

From the IceCube Upgrade to IceCube-Gen2

Albrecht Karle (University of Wisconsin-Madison)
On behalf of the IceCube-Gen2 Collaboration

August 26, 2024



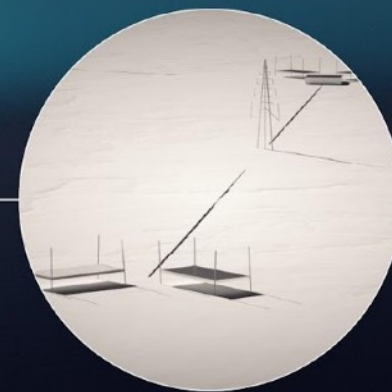
ICECUBE GEN2



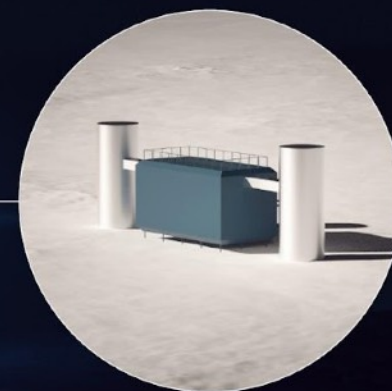
Radio Array | Station



Optical Array | Sensor



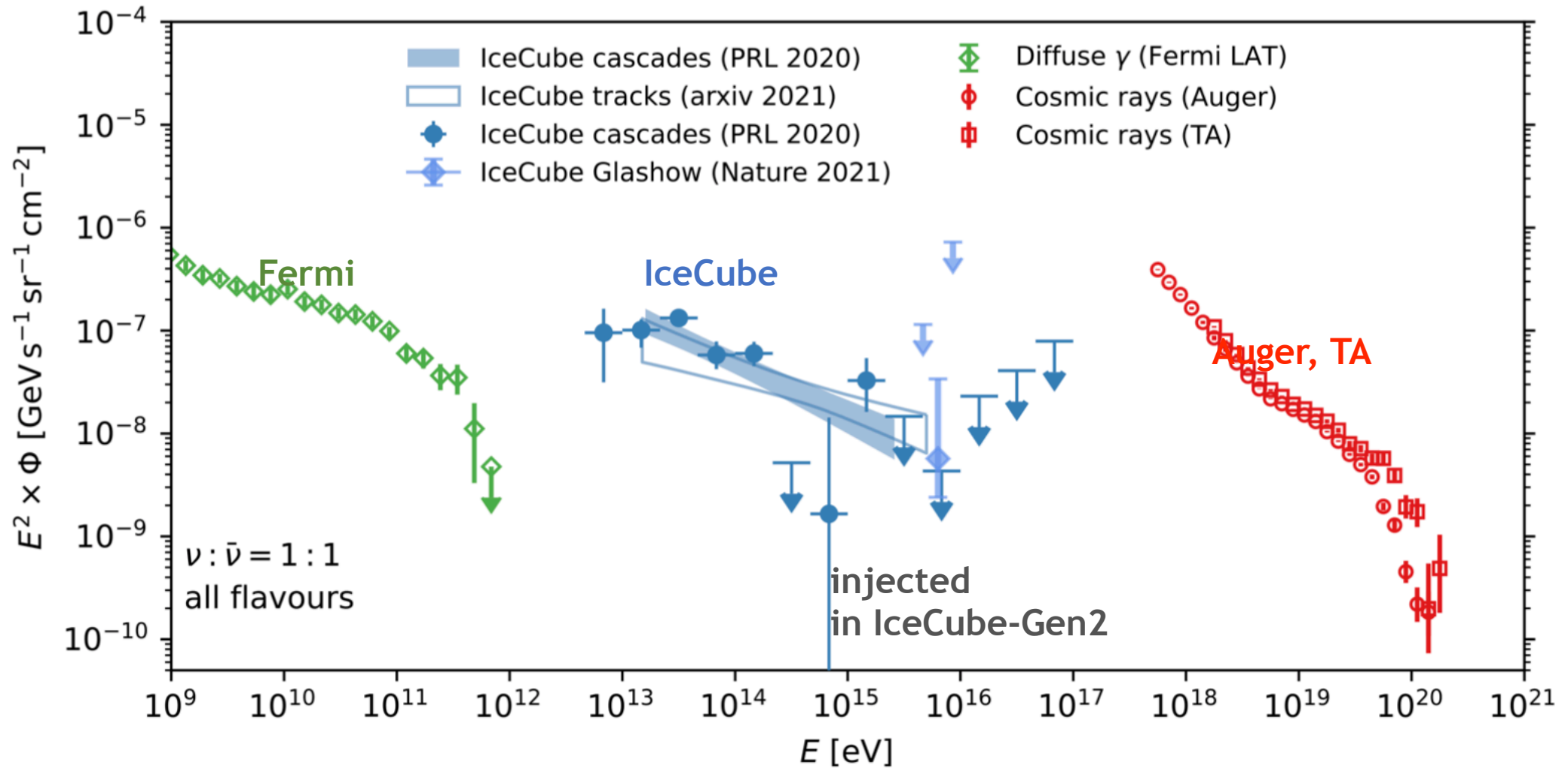
Surface Array | Station



IceCube | Laboratory

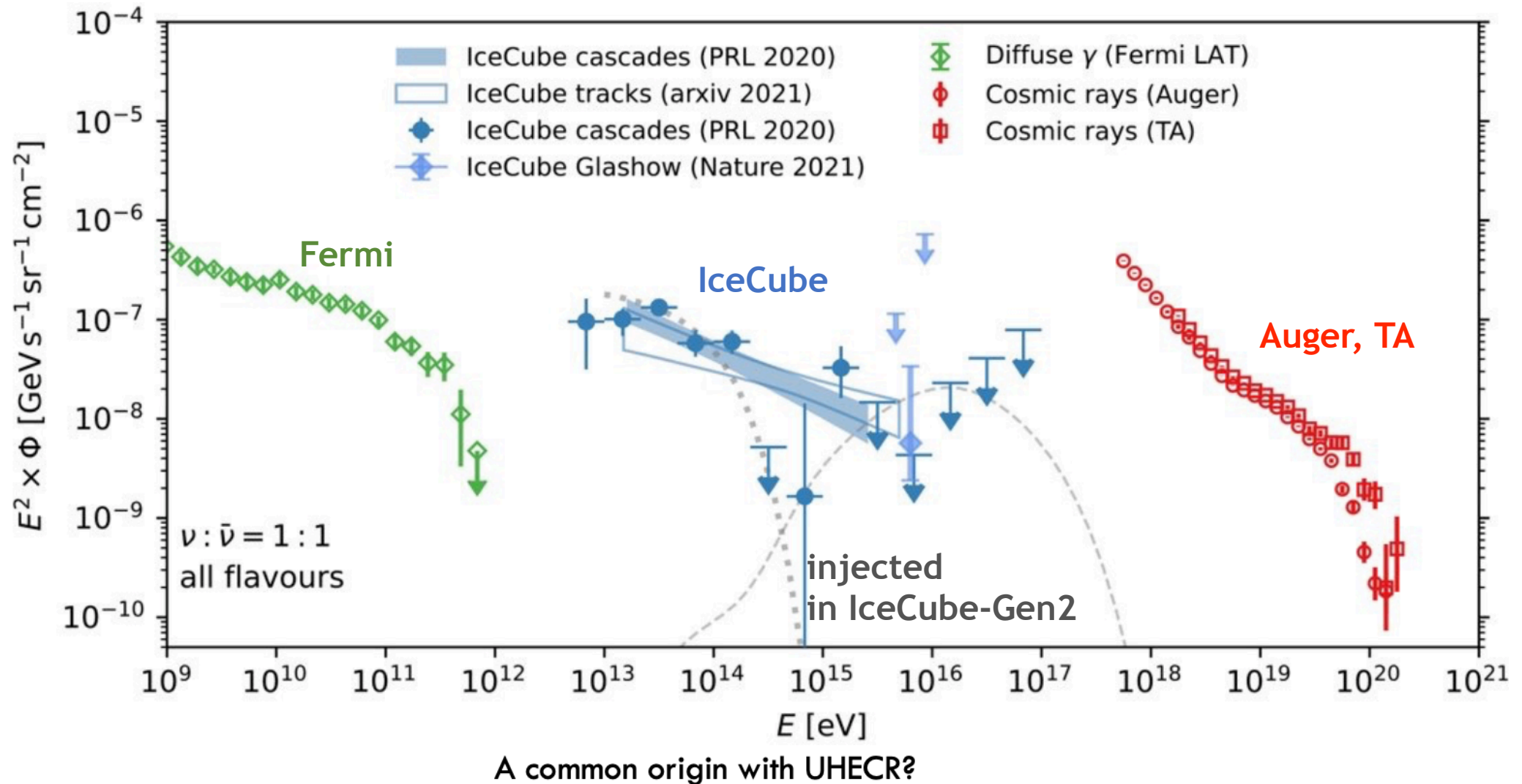
Understanding cosmic particle acceleration through multimessenger observation

3



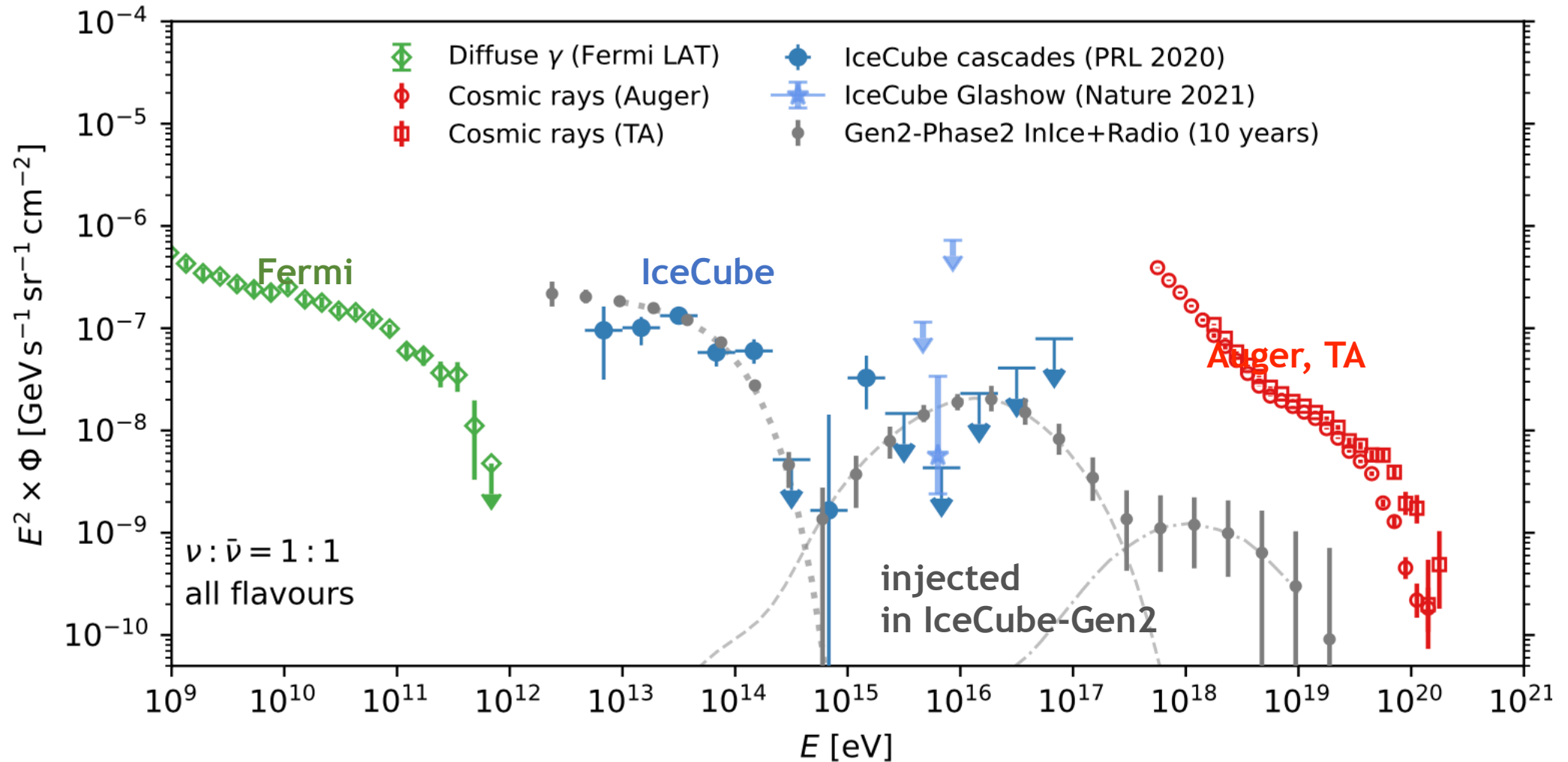
Understanding cosmic particle acceleration through multimessenger observation

4



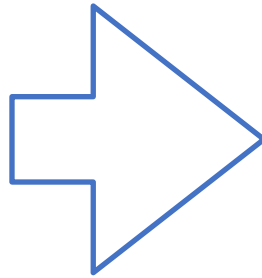
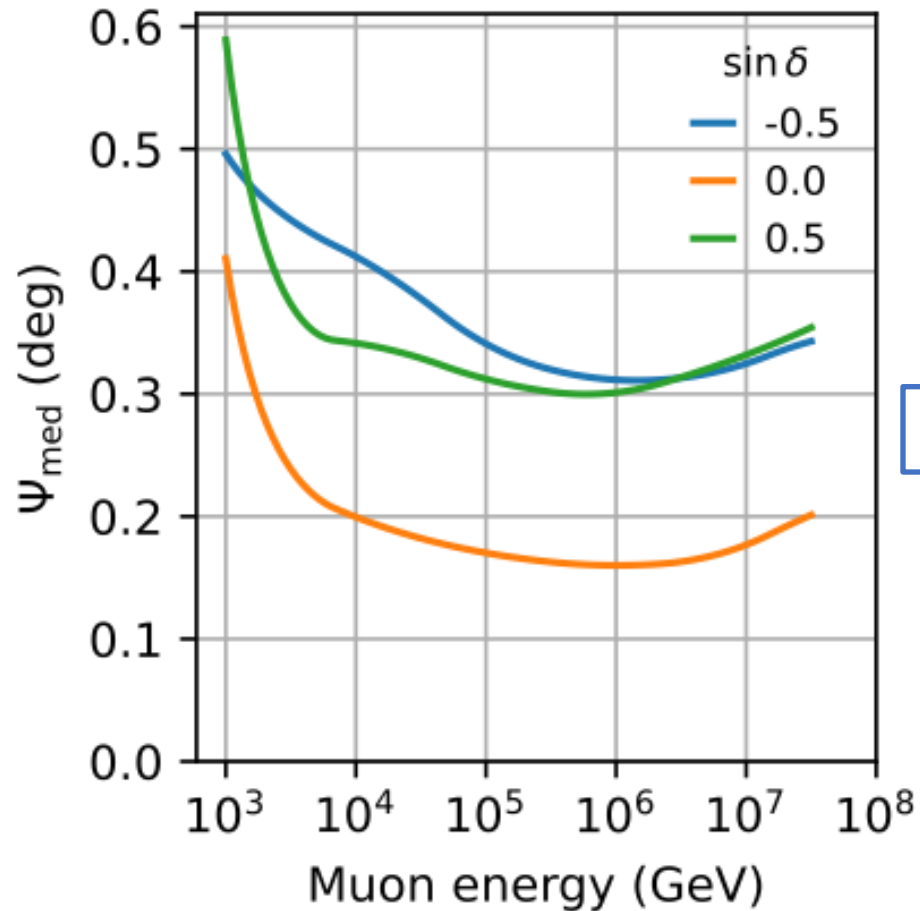
Understanding cosmic particle acceleration through multimessenger observation

