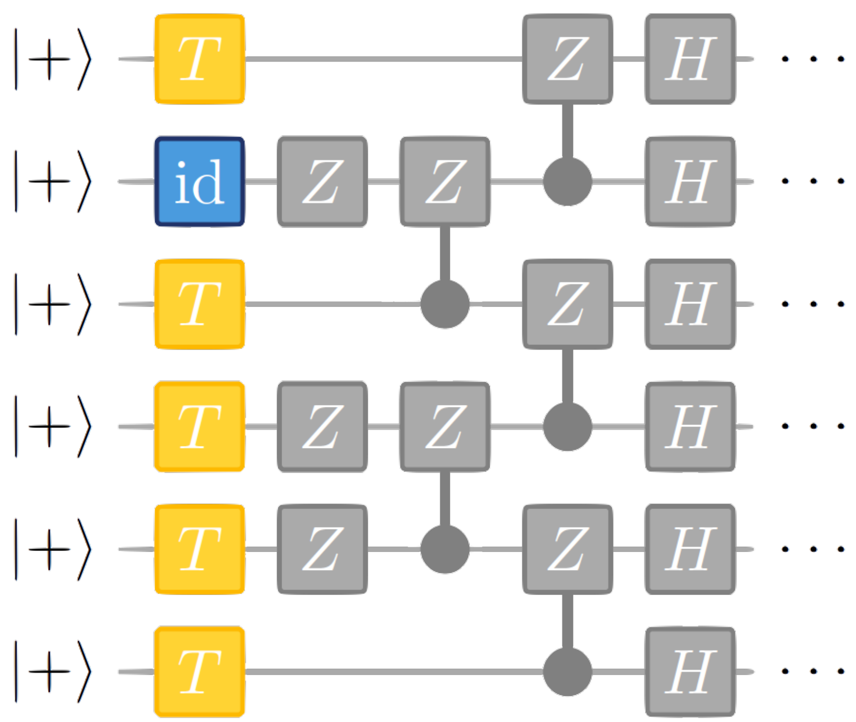
  Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)

  Mann, Bremner, arXiv:1711.00686

- Relate quench architecture to post-selected measurement-based quantum computing

…eoretic conjectures are true a …ple from the outcome distribution …istance

- Universal quantum circuit for postBQP



- It is #P-hard to approximate the outcome distribution

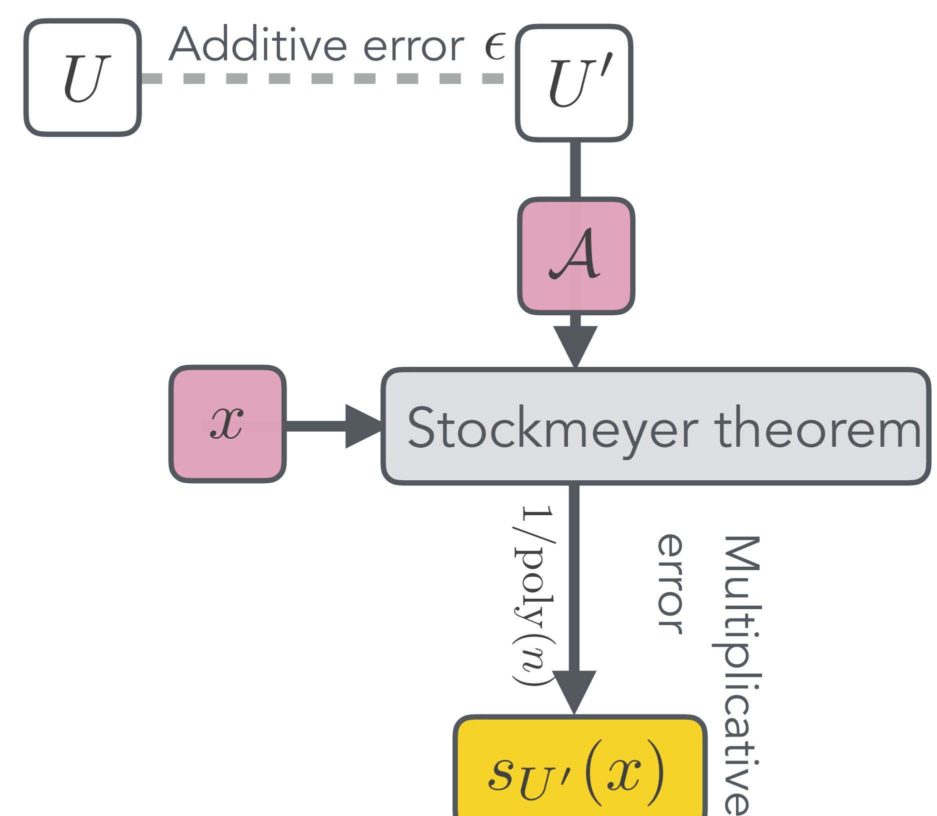
- Polynomial hierarchy (similar P≠ NP)
- Average-case complexity

