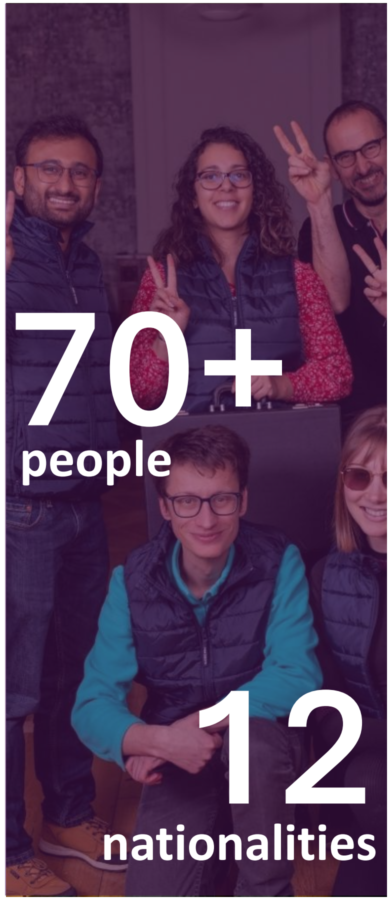
Randomized measurements for large-scale quantum experiments

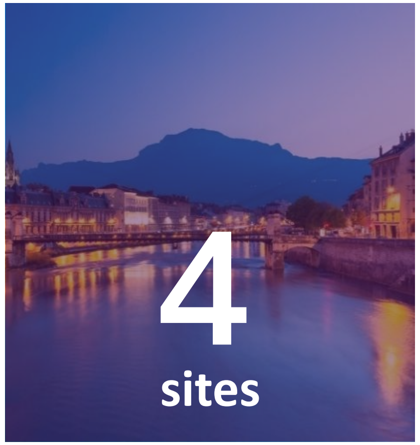
Benoit Vermersch

Quobly, and LPMMC Université Grenoble Alpes (on leave)

UTC Quantum Workshop at Chattanooga, Tennessee

Quobly was launched in November 2022



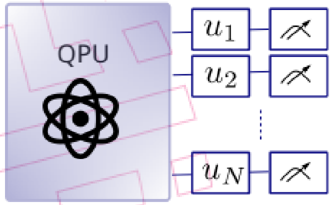


Our networks: IEC, ISO, MINALOGIC, EIC Scaling Club Selected Club Member, le lab quantique, QuIC, QuantAlps, #QEI, Quantum Flagship, France 2030, Les Maisons du Quantique, France Deeptech, Creative Destruction Lab, Le HUB Quantique, Teratec

Quantum Information Team @ Quobly

Measurements & Benchmarking

Data acquisition



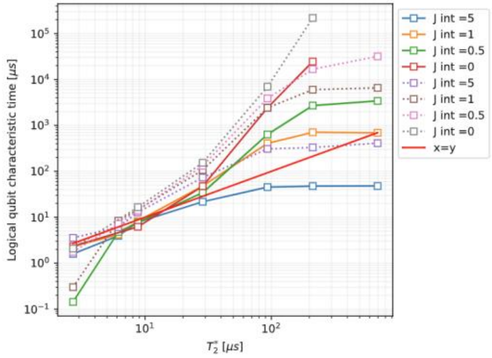
Measurements data

Postprocessing

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

Architectures and quantum error correction

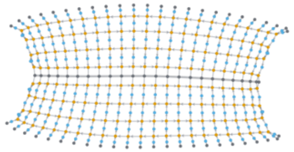
Surface-17 code



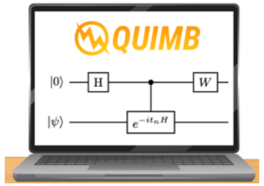
Tensor-Network Simulations & quantum algorithms R&D (open-source)

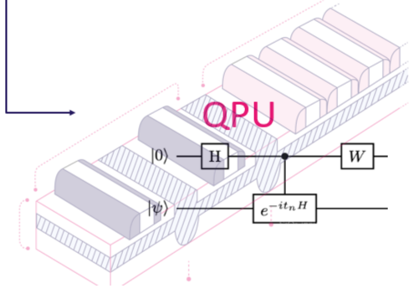
Classical preprocessing

Large scale compilation,
Tensor quantum programming,
Qubitization



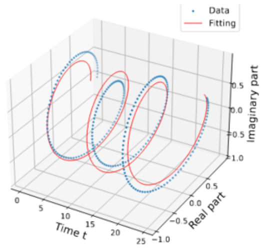
Internal Simulator





Classical postprocessing

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



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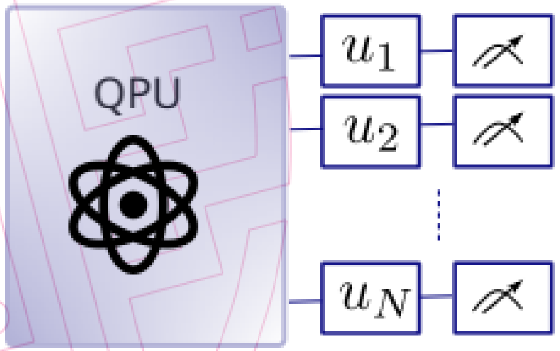
Randomized measurements for large-scale experiments

