# Resilient multi-mode superconducting qubit design with evolutionary algorithms

**Pablo García-Azorín,** University of the Basque Country (UPV/EHU)

F. Cardenas-López, G. Huber, M. Werninghaus, G. Romero, S. Fillip, and M. Sanz

pablo.garciaa@ehu.eus
mikel.sanz@ehu.eus

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Universidad del País Vasco — Euskal Herriko Unibertsitatea

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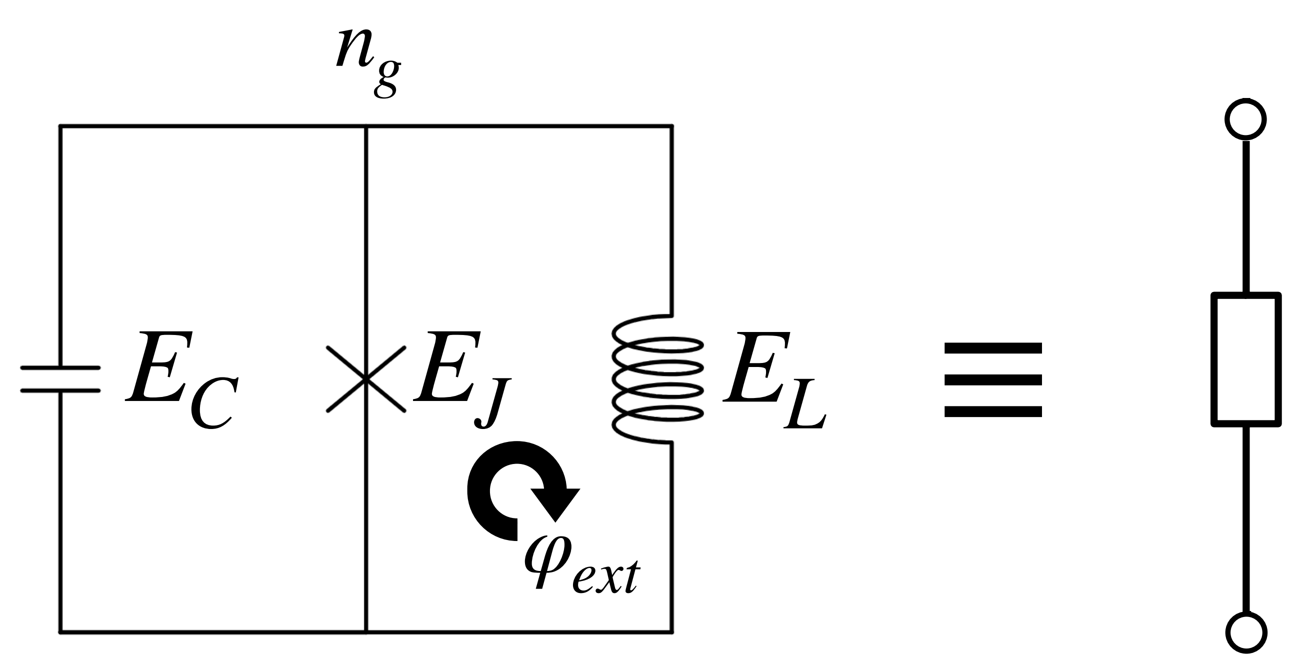
# Flexibility of the platform and motivation

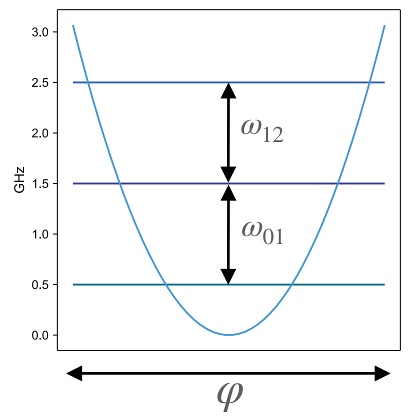
## Single-mode

$$\hat{H}_m = 4E_C\left(\hat{n}_m + n_g\right)^2 + \frac{E_L}{2}\left(\hat{\varphi}_m + \varphi_{ext}\right)^2 - E_J\cos\hat{\varphi}_m$$



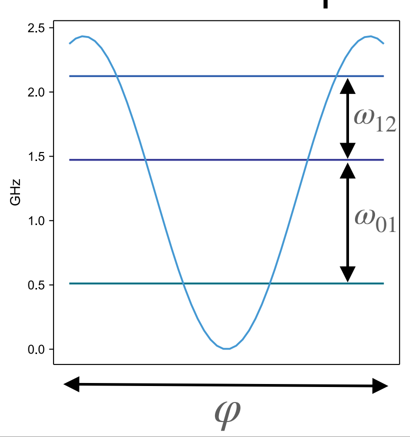

**Harmonic** Oscillator

$E_J = 0$
$E_L \neq 0$
$E_C \neq 0$




"***Transmon***" qubit

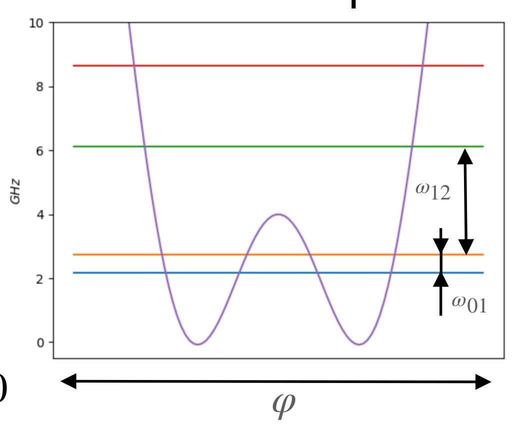
$E_L = 0$
$E_J \gg E_C$




"***Fluxonium***" qubit

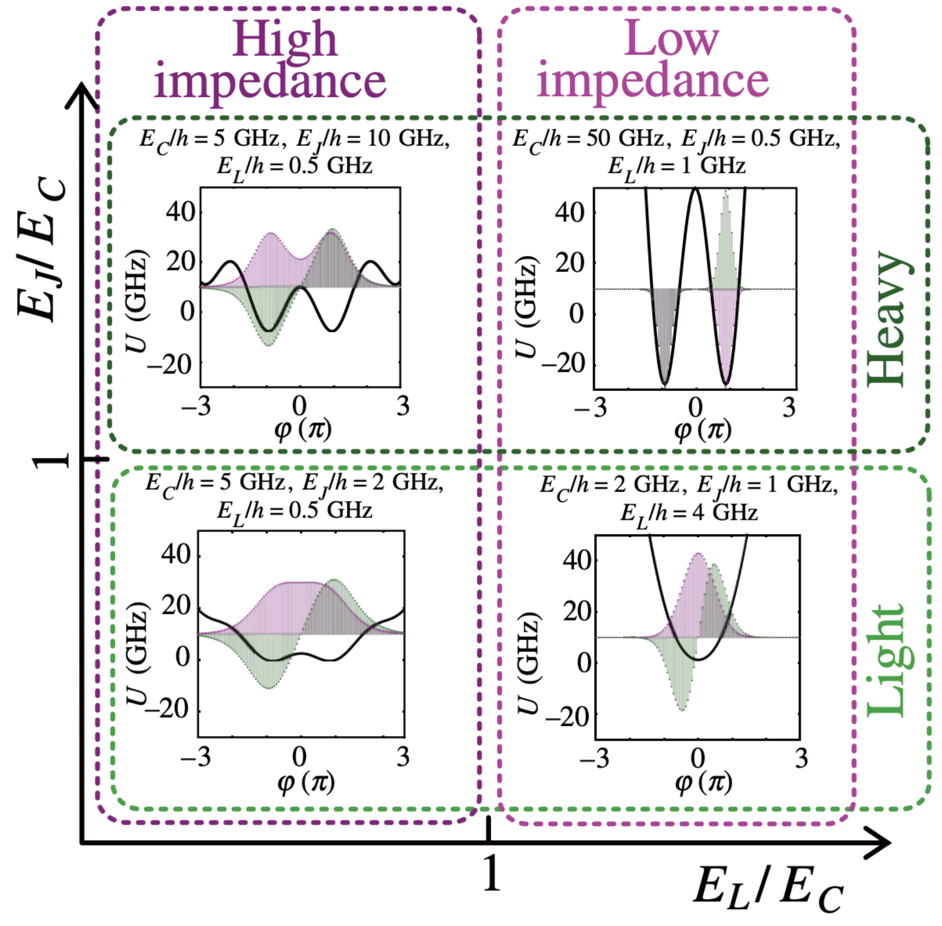
$E_J > E_C$
$E_J > E_L$
$E_L \sim E_C$

$\varphi_{ext} = 0.5\Phi_0$

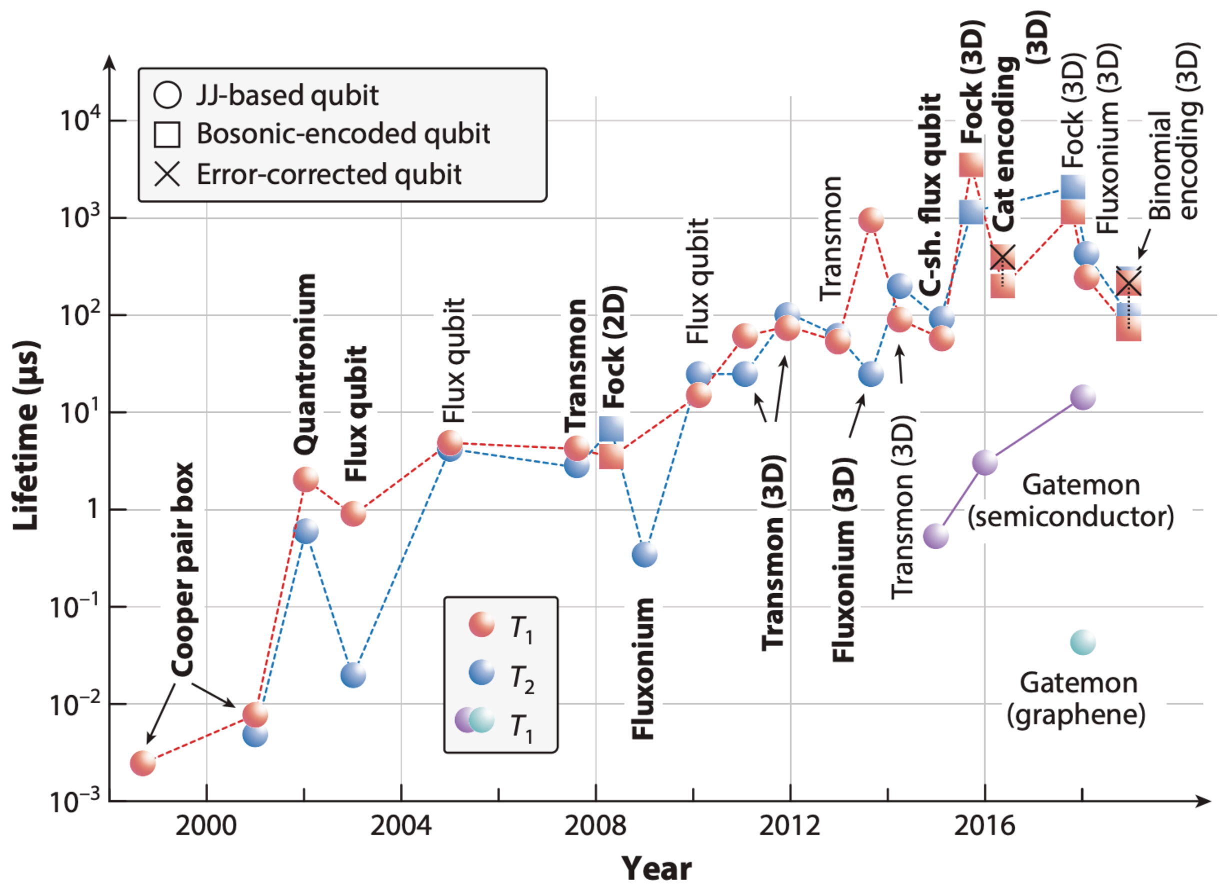



In single-mode devices requirements for good performance **conflict***

*Gyenis, A., Di Paolo, A., Koch, J., Blais, A., Houck, A. A., & Schuster, D. I. (2021). Moving beyond the transmon: Noise-protected superconducting quantum circuits. *PRX Quantum*, 2(3), 030101.



