Analog quantum simulations

What we have, what we would like to have,
and the potential for seeing quantum advantages

Jens Eisert, Freie Universität Berlin
Challenges in Quantum Computation Workshop, Berkeley, June 2018

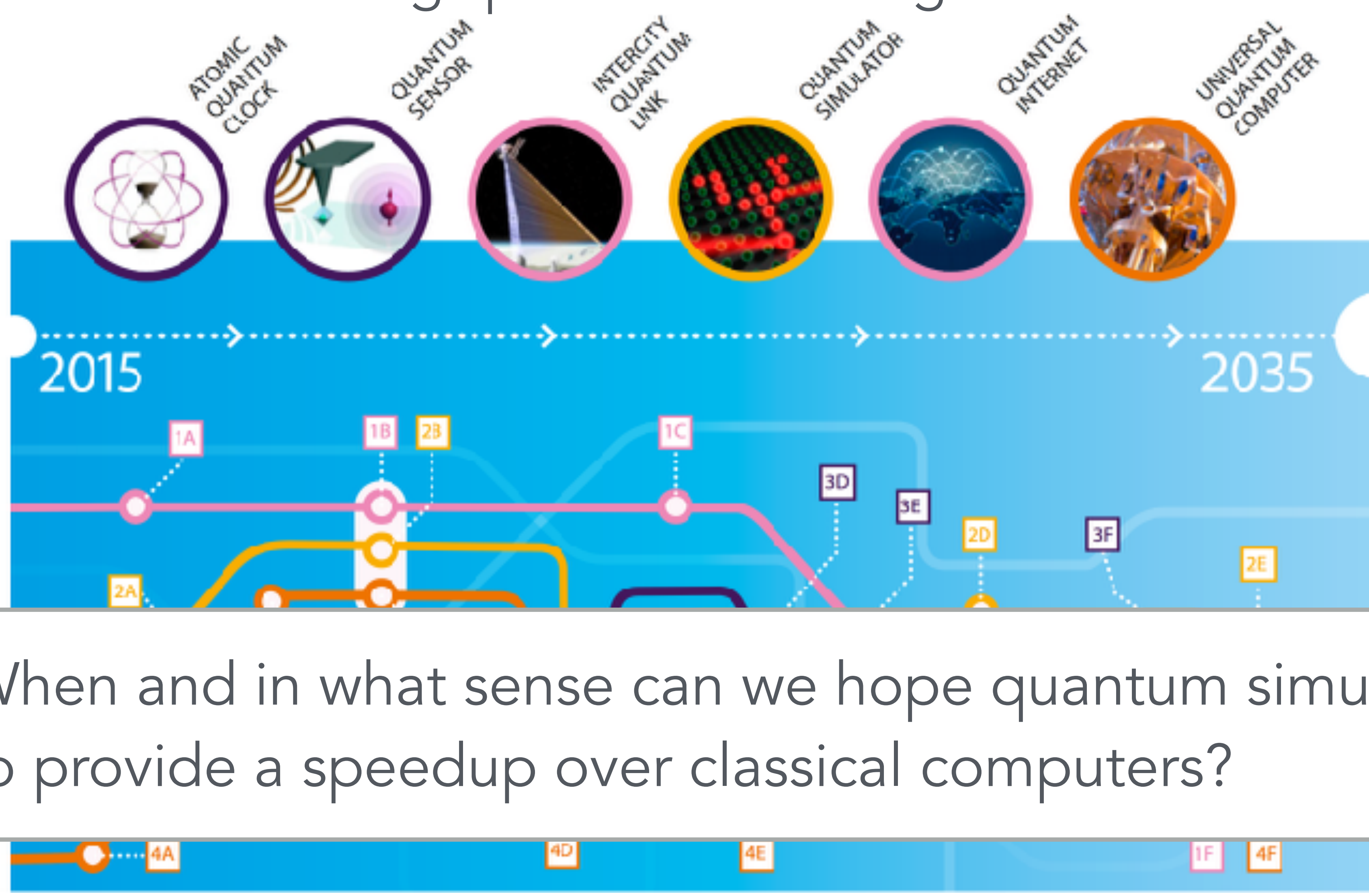
Analog quantum simulations

What we have, what we would like to have,
and the potential for seeing quantum advantages

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

Analog quantum simulations

What we have, what we would like to have,
and the potential for seeing quantum advantages

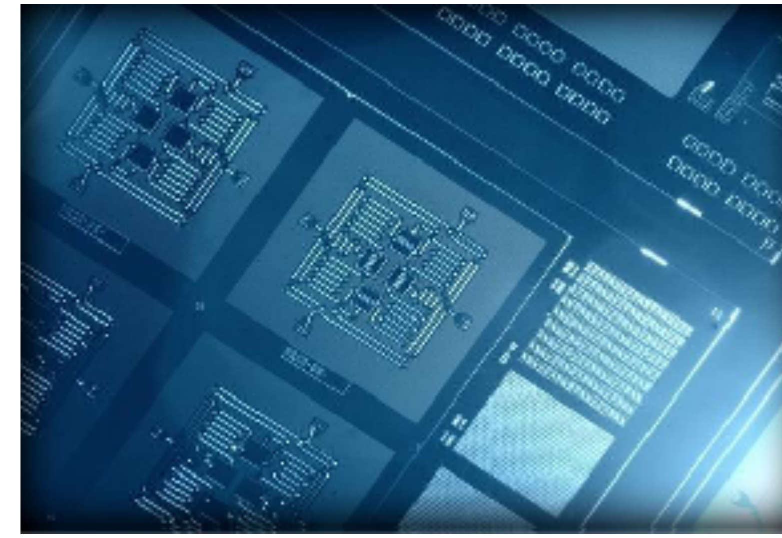


- When and in what sense can we hope quantum simulators to provide a speedup over classical computers?

