Development of an Optical Module for IceCube-Gen2

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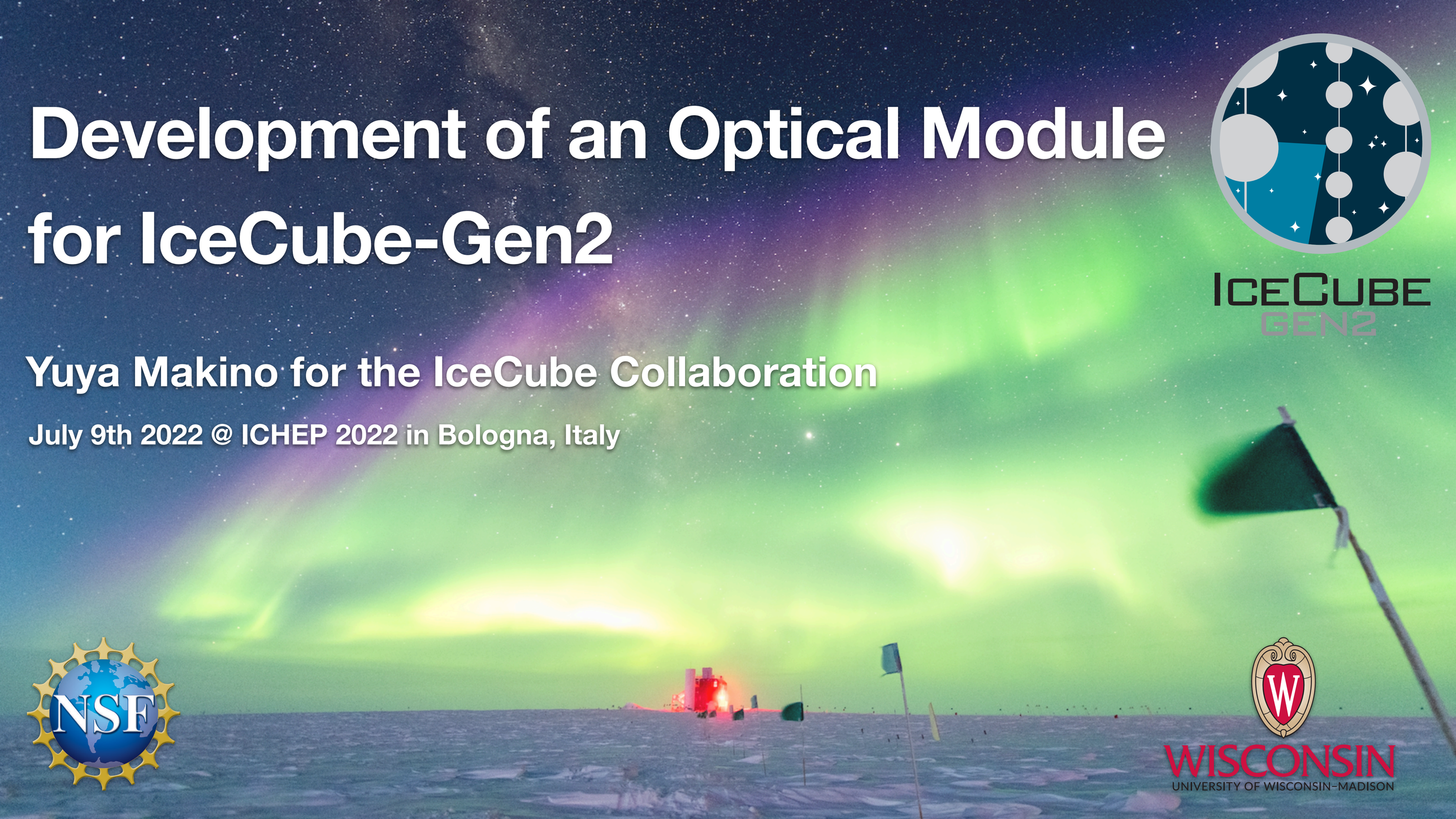
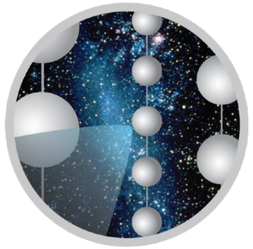
July 9th 2022 @ ICHEP 2022 in Bologna, Italy

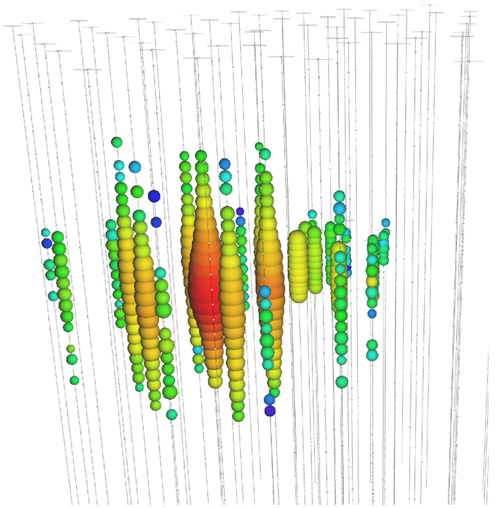


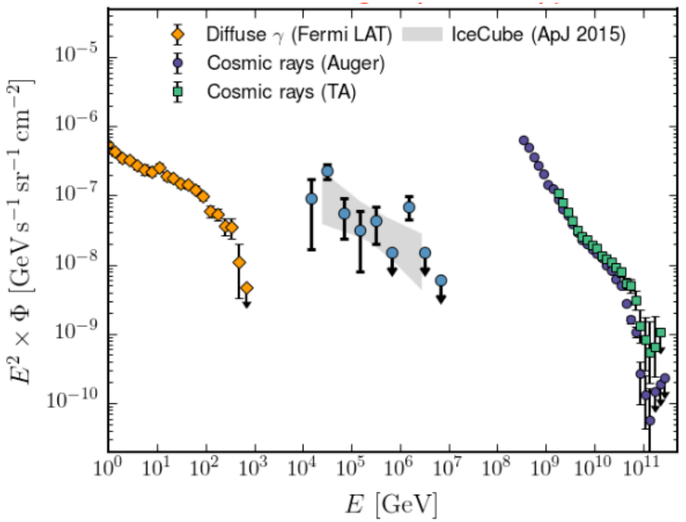
IceCube and IceCube-Gen2



ICECUBE

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

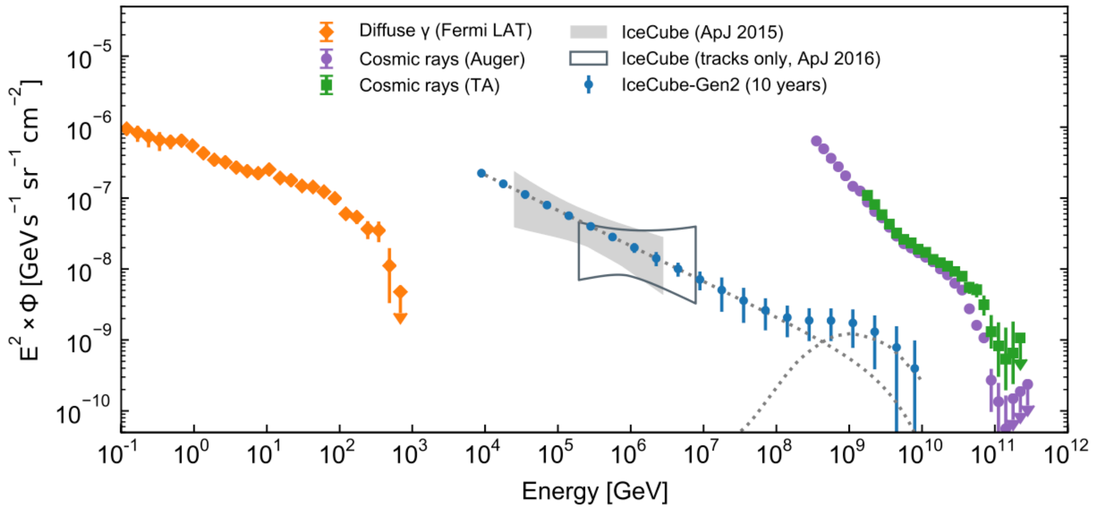




- Discovery of astrophysical neutrino flux (2013)
- Evidence for Blazars as neutrino sources (2018)
- First astrophysical tau neutrino measurements (2020)

