Hardware requirements for useful superconducting quantum computers

Manuel Pino García, 22/05/2024
Universidad de Salamanca

In collaboration:

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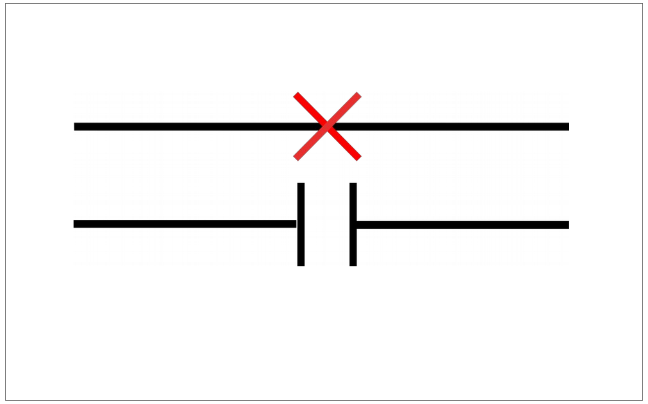
Quinfog CSIC (Madrid),
M. Hita-Pérez
Quilimanjaro Quantum Tech.

Quantum materials for quantum technologies

Quantum materials for quantum technologies

Superconducting circuits



What it this talk about?

Quantum materials for quantum technologies

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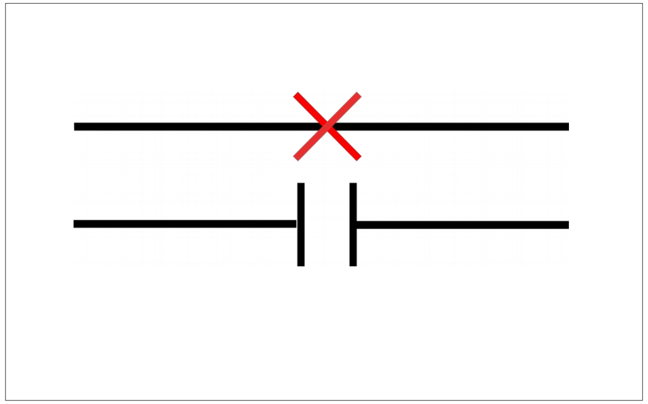
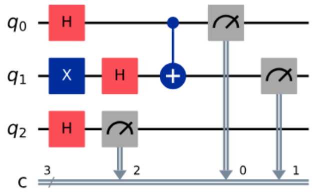
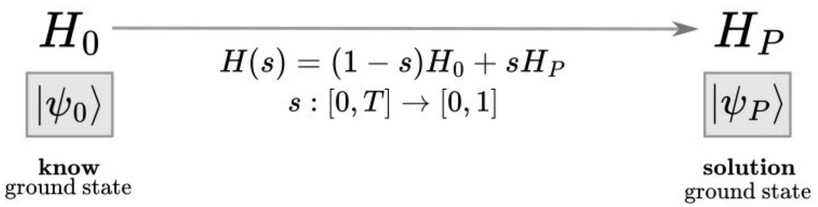


Quantum computing

Gate model



Adiabatic Quantum Computing



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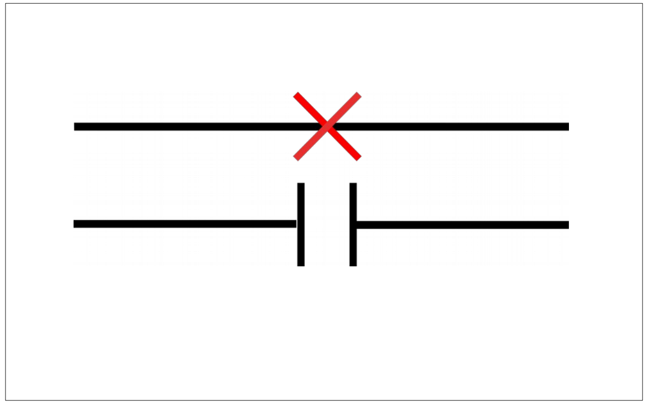

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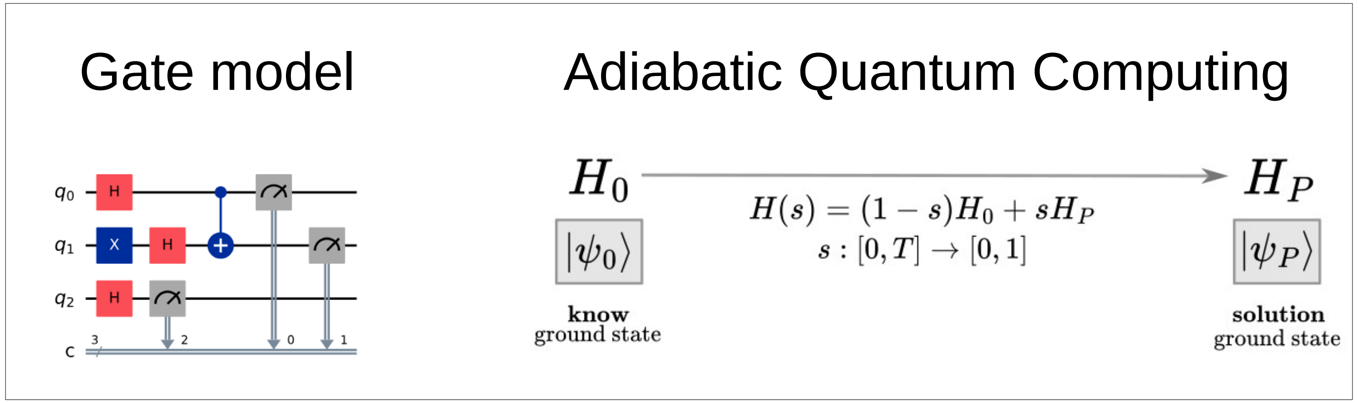

From building blocks, we design qubits and connections

What are bottleneck in superconducting hardware? How to overcome them?

- Superconducting qubit use Josephson junction

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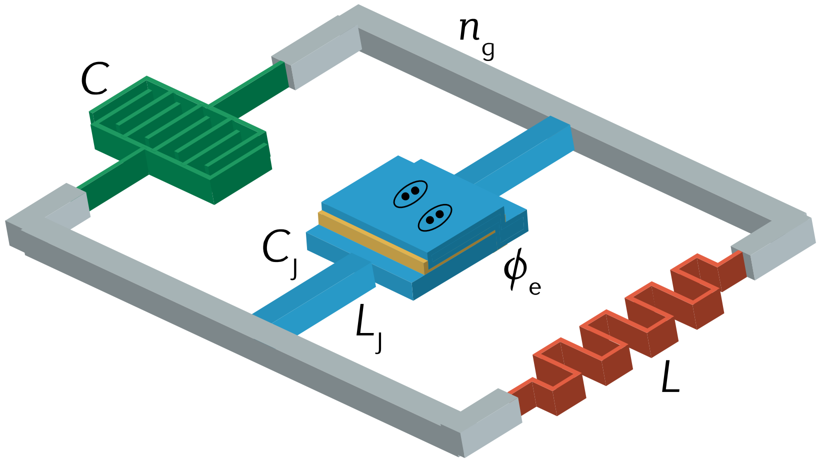

I. Siddiqi, Nat. Rev. Mat. 6.10 (2021): 875-891

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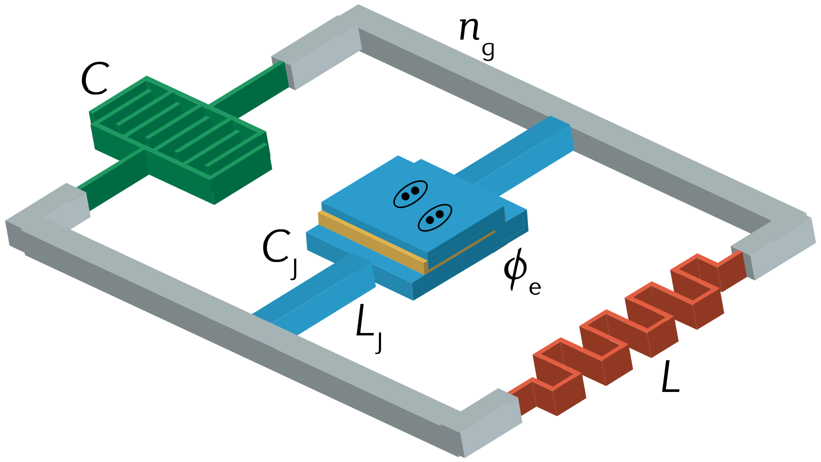

