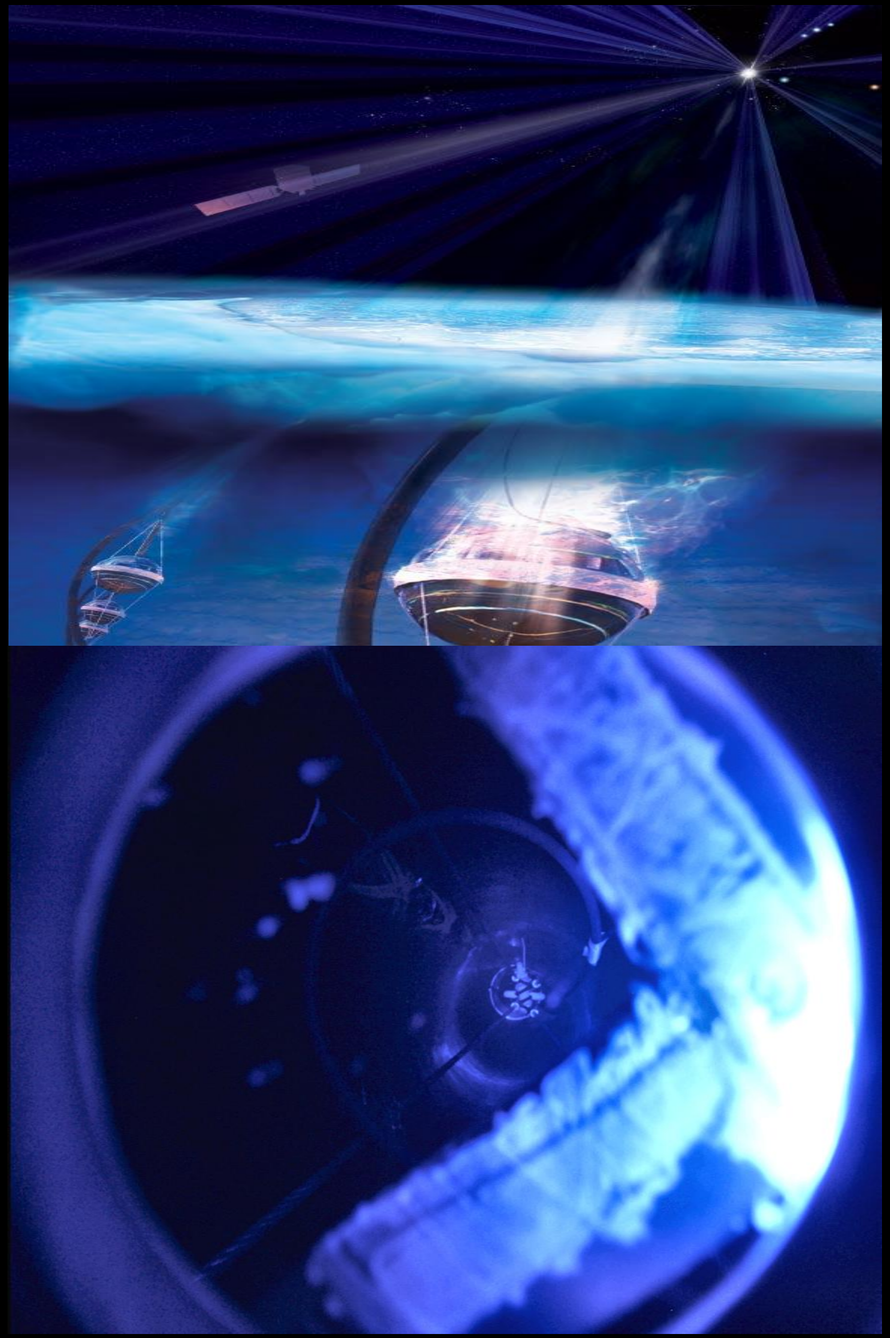


Construction and Cosmic rays Muon-Based Optical Modules Validation for IceCube-Gen2 Neutrino Observatory

2025 IceCube Summer Student Program
Wisconsin IceCube Particle Astrophysics Center (WIPAC), University of Wisconsin-Madison
Madison, WI | United States

Sino-Thai International Summer School on High Energy Physics and Astrophysics (STISS) 2026
July 23th, 2026 at Ruyuan Shaoguan, China

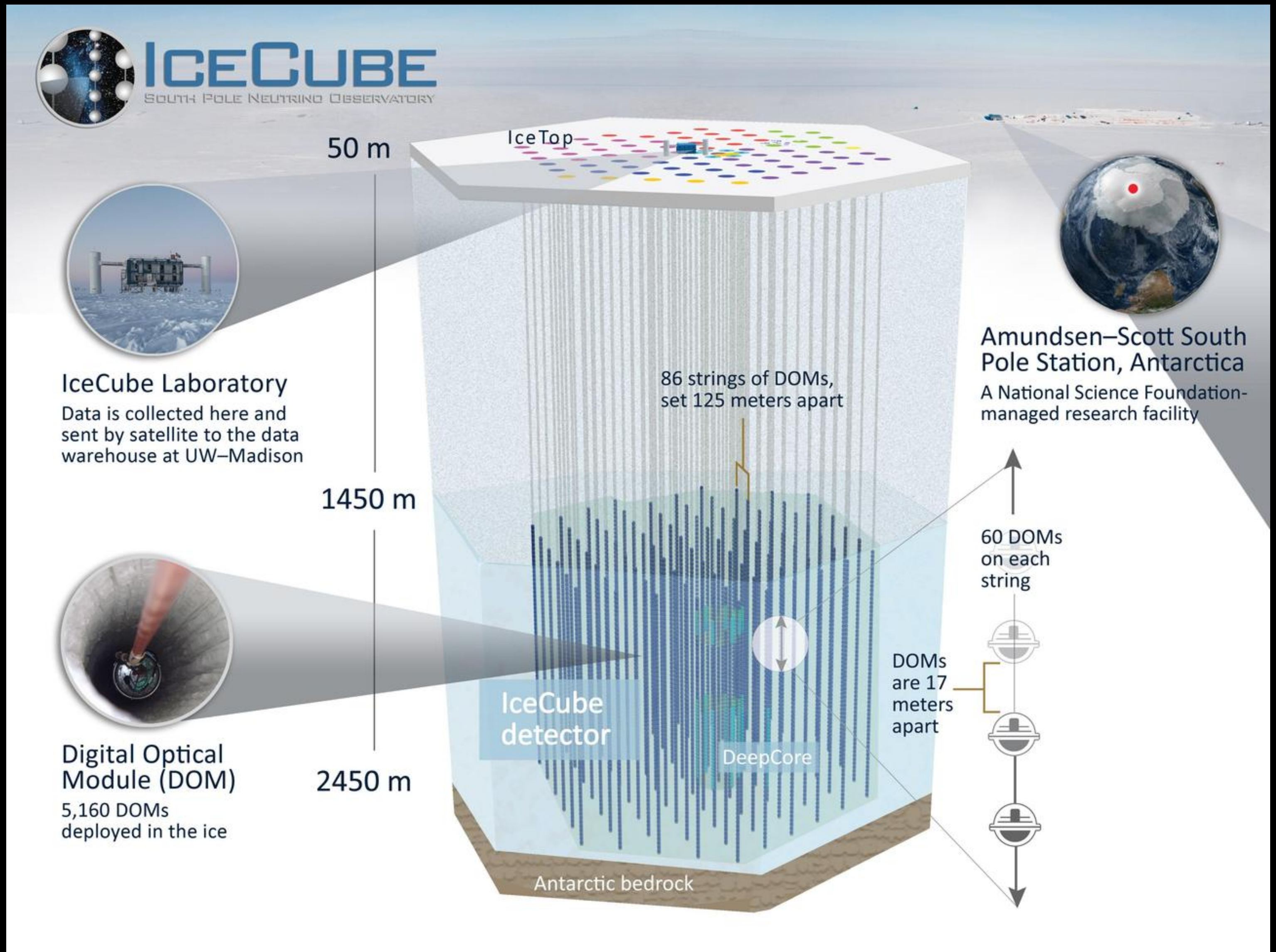
Thammarat Yawisit (Pound)

School of Engineering

King Mongkut’s Institute of Technology Ladkrabang (KMITL)

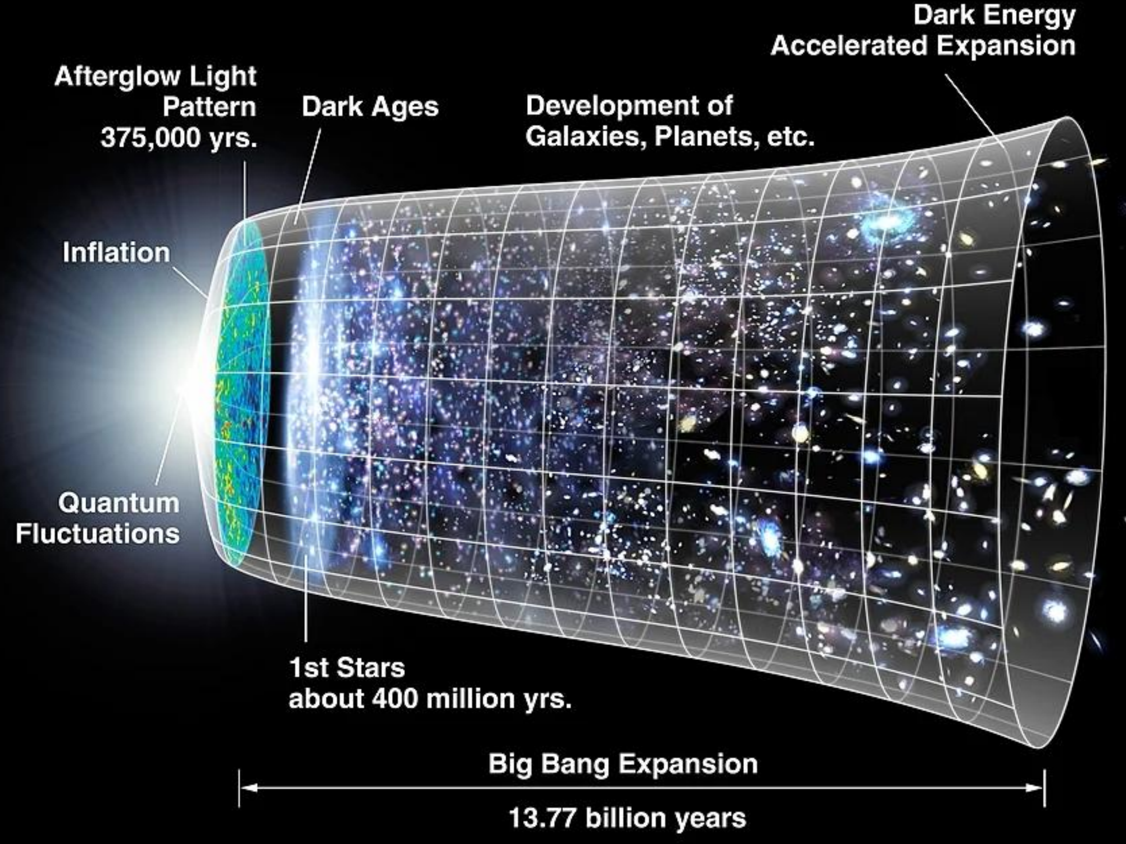
Bangkok, Thailand

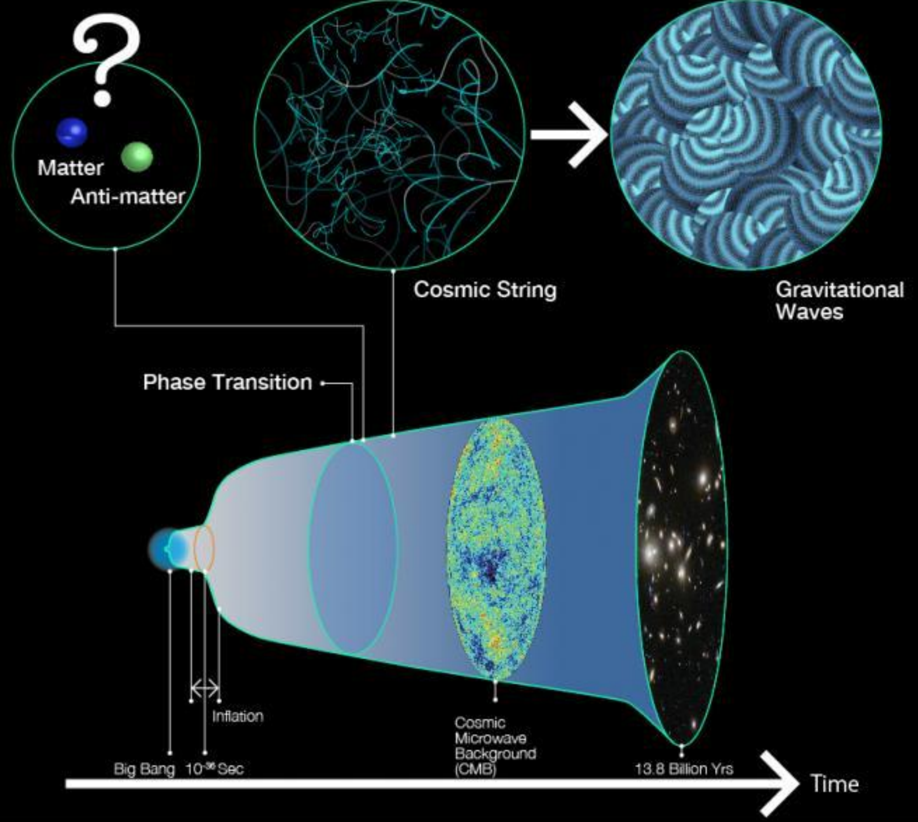
IceCube's overview



- Large-scale neutrino experiment, located deep under the ice at the Amundsen-Scott South Pole Station, Antarctica
- Detects **astronomical neutrinos** from space to study the most extreme objects in the universe, such as
  - Black holes
  - Neutron stars
  - Supernovae
  - Active galactic nuclei (AGN) / Blazar / Quasar
  - GD, CCSN, TDE, GRB, etc.

- By tracking neutrinos, IceCube intend to answer fundamental questions about the origin of cosmic rays, dark matter, and extreme astrophysical processes



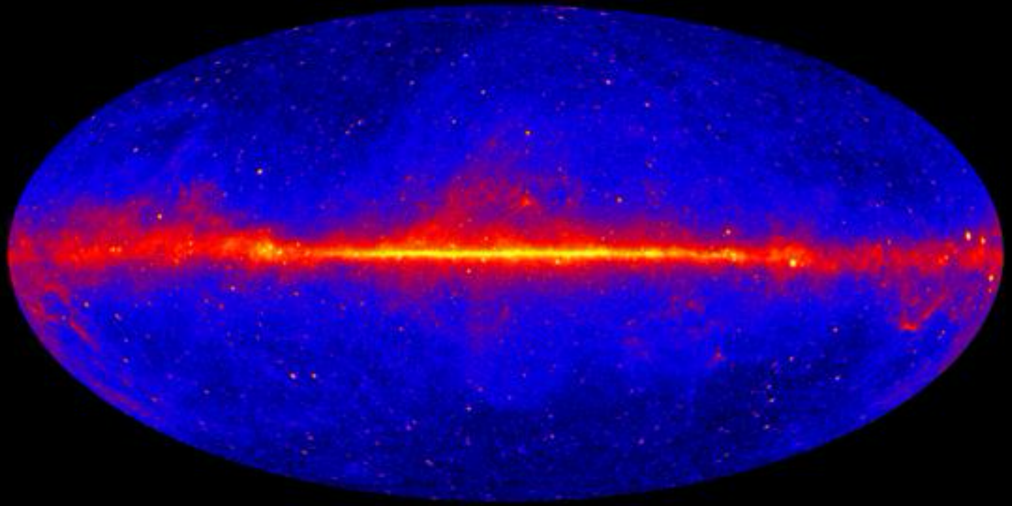


Astrophysical Sources Motivate Different Detector-Response Regimes

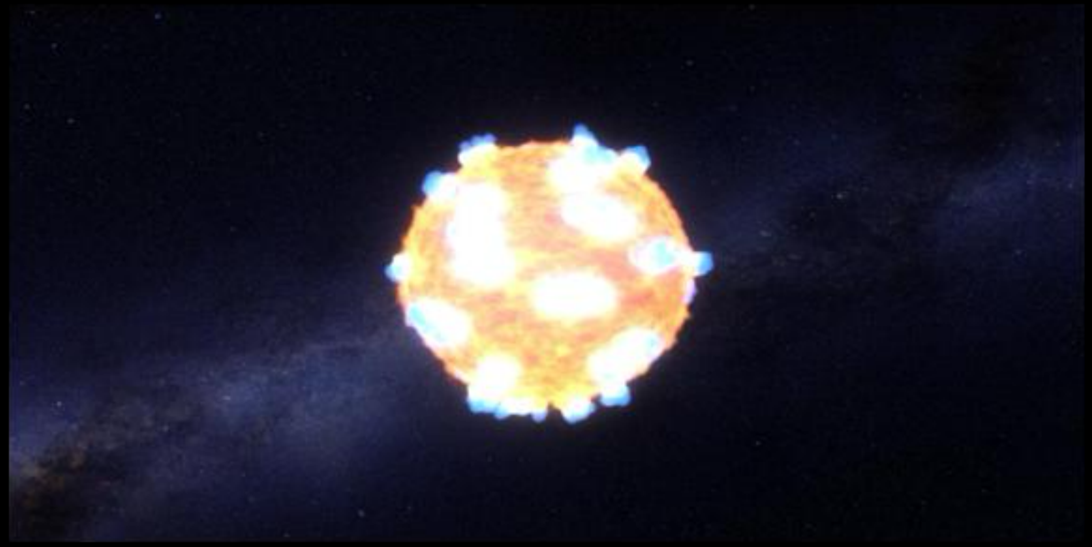
KMITL

→ High-energy neutrino candidates range from distributed emission to short, highly modulated transients

Galactic diffuse
Extended, distributed emission

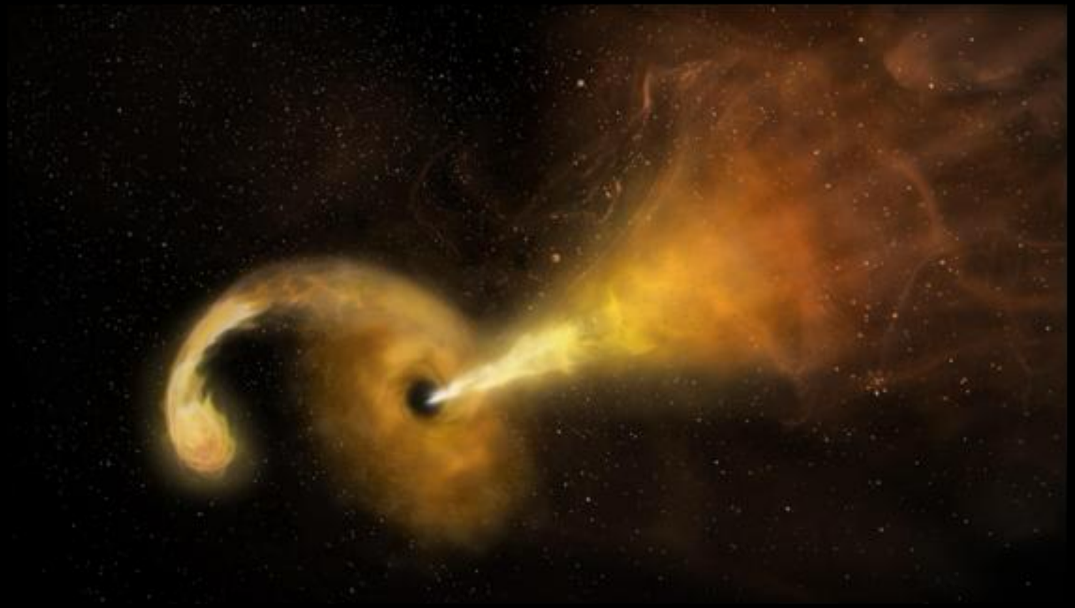


Core-Collapse Supernova (CCSN)
Stellar-collapse transient

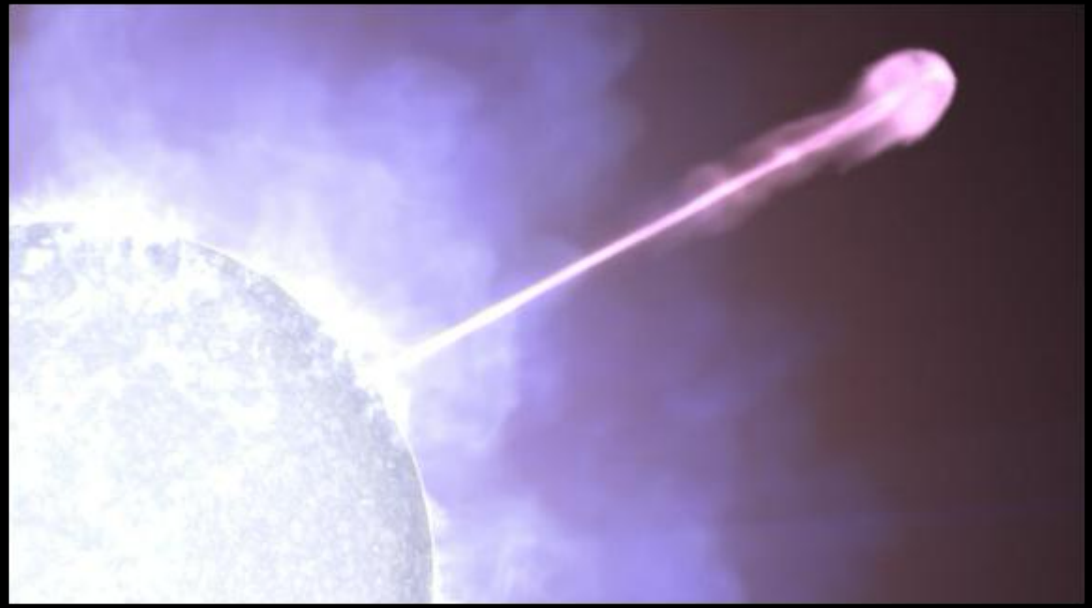


AGN / Blazar / Quasar
Variable relativistic jet

Tidal Disruption Event (TDE)
Evolving stellar-disruption transient



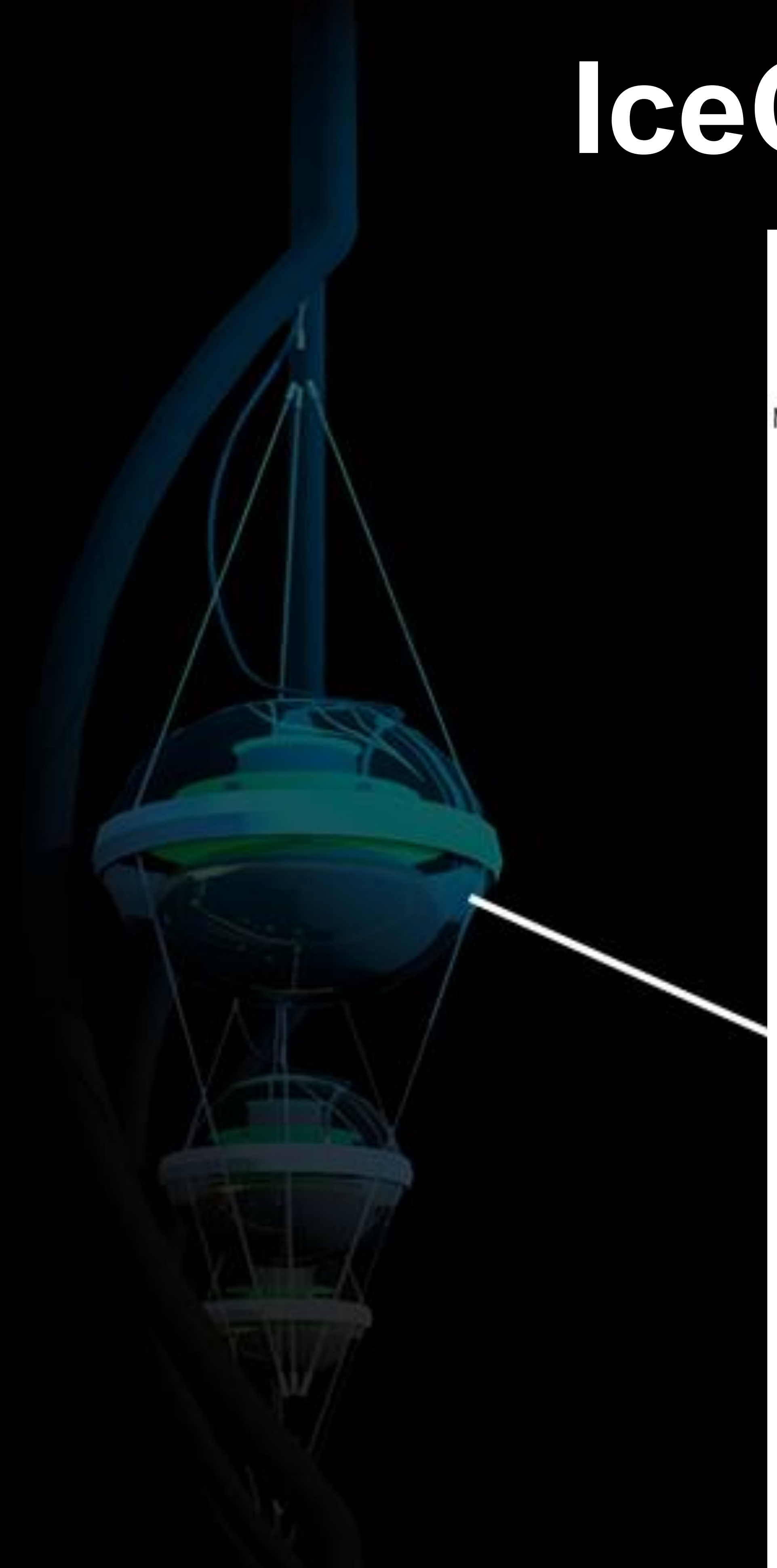
Gamma Ray Burst (GRB)
Short, intense relativistic burst

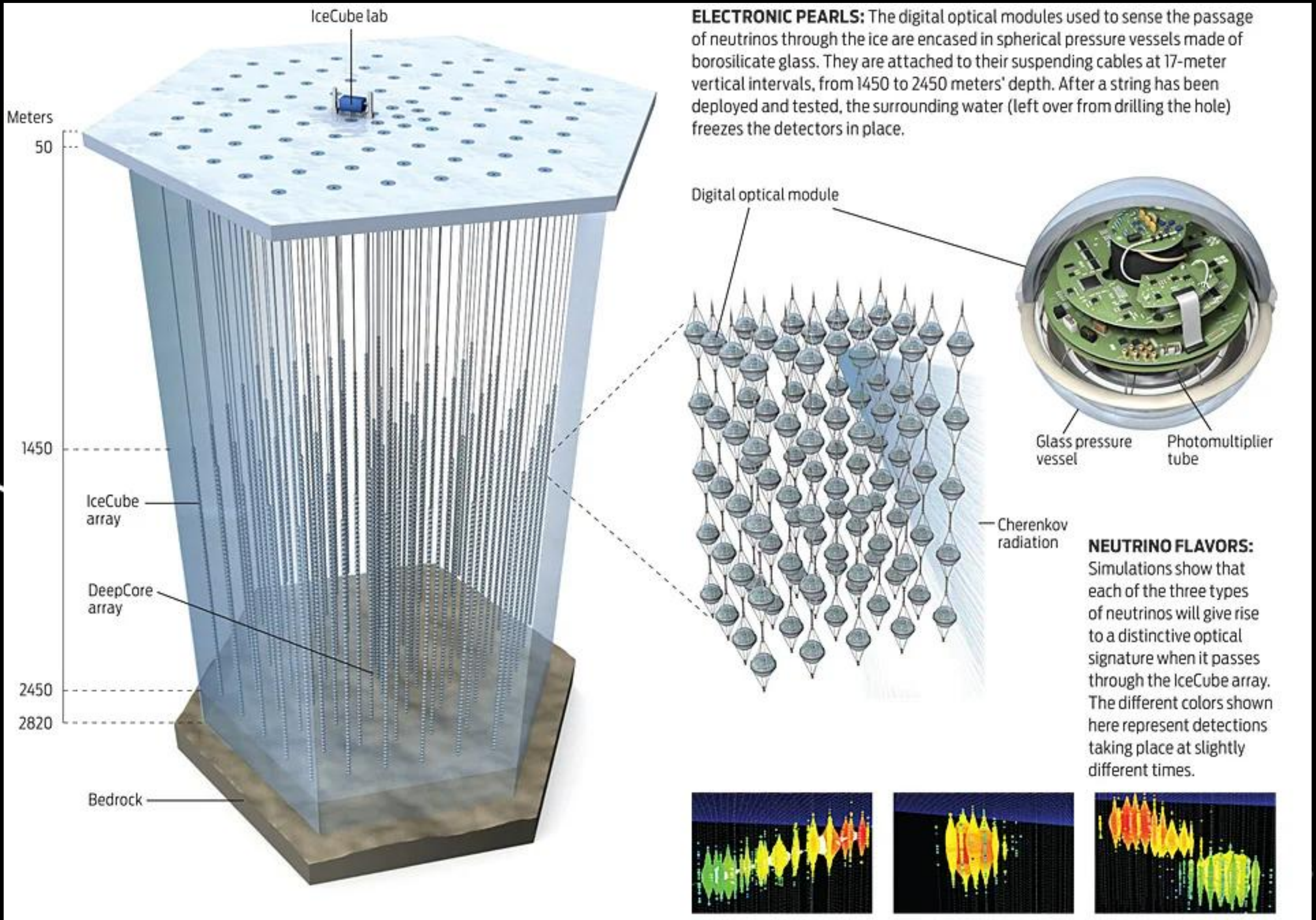


- *Different source environments motivate different temporal modulation, channel occupancy, and visibility stress*
- *The diagnostic acts on the measured waveform structure, not on the astrophysical source label*
- *Source labels define controlled detector-response stress regimes; they aren't source classifiers, event-rate predictions, or detector-performance forecasts*

NASA/DOE/Fermi LAT Collaboration; NASA/Ames/STScI; NASA Goddard Space Flight Center; NASA Goddard Space Flight Center; NASA Goddard Space Flight Center/CI Lab.

IceCube Detector





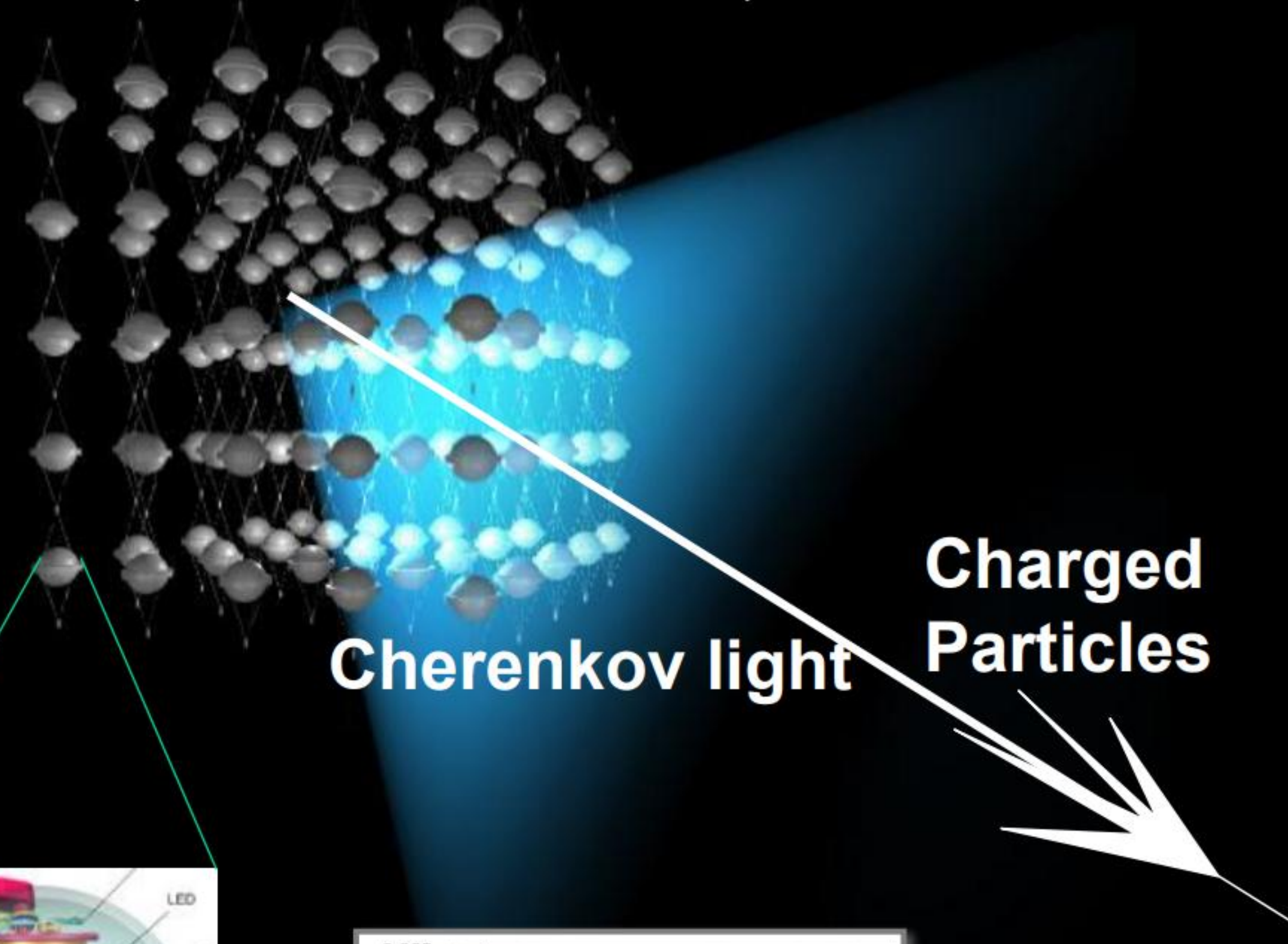
Detection principle?

