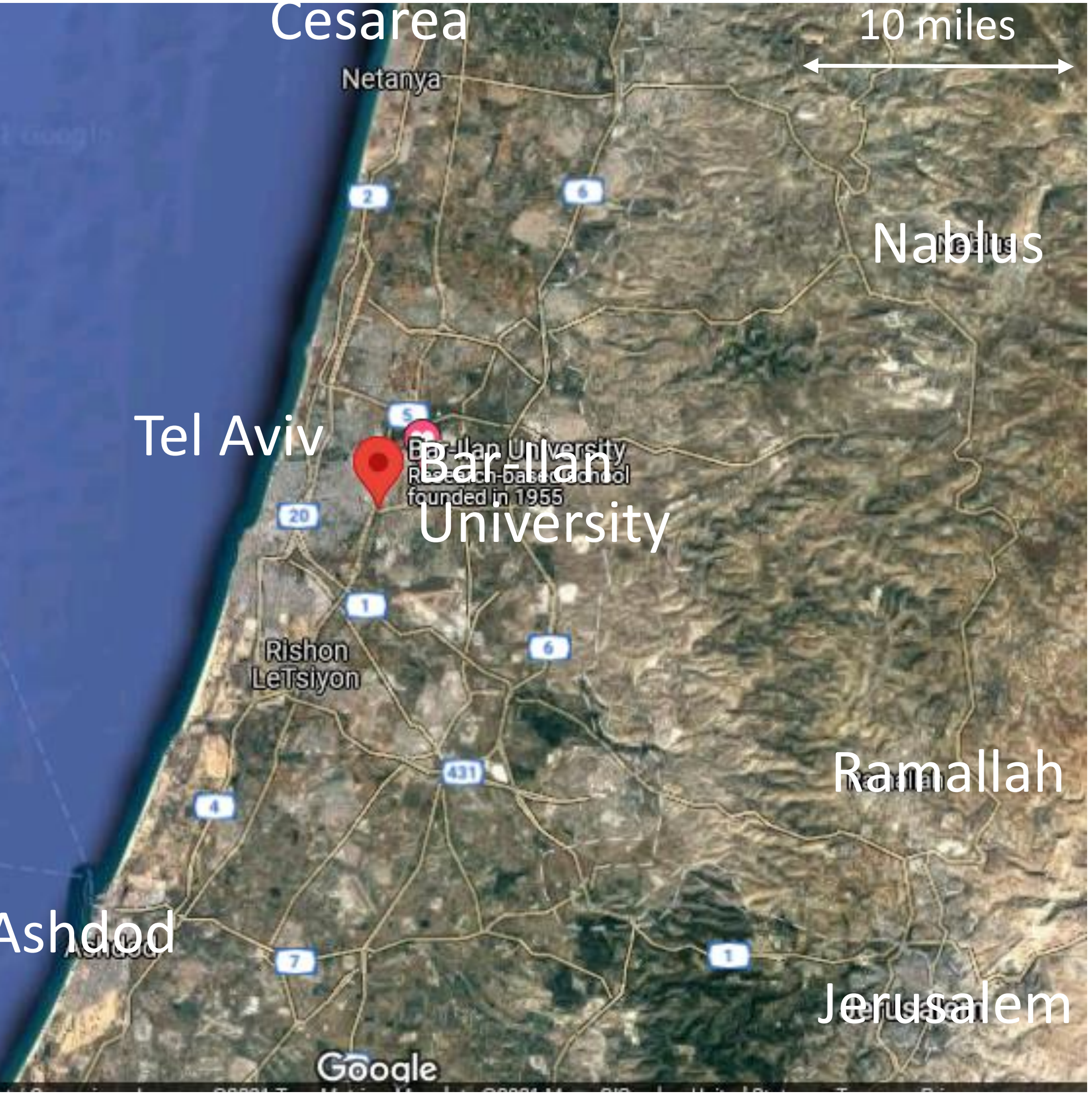
QIQT23 – June 1st, 2023

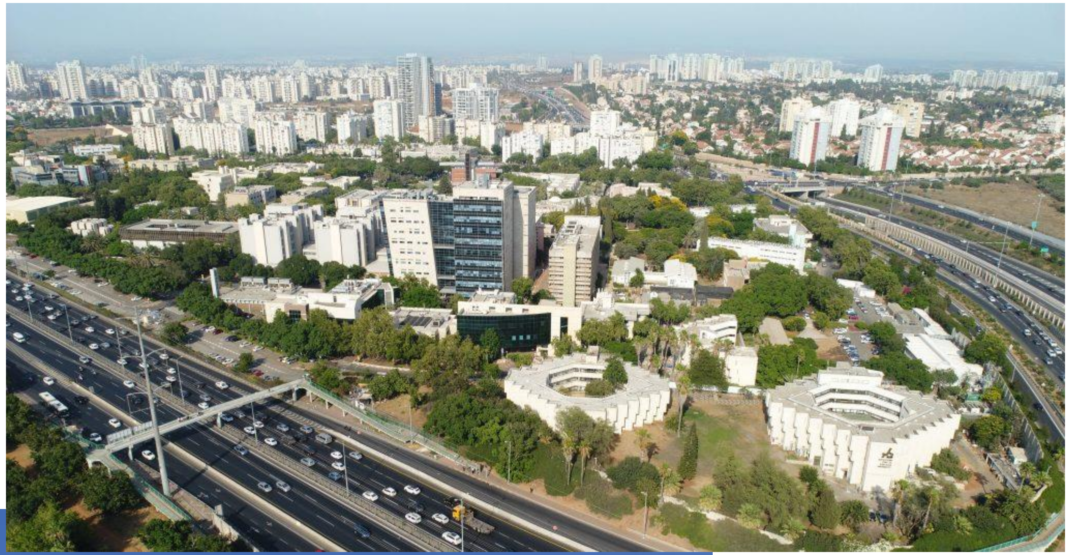
# Quantum Simulations using quantum computers on the cloud

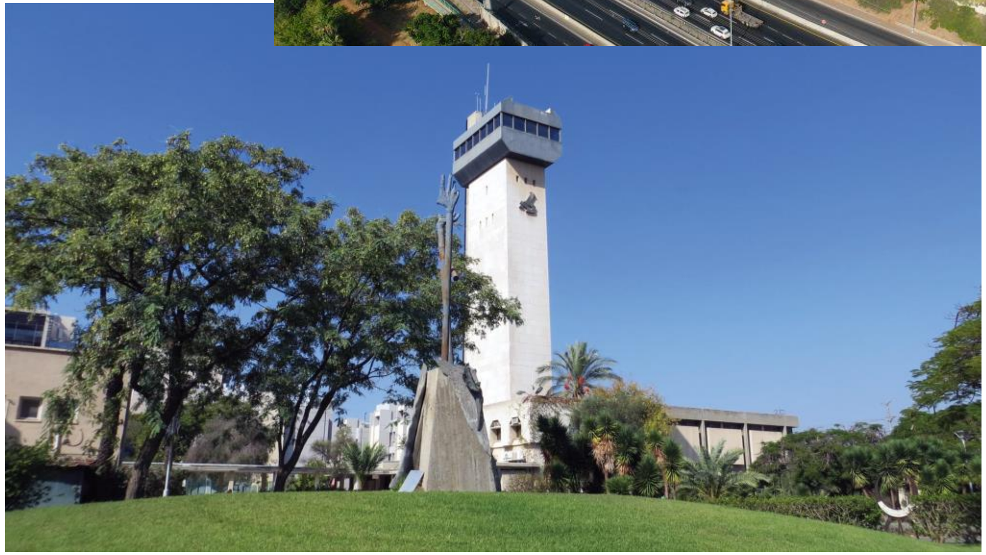
Emanuele Dalla Torre

Bar-Ilan University

# Bar-Ilan University (established 1955)





20,000 students, 1350 faculty members

# Dynamics of complex quantum systems

Eran Sela
Tel Aviv University

Sourin Das

Sowrabh Sudevan

IISER Kolkata

rigetti

Matthew Reagor

Maxime Dupont

Bram Evert

Atanu Rajak
BarIlan → Kolkata

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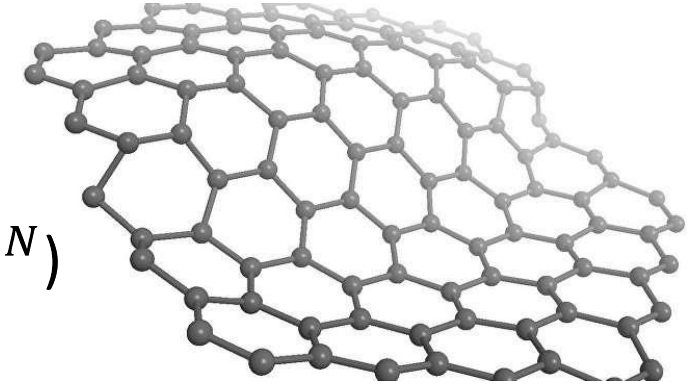
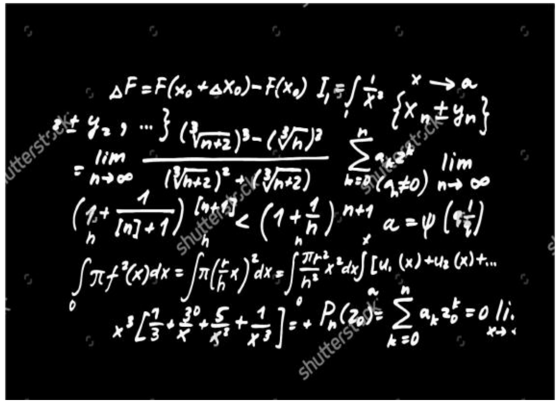
# Quantum simulations

Quantum molecules/material

State vector: $2^N$ complex numbers
(instead of a single number of size $2^N$)



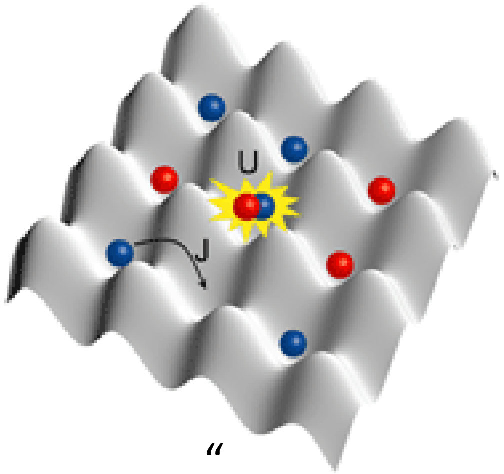
Quantum field theories



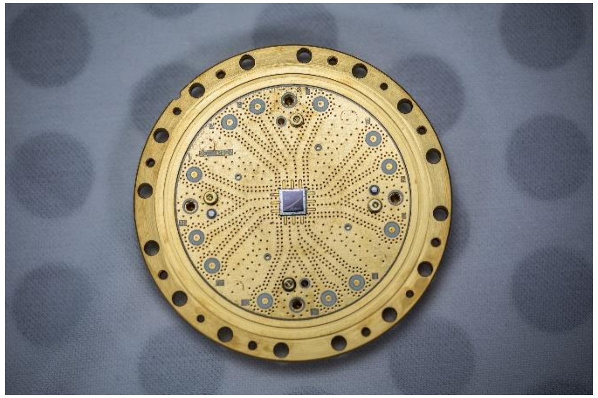
Classical supercomputers


“If I try my best to make the equations look as near as possible to what would be imitable by a classical probabilistic computer, I get into trouble.” – Richard Feynman

