Designing a Calibration System for the Outer Detector of the nEXO Experiment

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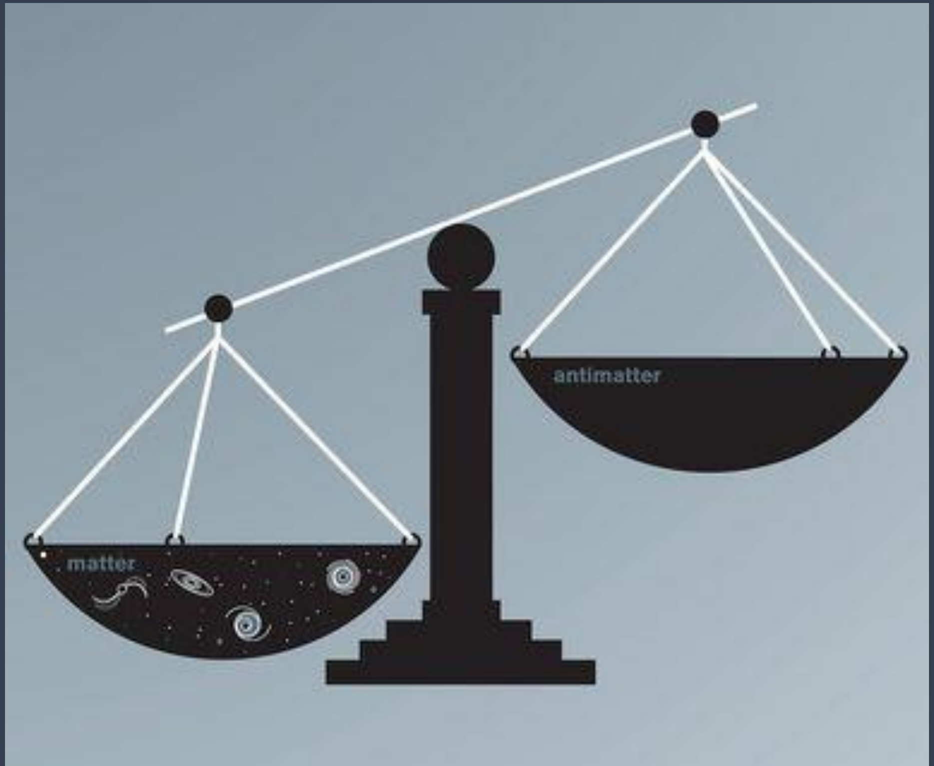
MATTER ASYMMETRY

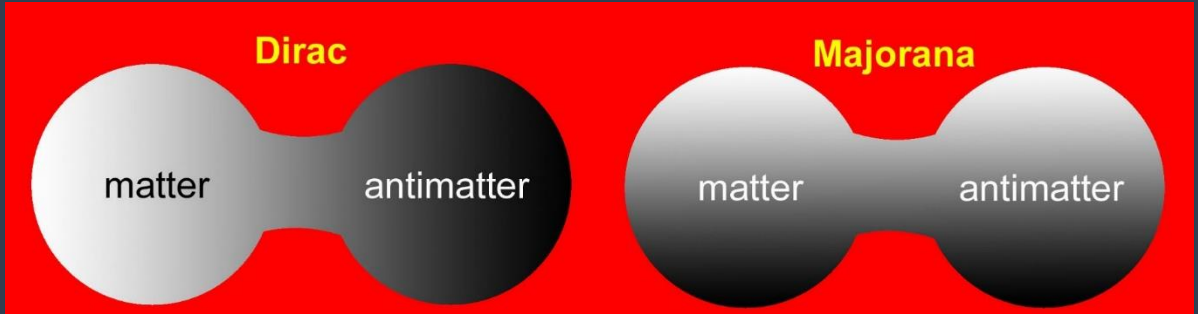
Why does our world happened to be full of matter?

One way to answer this question is to ask whether neutrinos are Dirac or Majorana particles.

Searching for neutrinoless double beta decay is a pathway to study the nature of neutrinos.



Picture Credit: Symmetry Magazine



Picture Credit: Fermilab at work, News at work

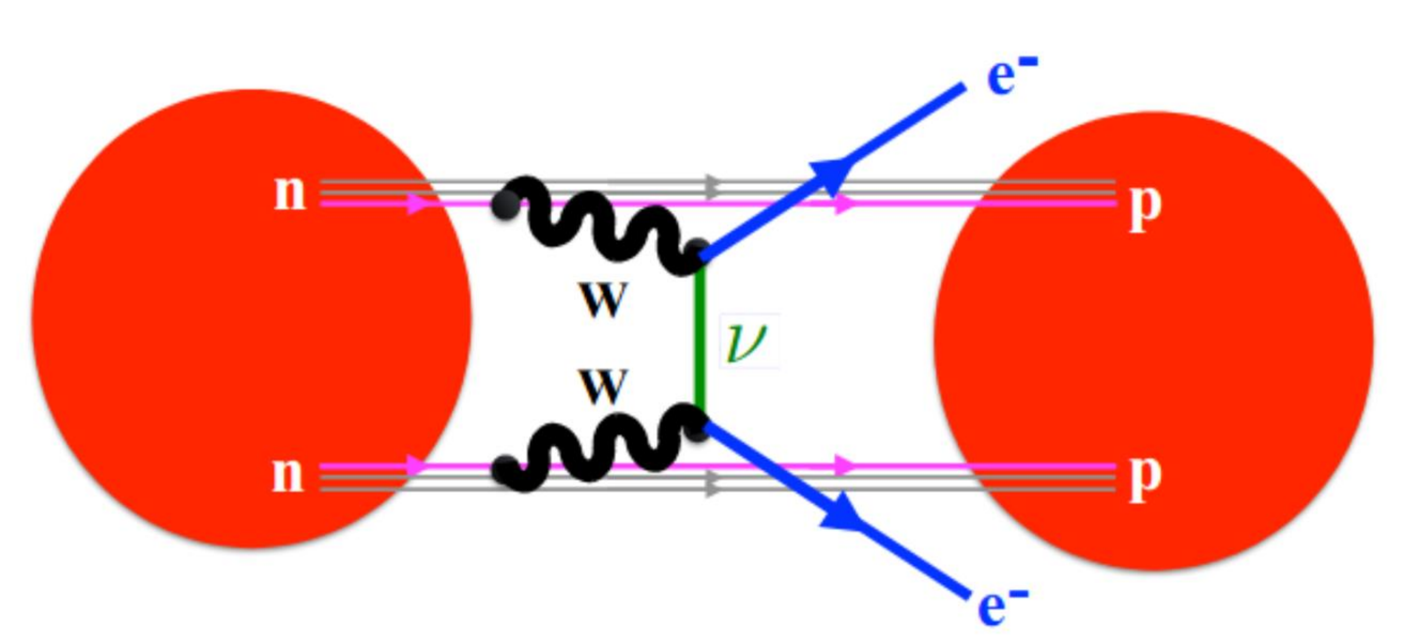
0νββ DECAY

2νββ decay

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z+2}X + 2e + 2\bar{\nu}$$

0νββ decay

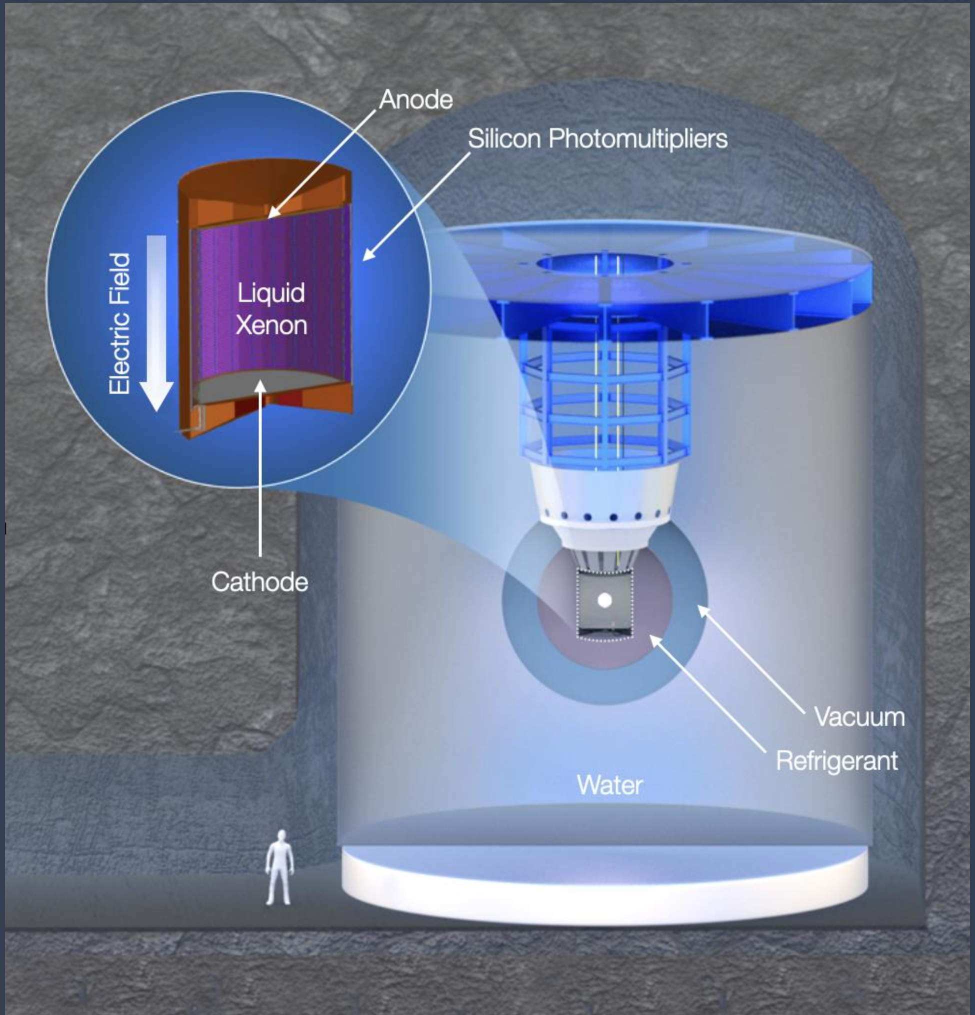
$$^{A}_{Z}X \rightarrow \, ^{A}_{Z+2}X + 2e$$



