Engineering Effective Interactions for Bose-Einstein Condensates of Photons

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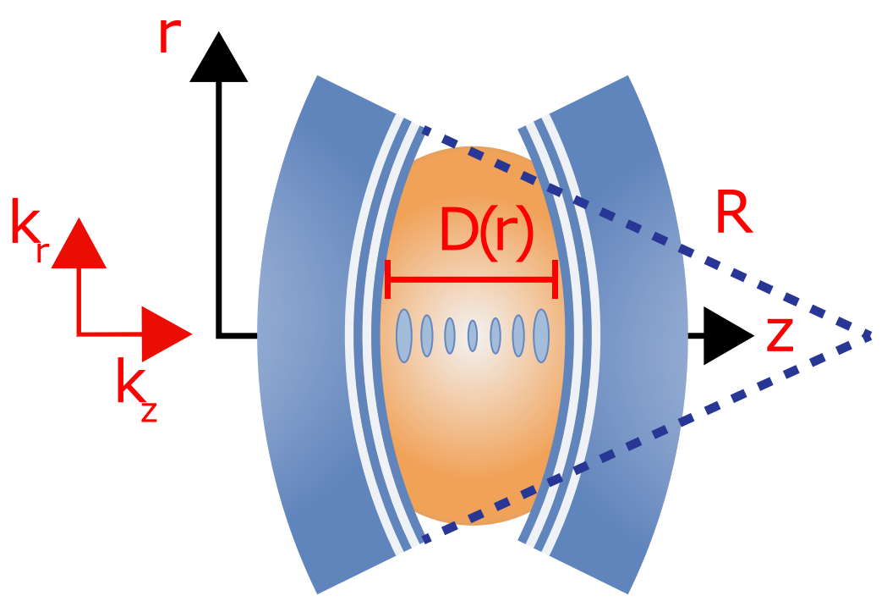
Overview

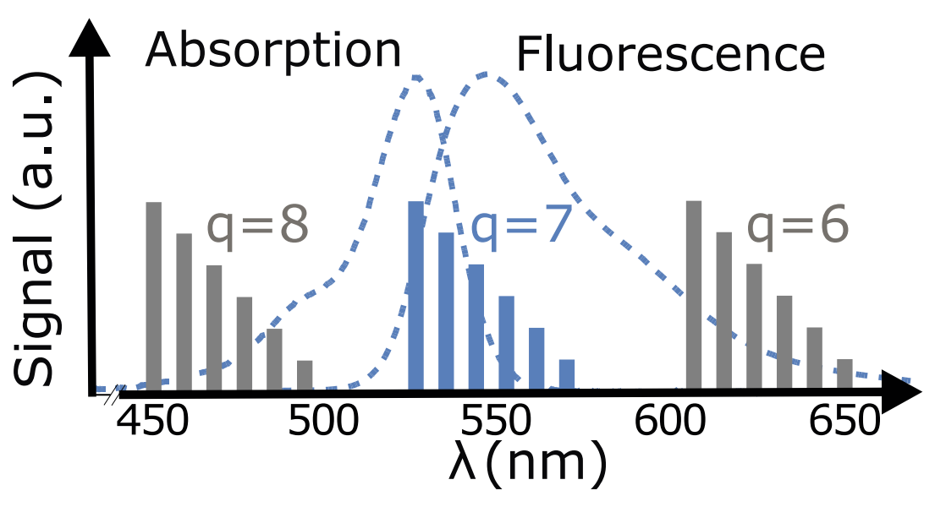
Bose-Einstein condensation can be observed with ultracold atomic gases, polaritons, and since about a decade ago also with low-dimensional photon gases. Bose-Einstein condensates of photons have been realized in dye-solution filled optical microcavities, where a wavelength-size small mirror spacing imprints a low-frequency cutoff with a spectrum of photon energies above the low-frequency cutoff and thermalization of photons being achieved by repeated absorption-reemission processes on the dye molecules [1]. In the presence of an effective photon interaction, the energetically driven optical state preparation method can in future in lattice potentials provide a route for exploring highly correlated and entangled states [2].Here we report the generation of effective Interactions, which is a third order nonlinearity, by cascading second order nonlinearities in a double resonant setup (see [3] corresponding theory). Our demonstration experiment builds upon a triply resonant optical parametric oscillator setup, with independent control of the cavities for the pump and subharmonic wavelengths respectively. The achieved effective Kerr-nonlinearity of periodically poled lithium niobate (PPLN) of 4.2(3)e^{-11} cm^2/W is two orders of magnitude above the intrinsic Kerr-nonlinearity of the used PPLN crystal.

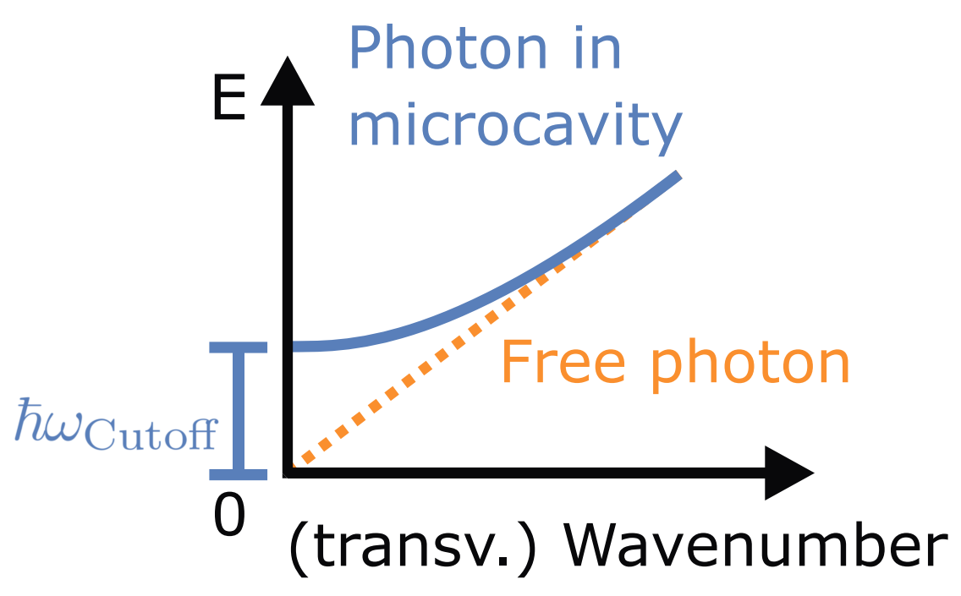
Bose-Einstein Condensation of Photons

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.

