Driven-Dissipative Quantum Dot Circuit-QED systems

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Phys. Rev. B, **94**, 035434 (2016)
Phys. Rev. B, **94**, 121305 **(R)** (2016)

Collaboration

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B. K. Agarwalla (Toronto)
S. Mukamel (Irvine)
D. Segal (Toronto)
Y. Imry (Weizmann)
R. Hartle (Göttingen)

Also,

Phys. Rev. B **92**, 045309 (2015)
Phys. Rev. B **91**, 245429 (2015)
Phys. Rev. B, **90**, 125402 (2014)

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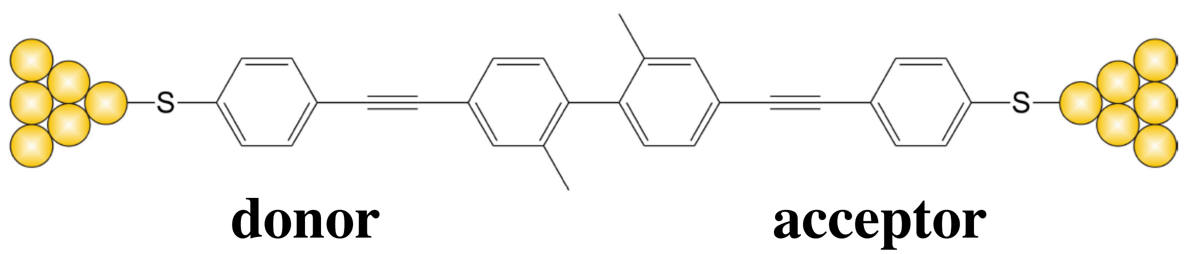
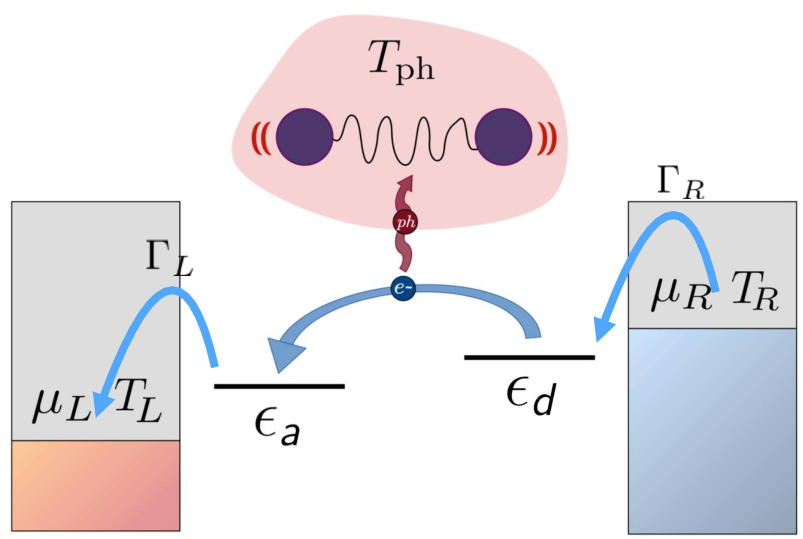
Engineered Hybrid Quantum Systems:

Electron-vibration interaction:
(Nano-Electromechanical system)



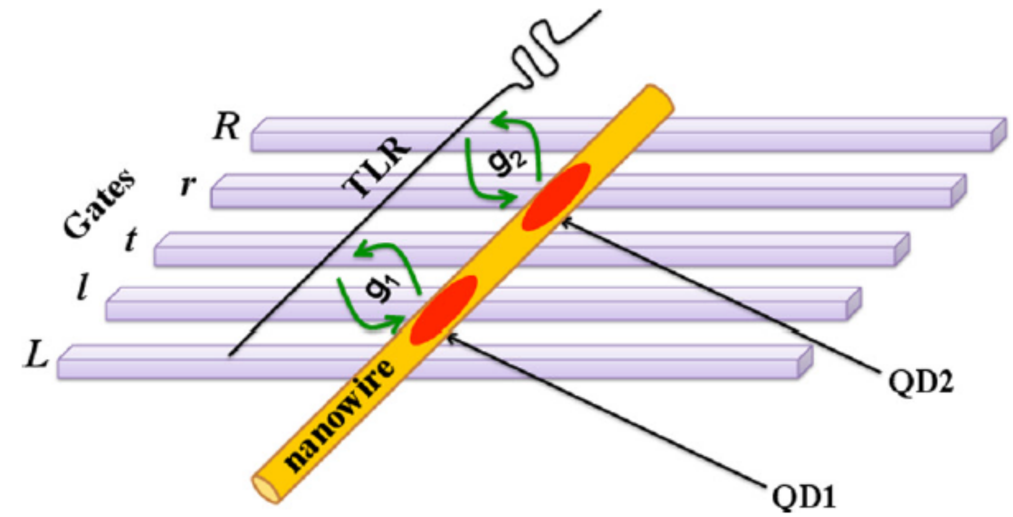
Ballman et al., Phys. Rev. Lett. 109, 056801 (2012)



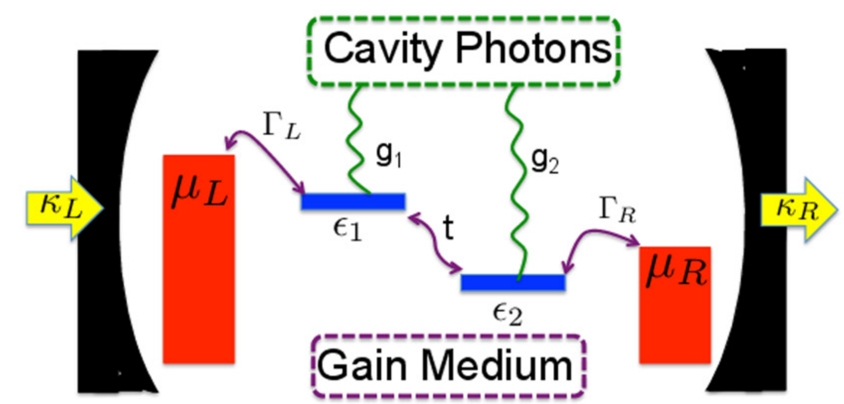
Donor-Acceptor model

Hartle, **Kulkarni,** Phys. Rev. B 91, 245429 (2015)
Analogy between molecular junctions and QD-cQED systems

Electron-Photon interaction:
Circuit-Quantum Electrodynamics



… , J Petta et al, **Nature 490**, 380 (2012)

