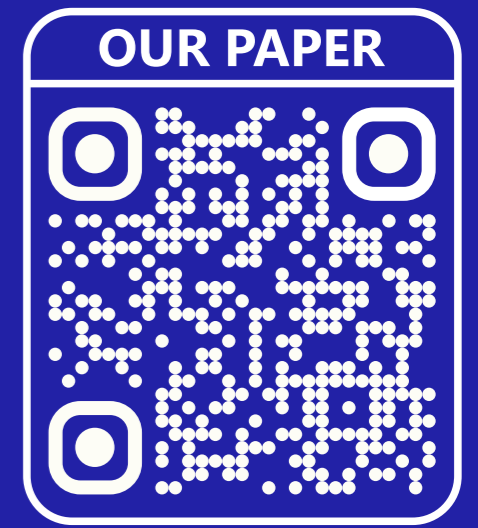


Microwave two-photon threshold detector based on a Josephson photomultiplier

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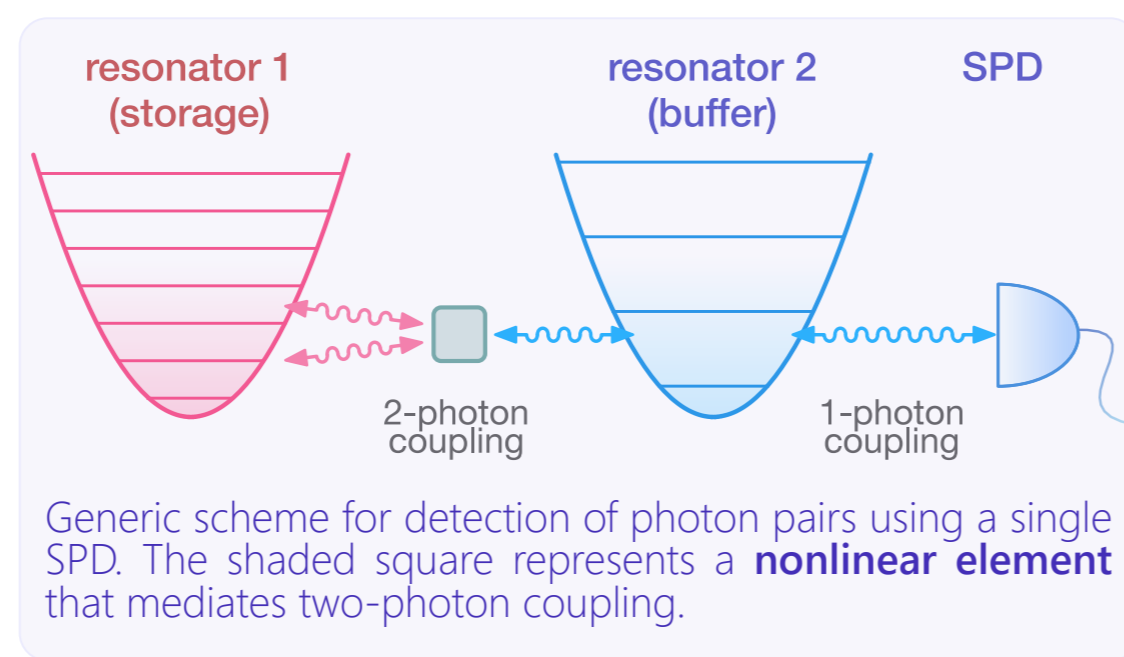
1 Key idea and result

We propose the extension to the **Josephson photomultiplier (JPM)** that transforms it into a **two-photon threshold detector**. Such a detector absorbs a pair of photons and delivers a “click” only when there are at least two photons in the measured mode. For achieving a two-photon threshold, we couple the JPM to a **dimer of resonators** composed of two lumped-element resonators interacting via an **asymmetric dc SQUID**. Specific tuning of the resonator frequencies and the external flux through the SQUID coupler allows us to engineer a **two-photon coupling** between the resonators. This coupling gives rise to the conversion of a photon pair from one resonator into a single photon in another resonator that enables a selective response to quantum states with at least two photons.

