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Photon counting statistics and quantum noise measurements.

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Abstract

In quantum mechanics, light is considered a stream of photons. This photon stream has fluctuations due to the stochastic nature of photons. Photon fluctuations follow three different types of statistical distributions: Poissonian, super-Poissonian, and sub-Poissonian. Poissonian statistics are characterized by having a standard deviation (σ) equal to the root-mean-square ($\sqrt{\bar{n}}$); super-Poissonian statistics are characterized by $\sigma > \sqrt{\bar{n}}$; and sub-Poissonian statistics are characterized by $\sigma < \sqrt{\bar{n}}$. In the classical model these statistics correspond to light from different sources, the coherent light in the classical model corresponds to the Poissonian statistics and the thermal light corresponds to the super-Poissonian statistics. However, sub-Poissonian statistics doesn't have a classical interpretation and is direct proof of the photonic nature of light. Even for constant intensity light sources one observes stochastic variations in the number of counts. The noise associated with these measurements is called shot noise. Shot noise is a type of quantum noise, its main characteristic is that it depends only on the intensity of the light. In this work, photon counting techniques were used to characterize the statistics of a coherent light source and a pseudo-thermal light source as well as measuring quantum noise. Photon counting techniques require low intensity light beams and use a very sensitive photodetector along with an electronic counter to record the number of photons within a time interval τ specified by the user. This approach successfully showed Poissonian statists and super-Poissonian statistics apply for coherent light and pseudo thermal light. Measurements of quantum noise successfully characterized shot noise as photon fluctuations that depend only on light power.

Photon statistics

The **probability** of observing K photons during a time interval τ is given by Mendel's formula

$$P(K) = \int_0^\infty \frac{1}{K!}(\alpha W)^K e^{-\alpha W} P_W dW$$

- **W** is the energy reaching the photocathode during a time interval τ
- **α** is defined as $\alpha = \frac{\eta}{h\omega}$
- Where **η** is the quantum efficiency of the detector.
- P_W is the **probability density function** of W

For **coherent light** the W is assumed to be well defined:

$$P(W) = \delta(W - \overline{W})$$

Assuming intensity constant over time (**coherent** state). The integration yields:

$$P(K) = \frac{\overline{K}^K}{K!} e^{-\overline{K}}$$

For **thermal light the variation** of the intensity of the beam can not be ignored.

$$P(W) = \frac{1}{\overline{W}} \exp\left(-\frac{W}{\overline{W}}\right)$$

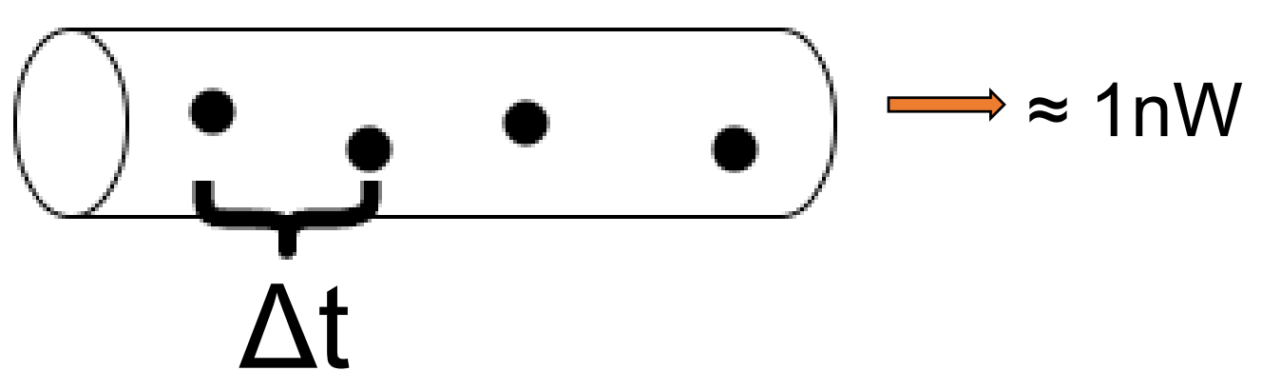
The integration now yields **Bose-Einstein** distribution, which follows super-poissonian statistics.

$$P(K) = \frac{1}{1+\overline{K}}\left(\frac{\overline{K}}{1+\overline{K}}\right)^K$$

Pseudo Thermal light statistics is somewhere in the middle of a **poissonian** and **super** poissonian.

Quantum noise measurements

Quantum noise is a manifestation of the uncertainty principle. In particular, **shot noise** refers to the fluctuations in the number of photons detected due to the discrete nature of photons.



