Quantum simulations with quantum hardware, Feb 7, 2022

Quantum Simulations using quantum computers on the cloud

Emanuele Dalla Torre

Bar-Ilan University

Dynamics of complex quantum systems

Bar-Ilan University


Daniel Azses (→ Tel Aviv University)


Avi Pe'er


Marcello Calvanese Strinati (→Rome)


Leon Bello (→Princeton)

rigetti


Matthew Reagor


Maxime Dupont


Bram Evert

הקרן הלאומית למדע
ISRAEL SCIENCE FOUNDATION

QUANTUM MACHINES

amazon

Microsoft

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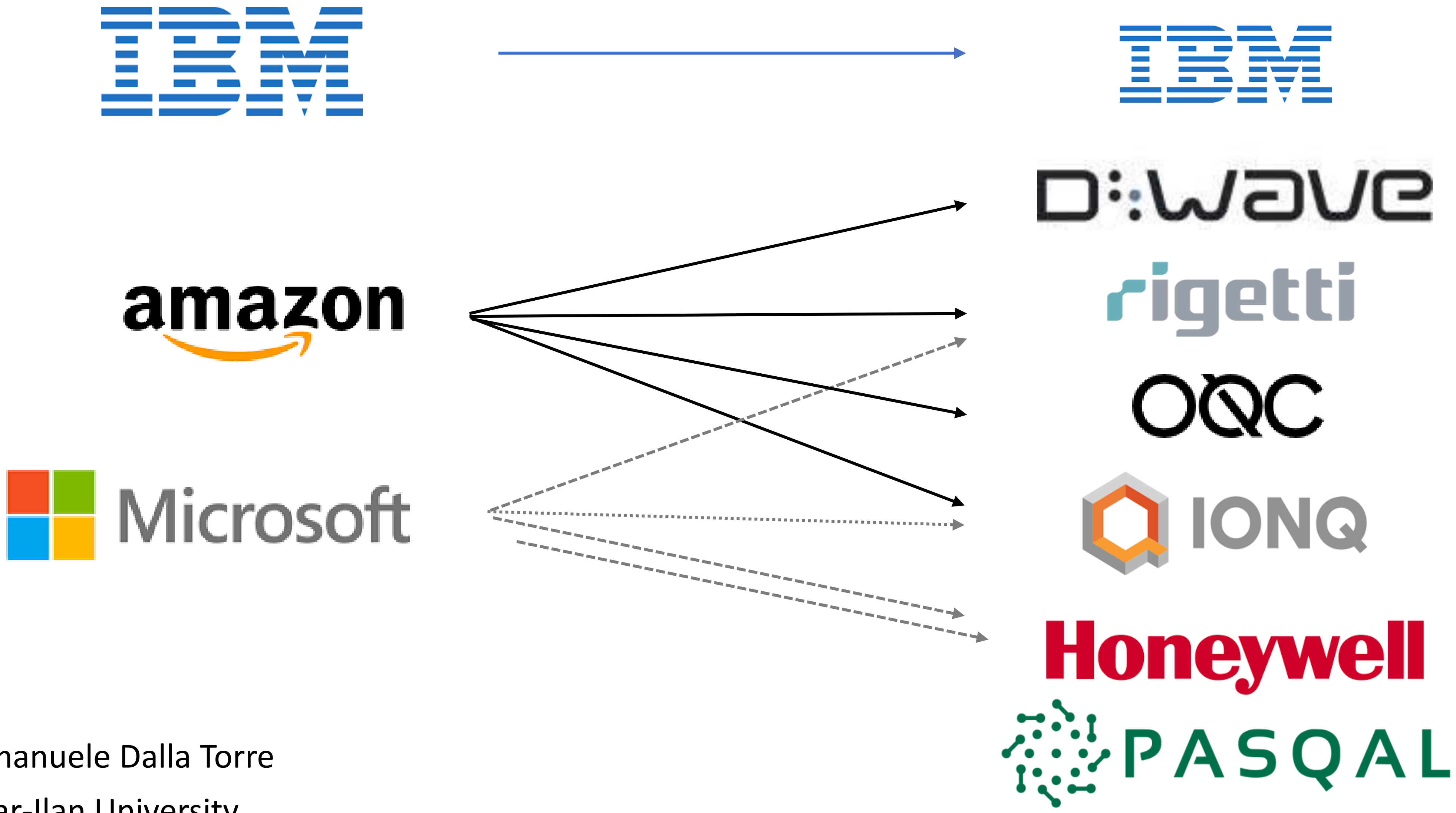
Quantum computing on the cloud: providers



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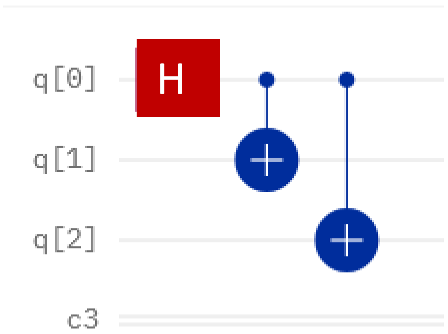
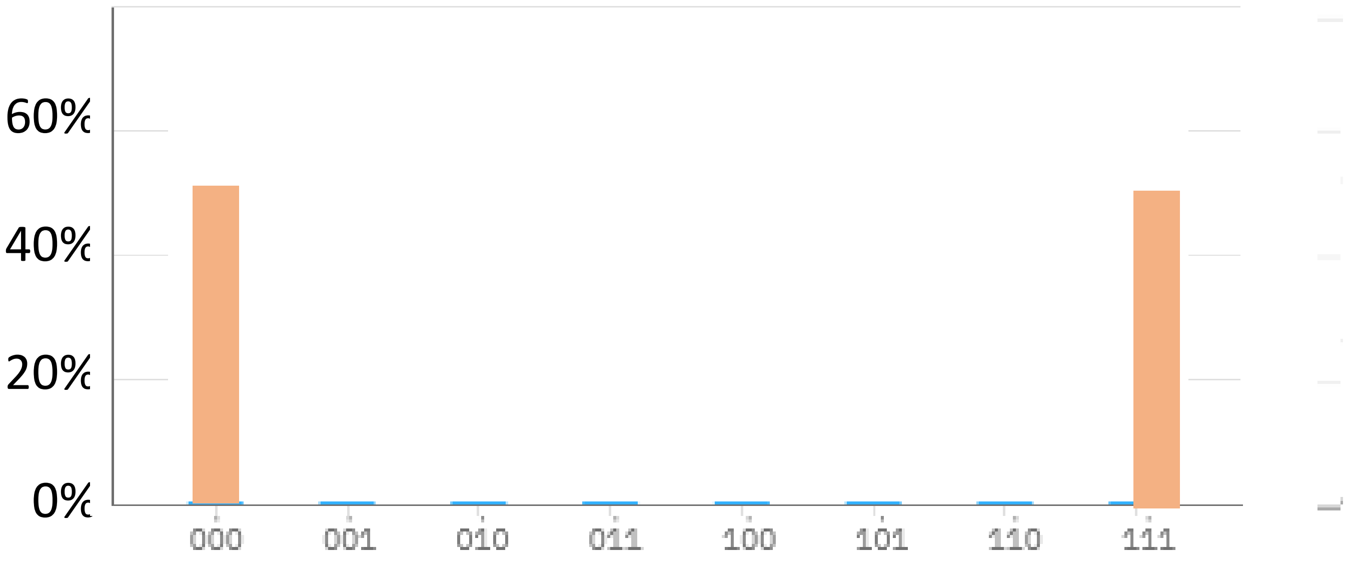
Quantum computers on the cloud: example

