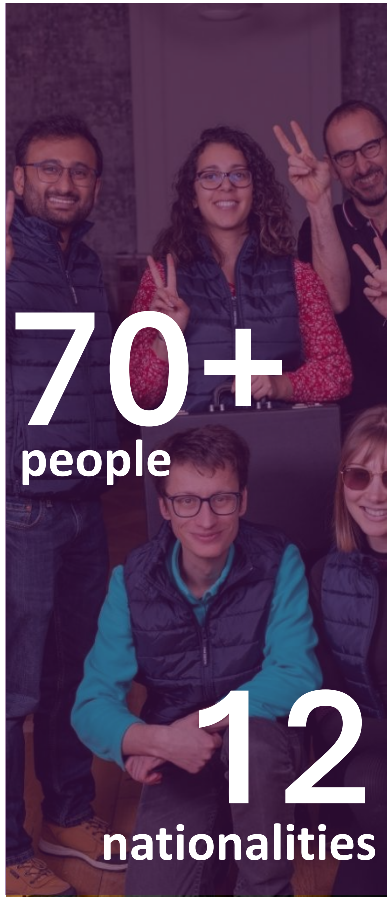
Randomized measurements for large-scale quantum experiments

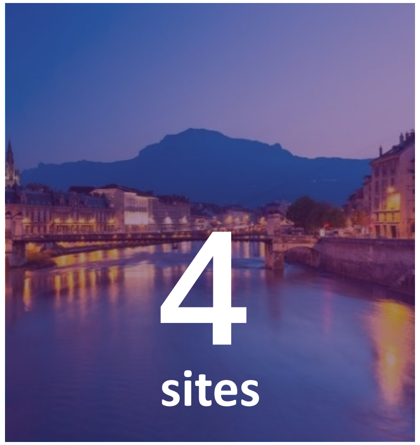
Benoit Vermersch

Quobly, and LPMMC Université Grenoble Alpes (on leave)

MIT Seminar

Quobly was launched in November 2022



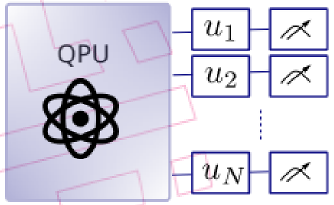


Our networks: IEC ISO MINALOGIC EIC Scaling Club Selected Club Member le lab quantique QuIC QuantAlps #QEI QUANTUM FLAGSHIP FRANCE 2030 LES MAISONS DU QUANTIQUE FRANCE DEEPTECH CREATIVE DESTRUCTION LAB Le HUB Quantique Teratec

Quantum Information Team @ Quobly

Measurements & Benchmarking

Data acquisition



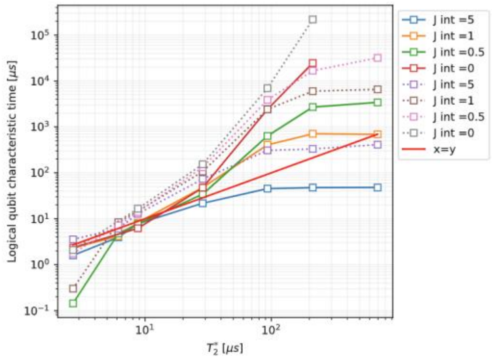
Measurements data

Postprocessing

Observables, Entanglement, Fidelity, XEB Fidelity, Tomography, etc

Architectures and quantum error correction

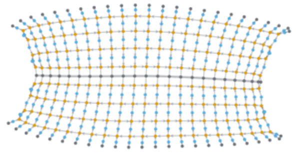
Surface-17 code



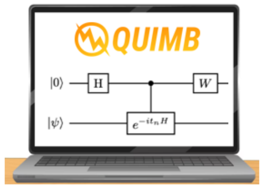
Tensor-Network Simulations & quantum algorithms R&D (open-source)

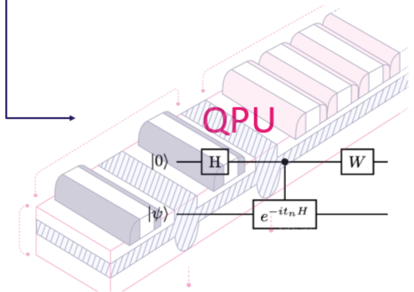
Classical preprocessing

Large scale compilation,
Tensor quantum programming,
Qubitization



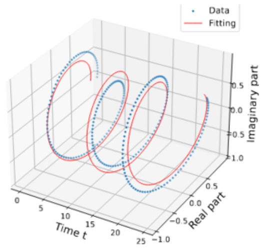
Internal Simulator





Classical postprocessing

Semi-Classical QFT
Time-series analysis
....
Benchmark with tensor-networks



Today's menu

Moderate scale randomized measurements

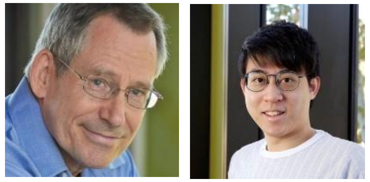
1) Motivations
2) Measurements of entanglement entropies
3) More advanced usage and "statistical tricks"

Large scale learning via randomized measurements

Randomized measurements for large-scale experiments


P. Zoller (UIBK)


A. Elben (Psi)

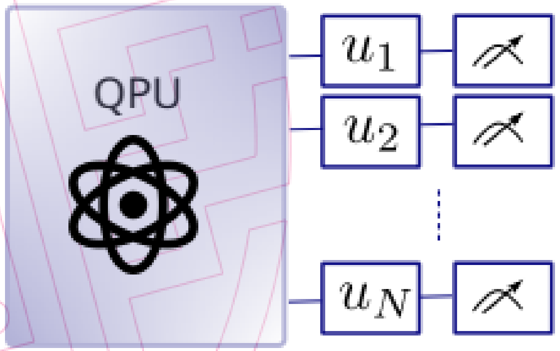

J. Preskill, R. Huang (Caltech)


R. Kueng (Linz)


J.I.C Cirac (MPQ

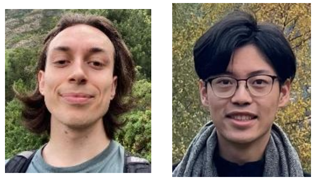

B. Kraus (TUM)

Randomized measurements

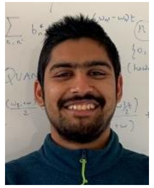



L. Piroli (Unibo)

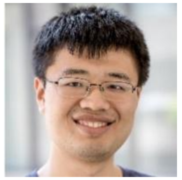

M. Serbyn. M. Ljubotina (ISTA)


M. Votto, W. Lam (UGA)

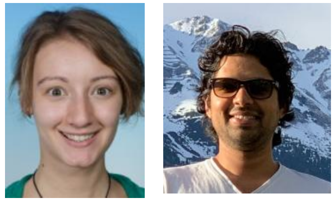

V. Vitale (Pasqal)


A. Rath (IQM)

Experiments


Xiao Mi (Google)


P.Jurcevic (IBM)


T. Brydges, M. Joshi,


C. Roos, R. Blatt (UIBK)


C. Lancien (UGA)

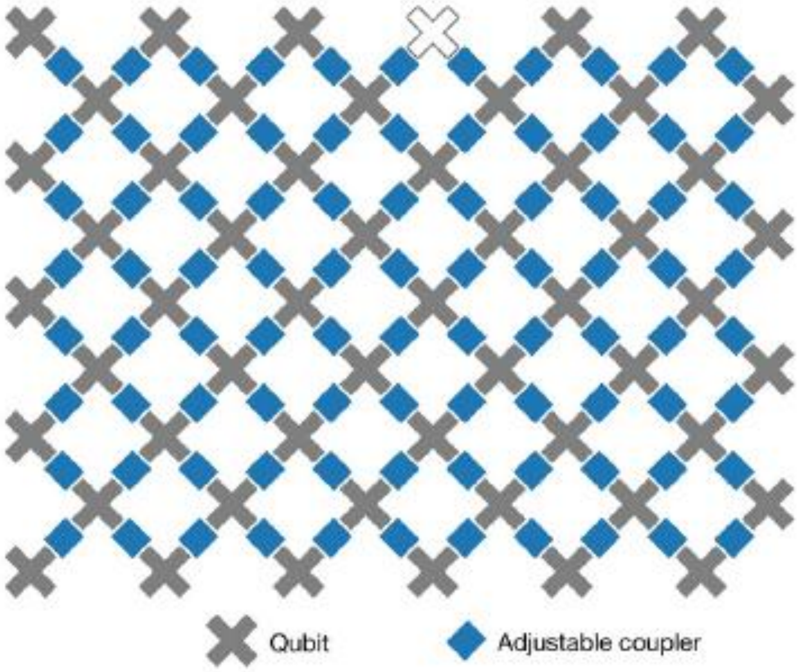
And many more…

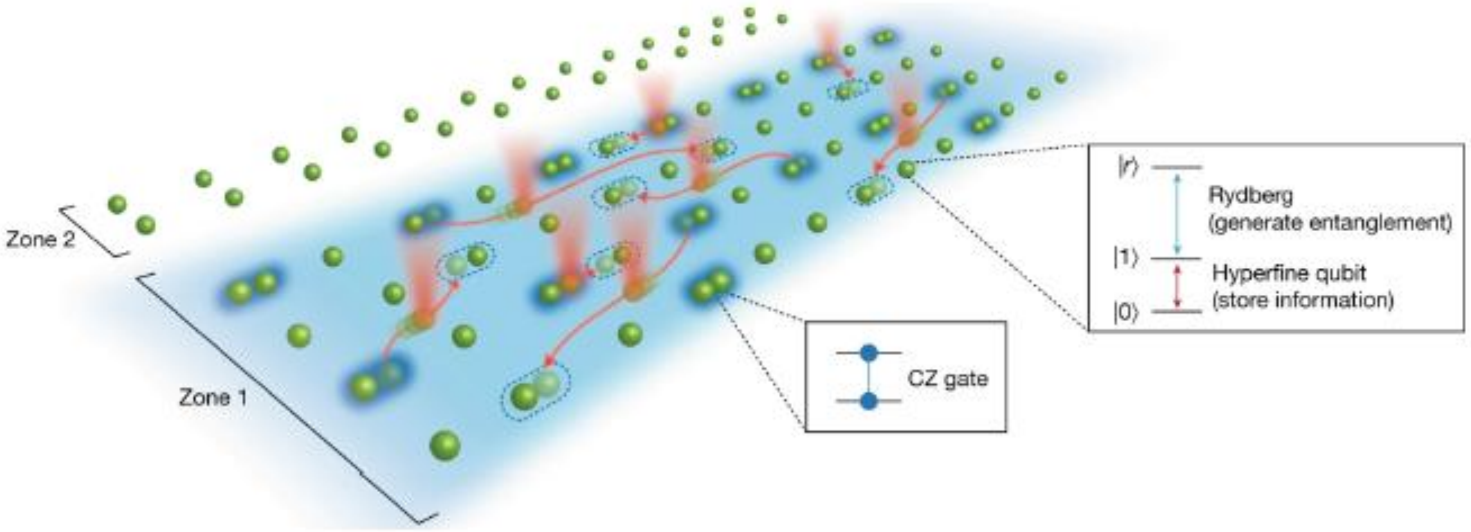
The randomized measurement toolbox A. Elben, S. T. Flammia, H.-Y. Huang, R. Kueng, J. Preskill, BV, P. Zoller, Nature Physics Review (2023).

