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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:

$$\frac{\gamma_0 \gamma}{|g|^2}\left(1+\left(\frac{\Delta\epsilon}{\gamma_0+\gamma}\right)^2\right) \leq N,$$

with – N; detuning, Δ; 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]

Fast coherent variables:

$$\frac{d}{dt}\langle b\rangle = -(\gamma_c + i\nu)\langle b\rangle + N g^* \langle v^\dagger c\rangle$$

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

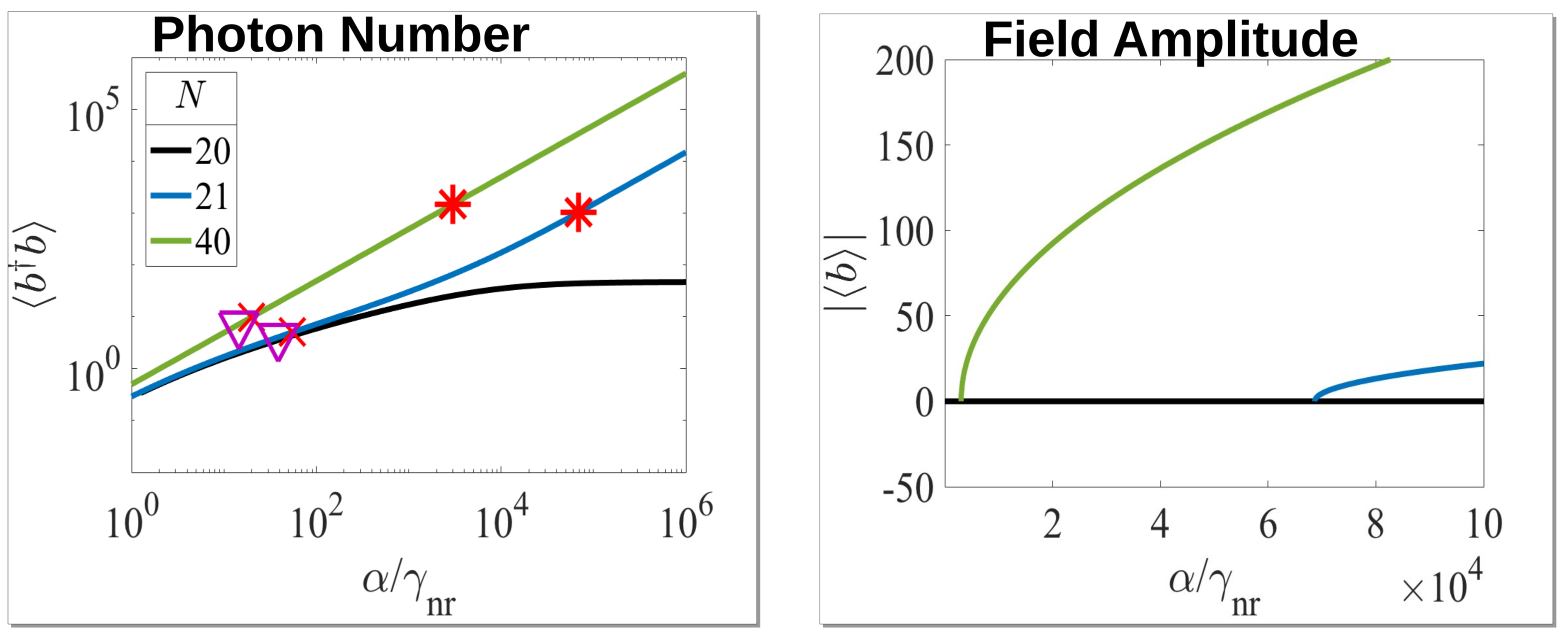
Slow incoherent variables:

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

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

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

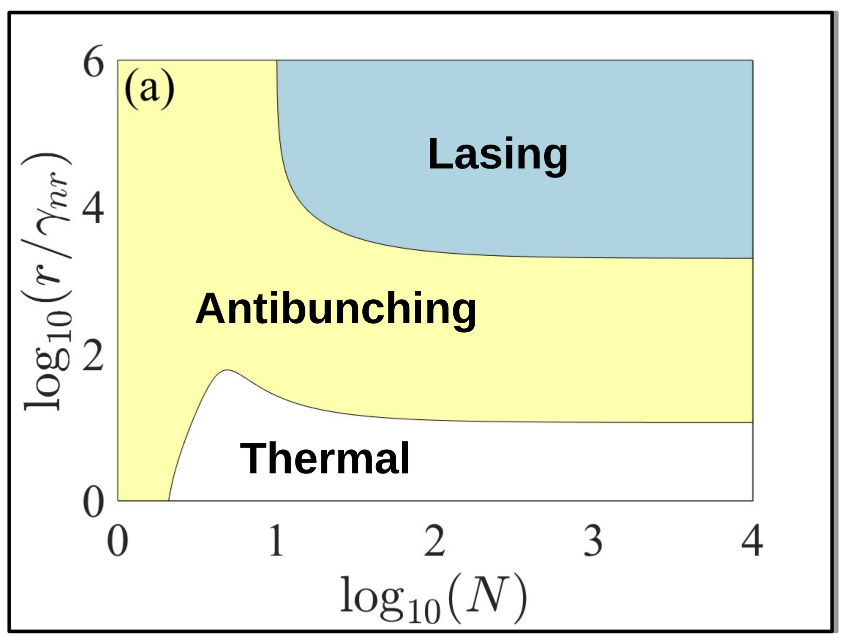
Thresholdless laser? [1]



- 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]



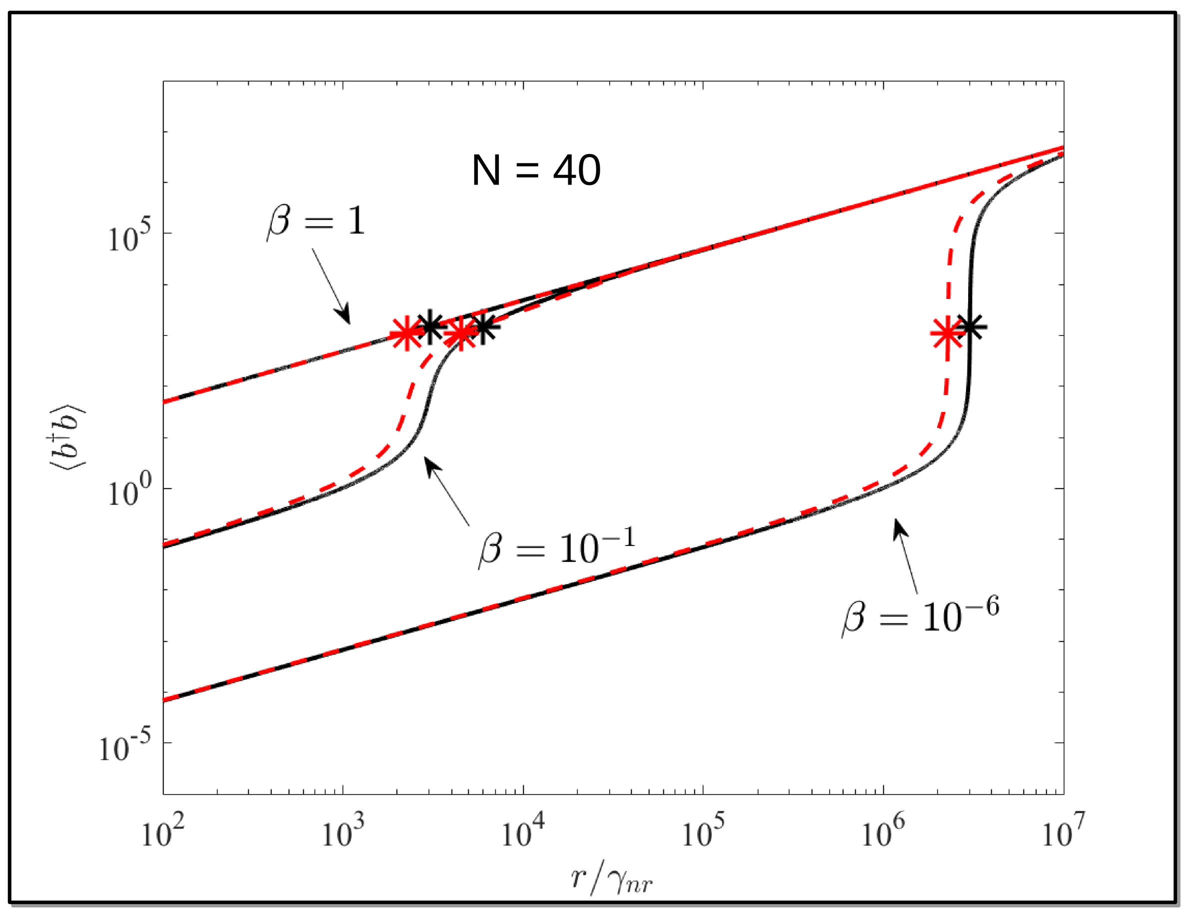
Generic transition

- Thermal emission
- Antibunching
- Lasing

Observable even for 10^4 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)