1. Photon dispersion relation in a dye-filled microcavity



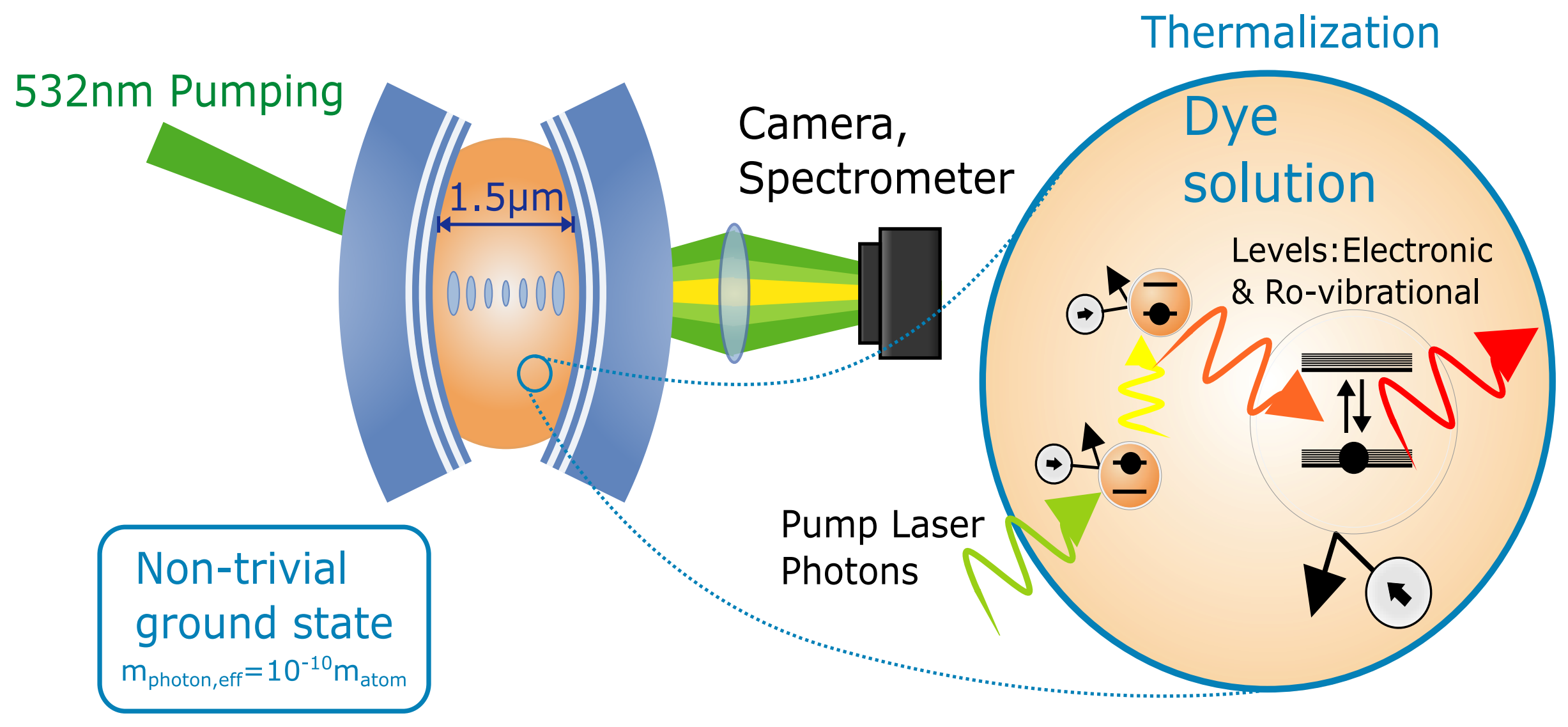




In paraxial approximation, the system is equivalent to a two-dimensional gas of massive bosons confined in a harmonic potential:

$$E(k_r,r) \simeq m_{Ph}\frac{c^2}{n^2} + \frac{\hbar^2 k_r^2}{2m_{Ph}} + \frac{1}{2}m_{Ph}\Omega^2 r^2 + m_{Ph}\frac{c^2}{n^3}\Delta n(r) \,\Big|\, m_{Ph} := \frac{\hbar q \pi n}{cD_0} \simeq 10^{-37}\mathrm{kg} \,\Big|\, \Omega := \frac{c}{n\sqrt{D_0 R/2}} \simeq 10^{11}\mathrm{Hz}$$

