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]

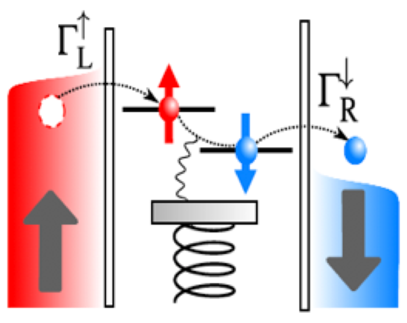
I. Spin-valve quantum-dot laser: breaking the RWA at weak coupling

System

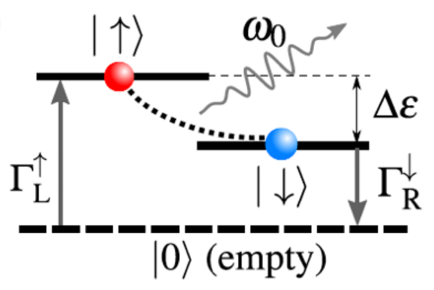
QD embedded between ferromagnetic leads carrying **spin-polarized current**

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**



High bias voltage



Three-level structure

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

Q: quality factor of resonator

$$P_\alpha = \frac{\Gamma_\alpha^\uparrow - \Gamma_\alpha^\downarrow}{\Gamma_\alpha^\uparrow + \Gamma_\alpha^\downarrow} \quad \text{polarization} \qquad P_L = -P_R = P$$

Methods

Master equation for system density matrix

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

Numerical solution for the steady state

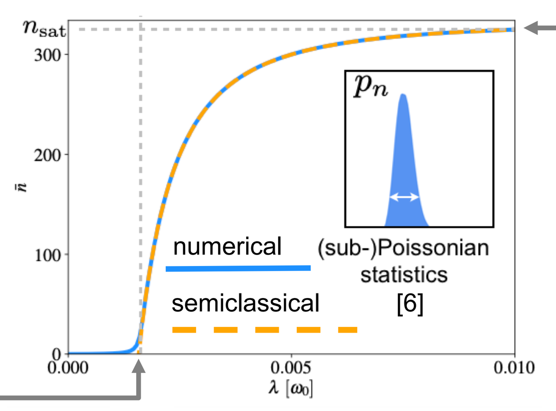
$b \approx \langle b\rangle$ (**semiclassical approximation**) → Nonlinear system of equations → Equivalence to three-level single-atom laser [5]

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

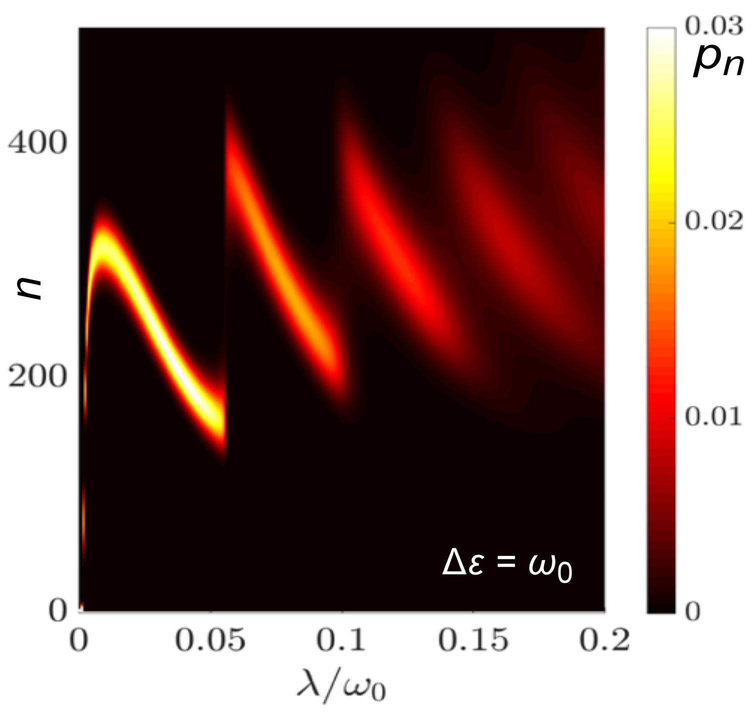
threshold coupling $\lambda_{\text{thr}} = \sqrt{\frac{\Gamma\omega_0}{4QP}}$

