Experimental demonstration of non-local magic in a superconducting quantum processor

*or
The story of bringing experiment and theory together
(Pragma (πρᾶγμα): Enduring, long-lasting love that develops over a long time.)

Theory

Università degli Studi di Napoli Federico II

NQSTI
National Quantum Science and Technology Institute

INFN
NAPOLI
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

Experiment

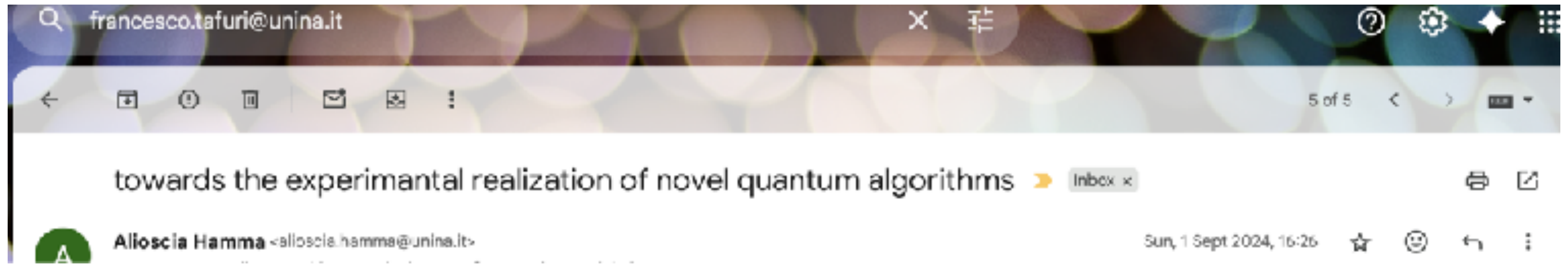
Jovan Odavić 25/06/2026 - IQT Nordics Symposium

UniNA quantum computer

- Unina host the first public quantum computer in Italy
- We were fortunate to start a collaboration

Prof. Tafuri at the unveiling of the first Italian public UniNA

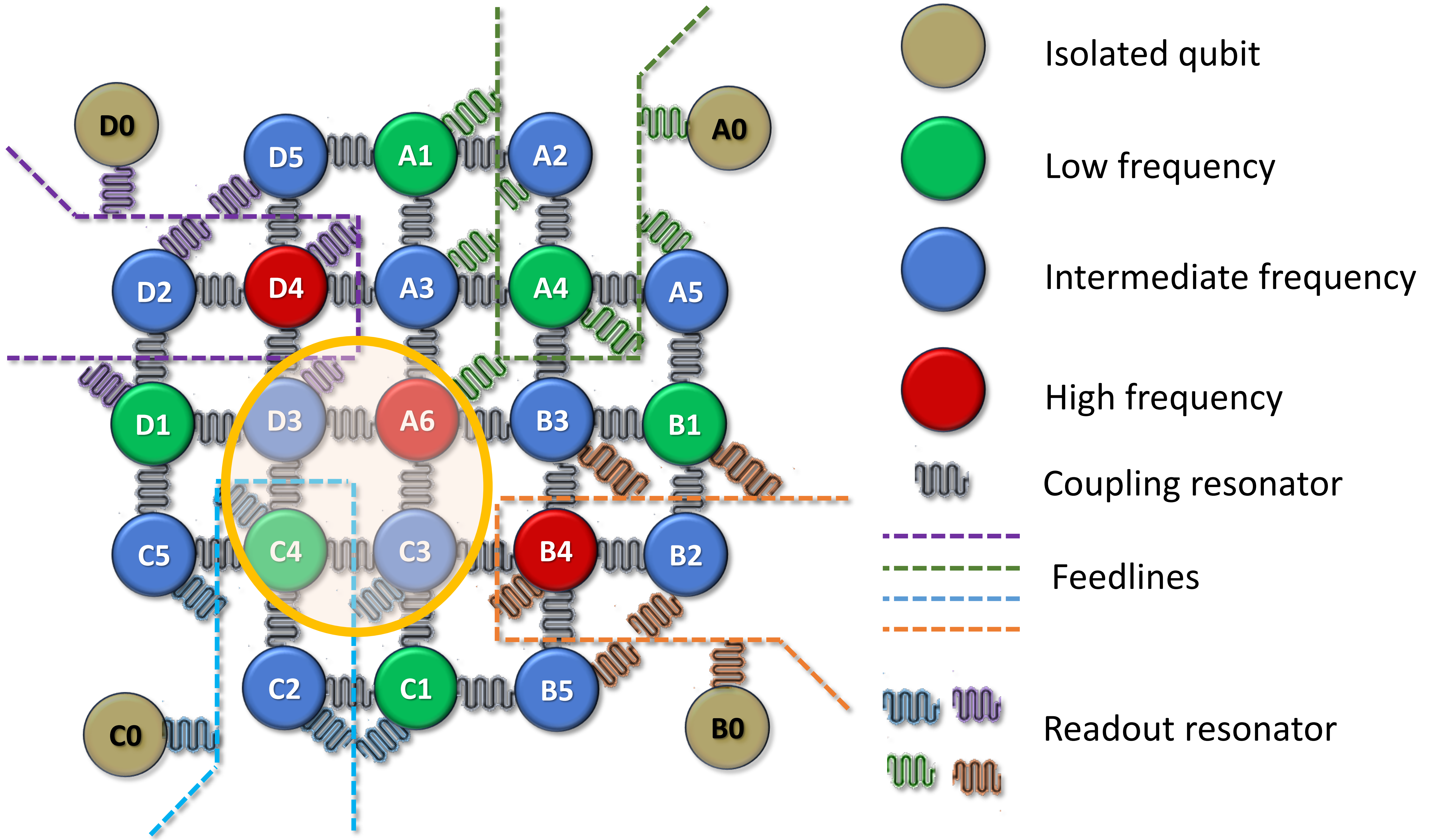
The collaboration - almost 2 years in the making



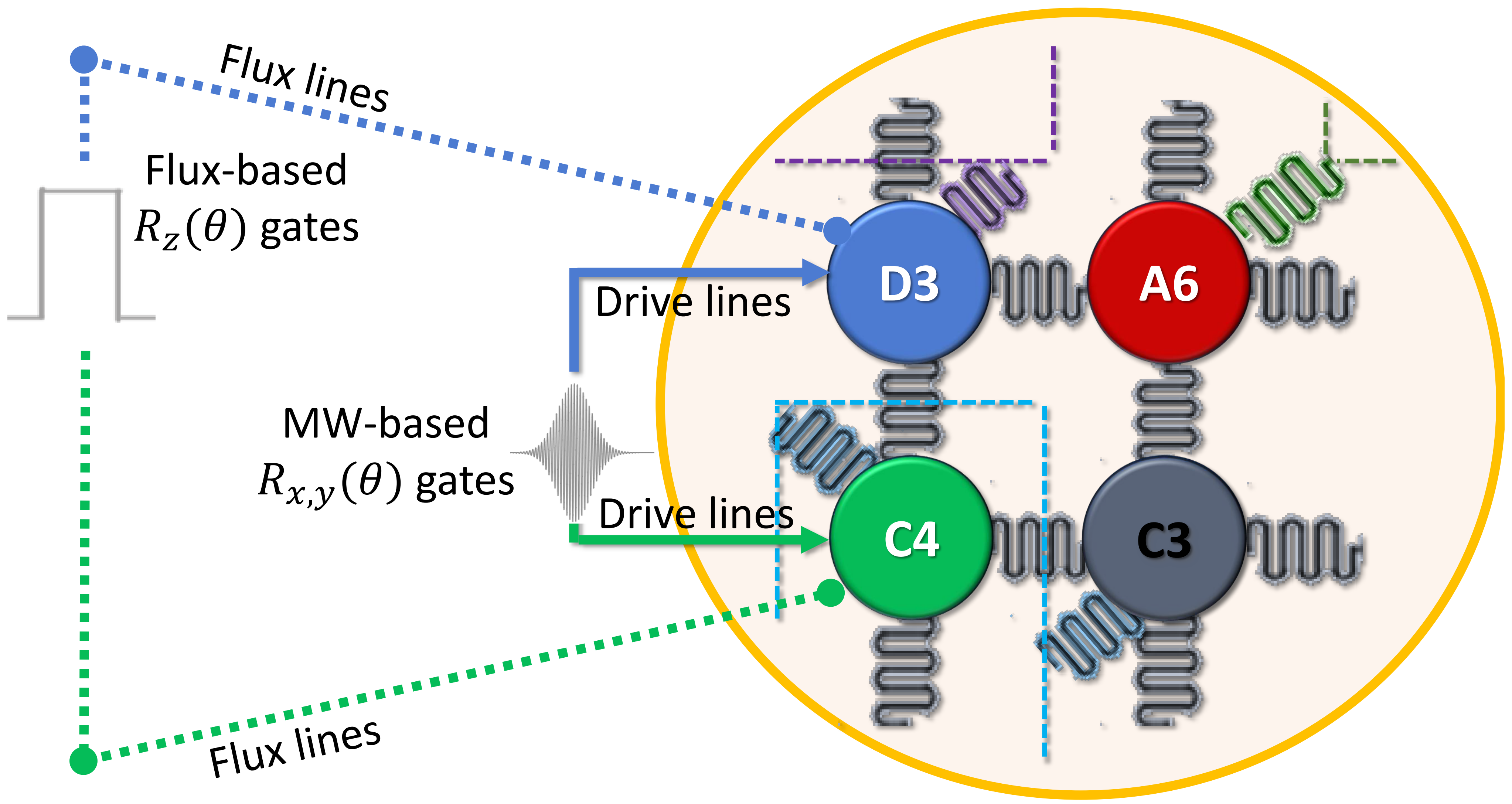
Theory group of Prof. Hamma

Experimental group of Prof. Tafuri

The quantum processing unit (QPU) - a Noisy Intermediate Scale Quantum (NISQ) chip



Superconducting Quantum Processing unit. Schematics of the processor. In yellow, isolated fixed-frequency qubits; in red, blue and green the high-, intermediate- and low-frequency qubits, respectively.