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

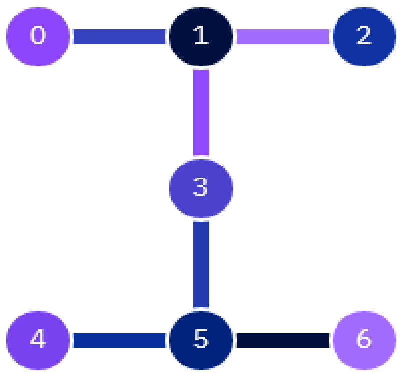
16
Quantum Volume

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:	134.72 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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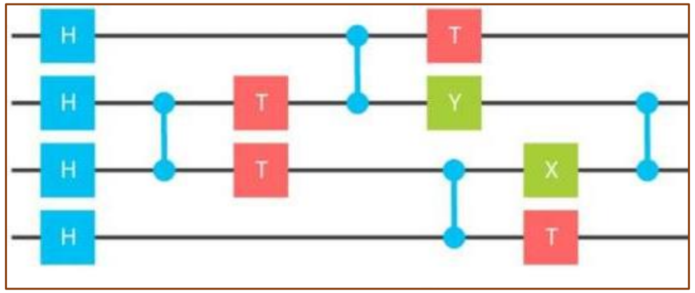
E. Pelofske, A. Bärtschi and S. Eidenbenz, "Quantum Volume in Practice: What Users Can Expect From NISQ Devices," in *IEEE Transactions on Quantum Engineering*, vol. 3, pp. 1-19, 2022, Art no. 3102119.

The great challenge of quantum computing

Model :

Unitary quantum computer

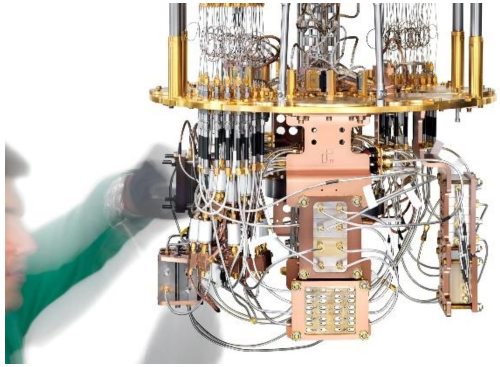


Better hardware
Quantum error correction

Noisy models

Reality :

Noisy superconducting circuits



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

1) Non local games with 6 qubits

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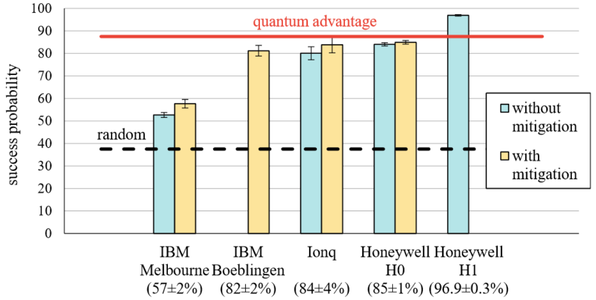

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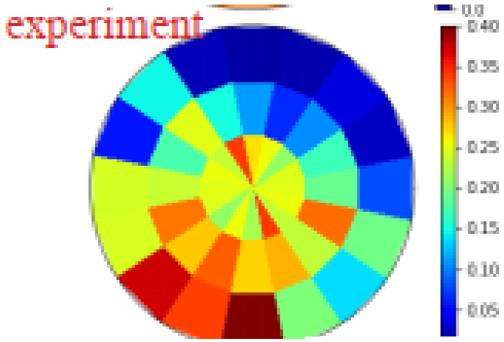

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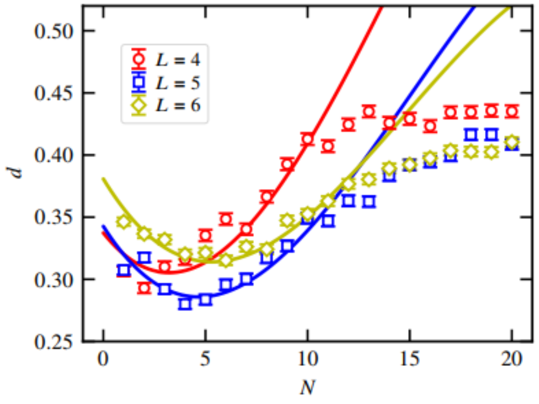

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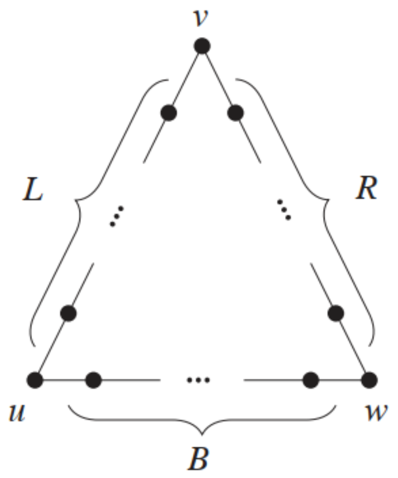
Non-local quantum games