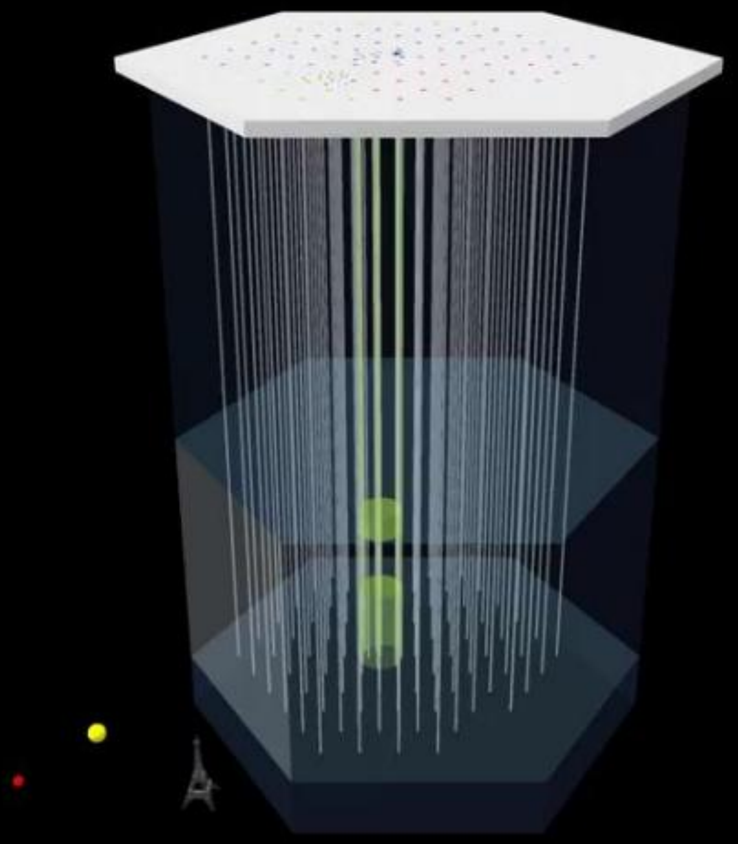
An array of photomultiplier tubes + Dark and transparent material

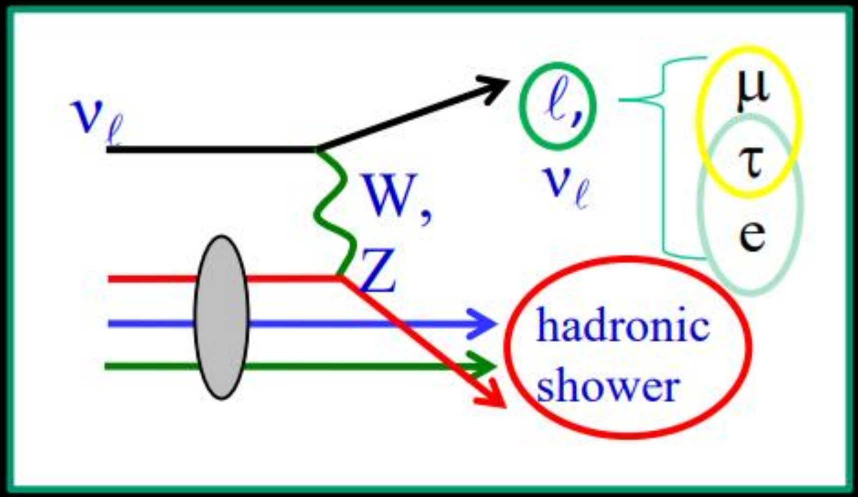
$$\frac{d^2N}{dx\,d\omega} = \frac{\alpha\, z^2}{c}\left(1 - \frac{1}{\beta^2 n^2(\omega)}\right)$$

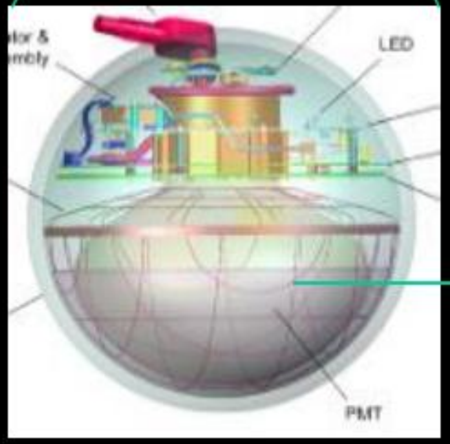
or

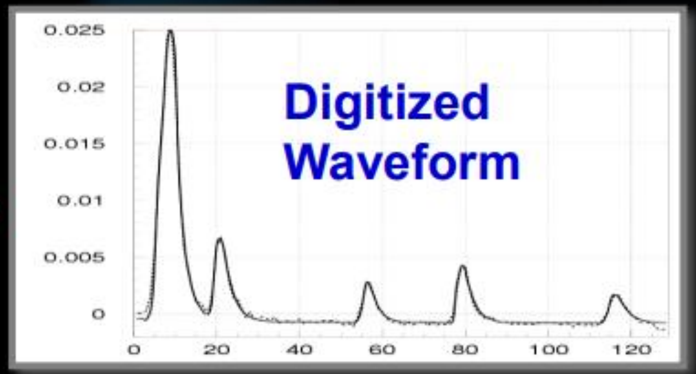
$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\,\alpha\, z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$











ν

$$\boxed{\cos\theta_C = \frac{1}{\beta\, n}}$$

IceCube Digital Optical Module (DOM)

penetrator

Flasher board

12 405nm LEDs

6ns up to 70ns FWFM

10^6 to 10^{11} photons

Pressure Vessel

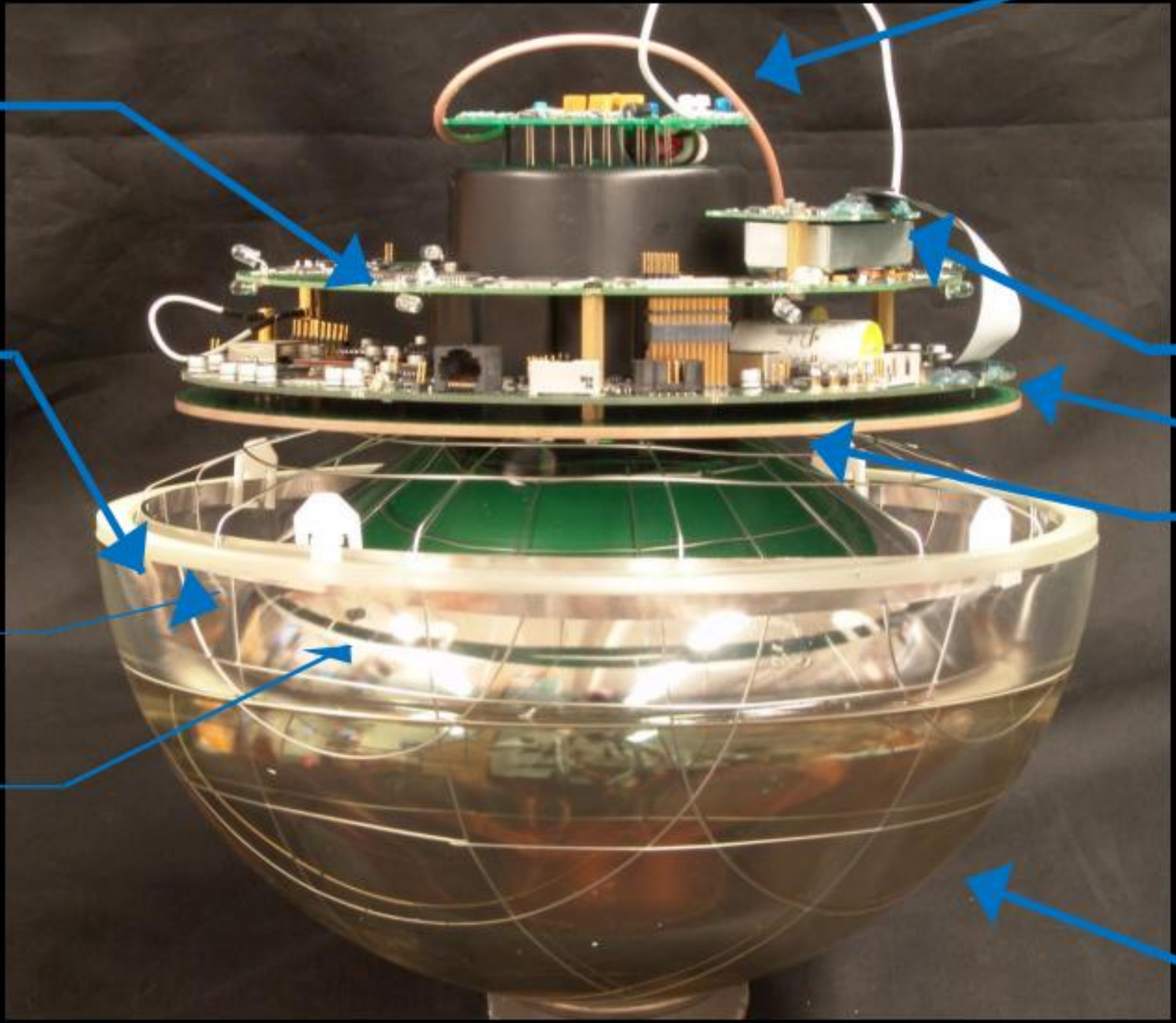
70 Mpa = 691 bar = 10152 psi rated

MuMetal

magnetic shield

1 PMT

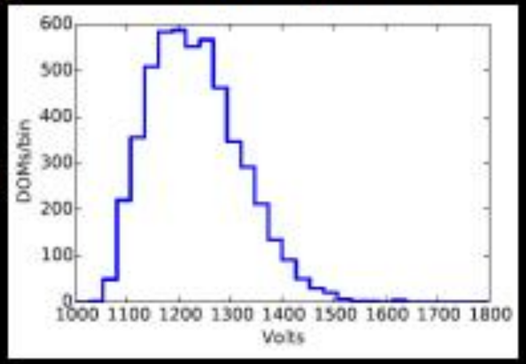
R7081-02



HV Base

anode signal output is AC-coupled using toroid transformer on the Board

PMT Gain 10^7



HV Control Board

Main Board

Delay Board

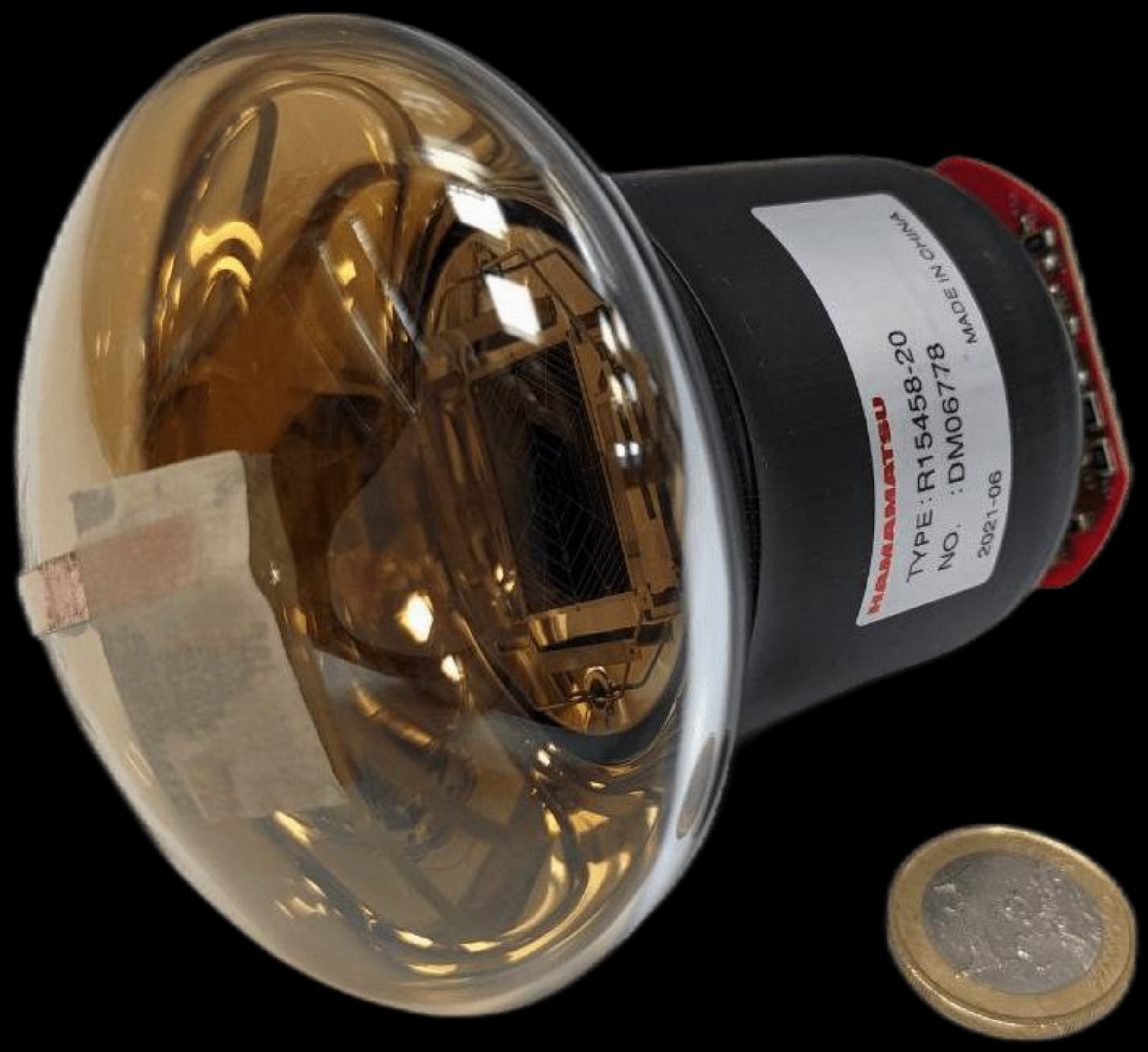
In order to record the waveform starting before the discriminator threshold crossing, the signal is first routed through the Delay Board (75ns)

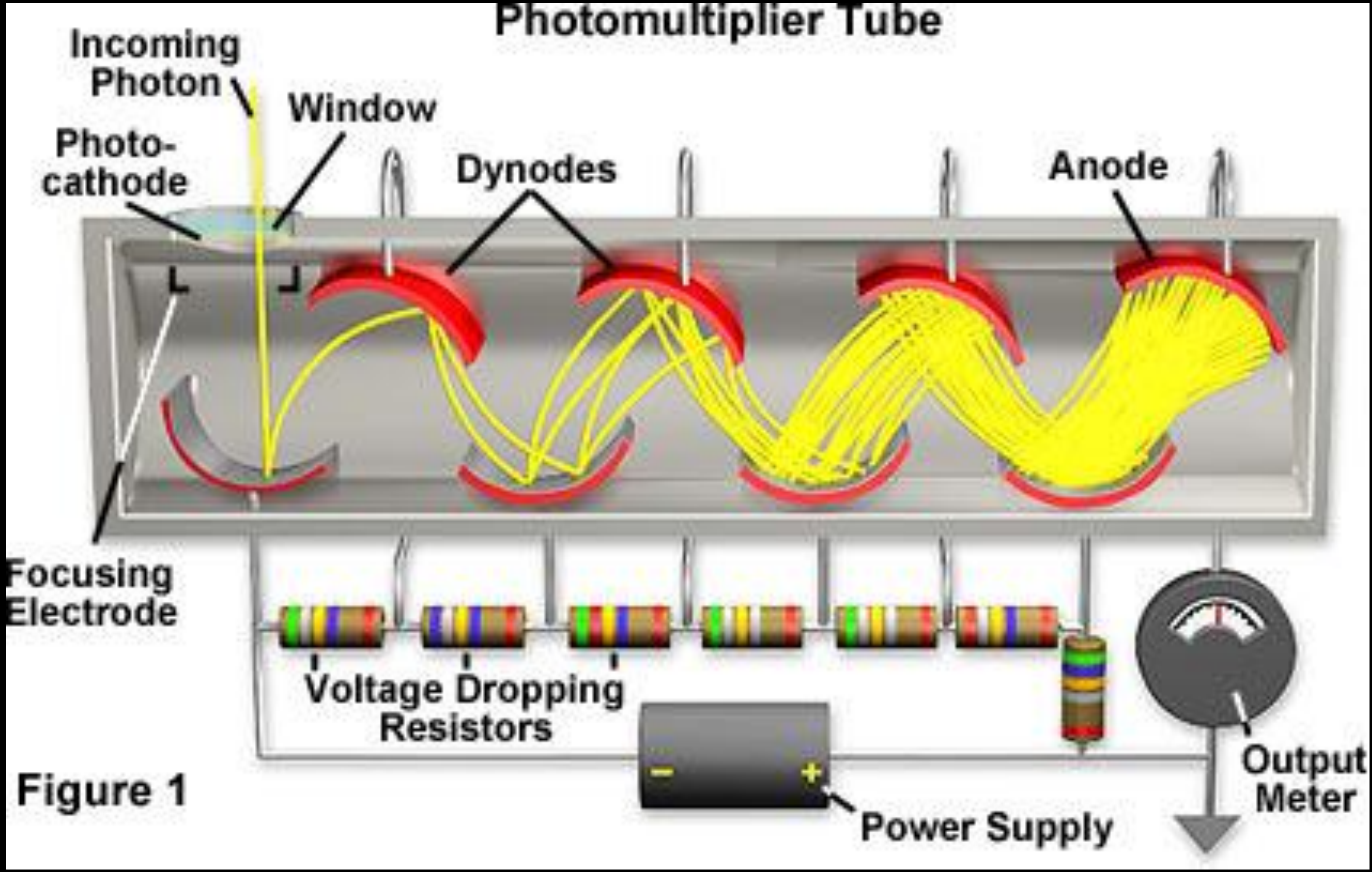
Silicone Gel

optical coupling

PMT is "Photomultiplier Tube"

A bit more about the Photomultiplier Tube (PMT)

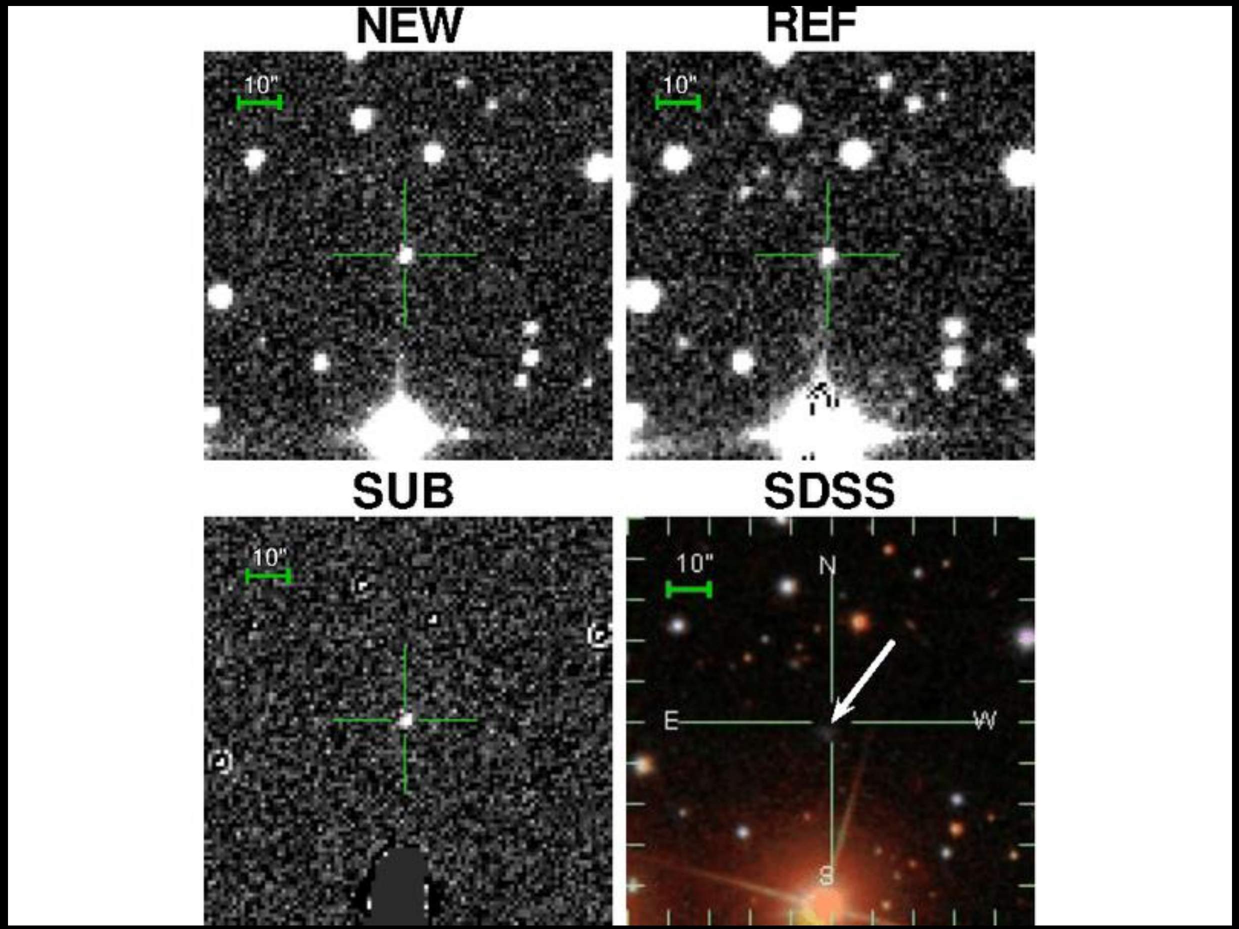


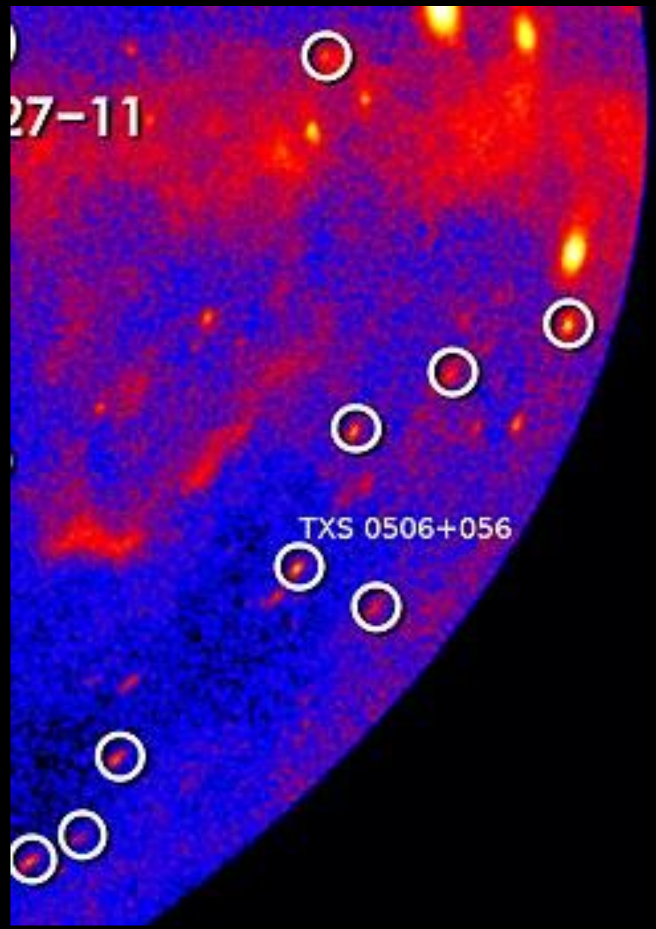


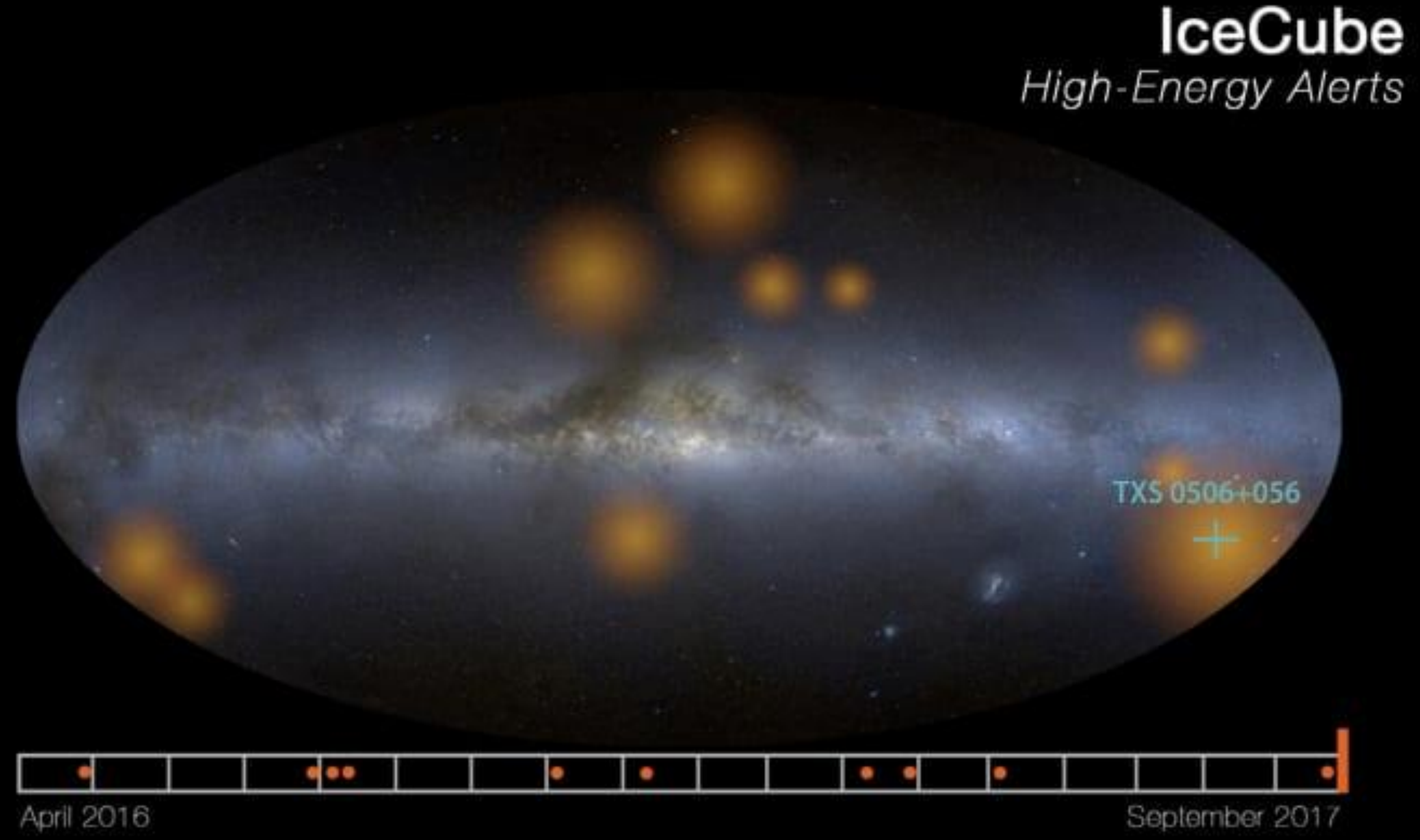
Outside

Inside PMT

Scientific Achievements of IceCube (Gen1)

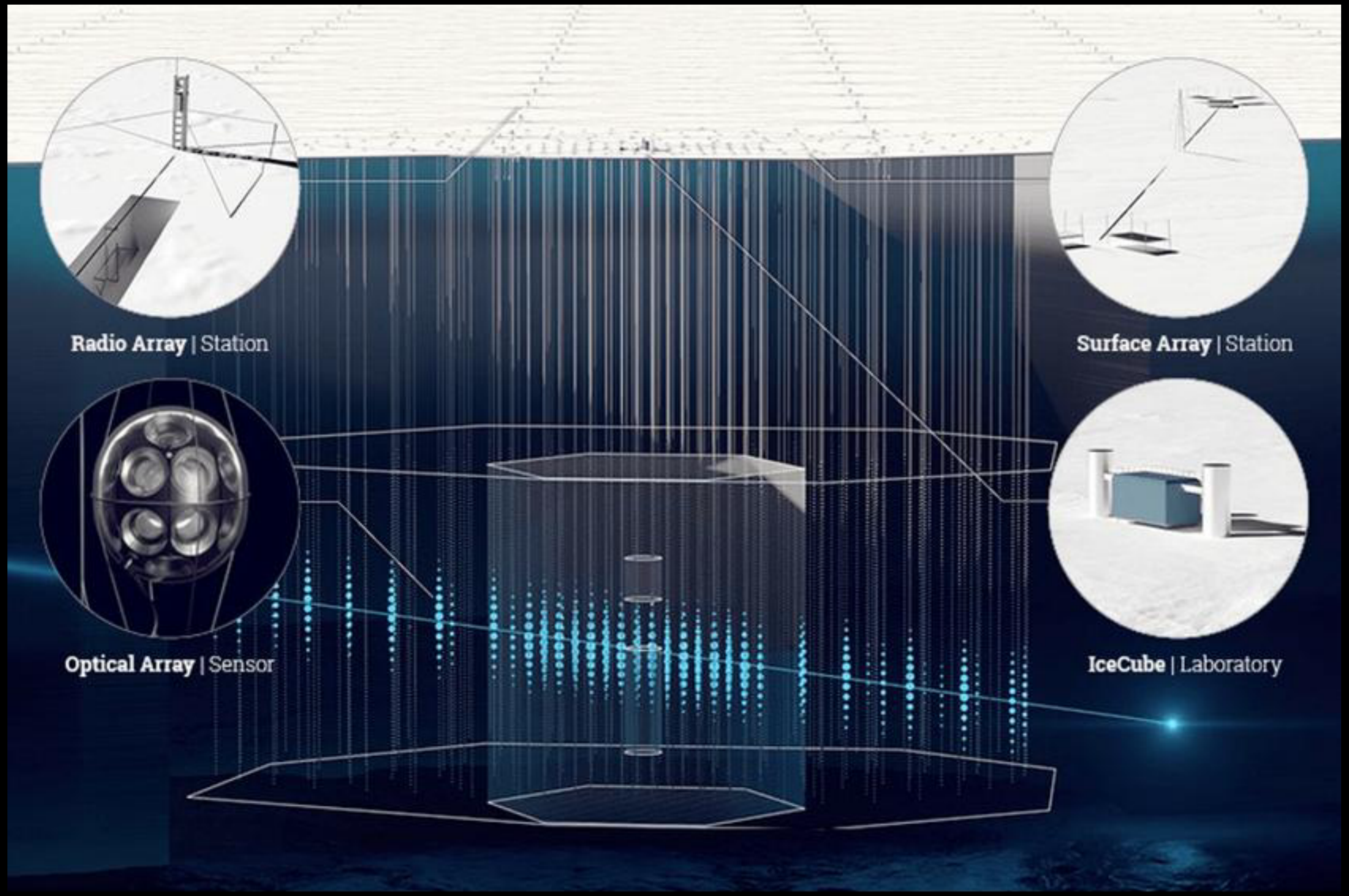


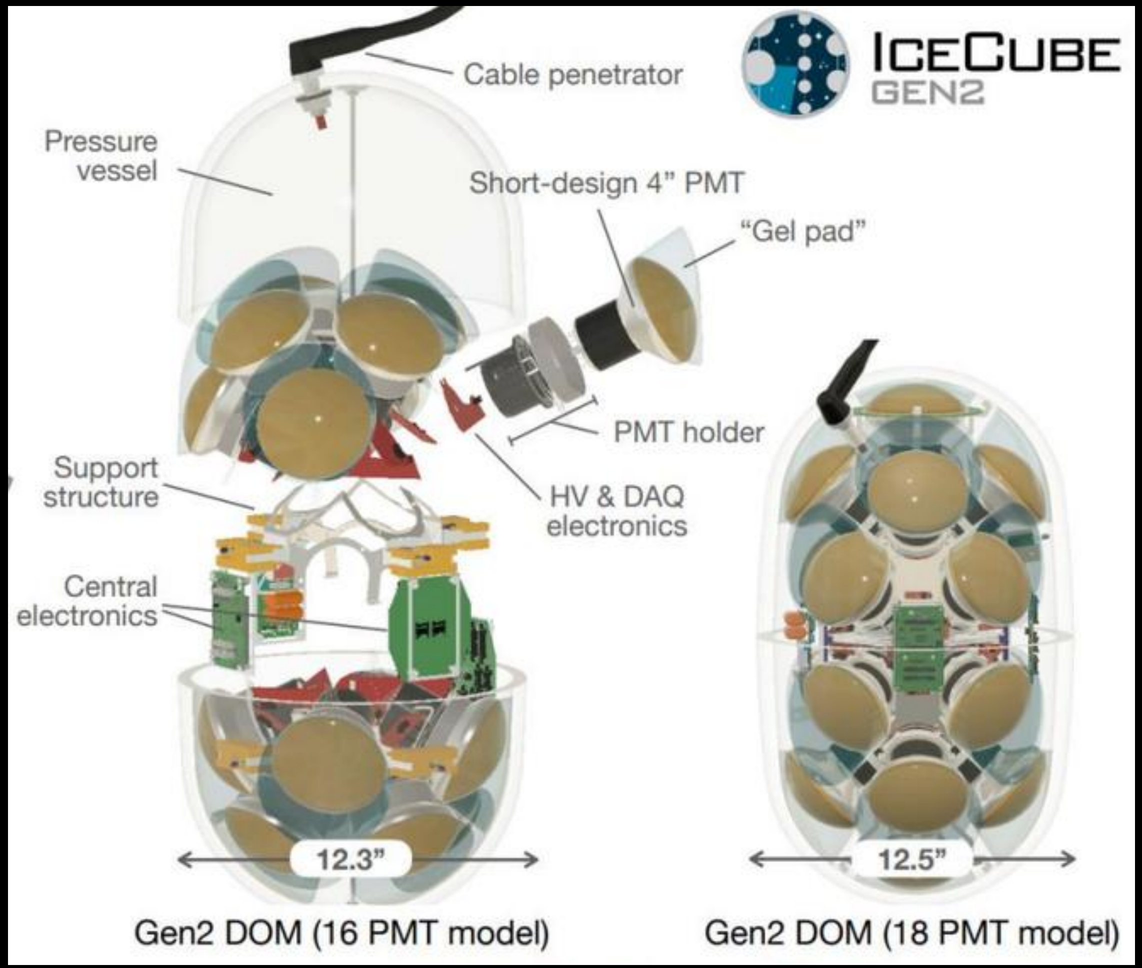




- Discovery of astrophysical neutrinos (2013)
- TXS 0506+056 blazar correlation (2017)
- Neutrino cross-section at PeV
- Atmospheric neutrino oscillations
- Foundation of multi-messenger astronomy

