IceCube-Gen2

From Discovery to Astronomy

IceCube Bootcamp
June 2023

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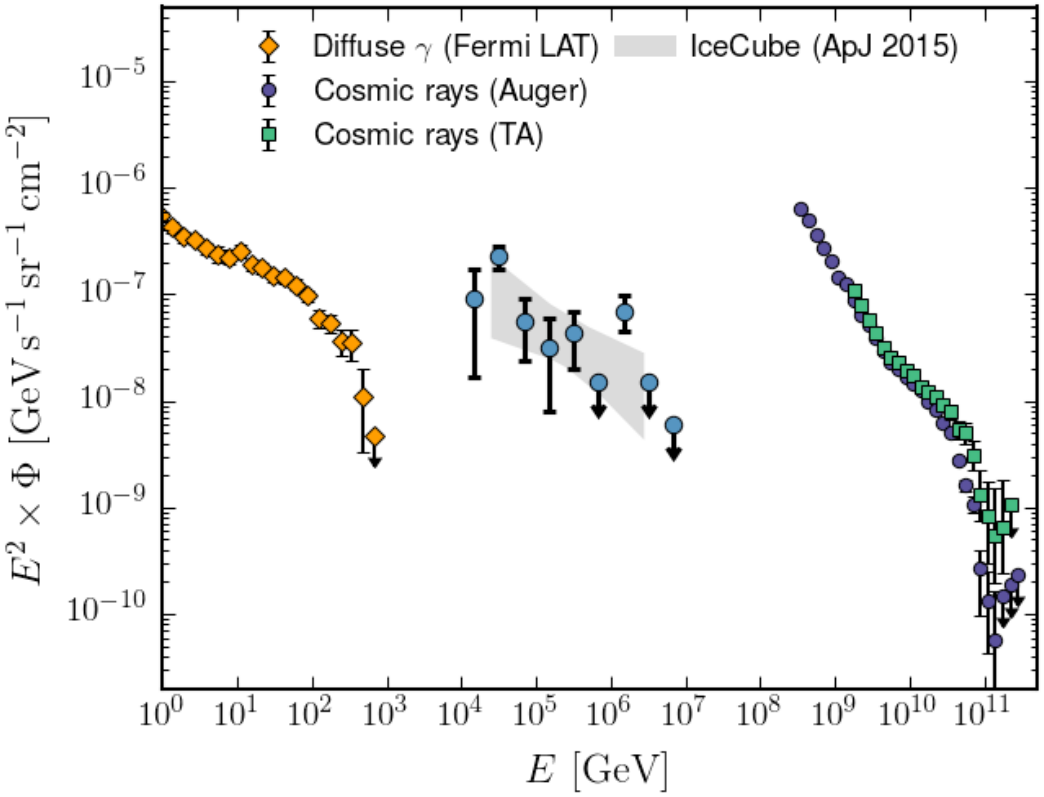
Univ. Wisconsin-Madison

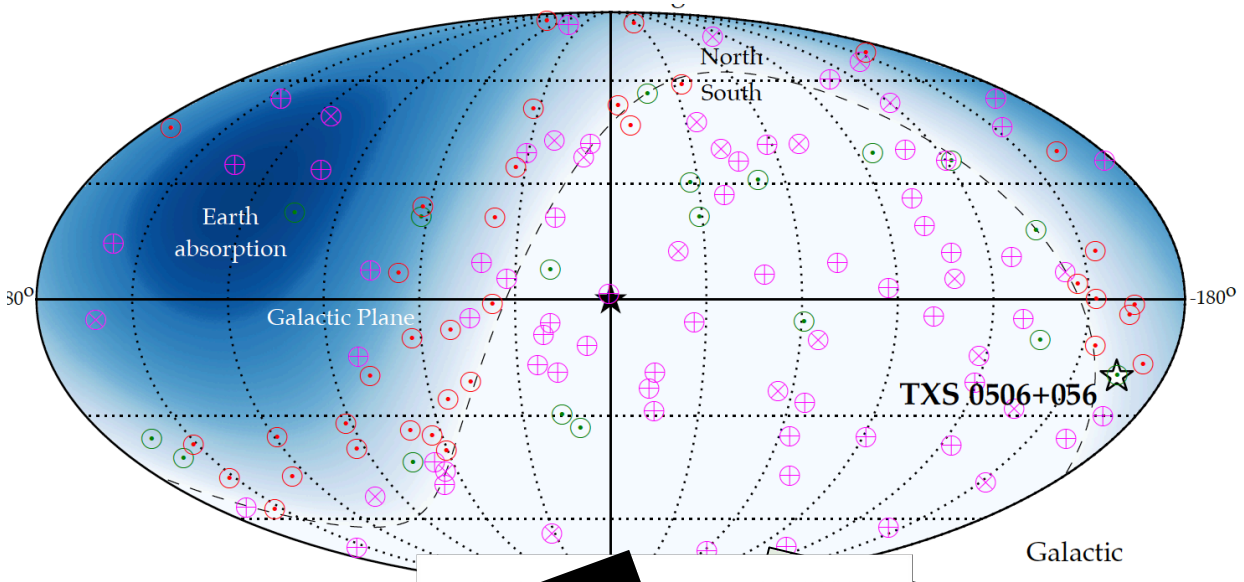
IceCube
GEN2

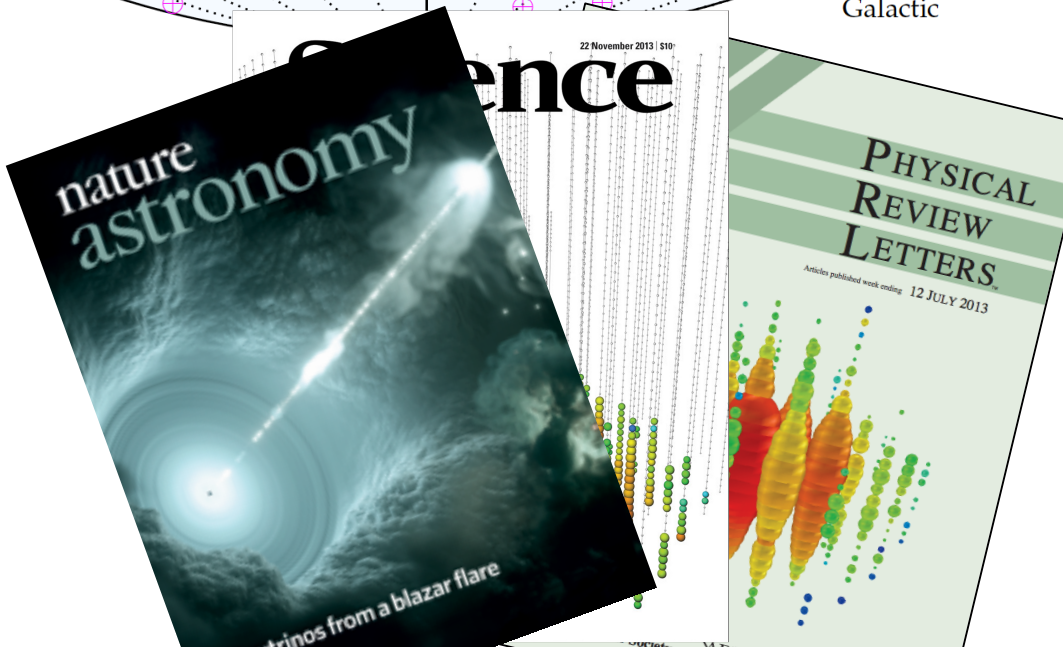
10 yrs of IceCube - a first view on the PeV Universe

Multimessenger spectroscopy



First sky map of cosmic neutrinos





Some highlights:

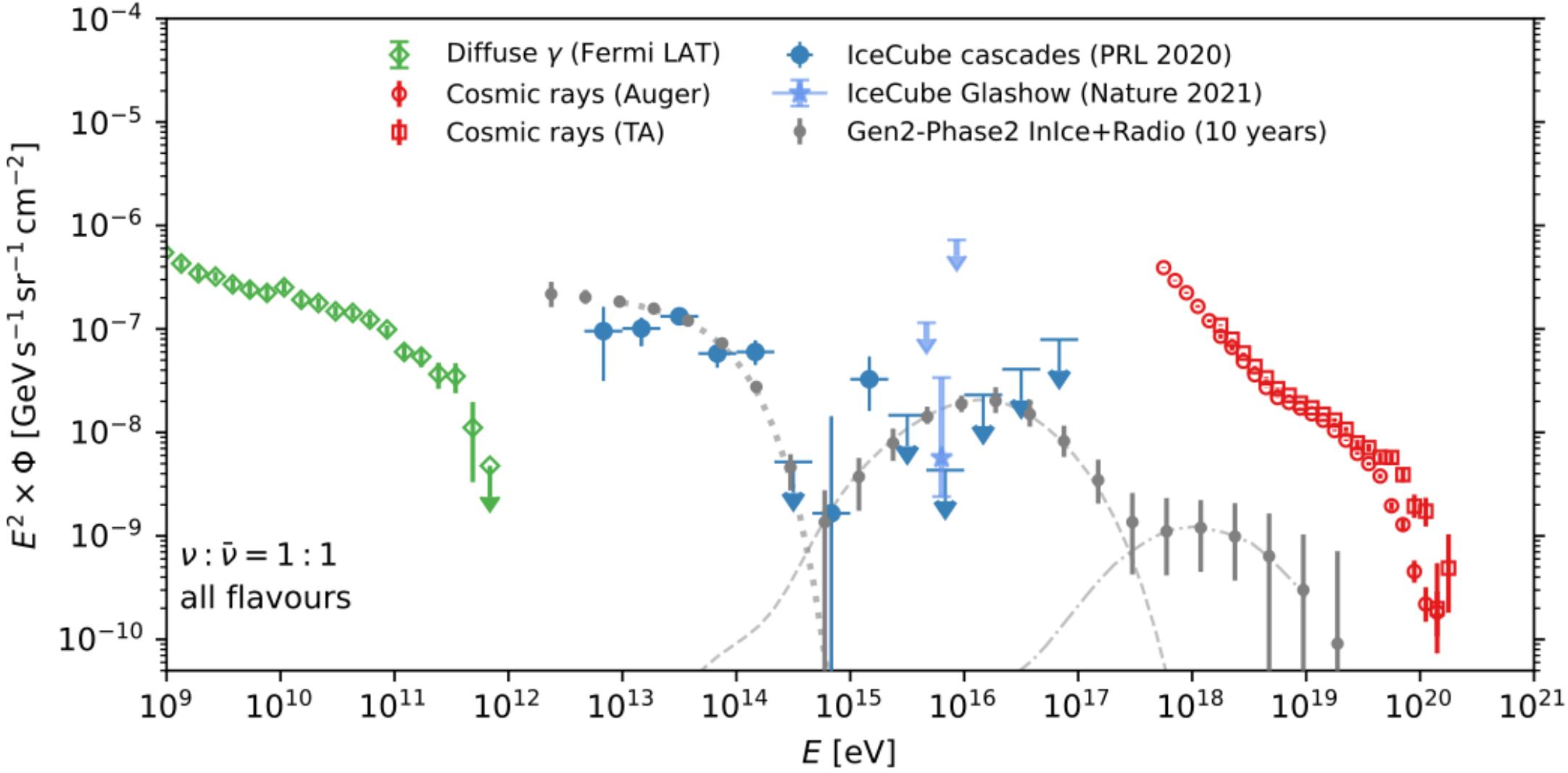
2013: Discovery of cosmic PeV neutrino flux

2018: Evidence for Blazars as neutrino sources

2019: Observation of first tau neutrino

IceCube GEN2

Understanding cosmic particle acceleration through multimessenger observation



ICECUBE GEN2

Detecting Cosmic Neutrinos

Event Rates are small.

Theory suggested:
Energy: 100 TeV to 1 PeV
Need target of 1 billion tons
or 1 km^3.

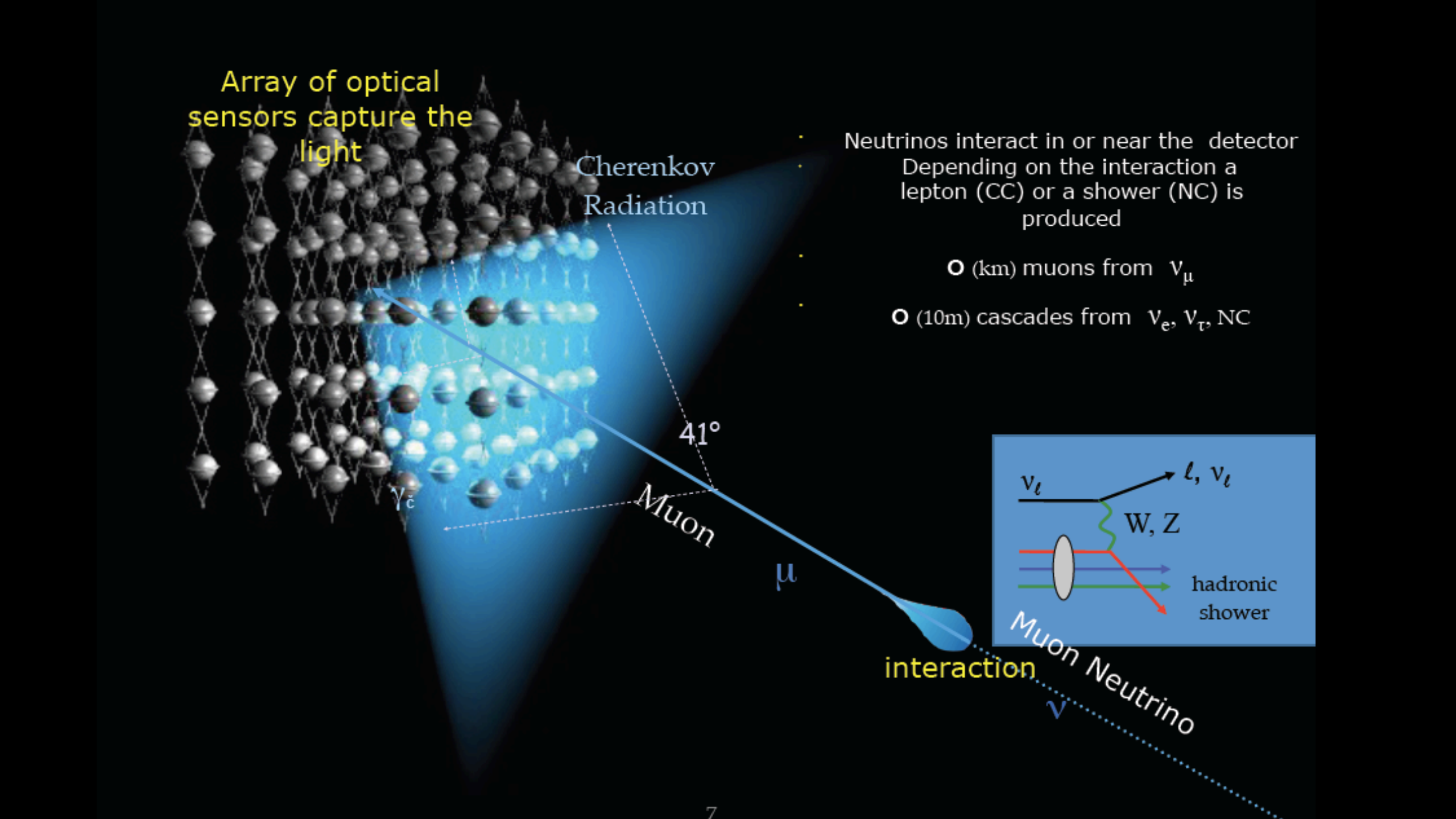
Optical Cherenkov method
using natural water/ice as target

—> the ice option: IceCube

At higher energies: 10^18
Event rates
1000 times smaller.

Need target of order 1000km^3

Radio detection of neutrinos


Array of optical sensors capture the light
Cherenkov Radiation
41°
γ_c
Muon
μ
Neutrinos interact in or near the detector
Depending on the interaction a lepton (CC) or a shower (NC) is produced
(km) muons from ν_μ
(10m) cascades from ν_e, ν_τ, NC
ν_ℓ
ℓ, ν_ℓ
W, Z
hadronic shower
interaction
Muon Neutrino
ν

Bert:
Energy 1 PeV

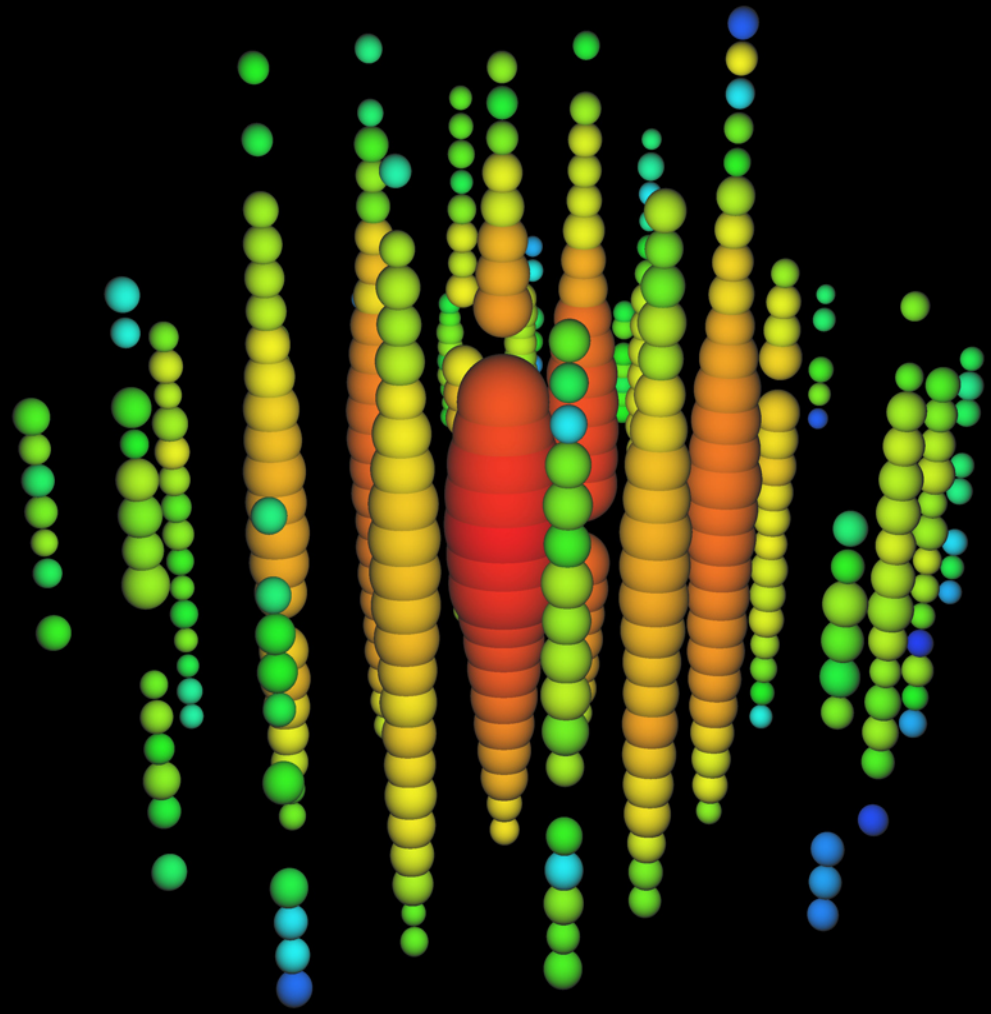
How well could we reconstruct
this event with fewer strings?

Analyzed event using only subsets of 20 IceCube strings spaced at 250m.

Result:
Vertex reconstruction:~ 12m
Angular resolution: ~30°
Energy resolution: 10%

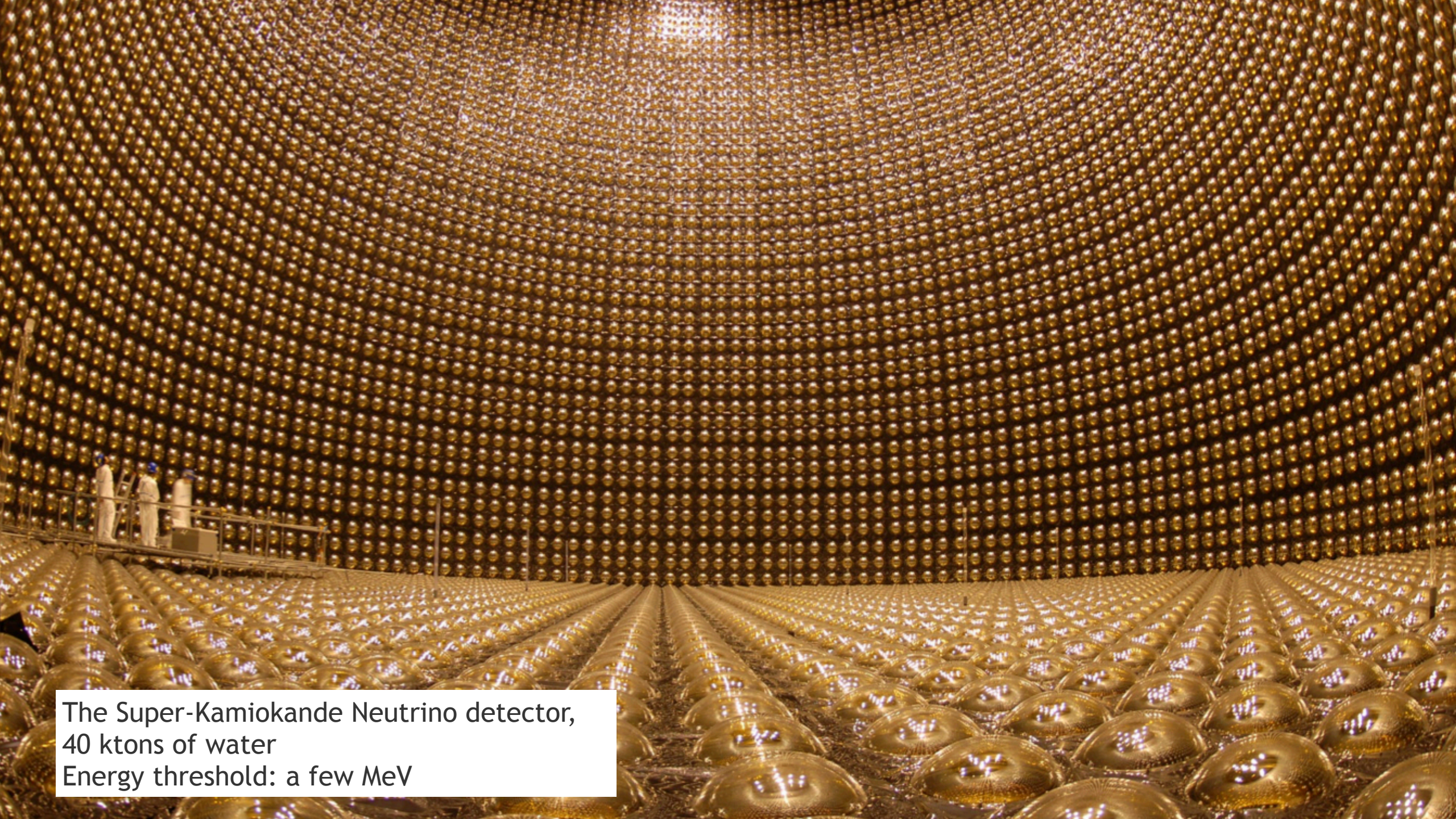
Same result for Ernie, the other PeV event.