2 Principle of operation

To implement the **two-photon threshold detector**, we propose using a single-photon detector (SPD) and two resonators referred to as the **storage resonator** and the **buffer resonator**. The SPD is coupled to the buffer resonator through a resonant single-photon interaction, which converts a photon in the resonator mode into an excitation in the SPD, triggering a “click”.

- The buffer resonator interacts with the storage resonator via a **nonlinear inductive coupler**.
- The resonator frequencies are tailored so that the frequency of the buffer resonator is twice the frequency of the storage resonator. This regime allows the coupler to mediate the resonant **two-photon interaction**, which leads to coherent conversion of a photon pair in the storage into a single photon in the



- The system exhibits substantially different behavior when two or more photons are present in the storage resonator than when it contains only one photon. In the latter case, the buffer remains in the vacuum state and the SPD does not click. When there are at least two photons in the storage, two-photon coupling between the resonators leads to population of the buffer resonator so the SPD can absorb a photon and deliver a click.

3 Two-photon coupling

Full quantum Hamiltonian of coupled resonators:

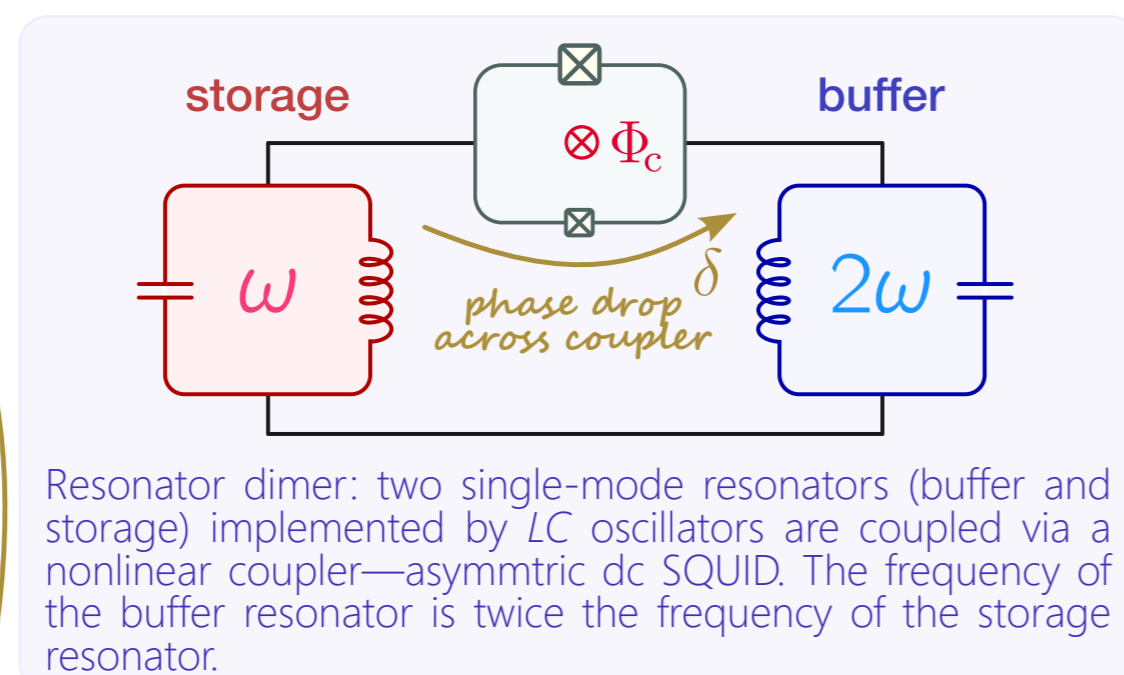
$$\hat{H}_{\text{rr}} = \sum_{j=1,2} \hat{H}_{rj} + \hat{H}_{\text{rr}}^{\text{int}}$$

