Kvantni računari - teorija i eksperimenti

*ili

Ljubavna priča između teorije i eksperimenta

(Pragma (πρᾶγμα): dugotrajna i postojana ljubav koja se razvija dugo vremena)

Teorija

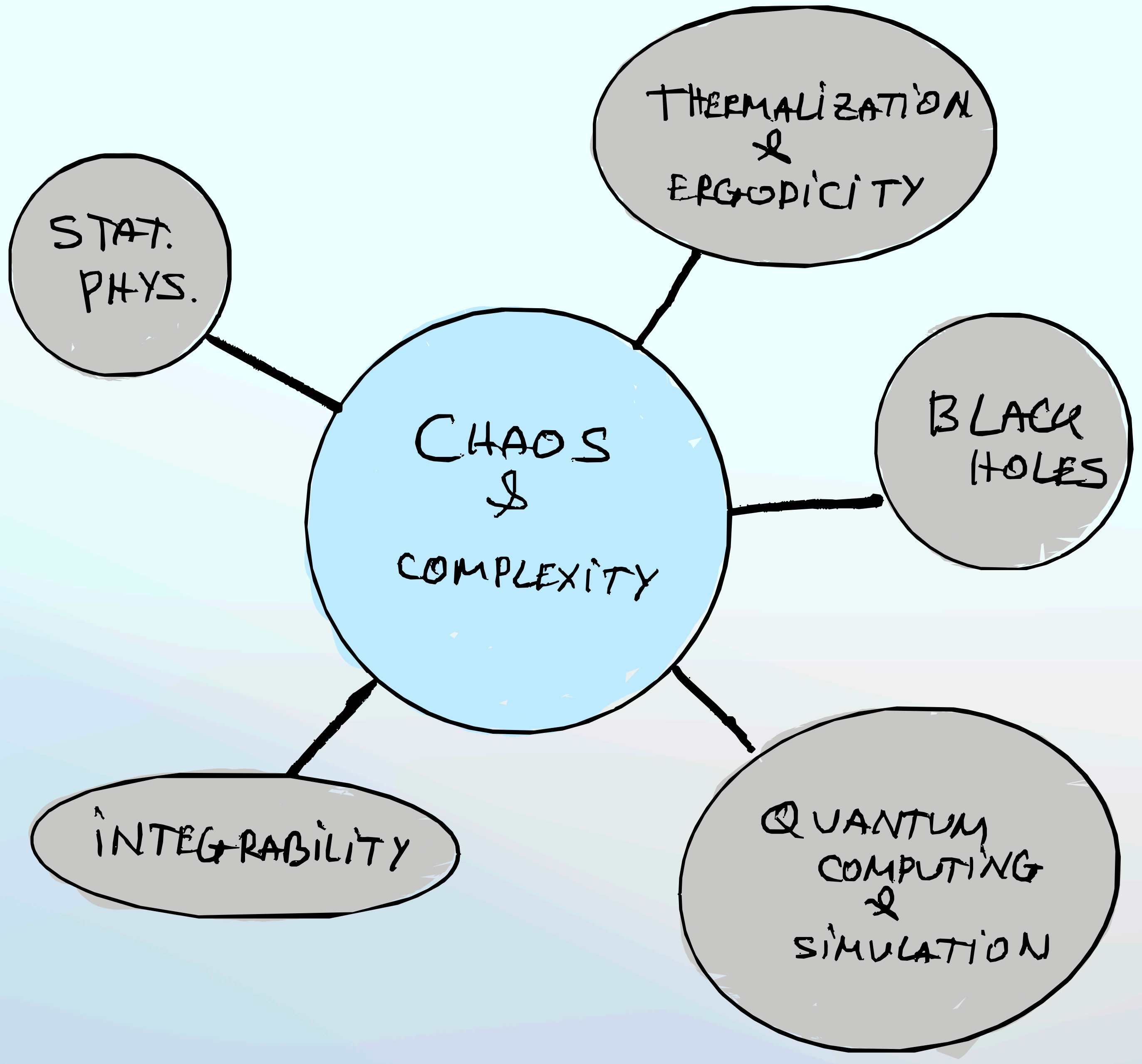
Eksperiment

Jovan Odavić 28/04/2026 - Novi Sad

arXiv: 2511.15576

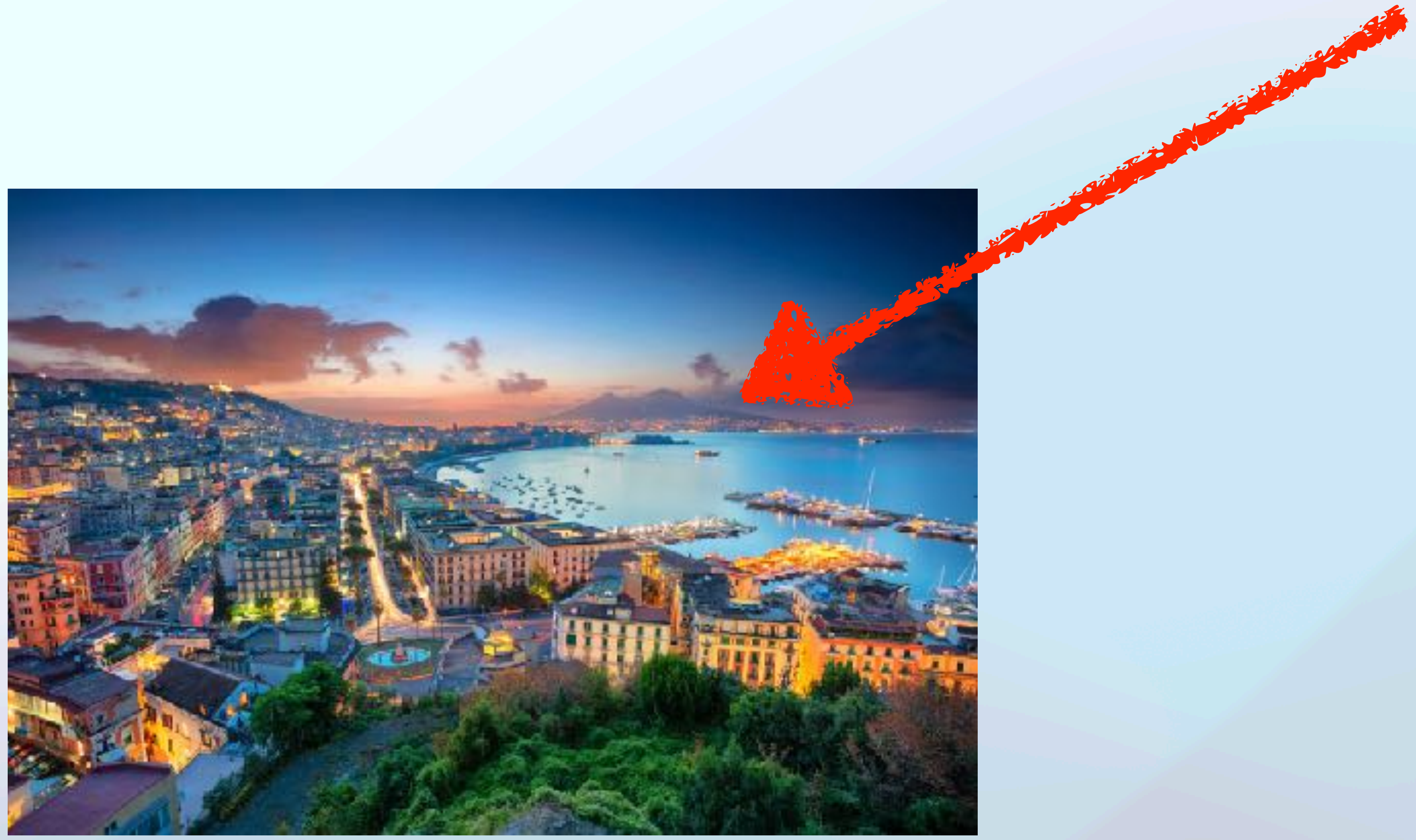
Nešto ukratko o meni

- Statistička fizika i fizika višečestičnih korelisanih sistema
- Teorija haosa i nelinearna dinamika
- Kvantna informatika



iz Novog Sada...

Vezuv



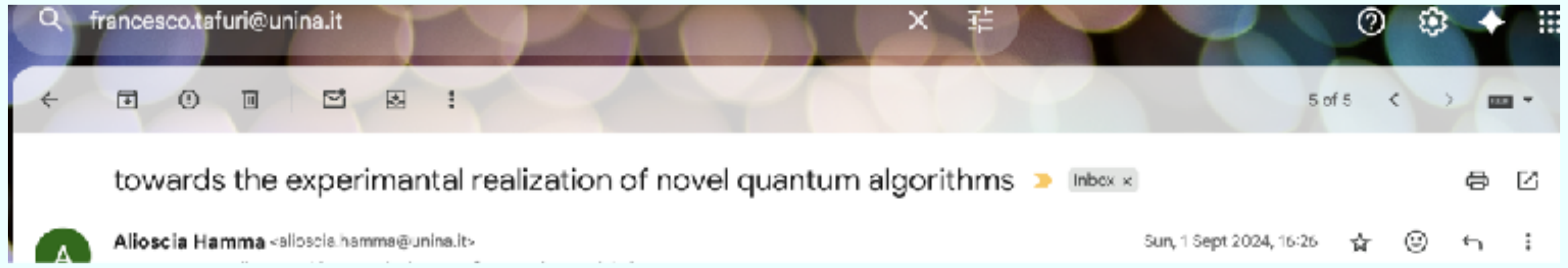
...u Napulj

Kvantni računar u Napulju

- Prvi kvantni računar u Italiji
- Imali smo privilegiju da radimo prve eksperimente + benchmarking
- Razvijaju se na univerzitetima i u velikim kompanijama (Google, Microsoft, Amazon, IBM)

prof. Tafuri na inauguraciji računara

Kolaboracija započeta pre više od godinu dana



Teorijska grupa prof. Hamma

Eksperimentalna grupa prof. Tafuri

Prošlogodišnja Nobelova nagrada

… za otkriće makroskopskog kvantno mehaničkog efekta tunelovanja i kvantizaciju u električnim kolima

Nobel Prize in Physics 2025

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

Michel H. Devoret

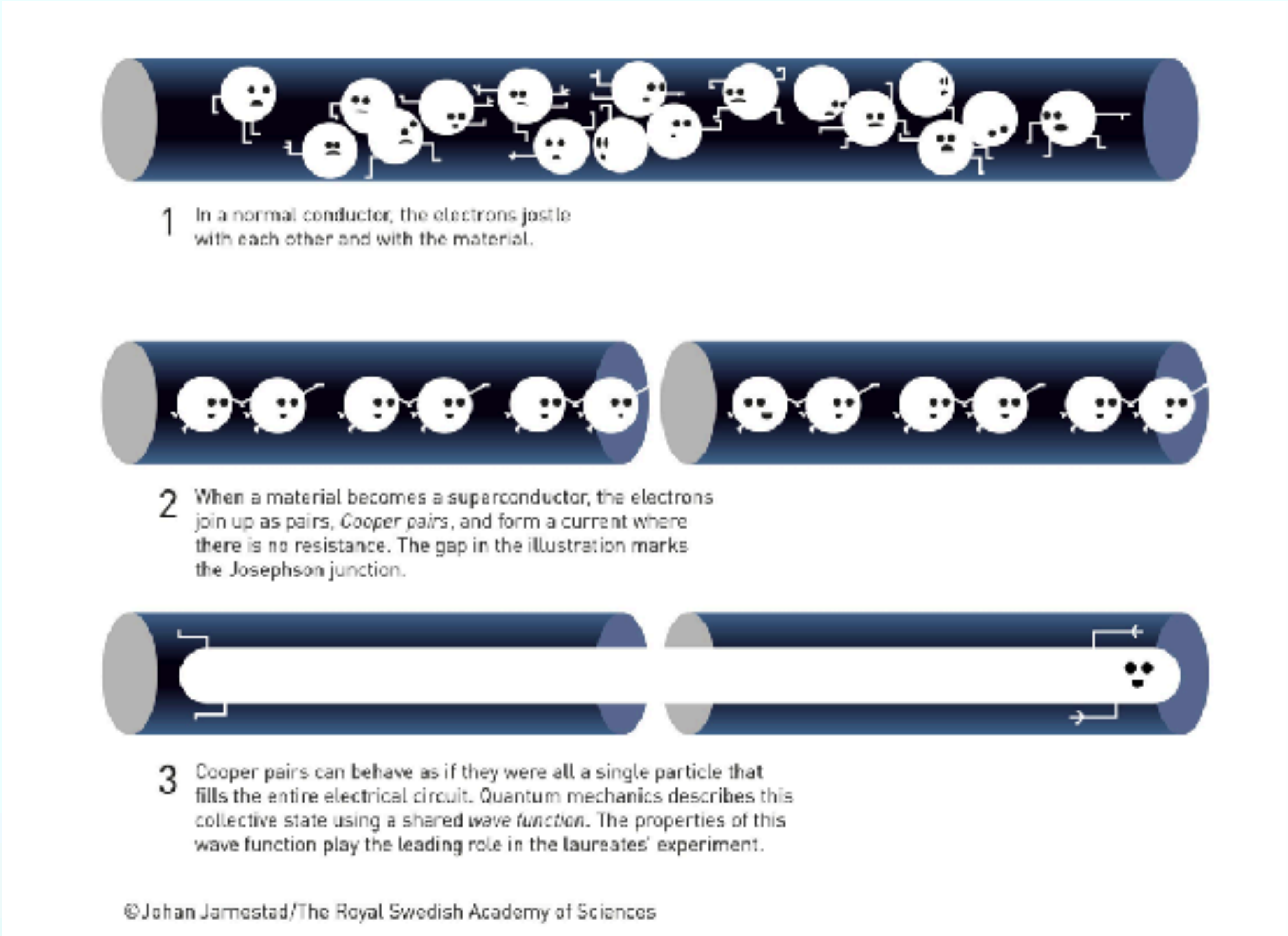
Prize share: 1/3

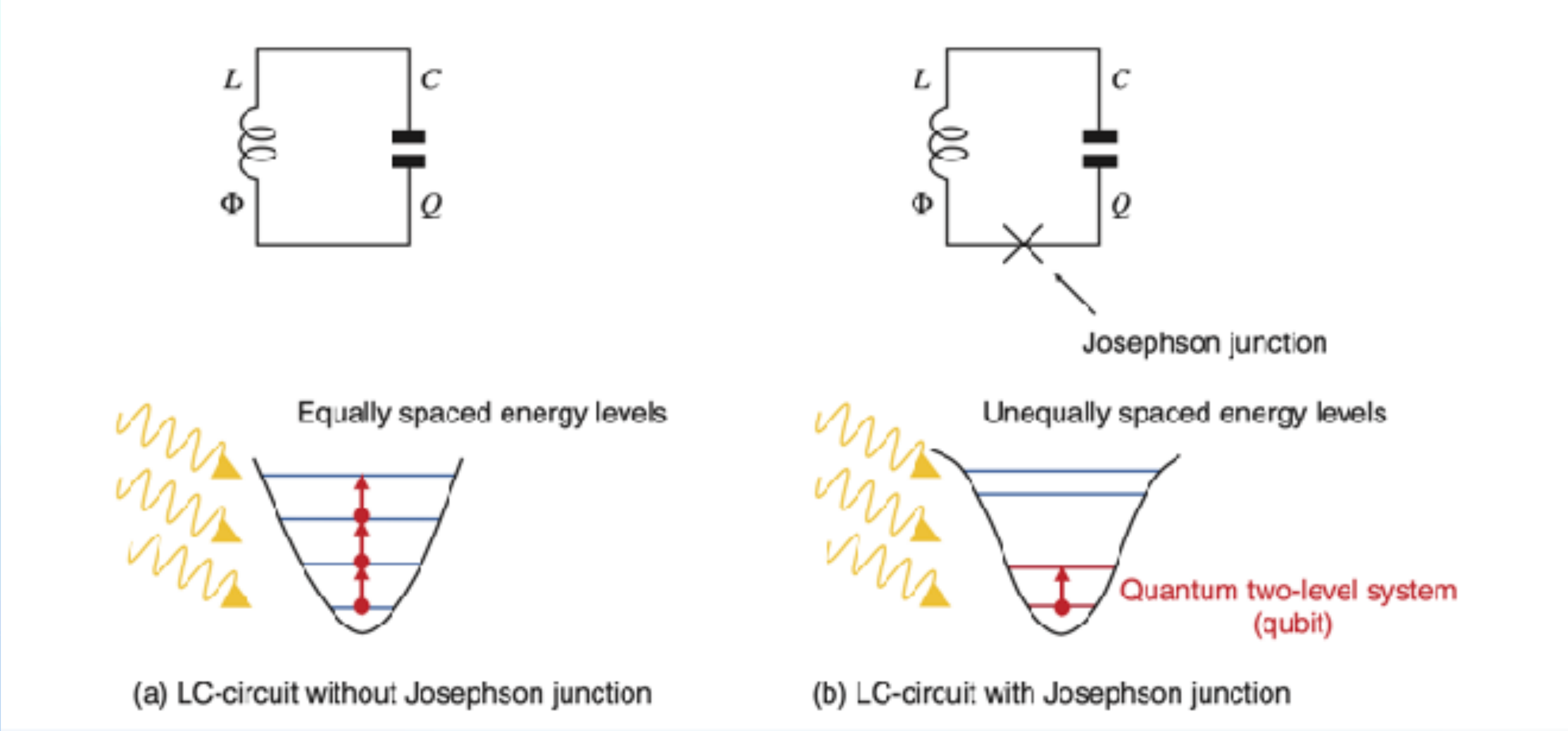
Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

Prize share: 1/3

Ključni detalji superprovodnih qubit-a





https://doi.org/10.53829/ntr200801sp6

Kvantni efekti -> potrebna niska temperatura!

