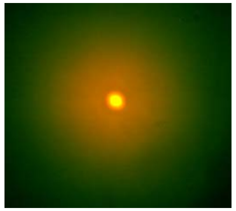
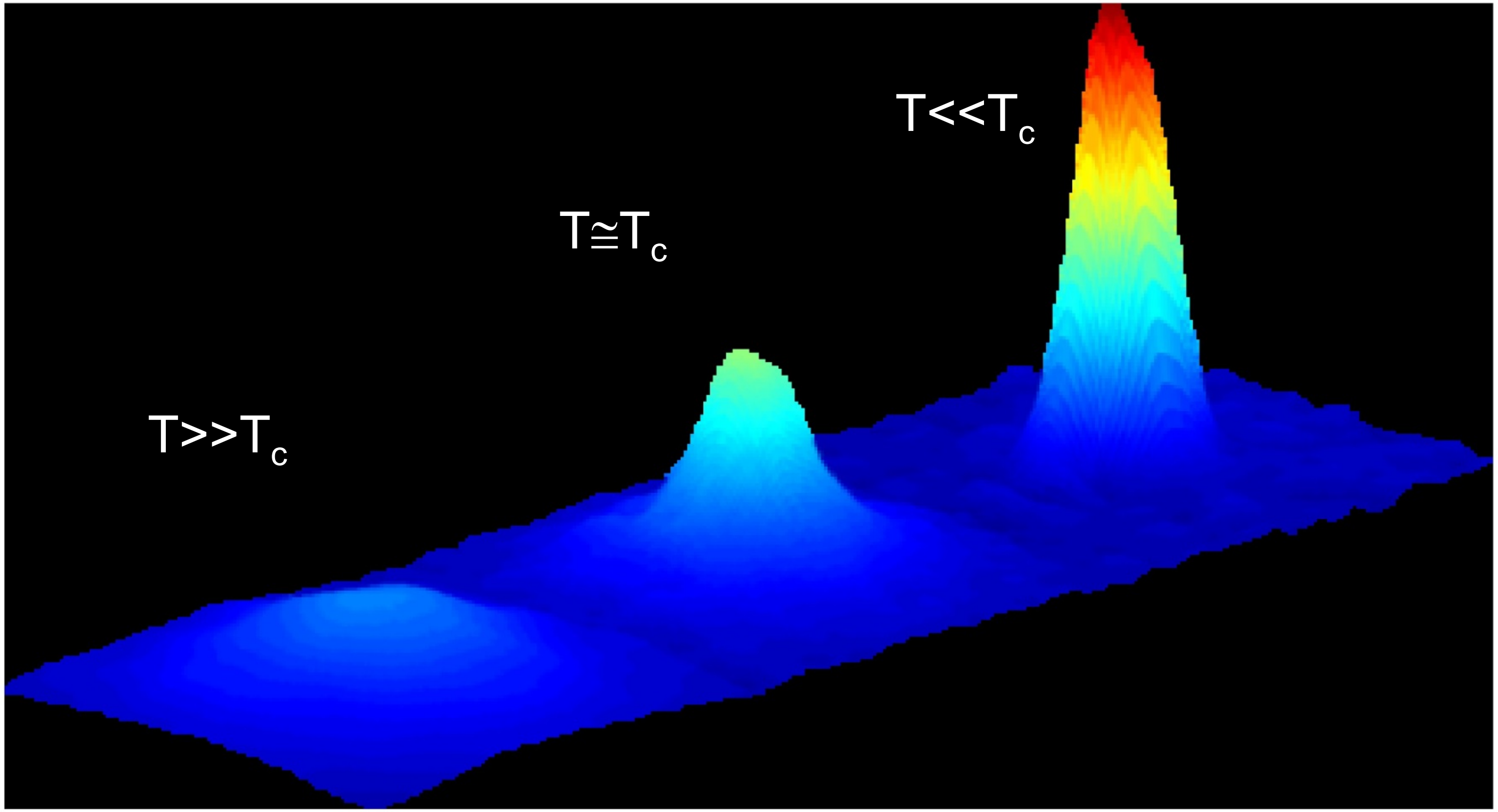


Bose-Einstein Condensation of Photons and Periodic Potentials for Light

Martin Weitz

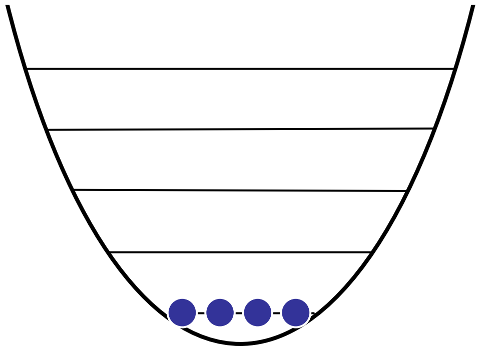
Institut für Angewandte Physik der Universität Bonn



BEC of rubidium atoms @ 180nK

Ground State of Bosonic Ensembles (3D-Regime)

atoms



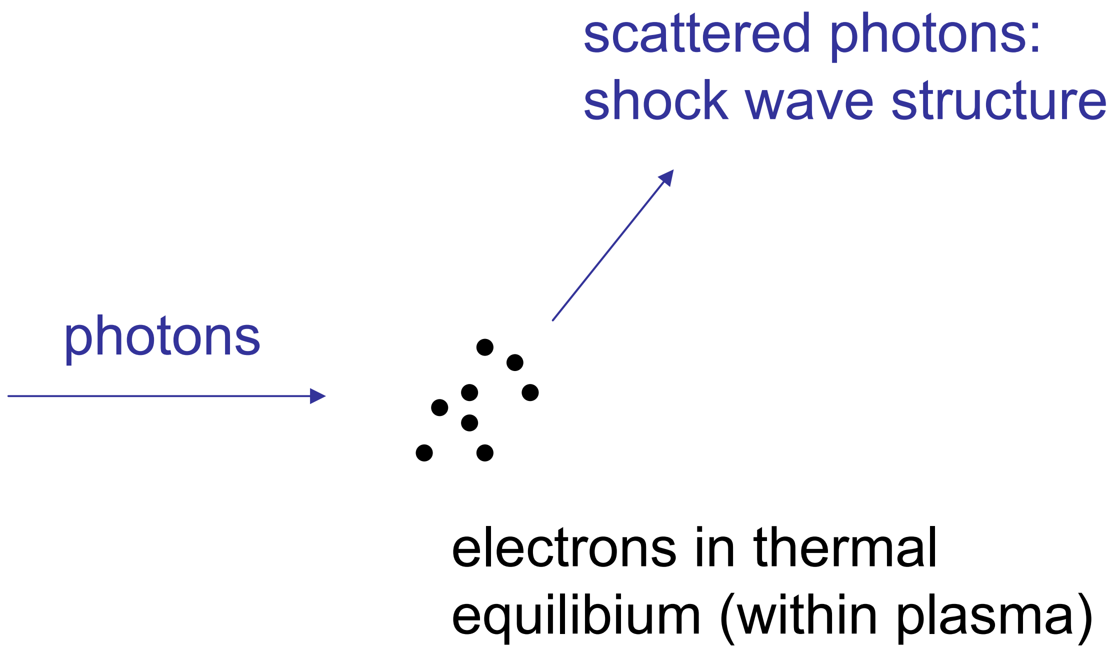
photons ?

Bose-Einstein condensate

[redacted]

Earlier Work related towards a Photon BEC

- Proposal for a photon BEC in Compton scattering off a thermal electron gas

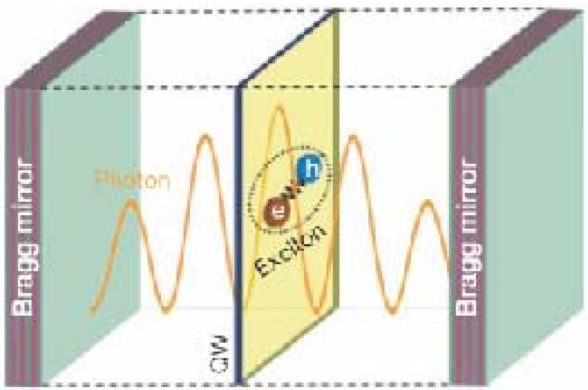


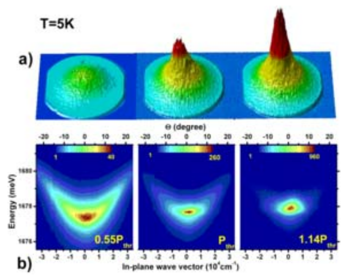
Zel‘dovich and Levich, 1969

… Earlier Work

- Exciton-polariton condensates

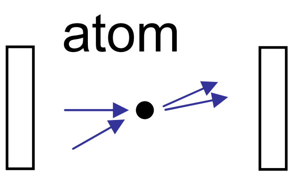
strong coupling (‚half matter, half light‘); in equilibrium for condensed part





Yamamoto, Deveaud-Pledran, Littlewood, Snoke, …

- Proposal for photon fluid in nonlinear resonator



photon-photon scattering
(four-wave mixing)

R. Chiao

Outline of Talk

- thermodynamics of a two-dimensional photon gas in a dye-filled optical microcavity

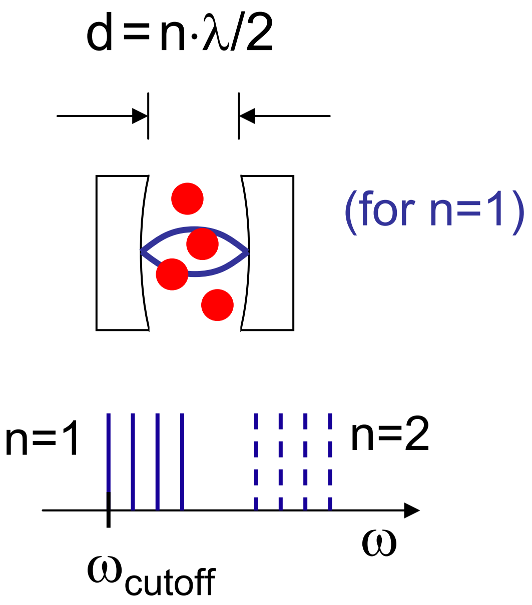
- Bose-Einstein condensation of photons

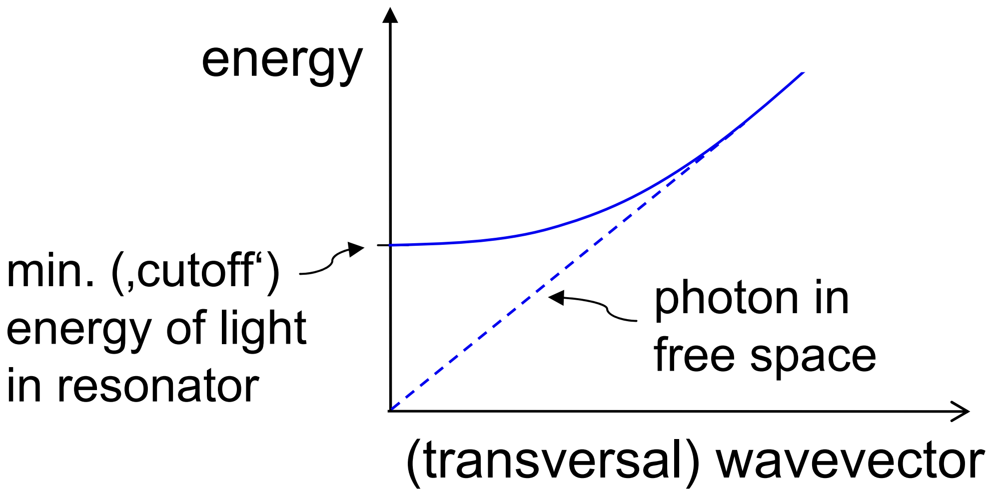
- condensate intensity correlations, grand canonical BEC

- periodic potentials for light

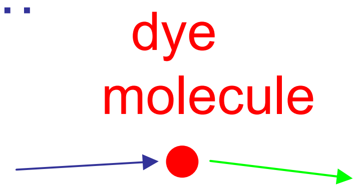
Bonn 2D-Photon Gas Experimental Scheme

- use curved-mirror microresonator to modify photon dispersion

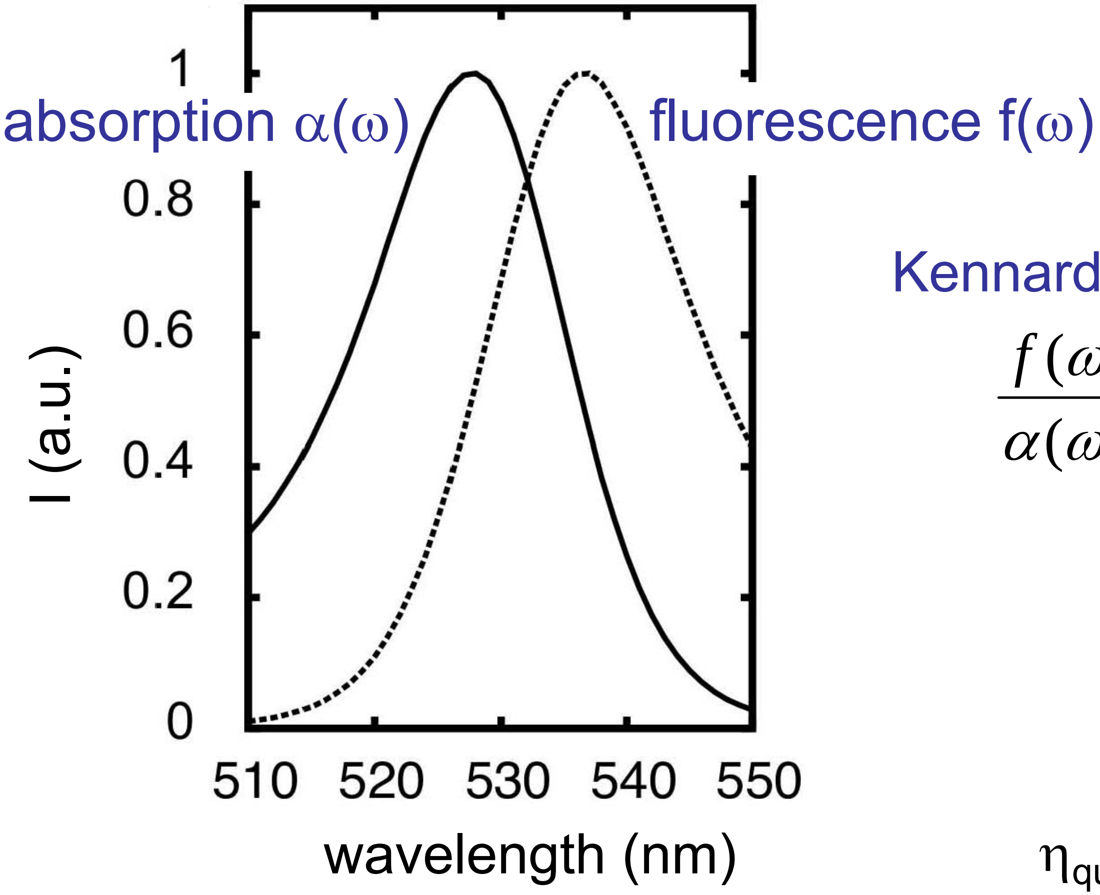




- thermal equilibrium of photon gas by absorption re-emission processes on dye molecules…



