The IceCube Upgrade & IceCube-Gen2

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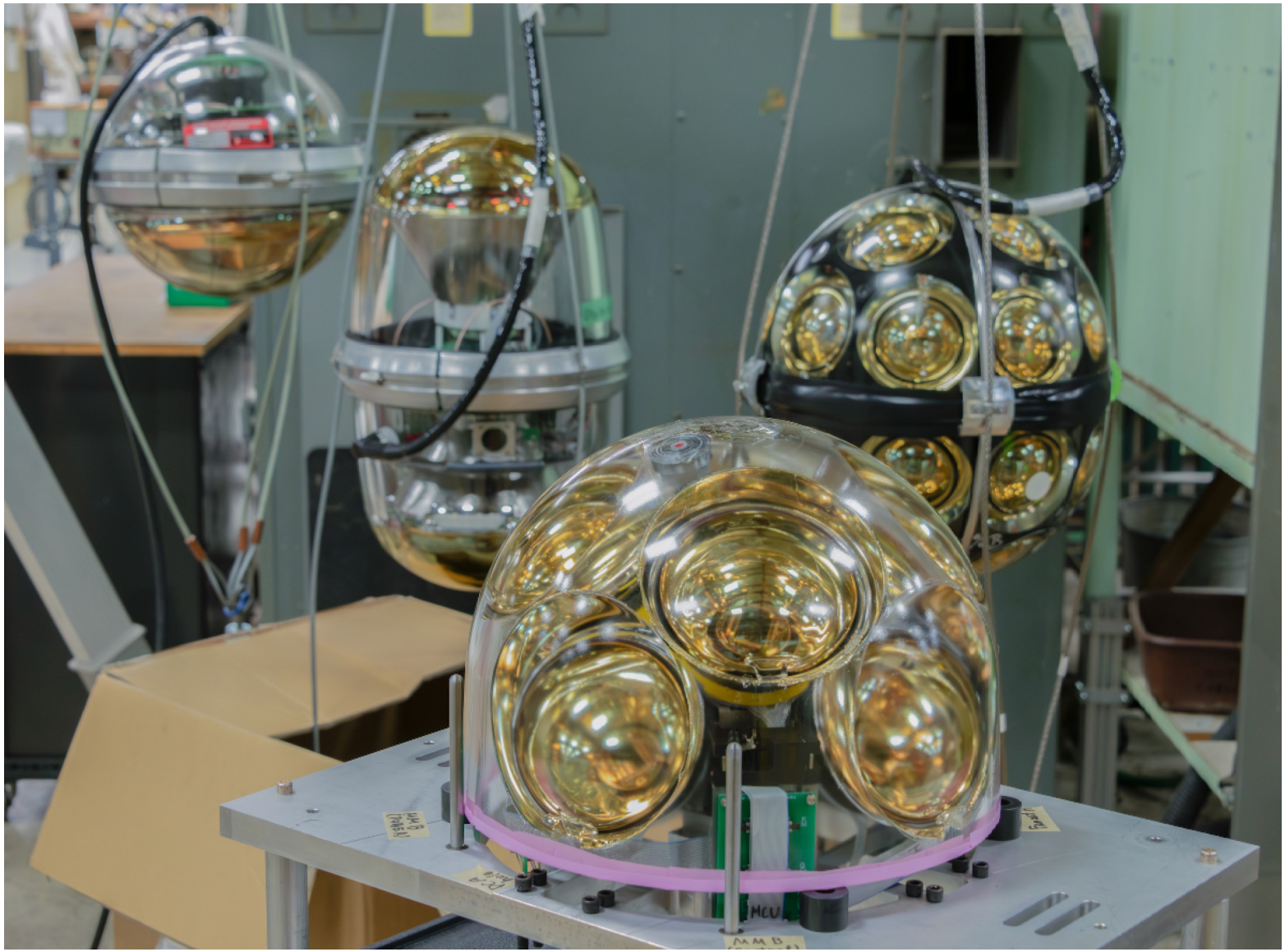
Introduction

Gen1
DOM

D-Egg

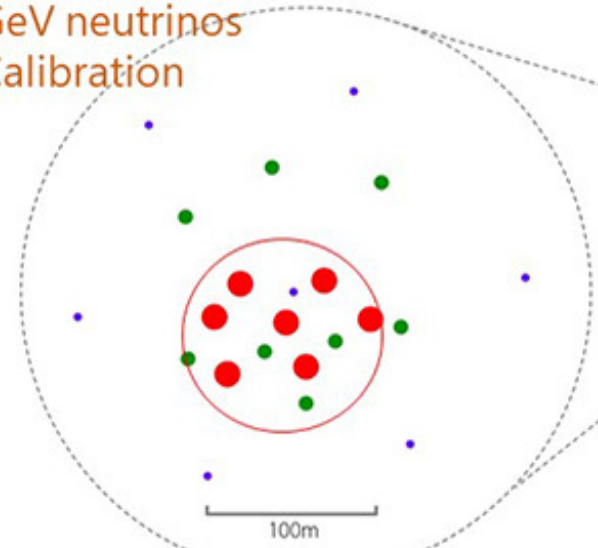


mDOM

LOM, or
Gen2 DOM

IceCube Upgrade (planned 2023-)

Optimized for
- GeV neutrinos
- Calibration

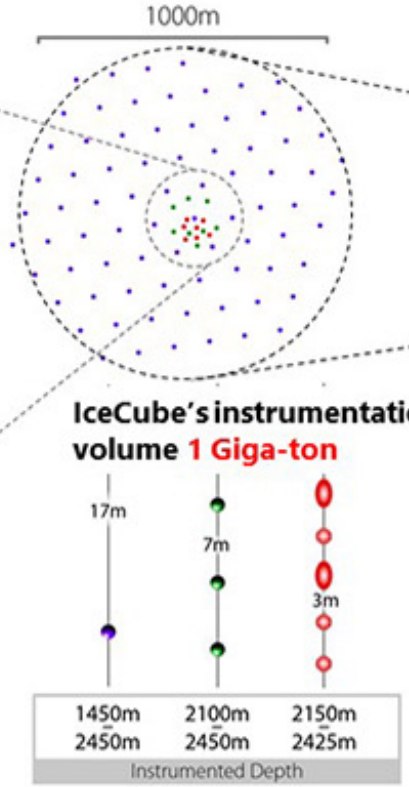


inner fiducial volume 2.2Mega-ton

IceCube DeepCore Upgrade

IceCube (2005-)

