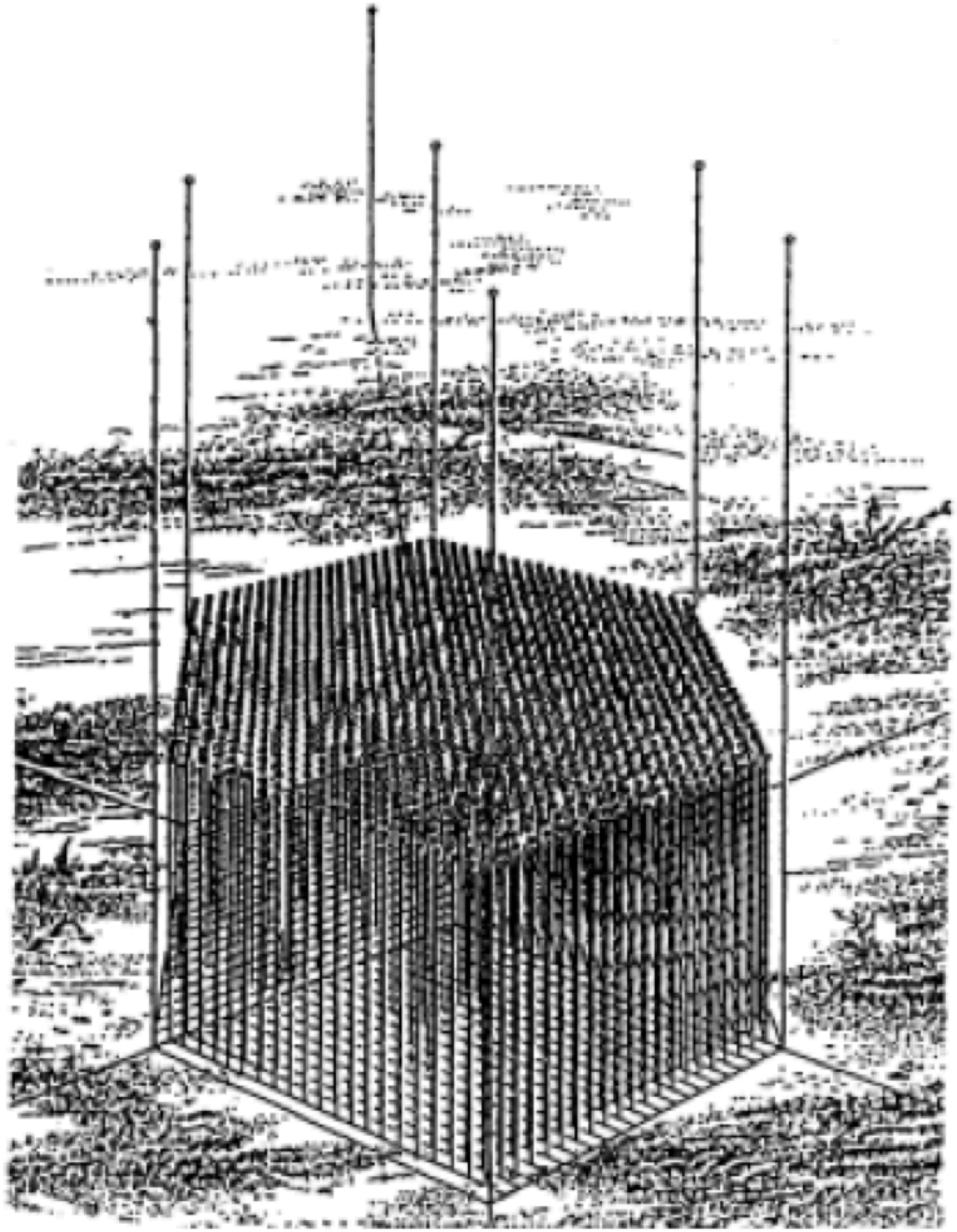
Neutrino Telescopes

Albrecht Karle
University of Wisconsin-Madison

Workshop on Ghost Particle Hunting and applications to World Peace
April 30, 2025

… on relatively scant information on the expected neutrino intensities and was difficult to justify in detail; the general idea was that neutrino cross section are small and high-energy neutrinos are scarce, so the detector had better be large:

A. Roberts, Rev. Mod. Phys. 64 (1992) 259. (Article about history of DUMAND)



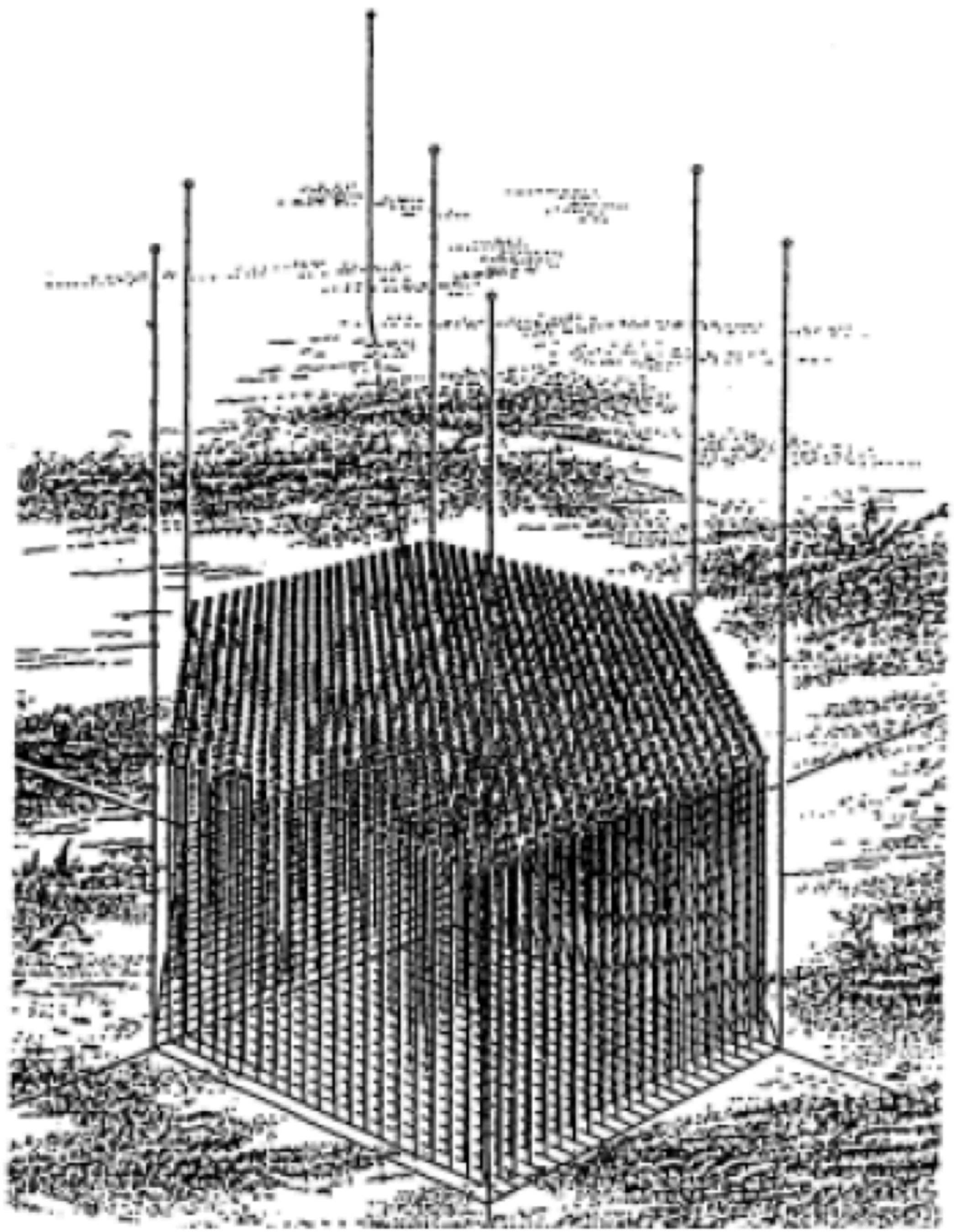
original conception from 1978:
1261 strings
22,698 Optical Modules
1.26 km3