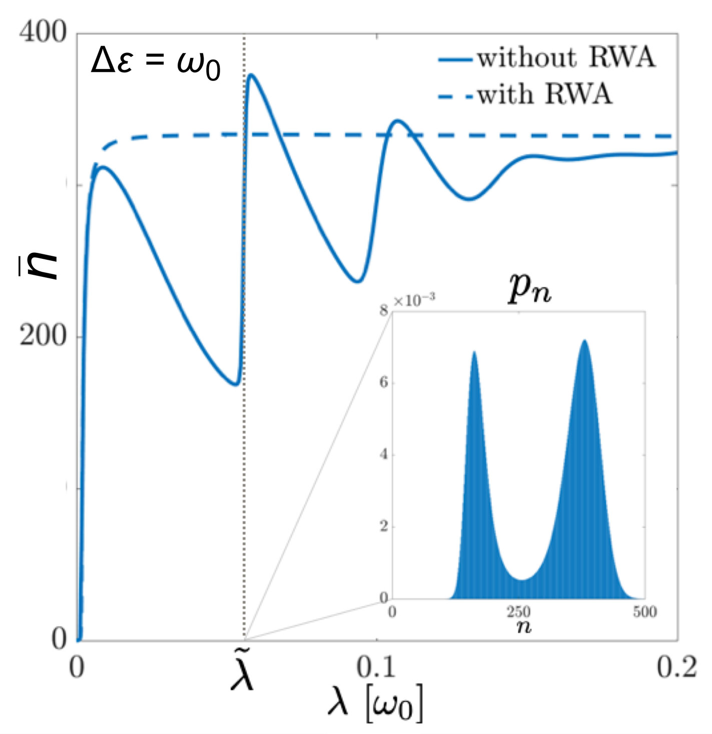


saturation

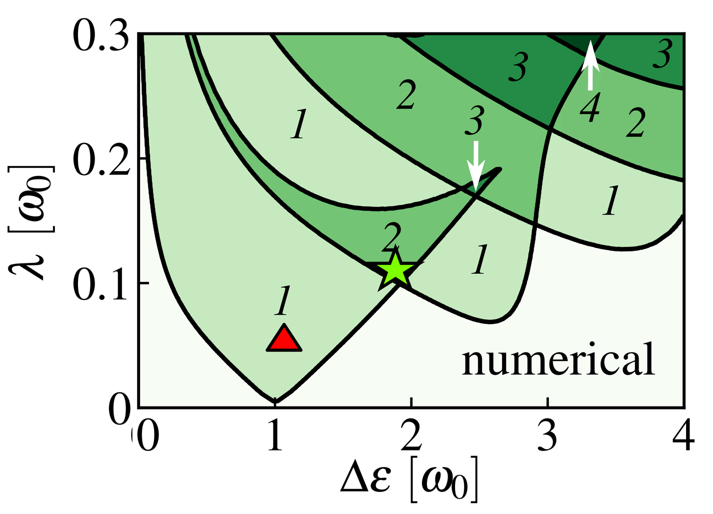
$n_{\text{sat}} = \frac{\Gamma QP}{3\omega_0}$

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

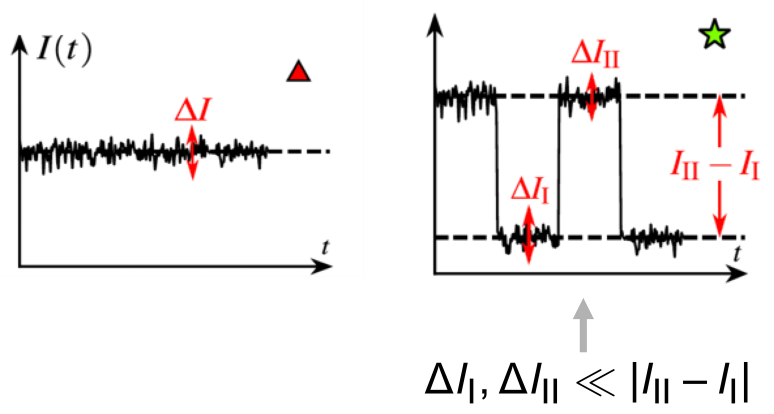




Stability diagram of resonator (# of stable amplitudes)