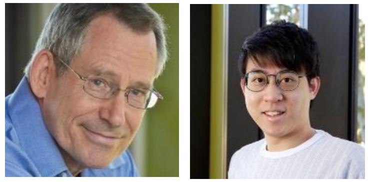
Randomized measurements



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


P. Zoller (UIBK)


A. Elben (Psi)


J. Preskill, R. Huang (Caltech)

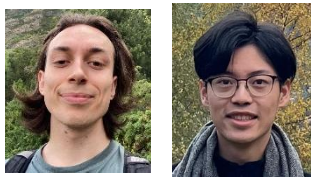

R. Kueng (Linz)


J.I.C Cirac (MPQ

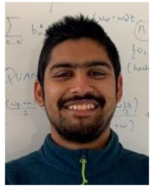

B. Kraus (TUM)


L. Piroli (Unibo)

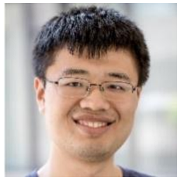

M. Serbyn. M. Ljubotina (ISTA)


M. Votto, W. Lam (UGA)

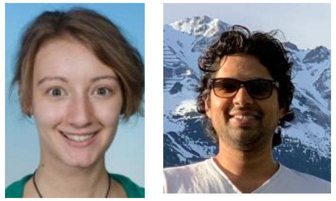

V. Vitale (Pasqal)


A. Rath (IQM)

Experiments


Xiao Mi (Google)


P.Jurcevic (IBM)


T. Brydges, M. Joshi,


C. Roos, R. Blatt (UIBK)

And many more…

UGA Université Grenoble Alpes
QuantAlps
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IQI
FWF
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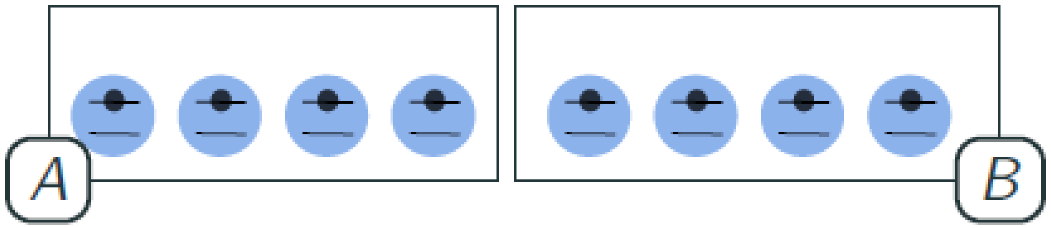
Motivation: Entanglement, a central quantity in quantum computing & quantum simulation



Entanglement is quantified via Entropies

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

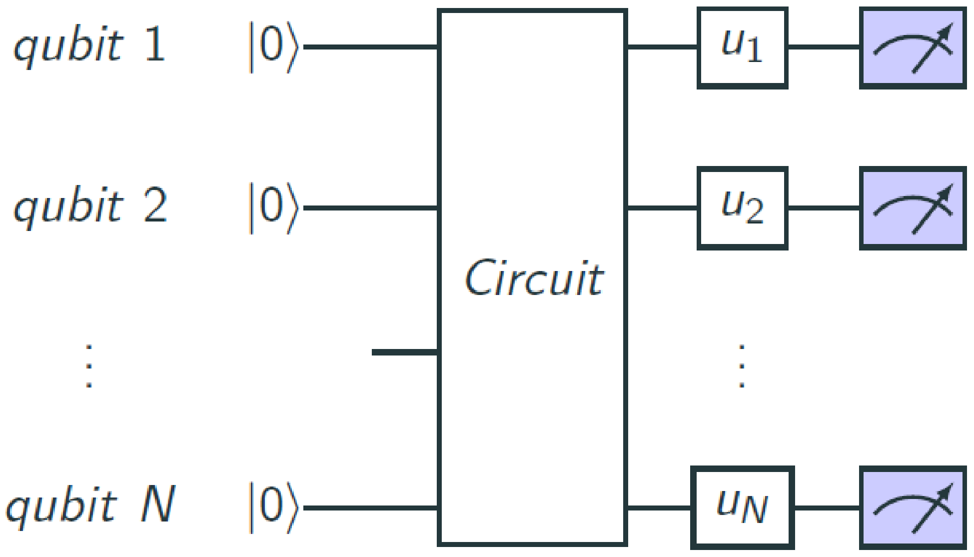
$$S_\alpha = \frac{1}{1-\alpha} \log[\mathrm{Tr}(\rho_A^\alpha)] \text{ Rényi entropies}$$

Purity

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

Entropies (related quantities) central to describe quantum computational complexity, and for understanding quantum simulation experiments (Eisert RMP 2010)