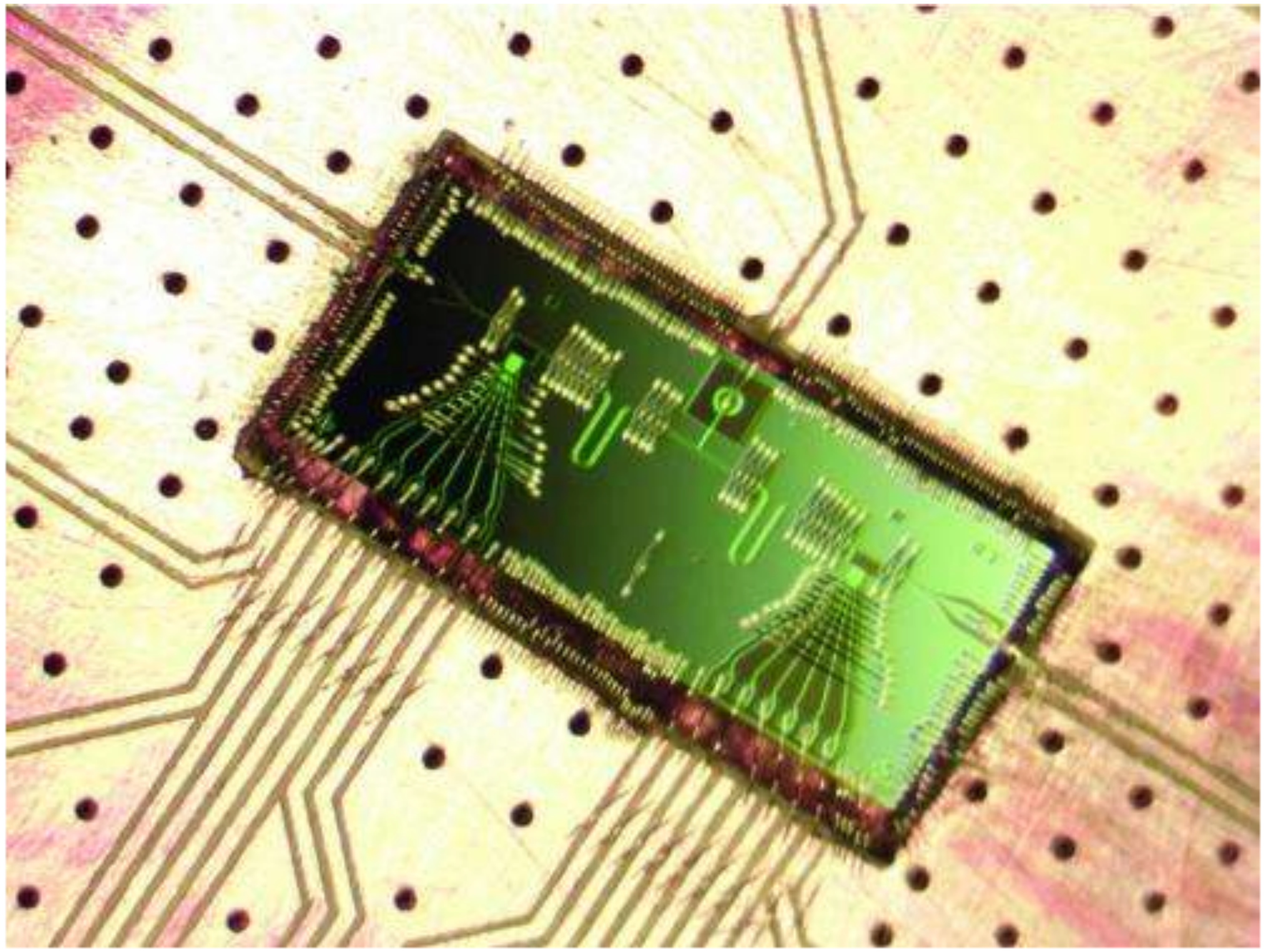


dc transport of electrons lead to photon emission: micromasers

PHYS.ORG

Rice-sized laser, powered one electron at a time, bodes well for quantum computing

January 15, 2015



Princeton University researchers have built a rice grain-sized microwave laser. Credit: Jason Petta, Princeton University

Science **347**, 285 (2015)
Petta Lab Princetron

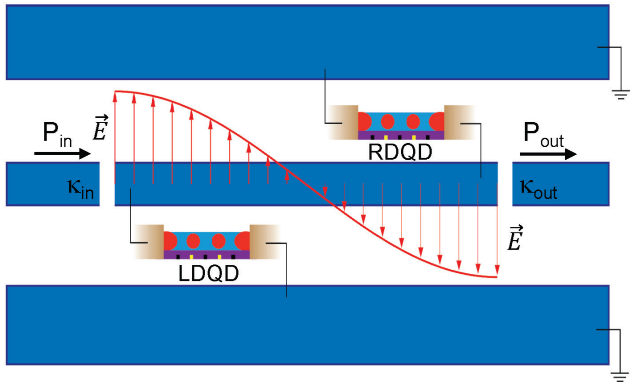
Circuit Quantum Electrodynamics Experiments

Experiments:

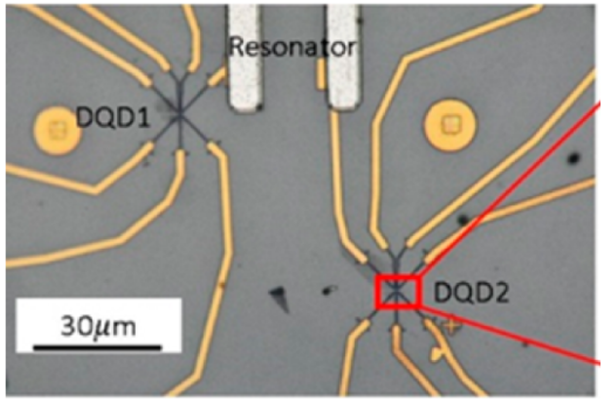
- **Experiments are widely tunable: Access to new parameter regimes**

- **Many circuit geometries can be achieved** : Thanks to versatile nano fabrication techniques

Photonic Gain (micromaser)



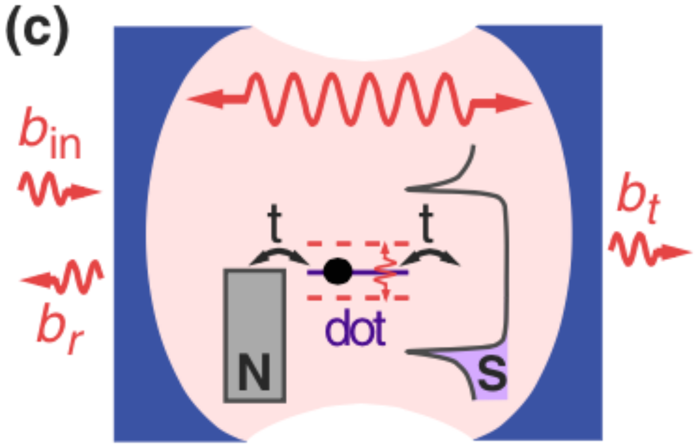
Science **347**, 285 (2015)



