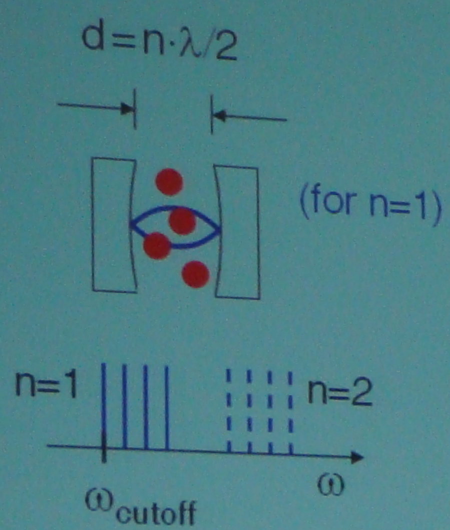
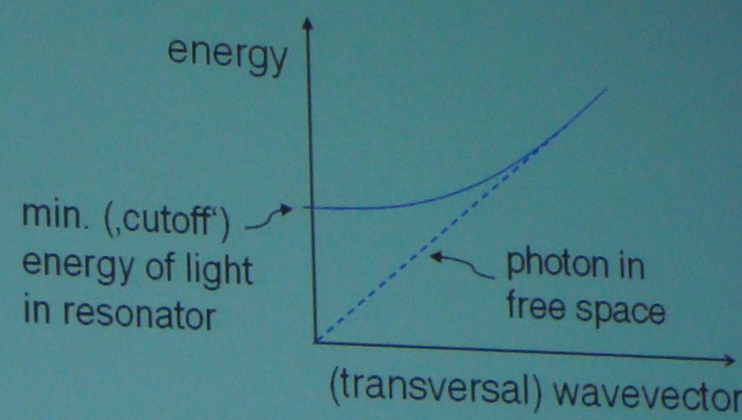
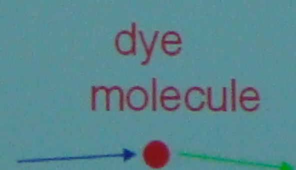
Bonn 2D-Photon Gas Experimental Scheme

- use curved-mirror microresonator to modify photon dispersion

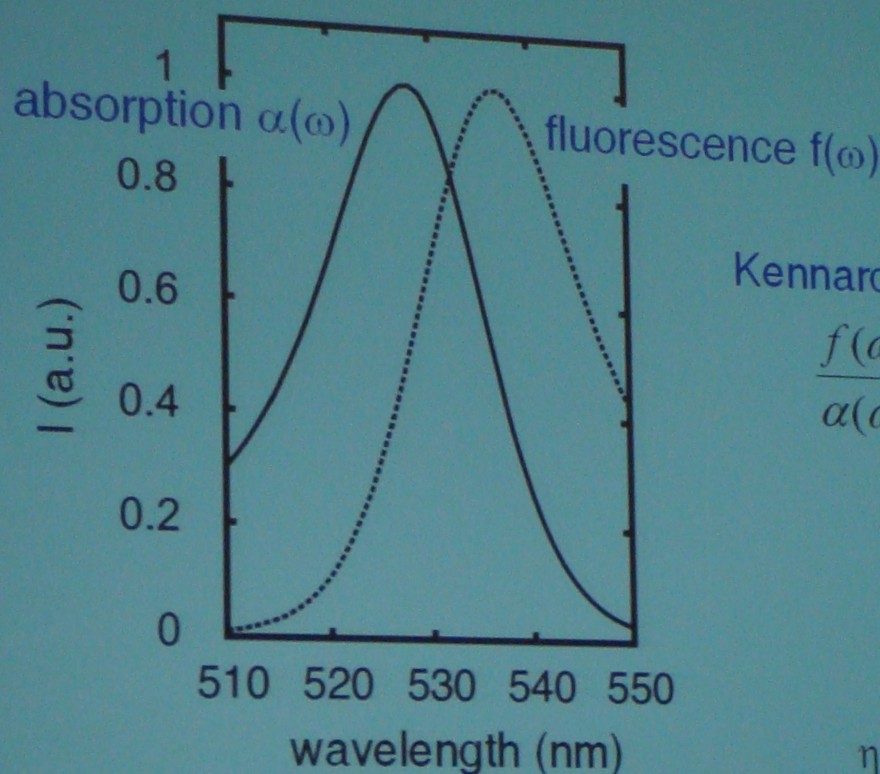




- thermal equilibrium of photon gas by scattering off dye molecules...



Spectrum of Perylene-Dimide Molecule (PDI)



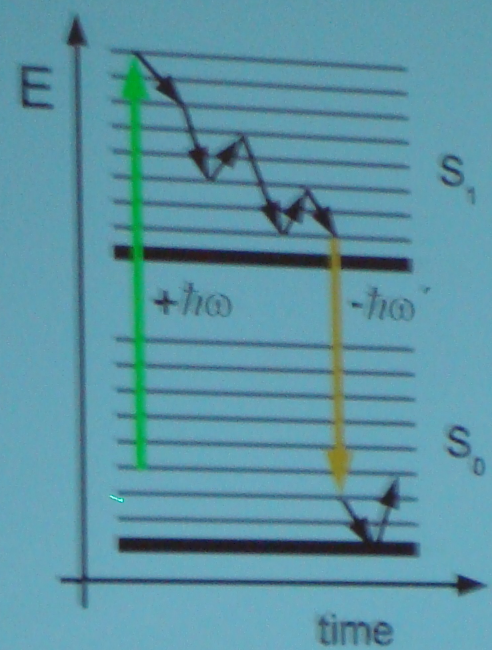
Kennard-Stepanov theory:

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

$\eta_{quantum} \cong 0.97$

Photon Gas Thermalization: Background

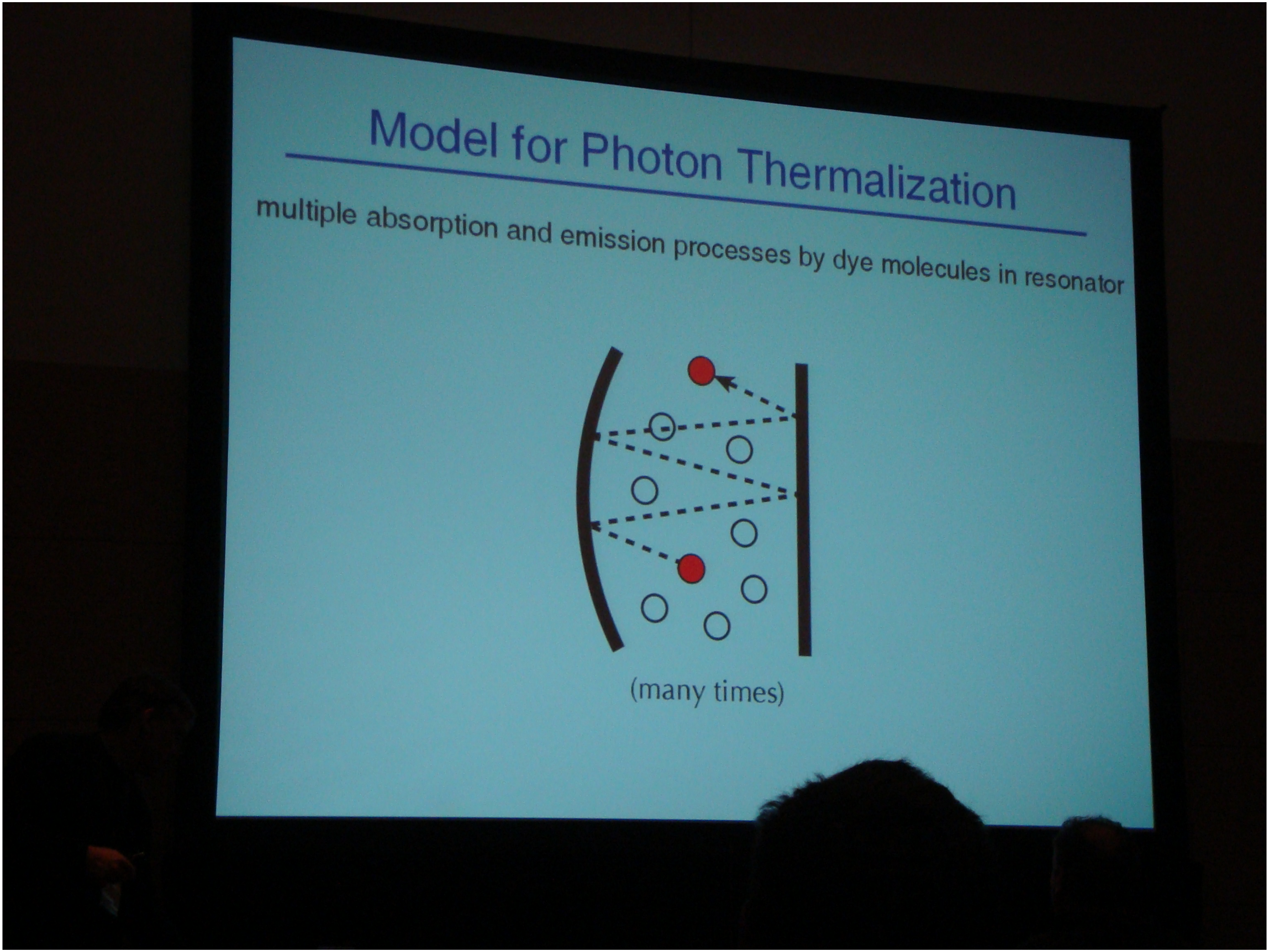
Collisionally induced thermalization in dye medium

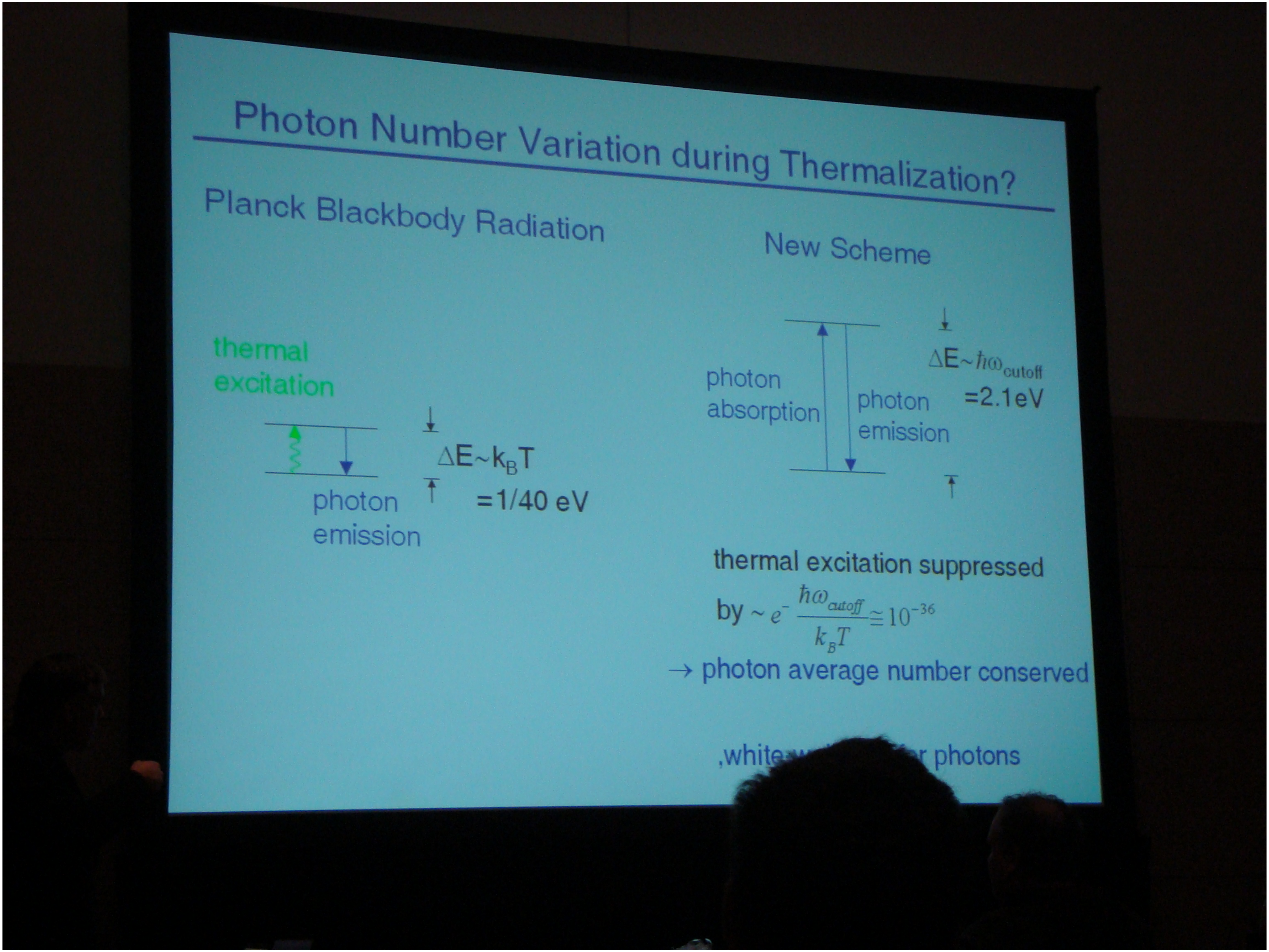


$$\frac{f(\omega)}{\alpha(\omega)} \propto \exp\left(-\frac{\hbar\omega}{k_B T}\right)$$

T: (internal rovibrational) temperature of dye solution

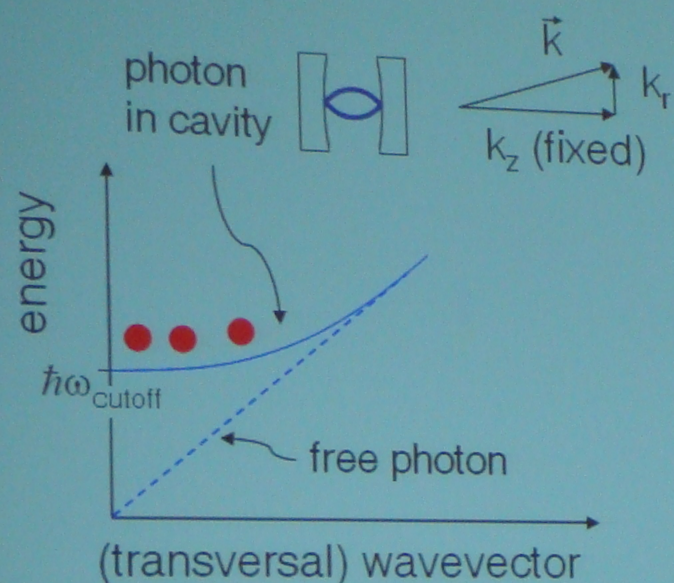
Kennard 1912, Stepanov 1956


Model for Photon Thermalization
multiple absorption and emission processes by dye molecules in resonator
(many times)


