Design of Optical Module Candidates for IceCube-Gen2

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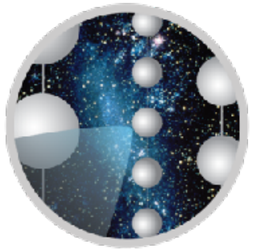
ICECUBE GEN2

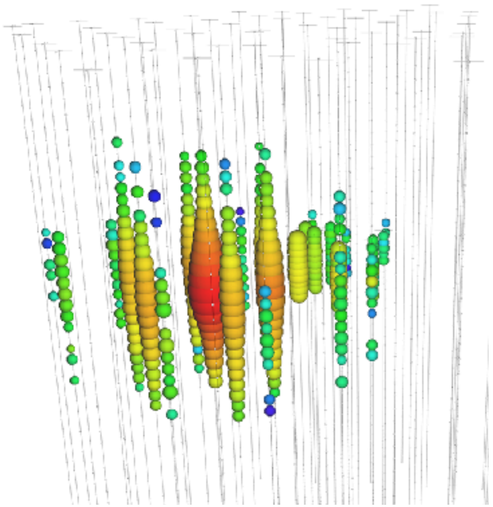
WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

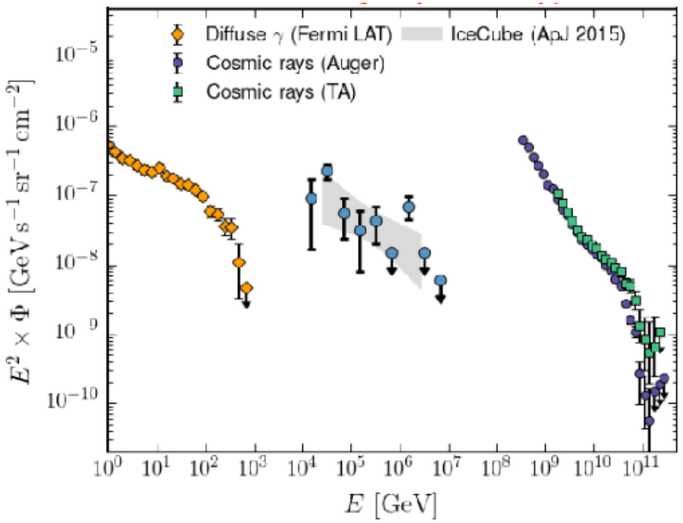
IceCube and IceCube-Gen2



ICECUBE

World's largest neutrino telescope (1Gton)
Full detector operation since 2011

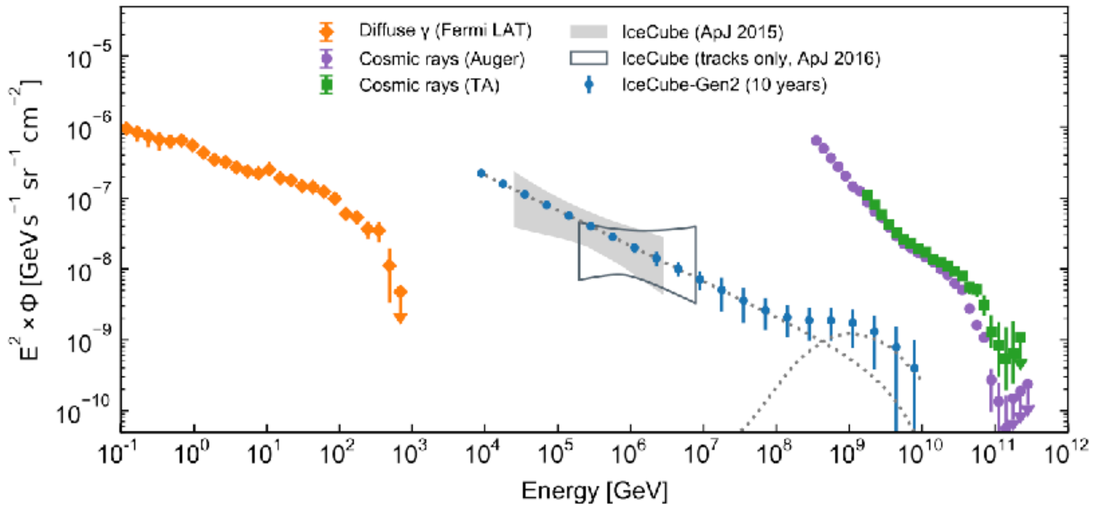




- Discovery of astrophysical neutrino flux (2013)
- Evidence for Blazars as neutrino sources (2018)
- High energy neutrinos from the Galactic Plane (2023)

ICECUBE GEN2

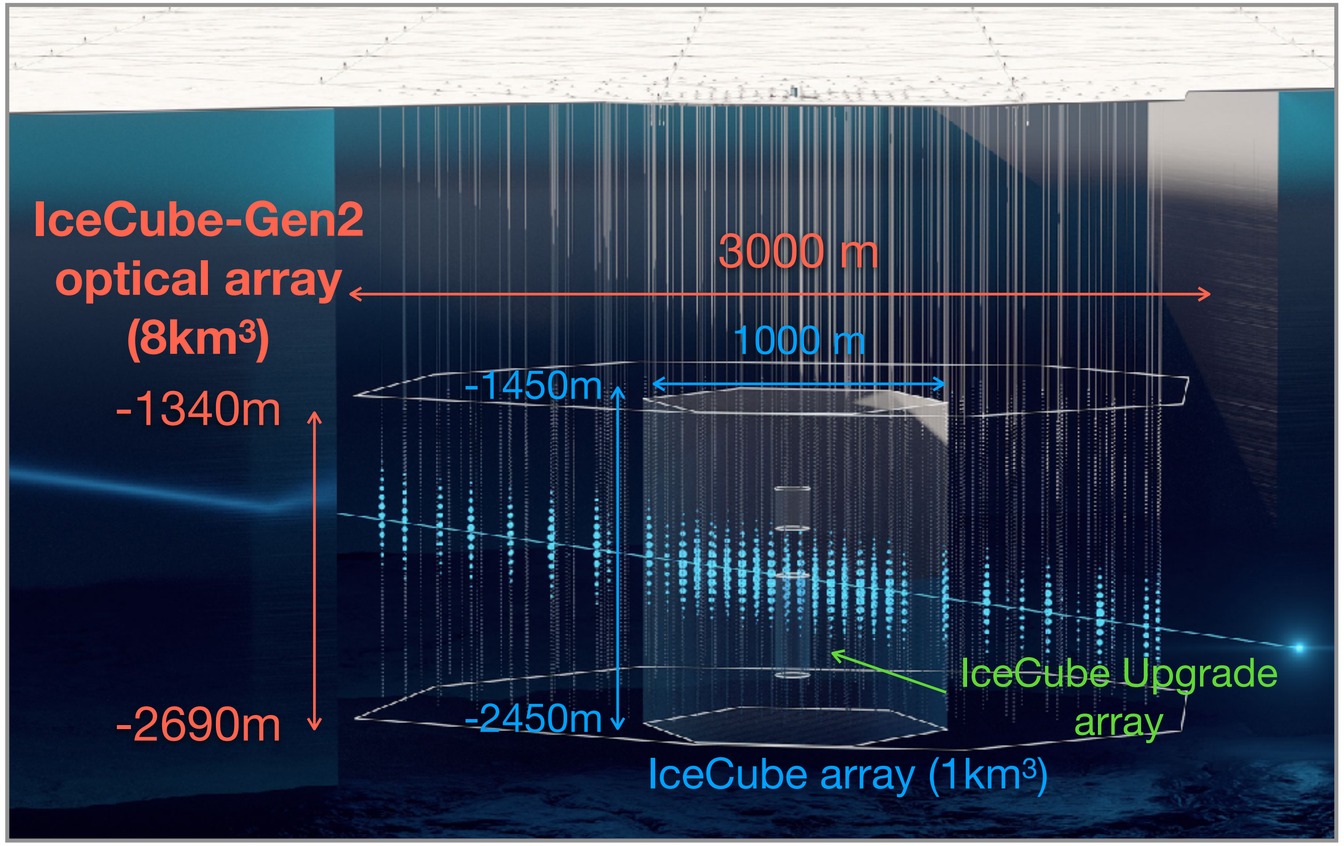
A high energy extension of IceCube
for the next decades of neutrino astronomy

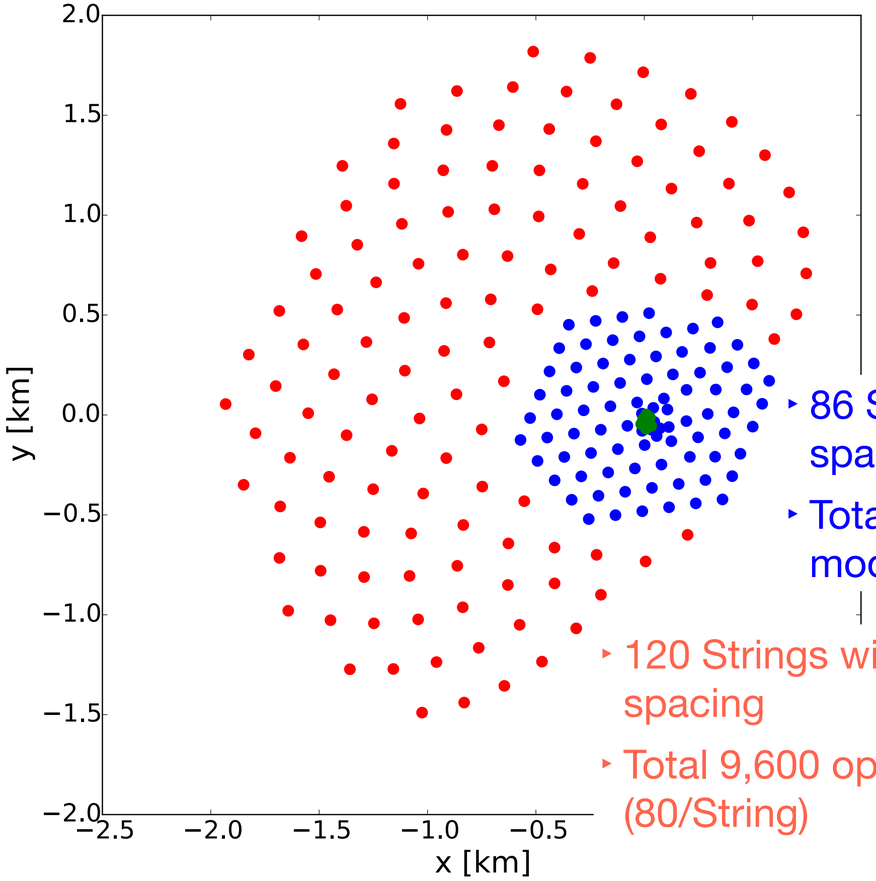


- From discovery to astronomy
- Aims 5x sensitivity from IceCube (>10x at >10TeV)
- Resolving high energy sky from TeV to EeV
- With Optical, Surface, and Radio arrays