UGA Université Grenoble Alpes · QuantAlps · FRANCE 2030 · IQI · FWF · cnrs · anr · quobly

LARGE-SCALE QUANTUM EXPERIMENTS

Nowadays several experiments realize large-scale programmable quantum many-body systems (∼100 qubits) [Arute, Nature ’19; Bluvstein, Nature ’22]

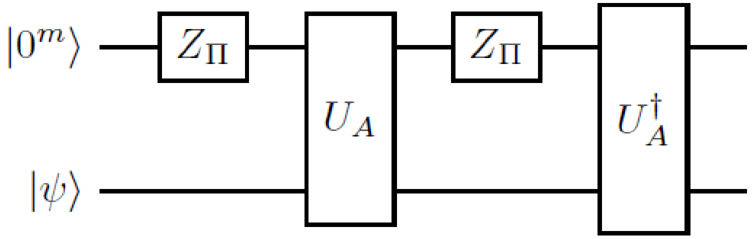


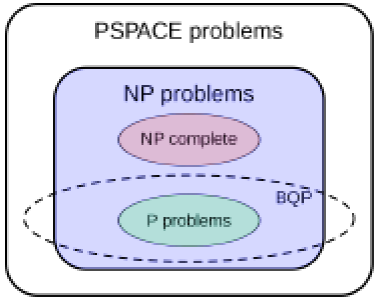


WHAT’S THE POINT OF LARGE-SCALE QUANTUM EXPERIMENTS

Quantum computing

Solves a classical problem or quantum problem via a quantum algorithm

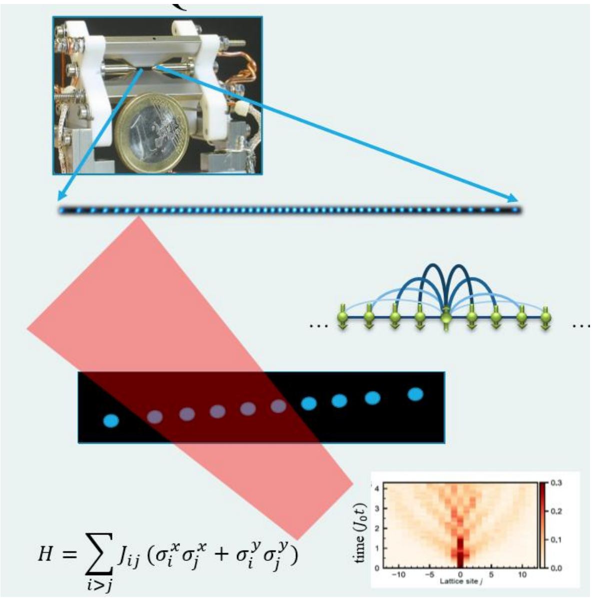




We hope to realize a computation that is not (easily) accessible to classical computers: Quantum advantage

Quantum simulation

Emulates many-body physics via an artifical quantum material



Credit
Manoj Joshi (IQOQI)

We want to obtain meaningful physical properties

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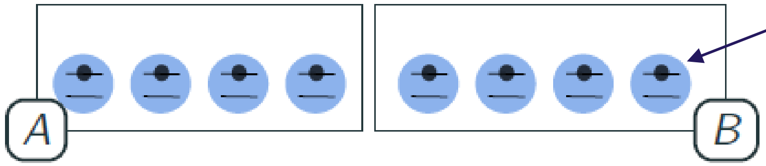
Entanglement: A central concept in quantum computing & quantum simulation

Qubit = {|0>,|1>}



A and B are entangled iff $|\psi\rangle \neq |\psi_A\rangle \otimes |\psi_B\rangle$

Example with two qubits. The Bell state $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ is entangled

Entanglement is quantified via Entropies

Reduced Density Matrix

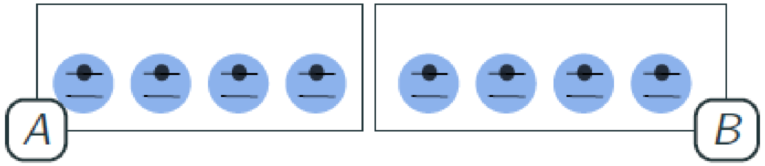
$$S_{\mathrm{vN}} = -\mathrm{Tr}[\rho_A \log(\rho_A)] \text{ von Neumann Entropies}$$

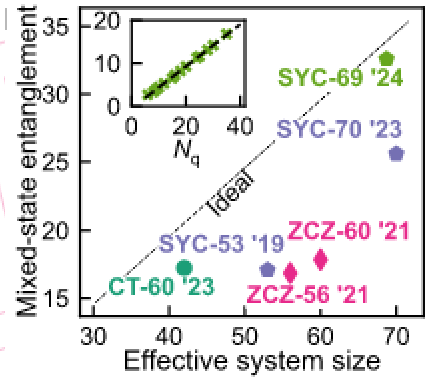
$$S_\alpha = \frac{1}{1-\alpha} \log[\mathrm{Tr}(\rho_A^\alpha)] \text{ Rényi entropies}$$

Purity

$$\mathrm{Tr}(\rho_A^2)$$

Entanglement: A central concept in quantum computing & quantum simulation

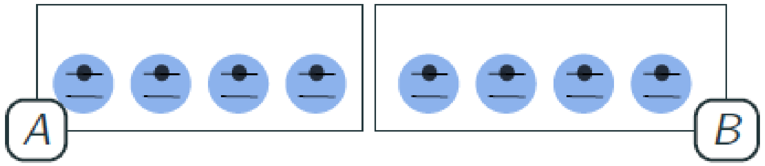


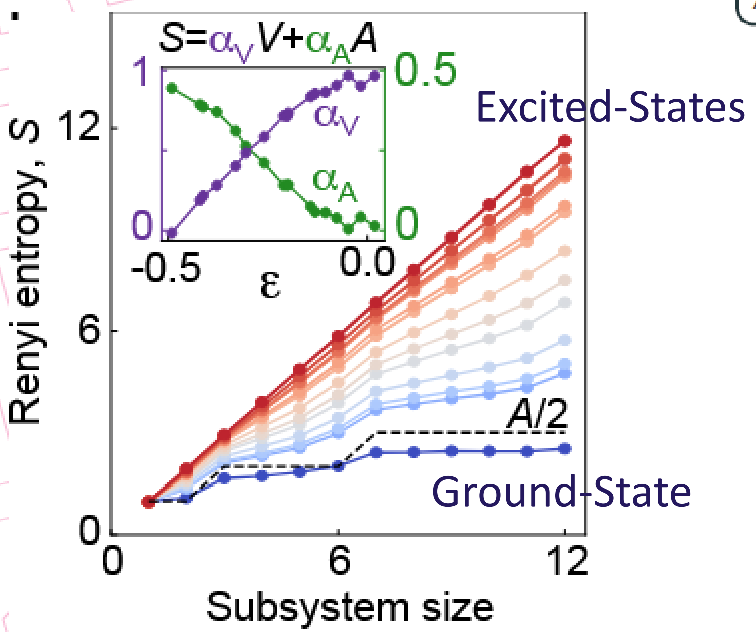


Andersen et al, Nature 2025

- Most basic non-classical feature of quantum computers.
- All important quantum algorithms involve quantum operations that generate entanglement.
- Quantum algorithms with a low level of entanglement can be efficiently simulated with a classical computer (Eisert RMP 2010)
- Universal predictions for large-scale quantum computers (eg Nahum PRX 2017)

Entanglement: A central concept in quantum computing & quantum simulation



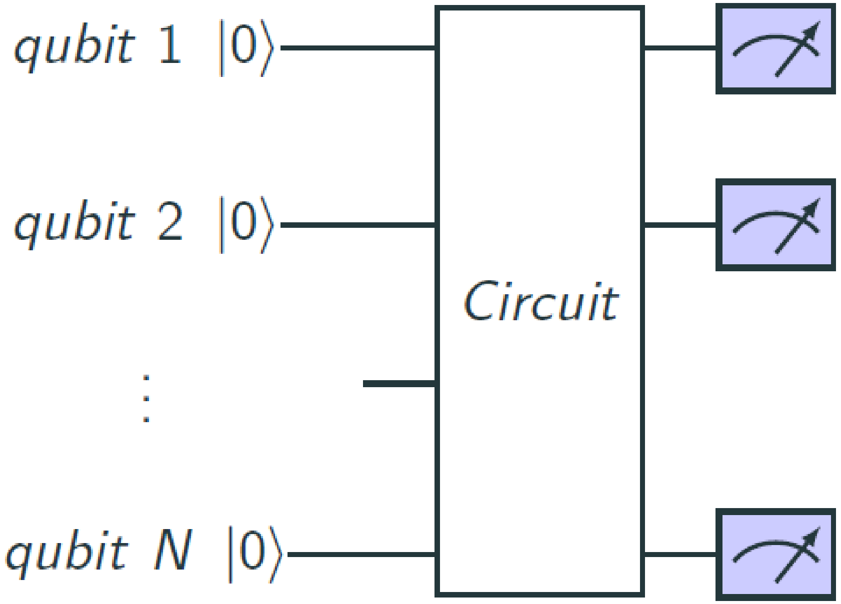


Andersen et al, Nature 2025

- Distinguish quantum phases in quantum simulation, spots quantum phase transitions (Eisert, RMP 2010)

- Describes many-body quantum dynamics, thermalization, disorder physics, etc

Measurements in quantum experiments

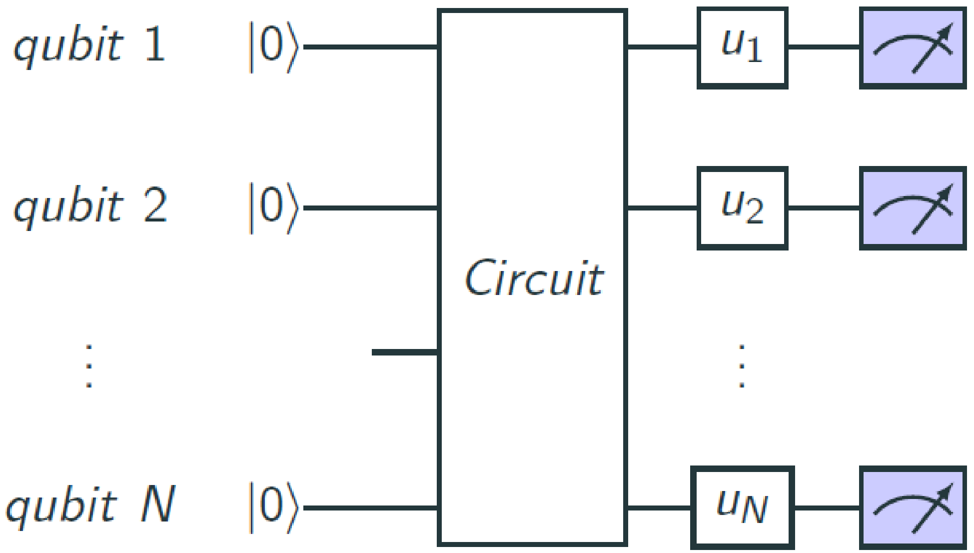


- Quantum measurements: the state $|s\rangle$ is measured with probability $\langle s|\rho|s\rangle$, in a certain measurement basis
- We have access to observables of the type $O\,|s\rangle = O(s)\,|s\rangle$.

$$\langle O\rangle = \sum_s \langle s|\rho|s\rangle\, O(s) \qquad (7)$$

- Measurement of 4^N observables: I can realize state tomography, i.e measure ρ.
- Can I measure the purity $\mathrm{Tr}(\rho^2)$ more directly?

Randomized measurements: A single data acquisition procedure



Repeat N_UxN_M times

- Randomized measurements: We measure $P_u(s) = \langle s|u\rho u^\dagger|s\rangle$, $u = u_1 \otimes \cdots \otimes u_N$.
- u_i chosen independently from the circular unitary ensemble (CUE)
- We extract quantities of interest from the statistics of $P_u(s)$, over random unitary transformations.