IceCube-Gen2, pushing the frontiers of neutrino astrophysics





- Next-Generation Neutrino Observatory with over 10,000 optical modules
  ⟶ covering 8 km³ of Antarctic ice for optical array, icetop array and radio array
- Requires new multi-PMT optical modules for enhancing sensitivity
  ⟶ Expands detection of high-energy neutrinos and rare astrophysical events

Candidates of optical modules design for IceCube-Gen2

LOM-16

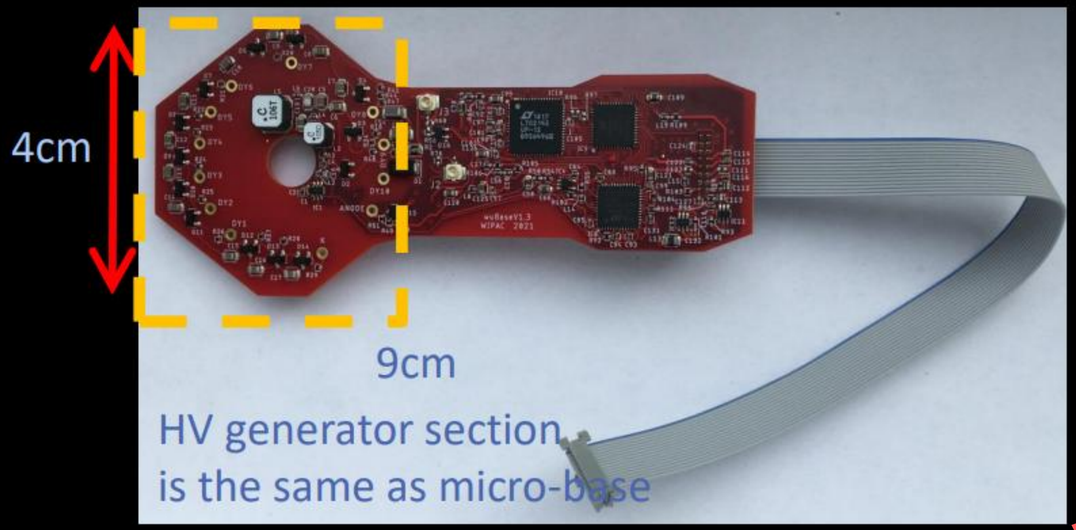
Madison, USA

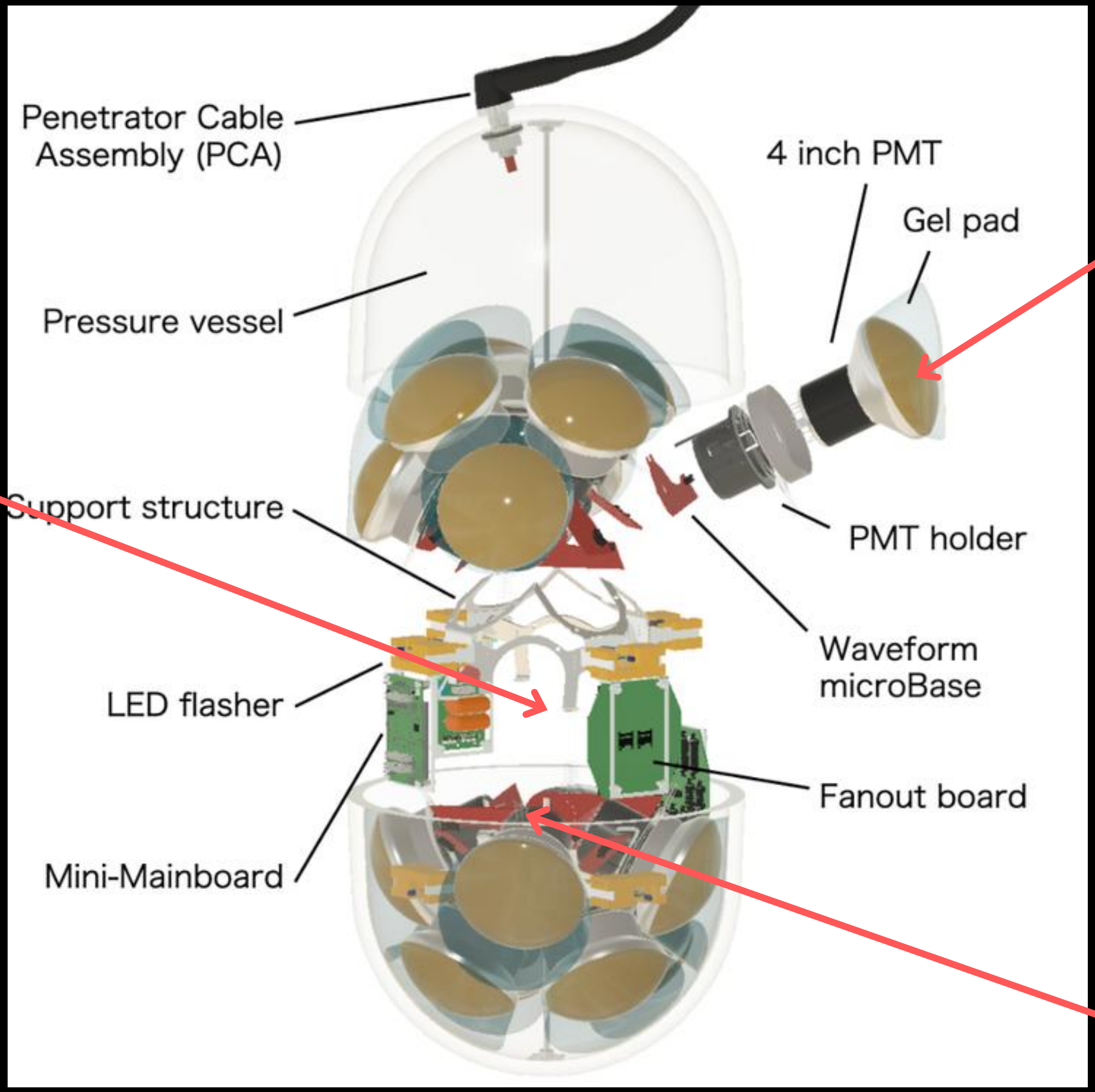
LOM-18

Chiba, Japan

- Two variations
  - LOM-16: 16 x 4" PMTs
  - LOM-18: 18 x 4" PMTs
- Sensitivities x4 better than Gen1 DOM
- 6 of each type will be deployed
  in IceCube Upgrade Array
  for the design verification this winter

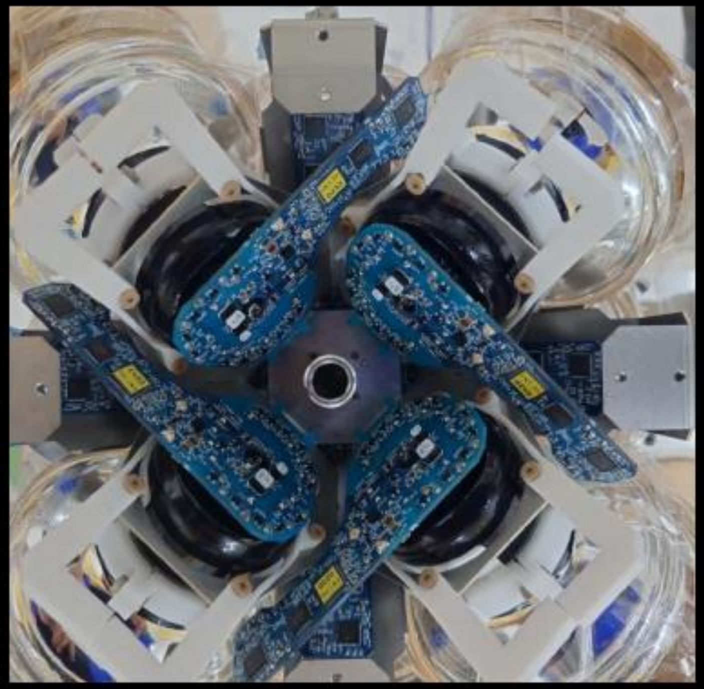
More about LOM-16





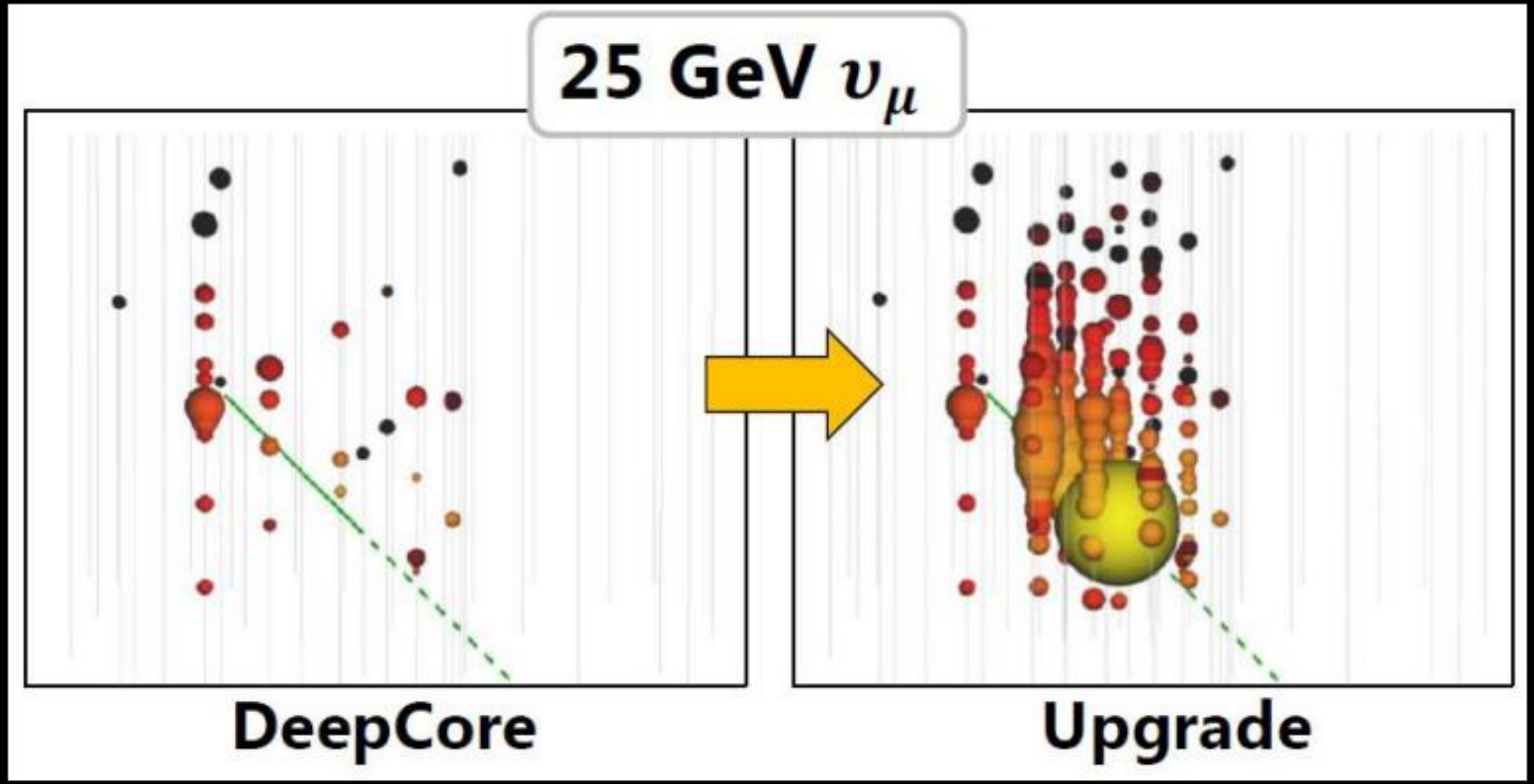
- Each PMT has 2 channel readouts
  - 60 MSPS)
  - Channel 1: High-Gain
    - for Single Photoelectron
  - Channel 2: Low-Gain
    - for Bright Events
    - High energy events

- 16 x 4" PMTs (Hamamatsu / NNVT)
- Gel Pads for mechanical / optical coupling between glass & PMTs



⟶ There are 10 of LOM-16s for the world's first batch

Benefits of Multi-PMT Optical Modules

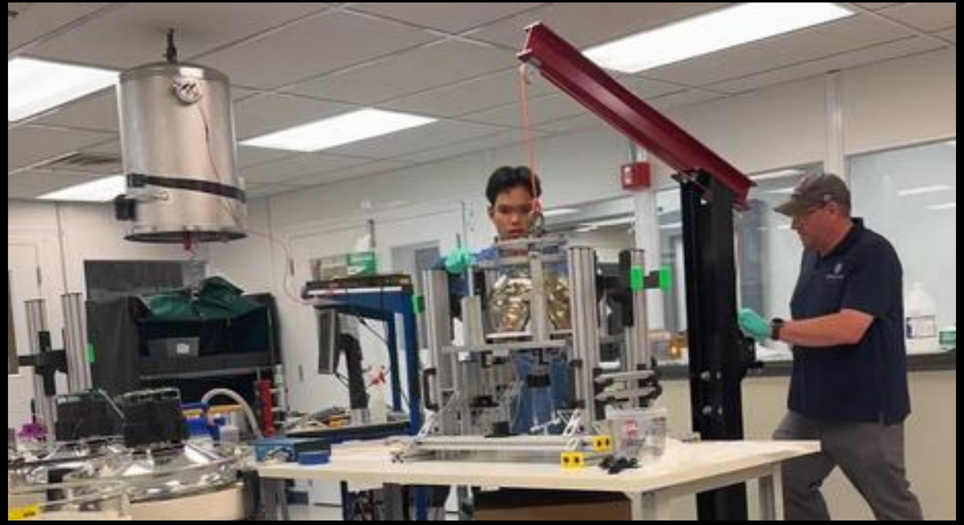


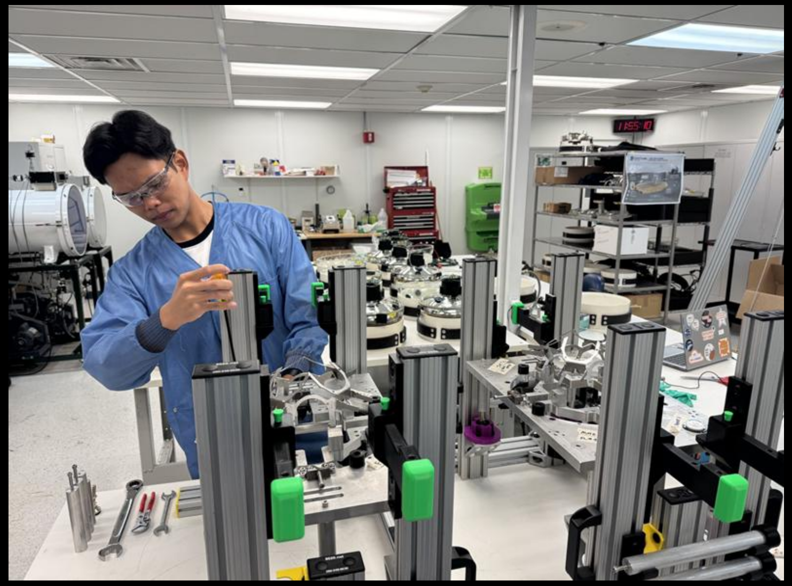
- Higher photocathode coverage & Lower dark noise
- Excellent directional sensitivity from 360° photon coverage
- Ideal for rare events, critical in high-energy & low-energy regimes

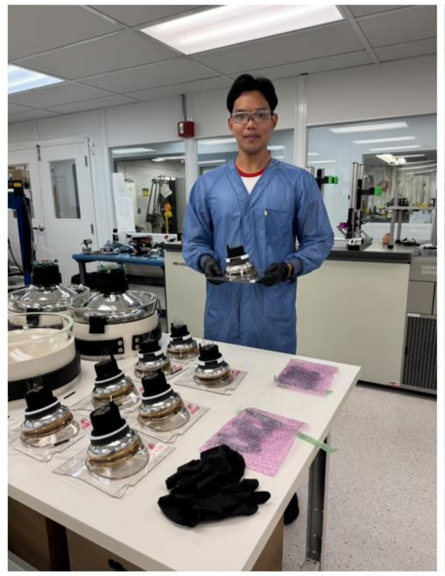
Construction of IceCube-Gen2 Optical Modules (LOM-16-09): Final module of the first batch Prepared for deploying in IceCube-Upgrade

Supported by Yuya Makino, LOM-Team and Physical Science Laboratory

LOM-16-09 Construction Process





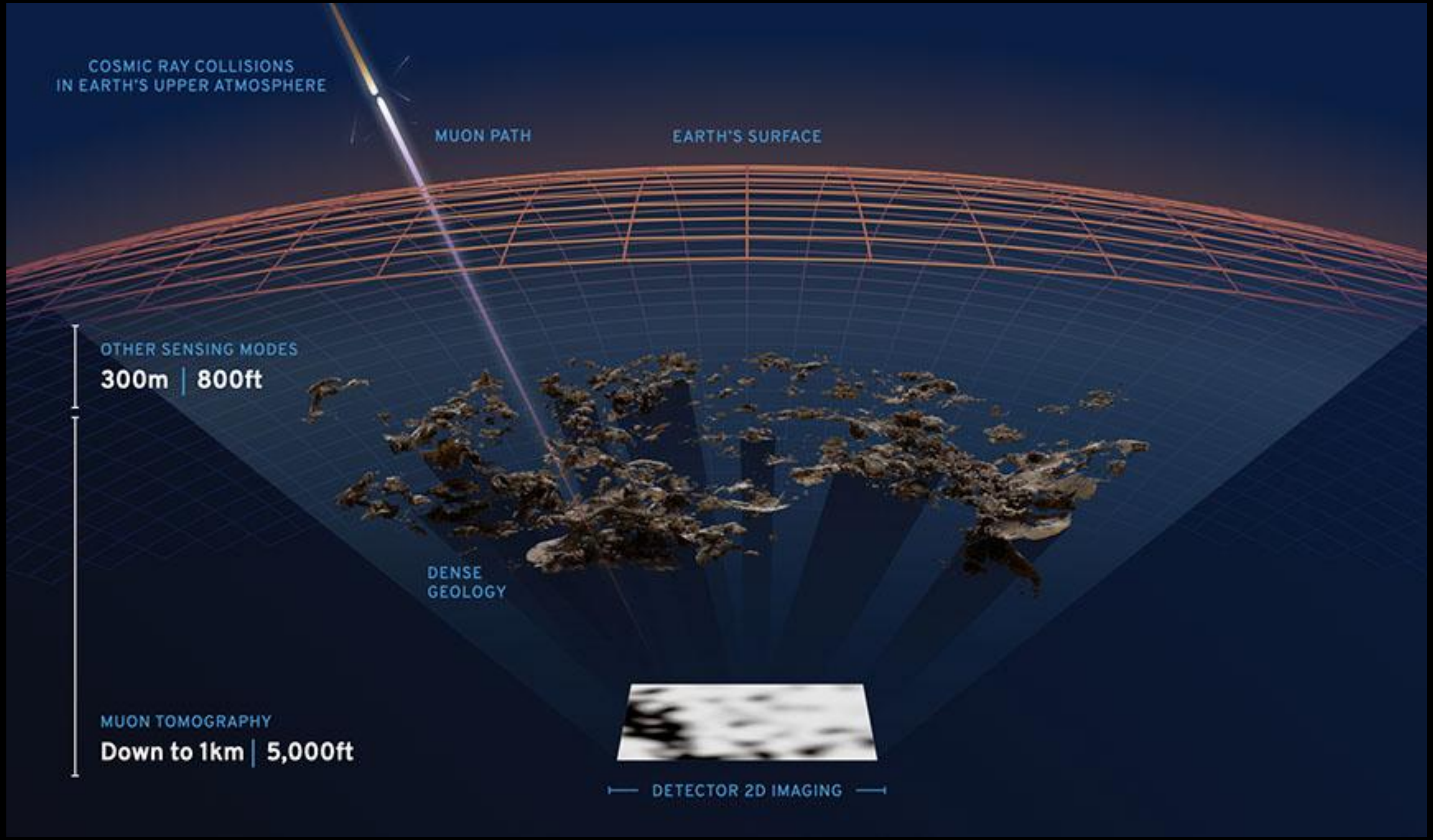


1 PMT Installation
2 Shielded Cover Integration
3 Wiring and Cable Management
4 Optical Gel Backfilling
5 Degassing & Vacuum Processing
6 Hemisphere Combination
7 Quality Control
8 Sealing

Design and Validation of a Cosmic Muon-Based Testing Method for IceCube-Gen2 Optical Modules

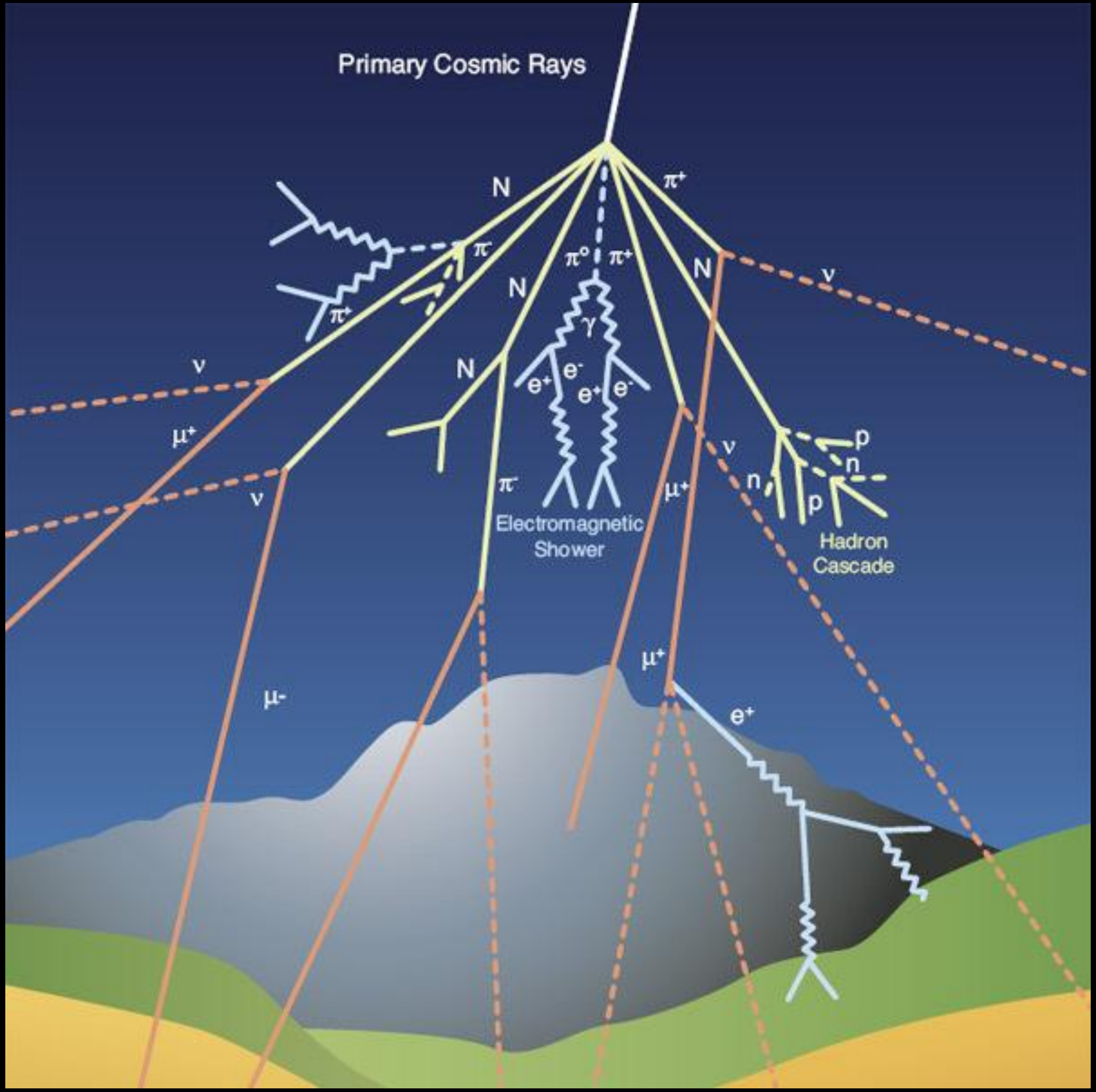
By Pound Thammarat, Yuya Makino, Chris Wendt

Primary objective for designing this testing method



- Construction and testing 10,000 modules across North America, Europe, Asia (and the Pole)
- Develop a cost-effective and consistent module testing procedure
- Introduced a muon-based module validation method for LOM-16
- Anywhere / Anytime & Scaleable to IceCube-Gen2

Why “Muon” ?



→ Atmospheric Cosmic rays

- Abundant (>100 Hz per module)
- Free & natural calibration source
- Penetrates module geometry
- Independent of flasher system
- Suitable for mass production (>10,000 modules)
- Applicable for south pole deployment

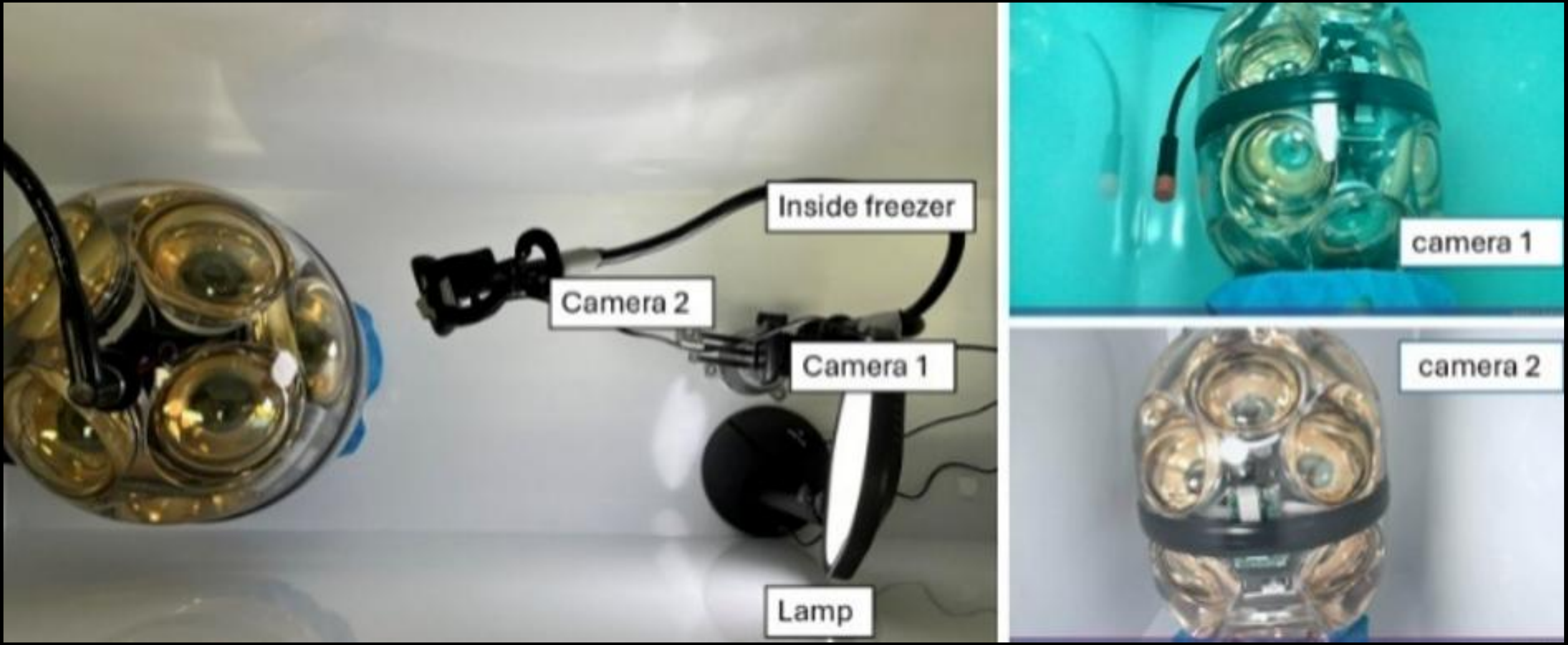
LOM-16 FAT & Muon Dataset

LOM-16 FAT Setup
(Chest Freezer)

- Intregrated LOM-16s have been tested through Final Acceptance Testing (FAT)
  - FAT: Basic functionality testing at various temperatures
  - All tested modules passed FAT

- During FAT, we had a muon run at -40 degree C
  - "Muon run" ⟶ High threshold run (few PEs), ~ 10 Hz /PMT
  - Nominal gain (5e6)
  - Data taking 10-30 min / module
  - This dataset wasn't used for LOM FAT Pass / Fail Conditions, but for future study ⟶ This project!

