IceCube-Gen2

From Discovery to Astronomy

IceCube Bootcamp
June 2022

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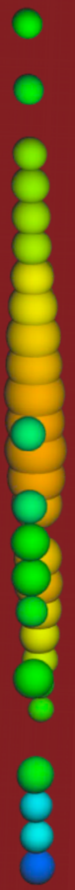
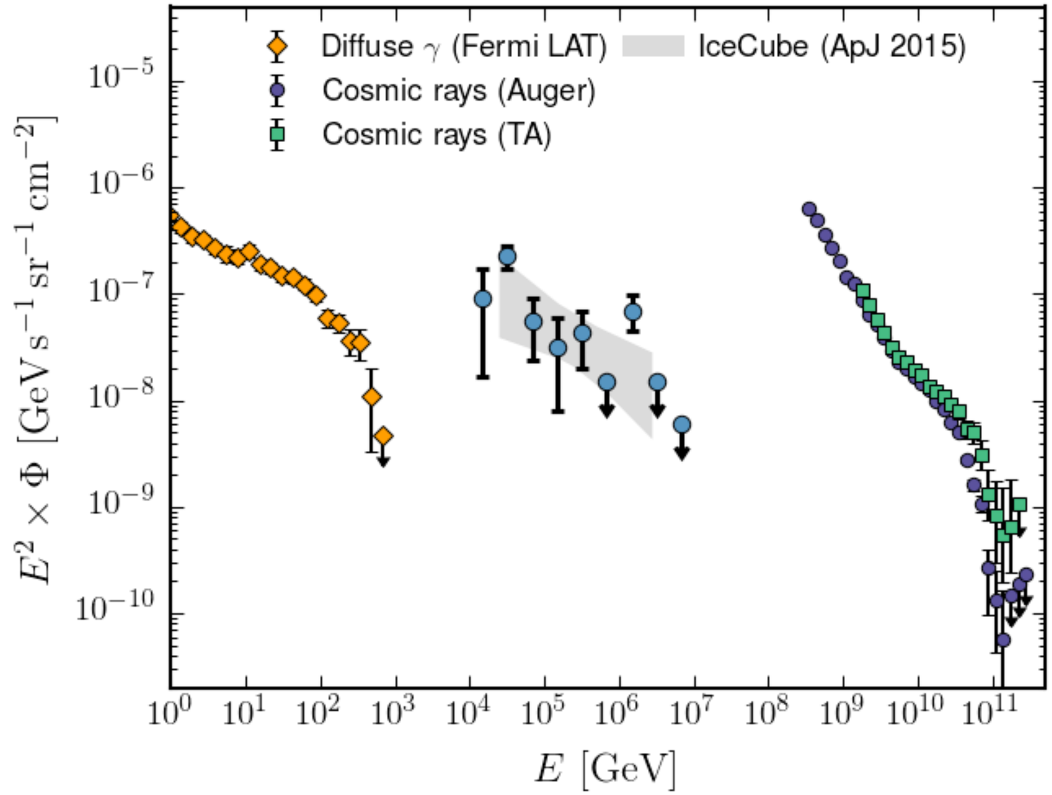
Univ. Wisconsin-Madison

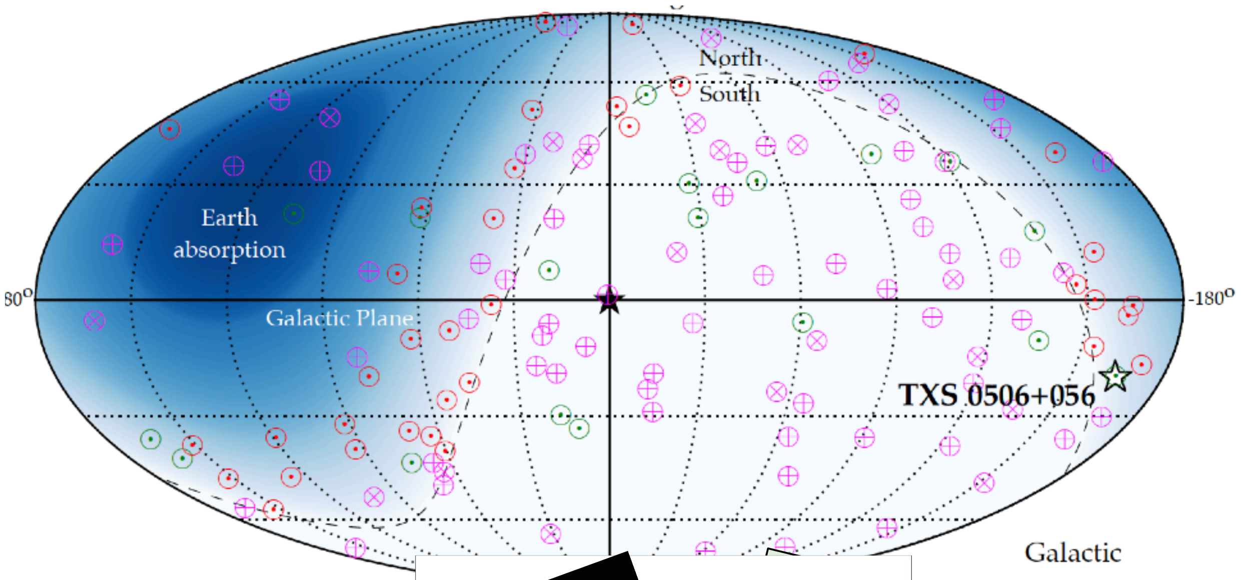
10 yrs of IceCube - a first view on the PeV Universe



Multimessenger spectroscopy



First sky map of cosmic neutrinos

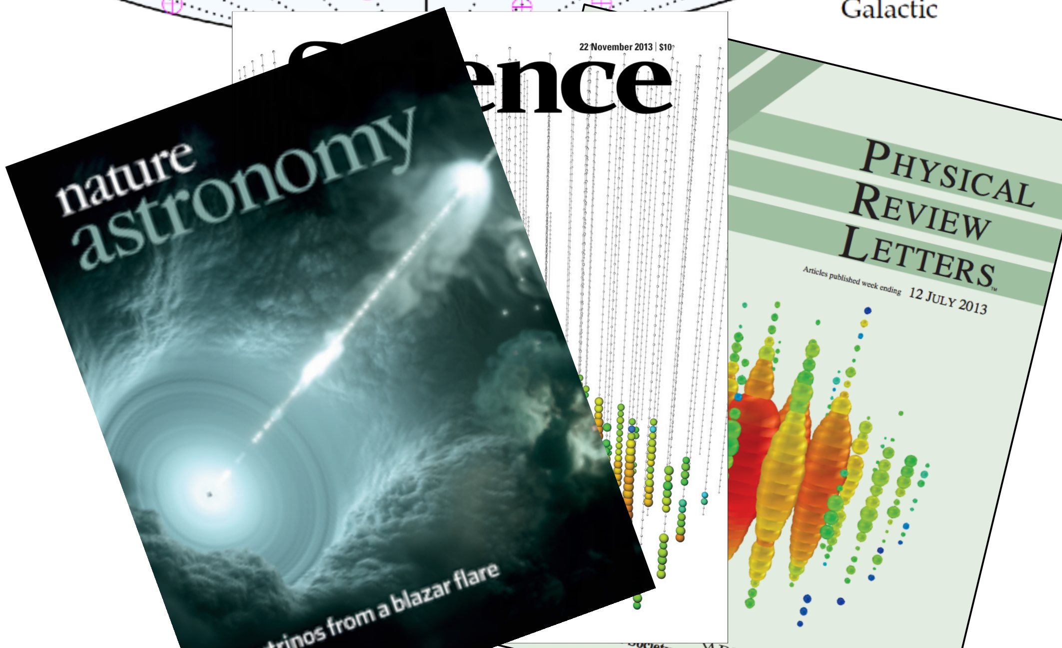


Some highlights:

2013: Discovery of cosmic PeV neutrino flux

2018: Evidence for Blazars as neutrino sources

2019: Observation of first tau neutrino



NSF

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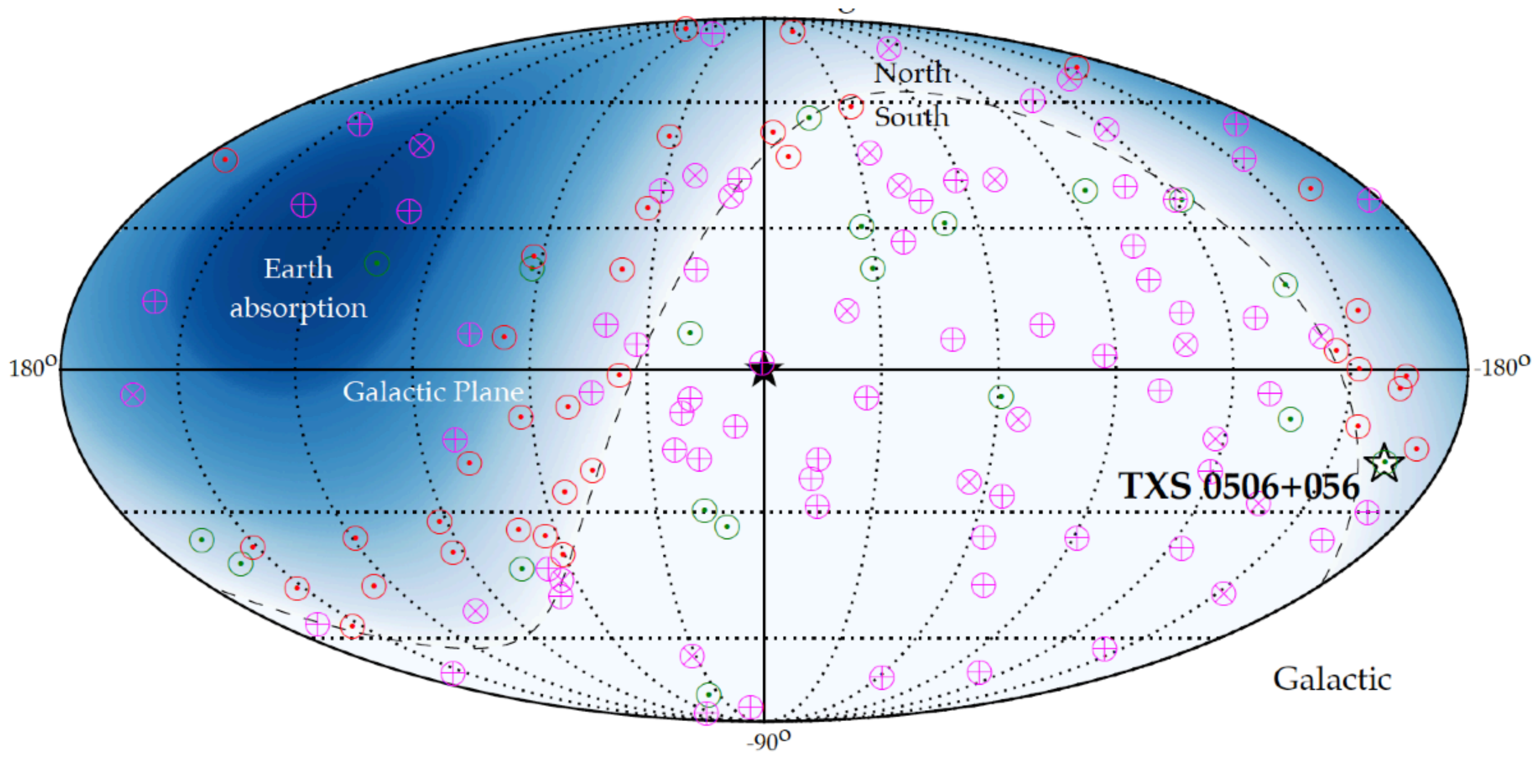
Scientific objectives: building on 10 yrs of IceCube

Resolving the high-energy sky from TeV to EeV energies



What are the sources of IceCube's high energy neutrinos?

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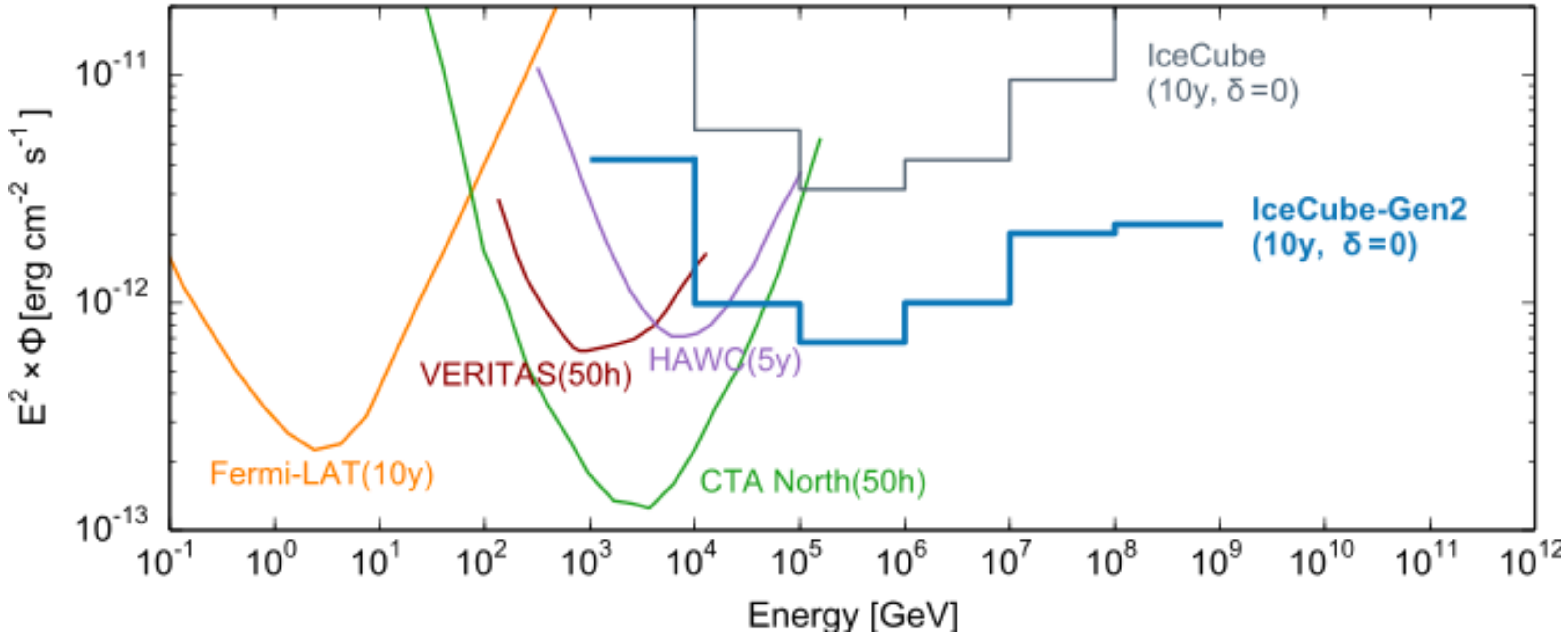
Understanding cosmic particle acceleration through multimessenger observation

