Spectral statistics in dissipative quantum chaos: from random matrices to quantum computers

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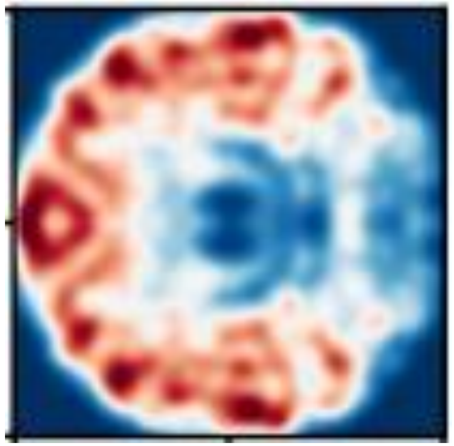

QOpen Kick-off Workshop
Lisbon, Portugal
30 April 2026

Royal Commission Exhibition of 1851 · TCM · University of Cambridge Cavendish Laboratory · Christ's College University of Cambridge · Funded by the European Union · cost European Cooperation in Science & Technology · QOpen Many-body Open Quantum Systems

Work with

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Theory: Phys. Rev. X **10**, 021019 (2020)
Experiment: arXiv:2506.04325 (2025)

This project was supported by a Research Fellowship from the **Royal Commission for the Exhibition of 1851**

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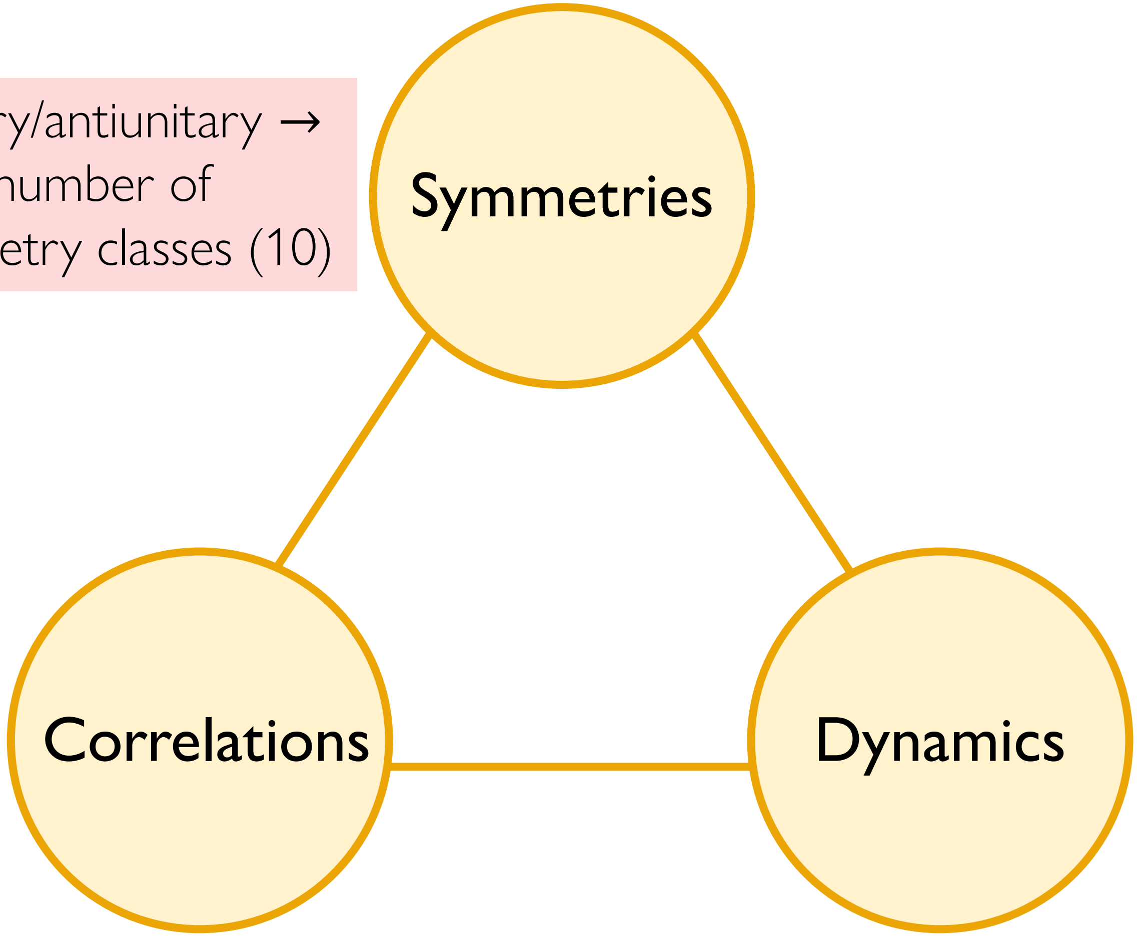
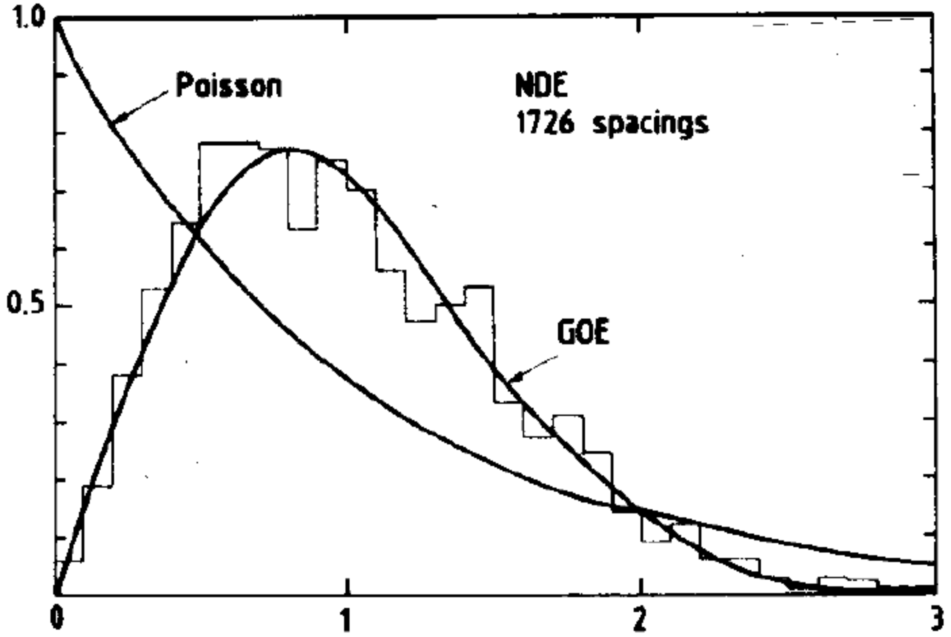
Symmetries – correlations – dynamics

Unitary/antiunitary → small number of symmetry classes (10)



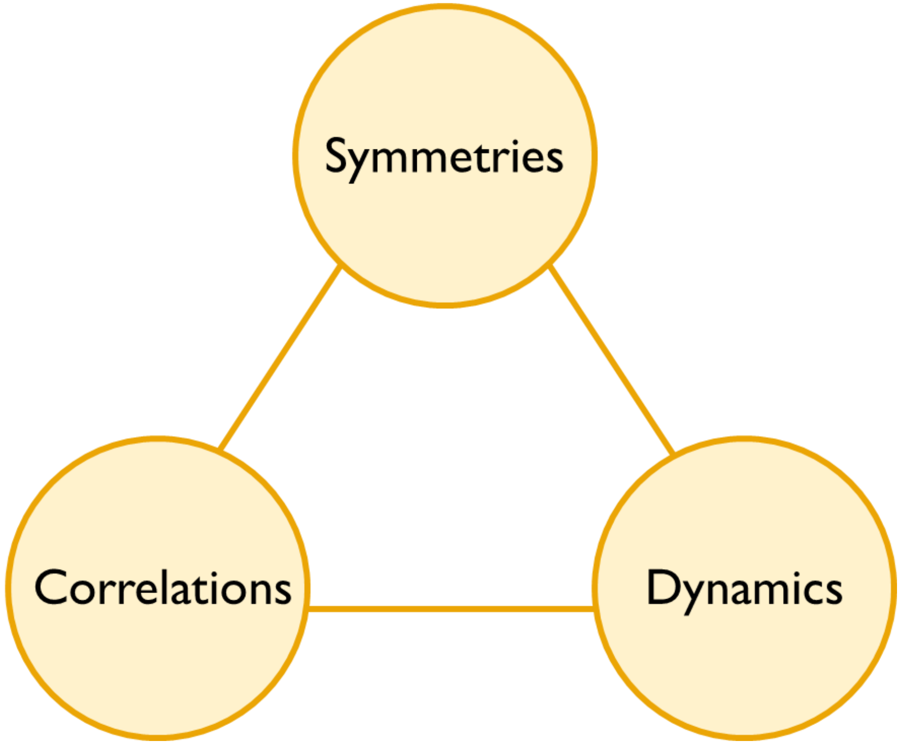
Universal correlations in RMT: bulk level repulsion, hard-edge, soft-edge

Quantum chaos conjectures: chaos ↔ RMT



O. Bohigas, *et al.* in *Nuclear Data for Science and Technology*, K. H Böchhoff (Reidel, 1983), p. 809.

Symmetries – correlations – dynamics



What about non-Hermitian quantum systems?

- Richer symmetry classification:
  - Non-Hermitian Hamiltonians → 38 classes;
  - (Many-body) Lindbladians
  - PT-symmetric Hamiltonians

[Bernard-LeClair, '02]
[Kawabata et al, PRX '19]
[Altland, Fleischhauer, Diehl, PRX'21]
[García-García, **LS**, Verbaarschot, PRX'22]
[**LS**, Ribeiro, Prosen, PRX'23]
[Kawabata et al, PRXQ'23]
[García-García, **LS**, Verbaarschot, Can, PRD'24]

- Correlations:
  - Bulk level repulsion (three classes); [Hamazaki et al PRR'20] [**LS**, Ribeiro, Prosen, PRX'20]
  - Hard-edge universality
  - Long-range [Li, Prosen, Chan, PRL'21] [García-García, **LS**, Verbaarschot, PRD'23]
  - Eigenvectors [**LS**, Ribeiro, Prosen, PRX'23] [Almeida, Ribeiro, Haque, **LS**, PRE'25]

- Dynamics:
  - How to justify the dissipative quantum chaos conjecture?
  - Semiclassical dissipative quantum dynamics?

The many facets of integrability and chaos in many-body open systems

Equilibrium isolated quantum systems

- Dynamical generator H
- (Equilibrium) state $\rho = e^{-\beta H}/Z$

Out-of-equilibrium open quantum systems

- Dynamical generator $\mathcal{L}$
- (Steady) state ρ_{ss}
- Transient eigenmodes (not states!)

Decoupling:
Chaos/integrability of $\mathcal{L} \not\Leftrightarrow$ chaos/integrability of ρ_{ss}

1. Spectral chaos and integrability
   - Complex spacing ratios

2. Steady-state chaos and integrability
   - Level statistics + NESS ETH
   - Complexity through operator size

[Richter, **LS**, Haque, PRE'25]

3. Transient-mode chaos and integrability
   - Lindbladian ETH
   - Lindblad many-body scars

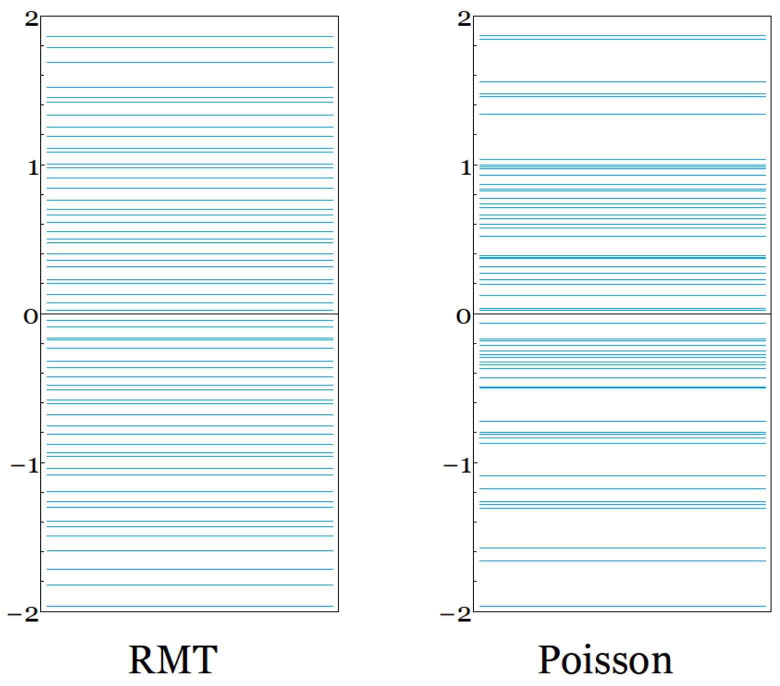
[García-García, **LS**, Verbaarschot, Yin, PRB'25]
[García-García, Lu, **LS**, Verbaarschot, PRE'26]
[Almeida, Ribeiro, Haque, **LS**, PRE'25]

