

Quantum Behavior in Mesoscale Lasers

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4.00pm Monday June 17, 2019, Session 1P14 FocusSession.SC3: Nanophotonics 2, Room 24 - 2nd Floor

Outline

The macroscopic semiconductor laser diode

- Second-order non-equilibrium phase transition with optical field as the order parameter
- Fluctuations enhance lasing emission below laser threshold and contribute to temperature dependence of semiconductor laser diode threshold current

Semiclassical master equations to describe mesolasers

- Comparison between mean-field and probabilistic picture
- Semiclassical system trajectories and photon blinking modelled by the Monte Carlo method

A quantum mechanical meso-laser model

- Steady-state properties as a function of pump and number of emitters
- Photon Fano-factor, excitation pinning, emission linewidth
- Symmetry-protected long-lived emitter states in meso-lasers

Future challenges

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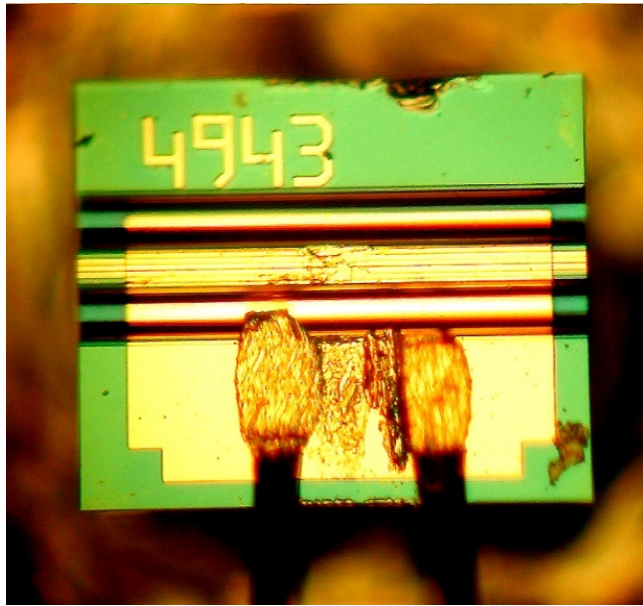
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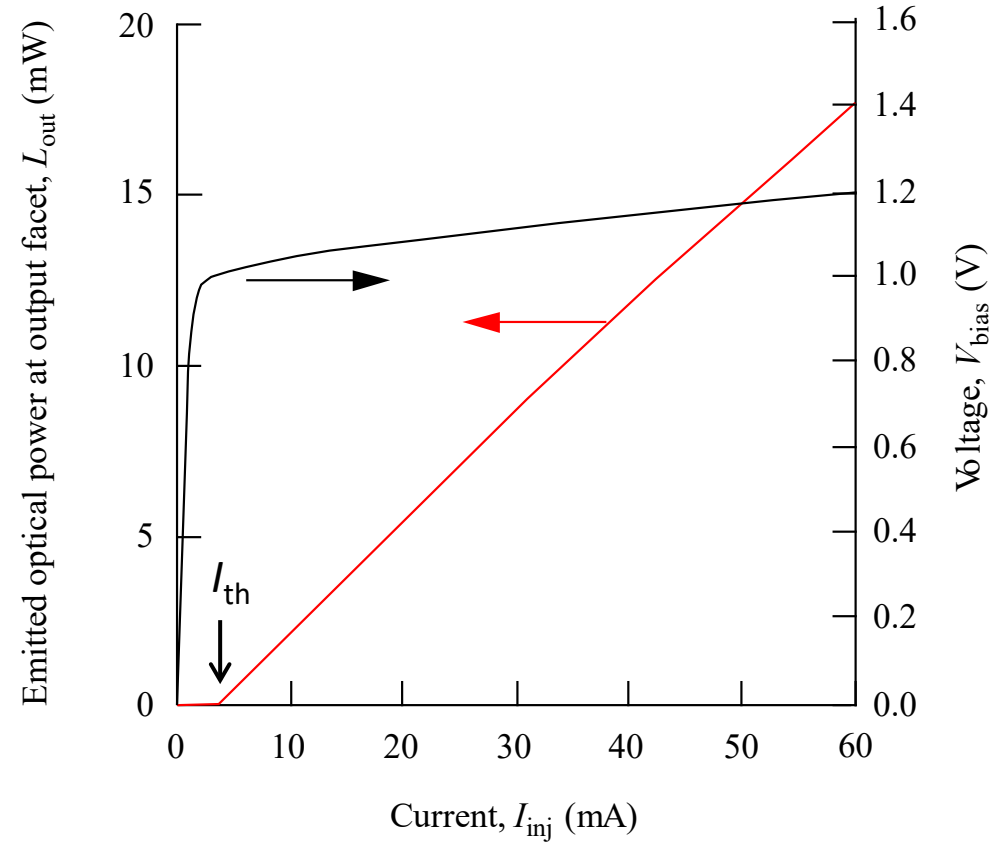
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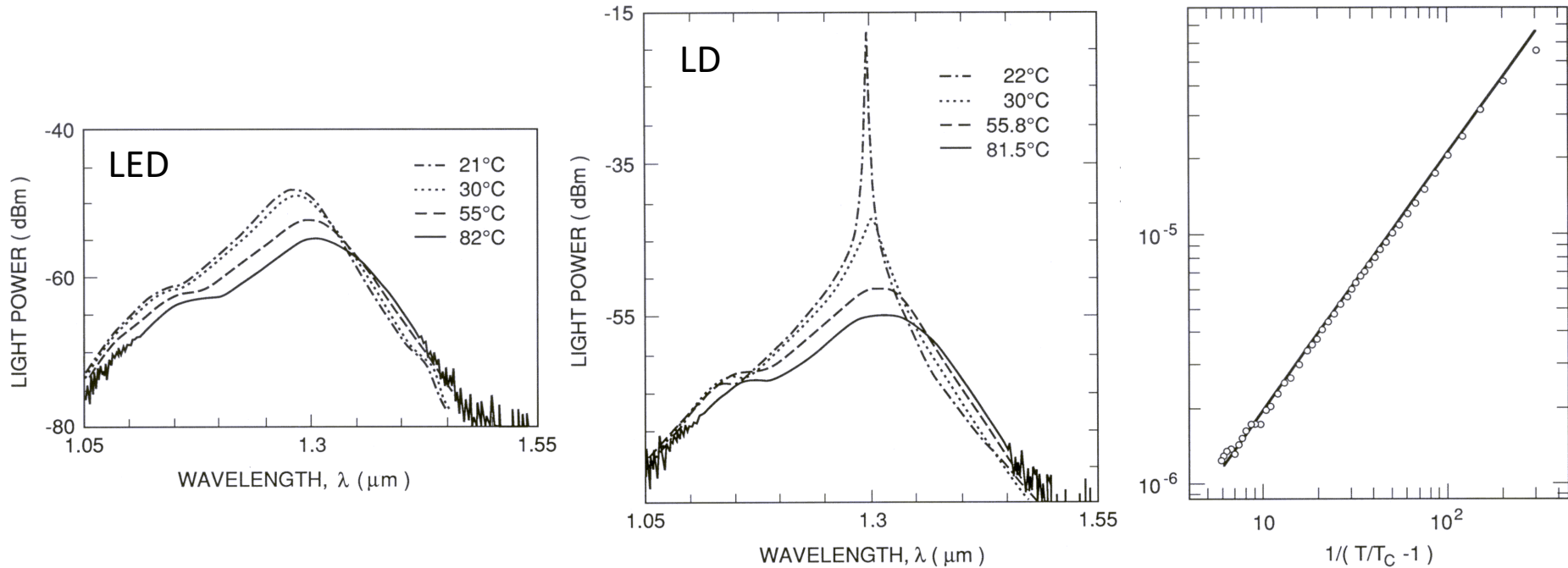


← 300 μm →



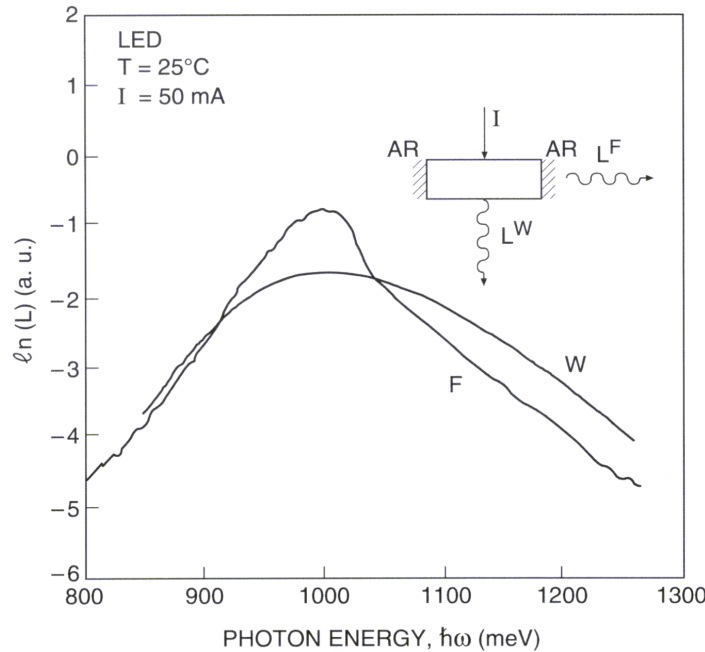
- Photons experience non-linear threshold behavior transitioning from disordered light (spontaneous emission) to ordered light (stimulated emission) with increasing pump current
 - Active volume $V = 300 \times 0.14 \times 0.8 \mu\text{m}^3 = 34 \times 10^{-12} \text{ cm}^3 = 34 \mu\text{m}^3$
 - $I_{\text{th}} = 3 \text{ mA}$, $\langle n \rangle = 2 \times 10^7$, $\langle s \rangle = 10^5$, $\beta = 10^{-4}$, 7 ps photon cavity round-trip
- Existing mean-field theories (rate equations and Gaussian noise - Langevin) applies to these large systems

