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Tensor Network Approaches for Simulations of Larger Superconducting Circuits

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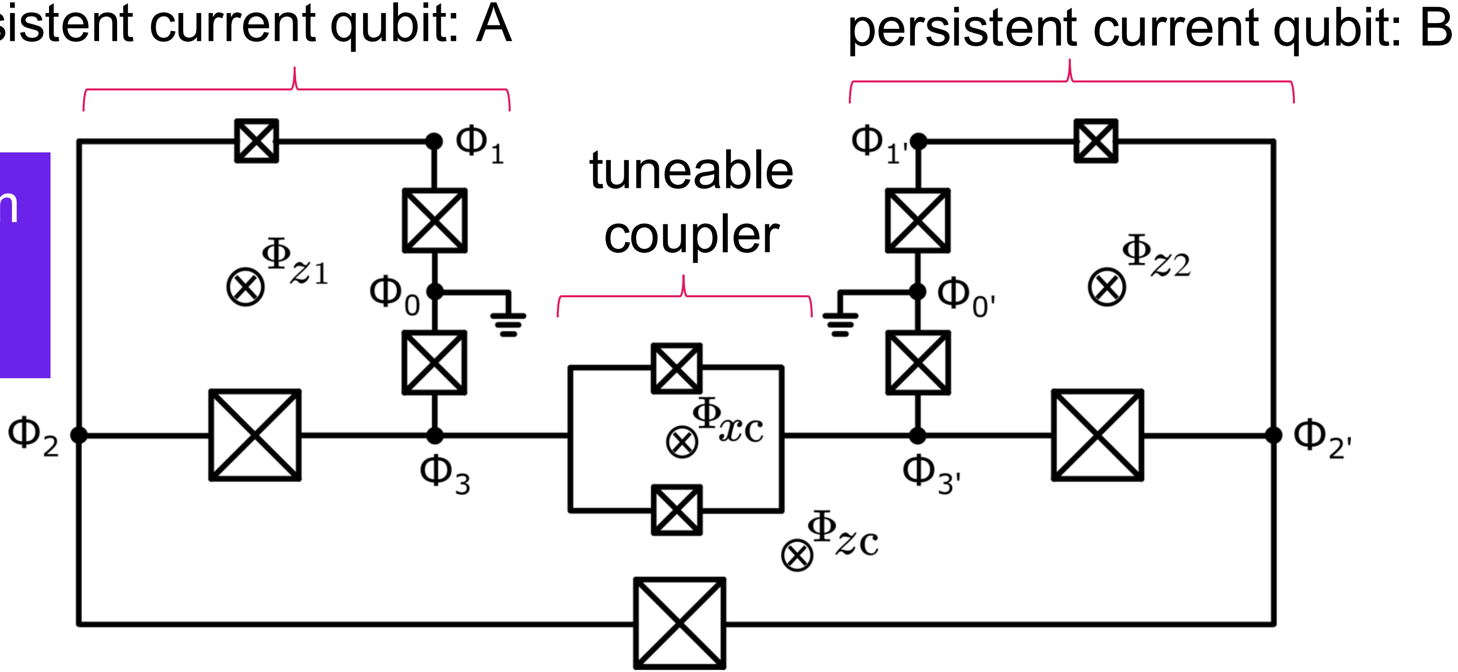
Problem: Simulation of a "larger" circuit



Circuit from Andrea's Poster

explore strong coupling regime (e.g. for non-stoquastic effects)