ICECUBE GEN2

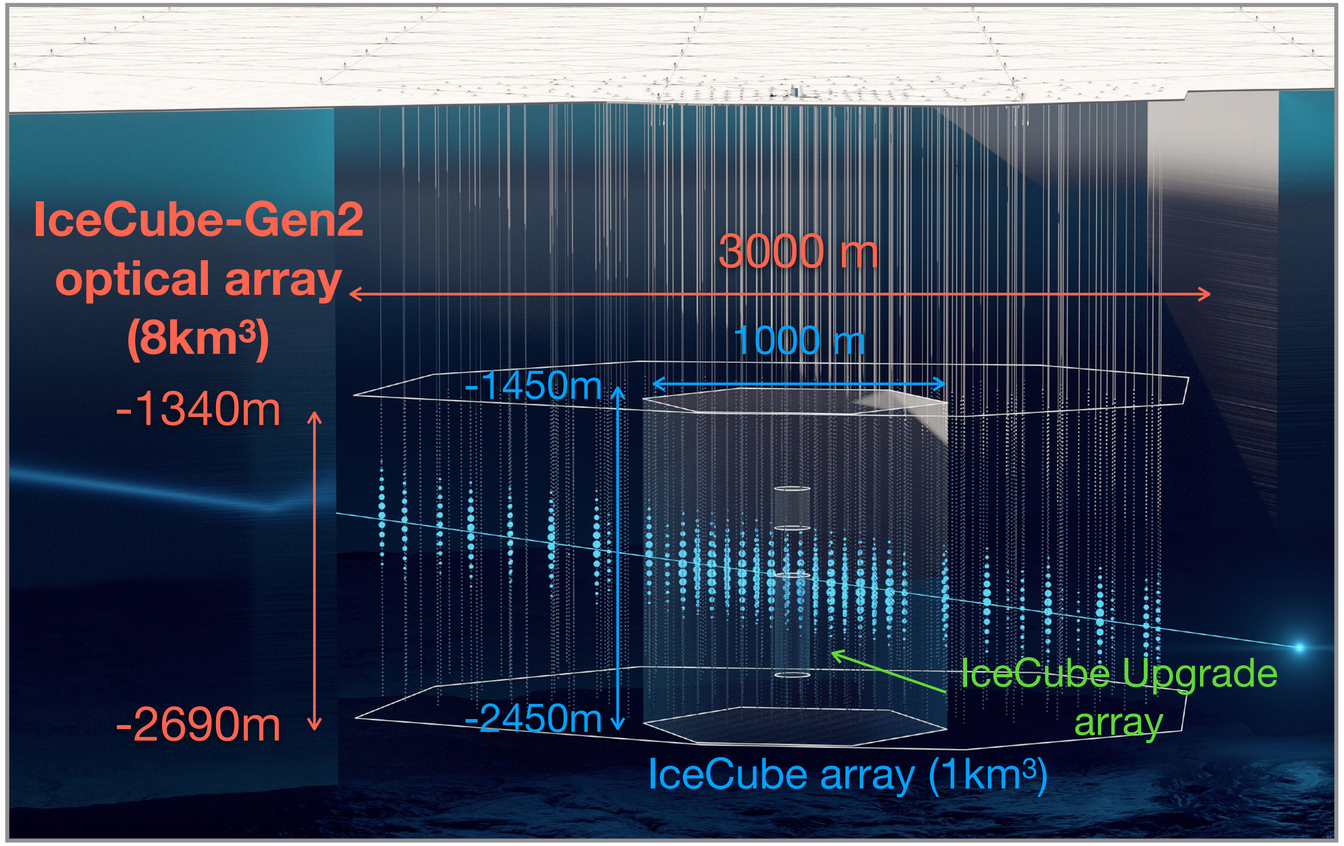
A high energy extension of IceCube
for the next decades of neutrino astronomy



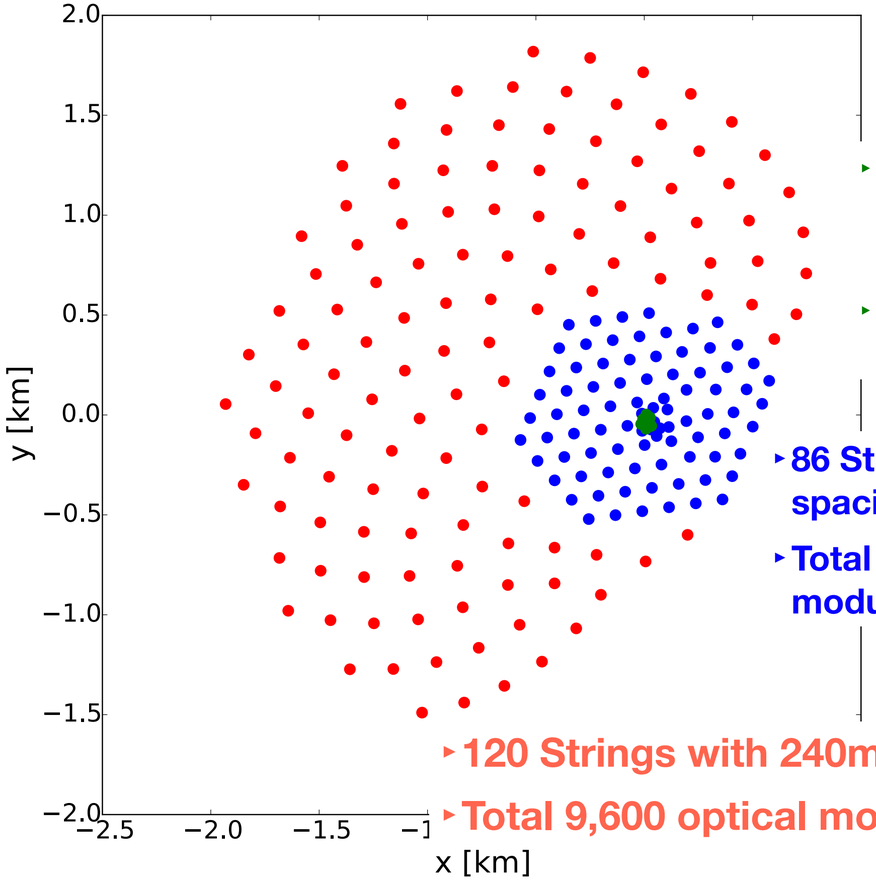
- From discovery to astronomy
- Aims 5x sensitivity from IceCube (>10x at >10TeV)
- Resolving high energy sky from TeV to EeV

