Detector Design
for the **Next Generation** of **IceCube Optical Modules**

ICEHAP Chiba

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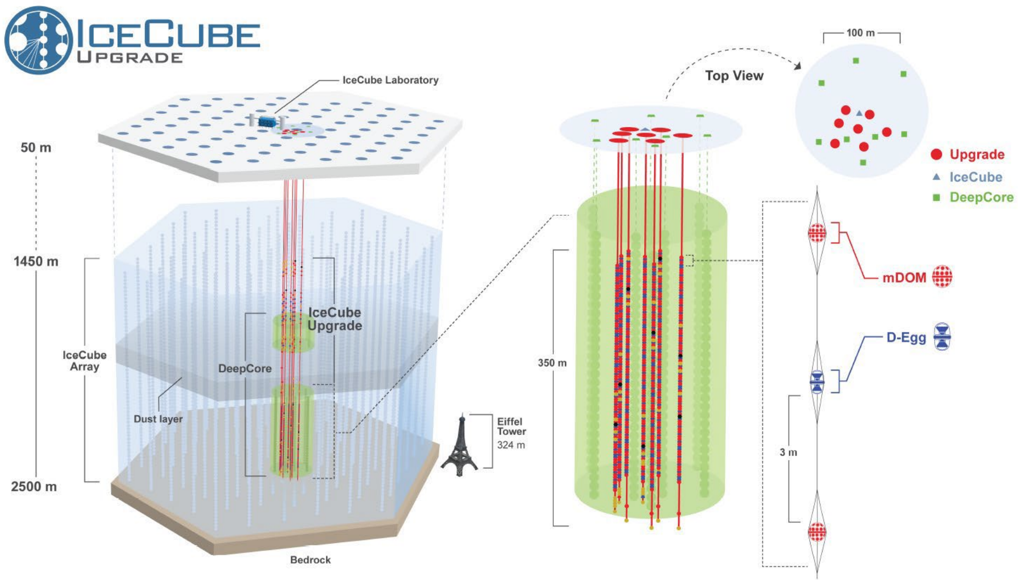
From IceCube-Upgrade to **IceCube-Gen2**

IceCube-Upgrade

IceCube Upgrade: **7 new strings** to be **deployed this season!**



3 subarrays: Shallow / **Physics** / Deep region

New Optical Modules:

D-Egg
277 sensors

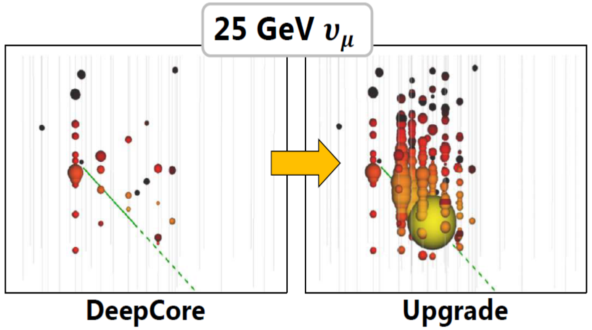
2x 8” high-QE PE PMTs

mDOM
402 sensors

24x 3” PMTs

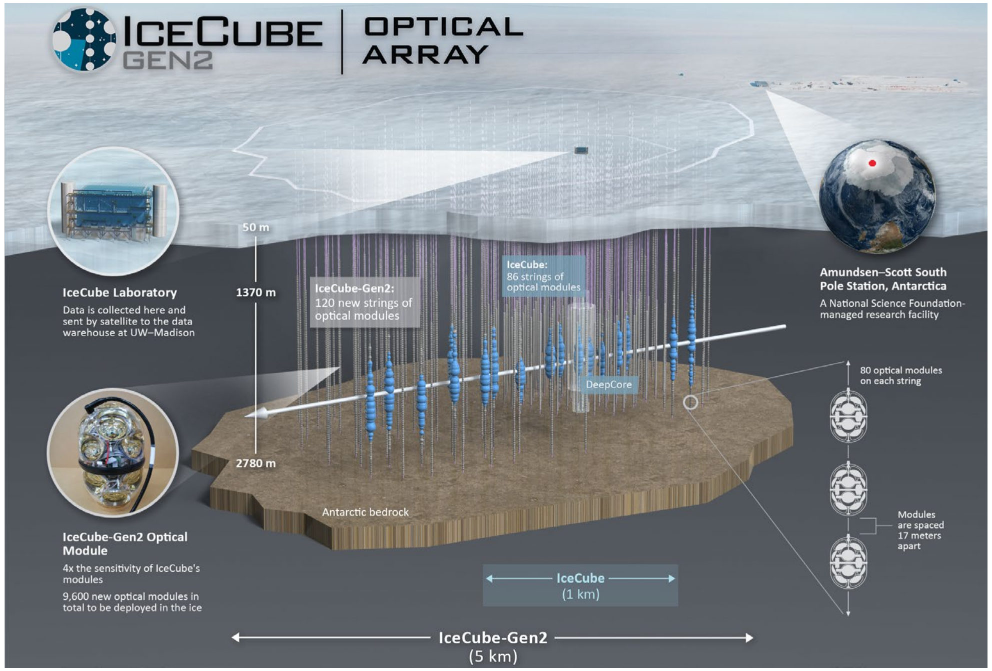
- **Dense instrumentation:** ~110 optical modules per string (+ calibration devices)
  - ▶ Detection of **low-energy neutrinos $\mathcal{O}$(1 GeV – 10 GeV)**