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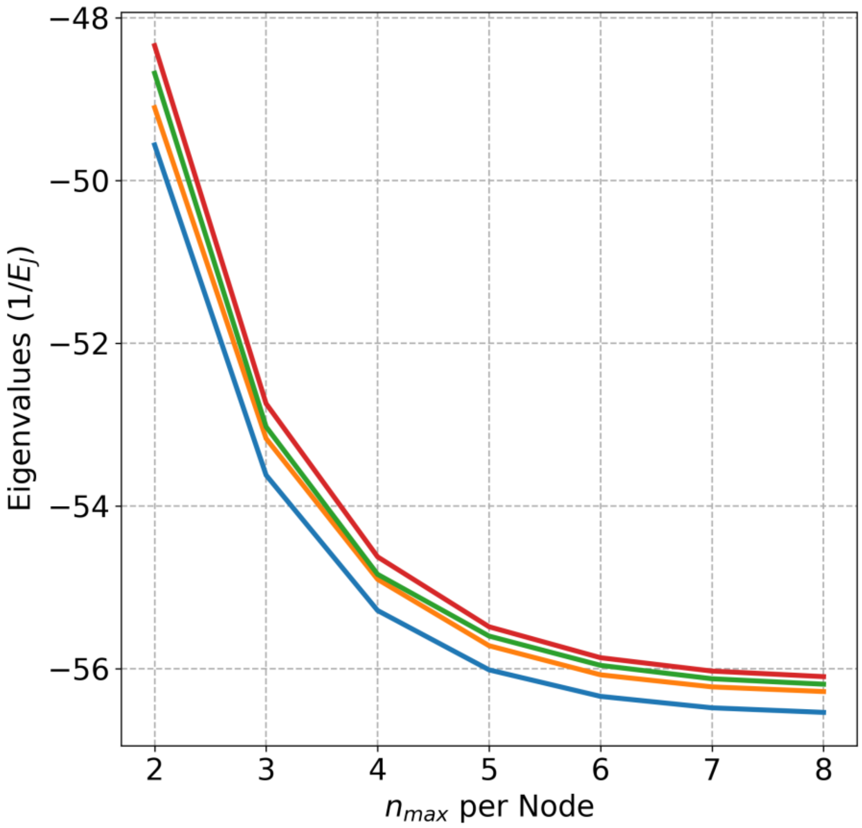
Problem: Simulation of a “larger” circuit

- matrix representation must converge on a suitable basis (here charges per node)
- But it does not converge