IceCube-Gen2 Array

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



*Gen2 also plans surface & in-ice radio arrays *(J. Phys. G 48 2021)*

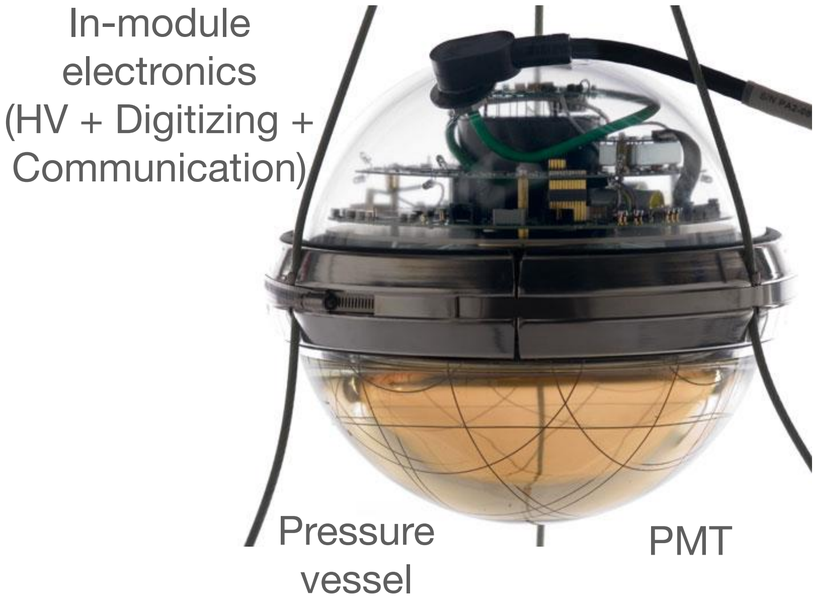


- Vertically & horizontally dense array with 7 Strings
- Total 700 optical modules
- **86 Strings with 125m spacing**
- **Total 5,160 optical modules (60/String)**
- **120 Strings with 240m spacing**
- **Total 9,600 optical modules (80/String)**

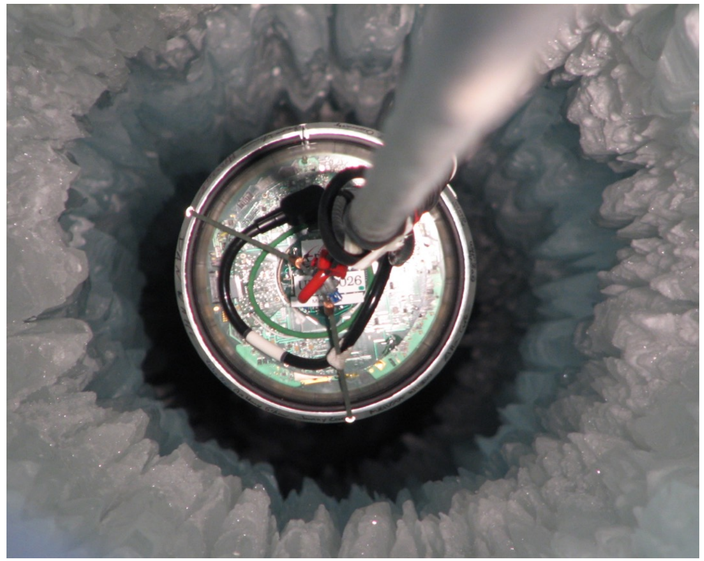
Improvement of Optical Module design is the key to success of IceCube-Gen2

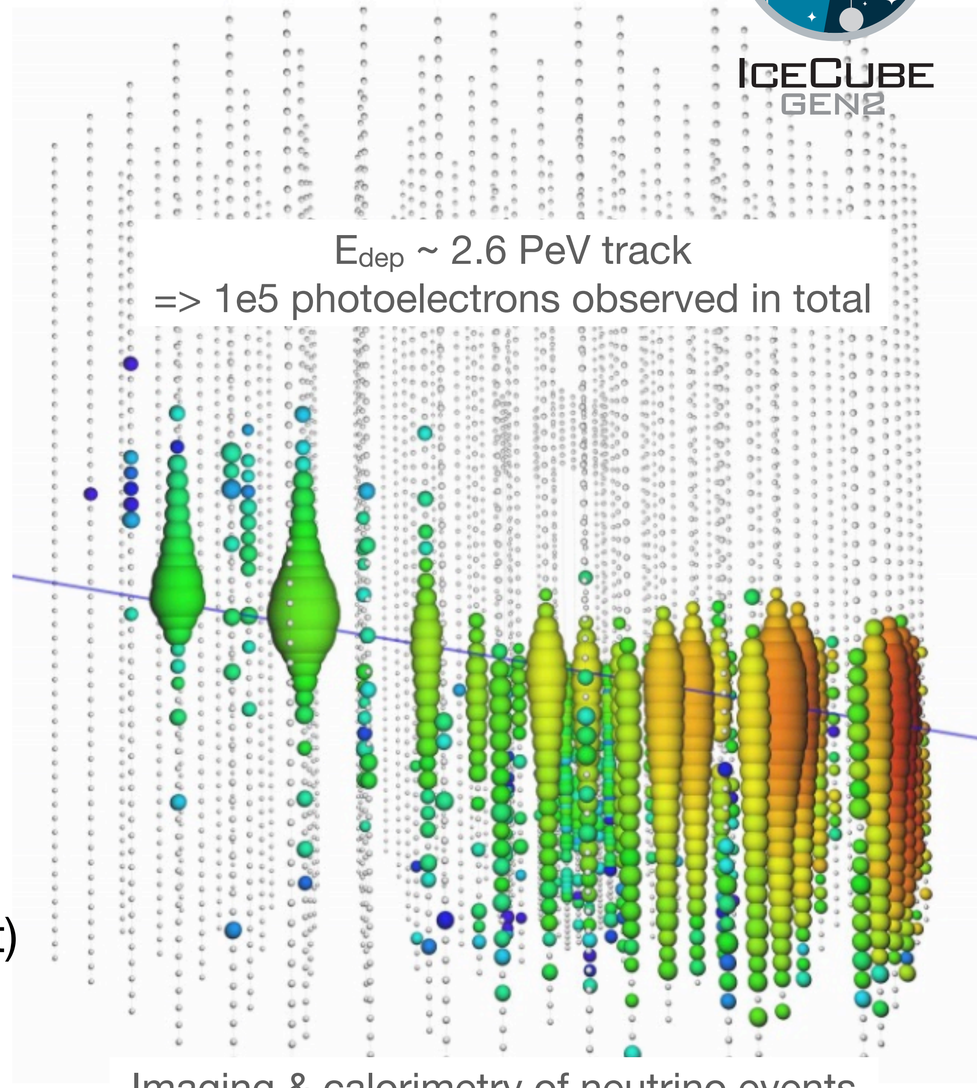
Optical Modules

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

Optical Module for IceCube-Gen2?