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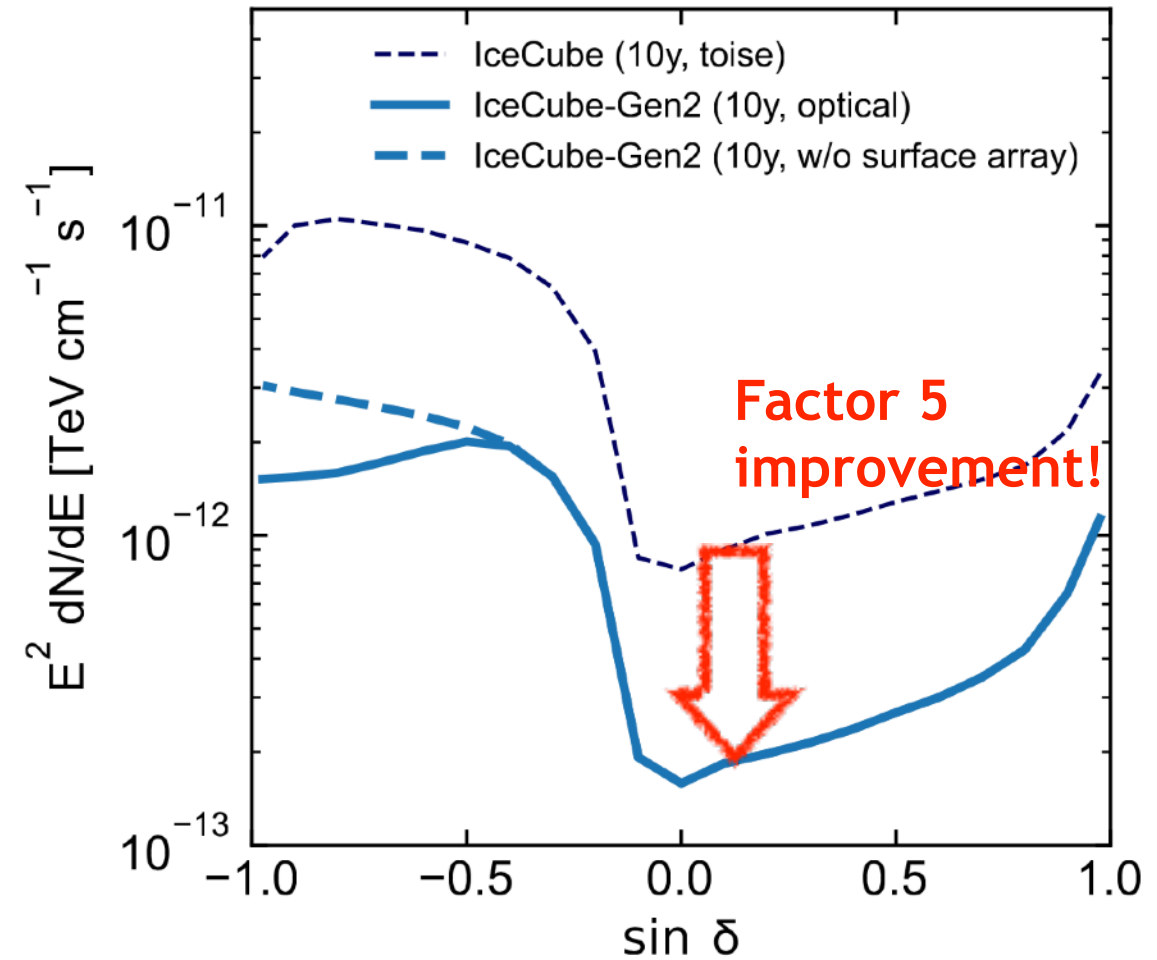


Angular resolution and sensitivity to Point Sources

Muons: $0.1 - 0.4^\circ$



Sensitivity to E^{-2} flux of point sources



IceCube-Gen2: Point Sources

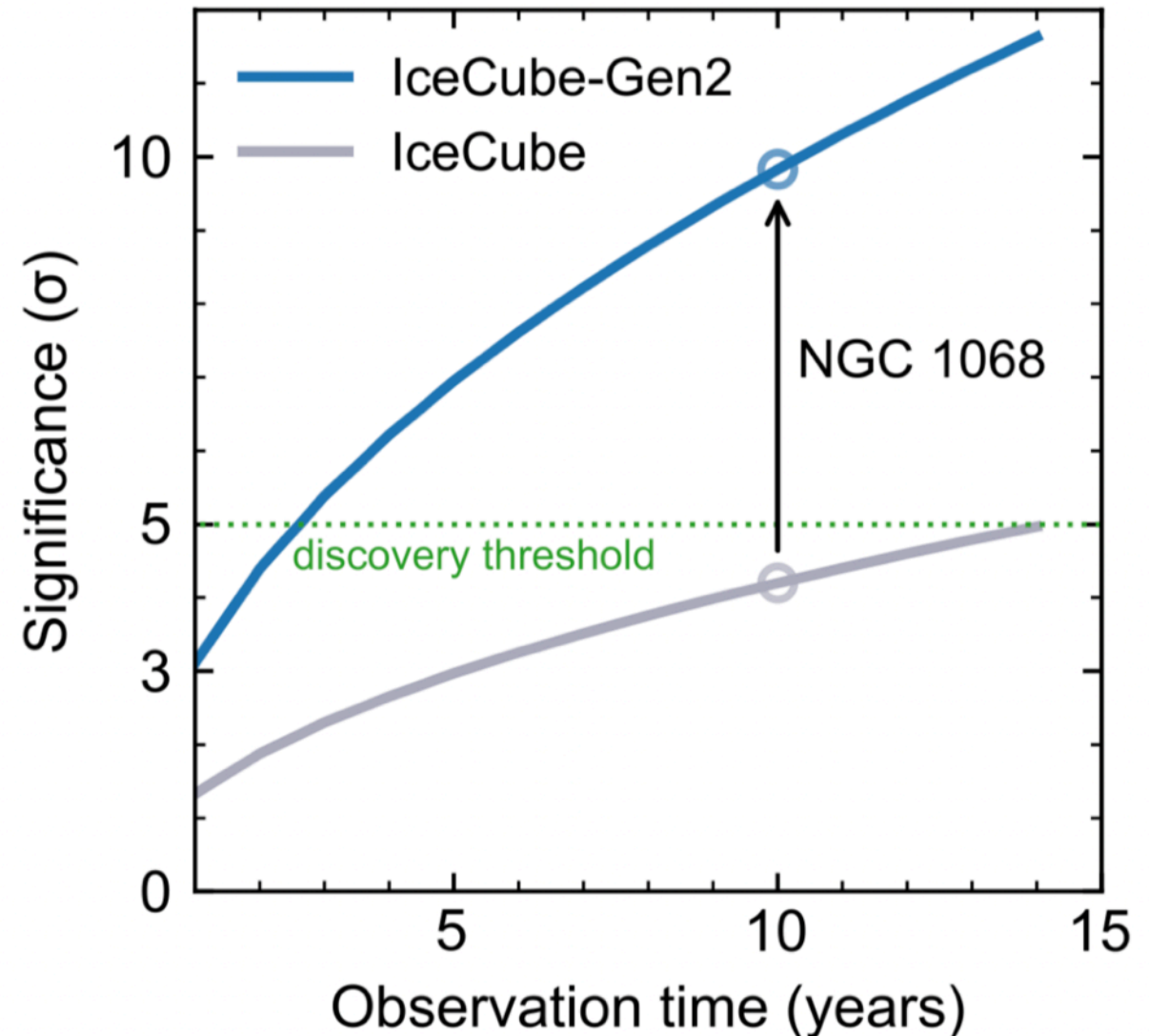
- 5 × improvement in effective area
- 2 × improvement in angular resolution

IceCube-Gen2 will allow to firmly discover the brightest AGNs on the neutrino sky.

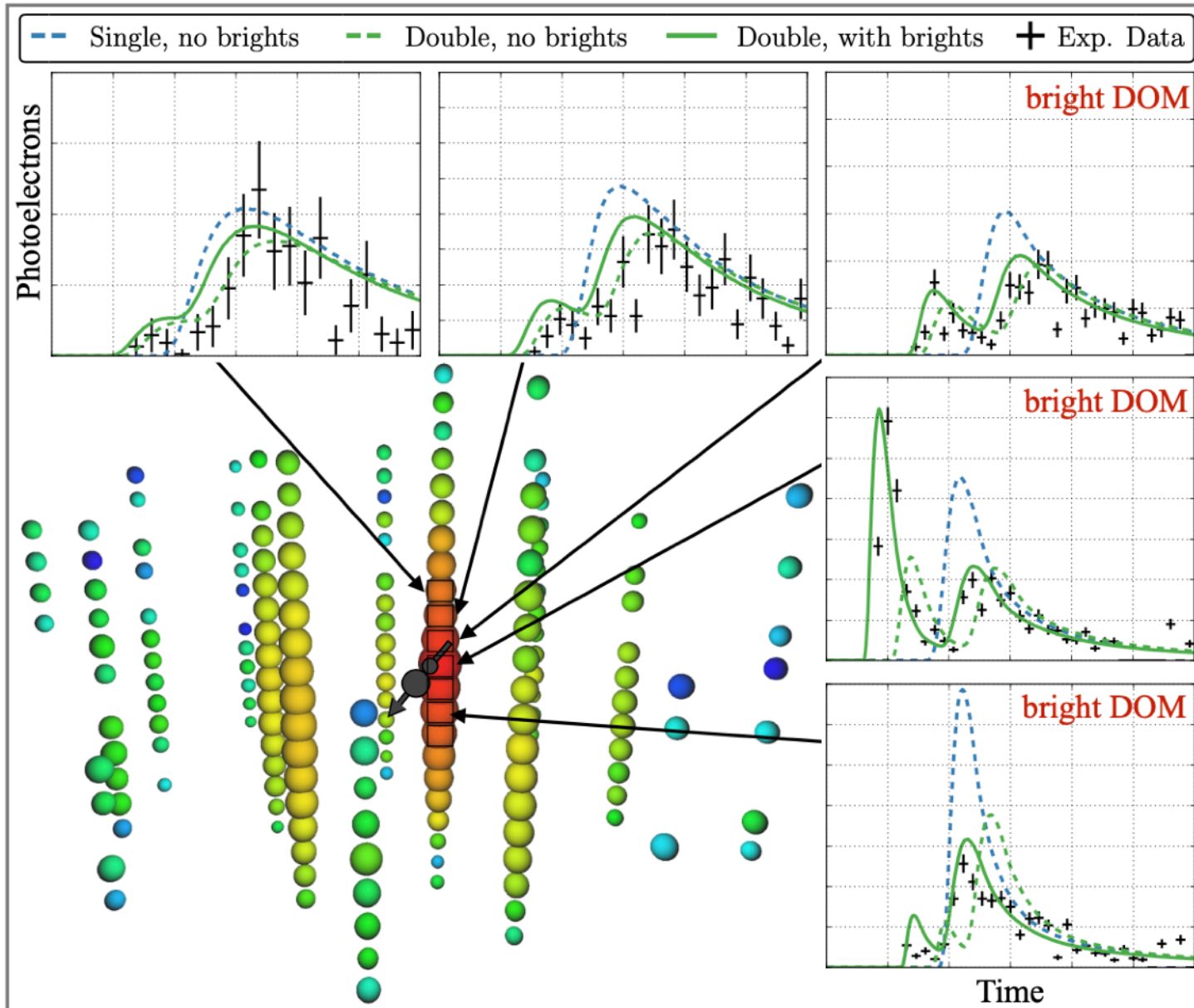
NGC1068: 10 σ after 10 years:

Precise measurement of the spectral shape of the neutrino emission

<https://icecube-gen2.wisc.edu/science/publications/tdr/>



A tau neutrino candidate with characteristic double pulse signature



Tau signature:

“double Bang” event

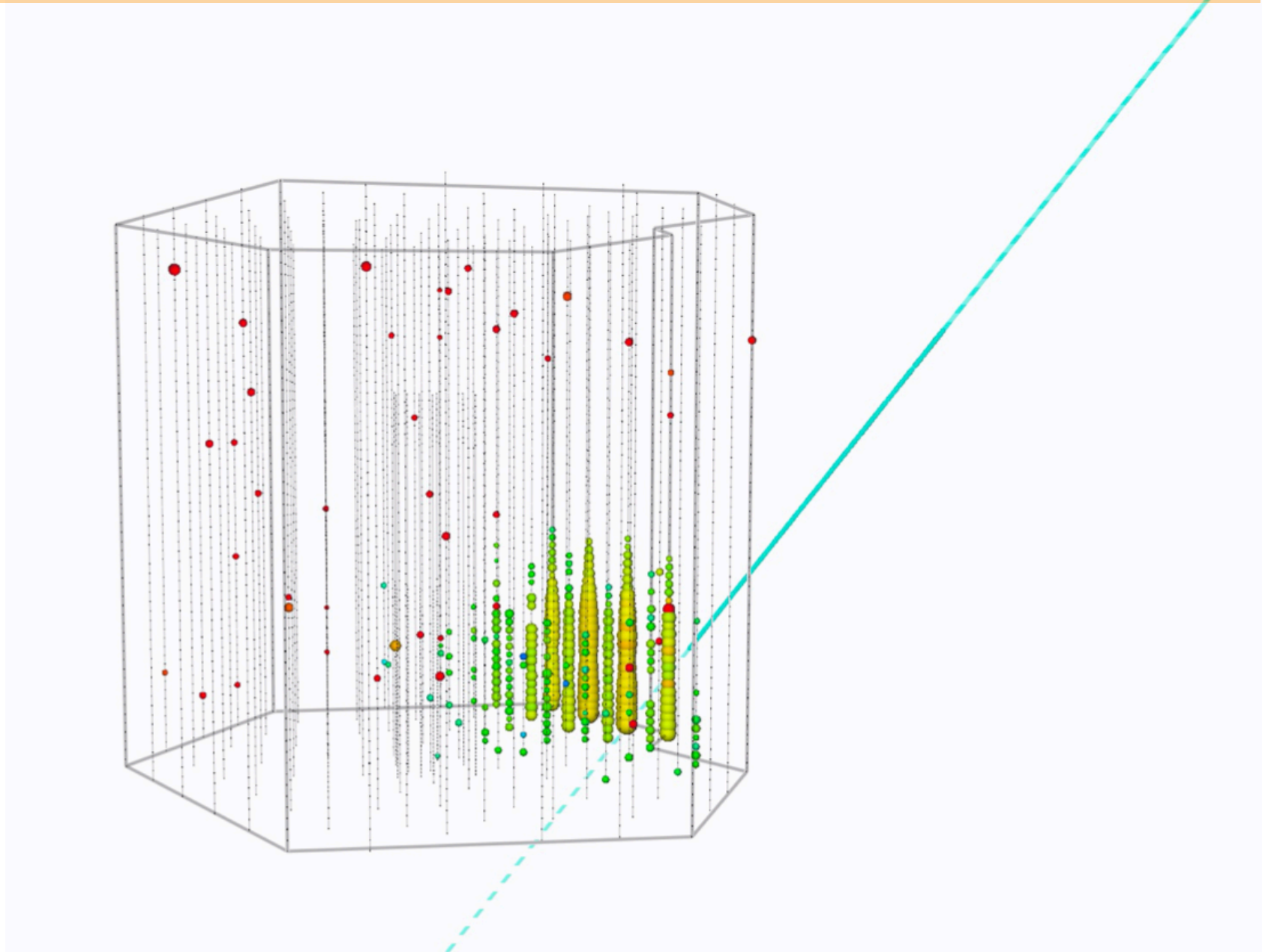
1st cascade: Initial neutrino CC

2nd cascade: tau decay

Decay length: $\sim 50\text{m/PeV}$

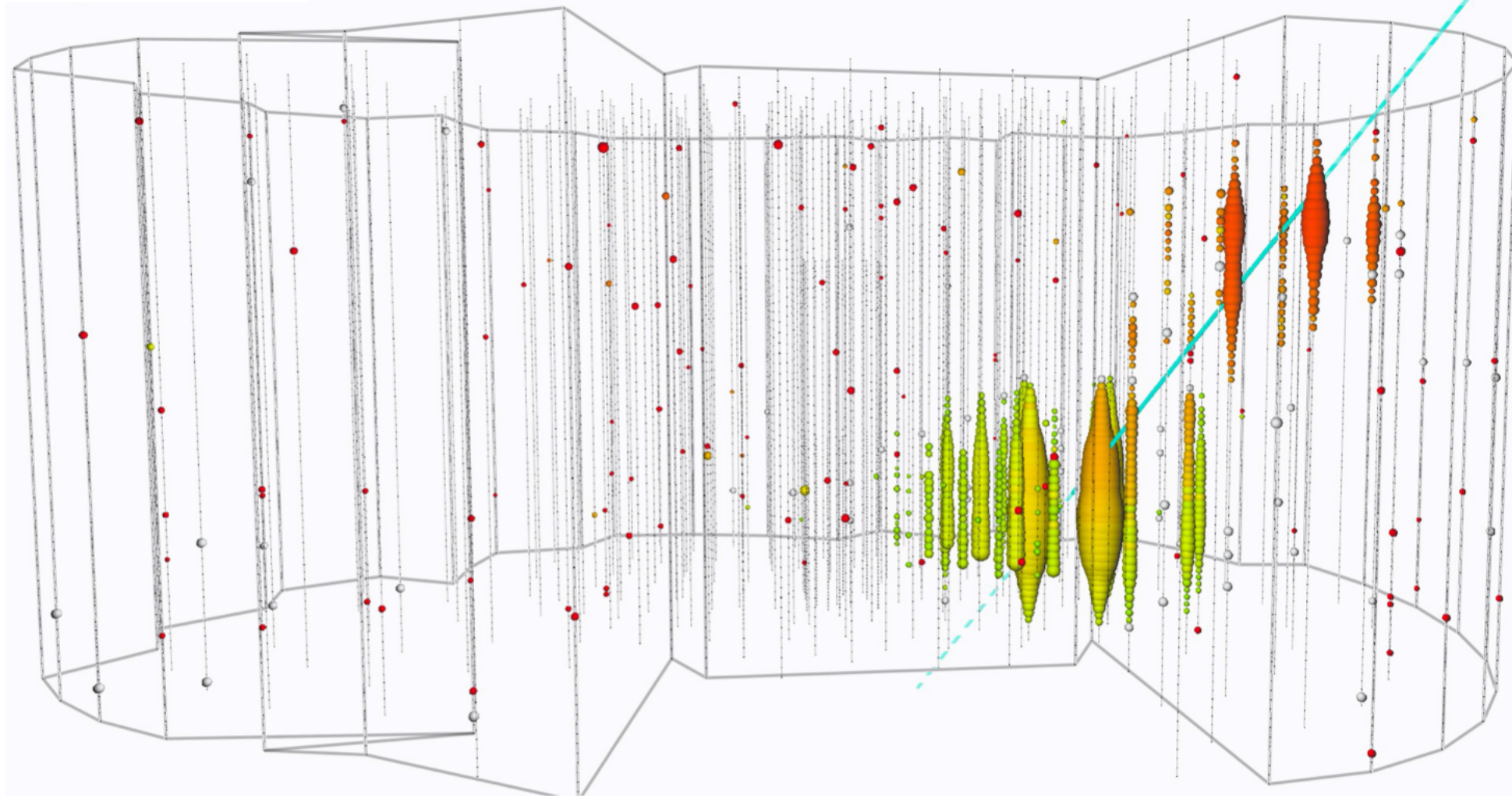
	Event #1	Event #2
Year	2012	2014
Energy of 1st cascade	1.2 PeV	9 TeV
Energy of 2nd cascade	0.6 PeV	80 TeV
Energy Asymmetry	0.29	-0.80
Length	16 m	17 m

A simulated event in IceCube - what is it?



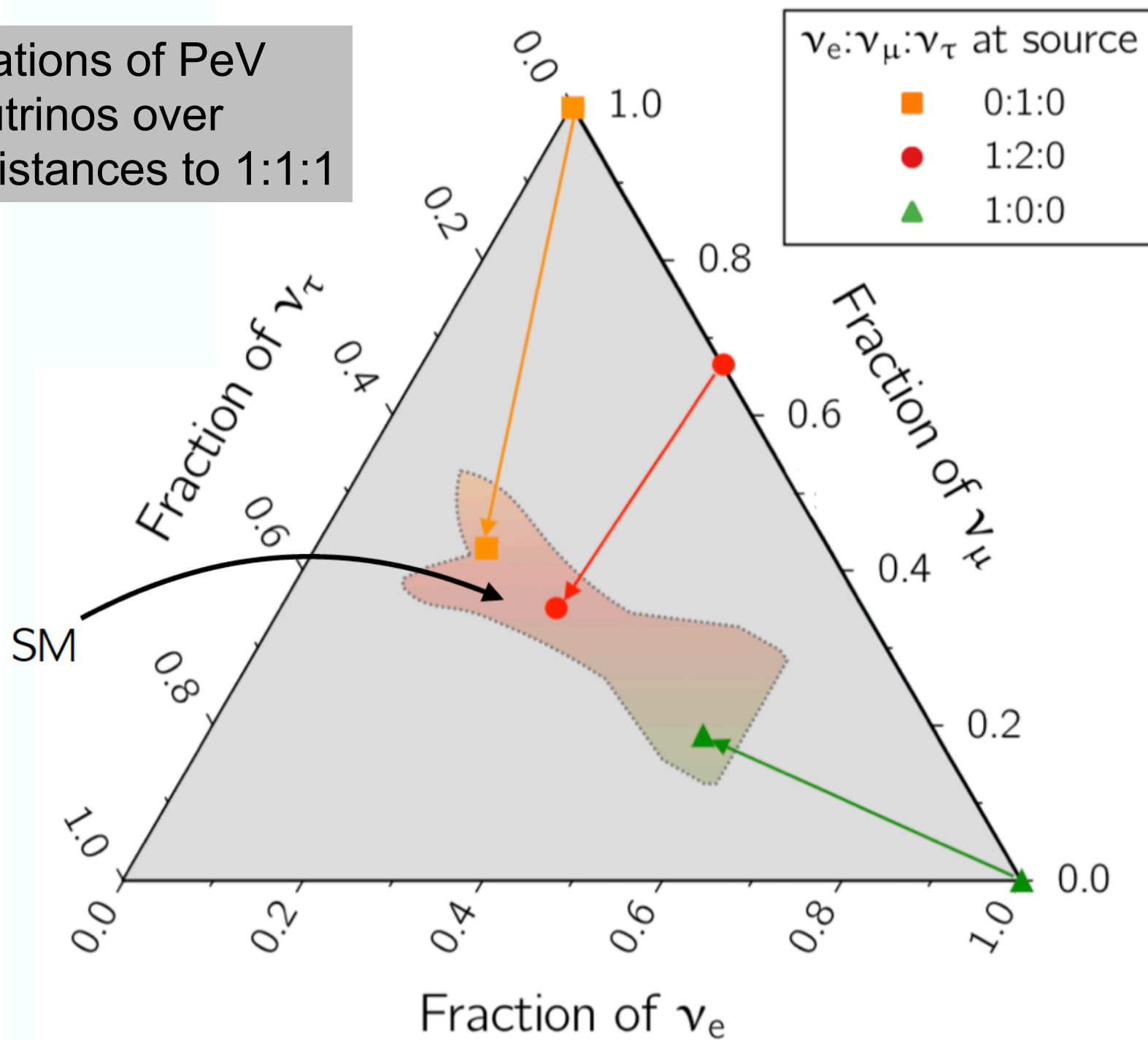
The same event in IceCube-Gen2

Size - Contained Volume matters.



oscillations of PeV
neutrinos over
cosmic distances to 1:1:1

The composition of
neutrinos at Earth
reveals mechanisms
at the cosmic source
region.