Ultracold atoms




Quantum computer on the cloud



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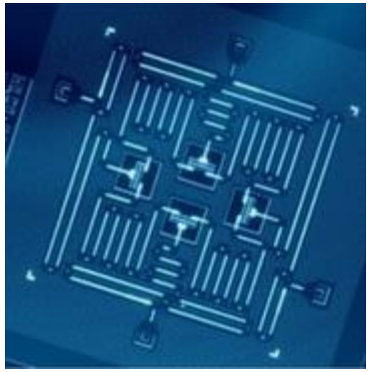
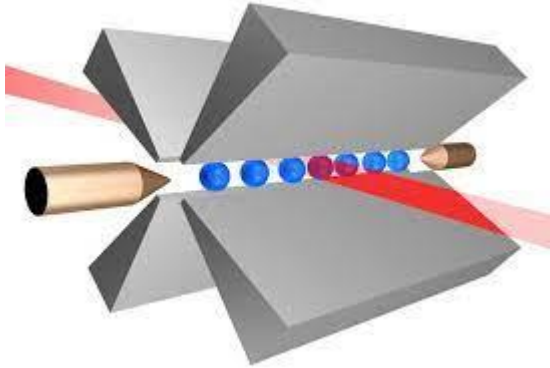
# Quantum computers - platforms

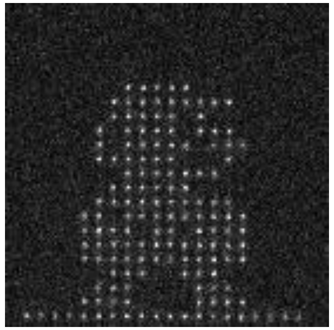
Superconducting circuits



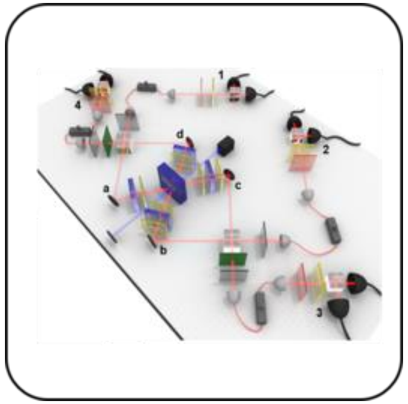
Trapped ions



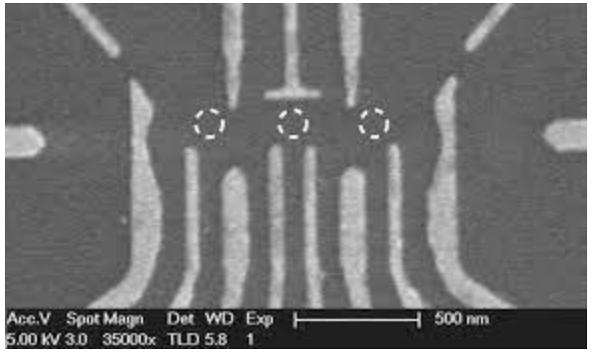
Rydberg atoms



Photons (MBQC)



Quantum wells (spin)




|QuEra⟩ Computing Inc.

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# Quantum computers - platforms

1. **Neutral atoms** in optical lattices (qubit implemented by internal states of neutral atoms trapped in an optical lattice)
2. **Trapped ion** quantum computer (qubit implemented by the internal state of trapped ions)
3. **Superconducting** quantum computing (qubit implemented by the state of small superconducting circuits [Josephson junctions])
4. **Photonics** optical frequency photon as qubits, large entangled cluster state
5. **Silicon Spin** computer (qubit given by the spin states of trapped electrons in a transistor)
6. **Twistronics –** magic angle graphene layers allow for local control of Josephson junction qubits
7. **Optical Quantum Dot** computer – optically controlled spin qubit integrated with the light source
8. **NV Diamond-based** quantum computer (qubit realized by the electronic or nuclear spin of nitrogen-vacancy centers in diamond)
9. **Metallic-like carbon nanospheres** quantum computers (spins of itinerant electron within these nanospheres)
10. **Electrons-on-helium** quantum computers (qubit is the electron spin)
11. **Spatial-based Quantum Dot computer** (qubit given by electron position in double quantum dot)
12. **Engineered quantum wells** quantum computing, which could in principle enable the construction of quantum computers that operate at room temperature
13. **Coupled quantum wire** (qubit implemented by a pair of quantum wires coupled by a quantum point contact)
14. **Nuclear magnetic resonance** quantum computer (NMRQC) implemented with the nuclear magnetic resonance of molecules in solution, where qubits are provided by nuclear spins within the dissolved molecule and probed with radio waves
15. **Solid-state NMR** quantum computers (qubit realized by the nuclear spin state of phosphorus donors in silicon)
16. **Cavity quantum electrodynamics** (CQED) (qubit provided by the internal state of trapped atoms coupled to high-finesse cavities)
17. **Molecular magnet** (qubit given by spin states)
18. **Fullerene-based ESR** quantum computer (qubit based on the electronic spin of atoms or molecules encased in fullerenes)
19. **Nonlinear optical** quantum computer (qubits realized by processing states of different modes of light through both linear and nonlinear elements)
20. **Linear optical** quantum computer (qubits realized by processing states of different modes of light through linear elements e.g. mirrors, beam splitters and phase shifters)
21. **Bose-Einstein condensate** quantum computer
22. **Transistor-based** quantum computer – string quantum computers with entrainment of positive holes using an electrostatic trap
23. **Rare-earth-metal-ion-doped inorganic crystal** quantum computers (qubit realized by the internal electronic state of dopants in optical fibers)
24. **Bound states of electrons localized in an array of nanowires**
25. **Point-defect spin qubits in engineered quantum wells**
26. **Electron spin qubits in graphene quantum dots or van der Waals heterostructures**
27. **Photonic quantum computation in a synthetic time dimension**
28. **…and more**

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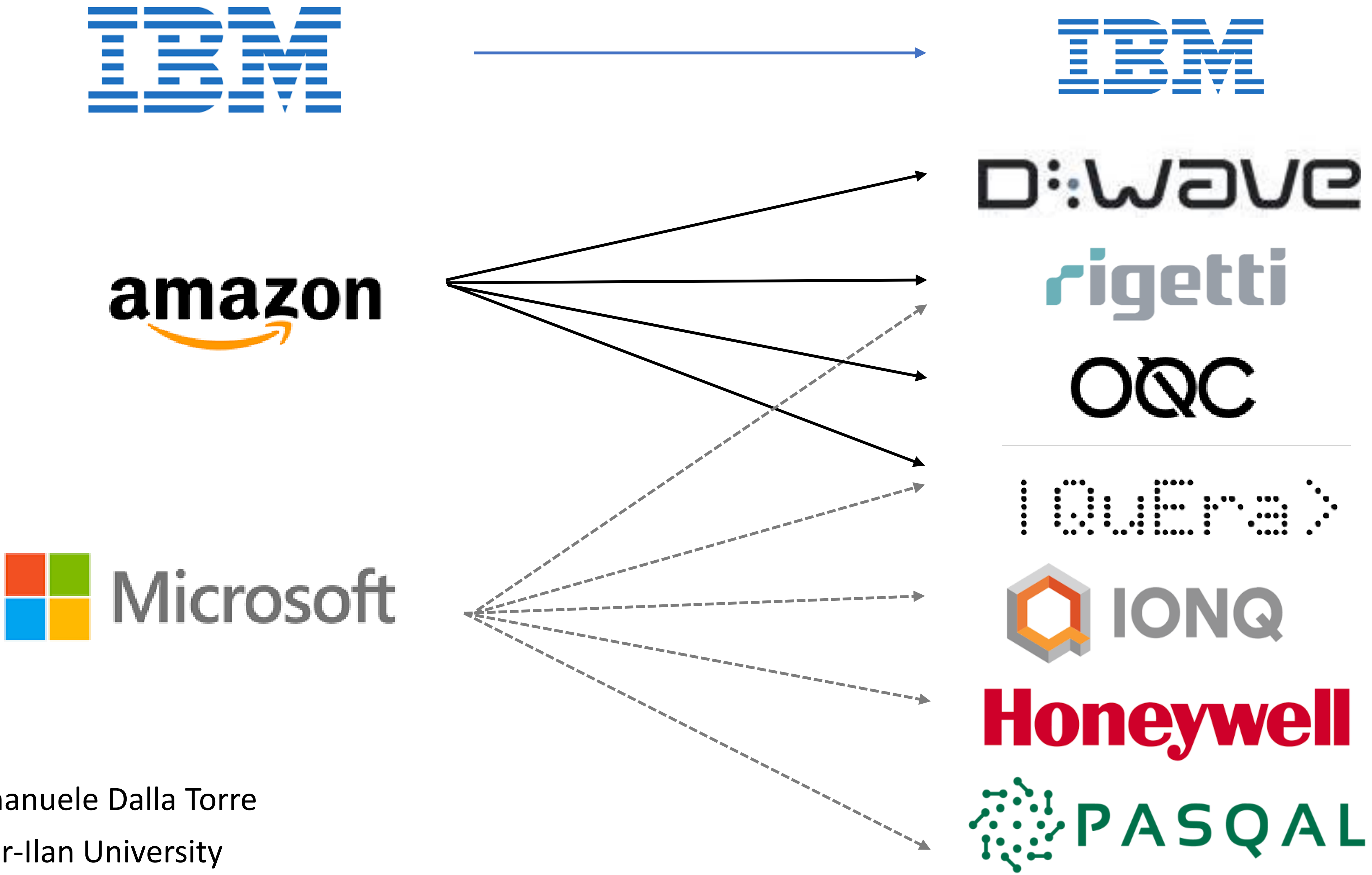
List by Serg Bell (Jacobs University) https://arxiv.org/abs/2203.17181