Nano Lett. 15, 6620 (**2015**),

photon mediated coupling between two distant quantum dots

- **Various types of Fermionic contacts**: *Normal, Superconducting, Ferromagnetic*



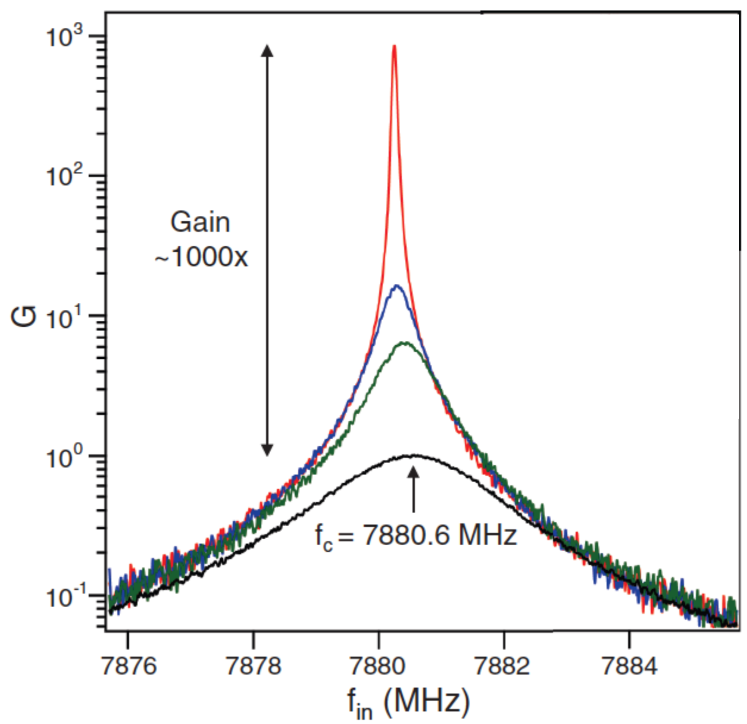
PHYS. REV. X **6**, 021014 (2016)

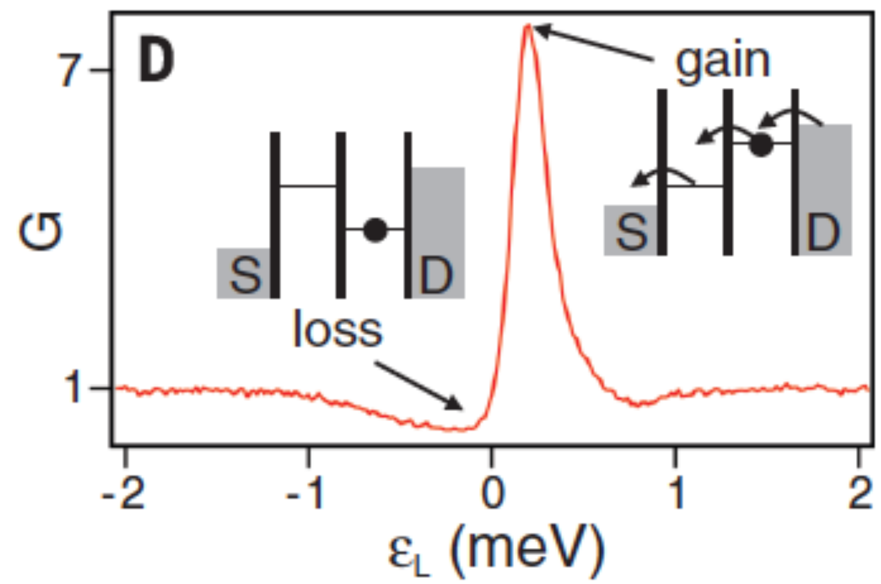
Excellent test bed to answer fundamental questions in quantum optics and quantum impurity systems

Experimental observables

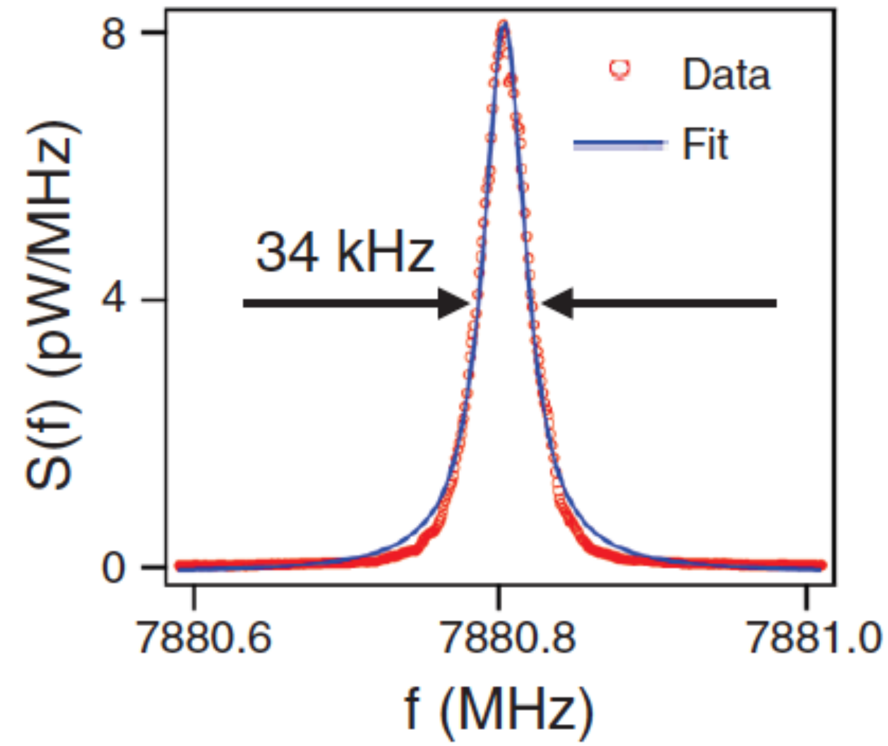
Photonic Measurements:

Photon Transmission (Gain)

