NEAR-TERM QUANTUM COMPUTING AND QUANTUM ADVANTAGES

JENS EISERT, FU BERLIN

SUMMER SCHOOL ON QUANTUM COMPUTING, AUG-SEP 2020

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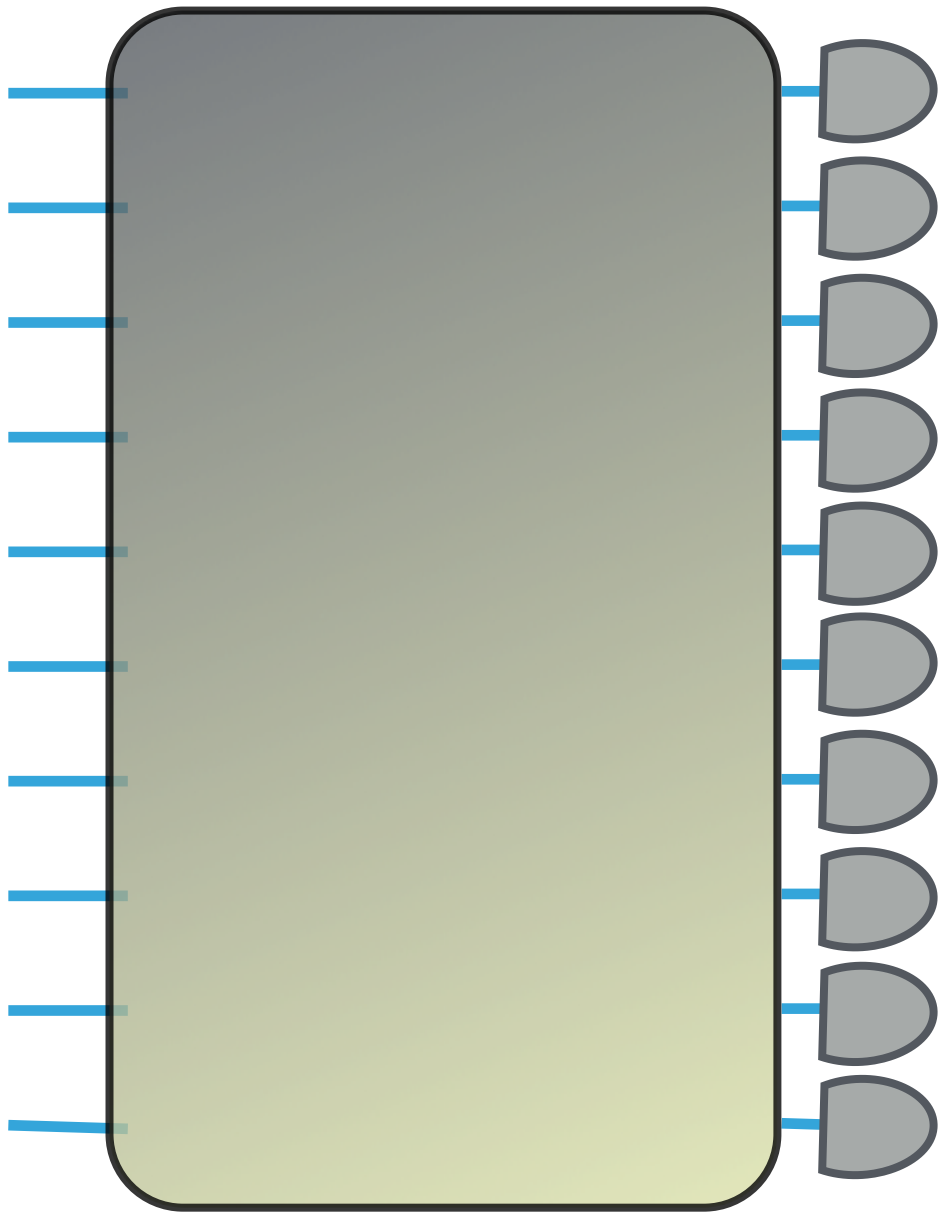
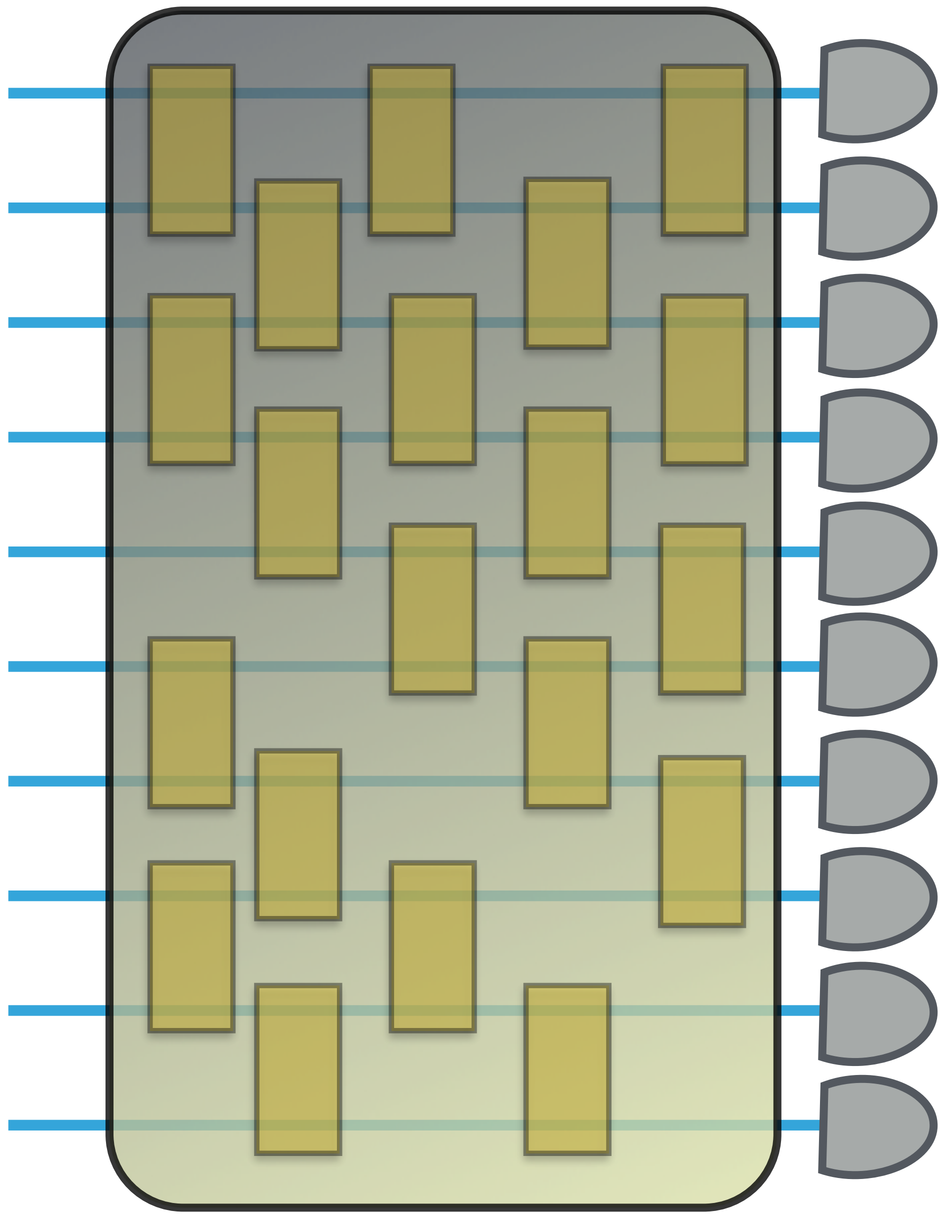
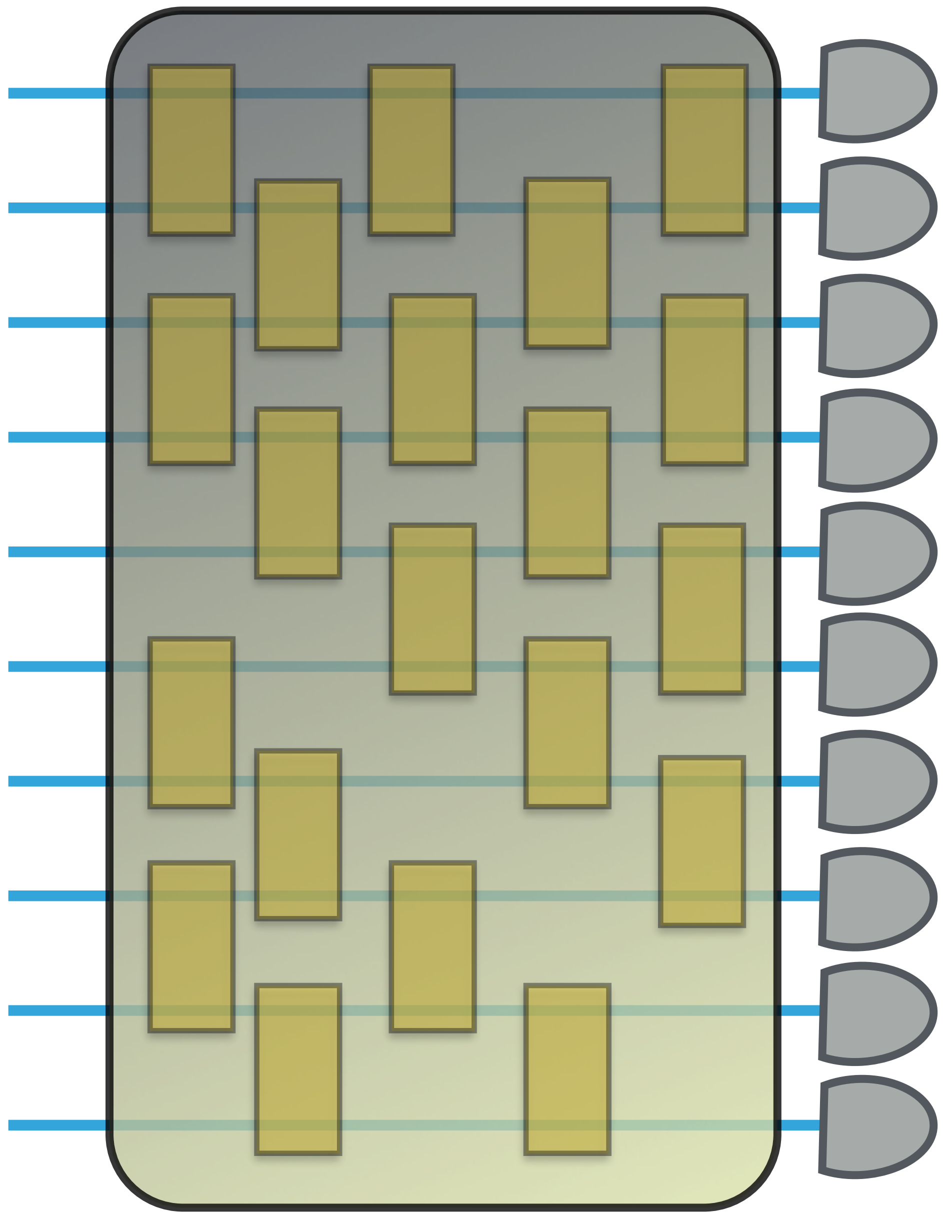




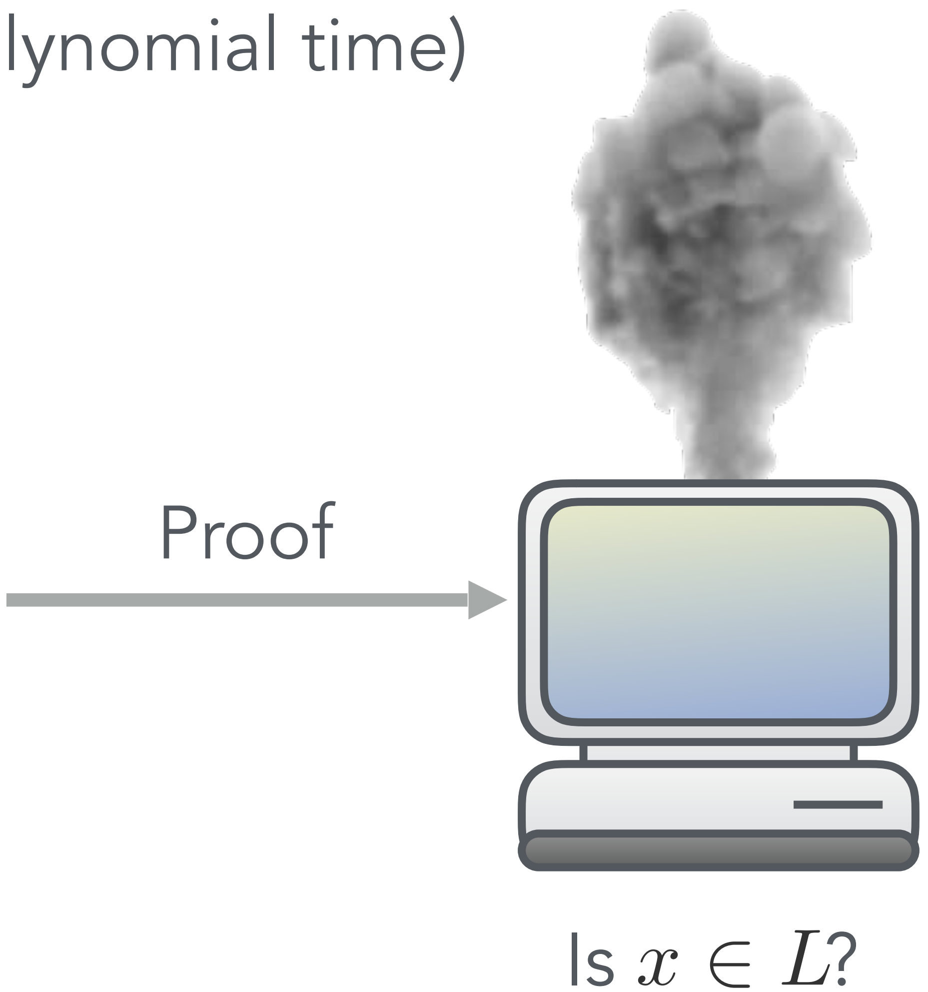
- **Quantum computers** solve some problems in NP in polynomial time



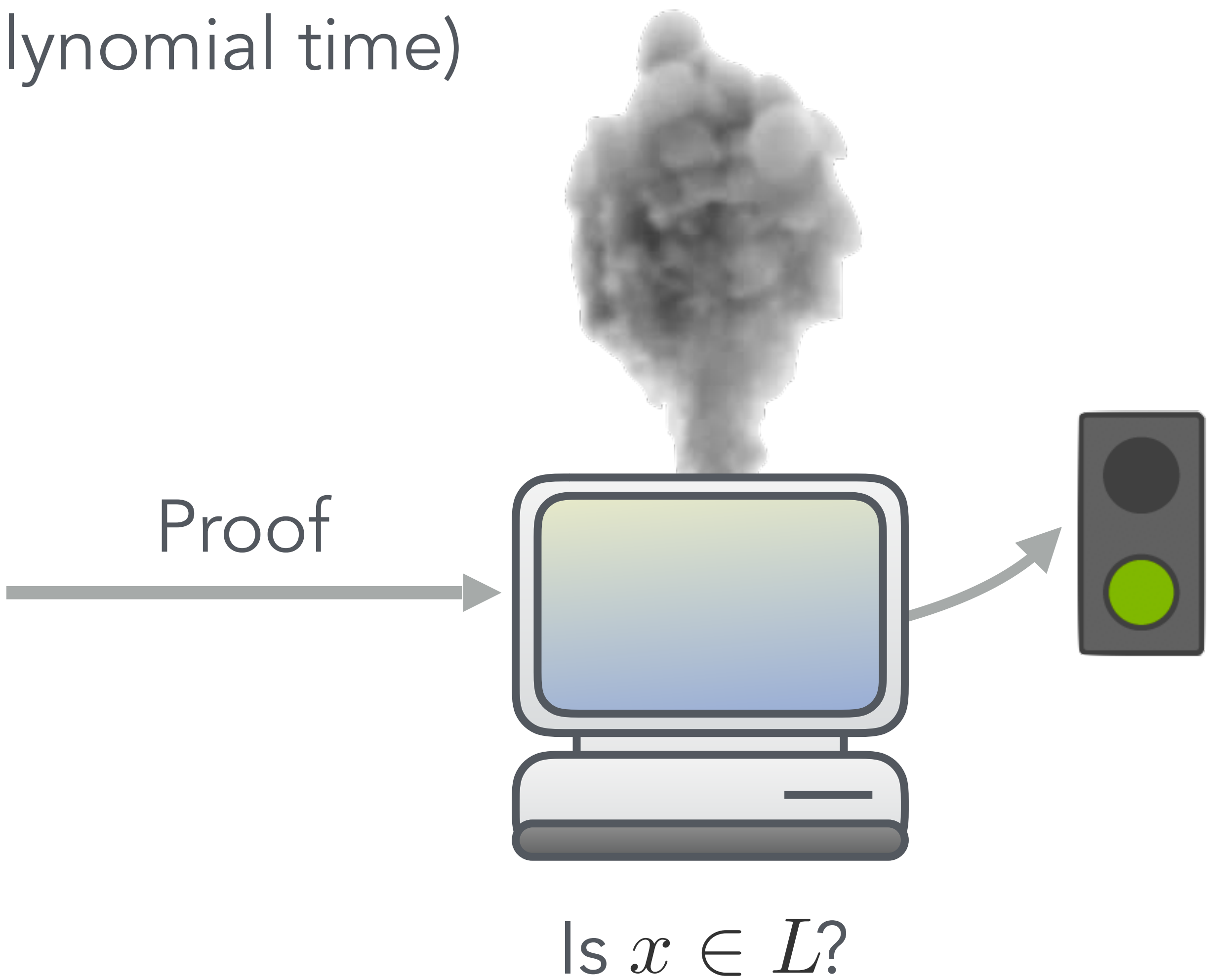
- **Quantum computers** solve some problems in NP in polynomial time
  - **NP** (non-deterministic polynomial time)

Is $x \in L$?

- **Quantum computers** solve some problems in NP in polynomial time
  - **NP** (non-deterministic polynomial time)

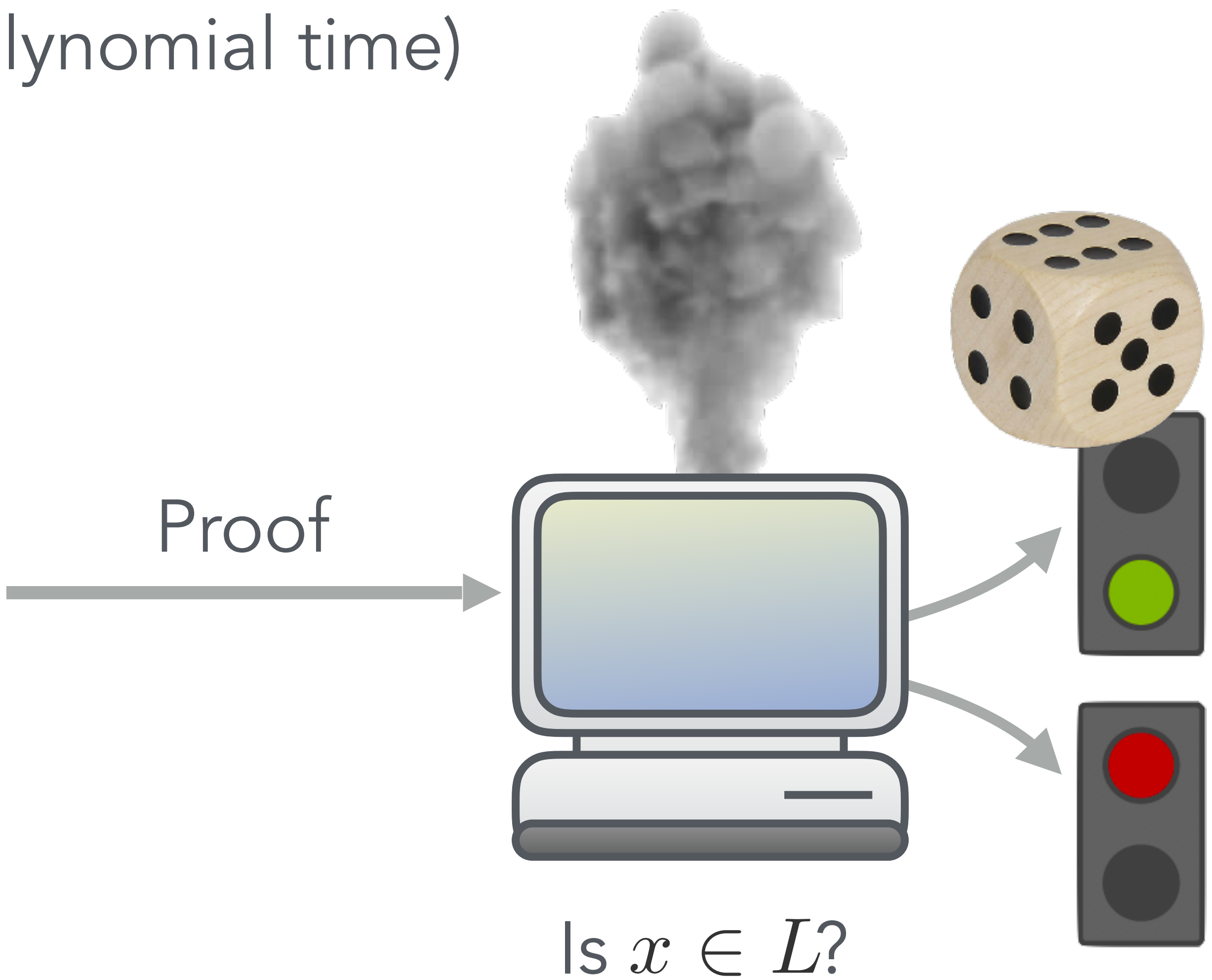


- **Quantum computers** solve some problems in NP in polynomial time
  - **NP** (non-deterministic polynomial time)



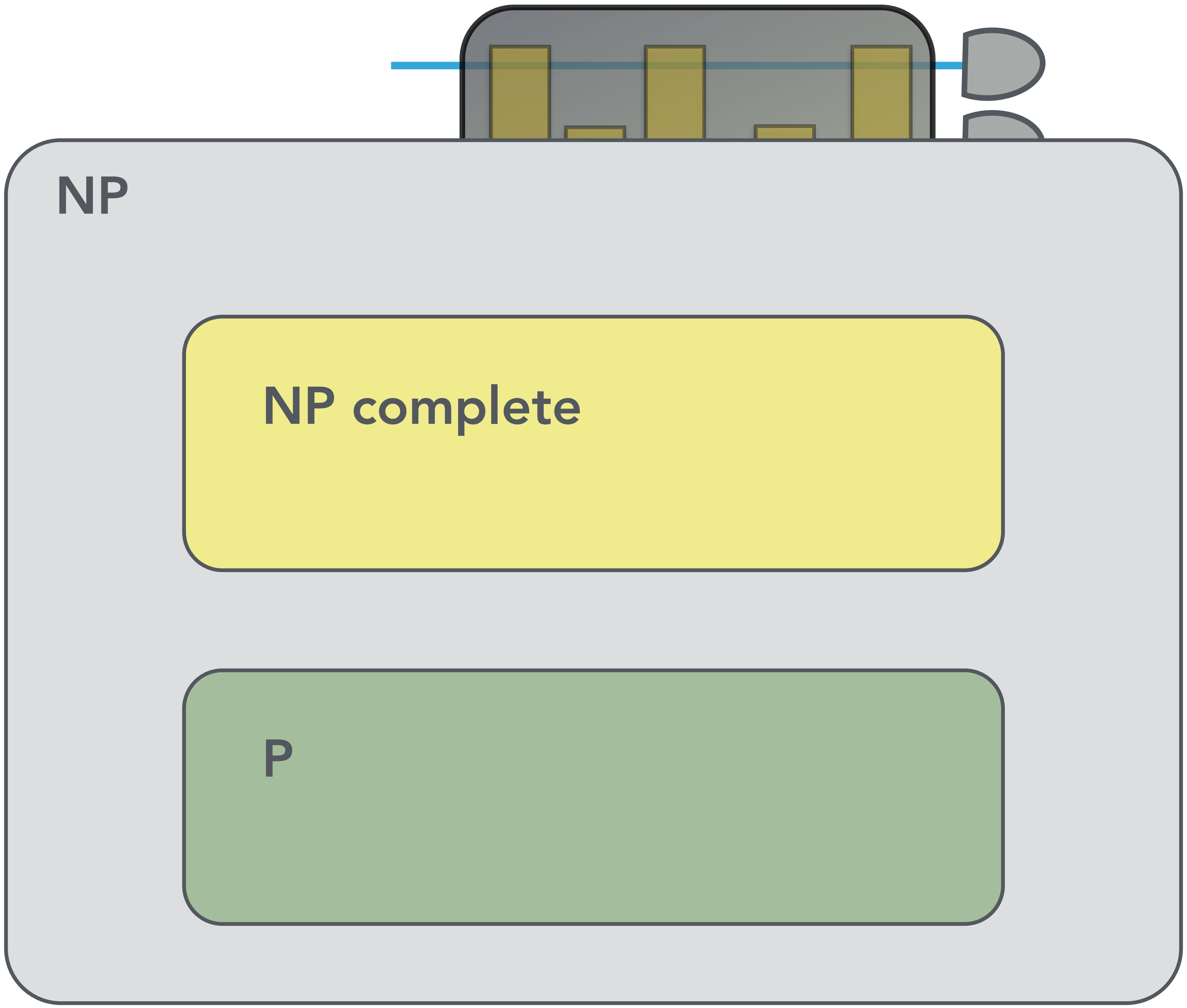
  - **Completeness:** If $x \in L$, there is proof that is accepted in polynomial time