Spectrum of Perylene-Dimide Molecule (PDI)



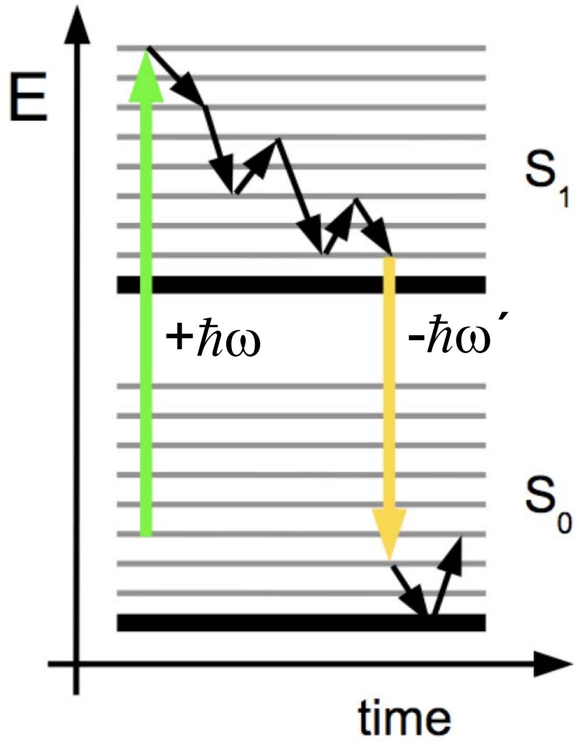
Kennard-Stepanov theory:

$$\frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

$\eta_{quantum} \cong 0.97$

Photon Gas Thermalization: Background

Collisionally induced thermalization in dye medium



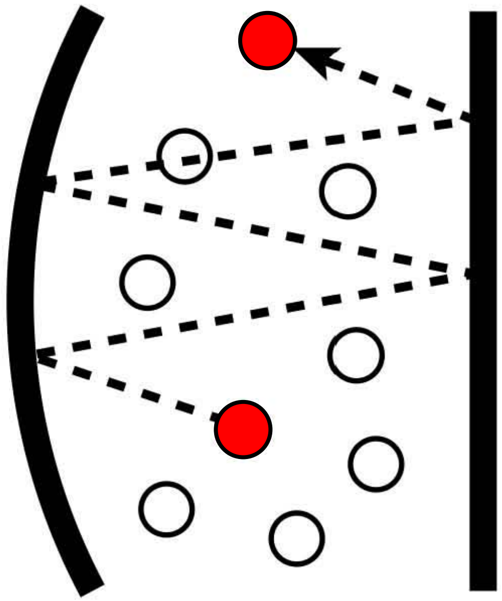
$$\frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

T: (internal rovibrational) temperature of dye solution

Kennard 1912, Stepanov 1956

Model for Photon Thermalization

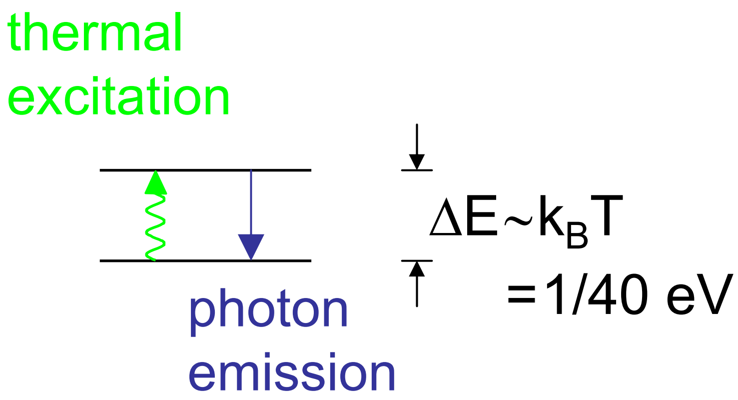
multiple absorption and emission processes by dye molecules in resonator



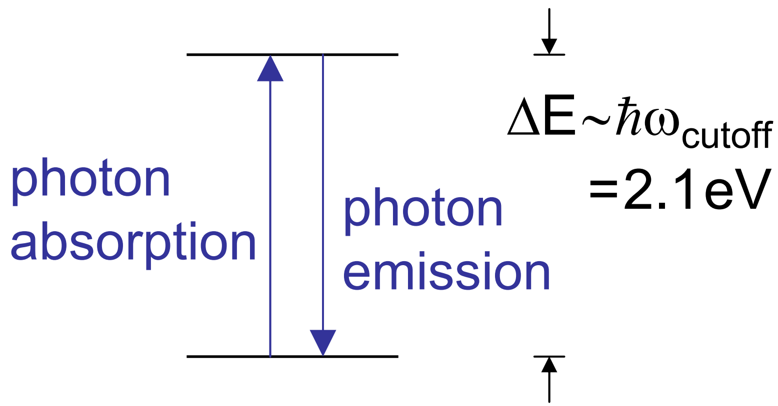
(many times)

Photon Number Variation during Thermalization?

Planck Blackbody Radiation



New Scheme



thermal excitation suppressed

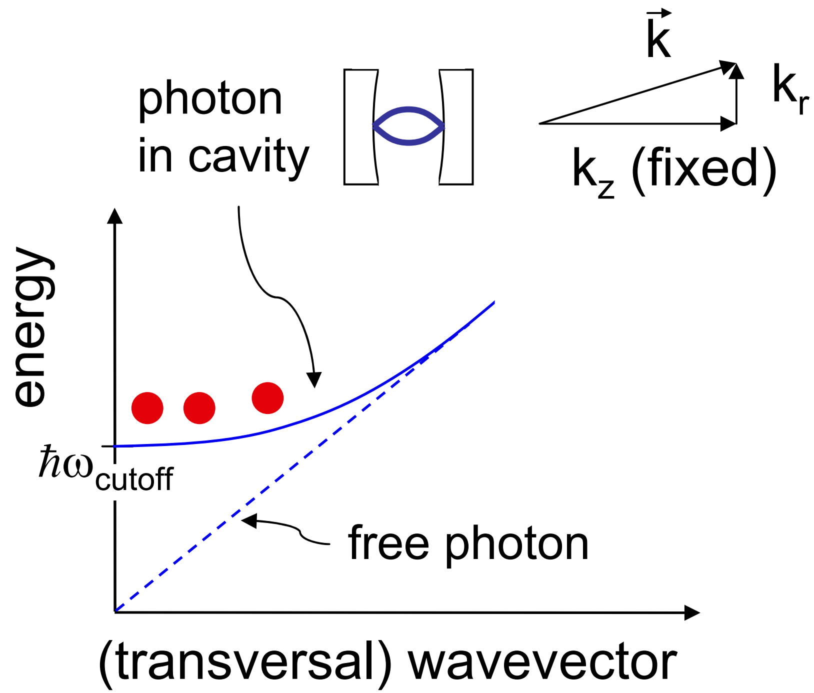
by $\sim e^{-\frac{\hbar\omega_{cutoff}}{k_B T}} \cong 10^{-36}$

$\rightarrow$ photon average number conserved

‚white-wall box‘ for photons

Photon Trapping versus Atom Trapping

- quadratic photon dispersion



In paraxial approximation ($k_z \gg k_r$):

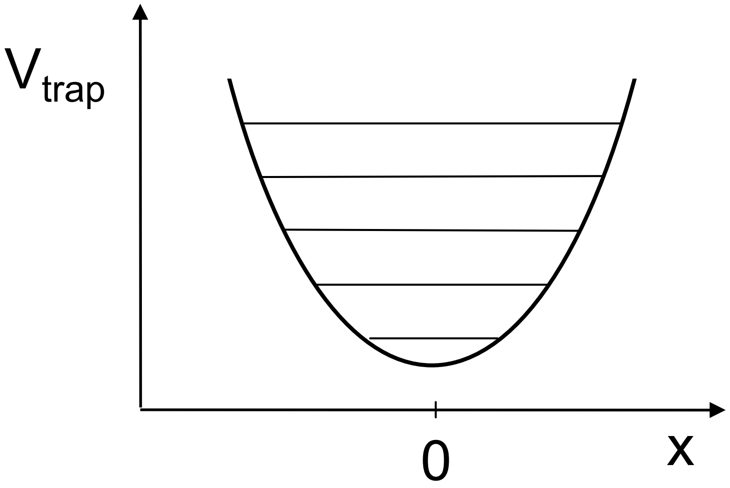
$$E = \hbar c\sqrt{k_z^2 + k_r^2} \cong \hbar c\left(k_z + \frac{k_r^2}{2k_z}\right)$$

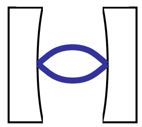
$$= m_{eff}c^2 + \frac{(\hbar k_r)^2}{2m_{eff}}$$

with $m_{eff} = \hbar k_z / c \equiv \hbar\omega_{cutoff} / c^2$

..Photon versus Atom trapping

- trapping potential from mirror curvature



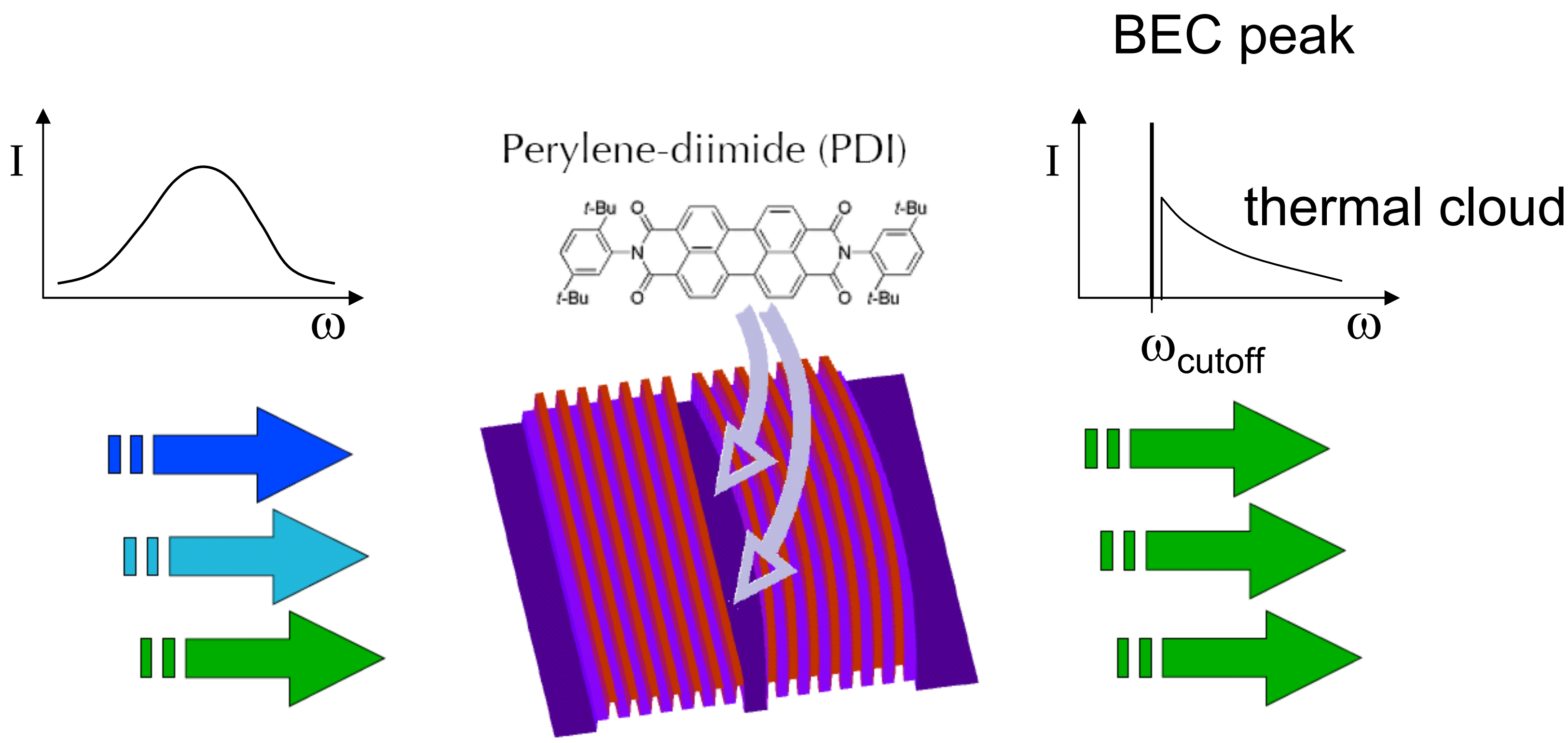


System formally equivalent to 2D-gas of massive bosons with $m_{eff} = \hbar\omega_{cutoff} / c^2$

