Simplex-embeddability of the stabilizer qubit

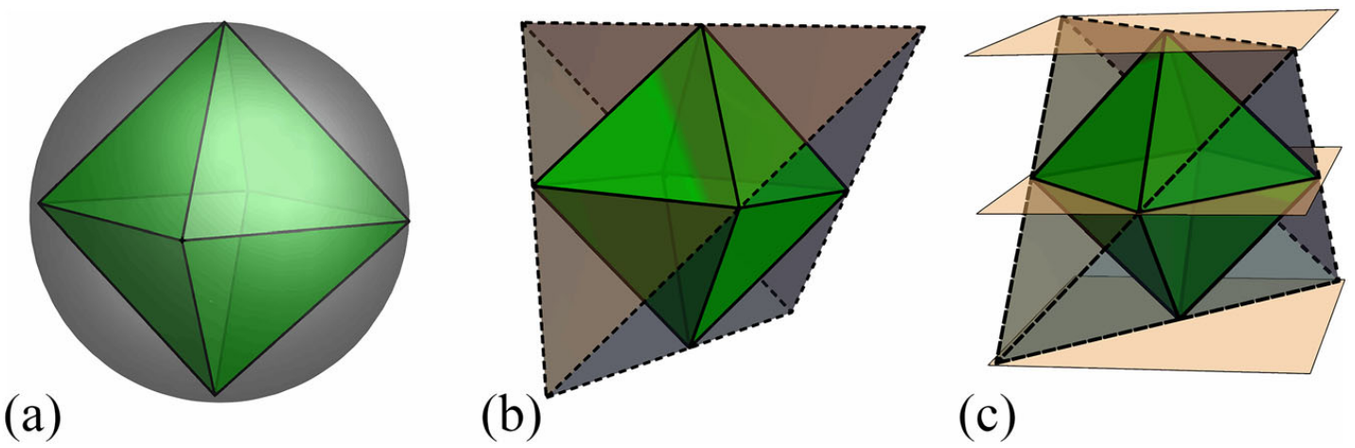

Fig. 3 | Relations between the state spaces of the qubit, stabilizer qubit[31] and classical four-level system. a The state space of the stabilizer qubit (in green) is embedded in the state space of the qubit, given by the gray ball; **b** the state space of the stabilizer qubit (in green) is embeddable within a tetrahedron (in gray), the state space of a classical four level system; **c** the embedding of the stabilizer qubit into the tetrahedron pictured here is such that any valid effect on the stabilizer qubit is also a valid effect on the tetrahedron. This requirement prevents, for example, the embeddability of the qubit into the tetrahedron (we know that the qubit is none-mbeddable because it is contextual). Here the orange planes represent the effect corresponding to the +1 outcome of the Pauli Z measurement: the upper plane intersects all states giving probability 1 for the outcome +1, the central plane those giving probability $\frac{1}{2}$ and the lower plane those giving probability 0.

A. Aloy, M. Fadel, T. D. Galley, C. L. Jones, and M. P. Müller, Nat. Commun. **17**, 2474 (2026).

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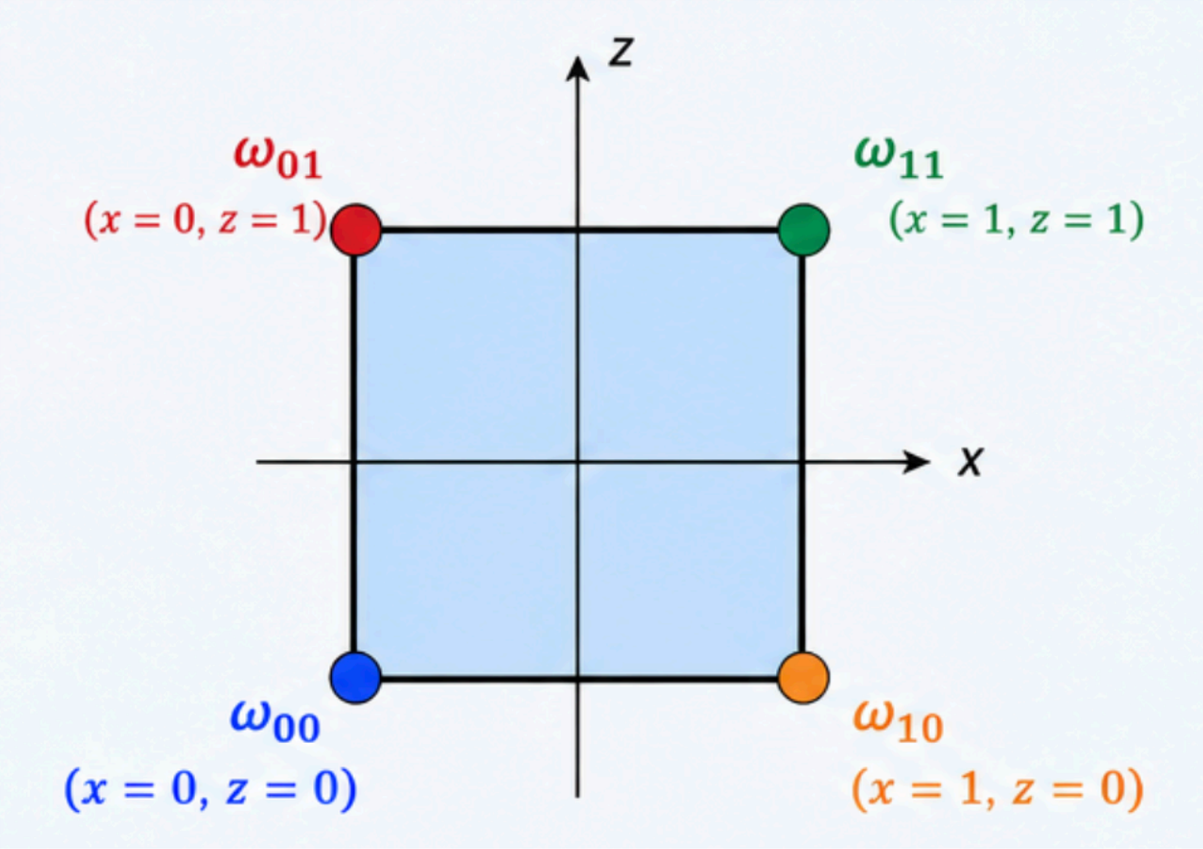

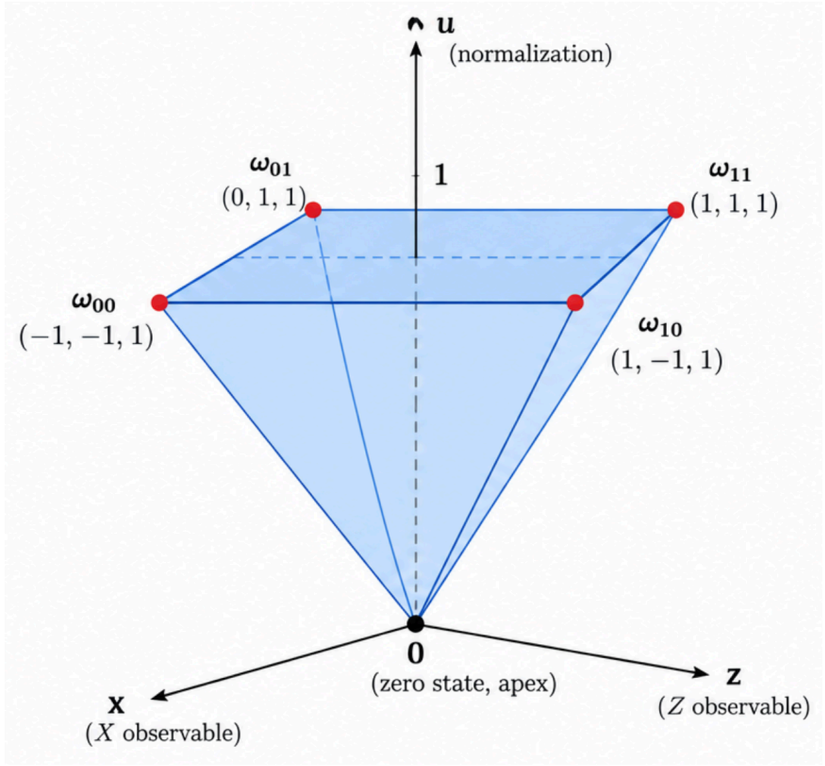

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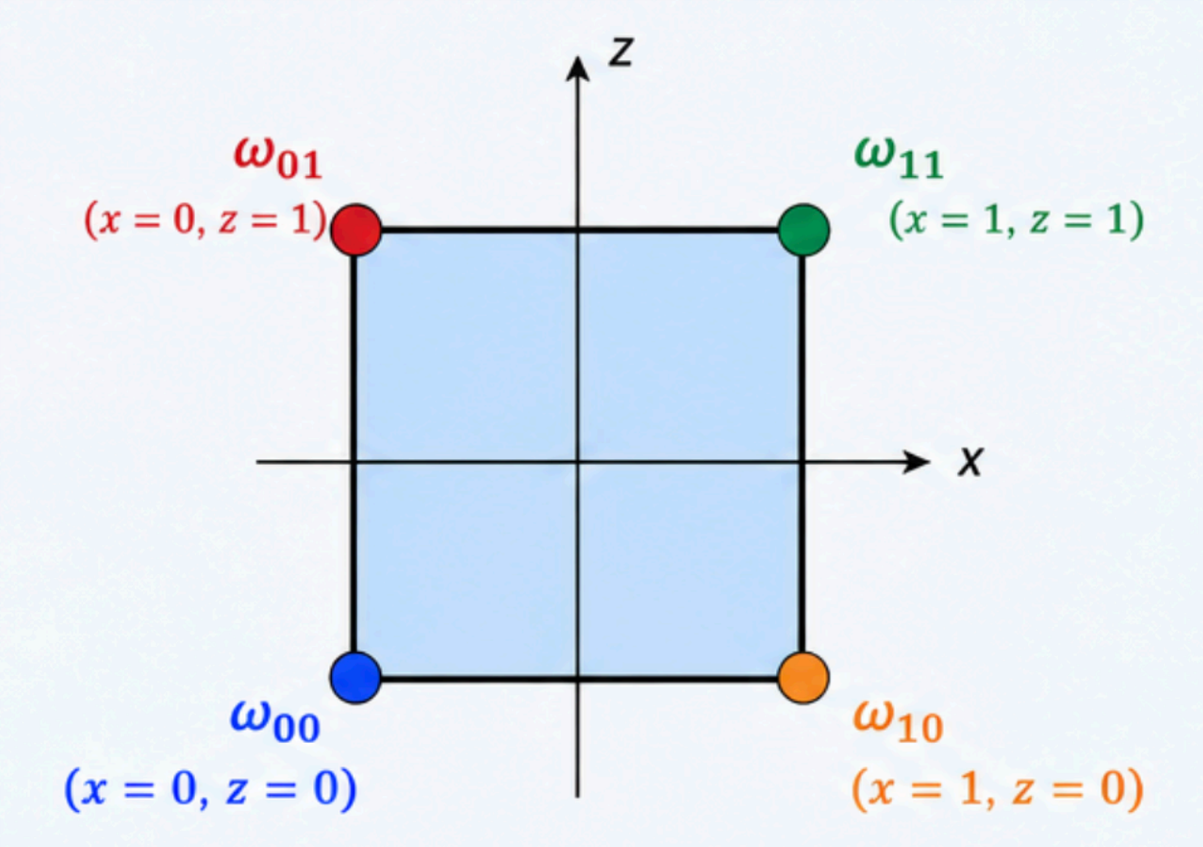