# Quantum computing on the cloud: providers

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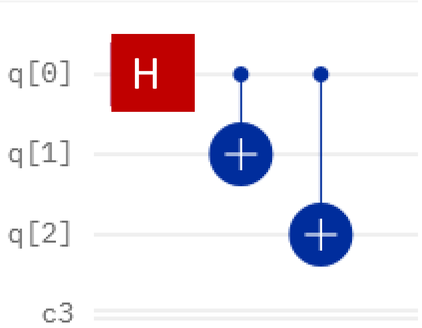
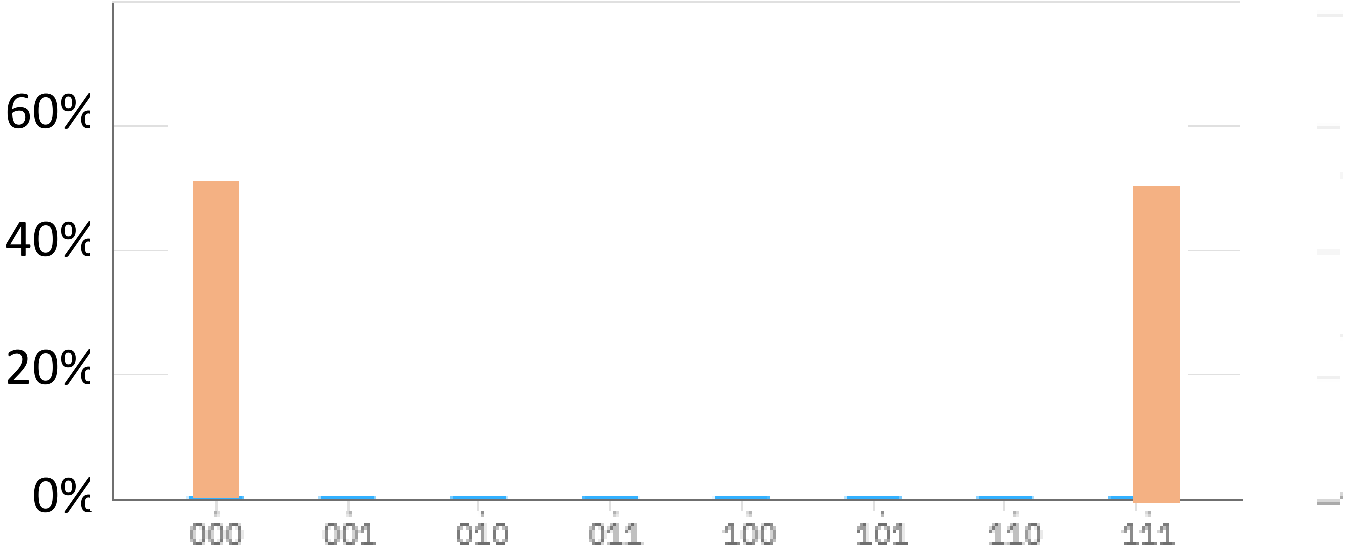
# Quantum computers on the cloud: example

IBM quantum experience (qiskit)

http://quantum-computing.ibm.com

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$$




ibmq_jakarta (13/09/2022)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# Noise and errors

## ibmq_jakarta

**Details**

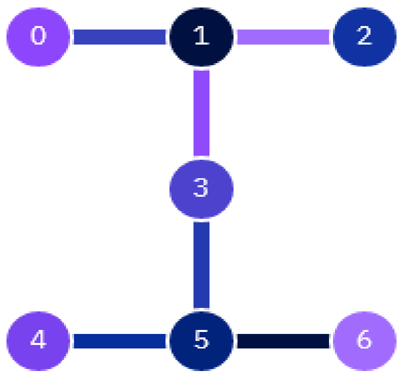
7 Qubits

16 Quantum Volume

| | |
|---|---|
| Status: | Online |
| Total pending jobs: | 3 jobs |
| Processor type: | Falcon r5.11H |
| Version: | 1.0.16 |
| Basis gates: | CX, ID, RZ, SX, X |
| Your usage: | 1866 jobs |
| Avg. CNOT Error: | 7.874e-3 |
| Avg. Readout Error | 2.959e-2 |
| Avg. T1: | [illegible] us |
| Avg. T2: | 36.25 us |
| Providers with access: | 1 Providers |
| Supports Qiskit Runtime: | Yes |

1%

3%




My thumb rule: "sum the errors until you reach 50%"

Largest square circuit = 5 qubit X 5 gate ⟷ $\mathbf{QV = 2^5 = 32}$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E. Pelofske, A. Bärtschi and S. Eidenbenz, "Quantum Volume in Practice: What Users Can Expect From NISQ Devices," in *IEEE Transactions on Quantum Engineering*, vol. 3, pp. 1-19, 2022, Art no. 3102119.

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# Quantum Volume reaches 5 digits for the first time: 5 perspectives on what it means for quantum computing

February 23, 2023

Quantinuum's H-Series team has hit the ground running in 2023, achieving a new performance milestone. The H1-1 trapped ion quantum computer has achieved a Quantum Volume (QV) of 32,768 ($2^{15}$), the highest in the industry to date.


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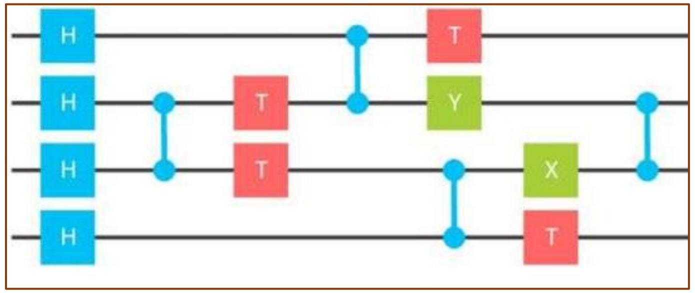
# The great challenge of quantum computing

Model :

Unitary quantum computer

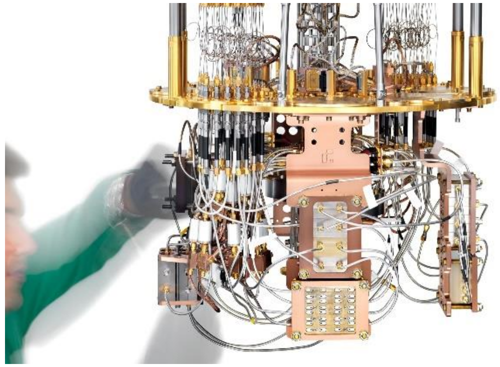



Better hardware
Quantum error correction

Noisy models

Reality :

Noisy superconducting circuits



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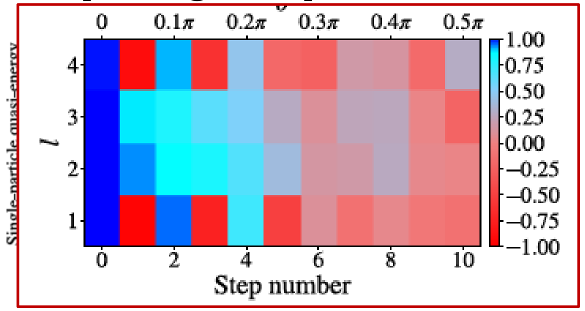
# Quantum simulations on quantum computers

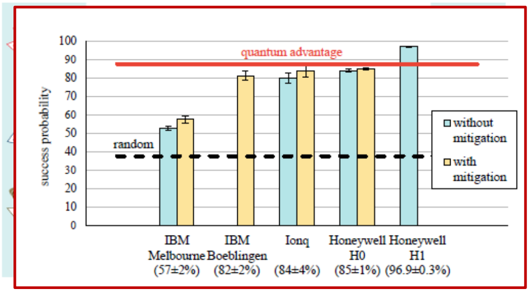
Actual results on real hardware with up to 6 qubits