Overall Testing Pipeline Setup



LOM-16s used in this study

LOM16-01
Nyx

LOM16-02
Stick of Butter

LOM16-05
Westfalian Watcher

LOM16-06
Starspawn

LOM16-07
Hutch

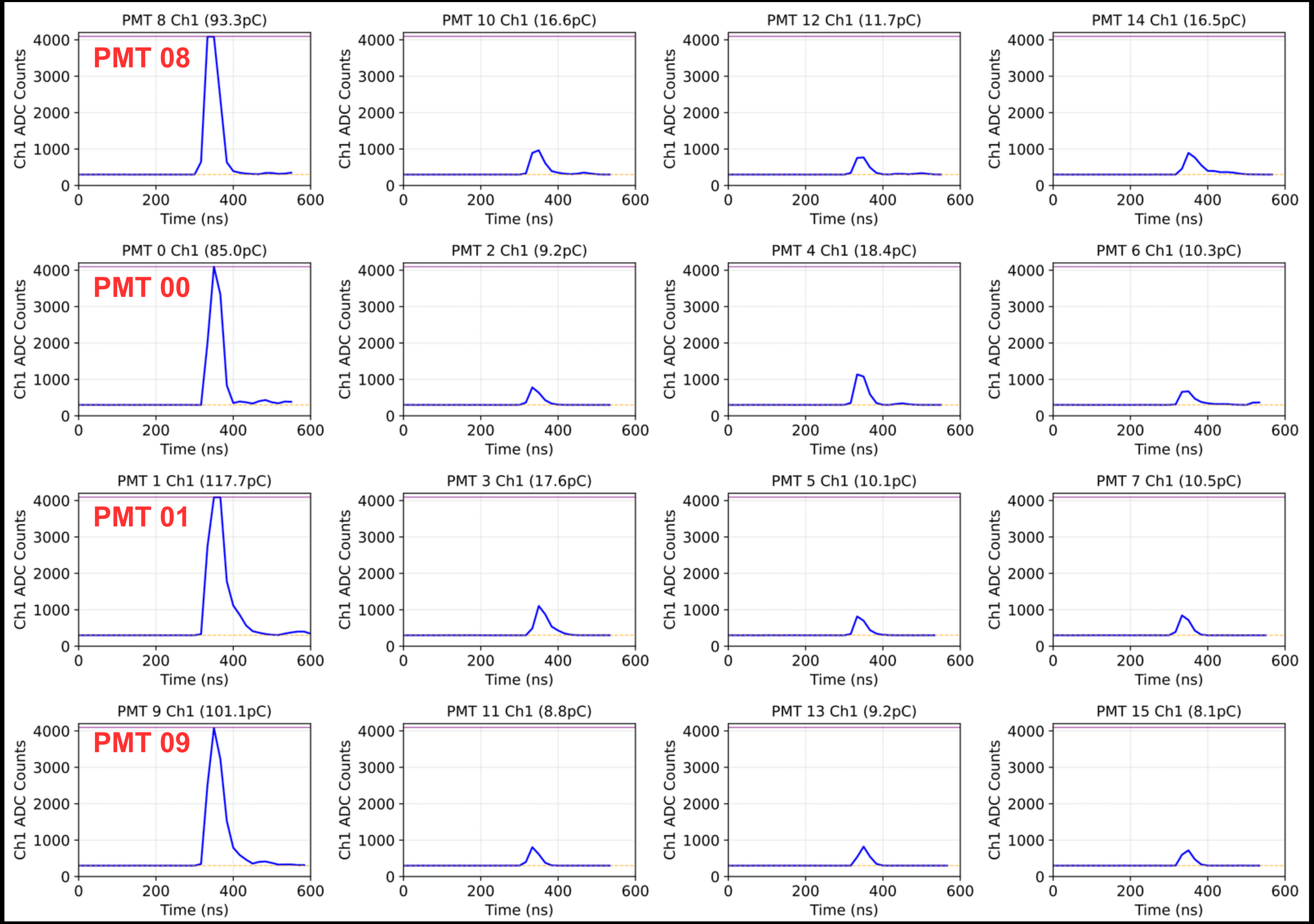
LOM16-08
Colossal Squid

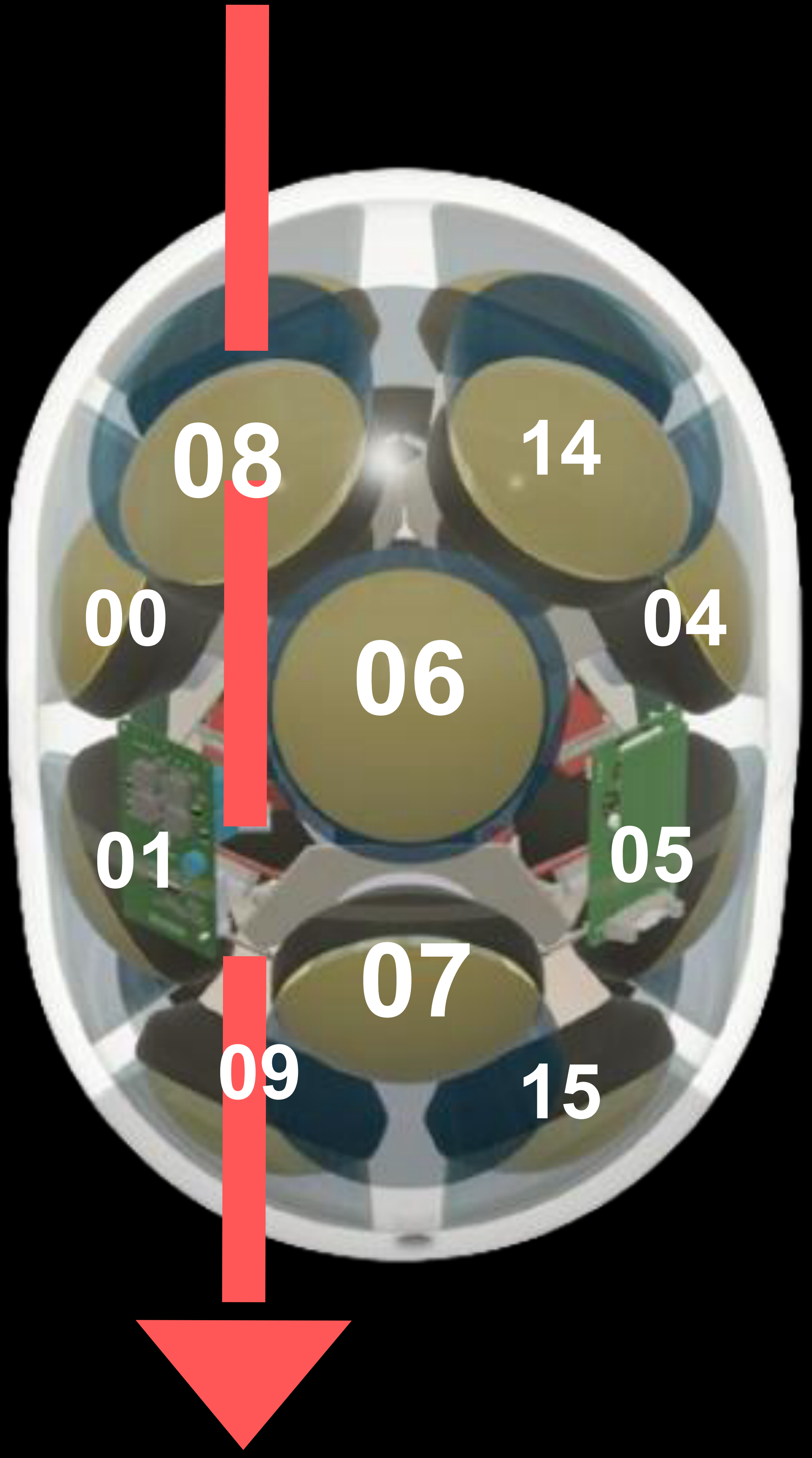
- Development of new module testing method using muons
- Introduced a muon-based module validation method for LOM-16
- Anywhere / Anytime & Scaleable to IceCube-Gen2 (10,000 modules)

- LOM-16-01 (NNVT)
- LOM-16-02 (Hamamatsu)
- LOM-16-05 (NNVT)
- LOM-16-06 (Hamamatsu)
- LOM-16-07 (NNVT)
- LOM-16-08 (NNVT)

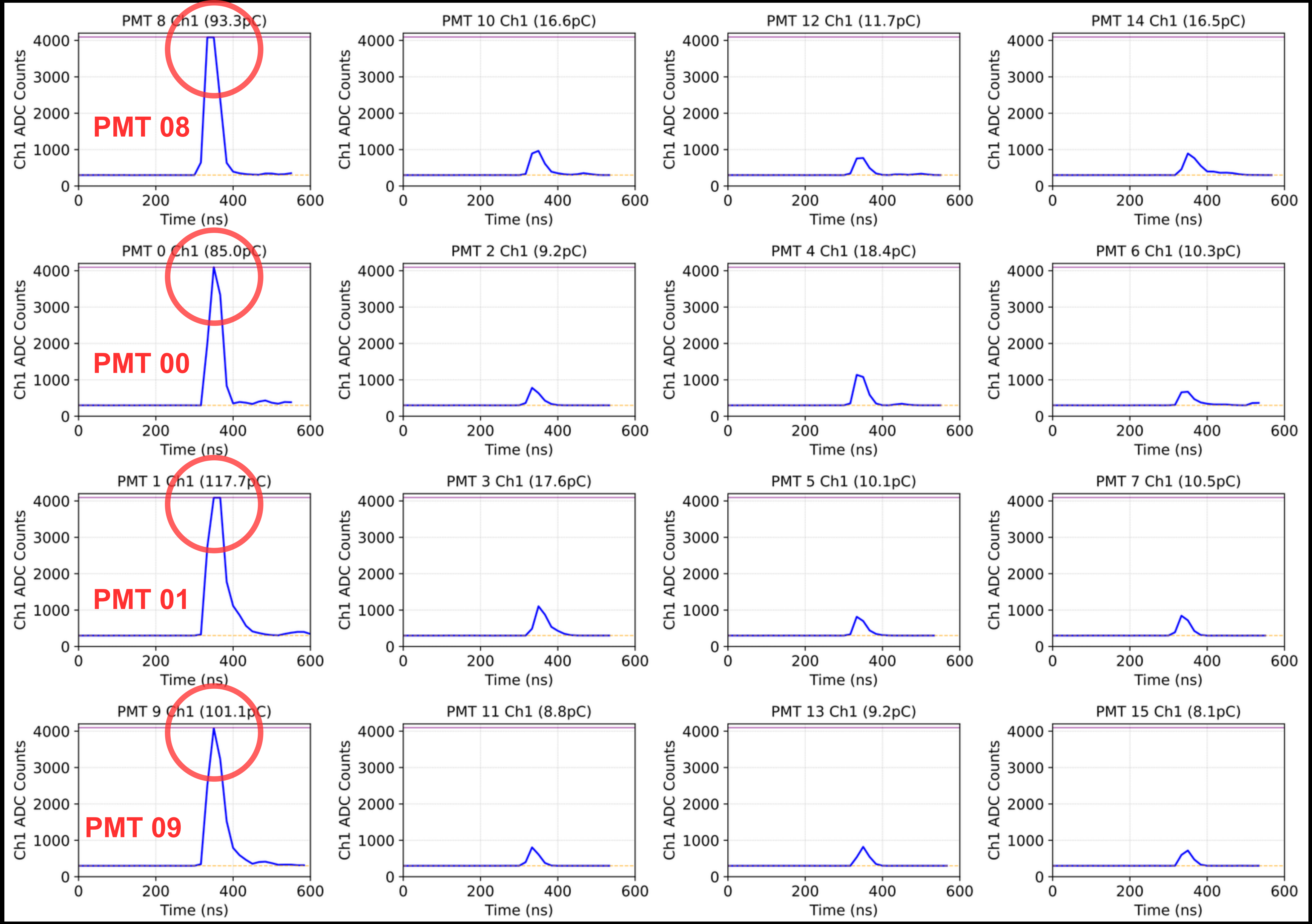
All were successfully deployed at the pole!!!

Muon event candidate?





Muon event candidate?

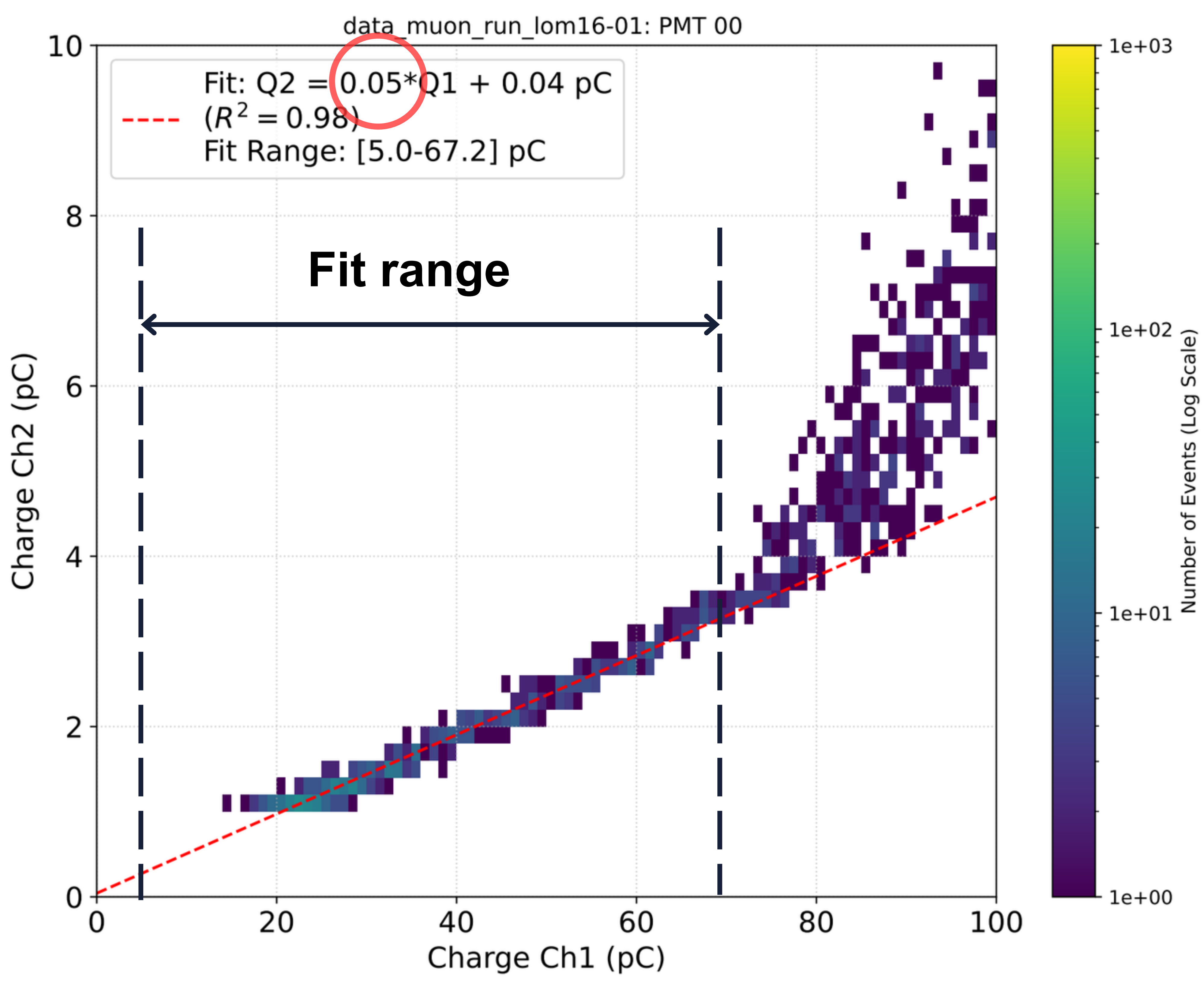


- 12 bit ADC (0-4095)
- baseline ~ 300 counts (~200 kHz)
- Muon events often cause ADC overflow in the high gain channel (ch1)

→ information from low gain channel is critical for muon analysis
(but tools not developed much!)

Ch1/Ch2 charge ratio

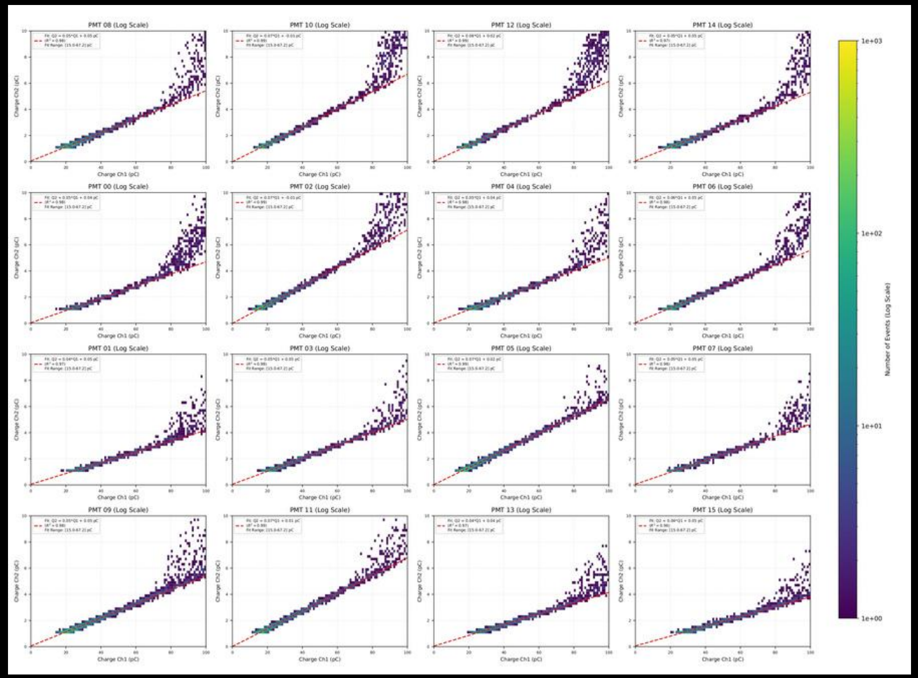
Example) LOM16-01 PMT 00



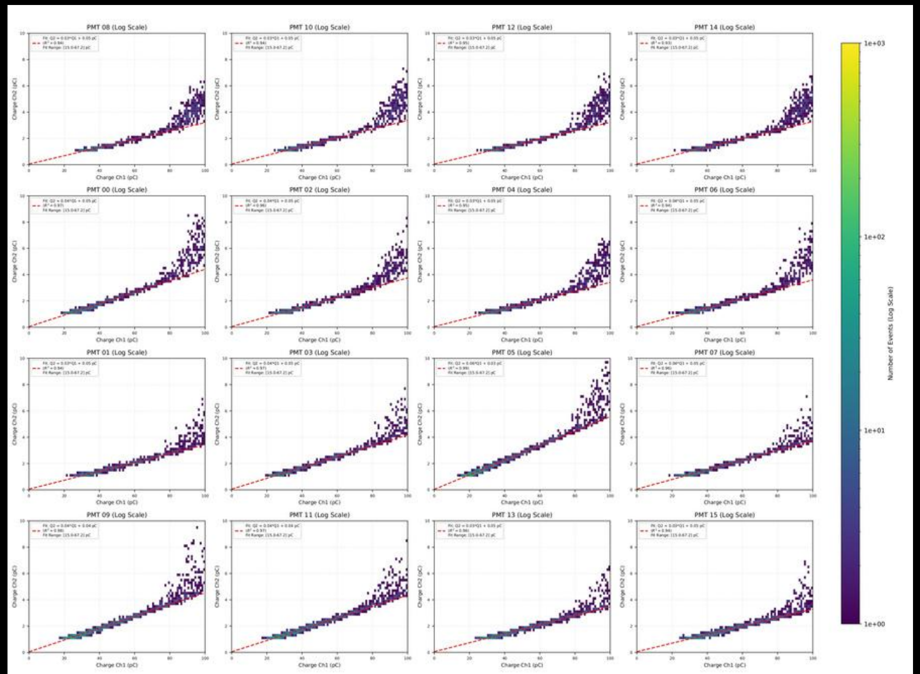
- The gain of low-gain channel (Ch2) can't be determined by SPE because of too small signals
- Estimated ch2 gain by fitting ch1/ch2 ratio where whole ch1 waveform stays within the ADC range.
- Fitting for all PMTs

Ch1 / Ch2 Charge ratio (96 PMTs)

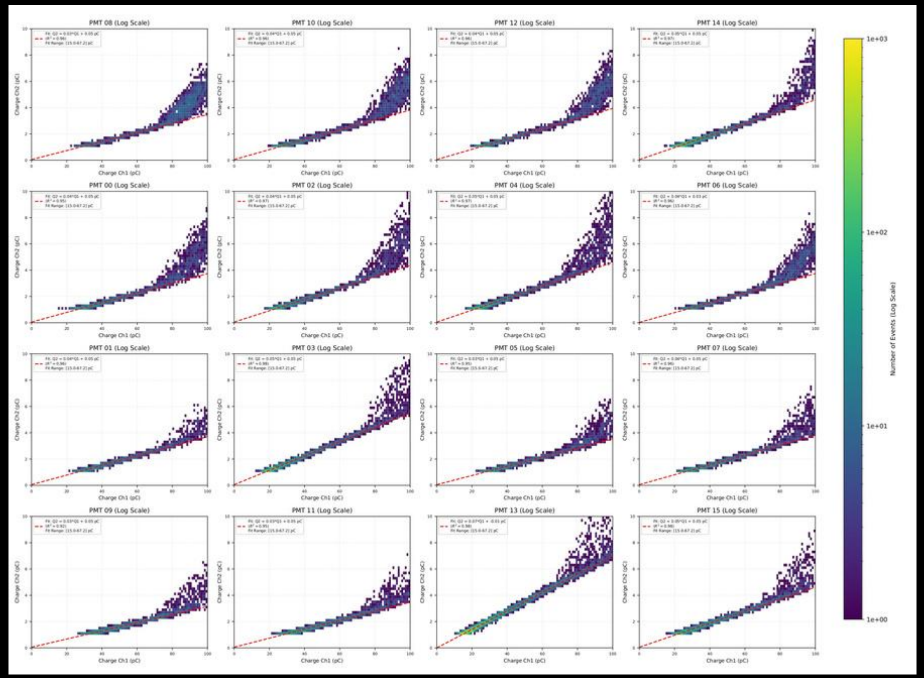
LOM-16-01



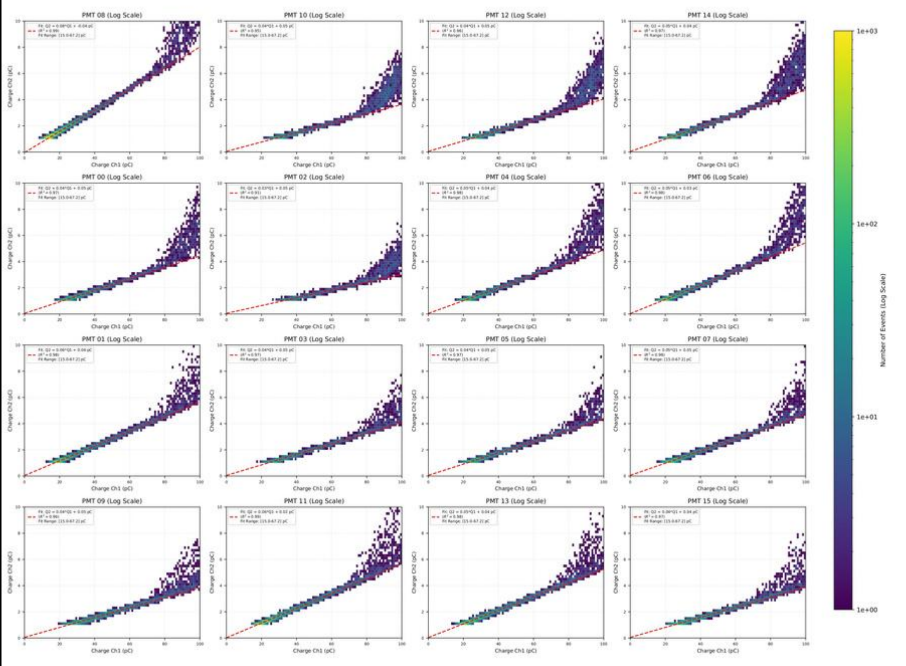
LOM-16-02



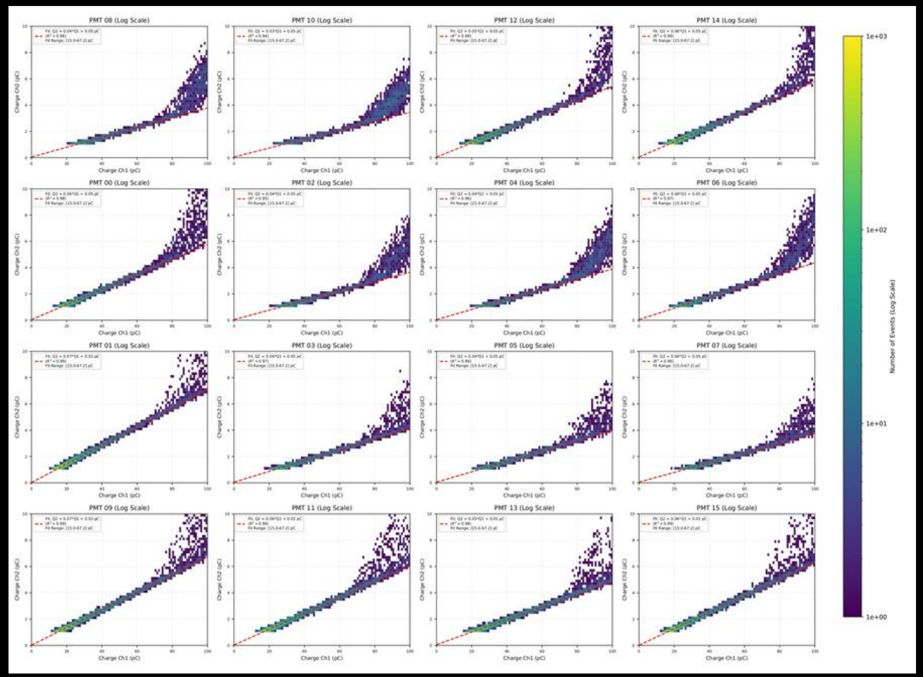
LOM-16-05



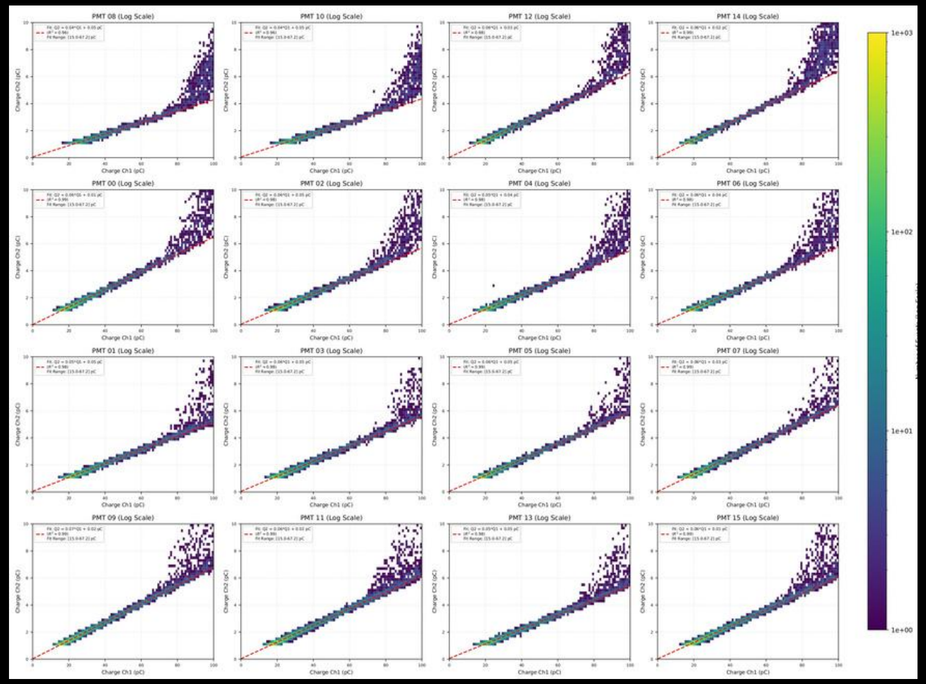
LOM-16-06



LOM-16-07



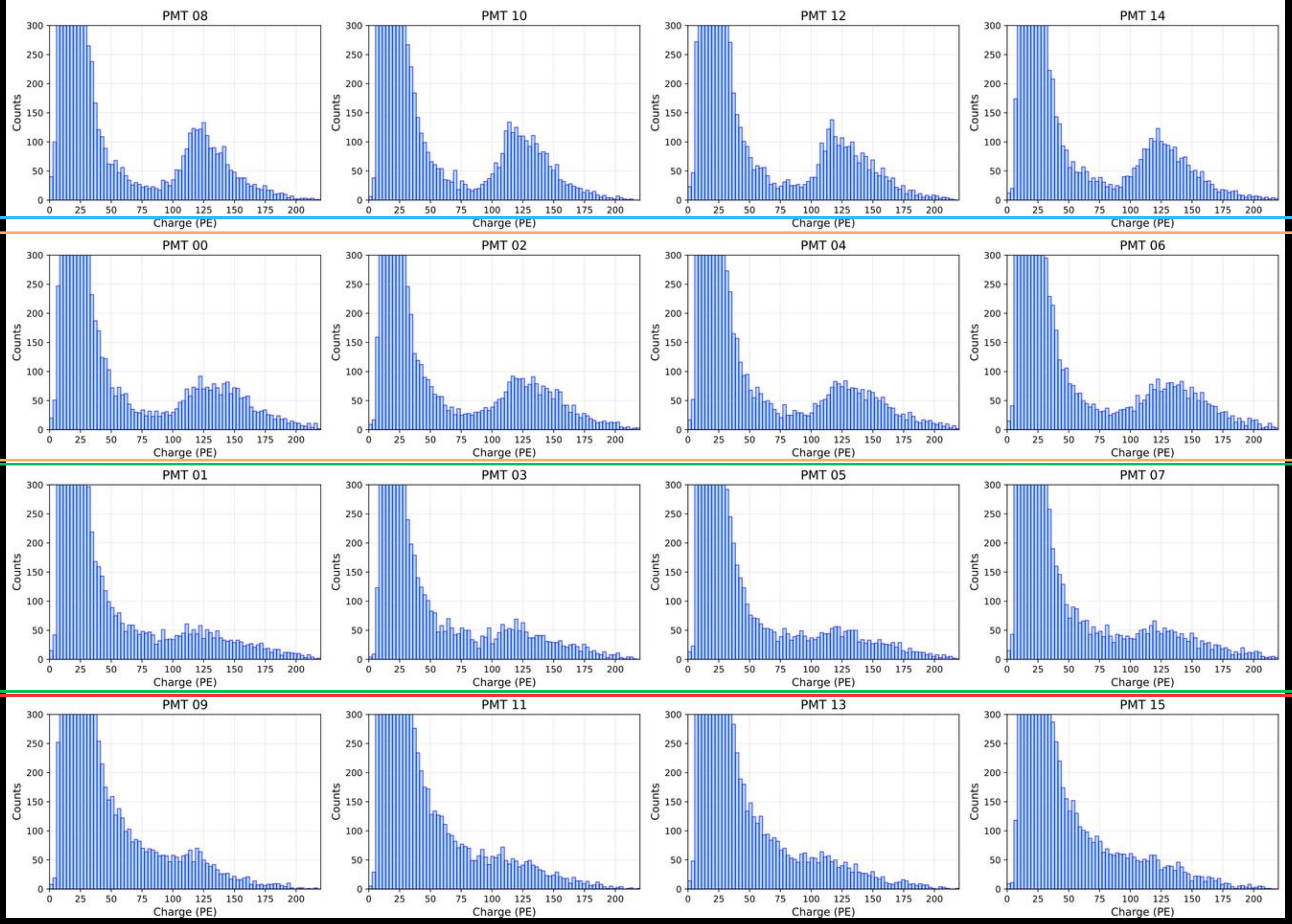
LOM-16-08



→ Use the results to calculate PE with ch2

Muon dataset charge distributions

Data (LOM16 - 06)



Upper Polar PMT

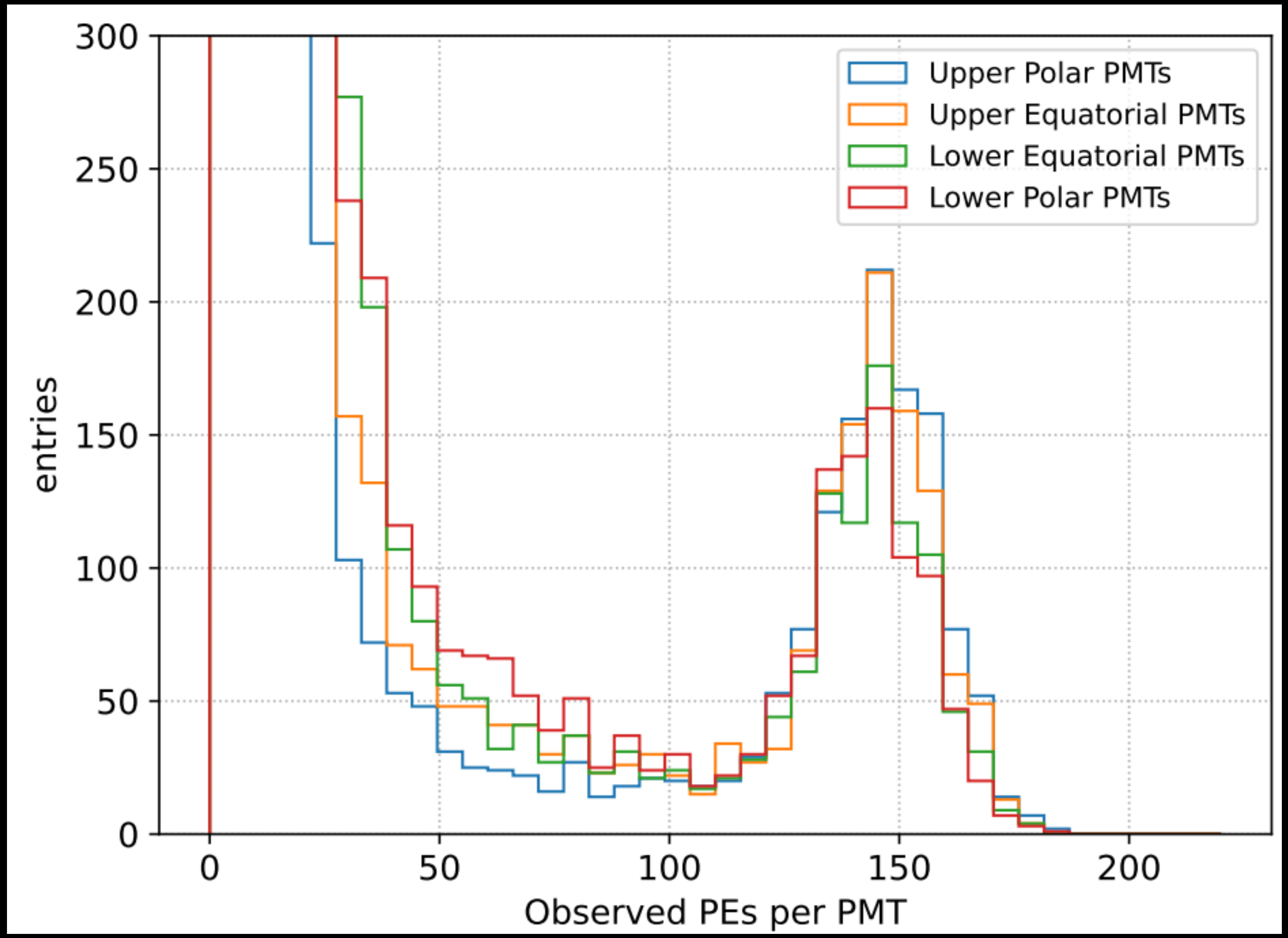
Upper Equatorial PMT

Lower Equatorial PMT

Lower Polar PMT

- Peak around 130 PEs
- Distributions broader in lower hemisphere

Simulation (GEANT4)

