

### Quantum Modelling and Photon Squeezing in Nanolasers Quantum Modelling and Photon Squeezing in Nanolasers

M A Carroll, G d'Alessandro, G L Lippi, G.-L Oppo, F Papoff

#### ▶ To cite this version:

M A Carroll, G d'Alessandro, G L Lippi, G.-L Oppo, F Papoff. Quantum Modelling and Photon Squeezing in Nanolasers Quantum Modelling and Photon Squeezing in Nanolasers. 9ème édition du congrès OPTIQUE de la Société Française d'Optique, Jul 2022, Nice, France. hal-03723305

HAL Id: hal-03723305

https://hal.science/hal-03723305

Submitted on 14 Jul 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## Quantum Modelling and Photon Squeezing in Nanolasers

M.A. Carroll<sup>1</sup>, G. D'Alessandro<sup>2</sup>, G.L. Lippi<sup>3</sup>, G.-L. Oppo<sup>1</sup> and F. Papoff<sup>1</sup>

<sup>1</sup>SUPA and Department of Physics, University of Strathclyde, Scotland, UK
<sup>2</sup>School of Mathematical Sciences, University of Southampton, Southampton SO17 1BJ, UK
<sup>3</sup>Universite Côte d'Azur, CNRS, Institut de Physique de Nice, France

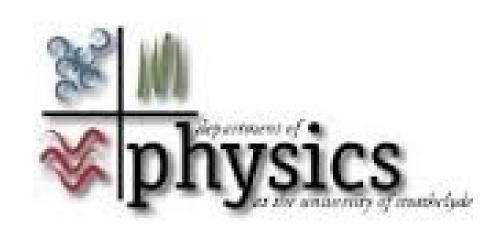


### **Model constituents**

- Fully quantised model for N Quantum Dots (Qds)
- Two-level systems (with one electron)
- Optical Cavity modes

### **Methods and Main Results**

- Dynamical systems methods identify laser threshold (bifurcation) depending on N, interaction and detuning
- Universal transition: thermal, antibunched and lasing emission
- Phase transition (incoherent-coherent emission) in the macroscopic limit





### **System stability**

Lasing (identified through Linear Stability Analysis) occurs if:

$$\frac{\gamma_0 \gamma}{|g|^2} (1 + (\frac{\Delta \epsilon}{\gamma_0 + \gamma})^2) \le N$$

with -N; detuning,  $\Delta$ ; decay rates, g; light-matter coupling, g

Common condition for single and multi electron models [2]

### Model

- ◆ Equations of motion (EoM) in the Heisenberg picture
- ◆ Two sets of variables: incoherent (slow) and coherent (fast)
- ◆ Coherent variables inclusion (historically neglected): proper description

# Coherent-Incoherent Model [1] $\frac{d}{dt}\langle b\rangle = -(\gamma_c + i\nu)\langle b\rangle + Ng^*\langle v^\dagger c\rangle$

$$\frac{d}{dt}\langle c^{\dagger}v\rangle = -(\gamma - i\nu_{\epsilon})\langle c^{\dagger}v\rangle + g^{*}\langle b^{\dagger}\rangle(2\langle c^{\dagger}c\rangle - 1)$$

$$\frac{d}{dt}\delta\langle b^{\dagger}b\rangle = -2\gamma_c\delta\langle b^{\dagger}b\rangle + 2N\Re g\delta\langle bc^{\dagger}v\rangle$$

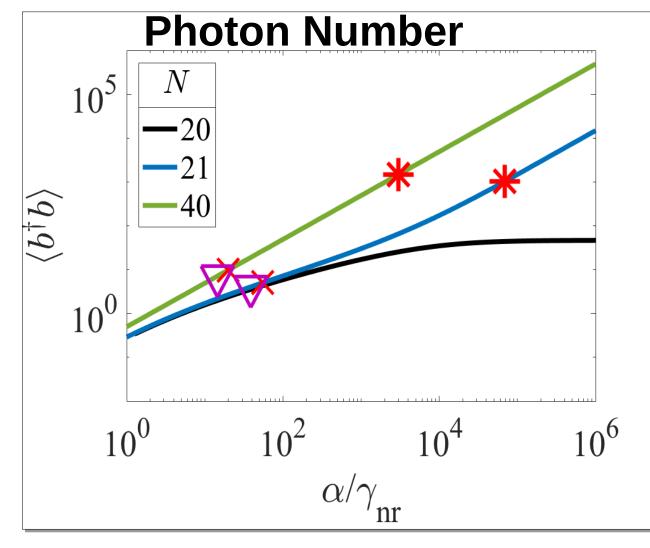
$$\frac{d}{dt}\langle c^{\dagger}c\rangle = r(1 - \langle c^{\dagger}c\rangle) - (\gamma_{nl} + \gamma_{nr})\langle c^{\dagger}c\rangle$$
$$-2\Re g(\delta\langle bc^{\dagger}v\rangle + \langle b\rangle\langle v^{\dagger}c\rangle)$$

