Dissipative Phases of a Bose-Einstein Condensate of Photons

Fahri Öztürk[1], Niels Wolf[1], Tim Lappe[2], Göran Hellmann[1], Jan Klaers[3], Frank Vewinger[1], Johann Kroha[2], Julian Schmitt[1], and Martin Weitz[1]

[1]Institut für Angewandte Physik, Universität Bonn, Wegelerstr. 8, 53115 Bonn, Germany
[2]Physikalisches Institut, Universität Bonn, Nussallee 12, 53115 Bonn, Germany
[3]Complex Photonic Systems (COPS), MESA+ Institute for Nanotechnology, University of Twente, 7522 NB Enschede, Netherlands.

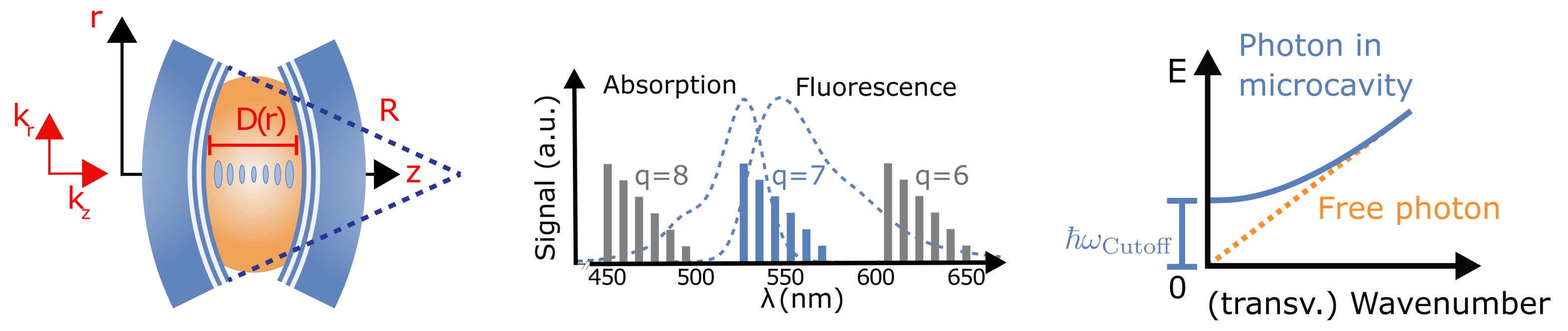
Overview

Bose-Einstein condensation has been observed with cold atomic gases, exciton-polaritons, and more recently also with low-dimensional photon gases e.g. in a dye solution-filled optical microcavity [1]. We here report on experiments observing a non-Hermitian phase transition in a photon Bose-Einstein condensate realized in the dye-microcavity platform. The dissipative phase transition occurs due to an exceptional point in the condensate that is associated with the (small) system losses. While usually Bose-Einstein condensation is separated by a smooth crossover to lasing, the presence of the here observed phase transition reveals a state of the light field characterized by a bi-exponential second order coherence that is separated by a phase transition from lasing [2]. In more recent work, we have performed a critical test of the thermal nature of the photon condensate coupled to the reservoir of photo-excitable dye molecules by probing the fluctuation-dissipation theorem in this system [3].

Bose-Einstein Condensation of Photons

Bose-Einstein condensation requires a thermalized gas of massive bosons. Photons are bosonic particles, they do not have a rest-mass and there is usually no number-conserving thermalization process, like two-body collisions between atoms. Therefore, both conditions have to be tailored in an experiment.