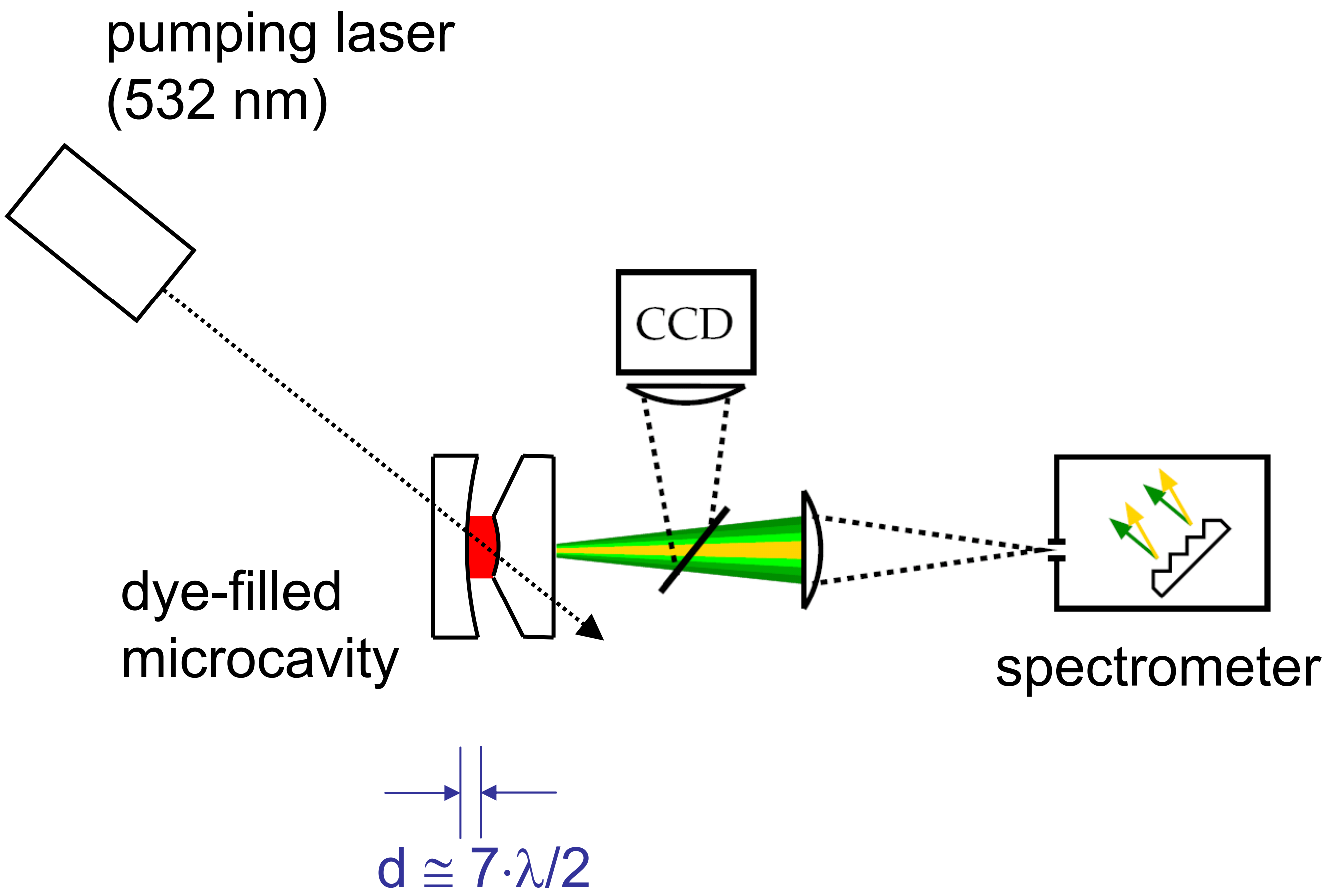
$$E = m_{eff}c^2 + \frac{(\hbar k_r)^2}{2m_{eff}} + \frac{1}{2} m_{eff} \Omega^2 r^2$$

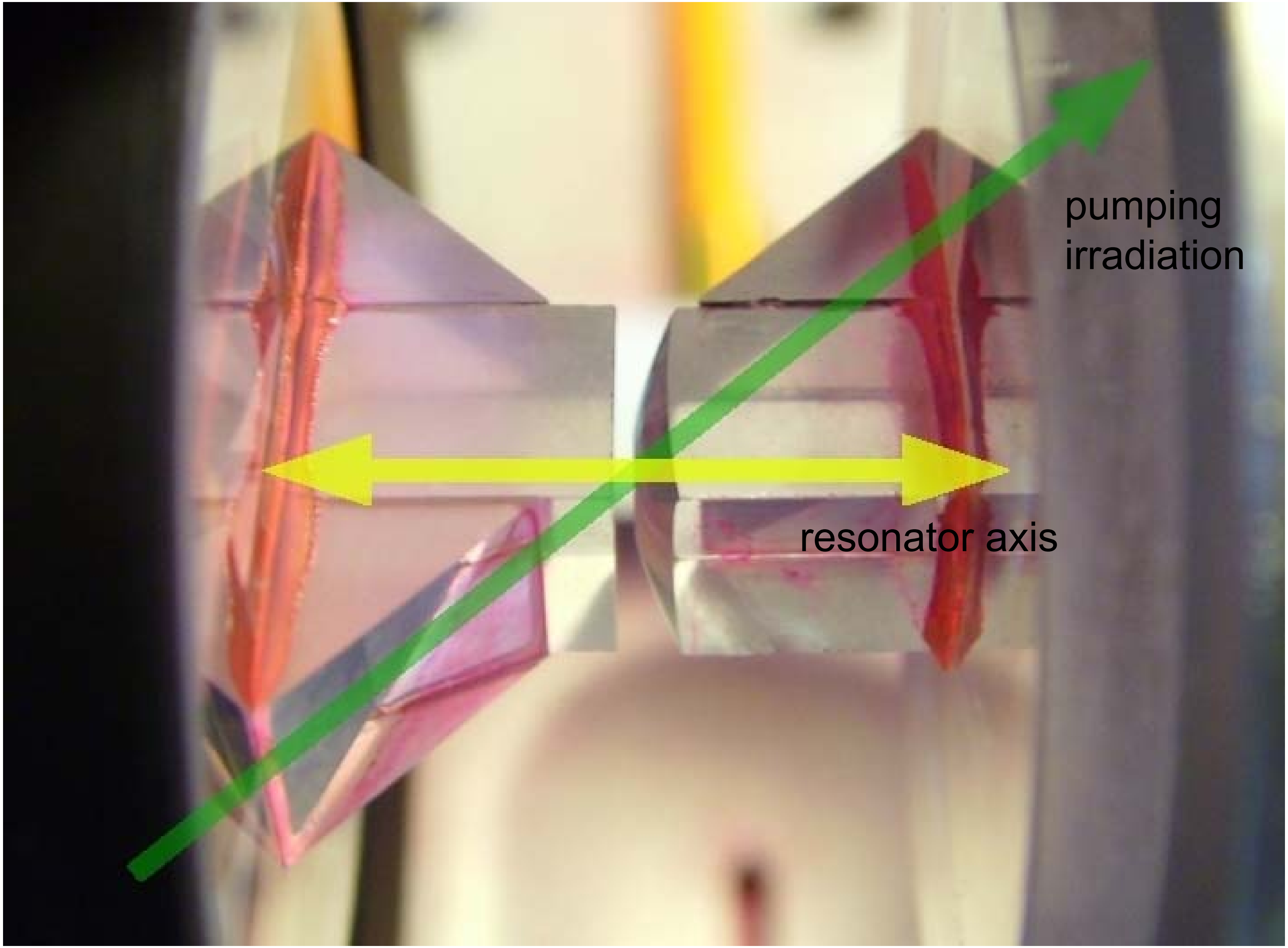
→ BEC expected for $N > N_c = \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2 \cong 77000$ (T=300K, $\Omega = 2\pi \cdot 4 \cdot 10^{10}$ Hz, $m_{eff} \cong 6.7 \cdot 10^{-36}$ kg $\cong 10^{-10} \cdot m_{Rb}$)

Two-Dimensional Photon Gas in Dye-Filled Optical Resonator

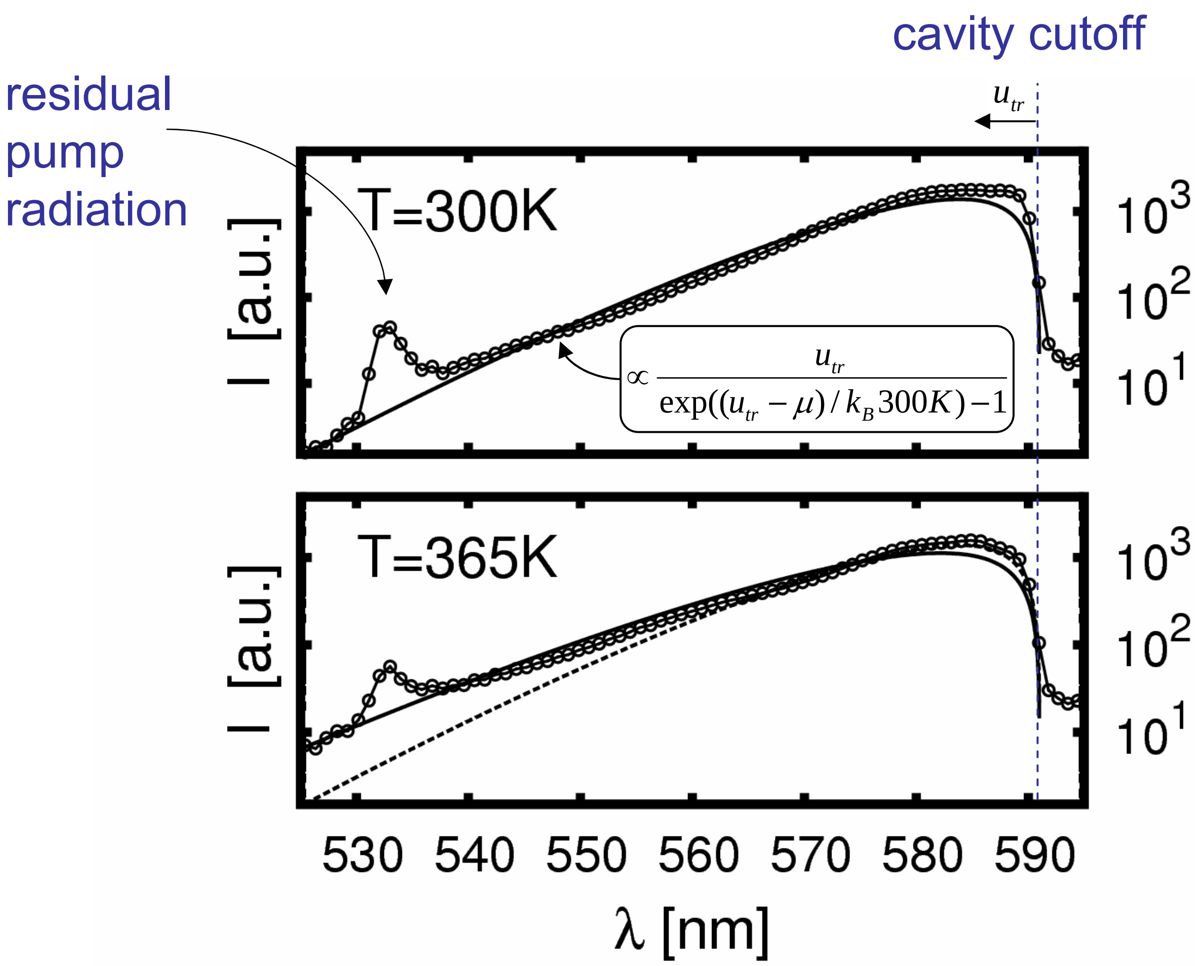


Experimental Setup: 2D Photon Gas




pumping
irradiation
resonator axis

Spectrum of Thermal Photon Gas in Cavity



from P_{out}=50(5) nW →

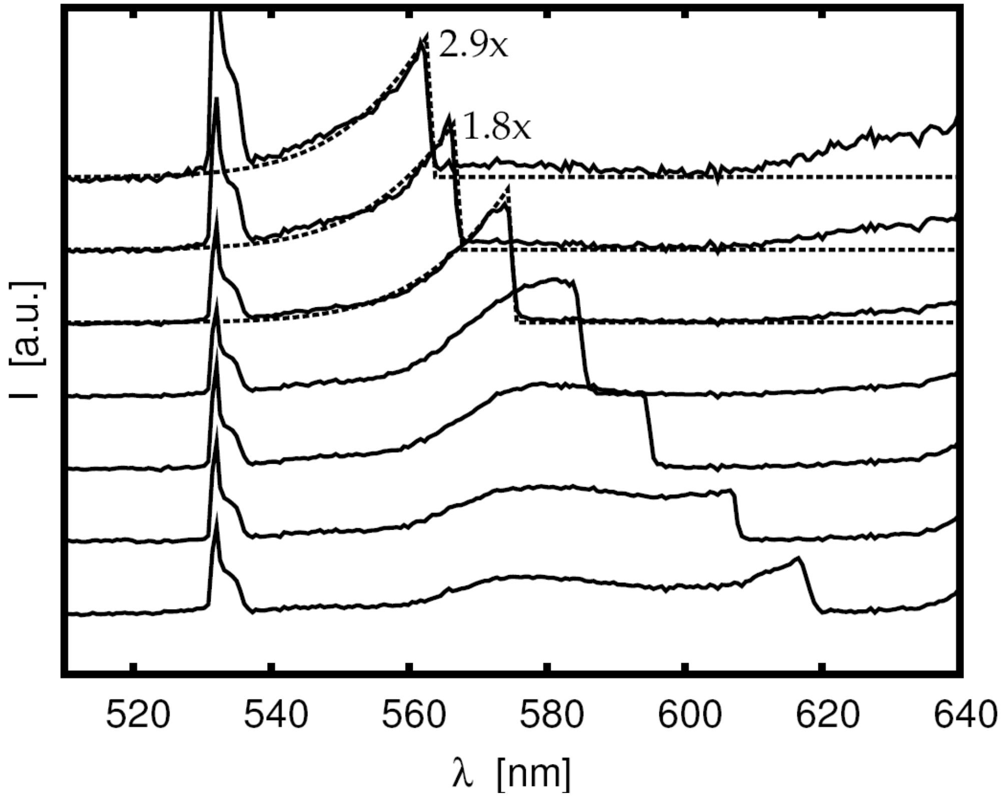
$\mu = -6.76(17) k_B T$

$\mu = -7.16(17) k_B T$

→ evidence for thermalized two-dimensional photon gas with $\mu \neq 0$!