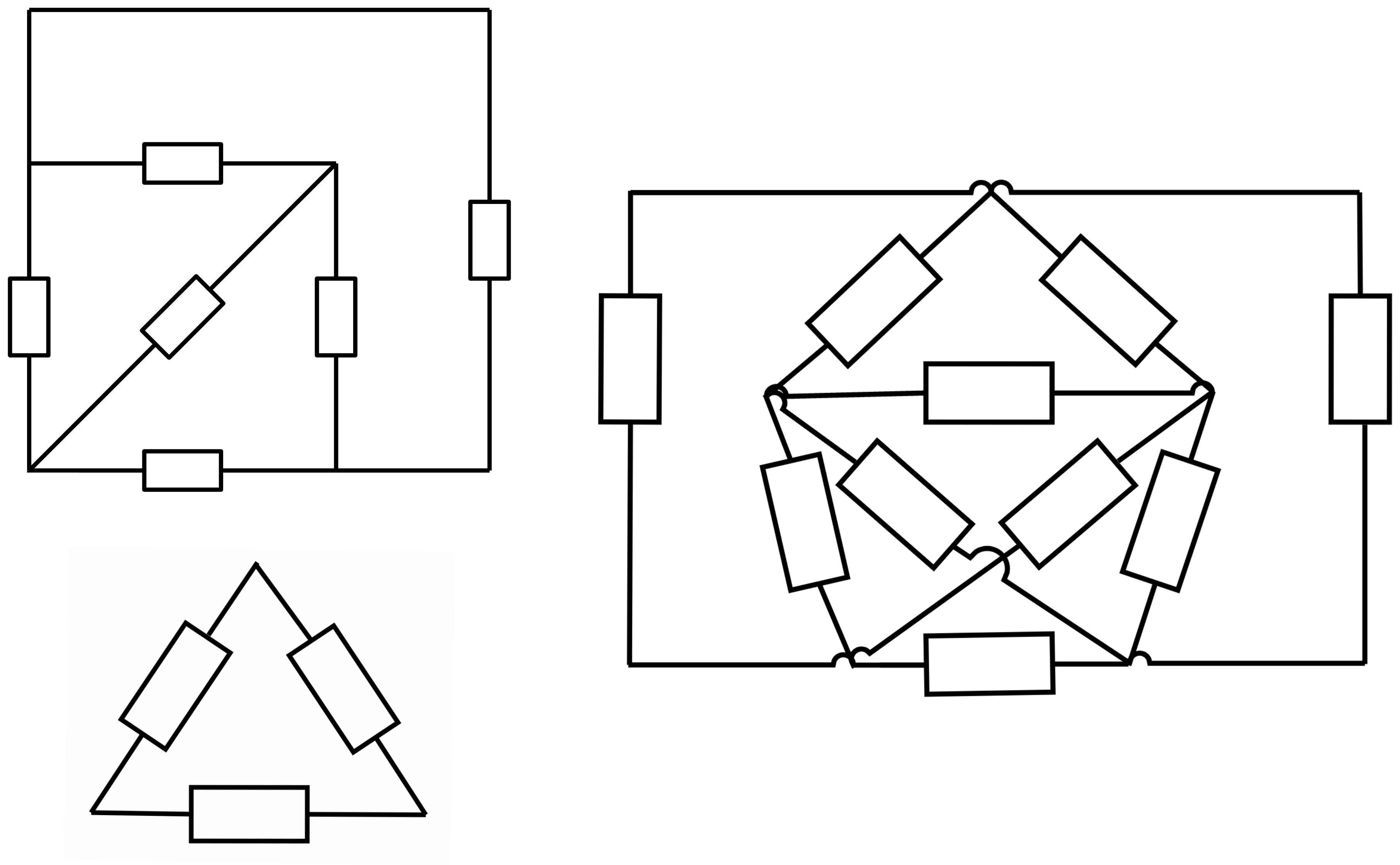

*Peruzzo, M., et. al. (2021). Geometric superinductance qubits: Controlling phase delocalization across a single Josephson junction. PRX Quantum, 2(4), 040341.

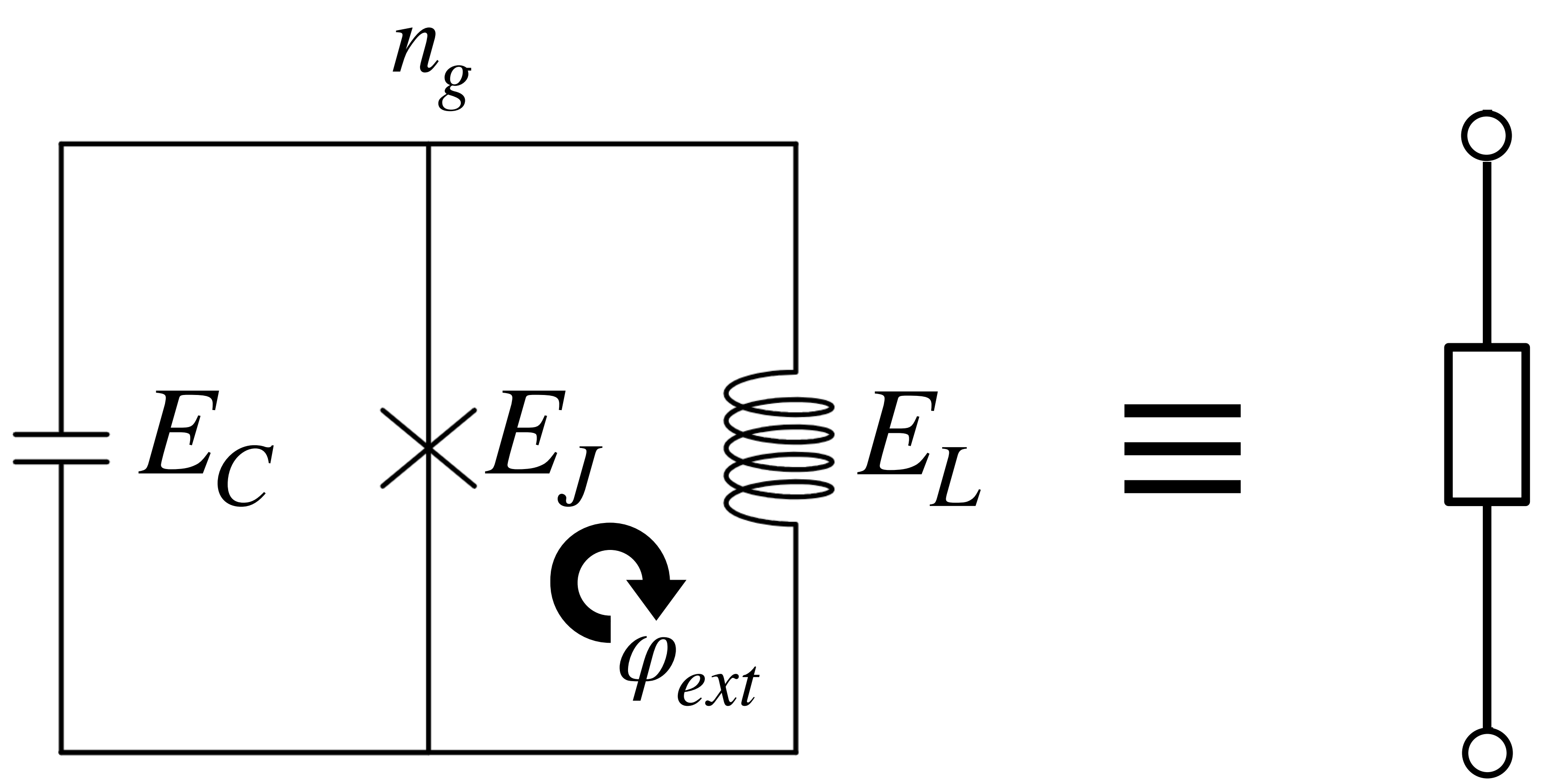



*M. Kjaergaard et al., Superconducting Qubits: Current State of Play Annual Review of Condensed Matter Physics 2020 11:1, 369-395

# Flexibility of the platform and motivation

What if we include **several elements** encoding **multiple modes**?






**Multi-mode**

$$\hat{H} = \sum_m \hat{H}_m\left(\hat{n}_m, \hat{\varphi}_m\right) + \sum_{nm} \hat{H}_{nm}\left(\hat{n}_n, \hat{n}_m, \hat{\varphi}_n, \hat{\varphi}_m\right)$$

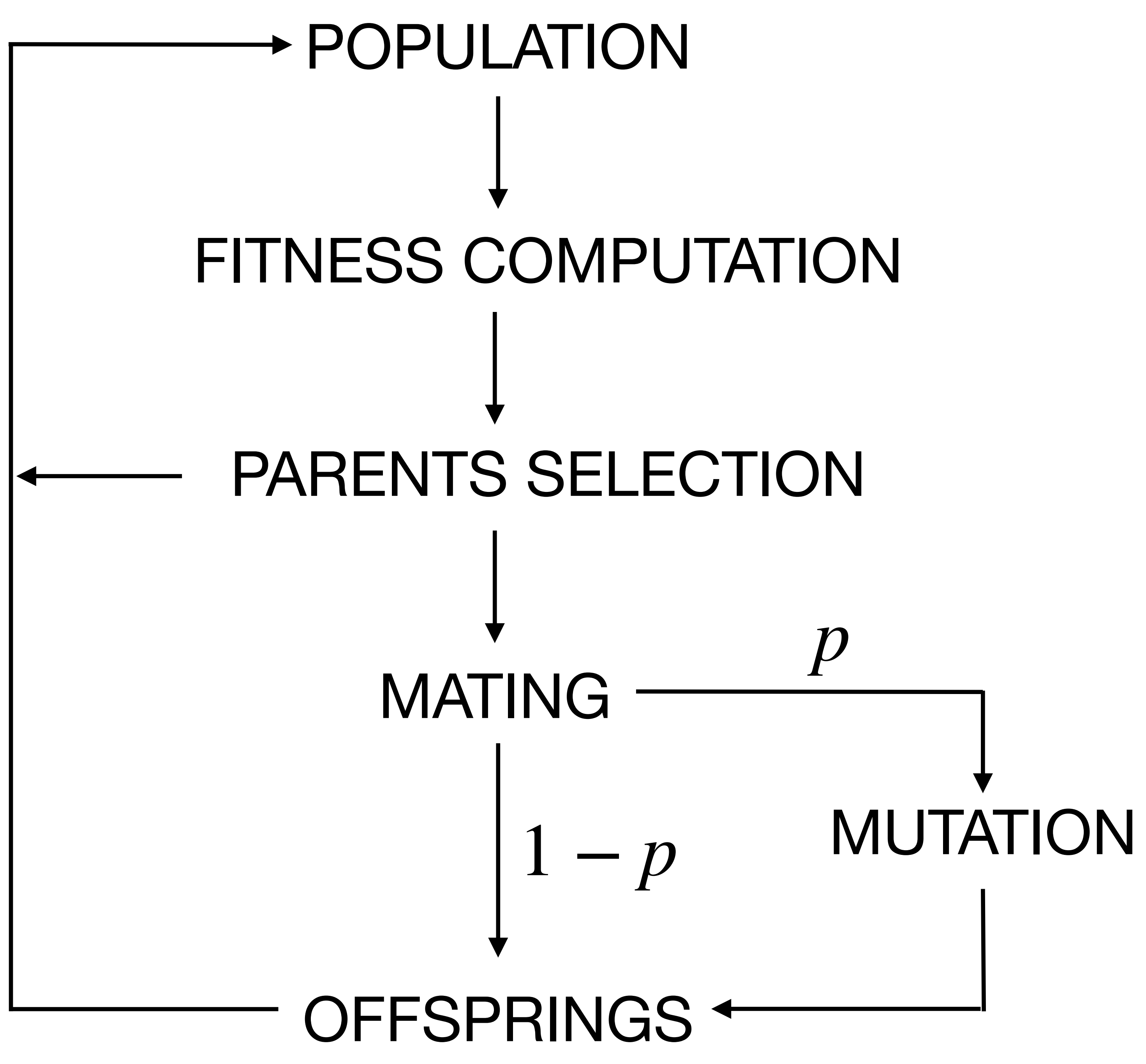
**Problems**

- The space of possible configurations grows (**large parameter space**)
- Computational **cost**

# Flexibility of the platform and motivation

How do we find configurations with **desired characteristics**?

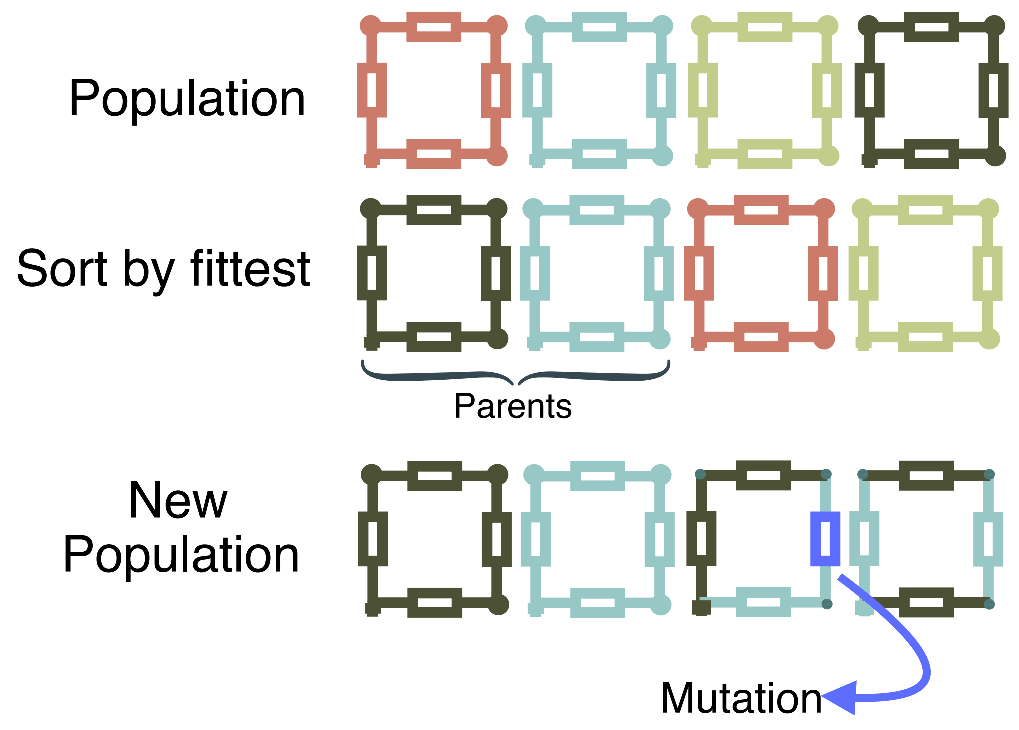
## Evolutionary algorithms (Genetic Algorithms)

