The Development of Directional Calibration in P-ONE

June 22nd, 2025

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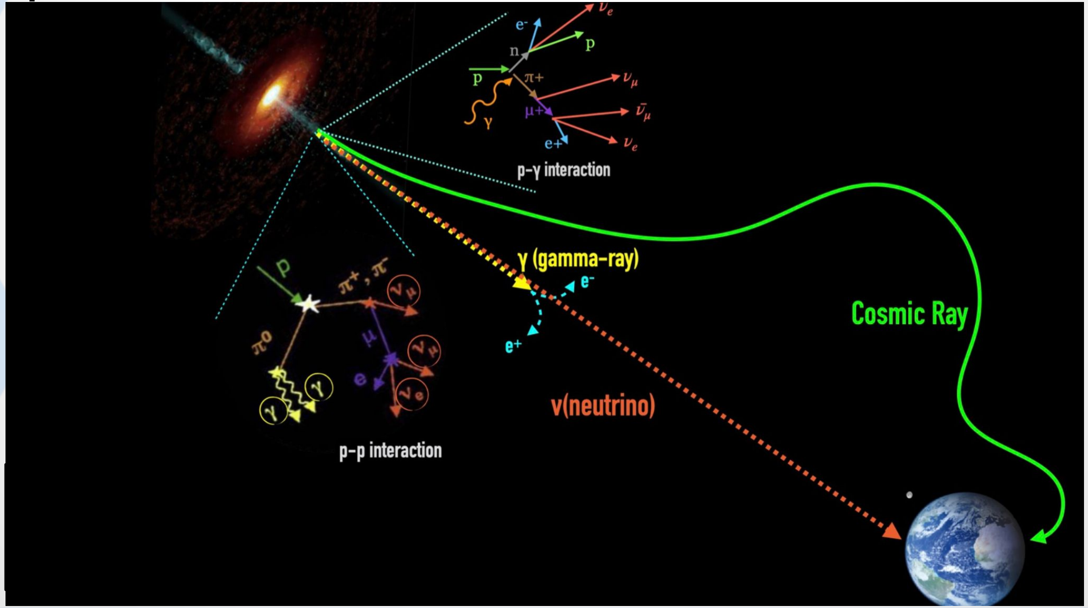
Neutrino Astronomy

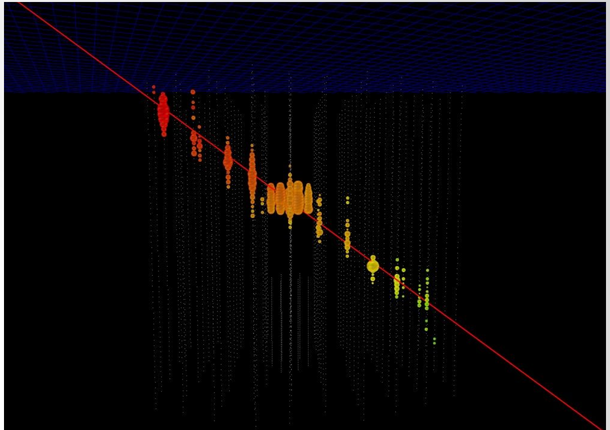
- Due to their weakly interacting nature, neutrinos are effective messengers of astronomical phenomena.
  - Can probe physics behind astrophysical accelerators through the use of **Neutrino telescopes.**

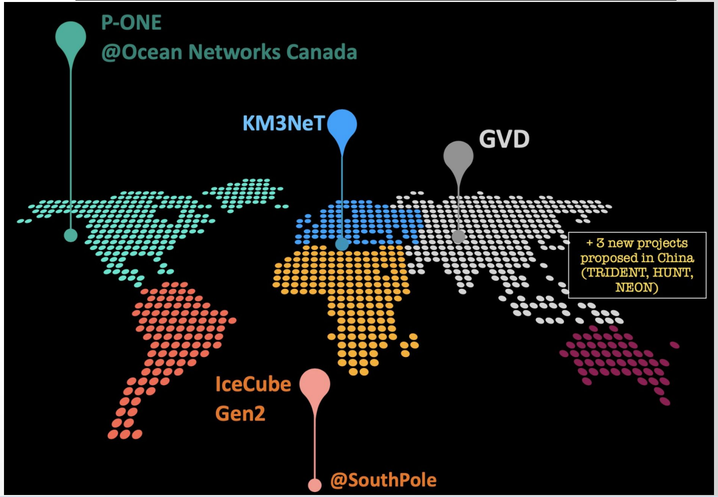


What is a Neutrino Telescope?

- Neutrino telescopes are deployed in large volumes of water or ice, where they search for interactions caused by neutrinos.
    - An array of strings with Optical Modules (OMs), which house Photomultiplier Tubes (PMTs) to detect light.

- Cherenkov light is produced by secondary particles created in **neutrino interactions.**
    - The secondary particle and neutrino trajectory can be reconstructed by using:
        - Amount of Cherenkov light detected.
        - The time of detection in each PMT.

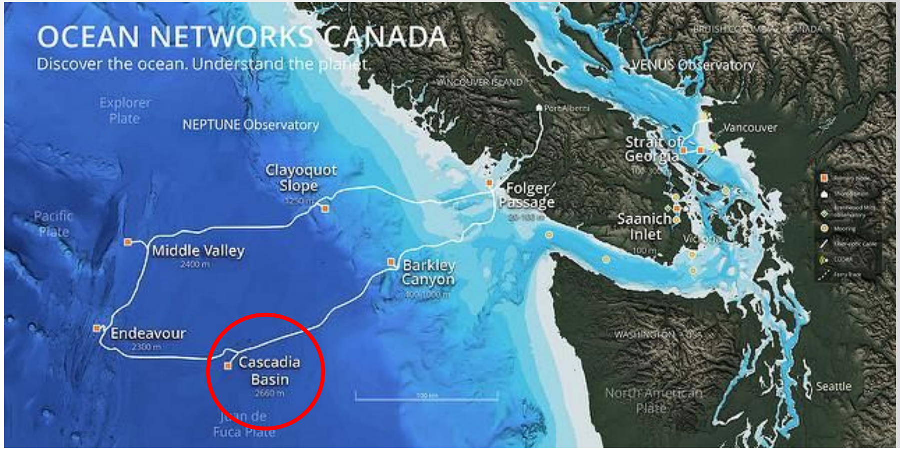

(IceCube, 2014)