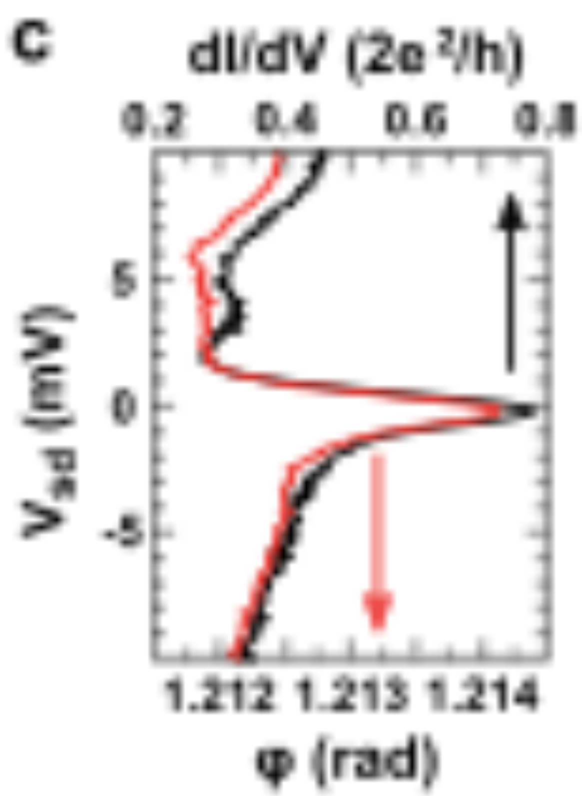




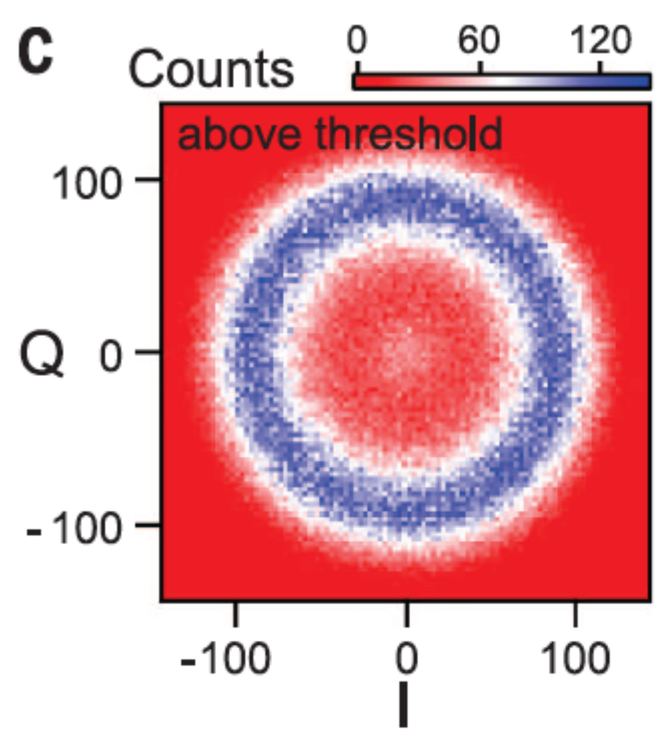
Emission Spectrum

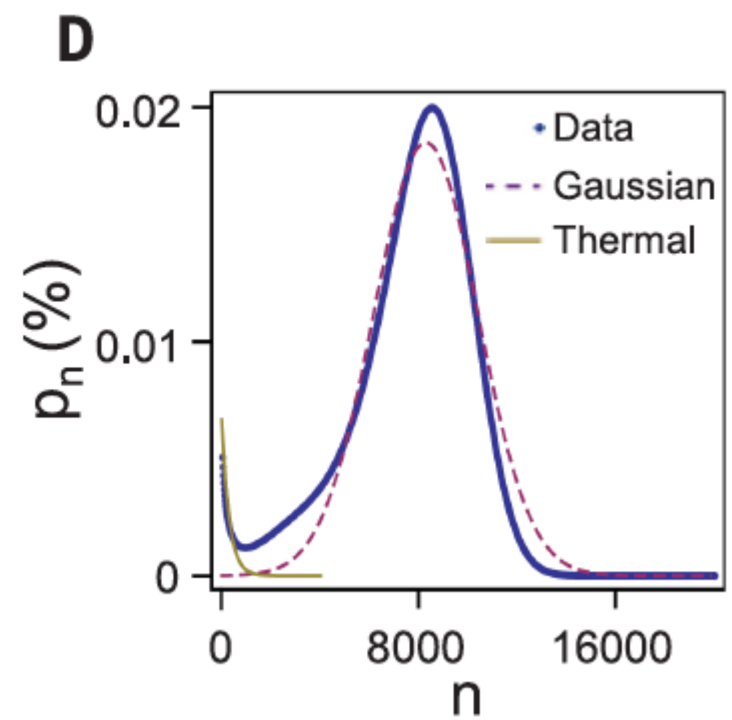


phase spectroscopy



Photon counting statistics





Model and Hamiltonian

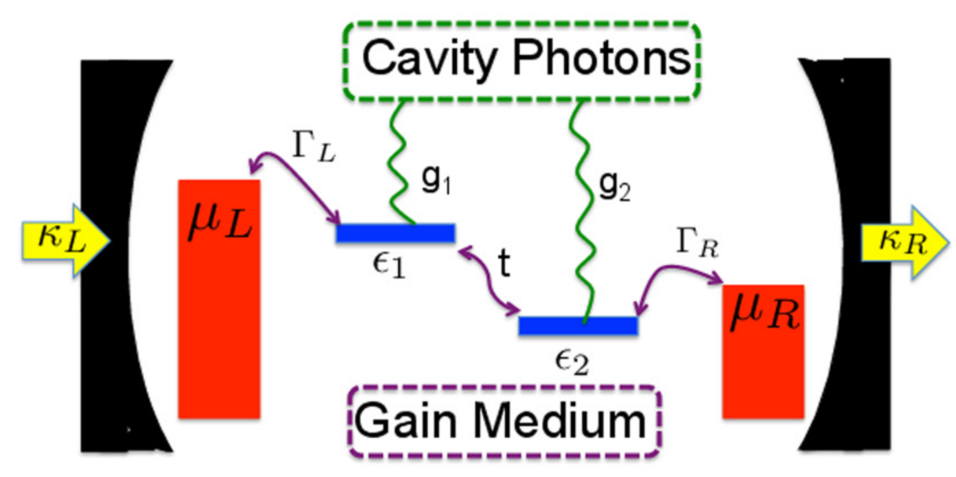
$$\hat{H}_T = \hat{H}_{el} + \hat{H}_{ph} + \hat{H}_{el-ph}$$

$$\hat{H}_{el} = \epsilon_1 \hat{c}_1^\dagger \hat{c}_1 + \epsilon_2 \hat{c}_2^\dagger \hat{c}_2 + t(\hat{c}_1^\dagger \hat{c}_2 + \hat{c}_2^\dagger \hat{c}_1) + \sum_{l \in L} \epsilon_l \hat{c}_l^\dagger \hat{c}_l$$

$$+ \sum_{r \in R} \epsilon_r \hat{c}_r^\dagger \hat{c}_r + \sum_{l \in L} v_l (\hat{c}_l^\dagger \hat{c}_1 + \hat{c}_1^\dagger \hat{c}_l) + \sum_{r \in R} v_r (\hat{c}_r^\dagger \hat{c}_2 + \hat{c}_2^\dagger \hat{c}_r)$$

