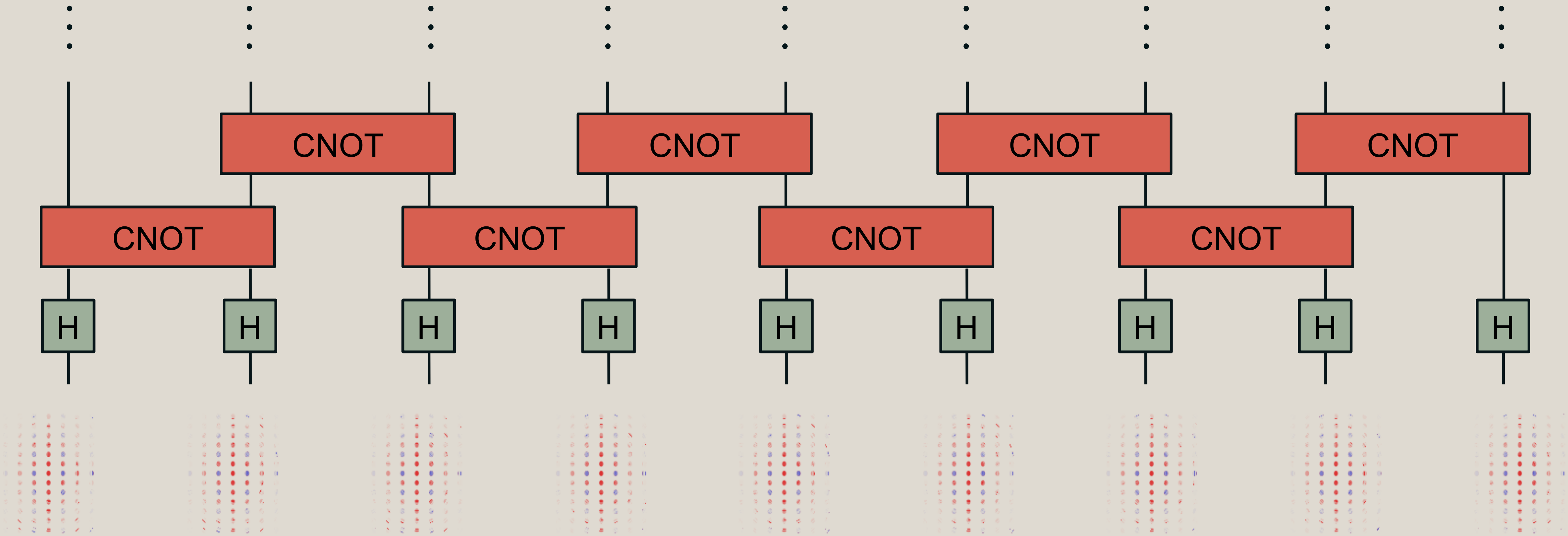
Efficient Simulation of Multimode Bosonic Systems: A Tensor Network and Monte Carlo based method

Jean-Baptiste Bertrand, Baptiste Royer

March 18th, 2024

INSTITUT QUANTIQUE UdS
CRSNG NSERC
CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE
Nord Quantique
Fonds de recherche Nature et technologies Québec

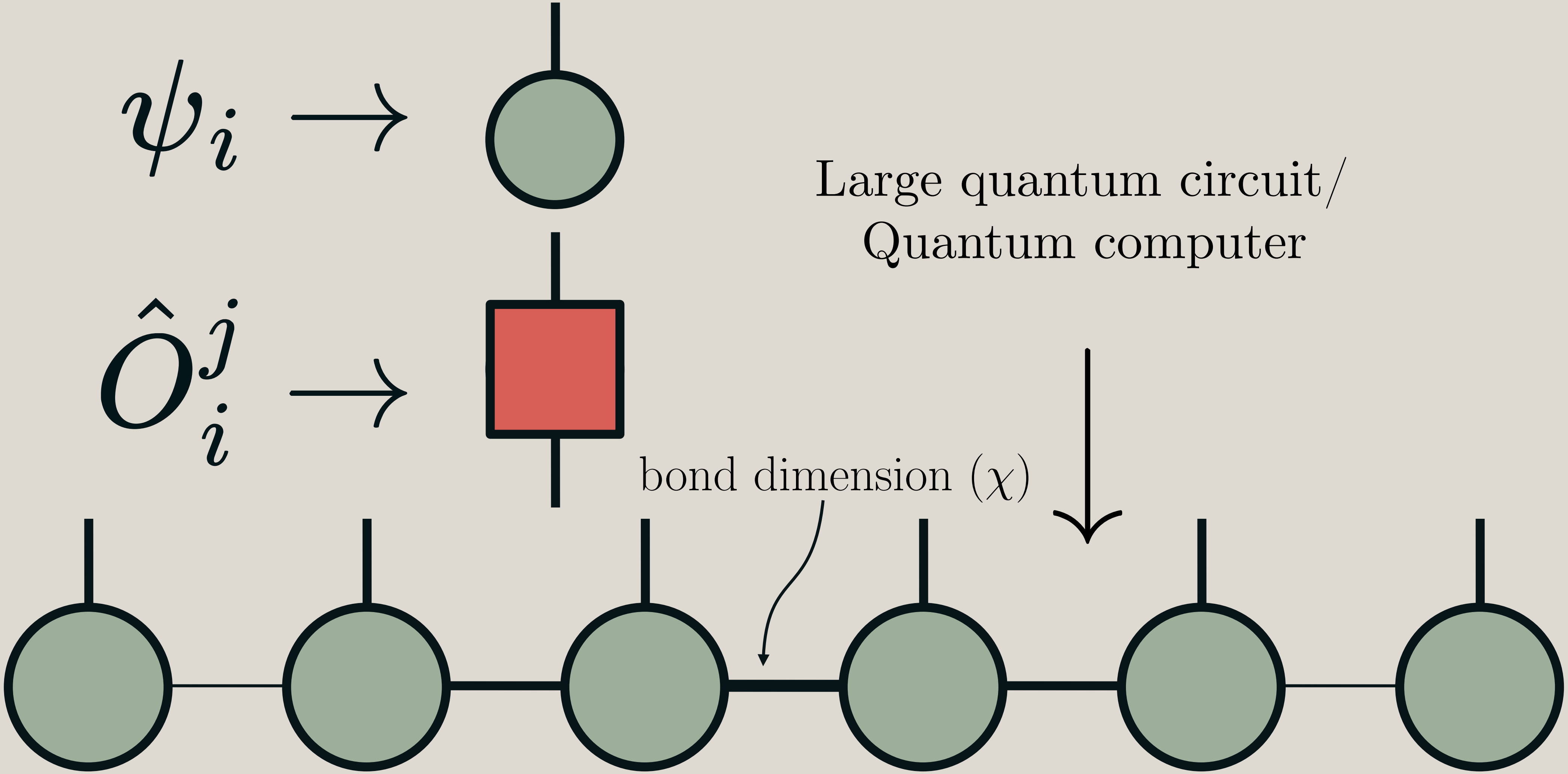
Goal: Simulate *large* quantum circuits where qubits are encoded in *bosonic modes*