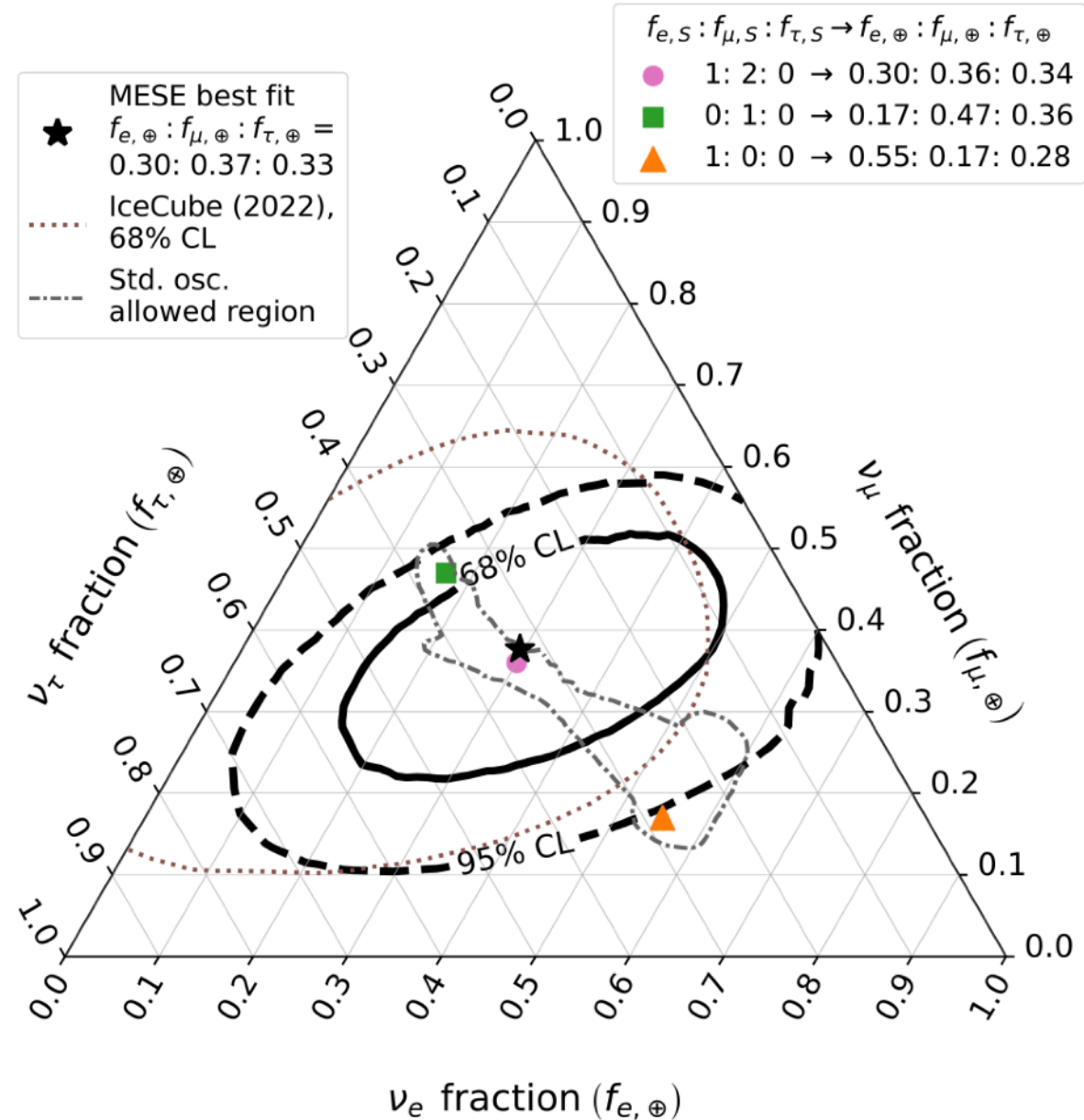


IceCube MESE flavor composition of cosmic neutrino flux

MESE = Medium Energy
Starting Events.
New Result

<https://arxiv.org/pdf/2510.24957>

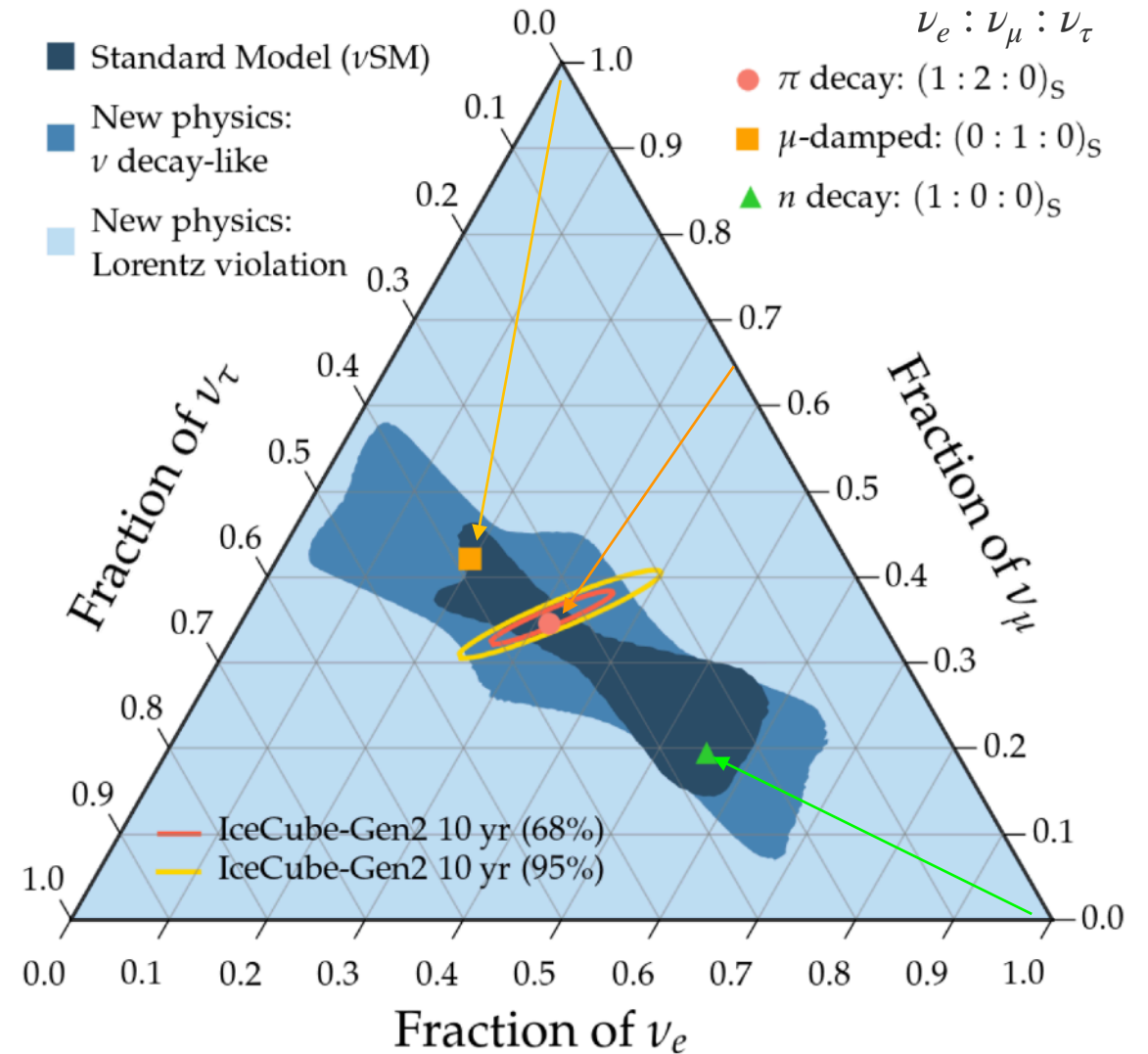
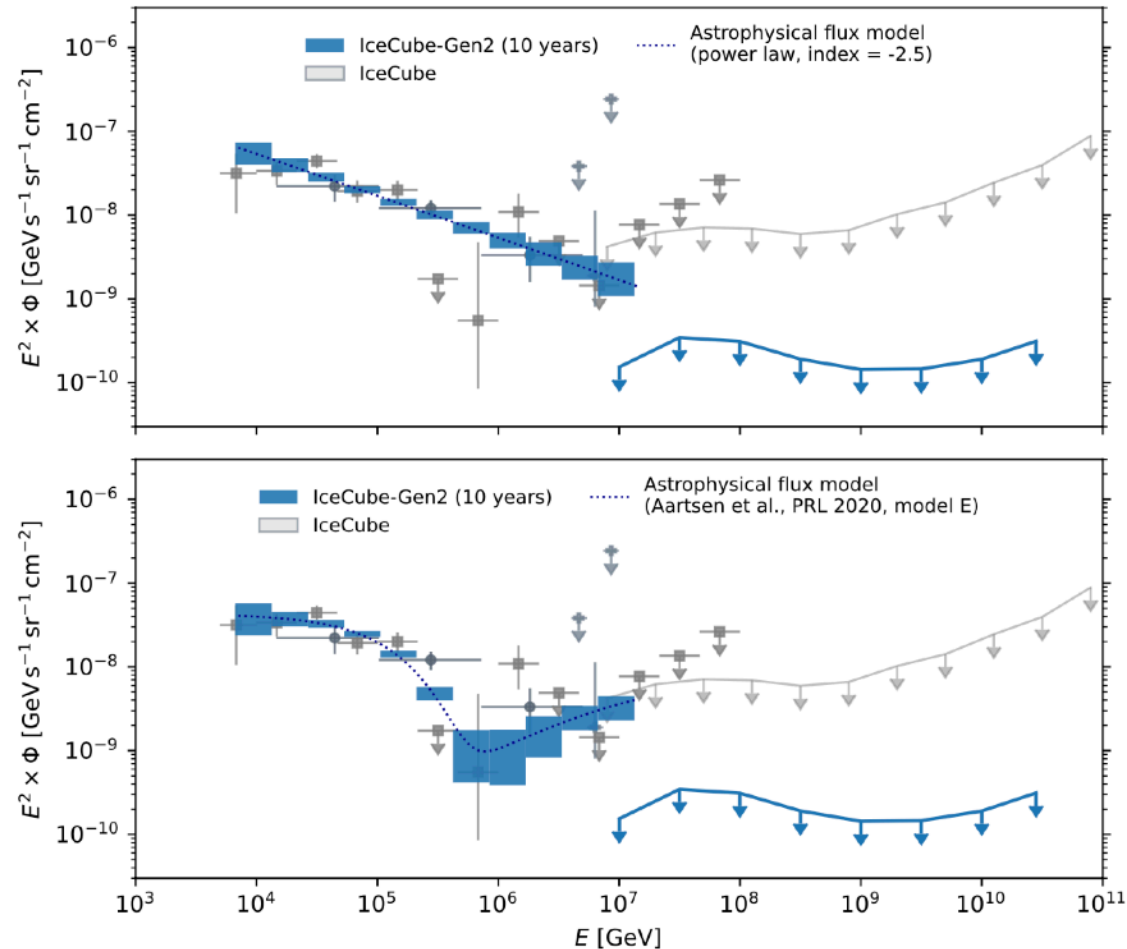
The composition of
neutrinos at Earth
reveals mechanisms
at the cosmic source
region.



Understanding the Origin of Cosmic Rays/Neutrinos at high energies

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Precise mapping of cosmic neutrino spectrum
from 1 TeV to 1 EeV
Energy dependent flavor measurements



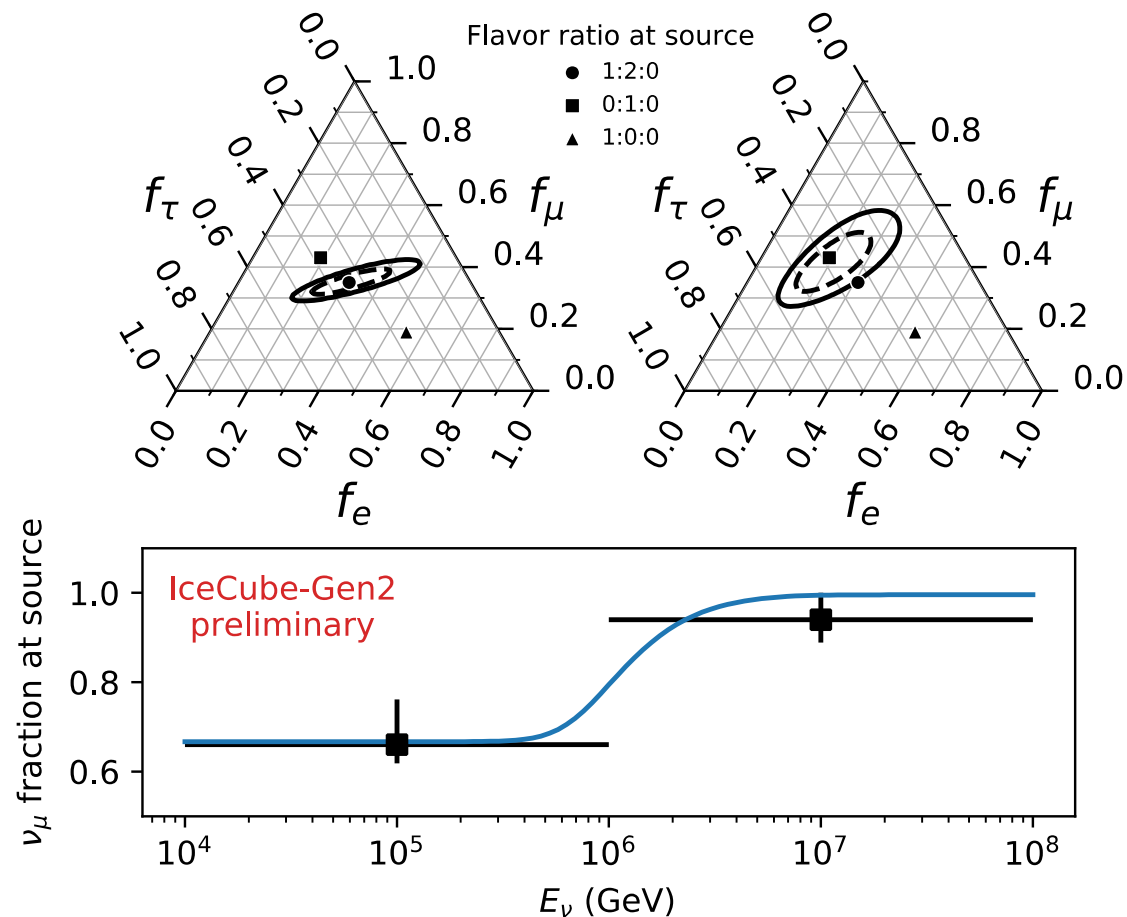
Adapted from Mauricio Bustamante, John F. Beacom, Walter Winter, PRL 2015.

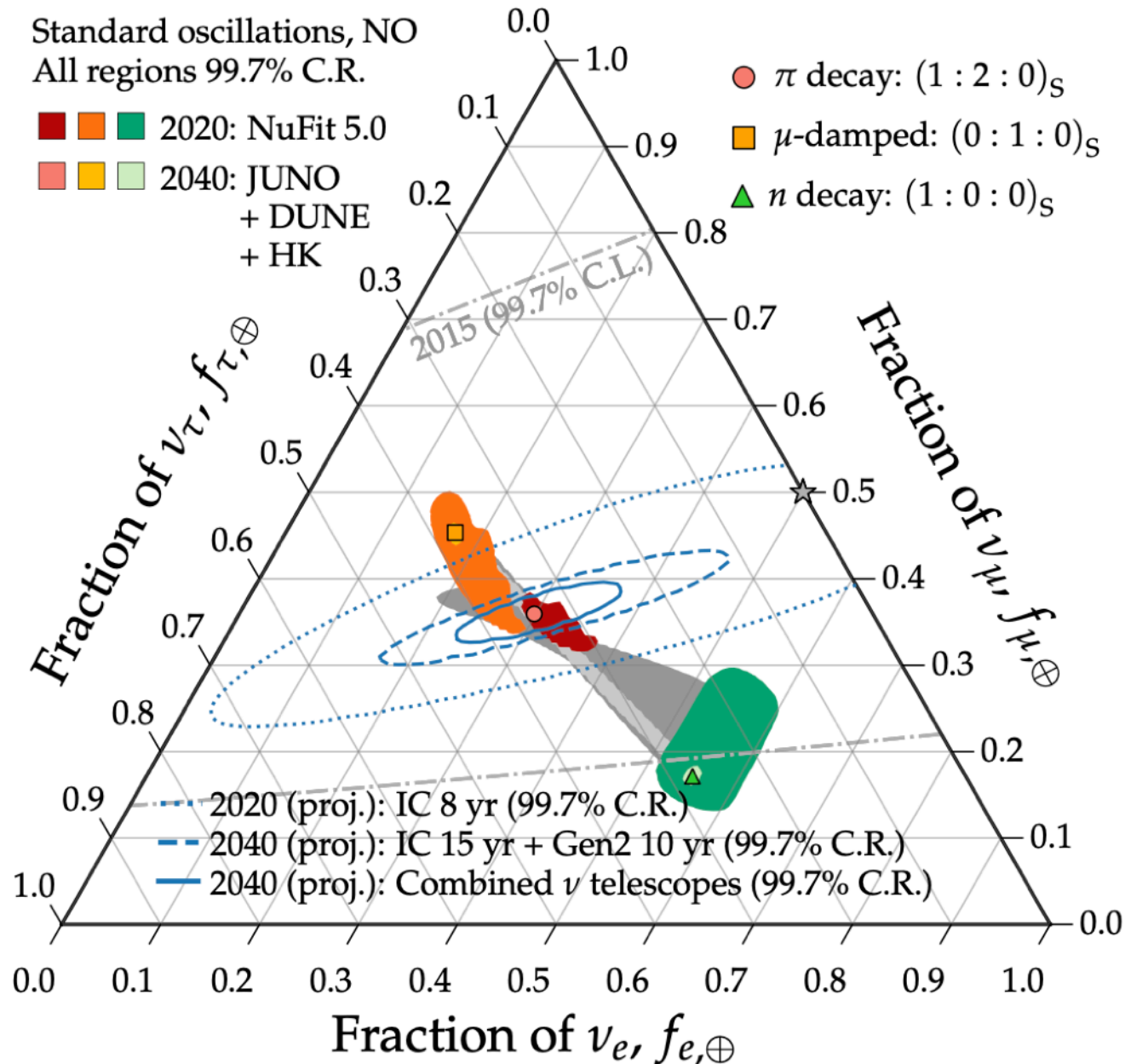
Requirements for IceCube-Gen2

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Enhanced sensitivity to neutrino flavors and the ability for flavor identification

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





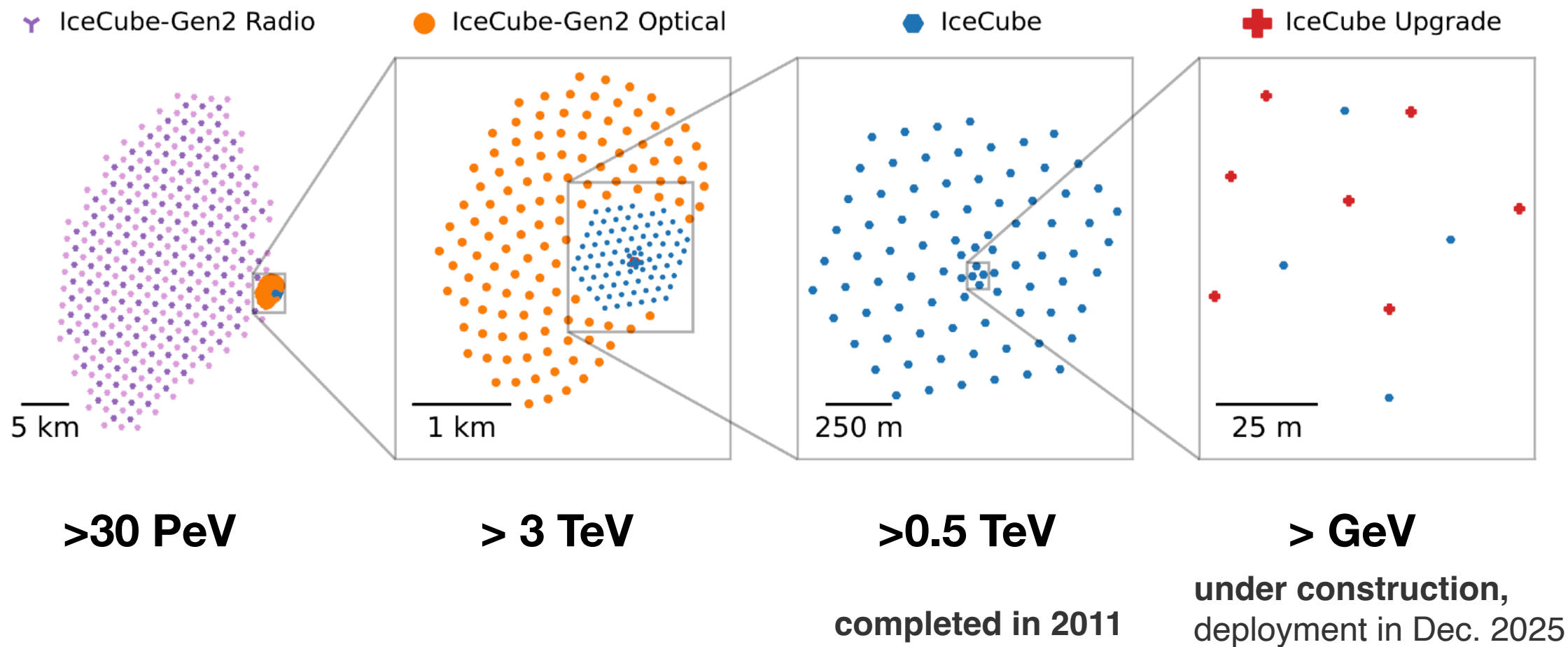
A bright future:
with exposure of > 200
 km^3 year we can measure
the flavor composition of
individual sources

