The 8th Workshop of SCAR Astronomy & Astrophysics
Phuket Thailand Sept 15- 19, 2025

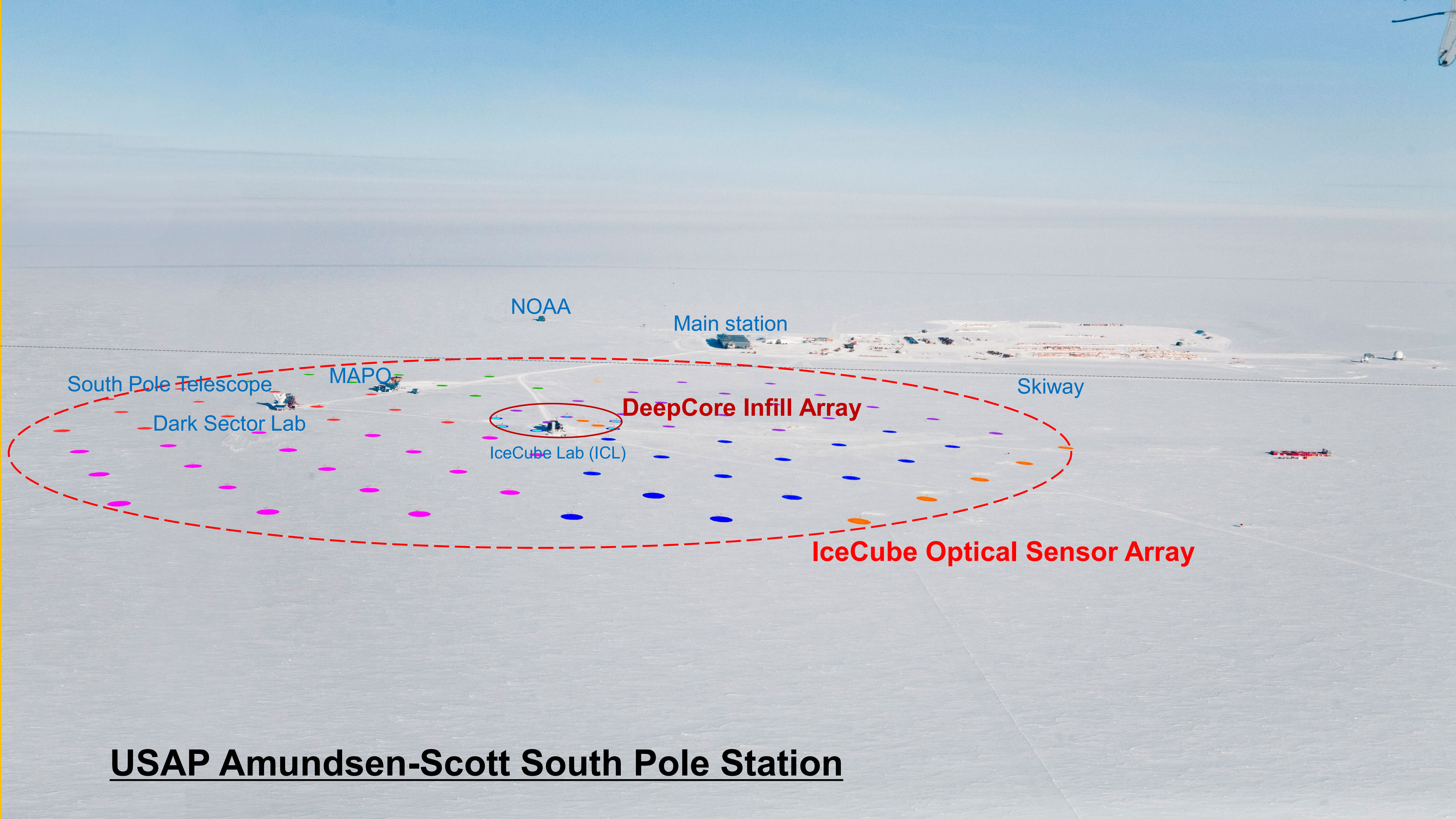
Advancing Neutrino Astrophysics with the IceCube Upgrade

Aya Ishihara, on behalf of the IceCube Collaboration
ICEHAP, Chiba University, Japan

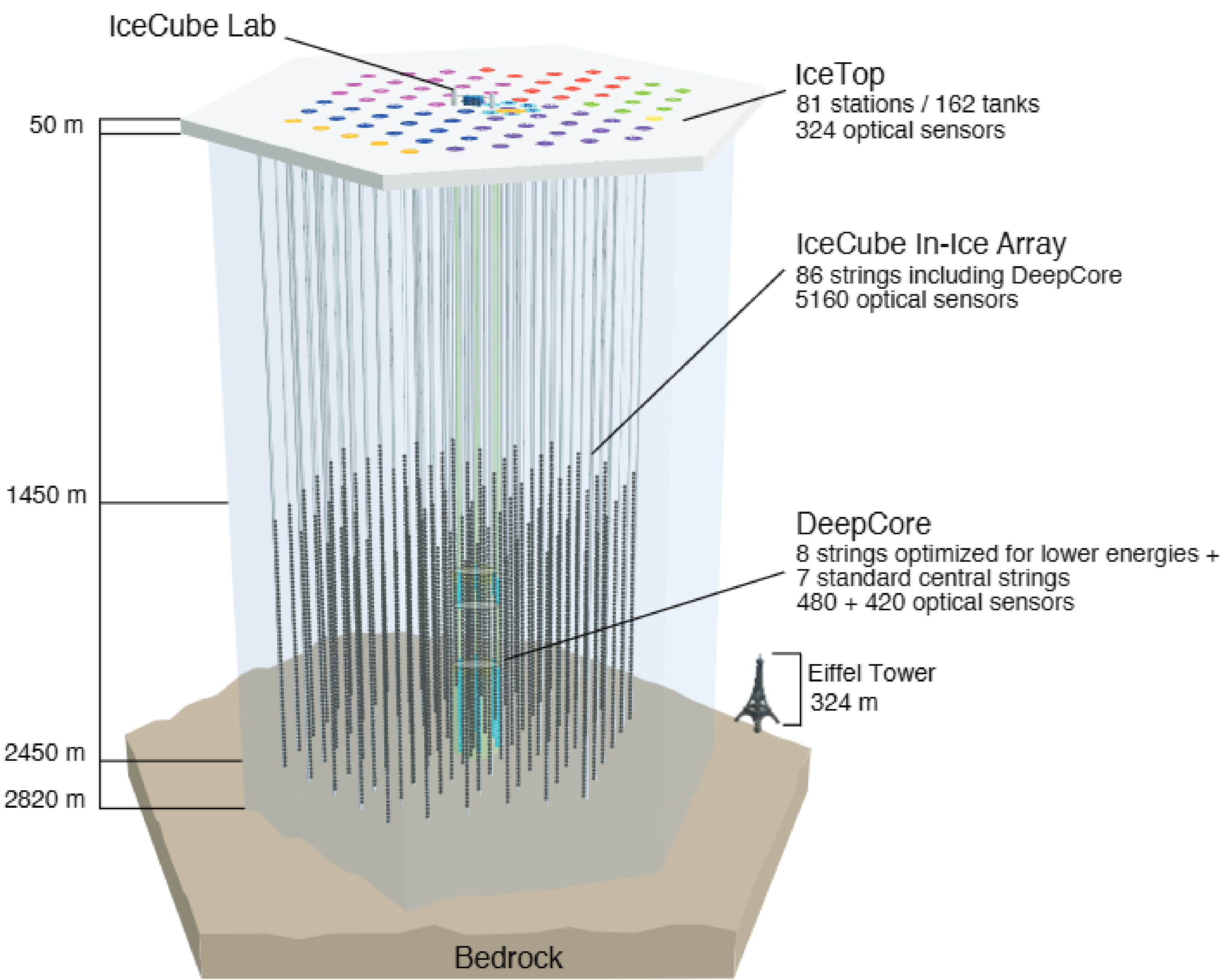
千葉大学 CHIBA UNIVERSITY

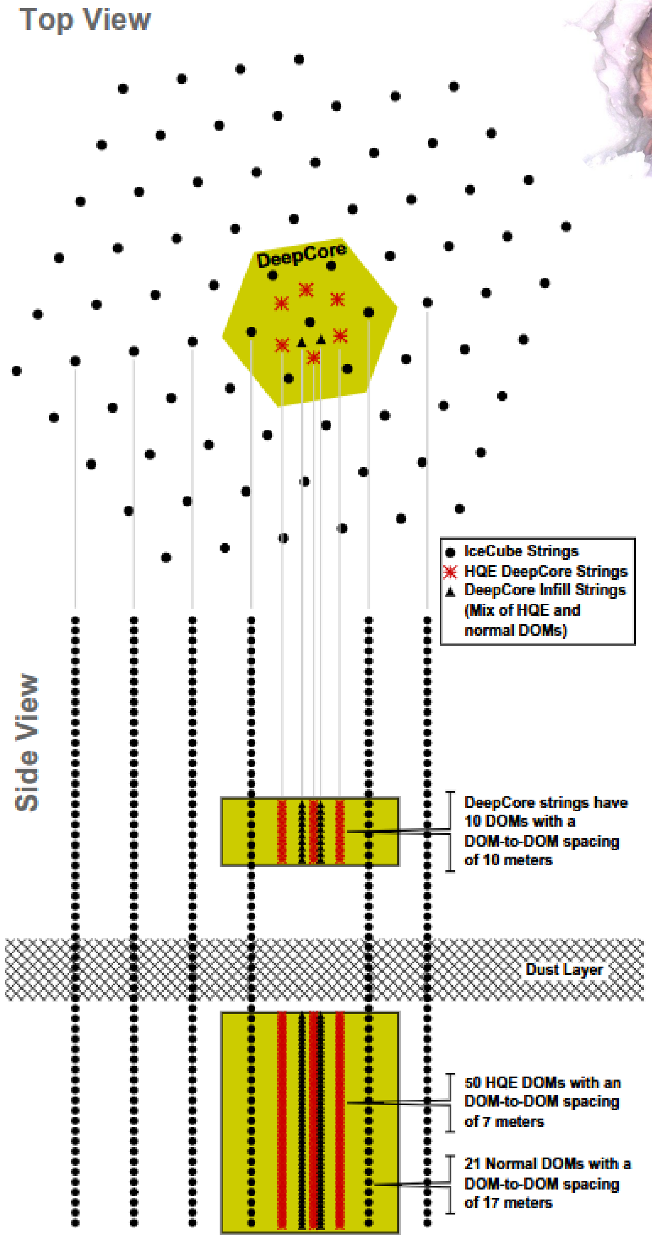
ICEHAP 千葉大学 ハドロン宇宙国際研究センター International Center for Hadron Astrophysics

September 16, 2025


NOAA
Main station
South Pole Telescope
MAPO
Skiway
DeepCore Infill Array
Dark Sector Lab
IceCube Lab (ICL)
IceCube Optical Sensor Array
USAP Amundsen-Scott South Pole Station

The IceCube Observatory





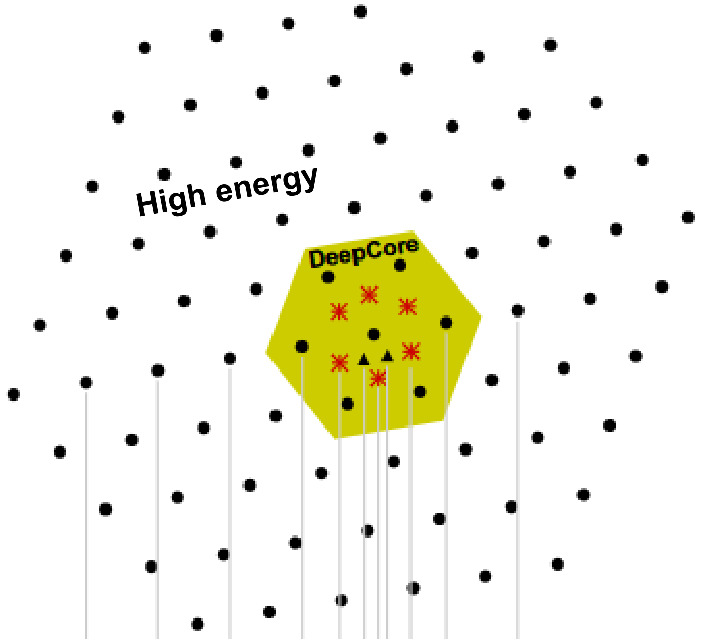
Configurations for different energies

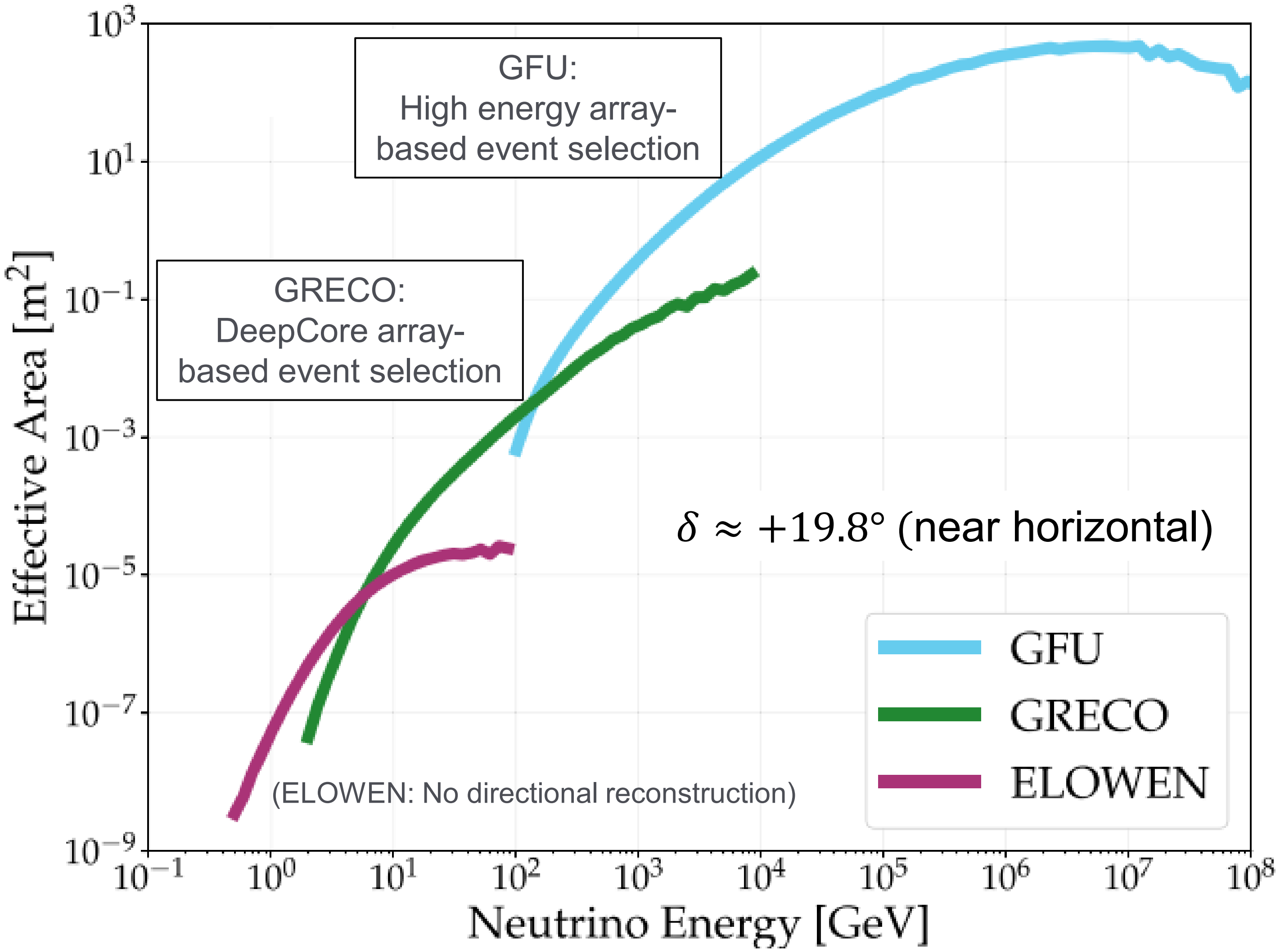
High energy array separation:

- 125m in horizontal
- 17m in vertical

DeepCore array separation:

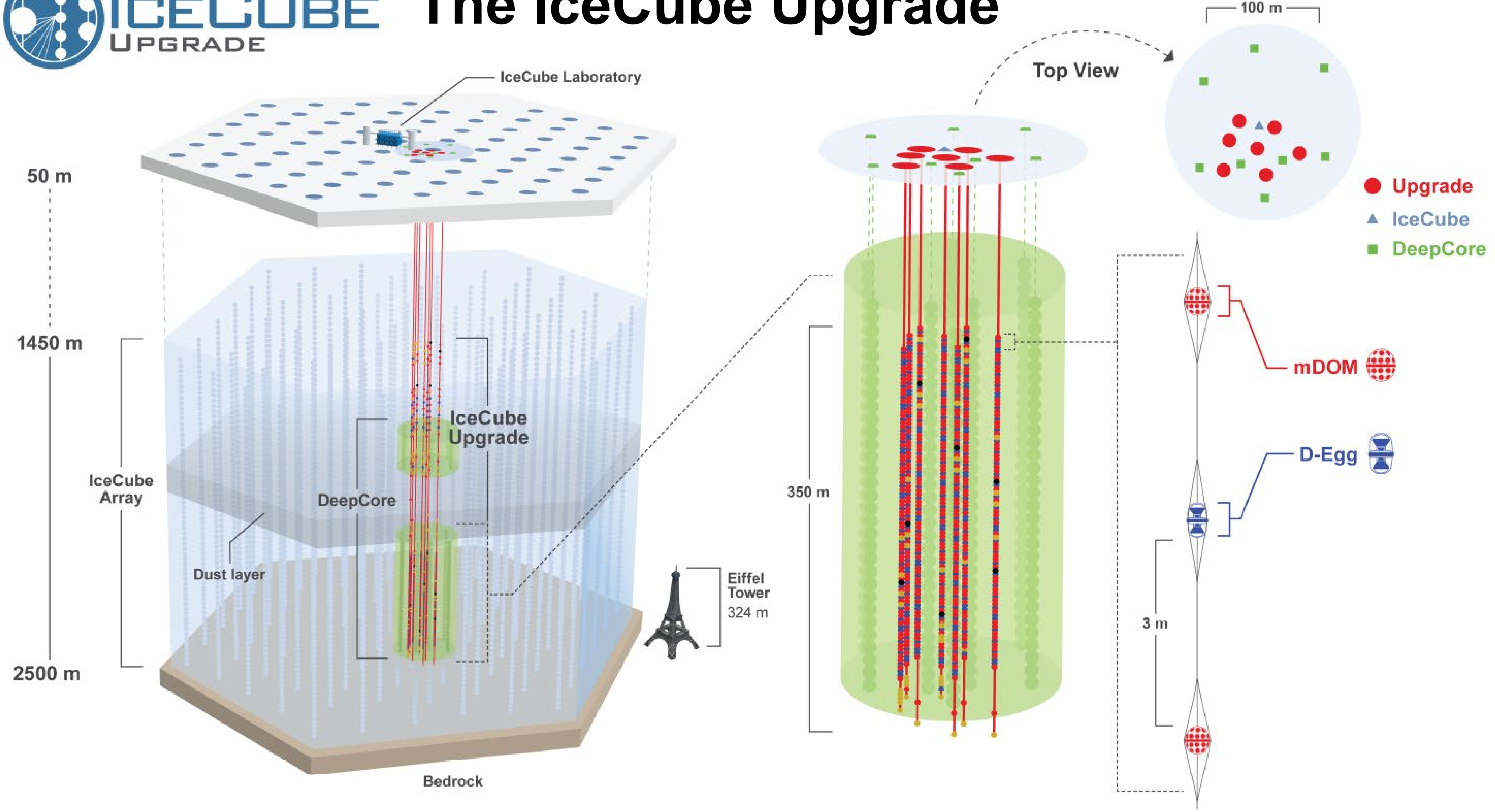
- 40-70m in horizontal
- 7m in vertical

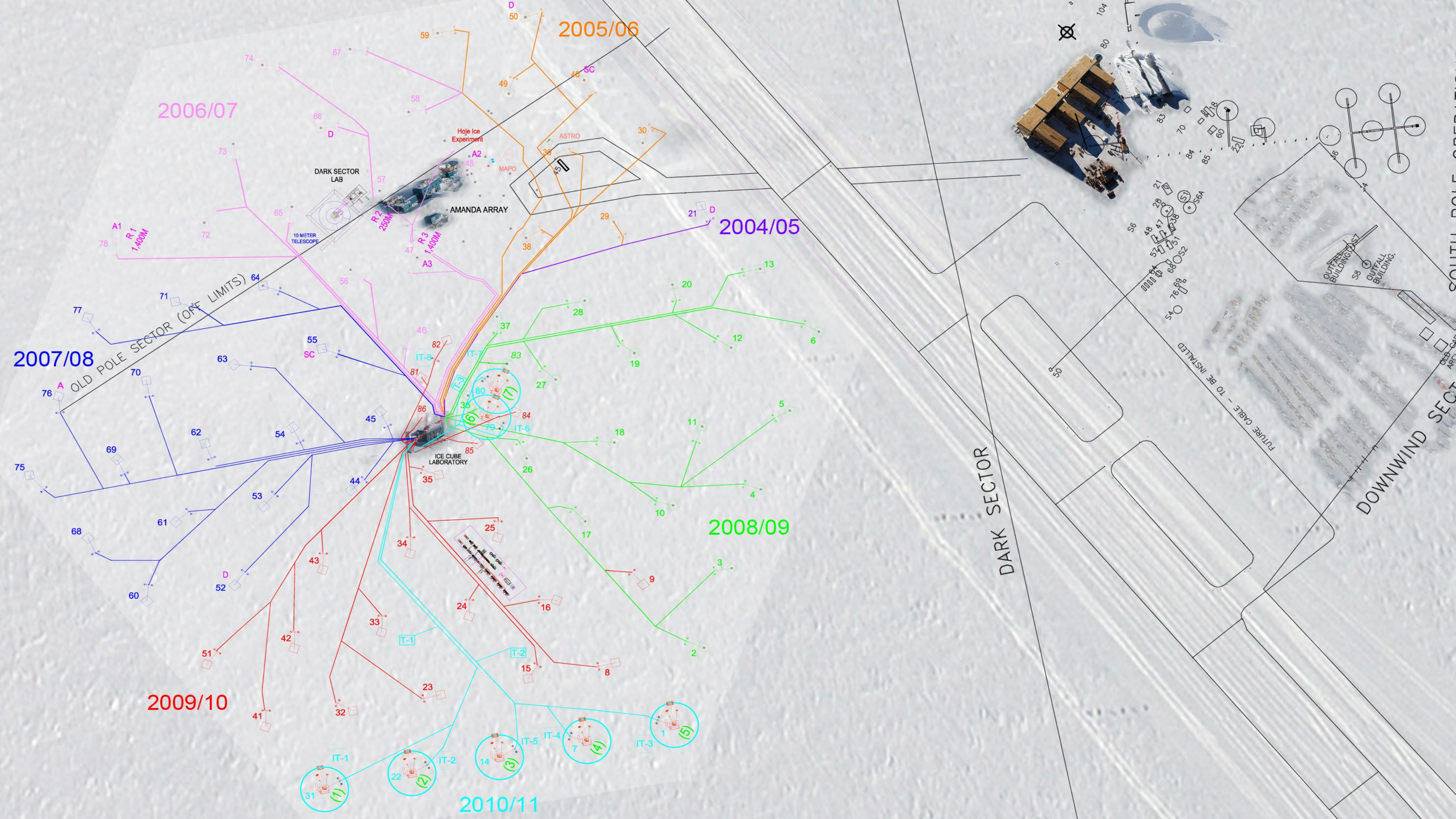




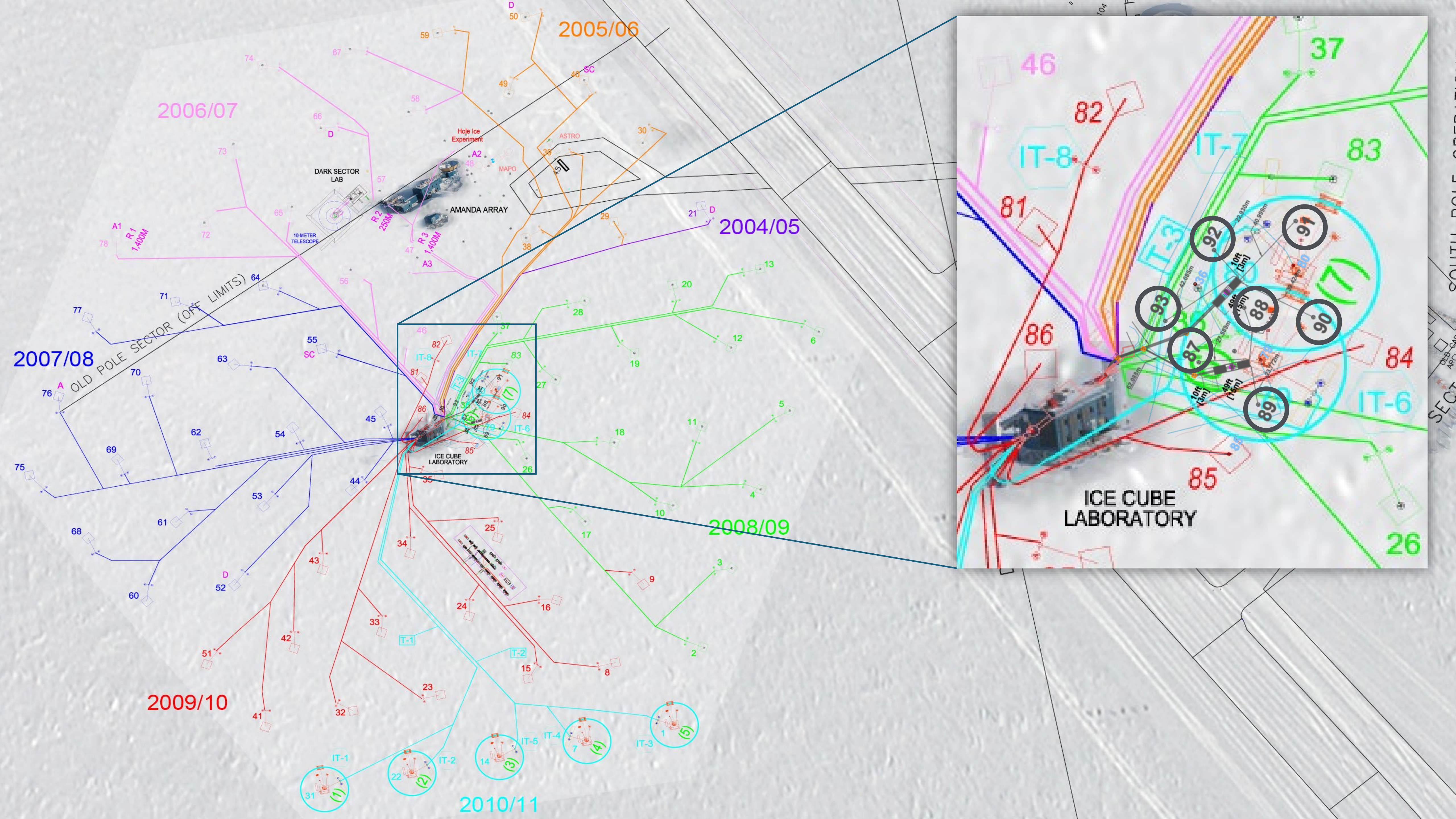
"*Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory*", IceCube Collaboration, ApJL 946 L26(2023)

The IceCube Upgrade





2005/06
2006/07
2004/05
2007/08
2008/09
2009/10
2010/11
OLD POLE SECTOR (OFF LIMITS)
DARK SECTOR LAB
10-METER TELESCOPE
AMANDA ARRAY
Hoje Ice Experiment
ASTRO
MAPO
ICE CUBE LABORATORY
DARK SECTOR
DOWNWIND SECT
FUTURE CABLE - TO BE INSTALLED
OUTFALL BUILDING



2005/06
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10-METER TELESCOPE
ASTRO
MAPO
R 2 250M
R 1 1,400M
R 3 1,400M
OLD POLE SECTOR (OFF LIMITS)
ICE CUBE LABORATORY
IT-1
IT-2
IT-3
IT-4
IT-5
IT-6
IT-7
IT-8
ICE CUBE LABORATORY

The IceCube Upgrade array

Construction is planned for the upcoming 2025/2026 South Pole season, starting next month, to be completed within a season

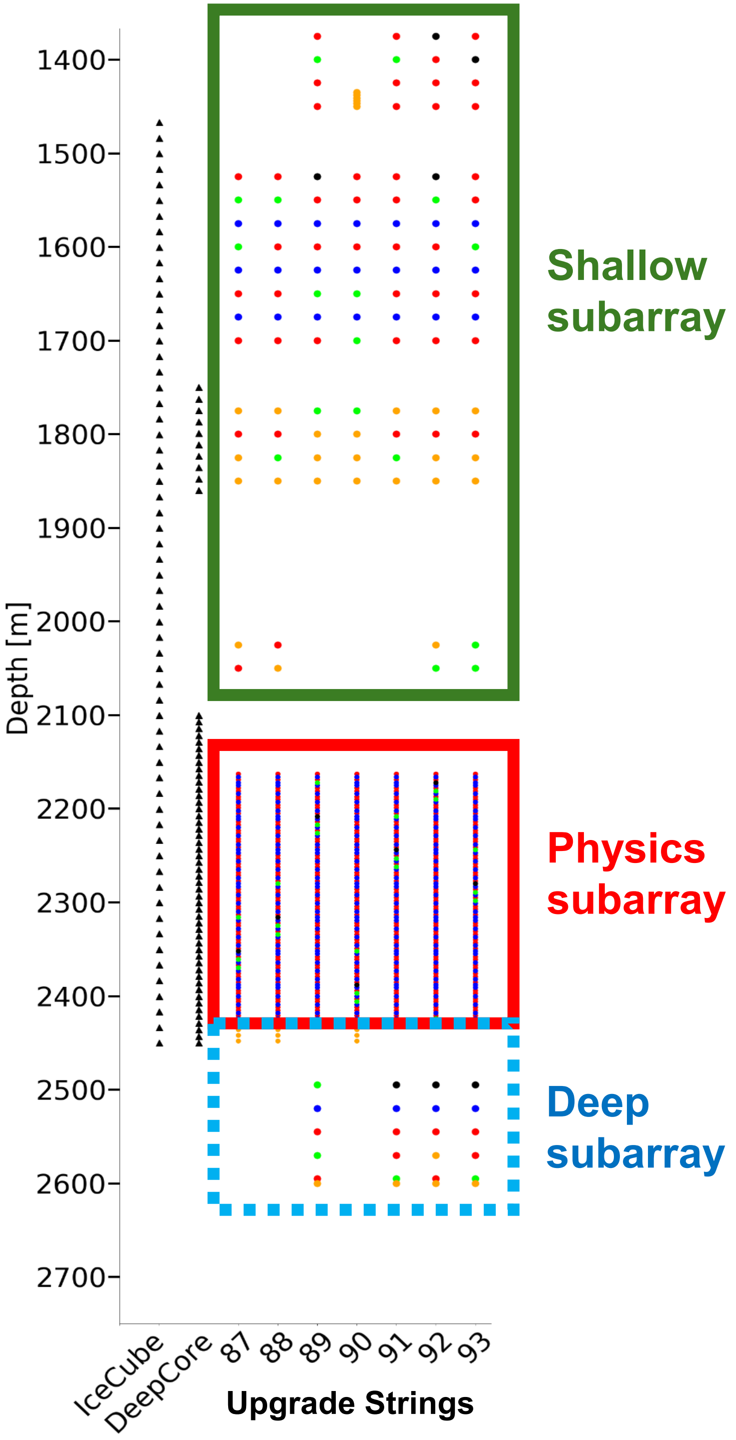
- Most of the equipment has already departed from its home institutions and is en route to the South Pole
- A large portion has already been at the South Pole since last year