IceCube-Gen2 Optical Array

IceCube-Gen2 will expands the IceCube's 1km^3 instrumented volume to 8 km^3



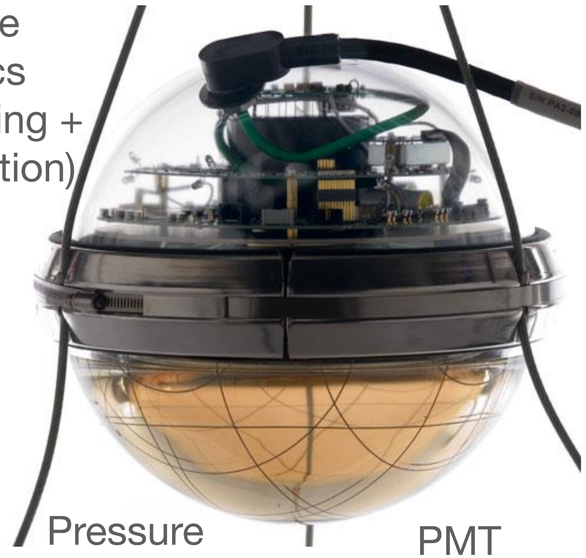


- 86 Strings with 125m spacing
- Total 5,160 optical modules (60/String)
- 120 Strings with 240m spacing
- Total 9,600 optical modules (80/String)

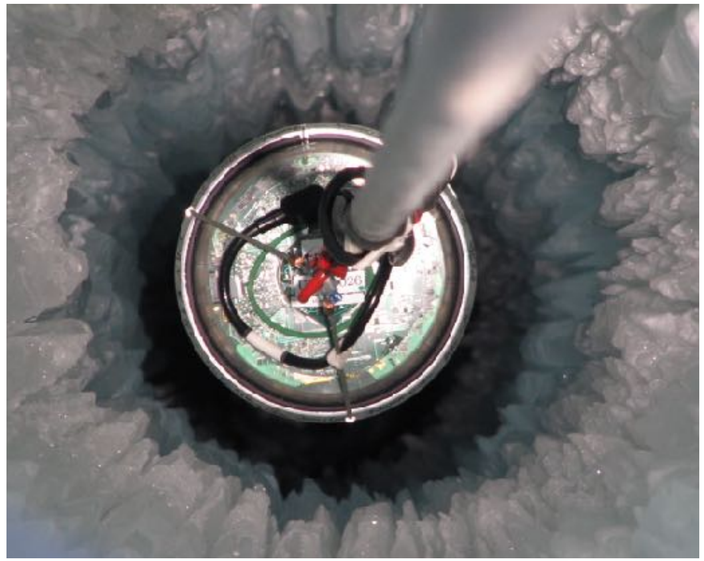
Improvement of the Optical Module is critical to achieve such a huge and sparse array of IceCube-Gen2

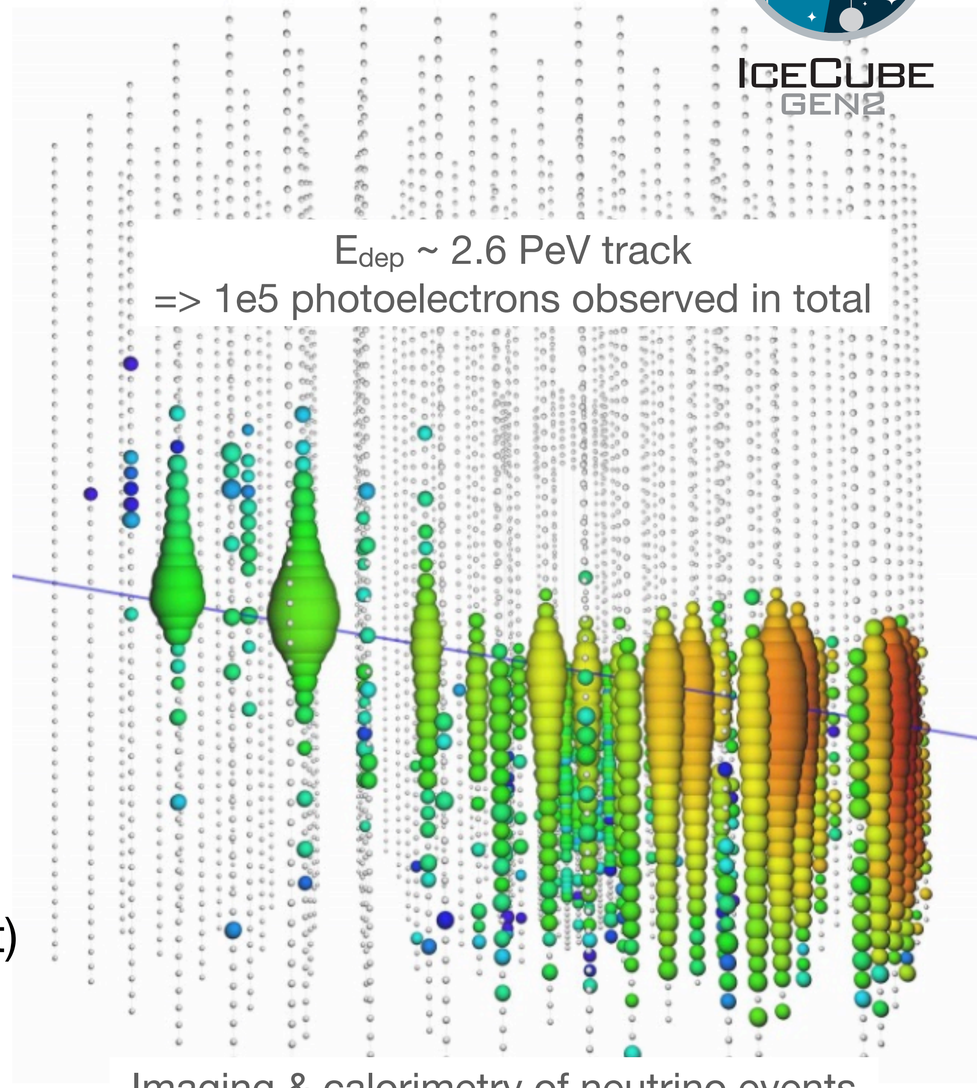
Optical Modules

IceCube Digital Optical Module (DOM)



Deployment into the deep ice sheet at the South Pole





Imaging & calorimetry of neutrino events with a 3D array of Optical Modules

- Photo sensor (PMT) & readout electronics in a pressure vessel
- 70 MPa rating (55 MPa observed at re-freezing phase after deployment)
- Operation temp range from -40C to -20C
- High reliability (No access after deployment for >10 yr operation)
- Very-expensive ice drilling cost proportional to the module diameter

IceCube Optical Modules and for Gen2

IceCube

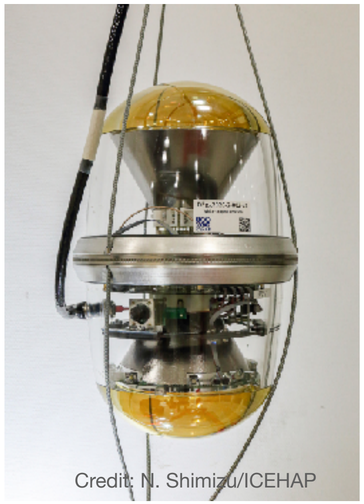
IceCube DOM

10” PMT & dia. 33 cm

>98% still in operation after 10 years

IceCube Upgrade

Low-energy extension & Ice calibration
(7 Strings around Deep Core in 2025/26)



D-Egg

2x 8” HQE PMTs & dia. 30 cm

mDOM

24x 3” PMTs & dia. 36 cm

- First Multi-PMT In-Ice Optical Module designs
- Designs tuned for low-E events & ice measurements
- Major updates in essential elements (pressure vessels, optical gel, electronics, and etc)
- **New production, testing facilities, and skilled R&D teams**

IceCube Gen2

High energy extension

Design goals?

IceCube-Gen2 Optical Module development is built on

- Successful design from IceCube
- Updates through IceCube-Upgrade

Design Goals

- What Optical Module do we want for a neutrino telescope with 240m string-spacing and 8 km^3 volume?
  - Highest per-module effective area targeting x4 improvement compared to IceCube DOM
  - Wide dynamic range: From single photoelectron (SPE) to PeV-class (and more) events
  - Directional information with a multi-PMT design for better reconstructions
- Reality hits when such a large-scale extension…
  - Module diameter needs to be less than 12.5” (320mm) to suppress the enormous drilling cost <= 13” for IceCube DOM
  - Limited South Pole infrastructure requires low power consumption, aiming 4W/module <= 5.7 W for IceCube DOM

The biggest challenge of Gen2 DOM development is

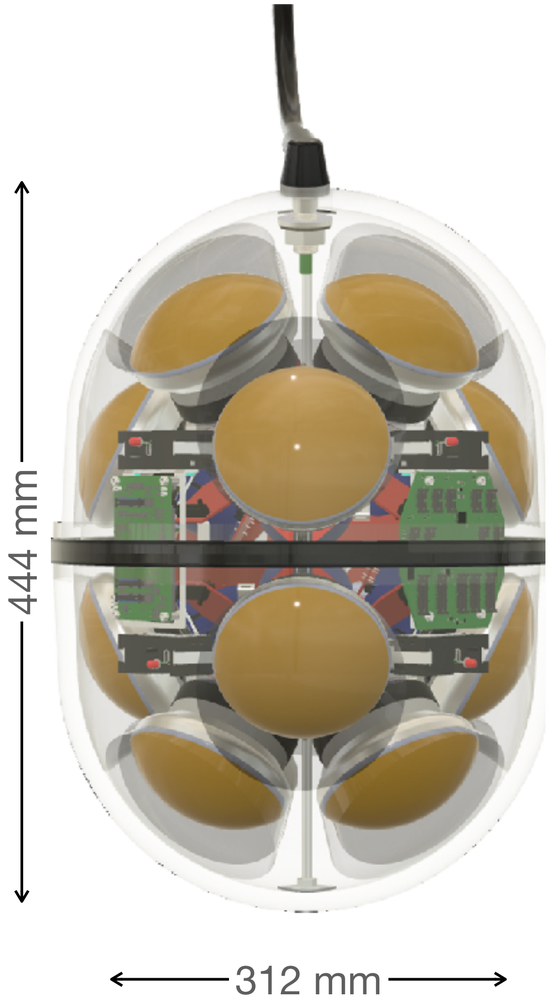
>4.0x IceCube DOM performance with a smaller module size