~ 100 dimension for one of these

$\sim 100^n$ dimension for all

Tensor Networks allow you to represent systems in more efficient ways



[1]Collura M *et al.* 2024 Tensor Network Techniques for Quantum Computation

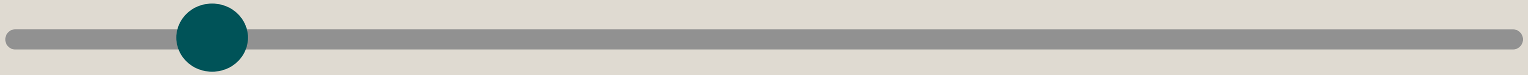
[2]Berezutskii A *et al.* 2025 Tensor networks for quantum computing (arXiv)

[3]Orus R 2014 Annals of Physics 349 117

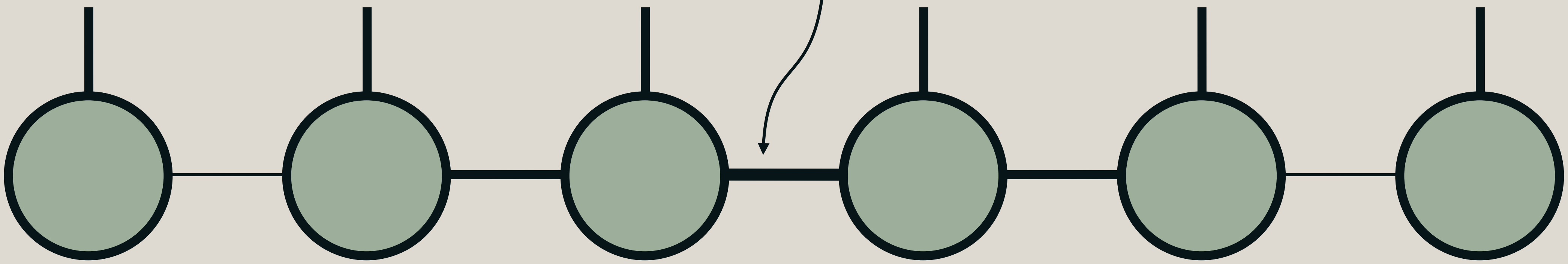
Tensor Networks allow you to represent systems in more efficient ways

χ :