Normalni metal—> kontinualni spektar kvazičestica

Superprovodnik—> otvori 'procep' (gap) u spektru i mogućnost diskretnih nivoa

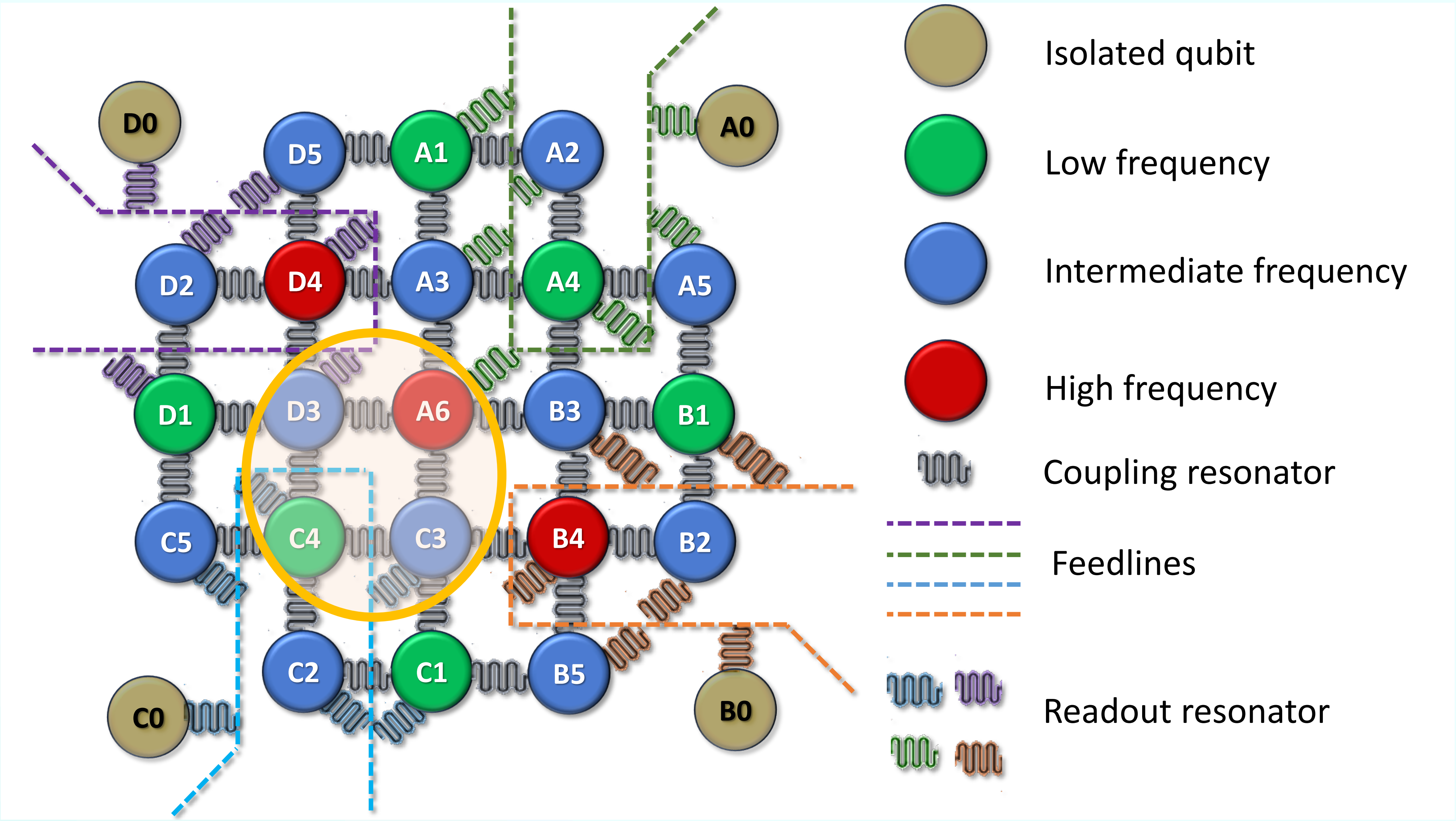
Poznati luster (CHANDELIER)

Napuljska laboratorija

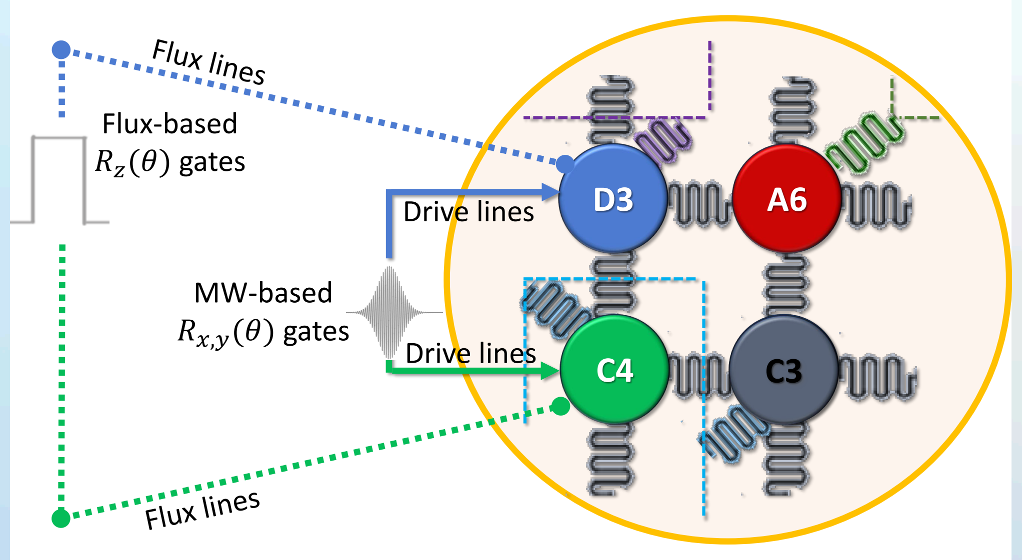
If one could use the quantum levels in this superconducting gap, these states would be expected to be similar to the electronic state of a free atom, i.e., it is characterized by the long-lived discrete energy spectrum.

Kvantni procesor - Noisy Intermediate Scale Quantum (NISQ) čip

John Preskill, Quantum **2**, 79 (2018)



Superprovodni kvantni procesor. Shema procesora.



Qubiti (D3-C4) sa kojima smo radili

60+ qubit procesor uskoro dostupan, ali takođe rade na novom tipu qubit-a

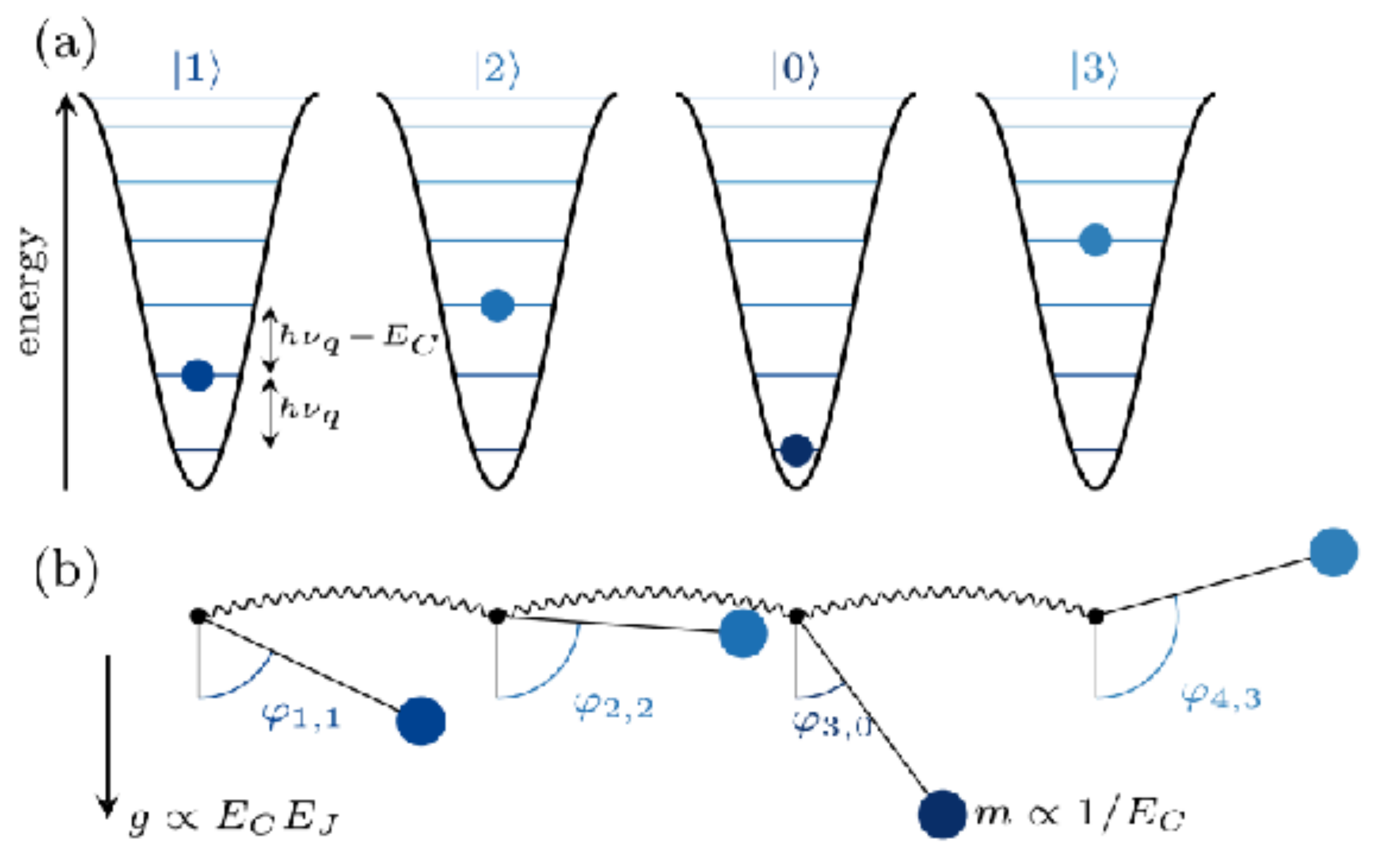
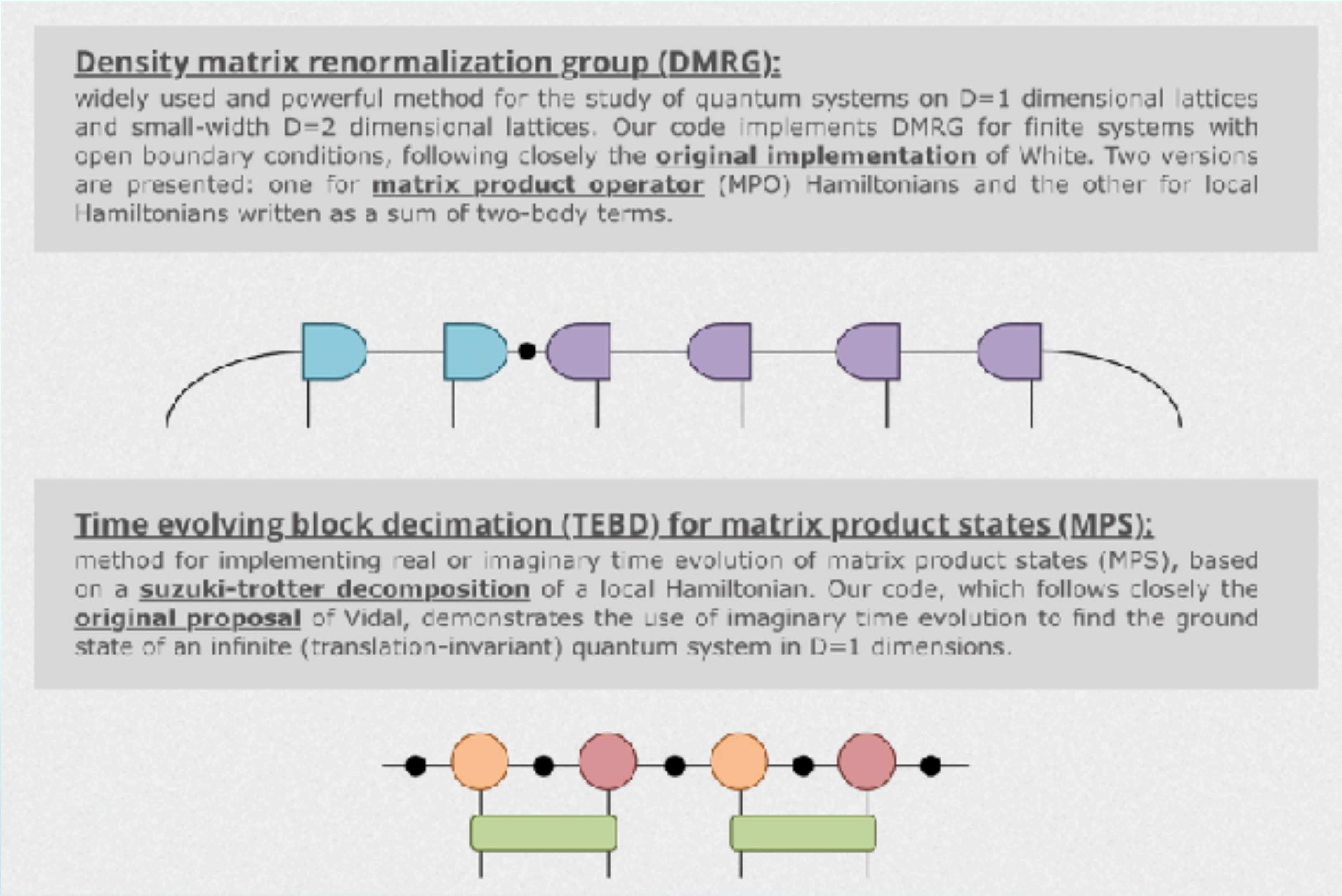


FIG. 1. Quantum vs classical transmon array. (a) A chain of four transmons initialized in the quantum state $|1203\rangle$ of the corresponding cos potentials, where the integers, $i = 1, 2, 0, 3$ correspond to the bound state energies E_i. (b) The corresponding classical rotors, initialized at angular deflections corresponding to the energies E_i as discussed in the main text, and the springs connecting the suspension points representing the angular momentum coupling.

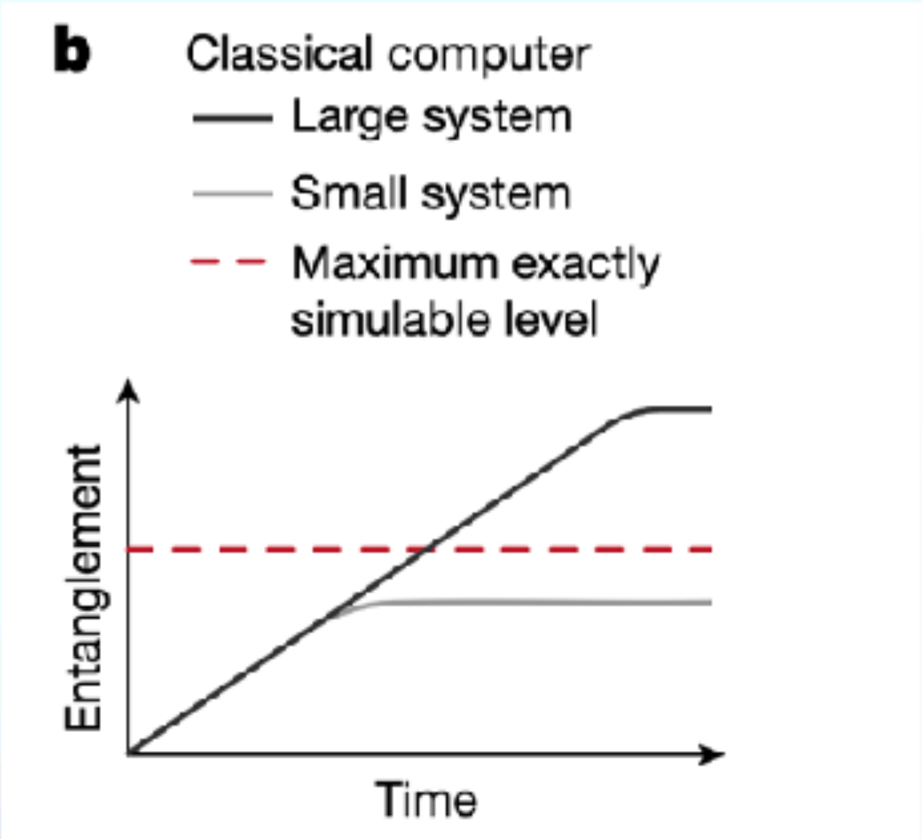
Klasični limit kvantnih računara

Zašto kvantni računari? —> simulacije mnogočestičnih kvantnih sistemi

- Simulacije veoma izazovne klasično —> Mali broj konstituenata ili aproksimacije za termodinamički relevantne i velike sisteme
- Uvid iz polja kondenzovane materije: efikasne simulacije koristeći tenzorke metode —> Matrix Product States and Density Matrix Renormalization Group: David Pérez-García , Norbert Schuch, and Frank Verstraete, Rev. Mod. Phys. **93**, 045003 (2021)



tensors.net



Shaw, A.L., Chen, Z., Choi, J. *et al.* Benchmarking highly entangled states on a 60-atom analogue quantum simulator. *Nature* **628**, 71–77 (2024). https://doi.org/10.1038/s41586-024-07173-x

Zapravo, kvantni računari bi trebalo da pomognu baš pri efikasnoj simulaciji kvantnih sistema!

Kvantno-informatički uvid

- Specifični tip <u>kvantnih kola</u>

- Isključivo kvantna kola sa **Clifford** elementima gde su završna stanja veoma **kvantno spregnuta (zapletenost ili 'entanglement')** stabilizujuća kola

Hadamard $H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$

Fazni element $S = \begin{bmatrix}1 & 0\\ 0 & e^{-i\pi/2}\end{bmatrix}$

kontrolisano+NOT $\text{CNOT} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$

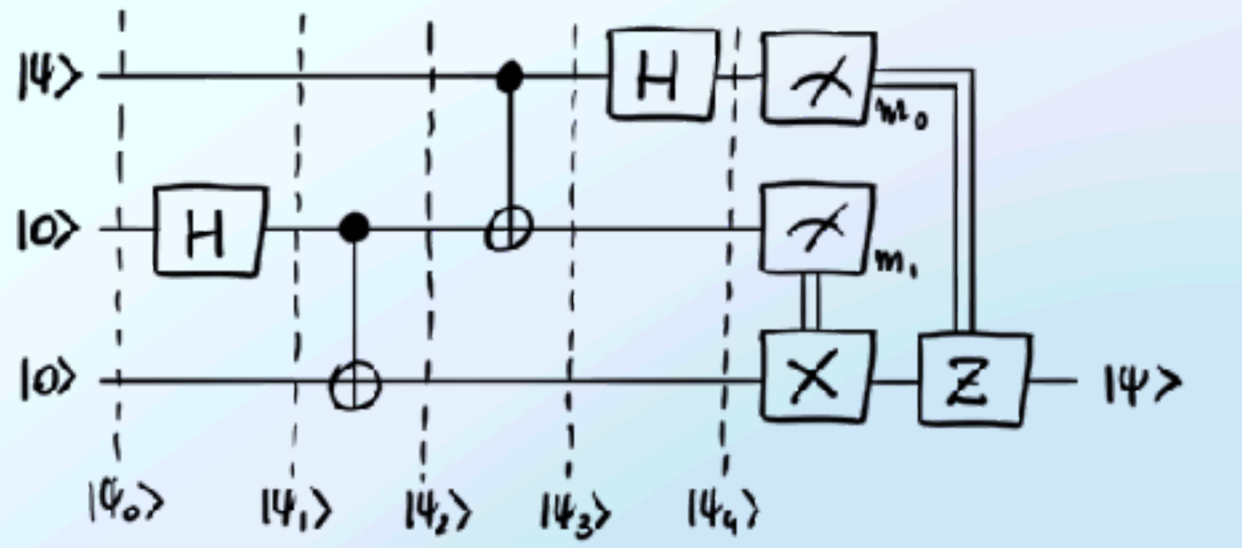
- Ne može svako kvantno kolo da se predstavi Clifford elementima!