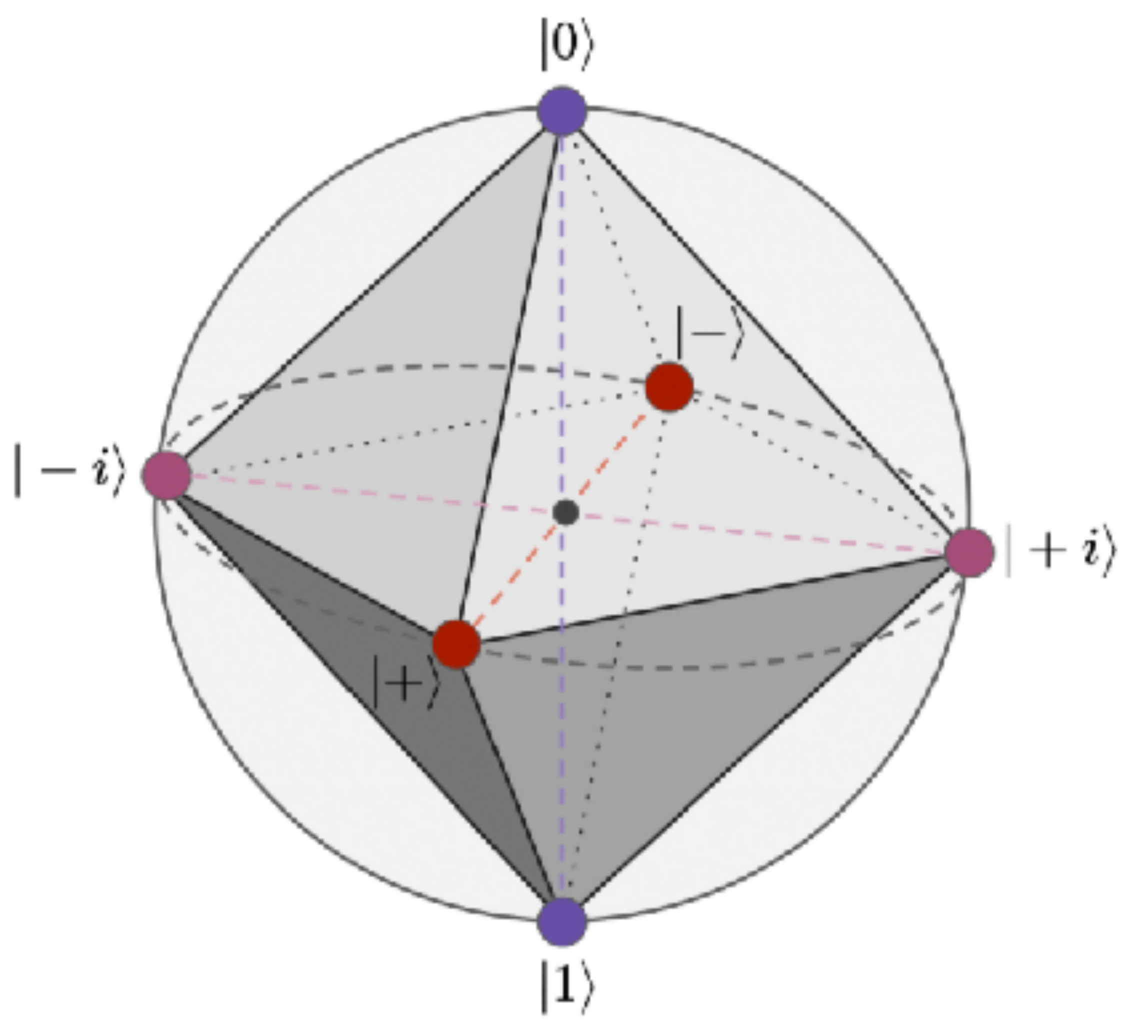
Focus on the investigated pair (D3-C4), coupled with a high-frequency qubit (A6), parked at its sweet spot and a low-frequency qubit (C3) at the anti-sweet spot (in black).

60+ qubit processor coming soon, but also for custom architecture developed at UniNa —> for more details ask the experimentalist

Let's talk about stabilizer states

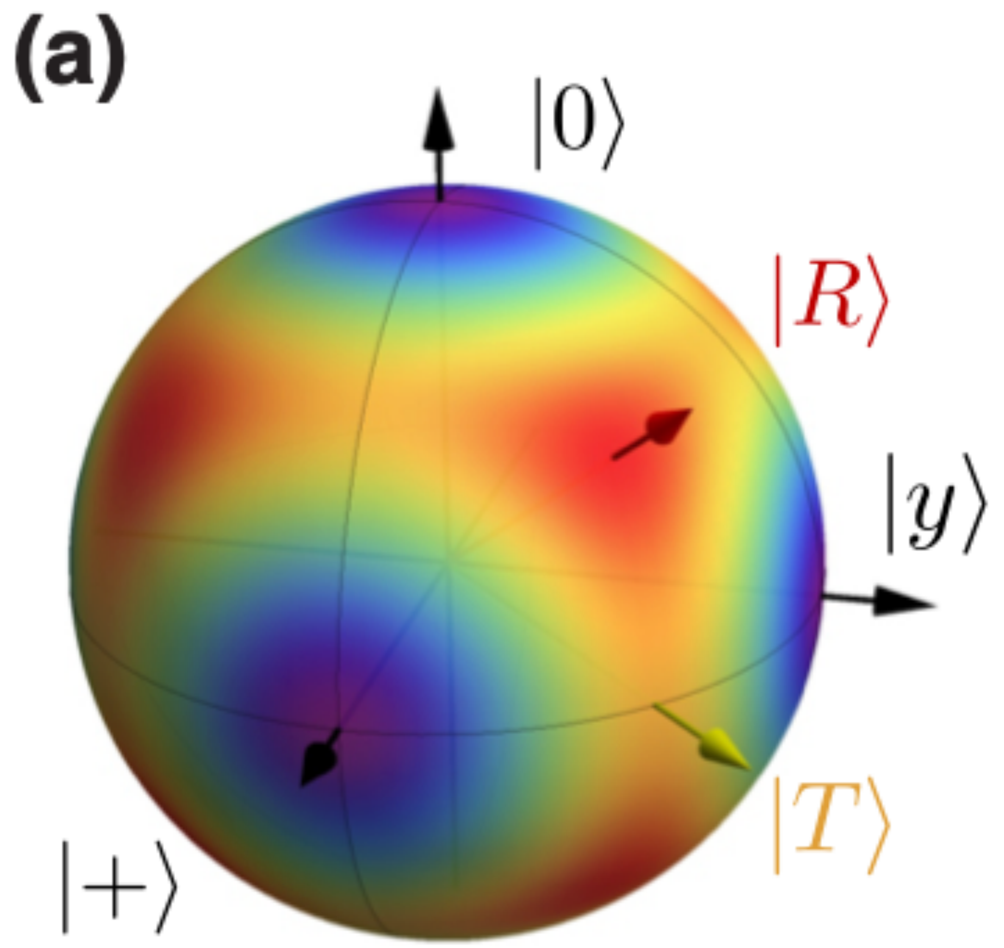
on the single qubit example

only exploring small patches of the full Hilbert space
—> 6 pure stabilizer state in case of 1 qubit



The octahedron in the Bloch sphere defines the states accessible via single-qubit Clifford gates (From https://pennylane.ai/qml/demos/tutorial_clifford_circuit_simulations).