Low
Very fast

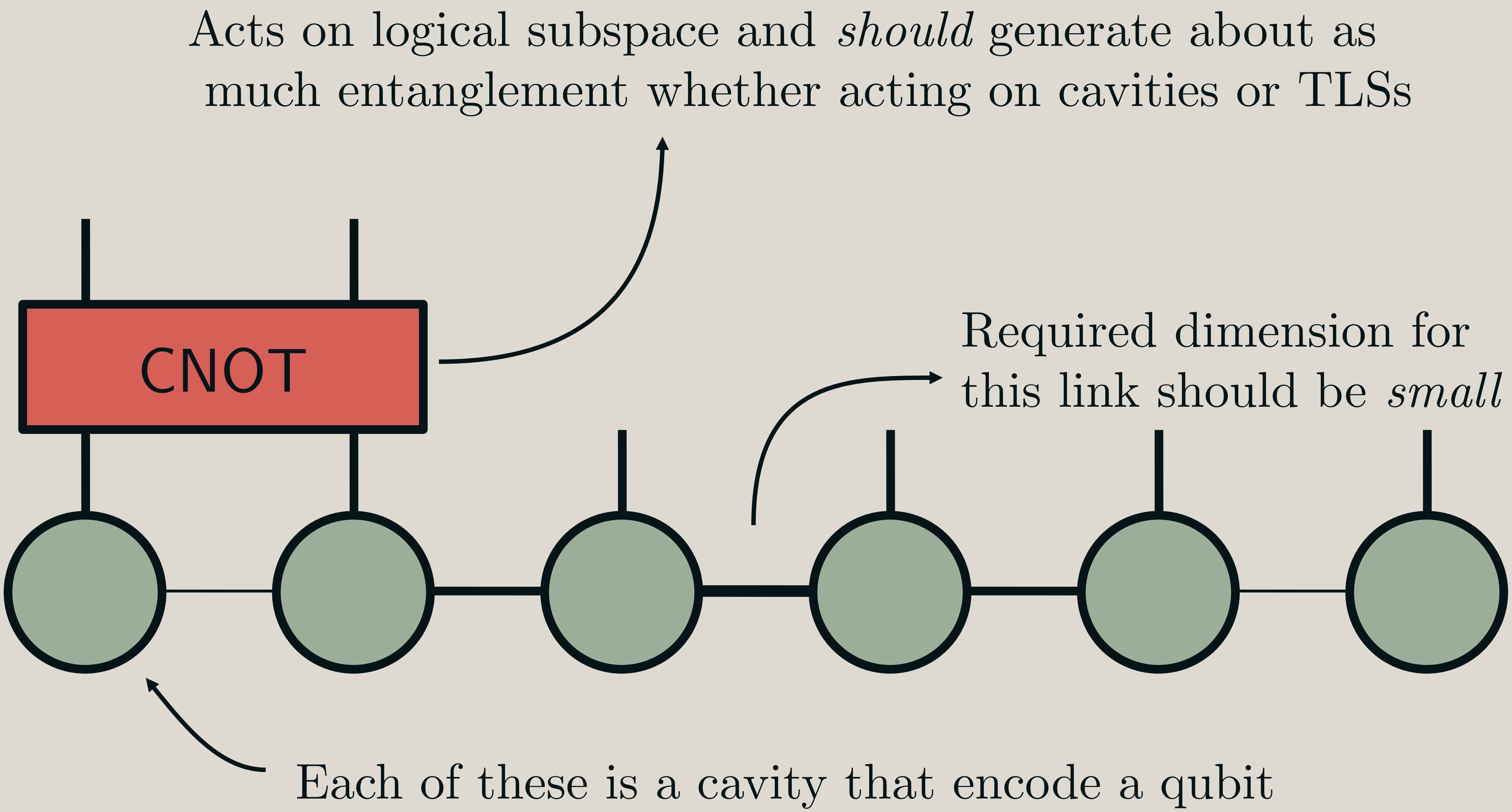


High
Very Accurate



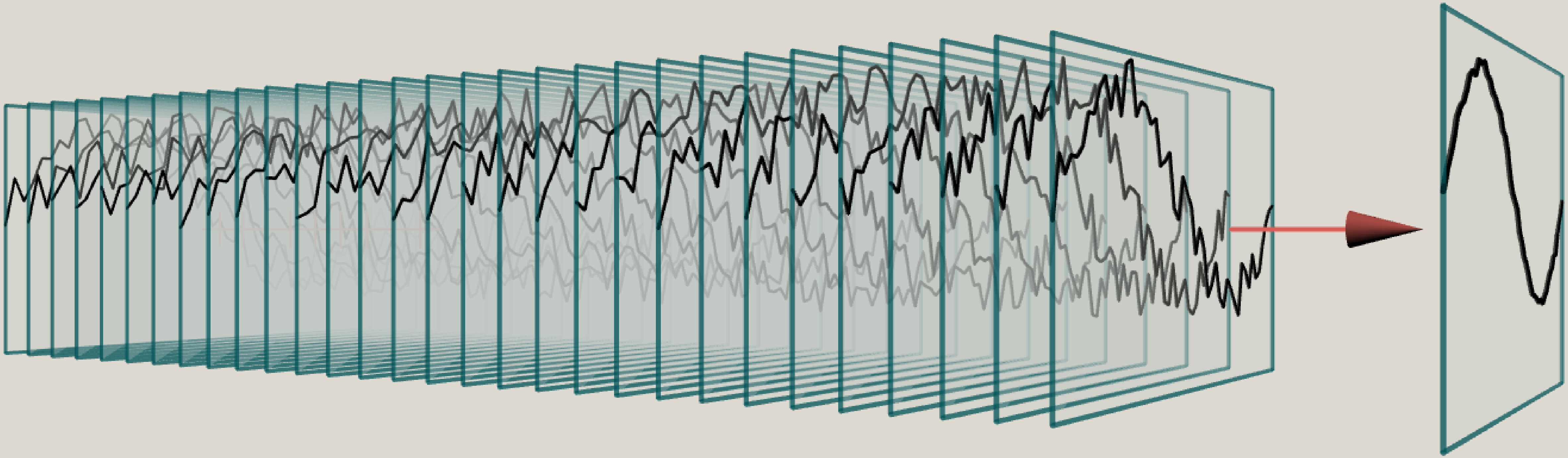
[1]Collura M *et al.* 2024 Tensor Network Techniques for Quantum Computation
[2]Berezutskii A *et al.* 2025 Tensor networks for quantum computing (arXiv)
[3]Orus R 2014 Annals of Physics 349 117

Low bond dimension should be required for bosonic circuits



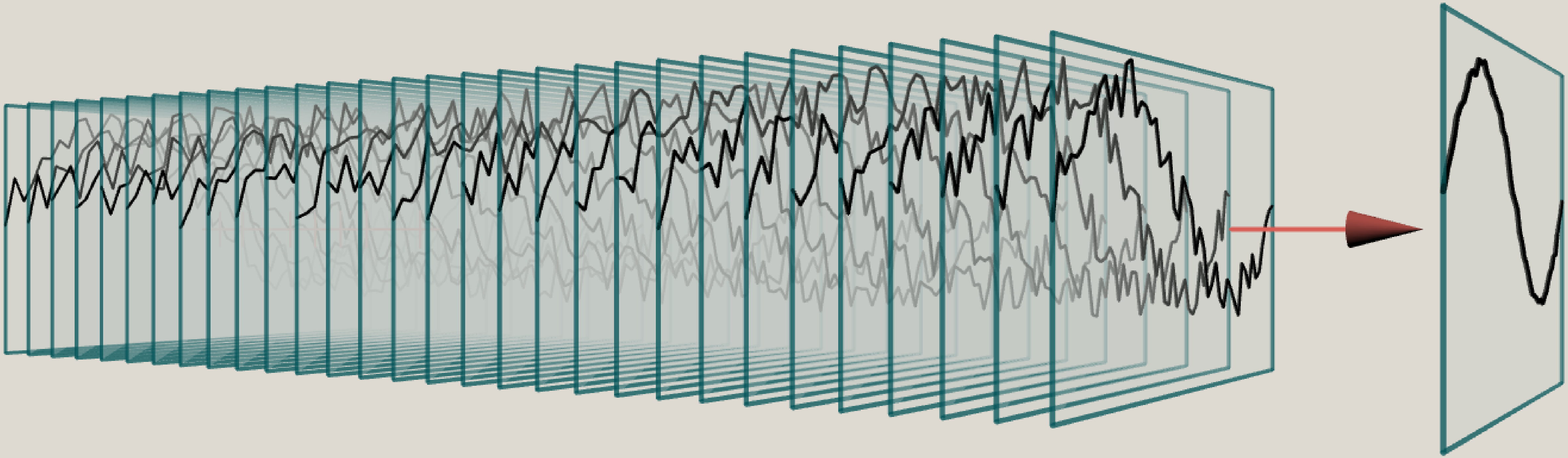
Monte Carlo: using vectors instead of density matrices