→ Don't need 100,000 photoelectrons to measure energy to 10%.



Dr. Strangepork

Deposited energy: 71 TeV
7.1 x 10^13 eV



The Super-Kamiokande Neutrino detector,
40 ktons of water
Energy threshold: a few MeV

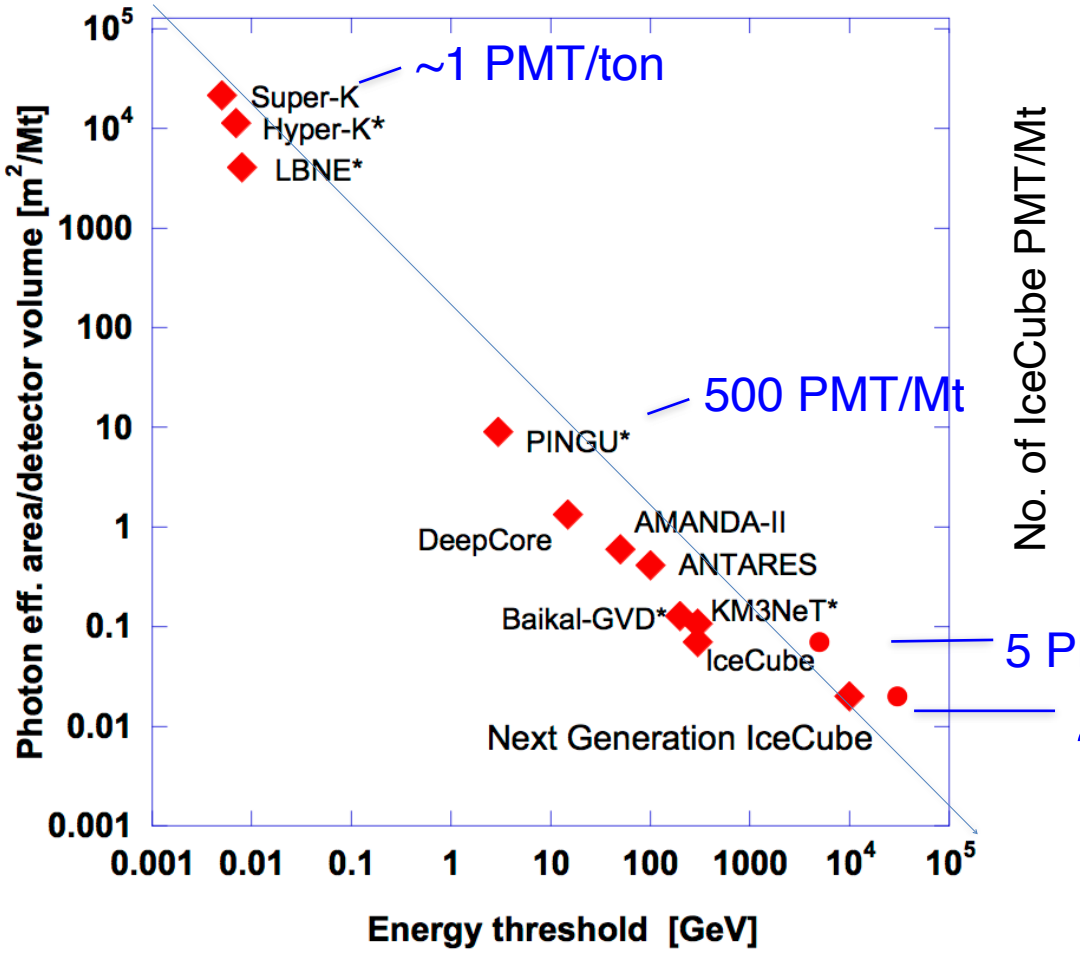
Water Cherenkov detectors: PMT coverage vs energy threshold

New evidence at higher energy → science requirement: focus on higher energy

We can reduce the PMT coverage (string density) by increasing the energy thre

Can we increase detection volume by an order of magnitude for similar cost?

This chart suggest yes.



Define:

Photon effective area =

Number of PMT

x Cathode area

x Quantum efficiency

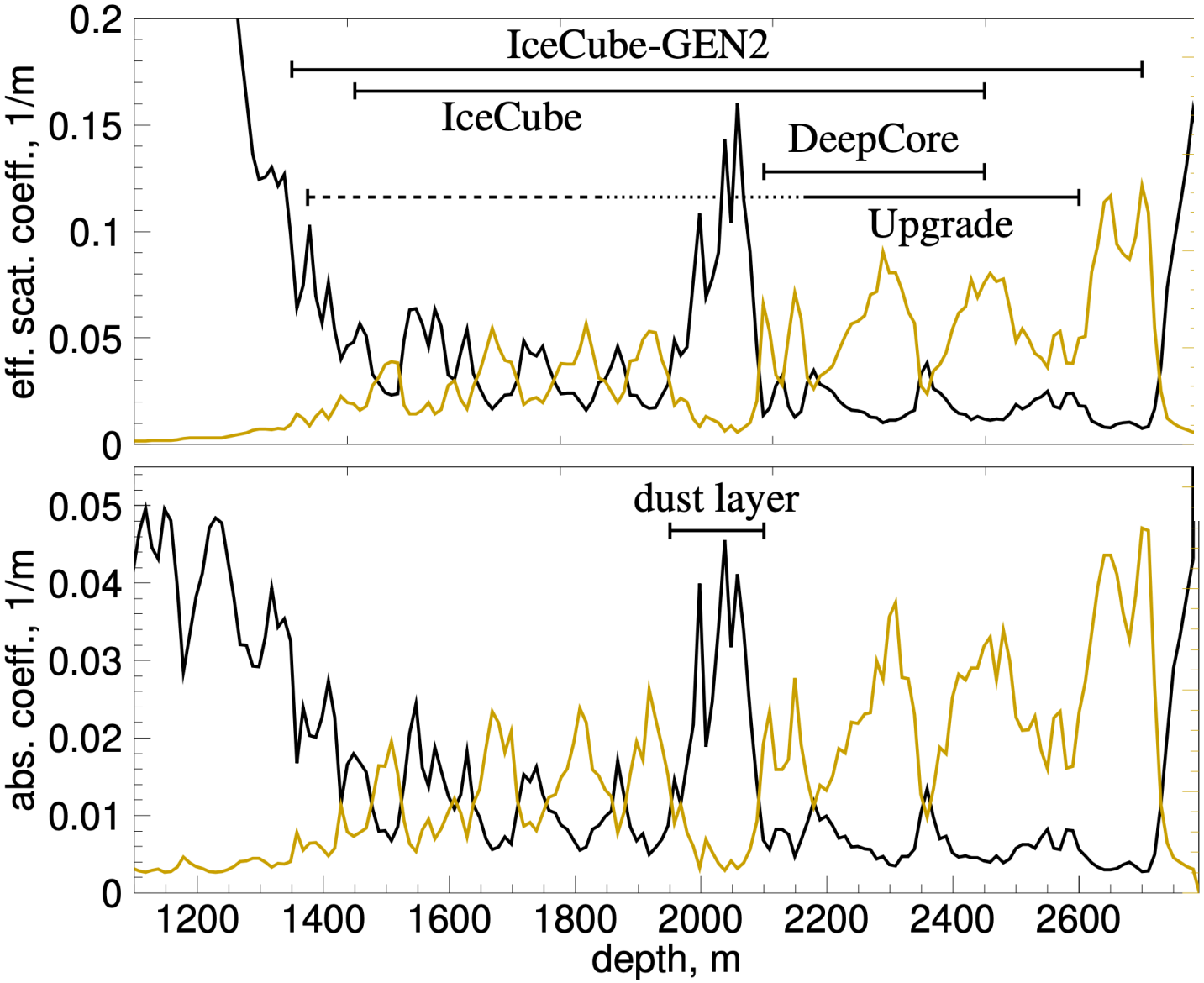
= equivalent area of 100% photon detection.

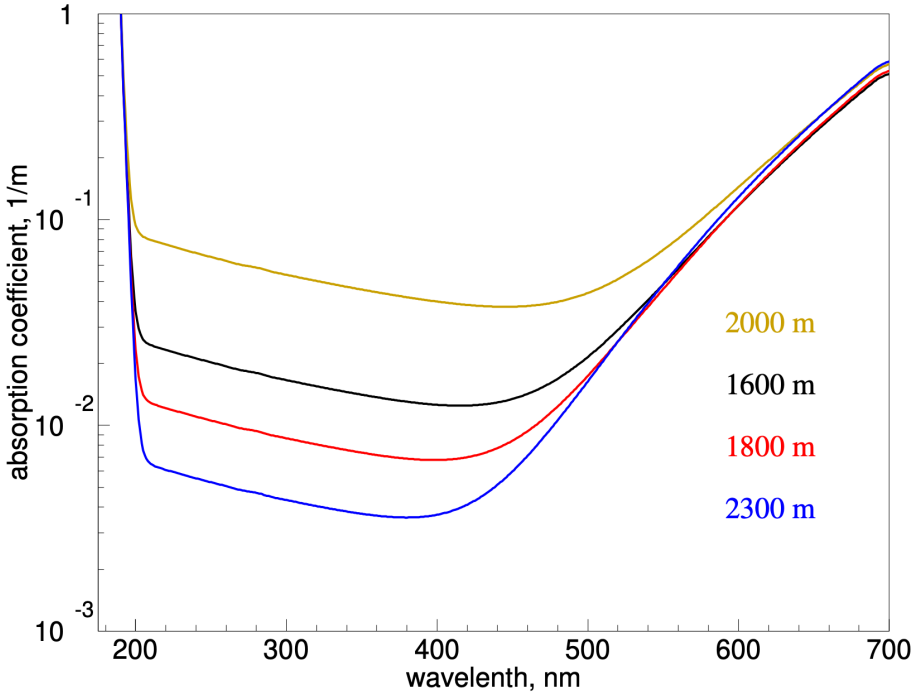
(collection efficiency not included here.)

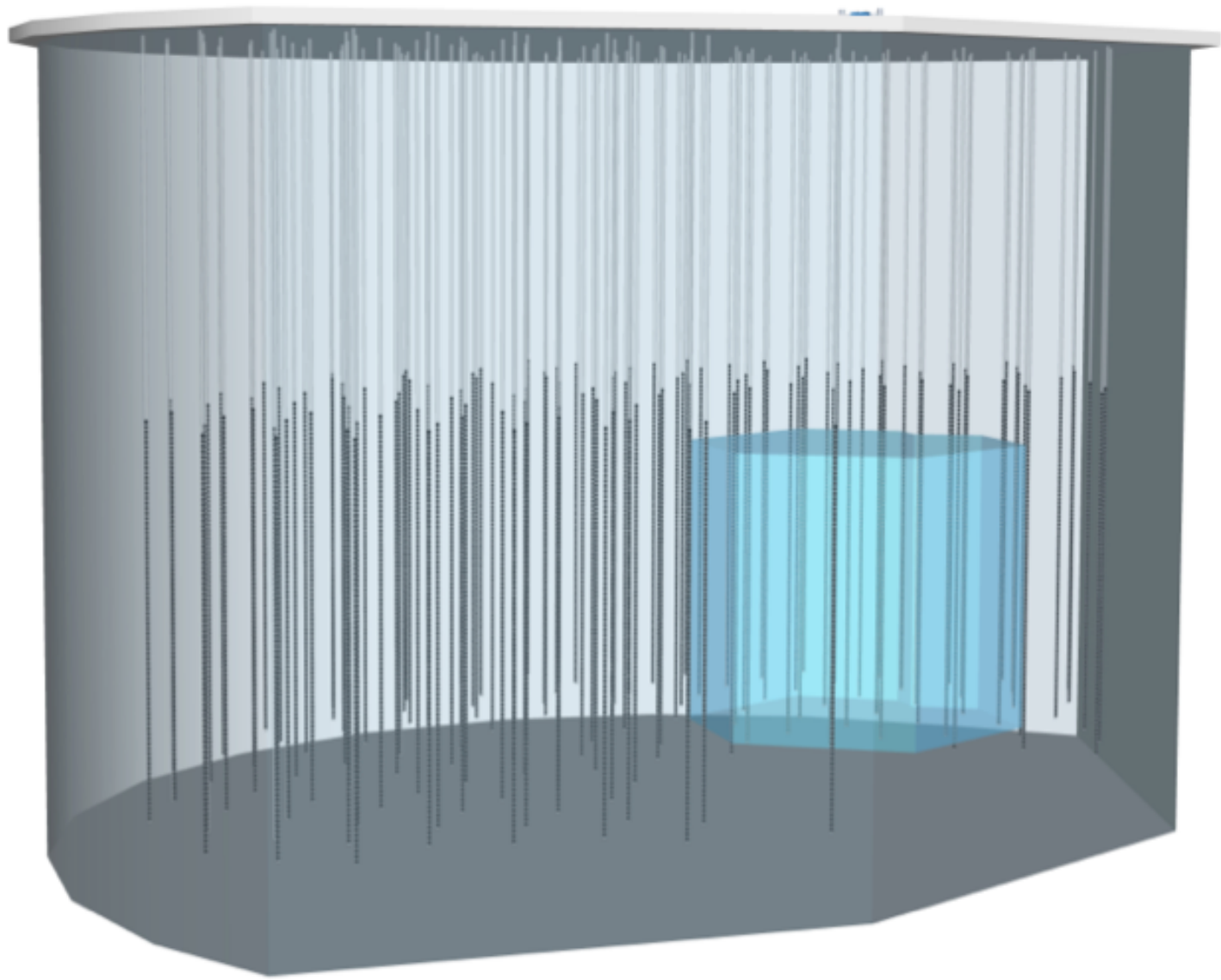
Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

Ice properties

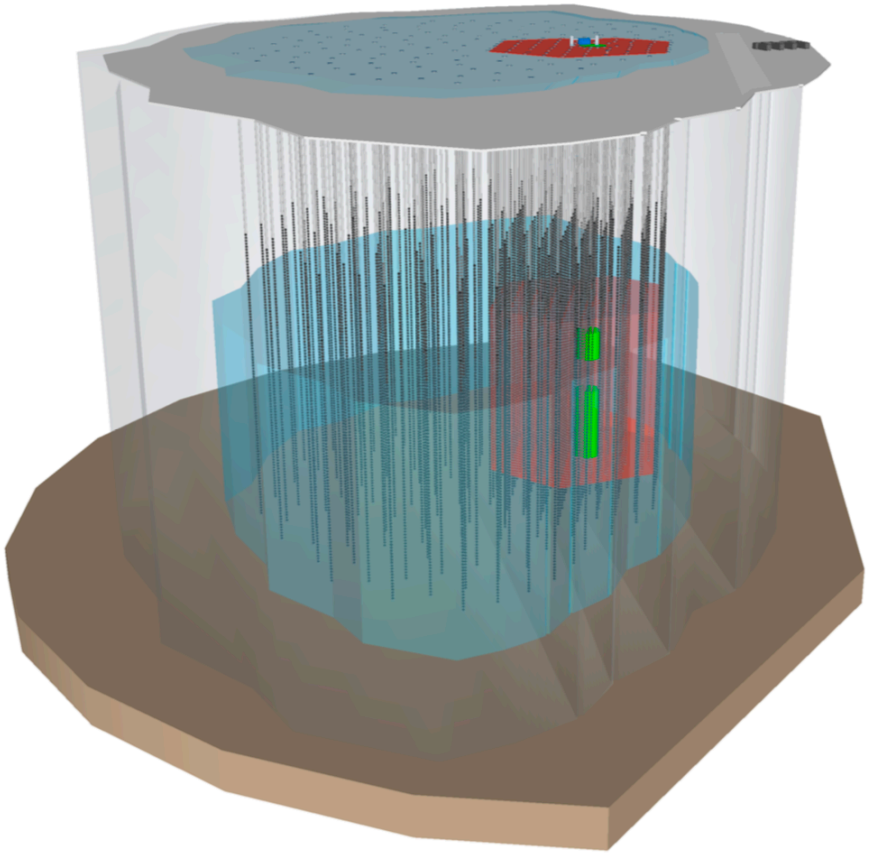


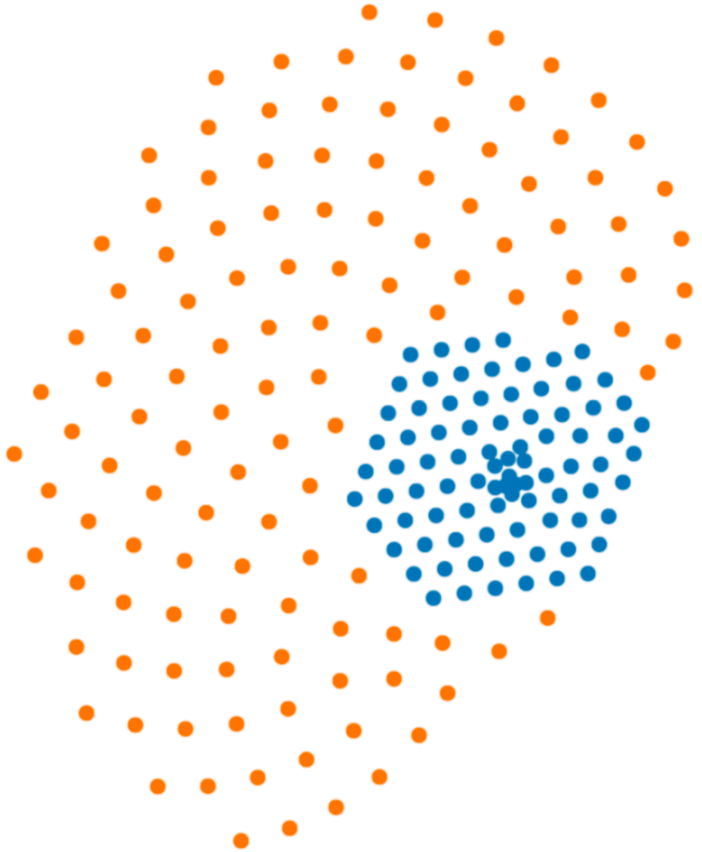




IceCube-Gen2

A Vision for the Future of Neutrino Astronomy in Antarctica (arXiv:1412.5106)





Artist's conception
120 strings at 240 m spacing

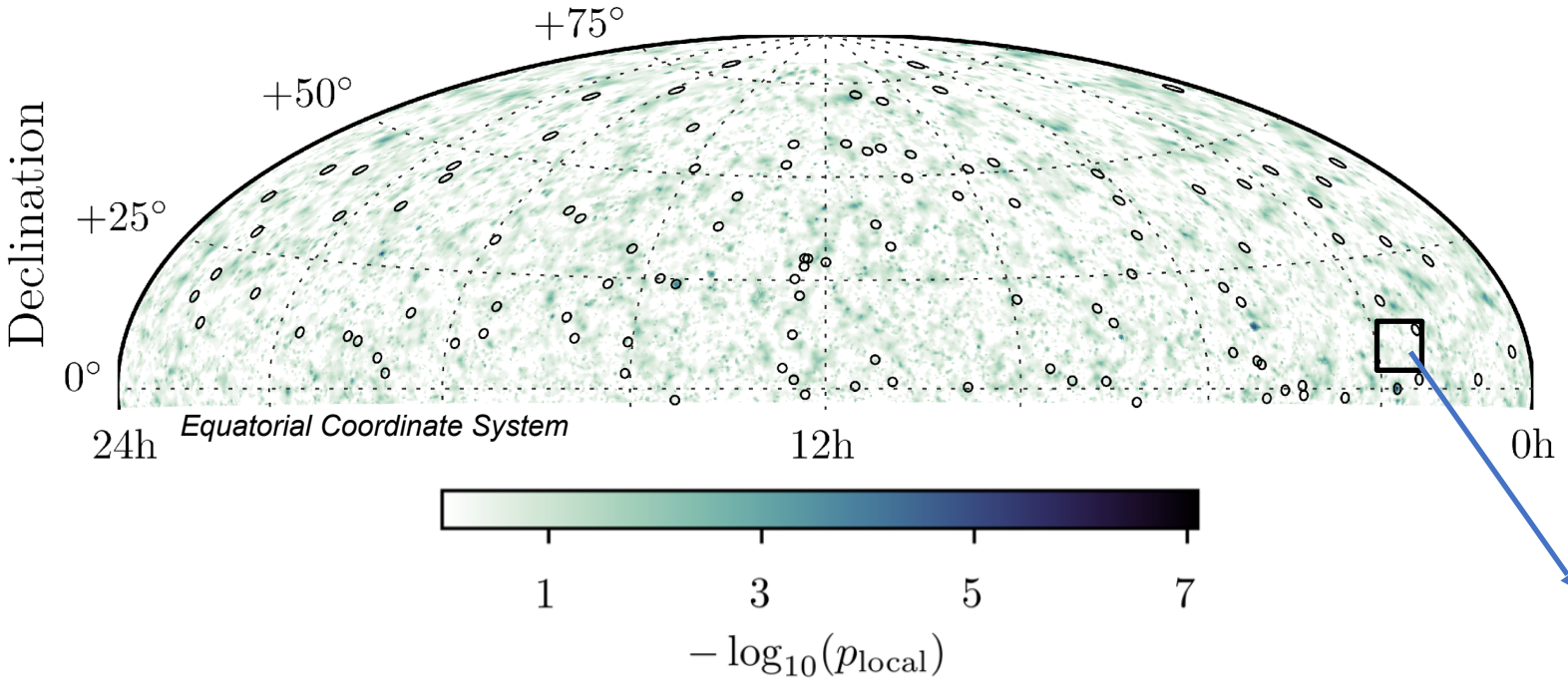
ICECUBE GEN2

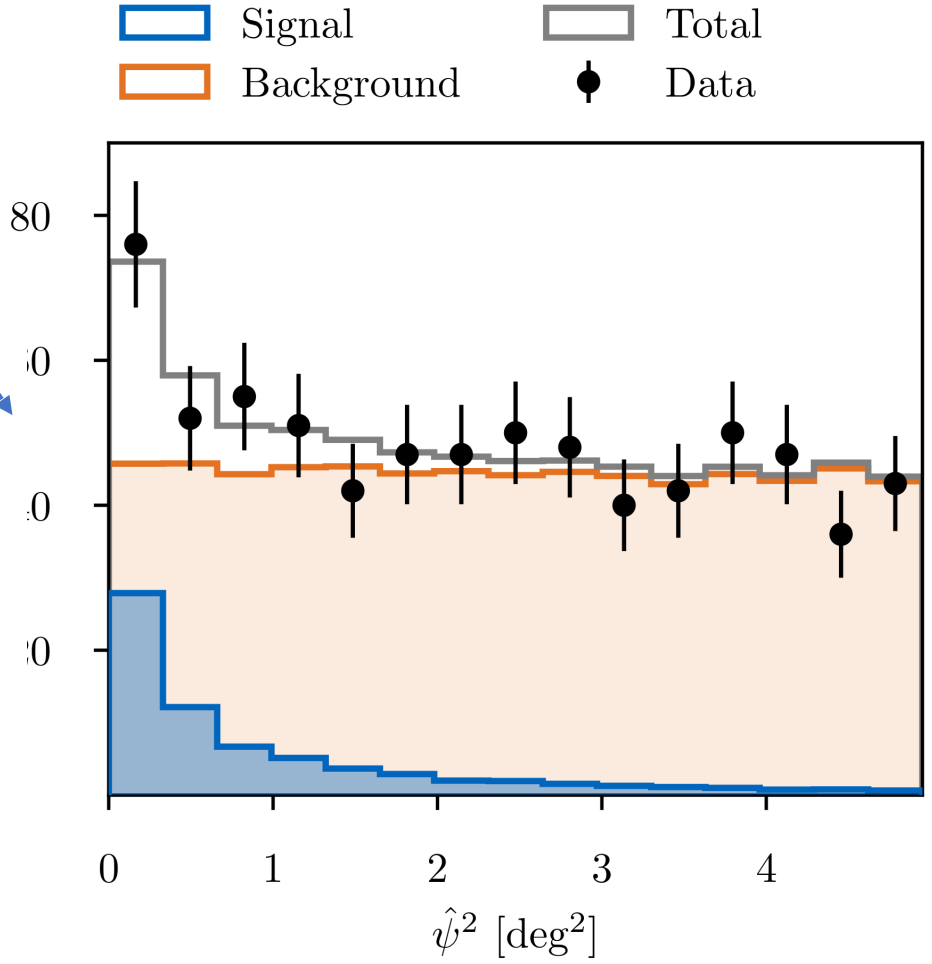
The next-generation IceCube: from discovery to astronomy

