Thermalization of Photons

Group meeting

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LETTERS

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nature physics

Thermalization of a two-dimensional photonic gas in a 'white wall' photon box

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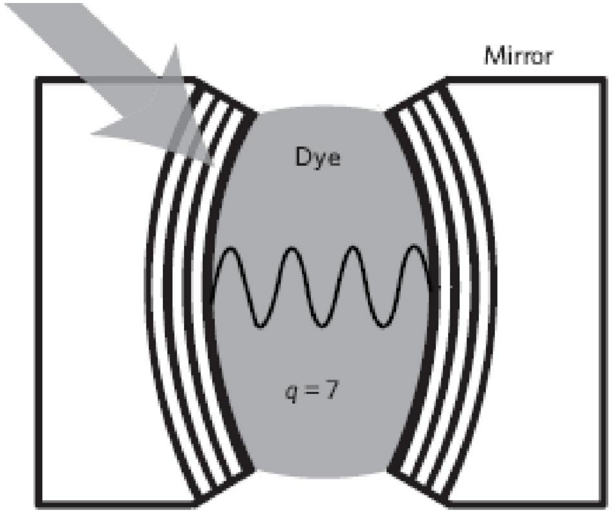


Outline

- Motivation: achieving macroscopic populated modes through quantum phase transition (comparing to lasers)
- Idea of this paper: thermalization of photons to a heat bath (grand canonical ensemble)
- Methods: dye-filled optical cavity, redistribution of photons through scattering in the solvent
- Results: thermally occupied cavity modes
- Discussions

Why use a cavity

- Modification of spontaneous emission, leading to a directional emission, easy for collection.
- Quantized modes, controllable mode spacing (both longitudinally and transversely). This means a reduced spatial dimensionality and energy spectrum.
- The cavity dispersion maps the modes to frequency, thus the output spectrum tells the mode distribution.
- The dispersion also introduces an effective mass for photon.
- Photon can be ‘trapped’ in a cavity.

Chemical potential

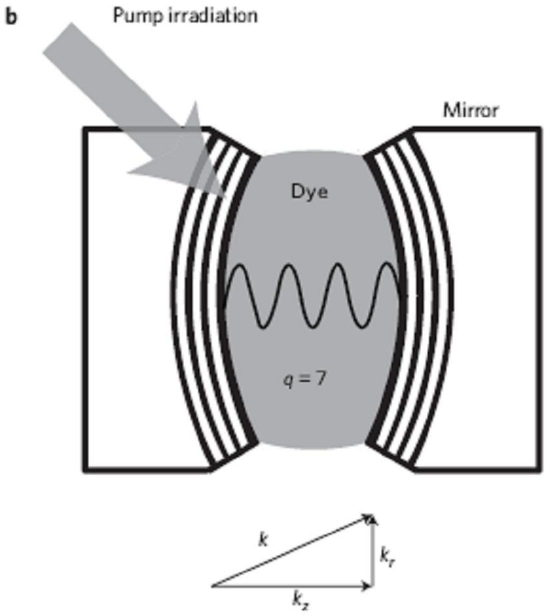
- Chemical potential μ is introduced to specify the fluctuation of particle numbers. Intuitively, it's the energy it takes to remove one particle from the equilibrium.
- Expected photon number:

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

- To measure μ , one can measure the cavity output photon number:

$$\sum_u n_{T,\mu}(u) = N_{\mathrm{ph}}$$

Some cavity parameters



- Reflectivity ~99.9985% (520-590nm)
- Radius of curvature R=1m
- Cross section 1mm x 1mm (for one)
- Distance: ~1.46um (~3.5 wavelength)
- Cutoff Freq.: ~570nm
- Fundamental mode waist: ~15um
- Dye solvent
- Pump 532nm, 45 °incidence

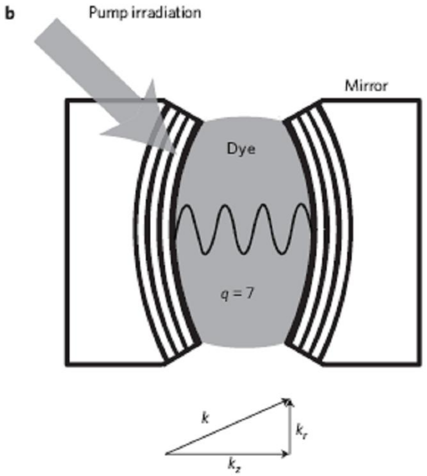
(compensate the losses, non-radiative decayto maintain a heat bath)

