Cherenkov Light Simulations with Chroma for nEXO's Muon Veto

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nEXO Experiment

A proposed neutrinoless double beta decay ($0\nu\beta\beta$) detector

- 5 tonne liquid xenon time projection chamber (TPC), enriched to 90% in ^{136}Xe
- Projected half-life sensitivity of 1.35 x 10^{28} years at 90% C.L. [1]

Why $0\nu\beta\beta$?

- Probe the nature of neutrinos as Majorana particles
- Violates lepton number conservation
- This would be physics beyond the Standard Model!

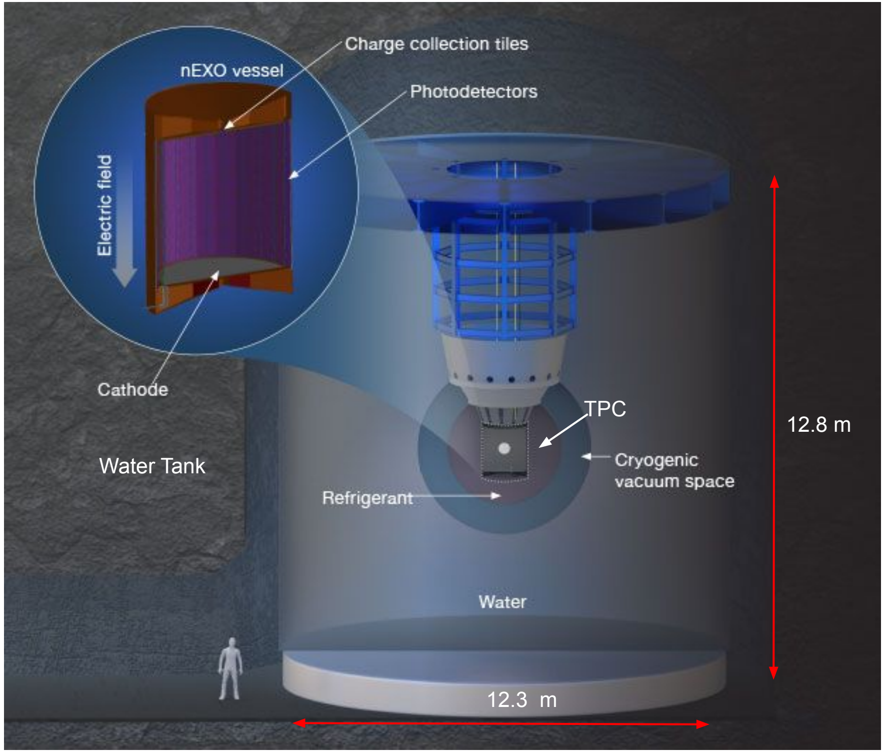


Image credit: Ryan Chen, nEXO

[1] nEXO Collaboration, et al. *nEXO: Neutrinoless Double Beta Decay Search beyond 10^{28} Year Half-Life Sensitivity.* 2021.

The Outer Detector (OD)

The TPC is submerged in a large water tank to shield it from radioactive background and acts as part of the muon veto.

- Filled with 1.5 kt of ultra-pure water
- Mounted inward facing photomultiplier tubes (PMTs) to detect muon Cherenkov light
  - The PMTs along with the water tank make up the OD