- **Quantum computers** solve some problems in NP in polynomial time
  - **NP** (non-deterministic polynomial time)



  - **Completeness:** If $x \in L$, there is proof that is accepted in polynomial time
  - **Soundness:** If $x \notin L$, no proof is accepted

- **Quantum computers** solve some problems in NP in polynomial time



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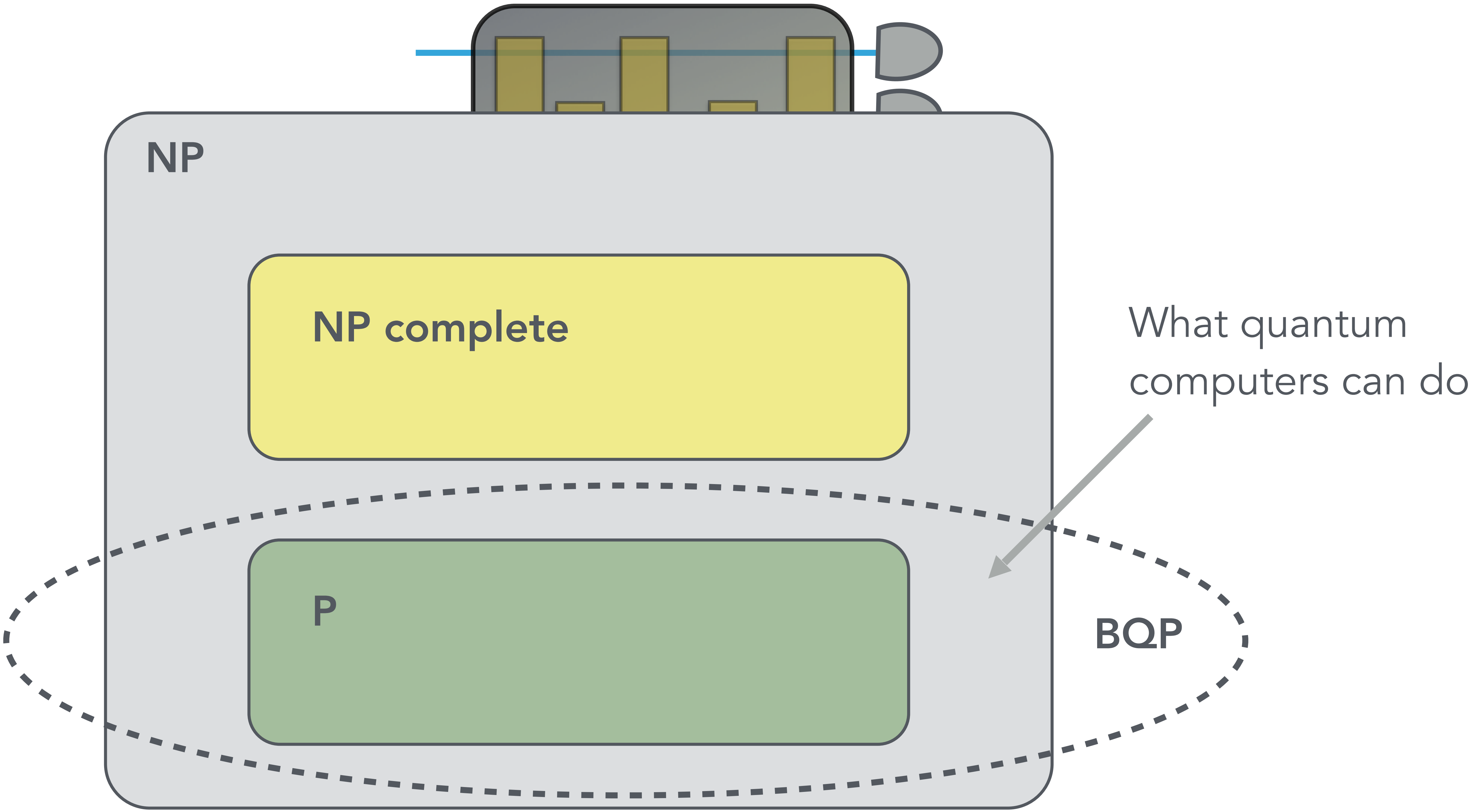

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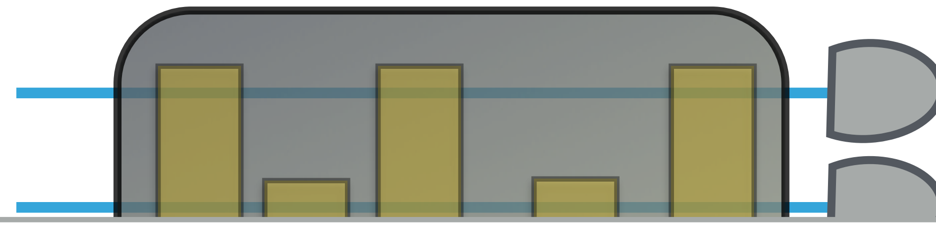


- Get factor of a large number N from the **period** p of the function

$$f(x) = a^x \bmod N$$

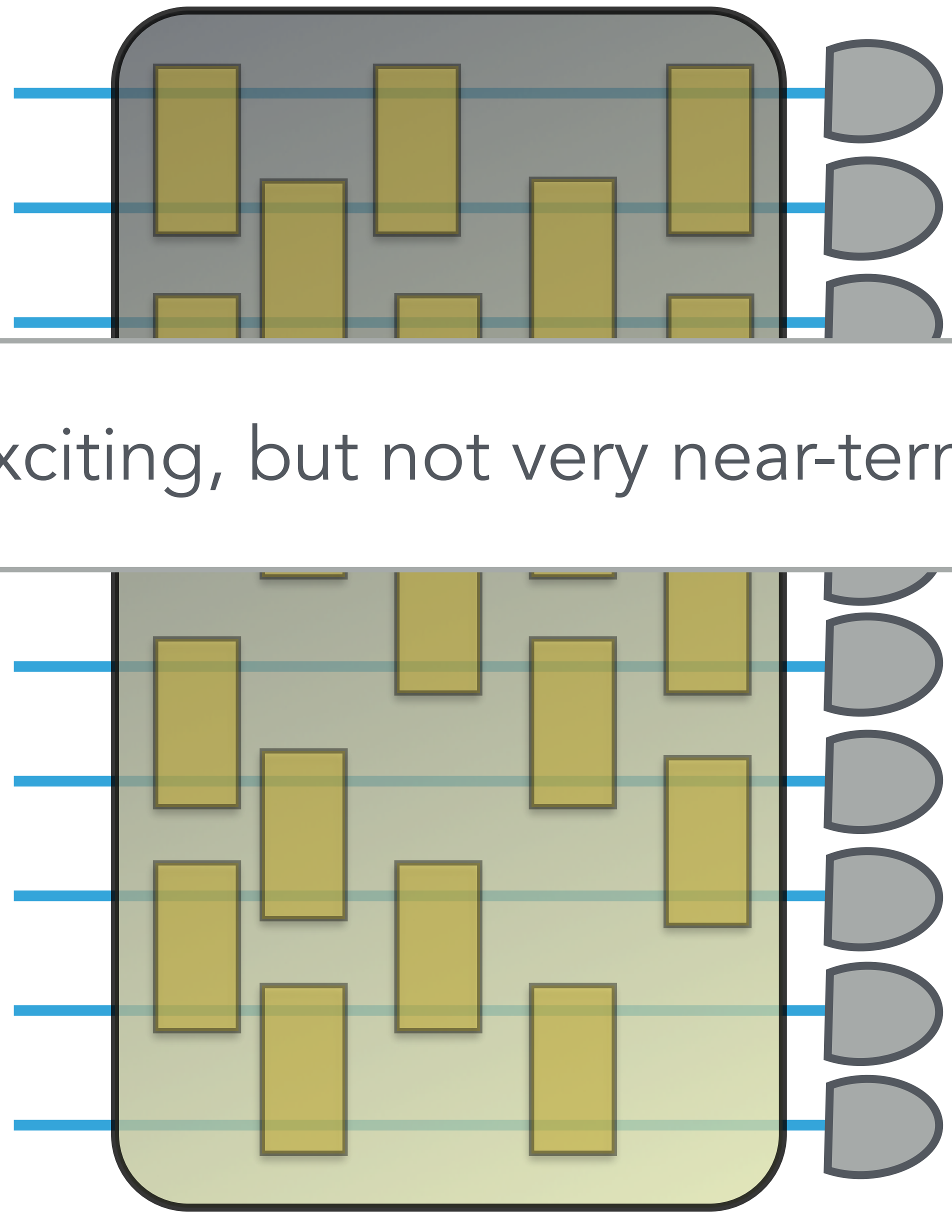
- Periods can be found using the **quantum Fourier transform**

$$\sum_{i=0}^{n-1} x_i |i\rangle \mapsto \sum_{i=0}^{n-1} y_i |i\rangle \text{ with } y_k = \frac{1}{\sqrt{n}} \sum_{j=0}^{n-1} x_j e^{2\pi i j k/n}$$

- Solves NP problem in poly time: Runtime $O((\log N)^3)$
- Best known classical algorithm $\exp(O((\log N)^{1/3}(\log \log N)^{2/3}))$

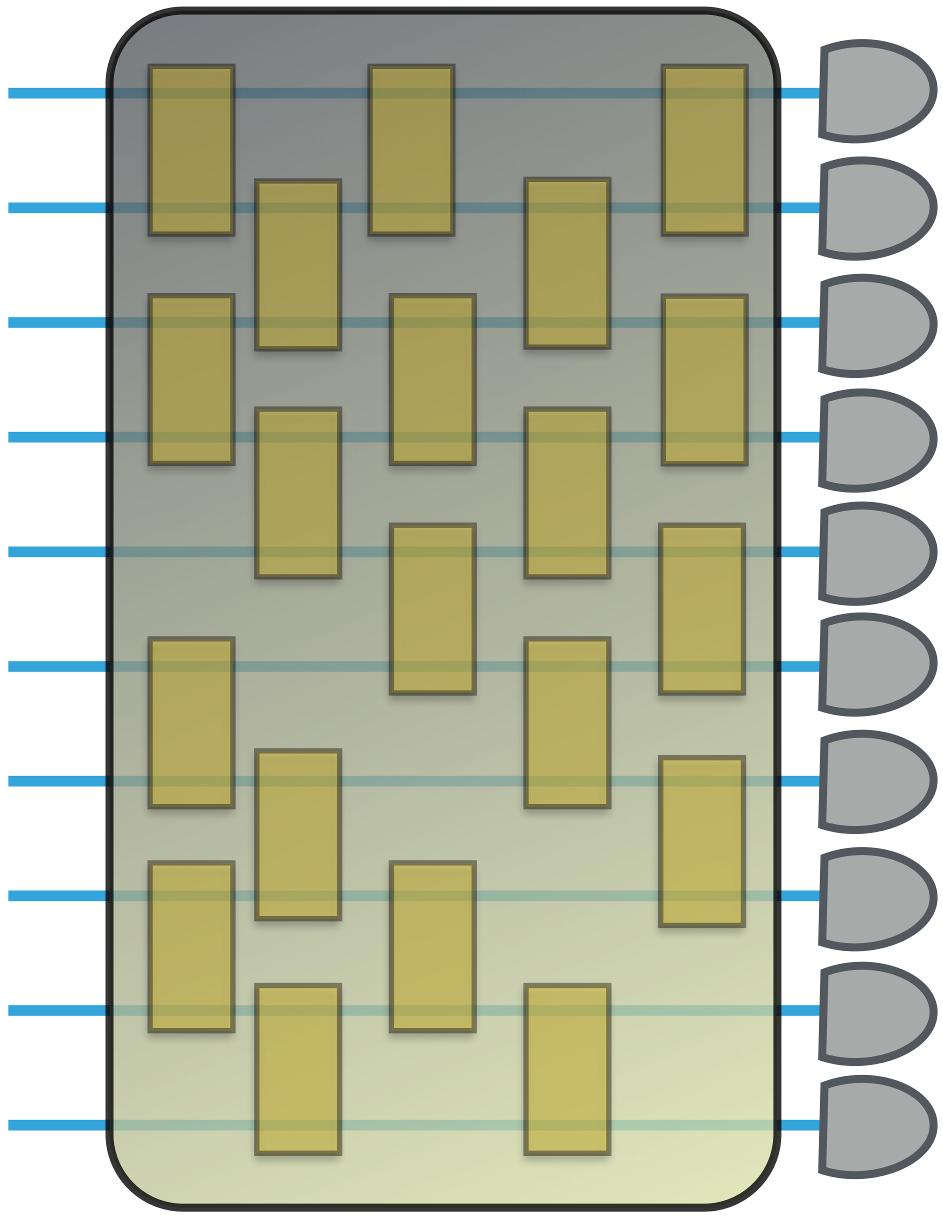
Shor, SIAM J Comp 26, 148 (1997)

- **Quantum computers** solve some problems in NP in polynomial time



- Very exciting, but not very near-term

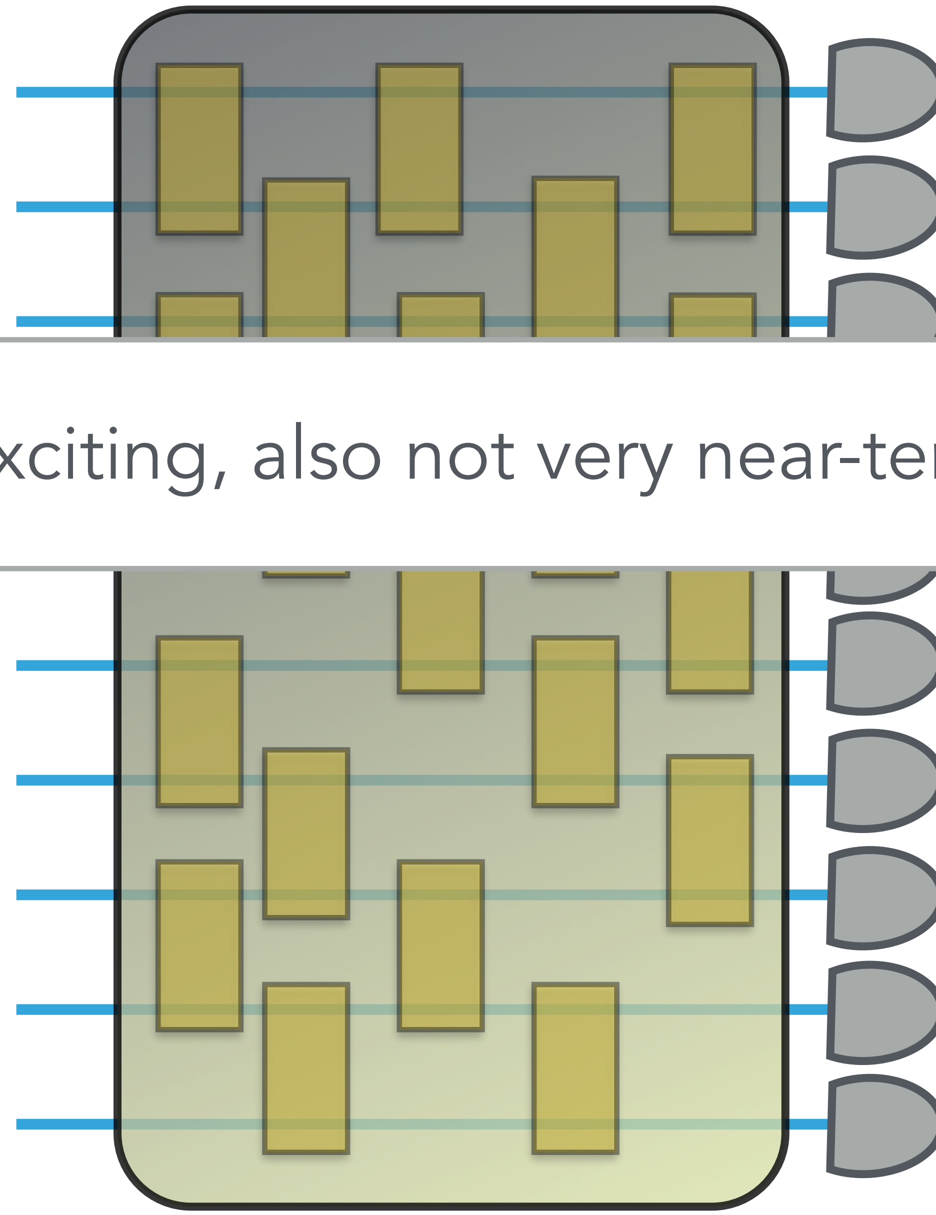
- **Quantum computers** solve some problems in NP in polynomial time



- **Quantum computers** solve some problems in NP in polynomial time

- Principal component analysis
  Lloyd, Mohseni, Rebenstrost, Nature Phys 10, 631 (2014)
- Matrix inversion and linear systems
  Harrow, Hassidim, Lloyd, Phys Rev Lett 103, 150502 (2008)
- Spectral analysis
  Steffens, Rebenstrost, Marvian, Eisert, Lloyd, New J Phys 19, 033005 (2017)
- Semi-definite programming
  Brandão, Kalev, Li, Lin, Svore, Wu, arXiv:1710.02581

- **Quantum computers** solve some problems in NP in polynomial time

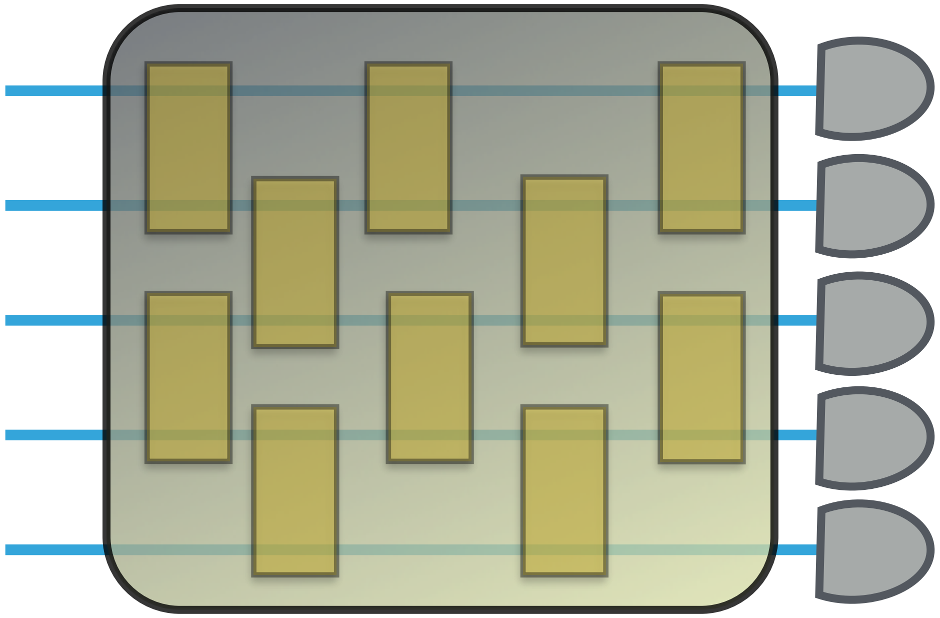


- Also exciting, also not very near-term

NEAR-TERM

QUANTUM COMPUTERS

- We presently have **small and noisy quantum computers**



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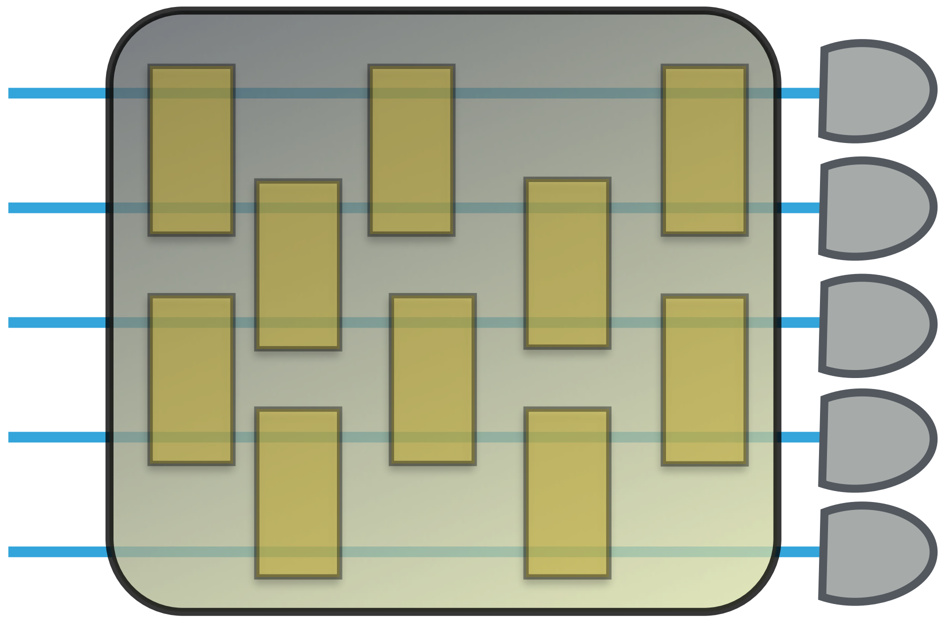
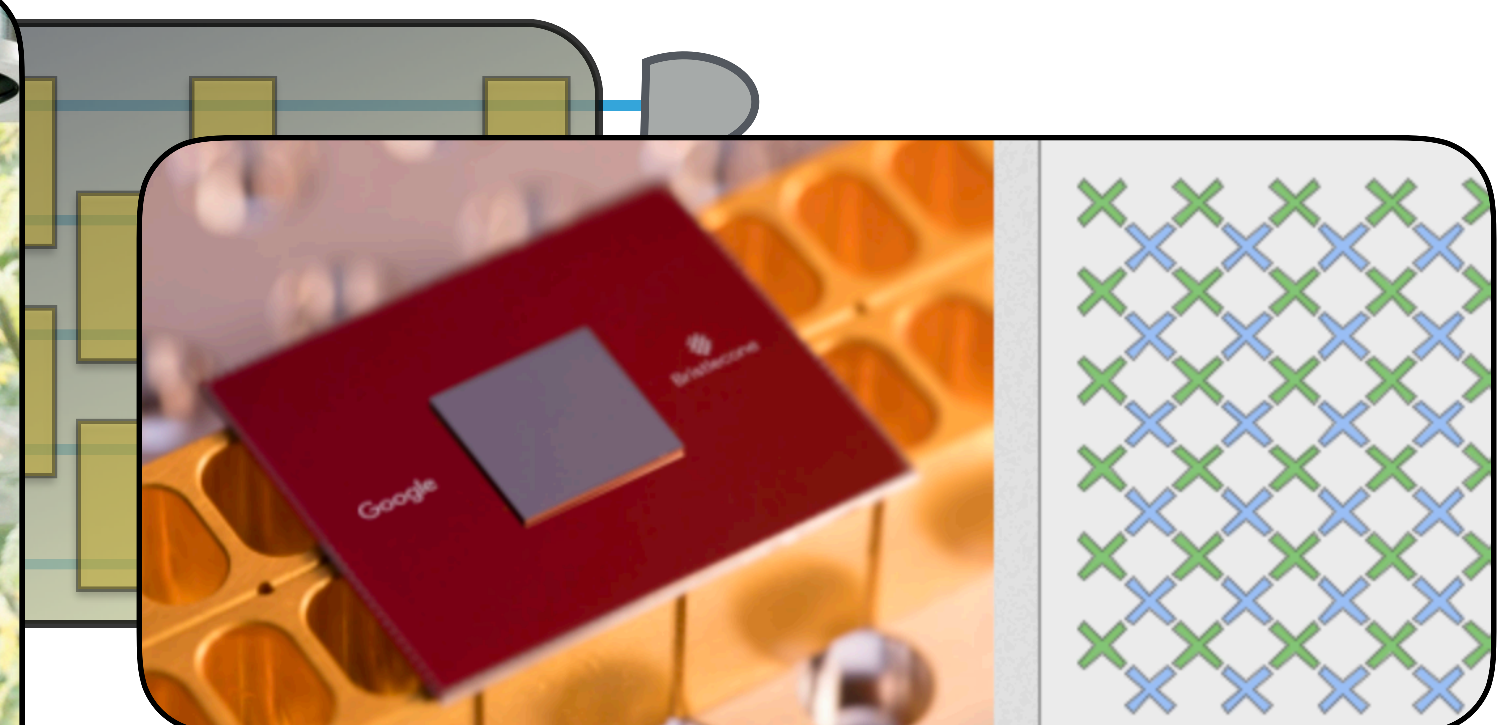
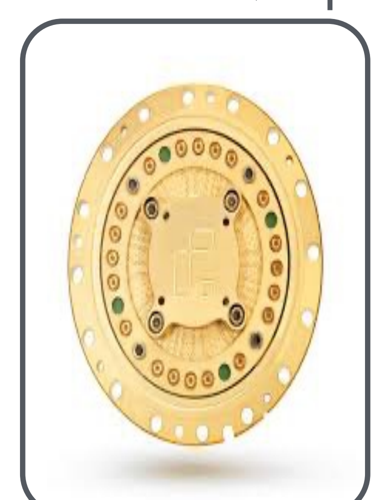