The Upgrade array will feature a unique configuration of

- seven new strings, each equipped with ~110 sensors and calibration devices
- enabling both precision calibration and low-energy physics studies

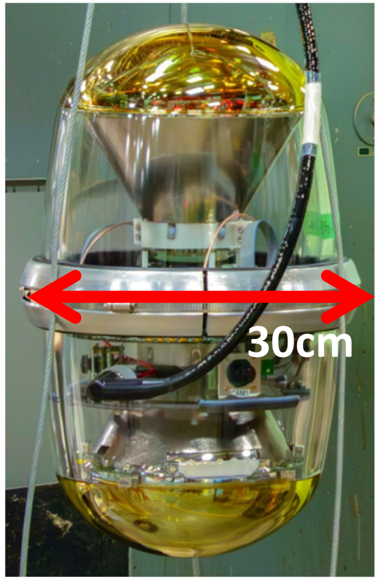
Three distinct sensor array configurations:

- **Physics subarray**
- **Shallow subarray**
- **Deep subarray**



Physics subarray

D-Egg 2 x 8" HighQE PMTs

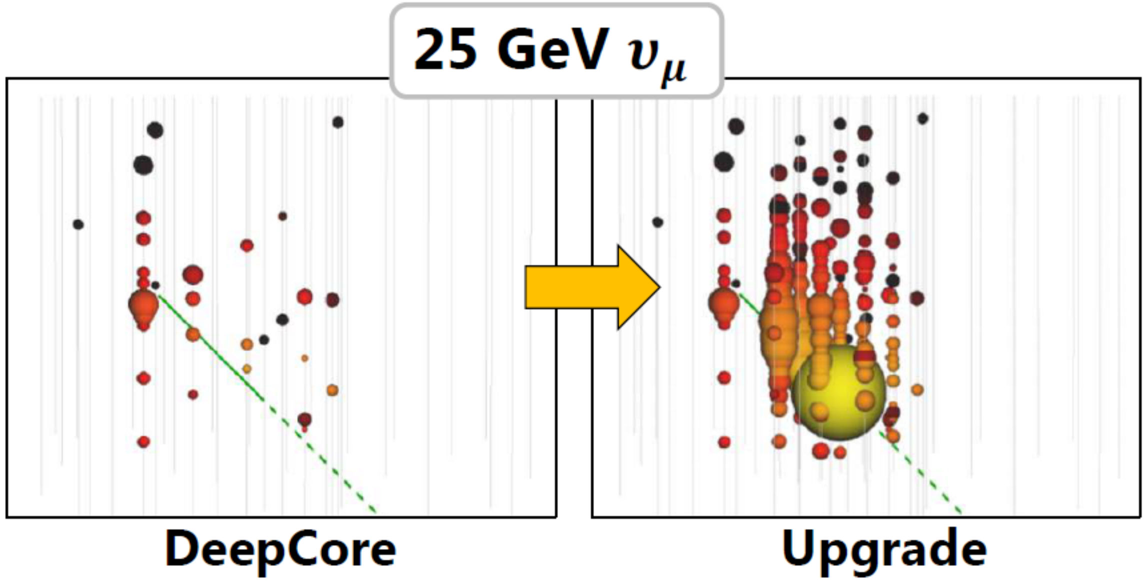


mDOM 24 x 3" PMTs

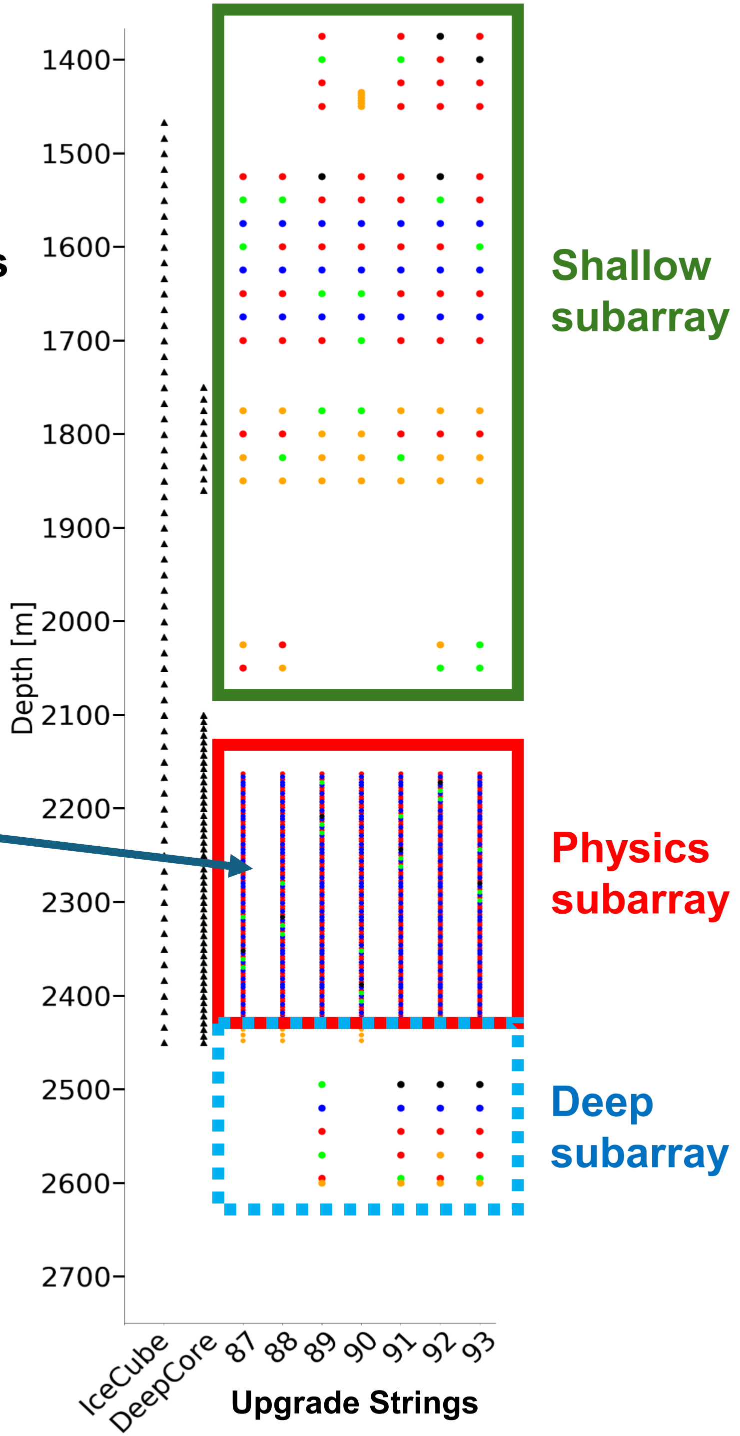
Each string with ~90 optical sensors

Physics subarray separation:
- ~20m in horizontal
- 3m in vertical

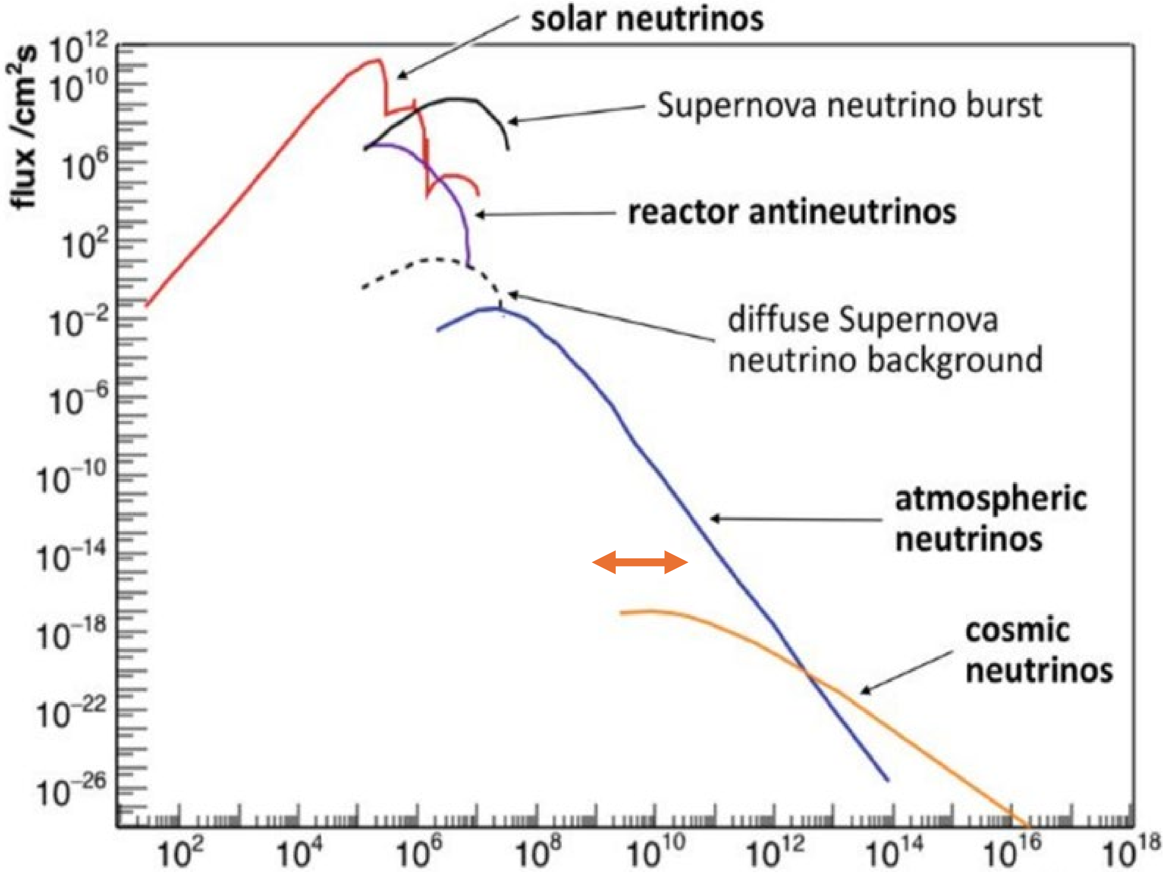
Detection of GeV neutrinos with >10 times more effective photocathode area per volume compared to DeepCore

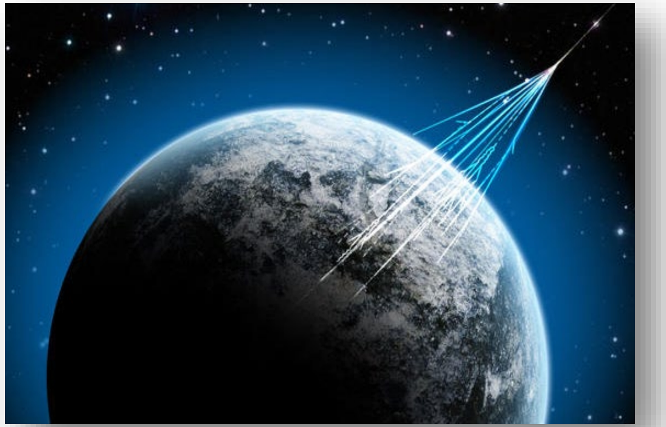


For O(10) GeV neutrinos
- 3 times better angular resolution
- 2 times better energy reconstruction