- Description of light in quantum mechanics consists of a train of discrete particles.
- The distance between photons is not constant.
- Even a beam with well-defined **flux** will nevertheless show photon number fluctuations

Photon flux is defined as

$$\Phi = \frac{IA}{\hbar\omega}$$

The probability of not detecting a particle within a time interval is given by

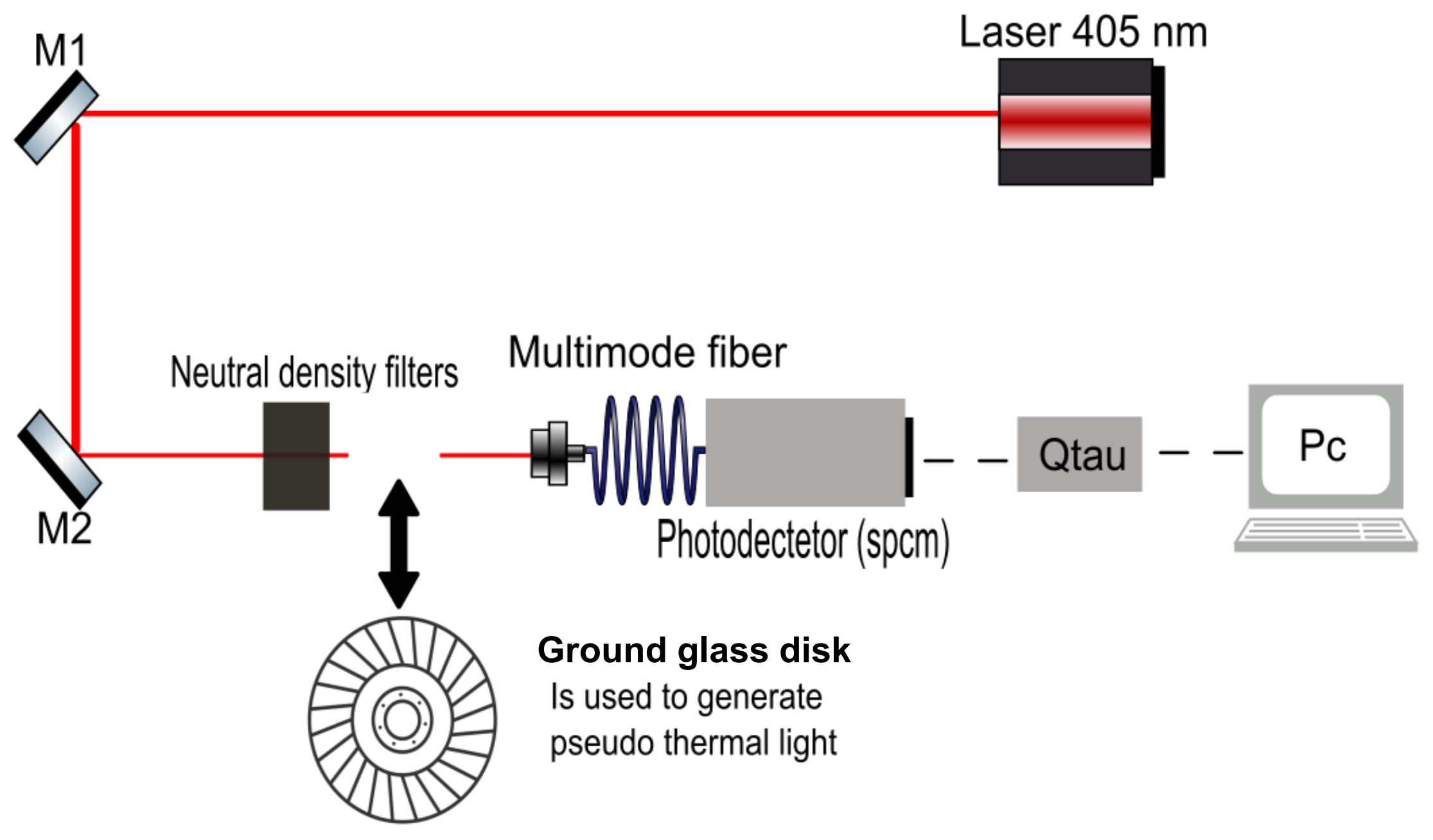
$$\mathbb{P}_0(t) = e^{-rt}$$

- r is the average rate of arrival

The probability of detecting K photons in a time interval is

$$\mathbb{P}_k(t) = \frac{(rt)^k}{k!} e^{-rt}$$

Photon counting setup



Photodetector
Single photon counting module (spcm)