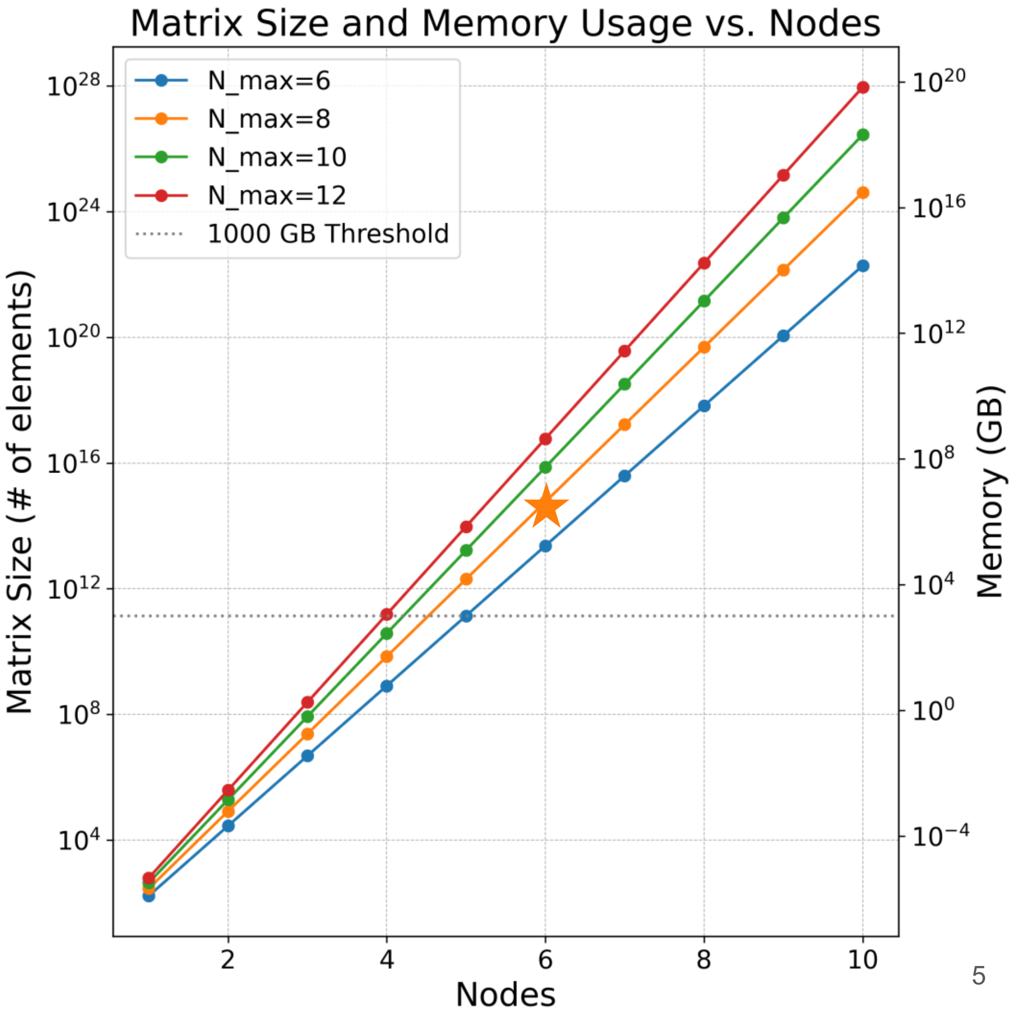
Bottleneck in exact diagonalisation

Our example run with 1 TB of RAM

- orange star: maximum sparse matrix size reached

General

- **Exponential** scaling
- Limitation already for modest circuits



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Discarded approximations

Born-Oppenheimer

- only linear interaction of subsystems
- need assumptions of the interaction mechanisms
- typical inductive interaction but not capacitance interaction

Hierarchical diagonalisation [1]

- Hamiltonians of the subsystems can get very large when capturing more coupling mechanisms

Do not capture strong coupling and all coupling terms.

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[1] Kerman, Andrew J. "Efficient Numerical Simulation of Complex Josephson Quantum Circuits." 2020 http://arxiv.org/abs/2010.14929.

Goal

Explore tensor networks techniques aiming to **accurately simulate superconducting circuits** of two qubits and **beyond**, considering **strong coupling and revealing all coupling terms.**

Method

Why are we using Tensor Networks?

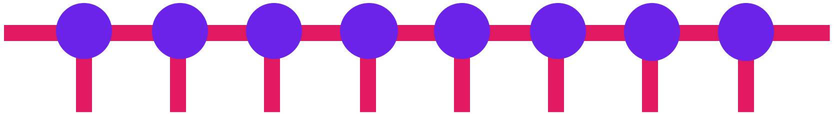
Generic entangled state

$$|\psi\rangle = \sum_{i_1,\ldots,i_N} \psi_{i_1,\ldots,i_N} |i_1\rangle \cdots |i_N\rangle$$

Specified by parameters

$$\mathcal{O}(\exp(N))$$

Tensor Networks: Product of simple objects
Some (very well tuneable) entanglement but still efficient



$$\mathcal{O}(\text{poly}(N))$$

Product state (or unentangled state)

$$|\Psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \cdots \otimes |\psi_N\rangle$$

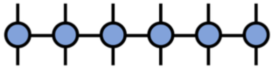
$$\mathcal{O}(N)$$

[4]

Workflow

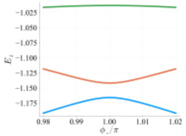
$\mathcal{H}(Q, \phi)$

Lumped Element Hamiltonian



Matrix Product Operator (MPO)

MPO for each term in the Hamiltonian:
OpSum in ITensors



Eigenvalues

Density matrix renormalization group algorithm (DMRG)

$\mathcal{H}_{eff}$

Effective Hamiltonian

Schrieffer Wolf Transformation (in tensor network framework)

$J_{\mu\nu}$

Coupling terms

Expansion in Pauli coefficients

Work in Progress

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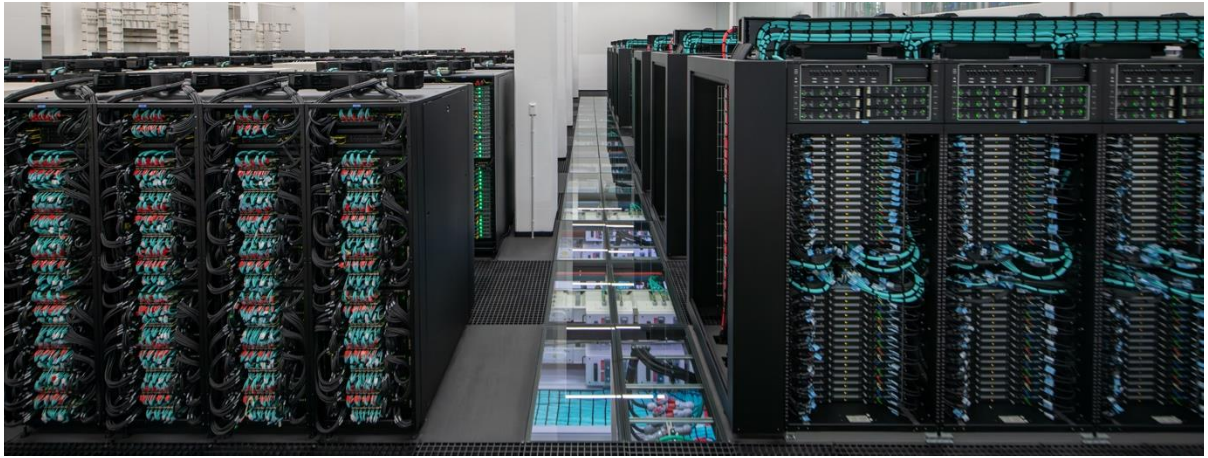
[2] Di Paolo et al "Efficient Modeling of Superconducting Quantum Circuits with Tensor Networks." 2021
[4] Tensors.Net, https://www.tensors.net/intro. Accessed 15 May 2025.

