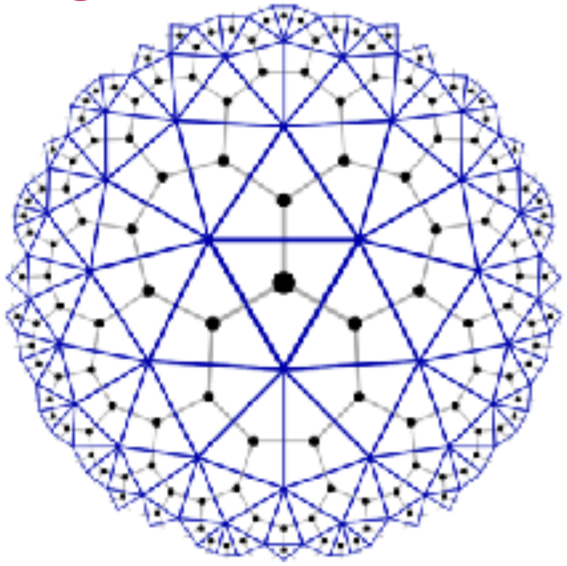
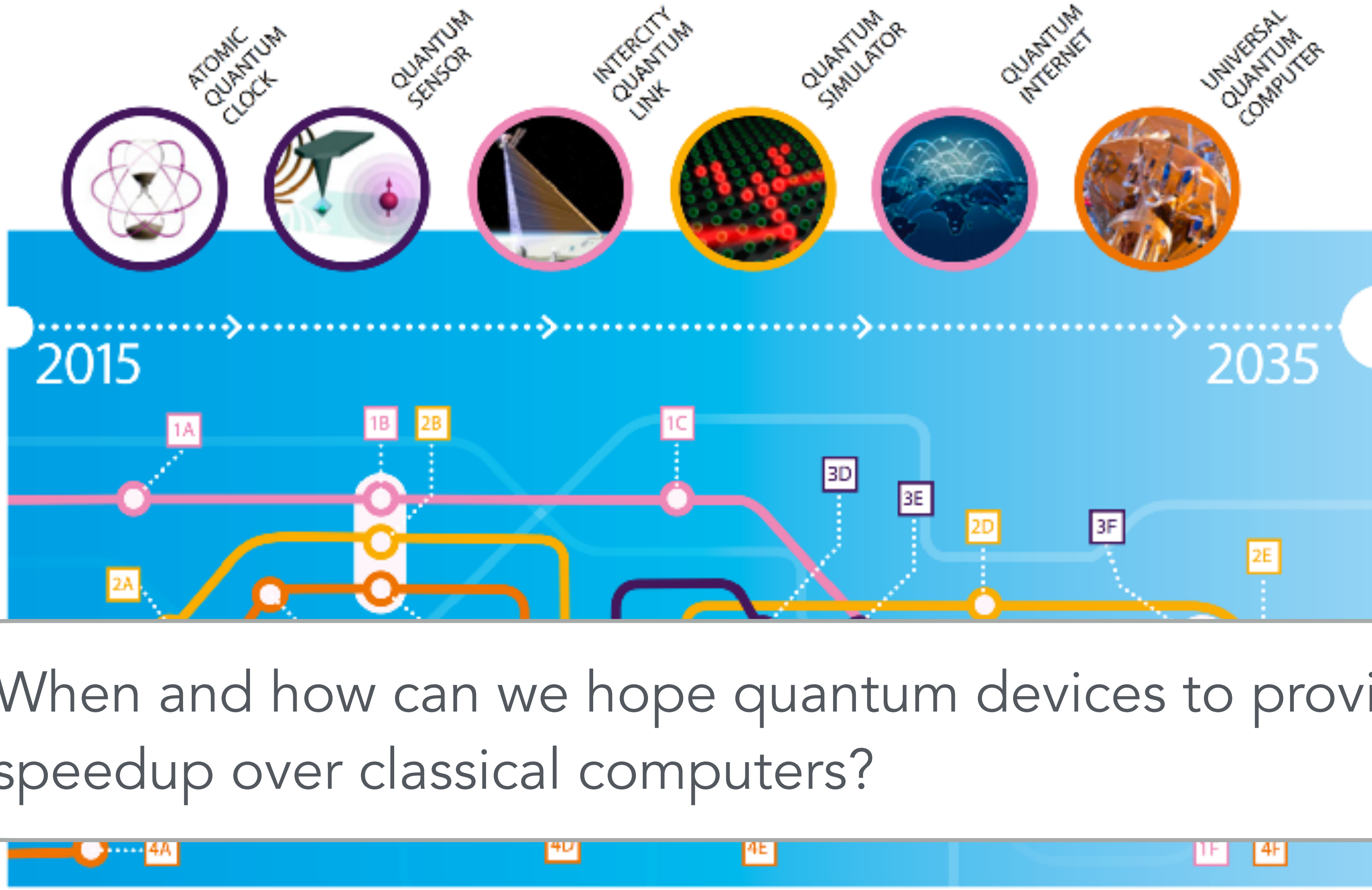
Towards quantum simulation showing super-polynomial speedups

Holography and criticality in matchgate tensor



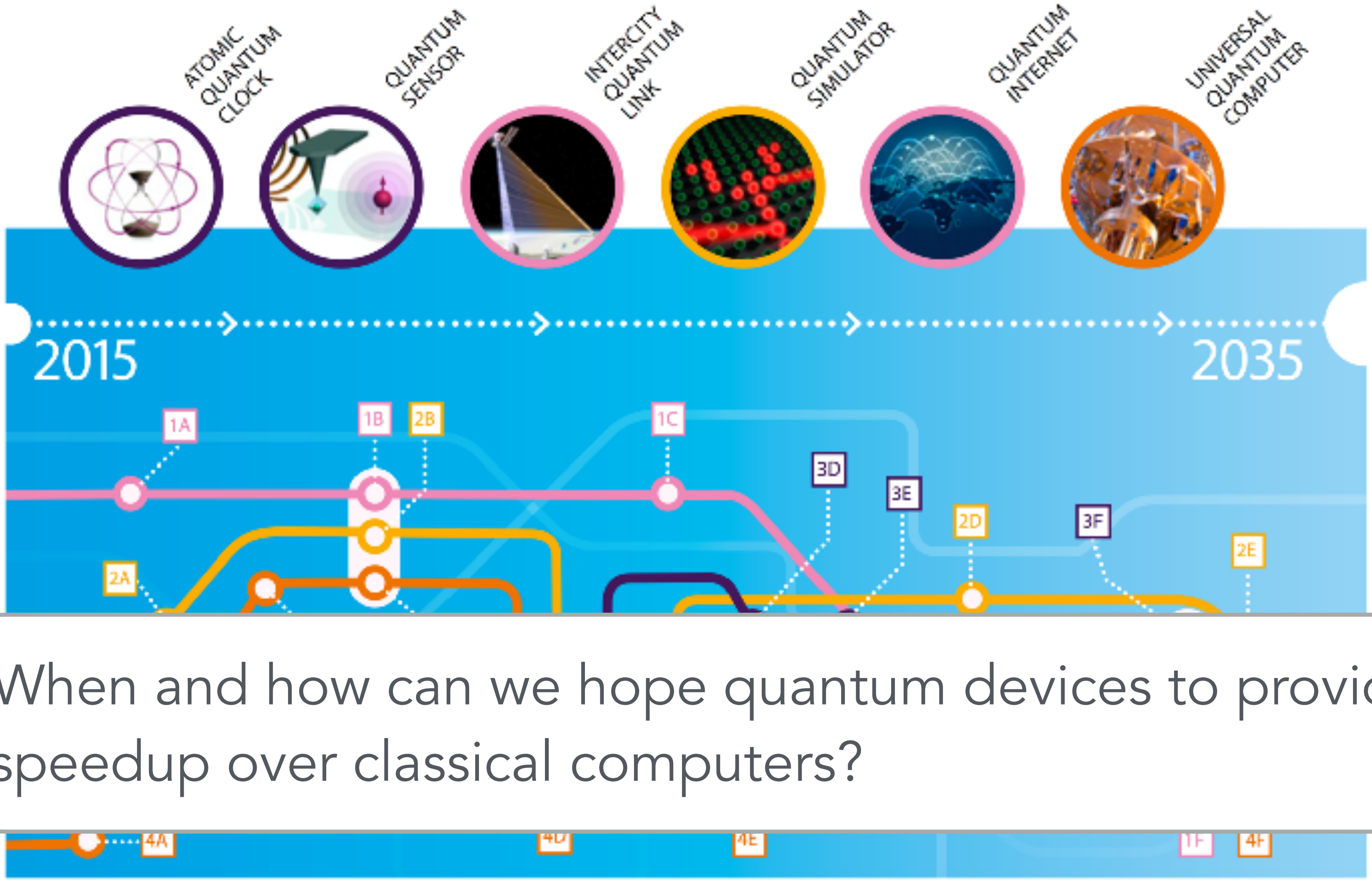
Jens Eisert, Freie Universität Berlin
With Dom Hangleiter, Martin Schwarz, Robert Raussendorf, Juan Bermejo-Vega

Towards quantum simulation showing super-polynomial speedups



- When and how can we hope quantum devices to provide a speedup over classical computers?

Towards quantum simulation showing super-polynomial speedups

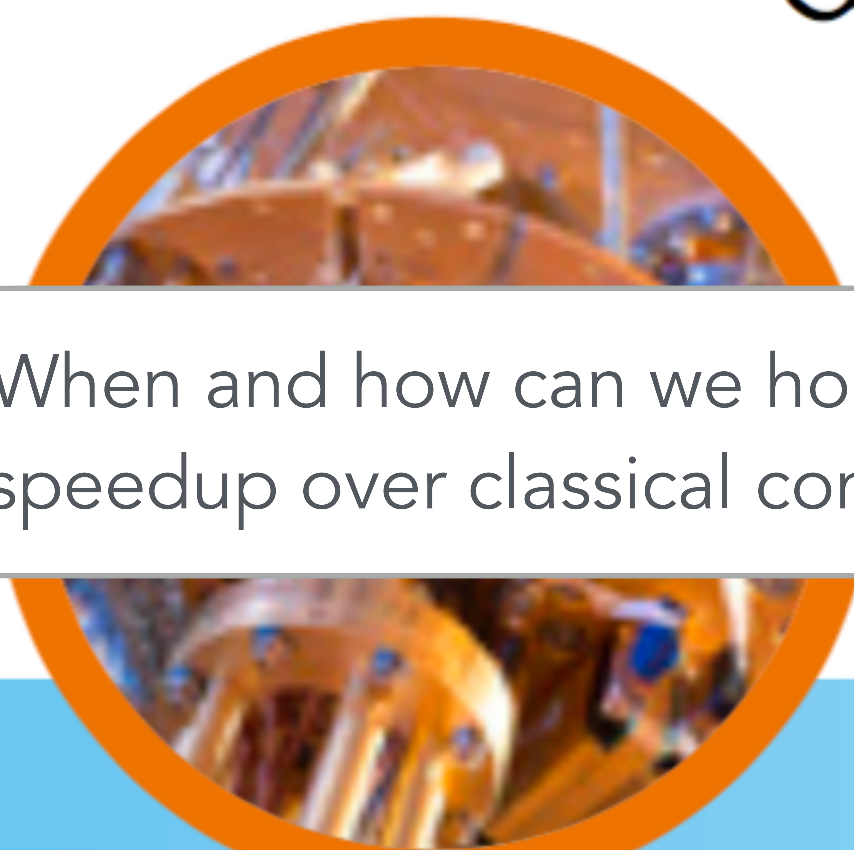


- When and how can we hope quantum devices to provide a speedup over classical computers?

QUANTUM INTERNET

UNIVERSAL QUANTUM COMPUTER

- IBM, Microsoft, Google efforts



- When and how can we hope quantum devices to provide a speedup over classical computers?

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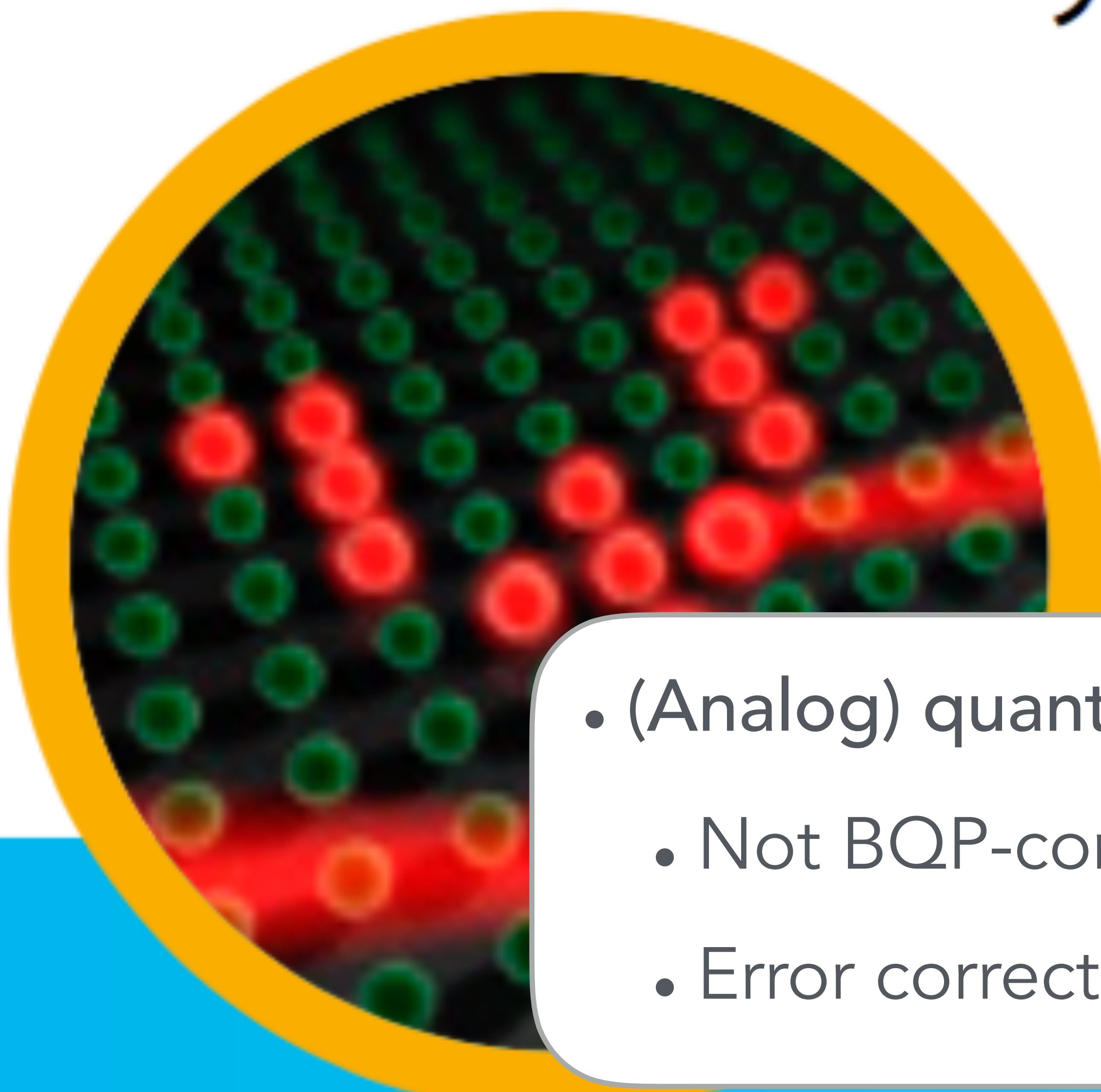

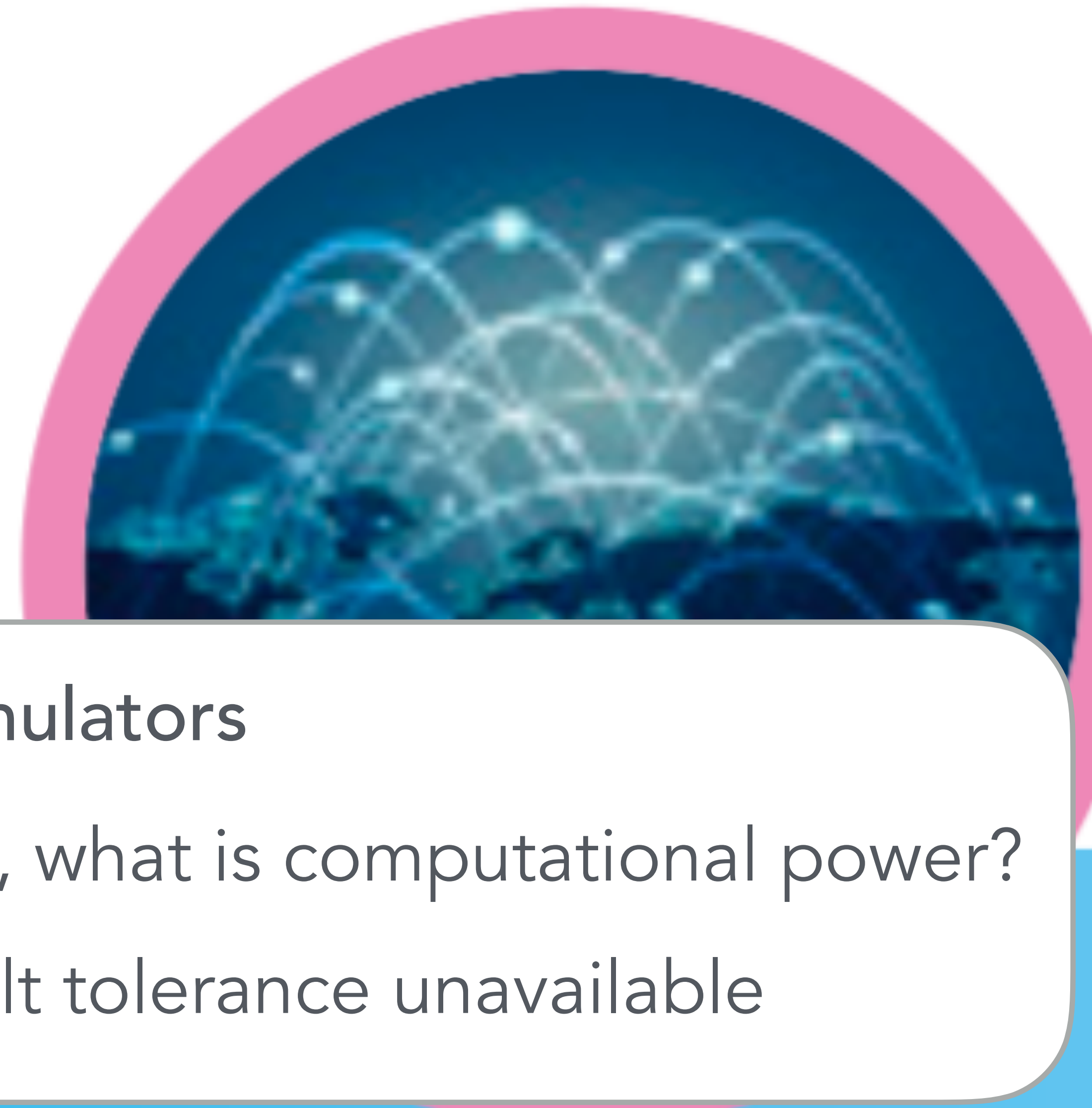

- (Analog) quantum simulators
  - Not BQP-complete, what is computational power?
  - Error correction/fault tolerance unavailable

