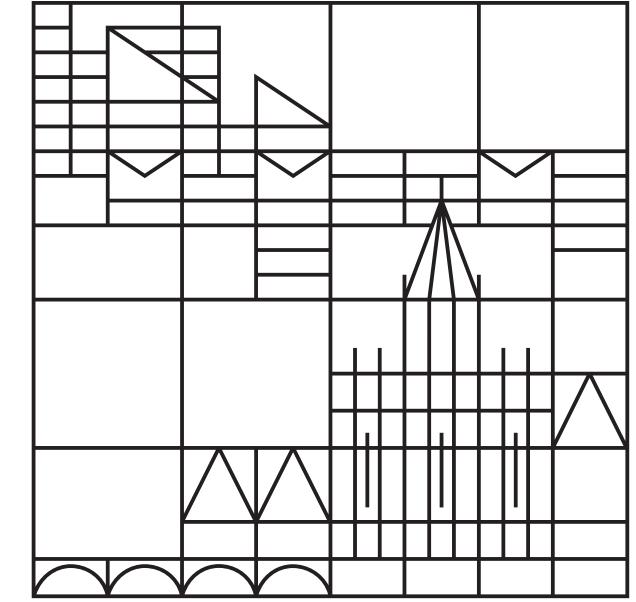


C03 Single-atom laser and single-photon pump in quantum-dot-based hybrid nanodevices

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Motivation and Goals

Hybrid mesoscopic devices: quantum dots (QDs) coupled to electromagnetic or mechanical resonators are a platform to tailor interactions between subsystems. They allow to explore new regimes of photon-electron and phonon-electron interaction and new mechanisms of heat exchange [1,2]

Mesoscopic transport (single-electron and Cooper-pair tunneling) can be exploited to drive harmonic resonators into **designed nonequilibrium states**

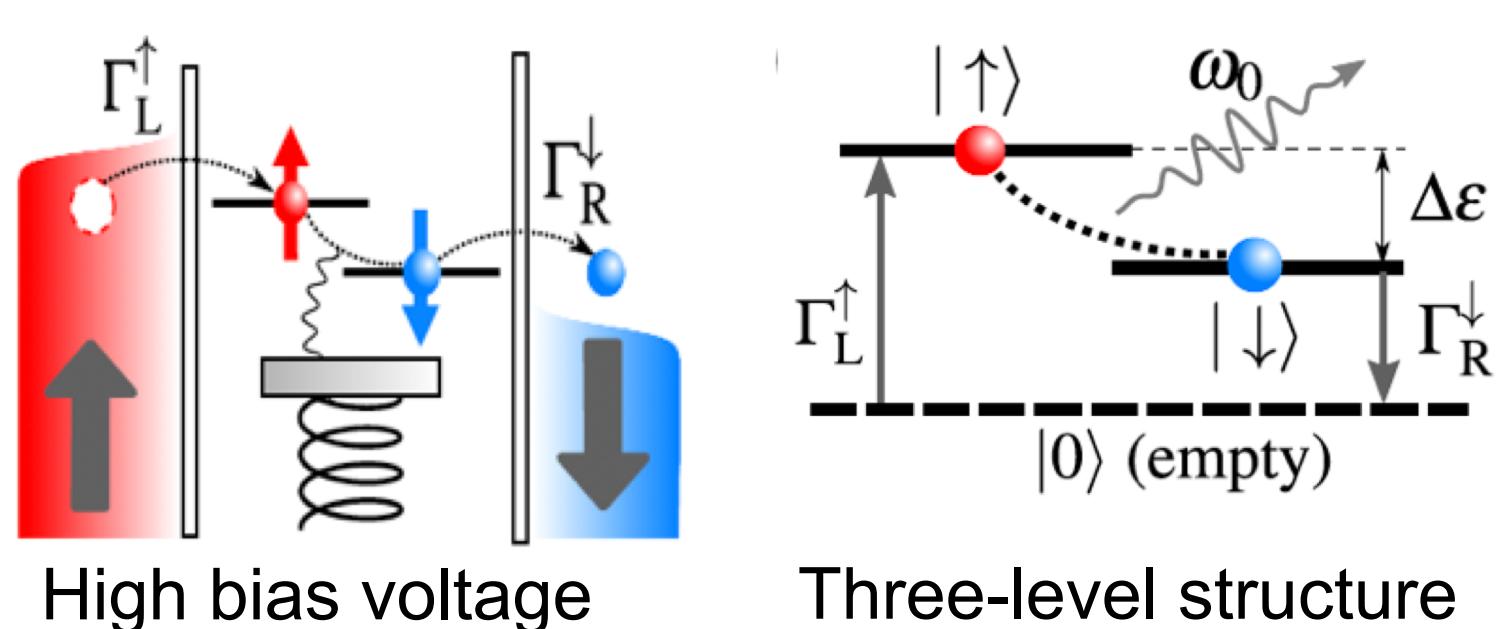
Main results:

- I. Multistability in a solid-state implementation of a single-atom laser and breakdown of rotating-wave approximation (RWA) without ultrastrong coupling [3]
- II. Simultaneous ground-state cooling and photon transfer between cavities using a Cooper-pair splitter (CPS) [4]

I. Spin-valve quantum-dot laser: breaking the RWA at weak coupling

System

QD embedded between ferromagnetic leads carrying **spin-polarized current**



Electron tunneling mediated by **spin-resonator coupling** to single resonator mode, with strength λ

Strong Coulomb interaction U in the dot: effective coherent dynamics given by **Rabi model**

$$H = \frac{\Delta\epsilon}{2}\sigma_z + \omega_0 b^\dagger b + \lambda\sigma_x(b + b^\dagger)$$

Q: quality factor of resonator

$$P_\alpha = \frac{\Gamma_\alpha^\uparrow - \Gamma_\alpha^\downarrow}{\Gamma_\alpha^\uparrow + \Gamma_\alpha^\downarrow} \text{ polarization}$$

$$P_L = -P_R = P$$

Methods

Master equation for system density matrix

Numerical solution for the steady state

$$b \approx \langle b \rangle \quad (\text{semiclassical approximation})$$

$$\dot{\rho} = -i[H, \rho] + \mathcal{L}_{\text{leads}}\rho + \mathcal{L}_d\rho$$

Nonlinear system of equations

Equivalence to three-level single-atom laser [5]