High Performance Computing

- in Julia using **ITensors** library [3]
- executing on CPUs, with GPU support
- deployment multiple nodes on the Mare Nostrum 5 supercomputer for **large-scale parallel simulations**



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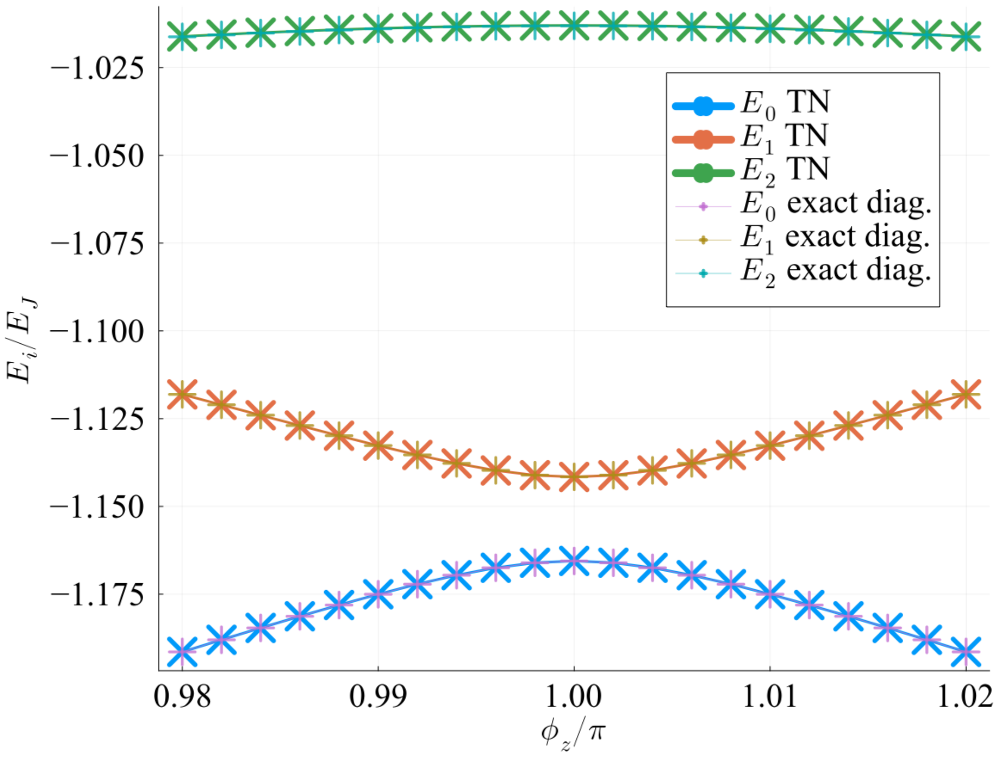
[3] "The ITensor Software Library for Tensor Network Calculations", Fishman et al. 2022