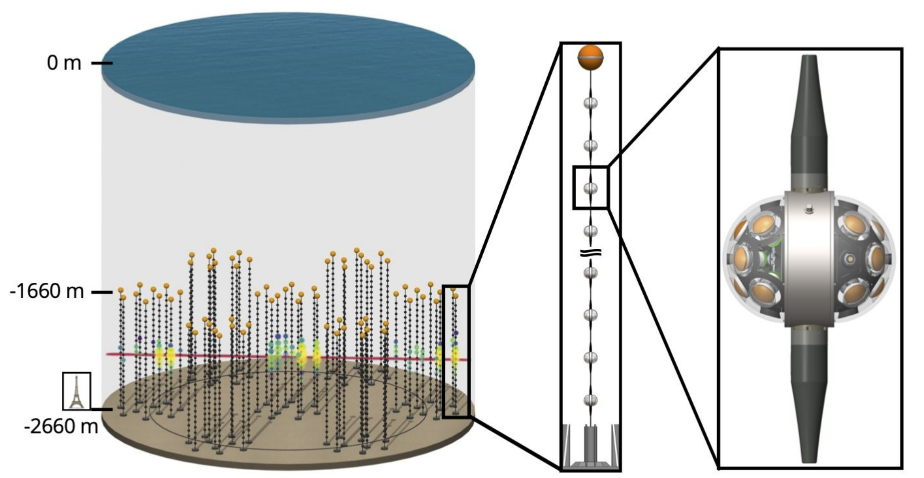


What is P-ONE?

- The Pacific Ocean Neutrino Experiment (P-ONE)
  - A neutrino telescope planned to be deployed off the coast of Vancouver Island.
  - It will be about 2.6 km deep in the ocean.

- Possible with the help of Ocean Networks Canada (ONC) and their NEPTUNE observatory.



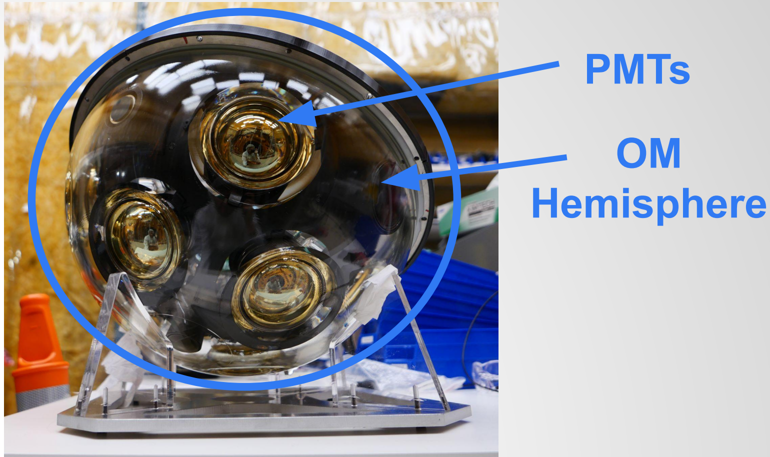


What is P-ONE?

- The full P-ONE array will span a cubic kilometre.
  - It will be optimized for neutrino energies in the TeV-PeV range.

- The first full P-ONE string (called P-ONE-1).
  - Planned for a wet test on June 23rd, 2026.
  - Deployment later this year.

- Directional calibration of P-ONE is important for defining sources of astrophysical neutrinos in the sky.



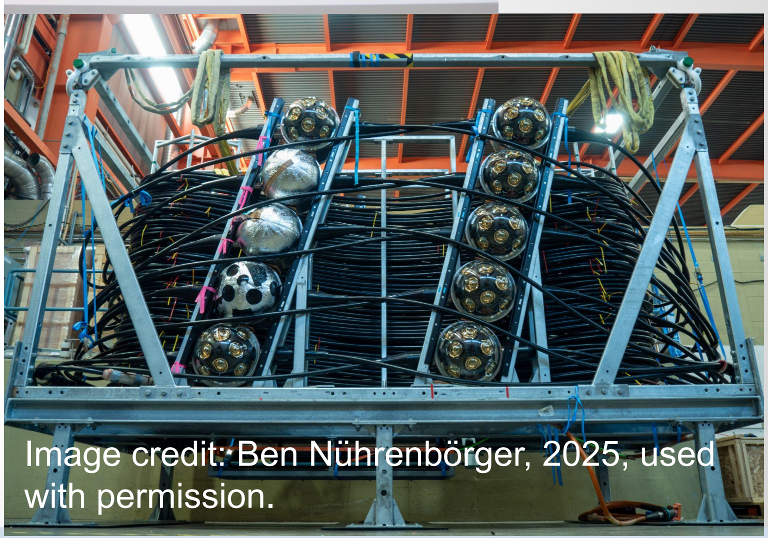


Image credit: Ben Nührenbörger, 2025, used with permission.