Neutrino Telescopes

Albrecht Karle
University of Wisconsin-Madison

John Learned Fest, April 30, 2025

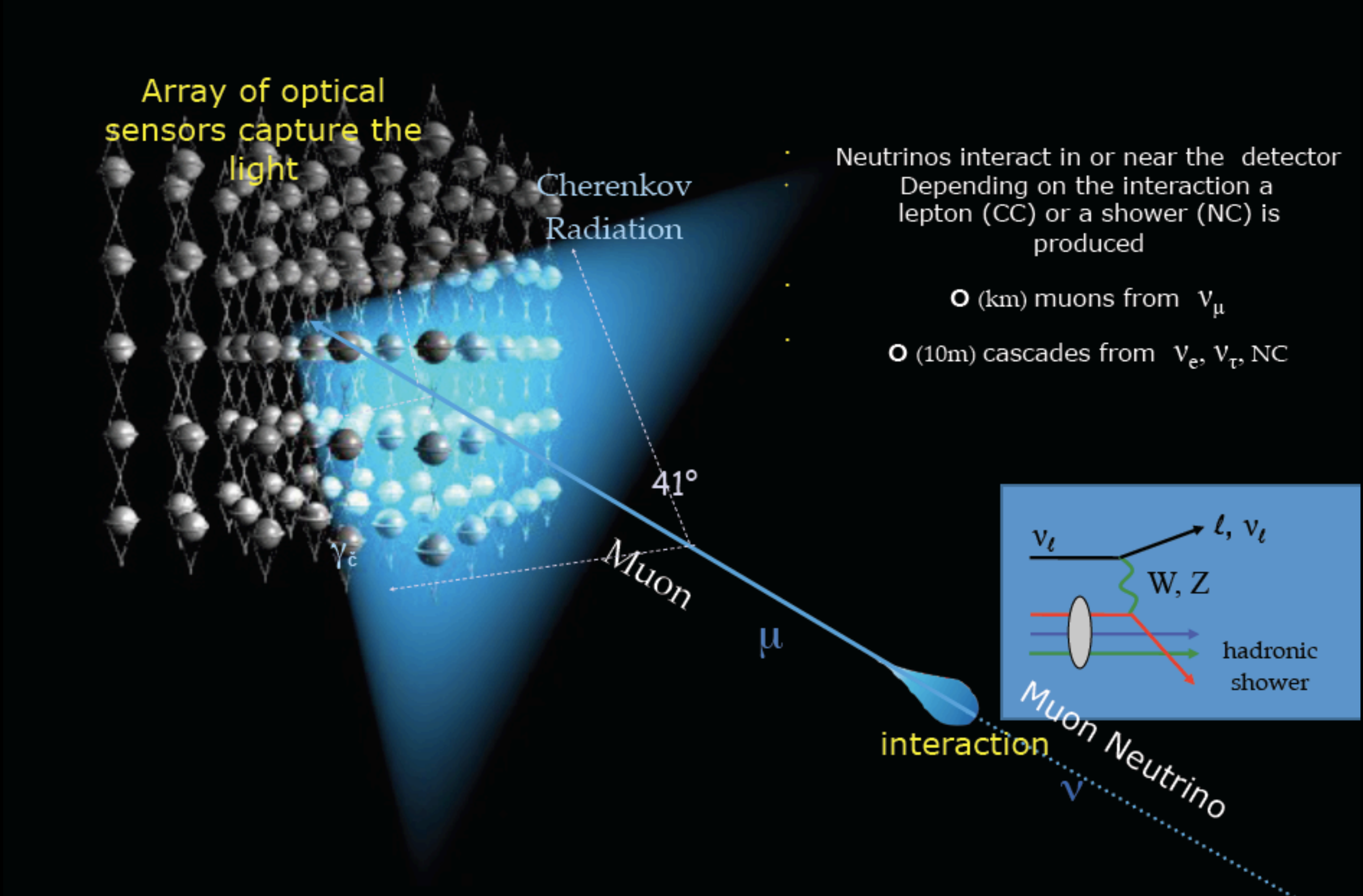
- Introduction
- Neutrino astronomy: The starting point
- IceCube, IceCube-Gen2
- Current and planned projects optical
- Ultra High Energies
- Outlook