Results: breakdown of RWA and multistability

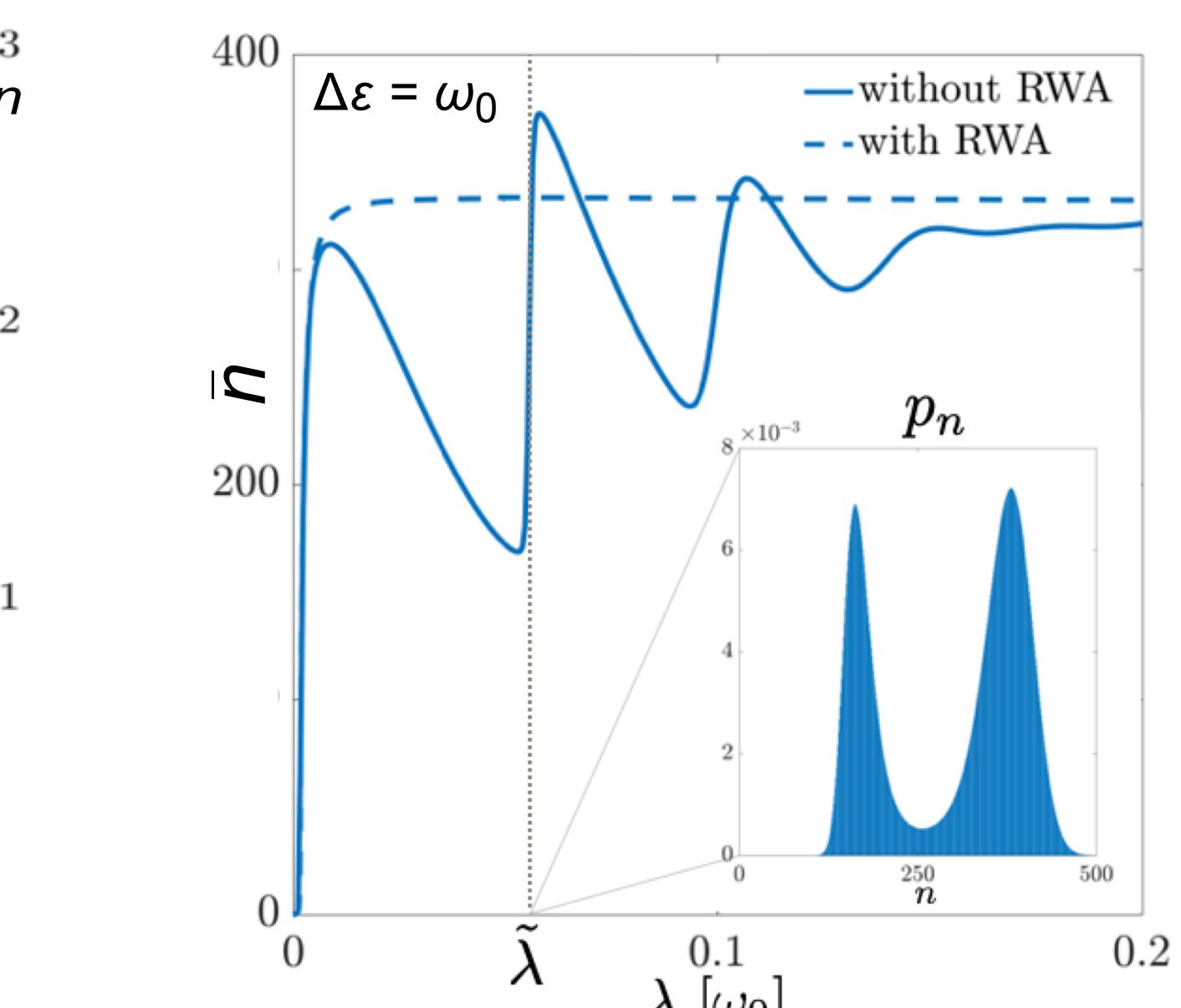
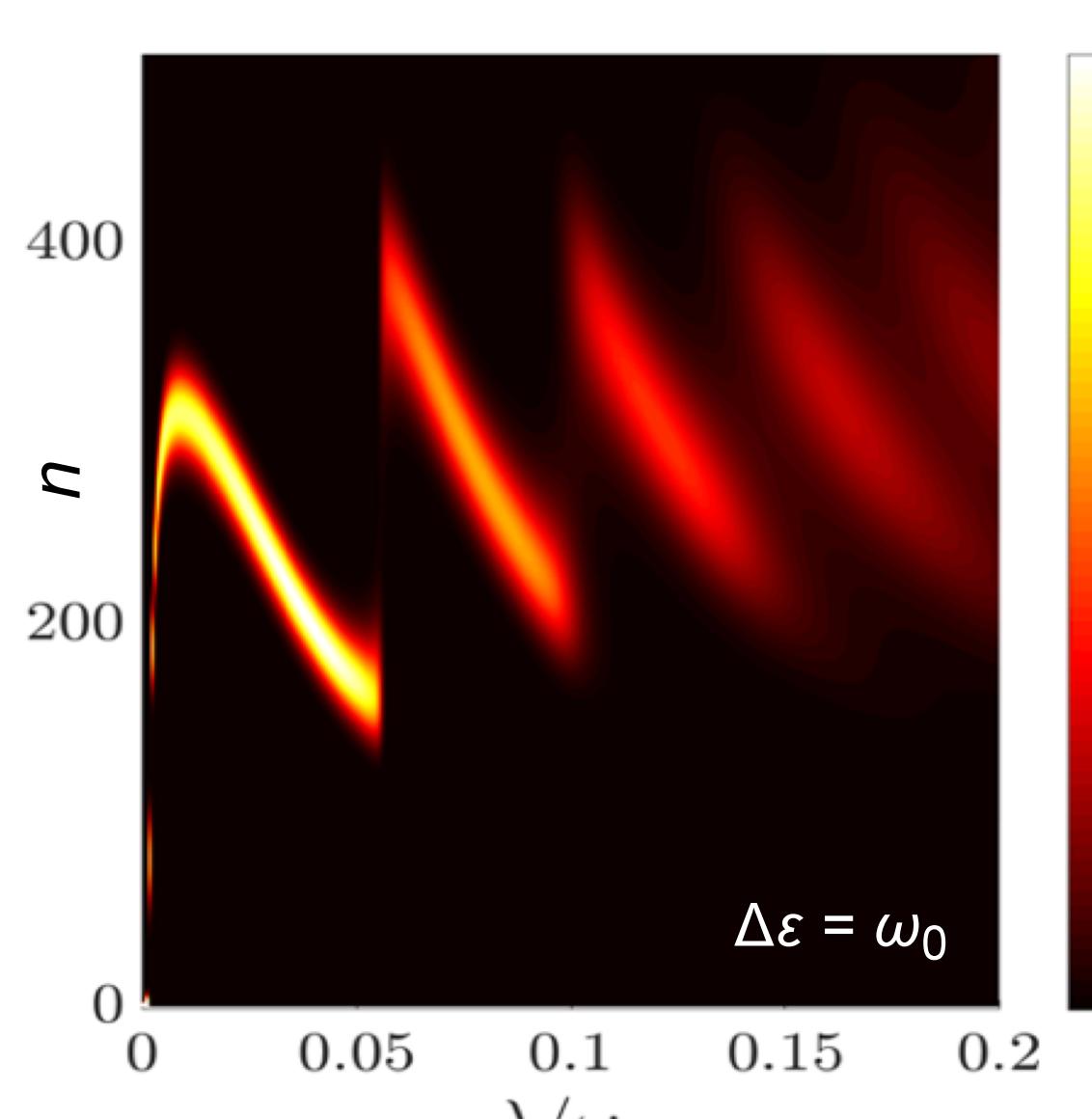
Jaynes-Cummings model: $H_{\text{RWA}} = \frac{\Delta\epsilon}{2}\sigma_z + \omega_0 b^\dagger b + \lambda(\sigma_+b + \sigma_-b^\dagger)$