For example, the purity formula (Elben, BV, et al, PRL 2018)

$$\mathrm{Tr}(\rho^2) = 2^N E_u\left[\sum_{s,s'}(-2)^{-D(s,s')}P_u(s)P_u(s')\right]$$

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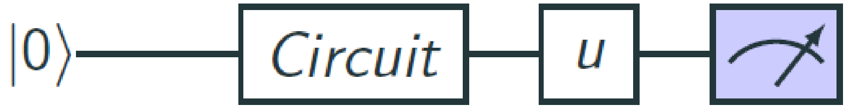
Original protocol: van Enk-Beenakker (PRL 2012)

- Consider a single qubit



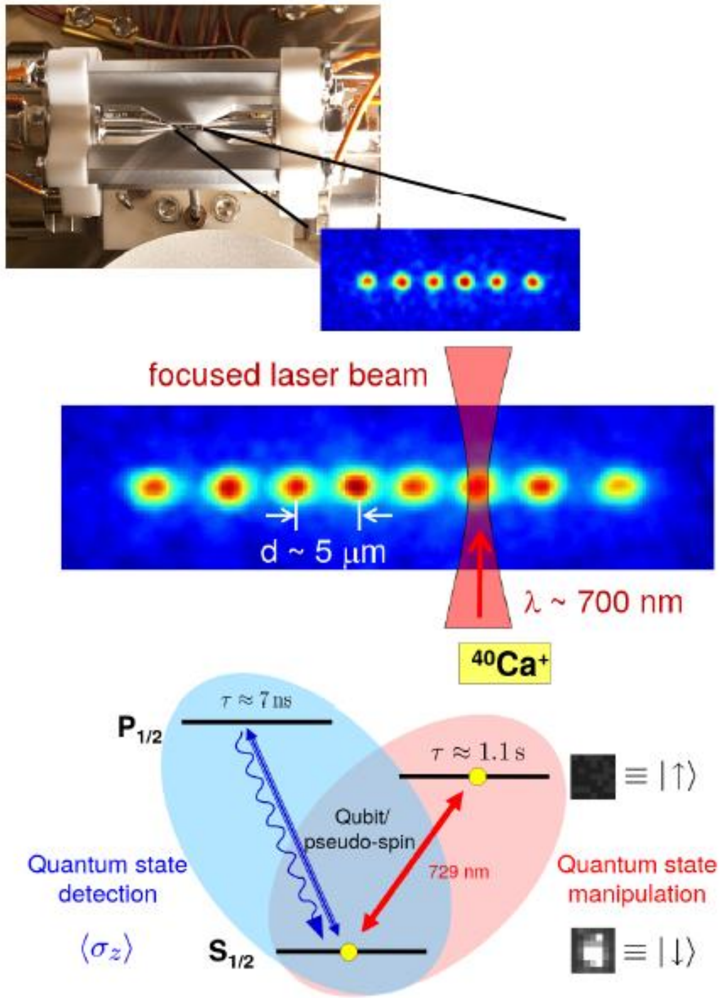
- We evaluate the statistics of
$P_u(s) = \langle s|u\rho u^\dagger|s\rangle = \sum_{m,n} u_{s,m}\rho_{m,n}u^*_{s,n}$

$$E[[P_u(s)]^2] = \sum_{m,n,m',n'} \rho_{m,n}\rho_{m',n'} E[u_{s,m}u^*_{s,n}u_{s,m'}u^*_{s,n'}] \qquad (2)$$

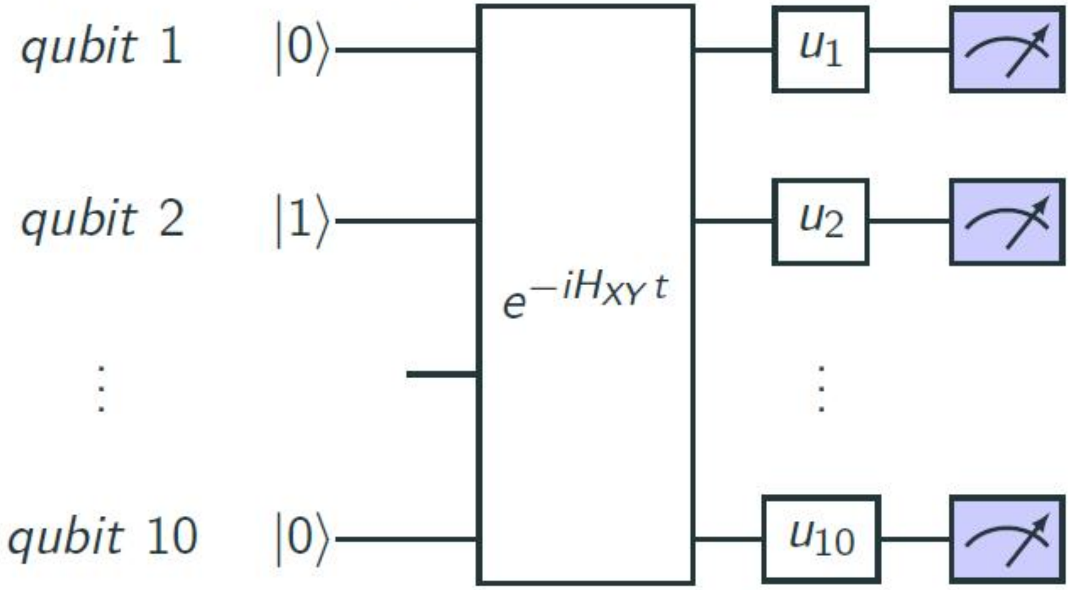
- Using Random Matrix Theory (2-design identities)

$$\overline{[P_u(s)]^2} = \frac{1}{6}\sum_{m,n,m',n'} \rho_{m,n}\rho_{m',n'}\left(\delta_{m,n}\delta_{m',n'} + \delta_{m,n'}\delta_{m',n}\right)$$
$$= \frac{1+\mathrm{Tr}(\rho^2)}{6} \qquad (3)$$

First demonsration: Brydges et al, Science 2019



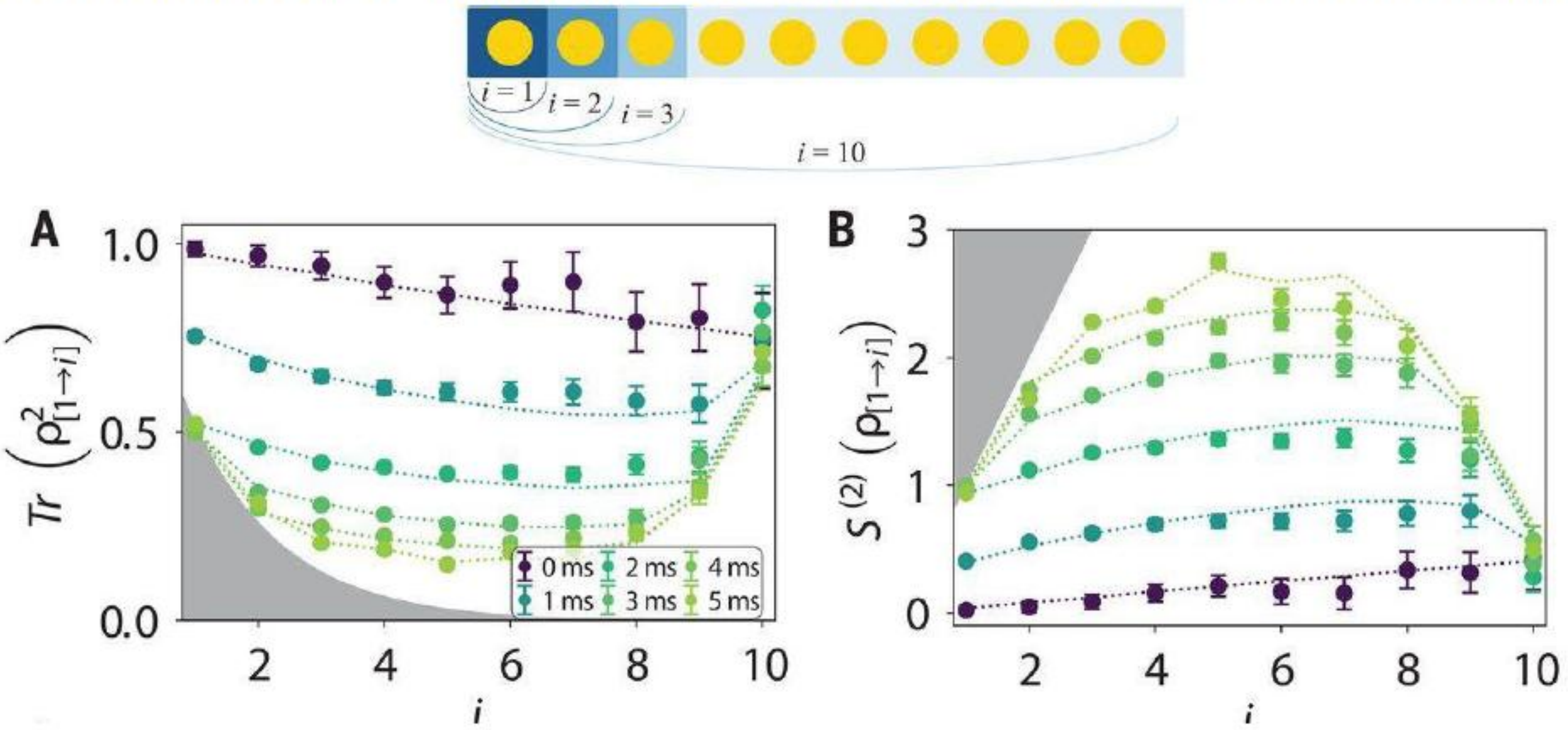
- A programmable quantum simulator



- Goal: Understand entanglement growth in a quantum system

First demonstration: Brydges et al, Science 2019

- Demonstration of randomized measurements with the measurement of the purity



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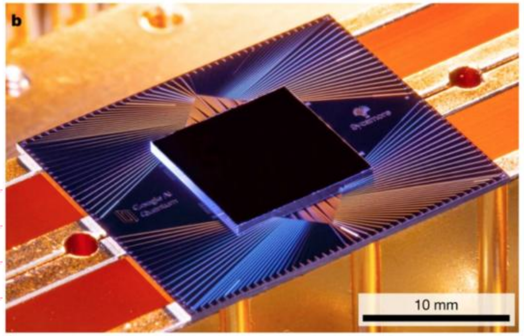
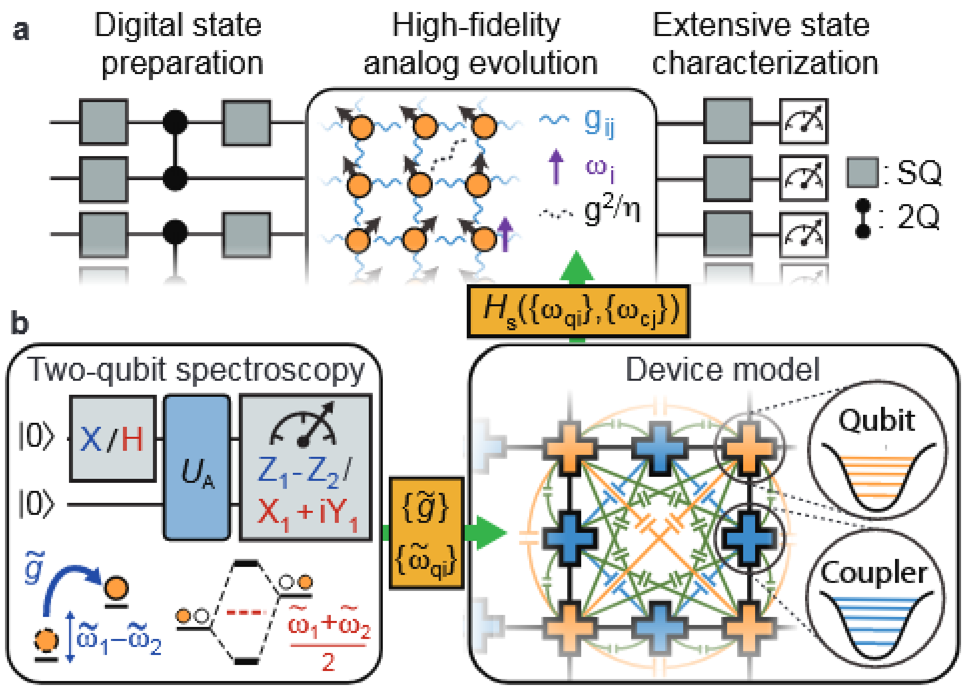
Recent use of RM: Andersen et al, Nature 2025

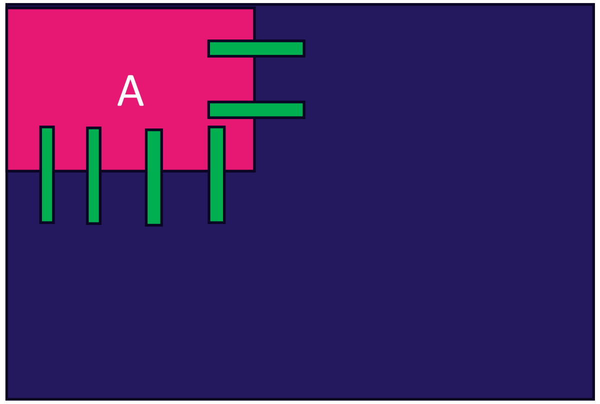


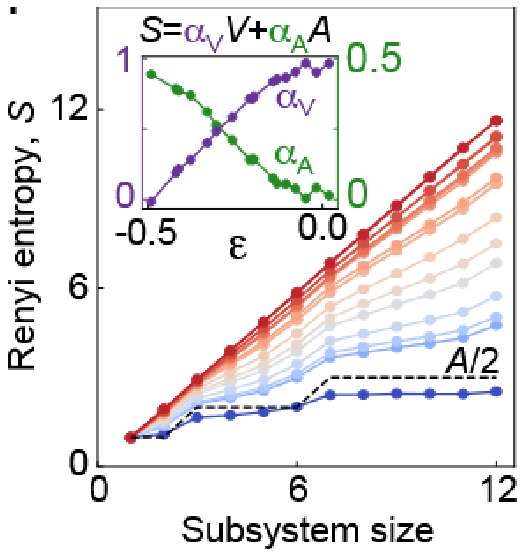
Quantum AI



Demonstration of entanglement’s area law
In the ground-state

Entanglement “links”