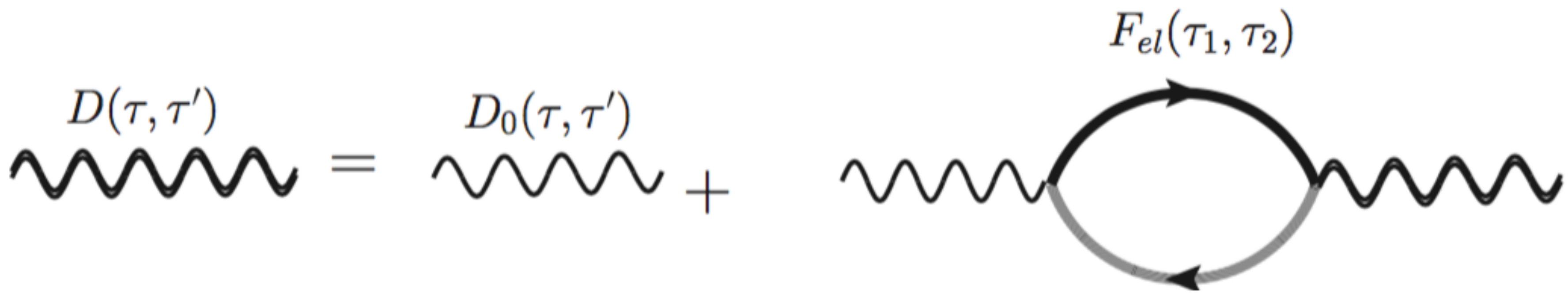
$$\hat{H}_{ph} = \omega_0 \hat{a}^\dagger \hat{a} + \sum_{j \in K} \omega_{jK} \hat{a}_{jK}^\dagger \hat{a}_{jK} + \sum_{j \in K} \nu_j \hat{a}_{jK}^\dagger \hat{a} + \mathrm{H.c.}$$

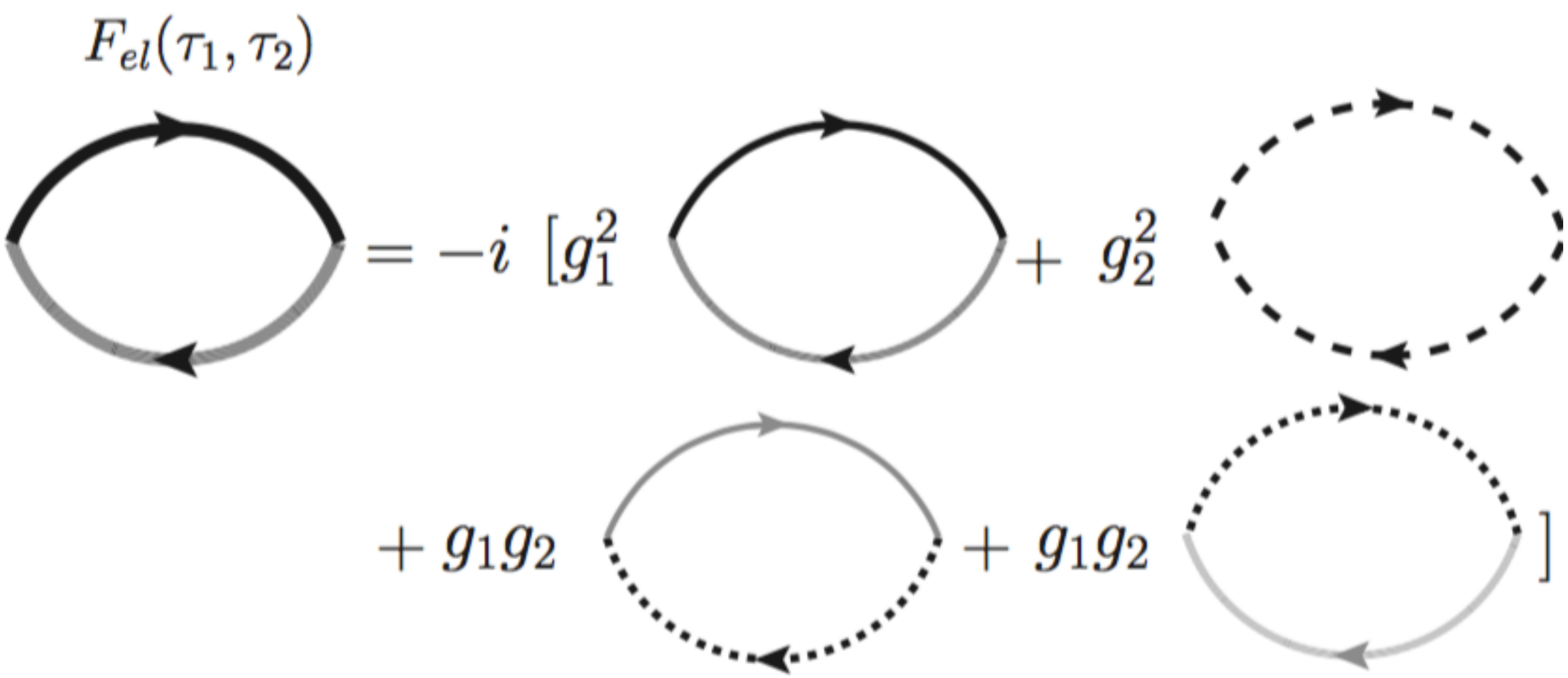
$$\hat{H}_{el-ph} = [g_1 \hat{n}_1 + g_2 \hat{n}_2](\hat{a}^\dagger + \hat{a})$$



Keldysh diagrammatic nonequilibrium Green's function

$$D(\tau,\tau') \equiv -i\langle T_c \hat{a}(\tau)\hat{a}^{\dagger}(\tau')\rangle$$ Photon





B. K. Agarwalla, **M. Kulkarni**, S. Mukamel, D. Segal, Phys. Rev. B, **94**, 035434 (2016)

Quantities of Interest

$$D(\tau,\tau') \equiv -i\langle T_c \hat{a}(\tau)\hat{a}^\dagger(\tau')\rangle$$

$$\langle \hat{n}_c\rangle \equiv i\int_{-\infty}^{\infty}\frac{d\omega}{2\pi}D^<(\omega)$$