Photon dispersion in cavity

Paraxial approximation

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

$$(k_z \gg k_r)$$

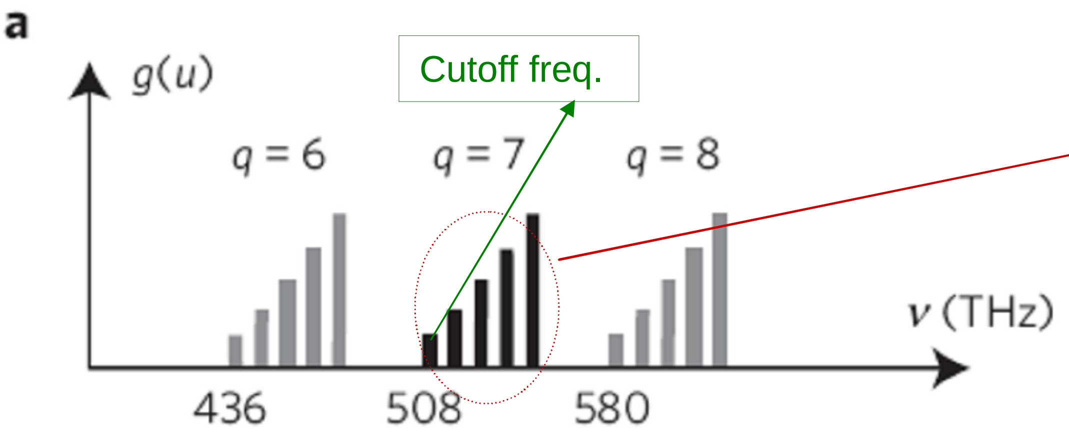


$$E \cong m_{\mathrm{ph}}c^2 + \frac{(\hbar k_r)^2}{2m_{\mathrm{ph}}} + \frac{1}{2}m_{\mathrm{ph}}\Omega^2 r^2 \qquad r \ll R$$

Effective non-relativistic
massive particles

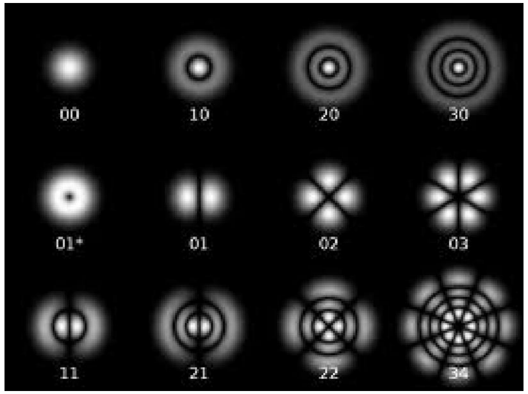
$$m_{\mathrm{ph}} = \hbar k_z(0)/c = \hbar\omega_{\mathrm{cutoff}}/c^2$$

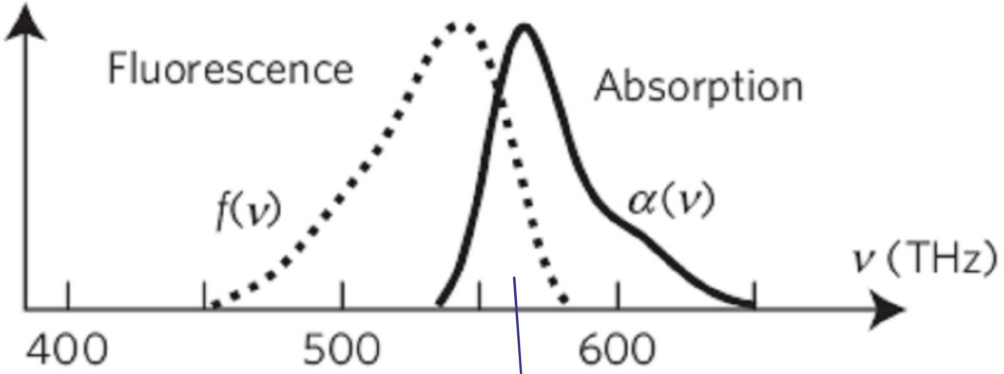
$$\Omega = c/\sqrt{D_0 R/2}$$



Cutoff freq.