J. Klaers, F. Vewinger, M. Weitz, Nature Phys. **6**, 512 (2010)

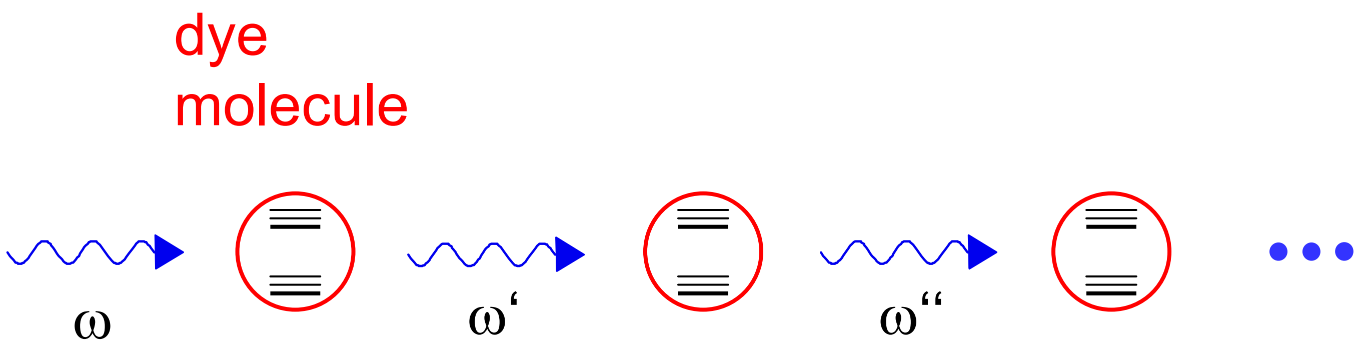
Spectra for Different Cavity Cutoff Frequencies



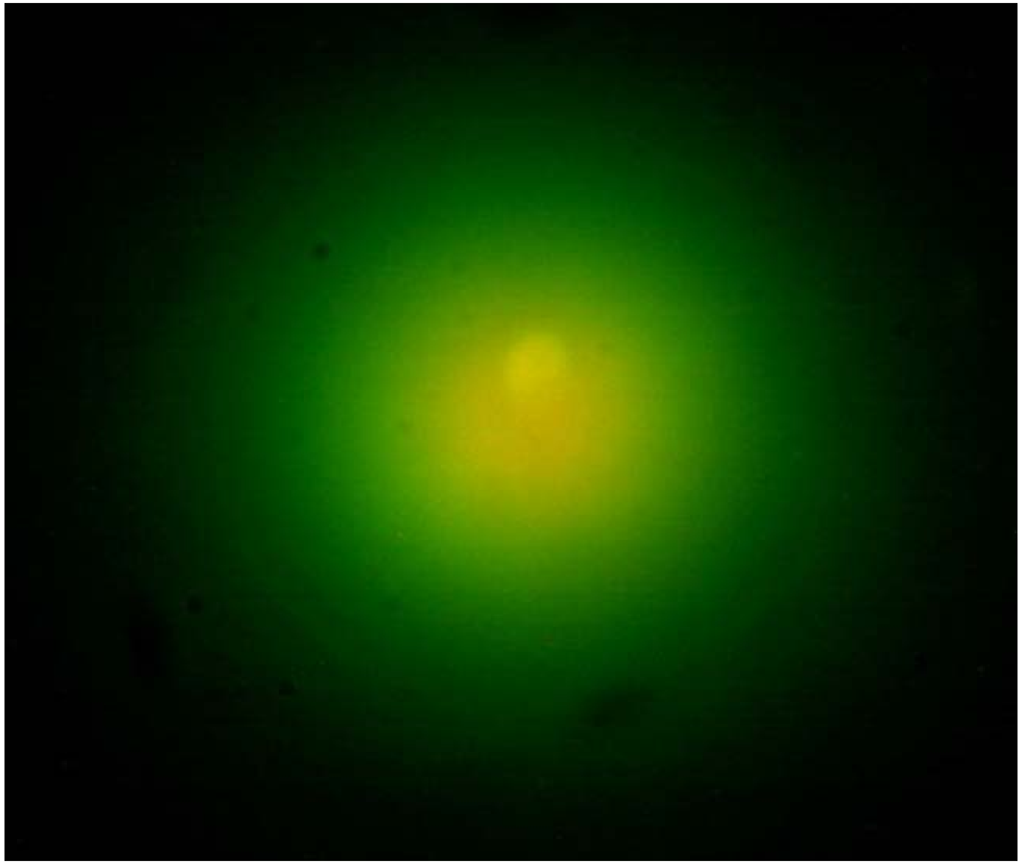
optically dense regime,

thermalization of photon gas

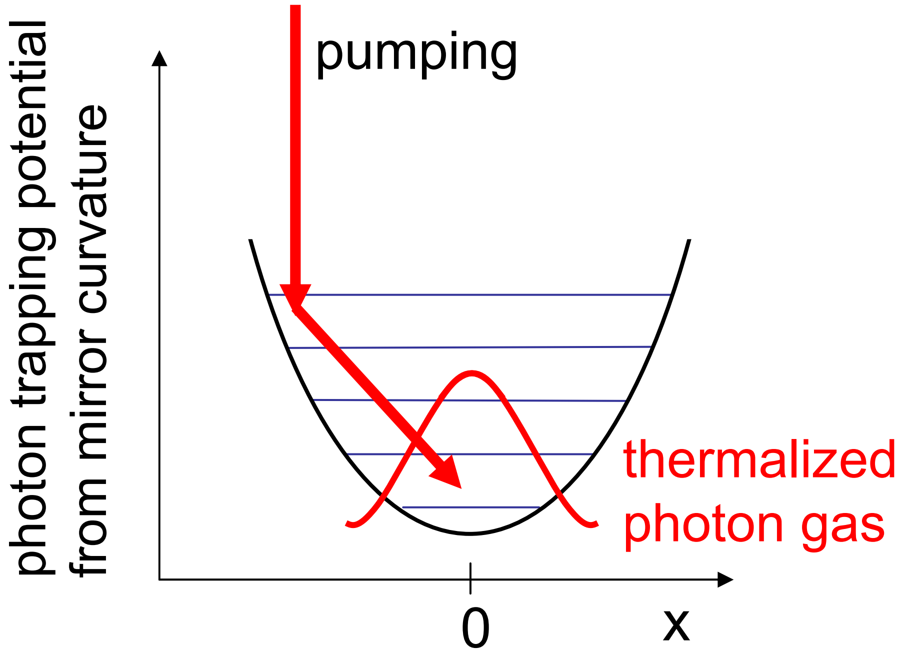
… Reabsorption: Required for Photon Thermalization



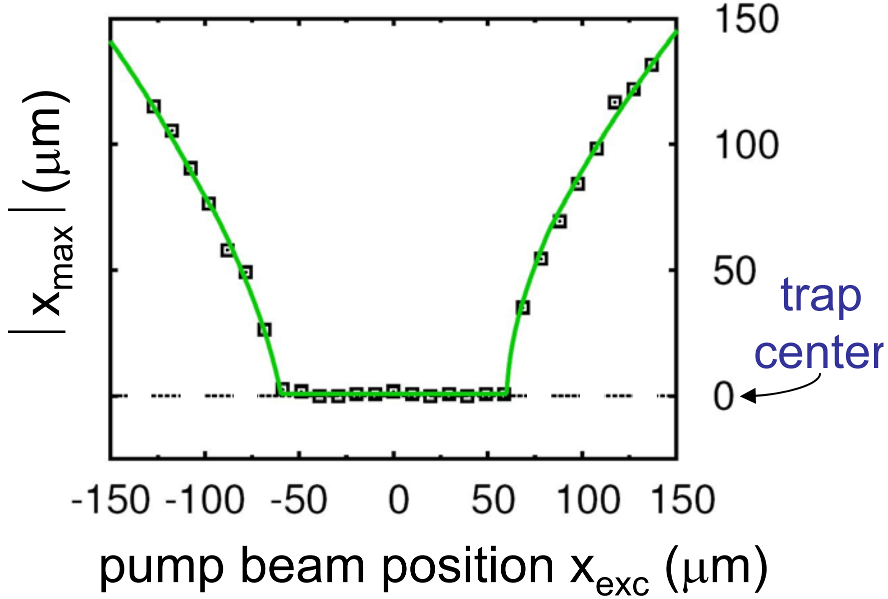
Snapshot: Thermalization of Photon Gas in Dye Microcavity

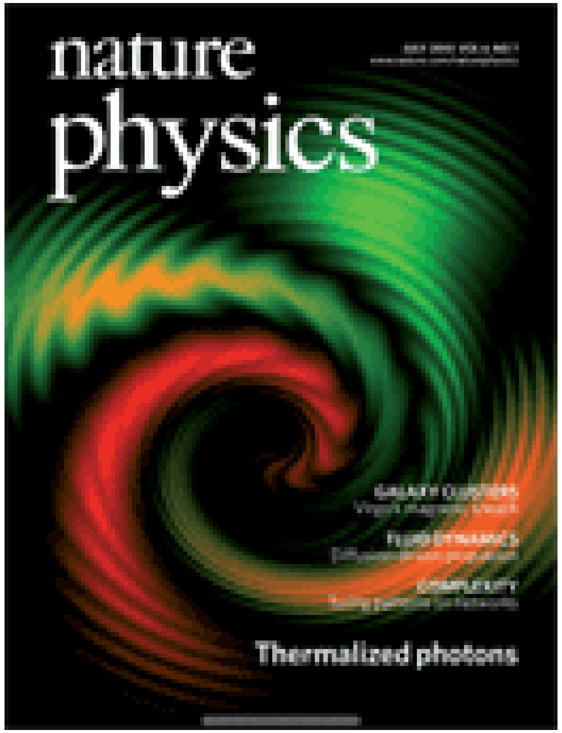


Thermalization – Photon Diffusion towards Center

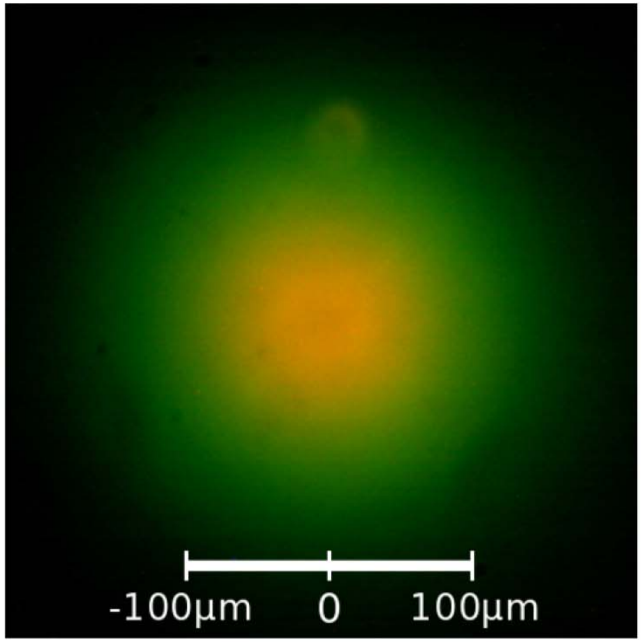


Experimental data

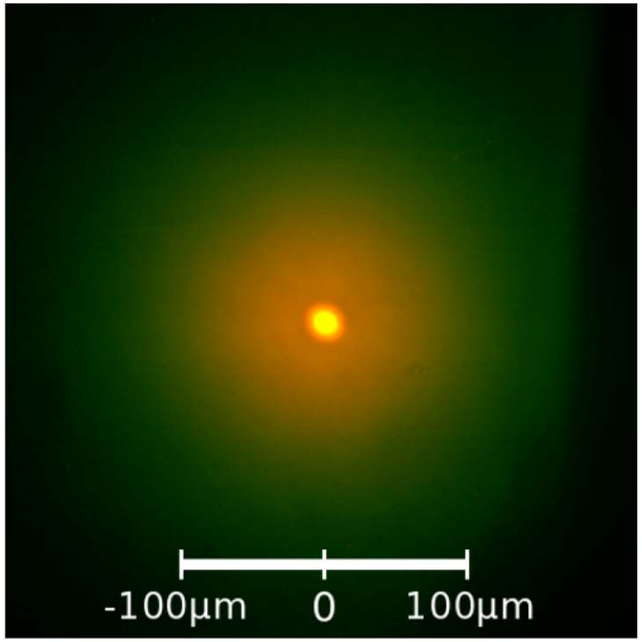



nature
physics
GALAXY CLUSTERS
FLUID DYNAMICS
COMPLEXITY
Thermalized photons

Photon Gas at Criticality



$N << N_c$



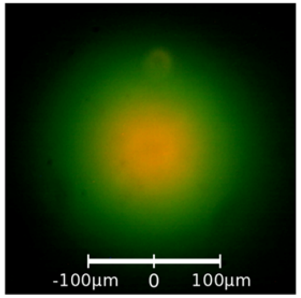
$N > N_c$

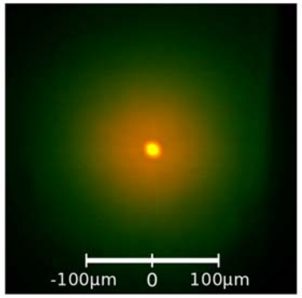
BEC!

Rh6G, duty cycle 1:16000, 0.5μs pulses

Bose-Einstein condensate of Light

below
threshold





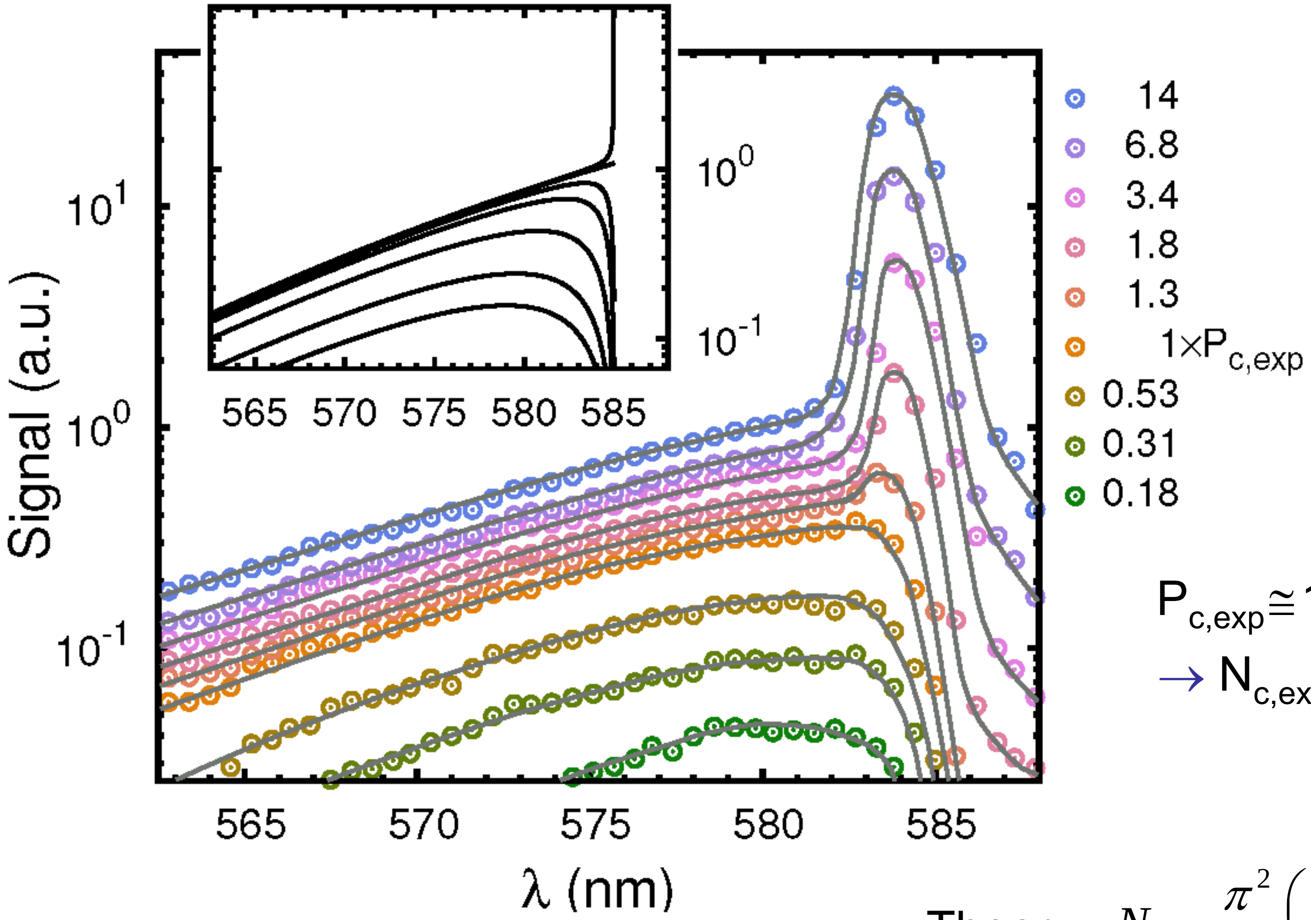
Bose-Einstein
condensate

Cooling
(or increase of $n\lambda_{db}^2$)