- **Goals:**
  - High-precision **atmospheric neutrino oscillation measurements**
  - Better **calibration of detector modules** (existing & new) & **ice**



IceCube-Gen2

IceCube Gen2: **Optical array** extension by 120 new strings

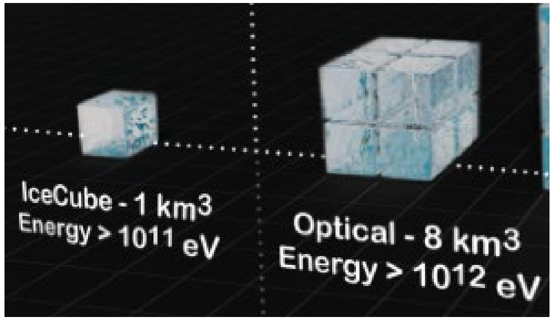


Long Optical Module (LOM):

- **18x (16x) 4” PMT**
- Elongated shape & **compact diameter**
- **Granularity** & **large effective area**

▶ **2× 6 prototypes to be deployed with IceCube-Upgrade!**

- **Large Volume:** 80 modules per string (+ calibration devices), **~10 000 detectors**
  - ▶ Increase of **detector volume to ~8 km³**
  - ▶ Larger detector spacing requiring **higher detection efficiency** and **wider dynamic range**
- **Goal:**
  - Detection of **high-energy events $\mathcal{O}$(GeV – PeV)**



Gen2-DOM
Design Verification & Unification

Current LOM Design(s)

Currently 2 Long Optical Module (LOM) Designs:

Combining benefits of

D-Egg (shape & weight) & **mDOM** (acceptance & granularity)

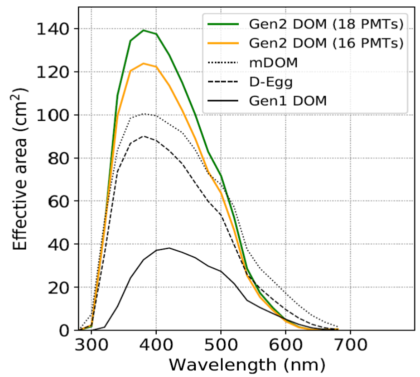
LOM-16:

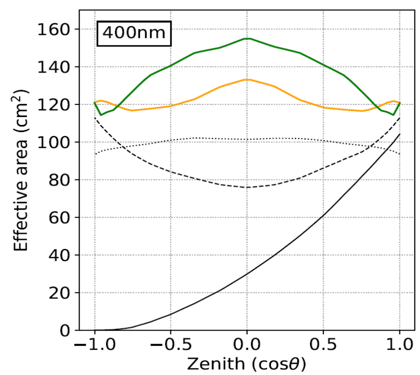
WIPAC Madison

- **16× 4” PMTs** in 2 layers per hemisphere

▶ Penetrator cable @top of module

▶ **Compact & light**





LOM-18:

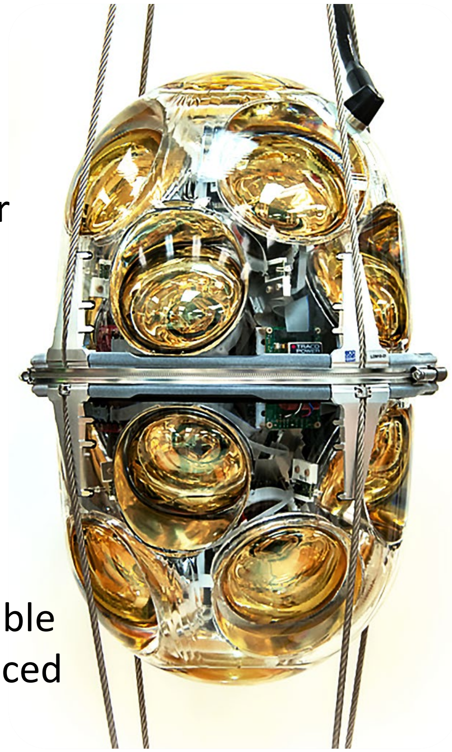
ICEHAP Chiba

- **18 × 4” PMTs** in 3 layers per hemisphere:

  2 additional 4” PMTs @ top / bottom of module

▶ Penetrator cable slightly displaced

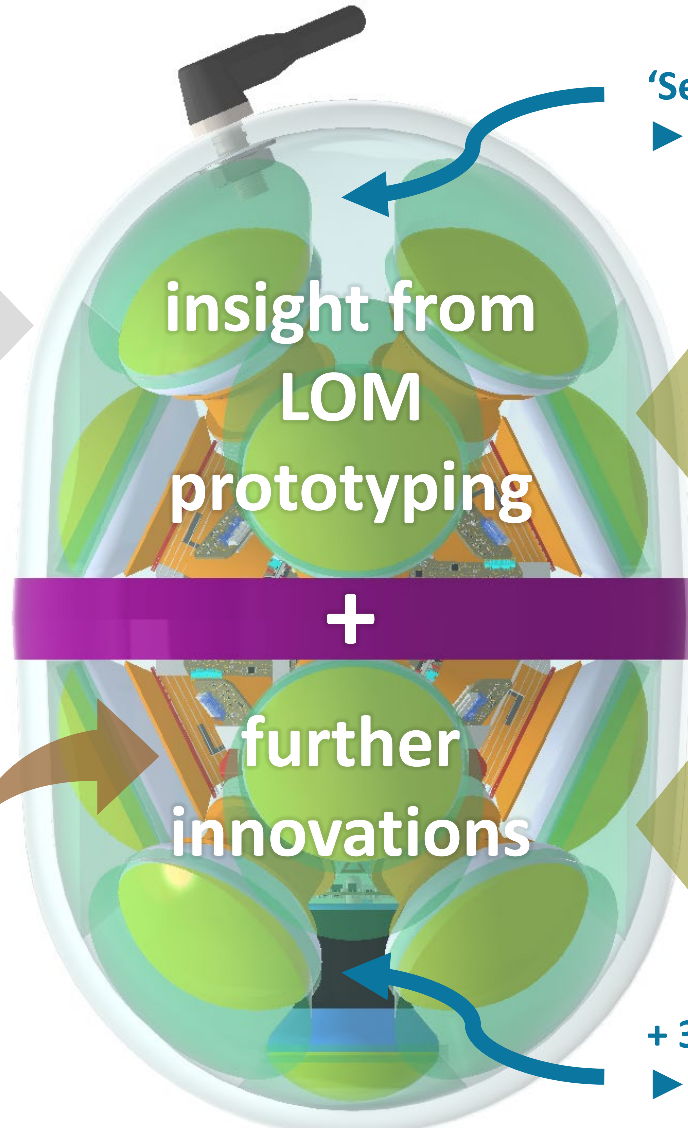
▶ **Larger glass vessel**



Unified Gen2-DOM Design

Elongated pressure vessel
- keep the weight manageable

Advanced PMT holding structure & pushing mechanism
- allowing for easy installation



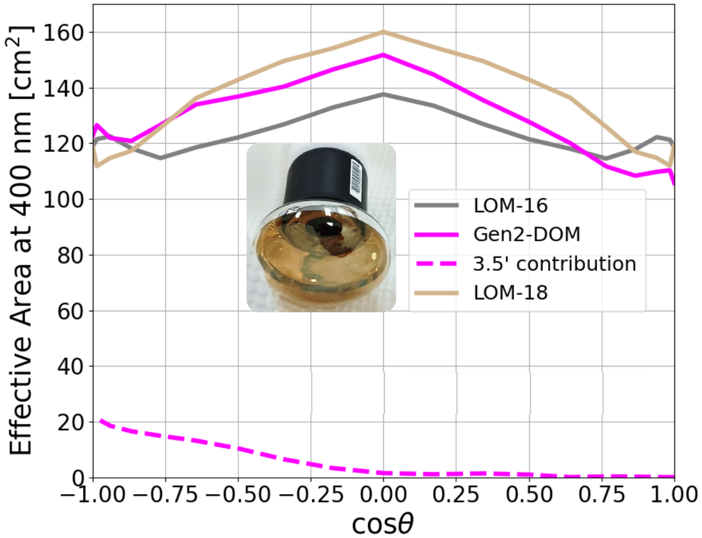
'Service space' @top
- 2" PMT FOM interface / calibration / …