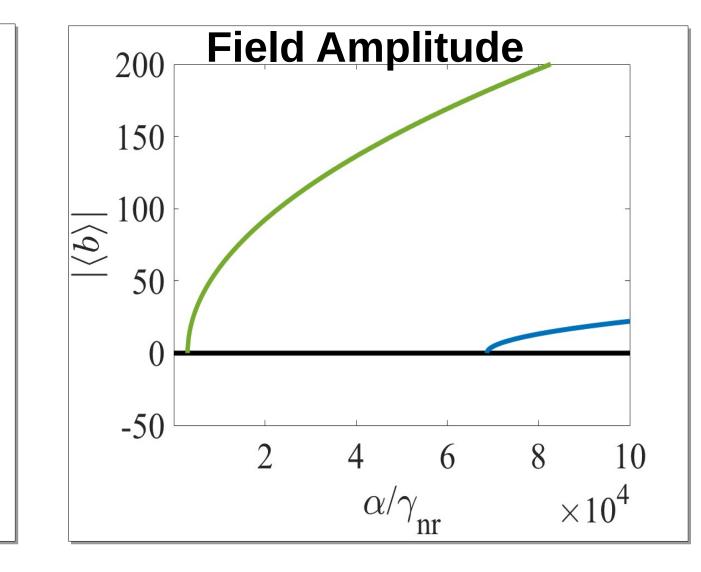
$$\frac{d}{dt}\delta\langle bc^{\dagger}v\rangle = -(\gamma_c + \gamma - i\Delta\nu)\delta\langle bc^{\dagger}v\rangle + g^* \Big[\langle c^{\dagger}c\rangle + \delta\langle b^{\dagger}b\rangle \Big(2\langle c^{\dagger}c\rangle - 1\Big) - |\langle c^{\dagger}v\rangle|^2\Big]$$

Fast coherent variables

Slow incoherent variables

### Thresholdless laser? [1]

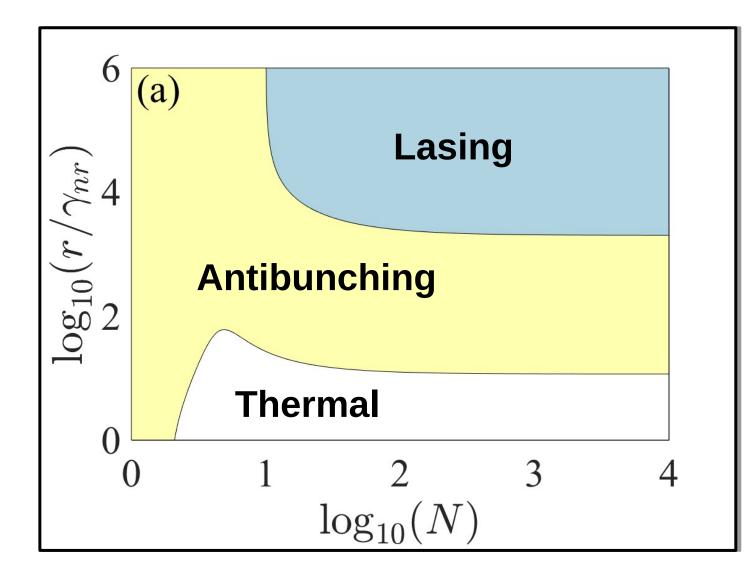




- Red stars mark lasing bifurcation
- Crosses and triangles mark threshold from the thermal to antibunching regime
- The coherent variables reintroduce a lasing bifurcation (threshold) for the thresholdless laser
- The bifurcation is followed by a non-zero coherent field (blue and green curves cf. Fig. (right))

A threshold exists for all devices (for any size): no thresholdless laser!