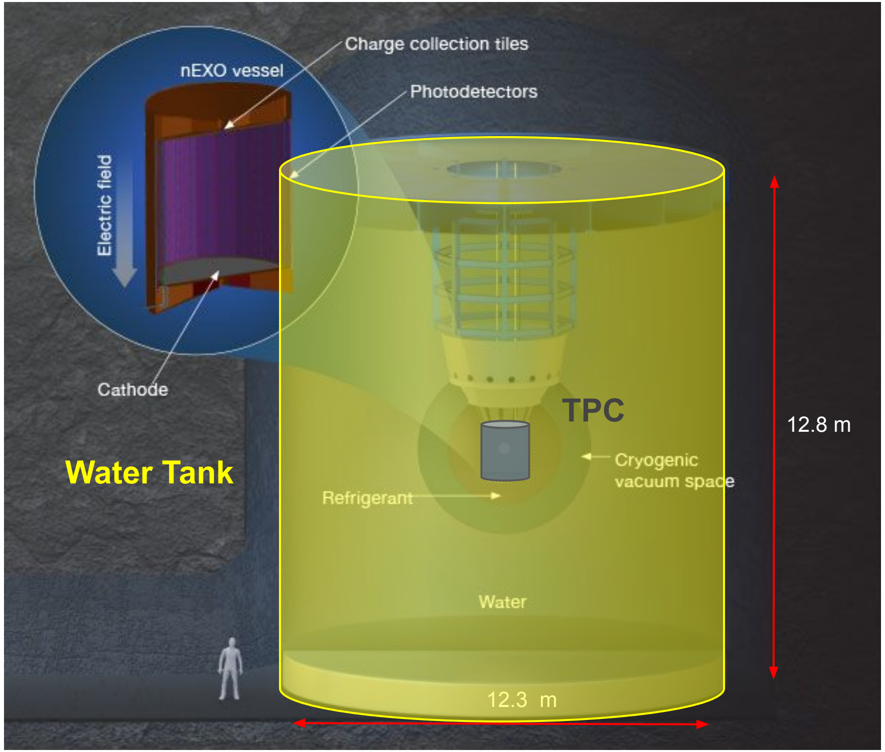


Image credit: Ryan Chen, nEXO

What we have been doing: simulating this using Chroma!

Chroma

- Ray-tracing package for optical photons
- GPU-based, configurable in Python
- At least 100x faster than comparable GEANT4 photon transport simulations

Simulation are controlled by input Yaml files:

- Easy to change the simulation set up without editing source code

Two part code:

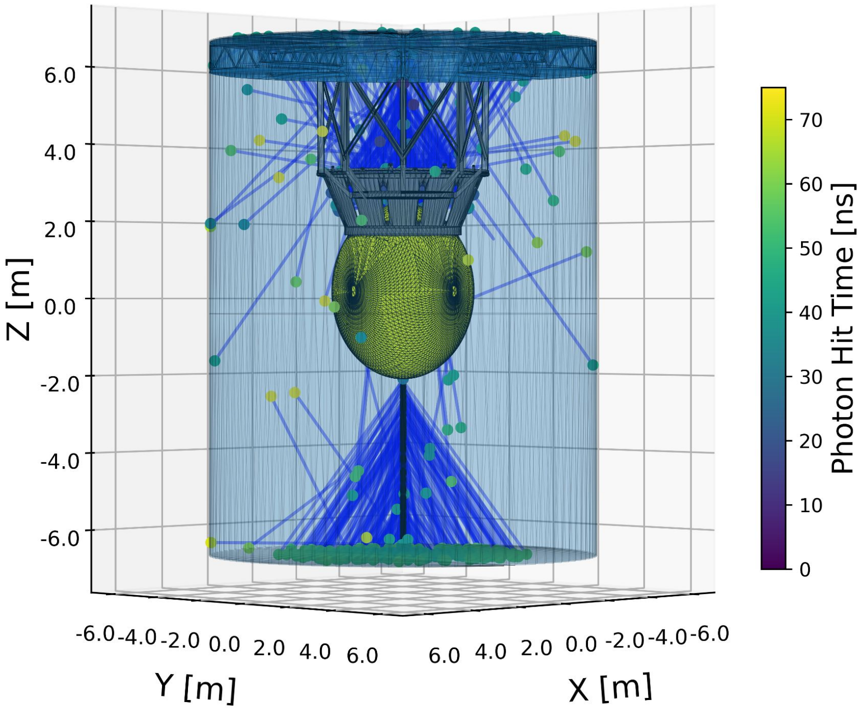
Chroma Singularity Container:
Chroma source code
CUDA drivers
Python packages

chroma-simulation GitHub repository:
Simulation scripts
Analysis scripts
Jupyter notebooks
Input data (CAD, muon data)

Our goal:

Use Chroma to generate simulations of nEXO's Outer Detector (OD) muon veto.