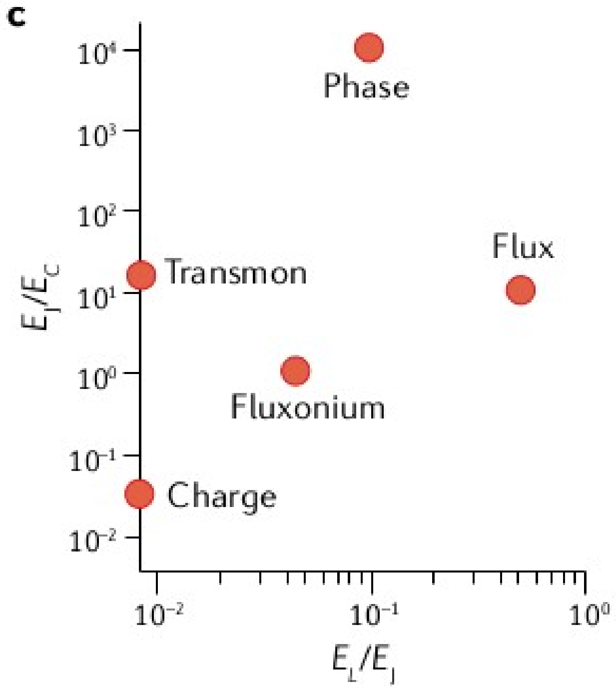

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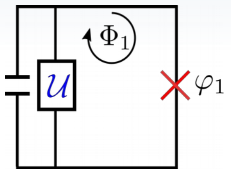

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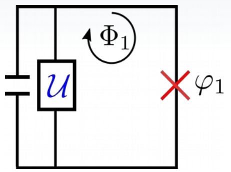

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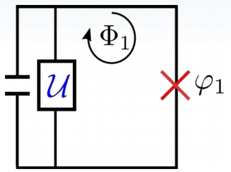

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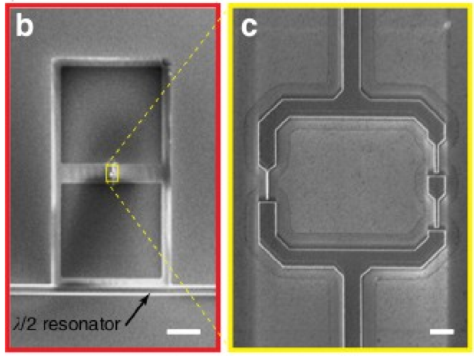
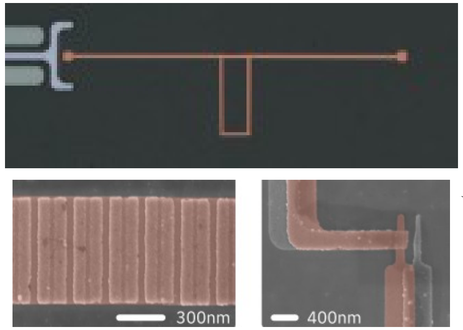


<u>Flux qubits</u> $\mathrm{T}\approx 85\mu s$

- Orlando, Mooij,... Mazo PRB (1999)

- F. Yan, ... W. D. Oliver Nat. Comm (2016)



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- R. A. Mencía, … Manucharyan ArXiv:2403.16780 (2024)

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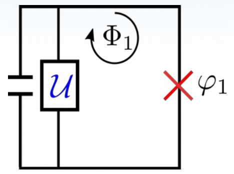
Brick: superconducting qubit



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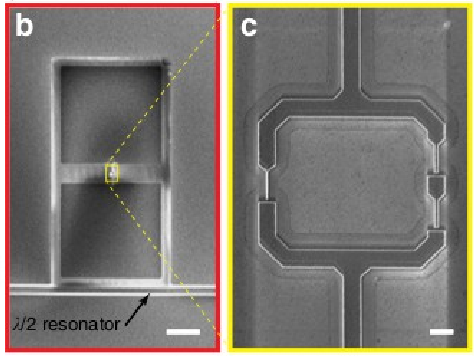

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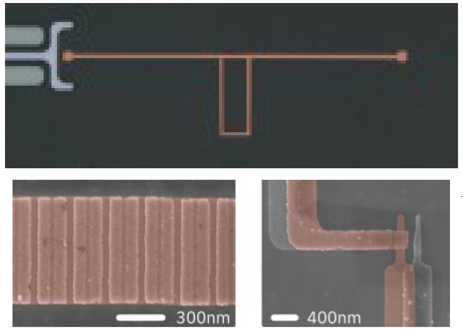

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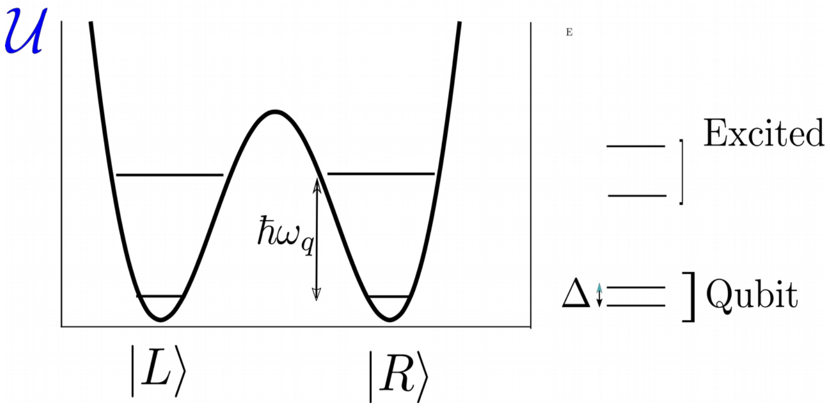

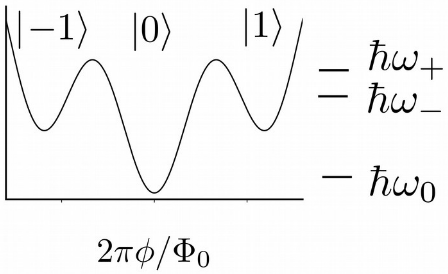

$$|\pm\rangle = \frac{|1\rangle \pm |-1\rangle}{\sqrt{2}}$$

- Hita-Pérez, Orellana, García-Ripoll <u>M. Pino</u> PRA (2023)

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- Sensibility to external fields --- > Open the door to noise

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    Kitaev (2001), Kouwenhoven Nature (2023), R. Aguado, La Rivista del Nuovo Cimento (2017)

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  This talk is all about this

What are hardware contraints?

- How to implement universal quantum computing?

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- We need minimum complexity for qubit-qubit interactions! For instance:

$$\mathrm{H} = \sum \Delta_i \sigma_i^z + \sum J_{ij}^{yy} \sigma_i^y \sigma_j^y + \sum J_{ij}^{xx} \sigma_i^x \sigma_j^x$$

This is all about the first part of the talk: Strength and form of qubit-qubit couplings

Goal: Flux qubits with complex couplings

Qubit-qubit:

Strong coupling
Quantum Monte-Carlo suffers sign problem (non-stoquastic)

Qubit-resonator:

New phenomena for LC-qubit strongly coupled in two directions

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New phenomena for LC-qubit strongly coupled in two directions

$$\mathrm{H} = \Delta \sigma^z + \omega b^\dagger b + g^x \sigma^x \left(a + a^\dagger\right) + i g^y \sigma^y \left(a - a^\dagger\right)$$

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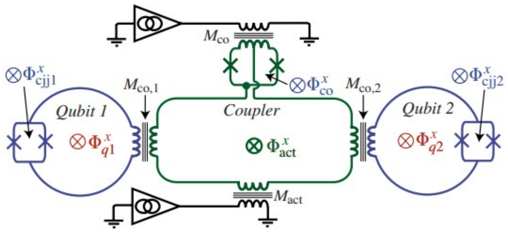

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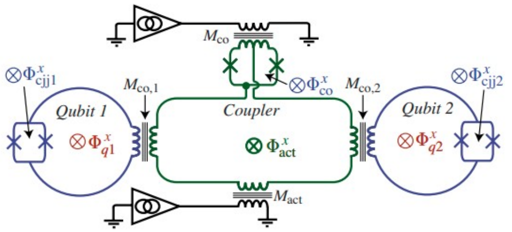
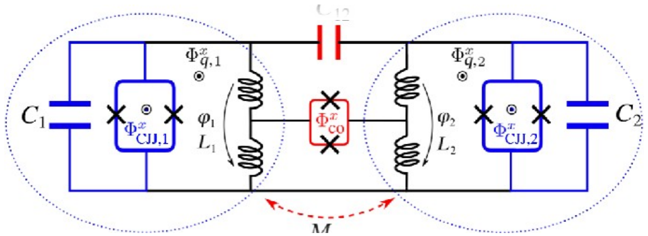
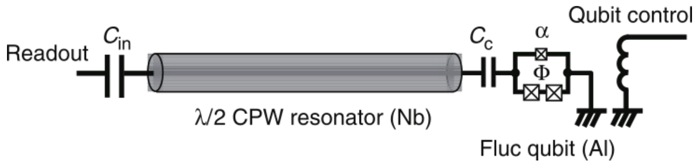


Harris et. al. (D-wave) PRB (2009)



Ozfidan, ...Amin (D-wave) PRApp (2020)



