LECTURE 11

Photon BEC

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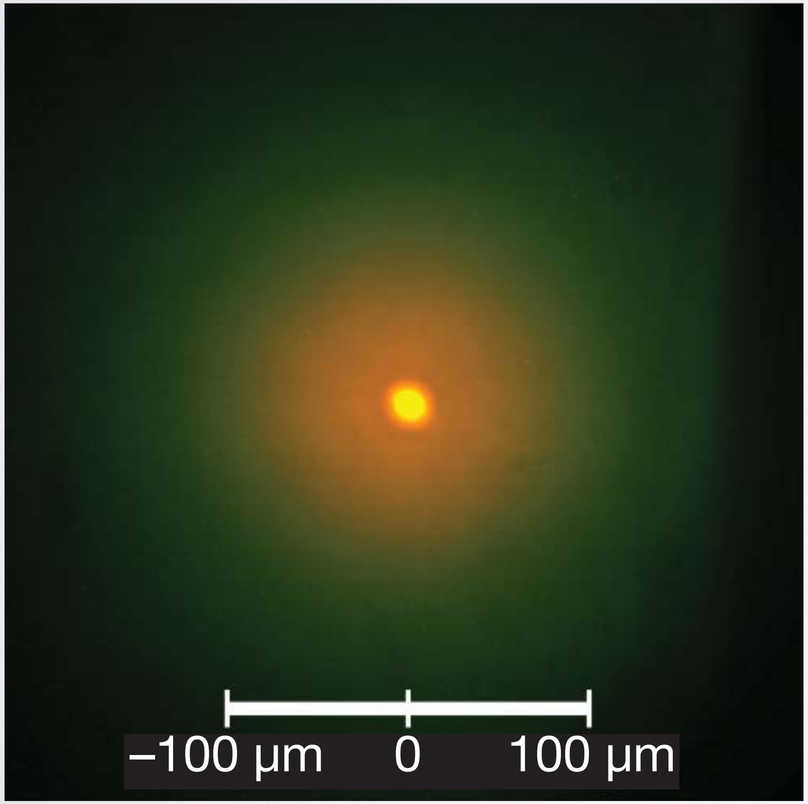
LETTER

doi:10.1038/nature09567

Bose–Einstein condensation of photons in an optical microcavity

Jan Klaers, Julian Schmitt, Frank Vewinger & Martin Weitz



The realization of a light source with a macroscopically populated photon mode that is not the consequence of a laser-like gain, but is rather due to an equilibrium phase transition of photons has so far been prevented by the lack of a suitable number-conserving thermalization process.

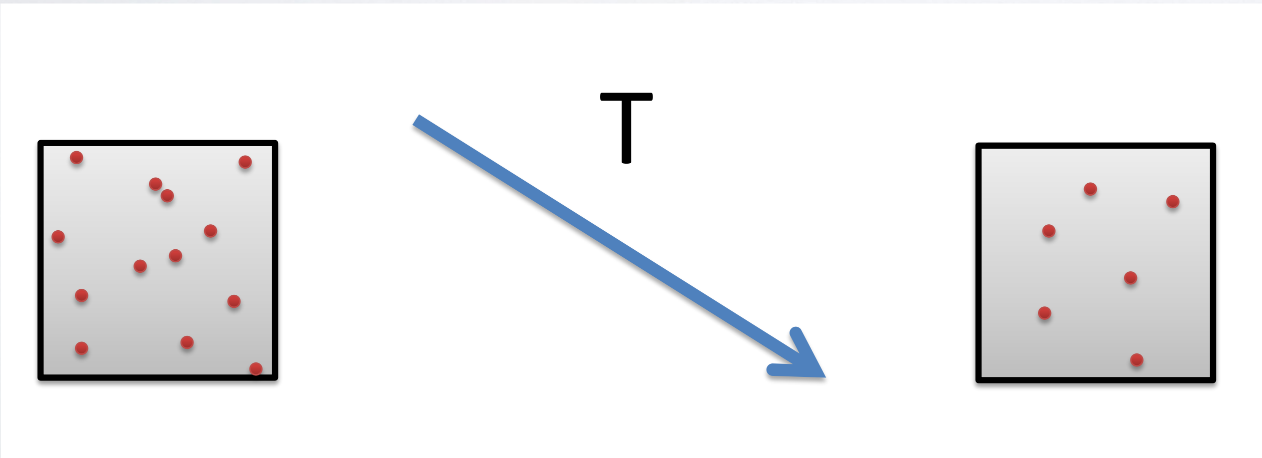
J. Klaers et al., Nature 468, 545 (2010)

Photon BEC

Non-interacting, zero mass particles

Photons are bosons, but their condensation was problematic so far.

- Photons have zero mass
- Photons do not interact
- The total number of photons is not conserved
- At low temperatures, photons disappear in the cavity walls instead of occupying the cavity ground state
- Photons can be brought to thermal equilibrium in a black box, but their number is not conserved, which implies that the chemical potential is either not well defined or strictly zero.



BETTER CAVITY !