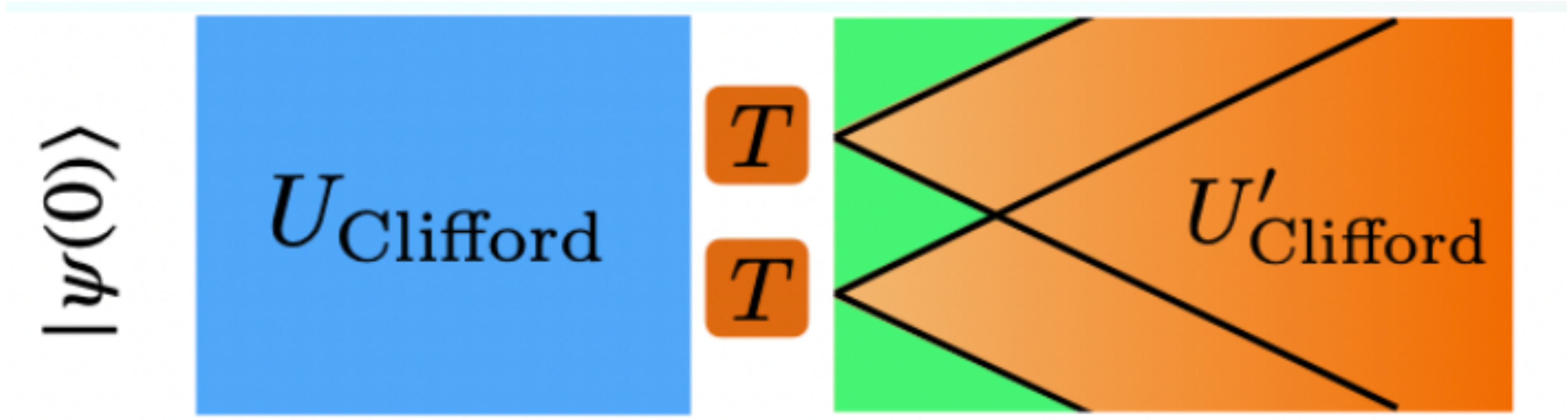
Non-Clifford gates allows for the exploration of the full Hilbert space



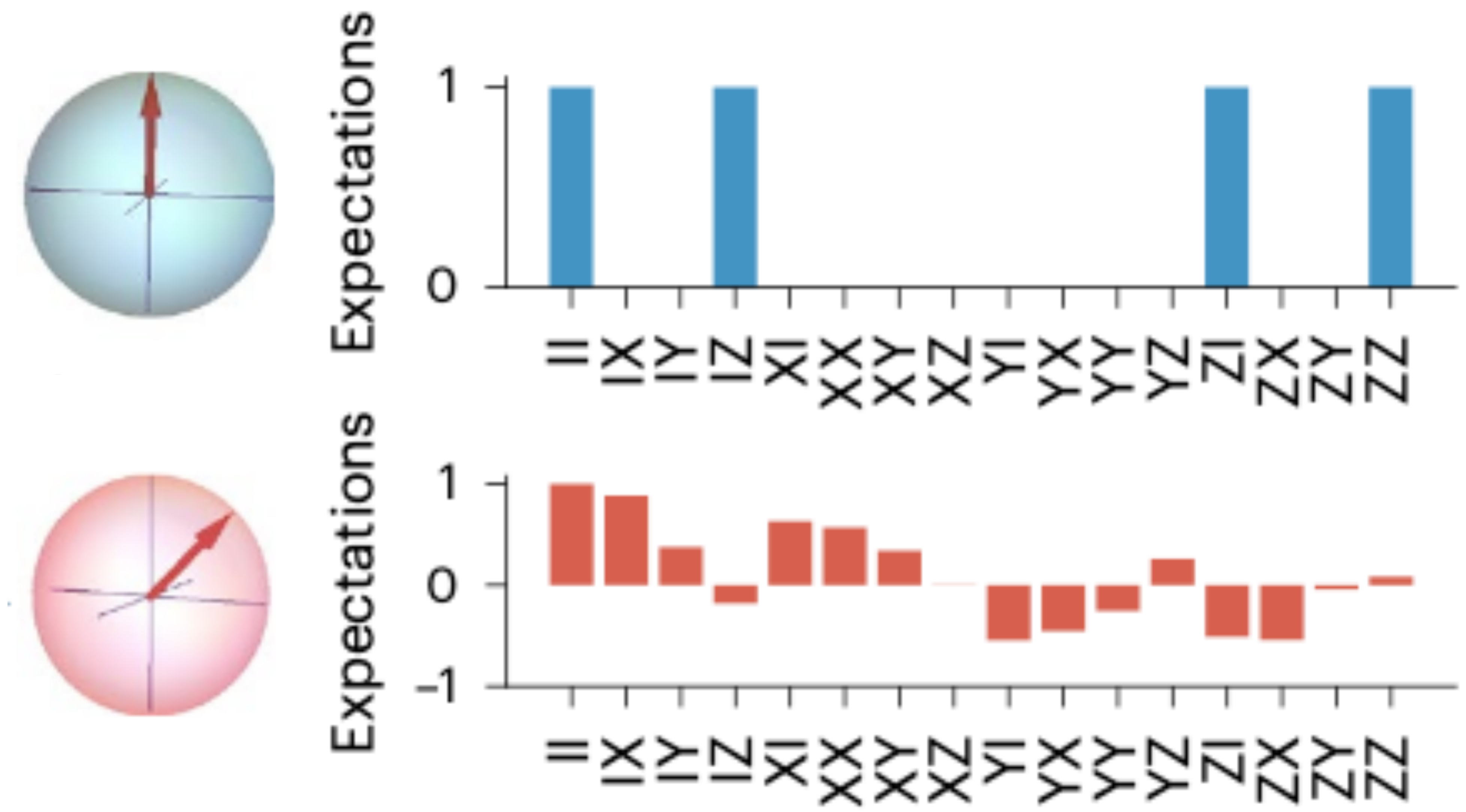
From PRX QUANTUM 4, 010301 (2023)

Everything beyond these points—>non-stabilizerness or “magic"

The effects of T-gate doping



From SciPost Phys. 9, 087 (2020)



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

Stabilizer Entropy as a quantity to capture the the departure from stabilizer states (zero for stabilizer states) L. Leone, S.F.E. Oliviero, A. Hamma PRL **128**, 050402(2022)

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

Stabilizer Entropy is efficiently experimentally measurable in multi-qubit systems

…. sampling via Randomized Measurements

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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