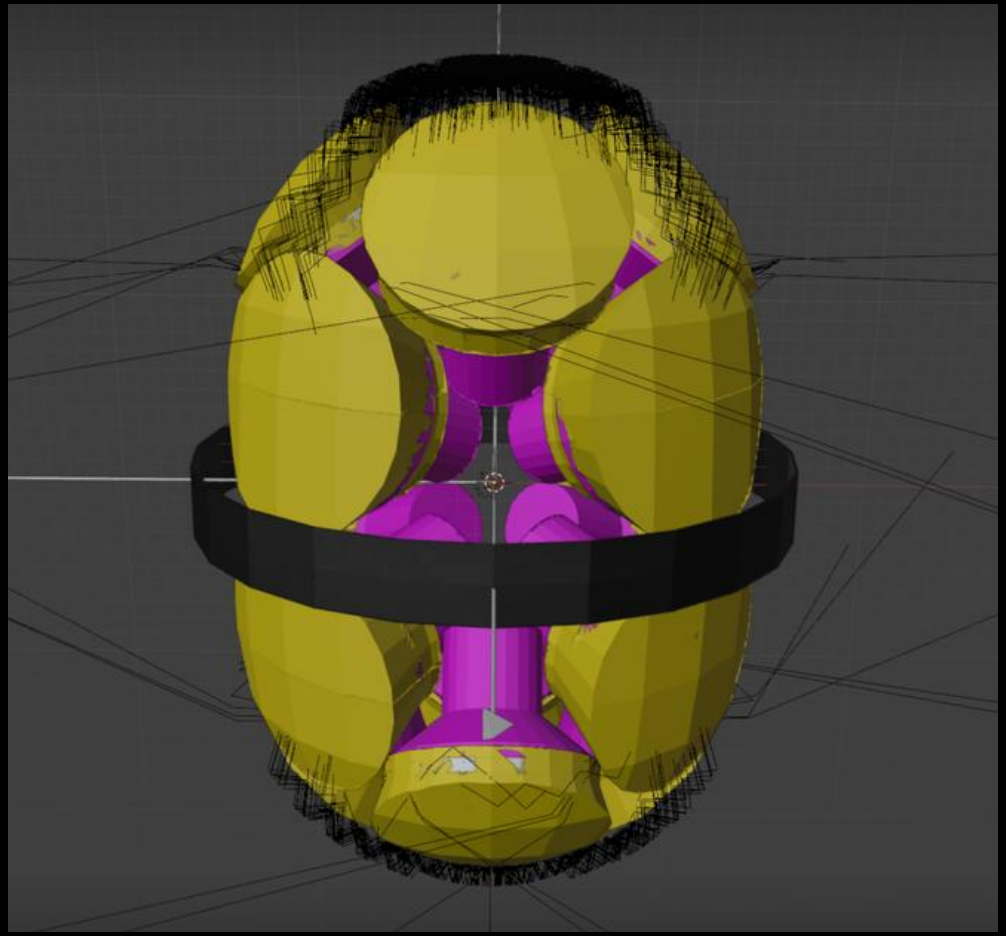


- Peak around 140 PEs
- Distribution shapes similar to data

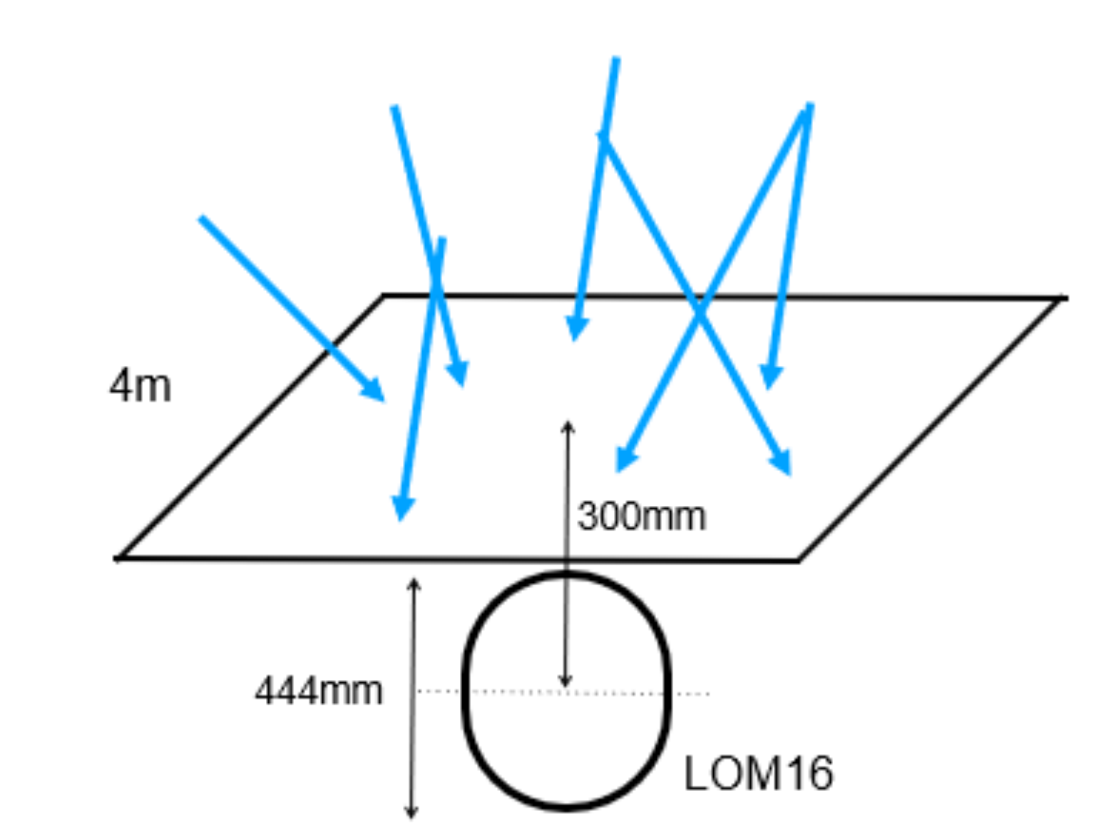
(Some muons can be stopped before reaching to the

Muon simulation with Geant4

LOM16 in GEANT4



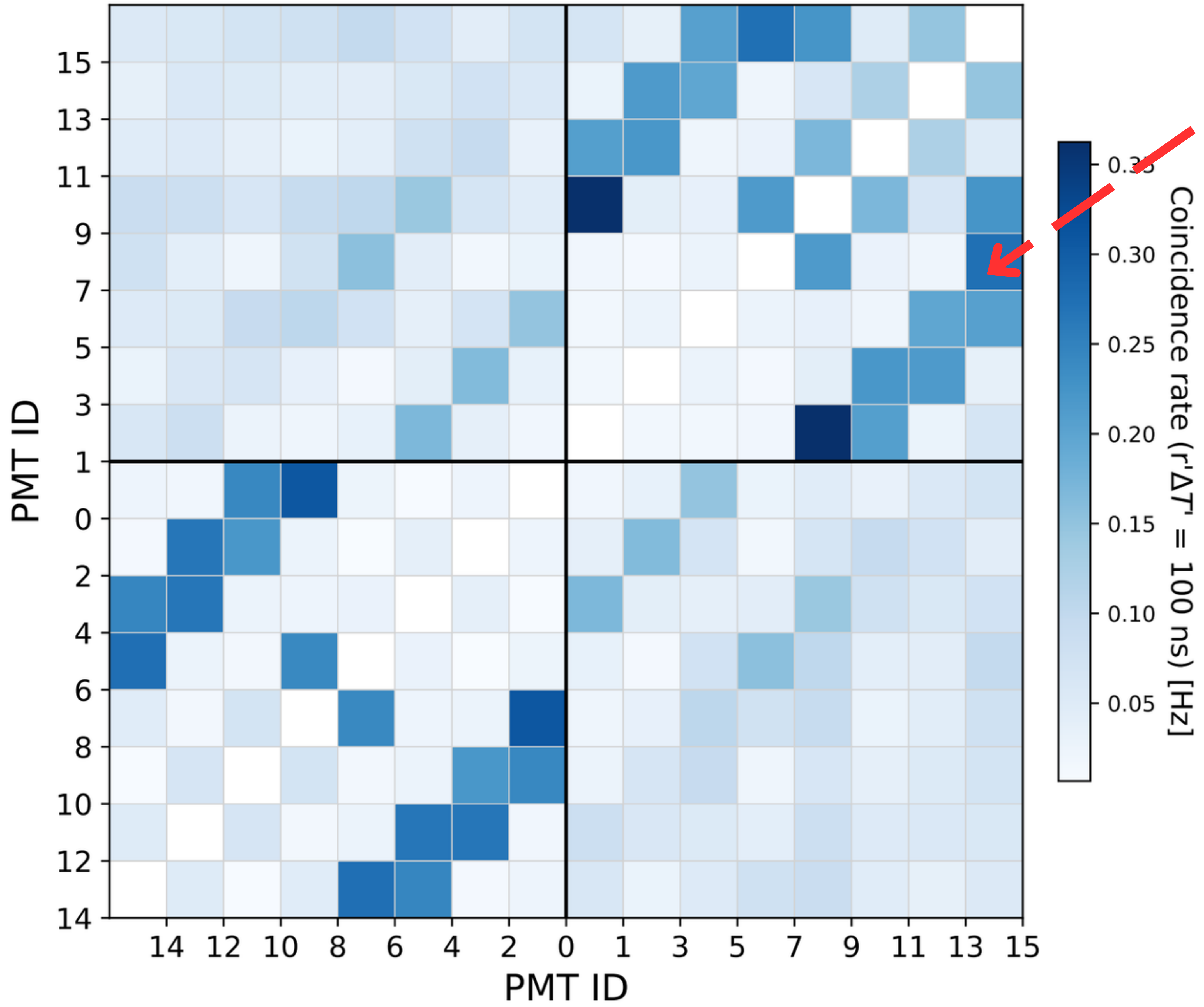
Simulation setup for Muon run



- **Generated LOM-16 muon dataset**
  - Worked with Nobu (Chiba)
  - Latest LOM-16 model implemented in GEANT4
- **Muon dataset**
  - Down going muons from all directions
  - 100,000 events (~3,000 hit the module)
  - Flux normalized by data from Particle Data Group

Coincidence rates (LOM-16-01)

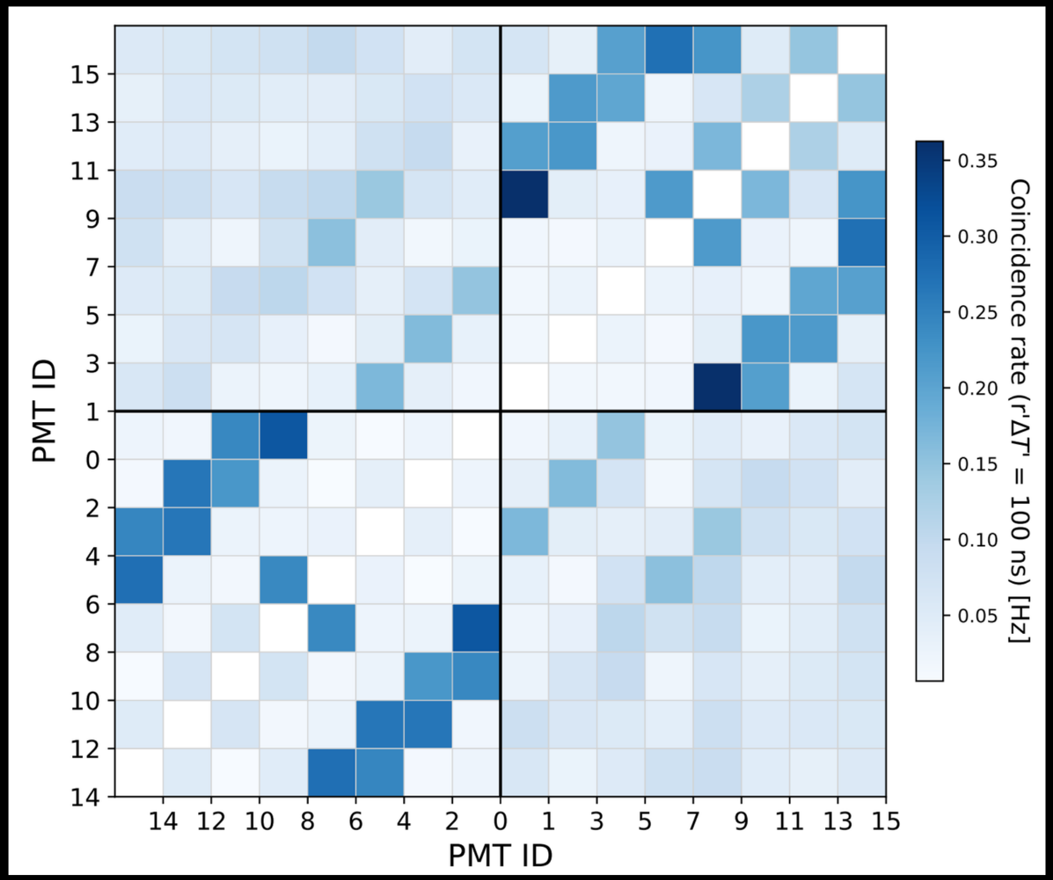
Data, Threshold 50 PE



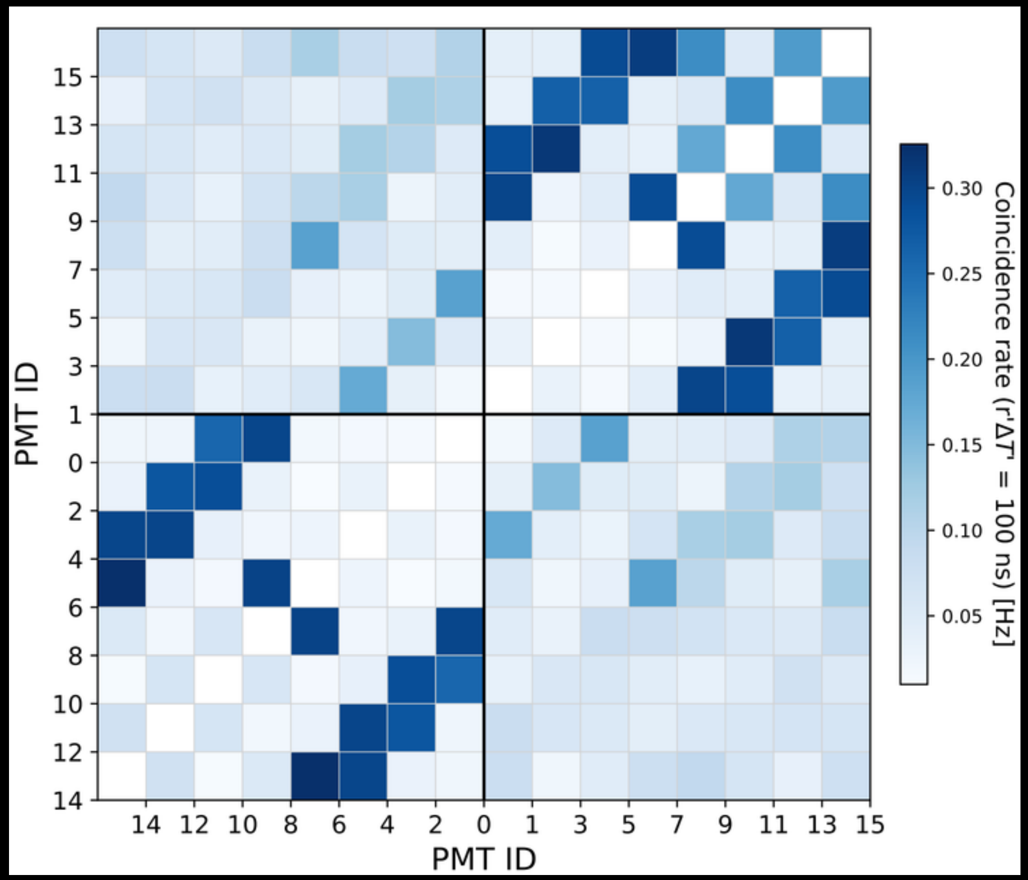
Example: Event rate of both PMT 15 & 07 see > 50 PEs in the same event