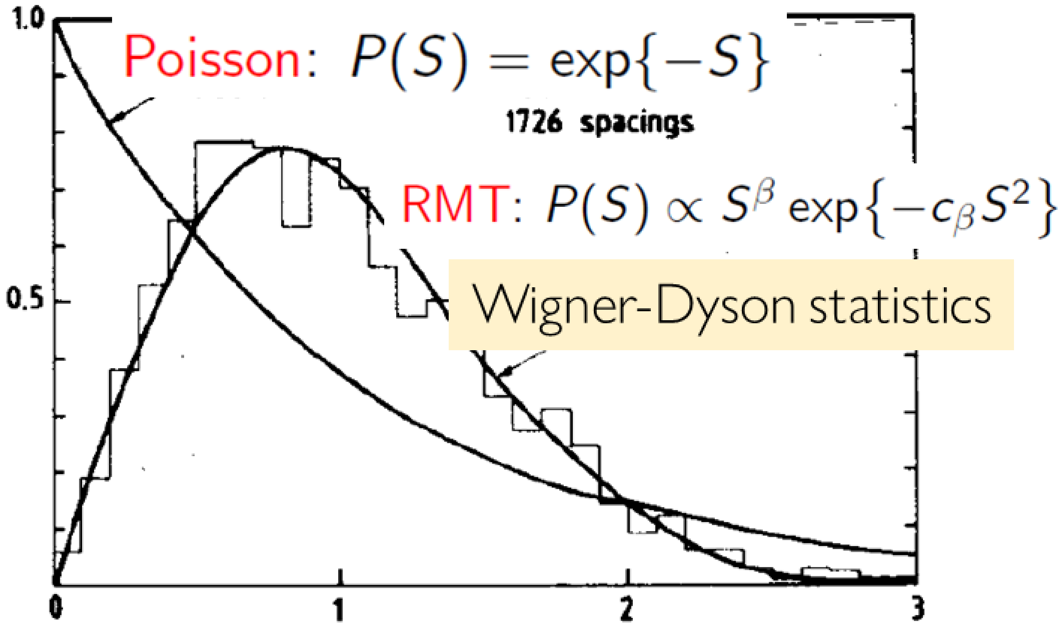
Spectral statistics in dissipative quantum chaos: from random matrices to quantum computers

Energy level correlations in closed quantum systems

Quantum chaos conjecture

Berry & Tabor '77: classical integrable systems $\Leftrightarrow$ Poisson quantum level statistics
Bohigas, Giannoni, & Schmit '84: chaotic semiclassical limit $\Leftrightarrow$ RMT quantum level statistics





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Energy level correlations in closed quantum systems

1. Wigner surmises

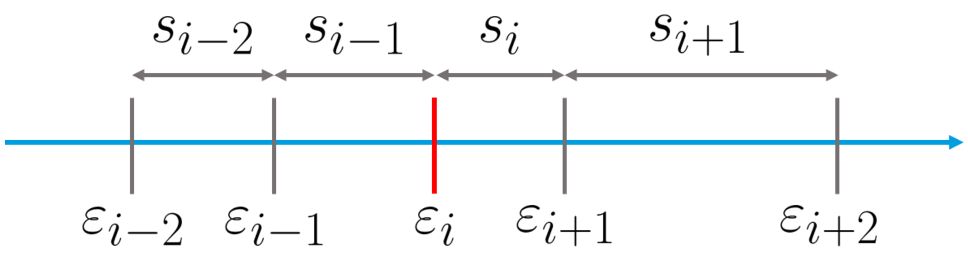
Small-N distributions describe large-N universal behaviour

2. Unfolding

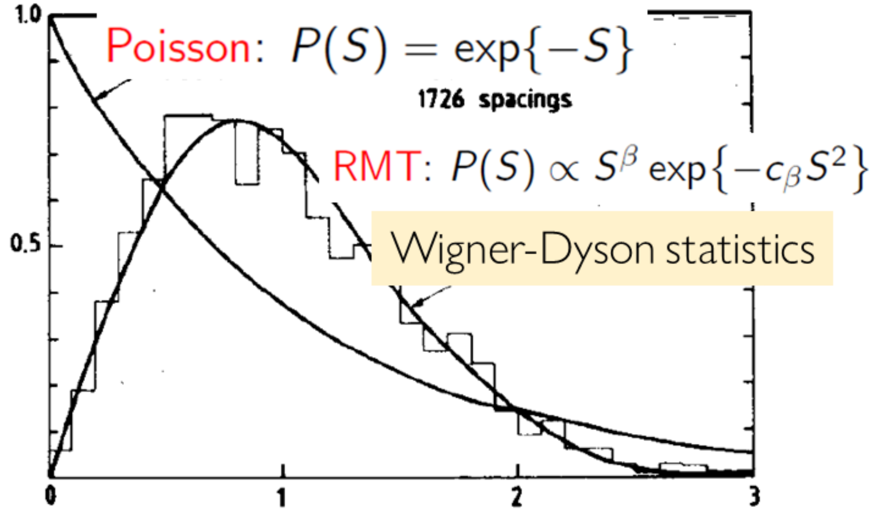
- Removes dependence from spectral density (very non-universal).
- Fix $\langle s \rangle = 1 \Leftrightarrow$ rescale levels using average density $\bar{\varrho}$.
- Can be difficult if $\bar{\varrho}$ is not known.

3. Consecutive spacing ratios

[Oganesyan, Huse, PRB **75**, 155111(2007)]; [Atas, Bogomolny, Giraud, Roux, PRL **110**, 084101(2013)]



$$r_i = \frac{s_{i+1}}{s_i}$$



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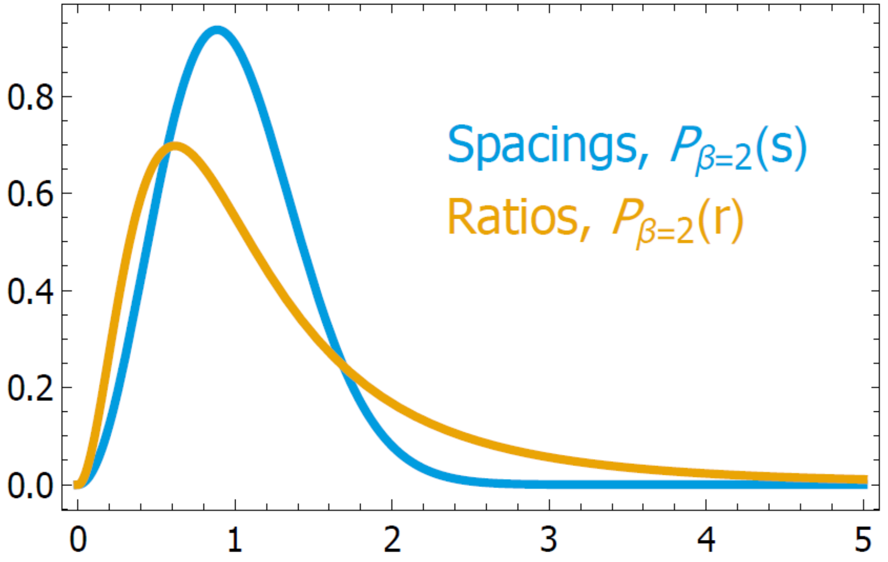

Energy level correlations in closed quantum systems

- Hamiltonians are classified by involutive symmetries (of irreducible blocks).

$$\mathcal{T}_+ H \mathcal{T}_+^{-1} = H, \qquad \mathcal{T}_+^2 = \pm 1, \qquad \mathcal{T}_+ \text{ anti-unitary} \qquad \text{(Time-Reversal Symmetry)},$$
$$\mathcal{T}_- H \mathcal{T}_-^{-1} = -H, \qquad \mathcal{T}_-^2 = \pm 1, \qquad \mathcal{T}_- \text{ anti-unitary} \qquad \text{(Particle-Hole Symmetry)},$$
$$\Pi H \Pi^{-1} = -H, \qquad \Pi^2 = 1, \qquad \Pi \text{ unitary} \qquad \text{(Chiral Symmetry)},$$

Symmetry class		$\mathcal{T}_+$	Π	$\mathcal{T}_-$
A	Unitary	0	0	0
AI	Orthogonal	+1	0	0
AII	Symplectic	−1	0	0
AIII_ν $(\nu \in \mathbb{N})$	Chiral unitary	0	+1	0
BDI_ν $(\nu \in \mathbb{N})$	Chiral orthogonal	+1	+1	+1
CII_ν $(\nu \in \mathbb{N})$	Chiral symplectic	−1	+1	−1
C	*Anti-pseudo-chiral unitary*[a]	0	0	−1
CI	*Anti-chiral orthogonal*[a]	+1	+1	−1
BD_ν $(\nu = 0, 1)$	*Pseudo-chiral unitary*[a]	0	0	+1
BDIII_ν $(\nu = 0, 1)$	*Anti-chiral symplectic*[a]	−1	+1	+1

[Haake, 4th edition]

10 symmetry classes (Altland-Zirnbauer)

3 universal classes of bulk level repulsion (time-reversal symmetry):

- A (GUE), $\mathcal{T}_+ = 0$
- AI (GOE), $\mathcal{T}_+^2 = +1$
- AII (GSE), $\mathcal{T}_+^2 = -1$

7 classes with hard-edge universality (repulsion from origin)

Energy level correlations in closed quantum systems

- Hamiltonians are classified by involutive symmetries (of irreducible blocks).

$$\begin{aligned}
&\mathcal{T}_+ H \mathcal{T}_+^{-1} = H, && \mathcal{T}_+^2 = \pm 1, && \mathcal{T}_+ \text{ anti-unitary} && \text{(Time-Reversal Symmetry)},\\
&\mathcal{T}_- H \mathcal{T}_-^{-1} = -H, && \mathcal{T}_-^2 = \pm 1, && \mathcal{T}_- \text{ anti-unitary} && \text{(Particle-Hole Symmetry)},\\
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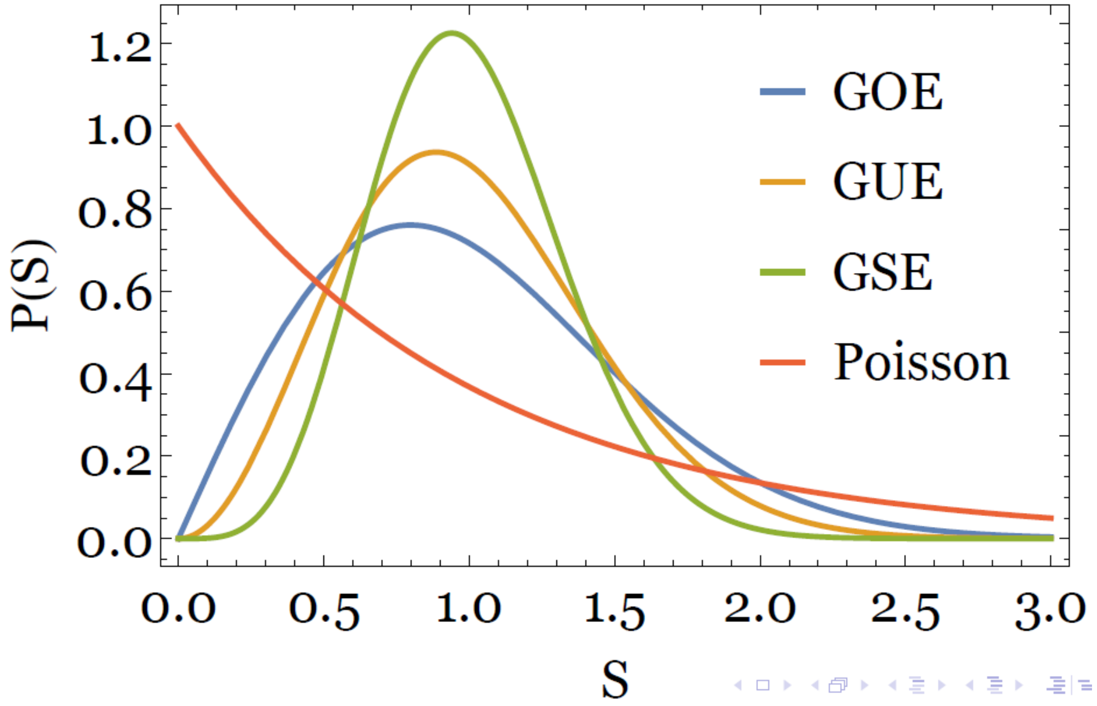
\end{aligned}$$



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- A (GUE), $\mathcal{T}_+ = 0$
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7 classes with hard-edge universality (repulsion from origin)

Level repulsion in non-Hermitian system

- In non-Hermitian systems, level repulsion determined by transposition symmetry. [Hamazaki et al, PRR '20]

$$H = C_+ H^\top C_+^{-1}, \qquad C_+ C_+^* = \pm 1$$

- 38 symmetry classes, but only 3 universal classes of level repulsion.