Cavity

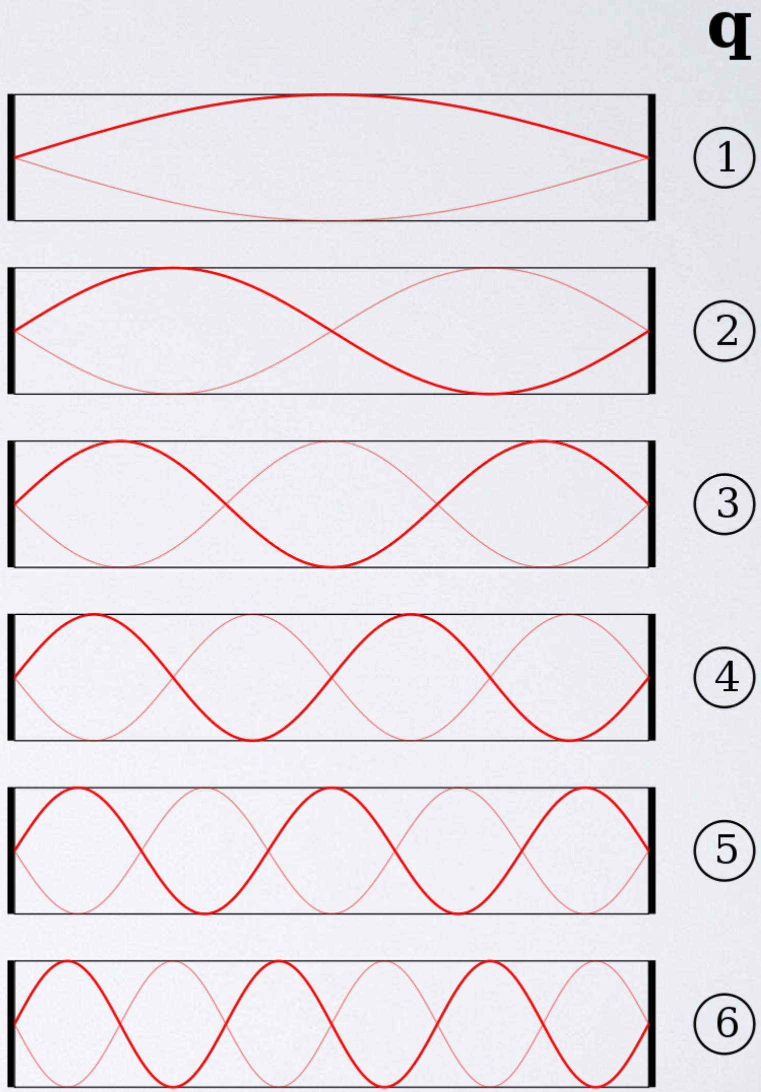
Localized modes

Photon wavelength depends on cavity length.

$$L = \frac{q}{2}\lambda$$

The frequency separation between any two adjacent modes, q and q+1:

$$\Delta\nu = \frac{c}{2nL}$$



Cavity

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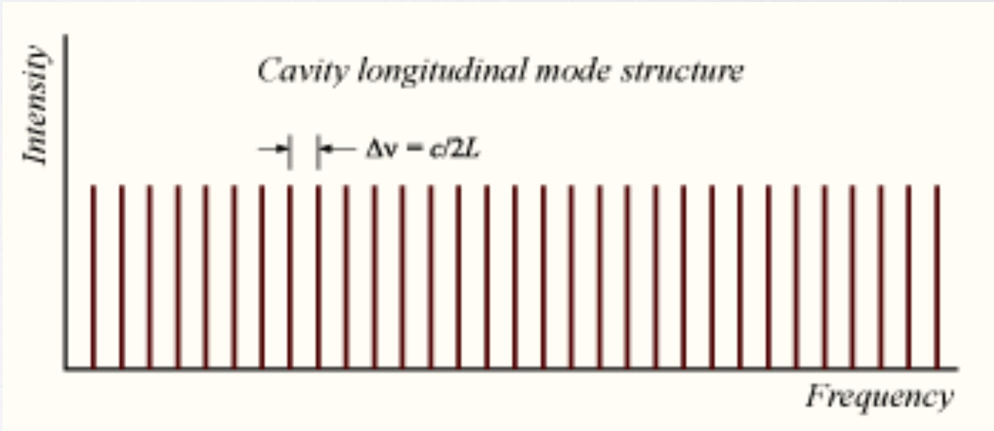

Optical cavity longitudinal mode structure:

Cavity

Localized modes

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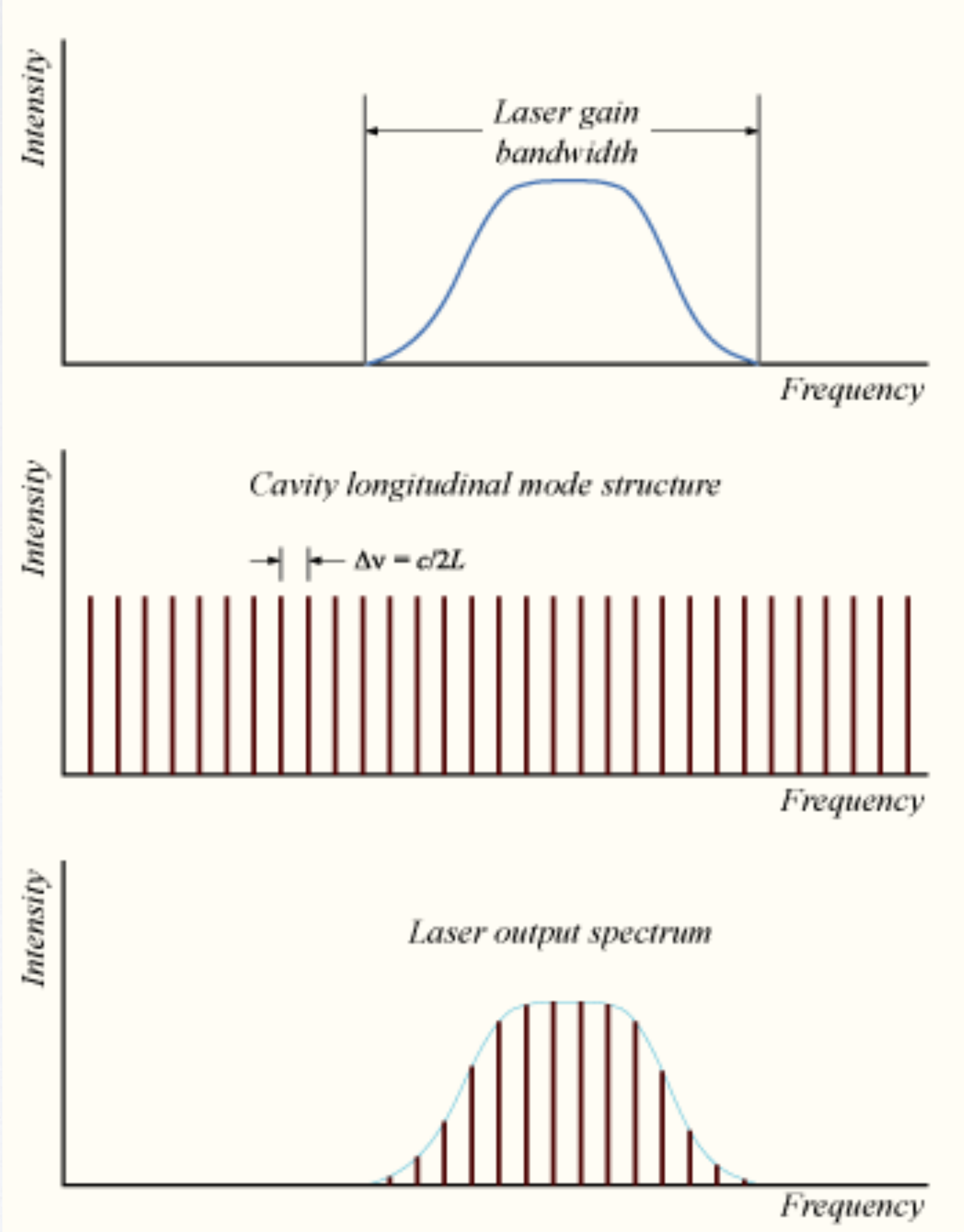
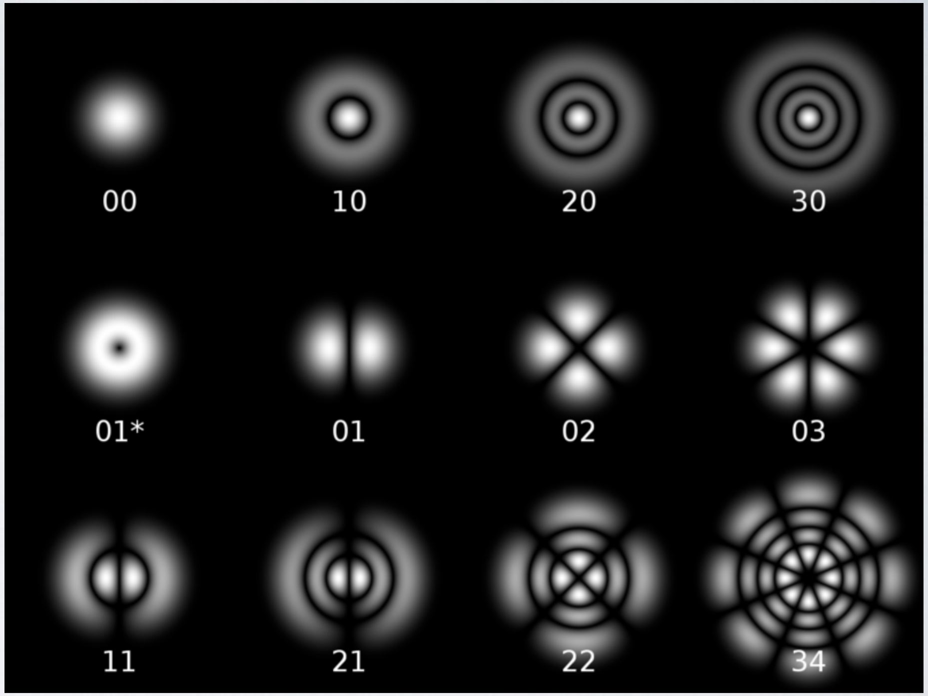
Optical cavity longitudinal mode structure:



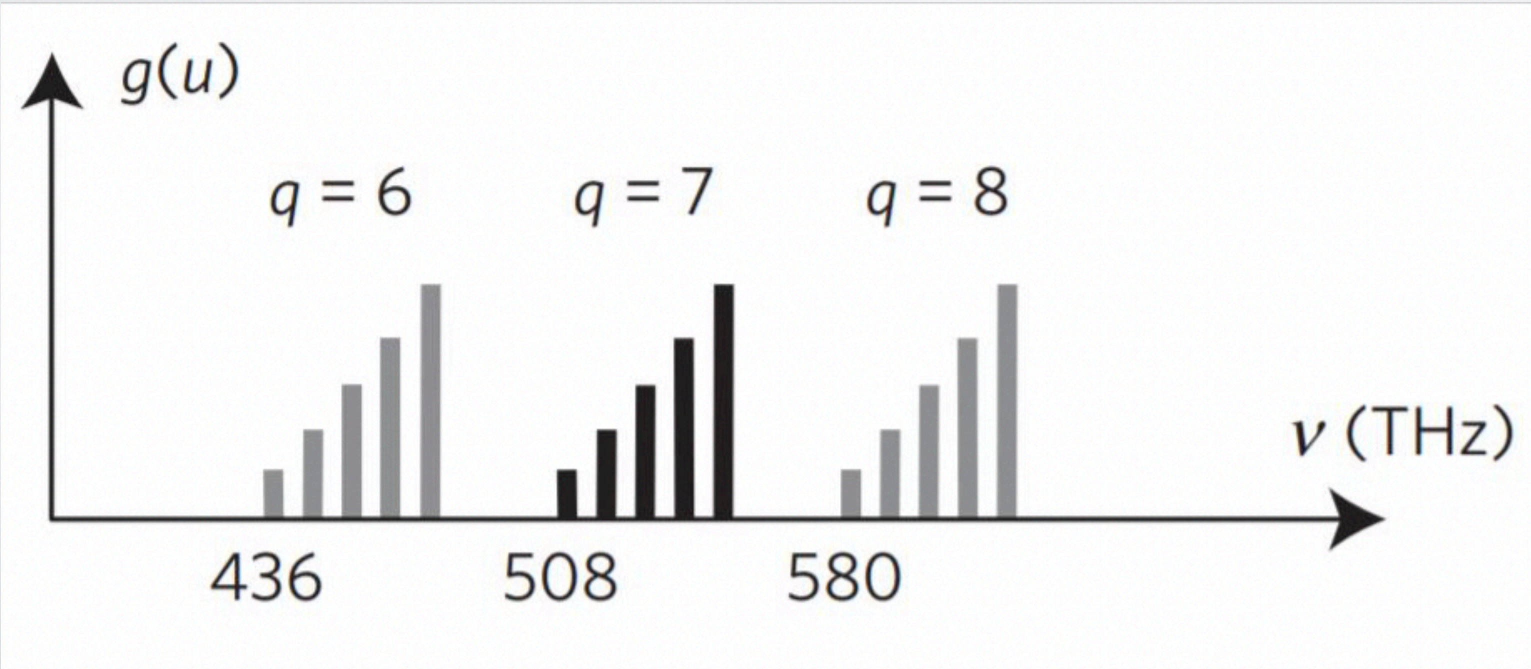
Cavity
Localized modes

Optical cavity transversal mode structure:

May differ in both frequency and the intensity pattern of the light.



In a cylindrical cavity



J. Klaers et al., Thermalization of a two-dimensional photonic gas in a 'white-wall' photon box. Nature Phys. 6, 512–515 (2010).

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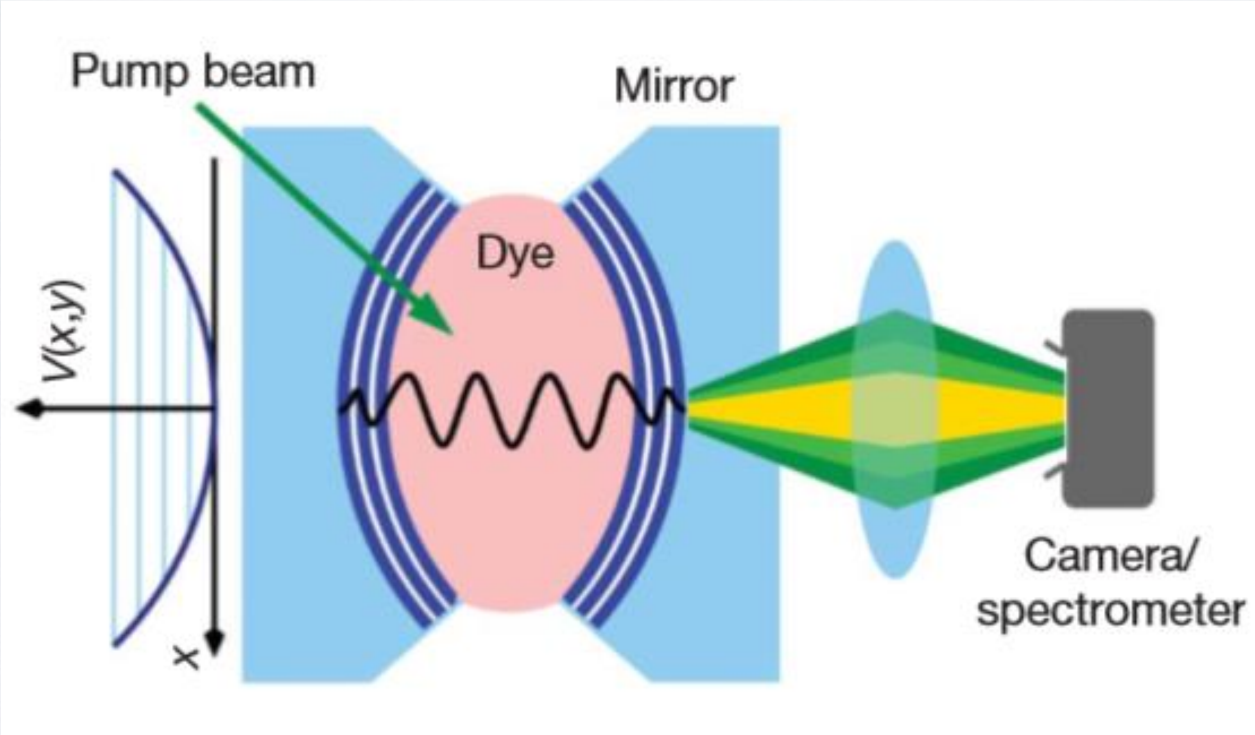
Experimental setup

J. Klaers et al., Nature 468, 545 (2010)

J. Klaers, M. Weitz, Bose-Einstein condensation of photons, arXiv:1210.7707

Fluorescent dye in a cavity



- Very short cavity (L = 1.46 μm)
- High reflectivity mirrors
- Mirrors generate effective trapping potential
- Rhodamine 6G dye