Diskretna kvantna mehanika

Svaka validna formulacija/representacija kvantne mehanike sačinjena je od 3 osnovna elementa

1. Priprema stanja
2. Unitarna evolucija —> Kvante kapije (quantum gates)
3. Merenje

Protokol za kvantnu teleportaciju kvantnog stanja

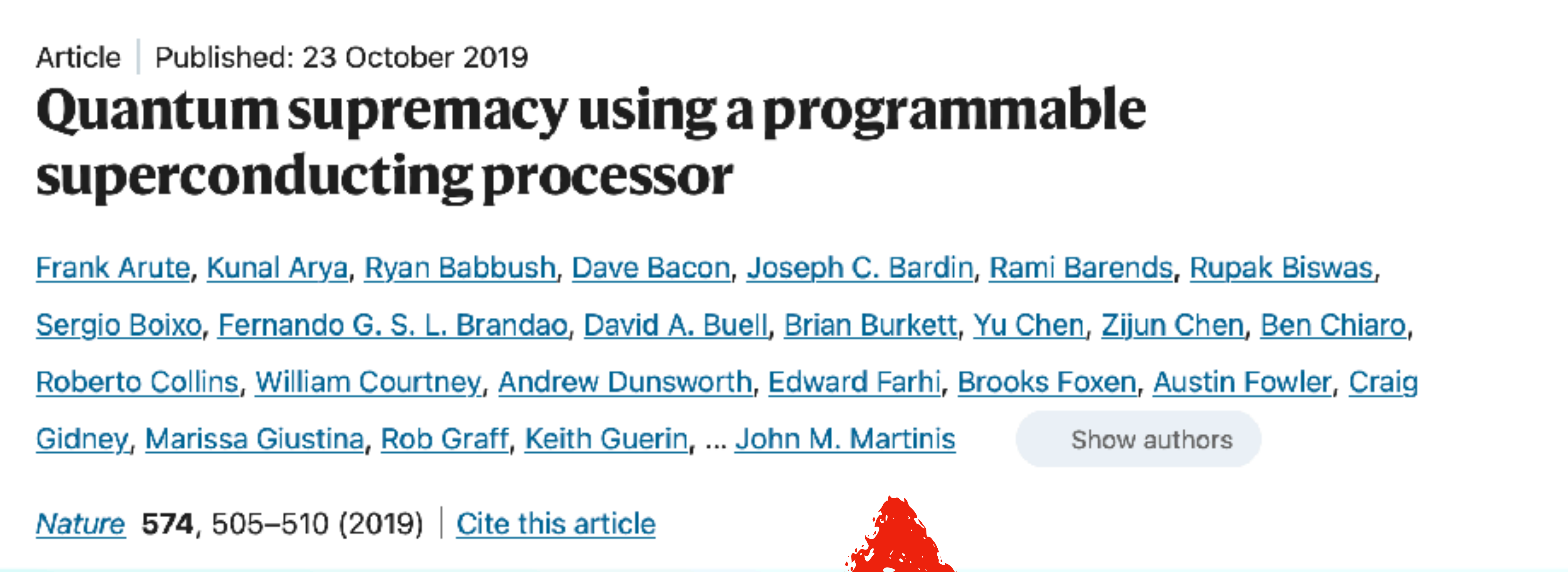


Muzičke note/ sa leva na desno. Početak, note i kraj.

*aproksimacija kontinuirane dinamike —->Troterizacija

Opovrgavanje Guglove tvrdnje o kvantnoj nadmoć iz 2019

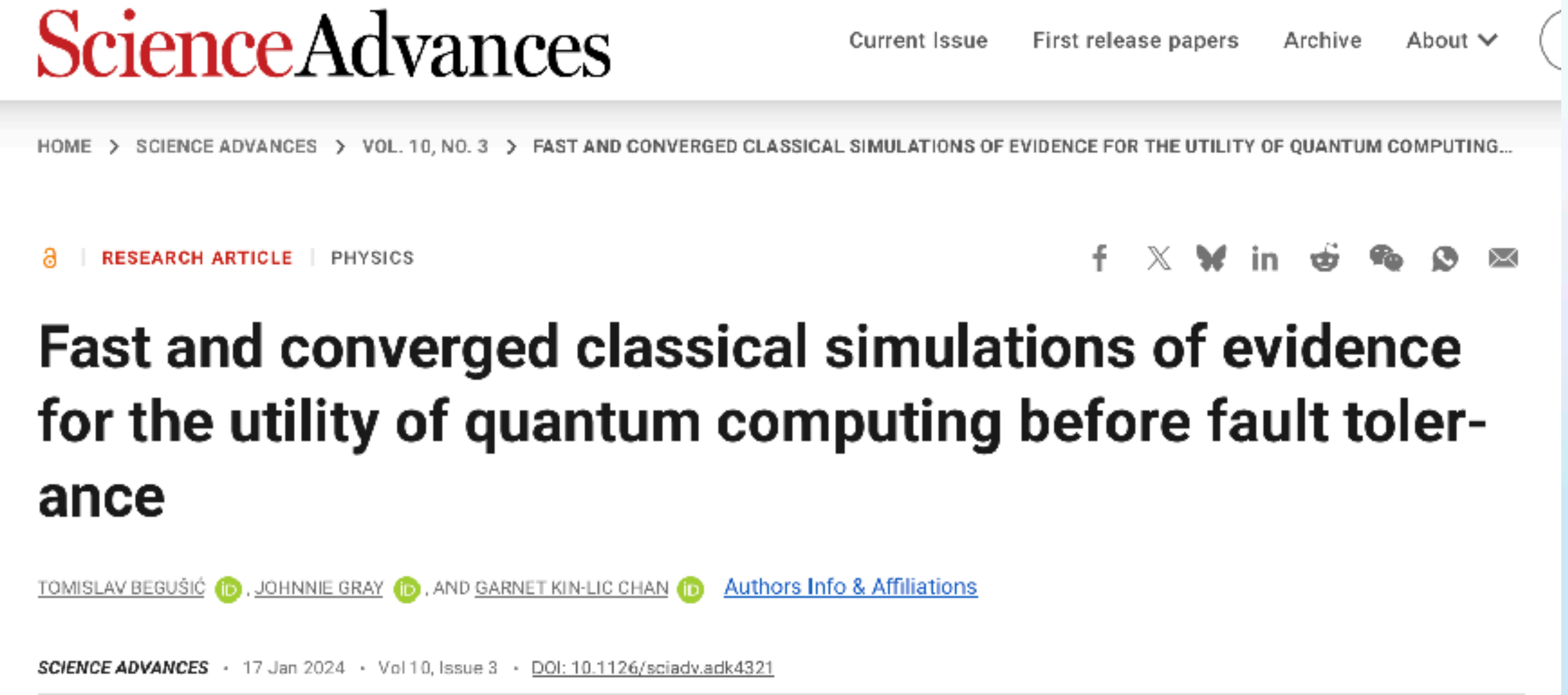
Jedan od pristupa je koristio blago perturbovana Clifford kola


Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, ... John M. Martinis Show authors

Nature **574**, 505–510 (2019) | Cite this article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RESEARCH ARTICLE | PHYSICS

Fast and converged classical simulations of evidence for the utility of quantum computing before fault tolerance

TOMISLAV BEGUŠIĆ, JOHNNIE GRAY, AND GARNET KIN-LIC CHAN Authors Info & Affiliations

SCIENCE ADVANCES • 17 Jan 2024 • Vol 10, Issue 3 • DOI: 10.1126/sciadv.adk4321

Dobitnik Nobelove nagrade

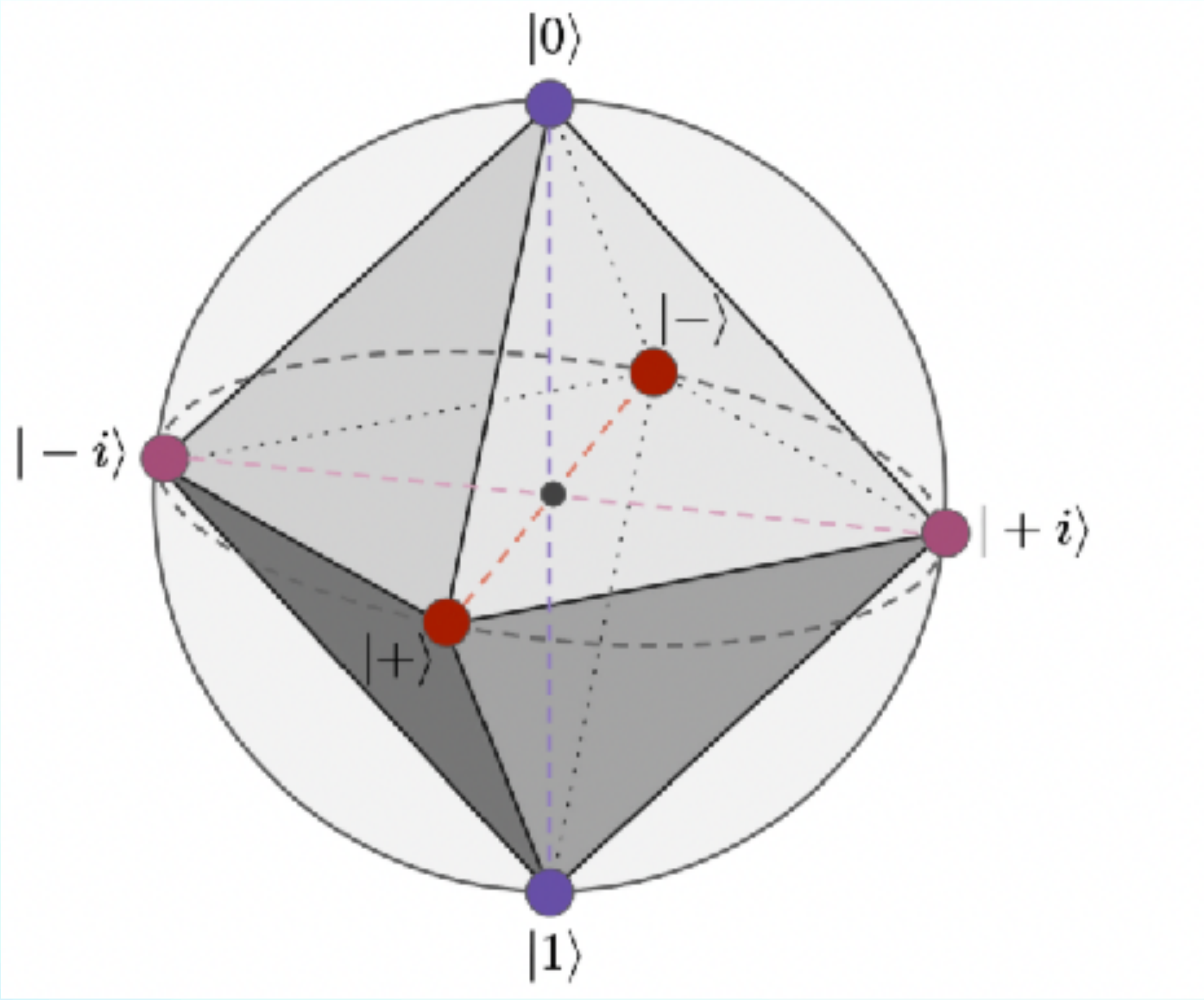
N.B. Preskočiću celokupno polje **'kvatne korekcije grešaka' (quantum error correction)** gde Clifford operacije igraju veoma bitnu ulogu —> sledeća Nobelova nagrada!

Stabilizatori stanja

na primeru jednog qubit-a

ograničen Hilbertov prostor —> 6 čistih kvantnih stanja

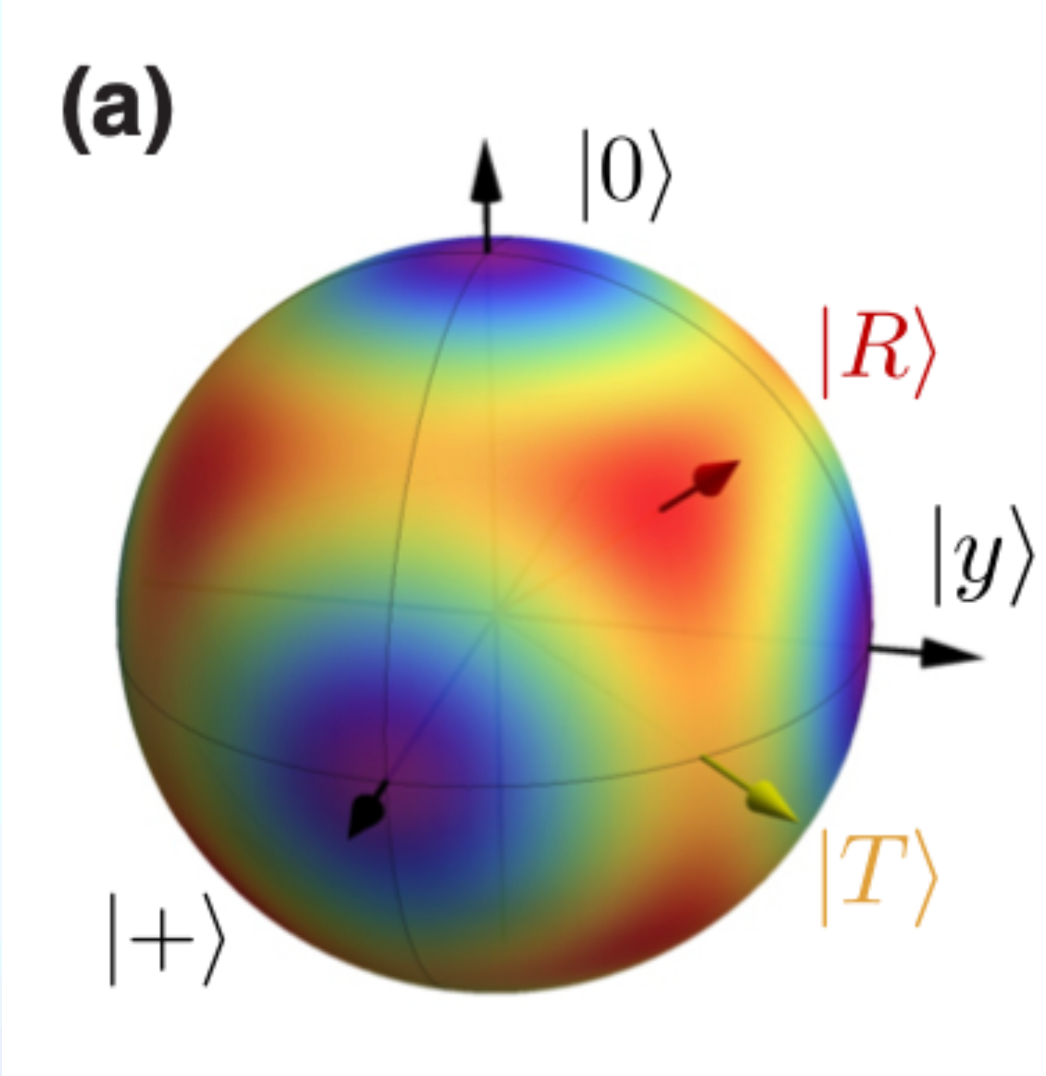
Ne-Clifford kvantne kapije omogućavaju istraživanje celokupnog Hilbertovog prostora



Oktaedar na Blohovoj sferi—-> Koristeći samo 1-qubit kvantne kapije (https://pennylane.ai/qml/demos/tutorial_clifford_circuit_simulations).

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$$

$$S = \begin{bmatrix}1 & 0\\ 0 & e^{-i\pi/2}\end{bmatrix}$$



PRX QUANTUM **4,** 010301 (2023)

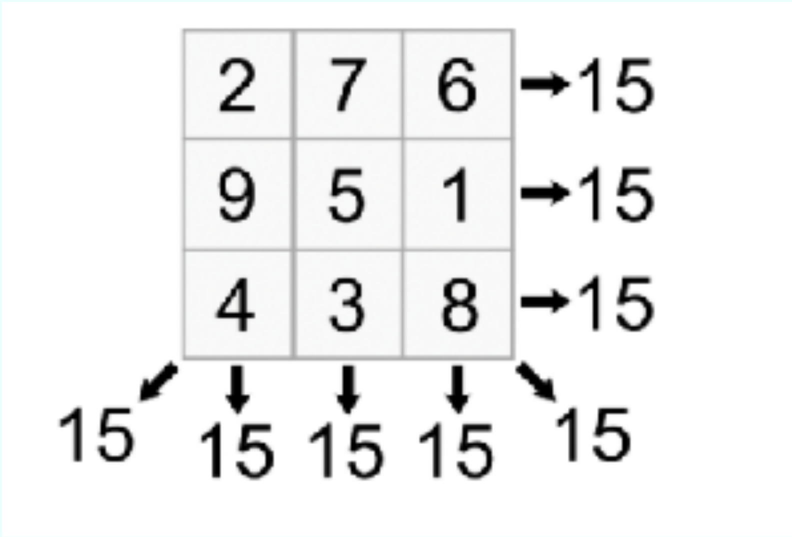
Sve van ovih 6 stanja **—>ne-stabilizatornost ili "magija"**

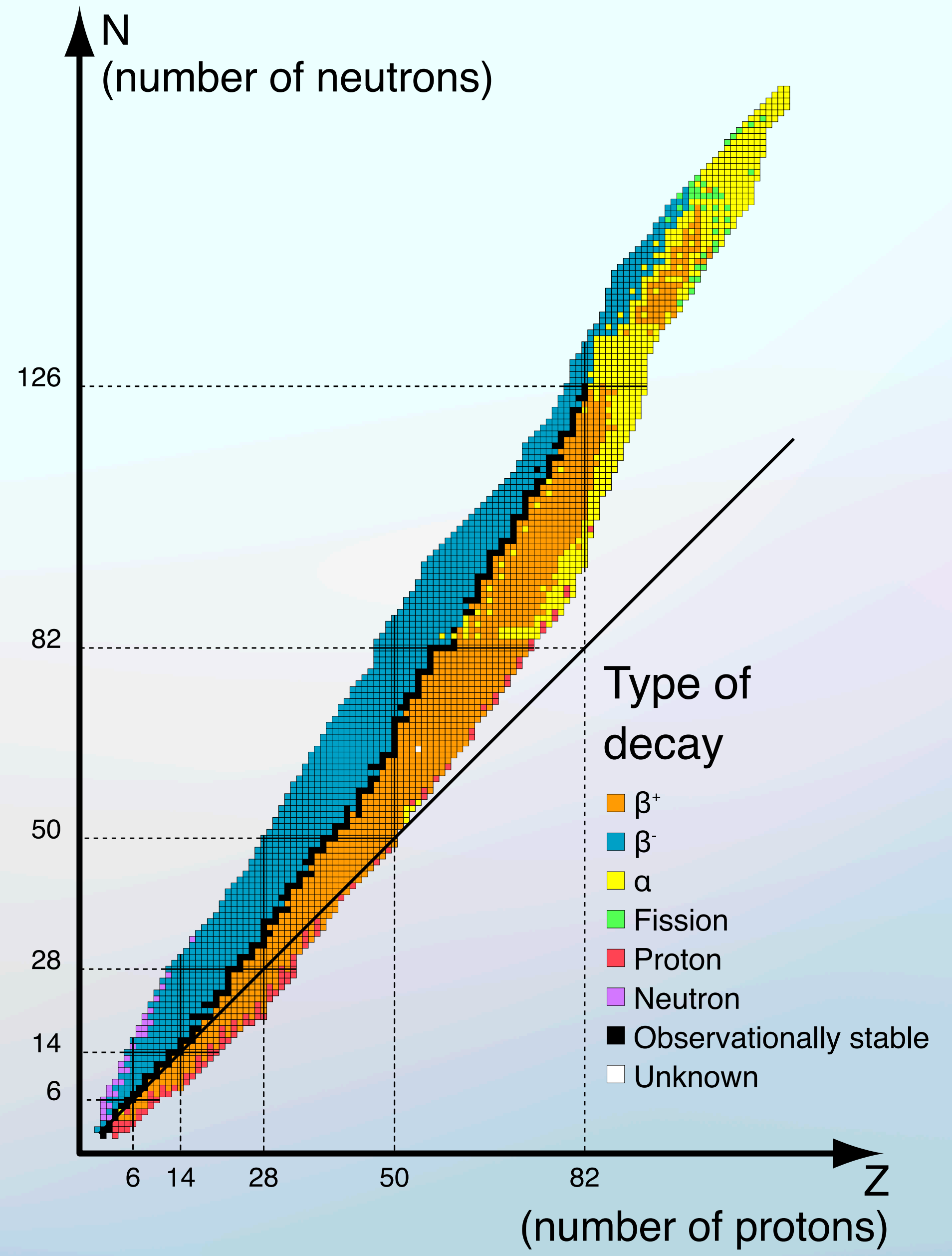
Magija u matematici i fizici?