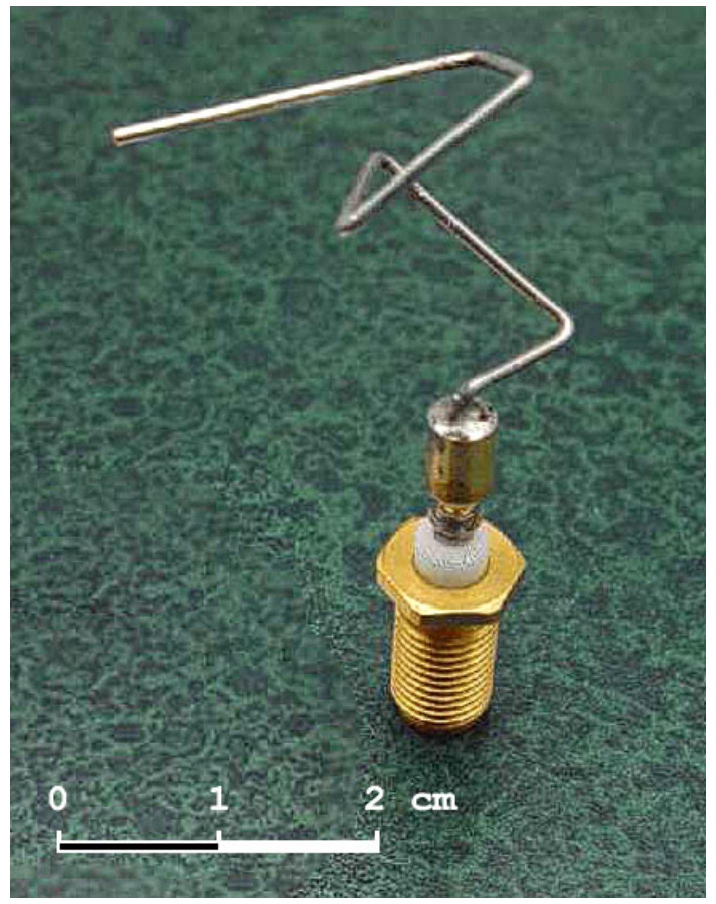



**Population based** algorithms, great for exploring **large parameter spaces** and finding fast **local minima**

Based on **recombination**

Capable of finding **resilient** solutions

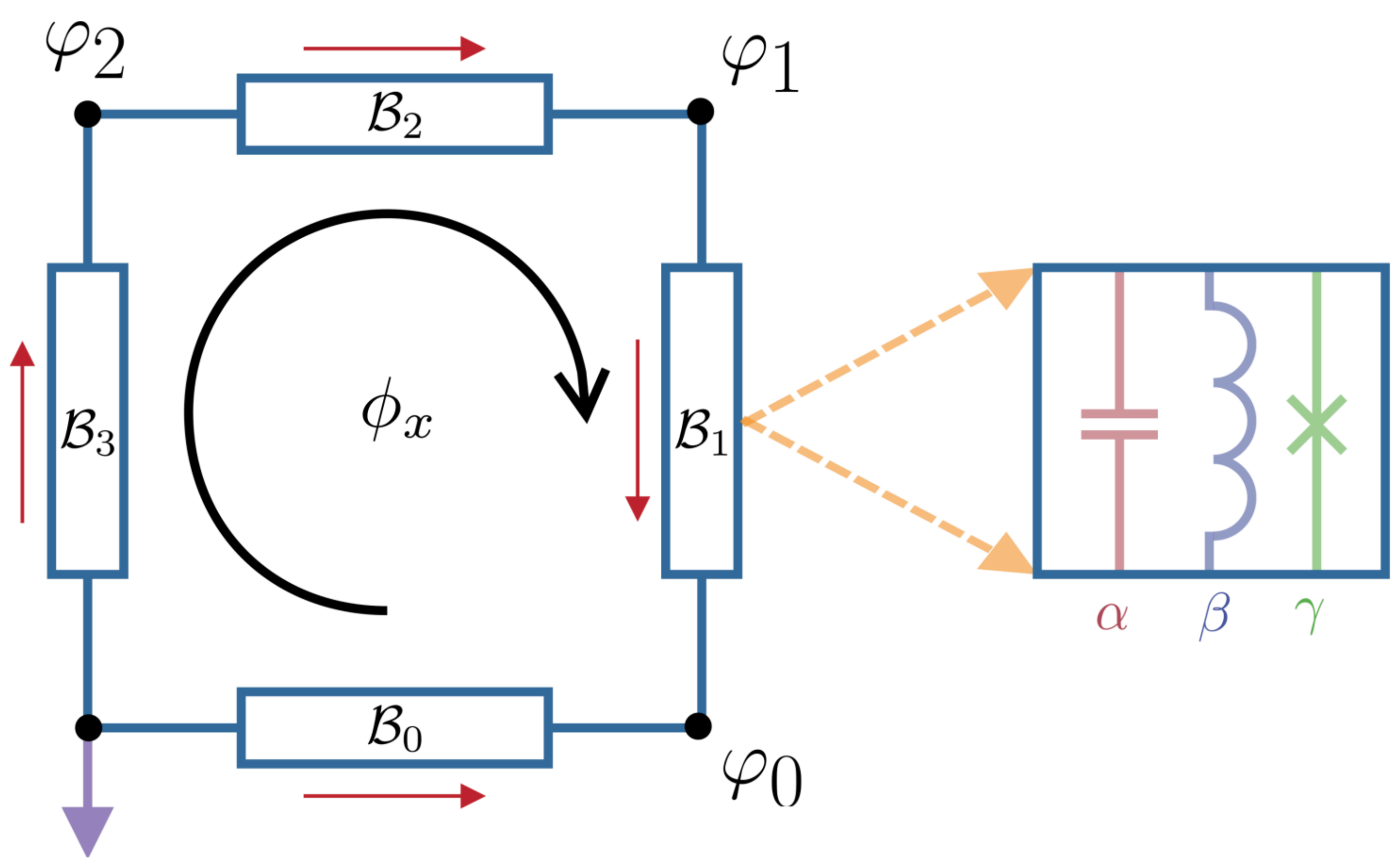


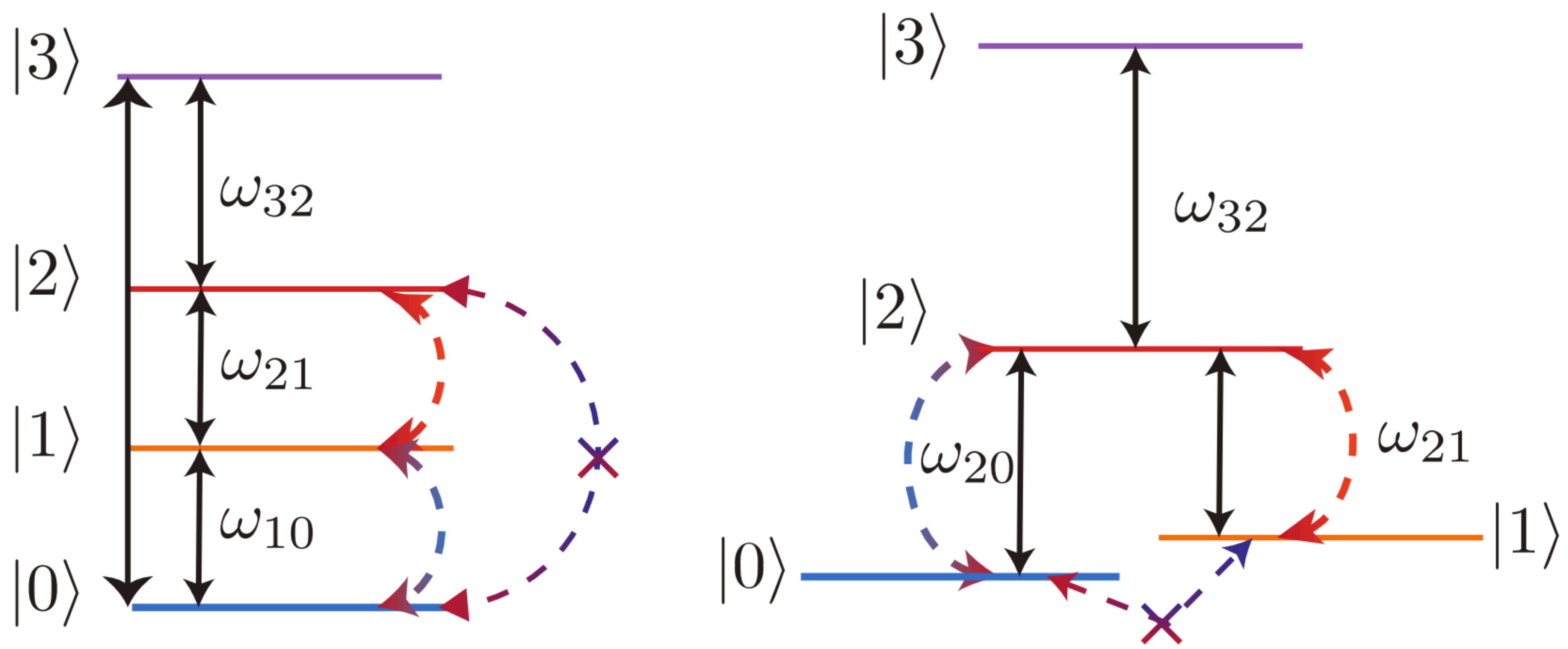

2006 NASA ST5 spacecraft antenna

# Superconducting circuit design via evolutionary algorithms

*Cárdenas-López, F. A., Retamal, J. C., Chen, X., Romero, G., & Sanz, M. (2023). Resilient superconducting-element design with genetic algorithms. arXiv preprint arXiv:2302.01837




- **Fixed** circuit structure and **automatized** Hamiltonian construction
- **Multi-loop** configurations




- Design of **lambda** and **ladder** systems as a proof of concept

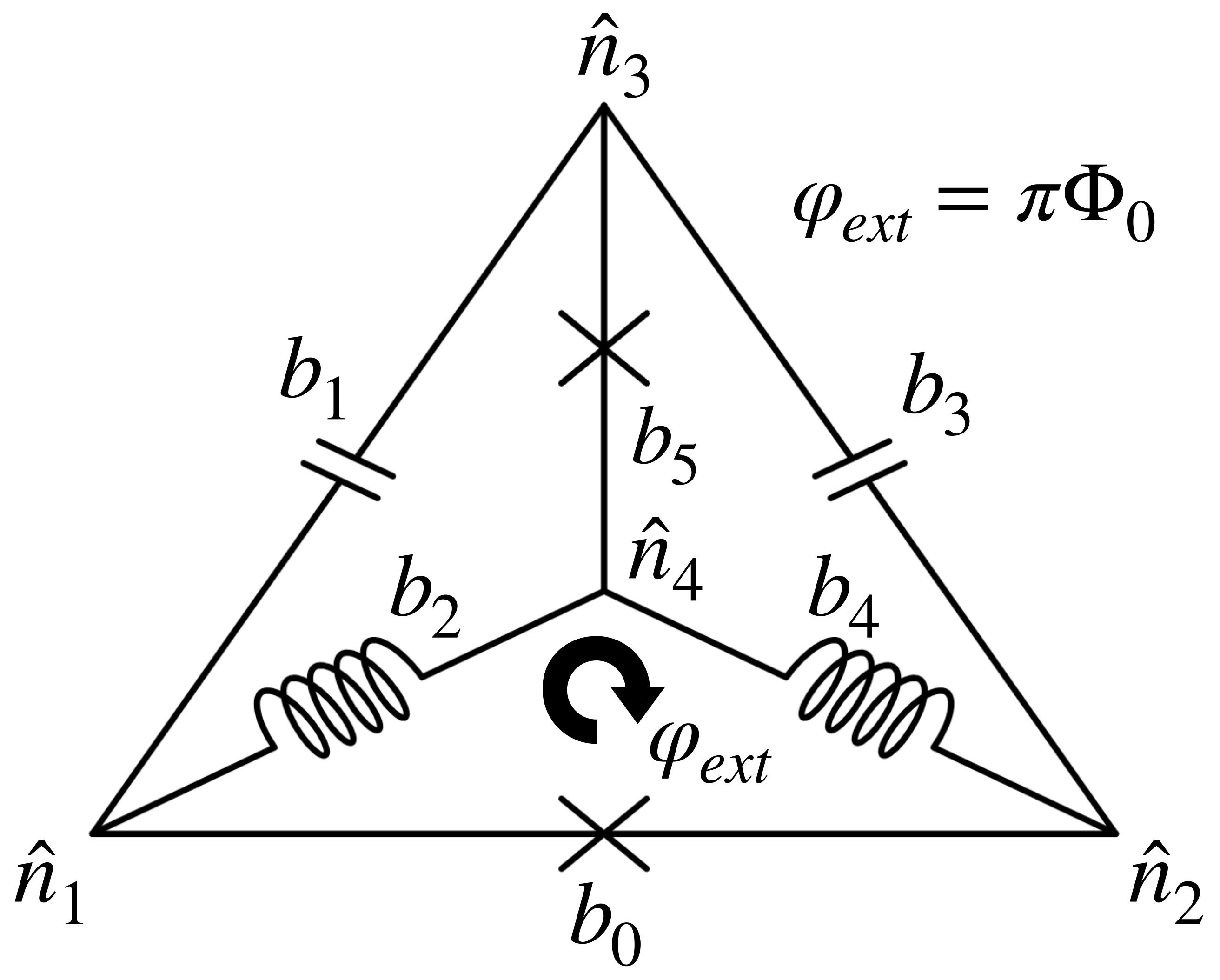
# Test-bed problem: Building a good performance qubit out of a multi-mode device

What are those **characteristics** that makes a superconducting circuit a good qubit?