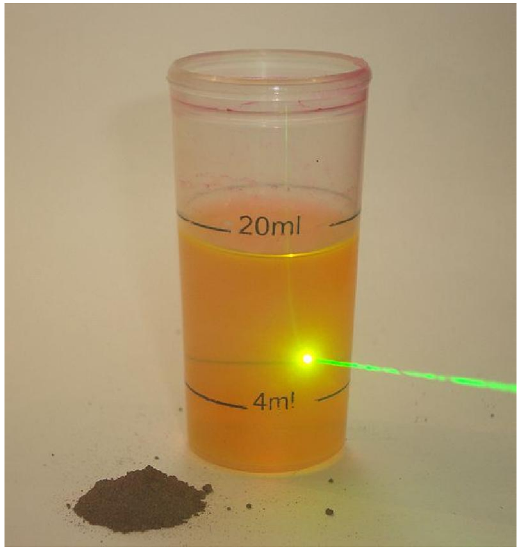
$$g(u) = 2(u/\hbar\Omega + 1)$$





749nm 599nm 499nm

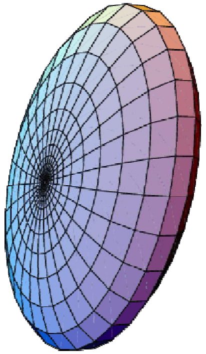
This also determines thermalization rate



http://en.wikipedia.org/wiki/Dye_laser

Temperature regime

“Trapped photon cloud”



- Confinement:
  - Longitudinal (FSR) $\sim 7 \times 10^{13}$ Hz
  - Cutoff frequency ~ 7 x FSR
  - Transverse $\Omega/2\pi$ $(\sim 4 \times 10^{10}$ Hz$)$
- Thermal excitation:
  - Longitudinal: neglegible $\exp(-\hbar\omega_{\text{cutoff}}/k_{\text{B}}T) \sim 10^{-36}$
  - Transverse: quasi-continuous

$$k_{\text{B}}T/\hbar\Omega \sim 160$$

- Thermalization (hand-waving)
  - An effective collision: photon-number-conserved scattering in the bath
- Bose-Einstein Distribution -> Boltzmann

Radiation field thermalization

- Coupling between two quantum number P and Q, the condition for thermalization is

$$\frac{R(P\to Q)}{R(Q\to P)}=\frac{\alpha_T(\omega_i)f_T(\omega_j)}{\alpha_T(\omega_j)f_T(\omega_i)}=\exp\left(-\frac{\hbar(\omega_j-\omega_i)}{k_\mathrm{B}T}\right)$$

Transition strength for absorption/fluor.

- Simplified Derivation:

$$\frac{f_T(\omega)}{\alpha_T(\omega)}\propto\frac{\int g'(e')p(e')A(e',\omega)\,\mathrm{d}e'}{\int g(e)\exp(-e/k_\mathrm{B}T)B(e,\omega)\,\mathrm{d}e}$$

$$p(e')\propto \mathrm{e}^{-e'/k_\mathrm{B}T}=\mathrm{e}^{-(e+\hbar(\omega-\omega_0))/k_\mathrm{B}T}$$