Gen2 DOM Design Candidates

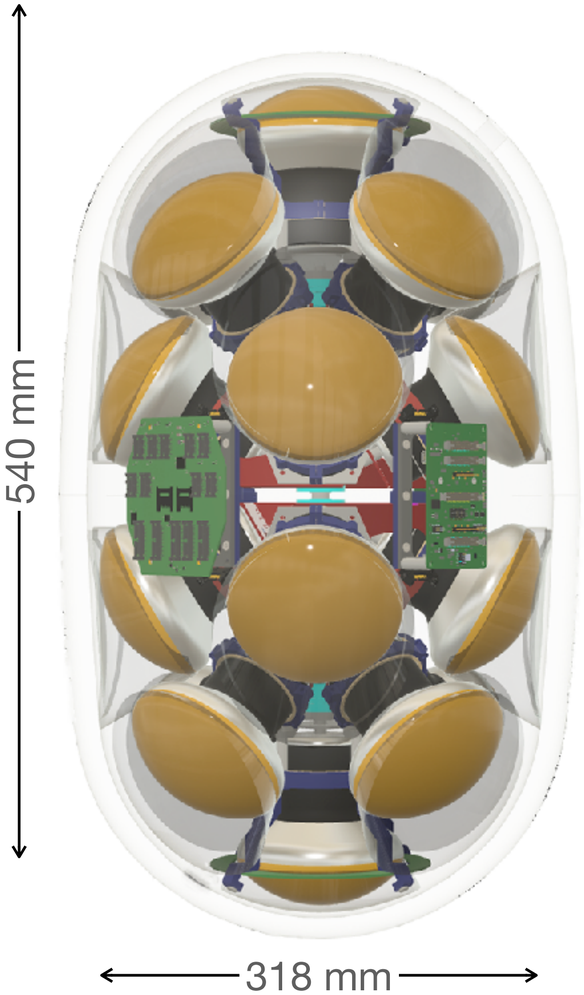
- Two design candidates; 16 and 18 PMT models
  - 18 PMT opt: Max effective area with a 12.5” vessel
  - 16 PMT opt: Relatively simple. Smaller size & weight
- Technologies & concepts inherited from Upgrade R&D

- 4” PMTs to maximize effective area
  - Largest possible for back-to-back layout
- Gel pads for optical coupling & light collector
  - Avoid complex holder structure (mDOM, Km3Net DOM)
  - Similar ideas investigated in other experiments (e.g. NIM A 958 (2020))
- Custom electronics designed for Gen2 needs
  - Single p.e. events to high energy neutrino events
  - Low power consumption & Compact design

