Bose-Einstein Condensation of Light

Martin Weitz

Institut für Angewandte Physik der Universität Bonn

Bose-Einstein condensation of atoms: matter waves in lockstep

T~100nK

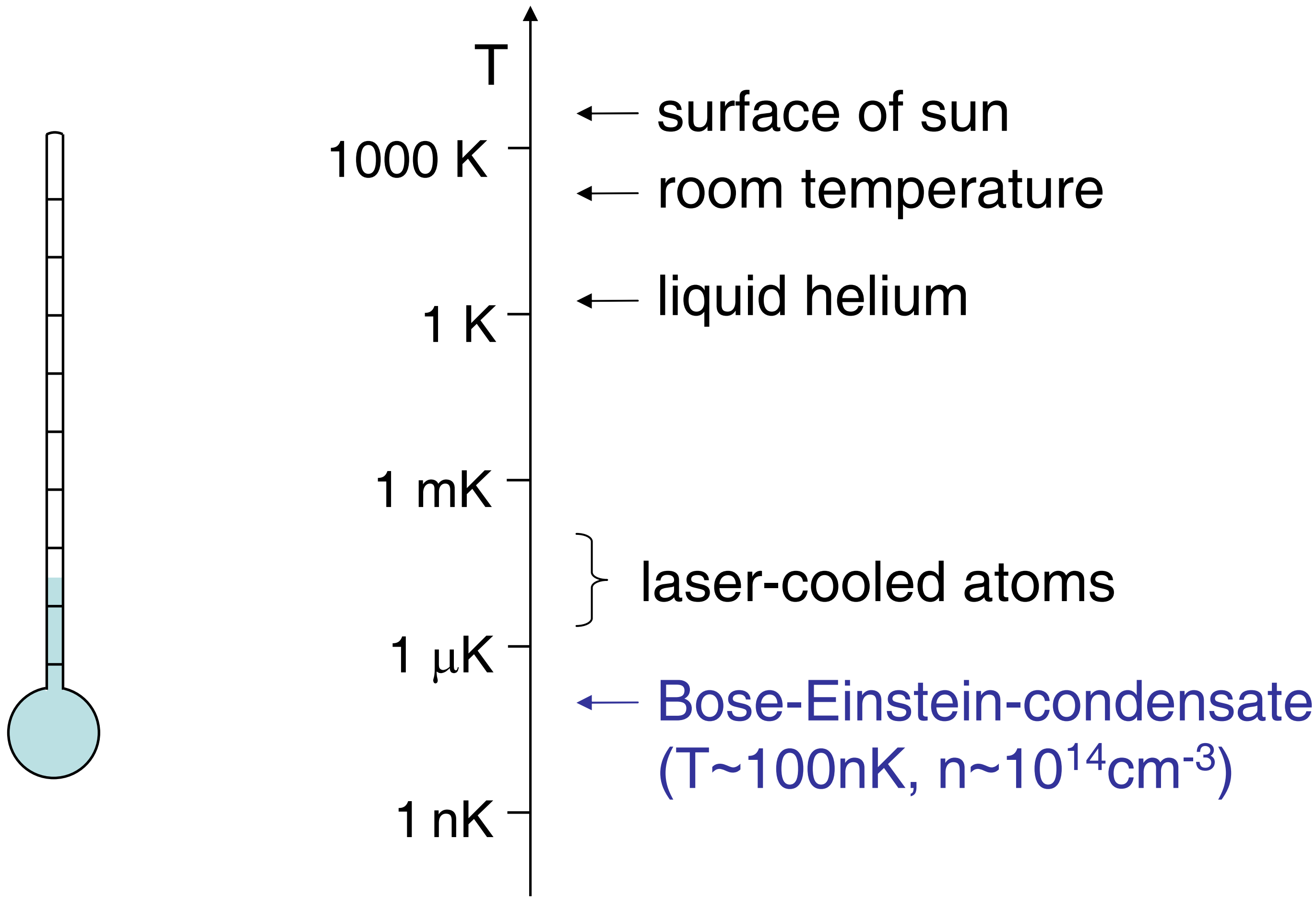
Outline of Talk

- cold atomic gases

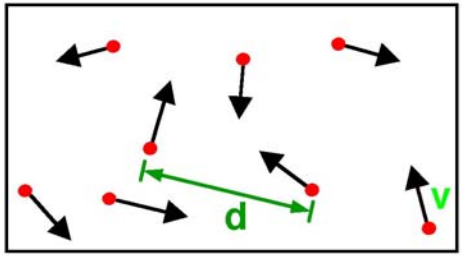
- thermodynamics of a two-dimensional photon gas in a dye-filled optical microcavity

- Bose-Einstein condensation of photons

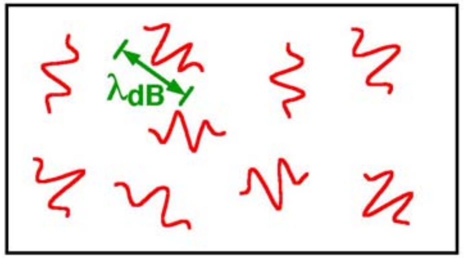
Cold Atomic Gases: Temperature Scale



From Thermal Gas to Bose-Einstein-Condensate



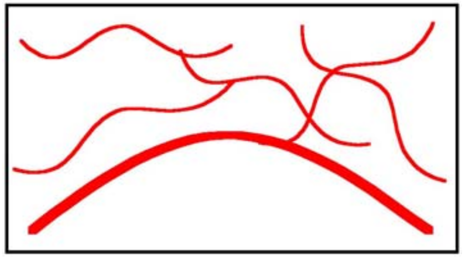
classical gas



cold gas, but $T>T_c$

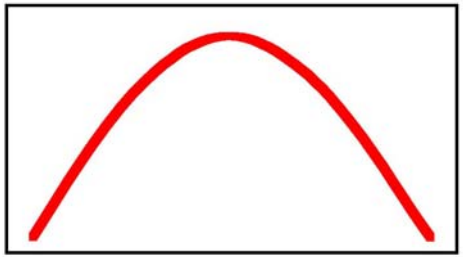
atoms show wave properties

$$\lambda_{dB} = h/mv \propto 1/\sqrt{T}$$



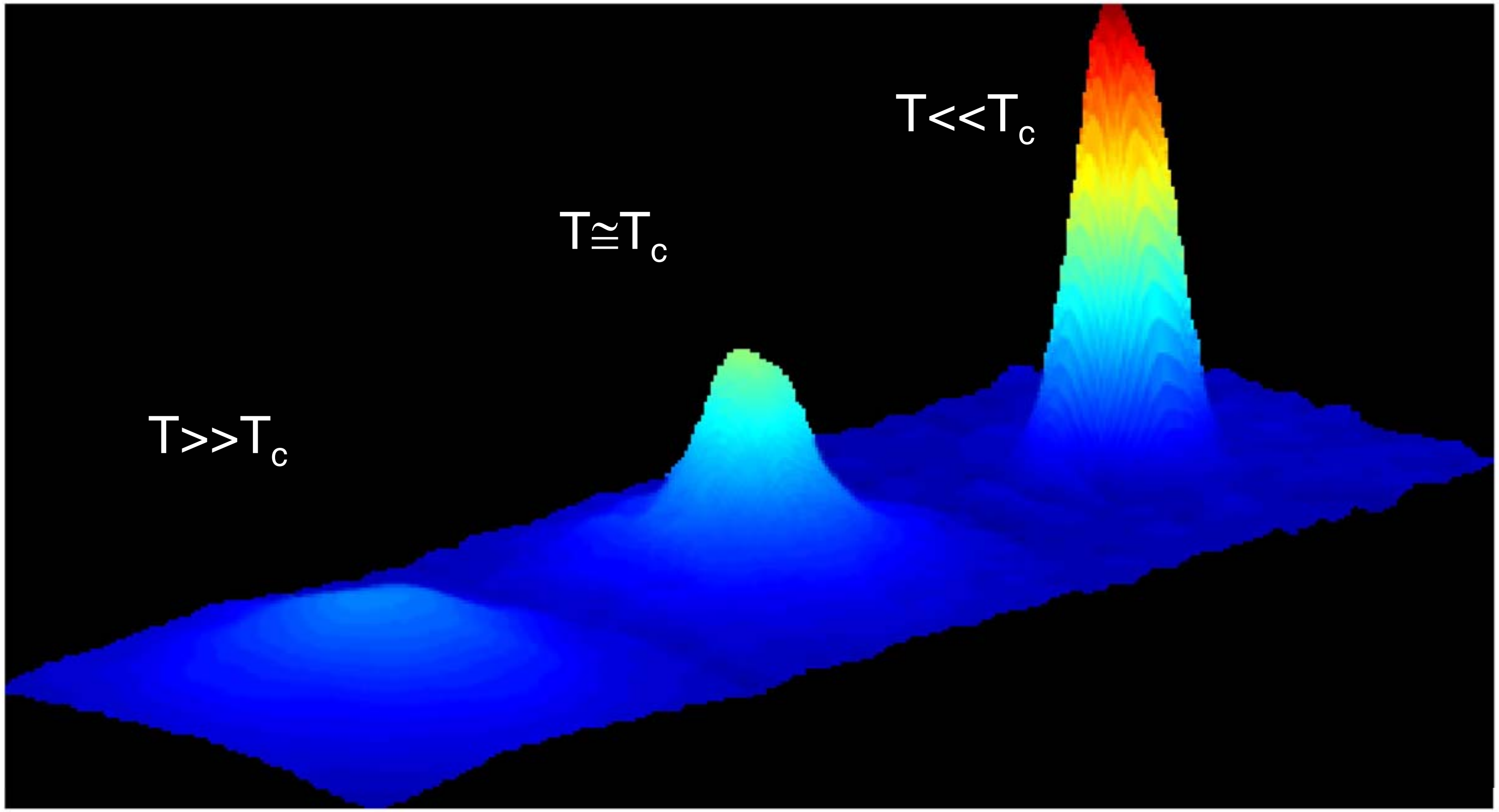
$T<T_c$

matter waves overlap → BEC



$T<<T_c$

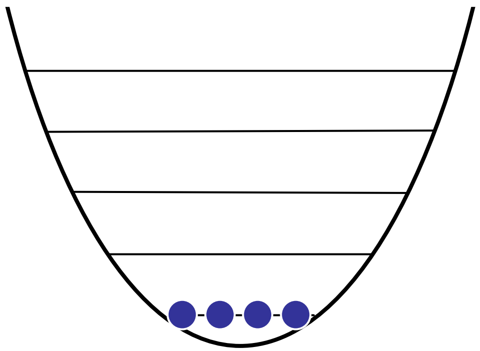
pure Bose-Einstein-condensate



BEC of rubidium atoms @ 180nK

Ground State of Bosonic Ensembles (3D-Regime)

atoms



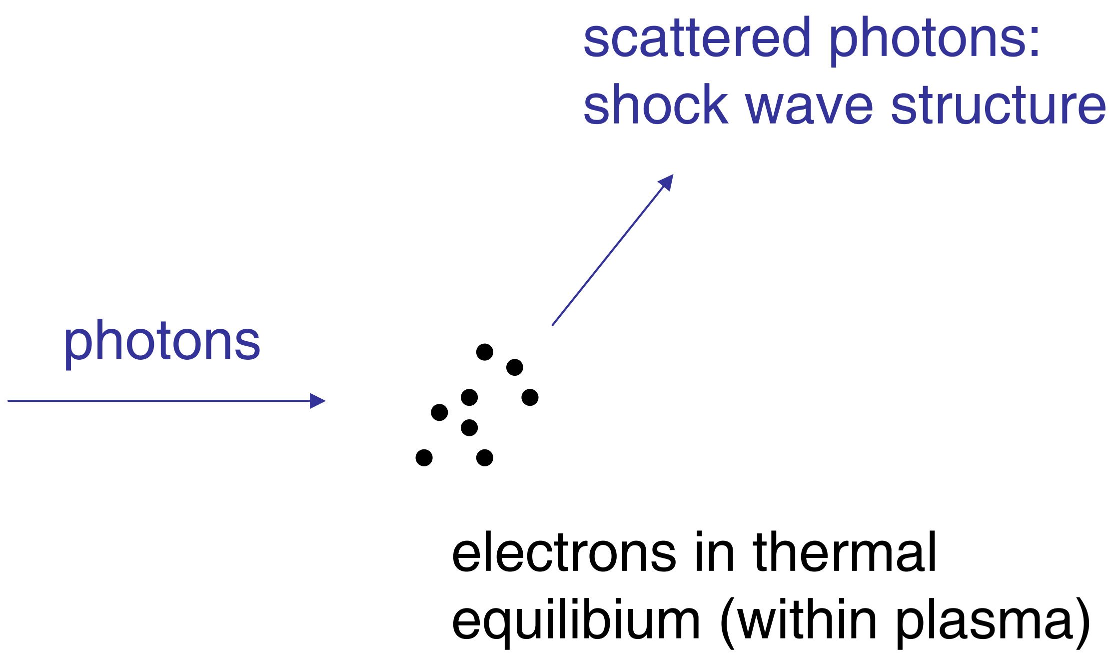
photons ?