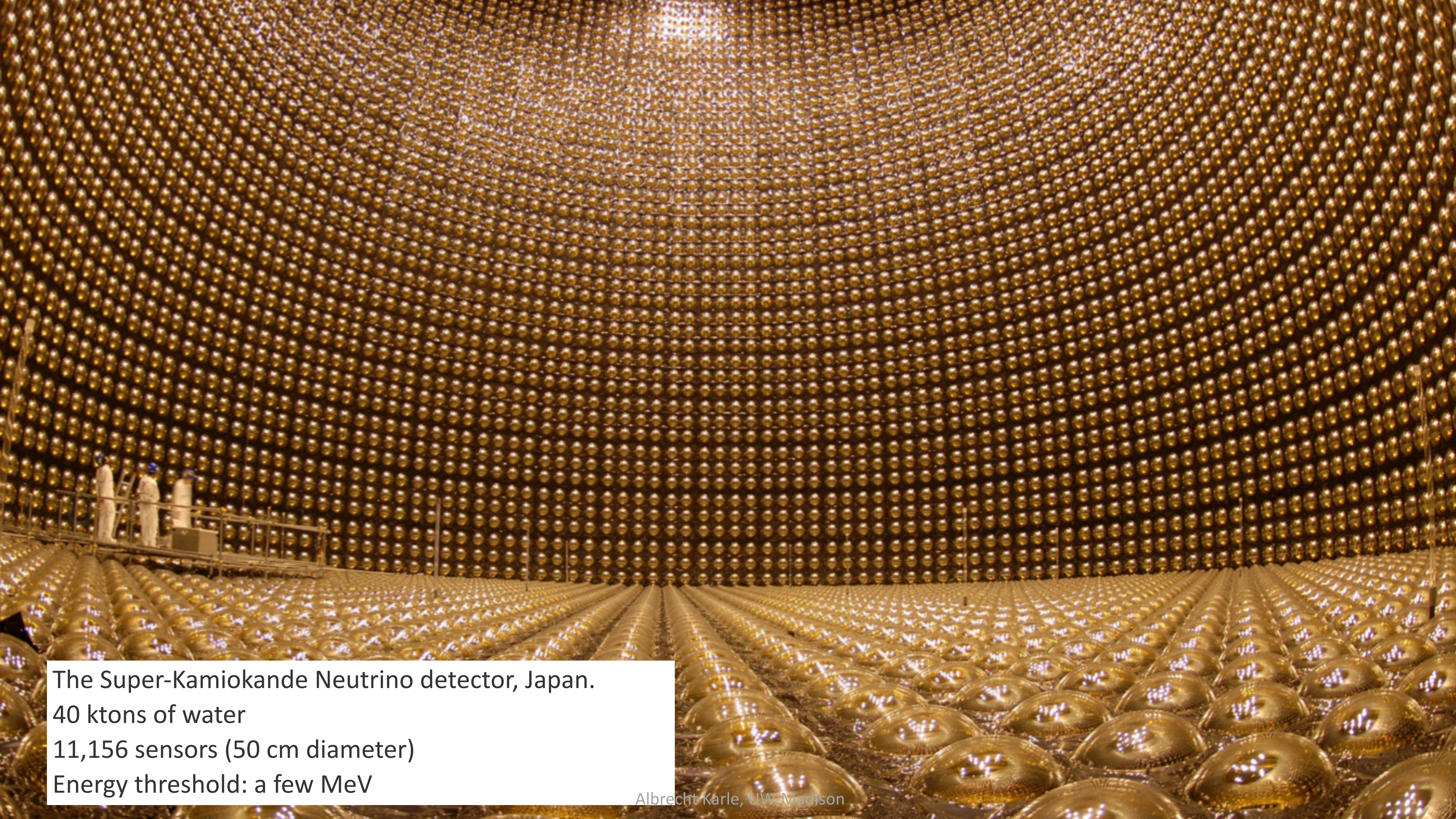


Detecting, discovering Cosmic Neutrinos
Event Rates and cross sections are small.

Target size of 1 km^3 was a long envisioned scale - and it proofed to be right to discover cosmic neutrinos.

Optical Cherenkov method,
proposed early in the 60ies
using natural water, and then ice, as target is the pre-eminent method, from GeV to >10 PeV.


Array of optical sensors capture the light
Cherenkov Radiation
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
41°
γ_c
Muon
μ
interaction
Muon Neutrino
ν
ν_ℓ
ℓ, ν_ℓ
W, Z
hadronic shower



The Super-Kamiokande Neutrino detector, Japan.
40 ktons of water
11,156 sensors (50 cm diameter)
Energy threshold: a few MeV

