Ongoing activities in WP2 at INFN-MIB

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Outline

- ❑Neutrino simulations
- ❑Shared SQUID device

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- ❑Shared SQUID device

Ideas for QUART&T device

- **High density neutrino environments** where neutrino flavor oscillations are affected by neutrino-neutrino quantum interaction.

- The Hamiltonian for a **two flavors oscillation** can be written as:

$$H = \sum_{k=1}^{N} \vec{b} \cdot \vec{\sigma}_k + \sum_{p<q}^{N} J_{pq}\, \vec{\sigma}_p \cdot \vec{\sigma}_q \qquad \text{with } \vec{\sigma}_k = (\sigma_k^x, \sigma_k^y, \sigma_k^z)$$

1. Vacuum mixing
2. MSW effect
3. Neutrino–neutrino interaction

- Quantum architecture to simulate this specific problem.

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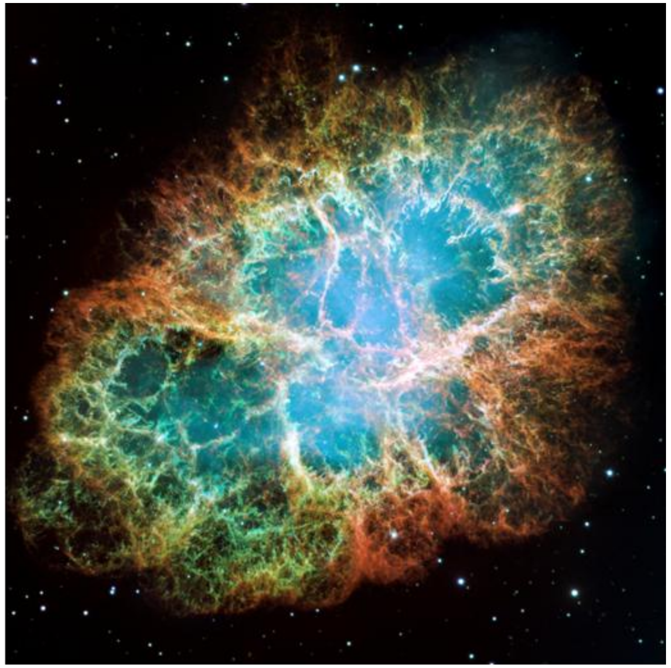
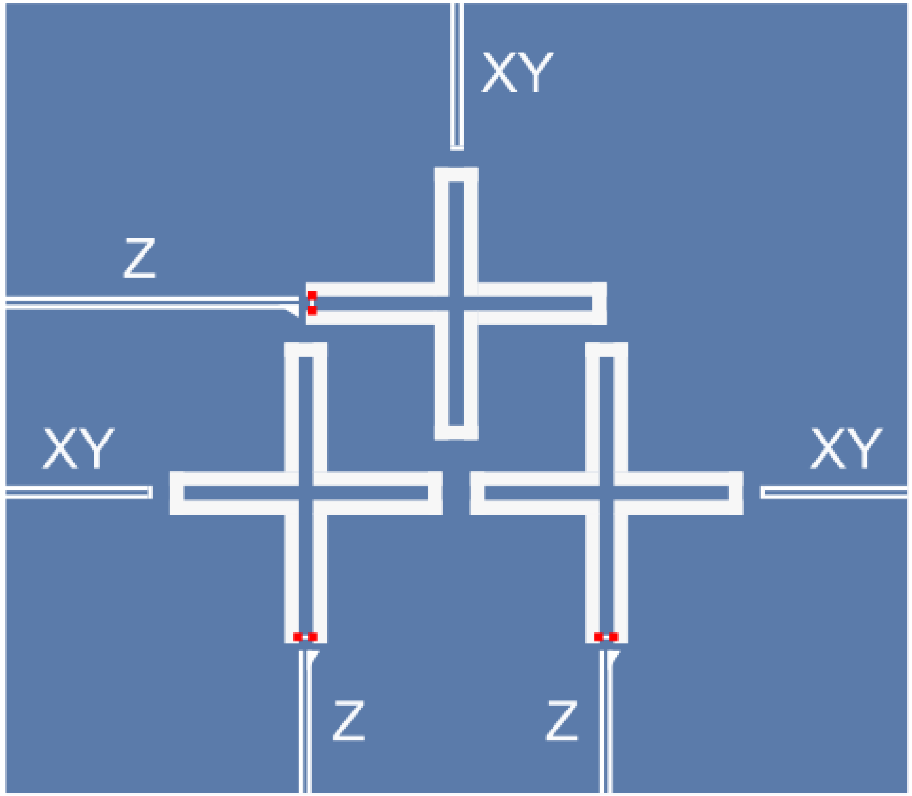


The Crab Nebula, a remnant of a supernovae.