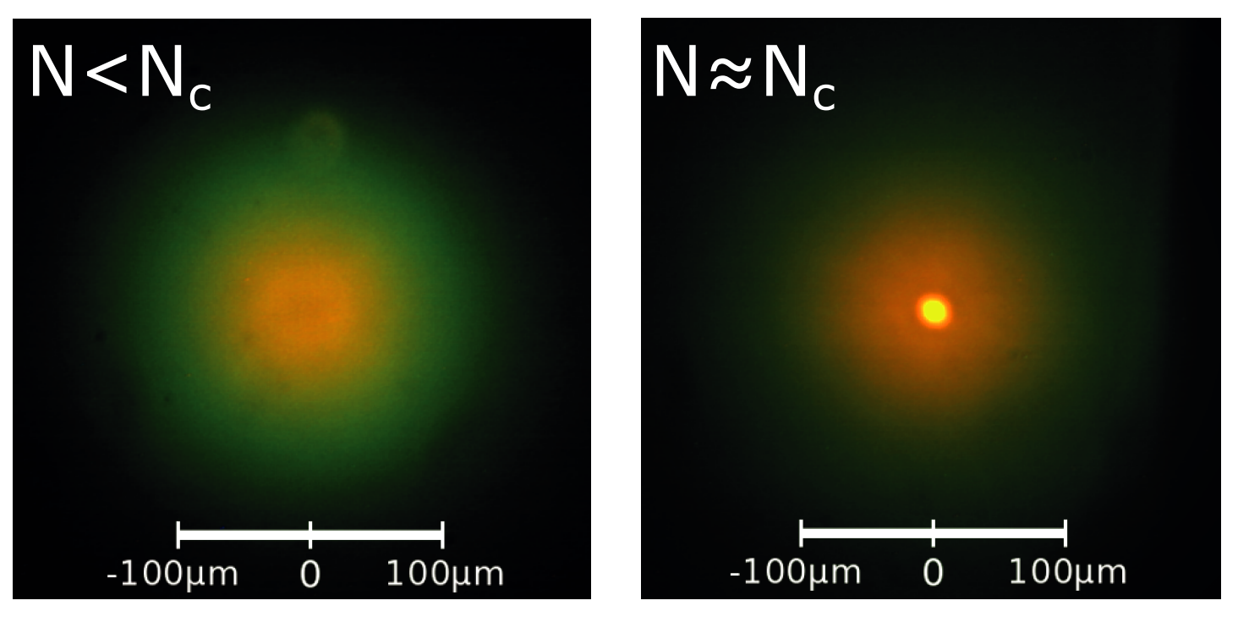
2. Thermalization of the 2D photon gas



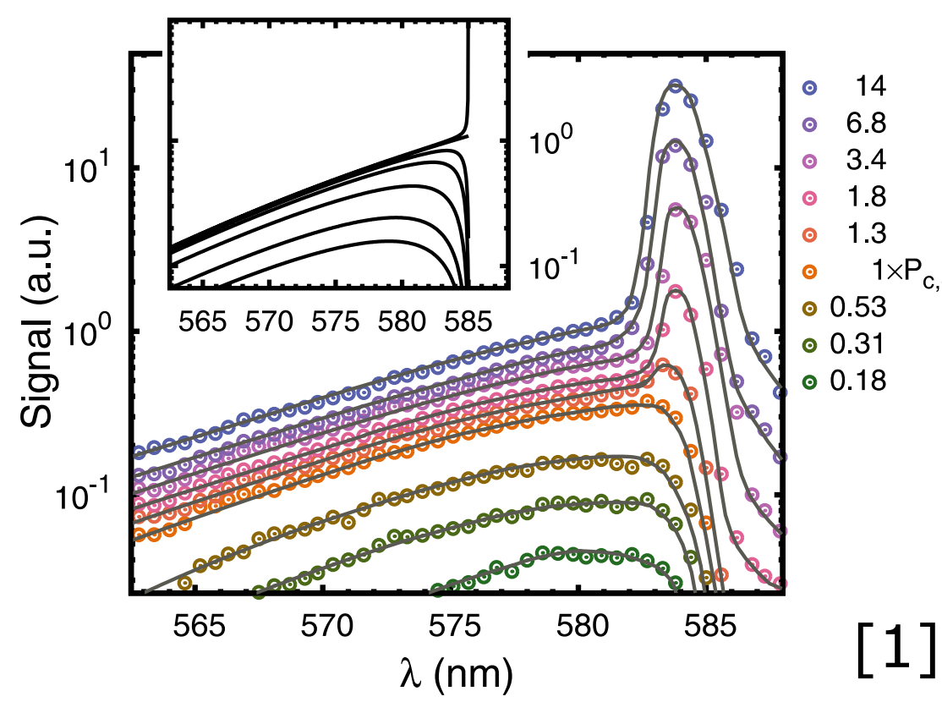
A number-conserving thermalization process is induced by repeated absorption and re-emission of photons by dye molecules. The thermalized gas of (massive) photons exhibits Bose-Einstein condensation at room temperature above a critical particle number of around 80.000 photons.