Fluctuations enhance light output below I_{th}



- Experimentally compare LED and LD using *same* geometry and active region
 - AR coat LD to make LED
- Landau-Ginzburg phase transition analogy for macroscopic semiconductor laser with below-threshold fluctuations into the lasing state
 - Intensity fluctuations scale as $1/(T/T_C - 1)^\gamma$
 - Experimentally $\gamma=1.04$, $T_C = 301.4$ K

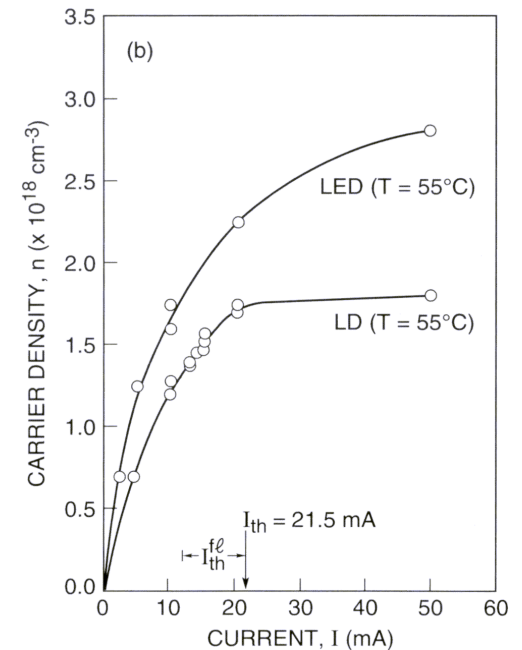
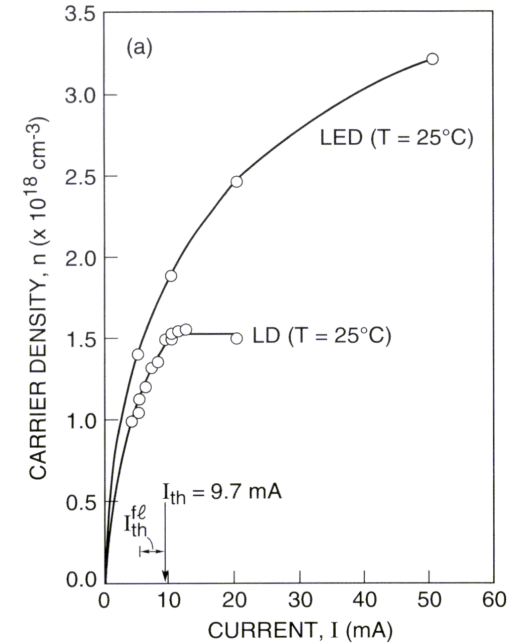
Fluctuations and carrier pinning



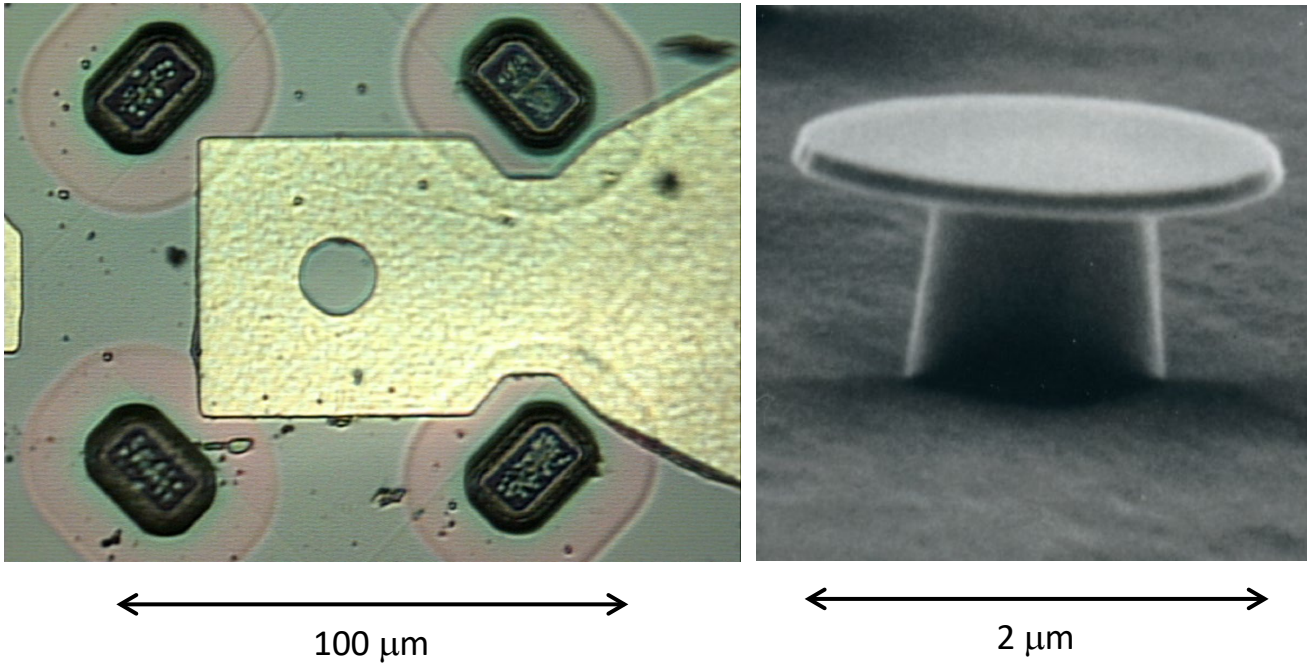
- Carrier number n from L_W (spontaneous emission)
 - Carrier pinning above threshold current
- Fluctuations in photons s remove carriers below threshold and contribute to the temperature dependence of laser diode threshold current, I_{th}
 - There is a contribution, I_{fi} , to the threshold current I_{th}
- Continuum mean-field rate equations set $\langle ns \rangle = \langle n \rangle \langle s \rangle$ and

$$d\langle n \rangle / dt = I - B\langle n^2 \rangle - a\Gamma\langle n - n_0 \rangle \langle s \rangle / V$$

$$d\langle s \rangle / dt = \beta B\langle n^2 \rangle + a\Gamma\langle n - n_0 \rangle \langle s \rangle / V - \kappa\langle s \rangle$$



Semiclassical master equations to describe mesolasers



- Fraction of spontaneous emission into lasing mode increases with decreasing optical cavity size
 - Phenomenological parameter β can increase from $\sim 10^{-5}$ to ≤ 1
 - Role of fluctuations is of increasing importance in mesolasers
 - *Control* of photon number and excitation number fluctuations is an outstanding challenge
- Capture physics of particle number quantization using master equations (a set of differential equations in continuous probability functions, P_{ns}) to describe quantized particle number states in the system

