# Particle Number Fluctuations in a Bose-Einstein Condensate of Light

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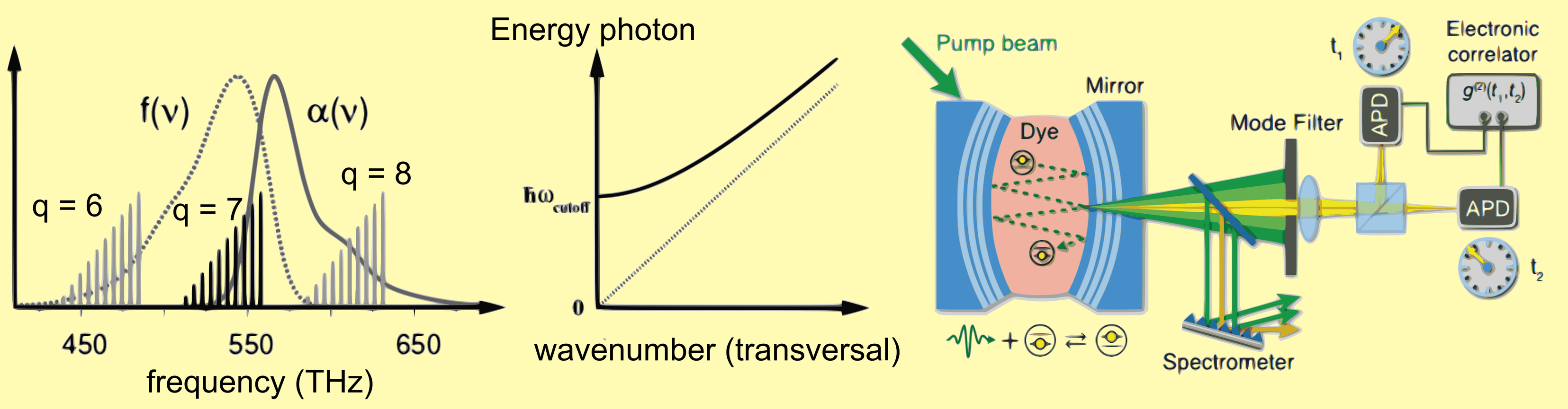
## Introduction

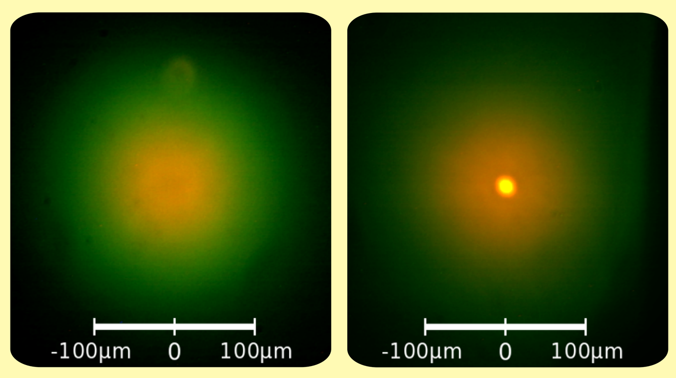
- **Fluctuations/noise** contain(s) a lot of information.
- Example: determination fractional charge quasiparticles quantum Hall effect by analyzing current fluctuations.
- Measuring fluctuating particle number in dilute atomic Bose-Einstein condensate is hard (particle number measurements destructive).
- 2010: first creation **condensate of photons** [2].
- 2014: dynamical measurements number fluctuations in photon condensate [3].

## Experiment




*Figures (modified) from Refs. [2,3]*

- Photons confined in a **dye-filled optical microcavity**.
- Emission and absorption of photons with longitudinal mode number *q = 7* dominates over other emission processes
  ⟶ **conserved** number of photons in cavity
- Photon gas is equivalent to a 2D harmonically trapped **massive** Bose gas.
- Experiment at **room temperature**.
- Hanbury Brown and Twiss experiment
  ⟶ measure number fluctuations




*before (L) and after (R) condensation*

## Theoretical Description

**Objective**: probability distribution $P(N_0)$ for the number of photons in the condensate $N_0$

- Energy functional BEC with macroscopic wavefunction $\phi_0(\mathbf{x})$

$$\Omega[\phi_0(\mathbf{x})] = \int \mathrm{d}\mathbf{x} \Big[ \frac{\hbar^2}{2m} |\nabla\phi_0(\mathbf{x})|^2 + V^{\mathrm{ex}}(\mathbf{x})\, |\phi_0(\mathbf{x})|^2 - \mu|\phi_0(\mathbf{x})|^2 + \frac{g}{2}\, |\phi_0(\mathbf{x})|^4 \Big]$$

kinetic energy ↗ external potential ↗ chemical potential ↗ photon interaction ↗

- Variational Ansatz wavefunction: $\phi_0(\mathbf{x}) \propto \sqrt{N_0}\exp(-|\mathbf{x}|^2/2q^2)$
- Minimized variational parameter: $q_{\min} = q_{\mathrm{ho}} \sqrt[4]{1 + \frac{\tilde{g}N_0}{2\pi}}$
  ⟶ Physical interpretation: proportional to condensate radius
  ⟶ Dimensionless interaction strength: $\tilde{g} \equiv mg/\hbar^2$
- In grand-canonical ensemble: $P(N_0) \propto \exp(-\beta\Omega[N_0])$
- Probability distribution for minimized energy:

$$P(N_0) \propto \exp[\beta N_0(\mu - \hbar\omega\sqrt{1 + \tilde{g}N_0/2\pi})]$$