1. Set up the OD geometry and optical properties
2. **Generate muons** that cross the OD
3. Generate the expected **Cherenkov light** from these high energy muons inside the water tank
4. Chroma **propagates the photons**, some are detected by the PMTs
5. Apply analysis work for **muon tagging efficiency** and lightmaps

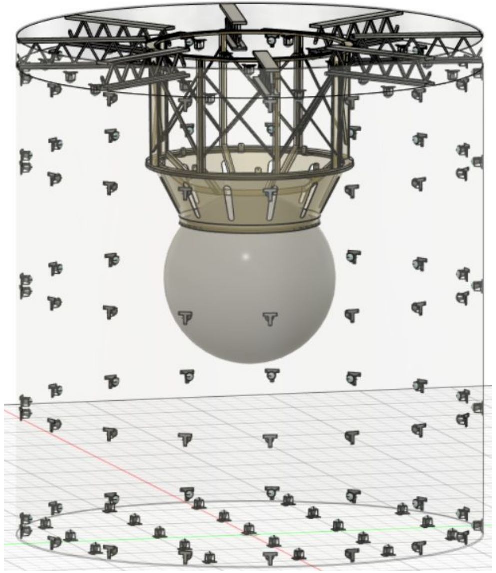


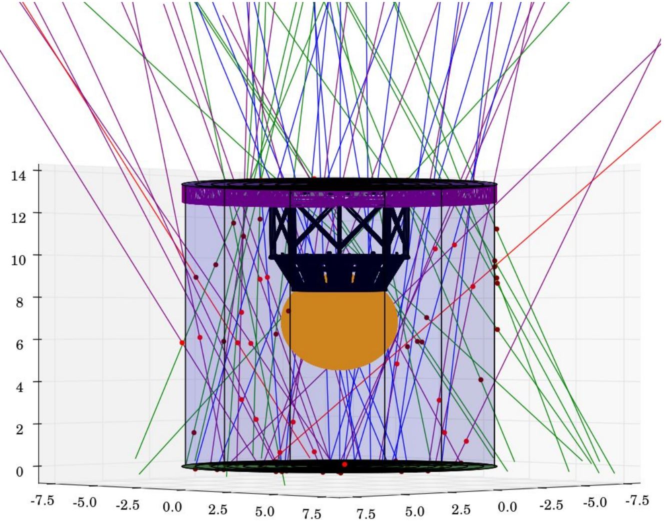
Paths of photons from a single muon.

CAD Models

Chroma requires CAD (.stl) files of the geometry. Models of the OD have been made in Fusion 360 of the:

- Water tank
- PMTs
- Outer cryostat
- Outer cryostat supports





Muon Generation - Regan Ross

Python code that produces a list of high energy muons to run simulation with.

Each muon in the produced file has:

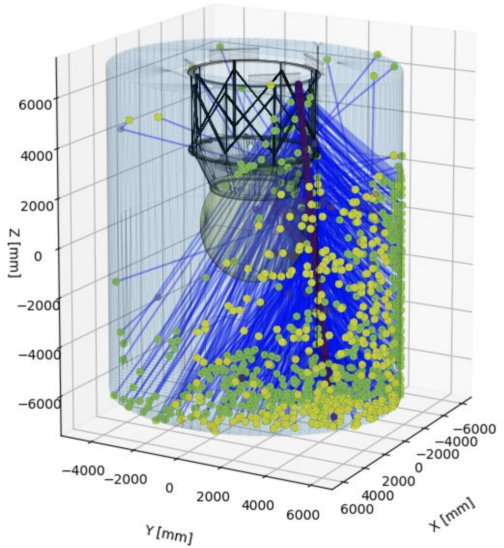
- Energy [GeV]
- Angle
- Entry position from tank
- Exit position from tank

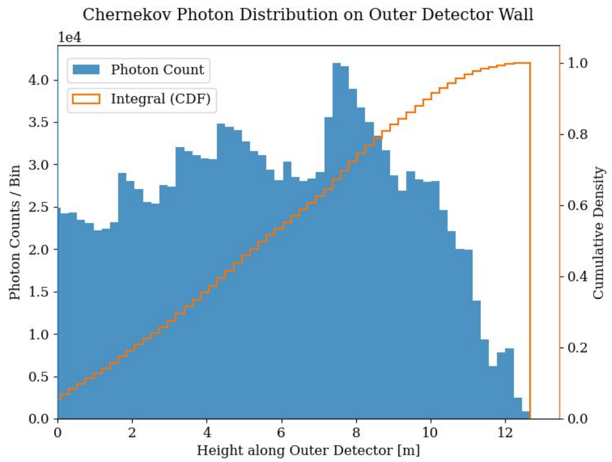
Cherenkov Light

For each muon, Cherenkov light must then be generated correctly. This requires:

1. Number of Photons → Frank-Tamm formula
2. Location → Random position along muon path
3. Direction → Cherenkov angle & azimuthal angle
4. Wavelength → Sample from distribution
5. Timing from muon entry to WT

Then each photon is passed to the Chroma source code to be propagated.





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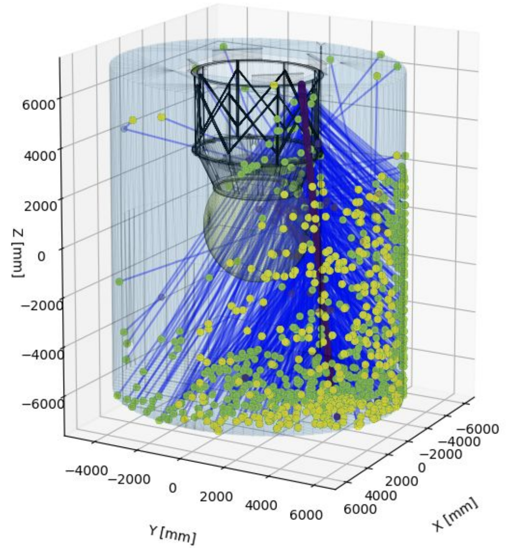

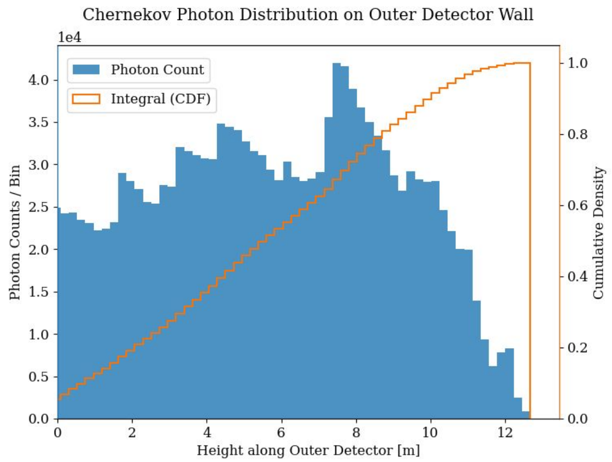

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1) Number of Photons

Integrating the Frank-Tamm formula [2].

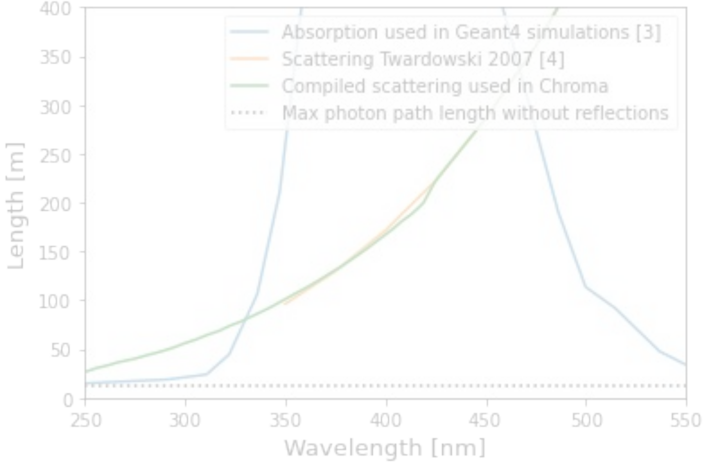
$$N = 2\pi\alpha\left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)\left(1 - \frac{1}{\beta^2 n^2}\right)$$

N : The number of photons that are released per length
n : Index of refraction
β = v/c : Set by muon's energy
$\lambda_{min/max}$: Minimum and maximum wavelengths
α : Fine structure constant

