Title: Reliable quantum computational advantages from quantum simulation

Speakers: Juani Bermejo Vega

Collection: Foundations of Quantum Computational Advantage

Date: April 30, 2024 - 10:00 AM

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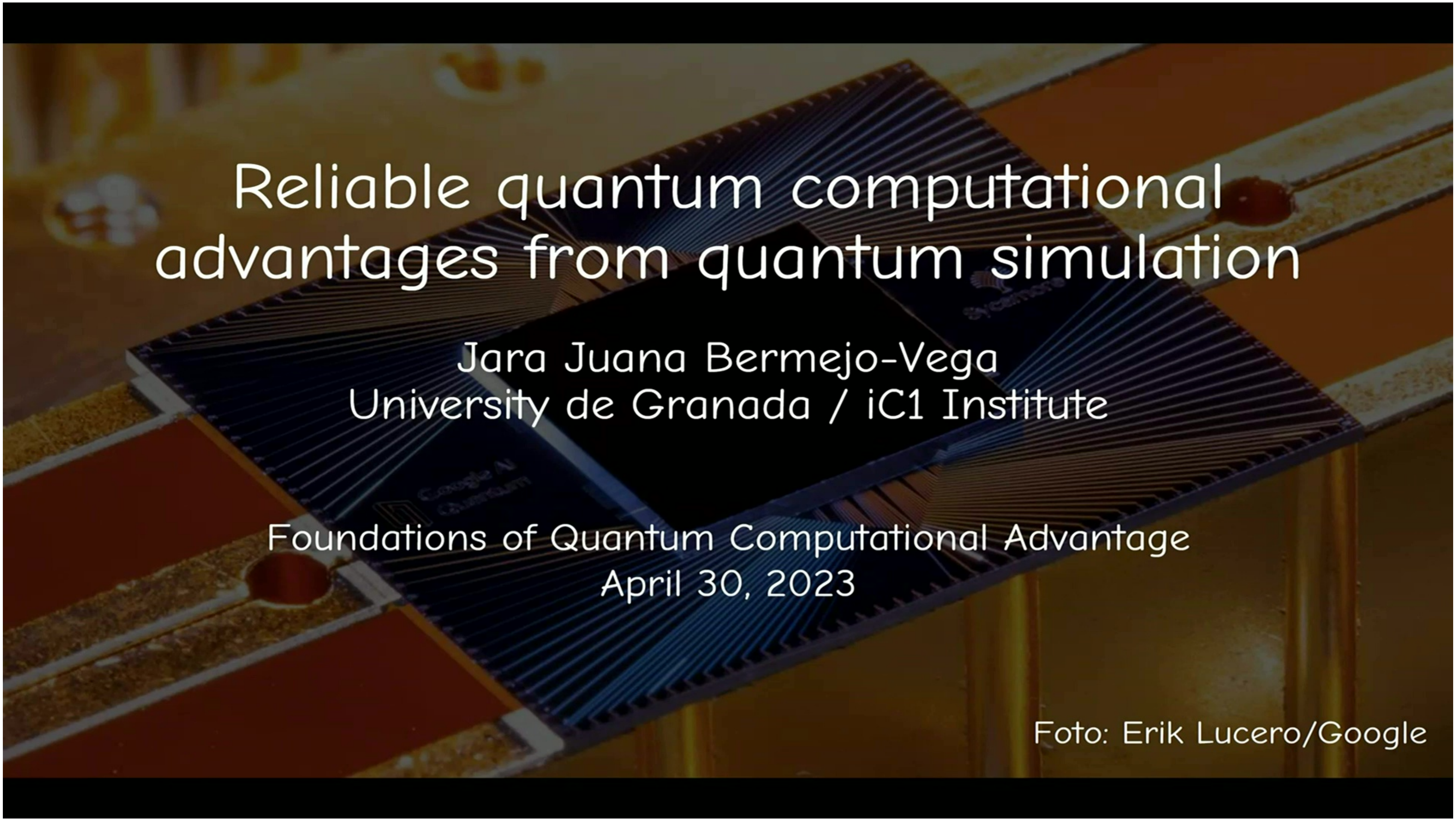
Abstract: Demonstrating quantum advantages in near term quantum devices is a notoriously difficult task. Ongoing efforts try to overcome different limitations of quantum devices without fault-tolerance, such as their limited system size or obstacles towards verification of the outcome of the computation. Proposals that exhibit more reliable quantum advantages for classically hard-to-simulate verifiable problems lack, at the same time, practical applicability. In this talk we will review different approaches to demonstrate quantum advantages inspired from many-body quantum physics. The first of them use entangled quantum resources such as cluster states, which are useful to demonstrate verifiable quantum advantages based on sampling problems (Theory proposal Phys. Rev. X 8, 021010, 2018 and recent experimental demonstration arXiv preprint arXiv:2307.14424). The second probe measurement of many-body quantities such as dynamical structure factors in quantum simulation setups (Proceedings of the National Academy of Sciences 117 (42), 26123-26134).


Reliable quantum computational
advantages from quantum simulation
Jara Juana Bermejo-Vega
University de Granada / iC1 Institute
Foundations of Quantum Computational Advantage
April 30, 2023
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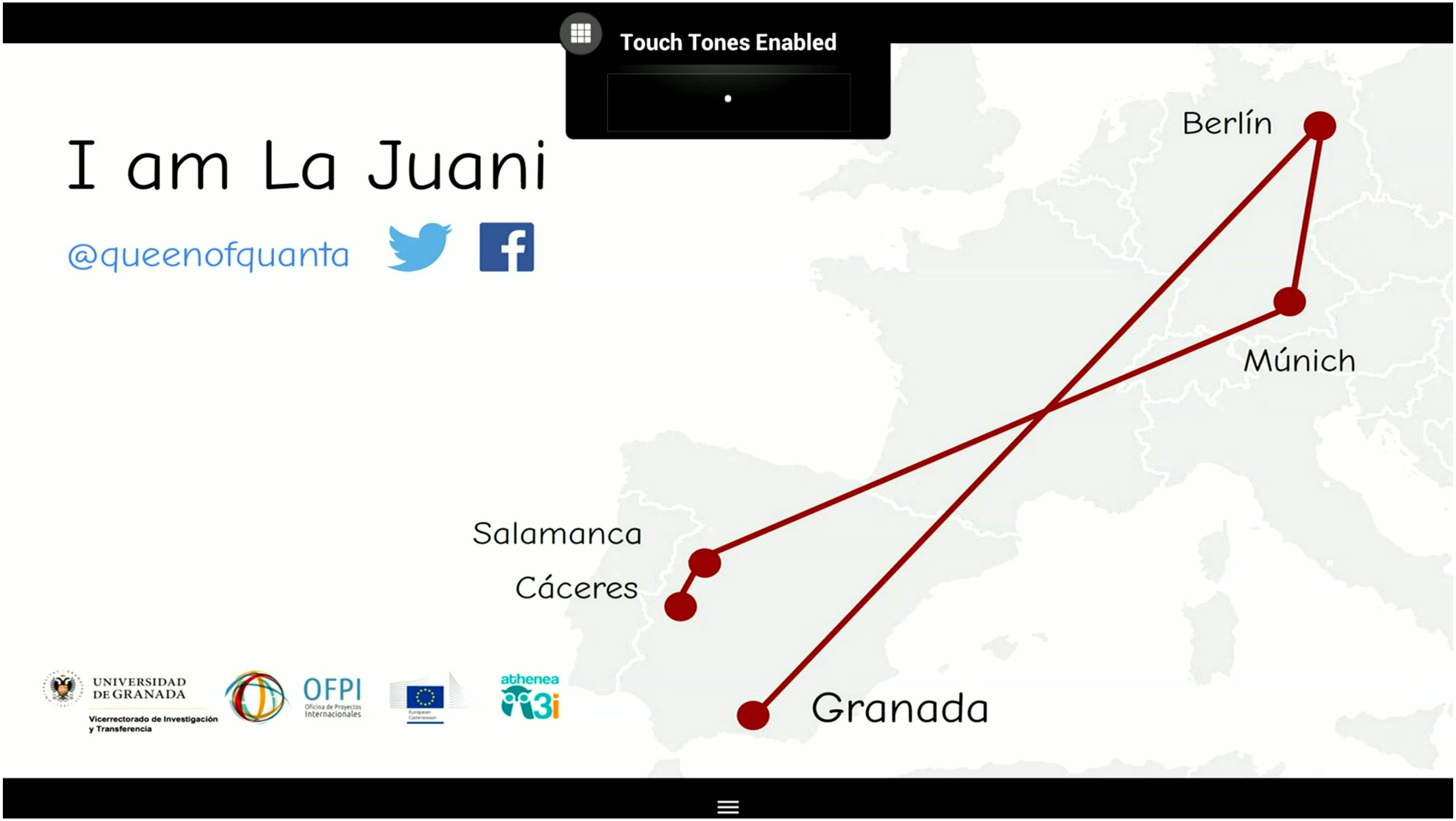
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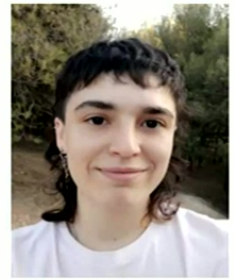
Quantum Computing, Information & Thermodynamics