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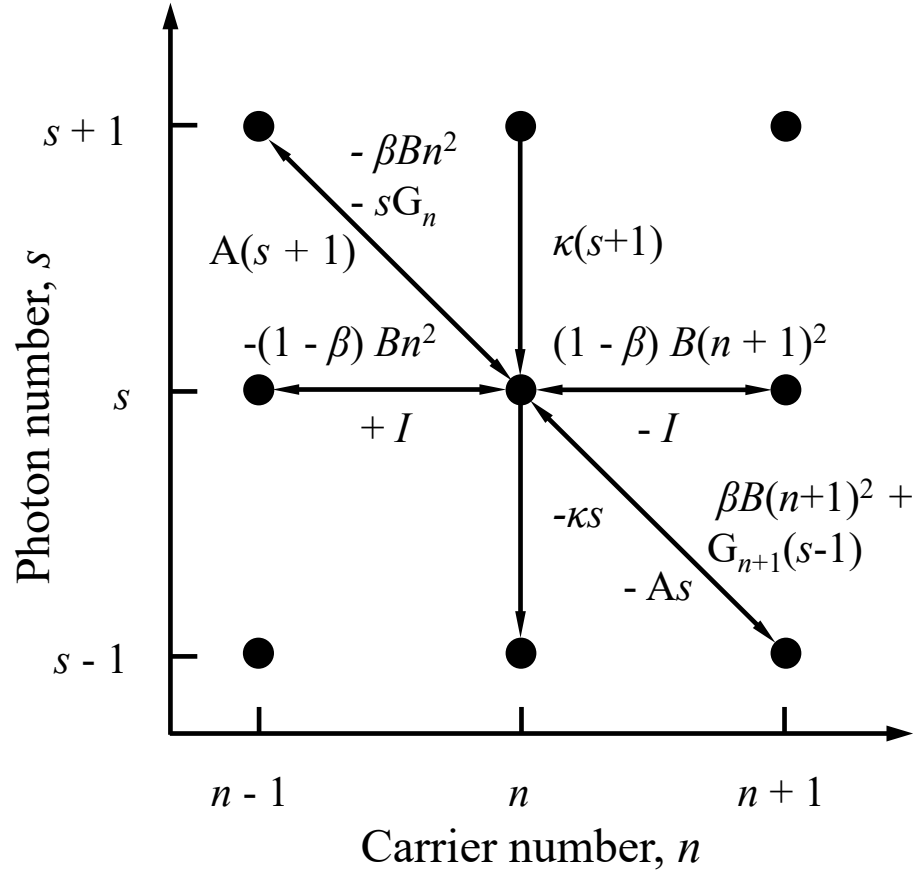
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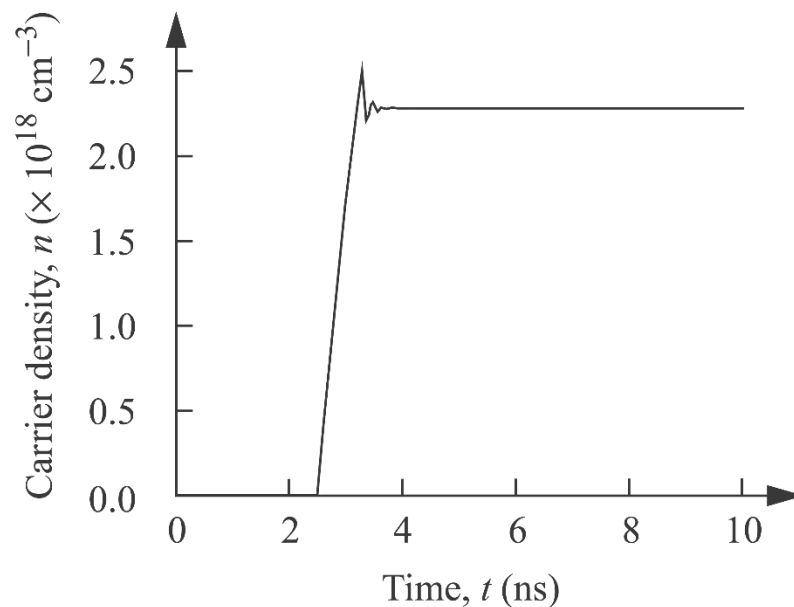
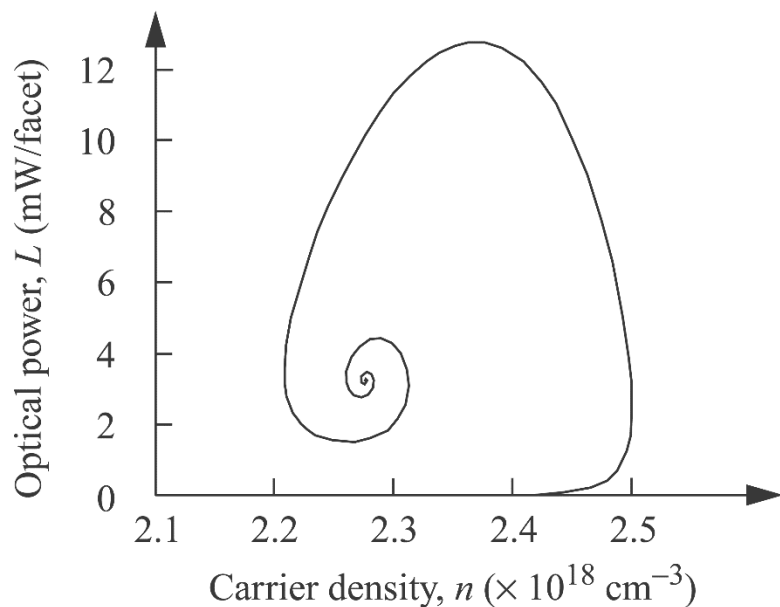
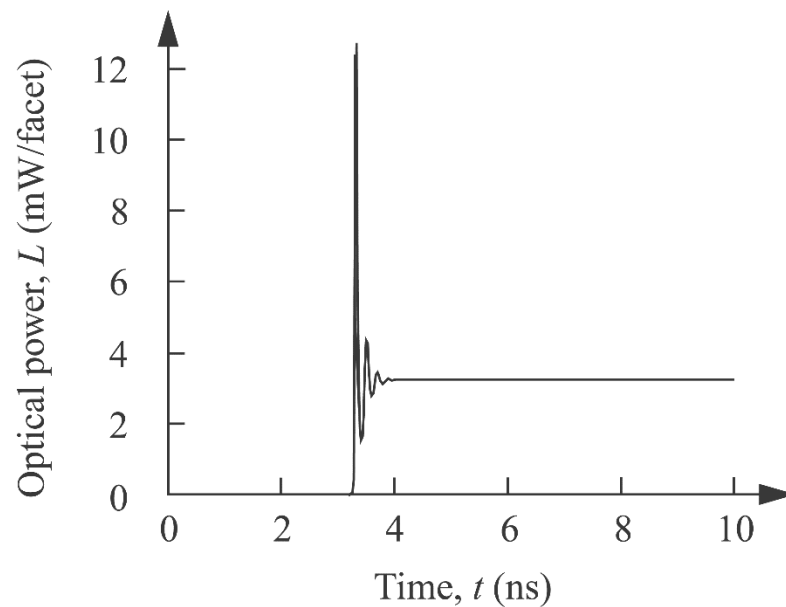
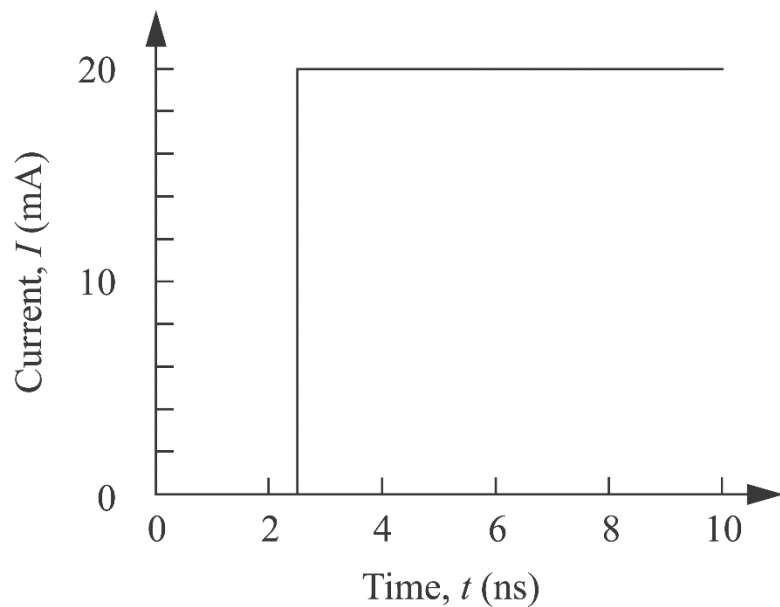
Semiclassical master equations to describe mesolasers



$$\begin{aligned} \frac{dP_{n,s}}{dt} = & -\kappa(sP_{n,s} - (s+1)P_{n,s+1}) - (sG_nP_{n,s} - (s-1)G_{n+1}P_{n+1,s-1}) - (sAP_{n,s} - (s+1)AP_{n-1,s+1}) \\ & - \beta B(n^2P_{n,s} - (n+1)^2P_{n+1,s-1}) - (1-\beta)B(n^2P_{n,s} - (n+1)^2P_{n+1,s}) - I(P_{n,s} - P_{n-1,s}) \end{aligned}$$

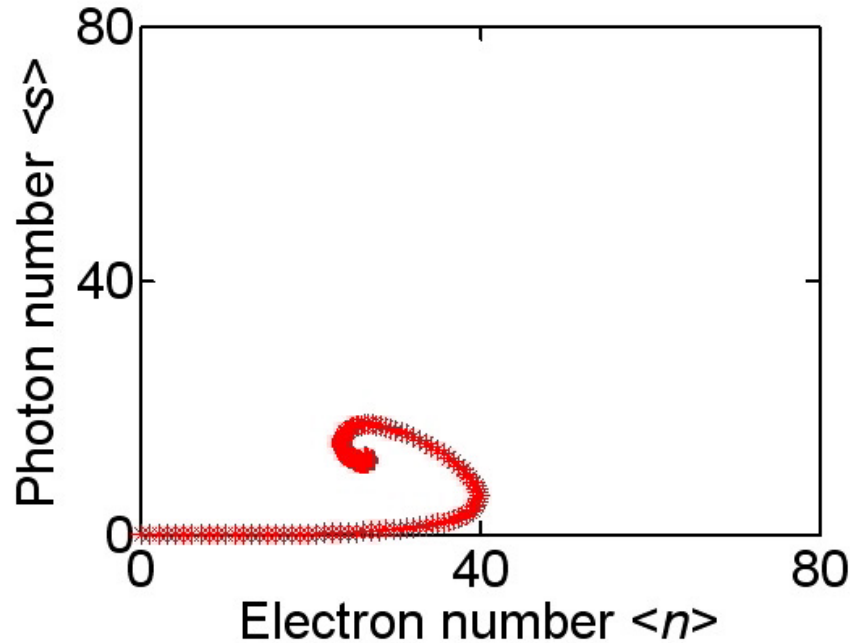
- Capture physics of particle number quantization
 - Quantize photon number s and excited emitter electron particle number n , correlations $\langle ns \rangle \neq \langle n \rangle \langle s \rangle$, photon energy $\hbar\omega_0$