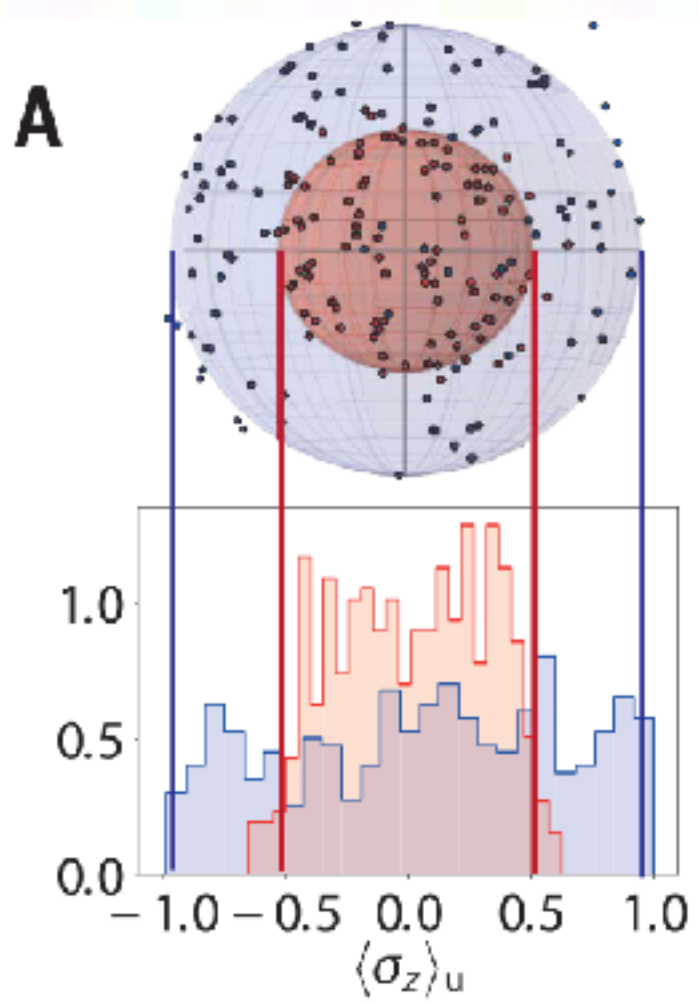
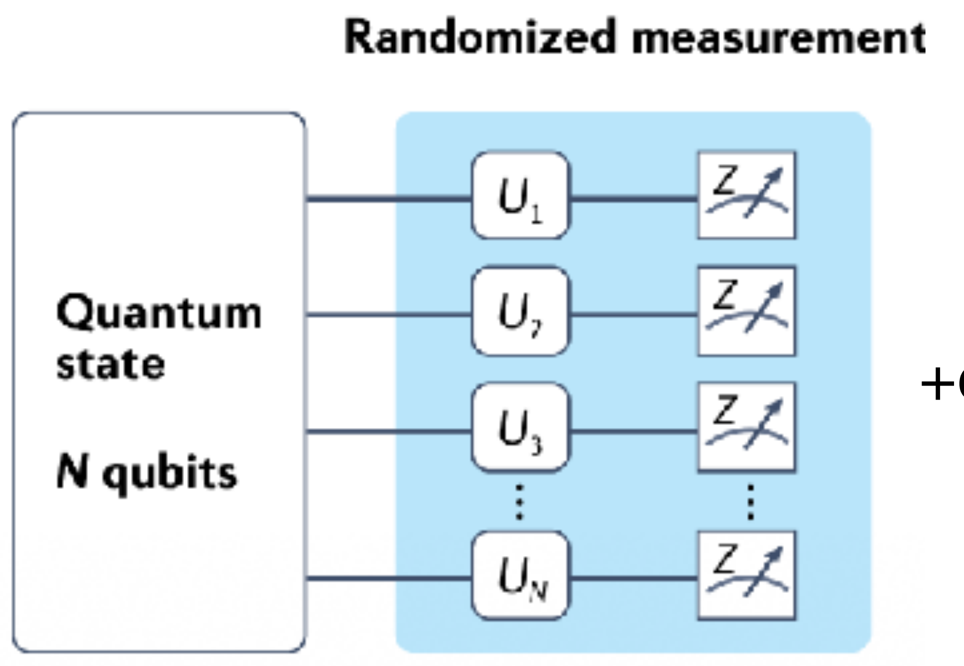
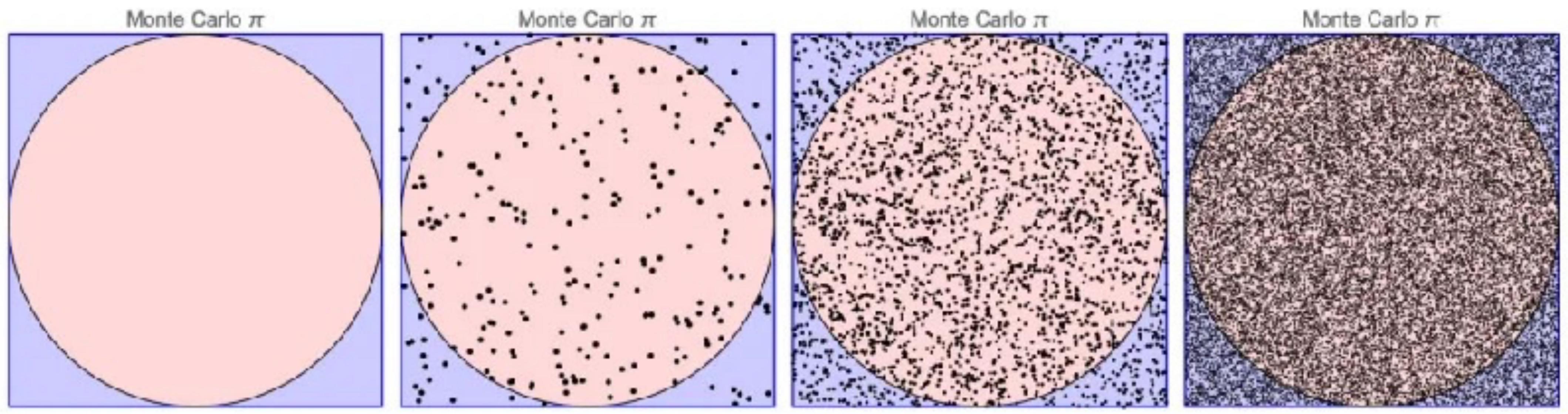


Fig. 1. Measuring second-order Rényi entropies through randomized measurements. (**A**) Single-qubit Bloch sphere. The purity is directly related to the width of the distribution of measurement outcomes after applying random rotations u_i. Initial pure state (blue) and mixed state (red) cases are shown.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



+classical post-processing

personally reminds me of Monte-Carlo sampling



What is Non-Local magic?

- Non-Local magic appears when magic gets **spread around** in a state with entanglement: PRX Quantum 6, 040375 (2025)
- Intrinsically related to entanglement.
- Protocol: preparing non-local states and trying to **erase it** locally**.**
- **NL magic has not yet never been measured!**

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

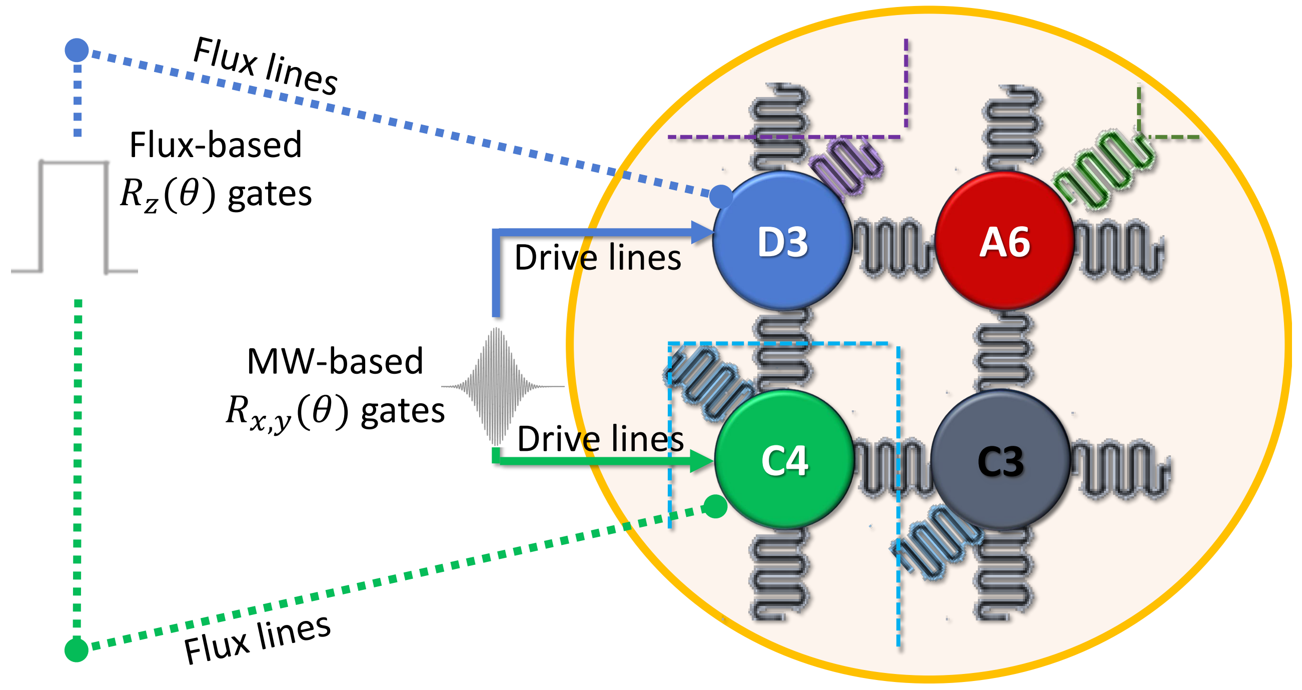
Artistic visualization of entanglement between two spins/qubits

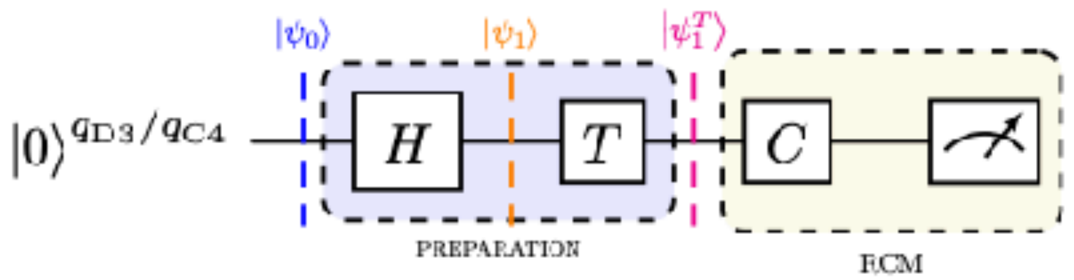
NL magic has not yet been experimentally measured!

So we do it!