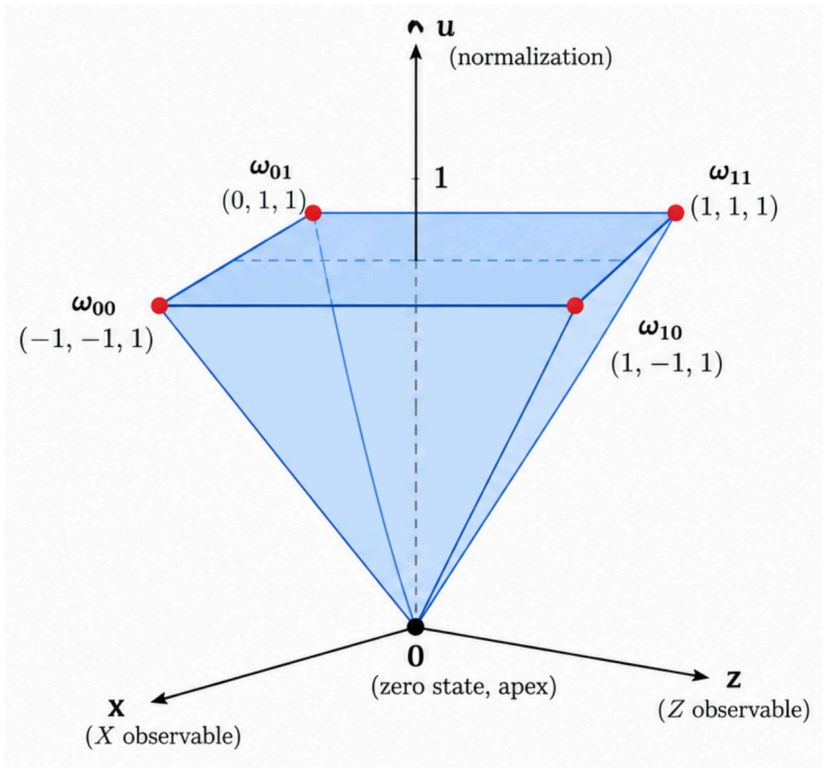

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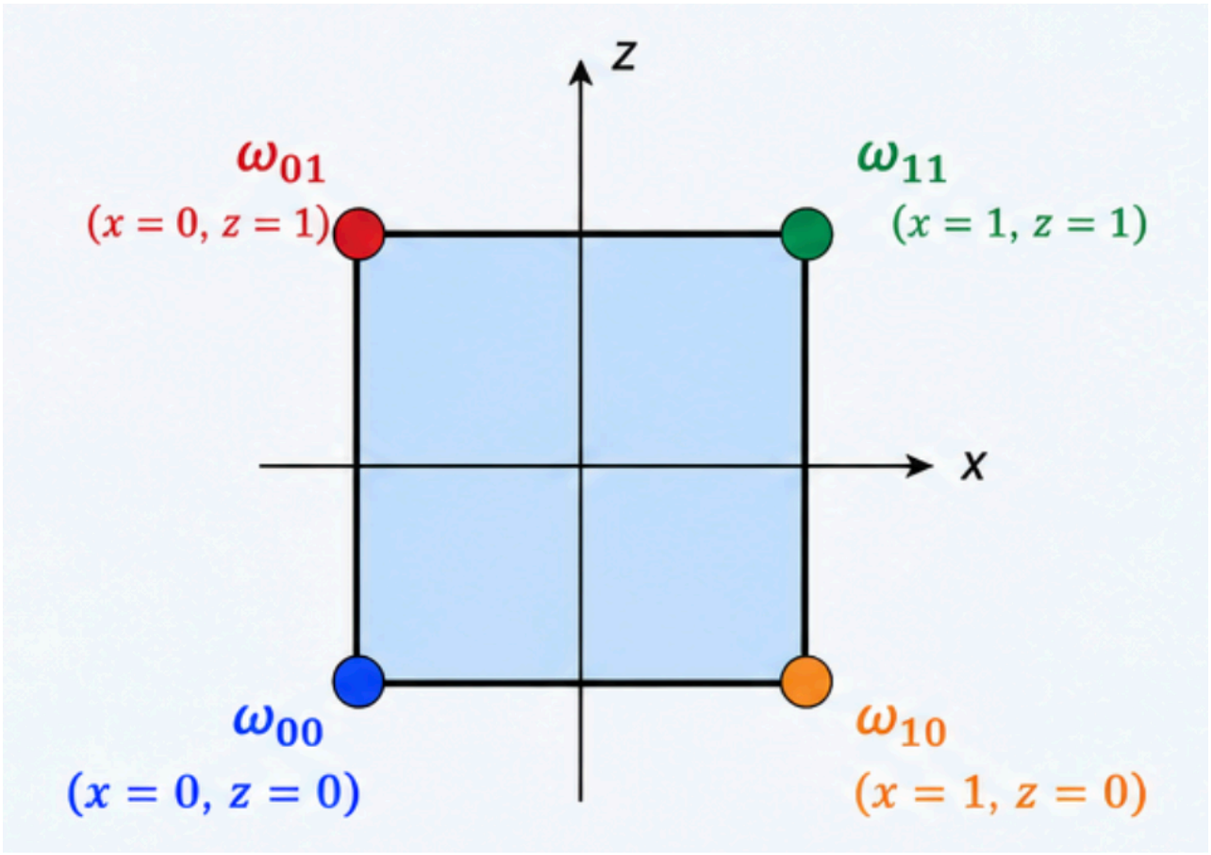

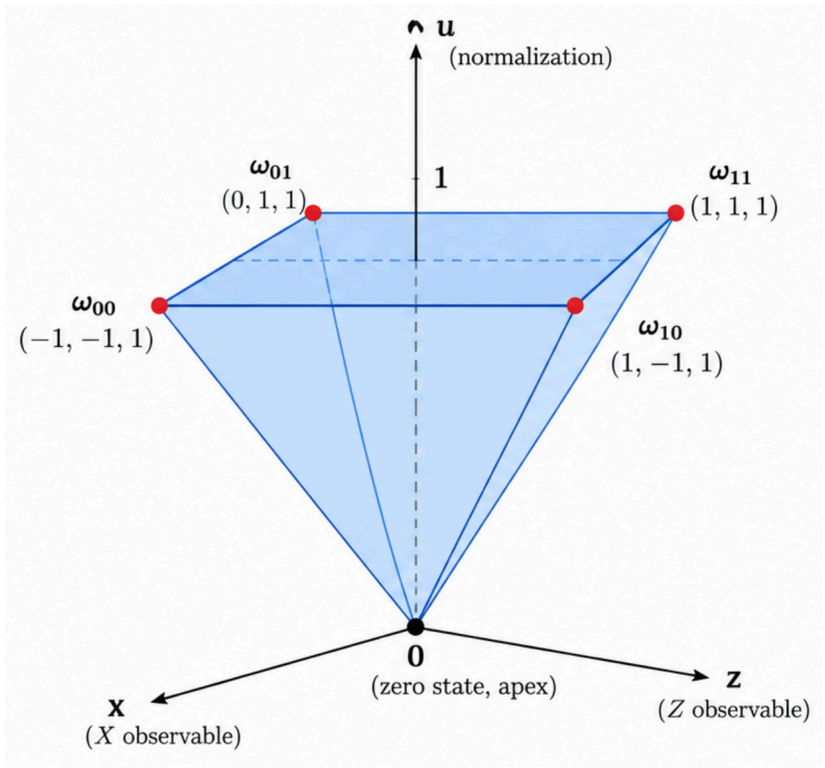

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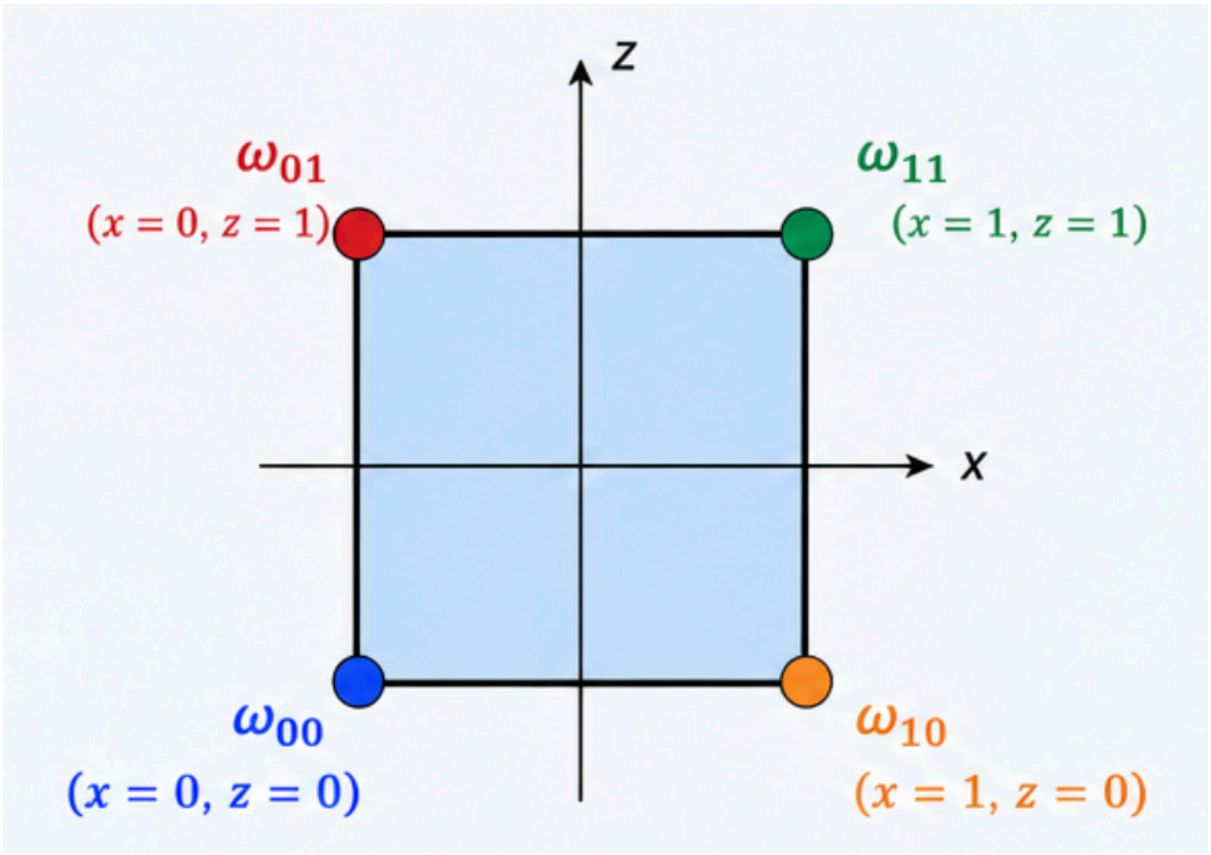