Jara Juana Bermejo Vega


Daniel Manzano


Rhea Alexander


Álvaro Tejero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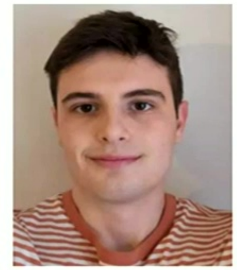
Antonio Jesús Rivera Pérez

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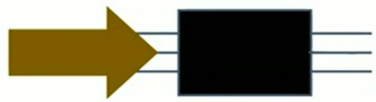
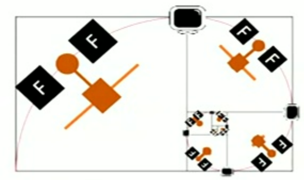
Quantum and Classical Computing in Granada

Quantum foundations



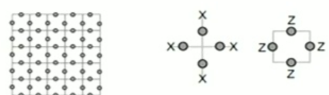
JBV, Delfosse, Browne, Okay, Raussendorf, *PRL* 119 (2017)
Raussendorf, Browne, Delfosse, Okay, **JBV** , *PRA* 95 (2017)
Delfosse, Okay, **JBV**, Browne, Raussendorf, *NJP* 19 (2017)

Quantum algorithms



JBV, Zatloukal, arXiv:1509.05806 .
JBV, Lin, Van den Nest, arXiv:1409.4800 .

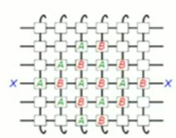
Classical simulation



JBV, Van den Nest, QIC 14, No 3&4 (2014)
JBV, Lin, Van den Nest, QIC 5&6 (2016),

Machine learning

Many-body theory



Stephen, Nautrup, **JBV**, Eisert, Raussendorf, Quantum 3 (2019)

Near term quantum devices

FEDER
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Quantum Machine learning

Entanglement detection with classical deep neural networks

Julio Ureña, Antonio M. Sojo, Jara J. Bermejo-Vega, and Daniel Manzano

Electromagnetism and Matter Physics Department and Institute Carlos I of Theoretical and Computational Physics, University of Granada, E-18071, España.

Entanglement is one of the most important features of quantum mechanics, and its detection and classification is a hard problem. In this paper we present a novel approach to this problem by training a multi layer perceptron to detect entanglement in two and three qubits systems. Our network achieves high efficiencies around 100% in the two qubits case and above 90% for the three qubits one. We also show that is possible to train the network to classify the states between the different entanglement families with a success ratio up to 77%.

Granada Quantum Machine Learning Group

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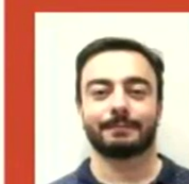
Prof. Carlos Pérez-Espigares

Dr. Jara J. Bermejo-Vega



Prof. Ricardo Gutiérrez

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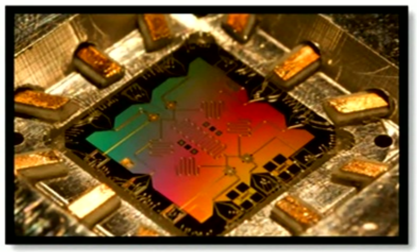
Noisy Intermediate Scale Quantum computers (NISQ)

☺️ Quantum computers offer advantages in computation

☺️ 50-1000 qubits devices are under construction

QUANTUM FLAGSHIP



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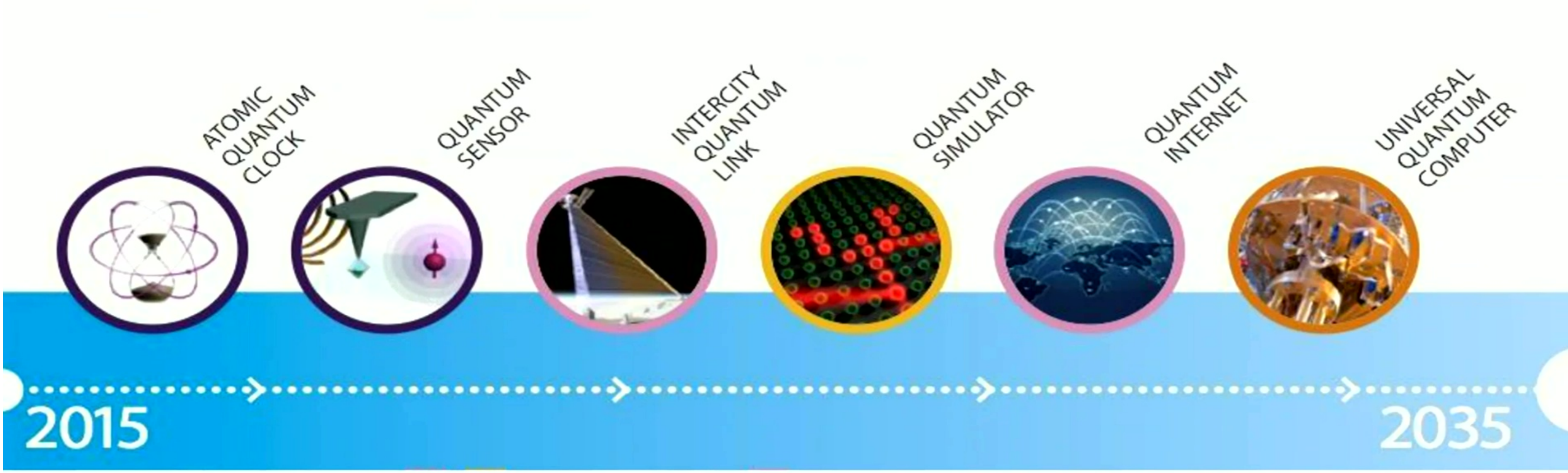
☹️ Quantum applications are hard to find and implement

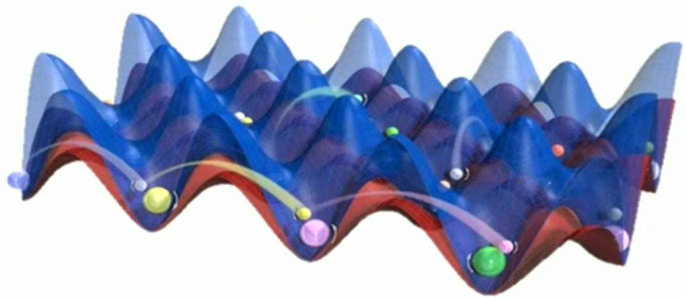
Quantum simulations can offer **practical** quantum advantages



Quantum Simulation

Dynamical quantum simulators (e.g., using 10^4-10^5 cold atoms in optical lattices) cannot be efficiently classically simulated with state-of-the-art tensor-network algorithms (a la DMRG). *But are these good enough?*

Trotzky et. al., Nature Phys. 8 (2012), Choi et al., Science 352 (2016)

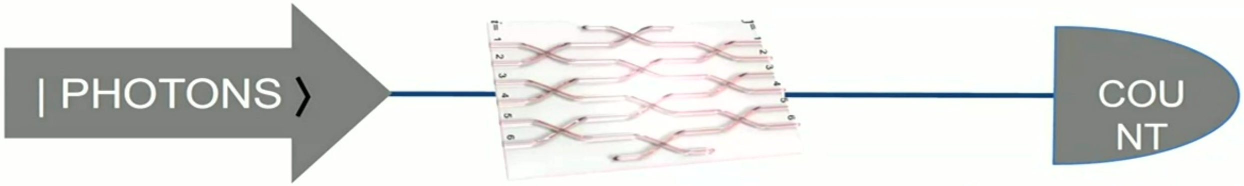


$$\hat{H} = \sum_j \left[-J \left(\hat{a}_j^\dagger \hat{a}_{j+1} + \text{h.c.} \right) + \frac{U}{2} \hat{n}_j (\hat{n}_j - 1) + \frac{K}{2} \hat{n}_j j^2 \right]$$

Quantum Sampling problems offer **complexity-theoretic** advantages

Boson sampling

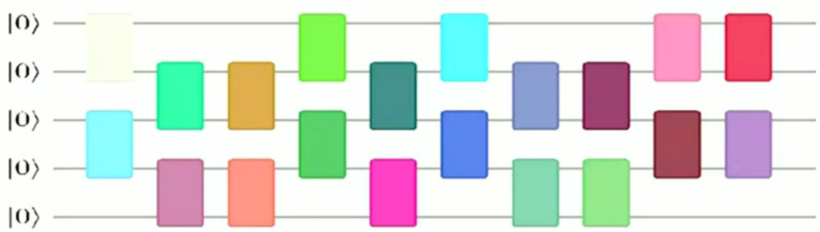
Generates random numbers using a random photonic circuit, hard to simulate based on complexity theoretic evidence.