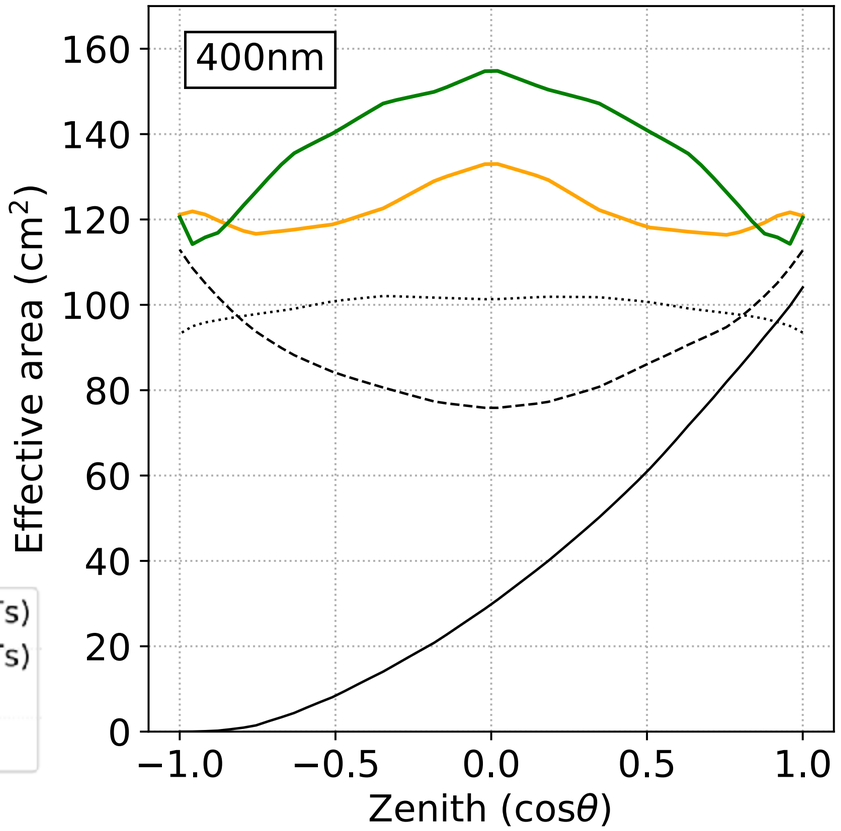
16 PMT model

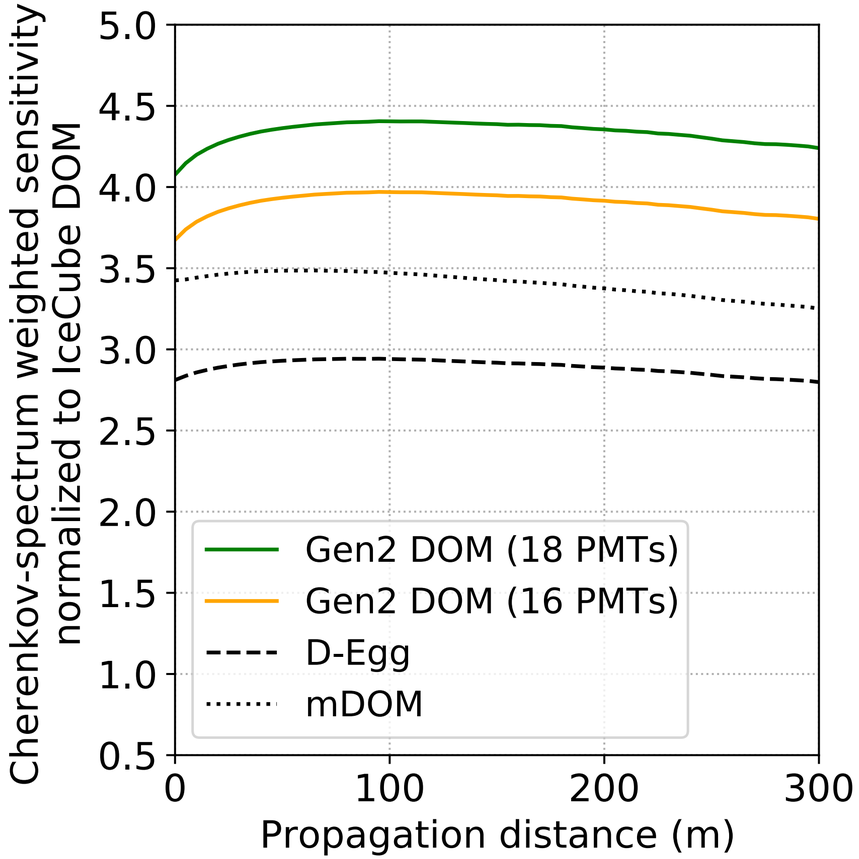


18 PMT model



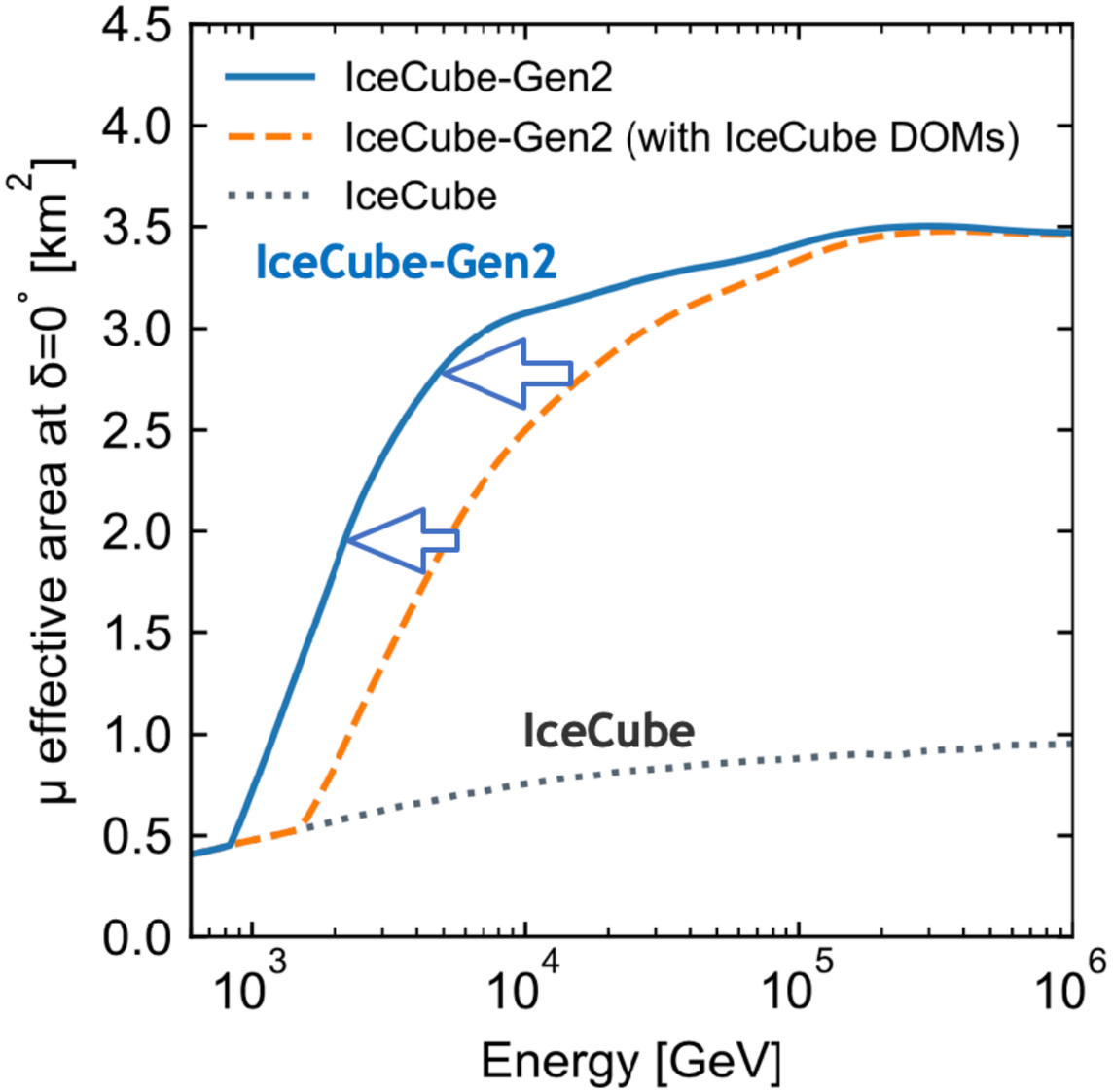
Expected Performance

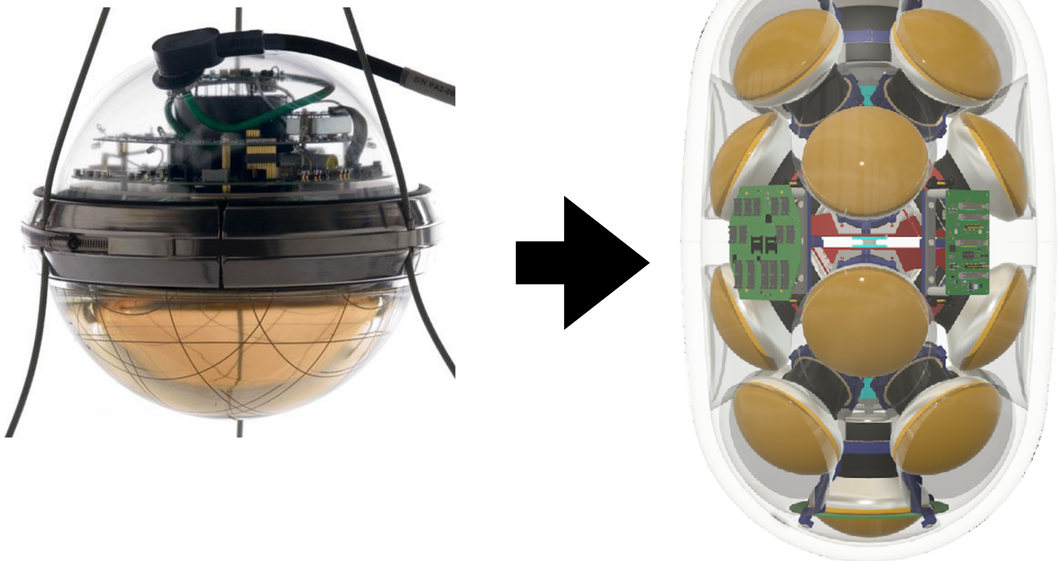




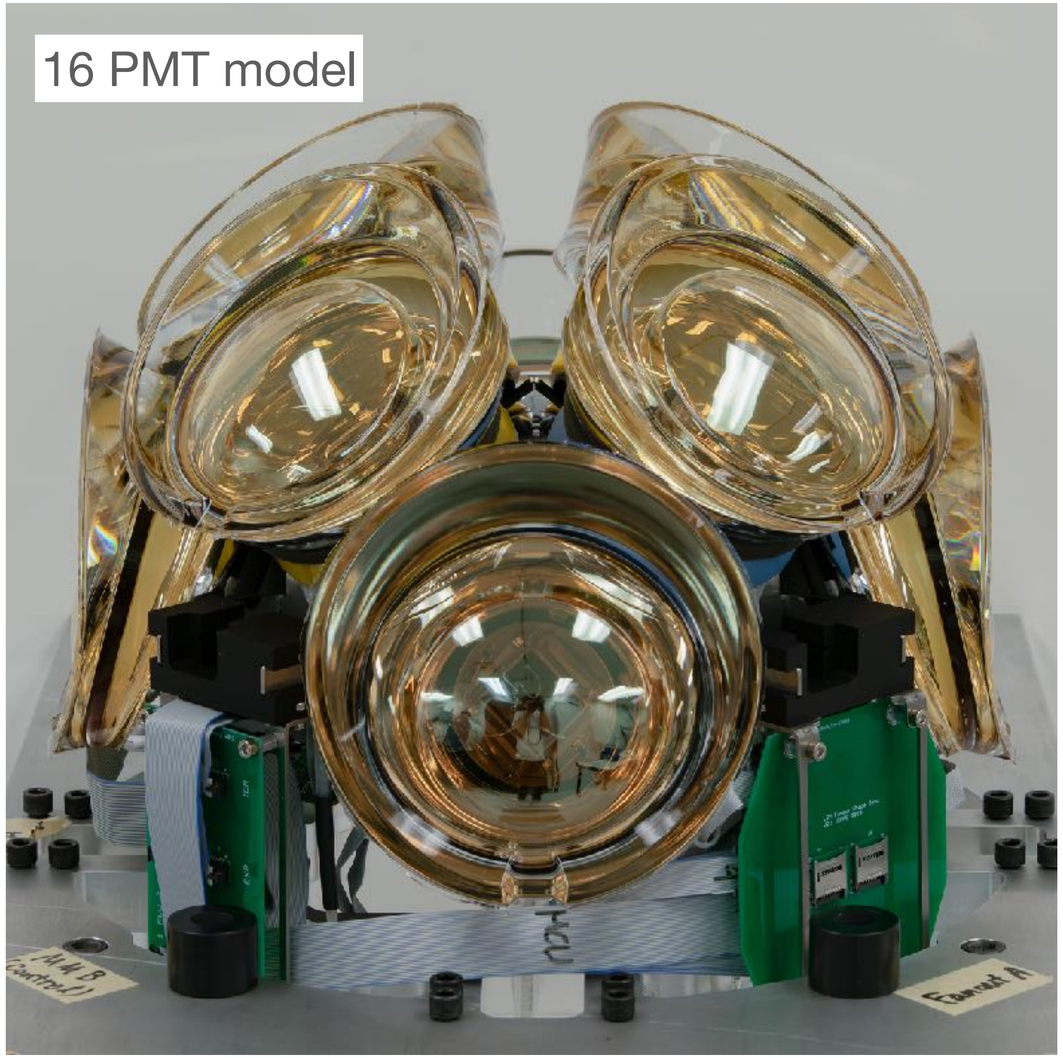
- Improved sensitivity at the horizontal directions
- 16 and 18 PMT models show **factor-of-4 improvements from IceCube**
  - Either options will be the most sensitive DOM design among other IceCube Optical Modules despite smaller vessels

Expected performance



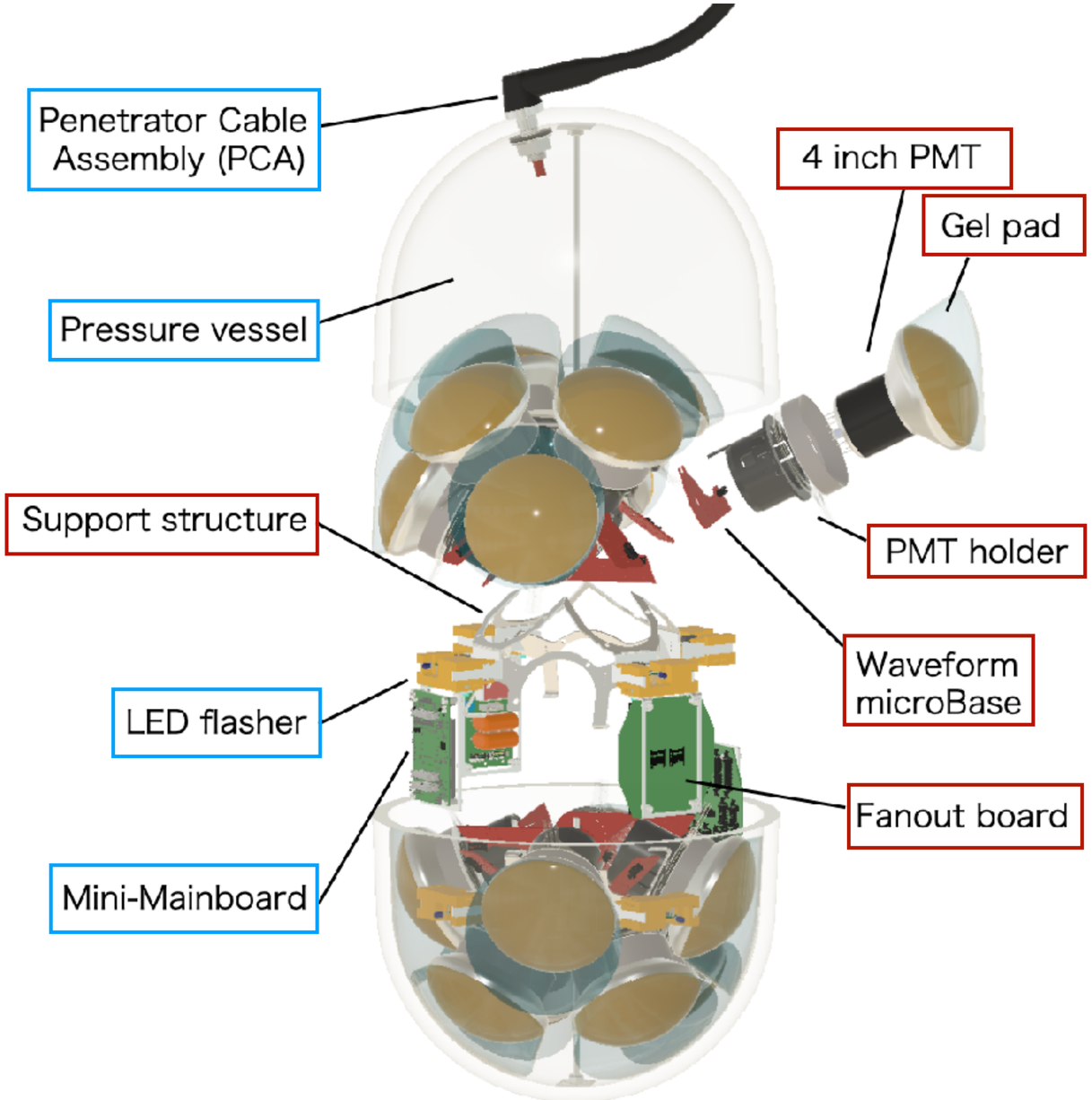


Gen2 DOM Design Candidates: Status



Not just looks-good-in-CAD-and-simulation, but the development is already very advanced