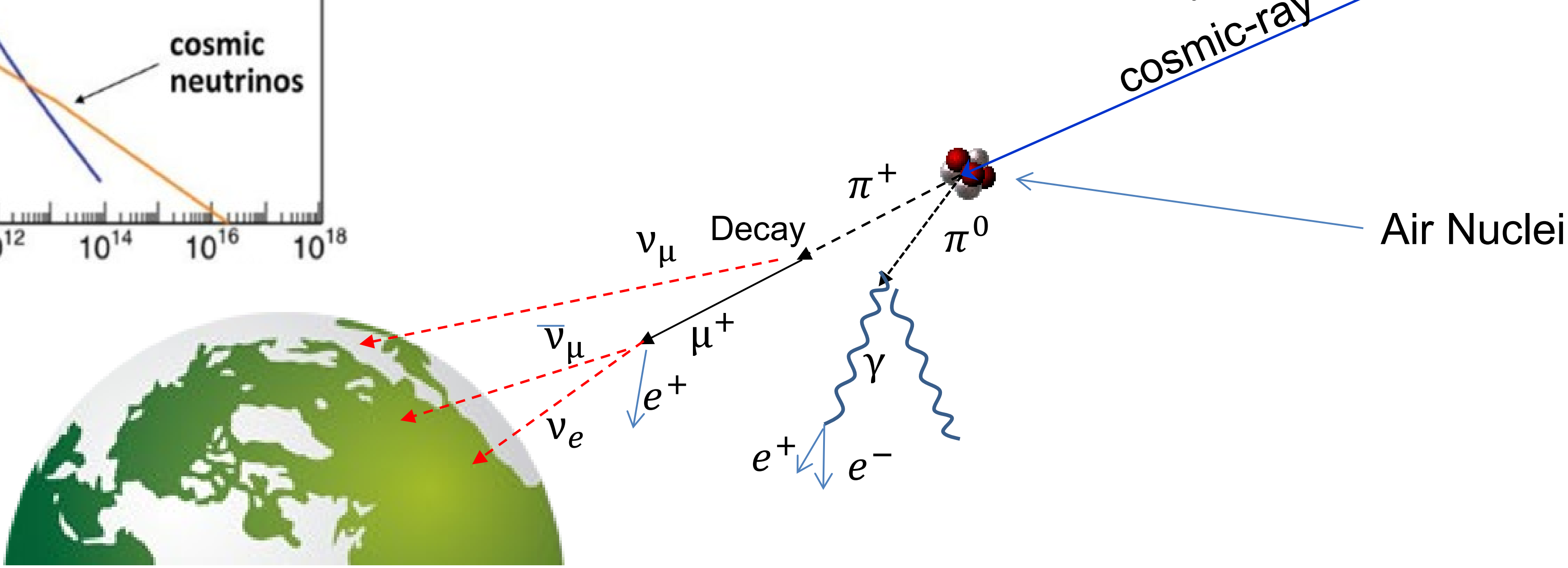


Where are GeV neutrinos from？



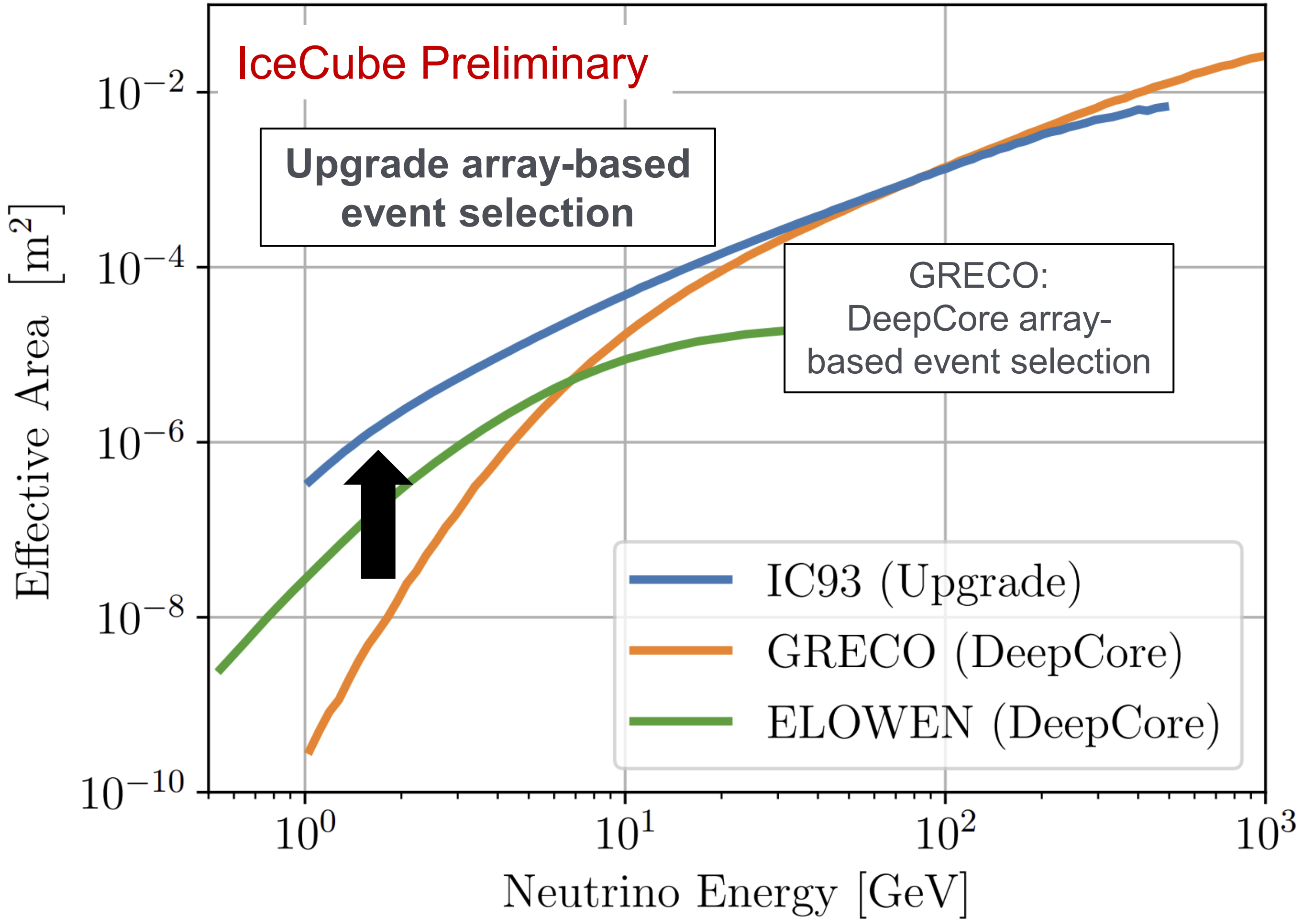


Atmospheric Neutrinos
cosmic-ray up to knee (~3PeV) : ν from π and K decay
around and above knee: ν from charmed meson decay



Cosmic Neutrinos
Cosmic neutrinos are predicted in GeV region, hindered by the dominant flux of atmospheric neutrinos in this energy range

Physics subarray performance



"*Prospects for GeV Neutrino Transient Searches with the IceCube Upgrade*"
(Yukiho Kobayashi, PoS-ICRC2025-1076, https://arxiv.org/abs/2507.16050)

Measurements of neutrino oscillation parameters

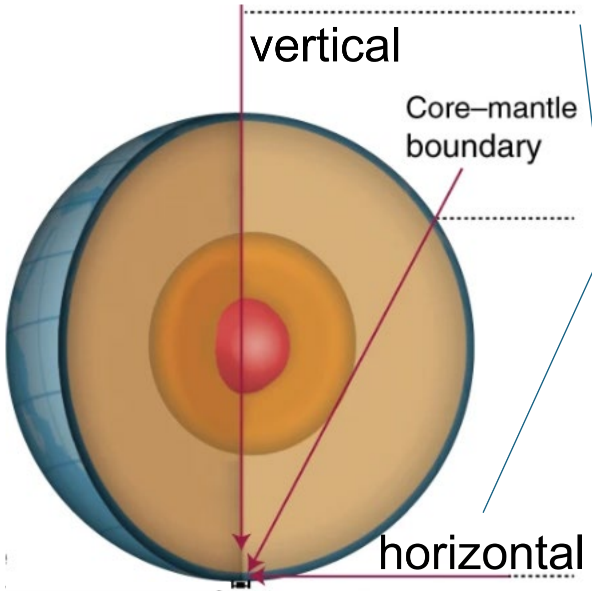
- Access to the matrix which describes **how neutrino flavor states** $(\nu_e, \nu_\mu, \nu_\tau)$ **mix into mass eigenstates** (ν_1, ν_2, ν_3)
- Sensitivity to the **neutrino mass ordering**—i.e., identifying which mass eigenstate is the heaviest
- Pimary signatures: **the disappearance of muon neutrinos** and **the appearance of tau neutrinos**

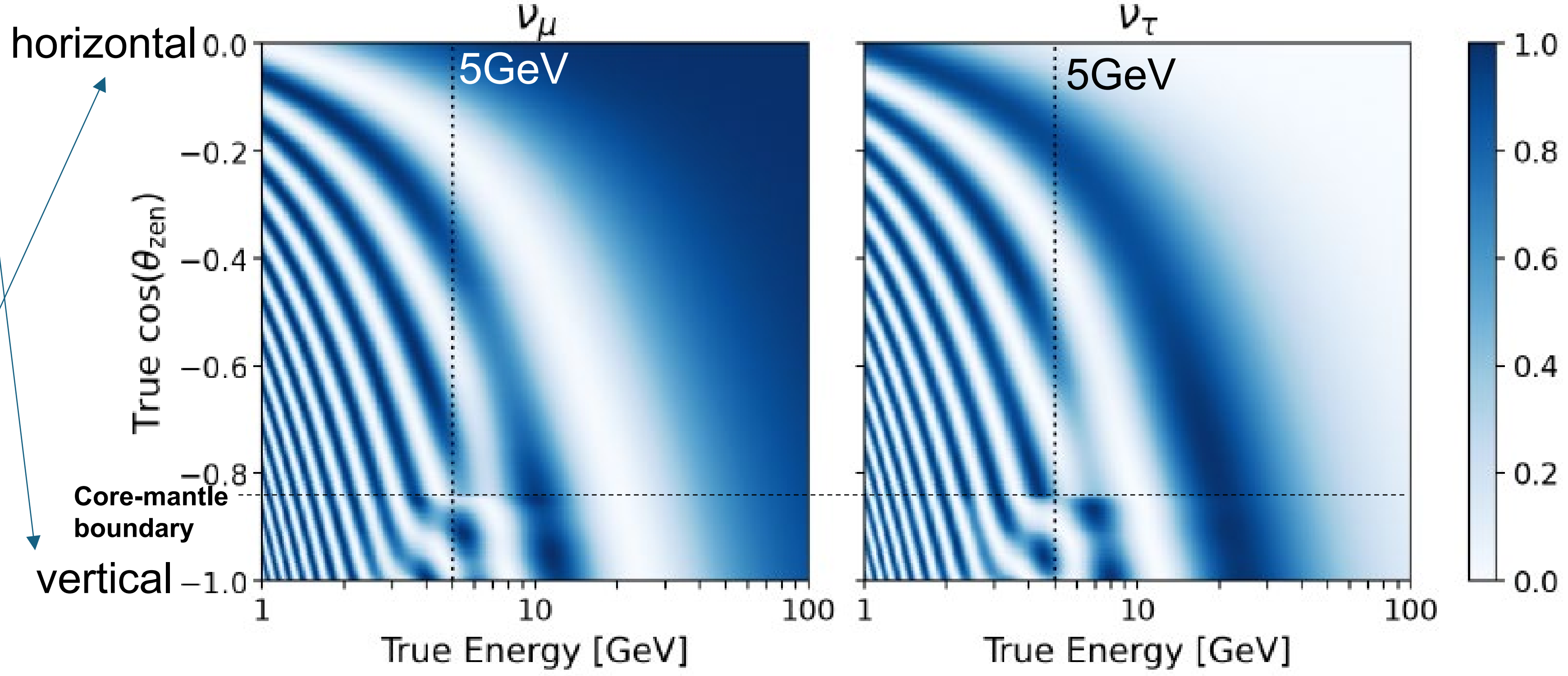
$$P(\nu_\mu \to \nu_\mu) \approx 1\text{–}4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$U_{\mu 3} = \sin\theta_{23}\cos\theta_{13}$$

$$P_{\nu_\mu \to \nu_\tau} = \sum_{j,k} U_{\mu j} U^*_{\tau j} U^*_{\mu k} U_{\tau k} \exp\left(i\frac{\Delta m^2_{jk} L}{2E_\nu}\right)$$

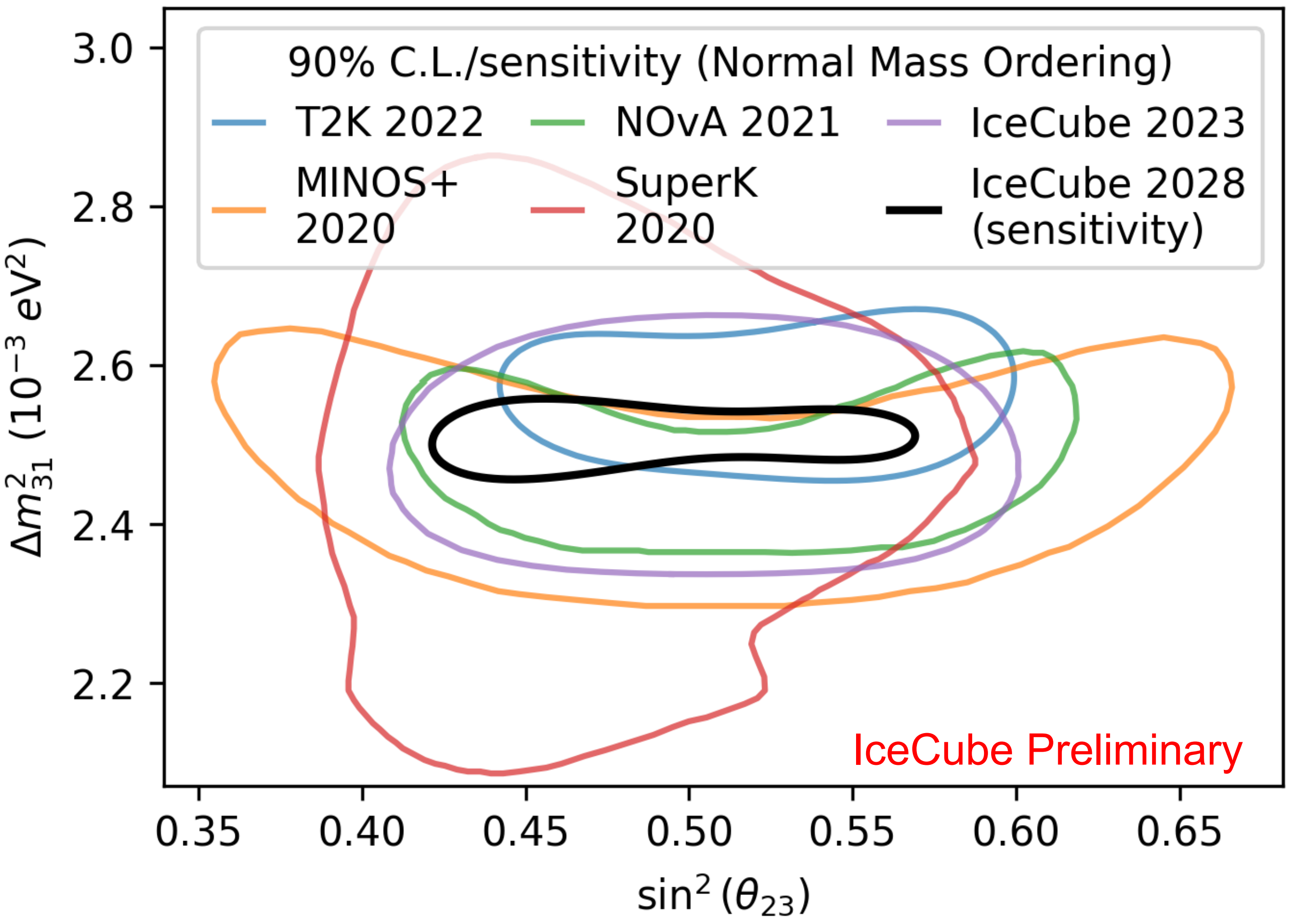
$$\approx \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$





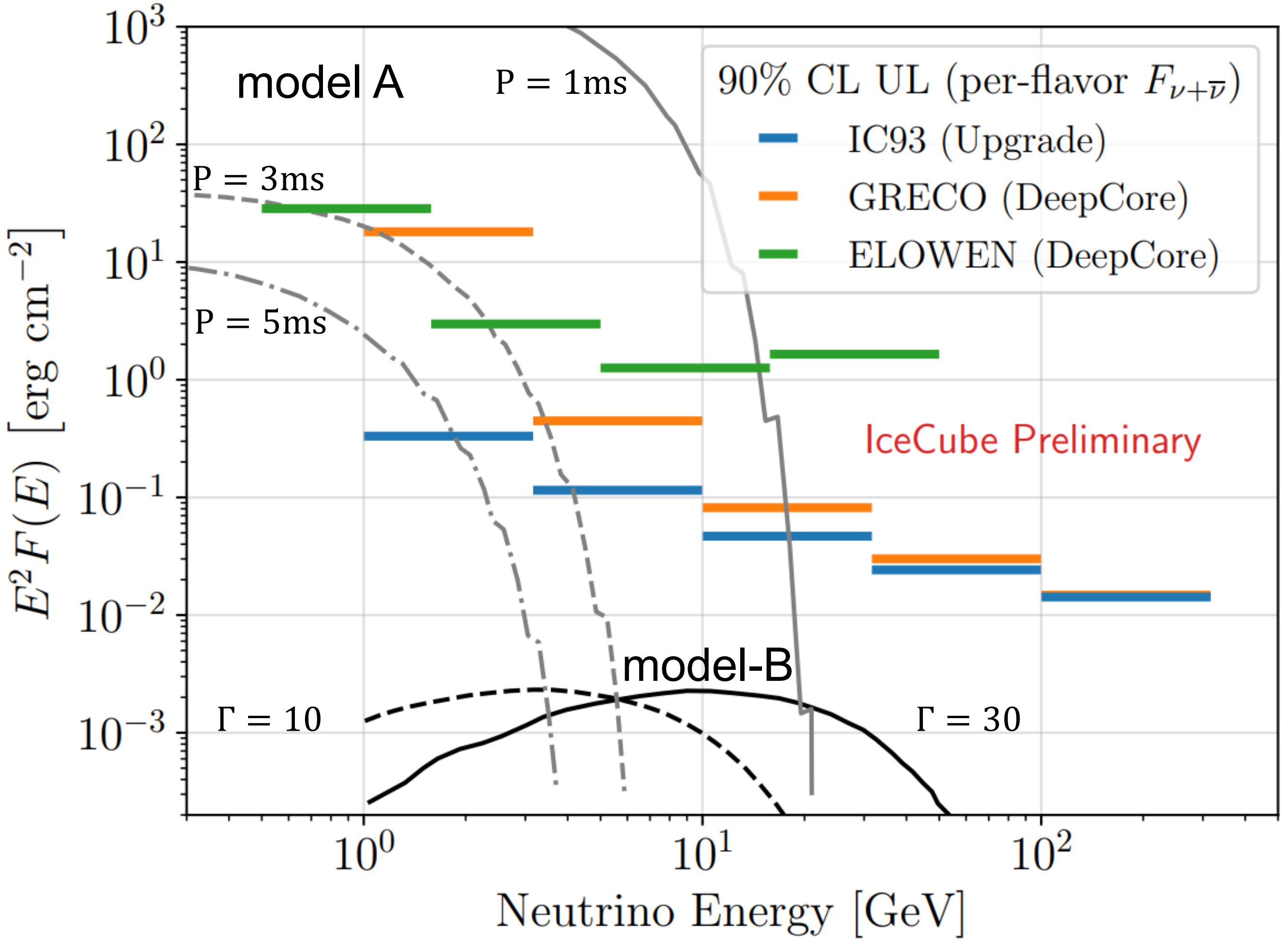
Probability of a muon neutrino oscillating to each flavor