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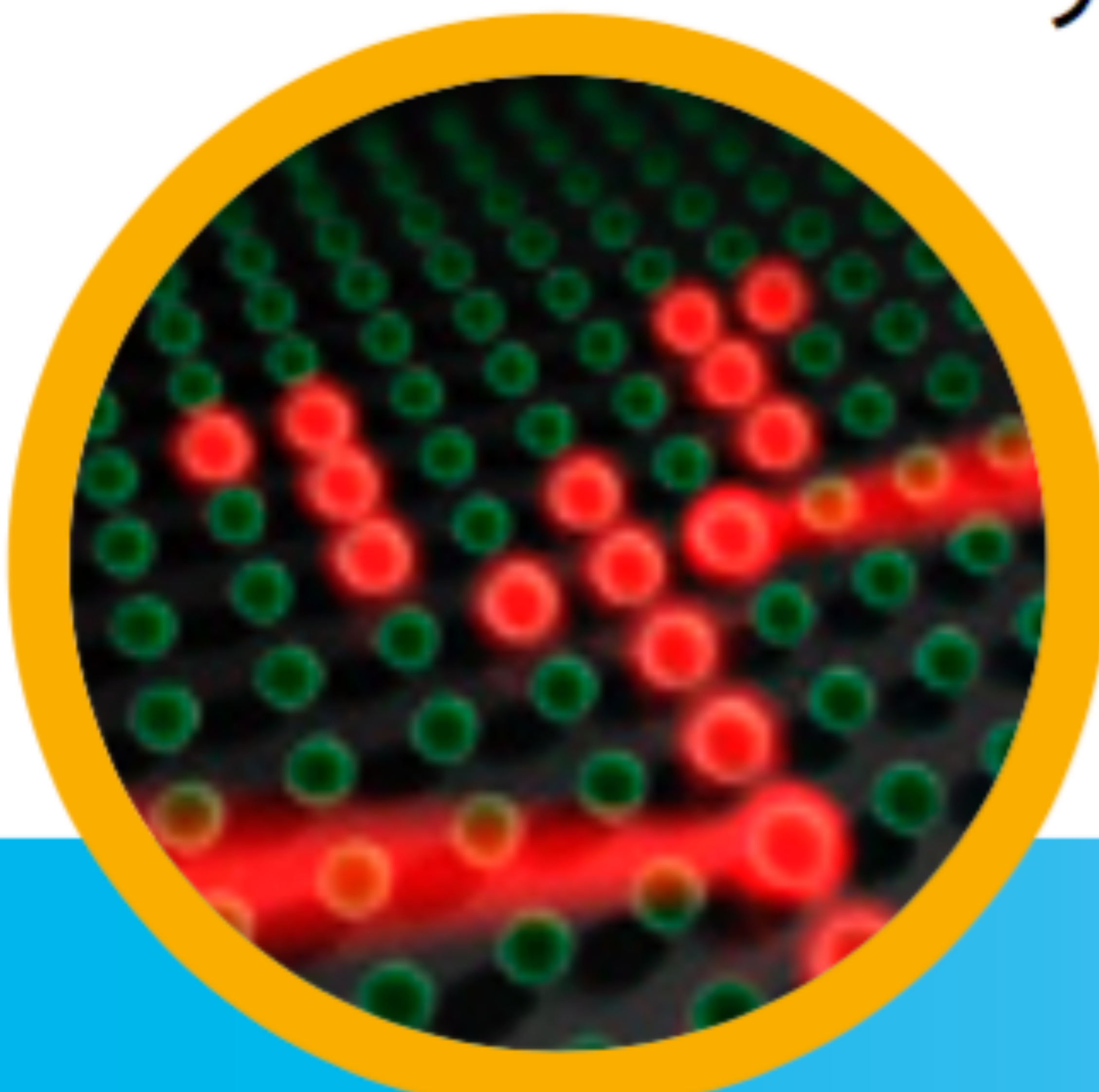

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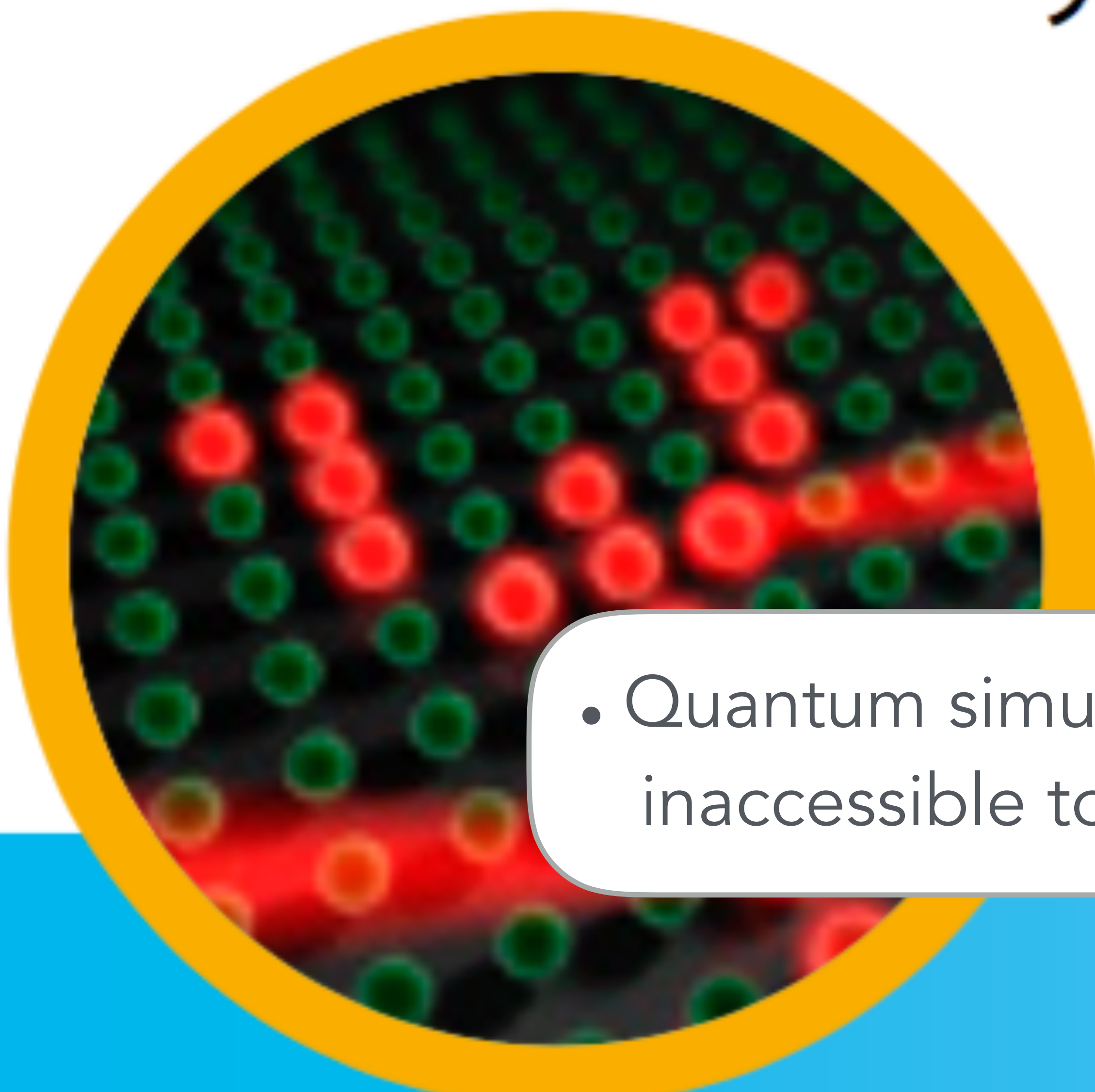

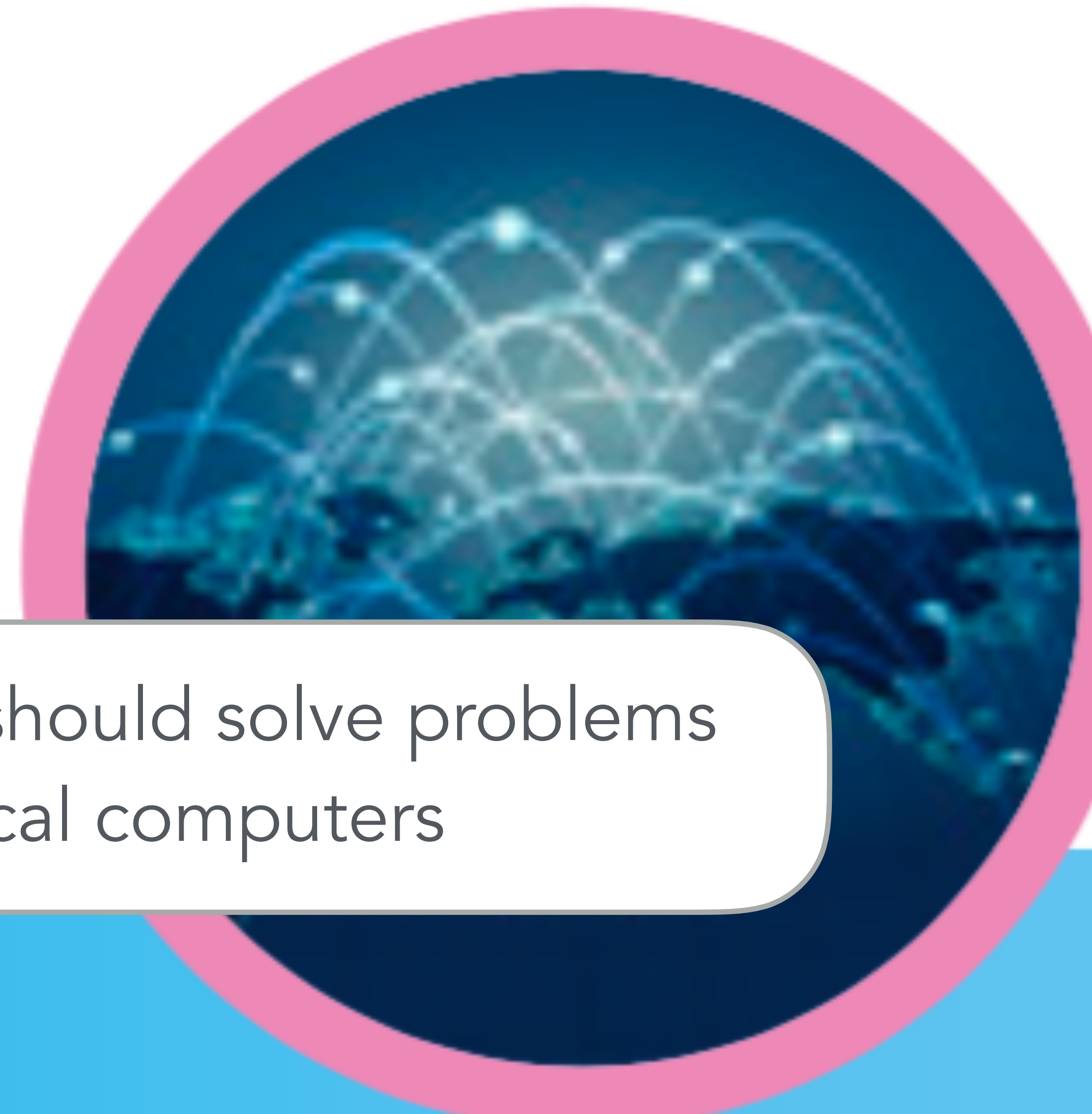

- Quantum simulators should solve problems inaccessible to classical computers

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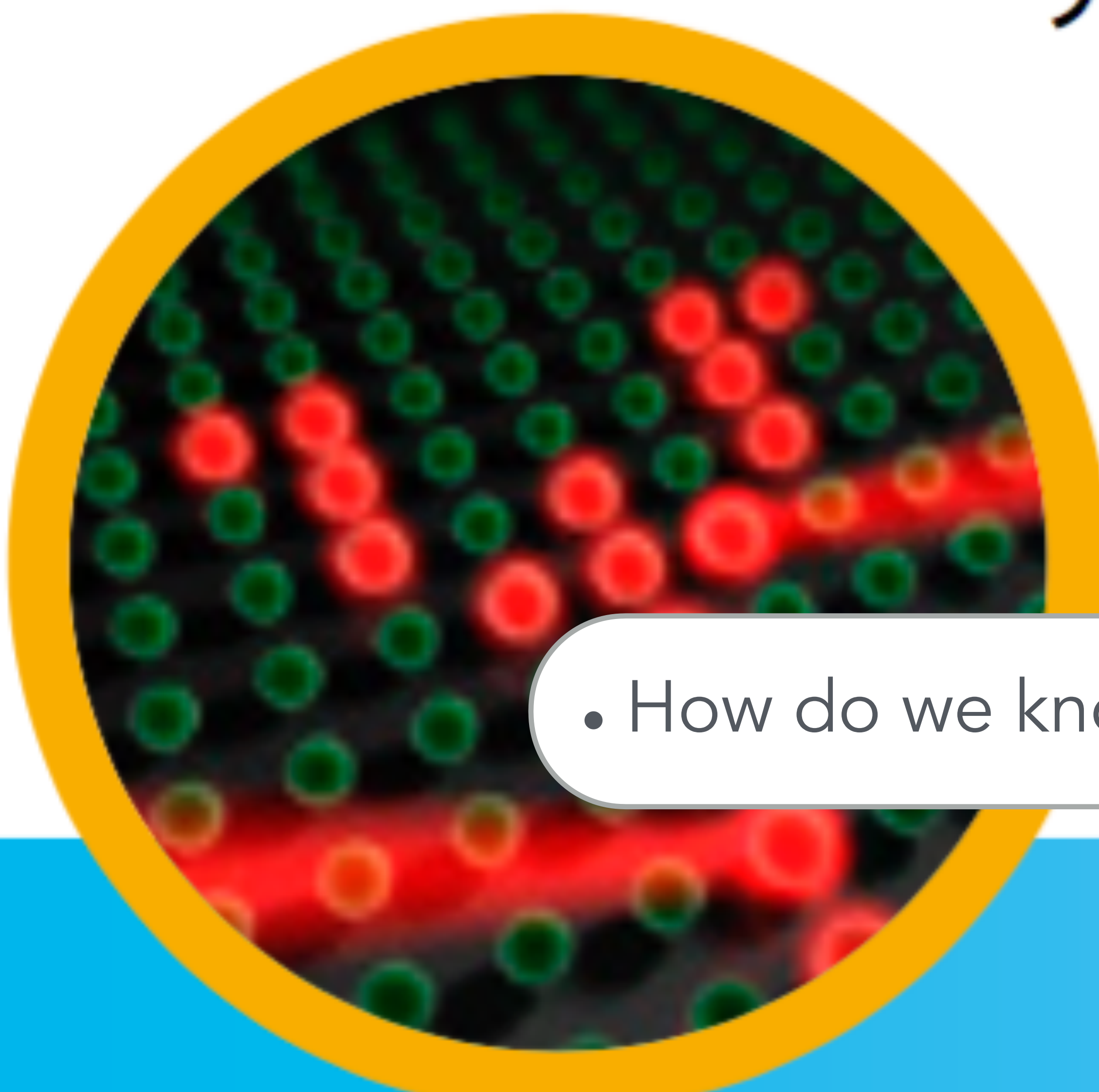
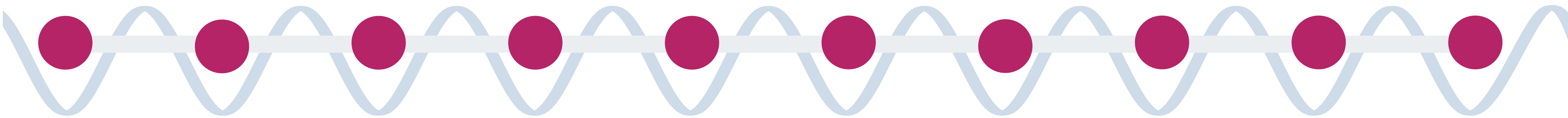


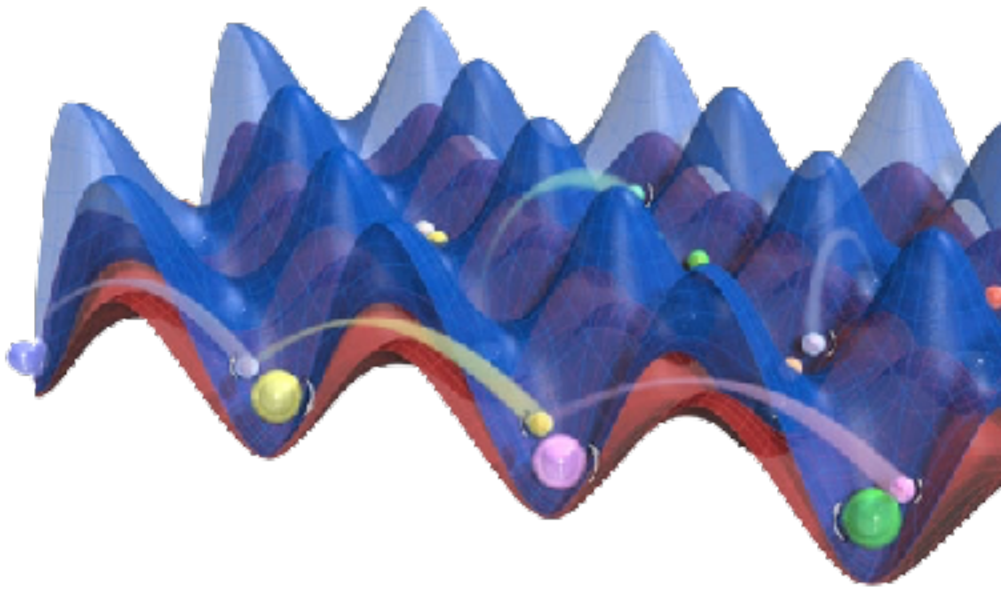
- How do we know we have done the right thing?

(Analog) quantum simulators

Analog quantum simulators

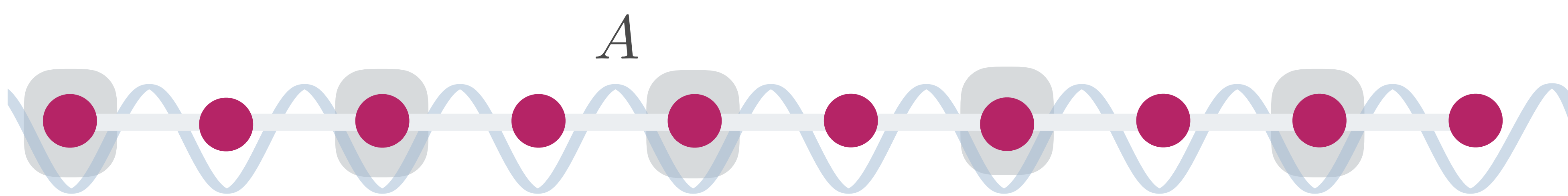


- **Cold atoms in optical lattices** most advanced

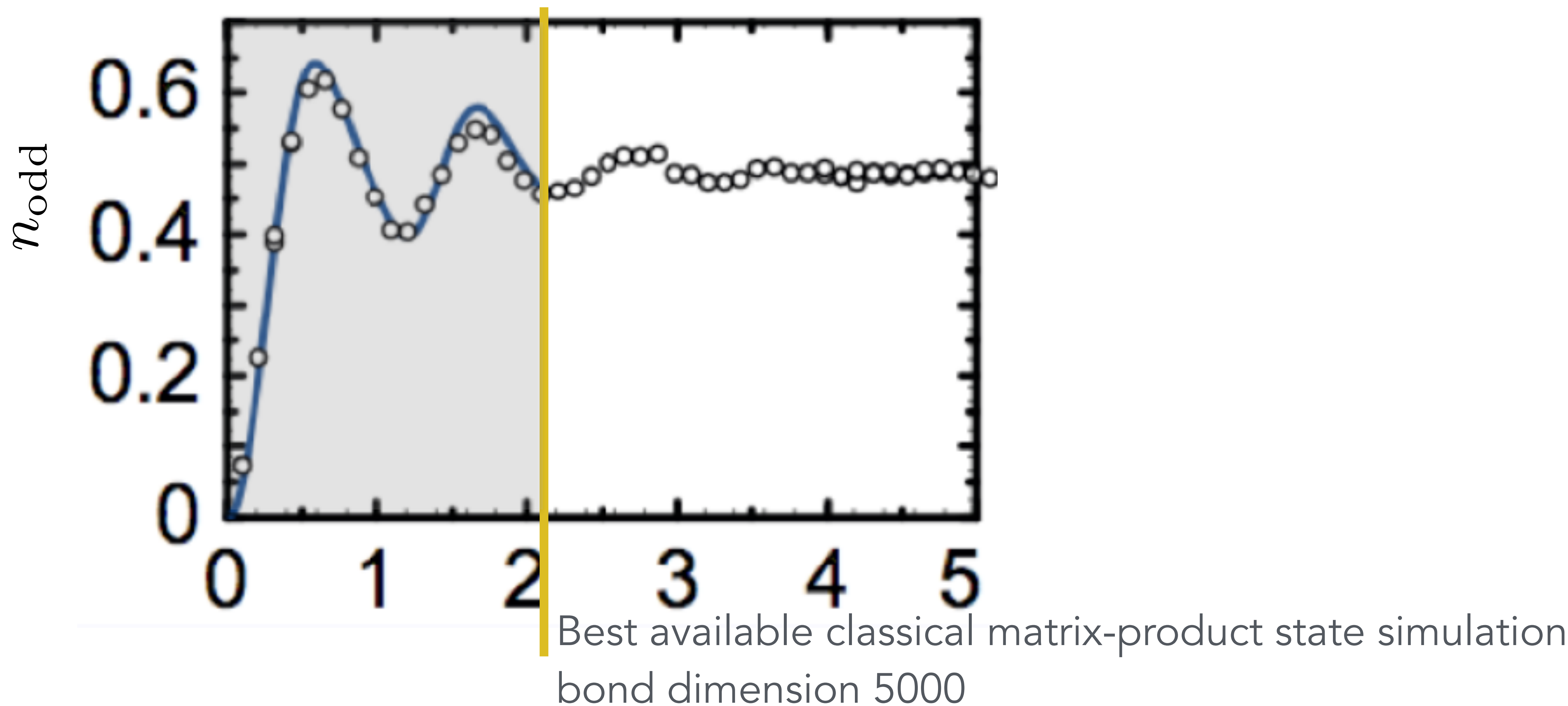


- Probe **local Hamiltonians**, up to $\sim 10^5$ sites
    - Ground state problems
    - "Quenches" $\rho(t) = e^{-itH} \rho e^{itH}$ (time evolution)
    - Slow evolutions, reminiscent of adiabatic quantum computing