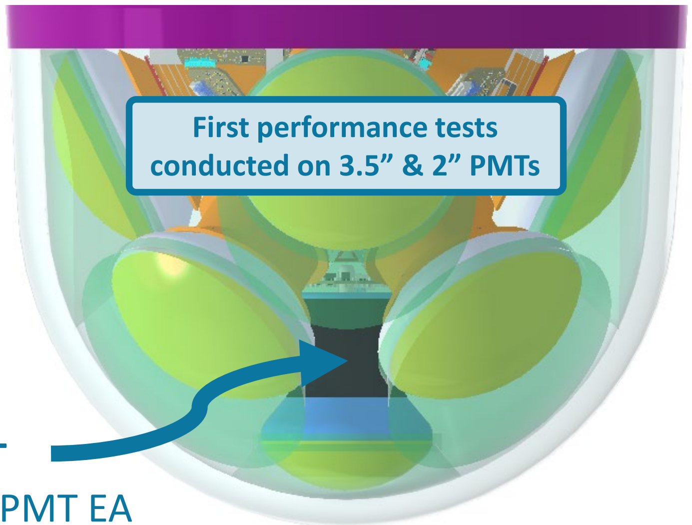
16× 4" PMTs
- 2 layers per hemisphere

+ 3.5" bottom PMT
- effective area increase

Gen2-DOM: Top & Bottom Space

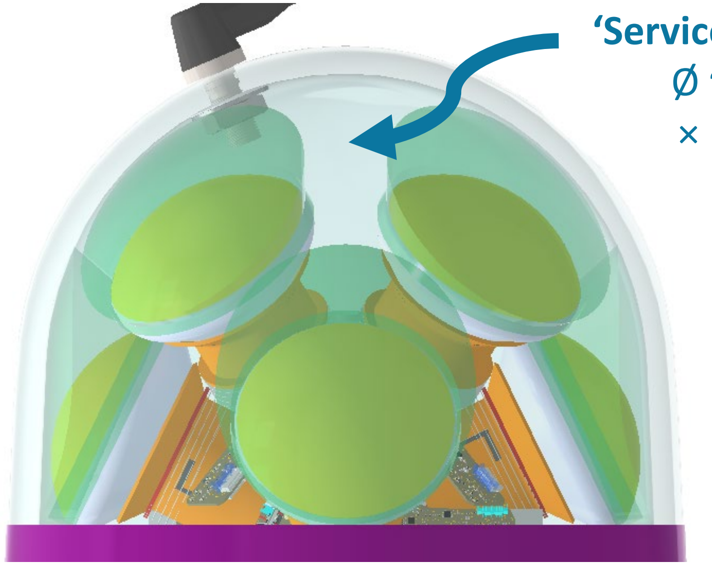
Gen2-DOM: Bottom PMT effective area



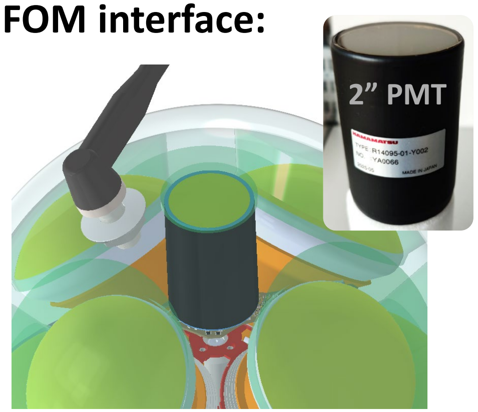


3.5” PMT
~0.6× 4” PMT EA

Gen2-DOM: ‘Service Space’ @upper hemisphere



Currently optimised for
FOM interface:



Many other important applications!

- Upgraded flasher
- Scintillator module
- Camera
- Acoustic devices
- …

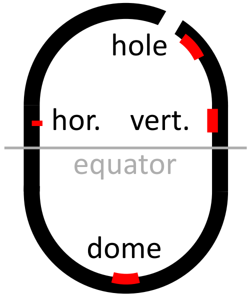
Glass Vessel Pressure Test

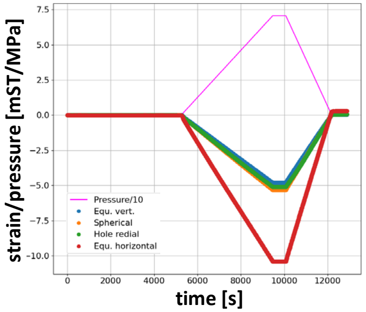
Laboratory Tests @JAMSTEC: 70 MPa (700 bar)

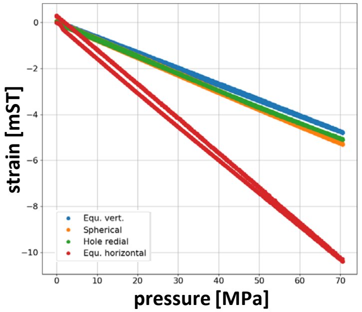
- **Gen2-DOM vessel:**
  Okamoto borosilicate glass

  Elongated shape,
  14 mm thickness

- **PCA:** IceCube-Upgrade

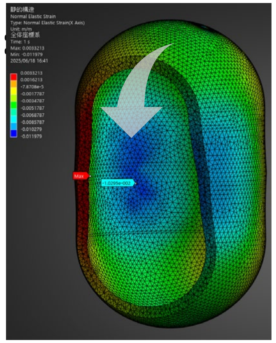
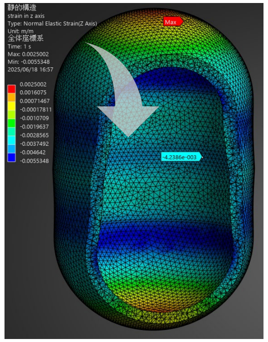




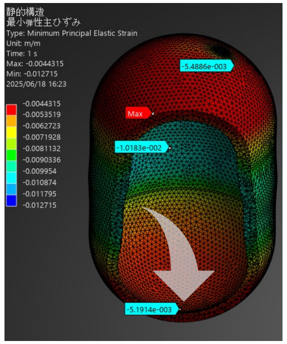


FE Simulation: 70 MPa

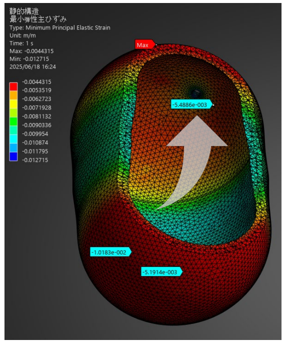
Equator region:

Horizontal	Vertical
	
-10.2 mST	-4.2 mST

Dome region: -5.2 mST



Hole region: -5.5 mST



- Almost perfect (≤ 5%) **agreement between measurement runs** @ 50 MPa & 70 MPa

Region	strain/pressure [mST/MPa]		
	50 MPa run	70 MPa run	70 MPa sim.
Equator (horizontal)	0.148	0.147	0.146
Equator (vertical)	0.071	0.068	0.060
Dome (radial)		0.075	0.074
Hole (radial)	0.073	0.071	0.079

- FE simulation **correctly predicts measurement** for most regions
- Vertical **strain at equator underestimated** by ~15%

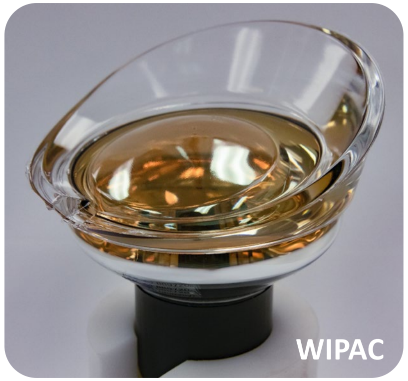
Gel Pad Design

Optical Coupling of PMTs to Glass Vessels:

- **Silicone-based conical gel pads** with matching refractive index acting as **light concentrators**
- 2-step production process…

Gel Pad Casting:
ShinEtsu OSN-3547-HE-A/B

- 2-component epoxy allowing for **tuning of flexibility / rigidity**
- **> 98% transparency** in Cherenkov UV range



- Custom vacuum-formed PE (PET-G) molds for casting **hollow pads directly onto the PMT**

► Curing at low atmospheric pressure to remove bubbles

Sensor Installation:

- Attachment of precast **gel pad rims** to **inner glass surface**
- Sealing via spring (bladder) mechanism

- **Backfilling of cavities** with **uncured optical gel**

► Curing at low atmospheric pressure to remove bubbles

Gen2-DOM Readout Board

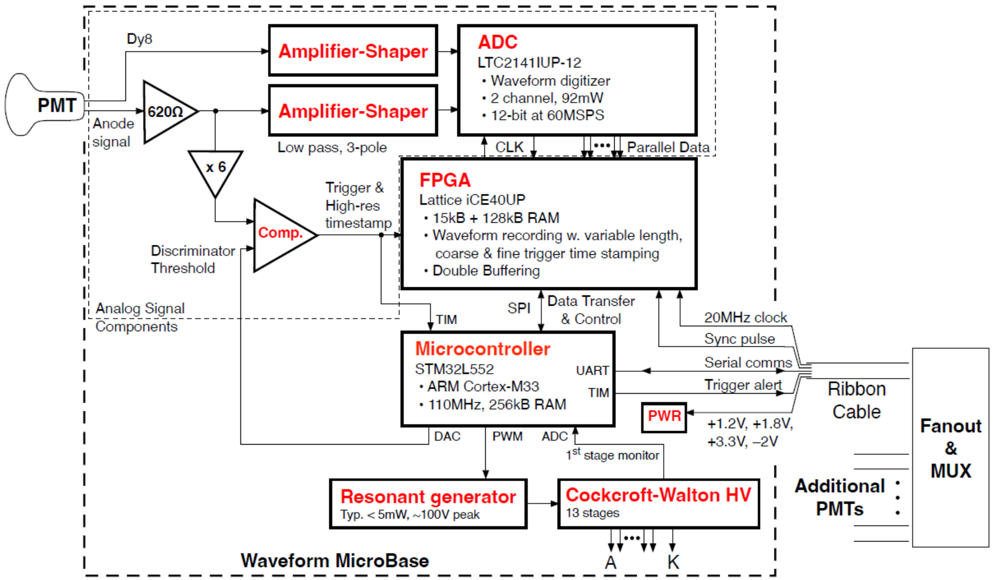
Waveform Microbase: wuBase

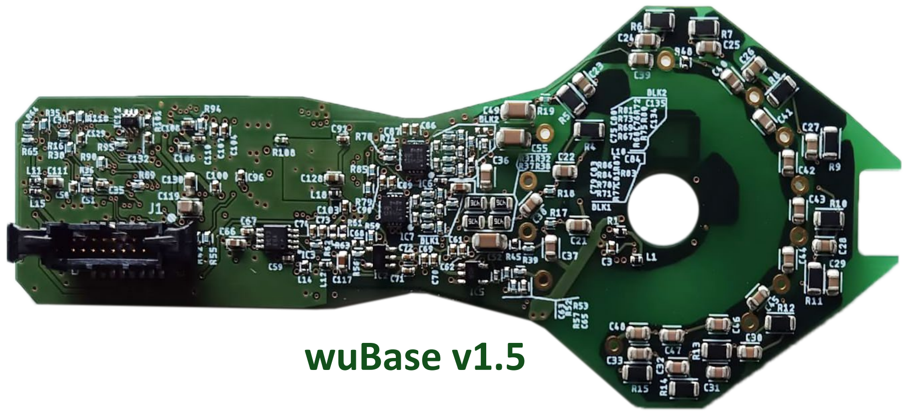
- **Active Cockroft-Walton HV generation:** Same as for mDOMs
- **Waveform digitisation:** Two-channel 12-bit ADC @60MSps