Photon number

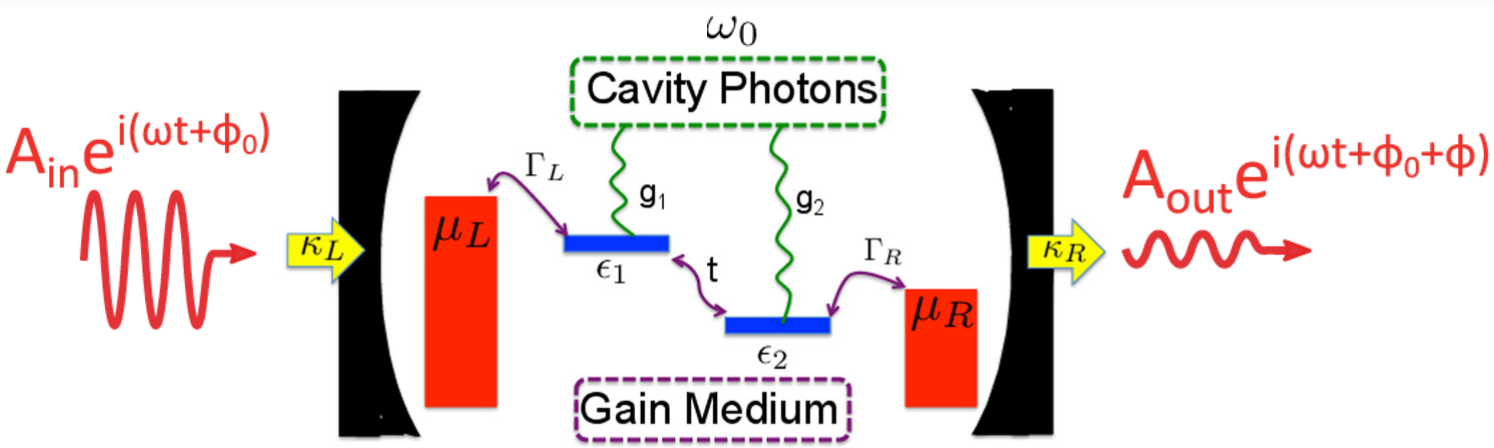
$$S(\omega) = \int_{-\infty}^{\infty} dt\,\langle \hat{a}^\dagger(0)\hat{a}(t)\rangle e^{i\omega t} = i\,D^<(\omega)$$

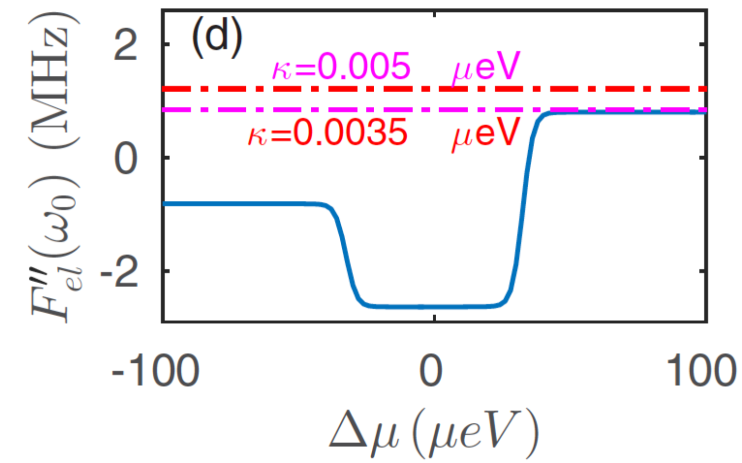
Power Spectrum

$$t(\omega) = \frac{i\kappa}{(\omega-\omega_0)+i\kappa-\chi_{el}^r(\omega)} = i\kappa D^r(\omega)$$

Transmission and Phase-Response

Principles for Giant Photon Gain





- **Transmission function (GAIN) in microwave photon**

cavity decay rate

Response function of the cavity mode

$$t(\omega) \equiv i\kappa D^r(\omega) = \frac{i\kappa}{(\omega - \omega_0 - F'_{el}(\omega)) + i(\kappa - F''_{el}(\omega))}$$

$$D^r(t) = -i\theta(t)\langle[a(t), a^\dagger(0)]\rangle$$

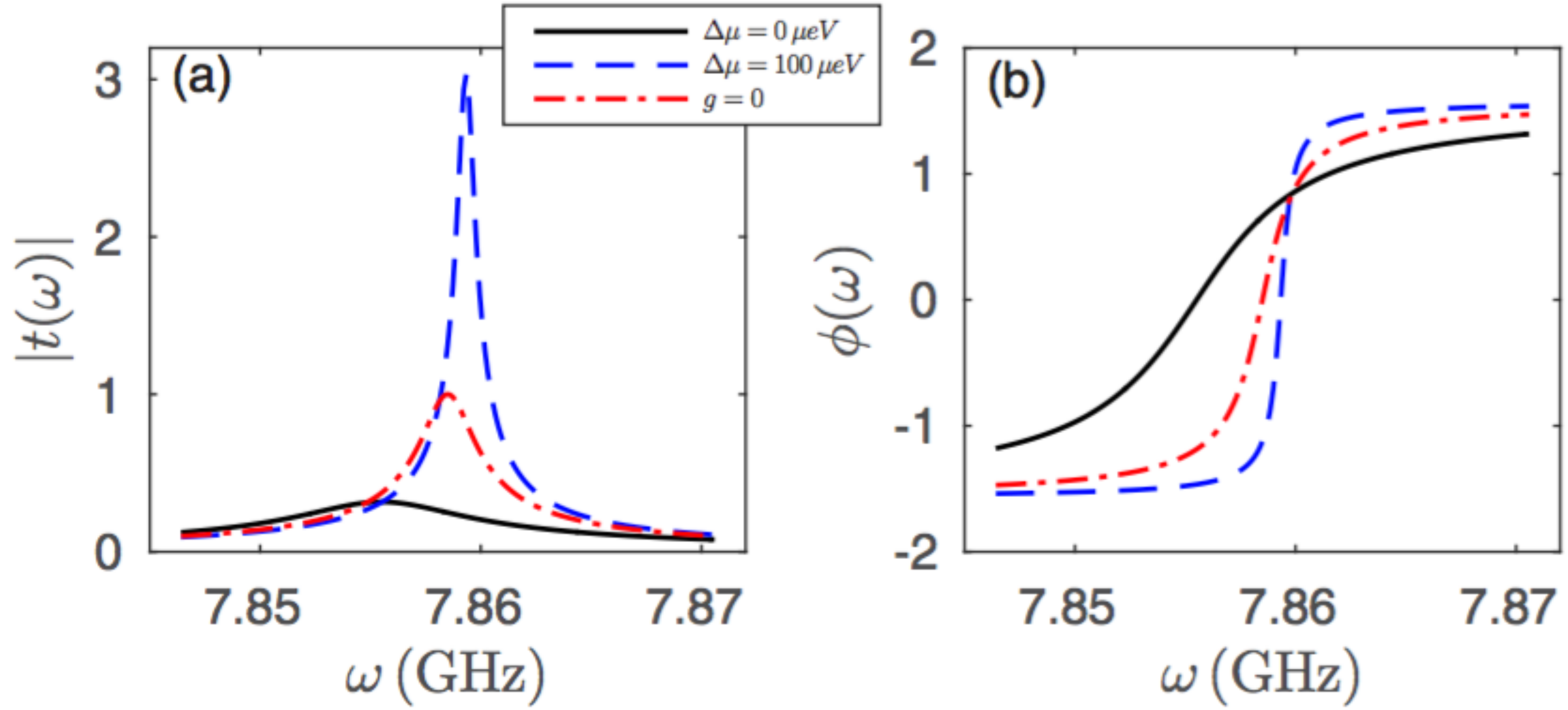
Electronic Property: Flip signs for finite current