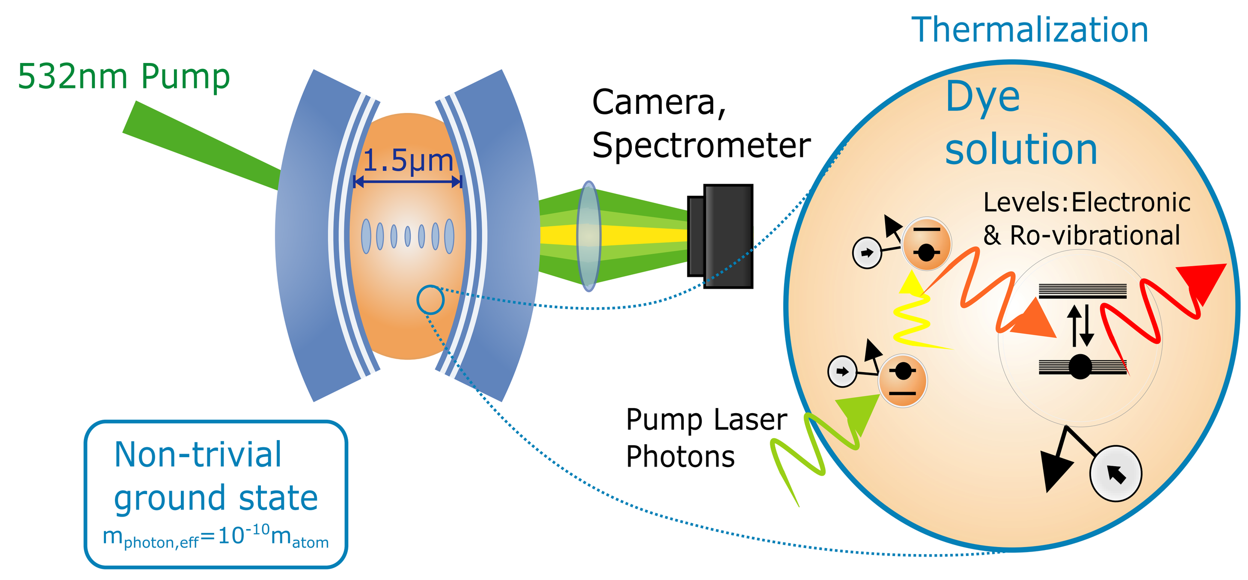
Photon dispersion in dye-filled microcavity



In paraxial approximation, the system is equivalent to a two-dimensional gas of massive bosons confined in a harmonic potential:

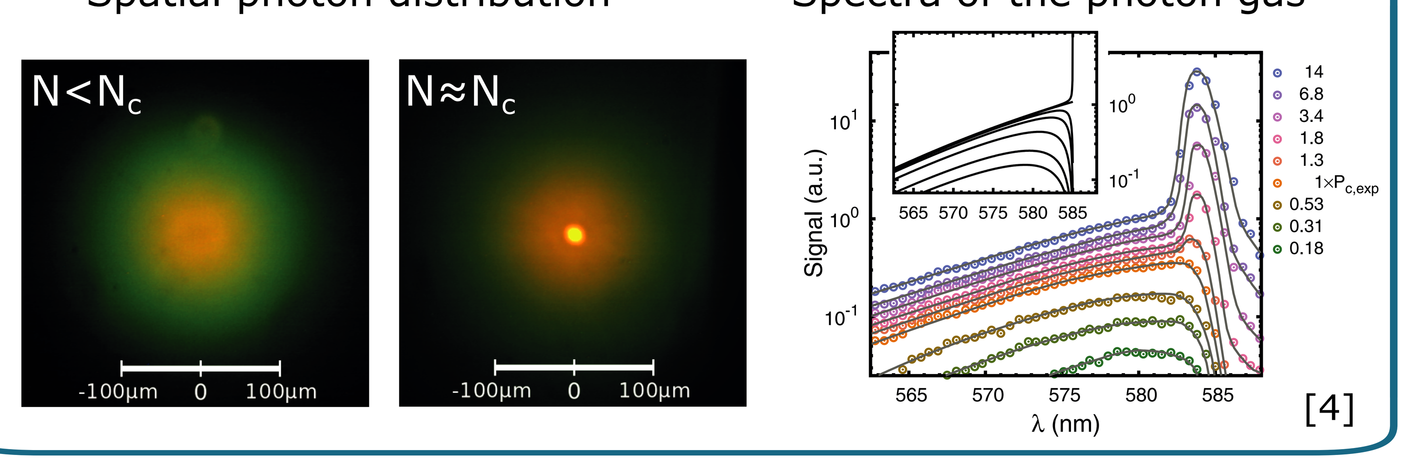
$$E(k_r, r) \simeq m_{Ph}\frac{c^2}{n^2} + \frac{\hbar^2 k_r^2}{2m_{Ph}} + \frac{1}{2}m_{Ph}\Omega^2 r^2$$