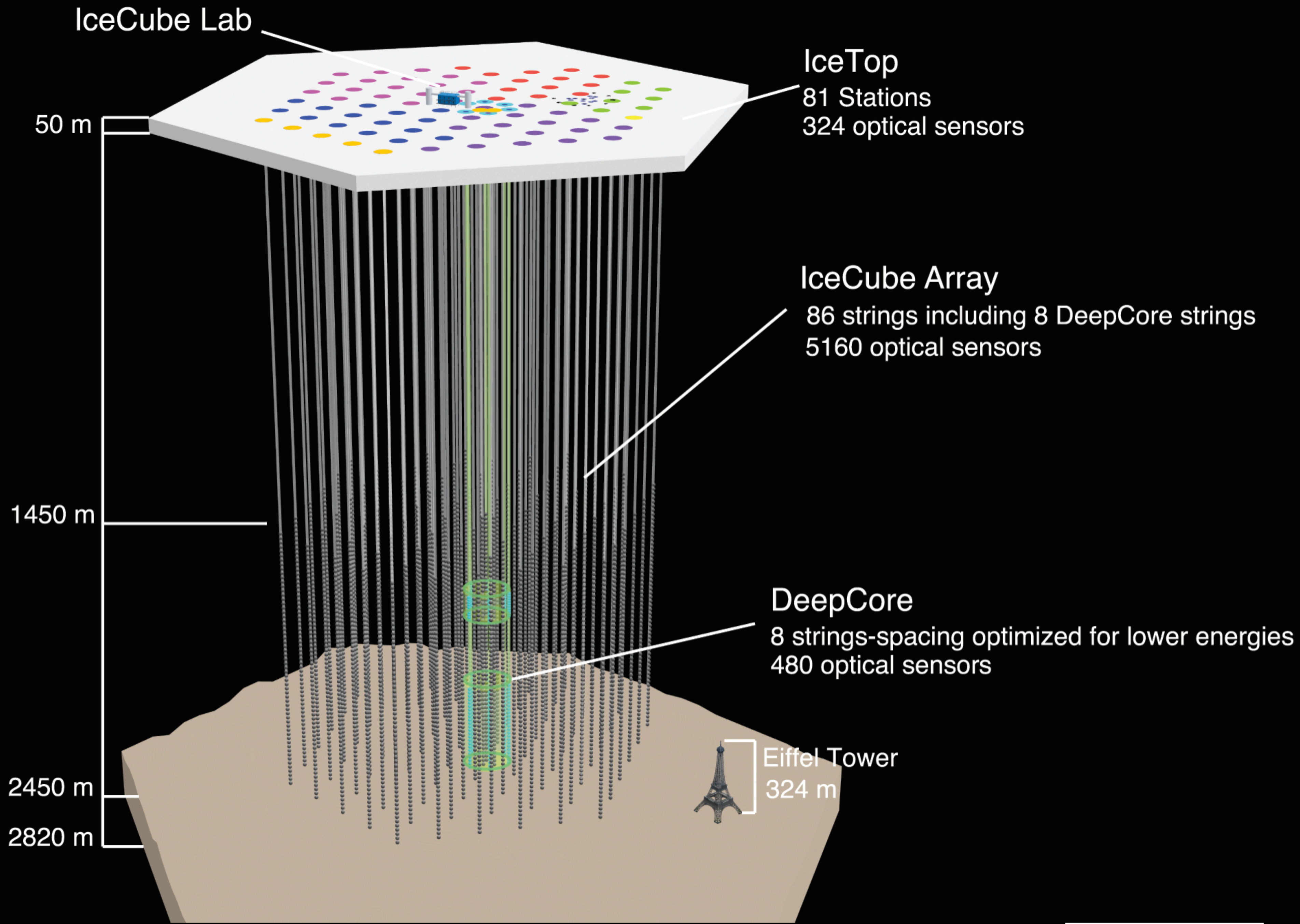
IMB

Threshold: ~ 30 MeV

The IceCube Neutrino Observatory

Completed 1/2011

Energy threshold: ~500 GeV

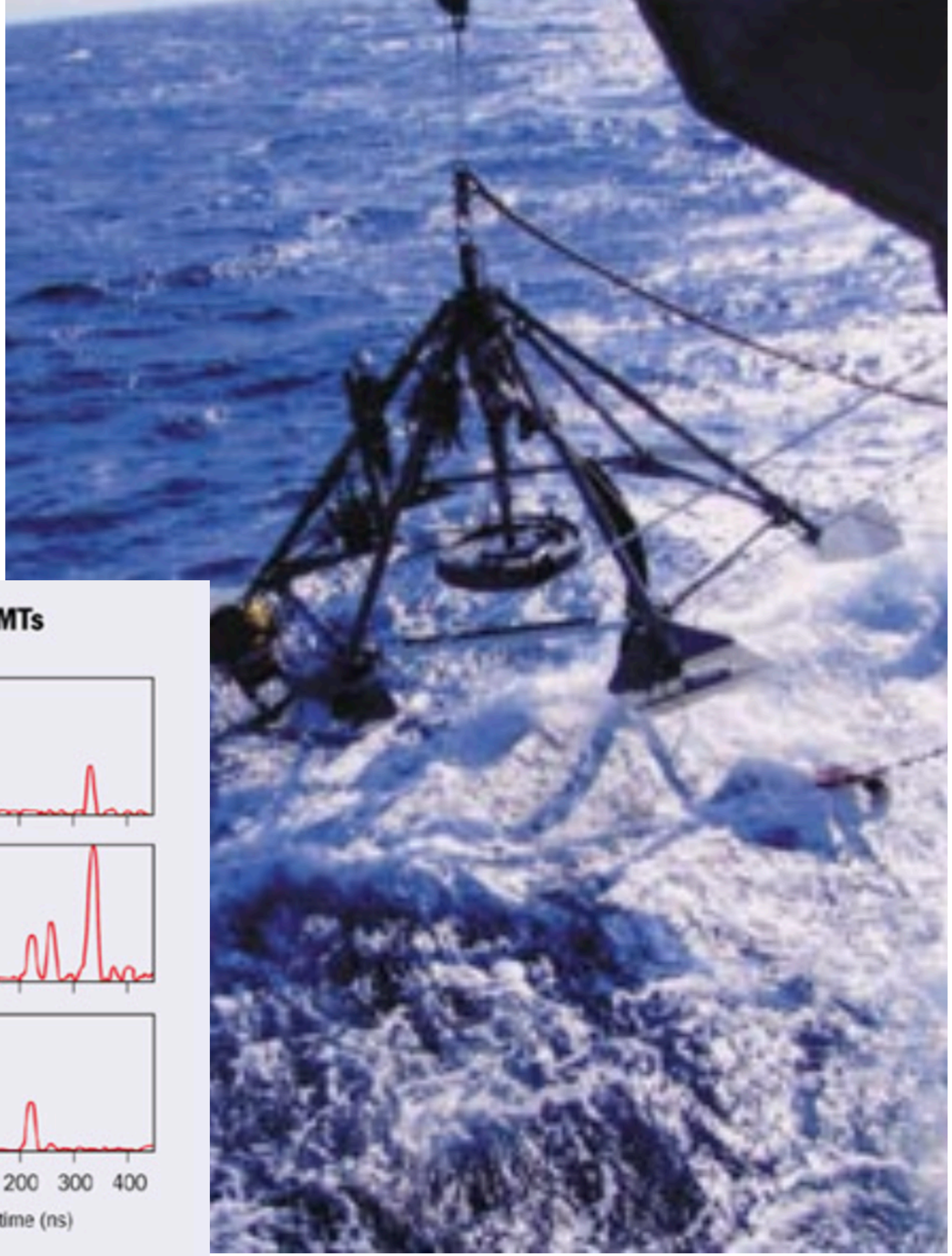


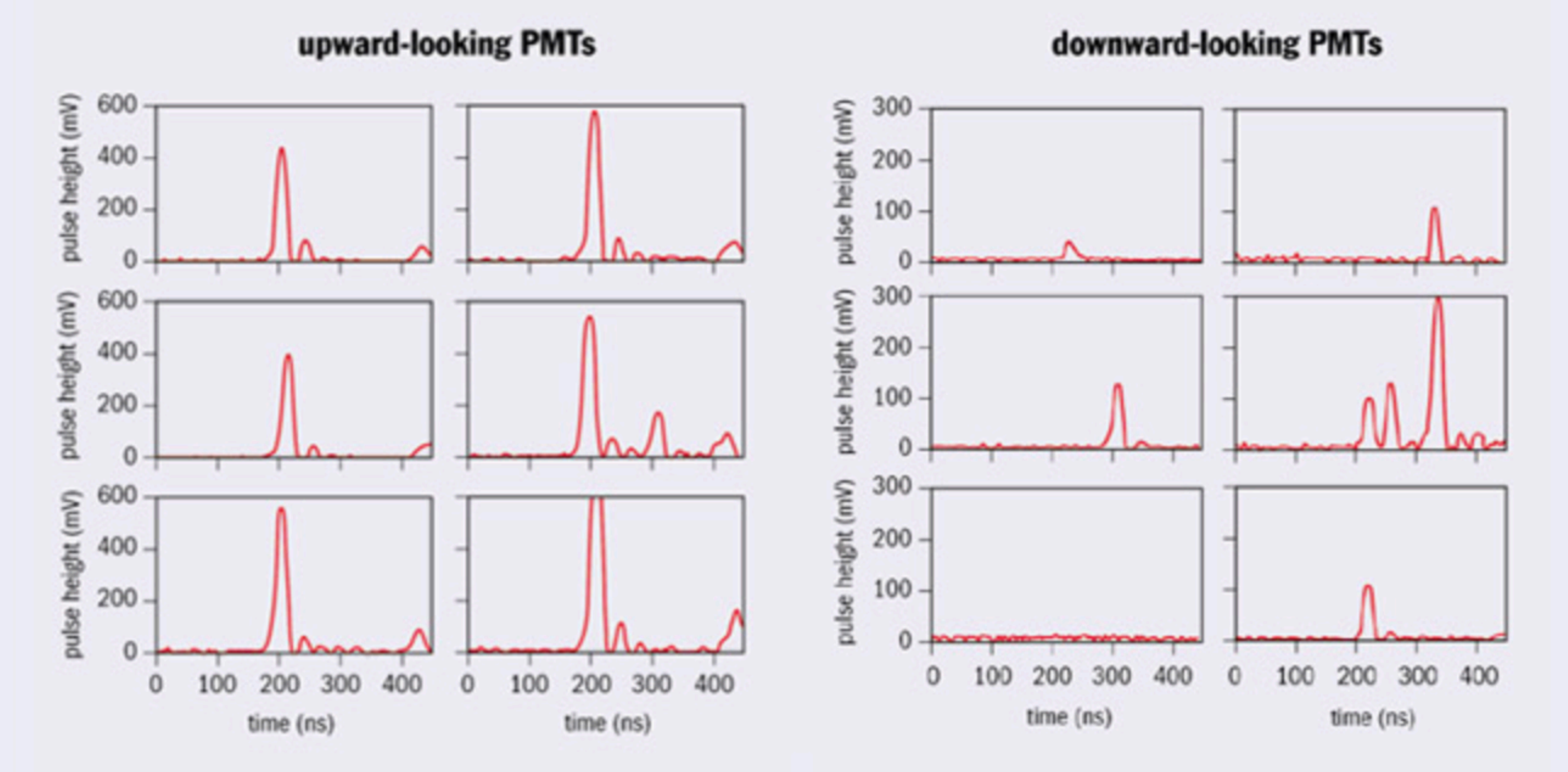
The four neutrino telescope projects in the 1990ies (eg ICRC Rome 1995)

- DUMAND
- Baikal
- NESTOR (Mediterranean)
- AMANDA (The ice option)

NESTOR

April 2003:
NESTOR sees Muons at the Bottom of the Sea.