Yamamoto,… Nakamura NJP 2014

- Only focuss on charge coupling $$H = H_0 + \frac{q_1 q_2}{\bar{c}_g}$$

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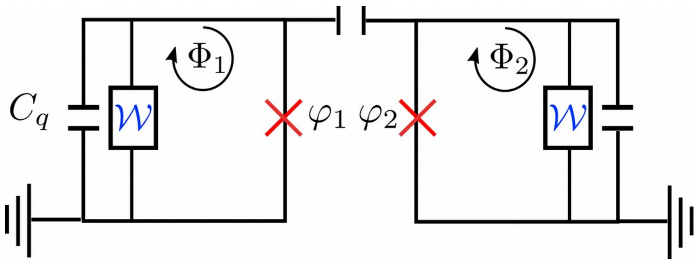

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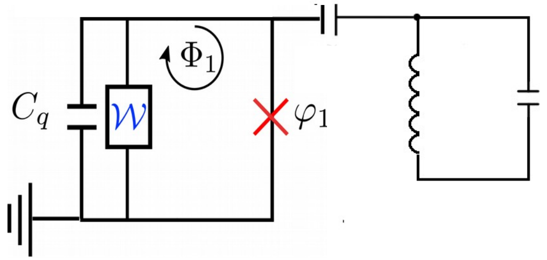
$$q_q = \frac{\Phi_0}{2\pi}\frac{C_q \Delta\varphi_\star}{\hbar}\sigma_i^y$$

$$q_r = \sqrt{\frac{\hbar}{2Z}} i(b - b^\dagger)$$



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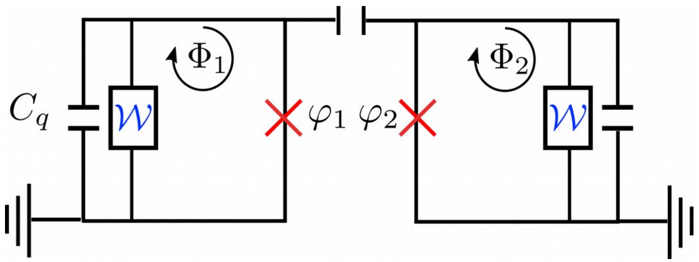

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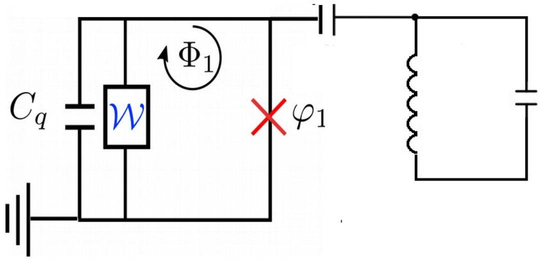

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Usual approach, project on non-interacting qubit subspace

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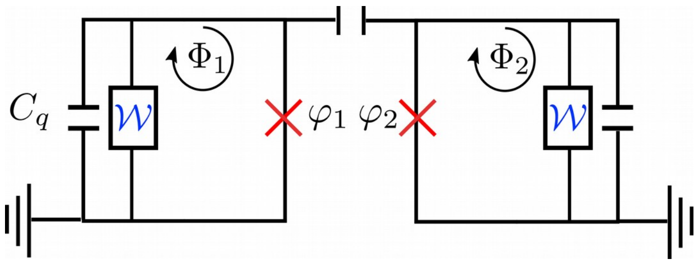

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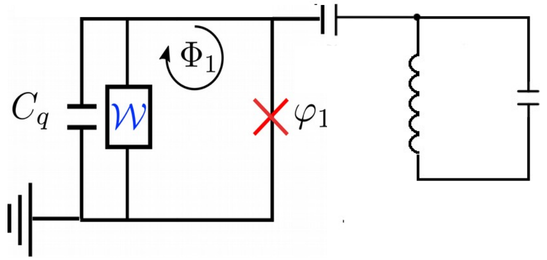

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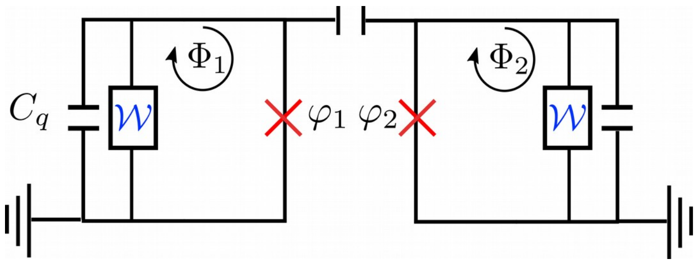

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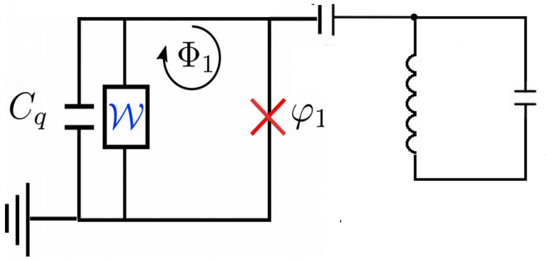

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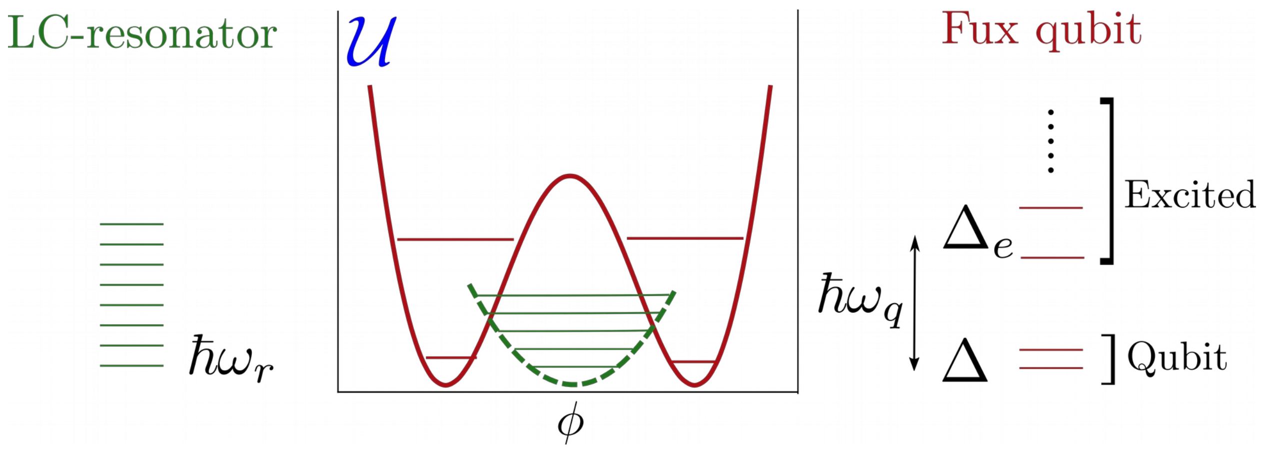

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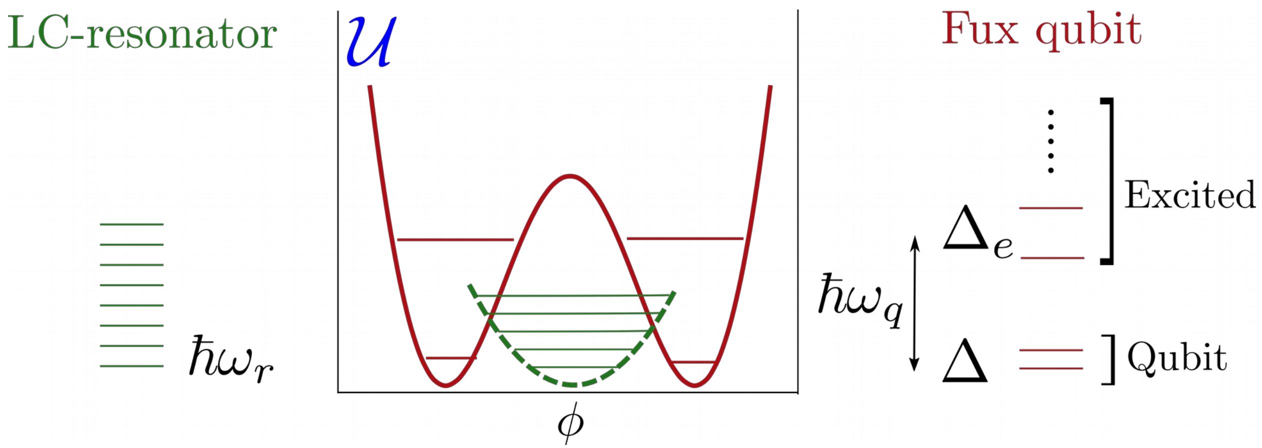