## DiVincenzo's Criteria

1. A scalable physical system with **well-characterized** qubit → Large anharmonicity or restricted transition rules
2. The ability to initialize the state of the qubits to a simple fiducial state → Qubit frequency above thermal frequency $K_B T/h \sim 0.4\, GHz$
3. Long **relevant decoherence times** → Noise protection
4. A "universal" set of **quantum gates** → Addressability through external drives
5. A qubit-specific **measurement capability** → Addressability through external drives

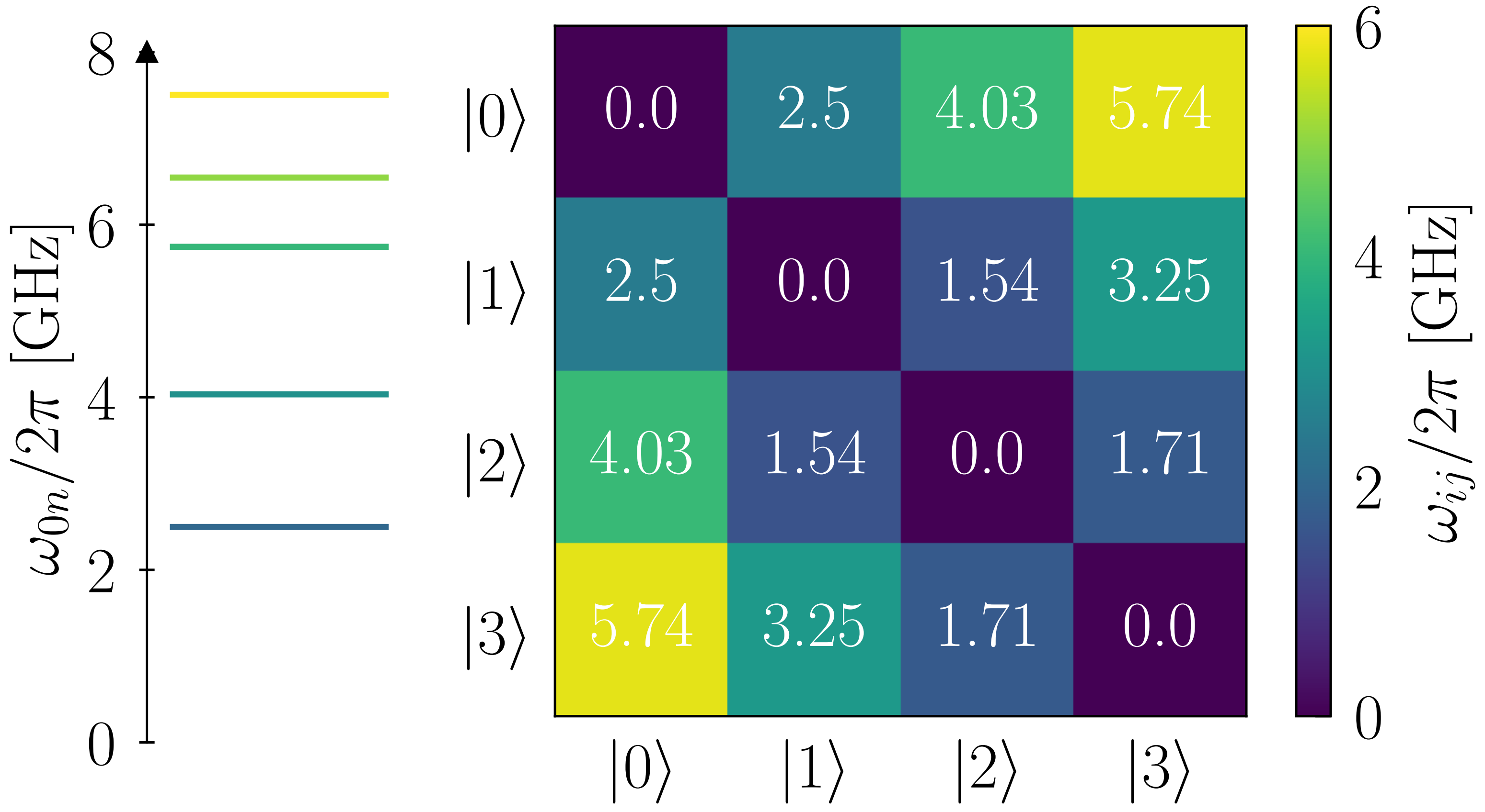
# Qubit proposal



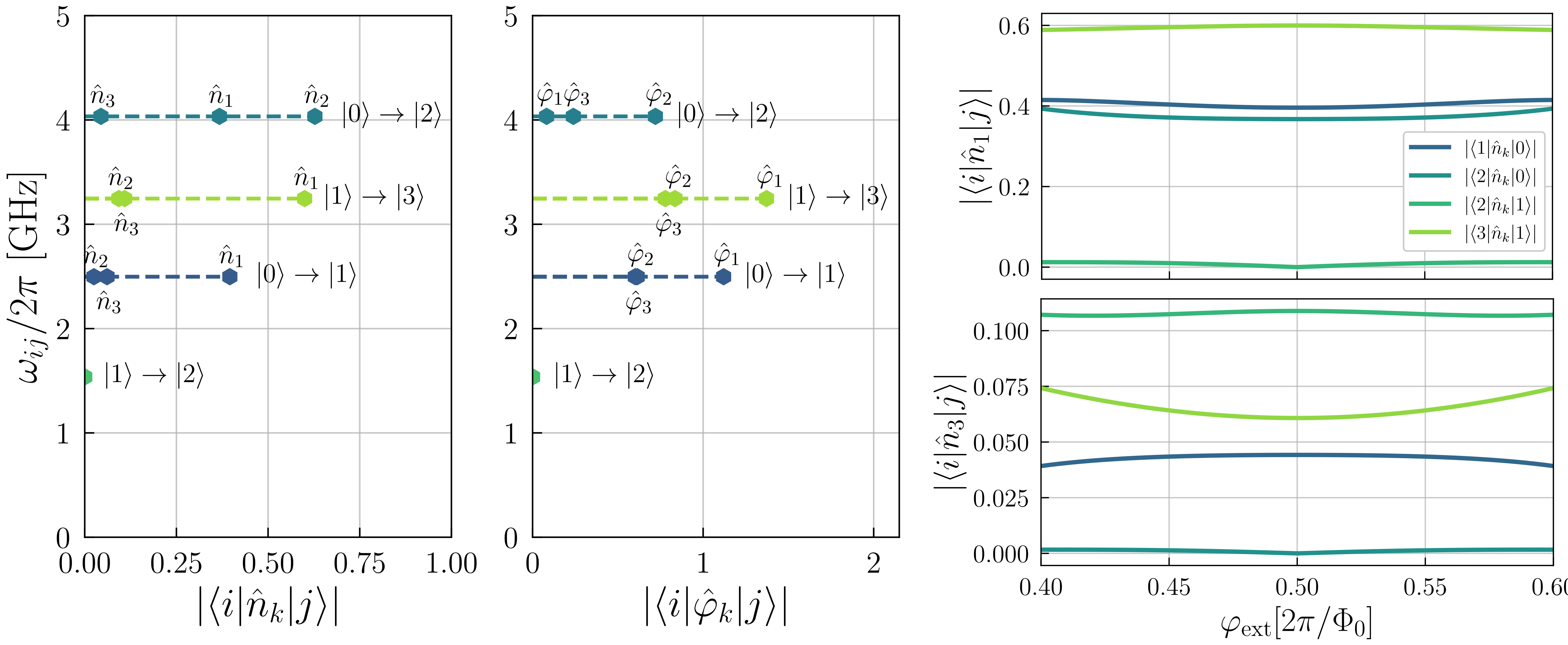

| **Branch** | $b_0$ | $b_1$ | $b_2$ | $b_3$ | $b_4$ | $b_5$ |
|---|---|---|---|---|---|---|
| $C_{branch}[fF]$ | 11.6 | 12.5 | 15.3 | 12.3 | 10.3 | 11 |
| $Ej_{branch}[GHz]$ | 2.5 | - | - | - | - | 6.85 |
| $L_{branch}[nH]$ | - | - | 35 | - | 33 | - |

- Large **anharmonicity** with $\omega_q$ well above thermal frequency
- Restricted **transitions rules**