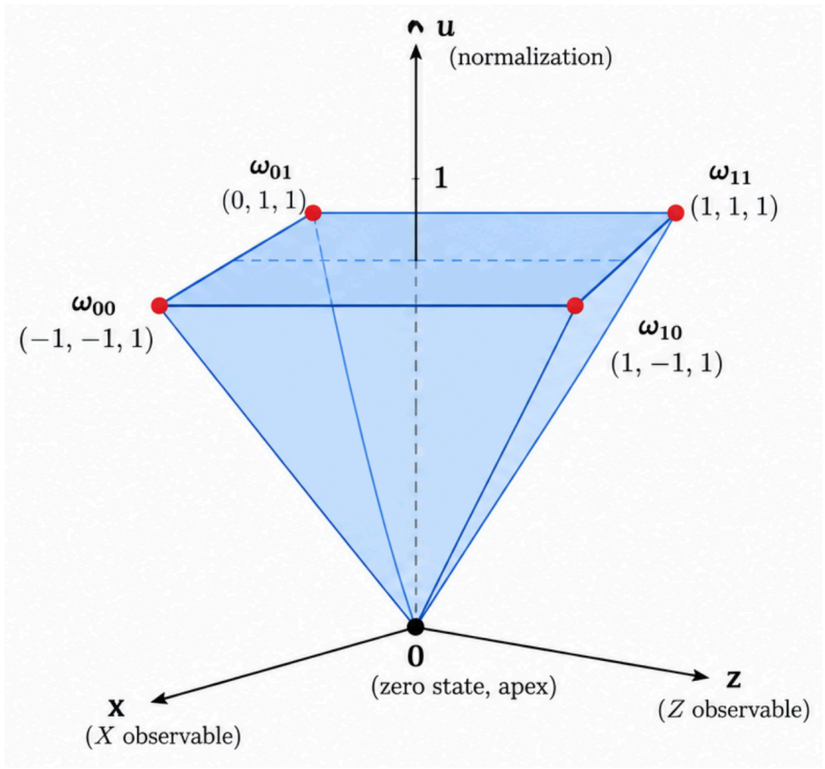

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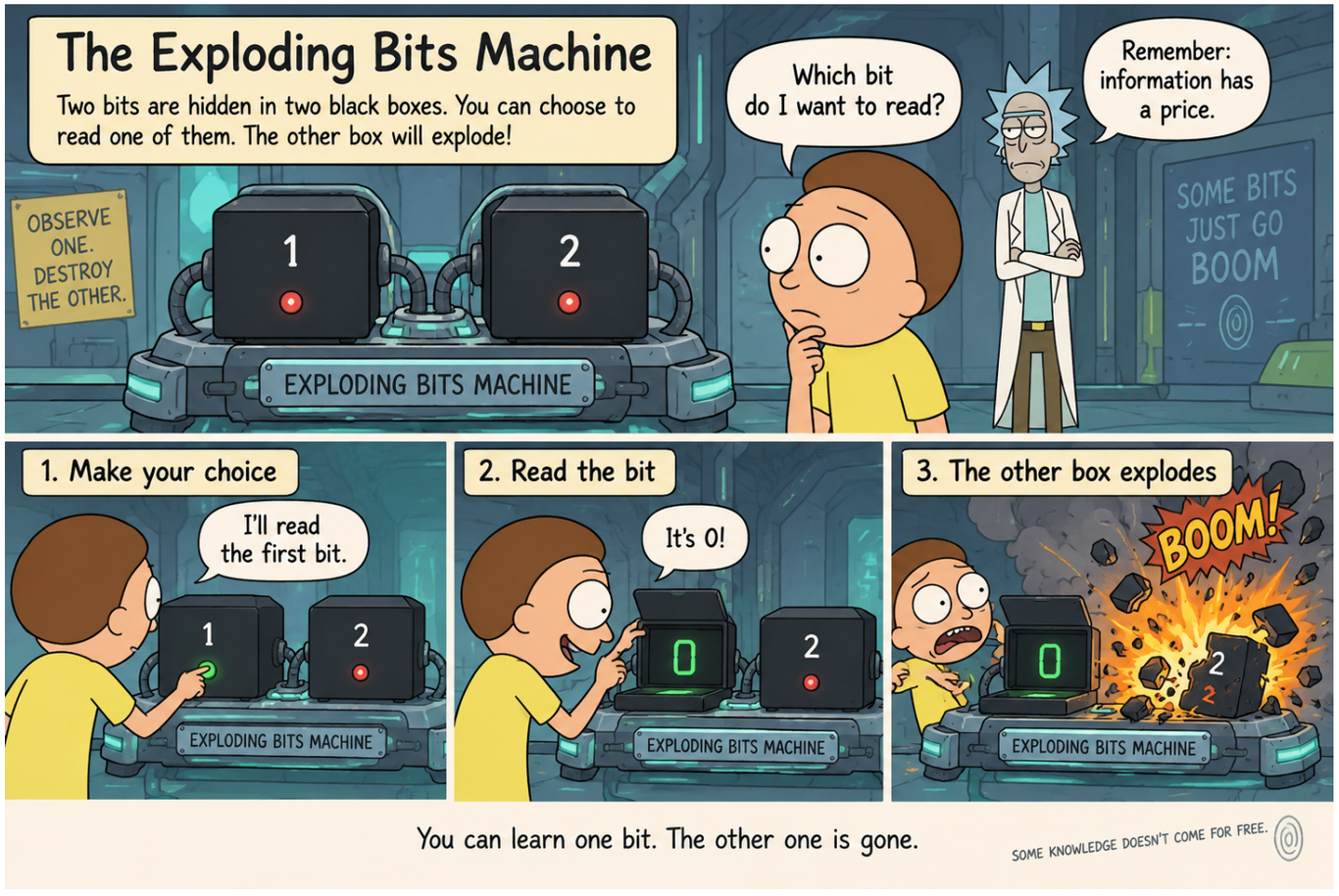

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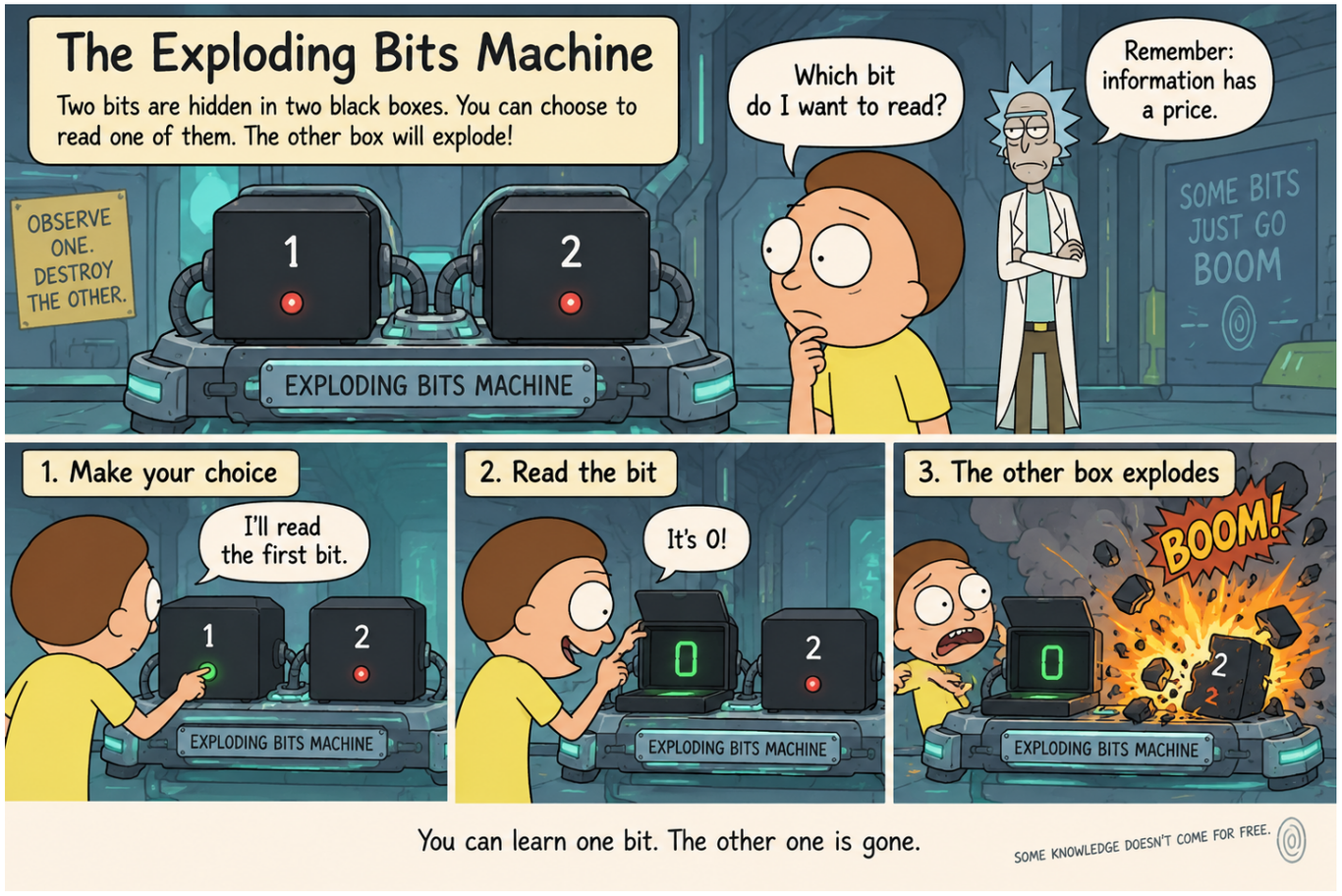