### Topological phases in 1d



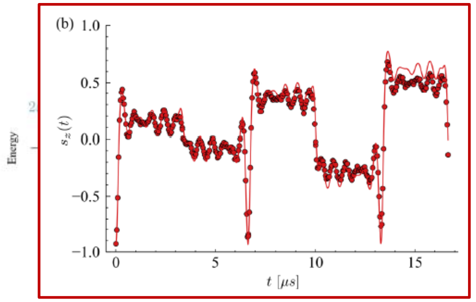

PRL 2020, PRB 2021

### Nonlocal games



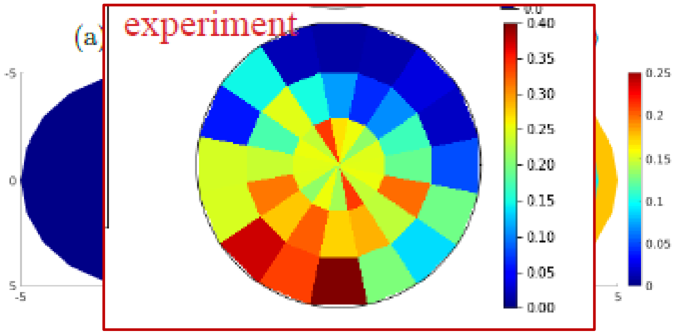

Adv Q Tech 2022

### Long-range interactions



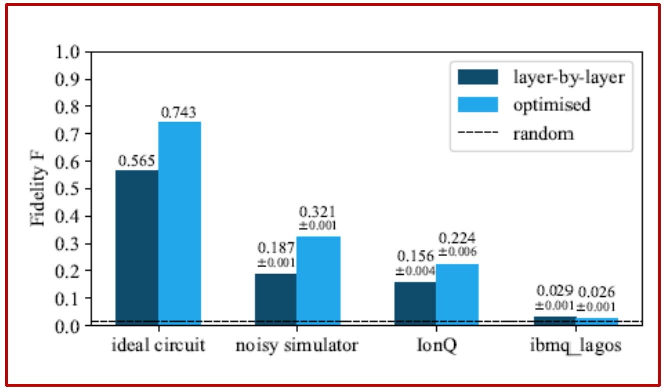

PRR 2021

### Bose-Einstein condensates



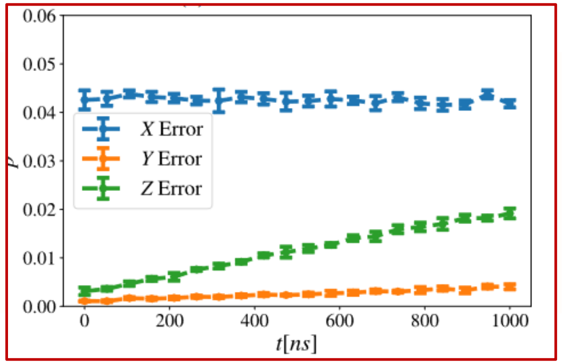

PRL 2022

### Quantum state encoding




arxiv

### Quantum error detection

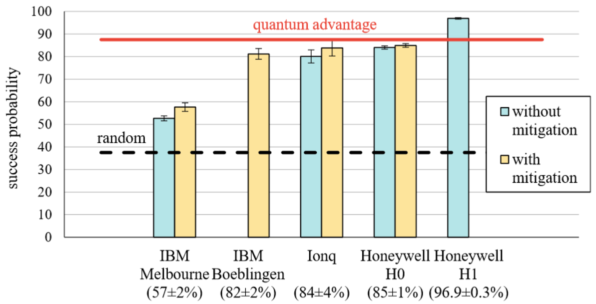



arXiv :2303.15508

# What can you do with few qubits (and is it interesting?)

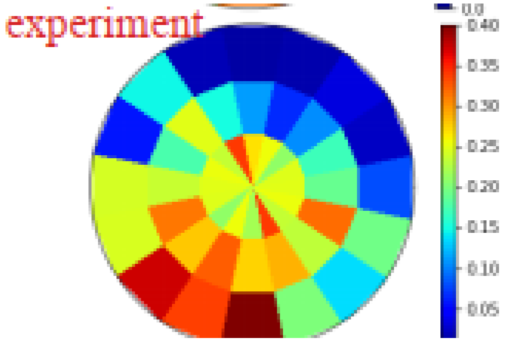
## 1) Non local games with 6 qubits

**Sheffer, Azses, Dalla Torre, *Playing nonlocal games with 6 noisy qubits on the cloud, Adv. Quant. Tech 2021***



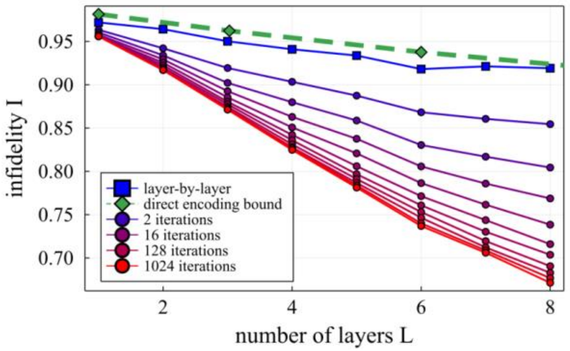

## 2) Simulating a BEC with 5 qubits

Dalla Torre, Reagor, *Simulating long-range coherence of atoms and photons in quantum computers, PRL 2023*




## 3) Optimal encoding of quantum states

Ben Dov, Shnaiderov, Makmal, Dalla Torre *Approximate encoding of quantum states using shallow circuits* arXiv:2207.00028





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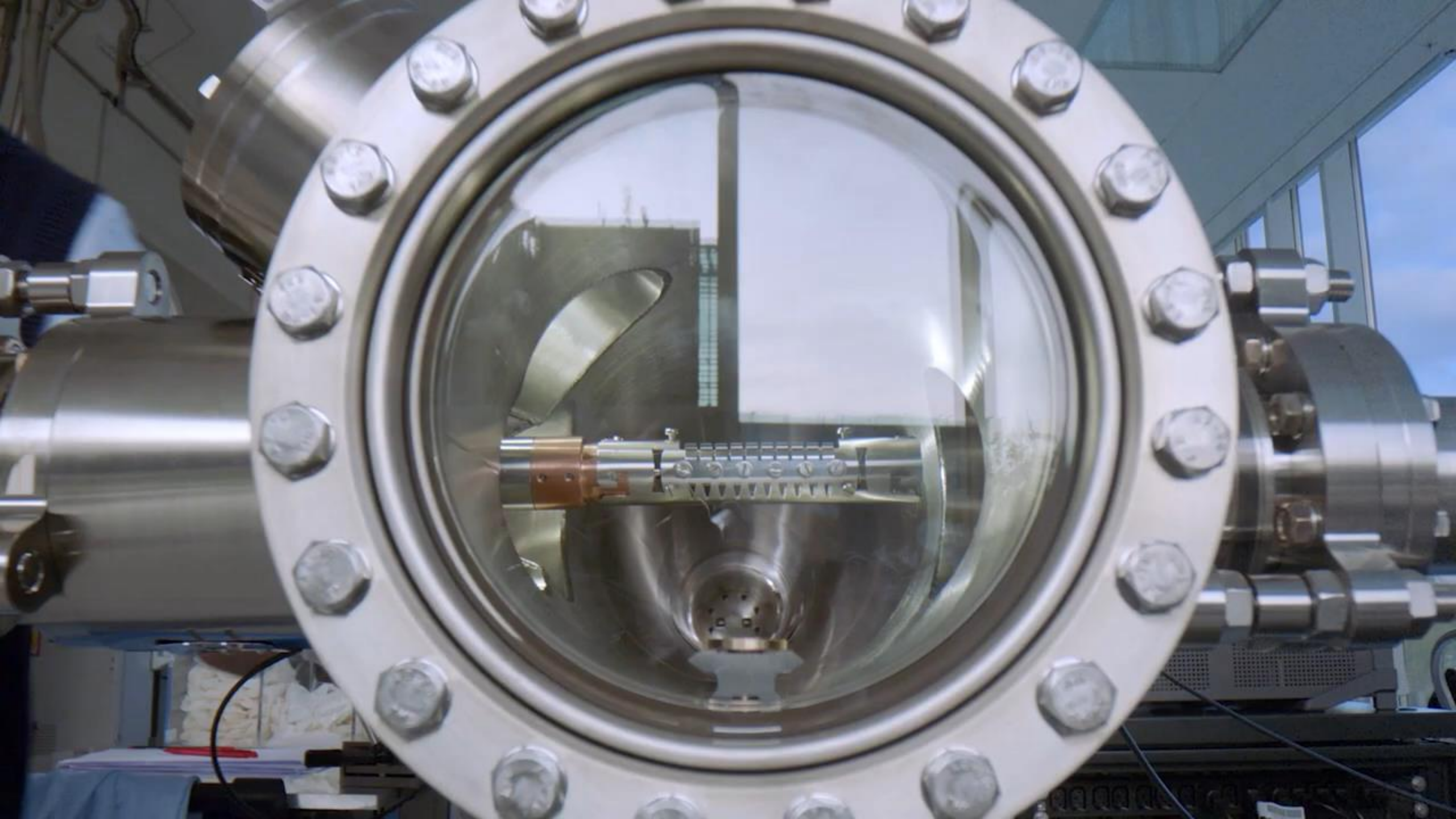


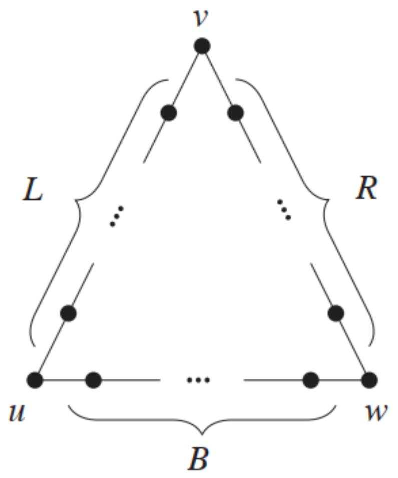
# Non-local quantum games

## a.k.a. Bell inequalities with many qubits

Example: “triangle game”

Bravyi, Gosset & Konig, Science 2018

Daniel & Myiaka, PRL 2021




$$\langle P(\mathrm{win})\rangle_{\mathrm{quantum}} = 1$$

$$\langle P(\mathrm{win})\rangle_{\mathrm{classical}} < 7/8$$

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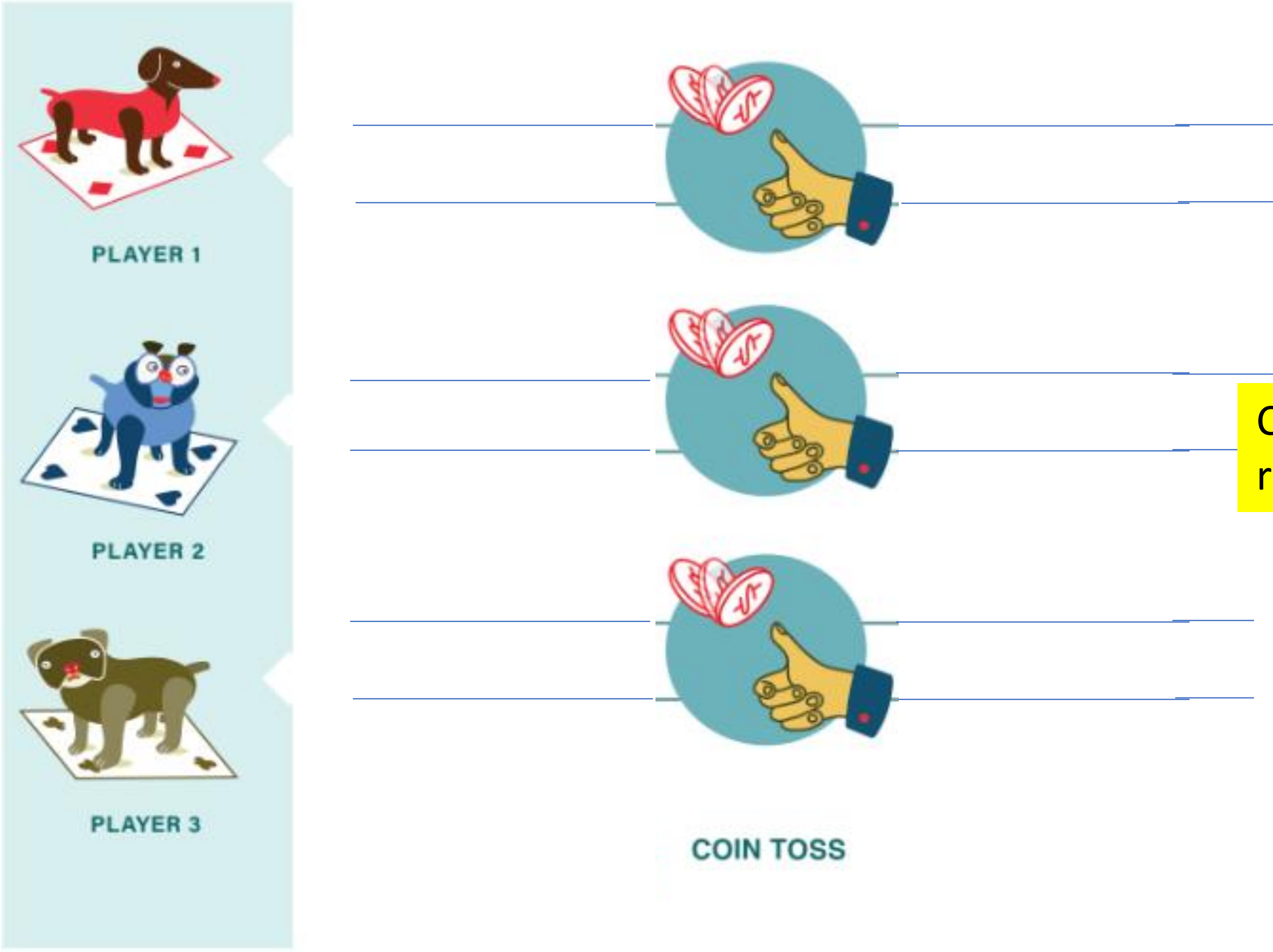
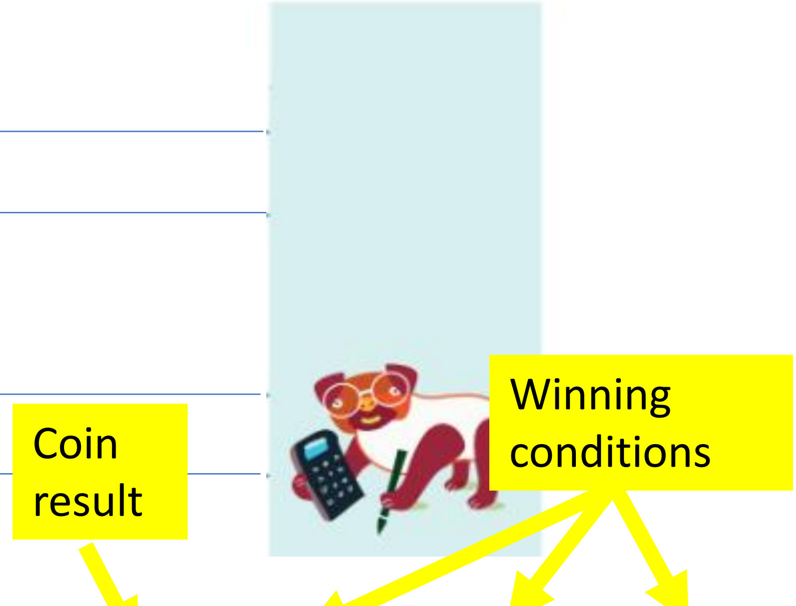
# Minimal realization : 3 players = 6 qubits




