Development of advanced photon-detection techniques for neutrinoless double beta decay studies with nEXO

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CASST

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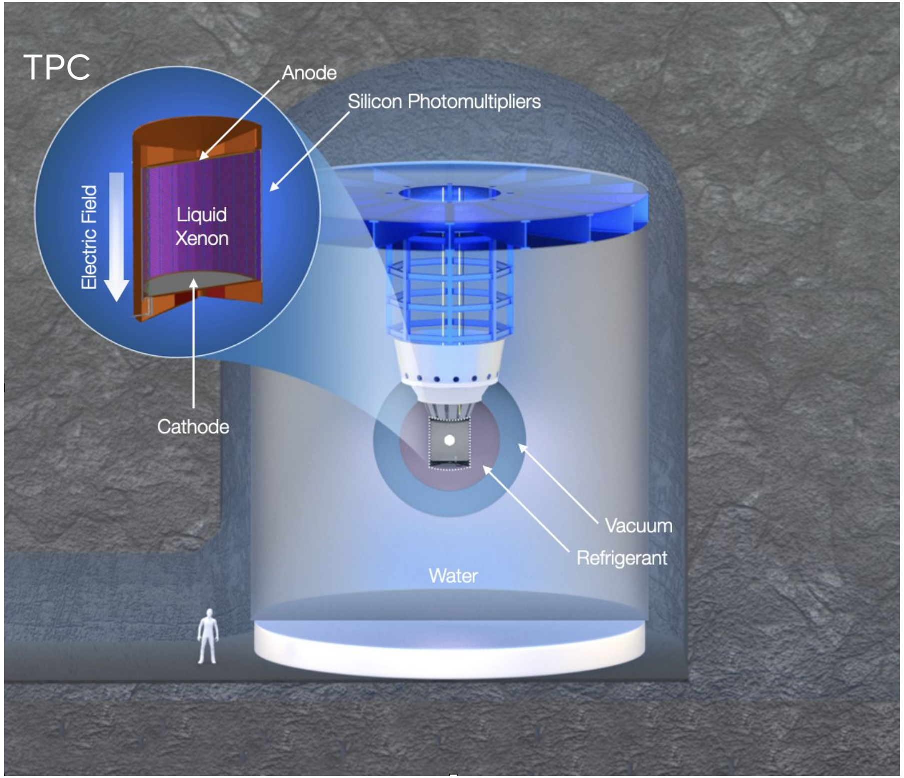
nEXO | McGill

nEXO experiment at SNOLAB

- Search for $0\nu\beta\beta$ decay in 5 tons of liquid Xe enriched to 90% in ^{136}Xe, in a time projection chamber (TPC)

- Expanding our knowledge of the neutrino

- 2 km underground to reduce background from cosmic radiation



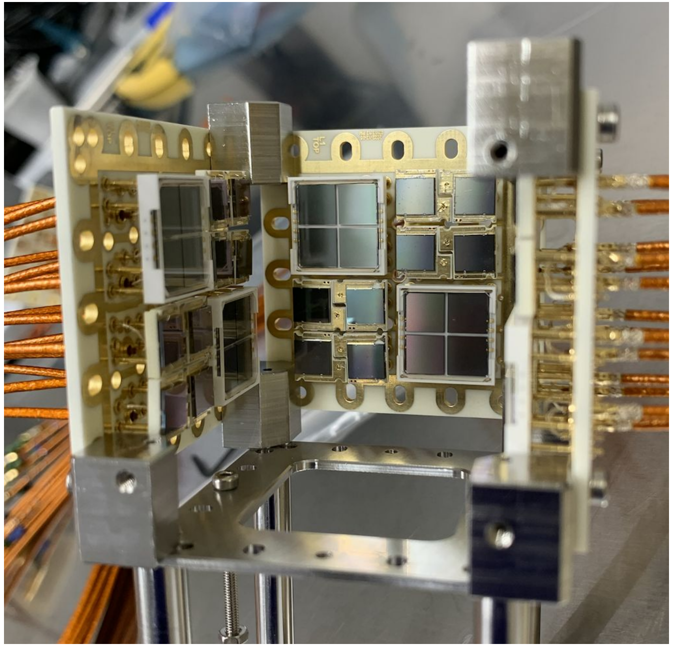
Silicon photomultipliers testing

- 1 cm^2 matrix of 50µm single-photon avalanche diodes (SPADs)