IBM Research

Google

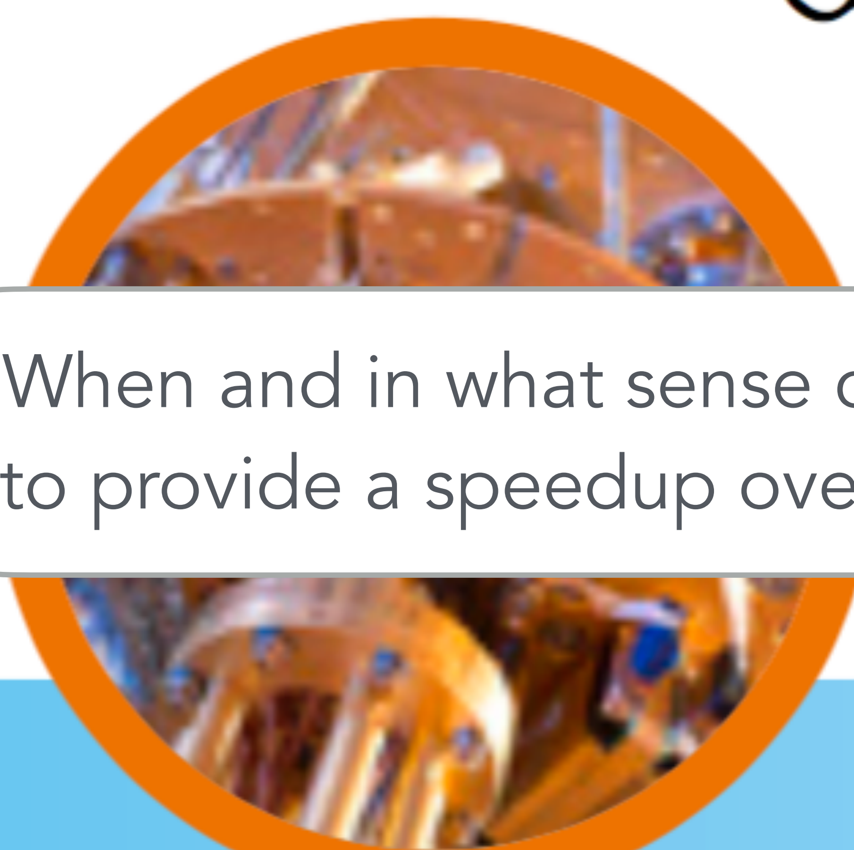
Microsoft Research



- 20-50 qubit quantum devices
- Noisy intermediate scale quantum computers

QUANTUM INTERNET

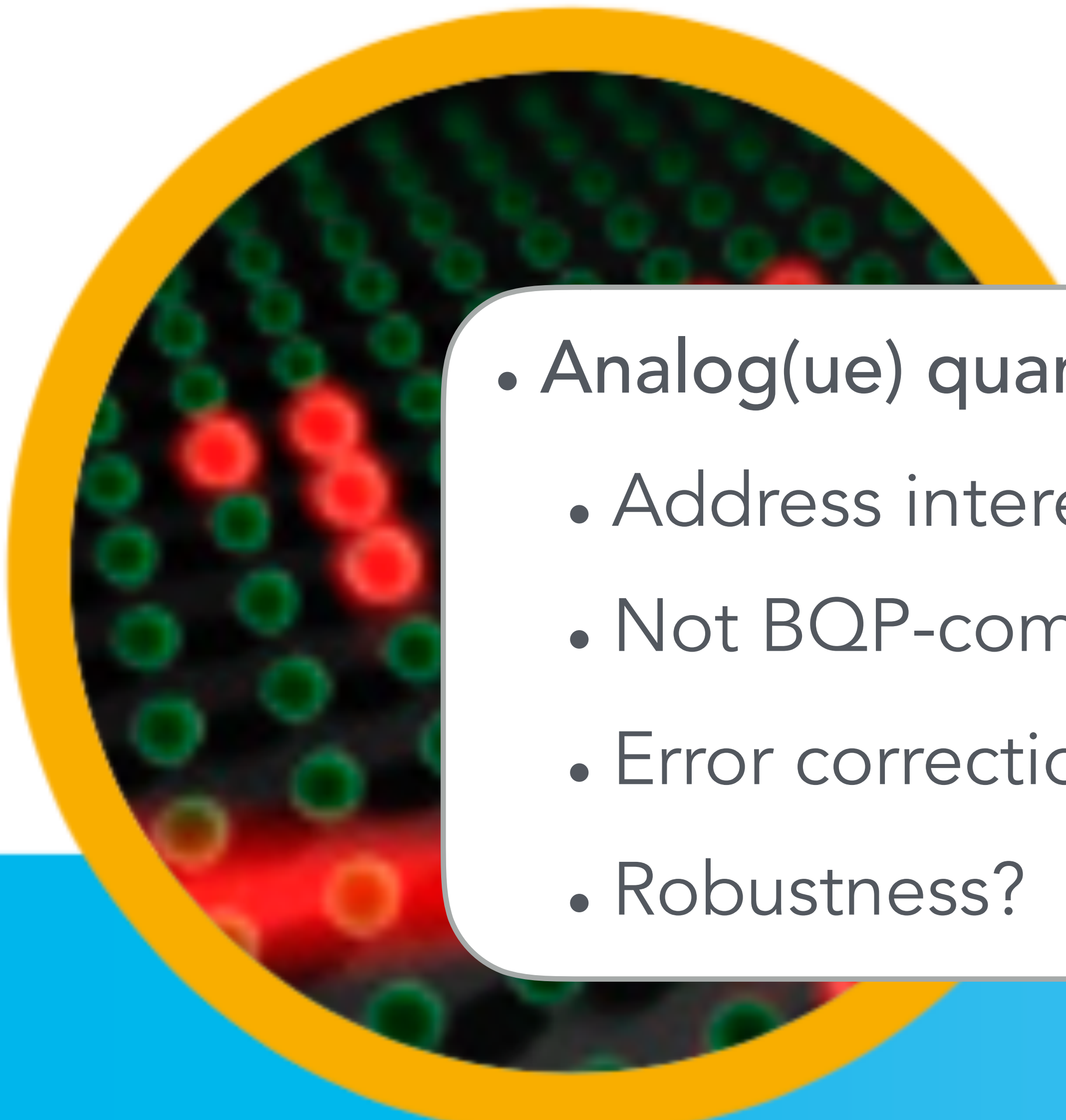
UNIVERSA… QUANTUM COMPUTER

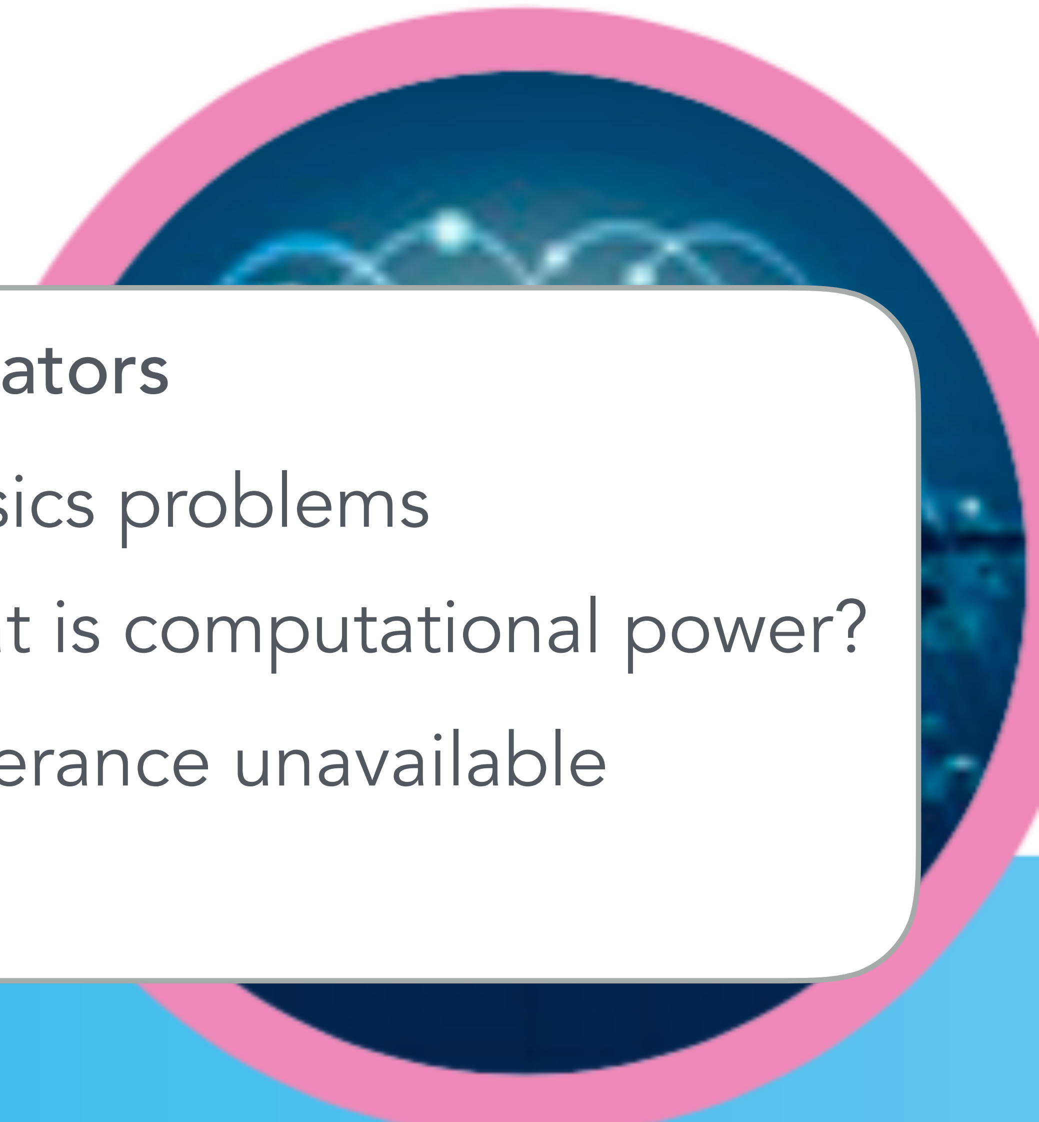


- When and in what sense can we hope quantum simulators to provide a speedup over classical computers

...RCITY QUANTUM LINK

QUANTUM SIMULATOR





- **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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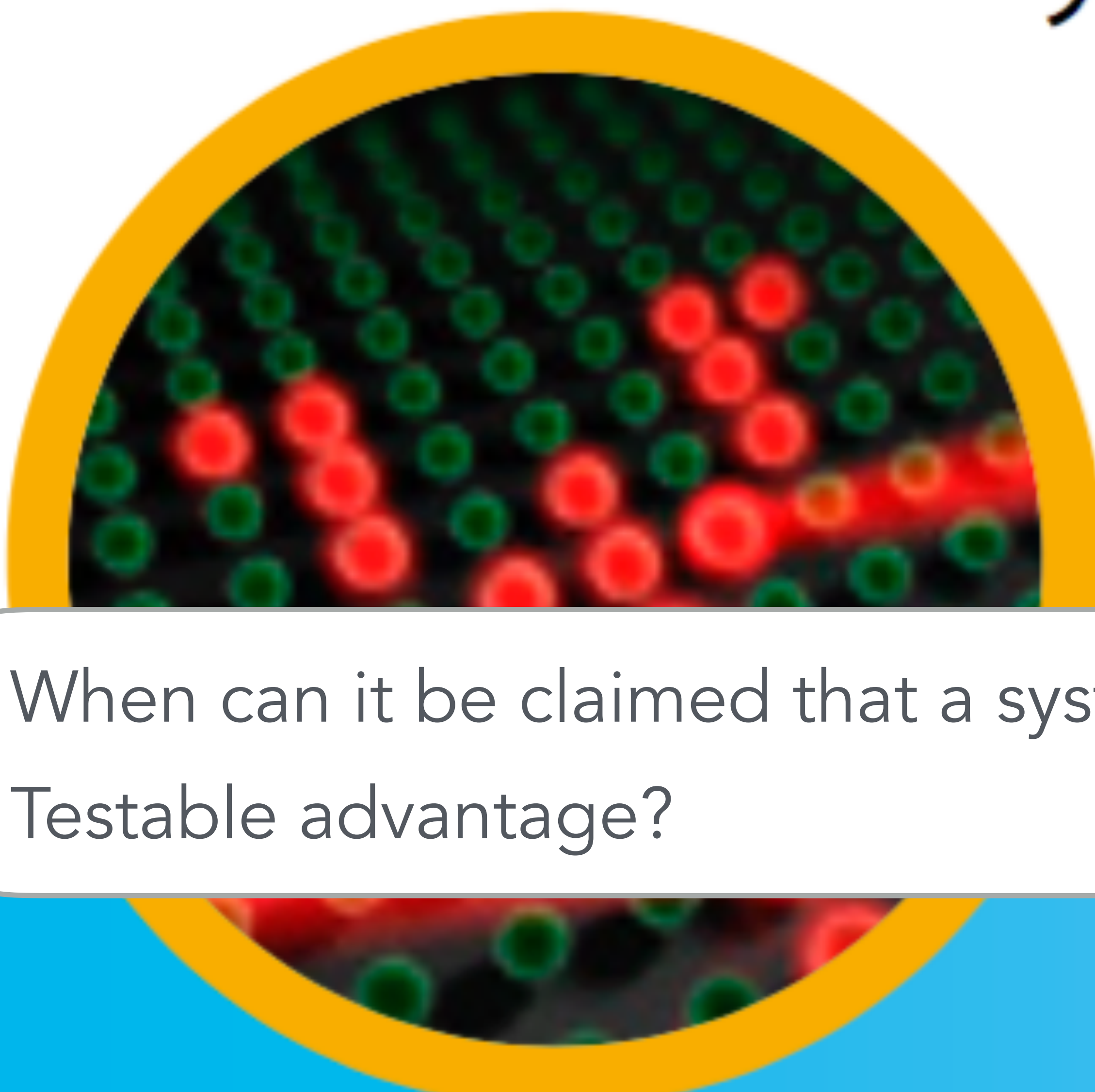
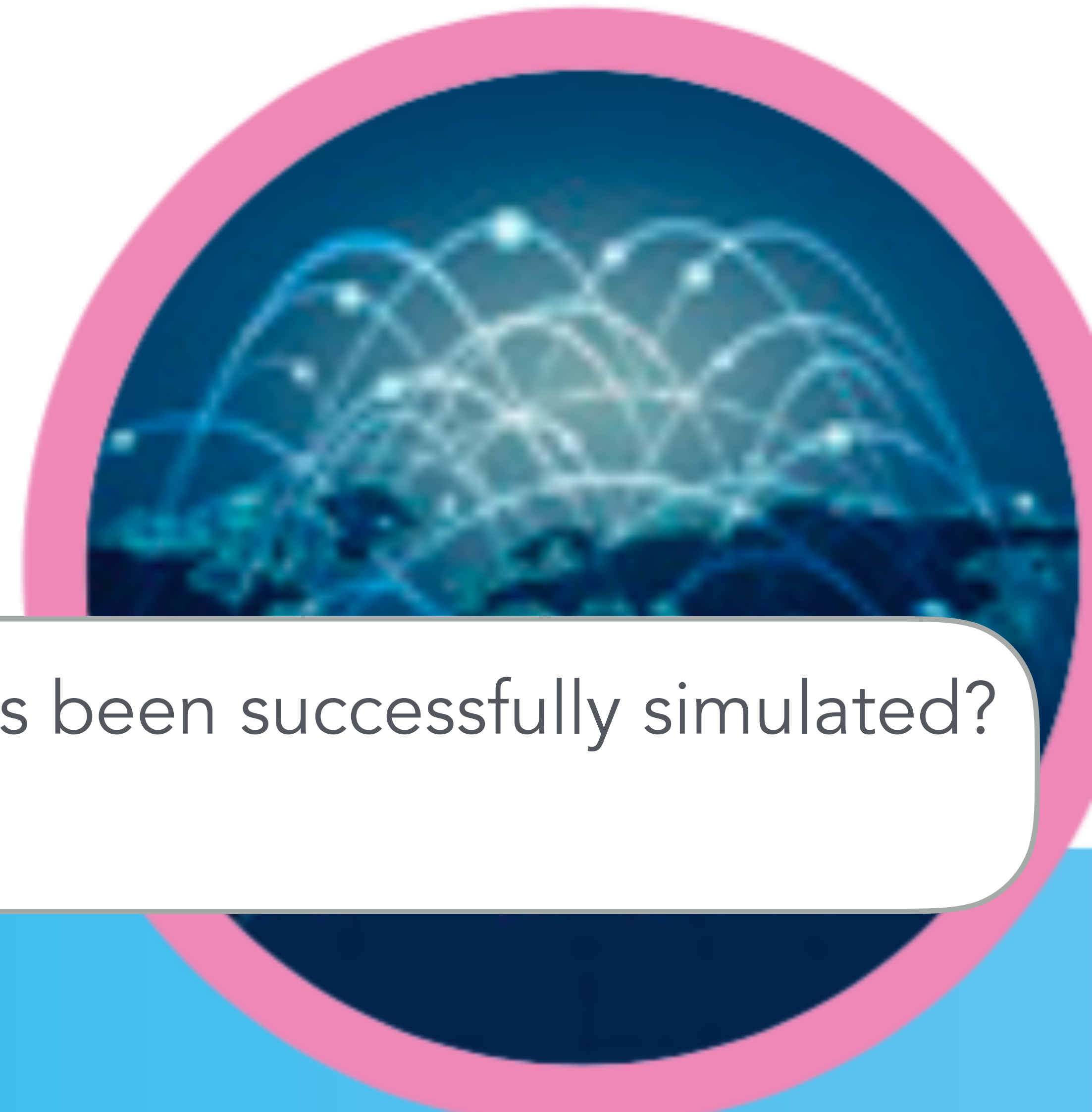
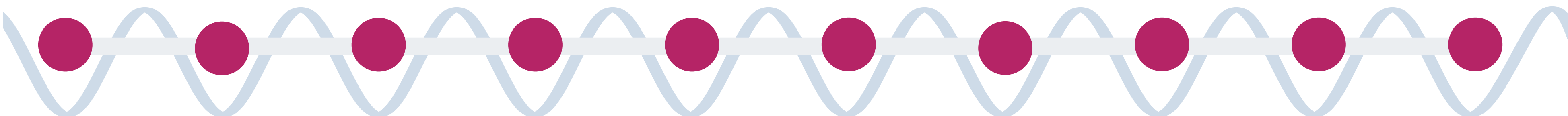




- When can it be claimed that a system has been successfully simulated?
- Testable advantage?