Analog device

Key idea:

1. Realize an **analog block** which realize an all-to-all connectivity using YY (capacitive) interaction (we are currently working on 3 qubits);



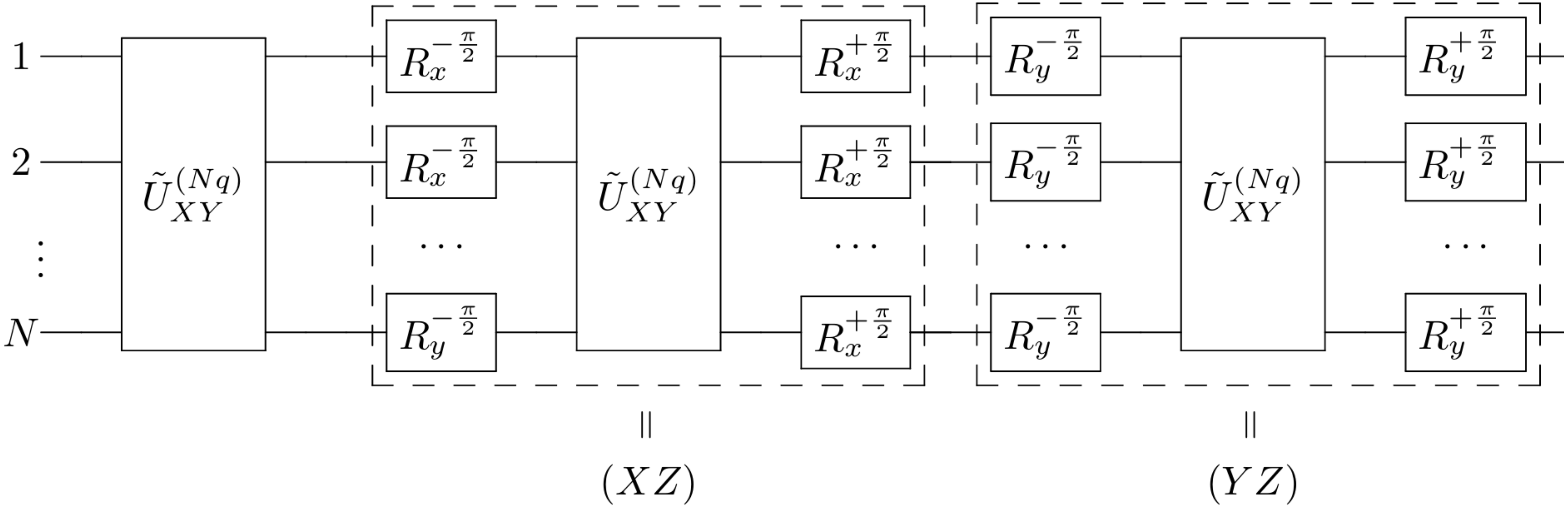
$$H^{(Nq)} = -\sum_{k=1}^{N} \frac{\omega_k}{2} \sigma_z^{(k)} + \sum_{p<q} g_{pq} \sigma_y^{(p)} \sigma_y^{(q)}$$

Hamiltonian of N qubits capacitively coupled

Analog device

Key idea:

2. Use a sequence of single qubit gate and analog block to simulate the neutrinos hamiltonian.



- 3 analog blocks separated by $4 \cdot N$ single qubit gates;
- Each analog block has the same **time length** which correspond to the desired simulation time;

Digital Vs Analog

Simulating quantum objects has two important limitations:

- **Trotter error** requires splitting the simulation into many small time steps, setting a lower bound on the number of steps needed for a given interaction time.
- **Gate fidelity** limits the number of gates, imposing an upper bound on the steps possible for a given interaction time.