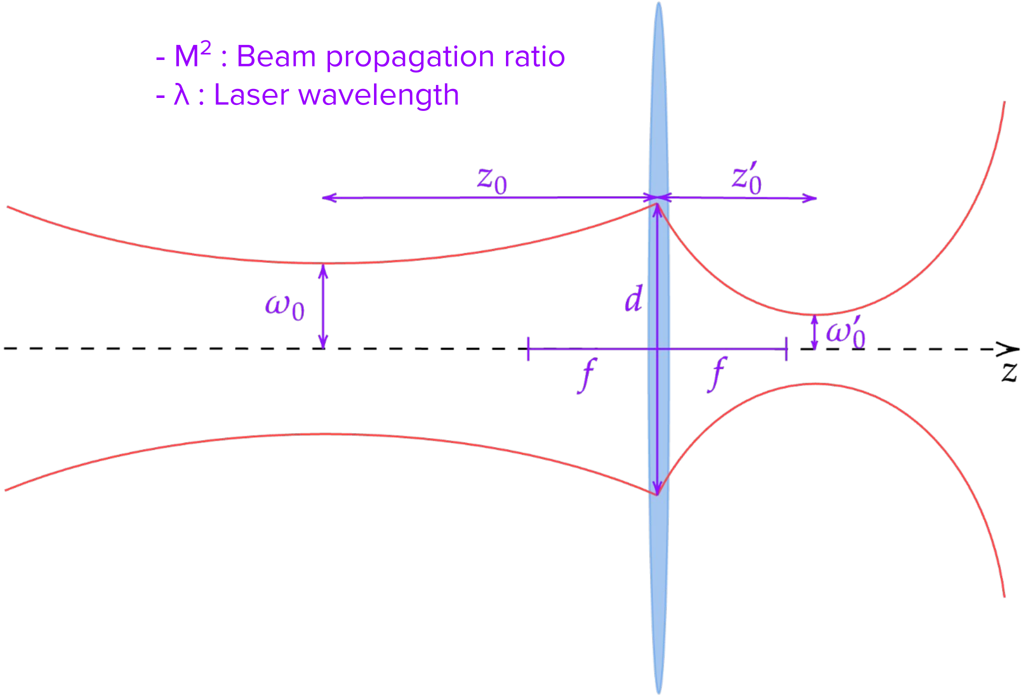
- Avalanche effect produces a large current pulse in response to a single photon of light

Goal: Test and characterize every SPAD of each SiPMs

~50 000 in nEXO



Focus a laser beam into a 50 µm SPAD



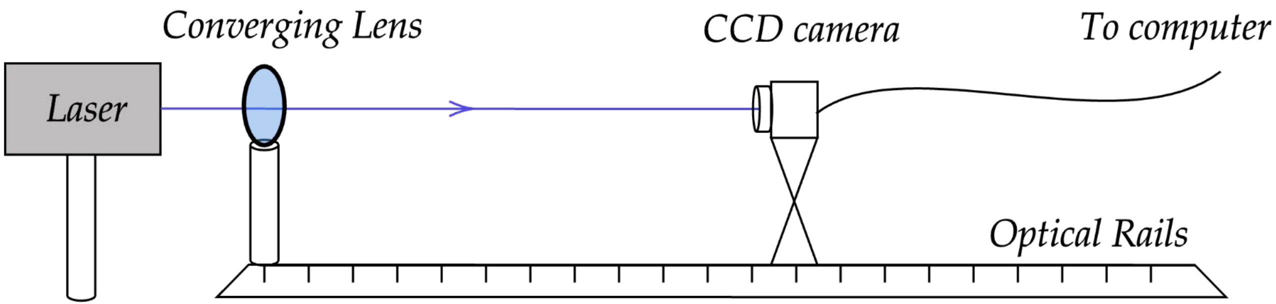
- Beam model: Gaussian Beam

$$I\left(r,z\right)=I_0\left(z\right)e^{-\frac{2r^2}{\omega^2(z)}}$$

- Size of the focused spot for a collimated beam:

$$\omega'_0=\frac{2M^2\lambda f}{\pi d}\ at\ z'_0\approx f$$

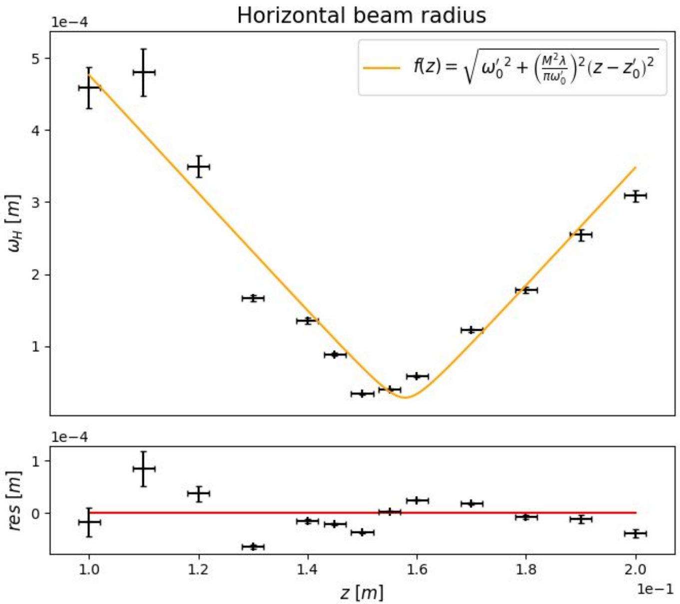
Laser source characterization



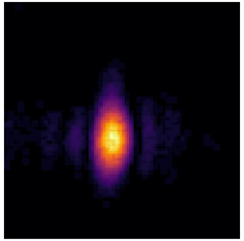
- Axial dependence of beam radius: $\omega(z) = \sqrt{\omega_0'^2 + \left(\frac{M^2\lambda}{\pi\omega_0'}\right)^2 (z - z_0')^2}$

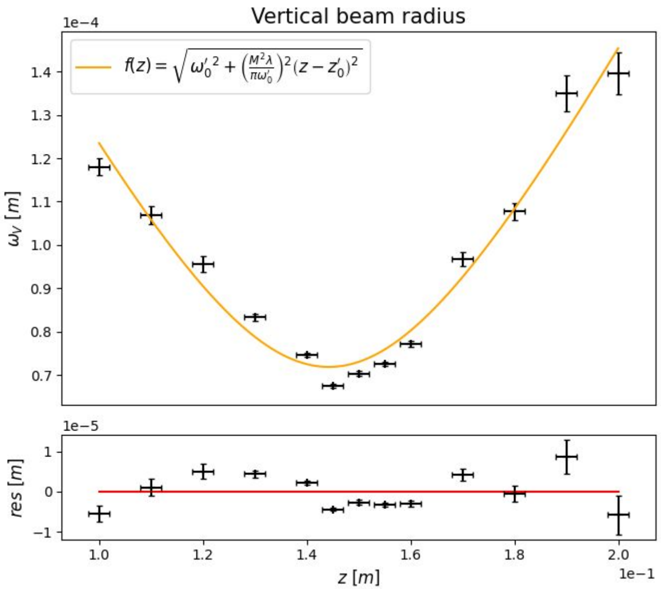
- Measure the beam radius: $\omega(z) = 2\sigma(z)$

Results and implications on the scanning set-up



$$M^2 = 1.63 \pm 0.19$$
$$\Rightarrow d_{min} = 4.67 \pm 0.12\ mm$$





$$M^2 = 1.14 \pm 0.03$$
$$\Rightarrow d_{min} = 3.27 \pm 0.03\ mm$$

Number of photons detected per laser pulse

- Counting experiment, pulses are independent: $p(N) = \frac{\overline{N}^N e^{-\overline{N}}}{N!}$

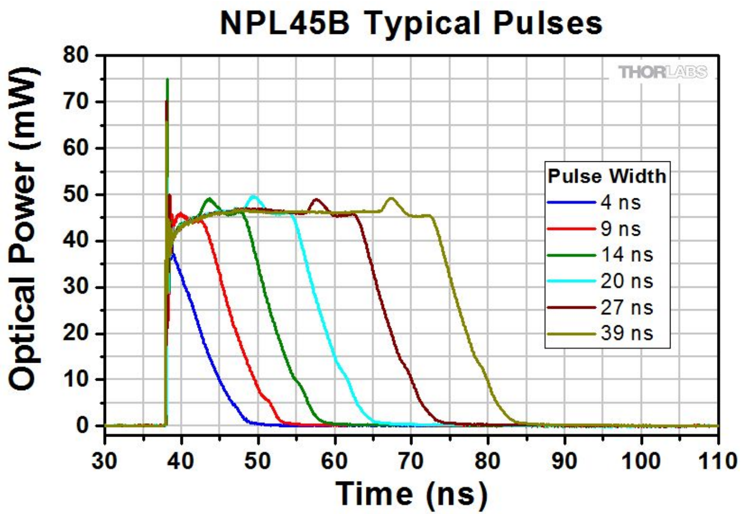
$$\longrightarrow \quad \overline{N} = \frac{E}{h\nu} = \frac{PT\lambda}{hc}$$