Validity of RWA: $\lambda\sqrt{n} \ll \Delta\epsilon, \omega_0$

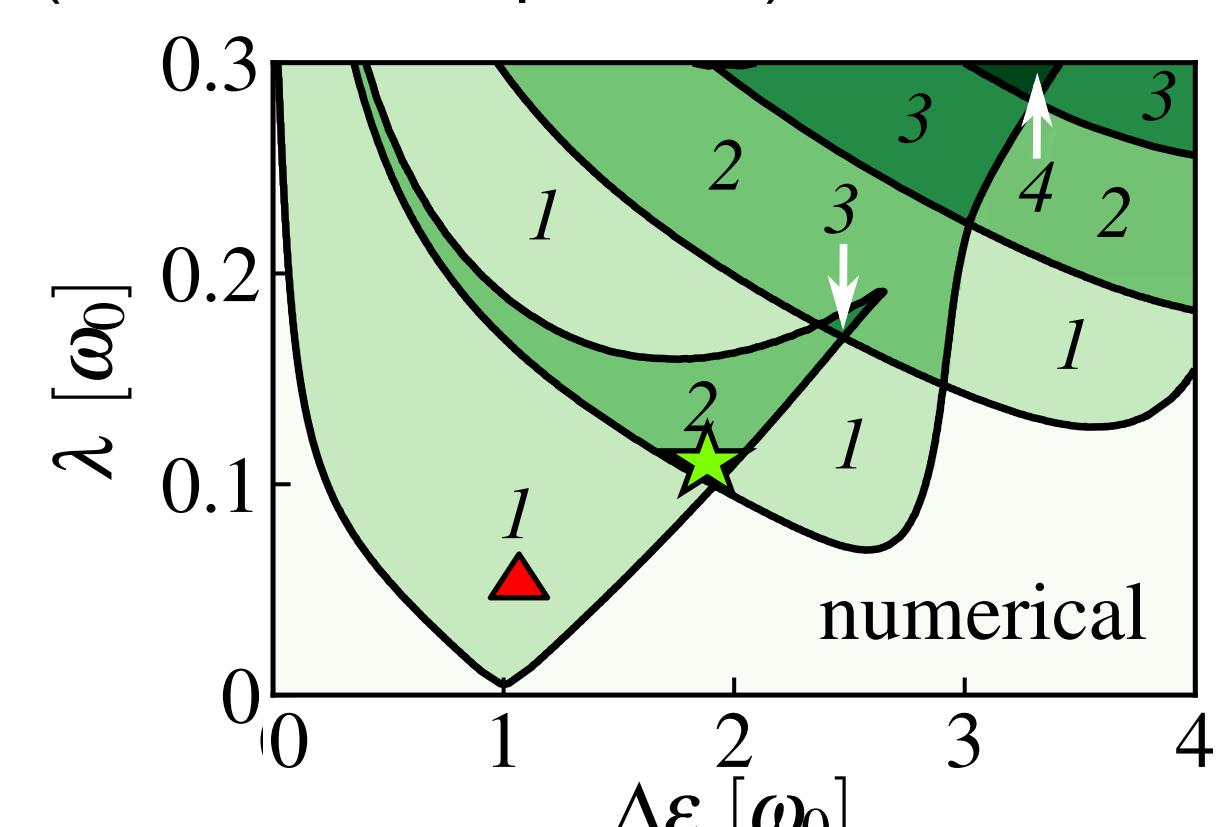
$$\text{threshold coupling } \lambda_{\text{thr}} = \sqrt{\frac{\Gamma_0}{4QP}}$$