<https://arxiv.org/pdf/2012.12893>

Song, Li, Arguelles, Bustamente, Vincent

IceCube-Gen2: A wide-band observatory

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



IceCube-Gen2

Technical Design Report

Part I: Science and Conceptual Design

Part II: Detector & Performance

**Part III: Detector Construction and
Logistical Support Requirements**

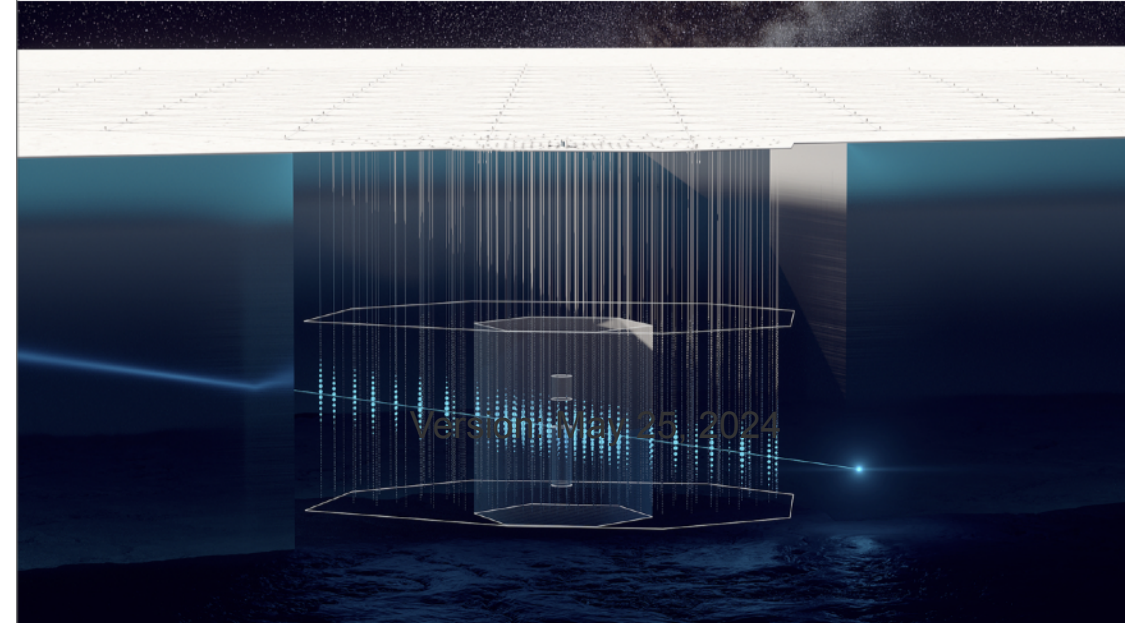
Download here:

<https://icecube-gen2.wisc.edu/science/publications/tdr/>

(350 pages)



ICECUBE-GEN2 TECHNICAL DESIGN



The IceCube-Gen2 Neutrino Observatory

Parts I and II

~~(Part III will be released at a later time.)~~

and now: Part III

Version: May 25, 2024

Scope: 1. The Optical Cherenkov Array

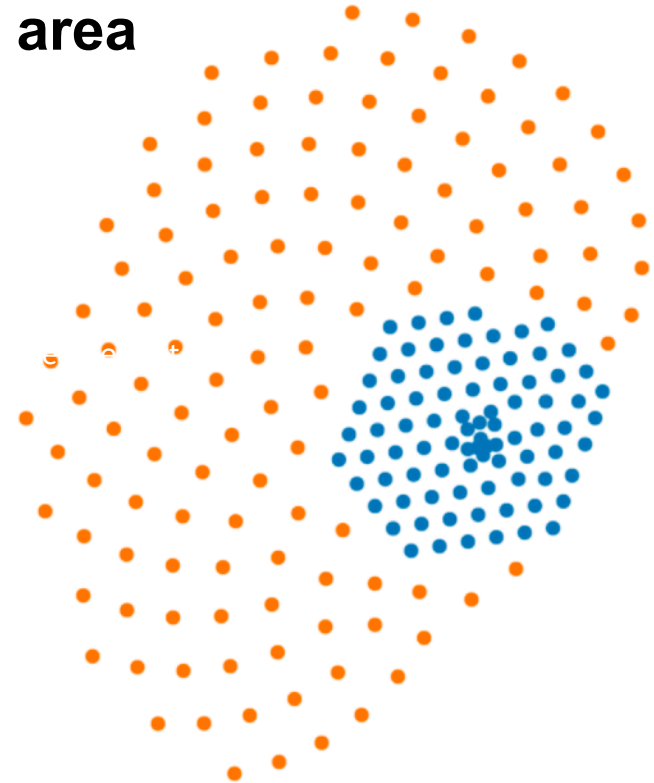
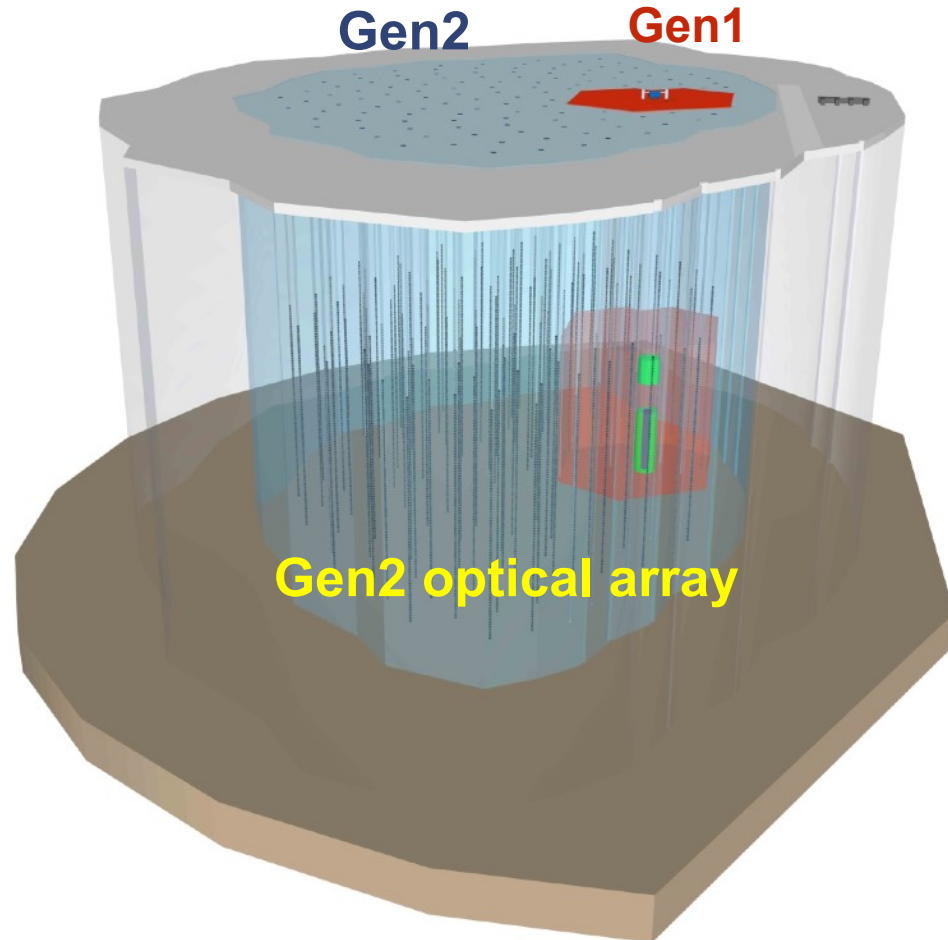
The main detector component.