- We presently **have** small and noisy quantum computers

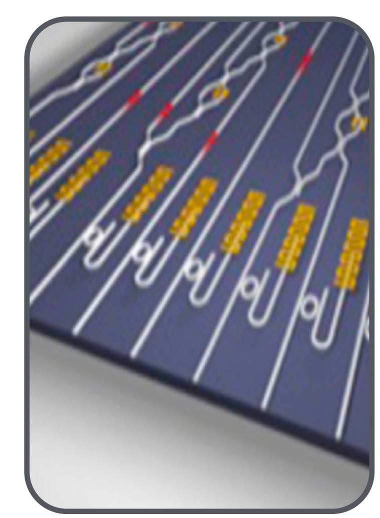
IBM's 53 qubit superconducting device



Google's 53/72 (Brizzlecone) qubits devices

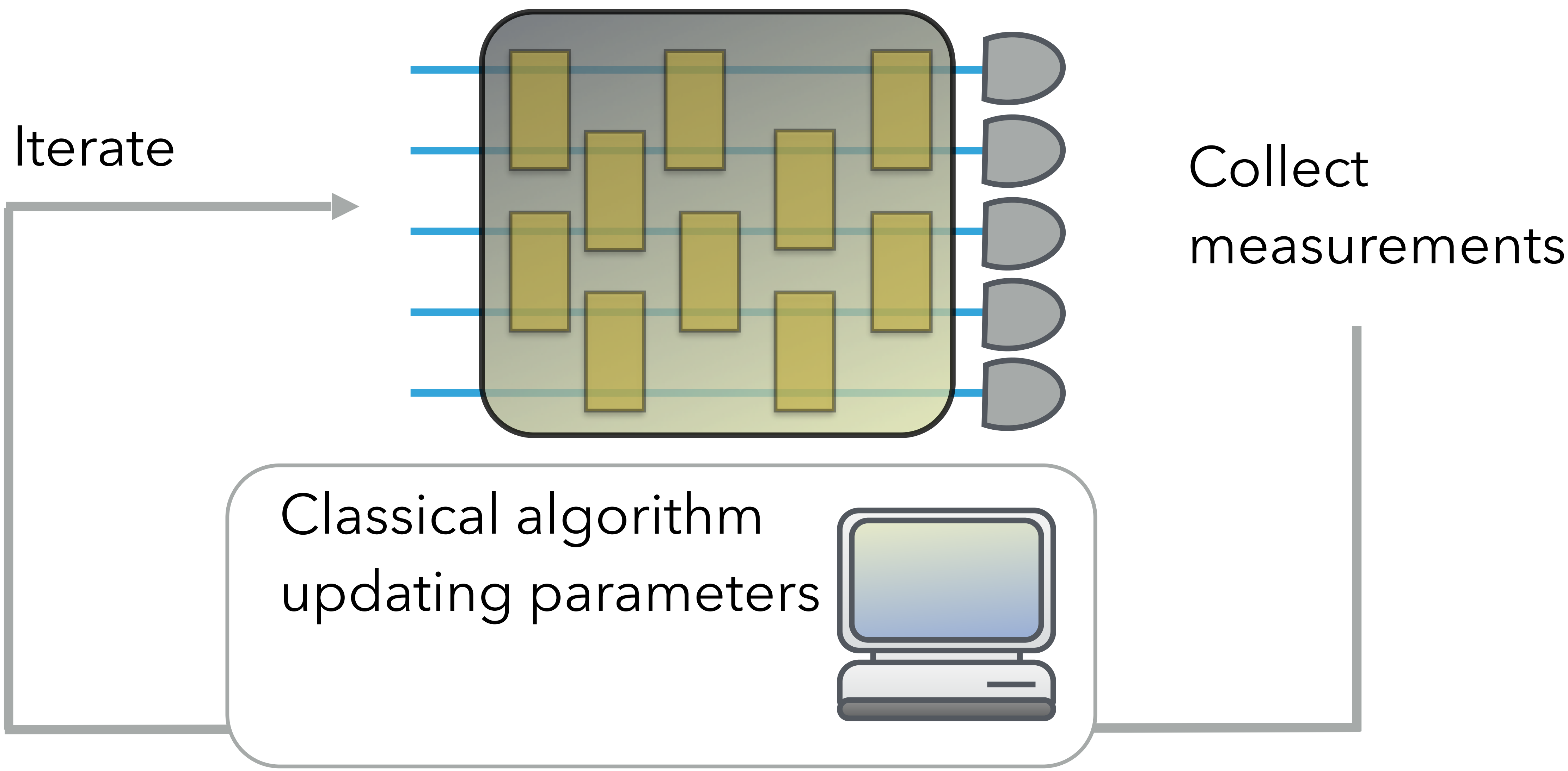


Rigetti



PsiQuantum

- We presently **have** small and noisy quantum computers



- **Heuristically** encouraging performance

McClean, Romero, Babbush, Aspuru-Guzik, New J Phys 18, 023023 (2016)

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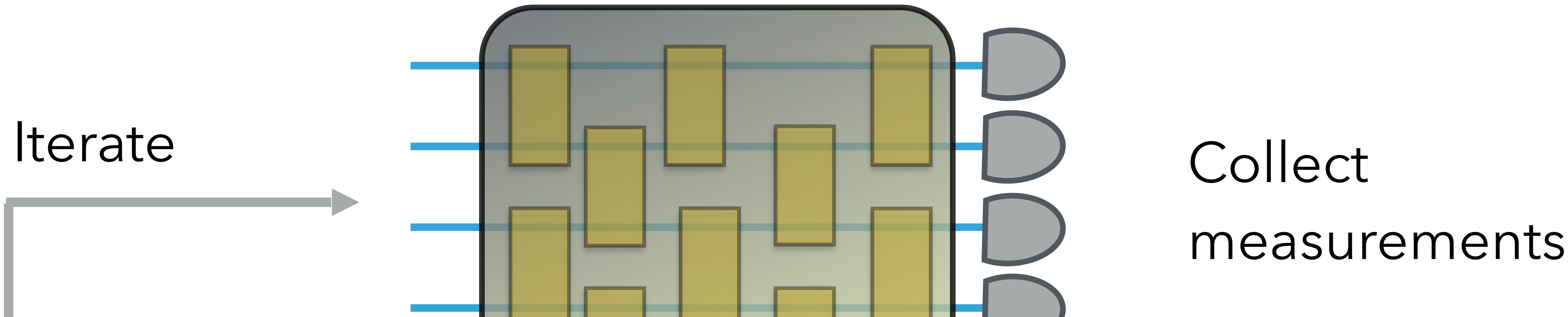

- **Variational quantum eigensolver** (VQE)

$$\min \langle\psi(\theta)|H|\psi(\theta)\rangle$$

- Applications in quantum chemistry etc

- **Heuristically** encouraging performance

Peruzzo, McClean, Shadbolt, Yung, Zhou, Love, Aspuru-Guzik, O'Brien, Nature Comm 5, 4213 (2014)
Kandala, Mezzacapo, Temme, Takita, Brink, Chow, Gambetta, Nature 549, 242 (2017)

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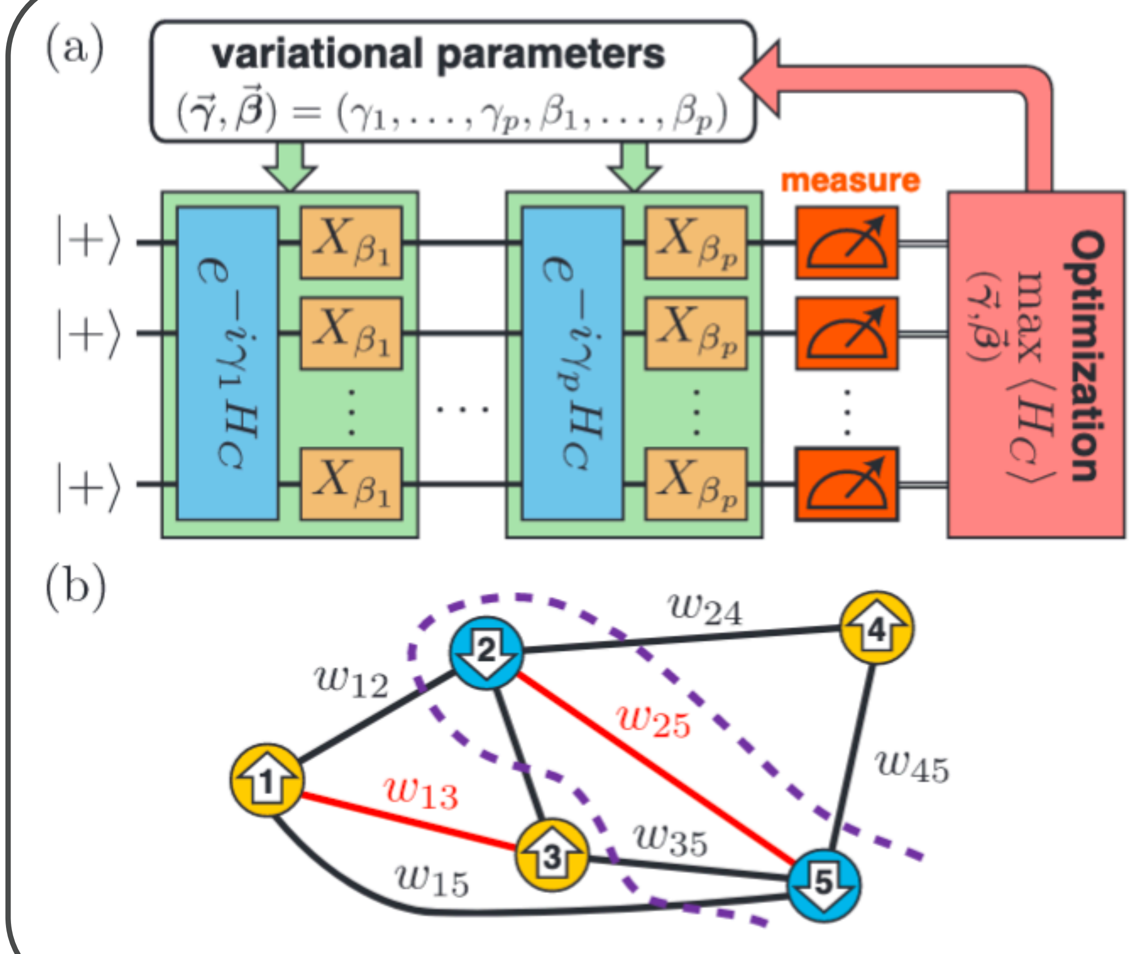
- Quantum approximate optimization algorithm (QAOA)



- Combinatorial optimization problems (e.g., MaxCUT)
- Goal: determine binary string maximizing a given classical objective function

$$C : \{-1, 1\}^n \to \mathbb{R}_{\geq 0}$$

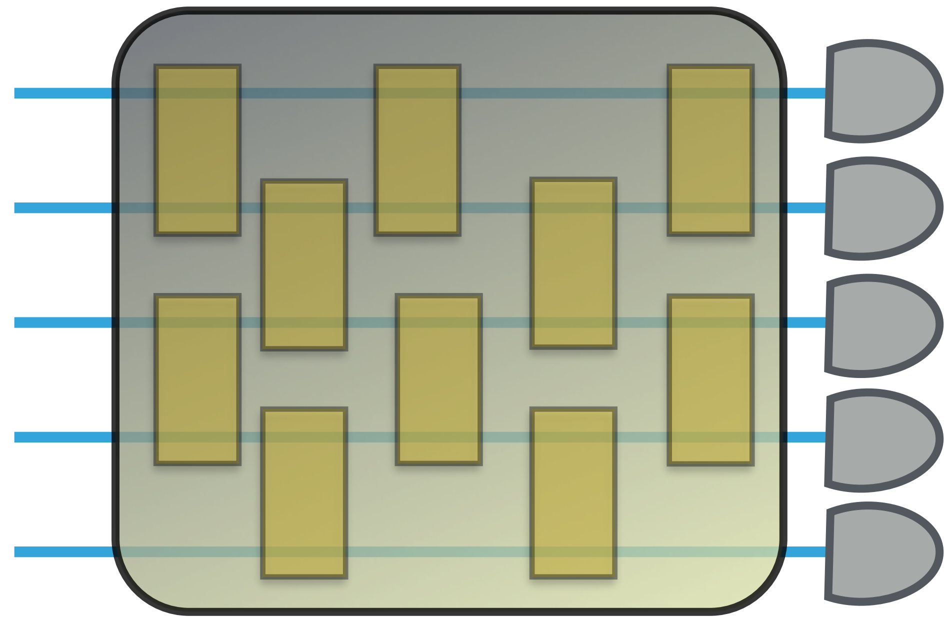
- Aims to find a string achieving a desired approximation ratio

$$\frac{C(z)}{C_{\max}} \geq r$$

- Not yet so well understood beyond single layer

Farhi, Goldstone, Gutmann, arXiv:1411.4028 (2014)
Zhou, Wang, Choi, Pichler, Lukin, arXiv:1812.01041

- In variational algorithms, loss function $\mathcal{L} : \mathbb{R}^d \to \mathbb{R}$ needs to be optimized



Parameters $\theta \in \mathbb{R}^d$

- Estimate the gradient for update

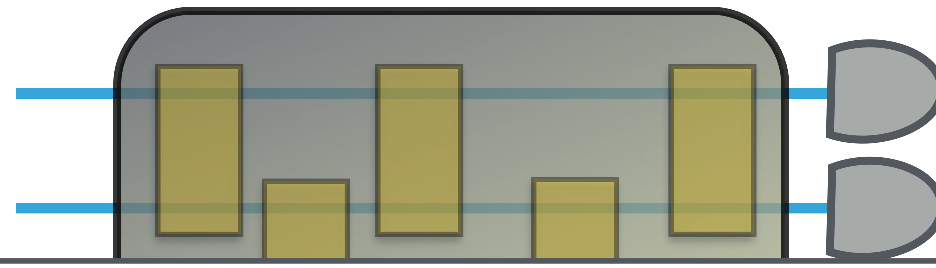
$$\partial\mathcal{L}(\boldsymbol{\theta})/\partial\theta_i$$

- Estimate expectation values

$$\langle O_i \rangle_{\boldsymbol{\theta}} = \langle \mathbf{0} | U^\dagger(\boldsymbol{\theta}) O_i U(\boldsymbol{\theta}) | \mathbf{0} \rangle$$

CLASSICAL-QUANTUM HYBRID ALGORITHMS

- In variational algorithms, loss function $\mathcal{L} : \mathbb{R}^d \to \mathbb{R}$ needs to be optimized



- **Parameter shift rule:** A quantum circuit $U(\theta), \theta \in \mathbb{R}^d$, satisfies a K-term shift rule, if [...]

$$\frac{\partial}{\partial \theta_i} \langle O \rangle_{\boldsymbol{\theta}} = \sum_{k=1}^{K} \gamma_{k,i} \langle O \rangle_{\boldsymbol{\theta}_{k,i}}$$

- Estimate the gradient for update

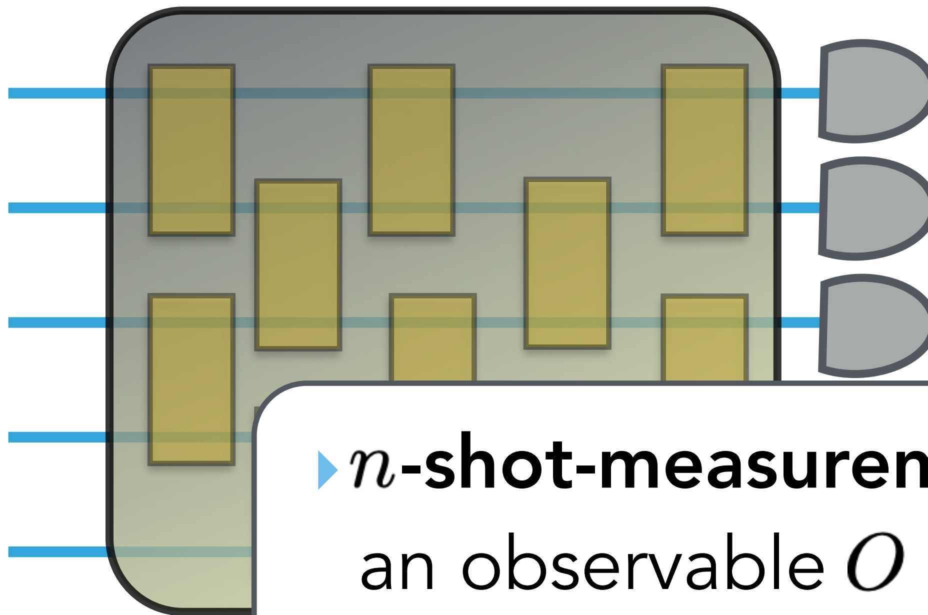
$$\partial \mathcal{L}(\boldsymbol{\theta}) / \partial \theta_i$$

- Estimate expectation values

$$\langle O_i \rangle_{\boldsymbol{\theta}} = \langle \mathbf{0} | U^\dagger(\boldsymbol{\theta}) O_i U(\boldsymbol{\theta}) | \mathbf{0} \rangle$$

Mitarai, Negoro, Kitagawa, Fujii, Phys Rev A 98, 032309 (2018)
Schuld, Bergholm, Gogolin, Izaac, Killoran, Phys Rev A 99,032331 (2019)

- Can be improved by stochastic gradient methods

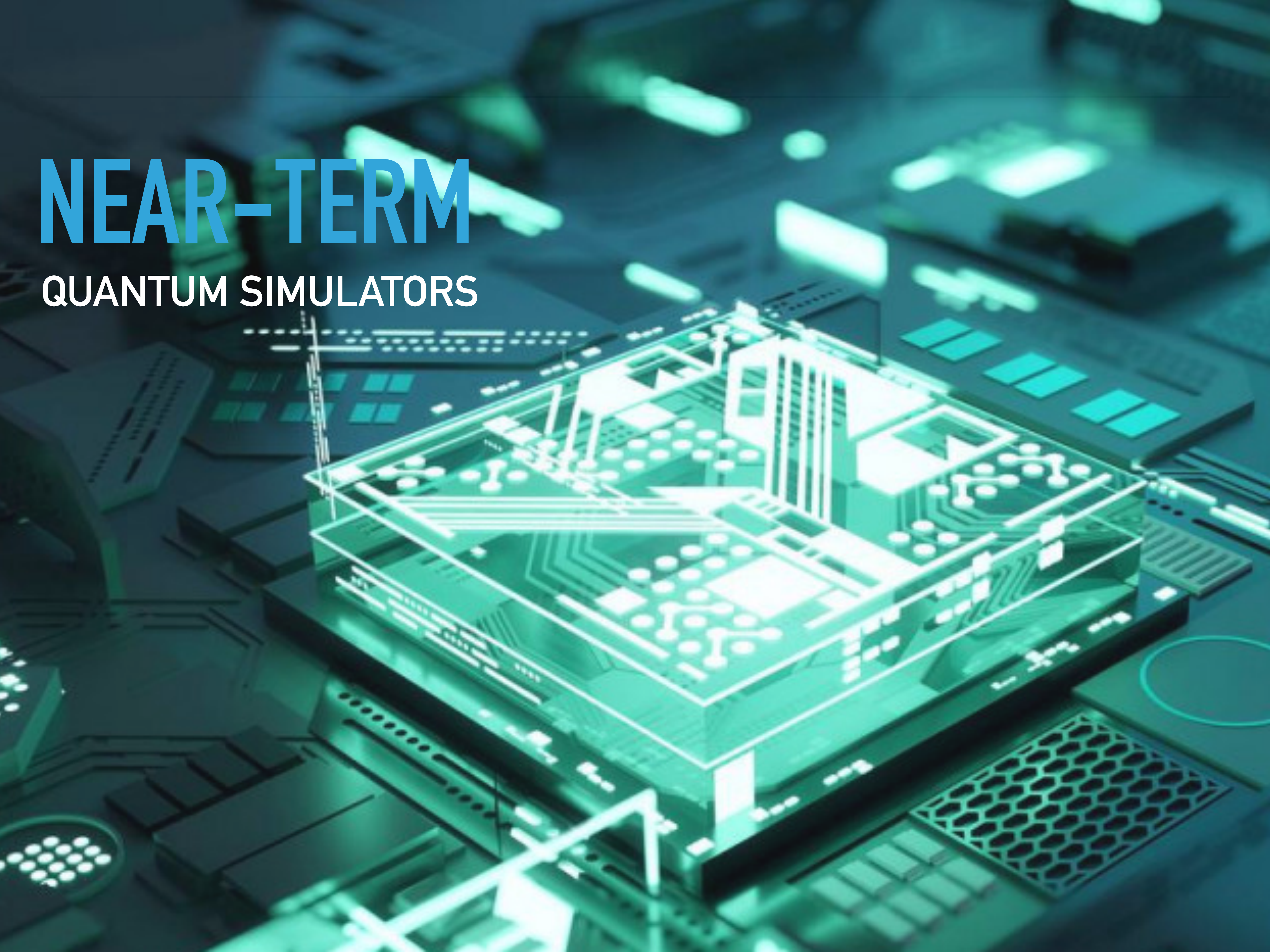


Para

- **n-shot-measurements:** Measure n times an observable O on $U(\theta)|0\rangle$, so that

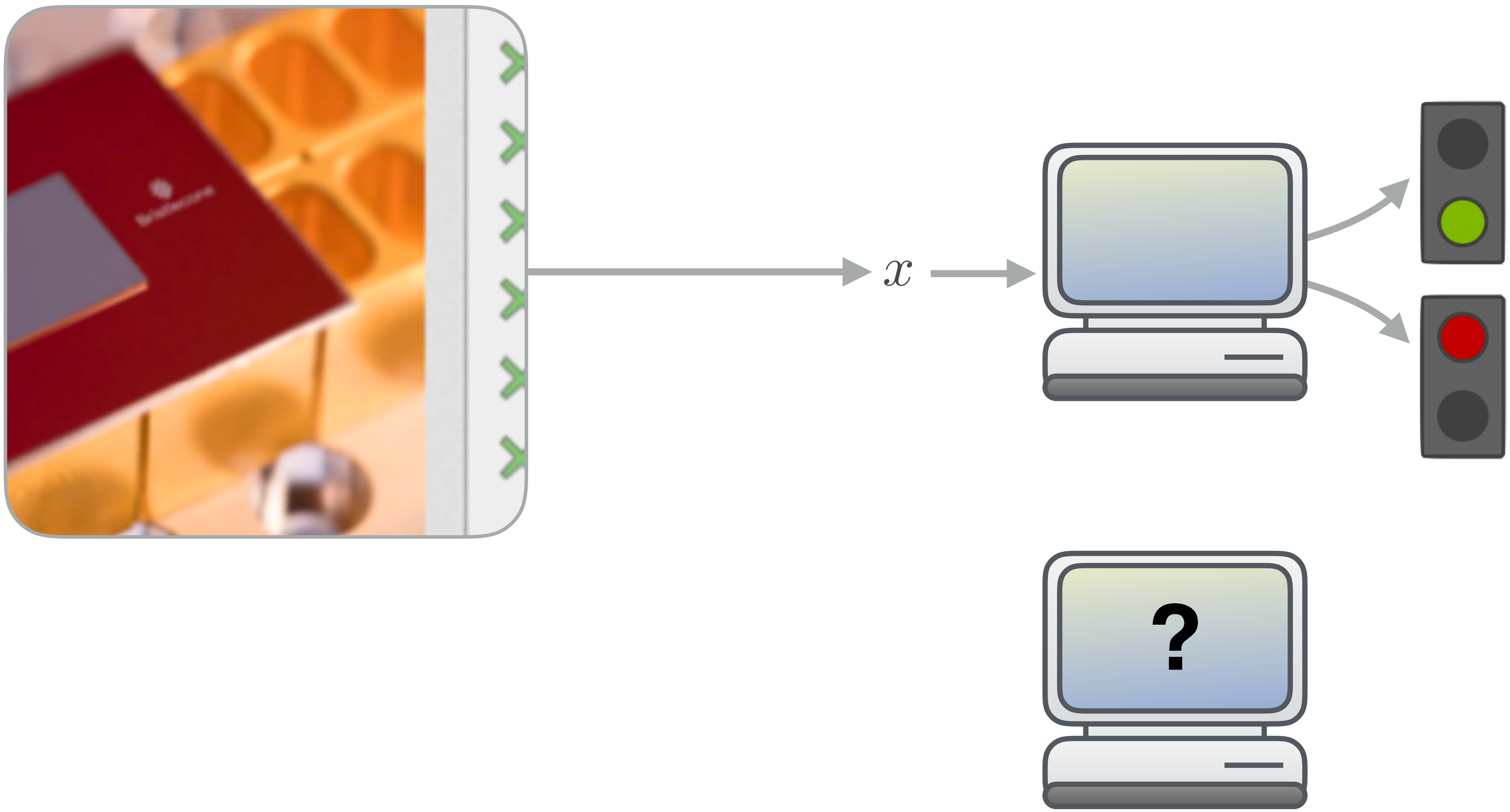
$$\mathbb{E}[\tilde{o}^{(n)}(\boldsymbol{\theta})] = \langle O \rangle_{\boldsymbol{\theta}}$$

Sweke, Wilde, Meyer, Schuld, Fährmann, Meynard-Piganeau, Eisert, Quantum 4, 314 (2020)


NEAR-TERM
QUANTUM SIMULATORS

QUANTUM SIMULATORS

- Can we hope noisy, realistic quantum devices to provide a speedup over classical computers?