1,536 resolution coincidences for 6 LOM-16s

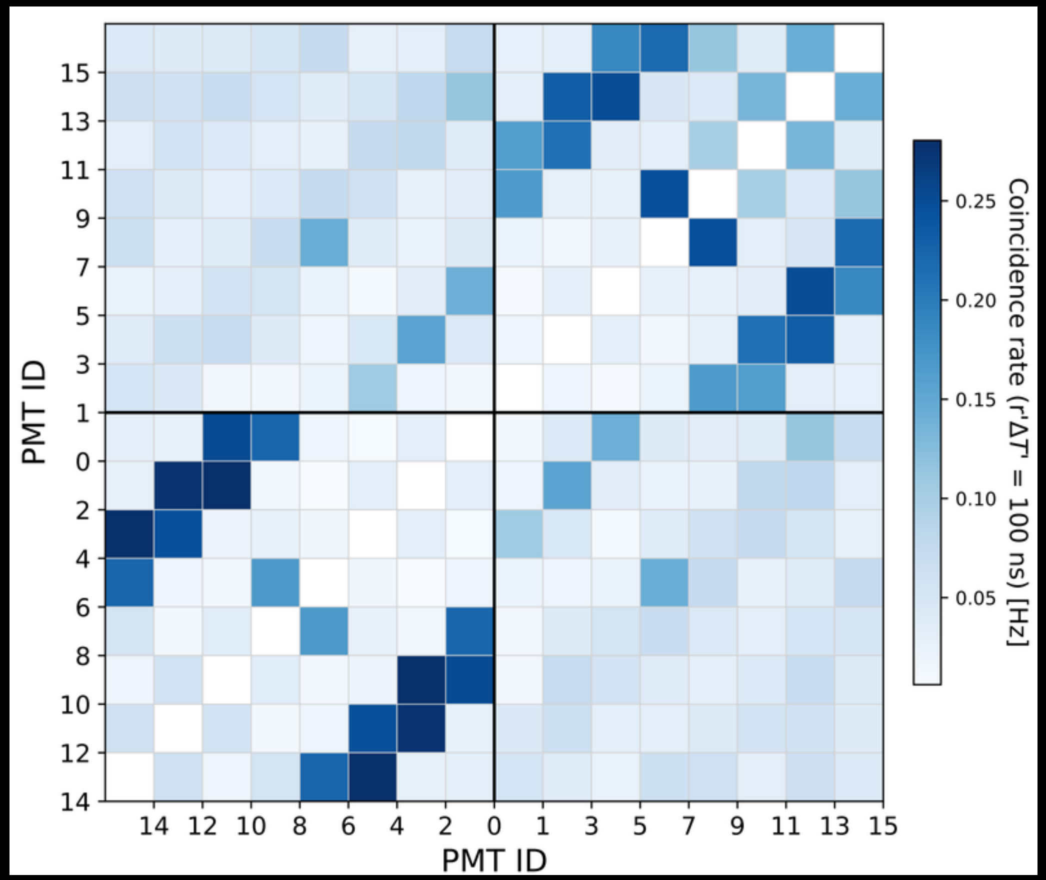
LOM16-01



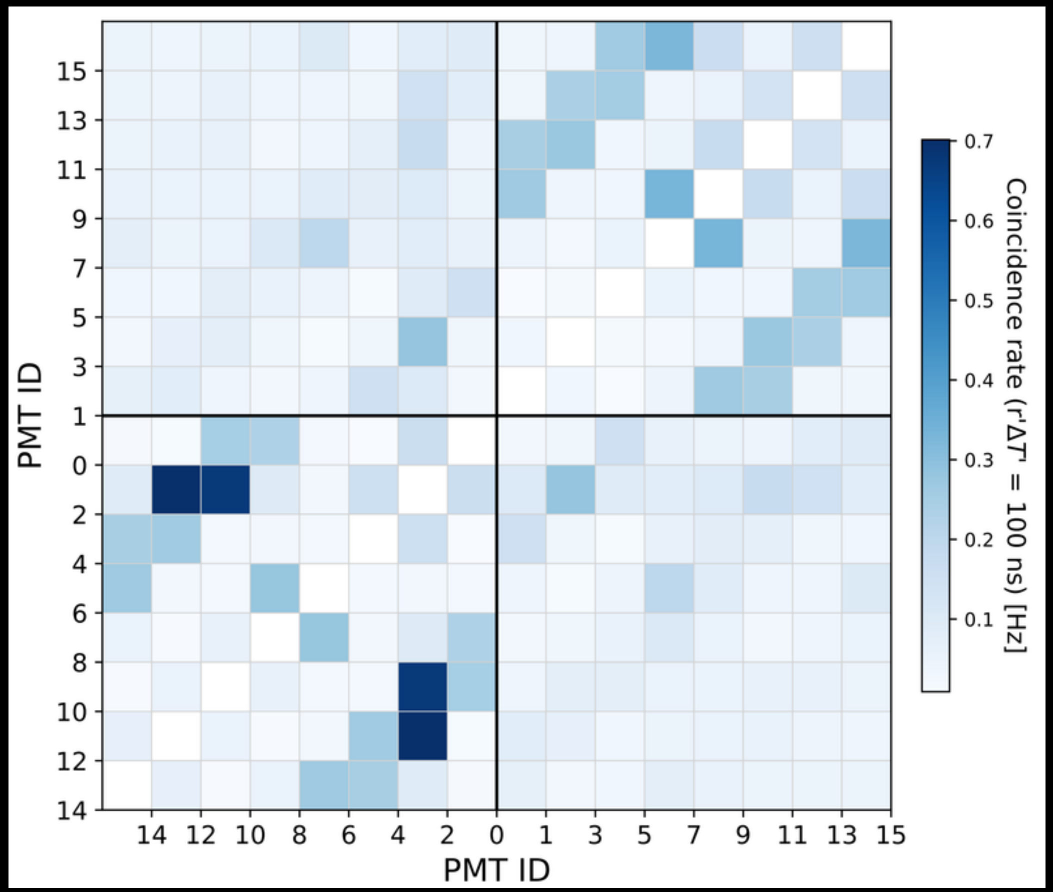
LOM16-02



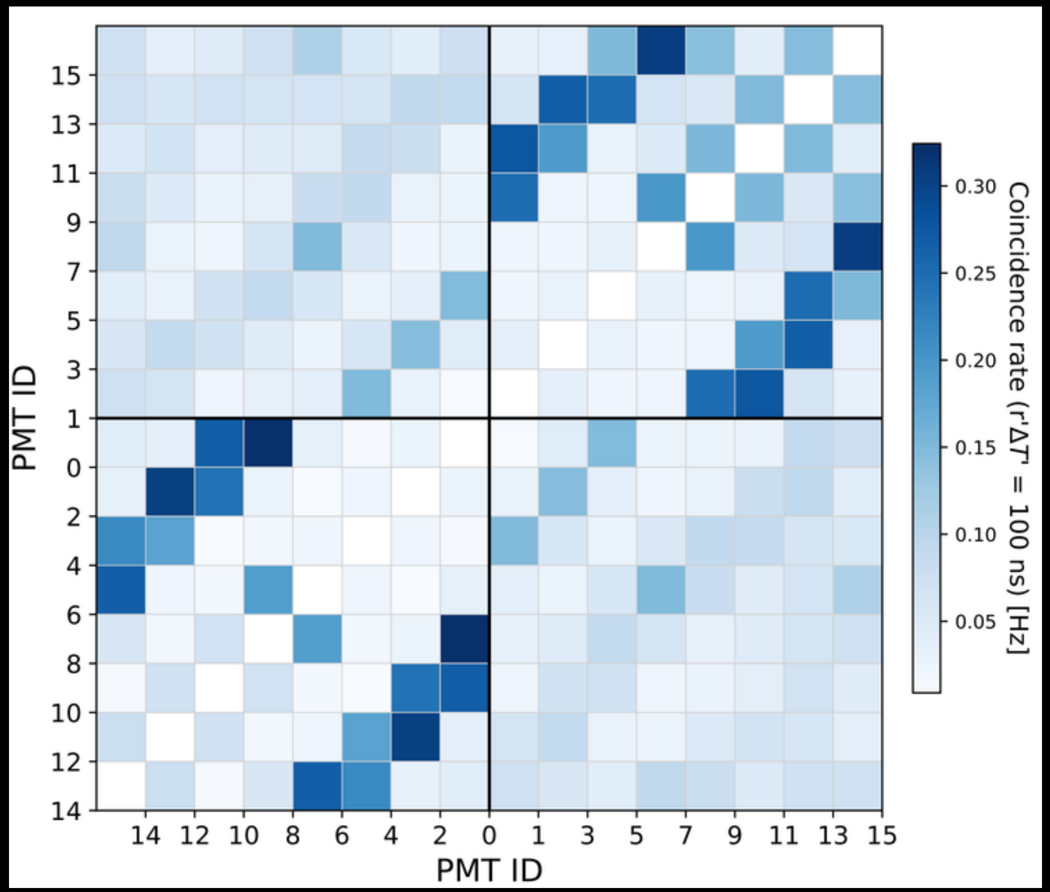
LOM16-05



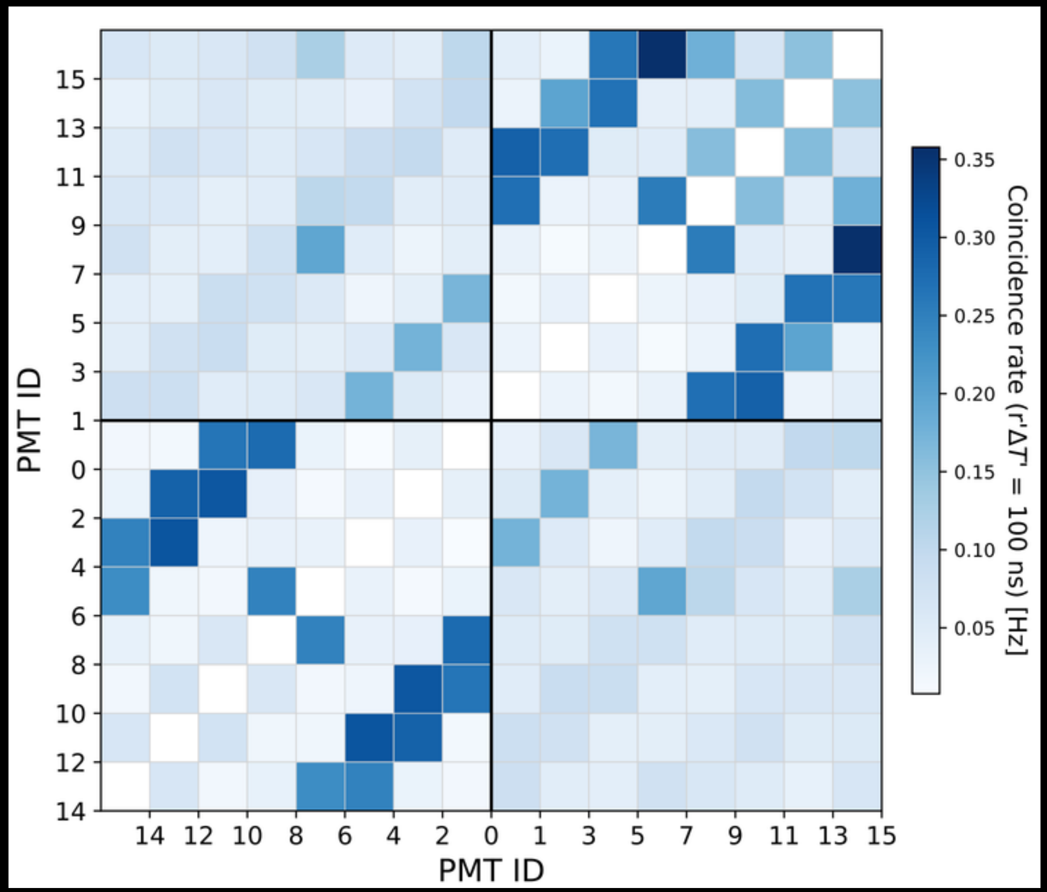
LOM16-06



LOM16-07

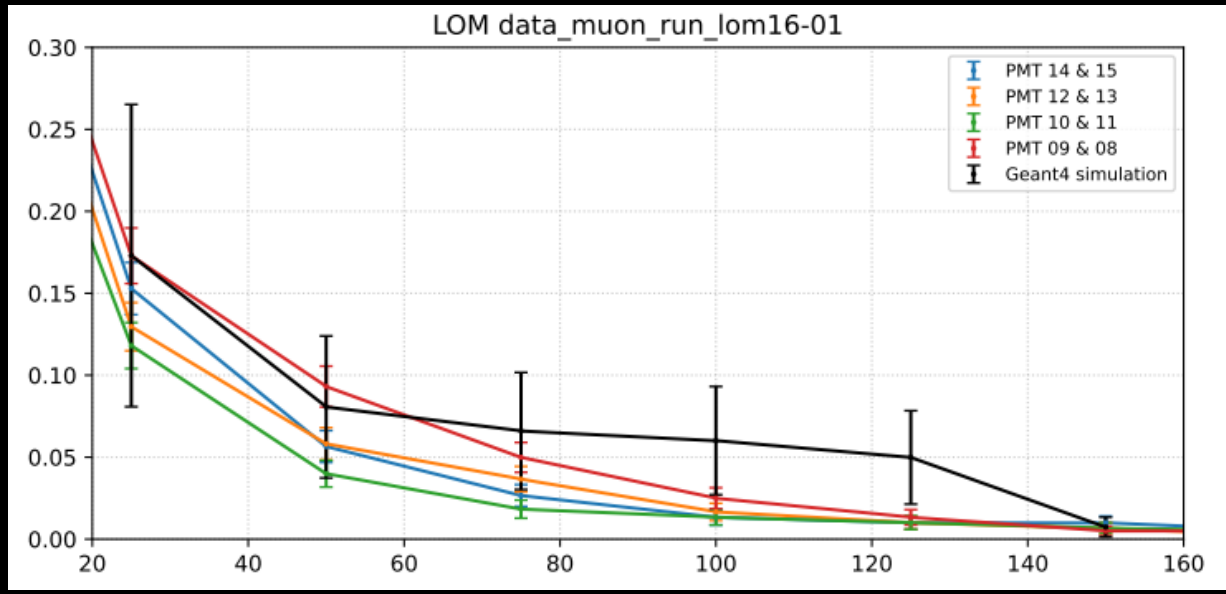


LOM16-08

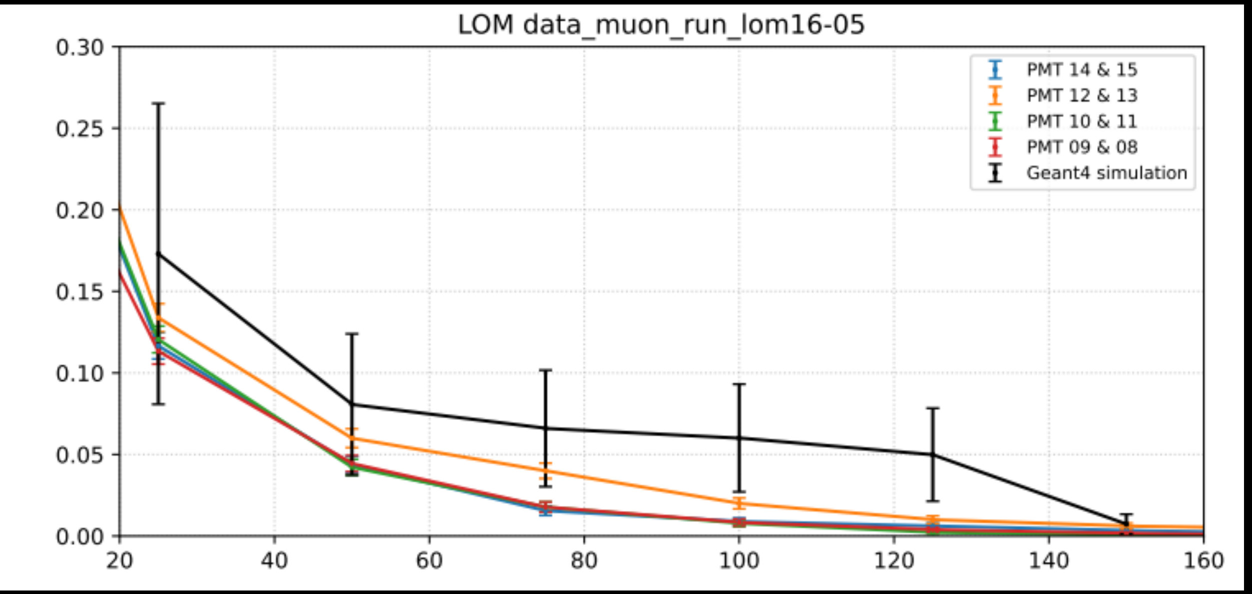


All LOM-16s coincidence rate

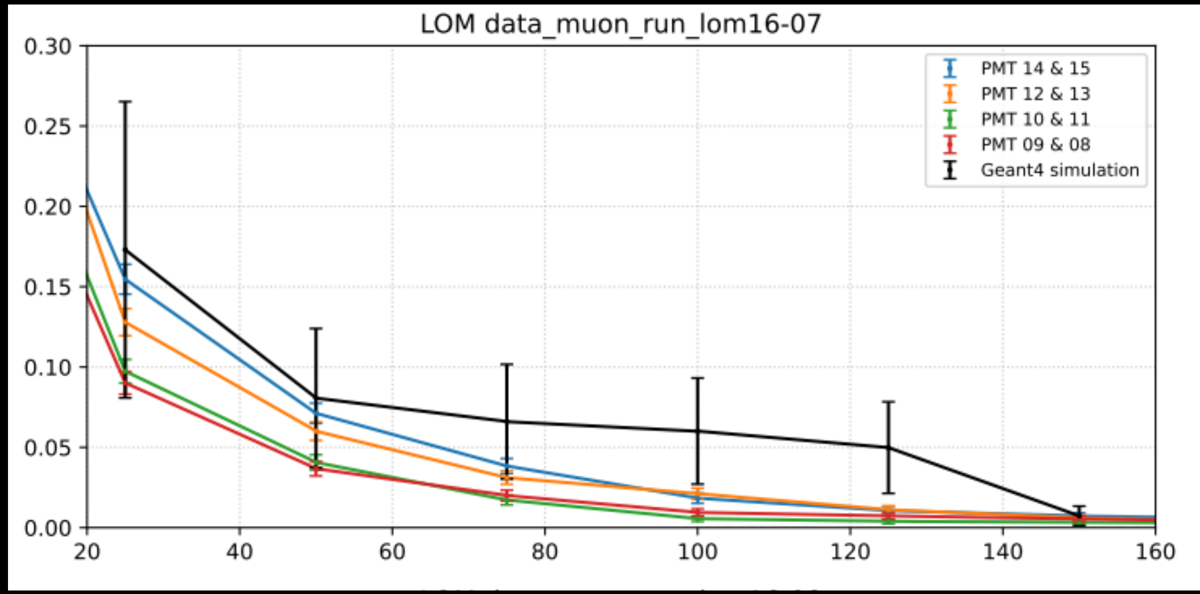
LOM16-01



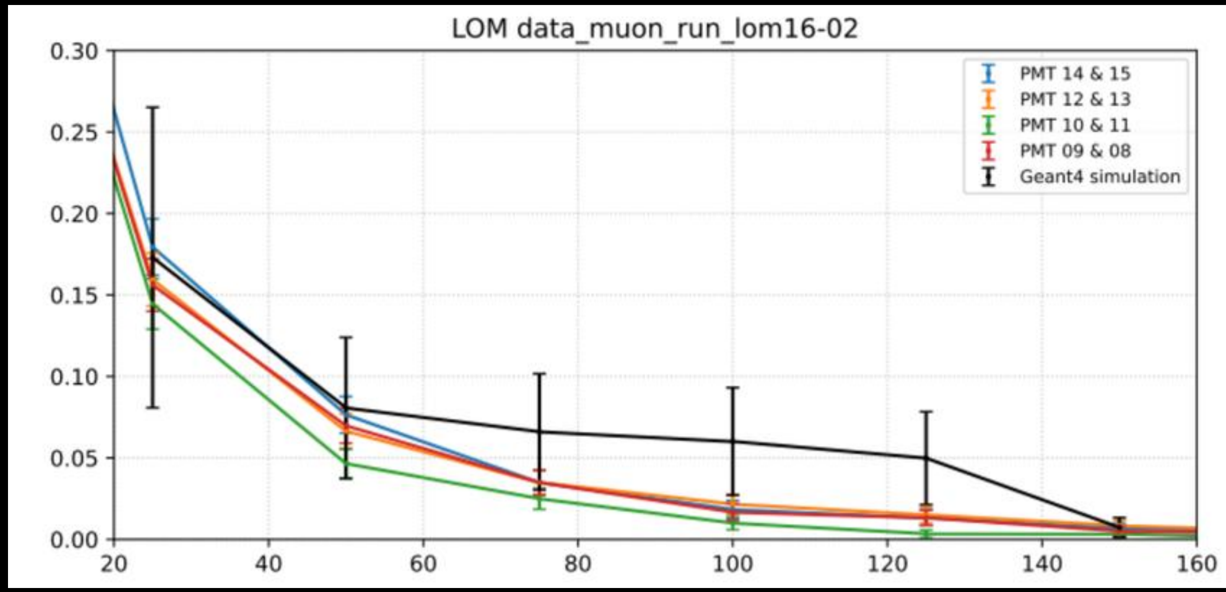
LOM16-05



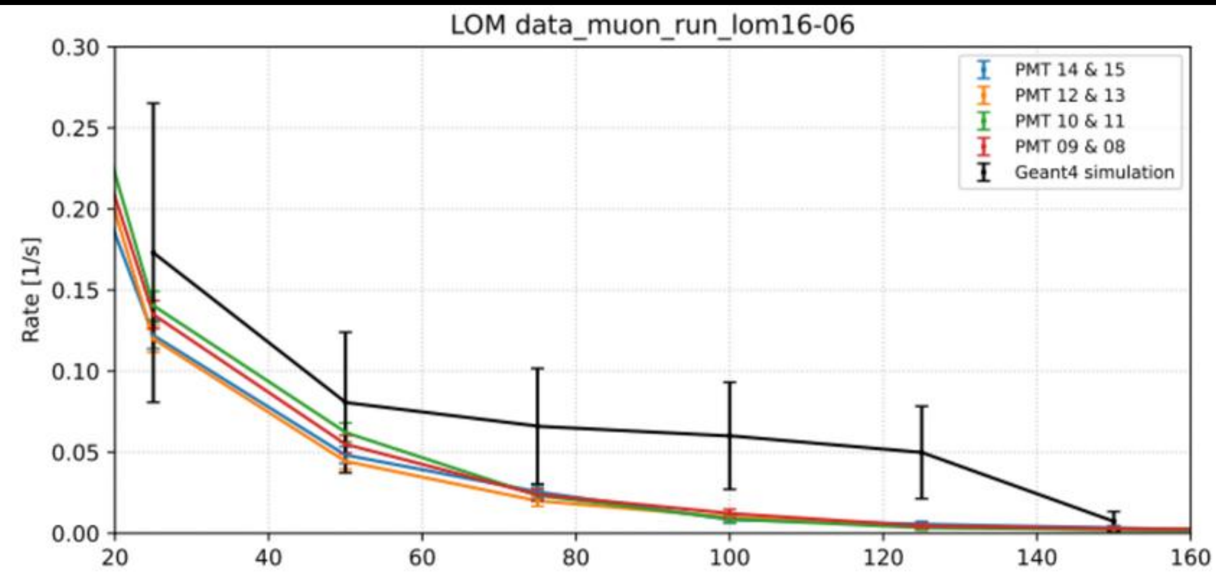
LOM16-07



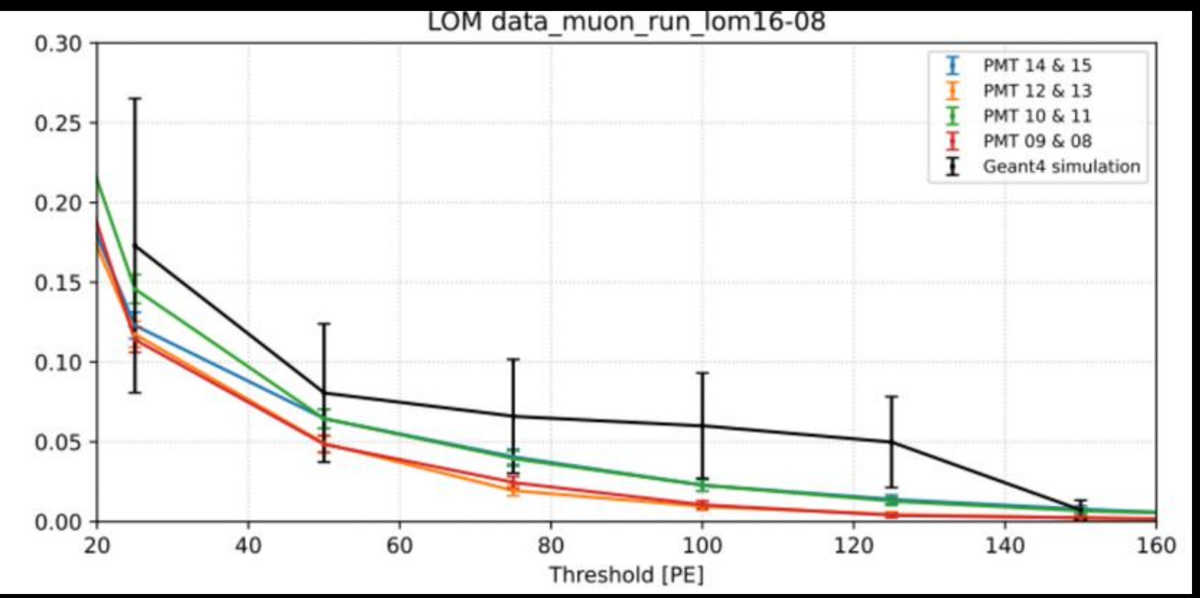
LOM16-02



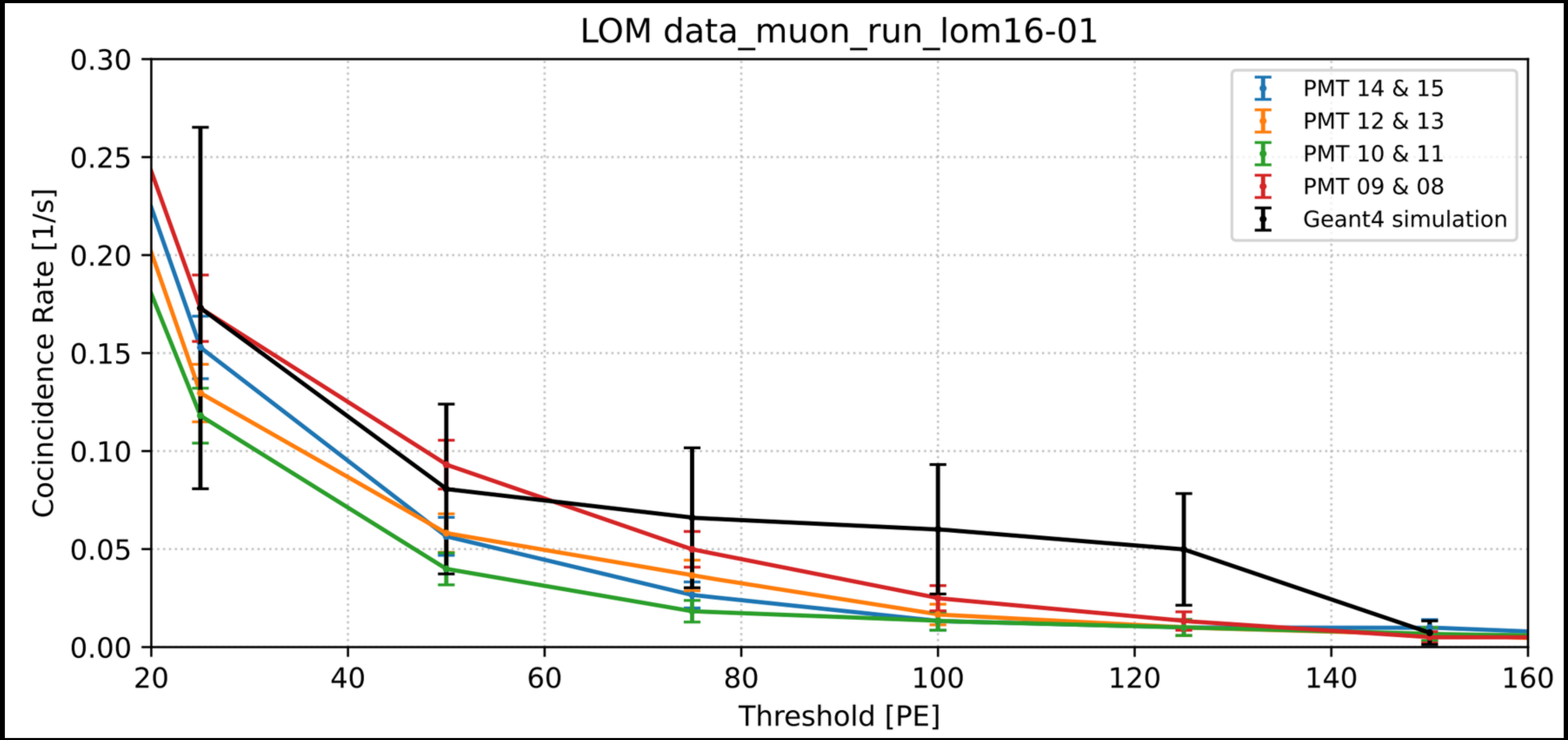
LOM16-06

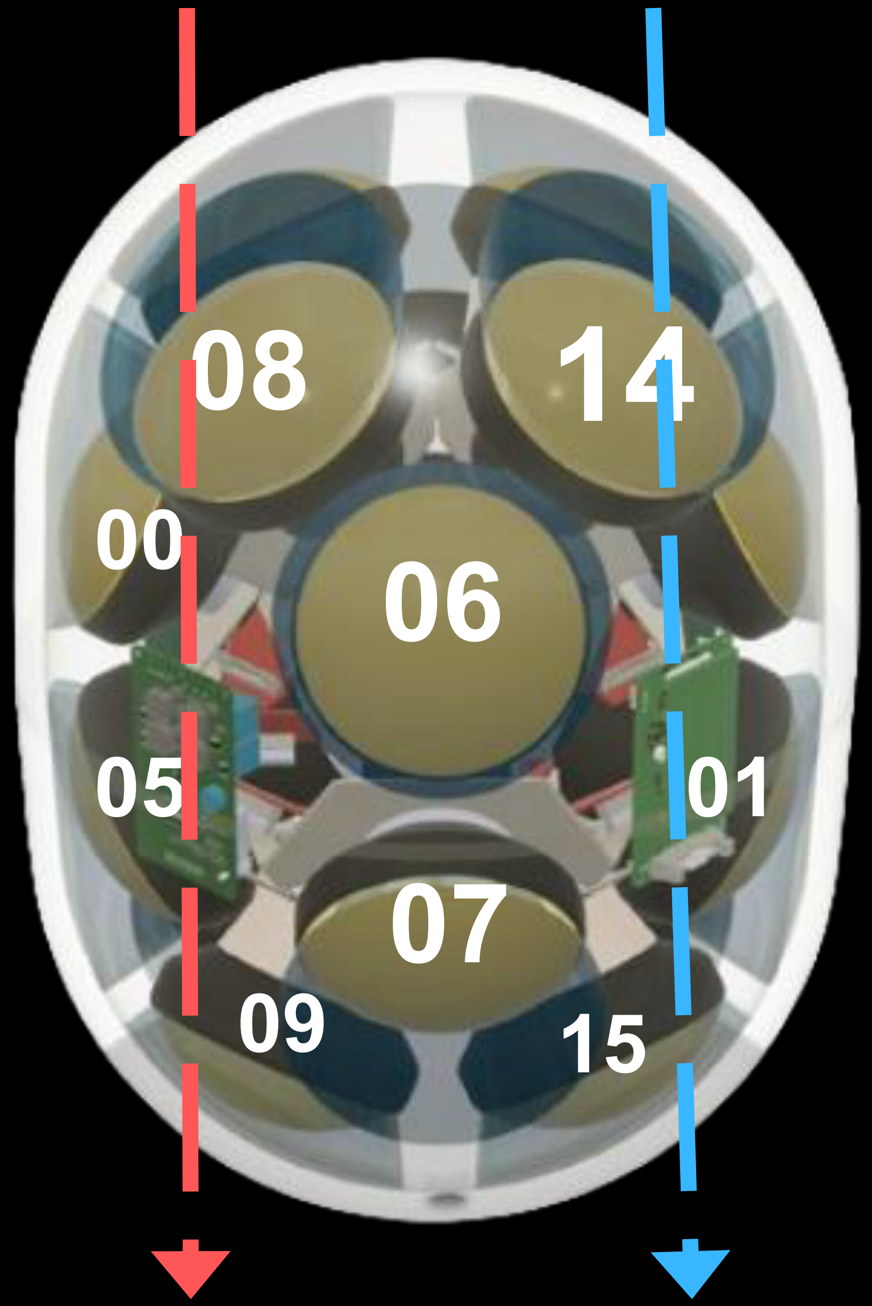


LOM16-08



Vertical muon event rate (angular response)



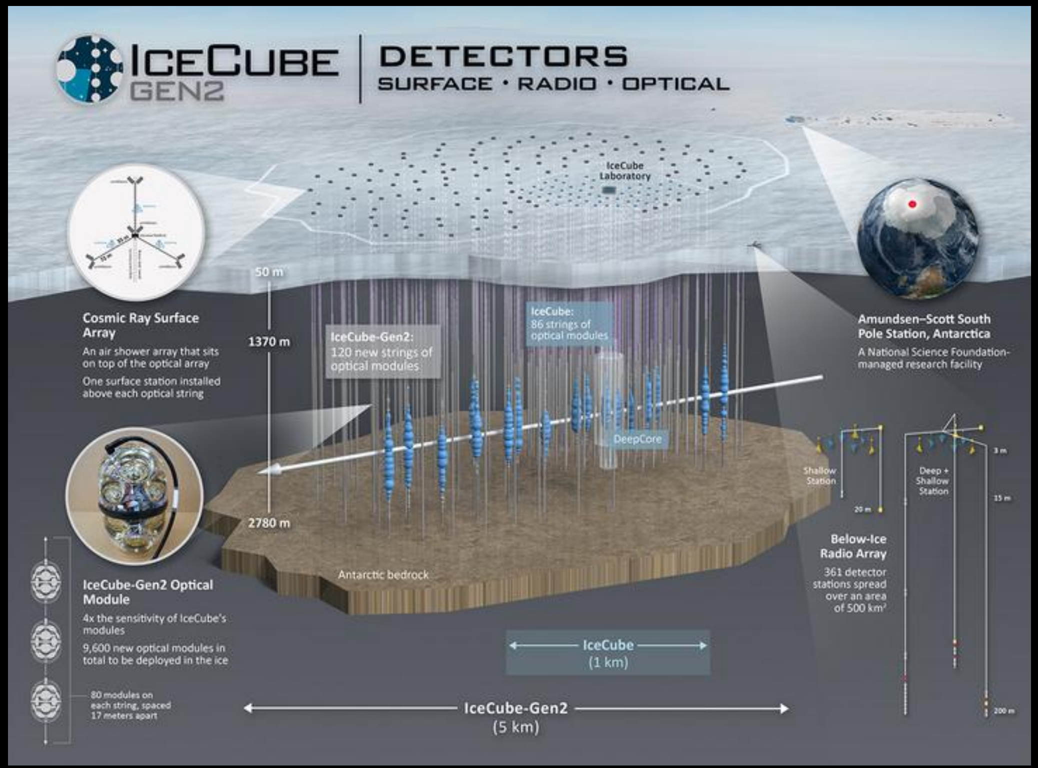


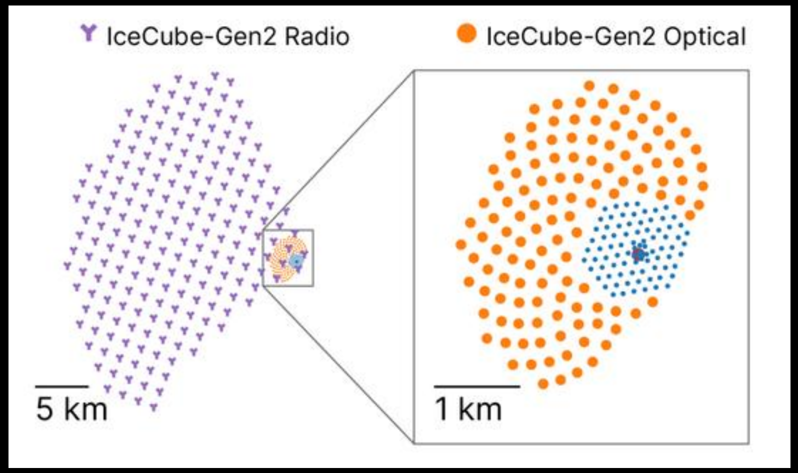
- **Data)** Coincidence rates for the polar PMT pairs are close to each other
- **Data / Simulation)** Agreement reasonably good
- **Proposal:** This measurement can be a good demonstration of the module / system working correctly in the mass production phase

Design and Validation of a Cosmic Muon-Based Testing Method for IceCube-Gen2 Optical Modules

Thammarat Yawisit[1]*, Yuya Makino[2], Christopher Wendt[2]
[1] King Mongkut's Institute of Technology Ladkrabang, Thailand
[2] Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, United States

Overview





- IceCube-Gen2 will deploy ≈ 10,000 optical modules to enhance sensitivity to TeV–PeV neutrinos, requiring scalable quality control.
- We present a cosmic muon–based testing protocol using naturally occurring atmospheric muons as an intrinsic calibration source.
- The method integrates waveform inspection, charge distribution profiling, and inter-channel charge correlation to assess micro-base electronics performance.
- Validated on six LOM-16 modules, including the first South Pole deployment batch, the protocol enables physics-informed, large-scale quality assurance without external calibration systems.

Optical Module Setup

- Integrated LOM-16 modules were tested through the standard Final Acceptance Testing procedure, FAT includes basic functionality checks under multiple temperature conditions; all tested modules successfully passed FAT.
- During FAT, a dedicated cosmic muon run was performed at −40 °C, representative of South Pole operating conditions, The muon run employed a high-threshold configuration (few photoelectrons), yielding a trigger rate of approximately 10 Hz per PMT at a nominal gain of 5×10^6.
- Data were collected for 10-30 minutes per module, while the muon dataset was not used for FAT pass/fail decisions, it forms the basis of the physics-informed validation study presented here.

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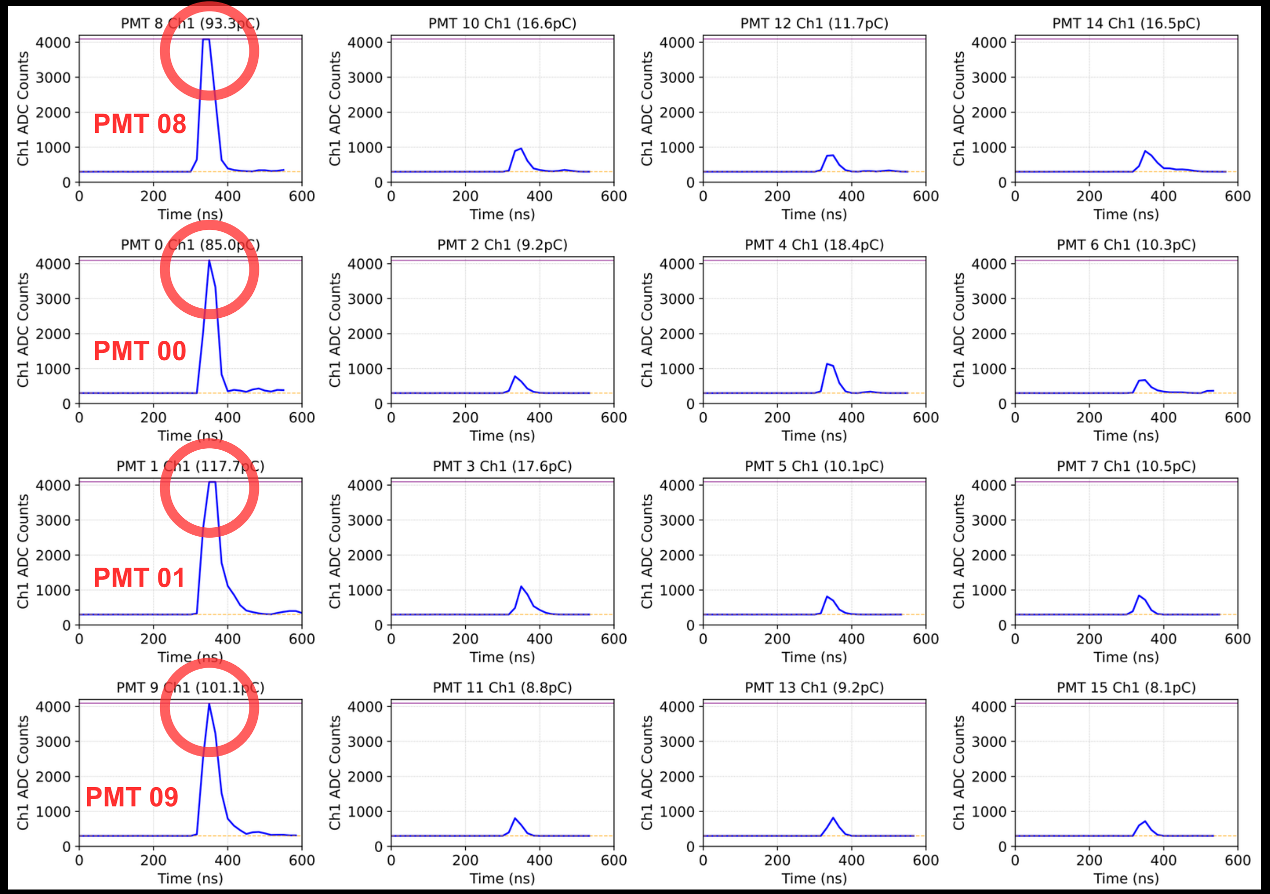
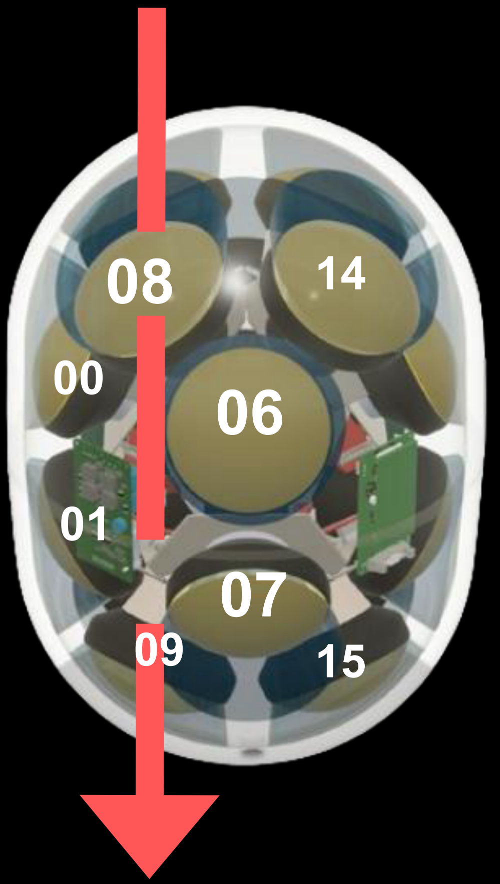
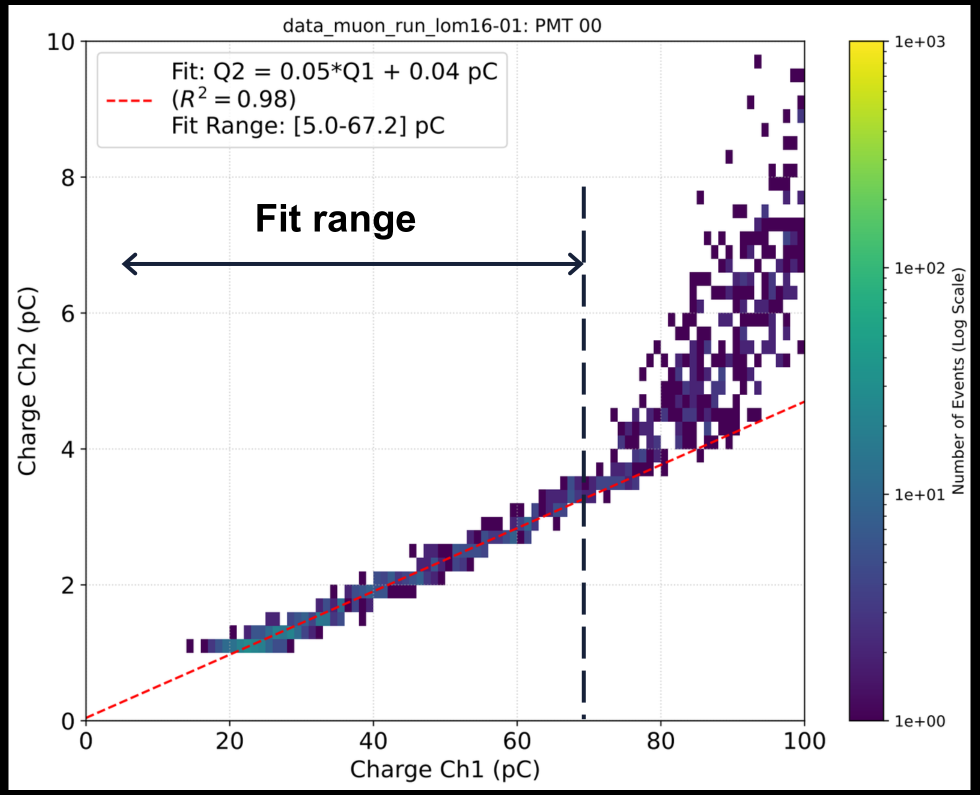
Muon Event Candidate





- PMT waveforms are digitized using a 12-bit ADC, providing a dynamic range of 0–4095 ADC counts, with a baseline level of approximately 300 counts while high-energy cosmic muon events frequently drive the high-gain readout channel (Ch1) into ADC overflow.
- In such events, the low-gain channel (Ch2) remains unsaturated and preserves pulse shape and charge information, consequently, information from the low-gain channel is critical for accurate charge reconstruction and muon analysis. While low-gain analysis tools are still under active development, this study demonstrates the necessity and future potential of dual-gain readout for robust detector validation.

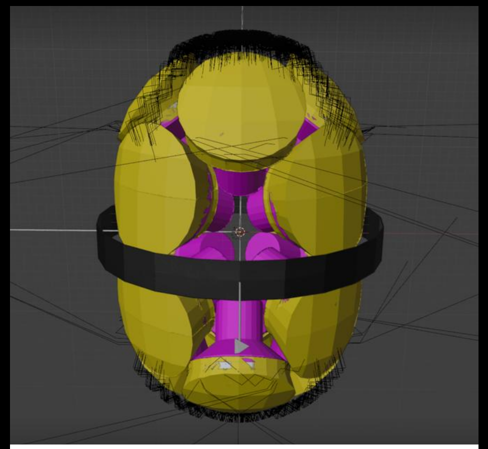
Charge-ratio correlation



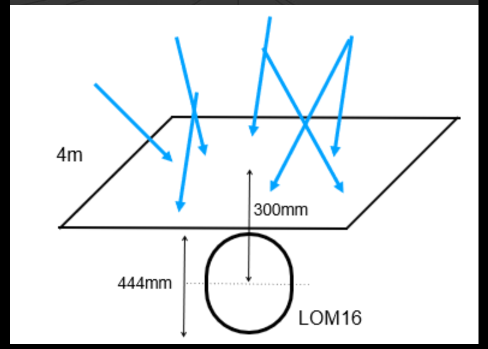
- The gain of the low-gain channel (Ch2) cannot be determined using single-photoelectron (SPE) calibration due to its intrinsically small signal amplitudes. Instead, the Ch2 gain is estimated by fitting the charge ratio between the high-gain (Ch1) and low-gain (Ch2) channels and only events in which the full Ch1 waveform remains within the ADC dynamic range are used, ensuring reliable charge integration. A linear fit to the Ch1–Ch2 charge correlation yields the relative gain factor. This procedure is performed independently for all PMTs across the tested LOM-16.

GEANT4 Simulation-Based

LOM16 in GEANT4



Simulation setup



- A dedicated LOM-16 cosmic muon dataset was generated using GEANT4. The latest LOM-16 geometry, including the full PMT layout and internal structure, was implemented in the simulation. Down-going atmospheric muons were generated from all directions over the upper hemisphere, a total of 100,000 muon events were simulated, of which approximately 3,000 intersected the optical module, and simulated event rates were normalized using the atmospheric muon flux reported by the Particle Data Group (PDG), enabling direct comparison with experimental data.