$$n_{\text{sat}} = \frac{\Gamma_0 P}{3\omega_0}$$

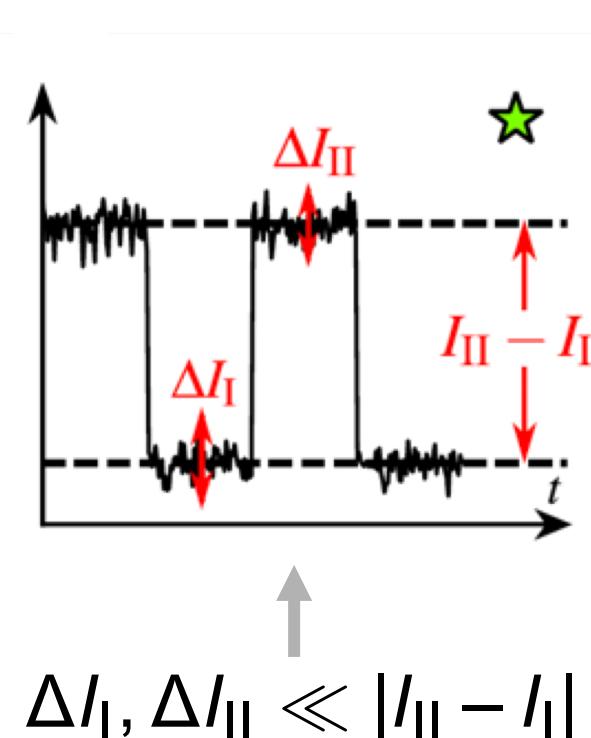
RWA breakdown without ultrastrong coupling: $\lambda\sqrt{n} \approx \omega_0$ achievable for $\lambda \ll \omega_0$



Stability diagram of resonator (# of stable amplitudes)



Detection of multistability through current measurement



II. Pumping photons between cavities with a Cooper-pair splitter

System

- Central superconductor proximitizing two QDs [7]
- QDs tunnel-coupled to negatively-biased normal leads
- Each QD capacitively coupled to **local resonator**

Coherent coupling between singlet and empty states: **Andreev bound states** $|\pm\rangle$

$$H = \sum_{\alpha\sigma} N_{\alpha\sigma} - \frac{\Gamma_S}{2}(d_{R\uparrow}^\dagger d_{L\downarrow}^\dagger - d_{R\downarrow}^\dagger d_{L\uparrow}^\dagger + \text{H.c.}) + \sum_{\alpha} \omega_{\alpha} b_{\alpha}^\dagger b_{\alpha} + \sum_{\alpha\sigma} \lambda_{\alpha}(b_{\alpha} + b_{\alpha}^\dagger)N_{\alpha\sigma}$$

Methods

- Transition rates between eigenstates calculated through Fermi's Golden Rule
- Master equation for eigenstates populations [8]

$$\dot{P}_i = \sum_j (w_{i\leftarrow j}P_j - w_{j\leftarrow i}P_i)$$

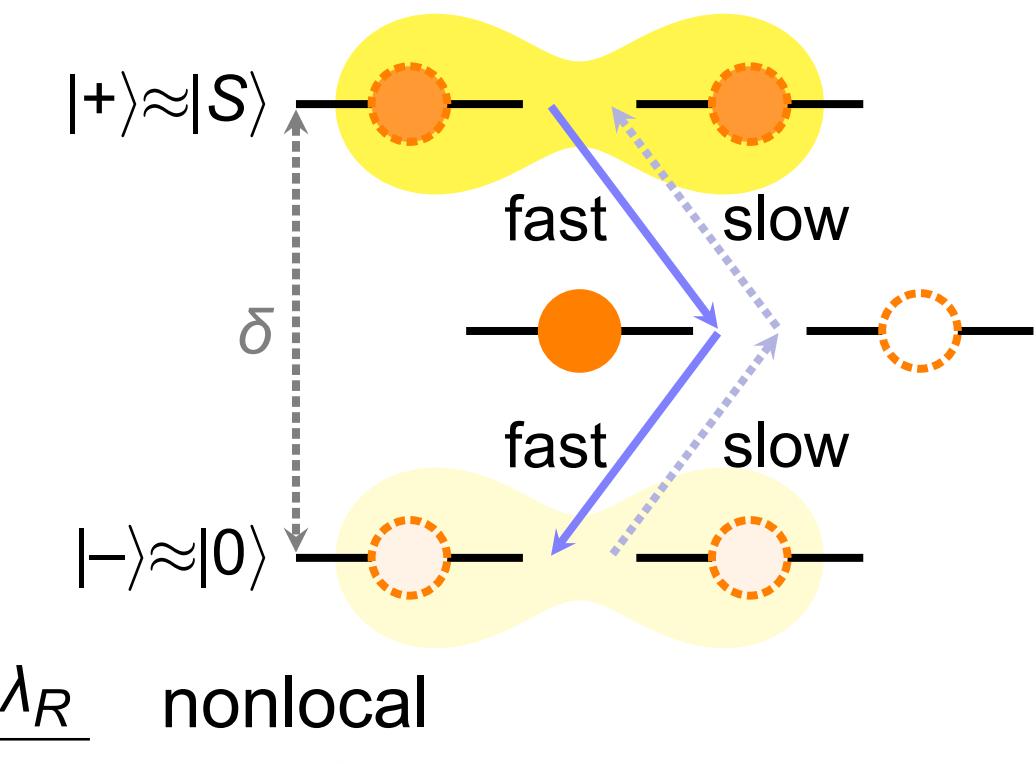
Numerical solution for steady populations