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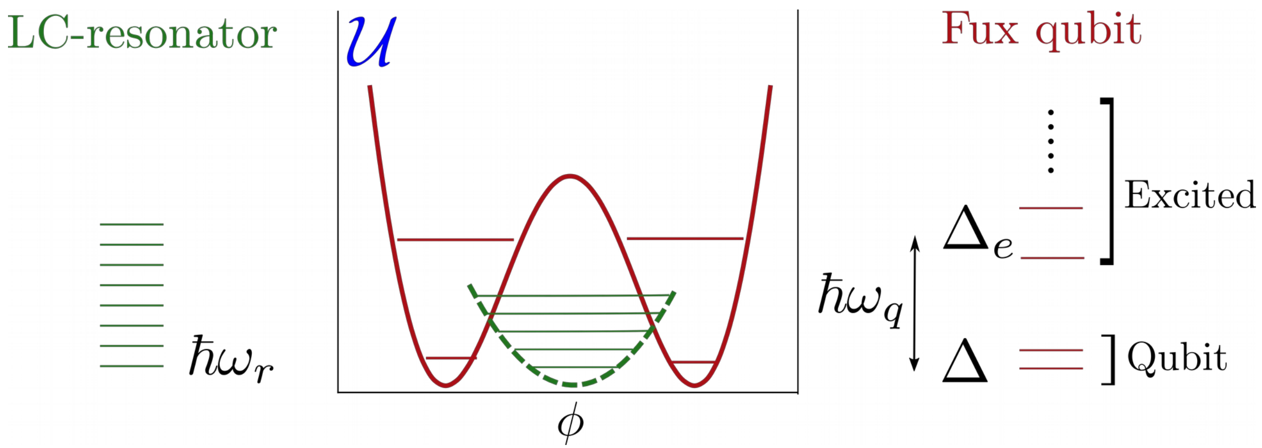

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Qubit-resonator coupling. YES!

☺

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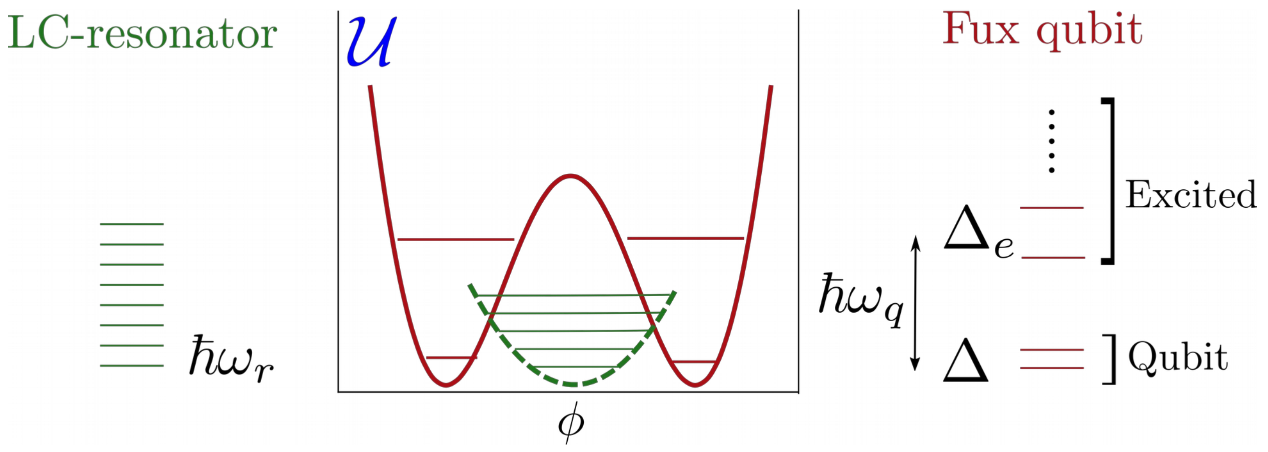

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Qubit-qubit coupling. NO! – > Need to sum up full series

$$V_{qe} \sim \hbar\omega_q$$
$$\mathcal{M}_n \sim 1$$

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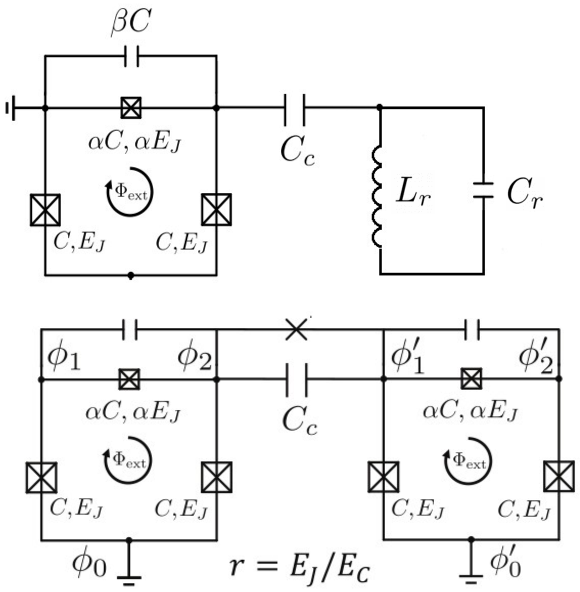

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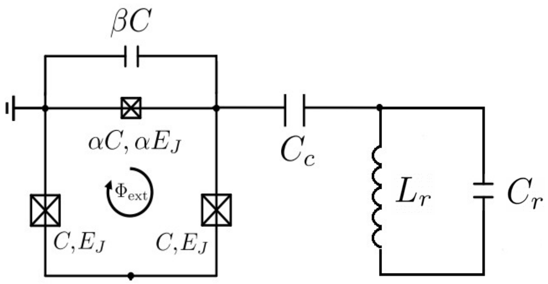

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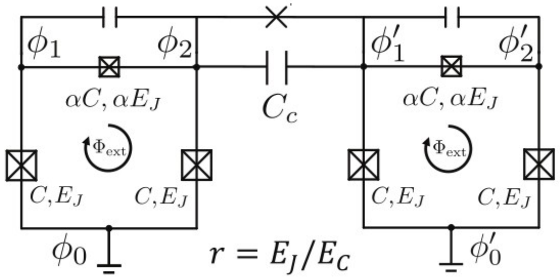

Summary of qubit-qubit and qubit-resonator

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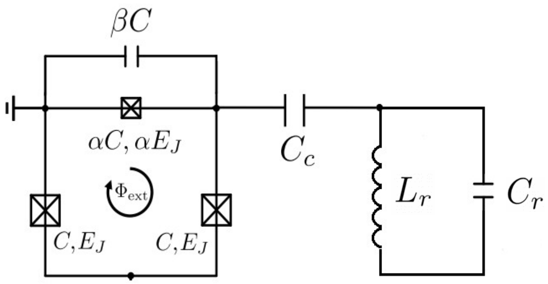

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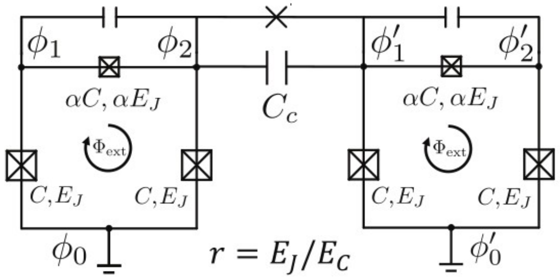

- Future work: similar technics to understand effective qubits coupling in other setups

Hita-Pérez, Jaumá, Pino, García-Ripoll PRApp (2022),
Hita-Pérez, Jaumá, Pino, García-Ripoll. Appl. Phys. Lett (2021)

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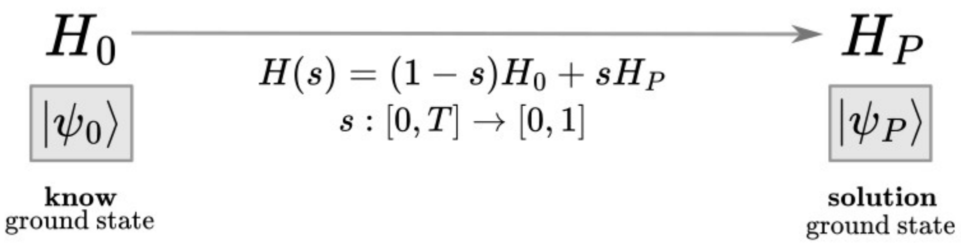

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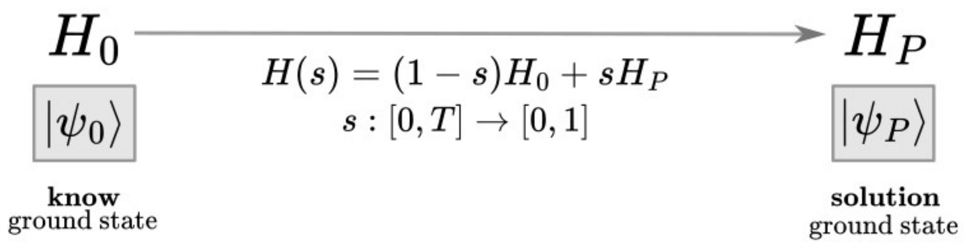

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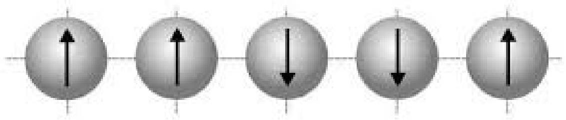
1D nearest-neighbours --- > Trivial