Continuum mean-field rate equation prediction



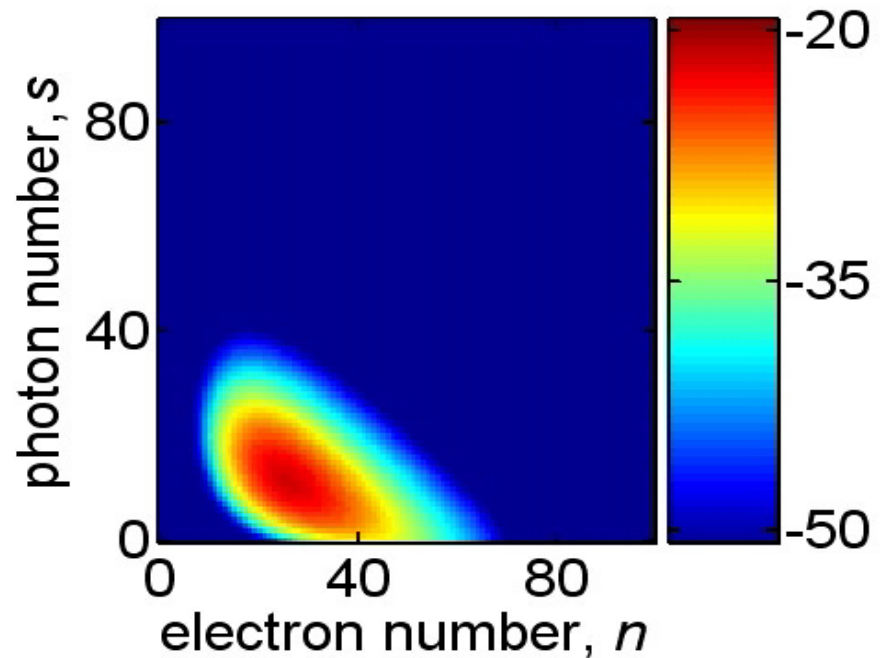
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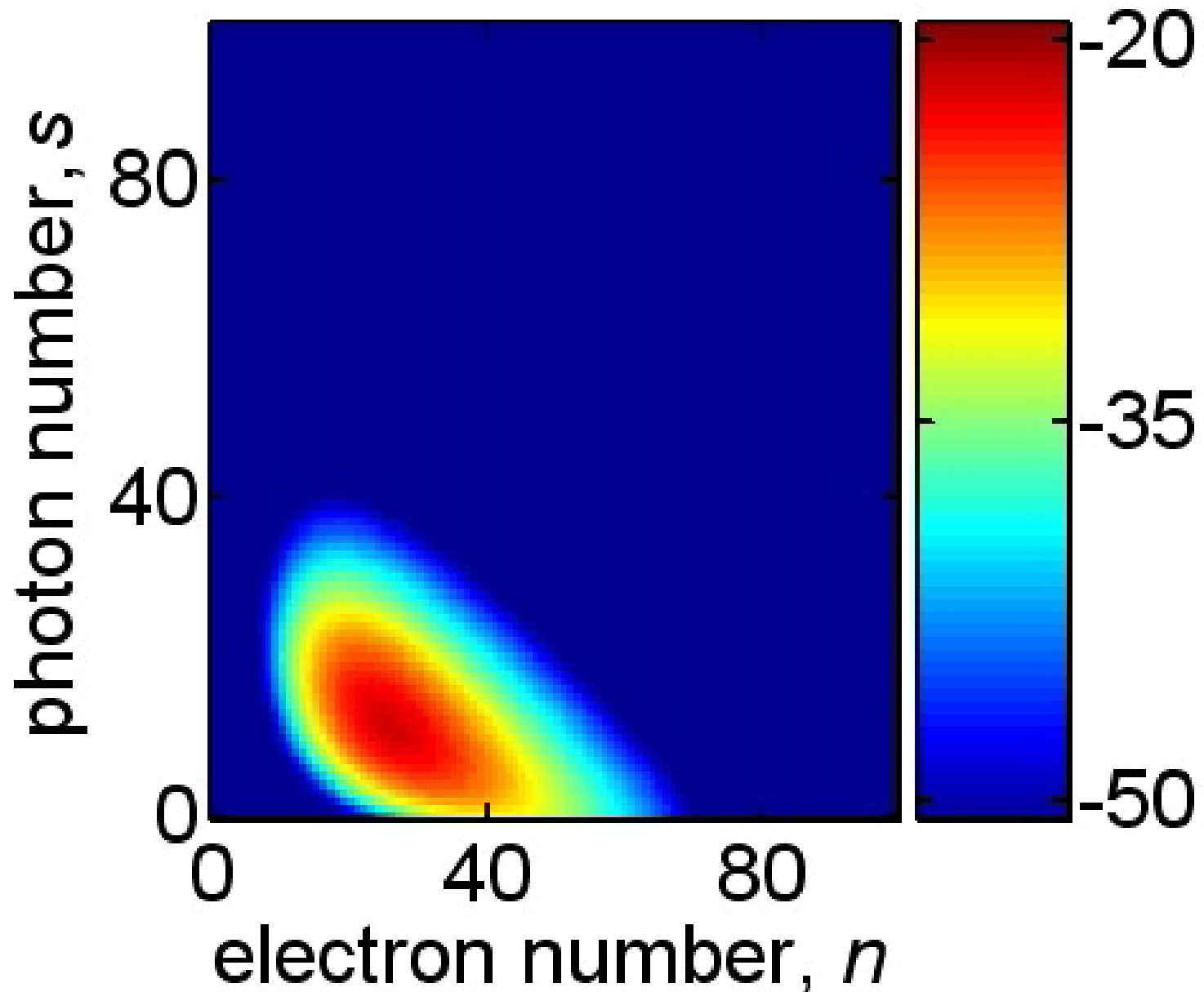
Approximate first moment ($\langle n \rangle$, $\langle s \rangle$)
continuum mean-field model

Modeling discrete quantum system using continuum probability functions, $P_{n,s}$

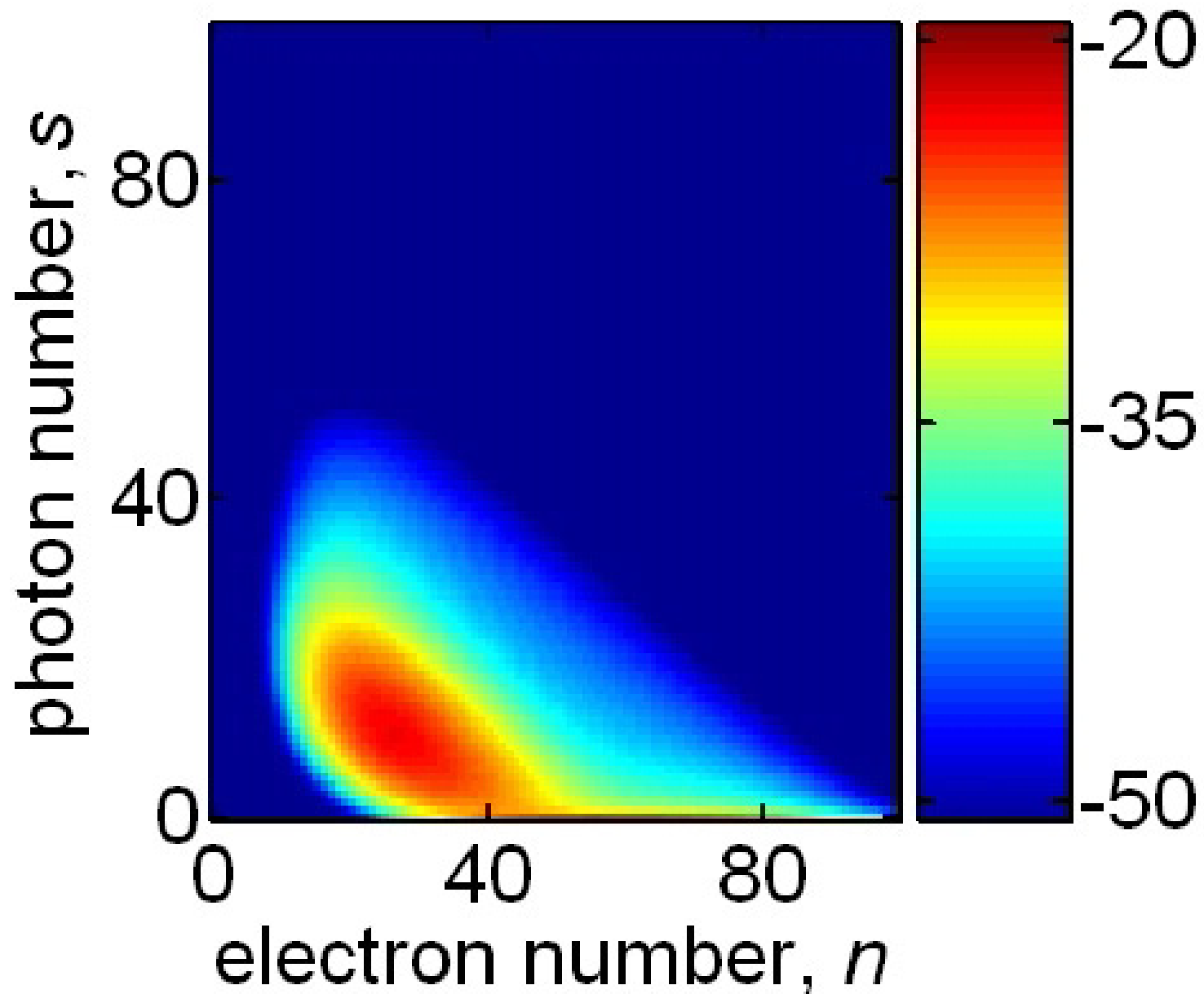


Probabilistic semiclassical master equation picture, $P_{n,s}$ for n electron excitations and s photons in the cavity