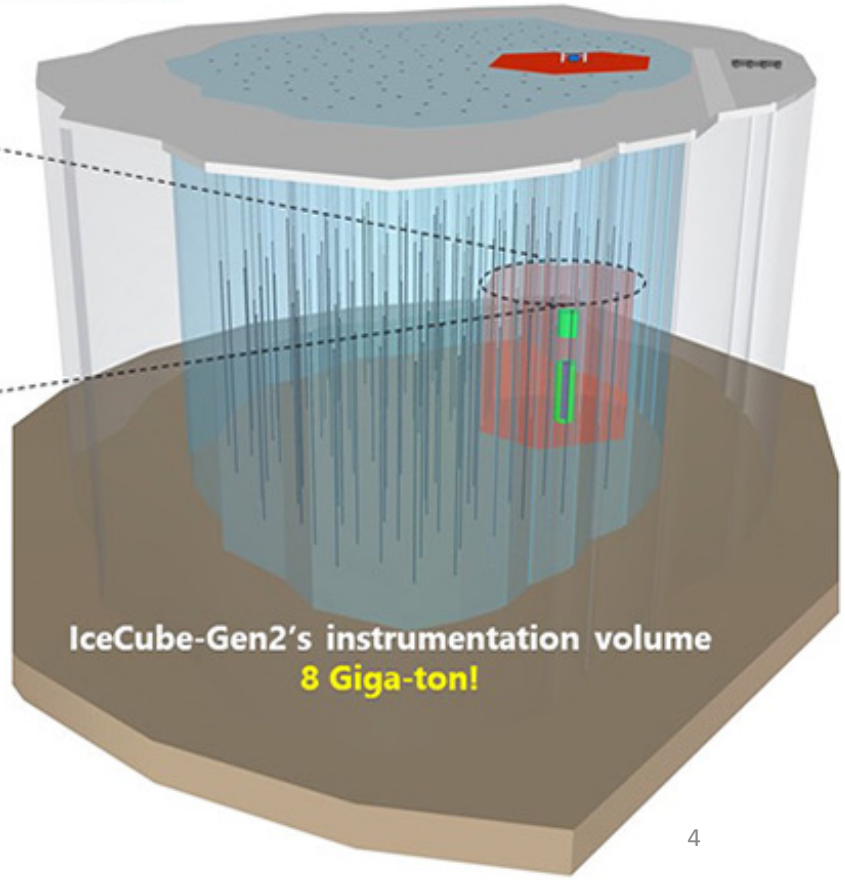
Optimized for
- Diffuse high energy cosmic neutrinos



IceCube's instrumentation volume 1 Giga-ton

IceCube-Gen2 (planned 2026-)

Optimized for
- Cosmic neutrino point sources

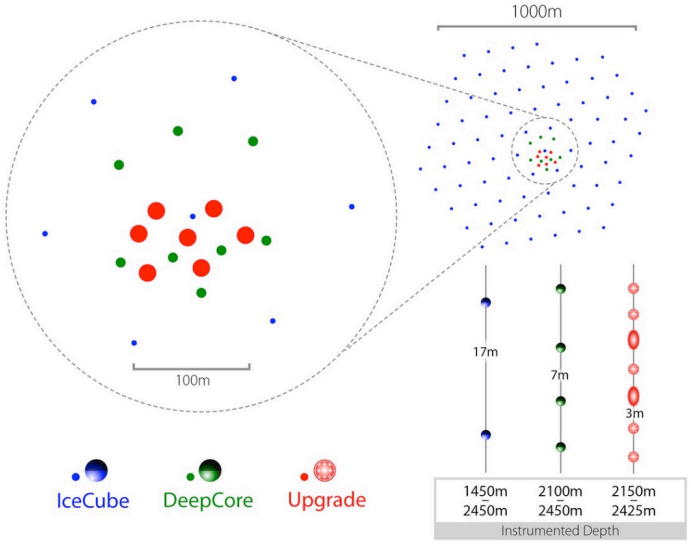


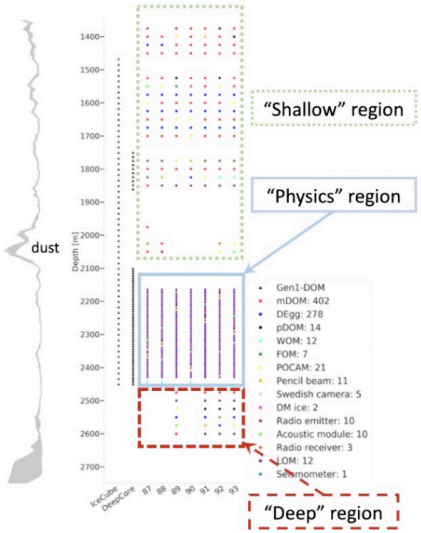
IceCube Upgrade

IceCube Upgrade Project Scope

- Neutrino Oscillation Physics (“Physics”)
  - Primarily with a dense array of photosensor modules in the deep, clear ice
  - Modules of two types (D-Egg and mDOM)
- Ice & Detector Calibration Improvements (“Calibration”)
  - Enhances the science return of the full IceCube array, including prior data
  - Devices on each optical module (cameras, LED pulsers, inclinometers, etc.) and stand-alone modules (POCAM, Pencil beam, Acoustics, pDOM)
- Research & Development toward Gen2 IceCube (“R&D”)
  - Small numbers of various R&D sensors, potential optical modules, test stands for radio detection, and tools for managing the Gen2 strings
- And in order to build this array, we require the drill & installation system with three Field Seasons (FS1-FS3) on the ice in 2023-24, 2024-25, & 2025-26

Project Scope





Type	String	87	88	89	90	91	92	93	Total
Optical modules	mDOM	58	58	57	53	60	58	58	402
680	D-Egg	39	40	40	40	40	39	40	278
devices	POCAM	2	2	5	3	2	3	4	21
47	Pencil Beam (PB)	1	2	1	2	3	1	1	11
	Acoustic Module (AM)	2	1	2	1	1	1	2	10
	Swedish Camera (SWE)	1	1	0	1	0	1	1	5
R&D devices	pDOM	1	1	2	1	2	4	3	14
61	Long Optical Module (LOM)	0	1	2	1	3	3	2	12
	DM-ice	0	1	0	1	0	0	0	2
	Radio Pulser (RP)	2	1	1	5	0	0	1	10
	Radio Receiver (RR)	1	0	0	0	0	2	0	3
	Wavelength-shifting Optical Module (W	4	3	0	3	0	1	1	12
	Fiber-optic Optical Module (FOM)	2	1	1	0	1	1	1	7
	Seismometer (SM)	1	0	0	0	0	0	0	1
Pressure sensors	Paro Pressure Sensor	1	1	1	1	1	1	1	7
ALL	ALL	115	113	112	112	113	115	115	795

Minor revision undergoing for calibration/special devices placement in strings (very small changes)

Load on each string is calculated specifically on the properties of various sensors.
Max load on sensors: 850 kg
Max load on cables: 1460 kg