## Energy spectrum

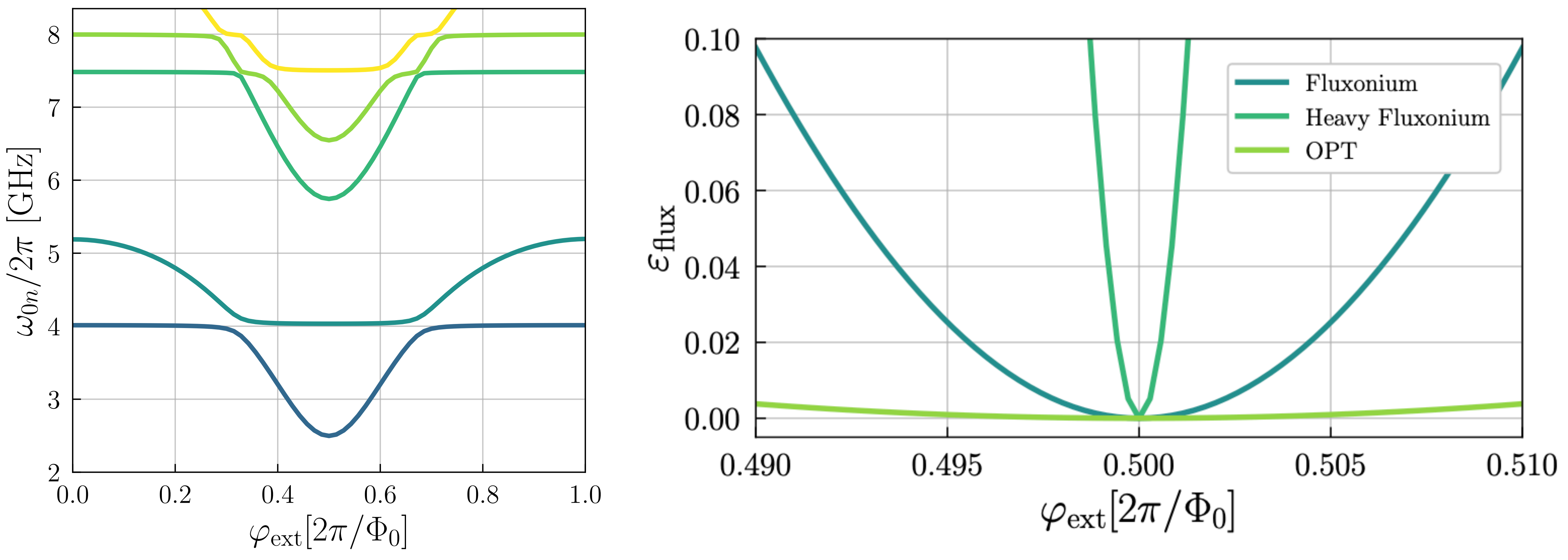



## Matrix elements



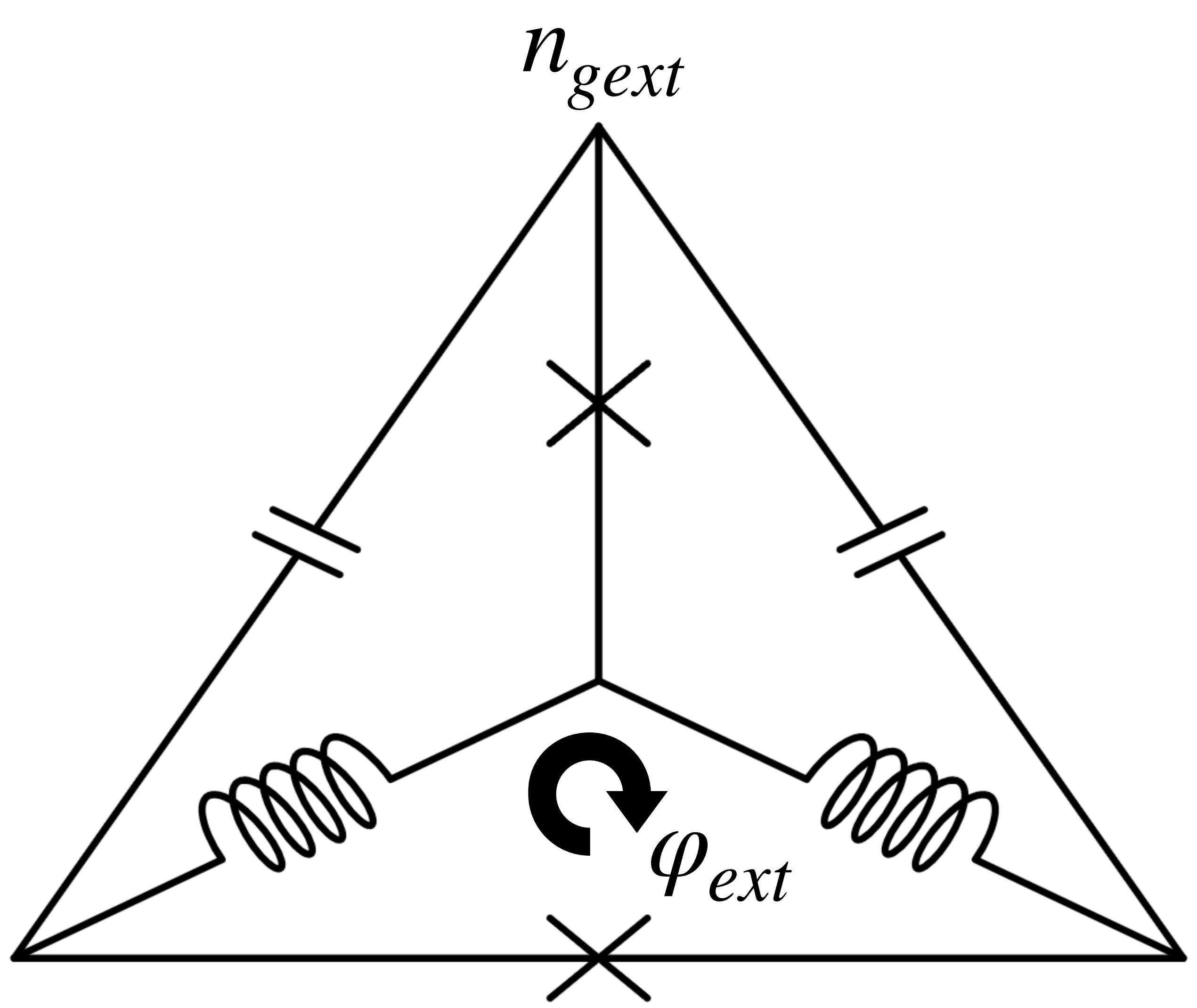
# Noise resilience

## External Flux dispersion

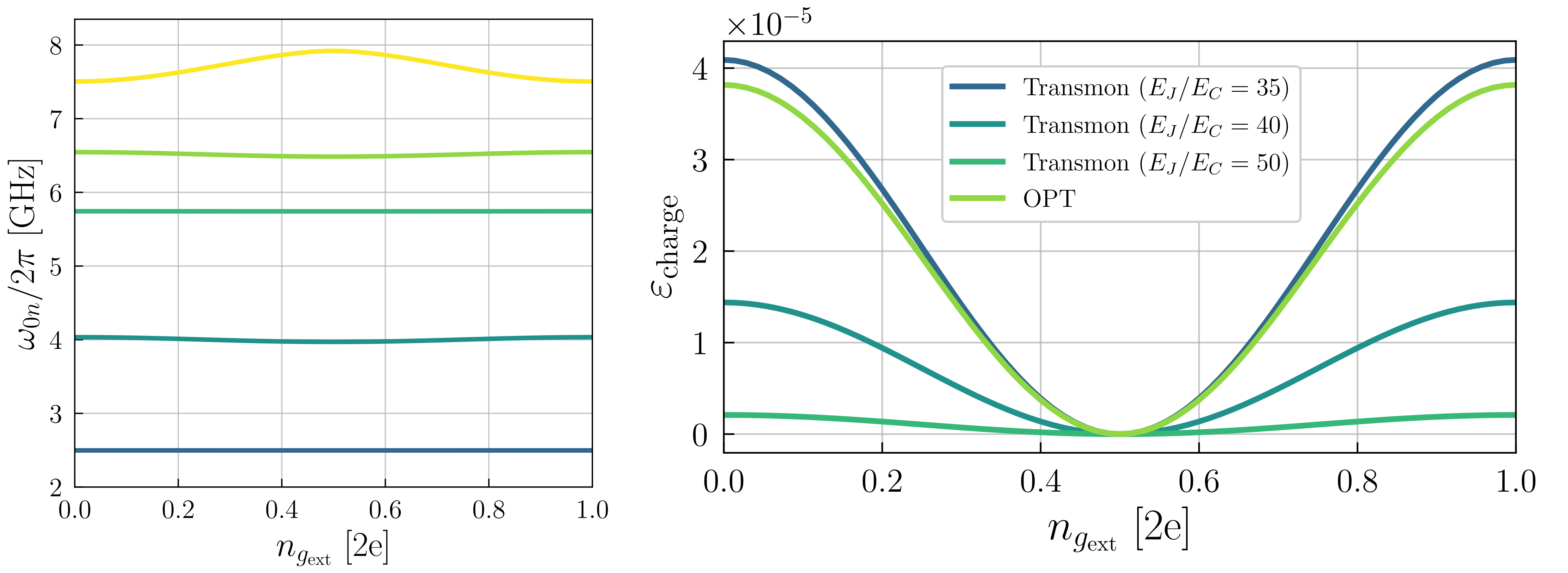



- **Two** flux-like and **one** charge-like modes
- **Strongly coupled** modes
- Susceptibility both to **external charge bias** and **external flux bias**

Fluxonium $\{E_J = 4, E_C = 1, E_L = 1\}$ GHz
Heavy Fluxonium $\{E_J = 3.395, E_C = 0.479, E_L = 0.132\}$ GHz




## External charge dispersion



# Coherence time estimation

## Depolarization errors

- **Depolarisation channels considered:** Dielectric losses, resistive losses and qp tunneling
- All possible transitions into or out from the **computational space** considered
- Estimation for a device with **multiple branches**

$$\Gamma_1^{\lambda} = \sum_{b_n \in B} \sum_{ij} \frac{1}{\hbar^2} \left| \langle i | \hat{O}_{\lambda}^{b_n} | j \rangle \right|^2 S_{\lambda}^{b_n}(\omega_{ij})$$

## Dephasing errors

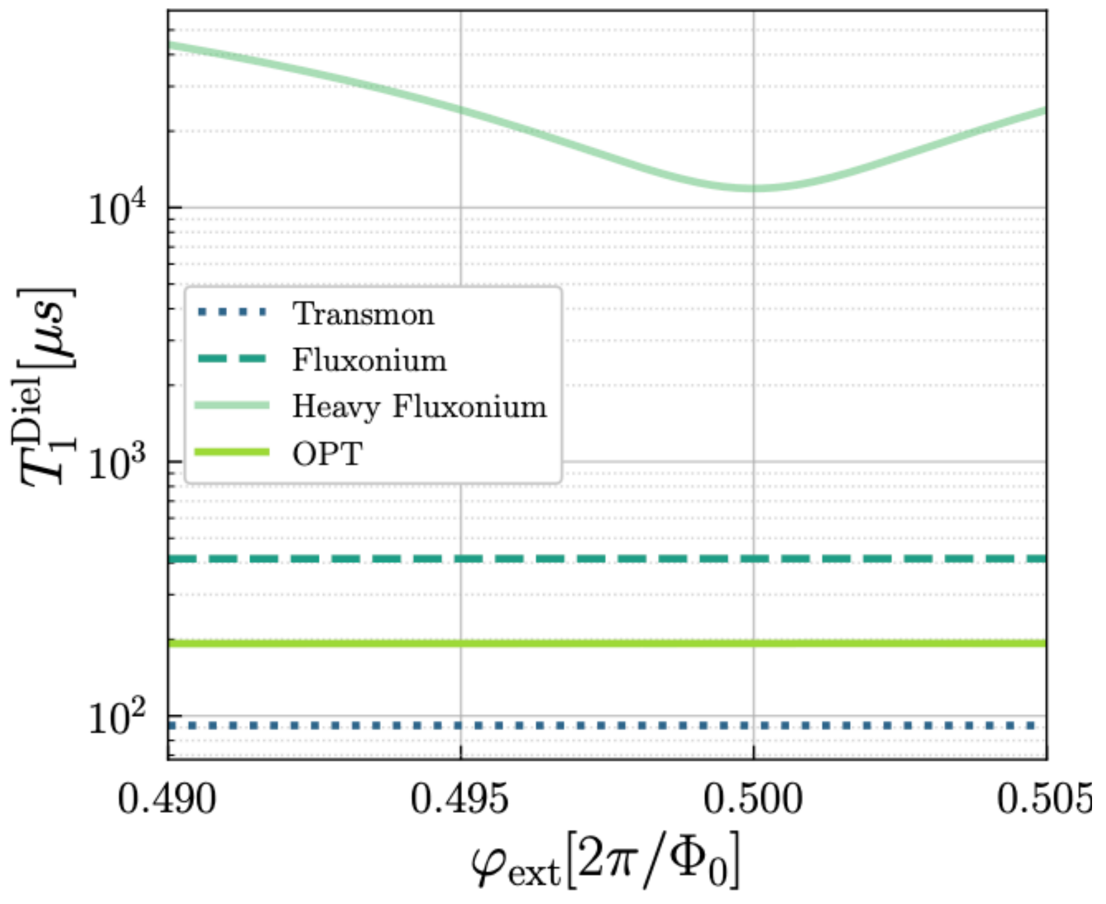
- **Dephasing channels considered:** 1/f noise sources
- Two **external effects** inducing dephasing: charge and magnetic flux
- Estimation for a device with **multiple branches**

$$\Gamma_{1/f}^{\lambda} = \sqrt{2} A_{\lambda} \left| \frac{\partial \omega_{01}}{\partial \lambda} \right| \sqrt{|\ln \omega_{ir} t|}$$