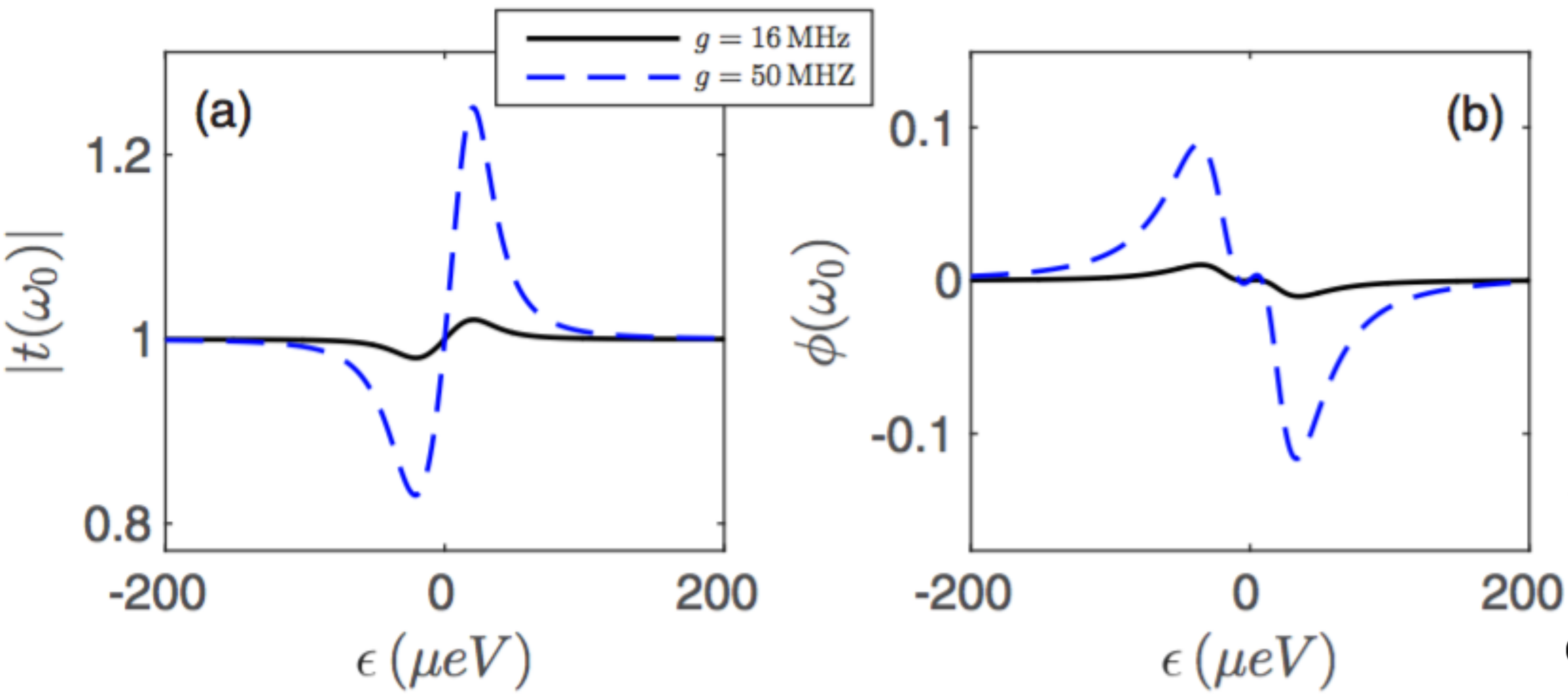
- **Exact Result (NEGF):**

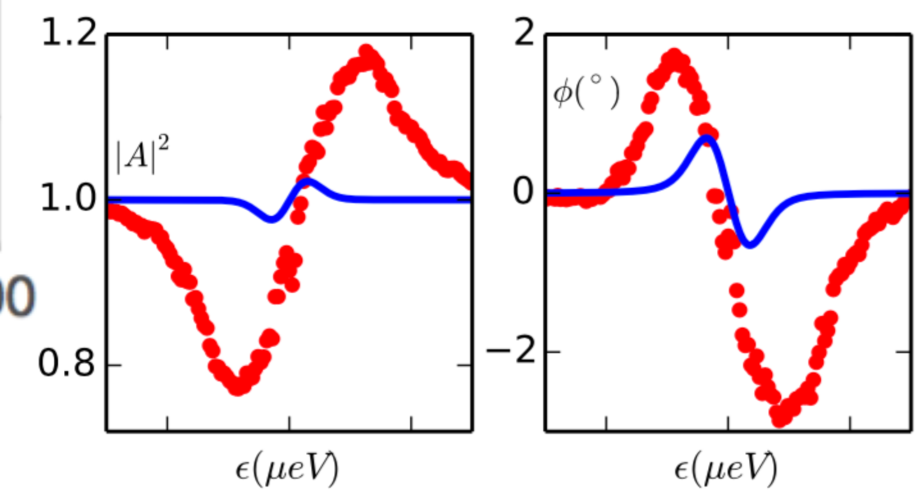
Sum Rule for Transmission	$\int_{-\infty}^{\infty} \frac{d\omega}{2\pi} t(\omega) = \frac{\kappa}{2}$

cavity decay rate

B. K. Agarwalla, **M. Kulkarni**, S. Mukamel, D. Segal, Phys. Rev. B, **94**, 035434 (2016)
B. K. Agarwalla, **M. Kulkarni**, S. Mukamel, D. Segal, Phys. Rev. B, **94**, 121305 (**R**) (2016)





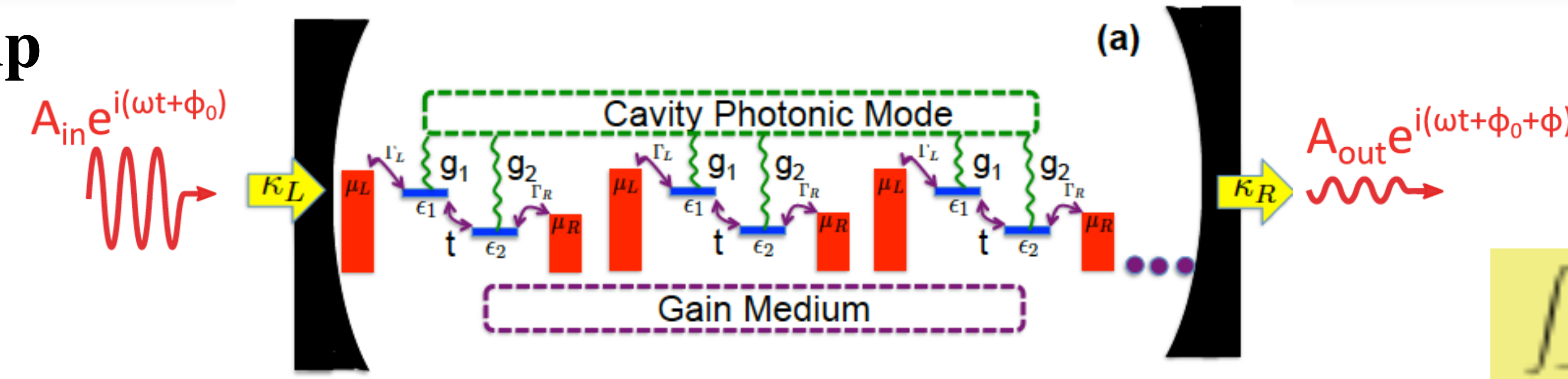


Princeton Experiment (Red)