$\rho \to$ expensive in memory, use $|\psi\rangle$ instead



Monte Carlo: using vectors instead of density matrices

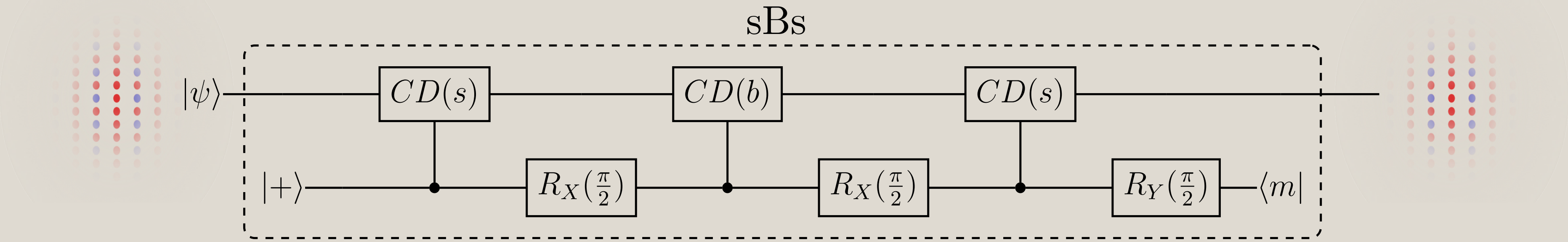
$\rho \to$ expensive in memory, use $|\psi\rangle$ instead



$$\operatorname{avg}\big(K_0 |\psi\rangle, K_0 |\psi\rangle, K_1 |\psi\rangle, K_0 |\psi\rangle, K_2 |\psi\rangle, K_0 |\psi\rangle, \ldots\big) \approx \mathcal{E}(\rho)$$

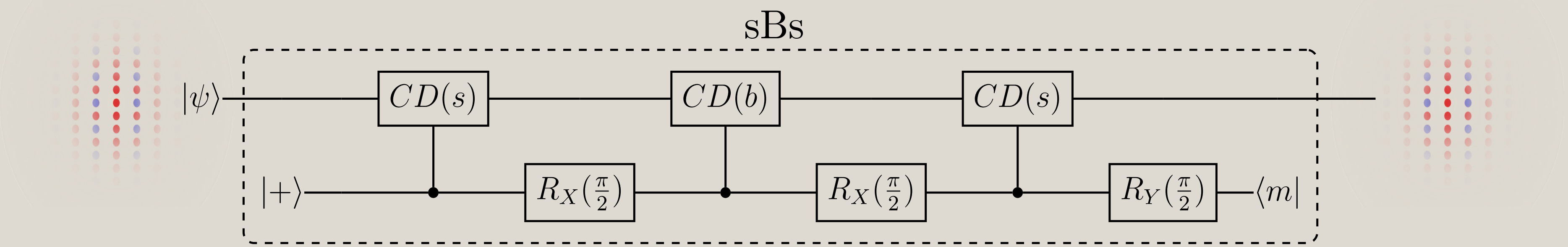
where $\mathcal{E}$ can be photon loss, dephasing, bit flip, etc.

Using the right basis: Better intuition and better performances



[1] Royer B, Singh S, Girvin S M 2020 Phys. Rev. Lett. 125 260509
[2] Hopfmueller F, Tremblay M, St–Jean P, Royer B, Lemonde M