# Coherence time estimation

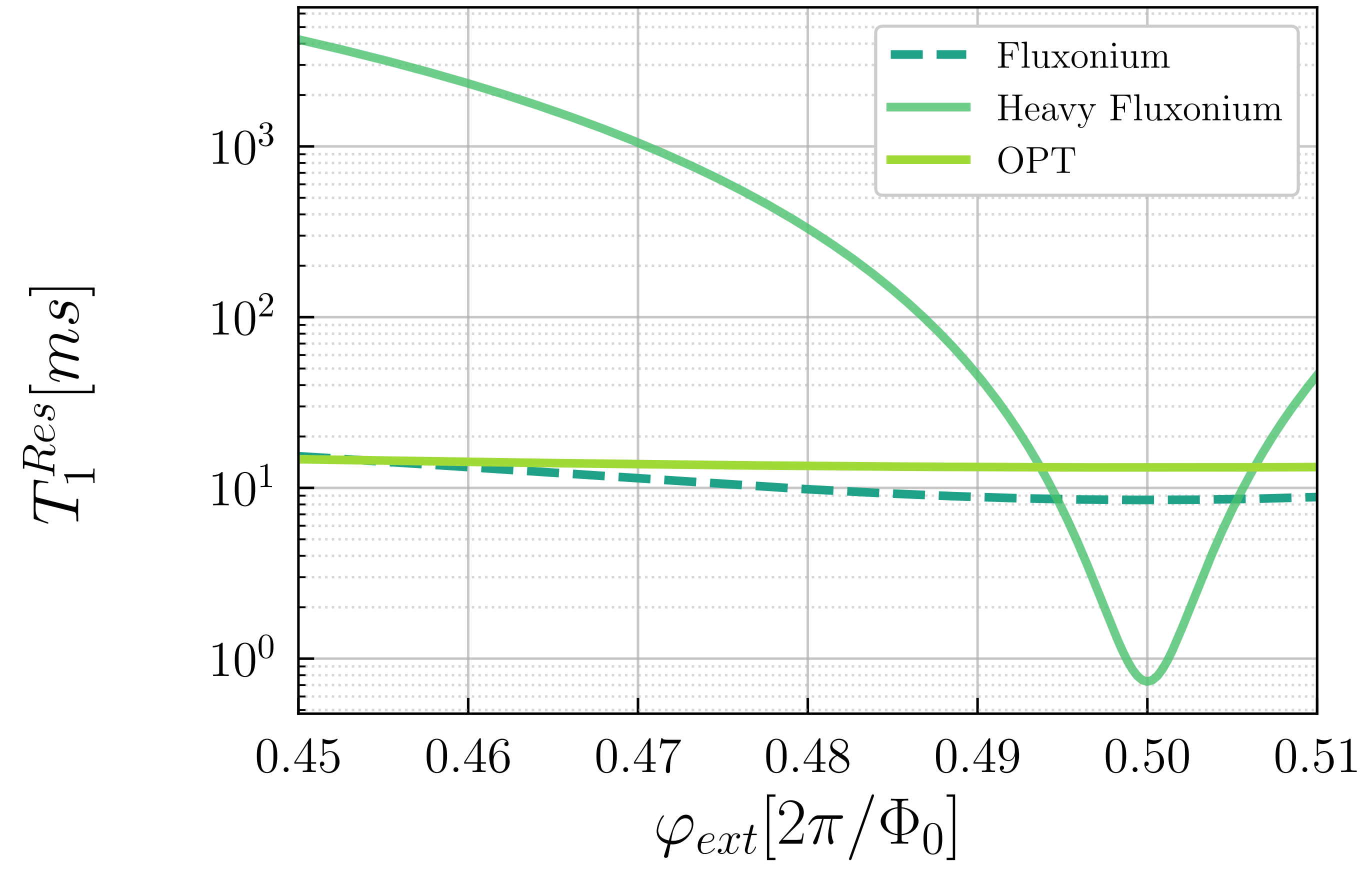
## $T_1$

### Dielectric losses in the capacitors




$Q_{Cap} \sim 3{\cdot}10^6$

### Resistive losses in the inductors

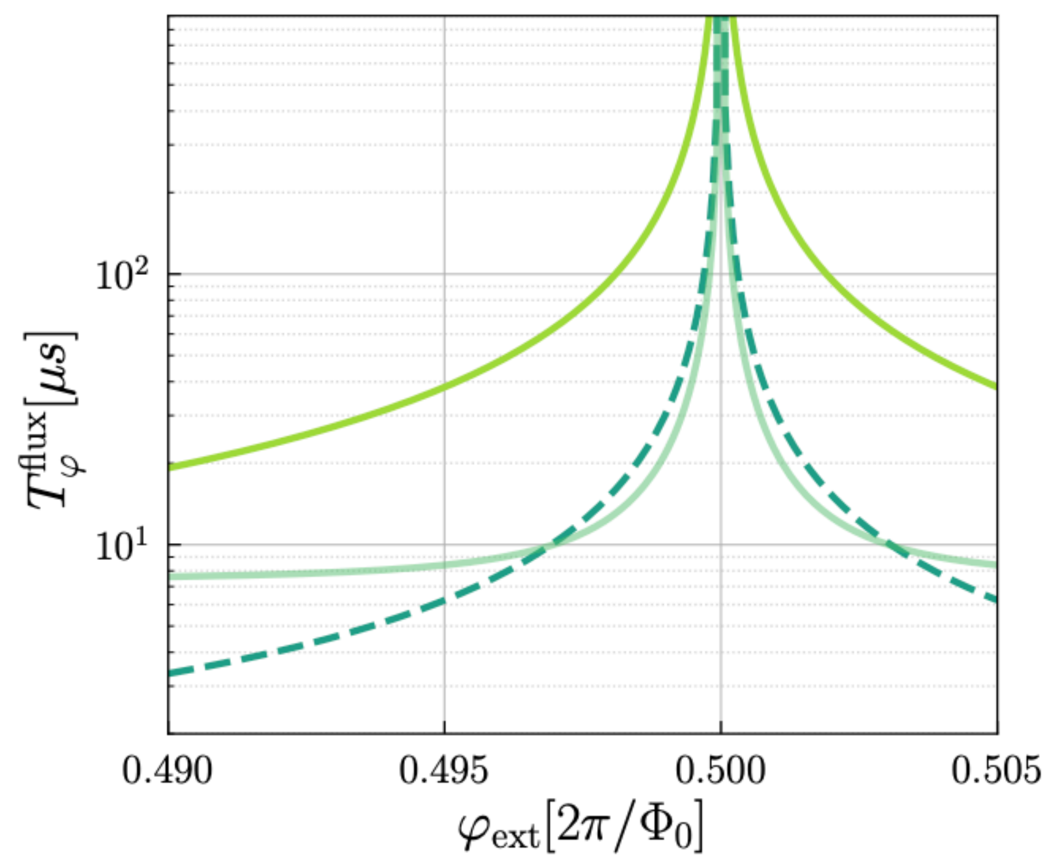



$Q_{Ind} \sim 5{\cdot}10^8$

## $T_\varphi$

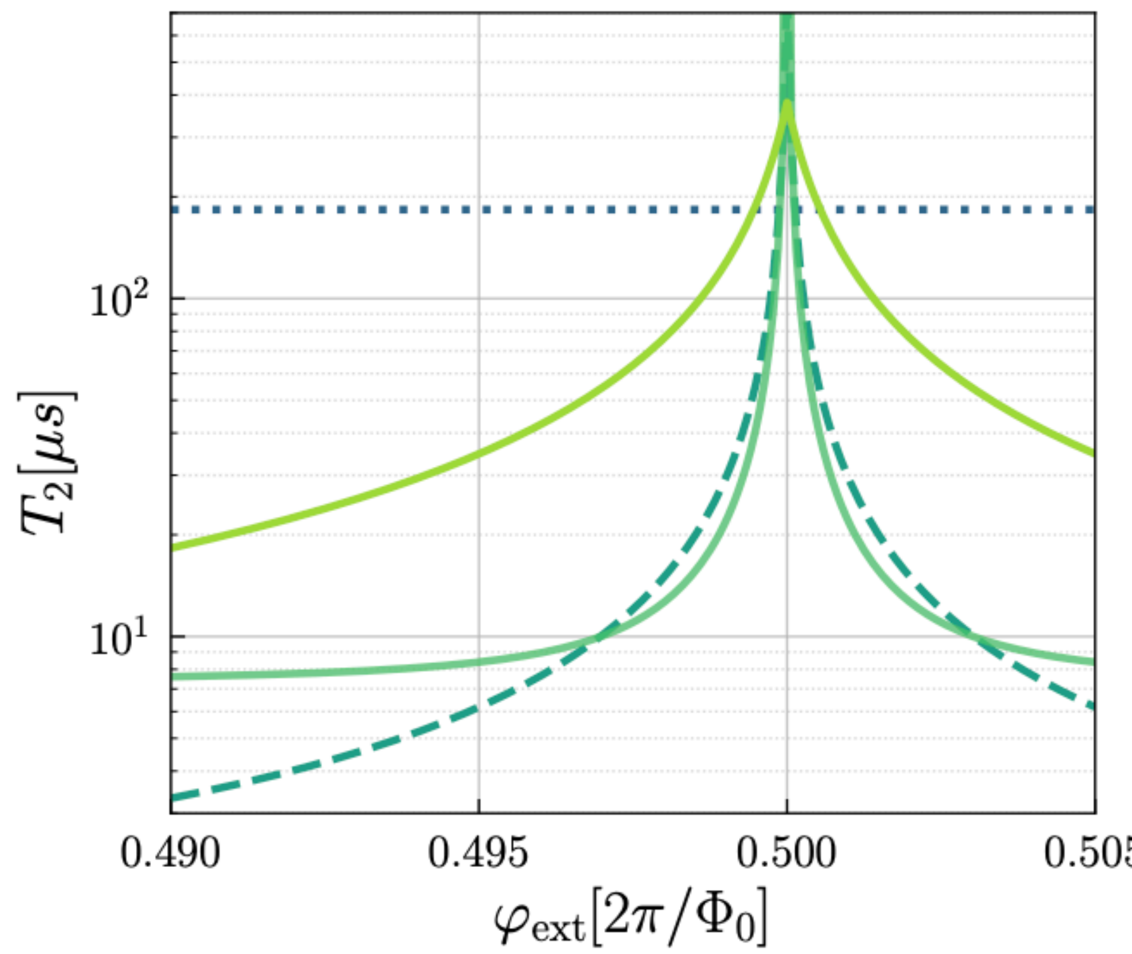
### 1/f flux noise

$A_{\varphi_{ext}} \sim 10^{-6}\Phi_0$




## $T_2$

$$= \left(\frac{1}{2T_1} + \frac{1}{T_\varphi}\right)^{-1}$$



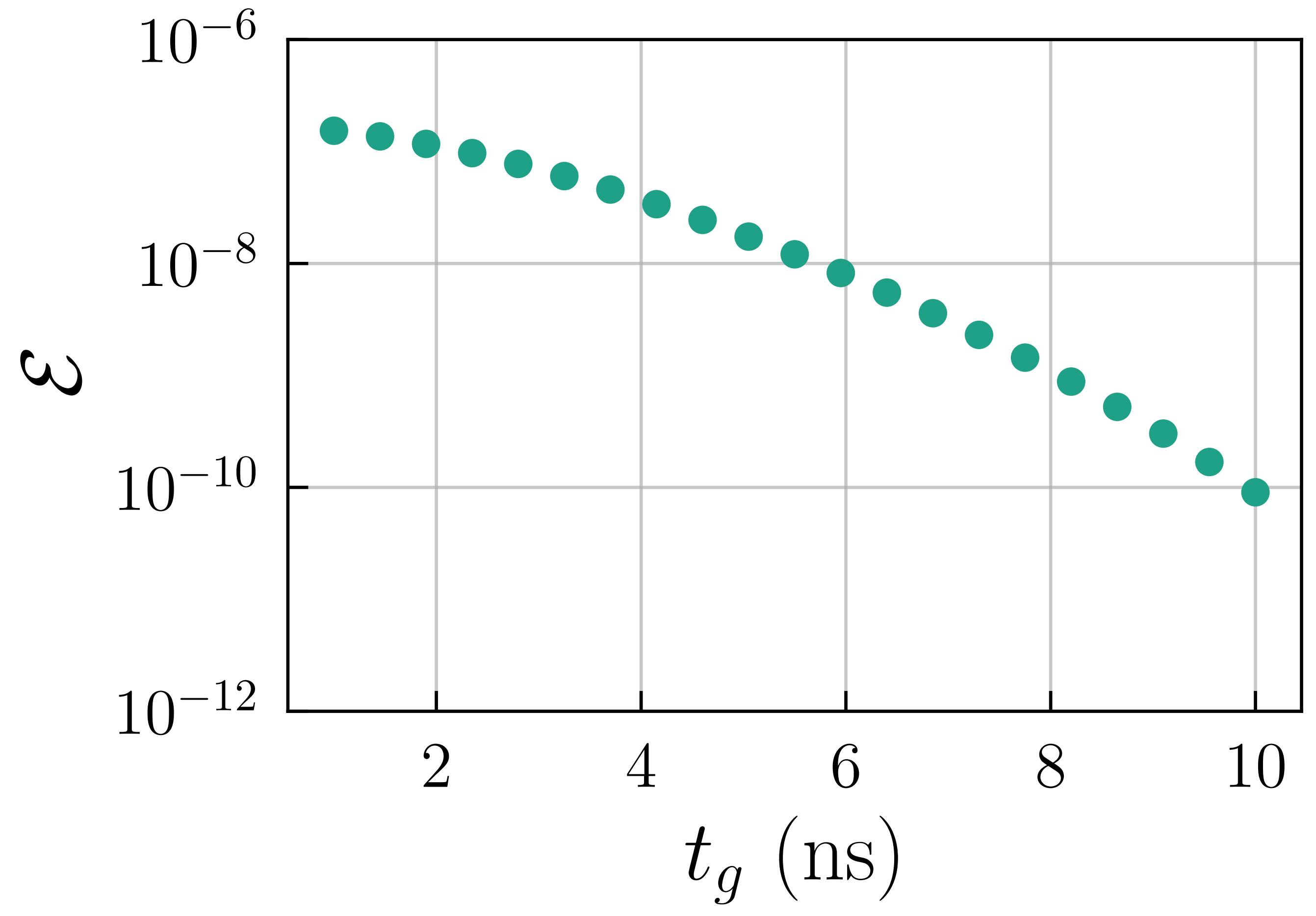
# Gate simulations

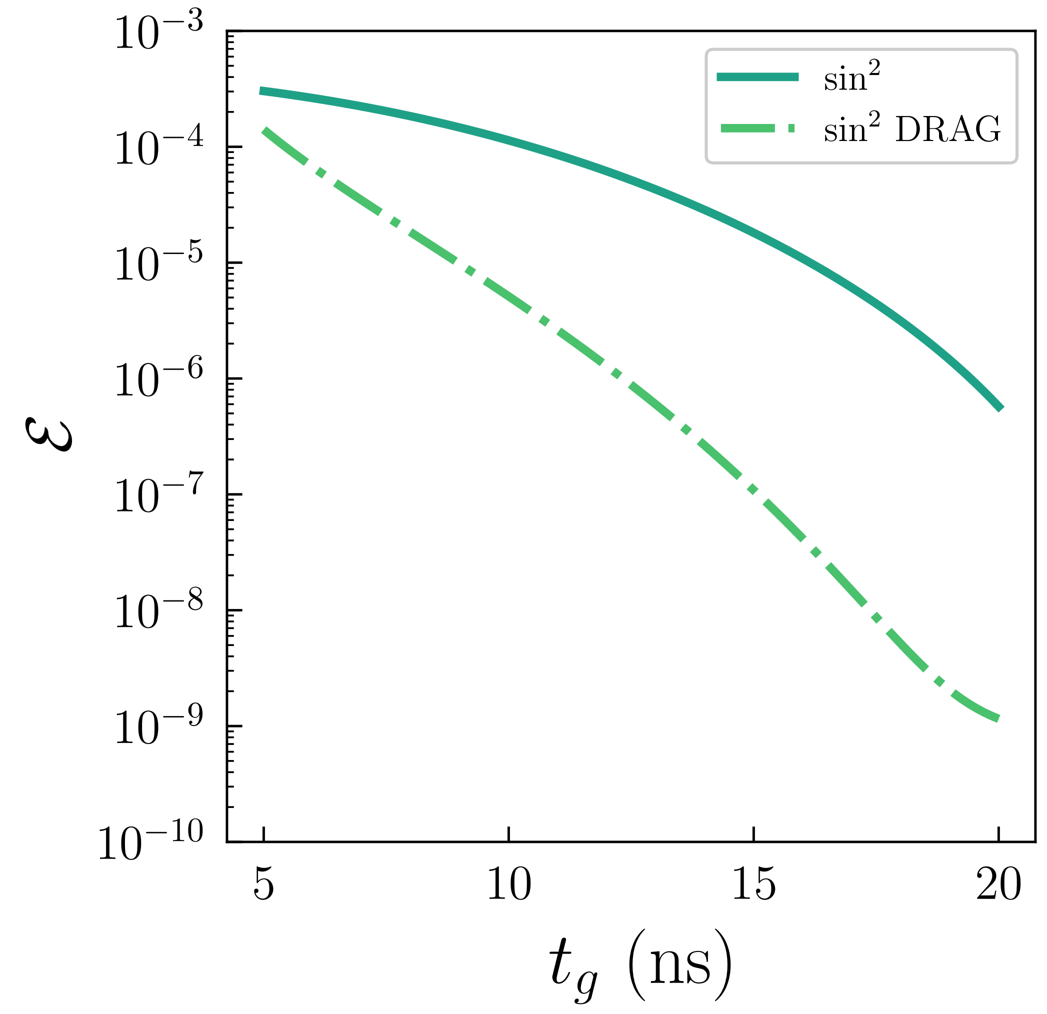
- Increased **anharmonicity** and **qubit frequency** allows faster gates without breaking the RWA ($\omega_q = 2.5\,\mathrm{GHz}$ and $\alpha_{13} \sim 750\,\mathrm{MHz}$)

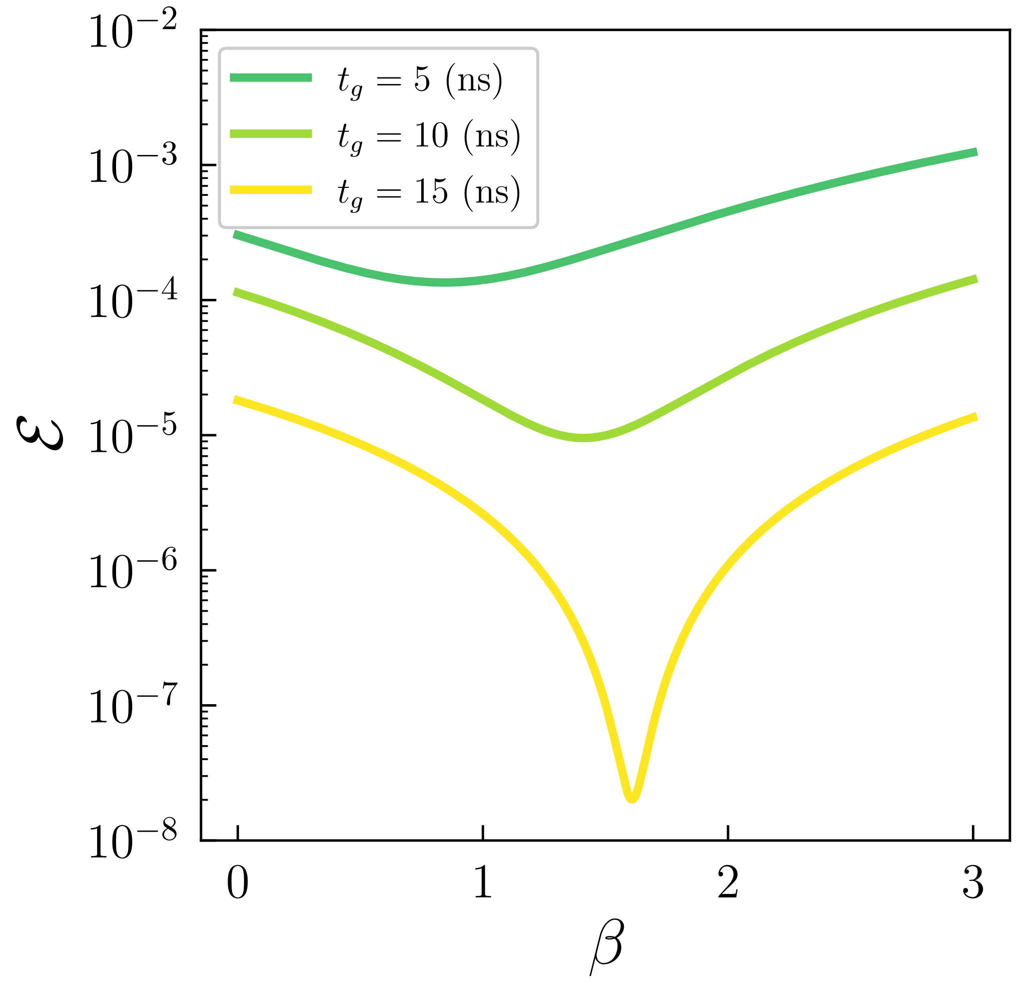
- Suppressed usual **leakage** channels $\langle 2 \,|\, \hat{n}_1 \,|\, 1 \rangle = 0$