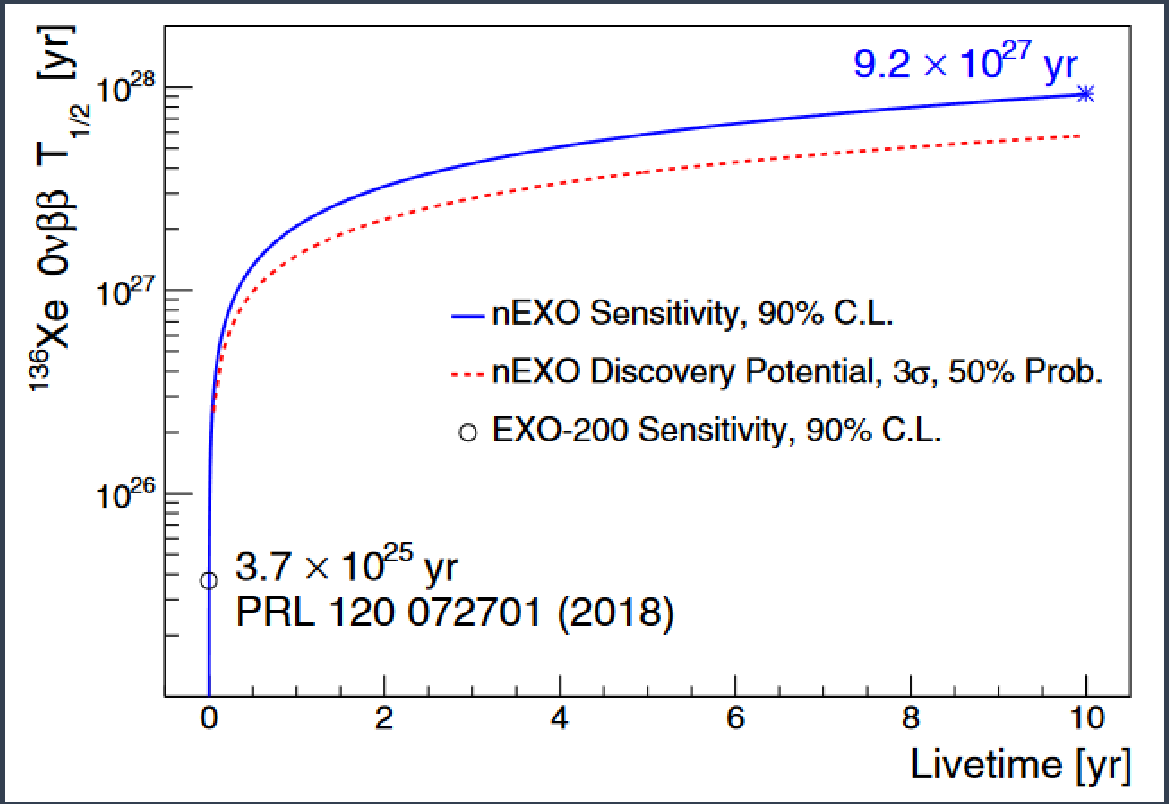
Picture Credit: ETC, European Center for Theoretical Studies in Nuclear Physics and Related Areas

0νββ decay, if observed, would demonstrate the violation of the lepton number conservation and Majorana nature of neutrinos.

nEXO EXPERIMENT



Picture Credit: The nEXO Experiment



Picture Credit: Sensitivity and discovery potential of the proposed nEXO experiment to neutrinoless double-β decay

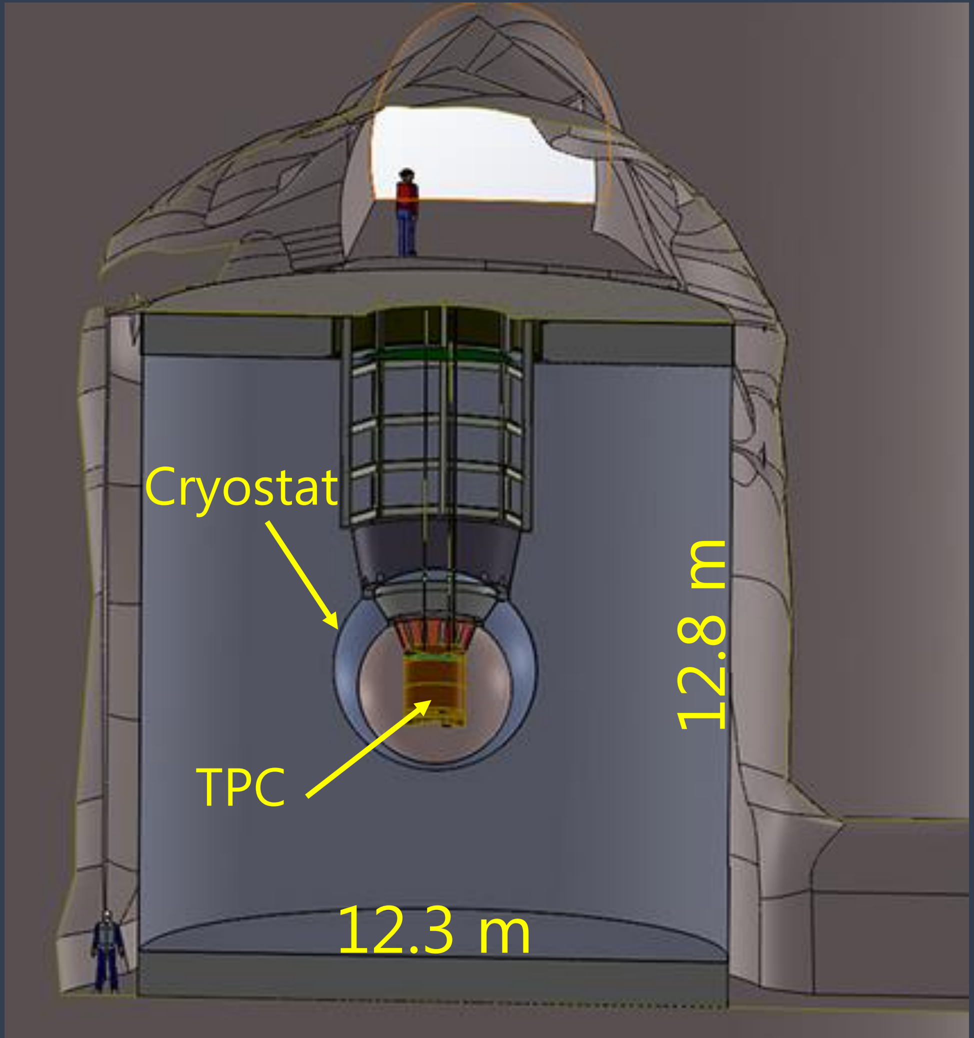
The nEXO Experiment is designed to search of 0νββ decay to a level of 10^{28} years with 5 tonnes of liquid xenon.