Pointsources sensitivity

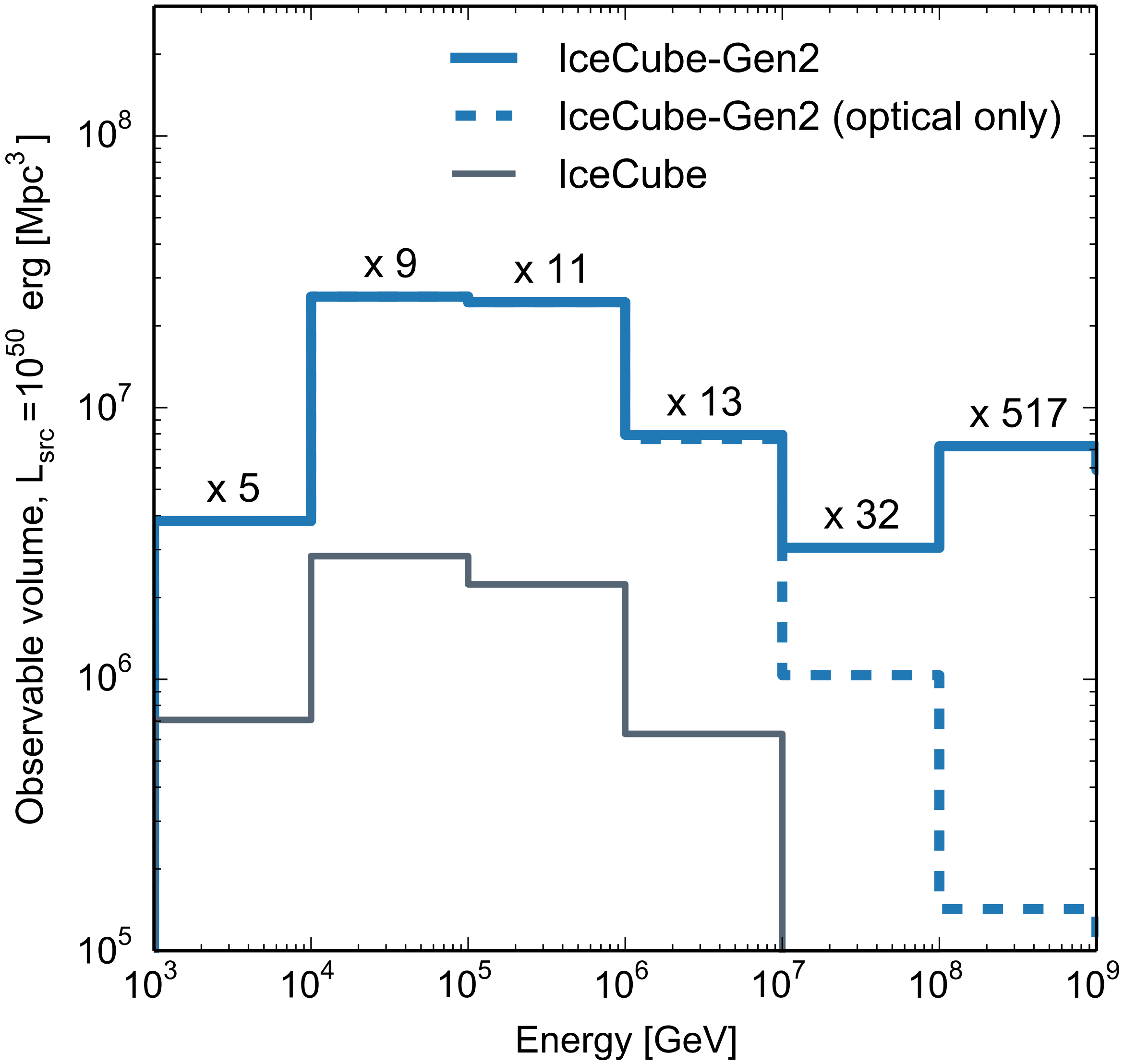
Completing the multi-wavelength view of the Universe



Observable volume with IceCube-Gen2

Expand energy range to beyond 10^{18} eV with sensitivity improved by two orders of magnitude

Uniform sensitivity over large energy range over more than 6 orders of mag energies.



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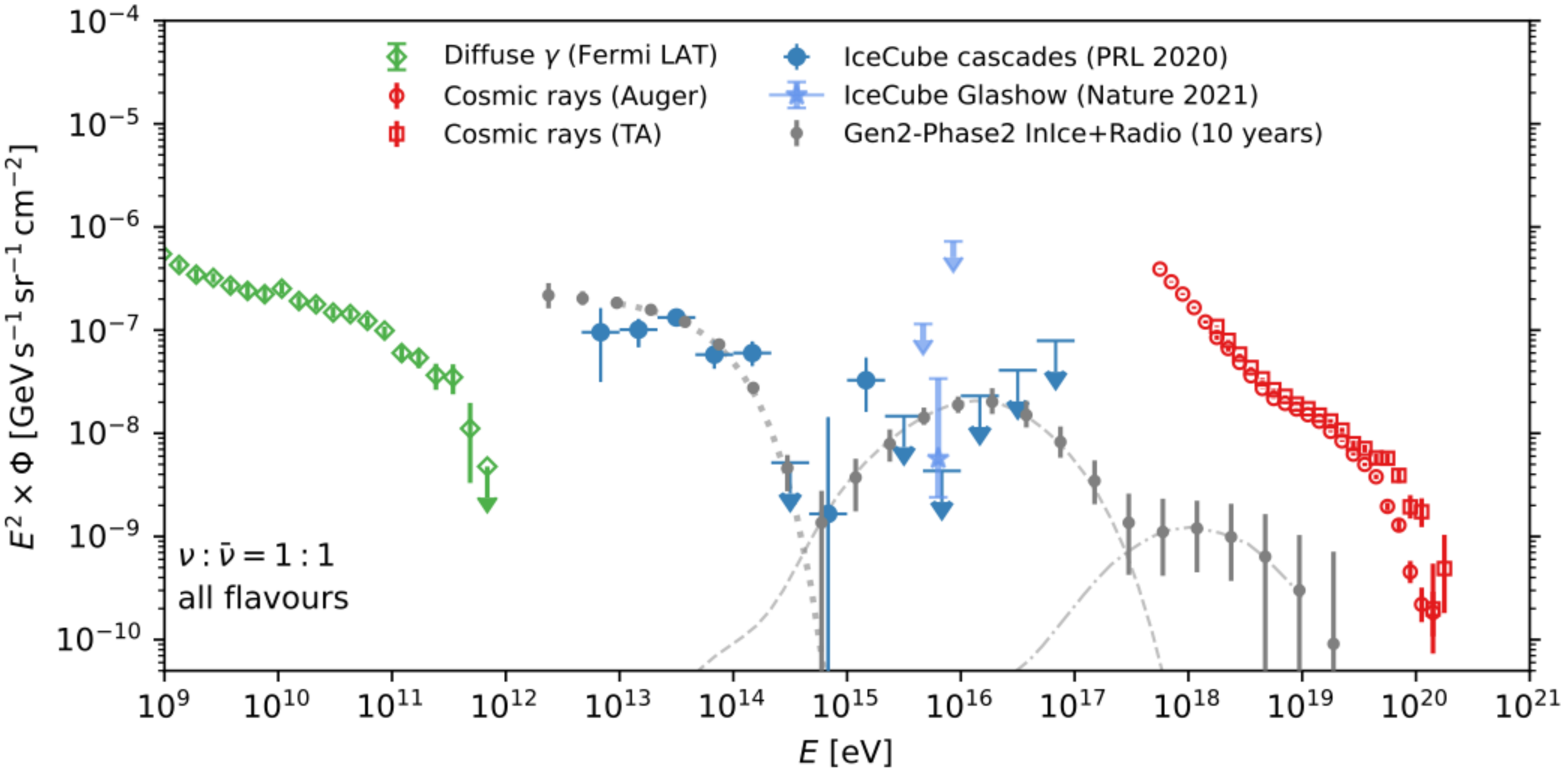
Understanding cosmic particle acceleration through multimessenger observation

Diffuse neutrino flux:

Completing the multi-wavelength view of the Universe



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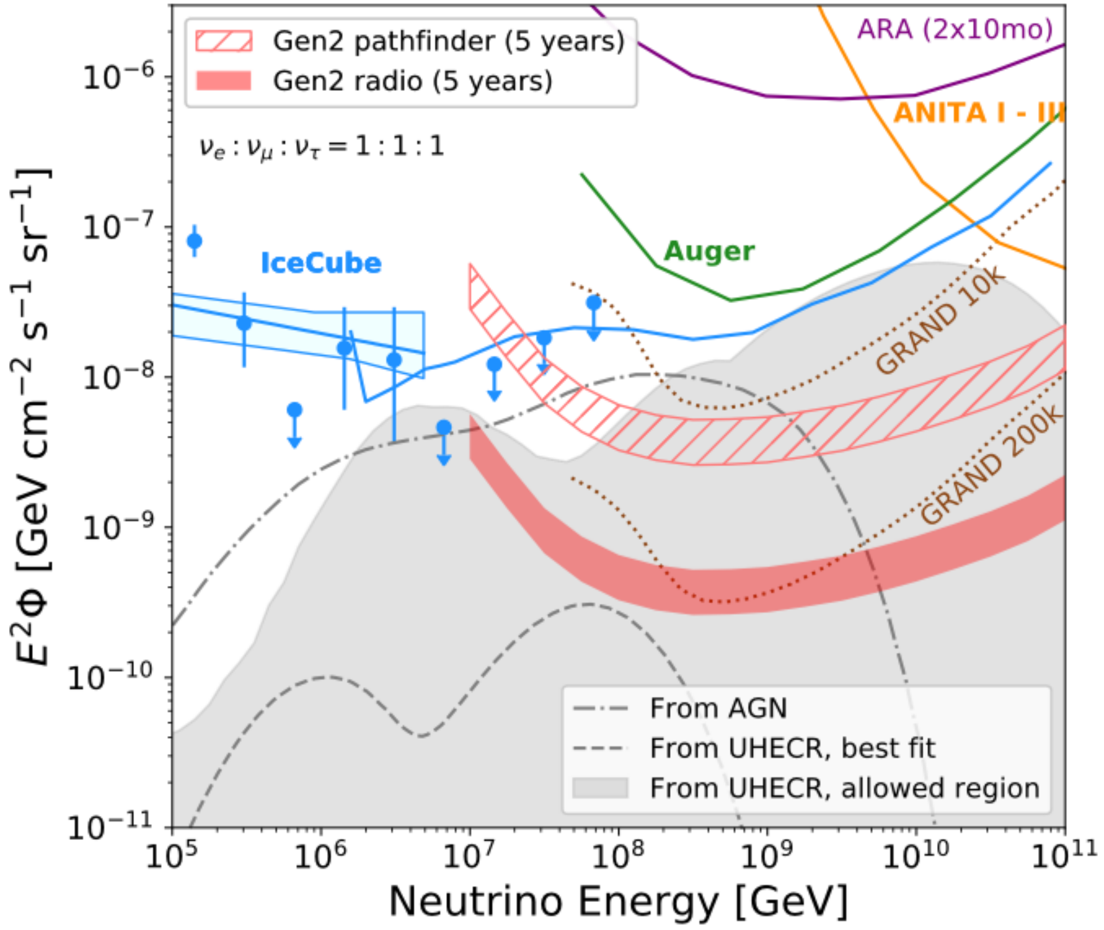
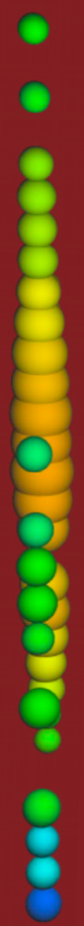
Revealing the sources and propagation of the highest energy particles in the universe

Probing source populations and composition of highest energy cosmic rays

Abby's talk on radio detection.



ICECUBE GEN2



Neutrino production mechanisms with cosmic rays:

Accelerate protons and have them interact.

Result: Pions and other stuff

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

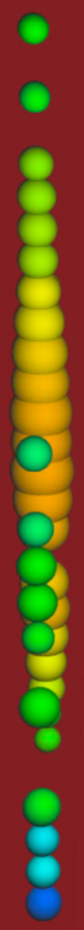
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
~~$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$~~

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

- π decay: $(1:2:0)_S$
- μ-damped: $(0:1:0)_S$
- n decay: $(1:0:0)_S$

ICECUBE GEN2



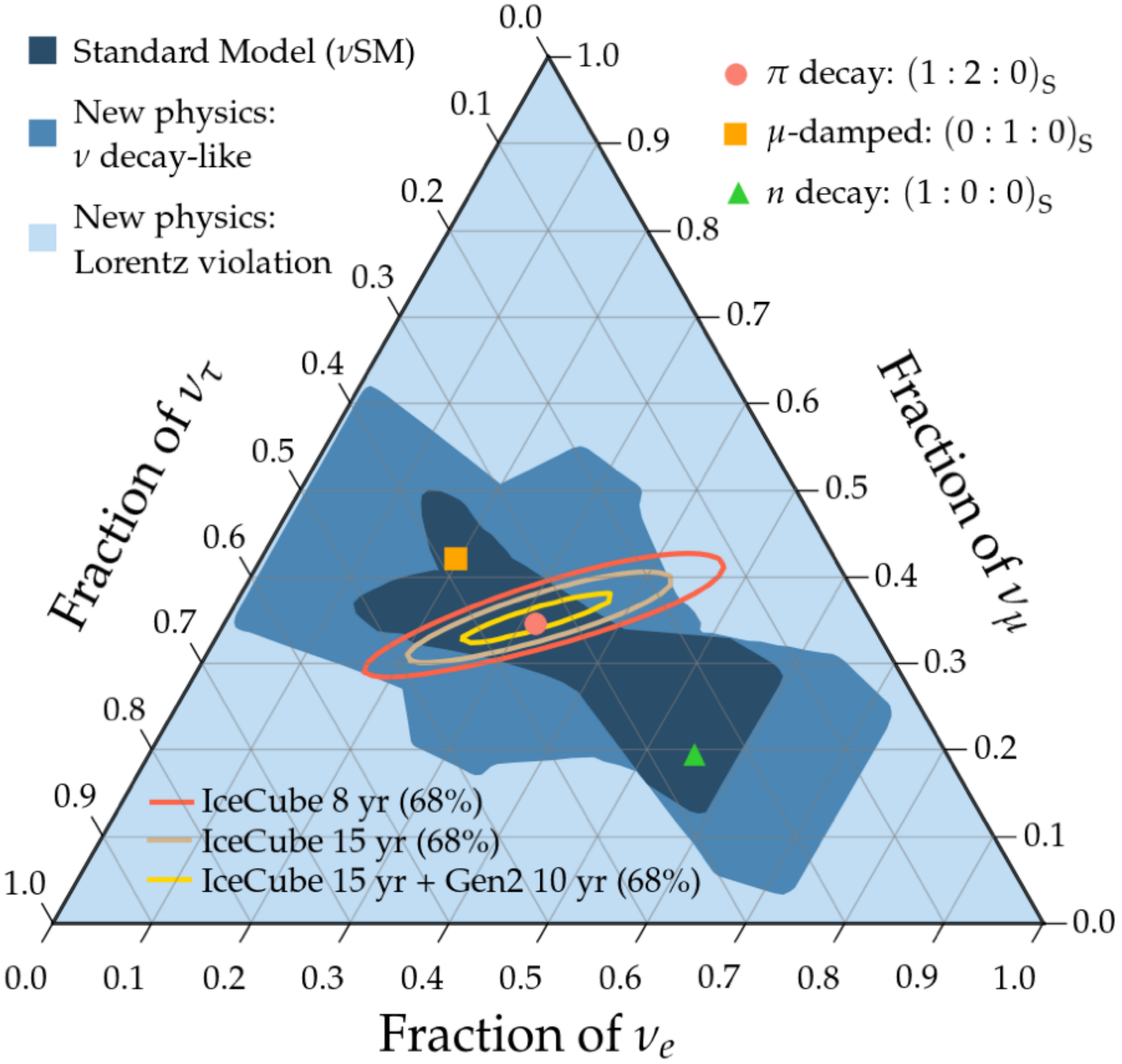
Probing fundamental physics with high-energy neutrinos