7 strings of detector embedded within current DeepCore / IceCube strings

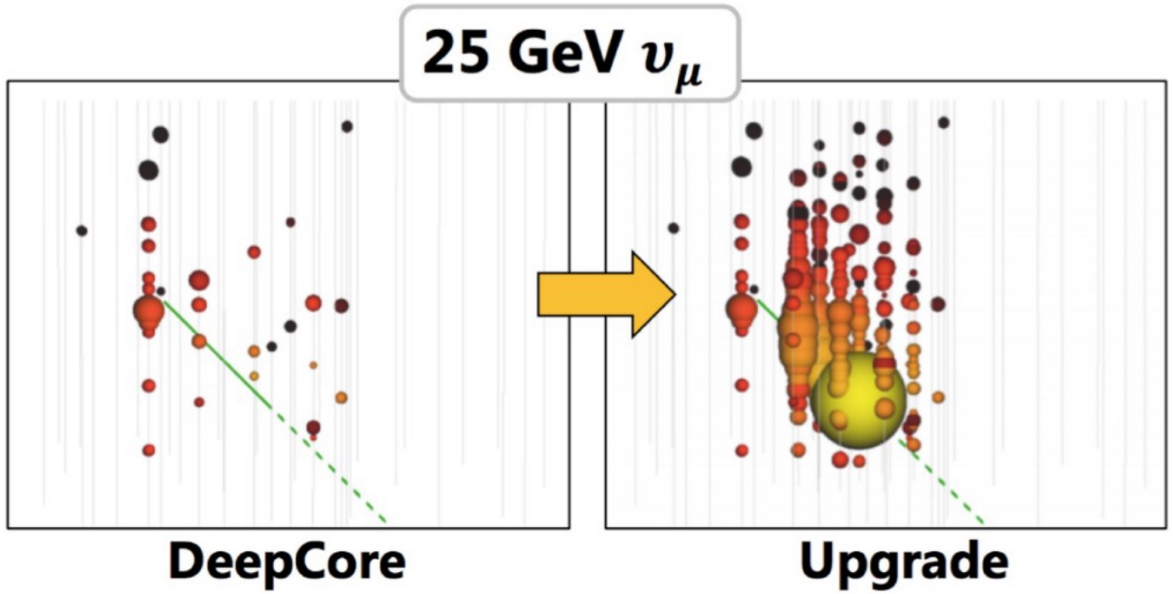
693 Optical sensors:

- 278 D-Eggs (2x 8" PMT)
- 14 PDOMs
- Readout through IceCube DAQ
- 402 mDOMs (24x 3" PMT)
- Calibration devices
- Common communications (ICM board)

Additional objectives/devices:

- R&D modules
- Measurements of the ice properties

Low energy neutrinos in the Upgrade

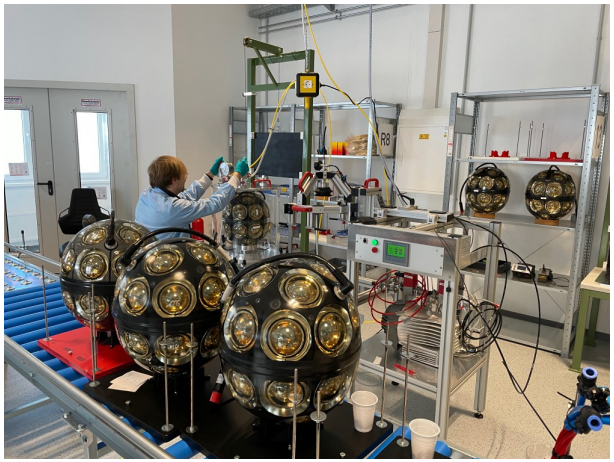


Deep-ice Sensor Modules

D-Eggs awaiting FAT

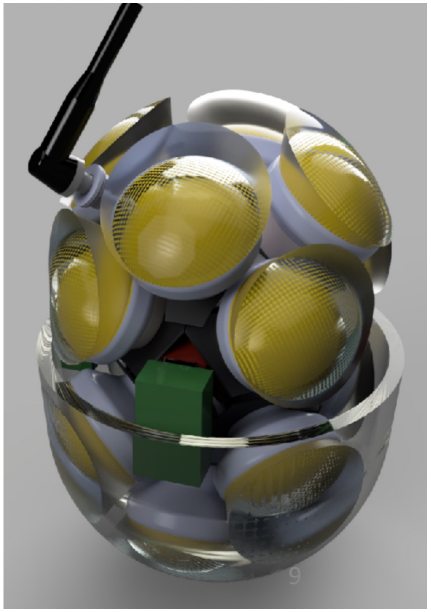
D-Egg Dark Freezer Lab
Modules are in the boxes

mDOM integration



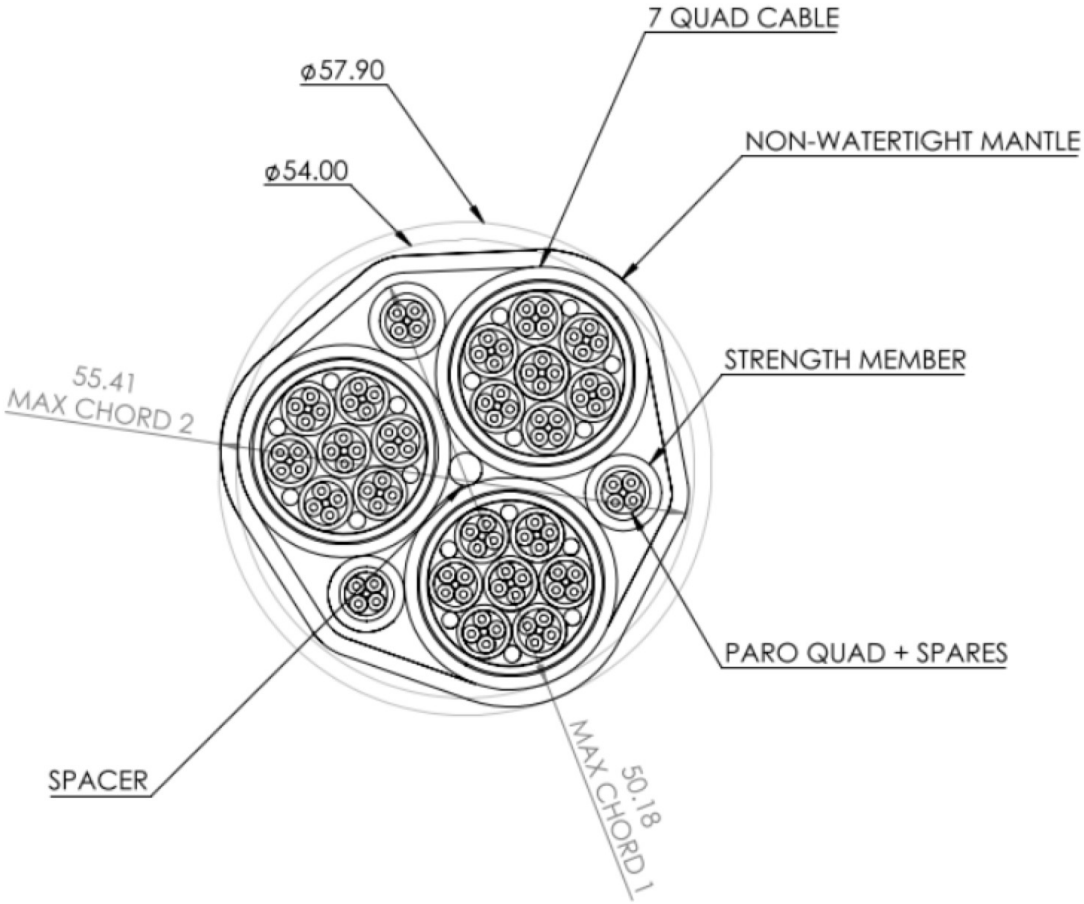
WOM prototype

LOM-16 model



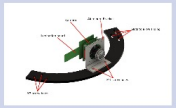
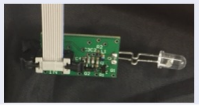
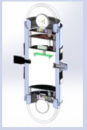
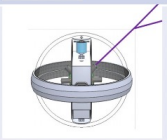