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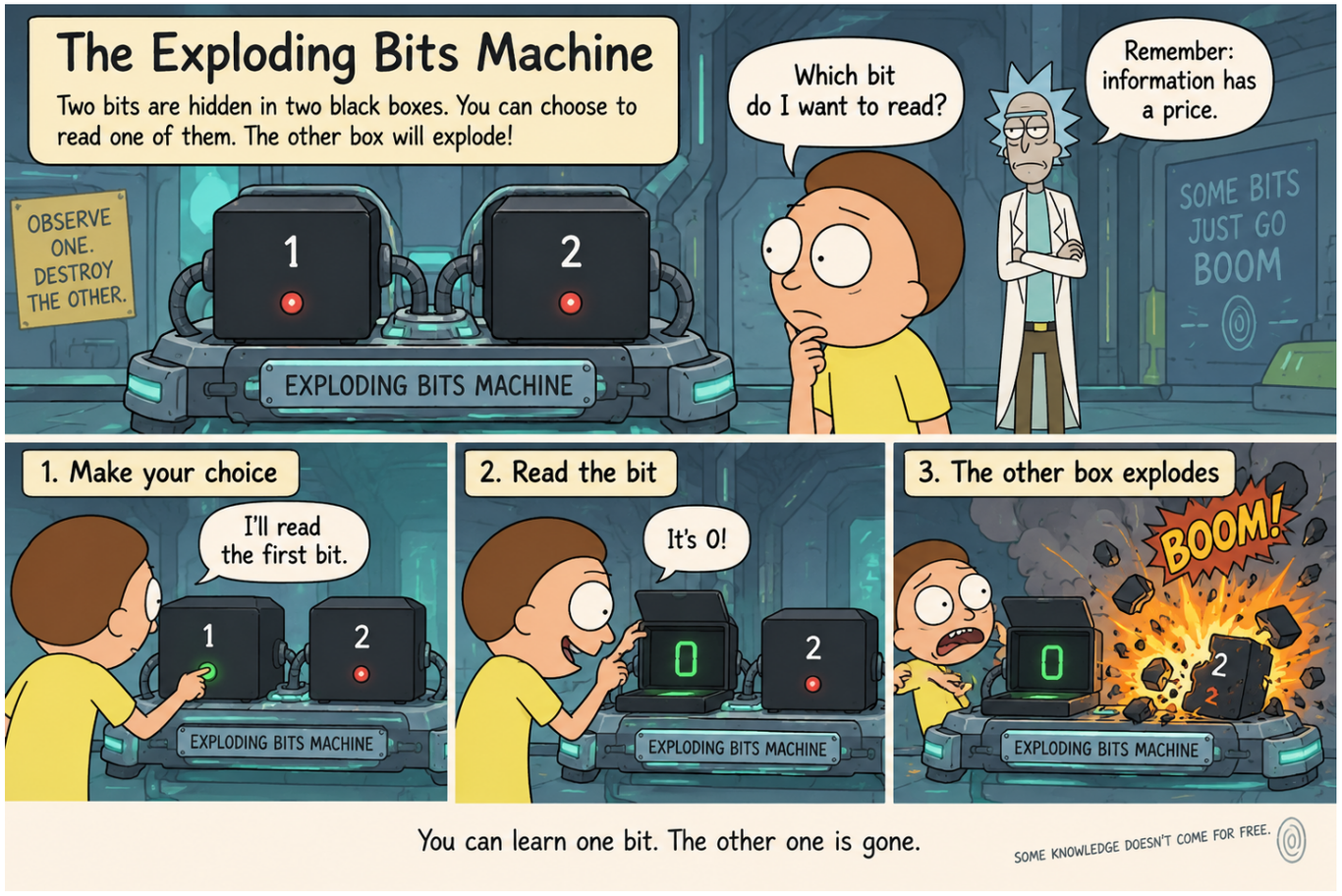

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This would exactly be the case in a classical "exploding bits machine".

Certifying generalized contextuality experimentally

nature COMMUNICATIONS

ARTICLE

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An experimental test of noncontextuality without unphysical idealizations

Michael D. Mazurek[1,2], Matthew F. Pusey[3], Ravi Kunjwal[4], Kevin J. Resch[1,2] & Robert W. Spekkens[3]

To make precise the sense in which nature fails to respect classical physics, one requires a formal notion of classicality. Ideally, such a notion should be defined operationally, so that it can be subject to direct experimental test, and it should be applicable in a wide variety of experimental scenarios so that it can cover the breadth of phenomena thought to defy classical understanding. Bell's notion of local causality fulfils the first criterion but not the second. The notion of noncontextuality fulfils the second criterion, but it is a long-standing question whether it can be made to fulfil the first. Previous attempts to test noncontextuality have all assumed idealizations that real experiments cannot achieve, namely noiseless measurements and exact operational equivalences. Here we show how to devise tests that are free of these idealizations. We perform a photonic implementation of one such test, ruling out noncontextual models with high confidence.

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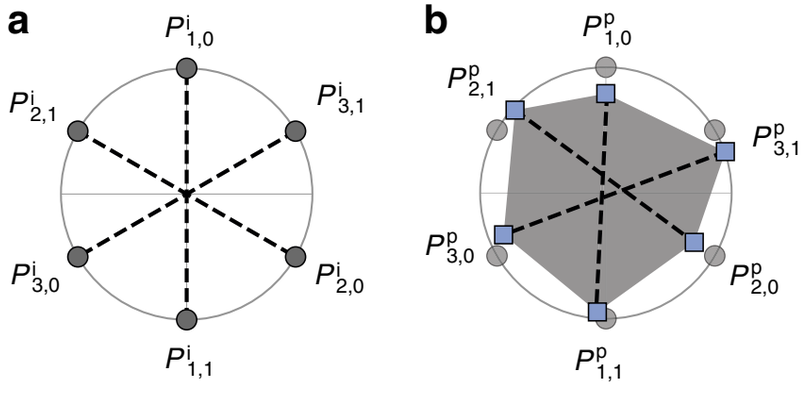
QT admits A=1 for the qubit. The proof is essentially the earlier of Spekkens!



Dealing with inexact operational equivalences

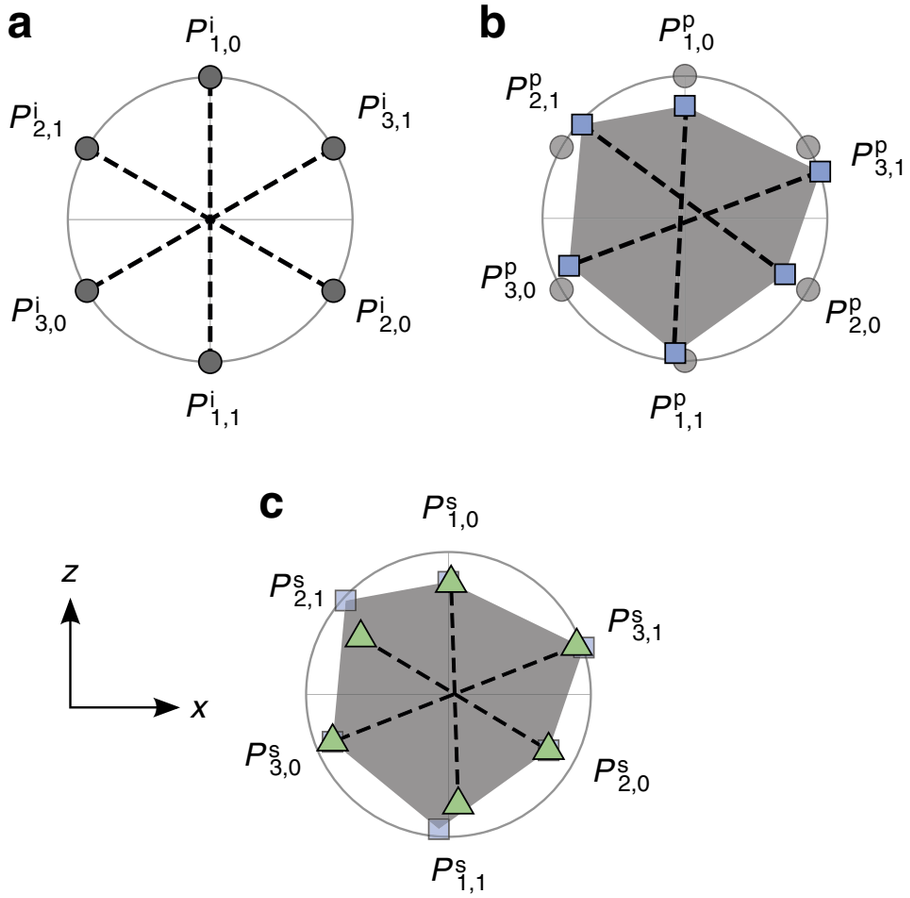


Figure 1 | Solution to the problem of inexact operational equivalences. Here, we illustrate our solution for the case of preparations under the simplifying assumption that these are confined to the $\boldsymbol{x}-\boldsymbol{z}$ plane of the Bloch sphere. For a given pair, $P_{t,0}$ and $P_{t,1}$, the midpoint along the line connecting the corresponding points represents their equal mixture, P_t. (**a**) The target preparations $P^{\mathrm{i}}_{t,b}$, with the coincidence of the midpoints of the three lines illustrating that they satisfy the operational equivalence (4) exactly. (**b**) Illustration of how errors in the experiment (exaggerated in magnitude) will imply that the realized preparations $P^{\mathrm{p}}_{t,b}$ (termed primary) will deviate from the ideal. The lines indicate that not only do these preparations fail to satify the operational equivalence (4), but since the three lines do not all meet at the same point, no mixtures of the $P^{\mathrm{p}}_{t,0}$ and $P^{\mathrm{p}}_{t,1}$ can be found at a single point independent of t. The set of preparations corresponding to probabilistic mixtures of the $P^{\mathrm{p}}_{t,b}$ are depicted by the grey region. (**c**) Secondary preparations $P^{\mathrm{s}}_{t,b}$ have been chosen from this grey region, with the coincidence of the midpoints of the three lines indicating that the operational equivalence (4) has been restored. Note that we require only that the mixtures of the three pairs of preparations be the same, not that they correspond to the completely mixed state.

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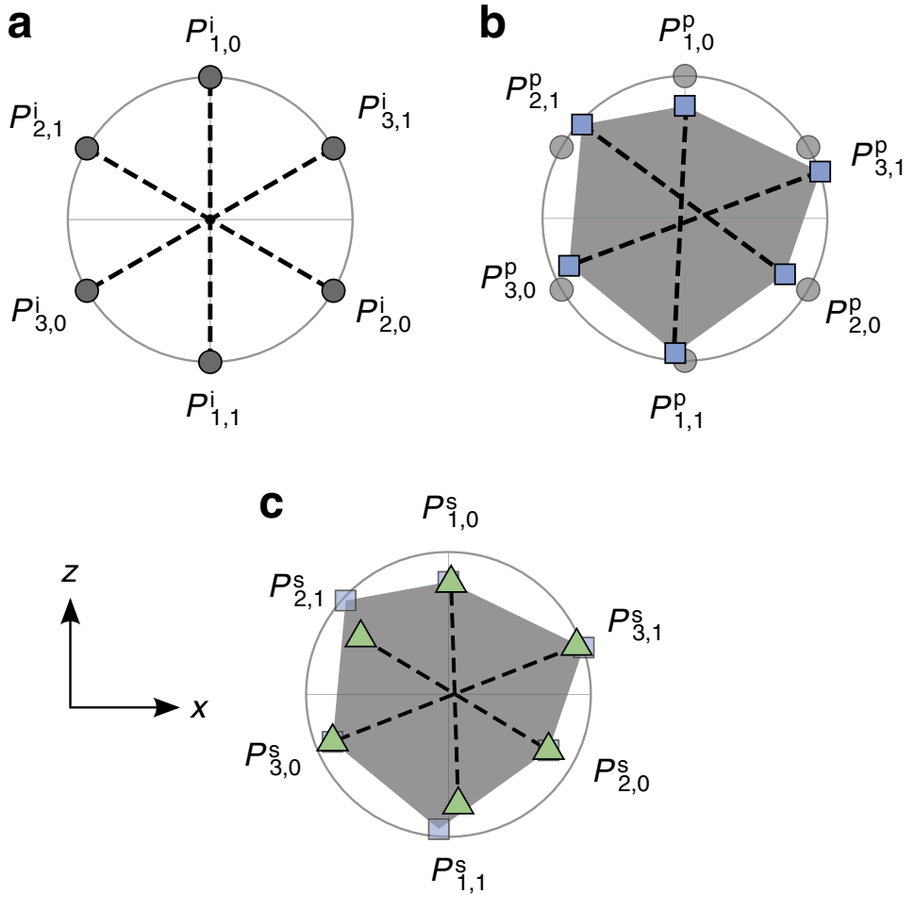

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Intuitively, all this works because of an intuitive form of "continuity" of deformations of convex bodies in finite dimensions.