resonators interactions

$$\hat{H}_{rj} = \hbar\omega_{oj}\hat{a}_j^\dagger\hat{a}_j - \hbar\sum_{k\geq 3}(-1)^{(j-1)k}g_{kj}(\hat{a}_j^\dagger + \hat{a}_j)^k$$

linear oscillator self-nonlinearities

- Resonators acquire weak self-nonlinearity from the SQUID coupler



$$\hat{H}_{\text{rr}}^{\text{int}} = -\hbar g_c(\hat{a}_1^\dagger - \hat{a}_1)(\hat{a}_2^\dagger - \hat{a}_2) + \hbar\sum_{k\geq 2} \sum_{l=1}^{k-1} g_{k-l}(\hat{a}_1^\dagger + \hat{a}_1)^{k-l}(\hat{a}_2^\dagger + \hat{a}_2)^l$$

linear capacitive coupling: single-photon exchange

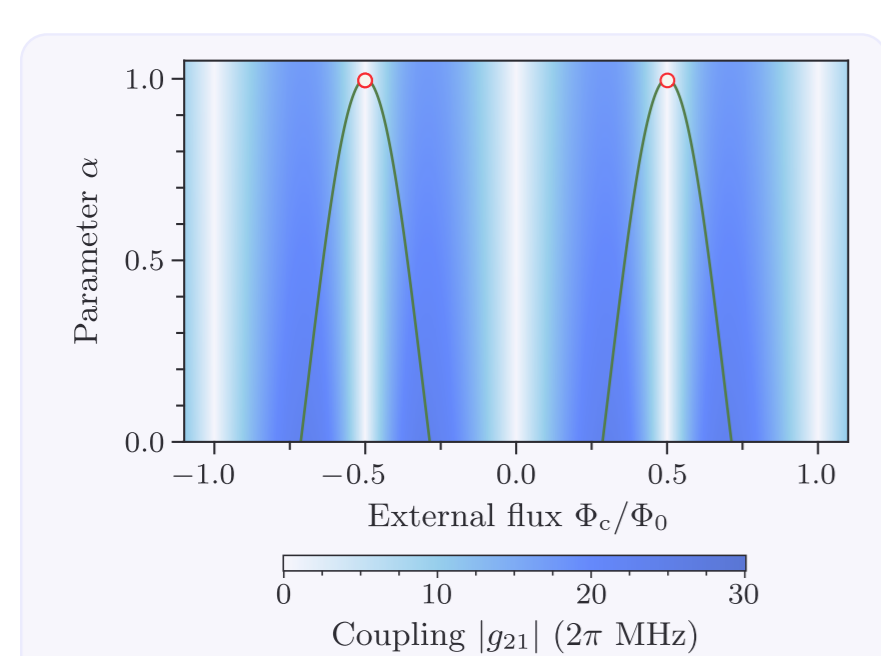
linear inductive coupling: single-photon exchange

nonlinear coupling: conversion of (k-l) photons in the storage resonator to l photons in the buffer

Josephson coupling energy

$$g_{k-l} = (-1)^{l+1} \frac{E_{\text{J}}^{\text{eff}}}{\hbar} \varphi_{\text{zp}1}^{k-l} \varphi_{\text{zp}2}^l u_k$$

$$u_k = (-1)^{\lfloor k/2 \rfloor} \begin{cases} \cos \delta, & \text{even } k \\ \sin \delta, & \text{odd } k \end{cases}$$



- By tuning the frequencies of the resonators, we make one of the couplings resonant. We require **two-photon coupling** to be resonant, so we set $\omega_{o1} \approx \omega_{o2}/2$
- By setting $\delta = \pm(n + 1/2)\pi$, we switch off all even-order couplings including cross-Kerr