Expected sensitivity to oscillation parameters



Sensitivity of the IceCube Upgrade to Atmospheric Neutrino Oscillations
(P. Eller, K. L. DeHolton, J. Weldert, R. Ørsøe, PoS-ICRC2023-1036, https://arxiv.org/abs/2307.15295)

Expected sensitivity to GeV neutrino transients



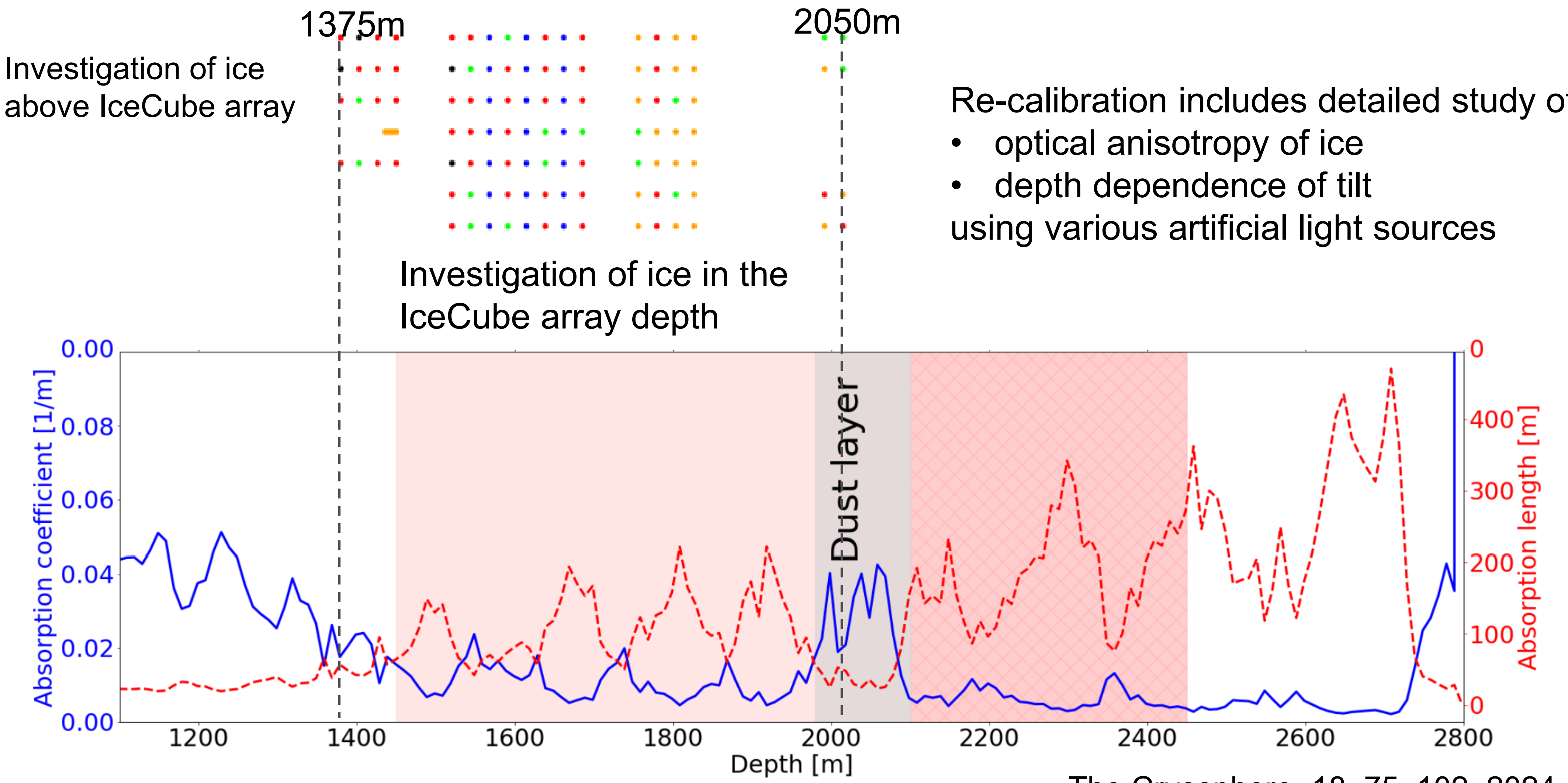
models-A (gray) different initial spin period P: core-collapse SN at 10kpc with strongly magnetized PNS from Carpio et al. **PRD 110, 083012 (2024)**

models-B (black) different Lorenz factor Γ: low-luminosity GRB at 10Mpc from Murase et al. **PRL 111, 131102 (2013)**

Prospects for GeV Neutrino Transient Searches with the IceCube Upgrade
(Yukiho Kobayashi, PoS-ICRC2025-1076, https://arxiv.org/abs/2507.16050)

Shallow subarray

- Re-calibration of the existing detector to improve understanding and inform better design choices for IceCube-Gen2
- Cross-calibration of IceCube optical modules with advanced electronics
- Testbed for IceCube-Gen2 optical module designs



Re-calibration includes detailed study of
- optical anisotropy of ice
- depth dependence of tilt

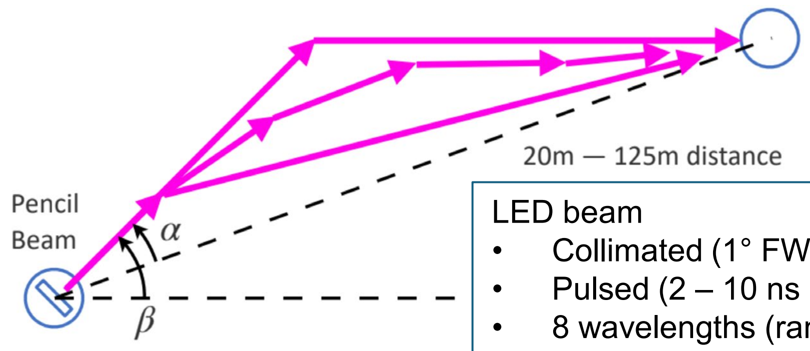
using various artificial light sources

The Cryosphere, 18, 75–102, 2024

Well-calibrated directed and diffuse light sources

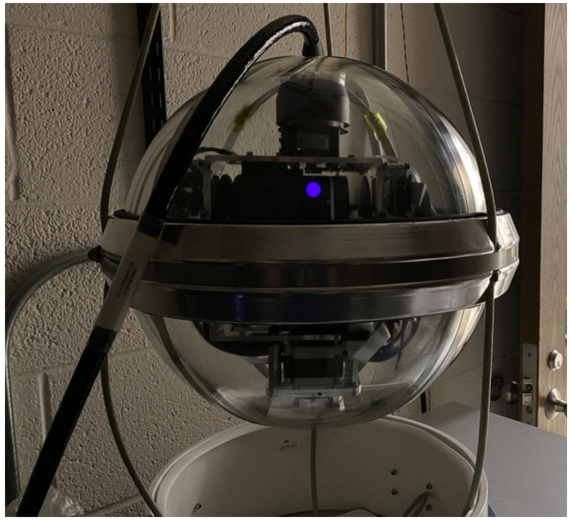
Pencil Beam

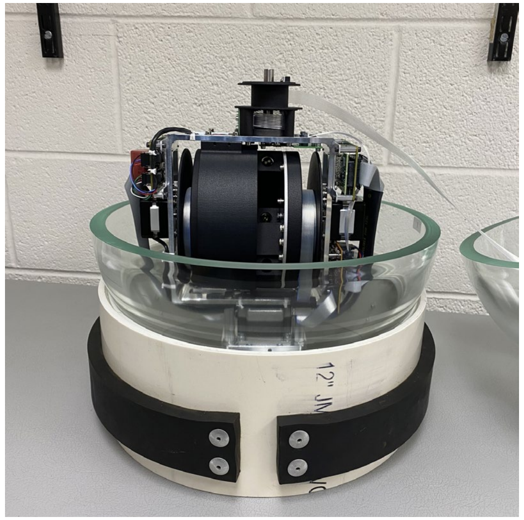
- Beams in any direction with 0.1° resolution
- Self-monitoring of beam brightness
- Study ice anisotropy and scattering properties



LED beam
- Collimated (1° FWHM divergence)
- Pulsed (2 – 10 ns FWHM)
- 8 wavelengths (range 355nm – 590nm)

Laser Beam
- Collimated, Pulsed, 405nm



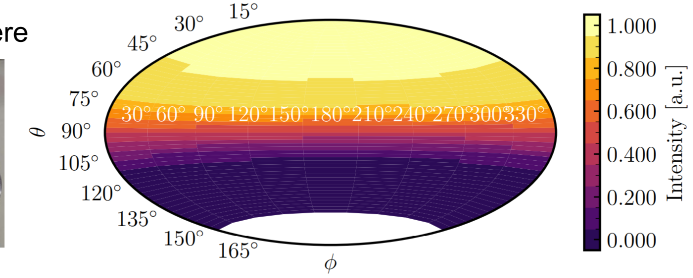


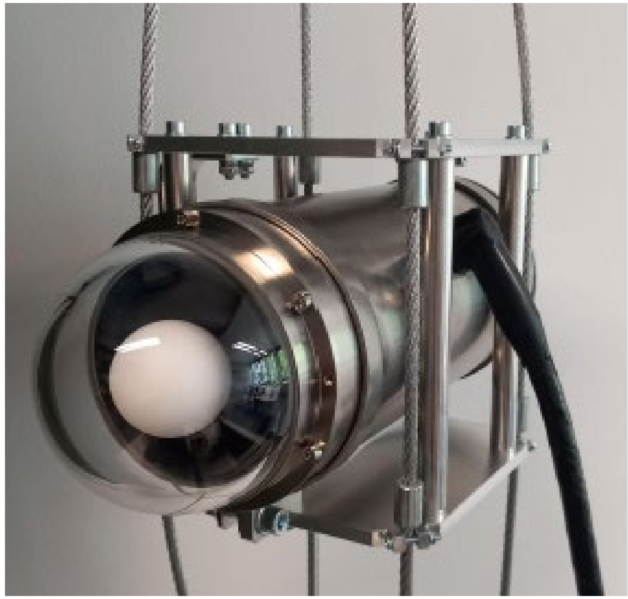
11 to be deployed in ice

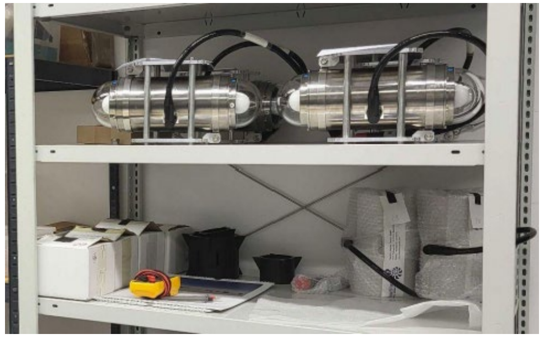
POCAM

- Absolutely-calibrated, self-monitoring, isotropic, nanosecond, high-intensity pulses, 5 wavelengths
- Study bulk and local ice properties
- Perform PMT efficiency studies

Optical PTFE Sphere







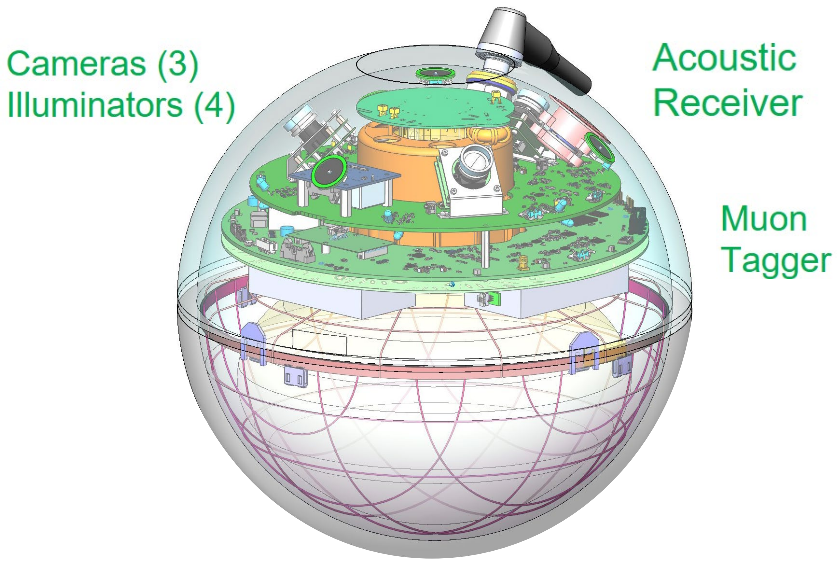
A self-monitoring precision calibration light source for large-volume neutrino telescopes (F. Henningsen et al 2020 JINST 15 P07031)

22 to be deployed in ice

Cross-calibration of optical modules

P-DOM: based on the existing IceCube DOMs with improved electronics

- Uses the same PMT, vessel, magnetic shield, and silicone gel, but with upgraded electronics
- New calibration devices include camera systems, acoustic receiver and muon tagger
- Cross-calibration with co-deployed artificial light sources and new optical modules