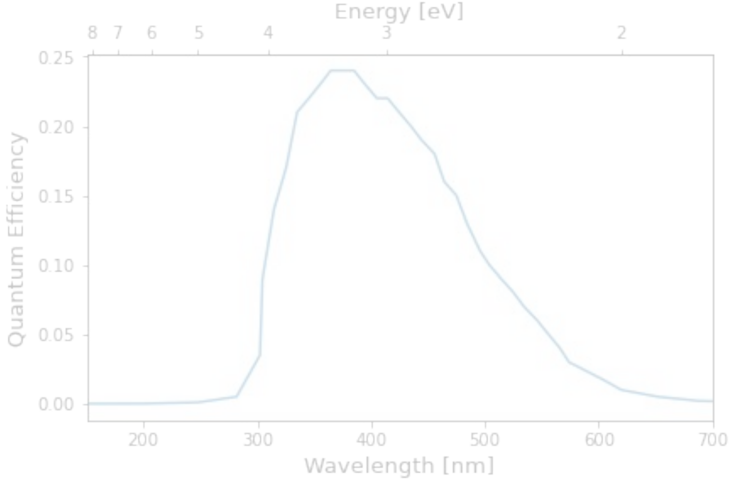
Requires a wavelength range:
λ = 290 - 600 nm

This range is based off of the spectrum of:

The absorption & scattering in pure water



The effective wavelength range of the PMTs [5]



[2] Handbook of Radioactivity Analysis (Third Edition), 2012, Pages 935-1019
[3] H2O data from nEXO-offline
[4] Twardowski, M. S., et al. "Optical Backscattering Properties of the 'Clearest' Natural Waters." Biogeosciences, vol. 4, no. 6, Nov. 2007, pp. 1041–58.
[5] Borosilicate (Pyrex) optical properties, according to DB XML files from Daya Bay DDDB/materials/pyrex.xml

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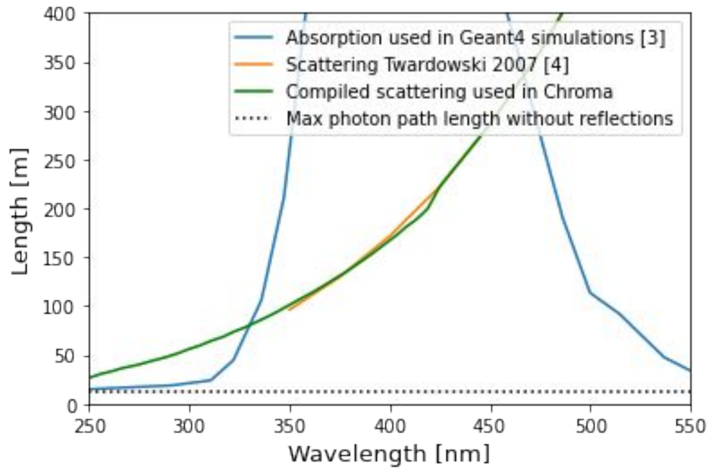

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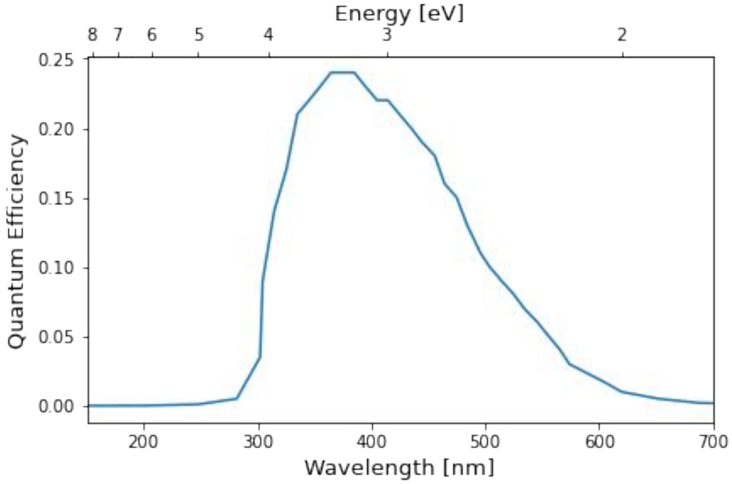