Analog quantum simulators

Analog quantum simulators

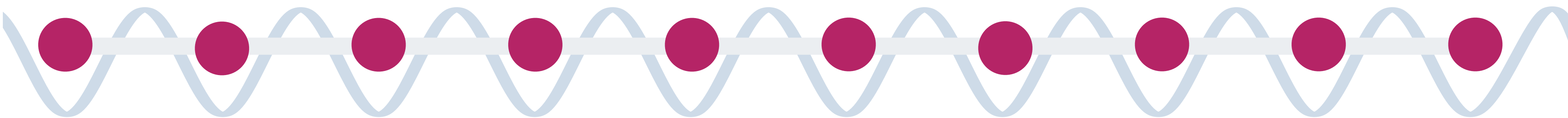


- "Analog", rather than discrete
- Probing questions in physics (not so much quantum chemistry)

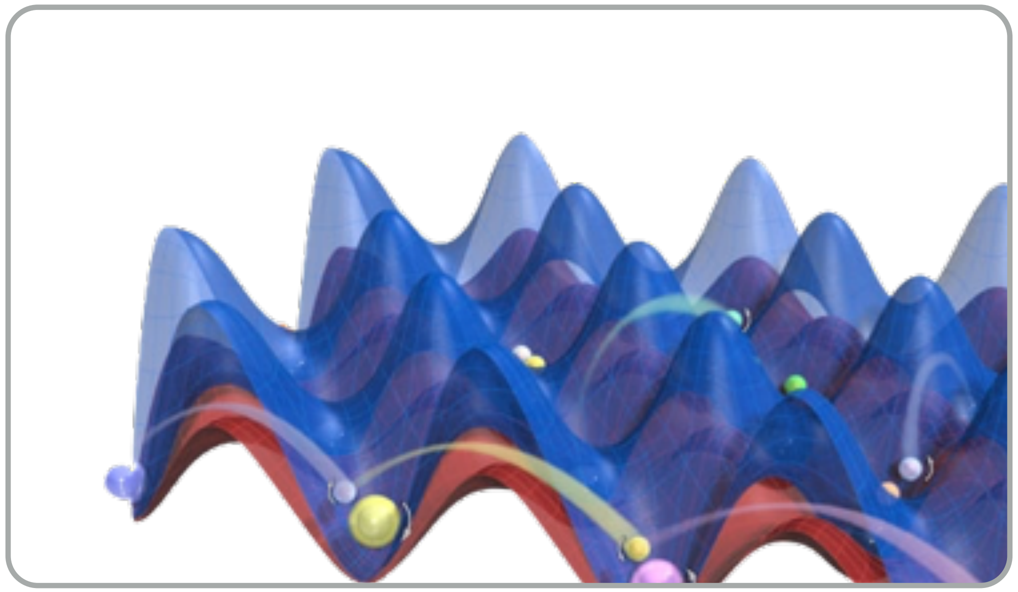
- **System size** n
- Local **Hamiltonians** with some levels of control
- **Noise** levels
- Classes of **preparations** and **measurements**

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

Analog quantum simulators



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

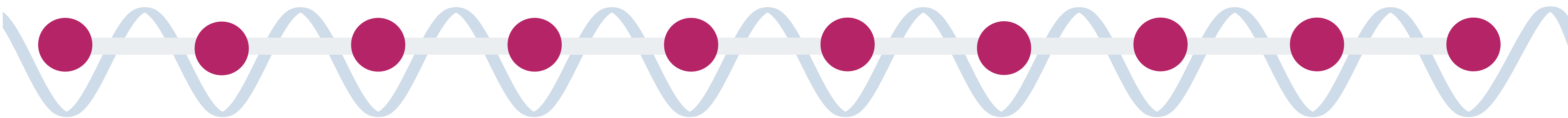


- Global control over $n \sim 10^5$ sites (1D-3D)
- Bosons and fermions
- Some tuneability
- Time-of-flight and in-situ measurements

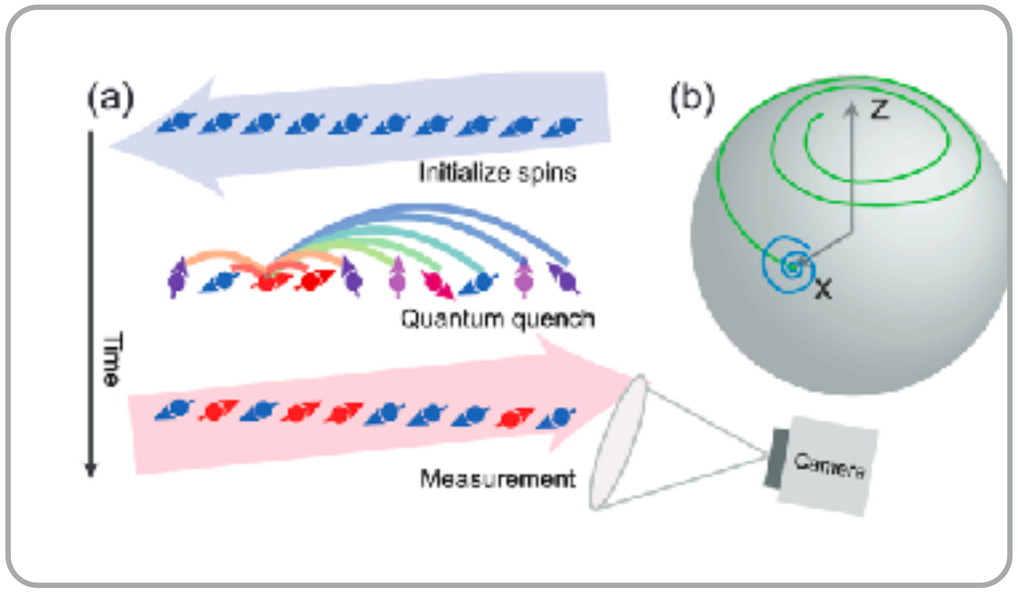
Bloch, Dalibard, Nascimbene, Nature Physics 8, 267 (2012)
Parsons, Mazurenko, Chiu, Ji, Greif, Greiner, Science, 353, 1253 (2016)

- Towards programmable potentials

Analog quantum simulators



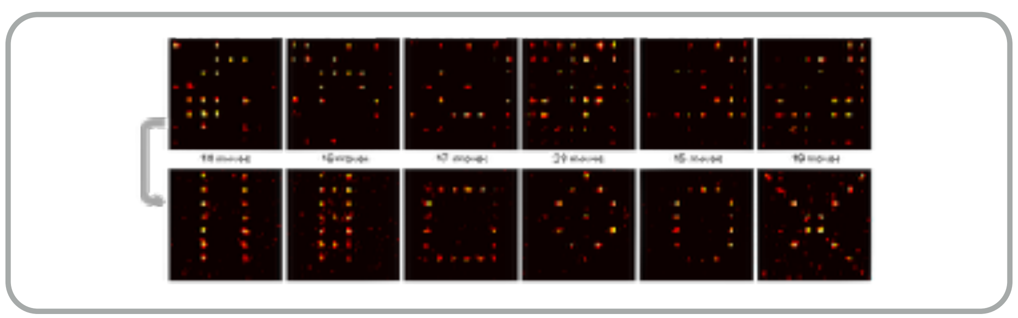
- Trapped ions



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

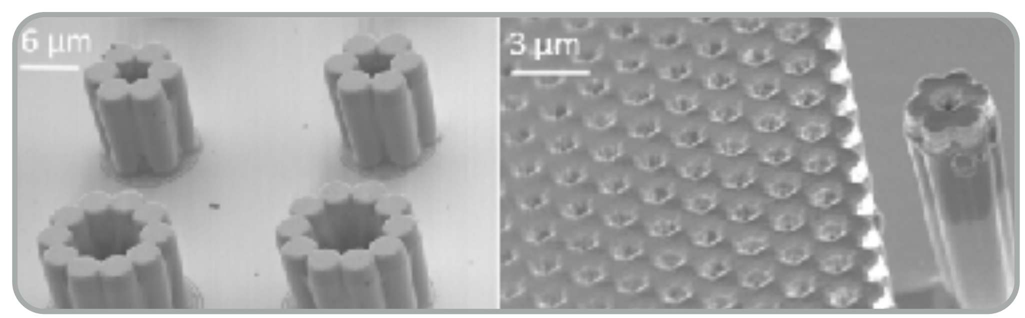
- Optical microtraps



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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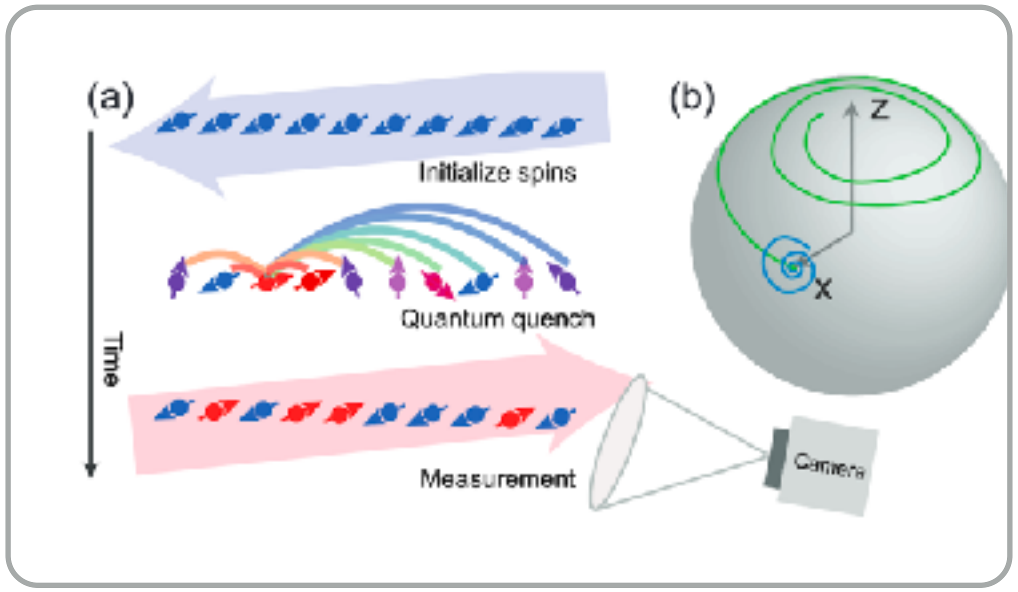

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Gorshkov, Gong, Monroe 551, 601 (2017)
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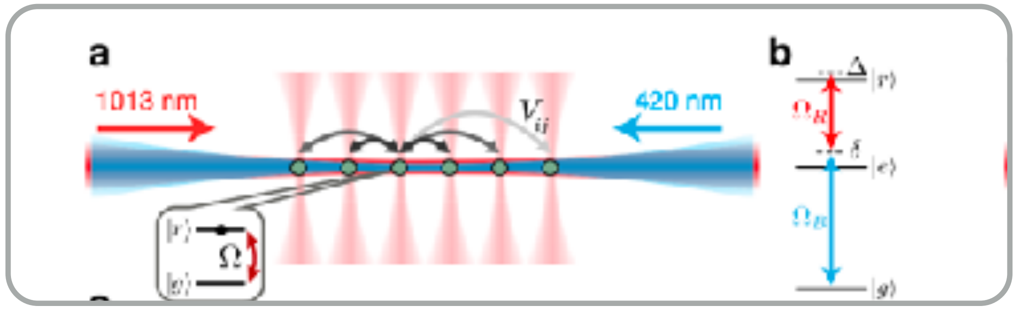
- $n \leq 53$
- Universal control
- Some global gates easier than others
- Tomographically complete measurements