▶ **Single-PE time resolution:** 2.6 ns

- **High-gain channel:** Pulse from **anode**
- **Low-gain channel:** Pulse from **dynode 8/10**

▶ **High dynamic range** of (1 – 5 000) PE in 25ns





wuBase v1.5

- Close collaboration with **Chiang Mai University (TH)**
- New manufacturer **HANA Electronics (TH)** to build $\mathcal{O}(20)$ boards (v1.5, w/o changes)

▶ **Replace connector -> FFC**

▶ Rearrange resistors

▶ **Adjust voltage** $^{+3.3}_{-2.0}$ V -> +5.0 V

▶ **(Far) future:** FPGA -> **ASIC…**

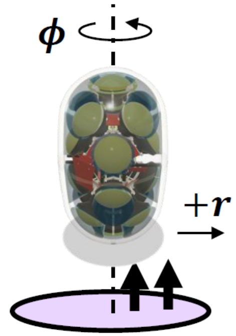
LOM 4π Scanning Station

Laser-Based Scanning System:

TSUJI Tomoyuki

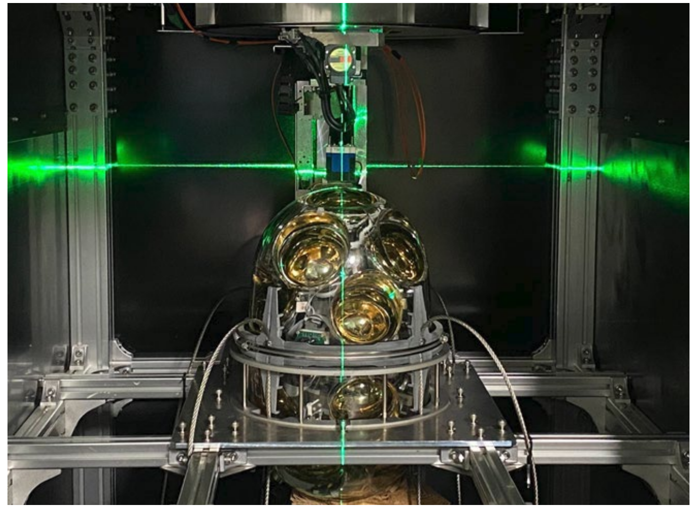
- Injection of photons from **bottom ($r\phi$)** or **side ($z\phi$)**

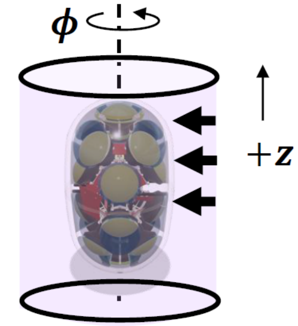
▶ Evaluation of **angular photo detection efficiency**



$r\phi$-scan

Δ (5mm, 6°)
1860 points, 30s





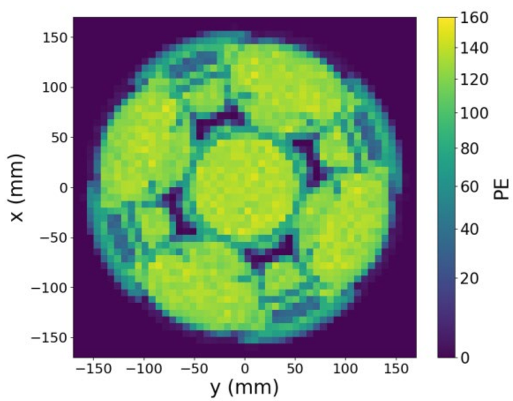
$z\phi$-scan

Δ (5mm, 6°)
1140 points, 30s

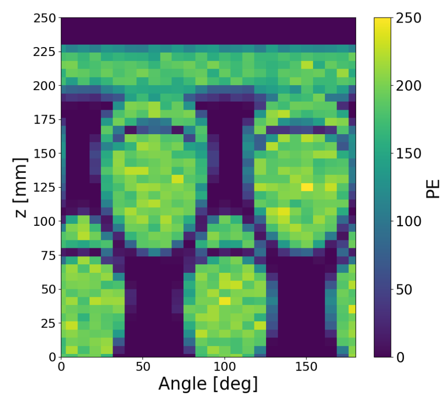
▶ Good **qualitative agreement** of measurement and simulation, **incl. modelling of gel pads**

- Setup **calibration ongoing**…

Simulation:

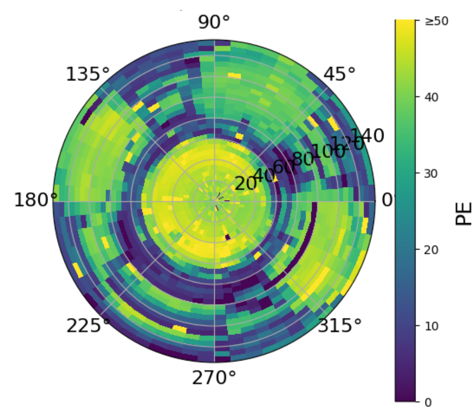


$r\phi$ scan

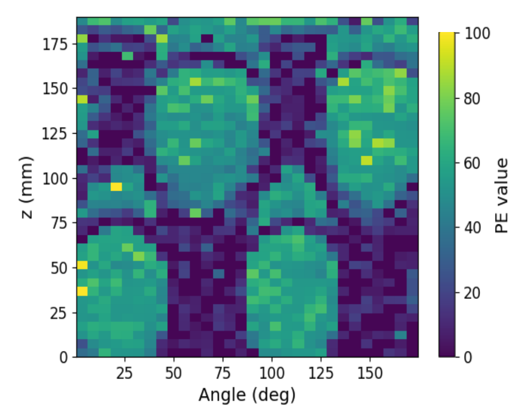


$z\phi$ scan

Measurement:



$r\phi$ scan



$z\phi$ scan

LOM-18 Glass Background Study

Birk's Law: Scintillation **light yield (*LY*)**

$$\frac{dL}{dx} = S\,\frac{dE/dx}{1 + k_B\, dE/dx + C(dE/dx)^2}$$

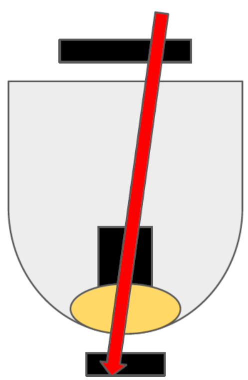
S: scintillation light yield [photons/MeV] , k_B: Birk's constant (quenching strength)

▶ Determined from FAT data & simulation

▶ **Scintillation and Cherenkov** light from **radioactive isotope (*RI*) decays**

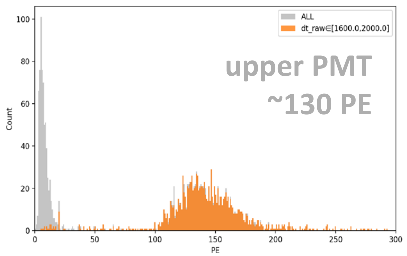
▶ **Scintillation and Cherenkov** light from **cosmic rays ($\mu^{\pm}$)**

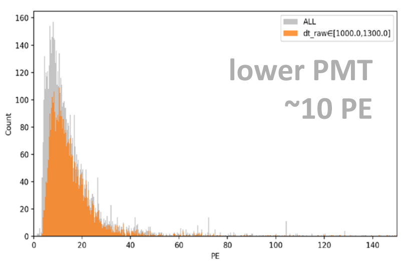
Cosmic Ray Measurement: $\mu^{\pm}$



- **4" PMT** within **LOM-18 glass vessel**
- Trigger provided by plastic scintillator tiles

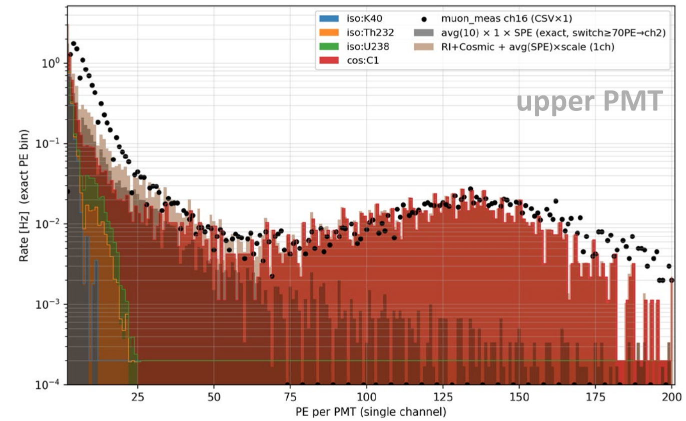
▶ Measurement of **scintillation & Cherenkov light** from **downward-going $\mu^{\pm}$**

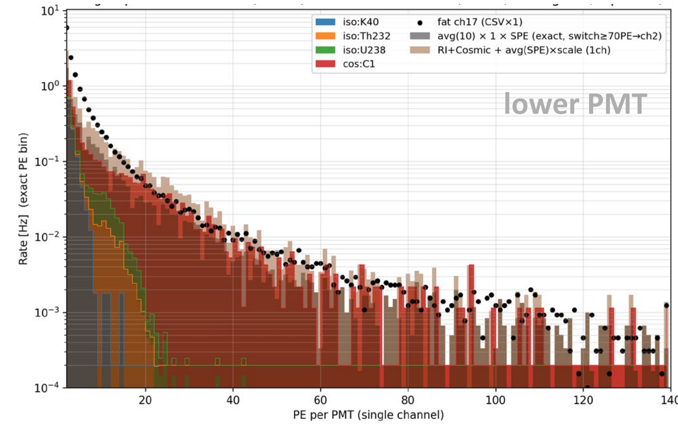




MC Simulation: ***RI* decays** KASAI Yujiro

- Using LY measured with cosmic $\mu^{\pm}$



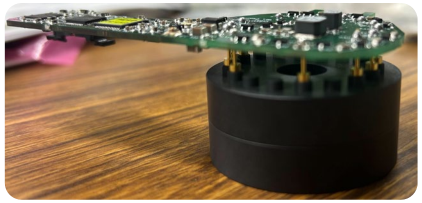


▶ **Good agreement** with FAT measurement

PMT Quality Control & Mass Inspection

ICEHAP PMT Test Stand: -20°C / -40°C (inside freezer)