Bose-Einstein-condensate

[redacted]

Earlier Work related towards a Photon BEC

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

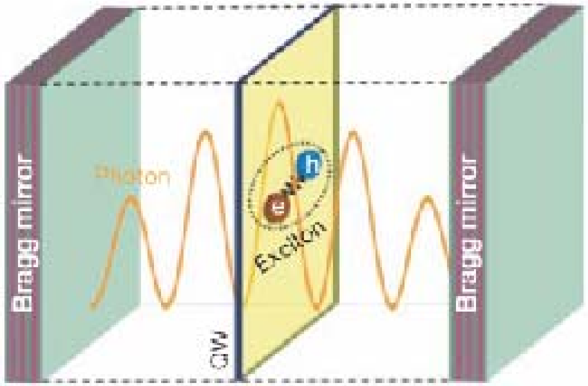


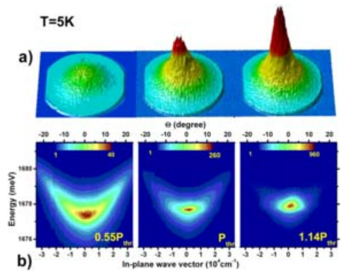
Zel‘dovich and Levich, 1969

… Earlier Work

- Exciton-polariton condensates

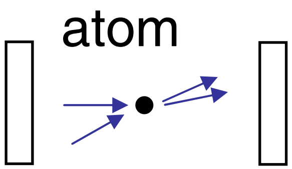
strong coupling (‚half matter, half light‘); in equilibrium for condensed part





Yamamoto, Deveaud-Pledran, Littlewood, Snoke, …

- Proposal for photon fluid in nonlinear resonator

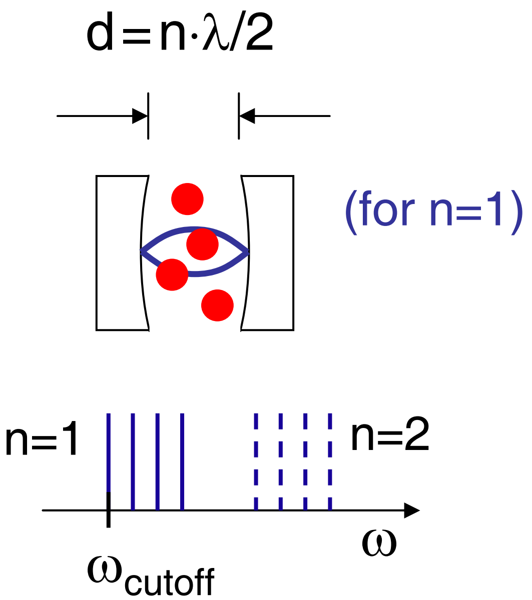


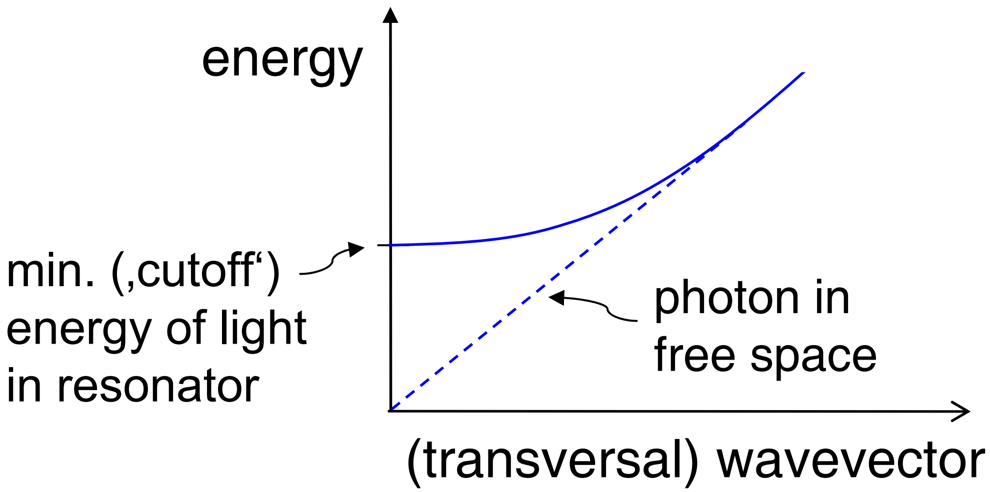
photon-photon scattering
(four-wave mixing)

R. Chiao

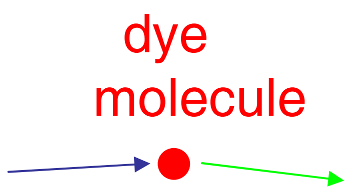
Bonn 2D-Photon Gas Experimental Scheme

- use curved-mirror microresonator to modify photon dispersion



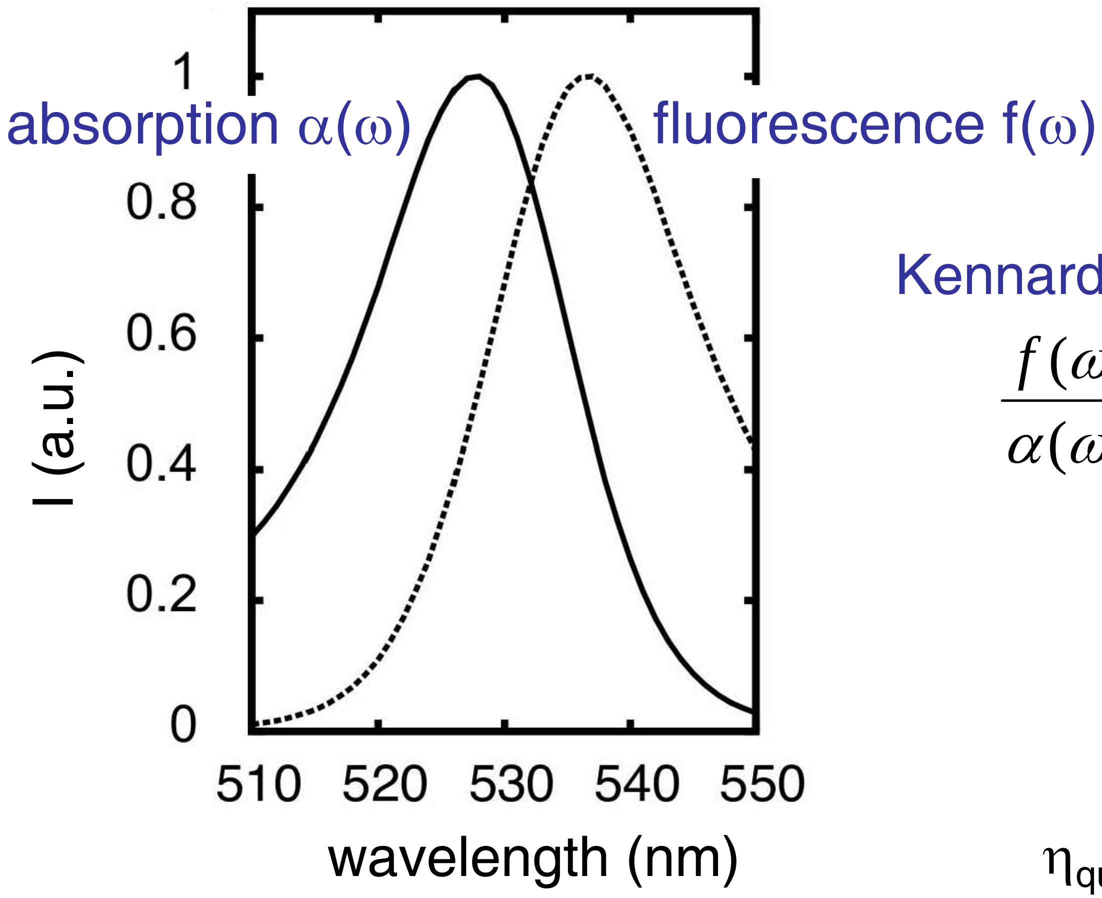


- thermal equilibrium of photon gas by scattering off dye molecules…



J. Klaers et al.

Spectrum of Perylene-Dimide Molecule (PDI)



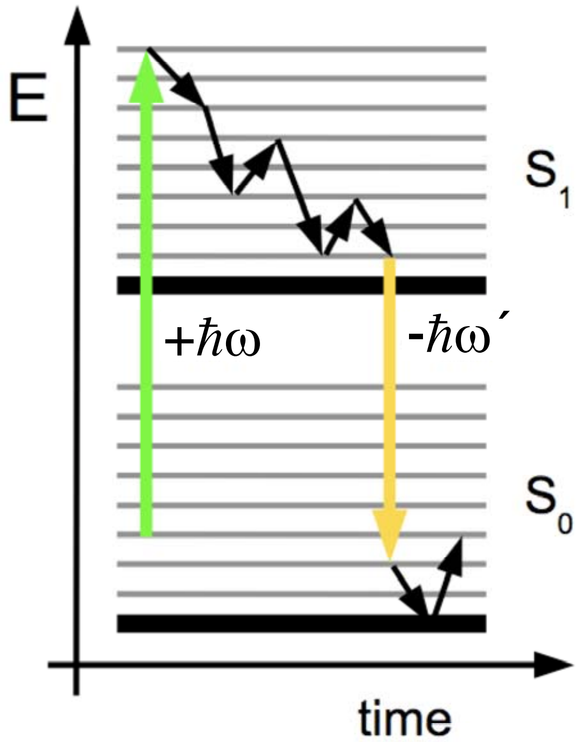
Kennard-Stepanov theory:

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

$\eta_{quantum} \cong 0.97$

Photon Gas Thermalization: Background

Collisionally induced thermalization in dye medium



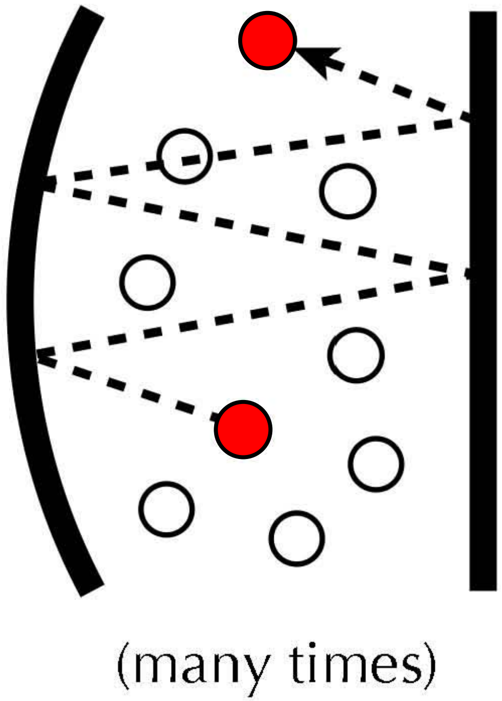
$$\frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

T: (internal rovibrational) temperature
of dye solution

Kennard 1912, Stepanov 1956

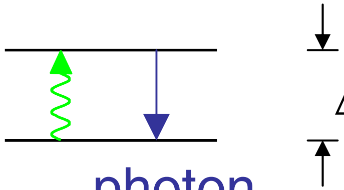
Model for Photon Thermalization

multiple absorption and emission processes by dye molecules in resonator

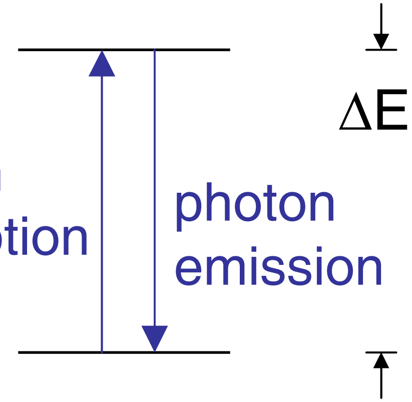


Photon Number Variation during Thermalization?