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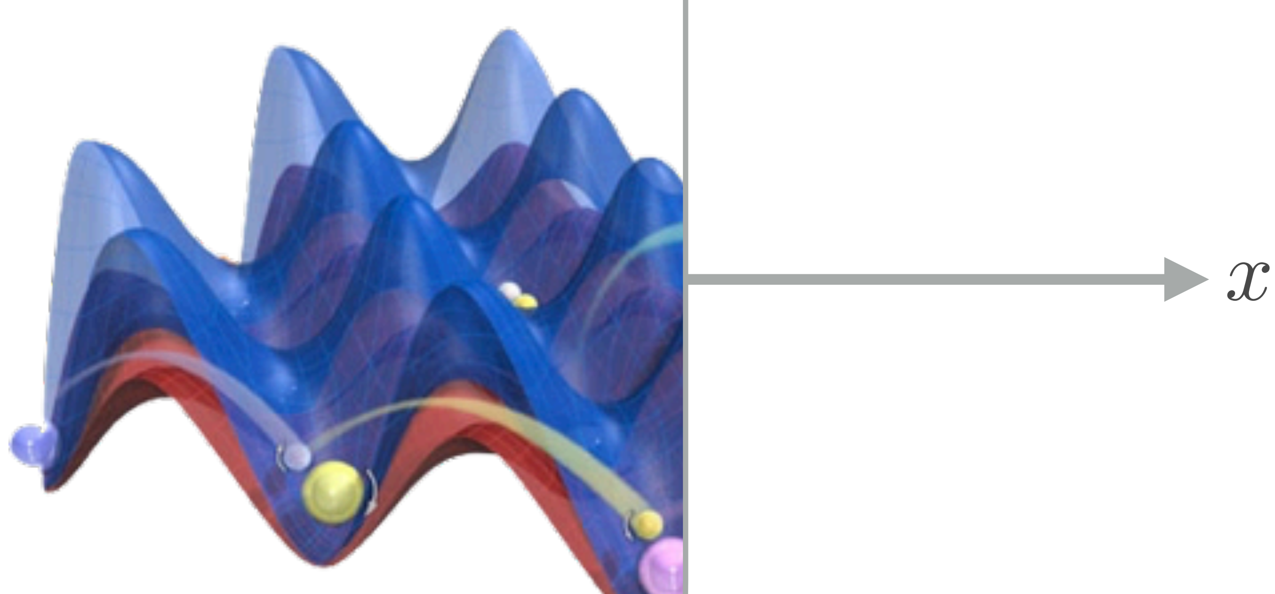
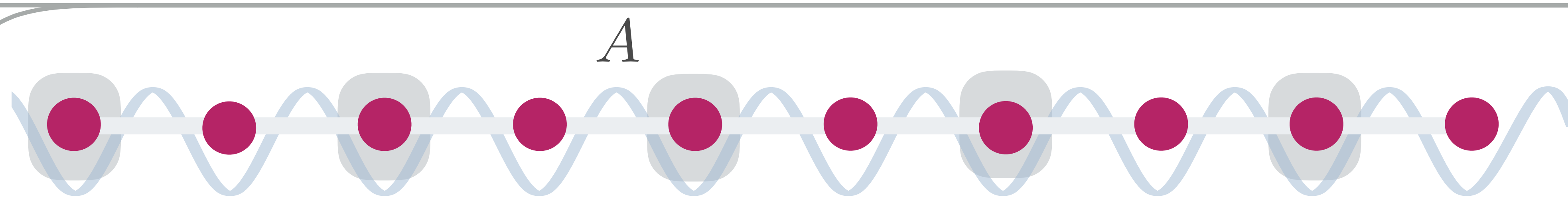
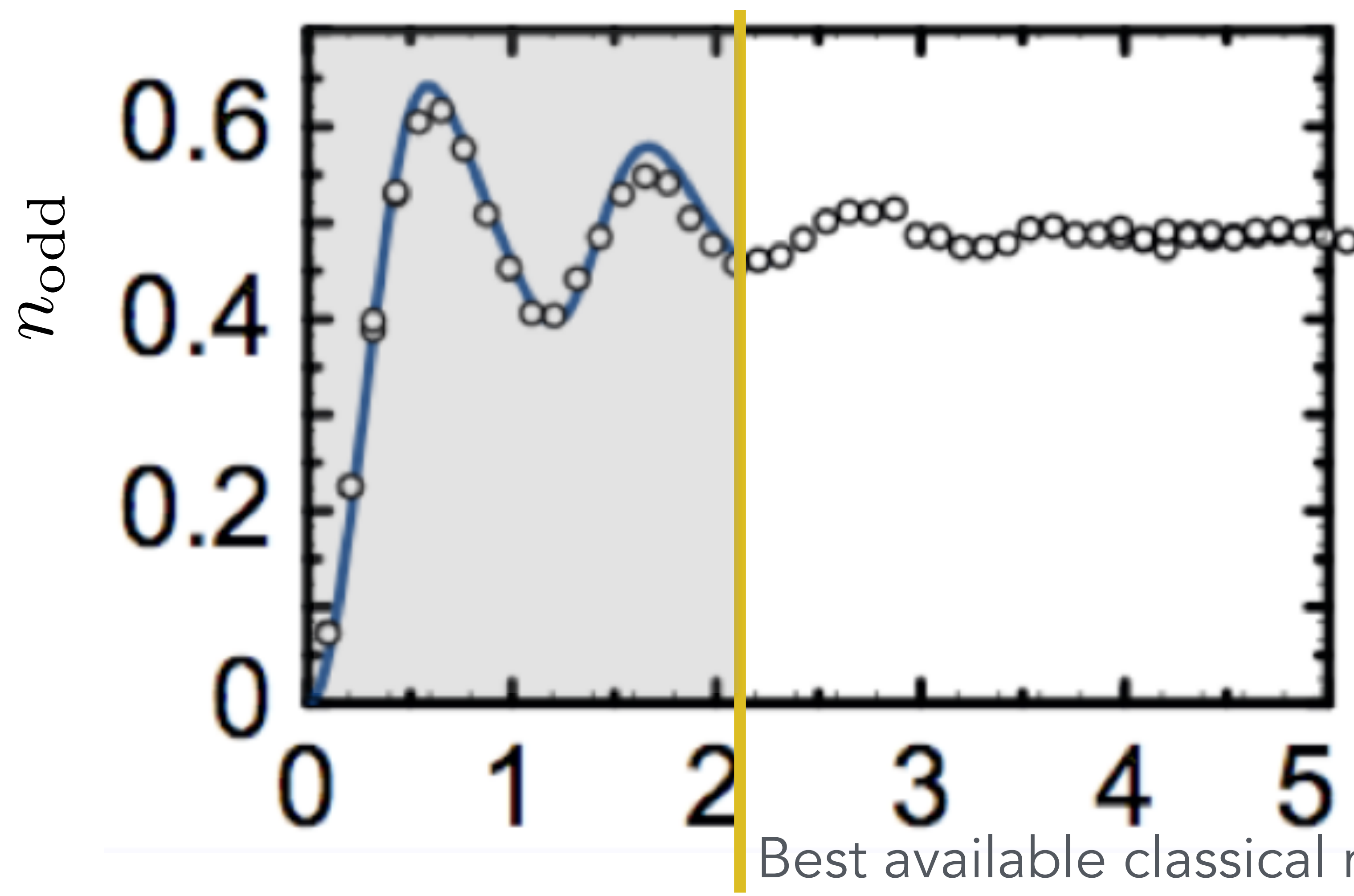


Quantur

- Ground state problems
- "Quenches" $\rho(t) = e^{-itH} \rho e^{itH}$ (time evolution)
- Slow evolutions, reminiscent of adiabatic quantum computing

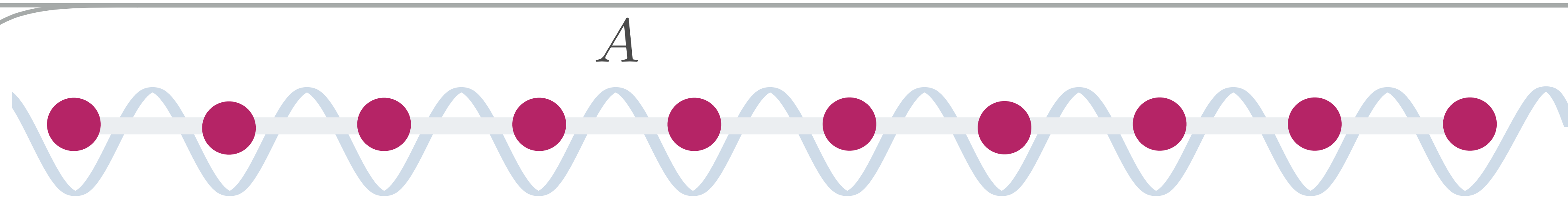


- **Equilibration and thermalisation** of atoms in optical super-lattices (MPQ)
- Imbalance as function of time for $|\psi(0)\rangle = |0,1,\ldots,0,1\rangle$ under Bose-Hubbard Hamiltonian

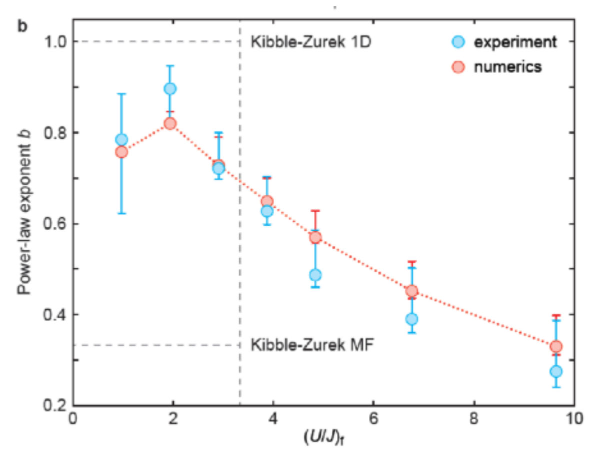


Best available classical matrix-product state simulation, bond dimension 5000

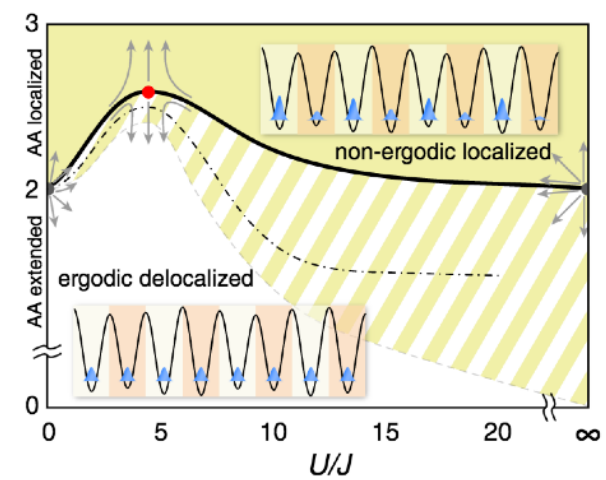
Trotzky, Chen, Flesch, McCulloch, Schollwoeck, Eisert, Bloch, Nature Phys 8, 325 (2012)



Kibble-Zurek mechanism



Many-body localization



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

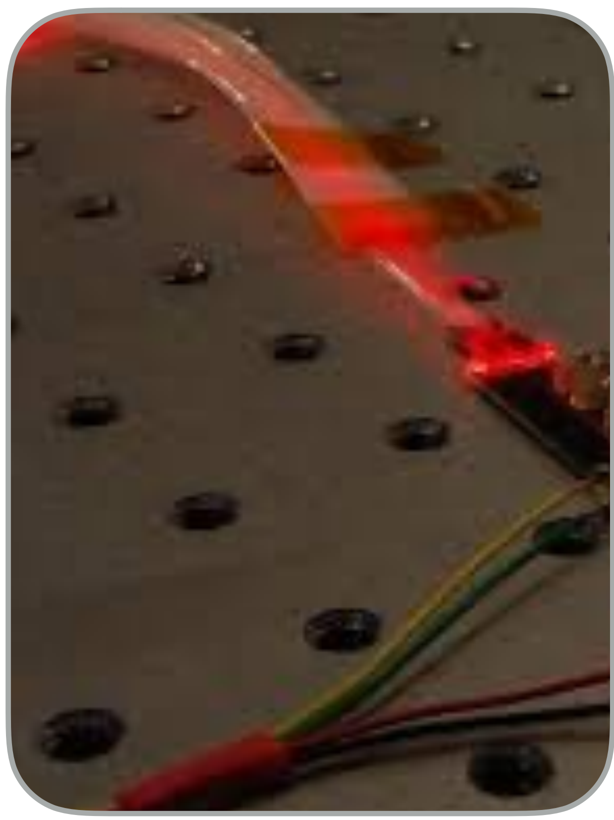
Schreiber, Hodgman, Bordia, Lüschen, Fischer, Vosk, Altman, Schneider, Bloch, Science 349, 842 (2015)

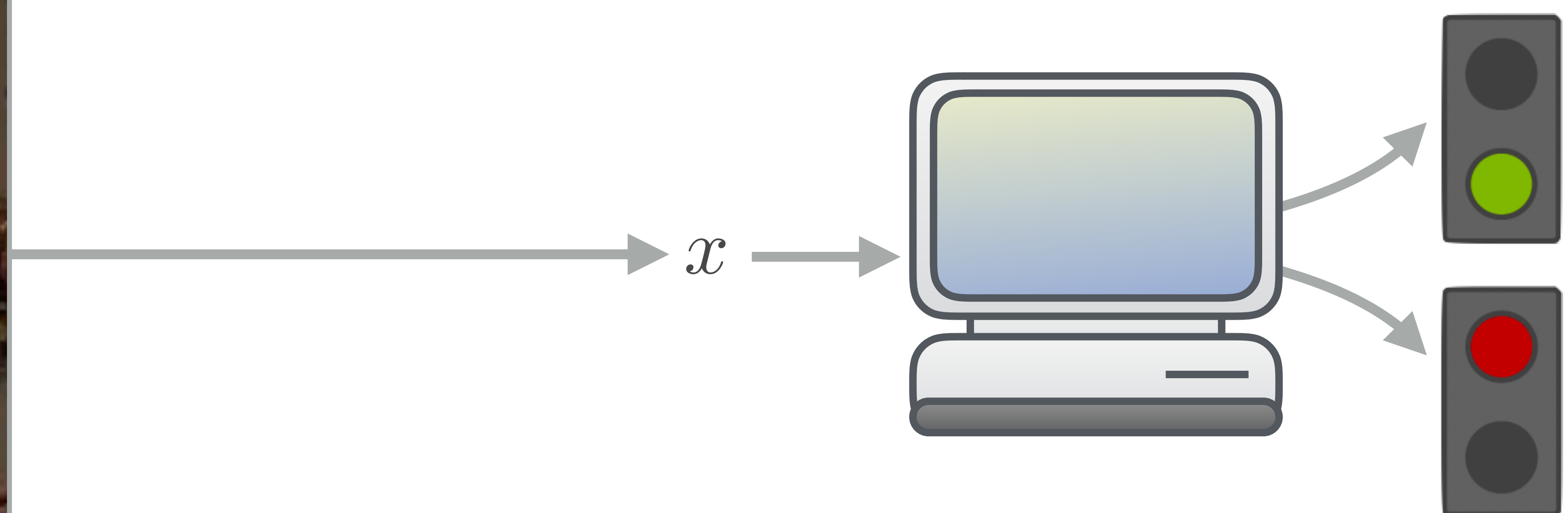
Braun, Friesdorf, Hodgman, Schreiber, Ronzheimer, Riera, del Rey, Bloch, Eisert, Schneider, Proc Natl Acad Sci 112 3641 (2015)

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

QUANTUM SUPREMACY

- Can we hope noisy, realistic quantum devices to provide a speedup over classical computers?





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THE QUEST FOR

QUANTUM ADANTAGES

QUANTUM ADVANTAGES OR “SUPREMACY”

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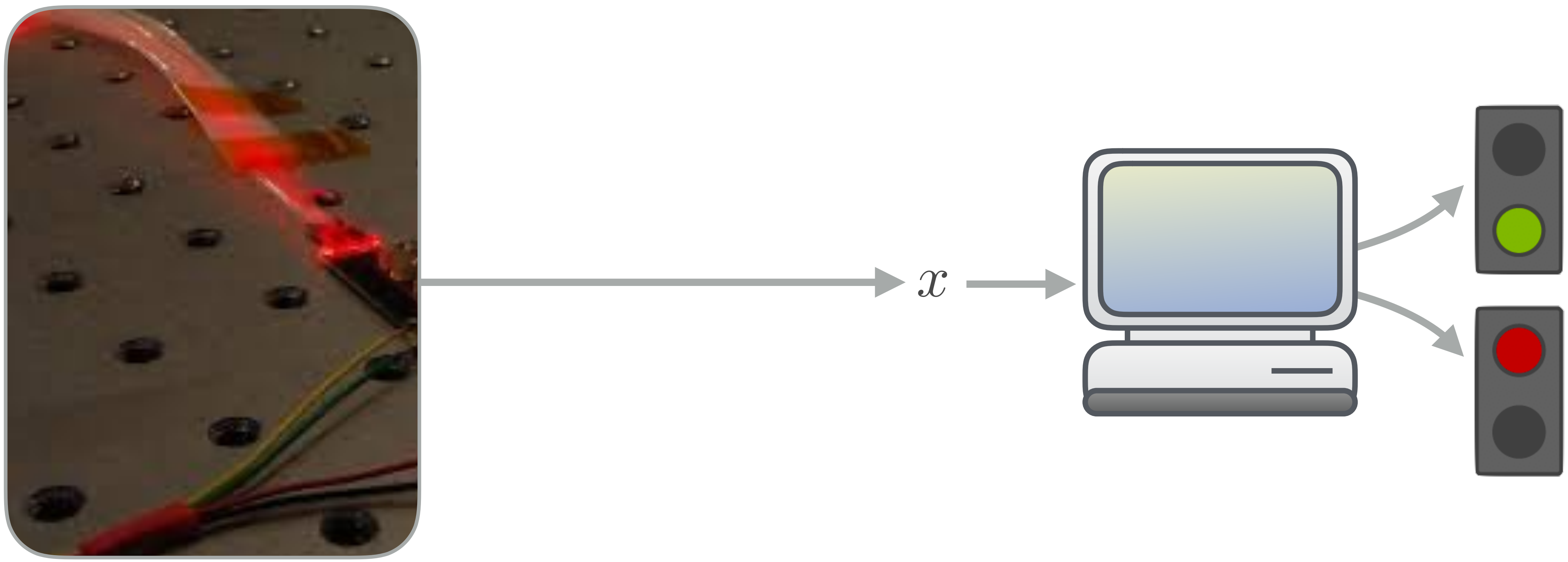

- To be safe against “lack of imagination”, must prove the hardness of the task in a complexity-theoretic sense

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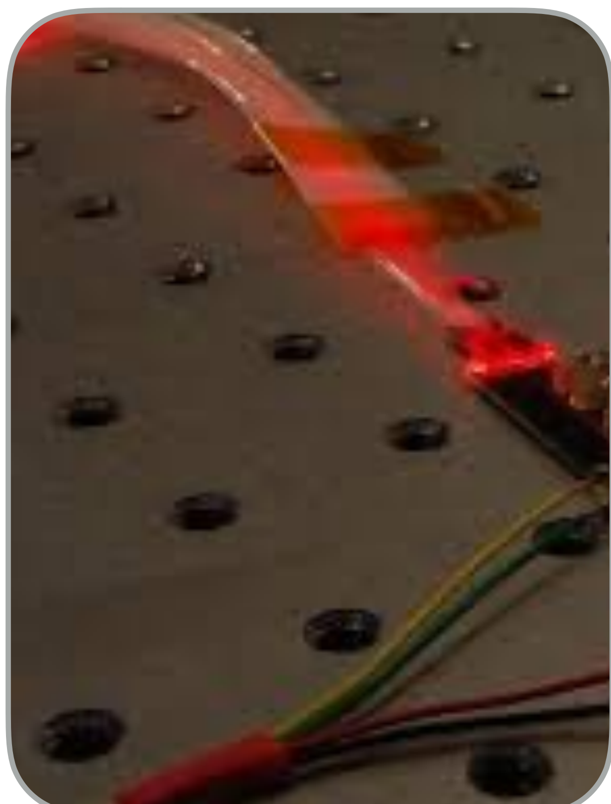