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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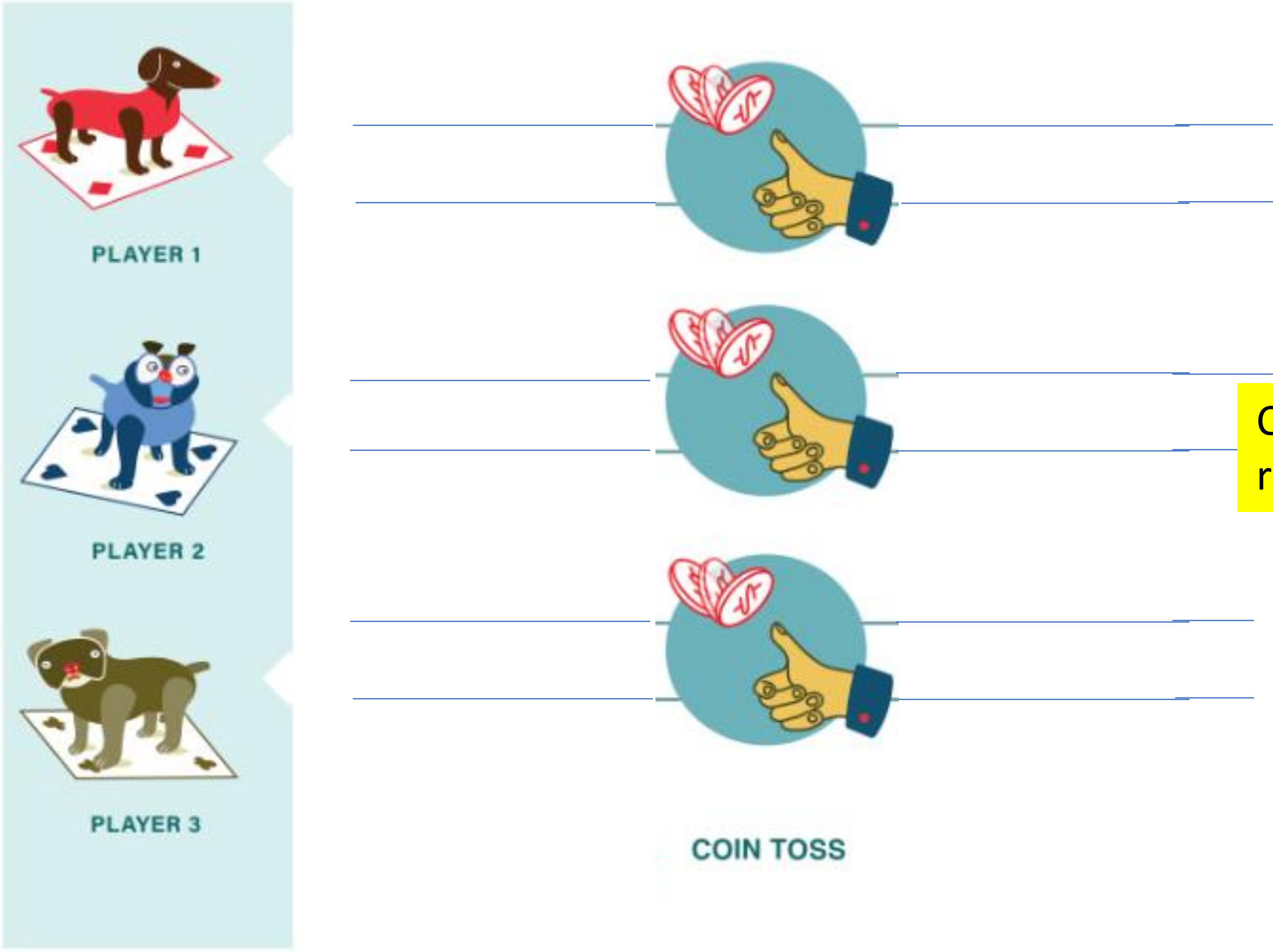
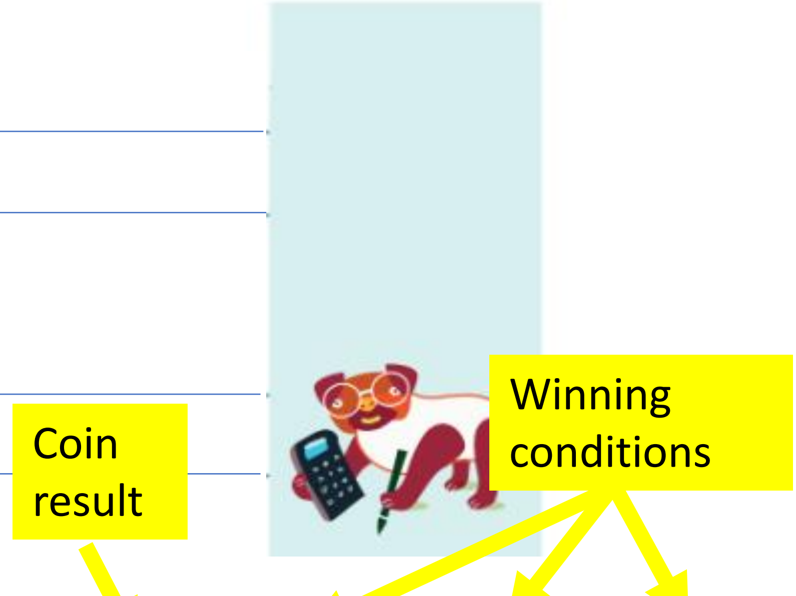
Minimal realization : 3 players = 6 qubits





	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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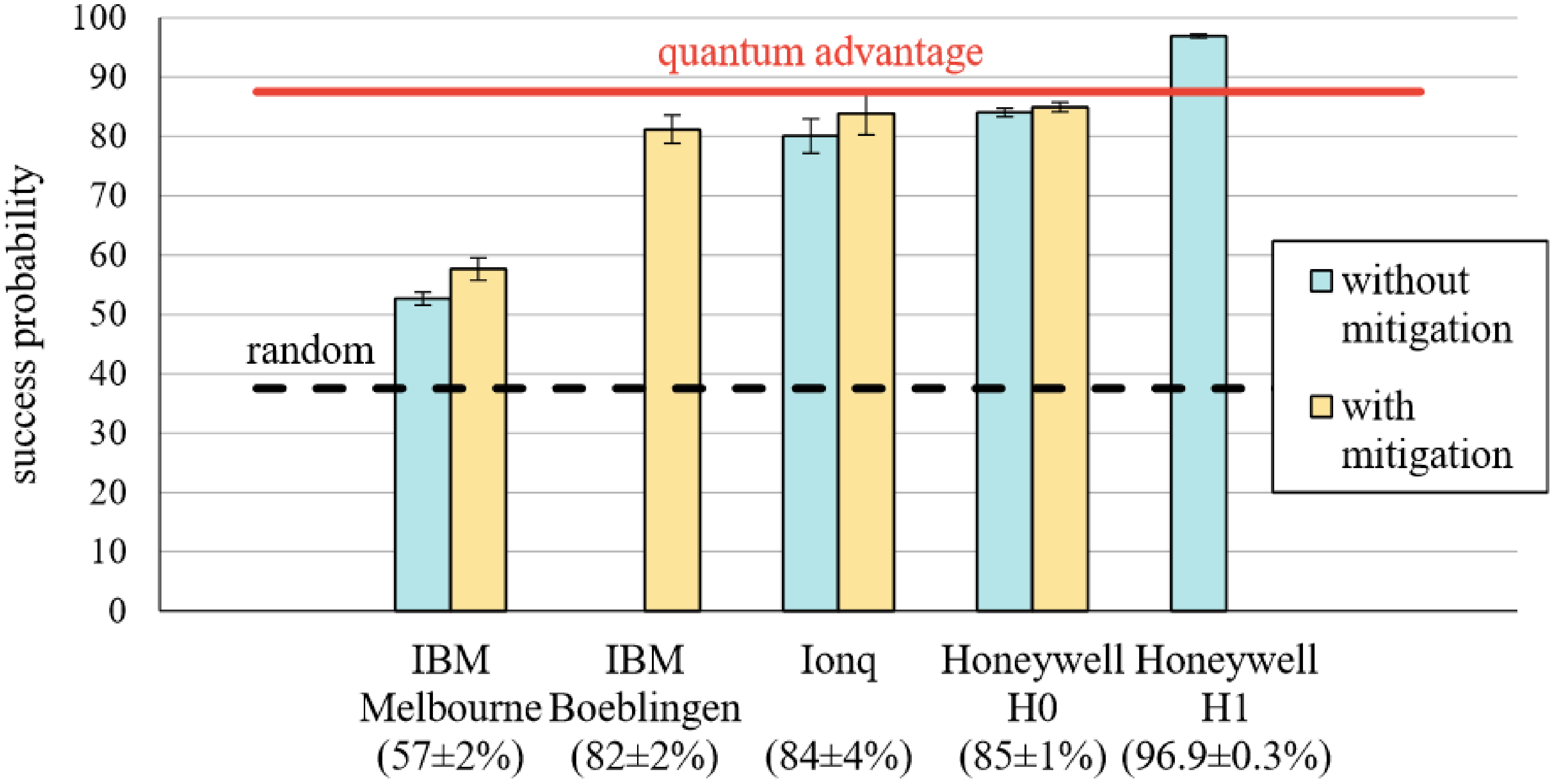
Triangle game (6 qubit) : results