IceCube

IceCube DOM

10” PMT & dia. 33 cm

IceCube Upgrade

Low-energy extension & Ice calibration

Deployment scheduled in 2025/26 season

mDOM

24x 3” PMTs & dia. 36 cm

D-Egg

2x 8” HQE PMTs & dia. 30 cm

IceCube Gen2

High energy extension

Design report in preparation

>98% still in operation without problems after 10 years

- 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 Optical Module development is built on

- Successful design from IceCube
- Updates through IceCube-Upgrade

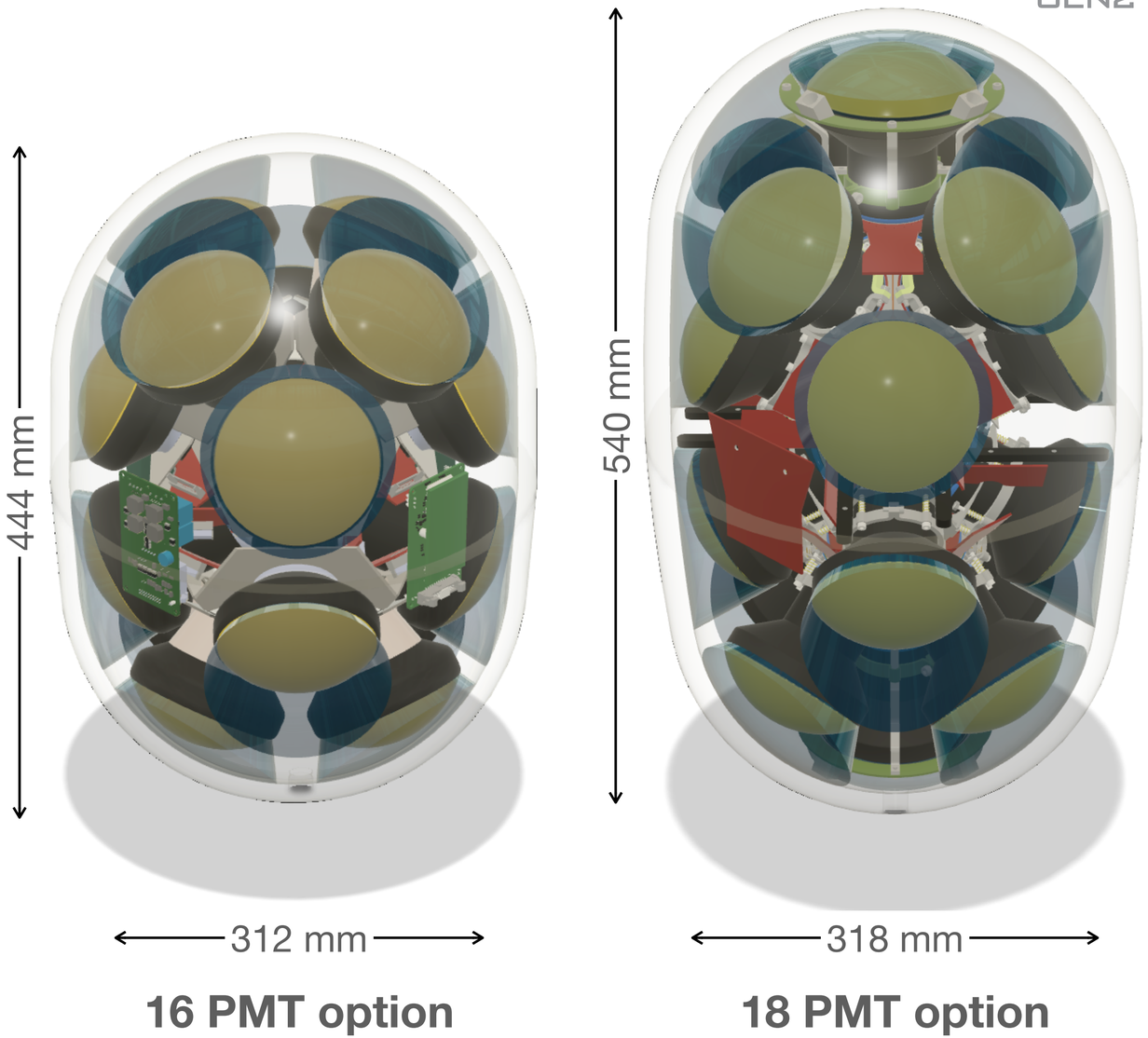
Design Goals

- What do we want for a neutrino telescope with 240m string-spacing and 8km^3 volume
  - Large photo effective area targeting > 3.0 x 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 less than 12.5” to suppress the drilling cost <= 13” for IceCube DOM
  - Low power consumption, aiming 4W/module <= 5.7 W for IceCube DOM

- The biggest challenge is >3.0x IceCube DOM performance with a smaller size
  - Maximize the inner volume for more photosensors -> Non spherical pressure vessel
  - Larger photocathode, but smaller PMTs to maximize effective area and achieve 4pi coverage