Bouland, Fefferman, Nirkhe, Vazirani, arXiv:1803.04402

- Anti-concentration

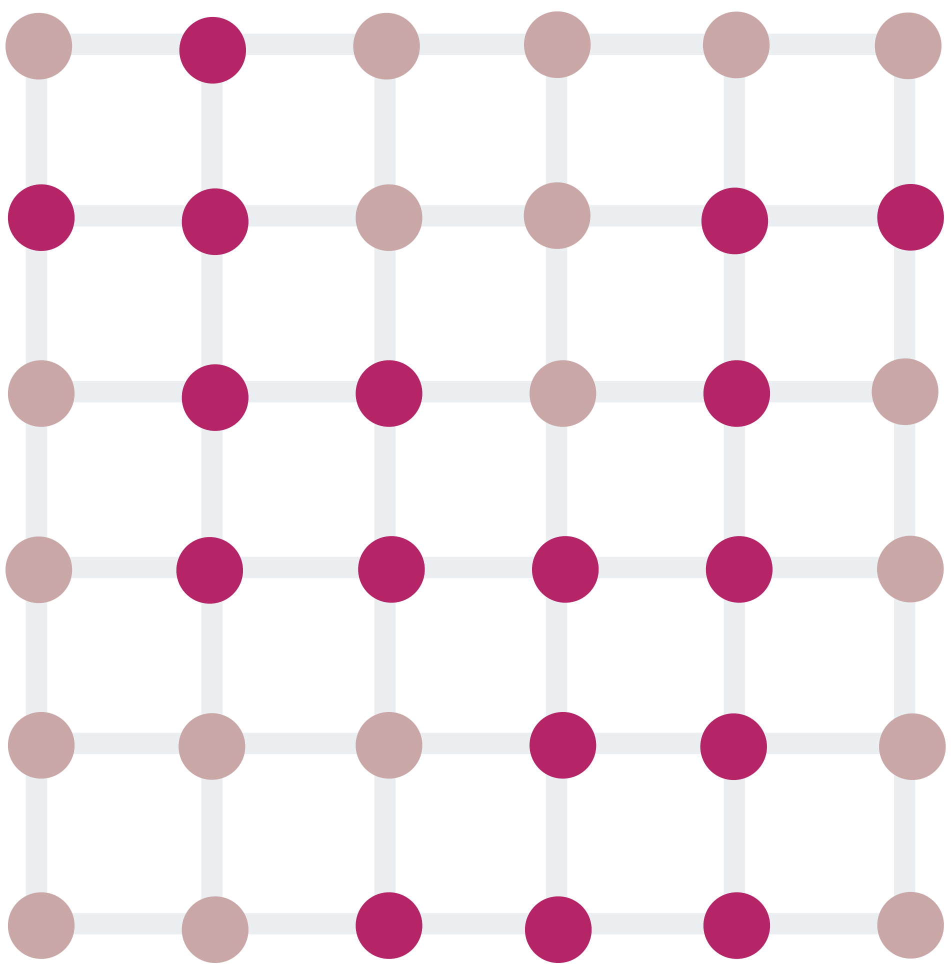
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)
Mann, Bremner, arXiv:1711.00686