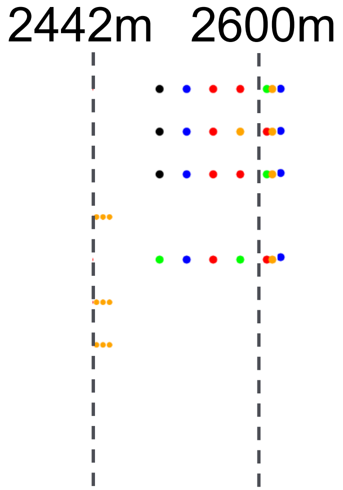


Deep subarray

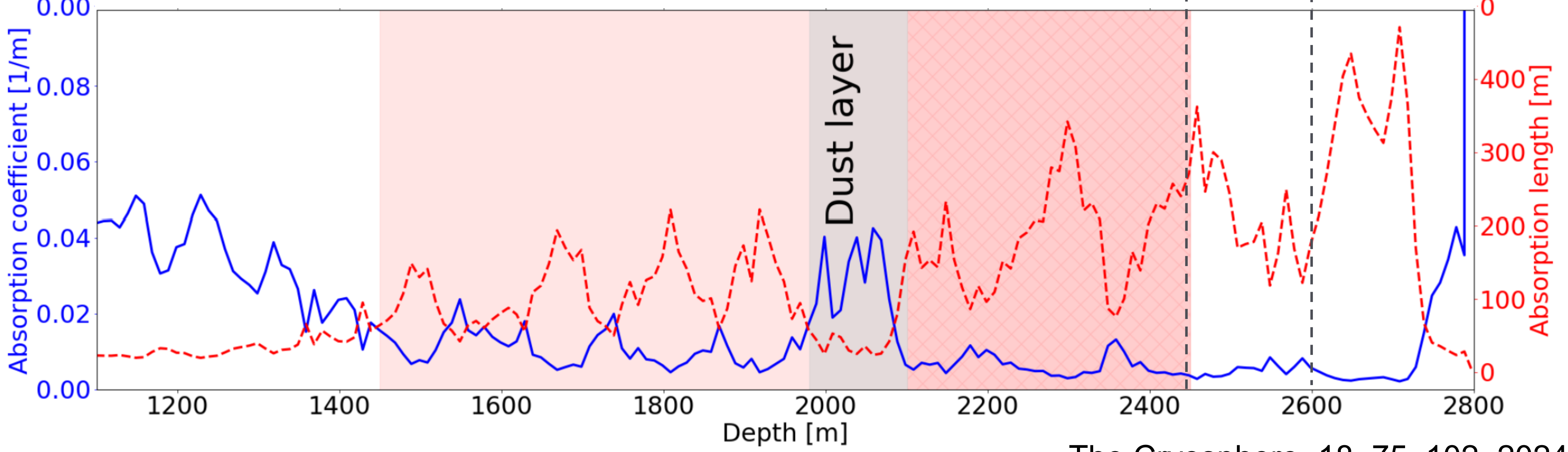
- Shares the main objectives of the Shallow subarray (including investigation of the deepest ice and testbeds in regions deeper than the IceCube depth)

In addition, unique opportunities with:

- Extending instrumentation into the deepest ice layers, enabling full-depth scanning from the surface to the deepest part of the array. Equipped with optical-sensor-based and camera-based logger systems for detailed ice studies
- Including seismometers at the closest position to the bedrock



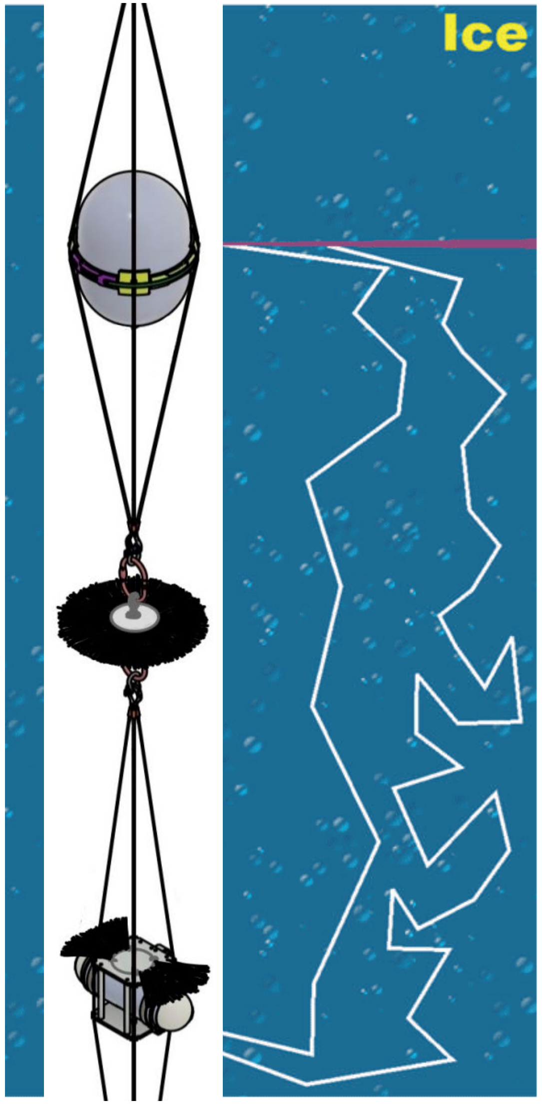
Investigation of ice below the IceCube array



The Cryosphere, 18, 75–102, 2024

Shallow to the deepest survey

Enabling full-depth scanning from the surface to the deepest part of the array



What the dust logger does?:

- Emits a horizontal laser beam into the surrounding ice
- As the light travels, it scatters off dust and impurities within the ice layer
- A small fraction of the scattered light returns to the instrument and is detected by onboard sensors
- Measurements are taken during string deployment
- This provides a depth-resolved map of optical scattering and multiple holes provides ice tilt models

Key components of the "Dust-logging" system

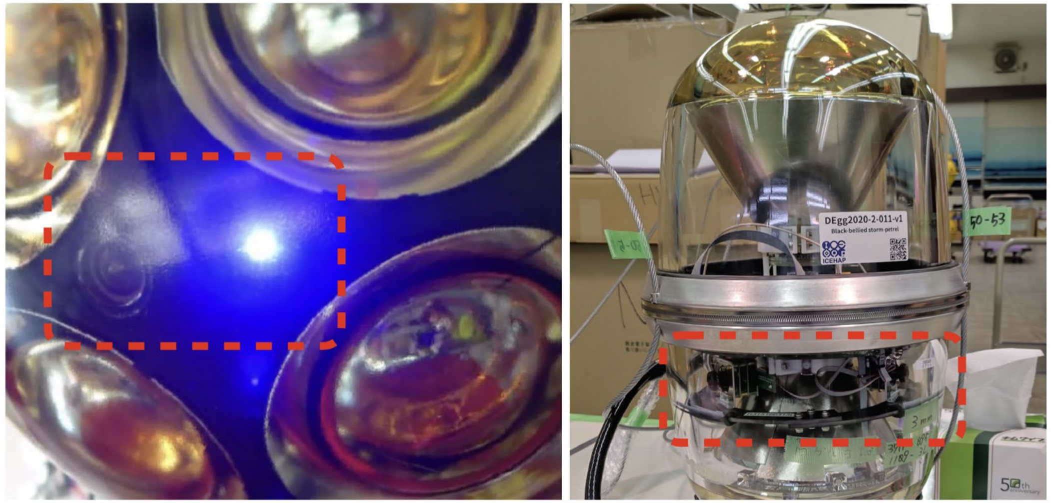
- A standard optical module acts as the detector
- A dedicated light source (modified POCAM), ~2 m away on the same string, acts as the emitter
- Baffles in between prevent light contamination from light traveling inside the water column

A co-deployed dust-logging instrument for the IceCube Upgrade and IceCube-Gen2, A. Eimer and M. Rongen, PoS-ICRC2025-1034, arXiv:2507.08430

Camera systems

Snapshot of ice in 2011. Central bubble column discovered by the Sweden Camera 1.0

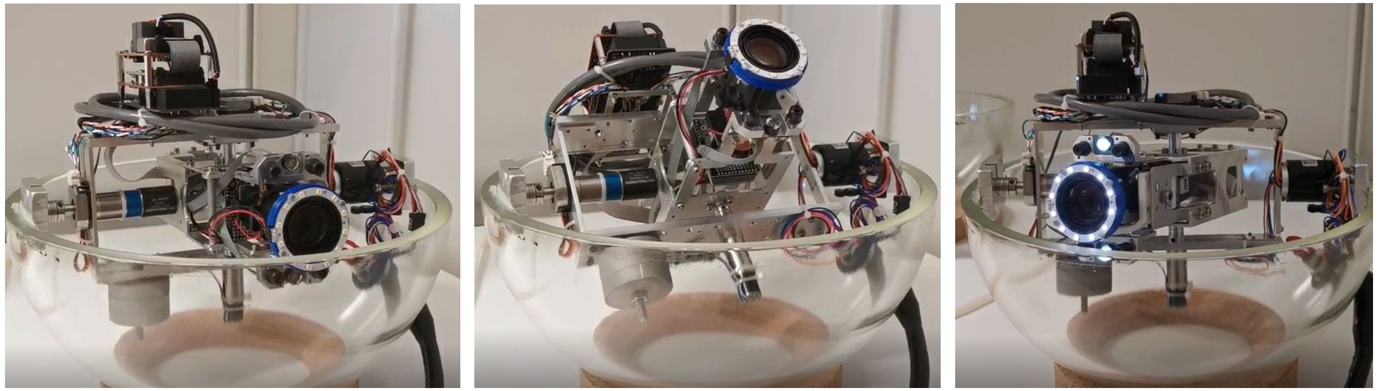
W. Kang, Phys. Sci. Forum 2023, 8(1), 49



Sweden Camera 2.0

- Deployed in targeted locations
- Steerable cameras with ~18× optical zoom
- Adjustable focus (from glass housing surface to infinity)
- Low-light sensitivity with high resolution
- Steerable illumination (lasers and LEDs)

Provides detailed images with a longe range in great depth

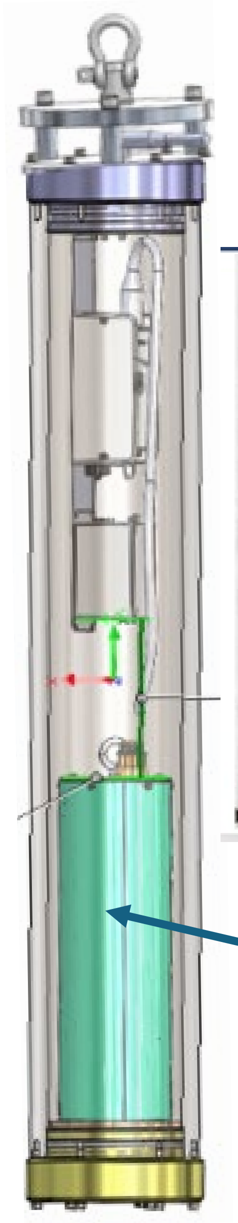


Upgrade Camera System

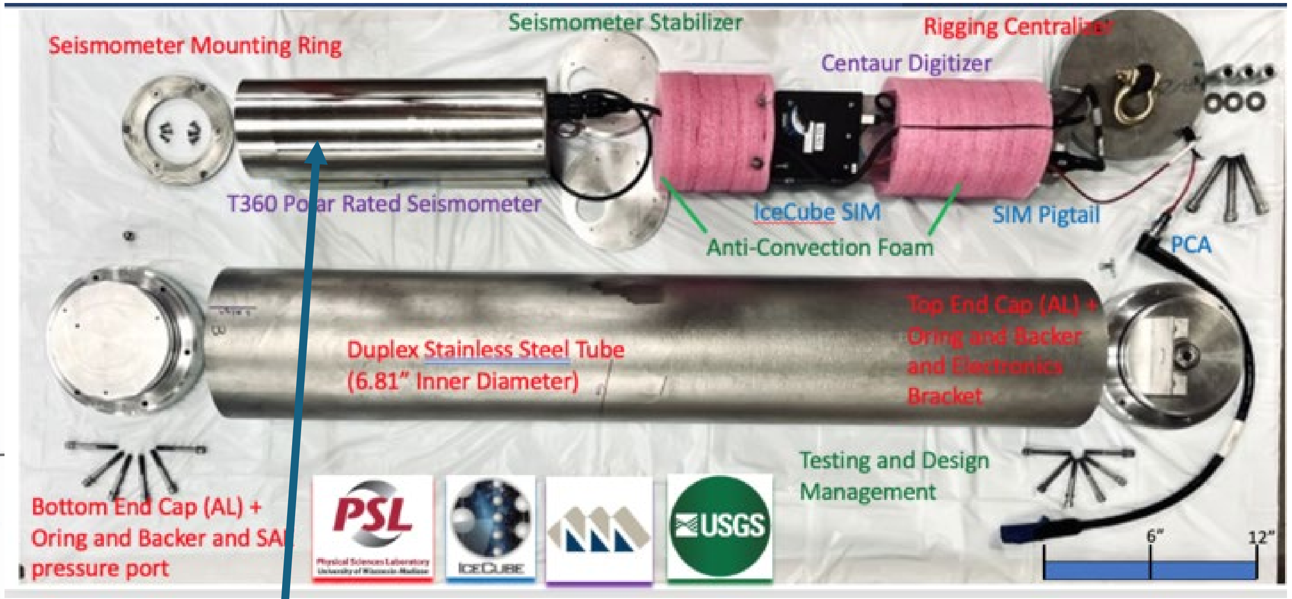
- Each of optical sensors (mDOM, D-Egg, pDOM) is equipped with three or four camera-LED pairs
- Survey the surrounding ice and refrozen drill holes
- Determining sensor positions and orientations

The deepest modules: Seismometers

- **A key location for global coverage:** Although many seismic stations exist worldwide, Antarctica remains one of the least instrumented regions for seismic coverage
- **Exceptionally quiet environment:** The South Pole has virtually no human-made vibrations or urban noise, making it one of the quietest places on Earth
- **Probing Earth's deep interior:** Seismometers record not only earthquakes but also Earth's free oscillations—studying these signals provides insight into the structure and properties of Earth's core and mantle



2 devices will be deployed at the depth of 2608m



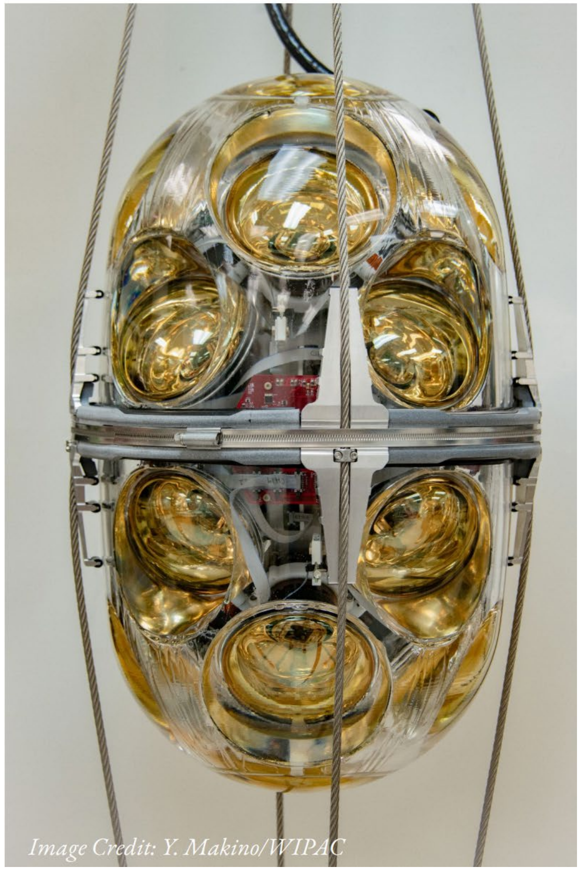
T360: A core sensing unit, designed to operate reliably in extreme polar conditions
- A mass–spring–sensor mechanism to convert ground motion into electrical signals with very high sensitivity