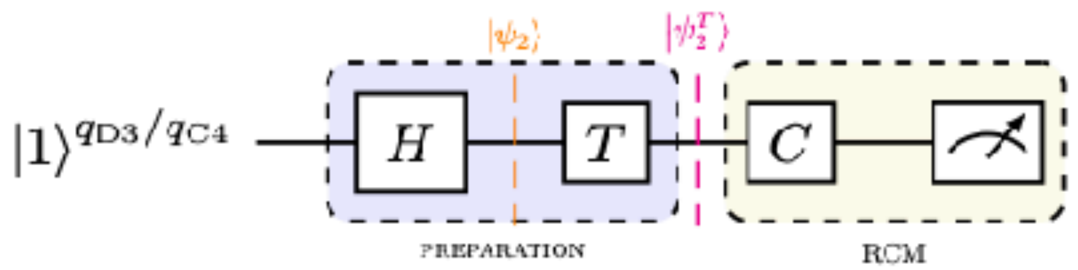
	Class 1	Class 2	Class 3
Notation	Local Magic(LM)	Local+Non-Local Magic(M)	Non-Local Magic(NLM)
Local	✓	✓	✗
Non-Local	✗	✓	✓
Local Erasure	Complete	Partial	Null

Benchmarks and identification of noise channels

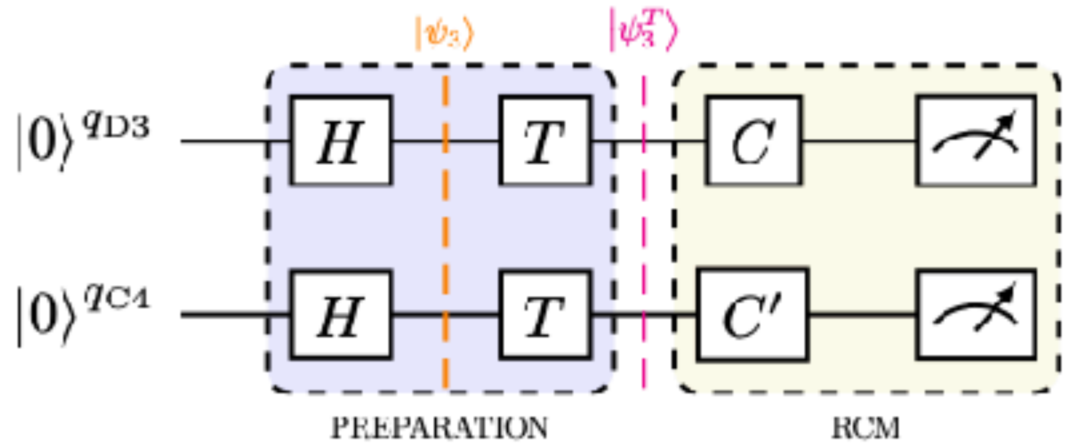




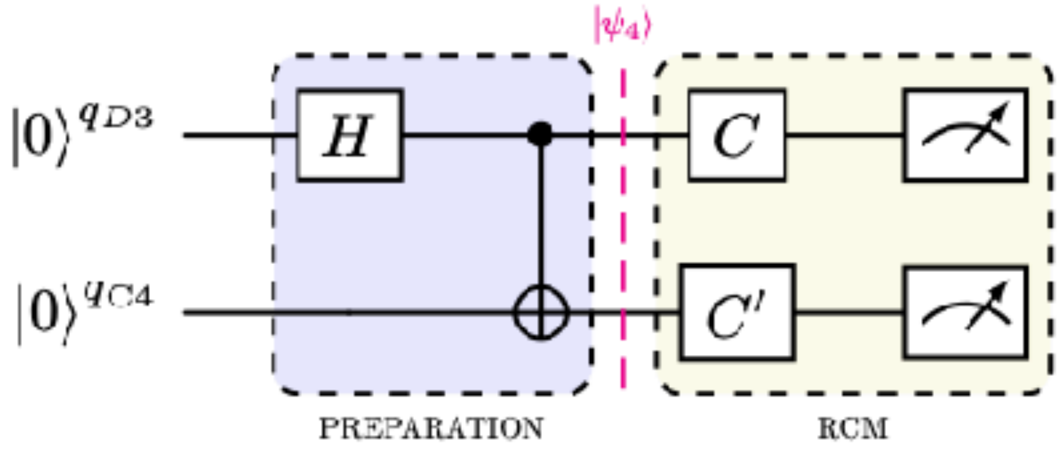
(a) Single-qubit state initially in the $|0\rangle$ state.



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



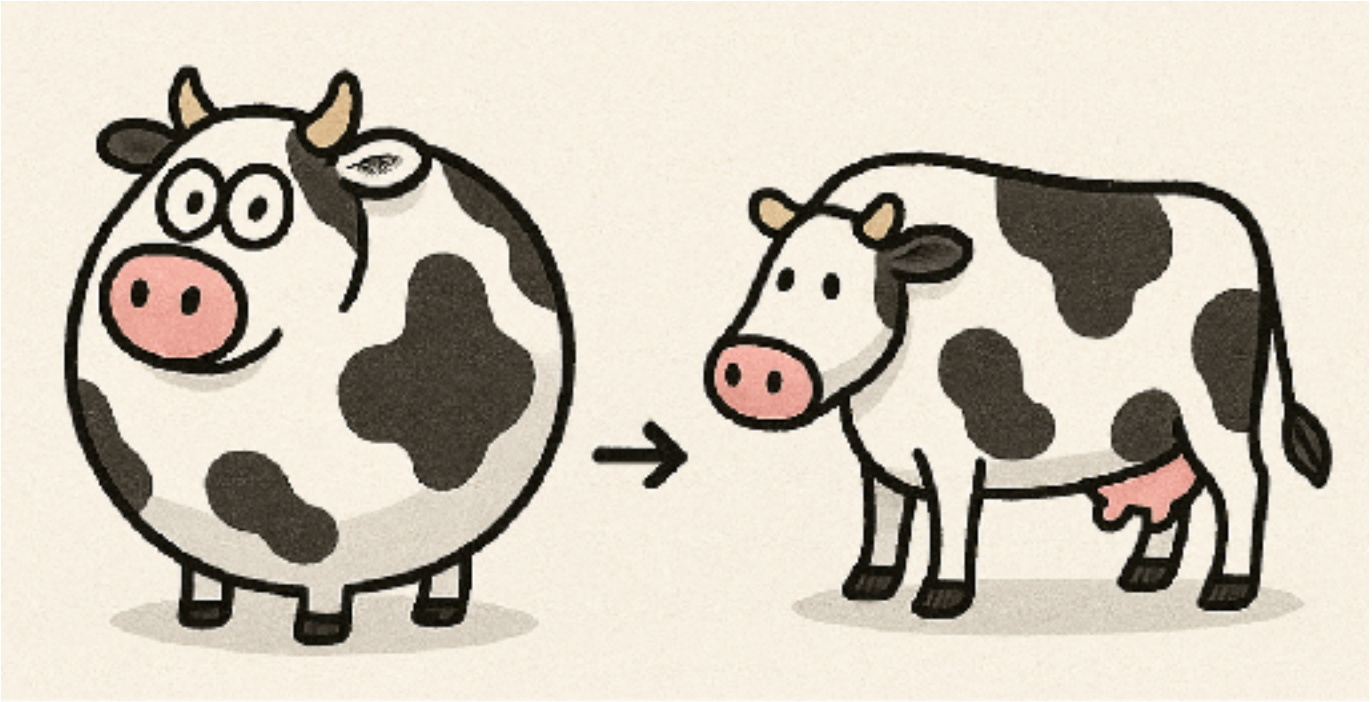
(c) Separable two-qubit states.



(d) Bell state.

	$F_{RO}(\%)$	$F_{RB}(\%)$	$T_2^{\mathrm{Echo}}(\mu s)$	$T_2^*(\mu s)$	$T_1(\mu s)$	$M_2^{\exp}(\Psi^{M_2^{\mathrm{th}}=0})$	$M_2^{\exp}(\Psi^{M_2^{\mathrm{th}}\neq 0})$
(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	$\|\Psi_1^T\rangle$ 0.4 ± 0.1
						$\|\Psi_2\rangle$ 0.1 ± 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	$\|\Psi_1^T\rangle$ 0.4 ± 0.1
						$\|\Psi_2\rangle$ 0.1 ± 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.