Symmetry class		$\mathcal{T}_+$	Π	$\mathcal{T}_-$
A	Unitary	0	0	0
AI	Orthogonal	+1	0	0
AII	Symplectic	−1	0	0
AIII$_\nu$ ($\nu \in \mathbb{N}$)	Chiral unitary	0	+1	0
BDI$_\nu$ ($\nu \in \mathbb{N}$)	Chiral orthogonal	+1	+1	+1
CII$_\nu$ ($\nu \in \mathbb{N}$)	Chiral symplectic	−1	+1	−1
C	*Anti-pseudo-chiral unitary*[a]	0	0	−1
CI	*Anti-chiral orthogonal*[a]	+1	−1	−1
BD$_\nu$ ($\nu = 0, 1$)	*Pseudo-chiral unitary*[a]	0	0	+1
BDIII$_\nu$ ($\nu = 0, 1$)	*Anti-chiral symplectic*[a]	−1	−1	+1

[Haake, 4th edition]

Relevant non-Hermitian symmetry classes are:

- A ≡ A† (GinUE)
- AI† — least level repulsion
- AII† — most level repulsion

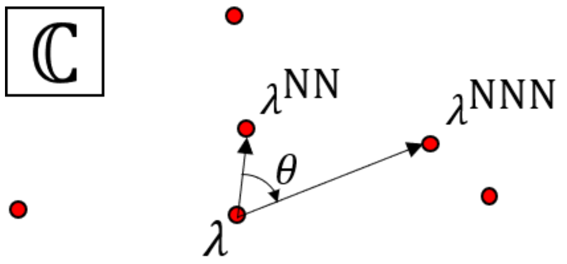
A — general matrix (complex non-symmetric)
AI† — complex symmetric $H = H^\top$
AII† — "quaternionic" symmetric $H = \Sigma_y H^\top \Sigma_y$

See also:
[Kawabata et al, PRX '19],
[**LS**, Ribeiro, Prosen, PRX 13, 031019 (2023)]

Complex spacing ratios

[LS, Ribeiro, Prosen, Phys. Rev. X 10, 021019 (2020)]

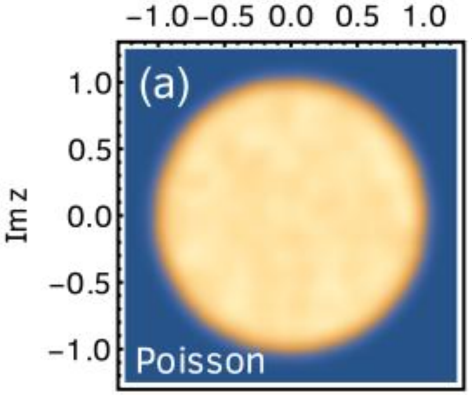
Definition



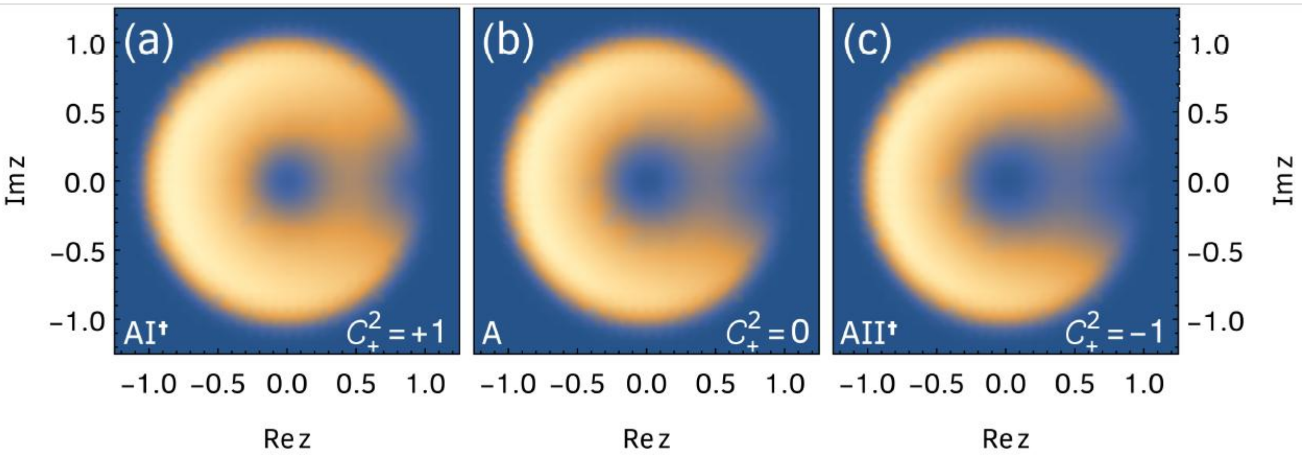
$$z = \frac{\lambda^{\mathrm{NN}} - \lambda}{\lambda^{\mathrm{NNN}} - \lambda} \equiv r e^{i\theta}$$

Numerically: no unfolding
Analytical results possible

Integrable



Chaotic



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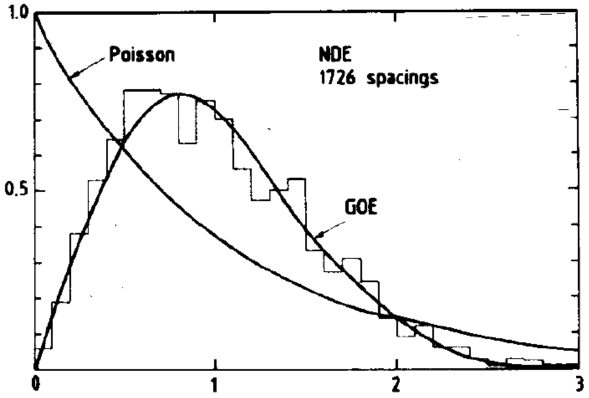

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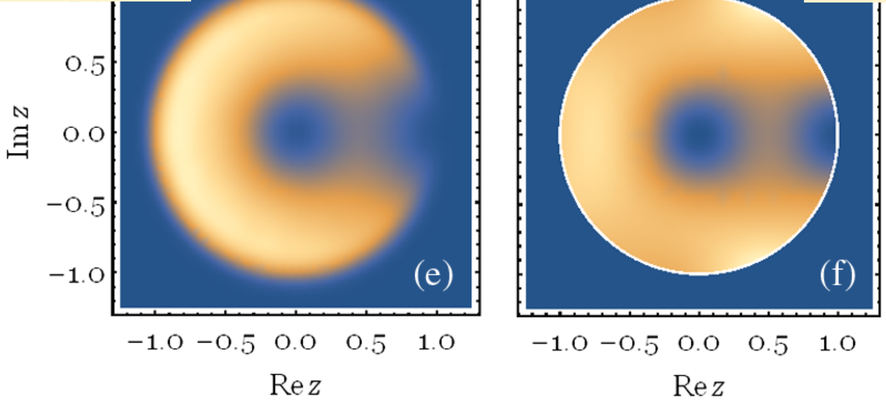
Analytical probability distribution

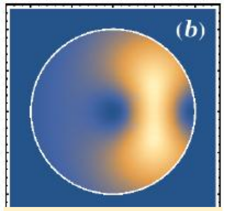
[LS, Ribeiro, Prosen, Phys. Rev. X 10, 021019 (2020)]

Wigner-like surmise for the na
eigenvalue gas on the torus (TUE)

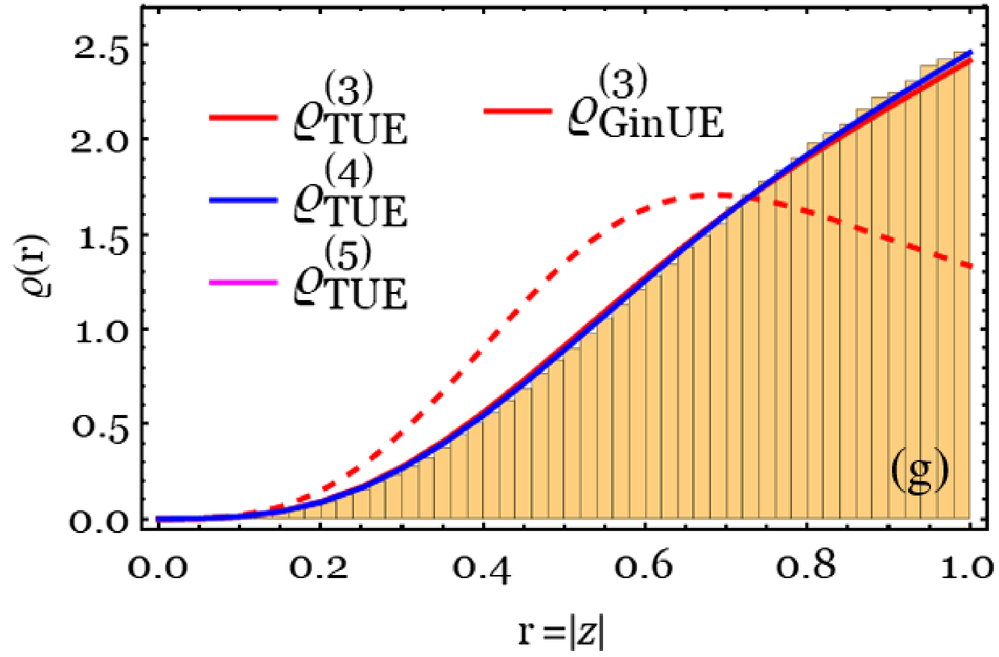
Numerics GinUE, $N = 10^4$

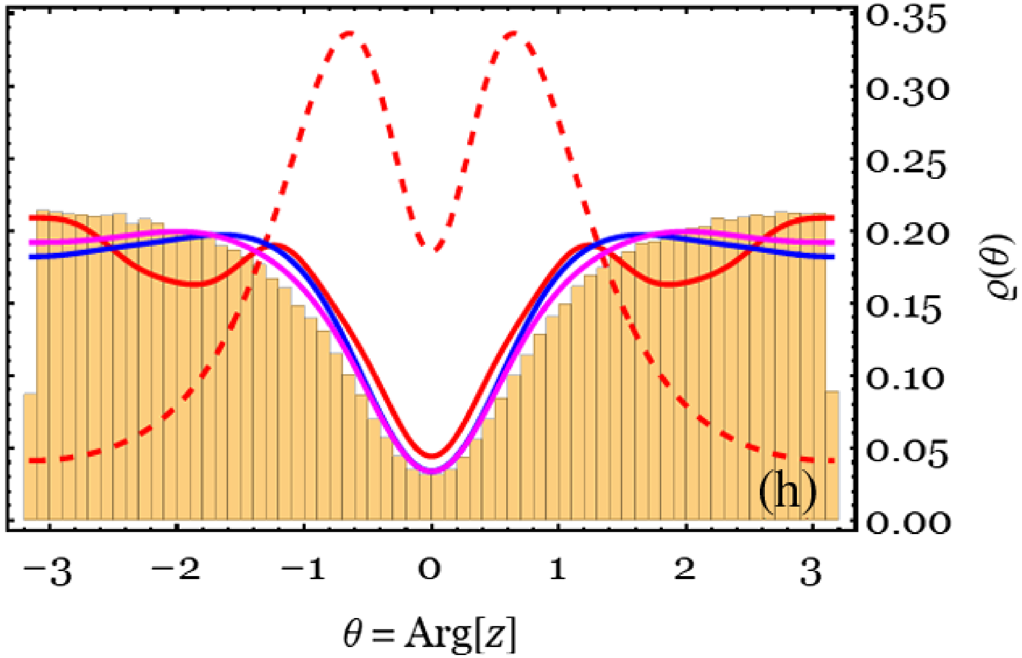
Analytics TUE, $N = 3$





$N = 3$ GinUE





Analytic results for GinUE as $N \to \infty$: [Dusa, Wettig, PRE'22]

Spectral statistics in dissipative quantum chaos: numerical interlude

Examples I. Non-Hermitian SYK Hamiltonian

The non-Hermitian SYK model: N Majorana fermions with all-to-all random q-body interactions