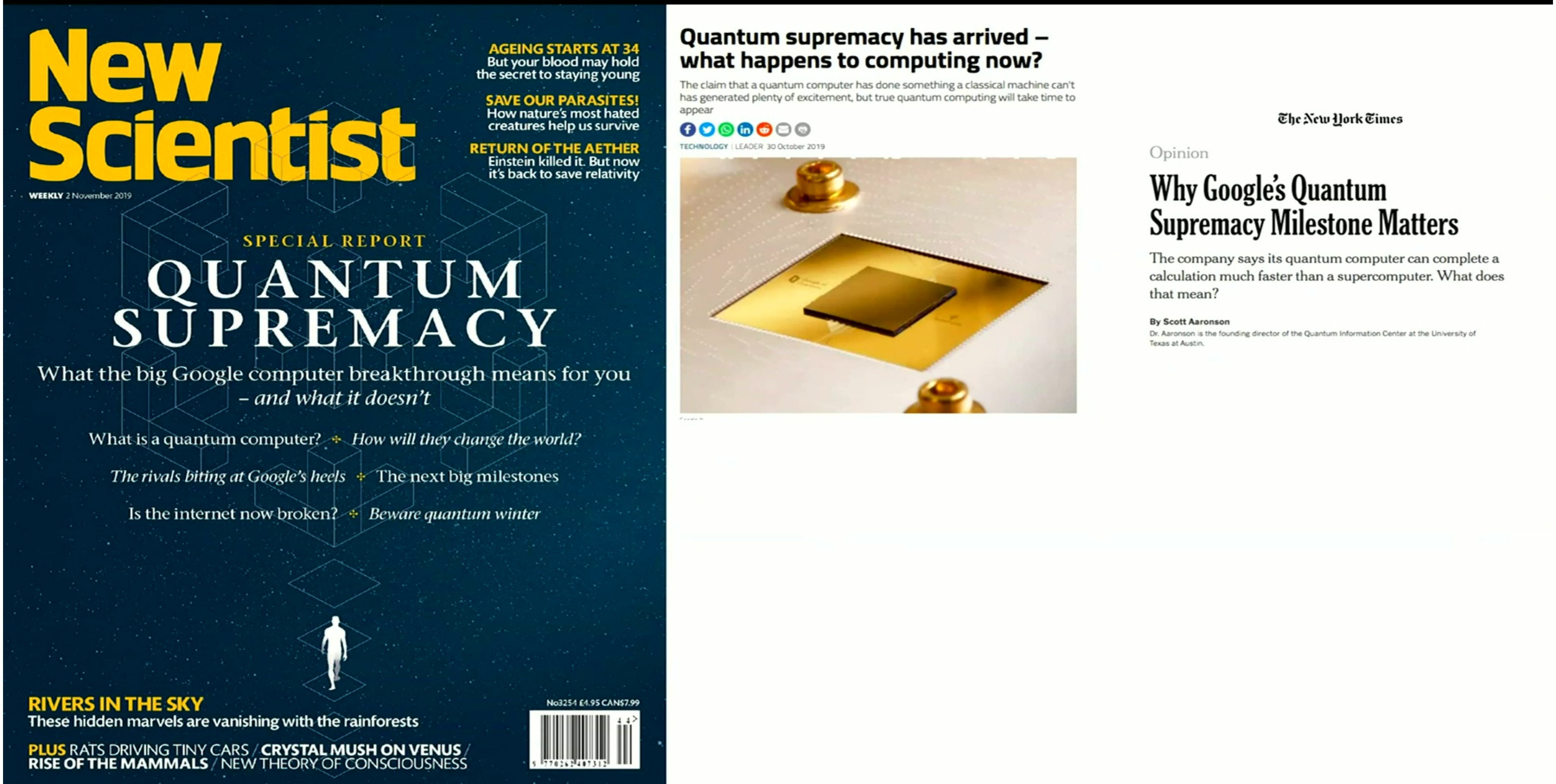
Aaronson, Arkhipov, Th. Comp. 9 (2013)

Random circuit sampling ("Google")

They apply a long circuit of random physical interactions on superconducting qubits.



Boixo et al., Nature Phys. 14 (2016)
Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Arute, Nature, Vol 574, 505 (2019)



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Quantum supremacy has arrived – what happens to computing now?
The claim that a quantum computer has done something a classical machine can't has generated plenty of excitement, but true quantum computing will take time to appear
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The New York Times
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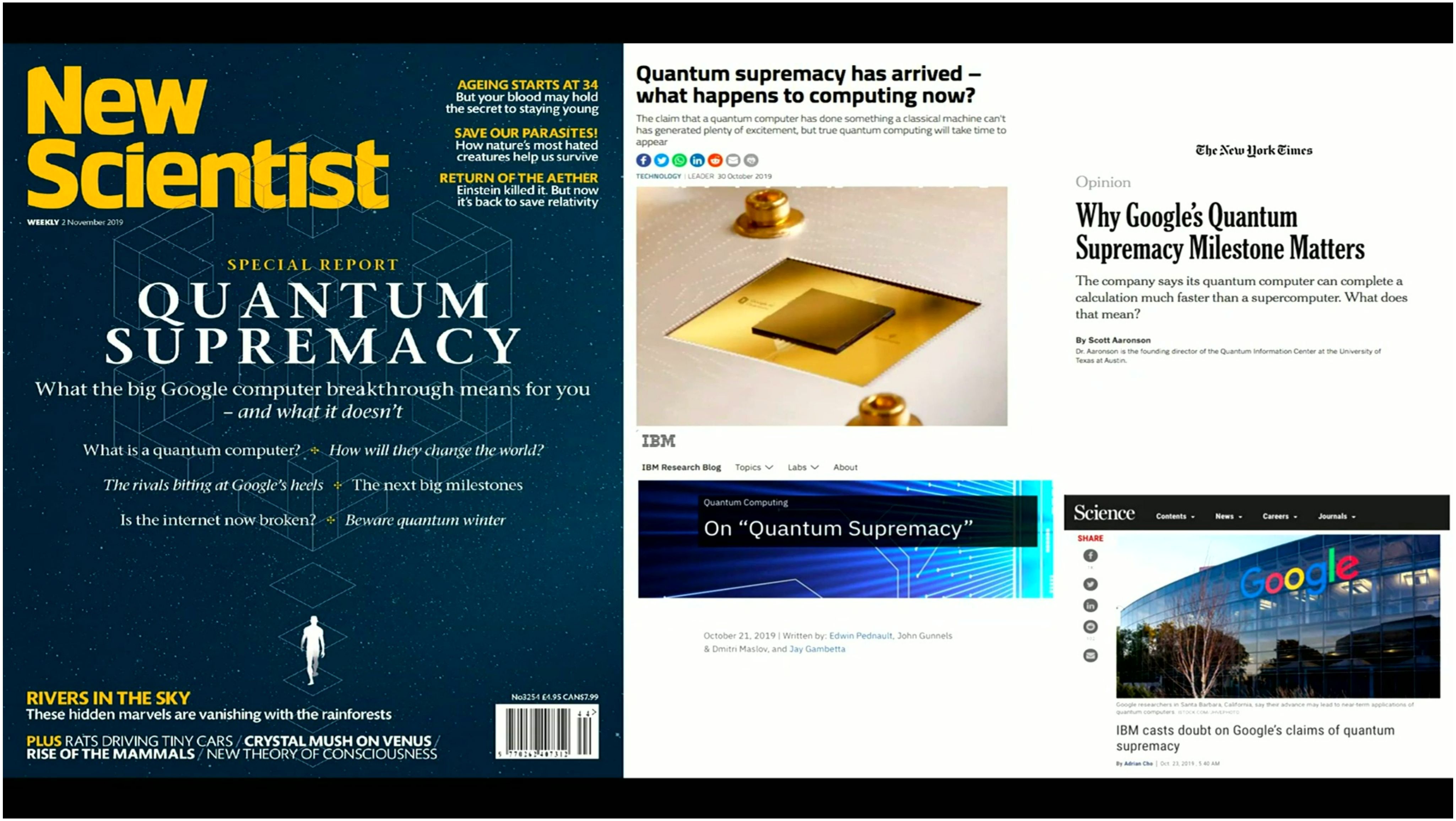
The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?
By Scott Aaronson
Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.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On "Quantum Supremacy"
October 21, 2019 | Written by: Edwin Pednault, John Gunnels & Dmitri Maslov, and Jay Gambetta
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IBM casts doubt on Google's claims of quantum supremacy
By Adrian Cho | Oct. 23, 2019, 5:40 AM