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3) Direction

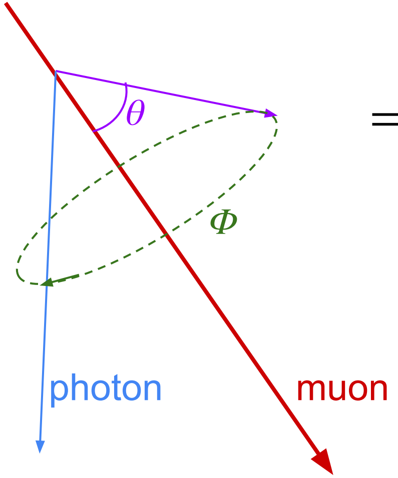
The **Cherenkov angle (θ)** is a function of the muon's energy and the index of refraction.

$$\theta = arccos(\frac{1}{\beta n}) \approx 41.2^{\circ}$$

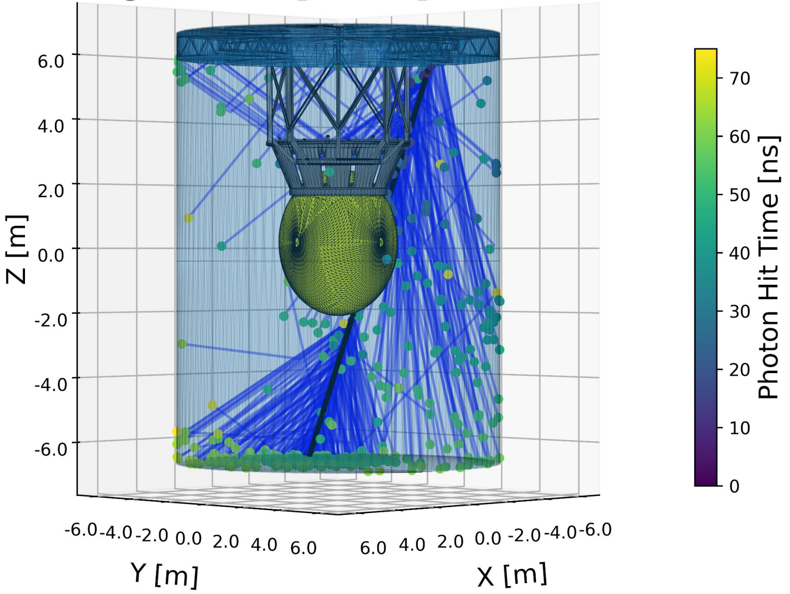
For β very close to 1 and n = 1.33

Each photon's direction is calculated by:

1. Rotating a vector along the muon's direction by θ wrt the muon vector
2. Rotating around the muon vector by a random angle, $\Phi \in [0, 2\pi]$



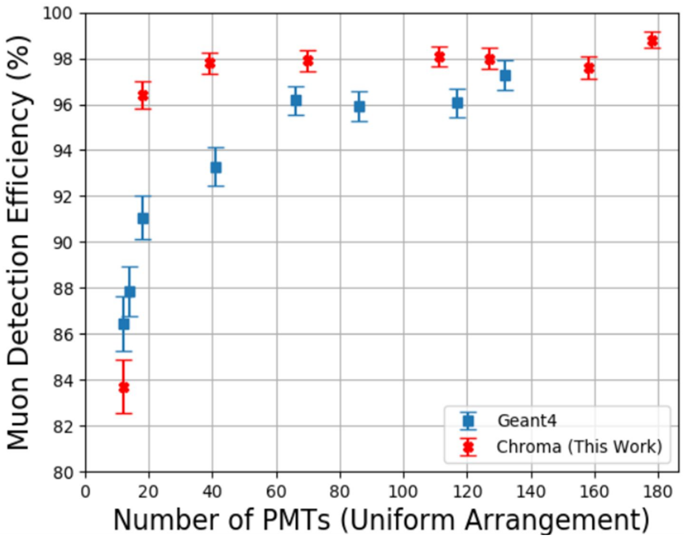
$\Rightarrow$ Together these give the characteristic cone shape of the Cherenkov radiation.