Digital

- High number of gates per simulation step
- High fidelity 2 qubit gates (99.9%)

Analog

- Hardware optimization: low number of gates per simulation step
- Uncertain analog block fidelity
- Reduced trotter error due to less non-commuting gates

Analog device – simulation results

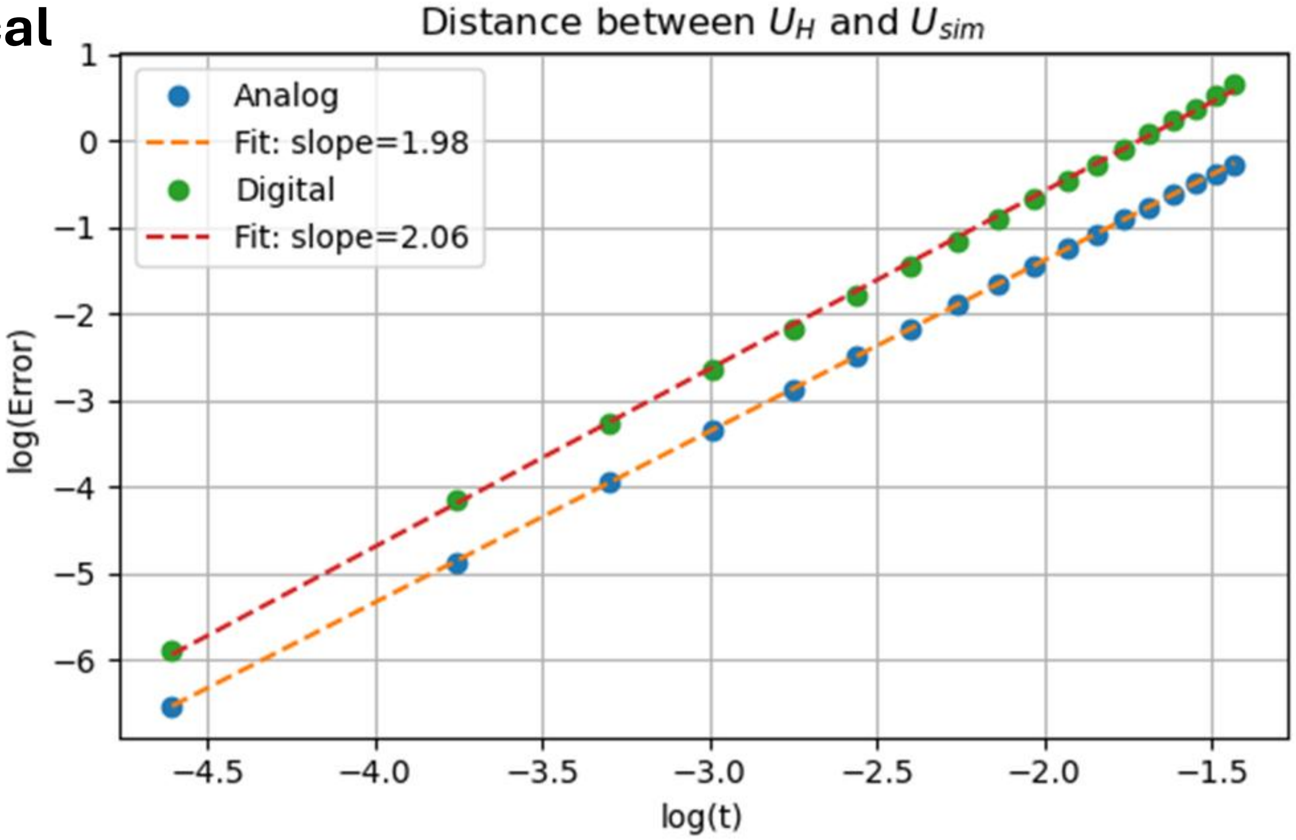
3 qubit-device **qutip simulations** and **analytical analysis** to quantify the analog advantage.

⇩

This will determine the analog block fidelity required to overcome a digital quantum computer.

$$\|\mathscr{A}(t)\| = \mathcal{O}\left(\widetilde{\alpha}_{\mathrm{comm}} t^{p+1}\right)$$

Theoretically additive error (trotter error).
Quantifying $\tilde{\alpha}_{comm}$ is fundamental to quantify the analog advantage.