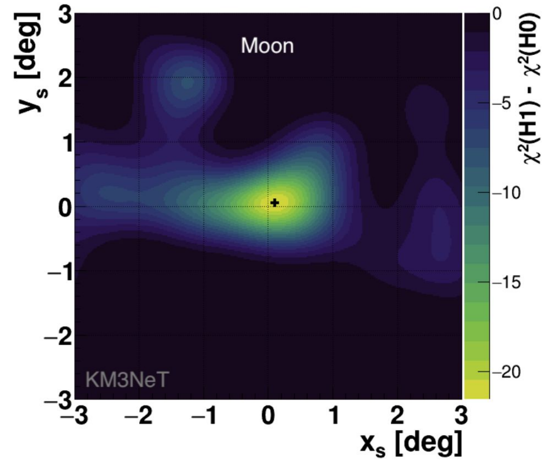
Calibration of Reconstructed events

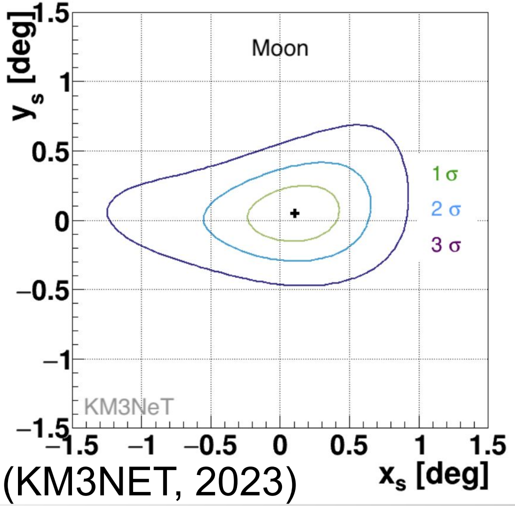
- Unable to shoot particles with a known direction into our neutrino telescope for calibration.

- Typically, the Moon's shadow is used to determine the angular resolution and pointing accuracy of a neutrino telescope.
    - In this study, the radial profile of the deficit of cosmic rays around the Moon defines your angular resolution.

- Other complementary methods for validating pointing accuracy have been attempted.

- These calibration methods have limitations, wouldn't it be better if we had a way to estimate pointing accuracy event by event?





(KM3NET, 2023)

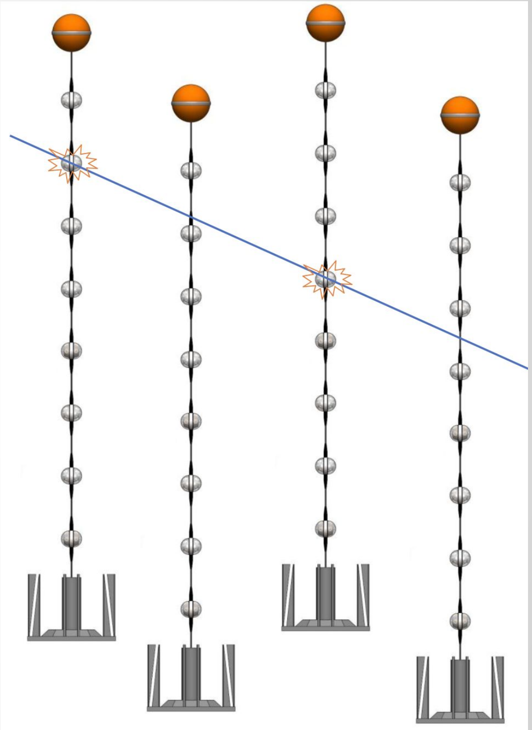
What is the MIST?

- We can utilize **atmospheric muons!**

- Muon In-Situ Tracker calibration system (MIST) sits within each P-ONE module (used on P-ONE-1)

- Uses muons, via ionization in scintillators, to verify the pointing resolution of the PMT event reconstruction.
  - A muon will travel through the water and interact with at least two MISTs located in separate OMs.
  - We can then compare the resulting reconstruction from the PMTs to the calculated vector from the MIST.

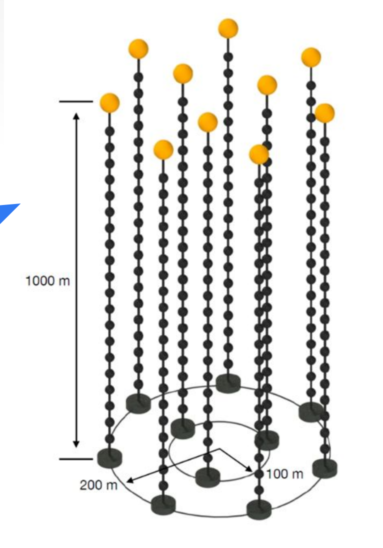
- Uses SiPMs coupled to scintillators as photodetectors

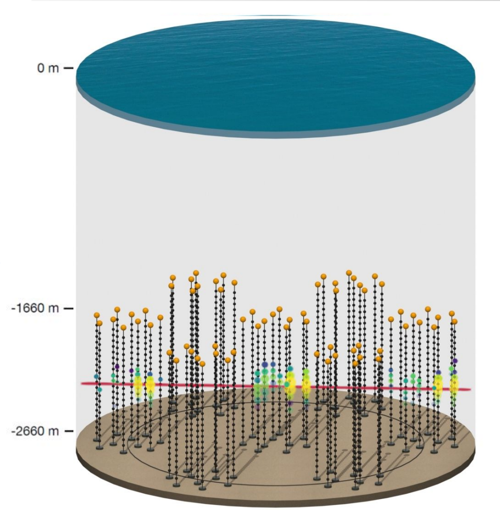


MIST Event Rate

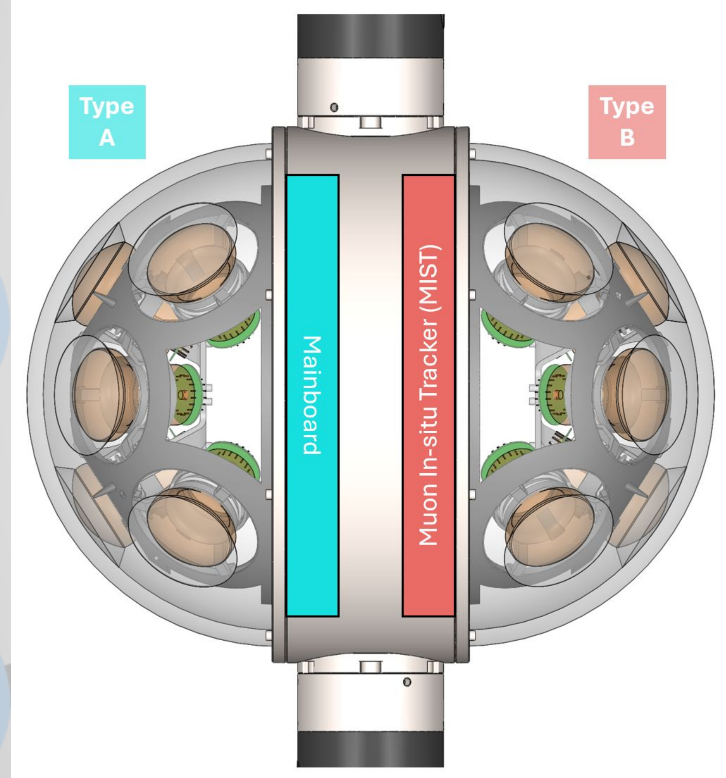
- The rate of potential muons that the MIST will see mainly depends on the spacing between OMs.
  - **P-ONE Cluster**: This will be a cluster of lines (about 10). Here we would expect MIST to observe about 2 muon events per year.
  - **P-ONE**: This is the full array. We would expect MIST to observe about 40 muon events per year.