### **Photon Antibunching [4]**



### **Generic transition**

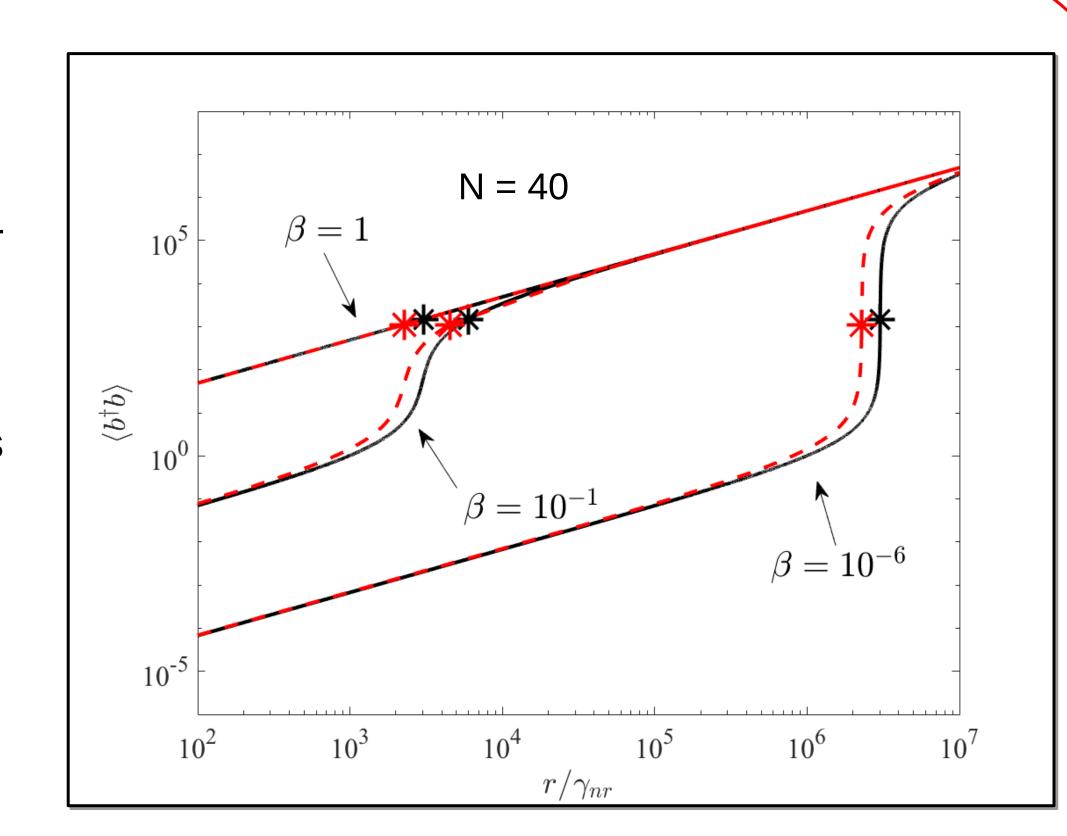
- Thermal emission
- Antibunching
- Lasing

Observable even for 10<sup>4</sup> QDs (mesoscopic laser)

## Recovering the macroscopic threshold

- Comparing the single and multi electron models

   the lasing bifurcation occurs at lower pump for
  the multi electron system
- As the volume of the devices approaches the macroscopic limit (thermodynamic limit) the threshold moves from the upper branch towards the inflection point [3]
- A bifurcation occurs in all cases however, it is only the curve that undergoes a second-order *phase transition*.
- Below (above) the bifurcation the emission is fully incoherent (partially coherent).



## Conclusions

- We have derived a new quantum laser model that contains both coherent and incoherent variables.
- Through linear stability analysis we find a critical number of QDs required for lasing to happen.
- We show that there is a threshold for the so-called thresholdless laser.
- Our model predicts an antibunching regime that precedes the lasing regime even at mesoscopic emitter numbers.
- We show that a second-order phase transition occurs in the thermodynamic or macroscopic limit.

### References

- [1] Phys. Rev. Lett. **126**, 063902 (2021)
- [2] Phys. Rev. A **75**, 013803 (2007)
- [3] Phys. Rev. A **50**, 4318 (1994)
- [4] Appl. Phys. Lett. **119**, 101102 (2021)