Effective Hamiltonian:

$$\hat{H}_{\text{rr}} \approx \hbar\sum_j \omega_j \hat{a}_j^\dagger \hat{a}_j - K_j \hat{a}_j^{\dagger 2} \hat{a}_j^2 + \hbar g_{21}(\hat{a}_1^{\dagger 2} \hat{a}_2 + \hat{a}_2^\dagger \hat{a}_1^2)$$

induced self-Kerr nonlinearity two-photon coupling

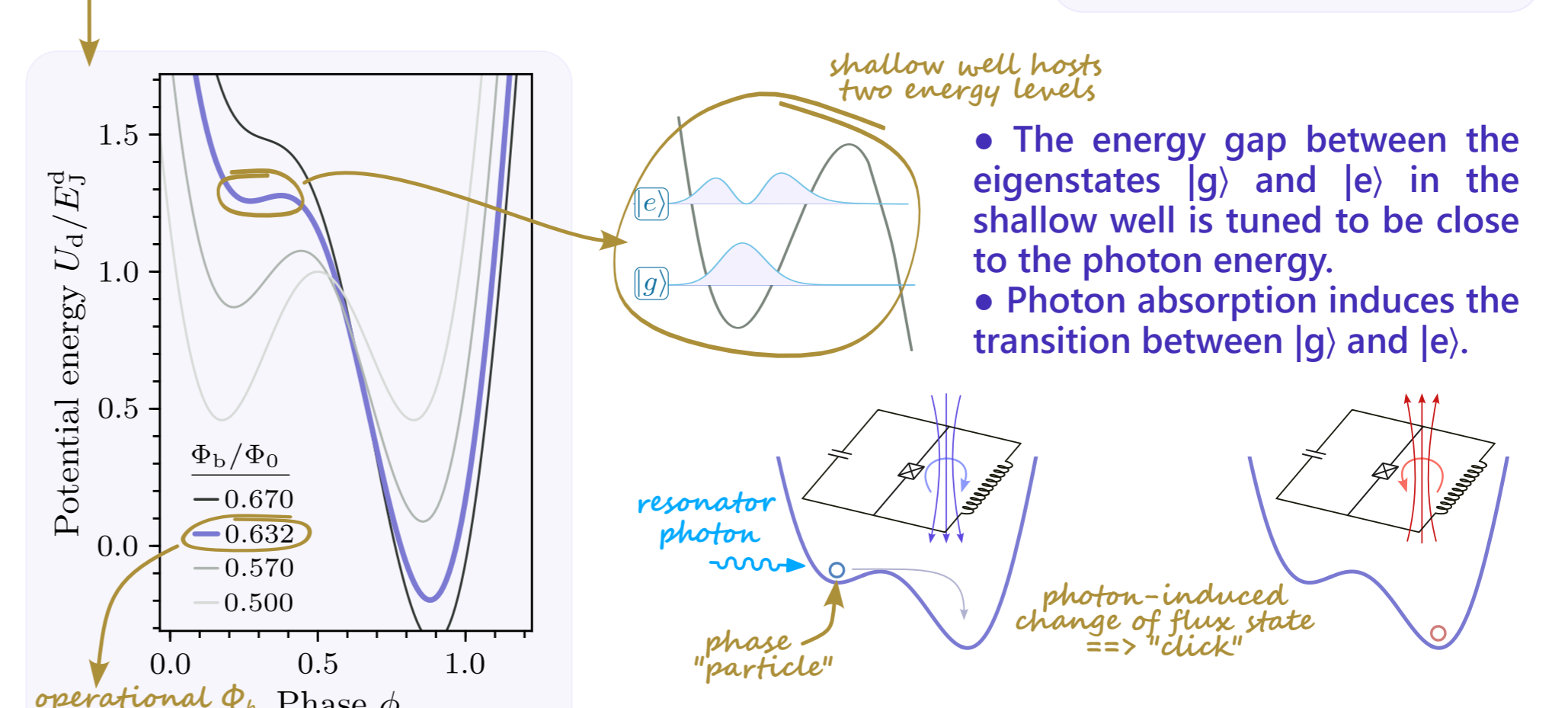
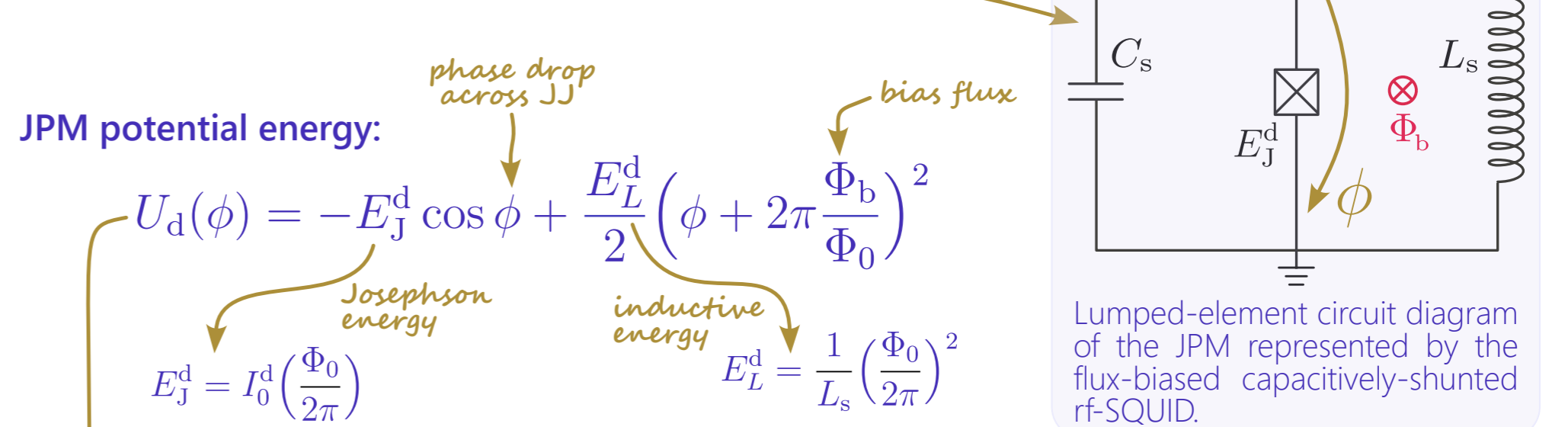
Two-photon coupling rate:

$$g_{21} = \frac{1}{2} \frac{E_{\text{J}}^{\text{eff}}}{\hbar} \varphi_{\text{zp}1}^2 \varphi_{\text{zp}2} \sin \delta.$$

4 Josephson photomultiplier

- JPM operates as a **single-photon threshold detector**, generating a macroscopic “click” response upon the absorption of a single photon per operating cycle provided there is at least one photon in the measured mode

- JPM is a **capacitively-shunted rf SQUID**



- $|e\rangle$ lies close to the top of the barrier, so the excitation can relax to the eigenstates in the deep well and rapidly “fall” down to the bottom level.
- This results in a **classically distinguishable change** of the JPM flux state (“click”).
- By reading the JPM flux state, one infers whether the JPM has “clicked” or not.

5 Detector performance

- **Performance measure:**

Detection fidelity—the ability of the detector to distinguish a two-photon state from single-photon and vacuum states

$$\mathcal{F} = p_2 P_{\text{cl}|2} + p_{<2} (1 - P_{\text{cl}|<2}) = \frac{1}{2} (1 + P_{\text{cl}|2} - P_{\text{cl}|<2})$$

probability of 2 photon in the input state

probability of <2 photons in the input state

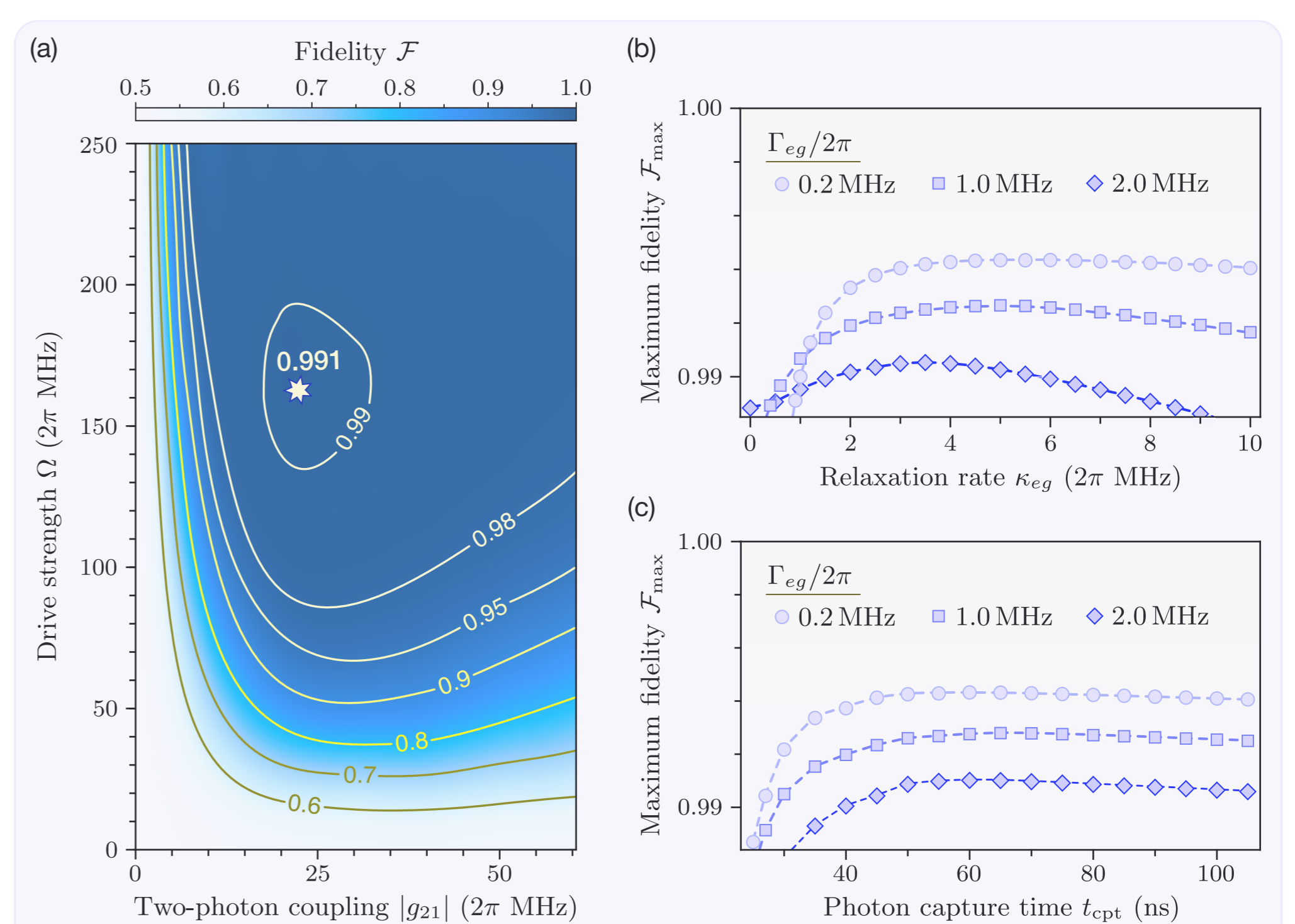
probability of correct discrimination of a 2-photon state from a state with <2 photons

probability of click when there are 2 photons (correct detection)

click probability when there is <2 photons (incorrect detection)

click probabilities are evaluated by solving the Lindblad ME that governs the quantum state evolution of the resonators-JPM system

Since we do not have a priori information about the input state, we assume $p_2 = p_{<2}$



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