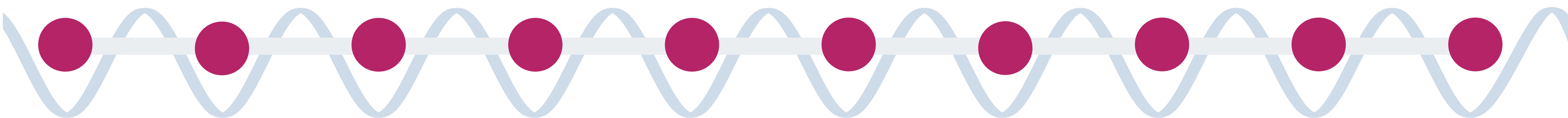
Analog quantum simulators



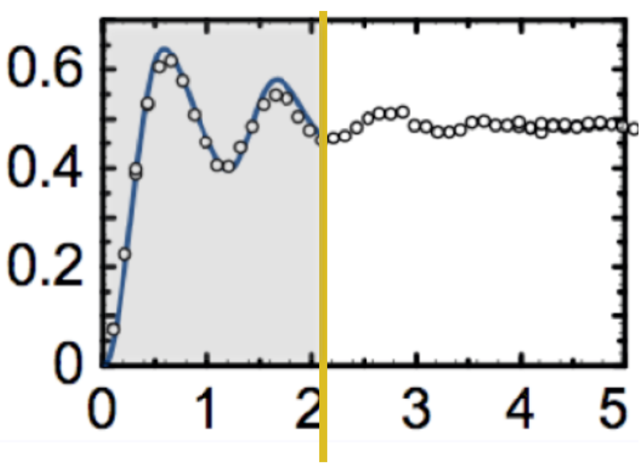
- **Equilibration and thermalisation** of atoms in optical super-lattices (MPQ)
- Imbalance as function of time for $|\psi(0)\rangle = |0, 1, \ldots, 0, 1\rangle$ under Bose-Hubbard Hamiltonian



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



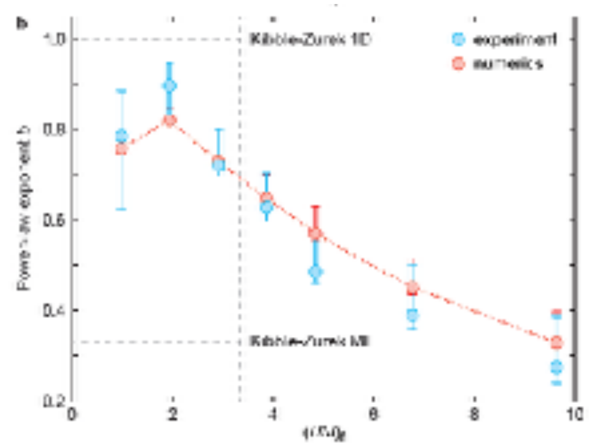
Equilibration



Short times can be efficiently simulated

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

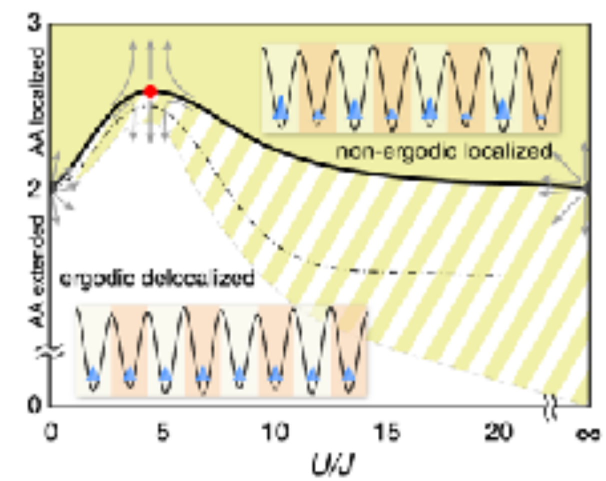
Kibble-Zurek mechanism



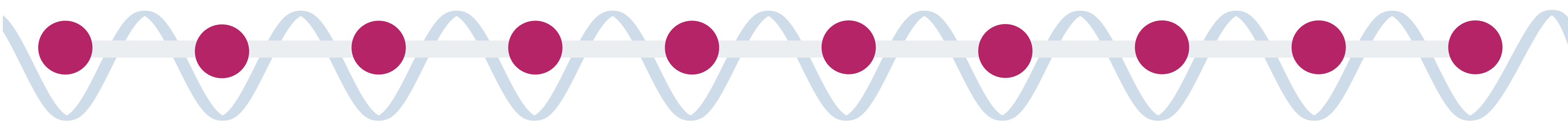
1D systems can be efficiently simulated, 2D systems not

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

Many-body localization



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



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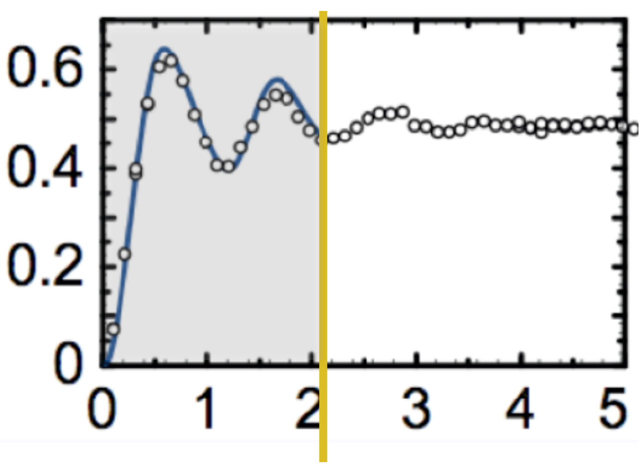

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Trotzl
Eiser

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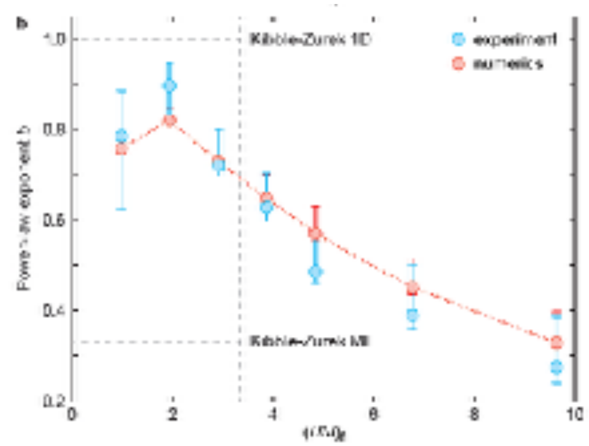

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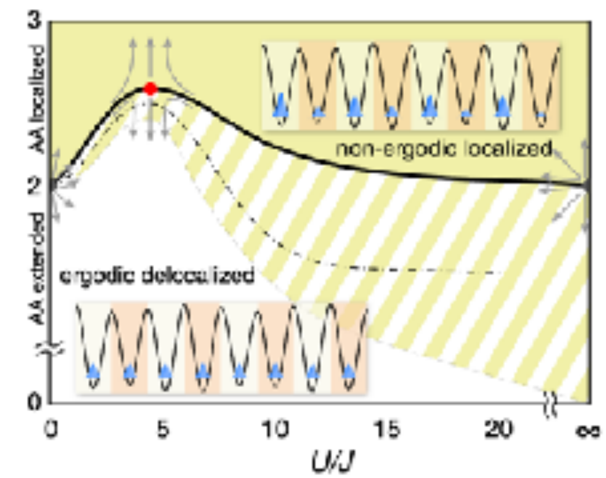


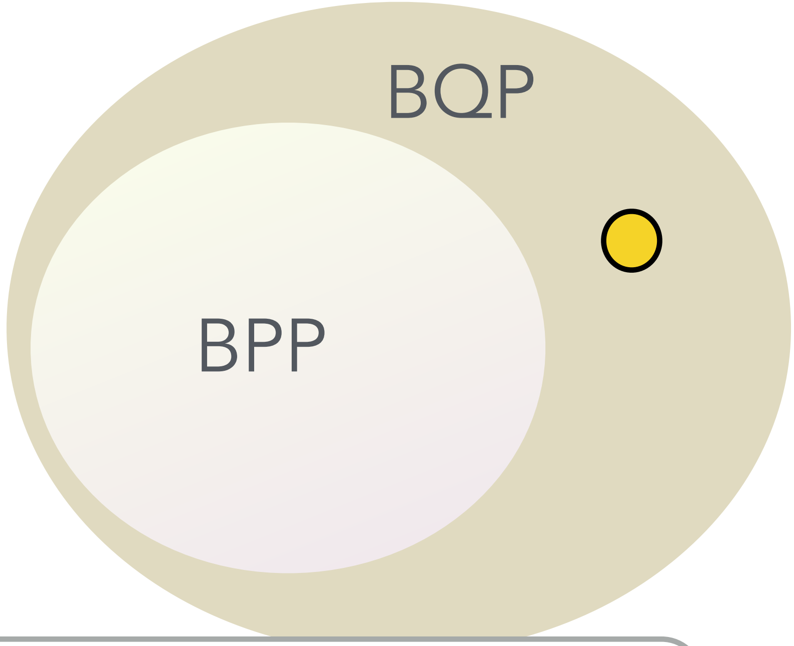
Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk
Altman, Schneider, Bloch, Science 349, 842 (2015)

- **Dynamical quantum simulators**

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

- Cleverer simulation method?

Need for intermediate problems



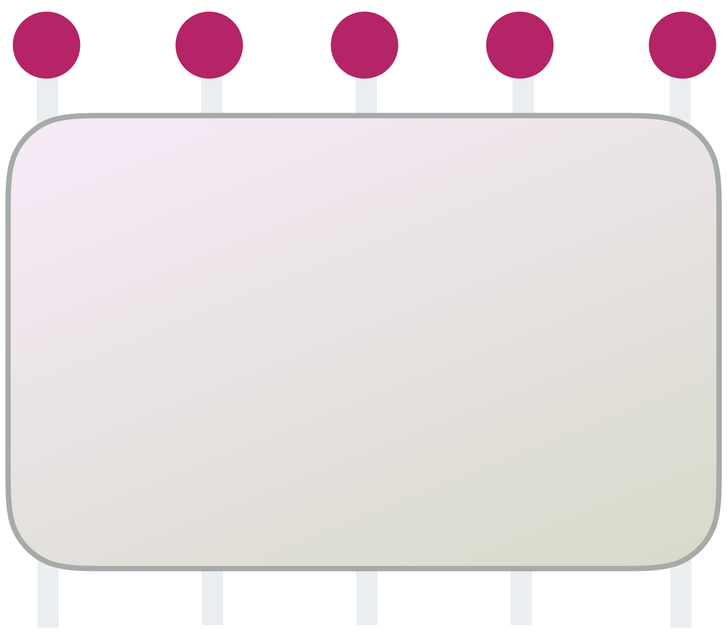
- **Intermediate problems**

To be sure, we must prove the hardness of the task: Identify a (feasible) task that lies outside of BPP, but is not BQP hard

Super-polynomial computational speedups

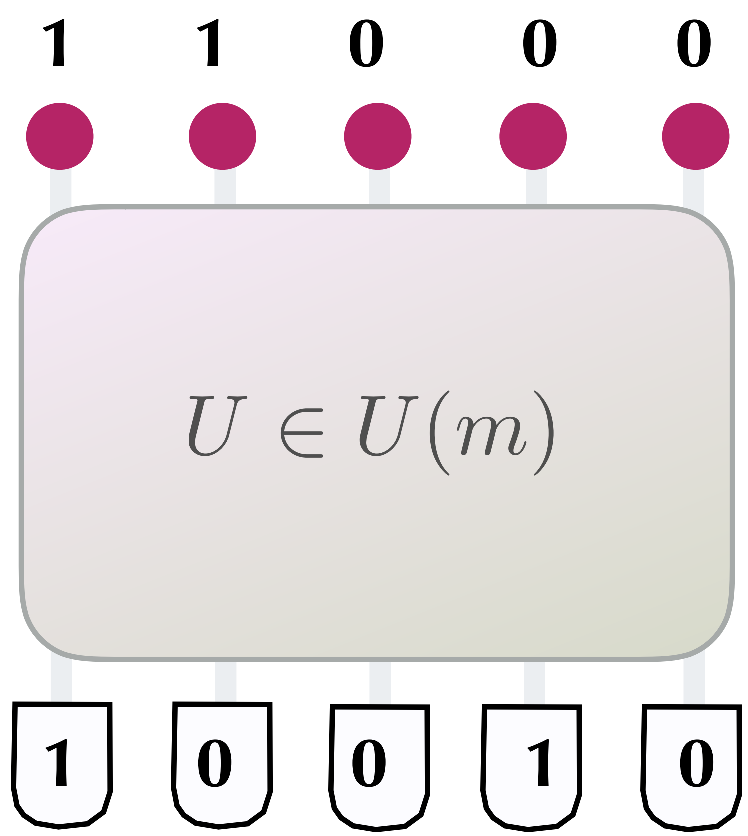
Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup
- Formerly dubbed “quantum computational supremacy”



Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup
- Boson sampling



- n bosons in m optical modes
- Haar random mode transformation $b \mapsto Ub$

$$b = (b_1, \ldots, b_m)^T$$

- Photon detection

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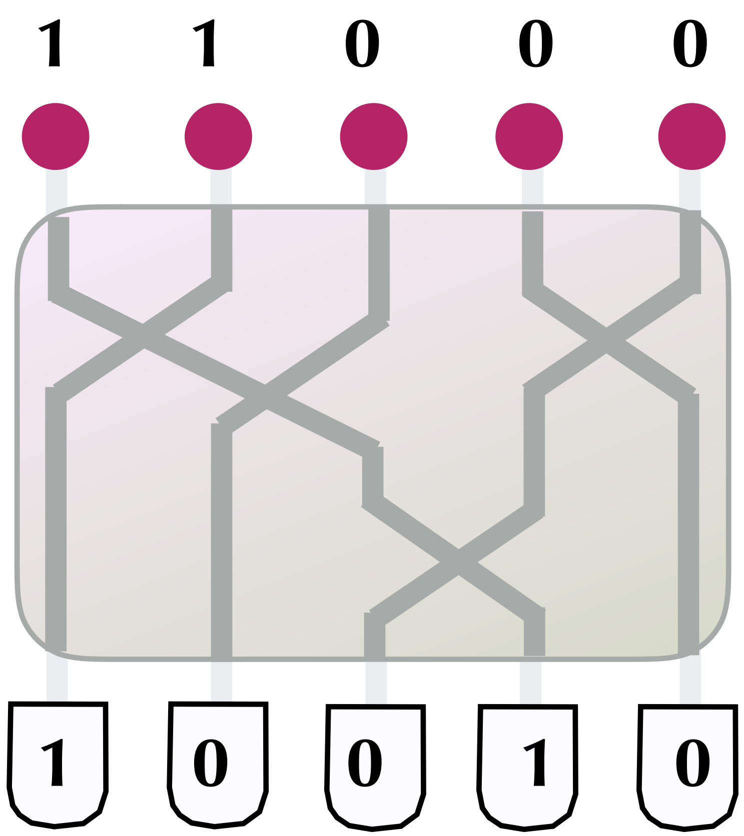

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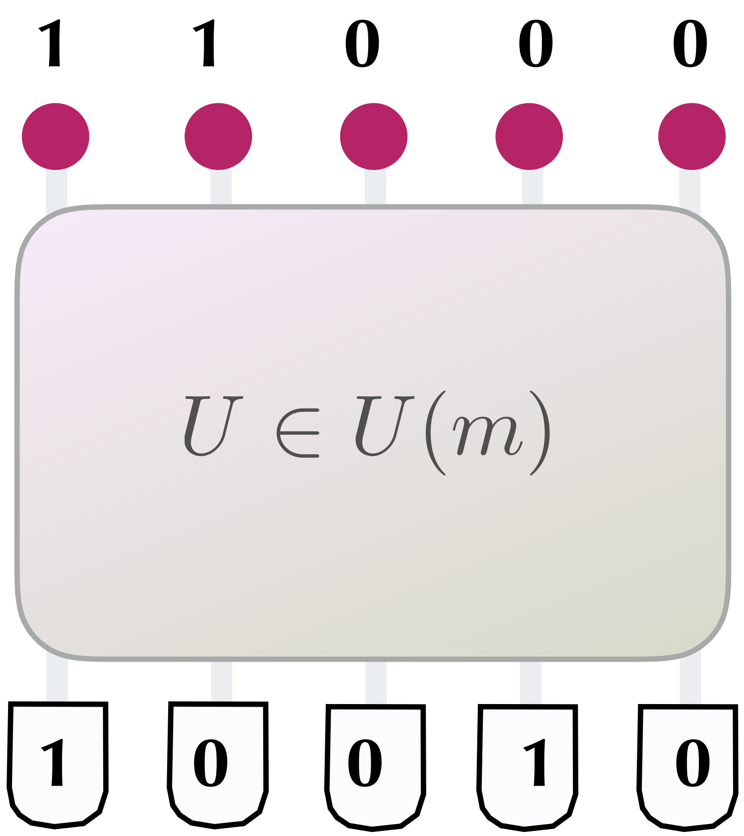

- n bosons in m optical modes
- Haar random mode transformation $b \mapsto Ub$

$$b = (b_1, \ldots, b_m)^T$$

- Photon detection

- **Theorem:**

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

Aaronson, Arkhipov, Th Comp 9, 143 (2013)

Super-polynomial speedups

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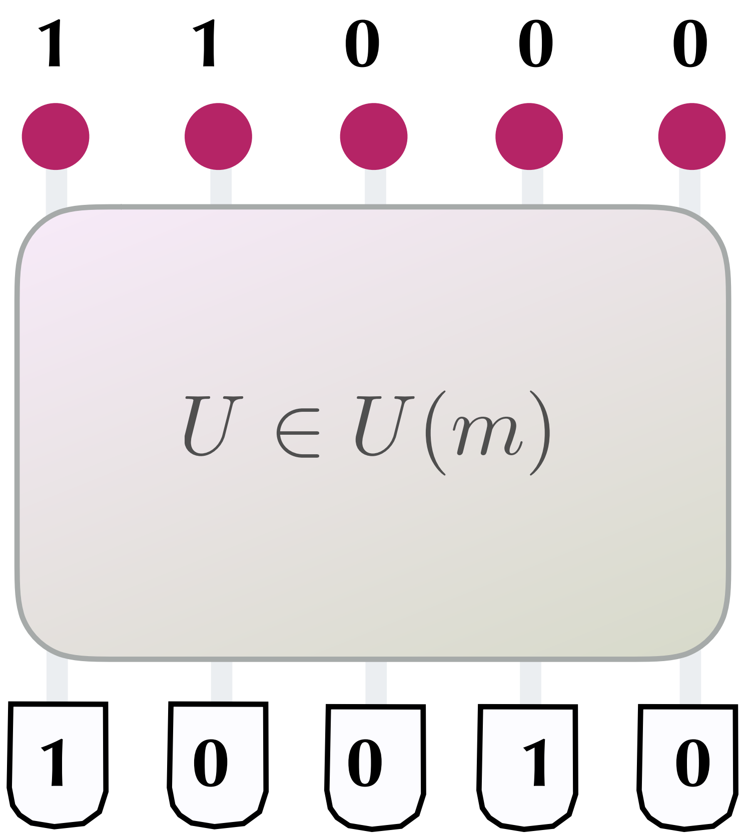