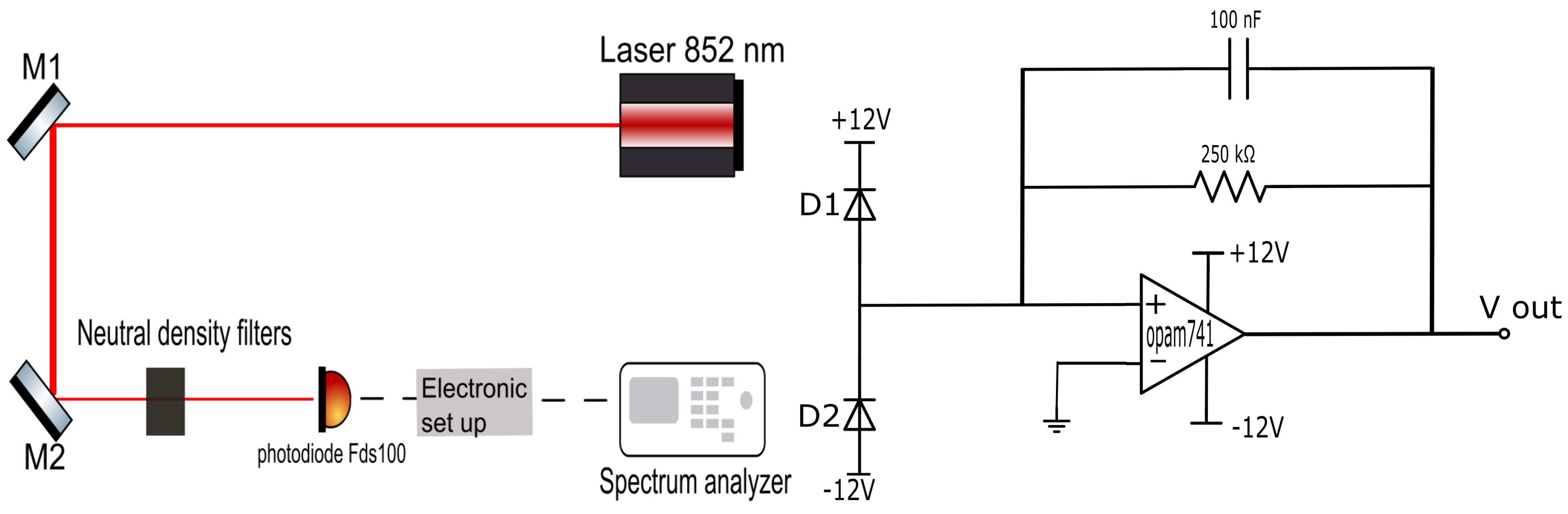
Quantum efficiency is around 25 % for 405 nm

Light Source:
Laser 405nm

Quantum noise measurements set up

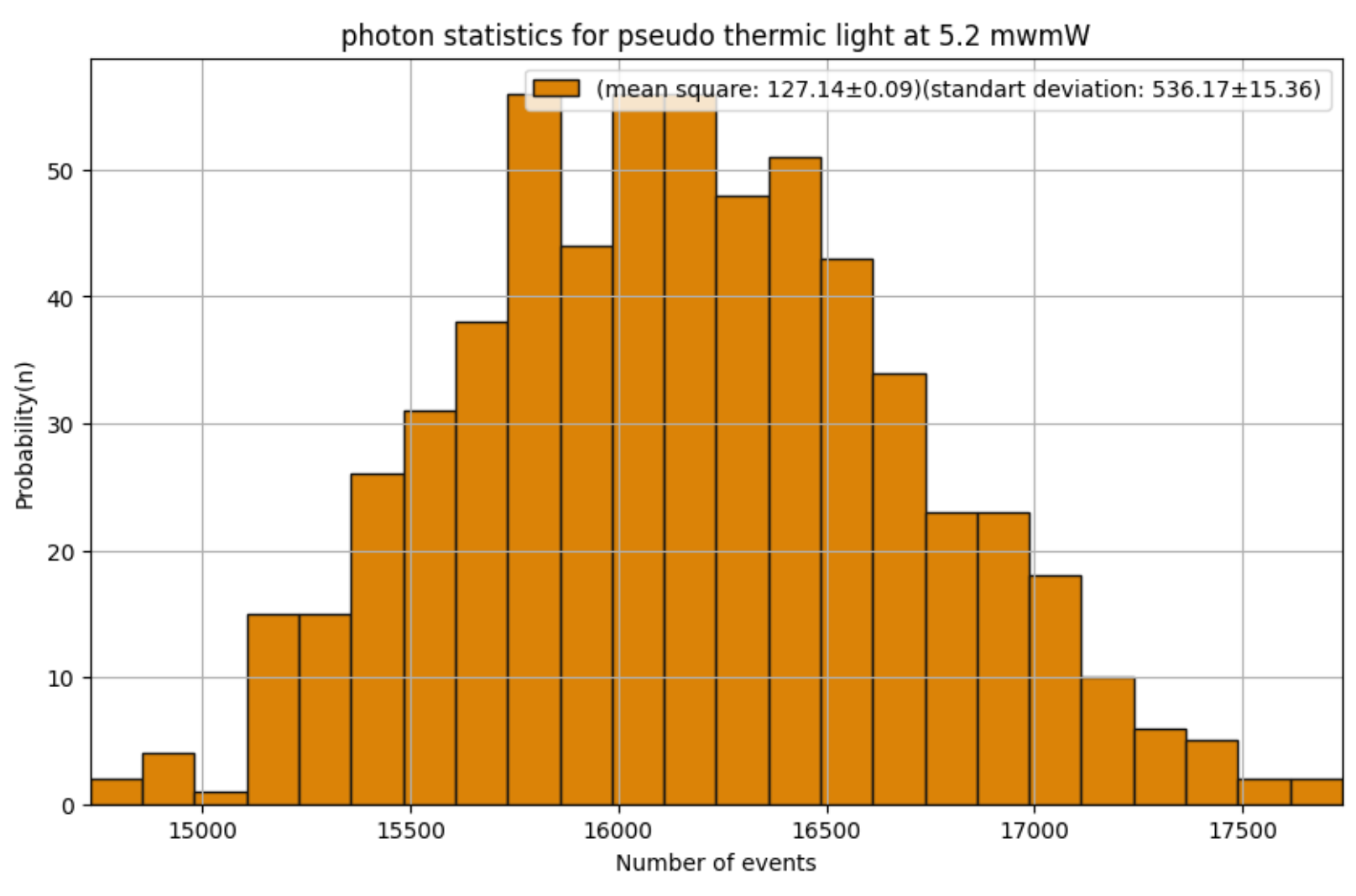
Electronic noise is often bigger than shot noise making it hard to measure shot noise.