Thermalization of the 2D photon gas by radiative contact to dye



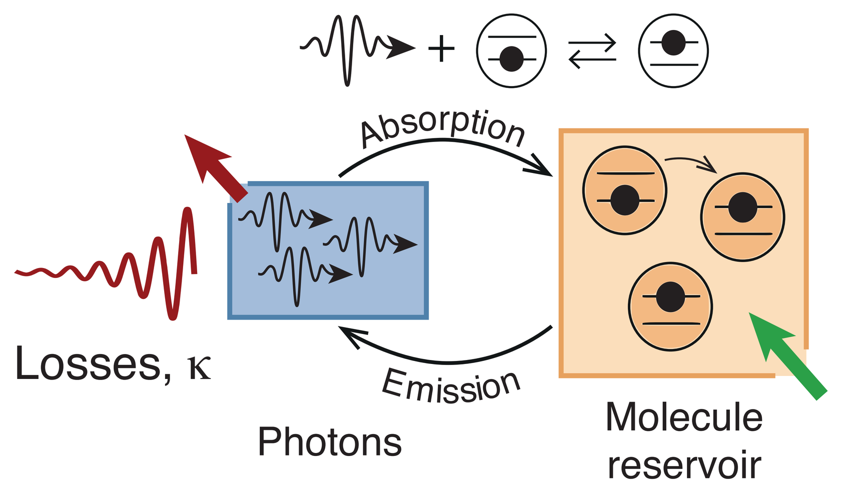
A number-conserving thermalization process is induced by repeated absorption and re-emission of photons by dye molecules. The thermalized gas of (massive) photons exhibits Bose-Einstein condensation at room temperature above a critical particle number of around 80.000 photons.

Experimental results



Grand Canonical Statistics

The steady-state particle flux from the pump beam through the dye microcavity condensate and out to the environment induces a modified behavior of the particle number fluctuations. The sum X of the condensate photon number $n(t)$ and dye molecular excitations $M_e(t)$ is conserved only on average, $X = n + M_e$ is constant.



Photon loss κ from mirror transmission (R>99.998%) and pumping P of the dye controls the open-system dynamics:

$$\dot{n} = -\kappa n - B_{abs}(M - M_\uparrow)n + B_{em}(n+1)M_\uparrow$$

$$\dot{M}_\uparrow = (M - M_\uparrow)(P + B_{abs}\, n) - B_{em} n M_\uparrow - M_\uparrow \Gamma_{sp}$$

Typical parameters

$B_{em} = 25$ kHz, $\kappa = 5$ GHz
$B_{abs} = 500$ Hz, $P = 50$ THz
$M \approx 10^9$, $\Gamma_{sp} = 0.24$ GHz

Non-Hermitian Phase Transition

The dynamics of the corresponding fluctuations Δn and ΔX around the mean can be derived from a Lindblad equation that incorporates the thermally driven fluctuations of the grand canonical system. For small deviations Δn and ΔX, this leads to a set of equations:

$$\frac{d}{dt}\begin{pmatrix}\Delta n\\ \Delta X\end{pmatrix} = \hat{A}\begin{pmatrix}\Delta n\\ \Delta X\end{pmatrix}, \text{ with the non-Hermitian matrix } \hat{A} = \begin{pmatrix}-2\delta & \omega_0^2/\kappa\\ -\kappa & 0\end{pmatrix}$$