Light Bulb

ground state:
filament off

Spectra for Densities around Photonic BEC Threshold



$P_{c,exp} \cong 1.55(60)$ W

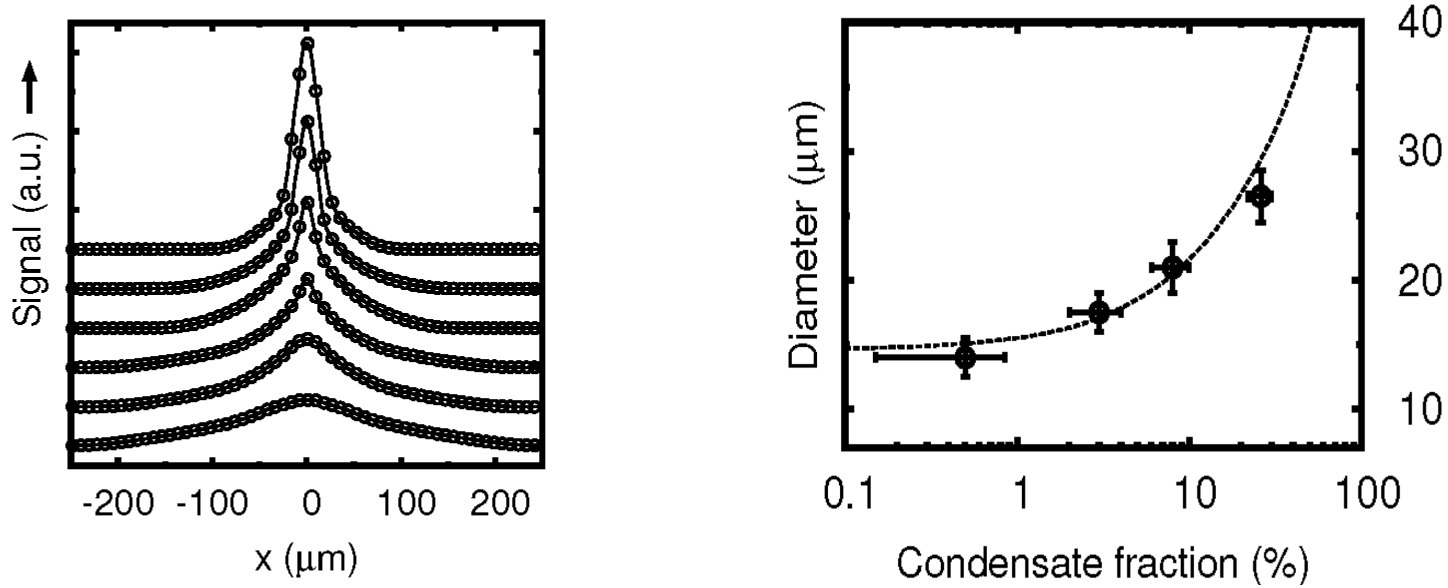
$\rightarrow N_{c,exp} \cong (6.3 \pm 2,4) \cdot 10^4$

Theory: $N_c = \frac{\pi^2}{3} \left(\frac{k_B T}{\hbar \Omega} \right)^2 \cong 7.7 \cdot 10^4$

J. Klaers, J. Schmitt, F. Vewinger, M. Weitz, Nature **468**, 545 (2010)

see also recent Imperial College experiment: J. Marelic and R. Nyman, PRA **91,** 033813 (2015)

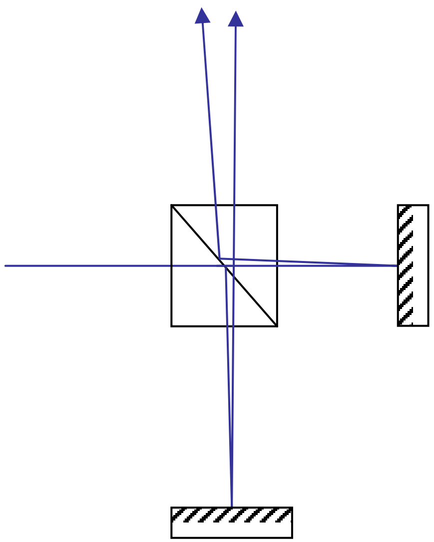
Spatial Intensity Distribution around BEC Threshold

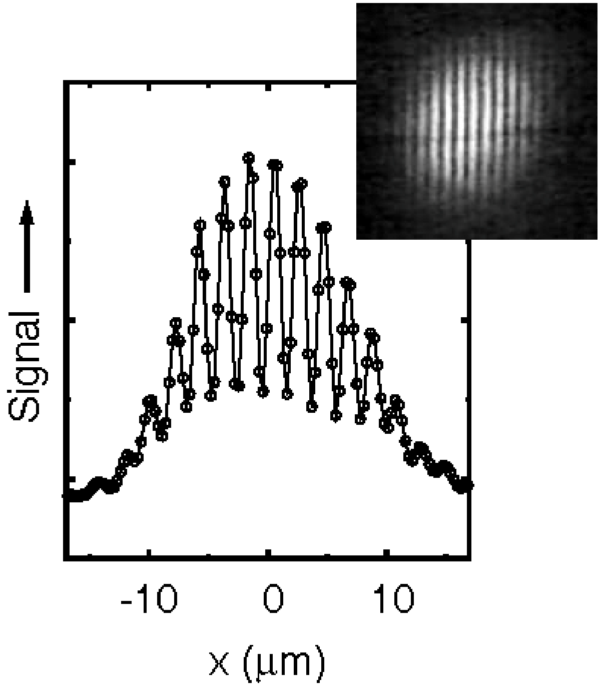


mode diameter increase could be explained by photon mean field interaction with $g_{eff,2D} \cong 7 \cdot 10^{-4}$ (too small for Kosterlitz-Thouless physics) $\rightarrow$ BEC expected

for atoms: $g_{eff,2D} \cong 10^{-1}$ - 10^{-2} (Dalibard,Phillips)

Michelson Interference Pattern above Photon BEC Threshold



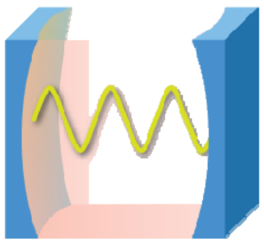


optical path length difference: 15 mm

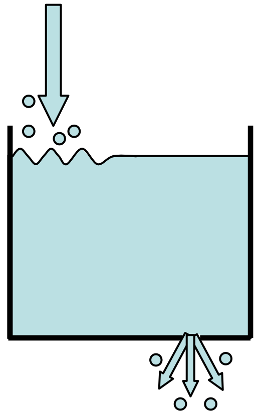
Bose-Einstein Condensation versus Lasing

equilibrium

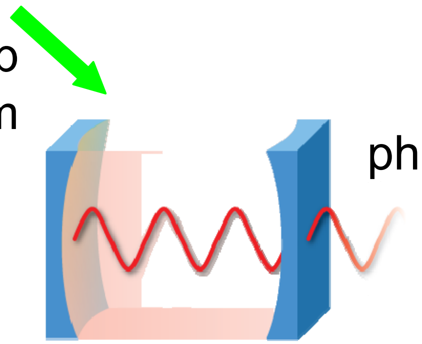
ideal photon box (with number-conserving thermalization & low-frequency cutoff) $\rightarrow$ BEC



out of equilibrium



pumping and losses dominate $\rightarrow$ laser, requires inverted active medium



see also: lasing a nonequilibrium phase transition (Haken,..), polariton BEC $\leftrightarrow$ polariton lasing.

Theory photon BEC vs. lasing: Klaers et al., Appl. Phys. B 2011, Kirton + Keeling, PRL 2013

Experimental Data: Laser to BEC Crossover

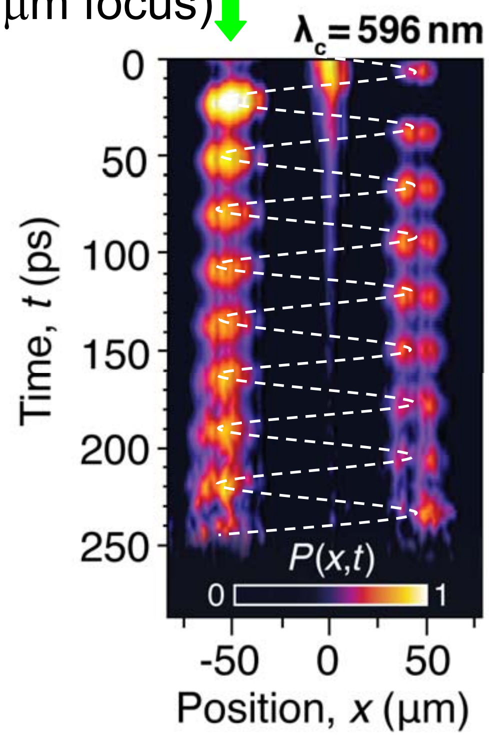
Low thermal contact

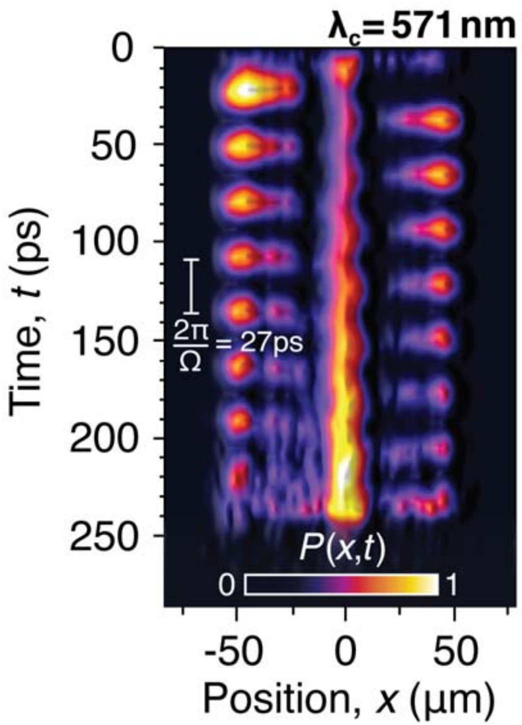
Thermalization of photons

pump beam
(27µm focus)

mode-locked
laser state

repetition
rate: 37 GHz





mode-locked
laser state

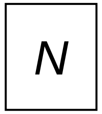
Bose-Einstein
condensate

J. Schmitt, T. Damm, D. Dung, F. Vewinger, J. Klaers, and M. Weitz, PRA **92**, 011602 (2015)

Grand Canonical BEC and Condensate Fluctuations

usual BEC

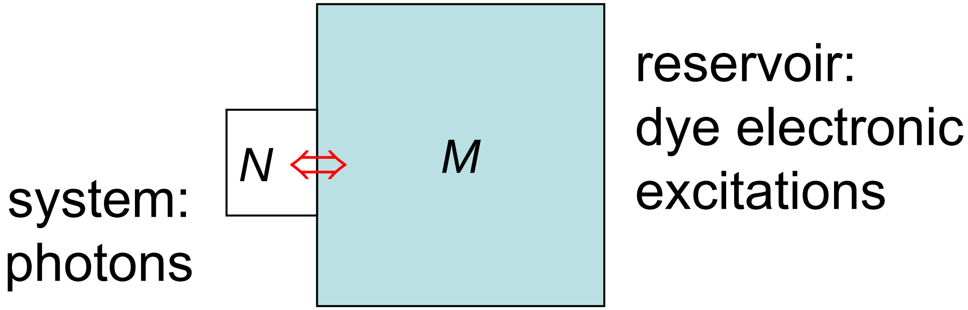
(e.g. cold atoms, polaritons..)
microcanonical ensemble