Probing neutrino oscillations over cosmic baselines

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

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

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



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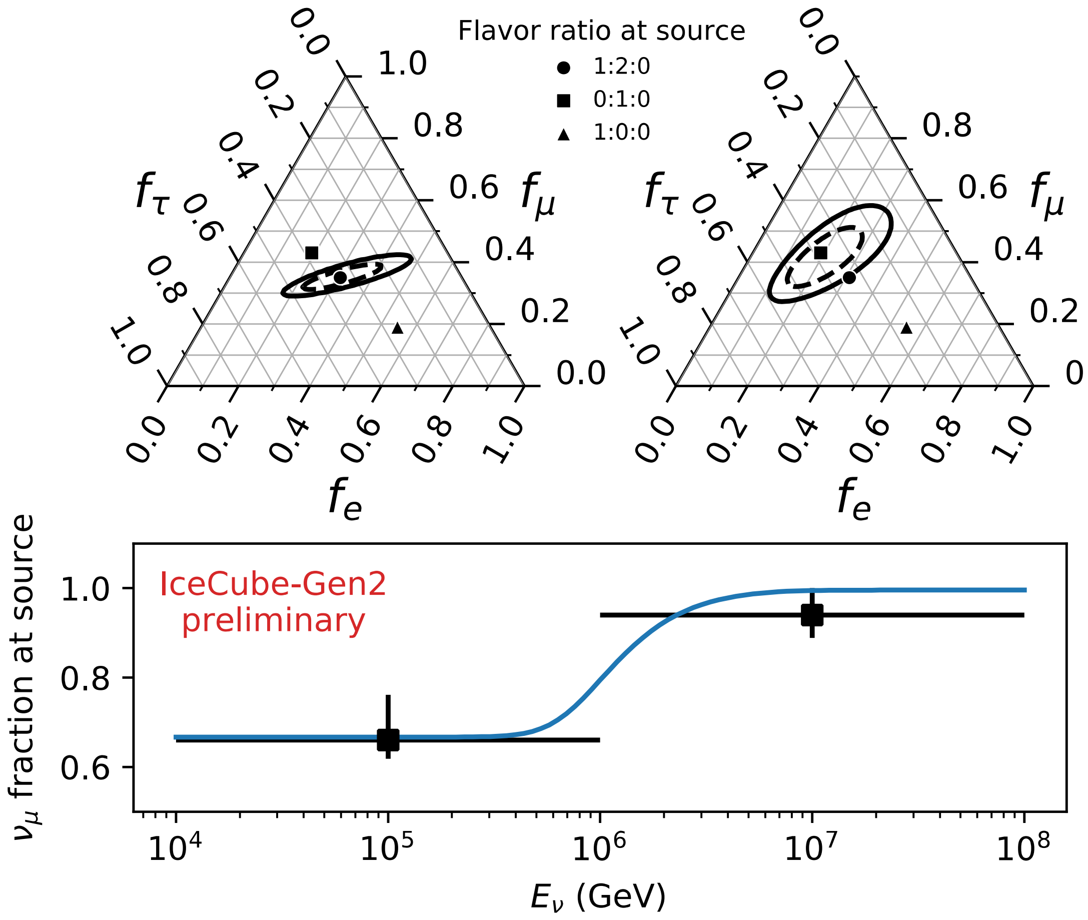
Requirements for IceCube-Gen2

Enhanced sensitivity to neutrino flavors and the ability for flavor identification



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

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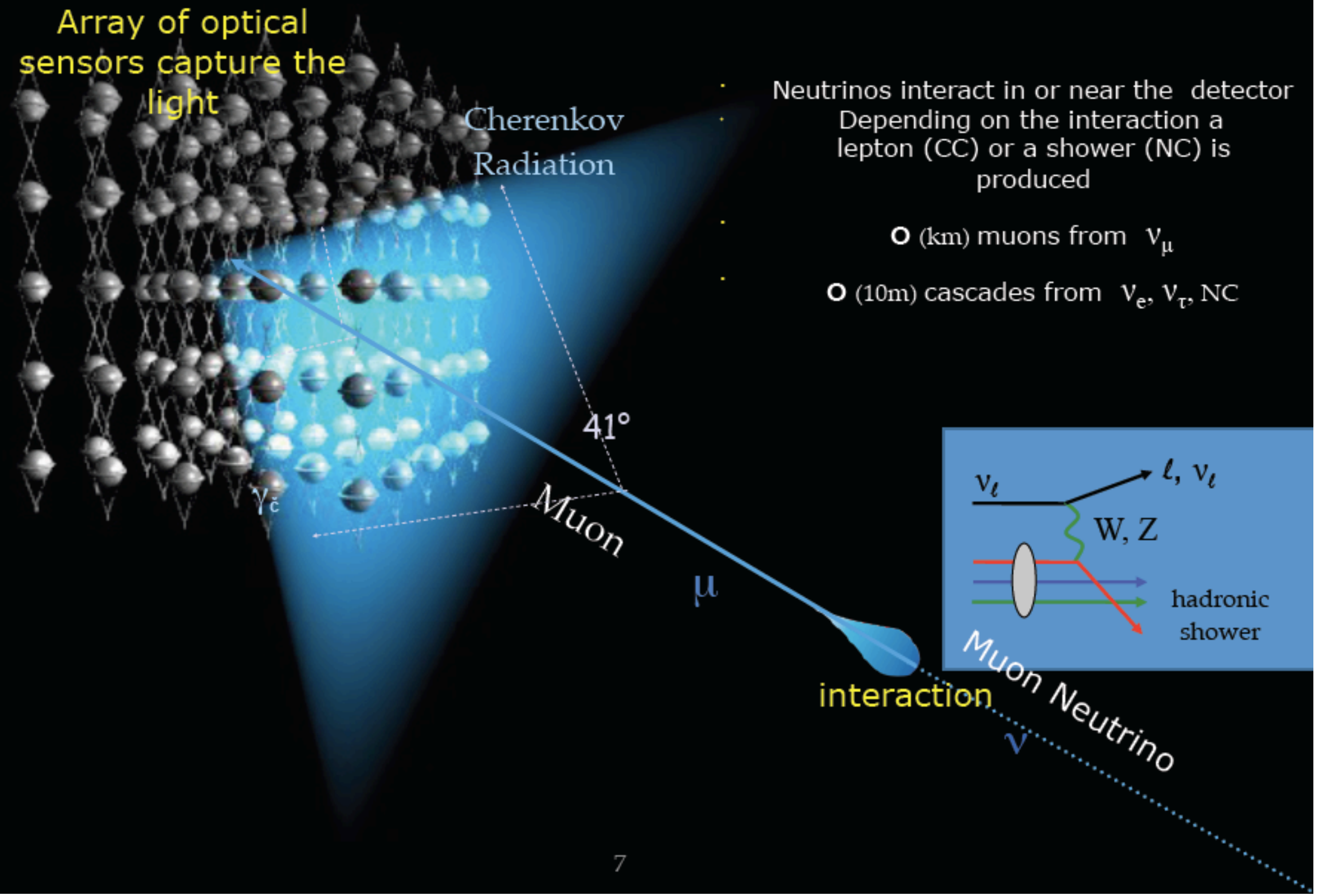
- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
  - O (km) muons from ν_μ
  - O (10m) cascades from ν_e, ν_τ, NC



Bert:
Energy 1 PeV

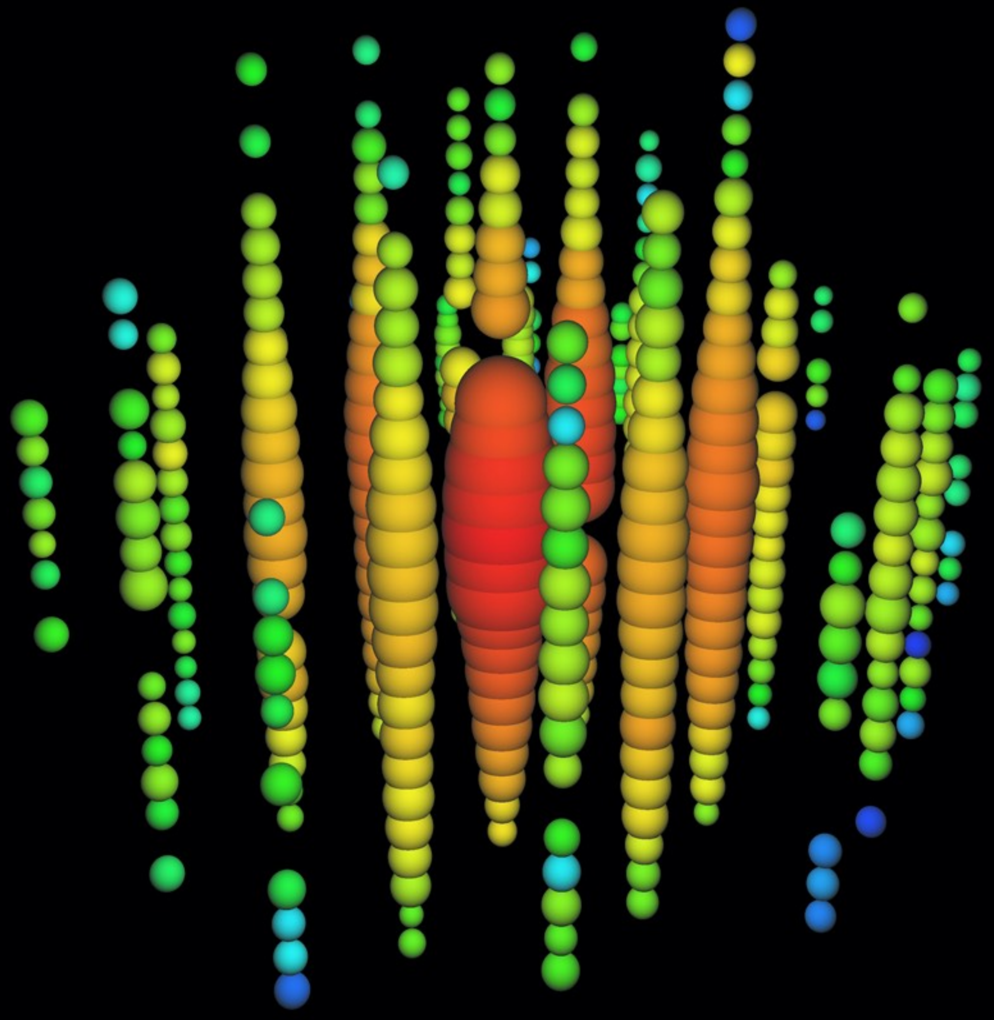
How well could we reconstruct
this event with fewer strings?

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

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

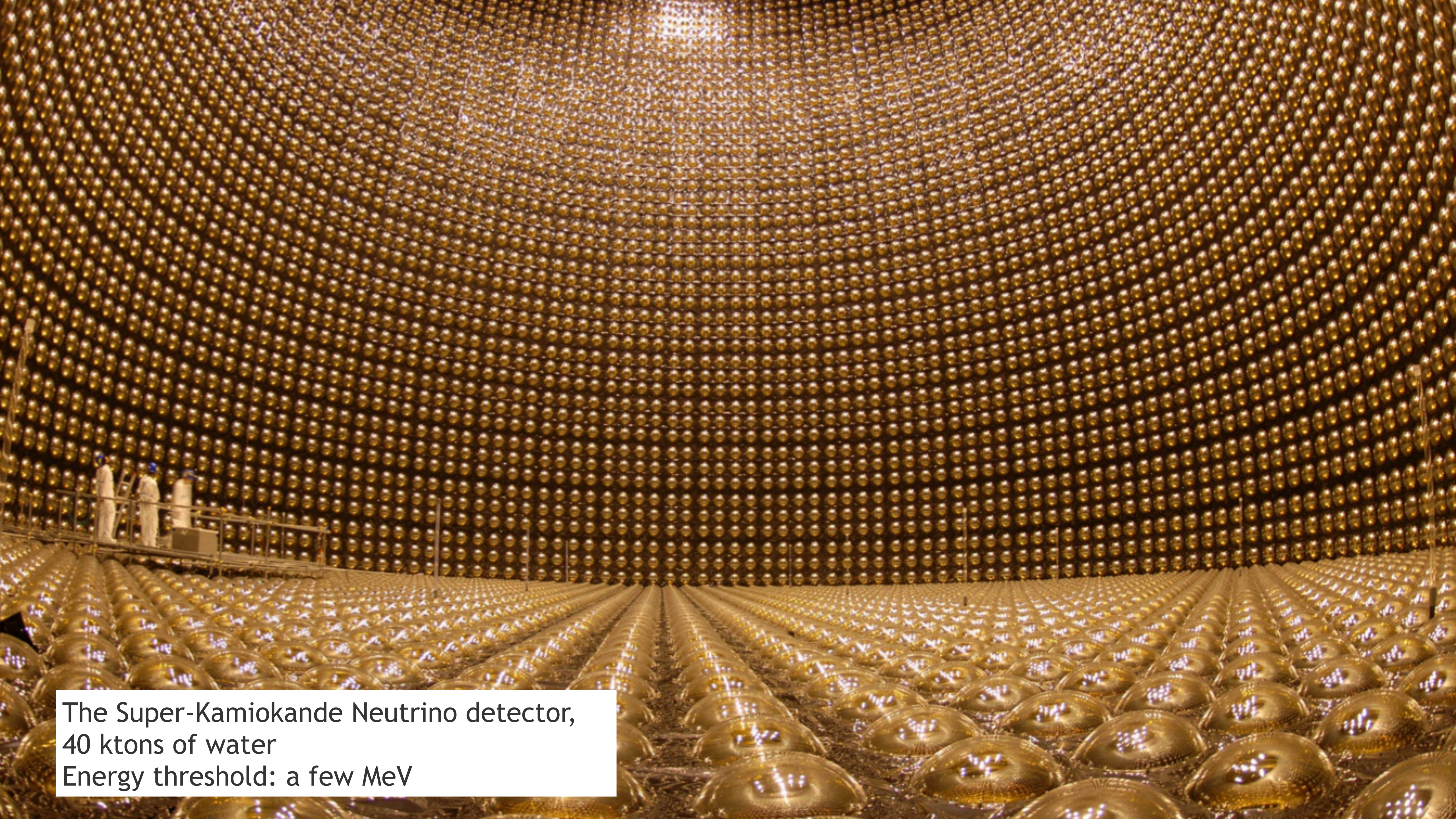
Same result for Ernie, the other PeV event.