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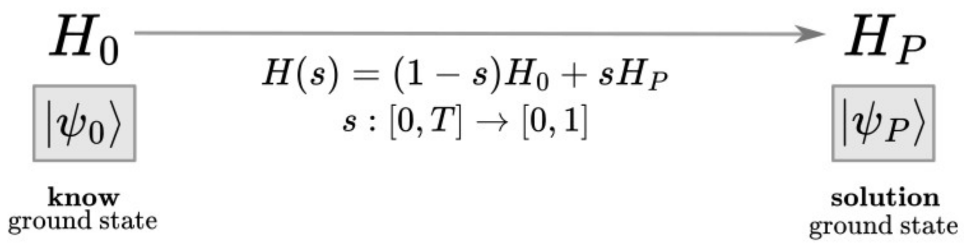

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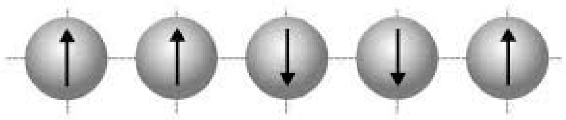
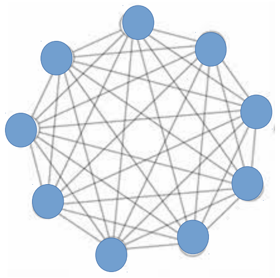


Fully connected --- > Spin-glass (NP-hard)



A. D. King, … Amin (2023), Computational supremacy in quantum simulation (2024)

- Try to look for spin-glasses not fully connected:

Non-complanar qasi-2D graphs

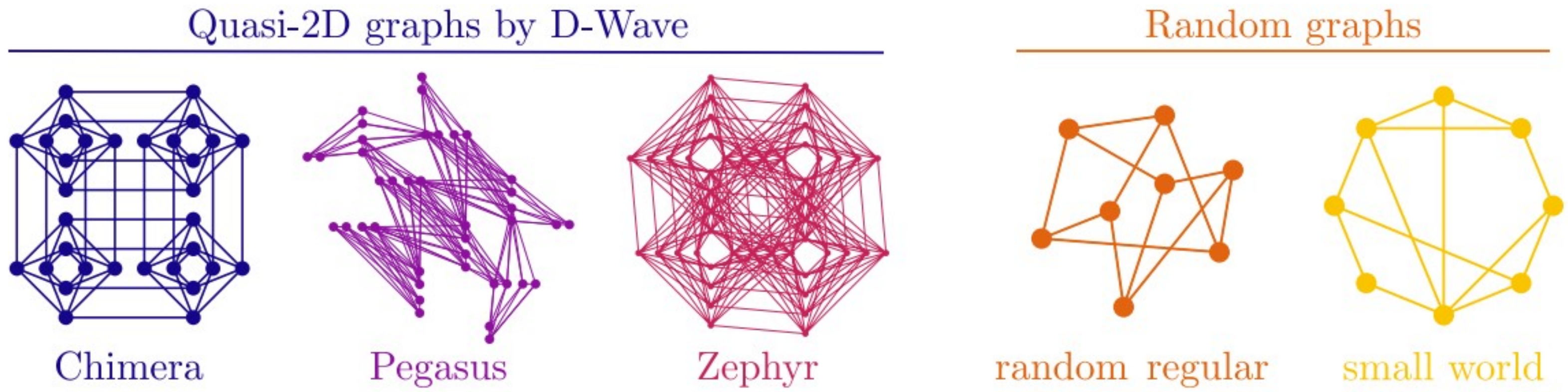
- Spin-glass state at T=0. Fernandez et al JPA (2019)
  Low-energy may be easy to approxmate

- Chimera, Pegasus, Zaphyr (d-wave graphs)

Mean field glasses $\mathrm{D} \approx \infty$

- Random regular graphs

- Small-world networks
  Katzgraber PRAPP(2018)



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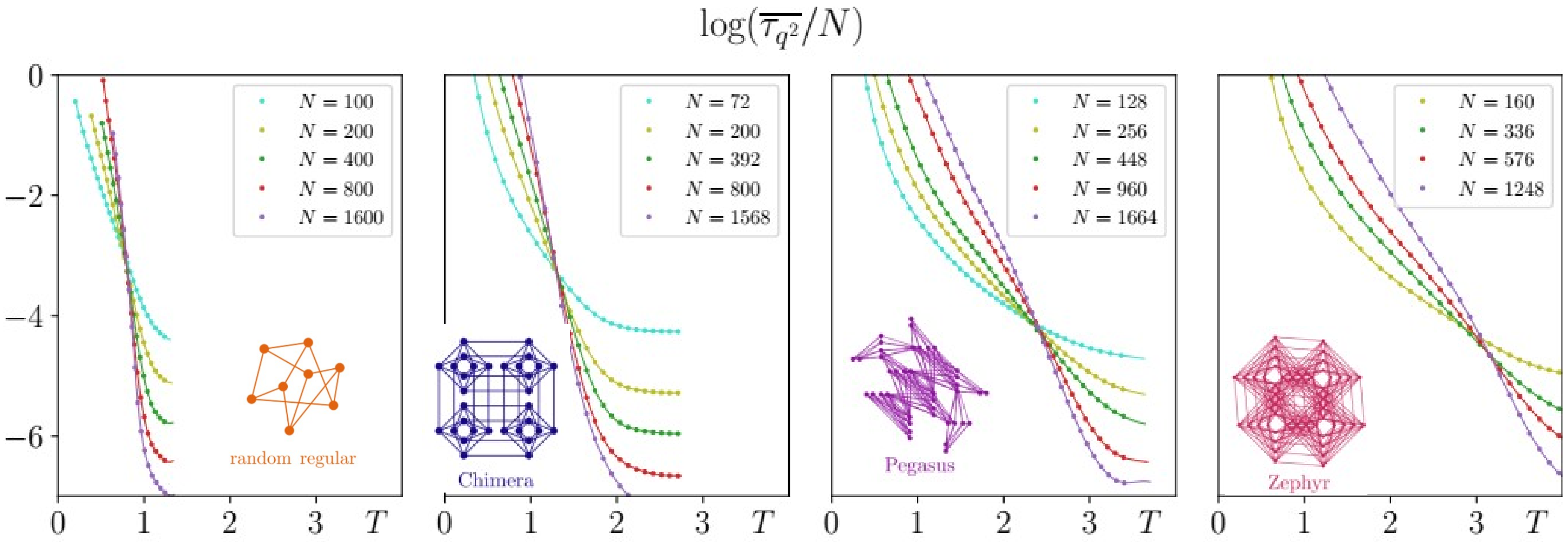

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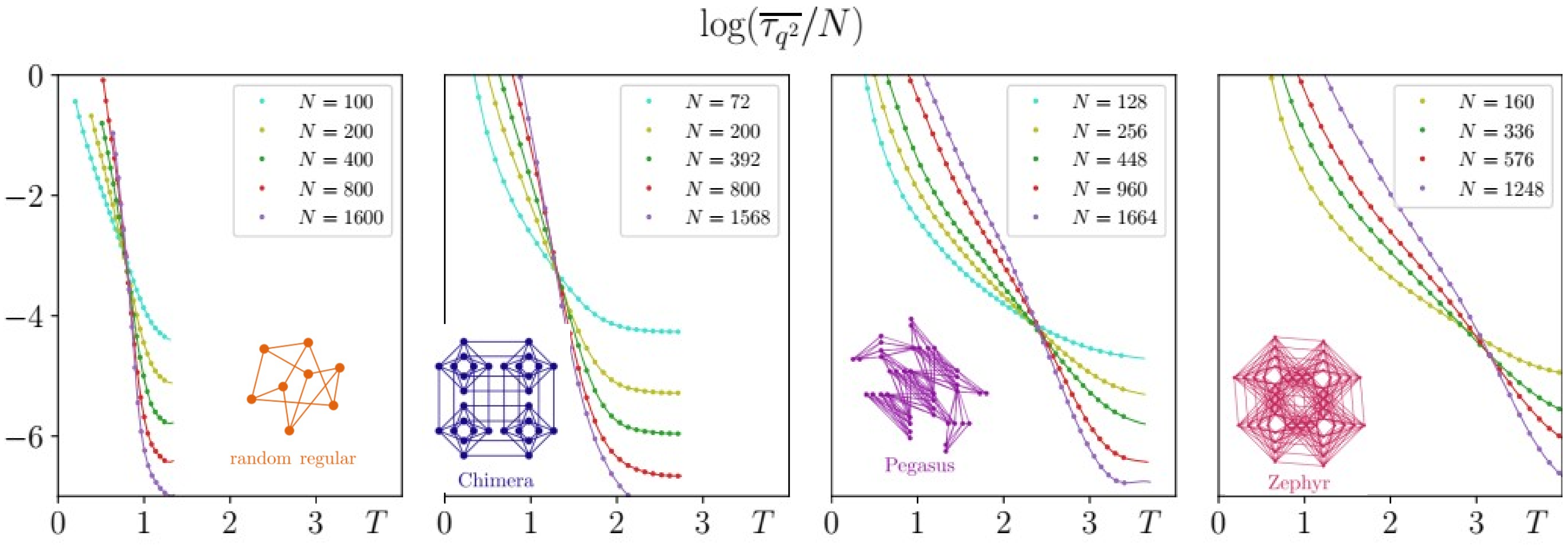

