XXIII Training Course in the Physics of Strongly Correlated Systems

October 4-9, 2021, Salerno

Quantum Simulations using quantum computers on the cloud

Emanuele Dalla Torre

Bar-Ilan University

Quantum computing on the cloud

Emanuele Dalla Torre

Bar-Ilan University

Research Partners

IBM

Microsoft

amazon

Inter-University Computation Center

Financial Support

Israel Science Foundation

On sabbatical with

rigetti

Quantum computing on the cloud **is a reality!**

Portals:

Hardware:

amazon

D:Wave

rigetti

Not available in Israel

Microsoft

IONQ

Very expensive

Honeywell

IBM

For free

IBM

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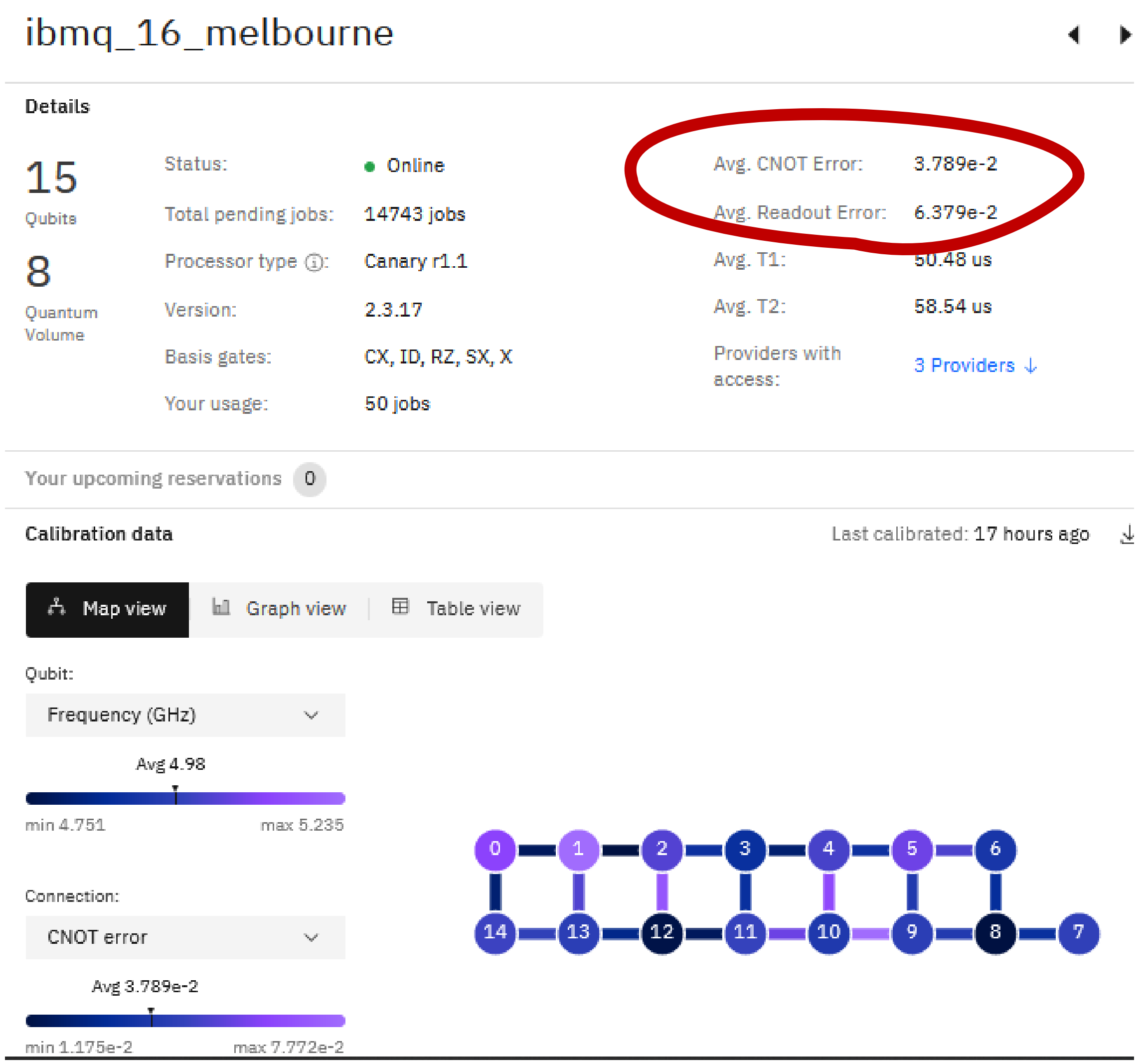
http://quantum-computing.ibm.com



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Cat state preparation

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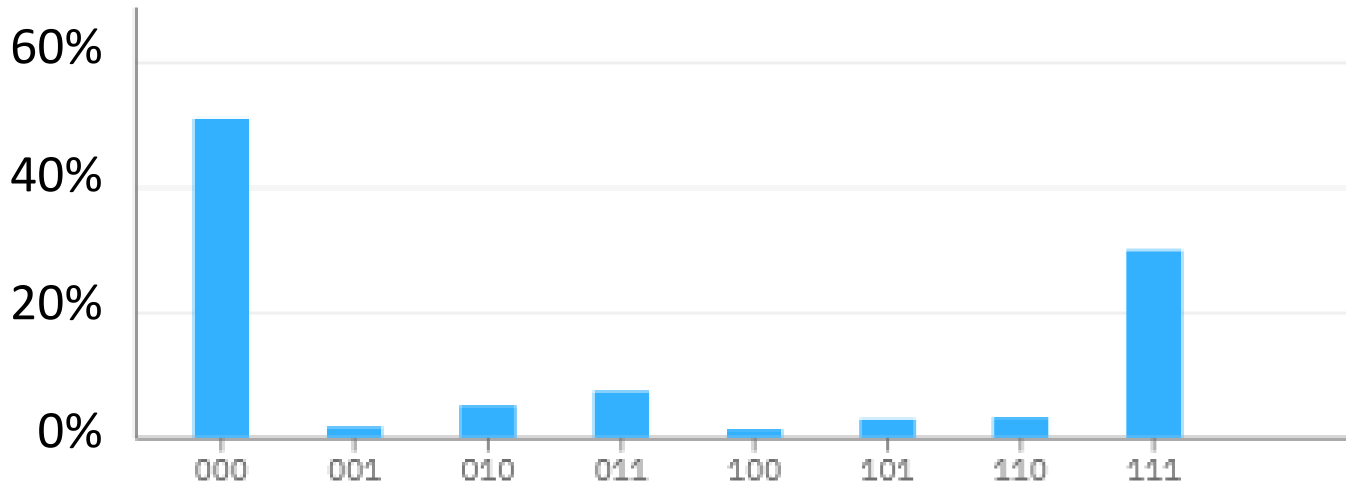

Demonstration of Shor's factoring algorithm for N=21 on IBM quantum processors

Unathi Skosana and Mark Tame*
Department of Physics, Stellenbosch University, Matieland 7602, South Africa

(Dated: March 26, 2021)

We report a proof-of-concept demonstration of a quantum order-finding algorithm for factoring the integer 21. Our demonstration involves the use of a compiled version of the quantum phase estimation routine, and builds upon a previous demonstration by Martín-López et al. in Nature Photonics 6, 773 (2012). We go beyond this work by using a configuration of approximate Toffoli gates with residual phase shifts, which preserves the functional correctness and allows us to achieve a complete factoring of $N = 21$. We implemented the algorithm on IBM quantum processors using only 5 qubits and successfully verified the presence of entanglement between the control and work register qubits, which is a necessary condition for the algorithm's speedup in general. The techniques we employ may be useful in carrying out Shor's algorithm for larger integers, or other algorithms in systems with a limited number of noisy qubits.