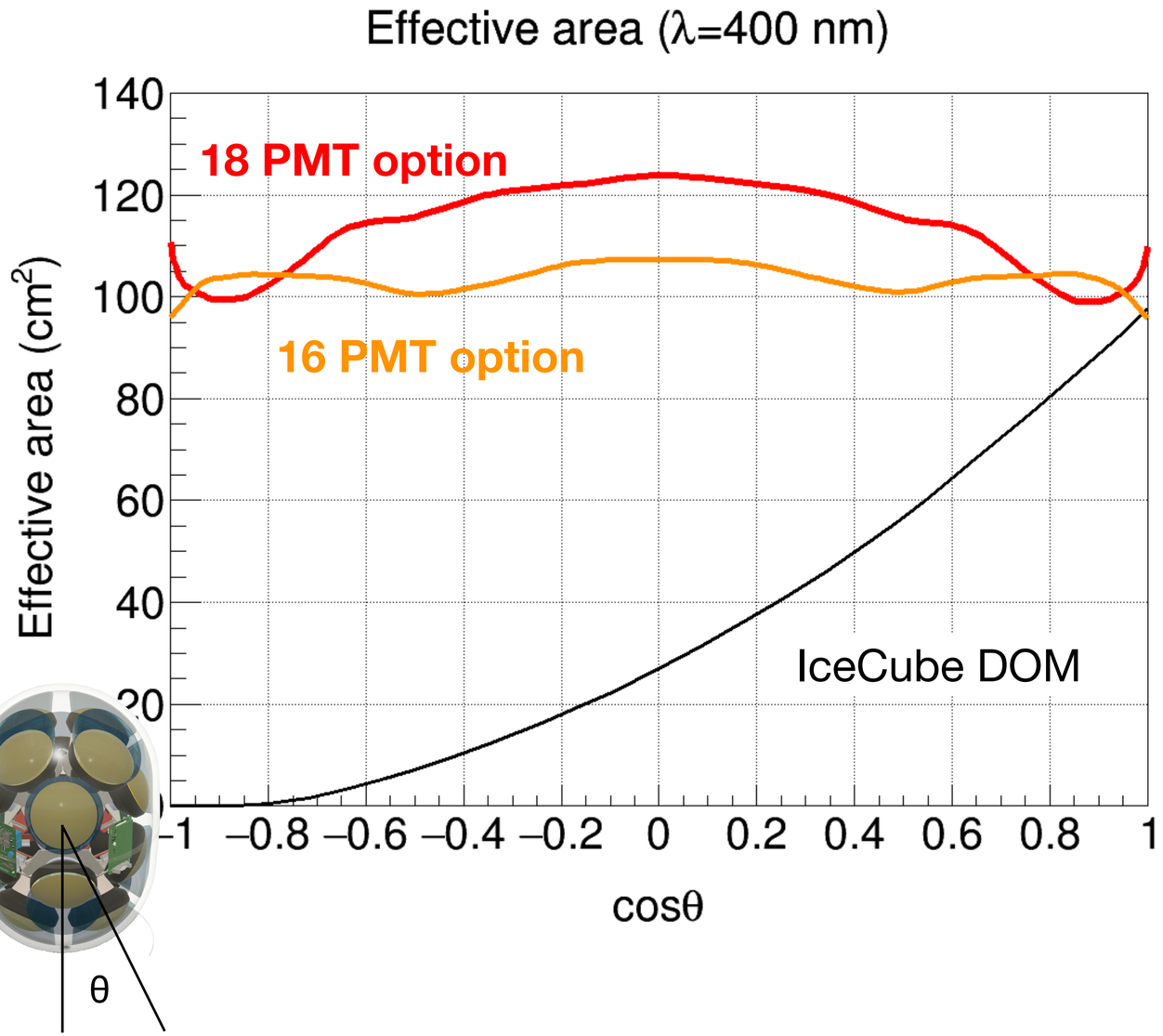
Gen2 Optical Module Design Candidates

- Two design candidates; 16 and 18 PMT options
  - Custom non-spherical pressure vessels
- 4” PMT is the best pick to maximize effective area
  - Back-to-back layout not feasible with > 4” PMTs
  - (*) Does not exist in the current lineups of PMT vendors
- PMTs are coupled to pressure vessels with “gel pads”
  - Cone shape enhances the effective area
- Custom electronics designed for Gen2 needs
  - Tuned for high energy events (dynamic range)
  - Low power consumption (infrastructure)
  - In-module data buffering (bandwidth)



16 PMT option **18 PMT option**

Expected Performances

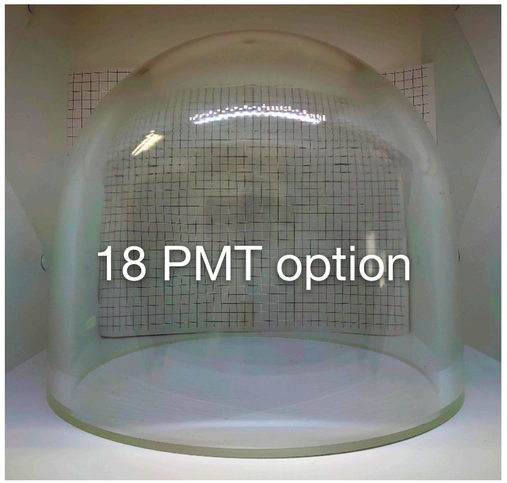


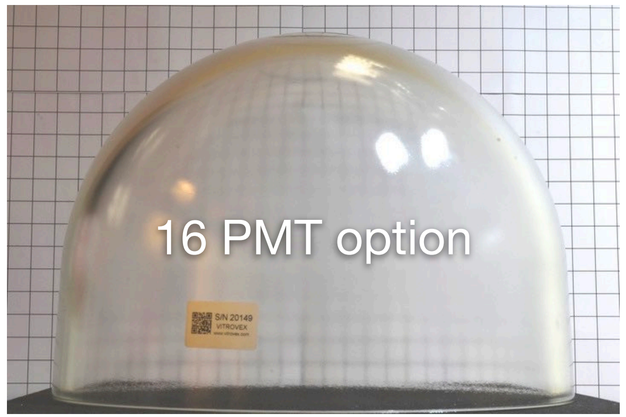
- 16/18 PMT options show 3.1/3.5x better effective areas compared to IceCube DOM
  - Estimated by Geant4-based simulation
  - Measured pressure vessel and gel transparencies, and PMT responses (e.g. photo detection efficiency as a function of photocathode positions) are taken into account
- Great improvements in the horizontal directions
  - Critical considering the 240m inter-string spacing

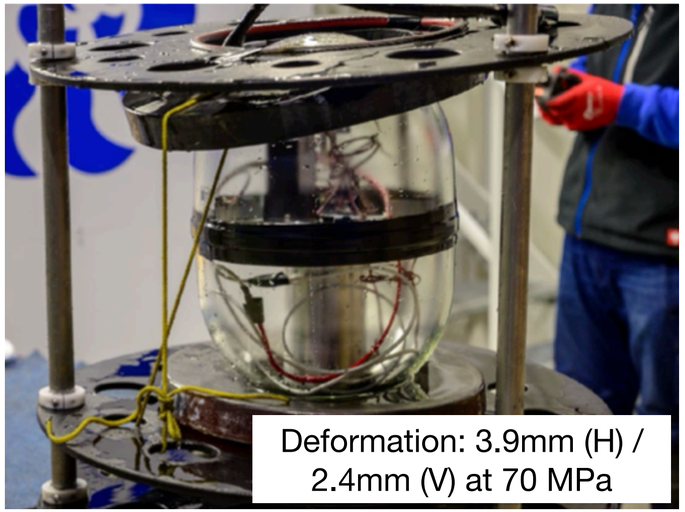
Pressure Vessels

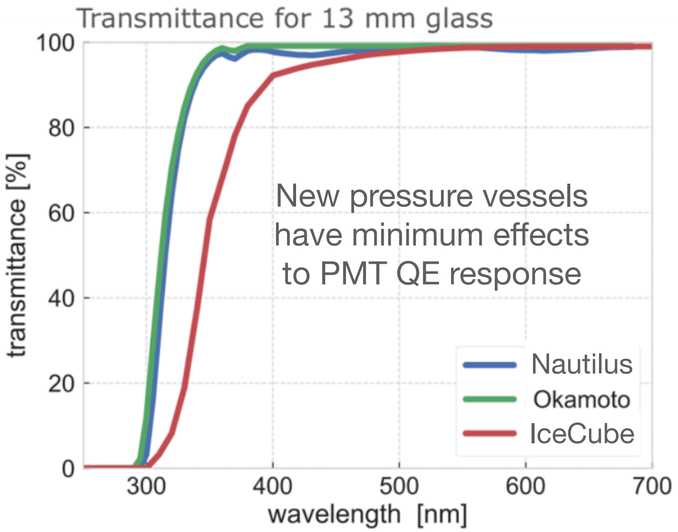
Diameter < 12.5” / 70 MPa rated / high UV transmittance / radioactivity as low as possible

- Two vendors: Okamoto (Japan) & Nautilus (Germany)
  - Since IceCube Upgrade
  - Keep-multiple-vendors strategy for essential components in Gen2
- Improved optical performances
  - >50% transmittance at 320 nm
  - Reduced K^{40}: 0.74 Bq/kg (Okamoto)
- Pressure rating have been proved with prototypes
- New harness design studies to minimize PMT-shadowing effect





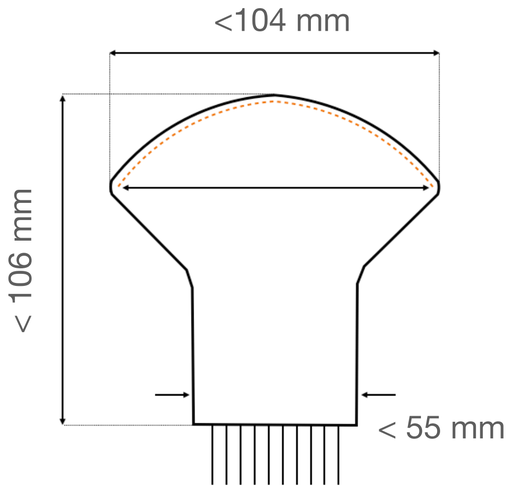




4 inch PMT

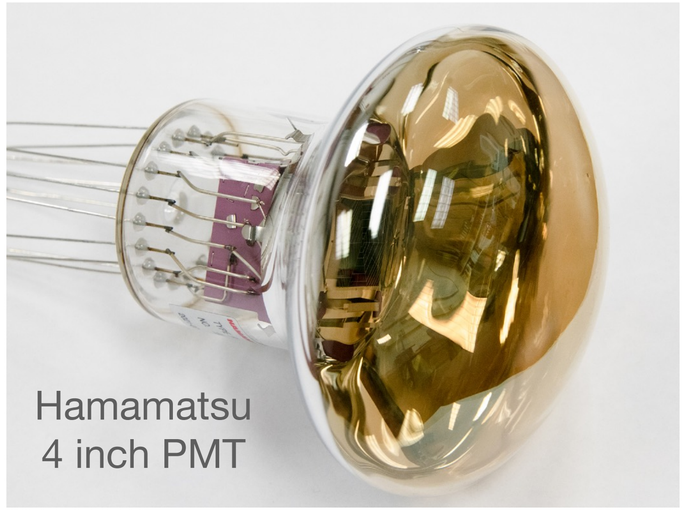
As short as possible accepting minimum compromise in performance