nEXO: Searching for Lepton Number Violation and Majorana Neutrinos

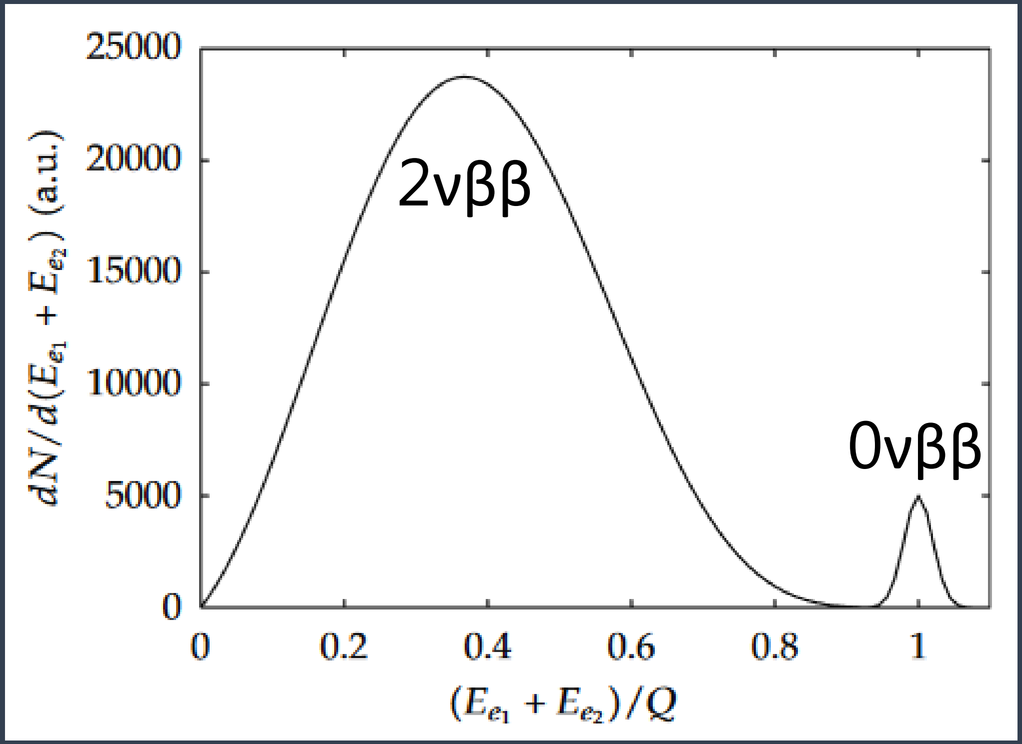
Speaker: Soud Al Kharusi

Jun 20, 2023, 1:45 PM

OUTER DETECTOR



Picture Credit: The nEXO Experiment



Picture Credit: Review Article, Neutrinoless Double-Beta Decay, Andrea Giuliani and Alfredo Poves

The nEXO Outer Detector is a shield that fully submerges the Time Projection Chamber and the Cryostat.

OUTER DETECTOR

The Outer Detector has three purposes:

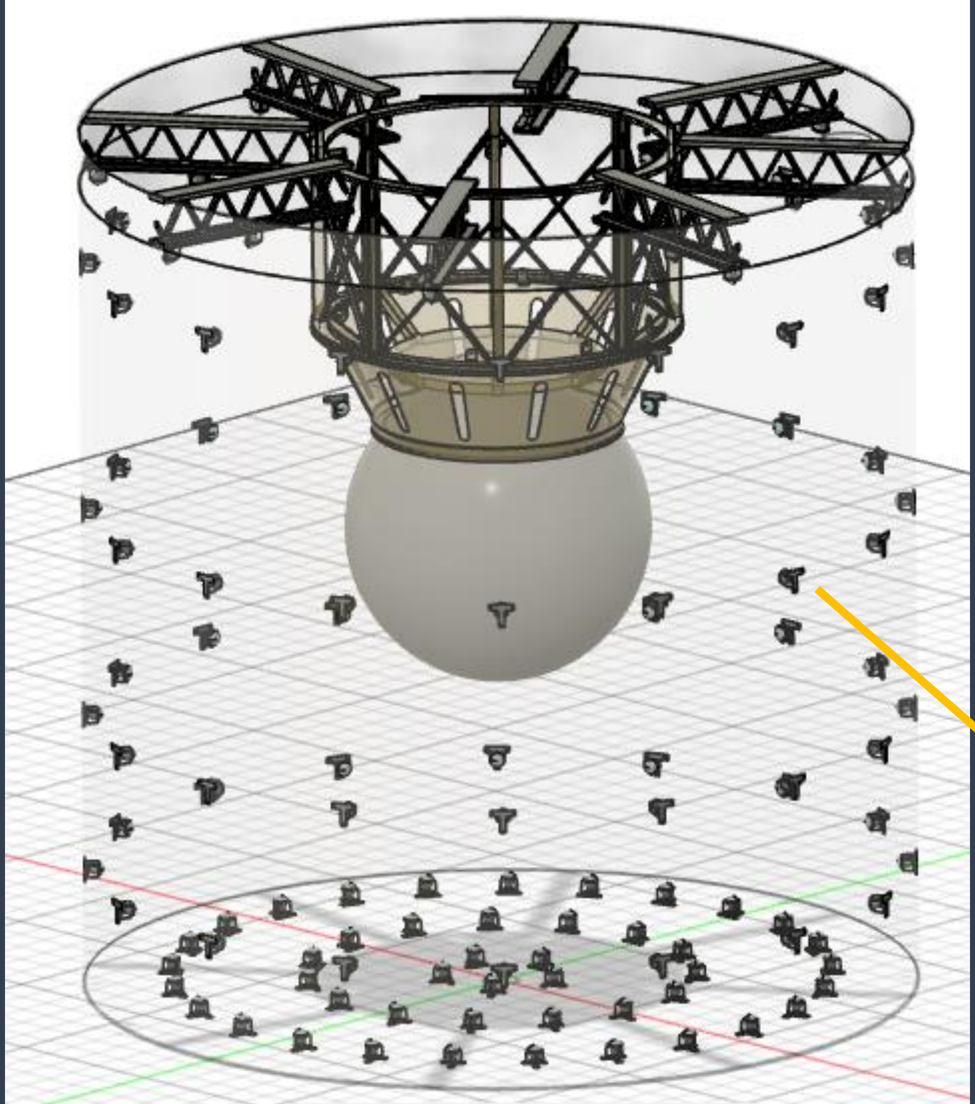
- Protects from external radiation → Passive shielding
- Moderates and stops neutrons → Passive shielding
- Functions as a Cherenkov detector → Active Shielding

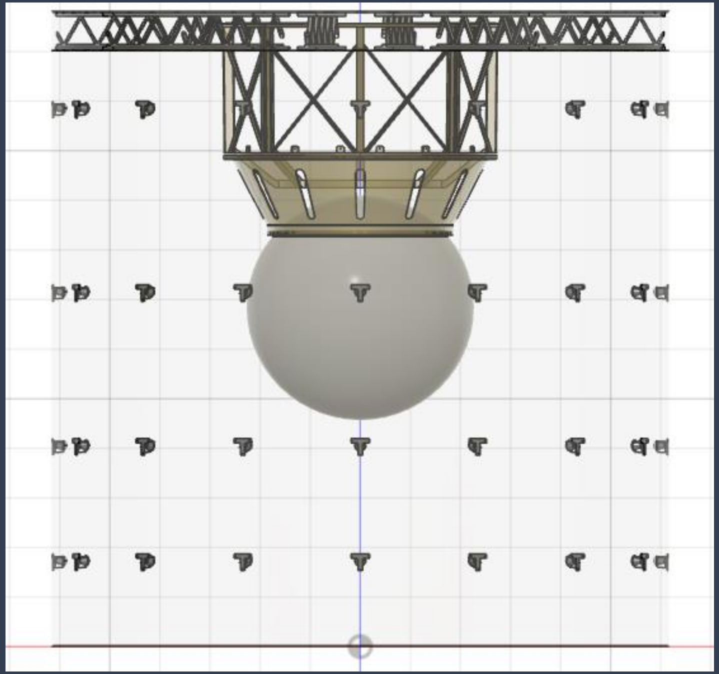
The Outer Detector contains an array of Photomultiplier tubes (PMTs), allowing it to function as a muon veto.