Photon Number Variation during Thermalization?
Planck Blackbody Radiation
thermal excitation
photon emission
ΔE~k_B T
=1/40 eV
New Scheme
photon absorption
photon emission
ΔE~ħω_cutoff
=2.1eV
thermal excitation suppressed
by ~ e^(−ħω_cutoff / k_B T) ≅ 10^−36
→ photon average number conserved

Photon Trapping versus Atom Trapping

- quadratic photon dispersion



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

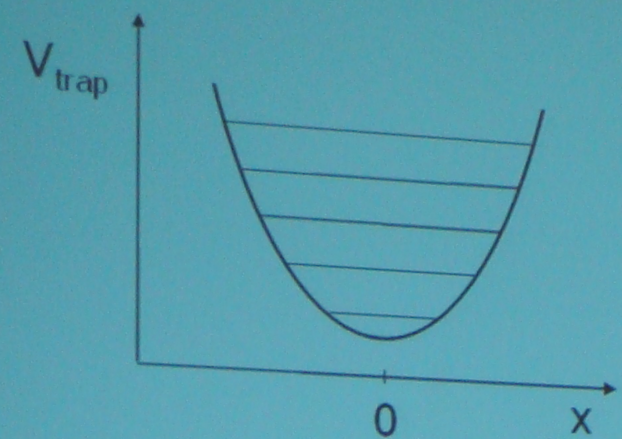
$$E = \hbar c\sqrt{k_z^2 + k_r^2} \cong \hbar c\left(k_z + \frac{k_r^2}{2k_z}\right)$$

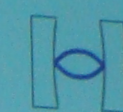
$$= m_{eff}c^2 + \frac{(\hbar k_r)^2}{2m_{eff}}$$

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

..Photon versus Atom trapping

- trapping potential from mirror curvature



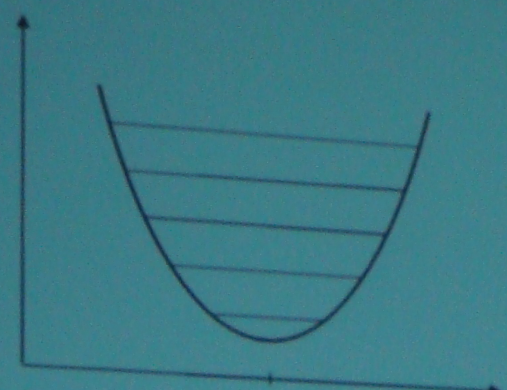


System formally equivalent to 2D-gas of massive bosons with $m_{eff} = \hbar\omega_{cutoff} / c^2$

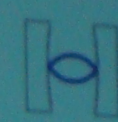
$$E = m_{eff} c^2 + \frac{(\hbar k_r)^2}{2 m_{eff}} + \frac{1}{2} m_{eff} \Omega^2 r^2$$

..Photon versus Atom trapping

- trapping potential from mirror curvature



resonator



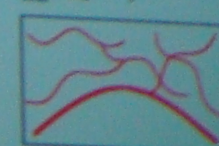
System formally equivalent to 2D-gas of massive bosons with $m_{eff} = \hbar\omega_{cutoff}/c^2$

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

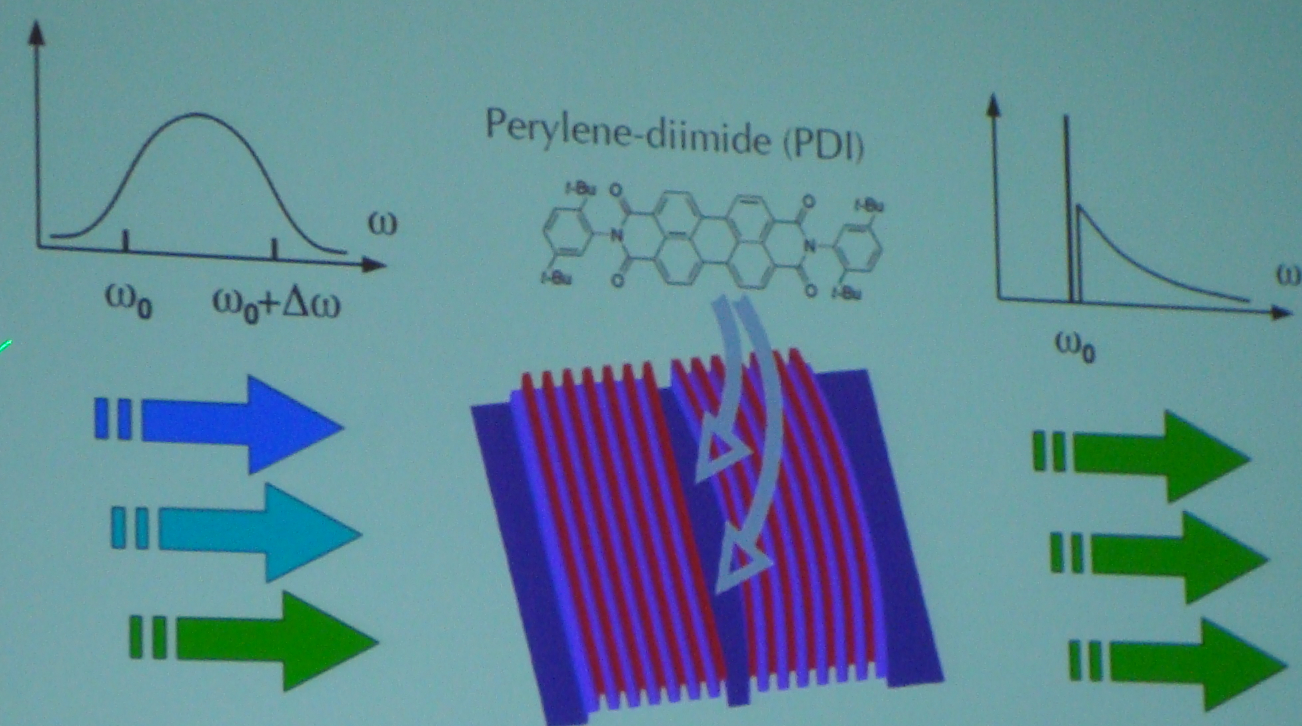
→ BEC expected for $N > N_c = \frac{\pi^2}{3}\left(\frac{k_B T}{\hbar\Omega}\right)^2 \cong 77000$ (T=300K, $\Omega = 2\pi \cdot 4 \cdot 10^{10}$Hz, $m_{eff} \cong 6.7 \cdot 10^{-36}$kg $\cong 10^{-10} \cdot m_{Rb}$)