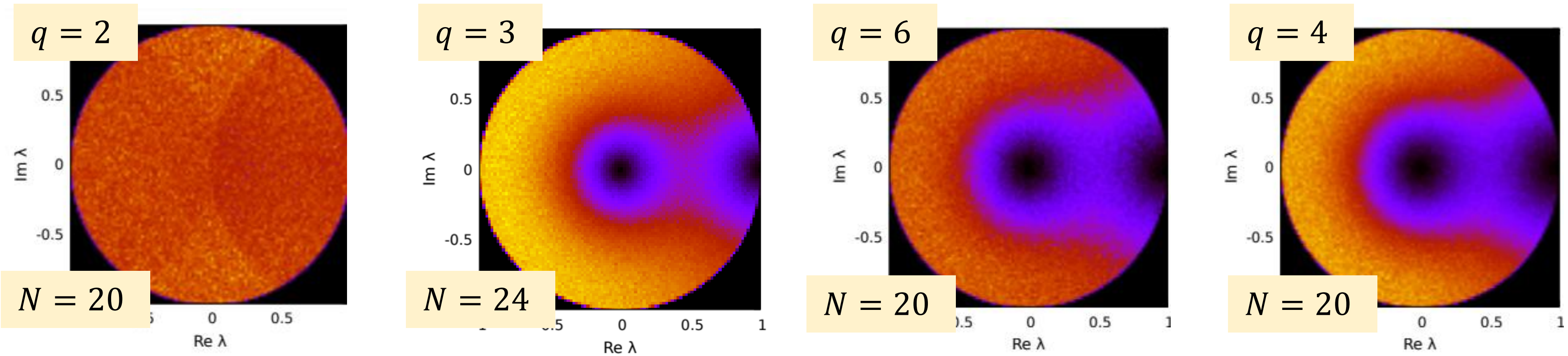
$$H = \sum_{i_1<i_2<\cdots<i_q}^{N} \left(J_{i_1 i_2 \cdots i_q} + \mathrm{i} M_{i_1 i_2 \cdots i_q}\right) \gamma_{i_1}\gamma_{i_2}\cdots\gamma_{i_q}$$

Full symmetry classification

$N \bmod 8$	0	2	4	6
$q \bmod 4 = 0$	$\mathrm{AI}^\dagger$	A	$\mathrm{AII}^\dagger$	A
$q \bmod 4 = 1$	$\mathrm{AI}^\dagger_+$	$\mathrm{AI}^\dagger_-$	$\mathrm{AII}^\dagger_+$	$\mathrm{AII}^\dagger_-$
$q \bmod 4 = 2$	D	A	C	A
$q \bmod 4 = 3$	$\mathrm{AI}^\dagger_+$	$\mathrm{AII}^\dagger_-$	$\mathrm{AII}^\dagger_+$	$\mathrm{AI}^\dagger_-$

Bulk level repulsion (only $\mathcal{C}_+^2$)

$N \bmod 8$	0	2	4	6
$q \bmod 4 = 0$	$\mathrm{AI}^\dagger$	A	$\mathrm{AII}^\dagger$	A
$q \bmod 4 = 1$	$\mathrm{AI}^\dagger$	$\mathrm{AI}^\dagger$	$\mathrm{AII}^\dagger$	$\mathrm{AII}^\dagger$
$q \bmod 4 = 2$	A	A	A	A
$q \bmod 4 = 3$	$\mathrm{AI}^\dagger$	$\mathrm{AII}^\dagger$	$\mathrm{AII}^\dagger$	$\mathrm{AI}^\dagger$



[García-García, **LS**, Verbaarschot, Phys. Rev. X 12, 021040 (2022)]

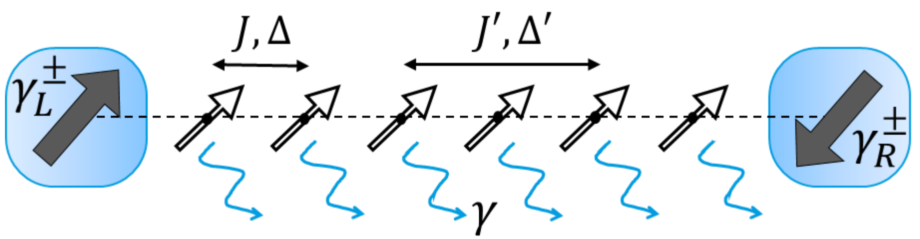
Examples II. Boundary-driven spin chains

[Richter, **LS**, Haque, Phys. Rev. E 111, 064103 (2025)]

$$\partial_t \rho = \mathcal{L}(\rho) = -i[H,\rho] + \sum_\mu \gamma_\mu \left(2L_\mu \rho L_\mu^\dagger - L_\mu^\dagger L_\mu \rho - \rho L_\mu^\dagger L_\mu\right)$$

$$H = J\sum_{j=1}^{N-1}(\sigma_j^x\sigma_{j+1}^x + \sigma_j^y\sigma_{j+1}^y + \Delta\sigma_j^z\sigma_{j+1}^z) + J'\sum_{j=1}^{N-2}(\sigma_j^x\sigma_{j+2}^x + \sigma_j^y\sigma_{j+2}^y + \Delta'\sigma_j^z\sigma_{j+2}^z)$$

Next-to-nearest-neighbour XXZ spin chain



$$L_l^+ = \sigma_1^+, \quad L_l^- = \sigma_1^-,$$
$$L_r^+ = \sigma_N^+, \quad L_r^- = \sigma_N^-,$$

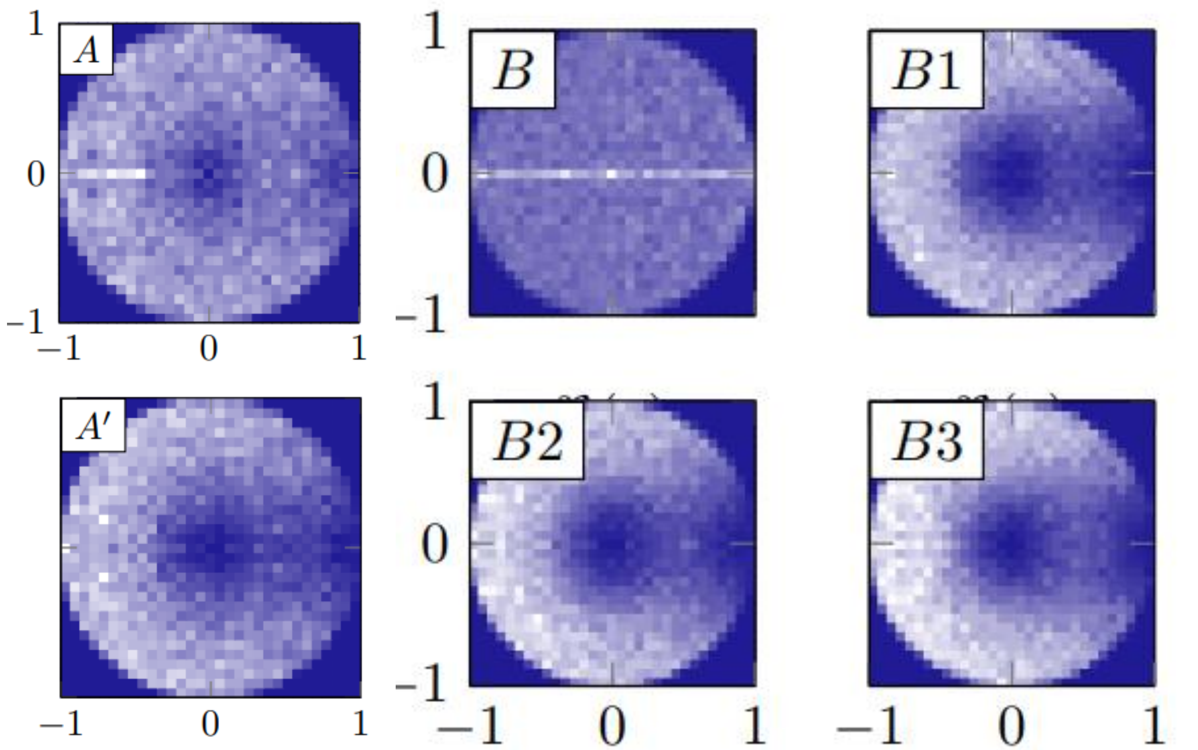
Boundary driving (sink/source)

$$L_j^{\mathrm{deph}} = \sigma_j^z, \quad j = 1, \ldots, N$$

Bulk dephasing

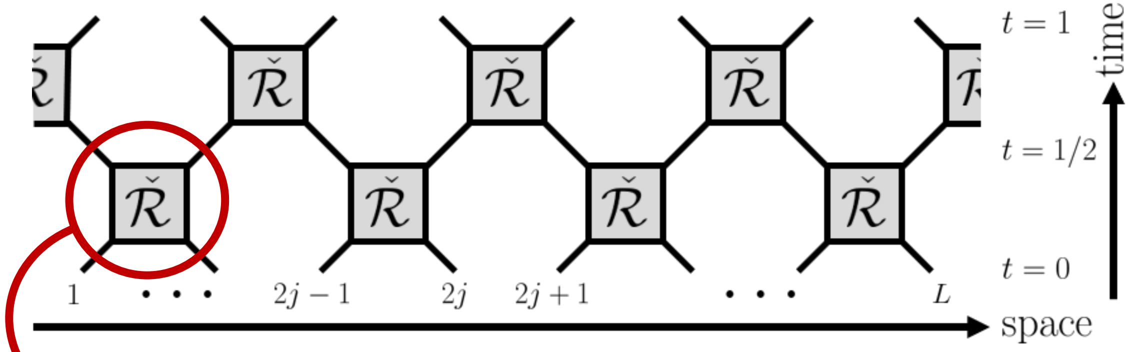
Integrable?

Model	J	Δ	J'	Δ'	γ^{deph}	γ_l^+	γ_l^-	γ_r^+	γ_r^-	$\mathcal{L}$	ρ_{ss}
A	1	1	0	0	0	0.6	0	0	1.4		✓
A'	1	1	1	1	0	0.6	0	0	1.4		
B	1	0	0	0	1.0/0.1	0.5	1.2	1.0	0.8	✓	✓
$B1$	1	0.5	0	0	1.0/0.1	0.5	1.2	1.0	0.8		
$B2$	1	0	1	0	1.0/0.1	0.5	1.2	1.0	0.8		
$B3$	1	0.5	1	0.5	1.0/0.1	0.5	1.2	1.0	0.8		



Examples III. Nonunitary quantum circuits

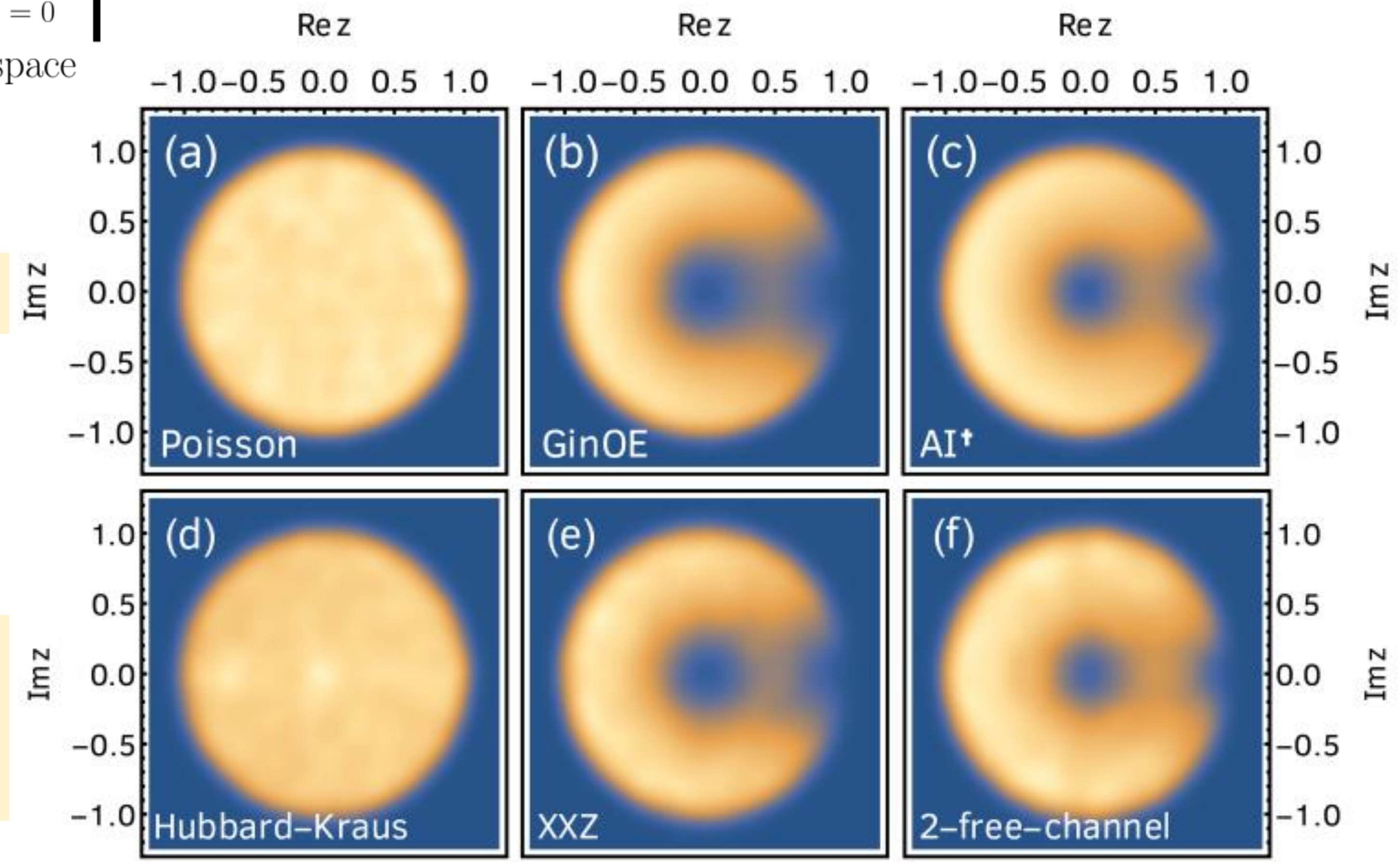
[**LS**, Ribeiro, Prosen Phys. Rev. B **103**, 115132 (2021)]