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



Dr. Strangepork

Deposited energy: 71 TeV
7.1 x 10^13 eV



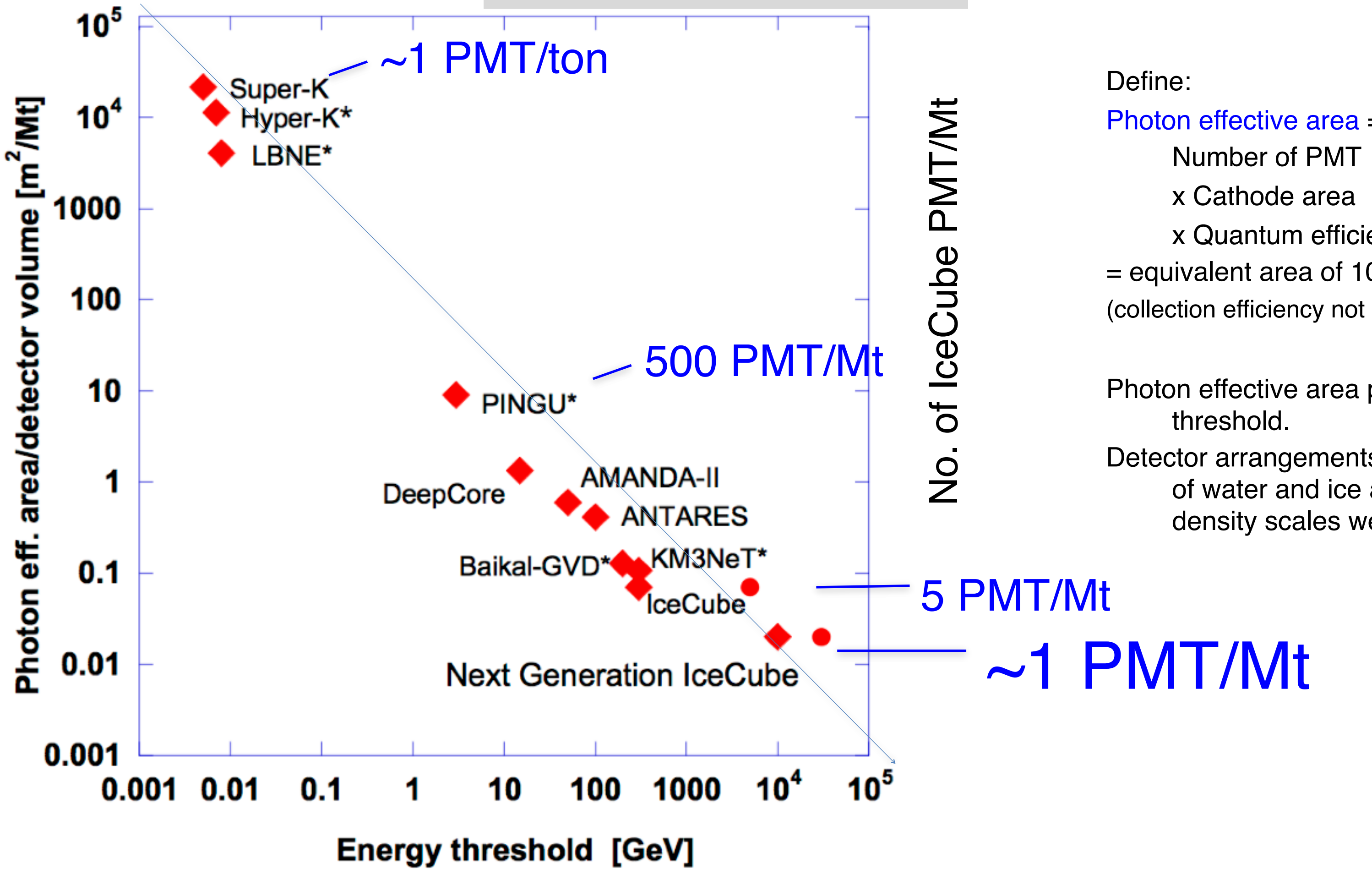
The Super-Kamiokande Neutrino detector,
40 ktons of water
Energy threshold: a few MeV

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 threshold.

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.)

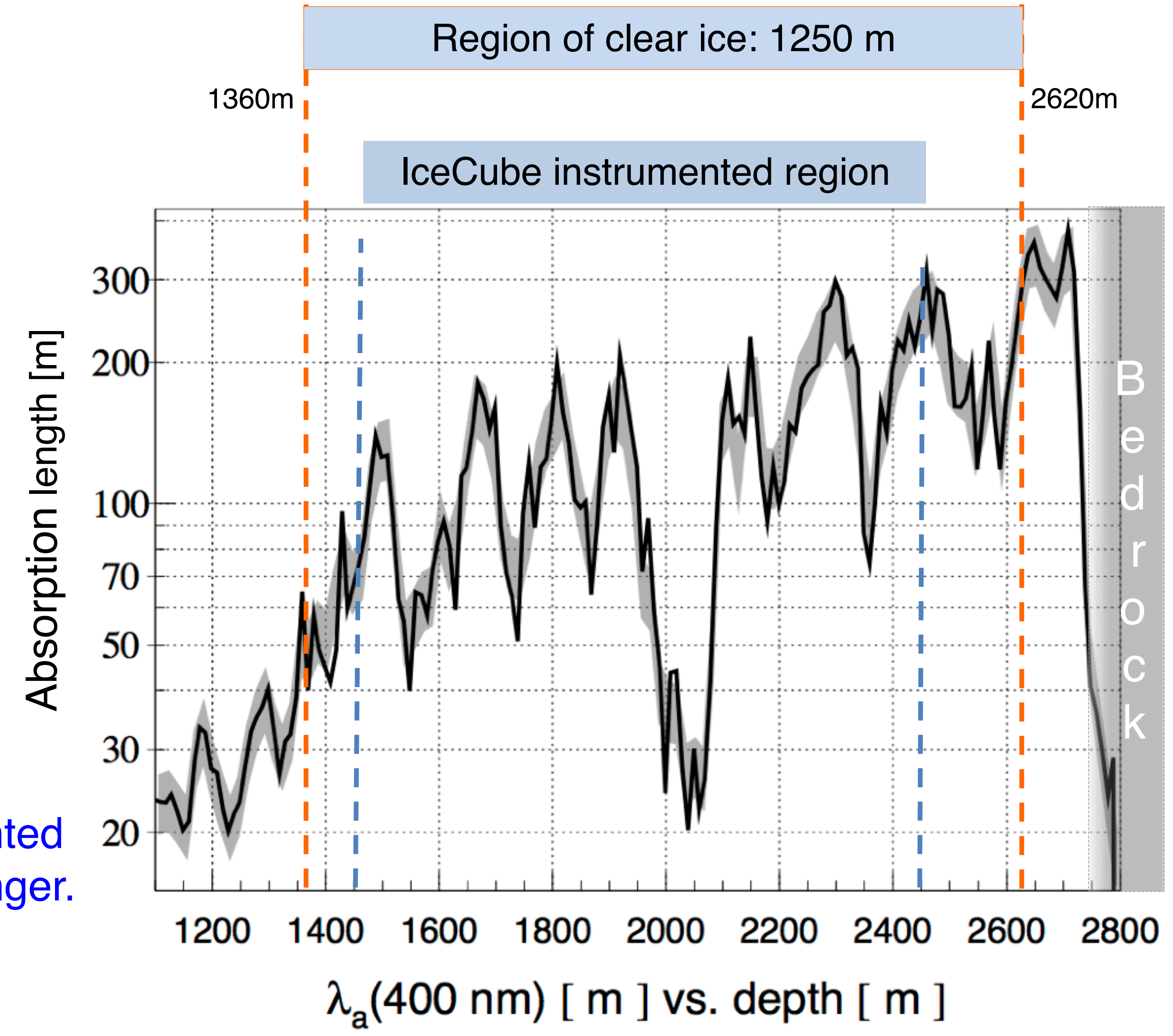
Photon effective area prop. ~ 1/Energy threshold.

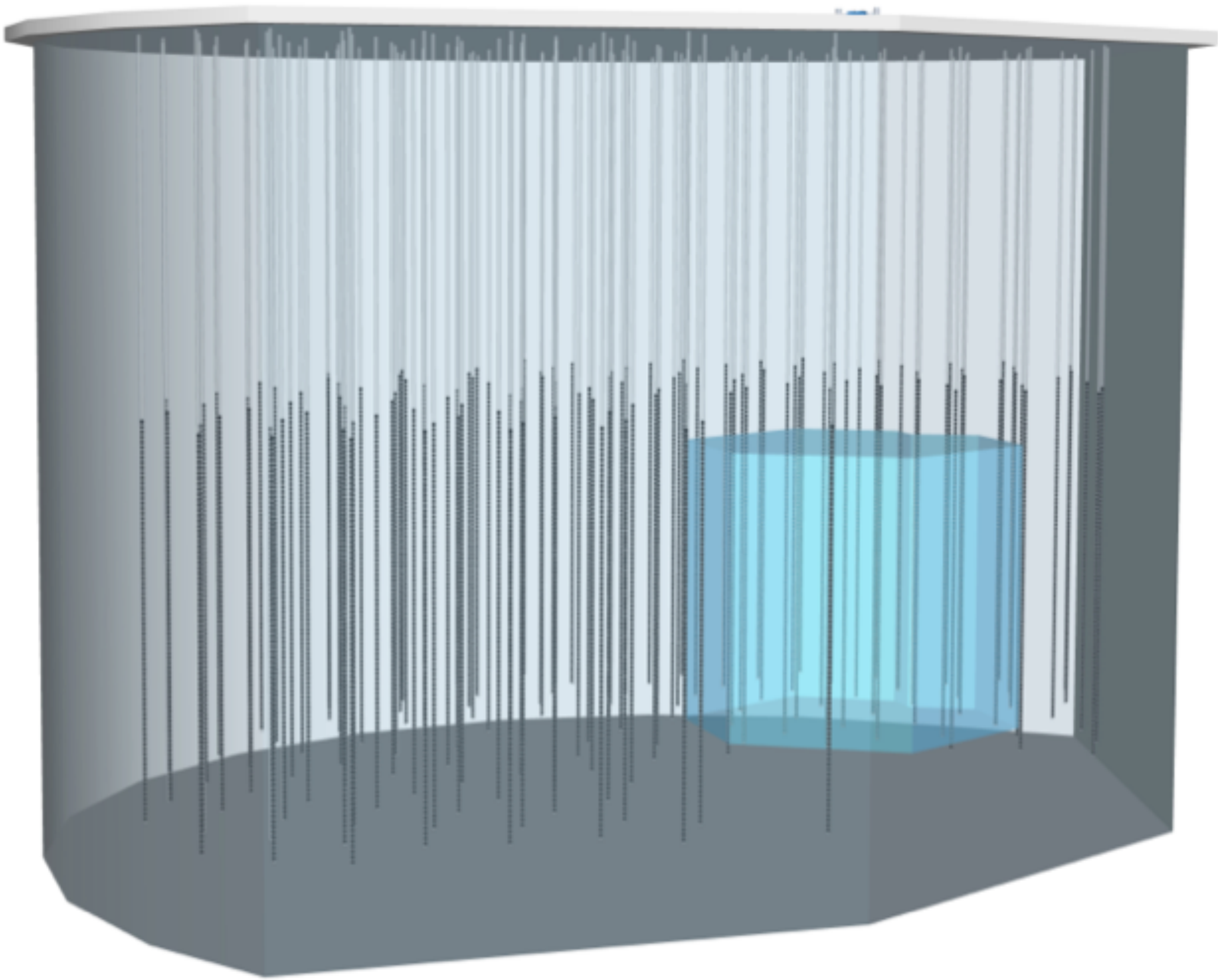
Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

Extending the region of ice to instrument with DOMs

- Bedrock estimated depth 2750m – 2850m
- 150 m to 200 m of very clear and usable ice below IceCube (need safety distance from bedrock)
- 100 m of good ice above

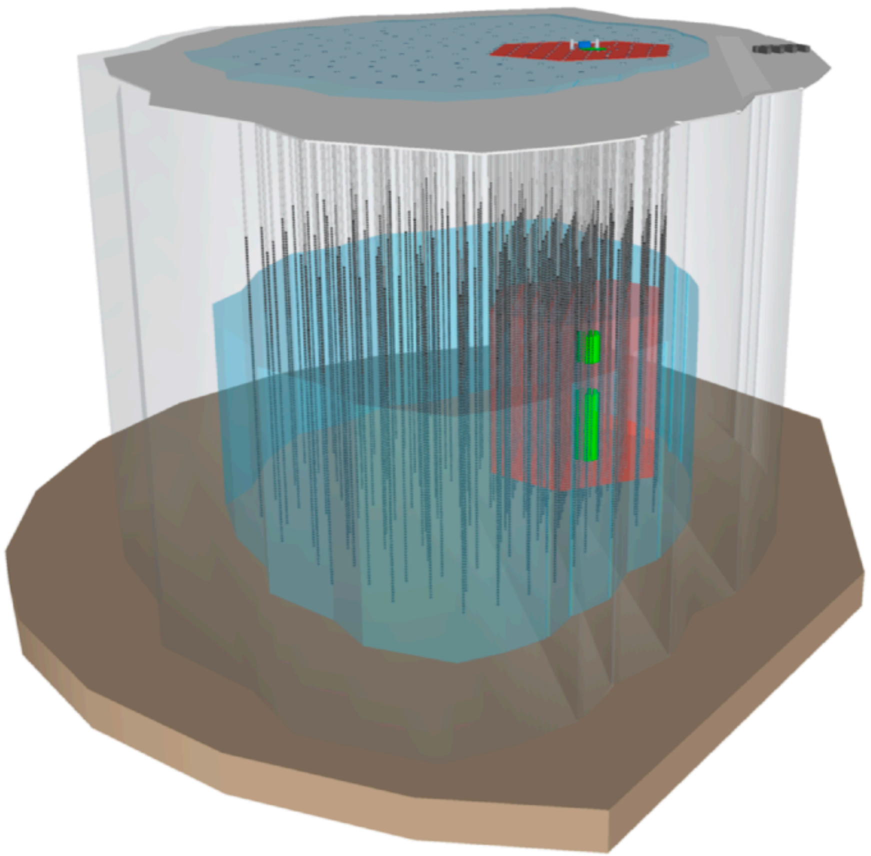
→Can make instrumented region 250 to 300m longer.