Kulkarni, Cotlet, Tureci **(PRB 2014)**

Principles for Giant Photon Gain

- **N-DQD Setup**



Sum Rule

$$\int_{-\infty}^{\infty} \frac{d\omega}{2\pi}\, t(\omega) = \frac{\kappa}{2}$$

Transmission function

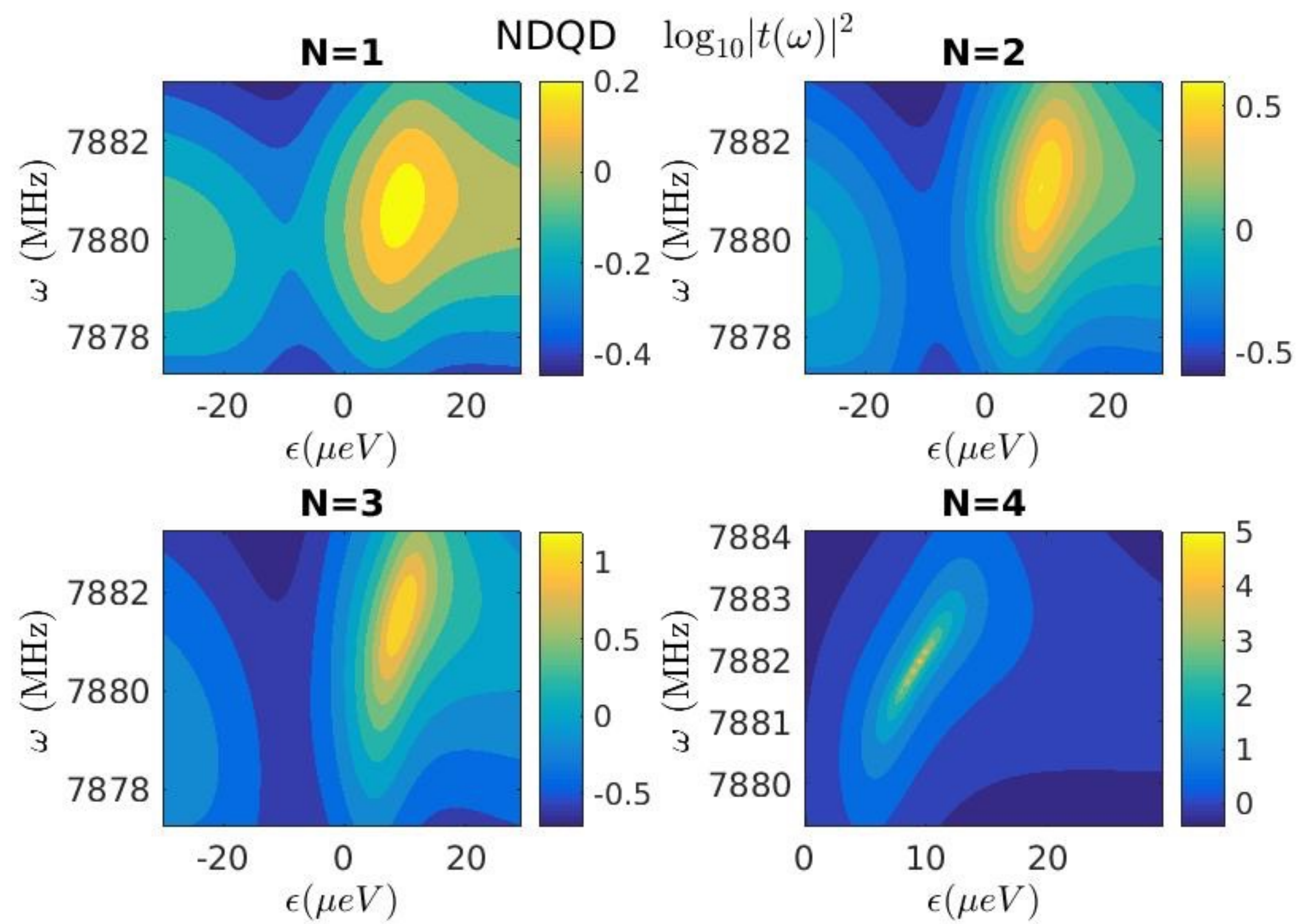
$$t(\omega) = \frac{i\kappa}{\big(\omega-\omega_0-NF'_{el}(\omega)\big)+i\big(\kappa-NF''_{el}(\omega_0)\big)}$$

- **Power Spectrum**

$$S(\omega) = i\frac{N\,F^{<}_{el}(\omega)}{\left[\omega-\omega_c-N\,F'_{el}(\omega)\right]^2+\left[\kappa-N\,F''_{el}(\omega)\right]^2}$$

- **Average photon number**

$$\langle \hat{n}_c\rangle = \frac{i\,N\,F^{<}_{el}(\omega_c)}{2\left[\kappa-N\,F''_{el}(\omega_c)\right]}$$



B. K. Agarwalla, M. **Kulkarni**, S. Mukamel, D. Segal, Phys. Rev. B, **94**, 121305 **(R)** (2016)

Conclusions

- We study the photonic and electronic properties of a non-equilibrium quantum dot coupled to a micro wave resonator
- DQD electronic system can serve as a gain medium for the cavity photons
- Key for realizing photon-source quantum devices,
- Major step forward towards quantum Hamiltonian and bath engineering of hybrid quantum systems (fighting dissipation)
- Identified photon-induced contributions to the current at both positive and negative detuning.

Phys. Rev. B, **94**, 035434 (2016), Phys. Rev. B, **94**, 121305 **(R)** (2016)

Outlook

Non-perturbative method for treating electron-photon interactions in multi-terminal setups
(work in progress -- Lu, Wang, Jiang, **Kulkarni**)

Exploring photon statistics, masing (work in progress -- Agarwalla, **Kulkarni**)

Rectification/Diodes (work in progress --- Lu, Wang, Jiang, **Kulkarni**)

Understanding heavy Fermions / Kondo physics with photons