Planck Blackbody Radiation



New Scheme



thermal excitation suppressed

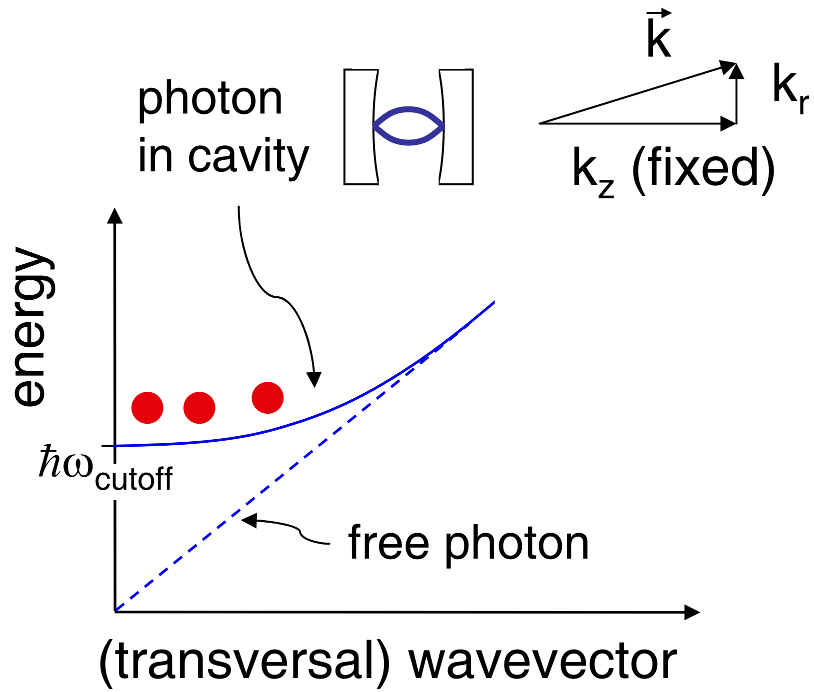
by $\sim e^{-\frac{\hbar\omega_{cutoff}}{k_B T}} \cong 10^{-36}$

$\rightarrow$ photon average number conserved

‚white-wall box' for photons

Photon Trapping versus Atom Trapping

- quadratic photon dispersion



In paraxial approximation ($k_z >> k_r$):

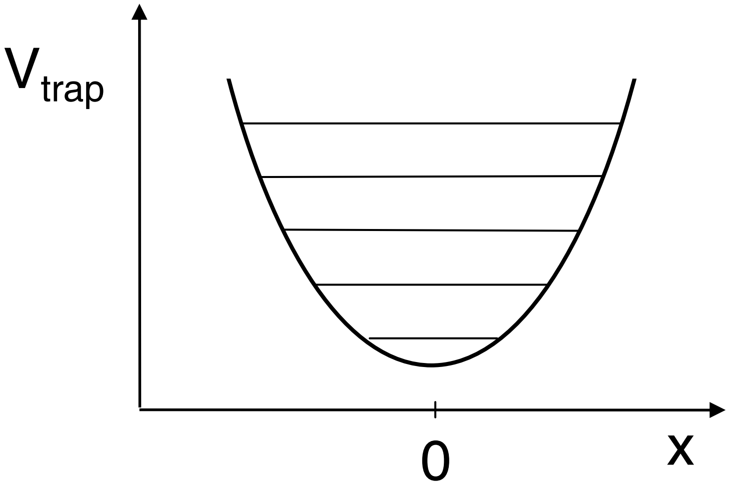
$$E = \hbar c \sqrt{k_z^2 + k_r^2} \cong \hbar c \left(k_z + \frac{k_r^2}{2k_z} \right)$$

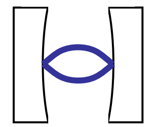
$$= m_{eff} c^2 + \frac{(\hbar k_r)^2}{2 m_{eff}}$$

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

..Photon versus Atom trapping

- trapping potential from mirror curvature



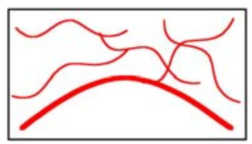


System formally equivalent to 2D-gas of massive bosons with $m_{eff} = \hbar\omega_{cutoff} / c^2$

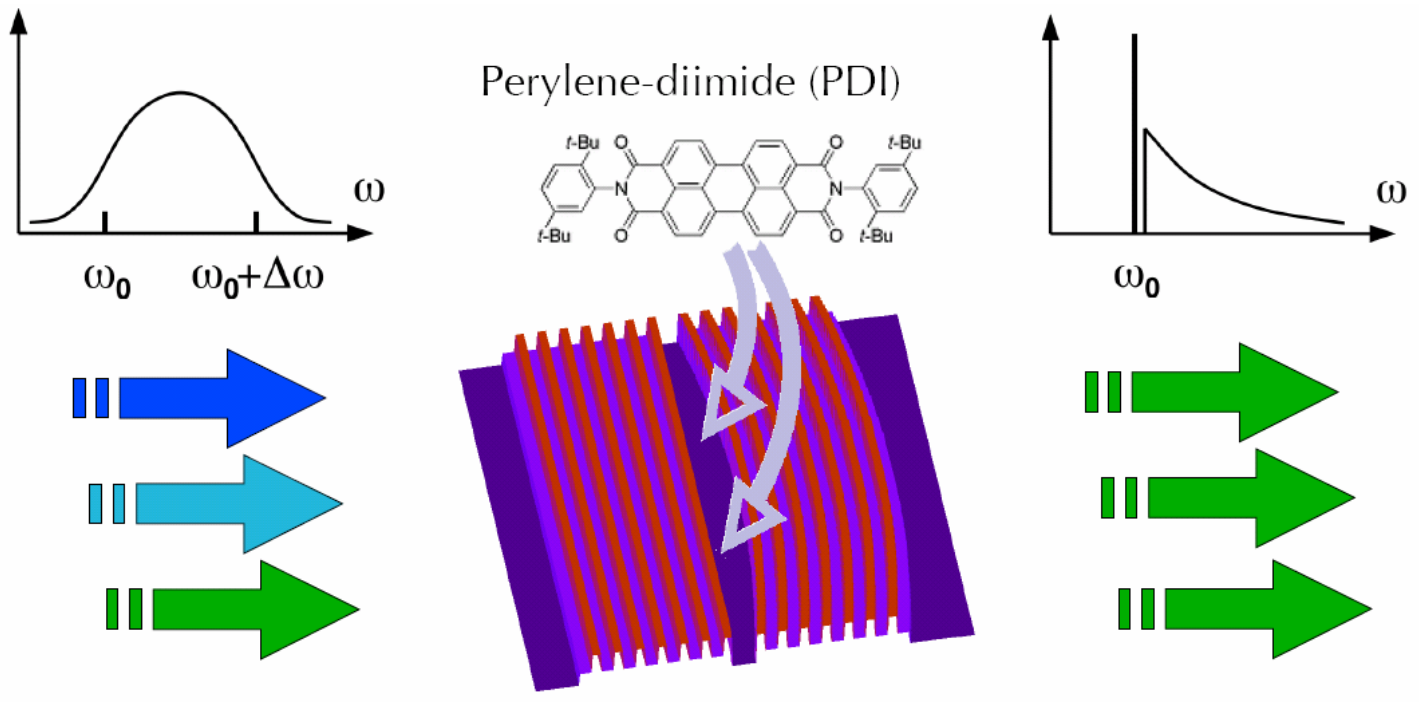
$$E = m_{eff}c^2 + \frac{(\hbar k_r)^2}{2m_{eff}} + \frac{1}{2} m_{eff}\Omega^2 r^2$$

$\rightarrow$ 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 $\cong 10^{-10} \cdot m_{Rb}$)