DVT

Main Cable Cross-section



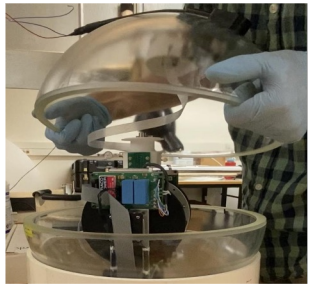
Upgrade Calibration Goals

1. Upgrade timing and geometry measurements
2. DOM optical efficiency determination *in situ* to better than 3%
3. 2x reduction in uncertainty due to refrozen hole ice
4. Determine the source and depth dependence of anisotropy in optical scattering in bulk ice
5. Measure acoustic properties of bulk ice for Gen2
6. Measure properties of ice below IceCube instrumented volume

Device	Goal
Cameras 	3
Flashers 	1, 6
POCAM 	2, 3, 6
PencilBeam 	4, 6
Acoustic Modules 	5, 6
Dust Logger	4, 6

Calibration Devices in the Upgrade

Precision Optical Calibration Module (POCAM) (21)



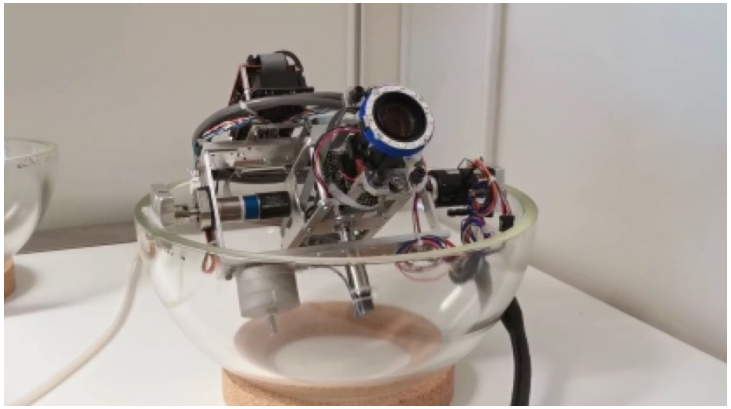
PencilBeam (11)

Onboard D-eggs, mDOMs and pDOMs:

- LED flashers
- Fixed focus cameras and illumination LEDs
- Mainboard-mounted magnetometers and accelerometers

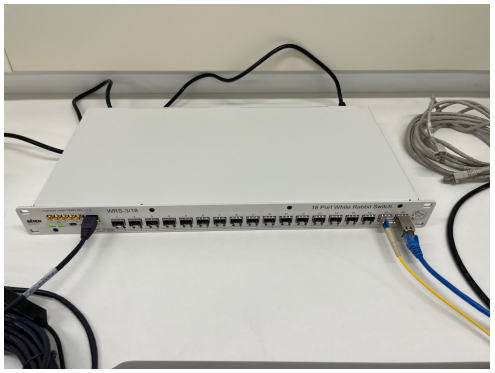
Acoustic Module (10)

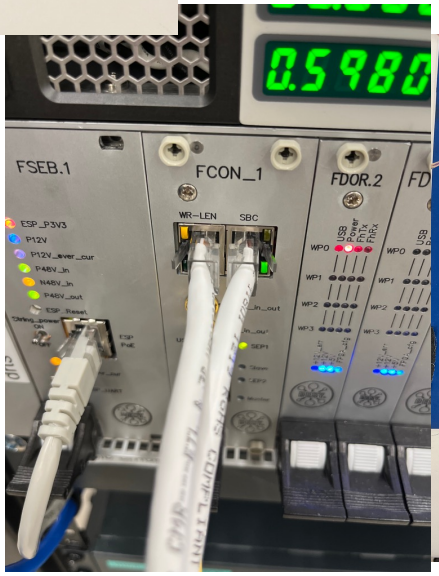
Pointable, zoomable camera

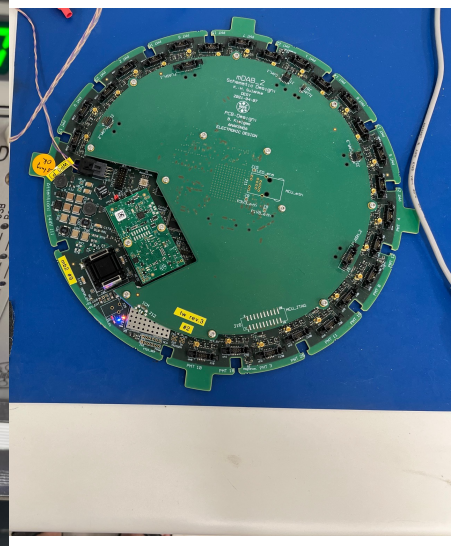


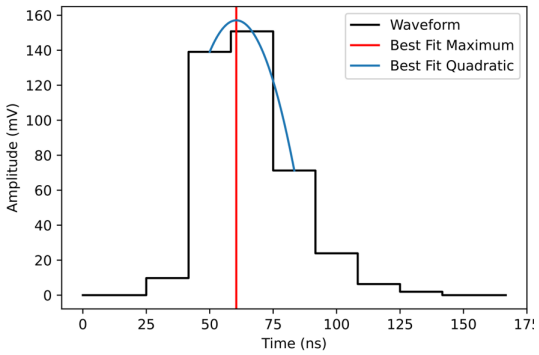
Sweden Camera 2.0 (5)