BEC versus Lasing

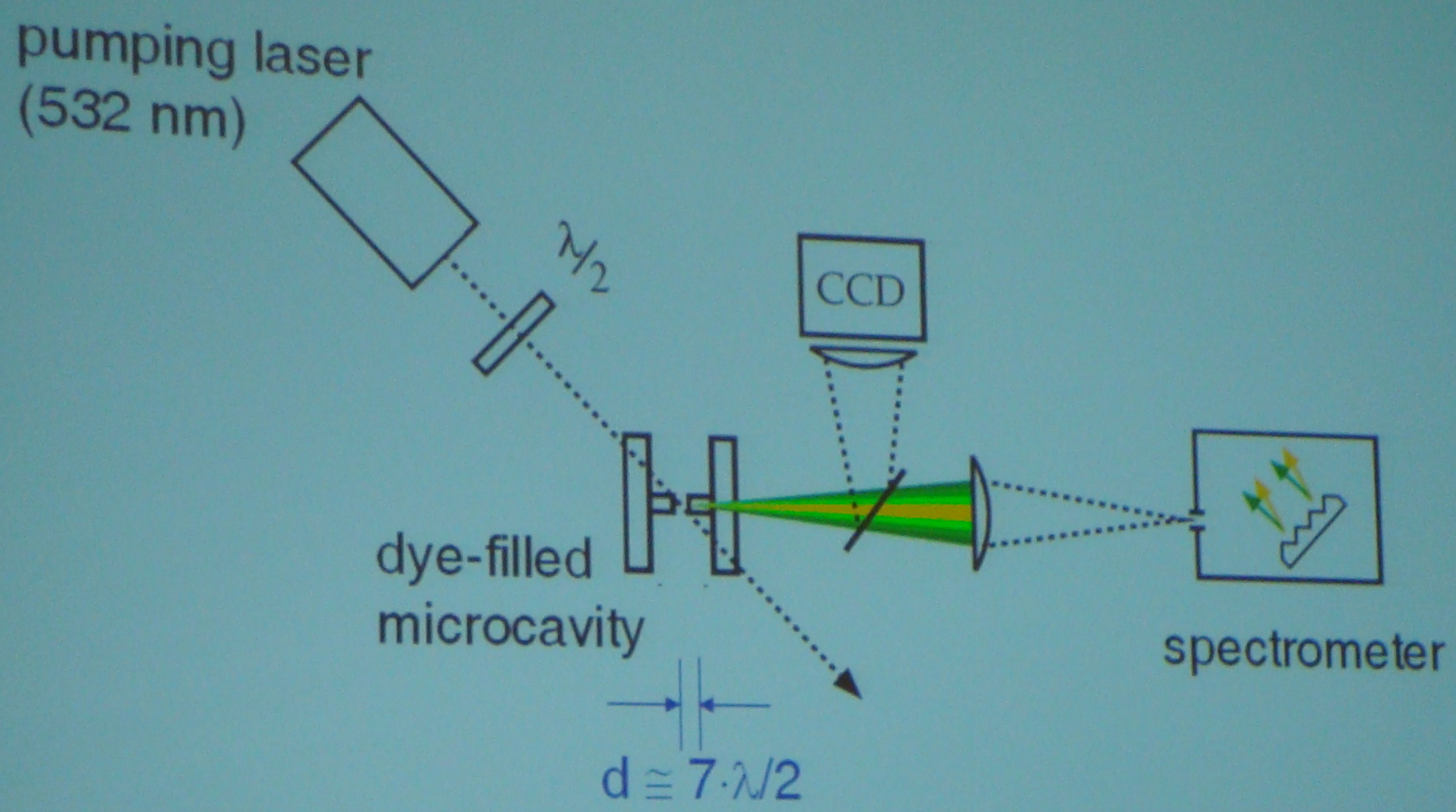
	Optical laser	Photon BEC
thermodynamic state:	far from equilibrium	thermal equilibrium
gain/thermalisation medium:	three or more levels, inversion (or quantum coherence, high coupling eff. to single cavity mode)	non-inverted two-level system sufficient (many transversal cavity modes)
phase transition 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 $n_{2D}\lambda_{dB}^2 \gtrsim 1$)