Preliminary Results

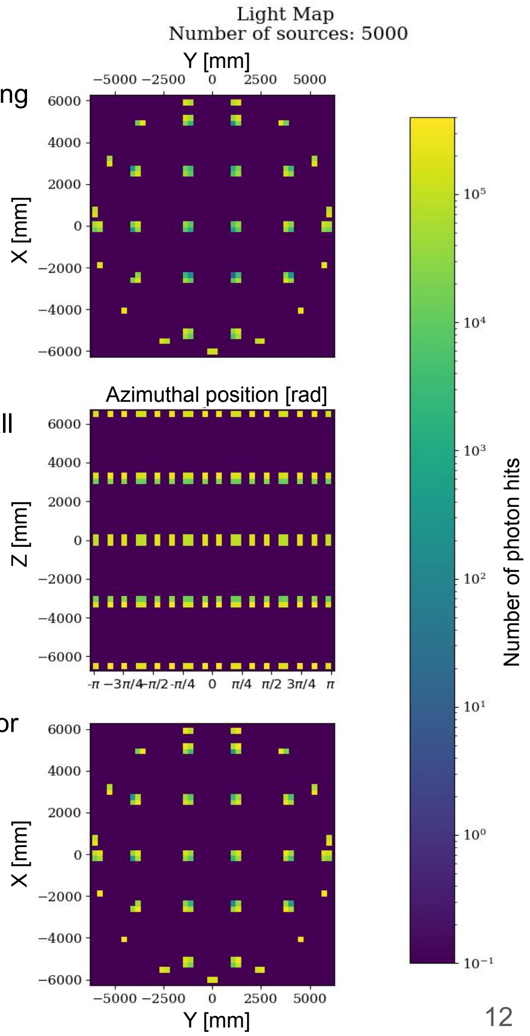
Simulation output includes:

- Where the photons hit
- Which photons are absorbed vs detected
- Resulting wavelength and timing distributions
- Dynamic range of PMTs



Left: Tagging efficiency with uniform PMT distribution (98% reflectivity, 200 ns window)

Right: Light map from 5000 muons using arrangement of 111 PMTs



Ongoing Work

Model PMT response - Liam Retty

- Poster: (U*) (POS-39) “PMT Response Simulation and Long-Term Reliability Studies for nEXO's Muon Veto”

  https://indico.cern.ch/event/1072579/contributions/4788636/

Use lightmaps for PMT placement optimization - Soud Al Kharusi

- Poster: (G*) (POS-42) “Simulating nEXO's Outer Detector with Chroma”

  https://indico.cern.ch/event/1072579/contributions/4788564/

Muon background generation - Regan Ross

- Poster: (U*) (POS-40) “Cosmogenic Muon Background Characterization for nEXO”

  https://indico.cern.ch/event/1072579/contributions/4788628/

Acknowledgments

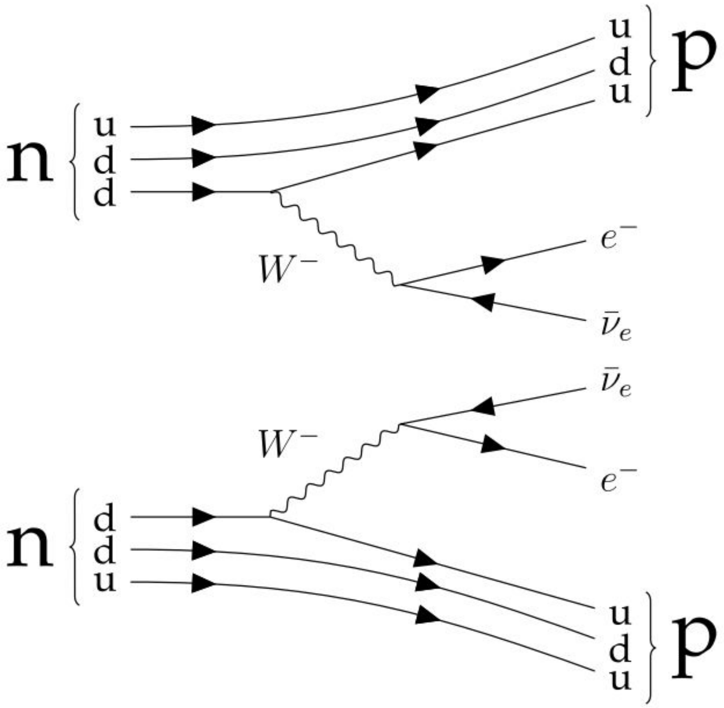
Undergrads: Liam Retty, Regan Ross, Megan McArthur