Results: nonlocal photon transfer between cavities

Energy splitting of Andreev states: $\delta = \sqrt{4\epsilon^2 + 2\Gamma_S^2}$

$|\epsilon| \gtrsim \Gamma_S \rightarrow$ weak charge hybridization

$\epsilon > 0 \rightarrow |+\rangle \approx |S\rangle, |-\rangle \approx |0\rangle \rightarrow$ strong asymmetry in transition rates

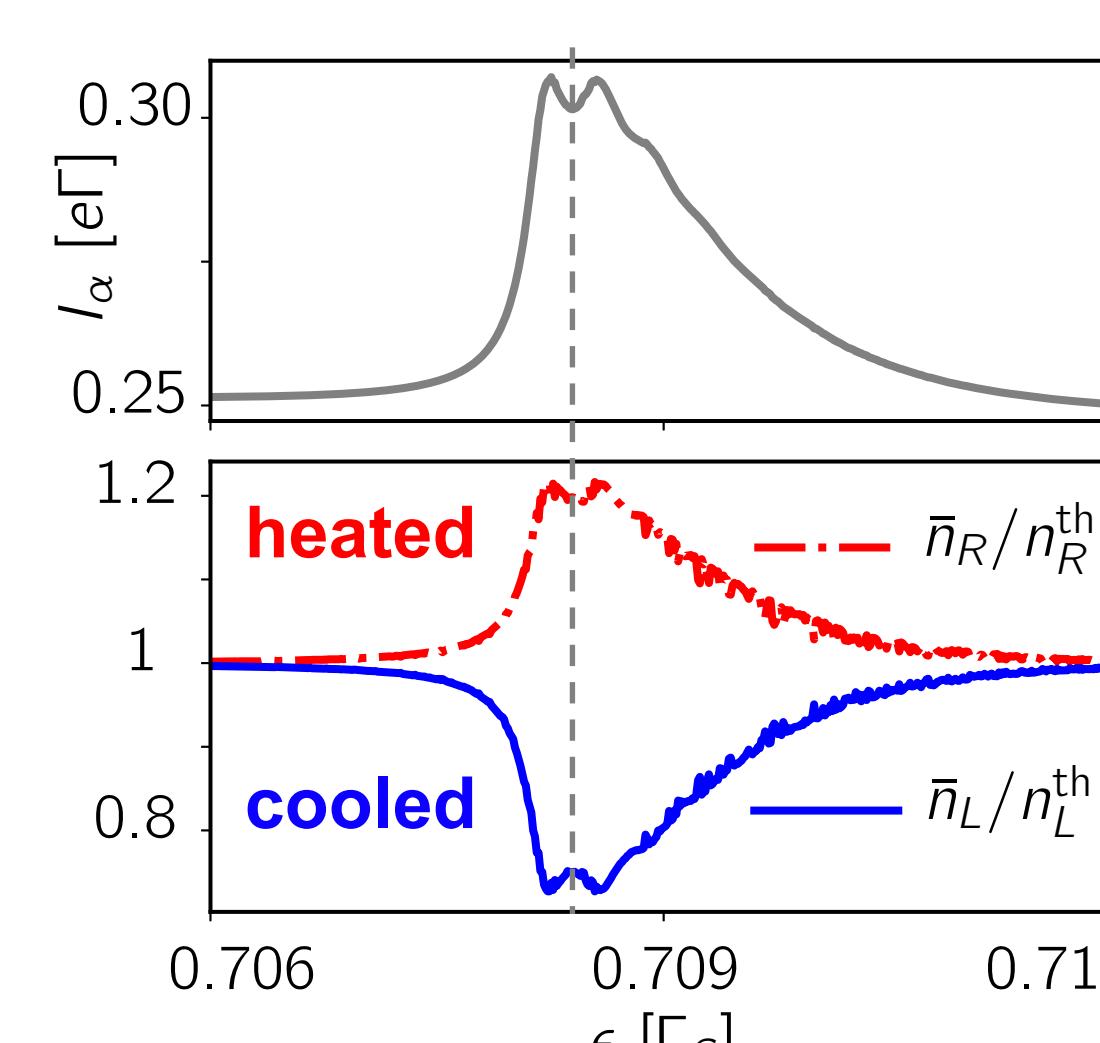