Evidence for neutrino emission from the nearby active galaxy NGC 1068 (M 77)

Analysis with improved calibrations

Science — Nov. 4, 2022





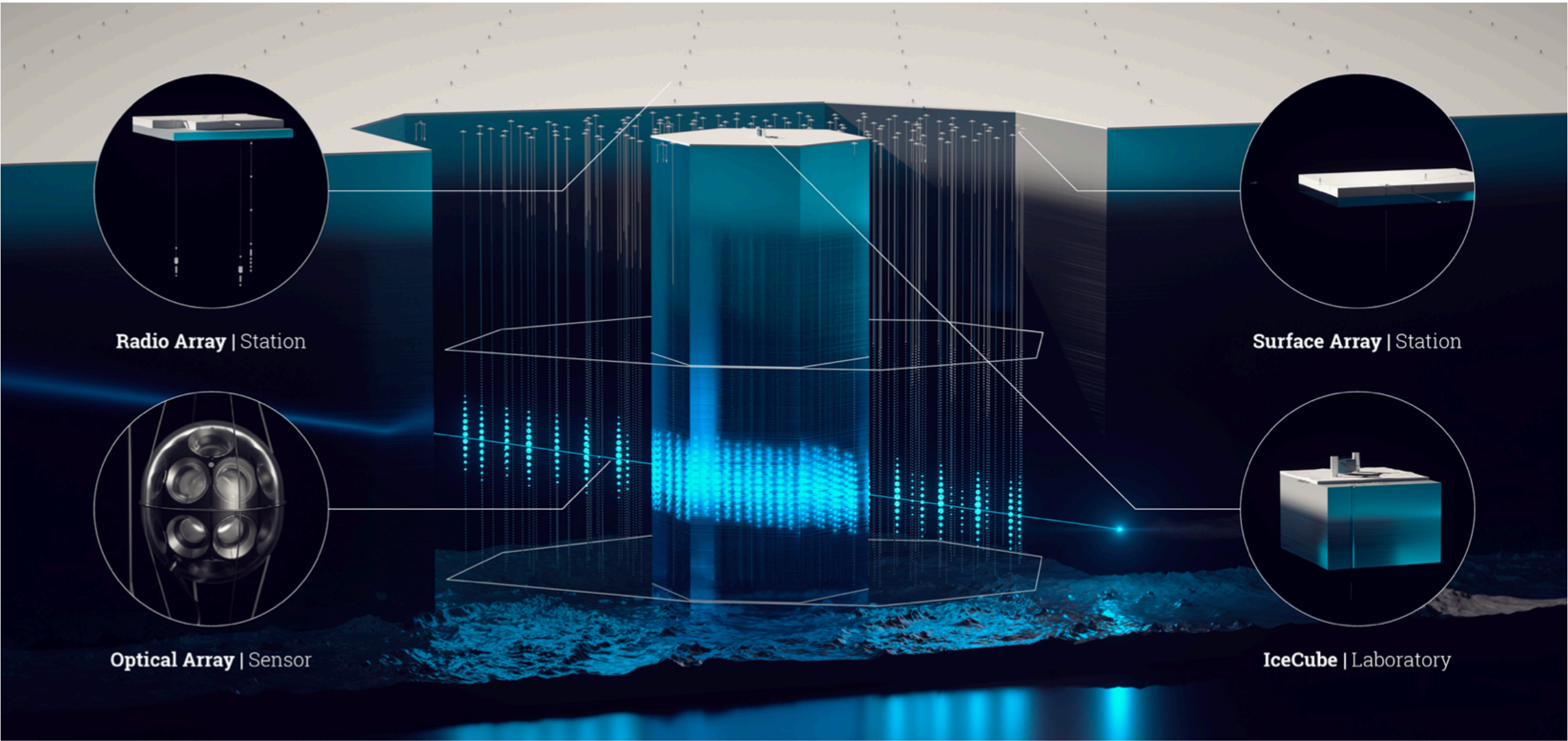
At the NGC 1068 location:

Astrophysical neutrino events = 79 $^{+22}_{-20}$

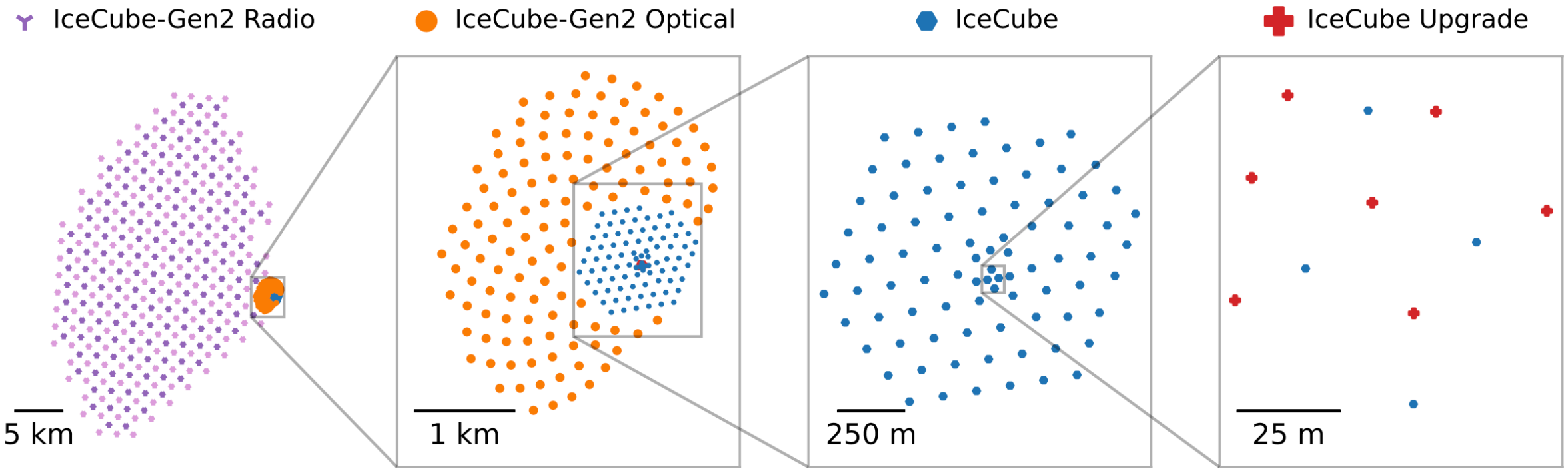
Spectral index = 3.2 ± 0.2

... significance 4.2σ

IceCube-Gen2



IceCube and IceCube-Gen2 — scales and energie ranges



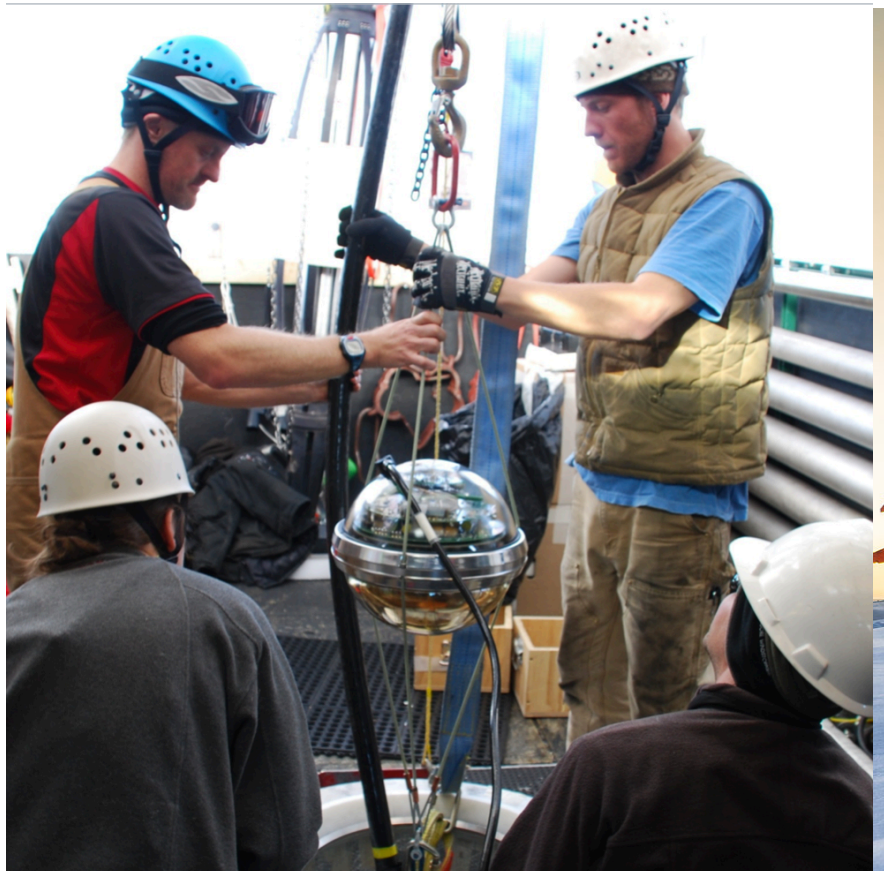
>10 PeV **> 5 TeV** **>0.5 TeV** **few GeV**

The foundation: IceCube is running very well

Optical sensors are extremely stable

Only 6 sensors were lost out of 5000
in the last 10 years.
Uptime averages 99% for the past 10 years.

→ Can run IceCube for many years as an integral part of IceCube-Gen2.



IceCube-Upgrade

In progress

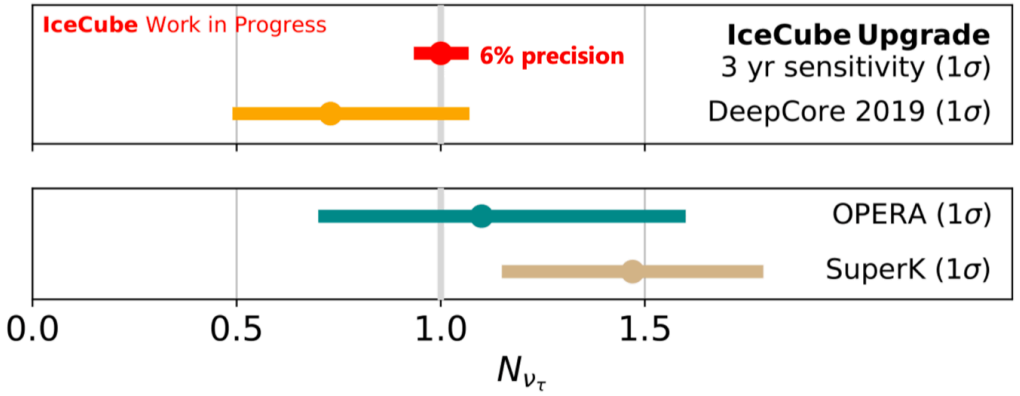
Scope:
Add 7 new strings, 700 sensors, densely packed in the center of IceCube.

Instrumented volume: 2 Mt
Energy threshold: ~ 1 GeV

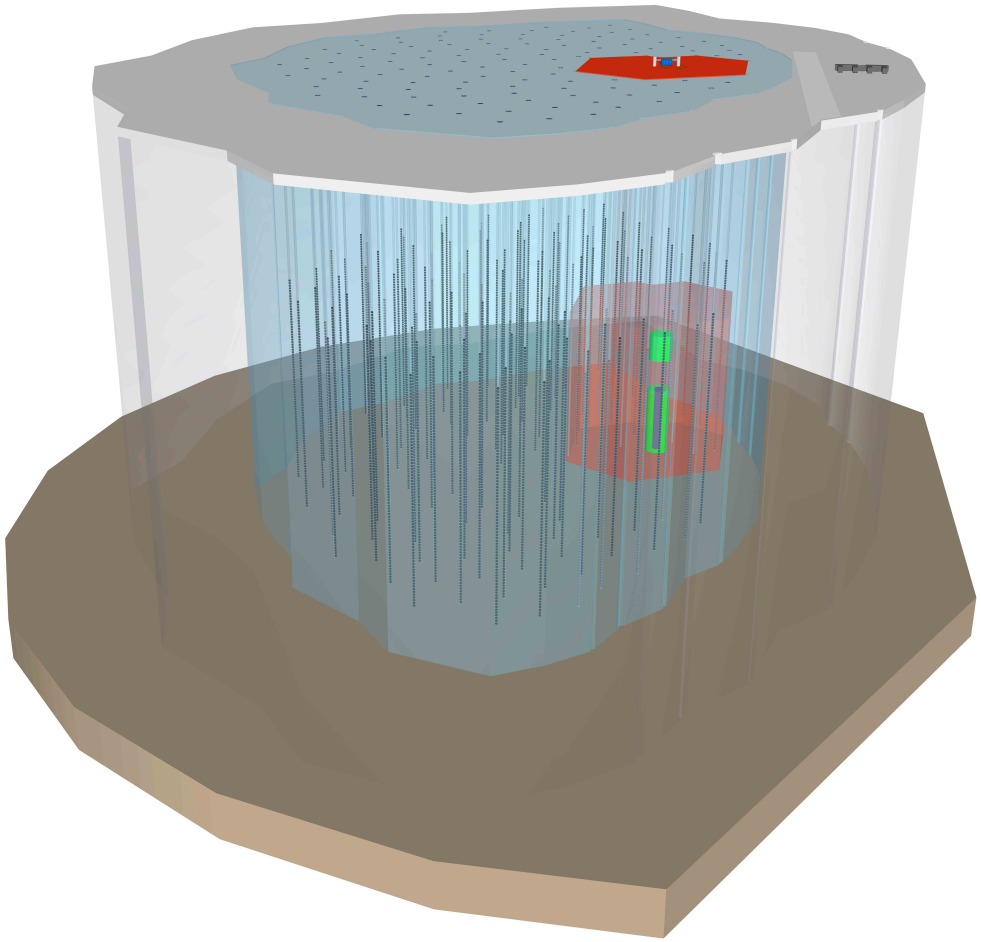
Science goals:
- Fundamental neutrino properties
- Improved calibration
- R&D, new instruments.

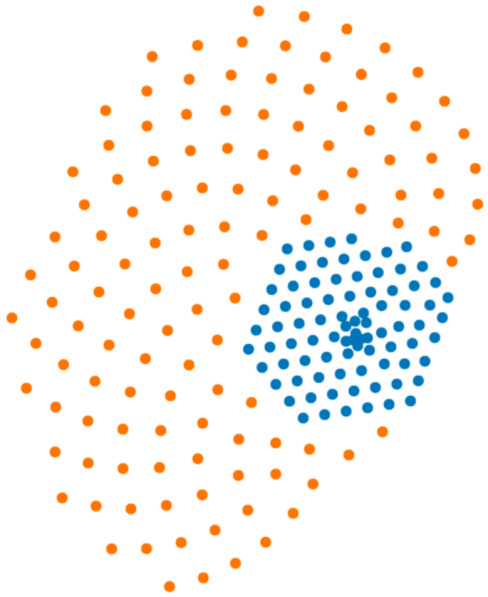
Project rebaselined after Covid delay.
Final installation: 2025/26 Pole season.

Science example:
Atmospheric tau neutrino appearance



IceCube-Gen2: the optical array





Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase

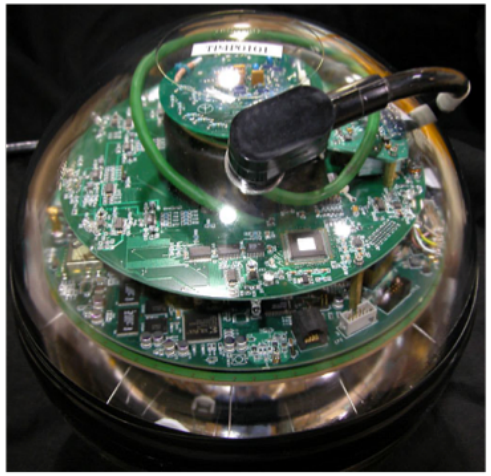
9600 optical sensors
120 strings

Why can we increase the spacing so much?

- The exceptional quality of the ice!
- Science goals shifted to higher energies based on knowledge gained with IceCube.
- Substantially improved sensor design.
- We were conservative with spacing in Gen1 (calibration)

Optical sensor development

IceCube sensor



Diameter 33 cm
10 inch photomultiplier (PMT)

IceCube Upgrade (under construction)
primary sensors

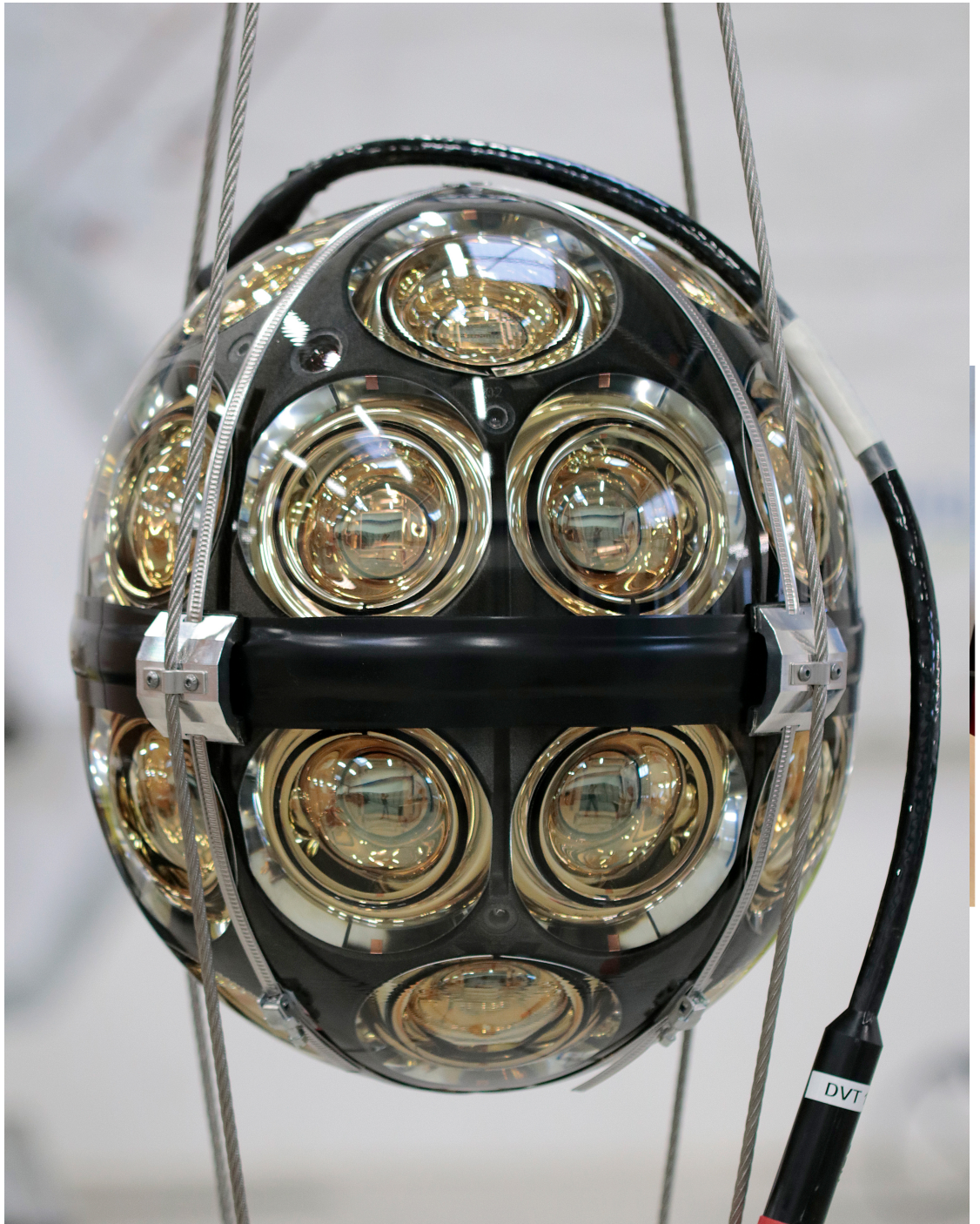
Directional information
24 x 3 inch PMT
Diameter 36 cm