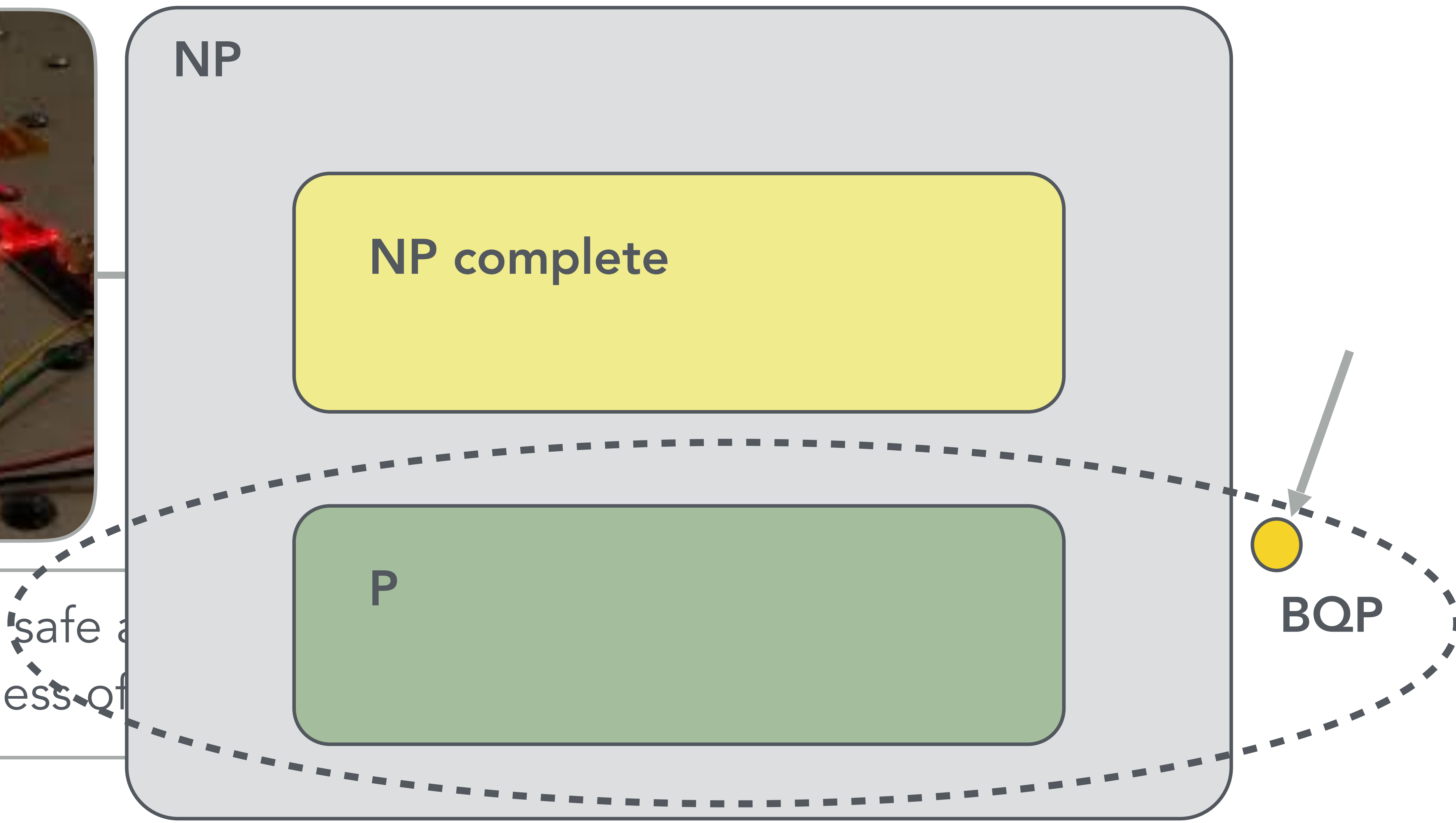

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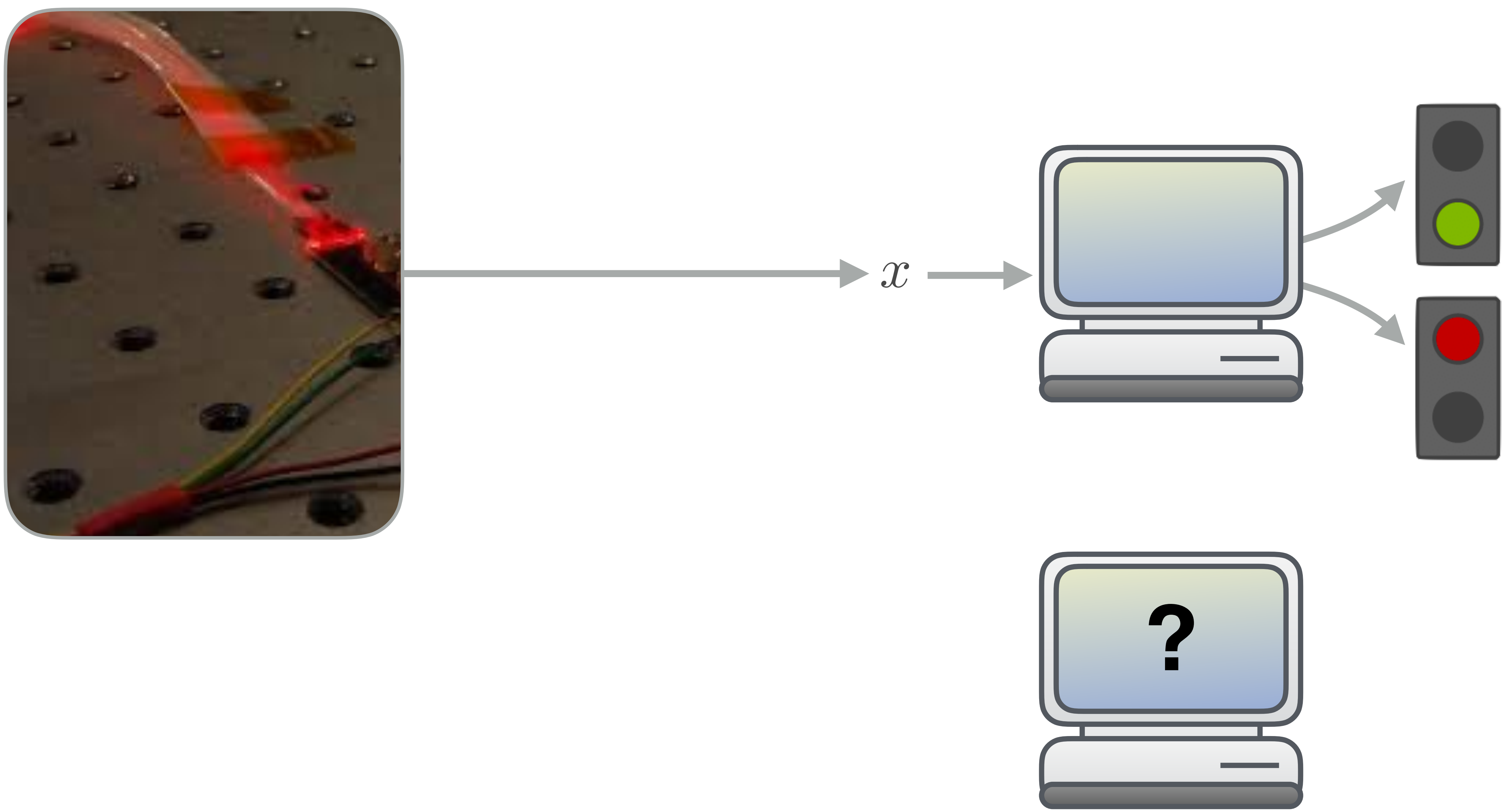
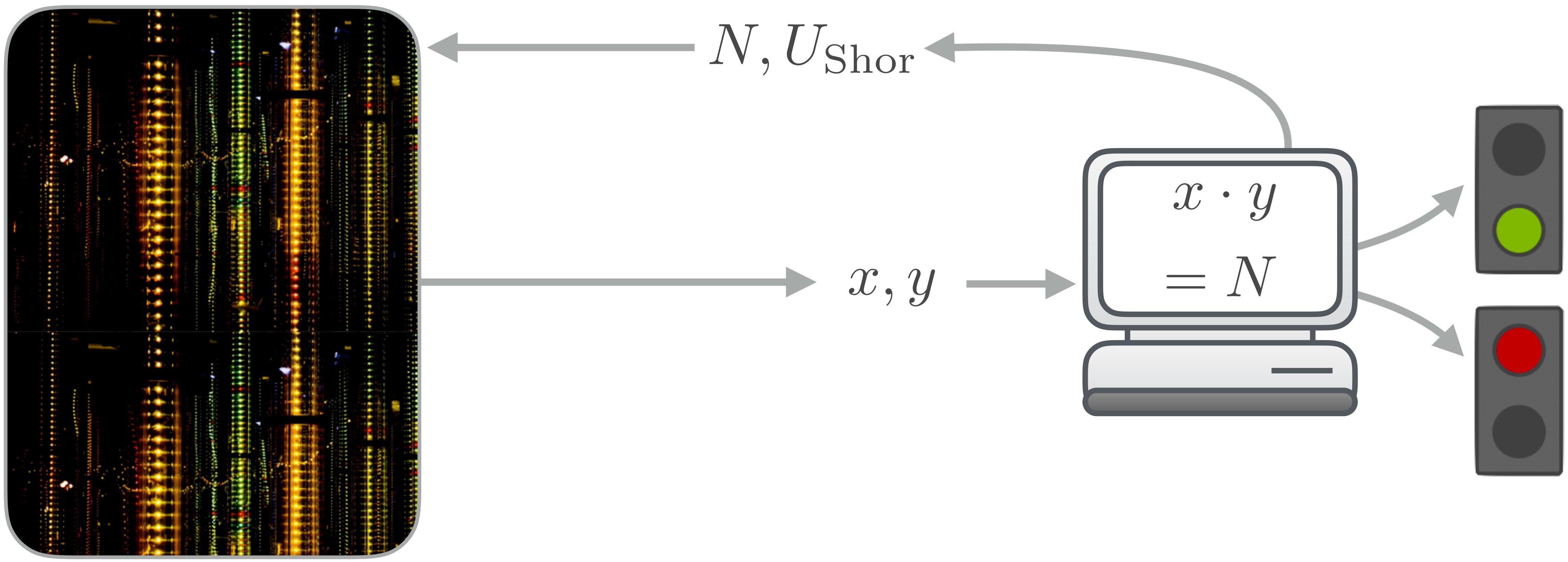


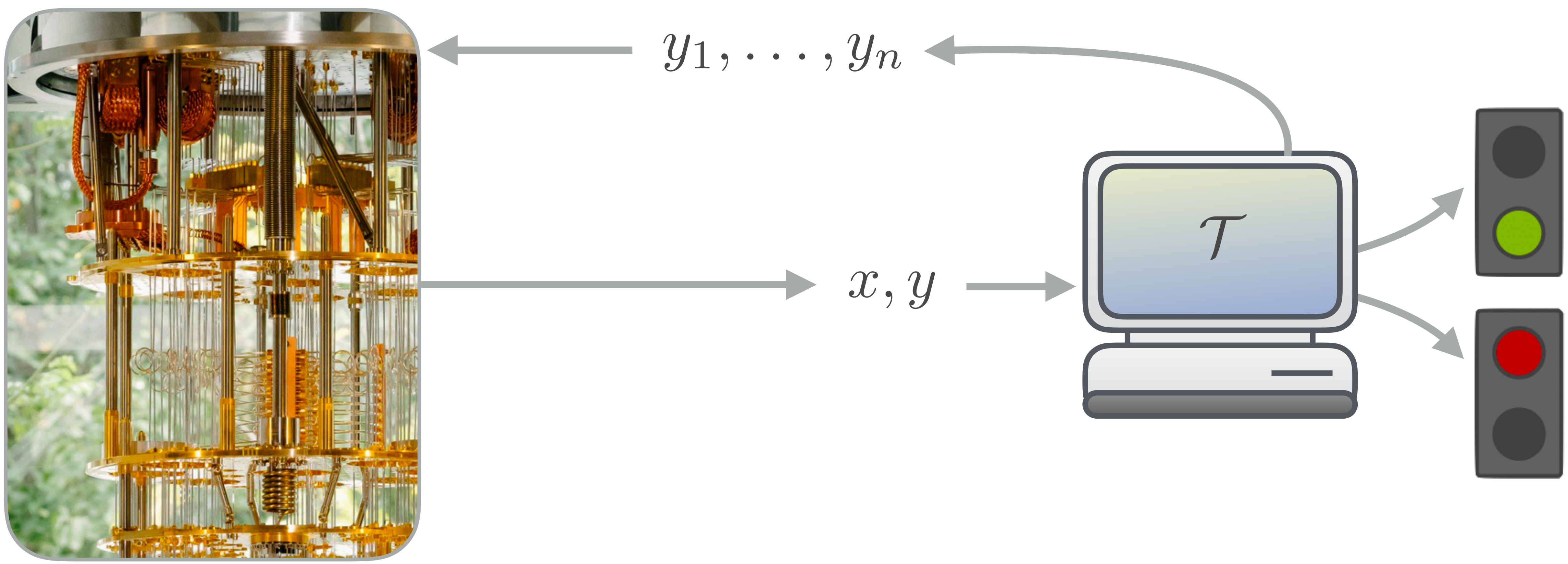
QUANTUM ADVANTAGES OR “SUPREMACY”

- **Computational Bell tests:** Does nature permit computations that are (exponentially) faster than probabilistic Turing machines?

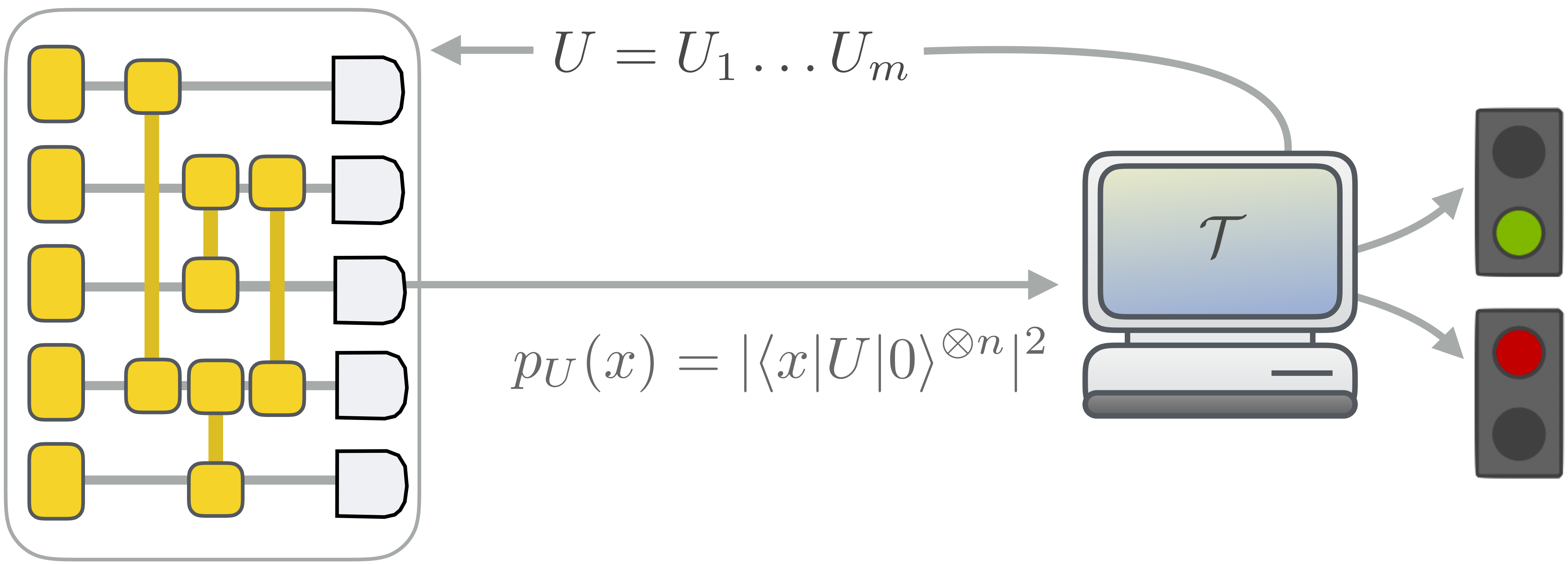


QUANTUM ADVANTAGES OR “SUPREMACY”

- Single round, classical data, “small” quantum device



- Sampling tasks natural for QC, but hard on classical computers



- **Random circuits**

Boixo, Isakov, Smelzanski, Babbush, Ding, Jiang, Bremner, Martinis, Neven, Nature Physics 14, 595-600 (2018)

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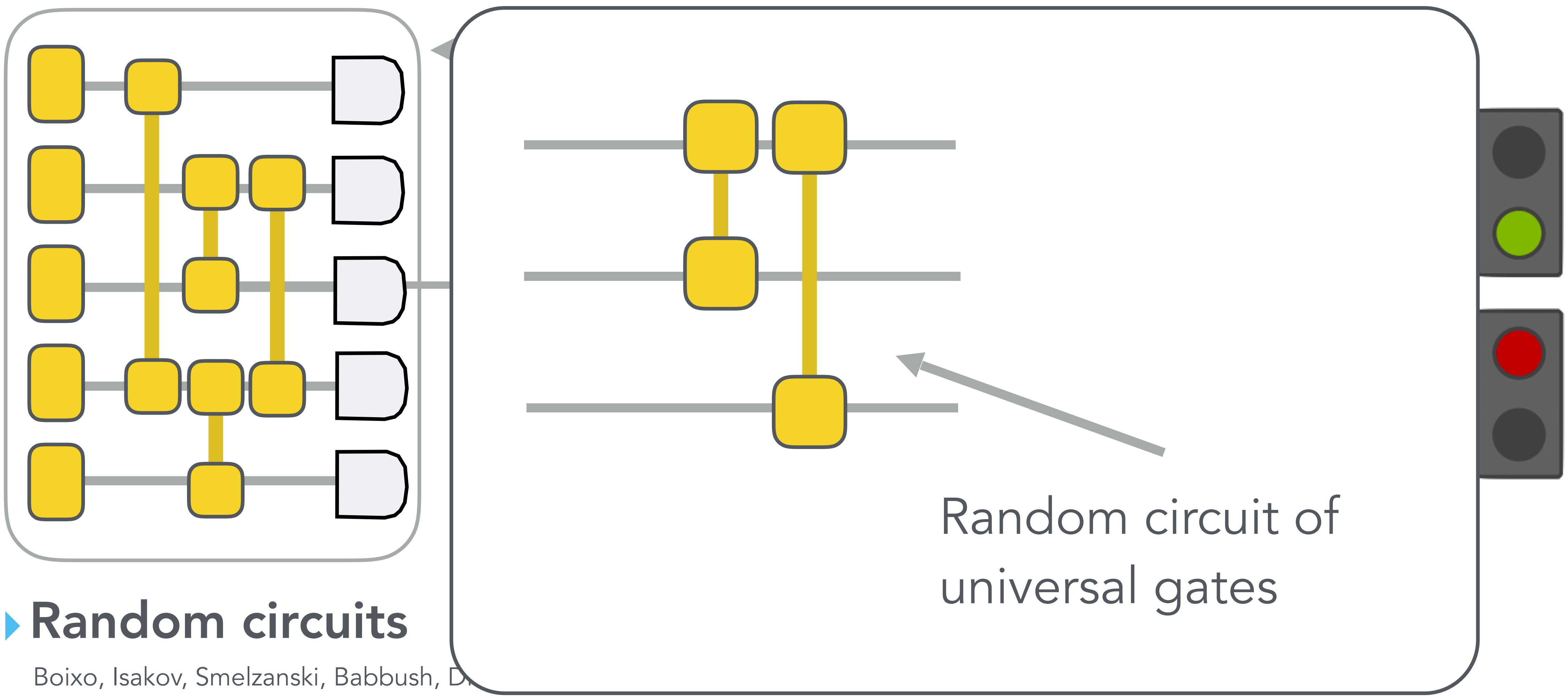

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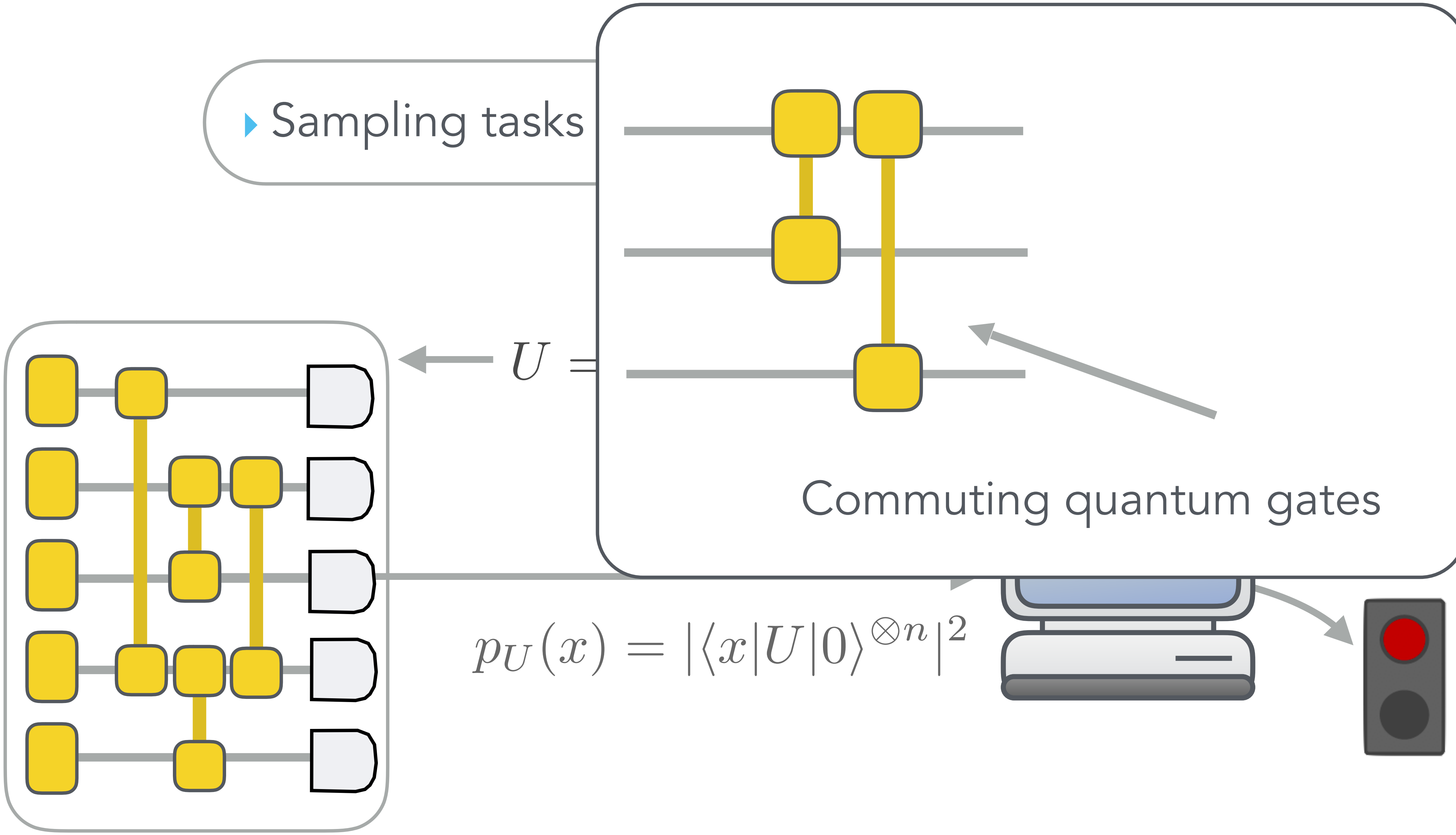
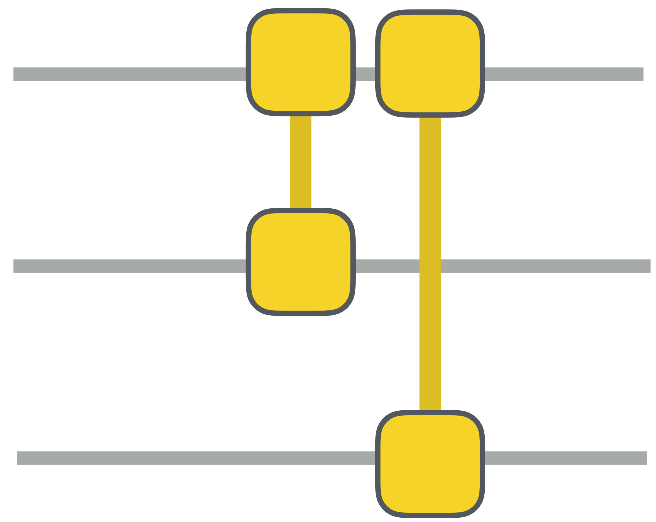