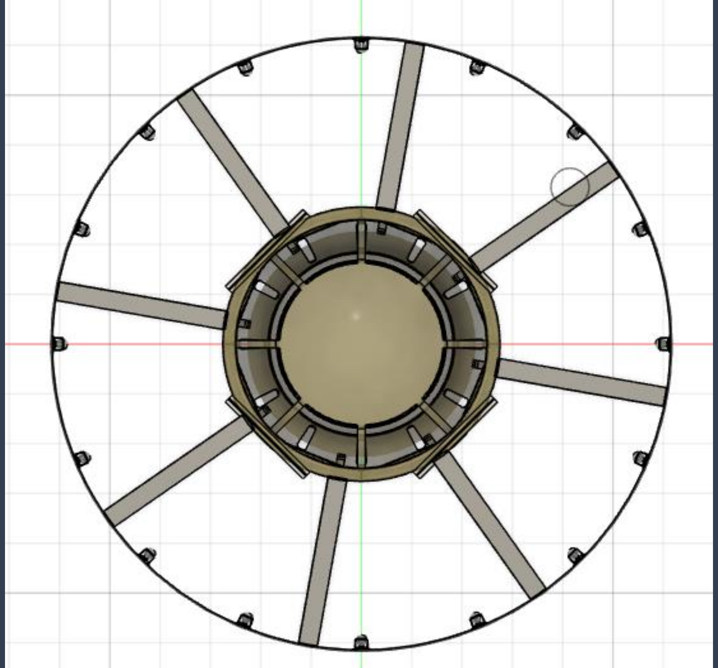
Picture Credit: nEXO pre-conceptual design report