Randomized measurements: A single data acquisition procedure



- 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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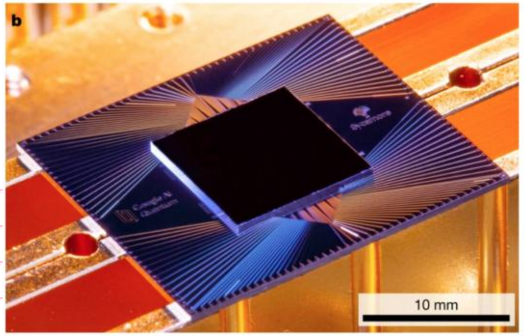
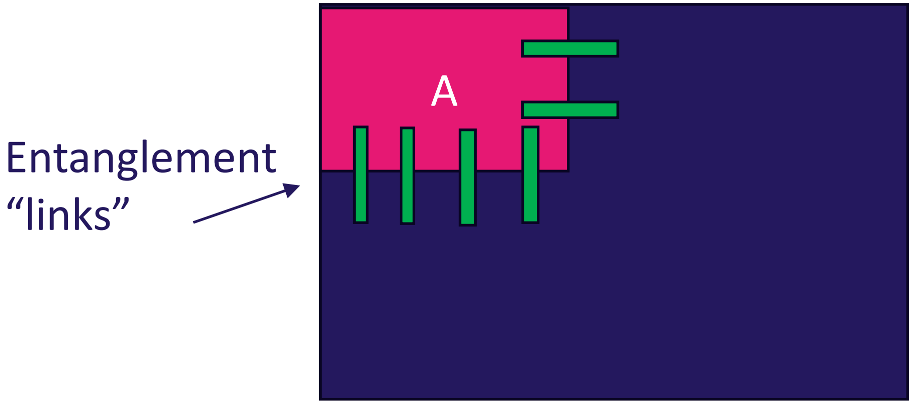
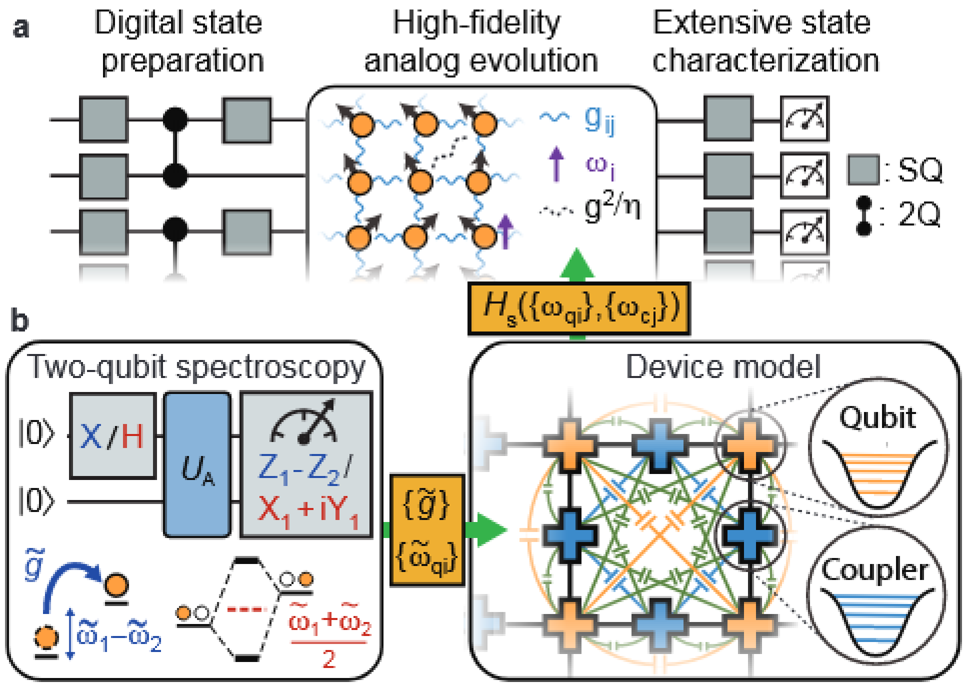
Recent use of RM: Andersen et al, Nature 2025