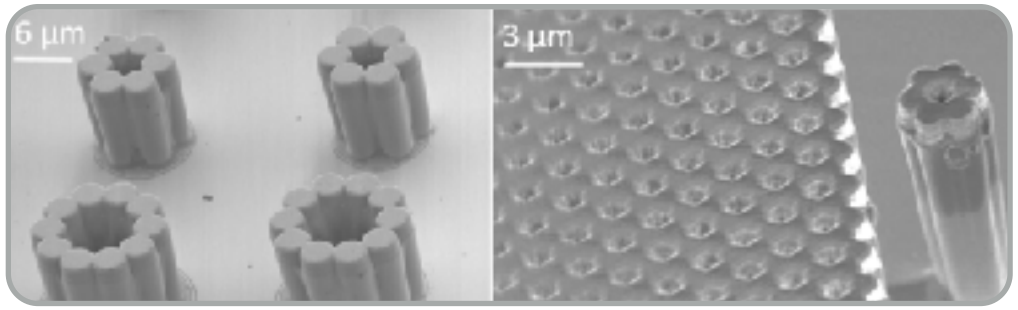
- Cold atoms in Rydberg states



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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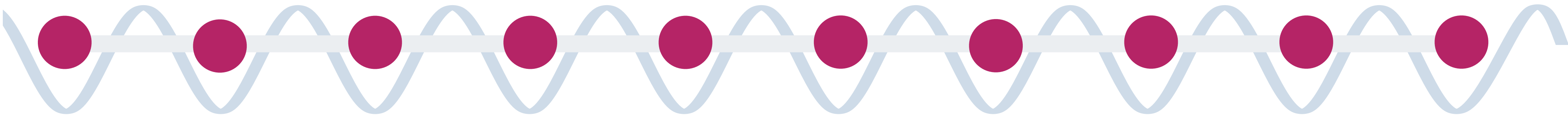

- **Time-dependent** problems ("quenches")

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

- 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)

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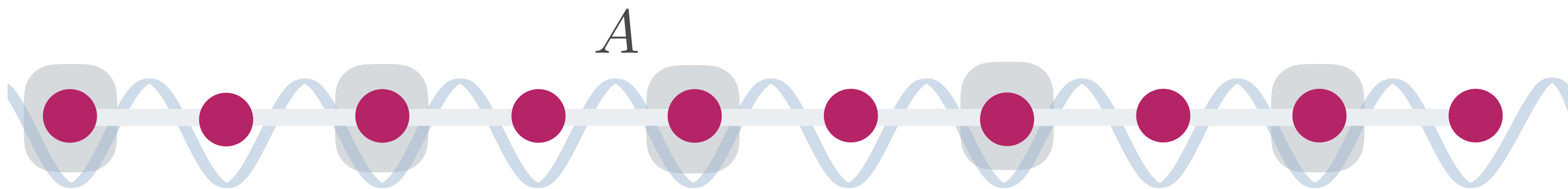
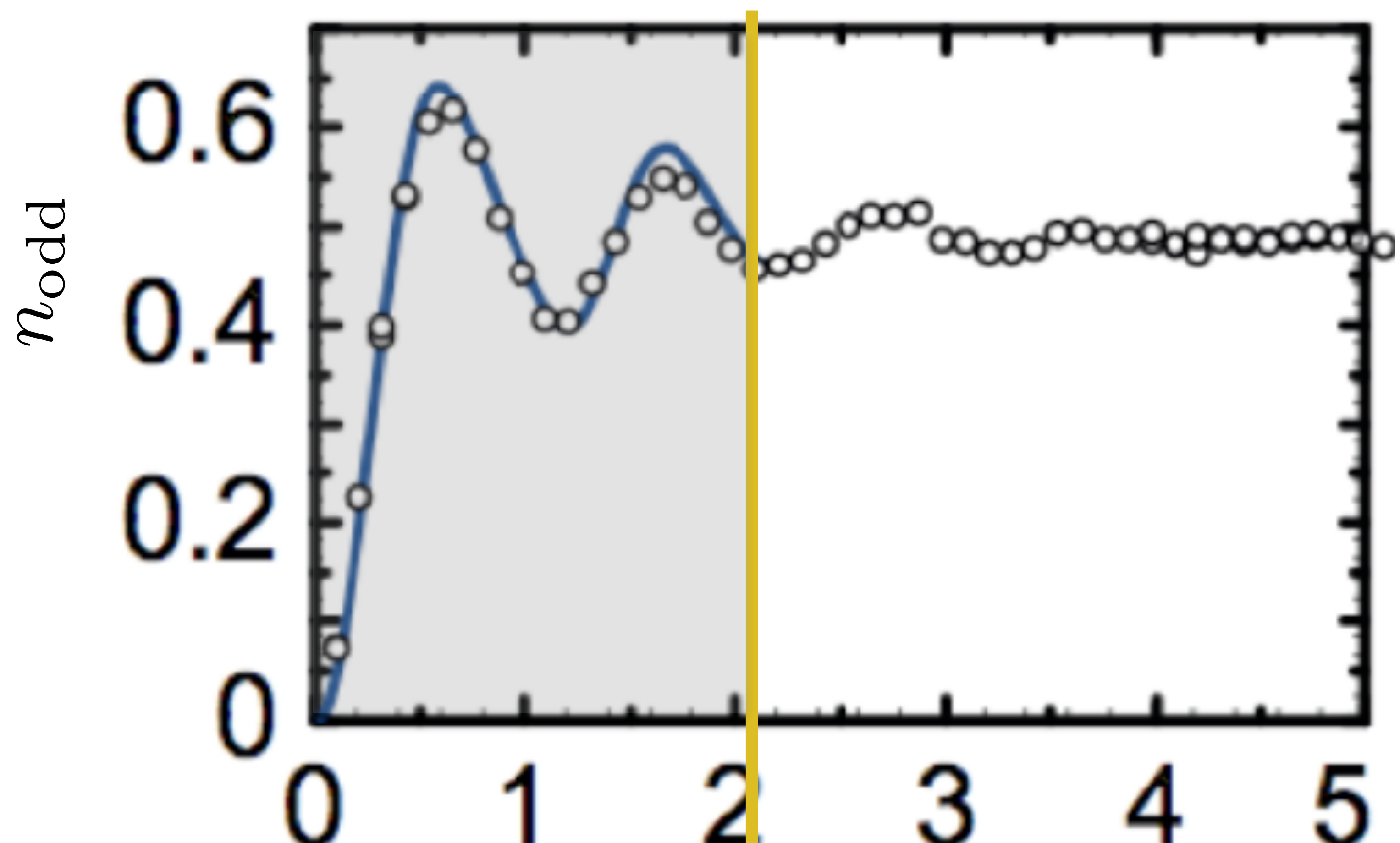


- **Time-dependent** problems (“quenches”)
  - Imbalance as function of time for $|\psi(0)\rangle = |0, 1, \ldots, 0, 1\rangle$ under Bose-Hubbard Hamiltonian (MPQ)

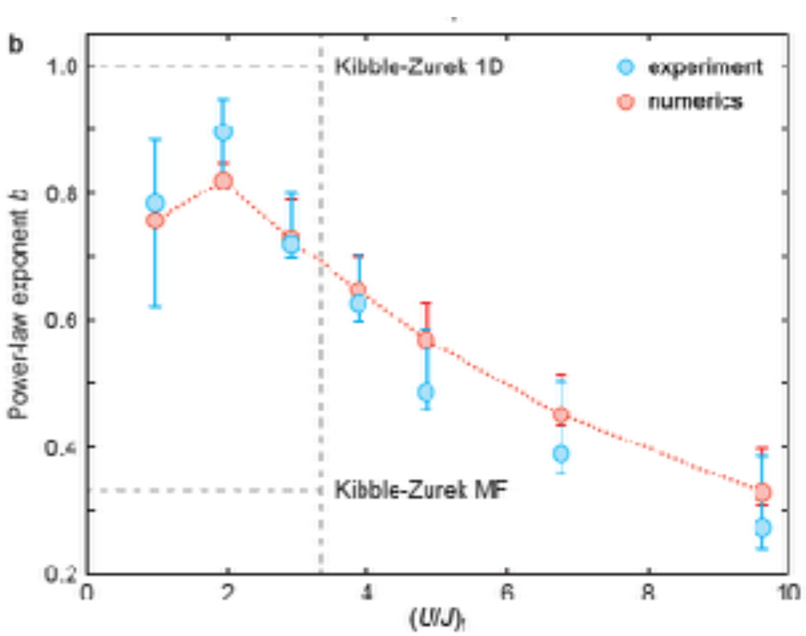


Best available classical tensor network simulation, bond dimension 5000

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

What can they probe?

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

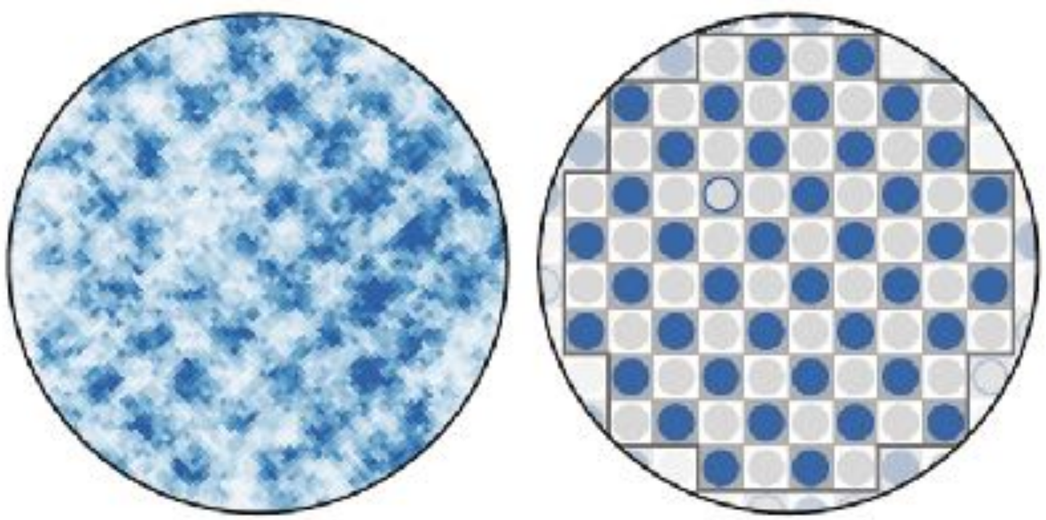


  - Probing scaling laws of correlations

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

What can they probe?