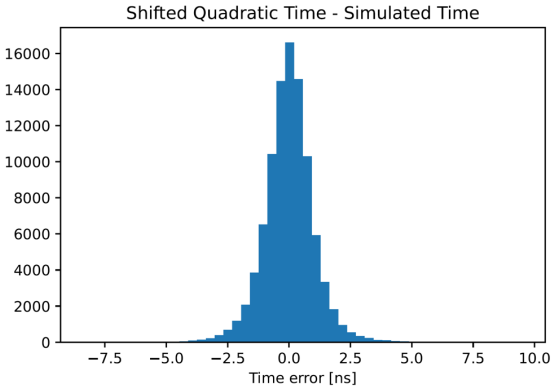
Surface bits









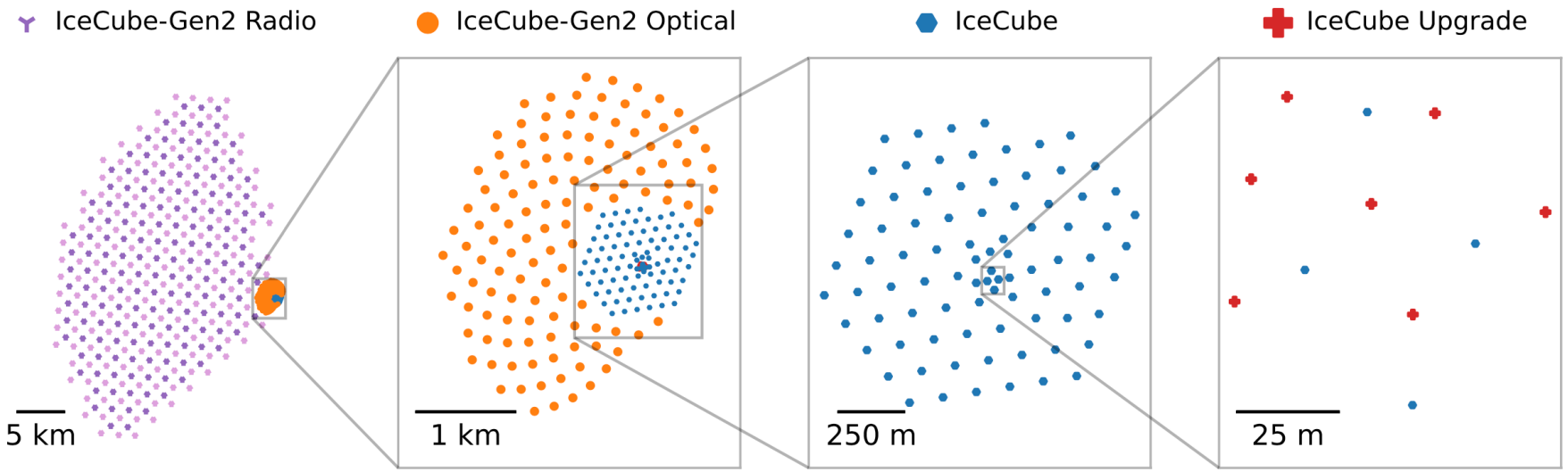


- FieldHub and DOM power supplies at DRTS
- mDOM mainboard for FieldHub testing
- FDOR cards, front plate assembly
- White Rabbit network testing loopback closeup
- White Rabbit switch for FieldHub optical input testing
- Performance metrics for mDOM on-board Feature extraction from simulated data

IceCube-Gen2

IceCube-Gen2: A wide-band observatory

Optimizing scales for leading sensitivity from 10^9 to 10^{20} eV



>30 PeV

> 3 TeV

>0.5 TeV

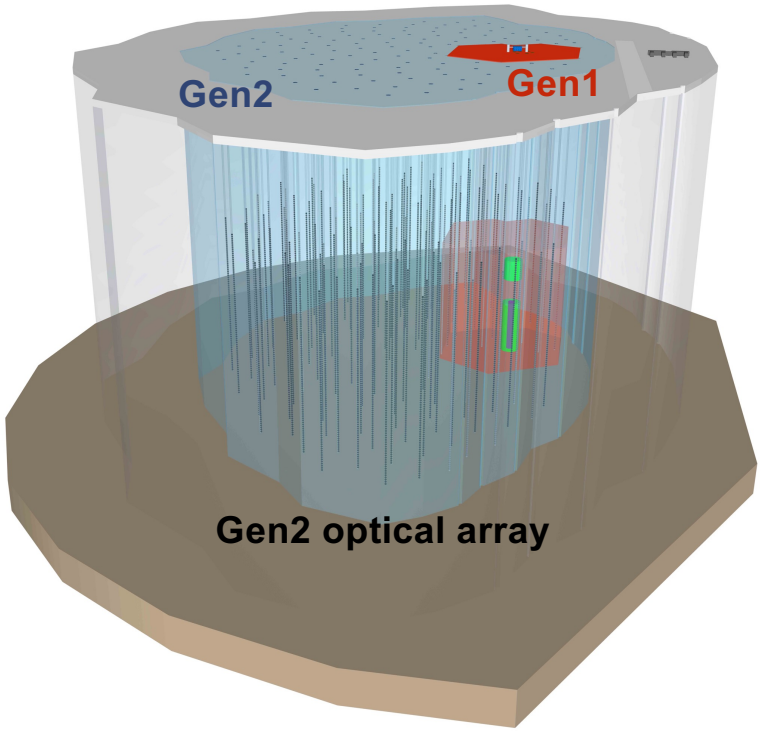
completed in 2011

> GeV

under construction,
installation in Dec 2025

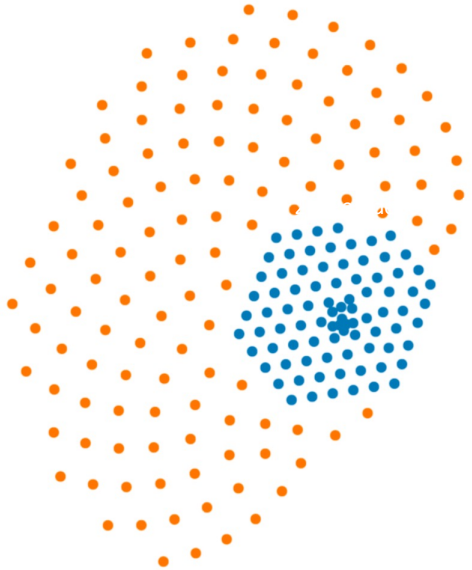
The Optical Cherenkov Array

The main detector component.



Instrumented Volume: 8 km^3

9600 optical sensors on
120 strings



Optical Module for IceCube-Gen2?