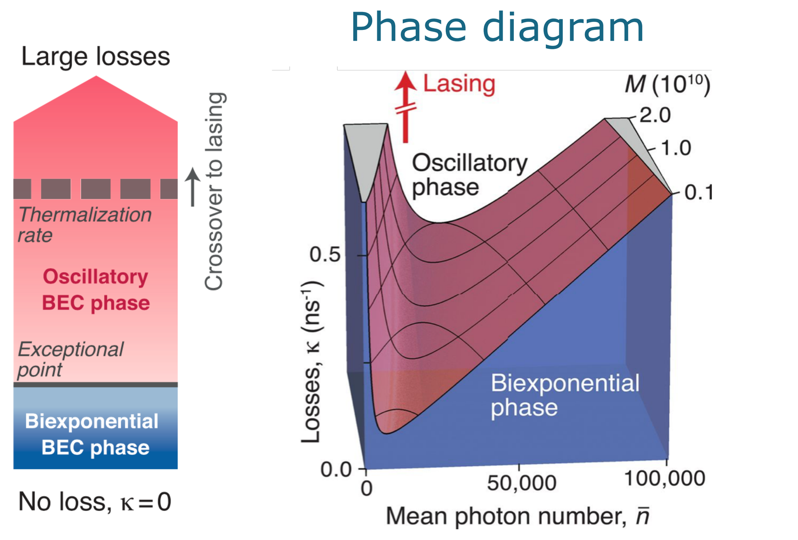
Pumping and loss modiefies the dynamics of $g^{(2)}(\tau)$. We identify two solutions, separated by an exceptional point ($\delta=\omega_0$):

$$g^{(2)}(\tau) = 1 + e^{-\delta\tau}\left(C_1 e^{-\sqrt{\delta^2-\omega_0^2}\tau} + C_2 e^{\sqrt{\delta^2-\omega_0^2}\tau}\right) + \text{c.c.}$$

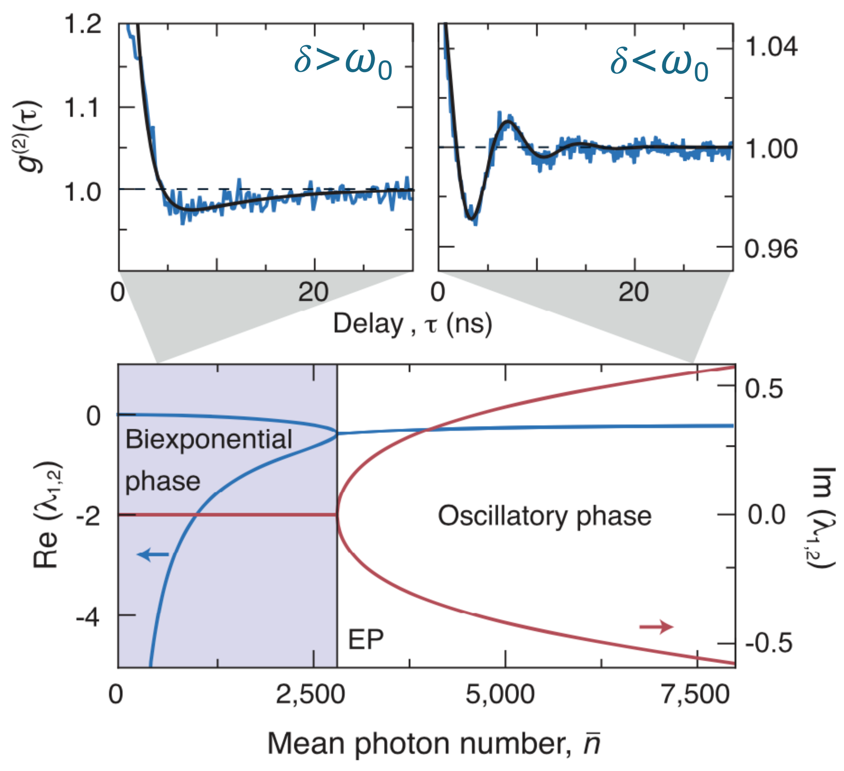
(free) oscillation frequency: $\omega_0 = \sqrt{\kappa B_{em}\bar{n}}$
damping:

$$\delta = \frac{1}{2}B_{em}(\bar{M}_{eff}/\bar{n} + \bar{n})$$

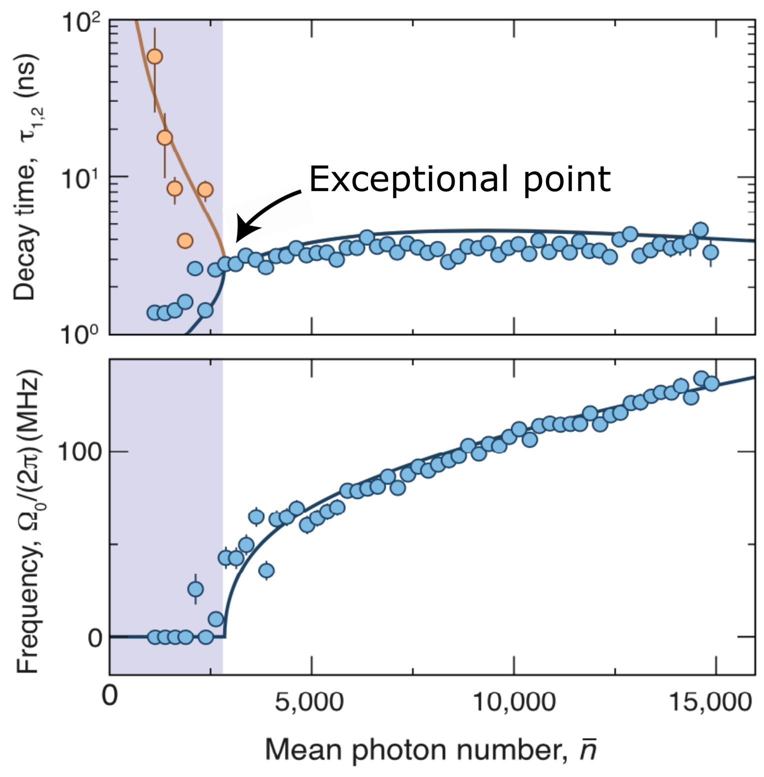
Phase diagram



Biexponential and oscillatory phases

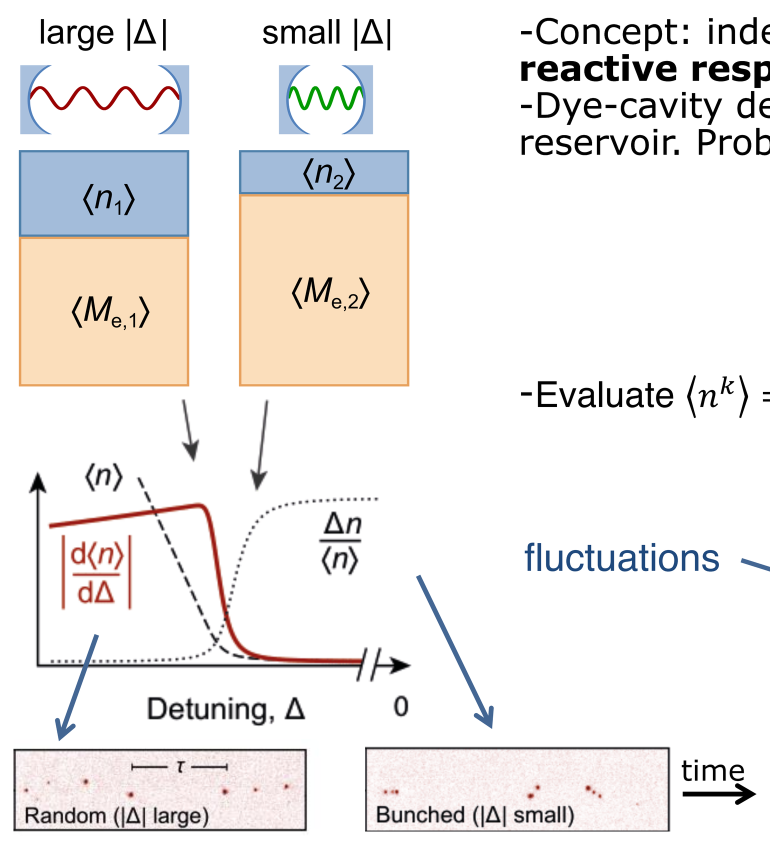


Phase transition at exceptional point



The state of a macroscopic quantum system on different sides of an exceptional point can be in two distinct regimes. We have observed the associated dissipative phase transition from an oscillatory to a biexponential dynamical phase of a dye microcavity photon Bose-Einstein condensate. This reveals a state of the light field, which, contrary to the usual picture of Bose-Einstein condensation, is separated by a phase transition from the phenomenon of lasing. For the future, the implementation of effective photon interaction, would allow us to study the interplay of interactions and non-Hermicity.