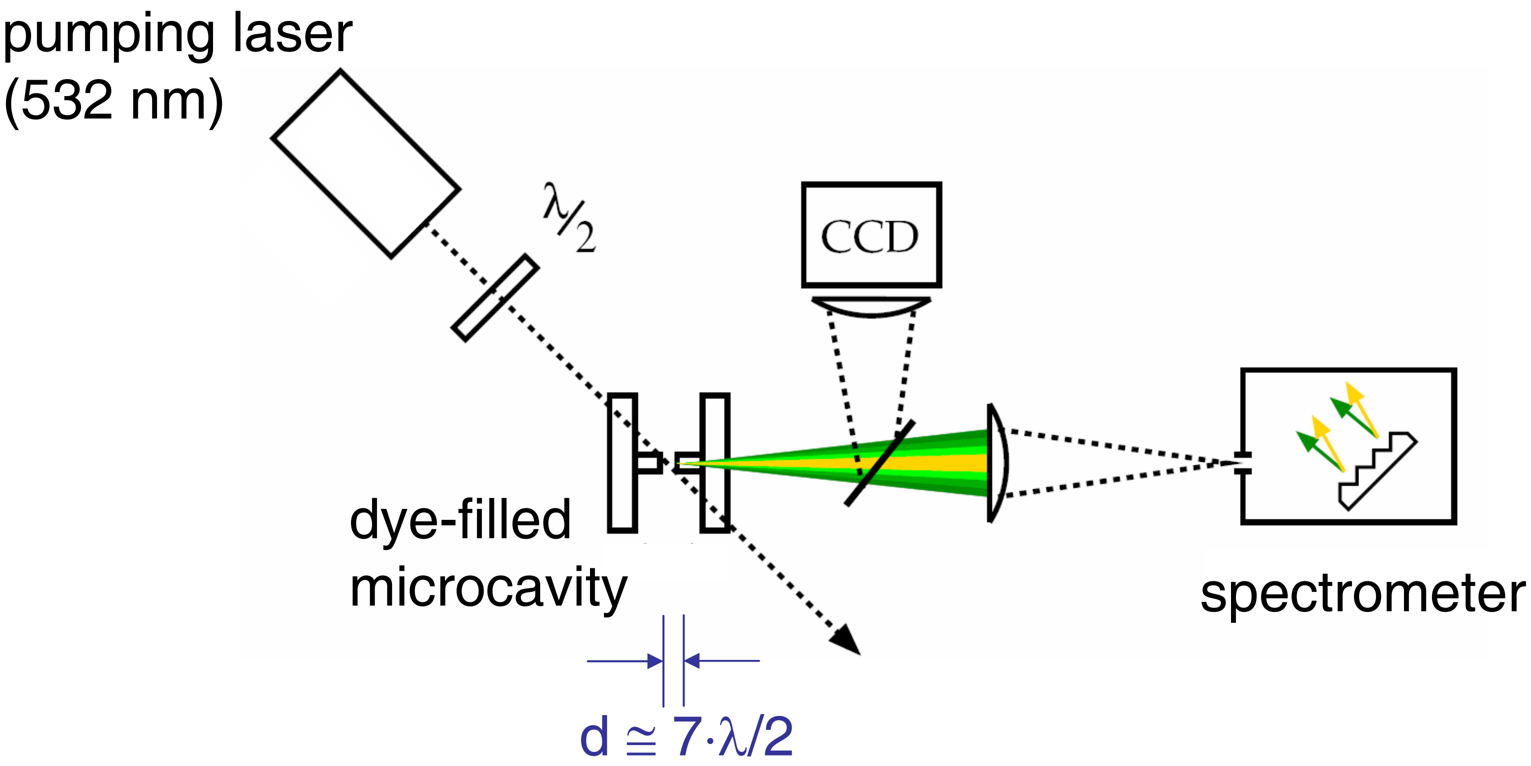
BEC versus Lasing

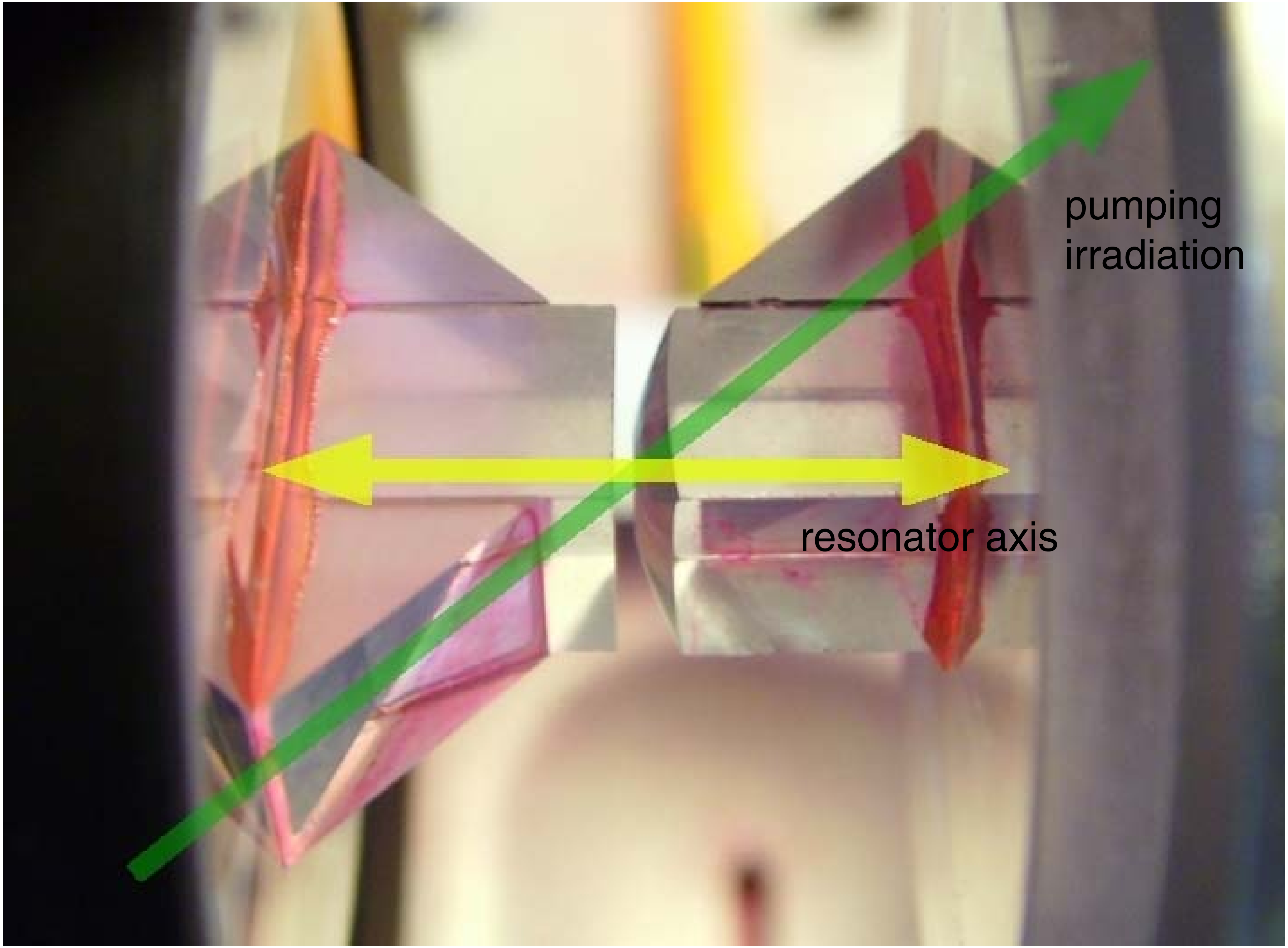
	Optical laser	Photon BEC
thermodynamic state:	far from equilibrium	thermal equilibrium
gain/thermalisation medium:	three or more levels, inversion (or quantum coherence, high coupling eff. to single cavity mode)	non-inverted two-level system sufficient (many transversal cavity modes)
phase transition condition:	for the lasing mode: gain (stim. emission) > loss 	$N > N_c = \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2$ (or $n_{2D}\lambda_{dB}^2 \gtrsim 1$) 

Two-Dimensional Photon Gas in Dye-Filled Optical Resonator



Experimental Setup: 2D Photon Gas

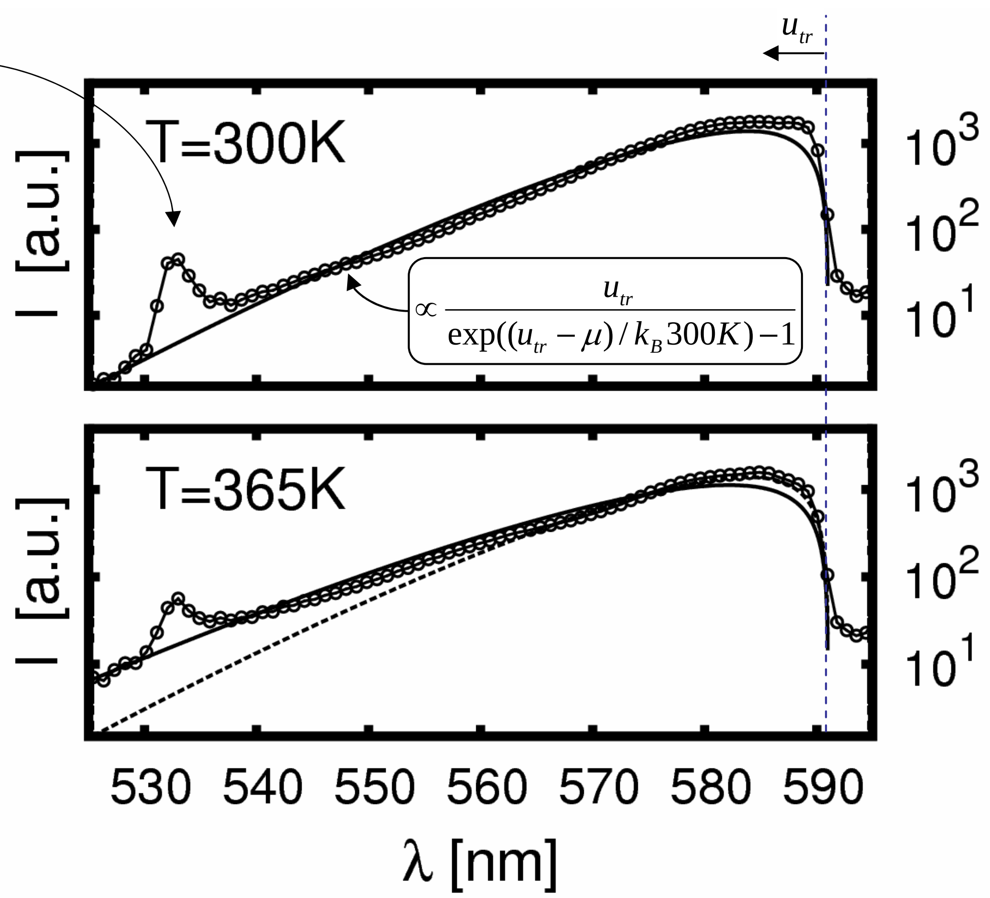



pumping
irradiation
resonator axis

Spectrum of Thermal Photon Gas in Cavity

cavity cutoff

residual pump radiation



from P_{out}=50(5) nW →

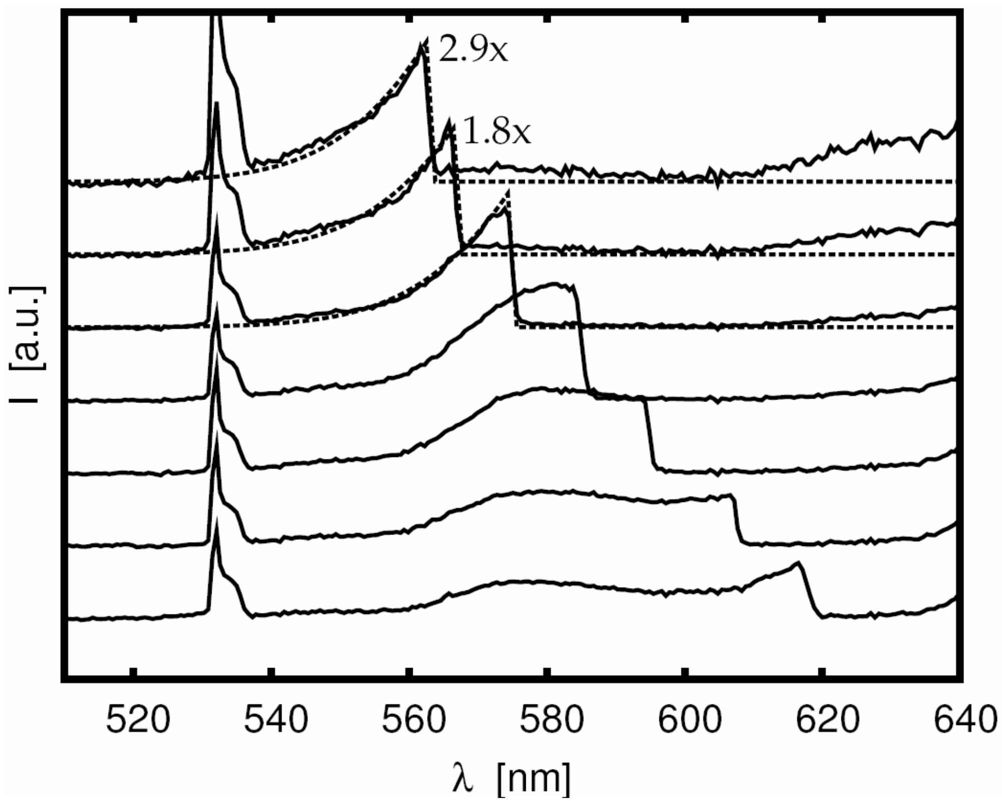
μ = -6.76(17)k_BT

μ = -7.16(17)k_BT

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

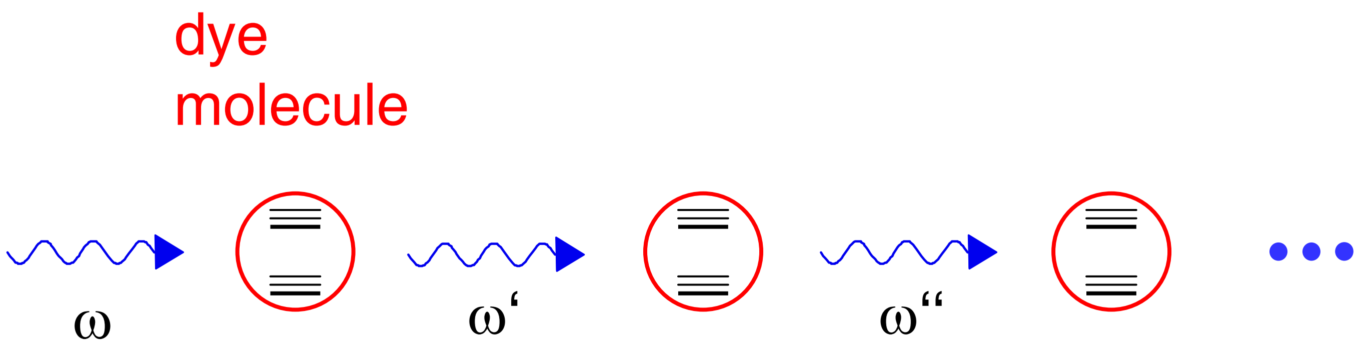
J. Klaers, F. Vewinger, M. Weitz, Nature Phys. **6**, 512 (2010)