| | $aaa$ | $bbb$ | $dea$ |
|---|---|---|---|
| 000 | $X_1X_3X_5 = 1$ | $X_2X_4X_6 = 1$ | |
| 001 | | $X_2X_4X_6 = 1$ | |
| 010 | | $X_2X_4X_6 = 1$ | |
| 011 | | $X_2X_4X_6 = 1$ | $X_1Y_3X_4Y_5 = -1$ |
| 100 | | $X_2X_4X_6 = 1$ | |
| 101 | | $X_2X_4X_6 = 1$ | $Y_1X_3Y_5X_6 = -1$ |
| 110 | | $X_2X_4X_6 = 1$ | $Y_1X_2Y_3X_5 = -1$ |
| 111 | | $X_2X_4X_6 = 1$ | |

$$\langle P(\text{win})\rangle_{\text{classical}} < 7/8$$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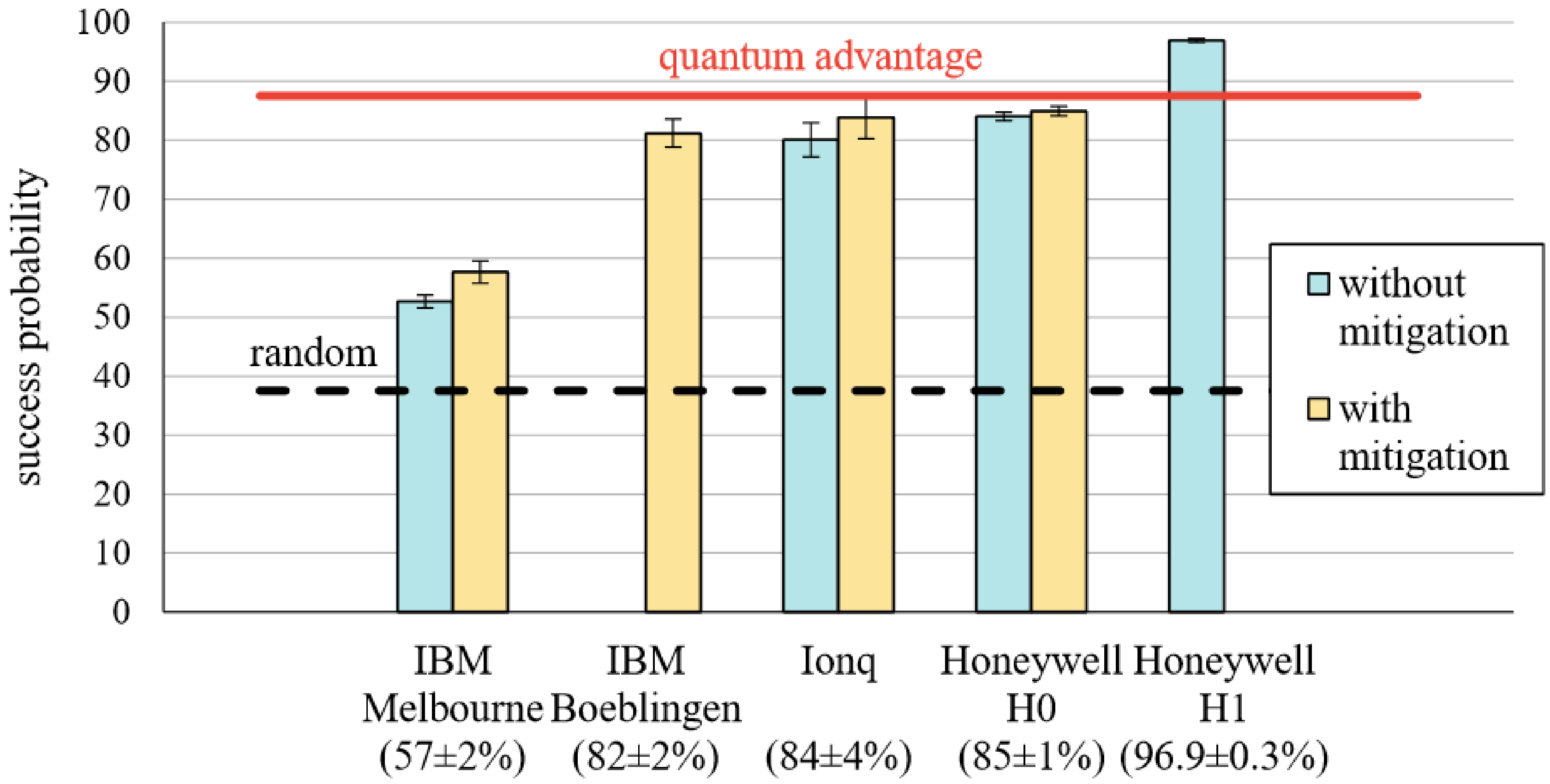
# Triangle game (6 qubit) : results




Sheffer, Azses, Dalla Torre, arXiv: 2105.05266
(See also: Daniel et al 2110.04277)

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# If all the students fail a test... lower the bar!

Stabilizers

$$s_i = Z_{i-1} X_i Z_{i+1}$$
$$s_i |\psi_{\text{cluster}}\rangle = |\psi_{\text{cluster}}\rangle$$

| | $aaa$ | $bbb$ | $dea$ |
|---|---|---|---|
| 000 | $X_1X_3X_5 = 1$ | $X_2X_4X_6 = 1$ | |
| 001 | | $X_2X_4X_6 = 1$ | |
| 010 | | $X_2X_4X_6 = 1$ | |
| 011 | | $X_2X_4X_6 = 1$ | $X_1Y_3X_4Y_5 = -1$ |
| 100 | | $X_2X_4X_6 = 1$ | |
| 101 | | $X_2X_4X_6 = 1$ | $Y_1X_3Y_5X_6 = -1$ |
| 110 | | $X_2X_4X_6 = 1$ | $Y_1X_2Y_3X_5 = -1$ |
| 111 | | $X_2X_4X_6 = 1$ | |

Sum of all products

$$S_{\text{all}} = 1 + \sum_i s_i + \sum_{i,j} s_i s_j + \cdots$$
$$S_{\text{all}} |\psi_{\text{cluster}}\rangle = 2^n |\psi_{\text{cluster}}\rangle$$

$$(S_{\text{all}})_{\text{classic,n=6}} \leq 28$$

Guhne, Toth, Hyllus, Briegel PRL (2005)

Optimal sum

$$S_{\text{optimal}} = \sum_{i,j} s_i s_j + \sum_{i,j,k} s_i s_j s_k + \sum_{i,j,k,l} s_i s_j s_k s_{k+1}$$

$$\left(S_{\text{optimal}}\right)_{\text{classic,n=6}} \leq 19$$

$$\langle S_{\text{optimal}} \rangle_{\text{IonQ}} = 41 \pm 0.5$$

Cabello, Guhne, Rodriguez PRA (2008)

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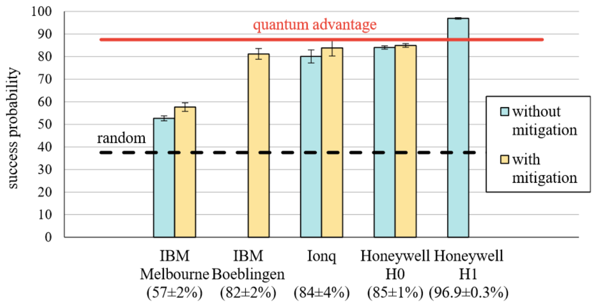
# What can you do with few qubits (and is it interesting?)