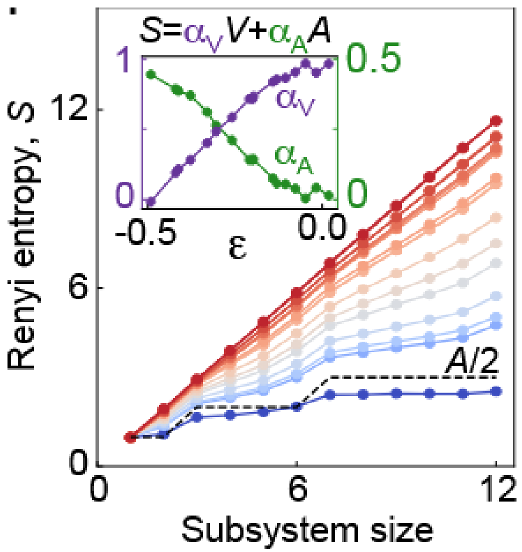


Quantum AI

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







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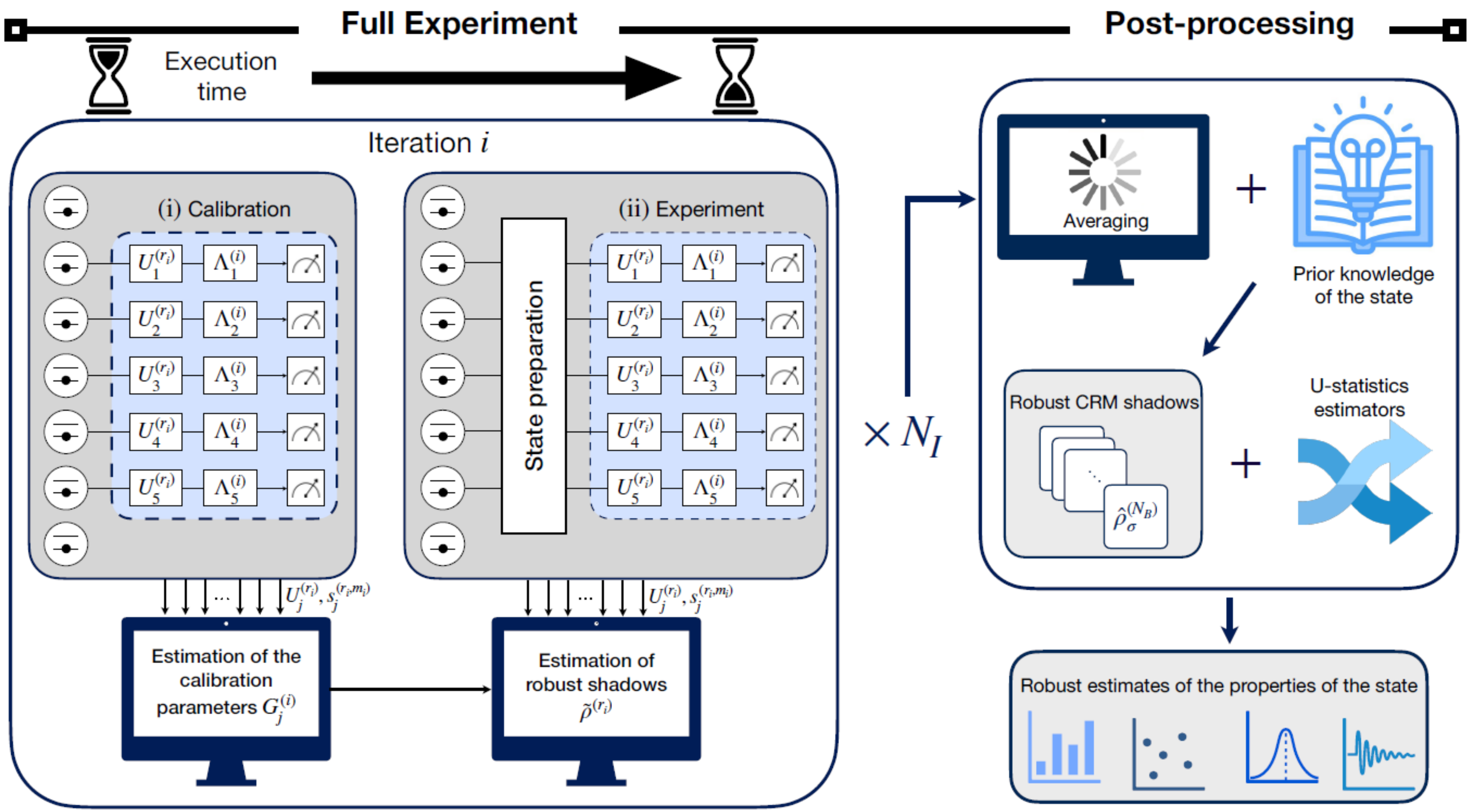
Experimental Robust Shadow Estimation (Vitale et al, PRX Q 2024)



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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)

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

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 $E[\tilde{\rho}^{(r,b)}] = \rho$

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

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
SR 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

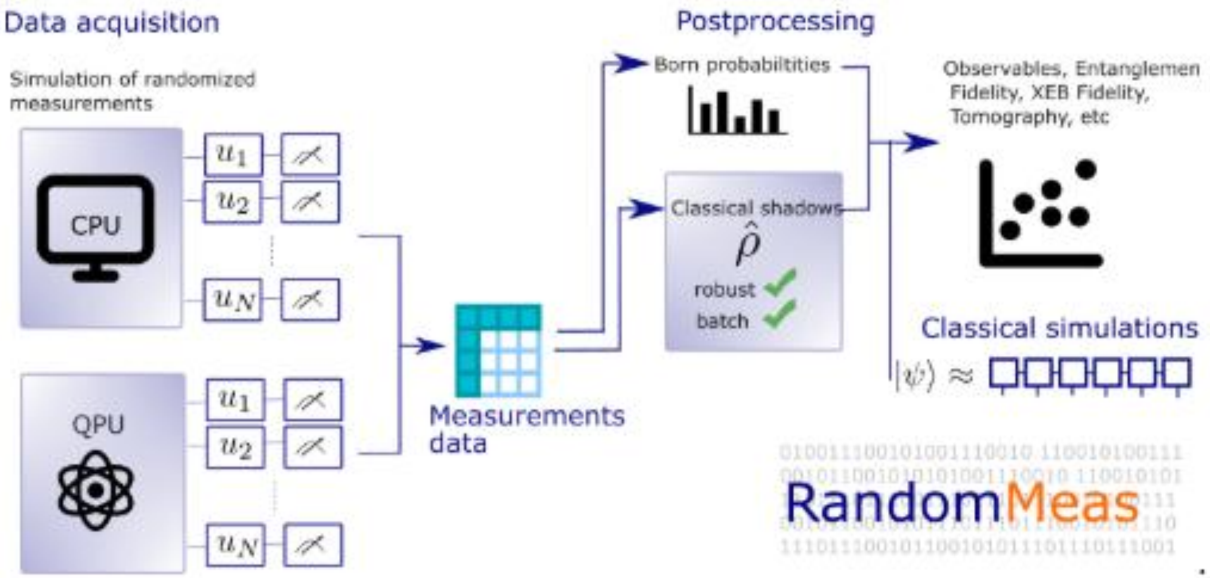
RandomMeas.jl: Open-Source Package

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 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!