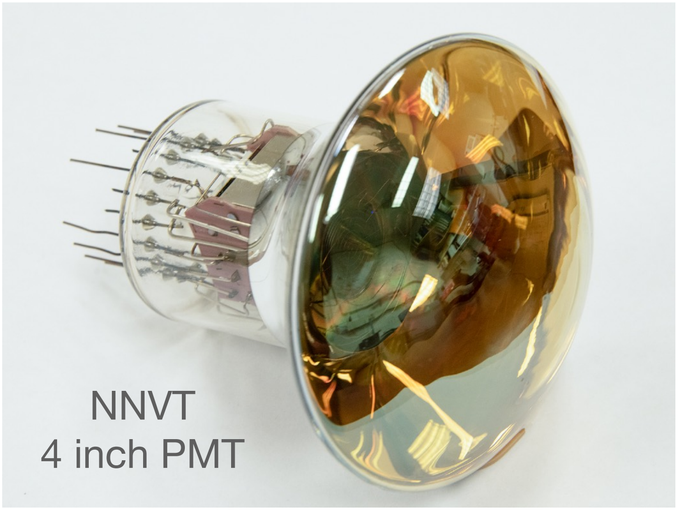
- Two vendors: Hamamatsu and North Night Vision Technology (NNVT)
  - Newly-designed 4inch box&line style dynode PMTs
  - NNVT has produced 15,000pcs 20” MCP-PMTs for JUNO
  - Keep multiple vendors for for Gen2!
- Very compact, 106mm (abs max.) long
  - (Potential) Caveat is moderate cathode uniformity (transit time and/or collection efficiency, for example)
- Confirmed prototypes from both vendors meet the requirements
  - Development/Improvement still ongoing
  - No public plots/numbers yet



Target numbers

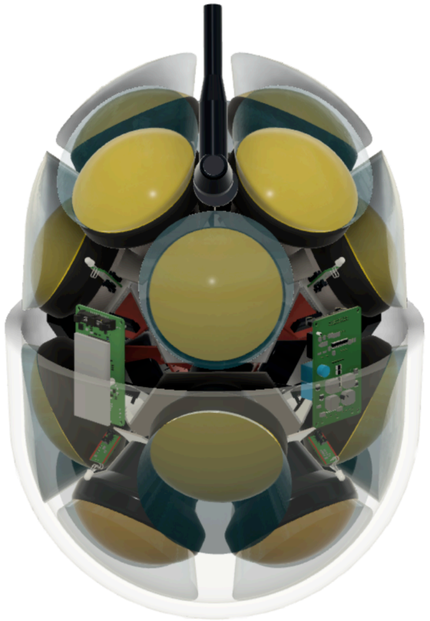
Parameter	Target value
Gain	5e6 @ <1500V
Transit Time Spread	< 8ns (FWHM)
Peak/Valley	>2
QE	>25% @400nm
Pre/late/after pulses	Less than 1/5/10%





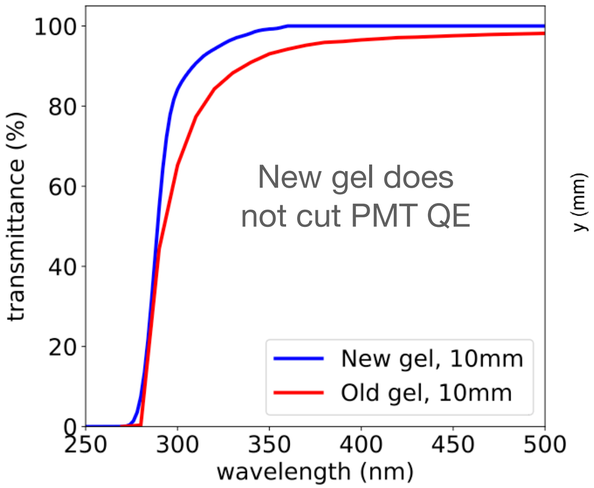
PMT Optical Coupling

- Silicone gel optically couples PMTs and pressure vessel
  - ShinEtsu X3547-HE developed for IceCube-Upgrade
  - High UV transmittance & good performance at low temp
- Investigating “gel pad” approach
  - Pre-casted gel on a PMT unlike conventional in-place potting styles used in other Optical Modules (original idea based on NIM A 958 (2020))
  - Alternative idea to avoid expensive (3D-printed) support structures
- Gel pad works as a photon collector, +65% effective area confirmed compared to a bare PMT
  - No reflector, but use total reflection at the cone surface
  - Lab measurement showed a good agreement with the simulation prediction