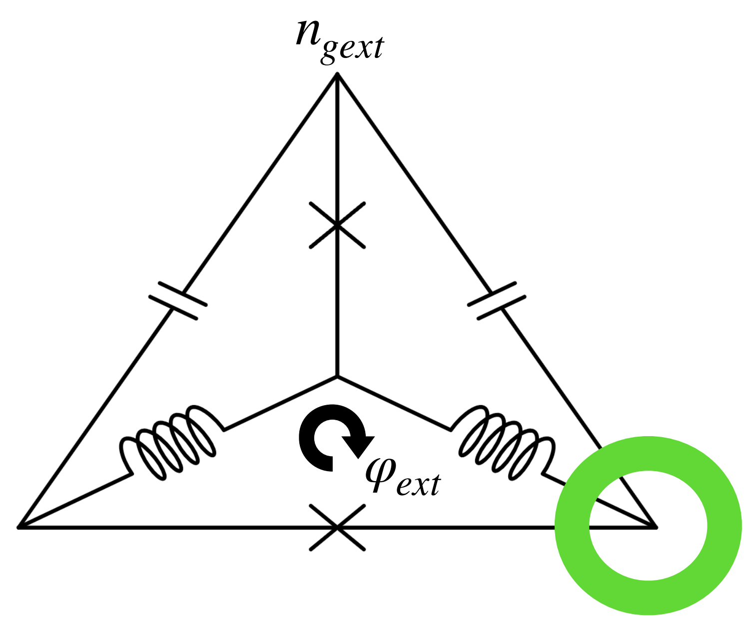
- **DRAG** protocol to suppress dephasing and critical leakage channels

- Detuning, amplitude and DRAG **parameter optimization** for lower error rates

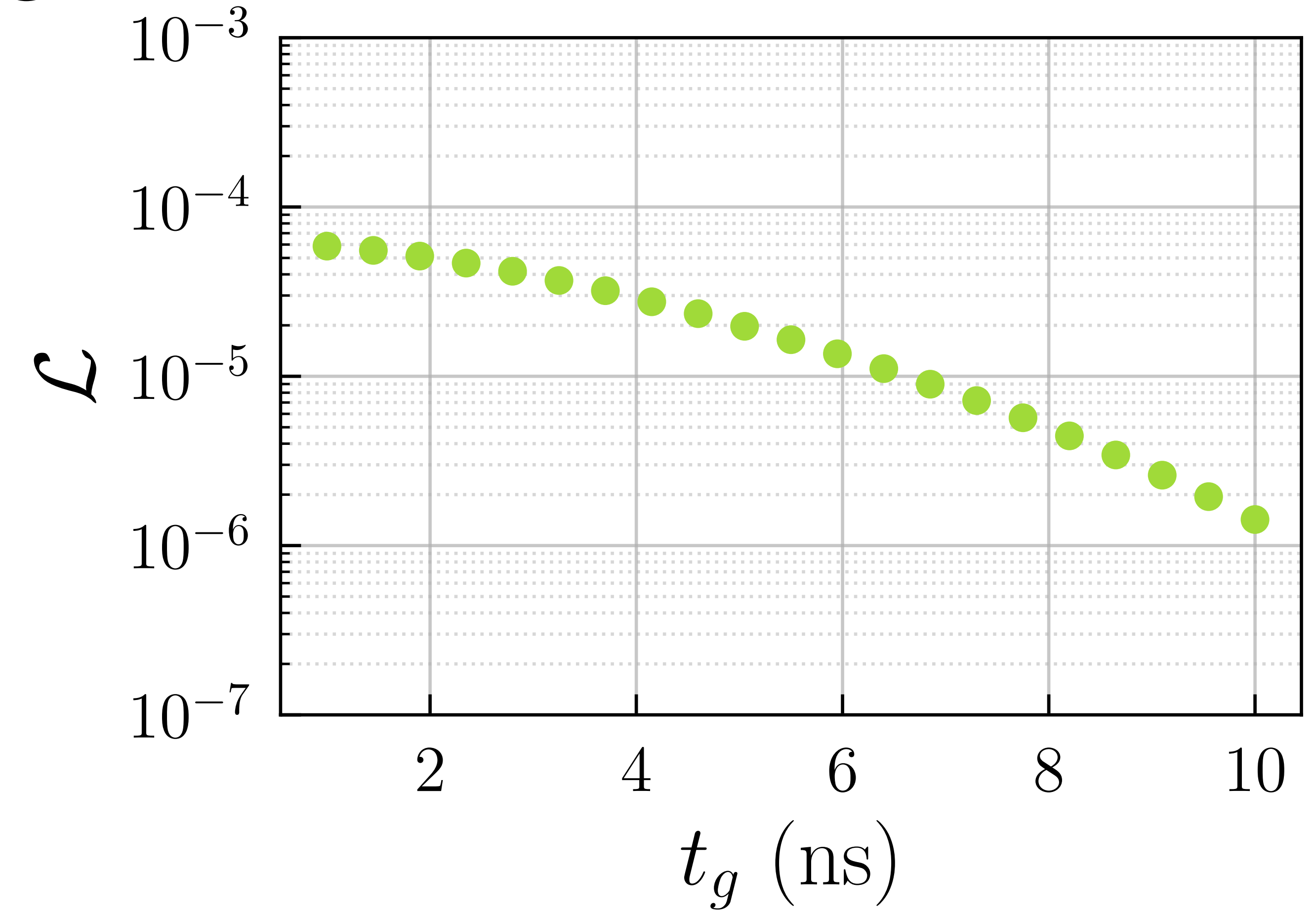


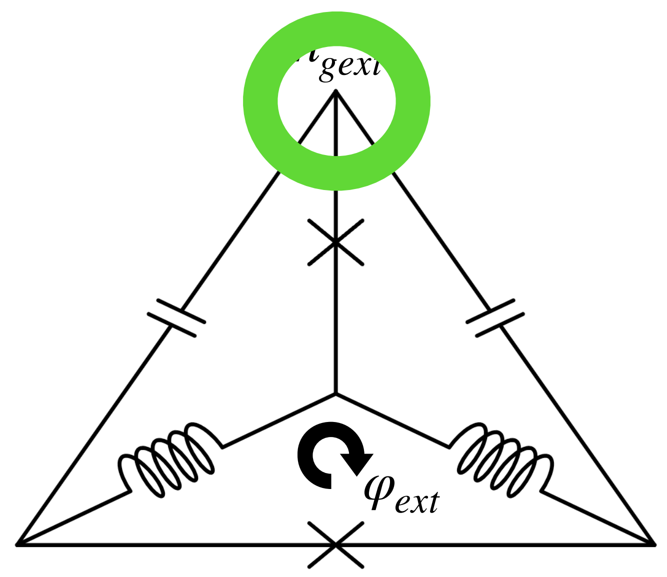

Driving of node $N_1$ of the system



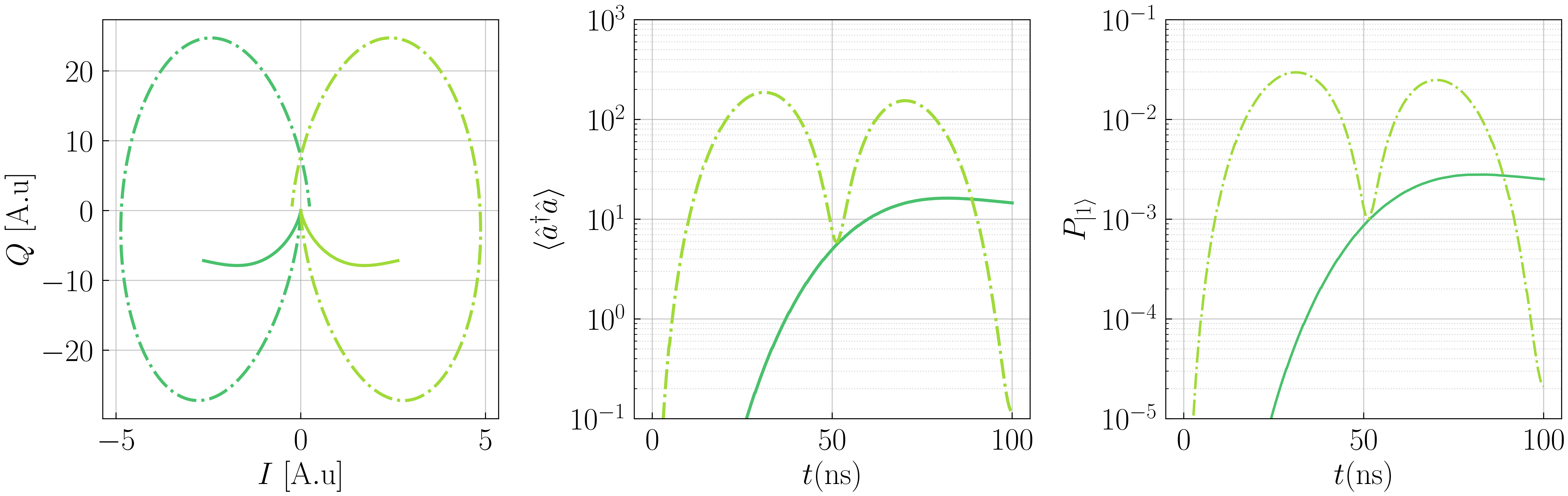

**Nelder-Mead** method for the optimization of $\{\Delta, \Omega, \beta\}$

# Readout and active reset

- **Driving** and **readout** points in different nodes of the system
- **Dispersive** readout
- Optimize **active reset** to maximize I-Q plane state separation and minimize resonator and qubit population at the end of the measurement process




Readout of node $N_3$ of the system




*F. Motzoi, L. Buchmann, C. DIckel, arXiv:1809.04116 [quant-ph] (2018)

# Resilience to fabrication fluctuations

**Procedure**

Generate **multiple circuits** where parameters are **chosen** based on a normal distribution of certain standard deviation $\sigma$ around the optimal point

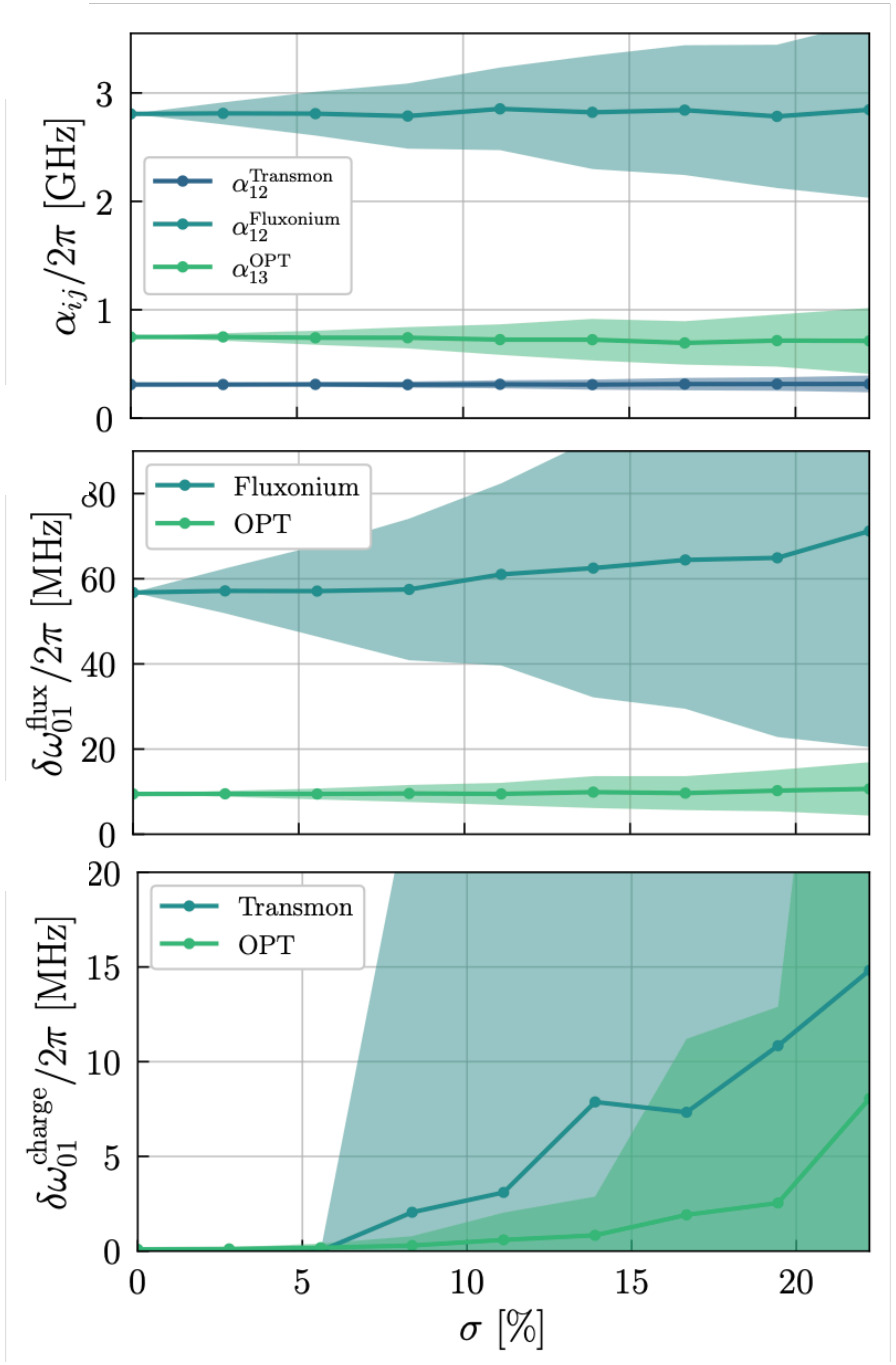
$$x = x_{optimal} \pm \delta x \qquad \delta x = D \cdot x_{optimal}$$