Using the right basis: Better intuition and better performances



$$\mathcal{H}_B = \boxed{\mathcal{H}_l} \otimes \boxed{\mathcal{H}_e}$$

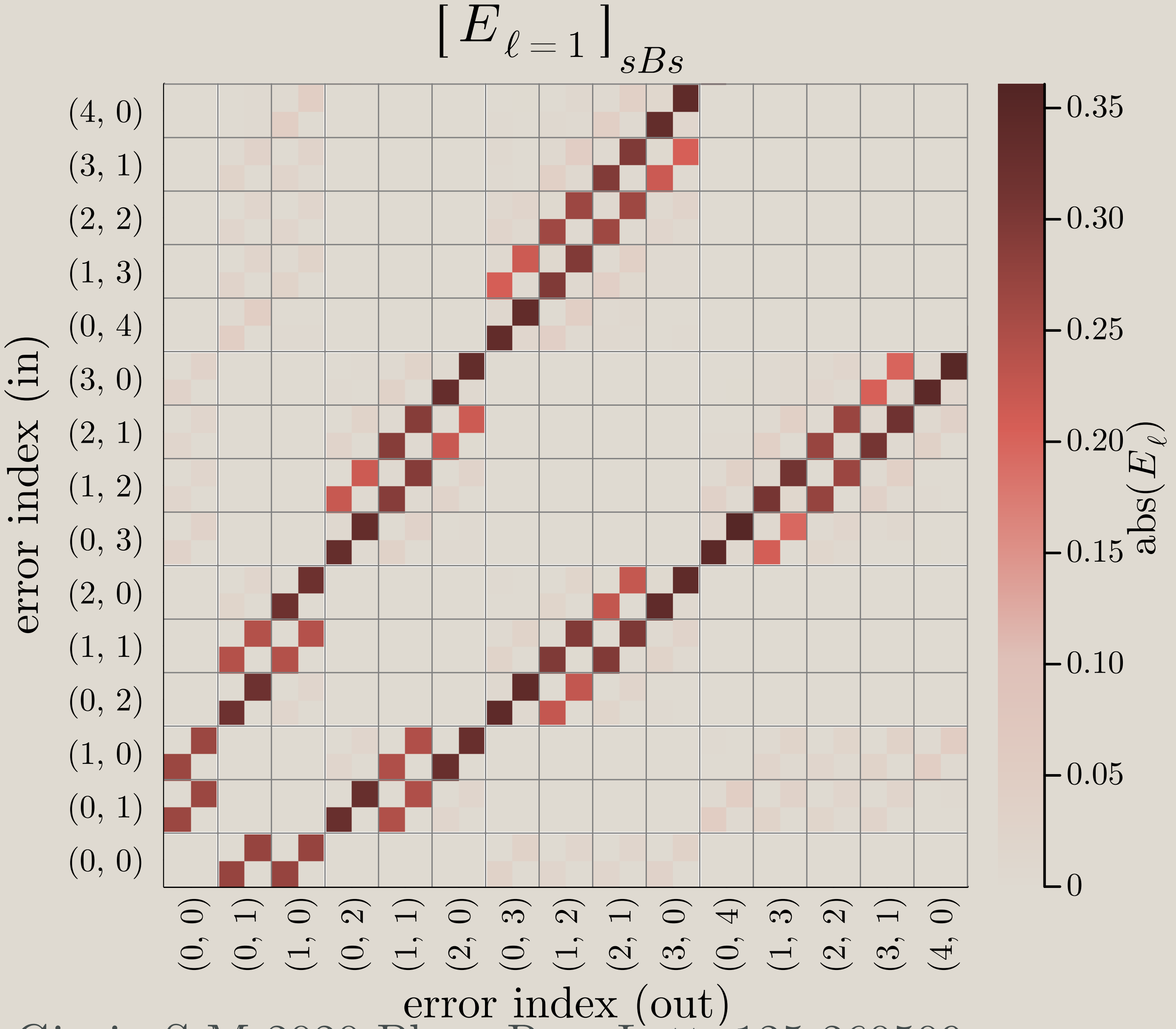
GKP codespace

Defined from sBs

$$|\psi\rangle = \sum_{n\in\mathbb{N}} c_n |n\rangle = \sum_{\mu\in\{0,1\}} \sum_{(e_p,e_q)\in\mathbb{N}^2} c_{\mu,e_q,e_p} \boxed{|\mu\rangle} \boxed{|e_q, e_p\rangle}$$

[1] Royer B, Singh S, Girvin S M 2020 Phys. Rev. Lett. 125 260509
[2] Hopfmueller F, Tremblay M, St–Jean P, Royer B, Lemonde M

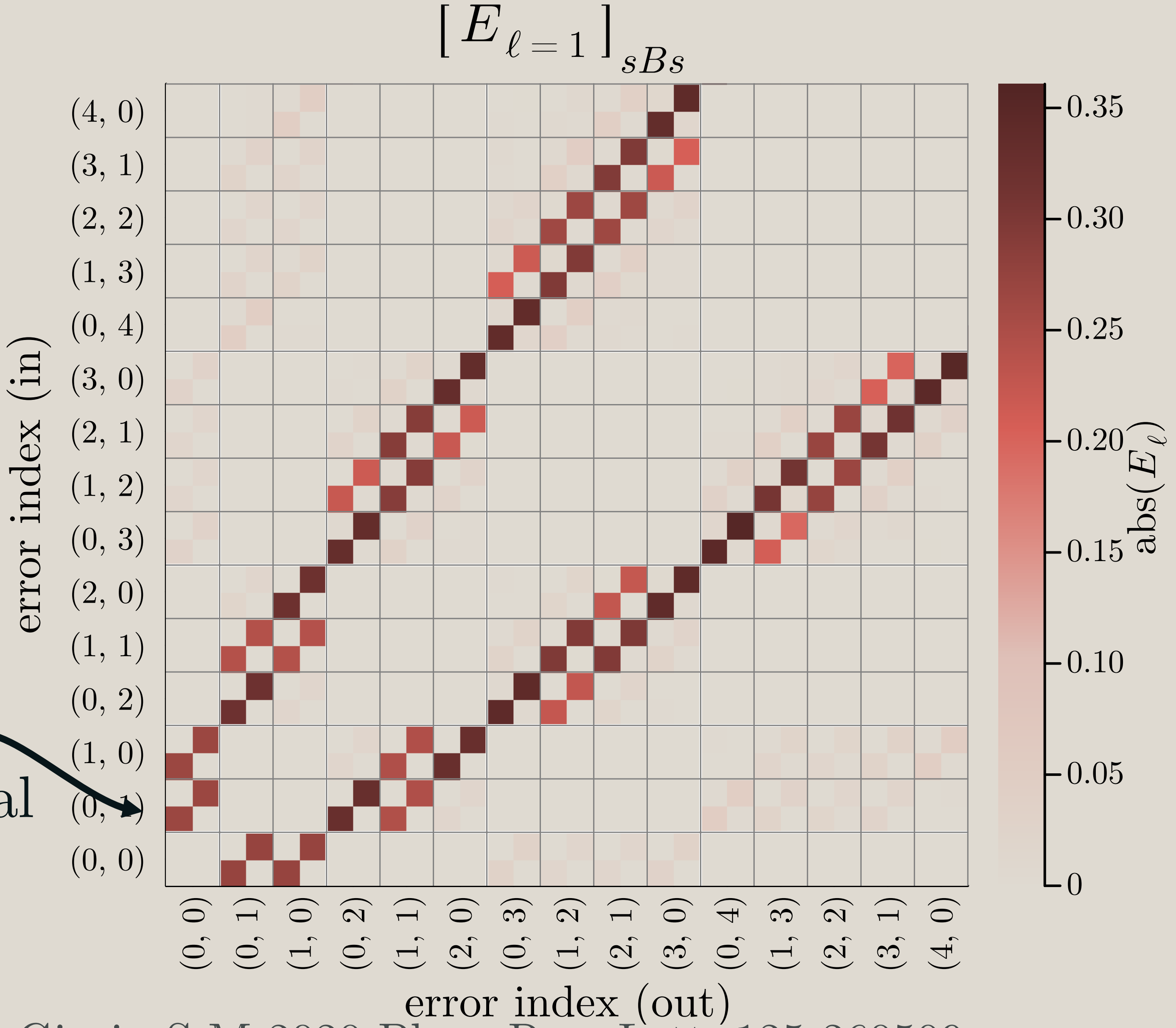
Using the right basis: Better intuition and better performances