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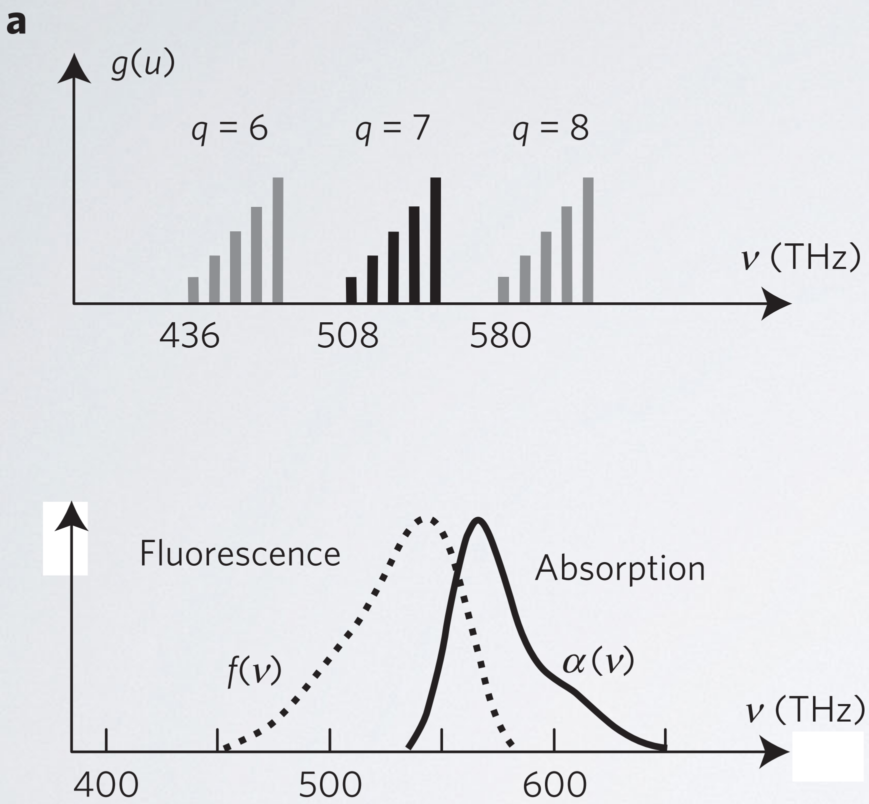
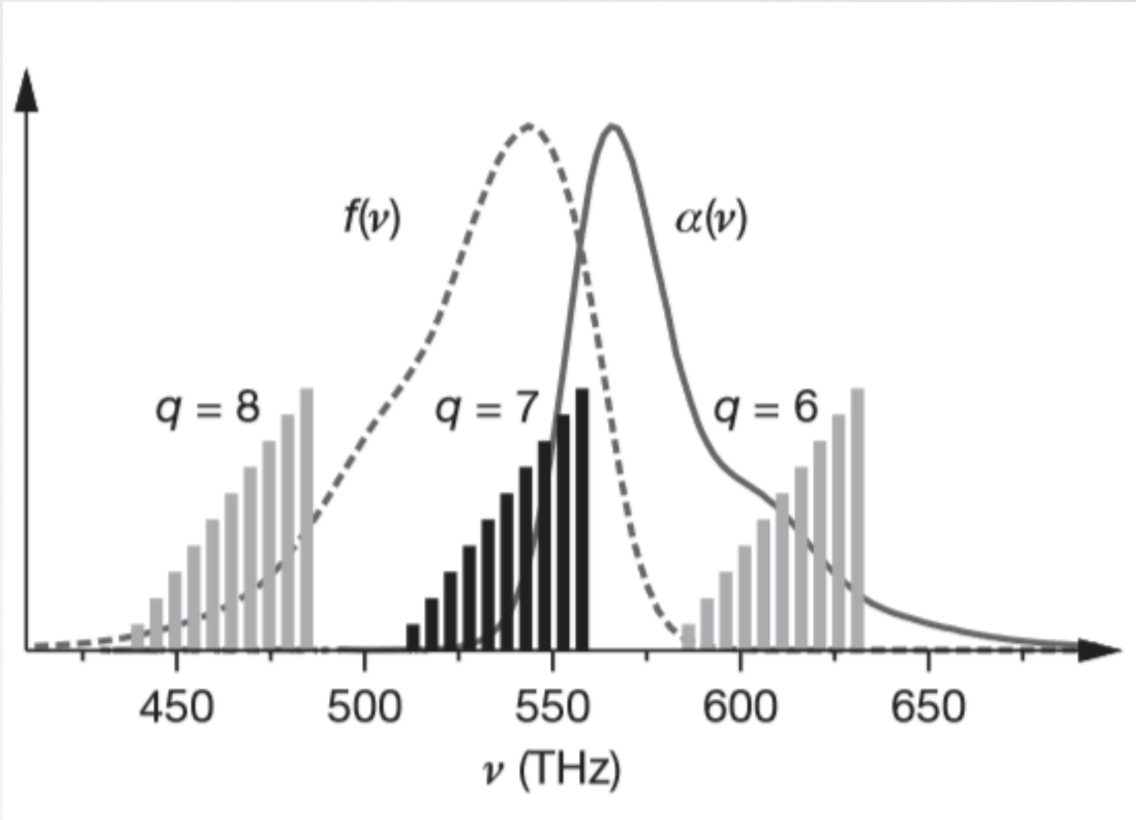
Experimental setup

J. Klaers et al., Nature 468, 545 (2010)

Only one longitudinal cavity mode in dye emission spectrum





$$g(u) = 2(u/\hbar\Omega + 1)$$

$\Omega/2\pi$ (~4×10^{10} Hz) denotes the spacing of transversal cavity modes; that is, the spacing is so small that the transverse motion is quasicontinuous.