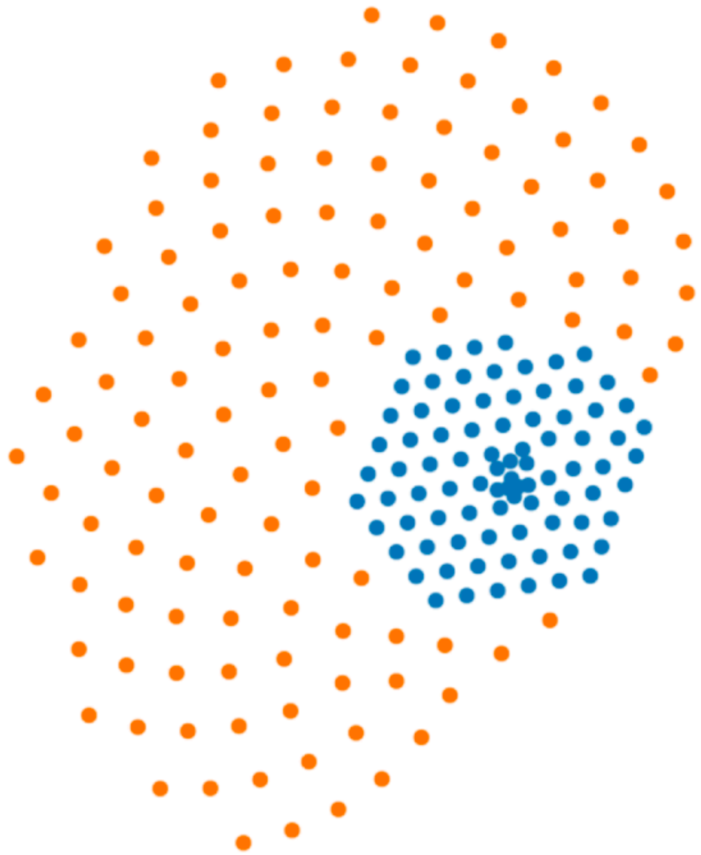




IceCube-Gen2

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





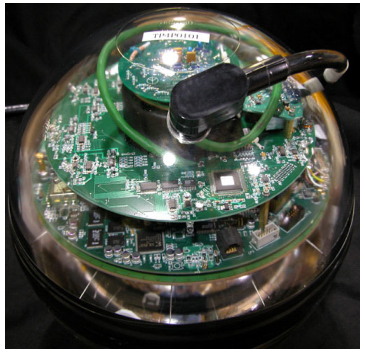
Artist's conception
120 strings at 240 m spacing

ICECUBE GEN2

The next-generation IceCube: from discovery to astronomy

Optical sensors

IceCube DOM



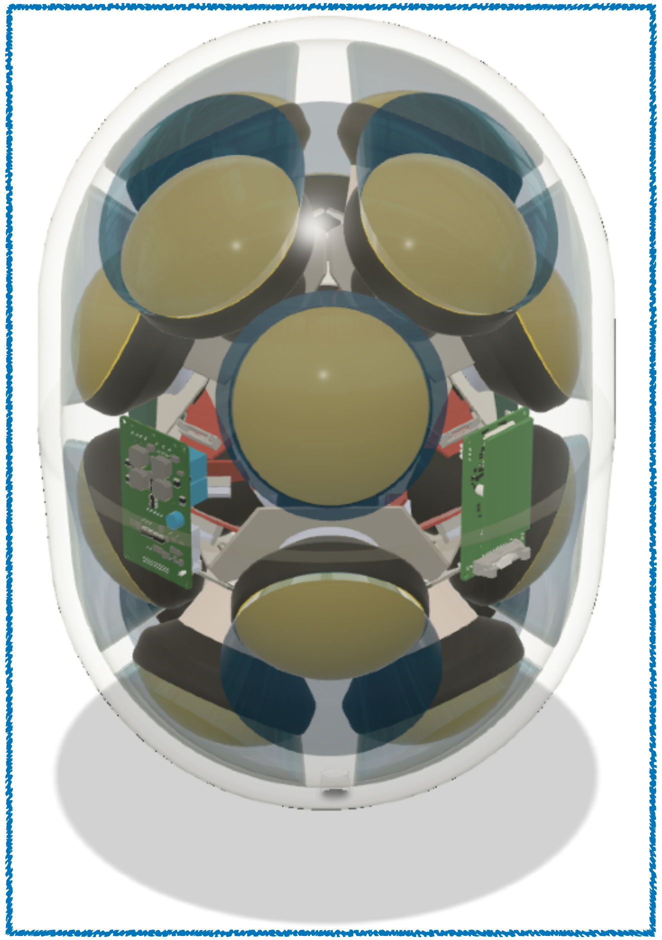
Diameter 33 cm
10 inch PMT

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

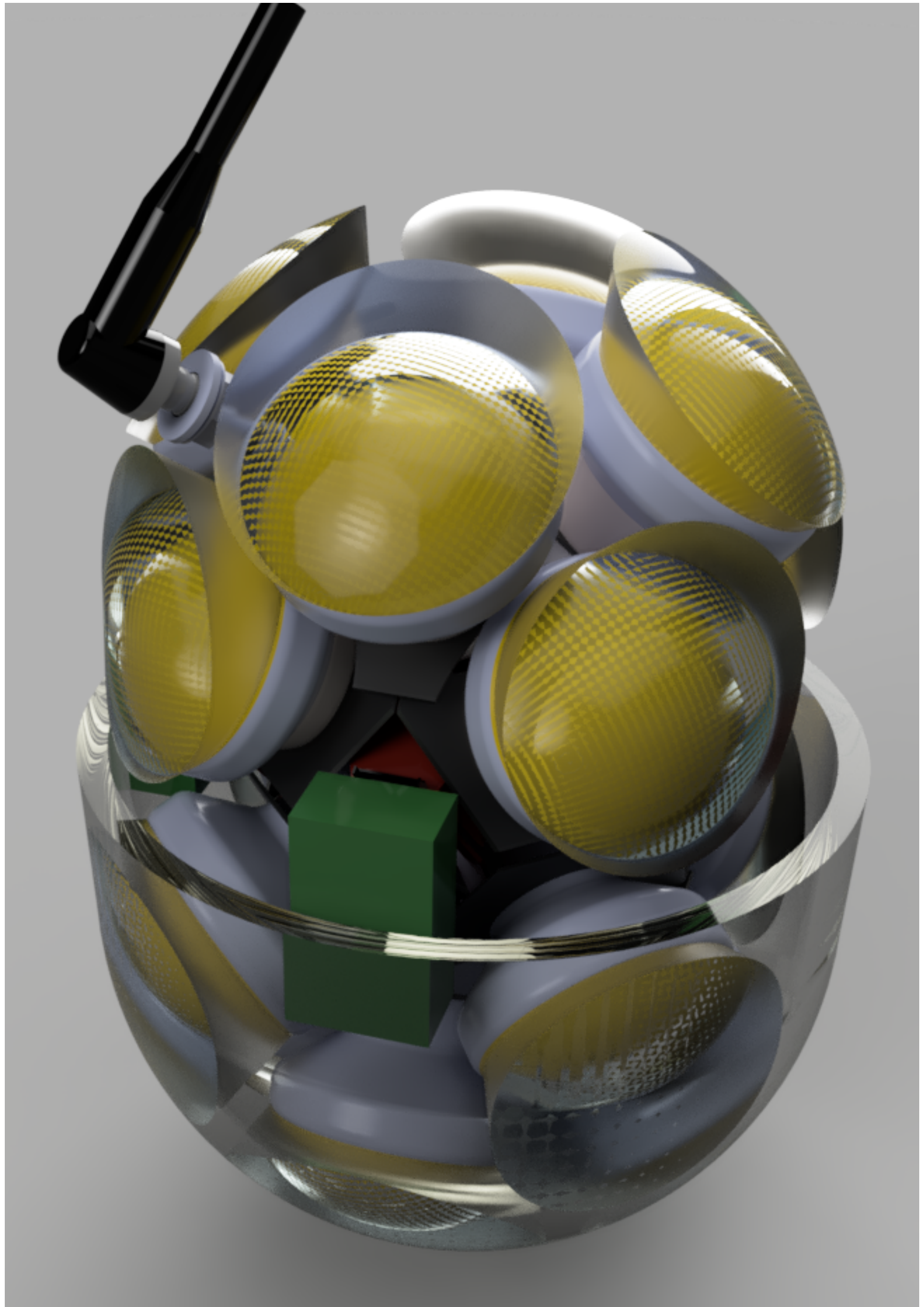


16 x 4 inch PMT
Smaller diameter 30 cm

ICECUBE GEN2

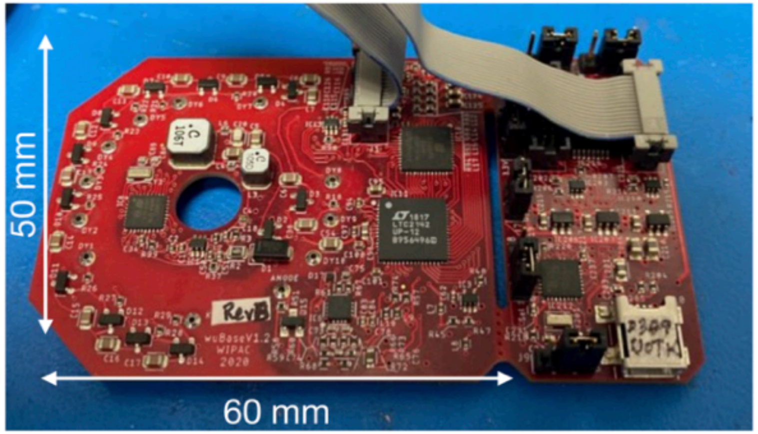
Gen2 optical module: LOM

- **LOM Design goals:**
  - Large photon effective area (QE, CE)
  - Pixels
  - Good PMT specs

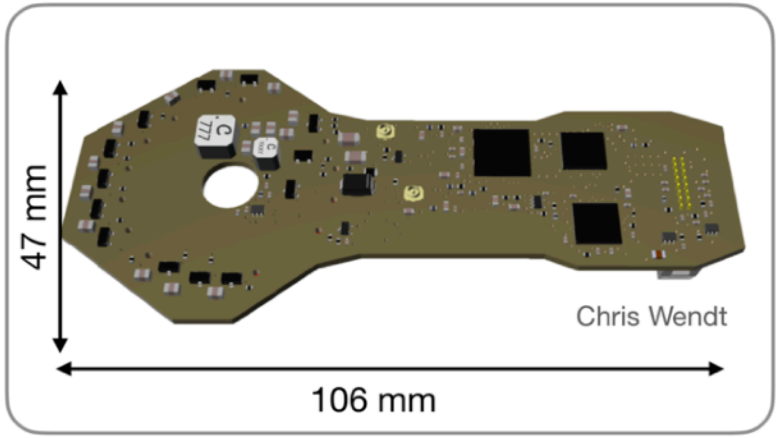


Support structure examples and base: progress with LOM 16 and LOM 18

wuBase V1.2 series



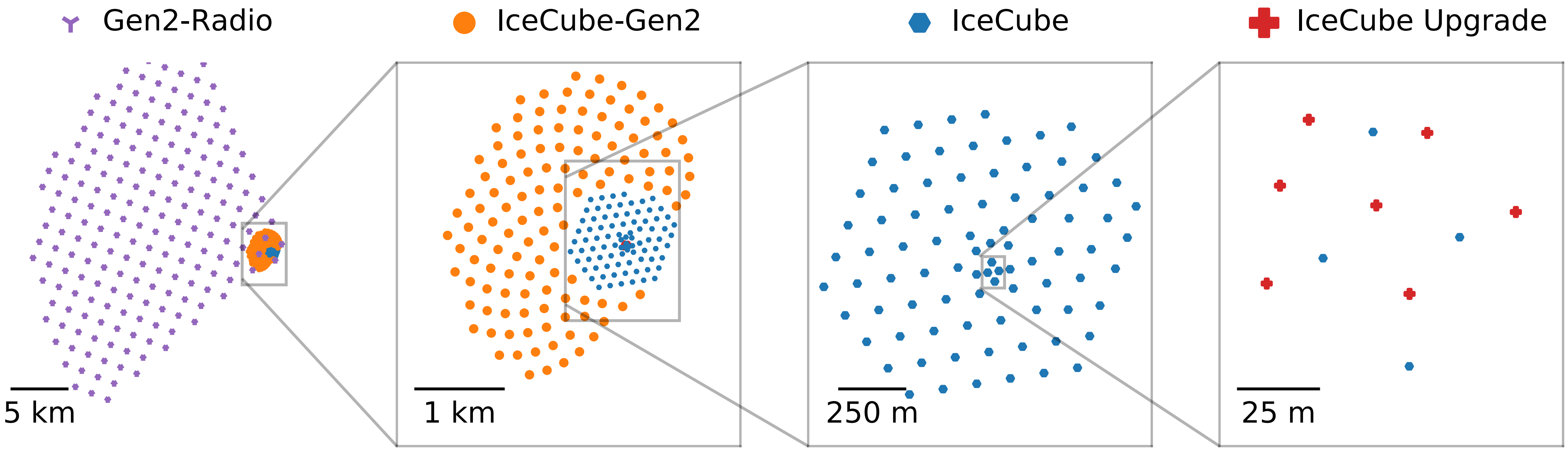
wuBase V1.3



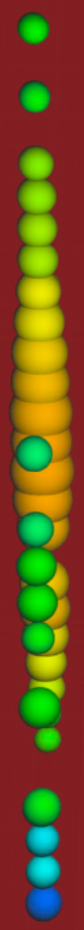
PMT base with integrated digitizer, timing, and Cockcroft Walton HV)

IceCube-Gen2 — scope

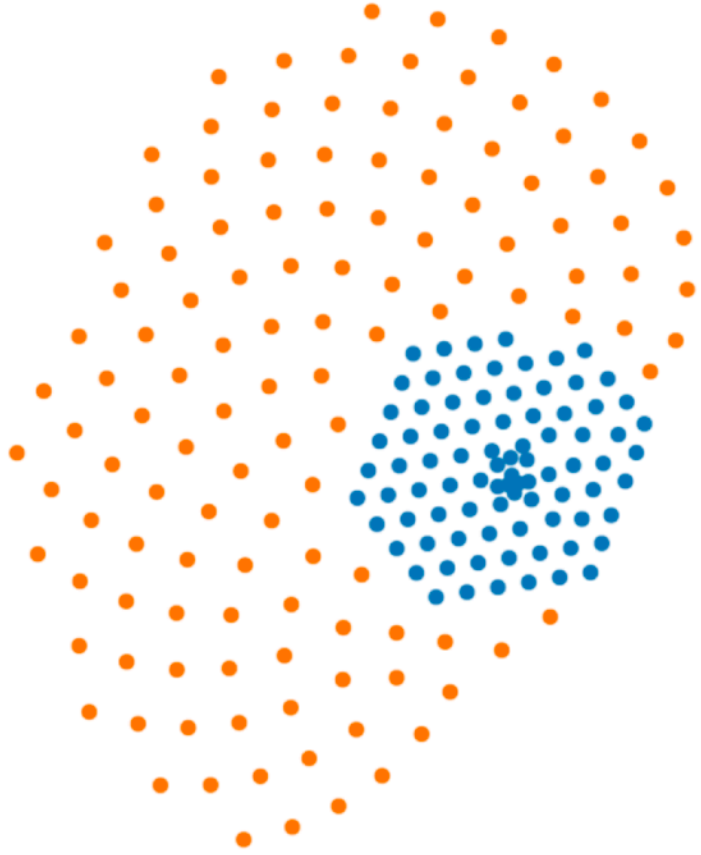
IceCube and Gen2 on different scales reflecting different energies



10 PeV **10 TeV** **1 TeV** **few GeV**



IceCube-Gen2



Ideally, uniform spacing of sensors.