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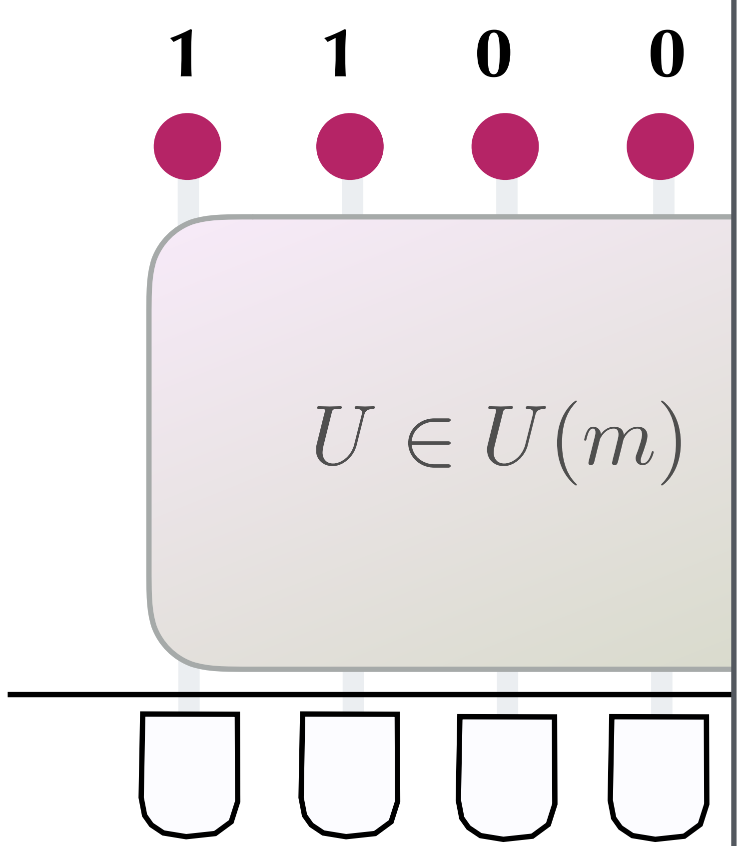
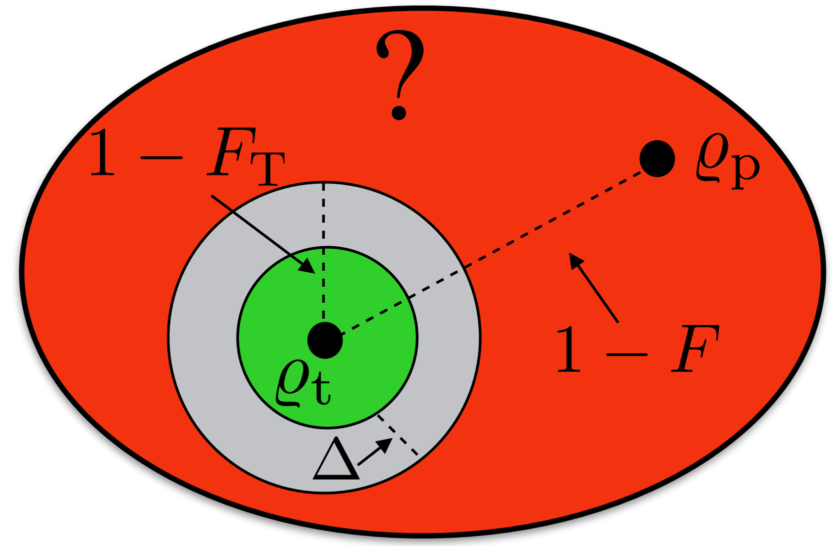


- **Certification** using **continuous-variables:**
- Target fidelity $F(\rho_t, \rho_p) \geq F_T$ with anticipated state ρ_t



- Can perform robust fidelity certfication, with

$$O\left(\frac{\text{poly}(m, 1/\Delta)}{\log(1/(1-\alpha))}\right)$$

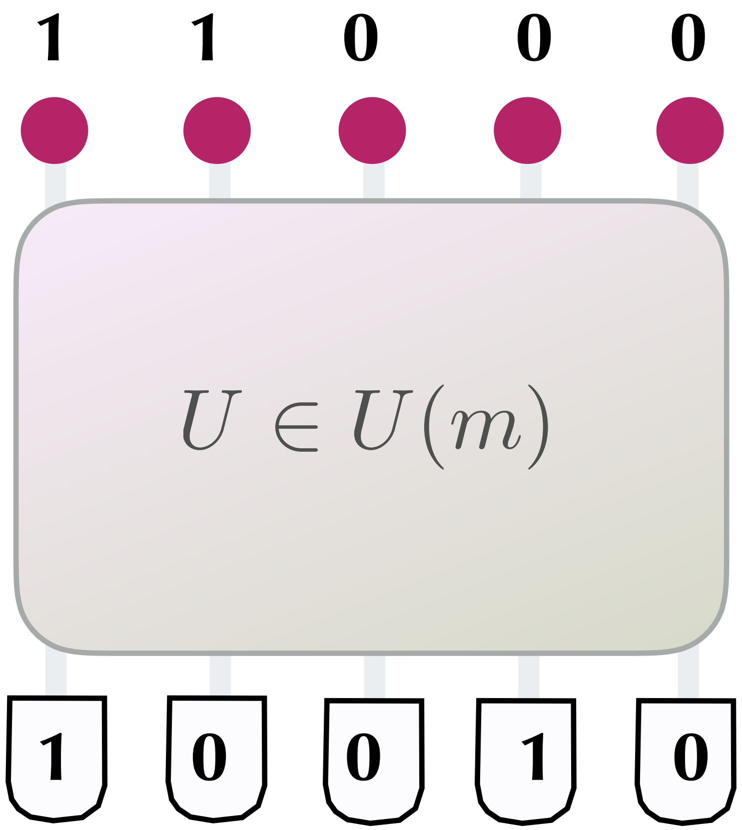
many preparations and **homodyne** measurements, with success probability α

Aolita, Gogolin, Kliesch, Eisert, Nature Communications 6, 8498 (2015)

- Not quite good enough

Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup
- Boson sampling



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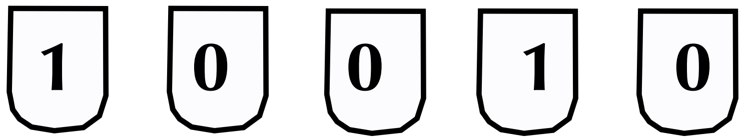


- Let $m \geq n^{5.1}$ and let $U \in U(m)$ be Haar random. Then with probability at least $1-\delta$, for every T and every $\epsilon > 0$, there exists a circuit of size $T\text{poly}(n, 1/\epsilon, 1/\delta)$ that samples a distribution that is ϵ-indistinguishable from the boson sampling distribution by circuits of size at most T

Gogolin, Kliesch, Aolita, Eisert, arXiv:1306.3995
Aaronson, Arkhipov, arXiv: 1309.7460
Trevisan, Tulsiani, Vadhan, Proc IEEE Conf Comp Complex, 126 (2009)
Brandao, private communication

Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup
- Boson sampling

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

Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup
- Boson sampling

  Aaronson, Arkhipov, Th Comp 9, 143 (2013)
- IQP circuits

  Bremner, Montanaro, Shepherd: Phys Rev Lett 117, 080501 (2016)
  Bremner, Jozsa, Shepherd, arXiv:1005.1407
- Random universal circuits

  Boixo, Isakov, Smelzanski, Babbush, Ding, Jiang, Bremner, Martinis, Neven, arXiv:1608.00263 (2016)
- Ising-type interactions

  Gao, Wang, Duan, Phys Rev Lett, 118, 040502 (2017)

+ : Provable classical hardness with l_1 -errors
(under reasonable assumptions)

- : Very hard to implement: Either
  - Hard to scale up with present technology
  - Arbitrary gate choices necessary
  - High (56) periodicity of Hamiltonian

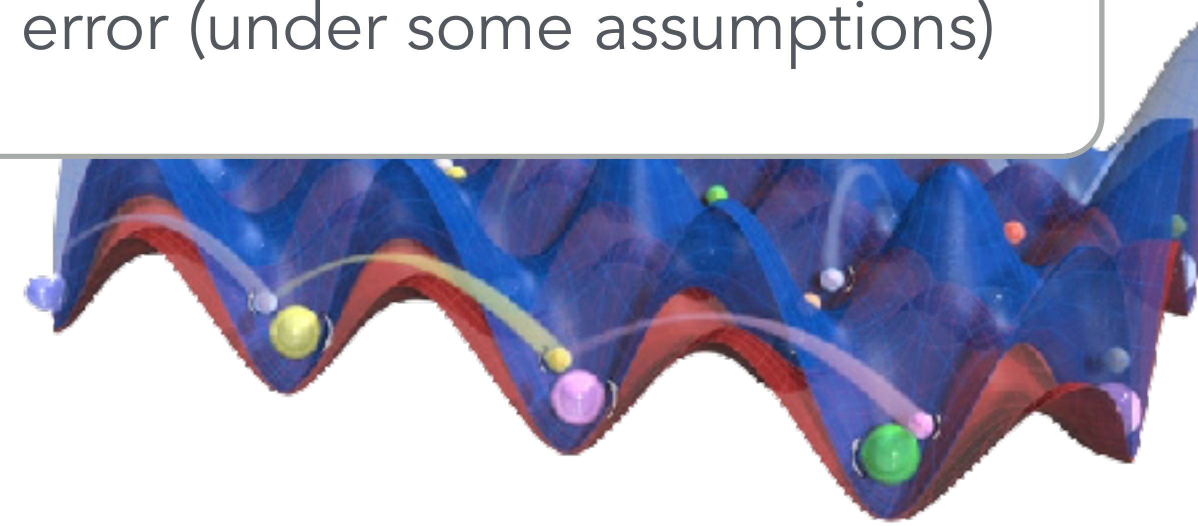
Feasible quantum simulators showing a speedup

Super-polynomial speedups

- **Aim:** Find **some** problem with strong evidence for super-polynomial speedup

Combine benefits of both worlds, bring speedups closer to experiment

- **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, arXiv:1703.00466

Simple Ising models

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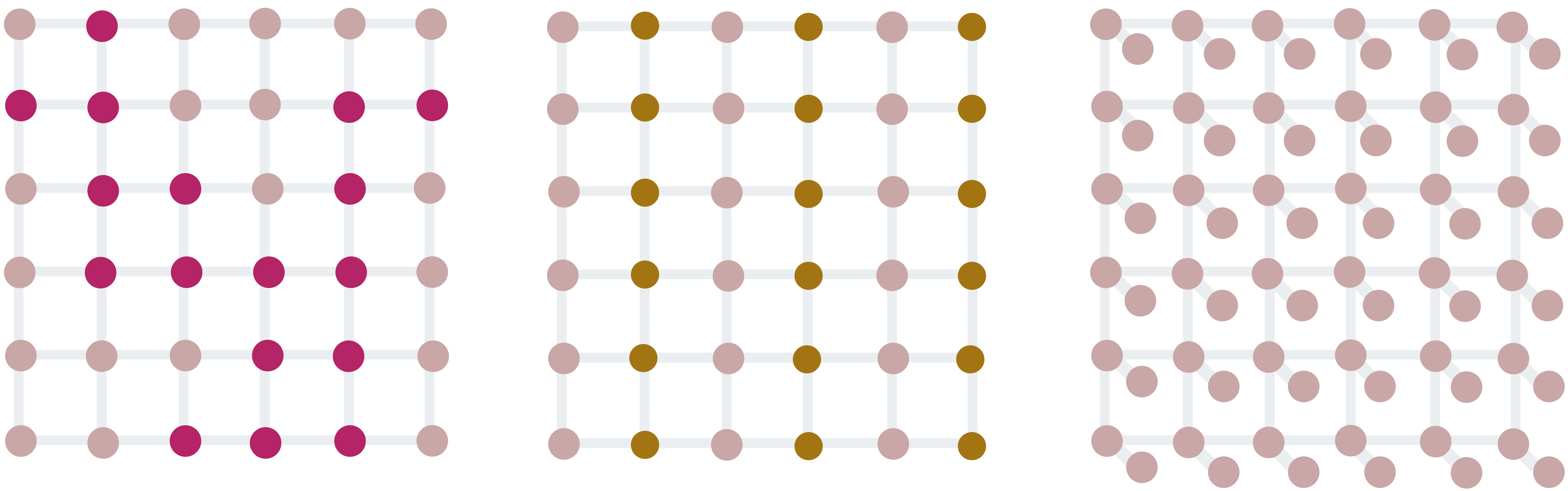


Random — Periodic — Translationally invariant

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

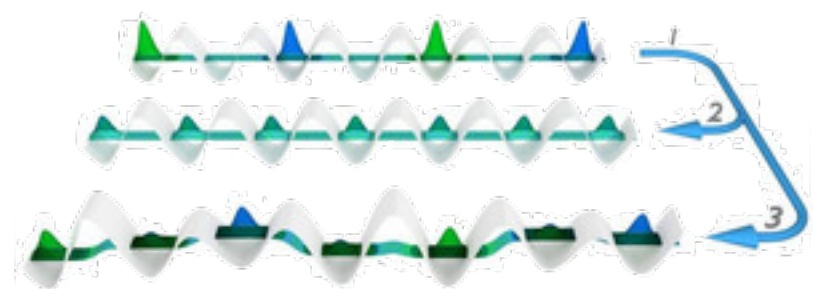
Simple Ising models

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

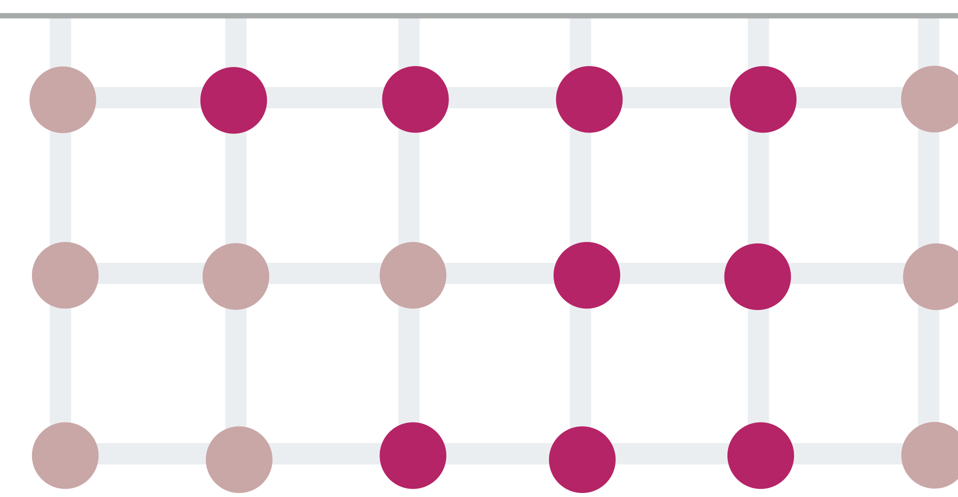
$$|\psi_\beta\rangle = \otimes_{i,j=1}^{n,m} (|0\rangle + e^{i\beta_{i,j}} |1\rangle)$$

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

- Reminscient of disordered optical lattices



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



Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

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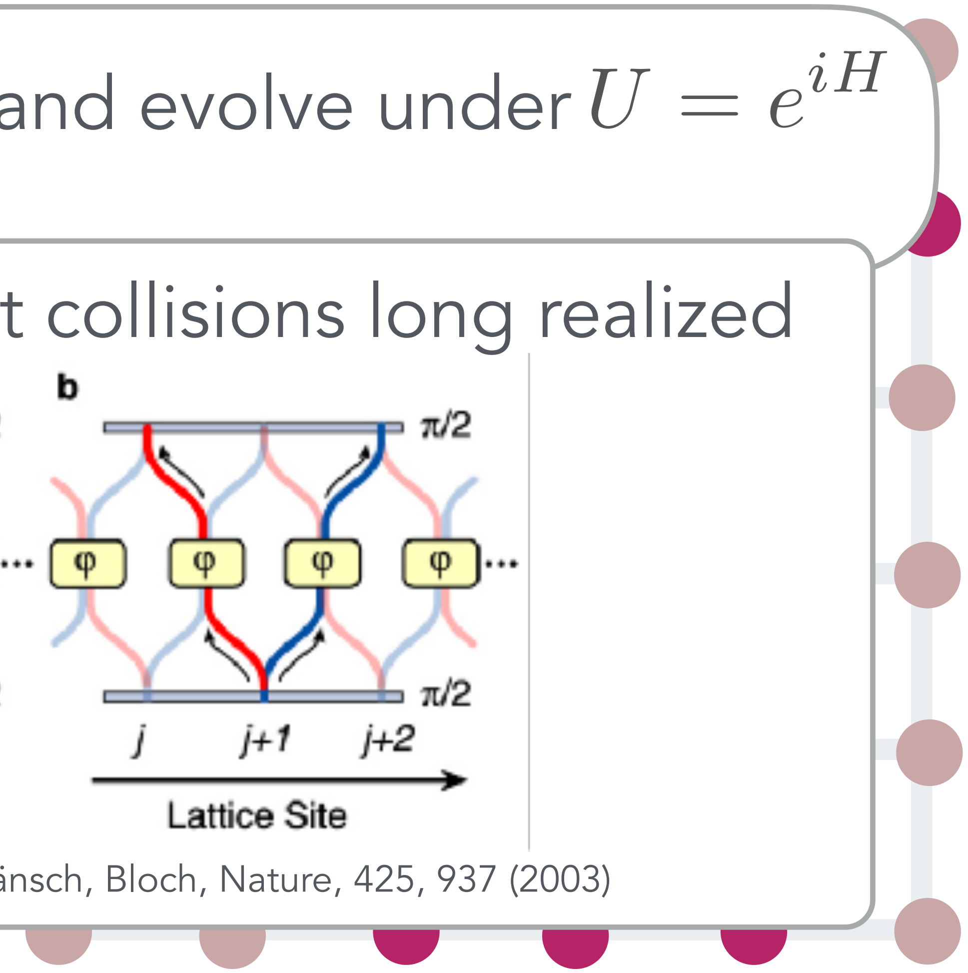
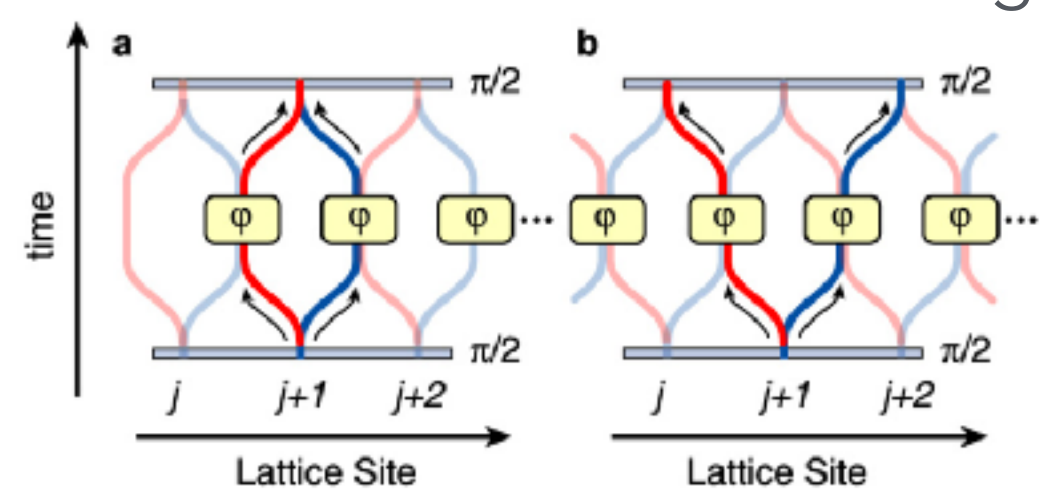
- **Quench** to $H = \sum_{(i,j)\in E} Z_i Z_j + \frac{\pi}{4} \sum_{i \in V} Z_i$ and evolve under $U = e^{iH}$