Spectra for Different Cavity Cutoff Frequencies

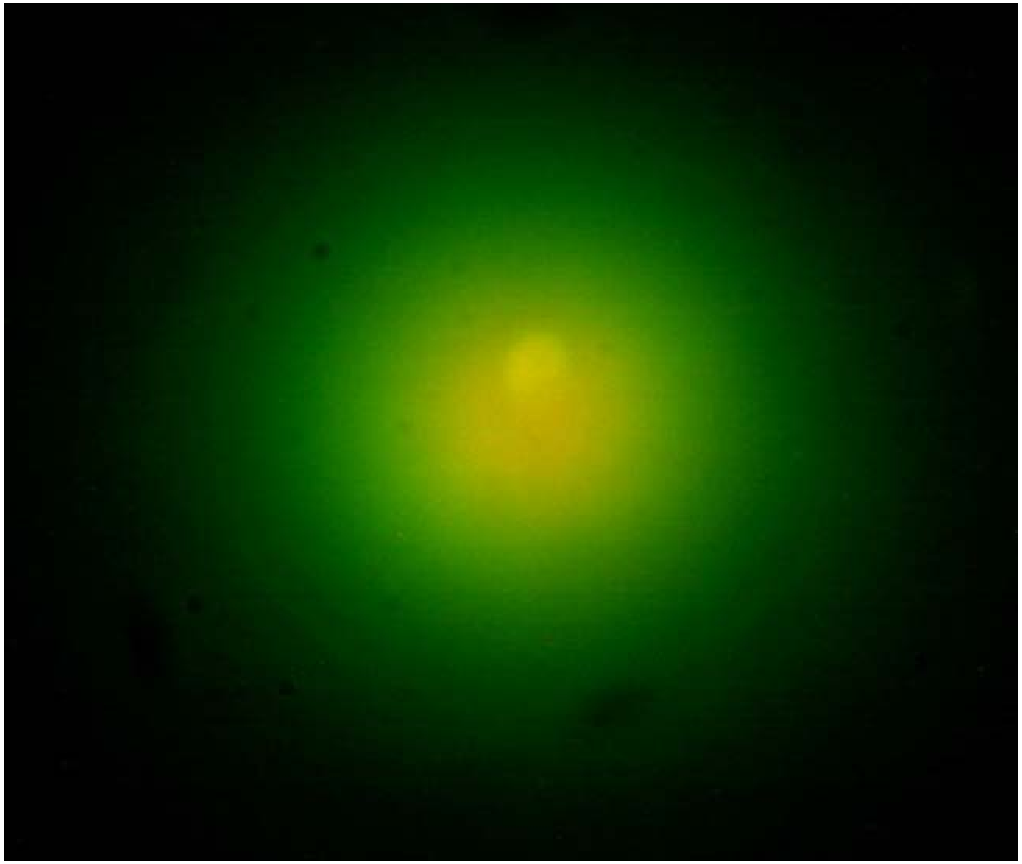


optically dense regime,
thermalization of photon gas

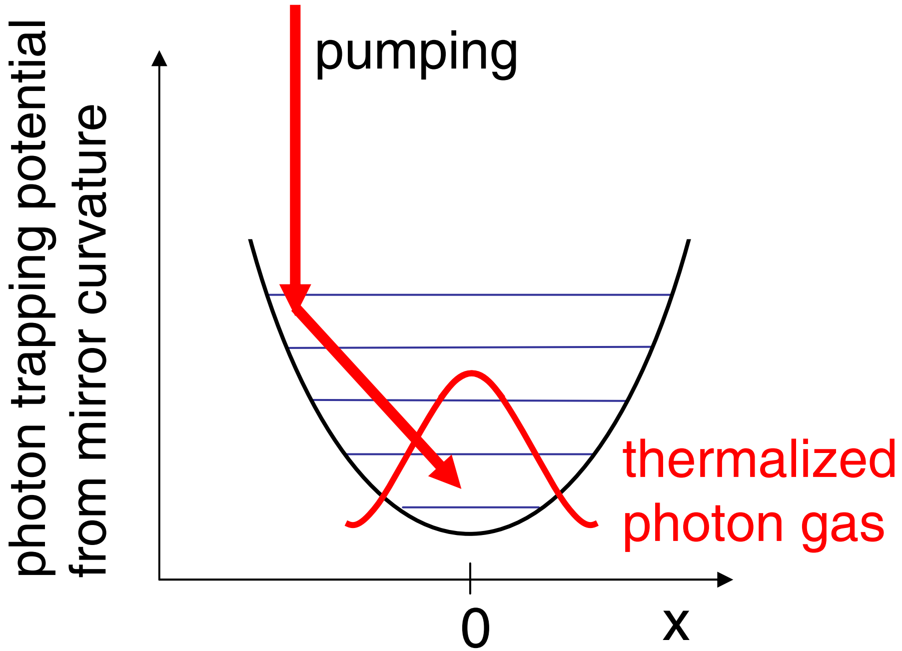
… Reabsorption: Required for Photon Thermalization



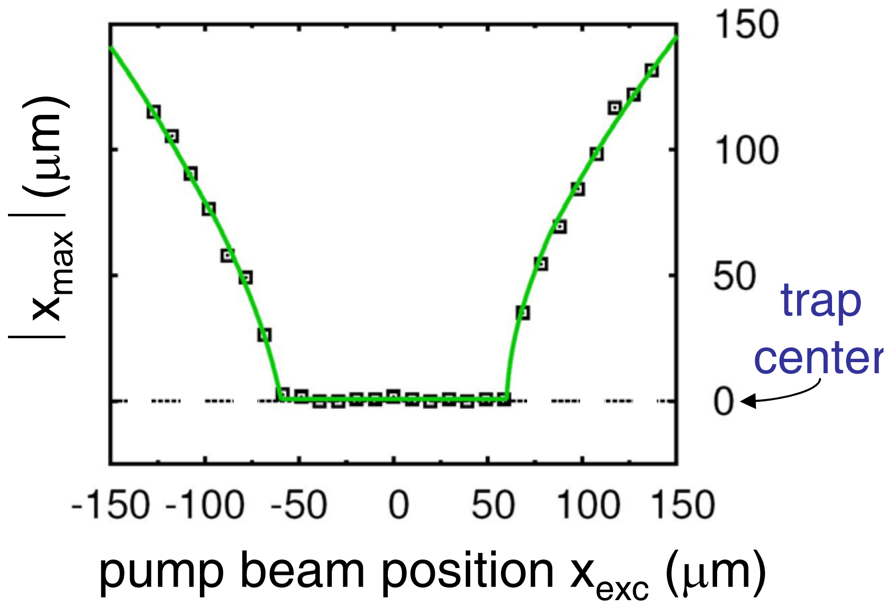
Snapshot: Thermalization of Photon Gas in Dye Microcavity

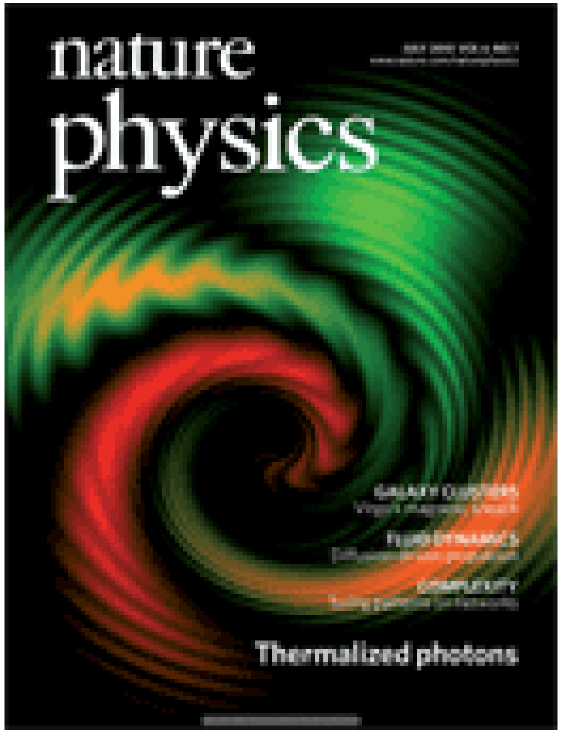


Thermalization – Photon Diffusion towards Center

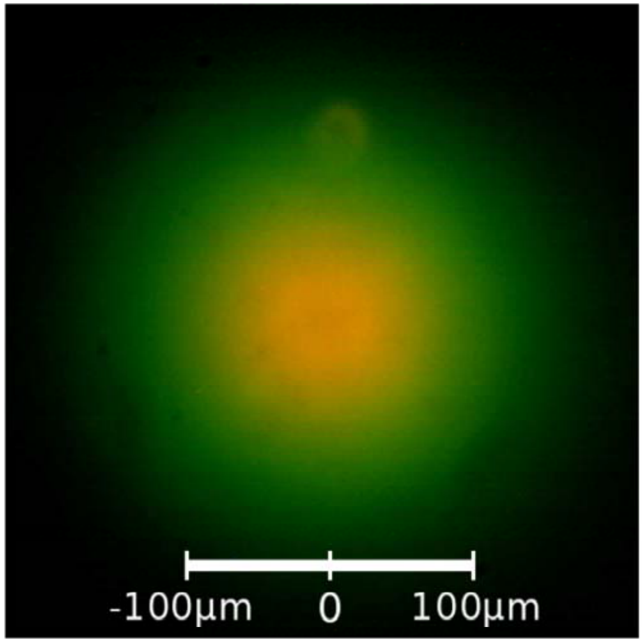


Experimental data

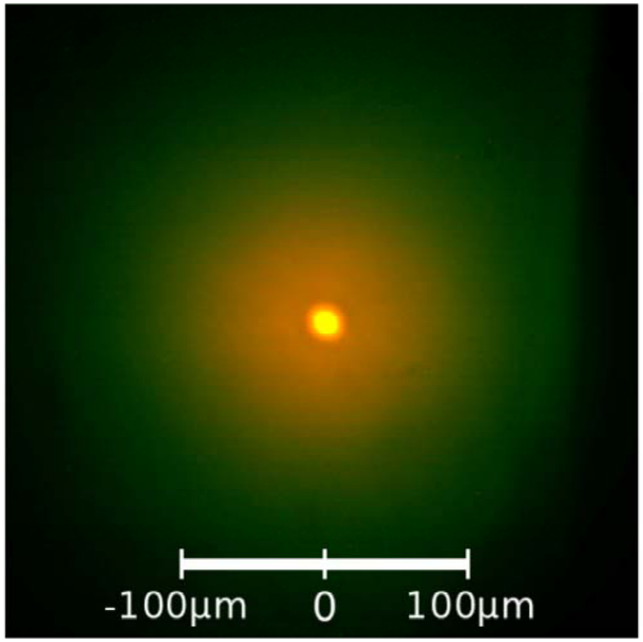



nature
physics
GALAXY CLUSTERS
FLUID DYNAMICS
COMPLEXITY
Thermalized photons

Photon Gas at Criticality



$N<<N_c$



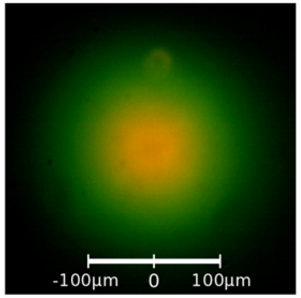
$N>N_c$

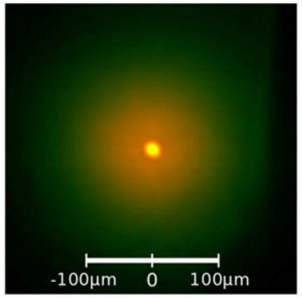
BEC!