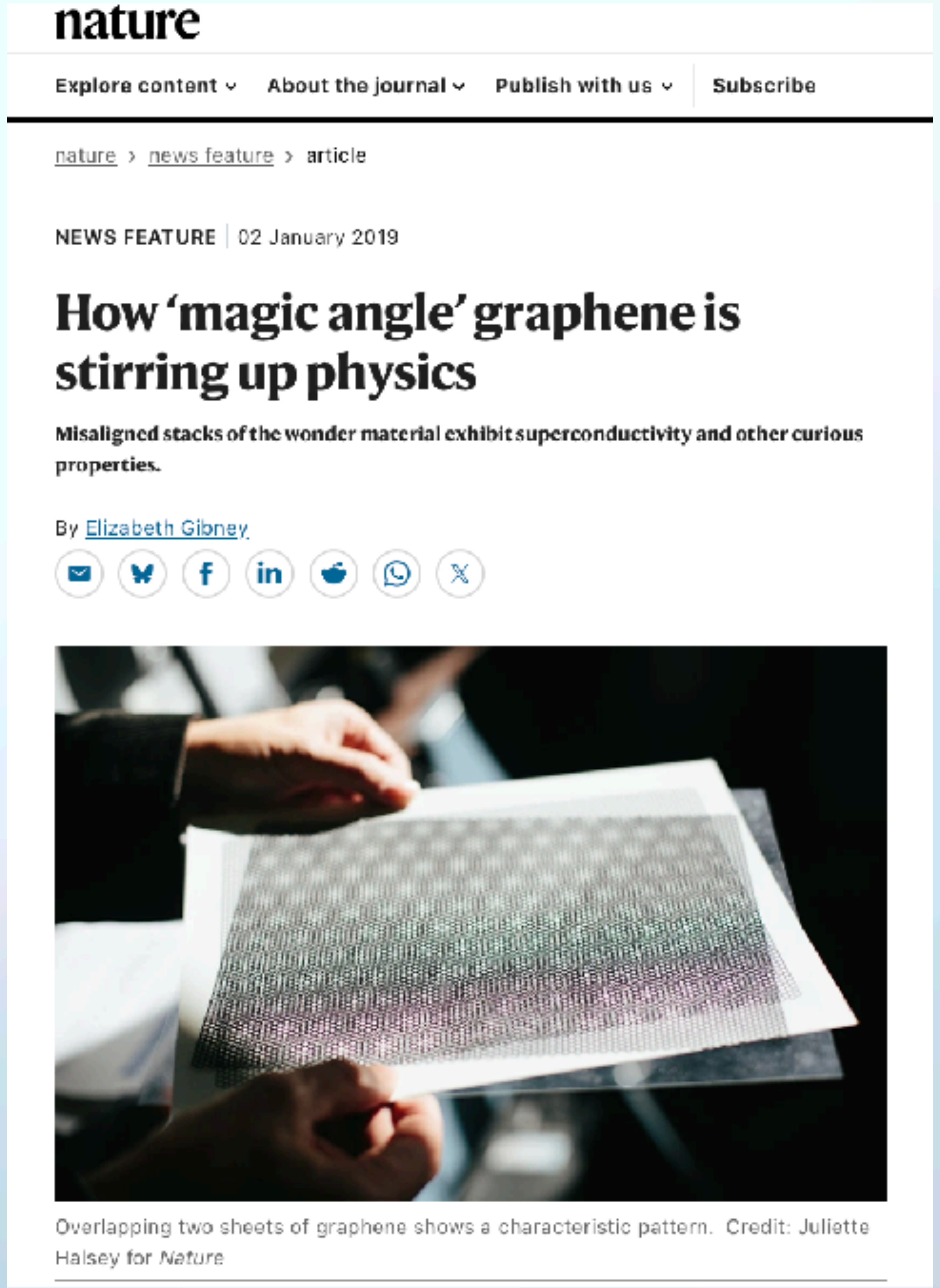
- Magični kvadrati, magični brojevi

- Magični broj nukleona u jezgru koji ga čini stabilnim (2, 8, 20,28, 50, 82, 126)

- Magični ugao u grafenu



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NEWS FEATURE | 02 January 2019

How 'magic angle' graphene is stirring up physics

Misaligned stacks of the wonder material exhibit superconductivity and other curious properties.

By Elizabeth Gibney

Overlapping two sheets of graphene shows a characteristic pattern. Credit: Juliette Halsey for *Nature*

Paradigma Clifford+T kvantnih kola

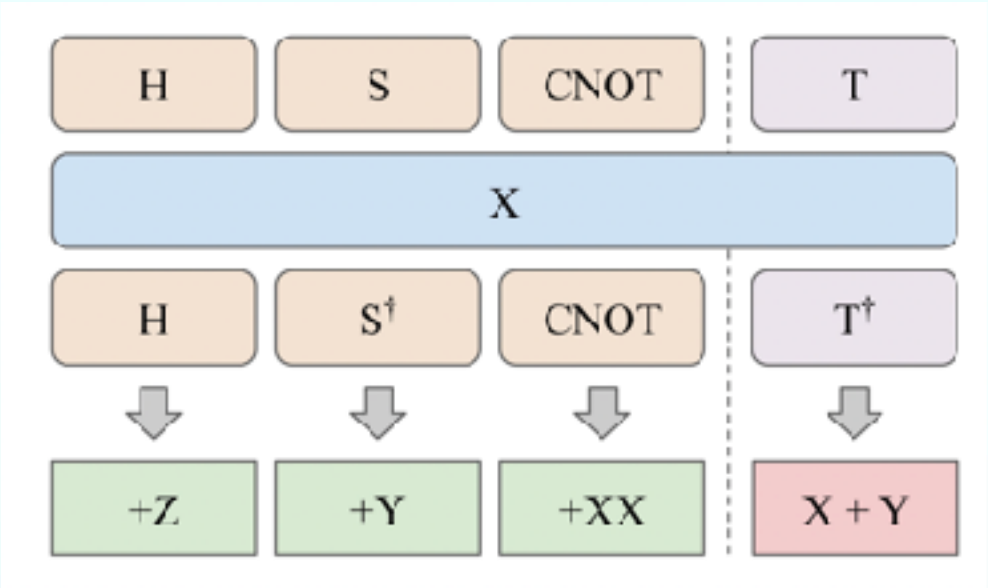
- Clifford metod za simulaciju kvantnih kola ne funkcioniše ukoliko se dodaju **T elementi** (1-qubit)

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$

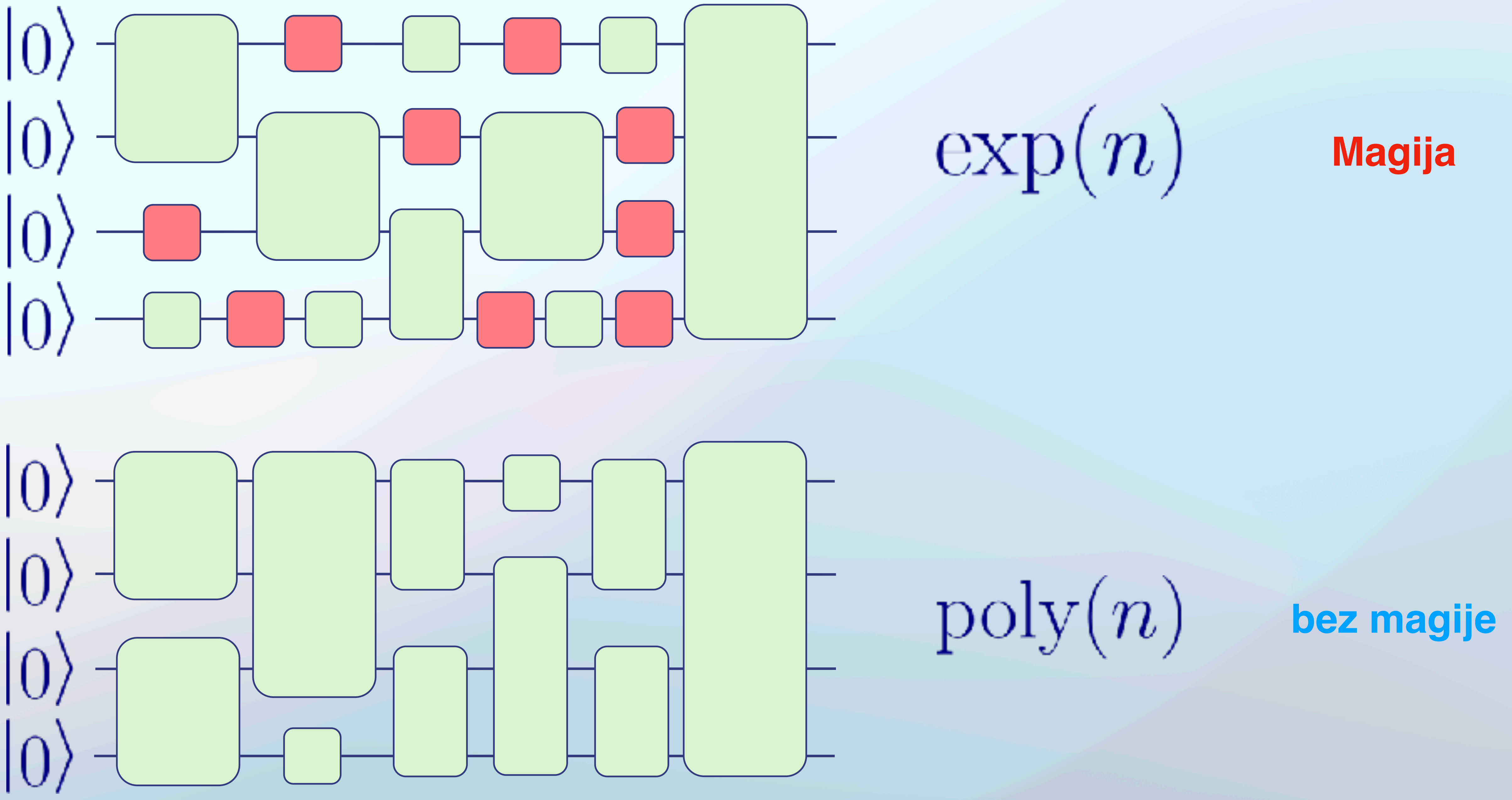
- Eksponencijalno teža simulacija ukoliko je magija prisutna —> Aaronson, S. and Gottesman, D. 'Improved Simulation of Stabilizer Circuits', Physical Review A, **70**(5) (2004)

cena simulacije kvantnih kola

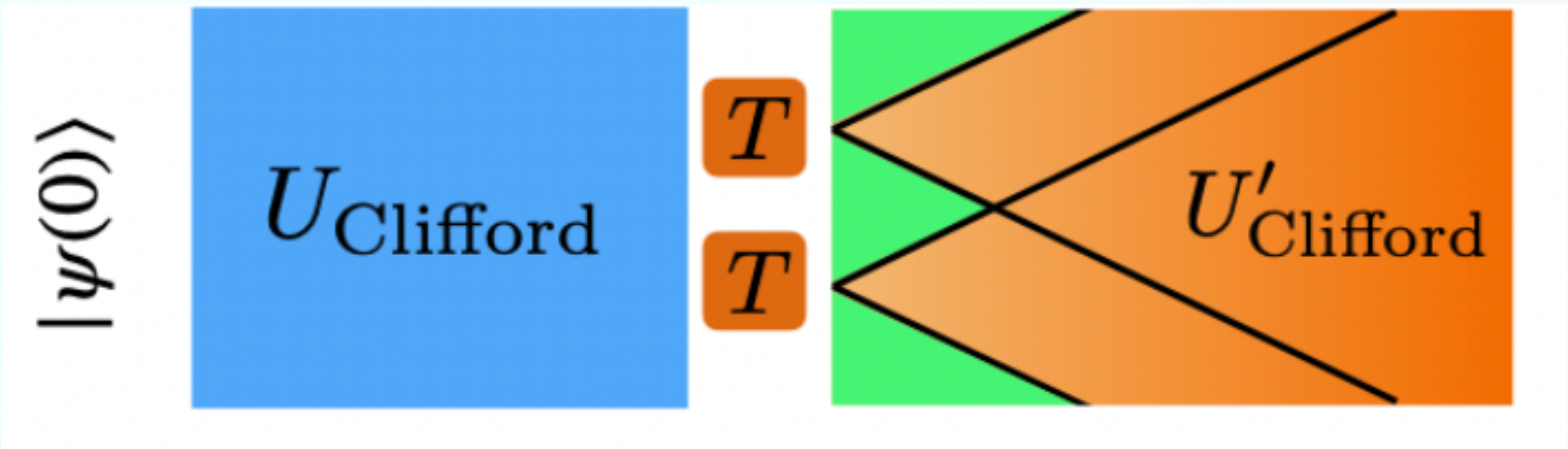
Dinamika operatora



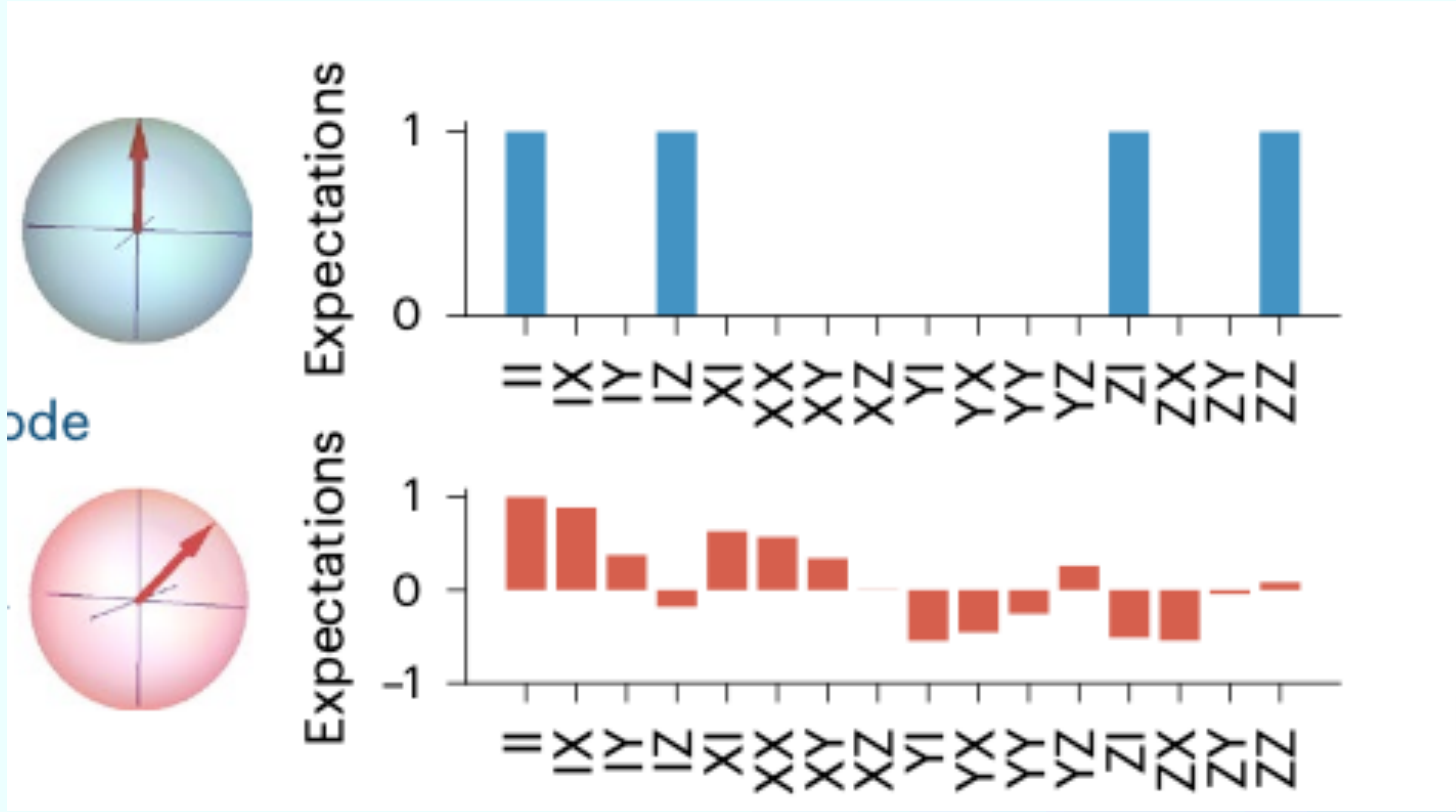
(https://pennylane.ai/qml/demos/tutorial_clifford_circuit_simulations).



Efekti T elemenata



SciPost Phys. 9, 087 (2020)



Niroula, P., White, C.D., Wang, Q. *et al.* Phase transition in magic with random quantum circuits. *Nat. Phys.* 20, 1786–1792 (2024)

Entropija stabilizacije kao observable kola kvantifikuje 'udaljenost' od stabilizatora (nula za ta stanja)

L. Leone, S.F.E. Oliviero, A. Hamma PRL **128**, 050402(2022)

$$M_\alpha(\psi) = \frac{1}{1-\alpha}\log_2 \mathcal{P}_\alpha(\psi), \qquad \mathcal{P}_\alpha(\psi) = \frac{1}{d}\sum_{P\in\mathcal{P}_N} |\mathrm{Tr}(P\psi)|^{2\alpha}, \qquad \psi = |\psi\rangle\langle\psi| \qquad d = 2^N$$

Entropija stabilizacije u eksperimentu

.... uzorkovanje (sampling) - Nasumična Merenja (Randomized Measurements)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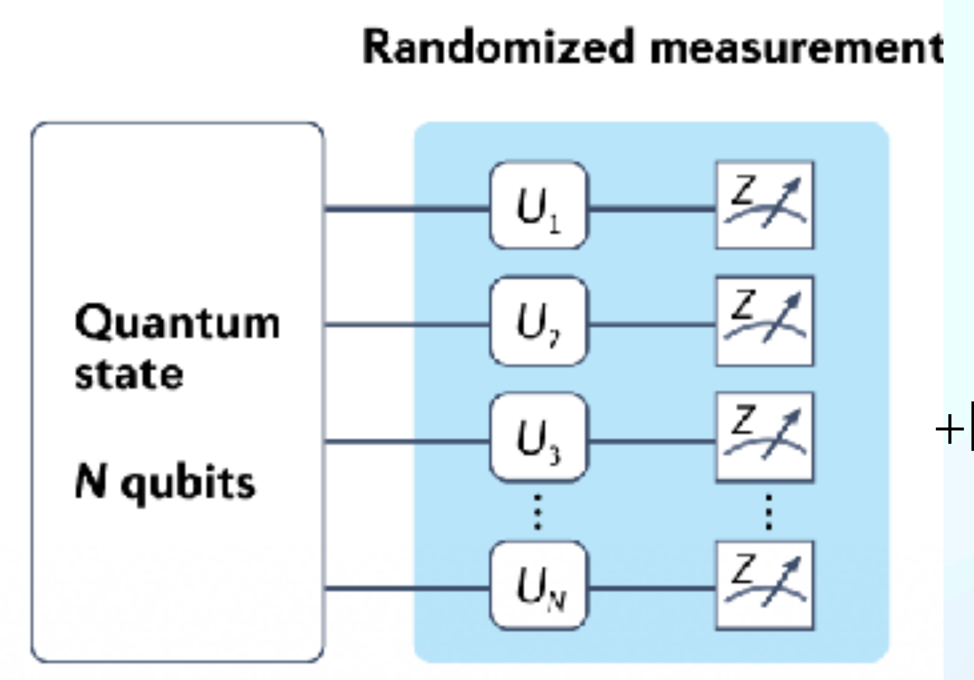
HOME > SCIENCE > VOL. 364, NO. 6437 > PROBING RÉNYI ENTANGLEMENT ENTROPY VIA RANDOMIZED MEASUREMENTS