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)





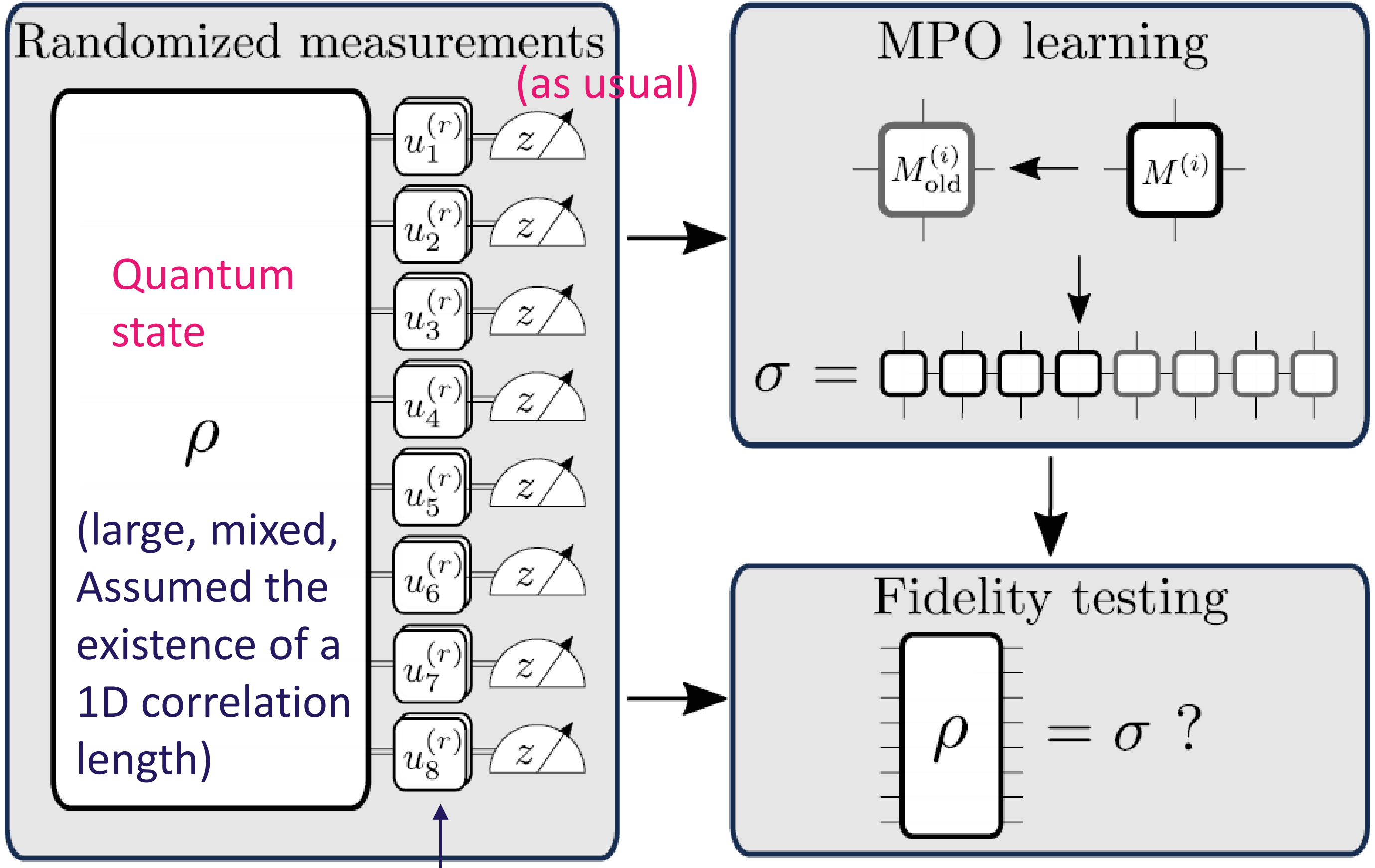
P. Zoller (UIBK) L. Piroli (Unibo) M. Serbyn. M. Ljubotina (ISTA) J.I.C Cirac (MPQ


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
…

Learning mixed quantums in large-scale experiments: General picture & usage



Polynomially Many Measurements

Matrix-Product-Operator (MPO)
Represents the quantum state as a 1D compressed object with linear cost in storage and manipulation

Classical Storage

Rapid Estimations of (any) physical quantities

Error Mitigation

Recompilation And coupling to Other QPUs

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Learning mixed quantums in large-scale experiments: Technical statements (boring but needed…)

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.