Surface Area: $\sim 6.5 \text{ km}^2$

Instrumented Volume: 8 km^3

9600 optical sensors
—> 8 x Photon detection area

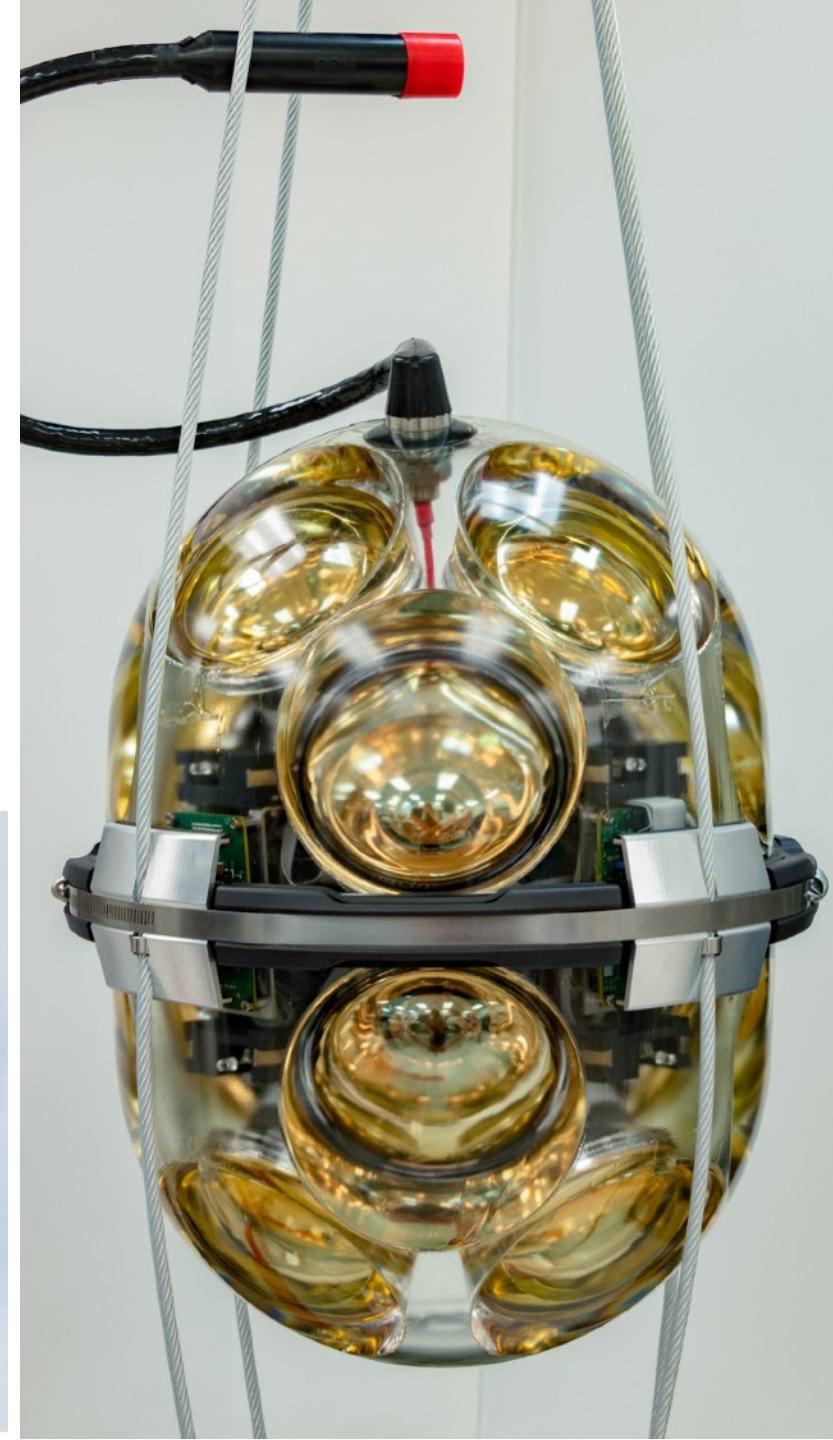
120 strings



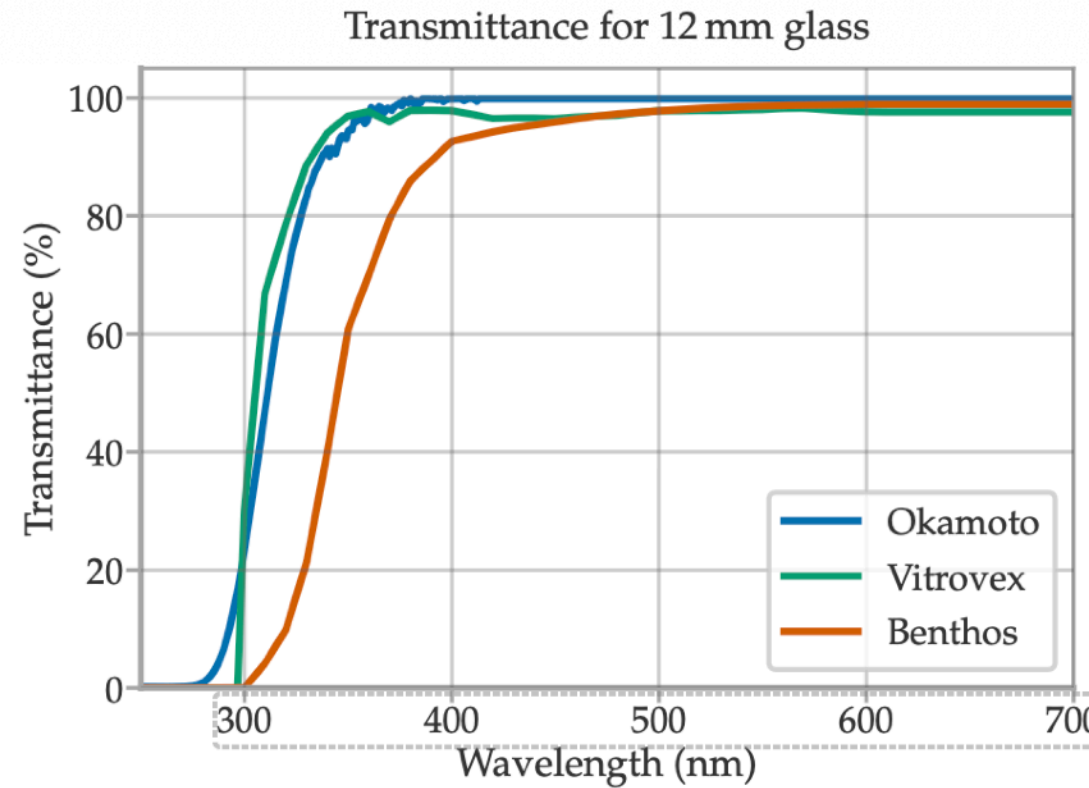
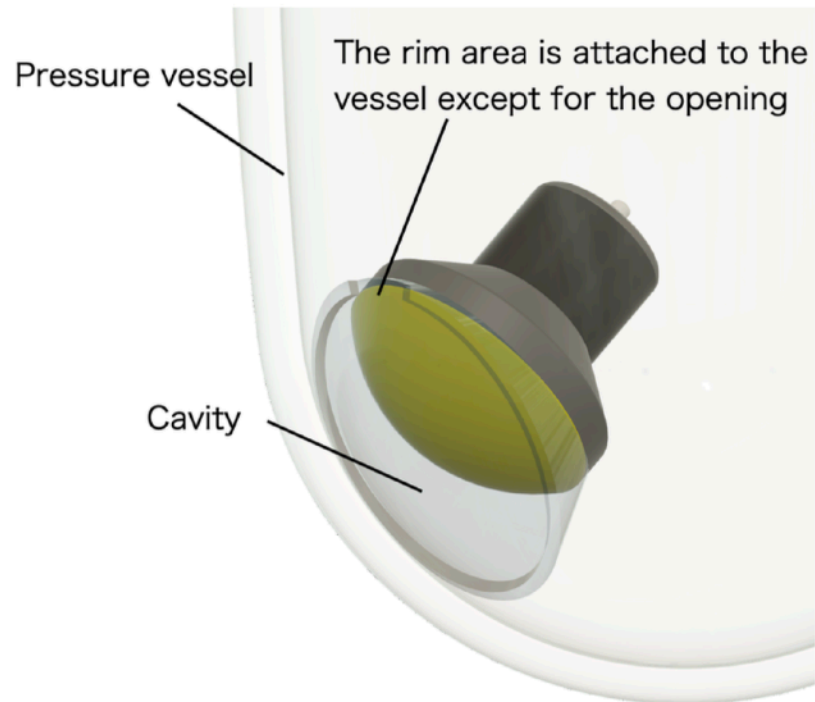
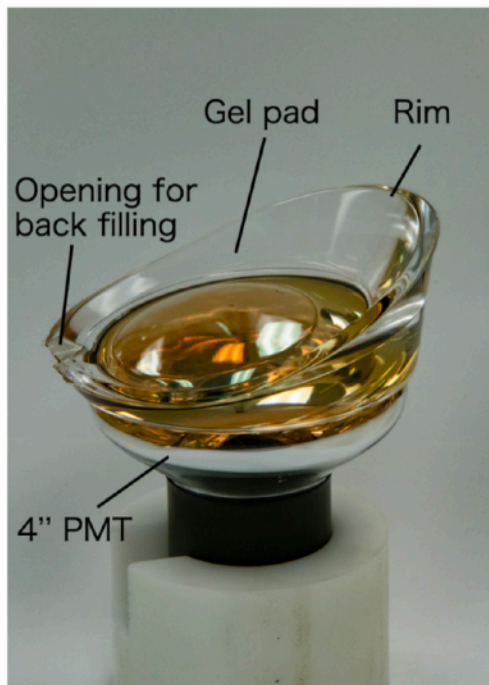
The Gen2 Digital Optical Module

- Evolution of the design developed for the IceCube Upgrade (mDOM / D-Egg)
- Smaller diameter (bore holes)
- 4 x IceCube Gen1 sensitivity
- Low power consumption

New 4-inch PMTs,
with digitizer on
base.



The Gen2 Digital Optical Module



The Gen2 Digital Optical Module: Dynamic range

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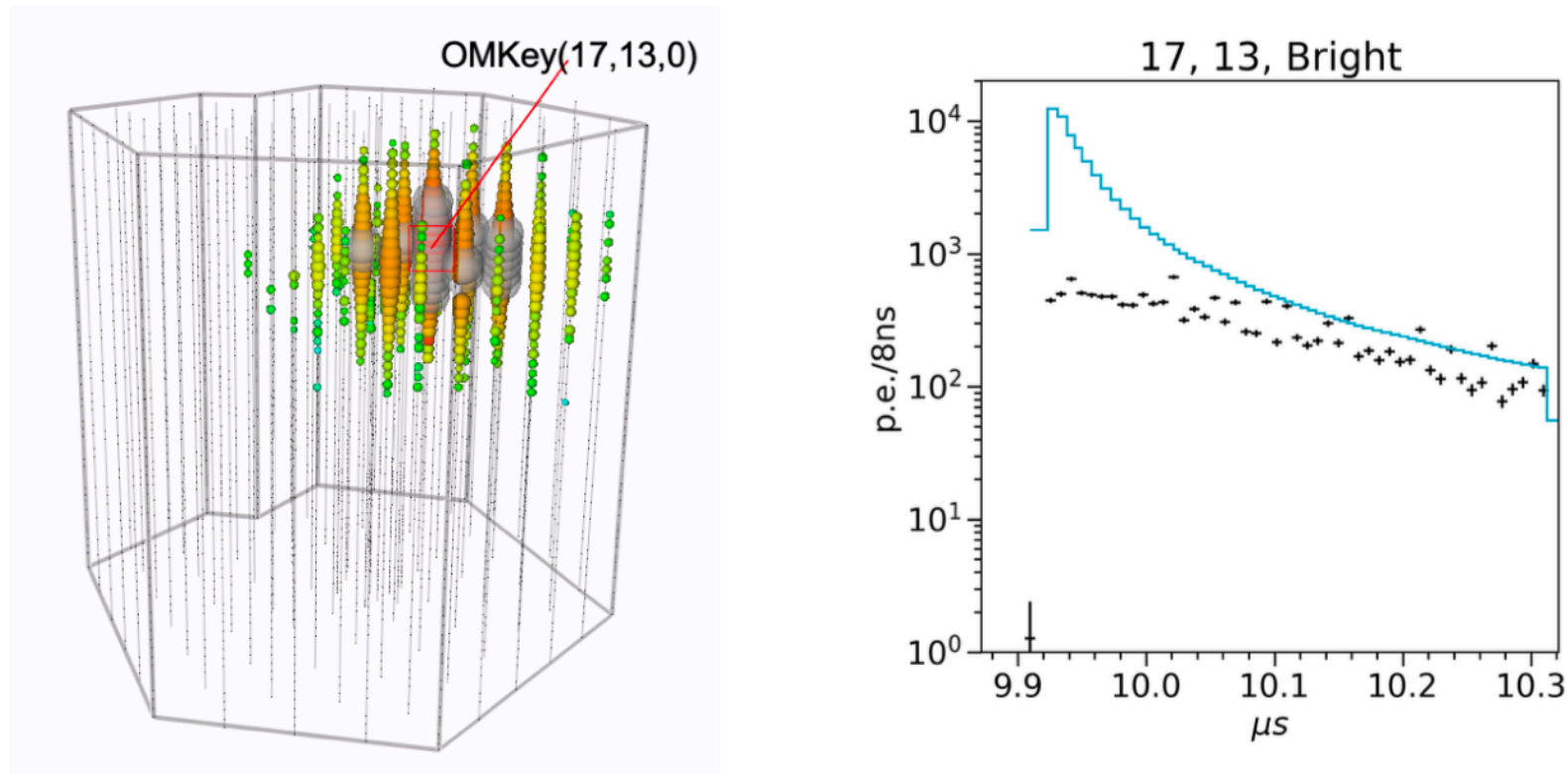


Figure 59: Left: An event display of the 2 PeV shower detected in IceCube with OM 13 on string 17 marked by the red line and box. DOMs that carry greater than ten times the mean total charge across all hit DOMs are classified as “Bright” (gray spheres) and excluded from use in reconstruction. Right: Observed (black) and expected (blue) distributions in time of the number of photoelectrons at IceCube DOM(17, 13), which is about 30 m from the reconstructed shower maximum of a 2 PeV particle shower. The expected distribution overshoots the observed data by a significant amount due to PMT saturation. The DOM is classified as “Bright” and currently excluded from IceCube event reconstruction.

The Gen2 Digital Optical Module: Dynamic range

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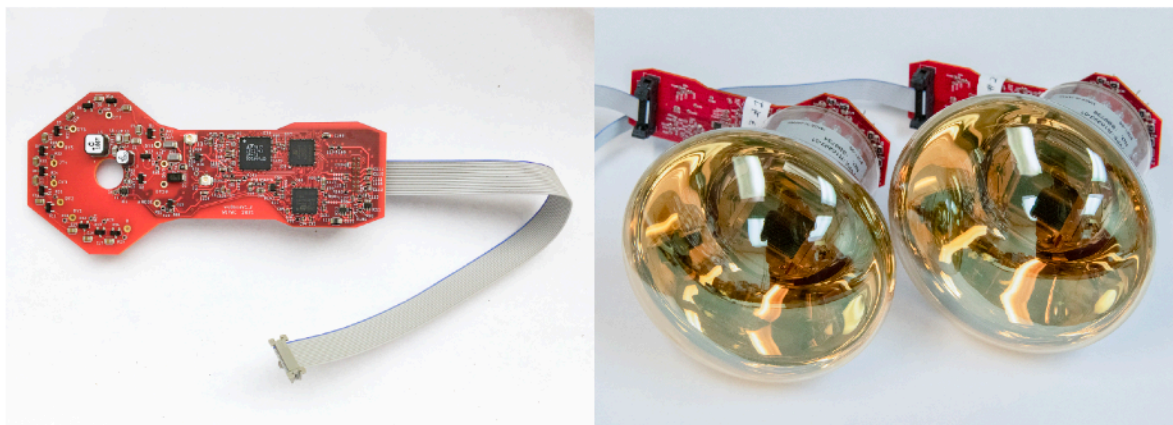
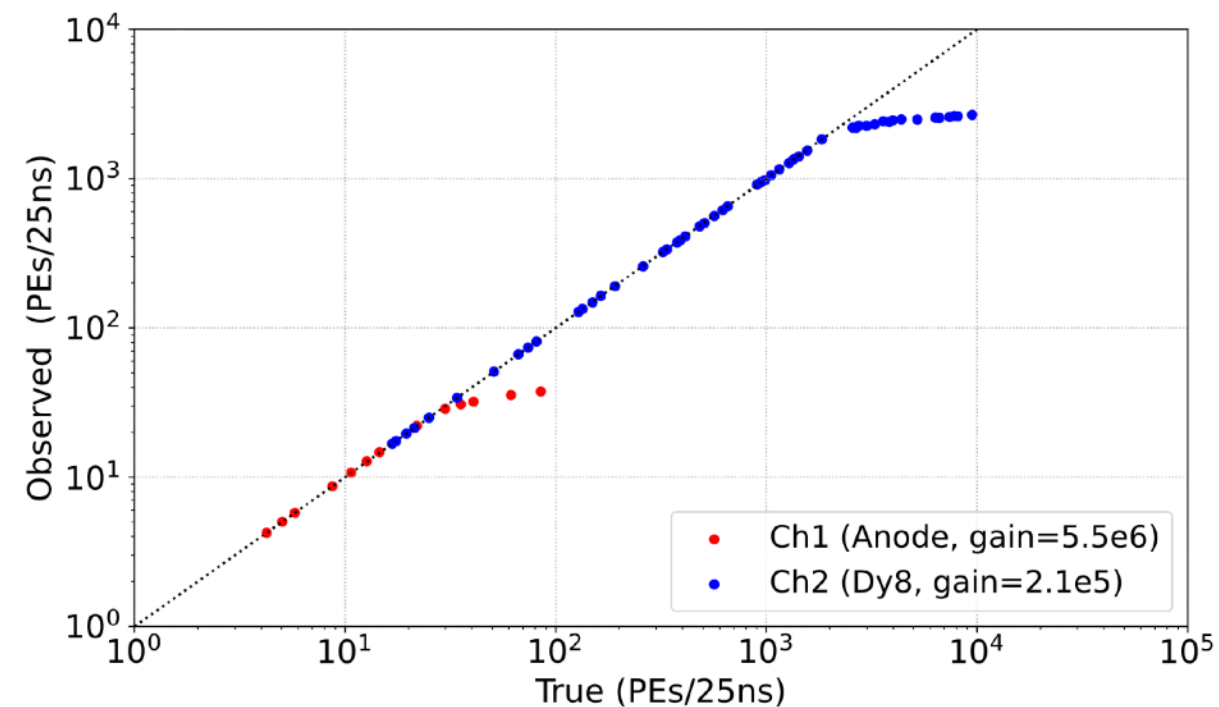
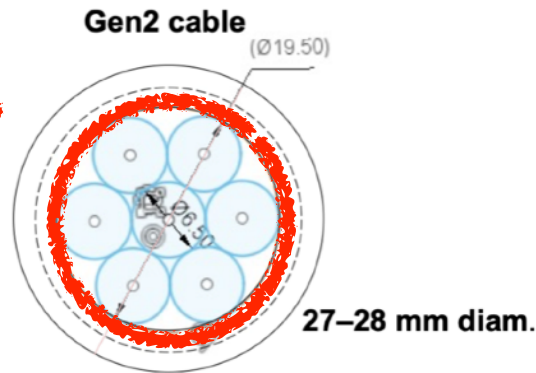


Figure 67: The new PMT base is shown on the left. It includes the HV generator, a 2-channel digitizer for anode and dynode signal and a microprocessor + FPGA. The shape is optimized to accommodate the space requirements inside the DOM. The picture on the right shows two 4-inch PMTs with base attached.