- P : Laser power
- T : Laser pulse duration
- λ : Laser wavelength

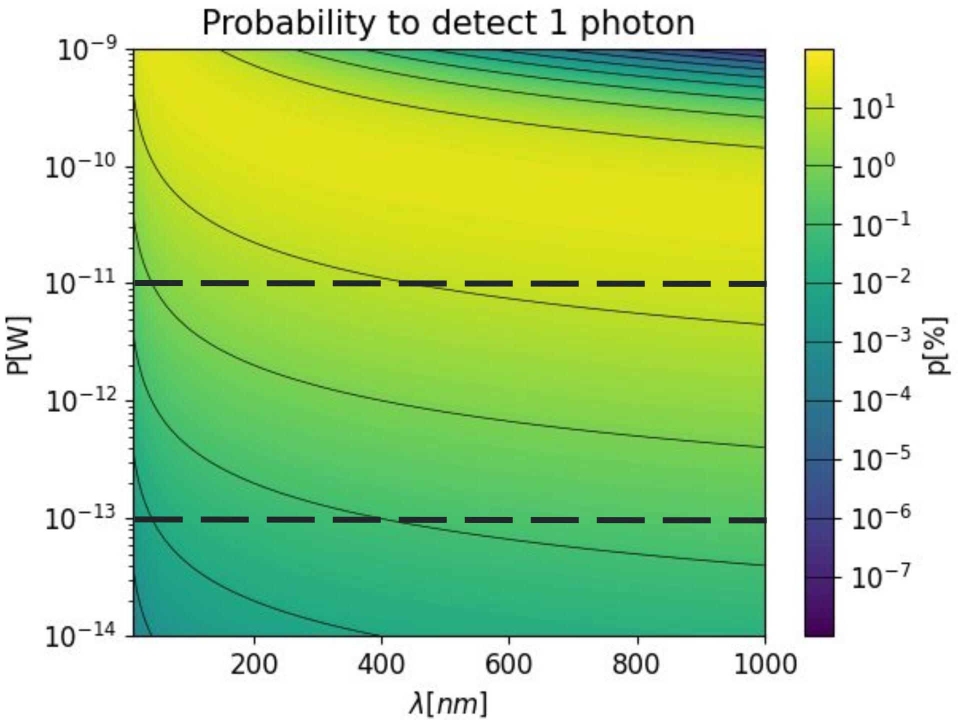
- For my laser:

$$\lambda = 450\ nm$$

$$\overline{N} = 3.39 \times 10^8$$



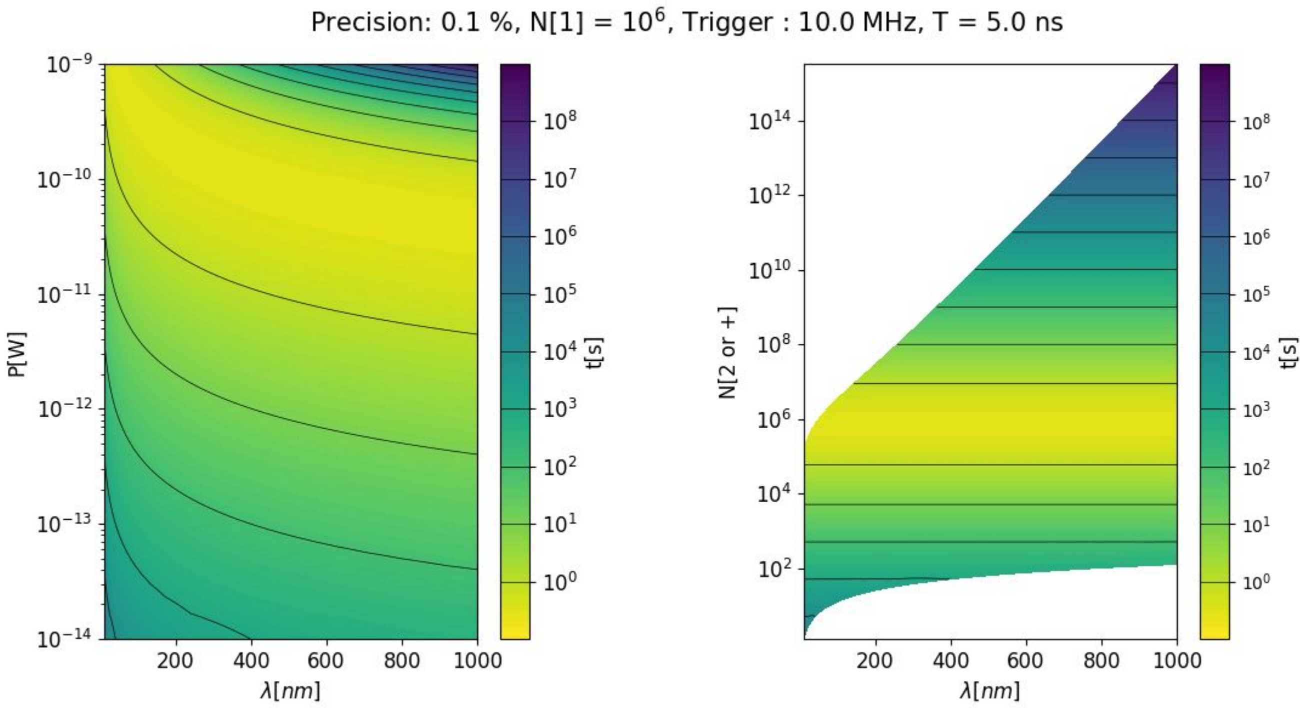
Results and implications on the scanning set-up



Reduce the optical power to

10^{-11} - 10^{-13} W

Required precision example



Precision: ϵ

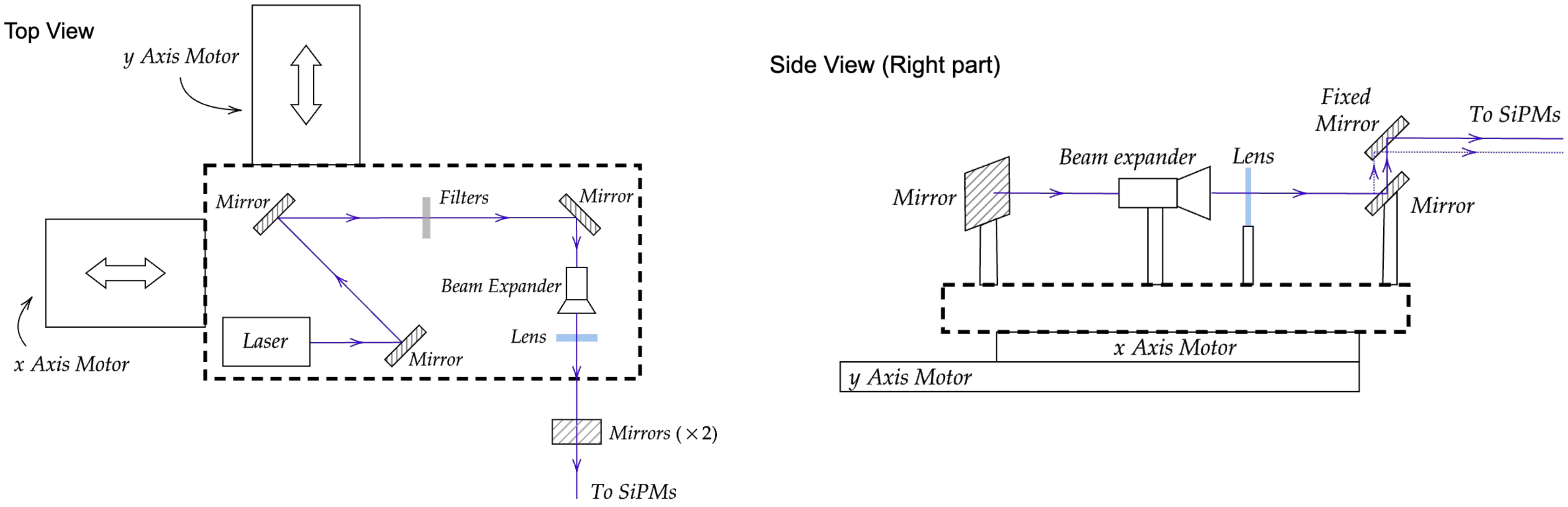
$$\longrightarrow \quad N[1] = \frac{1}{\epsilon^2}$$