Drilling holes is much effort, therefore: strings.

Spacing:

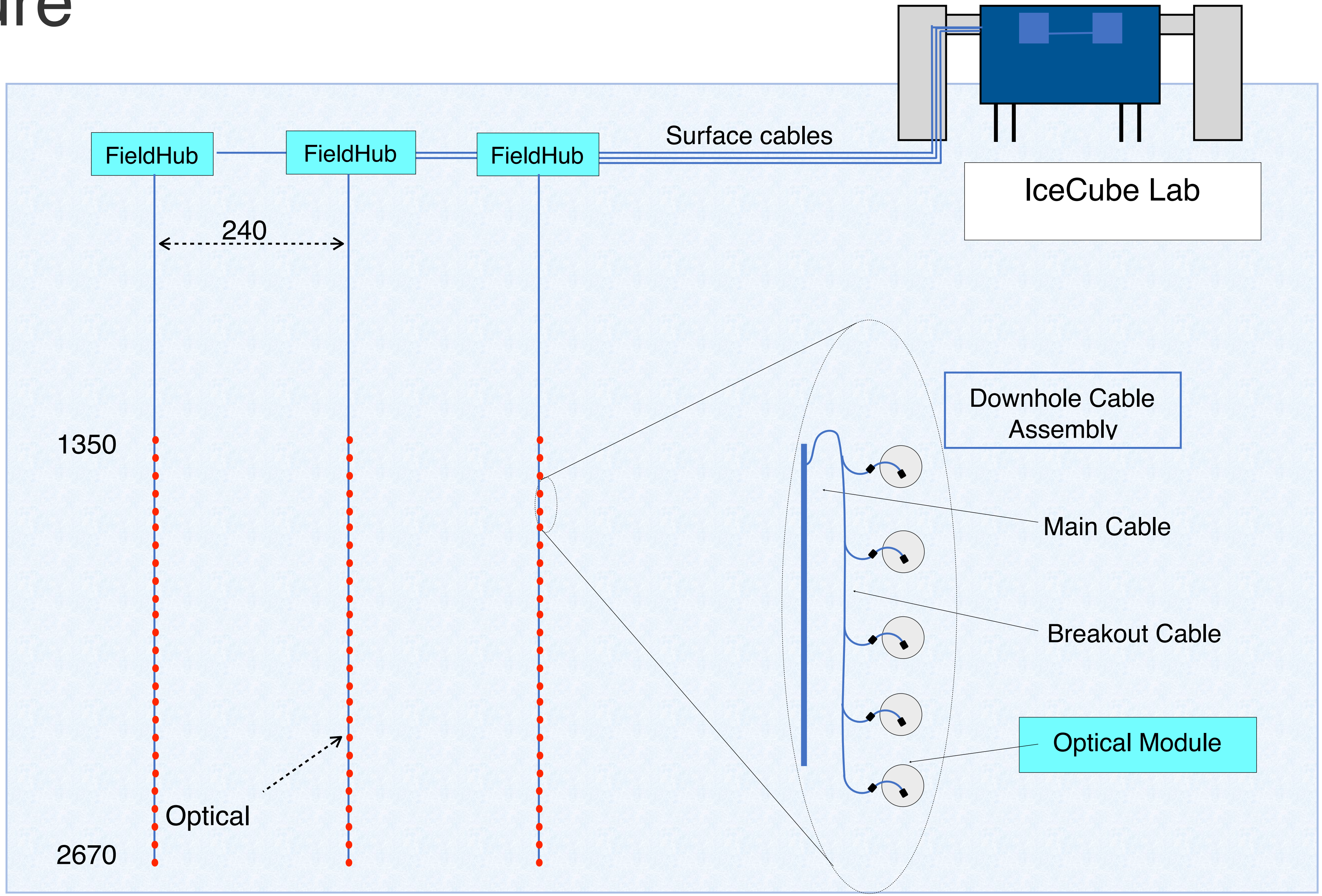
Strings: 125 m —> 240m

Sensors: 17 m —> 17m, but factor 3 more sensitive.

How can that work?

Architecture

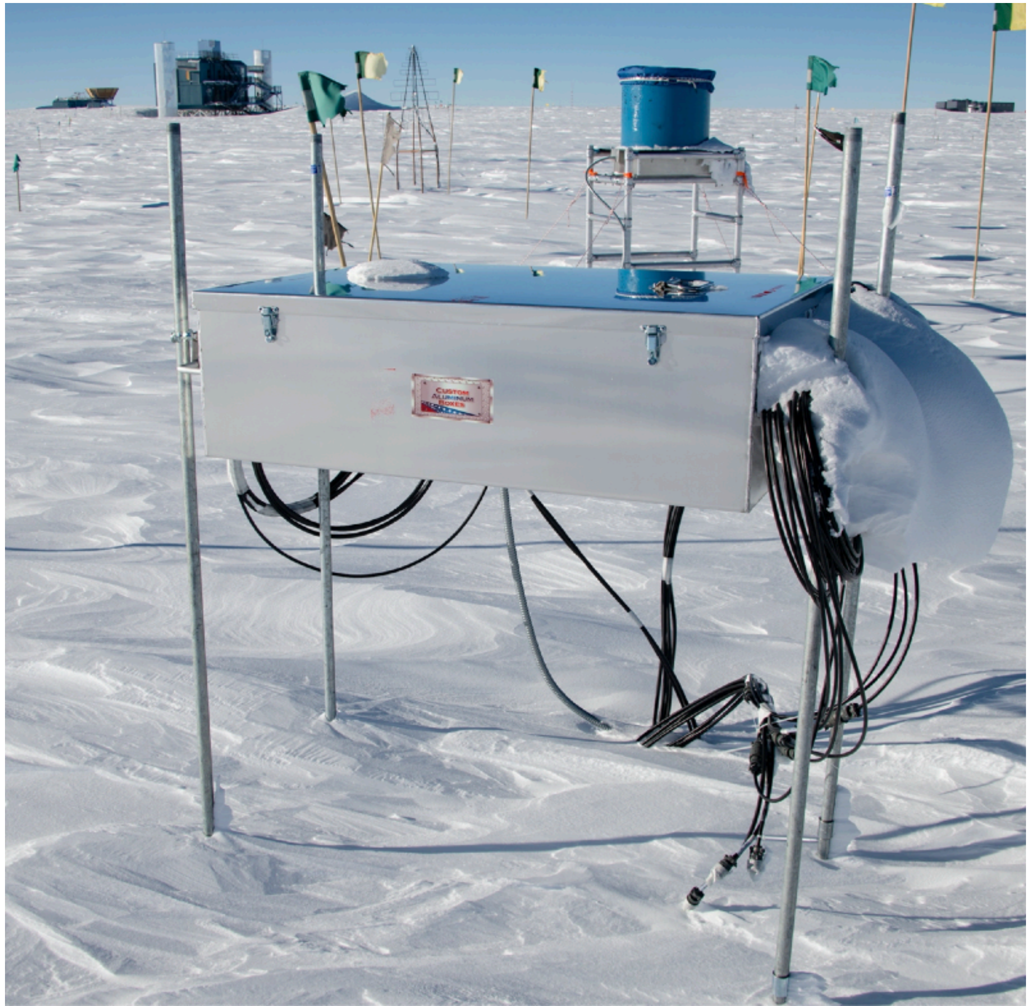
- Power and communications architecture: simplified requirements for cable hardware.



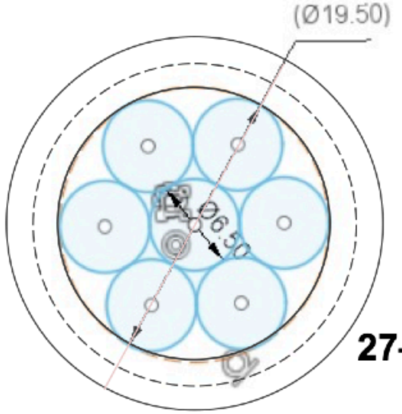
DAQ and cables

Trigger concept studies,
data rates remain compatible
with use of 7 quad main cable.
(6 DOMs/pair)
—> Yosuke’s talk

Field hub similar to
scintillator field hub: elevated, heated

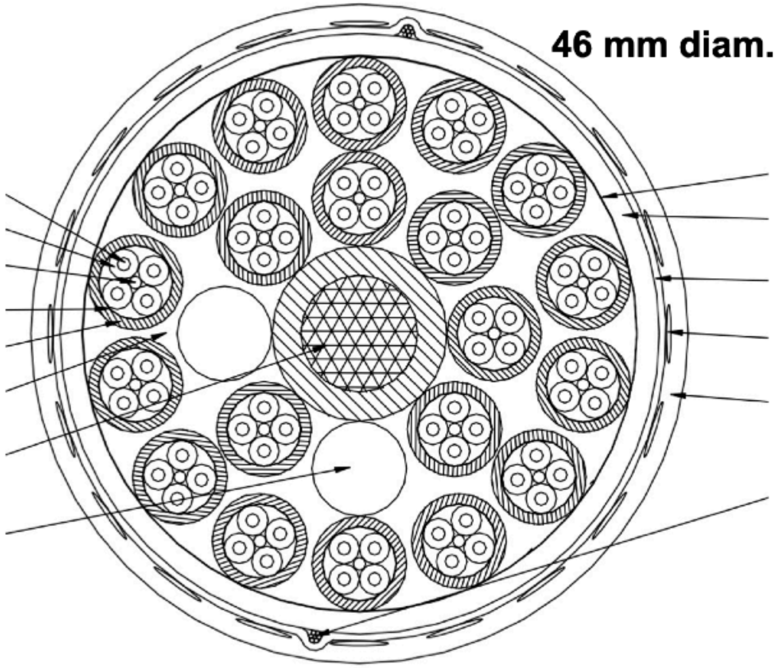


Gen2 cable



27–28 mm diam.

46 mm diam.

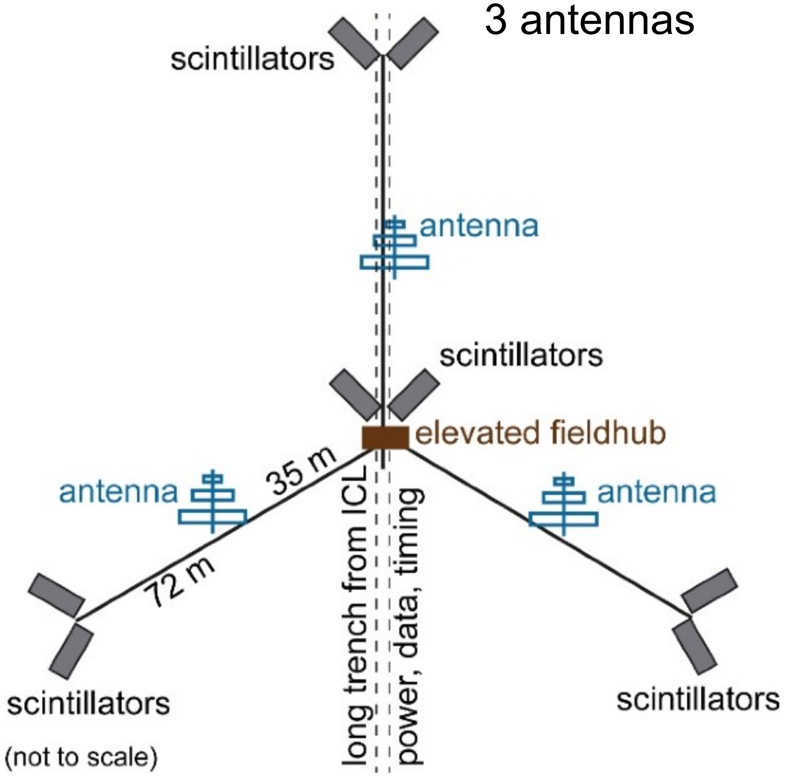


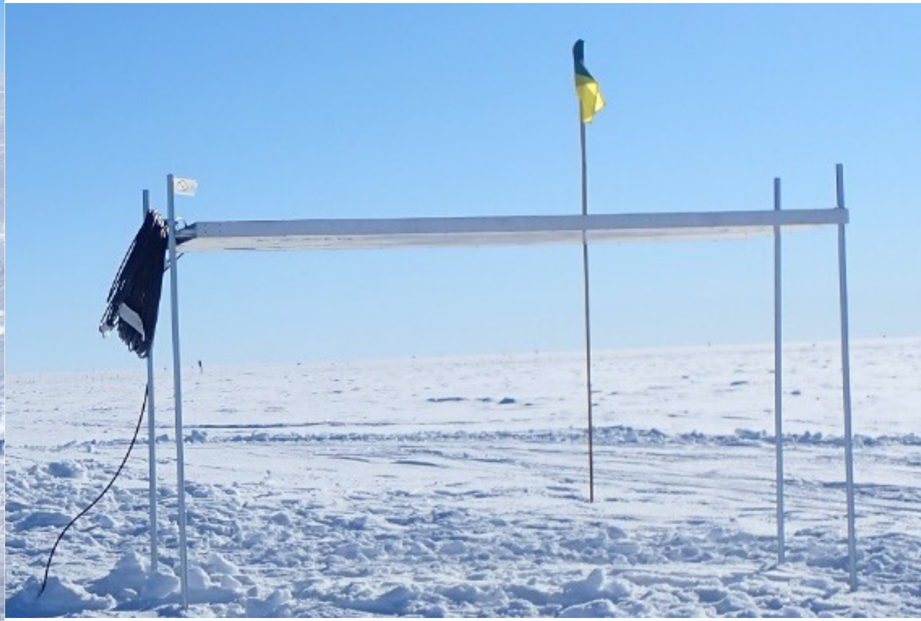
Gen1 cable (same scale)