Hubbard $\check{R}$-matrix (with imaginary interaction)
⇒ integrable circuit

RMT

Nonunitary quantum circuits



Integrable

Chaotic, no TRS

Chaotic, TRS

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Integrable and chaotic quantum maps in a quantum processor

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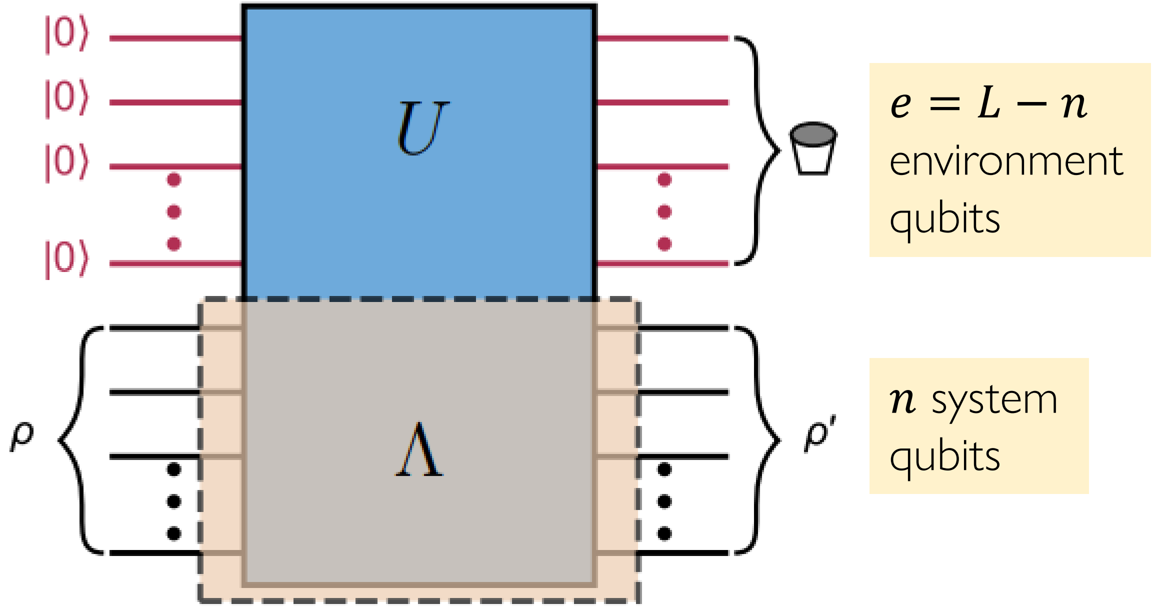
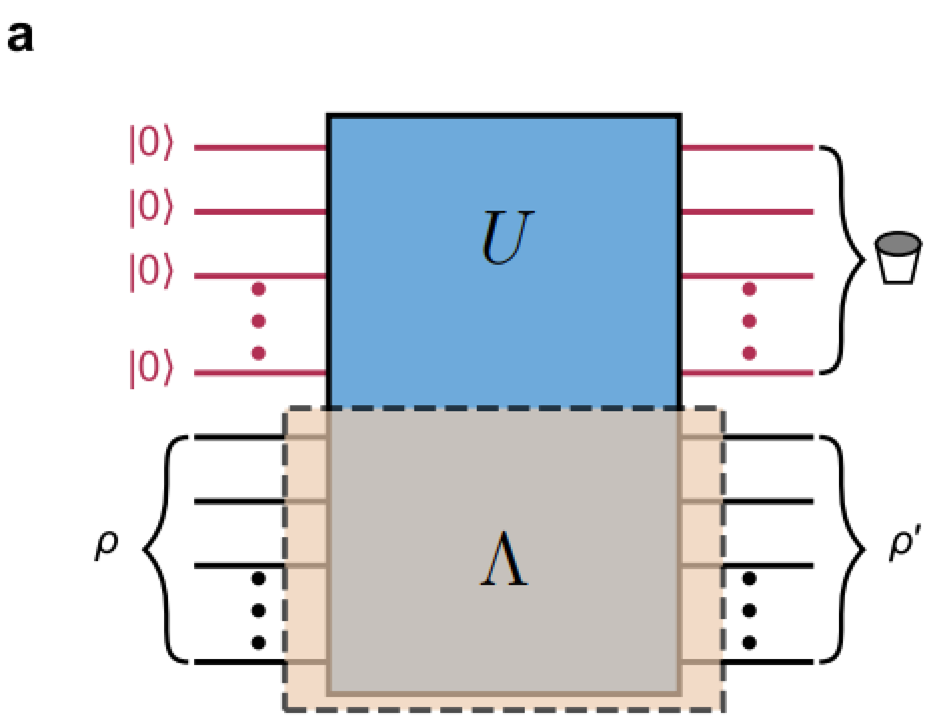


$$\rho' = \Lambda(\rho) = \sum_{j_1,\cdots,j_e} K_{j_1,\cdots,j_e}\rho K^\dagger_{j_1,\cdots,j_e}$$

$$K_{j_1,\cdots,j_e} = \langle j_1 \cdots j_e | U | 0_1 \cdots 0_e \rangle$$

[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

Integrable and chaotic quantum maps in a quantum processor

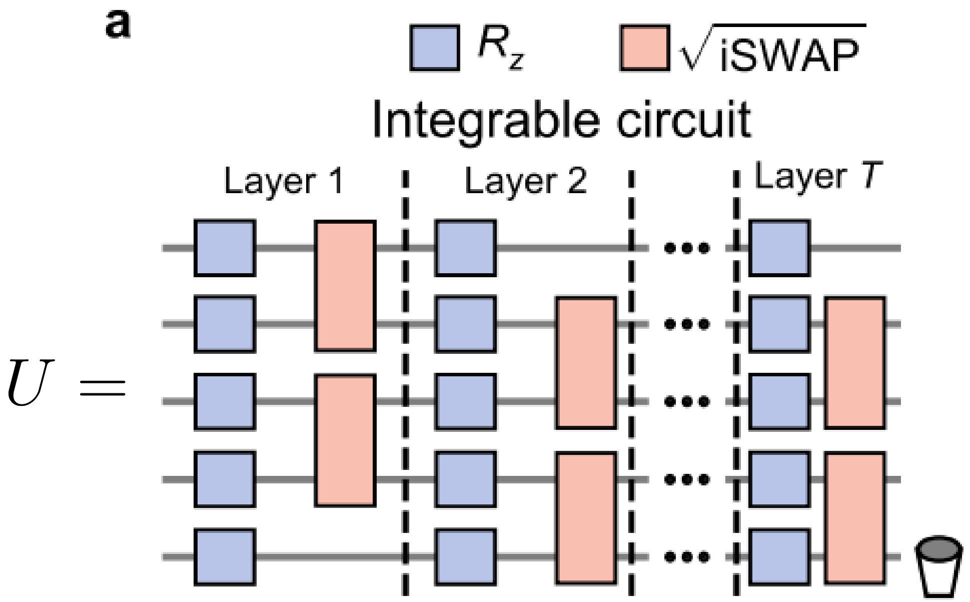


$e = L - n$ environment qubits

n system qubits

$$\rho' = \Lambda(\rho) = \sum_{j_1,\cdots,j_e} K_{j_1,\cdots,j_e} \rho K^{\dagger}_{j_1,\cdots,j_e}$$

$$K_{j_1,\cdots,j_e} = \langle j_1 \cdots j_e | U | 0_1 \cdots 0_e \rangle$$



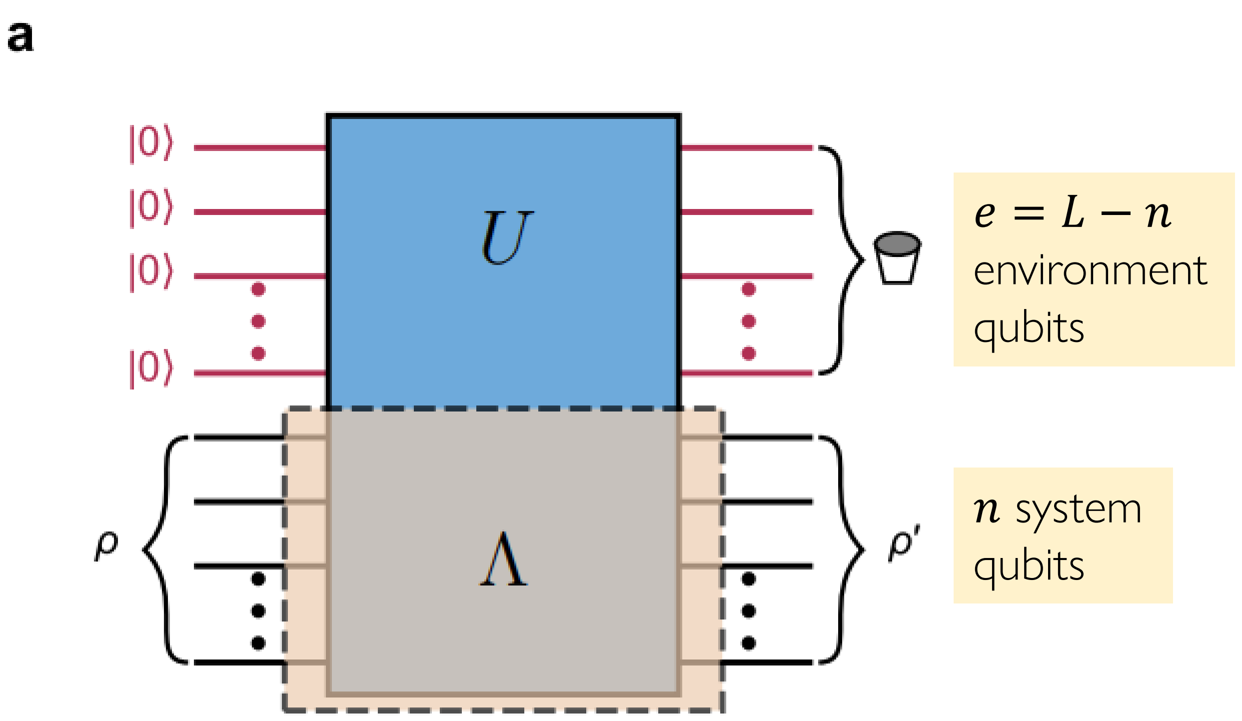
Matchgate circuit;
can be mapped to free fermions:

$$\sqrt{\text{iSWAP}} = e^{\mathrm{i}\frac{\pi}{8}(\sigma^x \otimes \sigma^x + \sigma^y \otimes \sigma^y)}$$

$$R_Z = e^{\mathrm{i}\frac{\theta}{2}\sigma^z}$$

[Wold,..., Denisov, **LS**, Wang, Ribeiro, 2506.04325]