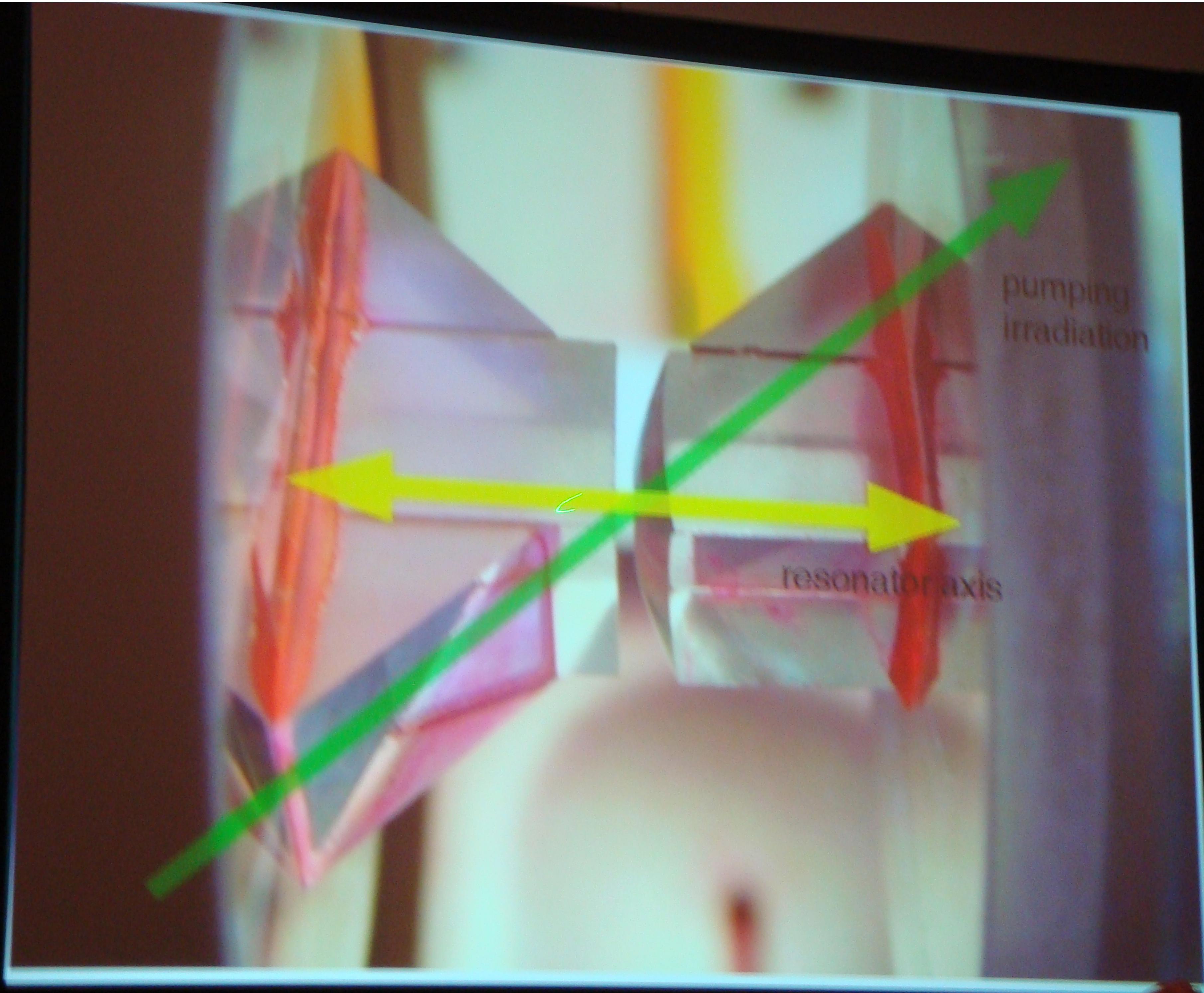


Two-Dimensional Photon Gas in Dye-Filled Optical Resonator

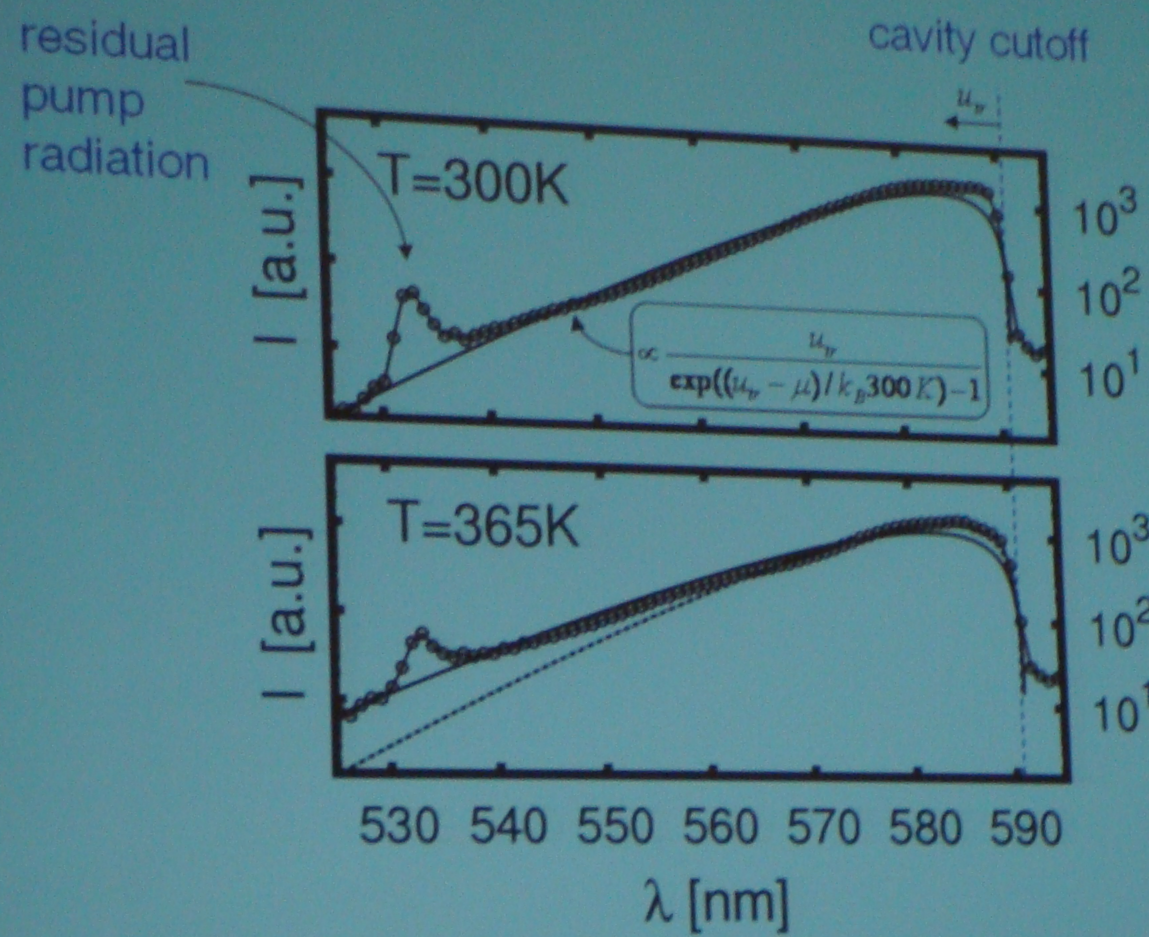


Experimental Setup: 2D Photon Gas



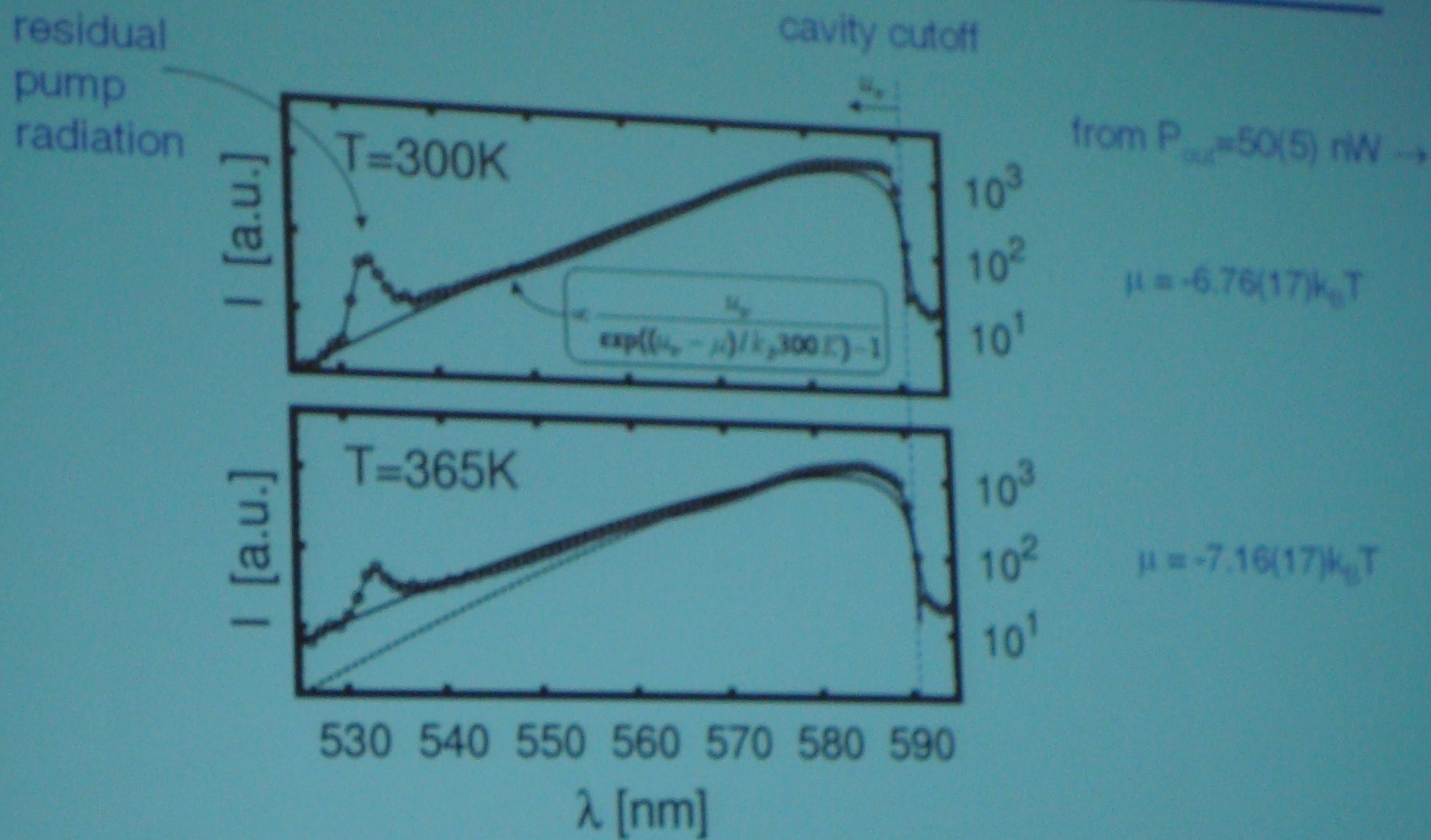

pumping
irradiation
resonator axis

Spectrum of Thermal Photon Gas in Cavity



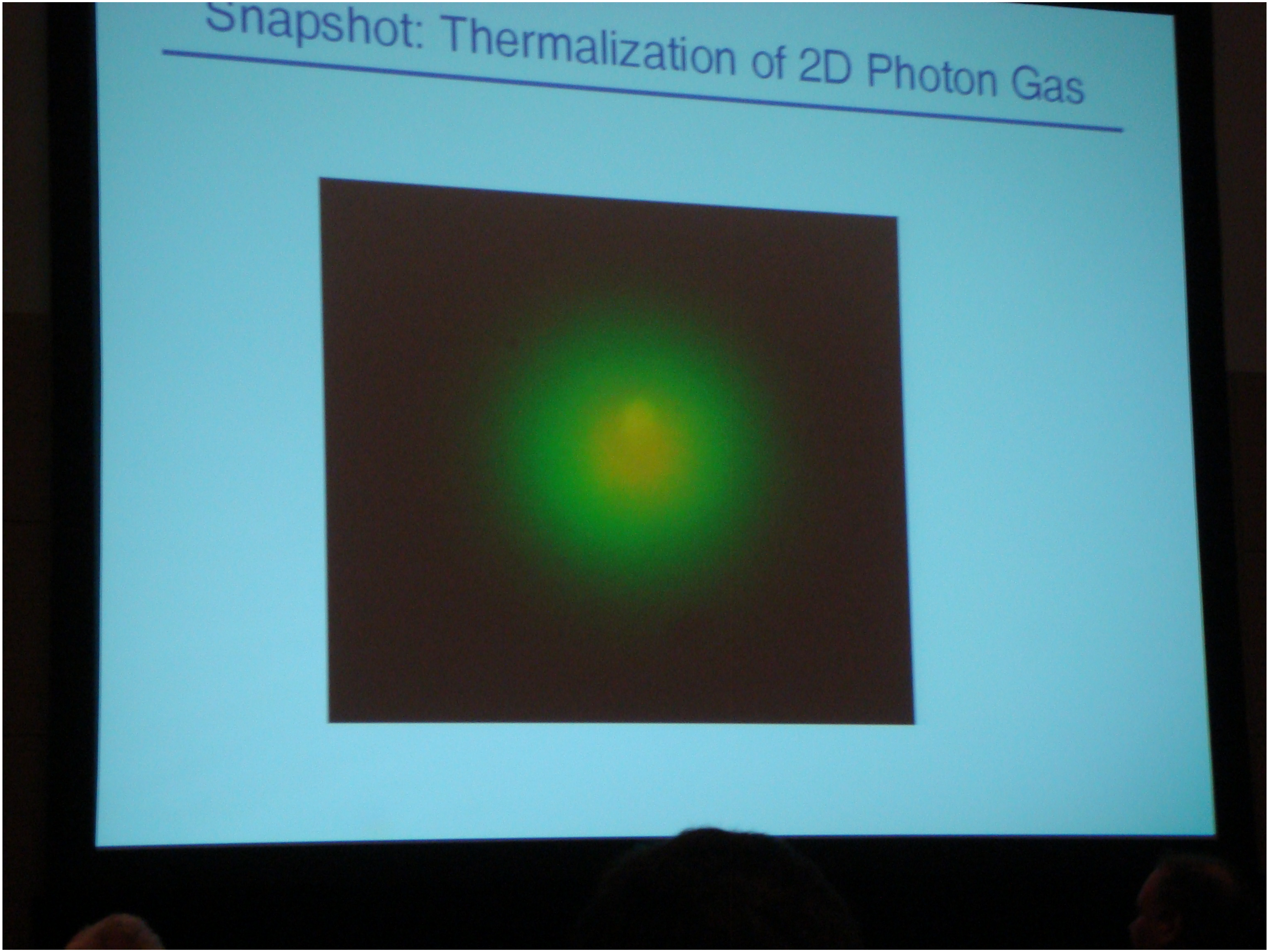