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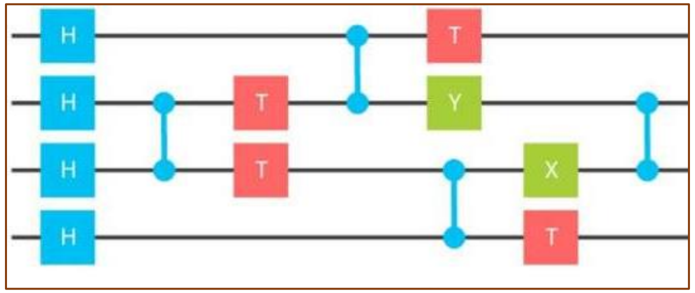
The main challenge

Model :

Unitary quantum computer



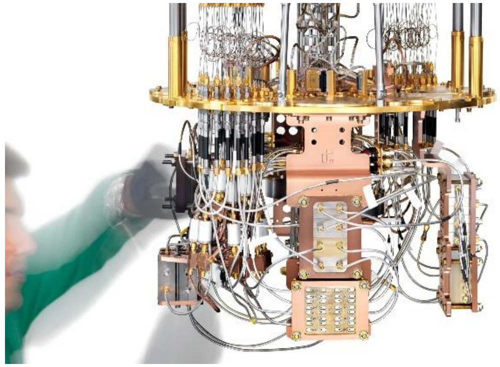
f.e. Shor algorithm (breaks RSA), quantum machine learning

quantum error correction

open quantum systems

Reality :

Noisy superconducting circuits



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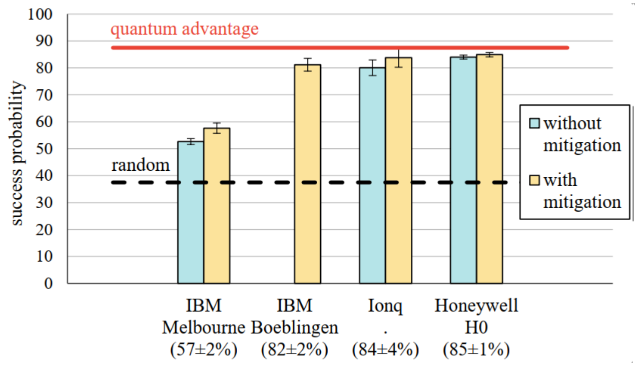
Three examples of quantum simulations

1. Noisy nonlocal games
arXiv:2105.05266



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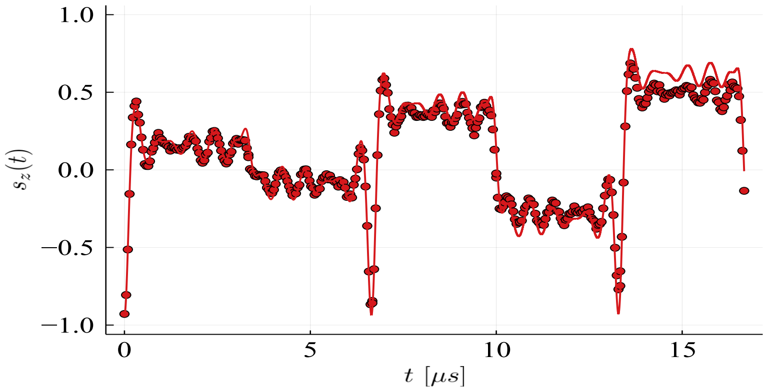

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arXiv:2002.04620 (PRL, 2020)
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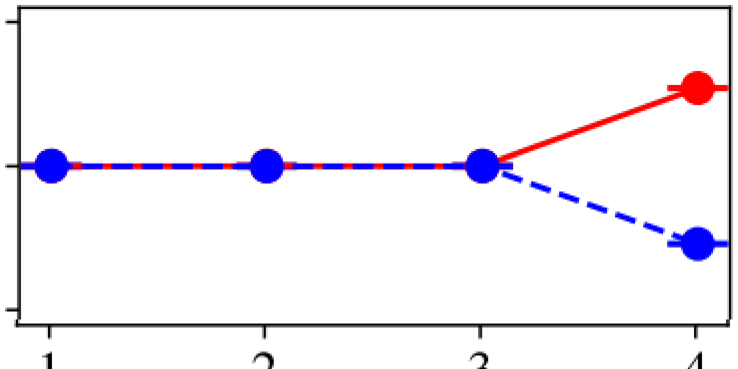

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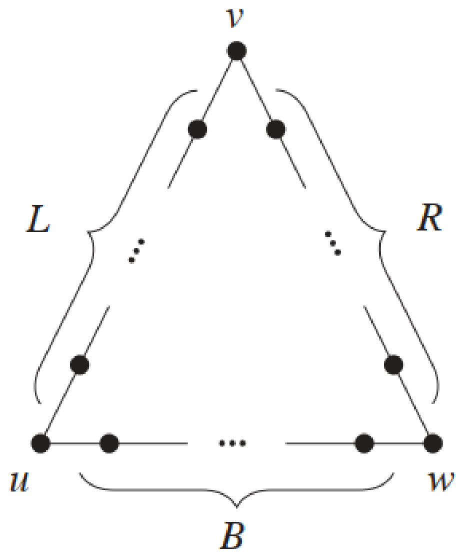
Bell inequality… with many qubits