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

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

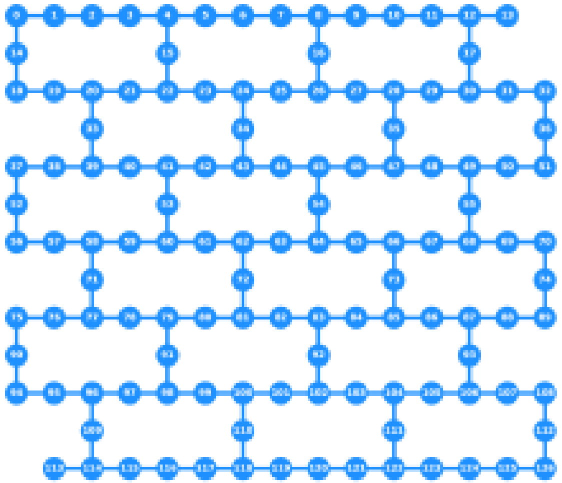
With the MPO

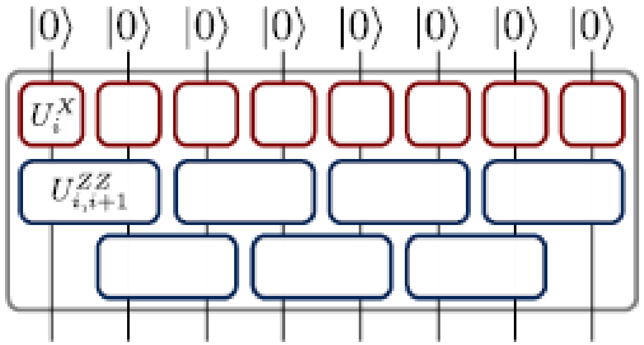
$$\sigma=\sum_{\{s_j\},\{s_j'\}} M^{(1)}_{s_1,s_1'}M^{(2)}_{s_2,s_2'}\dots M^{(N)}_{s_N,s_N'}\left|\{s_j\}\right\rangle\left\langle\{s_j'\}\right|$$

With arbitrary small total error and polynomially many measurements

Proof idea: Local gradient updates can be estimated faithfully from reduced classical shadows

Learning mixed quantums in large-scale experiments: Demonstration



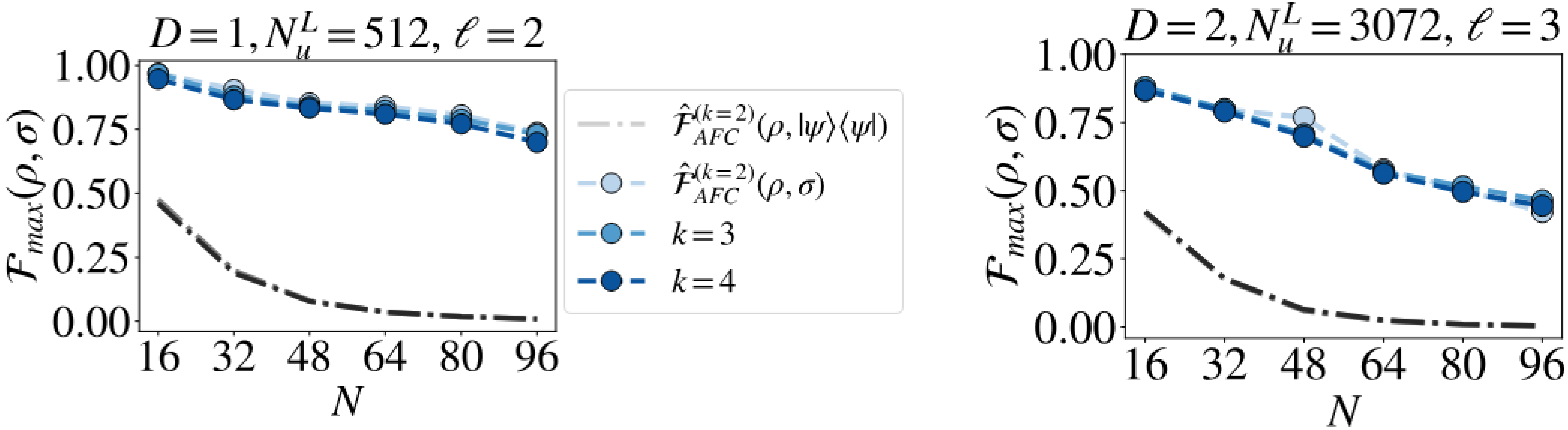


- Experimental setup: **superconducting quantum processor** (IBM Brisbane QPU), $N_{\text{tot}} = 96$ qubits, depth $D = 1, 2$ kicked Ising model

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

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

Learning mixed quantums in large-scale experiments: Demonstration

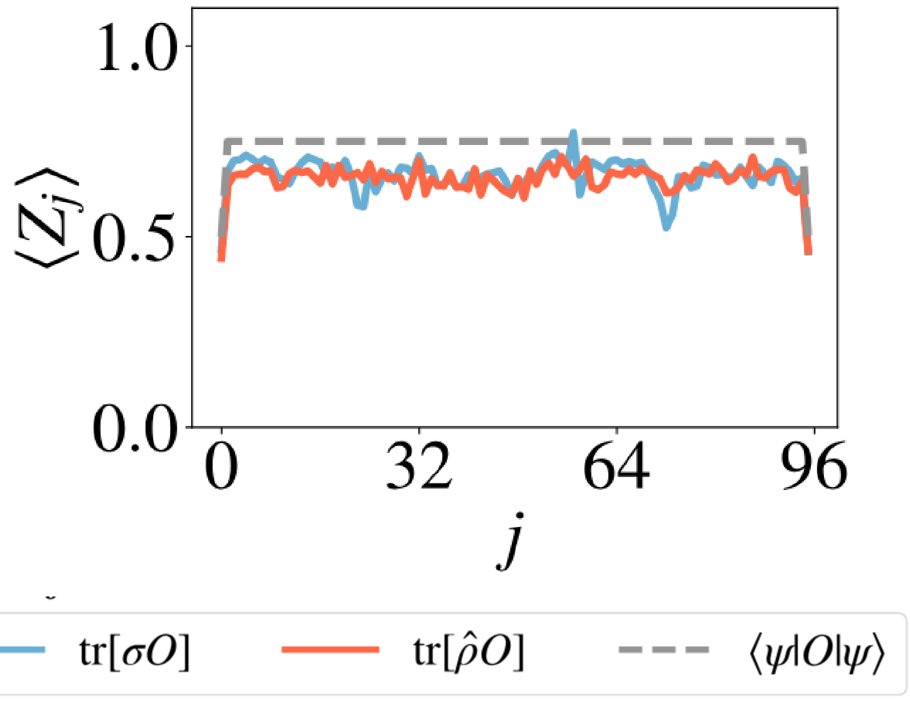


Experimental tomography of a N = 96 mixed qubit state (previous results: N = 20 qubits, MPS (Kurmapu et al PRXQ 2023) or Gibbs states (Joshi et al, Nature 2023)

The MPO σ captures the noisy features of the experiment.