[1] Royer B, Singh S, Girvin S M 2020 Phys. Rev. Lett. 125 260509

[2] Hopfmueller F, Tremblay M, St–Jean P, Royer B, Lemonde M

Using the right basis: Better intuition and better performances

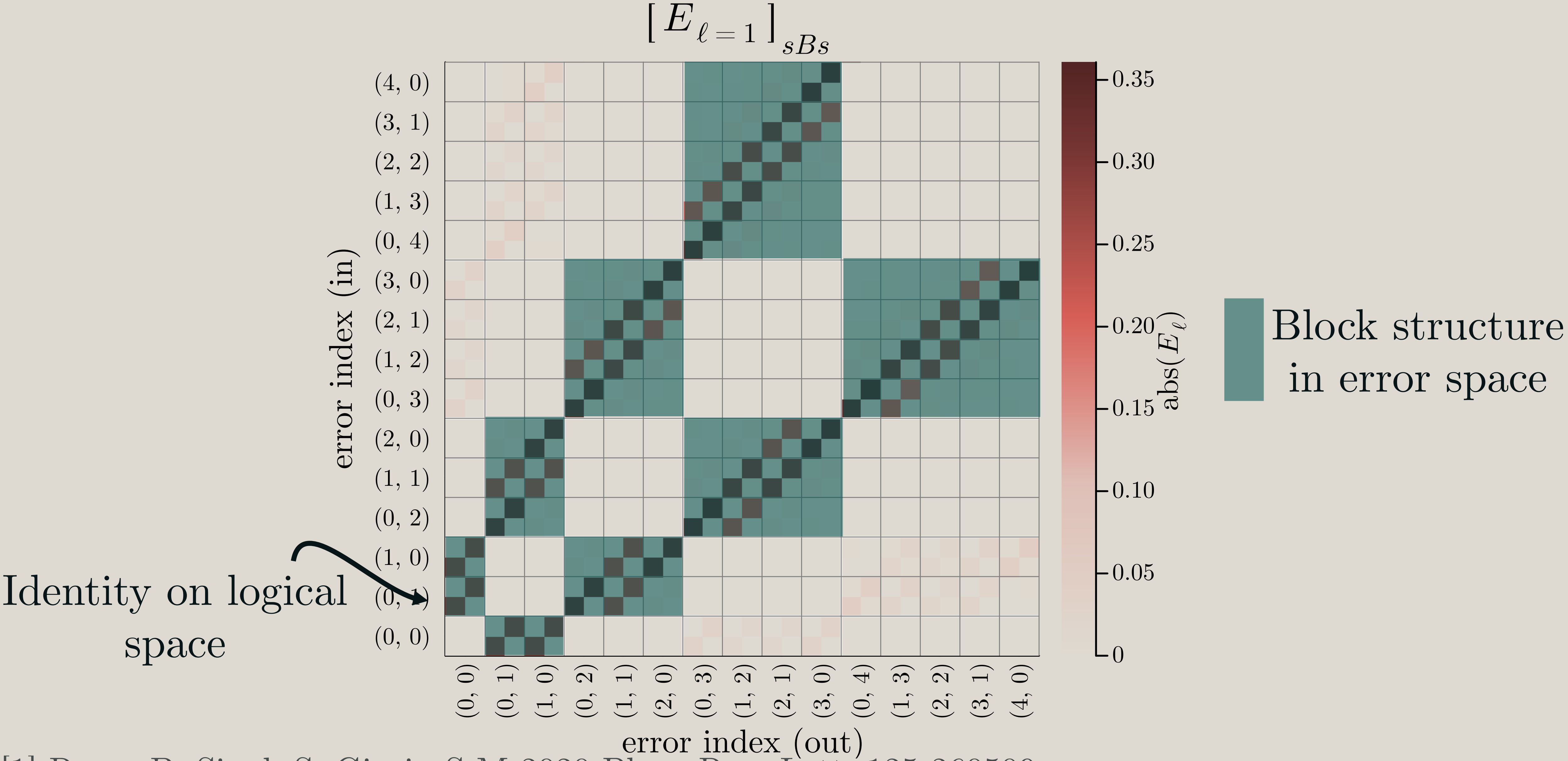


Identity on logical space

[1] Royer B, Singh S, Girvin S M 2020 Phys. Rev. Lett. 125 260509

[2] Hopfmueller F, Tremblay M, St–Jean P, Royer B, Lemonde M

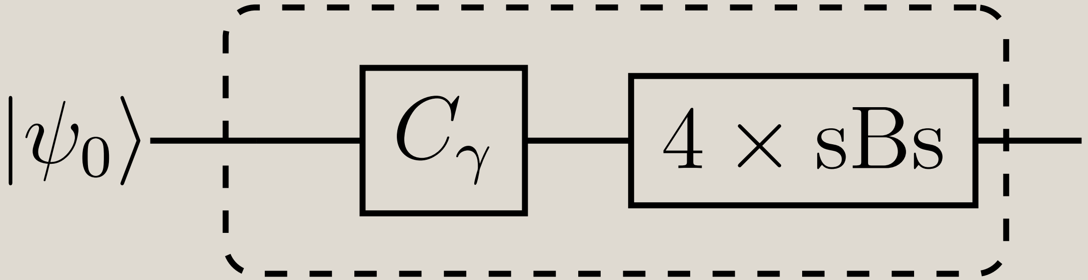
Using the right basis: Better intuition and better performances