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Main idea: on some physical system, implement as many preparation and measurement procedures as you can, and record the frequencies (probabilities). Then fit a GPT system to it.

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PRX QUANTUM **2,** 020302 (2021)

Experimentally Bounding Deviations From Quantum Theory in the Landscape of Generalized Probabilistic Theories

Michael D. Mazurek,[1,*,†] Matthew F. Pusey,[2,3,‡] Kevin J. Resch,[1] and Robert W. Spekkens[2]

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[3] *Department of Computer Science, University of Oxford, Wolfson Building, Parks Road, Oxford OX1 3QD, United Kingdom*

(Received 31 August 2020; accepted 1 March 2021; published 2 April 2021)

Many experiments in the field of quantum foundations seek to adjudicate between quantum theory and speculative alternatives to it. This requires one to analyze the experimental data in a manner that does not presume the correctness of the quantum formalism. The mathematical framework of generalized probabilistic theories (GPTs) provides a means of doing so. We present a scheme for determining which GPTs are consistent with a given set of experimental data. It proceeds by performing tomography on the preparations and measurements in a self-consistent manner, i.e., without presuming a prior characterization of either. We illustrate the scheme by analyzing experimental data for a large set of preparations and measurements on the polarization degree of freedom of a single photon. We first test various hypotheses for the

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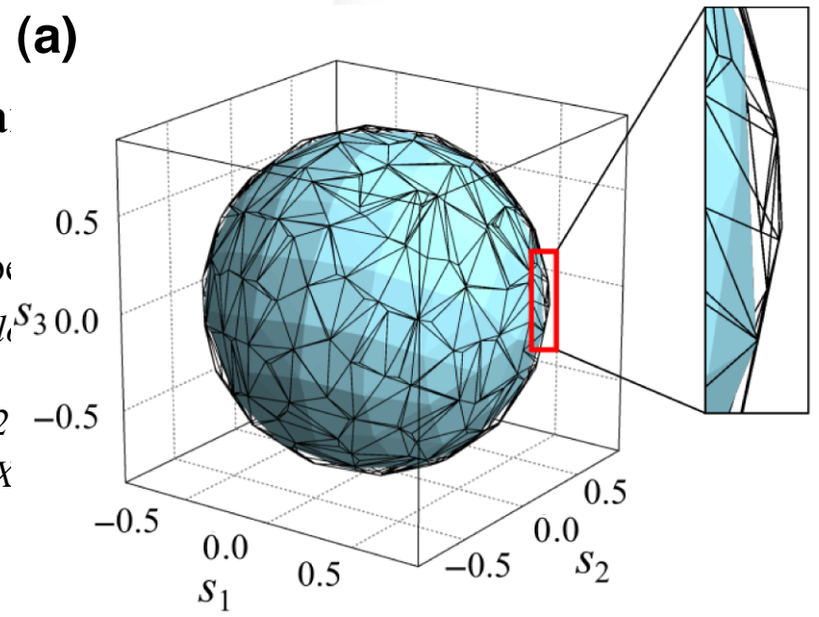

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Factor the matrix *D* numerically to determine *k* and the GPT A.

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nature communications

Article

https://doi.org/10.1038/s41467-026-69030-x

Theory-independent monitoring of the decoherence of a superconducting qubit with generalized contextuality

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Accepted: 23 January 2026

Published online: 07 February 2026

Check for updates

Albert Aloy[1,2], Matteo Fadel[3], Thomas D. Galley[1,2], Caroline L. Jones[1,2] & Markus P. Müller[1,2,4]

Characterizing the nonclassicality of quantum systems under minimal assumptions is an important challenge for quantum foundations and technology. Here we introduce a theory-independent method of process tomography and perform it on a superconducting qubit. We demonstrate its decoherence without assuming quantum theory or trusting the devices by modelling the system as a general probabilistic theory. We show that the superconducting system is initially well-described as a quantum bit, but that its realized state space contracts over time, which in quantum terminology indicates its loss of coherence. The system is initially nonclassical in the sense of generalized contextuality: it does not admit of a hidden-variable model where statistically indistinguishable preparations are represented by identical hidden-variable distributions. In finite time, the system becomes non-contextual and hence loses its nonclassicality. Moreover, we demonstrate in a theory-independent way that the system undergoes non-Markovian evolution at late times. Our results extend theory-independent tomography to time-evolving systems, and show how important dynamical physical phenomena can be experimentally monitored without assuming quantum theory.

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Characterizing the nonclassicality of quantum systems under minimal assumptions is an important challenge for quantum foundations and technology. Here we introduce a theory-independent method of process tomography and perform it on a superconducting qubit. We demonstrate its decoherence without assuming quantum theory or trusting the devices by modelling the system as a general probabilistic theory. We show that the superconducting system is initially well-described as a quantum bit, but that its realized state space contracts over time, which in quantum terminology indicates its loss of coherence. The system is initially nonclassical in the sense of generalized contextuality: it does not admit of a hidden-variable model where statistically indistinguishable preparations are represented by identical hidden-variable distributions. In finite time, the system becomes non-contextual and hence loses its nonclassicality. Moreover, we demonstrate in a theory-independent way that the system undergoes non-Markovian evolution at late times. Our results extend theory-independent tomography to time-evolving systems, and show how important dynamical physical phenomena can be experimentally monitored without assuming quantum theory.

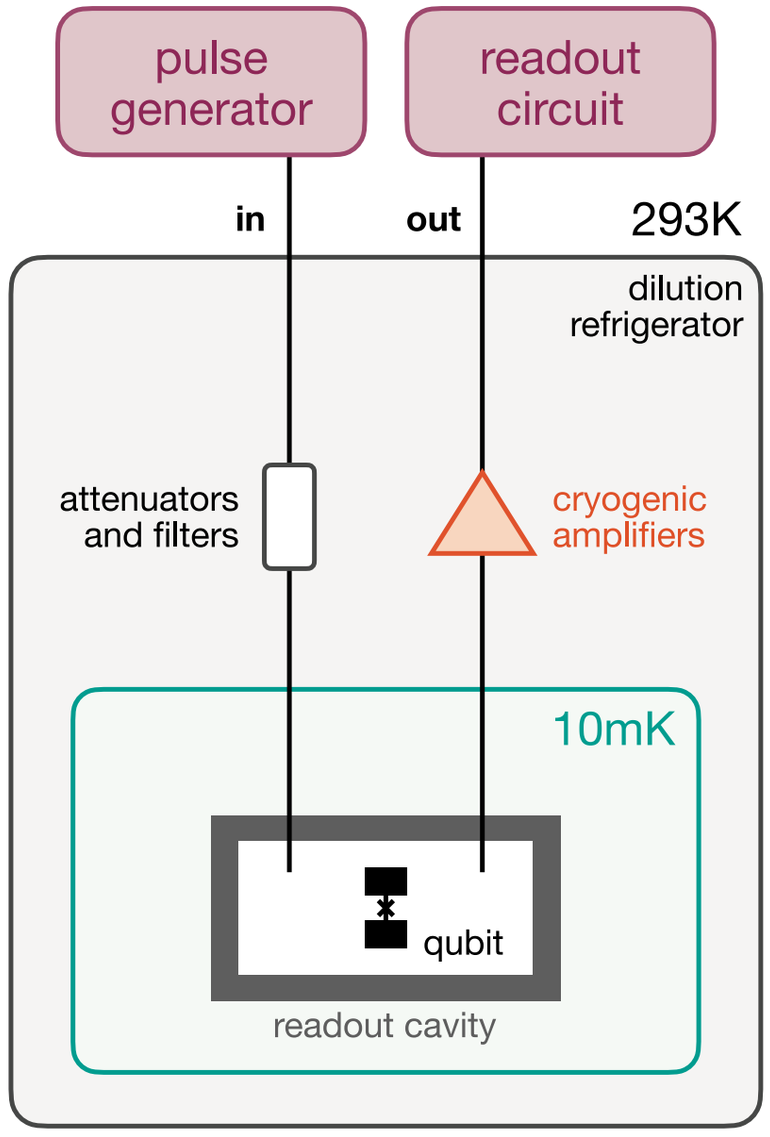

Fig. 9 | Schematic illustration of the experimental setup used in this work. The superconducting qubit device used in this work is hosted inside a three-dimensional microwave cavity cooled down at cryogenic temperature by a dilution refrigerator. Qubit state preparation and readout are controlled by microwave electronics at room temperature.

Please don't ask me... :)

Doing this to track time evolution theory-independently

nature communications

Article

https://doi.org/10.1038/s41467-026-69030-x

Theory-independent monitoring of the decoherence of a superconducting qubit with generalized contextuality

Received: 6 December 2024

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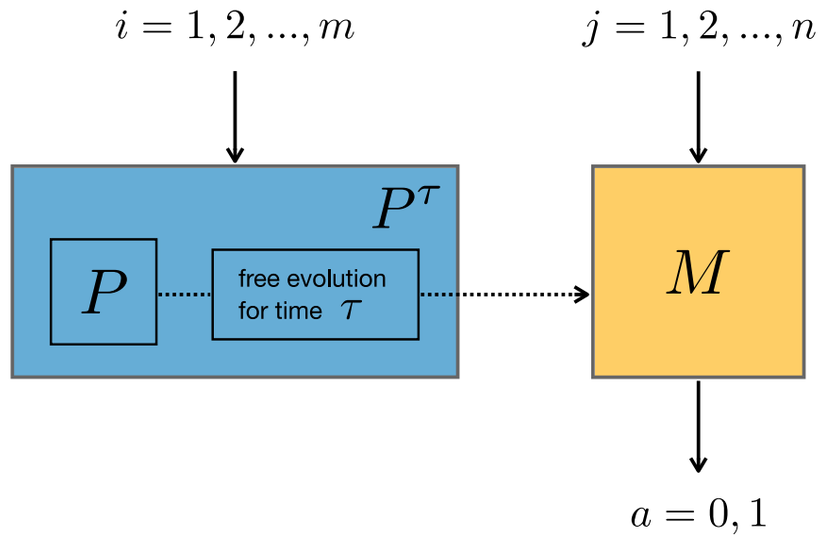

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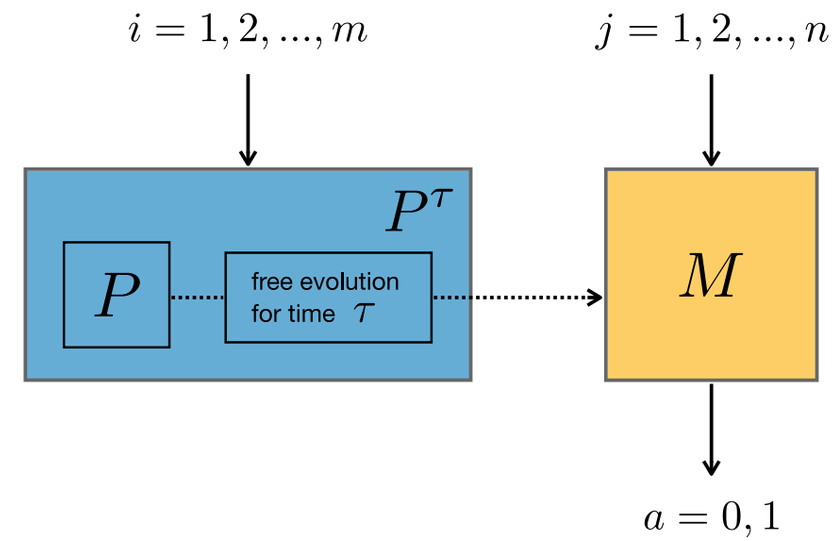