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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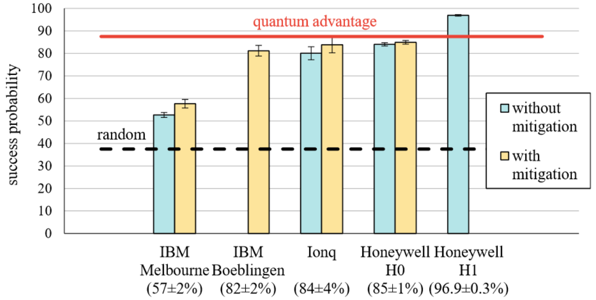

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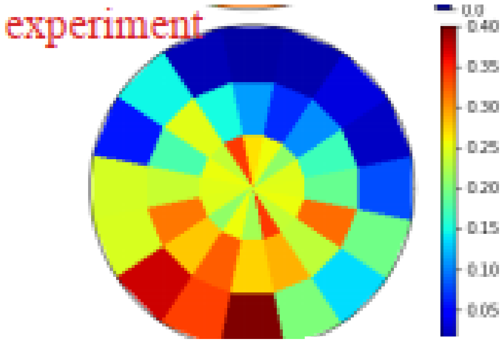

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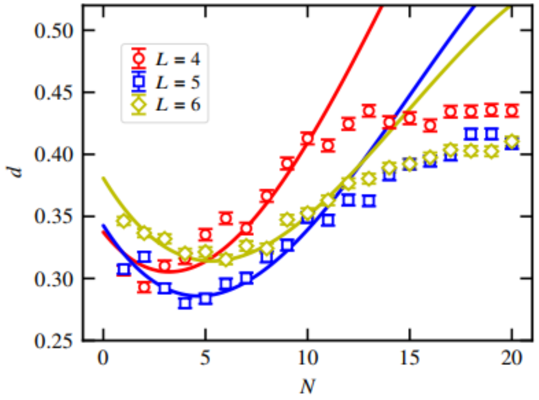

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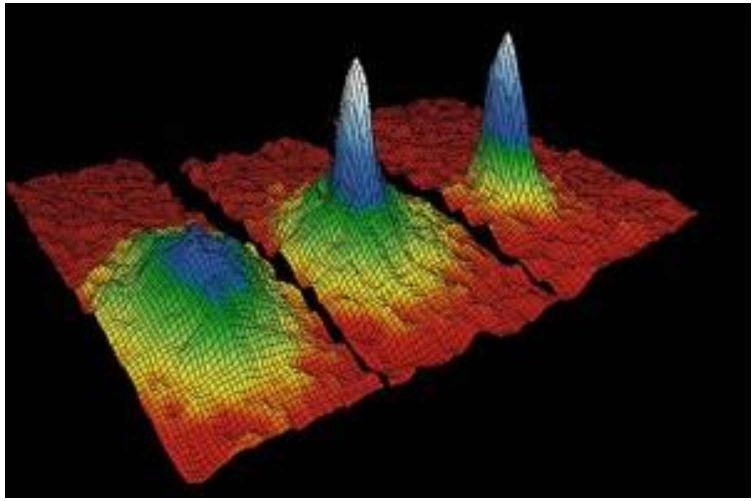
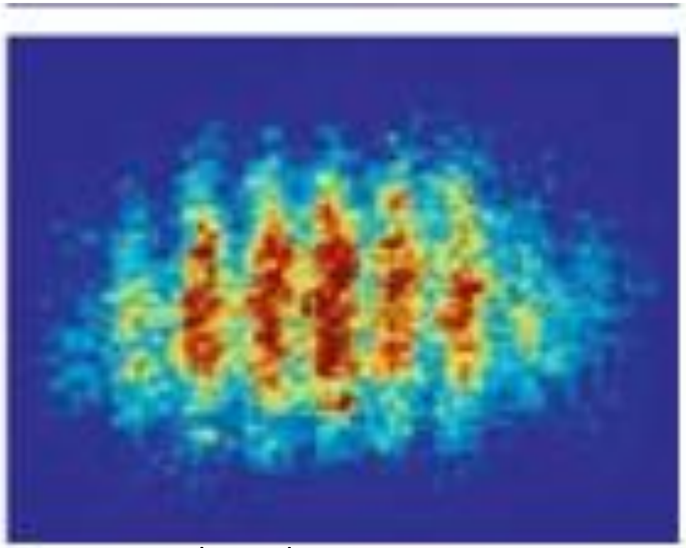
What is a Bose-Einstein condensate?

1. Macroscopic occupation of the ground state



Anderson et al, Science 1995

2. Interference / phase coherence



Schmiedmayer group 2005

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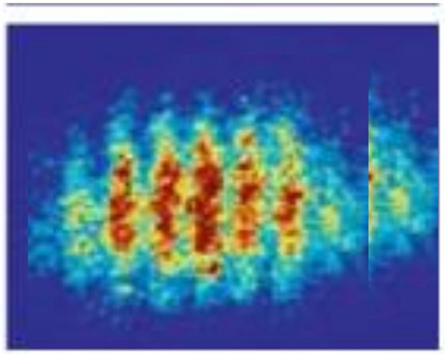
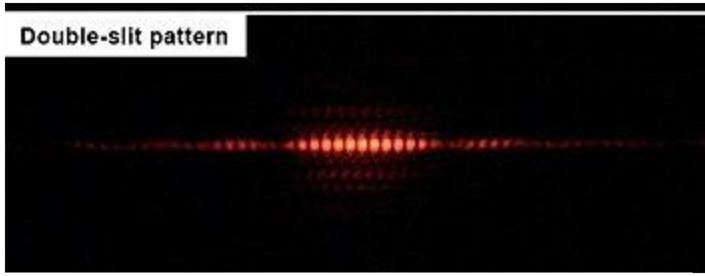
What is the difference between a BEC and a laser?