Rh6G, duty cycle 1:16000, 0.5µs pulses

Bose-Einstein condensate of Light

below threshold





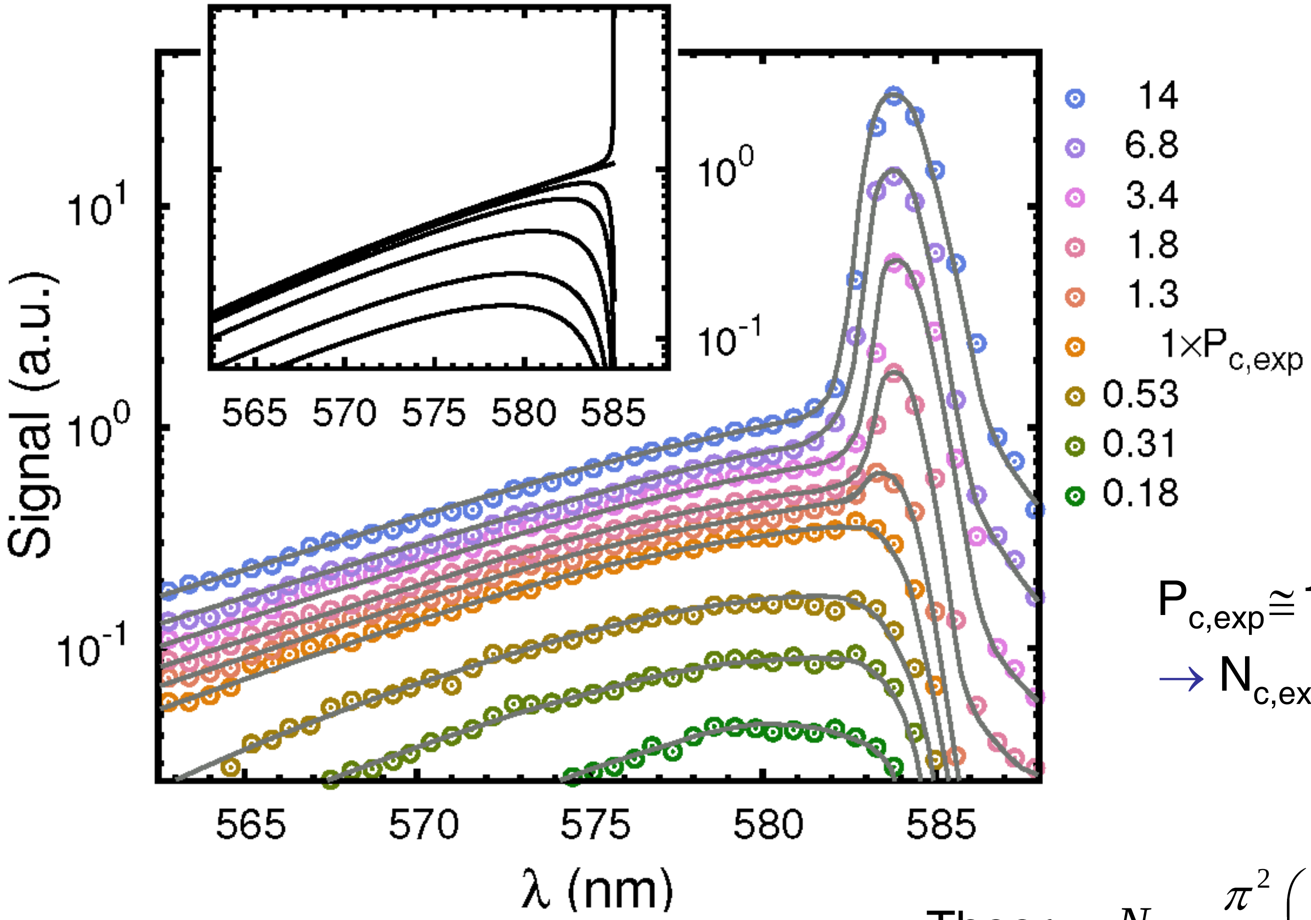
Bose-Einstein condensate

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

Light Bulb

ground state:
filament off

Spectra for Densities around Photonic BEC Threshold



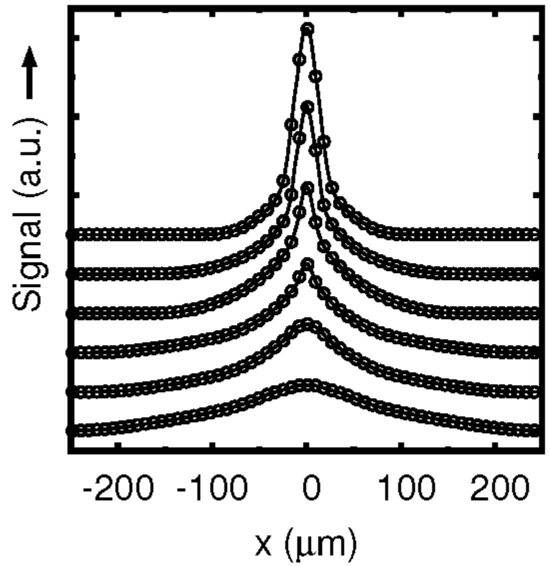
$P_{c,exp} \cong 1.55(60)$ W

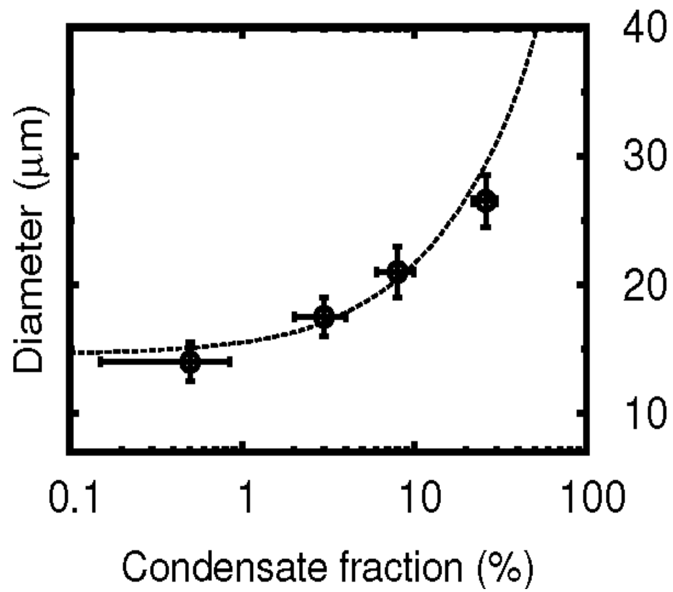
→ $N_{c,exp} \cong (6.3 \pm 2,4) \cdot 10^4$

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)

Spatial Intensity Distribution around BEC Threshold

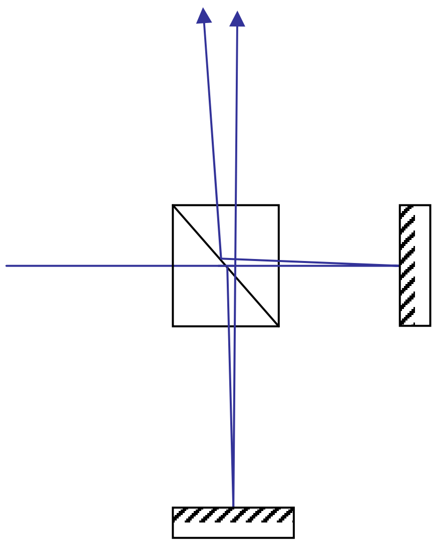


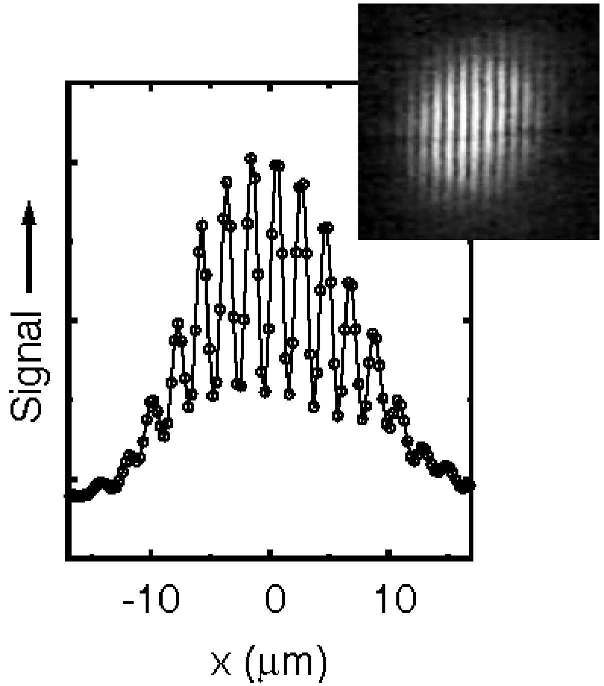


mode diameter increase could be explained by photon mean field interaction with $g_{eff,2D} \cong 7 \cdot 10^{-4}$ (too small for Kosterlitz-Thouless physics) → BEC expected

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

Michelson Interference Pattern above Photon BEC Threshold



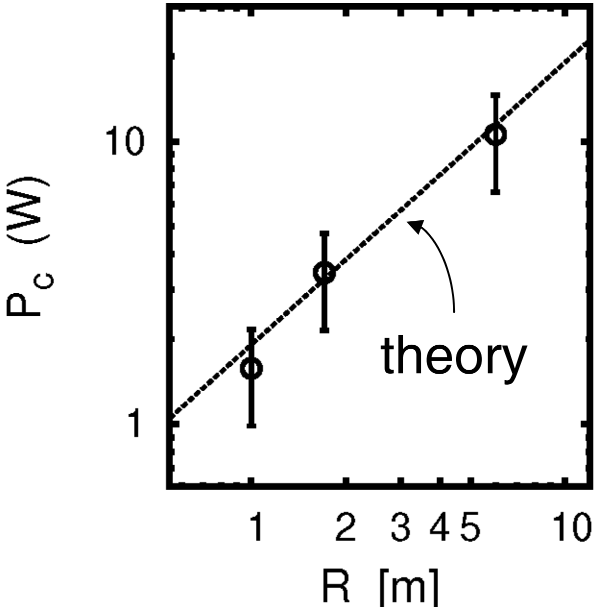


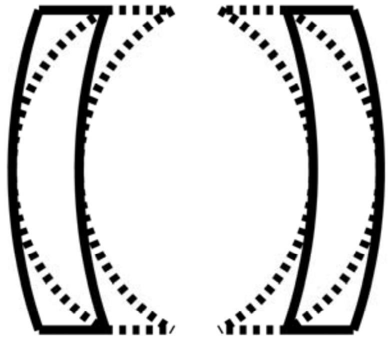
optical path length difference: 15 mm

Phase Transition Onset versus Resonator Geometry

expected critical optical power: $P_c = N_c \frac{\hbar\omega}{\tau_{rt}} = \frac{\pi^2}{12}(k_B T)^2 \frac{\omega}{\hbar c} R$

- Variation of mirror radius R

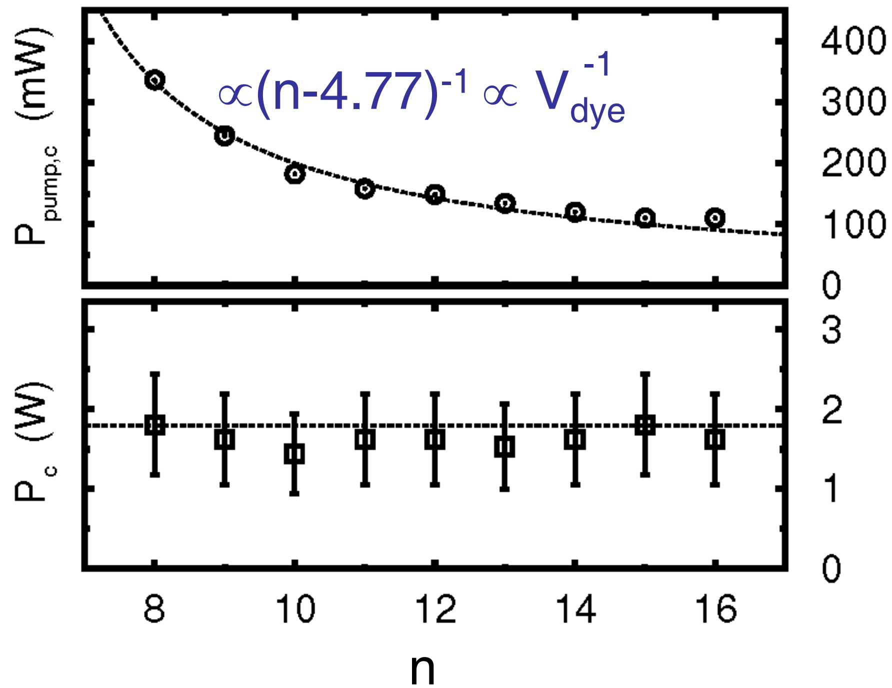


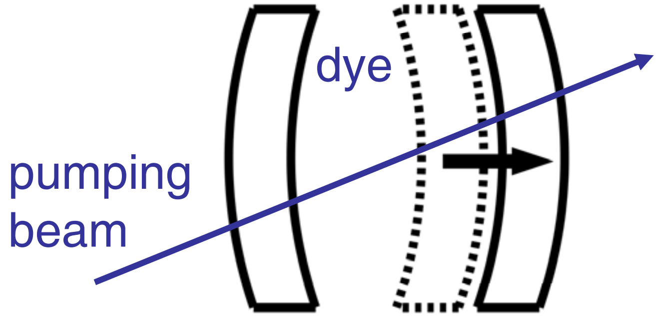


n=7, R variable

.. Phase Transition Onset

- Variation of resonator length





R=1m, n variable

$$P_c = \frac{\pi^2}{12}(k_B T)^2 \frac{\omega}{\hbar c} R$$

Published Results for the Phase Transition of a Microlaser

threshold lower for a small mirror spacing!