Time to perform Paralell Tempering “exploit” below the pseudo-critical temperature

Look for higher pseudo-critical temperature! Jaumá, García-Ripoll,Pino. Adv. Quant. Tech. (2023)

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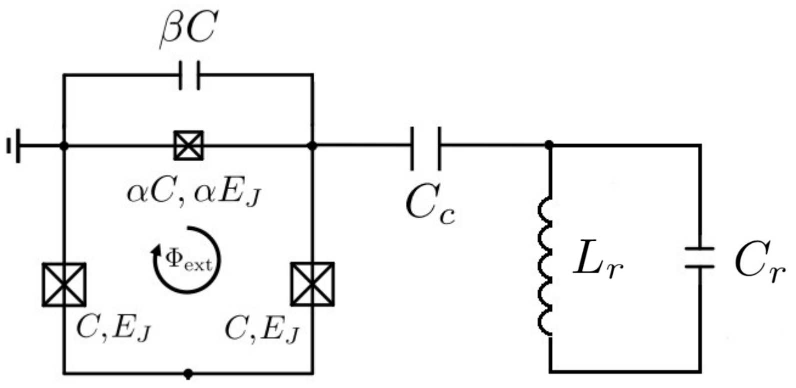
      Our work shows that planar graphs connections may be usefull

The end

Numerical results for coupling extracted with full SW transformation.

-



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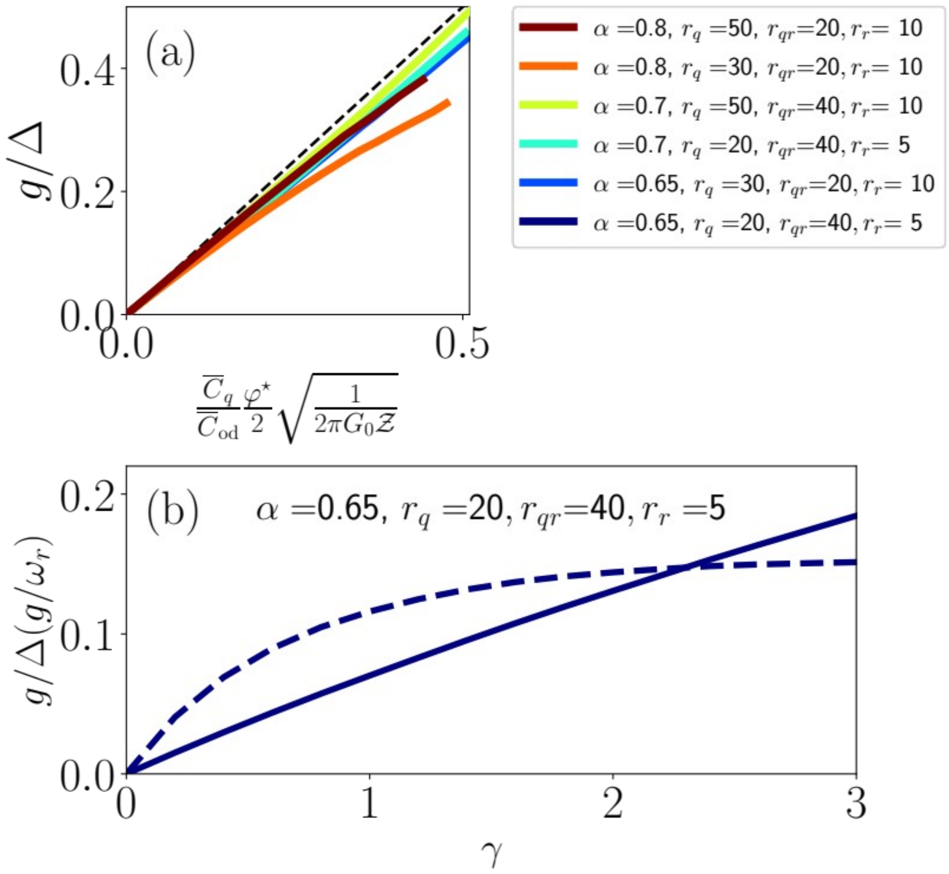

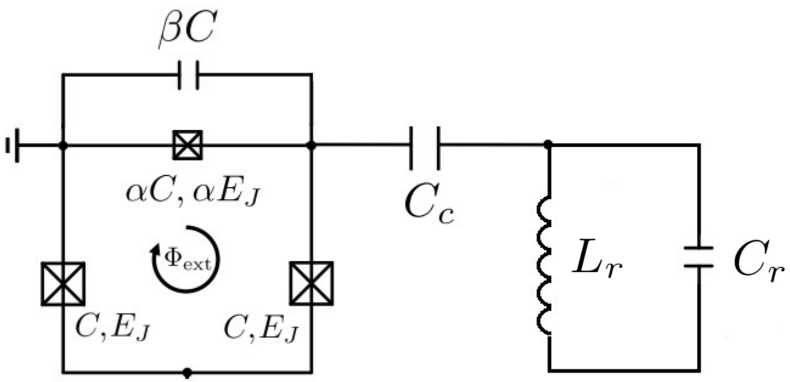

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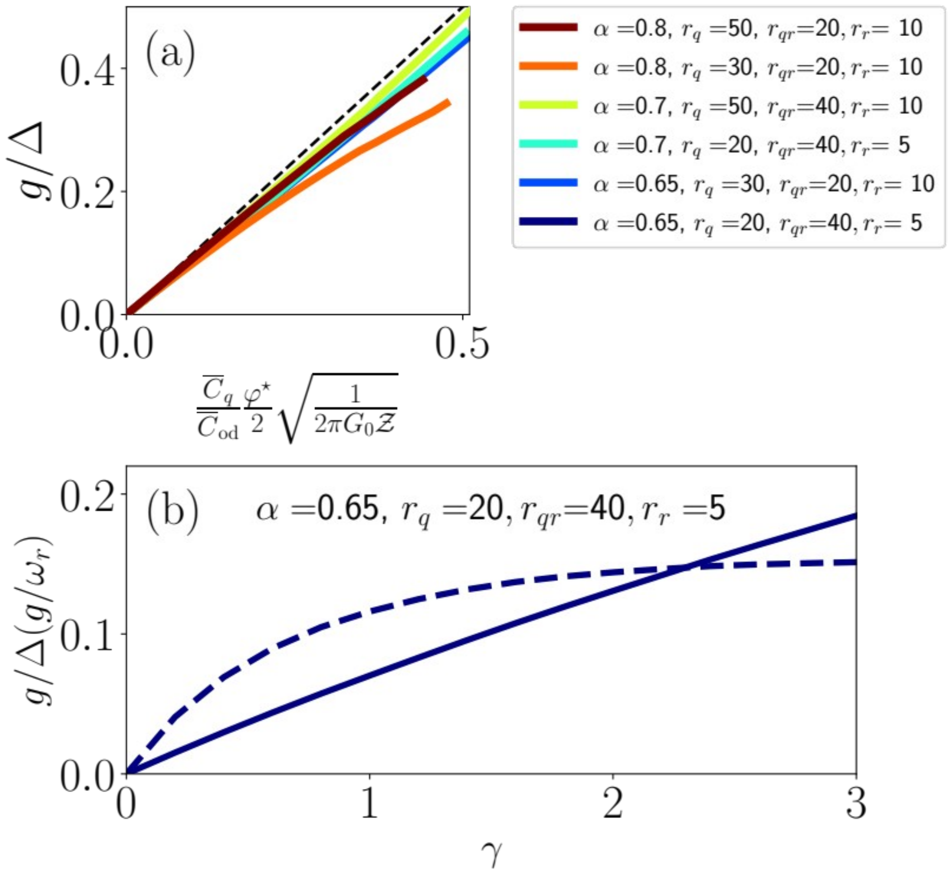