- Controlled coherent collisions long realized



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

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

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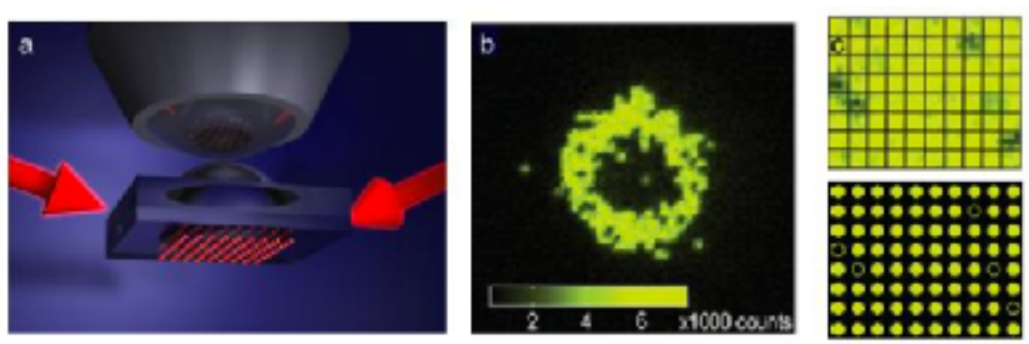
- Measure all qubits in X-basis

- 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, arXiv:1703.00466

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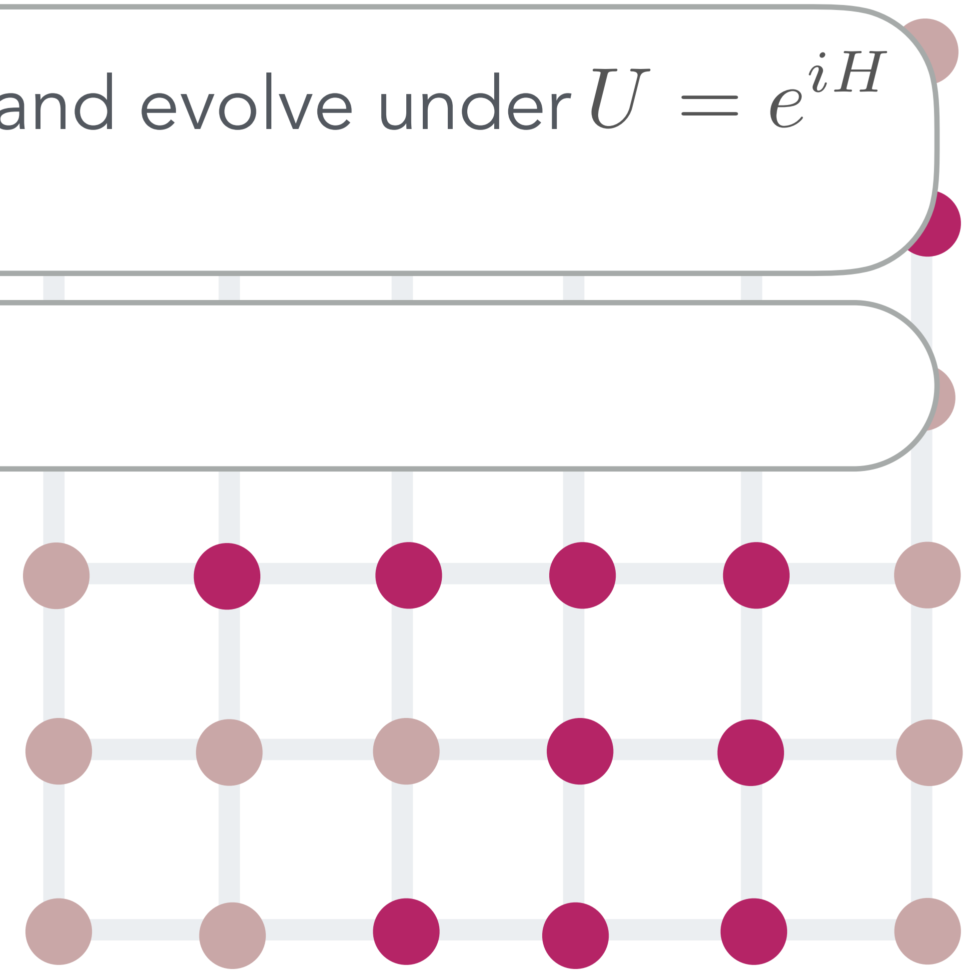
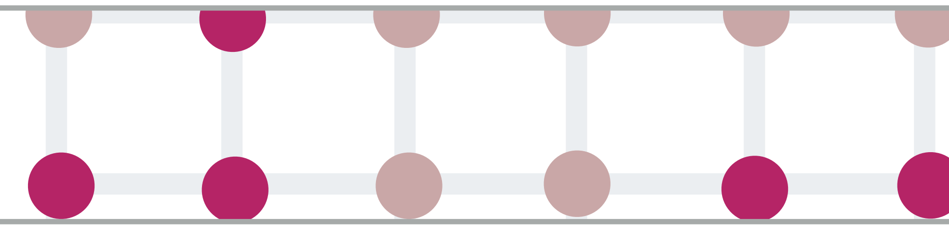


Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

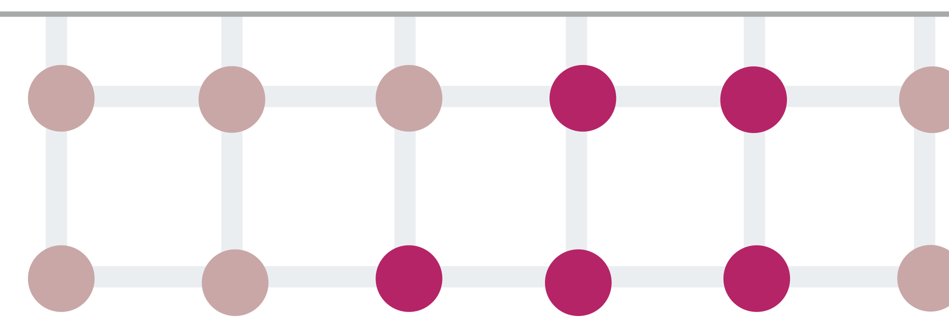
- **Theorem** (Hardness of classical sampling):

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



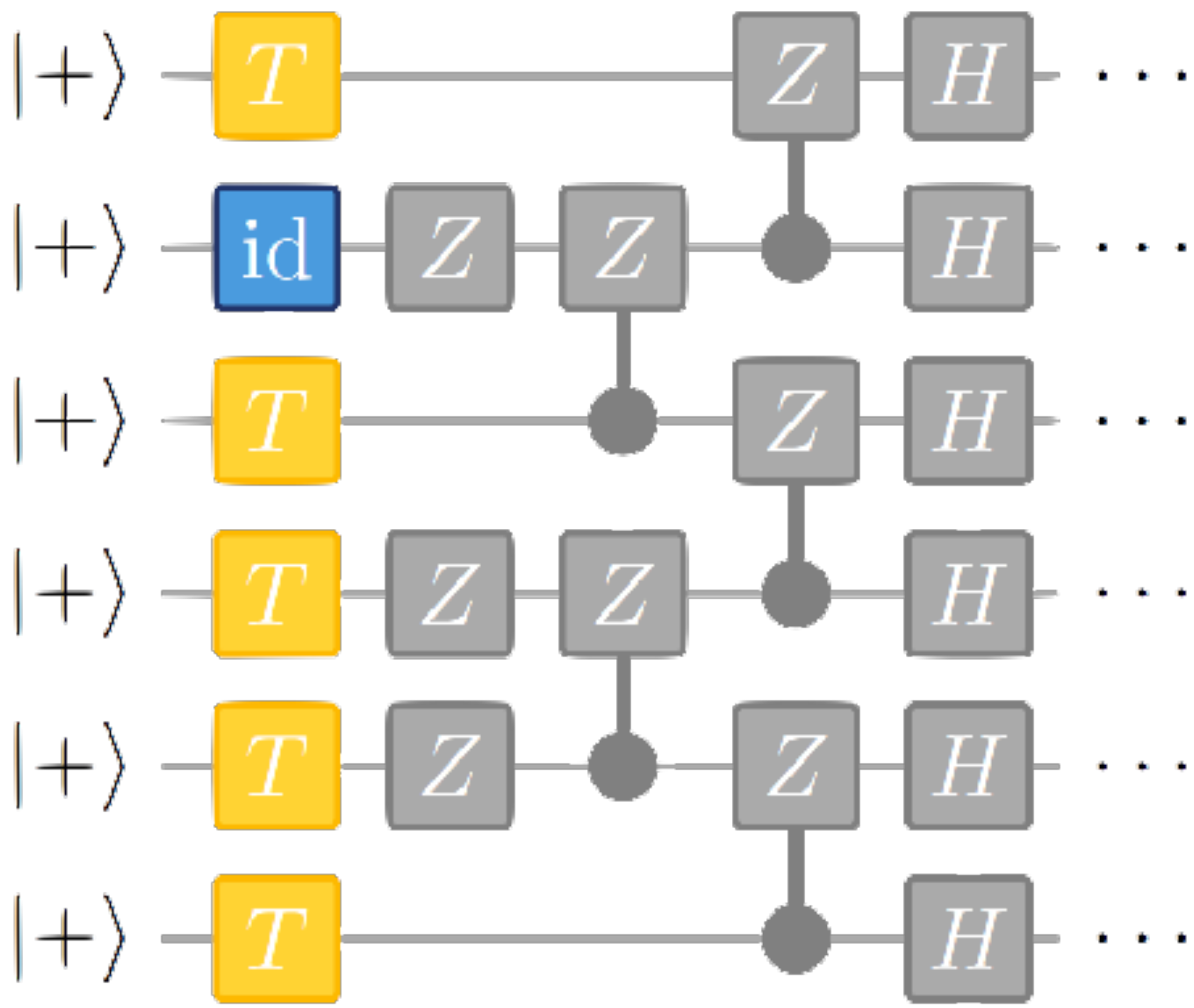
- **Lemma** (Approximation of outcome distribution in worst case):

It is #P-hard to approximate the outcome distribution of an all-X measurement $U|\psi_\beta\rangle$ to constant relative error

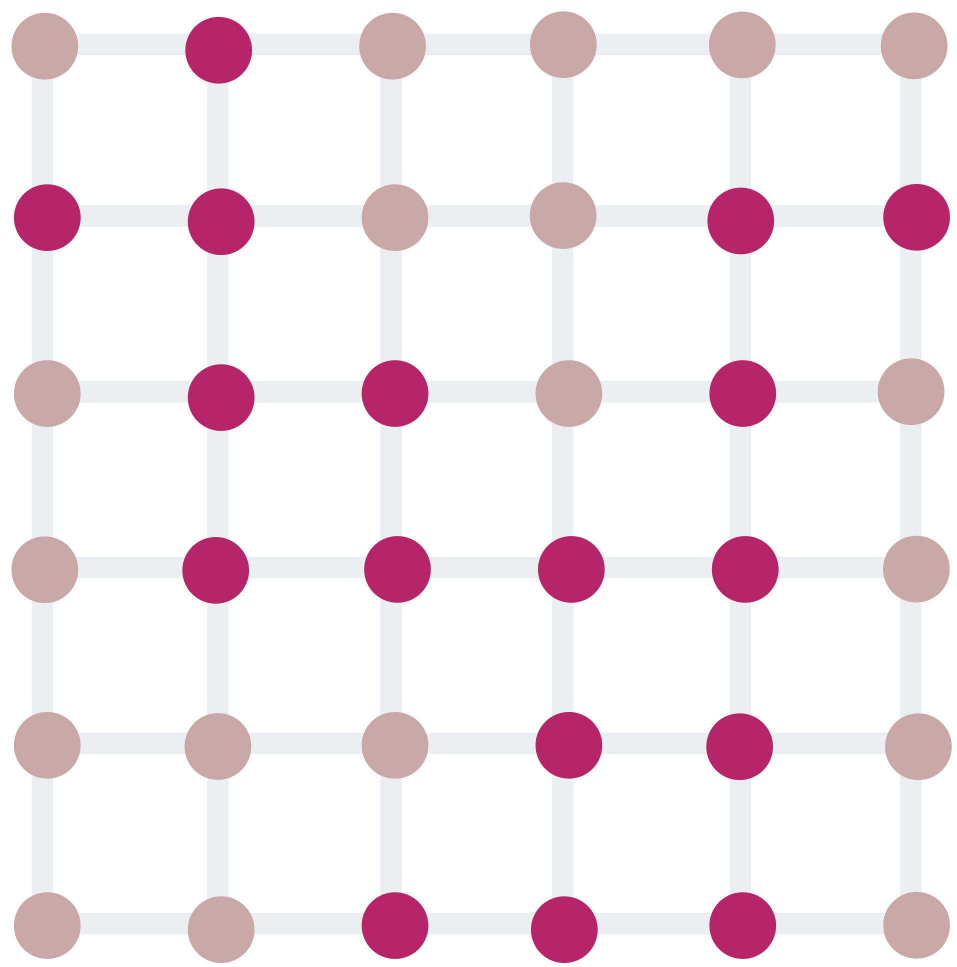


- **A hint at the argument:** Universal architecture for postBQP

Logical



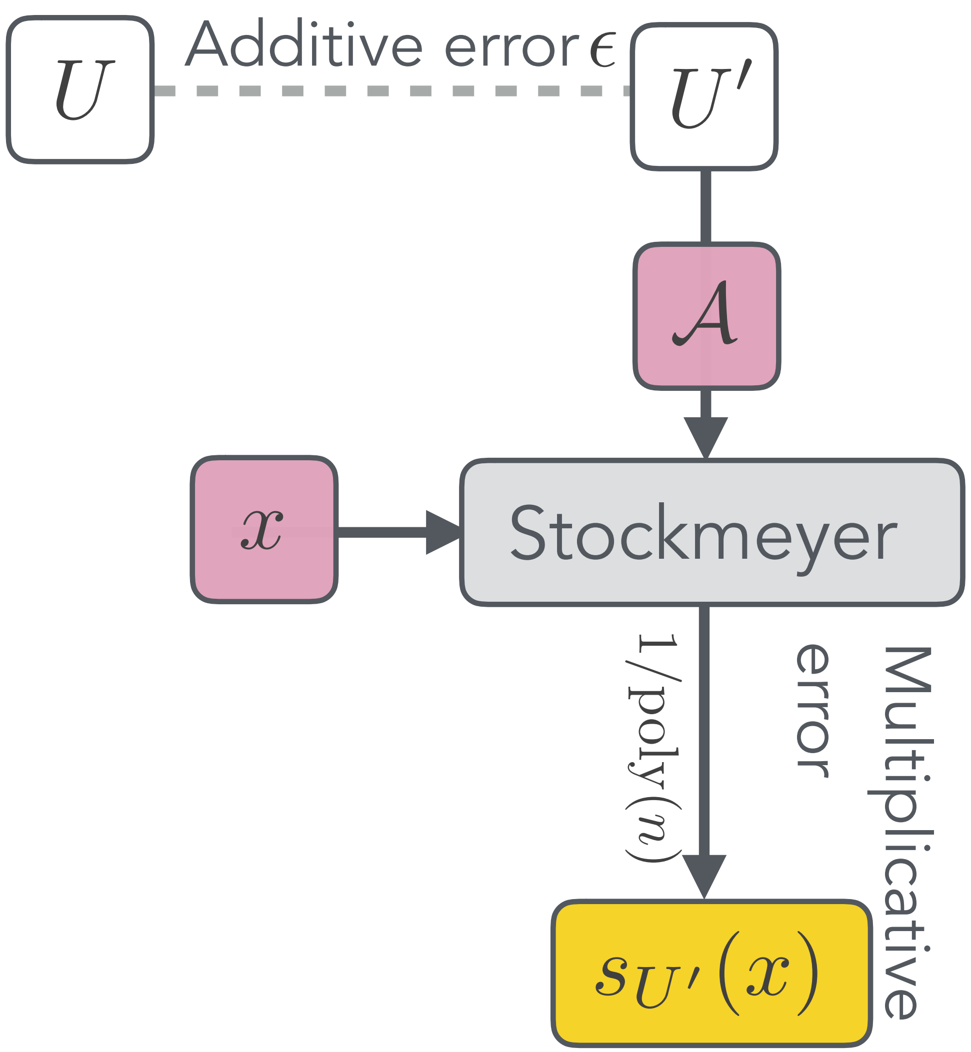
Physical



Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466
Building upon Mantri, Demarie, Fitzsimons, arXiv:1607.00758
Raussendorf, Phys Rev A 72, 052301 (2005)

Quantum simulators

- **Ingredients**
  - A classical algorithm $\mathcal{A}$ that samples from the output distribution of U' such that $\|p_{U'} - p_U\|_{l_1} \leq \varepsilon$
  - A binary string x



- Approximate sampling $\|p_U - p_{U'}\|_{l_1} < \epsilon$

- Stockmeyer error $|s_{U'}(x) - p_{U'}(x)| \leq \frac{p_{U'}(x)}{\text{poly}(n)}$

$$|s_{U'}(x) - p_U(x)| \leq \frac{p_U(x)}{\text{poly}} + \frac{\epsilon}{2^n \delta}(1 + o(1))$$

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

Complexity theoretic conjectures

- **Polynomial hierarchy:** The polynomial hierarchy is infinite (i.p. $P \neq NP$)
- **Average case complexity:** For a constant fraction of the instances it is as hard to sample from the outcomes of measurements as in worst case
- **Anti-concentration:** The output probabilities of $U|\psi_\beta\rangle$ anticoncentrate, i.e.,

$$\mathrm{prob}_U\left(|\langle a|U|\psi_\beta\rangle|^2 \geq \frac{1}{2^N}\right) \geq \frac{1}{e}$$

Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466

Complexity theoretic conjectures

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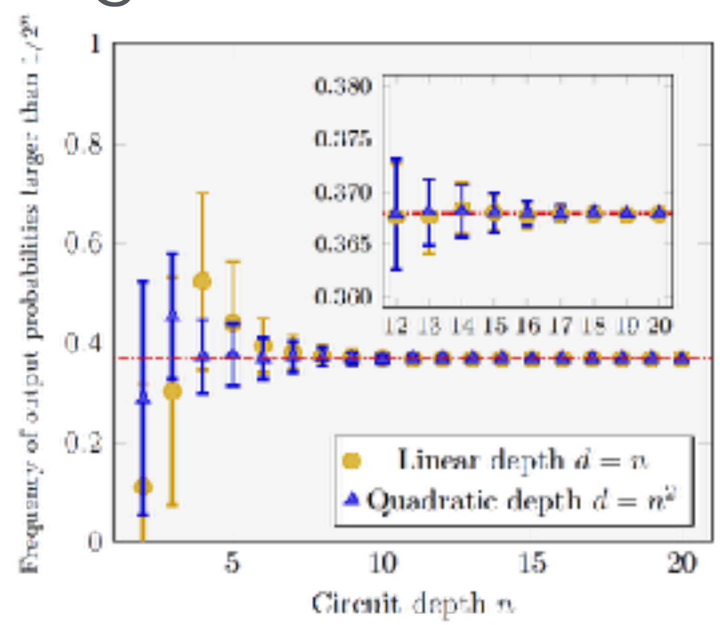
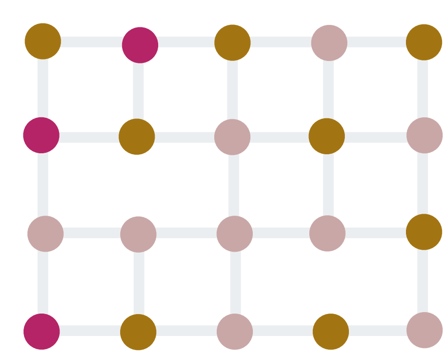
- **Anti-concentration:** The c... ntrate, i.e.,

$$\mathrm{prob}_U \left(|\langle a|U|\psi_\beta\rangle \right.$$

- Strong numerical evidence



- Rigorous proofs for random circuits



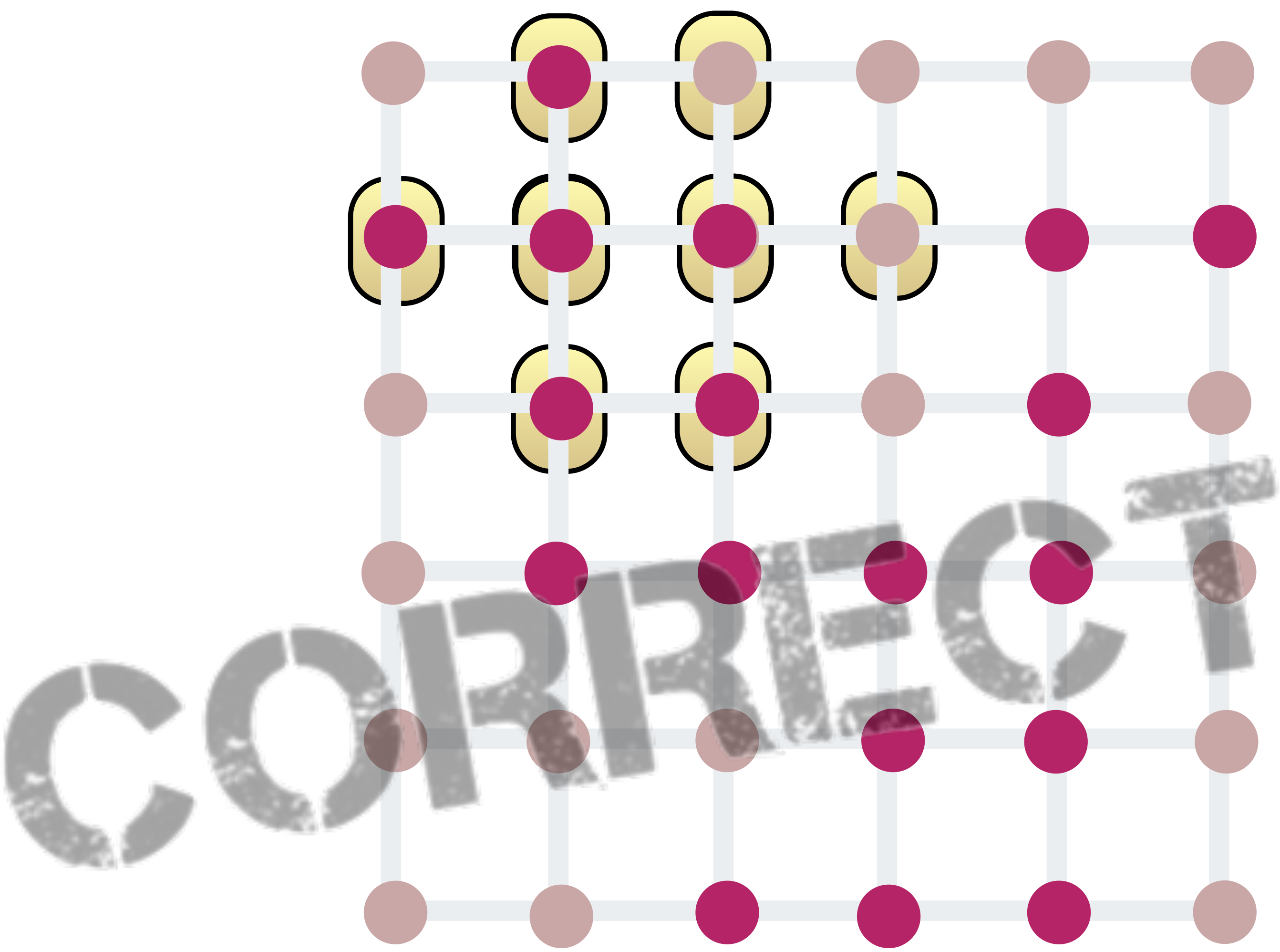
Hangleiter, Bermejo-Vega, Schwarz, Eisert, arXiv:1706.03786
Mann, Bremner, arXiv:1711.00686