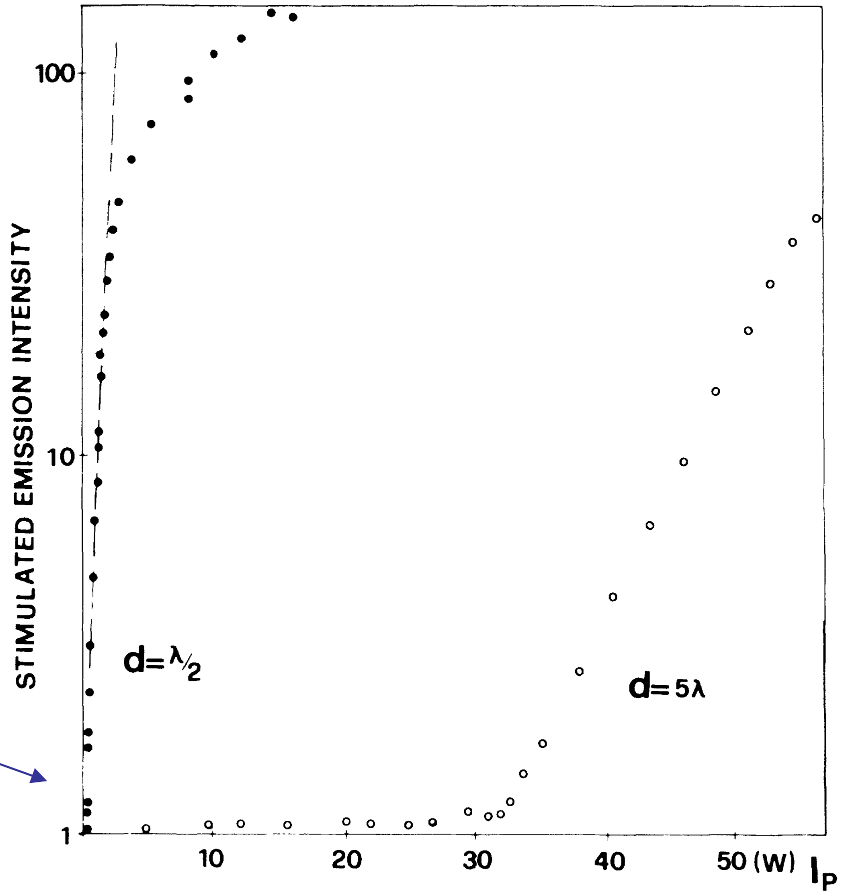
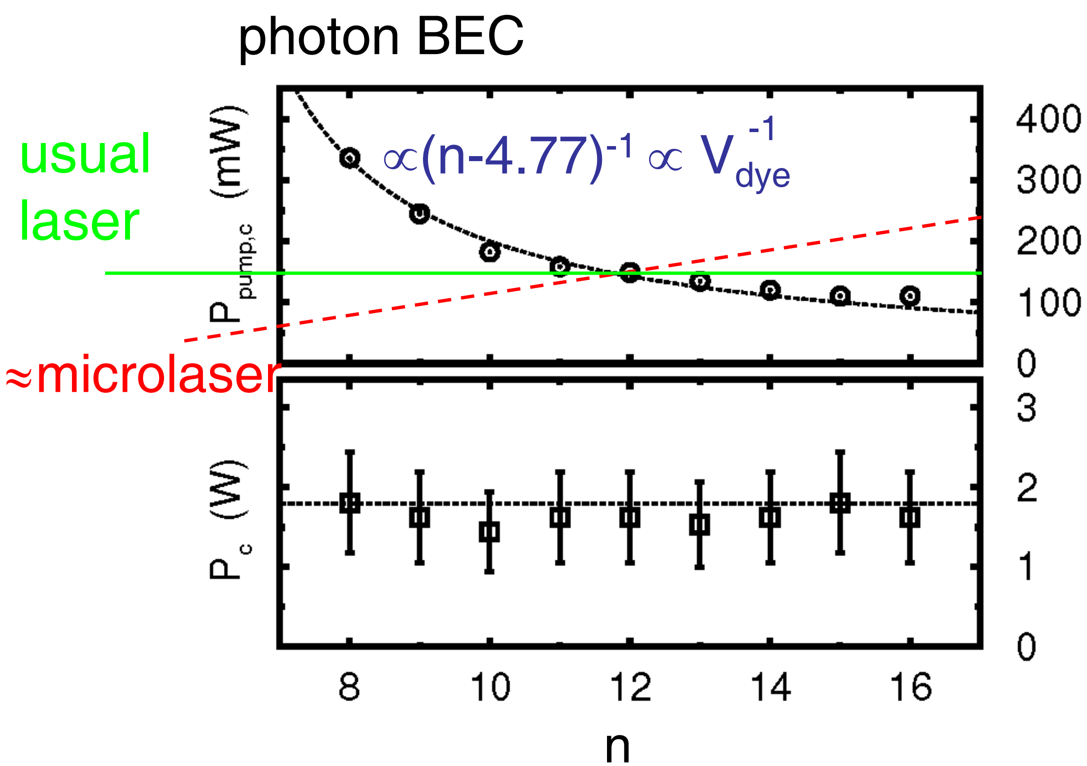


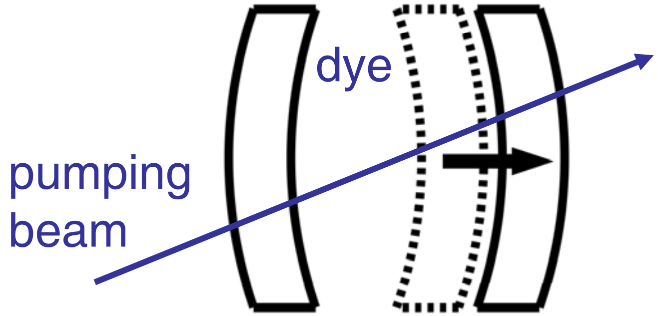
FIG. 1. Laser phase transitions for microcavity dimensions $d=\bar{d}\equiv\lambda/2$ and $d=5\lambda$. The emitted intensities shown for $d=5\lambda$ should be multiplied by 10 to be compared with the $\bar{d}$ data.

De Martini+Jacobovitz, PRL **60**, 1711 (1988)

.. Phase Transition Onset

- Variation of resonator length

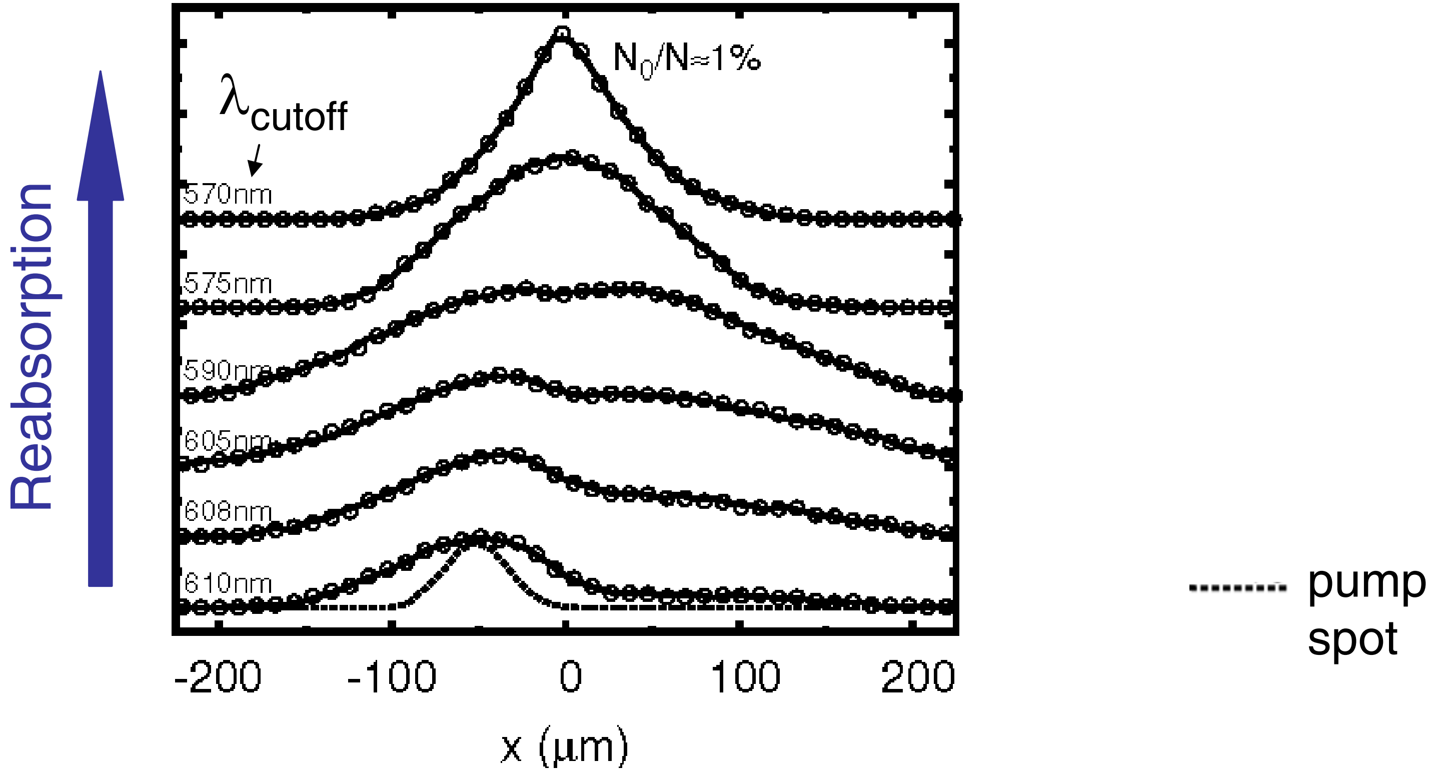




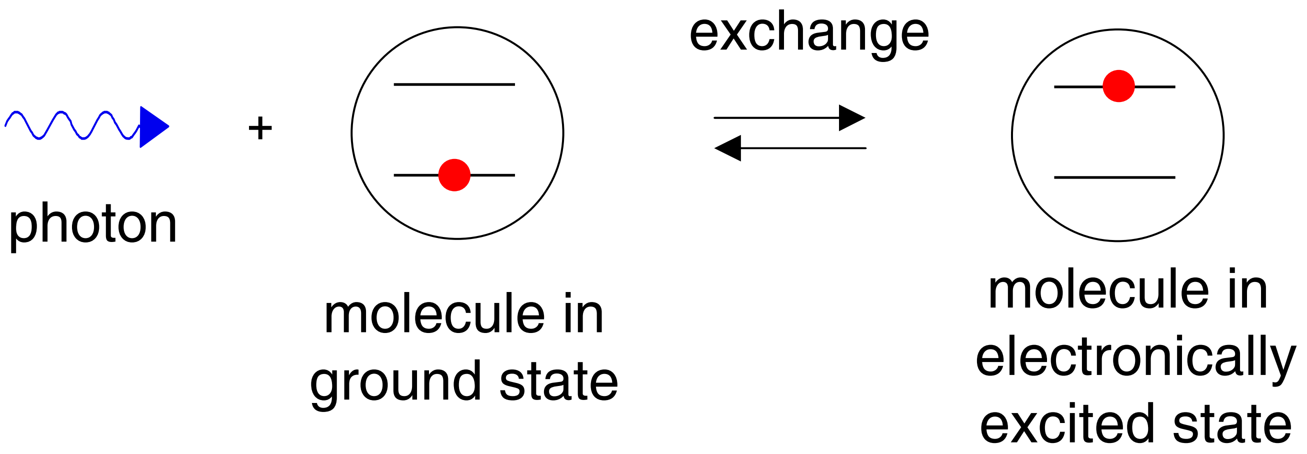
R=1m, n variable

$$P_c = \frac{\pi^2}{12}(k_B T)^2 \frac{\omega}{\hbar c} R$$

Condensation for Off-Center Pumping



Effective Particle Exchange of Photons with Dye Excitations

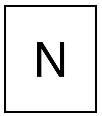


average photon number is fixed, but fluctuations of the photon number around the average value can occur

for a large number M of dye molecule, the photon gas is well decribed by a grandcanonical model

Ensembles for Bose-Einstein Condensation

usual BECs



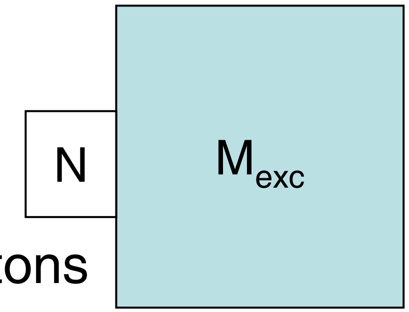
atom number fixed

microcanonical ensemble

(similar: canonical ensemble)

Poissonian particle statistics in condensed state, $g^{(2)}(0) = 1$

Photon BEC with dye reservoir



photons

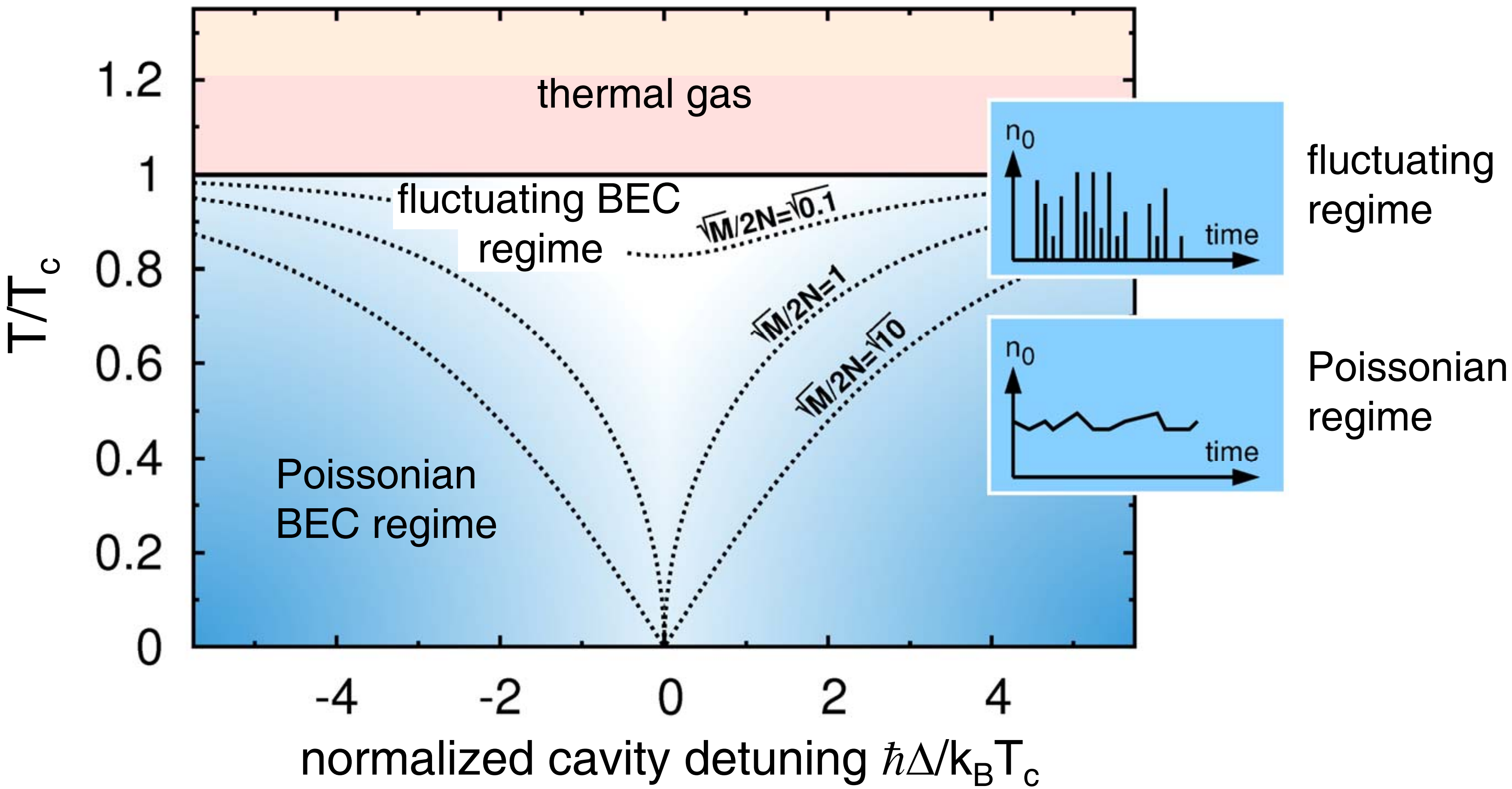
molecules in electronically excited state