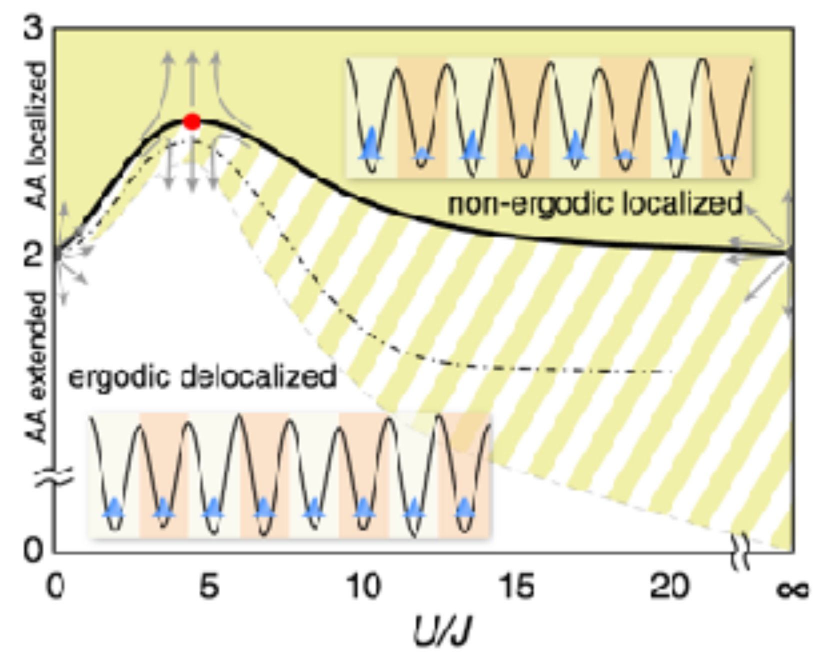
- **Ground state** problems
  - Hubbard model, probing high-Tc superconductivity



  - 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

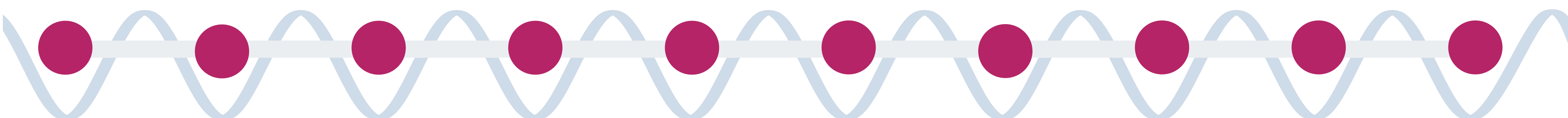
  - Many-body localization (1D-2D)



  - Debated in 2D

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

What can they probe?



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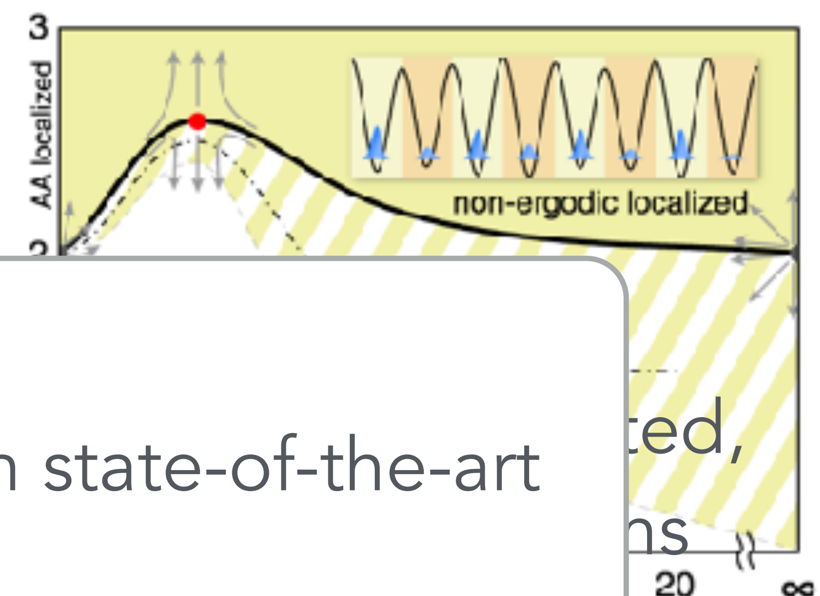

- **Quantum simulators**

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

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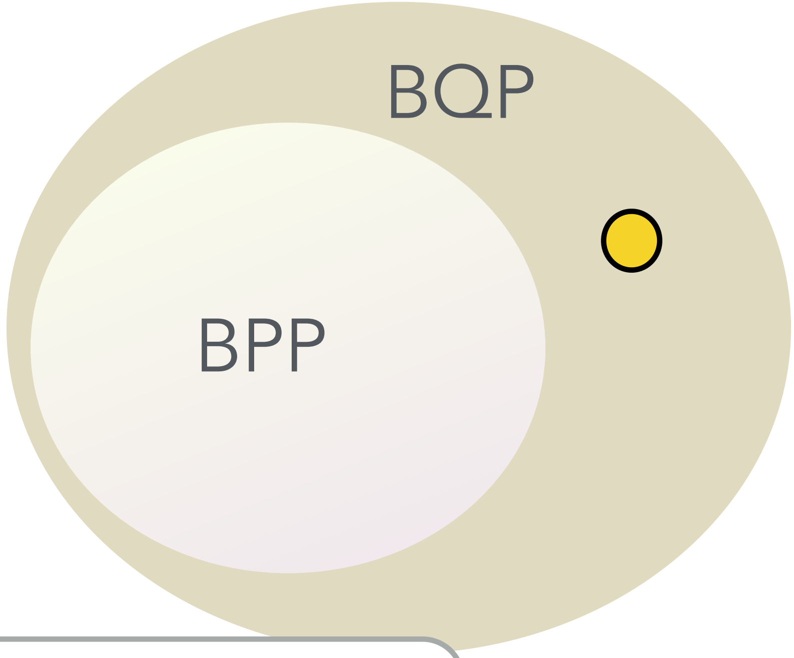
- Debated in 2D

- Cleverer simulation method?



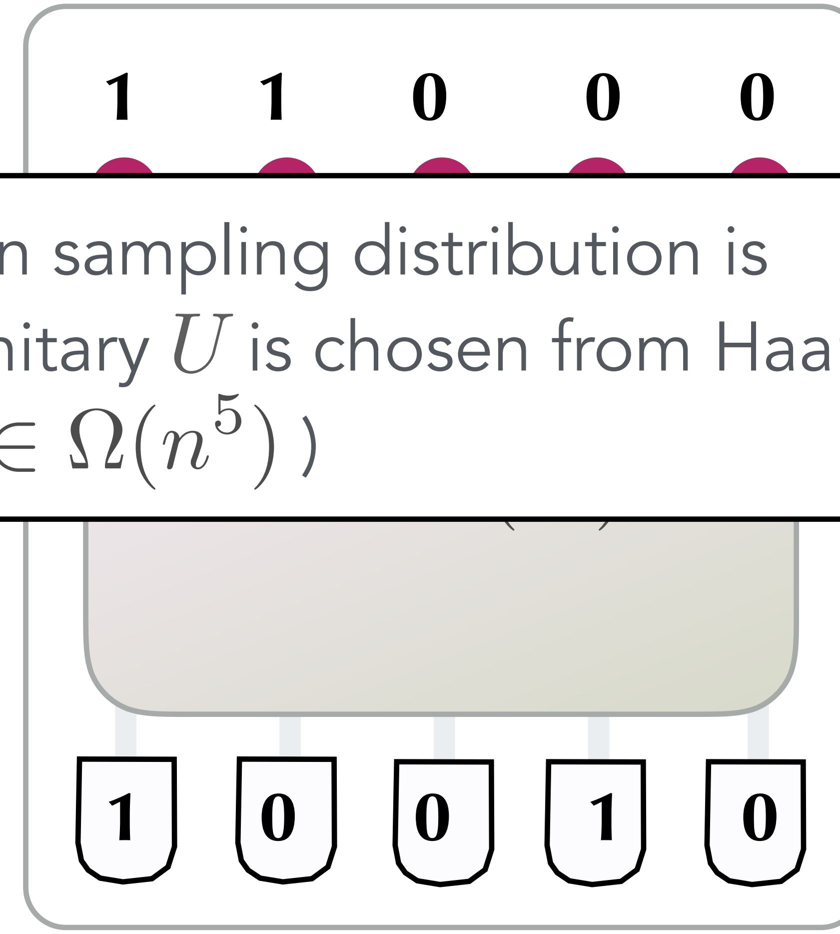
- **Intermediate problems**

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)



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 ($m \in \Omega(n^5)$)

- IQP and random universal circuits
  Bremner, Montanaro, Shepherd: Phys Rev Lett 117, 080501 (2016)
  Bremner, Jozsa, Shepherd, arXiv:1005.1407
  Boixo, Isakov, Smelzanski, Babbush, Ding, Jiang, Bremner, Martinis, Neven, Nature Physics 14, 595-600 (2018)
- Ising-type interactions (but, period 56 of unit cell)
  Gao, Wang, Duan, Phys Rev Lett, 118, 040502 (2017)

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

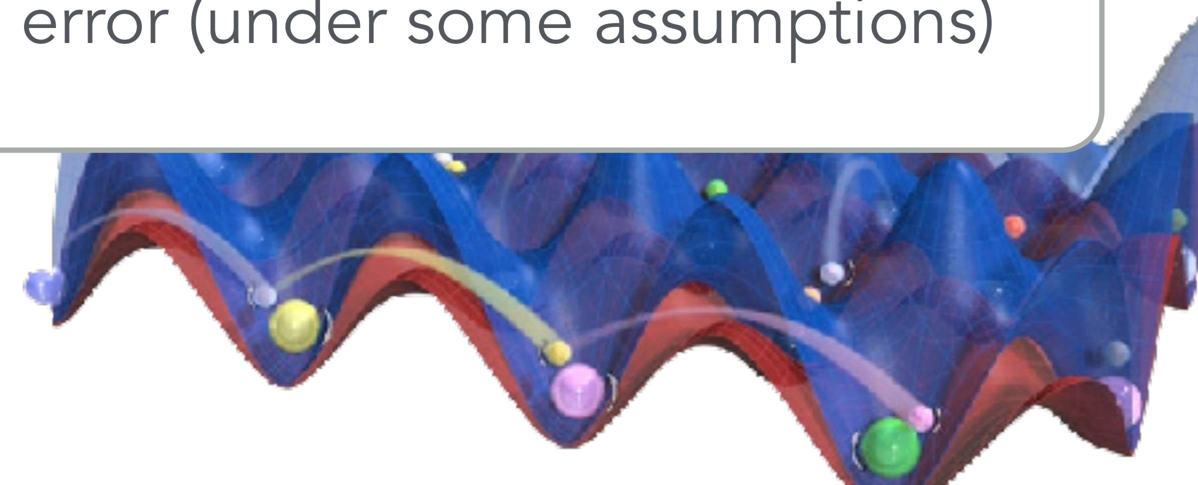
- **Challenging prescription**: It this possible to scale it up to provably hard regimes, in an architecture close to a quantum simulation?