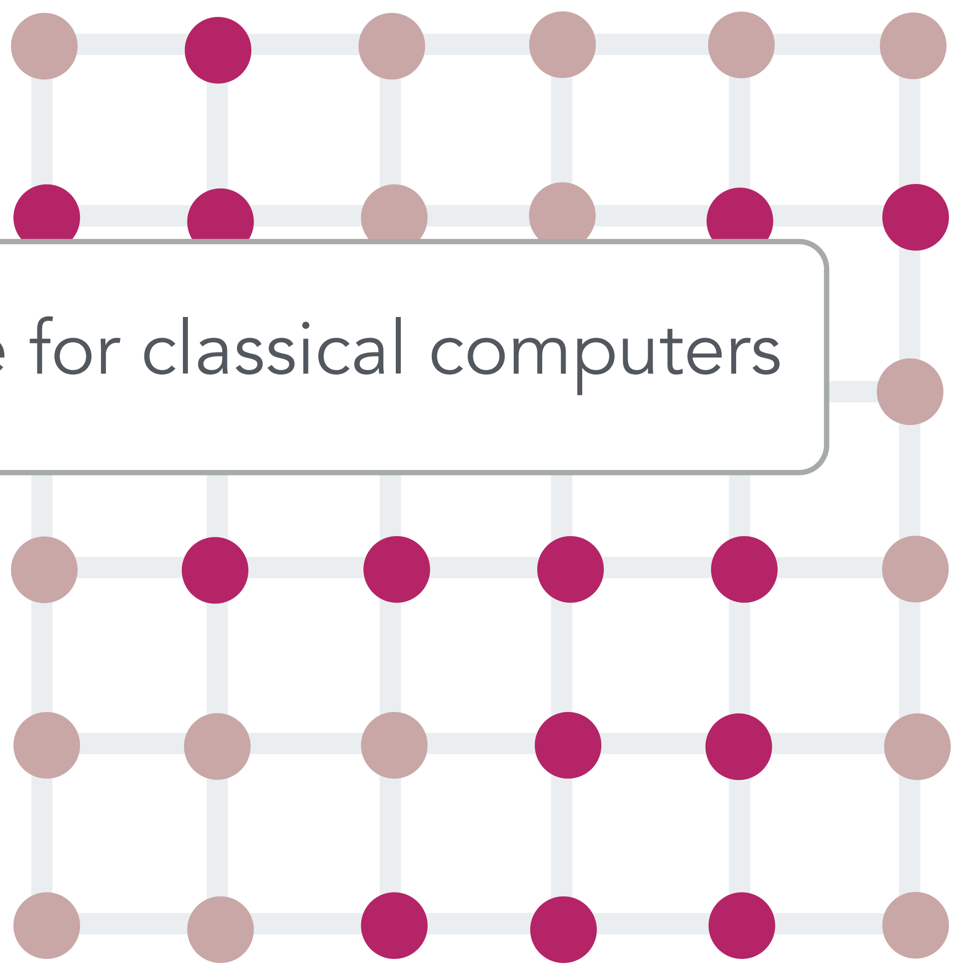
- Relate hardness of computing probabilities to hardness of sampling with additive errors



- **Theorem** (Hardness of classical sampling):

Assuming three highly plausible complexity-theoretic conjectures are true a classical computer cannot efficiently sample from the outcome distribution of our scheme up to constant error in l_1 distance





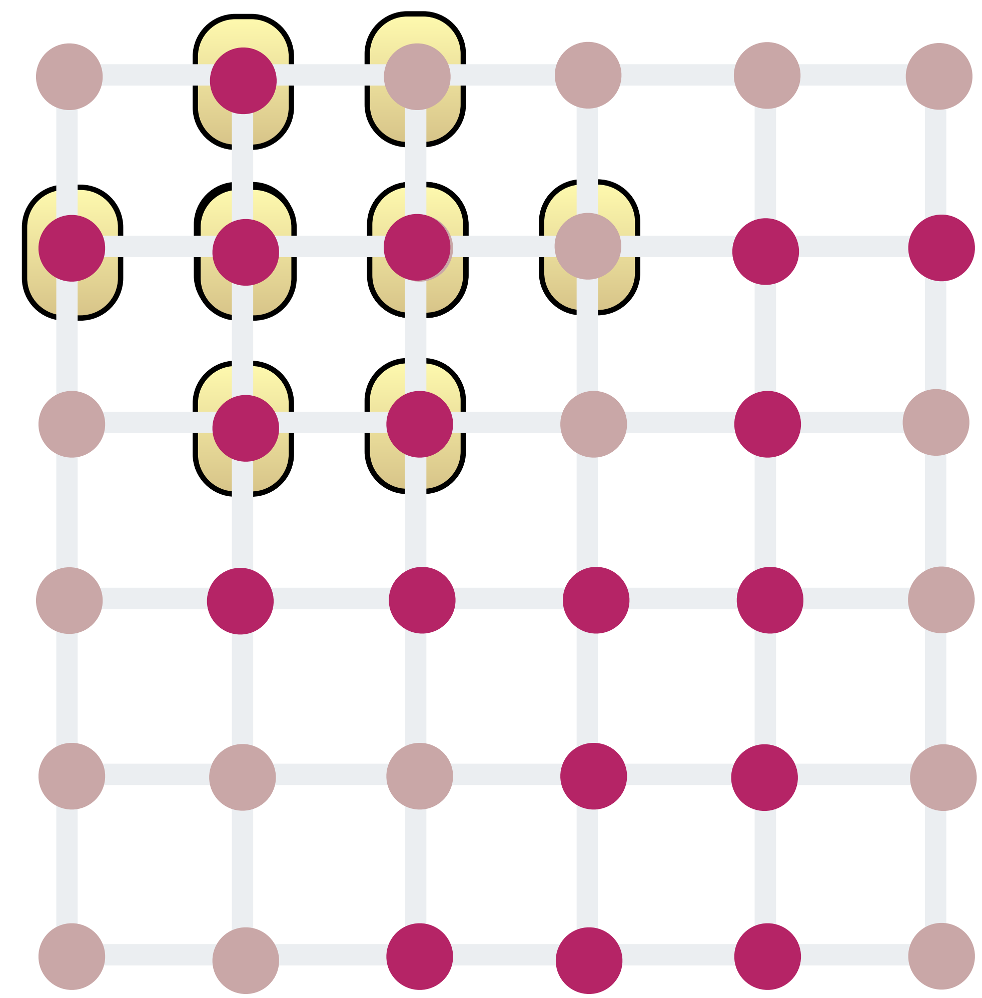
- This quantum simulation is intractable for classical computers