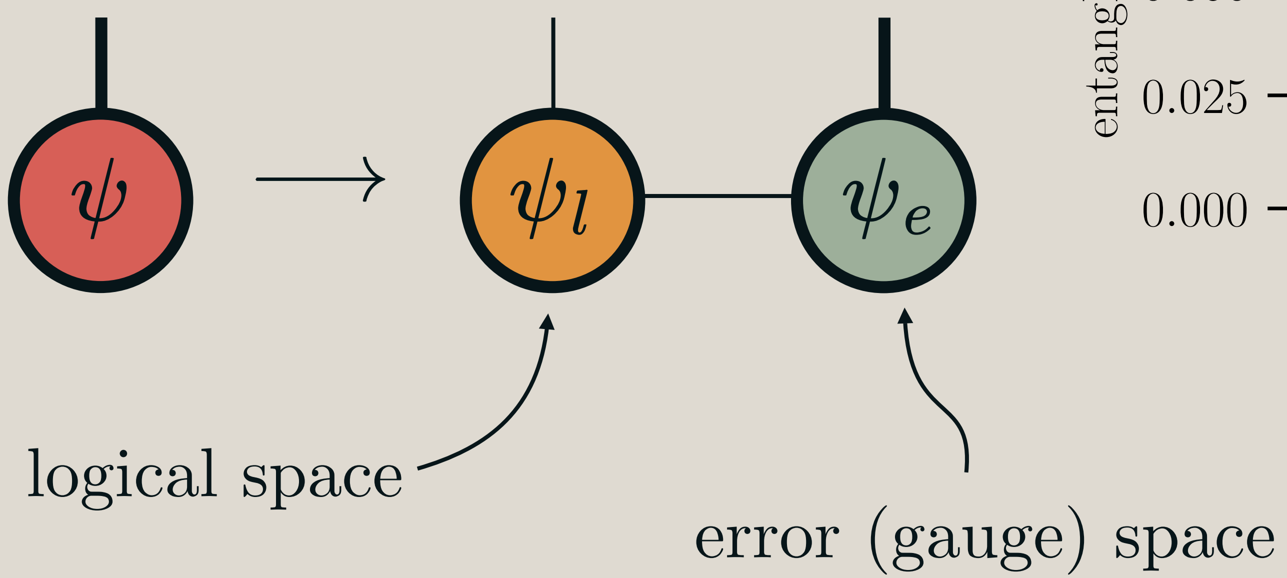


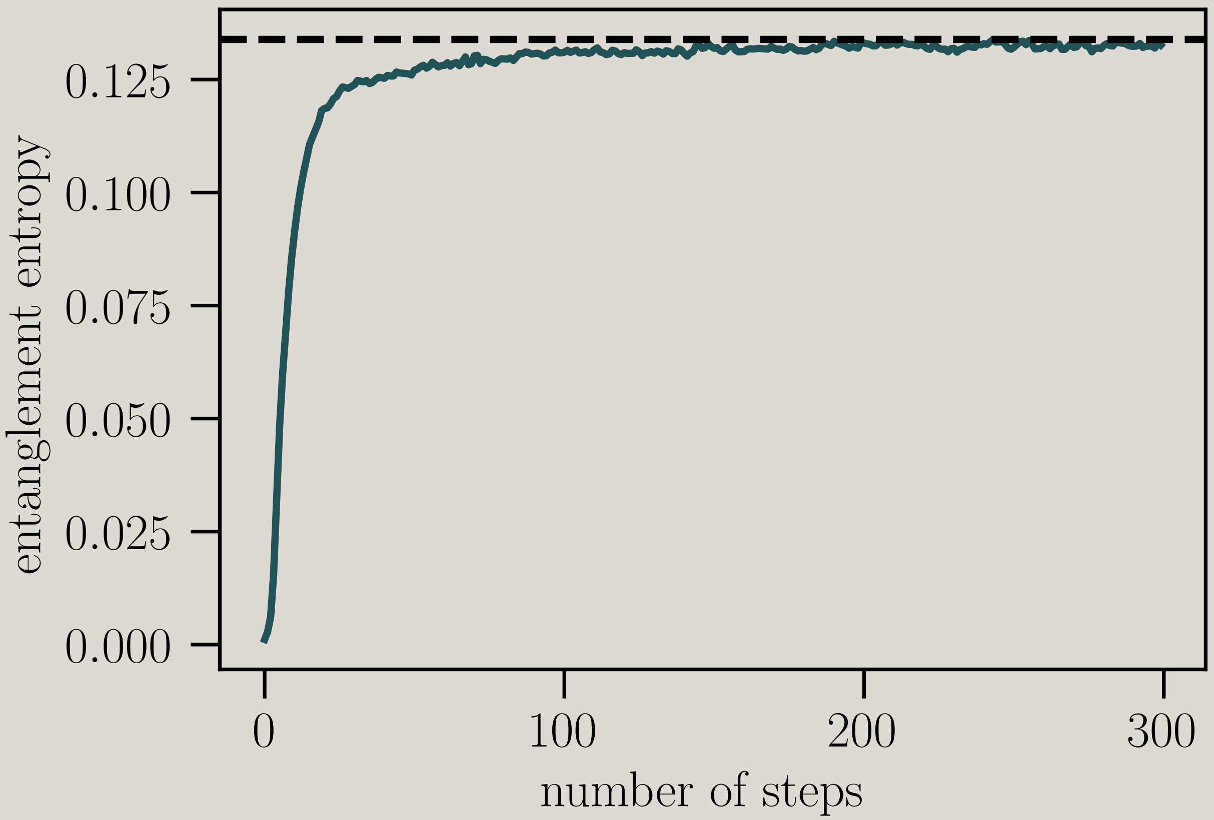
[1] Royer B, Singh S, Girvin S M 2020 Phys. Rev. Lett. 125 260509