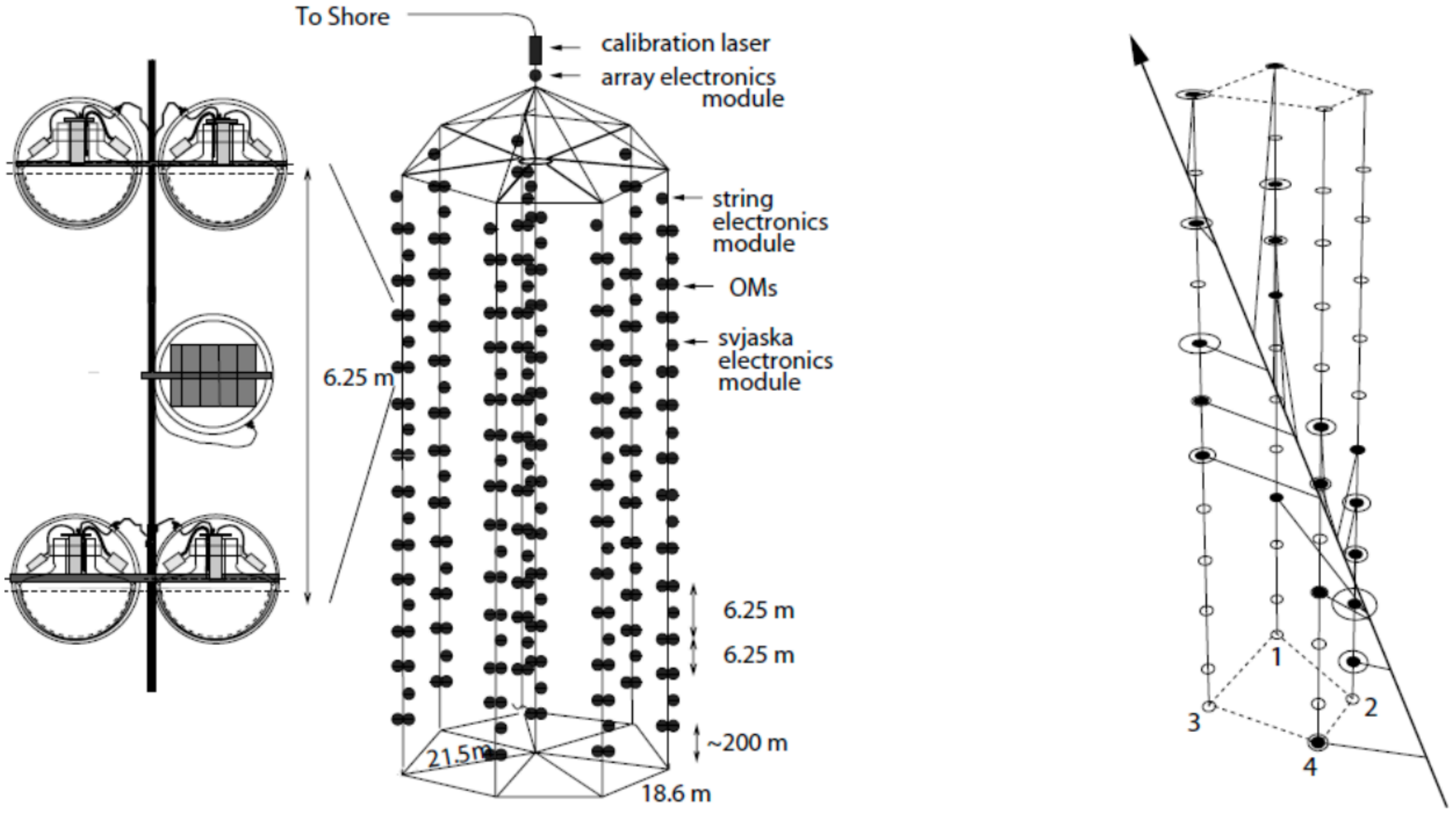




Baikal

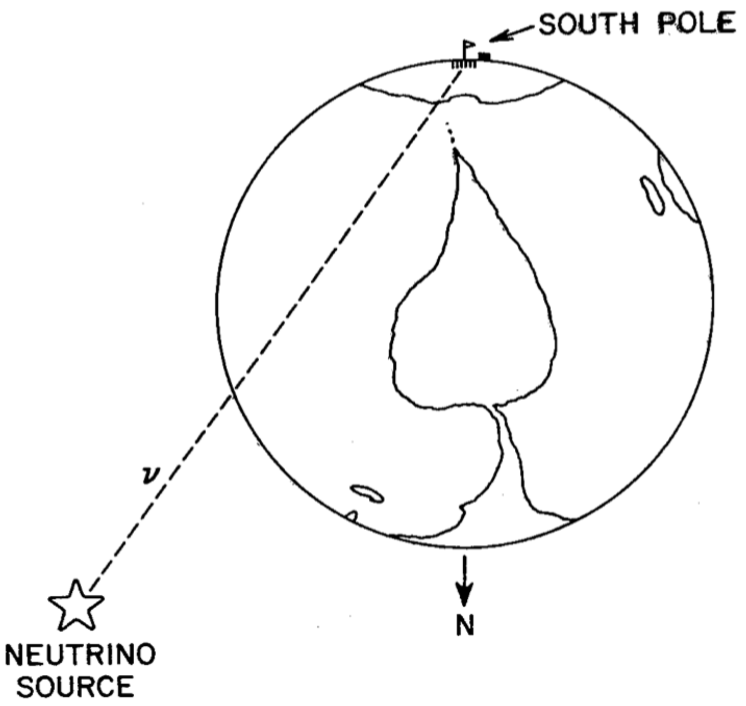
Baikal

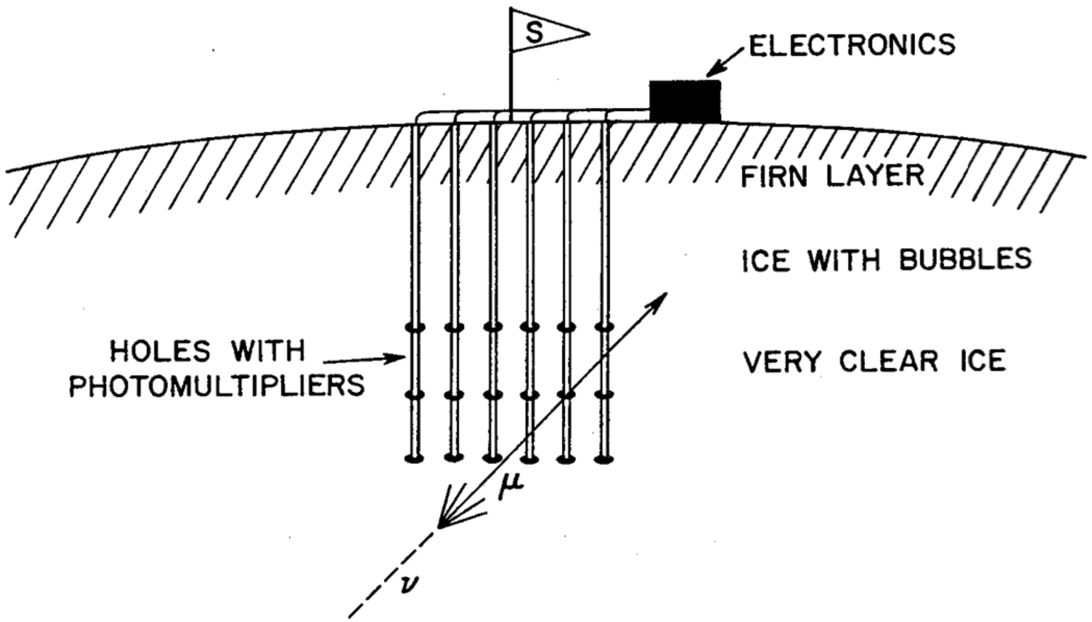
first upward muon in 1996 in 4 strings



The ice option - an early record:

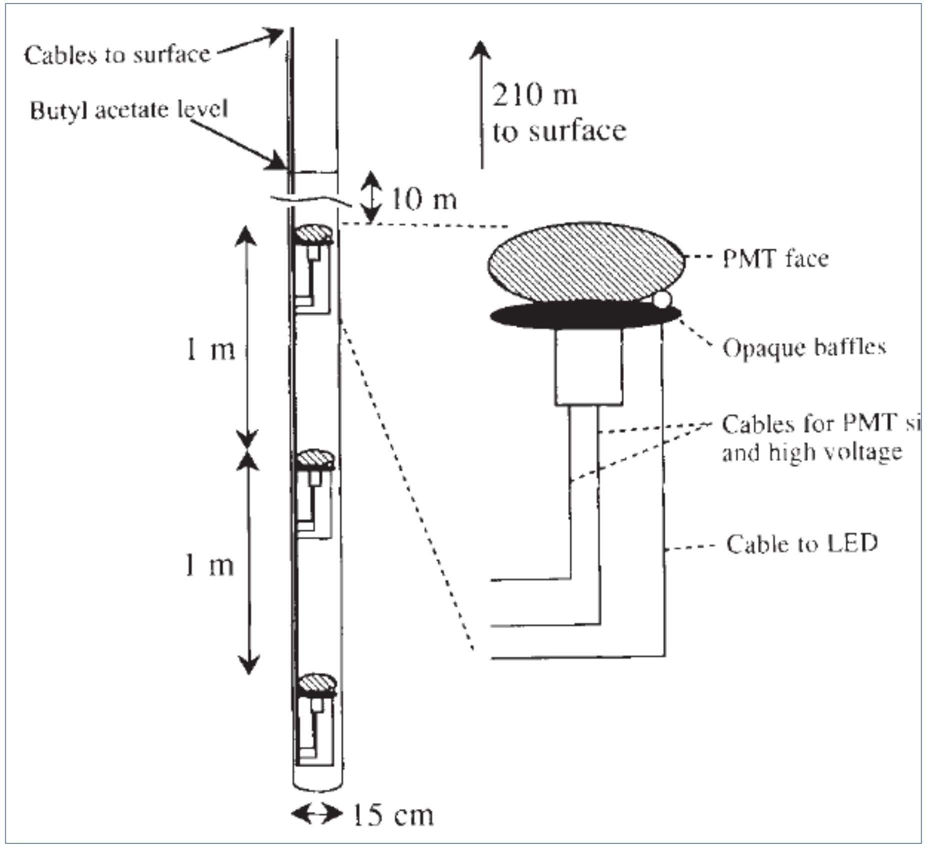
F. Halzen & J. Learned, 1988
High Energy Neutrino Detection in Deep Polar Ice





1990: Detection of cosmic ray muons using PMT in natural ice in Greenland.