A PMT assembly

OUTER DETECTOR

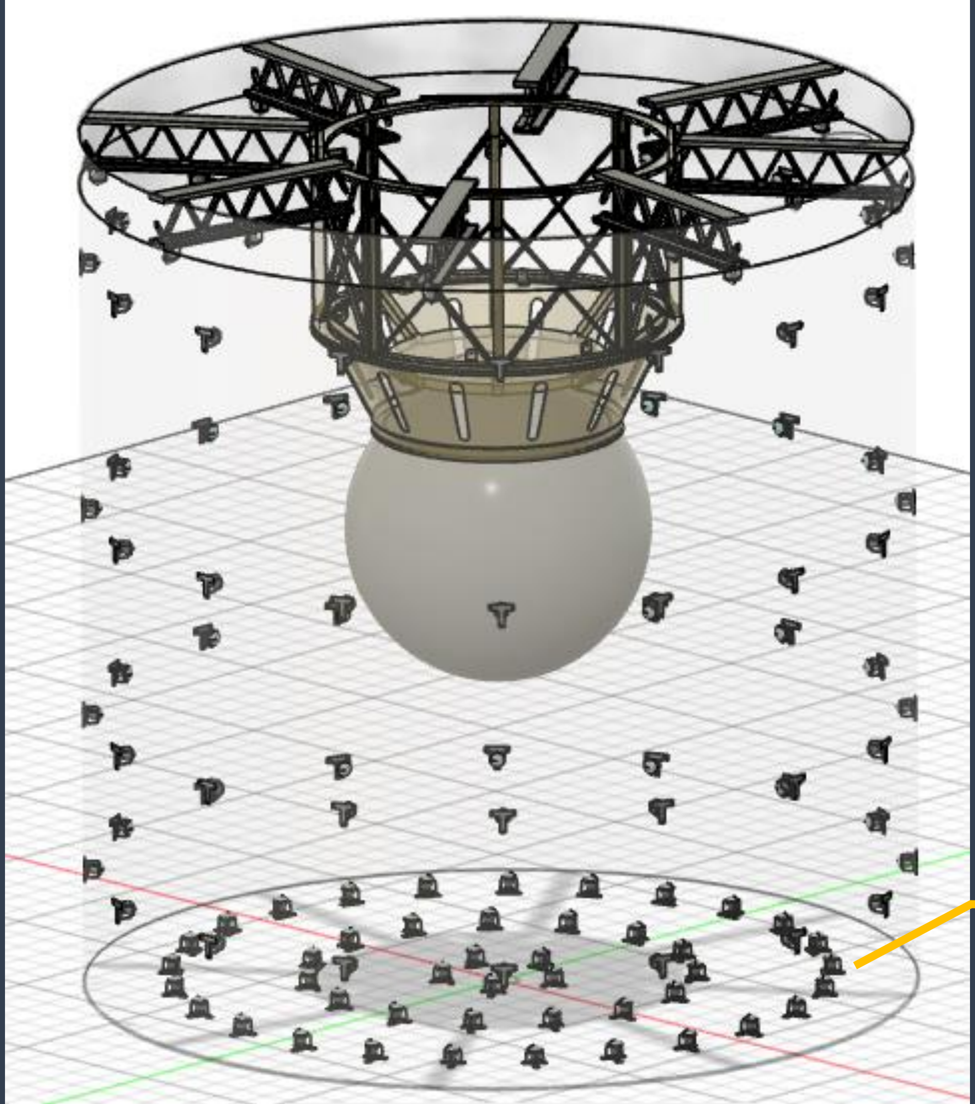


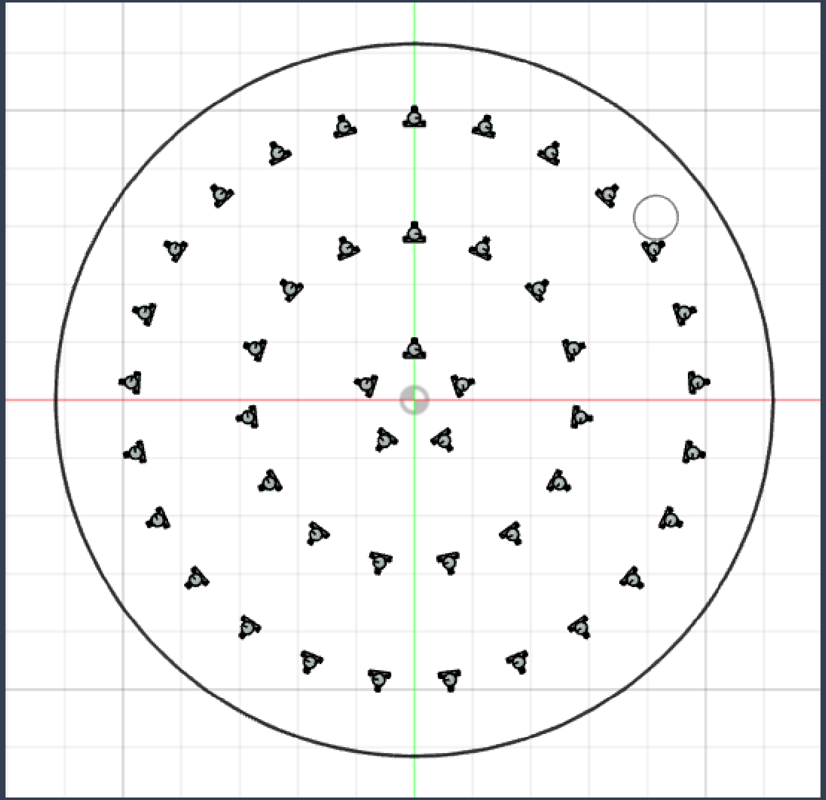




Side PMTs → 64 PMTs
16 columns and 4 rows

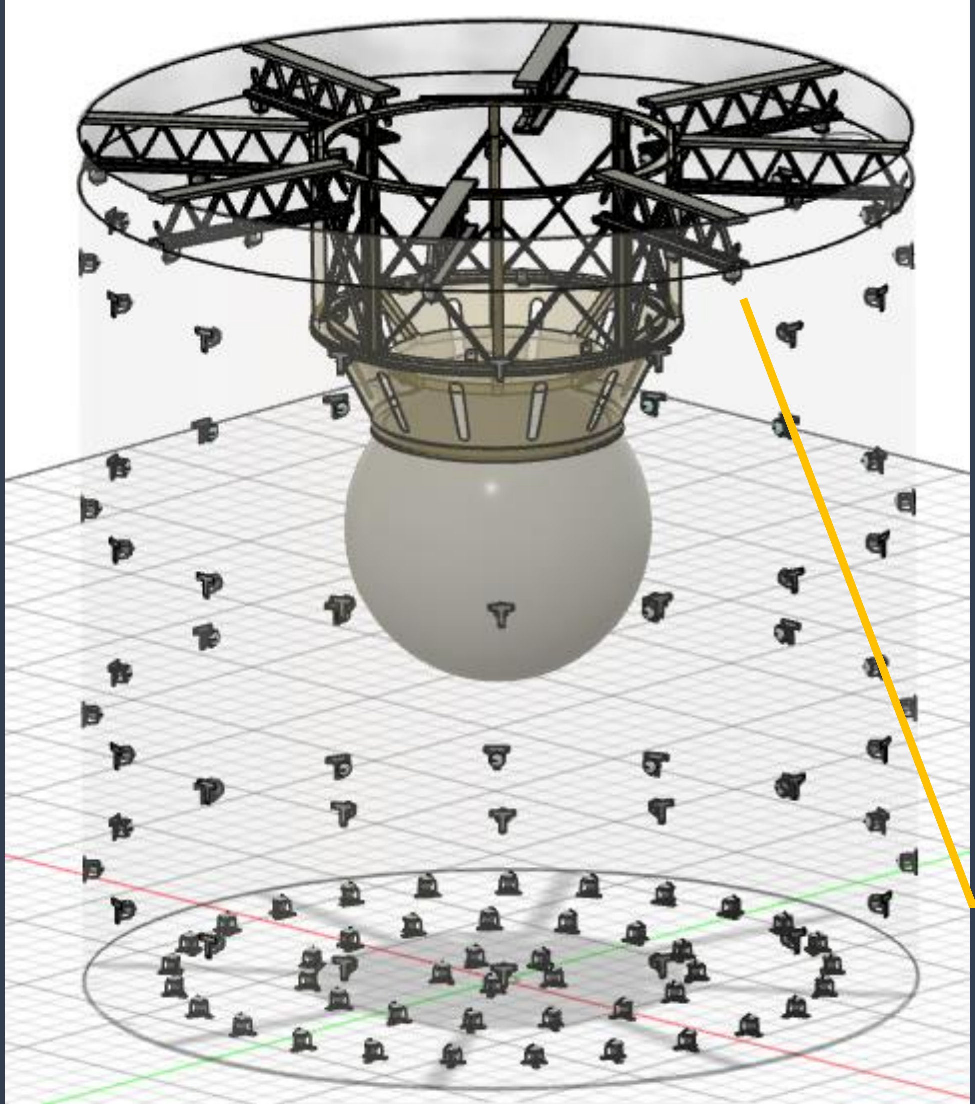
OUTER DETECTOR

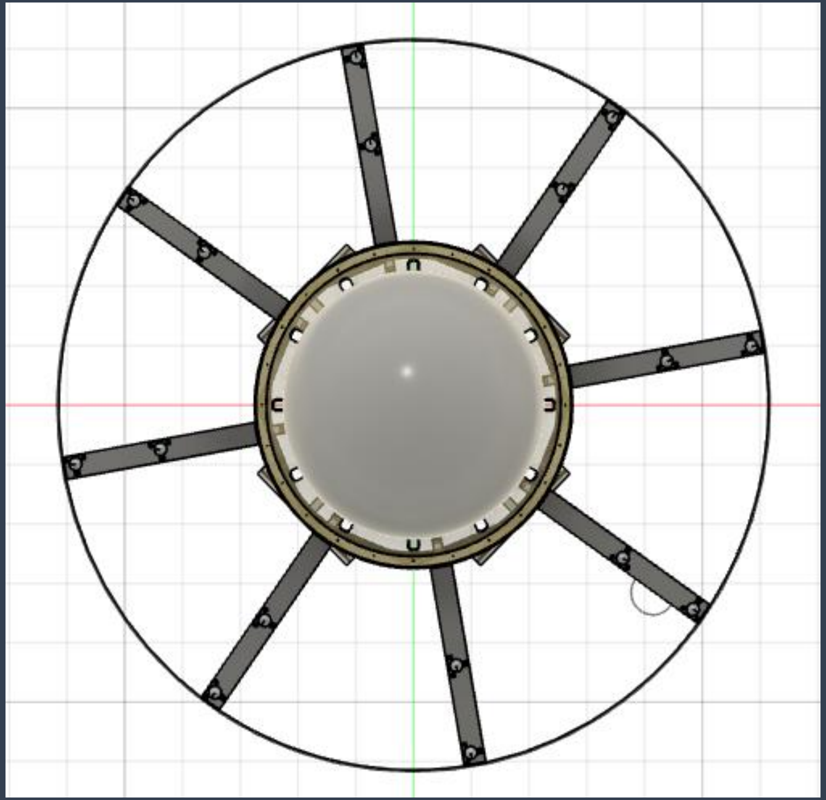




Bottom PMTs → 45 PMTs

OUTER DETECTOR





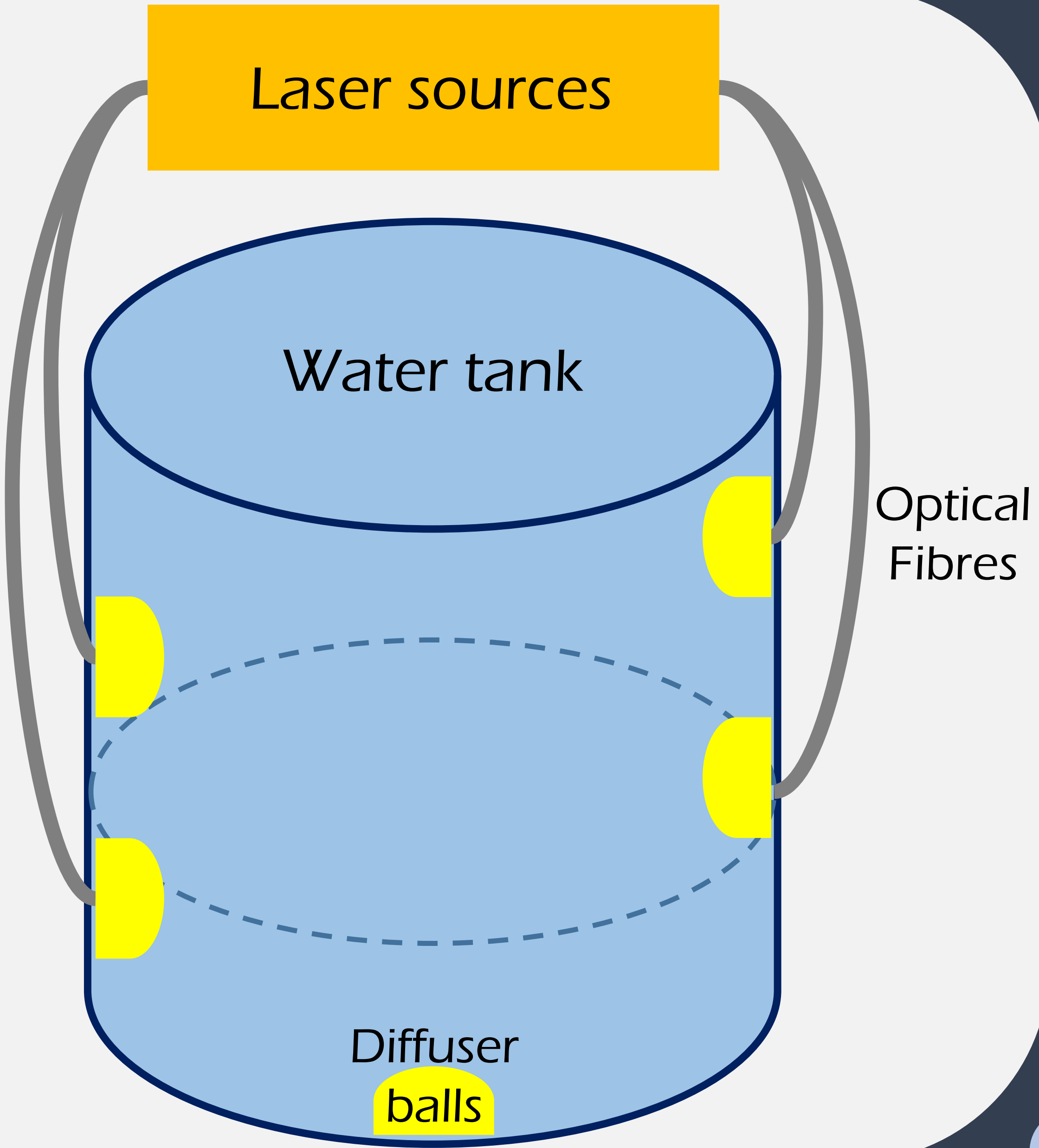
Truss PMTs → 16 PMTs

CALIBRATION SYSTEM

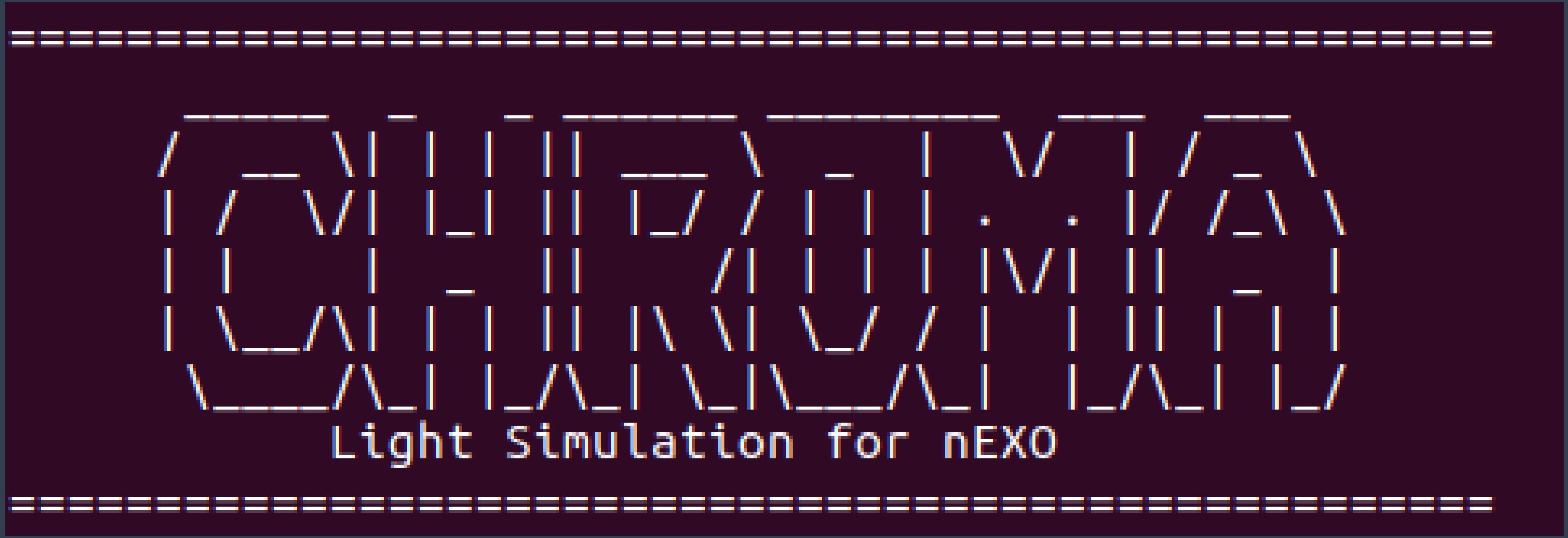
The timing properties of the PMT's readout system should be calibrated, and the optical properties of the water should be monitored.