For large reservoir size: grandcanonical ensemble

enhanced particle fluctuations in condensed state, $g^{(2)}(0) = 2$

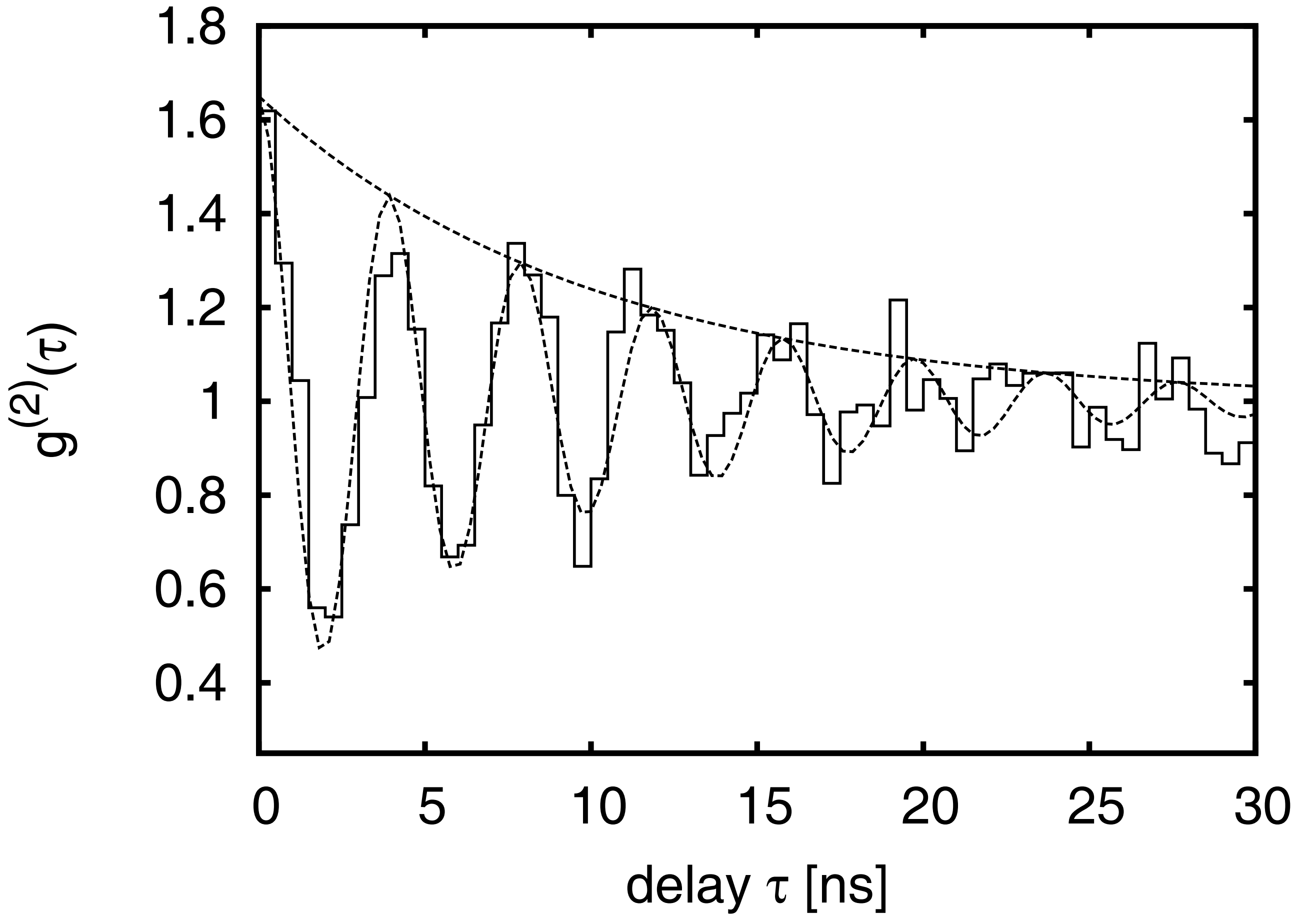
general theory grandcanonical BEC fluctuations: Fujiwara et al. (1970), Ziff et al. (1977), Holthaus (1998)

Expected Phase Diagram



J. Klaers et al., PRL **108**, 160403 (2012), see also: D. Sobyanin, PRE **85**, 061120 (2012)

Measured Photon BEC Intensity Correlation vs. Delay Time



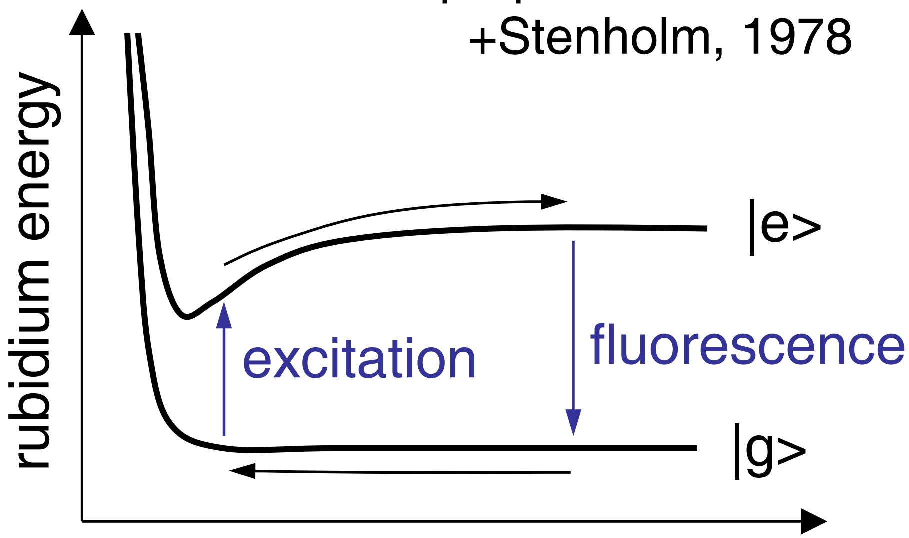
preliminary data,

grandcanonical regime

Laser Cooling by Collisional Redistribution

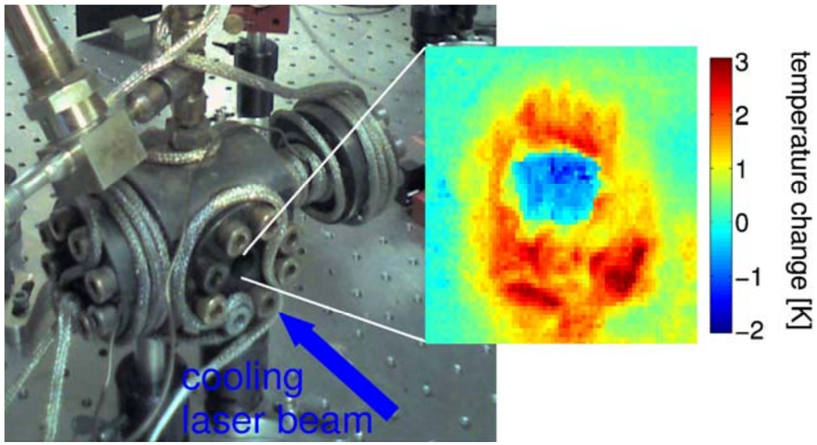
Cooling cycle

proposal: Berman +Stenholm, 1978



Experiment

Rb + 200 bar argon filled cell

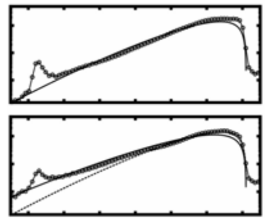


cooling inside cell: $410^0C \rightarrow -120^0C$

U. Vogl and M. Weitz, Nature **461**, 70 (2009);
A. Sass, U. Vogl, M. Weitz, to be published

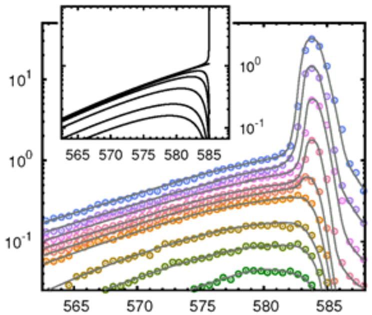
Conclusions

- thermal 2D-photon gas with nonvanishing chemical potential
  (average particle number conserved)

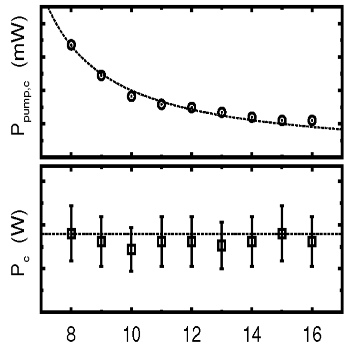


- Bose-Einstein condensation of photons. Signatures:

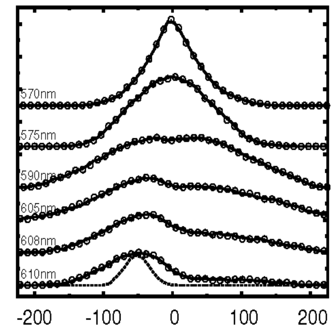
Bose-Einstein distributed photon energies



phase transition absolute value+scaling

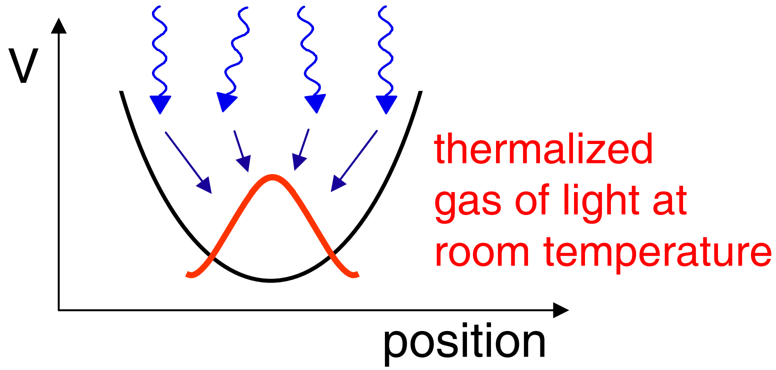


condensation for off-center pumping



Outlook

- photon thermalization:
  concentration of diffuse sunlight

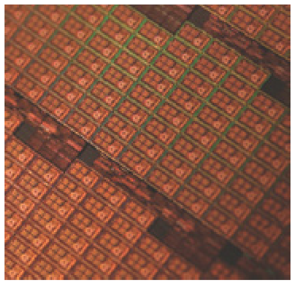


- photon BEC: new states of light

  (some) future directions:

  - canonical vs. grandcanonical photon ensemble regimes
  - study of quantum manybody states in periodic potentials

- light sources in new wavelength regimes, coherent UV sources



possible application:
lithography

universitätbonn

Quantum optics group, IAP Bonn:

J. Klaers
S. Kling
A. Sass
H. Brammer
J. Schmitt
T. Damm
C. Grossert
J. Ulitzsch
M. Leder
D. Dung
T. Burgermeister
S. Hüwe
P. Moroshkin
F. Vewinger

M. Weitz