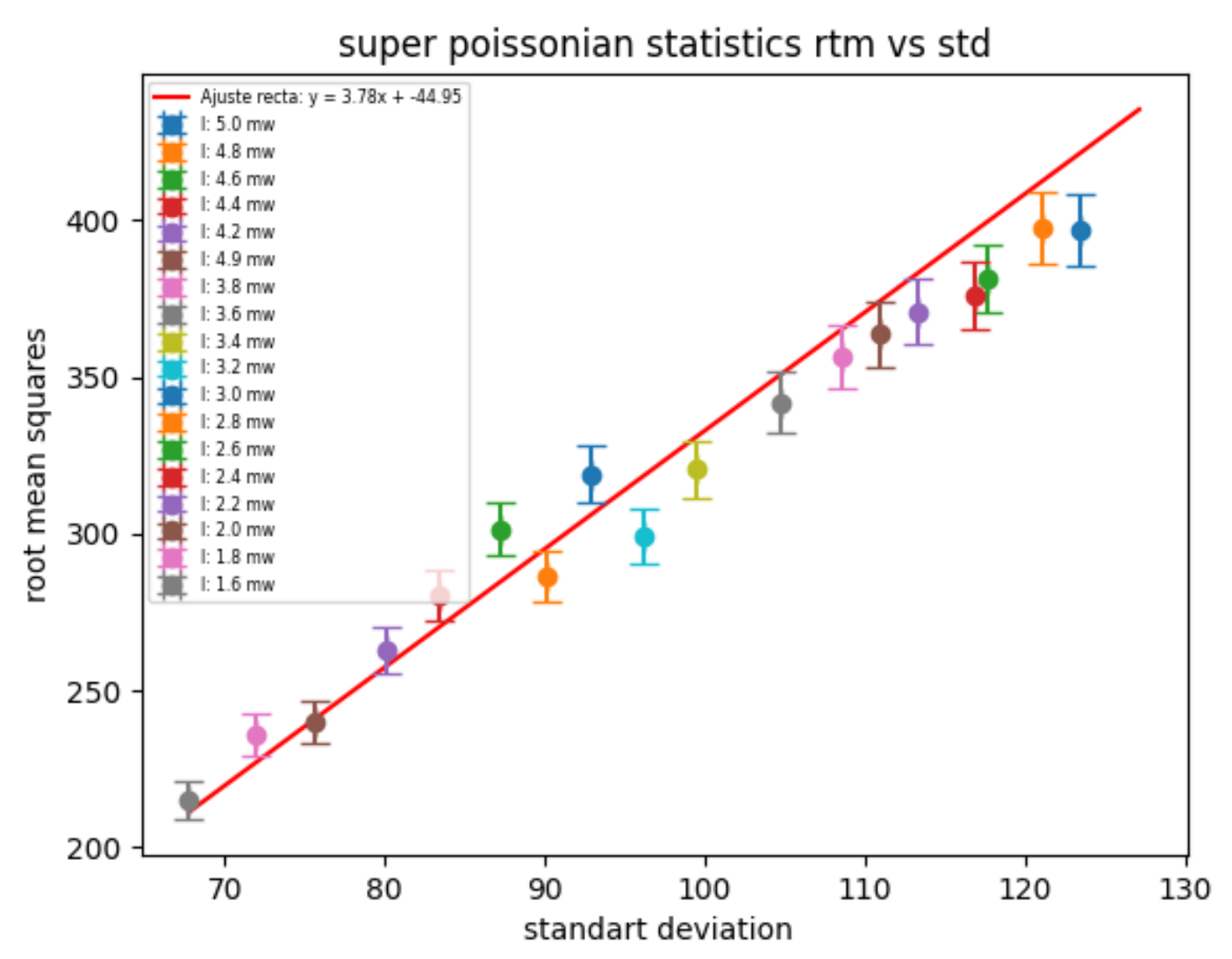
Measurements of shot noise require great amplification