R&D Status of Each Component

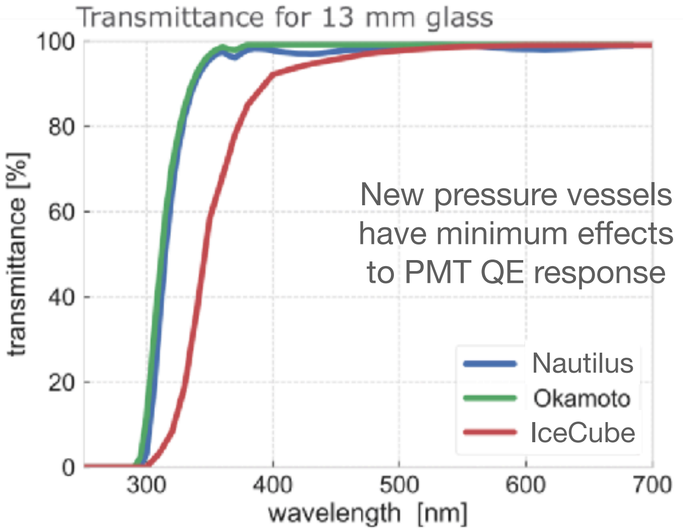


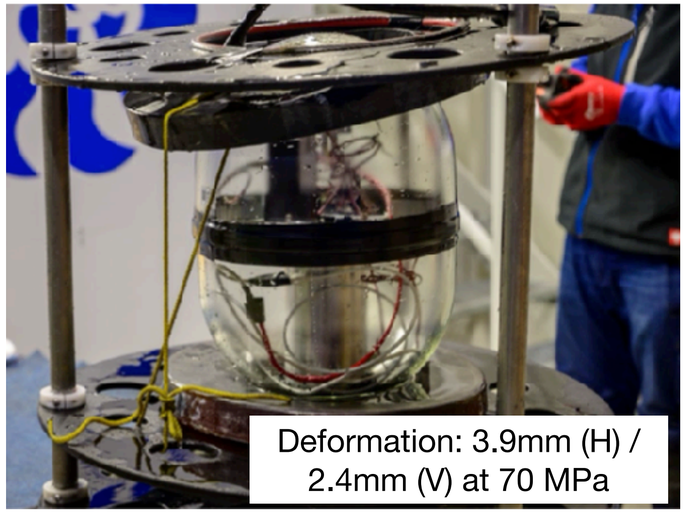
(*) 16 PMT model

Pressure Vessels

Diameter < 12.5” / 70 MPa rated / high UV transmittance / radioactivity as low as possible

- Okamoto Glass (Japan) & Nautilus (Germany)
  - Used for D-Egg and mDOM production
  - Glass material well studied through IceCube Upgrade development
  - Keep-multiple-vendors strategy for essential components in Gen2
- Improved optical performances
  - >50% transmittance at 320 nm (Both)
  - Reduced ^{40}K: 0.74 Bq/kg (Okamoto)
- Pressure rating have been proved with prototypes

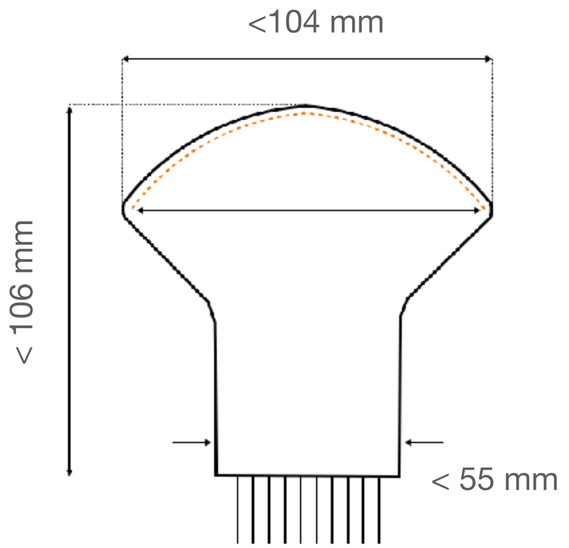




Compact-design 4 inch PMTs

As short as possible accepting minimum compromise in performance

- Two vendors: Hamamatsu and North Night Vision Technology (NNVT)
  - Newly-designed 4 inch box & line dynode PMTs
  - NNVT has produced 15,000pcs 20” MCP-PMTs for JUNO
  - Keep multiple vendors for for Gen2!
- Very compact, 106mm (abs max.) long
  - Potential caveat is moderate cathode uniformity (transit time and/or collection efficiency, for example)



Target numbers

Parameter	Target value
Gain	5e6 @ <1500V
Transit Time Spread	< 8ns (FWHM)
Peak/Valley	>2
QE	>25% @400nm
Pre/late/after pulses	Less than 1/5/10%

New compact-design 4 inch PMTs

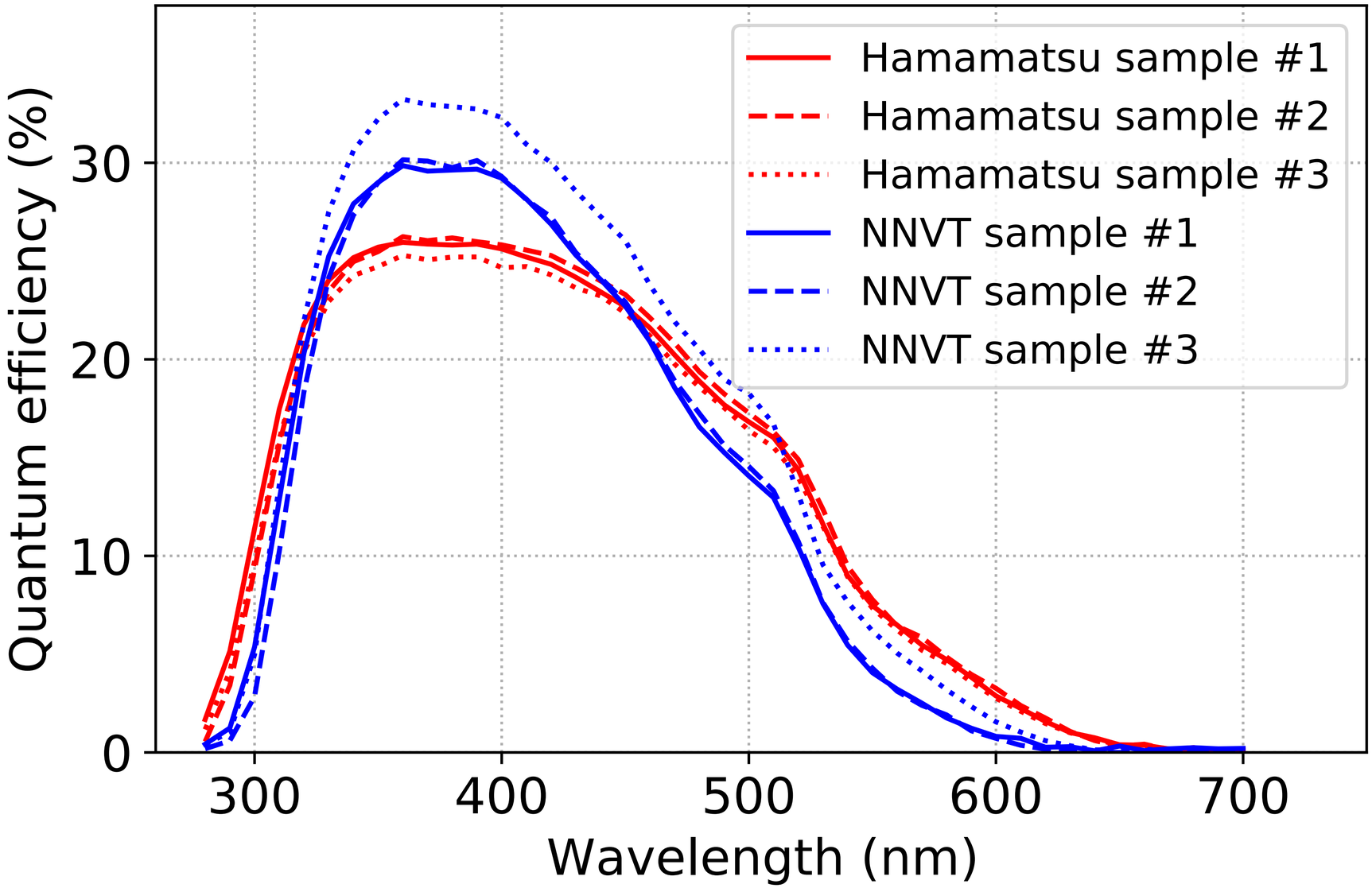
Hamamatsu Photonics K.K.