Experimental results: Harmonic Potential

Spatial photon distribution



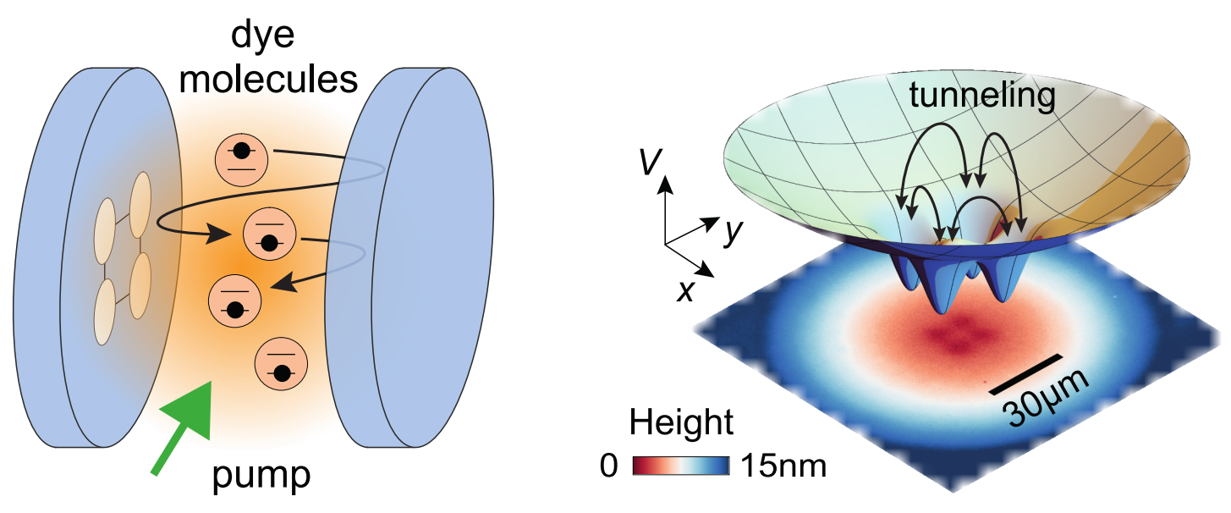
Spectra of the photon gas



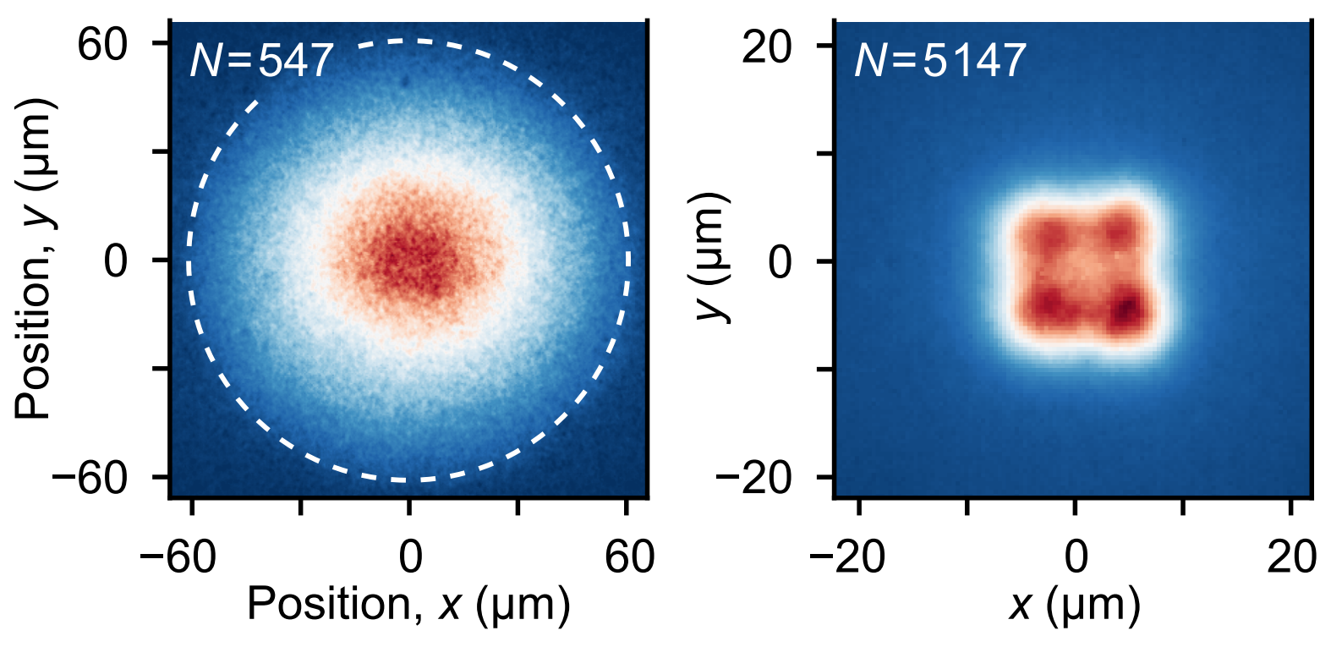
[1]

Experimental results: Lattice Potential

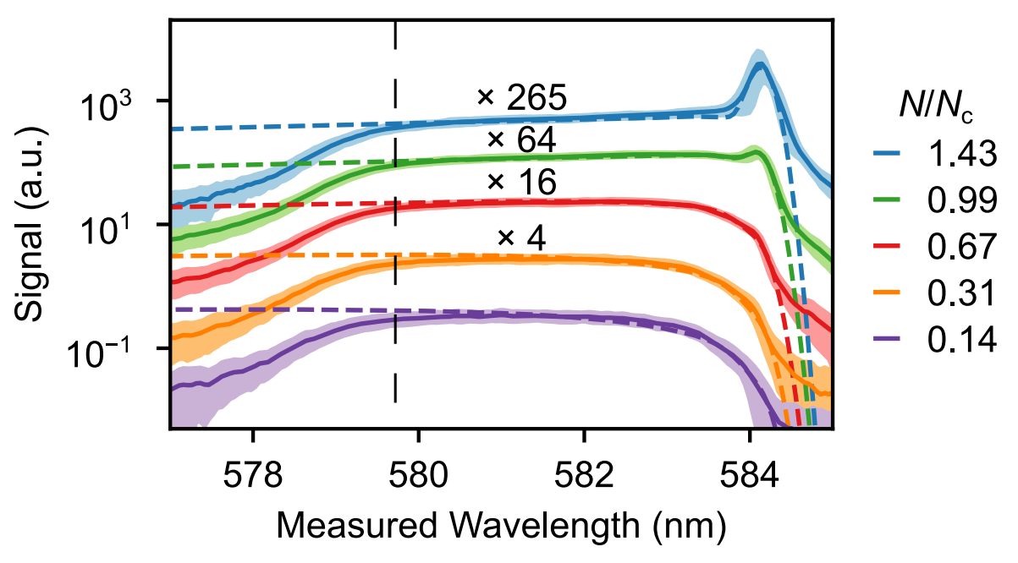
The technique of delamination enabled arbitrary mirror strurcturing and thus differnet potential types, e.g. lattice structures, box potentials and ring potentials.