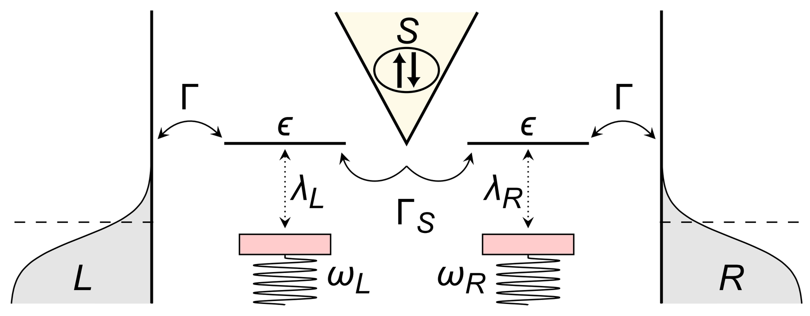


Detection of multistability through **current measurement**



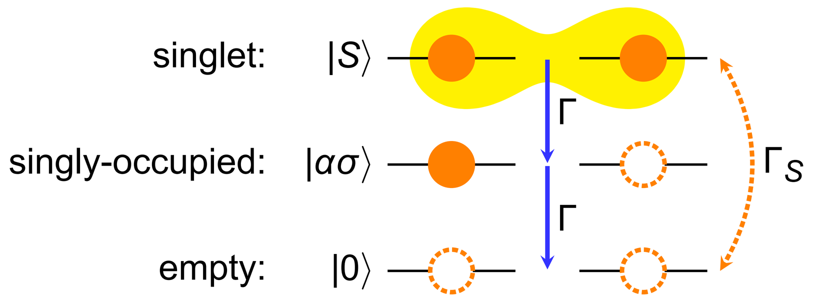
$\Delta I_I, \Delta I_{II} \ll |I_{II} - I_I|$

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



System

- Central superconductor proximizing 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]

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

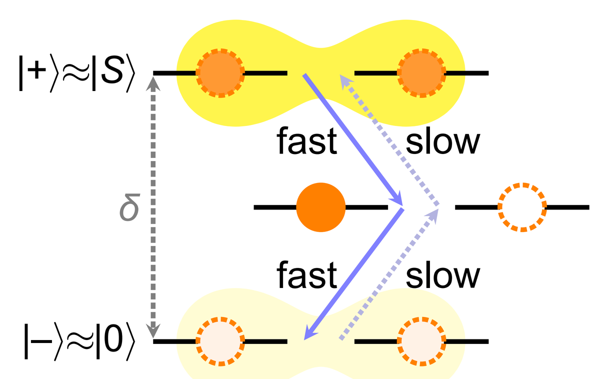
Numerical solution for steady populations

Results: nonlocal photon transfer between cavities

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

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

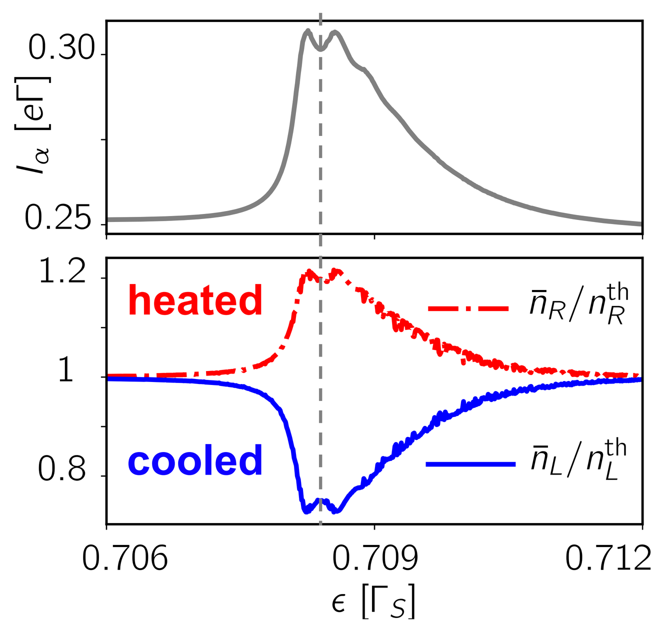
$\epsilon > 0$ → $|+\rangle \approx |S\rangle$, $|-\rangle \approx |0\rangle$ → strong asymmetry in transition rates