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Experimental setup

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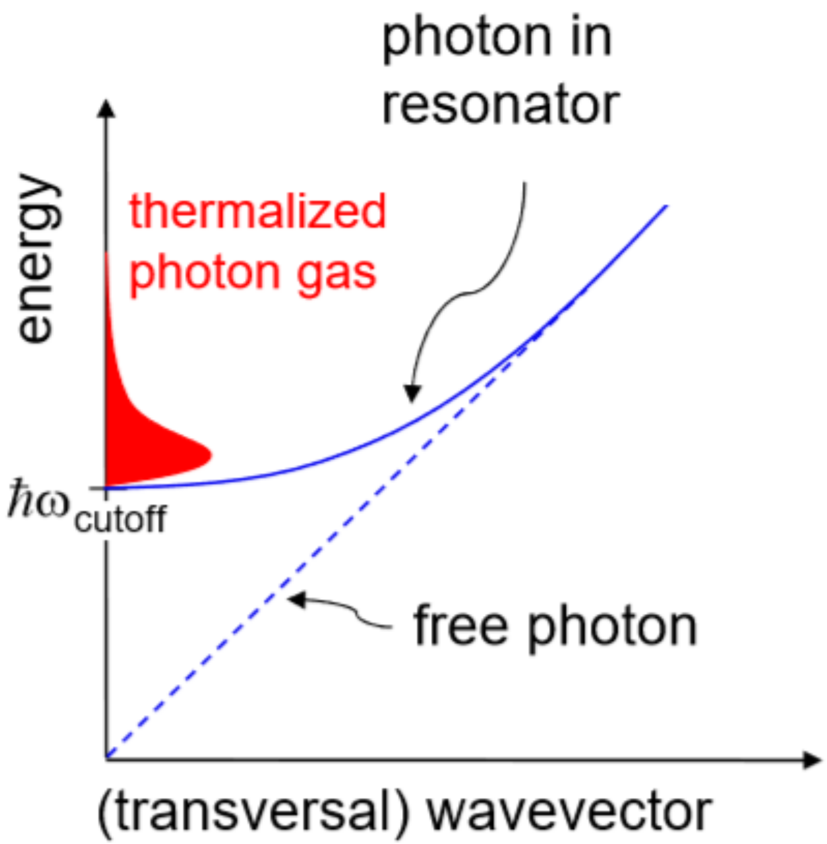
Minimum energy in the system is far above thermal energy.



$$E = \frac{\hbar c}{n_0}|k| = \frac{\hbar c}{n_0}\sqrt{k_z^2 + k_r^2}$$

$$m_{\text{ph}} = \hbar\omega_{\text{cut-off}}/c^2 \cong 6.7 \times 10^{-36}\ \text{kg}$$

$$\lambda_{\text{th}} = h/\sqrt{2\pi m_{\text{ph}} k_B T} \cong 1.58\ \mu\text{m}$$

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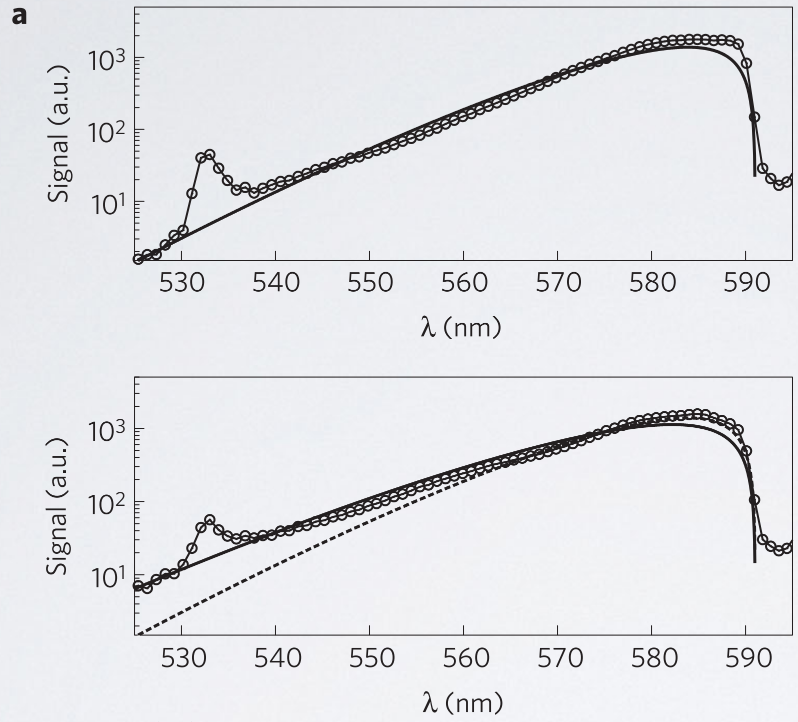
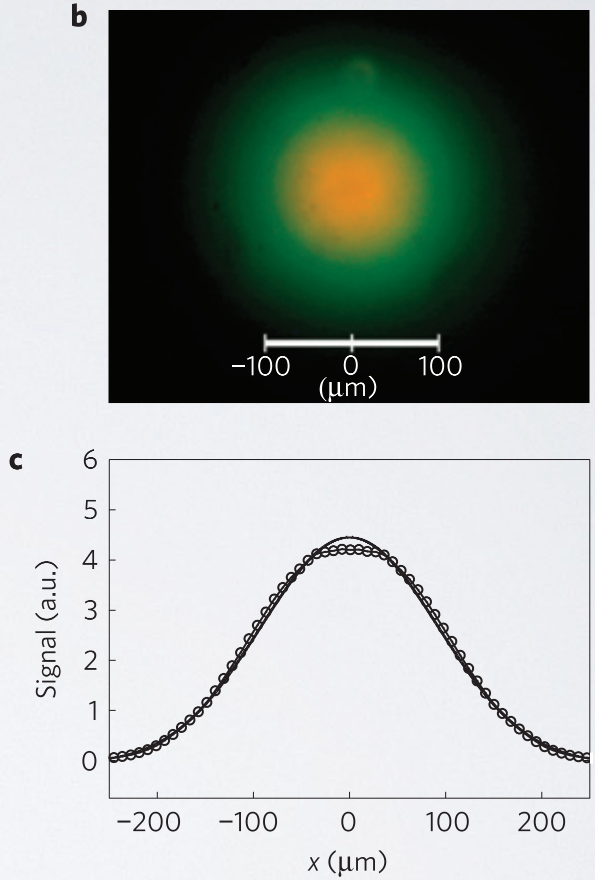
Experimental setup

Equilibrium is reached as photons are absorbed and emitted by dye molecules many times, with the interplay between fluorescence and absorption leading to a thermal population of cavity modes, making the photon gas equilibrate at the temperature of the dye solution.