Nature 353, 331-333 (26 September 1991)
Observation of muons using the polar ice cap as a Cerenkov detector
D. M. Lowder*, T. Miller*, P. B. Price*, A. Westphal*, S. W. Barwick†, F. Halzen‡ & R. Morse‡



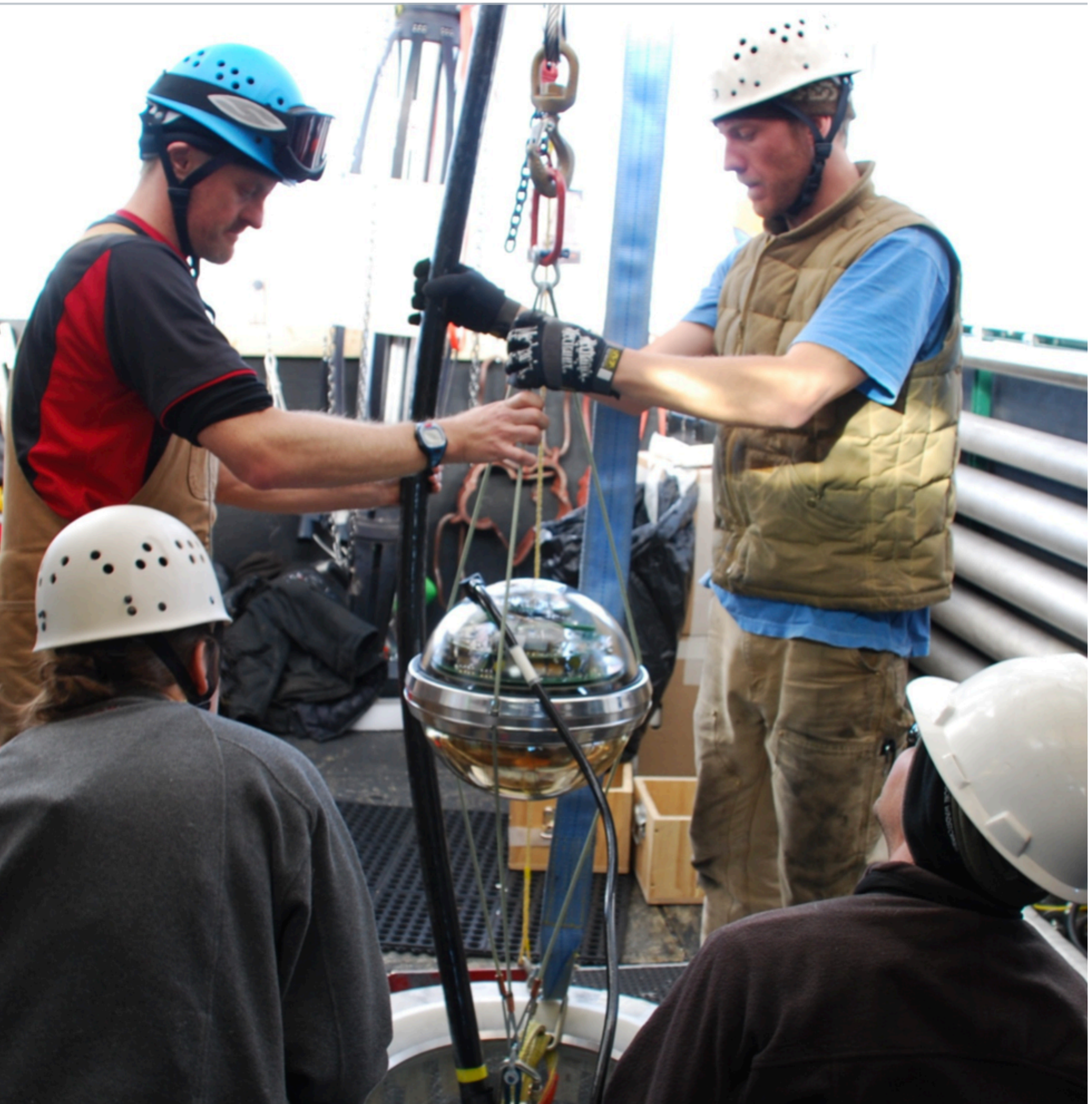
"…..Our results suggest that a full-scale Antarctic ice detector is technically quite feasible."