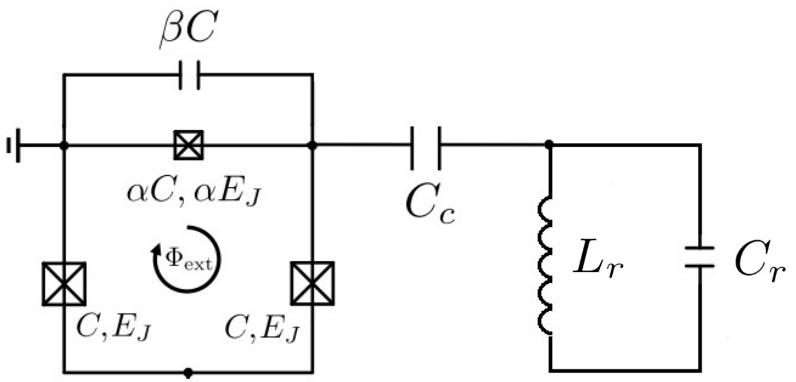

- <u>First order work up to ultra-strong coupling!</u>

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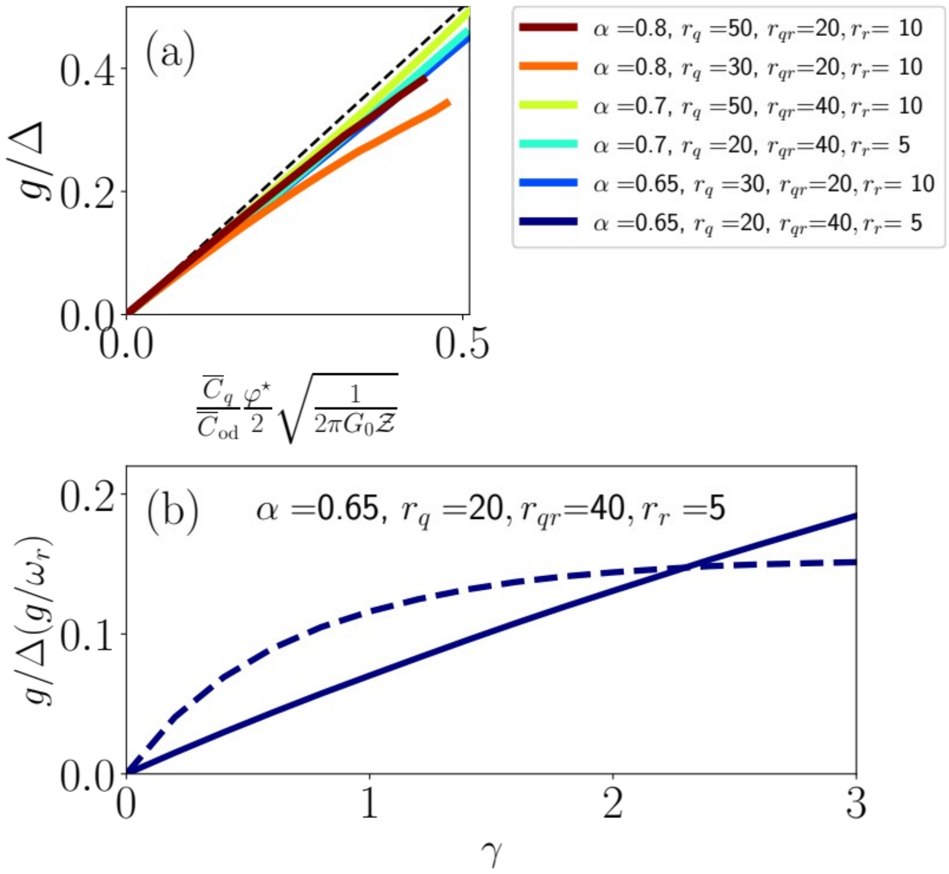

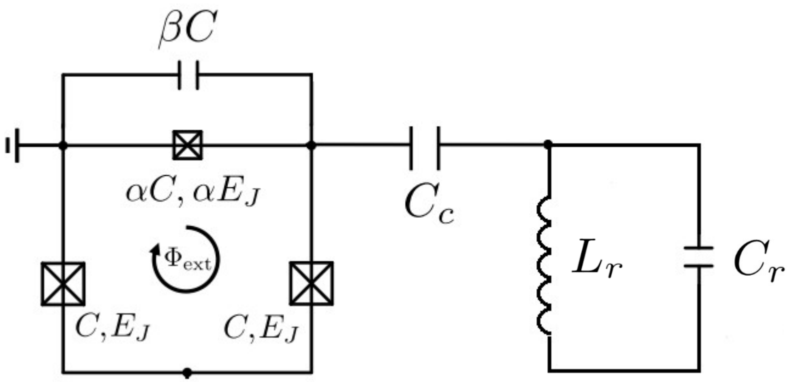

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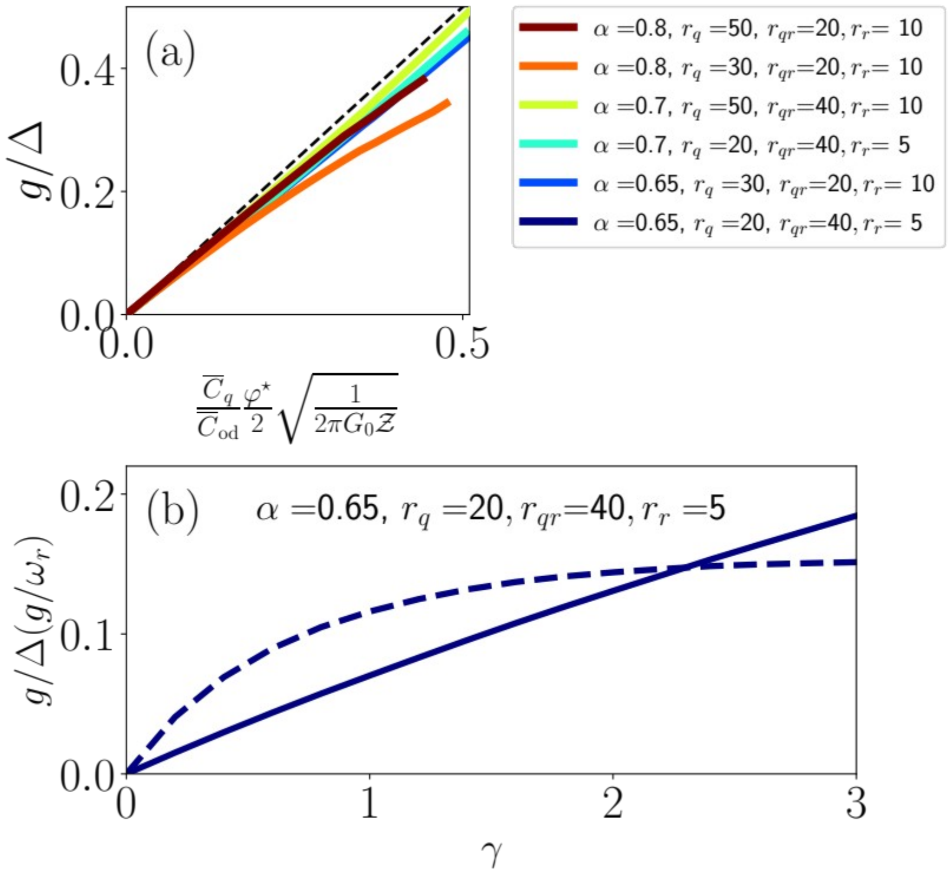

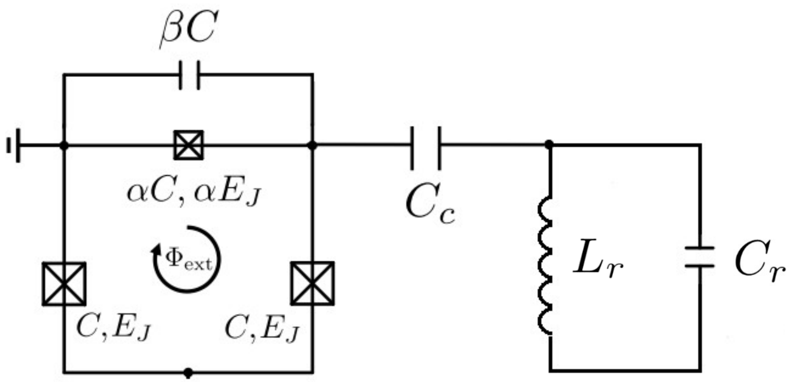

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Hita-Pérez, Jaumá, <u>Pino</u>, García-Ripoll PRApp (2022)