Preliminary Results

Single persistent current qubit

Spectra of TN exactly and exact diagonalisation **match** exactly



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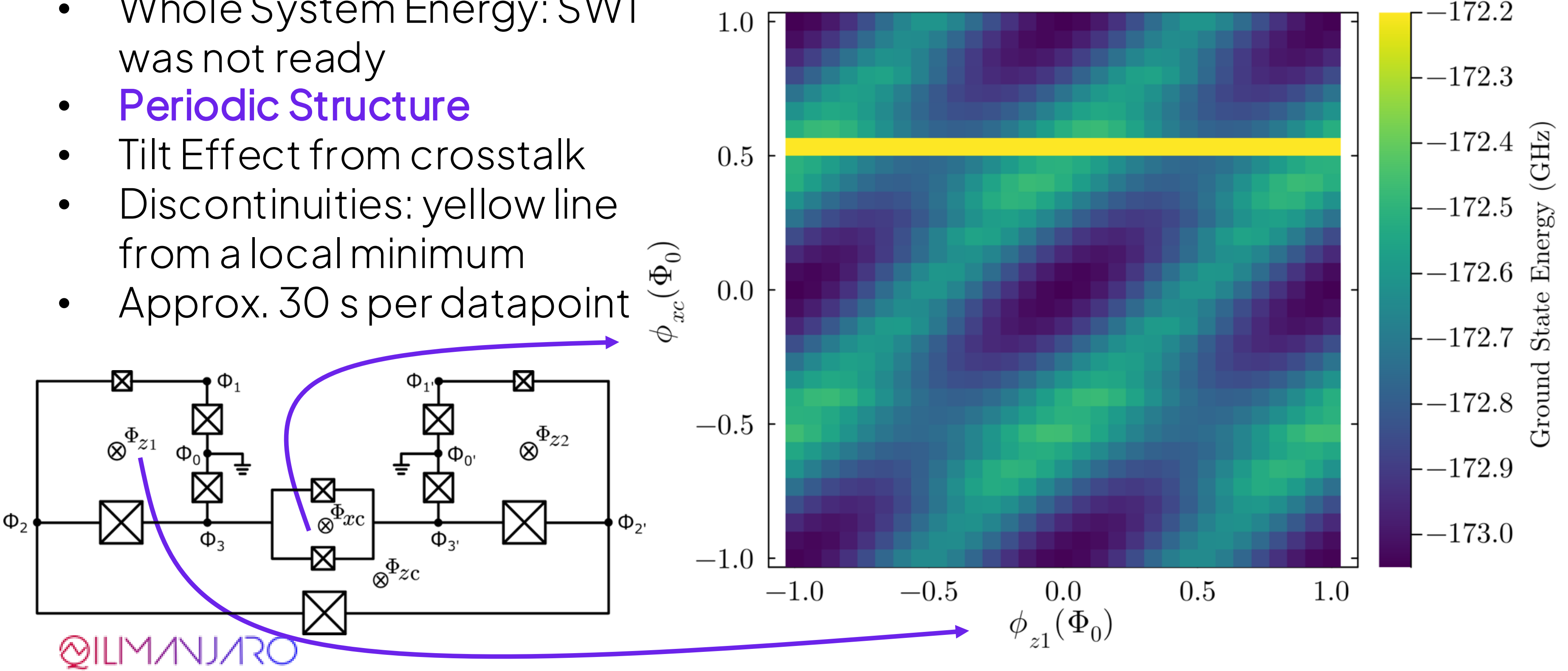
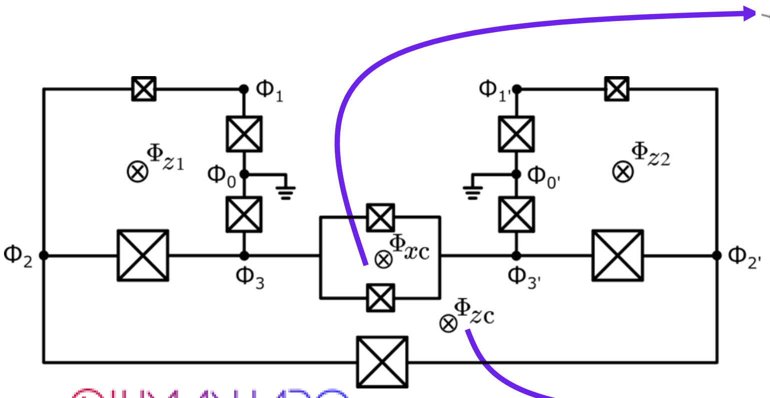
Two tuneable coupled persistent current qubits