... Eisert, arXiv:1703.00466

Complexity theoretic conjectures

- This quantum simulation is intractable for classical computers

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



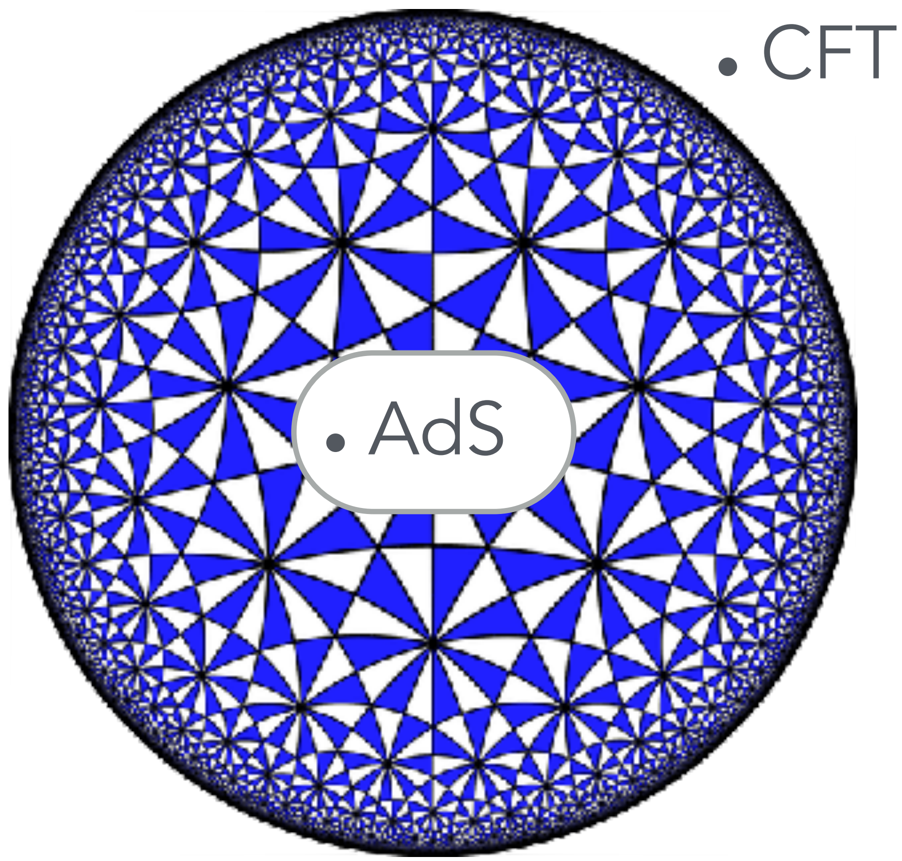
Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, arXiv:1703.00466
Hangleiter, M. Kliesch, M. Schwarz, J. Eisert, Quantum Sci Technol 2, 015004 (2017)
Cramer et al, Nature Comm 1, 149 (2010)

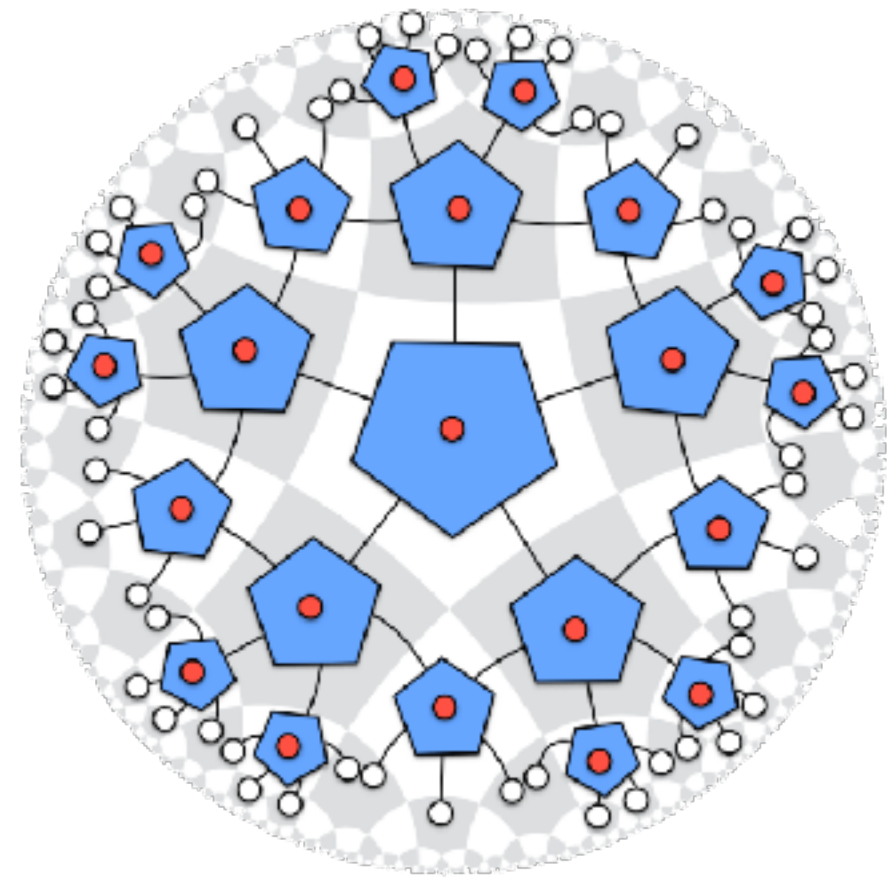
Summary

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

Teaser: Holography and criticality in matchgate tensor networks

Toy models for the AdS/CFT correspondence



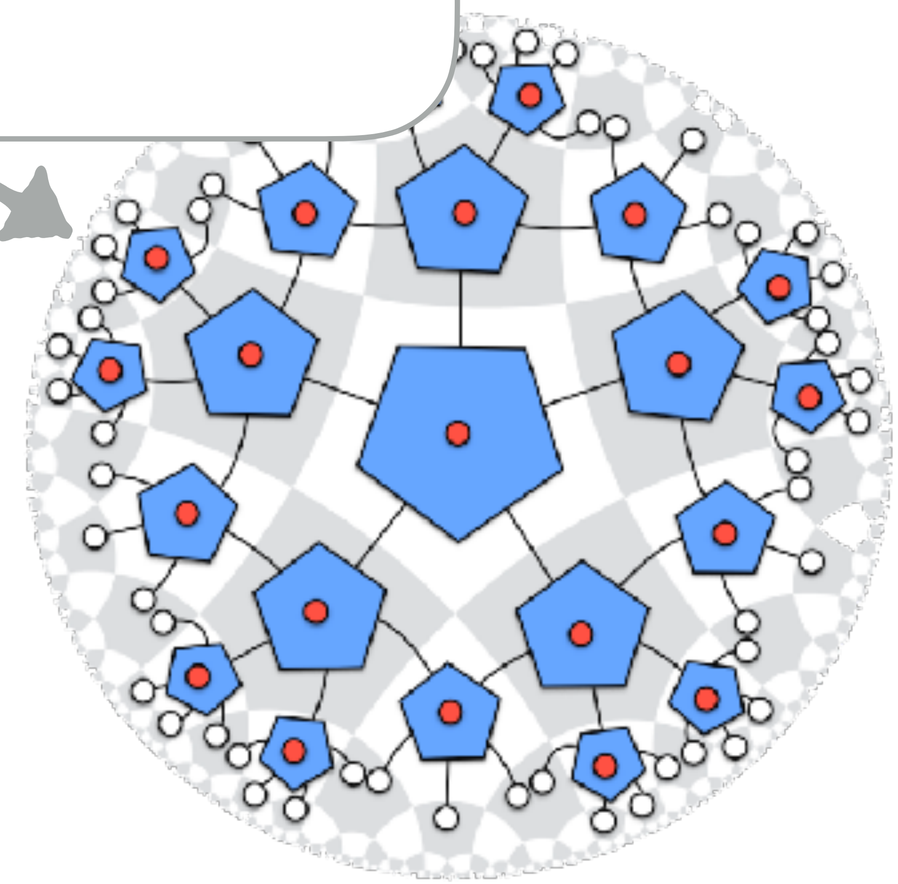


- Duality between Einstein gravity in $D+2$ Anti de Sitter spacetime and
- Conformal field theory in $D+1$ dimensions

Maldacena, Avd Th Math Phys 2, 231 (1998)
van Raamsdonk, Gen Rel Grav 42, 2323 (2010)

- **Quantum error correction:** Holographic pentagon code
    - Isometric tensor from bulk to boundary
    - Realizes Ryu-Takayanagi formula

Almheiri, Dong, Harlow, JHEP 1504, 163 (2015)
Pastawski, Yoshida, Harlow, Preskill, JHEP 2015, 149 (2015)
Ryu, Takayanagi, Phys Rev Lett 96, 181602 (2006)



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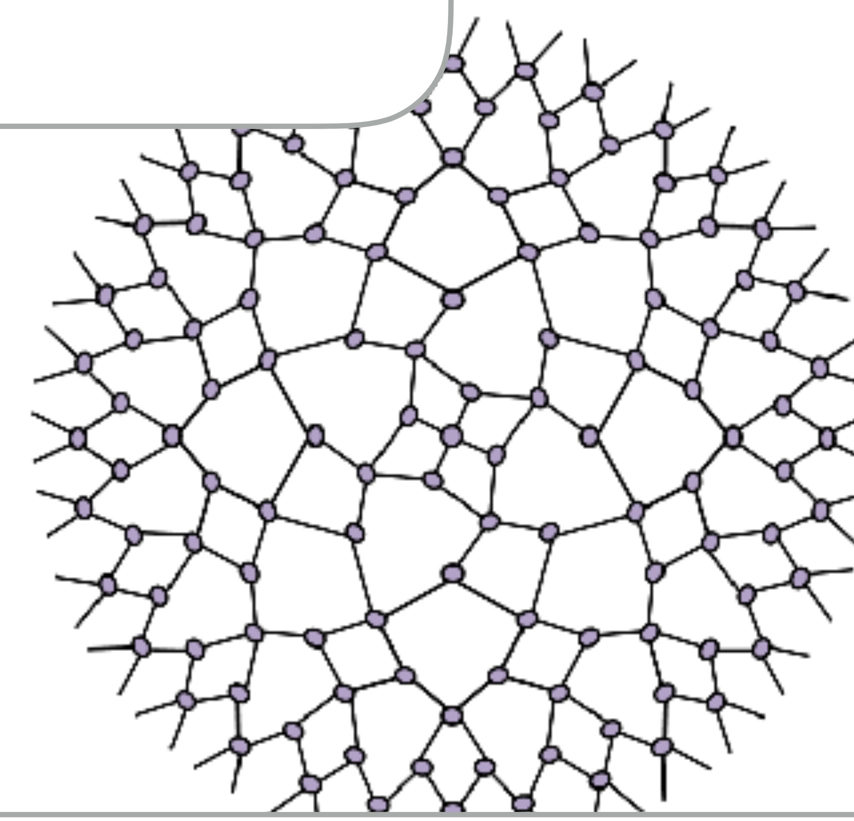

- **Multi-scale entanglement renormalization approach**
  - Realise critical Ising theory on boundary

  Vidal, Phys Rev Lett 101, 110501 (2008)
  Evenbly, Vidal, Phys Rev B, 79, 144108 (2009)
  Swingle, Phys Rev D 86, 065007 (2012)
  Haegeman, Swingle, Walter, Cotler, Evenbly, Scholz, arXiv:1707.06243

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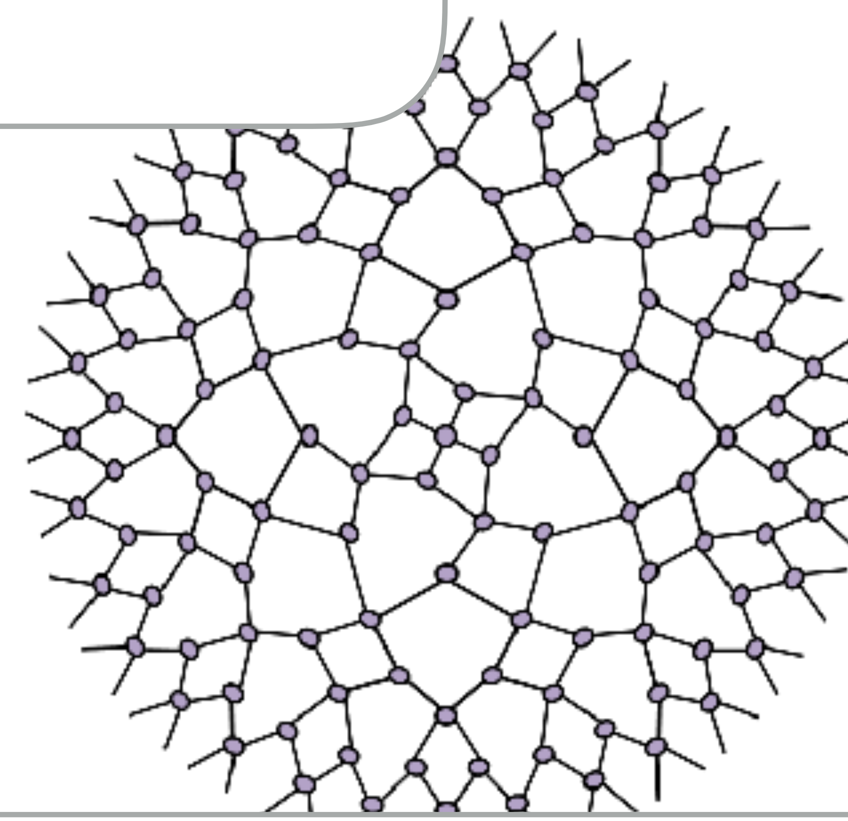
- Random tensors

  Hayden, Nezami, Qi, Thomas, Walter, Yang, JHEP 2016, 9 (2016)



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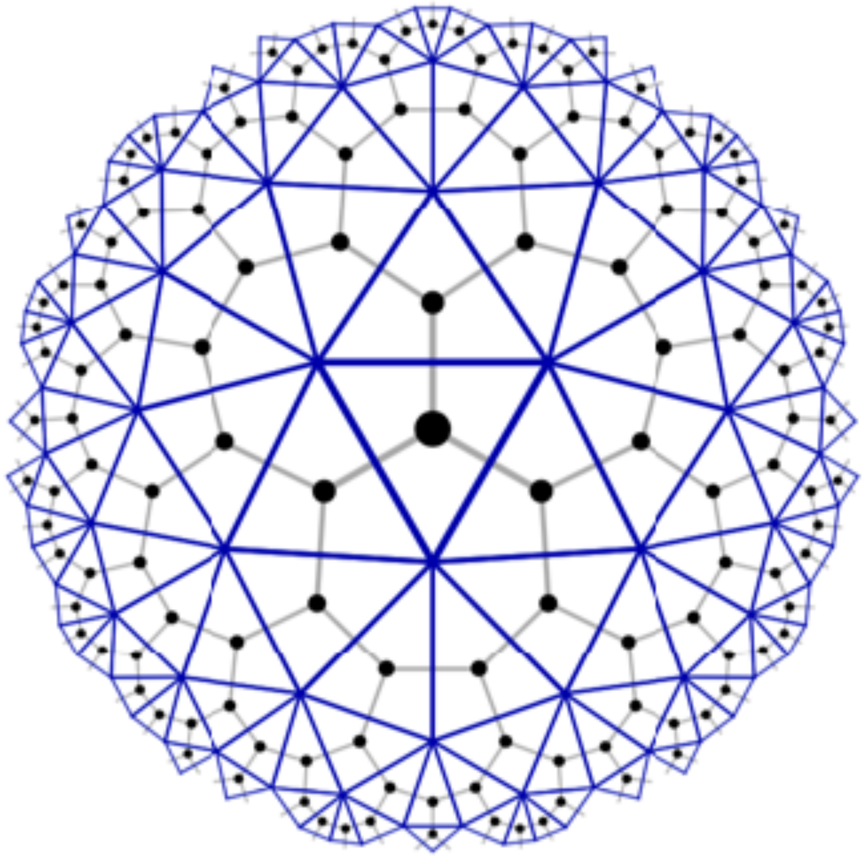
Matchgate tensor networks



- Can one embody them in a larger framework?