- Depending on the configuration, we can achieve angular resolution on the scale of 0.02° to 0.2°.





What is the MIST?



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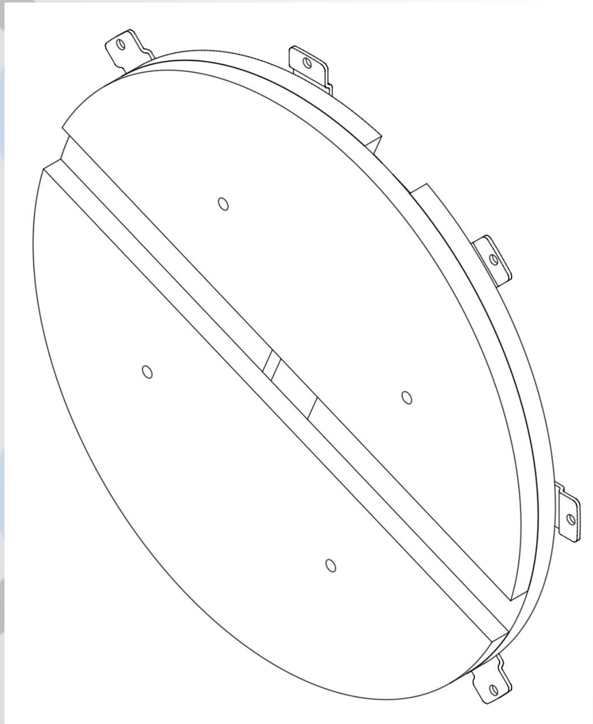
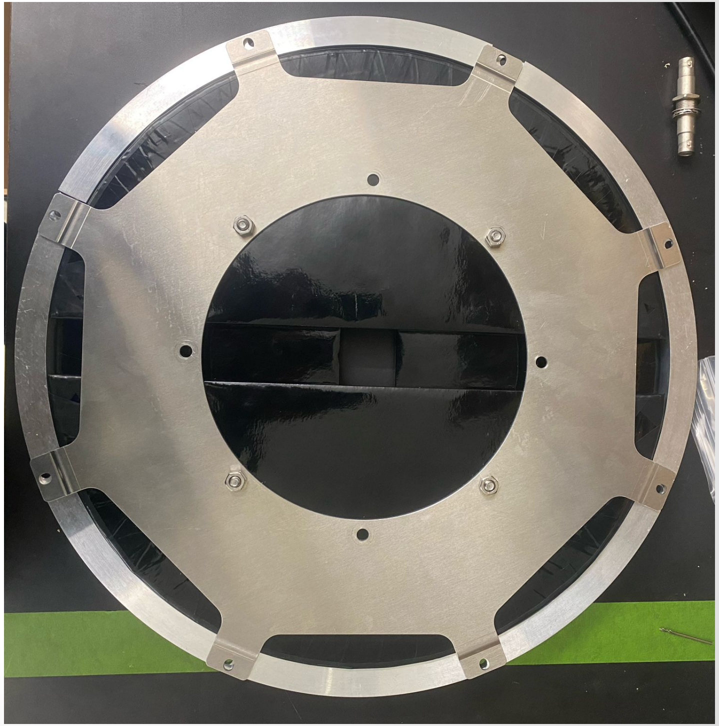
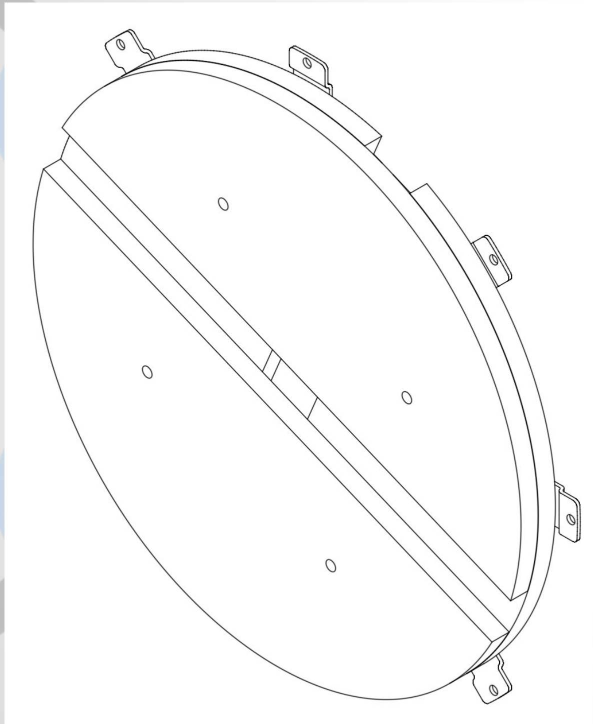
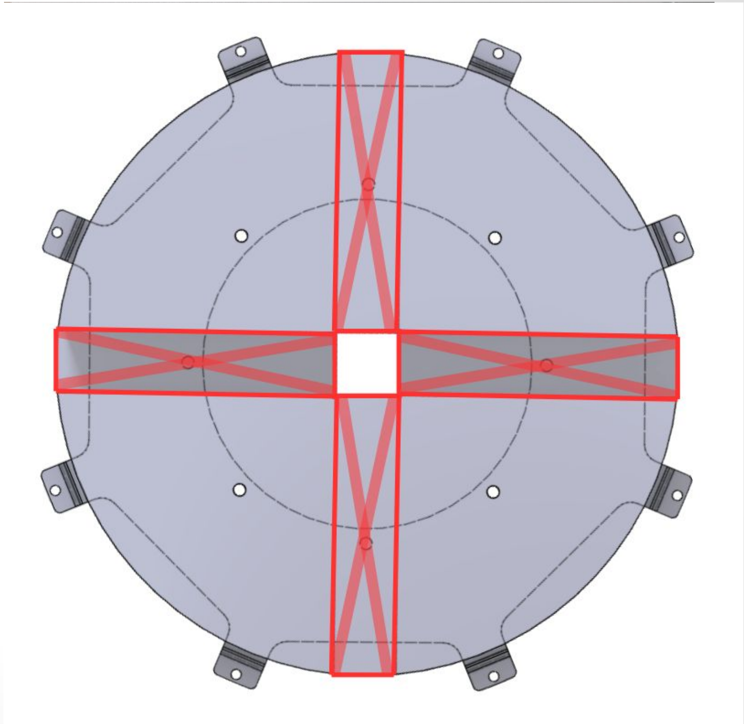