**Numerically** compute their characteristics

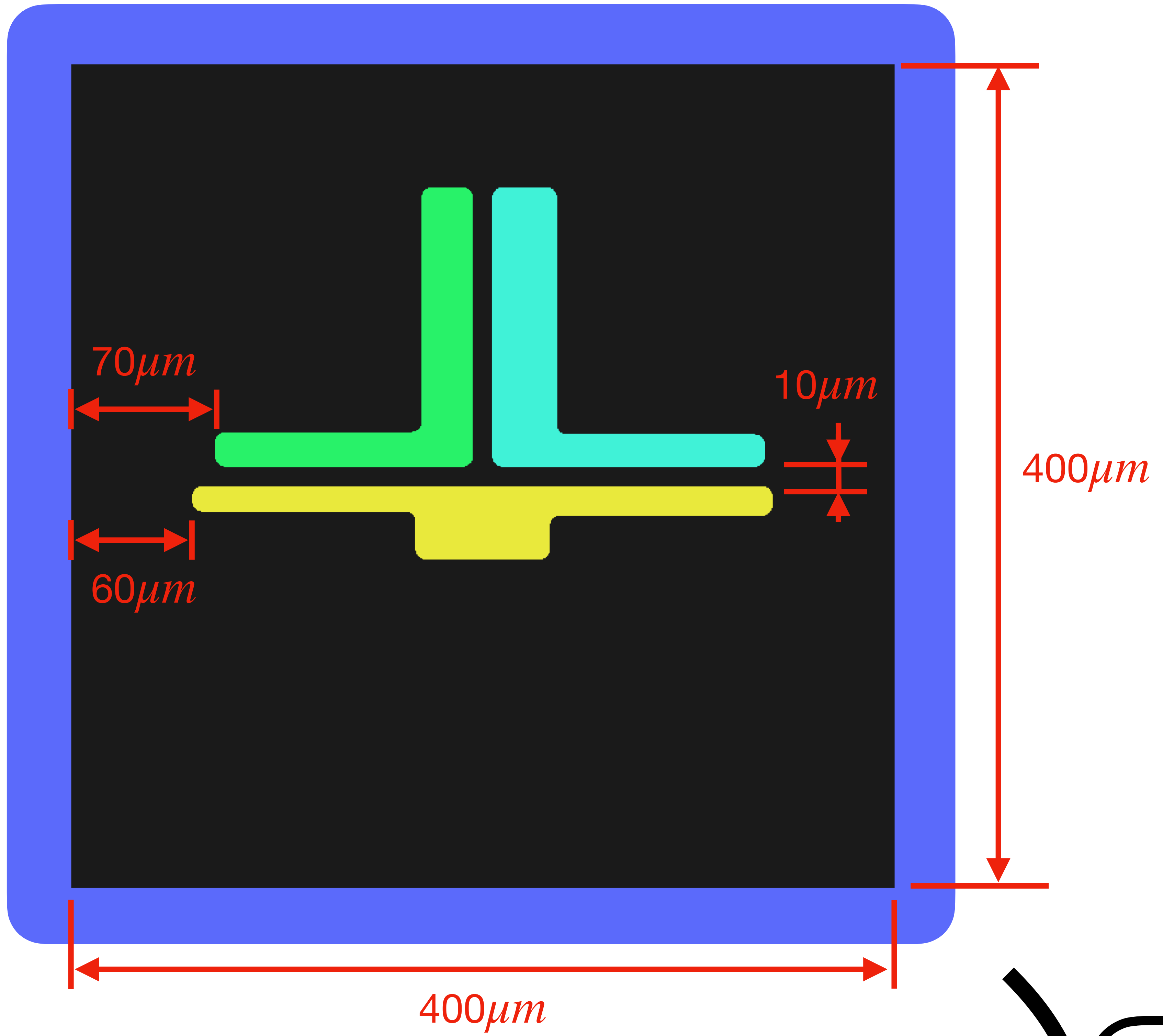
Compute the **mean** and **standard deviation**

**Characteristics** computed: anharmonicity, energy dispersion due to charge and flux fluctuations

Computed for **500 circuits** deviated from optimal solution



# Lithography optimization

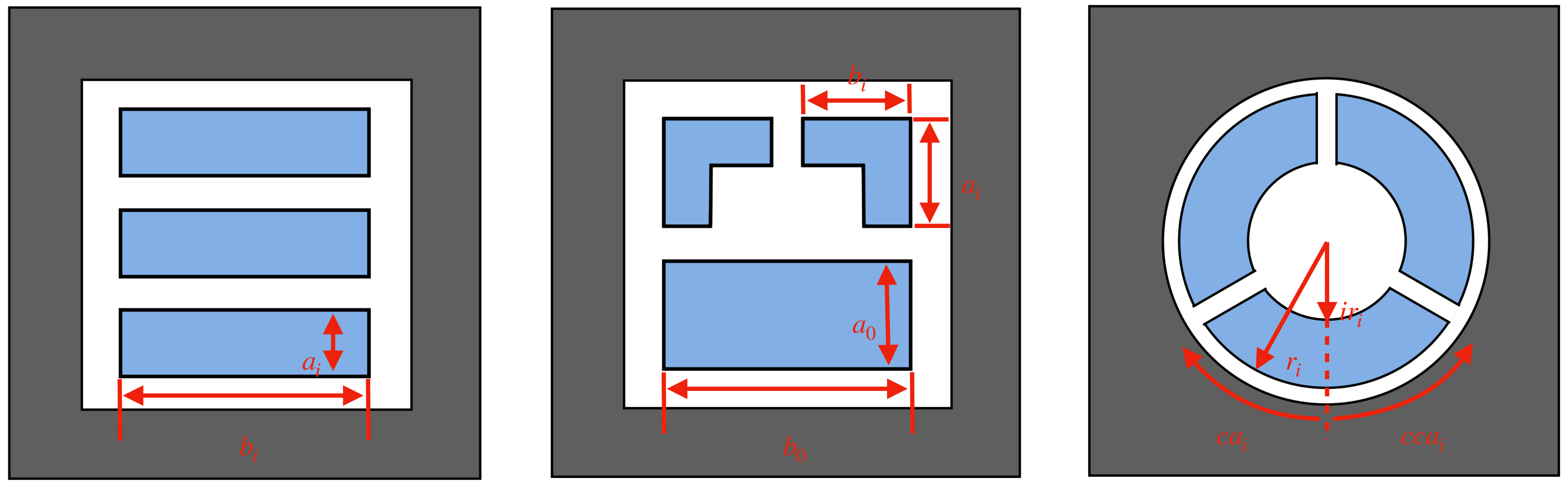



## Method

Generate **parametrized geometries** and **optimize** theirs parameters

**Constrain** to chip size and fabrication limitations

Optimize **footprint**



**Fast field solver**

**Approximated Capacitance Matrix**

**Target Capacitance Matrix**

$$C_{\text{approx}} = \begin{pmatrix} 32.3 & -9.9 & -9.3 \\ -9.9 & 33.7 & -9.7 \\ -9.3 & -9.7 & 35.1 \end{pmatrix} [fF] +$$

Expected **small extra C** between islands connected with JJ or JJ-arrays

$$C_{\text{target}} = \begin{pmatrix} 34.2 & -12.3 & -10.3 \\ -12.3 & 35.7 & -10.9 \\ -10.3 & -10.9 & 36.5 \end{pmatrix} [fF]$$

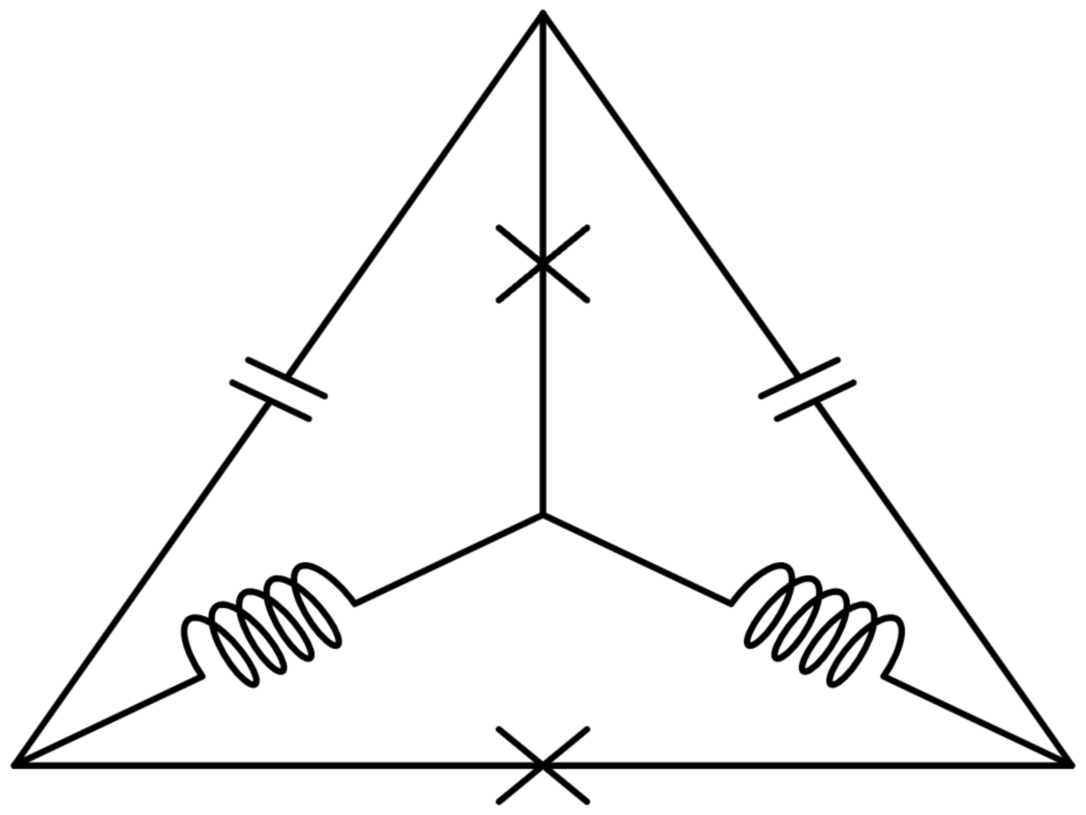
# Final remarks

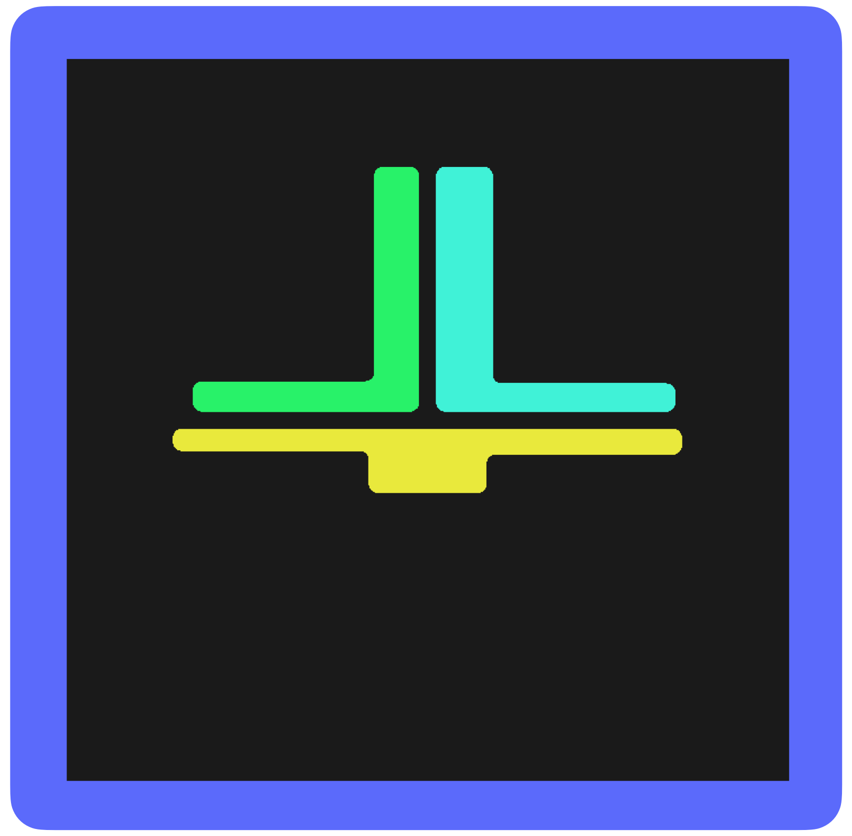
- **Evolutionary algorithms (EA)** allow us to explore the large landscape of possible devices and find resilient solutions

- Optimized device offering **large anharmonicity, reduced charge matrix elements** and **reduced dispersion**

- We have used EA to find a configuration **striking a balance** between manipulability and noise protection

- Proposed an automatized approach for going **from the lumped-element Hamiltonian description to the lithographic** design





# Perspectives

- Apply these set of techniques and tools to a wider range of problems, such as **multi-qubit systems** design and tailor made **couplers** for existing devices

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## Collaborators:

Francisco Cardenas-López

Gerhard Huber

Stefan Filipp

Guillermo Romero

Max Werninghaus

# Thank you for your attention!


**Contact**

pablo.garciaa@ehu.es

@pgaraz9

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