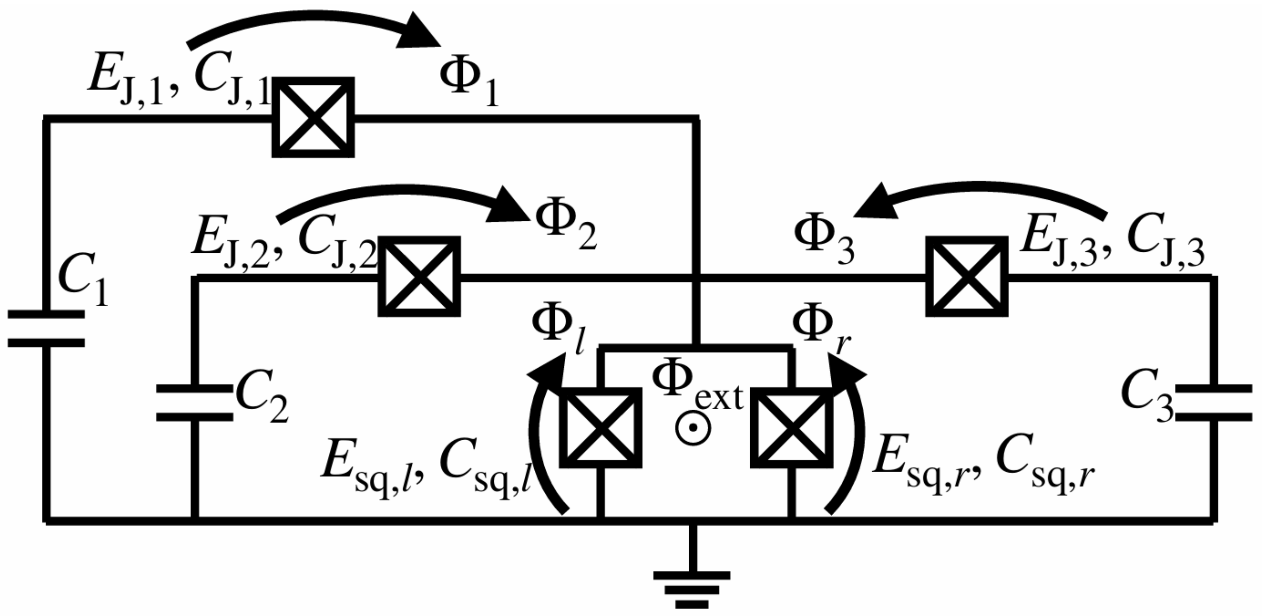


Outline

- ❑Neutrino simulations
- ❑Shared SQUID device ←←←

Device schematic

- 3 transmon qubits device;
- Each qubit superconducting current pass through the SQUID realizing the coupling – **current coupling** ;
- Coupling enabled by AC flux signals sended to the SQUID – **parametric coupling**;



Device analytics

- A change of variables allow us to obtain the simplest Hamiltonian. The coupling term is all contained in the **charging energy**.

$$\mathbf{E}_{\mathrm{C}} = \frac{e^2}{2}\left(\frac{1}{C_{\mathrm{sq},l} + C_{\mathrm{sq},r}}\begin{pmatrix}1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1\\ 1 & 1 & 1 & 1\end{pmatrix} + \begin{pmatrix}\frac{1}{C_1} & & & \\ & \frac{1}{C_2} & & \\ & & \frac{1}{C_3} & \\ & & & 0\end{pmatrix}\right)$$

In the limit of $C_{J,n} = 0$

The off-diagonal terms are large → strong coupling

- The eigenstates of the systems are delocalized between the transmon islands due to strong coupling.

$$< \Psi_{uncoupled}|\Psi_{coupled} > \sim 0.6$$

Parametric coupling

- Turned on by driving the SQUID at a specific frequency

https://doi.org/10.1103/6prx-zmdz

$$\hat{H}_{\text{sq}} = -E_J \cos\left(\frac{\pi \hat{\Phi}_{\text{ext}}}{\Phi_0}\right) \cos\hat{\phi}_2 - \delta E_J \sin\left(\frac{\pi \hat{\Phi}_{\text{ext}}}{\Phi_0}\right) \sin\hat{\phi}_2$$

$$\hat{\Phi}_{\text{ext}} = \alpha_p(t) = A_p \cos(\omega_p t + \varphi)$$

$$\hat{\phi}_2 \sim \left(\hat{b}_j^\dagger + \hat{b}_j\right)$$

$$\hat{H}_{\text{sq}} = -\sum_k g_k(A_p) \left[\sum_{n=1}^{3} \left(\lambda_n \hat{\sigma}_n^+ + \lambda_n^* \hat{\sigma}_n^-\right)\right]^k$$

Coupling of different orders between normal modes

RWA

$\alpha_p(t) = A_p \cos(\omega_{001\to110}\, t + \varphi)$

Three-body interaction

$\hat{H}_{int} \approx -J(A_p)\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_3$ + h.c.

$\alpha_p(t) = A_p \cos(\omega_{10\to01}\, t + \varphi)$

Two-body interaction

$\hat{H}_{int} \approx -J(A_p)\hat{a}_1^\dagger \hat{a}_2$ + h.c.