Our answer:
particle conservation!

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

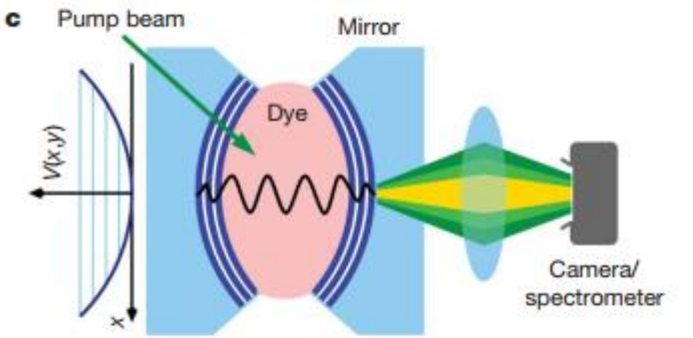


- BEC: number of atoms <u>conserved</u> → no global phase



- 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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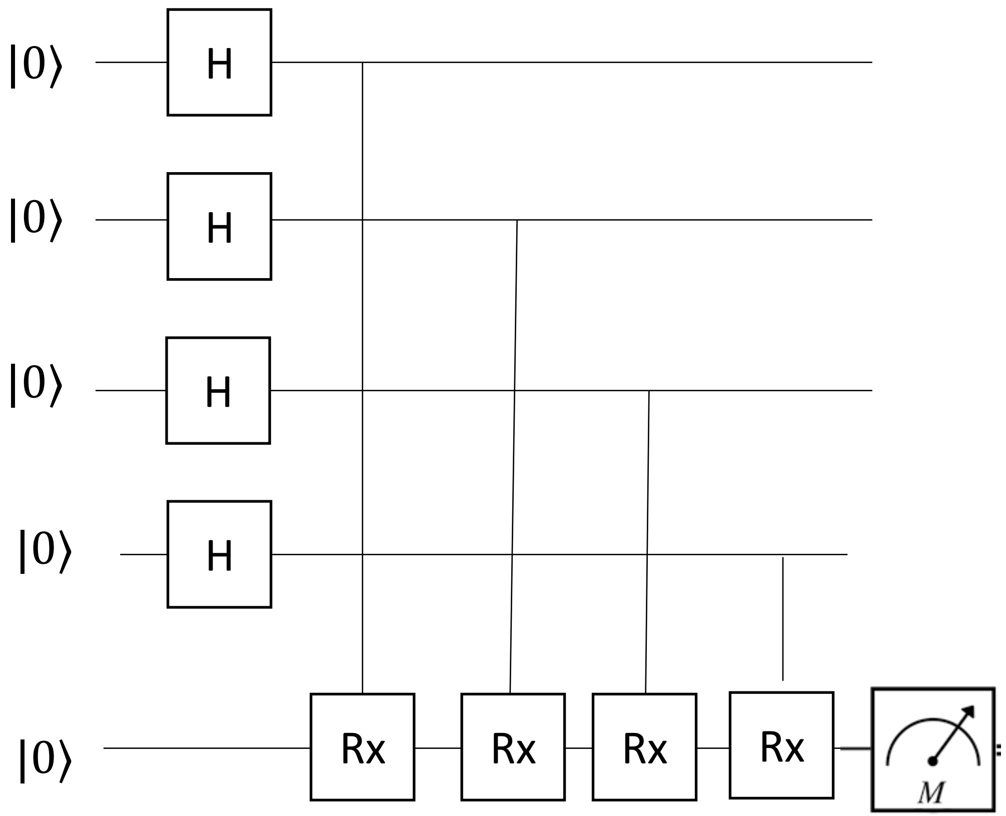
Our goal: simulate a BEC in a quantum computer

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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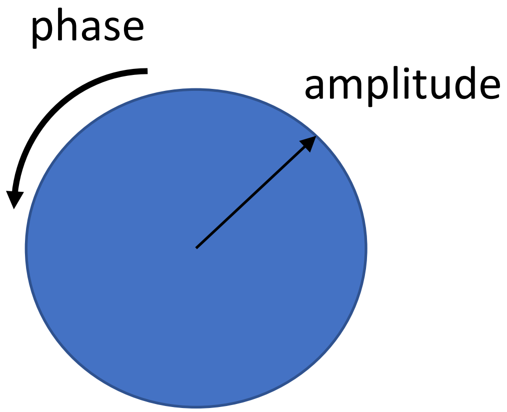
How to probe a BEC state?



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

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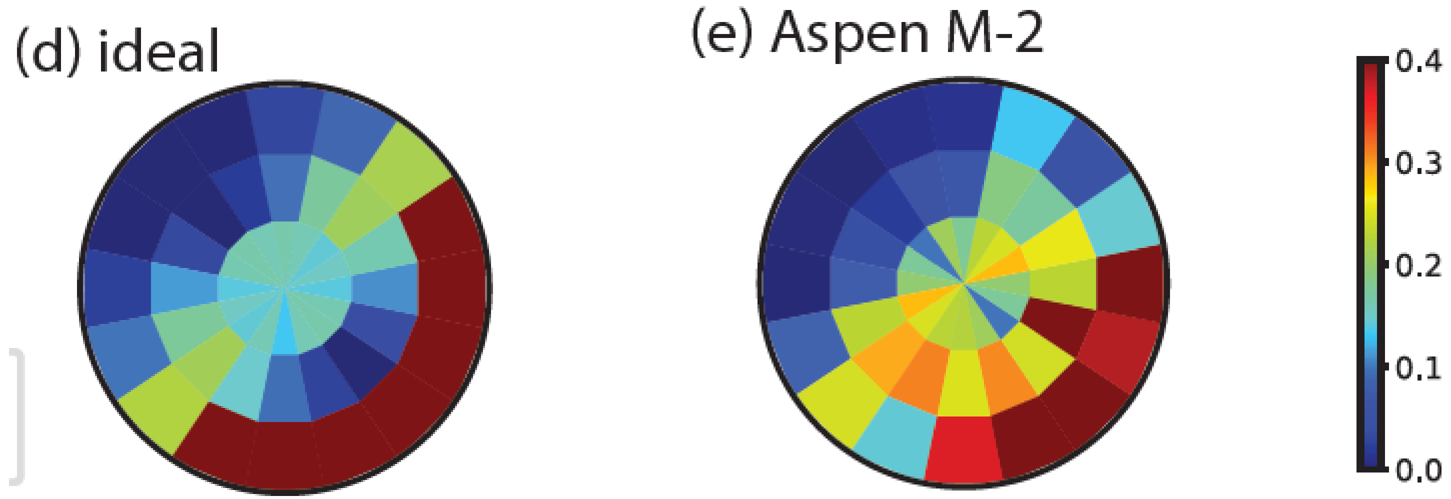
Results: 4 qubits + 1 ancilla



Why is this interesting?