Fluctuation-Dissipation Relation



-Concept: independently measure **number fluctuations** and **reactive response** duction of BEC to reservoir changes
-Dye-cavity detuning controls relative size of photon BEC and reservoir. Probability to find n photons:

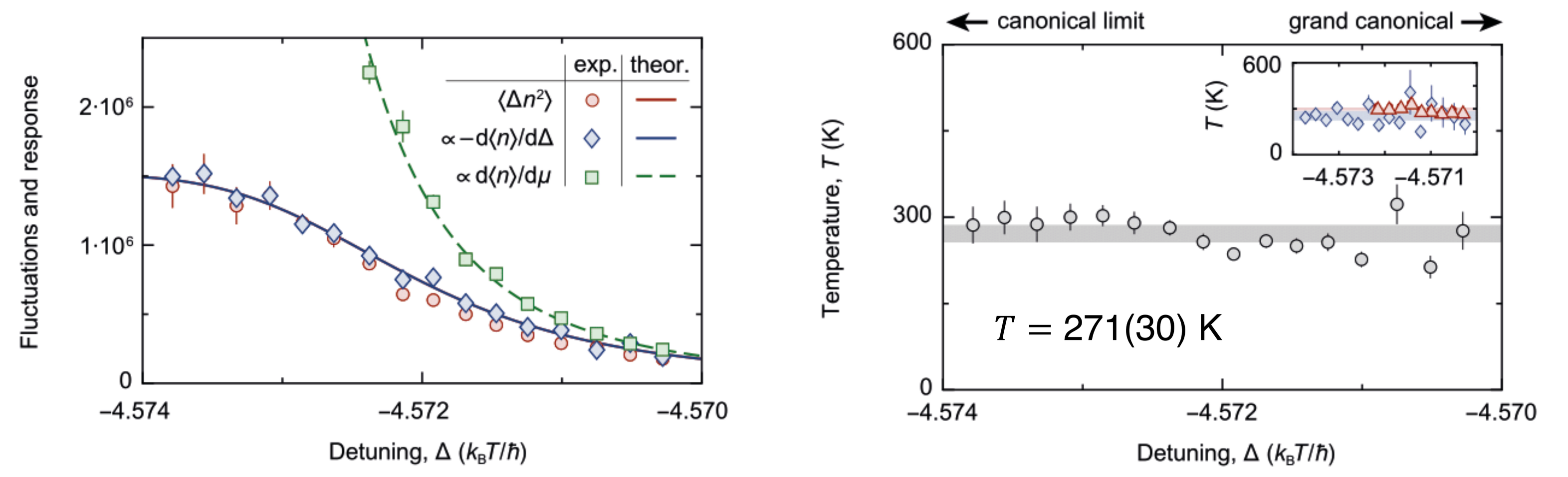
$$P_n = \frac{1}{Z}\frac{M}{(M - X + n)!\,(X-n)!}e^{-n\frac{\hbar\Delta}{k_B T}}$$

-Evaluate $\langle n^k\rangle = \sum n^k P_n \Rightarrow$ fluctuation-dissipation relation

$$\overline{\Delta n^2} = -\frac{k_B T}{\hbar}\left(\frac{d\bar{n}}{d\Delta}\right)_{X,T}$$

fluctuations → $\overline{\Delta n^2}$; response function → $\left(\frac{d\bar{n}}{d\Delta}\right)$; excitation number, temperature = const. → X,T

Fluctuation-based thermometry



References

[1] See, e.g.: Novel superfluids, Vol. 1, K. H. Bennemann and J. B. Ketterson (eds.) (Oxford University Press, Oxford, 2013).
[2] F. Öztürk et al., Science 372, 88 (2021)
[3] F. Öztürk et al., PRL, 130, 033602 (2023).
[4] J. Klaers et al., Nature 468, 545 (2010).
[5] C. Kurtscheid et al., Science 366, 894 (2019).