Time to reach precision:

$$\longrightarrow \quad t = \frac{N[1]}{pf}$$

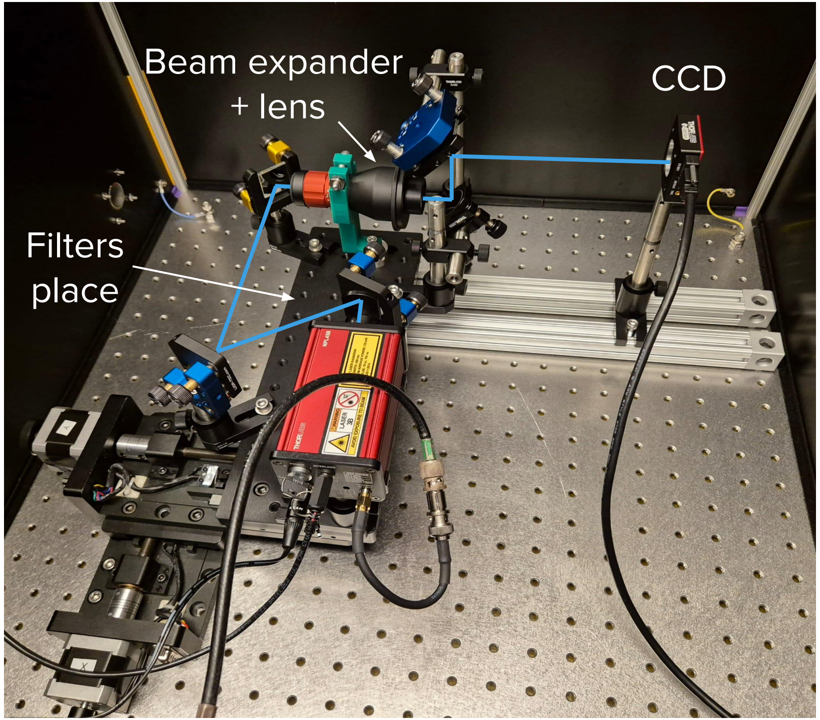
- p : Probability to have 1 photon
- f : Laser pulse frequency
- N[1] : Number of 1-photon detections

Experimental scanning set-up



SiPMs are positioned vertically, motors are controlled by a computer

Focusing the laser beam with the scanning set-up



- Expected values:

$$2\omega'_{0V} = 32.66 \pm 3.60 \mu m$$
$$2\omega'_{0H} = 21.22 \pm 3.18 \mu m$$

- Measured values:

$$2\omega'_{0V} = 36.20 \pm 1.70 \mu m$$
$$2\omega'_{0H} = 18.17 \pm 0.81 \mu m$$

What's next ?

- Put a SiPM and start counting photons!
- Play with the filters to find the best precision/time-to-wait ratio
- Start to characterize SiPMs

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Thanks for listening!

nEXO

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Sources

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- Siegman, P.A., & Ginzton, E.L. (1998). How to (Maybe) Measure Laser Beam Quality. https://api.semanticscholar.org/CorpusID:108297721

Add slide 1: Neutrinoless double beta decay

Neutrino: fermion, electrically neutral, weak interaction and gravity

In the standard model: particle ≠ antiparticle $\longrightarrow$ $2\nu\beta\beta$

$$\longrightarrow 2\ {}^1_0n \longrightarrow 2\ {}^1_1p^+ + 2e^- + 2\overline{\nu}_e$$