Spatial photon distribution



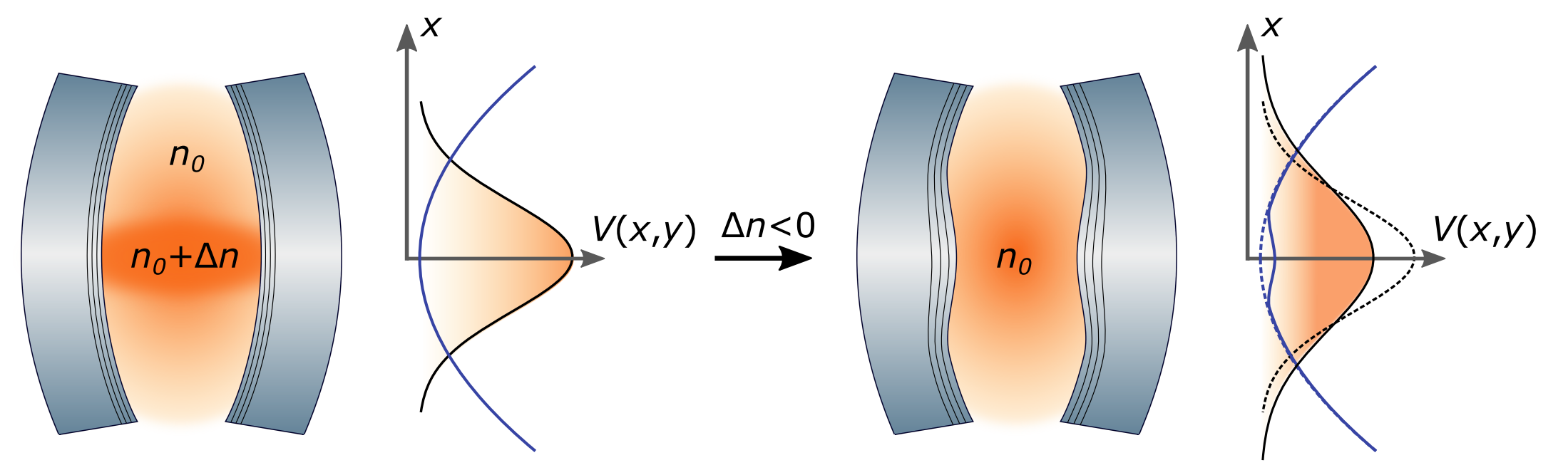
Spectra of the photon gas

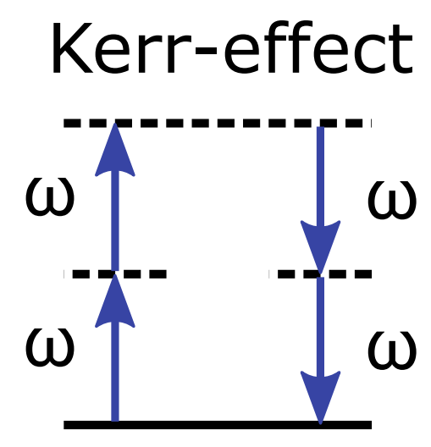


[4]

Effective Interacting Photon Gas

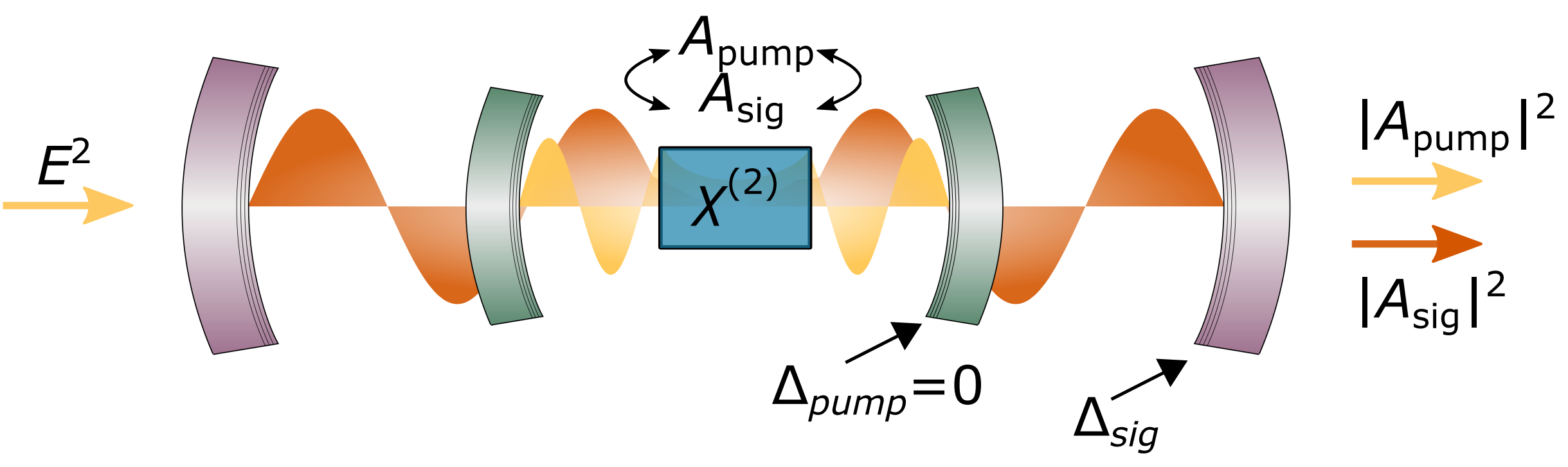
Effective interaction between photons could be introduced by a change of the roundtrip phase shift as a function of the photon density, implying a non-zero interaction energy.





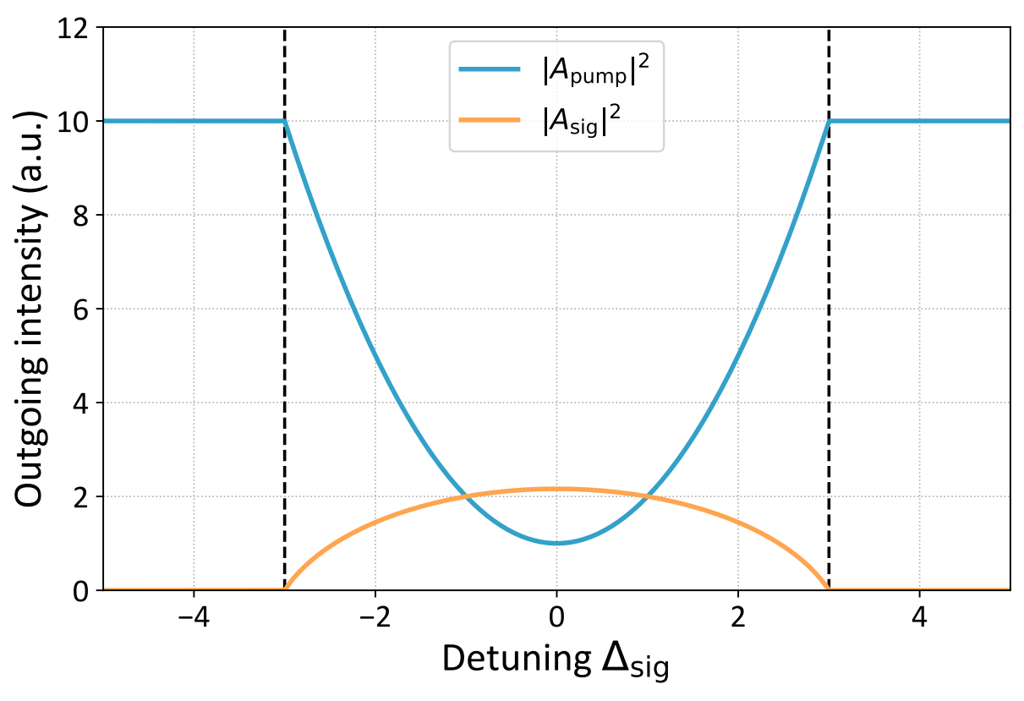
As the Kerr-coefficient of well known Kerr-media is not strong enough to achieve large effective interactions, an alternative approach builds on cascaded second order nonlinearities[5].