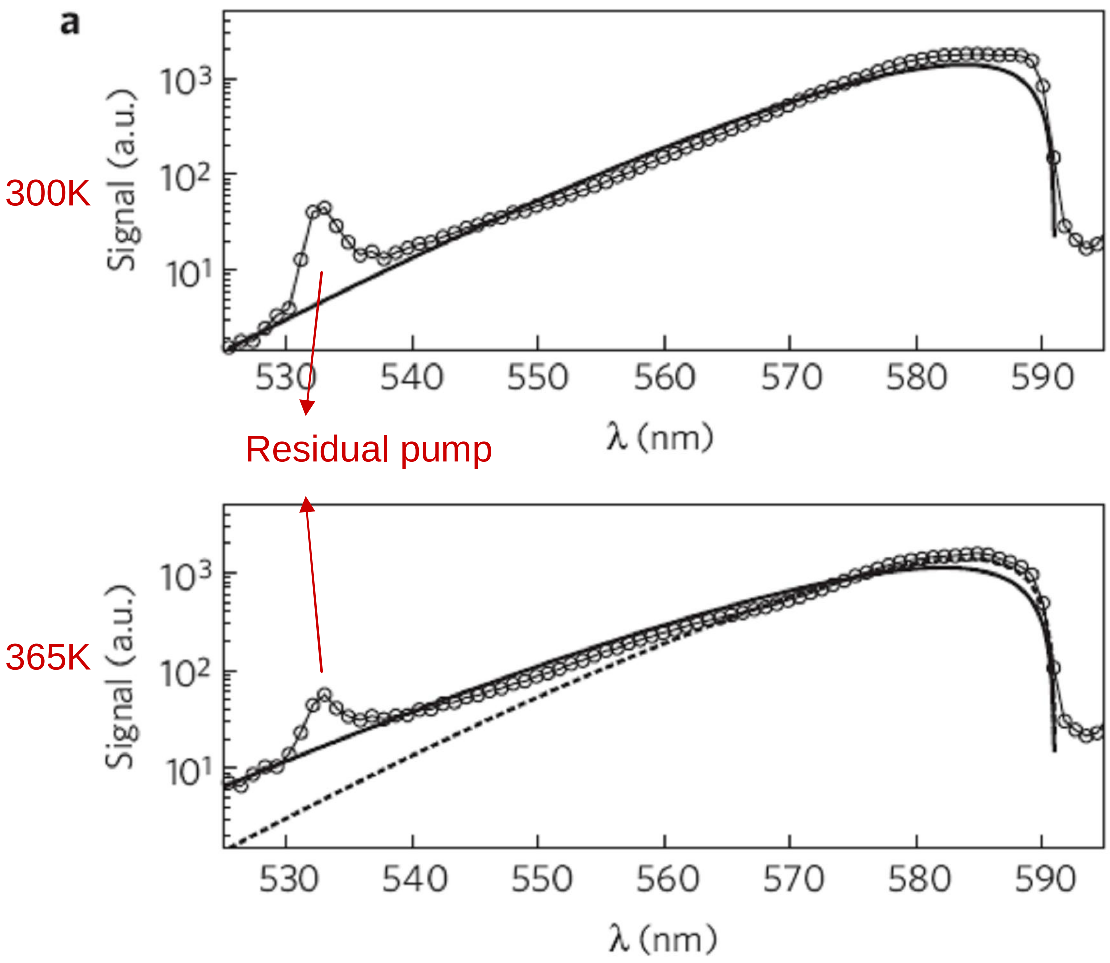
$$g'(e')A(e',\omega)\,\mathrm{d}e'=(2\hbar\omega^3/\pi c^2)g(e)B(e,\omega)\,\mathrm{d}e$$

Thus, $$f_T(\omega)/\alpha_T(\omega)\propto\omega^3\,\mathrm{e}^{-\hbar(\omega-\omega_0)/k_\mathrm{B}T}$$

See also: **PRA** 54, 4837, 1996

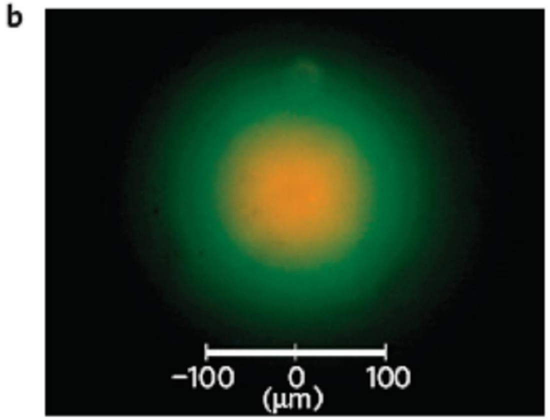
Results

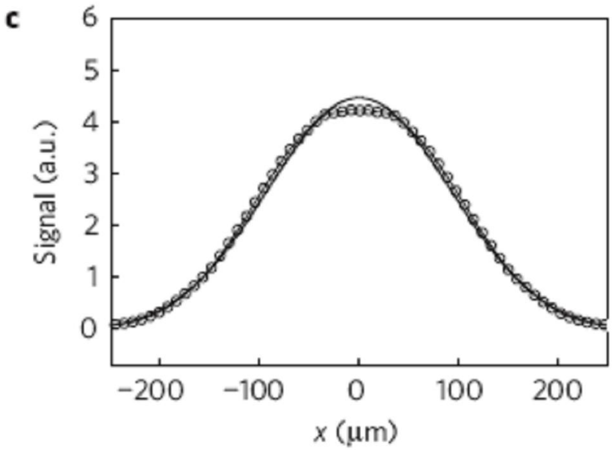
Why the shape?



Spectral instensity distribution. Solid line: theoretical prediction. Higher occupation of high quantum number modes.