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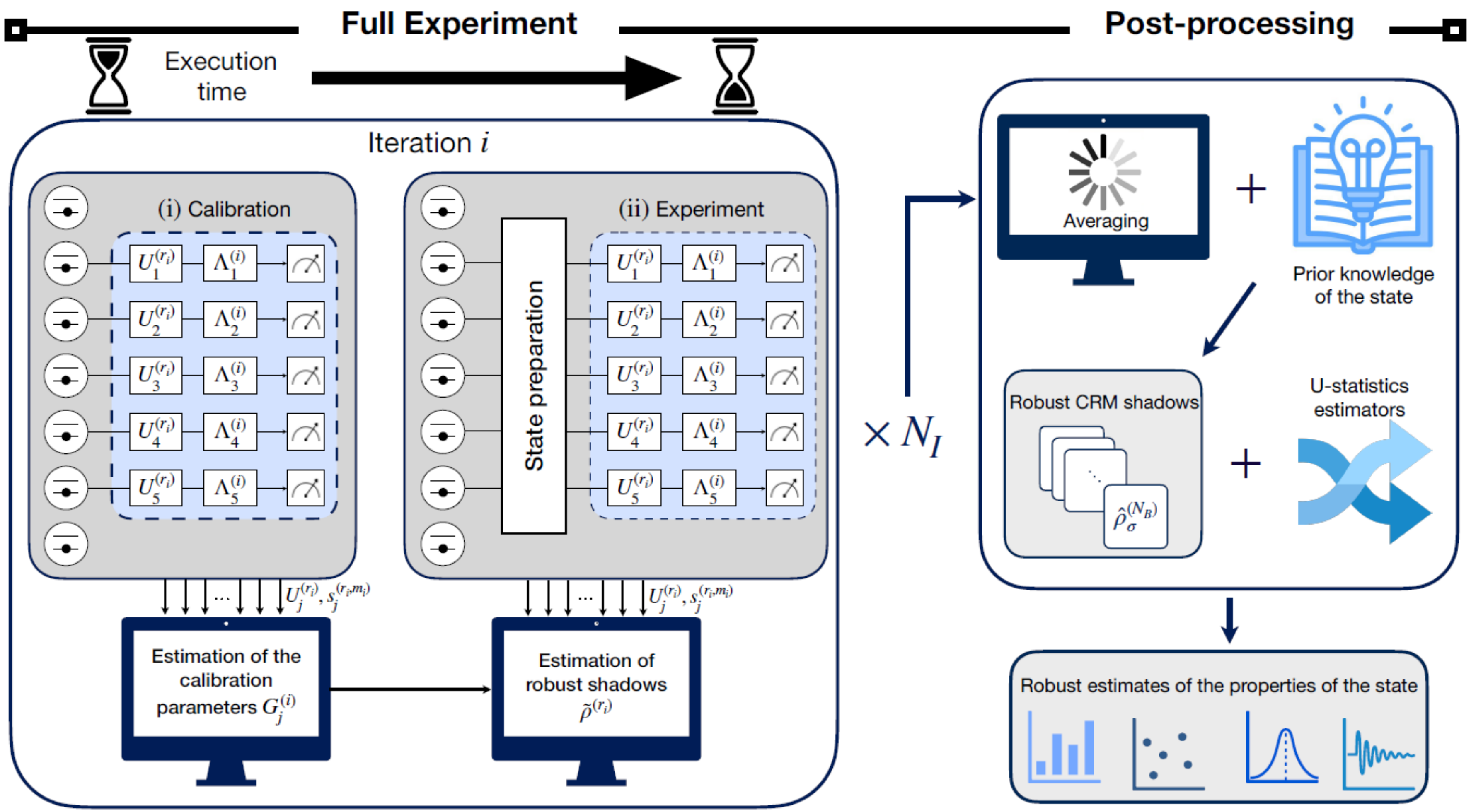
Today’s menu

Moderate scale randomized measurements

1) Motivations
2) Measurements of entanglement entropies
3) More advanced usage and “statistical tricks”

Large scale learning via randomized measurements

Experimental Robust Shadow Estimation and measurement of the quantum Fisher information (Vitale et al, PRX Q 2024)



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Beyond the purity: Classical Shadows as the modern framework to postprocess randomized measurements

Data are processed 'robust classical shadows' (Chen et al, PRX 2021, improving the seminal Caltech paper: Nature Physics 2020)

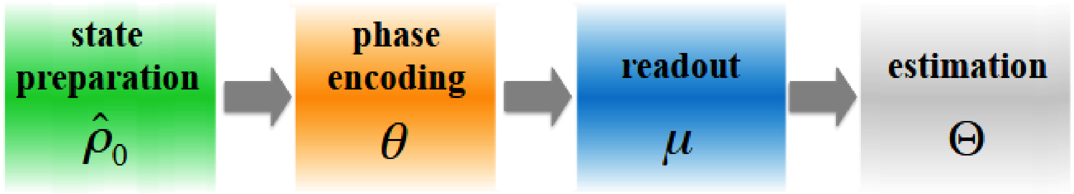
$$\tilde{\rho}^{(r,b)} = \bigotimes_{j=1}^{N} \left(\frac{3}{2F_b[j]-1} U_j^{(r)\dagger} |s_j\rangle \langle s_j| U_j^{(r)} + \frac{F_z[j]-2}{2F_b[j]-1} \mathbf{1} \right), \qquad (2)$$

where the calibration data of each batch b gives access to $F_b[j]$.

Estimations of functions of ρ are built based on the relation $E[\tilde{\rho}^{(r,b)}] = \rho$

$$\mathrm{tr}[\rho O] \simeq \frac{1}{N_u} \sum_r \mathrm{tr}[\hat{\rho}^{(r)} O], \ \mathrm{tr}[\rho^2] \simeq \frac{1}{N_u(N_u-1)} \sum_{r_1 \neq r_2} \mathrm{tr}[\hat{\rho}^{(r_1)} \hat{\rho}^{(r_2)}]$$

Quantum Fisher information measurements (Vitale et al, PRX Q 2024)



Quantum Cramer Rao bound on parameter estimation

$$(\Delta\theta)^2 \geq \frac{1}{mF_Q[\varrho, H]}, \qquad \varrho(\theta) = \exp(-iH\theta)\varrho_0 \exp(+iH\theta),$$

The Quantum Fisher information (A=H, mixed state version, Braustein and Caves, PRL 1994)

$$F_Q = 2 \sum_{(i,j),\lambda_i+\lambda_j>0} \frac{(\lambda_i - \lambda_j)^2}{\lambda_i + \lambda_j} |\langle i| A |j\rangle|^2 \text{ with } \rho = \sum_i \lambda_i |i\rangle\langle i|$$

Mapping the quantity to a measurable “shadow’ quantity

Multi-copy observable
MCO

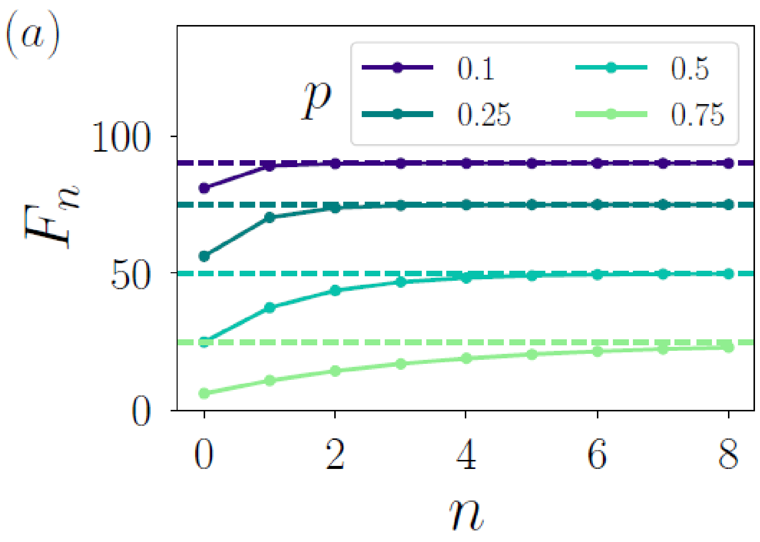
$$\mathrm{Tr}(O\rho^{\otimes n})$$

- Rath et al (PRL 2021): QFI is the limit of a series of MCO, i.e can be measured

Swap operator

$$F_n = 2\,\mathrm{Tr}\left(\sum_{\ell=0}^{n}(\rho\otimes\mathbf{1}-\mathbf{1}\otimes\rho)^2(\mathbf{1}\otimes\mathbf{1}-\rho\otimes\mathbf{1}-\mathbf{1}\otimes\rho)^{\ell}\mathbf{S}(A\otimes A)\right) \tag{10}$$

- The series convergences exponentially faster to the QFI: Example for noisy GHZ states ($N = 10$)



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Quantum Fisher information — Statistical Errors

- The series of MCO F_n is estimated via randomized measurements

$$F_n = \mathrm{Tr}(O\rho^{\otimes n}) = E[\mathrm{Tr}(O\rho^{(r_1)} \otimes \cdots \otimes \rho^{(r_n)})] \qquad (11)$$

- We provide analytical variance bounds ('error bars')

$$\mathbb{V}[\hat{F}_n] \leq \sum_{k=1}^{n} \frac{n!^2 2^{kN}}{k!(n-k)!^2(M-k+1)^k} \mathrm{Tr}([O_k]^2)$$

$$O_k = \frac{1}{n!} \sum_{\pi} \mathrm{Tr}_{\{k+1 \ldots n\}}(\pi^\dagger O \pi [\mathbf{1}^{\otimes k} \otimes \rho^{\otimes(n-k)}]) \qquad (12)$$

There will be a tradeoff in choosing n to control both systematic and statistical errors

We will probably need many measurements and postprocessing time, we will need some tricks to improve on that..

Trick 1: Common randomized measurements (BV et al, PRX Quantum 2023)

In some experimements we have a reference state in mind (eg GHZ state)

Reference state

$$\tilde{\rho}_{\sigma}^{(r_i)} = \tilde{\rho}^{(r_i)} - \sigma^{(r_i)} + \sigma \qquad \sigma^{(r)} = \sum_{\mathbf{s}} P_{\sigma}(\mathbf{s}|U^{(r_i)}) \bigotimes_{j=1}^{N} \left(3\, U_j^{(r)\dagger} |s_j\rangle\langle s_j| U_j^{(r_i)} - \mathbb{1}\right)$$

Robust classical shadow

Reference state shadow

Such shifted shadow is still an unbiased estimator of the density matrix $\mathbb{E}[\hat{\rho}_{\sigma}^{(r_i)}] = \rho - \sigma + \sigma = \rho$

But with improved variance properties

$$\mathbb{V}[\hat{O}] \leq \frac{n^2 ||O_A^{(1)}||_2^2}{N_U} \left(3^{N_A} ||\rho_A - \sigma_A||_2^2 + \frac{2^{N_A}}{N_M}\right) + \mathcal{O}\left(\frac{1}{N_U^2}\right)$$

n-copy observable

Functions of O and of the density matrix

Number of measurement settings

Number of shots per measurement settings

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Trick 1: Batching (Rath et al PRX Quantum 2023)

We group several shadows into N_B>n batches to simplify postprocessing

$$\hat{\rho}_\sigma^{(b)} = \frac{N_B}{N_I} \sum_{i=(b-1)N_I/N_B+1}^{bN_I/N_B} \left(\sum_{r_i} \frac{\tilde{\rho}_\sigma^{(r_i)}}{N_U} \right)$$

U-statistics estimations (R. Huang et al, Nature Physics 2020)

$$\hat{F}_0 = \frac{4(N_B-2)!}{N_B!} \sum_{b_1 \neq b_2} \mathrm{Tr}\left(\hat{\rho}_\sigma^{(b_1)} [\hat{\rho}_\sigma^{(b_2)}, A] A\right),$$

$$\hat{F}_1 = 2\hat{F}_0 - \frac{4(N_B-3)!}{N_B!} \sum_{b_1 \neq \cdots \neq b_3} \mathrm{Tr}\left(\hat{\rho}_\sigma^{(b_1)} \hat{\rho}_\sigma^{(b_2)} [\hat{\rho}_\sigma^{(b_3)}, A] A\right)$$

Postprocessing runtime: N_B^2, N_B^3, etc

Barely affects statistical errors in the `high accuracy regime'