2 x 8 inch PMT
Smaller diameter 30 cm

Gen2 sensor conceptual design

- narrow,
- 3 x IceCube DOM
- omni-directional

16 x 4 inch PMT
Smaller diameter 30 cm

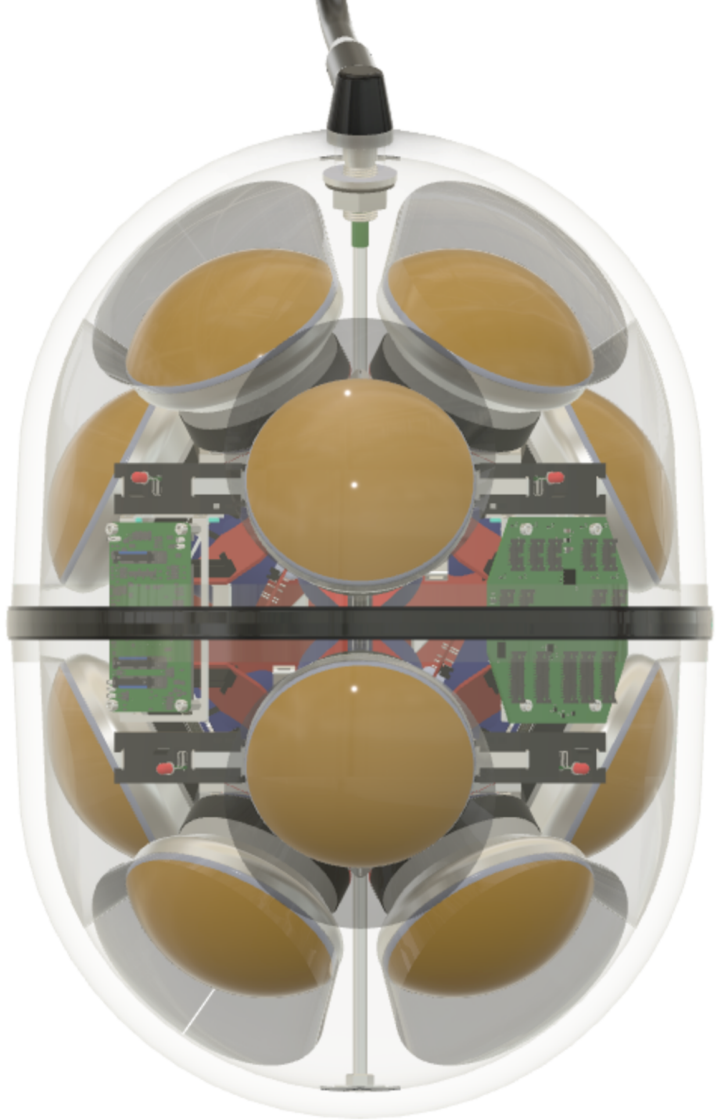

DVT


DEgg2020-2-002-v1
White-capped albatross
ICEHAP
CAM1

Sensor and Electronics

- **4-inch PMTs developed for IceCube-Gen2**
- **>3 x sensitivity**
- **>100 times dynamic range**
- **Less power**
- **Cost per photoelectron: <1/2 IceCube**

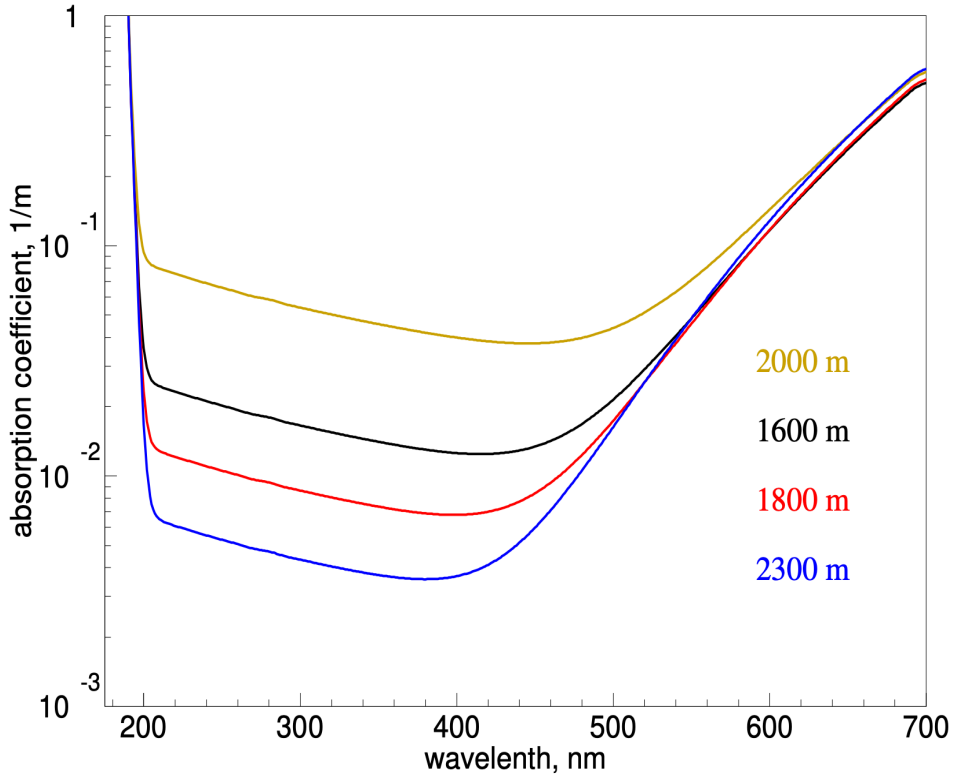
16 or 18 x 4 inch PMT
Diameter: 31 cm

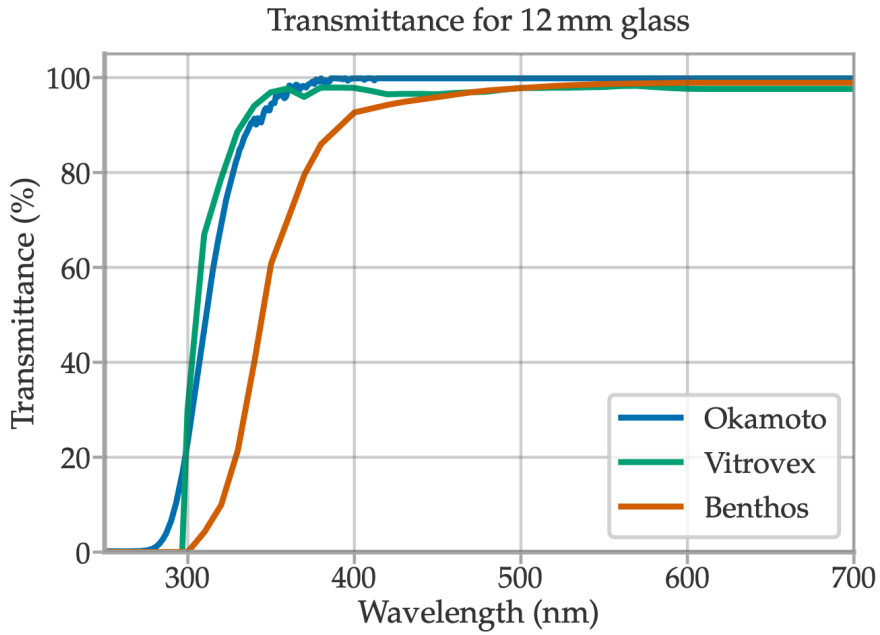


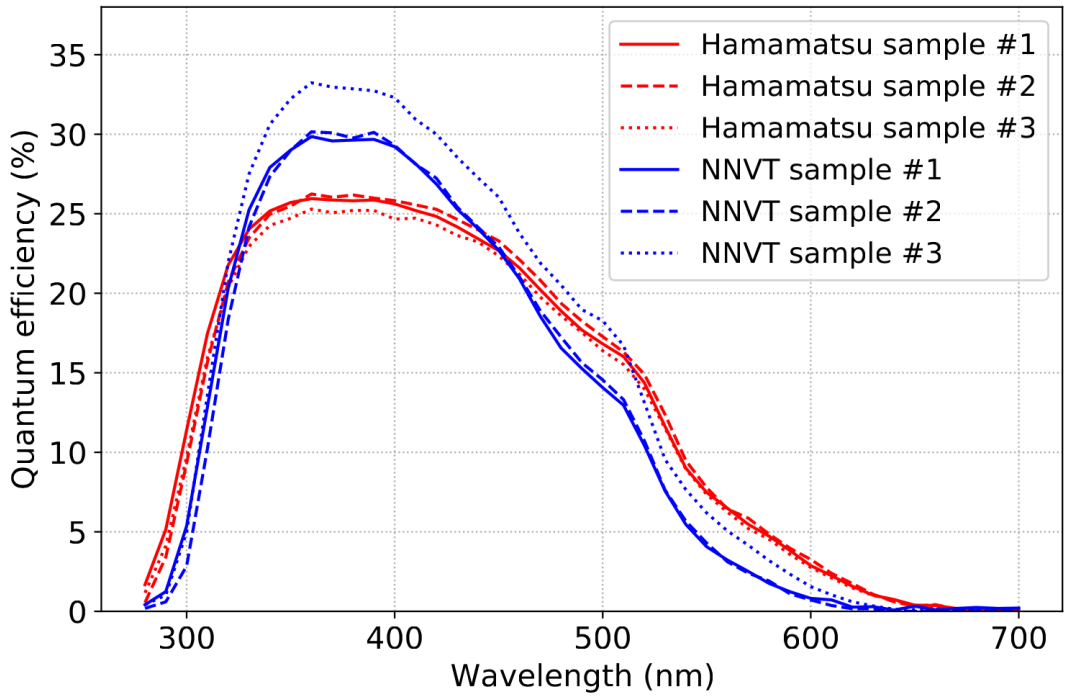
160,000 PMT

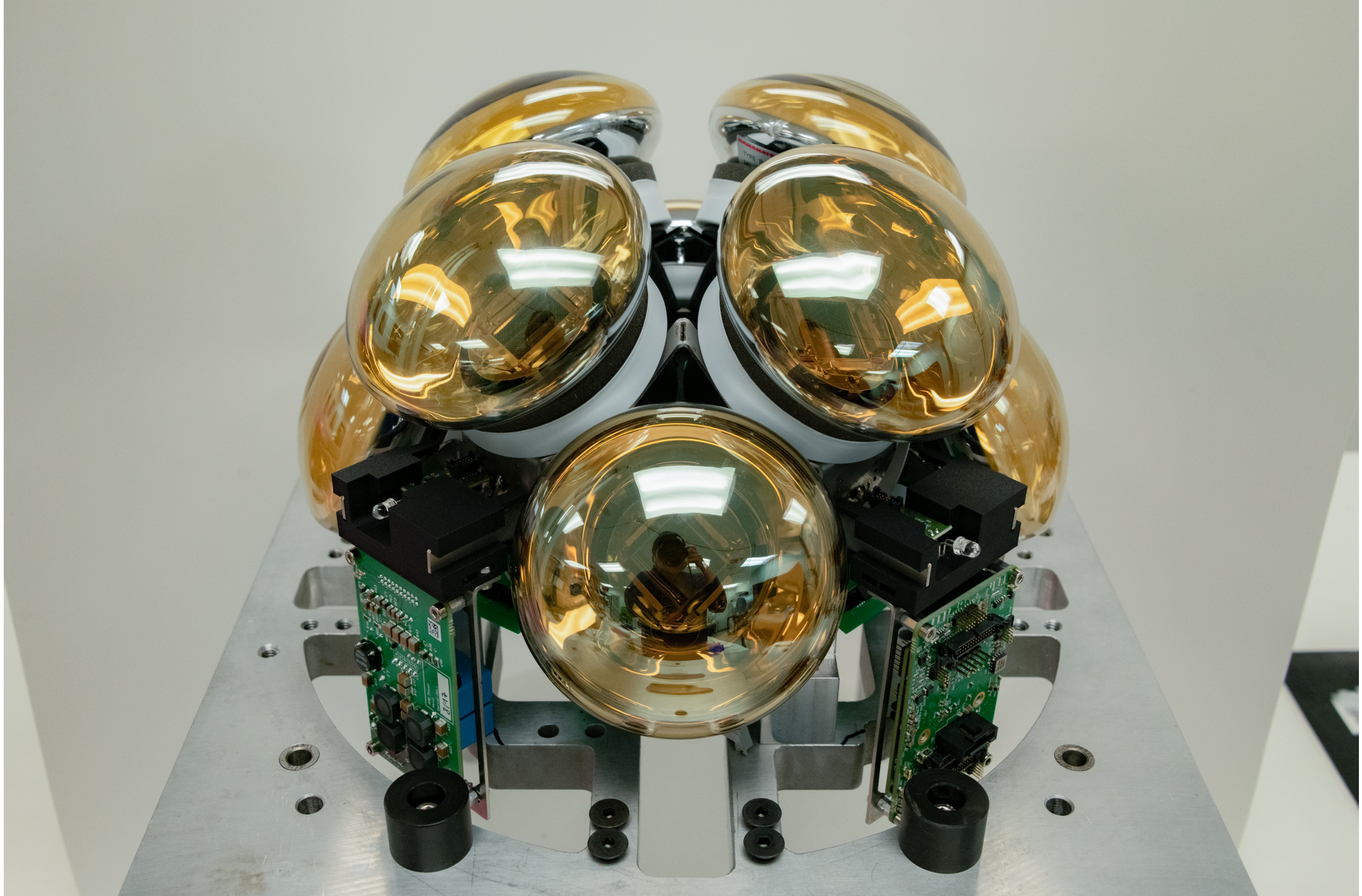
UV light is important

Ice is amazingly transparent in the UV!