The calibration system of the nEXO Outer Detector will consist of:

- Laser sources
- Optical fibres
- Diffuser balls



CHROMA

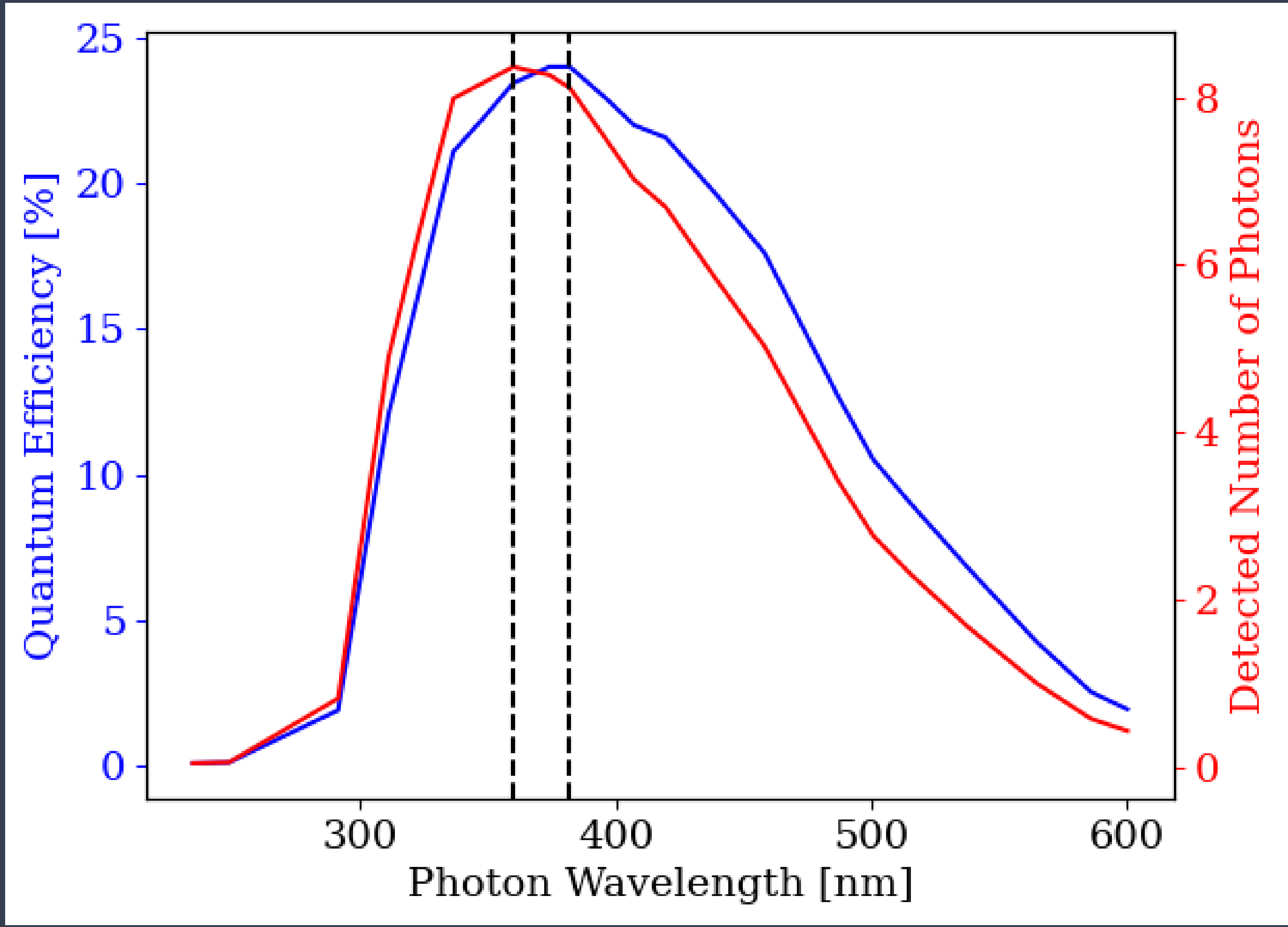


Utilizing a CUDA-enabled GPU, Chroma achieves remarkable performance, allowing it to propagate an impressive rate of 2.5 million photons per second within a detector featuring 29,000 photomultiplier tubes.

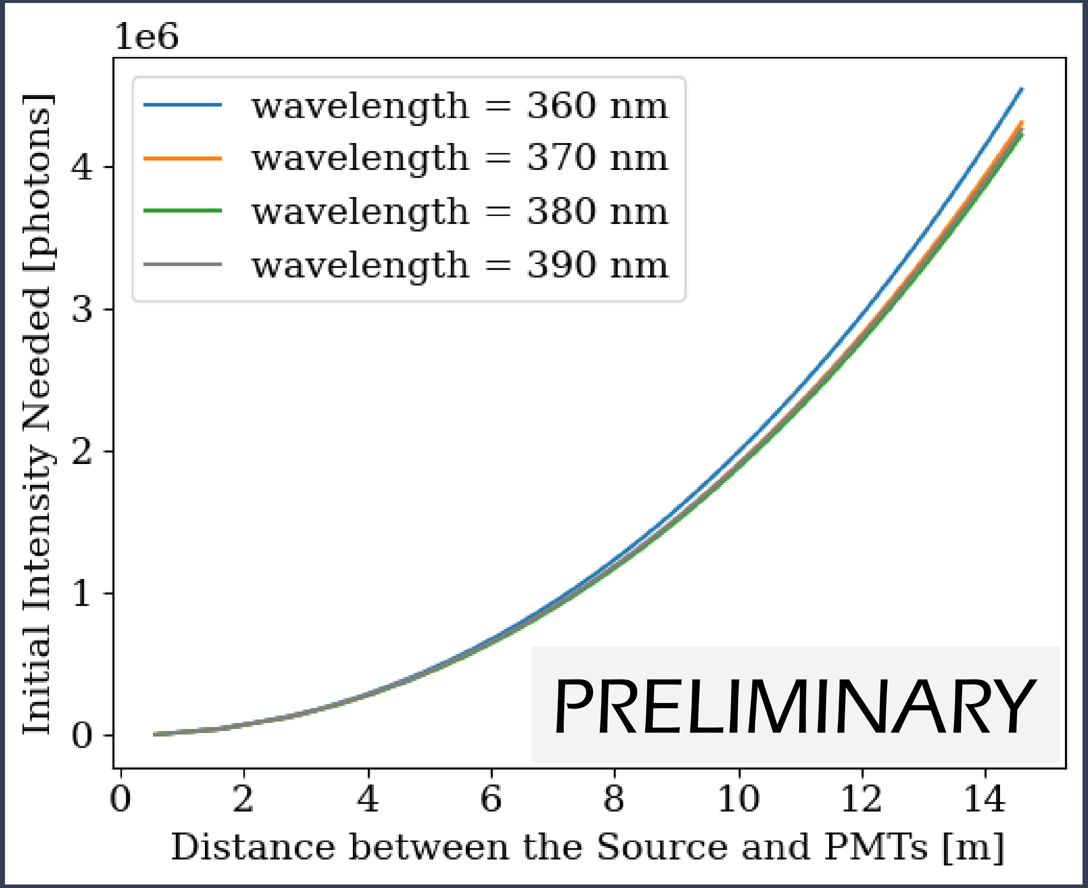
LASER SOURCE

Wavelength?

Does the source wavelength significantly affect the required intensity needed at each PMT location?



LASER SOURCE



The effect is only considerable for the PMTs located far from diffuser balls.