- Leftover phase coherence (use 1 ancilla instead of 2)
- The BEC state is more coherent than the laser state
- Method to benchmark current quantum computers

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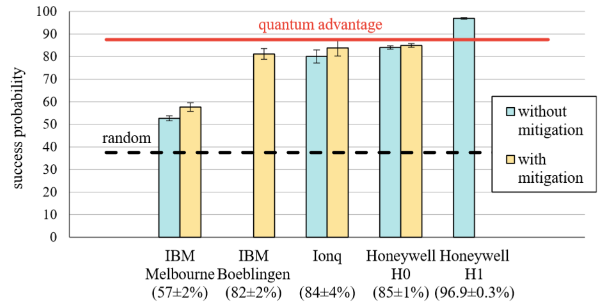

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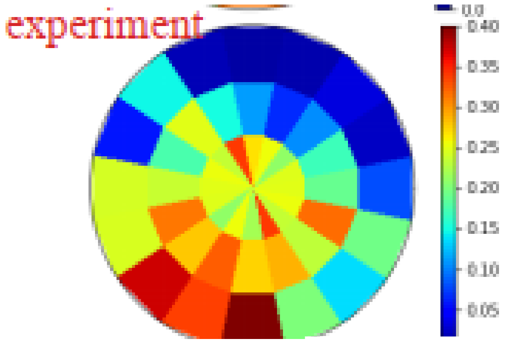

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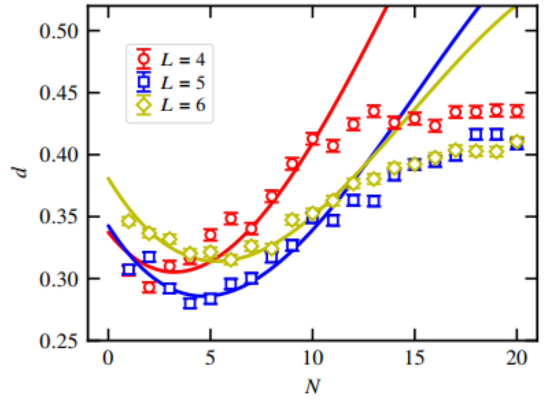

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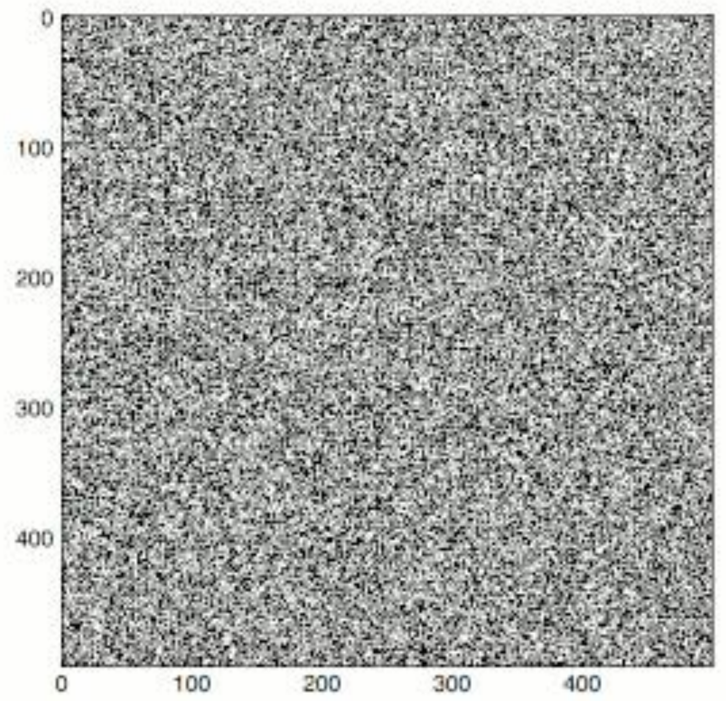
Adiabatic crossing a phase transition

- Gap closing: no adiabatic theorem
  (no exponential suppression)

- Power-law suppression (critical exponents)

  Kibble-Zurek scaling $d \sim v^{\frac{d}{\nu+z}}$



- Extended to the Floquet case by Russomanno & Dalla Torre EPL 2015

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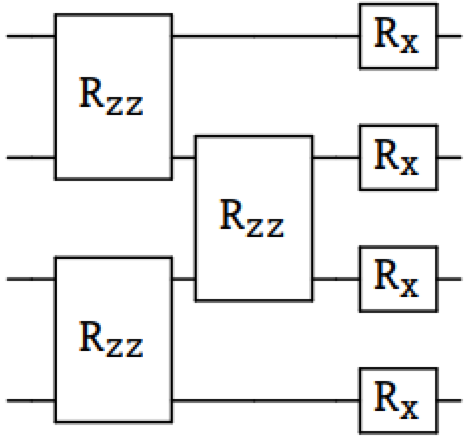
Wikipedia: Ising transition

Realizing a phase transition on a quantum computer



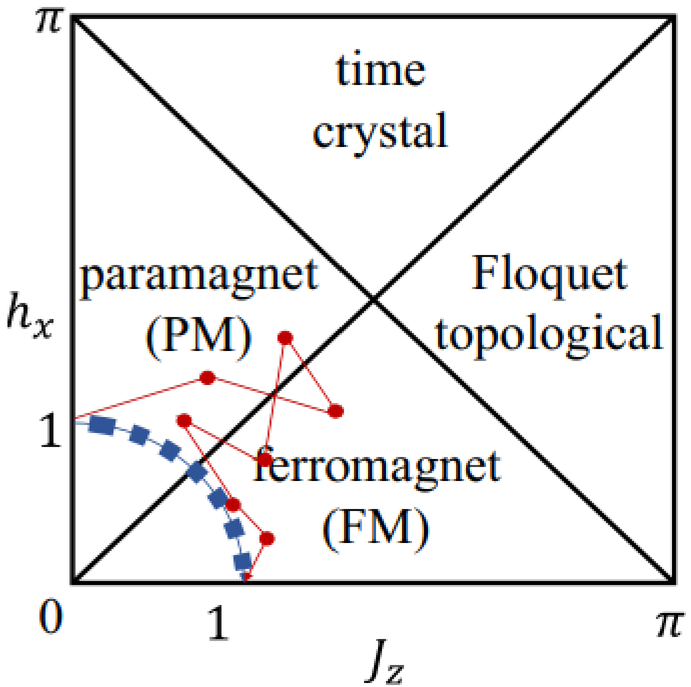
Floquet Ising model

$$H^{\mathrm{PM}} = -\sum_{i=1}^{L} X_i \quad \text{and} \quad H^{\mathrm{FM}} = -\sum_{i=1}^{L-1} Z_i Z_{i+1},$$