MIST Shape Redesign



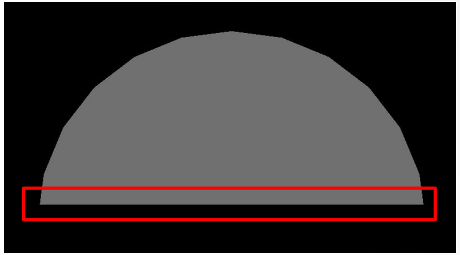


MIST Shape Redesign

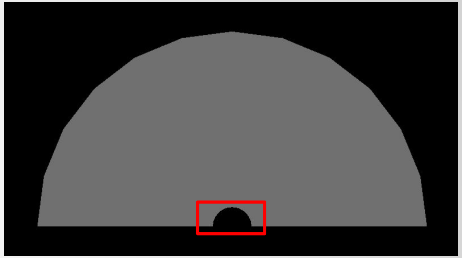
- Effective surface area from the P-ONE-1 scintillator:
  - P-ONE-1: 667.36cm^2

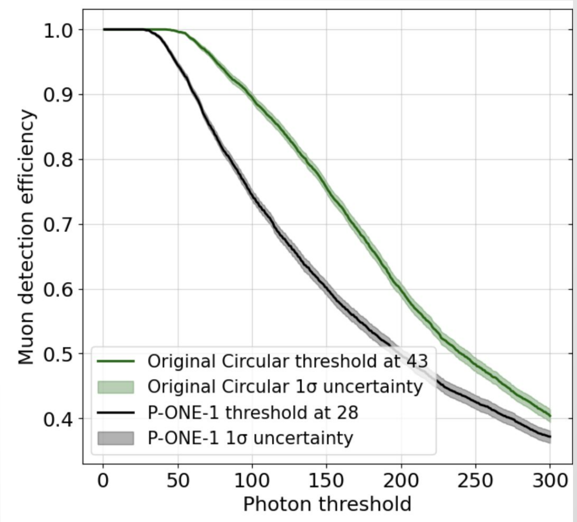
- Scintillator shape change motivated by:
  - In lab tests
  - A Geant4 simulation of varying scintillator shapes