Integrable and chaotic quantum maps in a quantum processor



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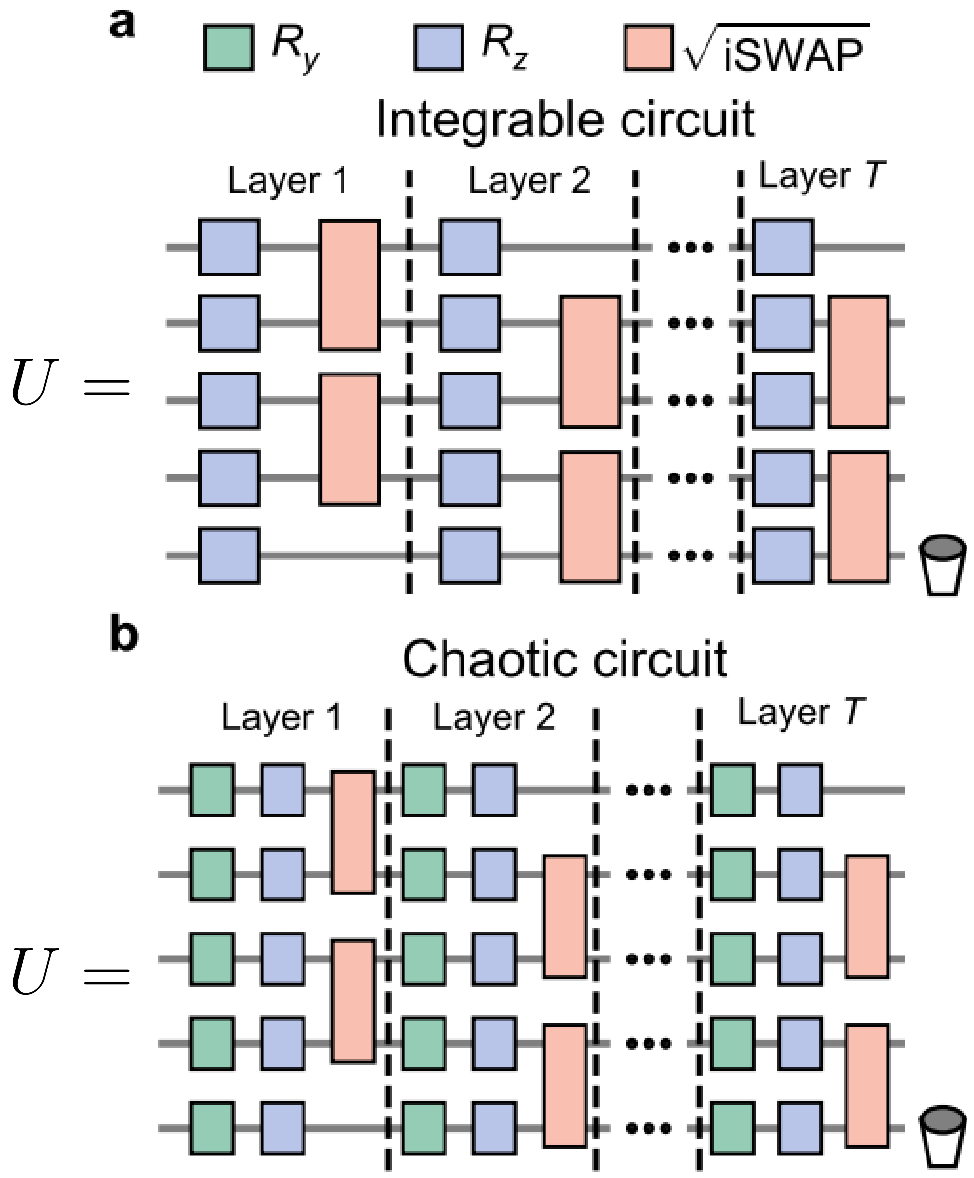
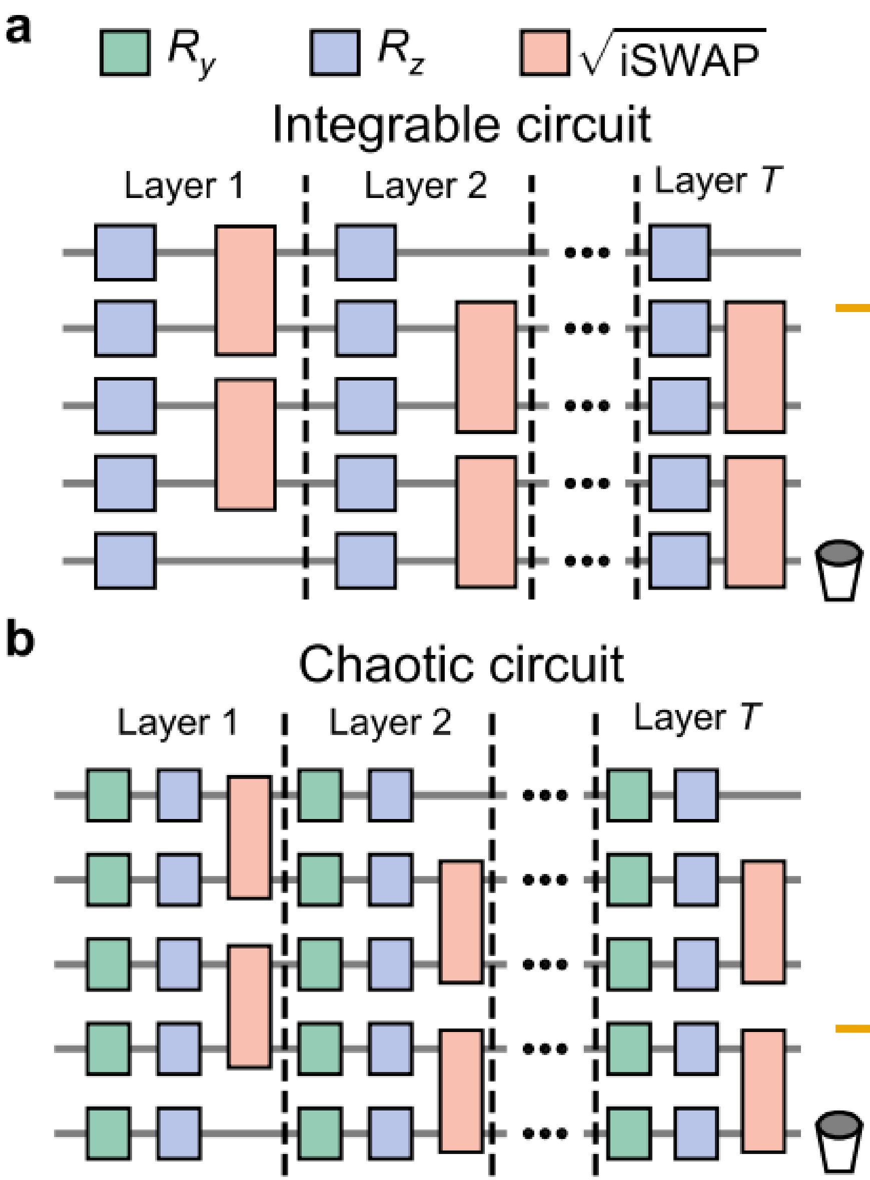
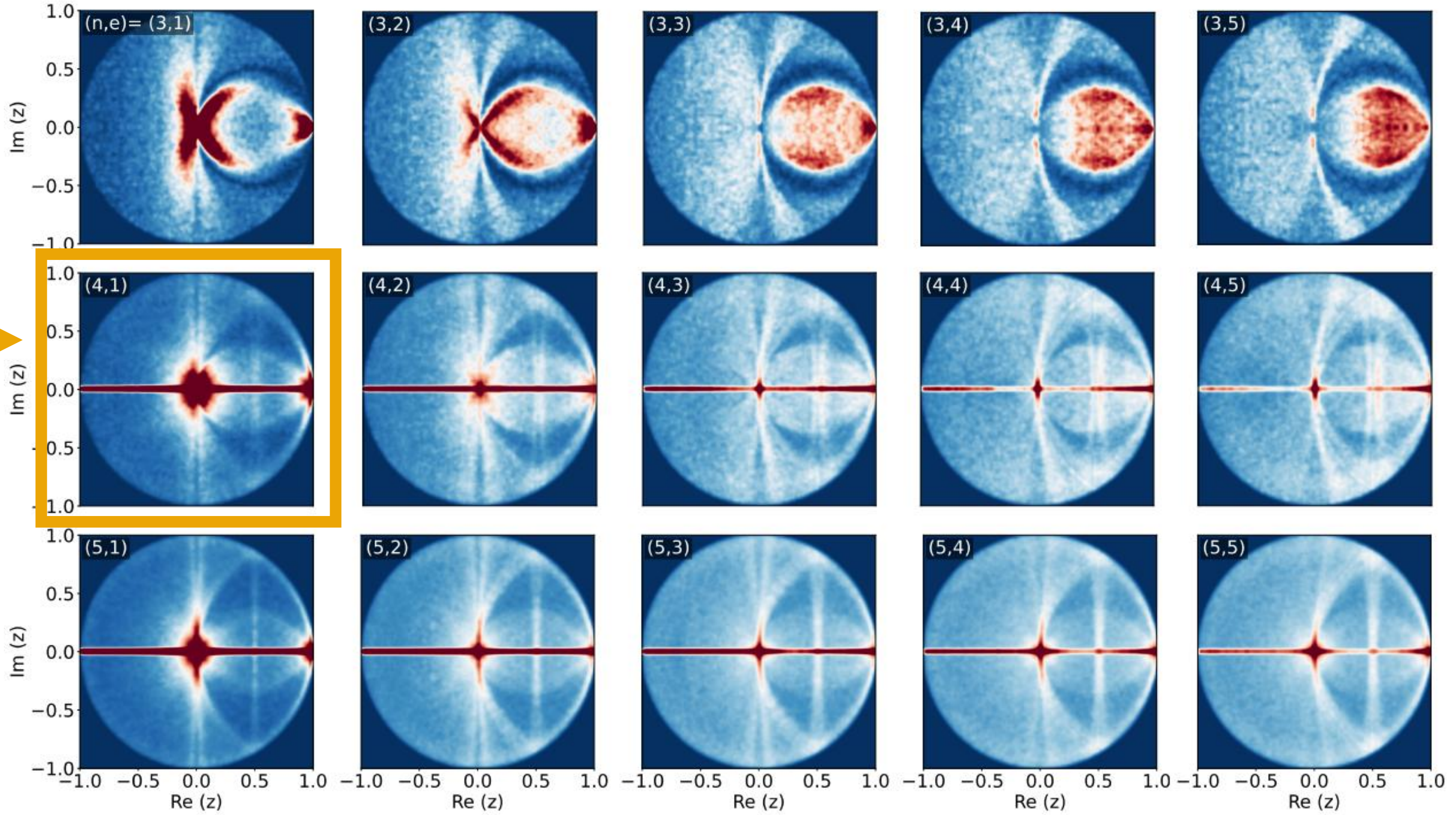


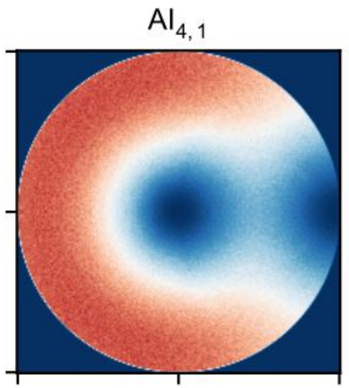
[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

Finite-size effects on CSR distributions

[Wold,..., Denisov, **LS**, Wang, Ribeiro, 2506.04325]

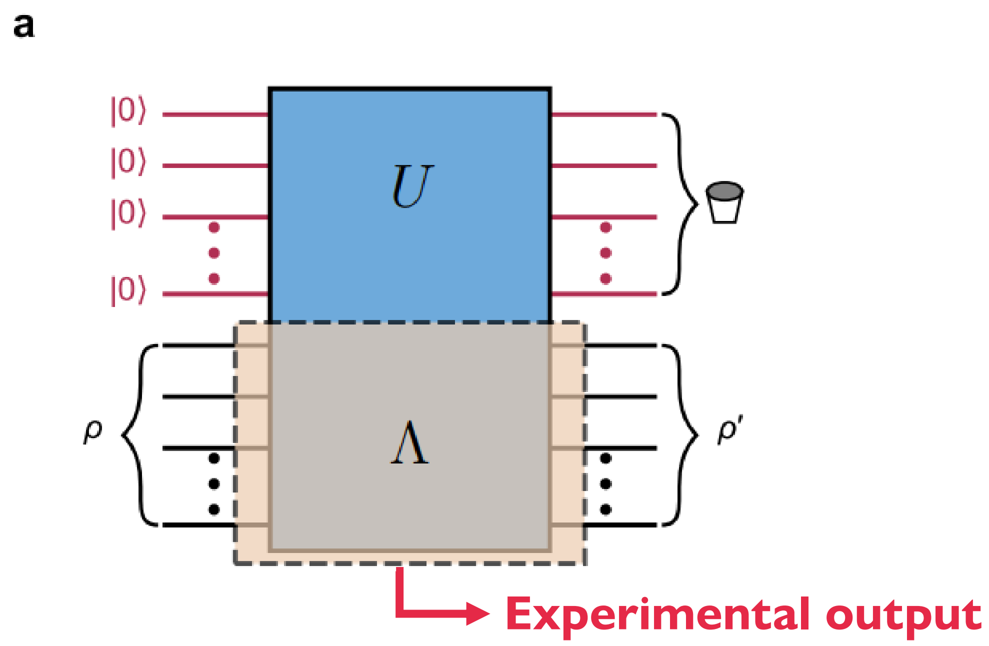






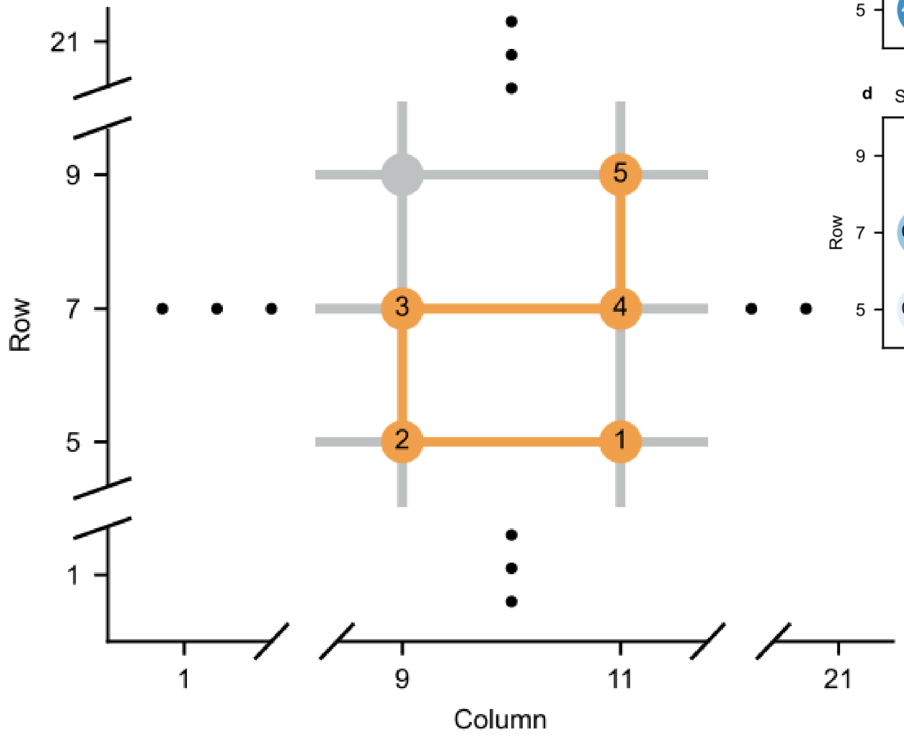
[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