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)

Verifiable quantum devices showing a quantum advantage

- One can with $\theta(N)$ many measurements detect closeness in l_1 -norm!

- Ground state of fictious frustration-free Hamiltonian
- **Much** simpler than fault tolerance



Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)
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Cramer et al, Nature Comm 1, 149 (2010)

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Verifiable quantum devices showing a quantum advantage

- **Common prejudice:** In order to be able to verify a quantum simulation, one needs to be able to efficiently simulate it

Summary, outlook and open questions

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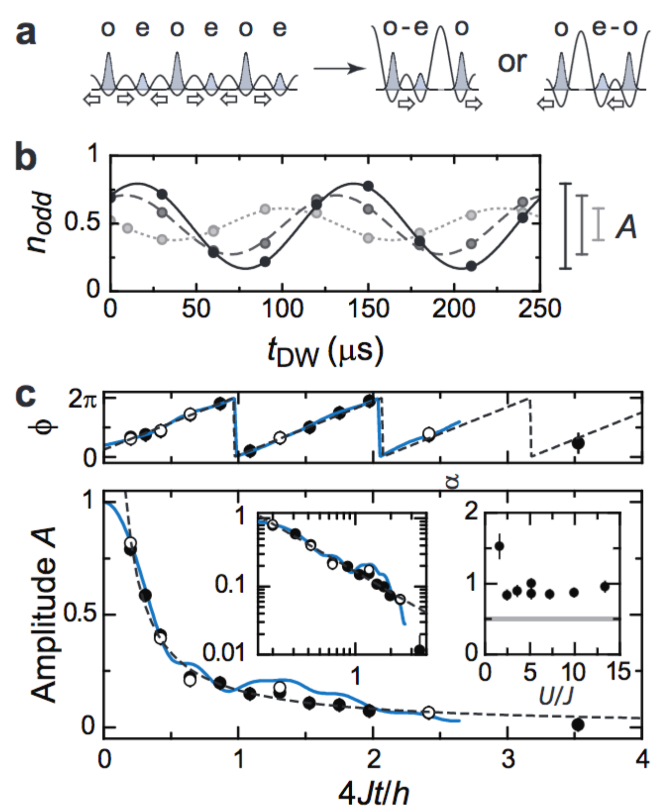
  - even if simulators exhibit quantum computational speedup

- Closer to physically more interesting schemes?
- More structured problems, optimization?