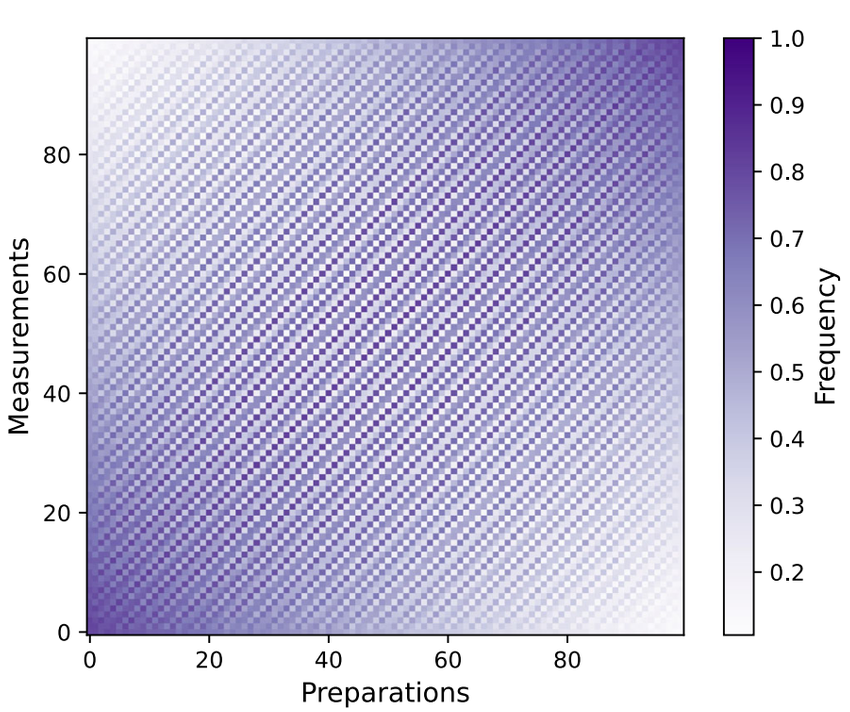

Fig. 2 | Frequency data collected in the experiment. Experimentally measured frequency of occurrence of the outcome $a = 0$ for the $m \times n$ table of preparations and measurements, for $\tau = 0$.

m=n=100, repeated 2000 times.

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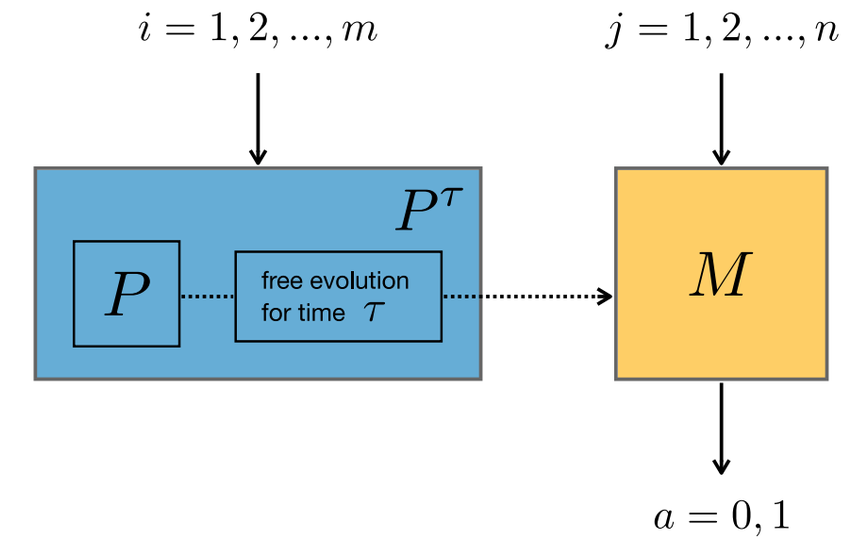

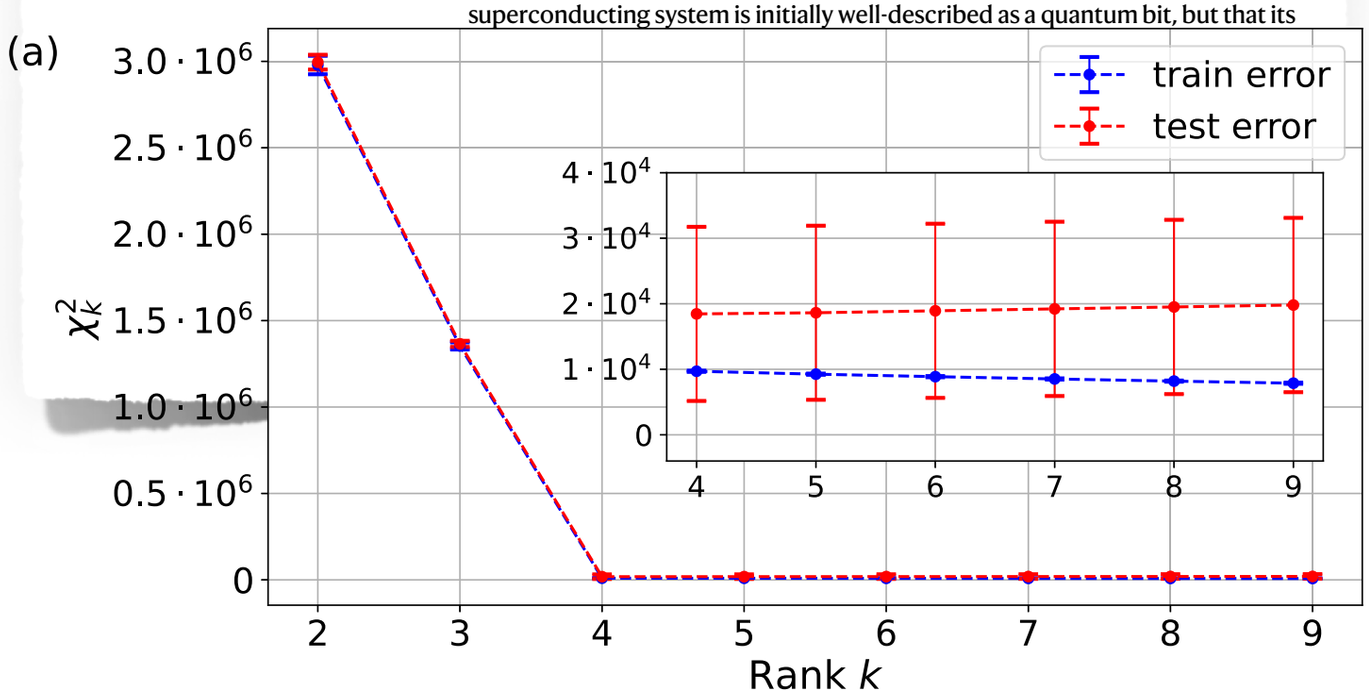

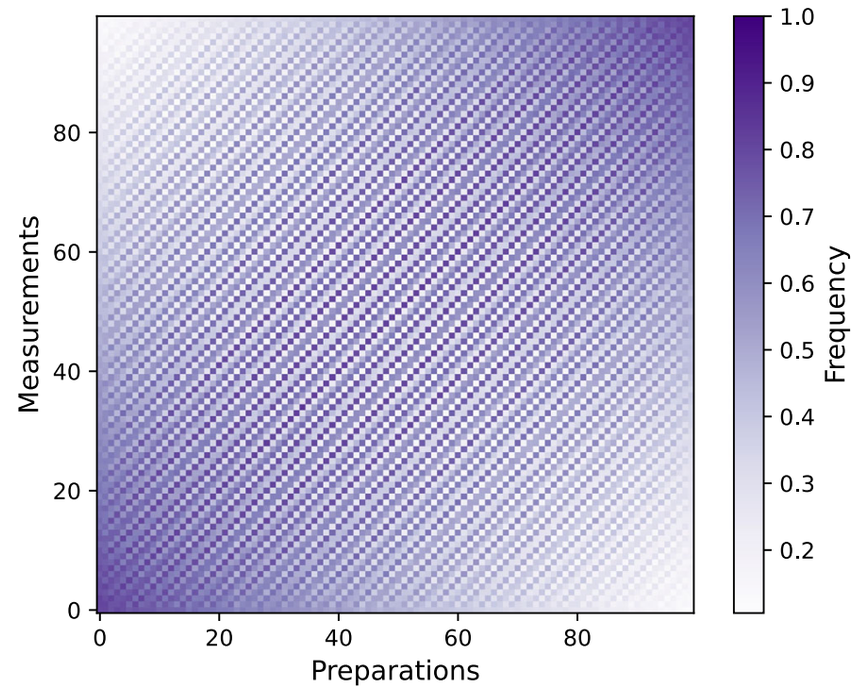

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Rank k=4 as the best explanation.

m=n=100, repeated 2000 times.

Result: it looks like a decohering Bloch ball...

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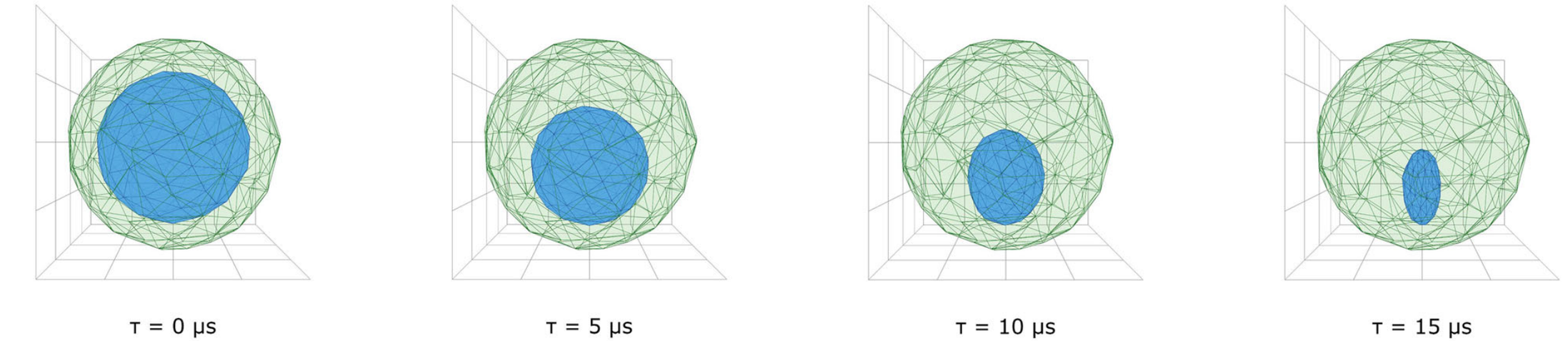

Fig. 6 | Evolution of the state space for different delay times. Plots of the consistent state space $\mathcal{S}_{\text{consistent}}$ (green) for all preparations, and realized state spaces $\mathcal{S}^{\tau}$ (blue) for varying wait times τ = [0, 5, 10, 15, 20, 30, 40, 50] μs.