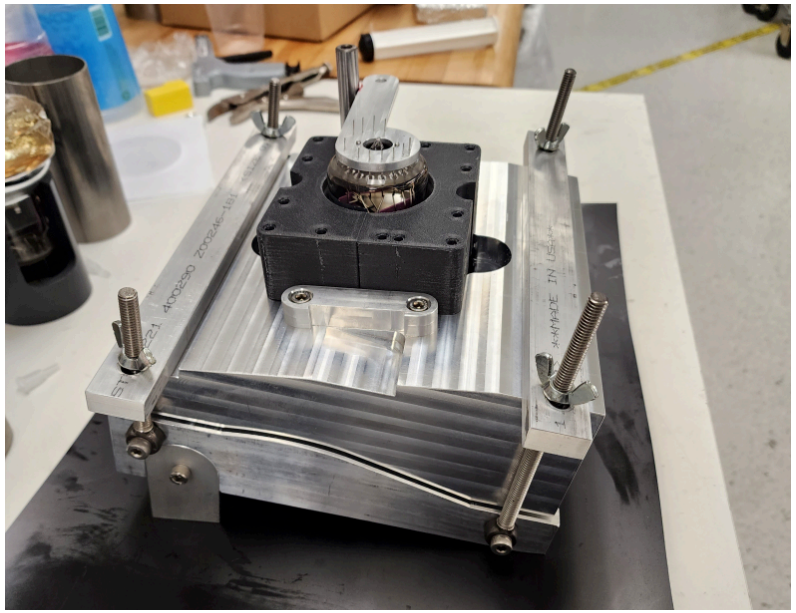


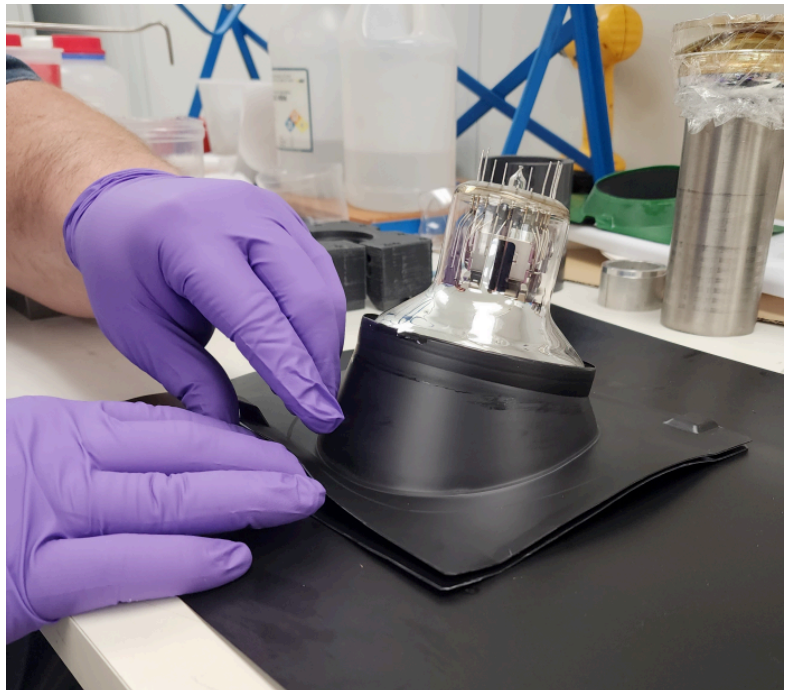




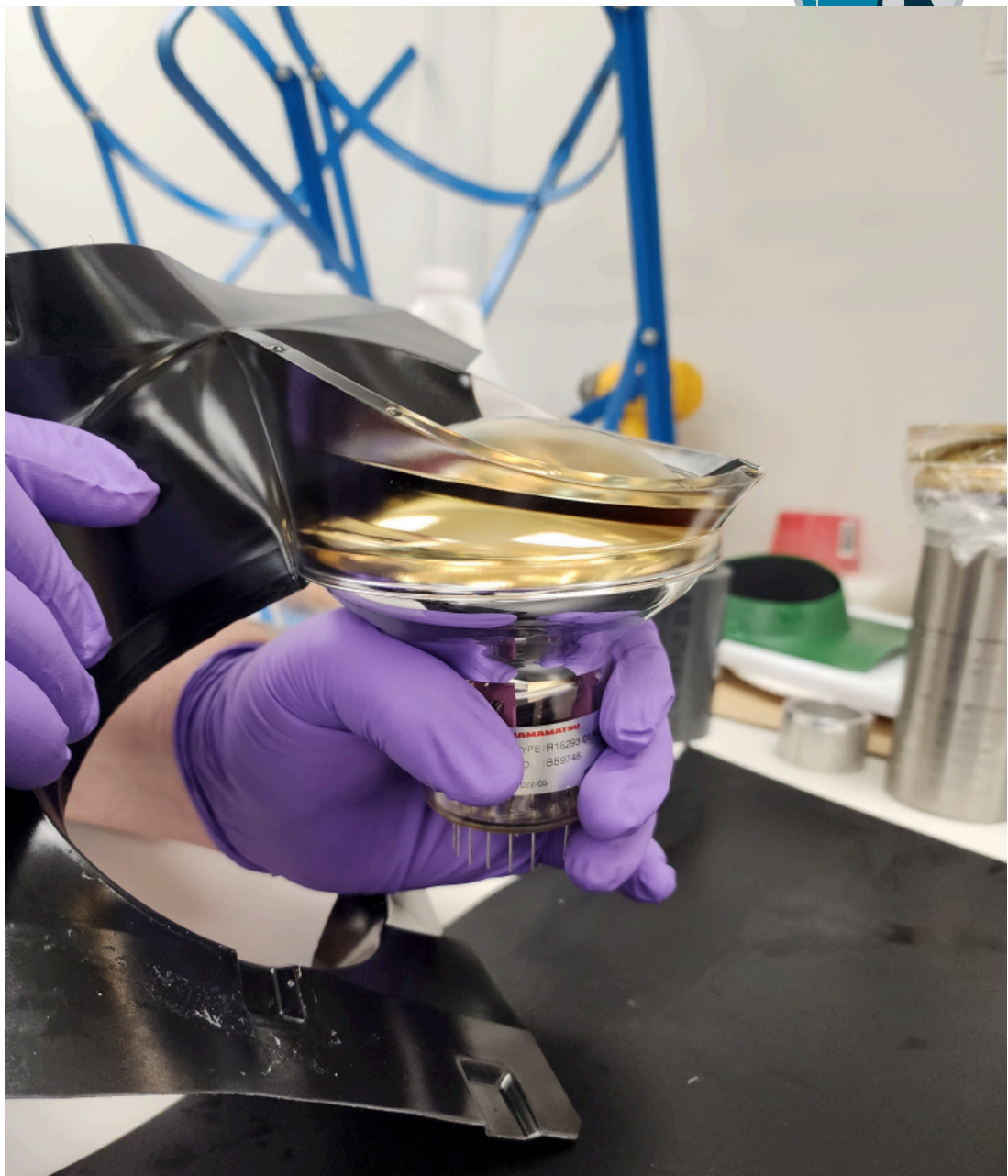


R&D Status: Gelpad

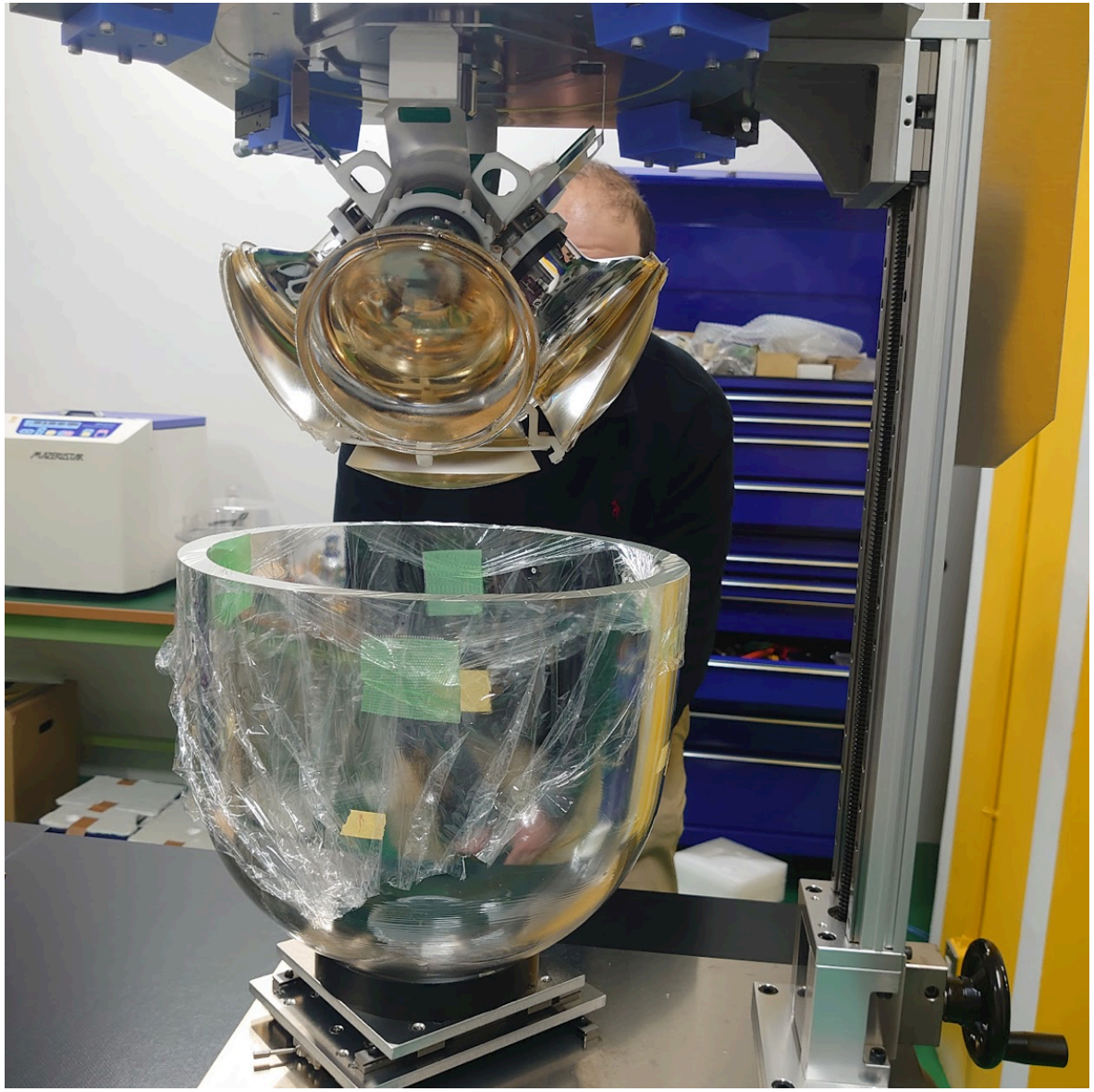




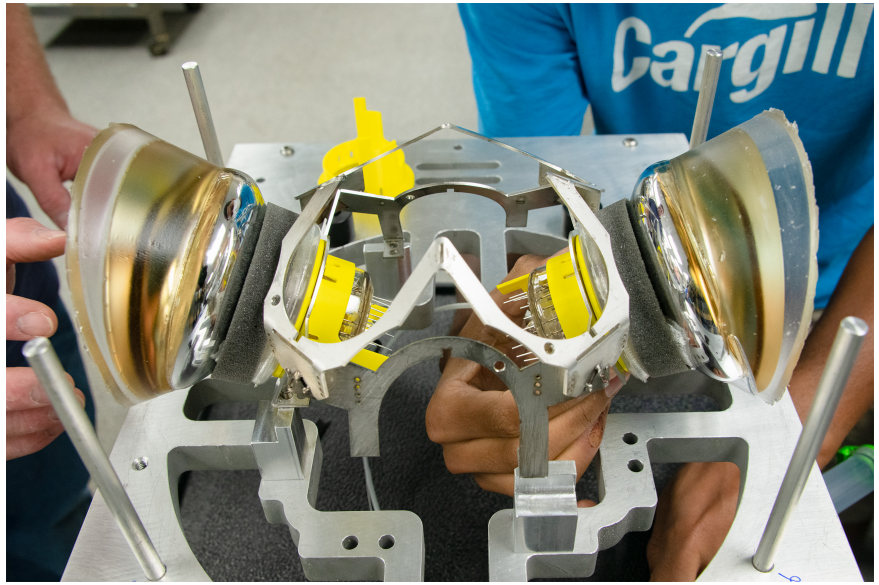
Gelpad casting on a 4 inch PMT



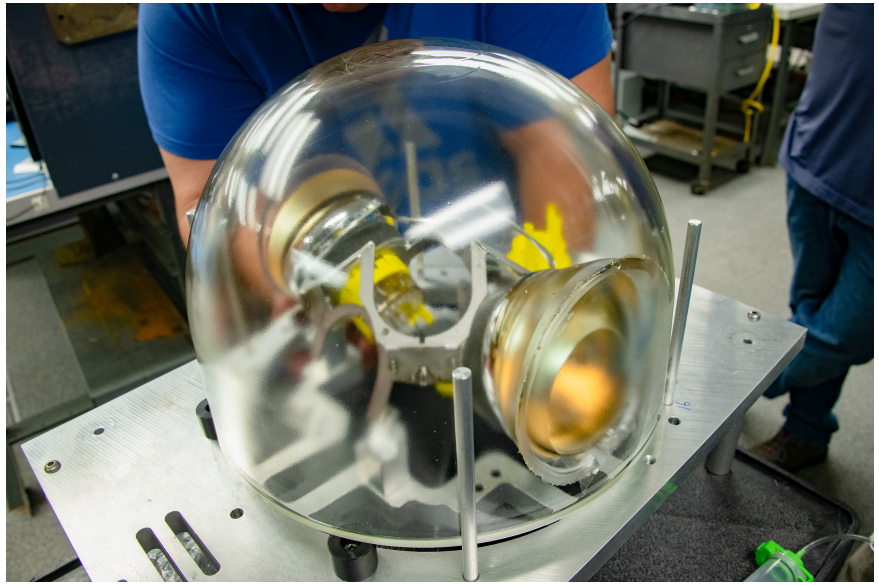
R&D Status: Integration



18 PMT opt Integration test



16 PMT opt Integration test

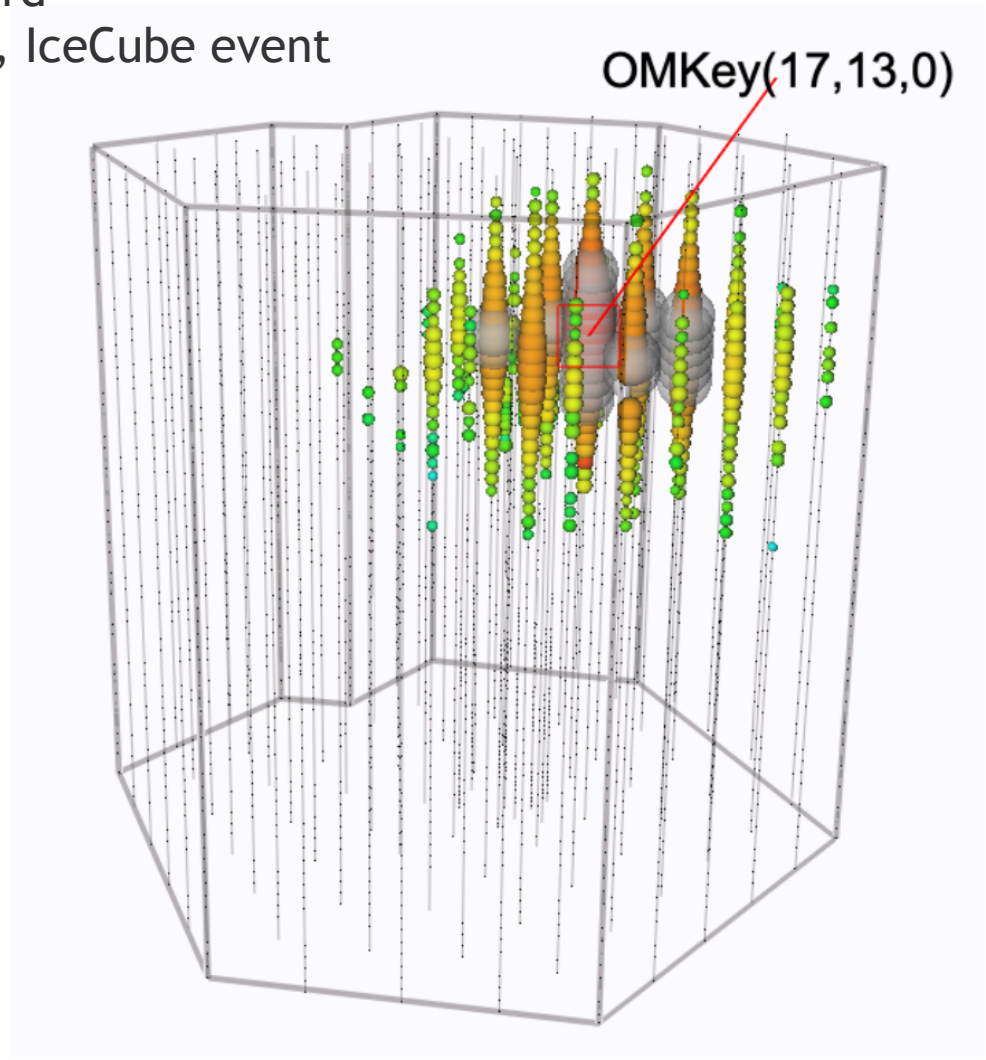


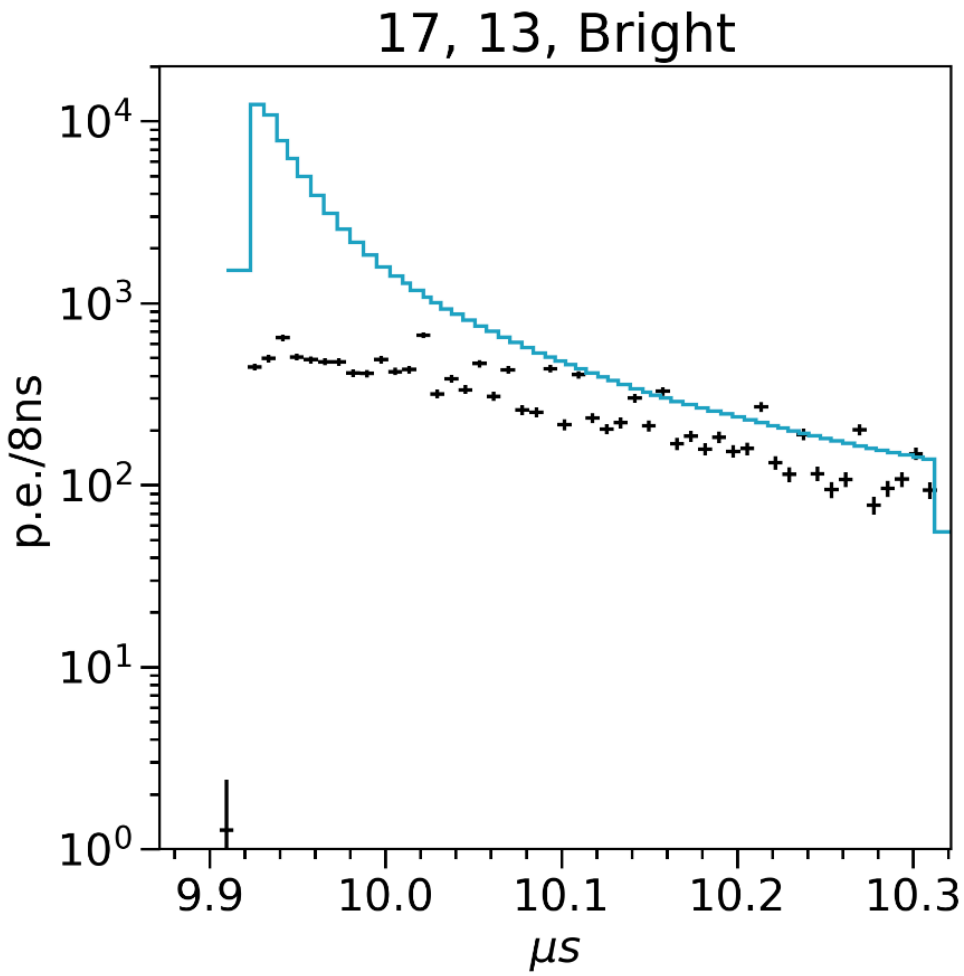
16 PMT opt Integration test

Dynamic range

Observe extremely energetic events
from close (30m) distance.

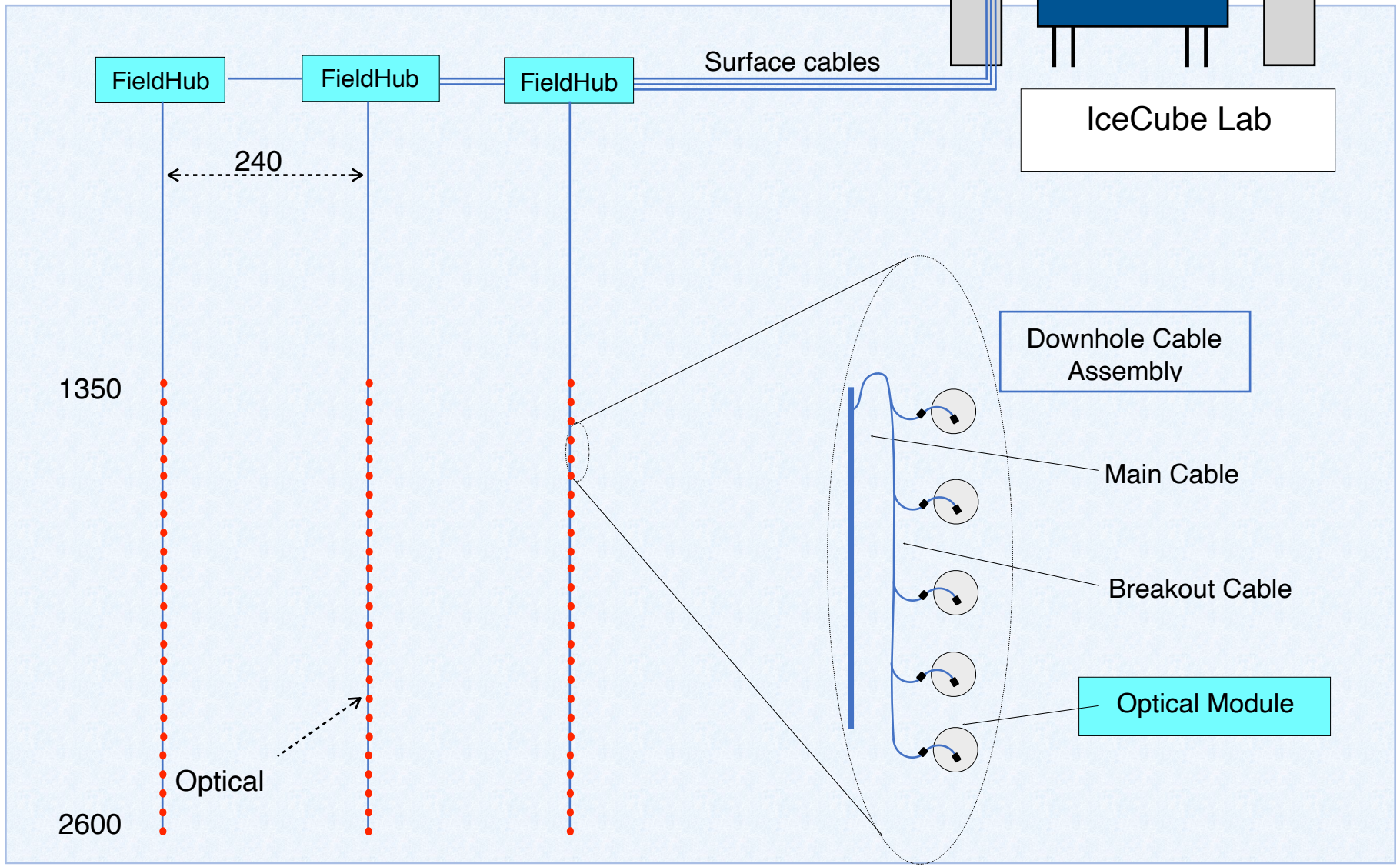
Big Bird
2 PeV, IceCube event





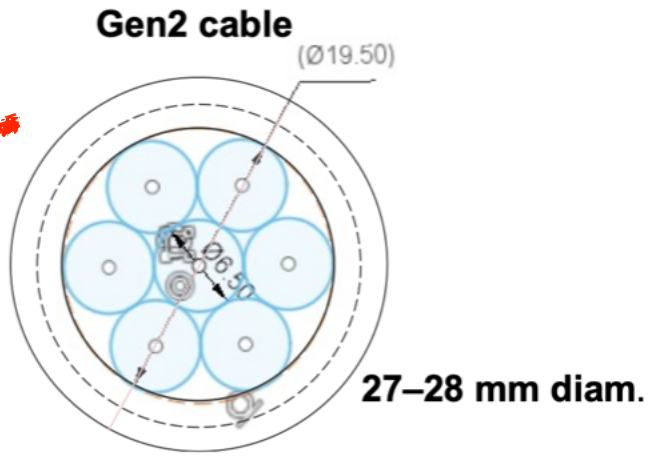
Architecture

- Power and communications architecture: simplified requirements for cable hardware.

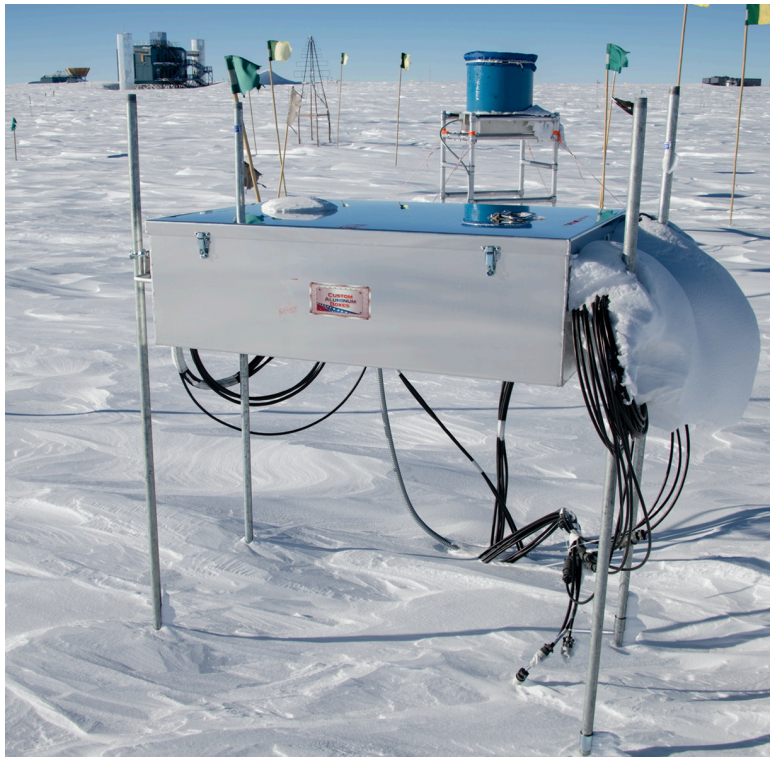


Data acquisition and cables

Upgrade cable.



Gen2 Fieldhub



IceCube: 2 DOMs/wire pair
Upgrade: 3 DOMs / wire pair
IceCube-Gen2: 6 Gen2-DOMs/wire pair (=18 x photo detection/wire pair)

This is possible due to a change in DAQ/trigger architecture:
Gen2 will not send all noise hits to the top.

Closed Caption box size

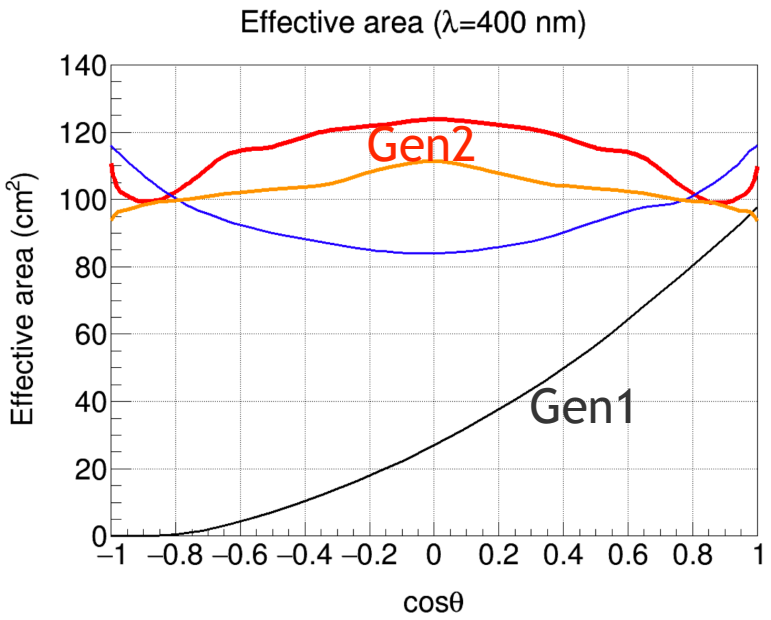
Higher Sensor sensitivity —> Larger Muon Effective Area