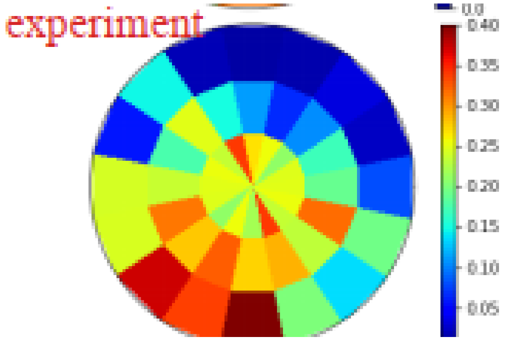
## 1) Non local games with 6 qubits

Sheffer, Azses, Dalla Torre, *Playing nonlocal games with 6 noisy qubits on the cloud, Adv. Quant. Tech 2021*




## **2) Simulating a BEC with 5 qubits**

**Dalla Torre, Reagor, *Simulating long-range coherence of atoms and photons in quantum computers, PRL 2023***




## 3) Optimal encoding of quantum states

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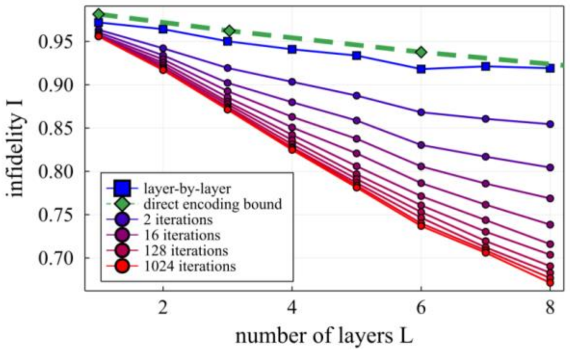



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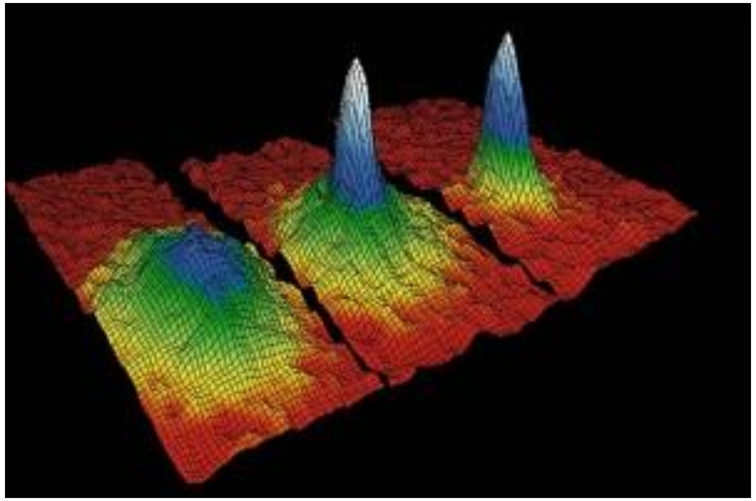
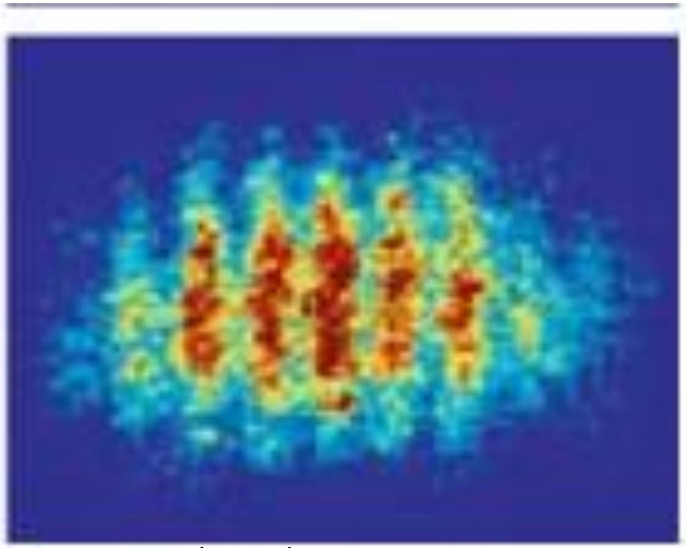
# What is a Bose-Einstein condensate?

1. Macroscopic occupation of the ground state



Anderson et al, Science 1995

2. Interference / phase coherence



Schmiedmayer group 2005

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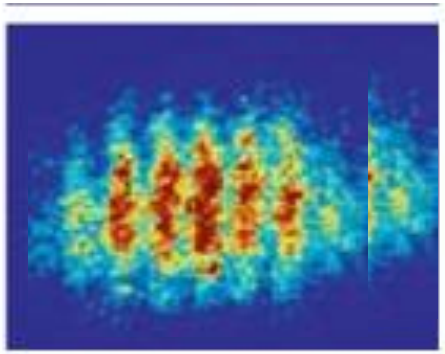
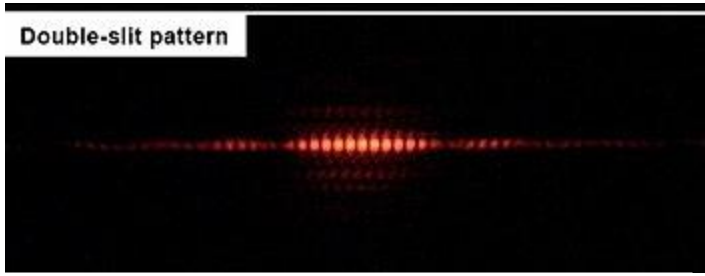
# What is the difference between a BEC and a laser?

Our answer:
particle conservation!

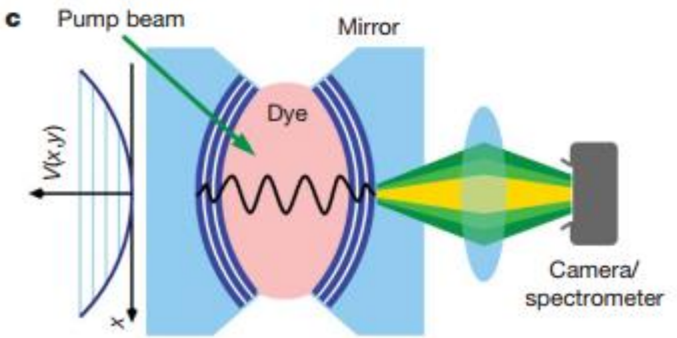
$$[n, \phi] = i$$



- BEC: number of atoms <u>conserved</u> → no global phase




- laser: number of photons <u>not conserved</u> → global phase




- BEC of light (in dye molecules): photons number not conserved & no global phase

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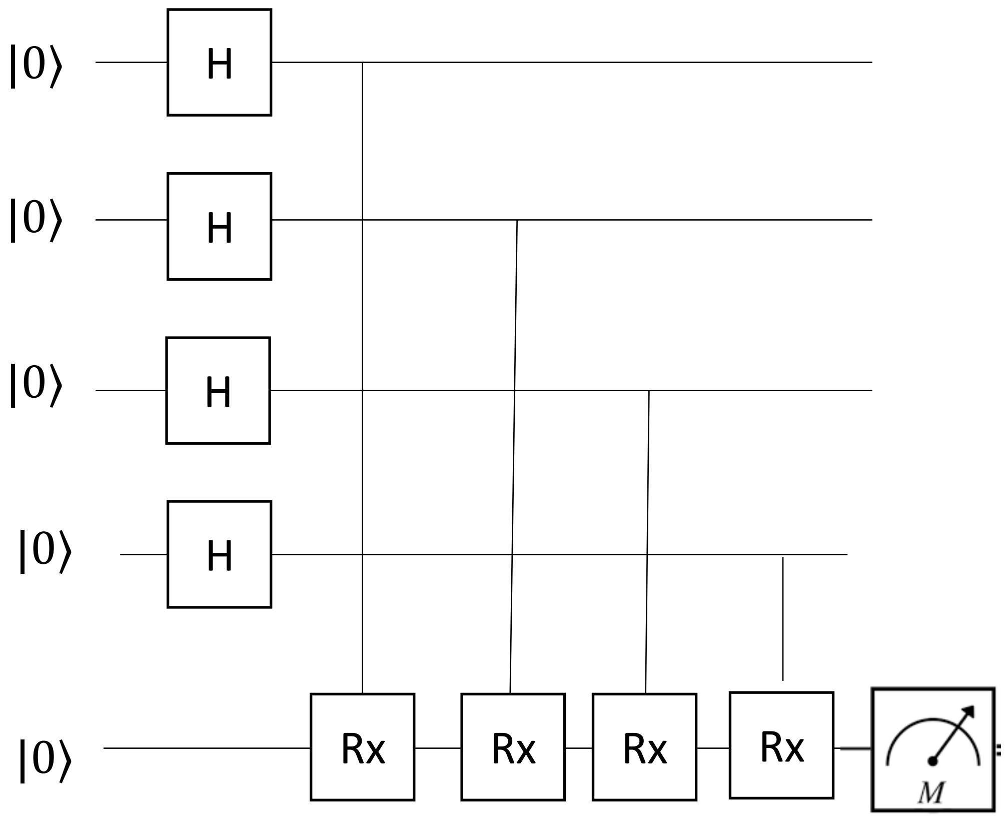
# Our goal: simulate a BEC in a quantum computer

**Step 1**:
prepare a coherent state of qubit excitations (analogous to the coherent state of a laser)

**Step 2**:
measure the total number of particles

**Step 3**:
post-select the correct number





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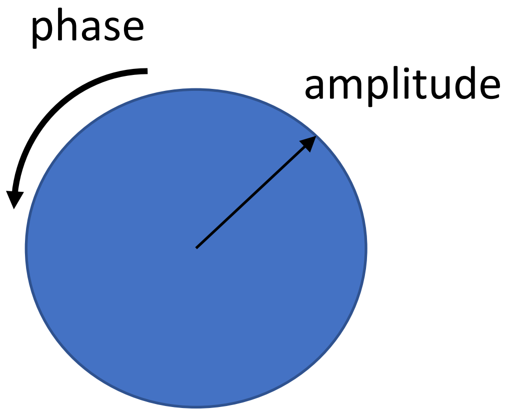
# How to probe a BEC state?

Order parameter: $S_\theta = \cos(\theta) S_x + \sin(\theta) S_y.$

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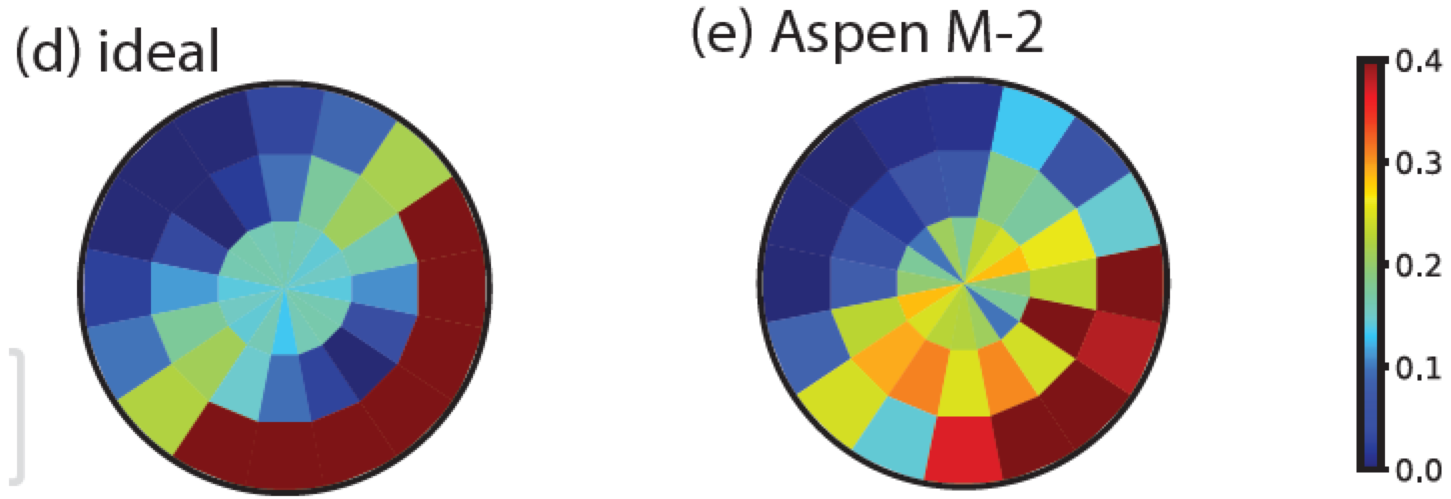
# Results: 4 qubits + 1 ancilla




Why is this interesting?