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

Magnetization



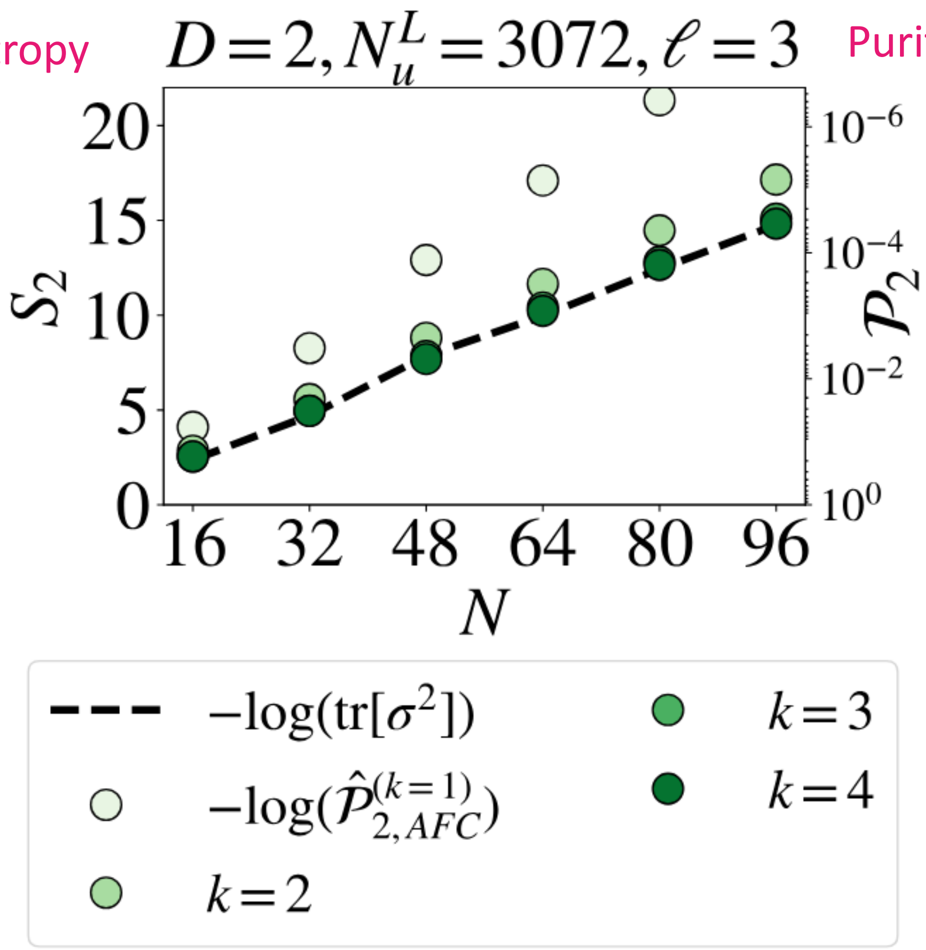
Direct contraction
Of the MPO

Estimation
through shadows
(lenghty calculation)

Estimation
of the ideal
Pure state

Entropy

Purity



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Learning mixed quantums in large-scale experiments: Applications

Quantum Error Mitigation:

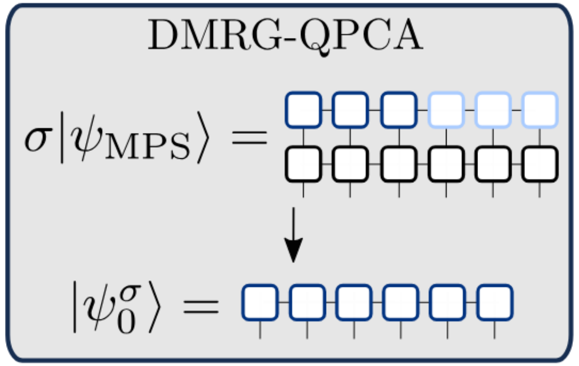
Based on a noisy experimental device, estimation of noiseless observable estimation values based on noise extrapolation, noise models & extra sampling, virtual distillation, etc (Cai et al, RMP 2023)