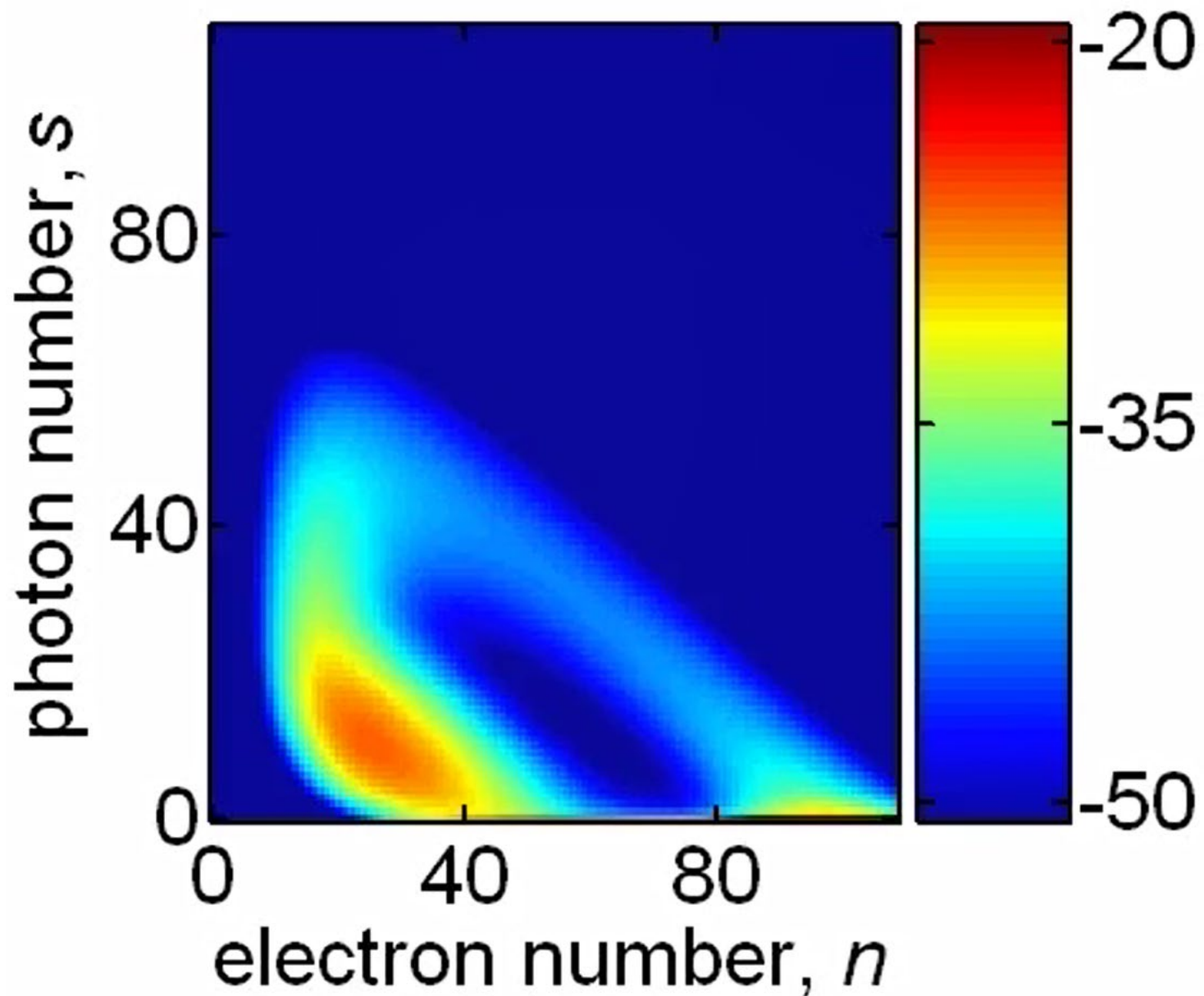
Time evolution of $10\log_{10}(P_{\text{ns}})$ for $\beta=1$



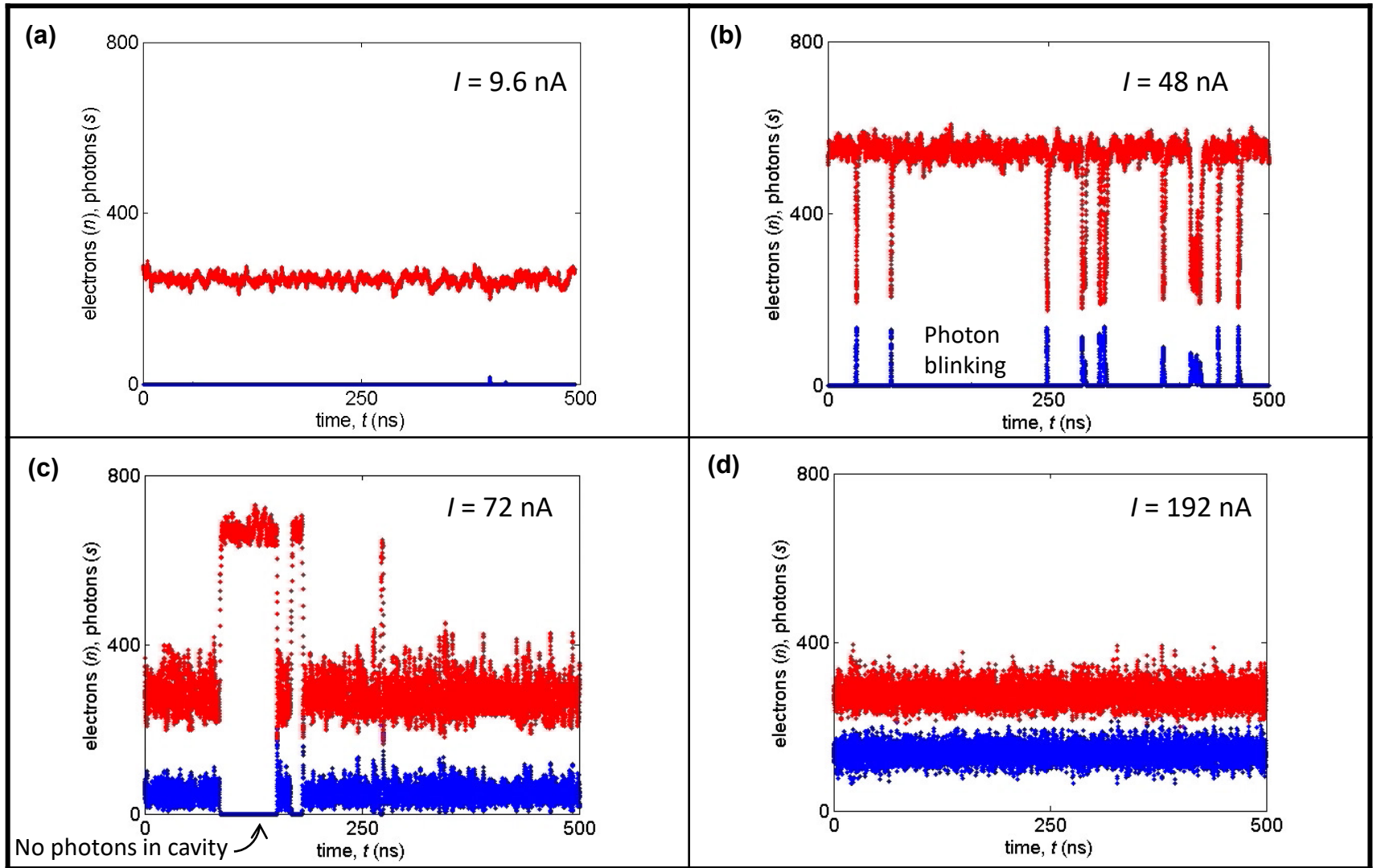
Time evolution of $10\log_{10}(P_{\text{ns}})$ for $\beta=0.1$



Time evolution of $10\log_{10}(P_{\text{ns}})$ for $\beta=0.01$



Semiclassical system trajectories by the Monte Carlo method



(a) $I = 9.6$ nA. (b) $I = 48$ nA. Note, photon blinking. (c) $I = 72$ nA. (d) $I = 192$ nA. Electrons (red), photons (blue).
 Parameters : Volume = $0.1\mu\text{m} \times 0.1\mu\text{m} \times 10\text{nm}$, $\Gamma = 0.25$, $a = 2.5 \times 10^{-18} \text{ cm}^2 \text{ s}^{-1}$, $B = 10^{-10} \text{ cm}^3 \text{ s}^{-1}$, $\beta = 10^{-4}$, $n_0 = 10^{18} \text{ cm}^{-3}$, $\alpha_i = 1 \text{ cm}^{-1}$, $n_r = 4$, $r = 1 - 10^{-6}$.