Resonance: $\delta(\epsilon) \approx \omega_L - \omega_R$

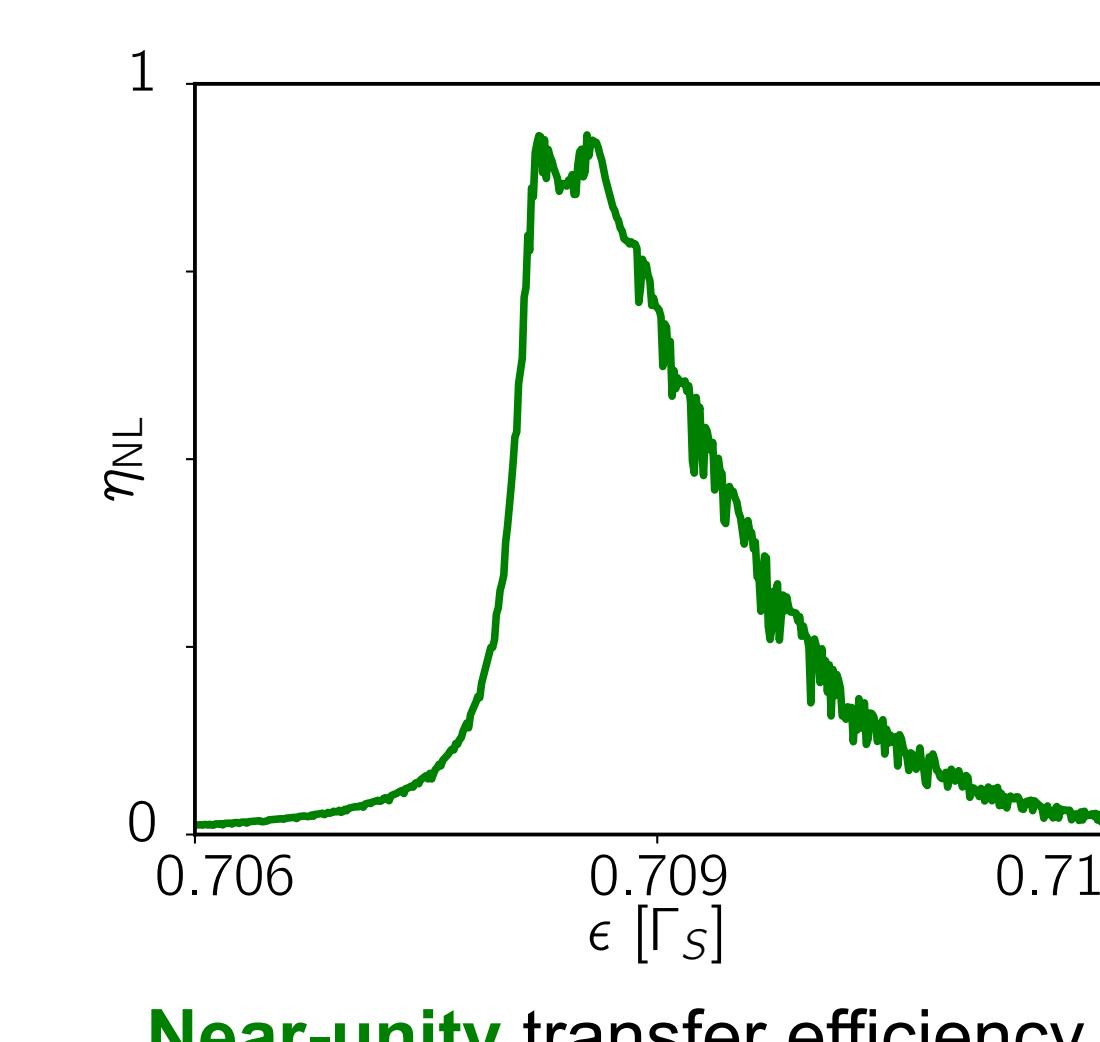
$$H_{\text{eff}} = \lambda_{\text{NL}}(b_L^\dagger b_R |-\rangle\langle| + b_L b_R^\dagger |+\rangle\langle|-)$$

$$\lambda_{\text{NL}} \approx \frac{\Gamma_S \epsilon}{\delta} \frac{\lambda_L \lambda_R}{\omega_L \omega_R} \text{ nonlocal coupling}$$