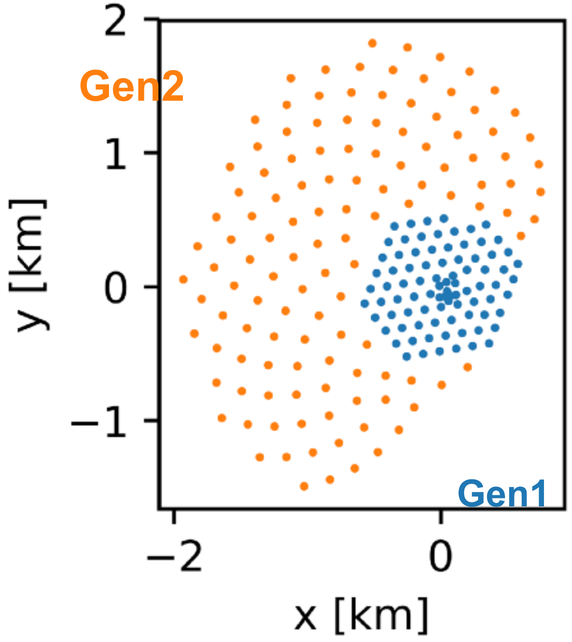
Gen2 Surface Array

Baseline design extends the planned IceTop enhancement to footprint of the IceCube-Gen2 optical array

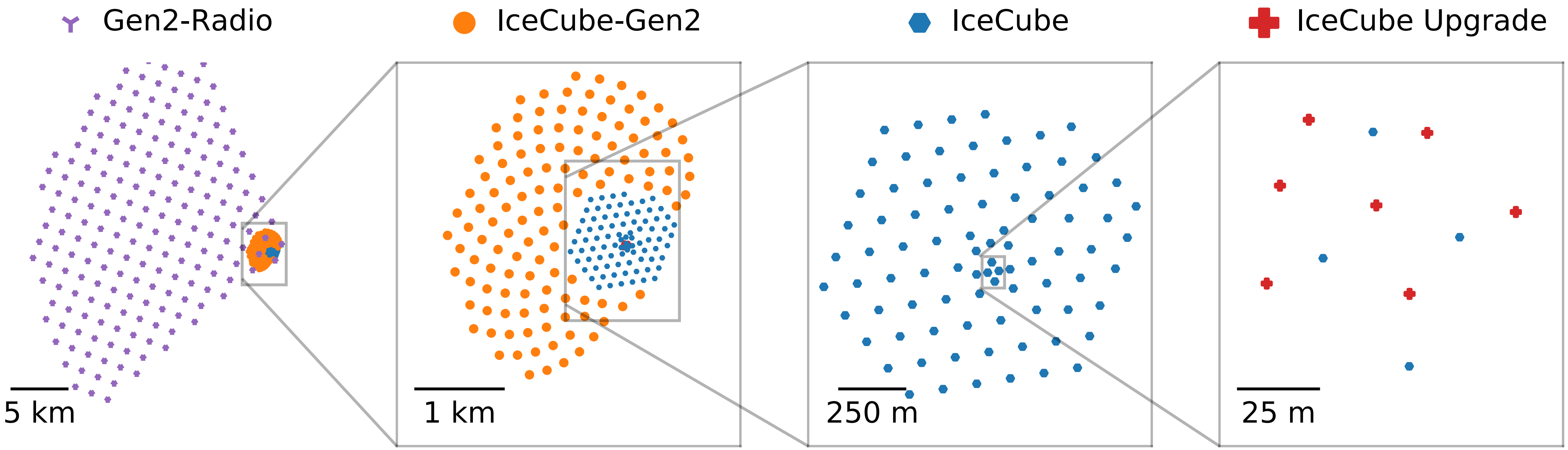
Station Design:
4 pairs of scintillators
3 antennas







IceCube-Gen2 — scope



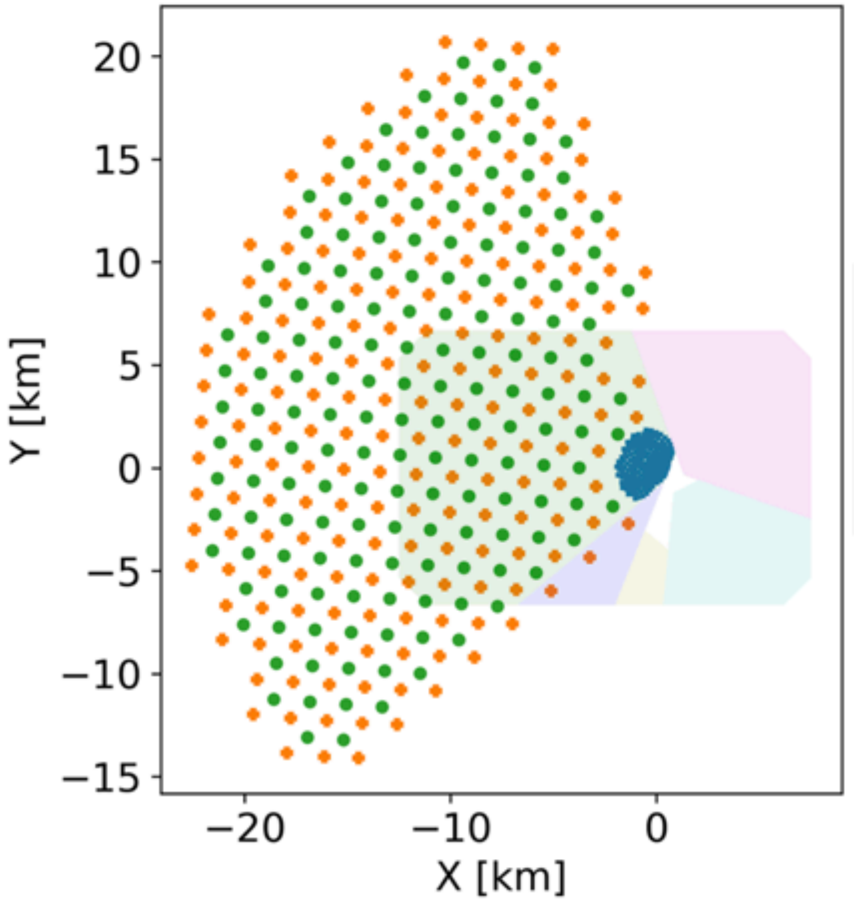
10 PeV

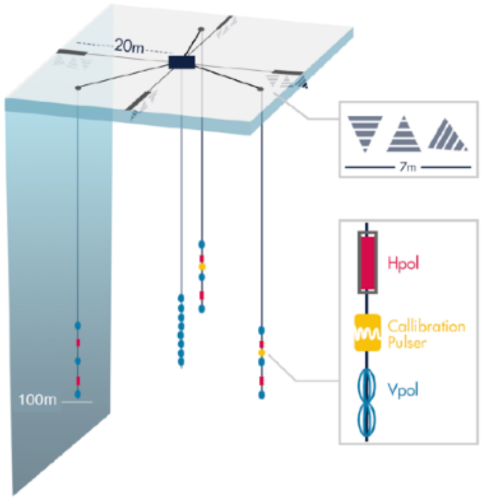
10 TeV

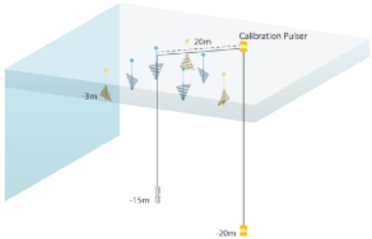
1 TeV

few GeV

The Gen2 radio array - options considered







Area: 500 km^2

300 stations

1000 km^3 of ice volume

Drilling
EHWD-Gen1

Current Status:

Received very good recommendations by Astro2020 decadal review.
(An assessment by done by National Academy every 10 years.)

IceCube Upgrade, 7 strings, under way, deploy in 2025/26.

Technical development is well under way.

Preparing a Technical Design Document to present to NSF.

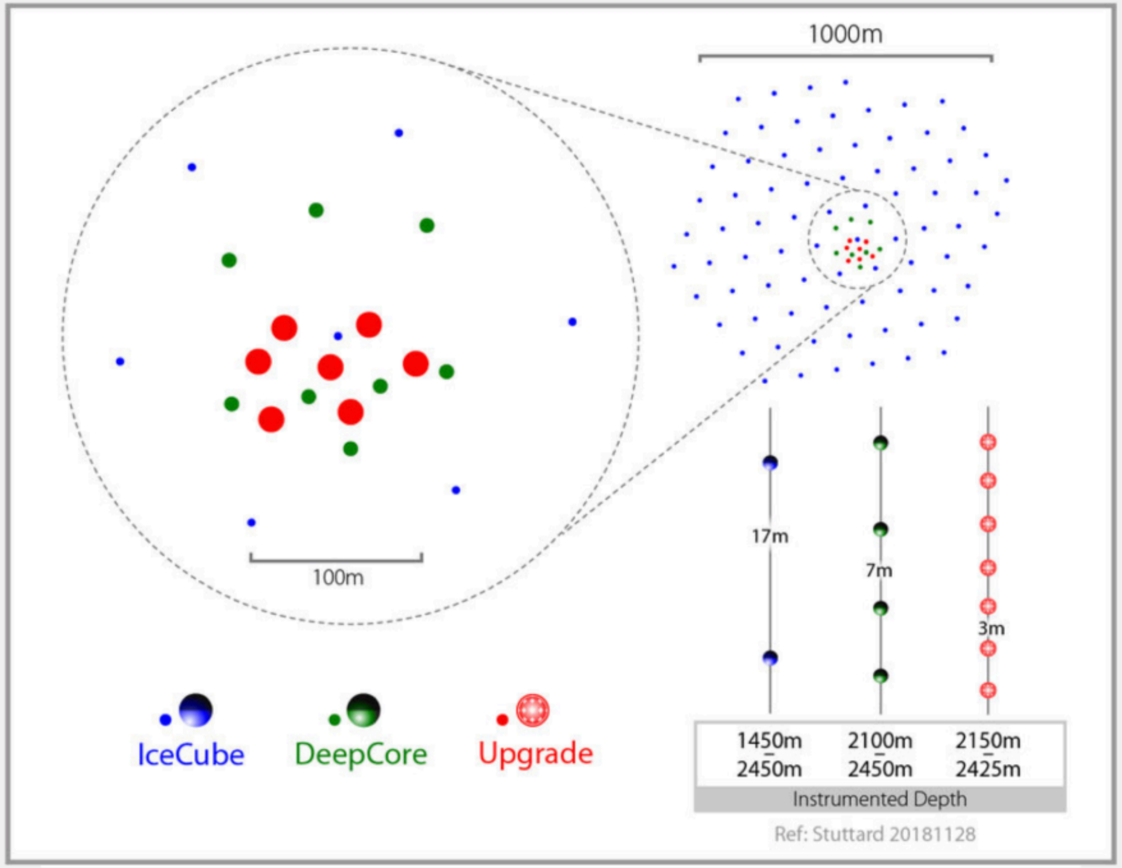
ICECUBE GEN2

IceCube Overview

- IceCube
  - DeepCore
  - IceTop

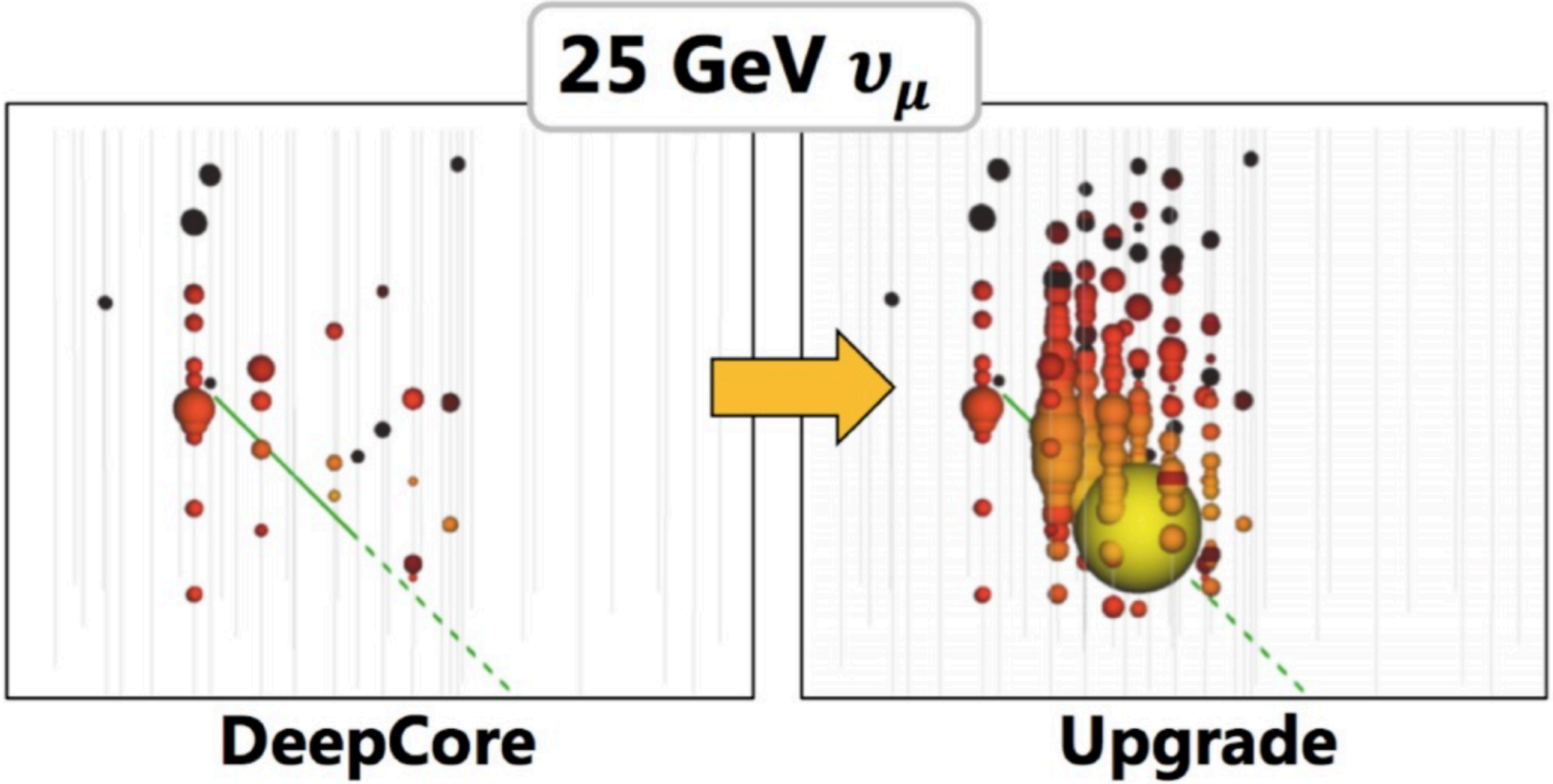
  } Done & Delivering

- Upgrade } Underway
- IceCube-Gen2
  - Full } Astro2020 Review Preliminary Design in Preparation