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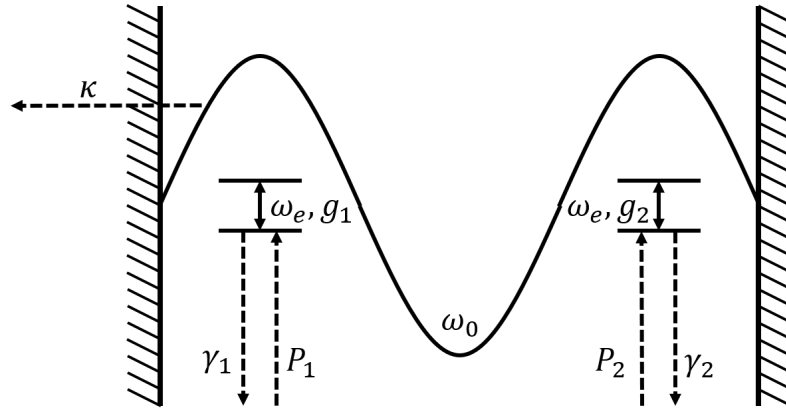
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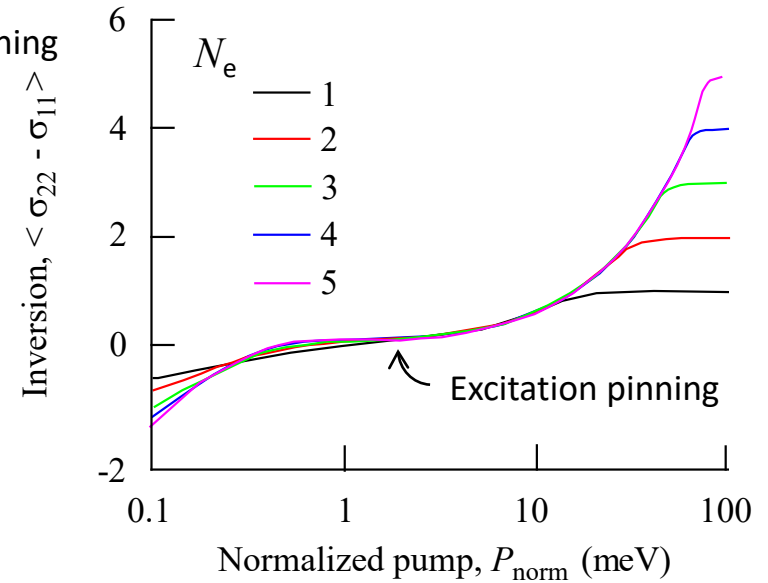
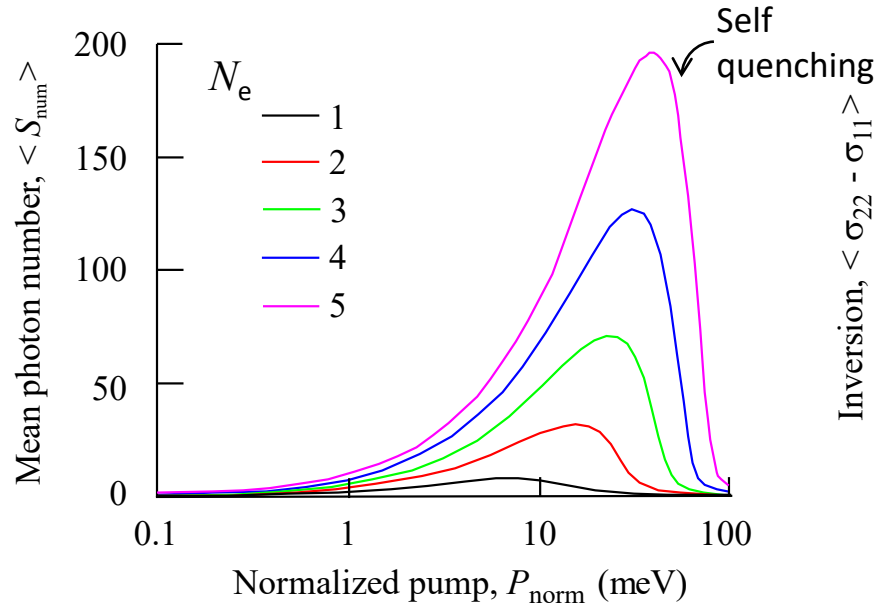
Solve open system with Linblad master equation:

(e.g. K. Roy-Choudhury and A. F. J. Levi, Phys. Rev. A **83**, 043827 (1-9) (2011))

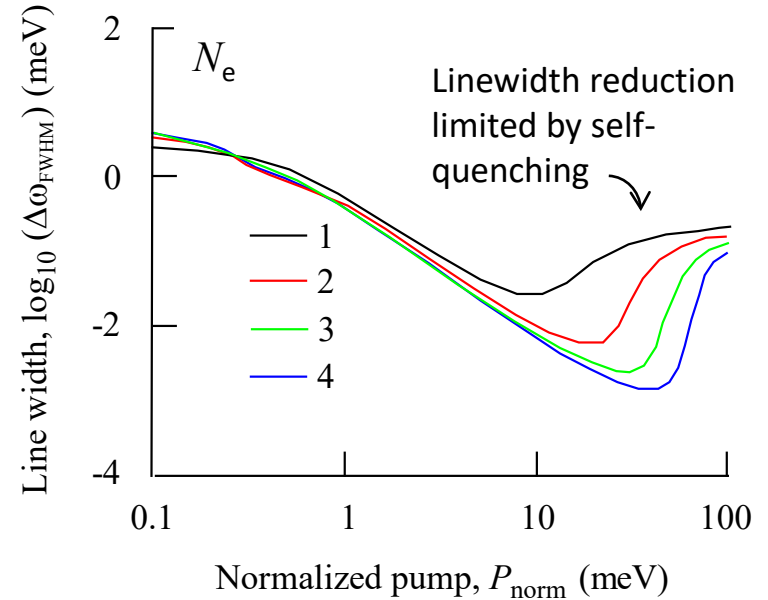
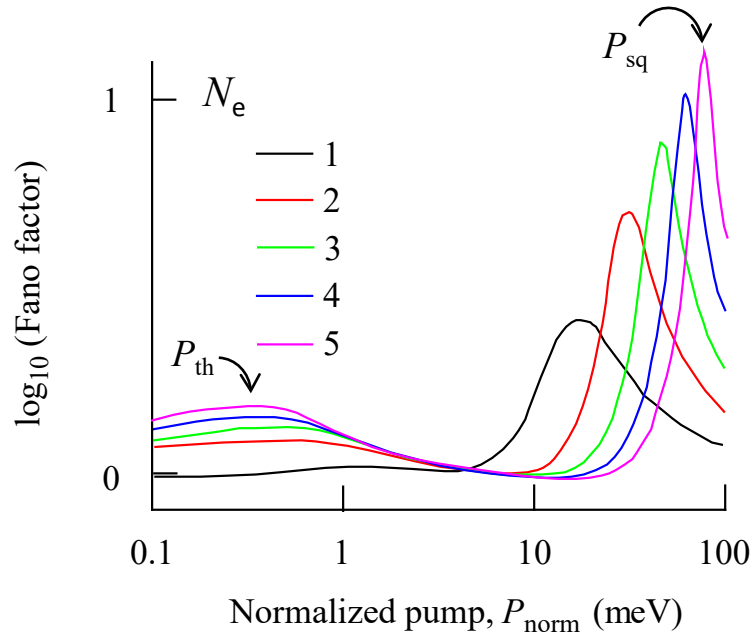
$$\begin{aligned} \frac{d\hat{\rho}}{dt} = & \frac{i}{\hbar} [\hat{\rho}, H_s] + \frac{\kappa}{2} (2\hat{b}\hat{\rho}\hat{b}^\dagger - \hat{b}^\dagger\hat{b}\hat{\rho} - \hat{\rho}\hat{b}^\dagger\hat{b}) \\ & + \sum_{n=1}^{N_e} \frac{\gamma_n}{2} (2\hat{\sigma}_n\hat{\rho}\hat{\sigma}_n^\dagger - \hat{\sigma}_n^\dagger\hat{\sigma}_n\hat{\rho} - \hat{\rho}\hat{\sigma}_n^\dagger\hat{\sigma}_n) \\ & + \sum_{n=1}^{N_e} \frac{P_n}{2} (2\hat{\sigma}_n^\dagger\hat{\rho}\hat{\sigma}_n - \hat{\sigma}_n\hat{\sigma}_n^\dagger\hat{\rho} - \hat{\rho}\hat{\sigma}_n\hat{\sigma}_n^\dagger) \end{aligned}$$

$$H_s = \hbar\omega_0\hat{b}^\dagger\hat{b} + \sum_{n=1}^{N_e} \hbar\omega_e\hat{\sigma}_n^\dagger\hat{\sigma}_n + \sum_{n=1}^{N_e} \hbar g_e (\hat{b}\hat{\sigma}_n^\dagger + \hat{b}^\dagger\hat{\sigma}_n)$$