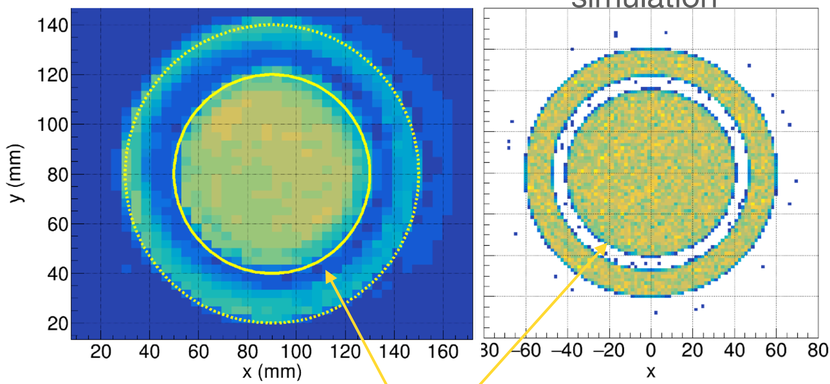
Gel pad on a 3” PMT

Curve matches the inner wall of pressure vessel



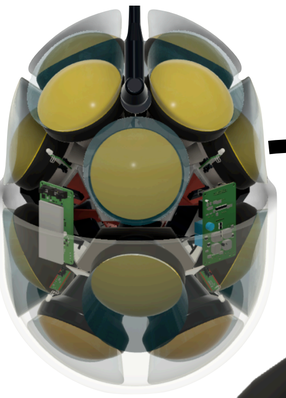
Lab measurement

Expectation from simulation

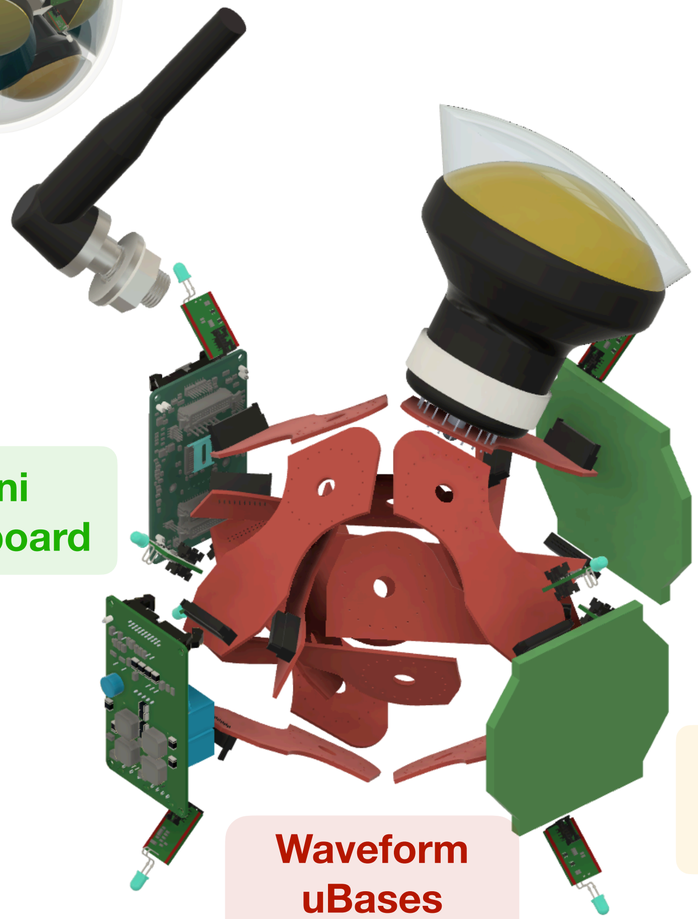


Gap is an artifact due to the prototype gel pad shape

In-Module Electronics



Electronics only



Mini mainboard

Waveform uBases (wuBases)

Fanout boards

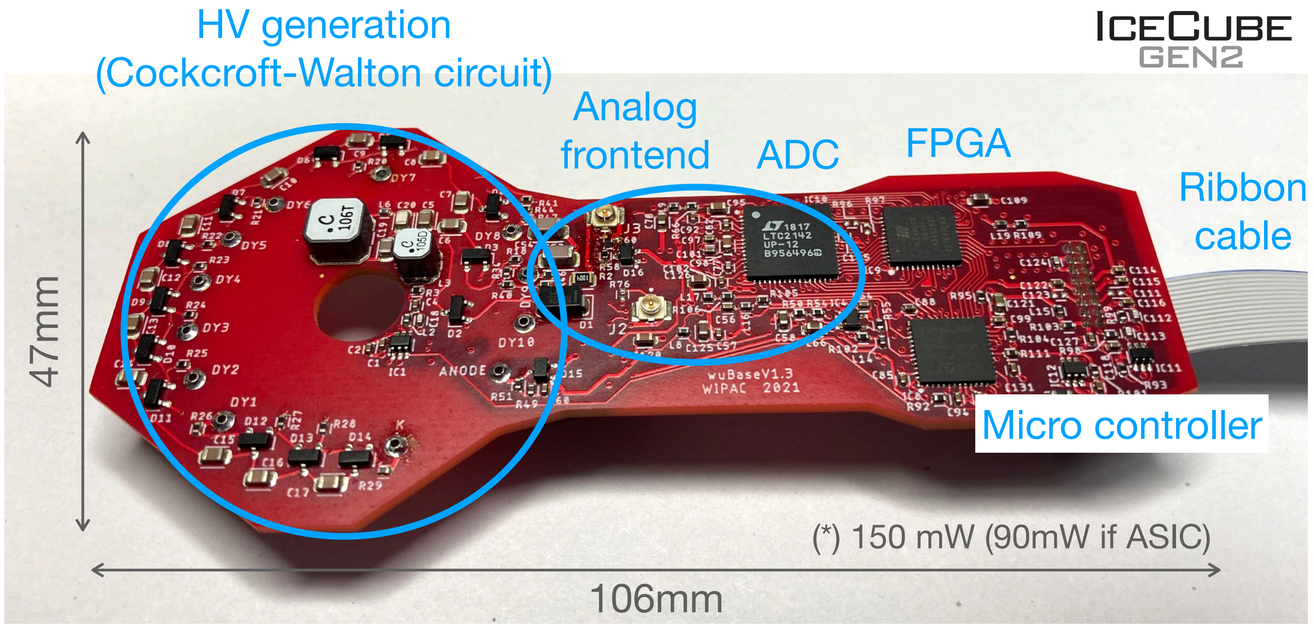
Limited space, Low power consumption,
Dynamic range from SPE to highest energy neutrino events

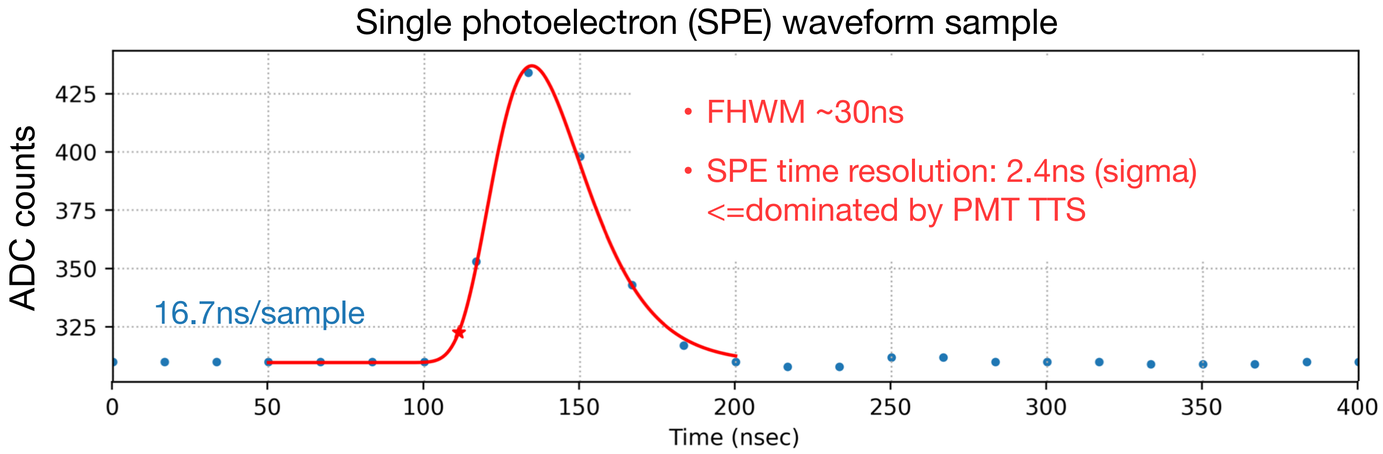
- Combination of specialized boards instead of a “big&central” board
  - Good match with the limited available space & No need for big / resource-expensive FPGAs
  - Re-purposing existing solutions from IceCube Upgrade
- Functionalities
  - Generate/regulate HV to each PMT
  - Digitization of signal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