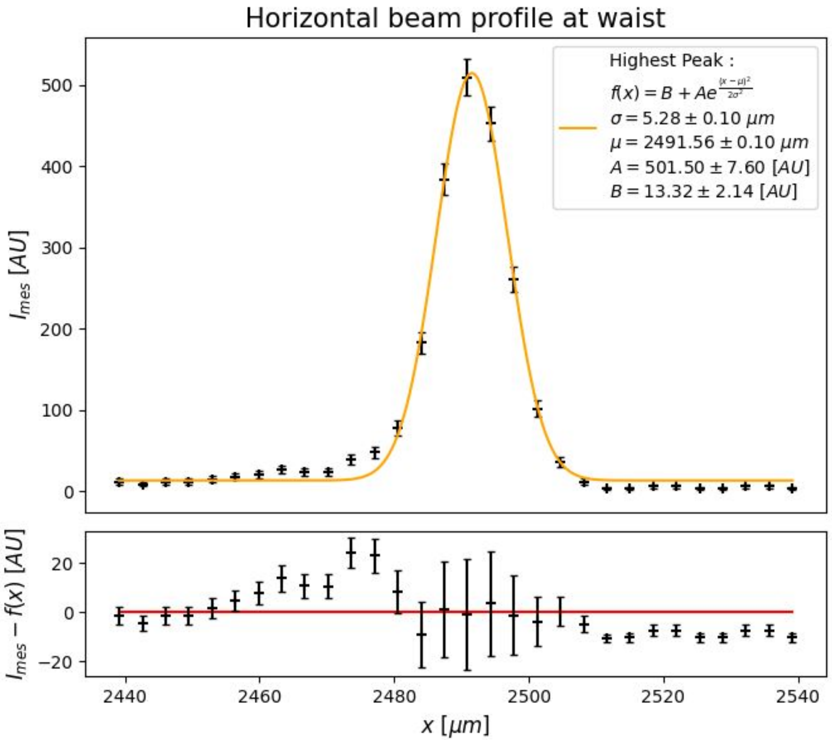
0 = 0 2 -2 lepton number conservation

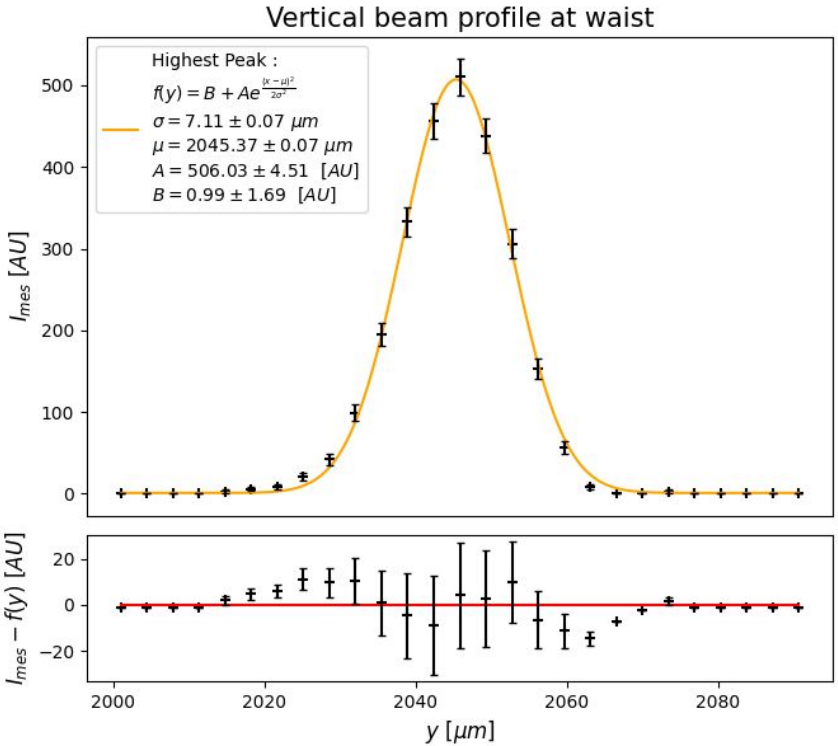
Massive & Majorana particle: particle = antiparticle $\longrightarrow$ $2\nu\beta\beta$ and $0\nu\beta\beta$