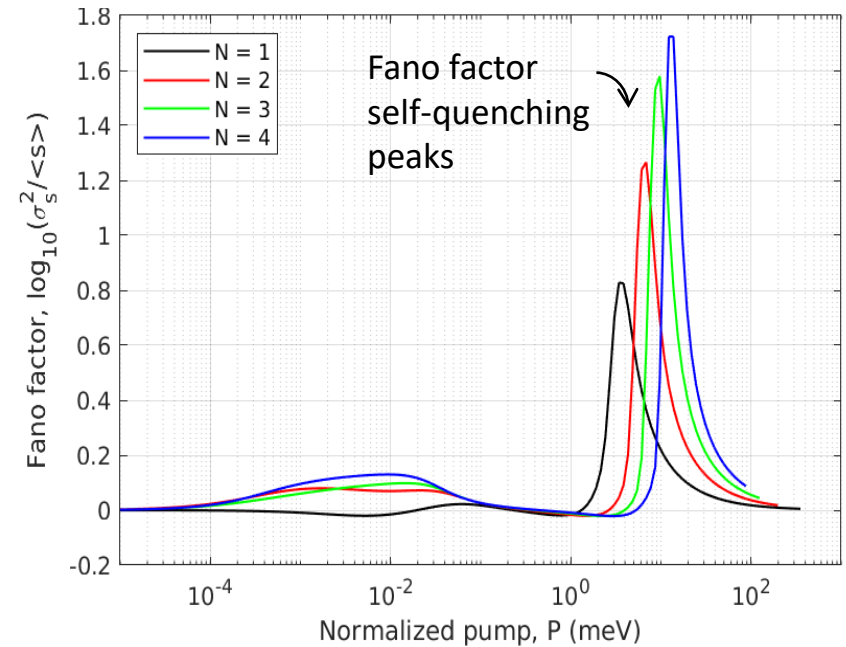
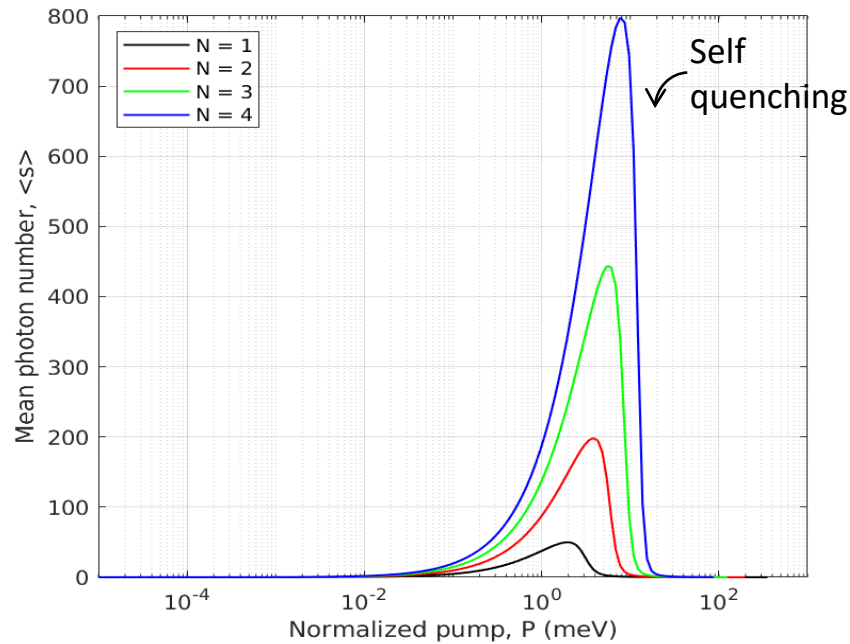
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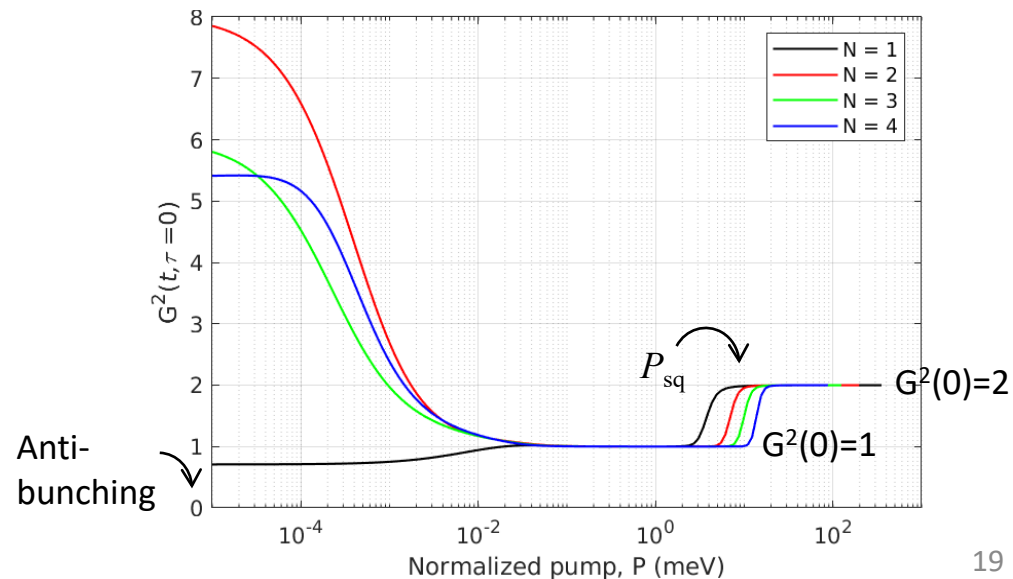
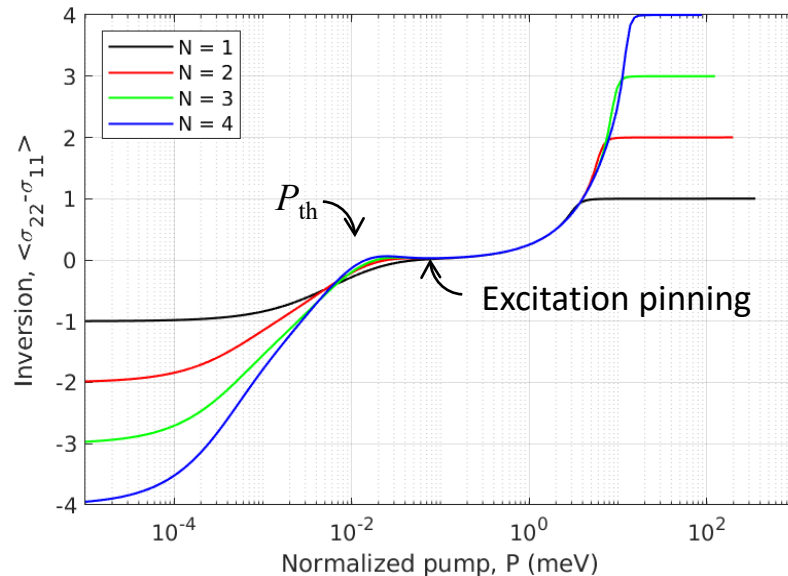
$g_e = 1$ meV, $\gamma = 0.1$ meV, $\kappa = 0.25$ meV, $\hbar\omega_e = \hbar\omega_0 = 1000$ meV



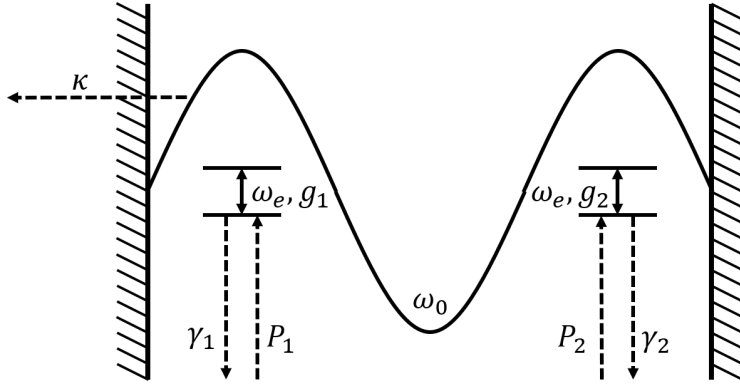
Steady-state properties as a function of pump and number of emitters



$$g_e = 0.1 \text{ meV}, \gamma = 0.001 \text{ meV}, \kappa = 0.01 \text{ meV}, \hbar\omega_e = \hbar\omega_0 = 1000 \text{ meV}$$



Symmetry-protected long-lived emitter states in meso-lasers



Photon Fano factor measures spread in photon number distribution normalized to mean photon number

$$\mathcal{F}(\hat{\rho}) = \frac{\sigma_s^2}{\langle s \rangle} = \frac{\text{Tr}(\hat{\rho} \hat{s}^2) - \text{Tr}(\hat{\rho} \hat{s})^2}{\text{Tr}(\hat{\rho} \hat{s})}$$