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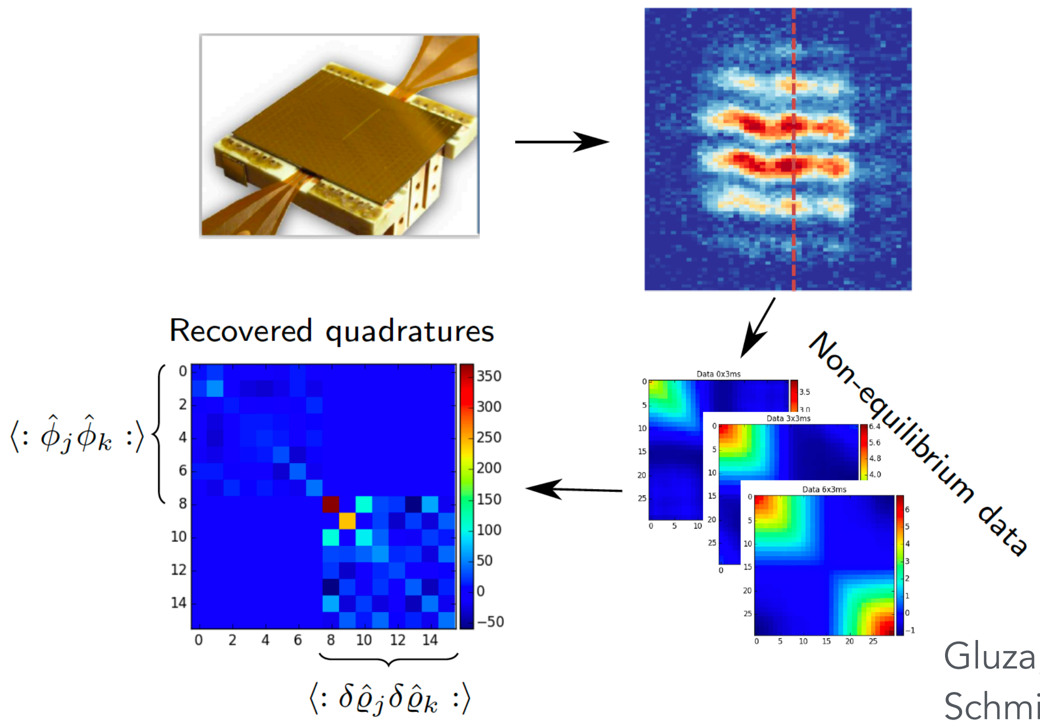

Gluza, Schweigler, Krumnow, Rauer, Schmiedmayer, Eisert, in preparation

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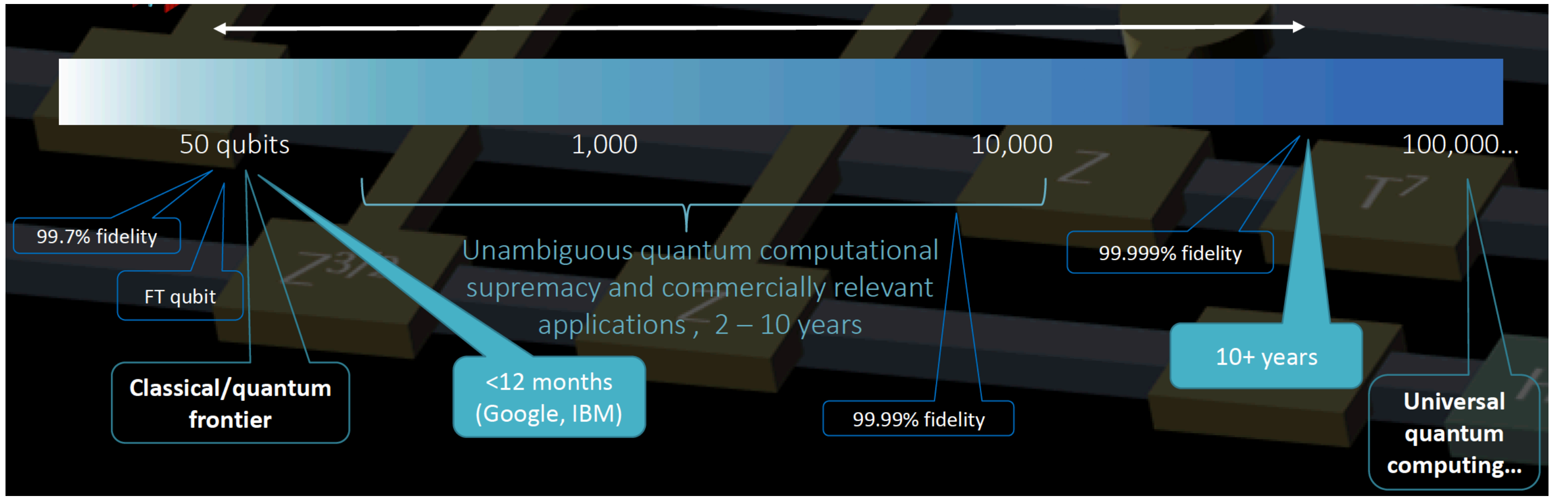

(Mick Bremner)

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Thanks for your attention!

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