[2] Hopfmueller F, Tremblay M, St–Jean P, Royer B, Lemonde M

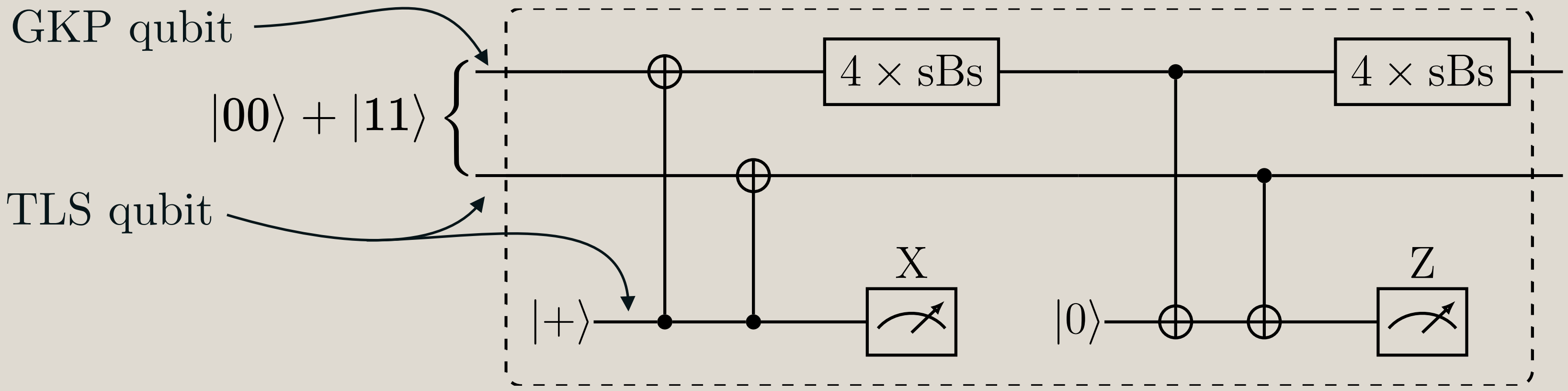
Single cavity: entanglement entropy between the logical and gauge space

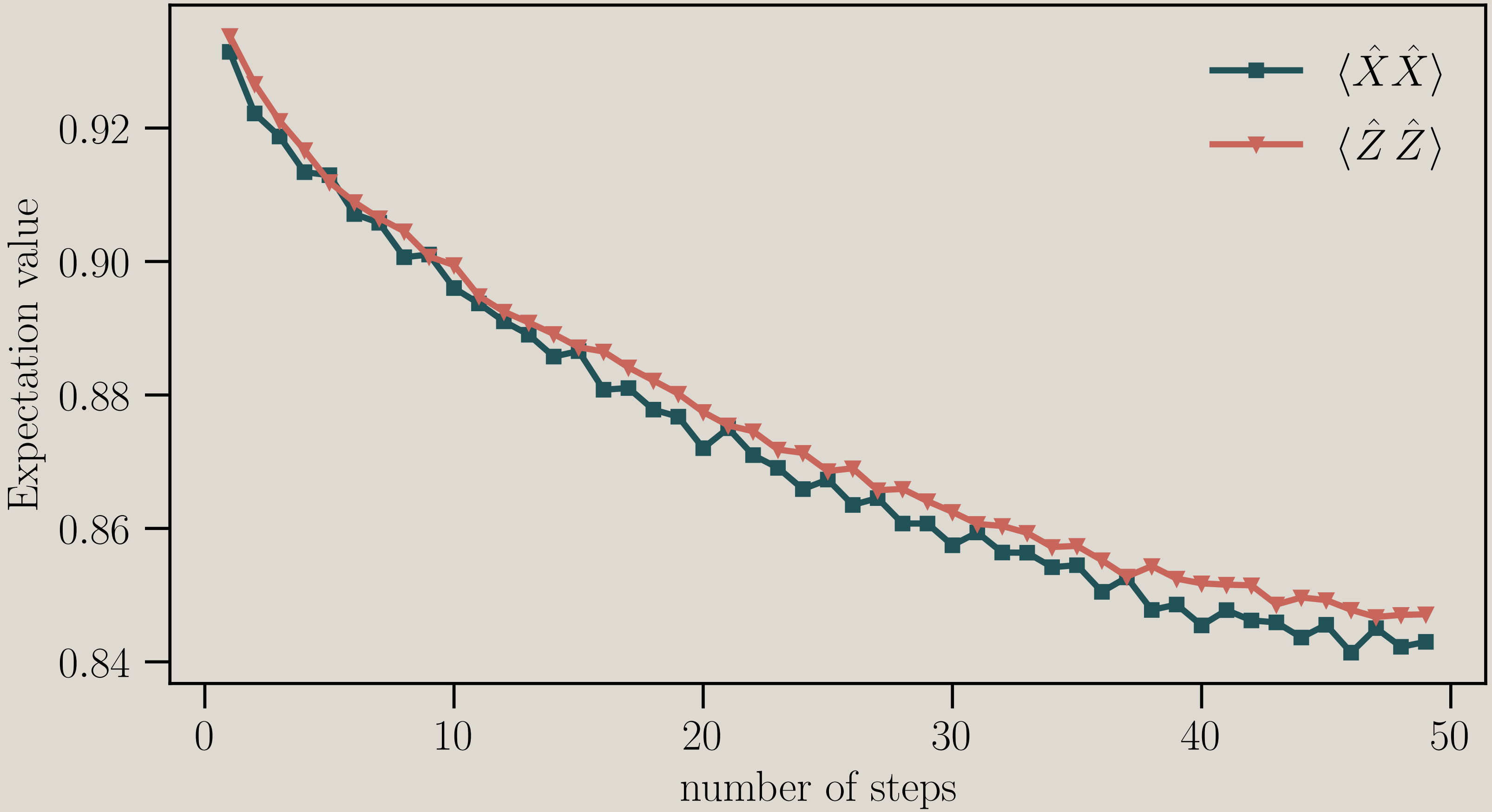






Results: Stabilizing a Bell Pair





Summary

Simulating systems with many cavities can be hard because of a large hilbert space. Tools like tensor networks, Monte Carlo and clever basis choice can all be combined to get better performances.

Looking Forward

- Simulating larger circuits
  - Simulating code concatenation
- The limits of the framework
  - Accuracy of noise representation
  - Exact effect of bond dimention
- Different tensor network structures