Full operation since 2011

IceCube DOM

10” PMT & dia. 33 cm

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

High energy extension

Design report in preparation

>98% still in operation without problems after 10 years

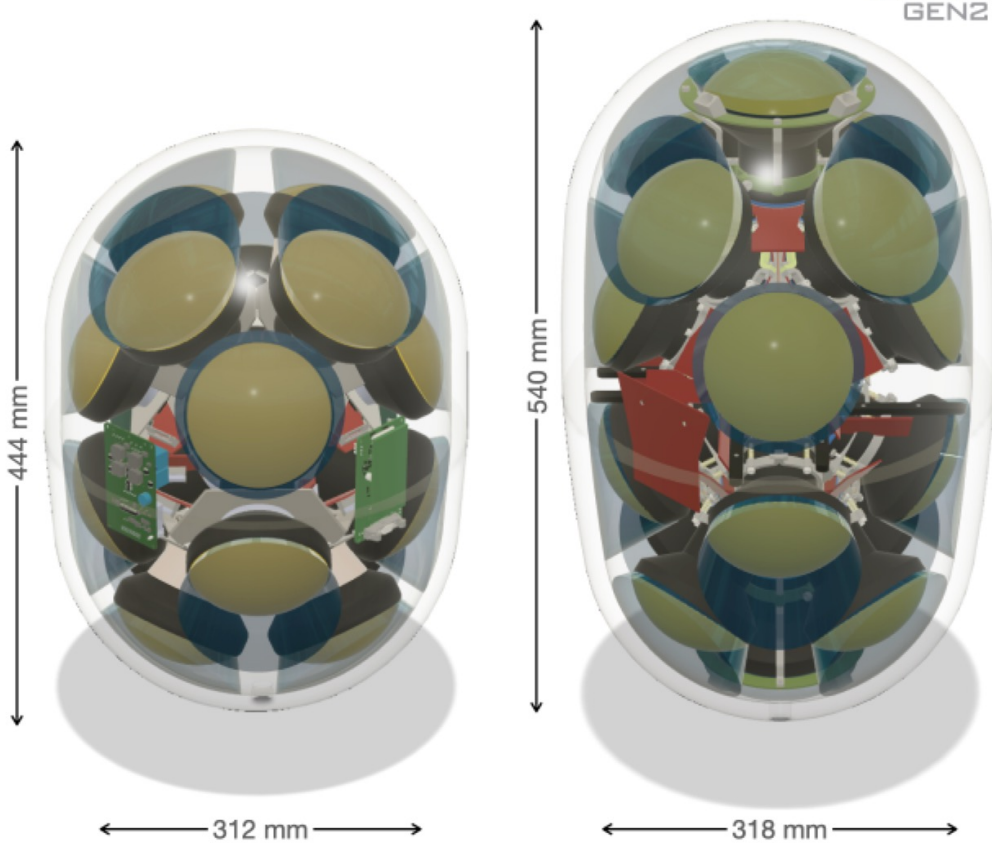
- First Multi-PMT In-Ice Optical Module designs
- Designs tuned for low-E events & ice measurements
- Major updates in essential elements (pressure vessels, optical gel, electronics, and etc)
- New production, testing facilities, and skilled R&D teams

IceCube-Gen2 Optical Module development is built on

- Successful design from IceCube
- Updates through IceCube-Upgrade

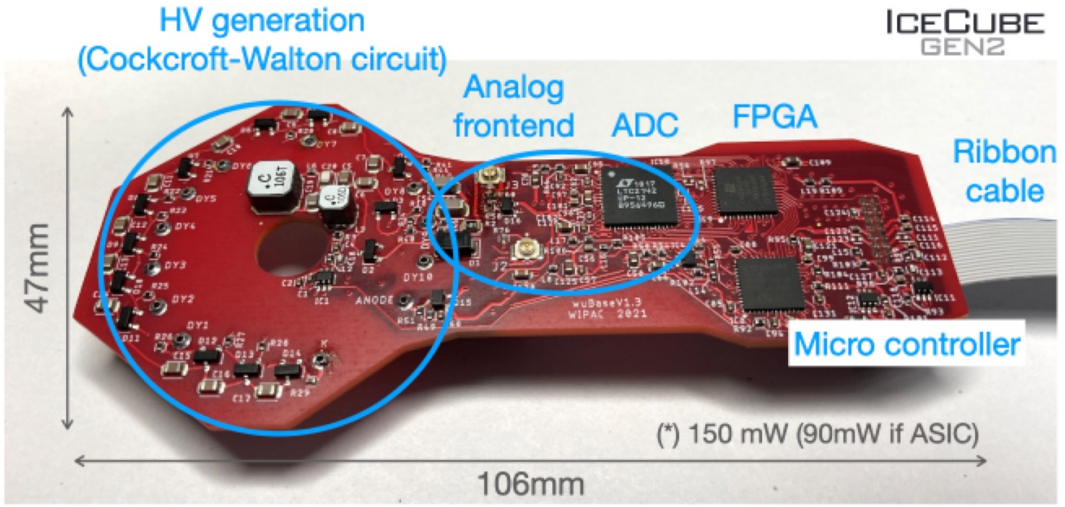
Gen2 Optical Module Design Candidates

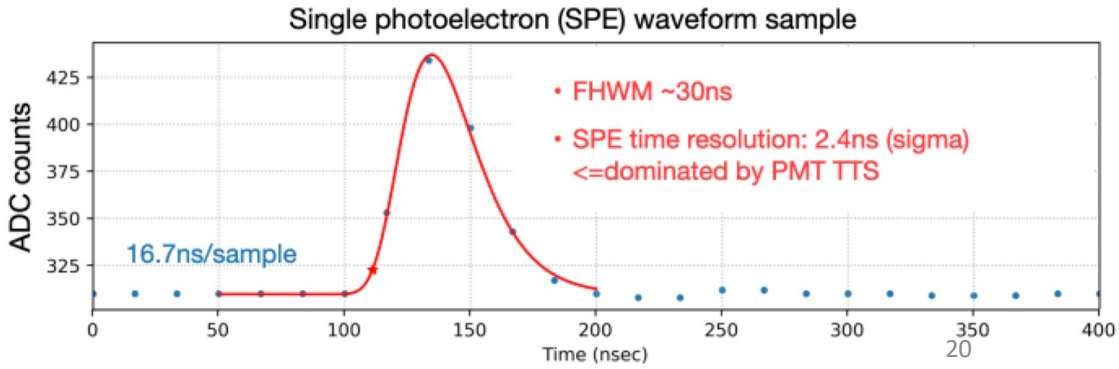
- Two design candidates; 16 and 18 PMT options
  - Custom non-spherical pressure vessels for both options
- 4” PMT is the best pick to maximize effective area
  - Back-to-back layout not feasible with > 4” PMTs
  - (*) Does not exist in the current lineups of PMT vendors
- PMTs are coupled to pressure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



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

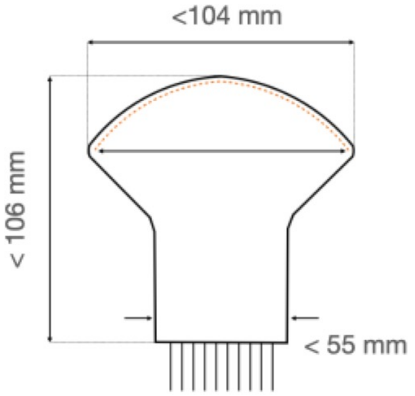




4 inch PMT

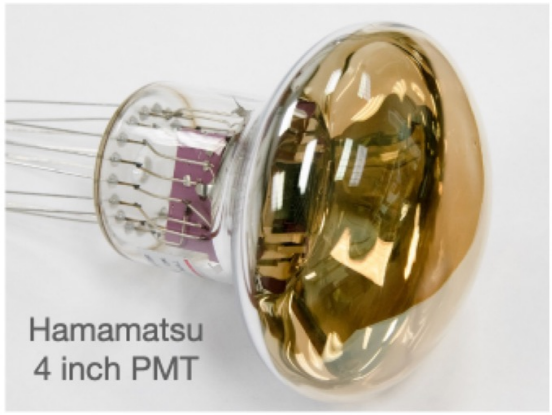
As short as possible accepting minimum compromise in performance