a.k.a. Non-local quantum games

Example: triangle game using a 1d cluster state

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

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



Bravyi, Gosset & Konig, Science 2018

Daniel & Myiaka, PRL 2021

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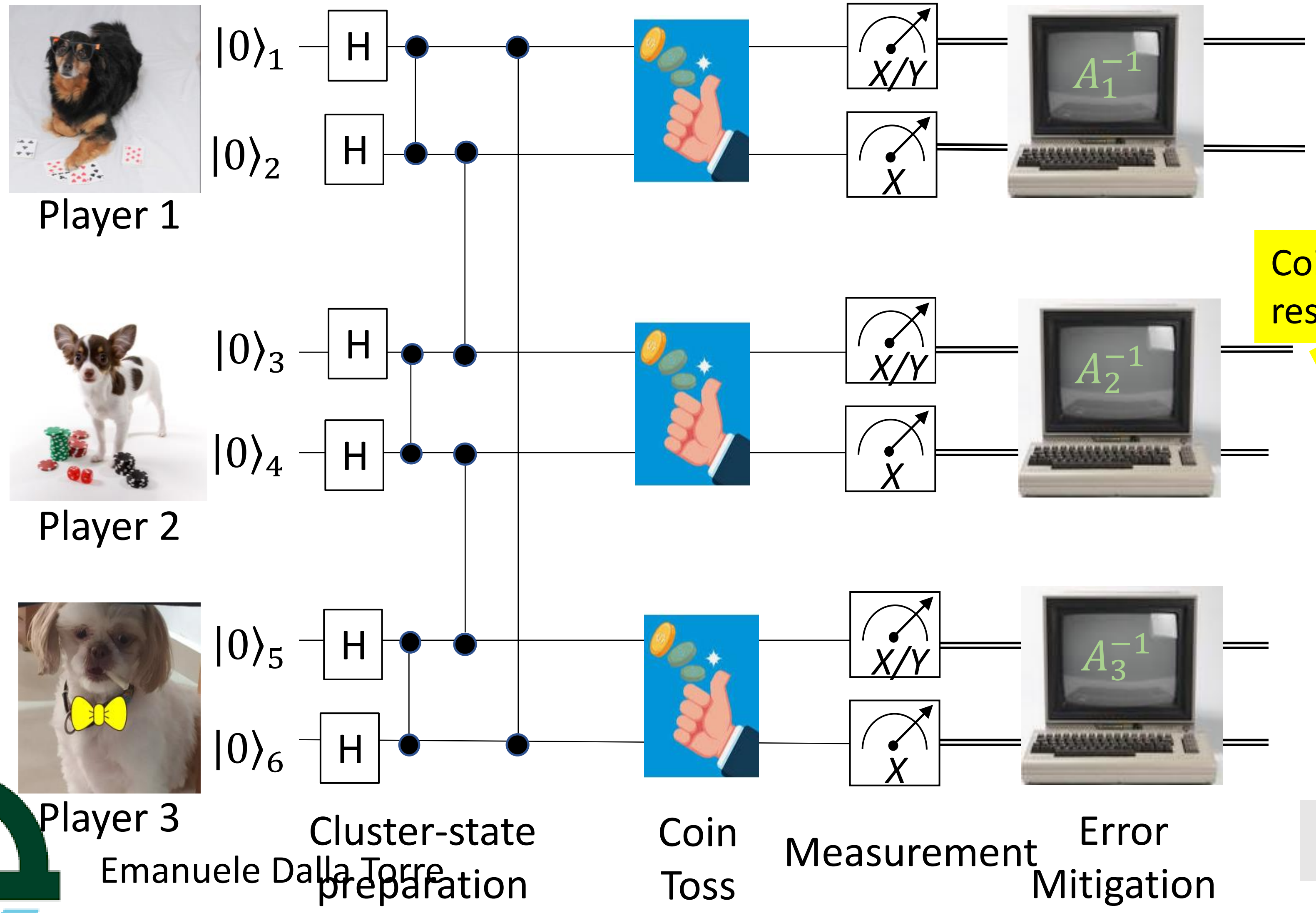
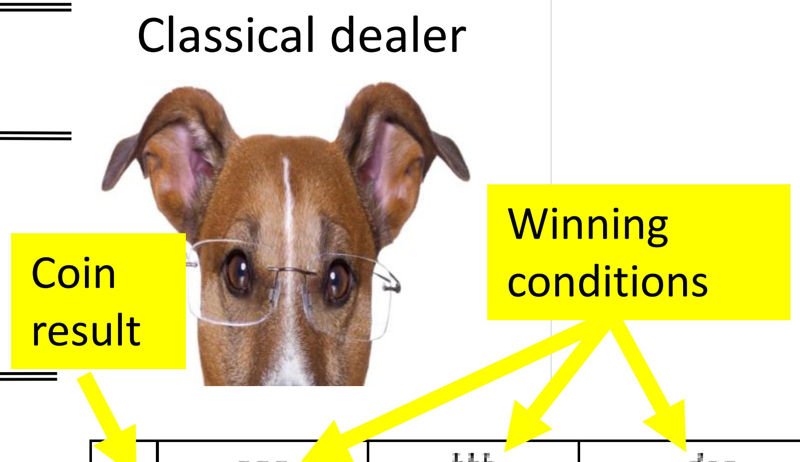
Minimal realization : 3 players = 6 qubits





	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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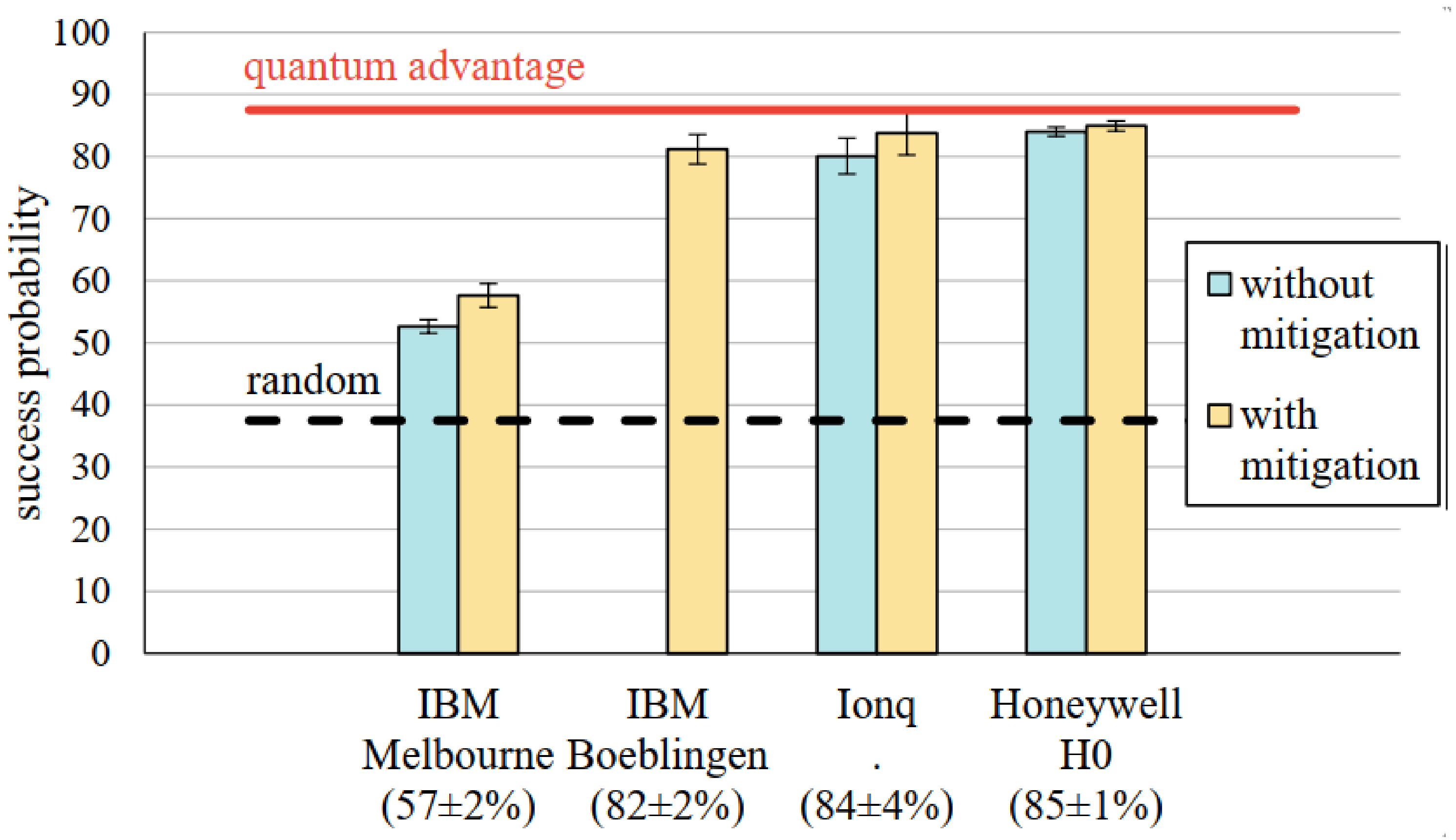
Triangle game (6 qubit) : results



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If all the students fail a test… lower the bar!