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 [illegible], 021010 (2018)
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)

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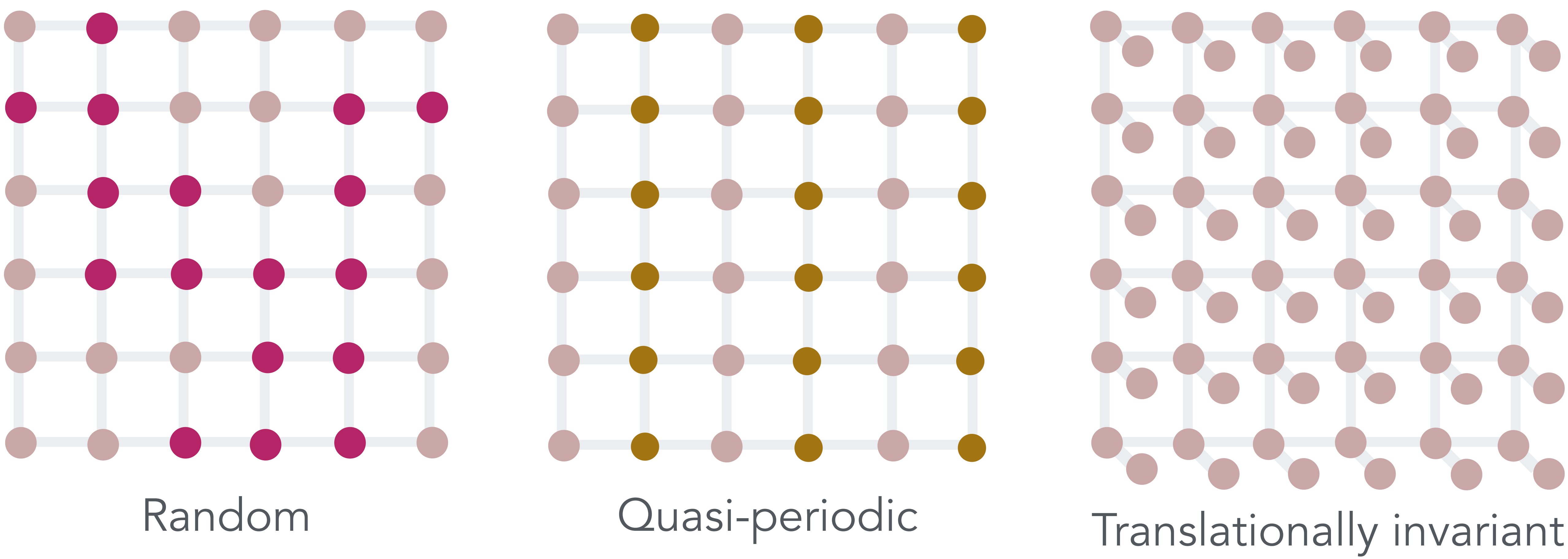

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Simple Ising models

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

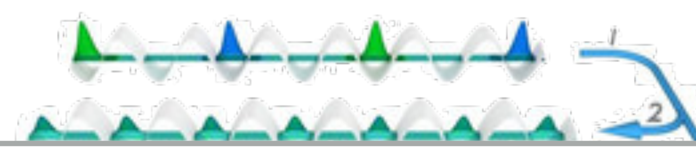
$$|\psi_\beta\rangle = \otimes_{i,j=1}^{n,m}(|0\rangle + e^{i\beta_{i,j}}|1\rangle)$$

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

- Quench to $H = \sum_{(i,j}$

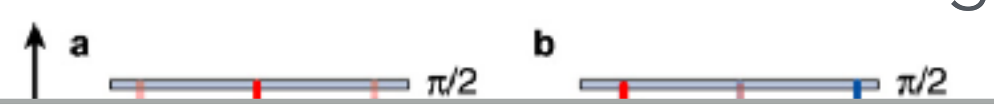
- Measure all qubits i

- Reminscient of disordered optical lattices

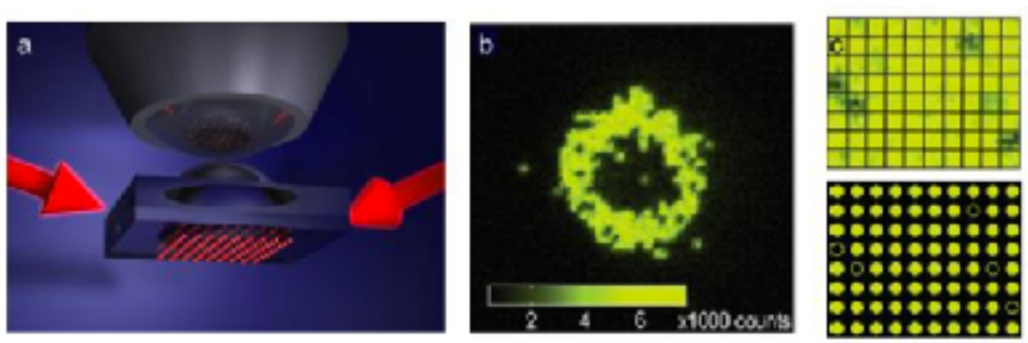


42 (2015)

- Controlled coherent collisions long realized



- 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)

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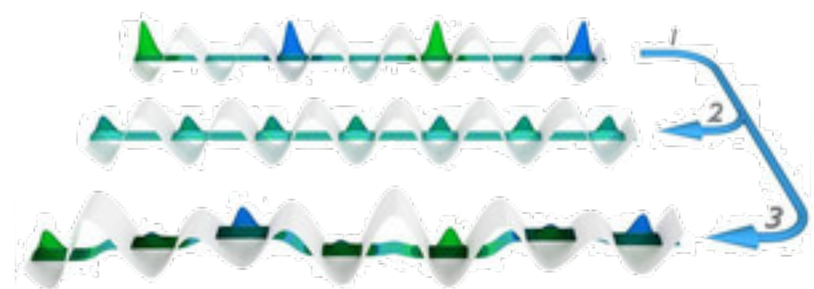

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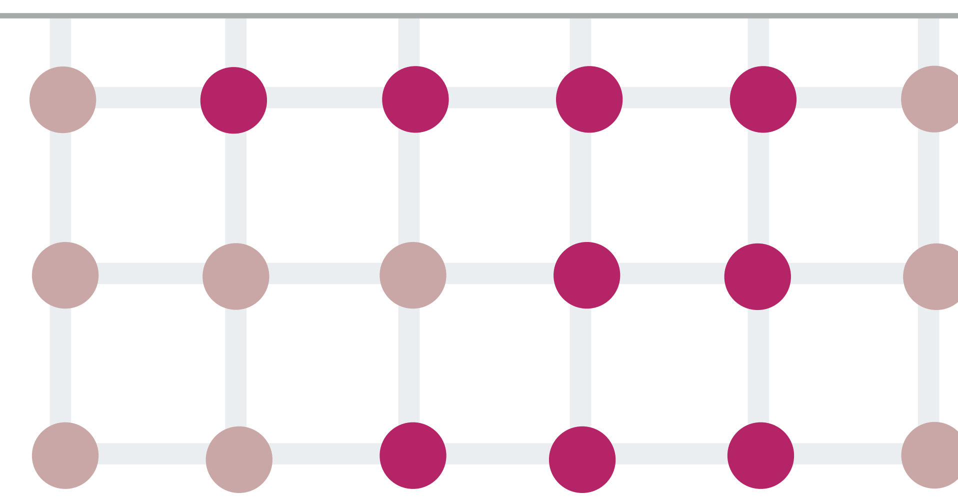

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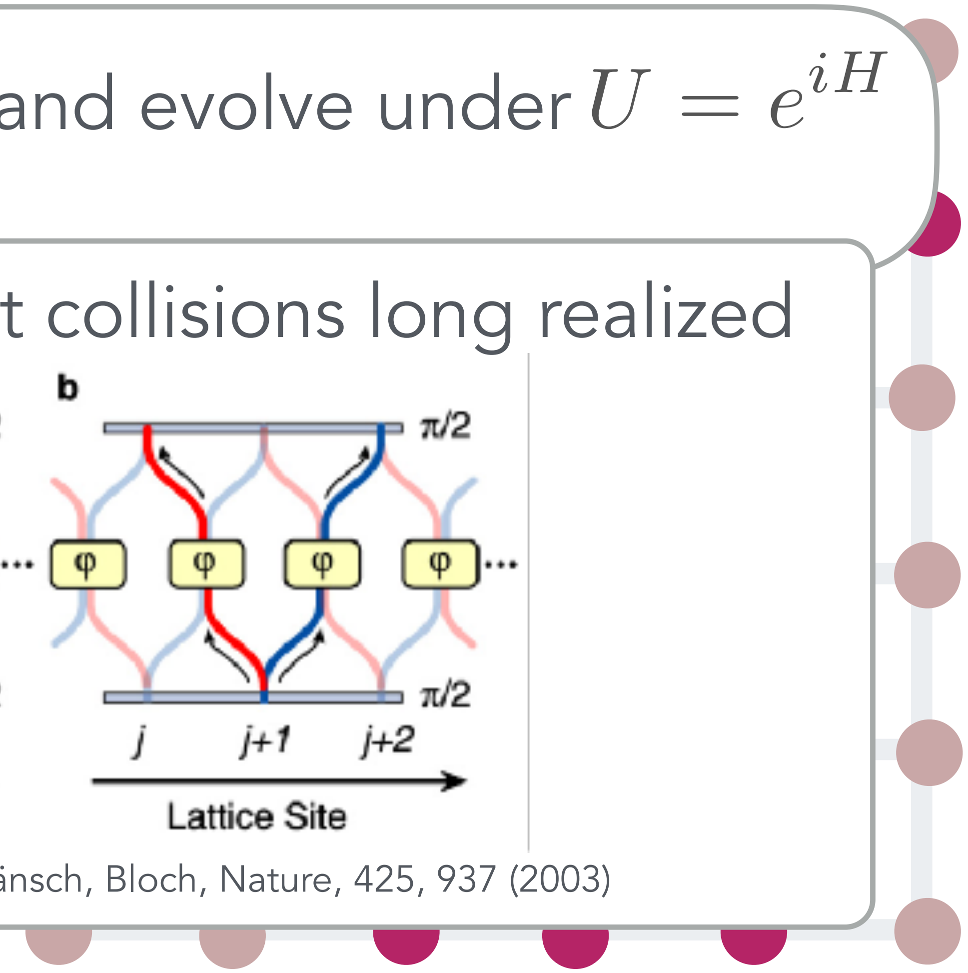

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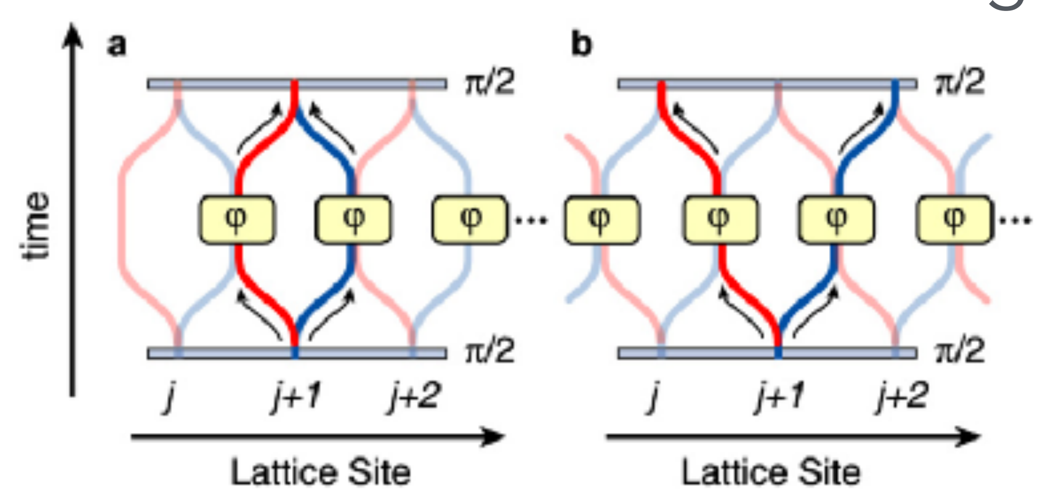

Mandel, Greiner, Widera, Rom, Hänsch, Bloch, Nature, 425, 937 (2003)