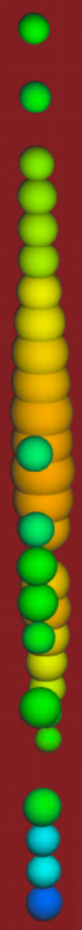


- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

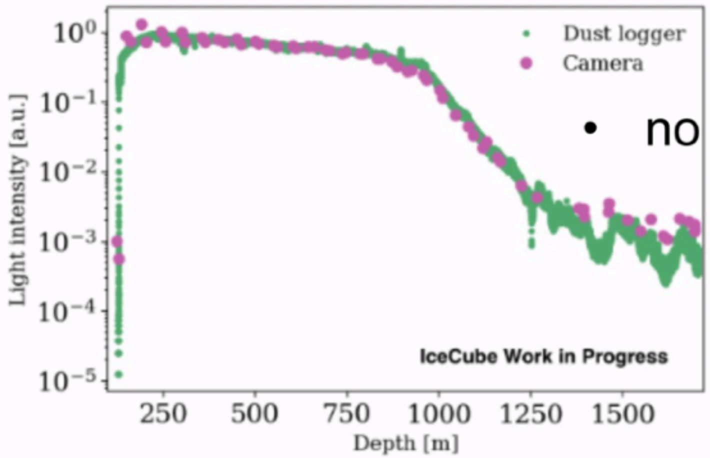
Low energy neutrinos in the Upgrade



ice: step by step

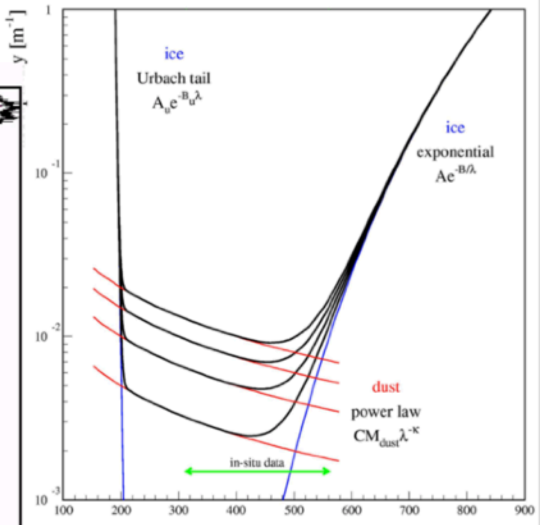


- no air bubbles/hydrates below 1350 m

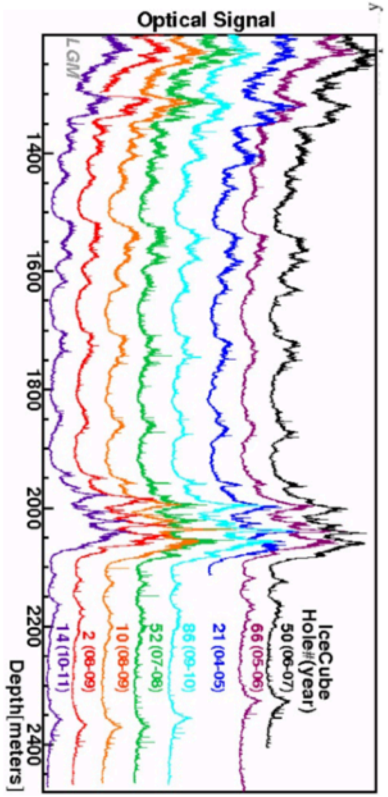


- hole ice ?

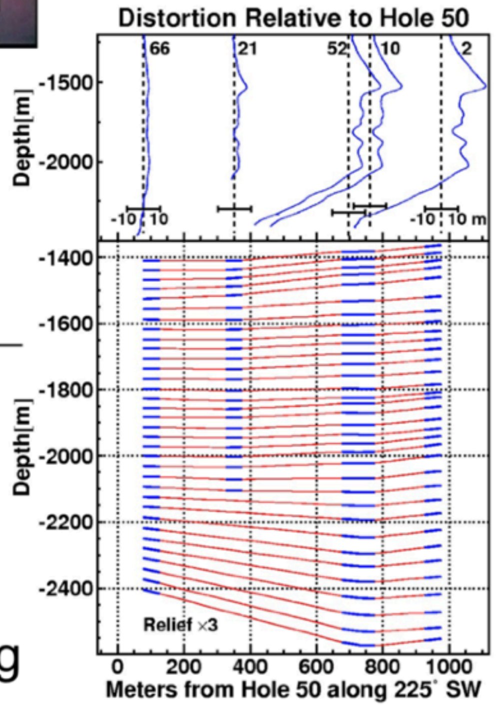
- > 100 m absorption length limited by dust



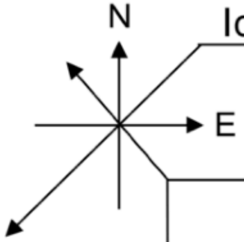
- ice layers



- tilted ice layers



- birefringence

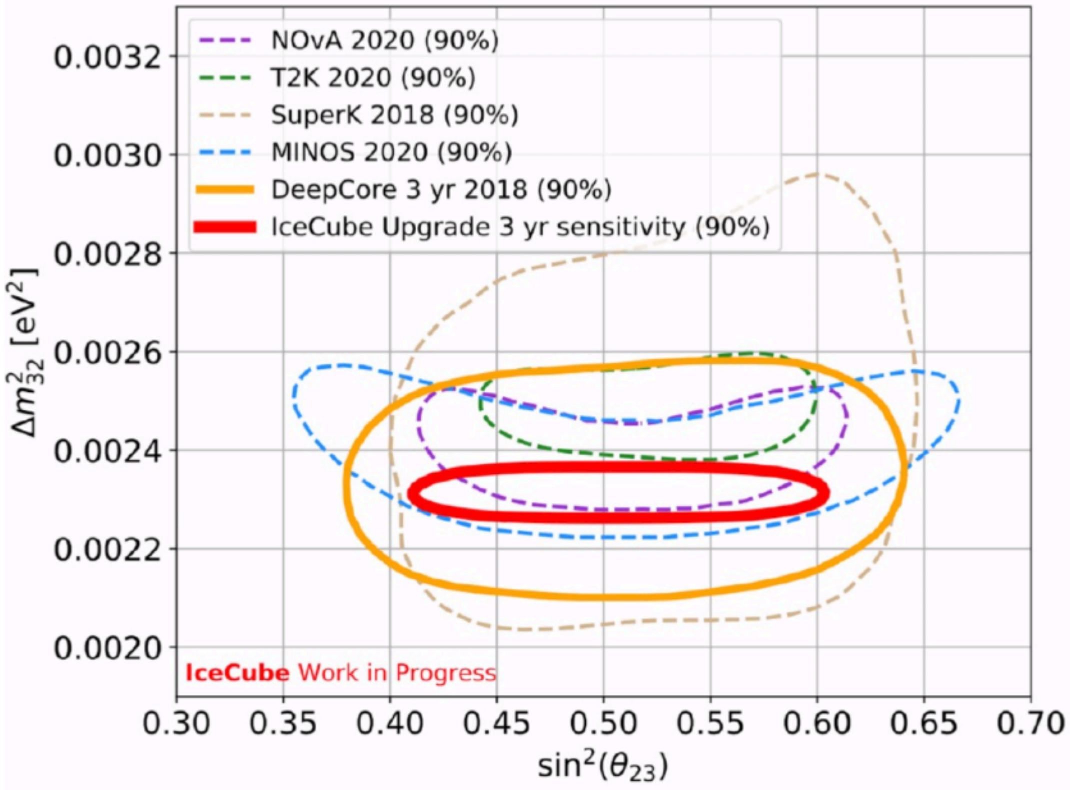


Ice Layer tilt direction
225° SW

Ice flow direction
41° NW

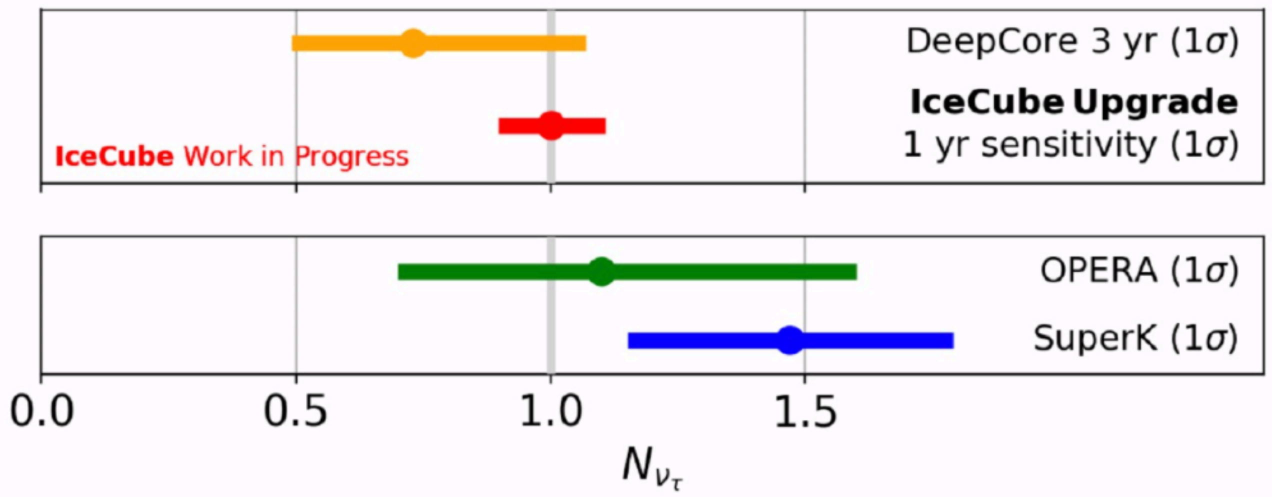
- anisotropy
~8% less scattering
41° NW

Atmospheric oscillation parameters



Strong sensitivity in 3 yrs or less

ν_τ normalisation



10% ν_τ norm in 1 yr

(6% in 3 yrs)

… and the improvements implemented between the 3 and 9.3-year DeepCore analyses have not been applied !

THE

The
High-energy
IceCube of the
Next
Generation

—> IceCube-Gen2

THE

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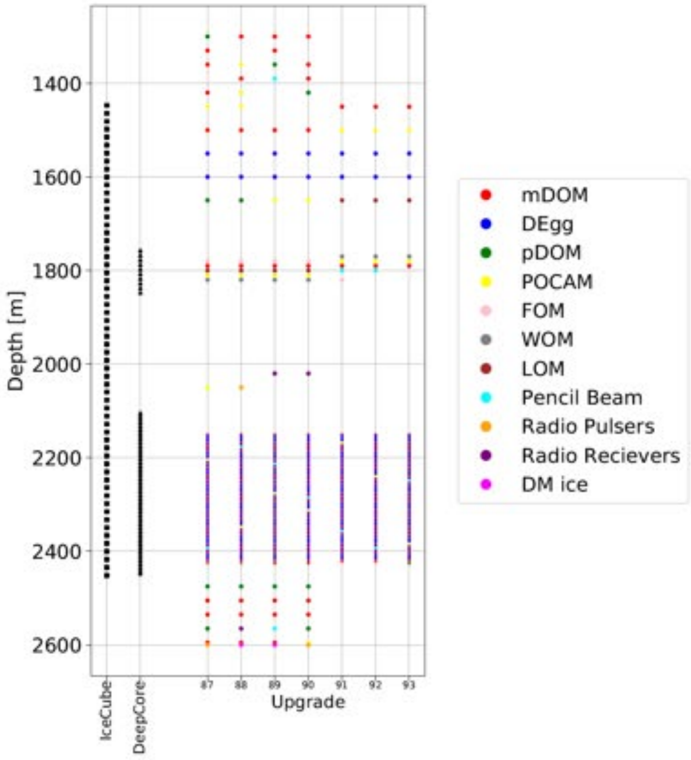
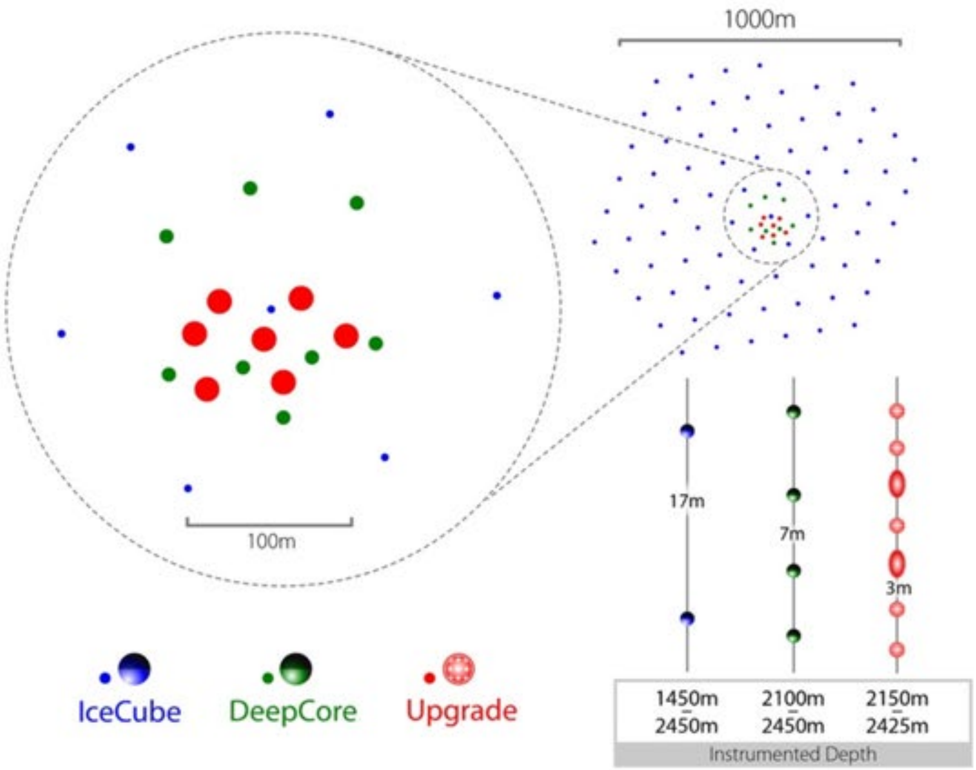
Project Objectives (Unchanged Since 2016)





7 strings - 693 Optical sensors:

- 277 D-Eggs (2x 8" PMT)
- 402 mDOMs (24x 3" PMT)
- 14 PDOMs
- Calibration devices

2 Mton effective volume for LE neutrino events:

- trigger down to 1 GeV
- 90% efficient at 3 GeV

Single Drill / Install Season

1. **Neutrino Properties**
2. **Recalibration and Reanalysis of IceCube Data**
3. **IceCube-Gen2 Research and Development**