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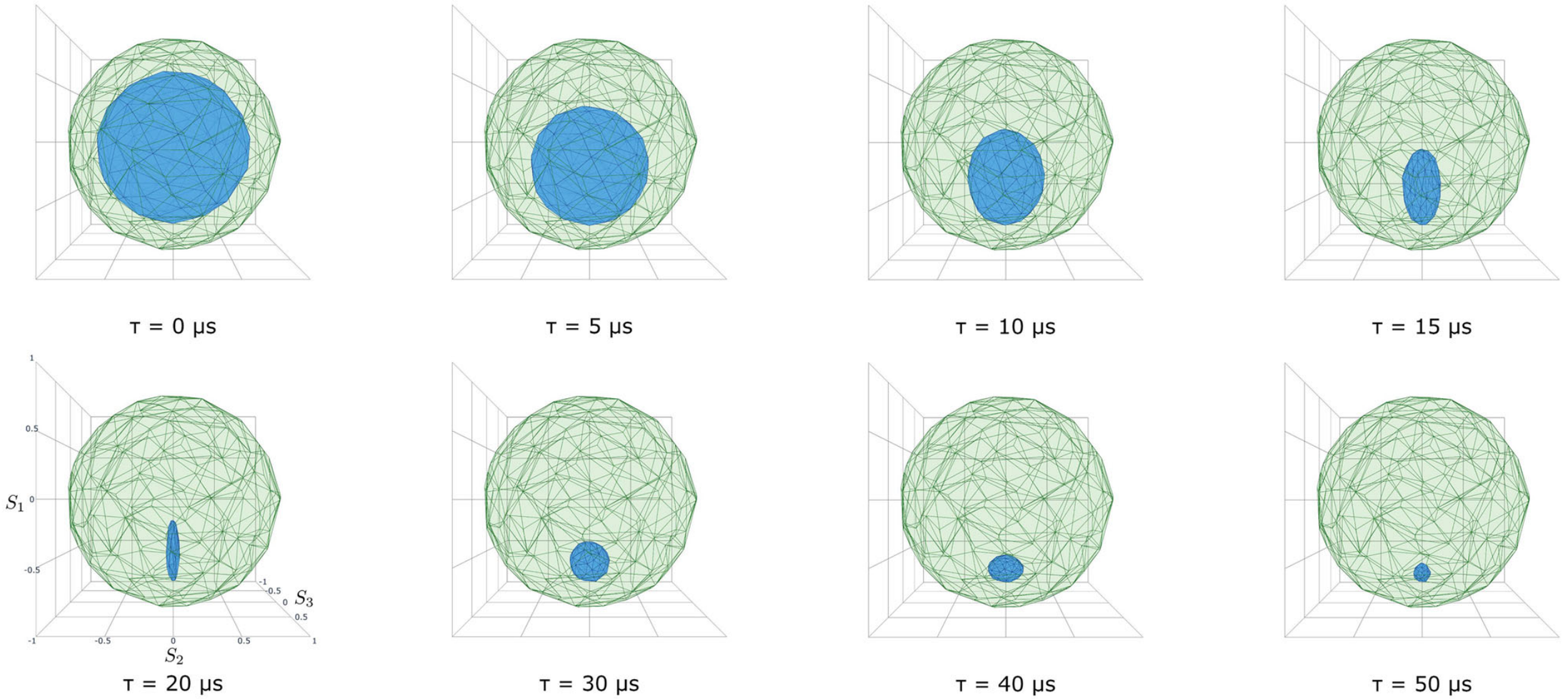

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Green: the set of vectors which would yield nonnegative probabilities on all numerically determined effects (max. possible state space)

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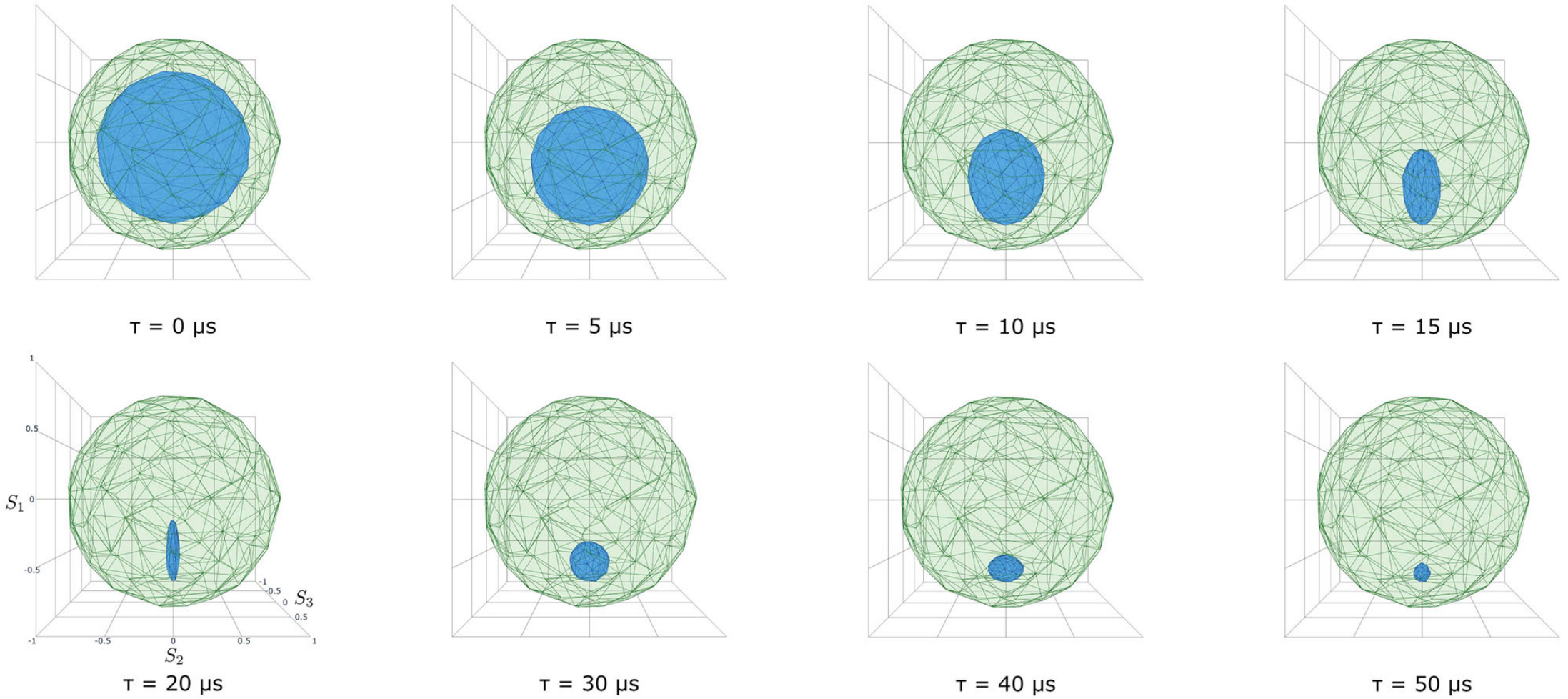

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"Movie" of the decoherence process without assuming quantum theory!

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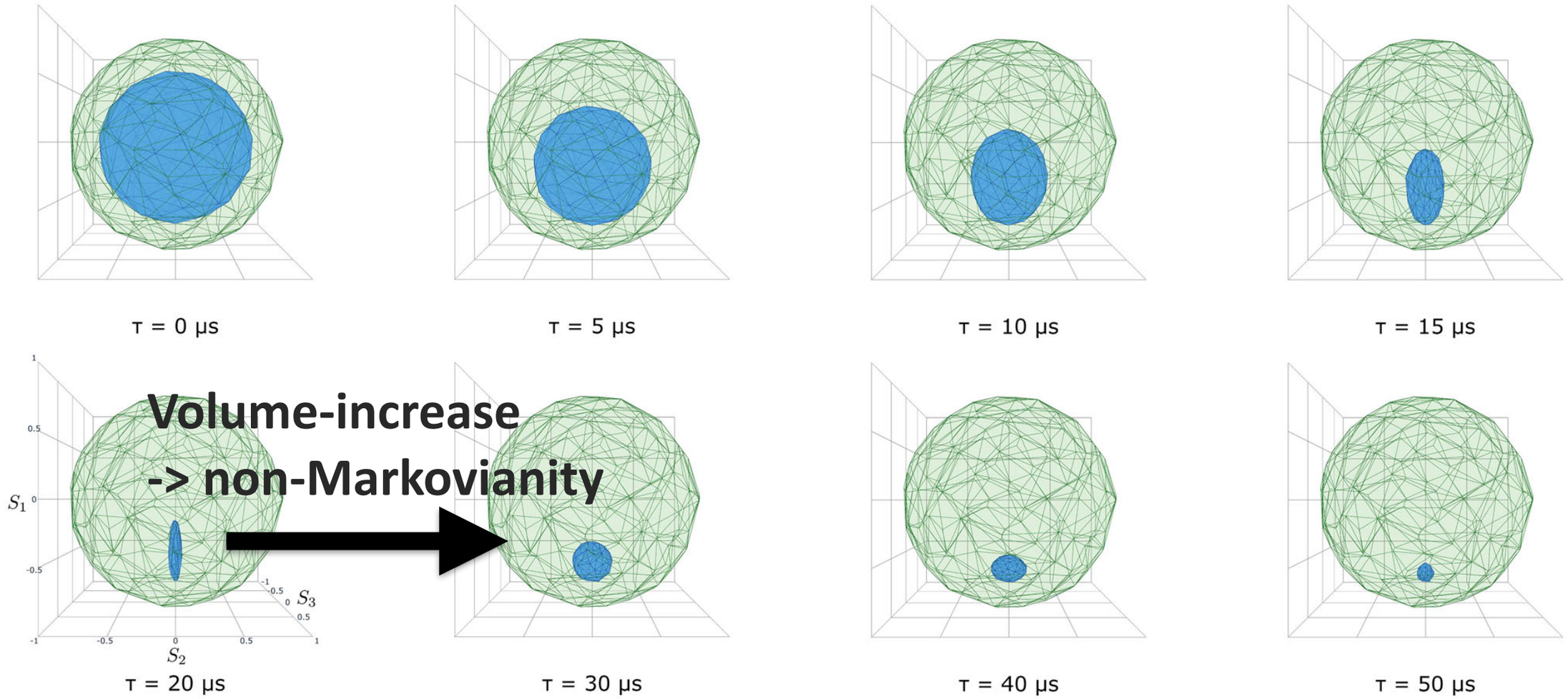