$N_e = 2$ symmetry-protected long-lived emitter state

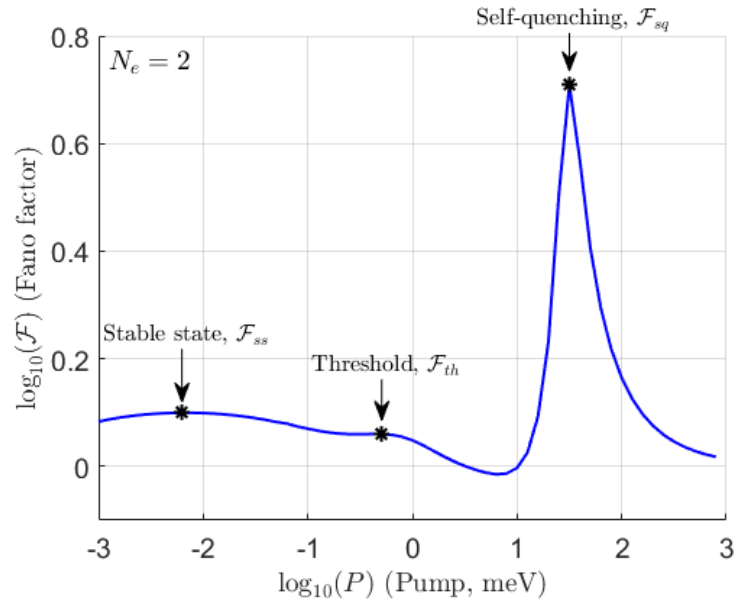
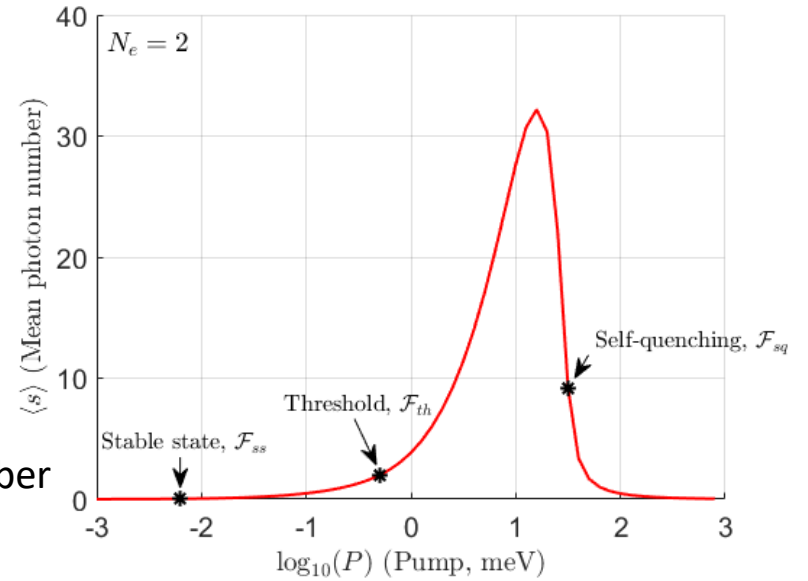
$$|\psi_{-}\rangle_e = \frac{1}{\sqrt{2}}(|10\rangle_e - |01\rangle_e)$$

$N_e = 2$ short-lived emitter state coupling to cavity mode

$$|\psi_{+}\rangle_e = \frac{1}{\sqrt{2}}(|10\rangle_e + |01\rangle_e)$$

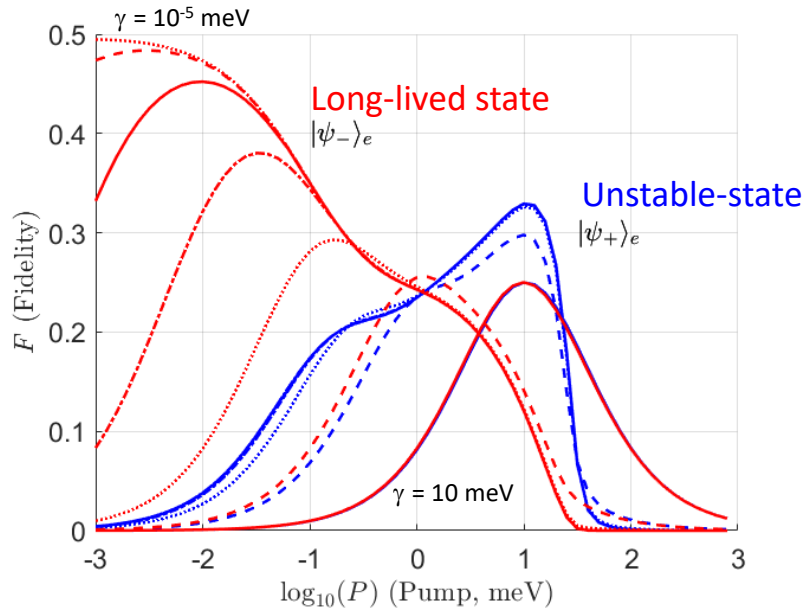
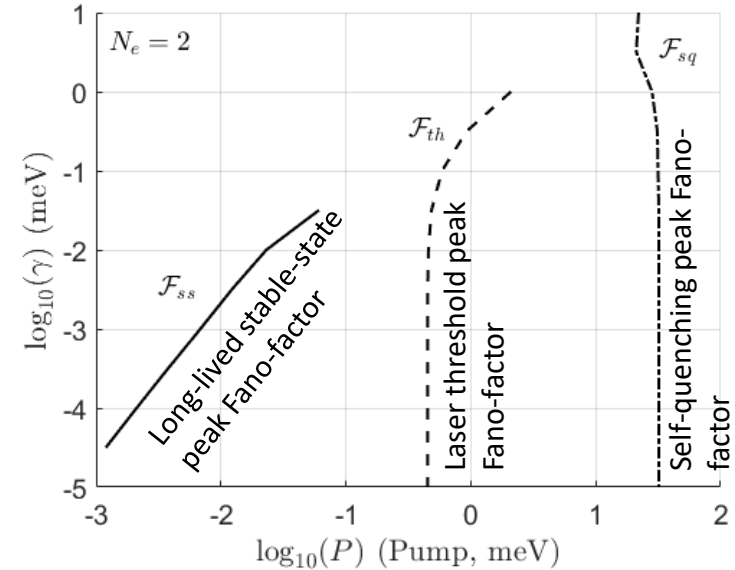
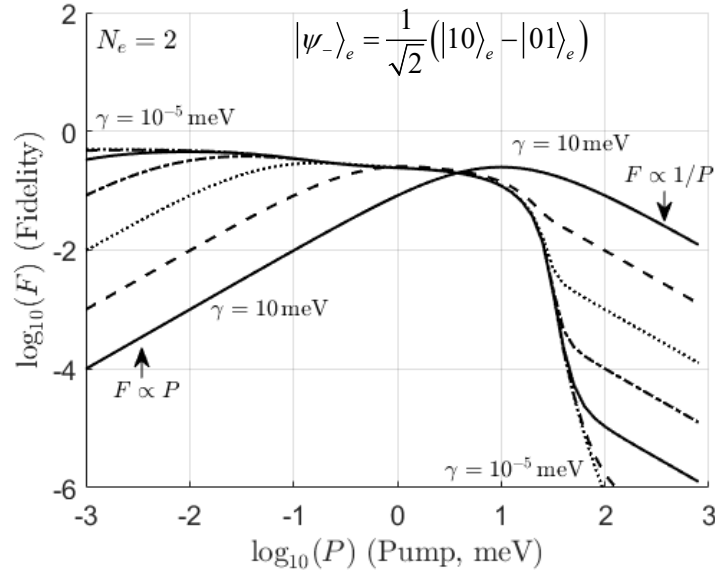
Fidelity measures similarity between two density matrices

$$F(\hat{\rho}_1, \hat{\rho}_2) = \text{Tr} \left[\sqrt{\sqrt{\hat{\rho}_1} \hat{\rho}_2 \sqrt{\hat{\rho}_1}} \right]^2$$



$g_1 = g_2 = g_e = 1$ meV, $\gamma_1 = \gamma_2 = \gamma = 10^{-3}$ meV, $\kappa = 0.25$ meV
 $P_1 = P_2$ and normalized to number of emitters

Behavioral regimes for long-lived emitter states in meso-lasers



$g = 1$ meV, $\gamma = 10^{-5} - 10$ meV, and $\kappa = 0.25$ meV

Values of pump, P , at which the Fano factor peaks for a given value of γ (loss into non-lasing modes) indicating transitions between regimes of different dynamic behavior

$N_e = 2$, $g = 1$ meV, and $\kappa = 0.25$ meV.

In phase transition analogy, Fano factor peaks *separate* different characteristic behavior

Lifetime τ_- of symmetry-protected long-lived state determined by γ and P , so can have $\tau_- > 1$ ns

Lifetime τ_+ of short-lived state determined by fastest process coupling to the cavity mode, in this case via g , so $\tau_+ \sim 1$ ps

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- Photon and excitation fluctuations in both classical macroscopic and mesoscale lasers play an important role in determining device performance
 - While mesoscale lasers might exhibit quantum behavior, there is no agreed *measure* of how much quantumness (wave-particle duality, identical indistinguishable particles, linear superposition of particle states, non-local entanglement of particles, ...)
- Fluctuations peak around transitions between characteristic behavioral modes of operation
 - Laser threshold: analogous to a second-order non-equilibrium phase transition with the optical field as the order-parameter
 - Self-quenching: excitation saturation
 - Symmetry-protected long-lived states
- Control of fluctuations and associated dissipation (n.b. the fluctuation-dissipation theorem) can result in useful device behavior
 - For example, a macroscopic laser diode operating close to the thermodynamic limit can have a lasing mode emission linewidth and photon Fano-factor that decreases with increasing injection current $I_{\text{inj}} > I_{\text{th}}$.
 - In contrast, the reduction in linewidth and reduction in photon Fano-factor in a mesolaser as pump is increased to values greater than P_{th} is limited by the existence of self-quenching as pump values approach P_{sq}
- Overcoming practical limitations associated with control of mesoscale laser behavior presents an interesting challenge whose successful solution might be demonstrated by suppression of fluctuations that occurs near laser threshold, self-quenching, or dissipation in symmetry-protected quantum states

Acknowledgements

Amine Abouzaid

James O’Gorman

Kaushik Roy-Choudhury

Walter Unglaub

K. Roy-Choudhury and A. F. J. Levi, “Quantum fluctuations and saturable absorption in mesoscale lasers” Phys. Rev. A **83**, 043827 (1-9) (2011))

Amine Abouzaid, Walater Unglaub, and A. F. J. Levi, “Behavioral regimes and long-lived emitter states in mesolasers” J. Phys. B **52**, 245401 (2019)

END