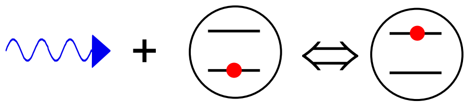


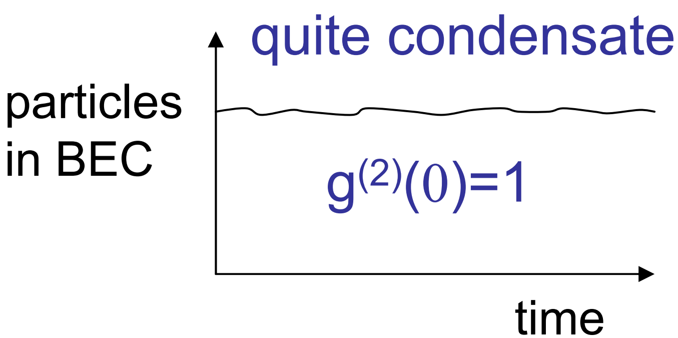
particle number fixed

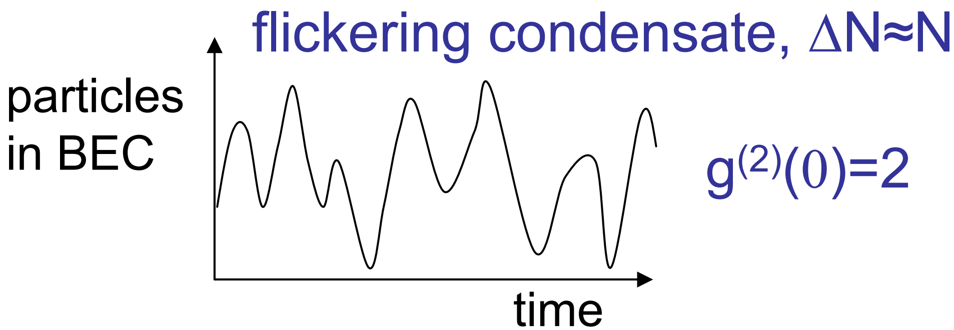
Grand canonical BEC

particle exchange with reservoir







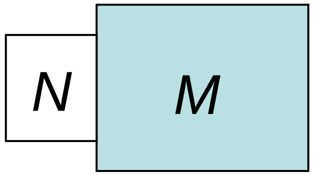


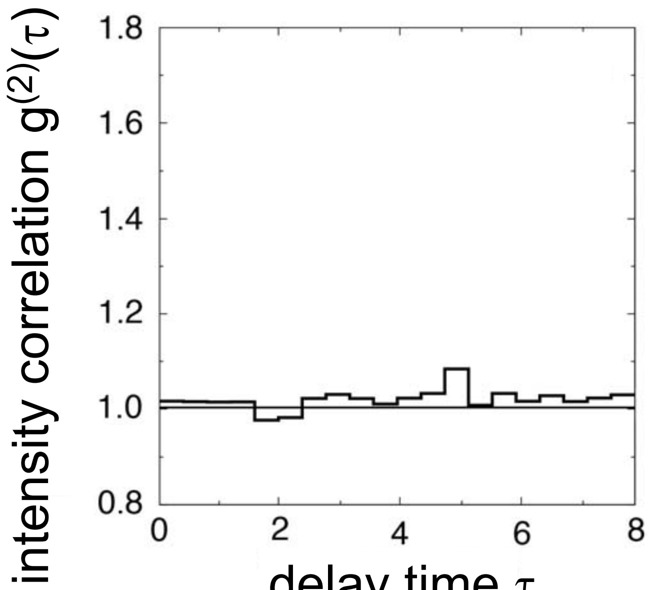
J. Klaers et al., PRL **108**, 160403 (2012), see also: D. Sobyanin, PRE **85**, 061120 (2012)
general theory grandcanonical BEC fluctuations: Fujiwara et al. (1970), Ziff et al. (1977), Holthaus (1998)

Photon Intensity Correlation in BEC Mode vs. Delay Time

condensate fraction: 56%

system size
large: $N > \sqrt{M}/2$

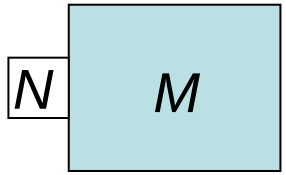


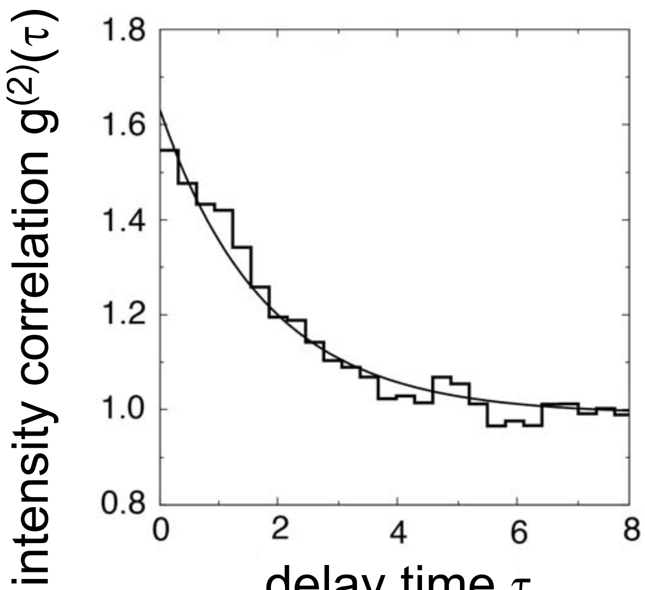


≈ (usual) canonical BEC regime
with Poissionian fluctuations

condensate fraction: 4%

system size
small: $N < \sqrt{M}/2$

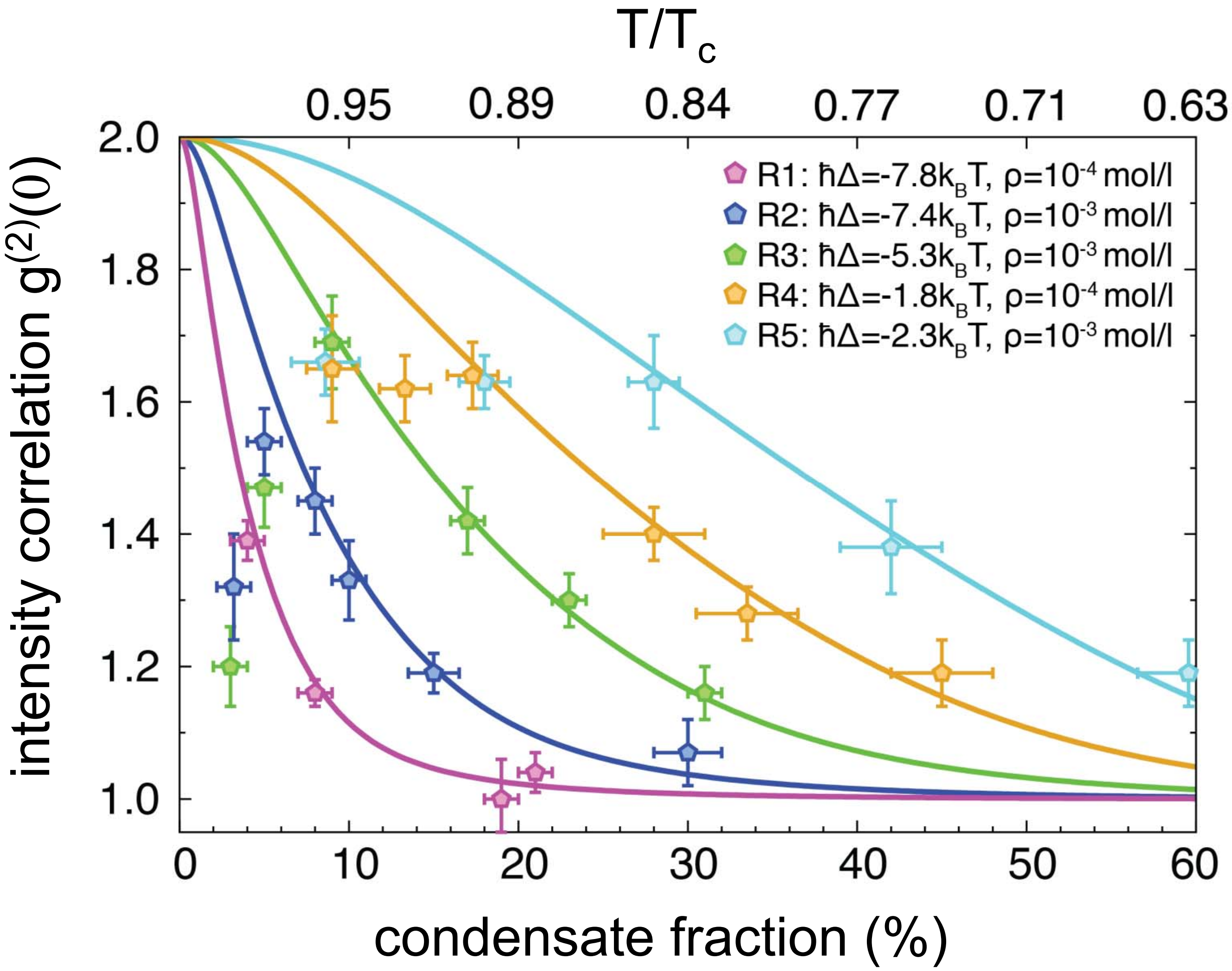


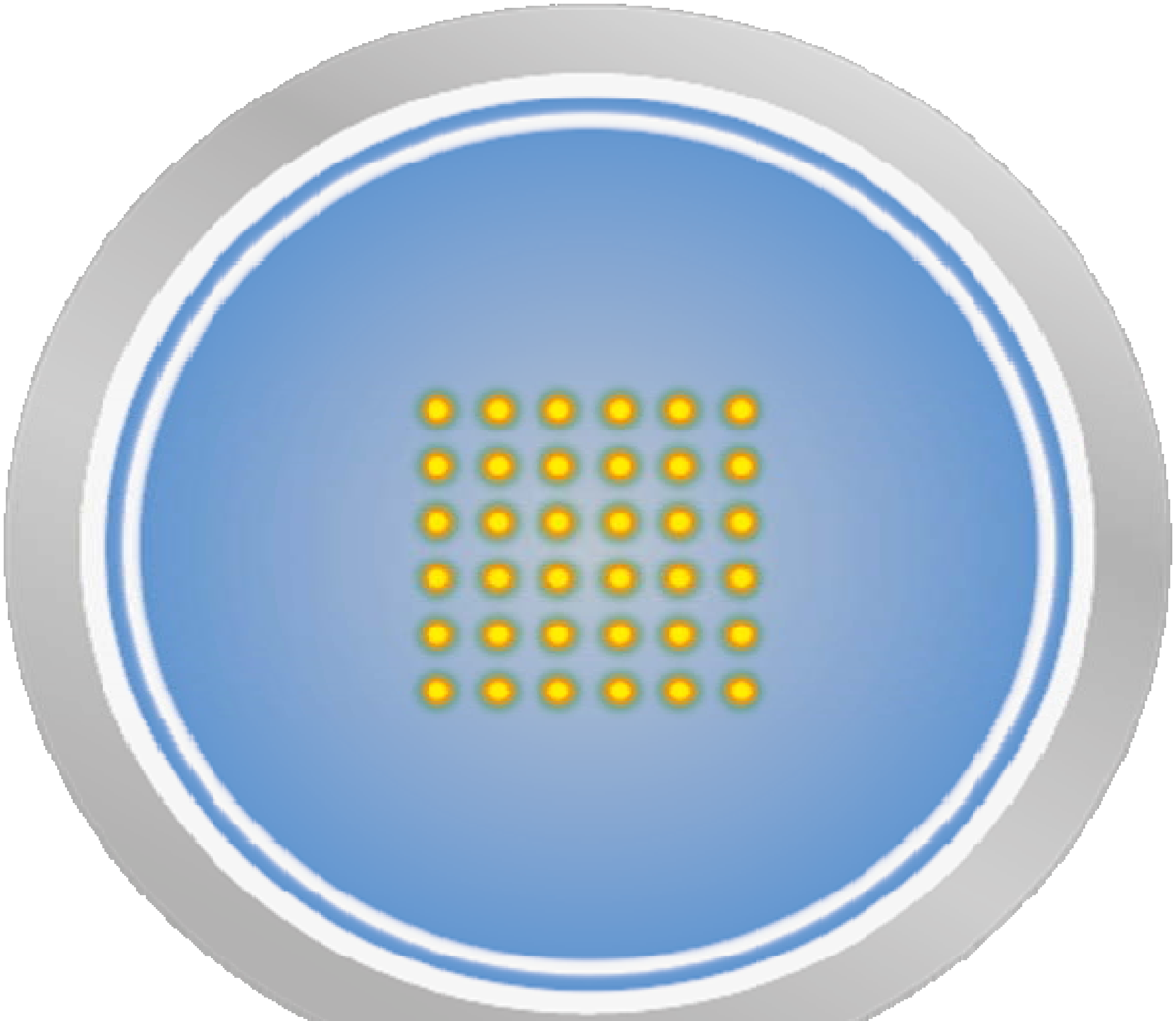


enhanced fluctuations → evidence
for grand canonical BEC regime!

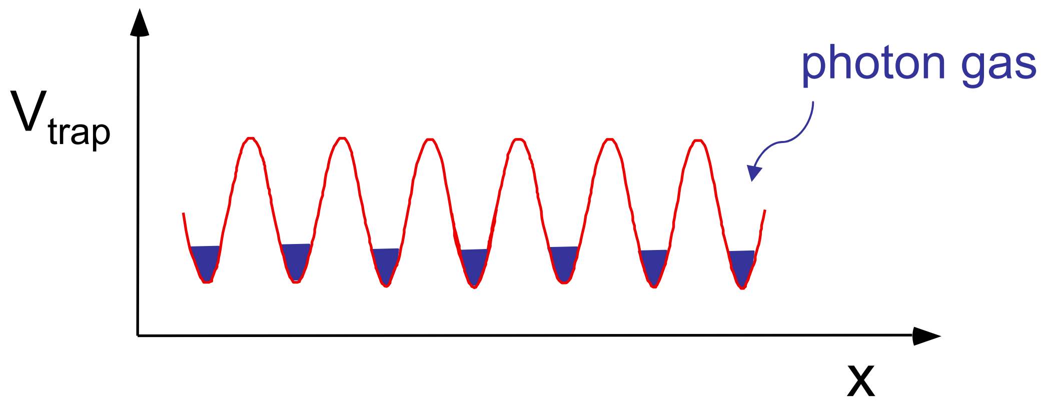
J. Schmitt, T. Damm, D. Dung, F. Vewinger, J. Klaers, M. Weitz, Phys. Rev. Lett. **112**, 030401 (2014)

Photon Intensity Correlation vs. Condensate Fraction





Periodic Potentials for Light: Motivation



Possible experiments:

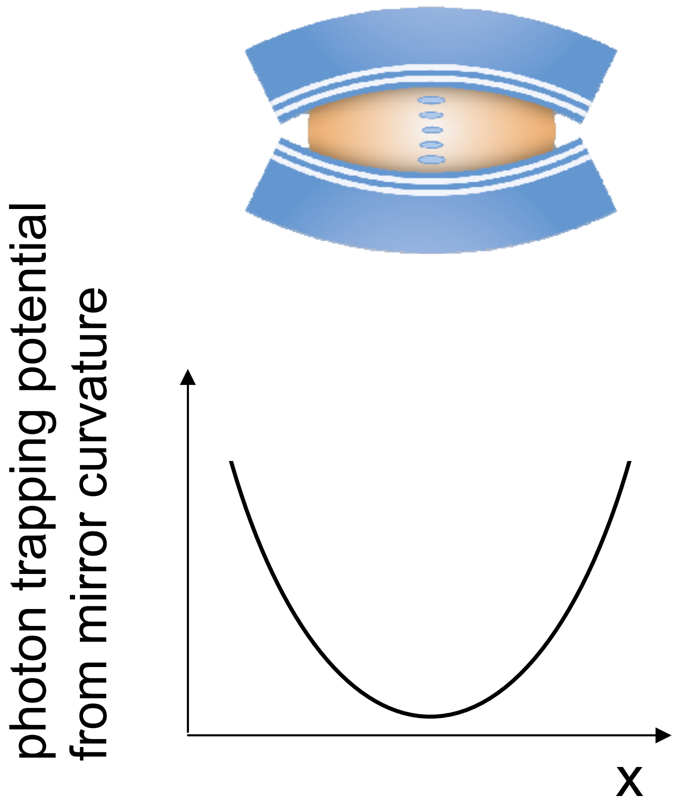
- strongly correlated quantum gases: Mott-insulator transition for photons
- artifical magnetic fields, quantum Hall states, ..