Our work

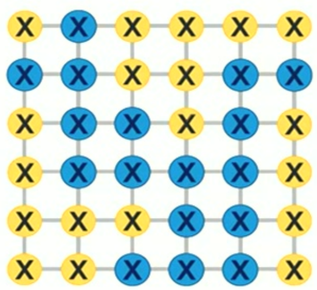
Two types of quantum advantages from quantum simulators

Result: simple Hamiltonian evolutions are "horribly hard" to simulate classically

Approximate sampling from shallow (constant-time) evolutions of 2D translation-invariant Hamiltonians is *impossible* assuming plausible* complexity-theoretic conjectures:

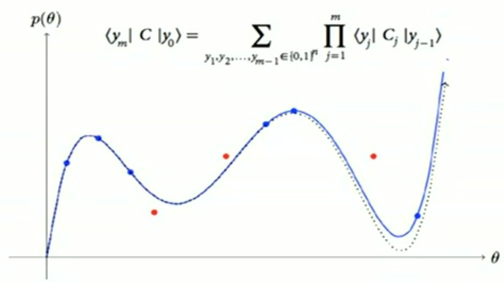
1) The Polynomial Hierarchy doesn't collapse
2) Anti-concentration ≈ "fairly flat" outputs
3) Approximate average-case hardness

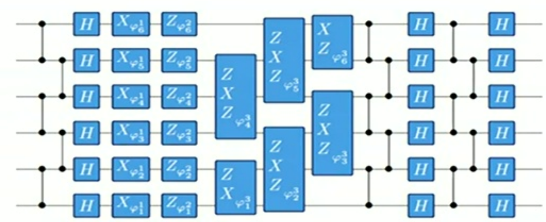
*Identical to random circuit sampling, slightly better than boson sampling



Protocols

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, *Phys. Rev. X* 8 (2018), arxiv:1703.00466





Proofs: anticoncentration & *exact* average case hardness

Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Hangleiter, Bermejo-Vega, Schwarz, Eisert, *Quantum* 2 (2018), arXiv:1706.03786
Haferkamp, Hangleiter, Fefferman, Eisert, Bouland, Bermejo-Vega, Upcoming!

Protocols

arXiv:1703.00466

Prepare N qubits on an $n \times m$ square lattice in a product state

$$|\psi_\beta\rangle = \bigotimes_{i=1}^{N} \left(|0\rangle + \mathrm{e}^{\mathrm{i}\beta_i}|1\rangle\right)$$

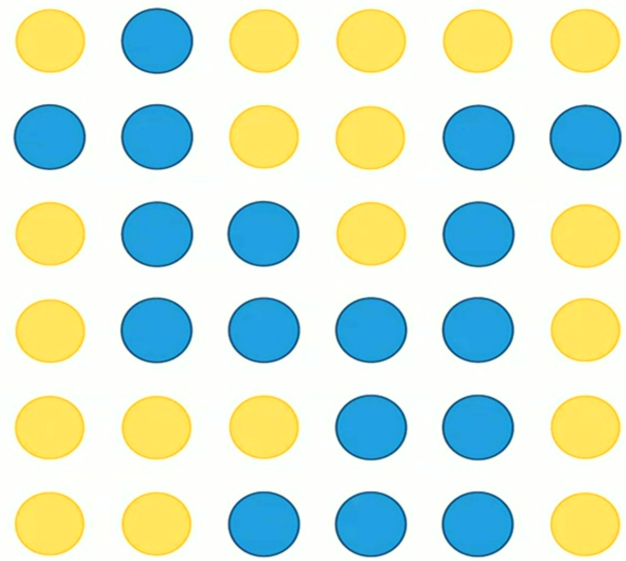
with $\beta_i \in \{0, \pi/4\}$ randomly.

Quench to

$$H = \sum_{(i,j)\in E} \frac{\pi}{4} Z_i Z_j - \sum_{i \in V} \frac{\pi}{4} Z_i.$$

and evolve under $U = e^{iH}$.

Measure all qubits in the X basis.



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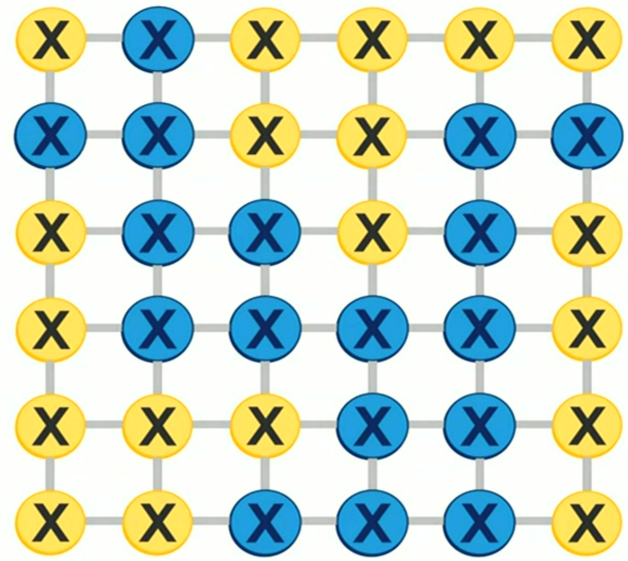

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arXiv:1

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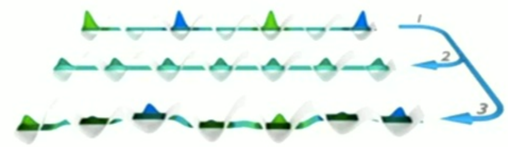
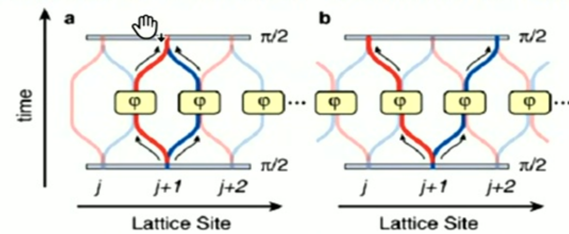
Measure all qubits in the X basis

Reminiscient of disordered optical lattices



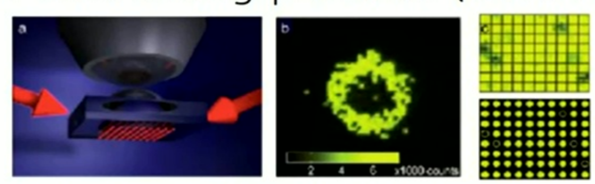
Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk, Altman, Schneider, Bloch, Science 349 (2015)

Controlled coherent collisions long realized



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

Single-site addressing possible (within limits)



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

Quantum Verification/Benchmarking:

How can we check if the quantum computation is working?

Challenges:

1. Tomographic methods exponentially costly, no fault-tolerant solutions
2. Classical efficient verification of sampling problems is hard

Hangleiter, Kliesch, Eisert,Gogolin, arXiv:1812.01023

Approach I

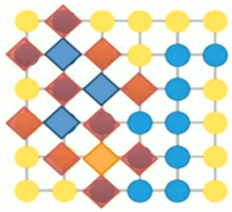
With additional noise/complexity assumptions, a few quantum samples + exponential classical processing is enough

Cross-entropy, HOG, BOG

Boixo et al., Nature Phys. 14 (2016)
Bouland, Fefferman, Nirkhe, Vazirani, Nature Phys arXiv:1803.04402
Aaronson, Chen, CCC 17

Approach II

With reliable single-qubit measurements, the fidelity of the prepared final state an be efficiently estimated



$$F(\rho_0, \rho) \geq 1 - \frac{\langle H \rangle_\rho}{\Delta}$$

Hangleiter, Kliesch, Schwarz, Eisert, Quant. Sc. Tech. 2, (2017)
Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, *Phys. Rev. X* 8 (2018), arxiv:1703.00466