P-ONE-1 Scintillator: Current



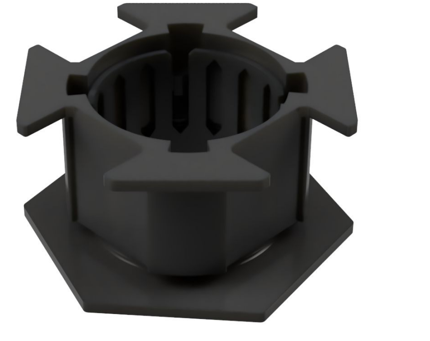
Circular Cut-Out Scintillator

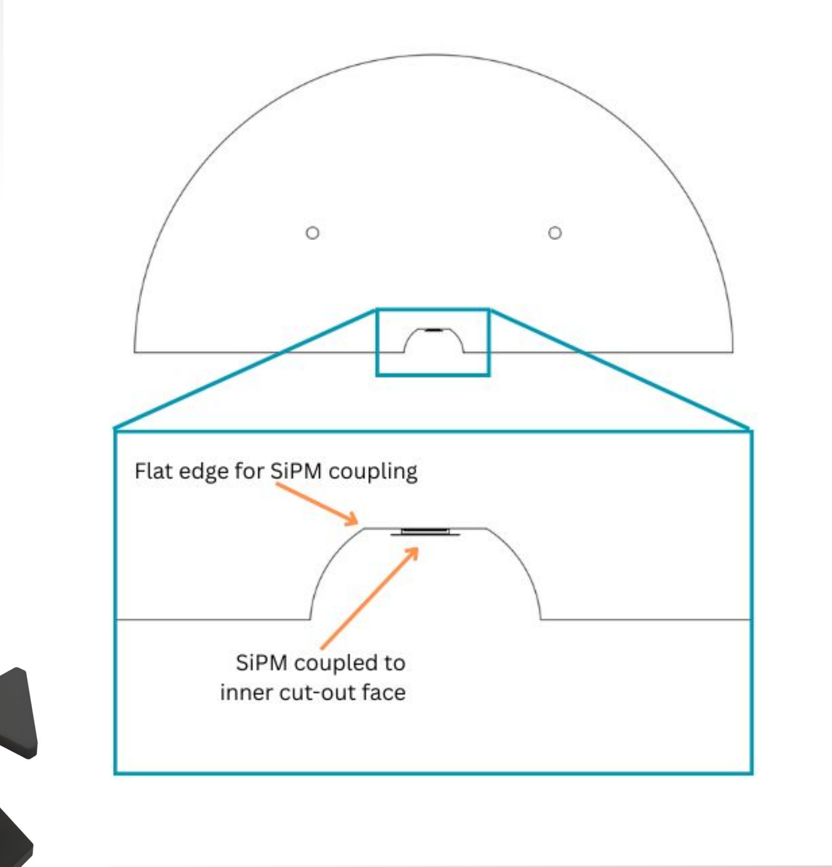




MIST Shape Redesign

- Effective surface area increase from the P-ONE-1 scintillator:
  - P-ONE-1: 667.36cm^2
  - Newest revision: 885.4cm^2
  - Amounting to a **32.7%** increase
- Flat edge on inner circle for easier photodetector coupling.
- Designed a ratcheting grommet to protect photodetectors.

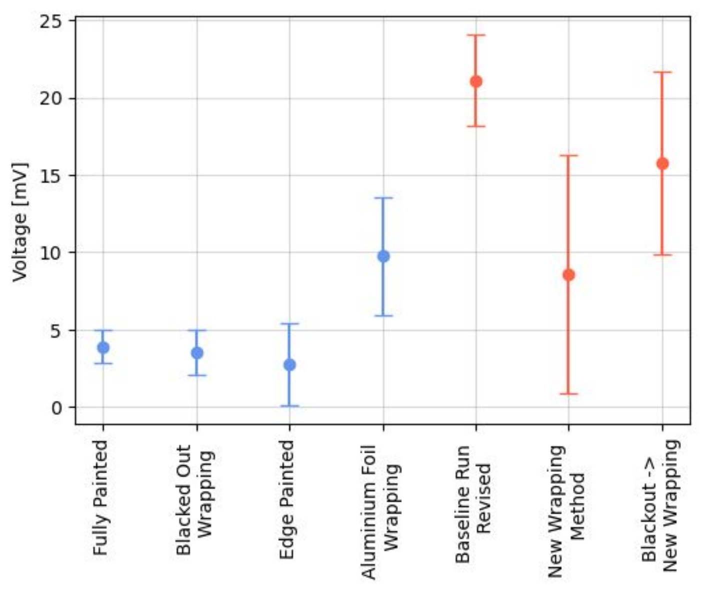


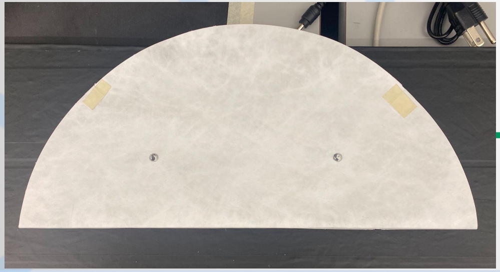


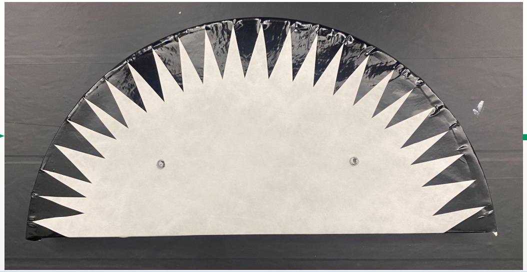
Scintillator Wrapping - Reflective Layer

- Used Tyvek to wrap P-ONE-1 scintillators.
  - Typically used as a protective layer in buildings.

- Tested various wrapping techniques; this included 2 different techniques with scintillator paint, aluminum foil, and various Tyvek wrapping techniques.
  - Scintillator paint yielded a very poor muon detection efficiency curve.
  - Plan to continue to use Tyvek for future P-ONE scintillators.







Summary

- P-ONE is a Neutrino telescope that will be deployed of the coast of Vancouver Island
    - The first full P-ONE string will be deployed in the fall
    - Are aiming to deploy the next few strings in 2028

- MIST will help verify P-ONE’s pointing resolution
    - Completely designed, built and produced at the UofA
    - This development and redesign helps us capture more muons leading to more calibration opportunities

Other Interesting things you can chat to me about:

- Possibility of identifying a muon passing through a PMT through a unique signal/energy deposit
- How making our scintillators thinner drastically reduces the muon detection efficiency

Image credit: Ben Nührenbörger, 2025, used with permission.

