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

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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, γ ; 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]

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

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

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

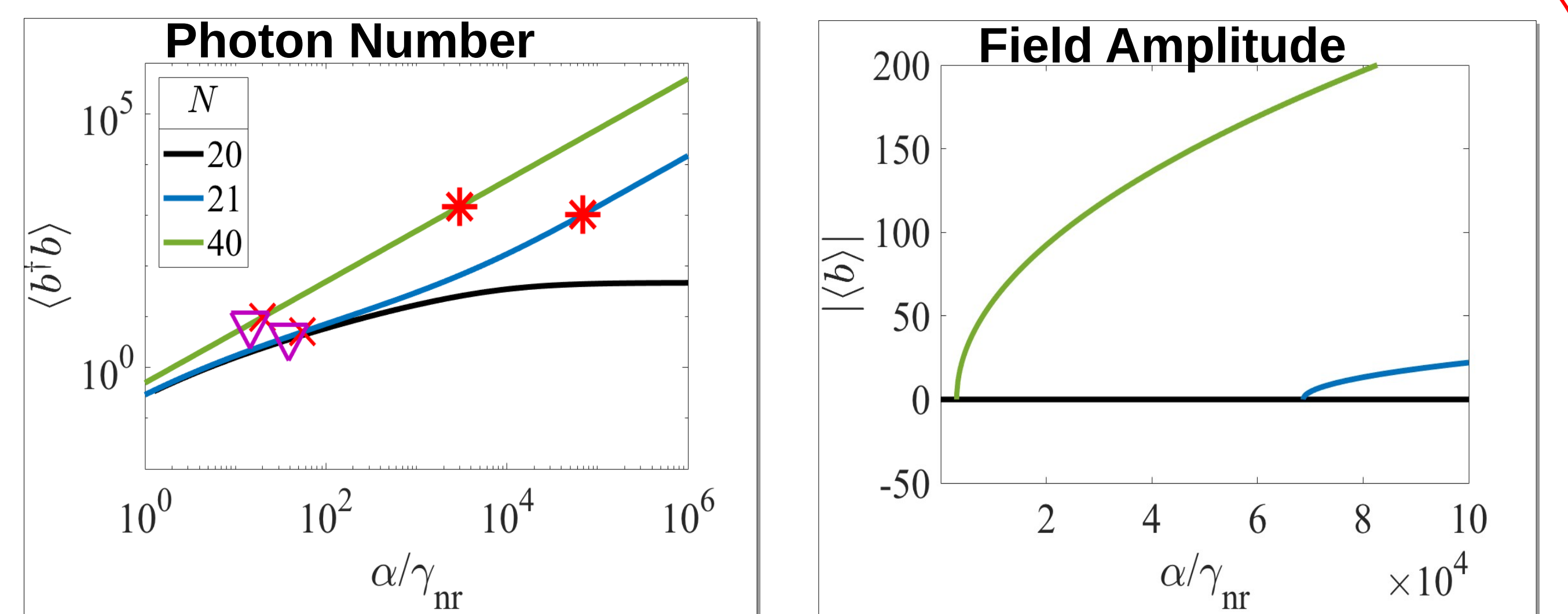
$$\frac{d}{dt} \langle c^\dagger c \rangle = r(1 - \langle c^\dagger c \rangle) - (\gamma_{nl} + \gamma_{nr}) \langle c^\dagger c \rangle - 2\Re g (\delta \langle bc^\dagger v \rangle + \langle b \rangle \langle v^\dagger c \rangle)$$

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

Fast
coherent
variables

Slow
incoherent
variables

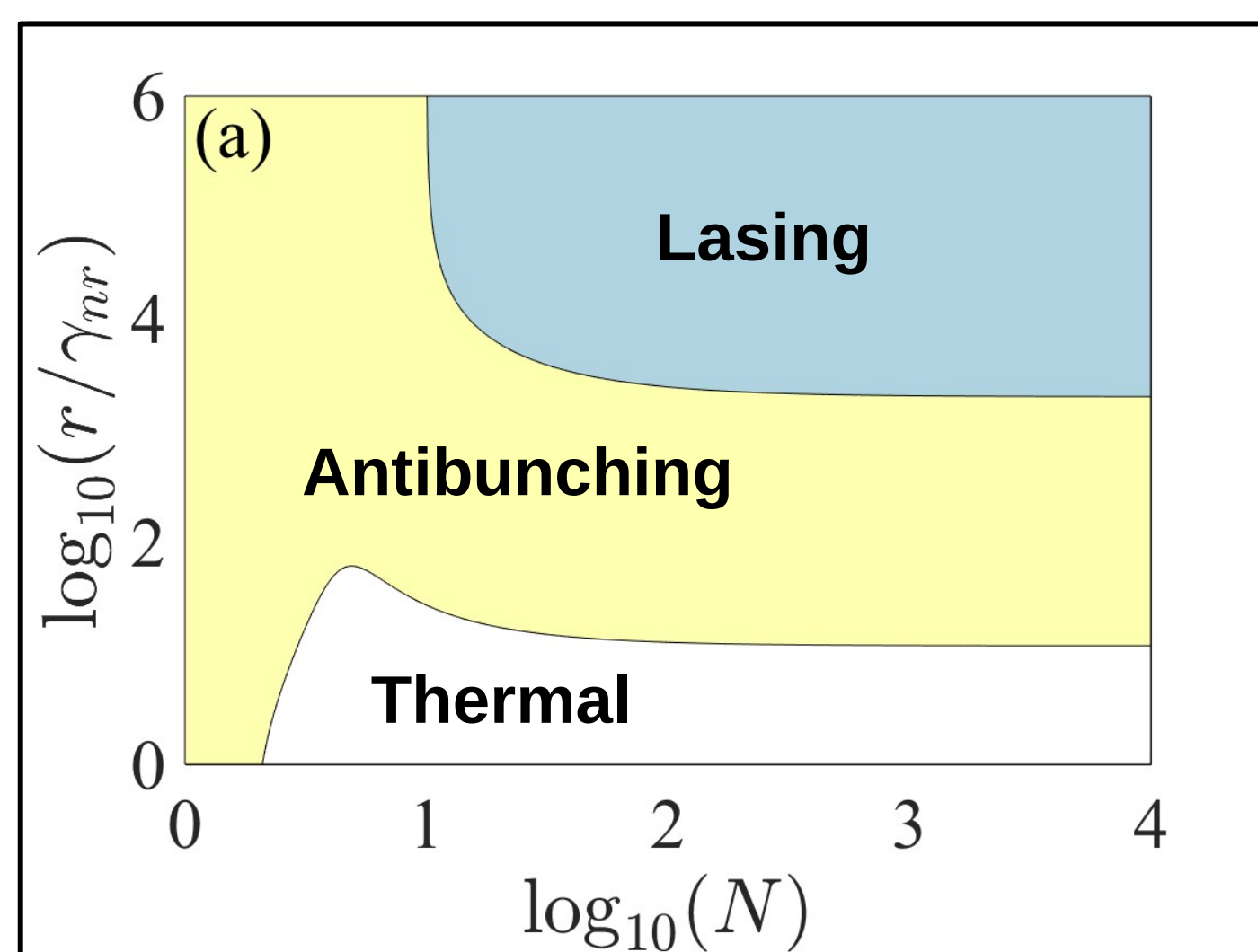
Thresholdless laser? [1]