$$\longrightarrow 2\ {}^1_0n \longrightarrow 2\ {}^1_1p^+ + 2e^-$$

0 ≠ 0 2 lepton number violation

Add slide 2: Extract the beam radius from the gaussian fit



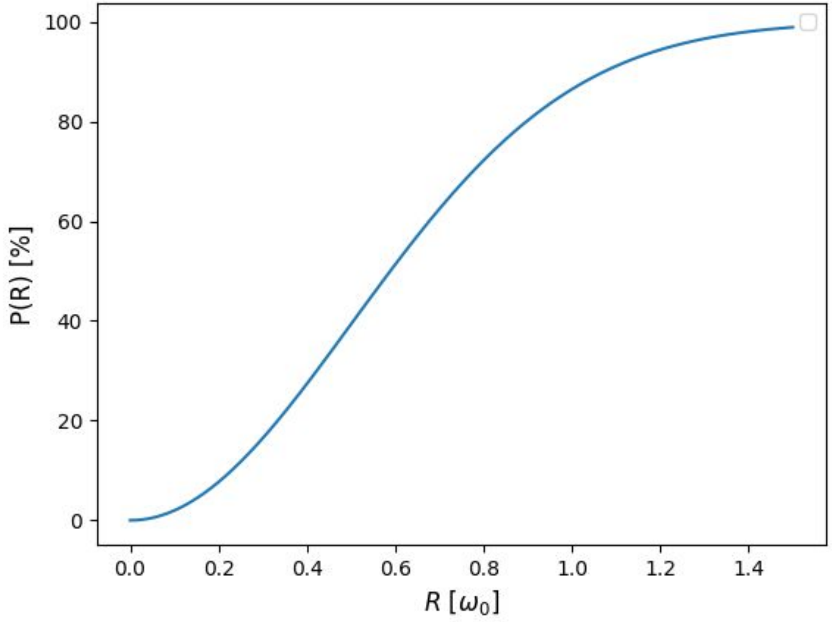


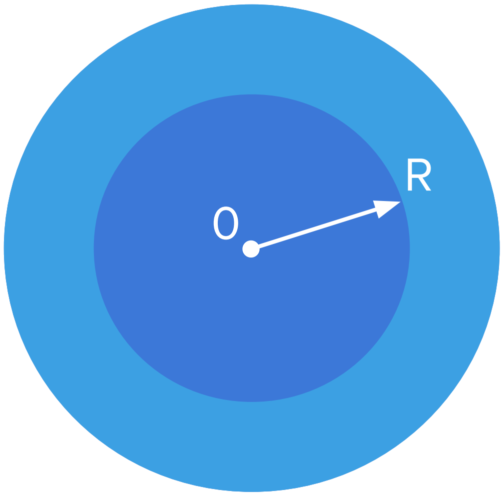
Add slide 3: One photon in a gaussian beam

$$I\left(r\right) = I_0 e^{-\frac{2r^2}{\omega_0^2}}$$

- Probability to observe a photon: $p(r)dA \propto I(r)dA$
- Normalisation: $\frac{p(r)}{1} = \frac{KI(r)}{\int_0^\infty KI(r)2\pi r dr}$ → $p(r) = \frac{2}{\pi\omega_0^2} e^{-\frac{2r^2}{\omega_0^2}}$
- Probability to find it between 0 and R: $P(R) = \int_0^R p(r)2\pi r dr = 1 - e^{\frac{-2R^2}{\omega_0^2}}$

Add slide 3: One photon in a gaussian beam





Add slide 4: All measurements for beam focusing

$$\begin{pmatrix} 2\omega'_{0V} = 42.37 \pm 0.45\mu m \\ 2\omega'_{0H} = 17.11 \pm 0.13\mu m \end{pmatrix}$$

$$\begin{pmatrix} 2\omega'_{0V} = 34.50 \pm 0.39\mu m \\ 2\omega'_{0H} = 20.84 \pm 0.15\mu m \end{pmatrix}$$

$$\begin{pmatrix} 2\omega'_{0V} = 37.53 \pm 0.80\mu m \\ 2\omega'_{0H} = 16.56 \pm 0.14\mu m \end{pmatrix}$$

$$\begin{pmatrix} 2\omega'_{0V} = 37.67 \pm 0.58\mu m \\ 2\omega'_{0H} = 16.84 \pm 0.16\mu m \end{pmatrix}$$

$$\begin{pmatrix} 2\omega'_{0V} = 36.71 \pm 0.71\mu m \\ 2\omega'_{0H} = 16.56 \pm 0.26\mu m \end{pmatrix}$$

$$\begin{pmatrix} 2\omega'_{0V} = 28.44 \pm 0.28\mu m \\ 2\omega'_{0H} = 21.12 \pm 0.40\mu m \end{pmatrix}$$

Add slide 5: Filters (data from Thorlabs)

OD of the filter	Transmission at 450 nm (%)
3	6.122×10^{-2}
4	5.301×10^{-3}
7	2.500×10^{-5}
8	9.789×10^{-7}