North Night Vision Technology (NNVT)

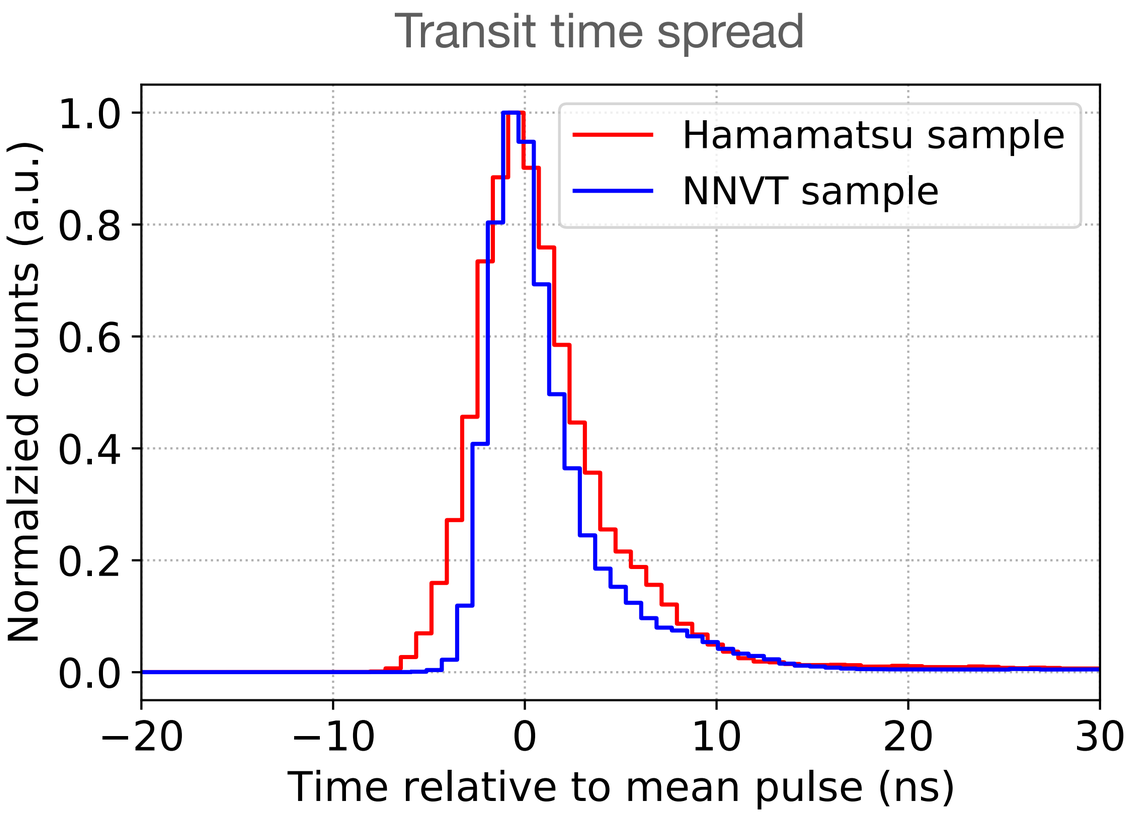
- Designs are finalized and we have already purchased >100 PMTs from each vendors
- Confirmed both PMTs meet our target numbers

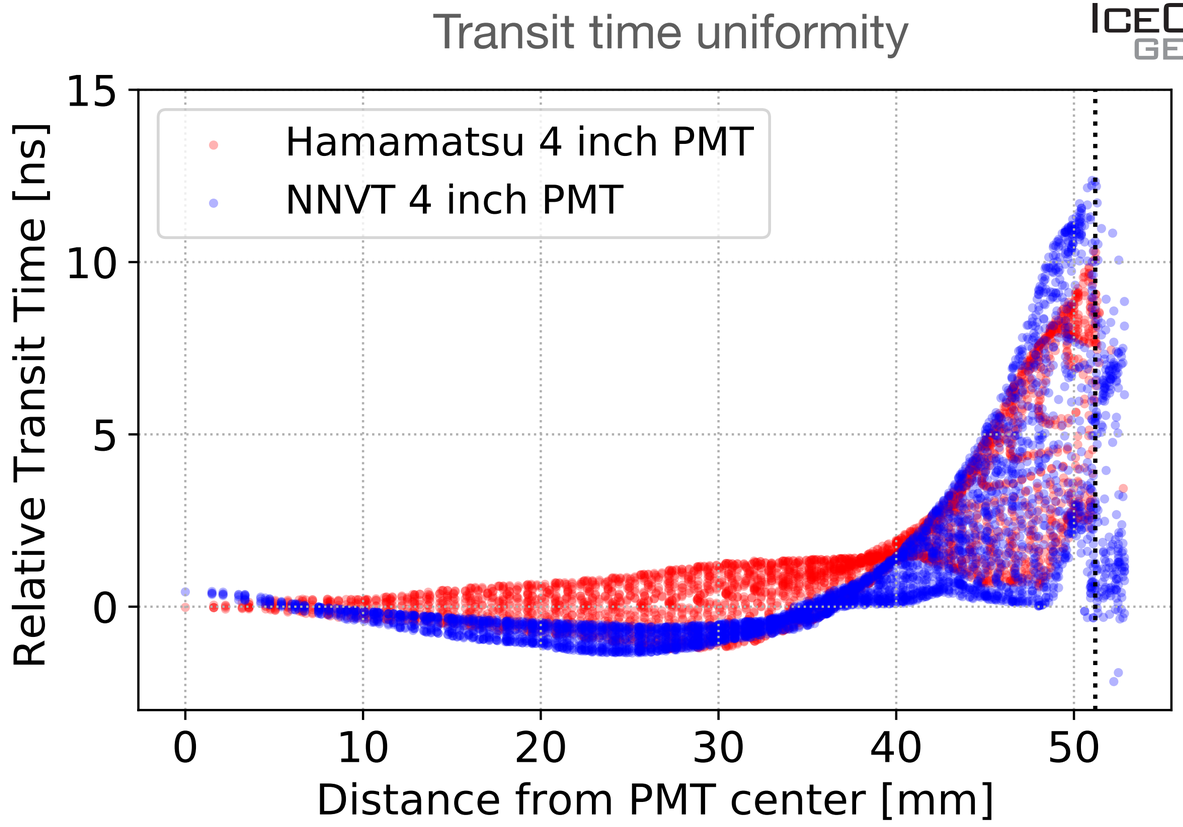
Delivered NNVT PMTs

New compact-design 4 inch PMTs



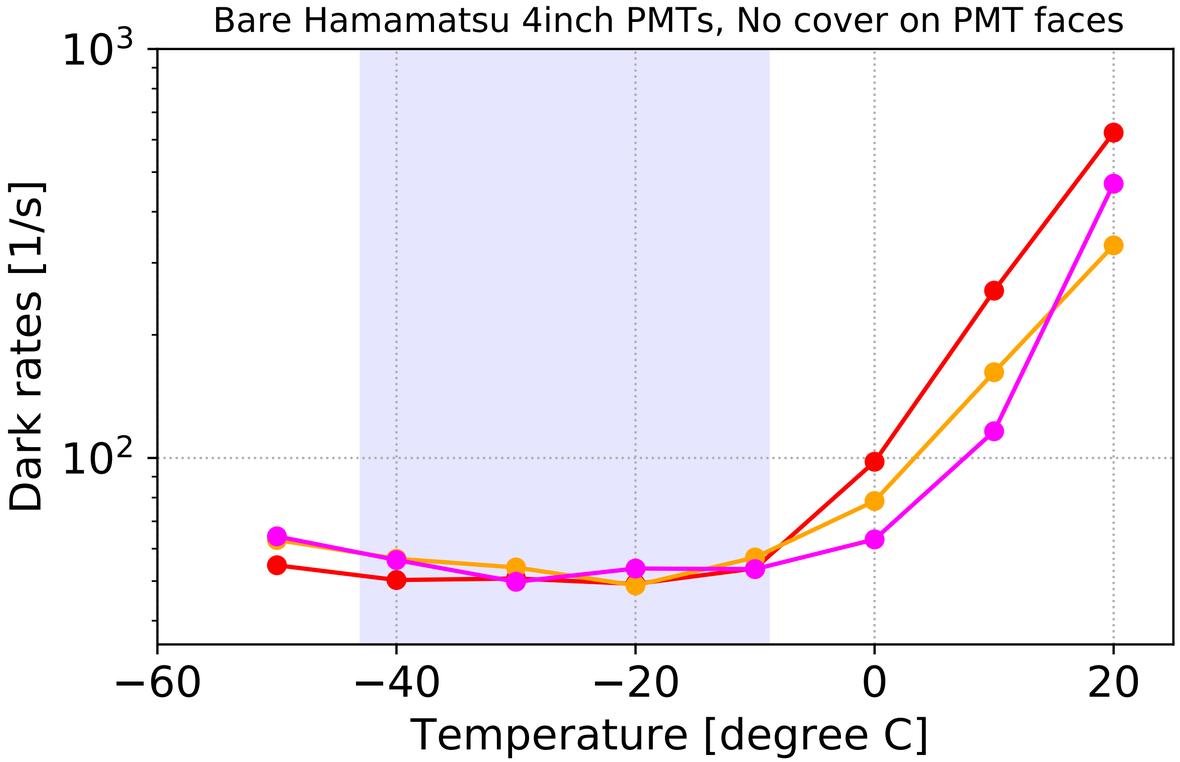
New compact-design 4 inch PMTs

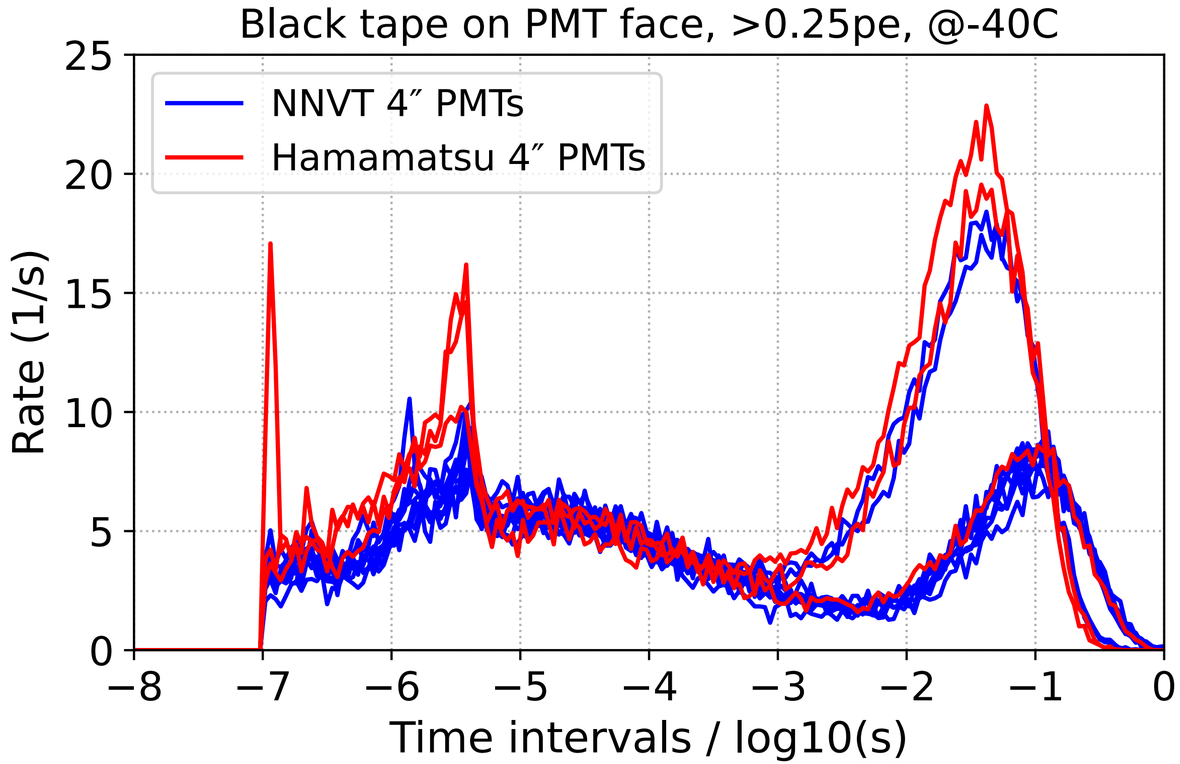




- Both PMT show good timing performances
- Uniform time response over the cathode area & Worse delayed responses at the edge was expected due to the short-length design, but the level is comparable with other PMTs used in other IceCube Optical Modules