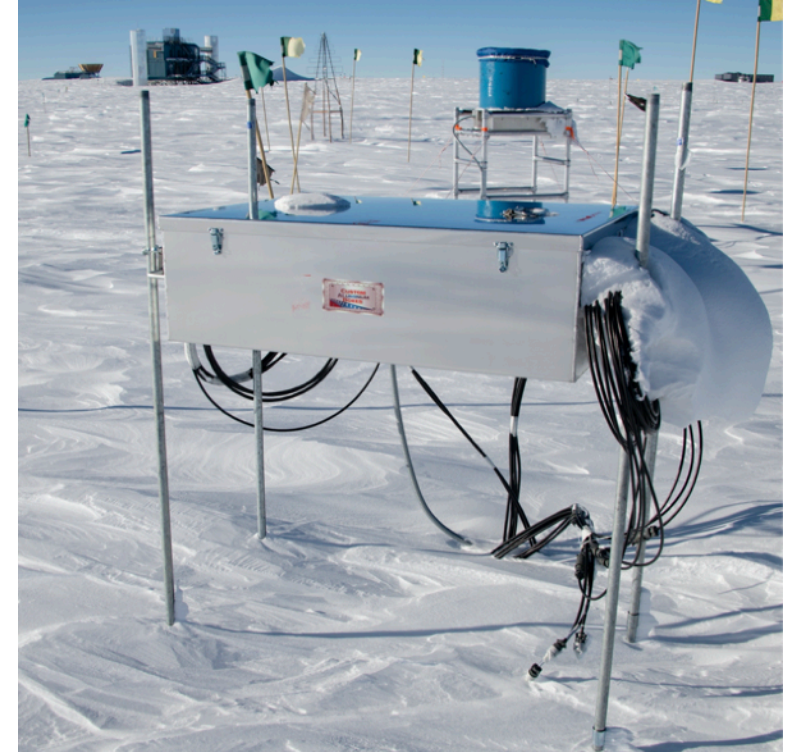


Data acquisition and cables

IceCube 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:

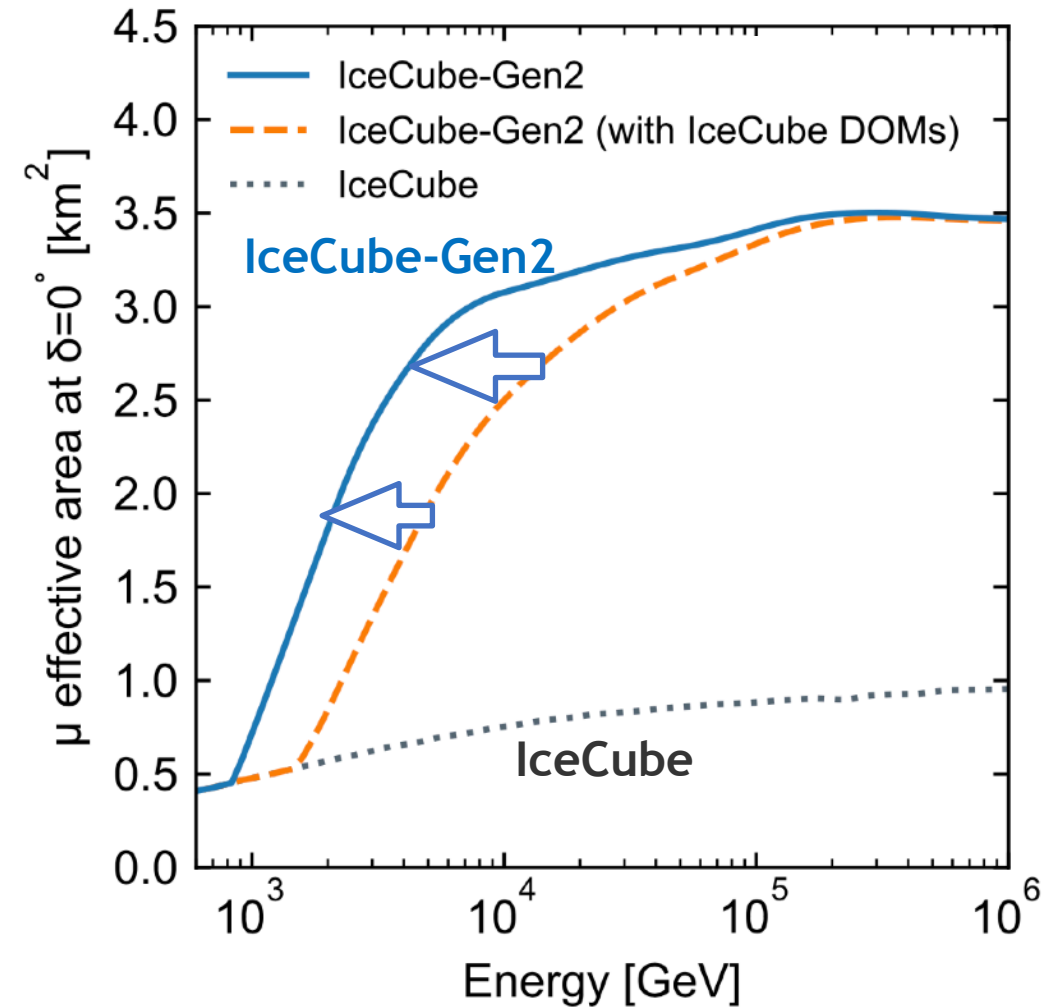
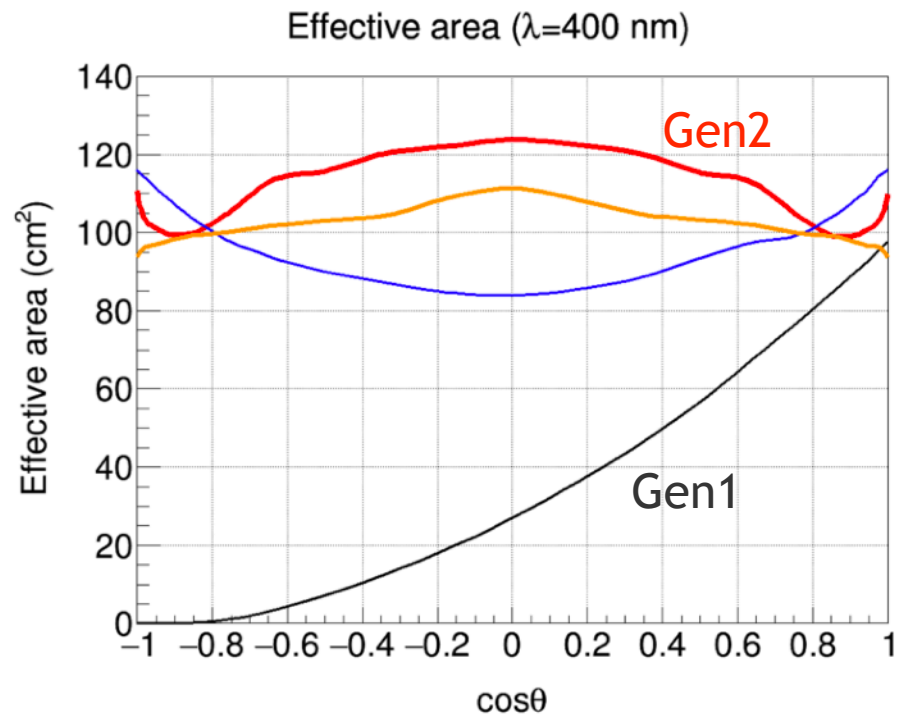
Gen2 will not send all noise hits to the top.

Higher Sensor sensitivity $\rightarrow$ Larger Muon Effective Area

Factor 4 more photons detected

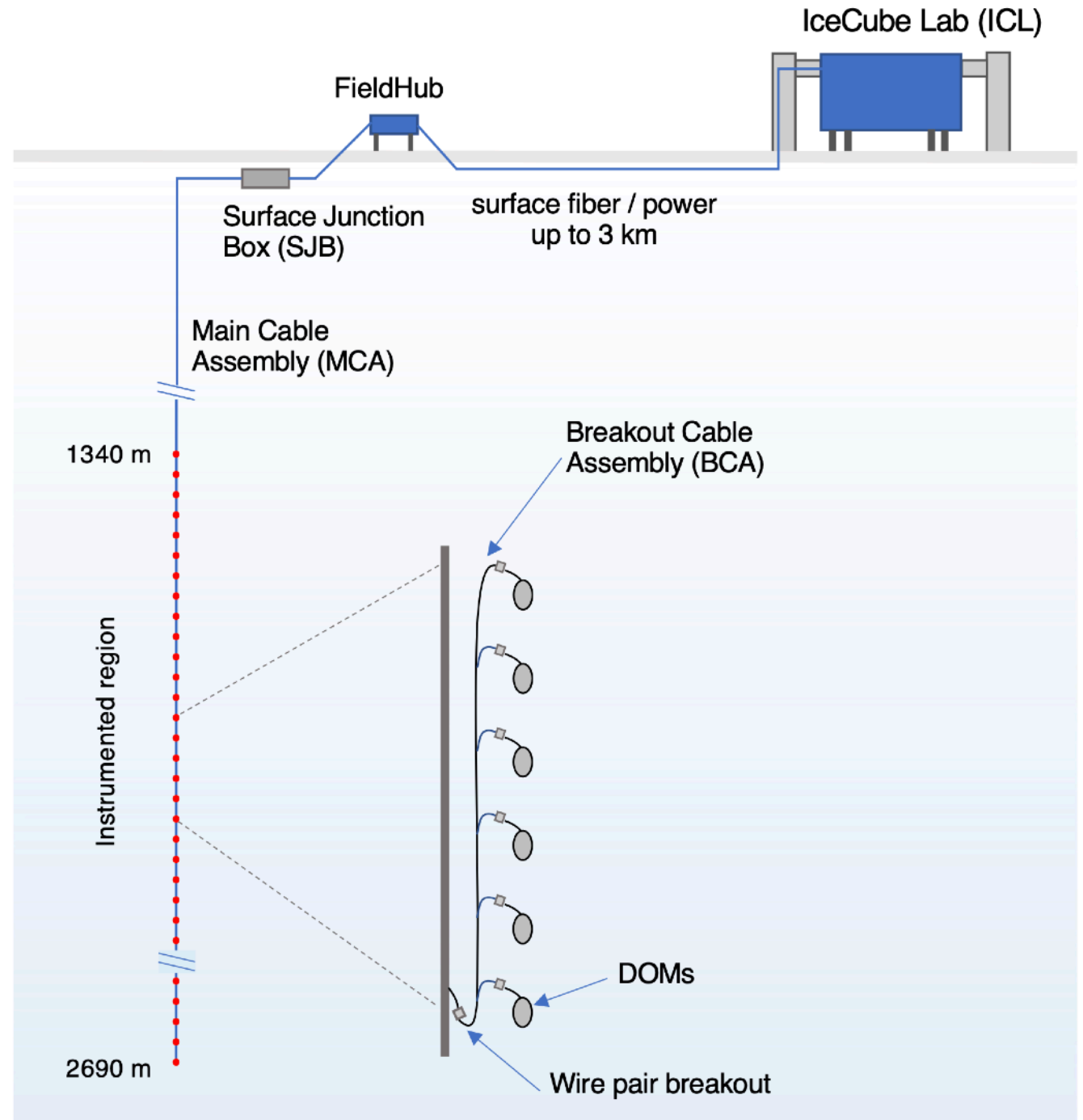
$\rightarrow$

- Lower energy threshold
- Angular resolution: $0.1 - 0.3^\circ$



Power and communications architecture

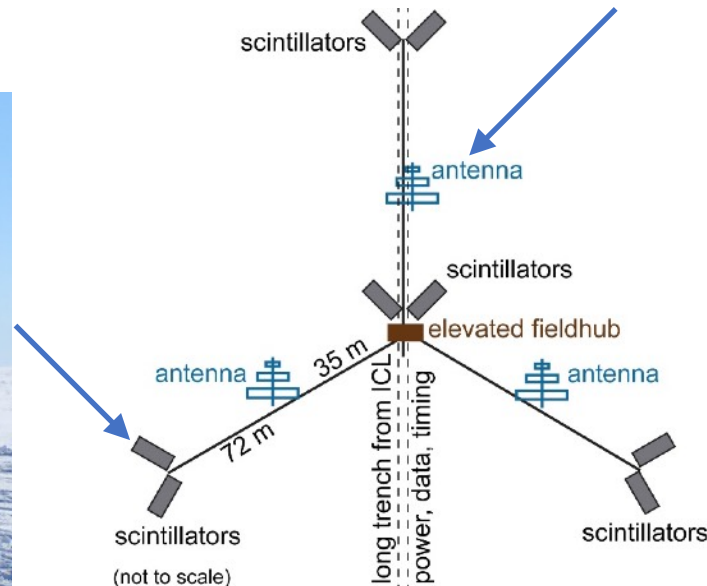
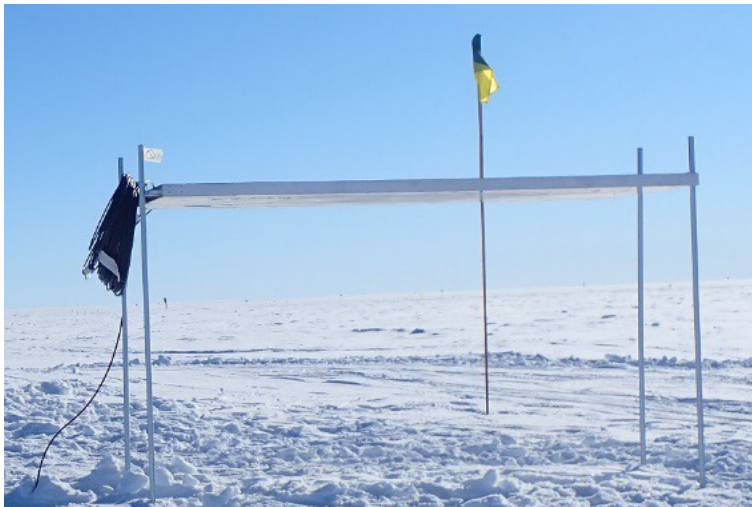
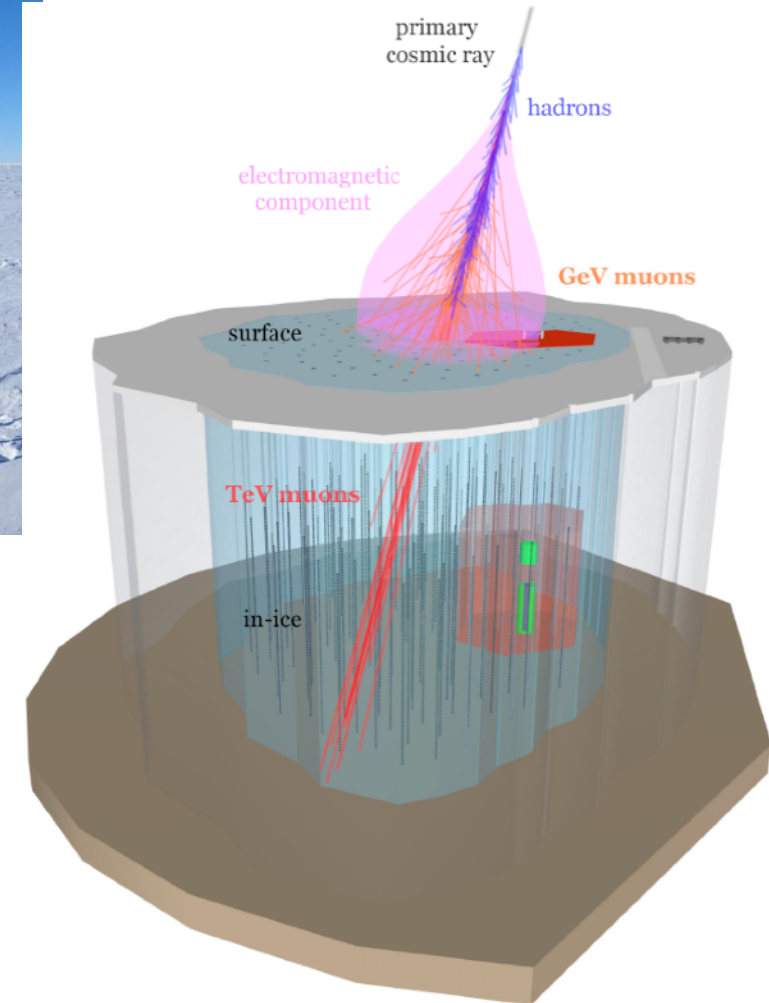
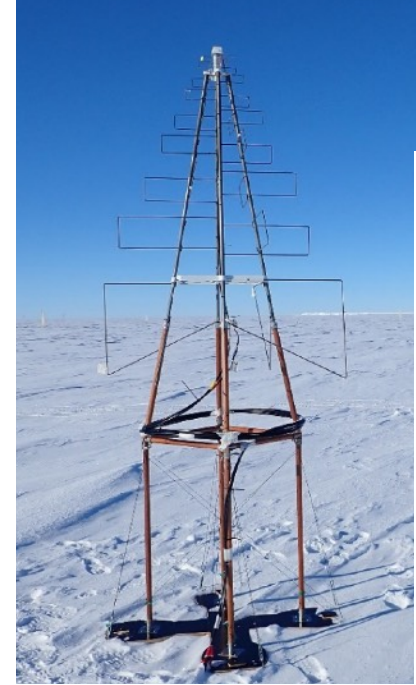
- “Fieldhub” on the ice.
- Revised trigger architecture
- Fewer copper cables are needed (60% less).
- This means also a big reduction of cargo (one million lb less.)