REPORT

Probing Rényi entanglement entropy via randomized measurements

TIFF BRYDGES, ANDREAS ELBEN, PETAR JURCEVIC, BENOÎT VERMERSCH, CHRISTINE MAIER, BEN P. LANYON, PETER ZOLLER, RAINER BLATT, AND CHRISTIAN F. ROOS
Authors Info & Affiliations

SCIENCE • 19 Apr 2019 • Vol 364, Issue 6437 • pp. 260-263 • DOI: 10.1126/science.aau4963



+klasična obrada podataka

sličnO Monte Karlo metodama u statističkoj fizici

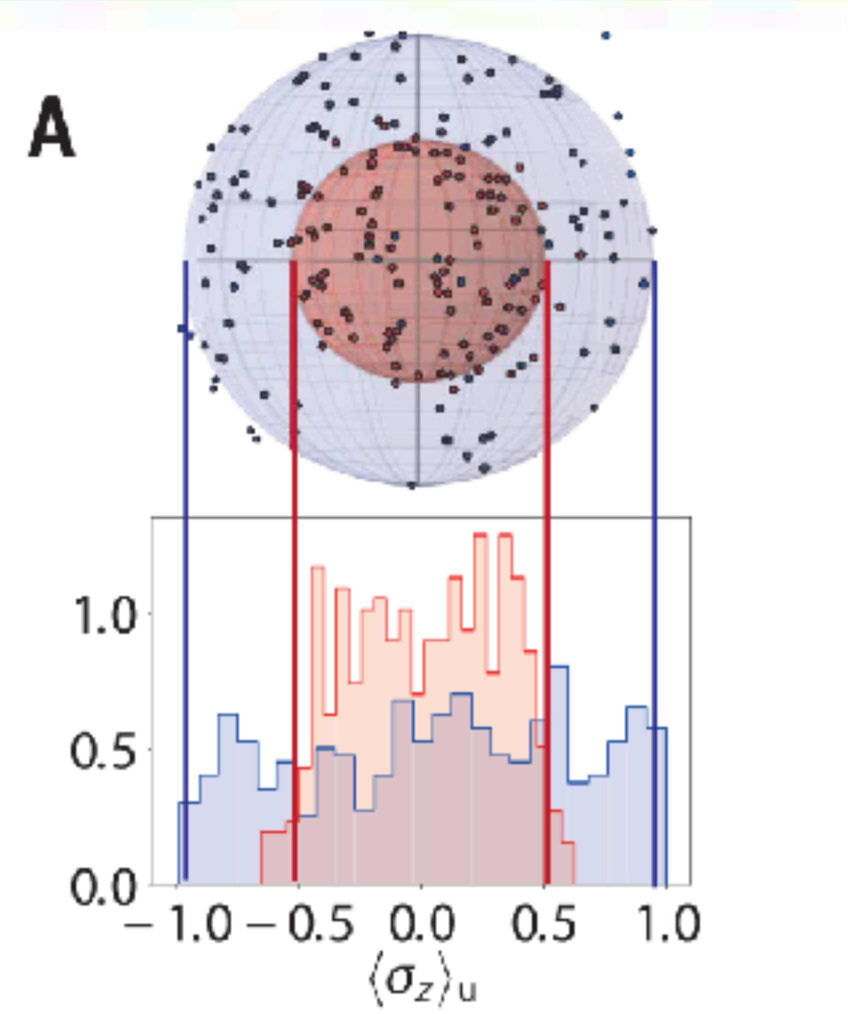
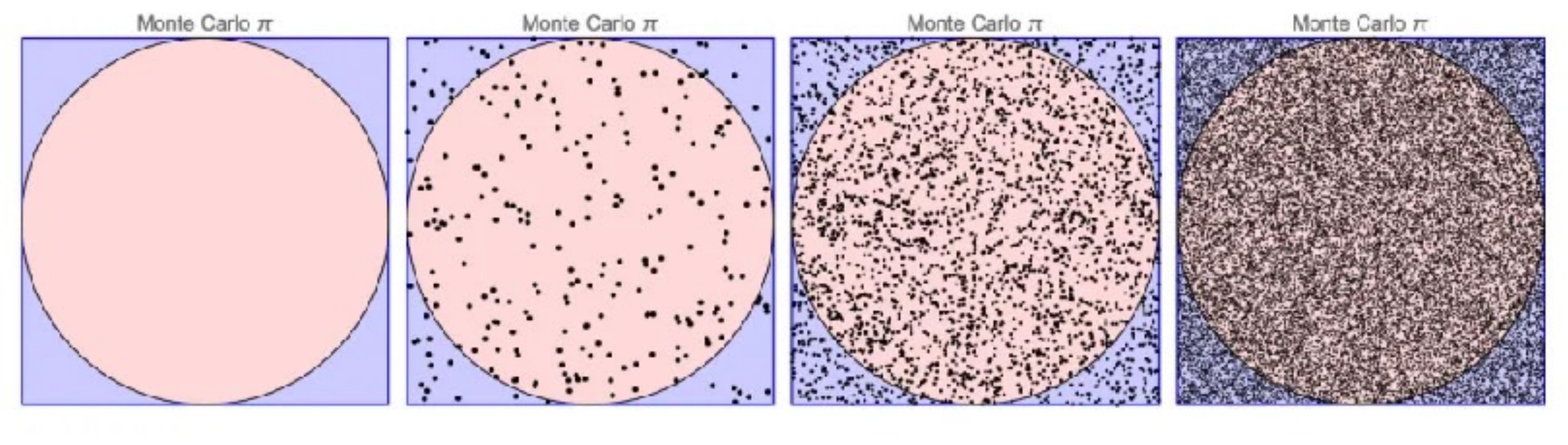


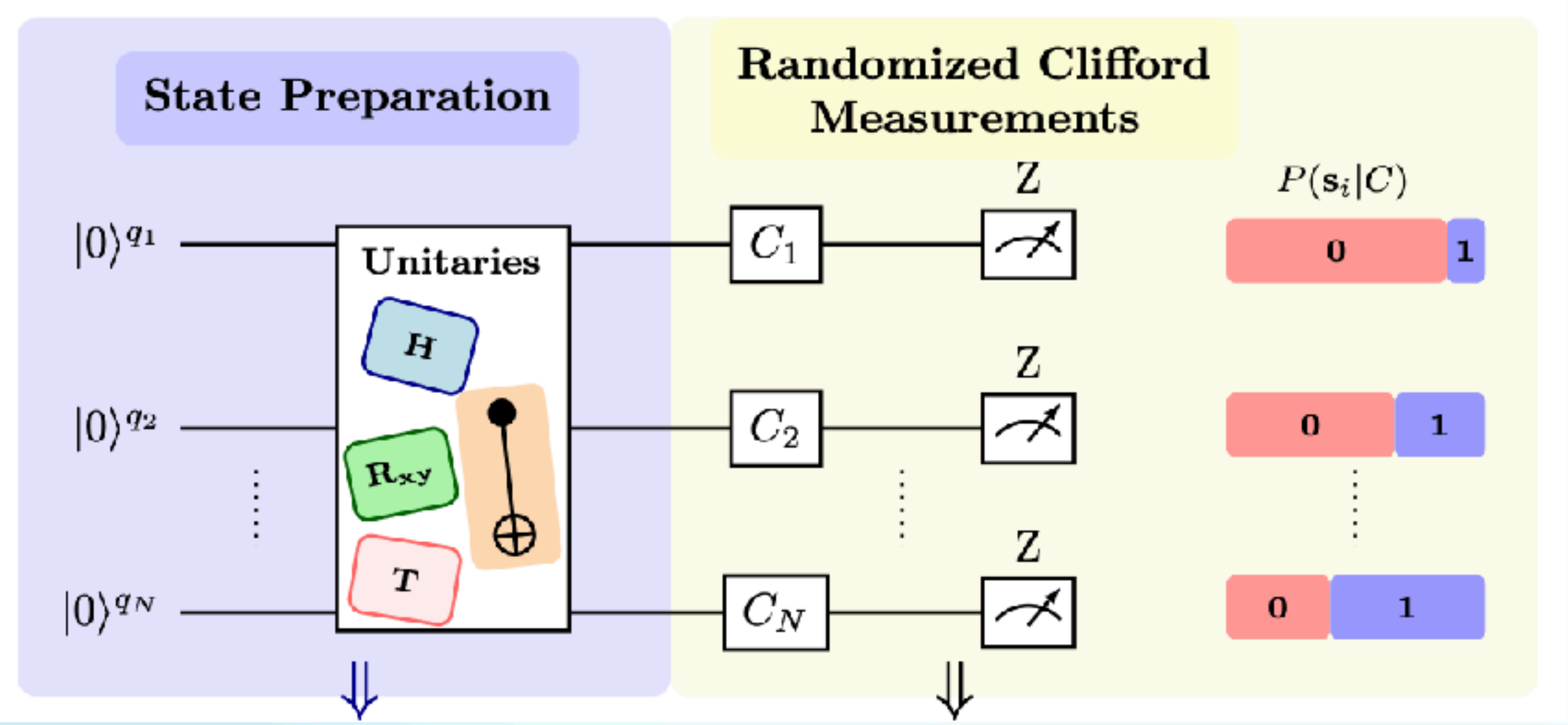
Fig. 1. Measuring second-order Rényi entropies through randomized measurements. (**A**) Single-qubit Bloch sphere. The purity is directly related to the width of the distribution of measurement outcomes after applying random rotations u_i. Initial pure state (blue) and mixed state (red) cases are shown. See text. (**B**) Generalization to multiple qubits: Measuring N_A-qubit



Nasumična Clifford Merenja - Randomized Clifford Measurement (RCM)

Oliviero, S.F.E. et al. 'Measuring magic on a quantum processor', npj Quantum Information, 8(1) (2022)

$$M_2(|\psi\rangle) = -\log_2 \mathcal{W} + \log_2 \mathcal{P} - \log_2 d,$$



24 Clifford 1-qubit operatora

A/P	I	X	Y	Z
I	I	X	Y	Z
H	H	XH	YH	ZH
HS	HS	XHS	YHS	ZHS
S	S	XS	YS	ZS
SH	SH	XSH	YSH	ZSH
HSH	HSH	$XHSH$	$YHSH$	$ZHSH$

Table I: Single-qubit Clifford gates (modulo global phase $U(1)$) used in Eqs. (2) and (3), where the columns are Pauli operators $P = \{I, X, Y, Z\}$ and rows are coset representatives $A = \{I, H, HS, S, SH, HSH\}$. H is the Hadamard gate, and S is the $\pi/2$ phase gate.

RCM protocol—> uzorkovanje stanja sa identičnom količinom magije

$$\mathcal{P} = d\sum_{\vec{\mathbf{s}}}(-2)^{-\|\vec{\mathbf{s}}\|_2}\,\mathbb{E}_C\left[P(\mathbf{s}_1|C)P(\mathbf{s}_2|C)\right], \quad \mathcal{W} = -\sum_{\vec{\mathbf{s}}}(-2)^{-\|\vec{\mathbf{s}}\|_4}\,\mathbb{E}_C\left[P(\mathbf{s}_1|C)P(\mathbf{s}_2|C)P(\mathbf{s}_3|C)P(\mathbf{s}_4|C)\right].$$

arXiv: 2511.15576

Šta je nelokalna magija?

- Nelokalna magija postoji u stanju koje je kvantno spregnuto (entangled): arXiv:2403.07056
- Protokol: pripremiti stanja sa nelokalnom magijom i zatim pokušati izbrisati lokalni deo

$$M_2^{\mathrm{NL}}(|\psi\rangle) = \min_{U_A, U_B} M_2(U_A \otimes U_B|\psi\rangle)$$

Vizuelizacija kvantne spletenosti i nelokalne magije u slučaju dva qubit-a ili kvantna spina-1/2. (Ilustracija: prof. dr. Slobodan Radošević)

arXiv: 2511.15576

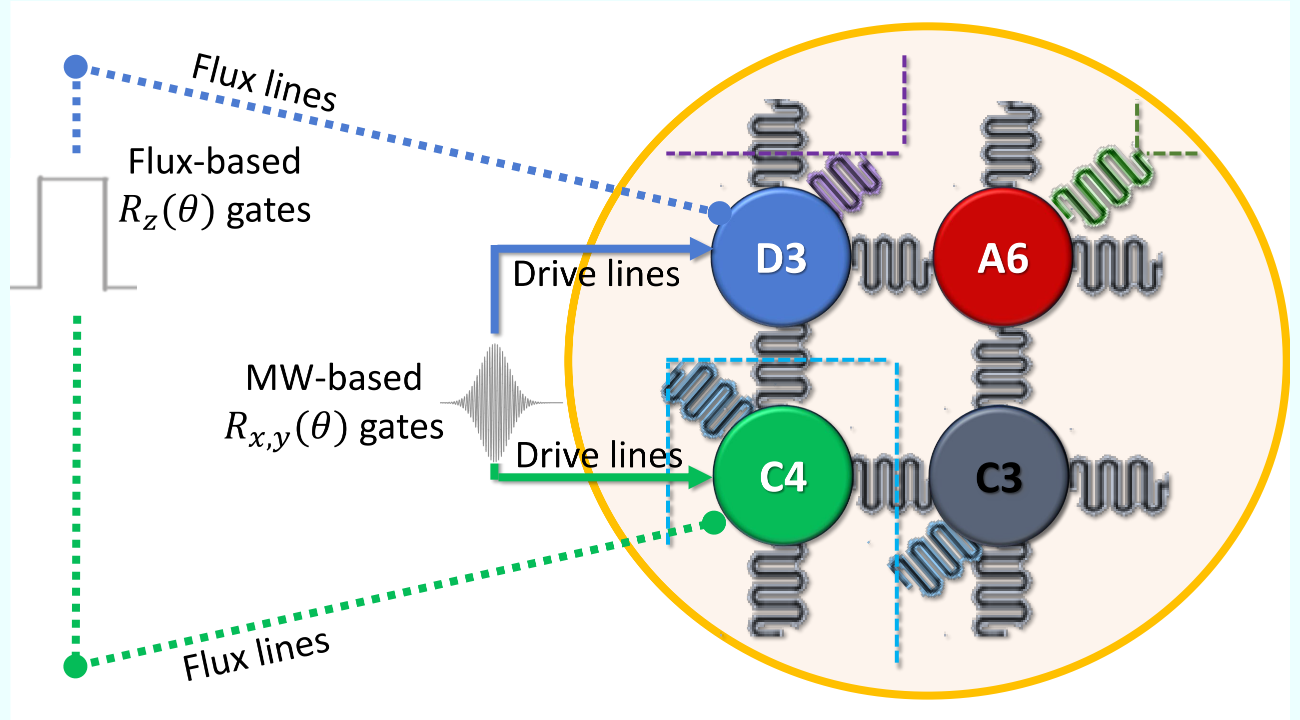
Nelokalna magija još nije eksperimentalno detektovana

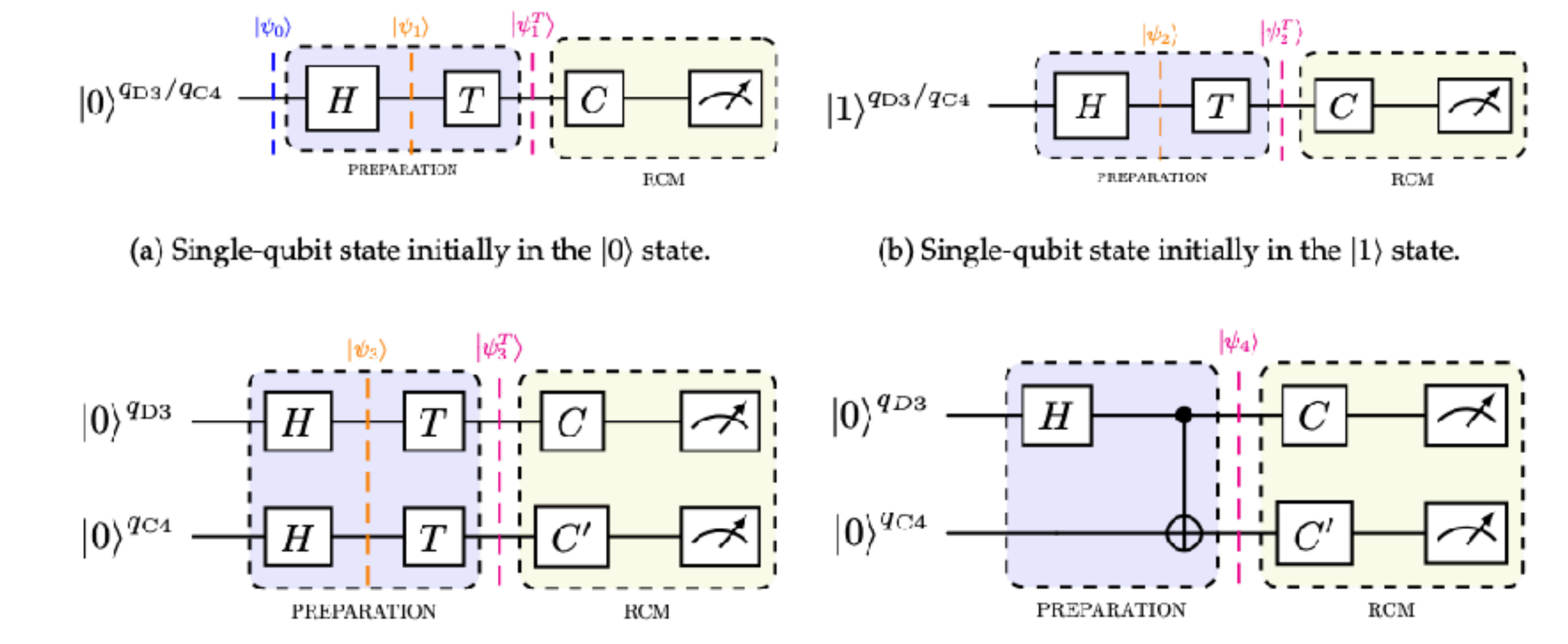
Stoga smo je po prvi put izmerili na kvantnom procesoru!

	Class 1	Class 2	Class 3
Notation	Local Magic(LM)	Local+Non-Local Magic(M)	Non-Local Magic(NLM)
Local	✓	✓	✗
Non-Local	✗	✓	✓
Local Erasure	Complete	Partial	Null

arXiv: 2511.15576

Referentni rezultati (benchmark) i identifikacija izvora šuma (noise)





(a) Single-qubit state initially in the $|0\rangle$ state.