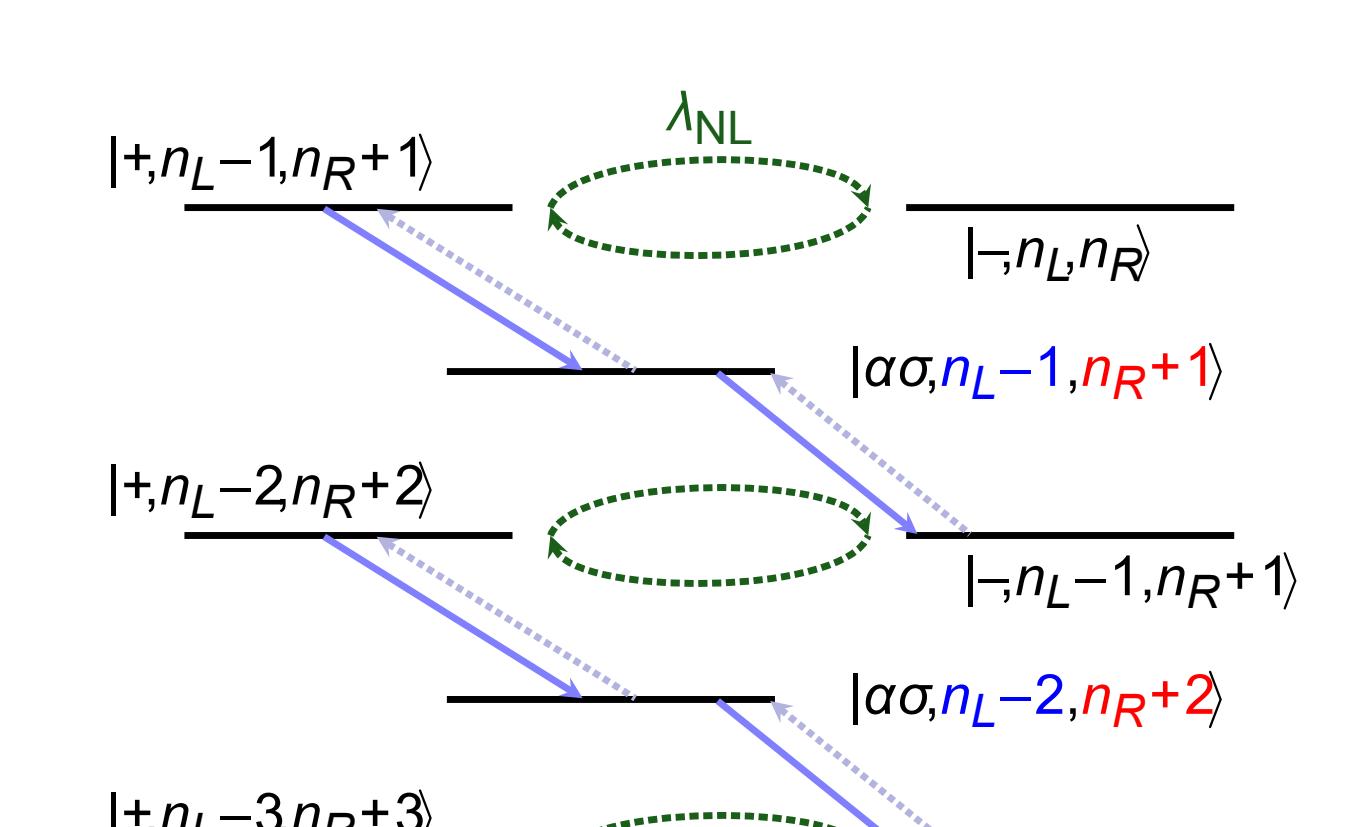
Current and photon occupation



Efficiency of photon transfer



Photon transfer mechanism



Energy quanta transferred per unit time: $|\dot{E}_L - \dot{E}_R| / (\omega_L - \omega_R)$

Rate of Cooper-pair injection: $(I_L + I_R)/(2e)$

Photons transferred per CP:

$$\eta_{\text{NL}} = \frac{2e|\dot{E}_L - \dot{E}_R|}{(I_L + I_R)(\omega_L - \omega_R)}$$

References

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