Can be mapped to free fermions

Phase diagram:

Khemani et al 2016 and references therein



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See also talk by Daniel Azses

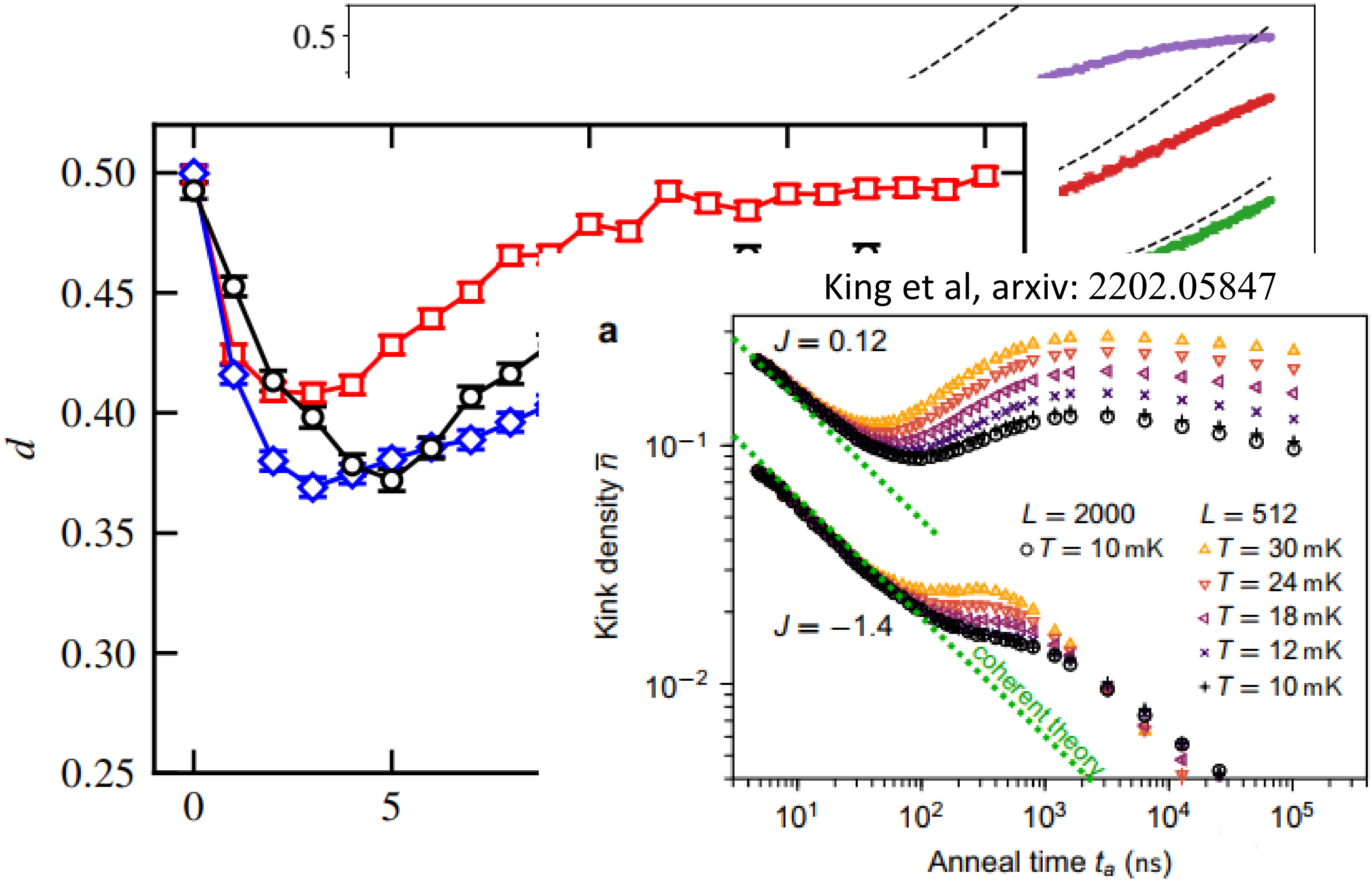
Noisy Floquet Kibble Zurek

Kibble-Zurek : $d \sim 1/N^{0.5}$

Noise : $d = \alpha\, N$

Phenomenological ans

$$d = \frac{1}{N^{0.5}} + \alpha N \Rightarrow$$



King et al, arxiv: 2202.05847

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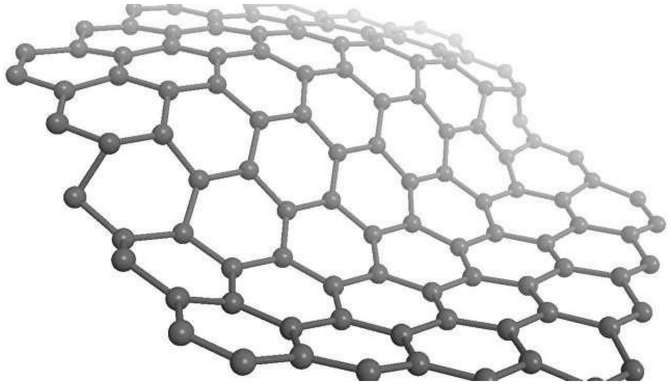
Summary: Quantum simulations