nEXO-OD group: Soud Al Kharusi, Thomas Brunner, Erica Caden, Caio Licciardi, Allen Odian, Ubi Wichoski, Ako Jamil, Remington Hill, David Hawkins, Lisa Kaufman

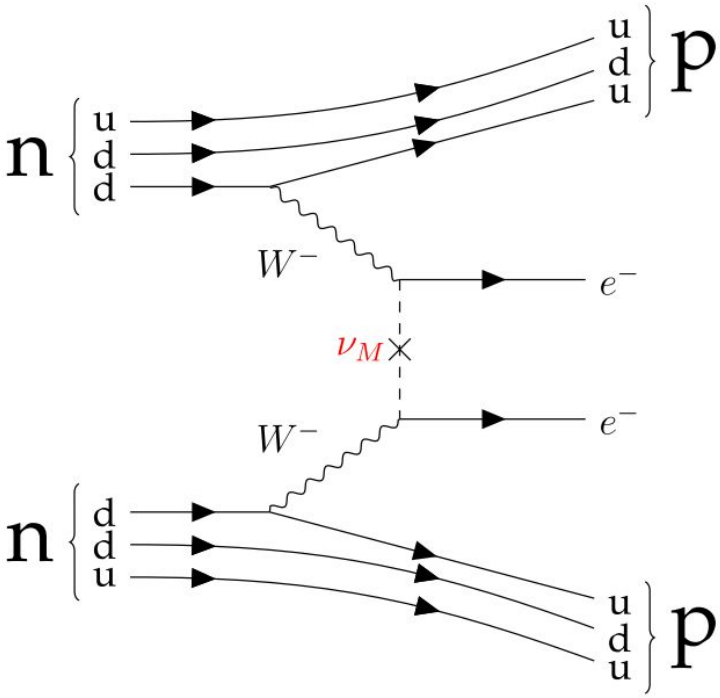
Extra Slides

Neutrinoless double beta decay

$2n \rightarrow 2p + 2e^- + 2\bar{\nu}$



$0\nu\beta\beta$: $2n \rightarrow 2p + 2e^-$



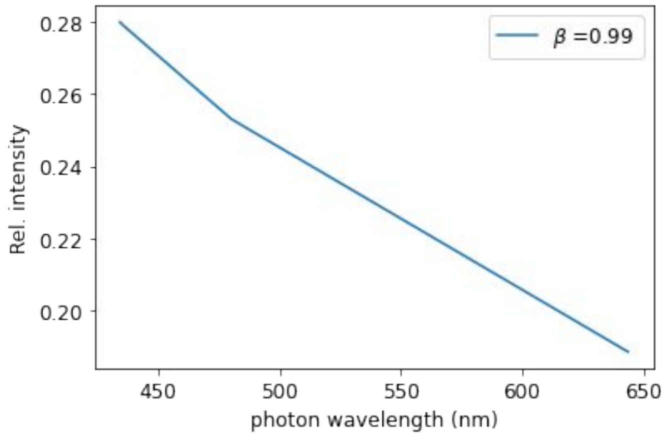
3) Wavelength

The wavelength of each photon is selected from a wavelength vs intensity distribution calculated from the Frank-Tamm Formula, specifically the form that gives the energy loss per unit length:

$$E_{loss} = \frac{1}{4\pi}\nu(1 - \frac{1}{\beta^2 n^2})$$

Where ν is frequency.

We then normalize this equation, which gives a distribution like this



We can then **interpolate** this data to result in a uniformly spaced array of wavelengths (and normalize once again)

- Currently set to between 290-600 nm in Chroma

From this, a **random sampler** is used to select each photon's wavelength, using the relative intensity as the weight of each possible wavelength.

Resulting distribution for 1000000 photons