- **Instantaneous quantum polynomial (IQP) circuits**

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

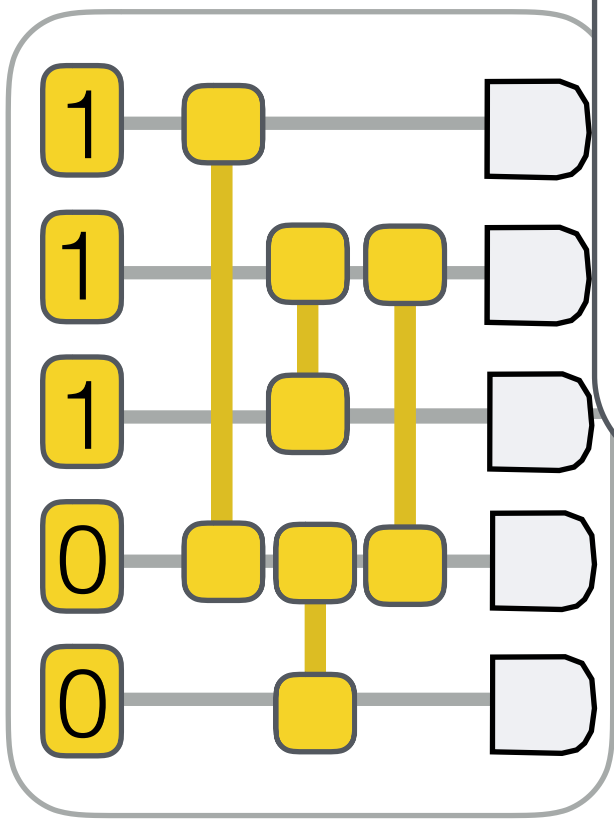
- Samp… …ers

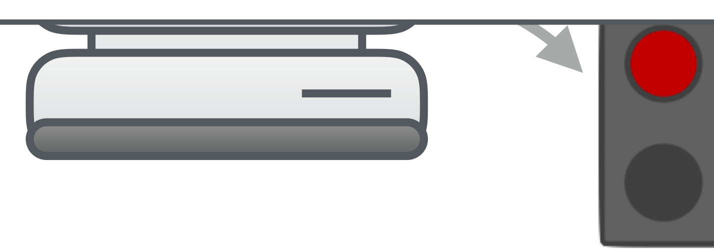


Unitary mode transformations

$$b^T \mapsto U b^T$$

with $b = (b_1, \cdots, b_n)$ and $U \in U(n)$ Haar-random





- **Boson sampling**

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

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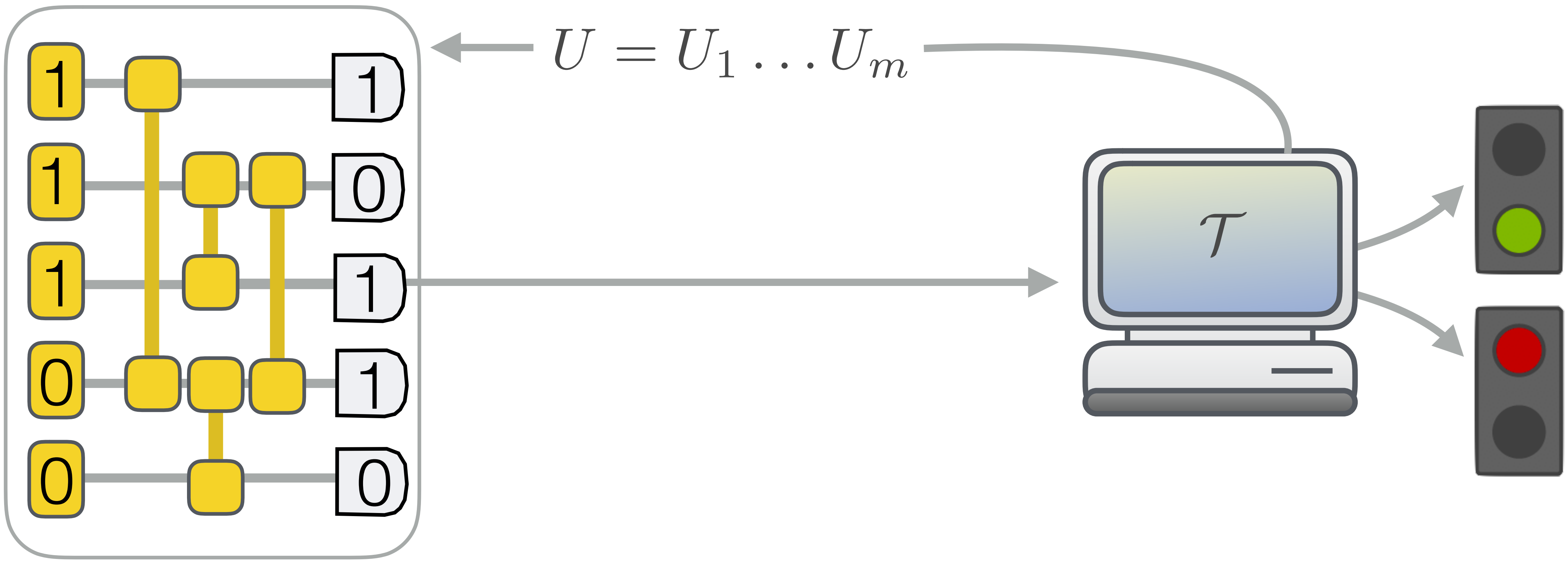

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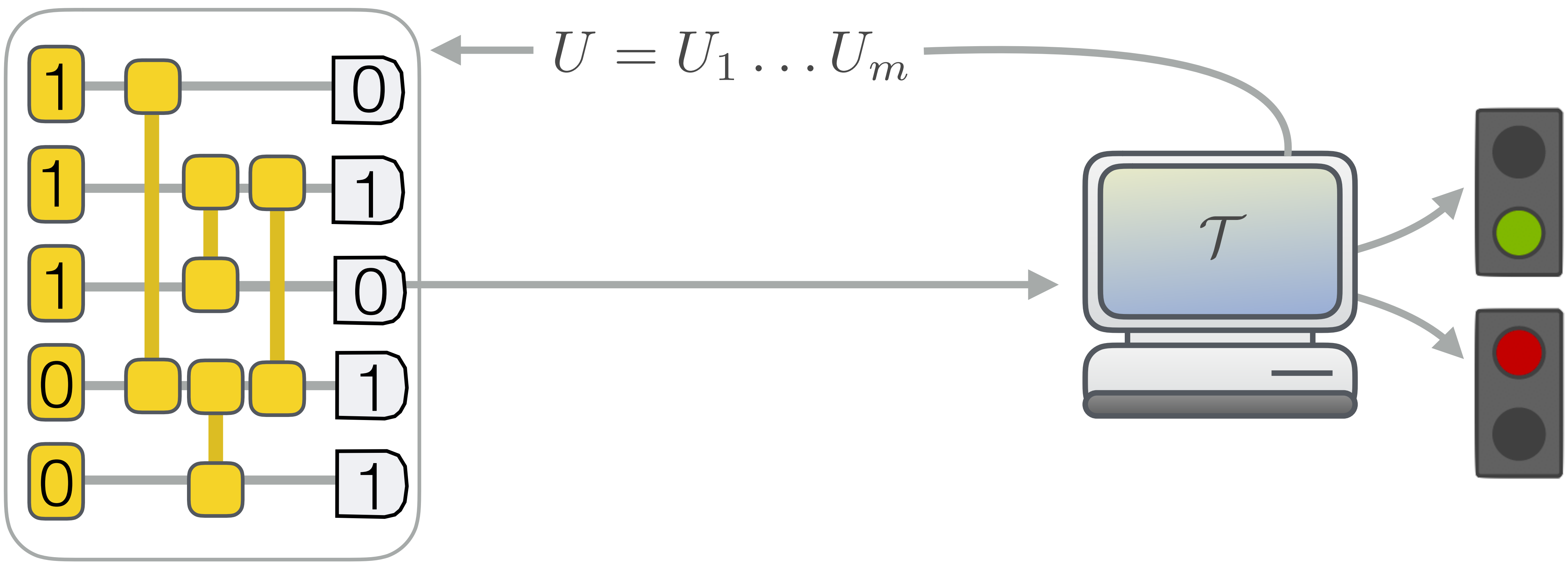

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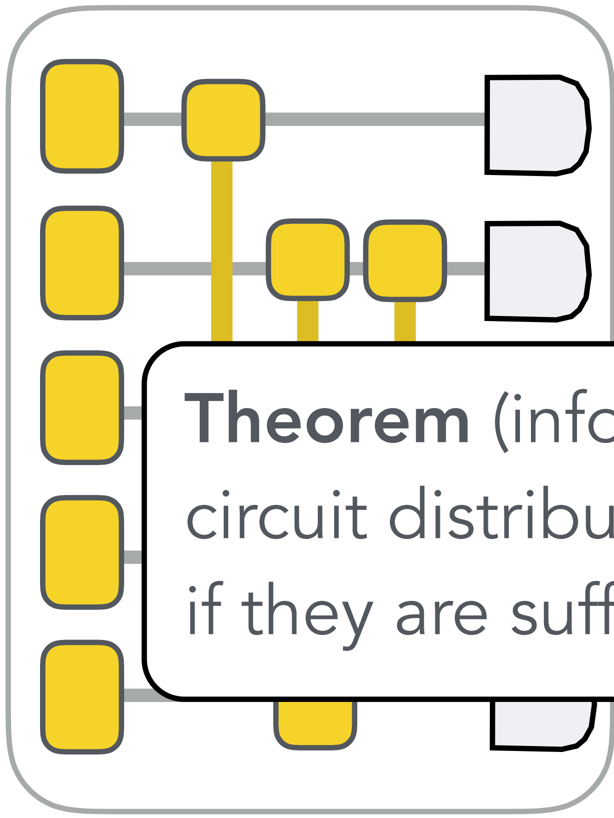


$U = U_1 \dots U_m$

Theorem (informal): Sampling from a distribution close in l_1 norm to random circuit distribution is "computationally hard" with high probability over circuits if they are sufficiently long


Science

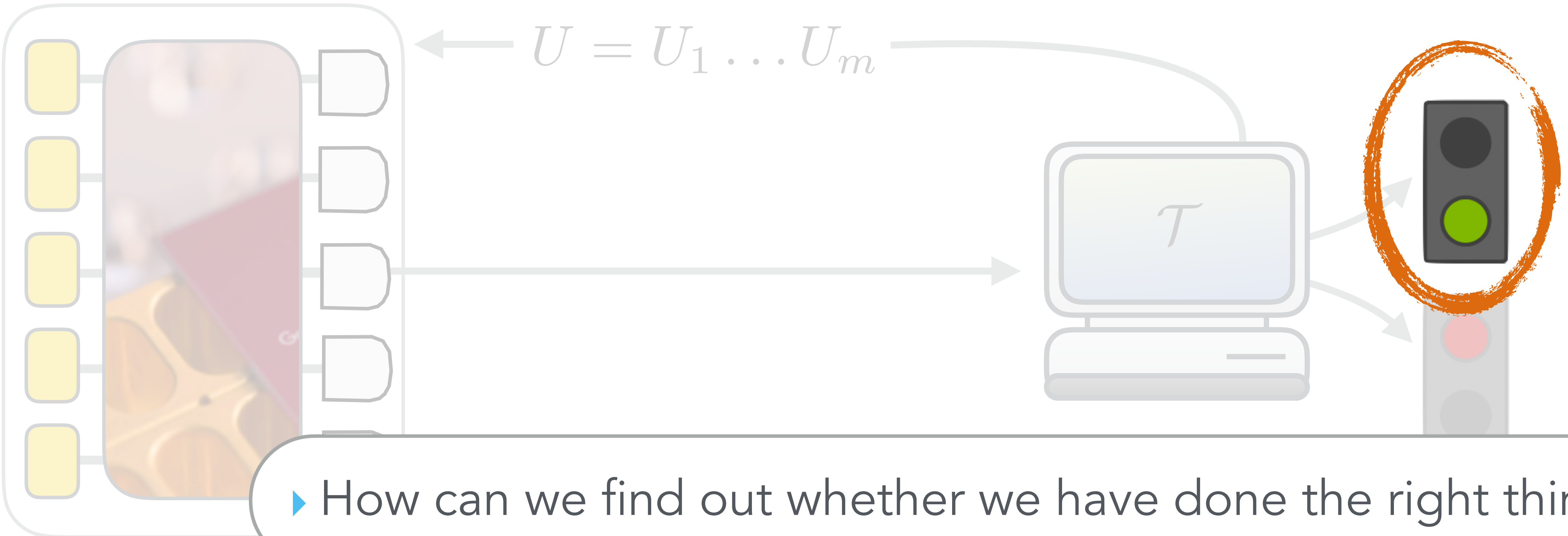
Google

Google claims it has achieved 'quantum supremacy' – but IBM disagrees

Task that would take most powerful supercomputer 10,000 years 'completed by quantum machine in minutes'

Arute, …, Martinis, Nature 574, 505 (2019)

VERIFICATION?



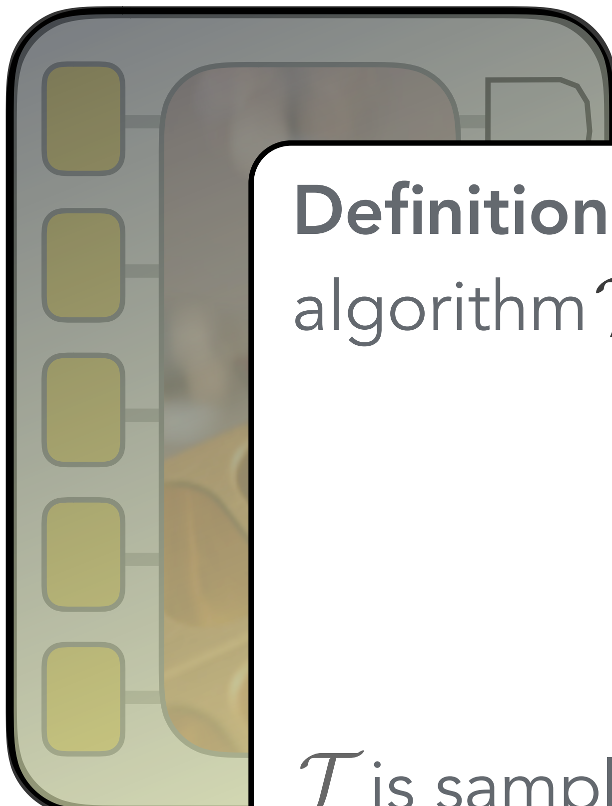
- How can we find out whether we have done the right thing?

BLACK BOX CERTIFICATION

LOOKING AT DATA FROM QUANTUM DEVICES

VERIFICATION?

Valiant, Valiant, ECCC 111 (2013)
Hangleiter, Kliesch, Eisert, Gogolin, arXiv:1812.01023
Harrow at al, in preparation



Definition: A black-box certification test with sample complexity m is an algorithm $\mathcal{T} : (\{0,1\}^n)^m \to \{0,1\}$

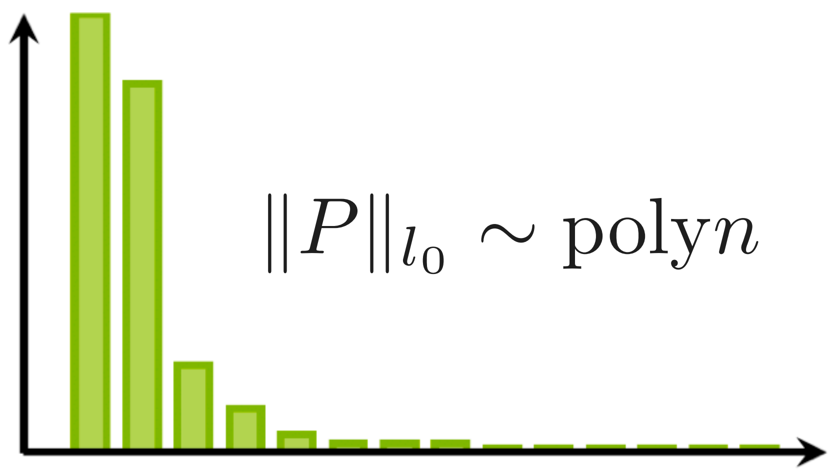
$$Q = P \;\Rightarrow\; \mathrm{Pr}_{X\sim Q}(\mathcal{T}(X) = 1) \geq \frac{2}{3}$$

$$\|Q - P\|_{l_1} > \epsilon \;\Rightarrow\; \mathrm{Pr}_{X\sim Q}(\mathcal{T}(X) = 1) < \frac{1}{3}.$$

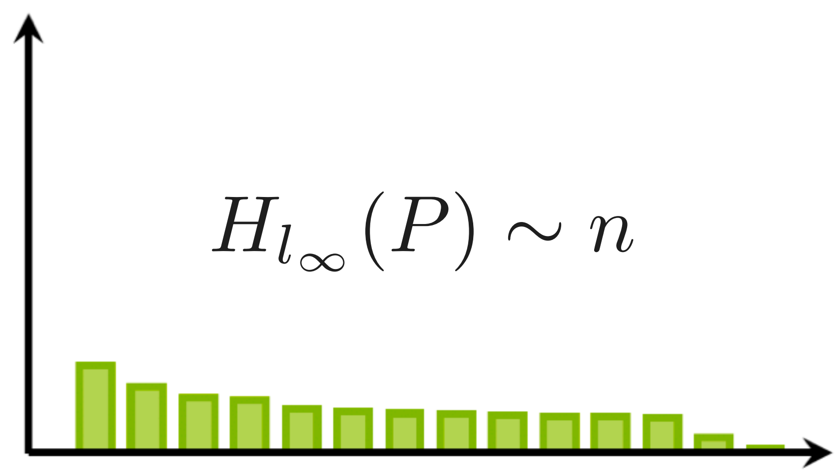
$\mathcal{T}$ is sample-efficient if $m \sim \mathrm{poly}\, n$

Valiant, Valiant, ECCC 111 (2013)
Hangleiter, Kliesch, Eisert, Gogolin, arXiv:1812.01023
Harrow at al, in preparation

- Concentration



- Anti-concentration



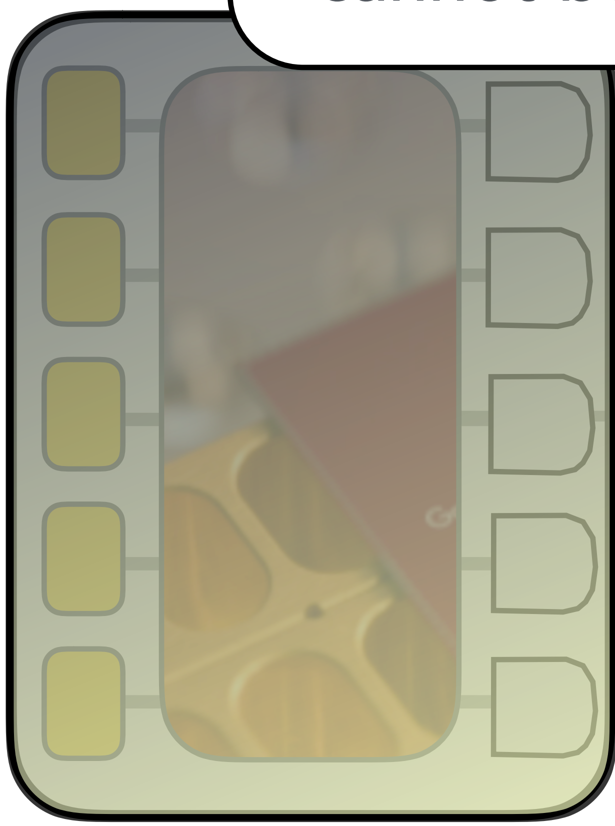
- Black box certifiable from $O(\mathrm{poly}(n))$many samples

- Every black-box test requires at least $O(\sqrt{2^n})$ many samples

Valiant, Valiant, ECCC 111 (2013)
Hangleiter, Kliesch, Eisert, Gogolin, arXiv:1812.01023
Harrow at al, in preparation

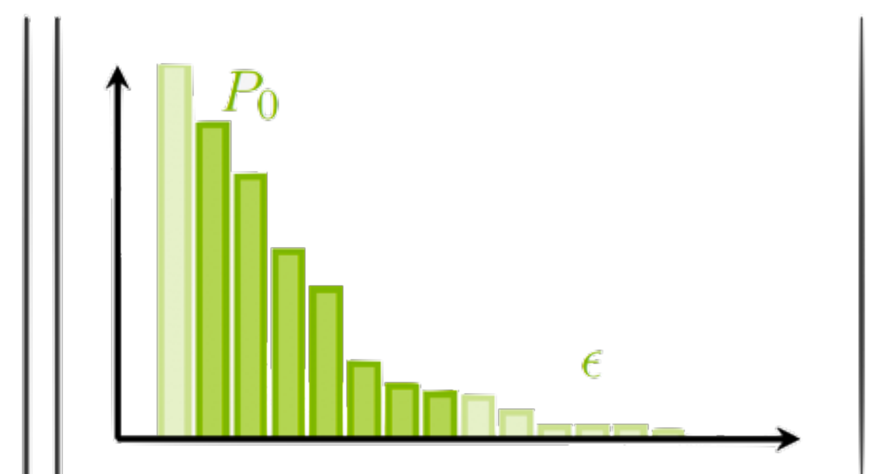
VERIFICATION?

- **Theorem** (informal): Boson sampling, IQP circuits, random circuits **cannot be black-box certified** from polynomially many samples



- One needs further assumptions

- Proof tool: $\|P_{-\epsilon}^{-\max}\|_{2/3} =$



$2/3$

Valiant, Valiant, ECCC 111 (2013)
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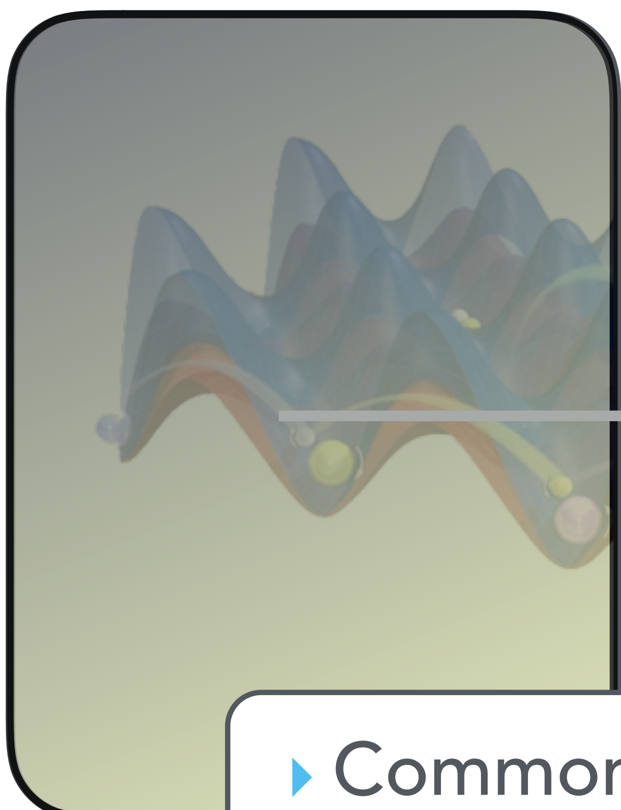

- **Common prejudice:** In order to be able to verify a quantum simulation, one needs to be able to efficiently simulate it

Valiant, Valiant, ECCC 111 (2013)
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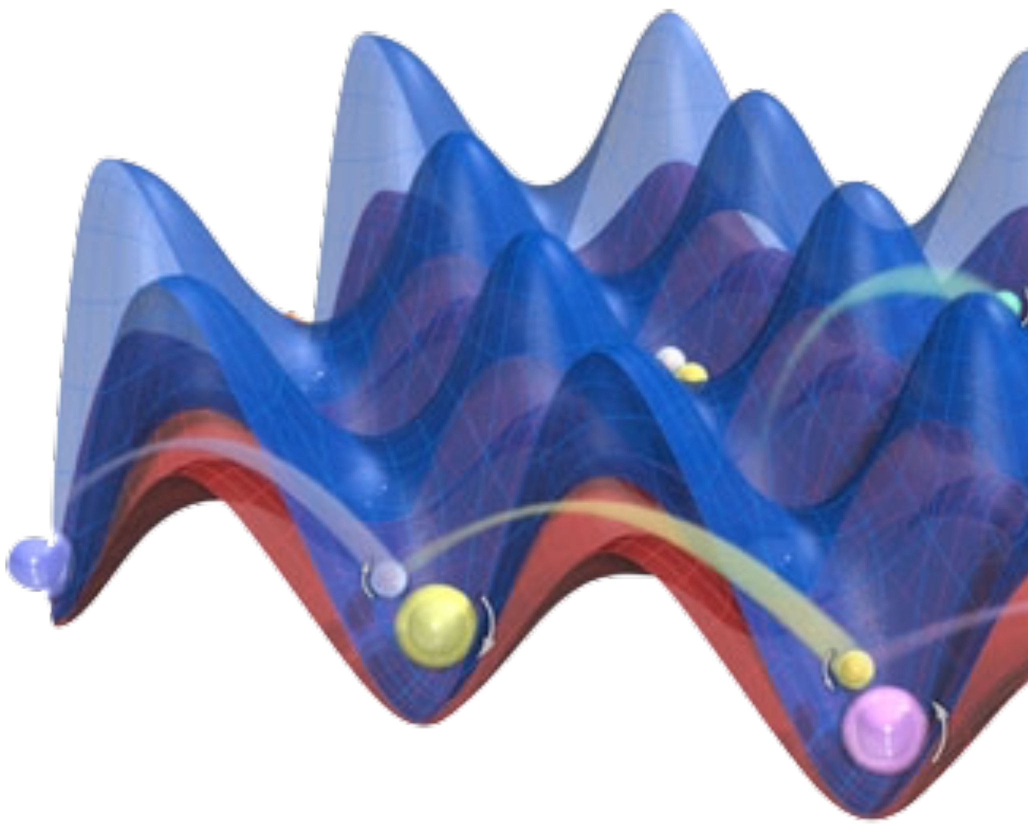


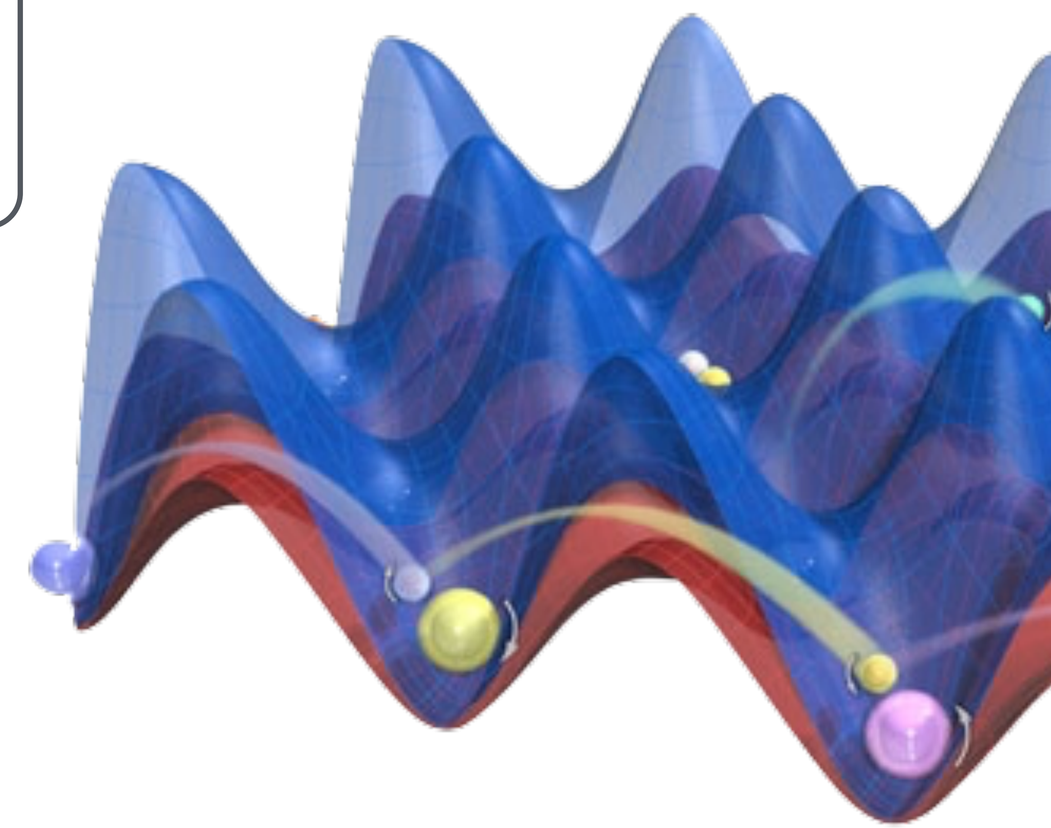
BEYOND BLACK BOXES

A SIMPLE NEAR-TERM QUANTUM ADVANTAGE SCHEME

A FEASIBLE SCHEME

- What is the **simplest conceivable scheme** that can show quantum supremacy?