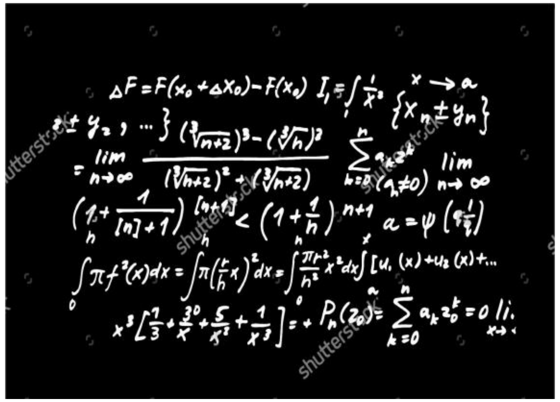
Quantum molecules/material

Size of Hilbert space = 2^{N_A}

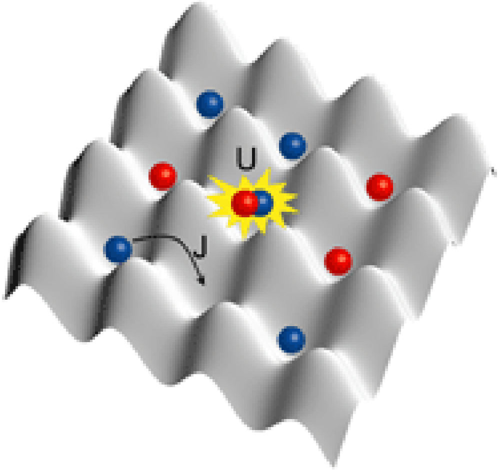


Classical supercomputers

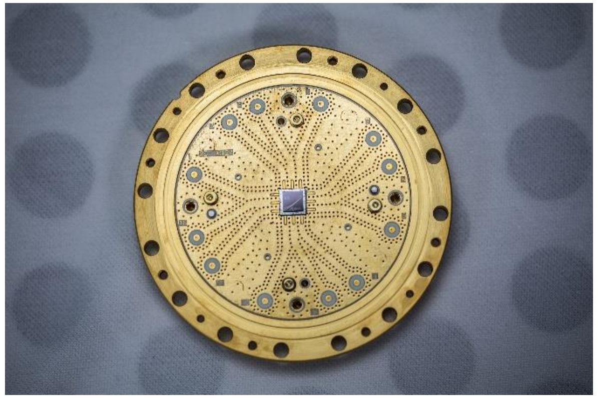
Quantum field theories



Ultracold atoms



Quantum computer on the cloud



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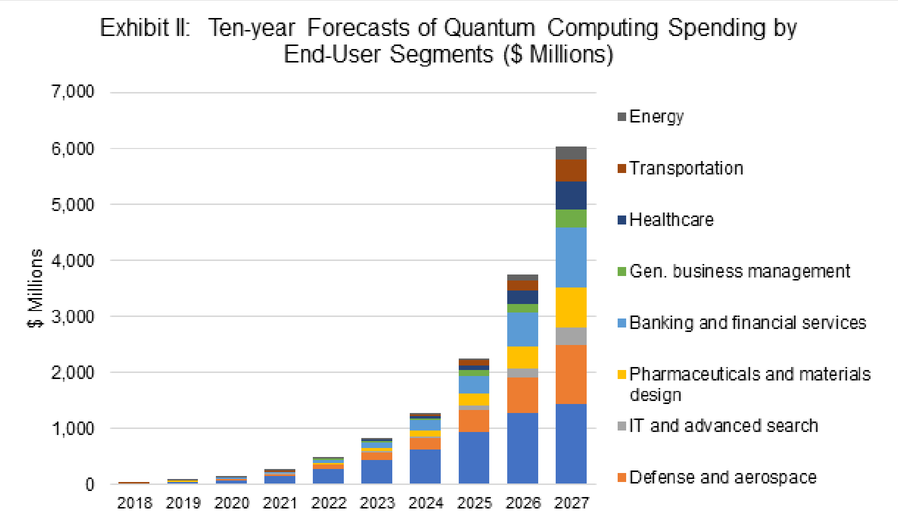
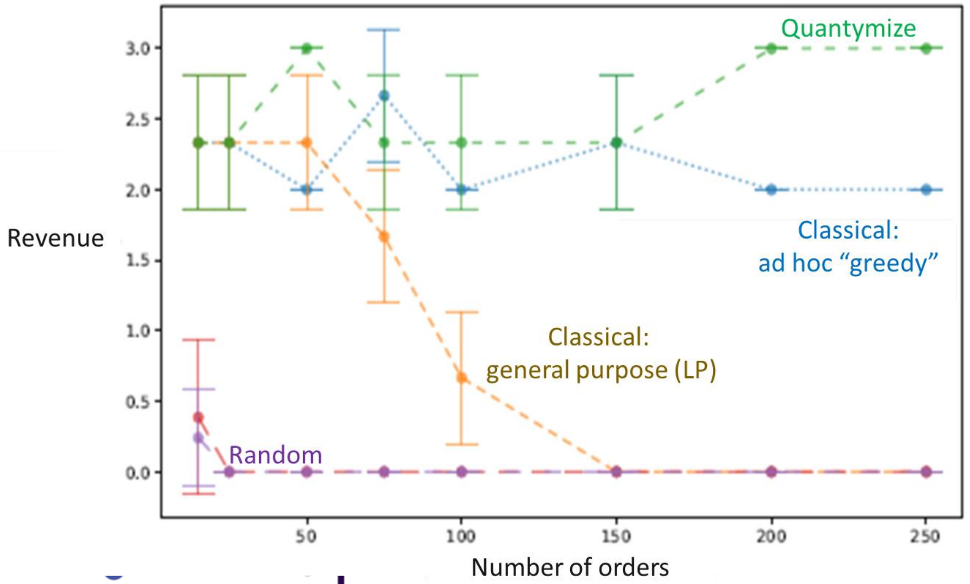
Quantymize in a nutshell

- Founded in 2022
- Team: 7 experts (Industry, Quantum, AI)
- **Purpose: Enabling 100x optimization capabilities using quantum computing**
- Solving large scale industry NP hard problems
  2 main models introduced in QC:
  - Resource allocation optimization
  - Drugs usage optimization

  In development:
  - Financial Portfolio Optimization
  - Automotive preproduction optimization
- Breakthrough results already today
- Funding seed investment



Source: IQT research



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using quantum computers on the cloud

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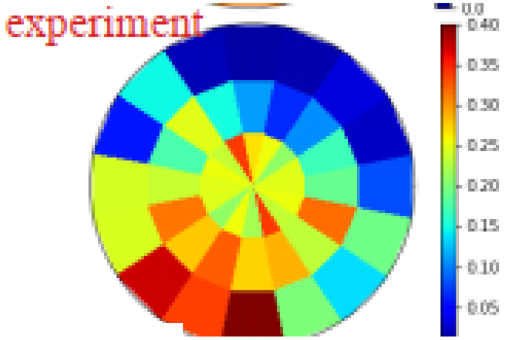

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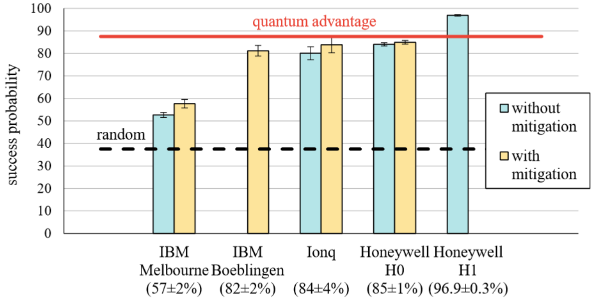
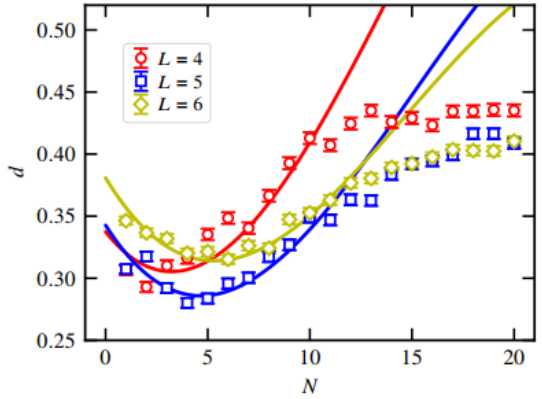


3) Crossing a phase transition with 5 qubits

Azses, Dupont, Evert, Reagor, Dalla Torre *Navigating the noise-depth tradeoff in adiabatic quantum circuits* (to be submitted)



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EXTRA SLIDES

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