- Method to benchmark current quantum computers
- Quantum circuits: "new" theoretical framework
- The BEC state is more coherent than the laser state

Emanuele Dalla Torre
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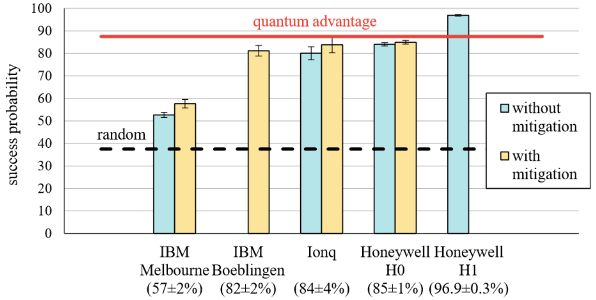
# What can you do with few qubits (and is it interesting?)

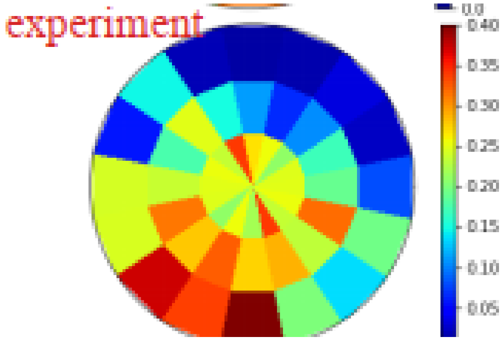
## 1) Non local games with 6 qubits

Sheffer, Azses, Dalla Torre, *Playing nonlocal games with 6 noisy qubits on the cloud, Adv. Quant. Tech 2021*



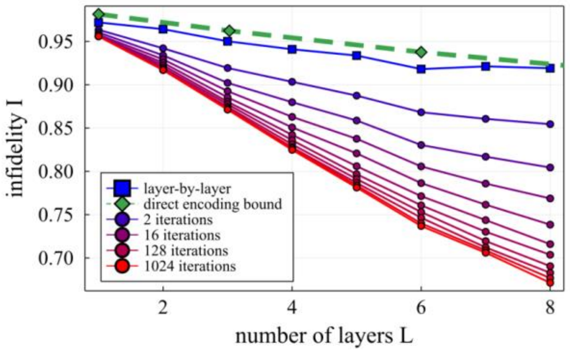

## 2) Simulating a BEC with 5 qubits

Dalla Torre, Reagor, *Simulating long-range coherence of atoms and photons in quantum computers, PRL 2023*




## **3) Optimal encoding of quantum states**

**Ben Dov, Shnaiderov, Makmal, Dalla Torre *Approximate encoding of quantum states using shallow circuits* arXiv:2207.00028**





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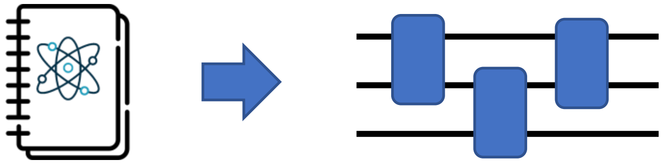
# Problem definition: quantum state encoding

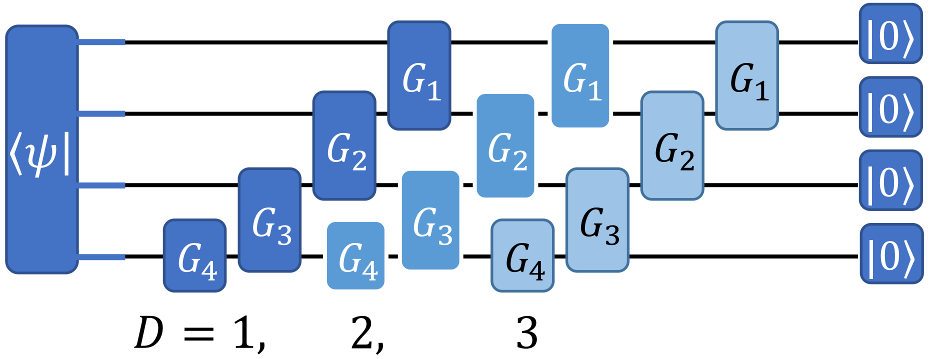


- Exact encoding of a quantum state **is hard**

$$\mathbf{N_{gates}} \sim \mathbf{2^{n_{qubits}}}$$

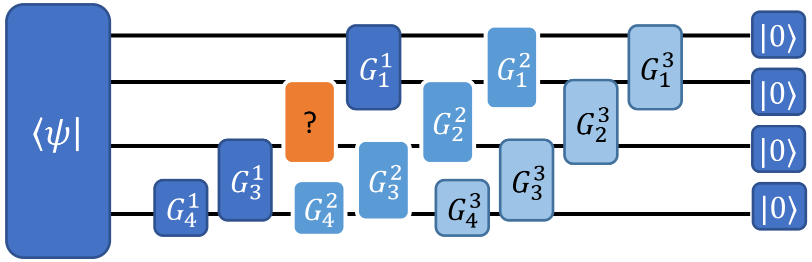
- Our approach: use approximate shallow encoder

$$\mathbf{N_{gates}} \sim \boldsymbol{n_{\mathbf{qubits}}} \cdot \boldsymbol{D}$$

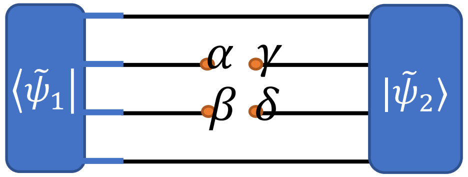


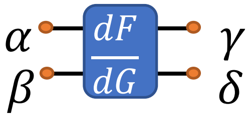

*Limited to target state with low-entanglement states (MPS)*

# Deterministic way to find the optimal encoding

$F(\{G_i\}) =$ 


1. Tensor tomography (16 Pauli strings)

$\frac{dF}{dG_2^1{}_{\alpha,\beta}^{\gamma,\delta}} =$ 

$=$ 


2. Find with the best unitary gate

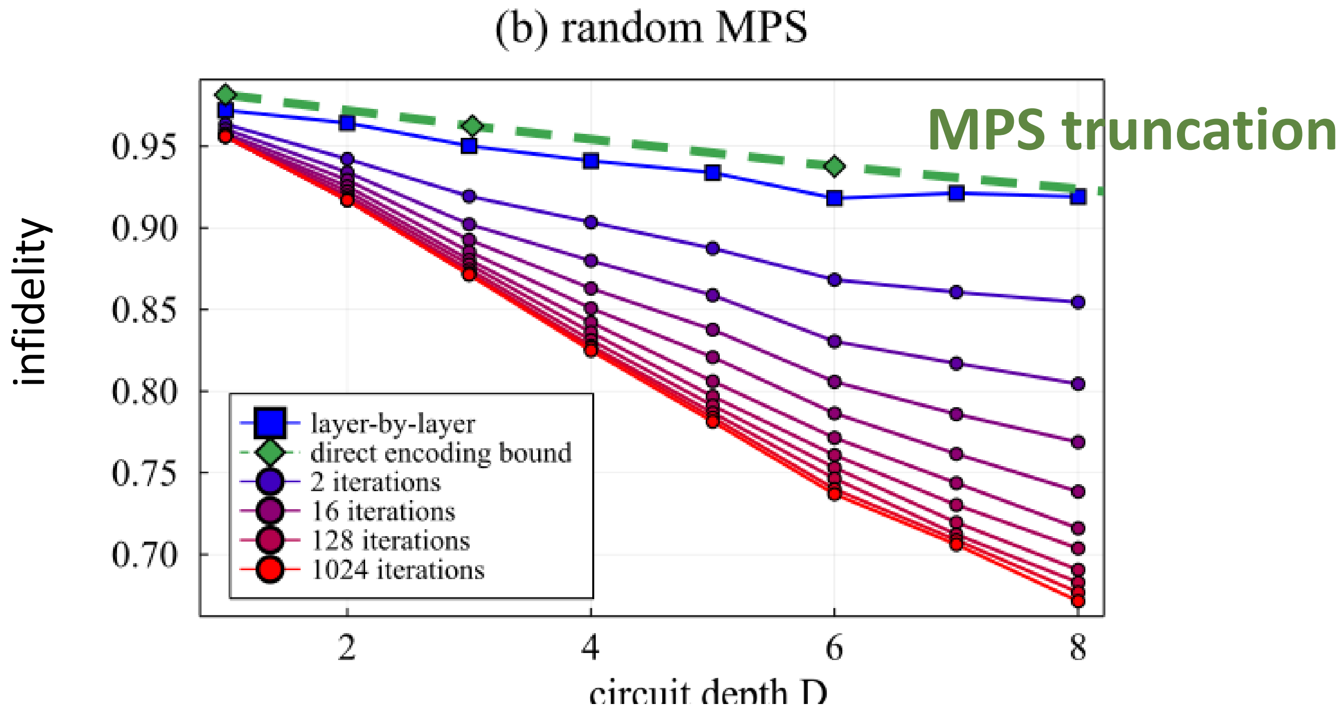
$$G_{new} = \left(\frac{dF}{dG}^{\dagger}\right)_{\text{unitary}}$$