Testbeds for IceCube-Gen2 prototype modules

See the next talk by Vivian O'Dell on the IceCube-Gen2

Optical Sensors for Upgrade

Two variants of optical sensor designs for IceCube-Gen2 are to be installed in Upgrade array

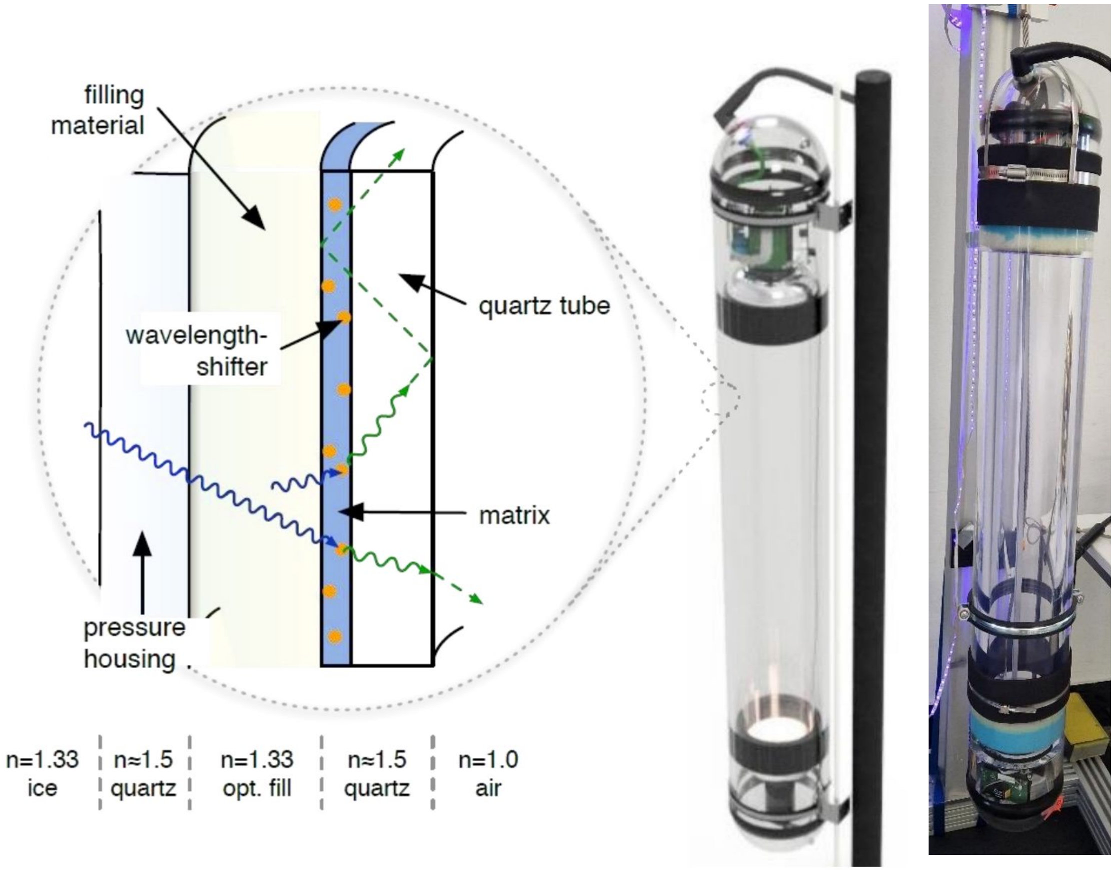


Currently merging two designs to create the best module design!

New ideas for cost-efficient designs: WOMs and FOMs

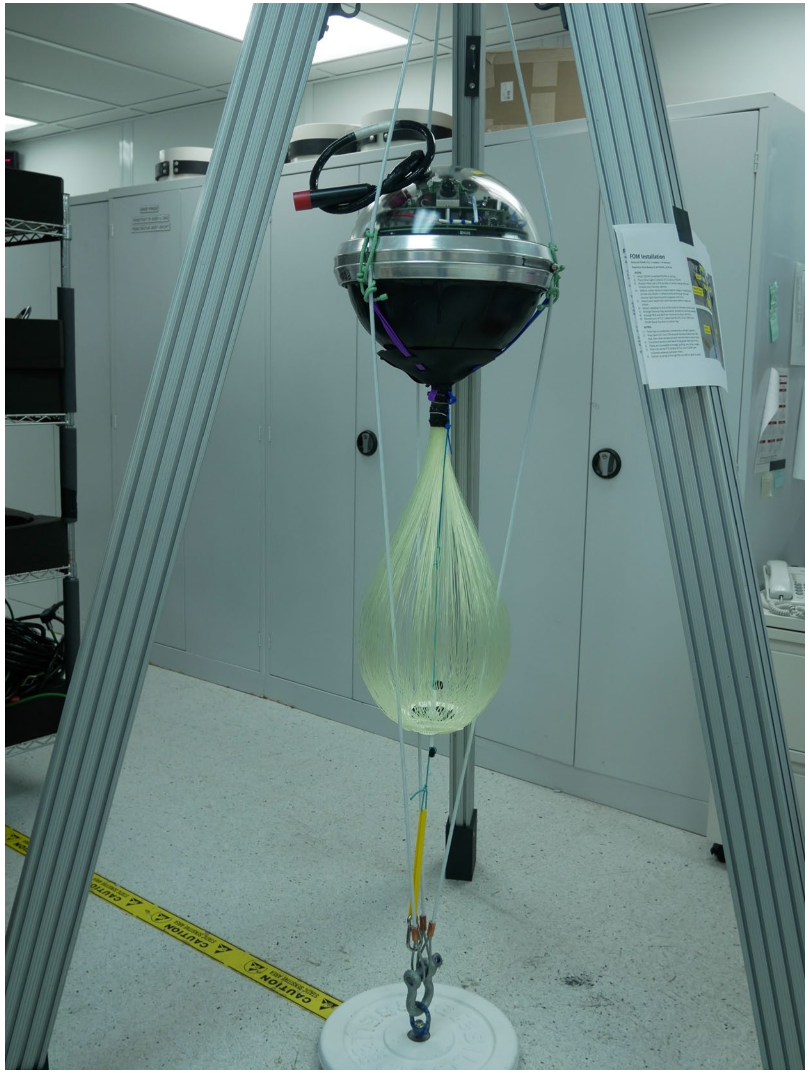
Optical modules with new ideas are also to be installed in the Upgrade array

Wavelength-Shifting Optical Module (WOM)



The Wavelength-Shifting Optical Module
Sensors **2022**, *22*(4), 1385

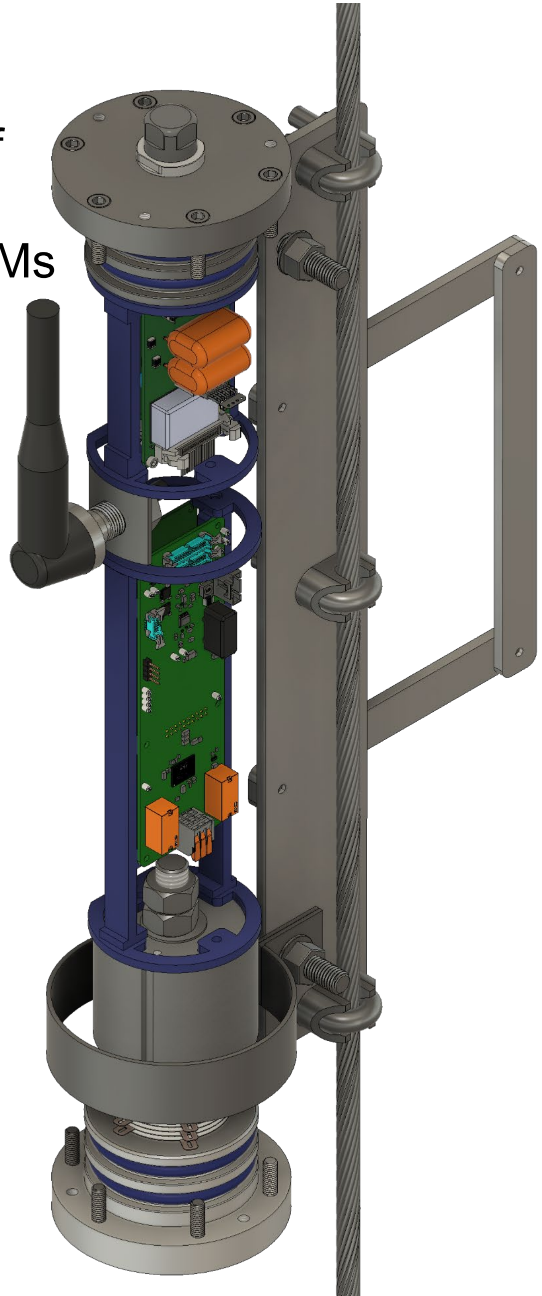
Fiber Optical Module (FOM)



Acoustic modules for Gen2 calibration

- **Proof of principle for Gen2**
  - Demonstration of technology readiness
  - Evaluation of acoustic media properties: attenuation, anisotropy, speed of sound over long ranges
- **3D-geometry calibration hybrid with optical devices**
  - Trilateration of positions of acoustic modules by acoustic transit times to 30 cm resolution
- **Glaciology**
  - Crystal orientation via acoustic wave propagation speed
  - Temperature gradients, layering and ice flow

- Transmission & reception of acoustic signals (5 - 40kHz)
- Receivers are also in P-DOMs



Summary

- The IceCube Upgrade
  - Construction planned for upcoming 2025/2026 South Pole season, starting next month
  - Adds 7 new strings with ~110 sensors and devices per string
  - Three subarrays: Physics, Shallow, Deep — each optimized for distinct calibration and physics goals
- Physics Goals & Performance
  - Enhanced sensitivity to GeV-scale neutrinos
  - At least 3× better angular resolution, 2× better energy reconstruction can be expected
  - Improved measurements of neutrino oscillation parameters and transient neutrino sources
- Calibration & Ice Studies
- Testbeds for the new optical sensors and the new calibration techniques

Deployment is just around the corner — stay tuned for exciting updates in physics and calibration from the IceCube Upgrade!

25-Apr	Totals								Full name
String	**87**	**88**	**89**	**90**	**91**	**92**	**93**	TOTAL	
mDOM	55	59	58	57	58	57	59	403	mDOM
DEgg	40	40	40	40	40	40	40	280	D-Egg
POCAM	3	2	5	3	3	3	3	22	POCAM
PB	1	2	1	1	3	2	1	11	Pencil Beam (PB)
SWE	1	1	1	1	0	2	1	7	Swedish Camera (SWE)
AM	2	1	2	1	1	1	2	10	Acoustic Module (AM)
pDOM	3	2	2	1	2	4	3	17	pDOM
WOM1	3	2	0	0	0	0	0	5	Wavelength-shifting Optical Module Empty (WOM1)
WOM2	0	0	0	2	1	1	1	5	Wavelength-shifting Optical Module Full (WOM2)
FOM	0	0	1	0	1	1	1	4	Fiber-optic Optical Module (FOM)
LOM-16	0	0	0	1	2	2	1	6	Long Optical Module 16 PMTs (LOM-16)
LOM-18	0	0	2	0	1	1	2	6	Long Optical Module 18 PMTs (LOM-18)
SM	0	1	0	1	0	0	0	2	Seismometer (SM)
LOMLoggerPOCAM	0	0	0	0	0	1	1	2	LOMLoggerPOCAM
iTemp	0	0	0	1	1	0	1	3	Tilt Temp Sensor (iTemp)
Paro	1	1	1	1	1	1	1	7	Pressure Sensor (Paro)
ALL	109	111	113	110	114	116	117	790	**TOTAL**
X	8	6	4	8	4	2	2		

Shallow region

- Above the dust layer
- 18 sensors max/string
- Spacing is 75 to 25 m
- Load is transferred at each sensor
- Similar to IceCube

Quad / String	87	88	89	90	91	92	93	Depth	distance to next sensor	Install Kit
	X	X	mDOM	X	mDOM	pDOM	mDOM	1375	25	S
	X	X	POCAM	X	PB	mDOM	pDOM	1400	25	S
	X	mDOM	mDOM	X	LOM-18	DEgg	mDOM	1425	25	S
1	X	mDOM	mDOM	X	mDOM	mDOM	mDOM	1450	75	S
	mDOM	mDOM	pDOM	mDOM	mDOM	pDOM	mDOM	1525	25	S
	AM	POCAM	FOM	mDOM	mDOM	POCAM	mDOM	1550	25	S
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	1575	25	S
2	POCAM	mDOM	mDOM	mDOM	mDOM	mDOM	POCAM	1600	25	S
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	1625	25	S
	mDOM	mDOM	POCAM	POCAM	mDOM	mDOM	mDOM	1650	25	S
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	1675	25	S
3	mDOM	mDOM	mDOM	POCAM	mDOM	mDOM	mDOM	1700	75	S
	pDOM	pDOM	POCAM	mDOM	FOM	FOM	FOM	1775	25	S
	mDOM	mDOM	mDOM	DEgg	POCAM	DEgg	mDOM	1800	25	S
	pDOM	PB	mDOM	DEgg	WOM2	WOM2	WOM2	1825	25	S
4	mDOM	mDOM	LOM-18	LOM-16	LOM-16	LOM-16	LOM-18	1850	125	S
	X	X	X	X	X	X	X	1975	25	S
	X	X	X	X	X	X	X	2000	25	S
	X	mDOM	X	mDOM	X	mDOM	POCAM	2025	25	S
5	X	DEgg	X	mDOM	X	POCAM	AM	2050	113	S

Physics region

- Most of the string
- quad 6 to 20, 90 devices/string
- Spacing is 3 m
- Load is never transferred within the region, just at the bottom and top of the region

Quad / String	87	88	89	90	91	92	93	Depth	distance to next sensor	Install Kit
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2163	3	P1
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2166	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2169	3	Px
	DEgg	DEgg	AM	DEgg	DEgg	pDOM	DEgg	2172	3	Px
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2175	3	Px
6	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2178	3	P6
	mDOM	mDOM	mDOM	mDOM	mDOM	PB	mDOM	2181	3	P1
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2184	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2187	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	POCAM	mDOM	2190	3	Px
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2193	3	Px
7	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2196	3	P6
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2199	3	P1
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2202	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2205	3	Px

. . .