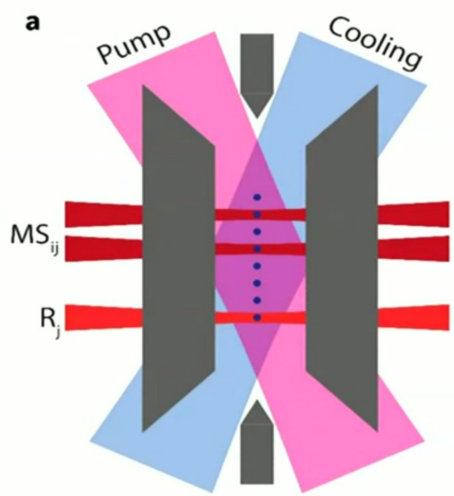
Experimental demonstration
(arXiv:2307.14424v1)

Verifiable measurement-based quantum random sampling with trapped ions

Martin Ringbauer,[1] Marcel Hinsche,[2] Thomas Feldker,[1,3] Paul K. Faehrmann,[2] Juani Bermejo-Vega,[2,4,5] Claire Edmunds,[1] Lukas Postler,[1] Roman Stricker,[1] Christian D. Marciniak,[1] Michael Meth,[1] Ivan Pogorelov,[1] Rainer Blatt,[1,3,6] Philipp Schindler,[1] Jens Eisert,[2,7,8] Thomas Monz,[1,3] and Dominik Hangleiter[9,10]

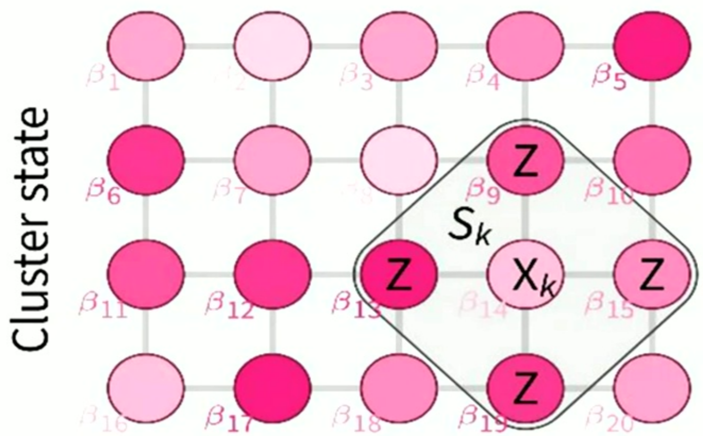
[1] *Universität Innsbruck, Institut für Experimentalphysik, Technikerstrasse 25, 6020 Innsbruck, Austria*
[2] *Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany*
[3] *Alpine Quantum Technologies GmbH, 6020 Innsbruck, Austria*
[4] *Departamento de Electromagnetismo y Física de la Materia, Avenida de la Fuente Nueva, 18071 Granada, Universidad de Granada, Granada, Spain*
[5] *Institute Carlos I for Theoretical and Computational Physics, Campus Universitario Fuentenueva, Calle Dr. Severo Ochoa, 18071, Granada, Spain.*
[6] *Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Otto-Hittmair-Platz 1, 6020 Innsbruck, Austria*
[7] *Helmholtz-Zentrum Berlin für Materialien und Energie, 14109 Berlin, Germany*
[8] *Fraunhofer Heinrich Hertz Institute, 10587 Berlin, Germany*
[9] *Joint Center for Quantum Information and Computer Science (QuICS), University of Maryland & NIST, College Park, MD 20742, USA*
[10] *Joint Quantum Institute (JQI), University of Maryland & NIST, College Park, MD 20742, USA*

(Dated: July 28, 2023)



Direct fidelity estimation

$$F = \frac{1}{2^N} \sum_{s \in \mathcal{S}} \langle s \rangle_\rho = \frac{1}{2^N} \sum_{s \in \mathcal{S}} \sum_{\sigma = \pm 1} \langle \pi_s^\sigma \rangle_\rho \cdot \sigma,$$



Requirements:

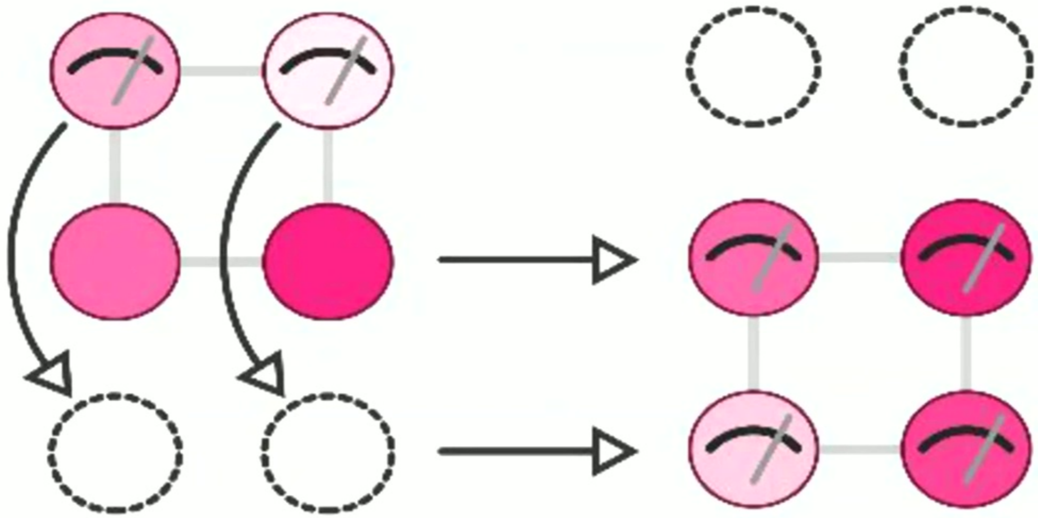
- single qubit measurements

Advantages (over XEB approaches):

- efficient in terms of both sample and computational complexity
- knowledge only of the measurement noise
- bounds the quality of the samples from a fixed quantum state
- system size efficient: estimates F with error ϵ using $1/\epsilon^2$ measurements

S. T. Flammia and Y.-K. Liu, Phys. Rev. Lett. 106, 230501 (2011).

Qubit recycling (non-adaptive MBQC with ions)



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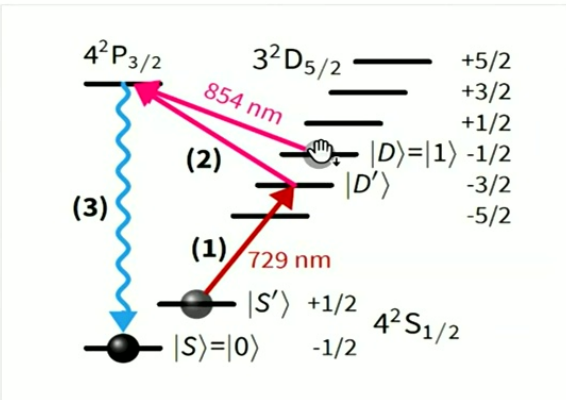
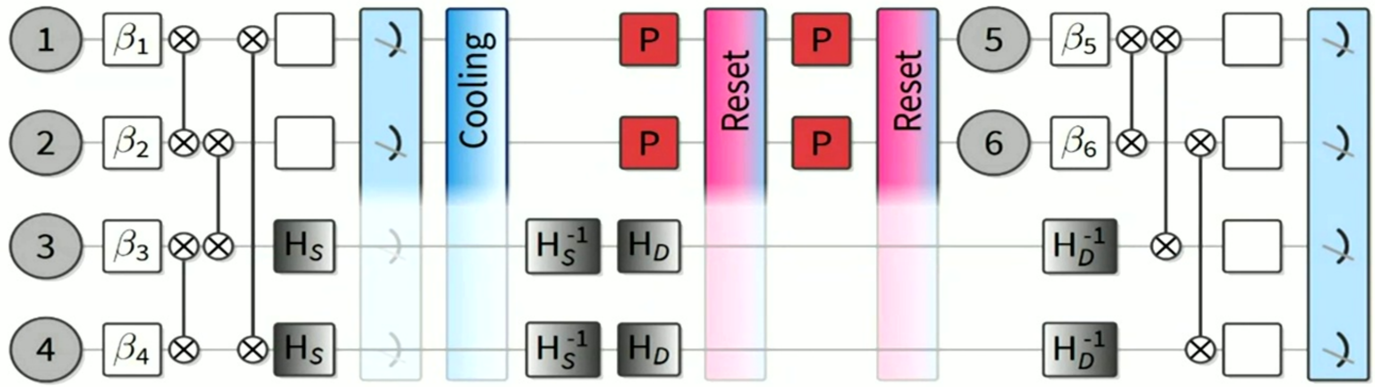
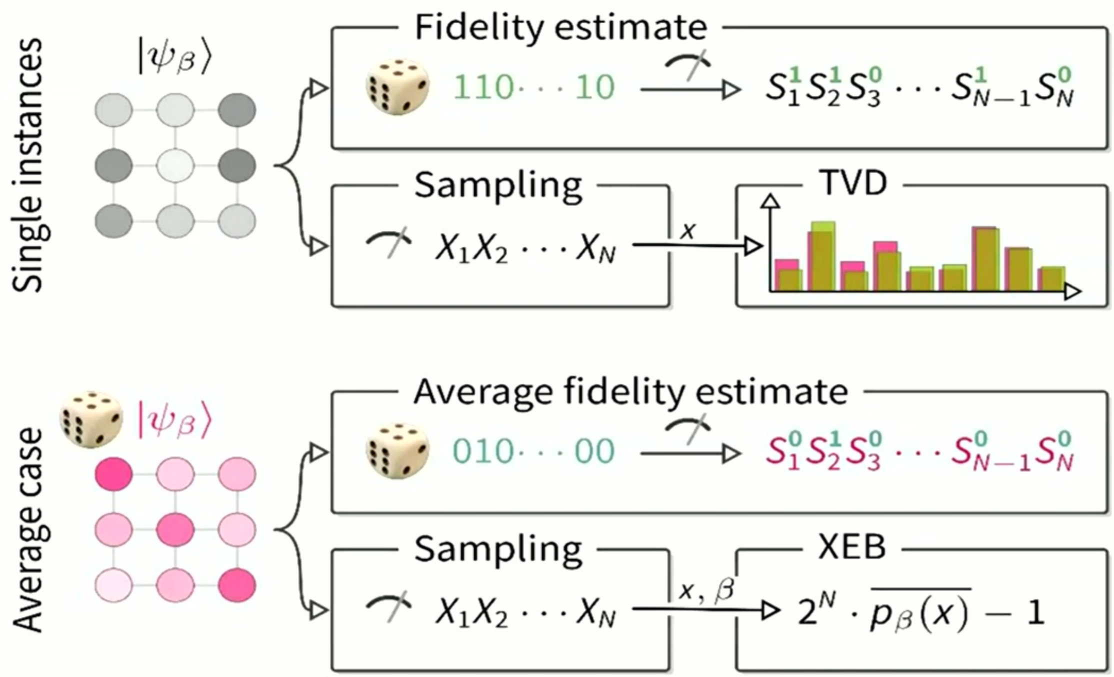