J. Klaers, F. Vewinger, M. Weitz, Nature Phys. **6**, 512 (2010)

Spectrum of Thermal Photon Gas in Cavity

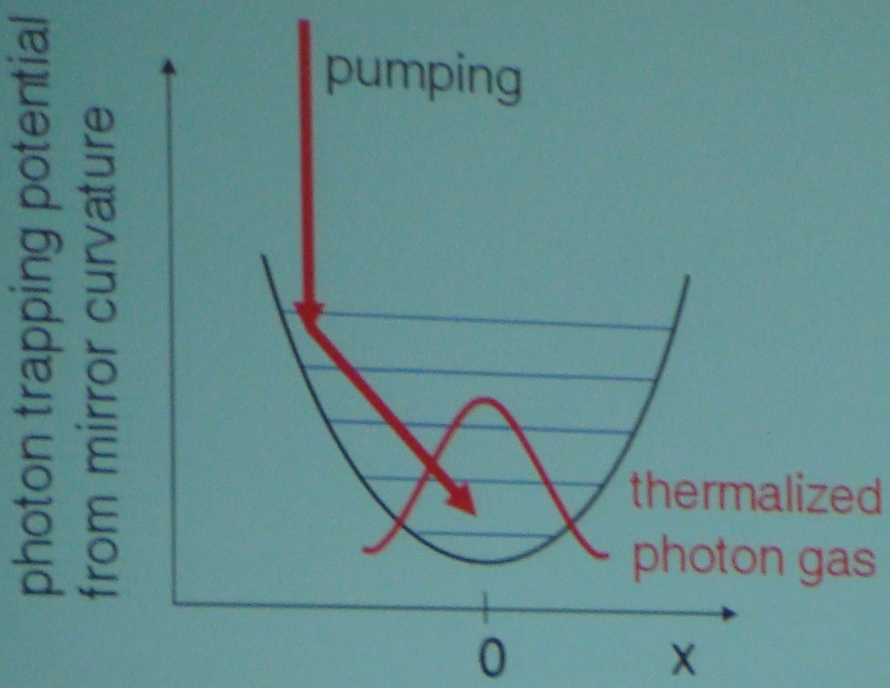


→ evidence for thermalized two-dimensional photon gas with $\mu \neq 0$!

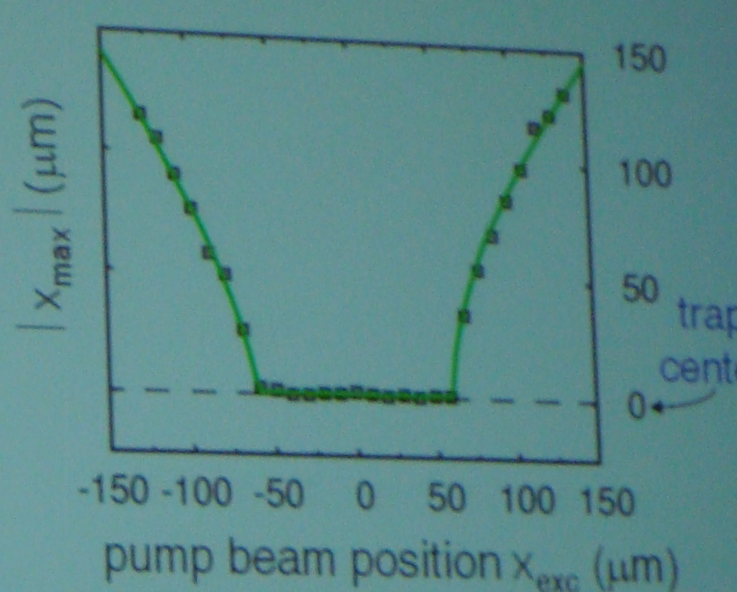
J. Klaers, F. Vewinger, M. Weitz, Nature Phys. **6**, 512 (2010)