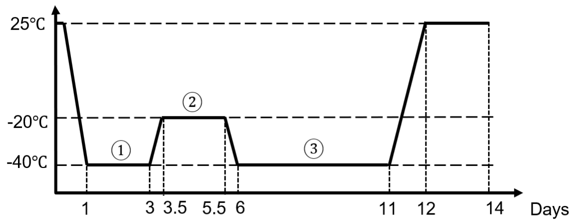
SENO Zenta
OMOTE Yuta

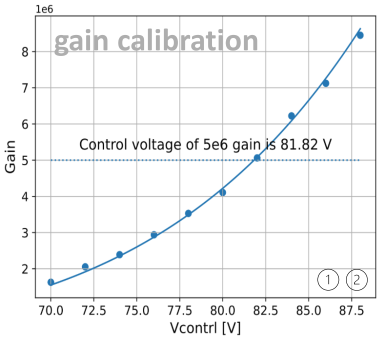


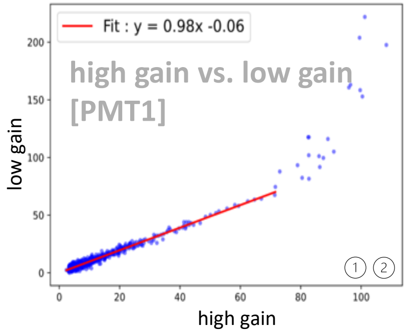
- **Simultaneous characterisation** of **8x 4"-PMTs**:

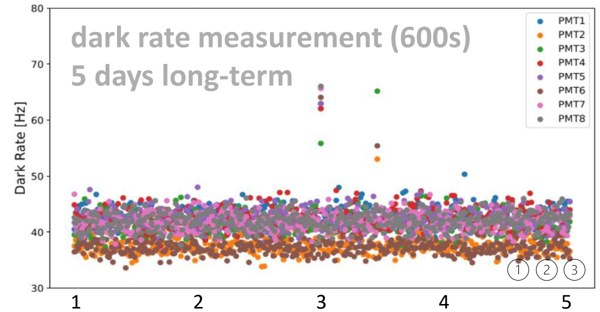
▶ **Gain calibration,** measurement of **low gain / high gain** & **dark rate @ -20°C / -40°C**

2-Week Measurement Cycle:









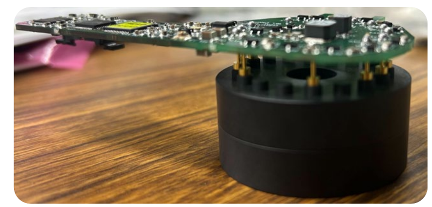
PMT Quality Control & Mass Inspection

ICEHAP PMT Test Stand: -20°C / -40°C (inside freezer)

SENO Zenta
OMOTE Yuta

communication board

photon injection (acrylic rod coupled to LED flasher)

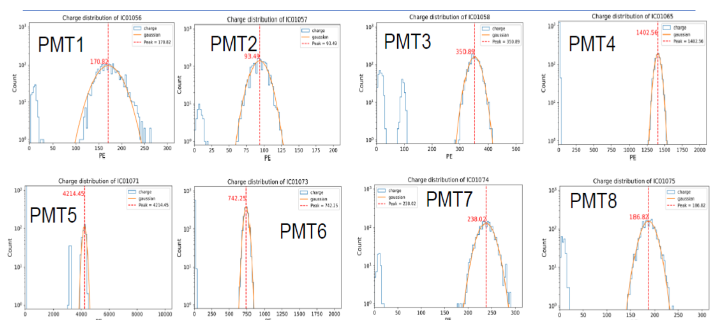


Preparation for mass production:

- **~10 000x 18 PMTs** to be characterised…

8 identical setups being constructed:

▶ **Simultaneous measurement** of **64 PMTs**



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Outlook

Outlook

Timeline & Milestones: Immediate & near future

- **IceCube-Upgrade (2025):** Deployment of **current LOM prototypes** (6x LOM-18, 6x LOM-16)
- **2026 - 2027:** **Unification of Gen2-DOM design**, production & test of **~100 modules**
  - ▶ **2026/11:** First prototype **Design Verification Test (DVT)**
  - ▶ **2027/06:** **Final Acceptance Test (FAT)**
- **2027-2028:** Preparation for IceCube **Gen2-DOM mass production**
  - ▶ **2027/11:** **Final prototype review & design**
  - ▶ 2028/10: Start of **Gen2-DOM mass production**…

Posters @ this Conference: IceCube-Gen2 Detector R&D

- ***Evaluation of the angle dependence of the light detection efficiency of the LOM-18 detector for IceCube-Gen2***
  TSUJI Tomoyuki
- ***Understanding the Contribution of Optical Signals from the New Photodetector LOM18 for the IceCube-Gen2***
  KASAI Yujiro
- ***Mass Inspection of Photomultiplier Tubes for the IceCubeGen-2 Experiment***
  SENO Zenta