Cascade in a cavity

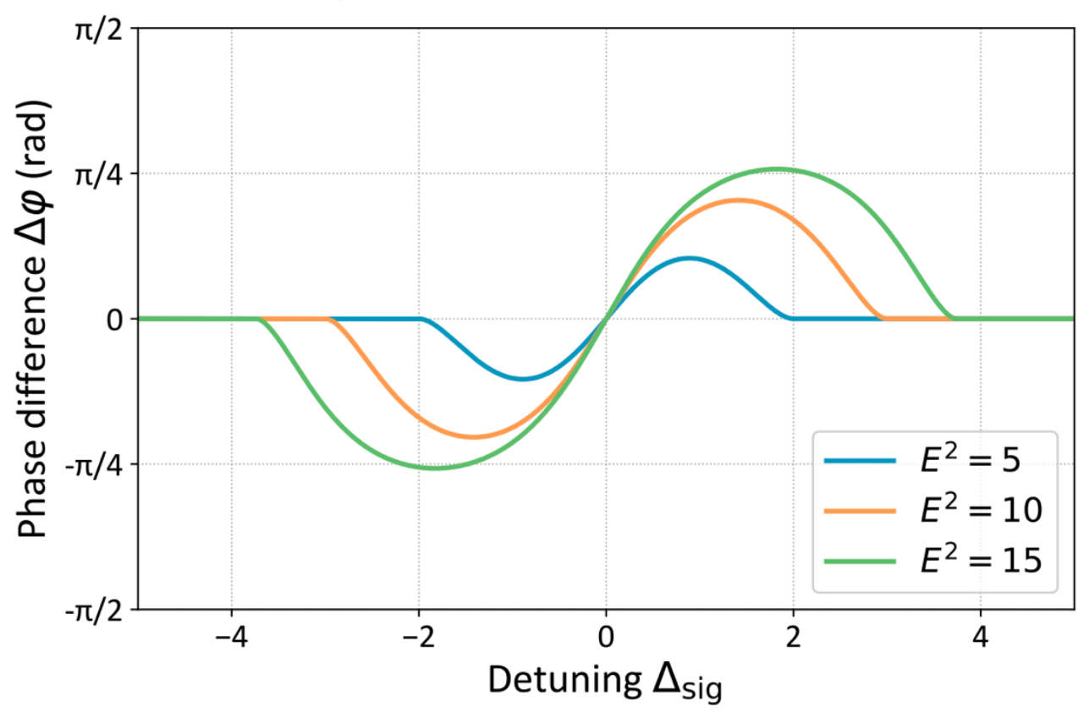


Resulting effective Kerr-coefficient: $n_2 I = \dfrac{\lambda_0}{2\pi L_c}\Delta\varphi$