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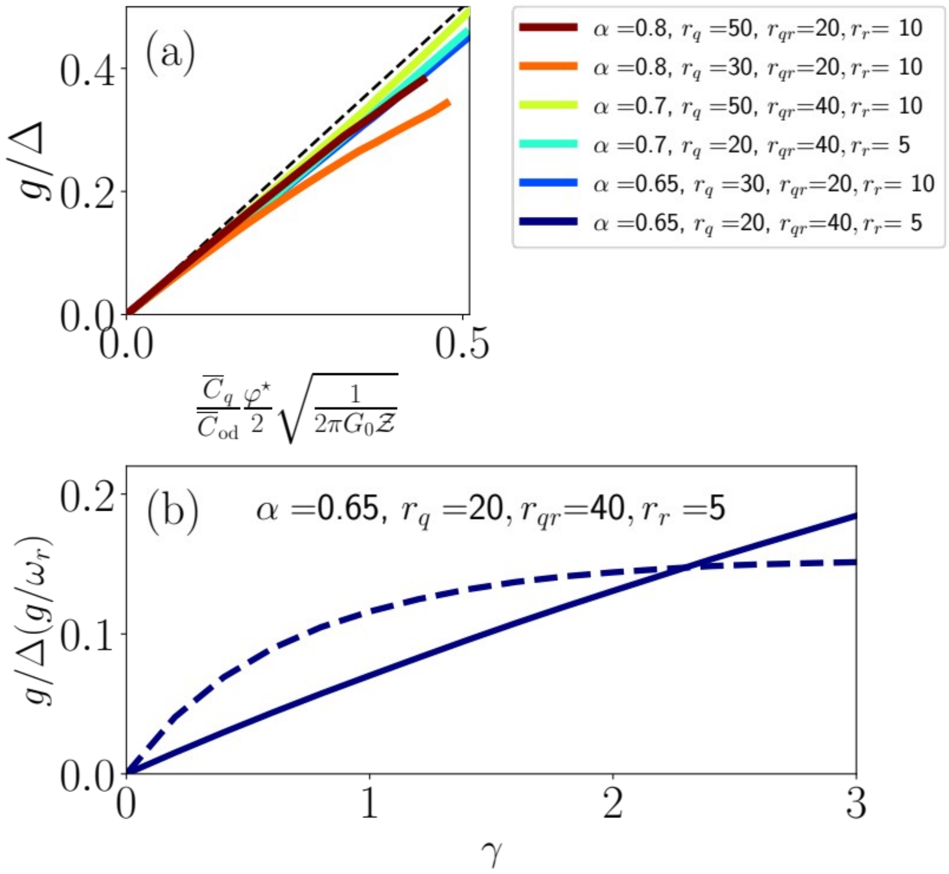

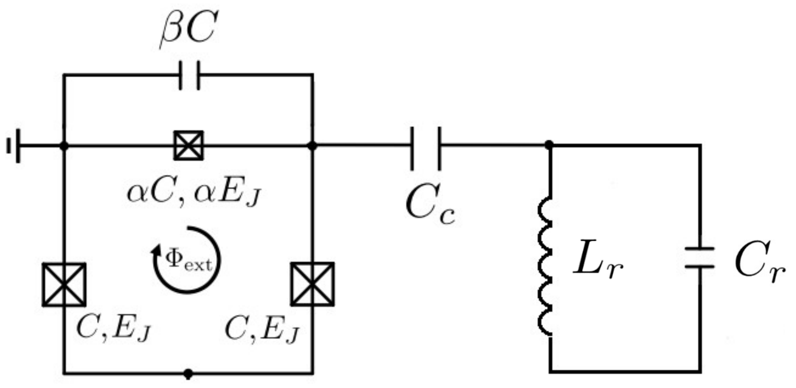

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Hita-Pérez, Jaumá, <u>Pino</u>, García-Ripoll PRApp (2022)

Different conclussion in Yoshiara, ... Semba Nat. Comm. (2022)

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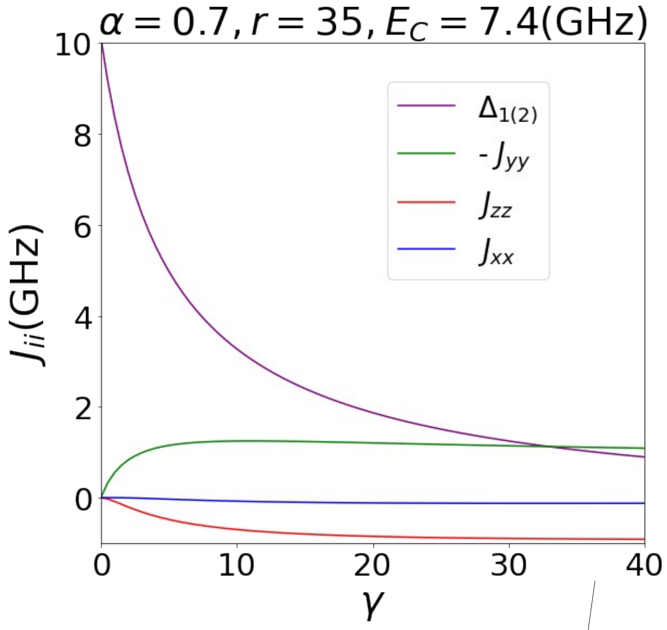
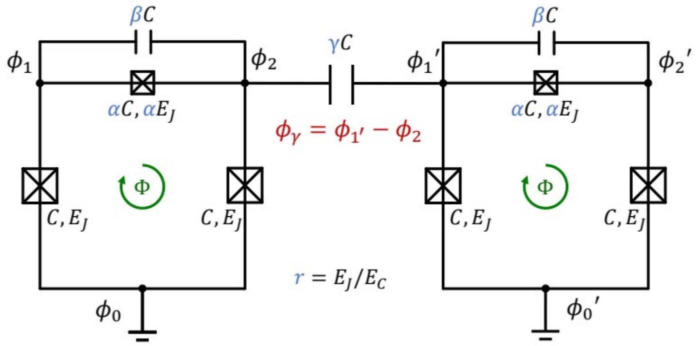
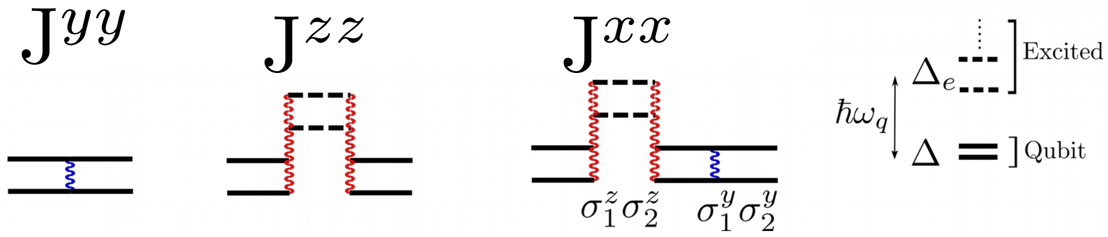
Hita-Pérez, Jaumá, Pino, García-Ripoll PRApp (2022),





- First order does not work! Diagrams

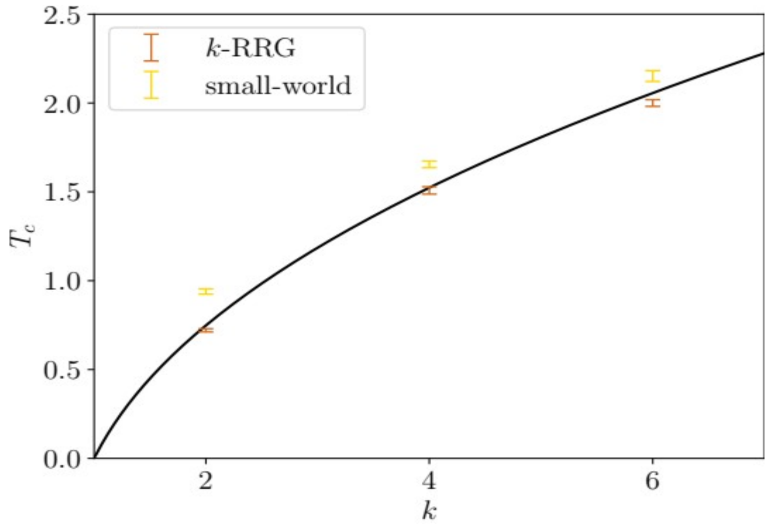


- Strong coupling $\sigma_1^+\sigma_2^- + \sigma_1^-\sigma_2^+$

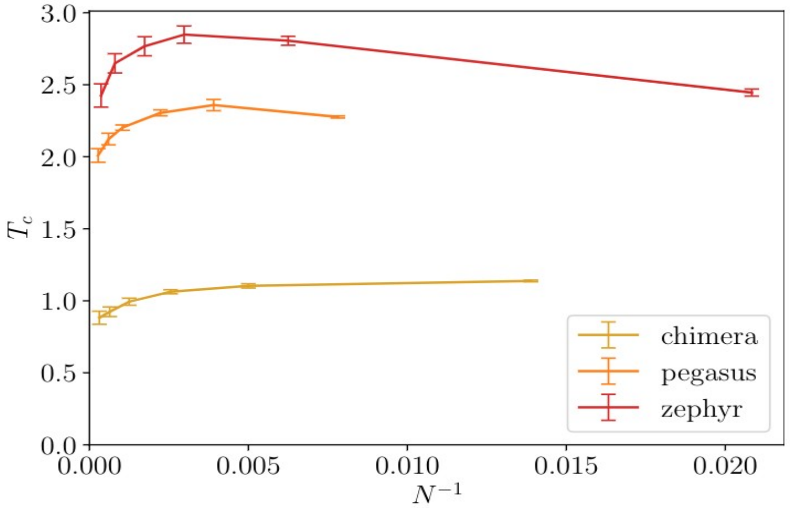
Hita-Pérez, Jaumá, Pino, García-Ripoll PRApp (2022)

- We compute spin-glass phase transition via Paralell Tempering

Mean field glasses



Non-complanar 2D graphs D-wave



- There is no phase spin-glass in D-wave lattice

Are D-wave lattice very bad!? Katzgraber, et al. PRX (2015)
Additional problems, temperature Chaos. Martin-Mayor et al. Sci. Rep. (2015)