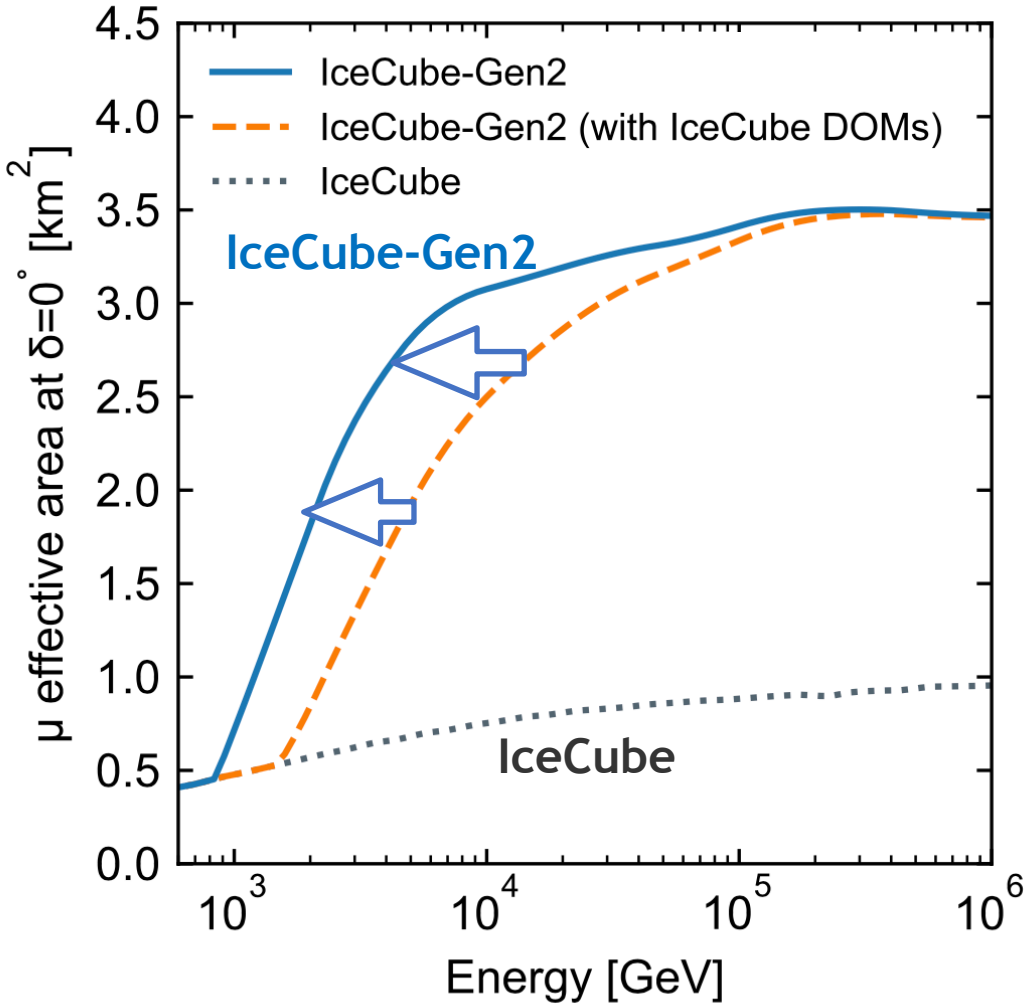
Factor 3 more photons detected

—>

- Lower energy threshold

- Angular resolution: 0.1 - 0.3°

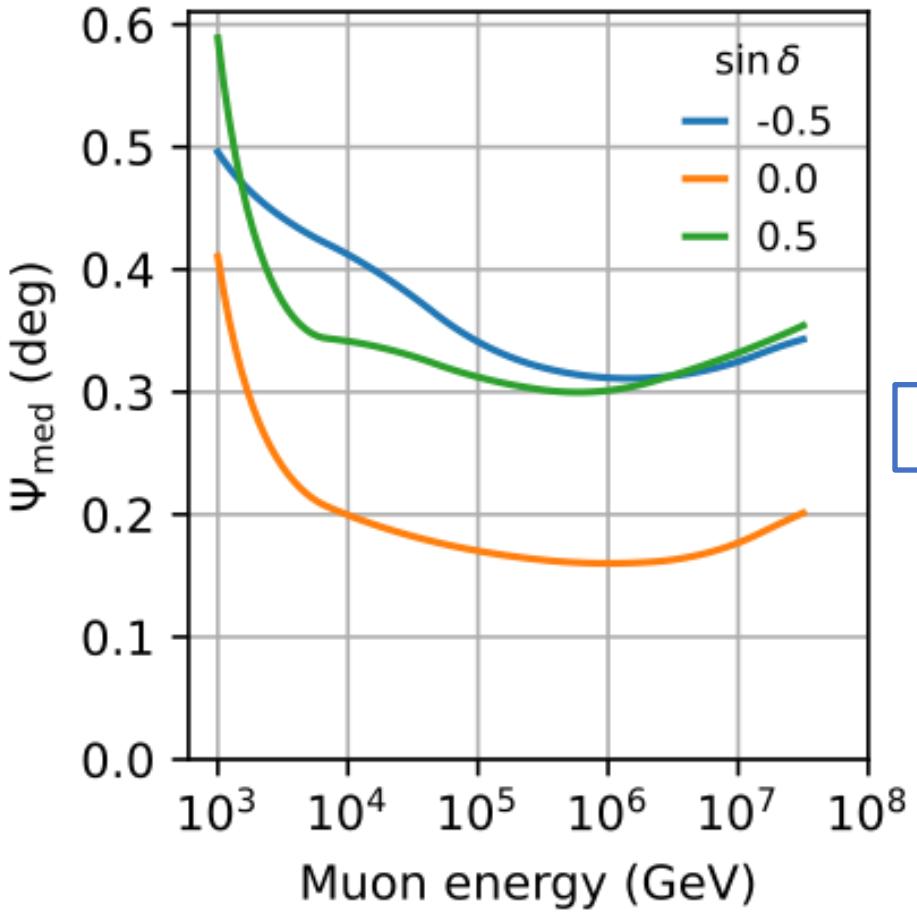


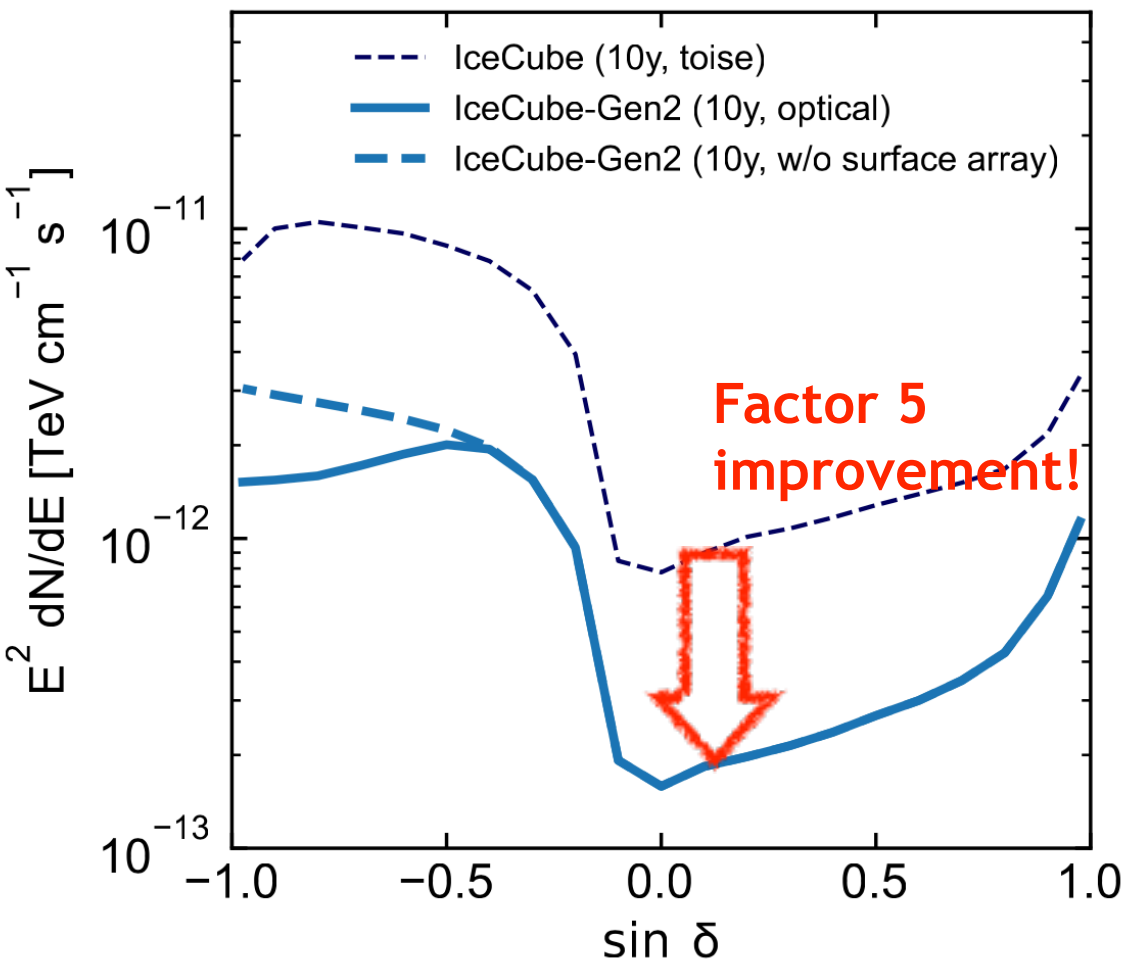


Closed Caption box size

Angular resolution and sensitivity to Point Sources

Muons: 0.1 - 0.4°

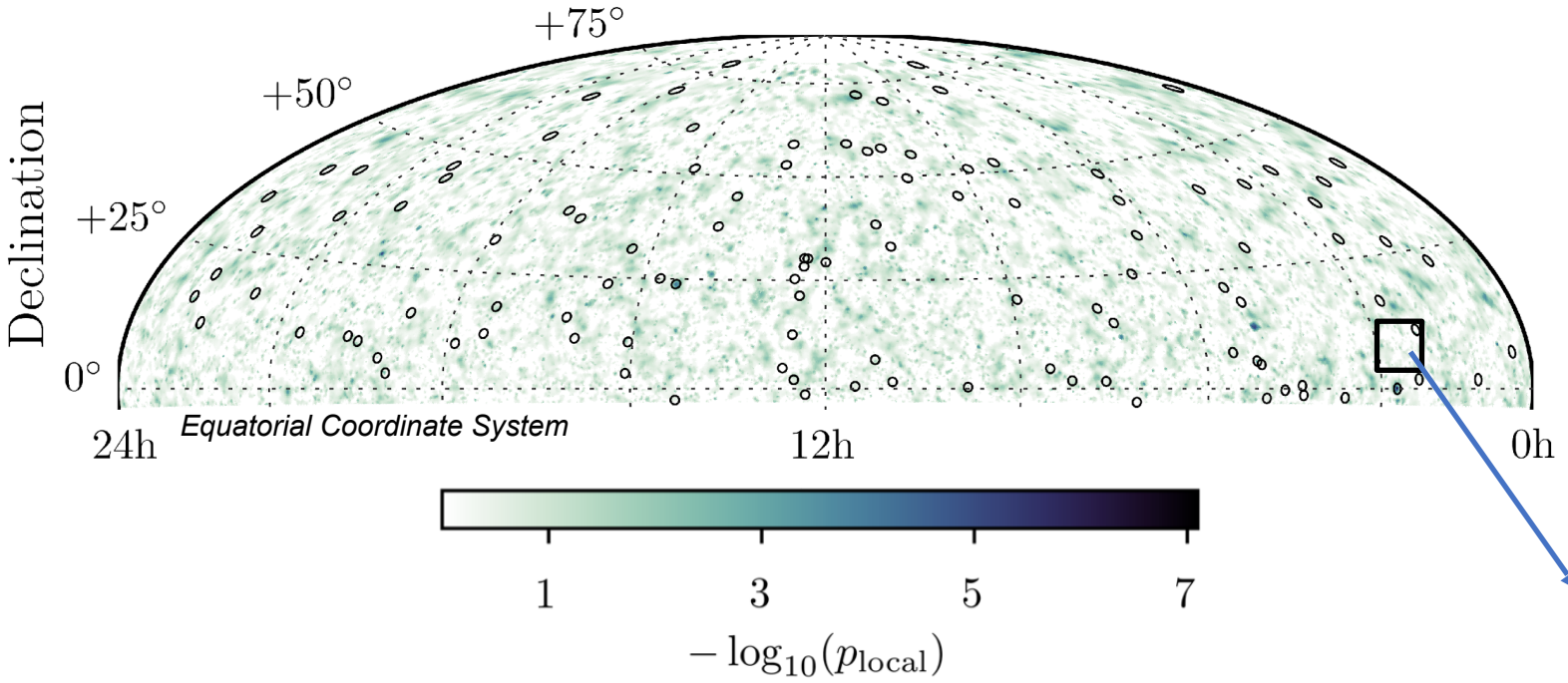


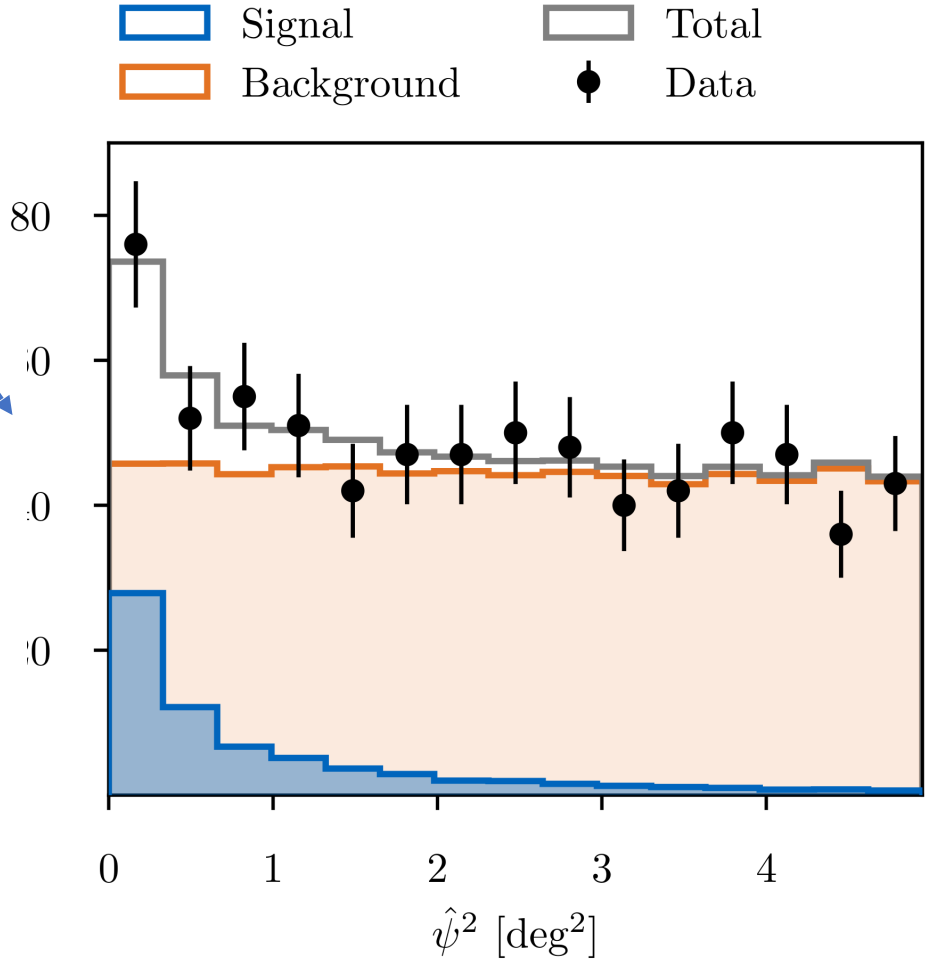


Evidence for neutrino emission from the nearby active galaxy NGC 1068 (M 77)

Analysis with improved calibrations

Science — Nov. 4, 2022





At the NGC 1068 location:

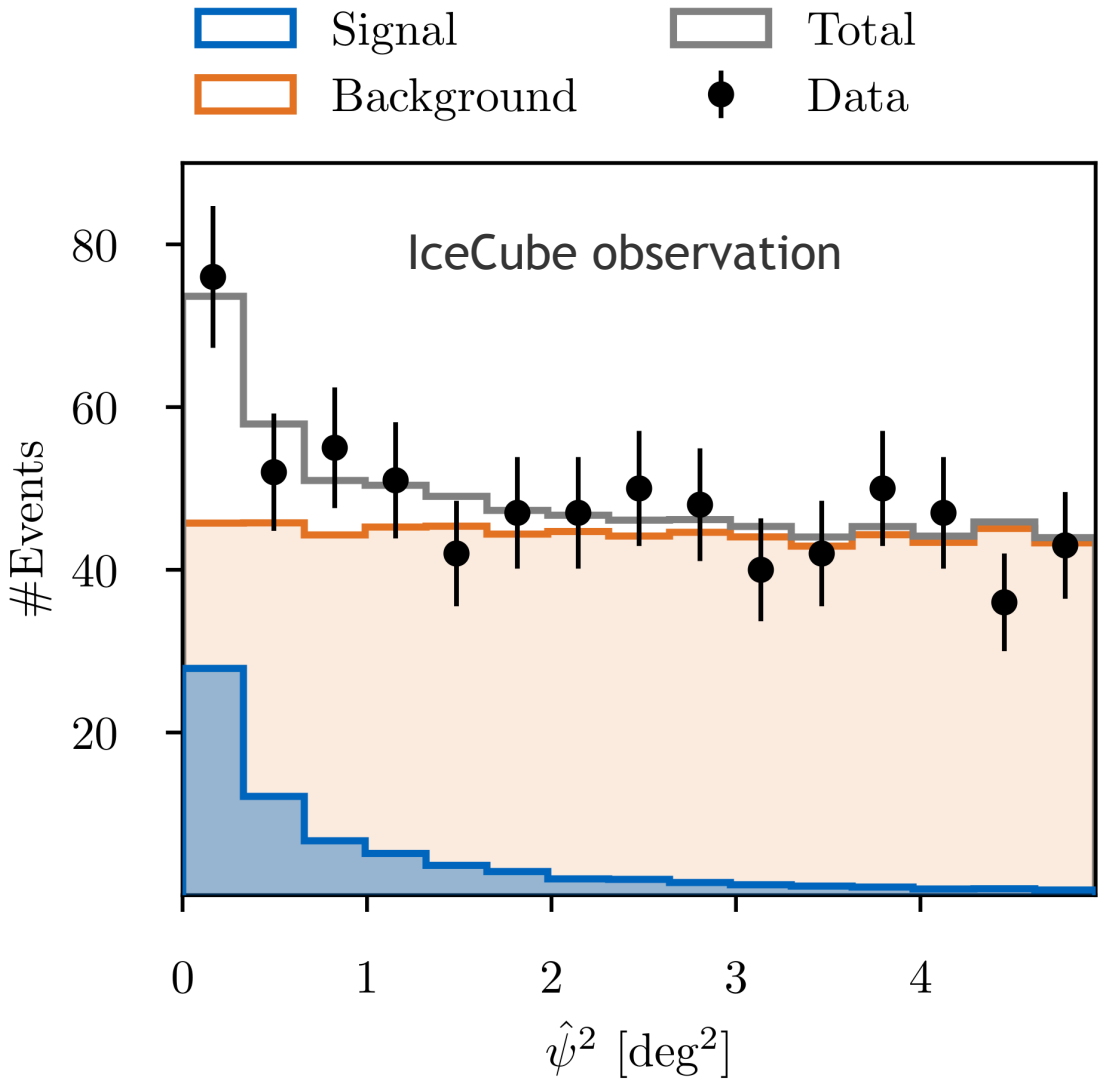
Astrophysical neutrino events = 79 $^{+22}_{-20}$

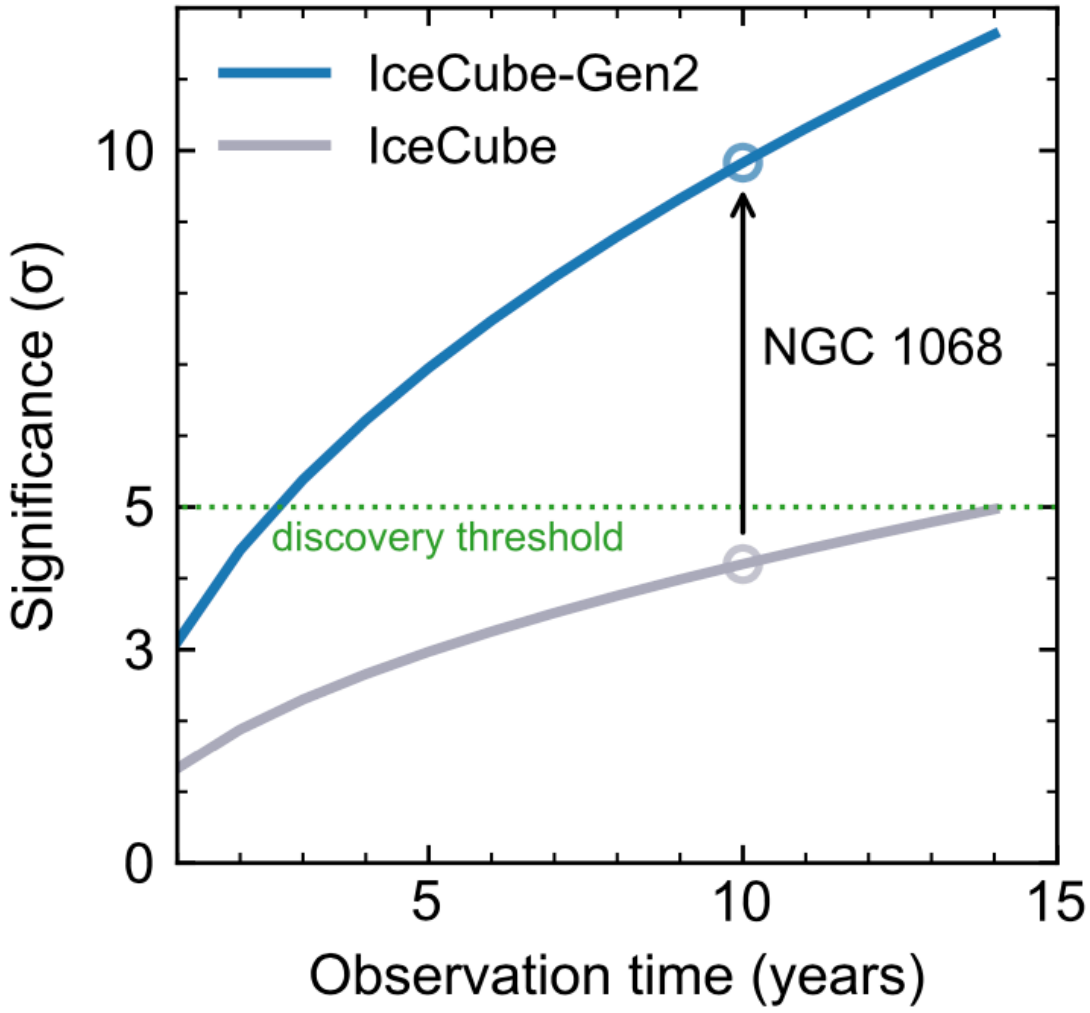
Spectral index = 3.2 ± 0.2

... significance 4.2σ

IceCube-Gen2 sensitivity: Point sources

How would NGC 1068look in Gen2?

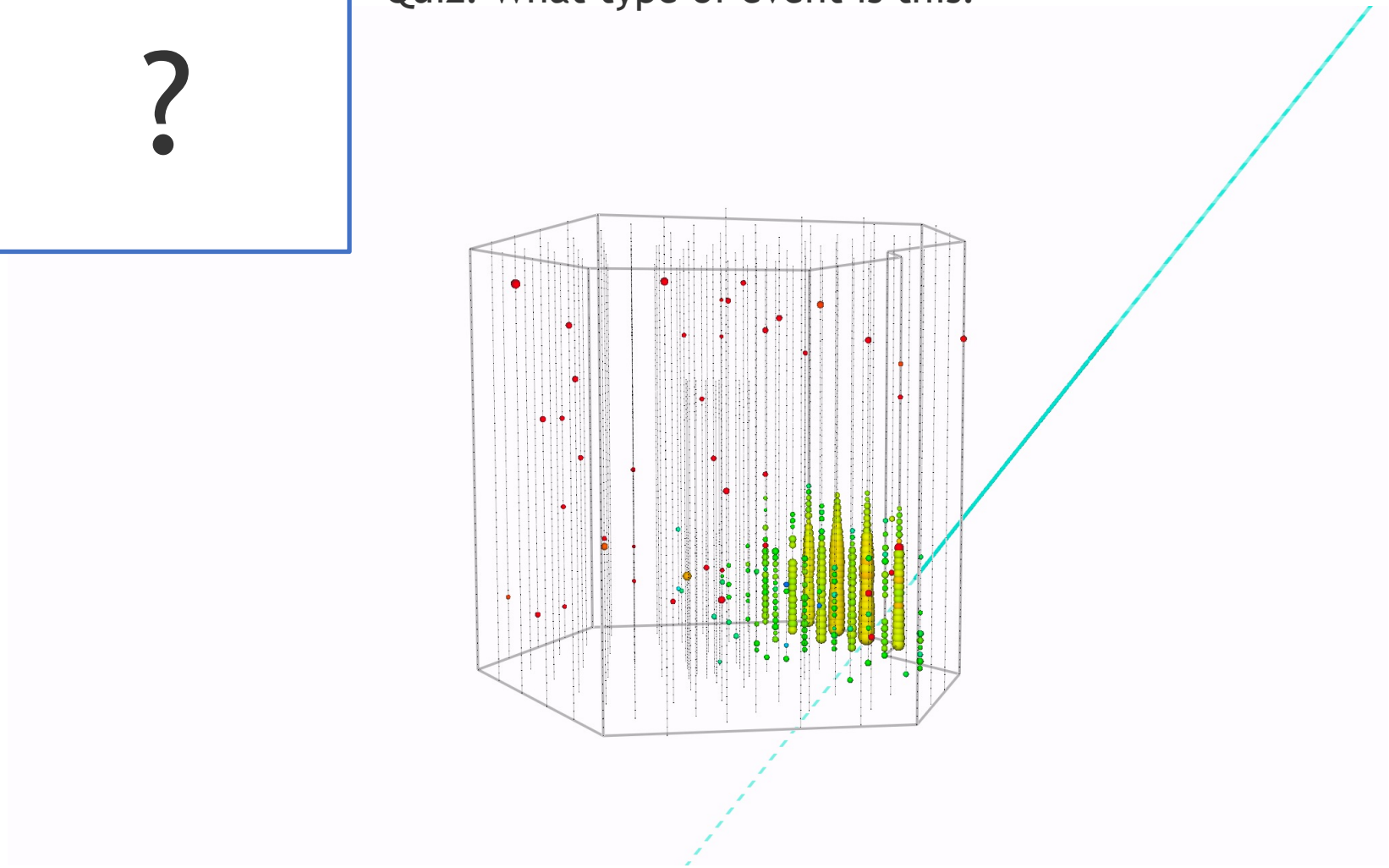




Neutrino Flavors:

?

Quiz: What type of event is this?



Neutrino production mechanisms with cosmic rays:

Accelerate protons and have them interact.