New compact-design 4 inch PMTs



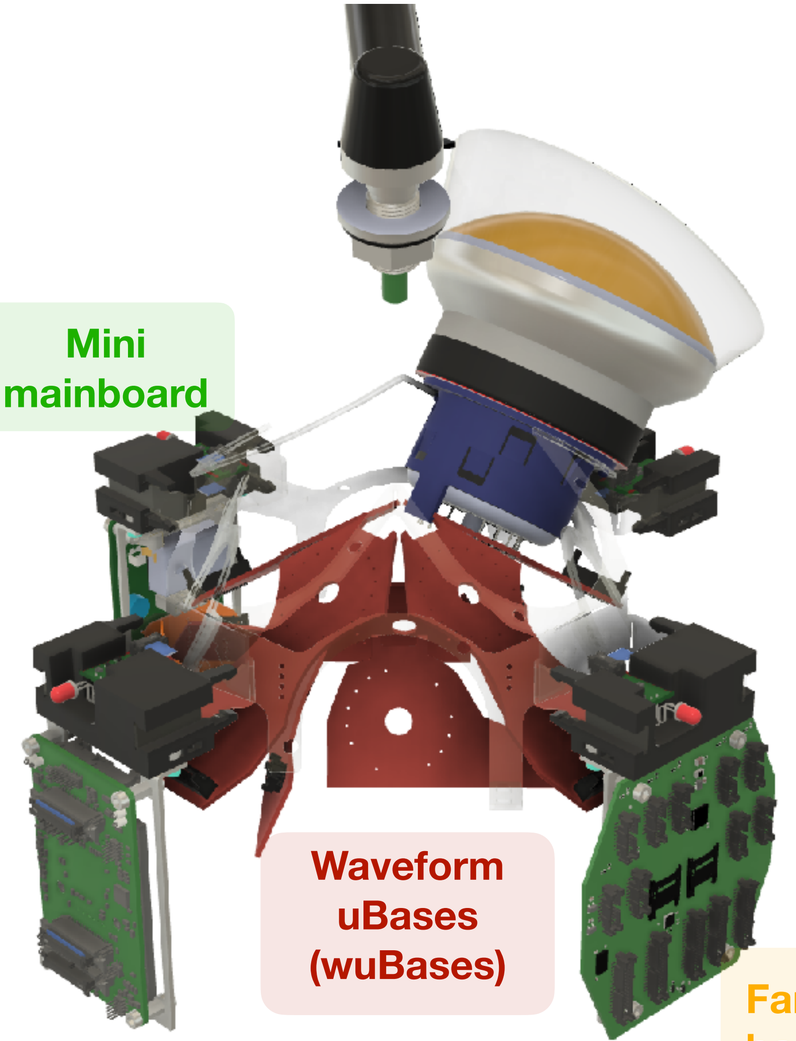


- South Pole deep ice sheet is an ideal environment in terms of the PMT noise
- Confirmed satisfactory low dark rates, including the details of contributions (thermal/random and “correlated” components), of both PMTs at low temperature

New compact-design 4 inch PMTs

Mechanical design & integration in the next Kareem’s talk

Electronics for IceCube-Gen2



Electronics only view

Limited space, Low power consumption,
Dynamic range from SPE to highest energy neutrino events

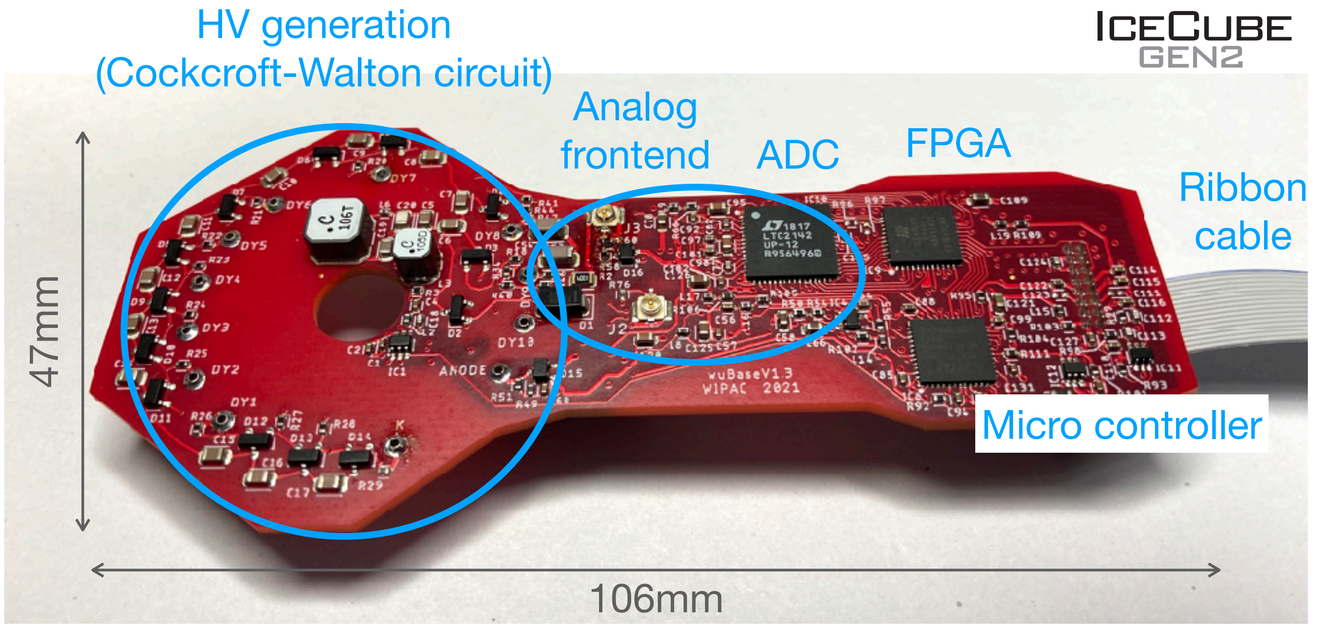
- Combination of specialized boards instead of a “big&central” board
  - Good match with the limited available space & No need for big / resource-expensive FPGAs
  - Re-purposing existing solutions from IceCube Upgrade
- Functionalities
  - Generate/regulate HV to each PMT
  - Digitization of signal waveforms from each PMT
  - Low level signal processing

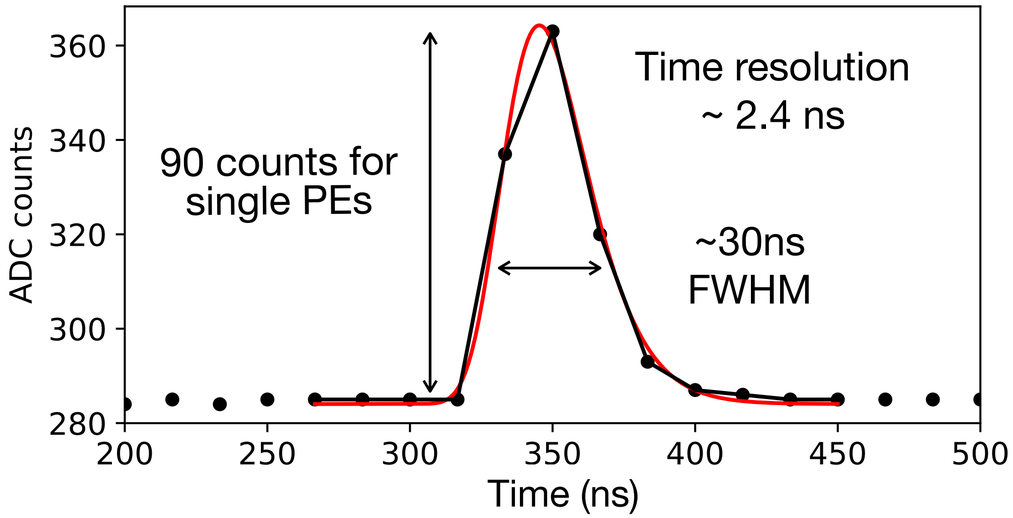
  → **Waveform uBases (wuBases)**
  - Command and data I/O multiplexing & data buffering → **Fanout boards**
  - Communication with surface computers for high level triggering and processing