$$n_{T,\mu}(u) = \frac{g(u)}{\exp\left(\frac{u-\mu}{k_B T}\right) - 1}$$

Figure 2 | Experimental spectra and intensity distribution. a, The connected dots give measured spectral intensity distributions for temperatures of 300 K (top) and 365 K (bottom) of the resonator set-up. The solid lines are theoretical spectra based on Bose–Einstein-distributed transversal excitations, and for illustration a $T = 300$ K distribution is also inserted in the bottom graph (dashed line). The measurements shown in this figure were carried out with rhodamine 6G dye dissolved in ethylene glycol ($c = 5 \times 10^{-4}$ M). Note that the spectral maximum of blackbody radiation at $T = 300$ K is at ~10 μm wavelength, that is, far to the red of the shown spectral regime. **b**, Image of the radiation emitted along the cavity axis at room temperature ($T = 300$ K), showing a shift towards shorter (higher energetic) optical wavelengths for off-axis radiation. **c**, Spatial intensity distribution at $T = 300$ K (connected circles) along with the theoretical prediction (solid line).

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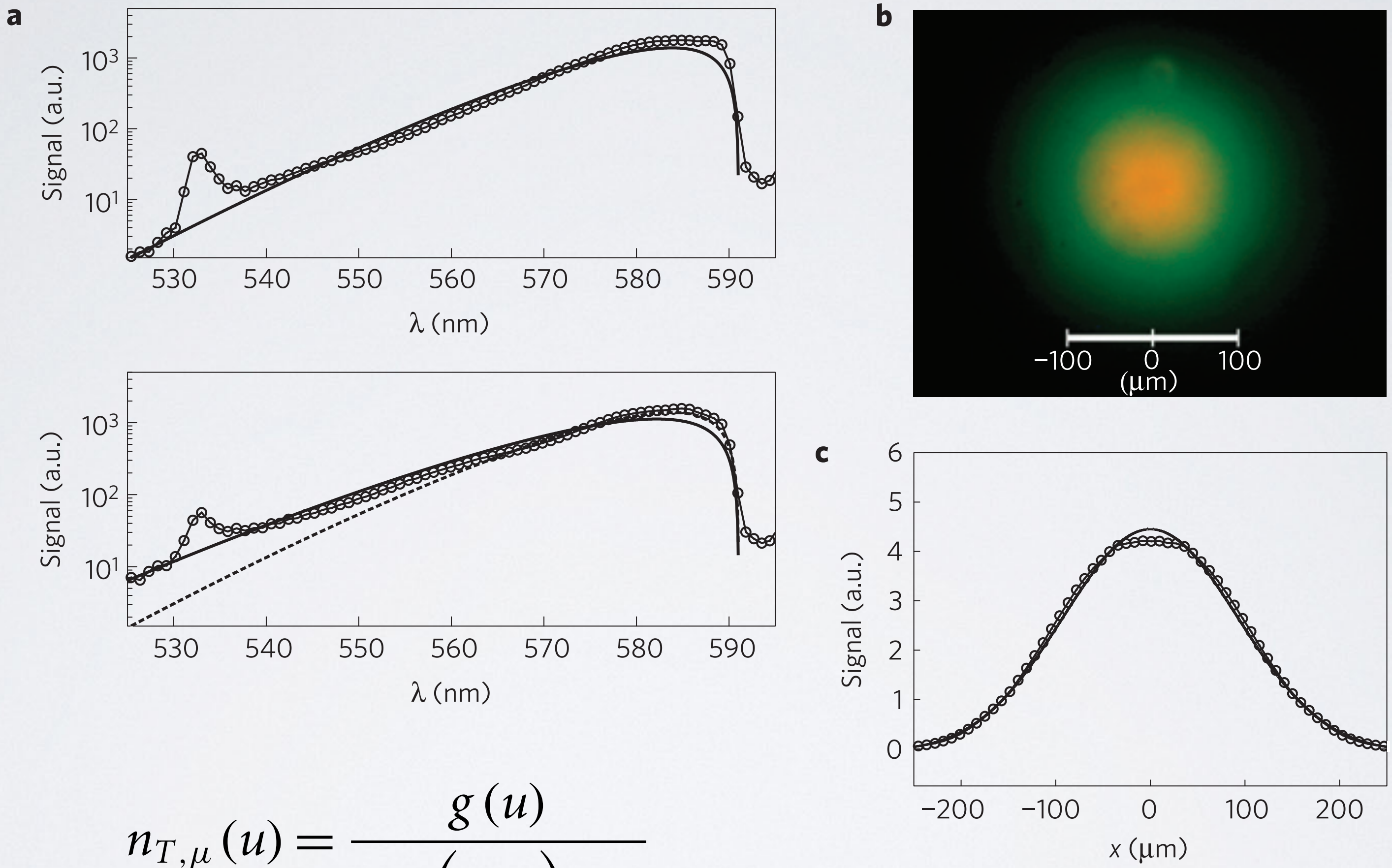
Results

Equilibrium is reached as photons are absorbed and emitted by dye molecules many times, with the interplay between fluorescence and absorption leading to a thermal population of cavity modes, making the photon gas equilibrate at the temperature of the dye solution.



$$n_{T,\mu}(u) = \frac{g(u)}{\exp\left(\frac{u-\mu}{k_B T}\right) - 1}$$

Result: $\mu \ll -k_BT$ and the term −1 in the denominator of the equation can be neglected and the distribution becomes Boltzmann-like.