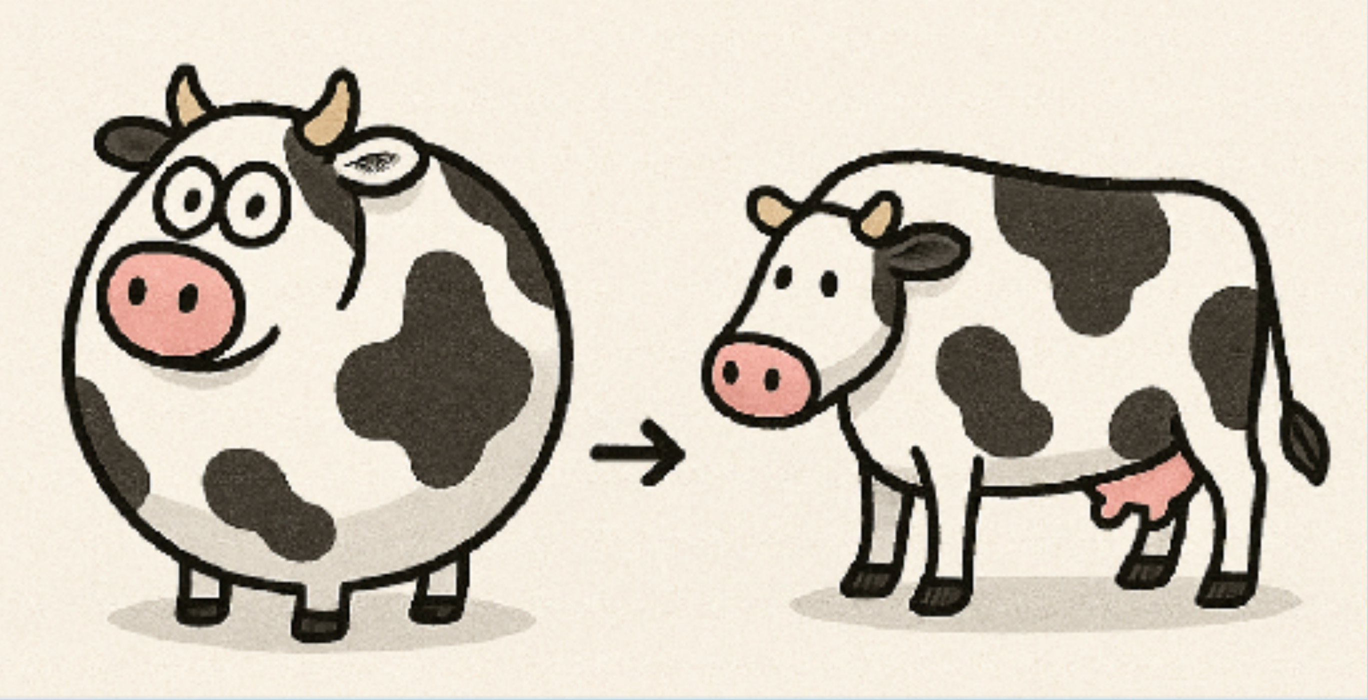
(b) Single-qubit state initially in the $|1\rangle$ state.

(c) Separable two-qubit states.

(d) Bell state.

	$F_{RO}(\%)$	$F_{RB}(\%)$	$T_2^{Echo}(\mu s)$	$T_2^*(\mu s)$	$T_1(\mu s)$	$M_2^{exp}(\Psi^{M_2^{th}=0})$	$M_2^{exp}(\Psi^{M_2^{th}\neq 0})$
(a)							
D3	94 ± 1	99.75 ± 0.01	31.1 ± 0.7	25 ± 6	23.3 ± 0.1	$\|\Psi_0\rangle$ 0.1 ± 0.1 $\|\Psi_1\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.5 ± 0.1
	96 ± 1	99.910 ± 0.002	39.9 ± 0.7	33 ± 6	30.0 ± 0.1	$\|\Psi_1\rangle$ 0.1 ± 0.1 $\|\Psi_2\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.4 ± 0.1 $\|\Psi_2^T\rangle$ 0.4 ± 0.1
C4	95 ± 1	99.925 ± 0.003	38.8 ± 1.1	24 ± 2	36.2 ± 0.1	$\|\Psi_1\rangle$ 0.1 ± 0.1 $\|\Psi_2\rangle$ 0.1 ± 0.1	$\|\Psi_1^T\rangle$ 0.4 ± 0.1 $\|\Psi_2^T\rangle$ 0.4 ± 0.1
(b)	$F_{RO}(\%)$	$F_{RB}(\%)$	$F_{RB}^{CZ}(\%)$	$Cross^{MW}(\%)$	$Cross^{ZZ}(kHz)$		
D3	83 ± 1	99.746 ± 0.014	99 ± 2	~ 0.12	~ 99	$\|\Psi_3\rangle$ 0.1 ± 0.1	$\|\Psi_3^T\rangle$ 0.8 ± 0.1
C4	91 ± 1	99.905 ± 0.003		~ 1.57	~ 100	$\|\Psi_3\rangle$ 0.1 ± 0.1	$\|\Psi_3^T\rangle$ 0.8 ± 0.1
(c)							
D3 C4	92 ± 1					$\|\Psi_4\rangle$ 0.2 ± 0.1	

Table 1: Experimental magic measured for the quantum states in Fig. 3. Systematic investigation of the experimental magic for single- and two-qubit quantum states, involving qubits D3 and C4, as a function of: the readout fidelity F_{RO}, the average single-qubit gates fidelity measured by Randomized Benchmarking, F_{RB}, both in the isolated case (a) and simultaneously (b), statistical relaxation, Ramsey and Echo coherence times (T_1, T_2^* and T_2^{Echo}, respectively). For the two-qubit circuits, we have also reported an estimation of the drive and ZZ crosstalk on the investigated pair [55–58]. A discussion on the error estimation is reported in App. B.



arXiv: 2511.15576

Naš posao kao teoretičara

1.2 Strategies to counter errors

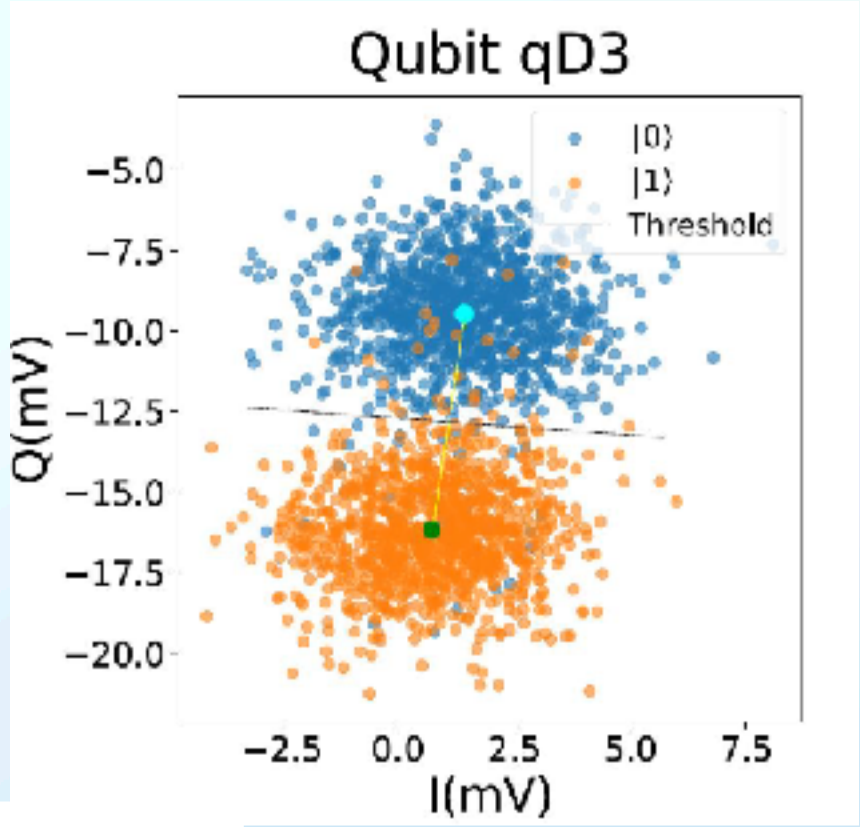
1. **Do nothing and hope for the best.** We can only run short circuits before our computation is overwhelmed by the noise. This regime is called the *Noisy Intermediate-Scale Quantum (NISQ) regime* [16].

Error Mitigation and Error Correction Lecture Notes - Philippe Faist

...je bio da razumemo i razložimo izvore grešaka koje naš procesor ima na osnovu preliminarnih i benchmark eksperimenata

Nasumični bit-flip

$$0 \to 1 \quad \text{or} \quad 1 \to 0.$$



1. Greške pri samom merenju

2. CNOT kvantni elementi (depolarizujući šum)

$$\mathcal{E}(\rho) = \frac{pI}{2} + (1-p)\rho. \tag{8.100}$$

The effect of the depolarizing channel on the Bloch sphere is illustrated in Figure 8.11.

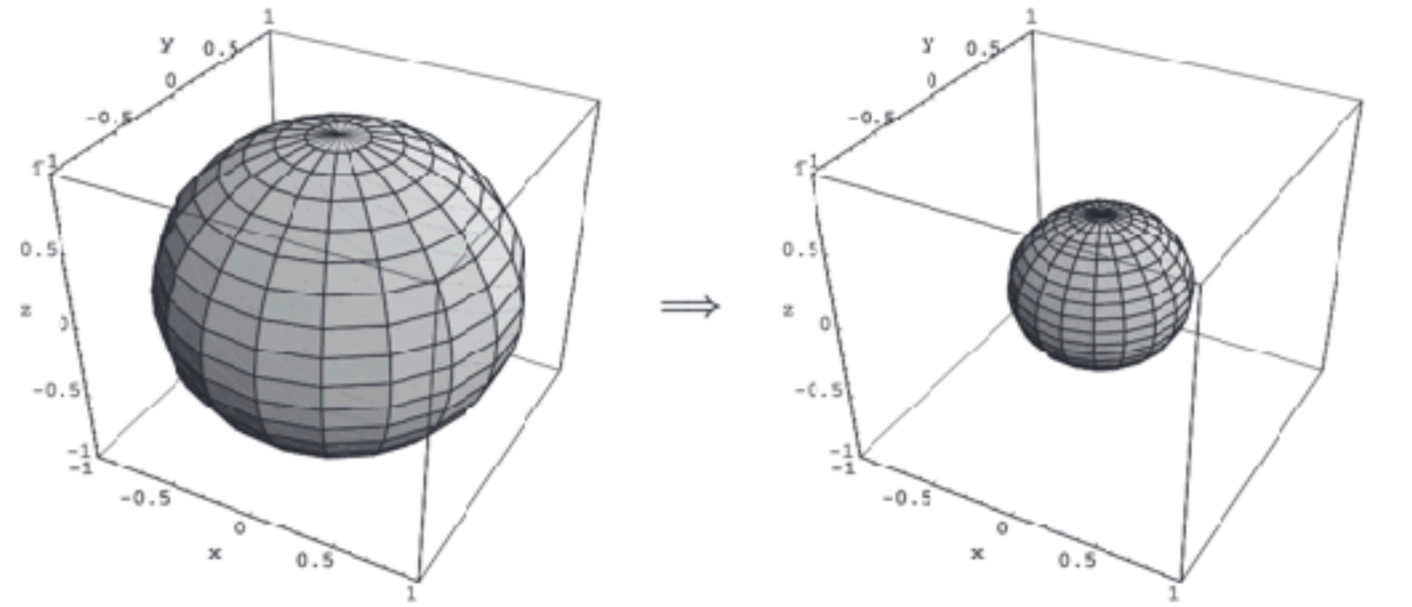
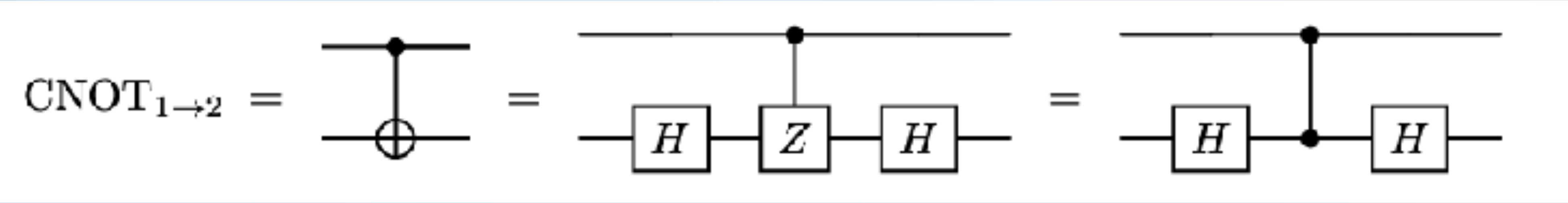
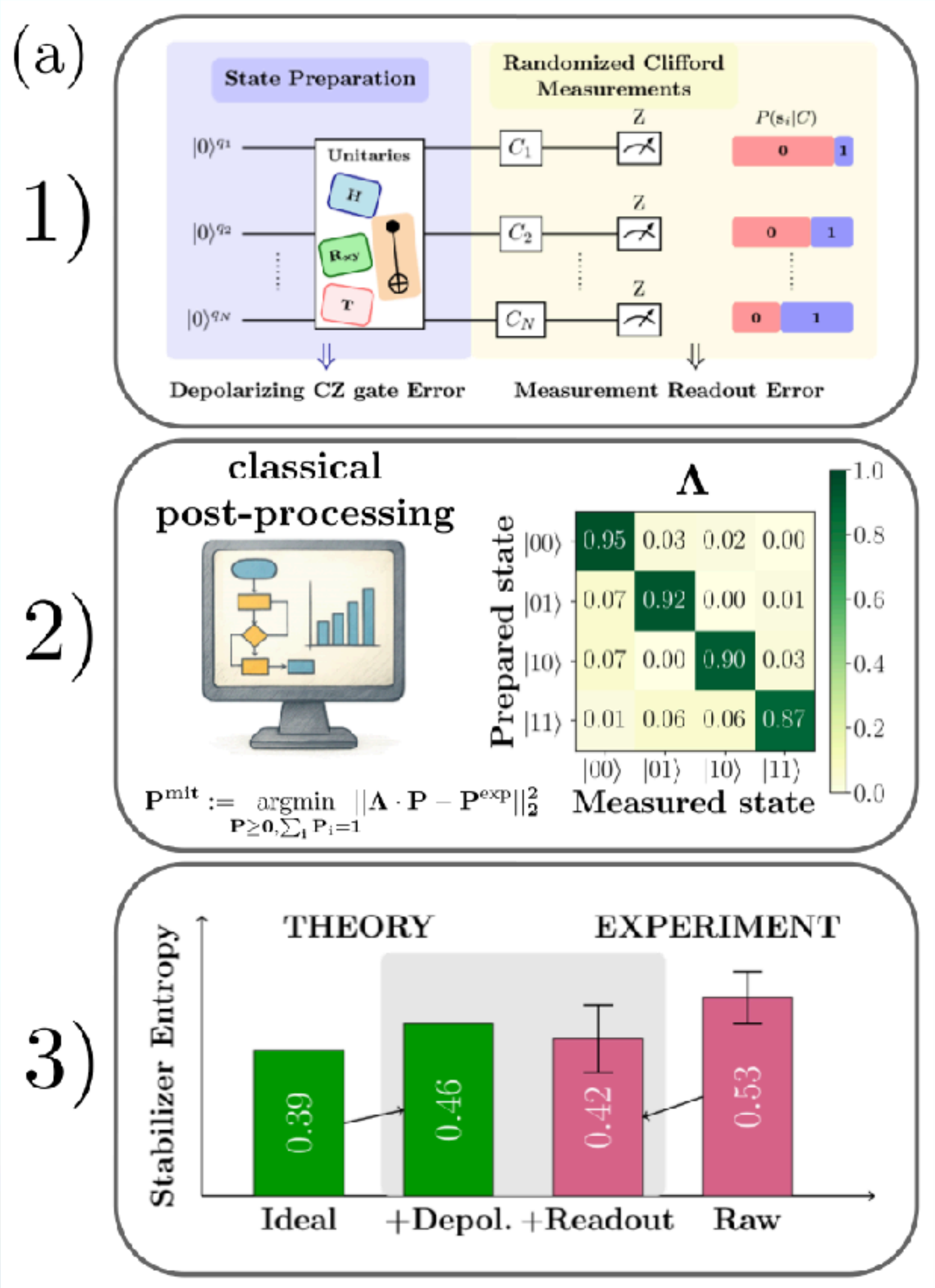


Figure 8.11. The effect of the depolarizing channel on the Bloch sphere, for $p = 0.5$. Note how the entire sphere contracts uniformly as a function of p.



arXiv: 2511.15576

Workflow



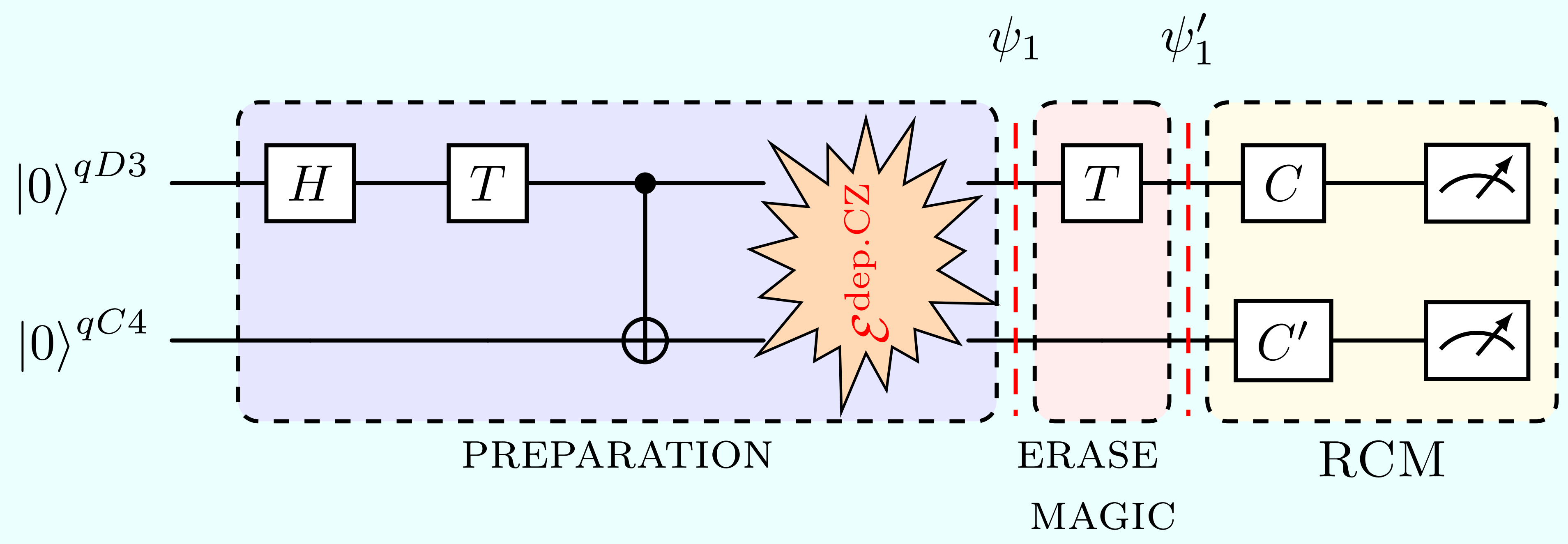
priča o sjedinjavanju teorije i eksperimenta

dvokraki pristup

arXiv: 2511.15576

Klasa 1: Lokalna Magija

Alternativni metod



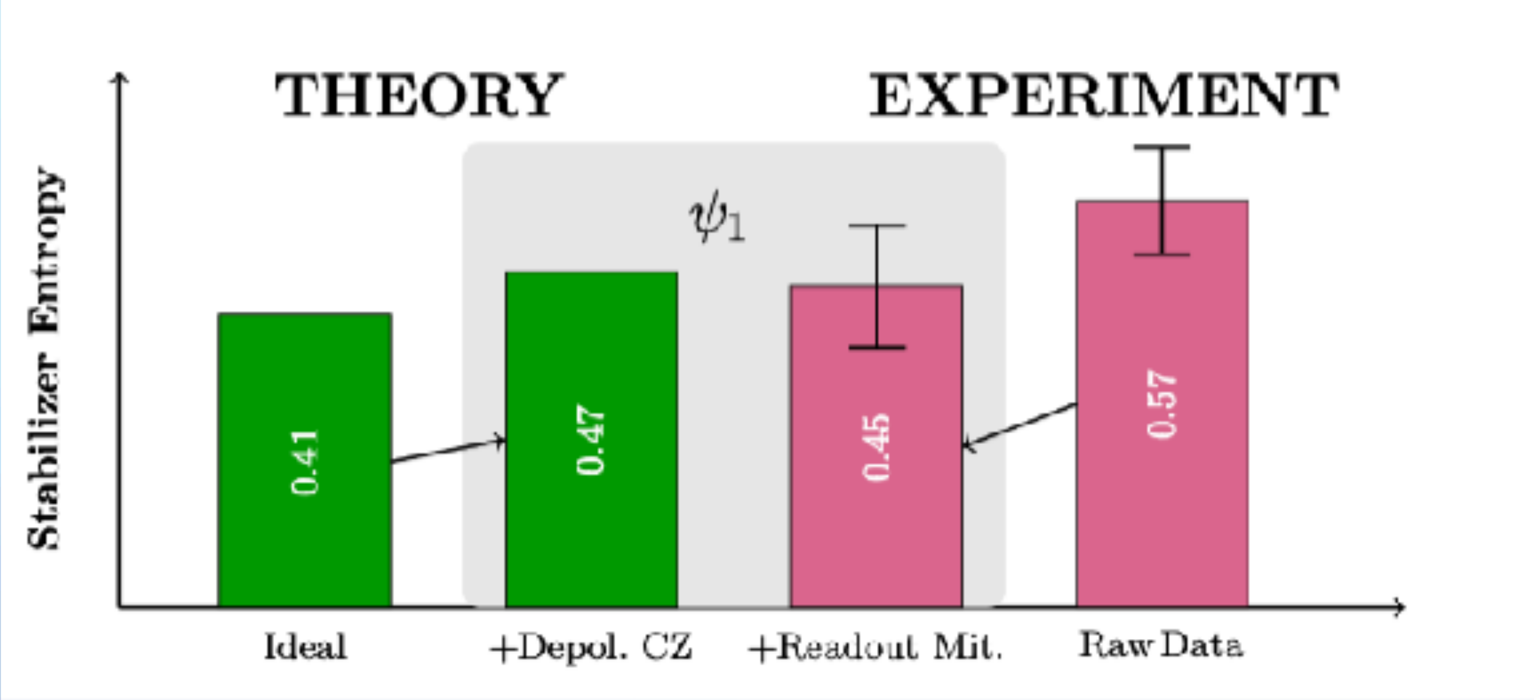
Circuit	State	Th. Purity	Exp. Purity	Th. Magic	Exp. Magic	NL-Magic (from RDM purity)
Preparation	ψ_1	0.92	**1.02** $\pm$ 0.04	0.47	**0.45** $\pm$ 0.06	
Prep.+Erasure	ψ_1'	0.92	**1.05** $\pm$ 0.06	0.11	**0.08** $\pm$ 0.08	**0.1176** $\pm$ 0.0007