Snapshot: Thermalization of 2D Photon Gas

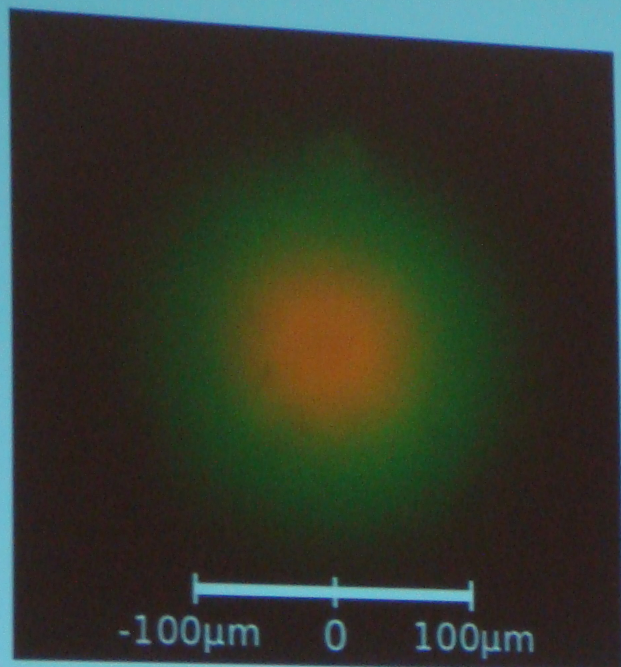
Thermalization – Photon Diffusion towards Center



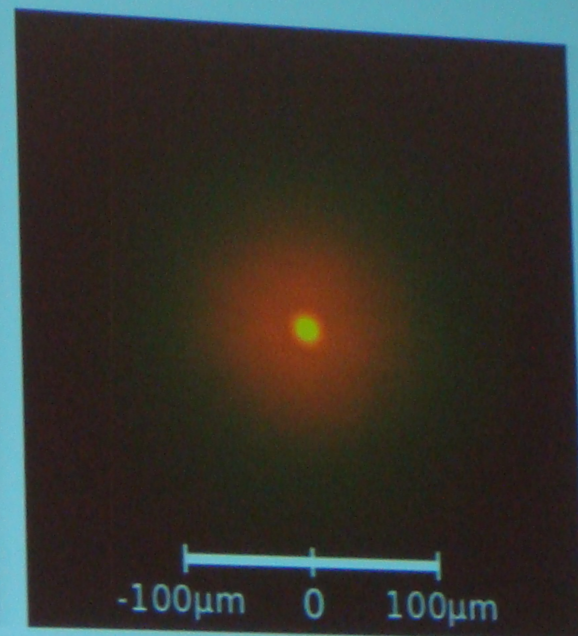
Experimental data



Photon Gas at Criticality



$N << N_c$

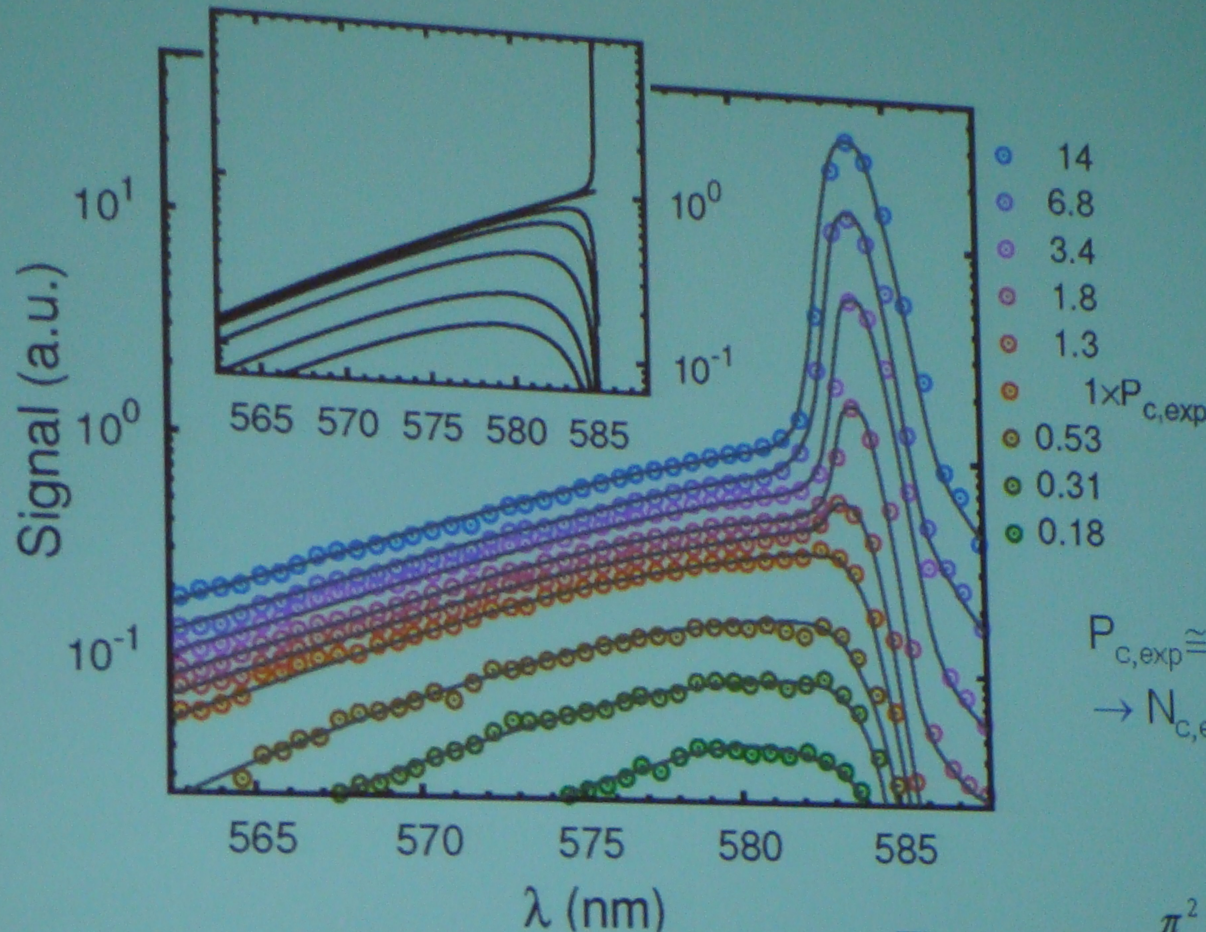


$N > N_c$

BEC!