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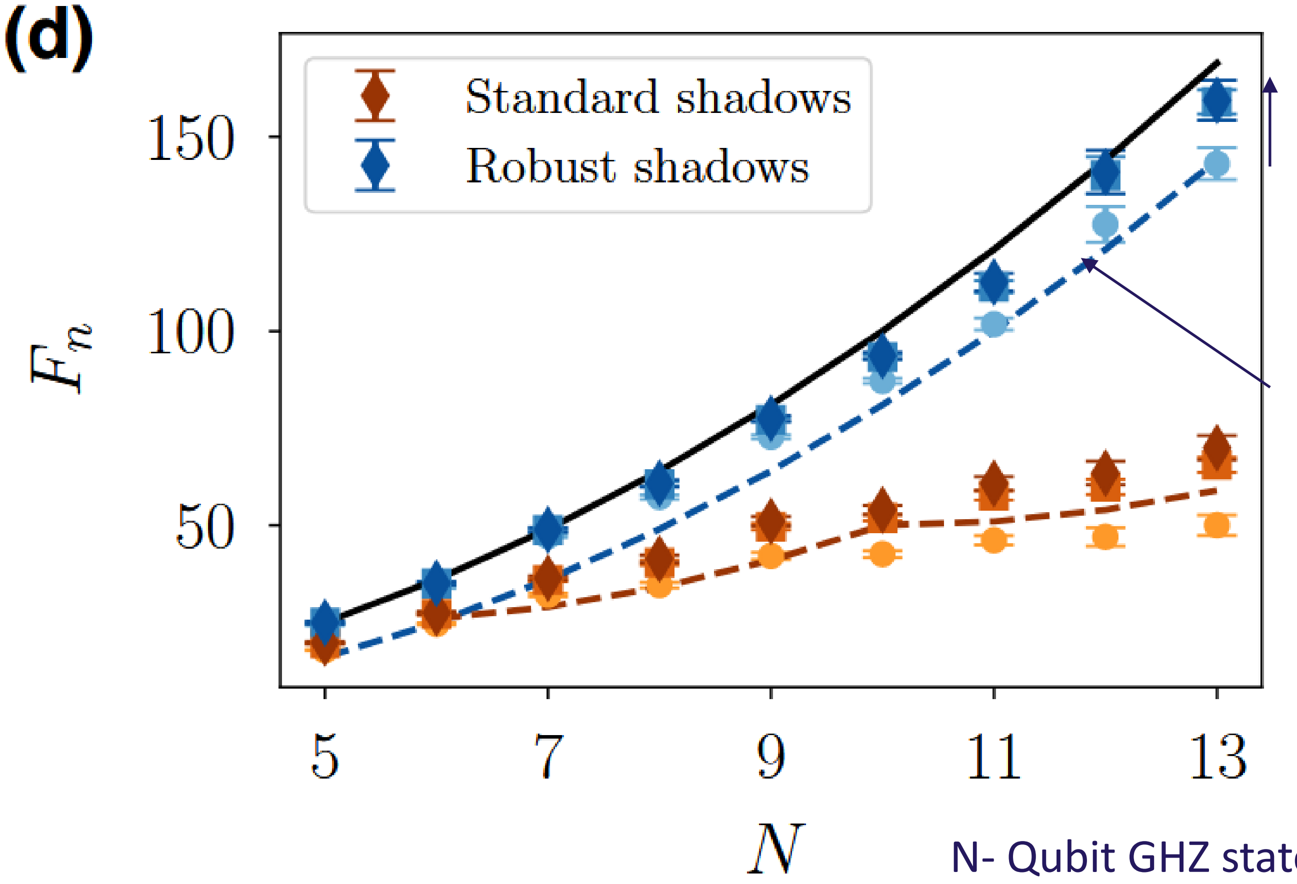
Quantum Fisher information measurements (Vitale et al, PRX Q 2024)

Petar Jurcevic
(IBM)

Vittorio Vitale



n=0,1,2

Limit for genuine multipartite
Entanglement detection

N- Qubit GHZ state

Some recent uses of randomized measurements to access entanglement

Quantities/Concepts	Platform	Reference
Entropies	Ions	Brydges et al Science 2019
OTOCs	Ions	Joshi et al, PRL 2020
Spectral Form Factors	Superconducting qubits	Dong et al, PRL 2025
Mixed-state entanglement*	Ions	Elben et al, PRL 2020
Cross-Platform verification*	Ions & superconducting qubits	Elben et al, PRL 2020 Zhu et al, Nature Comm 2022
Topological entropies	Superconducting qubits	Satzinger al, Science 2021
Symmetry resolved Entropies*	Ions	Vitale et al, Sci Post 2022
Entropies (live)	Ions	Stricker et al, PRX Q 2022
Operator entropies*	Ions	Rath et al, PRX Q 2023
Quantum Mpemba effect	Ions	Joshi et al, PRL 2024
Quantum Fisher information (Robust):	Superconducting qubits	Vitale et al, PRX Quantum 2024
Entropies (2D)	Superconducting qubits	Andersen et al, Nature 2025
Entropies (Robust)	Superconducting qubits	Hu et al, Nature Communications 16, 2943 (2025)
Entropies (large-scale) & tomography	Superconducting qubits	Votto et al, in preparation

* : Data from Brydges et al

First measurements

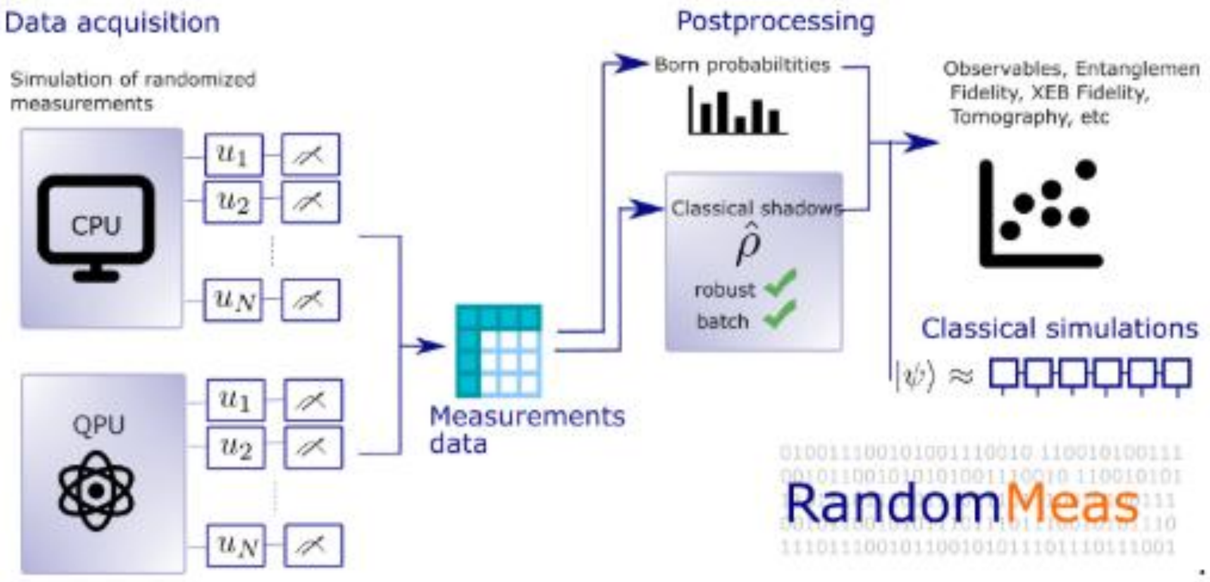
RandomMeas.jl: Open-Source Package

RandomMeas: The randomized measurement toolbox in Julia

docs dev | CI passing | License Apache 2.0

This package provides efficient routines for sampling, simulating, and post-processing randomized measurements, including classical shadows, to extract properties of many-body quantum states and processes. RandomMeas relies heavily on ITensors.jl.

A. Elben (Psi)



https://github.com/bvermersch/RandomMeas.jl & Julia's General Registry

Examples with Jupyter notebooks

Classical shadows

1. Energy/Energy variance measurements with classical shadows
2. Robust Shadow tomography
3. Process Shadow tomography
4. Classical shadows with shallow circuits
5. Virtual distillation

Quantum benchmark

6. Cross-Entropy/Self-Cross entropy benchmarking
7. Fidelities from common randomized measurements
8. Cross-Platform verification

Entanglement

9. Entanglement entropy of pure states"
10. Analyzing the experimental data of Brydges et al, Science 2019
11. Surface code and the measurement of the topological entanglement entropy
12. Mixed-state entanglement: The p3-PPT condition and batch shadows

Miscellanous

13. Noisy circuit simulations with tensor networks

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Summary first part & transition

Many physical quantities have been recently measured with RM: Experimentally friendly acquisition, and numerically friendly “universal” postprocessing.

Robustness/Practical aspects well understood and experimentally demonstrated

For the purity and related quantities, number of measurements scales as 2^{aN}, $a \approx 1$, implies typically $N < 14$

More info in our review **“The randomized measurement toolbox”**
Elben, Flammia, Huang, Kueng, Preskill, BV, Zoller, Nat Rev Phys 2023

Let’s expand this toolbox to large-scale systems reconstructions!

quobly

Large-scale entropies and tomography via randomized measurements

Probing many-body quantum states in large-scale experiments with randomized measurements, BV et al, Phys. Rev. X 2025

Learning mixed quantums in large-scale experiments (to appear on arxiv)

P. Zoller (UIBK)

L. Piroli (Unibo)

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J.I.C Cirac (MPQ

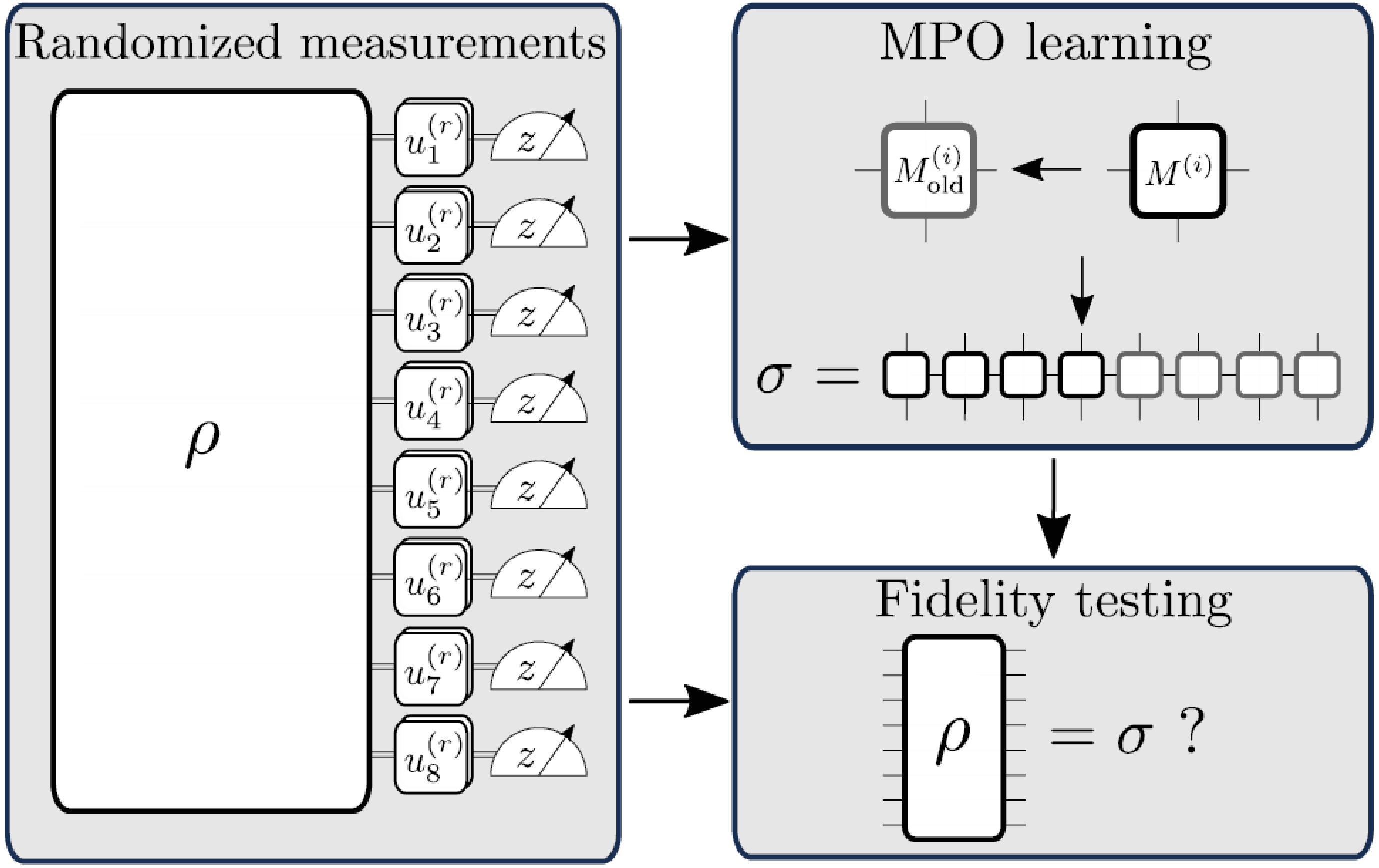
M. Votto (UGA)

C. Lancien (UGA)

Connections to MPS/MPO Gibbs State Tomography Litterature

Baumgratz et al, NJP 2013
Torlai et al, Nature Comm 2023
...
Anshu et al, Nature Physics 2021 (Review)
Joshi et al, Nature 2023
...