Photon counting Results

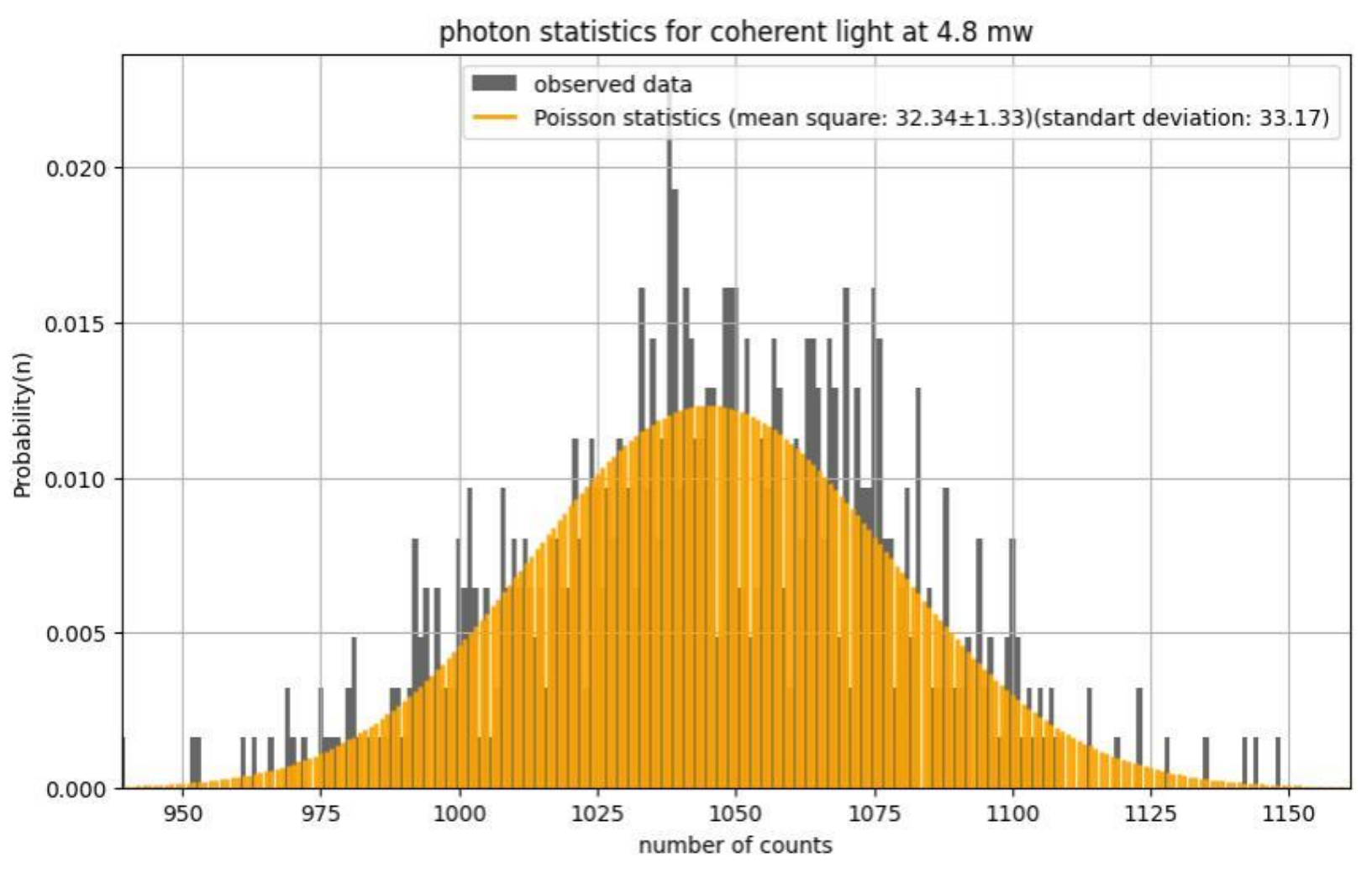
Pseudo thermic light statistics

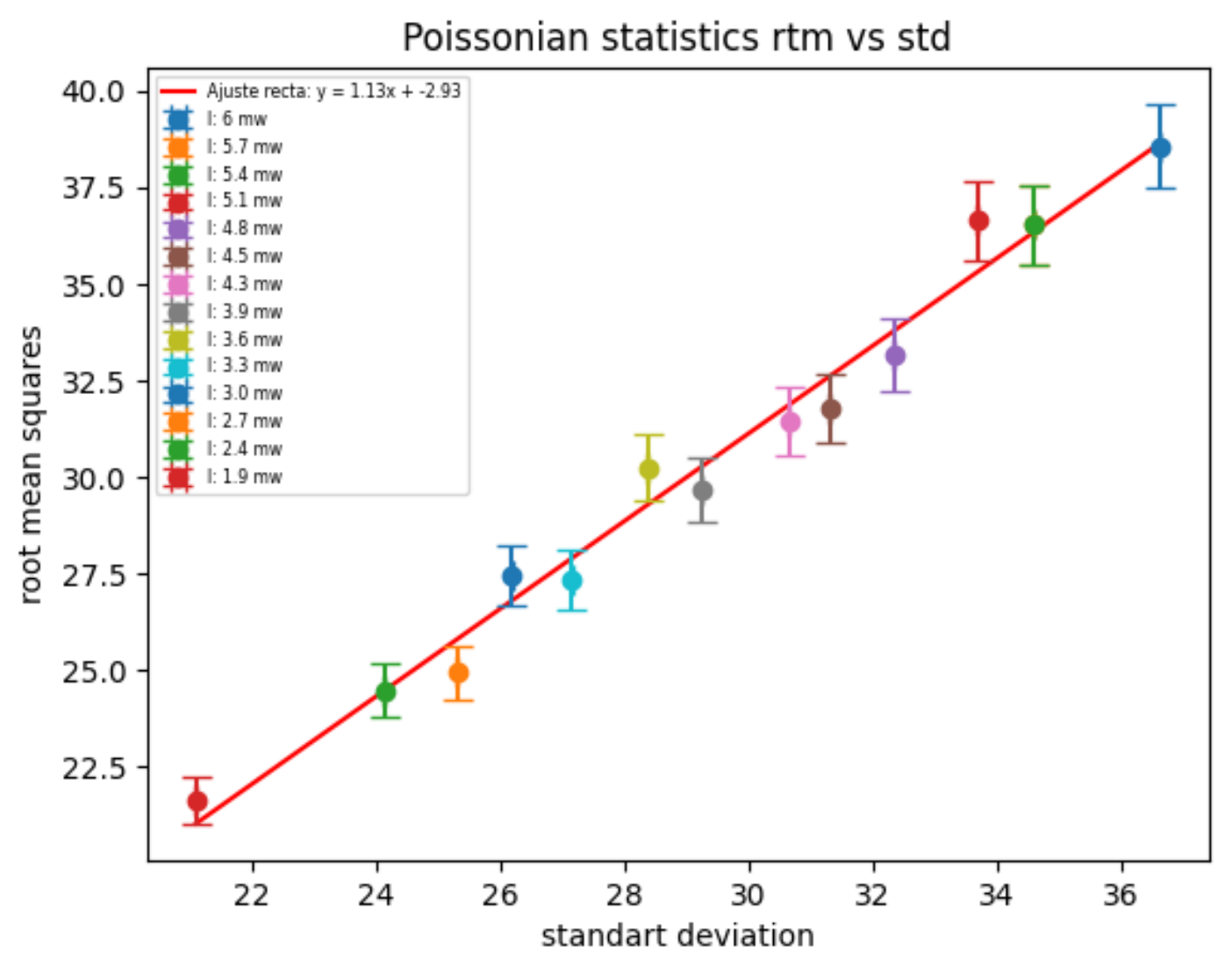




- The distribution found for pseudo-thermal light follows super-Poissonian statistics
- A slope of 3.78 is greater than 1, this shows that $\sigma > \sqrt{\bar{n}}$, which is a clear indicative of super-Poissonian statistics