Our job as theoreticians in this case

…identify and understand the noise channels from a big set of preliminary/benchmark data

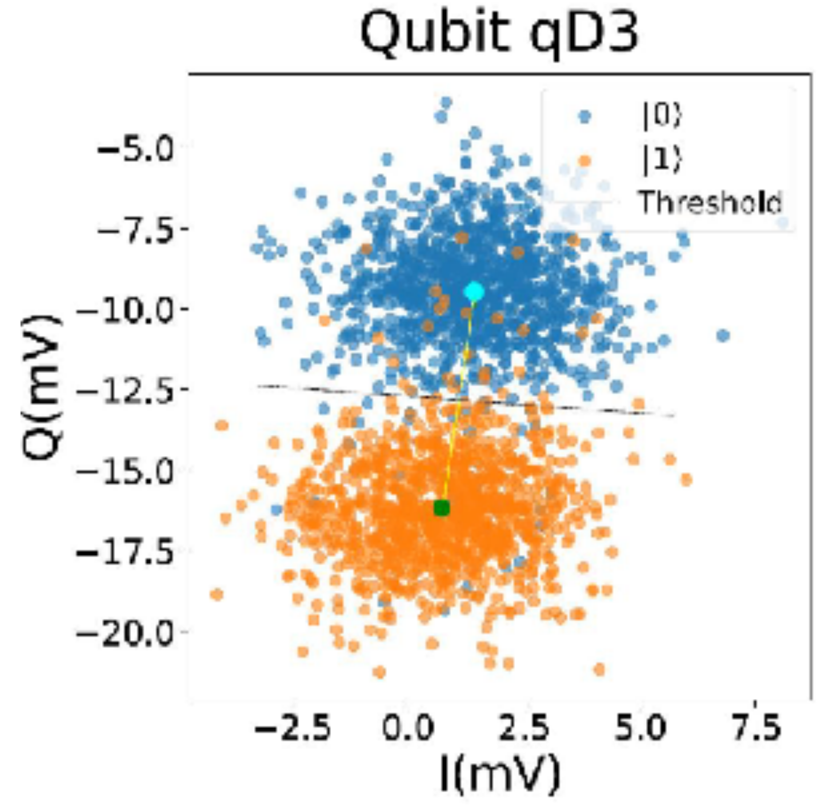
~~**1.2 Strategies to counter errors**~~

~~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].~~

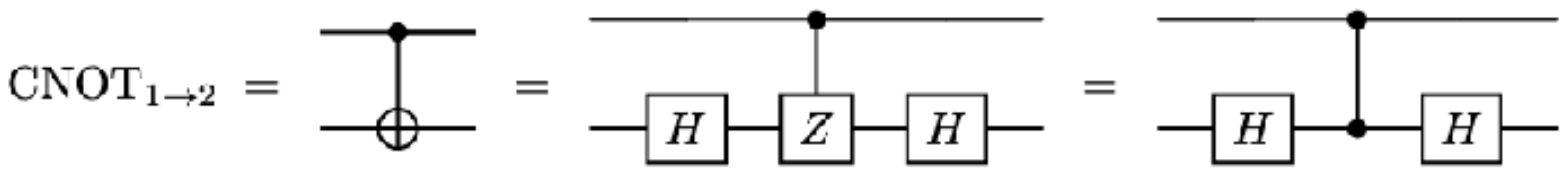
~~Error Mitigation and Error Correction Lecture Notes - Philippe Faist~~

Readout errors occur at the point of measurement, where, in the act of measurement, a bit string element is randomly flipped as

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



1. Measurement Readout Error
2. CNOT Gate Error (depolarizing noise)



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

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

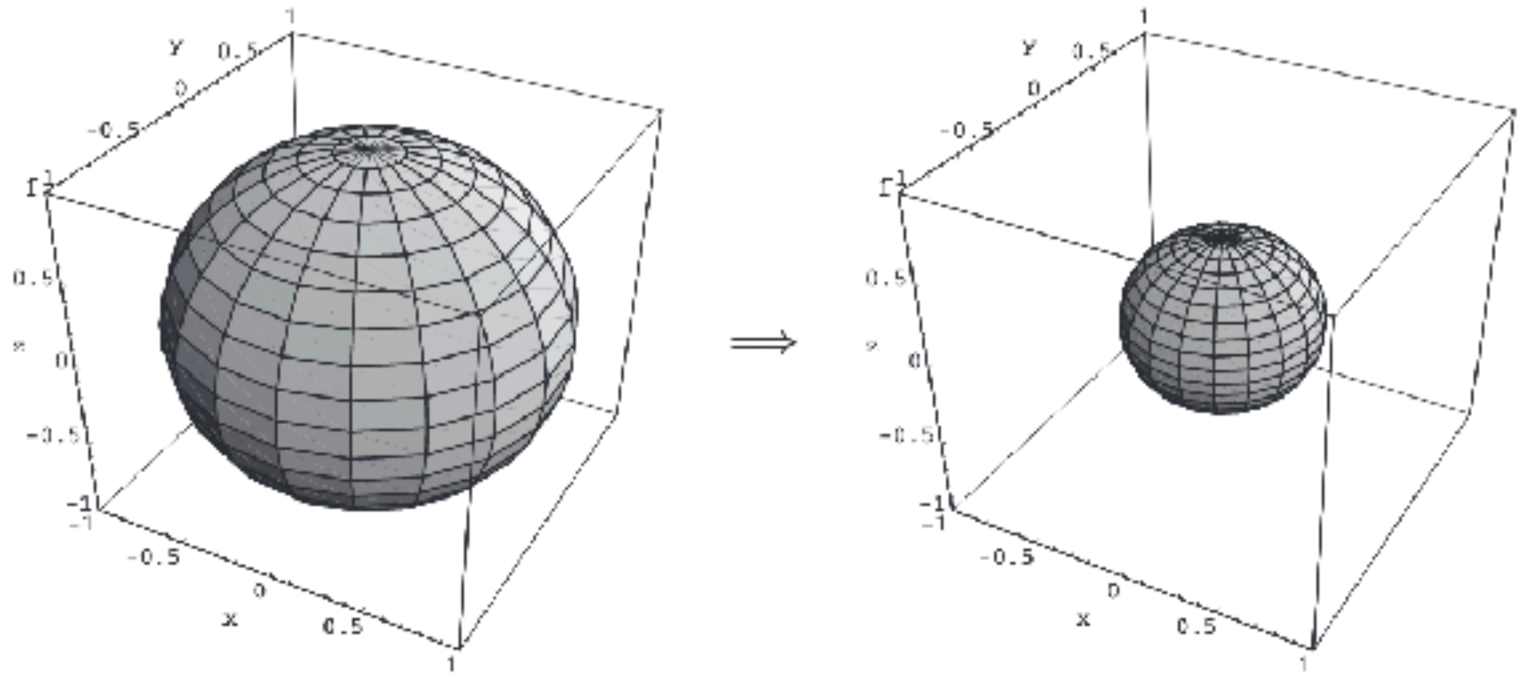
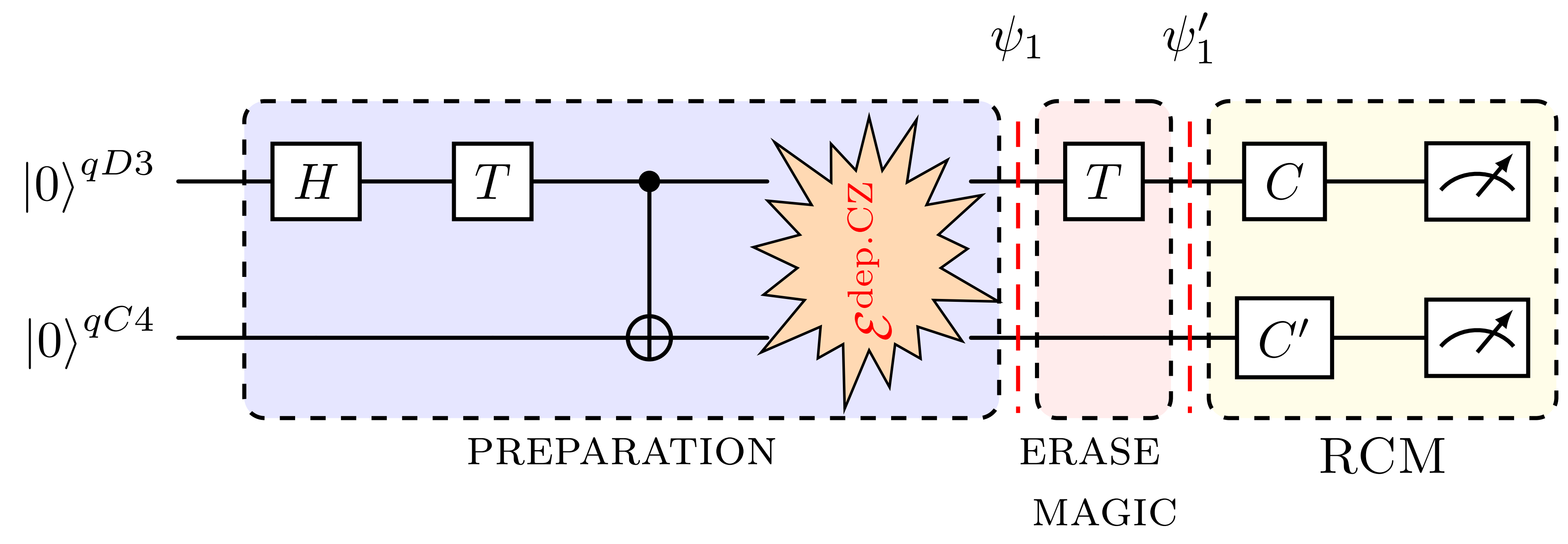