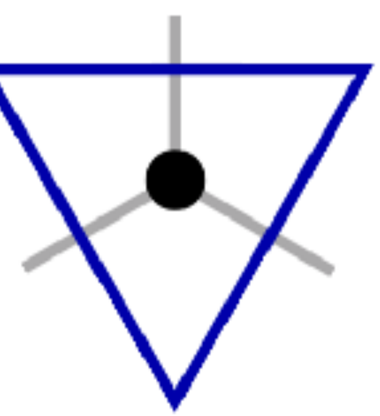
Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

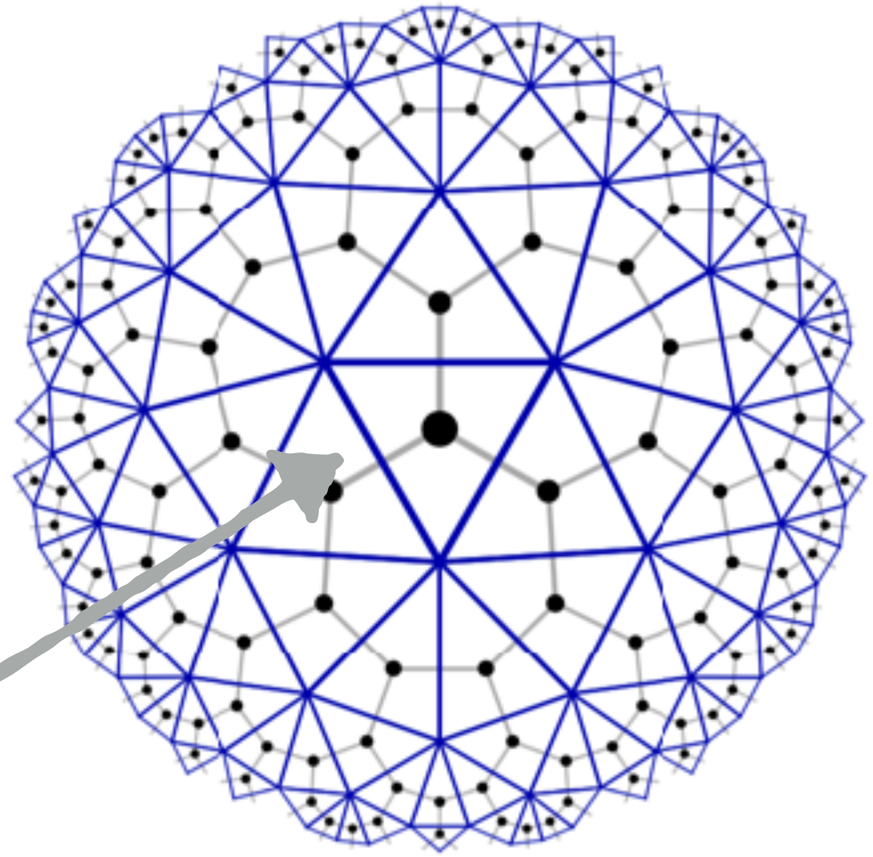
Matchgate tensor networks

- Matchgate tensor

$$T_v : \{0,1\}^{\times r} \to \mathbb{C}$$

per vertex $v \in V$





- Boundary state obtained by tensor contraction $|\psi\rangle = \sum_{j \in \{0,1\}^{\times L}} T(j)\,|j\rangle$

Bravyi, Cont Math 482, 179 (2009)
Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Matchgate tensor networks

- Grassmann-variate characteristic function

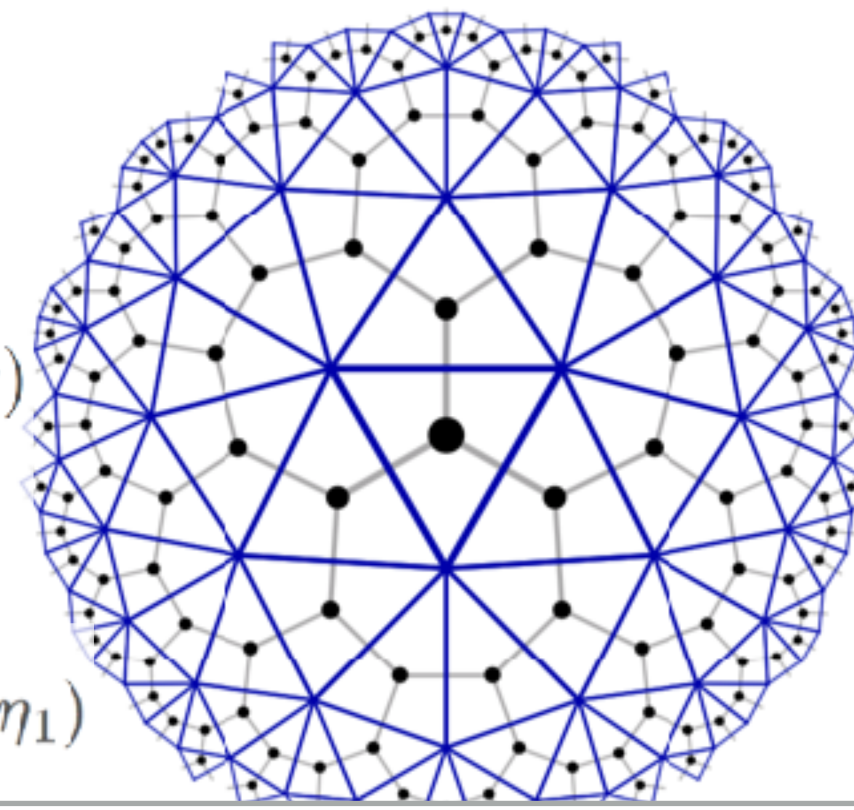
$$\Phi_T(\theta) = \sum_{j\in\{0,1\}^{\times r}} T(j)\theta_1^{j_1}\theta_2^{j_2}\dots\theta_r^{j_r}$$

$$\theta_k\theta_{k'} + \theta_{k'}\theta_k = 0$$

- Contraction $T_{1\star 2}(x,y) = \sum_{z\in\{0,1\}} T_1(x,z)T_2(z,y)$

gives

$$\Phi_{T_{1\star 2}}(\xi) = \int d\eta_1 \int d\theta_{r_1}\, \Phi_{T_1}(\theta)\Phi_{T_2}(\eta)\exp(\theta_{r_1}\eta_1)$$



- **Matchgate tensors:** Consider a rank-r tensor $T(x)$ with inputs $x \in \{0,1\}^{\times r}$, $T(x)$ is a matchgate if there exists an antisymmetric matrix $A \in \mathbb{C}^{r\times r}$ so that

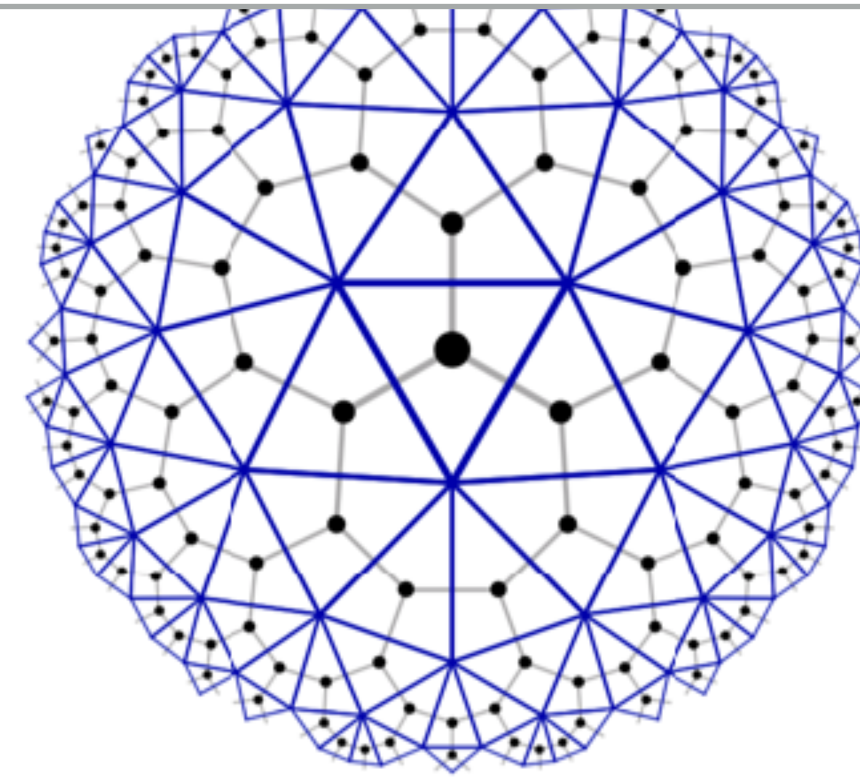
$$T(x) = \mathrm{Pf}(A_{|x\mathrm{XORz}})T(z)$$

where $\mathrm{Pf}(A)$ is the Pfaffian of A and $A_{|x}$ is the submatrix of A acting on the subspace supported by x

Bravyi, Cont Math 482, 179 (2009)
Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Contraction

- **Observation:** The contraction requires $O(L^2 N)$ steps for L boundary sites and N contracted tensors



- Generic even matchgate with $\bar{z} = 0$ has

$$\Phi_T(\theta) = T(\overline{0}) \exp\left(\frac{1}{2} \sum_{j,k=1}^{r} A_{j,k} \theta_j \theta_k \right)$$

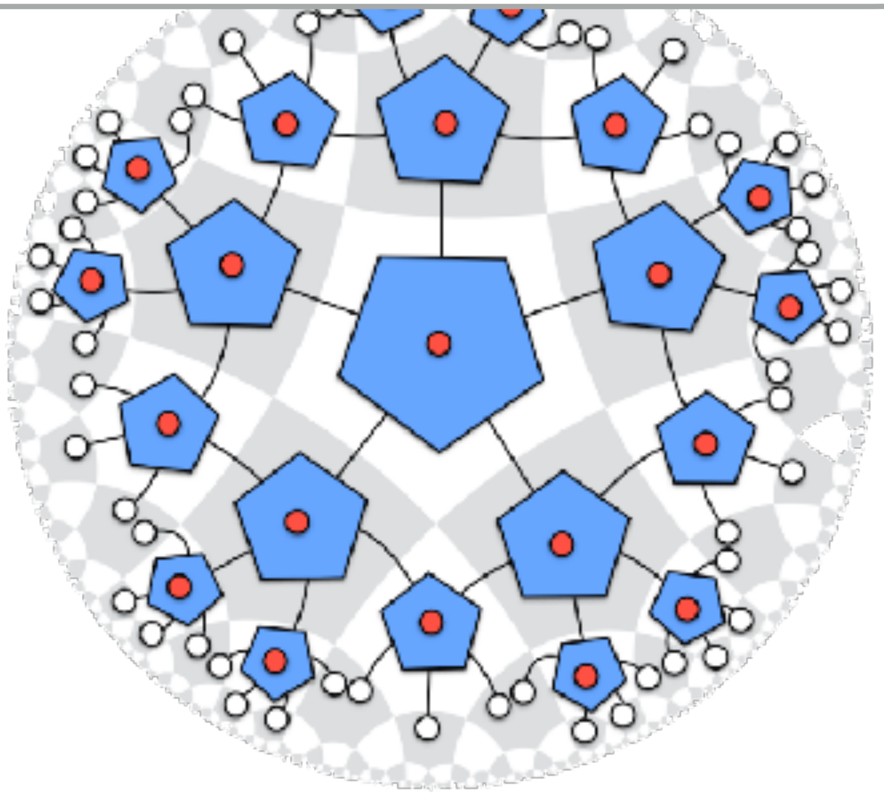
  with generating matrix A

- Gives rise to various tilings, models, etc

Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Relationship to Pentagon code

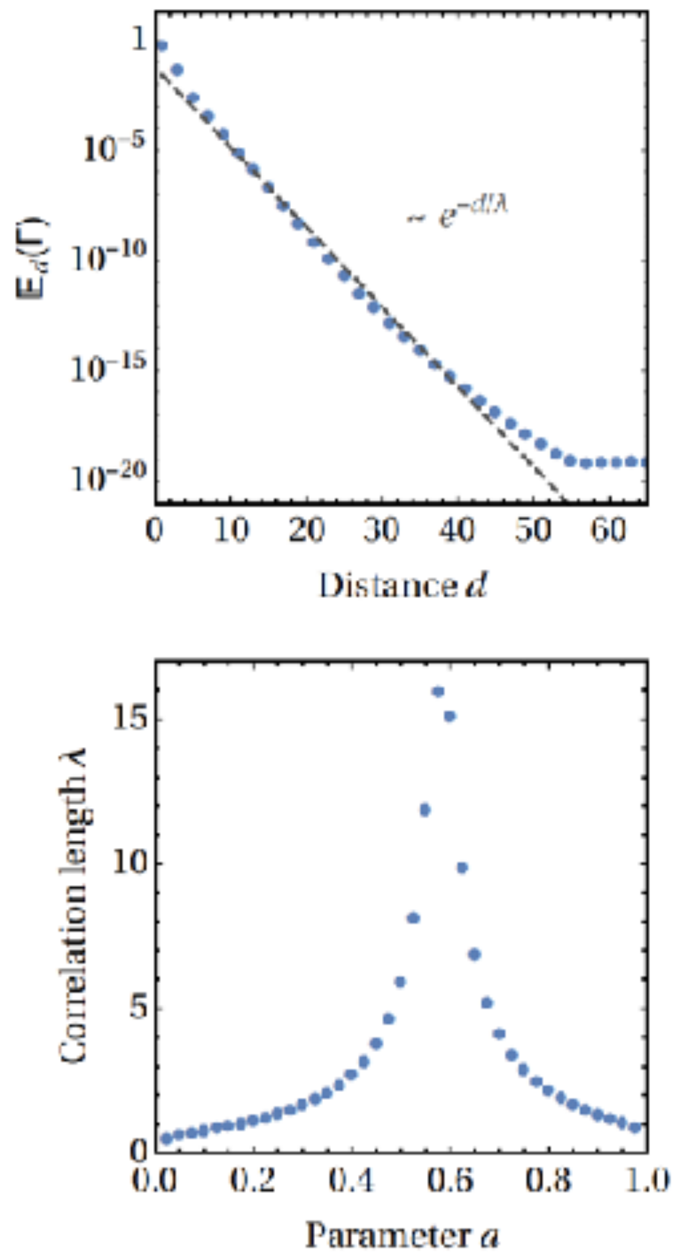
- **Observation:** The holographic pentagon code with computational basis input in the bulk yields a matchgate tensor on the boundary

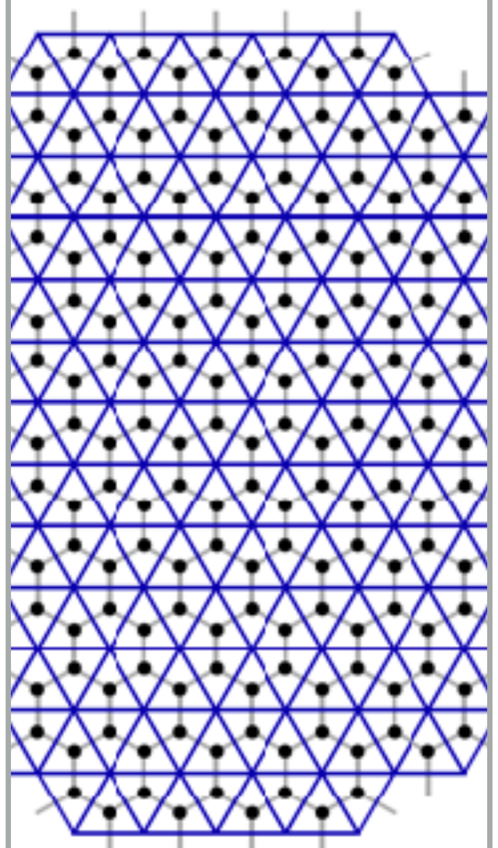


Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

ulk curvature

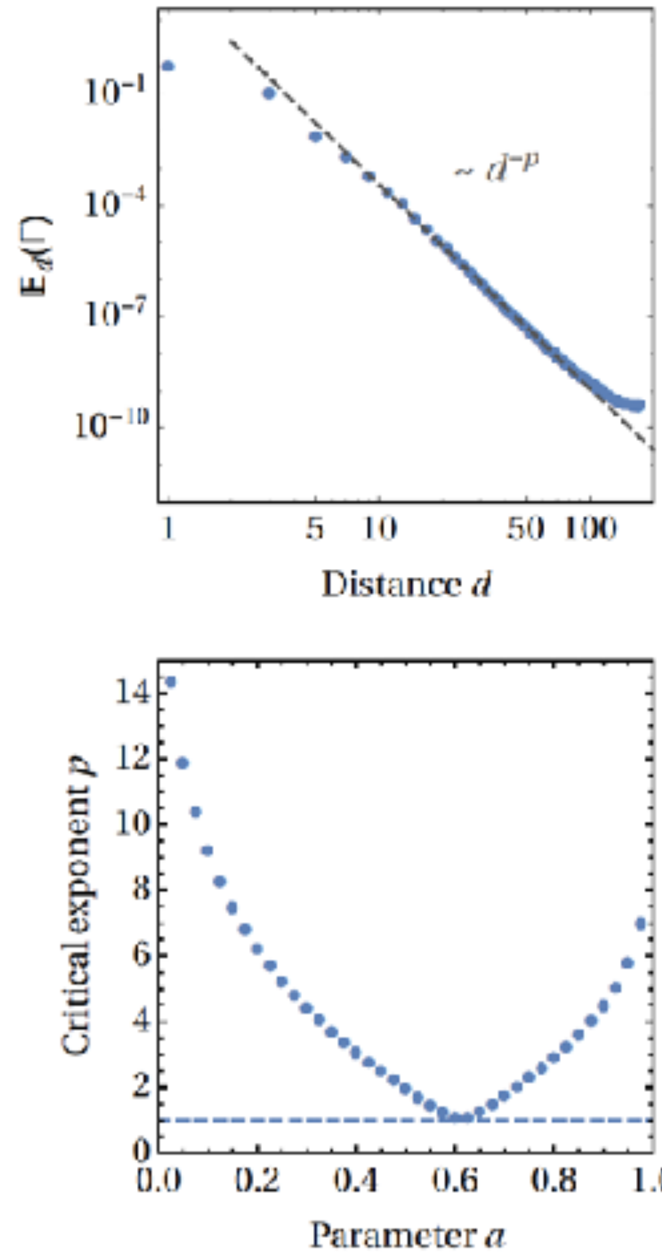
- $\{3,6\}$ gapped

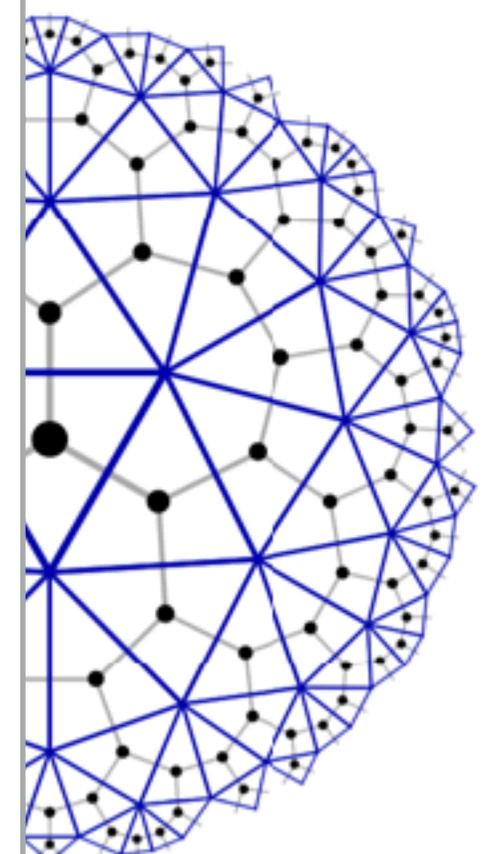




, 6} flat tiling

- $\{3,7\}$ critical



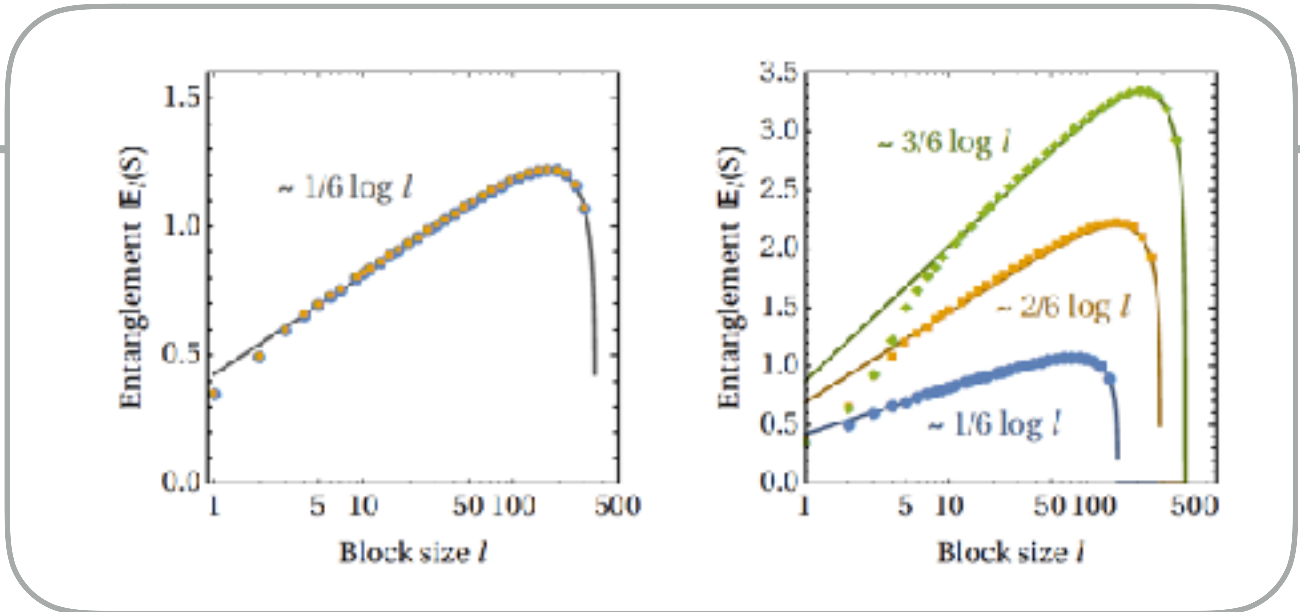


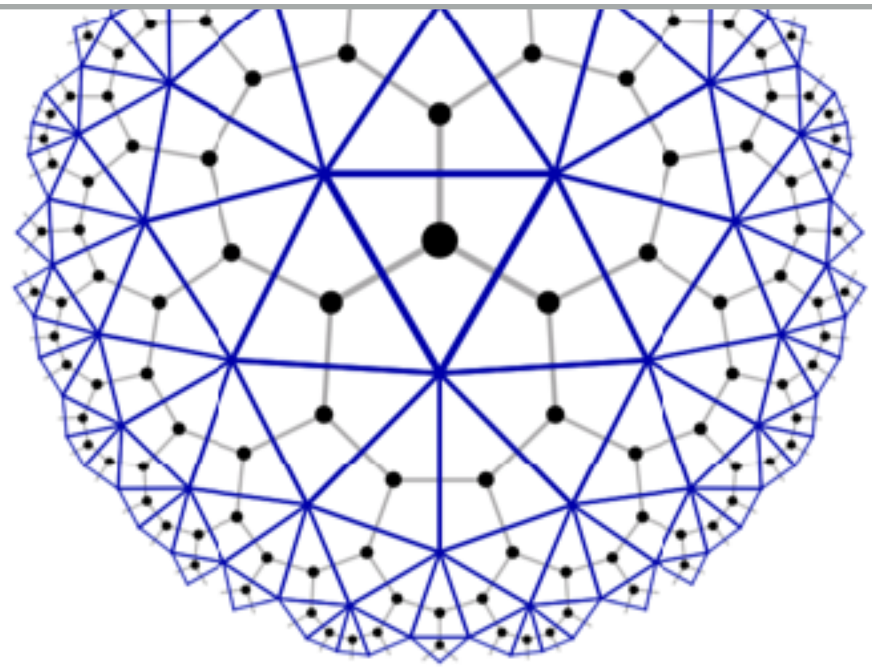
, hyperbolic tiling

- Specified by anti-symmetric 3×3-matrix A , governed by parameter a

Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Entanglement entropy of CFTs