Proposals: Plenio, Greentree, Angelakis, Türeci, Carusotto, Hafezi, Hartmann, Stoof ..

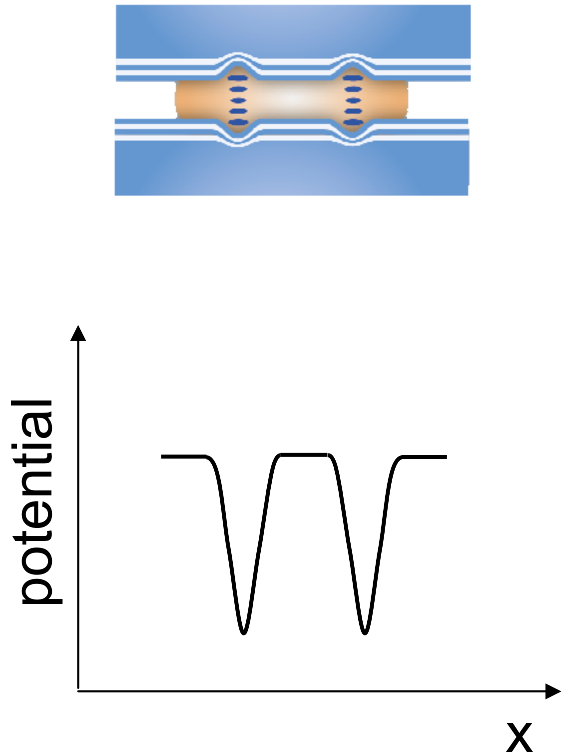
See also experimental lattice work in polaritons: Yamamoto, Bloch

One Approach: Use Mirror Stucturing to Create Variable Potentials for Light

Single trap



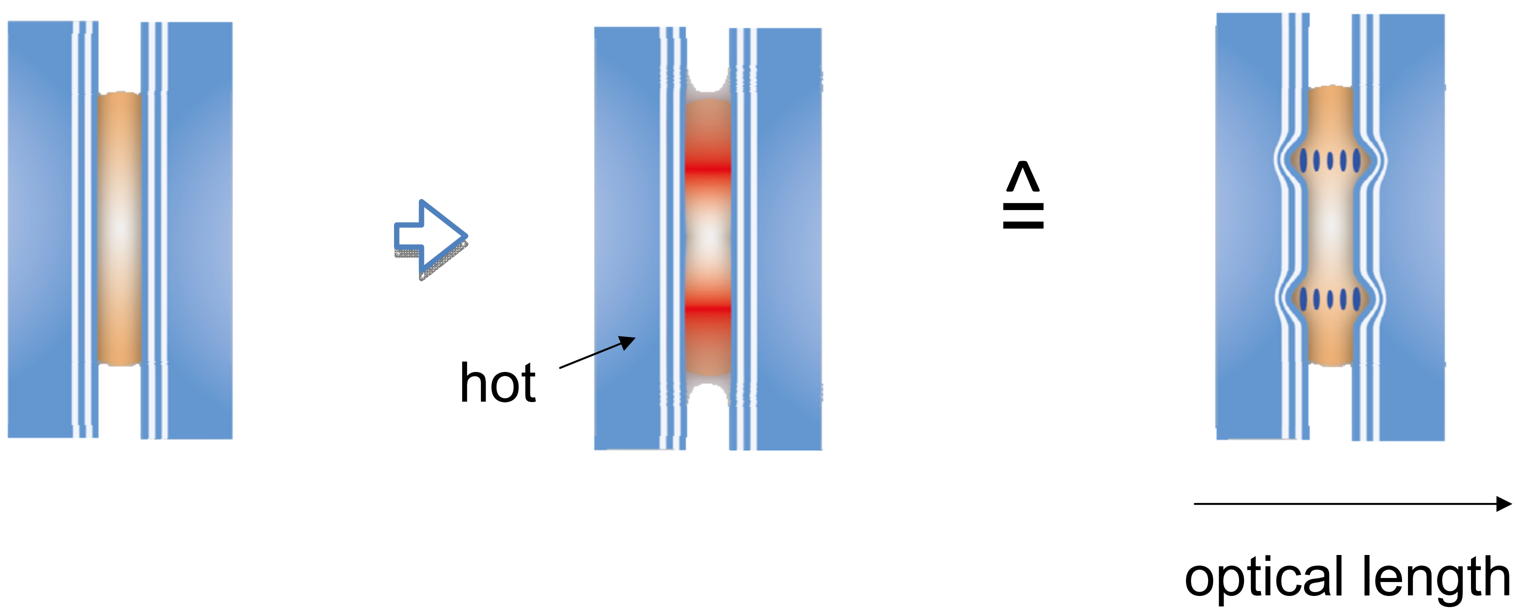
double well



Thermo-Optic Imprinting: Variable Potentials for Trapped Photon Gas

plane mirrors

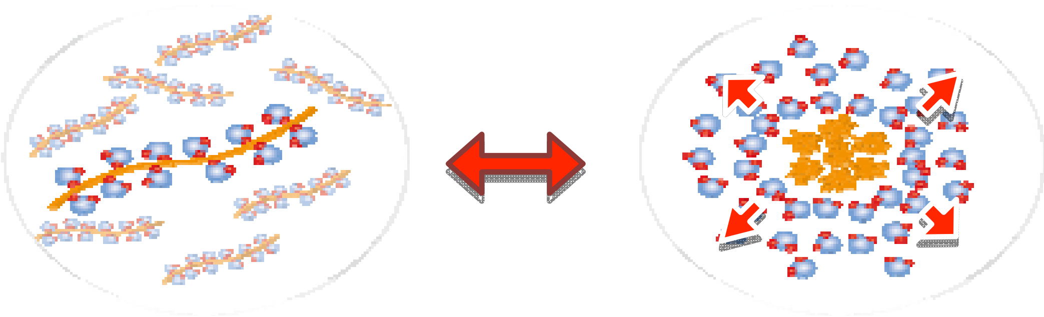
manipulate optical length locally by heating



Thermo-Sensitive Polymer (PolyNIPAM): Controlled Variation of Refractive Index

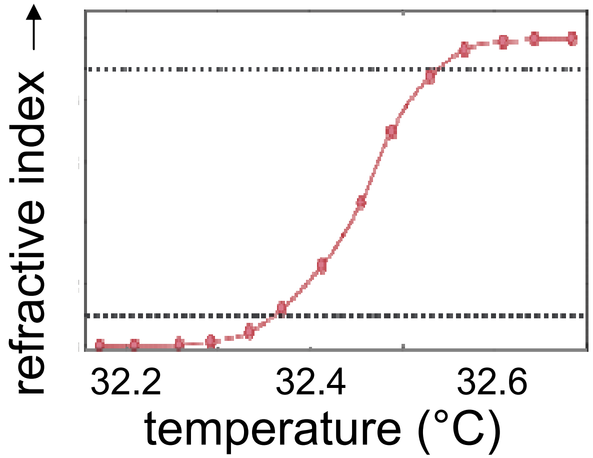
Low temperature: polymer chains in water (solvable)

High temperature: collapsed polymer chains

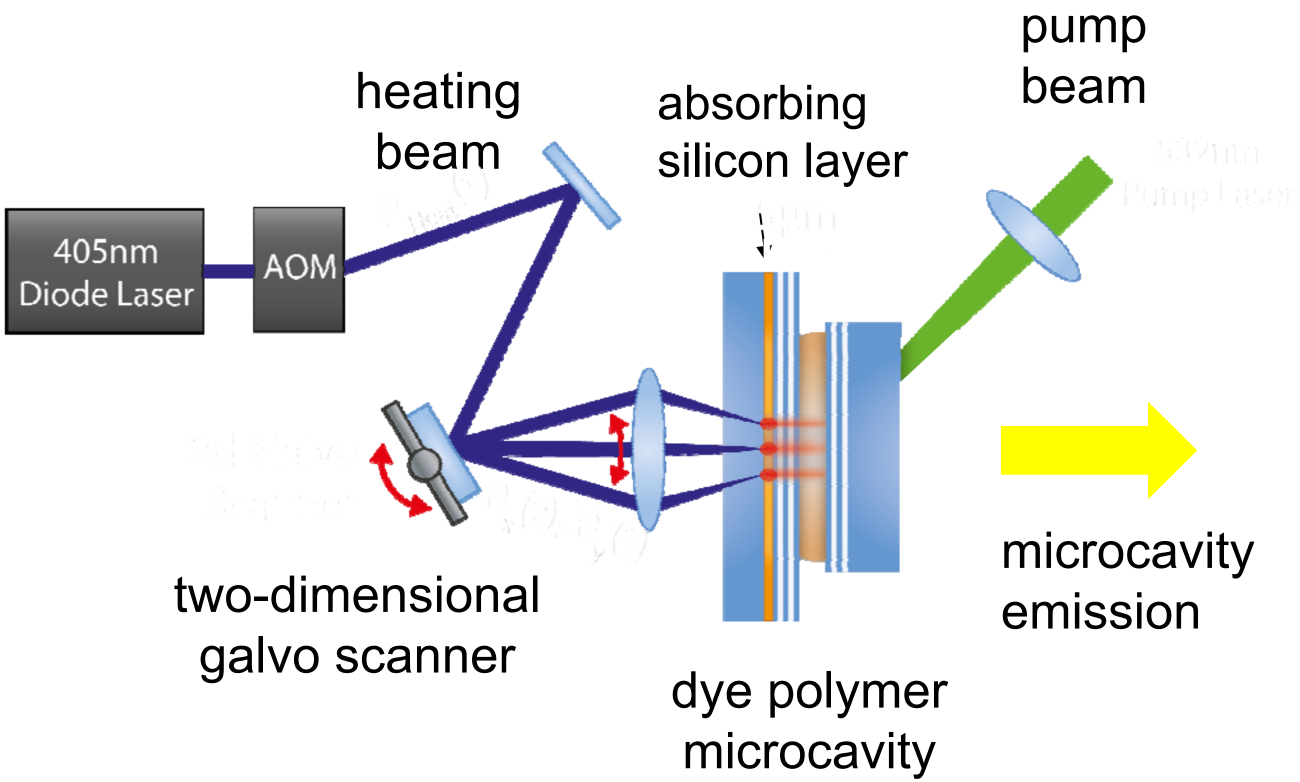


$n_{eff} \approx 1.35$

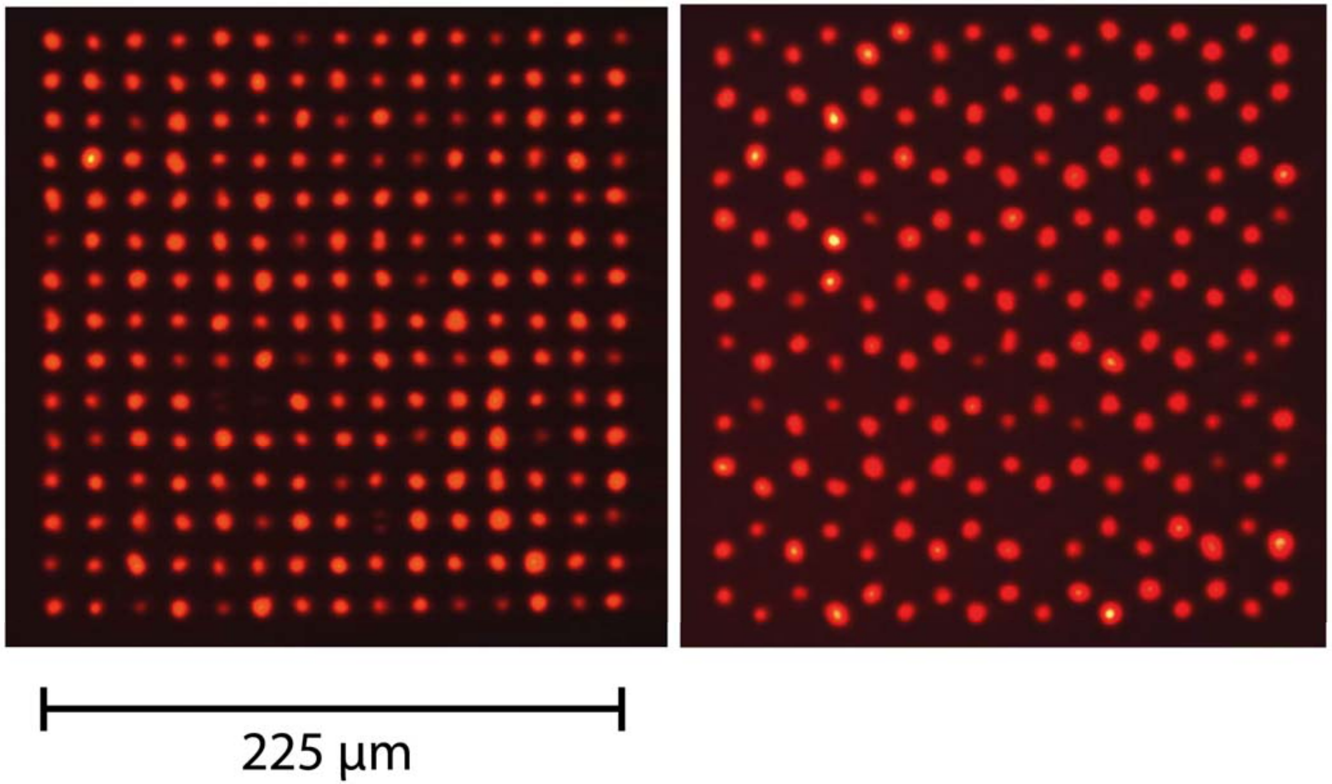
$n_{eff} \approx 1.46$



Setup for Generation of Lattice Potentials



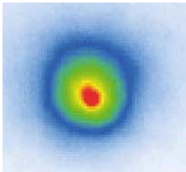
Dye Microcavity Emission for Photonic Lattice Potentials