Stabilizers

$$s_i = X_{i-1} Z_i X_{i+1}$$

$$s_i |\psi_{\text{cluster}}\rangle = |\psi_{\text{cluster}}\rangle$$

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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Three examples of quantum simulations

1. Noisy nonlocal games
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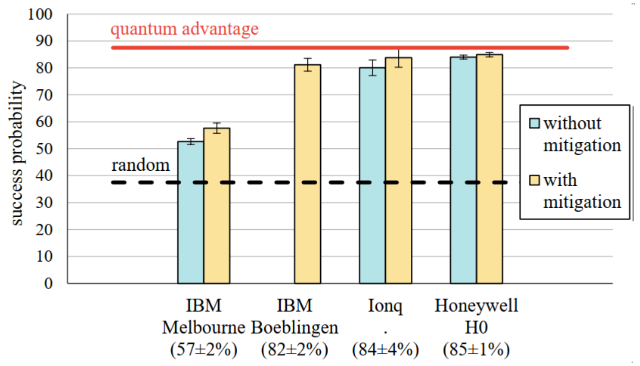

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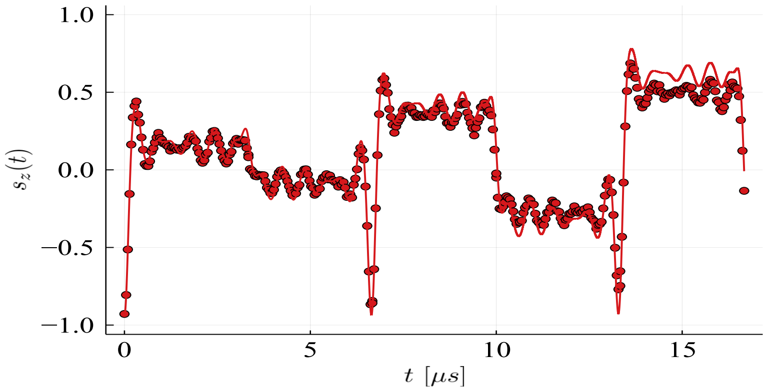

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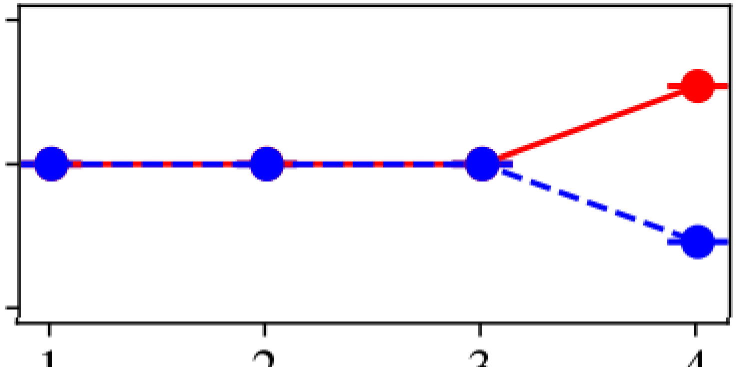

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Periodically driven single qubit

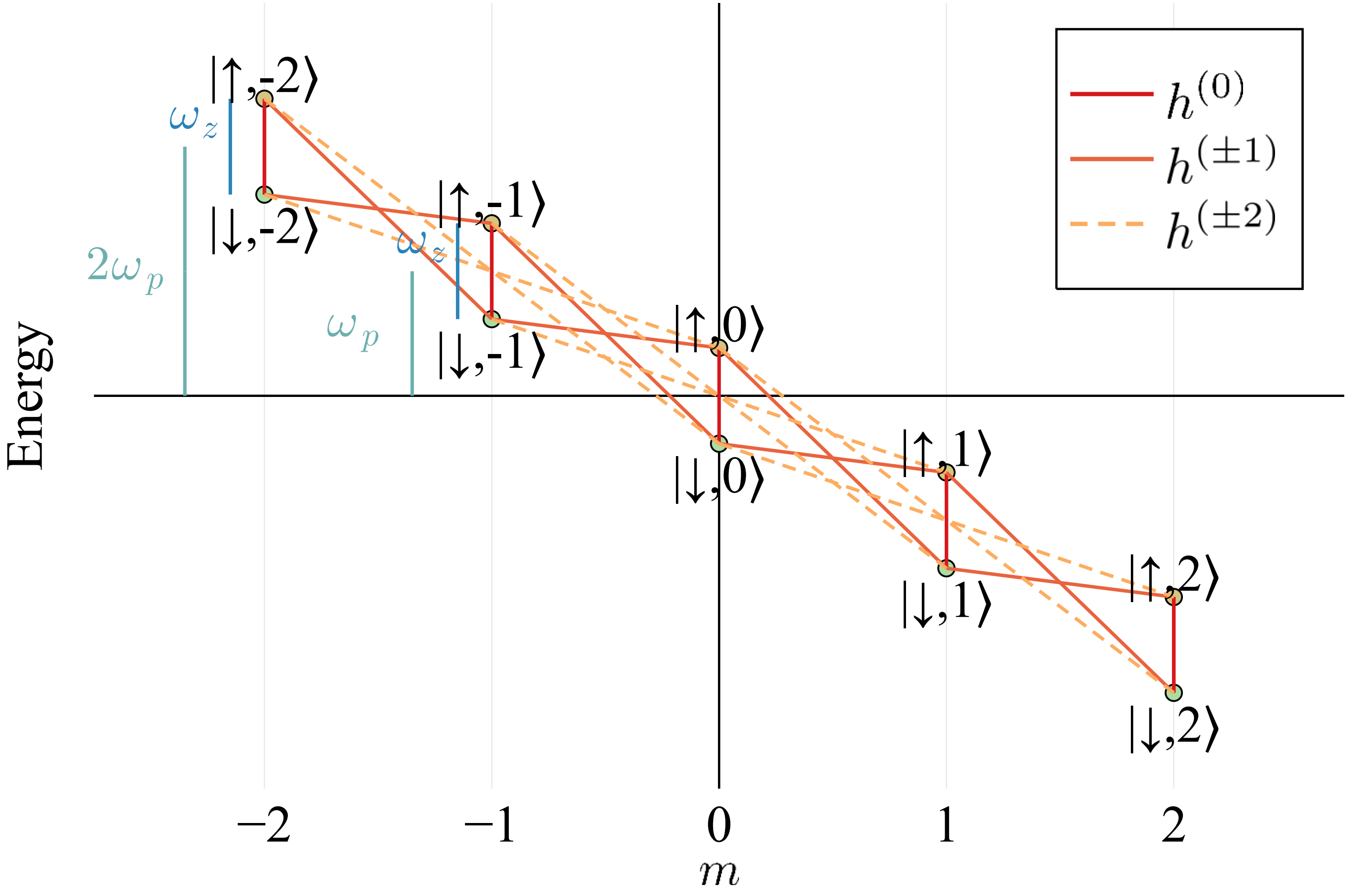
Main ingredient:

Pulse engineering:

$$H(t) = \omega_z \sigma^z + h(t)\sigma^x$$

Periodic drive (Floquet)

$$h(t+\tau) = h(t) \qquad \omega_p = \frac{2\pi}{\tau}$$



Floquet synthetic dimension

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Floquet engineering

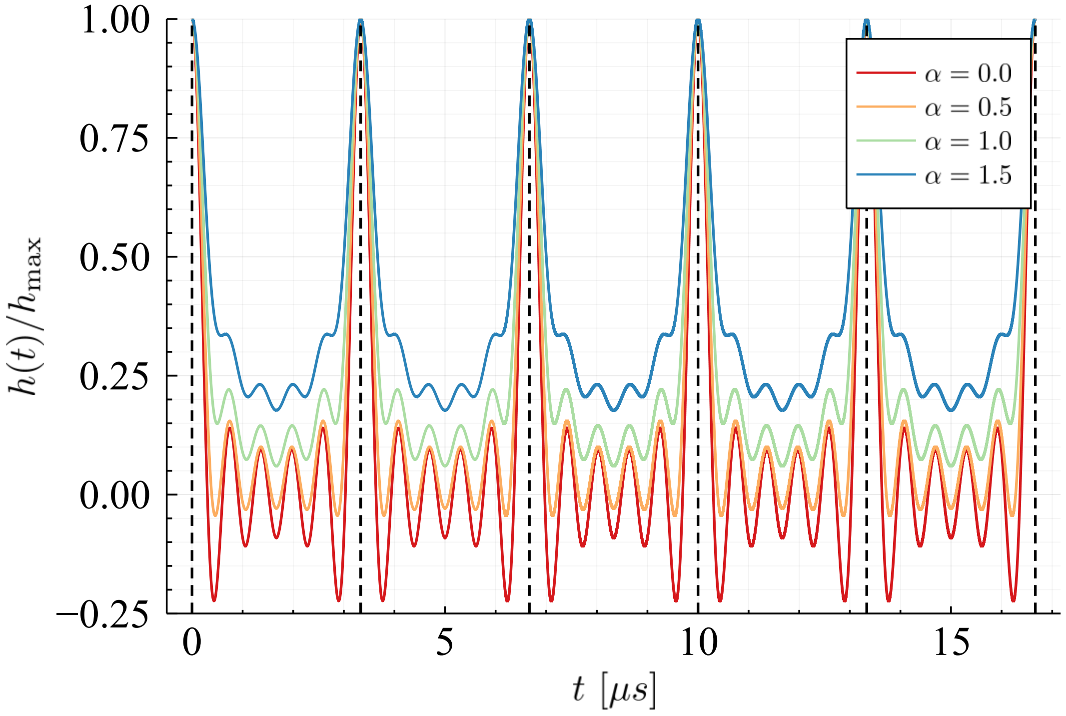
Long ranged coupling:

$$h^{(m)} = \frac{h_0}{(1+|m|)^{\alpha}}$$

Simulation of gravitational models &

unscreened Coloumb forces ($\alpha = 1$)!

M=5



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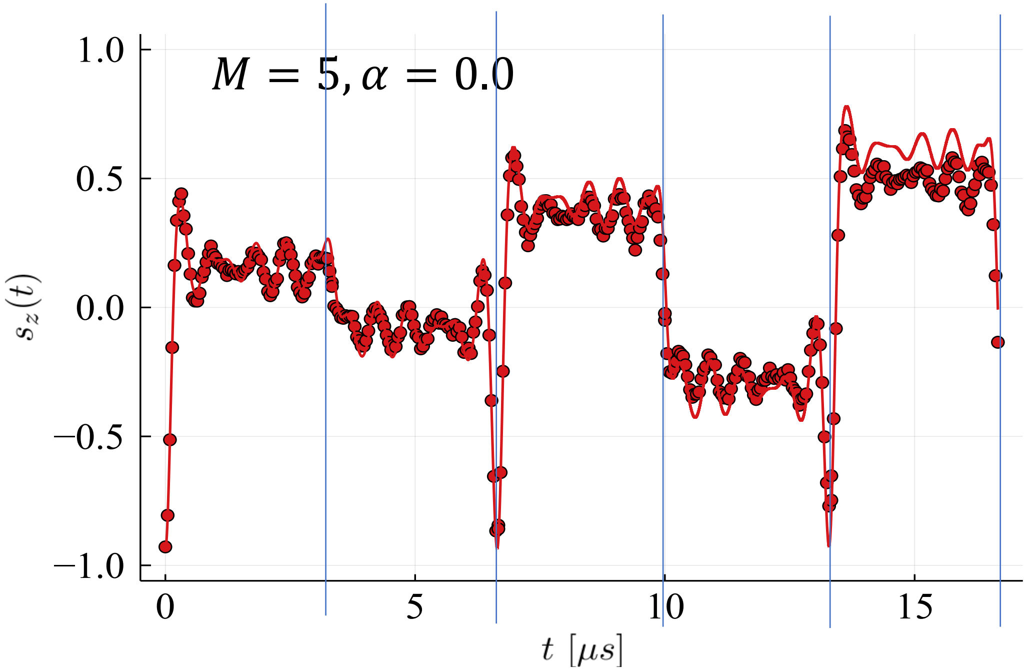
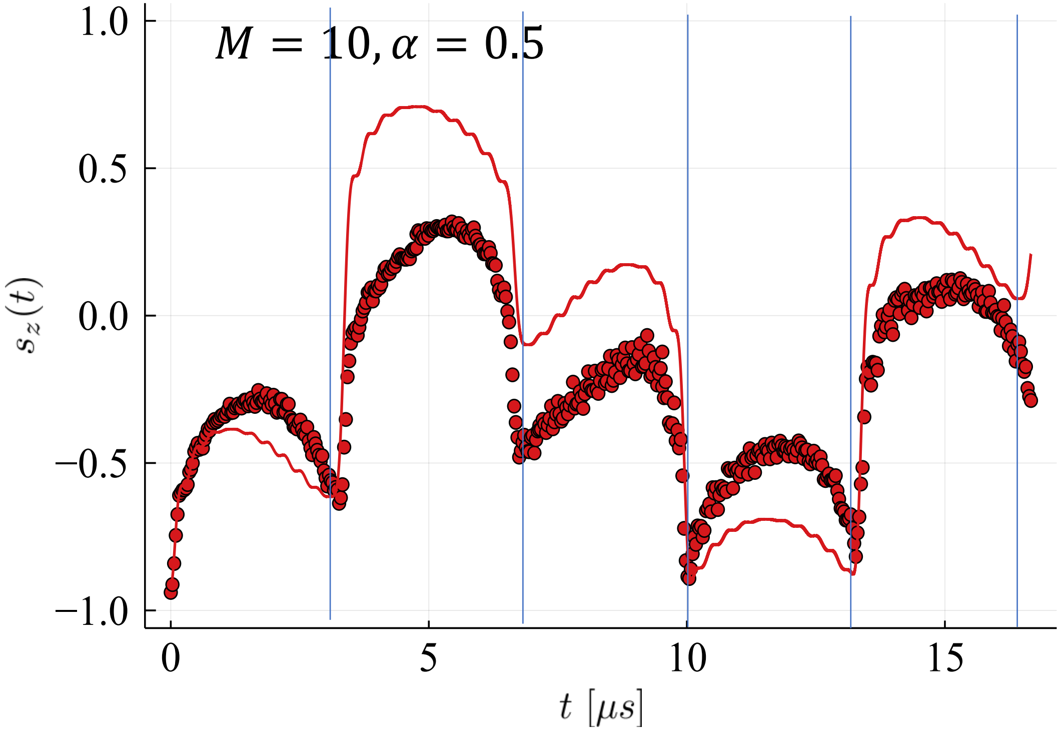
Result from a physical device