The initial intensity (I_0) needed for each PMT to detect 10 photons (I) as a function of the distance between a diffuser ball and the PMTs.

$$I_0 = \frac{I\, e^{\mu D}}{\varepsilon\, (r^2/4D^2)}$$

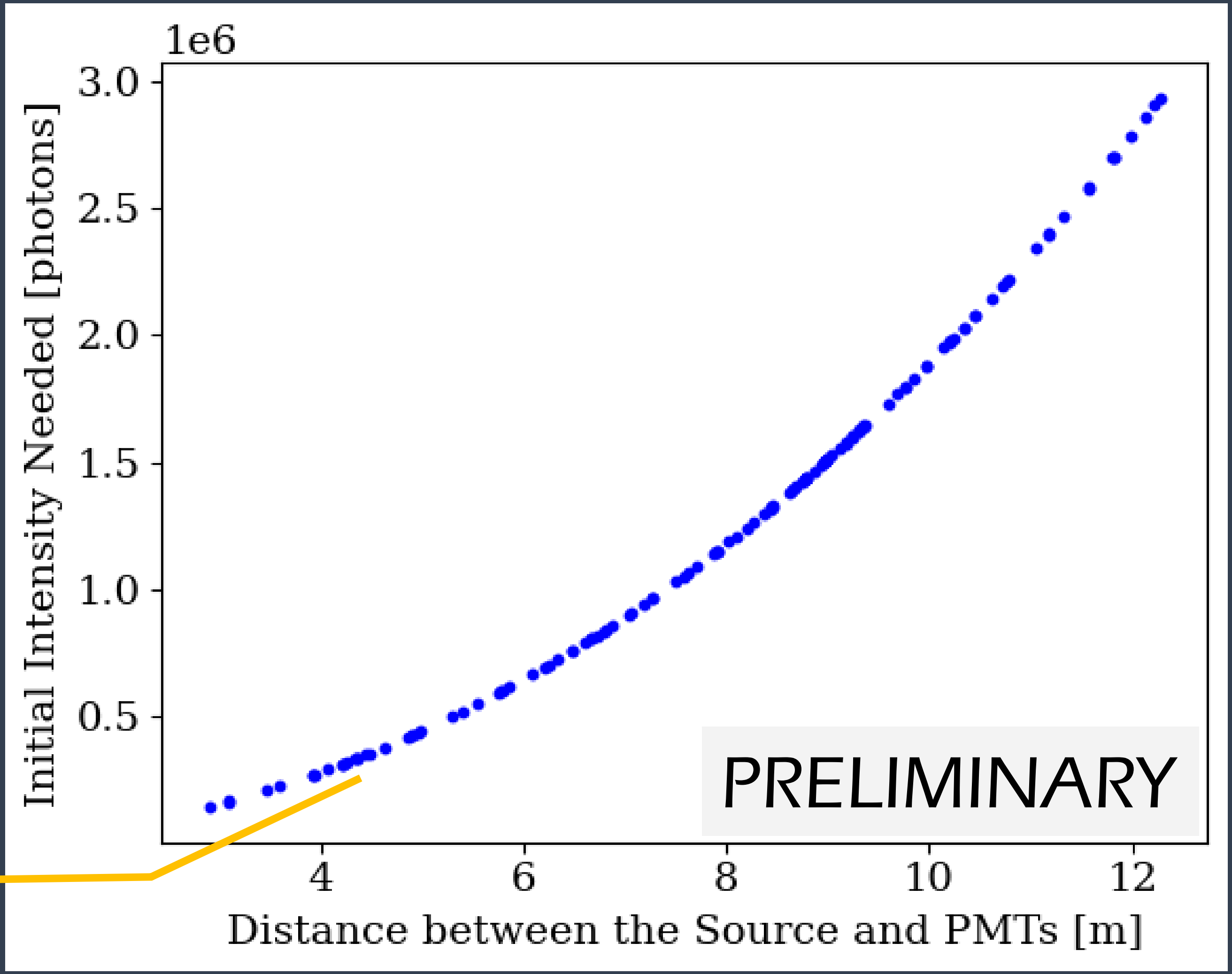
- Attenuation Coefficient (μ)
- Distance (D)
- Quantum Efficiency (ε)
- PMT Radius (r)

LASER SOURCE

Intensity?

Using the position of the diffuser ball, the plot provides information to determine the necessary intensity at each PMT location.

Channel IDs (closest to farthest)



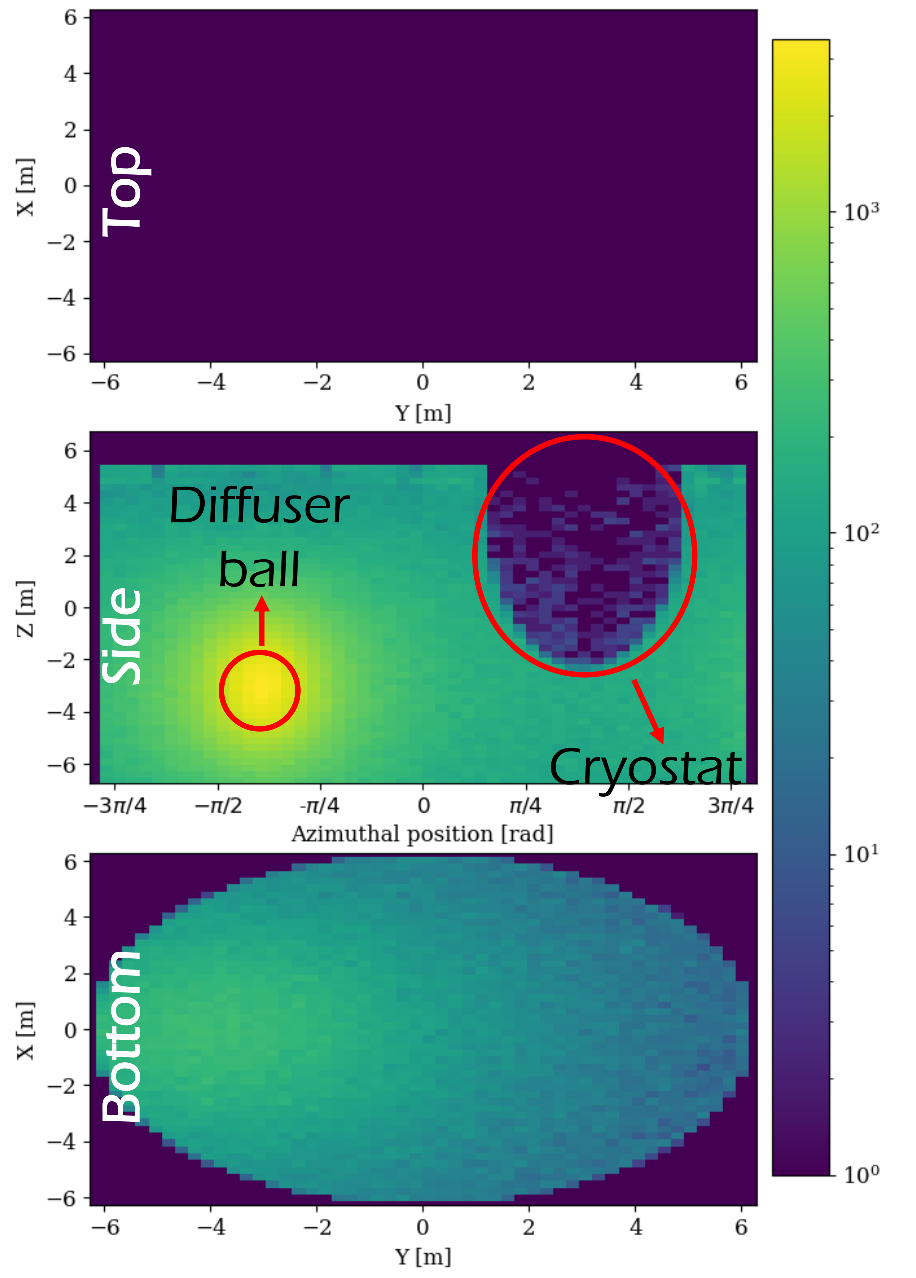
DIFFUSER BALLS

How many?

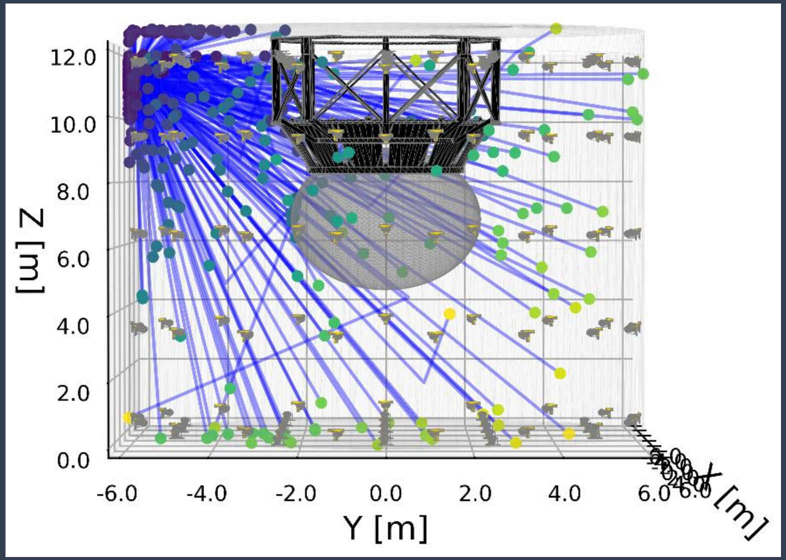
Four to six diffuser balls.