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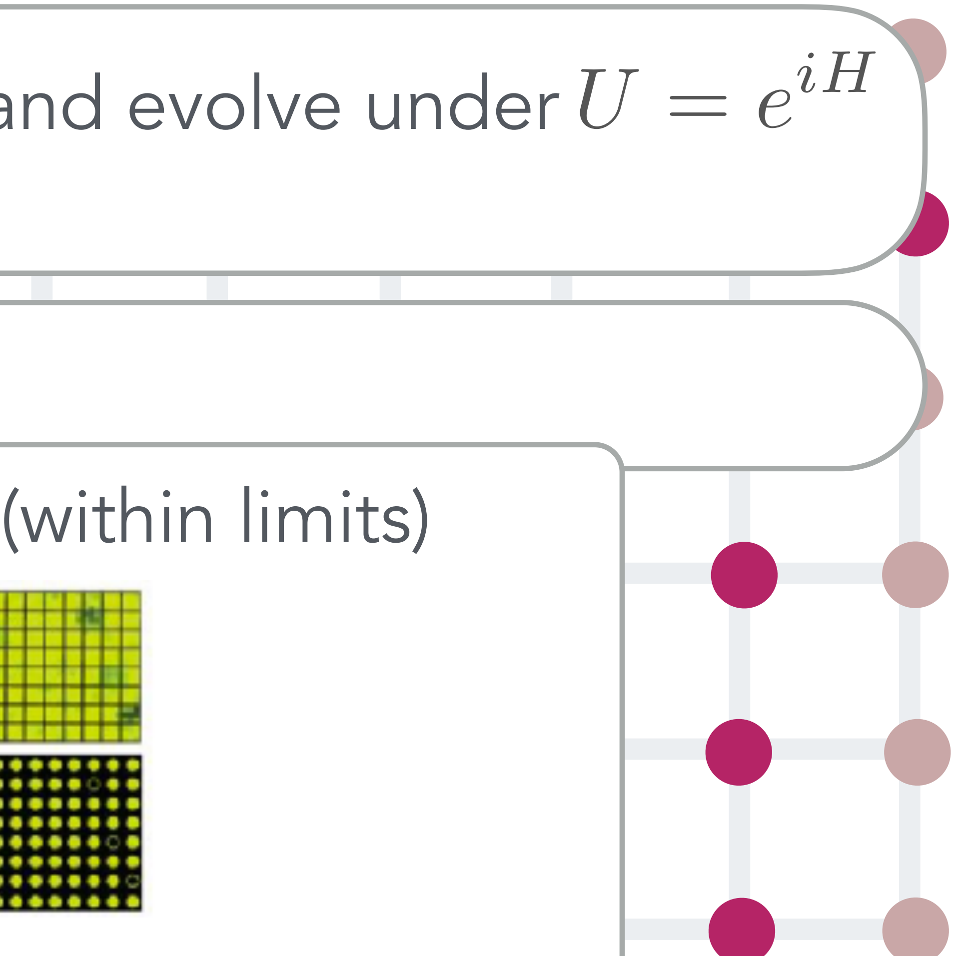
- Measure all qubits in X-basis



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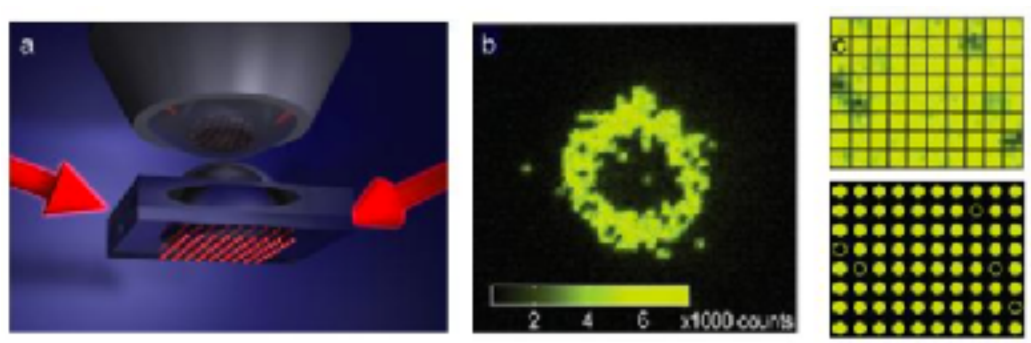

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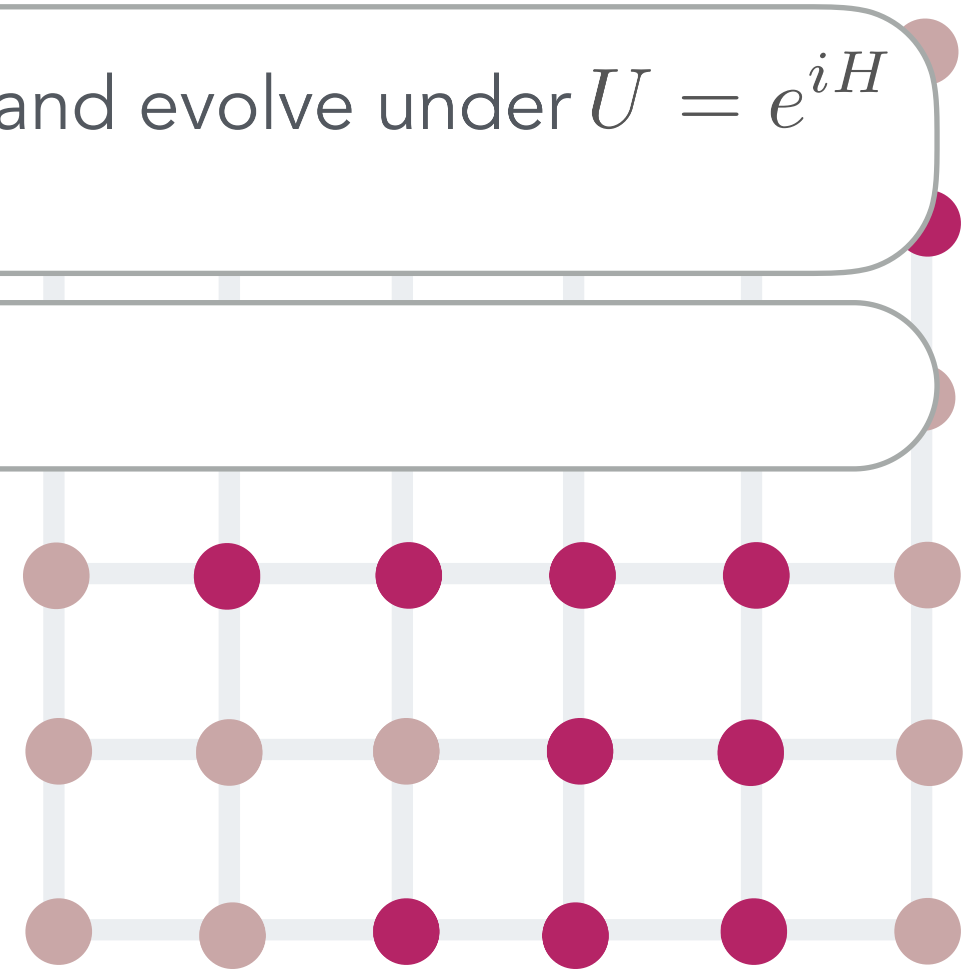

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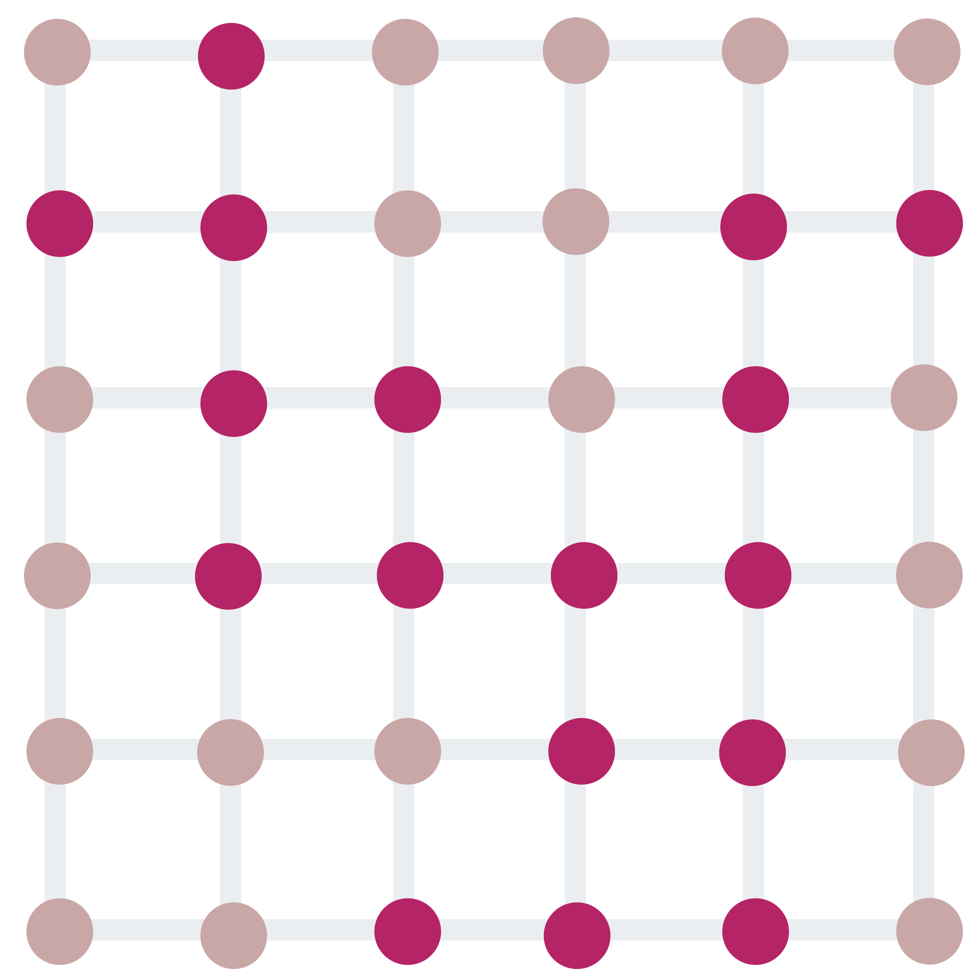
- **Theorem** (Hardness of classical sampling):

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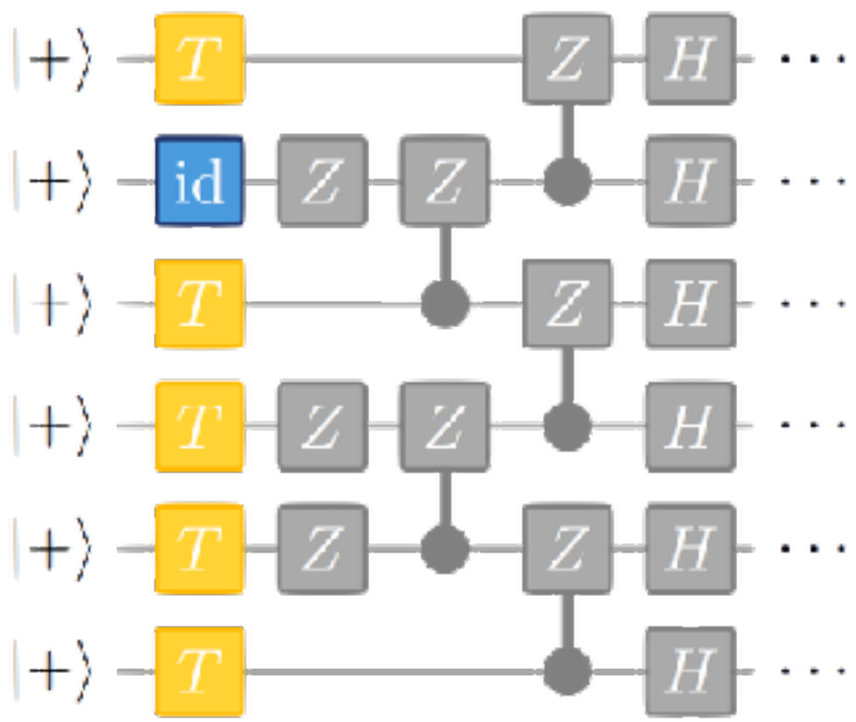
- Relate quench architecture to post-selected measurement-based quantum computing