Result: Pions and other stuff

$$pp \to NN + pions; \qquad p\gamma \to p\pi^0, n\pi^+$$

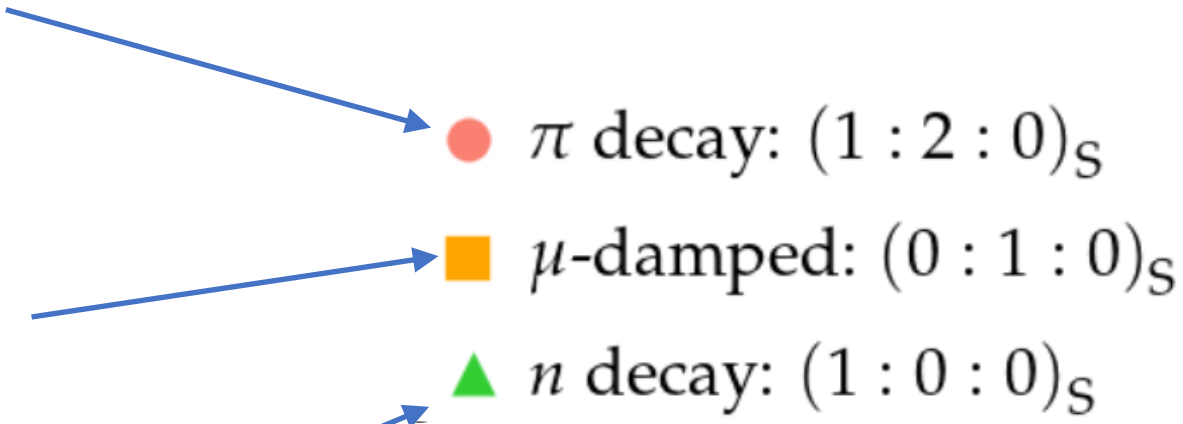
$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

~~$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$~~

$$n \to p + e^- + \bar{\nu}$$



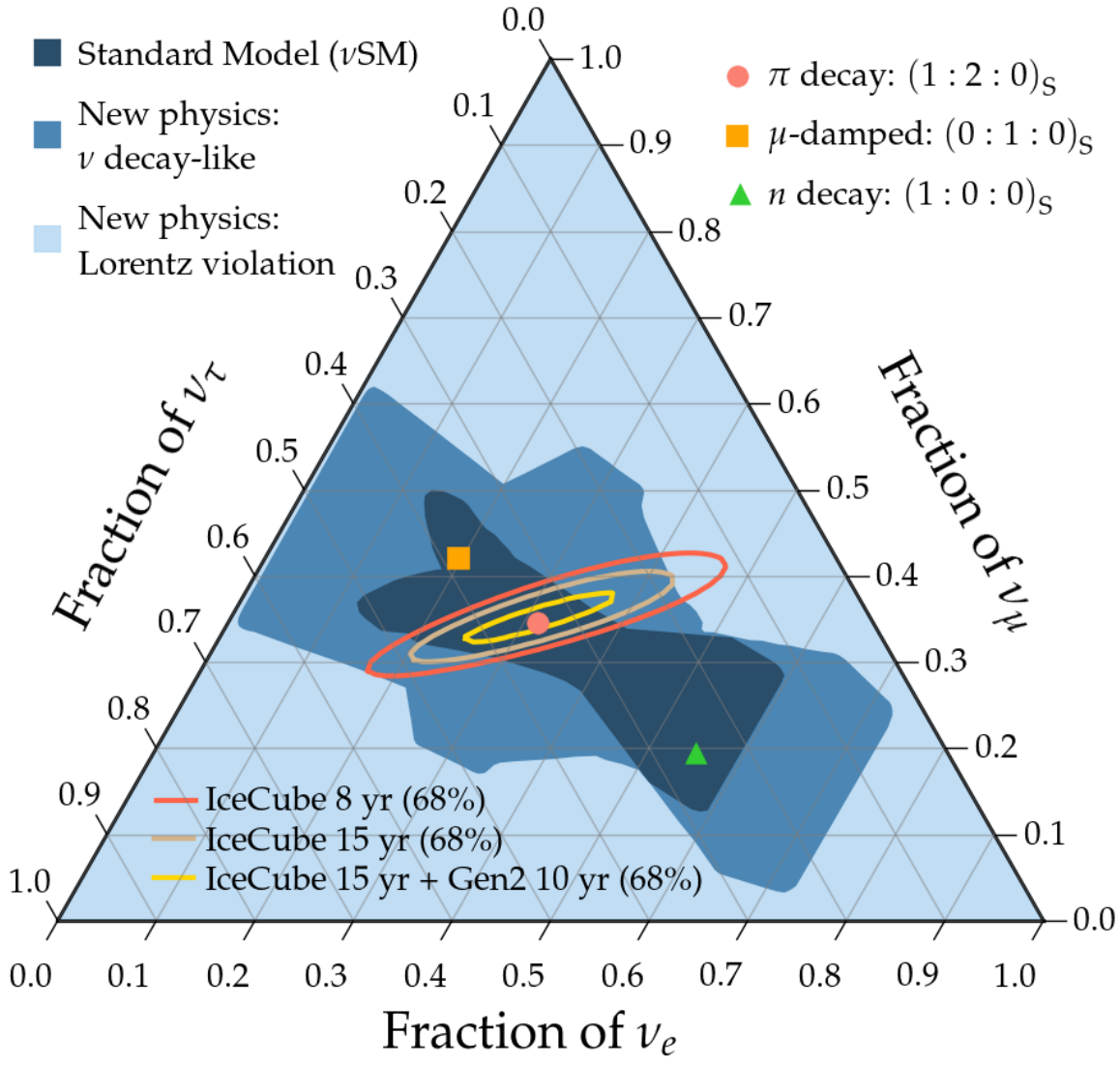
Probing fundamental physics with high-energy neutrinos

Probing neutrino oscillations over cosmic baselines

$pp \to NN + pions; \qquad p\gamma \to p\pi^0, n\pi^+$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



IceCube GEN2

Requirements for IceCube-Gen2

5. Enhanced sensitivity to neutrino flavors and the ability for flavor identification.

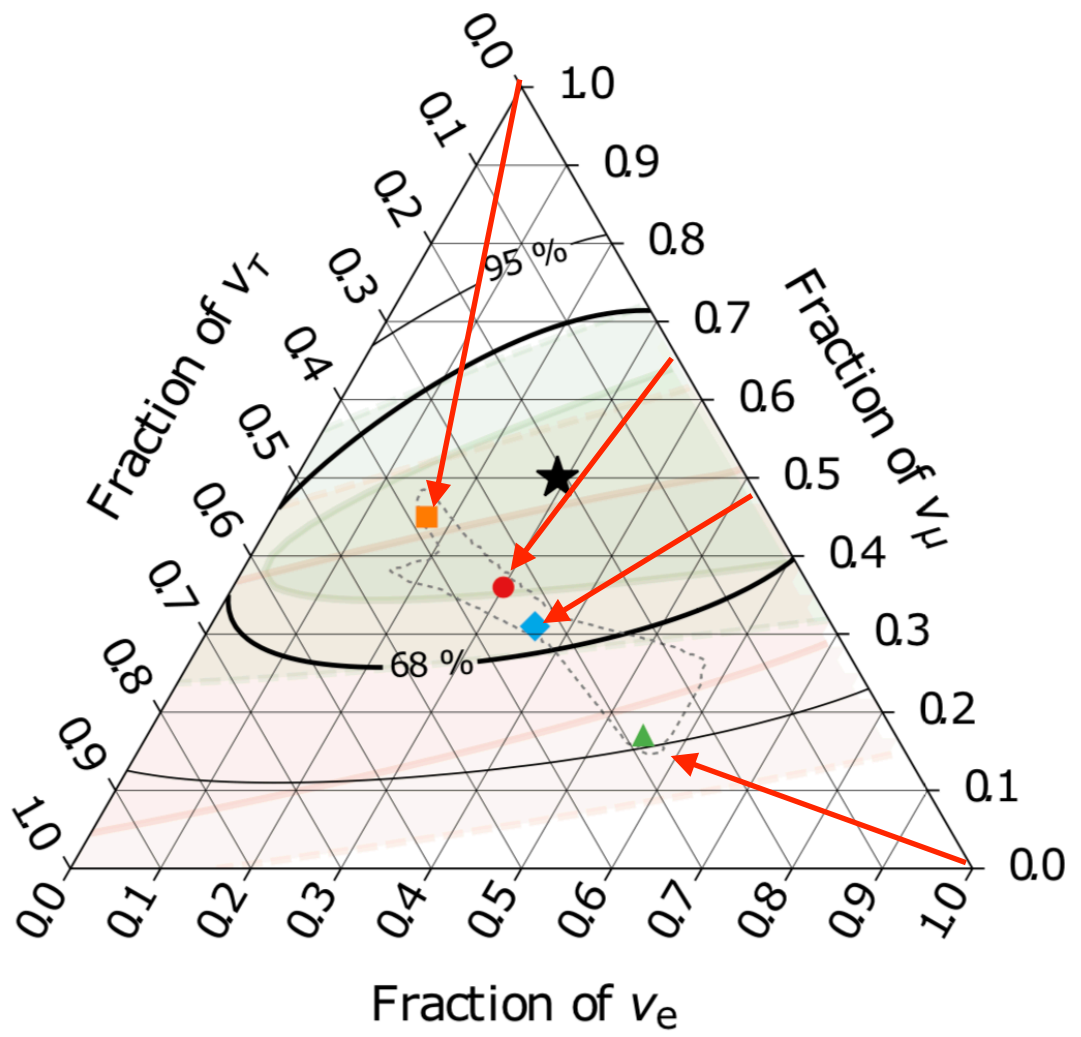
Neutrino flavor at the source: key information about production mechanism

Reminder of basic neutrino production

$$pp \to NN + pions; \qquad p\gamma \to p\pi^0, n\pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



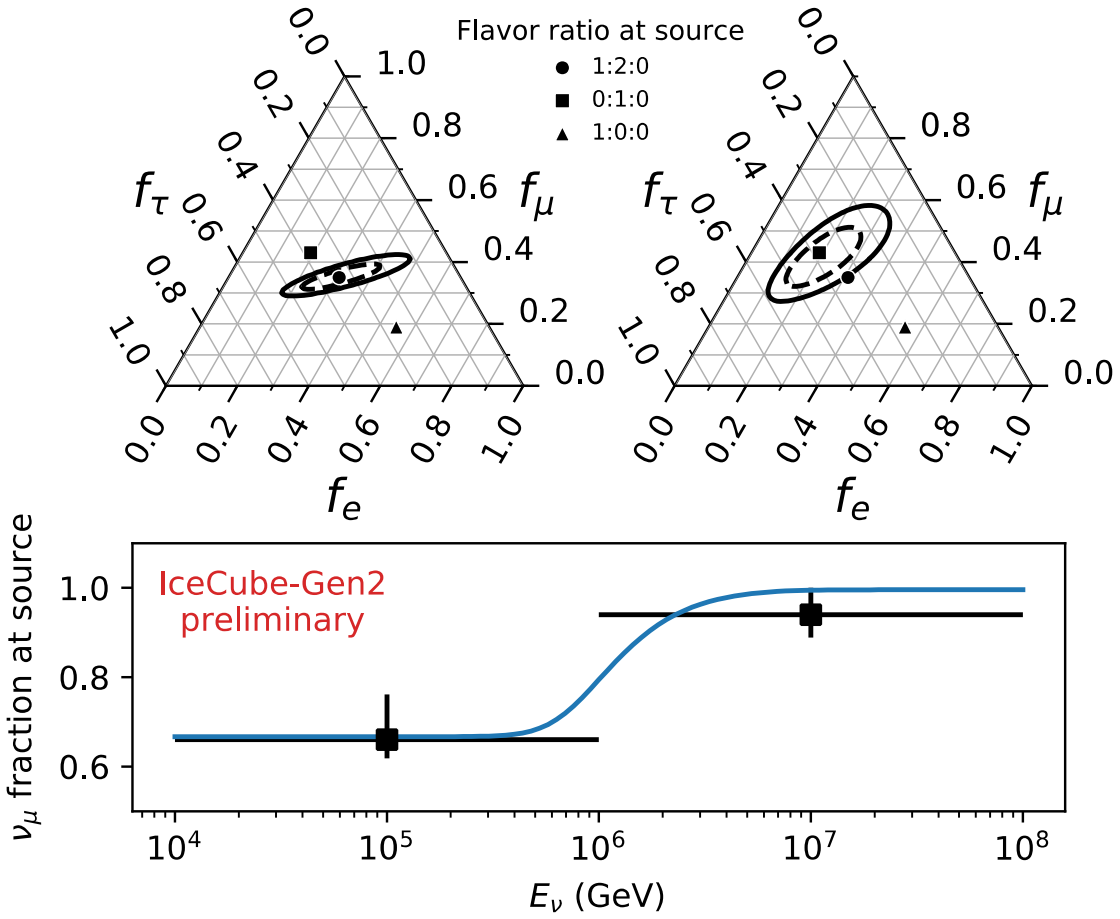
High-energy starting tracks	$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:
★ Best-fit: 0.29 : 0.50: 0.21	■ 0:1:0 → 0.17 : 0.45 : 0.37
Global fit (IceCube, APJ 2015)	● 1:2:0 → 0.30 : 0.36 : 0.34
Inelasticity (IceCube, PRD 2019)	▲ 1:0:0 → 0.55 : 0.17 : 0.28
3ν-mixing 3σ allowed region	◆ 1:1:0 → 0.36 : 0.31 : 0.33

IceCube GEN2

Requirements for IceCube-Gen2

Enhanced sensitivity to neutrino flavors and the ability for flavor identification

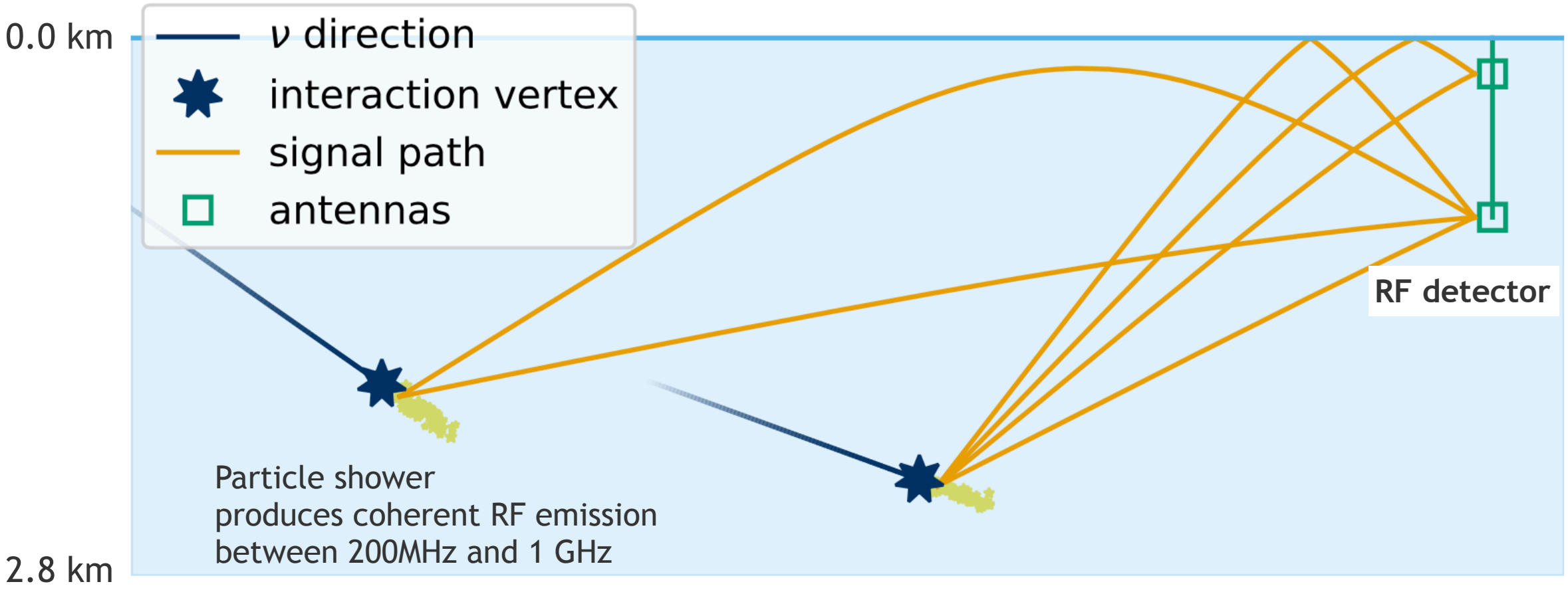
Measuring energy dependent neutrino flavor ratios (→BSM physics and nature of source)



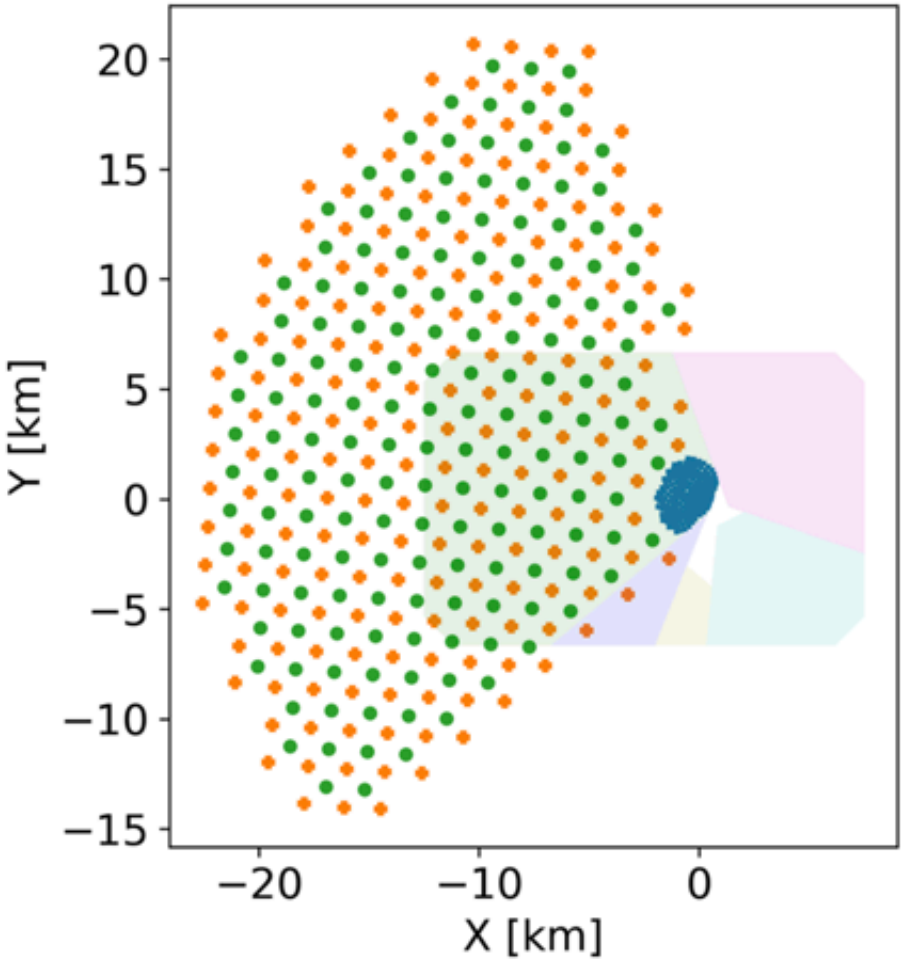
IceCube GEN2

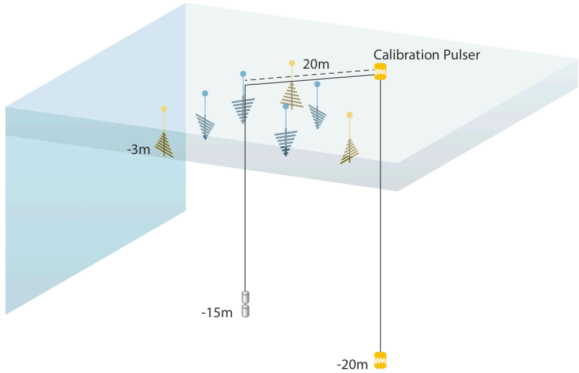
The IceCube-Gen2: the radio array

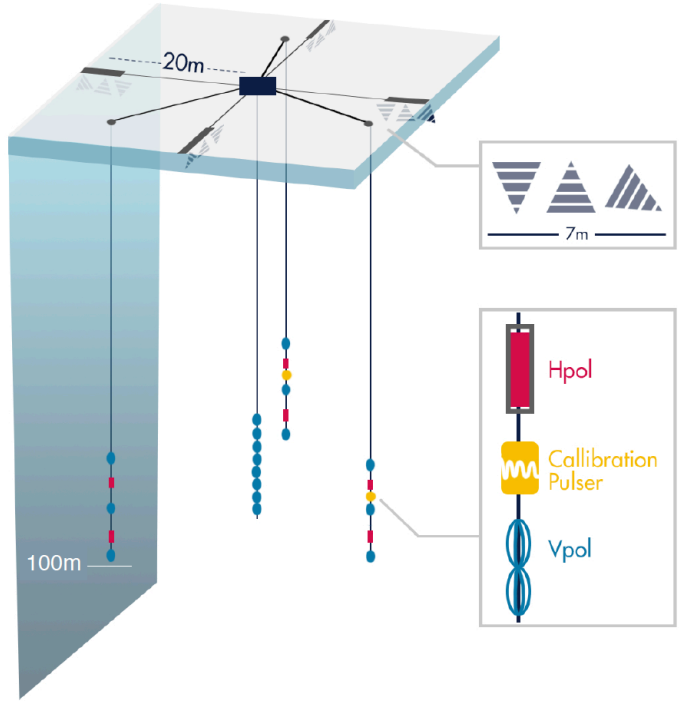
Askaryan Radio Detector array to complement optical detector at energies > 30 PeV