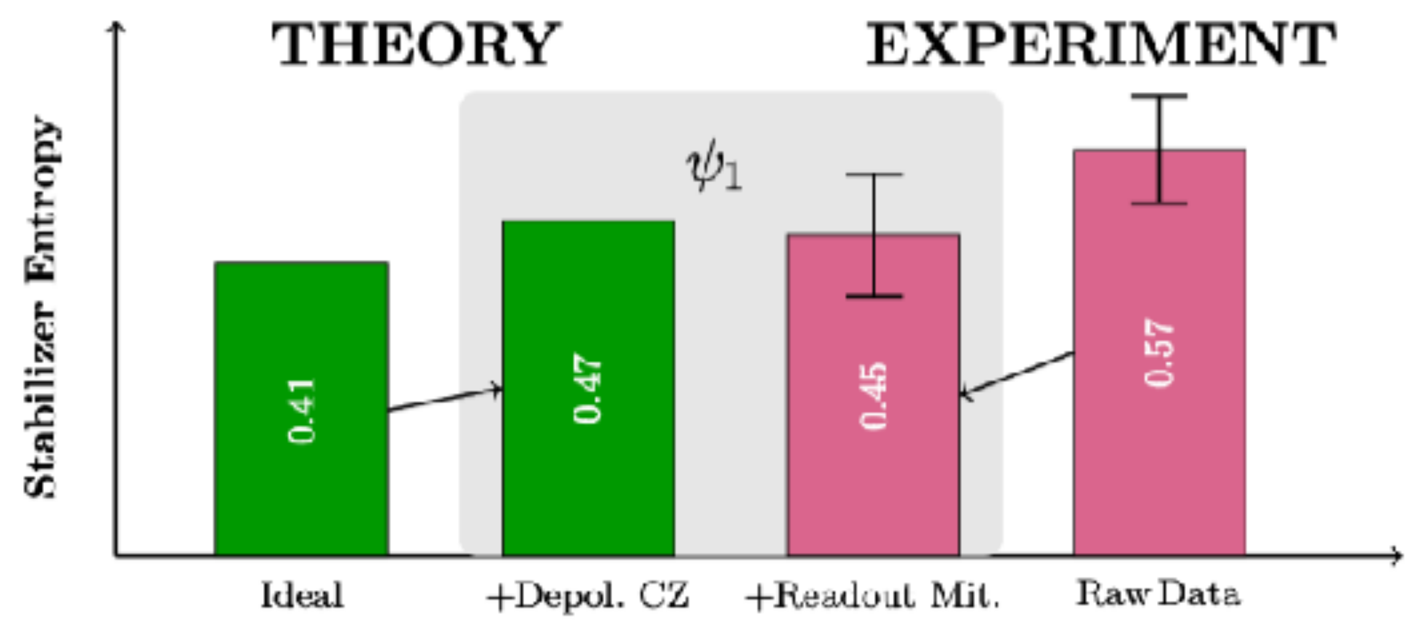
Figure 8.11. The effect of the depolarizing channel on the Bloch sphere, for $p = 0.5$. Note how the entire sphere

Class 1: Local Magic (L)



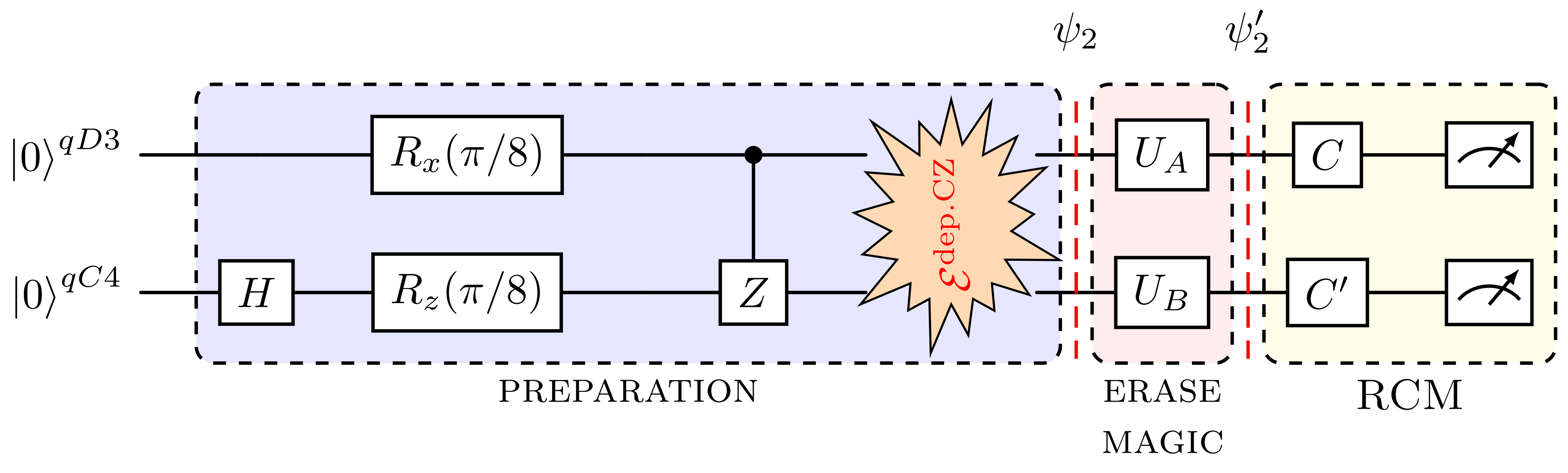
Circuit	State	Th. Purity	Exp. Purity	Th. Magic	Exp. Magic	NL-Magic (from RDM purity)
Preparation	ψ_1	0.92	$\mathbf{1.02} \pm 0.04$	0.47	$\mathbf{0.45} \pm 0.06$	
Prep.+Erasure	ψ_1'	0.92	$\mathbf{1.05} \pm 0.06$	0.11	$\mathbf{0.08} \pm 0.08$	$\mathbf{0.1176} \pm 0.0007$

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*.



Alternative but not as scalable method to evaluate NL magic

Class 2: Local+Non-Local Magic (M)



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

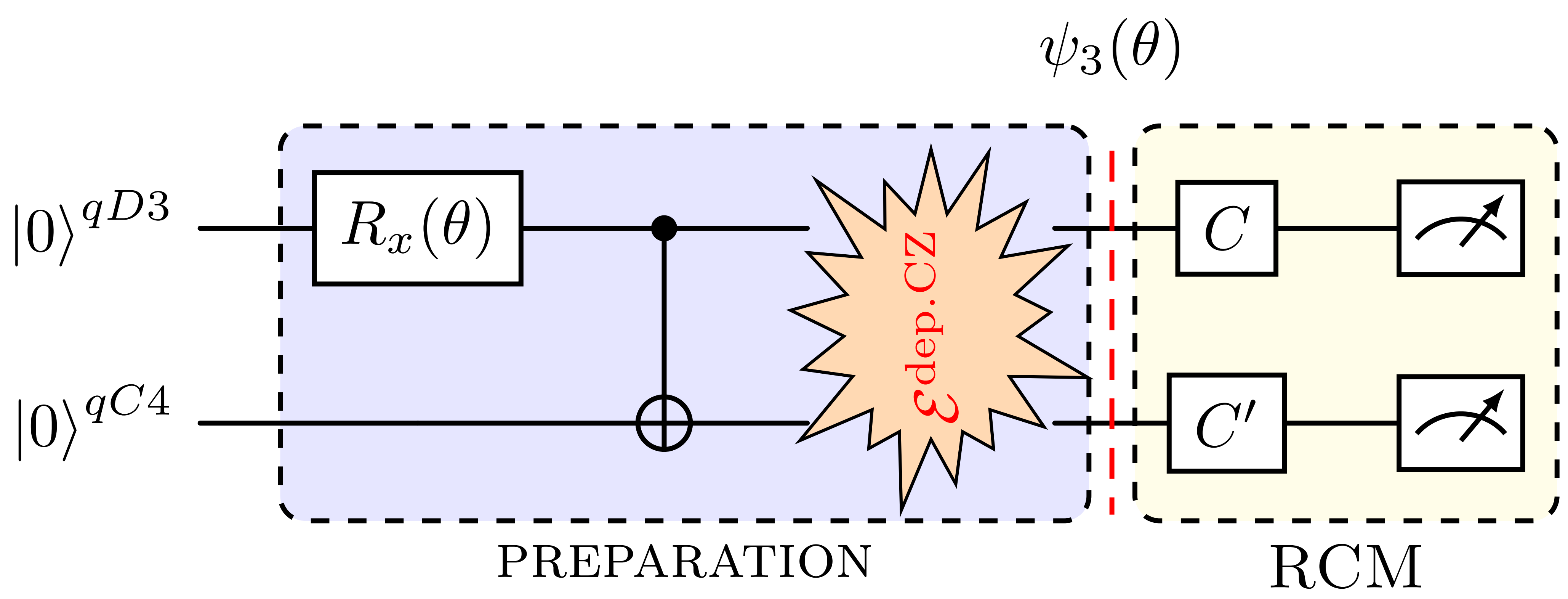
$$\alpha = \beta = \gamma = \delta = \eta = 0, \phi = 67.61^\circ$$