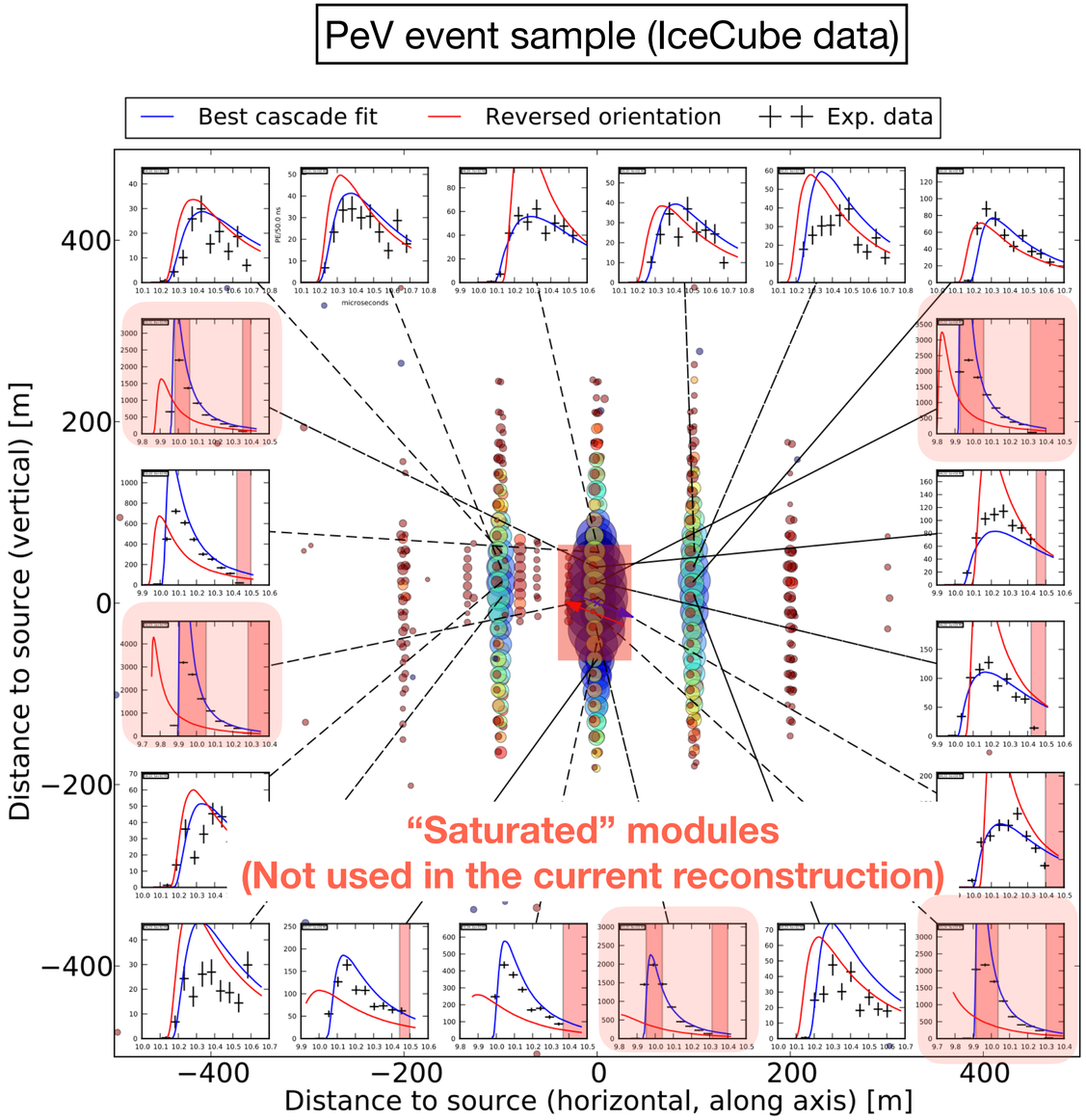
Waveform MicroBase

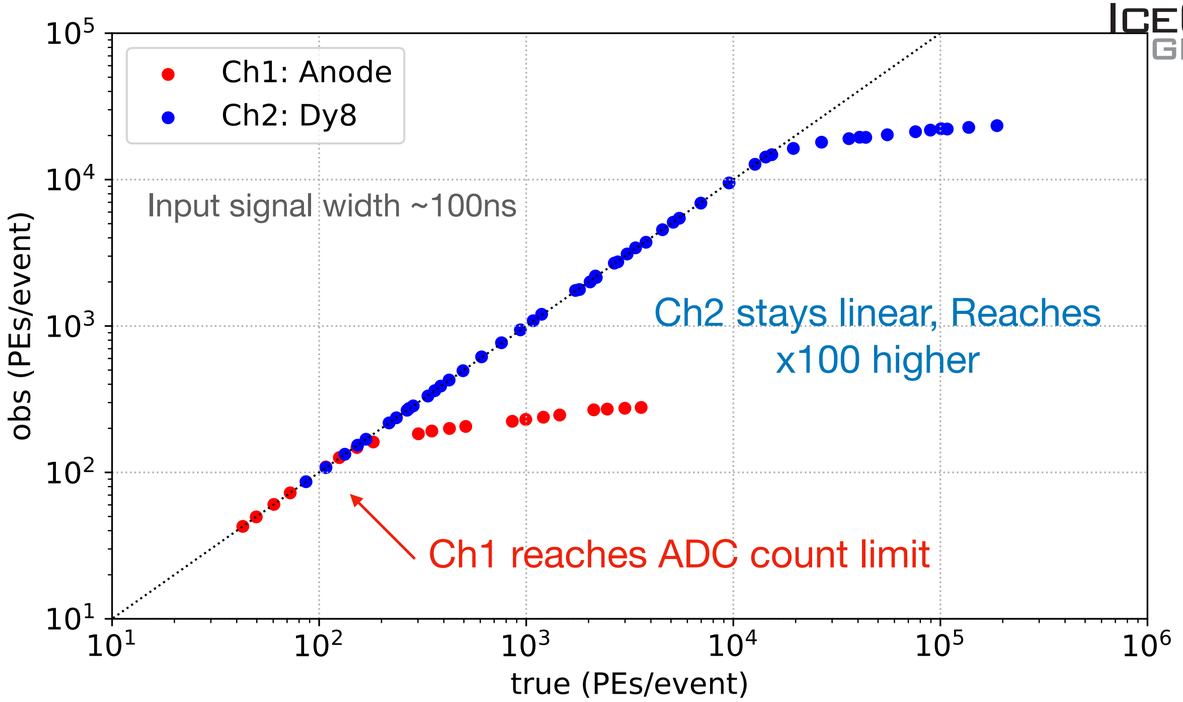
- Add DAQ feature to the existing custom HV base
  - HV base developed for the IceCube-Upgrade project
    - MicroBase (ref: PoS(ICRC2021) 1070)
  - Ribbon cable for controlling and data transfer
- DAQ functionalities
  - Continuous digitizing with 2-channel 12 bit ADC at 60MSPS and captured in a low-power 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





Specialized for high energy events





- Significant improvement with Anode & 8th dynode readout with 12 bit ADCs
  - IceCube DOM's main ADC: 3ch (all see anode, different gains), 10bit
- Confirmed dynamic range from SPE to 10,000 PEs/PMT
  - Response remains linear for even nearby PeV-class neutrino events
  - Improvement in both energy and angular reconstruction expected

Summary

- IceCube-Gen2 aims improved sensitivity from IceCube for the next decades of nu astronomy
  - <10x improvement at PeV
  - 120 Strings and 9,600 modules over a 8 km^3 instrumented volume
- Factor 3 improvement of effective area & smaller diameter required
- 16/18 x 4” PMTs in a non-spherical 70MPa-rated pressure vessel
  - Geant4-based study shows current designs have 3.1-3.5x improvement compared to IceCube DOM
  - Repurpose/update from the existing solutions from IceCube and IceCube Upgrade developments
  - Prototypes have been tested for all components as of summer 2022
  - Custom electronics tuned for high energy events
- First integration test planned early next year. Planning to deploy prototype modules at the South Pole as a part of IceCube-Upgrade in 2025/26
  - 12 modules outside the “physics region” of the array as proof of concept towards IceCube-Gen2
  - In-situ calibration with calibrated light sources of the Upgrade array