  - Simple **Hamiltonian** quantum simulation
  - **Hardness proofs** with l_1-norm error



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

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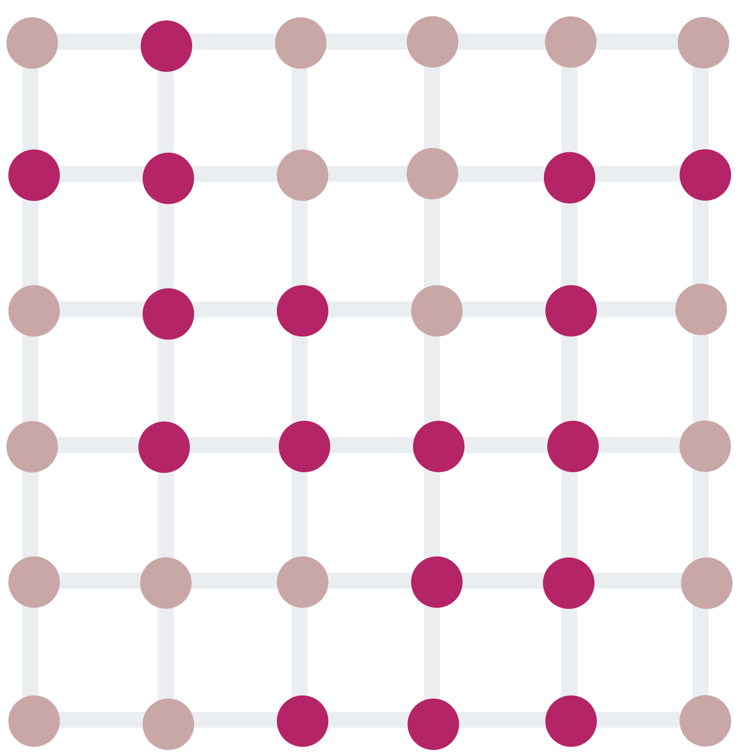
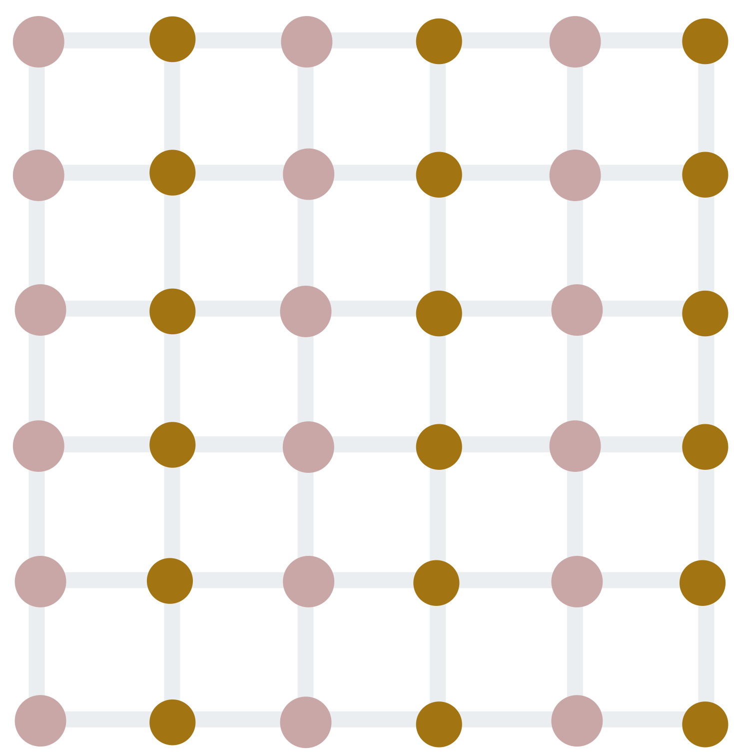
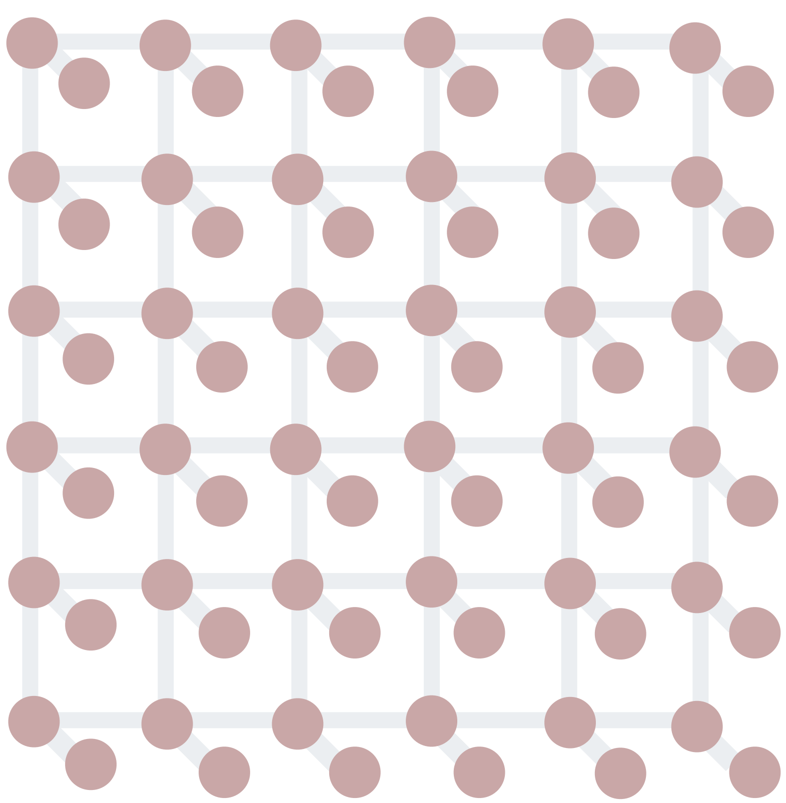


Random



Quasi-periodic



Translationally invariant

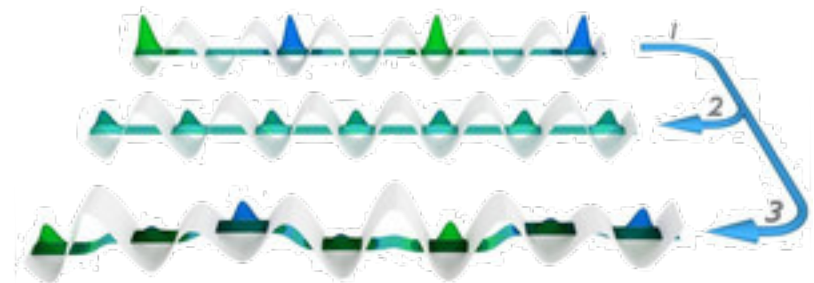
Bermejo-Vega, Hangleiter, Schwarz, Raussendorf, Eisert, Phys Rev X 8, 021010 (2018)

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

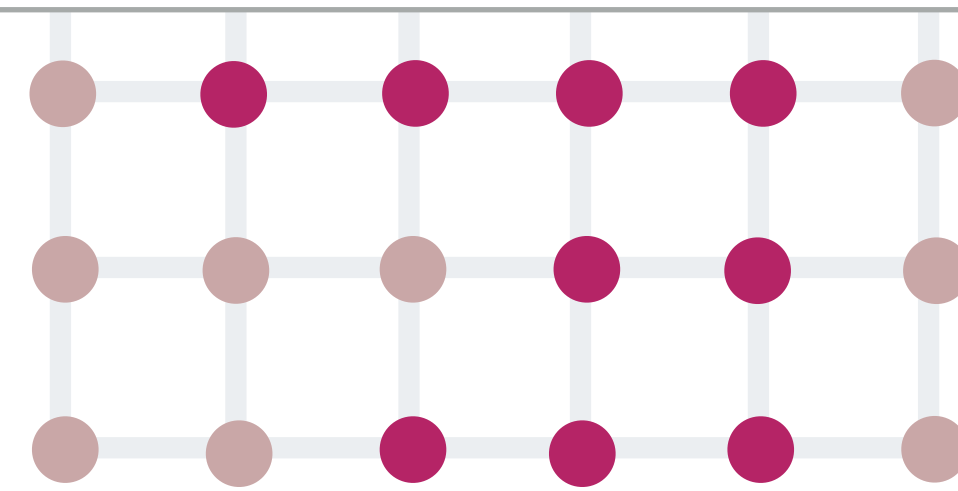
$$|\psi_\beta\rangle = \otimes_{i,j=1}^{n,m} (|0\rangle + e^{i\beta_{i,j}} |1\rangle)$$

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, Phys Rev X 8, 021010 (2018)

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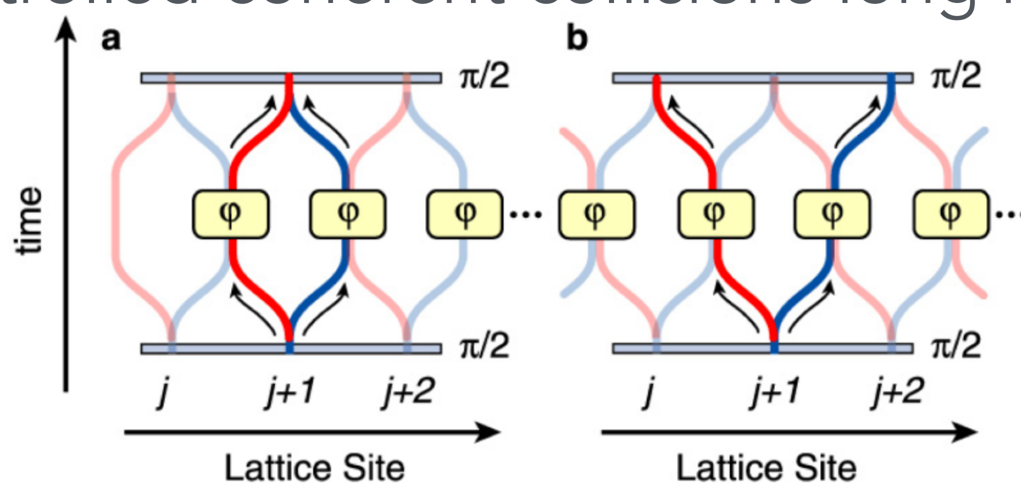
- Quench to $H = \sum_{(i,j)\in E} Z_i Z_j + \frac{\pi}{4} \sum_{i \in V} Z_i$ and evolve under $U = e^{iH}$

- Controlled coherent collisions long realized



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

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

SIMPLE ISING MODELS

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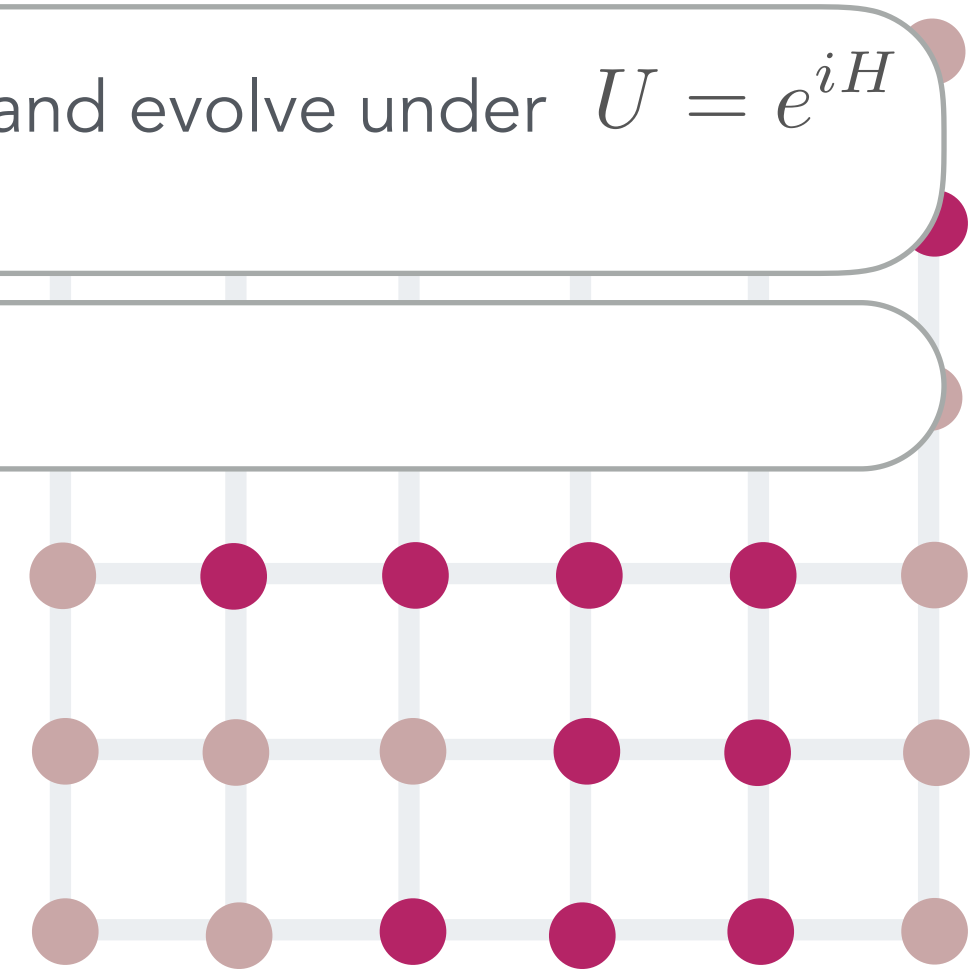
- Measure all qubits in X-basis



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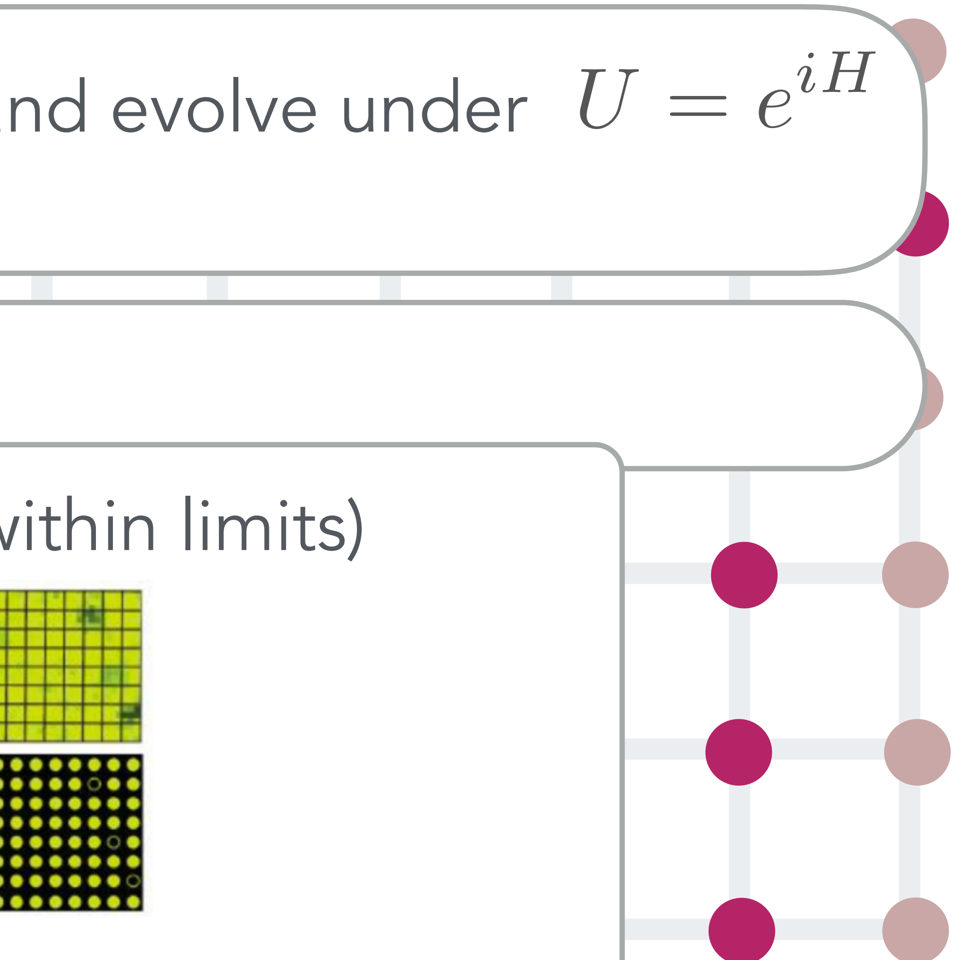
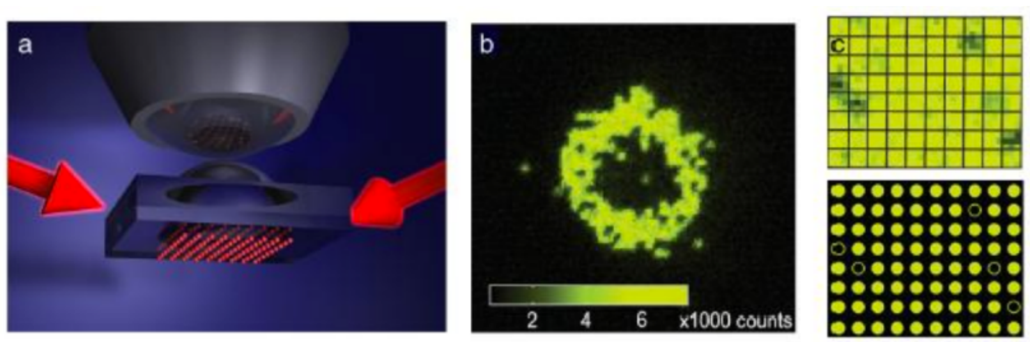


- Single-site addressing possible (within limits)

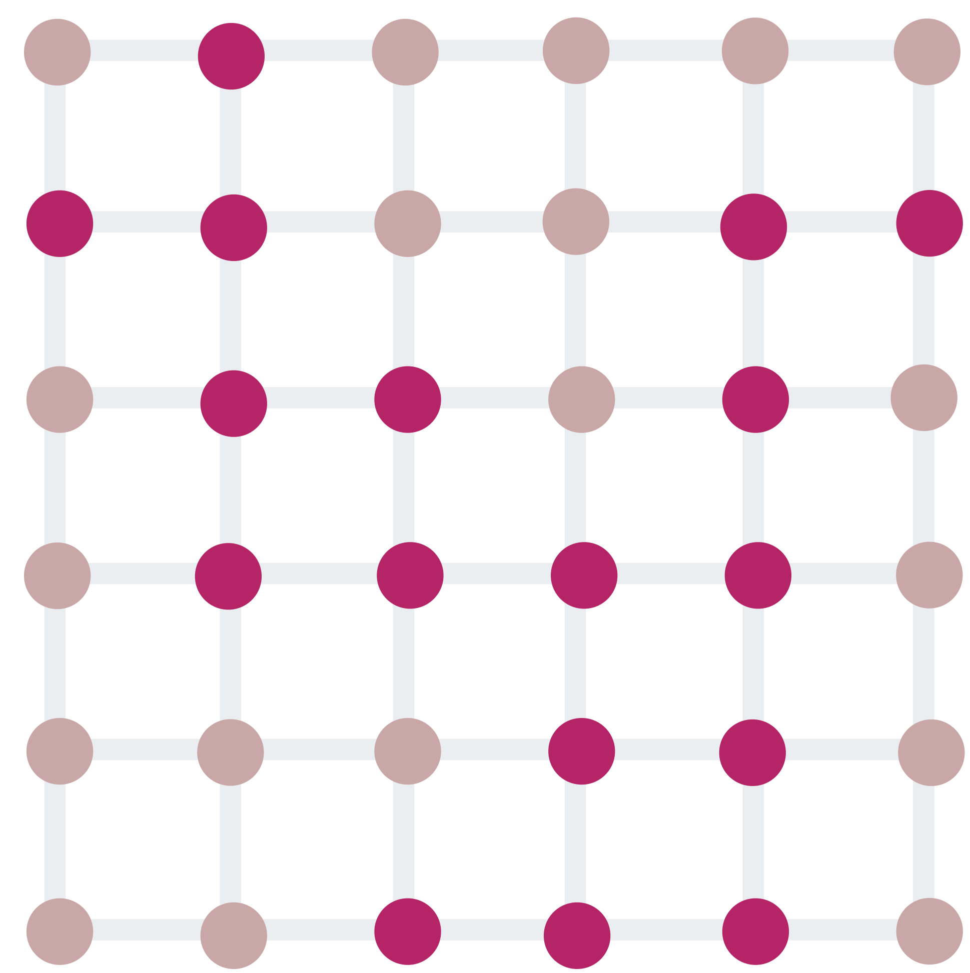


Bakr, Gillen, Peng, Foelling, Greiner, Nature 462, 74–77 (2009)
Weitenberg, Endres, Sherson, Cheneau, Schauß, Fukuhara, Bloch, Kuhr, Nature 471, 319 (2011)

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

Theorem (Hardness of classical sampling):

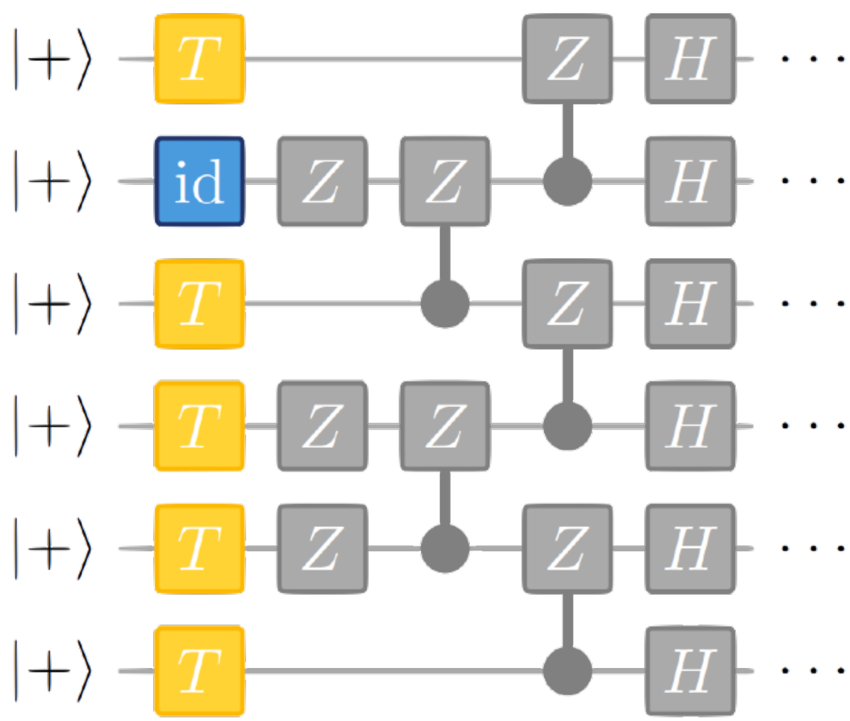
Assuming three highly plausible conjectures are true a classical computer cannot efficiently sample from the outcome distribution of our scheme up to constant error in l_1 distance