Goal a Tomography via randomized measurements



Matrix-Product-Operator (MPO)

Represents the quantum state as a 1D compressed object with linear cost in storage and manipulation

$$\sigma = \sum_{\{s_j\},\{s'_j\}} M^{(1)}_{s_1,s'_1} M^{(2)}_{s_2,s'_2} \dots M^{(N)}_{s_N,s'_N} \left|\{s_j\}\right\rangle \left\langle\{s'_j\}\right|$$

describe output states of one-dimensional noisy/finite depth quantumcircuits, as well as one-dimensional thermal states relevant to quantum simulation

K. Noh, L. Jiang, and B. Fefferman, Quantum 4, 318 (2020).
S. Cheng, C. Cao, C. Zhang, Y. Liu, S.-Y. Hou, P. Xu, and B. Zeng, Phys. Rev. Res. 3, 023005 (2021).
F. Verstraete, J. J. García-Ripoll, and J. I. Cirac, Phys. Rev. Lett. 93, 207204 (2004).
T. Kuwahara, A. M. Alhambra, and A. Anshu, Phys. Rev. X 11, 011047 (2021).

The learned state can be used to extract physical properties Conveniently (no more batching, etc) and for error mitigation, etc

Learning mixed quantums in large-scale experiments: Technical statements

We assume the existence of a finite correlation length in the MPO framework.

This implies the approximate factorization condition (Vermersch al Phys. Rev. X 2024)

$$\left| \mathrm{tr}[\rho_{ABC}^2]^{-1} \frac{\mathrm{tr}[\rho_{AB}^2]\mathrm{tr}[\rho_{BC}^2]}{\mathrm{tr}[\rho_B^2]} - 1 \right| \leq \alpha e^{-|B|/\xi_\rho^{(2)}}$$

This assumption is satisfied in 1D quantum circuits, quantum Gibbs states (Capel et al, arxiv: 2024 in particular)

Learning mixed quantums in large-scale experiments: Technical statements

Votto et al (arxiv:...) : In this case, one can learn the state using the inner product as cost function

$$\mathcal{F}_{\mathrm{GM}}(\rho,\sigma) = \frac{\mathrm{tr}[\rho\sigma]}{\sqrt{\mathrm{tr}[\rho^2\sigma^2]}}$$

With the MPO $\sigma = \sum_{\{s_j\},\{s'_j\}} M^{(1)}_{s_1,s'_1} M^{(2)}_{s_2,s'_2} \dots M^{(N)}_{s_N,s'_N} \left|\{s_j\}\right\rangle \left\langle\{s'_j\}\right|$

With arbitrary small total error and polynomially many measurements

Proof idea: Gradient w.r.t local tensors can be set to zero using the rule

$$\mathrm{tr}_{I_j\setminus\{j\}}[\sigma_{I_j}\partial_{M^{(j)}}\sigma_{I_j}] = \mathrm{tr}_{I_j\setminus\{j\}}[\rho_{I_j}\partial_{M^{(j)}}\sigma_{I_j}]$$

Classically computable

Finite support "observable", thus efficiently measurable

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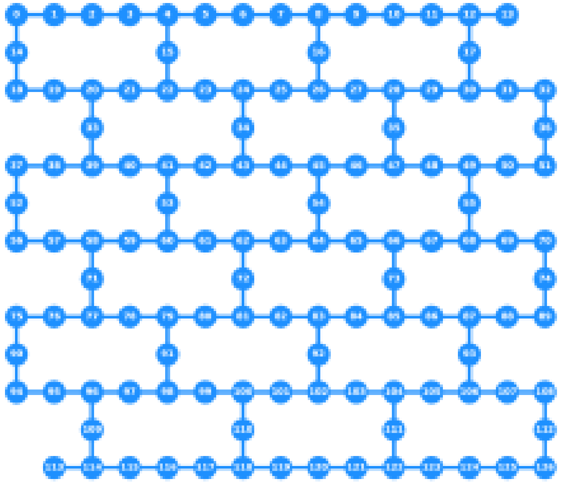
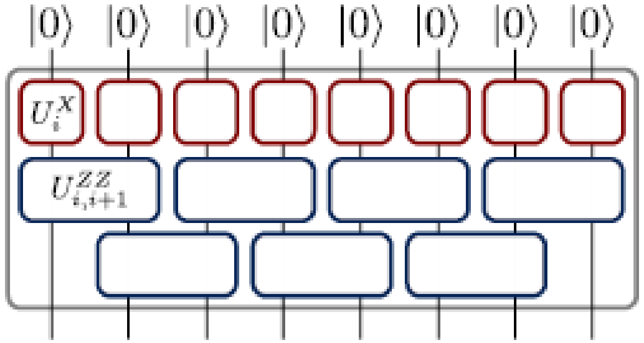
Learning mixed quantums in large-scale experiments: Demonstration



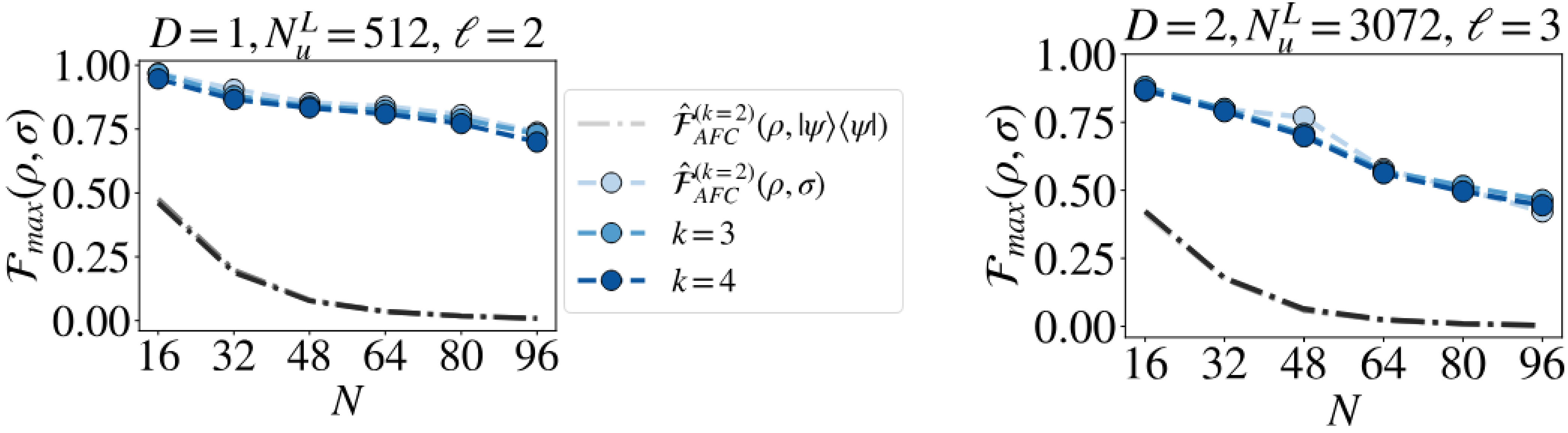


- Experimental setup: **superconducting quantum processor** (IBM Brisbane QPU), $N_{\text{tot}} = 96$ qubits, depth $D = 1, 2$ kicked Ising model

$$U_i^X = e^{-i\pi X_i/8}, \; U_i^{ZZ} = e^{i\pi Z_i Z_{i+1}/4}$$

- We perform $M = N_u \times N_M = D \cdot 3072 \times 1024$ measurements

Learning mixed quantums in large-scale experiments: Demonstration

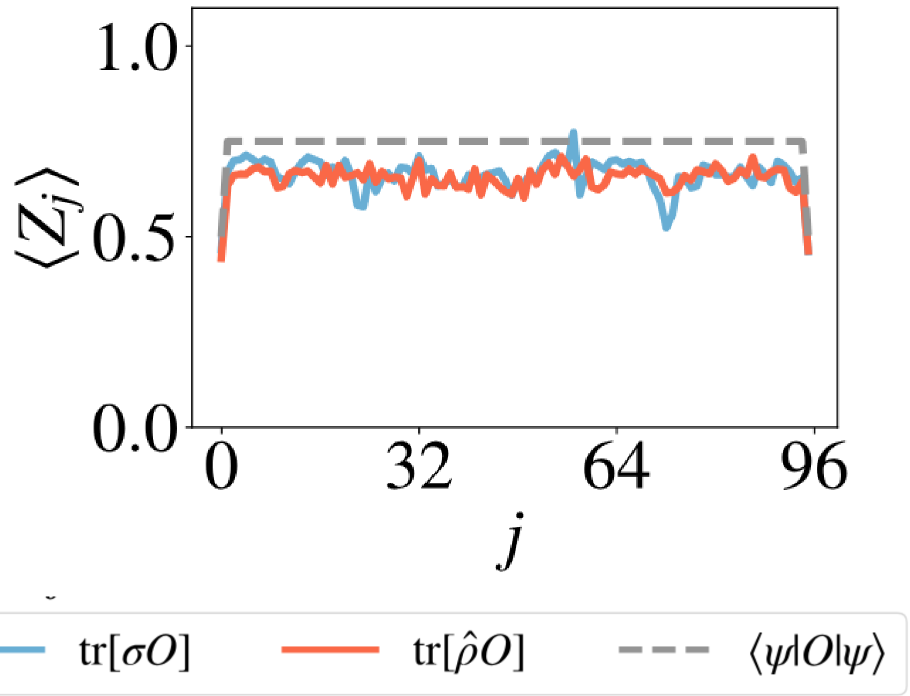


Experimental tomography of a N = 96 mixed qubit state (previous results: N = 20 qubits, MPS (Kurmapu et al PRXQ 2023) or Gibbs states (Joshi et al, Nature 2023)

The MPO σ captures the noisy features of the experiment.

Learning mixed quantums in large-scale experiments: Extracting physical quantities

Magnetization



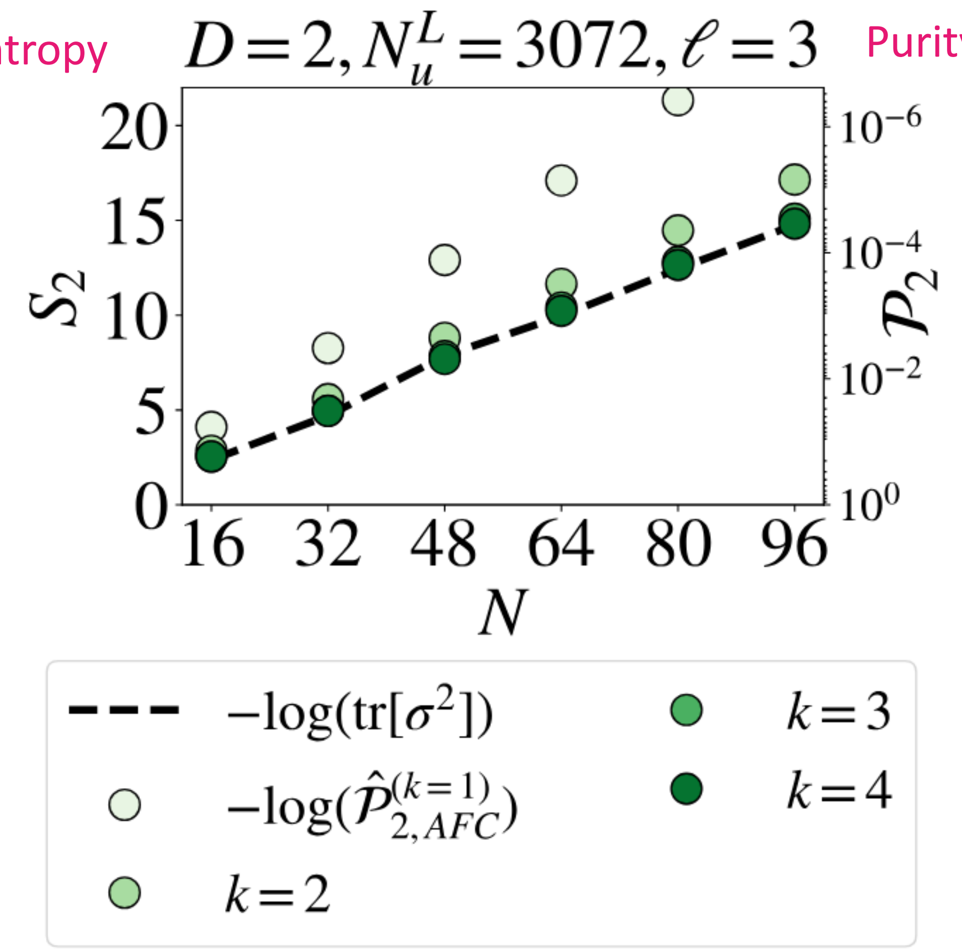
Direct contraction
Of the MPO

Estimation
through shadows
(lenghty calculation)