Table 2: Local Magic (LM) state results. Comparison of Purity and Magic for states ψ_1 (before) and ψ_1' (after) the erasure , as well as the value of non-local magic obtained from subsystem purity. The theoretical predictions for purity and magic are calculated by considering the CZ depolarizing error and compared with the experimental results after readout error mitigation. Details on the errors are reported in *Methods*.

$$|\psi\rangle = \sqrt{\lambda}|\psi_1^A\rangle|\psi_1^B\rangle + \sqrt{1-\lambda}|\psi_2^A\rangle|\psi_2^B\rangle$$

$$\psi_A := \mathrm{Tr}_B(|\psi\rangle\langle\psi|) \qquad \mathrm{Pur}(\psi_A) = \lambda^2 + (1-\lambda)^2 .$$

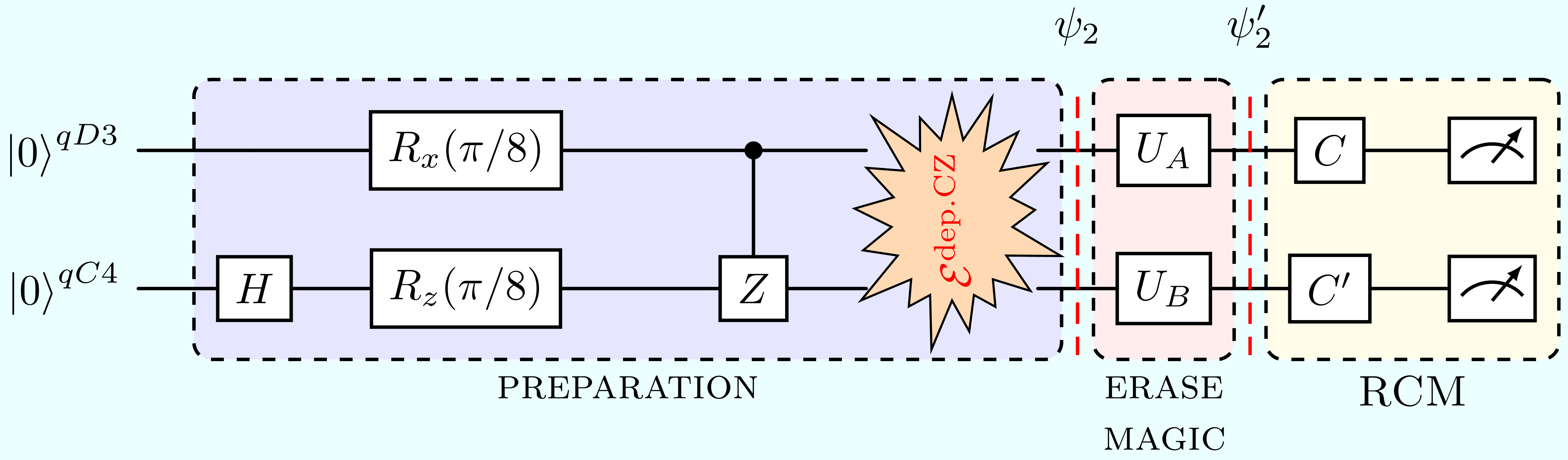
$$M^{\mathrm{NL}}(|\psi\rangle) = -\log_2\left(4\mathrm{Pur}(\psi_A)^2 - 6\mathrm{Pur}(\psi_A) + 3\right) .$$

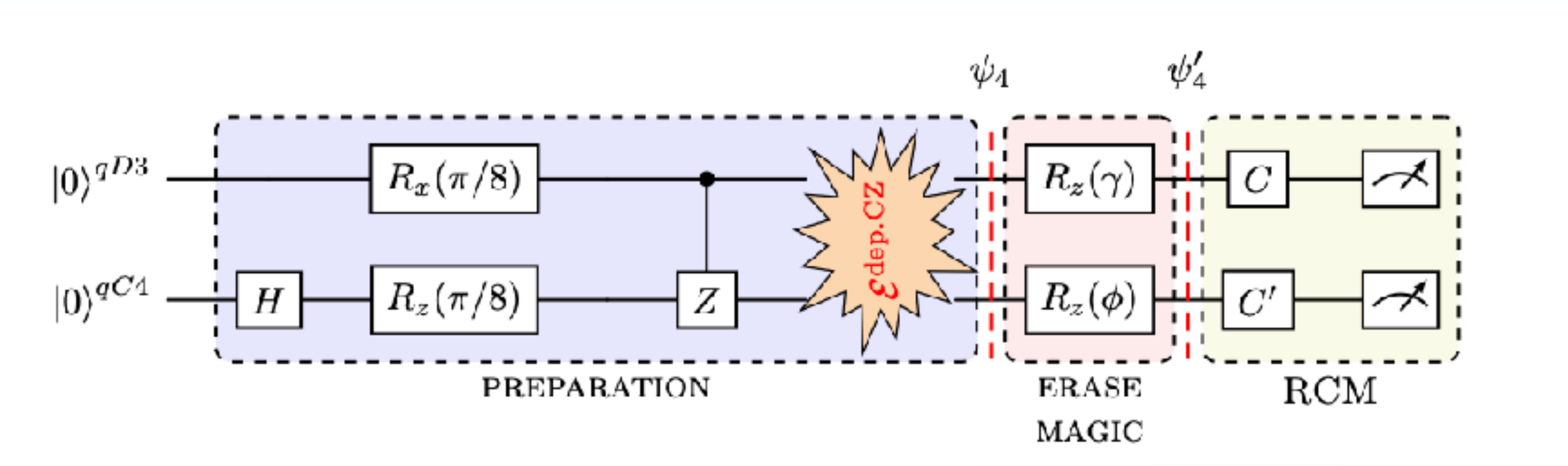


arXiv: 2511.15576

Closed-form za slučaj 2 qubit-a

Klasa 2: Lokalna+Nelokalna magija (M)



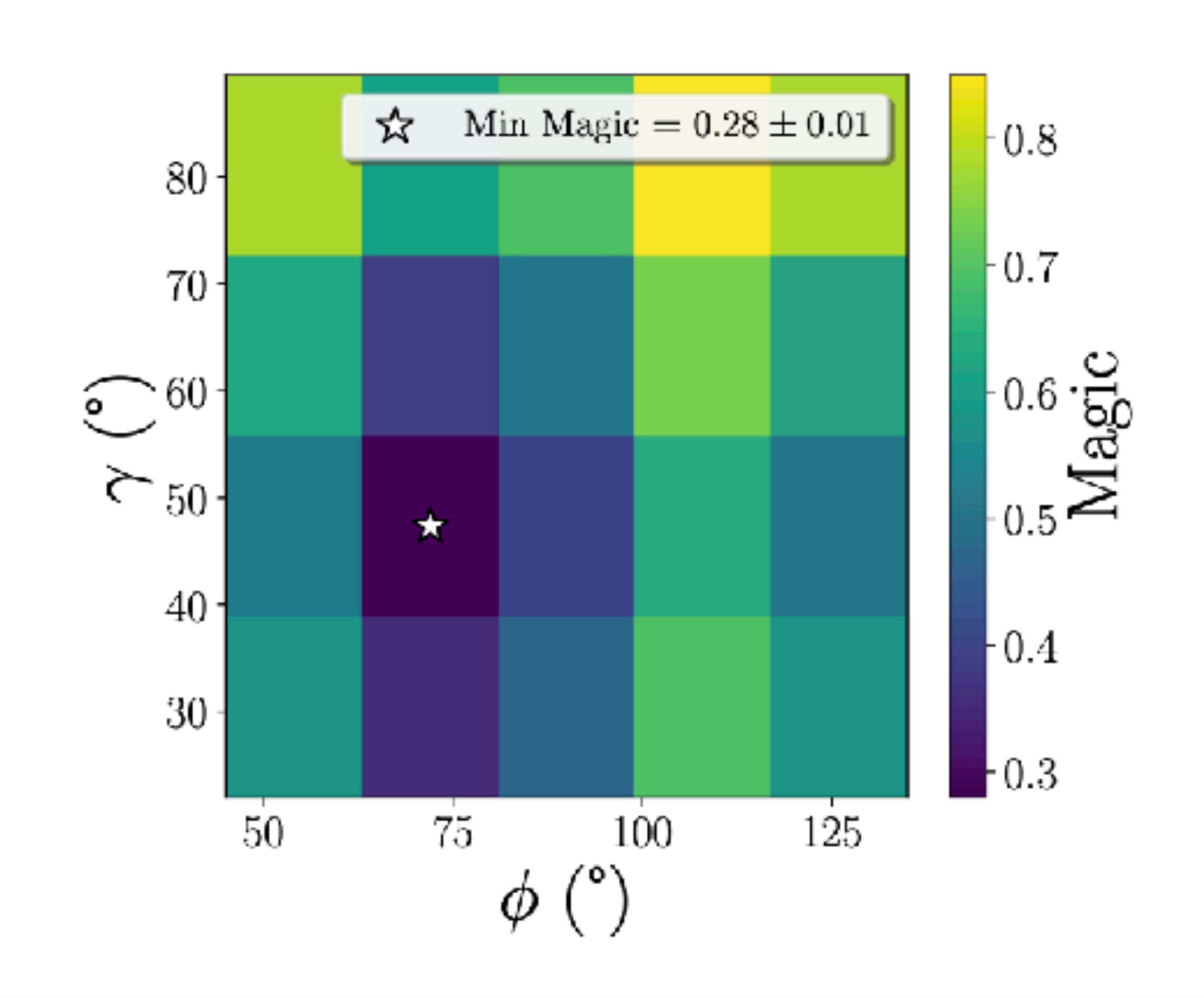


$$U_A = R_z(\alpha)R_y(\beta)R_z(\gamma)\ ,\ U_B = R_z(\delta)R_y(\eta)R_z(\phi)\ ,$$

$$\alpha = \beta = \gamma = \delta = \eta = 0, \phi = 67.61^\circ$$

Circuit	State	Th. Purity	Exp. Purity	Th. Magic	Exp. Magic	NL-magic (from RDM purity)
Preparation	ψ_2	0.95	**0.94** ± 0.04	0.44	**0.42** $\pm$ 0.09	
Prep.+Erasure	ψ_2'	0.95	**1.00** $\pm$ 0.05	0.3	**0.3** $\pm$ 0.1	**0.18** $\pm$ 0.07

Table 3: Local + Non-Local (M) magic quantum state results. Comparison of Purity and Magic for states ψ_2 (before) and ψ_2' (after) the erasure protocol, as well as the value of non-local magic obtained from subsystem purity. The theoretical predictions for purity and magic are calculated by considering the CZ depolarizing error and compared with the experimental results after readout error mitigation. Details on the errors are reported in *Methods*.



Ono što ostane je nelokalna magija!

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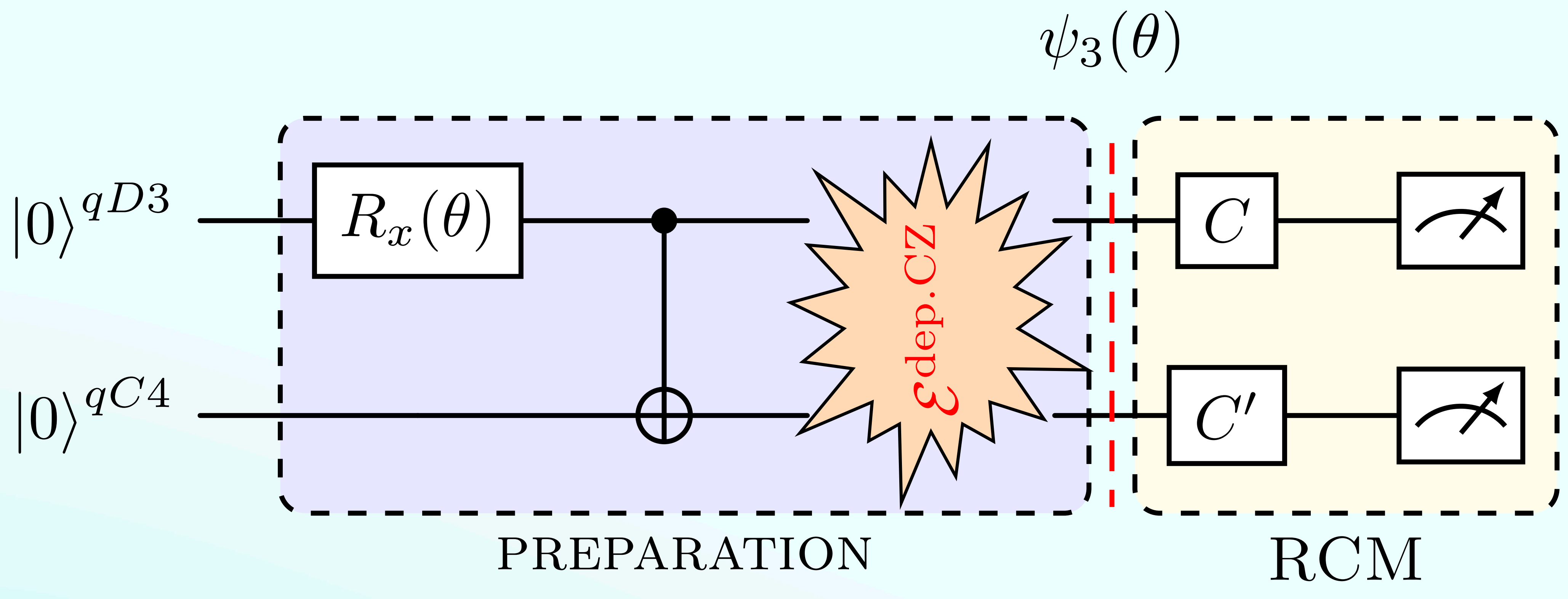
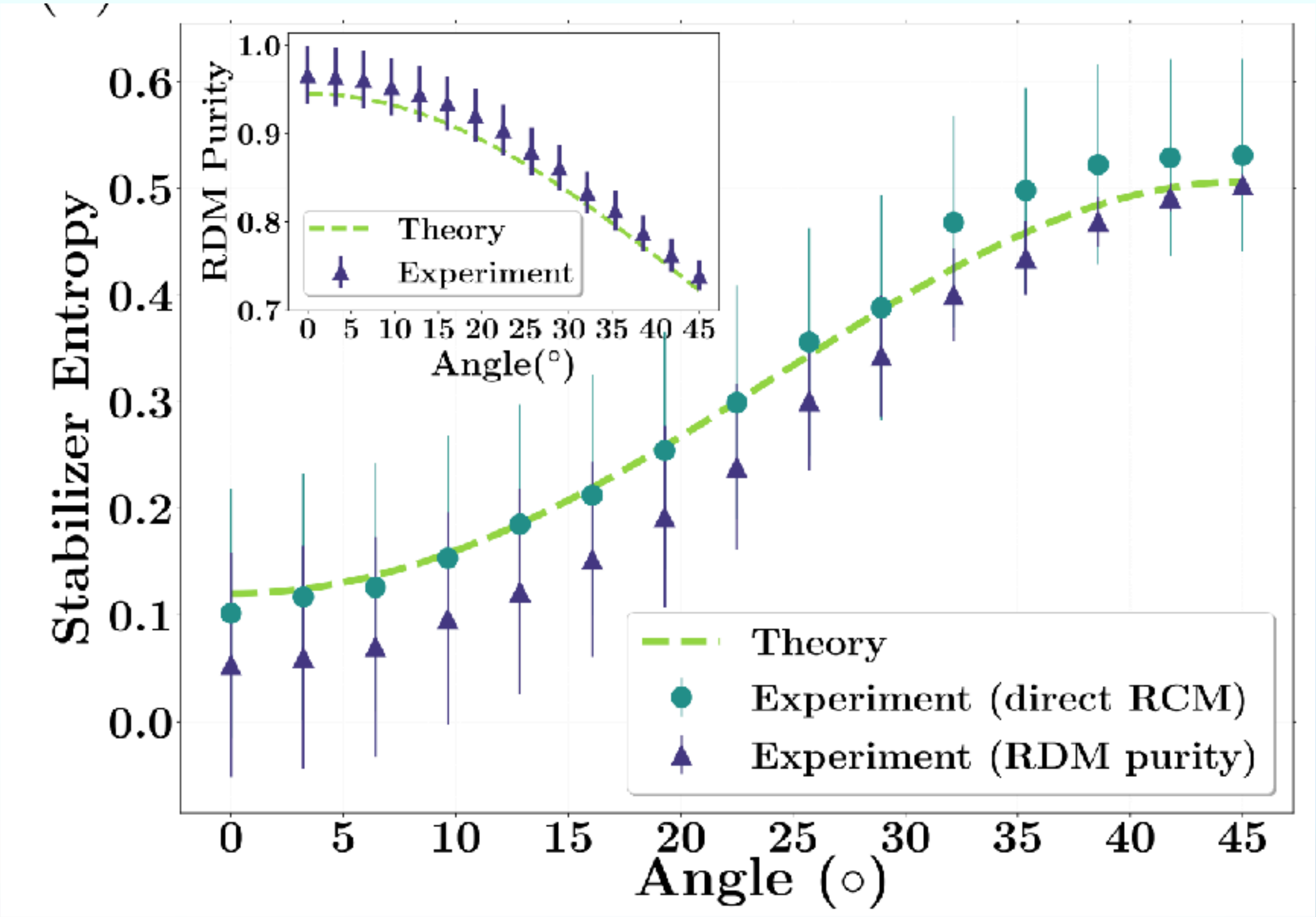
Klasa 3: Nelokalna magija (NLM)