OCEAN NETWORKS CANADA

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Queen's University

Georgia Tech

Duke University

Drexel University

SFU SIMON FRASER UNIVERSITY

Los Alamos NATIONAL LABORATORY

TRIUMF

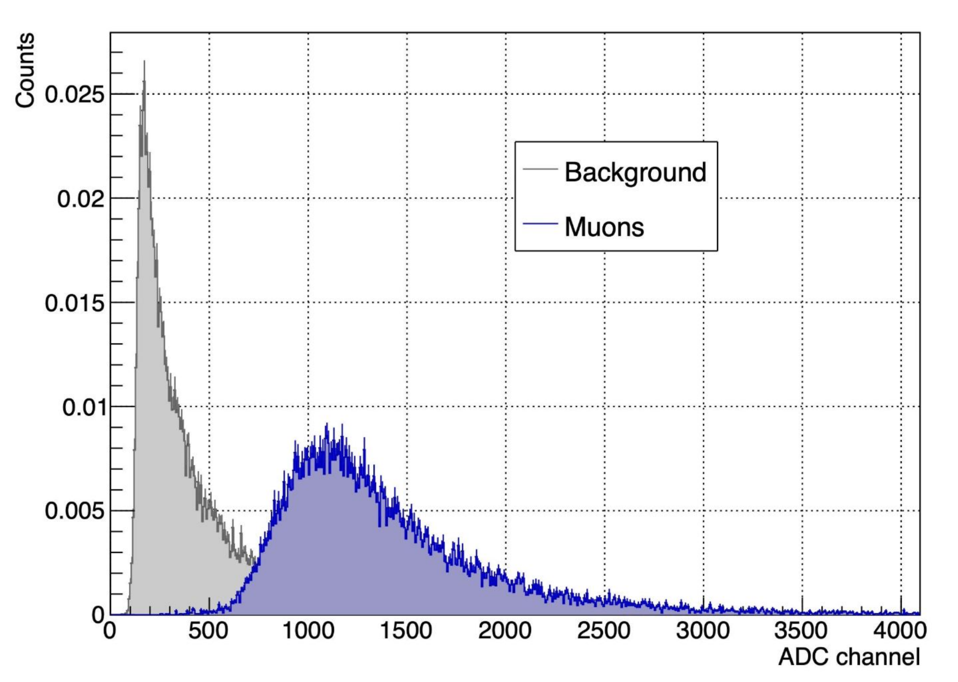
UNIVERSITY OF ALBERTA

THE UNIVERSITY OF CHICAGO

Elmhurst University

Background Mitigation

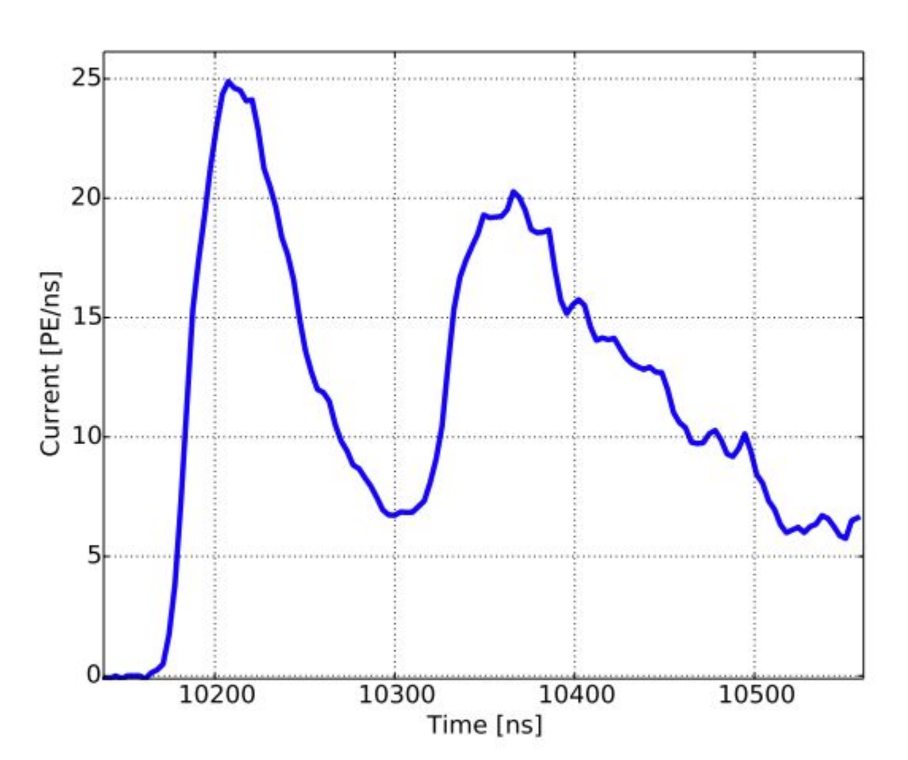
- This plot shows a method to discriminate against backgrounds
  - We run the scintillators in coincidence such that a top layer and bottom layer scintillator must trigger within a 8 ns time window
  - The grey here is the spectrum that corresponds to one scintillator while the blue is 2 scintillators



Double Bang from a Tau Neutrino

- A tau neutrino interaction has a characteristic “double bang”
  - A charge current interaction produces a tau lepton.
  - The produced tau would then rapidly decay, resulting in a second cascade.

- This appears as a double pulse if you have full waveform readout from a PMT.

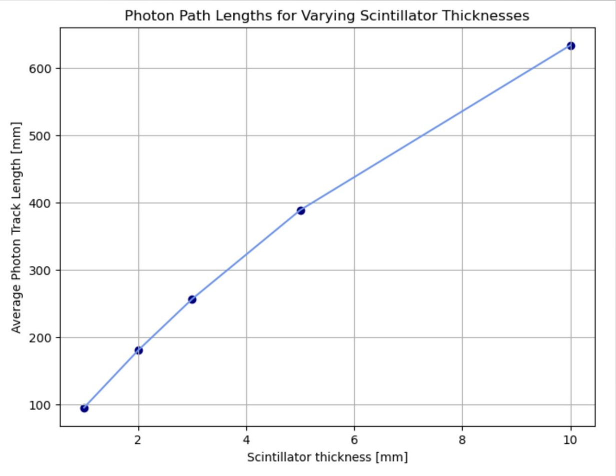


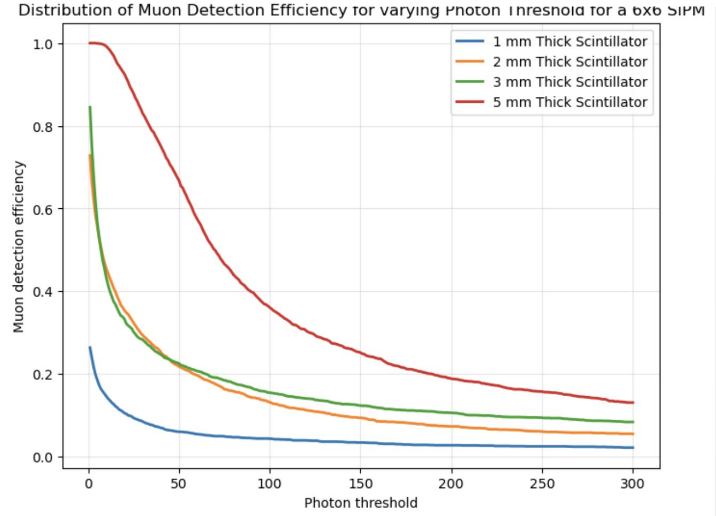
Muon Detection Efficiency for Thinner Scintillators