- SQUID asymmetric junction needed to turn on three-body interaction

Parametric coupling

- Interaction strength:

Two-body

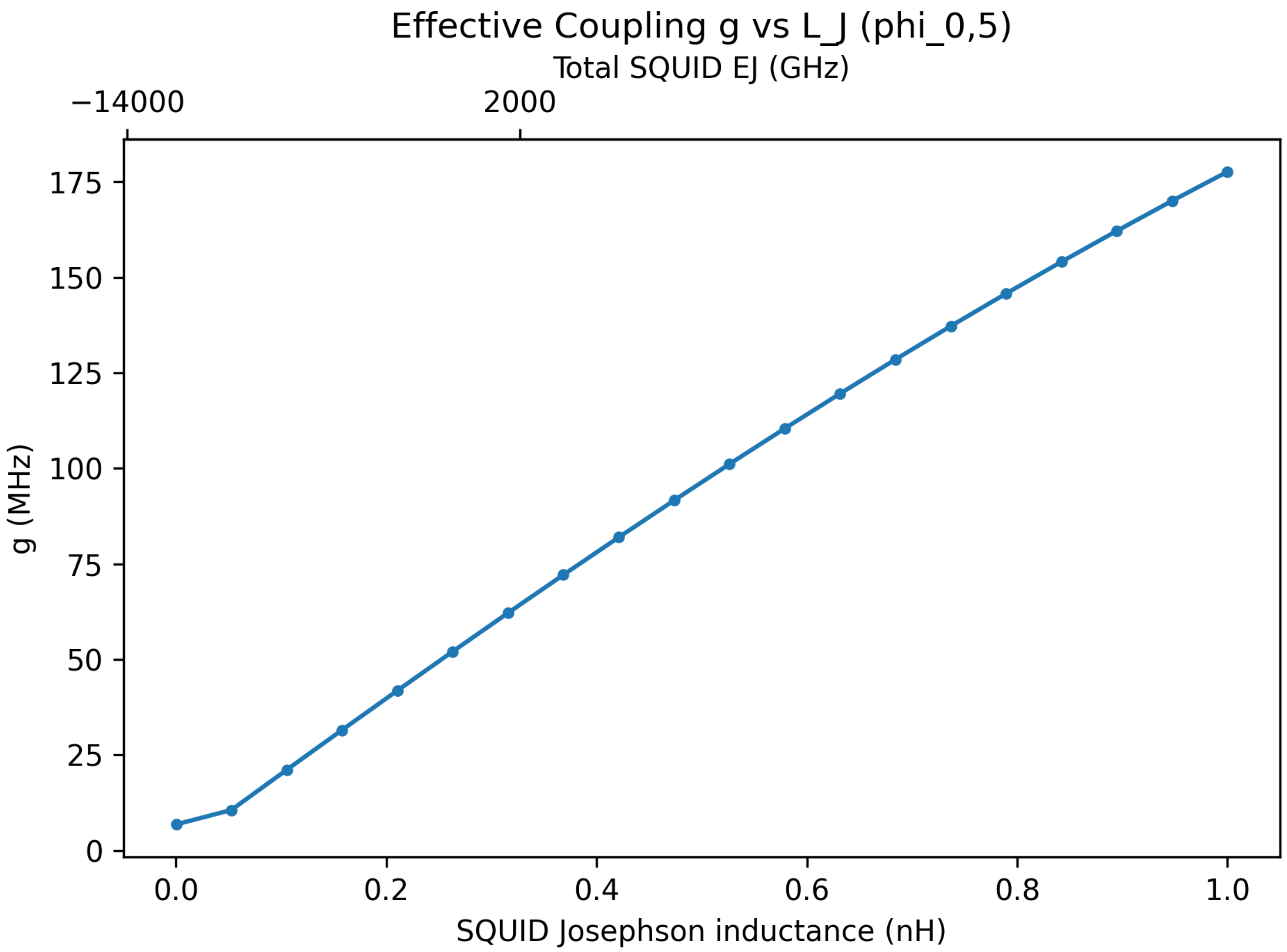
$$g = \frac{E_J}{2} sin\left(\frac{\pi}{\Phi_0}\Phi_b\right)\beta_{sq,1}\ \beta_{sq,2}\tilde{A}_p$$

$$g \sim 75\ MHz$$

Three-body

$$g = \frac{\delta E_J}{2\sqrt{2}} cos\left(\frac{\pi}{\Phi_0}\Phi_b\right)\beta_{sq,1}\beta_{sq,2}\beta_{sq,3}\tilde{A}_p$$