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

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 $H = -\sigma$



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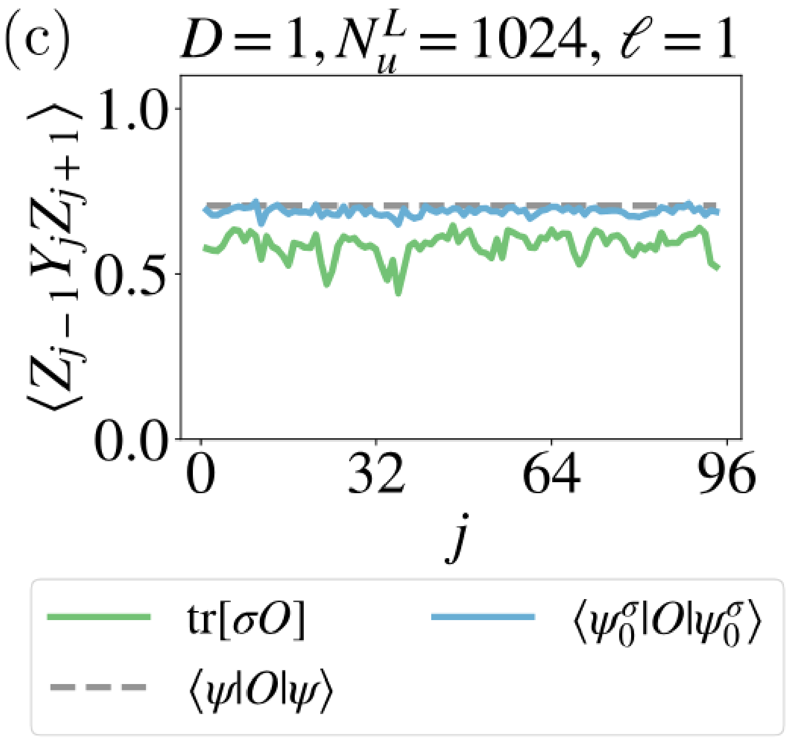
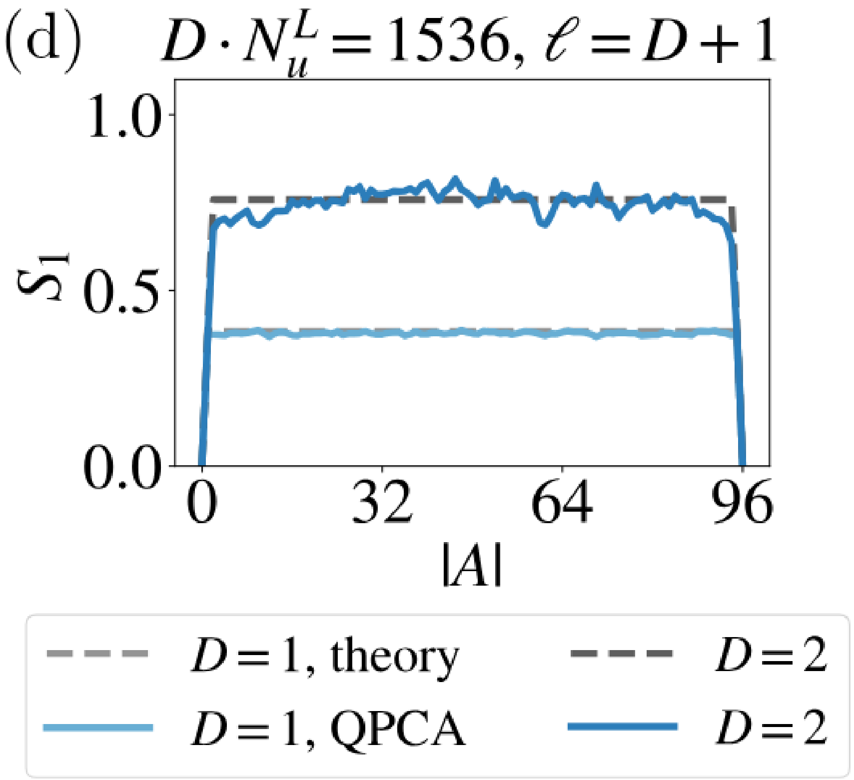
Learning mixed quantums in large-scale experiments: Applications





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

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Thank you

The Quantum Information Team at Quobly

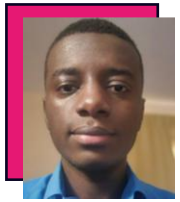
Benoît Vermersch

Thibaud Louvet

Carlos Ramos-Marimón

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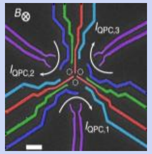
Quobly was born from the combined expertise of CEA and CNRS at Grenoble

ACADEMIC

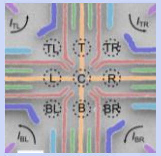
READY

2017 — nature COMMUNICATIONS



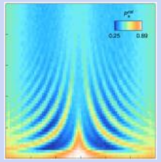
Coherent long-distance displacement of individual electron spins

2020 — nature nanotechnology



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

2021 — nature nanotechnology



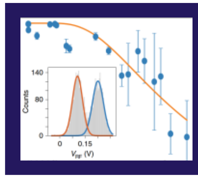
Distant spin entanglement via fast and coherent electron shuttling

DEVELOPING THE KNOW-HOW FOR CONTROLLING MULTIPLE SPIN QUBITS

INDUSTRY

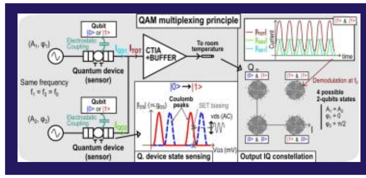
READY

MANUFACTURING SPIN QUBITS IN INDUSTRIAL ENVIRONMENTS



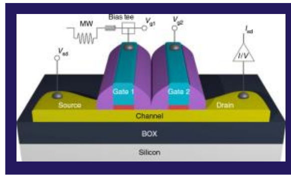
Gate-based high fidelity spin readout in a CMOS device

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