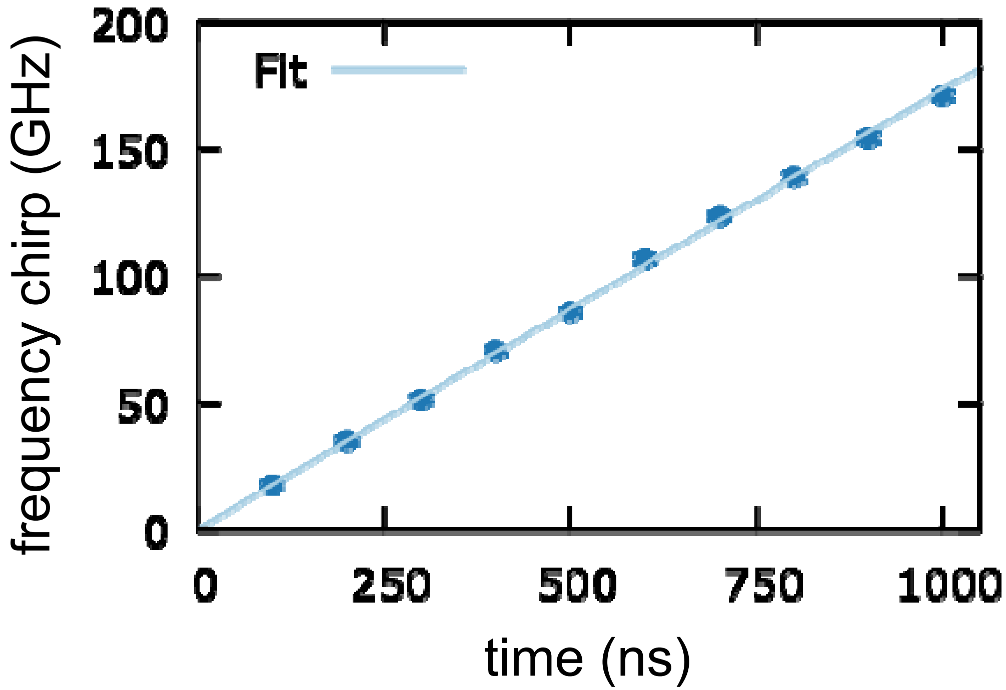


D. Dung et al, to be published

..A Nonperiodic Potential Pattern in Microcavity

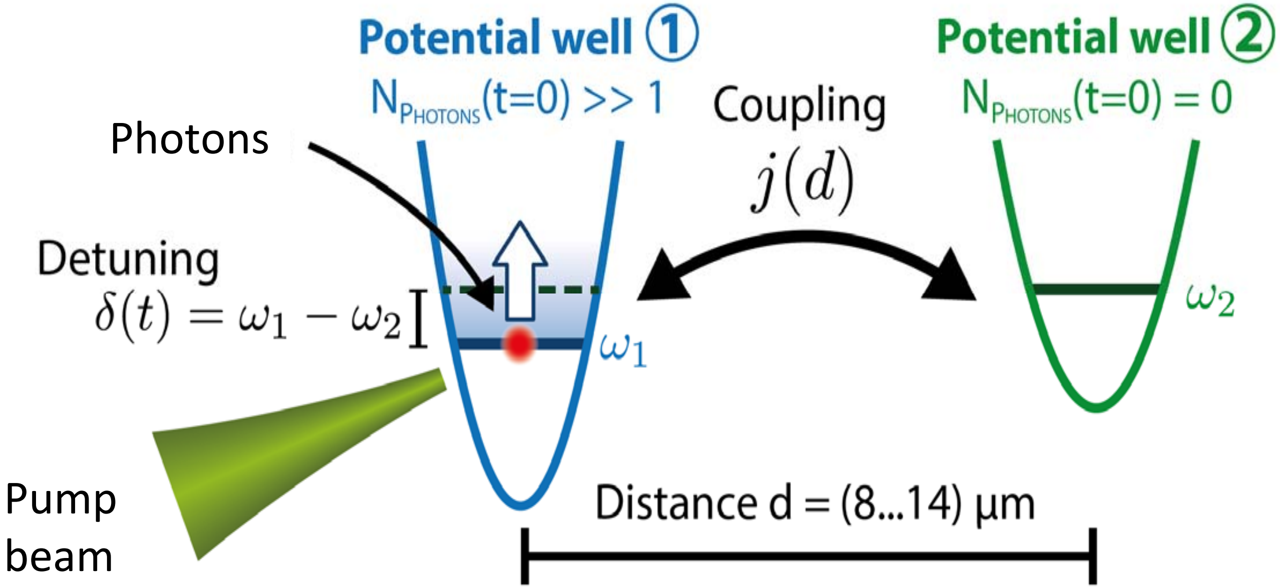
Spectral Analysis of the Emission of One Site: Investigating Effective Photon Interactions



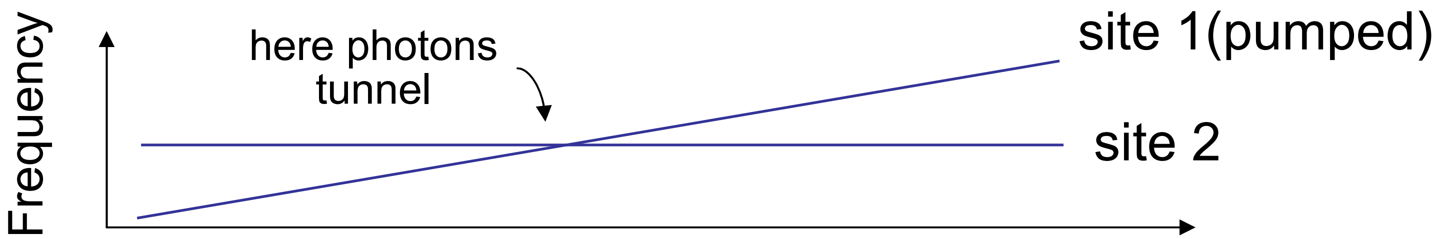


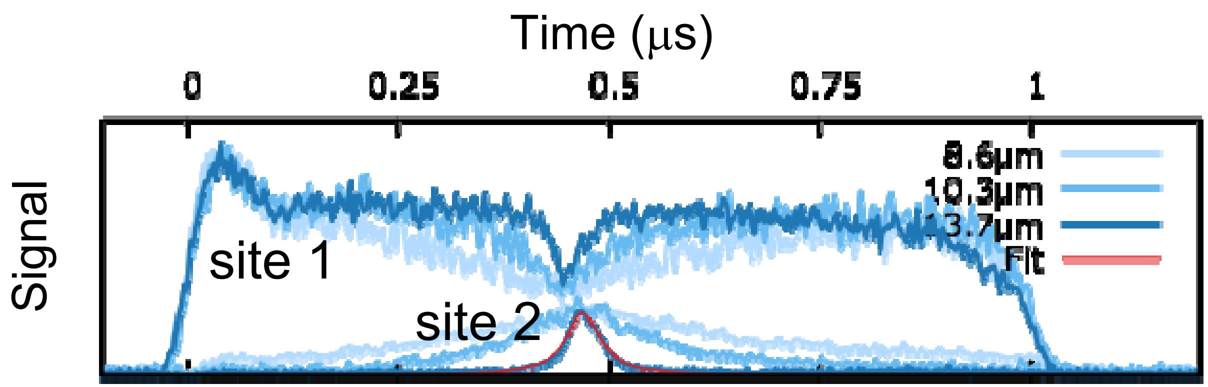
thermo-optic interactions occur temporally delayed
$\rightarrow$ frequency chirp of the emission

Coupling Two Sites in a Double-Well System



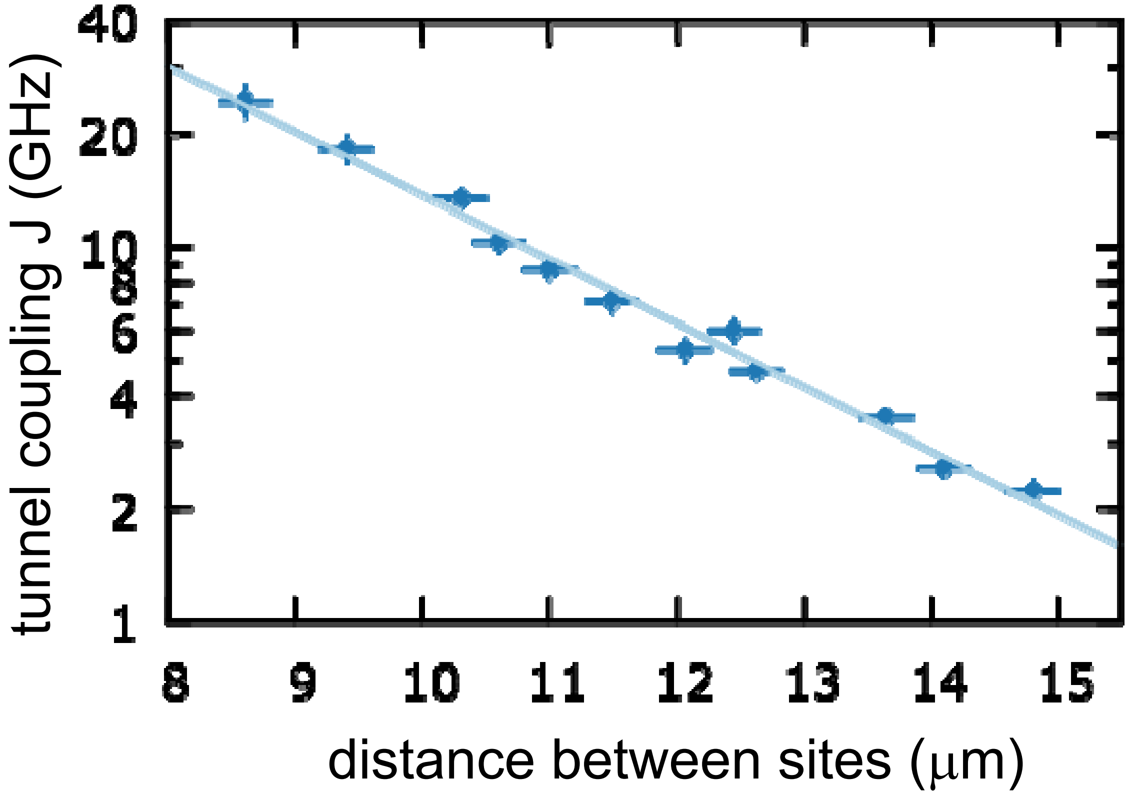
Extracting the Tunnel Coupling





we observe tunneling when the sites are tuned into resonance.
From the resonace width, the tunnel coupling can be extracted

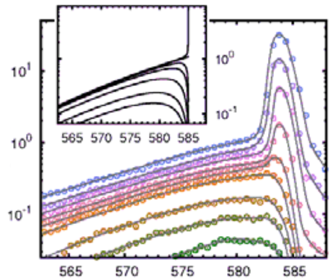
Tunnel Coupling Versus Distance Between Sites

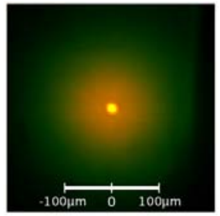


D. Dung et al, to be published

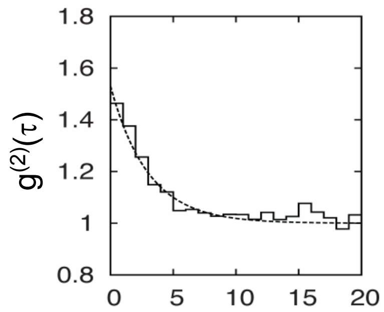
Conclusions

- thermalization of 2D-photon gas with nonvanishing chemical potential and Bose-Einstein condensation of photons

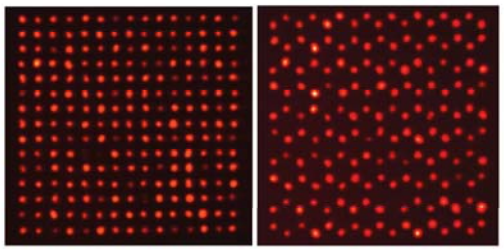


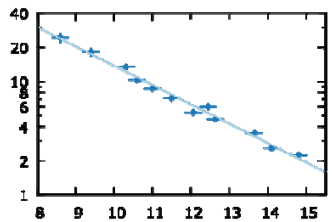


- observation of a grandcanonical BEC regime with enhanced intensity fluctuations



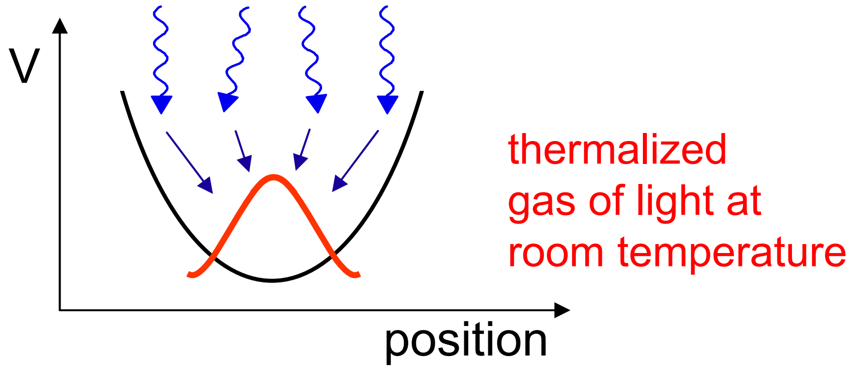
- variable potentials for photonic quantum gas. We see tunneling and effective photon interactions in double well system





Outlook

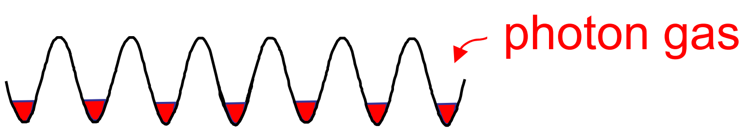
- photon thermalization:
  concentration of diffuse sunlight

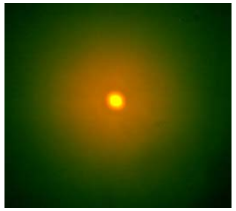


- photon BEC: new states of light

  (some) future directions:

  - grand canonical BEC regime: $g^{(1)}(\tau)$, superfluidity (?), …
  - Josephson physics for photons
  - study of quantum manybody states in periodic potentials





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