Tomographic experiment in a nutshell



Experiment: tomography yields the experimentally realized channel
Classical post-processing: diagonalize channel and compute CSR

superconducting quantum processor



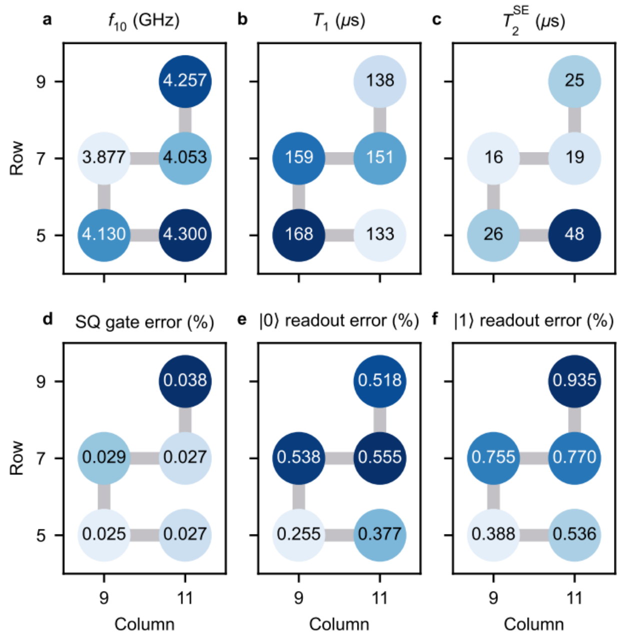
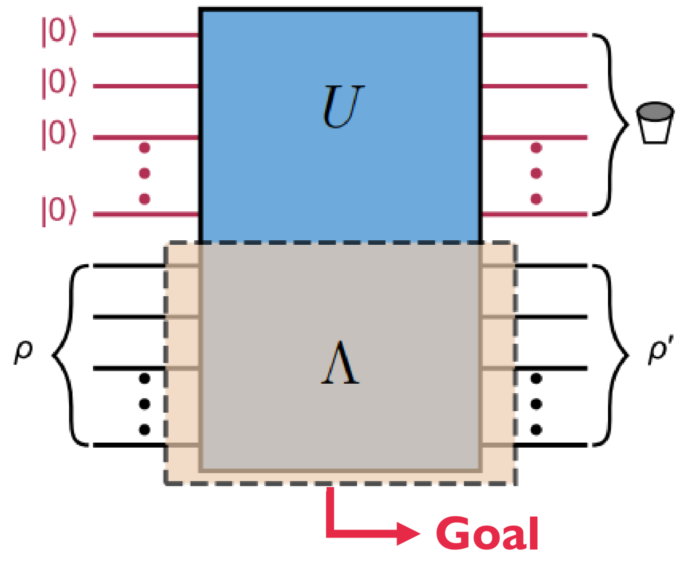


Figure S1. **Schematic of the five-qubit chain arrangement on the quantum processor.** There are 121 qubits (circles) and 220 tunable couplers (lines) on the processor, from which we choose 5 qubits and 4 couplers to perform the experiment. They are highlighted in orange in the diagram.

Tomographic experiment in a nutshell

[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

a



1

$$\mathcal{T}_r(\rho;\boldsymbol{\theta}) = \sum_{s=1}^{r} K_s(\boldsymbol{\theta})\rho K_s^\dagger(\boldsymbol{\theta}),$$

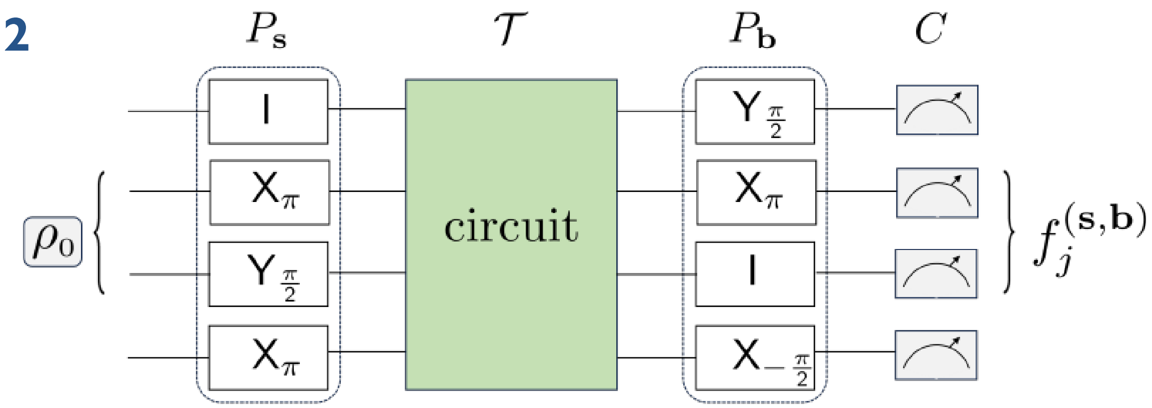
$$\sum_{s=1}^{r} K_s^\dagger(\boldsymbol{\theta})K_s(\boldsymbol{\theta}) = I_d,$$

A_{in}, A_C	G
$A_\rho \in \mathbb{C}^{d\times d}$ **SPAM**	$G \in \mathbb{C}^{dr\times d}$ **Map**
$\rho_0 = A_\rho A_\rho^\dagger / \mathrm{Tr}[A_\rho A_\rho^\dagger]$	$\mathrm{QR}(G) \to \{Q, R\}$
$A_C \in \mathbb{R}^{d\times d}$	$Q^T = [K_1 K_2 \ldots K_r]$
$C_{kl} = \lvert A_{C,kl}\rvert / \sum_{k=1}^{d} \lvert A_{C,kl}\rvert$	$\mathcal{T} = \sum_{s=1}^{r} K_s \rho K_s^\dagger$

[Wold, Ribeiro, Denisov, 2405.11625]

Parametrization

2



Tomography

$$\hat{p}_j^{\mathbf{s},\mathbf{b}}(\boldsymbol{\theta}) = \sum_{k=1}^{d} C_{jk} \cdot (P_{\mathbf{b}} \mathcal{T}(P_{\mathbf{s}} \rho_0 P_{\mathbf{s}}^\dagger; \boldsymbol{\theta}) P_{\mathbf{b}}^\dagger)_{kk}$$

3

$$L[A_{\text{in}}, A_C] = \sum_{\mathbf{s},j} (p_j^{\mathbf{s}} - f_j^{\mathbf{s}})^2 \qquad \textbf{SPAM}$$

$$A_s \longleftarrow A_s + \mu \nabla_{A_s} L[\{A_s\}], \quad s \in \{\text{in}, C\}$$

$$L[G] = \sum_{\mathbf{s},\mathbf{b},j} (p_j^{\{\mathbf{s},\mathbf{b}\}} - f_j^{\{\mathbf{s},\mathbf{b}\}})^2 \qquad \textbf{Map}$$

$$G \longleftarrow G + \mu \nabla_G L[G]$$

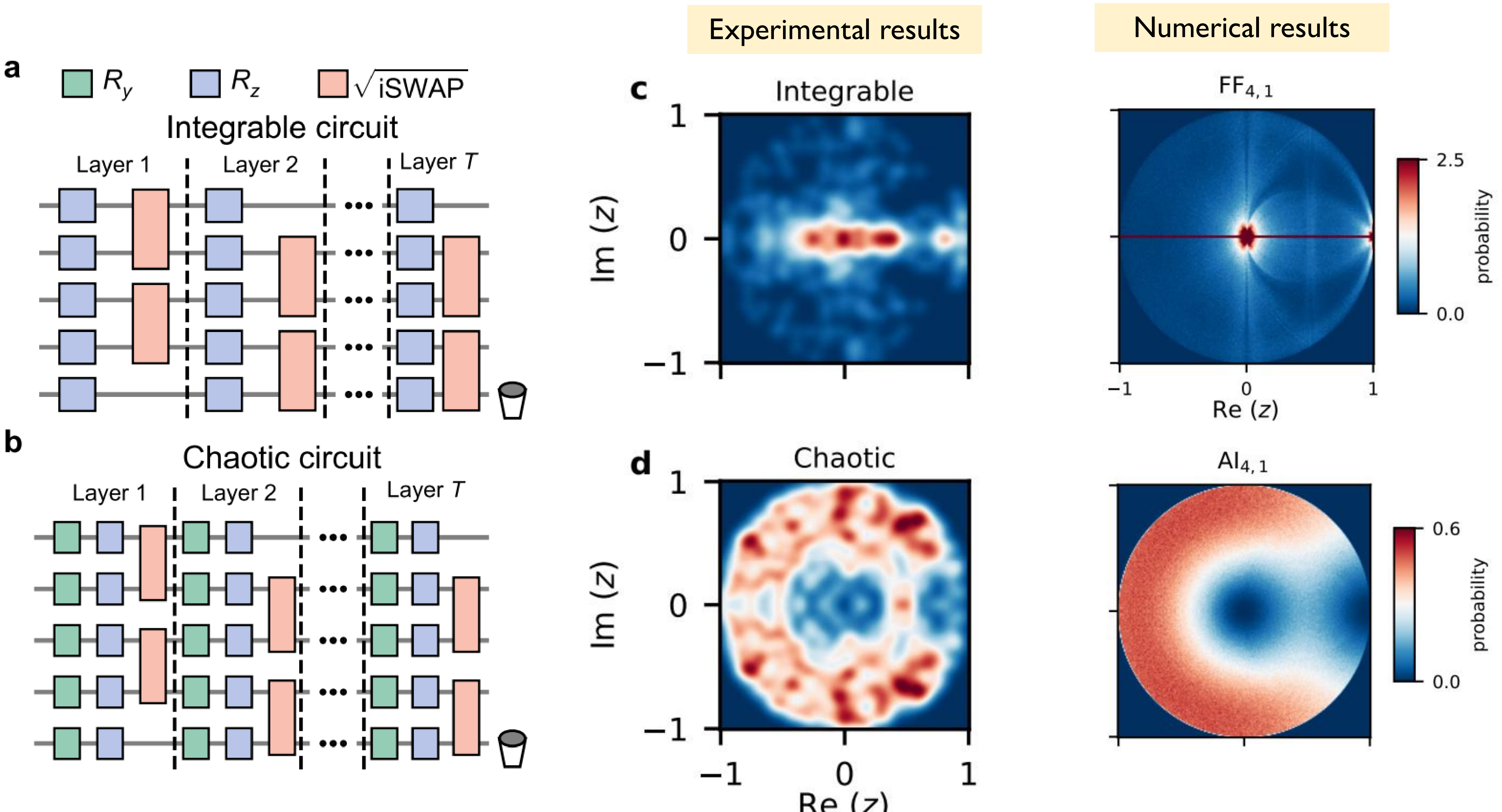
Optimization

Λ

Success!