## References

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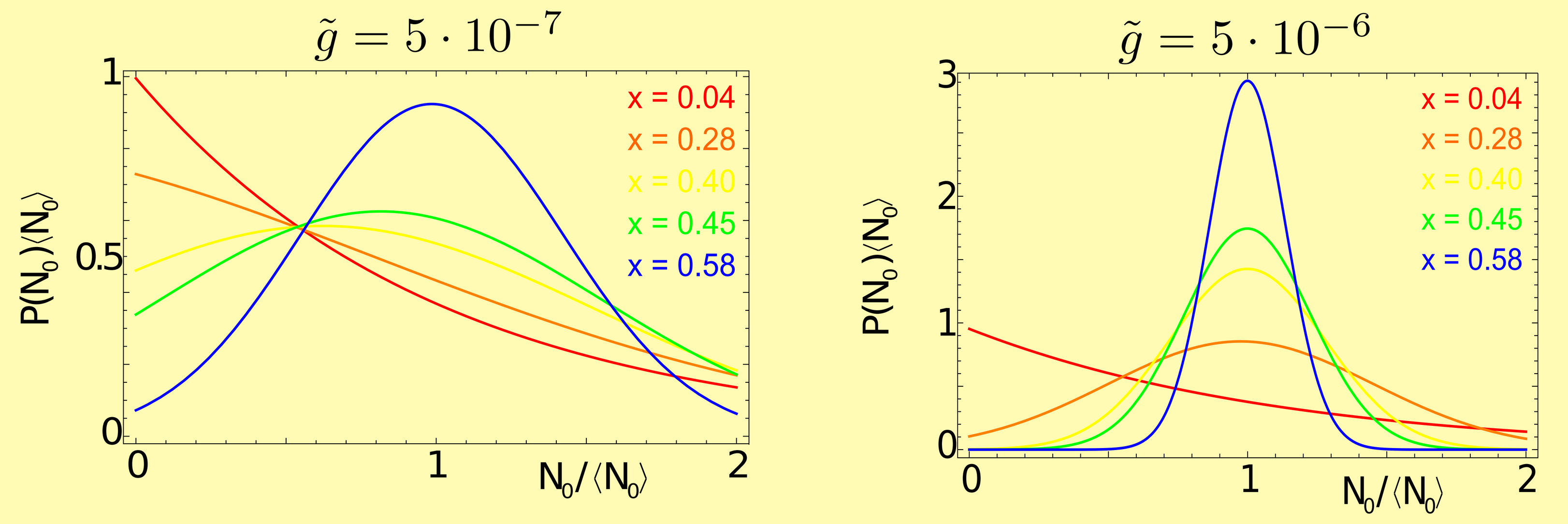
[1] E.C.I. van der Wurff *et al.*, Phys. Rev. Lett. **113**, 135301 (2014).
[2] J. Klaers *et al.*, Nature **468**, 545 (2010).
[3] J. Schmitt *et al.*, Phys. Rev. Lett. **112**, 030401 (2014).

## Main Results

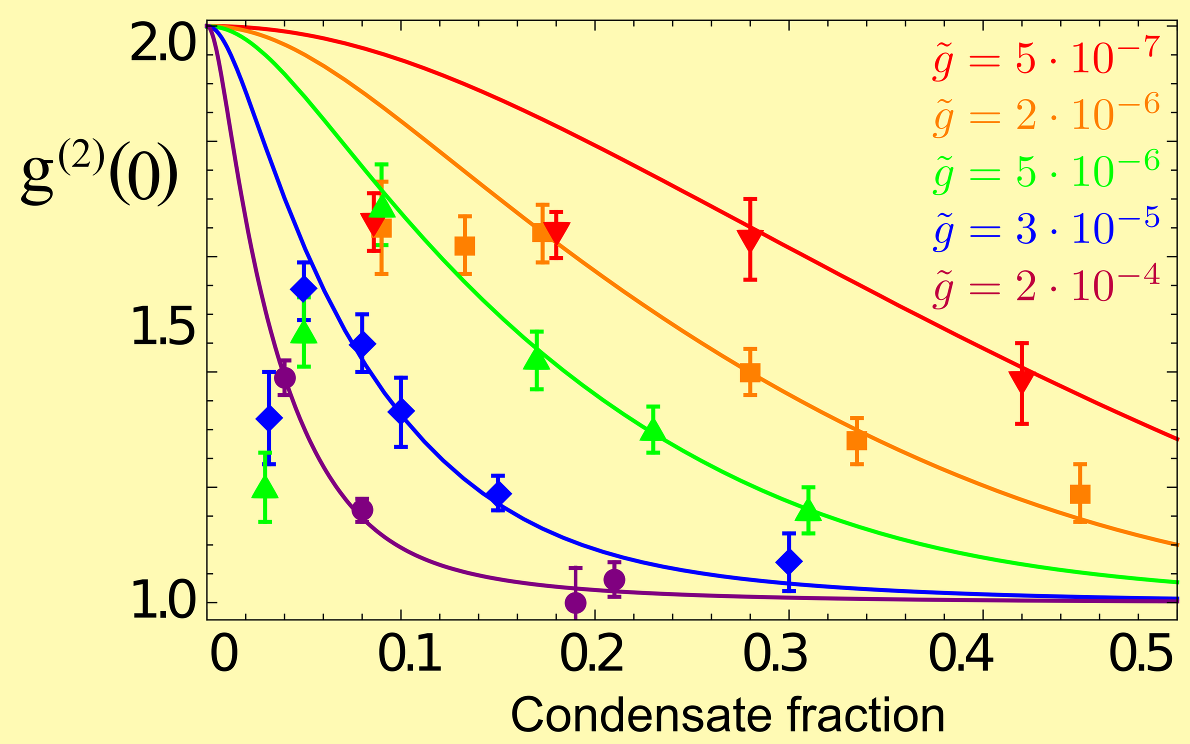
- Given a condensate fraction $x$ and interaction strength $\tilde{g}$, solve self-consistently for chemical potential $\mu$ and plot $P(N_0)$:




- Qualitatively: larger photon-photon interactions ( $x$ or $\tilde{g}$ larger)
  ⟶ $P(N_0)$ more peaked around $\langle N_0 \rangle$
  ⟶ **reduction** number fluctuations
- Quantitatively: **zero-time delay autocorrelation function:**

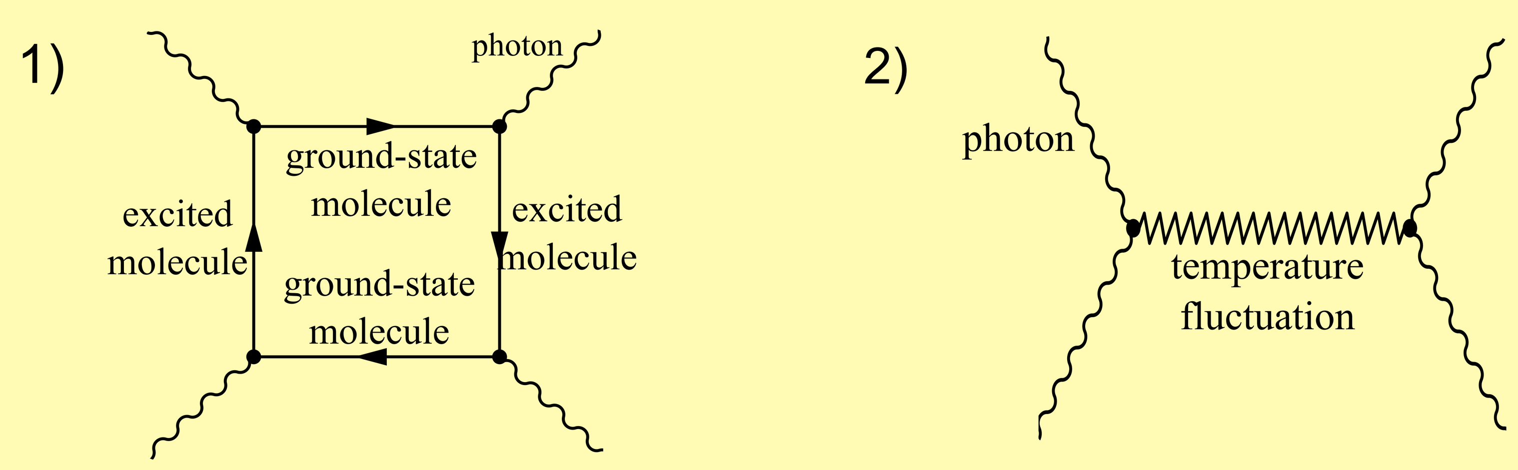
$$g^{(2)}(0) \equiv \frac{\langle N_0^2 \rangle}{\langle N_0 \rangle^2}$$

- Compare theory to measurements by using $\tilde{g}$ as fitting parameter:




- One direct measurement interaction strength for similar parameters to purple curve: $\tilde{g} \sim 10^{-4}$ ⟶ agrees with theory!

## Possible Interaction Mechanisms




1) **Dye-mediated photon-photons cattering**: due to repeated absorption and emission of photons by dye molecules

2) **Thermal lensing**: due to temperature-dependent index of refraction

- Both mechanisms: $\tilde{g}$ too small
  ⟶ Need systematic measurements for different dyes

## Conclusions

- Condensate of photons: **new experimental possibilities**, previously not accessible with condensates in dilute atomic gases.
- Explained recent experiments by assuming **contact interaction** for photons in condensate.
- More experimental input necessary to determine **nature** of interaction between photons.
- If photons interact via a contact interaction at long wavelengths
  ⟶ condensate is also a **superfluid**