- 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]



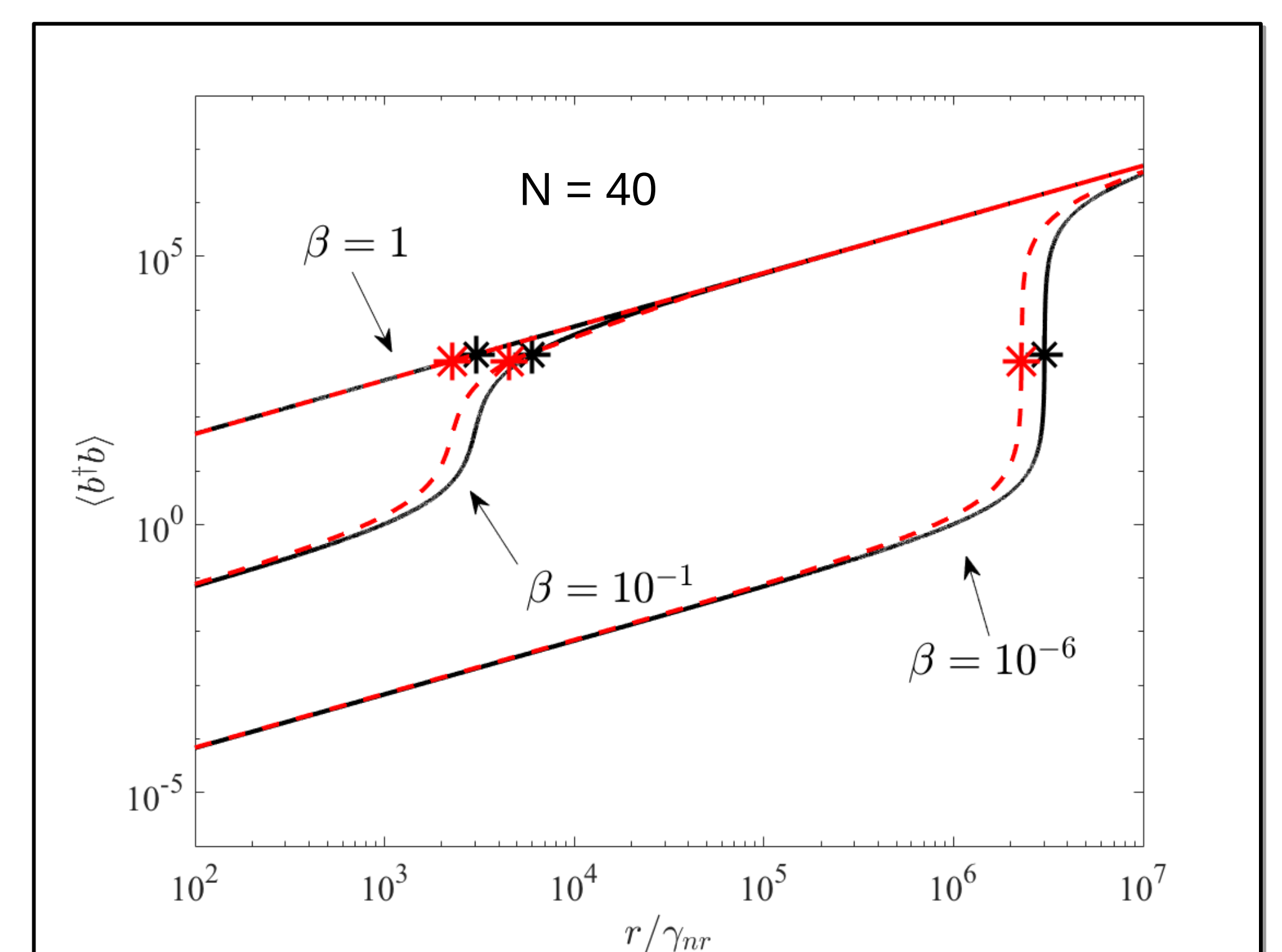
Generic transition

- Thermal emission
- Antibunching
- Lasing

Observable even for 10^4 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)