- $\{3,k\},\ k>6$, hyperbolic tiling

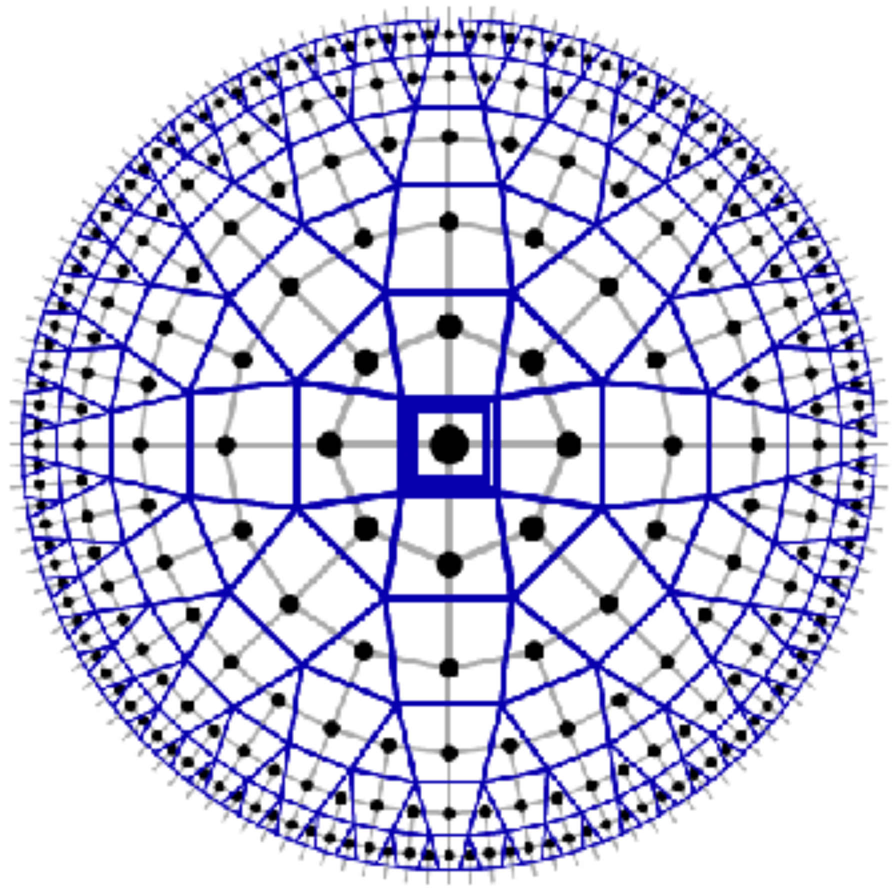
- CFT entanglement entropy: for $c=1/2$, $\epsilon\approx 0.08$, critical Ising theory

$$S_\ell=\frac{c}{3}\ln\left(\frac{L}{\pi\epsilon}\sin\frac{\pi\ell}{L}\right)\simeq\frac{c}{3}\ln\frac{\ell}{\epsilon}+O\left((\ell/L)^2\right)$$

and copies thereof

Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Translationally invariant MERA

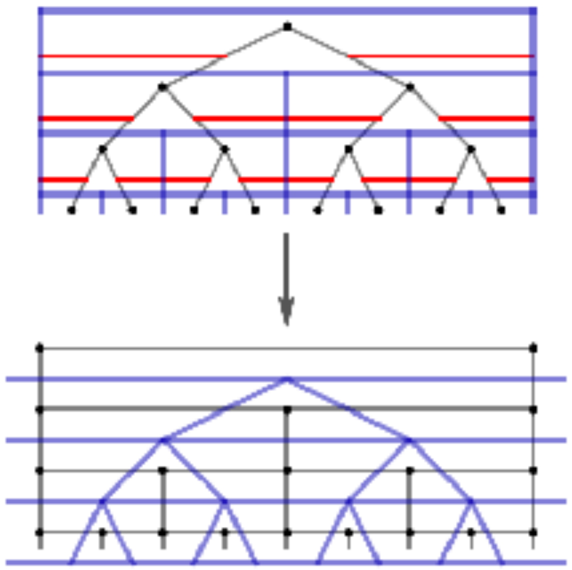


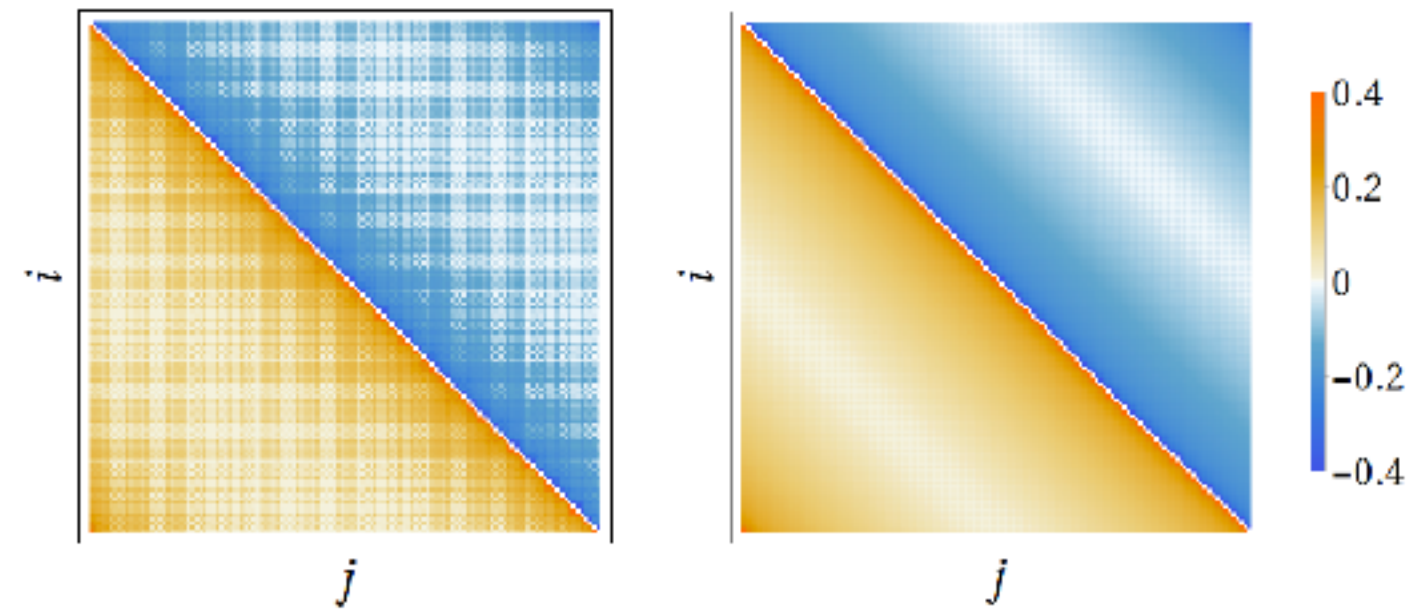
- Dual MERA of the hyperbolic plane

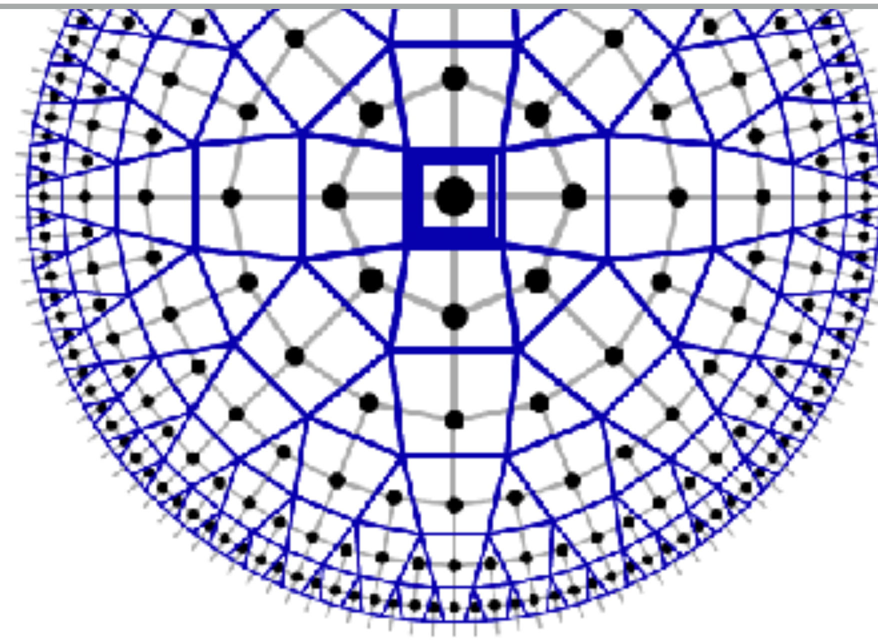
Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

Translationally invariant MERA

- Mapping between standard and block-dual MERA







- Dual MERA of the hyperbolic plane

- 3 and 4-leg tensors specified by 3×3 matrix A and 4×4 matrix B
- Gives translationally invariant state to very good approximation

Jahn, Gluza, Pastawski, Eisert, arXiv:1711.03109

More to play

- **Lesson:** Matchgate tensor networks provide versatile framework
  - Random tensors?
  - Interacting theories, connection to string-nets
  - Further connections to quantum error correction?
  - Etc

Summary

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- Is not fault tolerant, but can be **certified**

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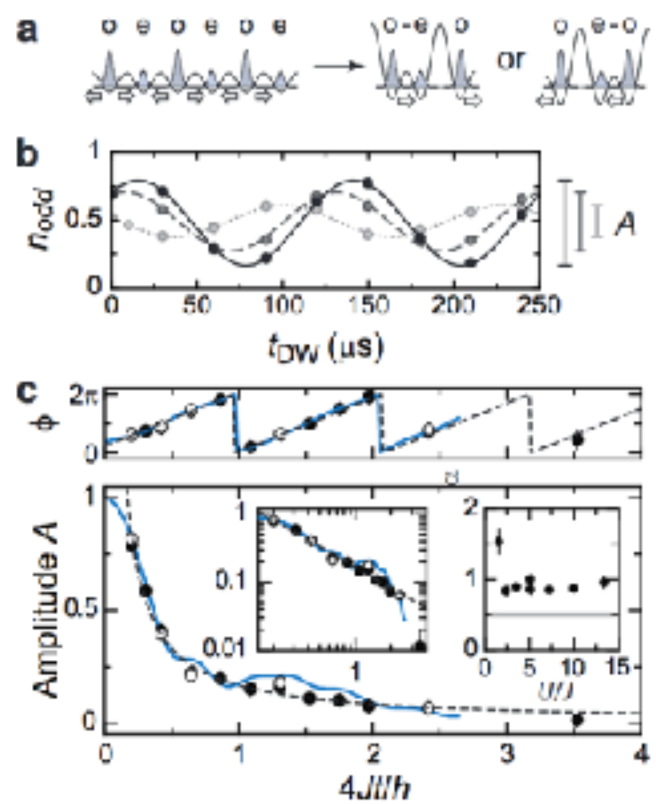

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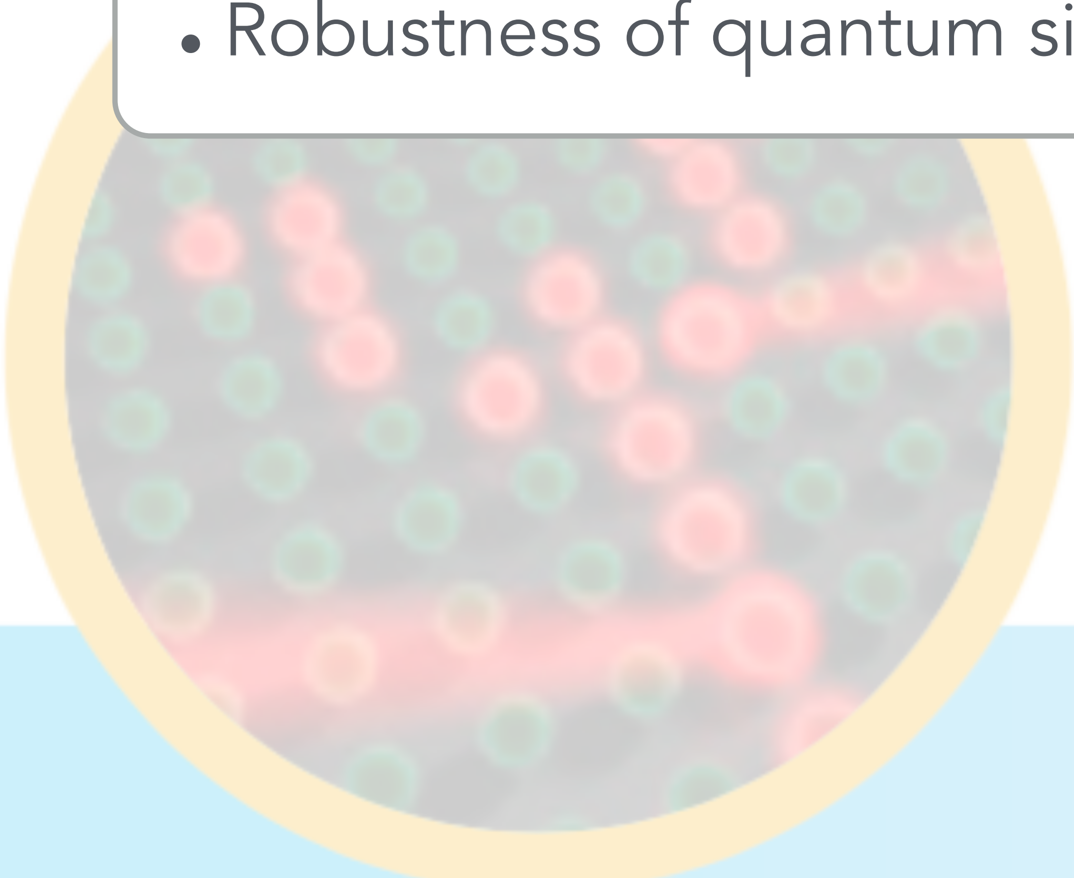

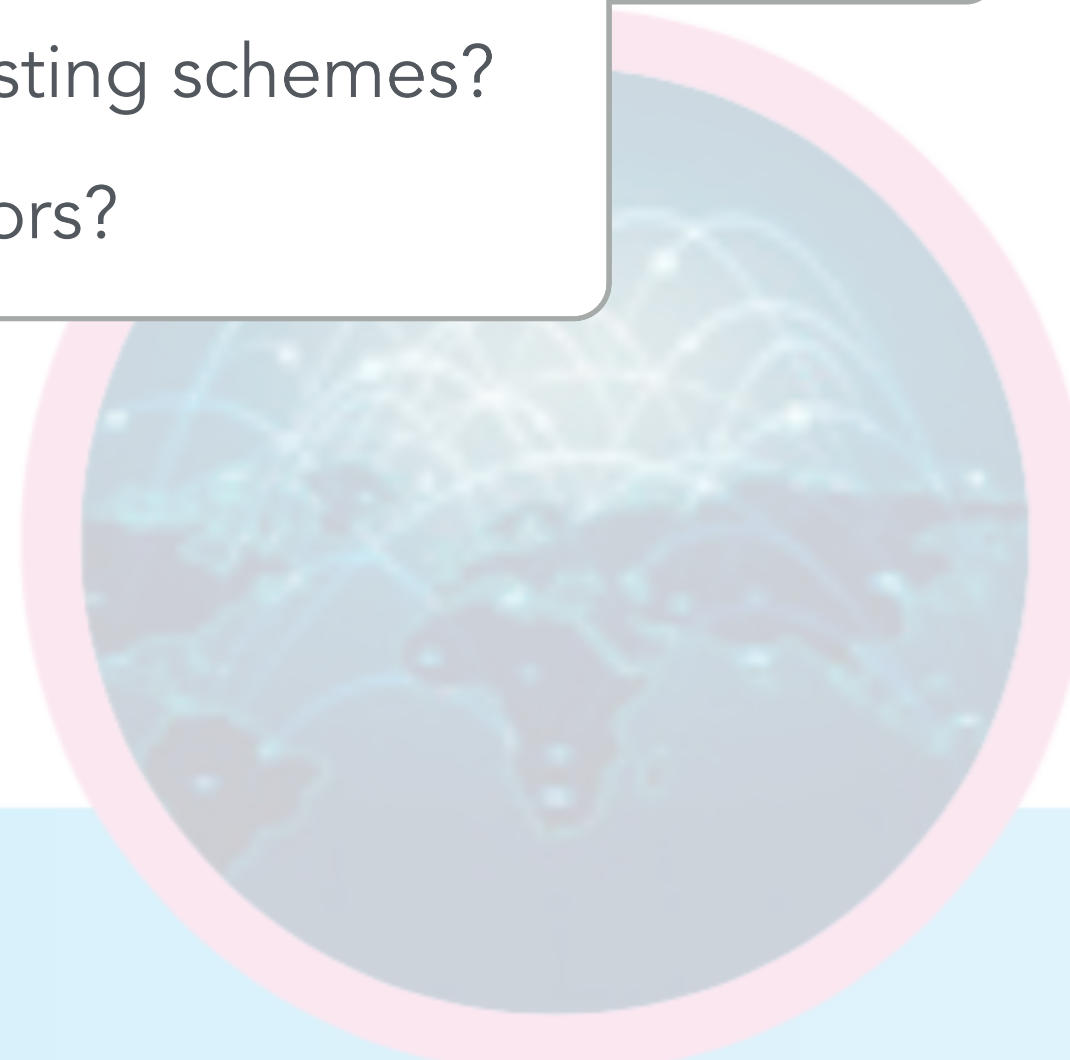

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- Is not fault tolerant, but can be **certified**
- One can efficiently assess **correctness** - even if simulators exhibit quantum computational speedups

- Closer to physically more interesting schemes?
- Robustness of quantum simulators?
- Features of basic quantum error correction?

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Thanks for your attention!

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