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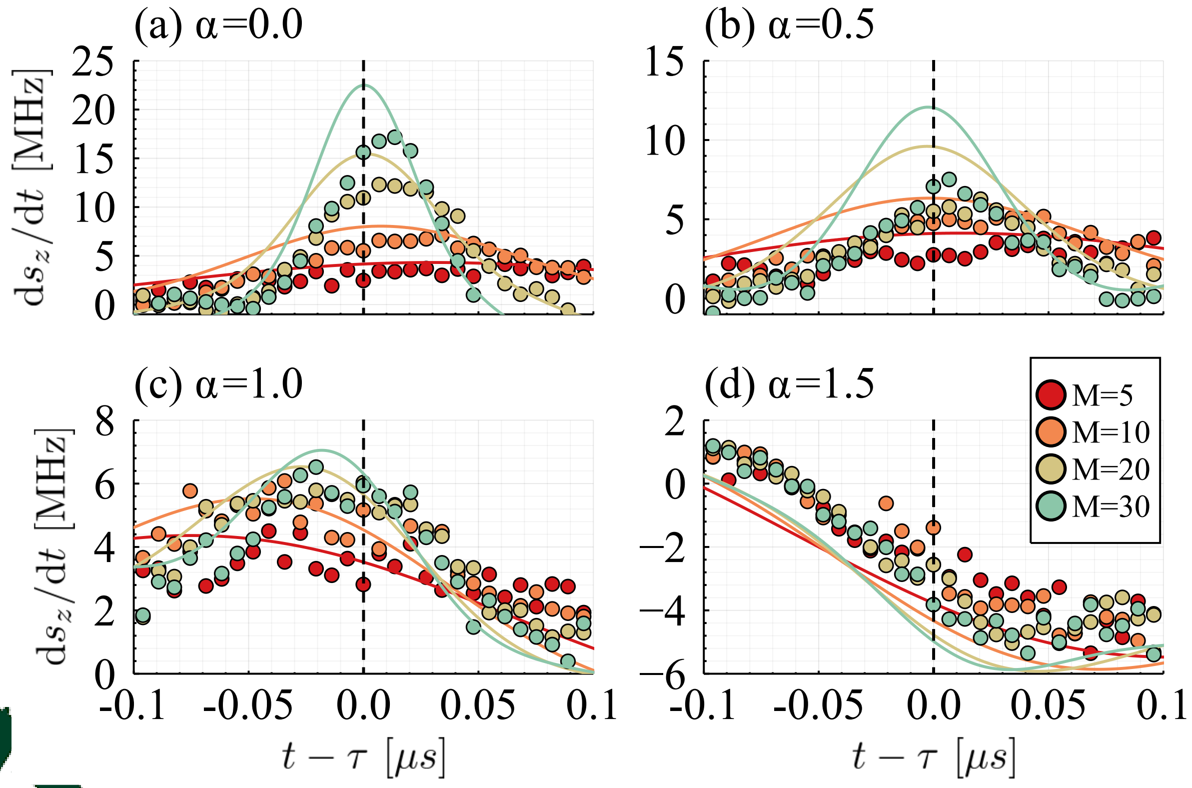
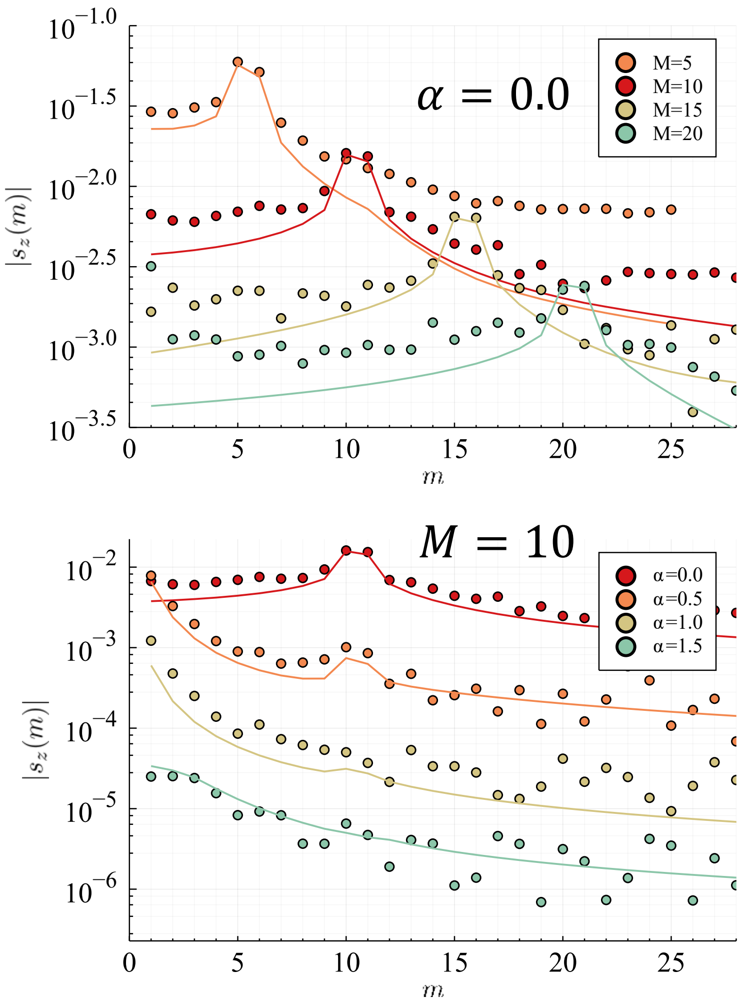
Transition from short range to long range

Time derivatives: $\frac{ds_z}{dt}(t=\tau) \sim \sum_m \frac{1}{|m|^\alpha}$



Long tails of the eigenstates:



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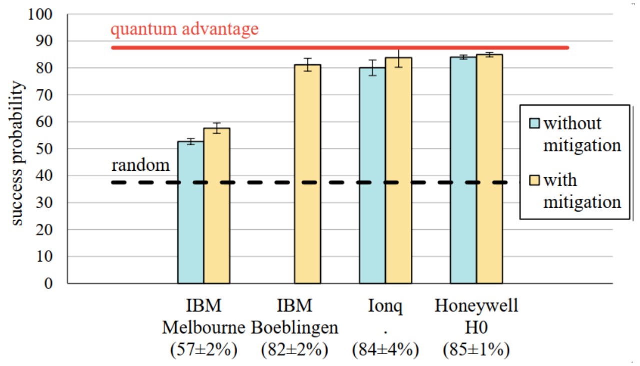

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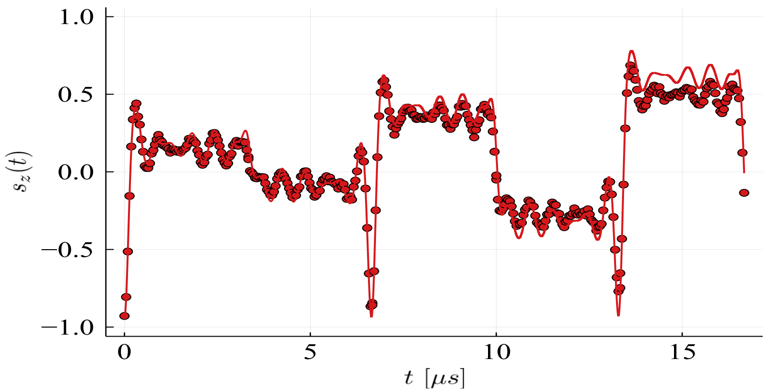

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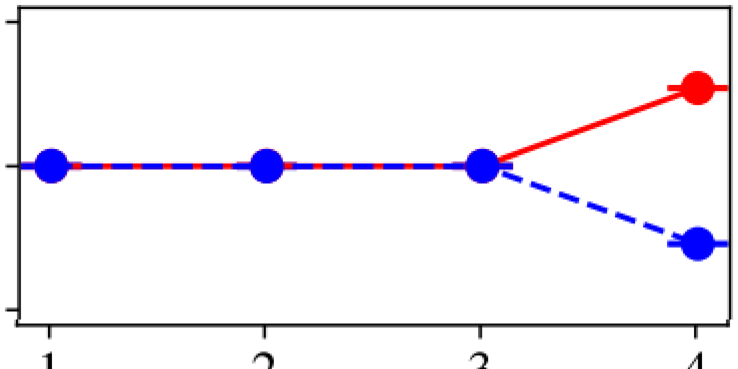

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Quantum phases of matter

Ordered

0 1 0 1 0 1 0 1

Disordered

0 1 1 0 0 1 0 1

Topological

0 1 1 0 0 1 0 1

Haldane (1982), AKLT (1987), den Nijs&Rommelse (1989), Dalla Torre,Berg&Altman (2006), ….