  → **Mini mainboard**

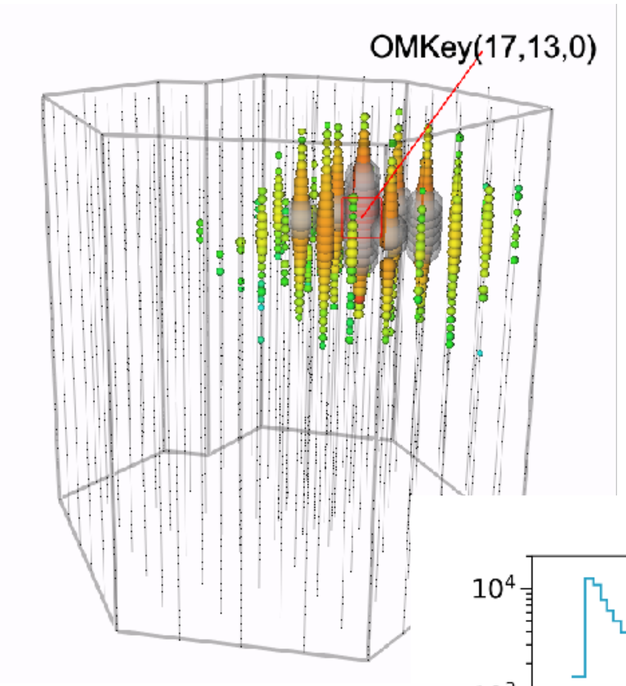
Waveform MicroBase

- Add DAQ feature to the existing custom HV base
  - Proven HV base design developed for the IceCube-Upgrade
    - MicroBase (ref: PoS(ICRC2021) 1070)
  - Ribbon cable for controlling and data transfer
- DAQ functionalities
  - Continuous digitizing with 2-channel 12 bit ADC at 60MSPS and captured in a low-power consumption FPGA
  - Record Anode (high gain) and 8th Dynode (low gain) signals
  - Microcontroller manages control and regulation of HV, and buffering and low-level processing of digital waveform data
  - Total power consumption 150 mW
    - 90 mW if ASIC

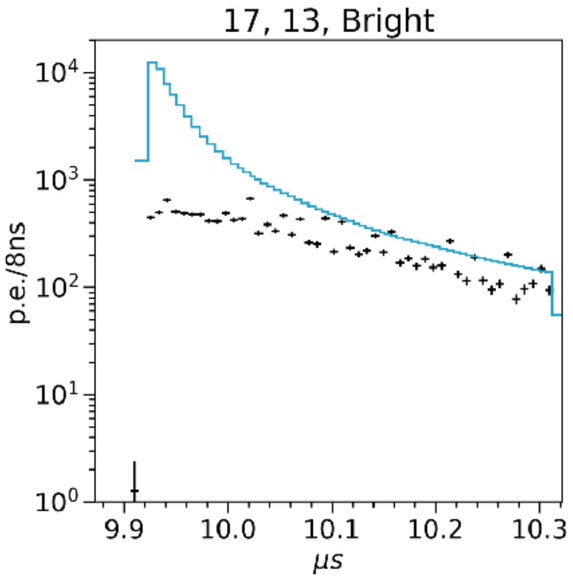


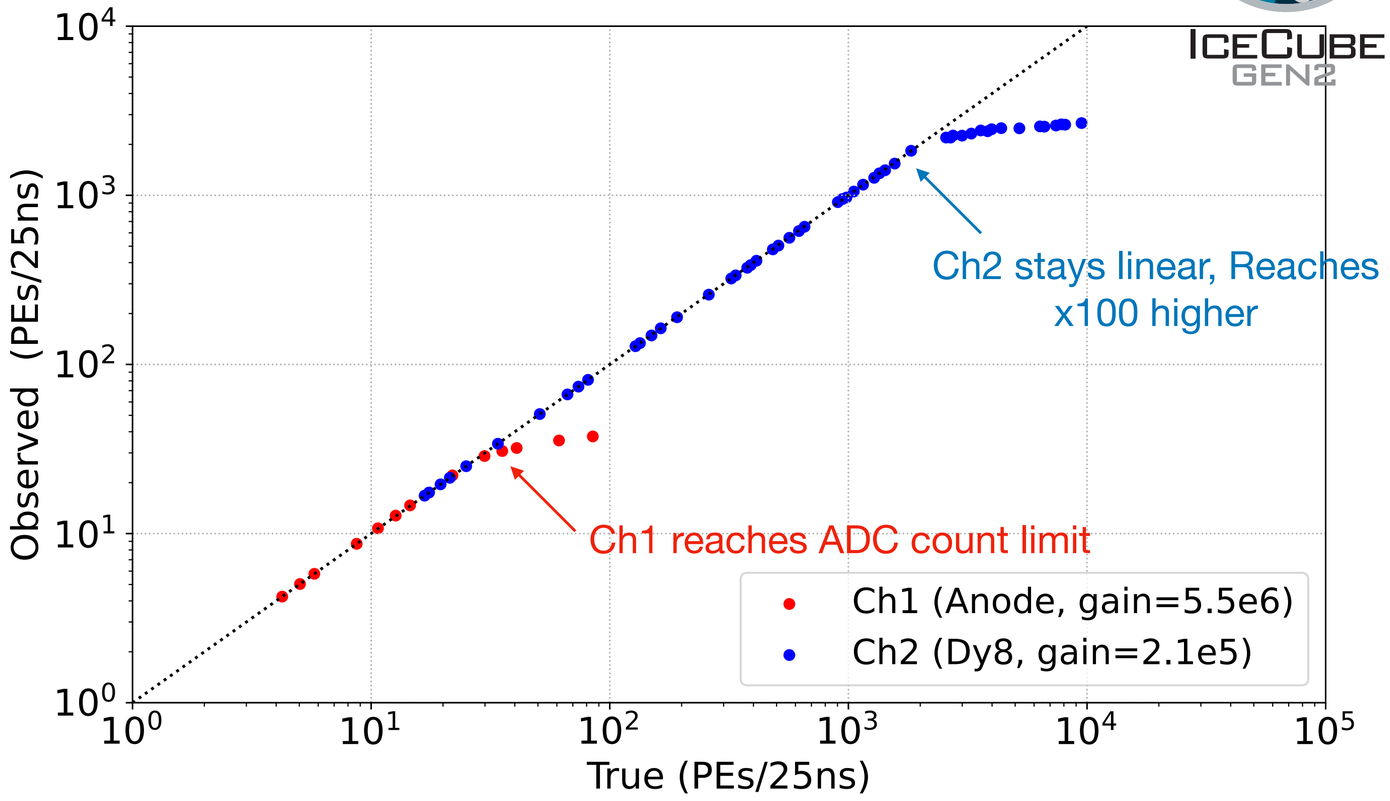


Wide Dynamic Range for High Energy Events



IceCube data

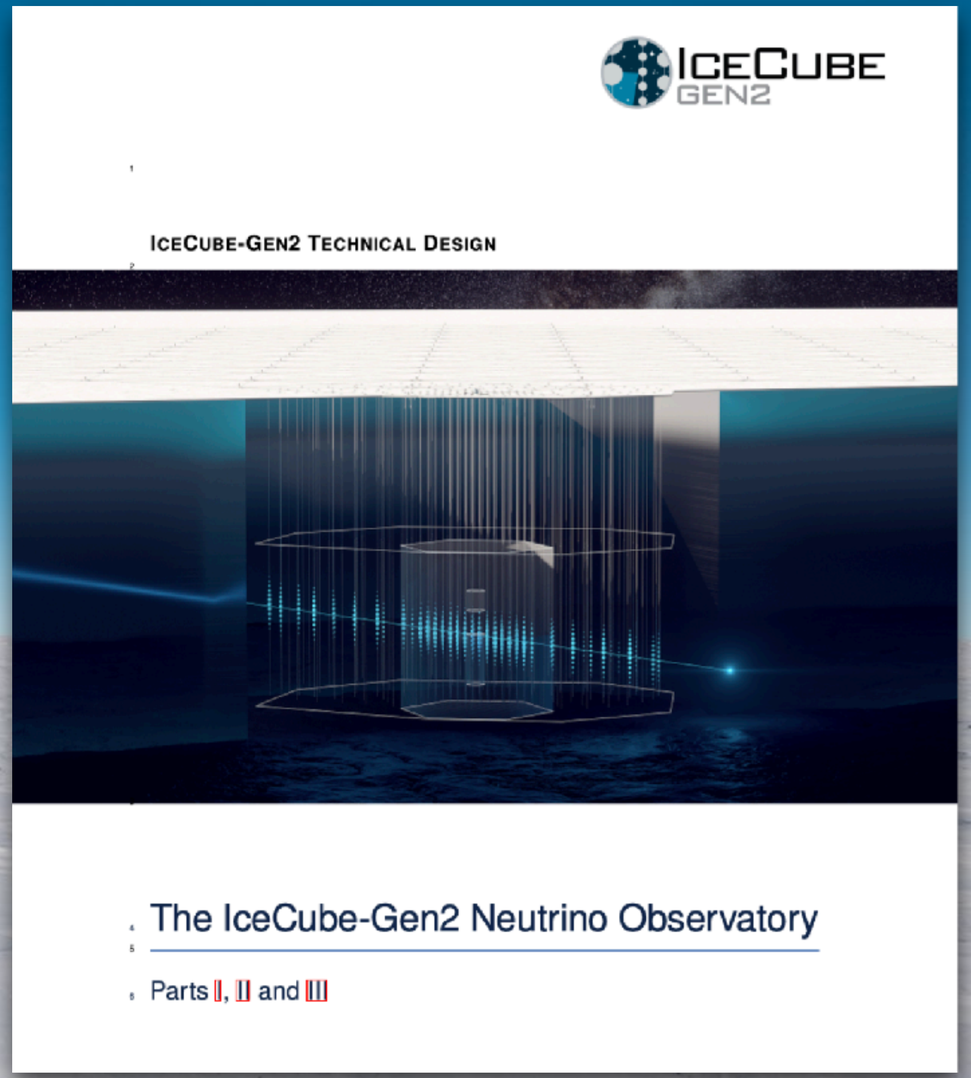




- Significant improvement with Anode & 8th dynode readout
- Wide dynamic range, 5,000 PEs/25ns each PMT
  - Prototype version already shows 2,000 PE/25ns, plan to extend to 5,000 PE /25ns by tuning electrical gain
  - Improvement in both energy and angular reconstruction expected

IceCube-Gen2 Technical Design Report

https://icecube-gen2.wisc.edu/science/publications/TDR




WARNING

Summary and Outlook

- Planned IceCube-Gen2 Optical Array requires Optical Modules to have the highest per-module sensitivity
- Proposed IceCube-Gen2 DOM designs expect to improve the sensitivity of IceCube DOM by a factor of 4
  - 16/18 4-inch PMTs in 12.5-inch pressure vessels
  - “Gel pad" approach is taken to reduce the module cost while keeping the optical performance
  - Electronics tuned for high energy neutrino events
- Fully functional module within this year, plan to deploy O(10) modules in the IceCube-Upgrade array (construction in 2025/26) to verify the design towards IceCube-Gen2