Rh6G, duty cycle 1:16000, 0.5µs pulses

Spectra for Densities around Photonic BEC Threshold



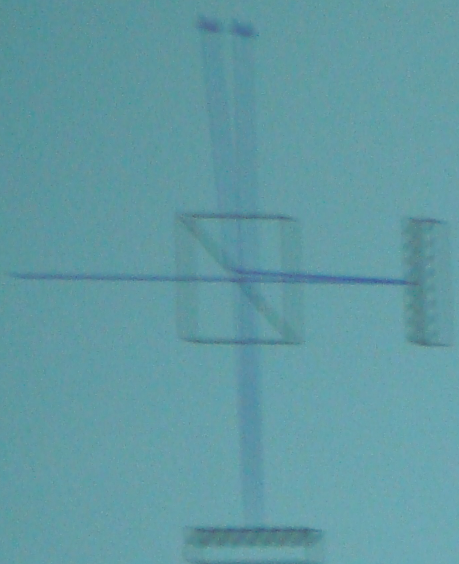
$P_{c,exp} \cong 1.55(60)$ W

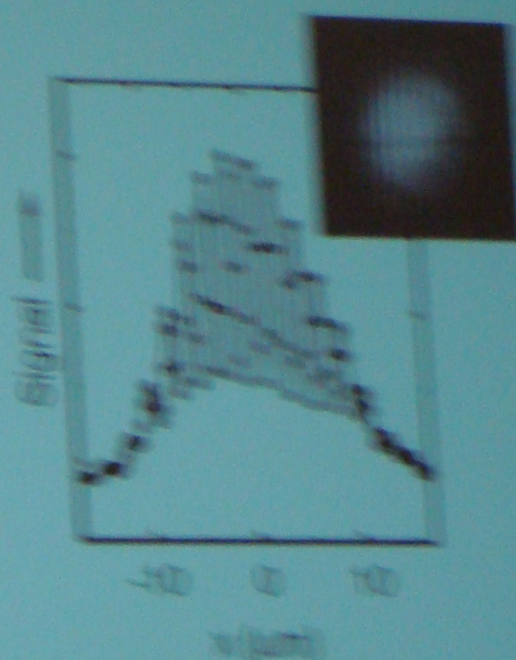
$\rightarrow N_{c,exp} \cong (6.3 \pm 2,4) \cdot 10^4$

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)

Michelson Interference Pattern above Photon BEC Threshold



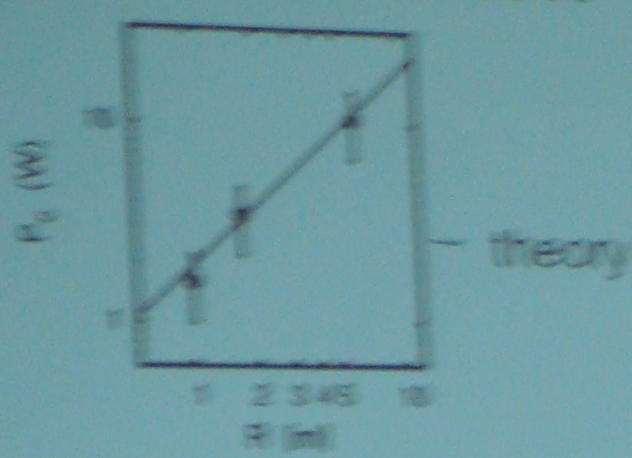


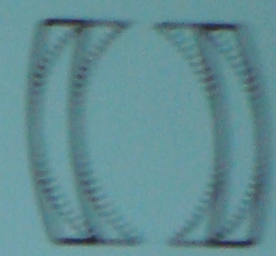
optical path length difference: 15 mm

Phase Transition Onset versus Resonator Geometry

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

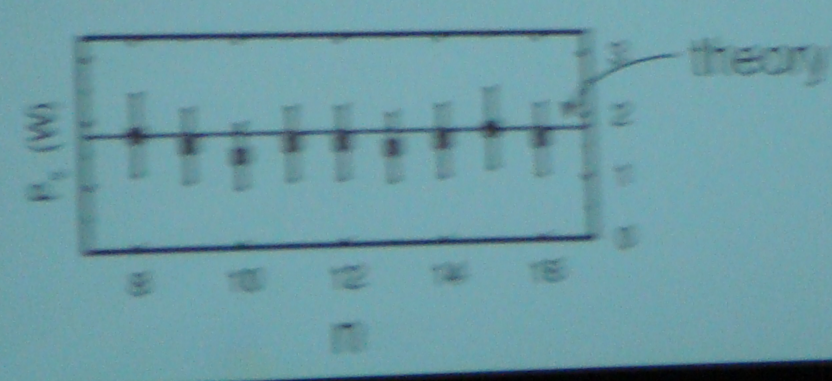
- variation of mirror radius R

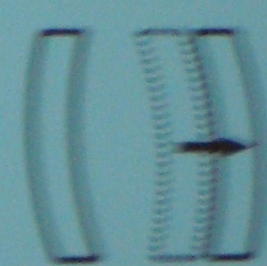




n=7, R variable

- variation of resonator length

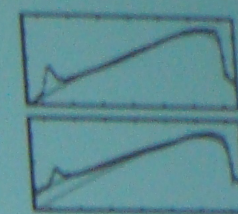




R=1m, n variable

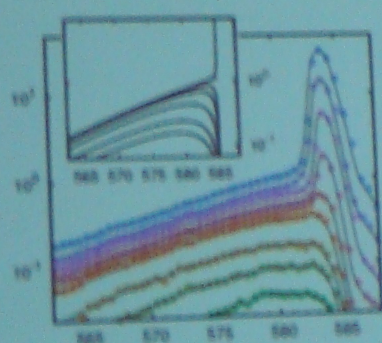
Conclusions

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

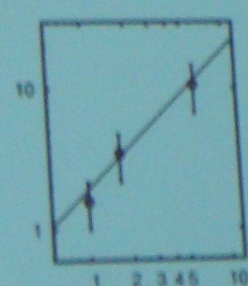


- Bose-Einstein condensation of photons. Signatures:

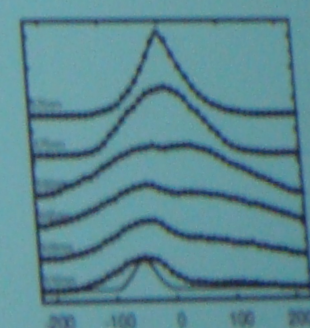
Bose-Einstein distributed photon energies



phase transition absolute value+scaling

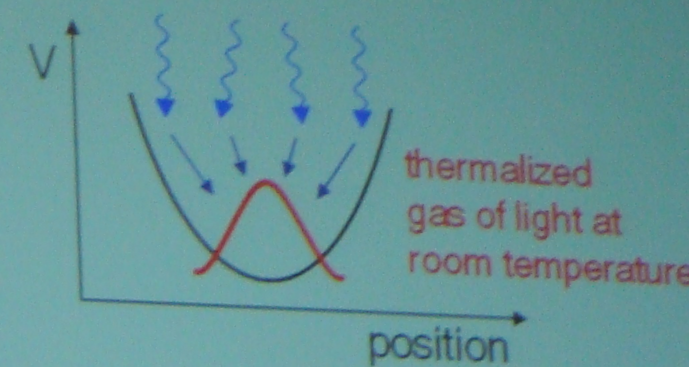


condensation for off-center pumping



Outlook

- photon thermalization:
  concentration of diffuse sunlight

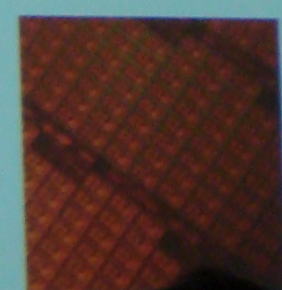


- photon BEC: new states of light

  if grandcanonical particle exchange: light ⇔ dye molecules
  → $g^{(2)}(0)=2$ expected in condensed state for negligile interactions

  (Klaers et al., arXiv:1201.0444)

- light sources in new wavelength regimes, coherent UV sources



possible application:
lithography