- Measurement (P ↔ S)
- P = Cooling Reset (S′ ⟶ D′)
- H_S = Recycling (S ⟶ D′ transition)
- H_D(D ⟶ S′)

Measuring the fidelity and XEB for our setup



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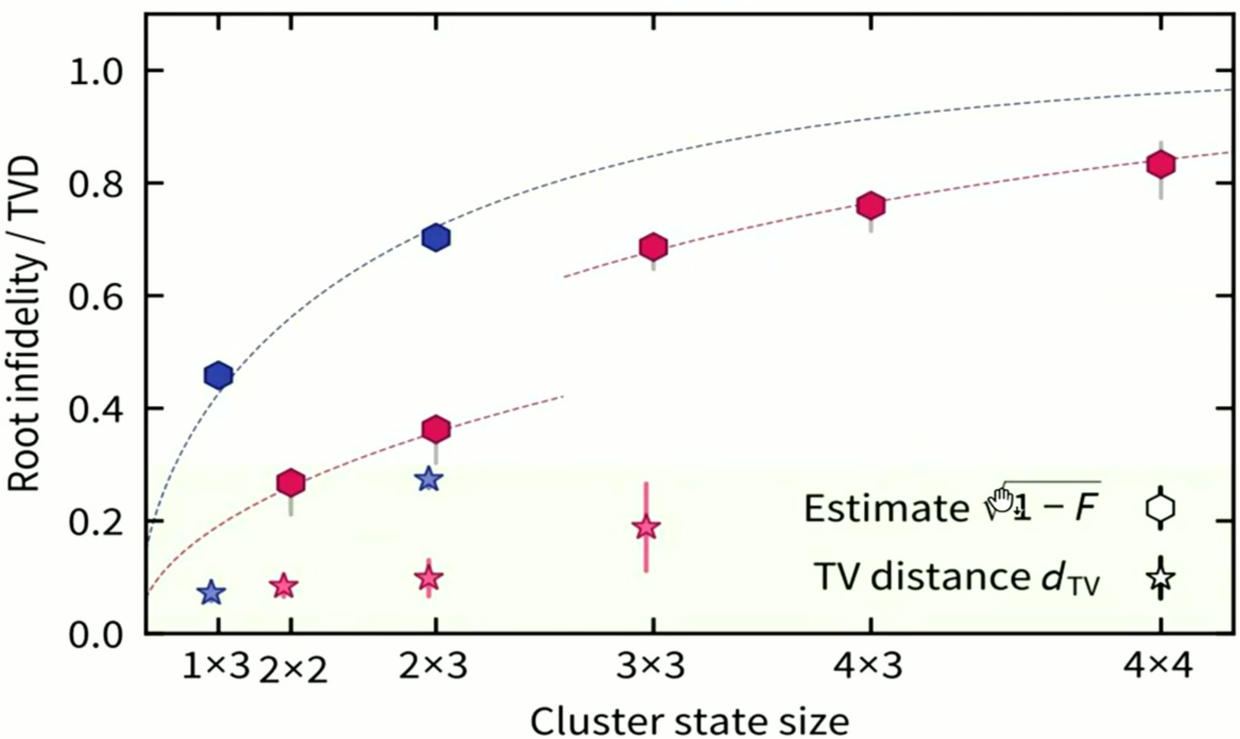
S. T. Flammia and Y.-K. Liu, Phys. Rev. Lett. 106, 230501 (2011).

Experimental results for single-instance verification of random cluster states



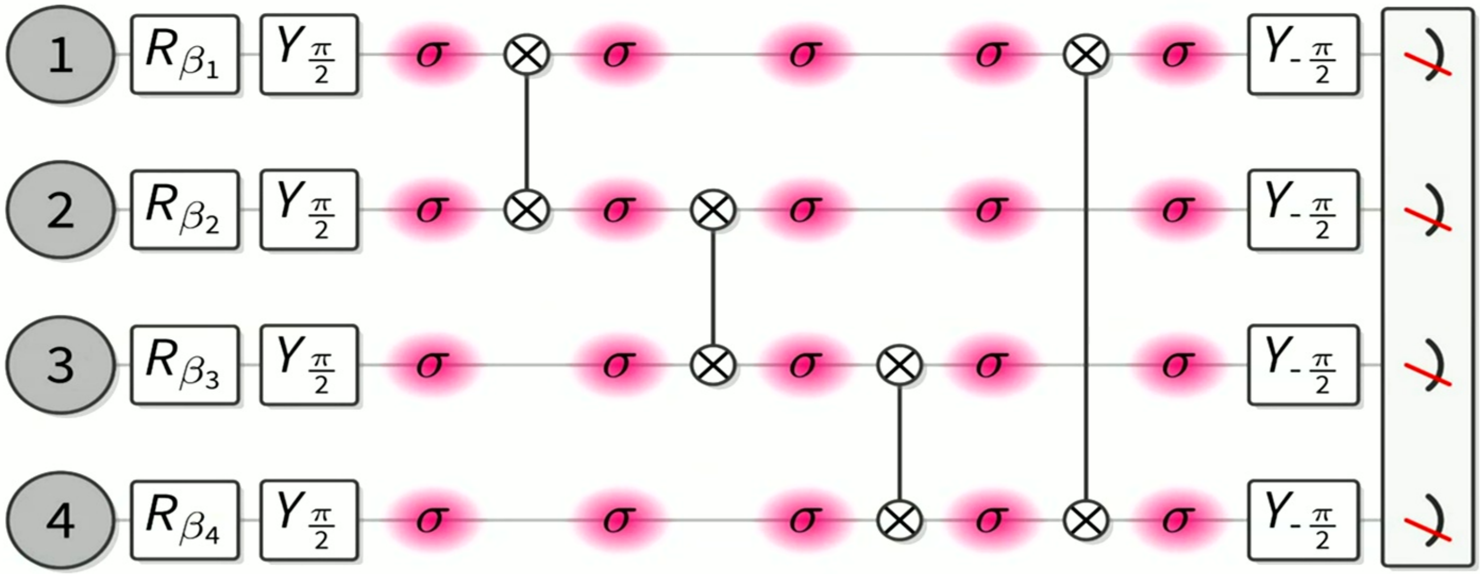
- Blue = with recycling (blue)
- Pink = without recycling
- Gray error bars = measurement noise (from benchmarking)
- Colored error bars = 3σ statistical error
- Shaded green area = acceptance region