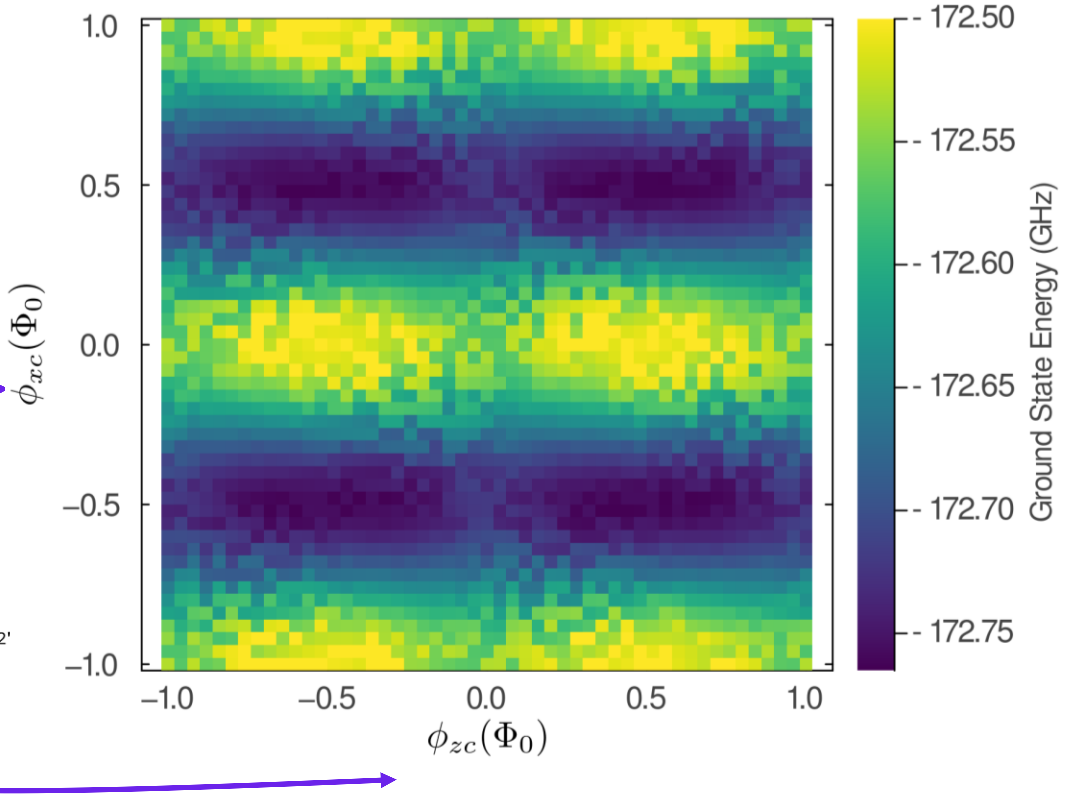
- Whole System Energy: SWT was not ready
- Periodic Structure
- Tilt Effect from crosstalk
- Discontinuities: yellow line from a local minimum
- Approx. 30 s per datapoint



Two tuneable coupled persistent current qubits

- Whole System Energy
- **Periodic Structure**
- wavefront propagation for increased parallelism.
- Discarded many outliers





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Outlook and Conclusion

Outlook

- **Refining** to **match with experimental results**
- Aid cross talk simulations (Andrea's poster)

- **Schrieffer-Wolff transformation** in the TN framework — **likely reveal coupling terms that approximate methods miss** [5]

- Machine-learning strategies to mitigate **local minima**

- Computational: improve **efficiency** and conclusive benchmark

- Harnessing **tensor network perspective** (e.g. study entanglement, fine tune bond dimensions)

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[5] Hita-Pérez et al "Three-Josephson Junctions Flux Qubit Couplings." 2021

Conclusion

- **Scalable Framework:** Designed, implemented, and are currently validating a methodology to break through computational bottlenecks in larger, strongly coupled circuits.

- **Preliminary Proof of Concept:** Our method surpass the computational limits of exact diagonalization.

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Acknowledgment and References

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1. Kerman, Andrew J. "Efficient Numerical Simulation of Complex Josephson Quantum Circuits." 2020 http://arxiv.org/abs/2010.14929.
2. Di Paolo, Agustin, Thomas E. Baker, Alexandre Foley, David Sénéchal, and Alexandre Blais. "**Efficient Modeling of Superconducting Quantum Circuits with Tensor Networks.**" 2021 https://doi.org/10.1038/s41534-020-00352-4.
3. "The **ITensor** Software Library for Tensor Network Calculations", Matthew Fishman, Steven R. White, E. Miles Stoudenmire, 2022
4. Tensors.Net, https://www.tensors.net/intro. Accessed 15 May 2025.
5. Hita-Pérez, María, Gabriel Jaumà, Manuel Pino, and Juan José García-Ripoll. **"Three-Josephson Junctions Flux Qubit Couplings."** 2021, https://doi.org/10.1063/5.0069530.

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Previous Work

"Efficient Modeling of Superconducting Quantum Circuits with Tensor Networks."
Di Paolo et al. 2011 [2]

- Applied to Fluxonia