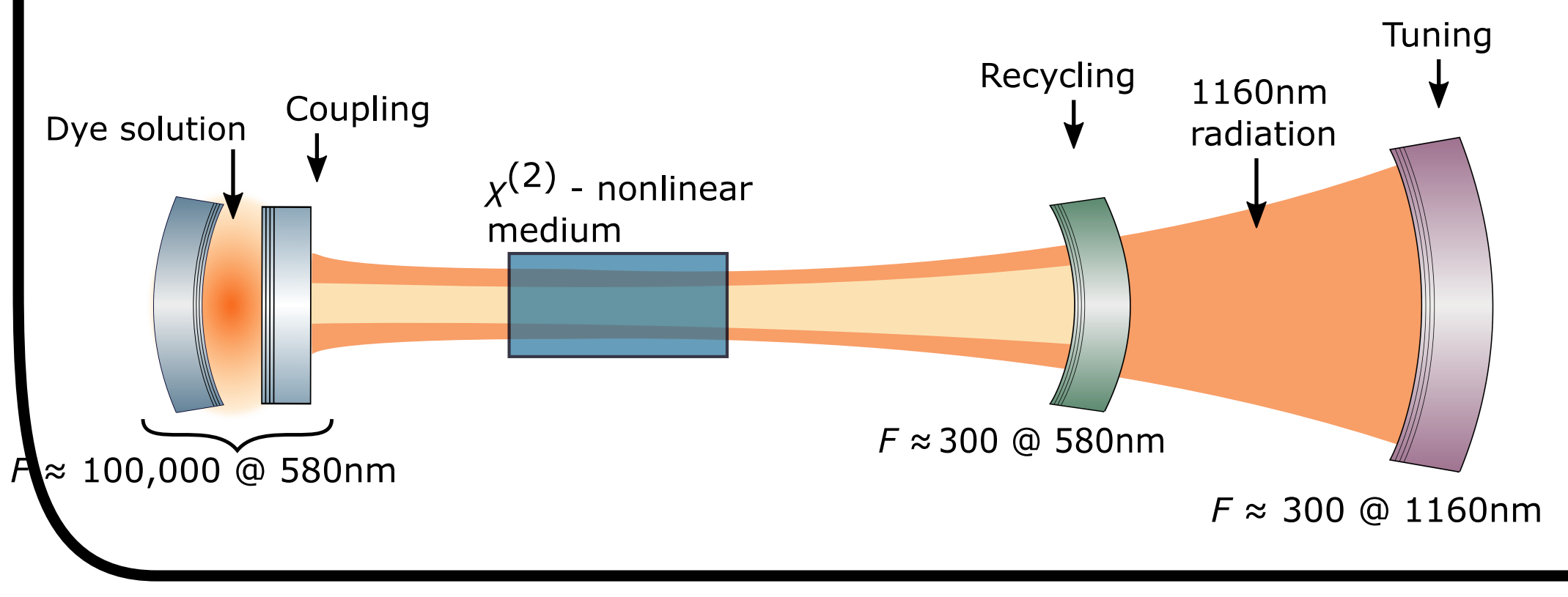
Resulting expected outgoing intensity



Resulting expected phase shift



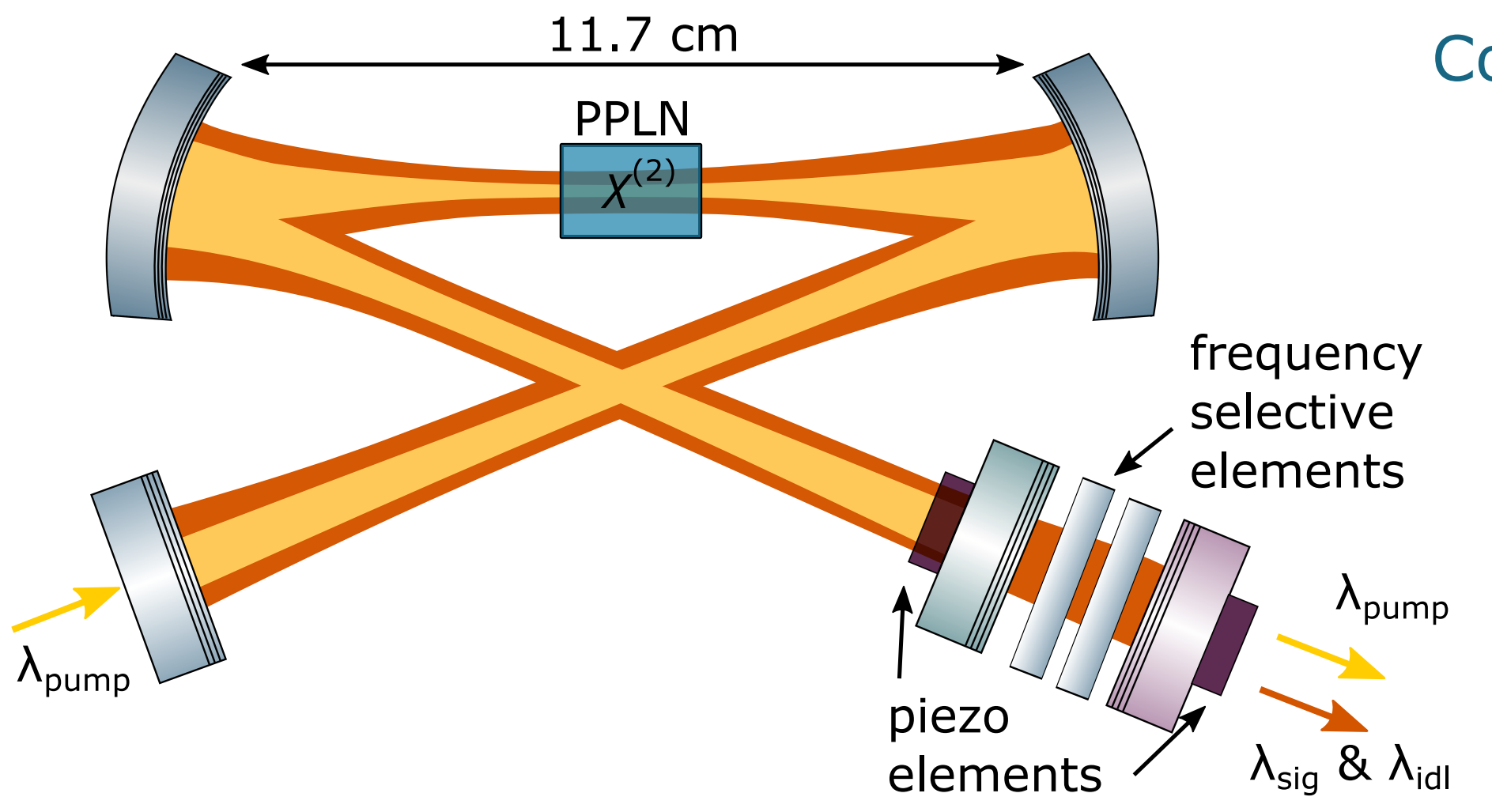
Possible Implementation in the Photon BEC



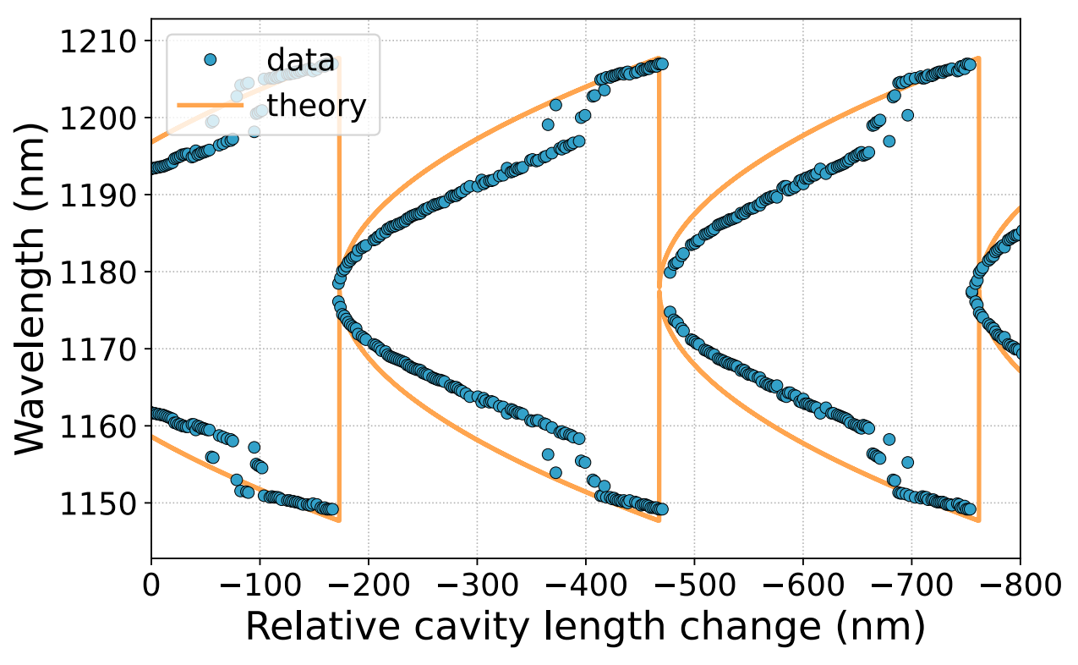
External coupled cavity containg a nonlinear medium alongside with an tunable cavity for the converted light, could enable tunable interactions in the photon BEC.