- Why thinner?
    - To be more cost and weight effective

- Can adjust Geant4 simulation to take any size thickness of scintillator
    - We would expect a significant decrease in photon production in thinner scintillators

- How making our scintillators thinner drastically reduces the muon detection efficiency



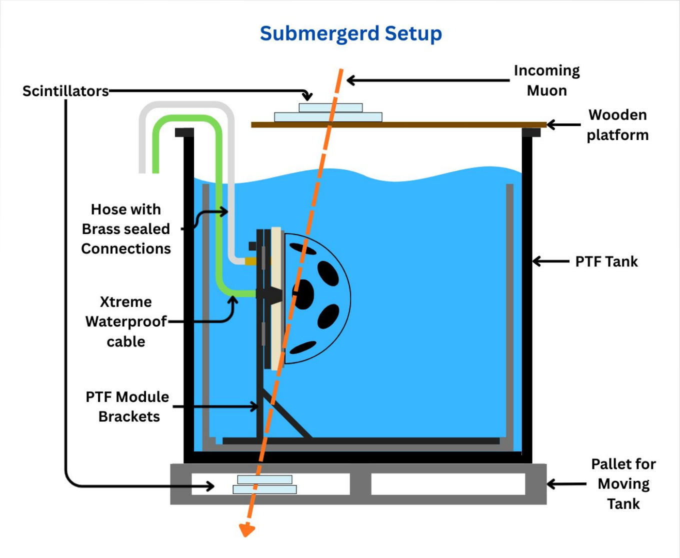


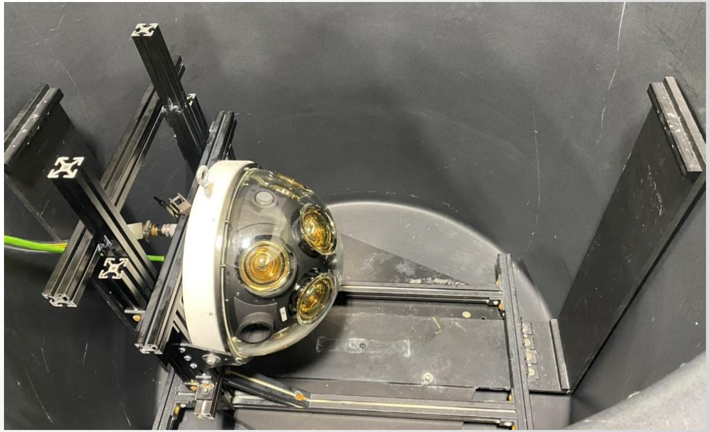
Unique PMT Muon Signal Measurement

- Possibility of identifying a muon passing through a PMT by measuring a unique signal/energy.
    - IceCube produced promising results of this measurement in air (Simon Pick, 2025).

- Could yield more data for directional calibration in addition to MIST triggers.

- Attempted to look for this using a Tank and P-OM at TRIUMF.
    - Did not see this unique signal in our set-up.
    - May have been limited in some areas.





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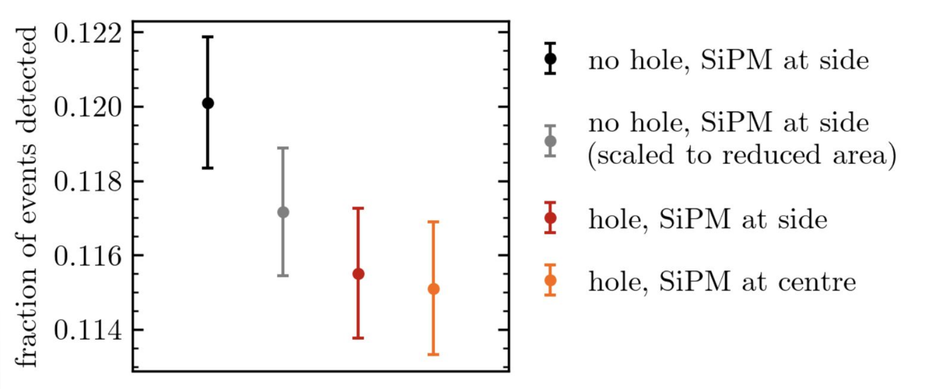
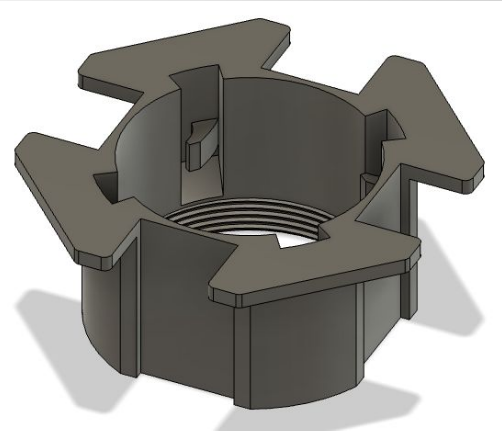
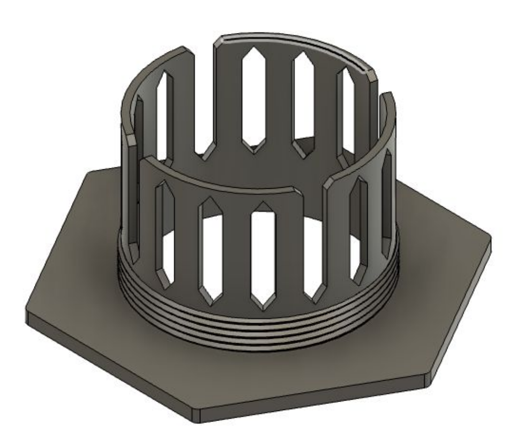


MIST Grommet

- Designed a ratcheting grommet to protect photodetector since it will be more vulnerable to damage from cables
- Accommodates varying assembly thicknesses
- Will 3D print these in PET-G
- Incorporated flat nut like edges so it can be forced off/broken with a adjustable wrench for disassembly
- Non-constraining with no pieces sticking into the feed through area





MIST Grommet