$$g \sim 15\ MHz$$



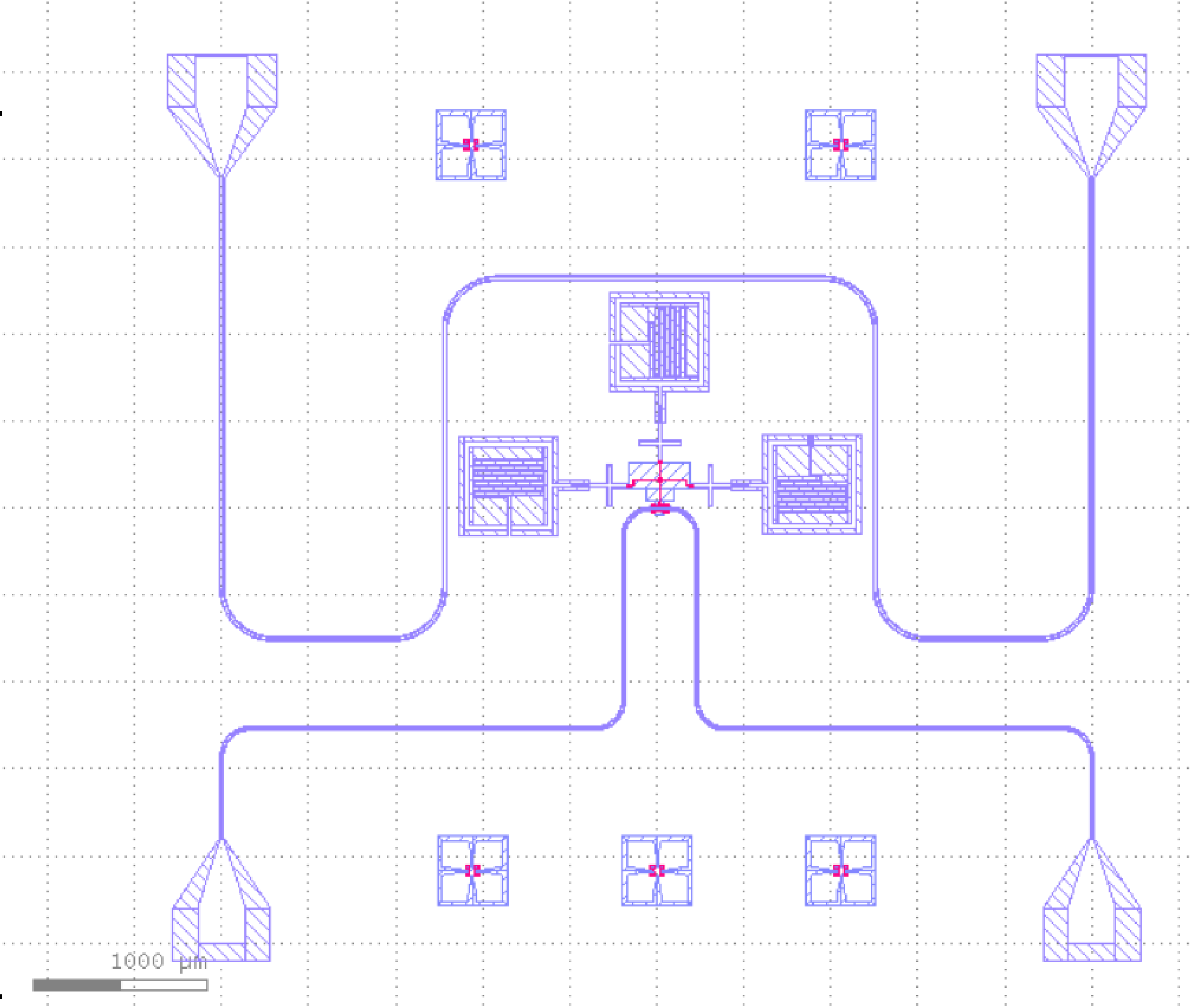
Device design

- 2 lines:
  - Feedline
  - Flux bias

- 3 readout resonators capacitively coupled;

- Metal island to connect the qubits JJs;

- Device fabricated @ Institute for Quantum Computing, Waterloo CA



Use of the device

- Analog block easily implementable applying a flux pulse made of 2 signal frequencies;
- Three body interaction achievable;
- Optimized GHZ state preparation through the three body interaction;