A Bose–Einstein condensate would be expected for $N_{ph} \rightarrow N_c = 80{,}400$ (at which $\mu \rightarrow 0$)

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Results

J. Klaers et al., Nature 468, 545 (2010)

The precise onset of BEC in the two-dimensional, harmonically trapped system can be determined from a statistical description using a Bose–Einstein distributed occupation of trap levels, giving a critical particle number of:

$$N_c = \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2$$

At room temperature (T 5 300 K): $N_c \cong 77{,}000$

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J. Klaers et al., Nature 468, 545 (2010)

Results

Increased pumping (photon density) lead to condensation

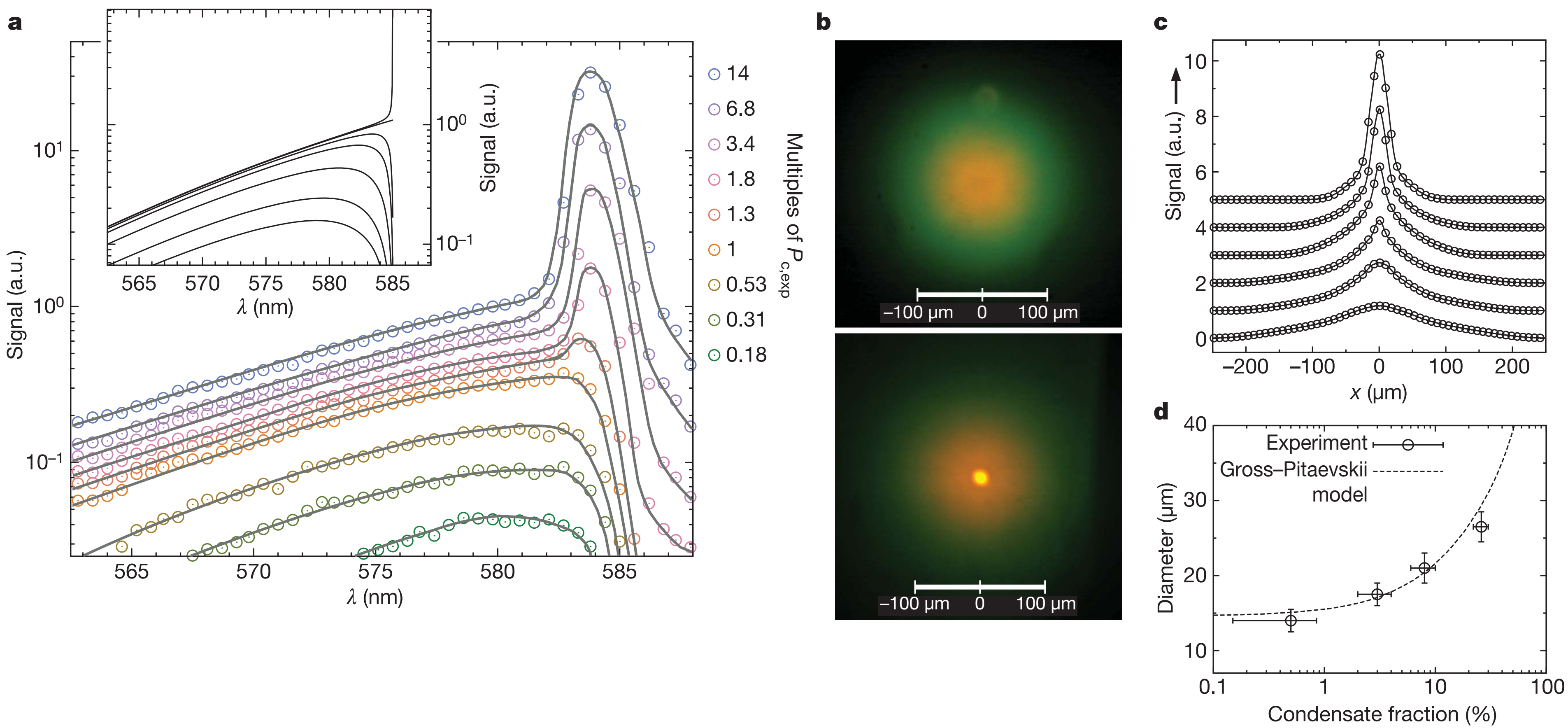

Figure 2 | Spectral and spatial intensity distribution. **a**, Spectral intensity distributions (connected circles) transmitted through one cavity mirror, as measured with a spectrometer, for different pump powers (see colour key). The intracavity power (in units of $P_{c,\,exp} = (1.55 \pm 0.60)$ W) is derived from the power transmitted through one cavity mirror. A spectrally sharp condensate peak at the cavity cut-off is observed above a critical power level, with a width limited by the spectrometer resolution. The inset gives theoretical spectra (solid lines) based on a Bose–Einstein distribution of photons for different particle numbers at room temperature[14]. a.u., arbitrary units. **b**, Images of the spatial radiation distribution transmitted through one cavity mirror both below (upper panel) and above (lower panel) criticality, showing a macroscopically occupied TEM_{00}-mode for the latter case. **c**, **d**, Cut through the centre of the intensity distribution for increasing optical pump powers (**c**) and width of the condensate peak versus condensate fraction, along with a theoretical model based on the Gross–Pitaevskii equation with an interaction parameter $\tilde{g} = 7 \times 10^{-4}$ (Methods) (**d**). Error bars are the systematic calibration uncertainties. $q = 11$ for **c** and **d**. All other measurements use $q = 7$.

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Sumary

- Dye with overlapping absorption and emission spectra and cut-off energy allows for photon thermalization
- After exceeding critical photon density, BEC appears
- No population inversion, as in lasers
- Spectral distribution shows Bose-Einstein distributed photon energies
- Observed onset of a phase transition occurs on a predicted absolute value of photon number
and shows the expected scaling with resonator geometry.

Further reading: **Bose-Einstein condensation of photons from the thermodynamic limit to small photon numbers**
by R. A. Nyman and B.T. Walker
arxiv.org 1706.09645

by M. Weitz's group in Bonn
by R. A. Nyman and B.T. Walke
by D. van Oosten's group in Utrecht