Triply Resonant OPO-Setup

This special triply resonant OPO allows for the realization of the cascaded second order nonlinearities due to two independently tunable cavities using the same conversion medium. The two independent cavities now correspond to two different resonances[6].

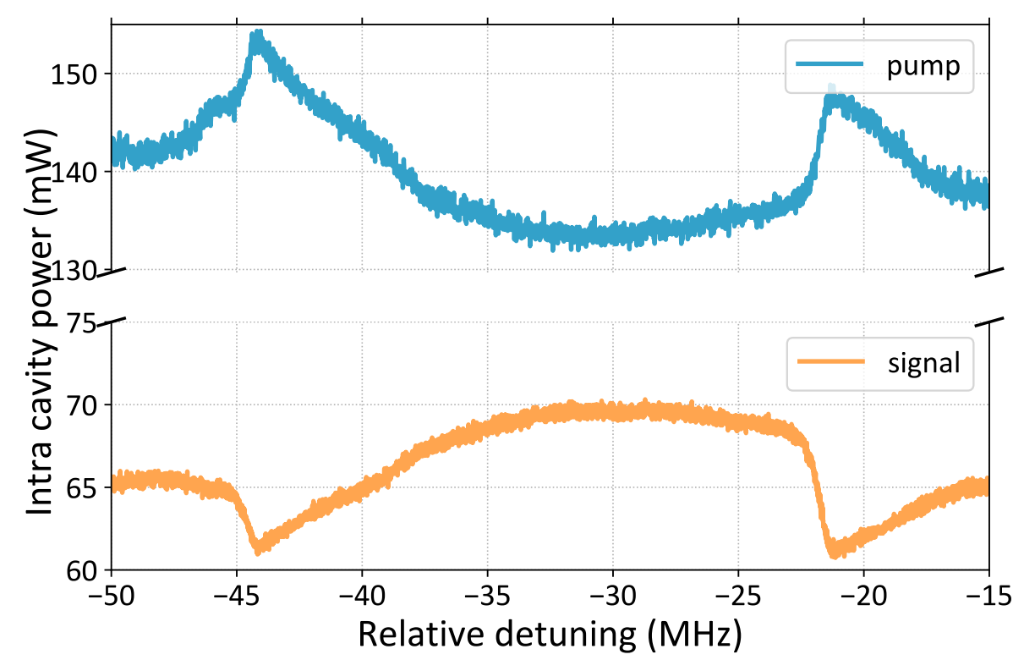


Converted Wavelength (T=40.7°C)

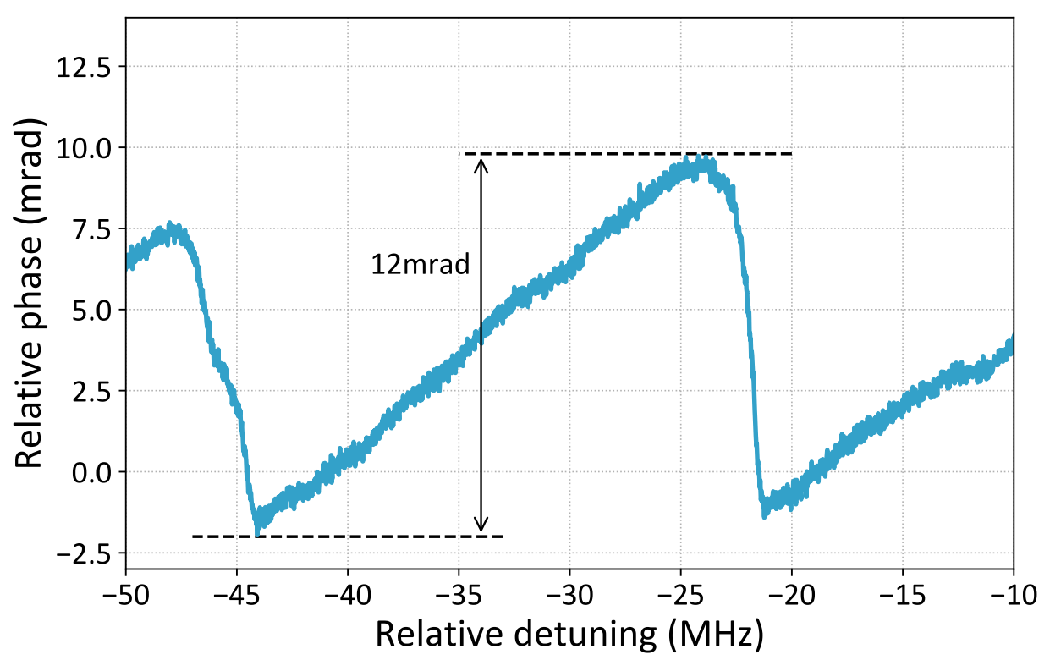


Mode jumps originated by multiple signal and idler pairs prohibit the fully resolved theoretical expectation. Suppression of non-degenerate signal and idler pairs is mandatory.

Resulting outgoing intensity



Resulting phase shift



	Kerr-coefficient (cm^2 W^{-1})	expected interaction strength
atomic BEC	-	10^{-2} to 10^{-1} [7]
Kerr-effekt (air)	1.05×10^{-18} [8]	-4.5×10^{-13}
Kerr-effekt (Rhodamine 6G)	$1.03(7) \times 10^{-11}$ [9]	$-4.4(3) \times 10^{-6}$
cascaded processes (meas.)	$\pm 4.2(3) \times 10^{-11}$	$\mp 1.8(1) \times 10^{-5}$

Combination of different Etalons introduce new resonace conditions, this should stabilize the OPO to the degenerate case. The mode distance of the OPO is 500MHz, with a total gain profile of 15THz.

References

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