M. Ringbauer, M. Meth, L. Postler, R. Stricker, R. Blatt, P. Schindler, and T. Monz,Nat. Phys. 18, 1053 (2022)

I. Pogorelov, T. Feldker, C. D. Marciniak, L. Postler, G. Jacob,
O. Krieglsteiner, V. Podlesnic, M. Meth, V. Negnevitsky, M. Stadler, B. Höfer, C. Wächter, K. Lakhmanskiy, R. Blatt, P. Schindler, and T. Monz,, PRX Quantum 2, 020343 (2021))

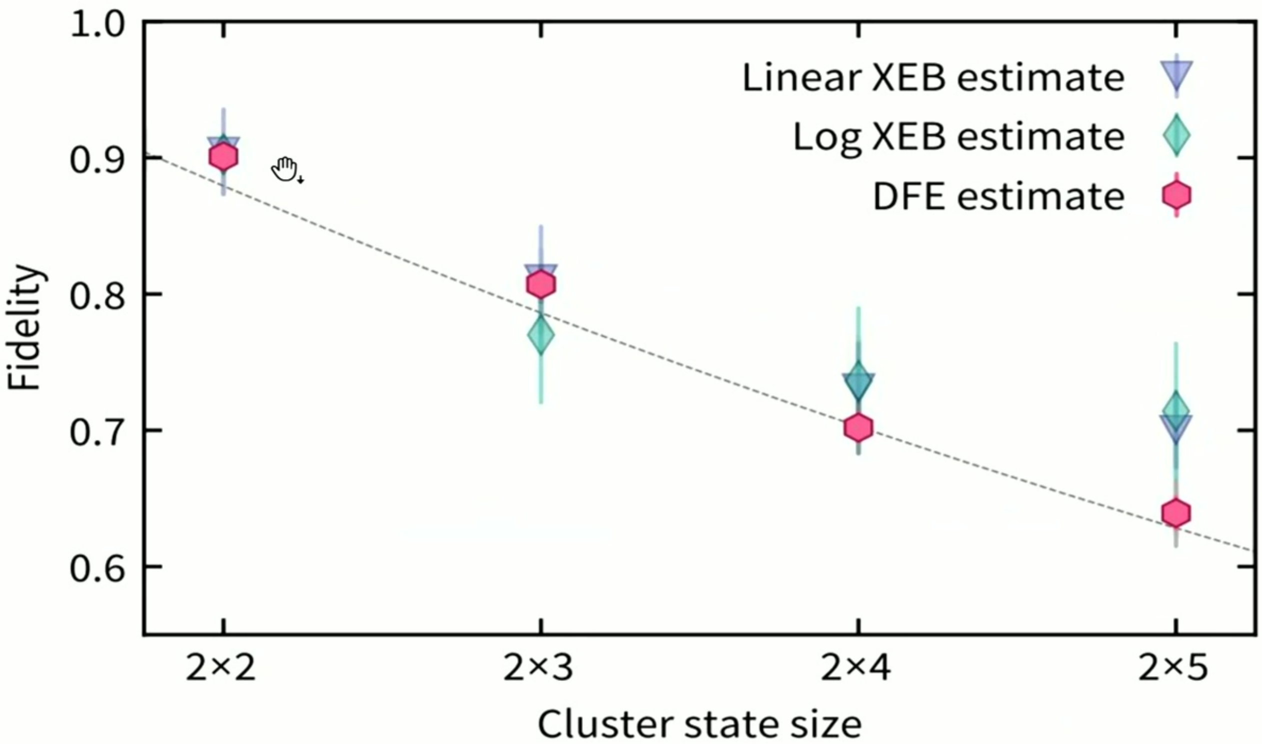
P. Schindler, D. Nigg, T. Monz, J. T. Barreiro, E. Martinez, S. X. Wang, Stephan Quint, M. F. Brandl, V. Nebendahl, C. F. Roos, M. Chwalla, M. Hennrich, and Rainer Blatt,, New J. Phys. 15, 123012 (2013).

Estimating the noise strength: verification with artificially induced phase noise



We add dephasing noise on all qubits after initial state preparation and each MS gate.
Rotation angles of Z rotations are drawn from normal distribution with zero mean and standard deviation σ ∈ [0, 0.2π] every 50 shots. For correlated noise, the parameters in each time step are chosen equally and for uncorrelated noise, they are chosen independently.

Experimental results for average performance verification



- Gray error bars = measurement noise (from benchmarking)
- Colored error bars = 3σ statistical error
- Gray shaded area = Fidelity prediction from calibration data gate fidelities of single-qubit gates f1Q = 99.8%, twoqubit gates f2Q = 97.5 ± 0.5%, and measurements fM = 99.85%,
- Dotted line: effective local Pauli error probability of 1.7%

M. Ringbauer, M. Meth, L. Postler, R. Stricker, R. Blatt, P. Schindler, and T. Monz,Nat. Phys. 18, 1053 (2022)

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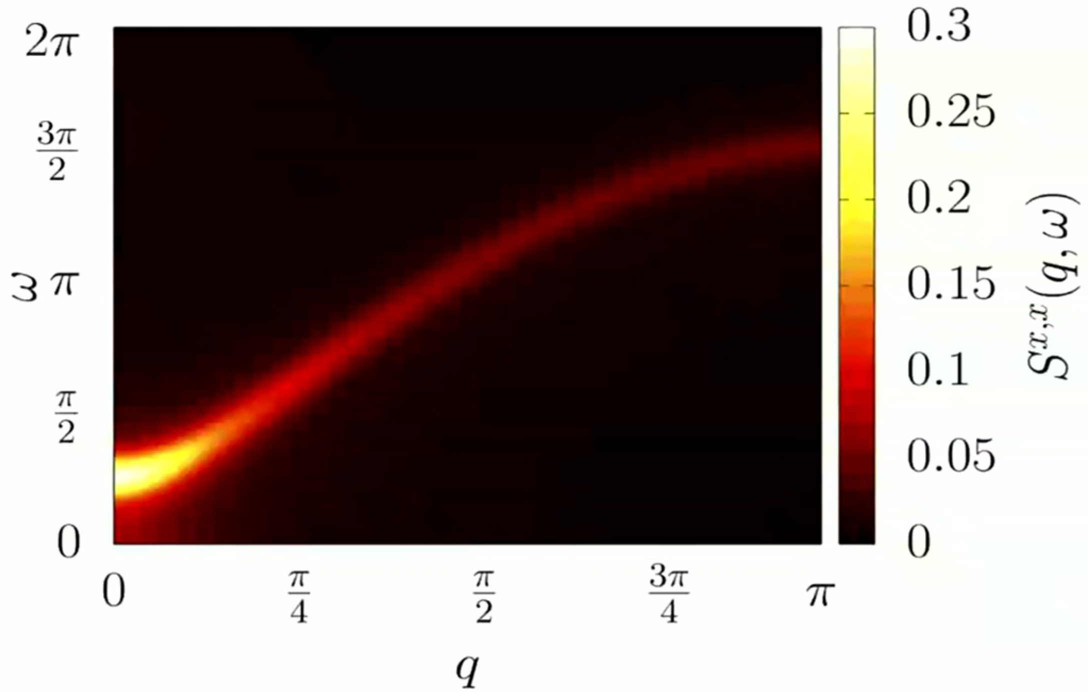
Direct fidelity estimation provides an efficient and scalable means of certifying both single instances and the average quality of MBQCS

Sample efficient: Larger systems can be verified with the same number of experiments as we have performed (30k -100 k shots)

Practical quantum advantage for measuring dynamical structure factors



ML Baez, M Goihl, J Haferkamp, J Bermejo-Vega, M Gluza, J Eisert

Proceedings of the National Academy of Sciences 117 (42), 26123-26134

Direct fidelity estimation provides an efficient and scalable means of certifying both single instances and the average quality of MBQCS

Sample efficient: Larger systems can be verified with the same number of experiments as we have performed (30k -100 k shots)

Applications: tool for verifying NISQ devices and quantum advantages based on sampling problems in MBQC