Estimation
of the ideal
Pure state

Entropy

Purity



Learning mixed quantums in large-scale experiments: Applications

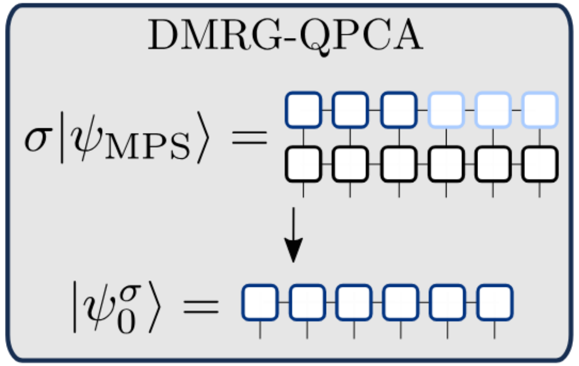
Quantum Error Mitigation:

Based on a noisy experimental device, estimation of noiseless observable estimation values
based on noise extrapolation, noise models & extra sampling, virtual distillation, etc (Cai et al, RMP 2023)

$$|\psi\rangle = U\,|\psi_0\rangle \longrightarrow \rho = \mathcal{U}(\gamma)\rho_0 \longrightarrow \langle O\rangle = \langle\psi|O|\psi\rangle$$

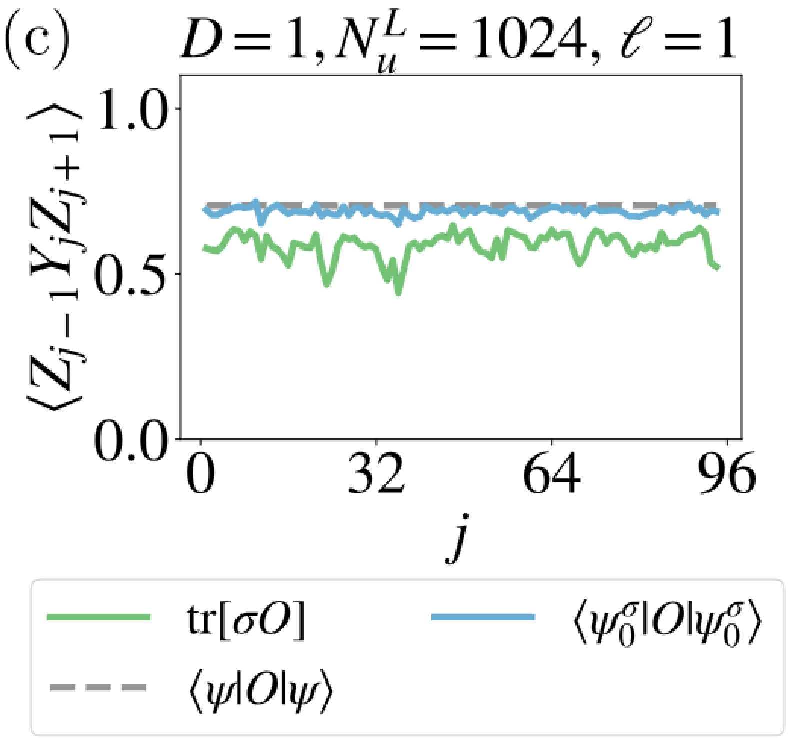
Here: Quantum Principal Component analysis (stronger version of virtual distillation)
via the DMRG algorithm of tensor-networks (Review: Schollwoeck, Annals of Physics, 2011)

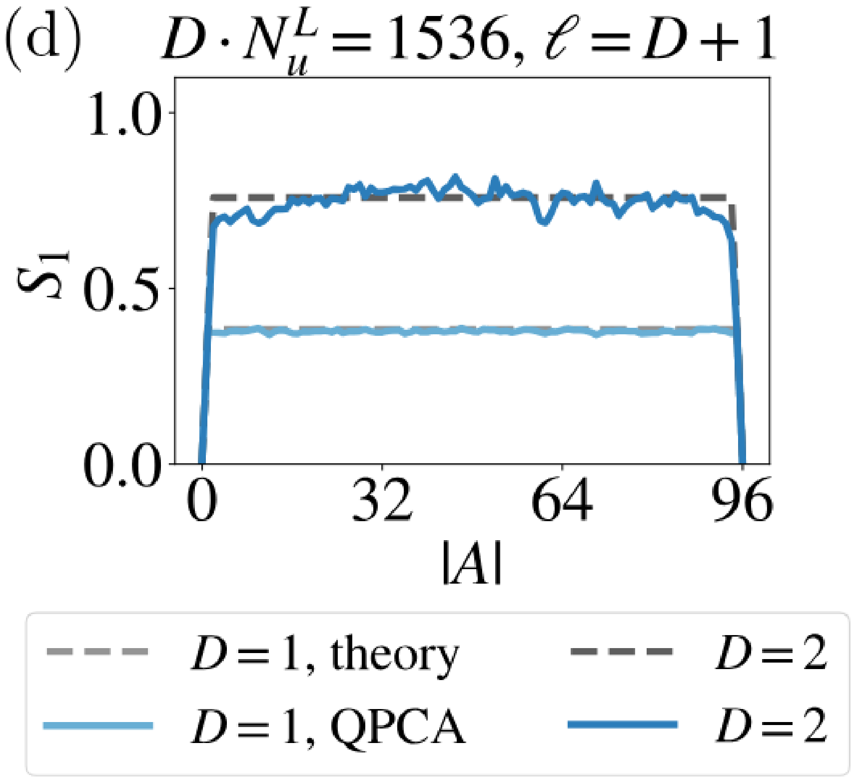
$$\rho = \sum_a \Lambda_a\,|\psi_a^\rho\rangle\,\langle\psi_a^\rho|, \text{ where } \Lambda_a > \Lambda_{a+1}$$



We search classically for the ground state of $H = -\sigma$

Learning mixed quantums in large-scale experiments: Applications





Large-scale resconstruction of noiseless expectation values, and von Neumann entanglement entropies
(Despite the original exponentially small original mixed state)

Conclusions and Thank you

The Quantum Information Team at Quobly


Benoît Vermersch


Thibaud Louvet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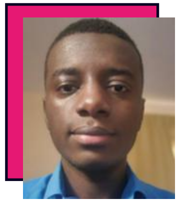
Nathan Miscopein


Dimitri Lanier


Amara Keita

Contact me if you want to know more, or join!

Probing many-body quantum states in large-scale experiments with randomized measurements, Phys. Rev. X 2025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Learning mixed quantums in large-scale experiments (to appear on arxiv)


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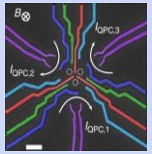
C. Lancien (UGA)

Quobly was born from the combined expertise of CEA and CNRS at Grenoble

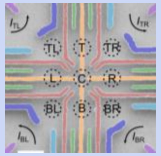
ACADEMIC READY

2017 — nature COMMUNICATIONS



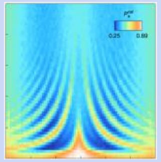
Coherent long-distance displacement of individual electron spins

2020 — nature nanotechnology



Coherent control of individual electron spins in a 2D array (9 quantum dots)

2021 — nature nanotechnology

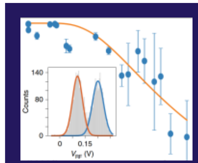


Distant spin entanglement via fast and coherent electron shuttling

DEVELOPING THE KNOW-HOW FOR CONTROLLING MULTIPLE SPIN QUBITS

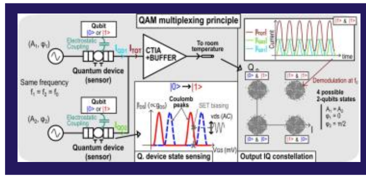
INDUSTRY READY

MANUFACTURING SPIN QUBITS IN INDUSTRIAL ENVIRONMENTS



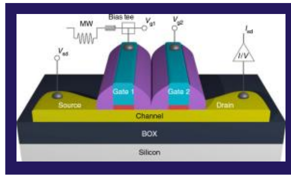
Gate-based high fidelity spin readout in a CMOS device

2019 — nature nanotechnology



Demonstrating QAM Multiplexing for Spin Qubits

2025 — IEEE



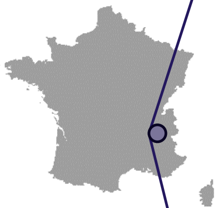
A CMOS silicon spin qubit

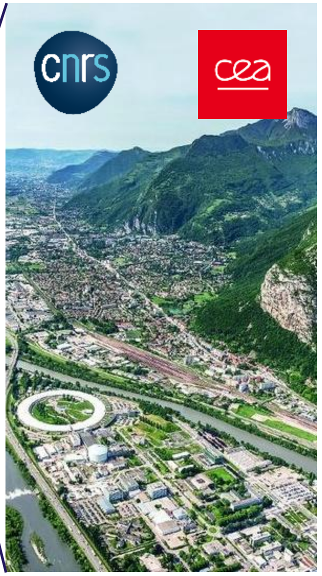
2016 — nature COMMUNICATIONS

A single hole spin with enhanced coherence in natural silicon

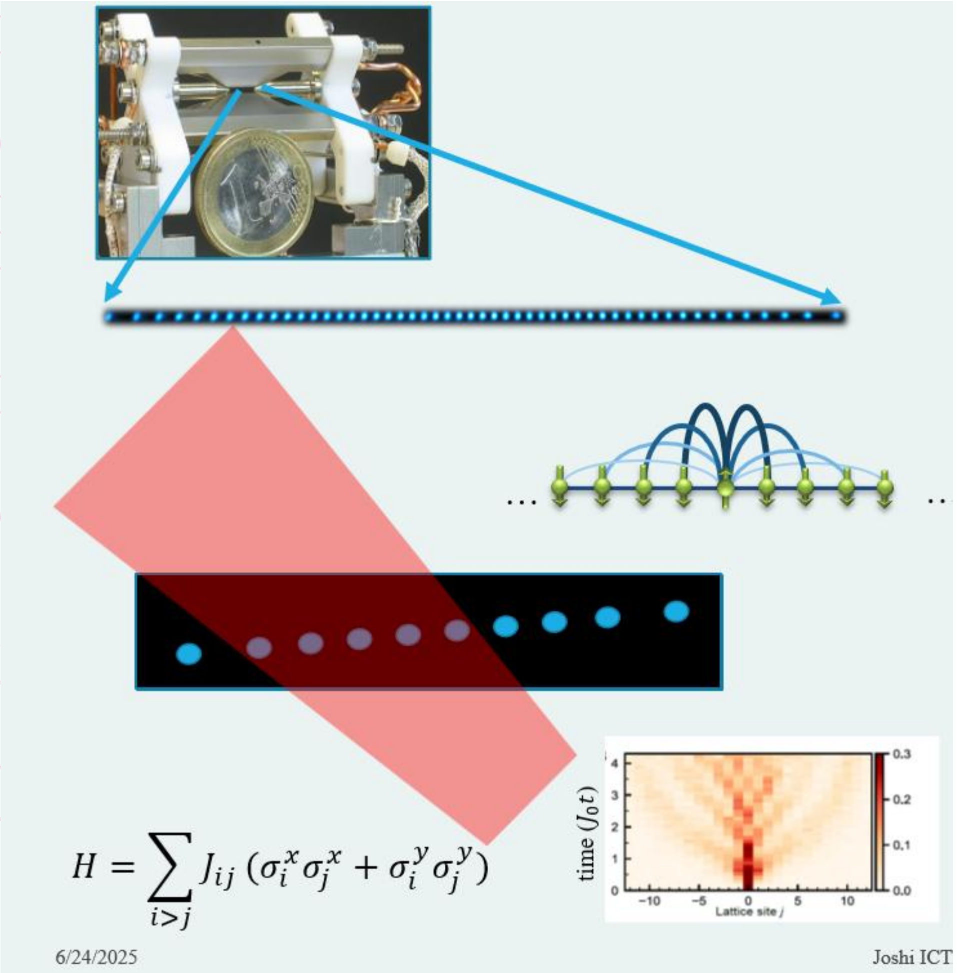
2022 — nature nanotechnology

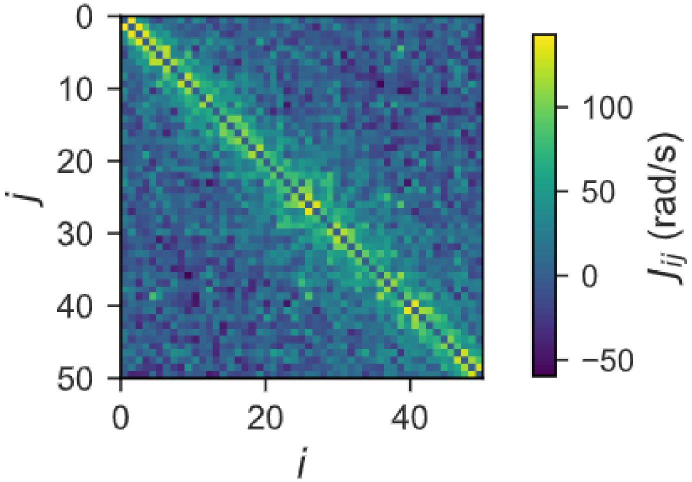
We leverage the semicon. industry's 60+ years of experience, fabless approach using commercial FD SOI technologies