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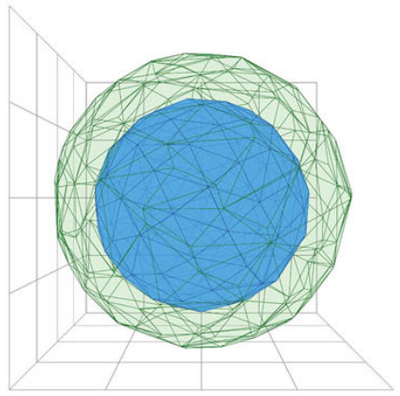
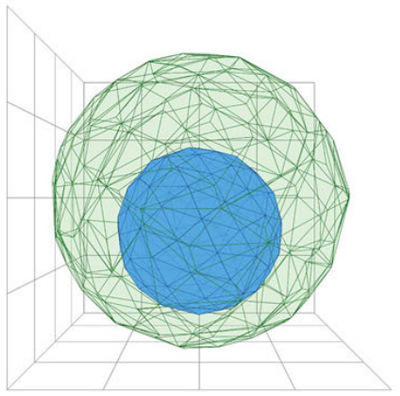
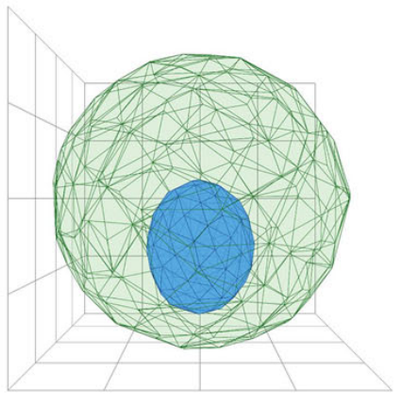
Systems becomes **noncontextual** between 10 and 15 µs



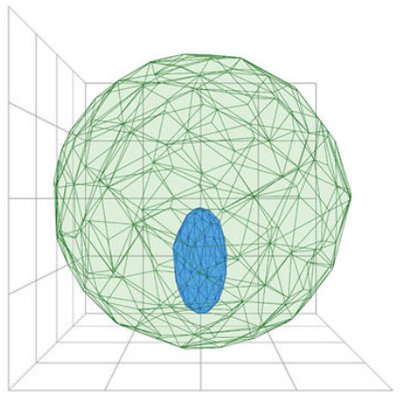
τ = 0 µs



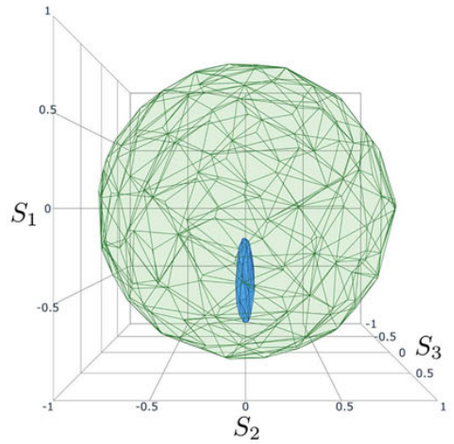
τ = 5 µs



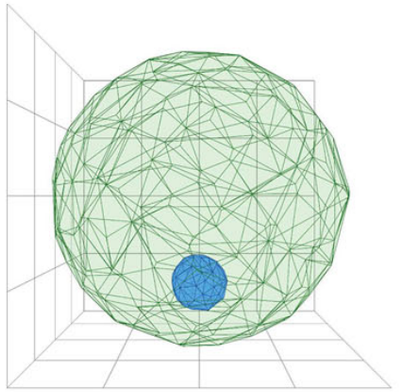
τ = 10 µs



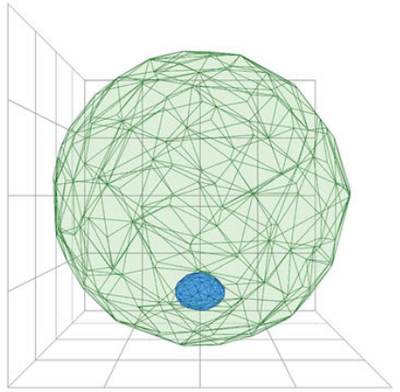
τ = 15 µs



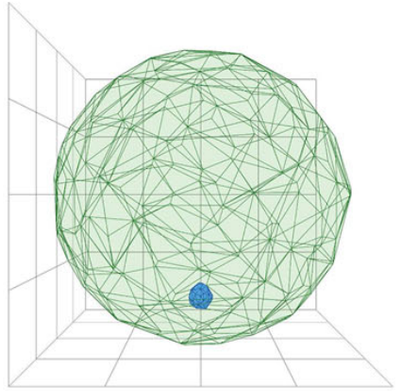
τ = 20 µs



τ = 30 µs



τ = 40 µs



τ = 50 µs

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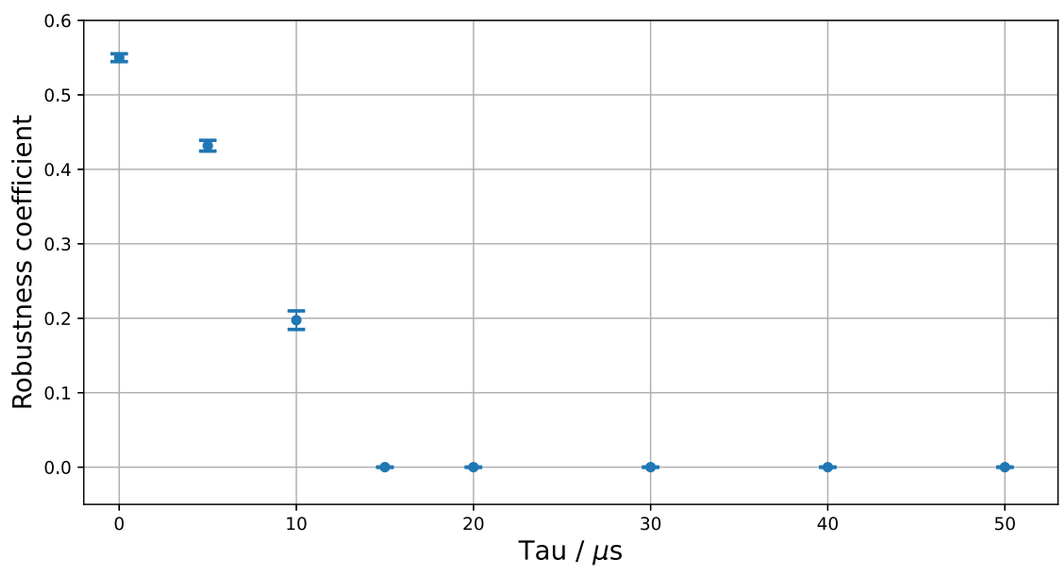
Amount of uniform noise r that has to be added such that the GPT system becomes noncontextual.
r>0 means generalized contextuality.



How to determine whether some complicated GPT is contextual?

PHYSICAL REVIEW LETTERS **132,** 050202 (2024)

Linear Program for Testing Nonclassicality and an Open-Source Implementation

John H. Selby,[1,*] Elie Wolfe,[2,†] David Schmid,[1,‡] Ana Belén Sainz,[1,§] and Vinicius P. Rossi[1,‖]
[1]*International Centre for Theory of Quantum Technologies, University of Gdańsk, 80-309 Gdańsk, Poland*
[2]*Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, Ontario N2L 2Y5, Canada*

(Received 16 November 2022; revised 12 November 2023; accepted 22 December 2023; published 30 January 2024)

A well-motivated method for demonstrating that an experiment resists any classical explanation is to show that its statistics violate generalized noncontextuality. We here formulate this problem as a linear program and provide an open-source implementation of it which tests whether or not any given prepare-measure experiment is classically explainable in this sense. The input to the program is simply an arbitrary set of quantum states and an arbitrary set of quantum effects; the program then determines if the Born rule statistics generated by all pairs of these can be explained by a classical (noncontextual) model. If a classical model exists, it provides an explicit model. If it does not, then it computes the minimal amount of noise that must be added such that a model does exist, and then provides this model. We generalize all these results to arbitrary generalized probabilistic theories (and accessible fragments thereof) as well; indeed, our linear program is a test of simplex embeddability as introduced in Schmid *et al.* [PRX Quantum **2**, 010331 (2021).] and generalized in Selby *et al.* [Phys. Rev. A **107**, 062203 (2023).].

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- Input: either the description of a GPT system, or of a set of quantum states and measurements.
- Output: whether it is **simplex-embeddable** and, if not, **amount r>0** of uniform noise that has to be added to become simplex-embeddable. Certifying r>0 replaces in some sense the violation of a NC inequality.

On the arXiv yesterday (**arXiv:2609.18671**)

On the arXiv yesterday (**arXiv:2609.18671**)

Theory-agnostic nonclassicality certification in an integrated photonic circuit

Vinicius P. Rossi*[1], Emanuele Polino*[2], Beatrice Polacchi[3,4], Valeria Cimini[3], David Schmid[5], John H. Selby[1], Giacomo Corrielli[6], Andrea Crespi[7,6], Roberto Osellame[6], Fabio Sciarrino[3], and Ana Belén Sainz[1,8]

Certifying nonclassicality without assuming any particular underlying physical theory constitutes both a foundational challenge and a requirement for device-independent protocols. Realizing such theory-independent certification in scalable architectures is essential for connecting fundamental tests with emerging quantum technologies. Integrated photonic circuits are a leading platform for scalable quantum information processing, motivating the development of rigorous methods to certify the nonclassical resources underpinning quantum advantage. In this paper, we report a theory-independent certification of generalized contextuality on a three-mode integrated photonic circuit. Our approach combines theory-agnostic tomography with simplex-embeddability certification—a framework that requires no assumptions about the underlying physical theory—and applies it to experimental data from a three-mode photonic circuit seeded by single photons. An independently constructed quantum model of the experiment provides a consistency check on the observed nonclassicality, without entering the certification as a theoretical assumption. The method rules out simplex-embeddability for our experimental data, providing robust, theory-independent evidence that our photonic circuit exhibits nonclassicality.

Topics of the lectures -- any questions?

- QT as a theory of probability
- Generalized Probabilistic Theories
- Reconstructions of QT from simple principles
- The gbit and its "exploding bits" model
- Kochen-Specker Contextuality
- (Spekkens') Generalized Contextuality
- Simplex embeddability
- The stabilizer qubit / short digression on computational speedup
- Noncontextuality inequalities
- GPT tomography and theory-independent experimental certification

The slides will soon be available on mpmueller.net. Some references:

- R. W. Spekkens, *Contextuality for preparations, transformations, and unsharp measurements*, Phys. Rev. A **71**, 052108 (2005).
- D. Schmid et al., *Characterization of Noncontextuality in the Framework of GPTs*, PRX Quantum **2**, 010331 (2021).
- M. P. Müller, *Probabilistic Theories and Reconstructions of QT (Les Houches Lecture Notes)*, SciPost Lect. Notes **28** (2021).
- M. D. Mazurek et al., *An experimental test of noncontextuality without unphysical idealizations*, Nat. Commun. **7**, 11780 (2016).
- M. D. Mazurek et al., *Experimentally Bounding Deviations From Quantum Theory in the Landscape of Generalized Probabilistic theories*, PRX Quantum **2**, 020302 (2021).
- A. Aloy et al., *Theory-independent monitoring of the decoherence of a superconducting qubit with generalized contextuality*, Nat. Commun. **17**, 2474 (2026).