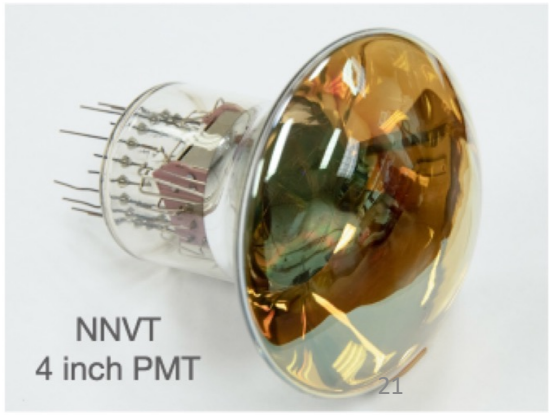
- Two vendors: Hamamatsu and North Night Vision Technology (NNVT)
  - Newly-designed 4inch box&line style dynode PMTs
  - NNVT has produced 15,000pcs 20” MCP-PMTs for JUNO
  - Keep multiple vendors for for Gen2!
- Very compact, 106mm (abs max.) long
  - (Potential) Caveat is moderate cathode uniformity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



Target numbers

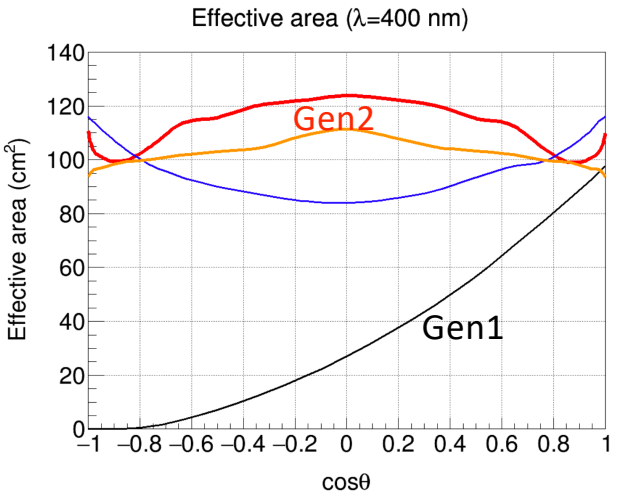
Parameter	Target value
Gain	5e6 @ <1500V
Transit Time Spread	< 8ns (FWHM)
Peak/Valley	>2
QE	>25% @400nm
Pre/late/after pulses	Less than 1/5/10%

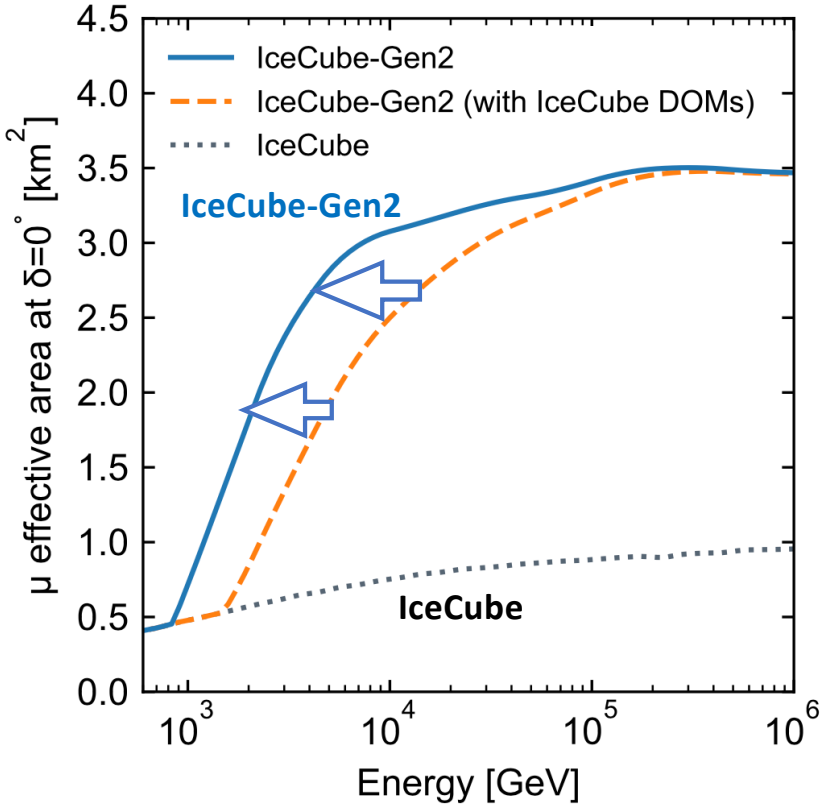




Higher Sensor sensitivity —> Larger Muon Effective Area

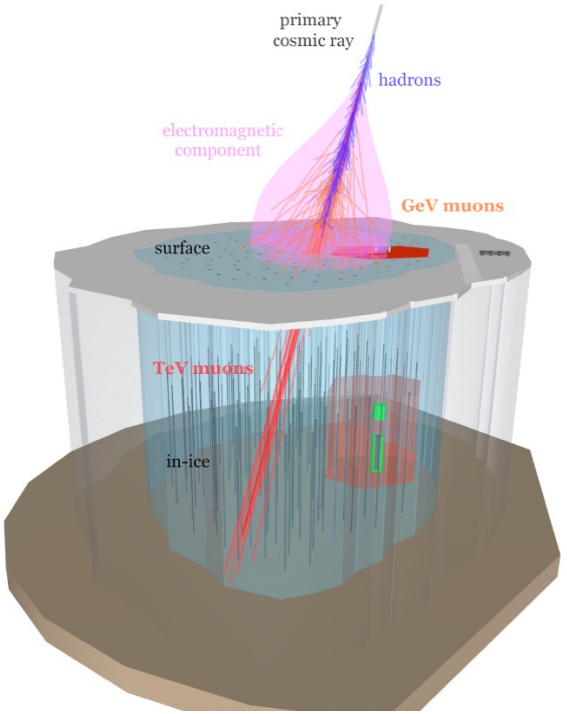
Factor 3 more photons detected
—>
- Lower energy threshold
- Angular resolution: 0.1 - 0.3°