$$A = U\,S\,V^{\dagger} \Rightarrow (A)_{\text{unitary}} = U\,V^{\dagger}$$

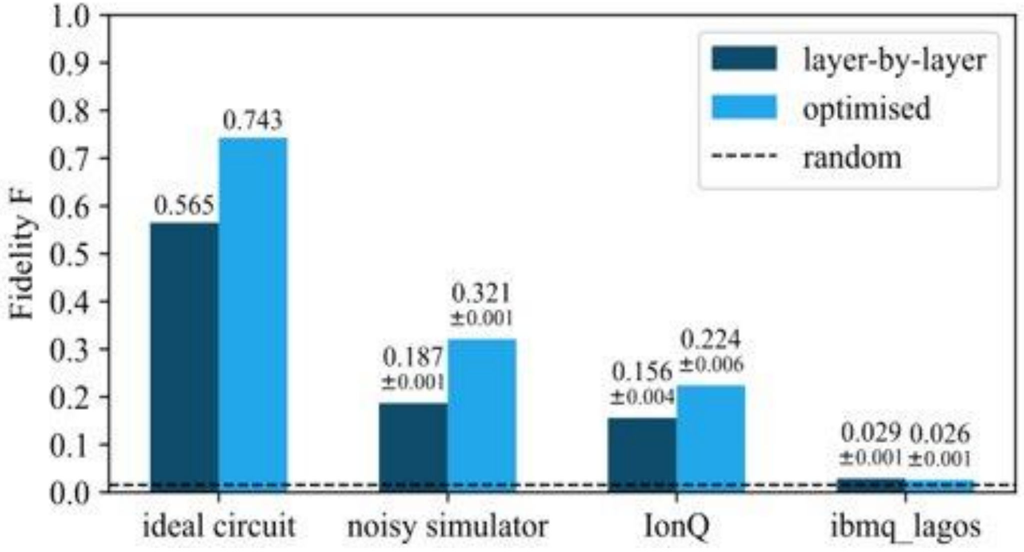
3. Repeat for each gate and loop

# Results

1. Optimal encoding of random MPS
(20 qubits)



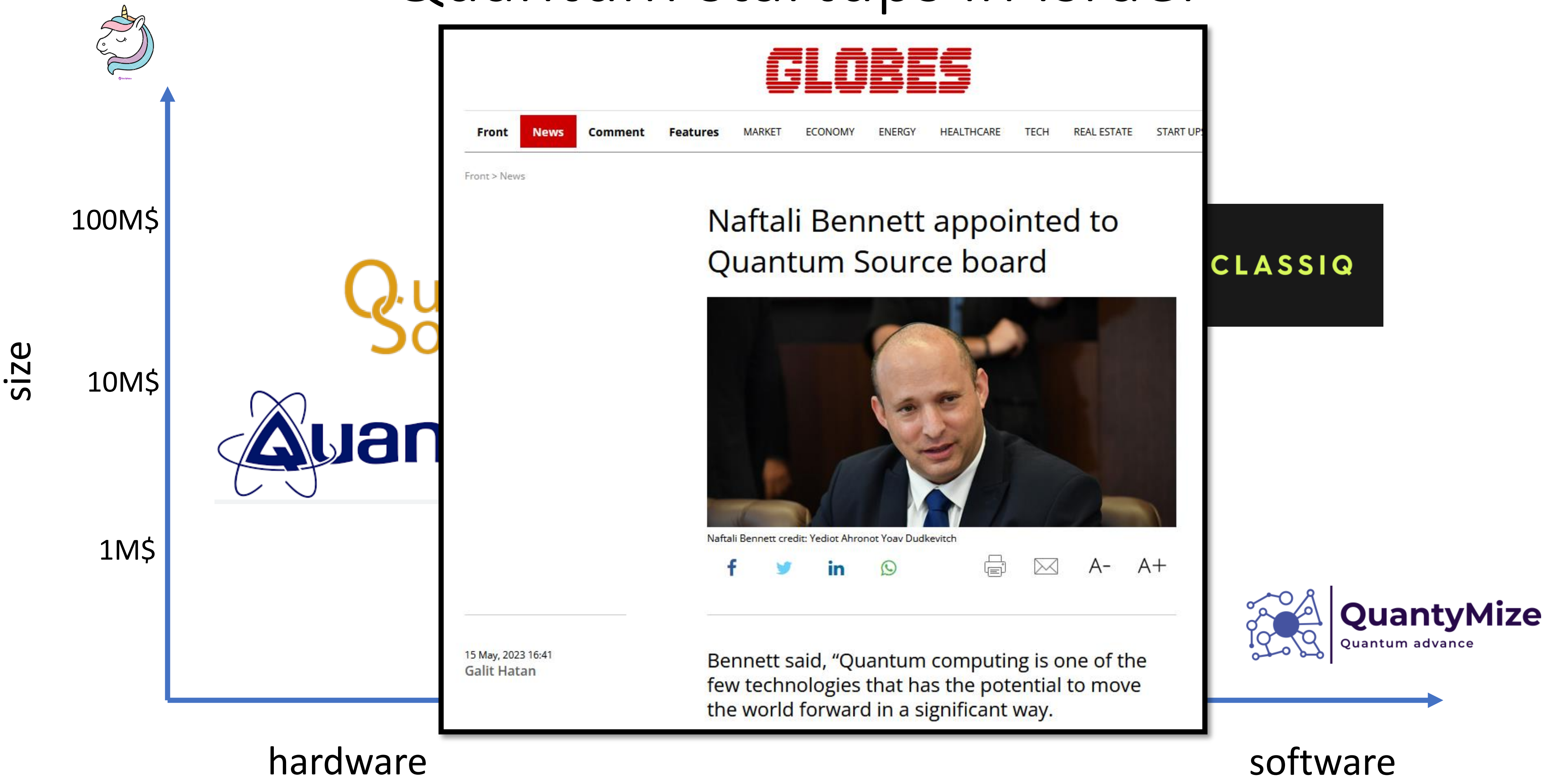

2. Experiment with 6 qubits



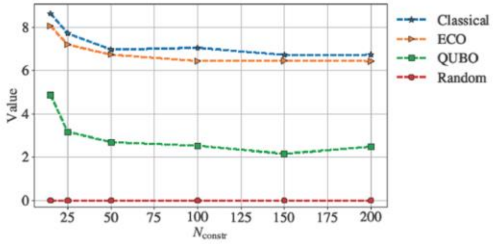

3. Shot noise -> Barren plataux

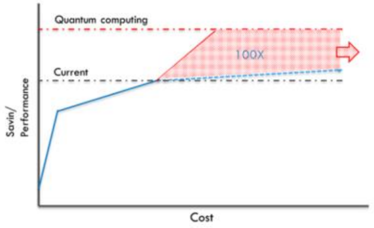
**Solution: use local cost function**

# Quantum startups in Israel



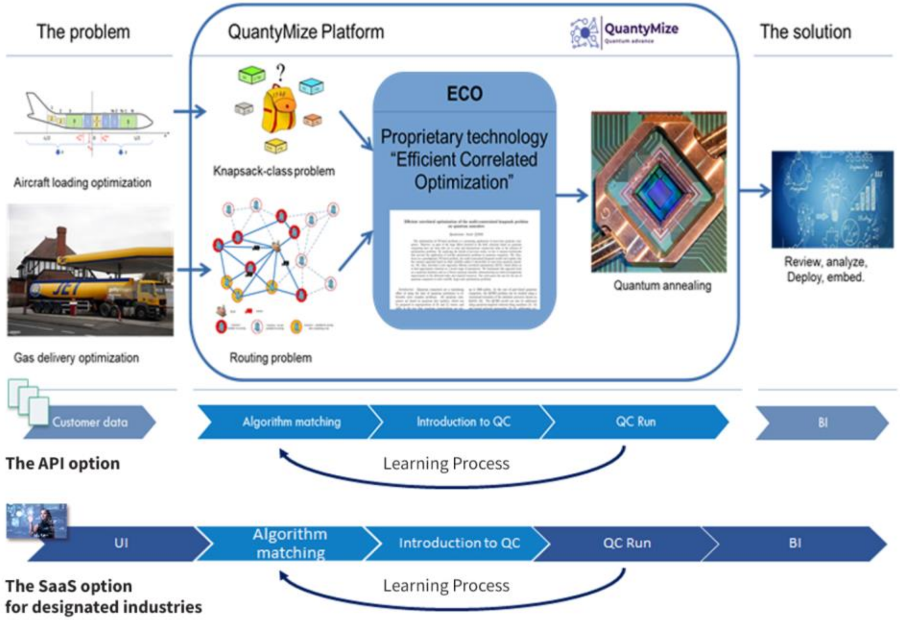

- **Quanty Mize - Founded in 2022**
- Team: 7 experts (industry, academy, 2 PhD , AI and technology experts)
- **Purpose: Enabling 100x optimization capabilities using quantum computing**
  Solving large scale industry NP hard problems;
  Infrastructure middleware based on proprietary algorithms
  and machine learning breakthrough in optimization
- ECO© (Efficient Correlated Optimization) Quantum advance algorithm developed paves the way for the use of quantum computers to solve real-life, large-scale optimization problems. delivers a **100X improvement** in the size of the problem that can be solved efficiently using quantum computers
- **Currently at seed funding stage: Raising $3M**




## How we are solving that

- Platform with runtime segment oriented
- Infrastructure middleware based on proprietary algorithms and Machine Learning: breakthrough in optimization
- Interface to most advanced and scalable quantum computing infrastructure
- Current focus: combinatorial optimization for foodtech, finance, resource allocation, logistics and more

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# Quantum Simulations
# using quantum computers on the cloud

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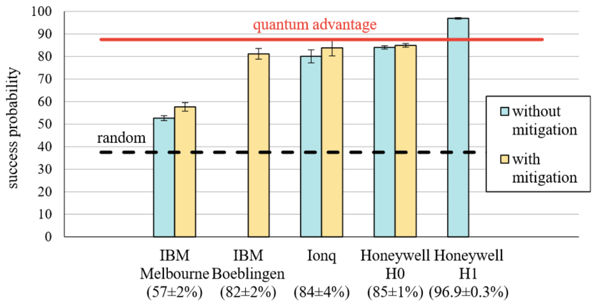


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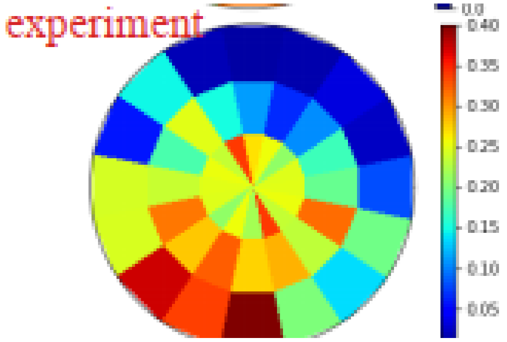


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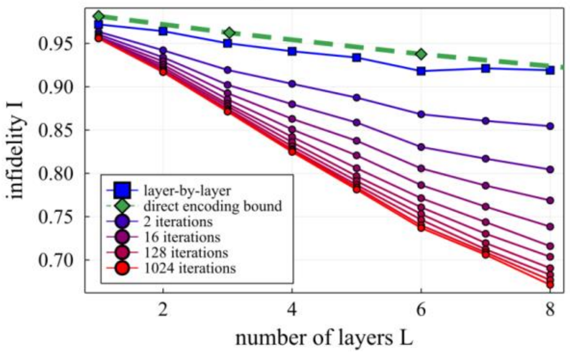



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