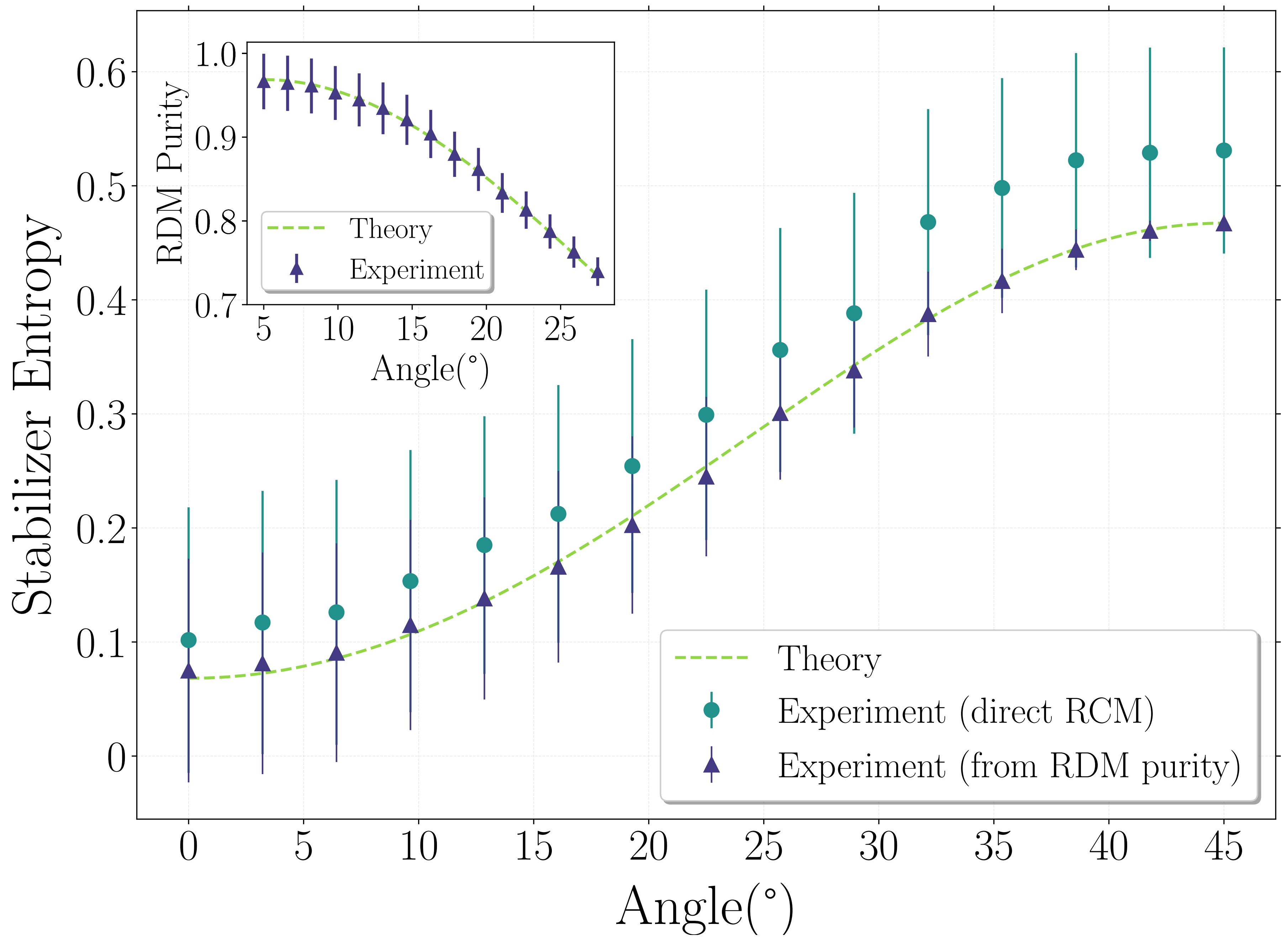
What's left is non-local magic!

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** ± 0.09	
Prep.+Erasure	ψ_2'	0.95	**1.00** ± 0.05	0.3	**0.3** ± 0.1	**0.18** ± 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*.

Class 3: Non-Local Magic (NLM)





All together—> smoking gun for experimental non-local magic in a superconducting QPU

Conclusions and Outlook

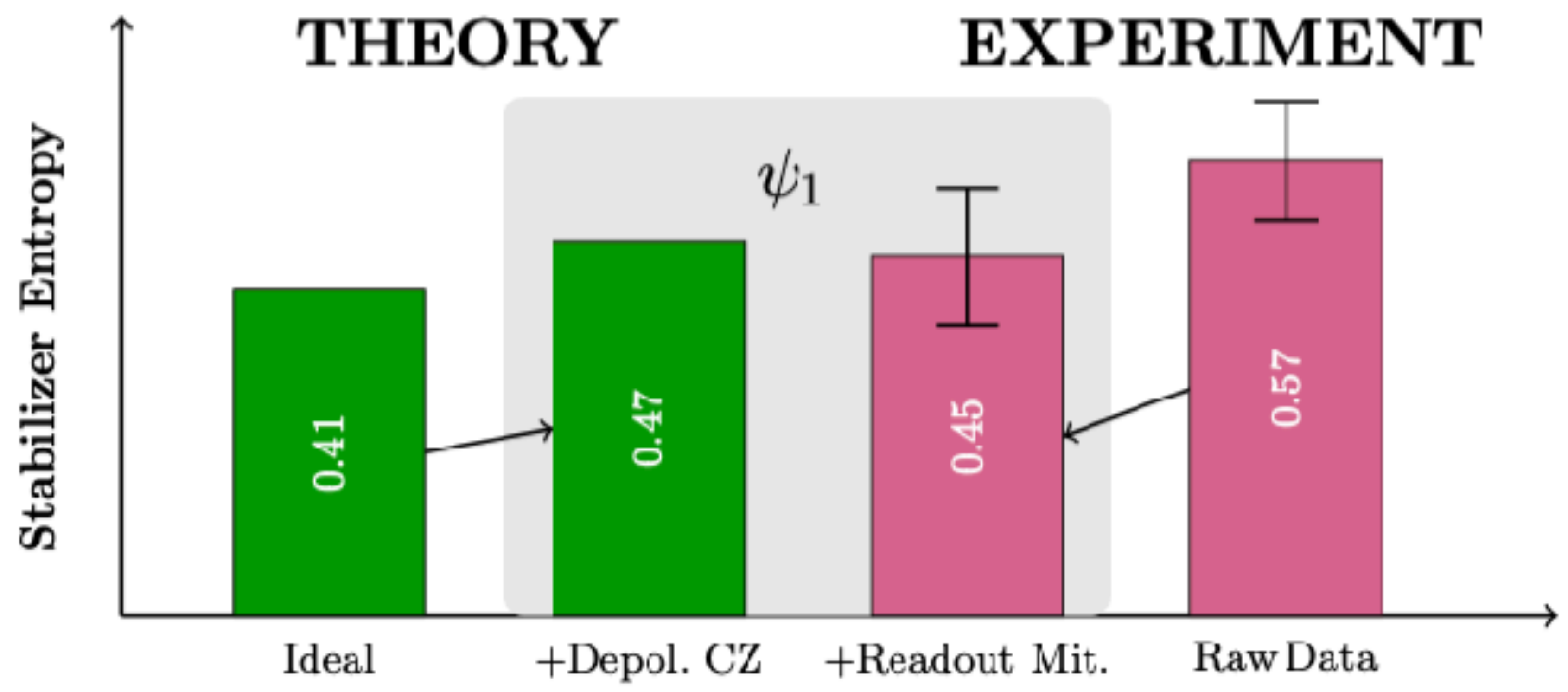
- Indeed a love story between experimentalist and theorists with a happy ending 💙

- First experimental demonstration of non-local magic using in-depth knowledge of QPU noise channels

- Error Mitigation applicable to all other future experiments of the UniNA QPUs

- RCM approach extendable large qubit numbers and other observables

- Non-Local magic in relation to AdS/CFT (arXiv:2403.07056)



The story of bringing <u>experiment</u> and <u>theory</u> together