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WHAT? DYNAMICAL STRUCTURE FACTOR FOR SPIN SYSTEMS

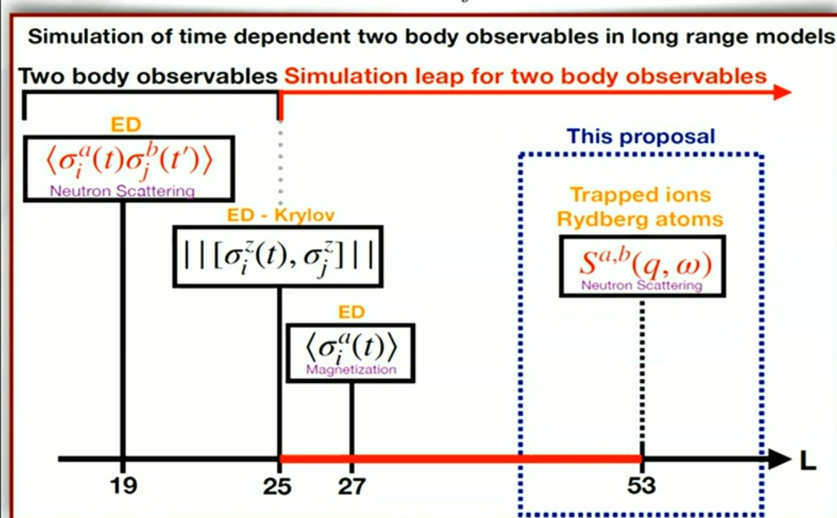
$$S^{a,b}(\mathbf{q},\omega) = \frac{1}{N}\sum_{ij}\int_{-\infty}^{\infty} dt e^{-i\mathbf{q}.(\mathbf{r}_i-\mathbf{r}_j)} e^{i\omega t} C_{i,j}^{a,b}(t)\,, \quad C_{i,j}^{a,b}(t) = \langle \sigma_i^a(0)\sigma_j^b(t)\rangle$$

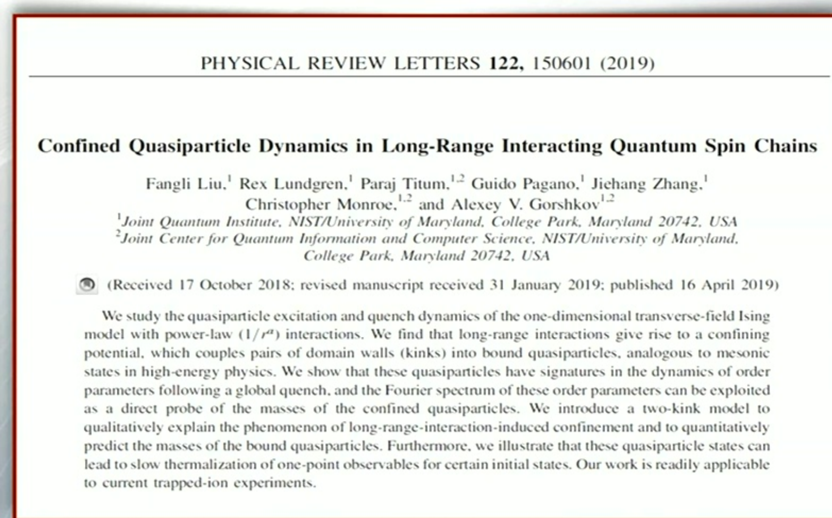
Approximating the dynamical structure factor $S^{\alpha,\beta}_{t_0,t_1}(q,\omega)$ within a constant error $\varepsilon \leq 1/8$ over an interval of time $[t_0, t_1]$ is BQP-hard.
For polynomially large ($t_1 - t_0 = \mathrm{poly}(n)$) then it is BQP-hard to approximate $S^{\alpha,\beta}_{t_0,t_1}(q,\omega)$ within an error $\varepsilon = \mathrm{poly}^{-1}(n)$.

arXiv: 1912.0607

J. Haferkamp, J. Bermejo-Vega, J. Eisert

$$\hat{H}(J,B) = \sum_i B_z \sigma_i^z - \sum_{i<j} \frac{J}{|r_i - r_j|^\alpha} \sigma_i^x \sigma_j^x$$





PHYSICAL REVIEW LETTERS **122,** 150601 (2019)

Confined Quasiparticle Dynamics in Long-Range Interacting Quantum Spin Chains

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We study the quasiparticle excitation and quench dynamics of the one-dimensional transverse-field Ising model with power-law ($1/r^\alpha$) interactions. We find that long-range interactions give rise to a confining potential, which couples pairs of domain walls (kinks) into bound quasiparticles, analogous to mesonic states in high-energy physics. We show that these quasiparticles have signatures in the dynamics of order parameters following a global quench, and the Fourier spectrum of these order parameters can be exploited as a direct probe of the masses of the confined quasiparticles. We introduce a two-kink model to qualitatively explain the phenomenon of long-range-interaction-induced confinement and to quantitatively predict the masses of the bound quasiparticles. Furthermore, we illustrate that these quasiparticle states can lead to slow thermalization of one-point observables for certain initial states. Our work is readily applicable to current trapped-ion experiments.

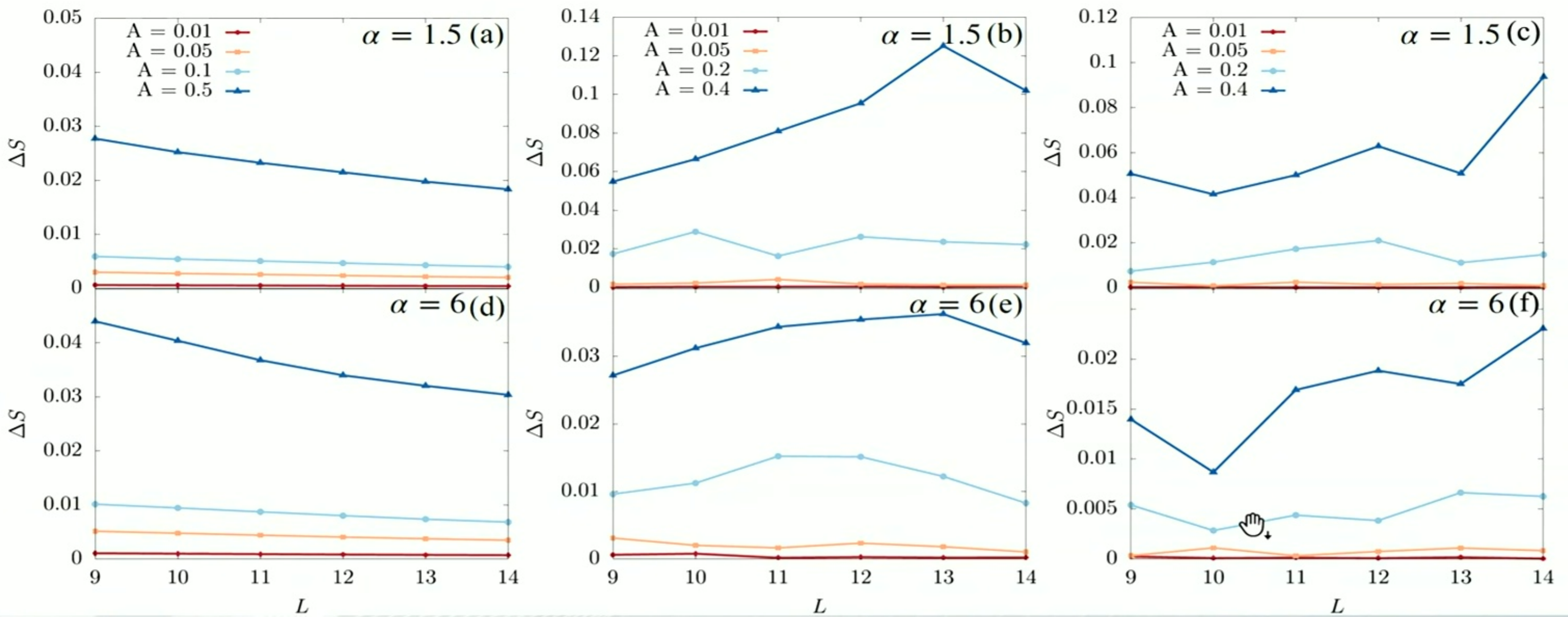
TEST CASES AND NOISE MODELS

MLB, et al. arXiv: 1912.0607

Long range scaling up to $L = 14$

$$\Delta S = \frac{1}{L^2 N_\omega} \sum_q \sum_\omega S(q,\omega)$$

Experiments have control up to $A \propto 0.01$



Globally fluctuating Ising couplings

Random Ising interactions

Random transverse field

Imperfection effects are negligible and scale in a controlled way up to $A \propto 0.05$

Existing quantum computers are entering a hard-to-simulate regime but demonstrating quantum advantages is still very challenging

Complexity theoretic proposal based on sampling problems of short Hamiltonian evolutions with advantages for quantum verification

Practical quantum advantage proposal for measuring dynamical quantum advantage in quantum simulators

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