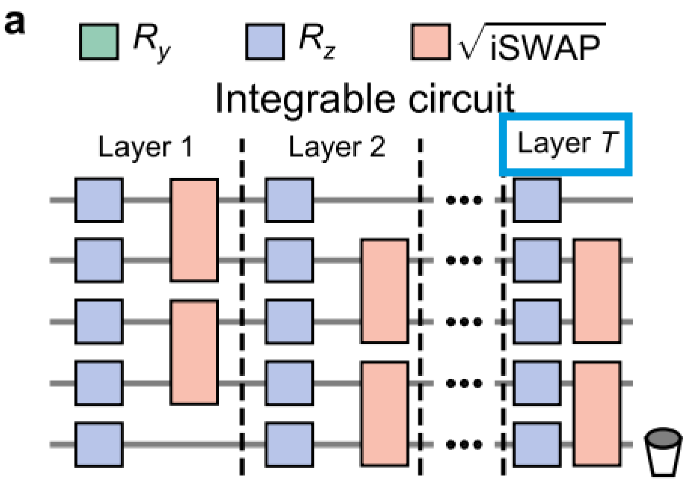
Experimental results

[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

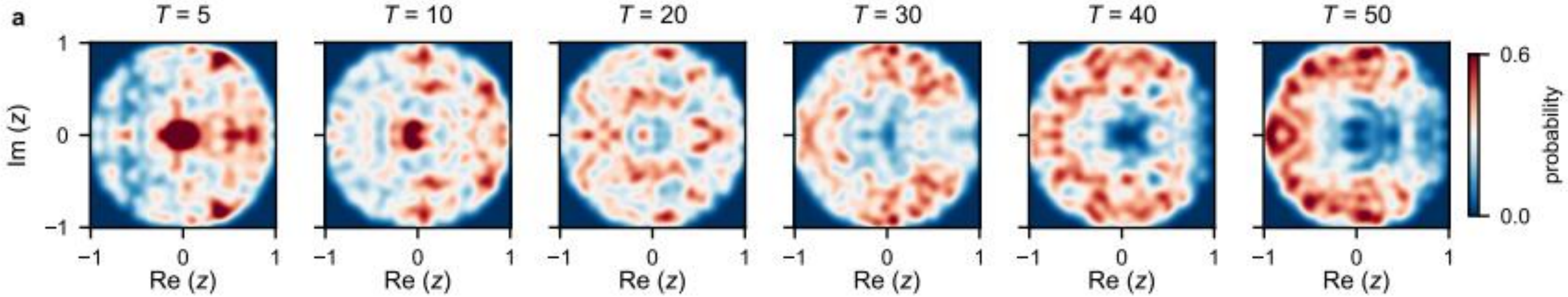


Intrinsic noise as a dissipative quantum chaotic process

[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

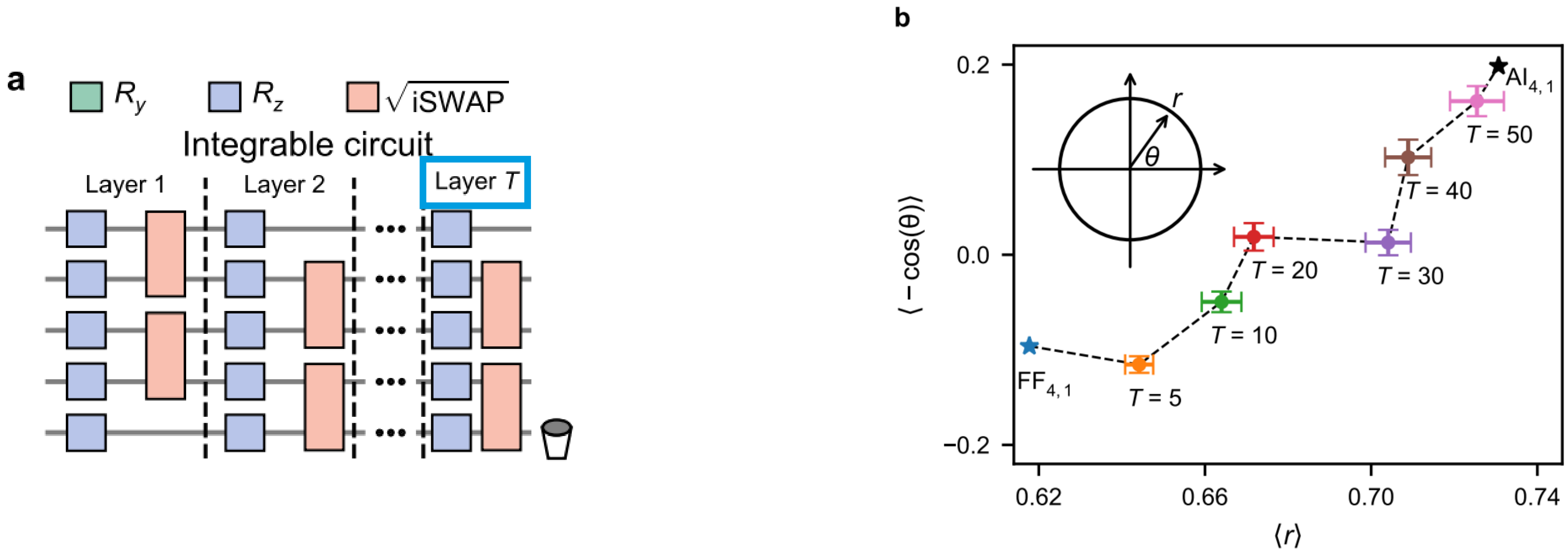


Integrability-to-chaos crossover on a noisy quantum computer → depth of quantum circuit

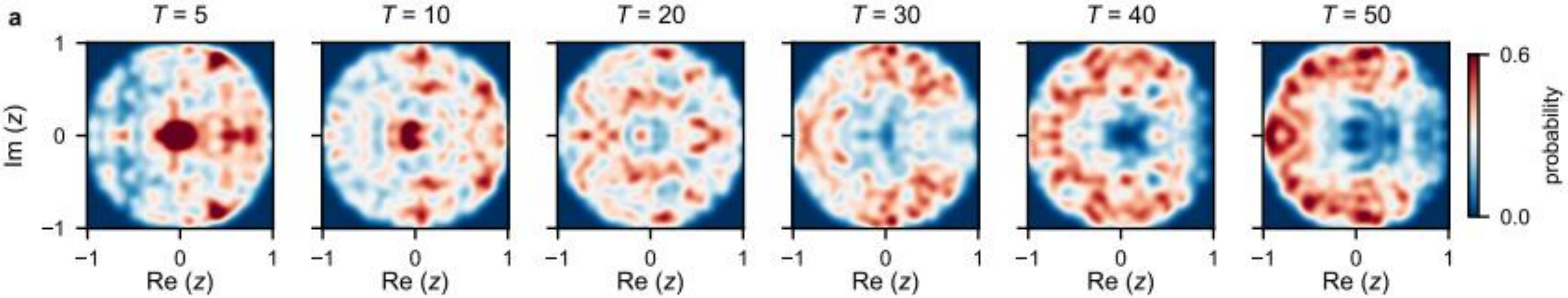


Intrinsic noise as a dissipative quantum chaotic process

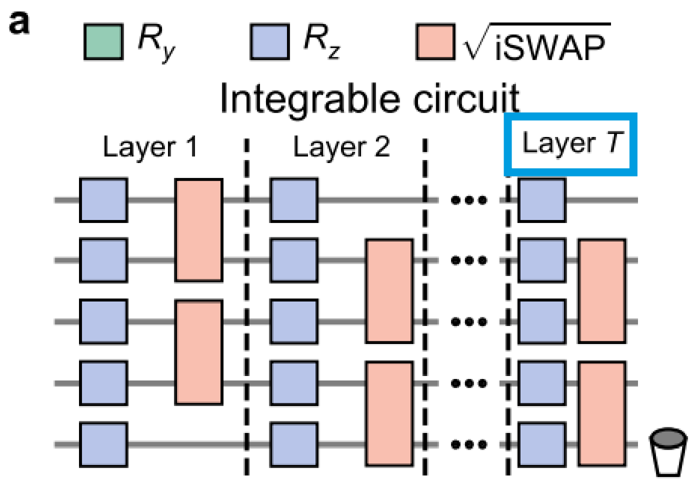
[Wold,…, Denisov, **LS**, Wang, Ribeiro, 2506.04325]

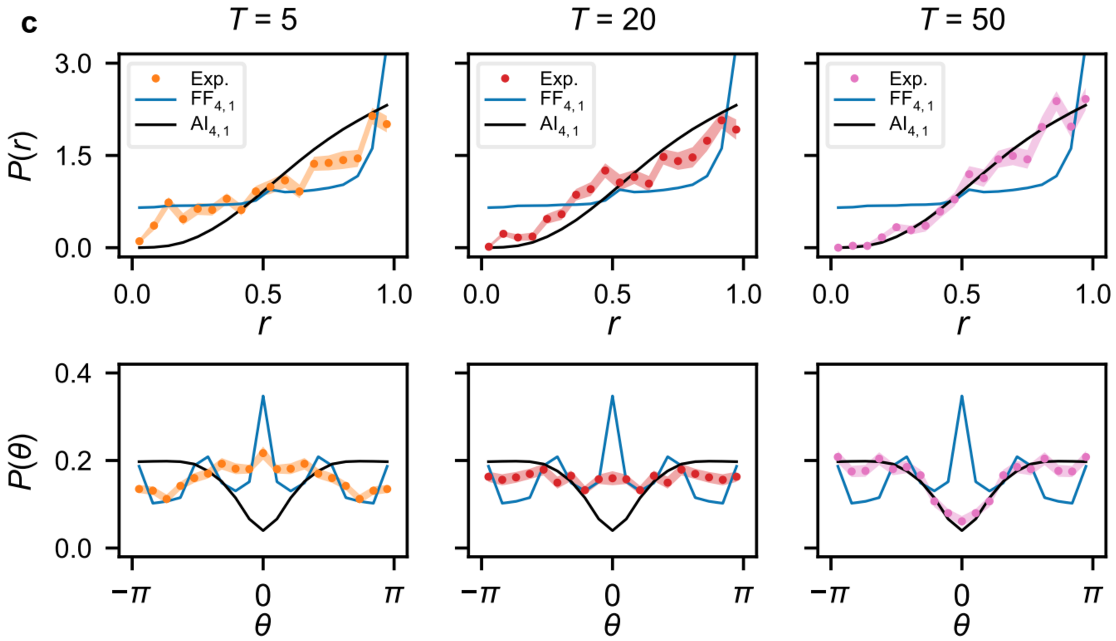


Integrability-to-chaos crossover on a noisy quantum computer → depth of quantum circuit

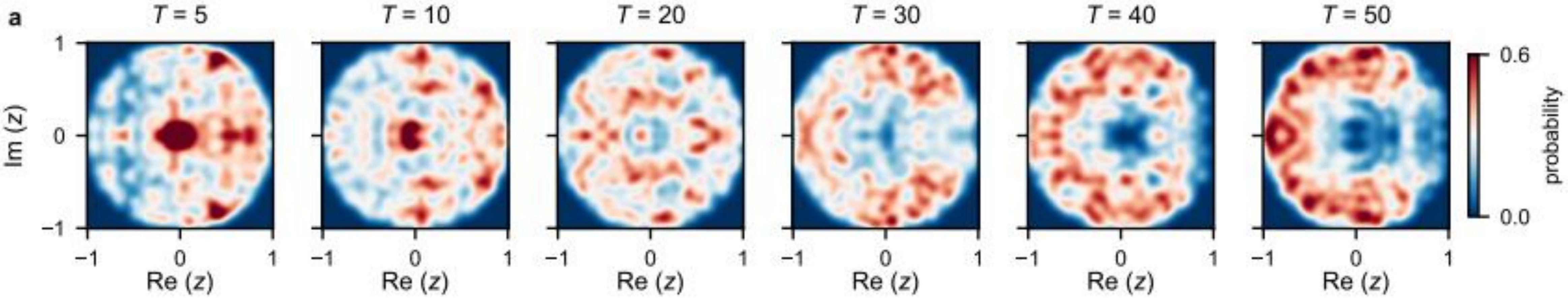


Intrinsic noise as a dissipative quantum chaotic process





Integrability-to-chaos crossover on a noisy quantum computer → depth of quantum circuit



Summary and conclusions

Complex spacing ratios measure spectral correlations in dissipative quantum chaos.
They distinguish integrable and chaotic dissipative quantum systems (and different universality classes).

Numerically: simple, clean, robust
Analytically: Wigner surmise
Experimentally: observed on a superconducting quantum processor

Integrability-to-chaos crossover with circuit depth – hardware noise is dissipative quantum chaotic process
Susceptibility to dissipative chaos – a new operational metric for benchmarking quantum processing platforms?

Theory:
Phys. Rev. X **10**, 021019 (2020)
Experiment:
arXiv:2506.04325 (2025)

Thank you for your attention.

This project was supported by a Research Fellowship from the **Royal Commission for the Exhibition of 1851**

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