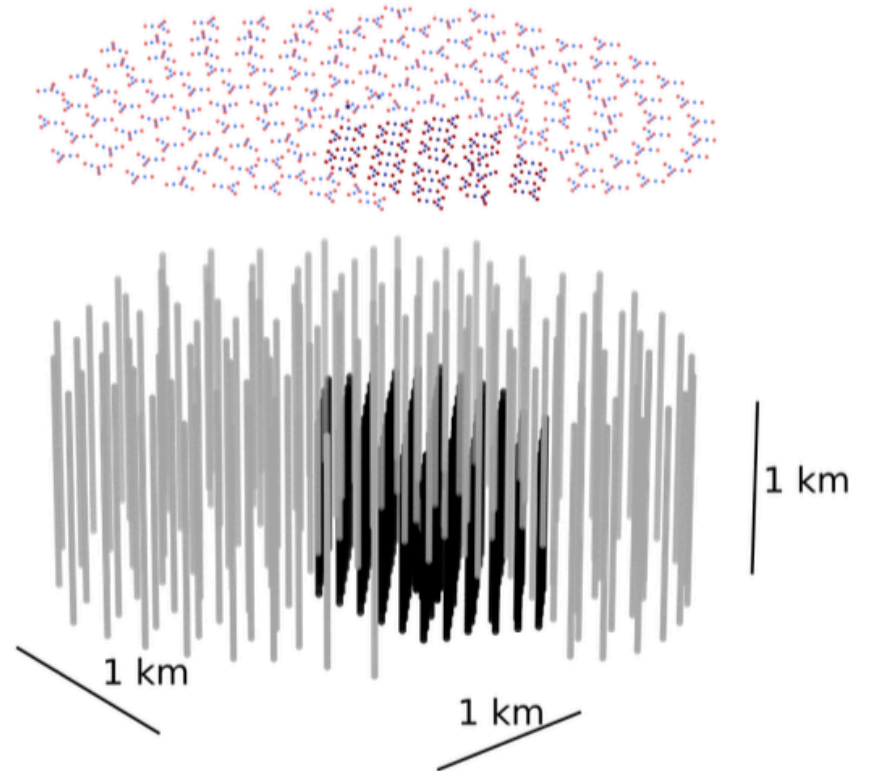
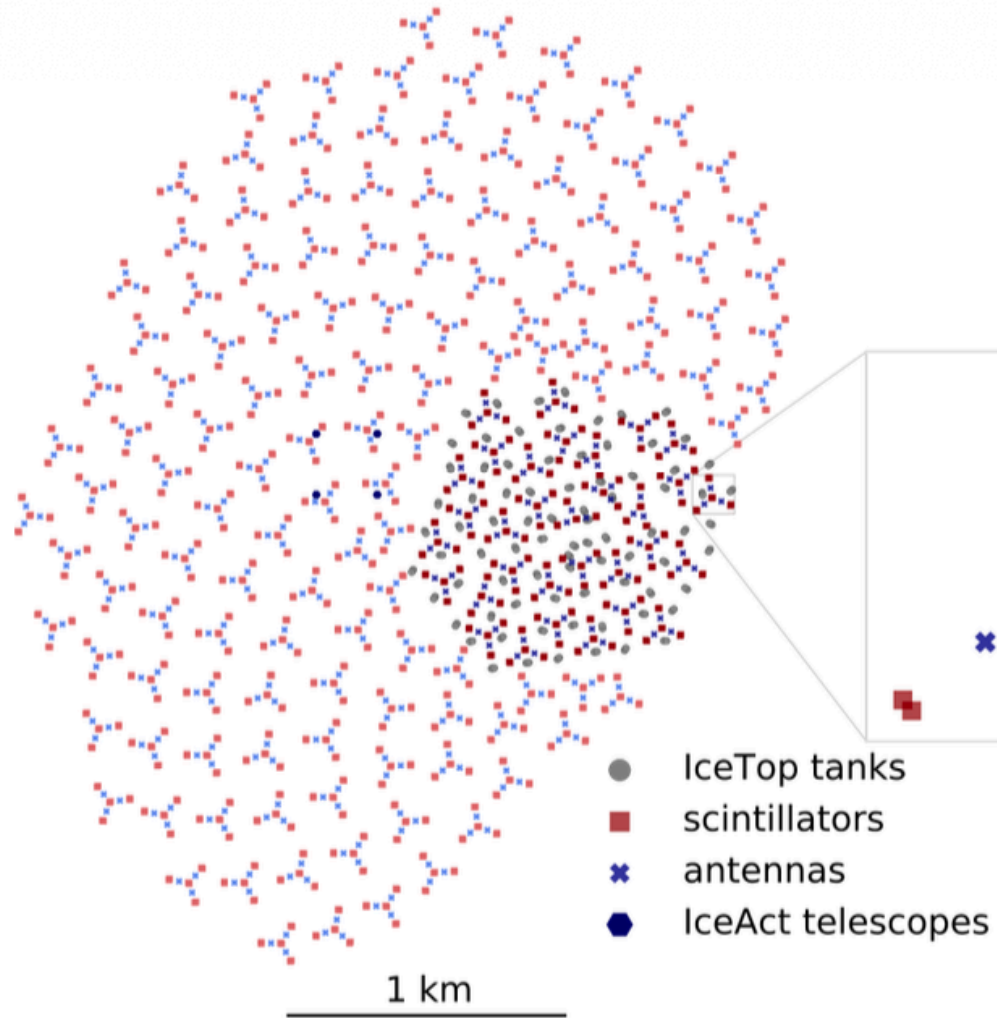
ICECUBE
GEN2

Scope: 2. 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

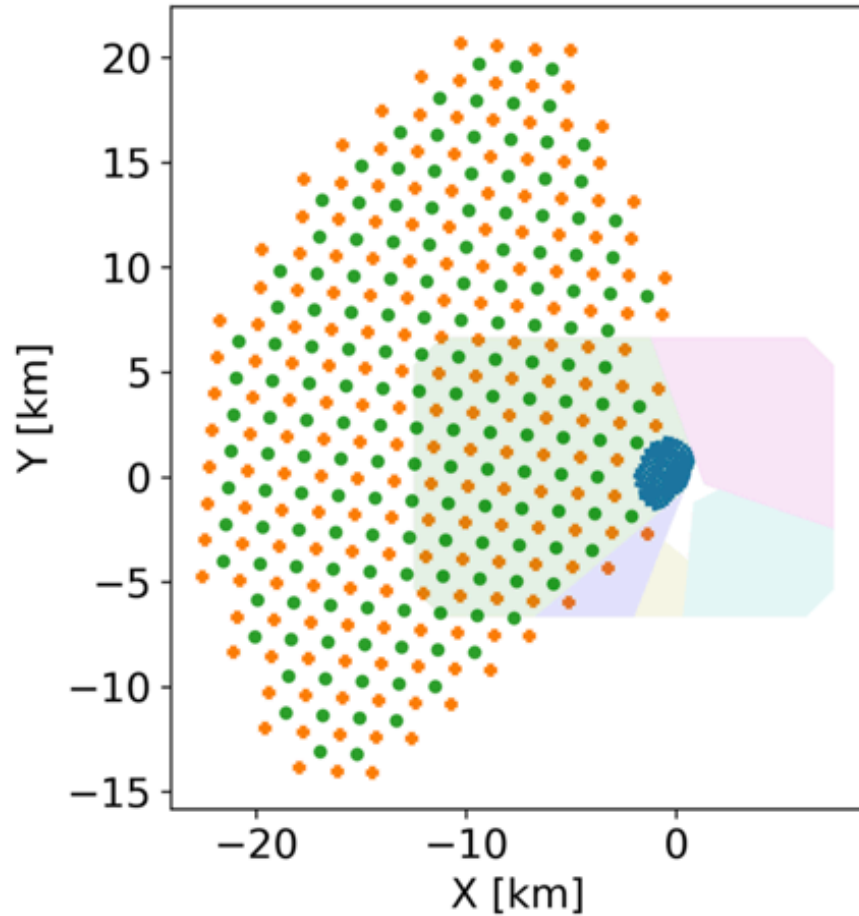


Scope: 2. The Surface Array



Scope: 3. The Gen2 radio array

Energy range from 30 PeV to well beyond EeV



361 stations

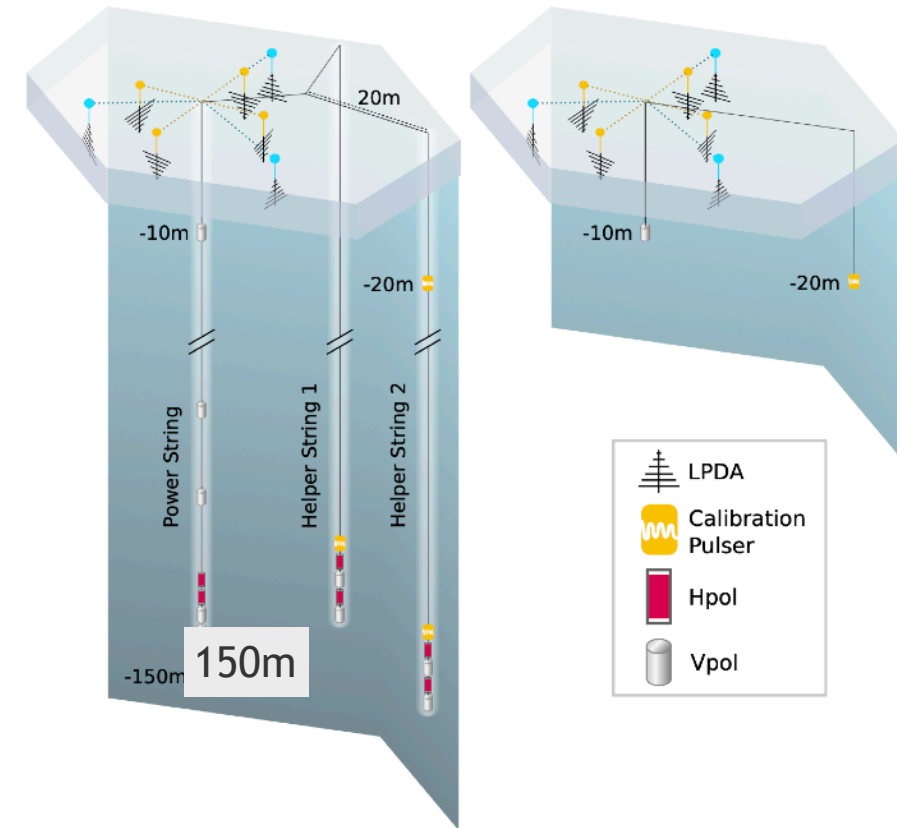
Area: 500 km²

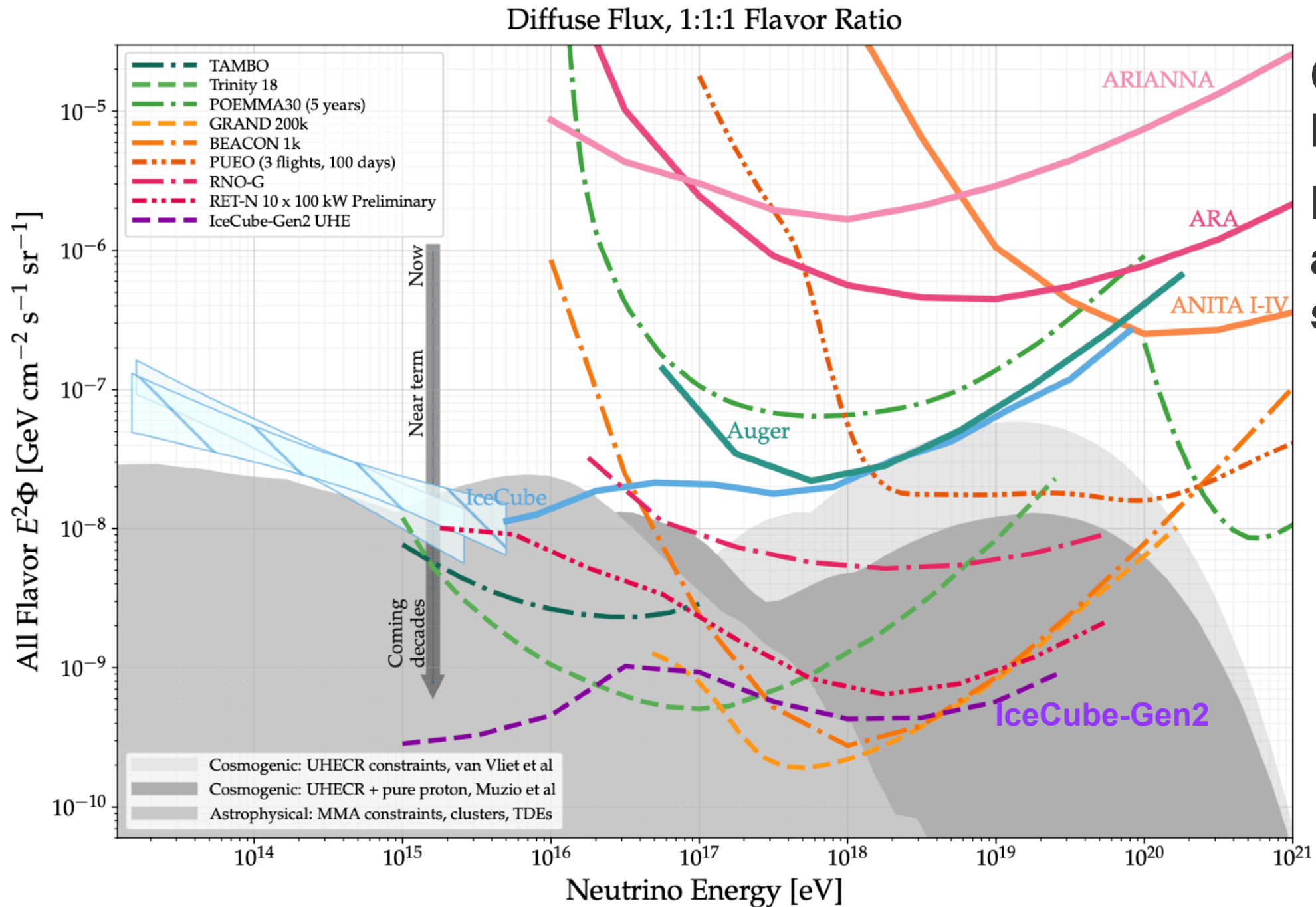
Ice target: 1000 km³

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

RNO-G:

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





Cosmic Neutrinos: Diffuse fluxes and sensitivities

High-Energy and
Ultra-High-Energy
Neutrinos: A
Snowmass White
Paper

<https://arxiv.org/abs/2203.08096>