The IceCube-Gen2: the radio array



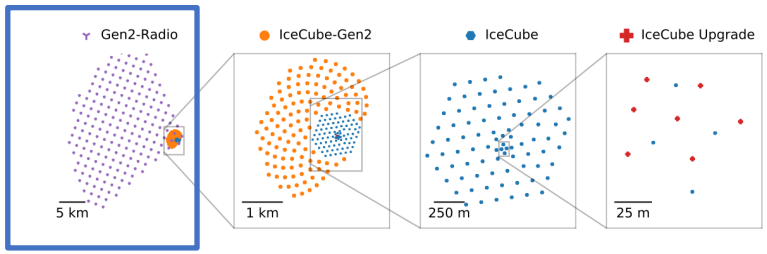




Area: 500 km^2

300 stations

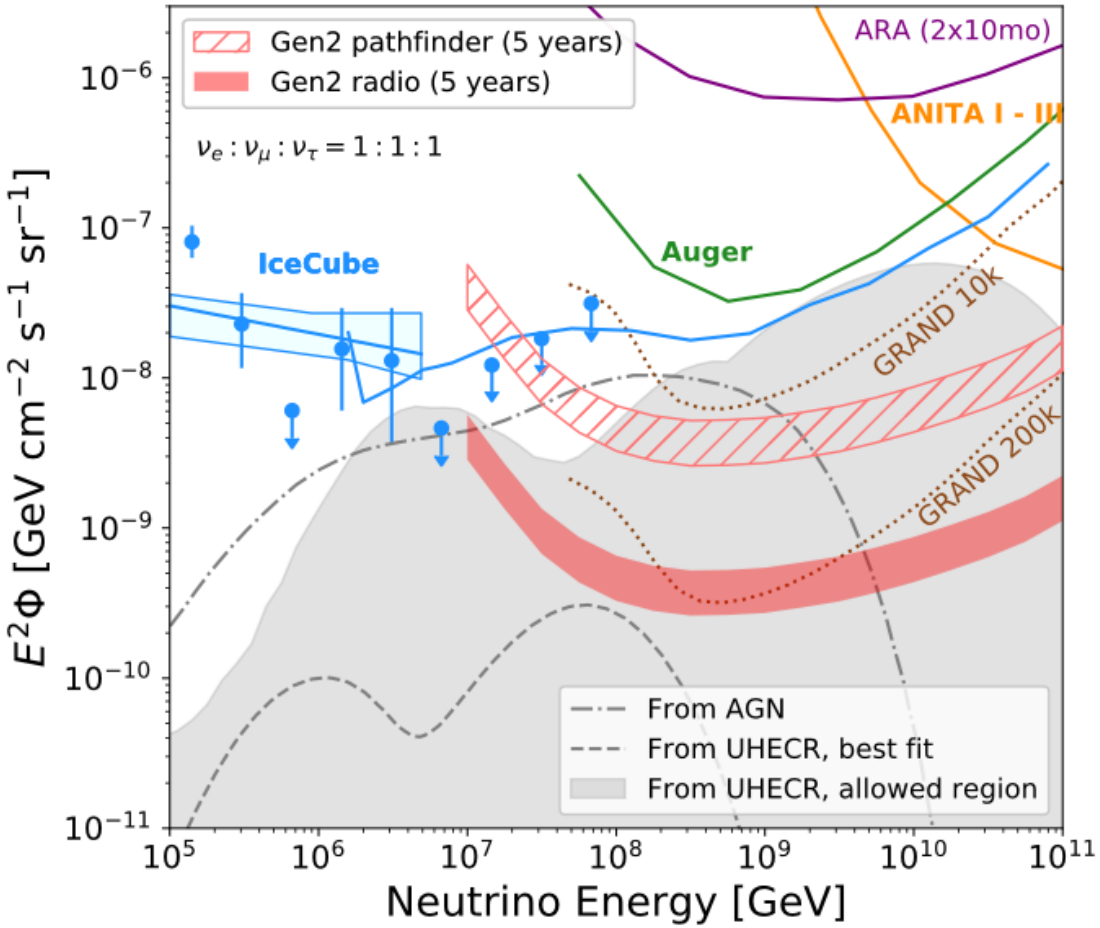
1000 km^3 of ice volume



Heritage: ANITA (Antarctica from balloon), ARA (South Pole), RNO-G (Greenland)

Scientific objectives: building on 10 yrs of IceCube

3. **Revealing the sources and propagation of the highest energy particles in the universe**



Probing source populations and composition of highest energy cosmic rays

IceCube GEN2

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

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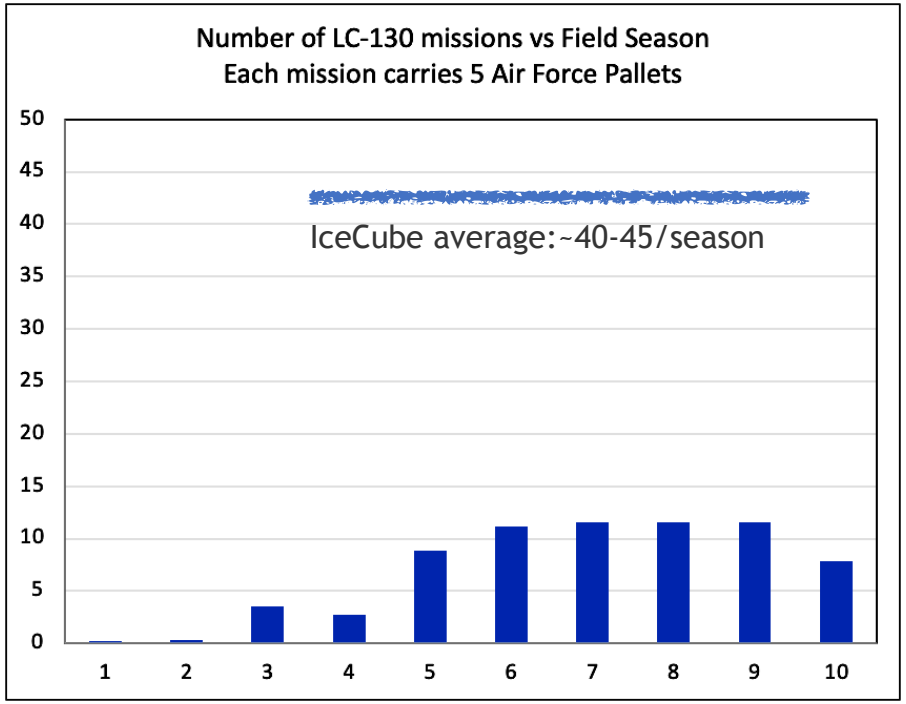
Logistical Support Example: LC-130 flights

LC 130 aircraft



Overland traverse

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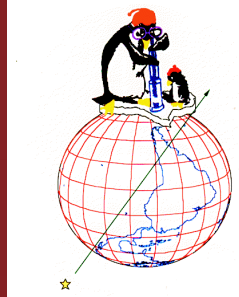
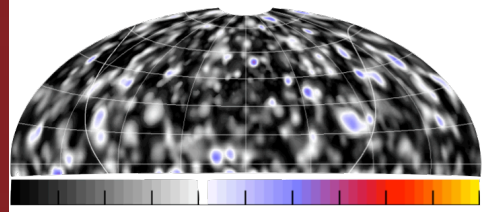
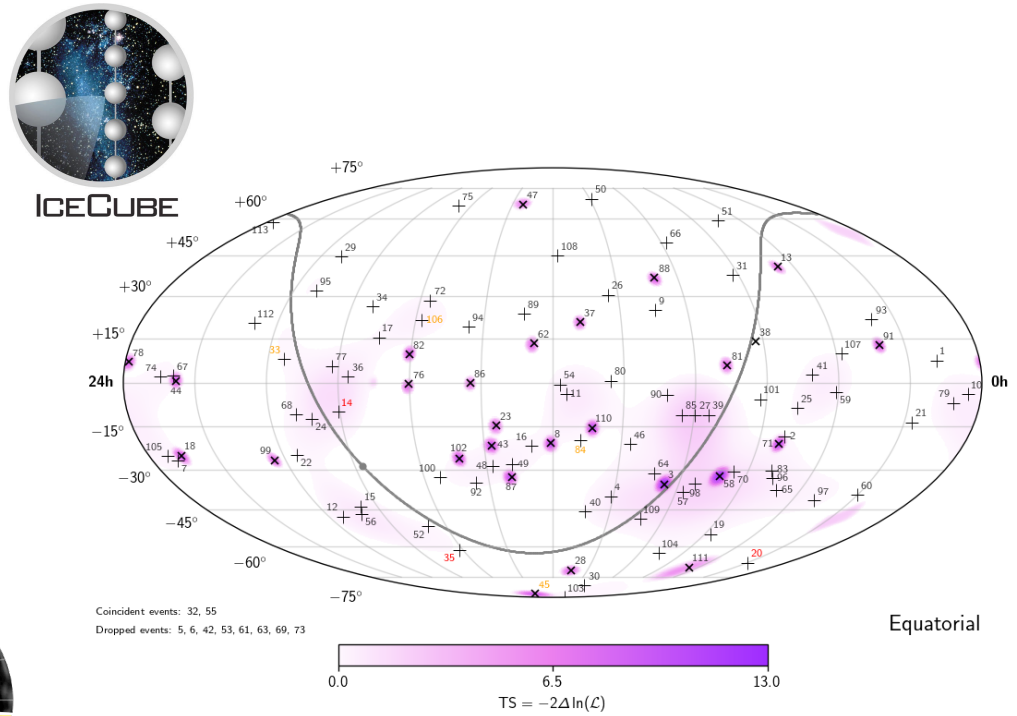
IceCube-Gen2: *From Discovery to Astronomy*







Gen2 Phase 1 (Upgrade) drill camp; January 29, 2020

$E < 300\,\text{TeV}$ $300\,\text{TeV} < E < 1\,\text{PeV}$ $1\,\text{PeV} < E$

1st atmospheric neutrinos in ice

Discovery of astrophysical neutrino flux

First source identified

2002 **AMANDA**

2004 **IceCube**

2013

2018 2020

2023 **Gen2 Phase 1 (Upgrade)**

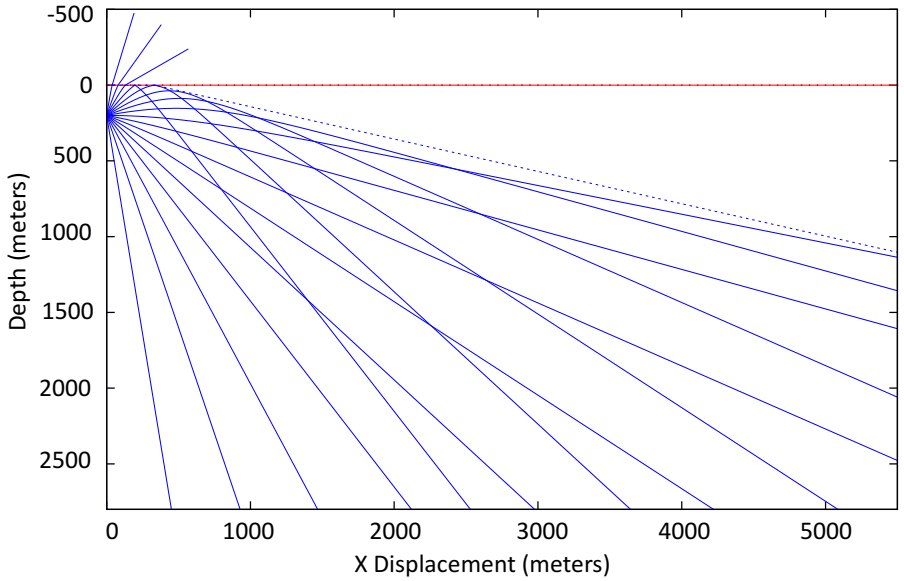
2026 **First full Gen2 deployment season**

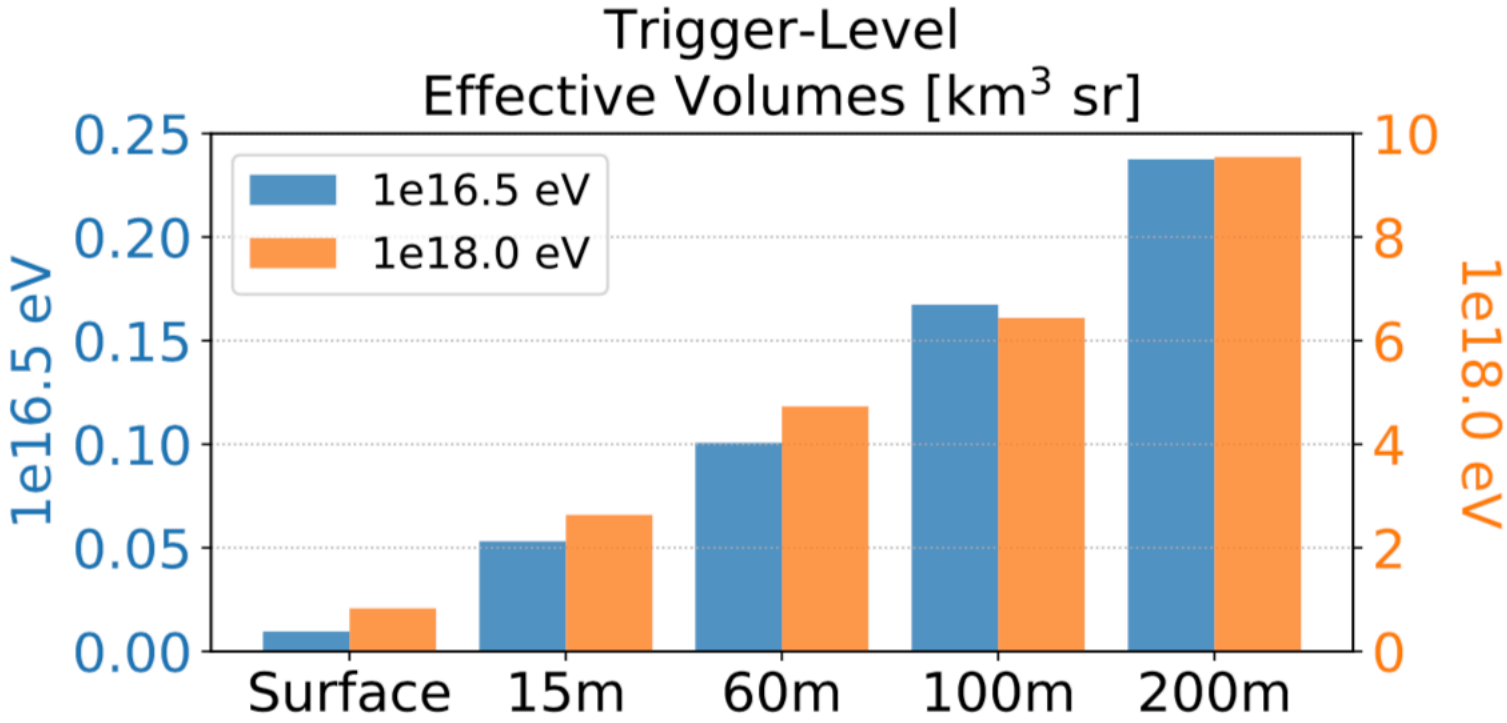
2032 **IceCube-Gen2** **Gen2 full detector completion**

NSF

ICECUBE GEN2

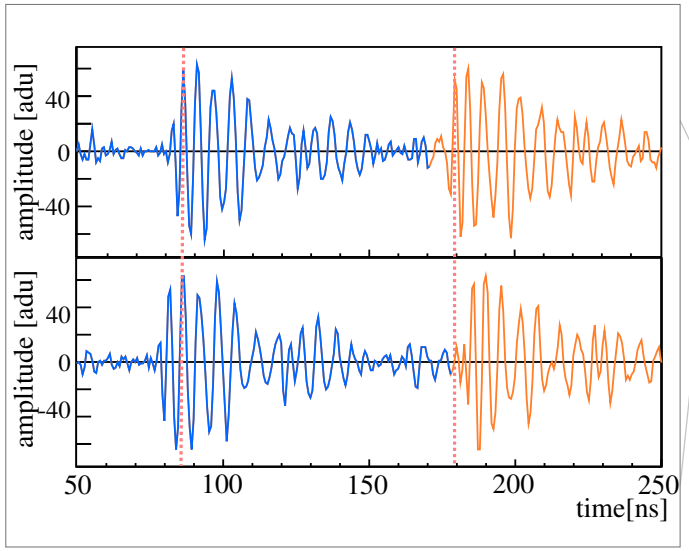
A deeper detector can see more events!

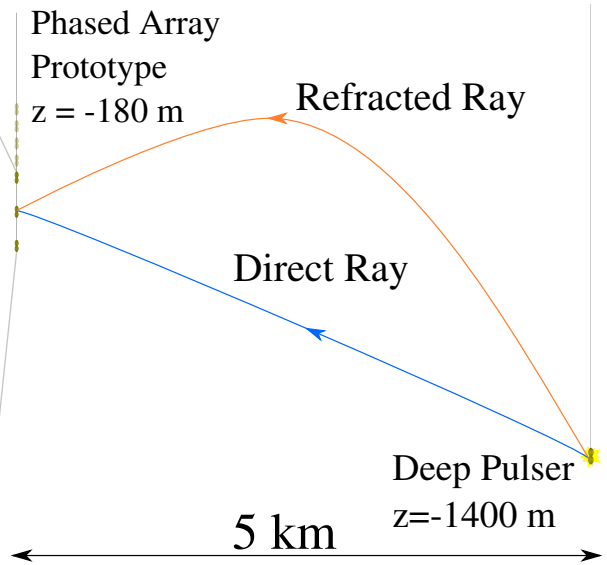


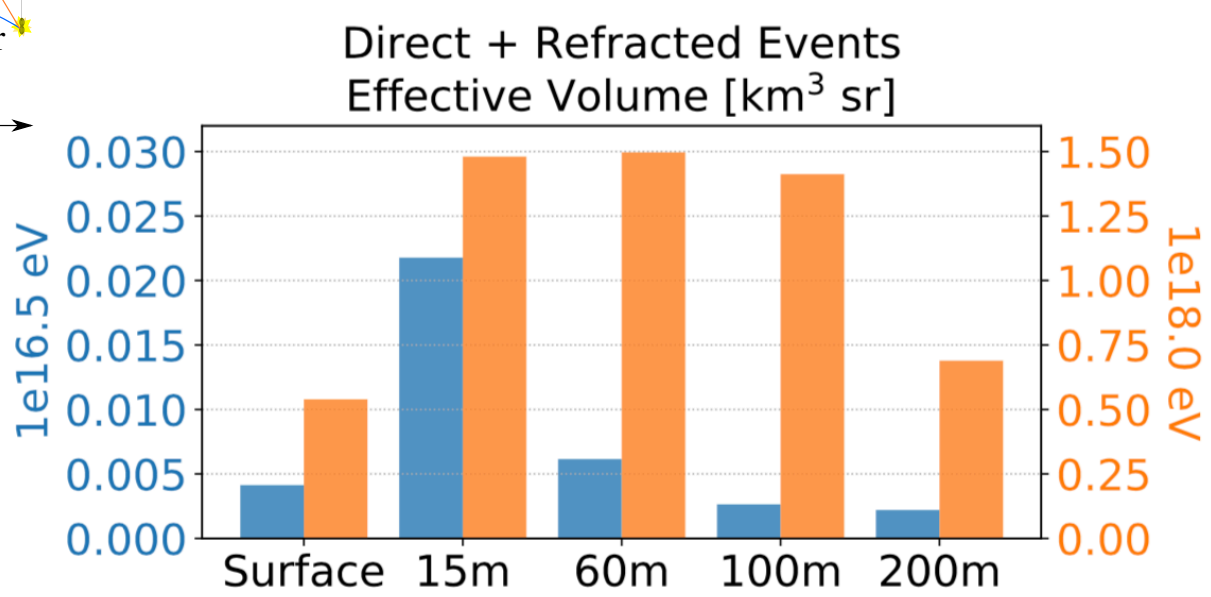


A shallow detector can compensate a little by using larger antennas which may be of higher quality and more gain.

A shallow detector will more often see double pulses
(substantial information gain: vertex and energy)







IceCube-Gen2 - Challenges: Radio array deployment

Drilling

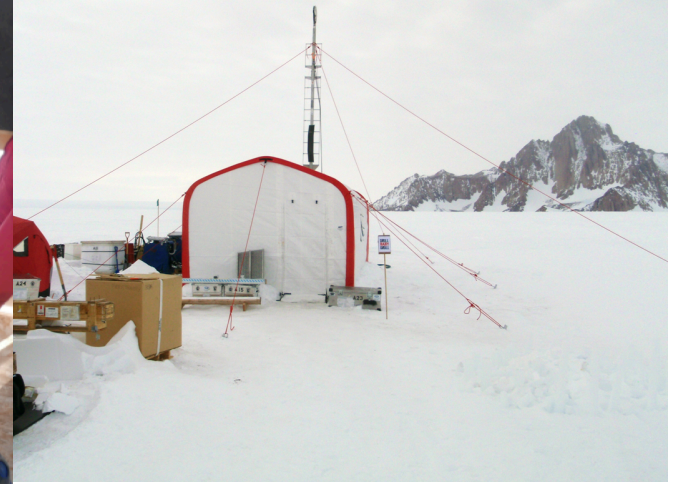
1. Drilling 600 holes for radio while a challenge, is conceptually straightforward.
2. Scalable solutions exist. ASIG drill is current reference. Requires to people to operate. can be turned on and off.
3. For production, a conceptually similar but more automated design of the British Antarctic Survey may be employed..

Population: 2 - 3 people/hole/day

Deployment

1. Deployment takes most of the labor. about 2/3 of the population will be needed for deployment.
2. Long distances require special safety considerations.
3. Good equipment for transportation: Field shelters, Arctic trucks.

ASIG drill
https://icedrill.org/equipment/agile-sub-ice-geological-drill.shtml



EHWD-Gen1

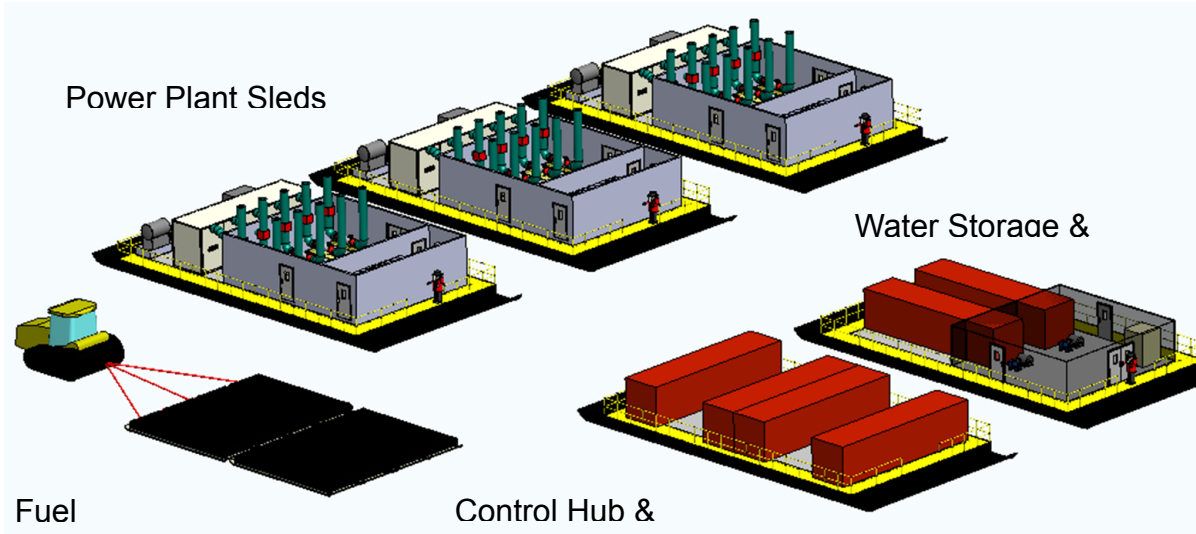
Hose reel

Mobile drill/deployment towers

EHWD heating plant: stationary
—> Gen2: mobile

Gen2 hot water drill - changes in requirements

- Mobility: IceCube drill was stationary per season. Gen2 string spacing requires a mobile drill. WDrill will be moved multiple times per season.
- Improved efficiency and lower maintenance technology
- Aim for higher drill speed. (Gen1: 2.1 m/min, Gen2 target close to 3 m/min)



IceCube GEN2