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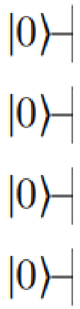
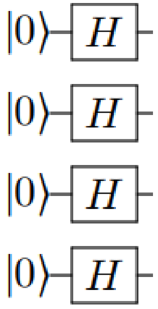
Quantum phases of matter

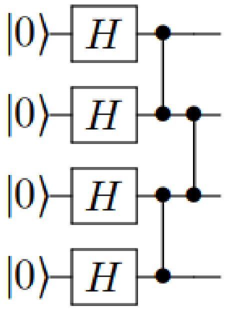
Ordered: Ising coupling



Disordered: Magnetic field



Topological: cluster model



Bat-el Friedman, Atanu)19) and ref. therein

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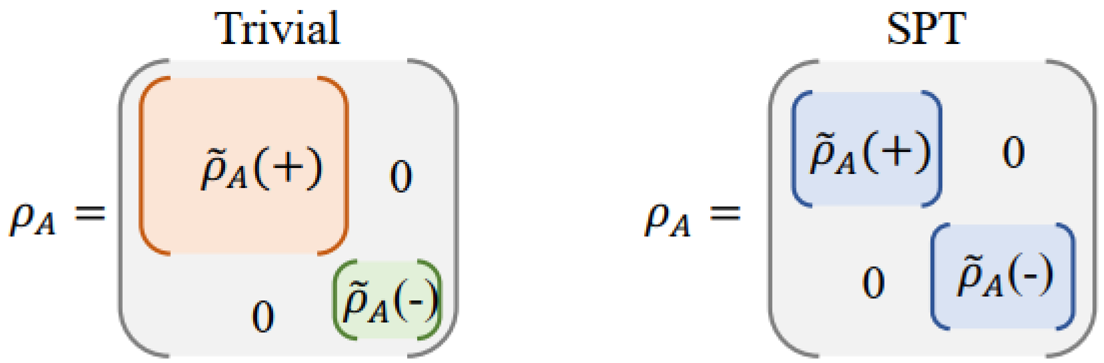
Symmetry resolved topological (SPT) phases

Pollmann-Turner-Berg-Oshikawa (2011), Chen-Gu-Liu-Wen (2012)

Symmetry $\rightarrow G\,|\psi\rangle = g|\psi\rangle \quad \rightarrow \quad [G, \rho_A] = 0$

Symmetry resolved

reduced density matrix:



Goldstein & Sela (PRL, 2018)

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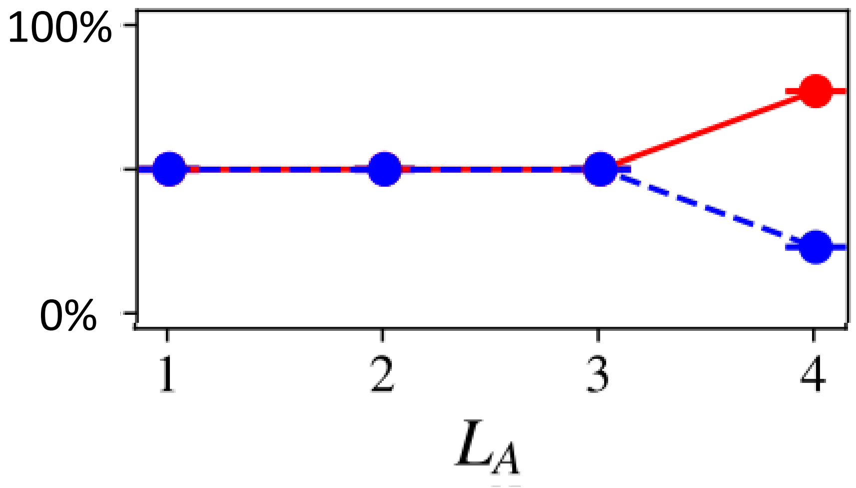
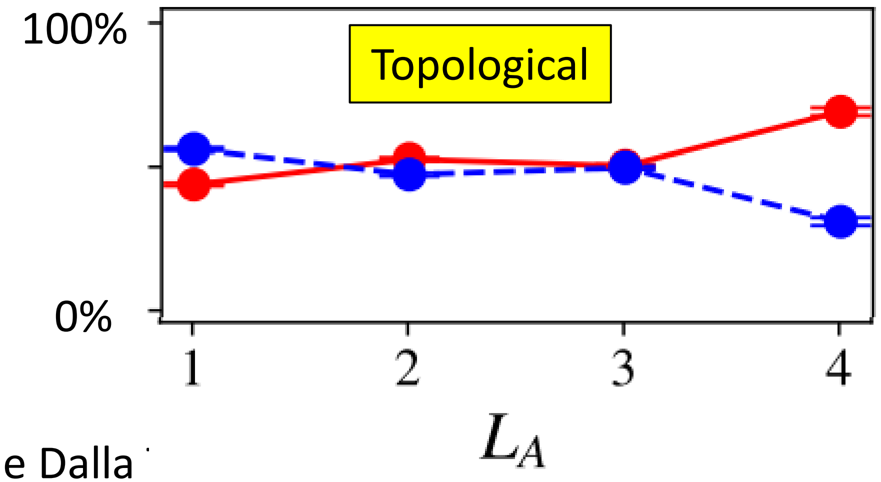
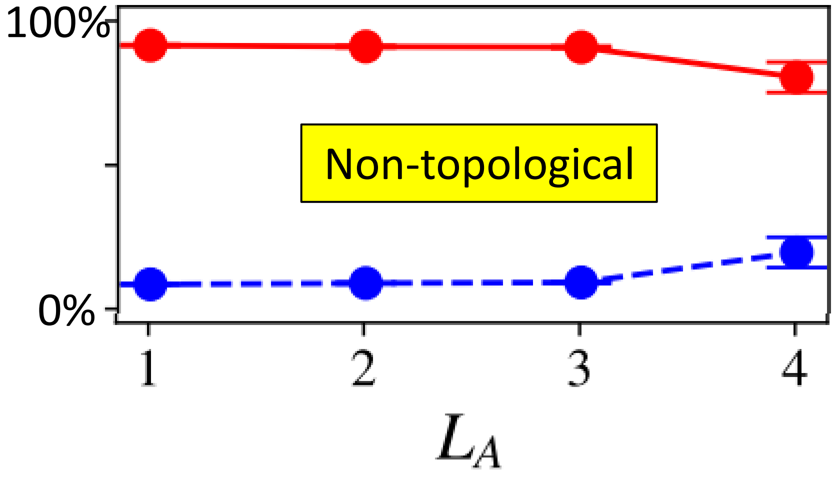
Identifying a topological phases