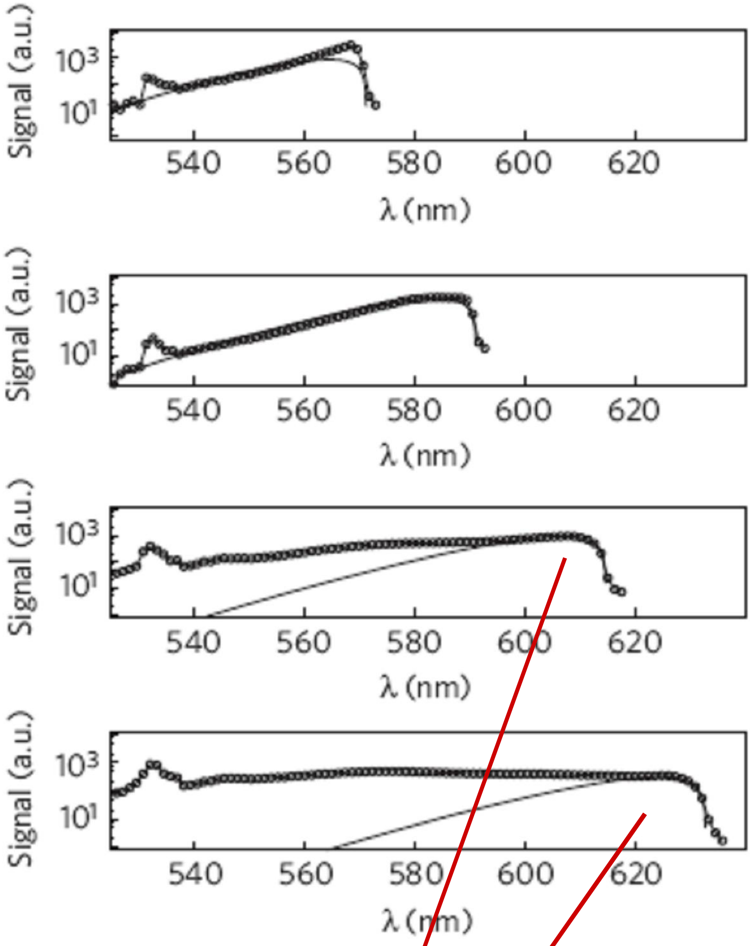
Color and shape

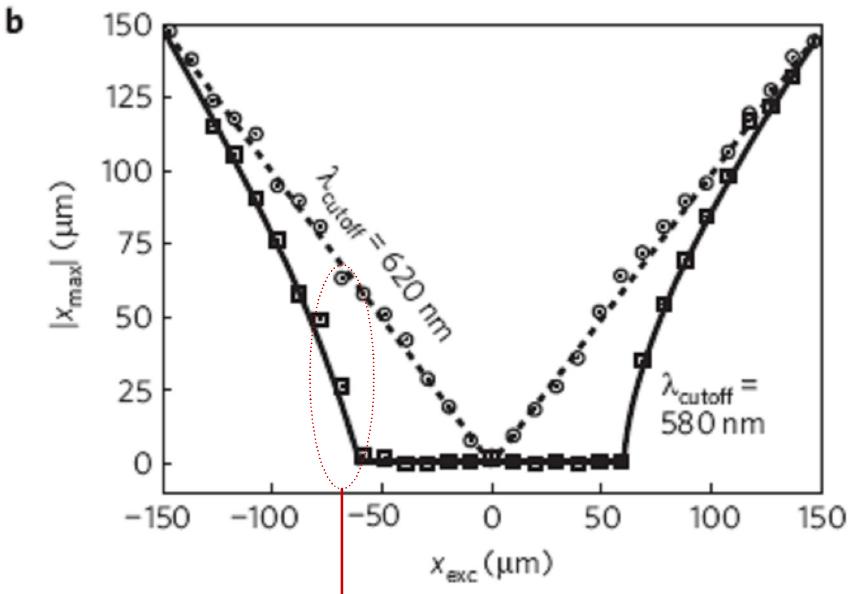




Spatial instensity distribution. Concentration effect, analogous to trapped atomic cloud.

Varied cutoff frequency
by tuning cavity

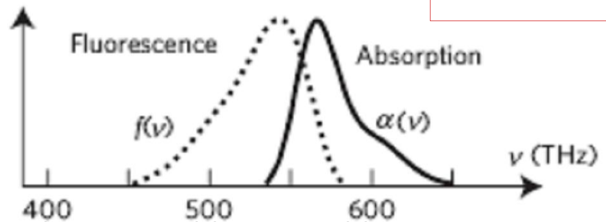




Position of intensity maximum vs. position of excitation focus.
At 620nm, weak absorption prevents enough scattering, thus no thermalization.

Not enough scattering for equilibrium

Attributed to a finite quantum efficiency; and 1D trap



749nm 599nm 499nm

Summary/dicussion

- Thermalization of photons by dye-filled cavity
- Lasing by cooling? (cool down to a phase transition)
- One way to increase scattering: 1D potential -> 3D, faster thermalization
- Centralized light spot: for light collection (solar cell?)
- Fraction of thermal/coherent, vs, Schawlow-Townes limit?