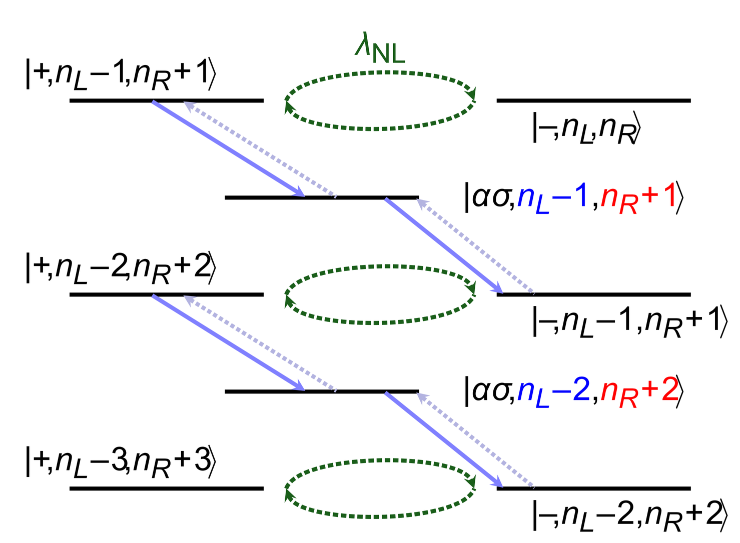
Resonance: $\delta(\epsilon) \approx \omega_L - \omega_R$

$H_{\text{eff}} = \lambda_{\text{NL}}(b_L^\dagger b_R|-\rangle\langle+| + b_L b_R^\dagger|+\rangle\langle-|)$ $\qquad \lambda_{\text{NL}} \approx \frac{\Gamma_S\epsilon}{\delta}\frac{\lambda_L\lambda_R}{\omega_L\omega_R}$ nonlocal coupling

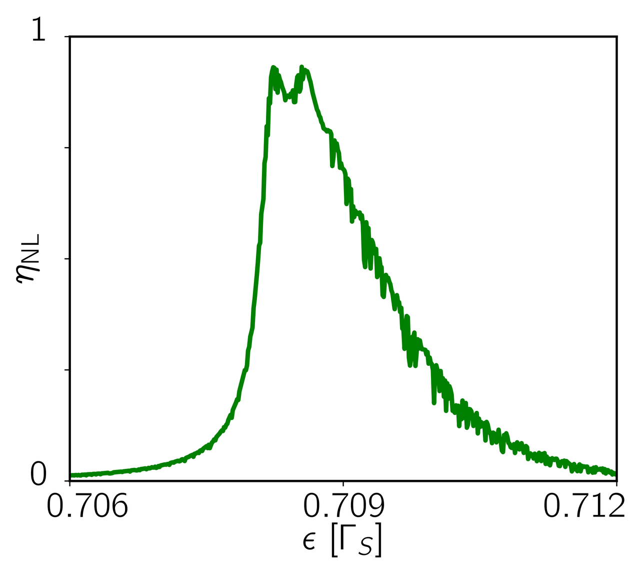
Current and photon occupation



Photon transfer mechanism



Efficiency of photon transfer



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:

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

Near-unity transfer efficiency

References

[1] X. Mi *et al.*, Nature **555**, 599 (2018).
[2] J.J. Viennot *et al.*, Science **349**, 408 (2015).
[3] **M. Mantovani** *et al.*, PRB **99**, 045442 (2019).
[4] **M. Mantovani** *et al.*, PRR **1**, 0330xx (2019).
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[6] H. Carmichael and L. Orozco, Nature **425**, 246 (2003).
[7] R. Hussein *et al.*, PRB **94**, 235134 (2012).
[8] M. Governale *et al.*, PRB **77**, 134513 (2008).

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