Simulation



Experiment





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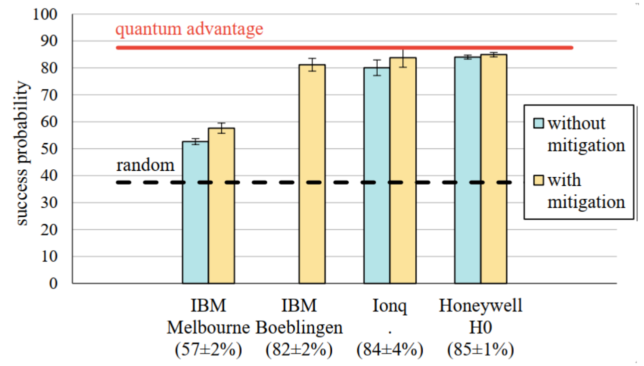

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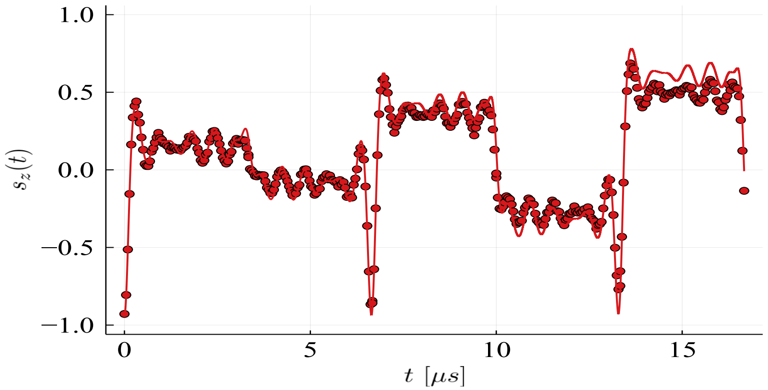

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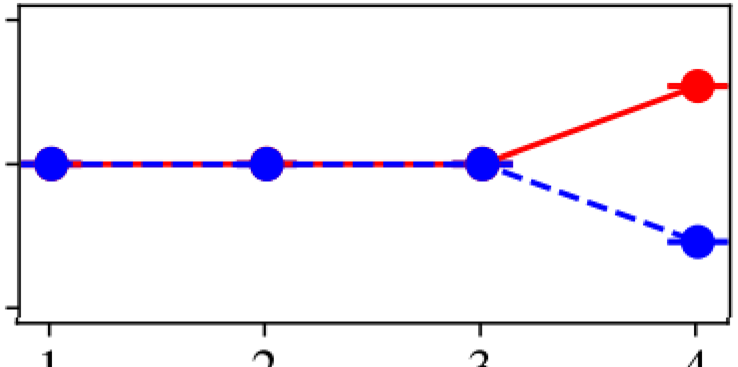

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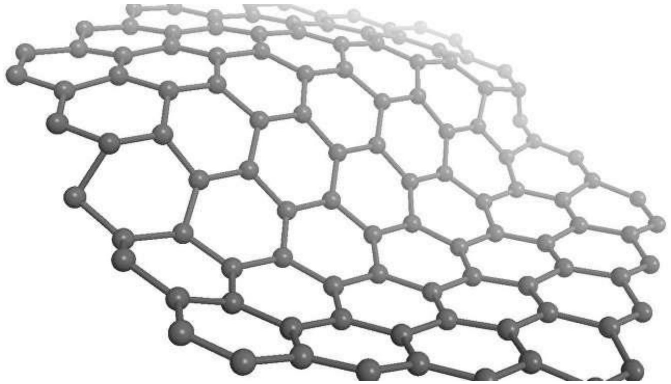
Summary: Quantum simulations

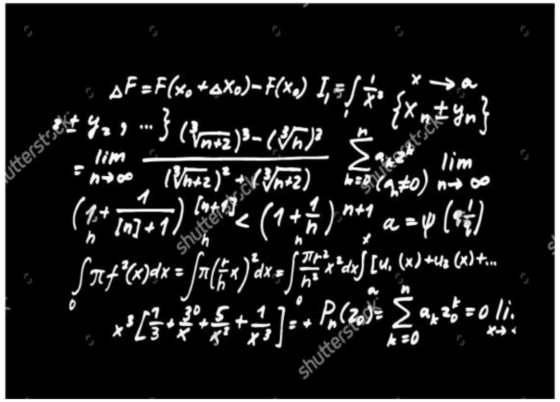
Quantum molecules/material

Size of Hilbert space = 2^{N_A}

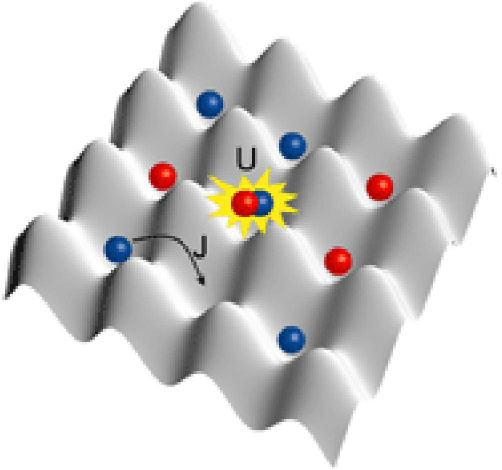


Classical supercomputers

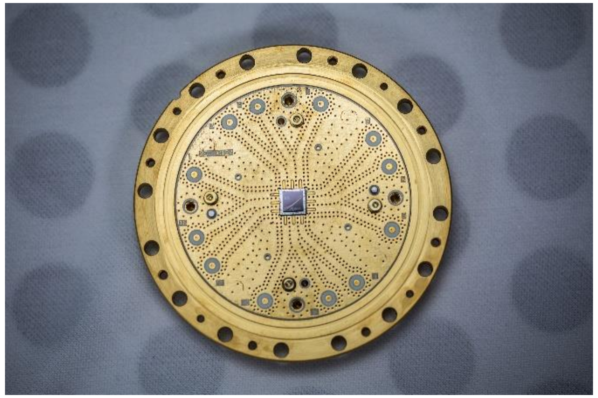
Quantum field theories



Ultracold atoms



Quantum computer on the cloud



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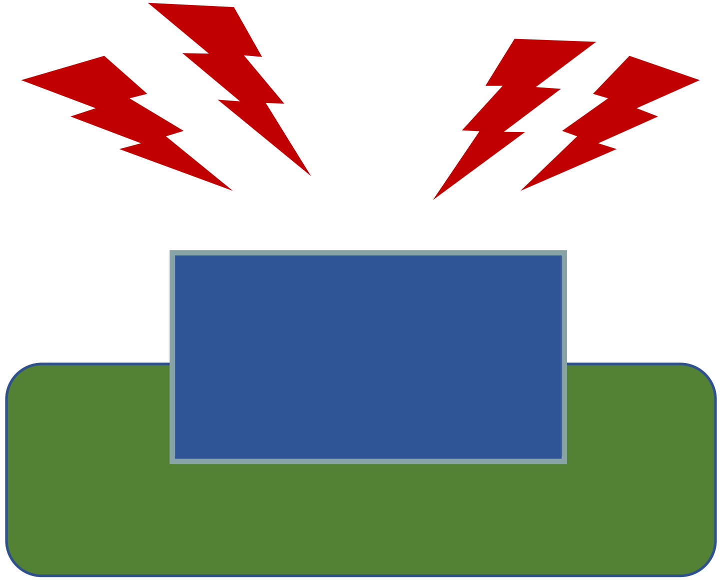
Quantum simulations with quantum computers on the cloud

Time dependent drive

Quantum system

Environment



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Noisy nonlocal games and error mitigation

arXiv:2105.05266

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Bar-Ilan University

EXTRA SLIDES

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Bar-Ilan University