Coherent light statistics

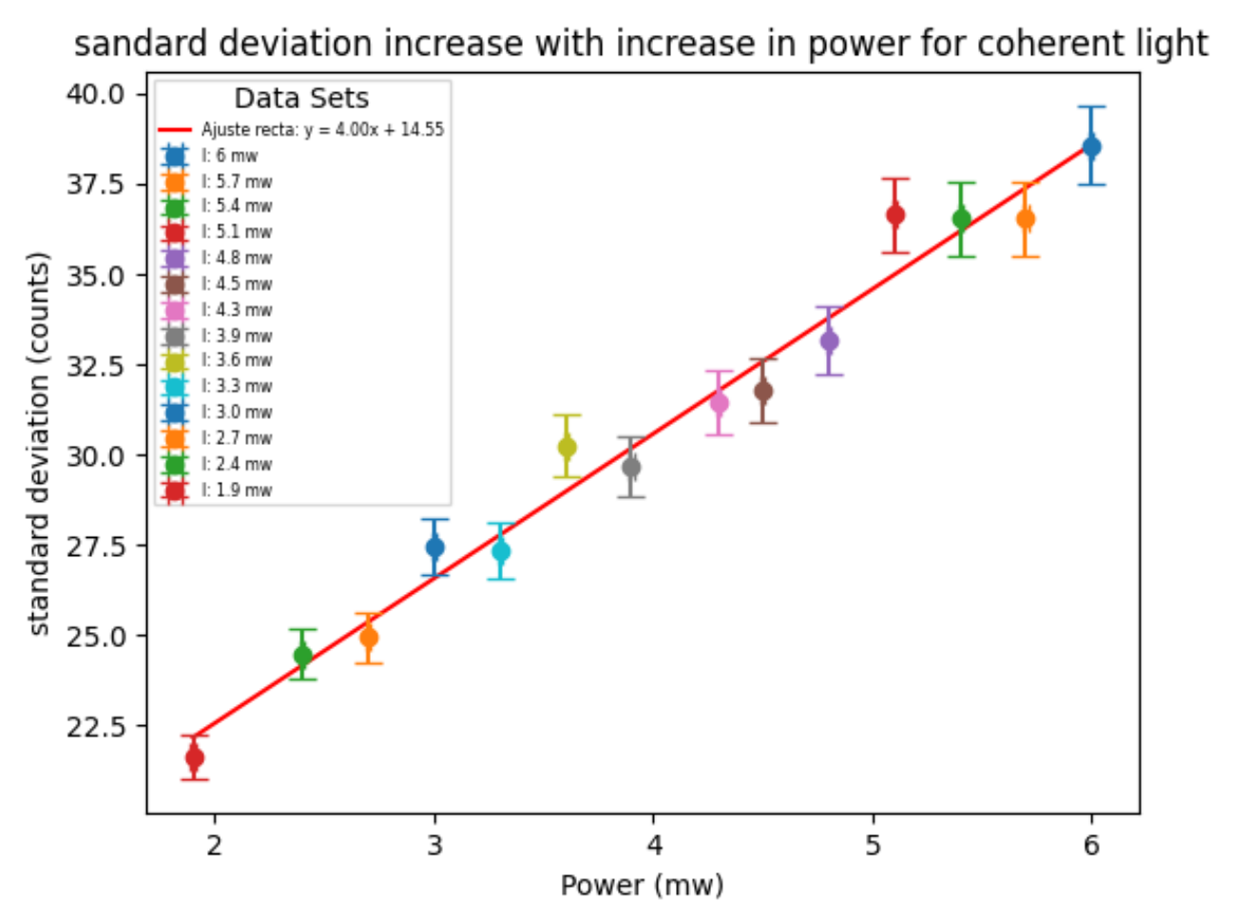


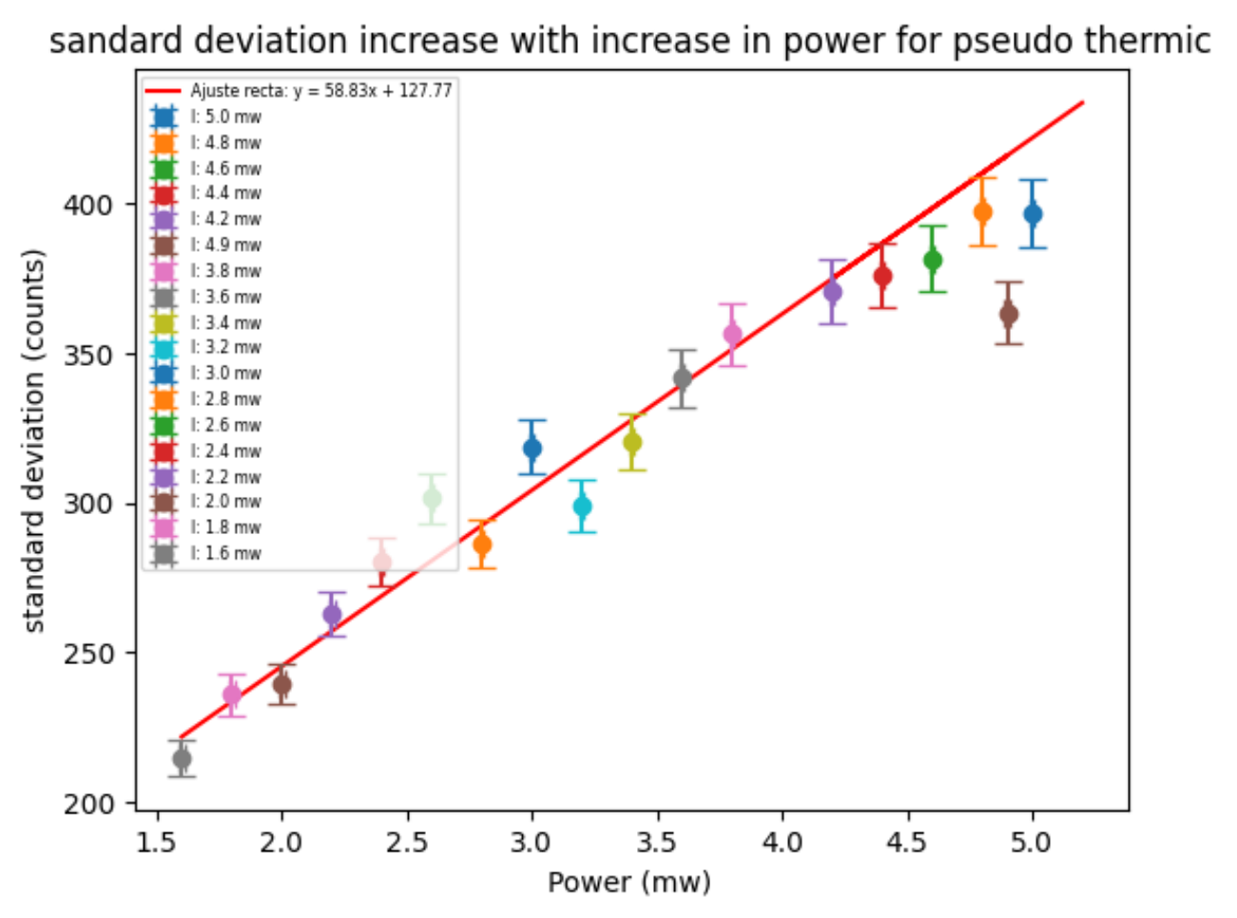


- The distribution found for coherent light follows Poissonian statistics
- A slope of approximately 1 shows that $\sigma \approx \sqrt{\bar{n}}$ which is a clear indicative of Poissonian statistics

Quantum noise measurements

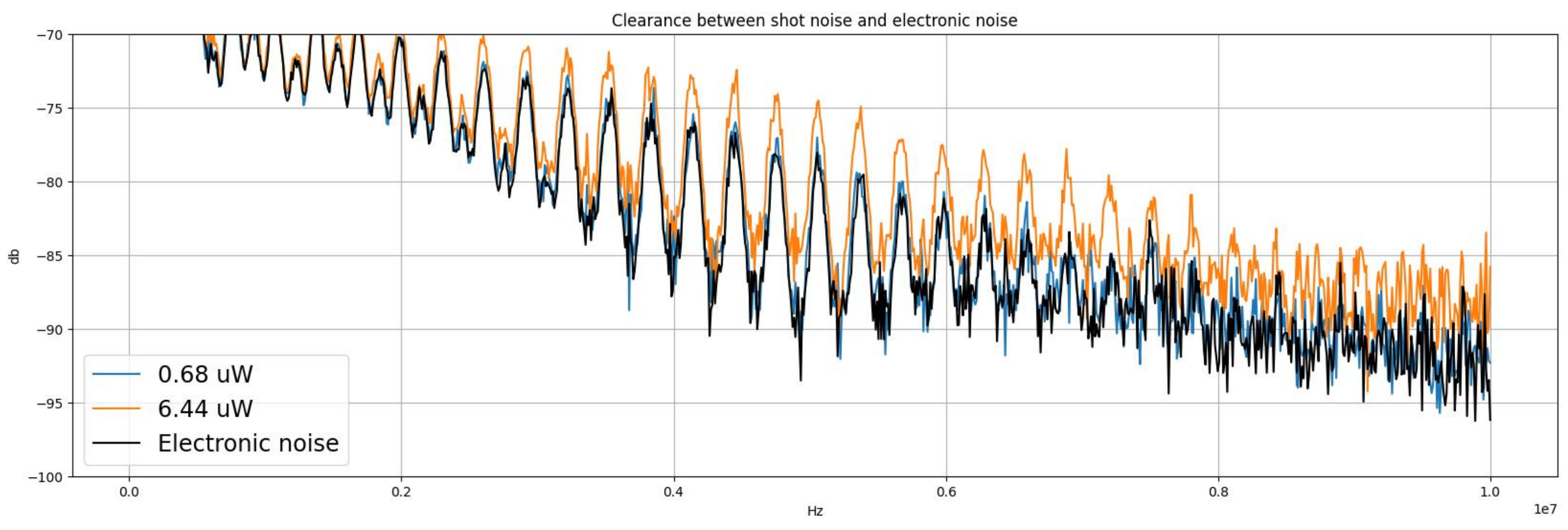
Shot noise in coherent pseudo thermic light sources





The standard deviation increases linearly with **power**, a direct consequence of the relationship between **shot noise** and the power of the light source

Shot noise in comparison to electronic noise.



The clearance between the **electronic noise** and **shot noise** is great enough to say that the measurements correspond to **shot noise** and not other types of noise.

Conclusions and Future Work

- There is a clear relationship between photon statistics in quantum mechanics and the classical model of light.
- Shot noise depends is caused by the uncertainty principle and depends only in power of the light beam.
- For future work electronic set up in quantum noise measurements needs improvements in order to obtain a greater clearance.

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