- Universal quantum circuit for postBQP



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

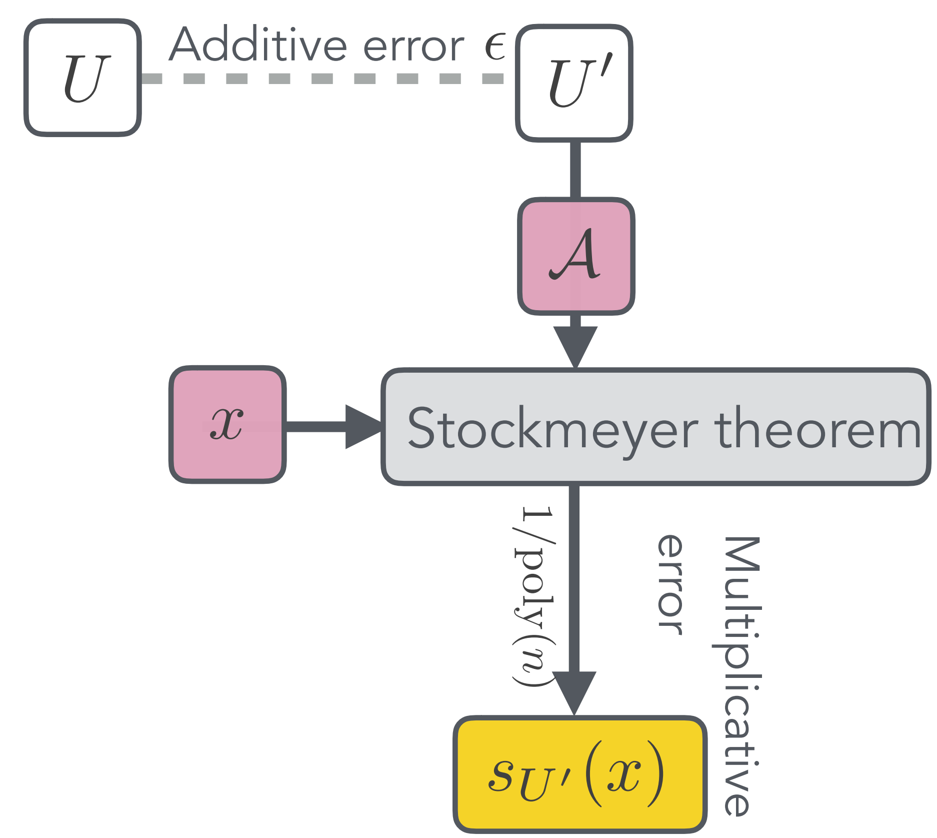
- Polynomial hierarchy (similar P≠NP)
- Average-case complexity

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

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

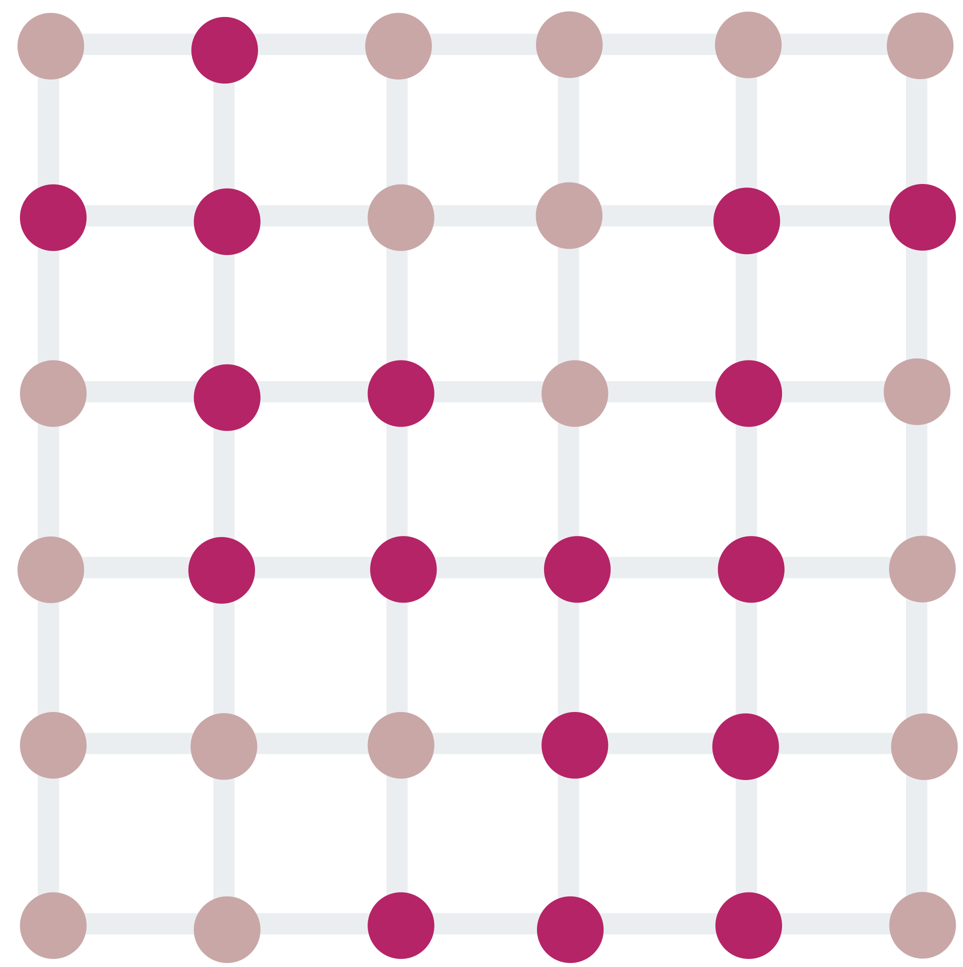
  Mann, Bremner, arXiv:1711.00686

- 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)
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)
Hangleiter, Kliesch, Schwarz, Eisert, Quantum Sci Technol 2, 015004 (2017)
Cramer et al, Nature Comm 1, 149 (2010)

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

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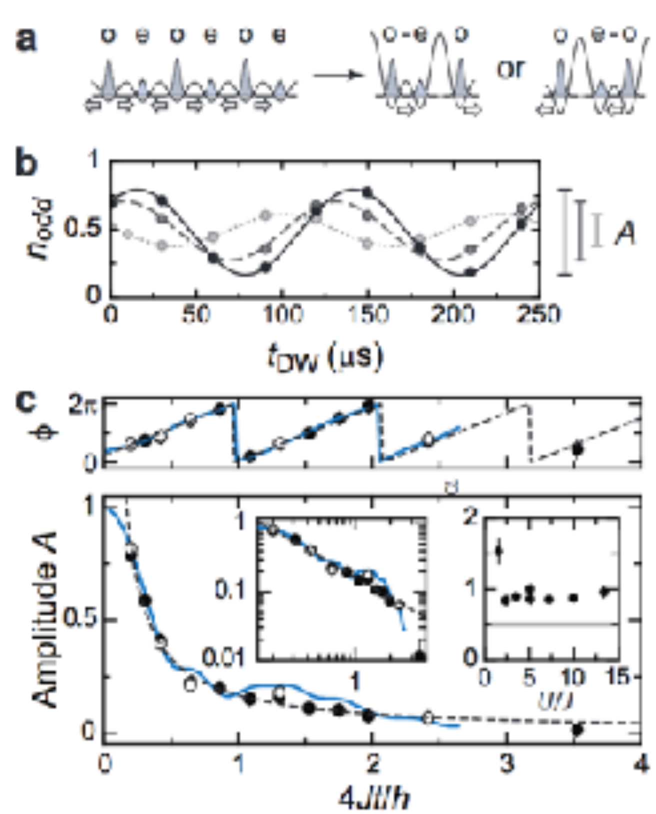

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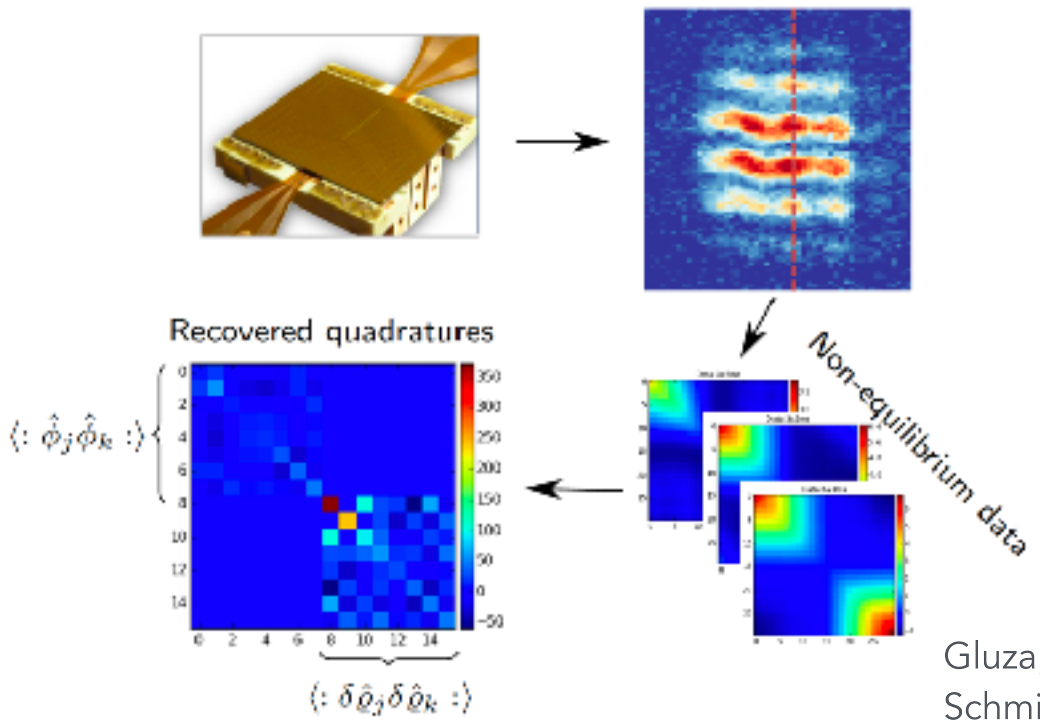

Gluza, Schweigler, Krumnow, Rauer, Schmiedmayer, Eisert, in preparation

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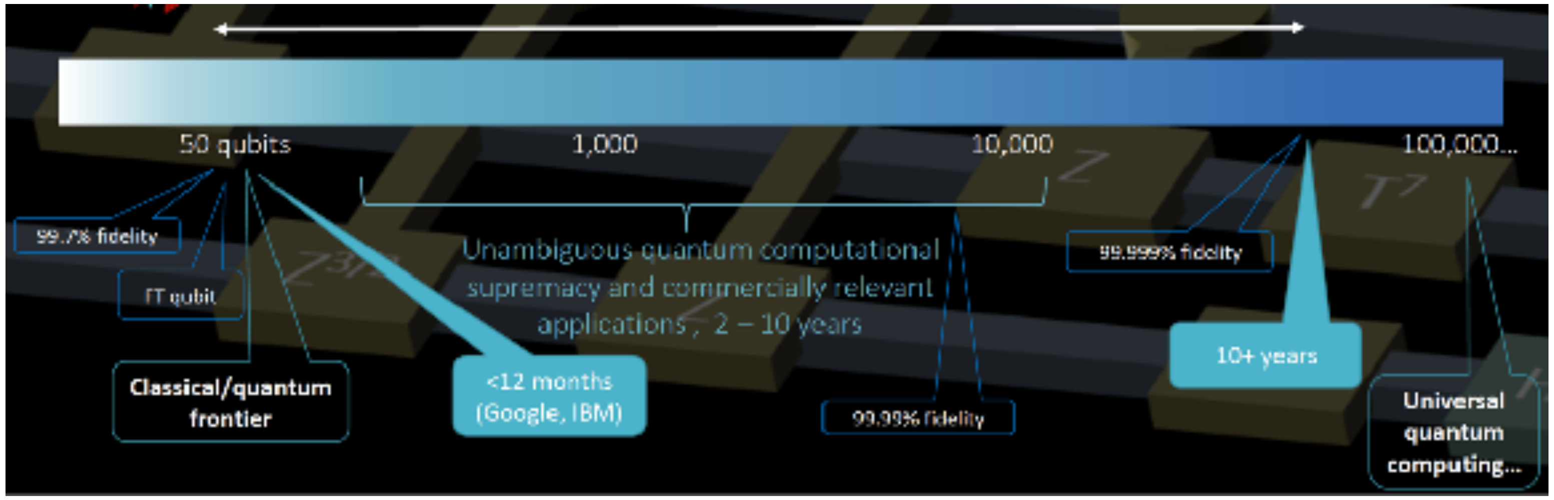

(Mick Bremner)

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Thanks for your attention!

http://www.physik.**fu-berlin**.de/en/einrichtungen/ag/ag-eisert