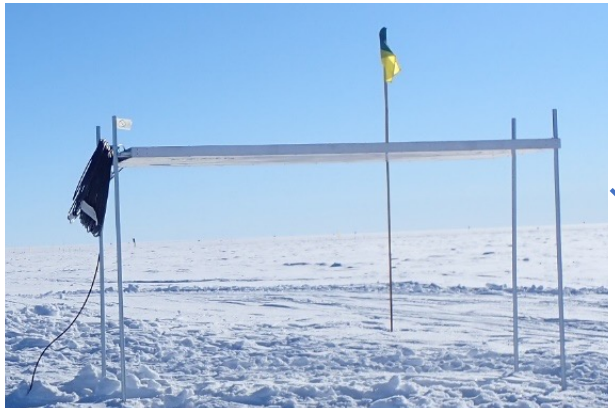


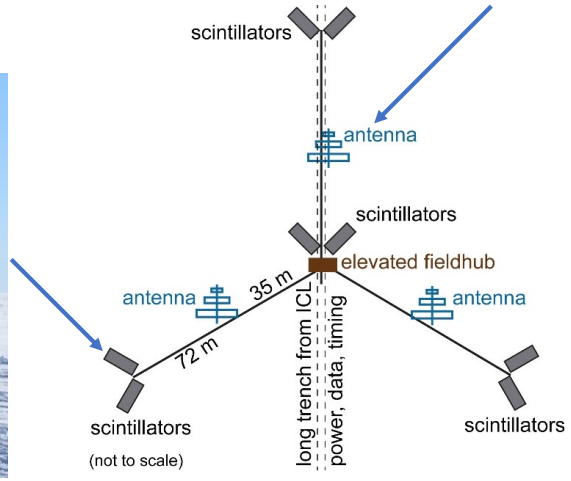


The Surface Array

- Veto for larger and purer sample of PeV neutrino candidates
- High accuracy for cosmic rays in the PeV to EeV region
  - particle physics in air showers
  - cosmic-ray astrophysics







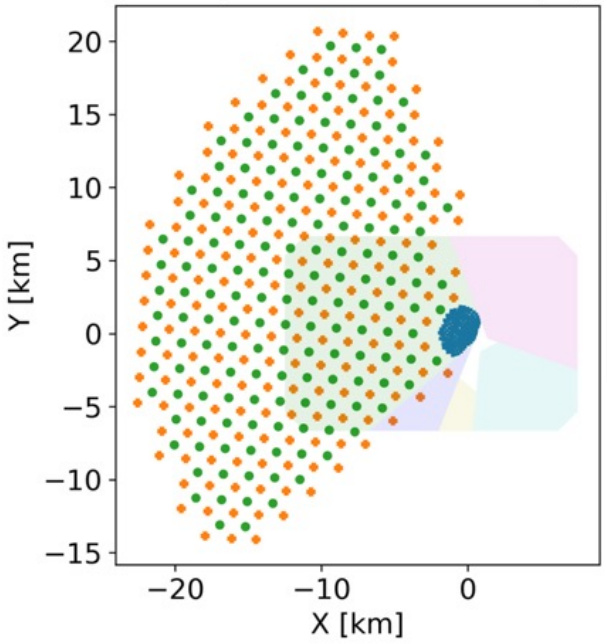
Reference design of Surface Array:

one station per optical string (120)

- 4 pairs of scintillators enabling low threshold for veto
- 3 radio antennas increasing accuracy at high energies

The Gen2 radio array

Energy range from 30 PeV to well beyond EeV



361 stations

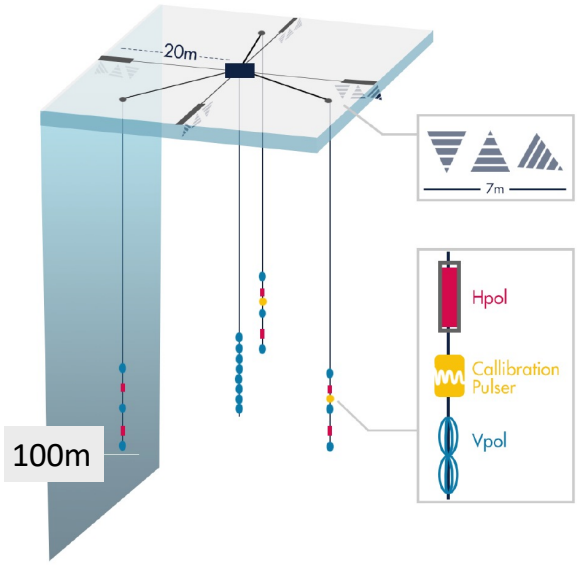
Area: 500 km^2

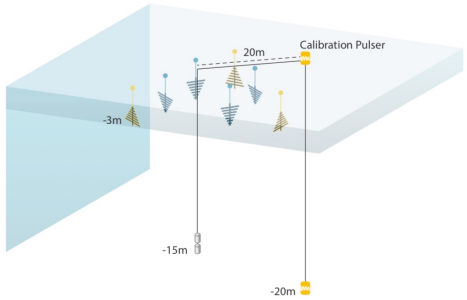
Ice target: 1000 km^3

The phased array trigger was successfully tested in ARA, is now used in RNO-G.

RNO-G:

- Currently in construction in Greenland
- 35 stations, 7 deployed (10% of Gen2)
- Serves as prototype array for Gen2.





Heritage: RICE (South Pole-AMANDA), ANITA (Antarctica from balloon), ARA (South Pole-IceCube), ARIANNA (Antarctic Coast), RNO-G (Greenland)

Logistical Support

1. Logistical Support provided by **NSF's Office of Polar Programs made IceCube possible**.
2. IceCube Gen1: 9.5 million lb of cargo + fuel, 300 LC 130 missions. Construction occurred simultaneously with the South Pole station completion and South Pole Telescope construction.
3. Logistical Support **requirements are well understood**.
4. **Strategies for logistical support exist**.
   1. Population of 60 people: → Temporary lodging summer camp.
   2. Cargo: Overland traverse is scalable (and lower cost than air transport).
5. All logistical **support will be on project budget. Successful logistics will require high-level prioritization and strategic planning at NSF's Polar Program**.

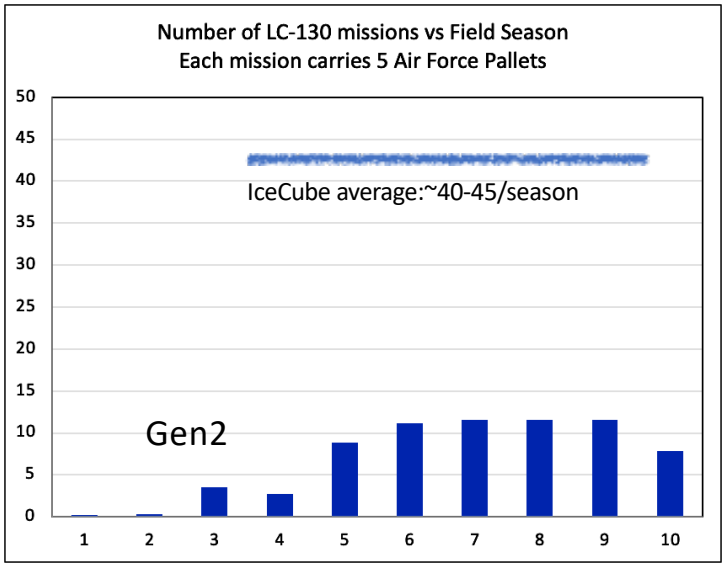
C17 transport (J. Donnenfeld)

Amundson Scott South Pole station (WikiMedia)

Logistical Support Example: LC-130 flights

LC 130 aircraft

Overland traverse



The Drill

ICU = IceCube Upgrade

EHWD = Enhanced Hot Water Drill

ICU Drill Schematic