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

- 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$\neq$ NP)
- Average-case complexity

Bouland, Fefferman, Nirkhe, Vazirani, arXiv:1803.04402

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

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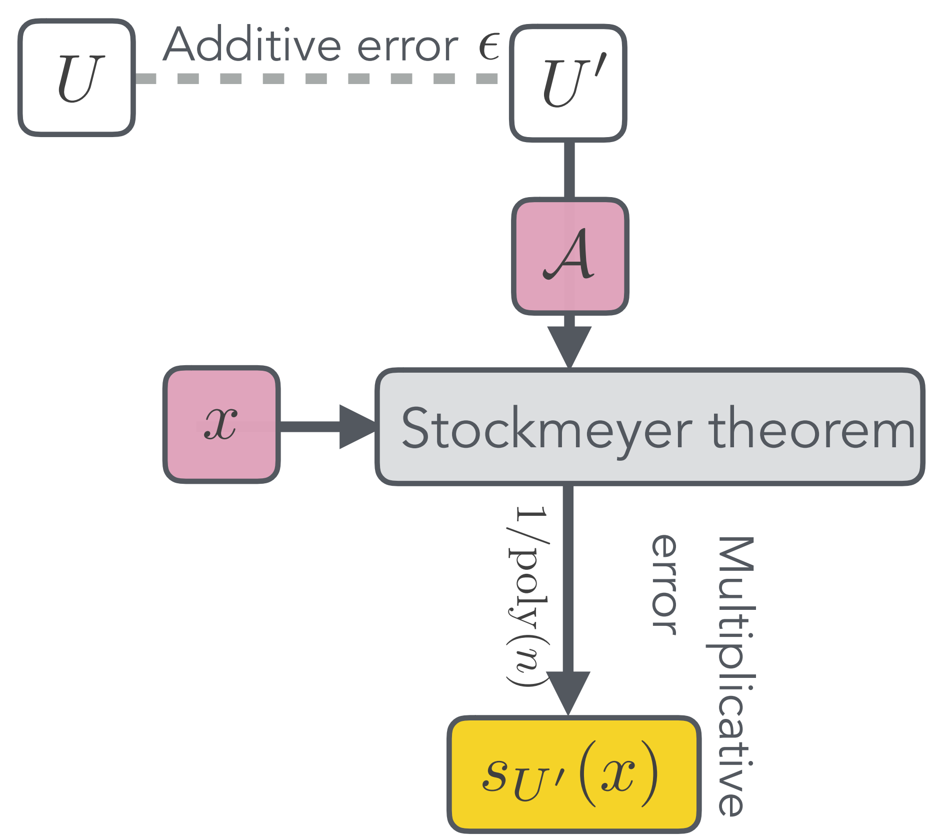

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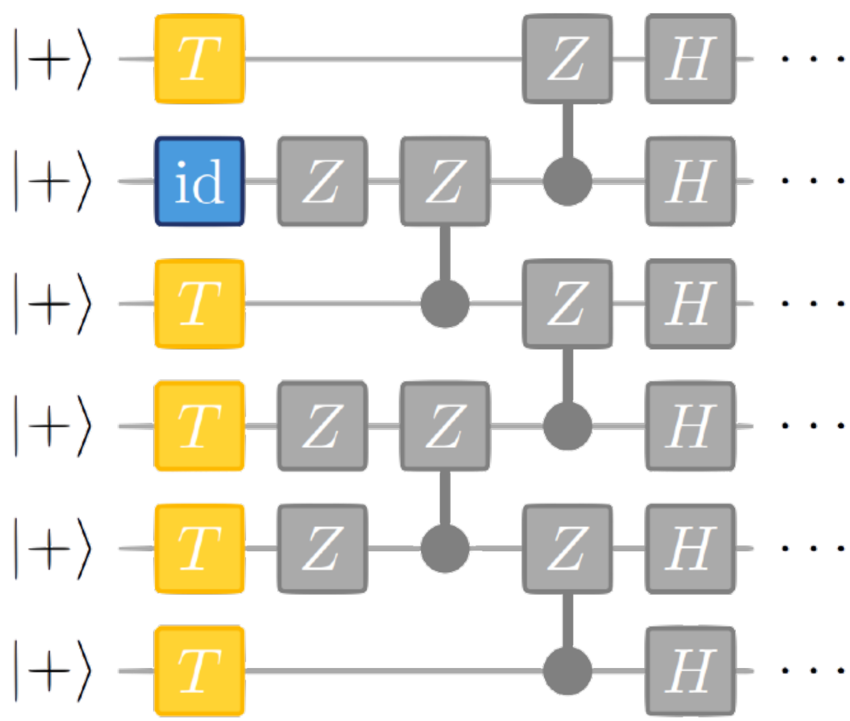

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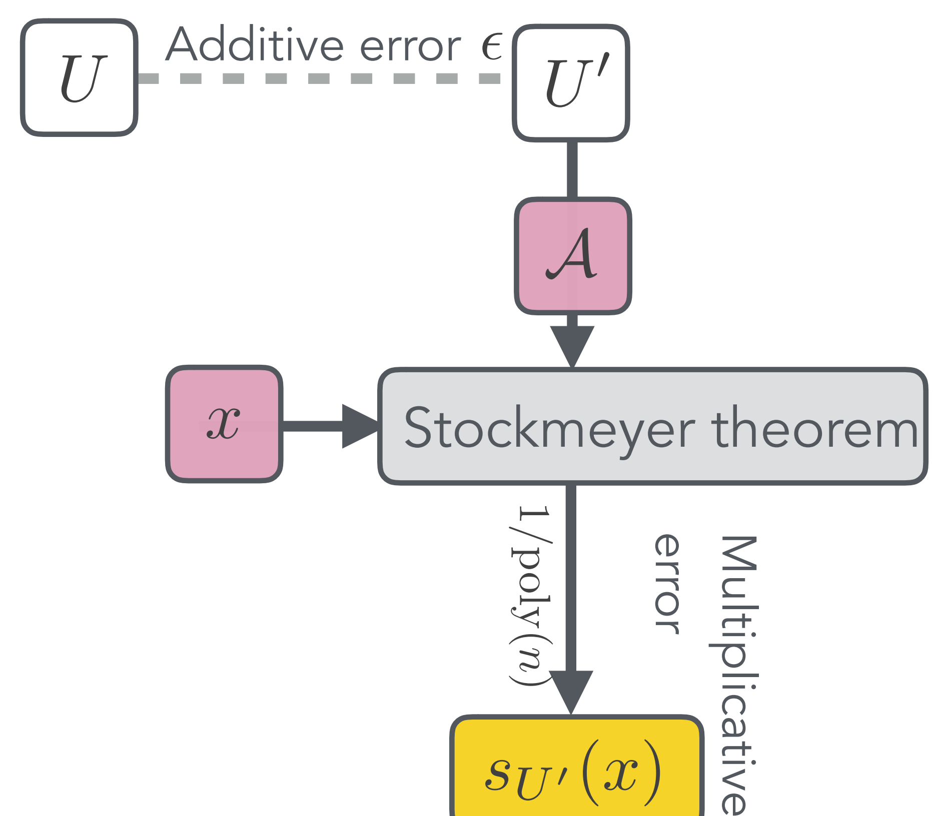

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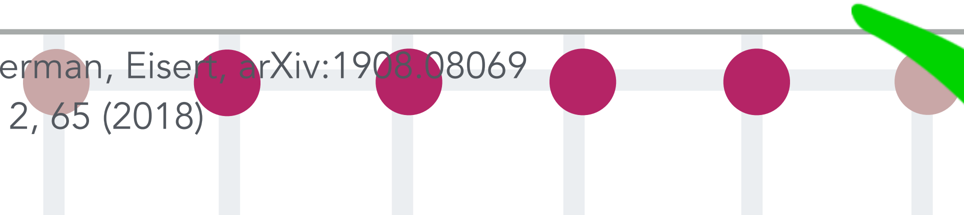
- **Theorem** (Anti-concentration):
- The output probabilities of a family of unitaries $\mathcal{U}$ **anti-concentrates** if there ex $\gamma > 0$ such that for all $x \in \{0,1\}^n$

$$\Pr_{U \in \mathcal{U}} \left(P_U(x) \geq \frac{\alpha}{2^n} \right) \geq \gamma$$



Haferkamp, Hangleiter, Bermejo-Vega, Bouland, Fefferman, Eisert, arXiv:1908.08069
Hangleiter, Bermejo-Vega, Schwarz, Eisert, Quantum 2, 65 (2018)
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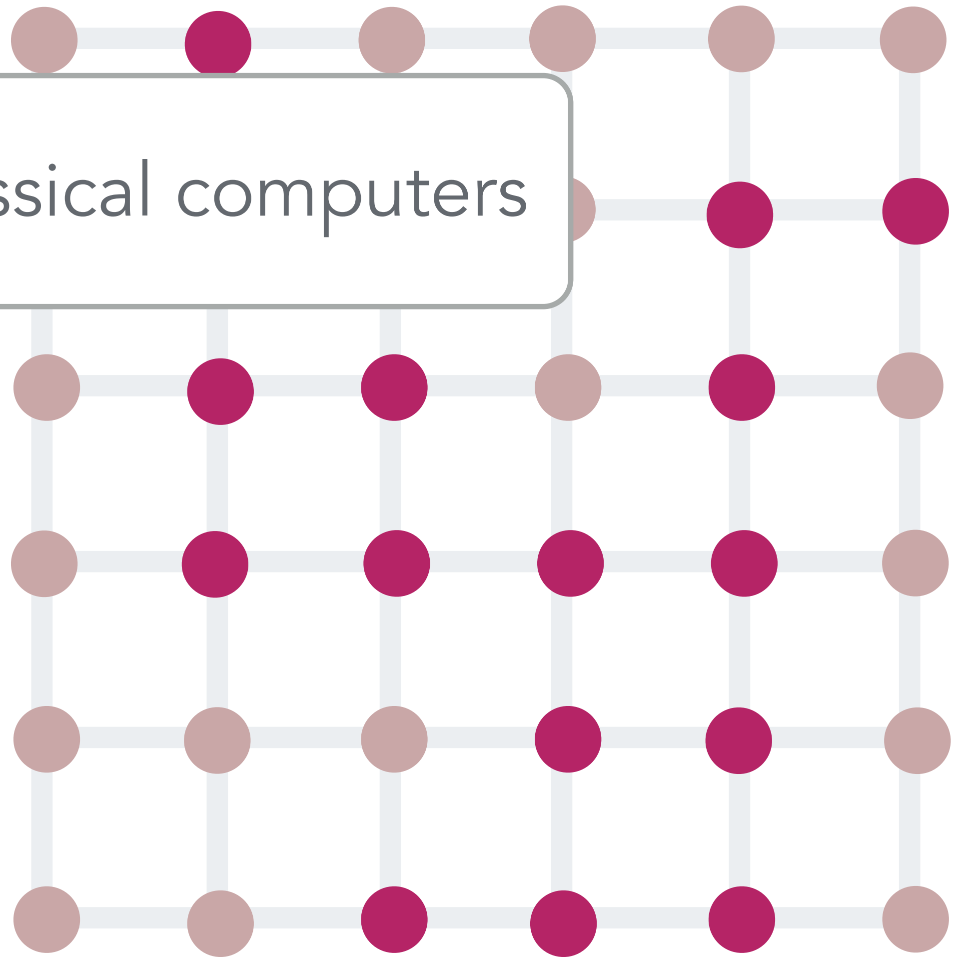
- **Theorem** (Average-case hardness): For multiplicative errors

Haferkamp, Hangleiter, Bermejo-Vega, Bouland, Fefferman, Eisert, arXiv:1908.08069

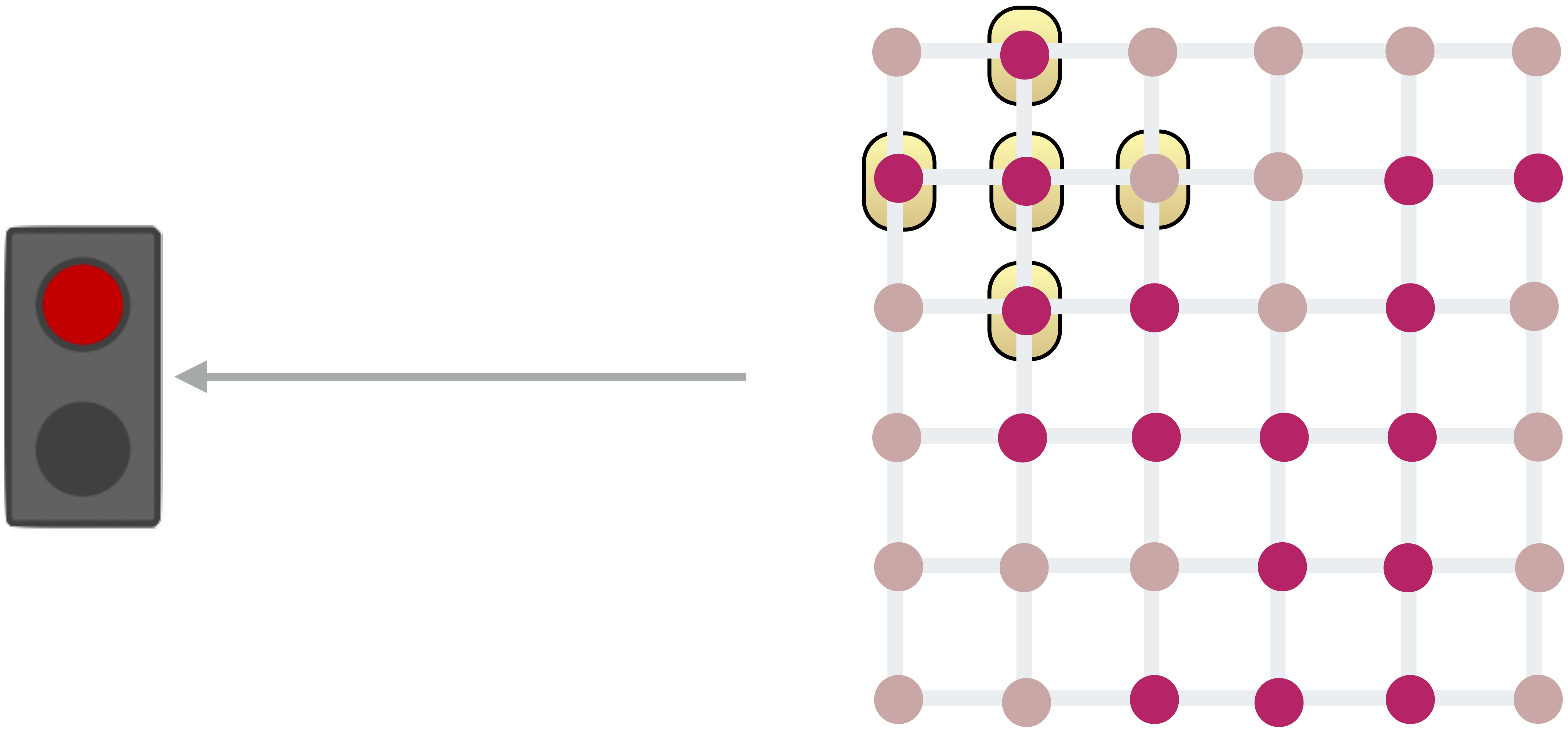


- Near-term devices intractable for classical computers

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

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

- Ground state of fictious frustration-free Hamiltonian



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SUMMARY, OUTLOOK AND OPEN QUESTIONS

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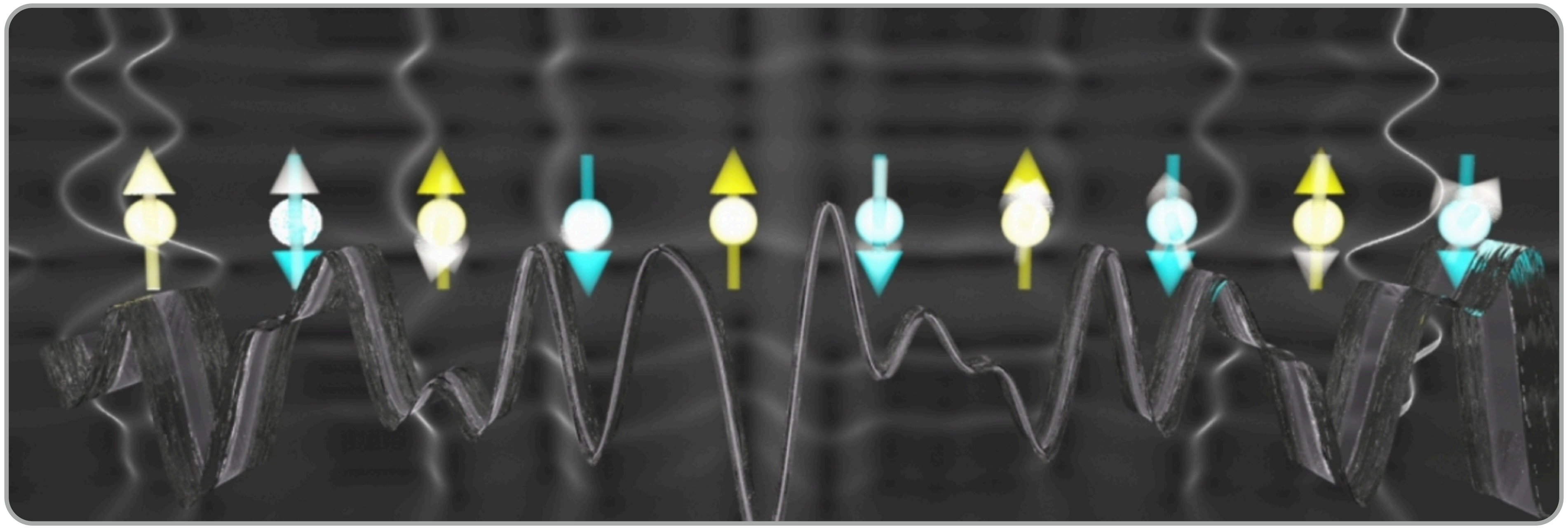

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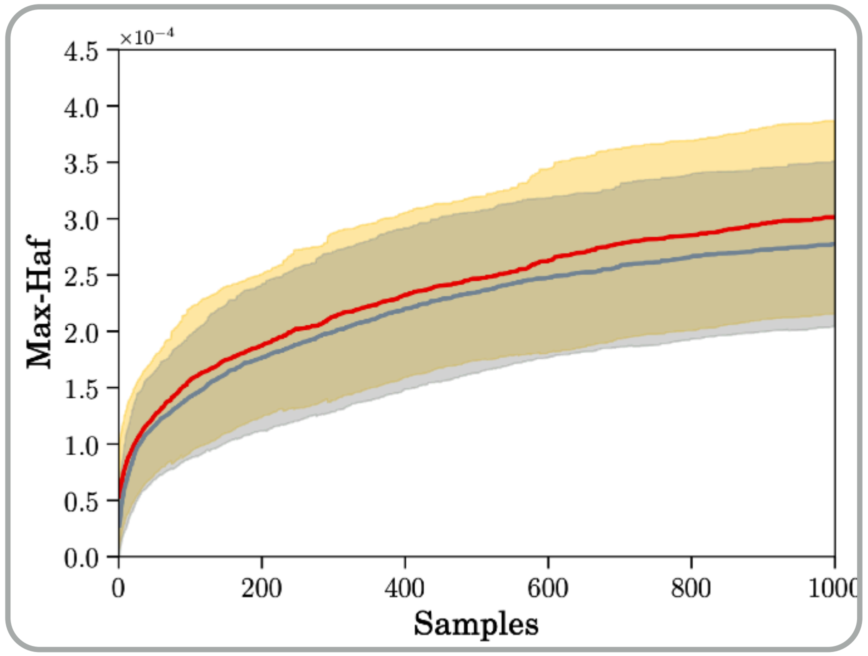

Arrazola, Bromley. Rebentrost, arXiv:1803.10731

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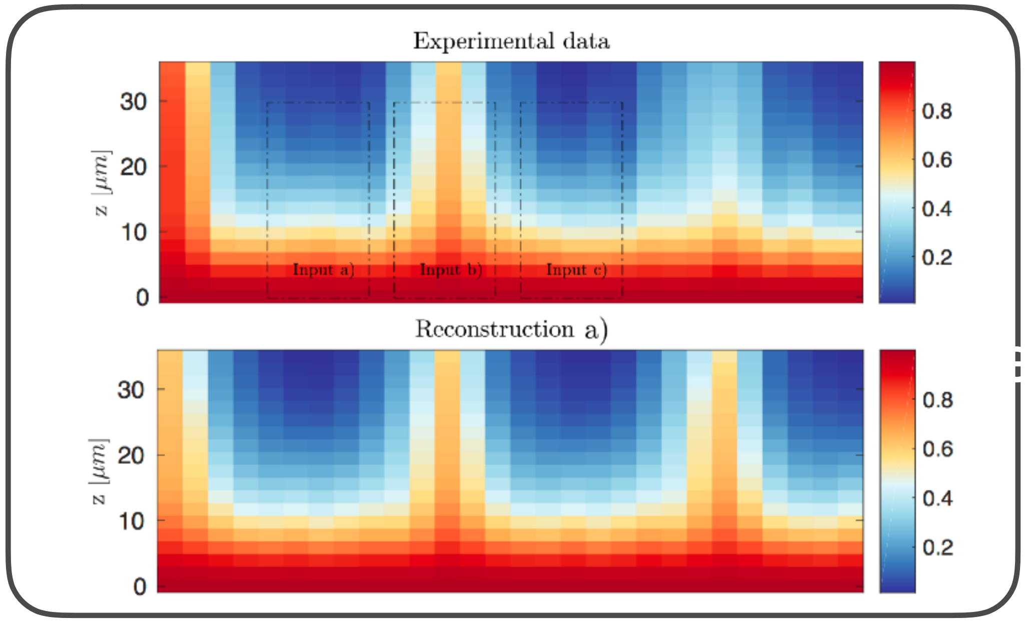

Schweigler, Gluza, Rauer, Spiriados, Eisert, Schmiedmayer,Comm Phys 3, 12 (2020)

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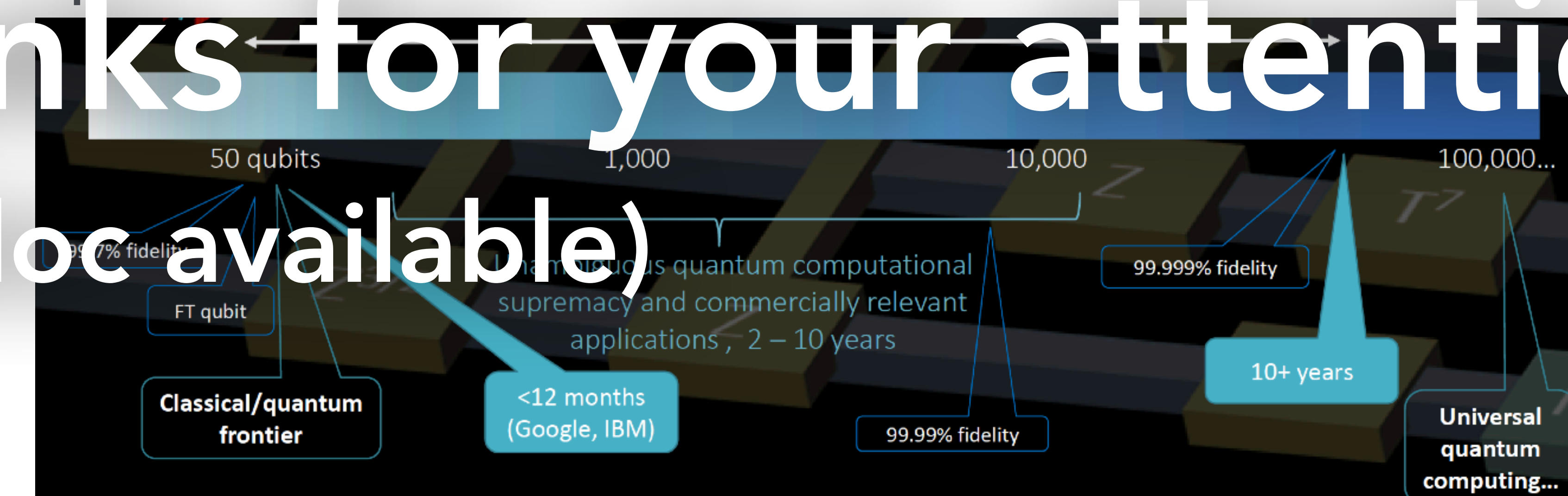
- Space-time trade-offs

Thanks for your attention!

(Postdoc available)



(Mick Bremner)