Back to ions: Experimental liouvillian learning with process shadows






Manoj Joshi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Barbara Kraus


Peter Zoller


Tristan Kraft


Tobias Olsacher


Lata Kh Joshi

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Back to ions: Experimental liouvillian learning with process shadows

$$\frac{d}{dt}\rho(t) = -i\,[H, \rho(t)] + D[\rho(t)]$$

$$H_{ij} = \sum_{\sigma_i,\sigma_j} h_{\sigma_i,\sigma_j}\ \sigma_i\sigma_j$$

$$D[\rho] = \sum_{i=1}^{N} D_i[\rho] \qquad D_i[\rho] = \sum_{\sigma_i,\sigma_i'} d_{\sigma_i,\sigma_i'}\left(\sigma_i\rho\sigma_i' - \frac{1}{2}\{\sigma_i'\sigma_i, \rho\}\right)$$

Goal: Learn the coefficients

- Wiebe et al. "Hamiltonian learning and certification using quantum resources." *PRL* (2014).
- Holzäpfel et al. "Scalable reconstruction of unitary processes and Hamiltonians." Phys Rev *A* (2015).
- Bairey, Arad, and Lindner. "Learning a local Hamiltonian from local measurements", PRL (2019).
- Evans, Harper, Flamia, "Scalable Bayesian Hamiltonian learning", arXiv:1912.07636 (2019)
- Li, Zou, and Hsieh. "Hamiltonian tomography via quantum quench", *PRL* (2020).
- Hu et al. "Ansatz-free Hamiltonian learning with Heisenberg-limited scaling." arXiv preprint arXiv:2502.11900 (2025).
- Olsacher et al. "Hamiltonian and Liouvillian learning in weakly-dissipative quantum many-body systems." *Quantum Science and Technology* (2025).
- …. Many more

One key application: Verified quantum simulation: Cai et al, arxiv:2311.14818, Trivedi et al, Nature Comm. 2025

Back to ions: Experimental liouvillian learning with process shadows

Theory: Stilck França, Daniel et al « Efficient and robust estimation of many-qubit {Hamiltonians », Nature. Comm. 2024

A closed linear system of equations, pair-wise

$$\frac{d}{dt}\mathrm{tr}(\rho_{ij}(t))O_{ij}\Big|_{t=0} =$$
$$-i\sum_{\sigma_i,\sigma_j}\mathrm{tr}\left([\sigma_i\sigma_j,\rho_i\rho_j]O_iO_j\right)\ h_{\sigma_i,\sigma_j}$$
$$+\sum_{\sigma_i,\sigma_i'}\mathrm{tr}\left(\sigma_i\rho_i\sigma_i'O_i-\frac{1}{2}\{\sigma_i'\sigma_i,\rho_i\}O_i\right)d_{\sigma_i,\sigma_i'}$$
$$+\sum_{\sigma_j,\sigma_j'}\mathrm{tr}\left(\sigma_j\rho_j\sigma_j'O_j-\frac{1}{2}\{\sigma_j'\sigma_j,\rho_j\}O_j\right)d_{\sigma_j,\sigma_j'}$$

$$\rho_{ij}=\rho_i\otimes\rho_j\bigotimes_{n\neq i,j}\frac{\mathbb{I}_n}{2}$$

$$O_{ij}=\sigma_i\sigma_j$$

Unique Pseudo-inverse for enough initial states and measurement observables

Postprocessing for each pair independtly gives a N^2 runtime postprocessing algorithm

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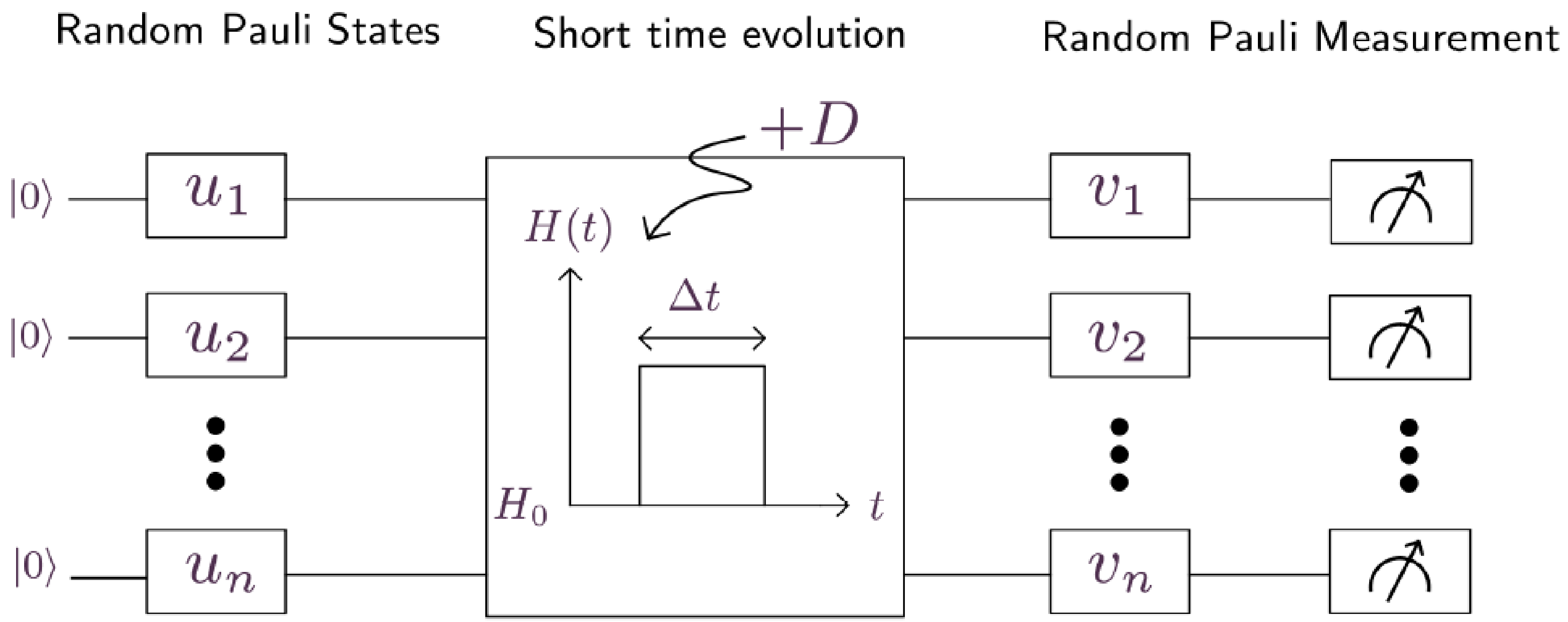
Back to ions: Experimental liouvillian learning with process shadows



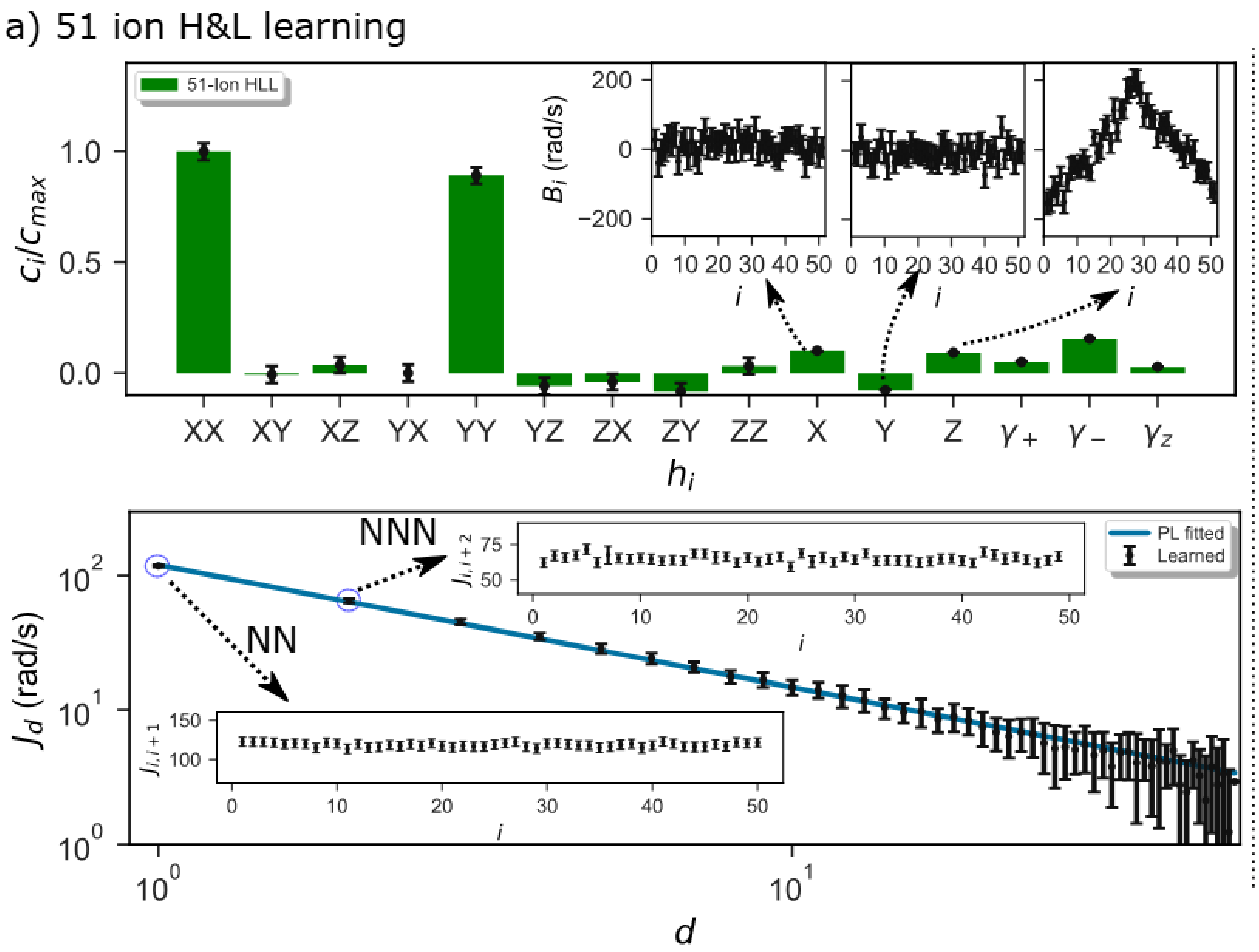
$$\frac{\sum_r \langle O_{ij}^{(r)} \rangle}{N_c}$$ is an unbiased estimation of $\mathrm{Tr}(\rho_{ij} O_{ij})$

Where the sum runs over the N_C "compatible" settings r defined such as

and such that the rotation v maps O_{ij} to the computational basis

The probability to have a compatible setting is independent of system sizes

Back to ions: Experimental liouvillian learning with process shadows



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