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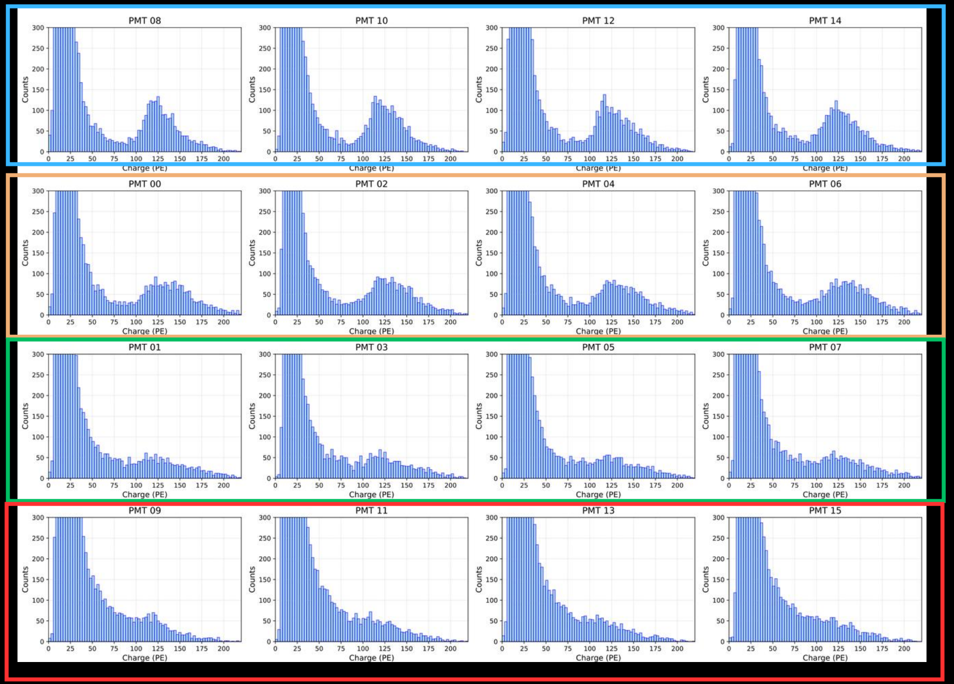
Muon Charge Distribution

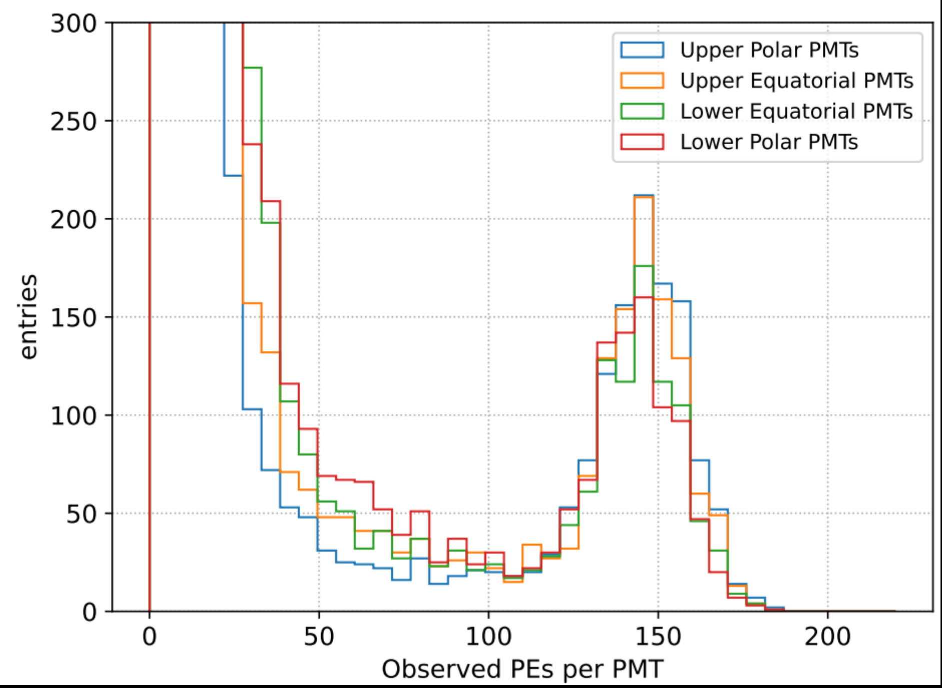


Upper Polar PMT

Upper Equatorial PMT

Lower Equatorial PMT

Lower Polar PMT



- The simulated muon-induced charge distributions exhibit a clear peak around 130-140 PEs

- Distributions in the lower hemisphere PMTs are systematically broader than those in the upper hemisphere.

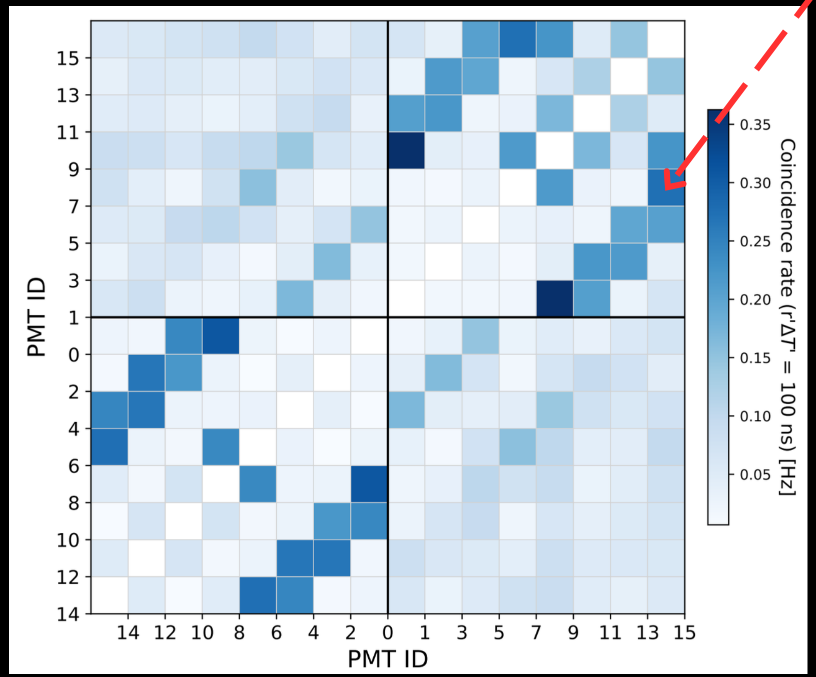
- These features are consistent with experimental data, reflecting geometric and optical asymmetries of the LOM-16 module.

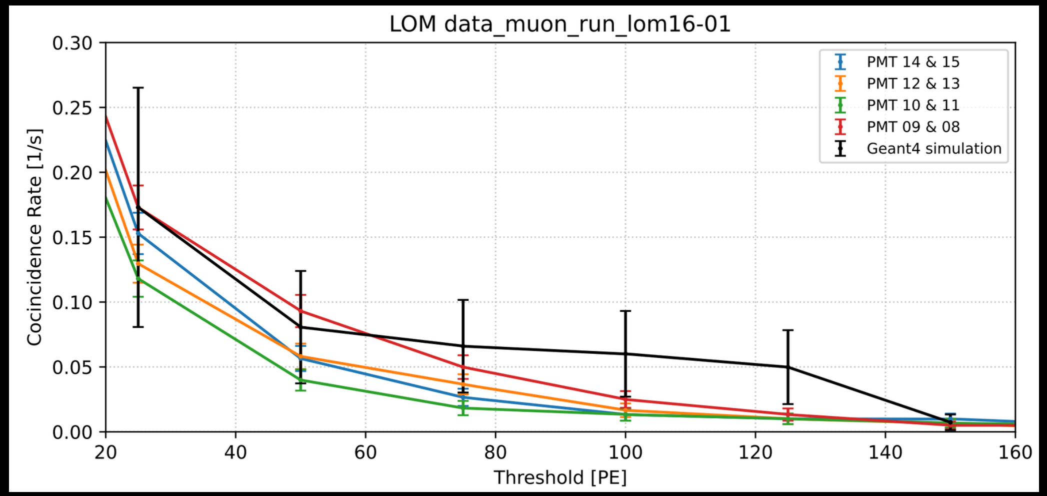
- Overall distribution shapes and peak positions show good agreement between simulation and data.

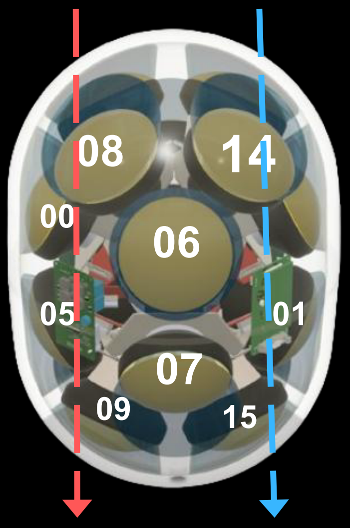
Coincidence Analysis & Vertical Muon Event Rate

Example: Event rate of both PMT 15 & 07 see > 50 PEs in the same event

Data, Threshold 50 PE







- Coincidence rates measured for polar PMT pairs are consistent with one another, indicating uniform module response.

- The measured coincidence rates show reasonably good agreement with GEANT4

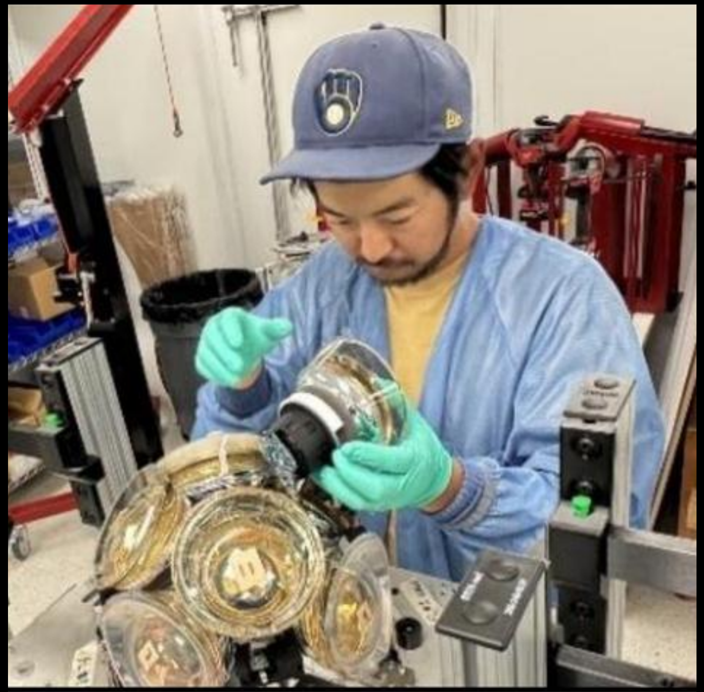
- This agreement demonstrates that both the optical module and the readout system operate as expected under cosmic muon illumination.

- We propose this coincidence-based measurement as a practical, physics-informed indicator of correct module and system performance during mass production.

Madison LOM Team (Summer 2025)

(dedicated for Jay Tang)

Christopher Wendt

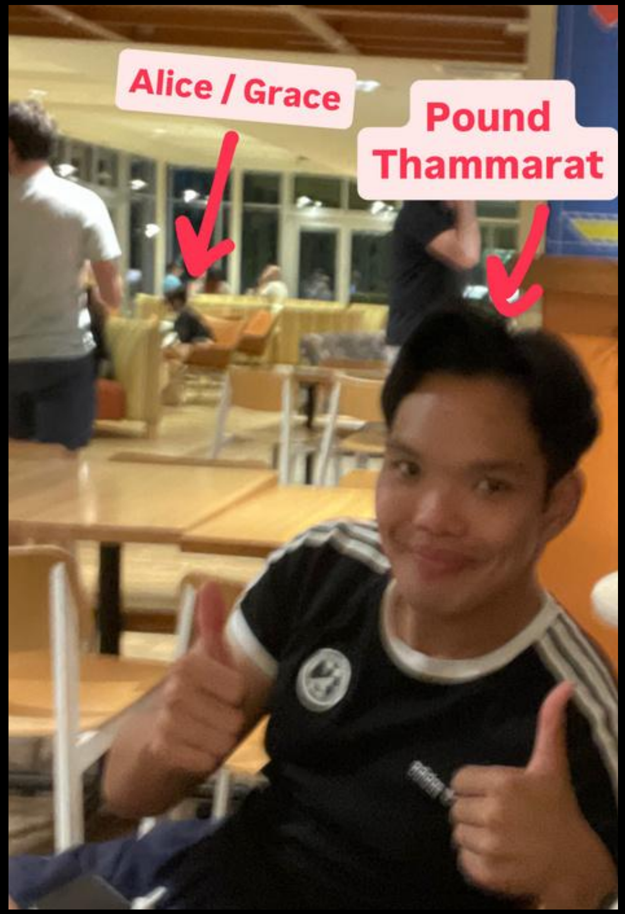


Yuya Makino

Delaney Butterfield

Andrew Arbuckle

Brian Landerud

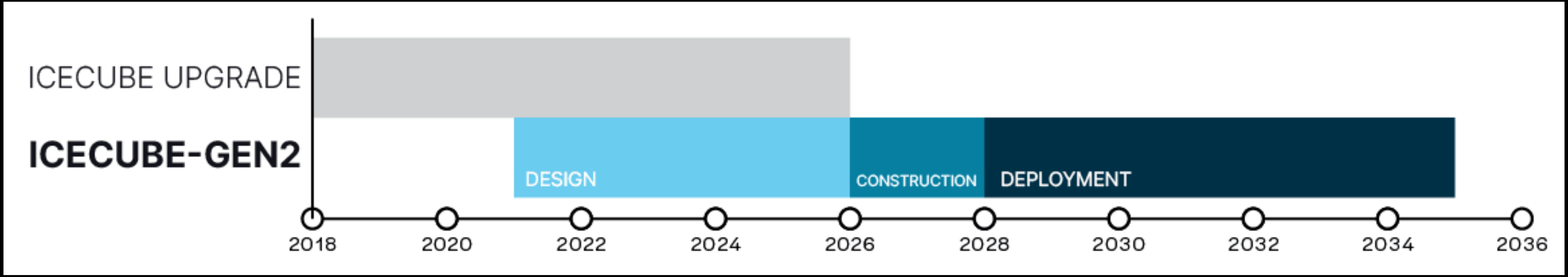


- 24/7 working for LOM team
- Hardware stuff (LOM-16-09)
- Software stuff (Muon analysis)
- Team Meeting every 2 days
- Work, work, and working

  for the next step of mankind !

Every weird stuff was assumed as “Tau Neutrino” !

Future (currently) Work



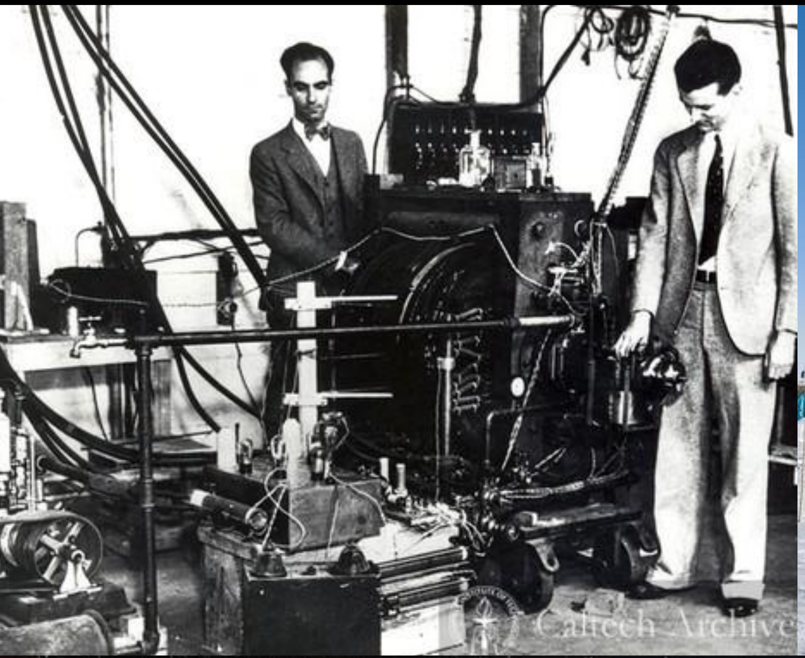
- Standardize (whatever) based testing into a full QA/QC protocol
- Expand analysis parameters and alternative particle sources
- Validate with real deployment results of the module(s) at the pole
- Integrate sim + lab test + in-ice data for designing 10,000+ Gen2 modules

LOM-16 deploying into the hole!

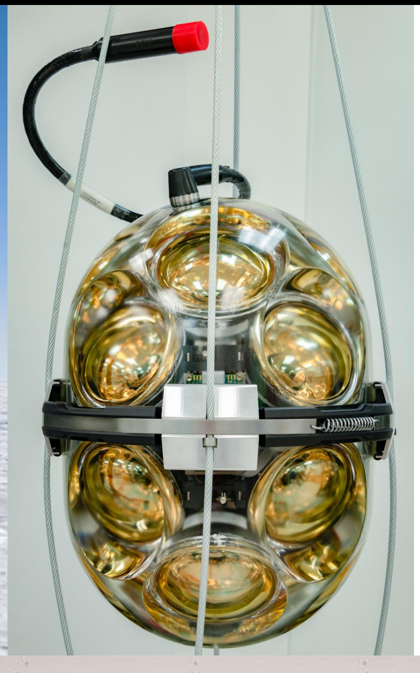
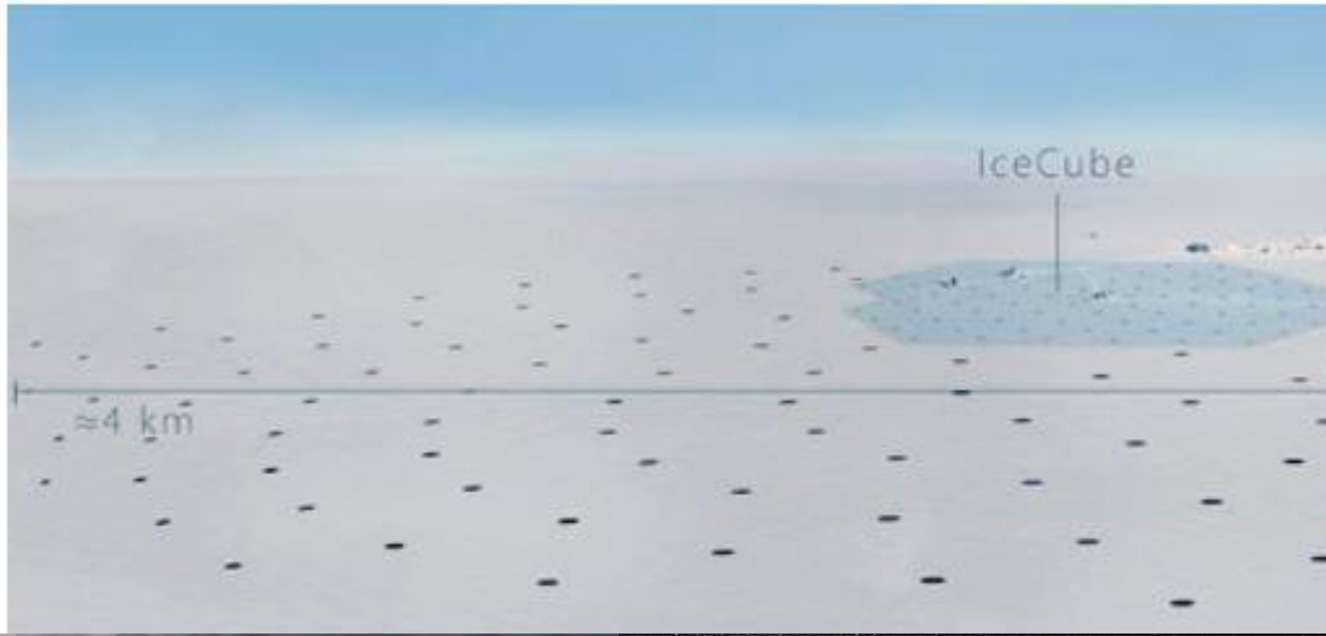


Big Thanks to Yuya Makino for sharing these pics!

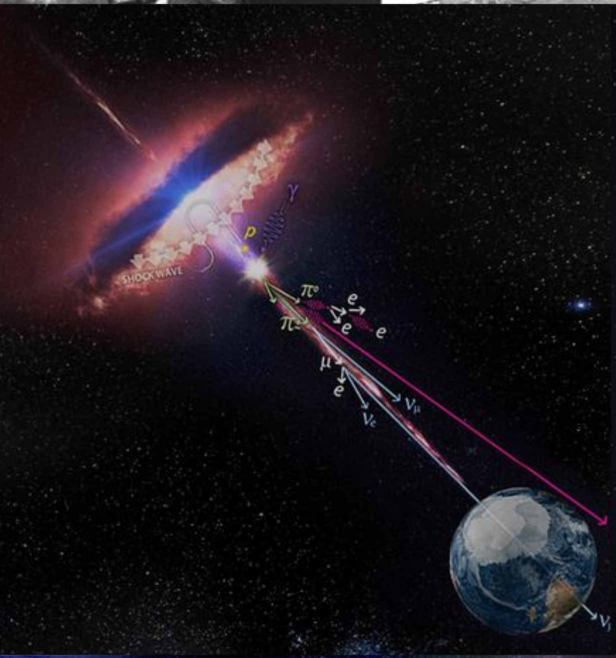
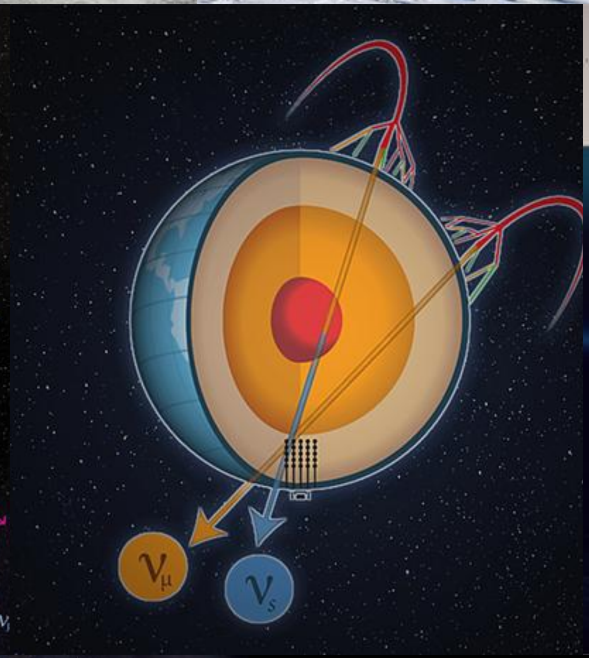
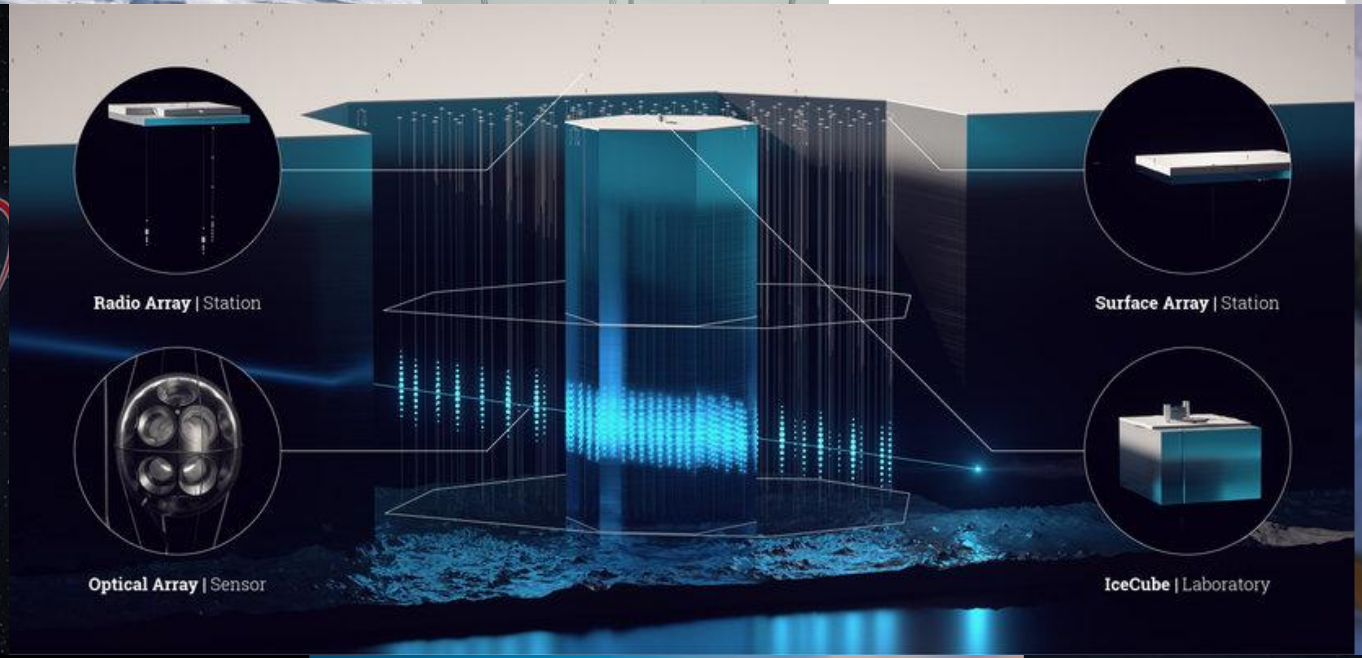
Thank you!



Caltech Archive

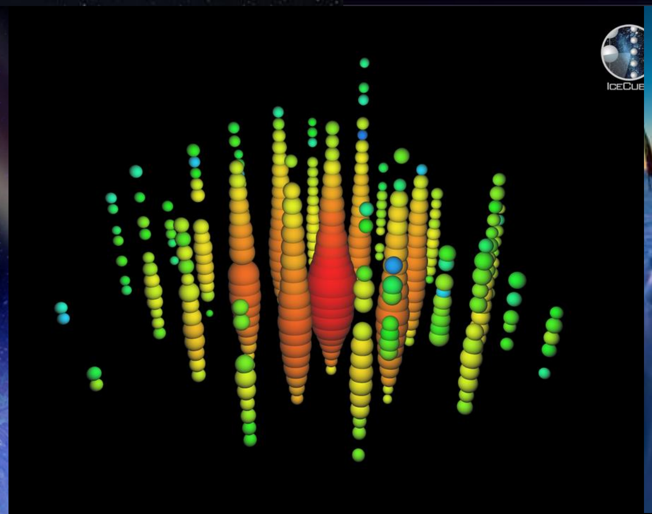




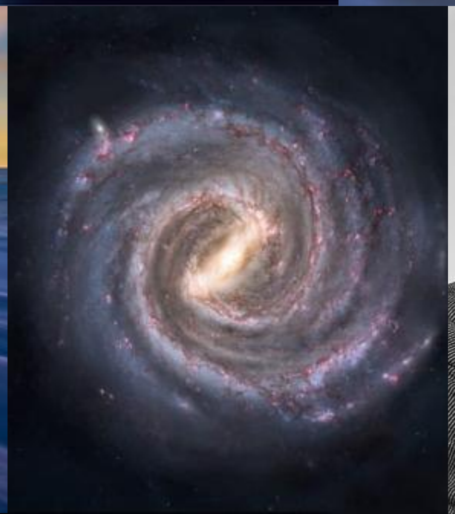
IceCube
≈4 km

Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory



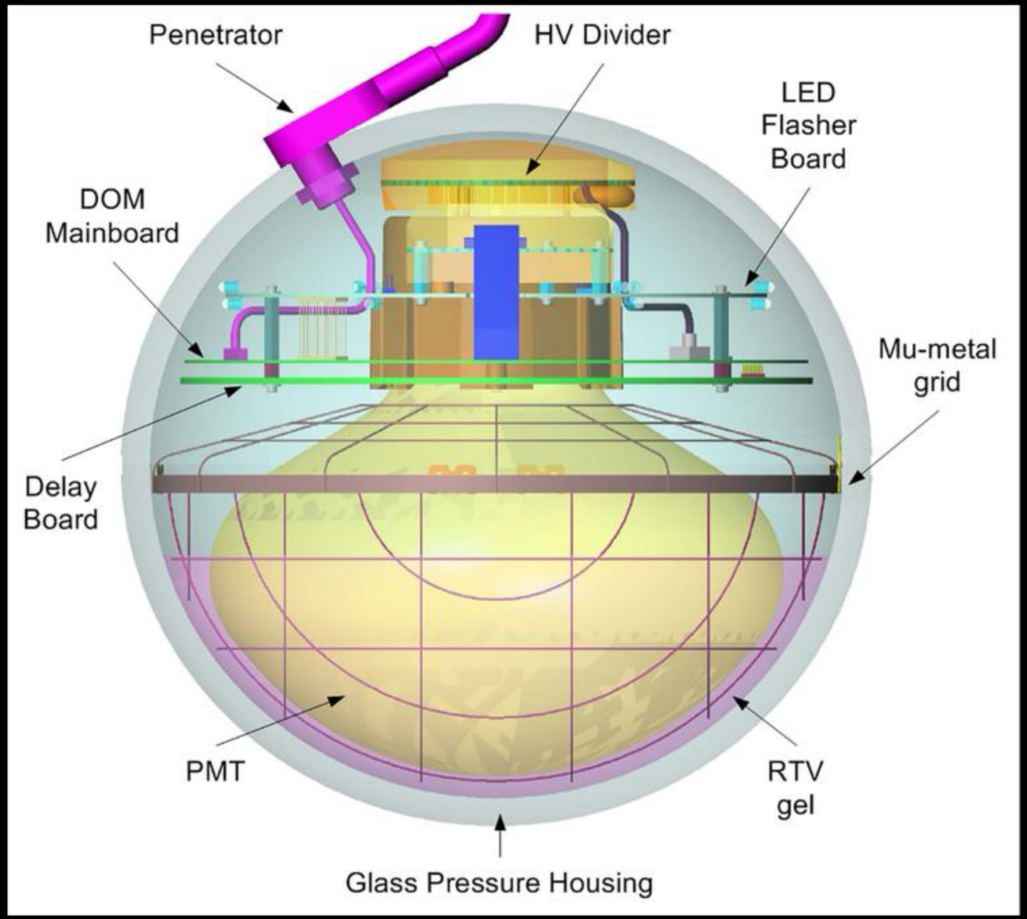



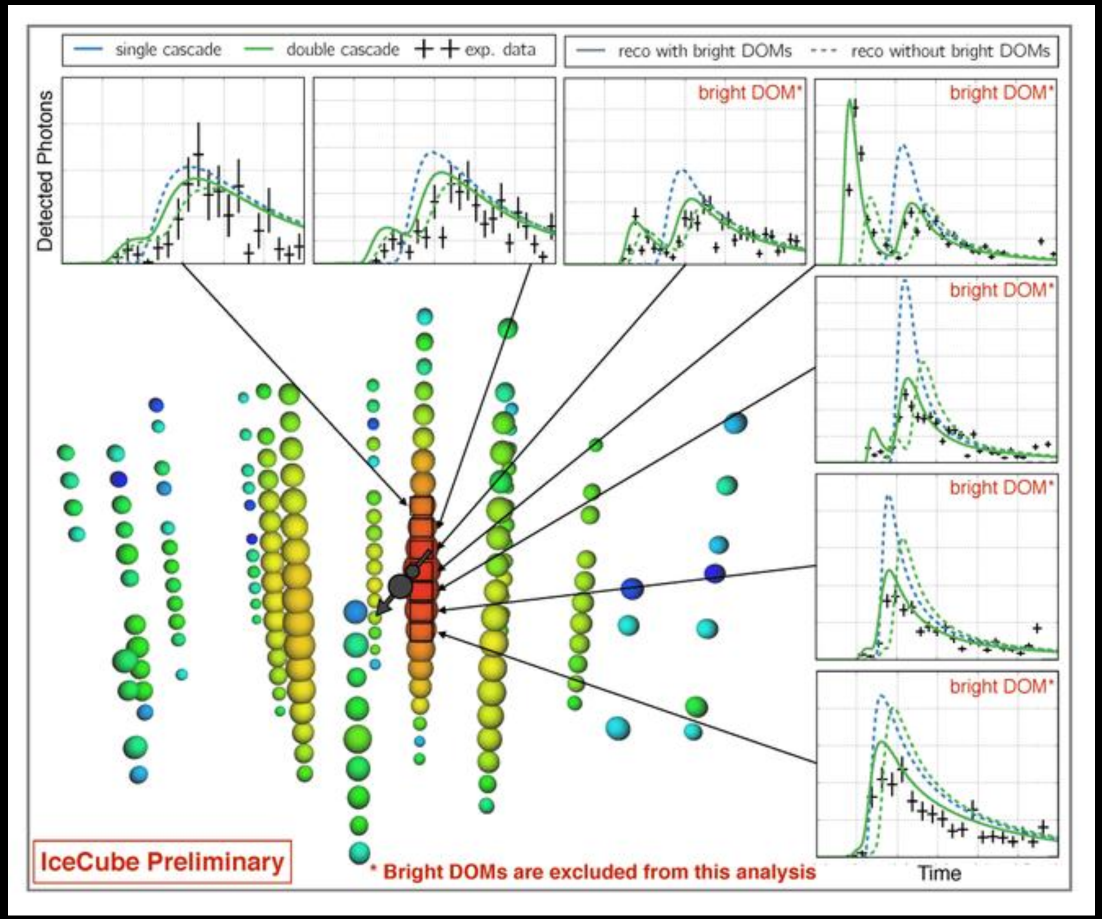


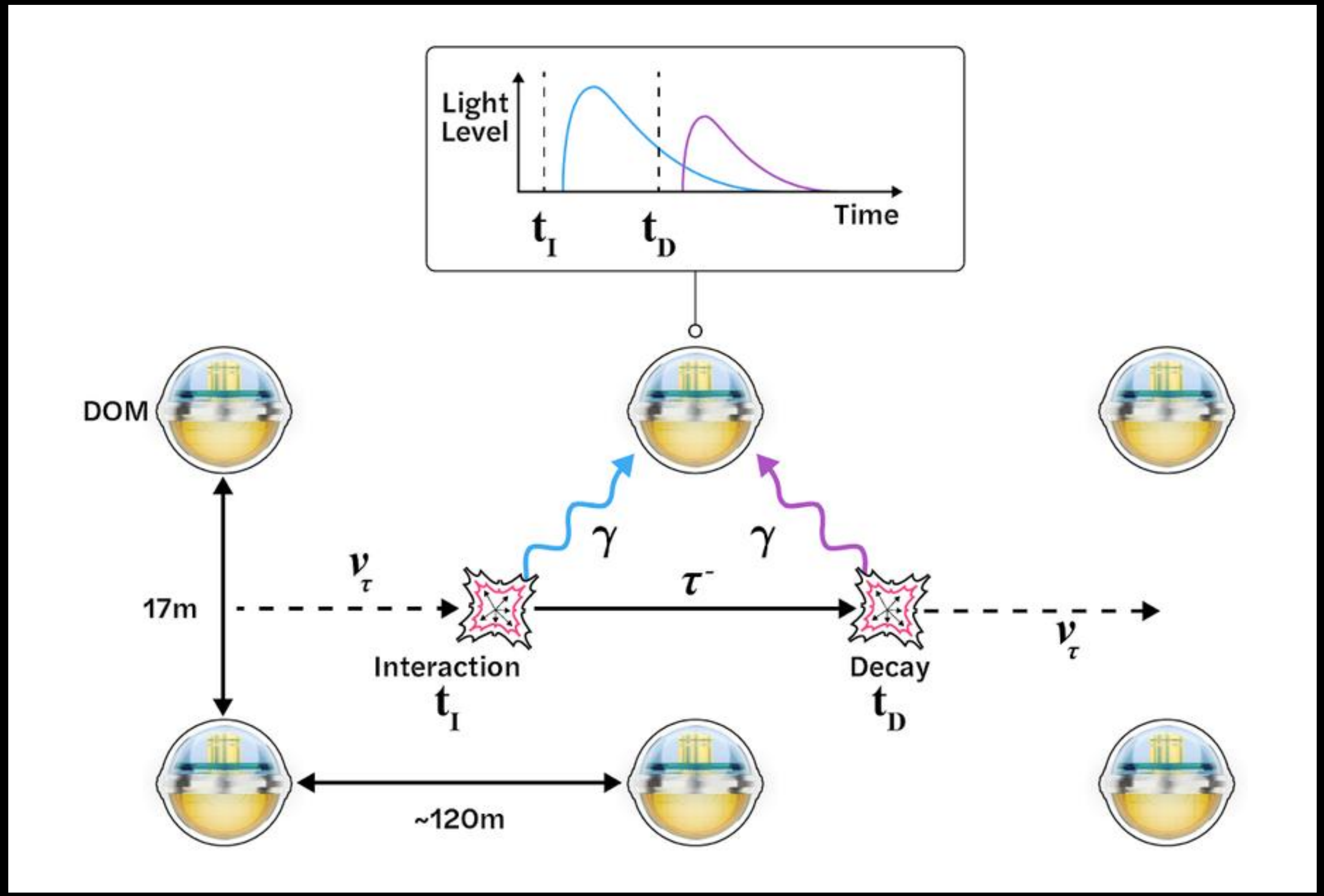
Some part of stayed in Madison

Backup
(Hardware)

Limitations of IceCube-Gen1's DOM







- Low module density → limited angular resolution
- Single 10" PMT (Photomultiplier Tube) → few directional photons
- Effective volume insufficient for rare events
- Sensitivity drop for PeV–EeV / tau neutrinos
- Need for >10,000 new modules and area expansion >7 km³

Why Multi-PMT Optical Modules?