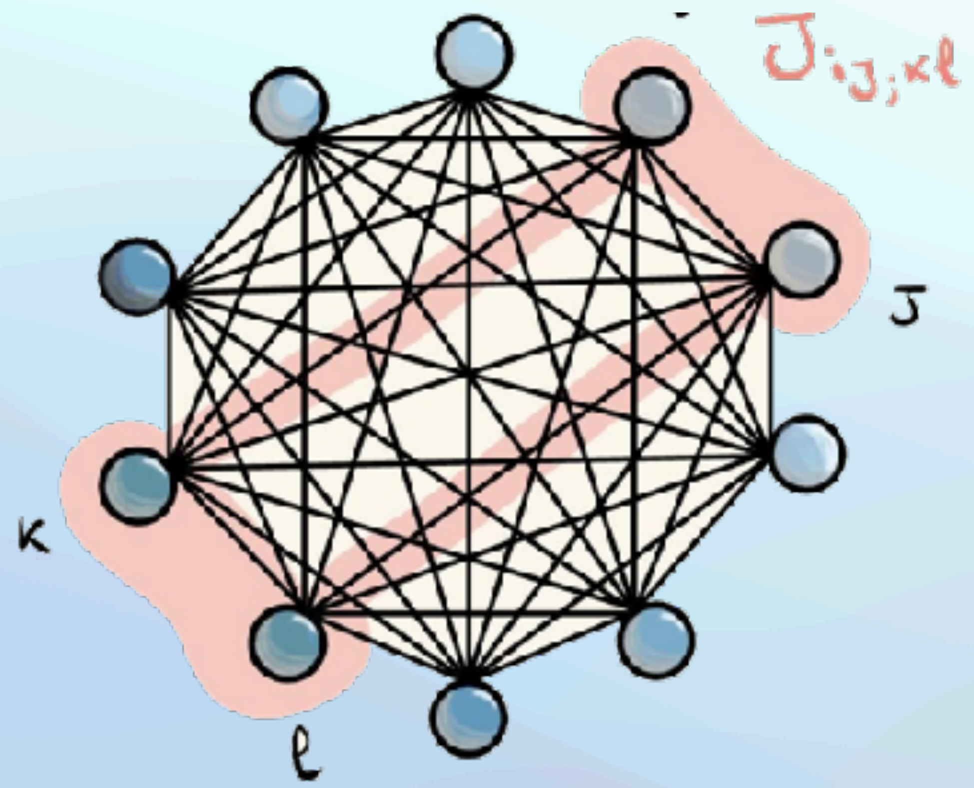


Sveukupno —> smoking gun eksperimentalne nelokalne magije

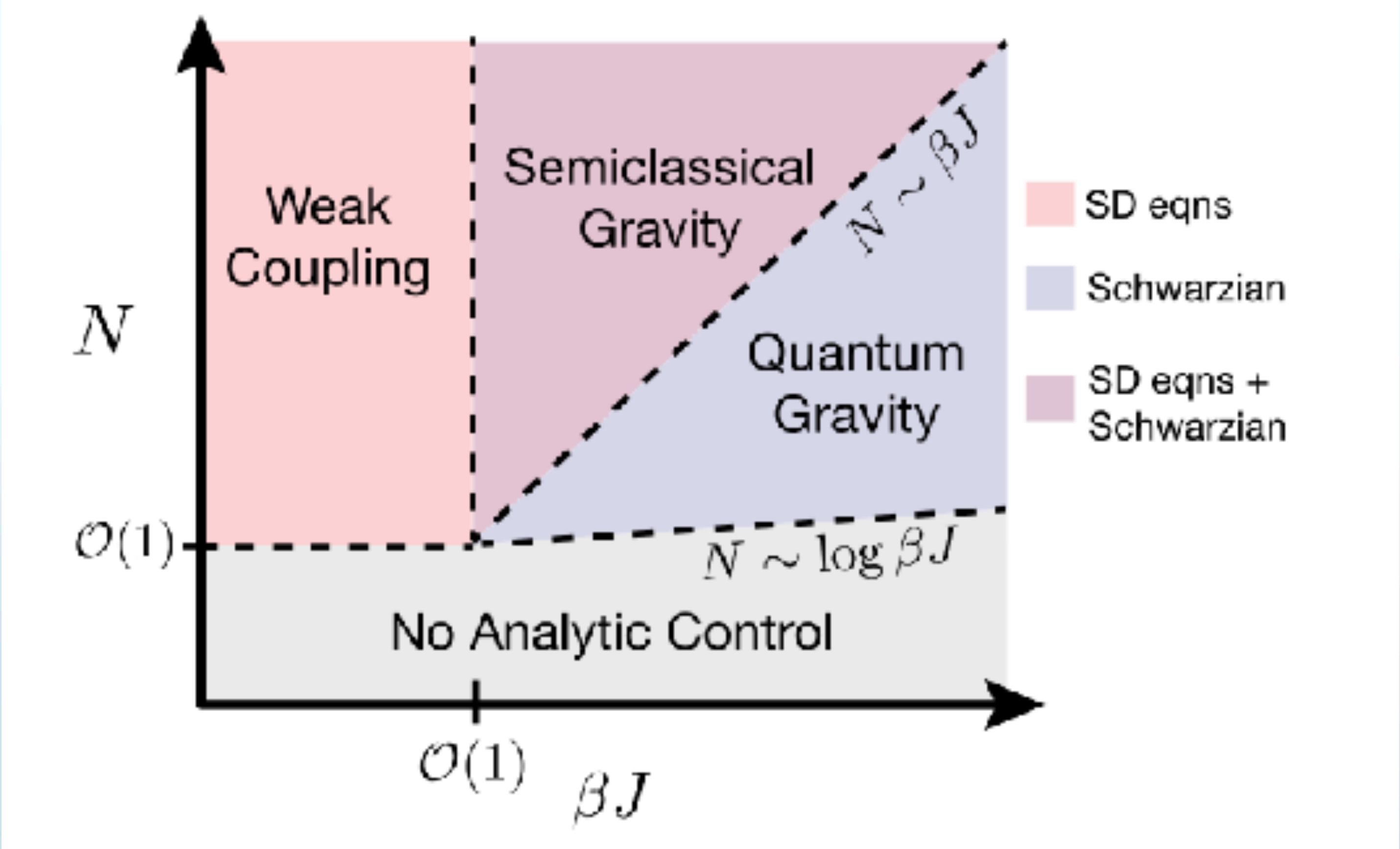
arXiv: 2511.15576

Perspektiva i budući rad

- Neki aspekti nelokalne magije imaju interpretaciju u AdS/CFT dualnosti? (Gravitational back-reaction is magical, arXiv:2403.07056)
- Simulacija strogo korelisanih sistema poput Sachdev-Ye-Kitaev (SYK) modela na kvantnim računarima. SYK kvantno haotični model koji opisuje neke aspekte crnih rupa.
- SYK model ima slično ponašanje niskodimenzionim teorijama gravitacije (Jackiw-Teitelboim (JT) theory i nearly-AdS2 spaces)



SYK model



Solvable limits of the SYK-4 model - PRL **126**, 030602 (2021)

Stabilizer entropy and entanglement complexity in the Sachdev-Ye-Kitaev model

Barbara Jasser[1,2,*], Jovan Odavić[2,3,†], and Alioscia Hamma[1,2,3,‡]

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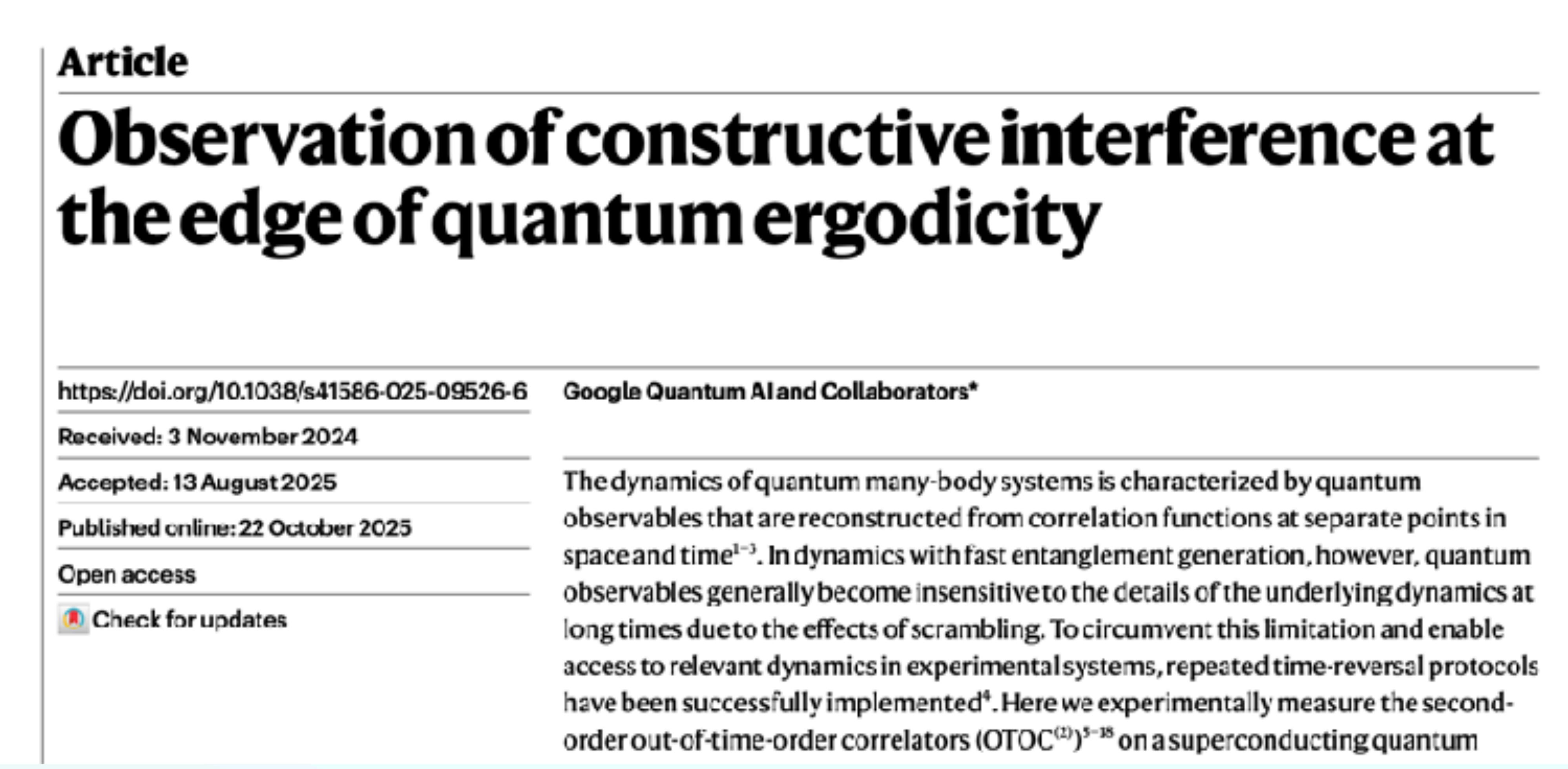
Phys. Rev. B **112**, 174204 – **Published 14 November, 2025**

DOI: https://doi.org/10.1103/rz86-47h3

Novi rad na ovu temu!

Kvantna nadmoć danas?



Article

Observation of constructive interference at the edge of quantum ergodicity

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Google Quantum AI and Collaborators*

The dynamics of quantum many-body systems is characterized by quantum observables that are reconstructed from correlation functions at separate points in space and time[1–3]. In dynamics with fast entanglement generation, however, quantum observables generally become insensitive to the details of the underlying dynamics at long times due to the effects of scrambling. To circumvent this limitation and enable access to relevant dynamics in experimental systems, repeated time-reversal protocols have been successfully implemented[4]. Here we experimentally measure the second-order out-of-time-order correlators (OTOC$^{(2)}$)[5–15] on a superconducting quantum

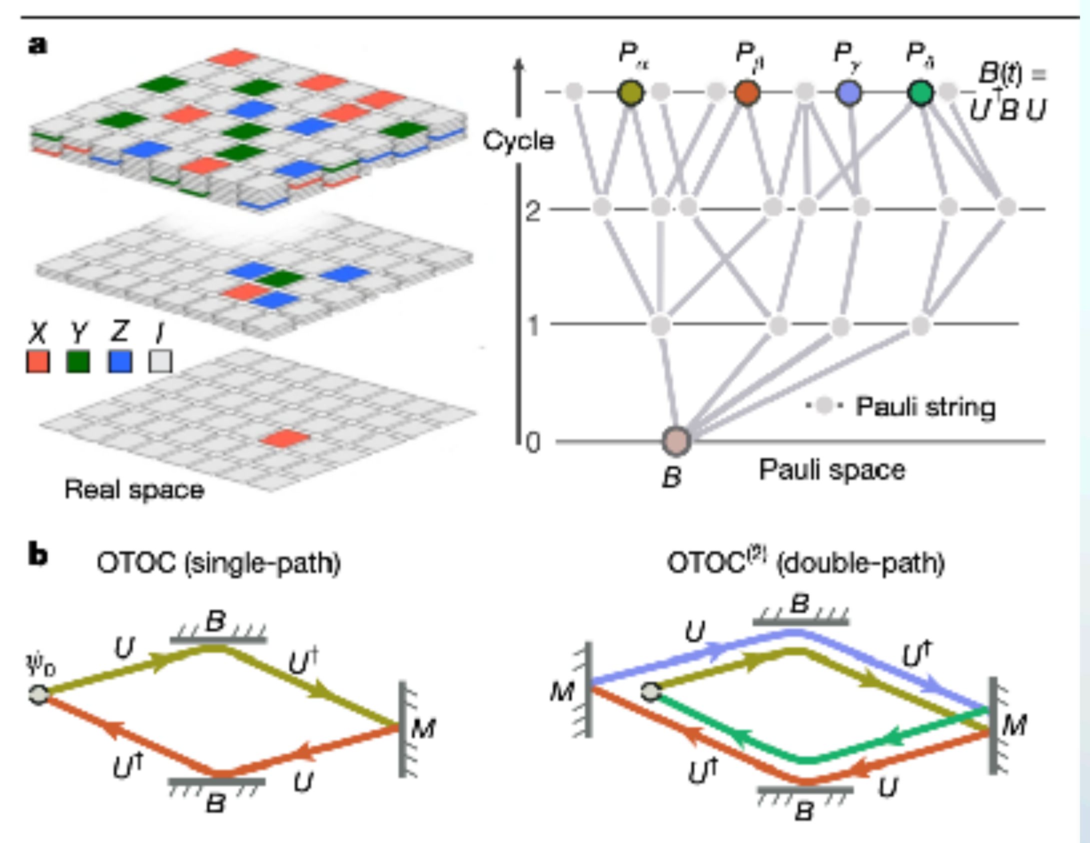
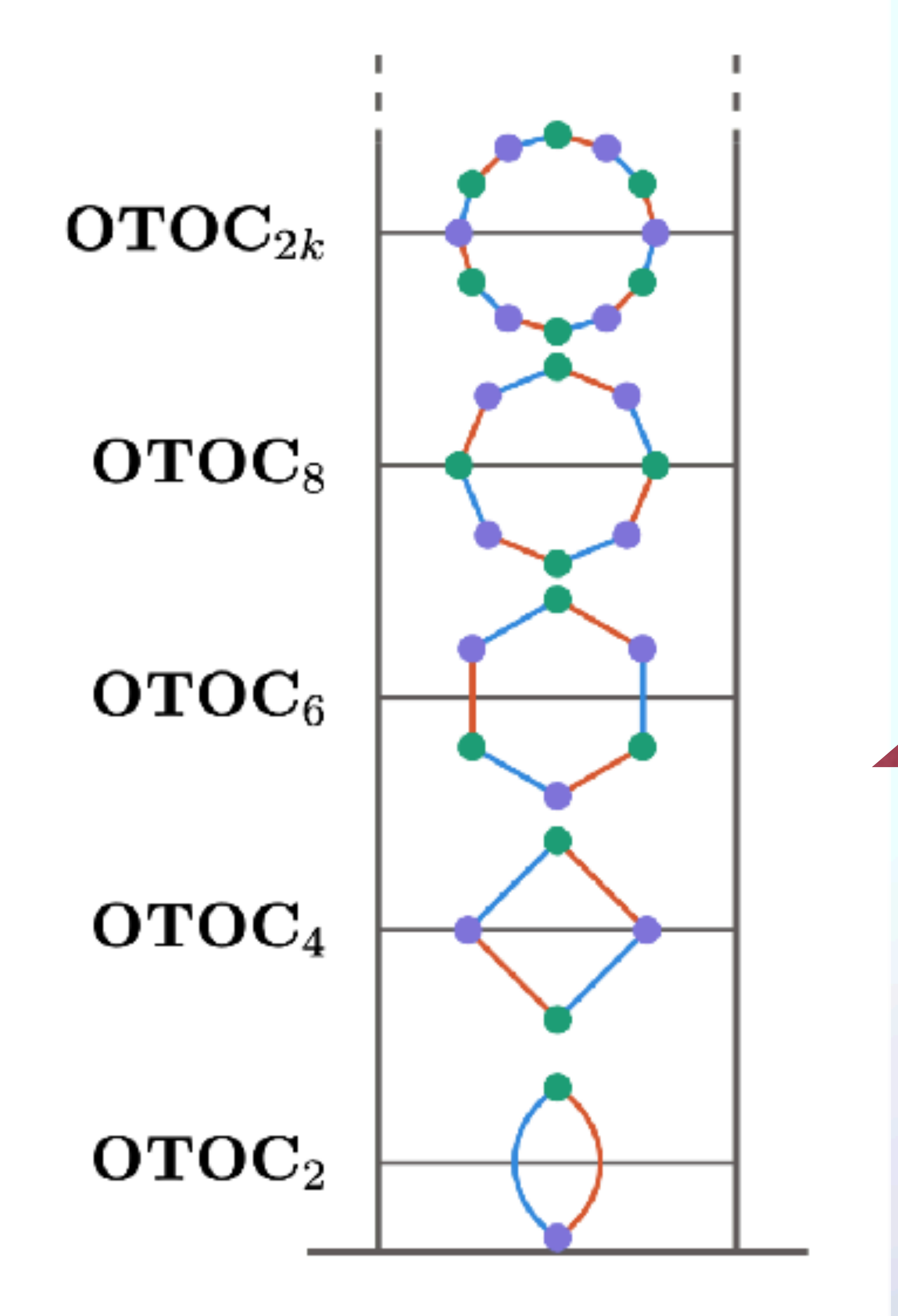


Fig. 1 | OTOCs as interferometers. a, When dynamical protocols involve echoing, the Heisenberg picture of the operator evolution is the natural framework for studying dynamics. **b**, OTOC and OTOC$^{(2)}$ can be viewed as time interferometers, which highlights their capability of refocusing on desired details and echoing out unwanted dynamics. See text for the definition of parameters.



Jakovljeve lestve komplesnosti

Hvala na pažnji!

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