Light map of
the Outer Detector

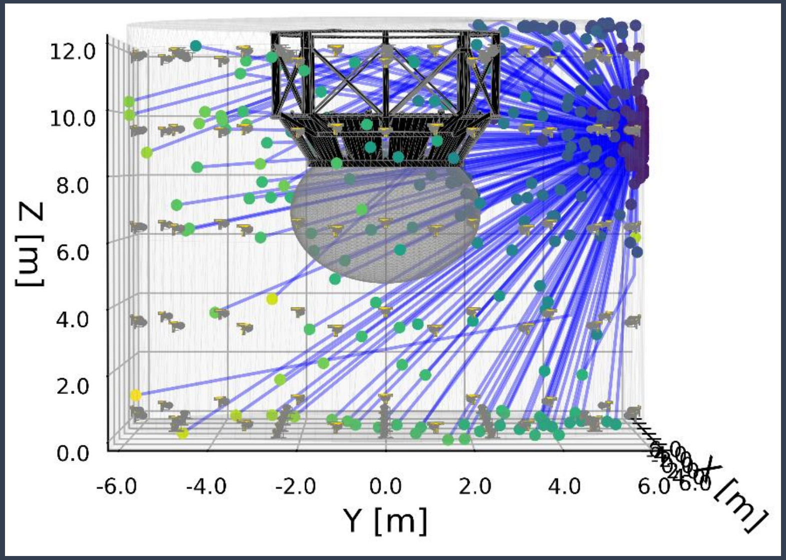
- Diffuser ball location:
  [0, -3, -4]
- Wavelength:
  380 nm
- Number of photons:
  1,000,000

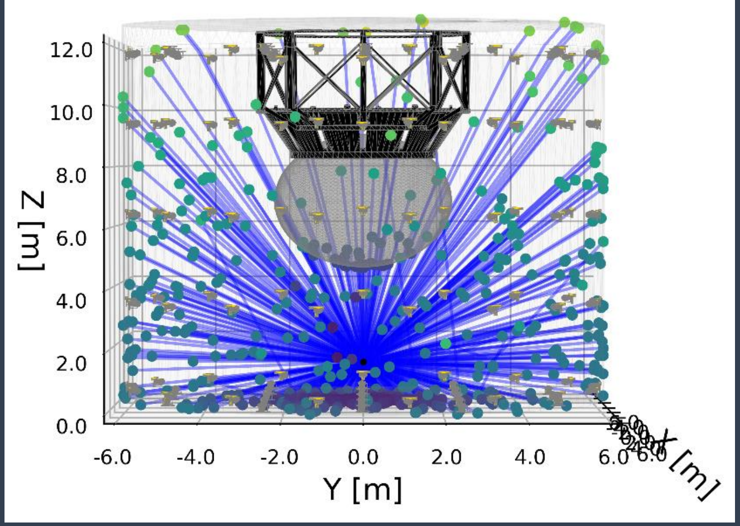


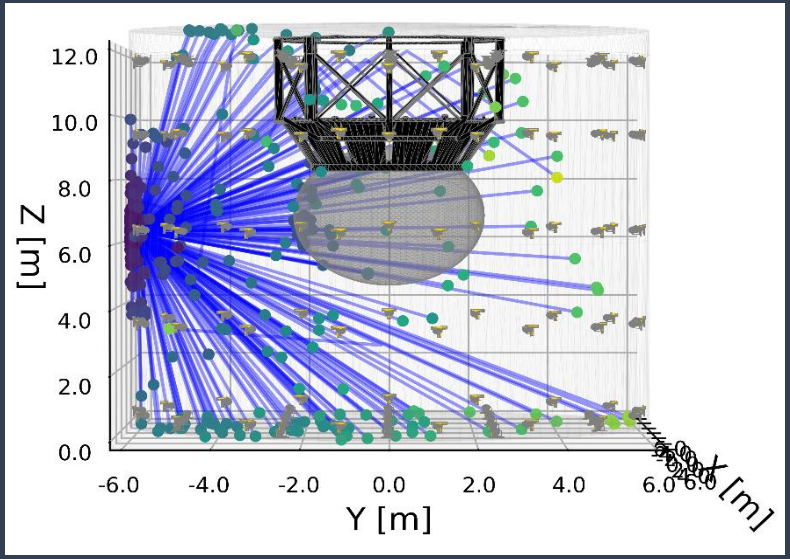
DIFFUSER BALLS

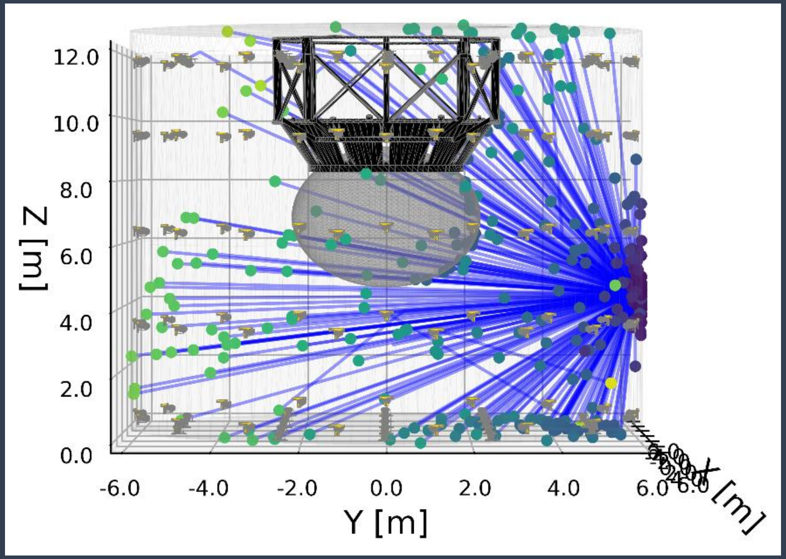


Location?









CONCLUSION

Calibration System for the Outer Detector of the nEXO Experiment:

- Laser sources with a wavelength range of 360 to 390 nm will be utilized.
- The calibration intensity for each photomultiplier tube can be determined.
- Optical fibres transmit light to 4 to 6 diffuser balls within the water tank, enabling the illumination of all photomultiplier tubes.

nEXO

SNOLAB

BNL

BACKUP

Frank-Tamm Formula

The Frank-Tamm formula yields the amount of Cherenkov radiation emitted on a given frequency as a charged particle moves through a medium at superluminal velocity.

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \int \mu(\omega)\, \omega \left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) d\omega$$

$$\frac{dE}{dx} = \frac{q^2}{4\pi} \mu(\omega) \left(1 - \frac{c^2}{v^2 n^2(\omega)}\right) \left(\frac{\omega^2}{2}\right)$$

The Frank-Tamm formula provides the total amount of energy radiated per unit length.

BACKUP

```
[22.32576903 22.51756212 22.80998164 23.6526877  24.80611367 25.79510278
 26.49648878 27.19523543 28.79736091 29.99648443 31.29671874 32.2048756
 32.98691989 34.12278837 34.77839818 36.01571027 37.14707255 38.2305452
 39.66346214 40.93865875 43.2960859  48.75707443 50.72012338]
Total number of photons per mm:  29.42749757568459 8
```

Calculation of the Cherenkov light yield from low energetic secondary particles accompanying high-energy muons in ice and water with Geant4 simulations

Leif Rädel[a], Christopher Wiebusch[a,*]

[a]*III. Physikalisches Institut, RWTH Aachen University, Otto Blumenthalstrasse, 52074 Aachen, Germany*

25 photons/mm for 300 – 500 nm

WolframAlpha computational intelligence.

(2*pi*(1/137)*(1/300- 1/500)*(1-1/((0.9999*1.34)**2)))*1e6

NATURAL LANGUAGE   MATH INPUT   EXTENDED KEYBOARD   EXAMPLES   UPLOAD   RANDOM

Input interpretation

$$\left(2\pi \times \frac{1}{137}\left(\frac{1}{300} - \frac{1}{500}\right)\left(1 - \frac{1}{(0.9999 \times 1.34)^2}\right)\right) \times 1 \times 10^6$$

Result   More digits

27.0878…

27 photons/mm for 300 – 500 nm