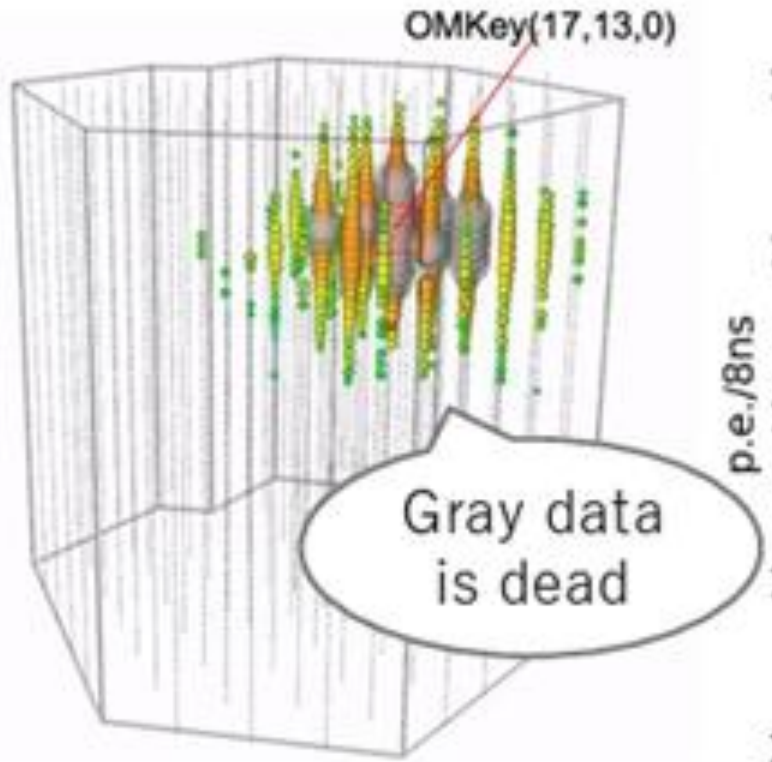
Gen1

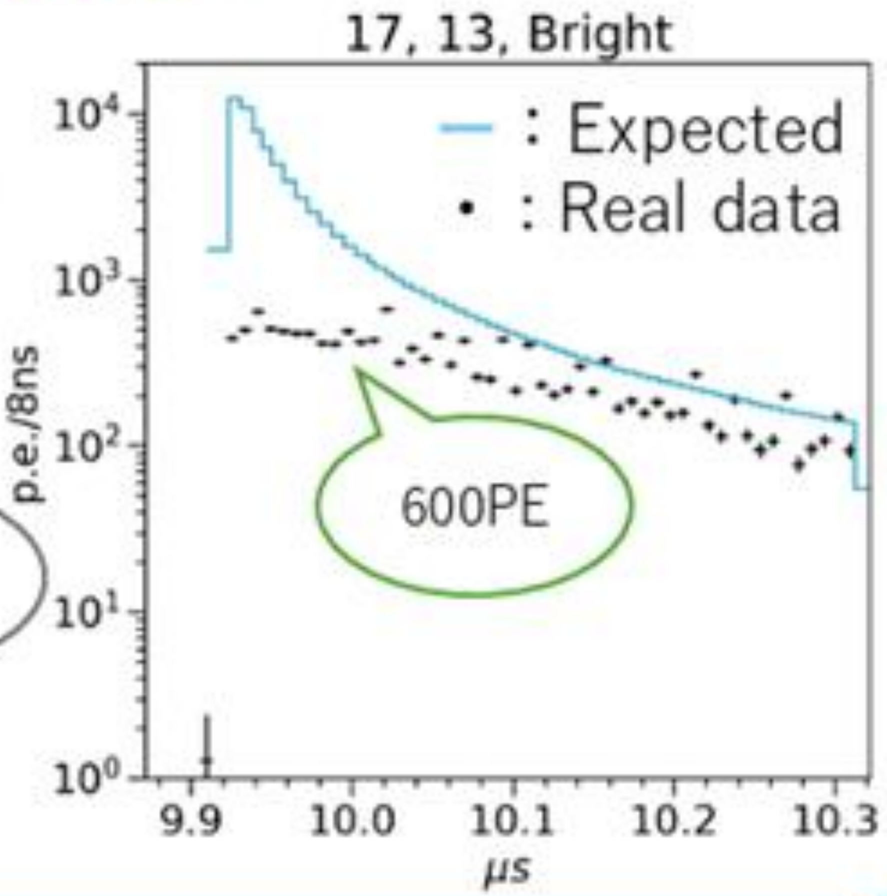
- Too **bright** light saturates PMTs

Dynamic range must be **Improved** !

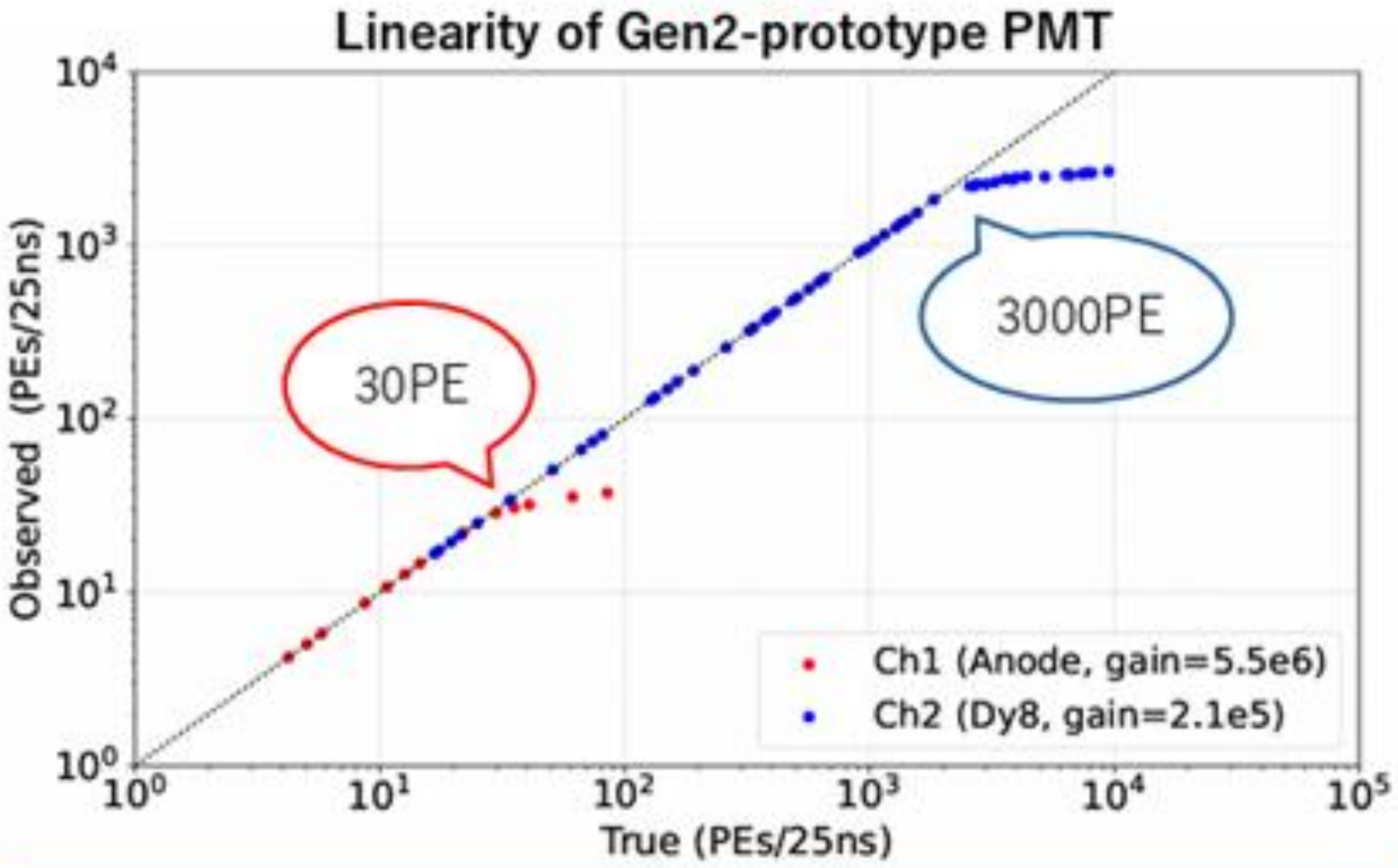
Solution : Ch1 (low gain) & Ch2 (high gain)

Gen 1



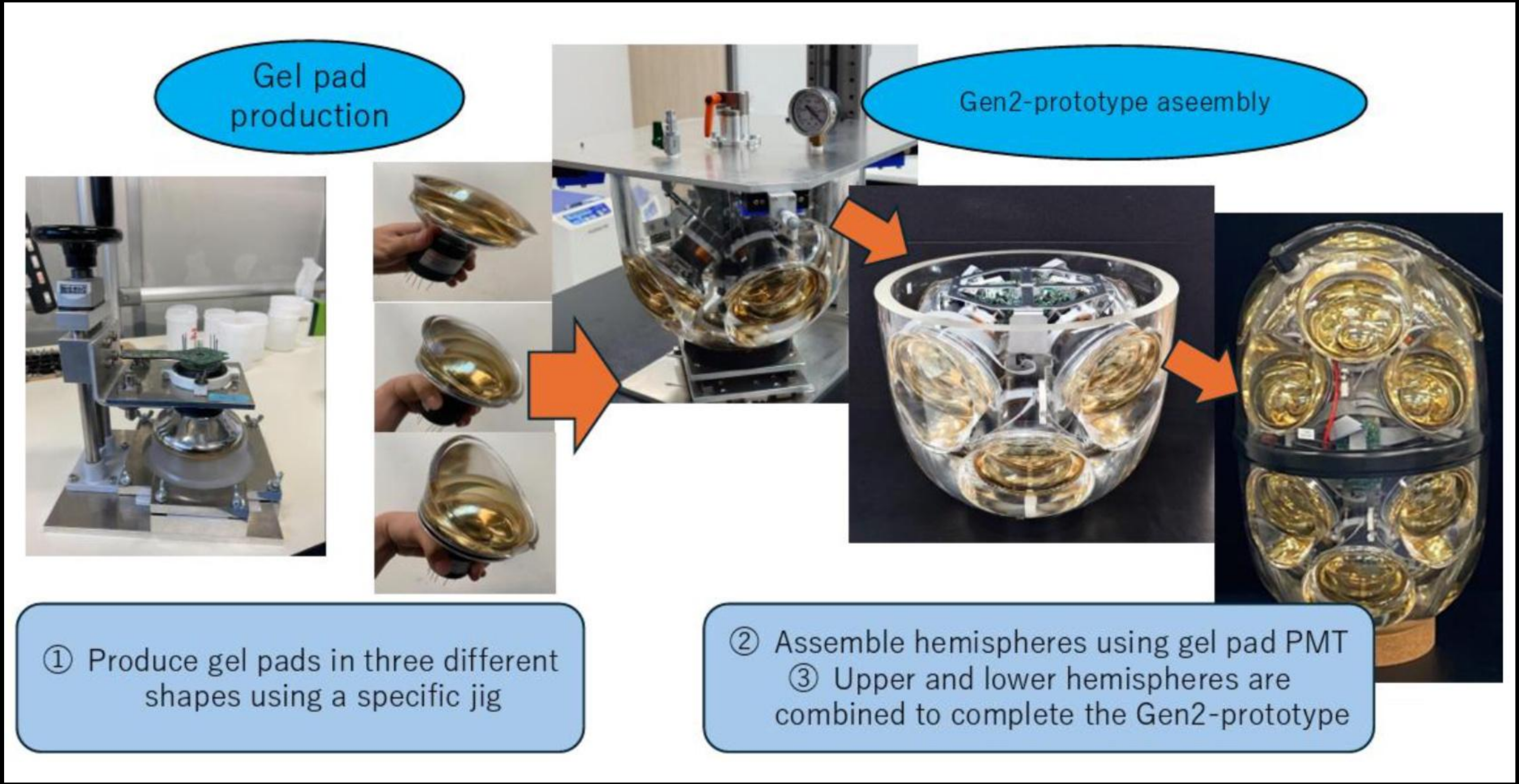


Gen 2



→ The greater the energy range, the higher the accuracy!

PMT Preparation before constructed



Prototype optical-module production and assembly workflow for Gen2-prototype
[Credit: Yuma Makino and ICEHAP, Chiba University]

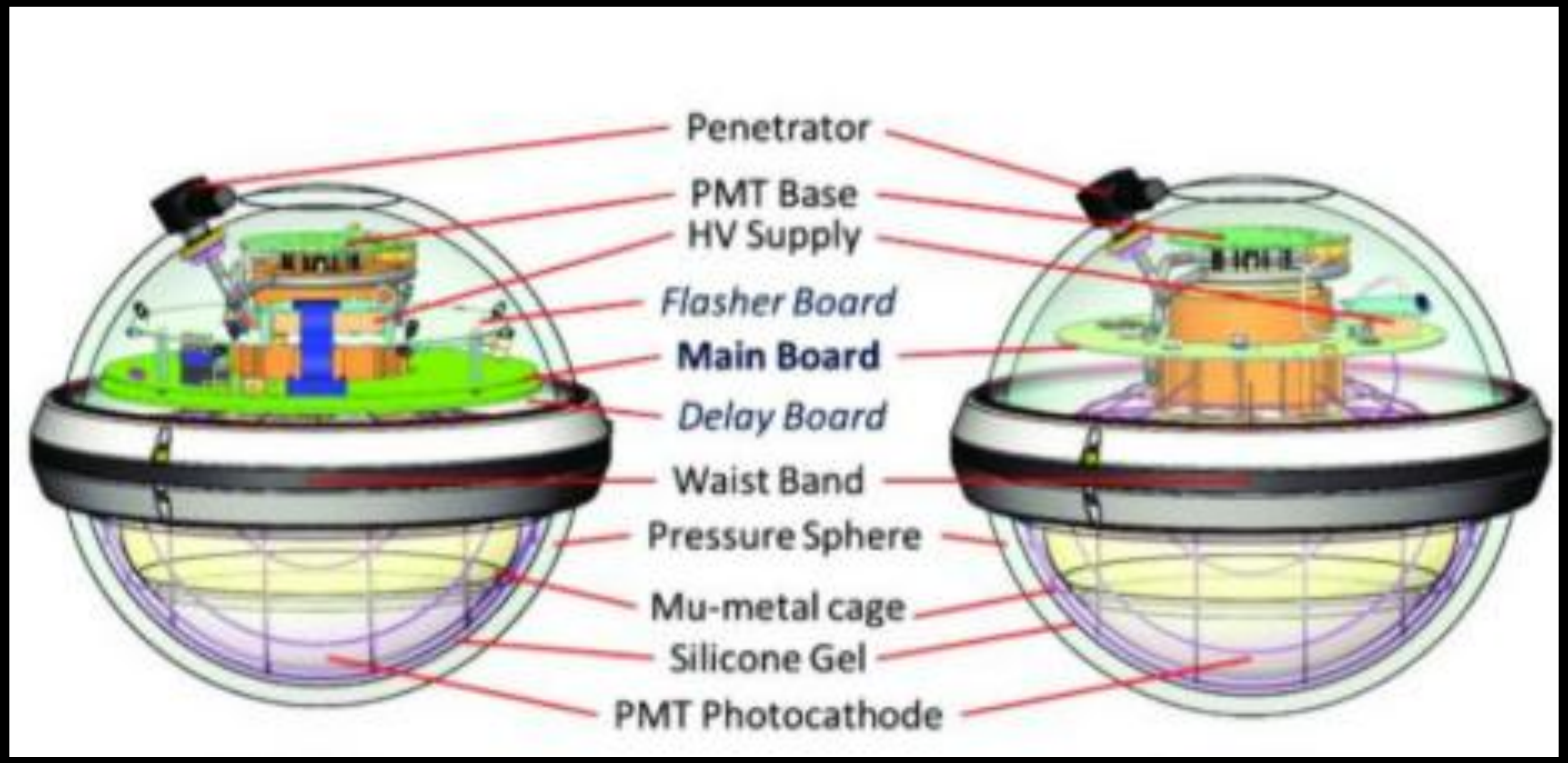
2 Shielded Cover Integration

mDOM support structure
(similar as other multi-PMT Optical Modules)

16 PMT model
support structure

- Simple metal sheets instead of complex & expensive 3D-printed ones that are commonly used for other multi-PMT Optical Modules
- Need less optical gel as the gel don’t have cover entire assembly (weight and cost)
- Gel needs to be casted on PMTs without support (as a mold) of the structure

Other Optical Module Candidates for IceCube-Gen2

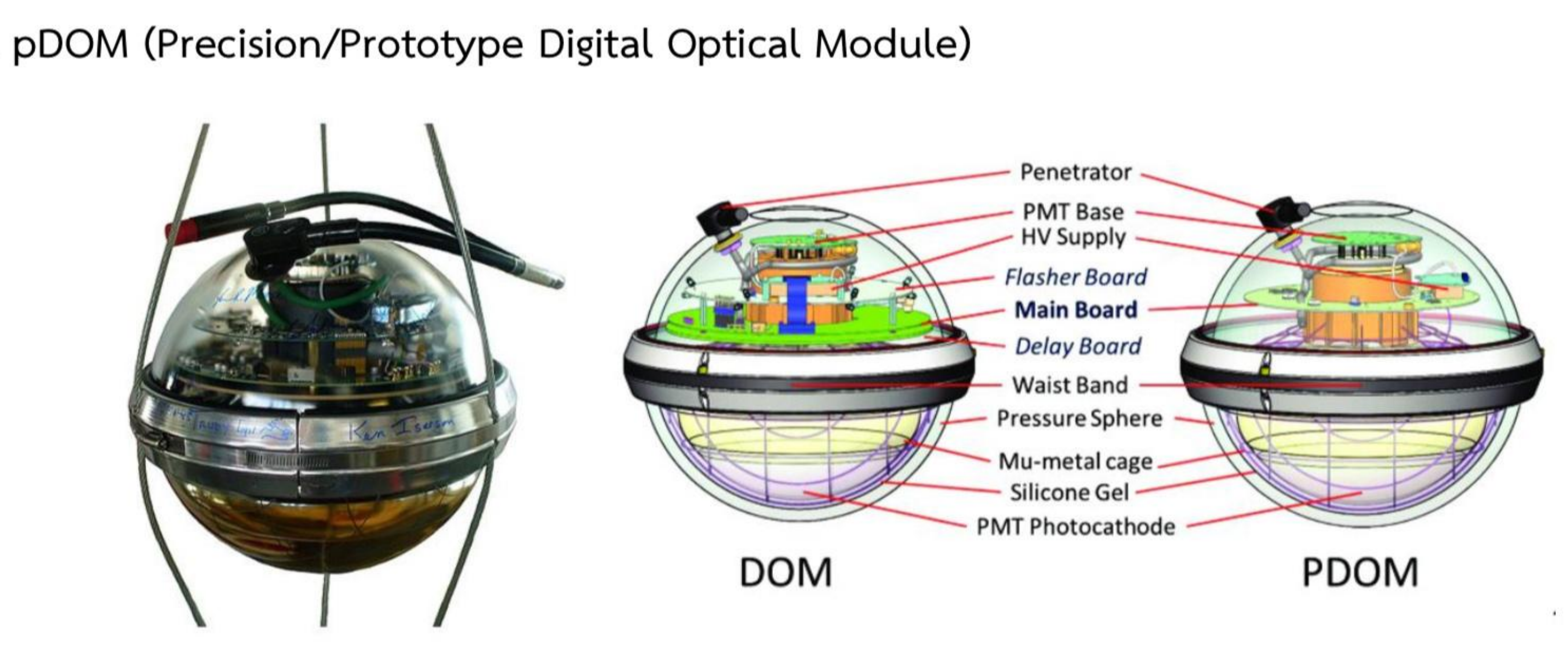


mDOM

D-Egg

pDOM

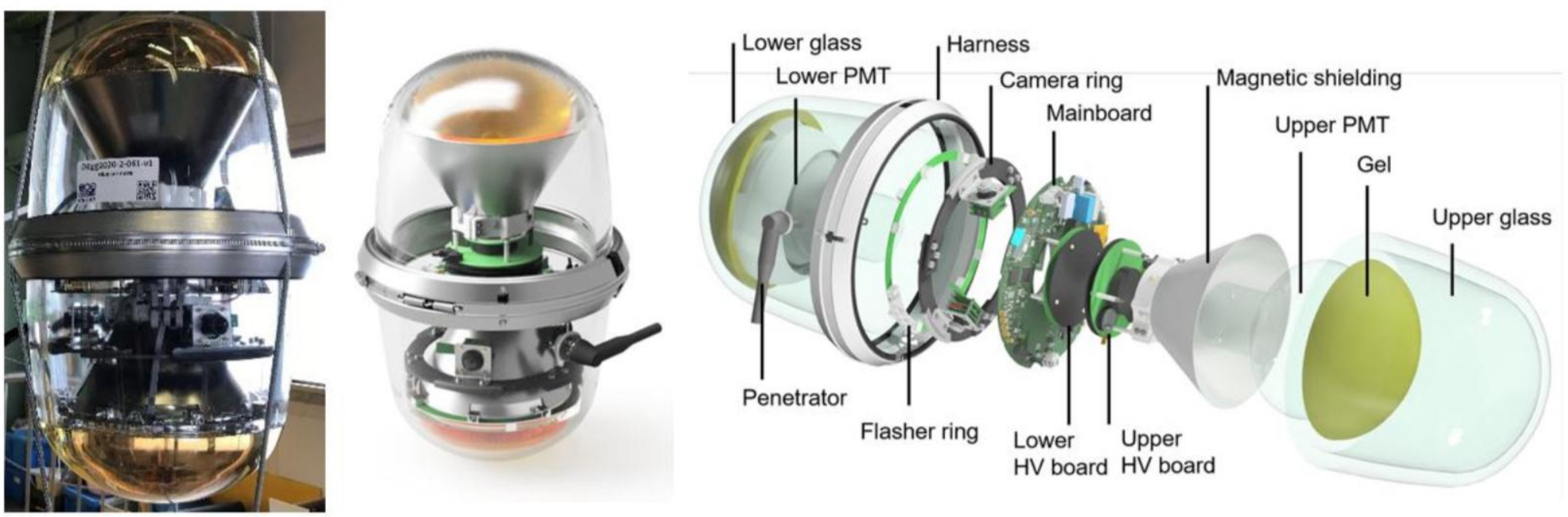
IceCube-Gen2 Optical Module Design Candidates



→ **Increasing Gen1's DOM accuracy and dynamics range**

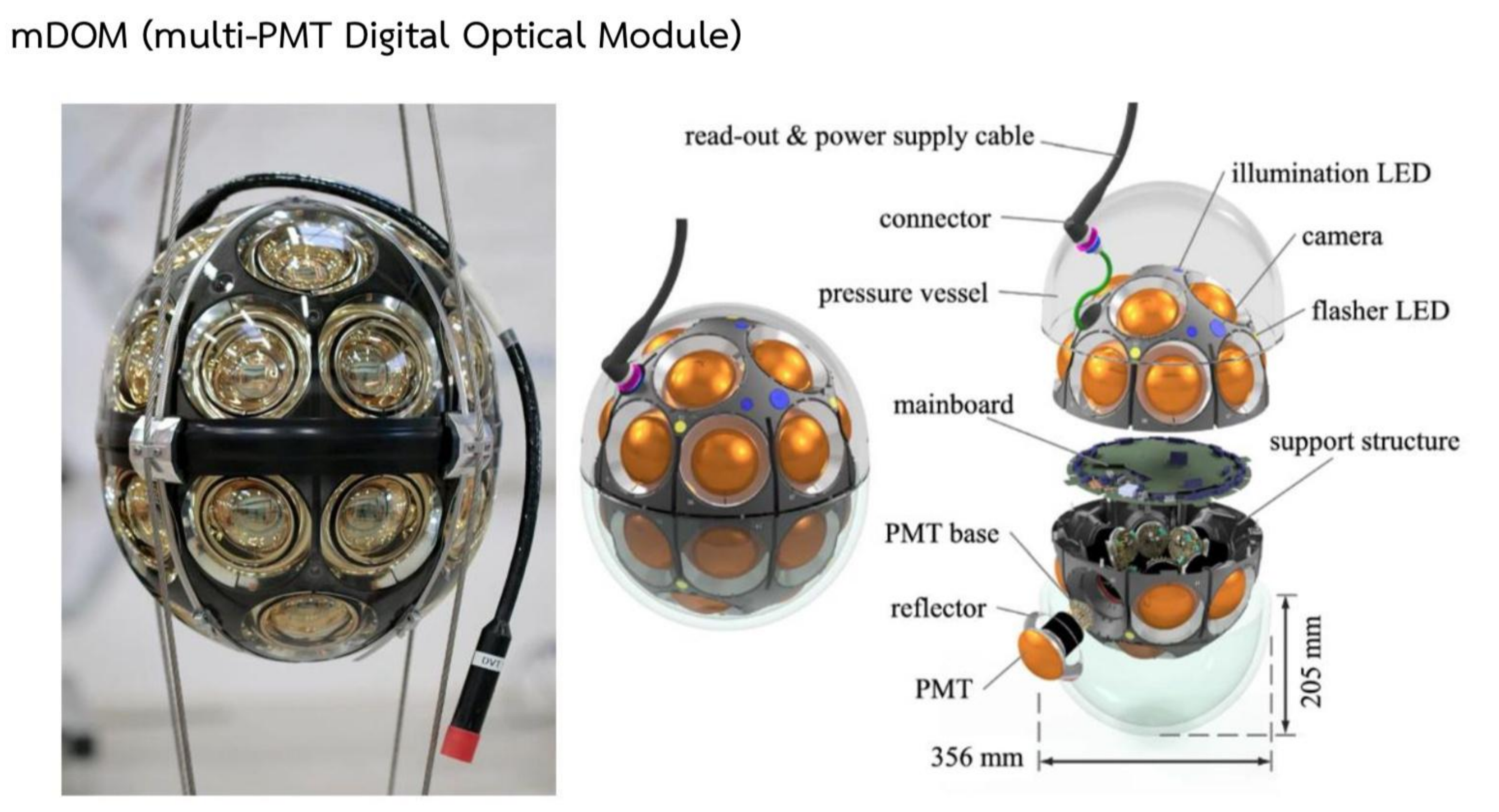
IceCube-Gen2 Optical Module Design Candidates

4. D-Egg (Dual Optical Module – Egg shape)



→ 8" PMT upward and downward!

IceCube-Gen2 Optical Module Design Candidates



→ increasing effective photocathode area of multiple-PMT

Conversion from Charge (pC) to Photoelectrons (PE)

In Photomultiplier Tubes (PMTs), the detected signal is fundamentally related to the number of photoelectrons (PEs) generated at the photocathode by incoming photons. These initial photoelectrons are then multiplied through a series of dynodes, resulting in an amplified current pulse. The integral of this current pulse over time yields the total charge, typically measured in picoCoulombs (pC).

To convert the measured charge ($Q_{measured}$) back to the number of photoelectrons (N_{PE}), the gain of the PMT and the elementary charge of an electron are utilized. The fundamental relationship is based on the charge produced by a single photoelectron passing through the PMT's amplification stages.

The charge generated by one photoelectron (Q_{1PE}) can be calculated as

$$Q_{1PE} = G \times e$$

Where

- Q_{1PE} is the charge corresponding to one photoelectron (in Coulombs).
- G is the gain of the PMT, representing the average number of electrons produced at the anode per initial photoelectron (dimensionless, or electrons/PE).
- e is the elementary charge of an electron (1.602×10^{-19} Coulombs/electron).

Since the measured charge is typically in picoCoulombs (pC), and $1\ C = 10^{12}$ pC, the charge per photoelectron in *pC* is

$$Q_{1PE}\ (pC) = G \times e \times 10^{12}$$

Consequently, the number of photoelectrons N_{PE} for a given measured charge $Q_{measured}$ is determined by dividing the measured charge by the charge equivalent of a single photoelectron

$$N_{PE} = \frac{Q_{1PE}\ (pC)}{Q_{measured}\ (pC)}$$

$$N_{PE} = \frac{G \times e \times 10^{12}}{Q_{measured}\ (pC)}$$

In this analysis, a PMT gain (G) of $5{\times}10^{6}$ electrons/PE was used. Therefore, the charge equivalent for a single photoelectron was calculated as

$$Q_{1PE}\ (pC) = \left(5{\times}10^{6}\right) \times \left(1.602{\times}10^{-19}\ C\right) \times 10^{12}\ pC/C$$

Ratio between Photoelectron (PE) and Charge (pC) in Ch1

1 PE = 0.8 pC

$$Q_{1PE}\,(pC) \approx 0.801\ pC$$

This conversion factor was then applied to all measured charge distributions, enabling the interpretation of signal strength in terms of fundamental photoelectron counts. The precision of this conversion is critically dependent on the accuracy of the PMT gain value.

Find Channel 2's Gain from "Ch1/Ch2 Charge Correlation"

The integrated charge on Ch2, Q_{Ch2} is plotted against the corresponding charge on Ch1, Q_{Ch1} for coincident events. A linear fit to this distribution yields a slope $R_{Ch2/Ch1}$ representing the average ratio of Ch2 to Ch1 charge response. The gain of Ch2 can then be obtained as

$$G_{Ch2} = R_{Ch2/Ch1} \times G_{Ch1}$$

Linear Charge Correlation

- Experimental results show a linear correlation between the charges measured in Channel 1 (Q_1) and Channel 2 (Q_2), both in pC.
- This correlation is expressed as: $Q_2 = m_2 \times Q_2 + C$ (Equation 3)
  - Where m is the slope of the fitted line, and C is the y-intercept.

Using linear function to find slope (gain ratio between Ch1 & Ch2)

In order to use Ch2 charges as substitutes for Ch1 charges in overflow cases, a calibration factor between the two channels must be determined. This is achieved by analyzing events in which both Ch1 and Ch2 record unsaturated waveforms from the same PMT. For each PMT, the integrated charges Q_{Ch1} and Q_{Ch2} from coincident events are plotted against each other

$$Q_{Ch1} = m \cdot Q_{Ch2} + c \qquad m = \frac{\Delta Q_2}{\Delta Q_1}$$

Where

- *m* is the gain ratio between Ch1 and Ch2.
- c is the intercept, which ideally approaches zero in a properly calibrated system.

In practice, Channel 1 is often the higher-gain or reference channel, and Channel 2 is a lower-gain or monitor channel observing the same events. Here, m can be interpreted as: "How many pC in Channel 2 correspond to 1 pC in Channel 1". Thus, m serves as a direct indicator of the gain ratio. Rearranging for G_2

$$G_2 = m \times G_1$$

We know G1 is 0.8, If we know each "m" ⟶ We'll get Ch2 gain