Quad / String	87	88	89	90	91	92	93	Depth	distance to next sensor	Install Kit
18	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2394	3	P6
	mDOM	mDOM	mDOM	PB	mDOM	mDOM	mDOM	2397	3	P1
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2400	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2403	3	Px
	mDOM	mDOM	mDOM	POCAM	mDOM	mDOM	mDOM	2406	3	Px
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2409	3	Px
19	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2412	3	P6
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2415	3	P1
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2418	3	Px
	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2421	3	Px
	DEgg	DEgg	DEgg	DEgg	DEgg	AM	DEgg	2424	3	Px
	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	DEgg	2427	3	Px
20	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	mDOM	2430	12	P6

Deep region of short strings

- MCA ends at 2444 m
- Bottom sensor at 2457 m
- Eye wires used to extend to the bottom instrument
- Load is not transferred (MCA not present)

tbd

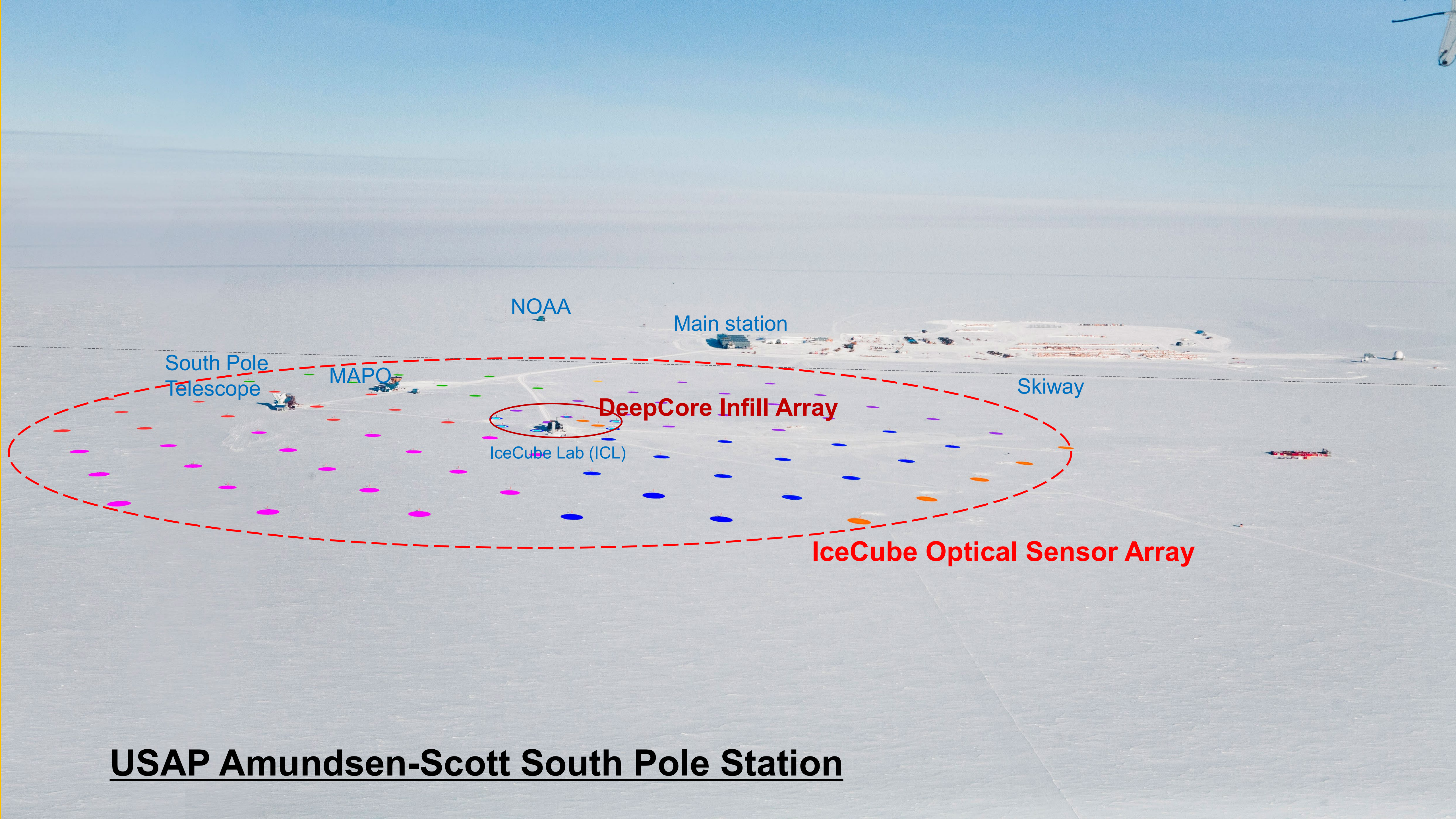
Quad / String	87	88	89	90	91	92	93	Depth	distance to next sensor	Install Kit
	WOM1	WOM1		WOM2				2442	3	DS
	WOM1	WOM1		WOM2				2445	3	DS
	WOM1	mDOM		mDOM				2448	3	DS
	POCAM	X		X				2451	3	DS
	DEgg	X		X				2454	3	
21	mDOM	SM		SM				2457	0	DS
22								2457	0	
23				iTemp						
24	Paro	Paro		Paro						
	WS	WS		WS				2457		

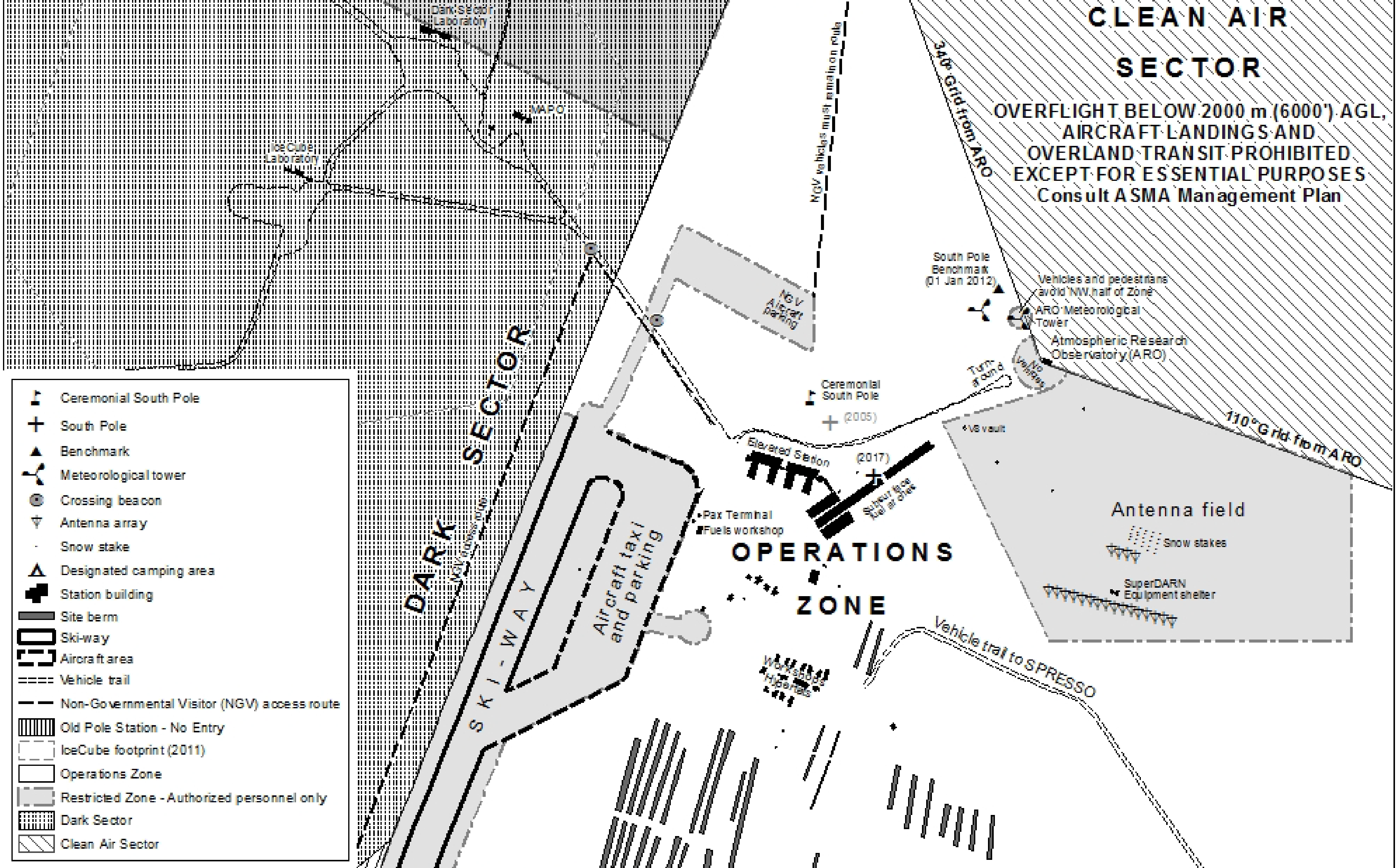
Deep region of long strings

- MCA ends at 2444m
- Bottom sensor at 2604m
- Dyneema rope chain used
  to extend to bottom
- Load is not transferred (MCA not present)

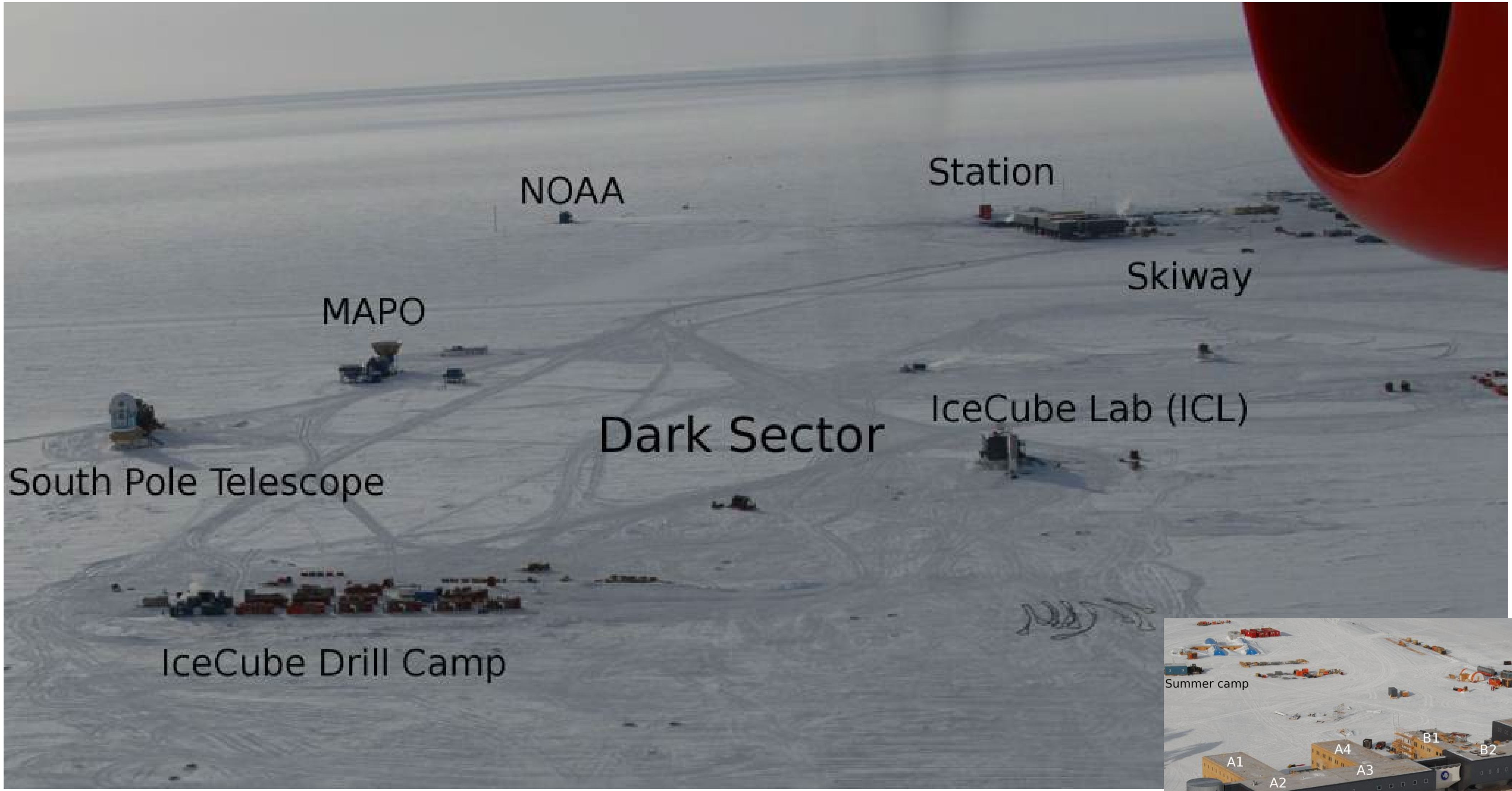
Quad / String	87	88	89	90	91	92	93	Depth	distance to next sensor	Install Kit
			mDOM		mDOM	mDOM	mDOM	2475	25	DL
			LOM-18		LOM-16	LOM-18	LOM-18	2500	25	DL
			POCAM		pDOM	pDOM	pDOM	2525	25	DL
			DEgg		DEgg	PB	mDOM	2550	25	DL
			AM		POCAM	DEgg	DEgg	2575	25	DL
21			SWE		PB	LOM-16	LOM-16	2600	0	DL
22						LOMlogge	LOMLogge	2602	0	DL
23					iTemp		iTemp	2603		
24			Paro		Paro	Paro	Paro	2604		
			WS		WS	WS	WS	2608		

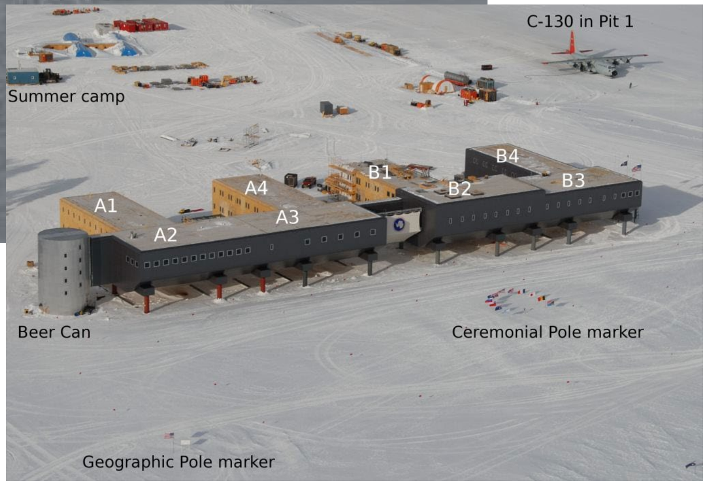
93 (L)
Paro (2623.5m) 158.85m 20 m below bottom
iTemp (2623.5m) 20 m below bottom


NOAA
Main station
South Pole
Telescope
MAPO
Skiway
DeepCore Infill Array
IceCube Lab (ICL)
IceCube Optical Sensor Array
USAP Amundsen-Scott South Pole Station



CLEAN AIR
SECTOR
OVERFLIGHT BELOW 2000 m (6000') AGL,
AIRCRAFT LANDINGS AND
OVERLAND TRANSIT PROHIBITED
EXCEPT FOR ESSENTIAL PURPOSES
Consult ASMA Management Plan
340° Grid from ARO
110° Grid from ARO
Dark Sector Laboratory
MAPO
IceCube Laboratory
NGV vehicles must remain on route
NGV Aircraft parking
South Pole Benchmark (01 Jan 2012)
Vehicles and pedestrians avoid NW half of Zone
ARO Meteorological Tower
Atmospheric Research Observatory (ARO)
No vehicles
Turn around
Ceremonial South Pole
(2005)
(2017)
Elevated Station
VS vault
Antenna field
Snow stakes
SuperDARN Equipment shelter
Pax Terminal
Fuels workshop
OPERATIONS
ZONE
DARK SECTOR
NGV access route
SKI-WAY
Aircraft taxi and parking
Vehicle trail to SPRESSO
Workshops Hypertats
Ceremonial South Pole
South Pole
Benchmark
Meteorological tower
Crossing beacon
Antenna array
Snow stake
Designated camping area
Station building
Site berm
Ski-way
Aircraft area
Vehicle trail
Non-Governmental Visitor (NGV) access route
Old Pole Station - No Entry
IceCube footprint (2011)
Operations Zone
Restricted Zone - Authorized personnel only
Dark Sector
Clean Air Sector


NOAA
Station
Skiway
MAPO
IceCube Lab (ICL)
Dark Sector
South Pole Telescope
IceCube Drill Camp


C-130 in Pit 1
Summer camp
B4
B1
A4
B2
B3
A1
A3
A2
Beer Can
Ceremonial Pole marker
Geographic Pole marker