1991/92: First tests at the South Pole

- Small PMTs deployed
- First test of hot water drilling at South Pole

Heaters and pumps to melt the holes

Fast Forward: IceCube



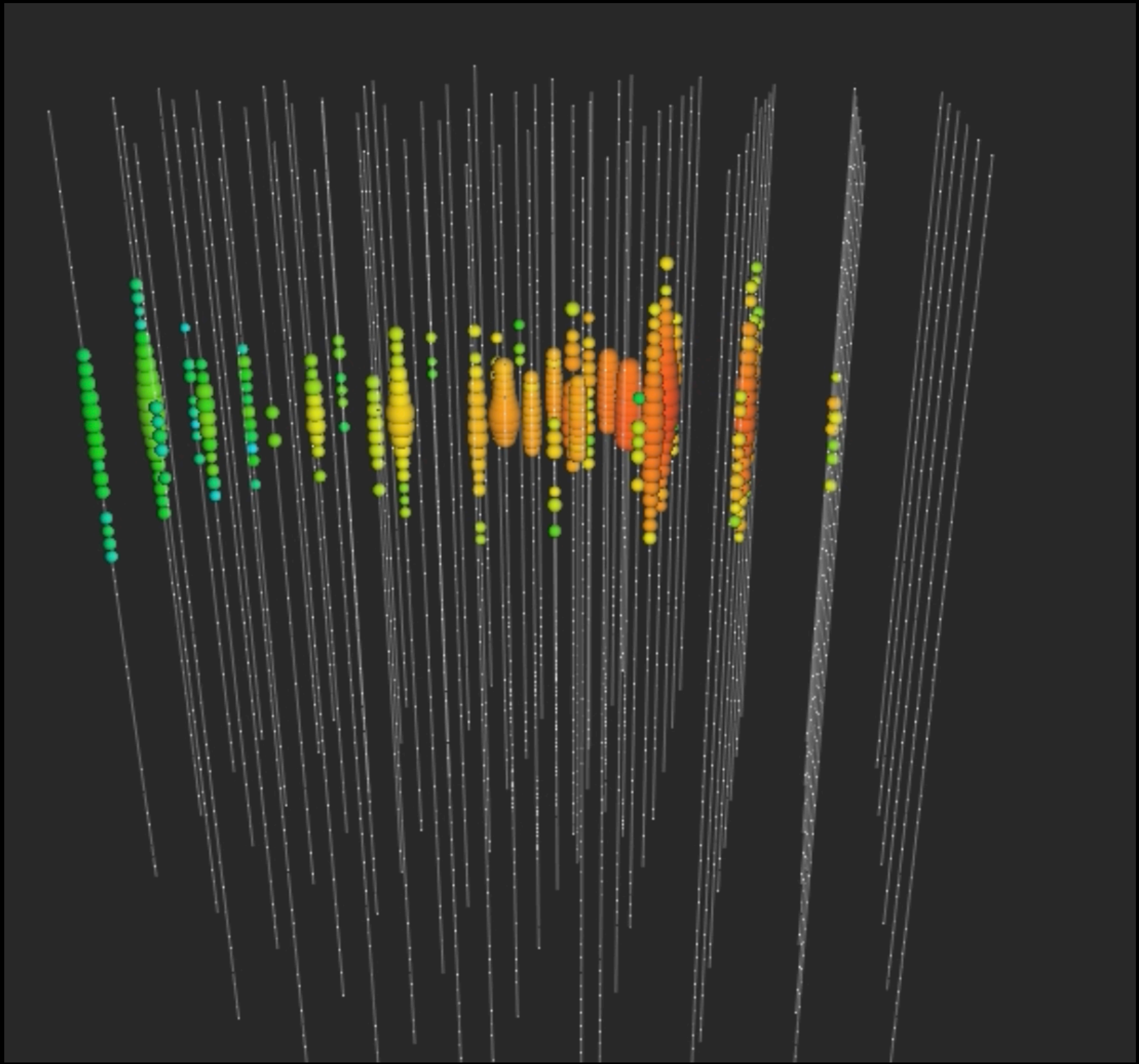
Optical sensors are extremely stable and reliable.

Uptime well above 99%.

Only 6 sensors were lost out of 5000 in the last 10 years.

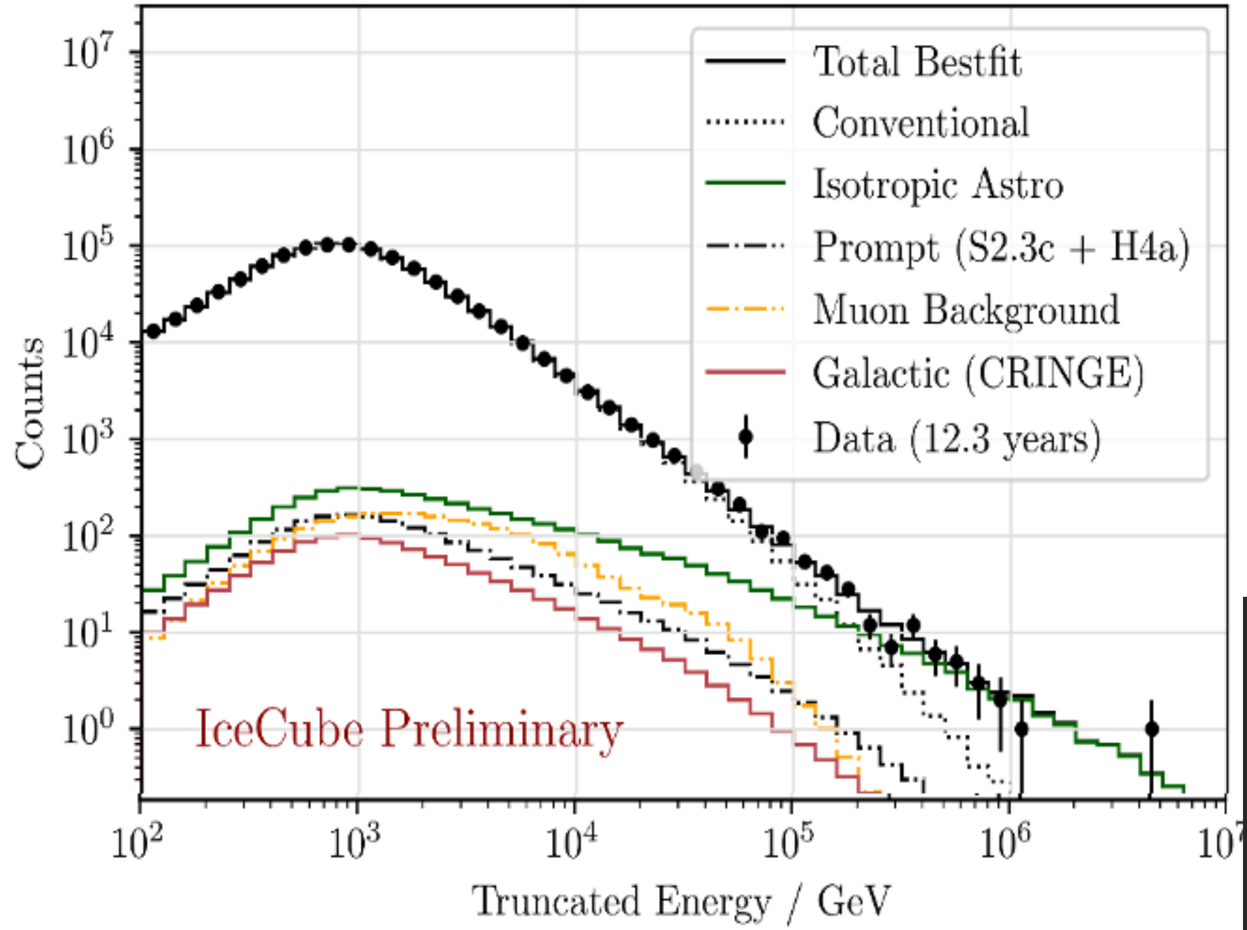
Starting muon track
Deposited energy: 71 TeV
7.1 x 10^13 eV

Starting muon track
Deposited energy: 71 TeV
7.1 x 10^13 eV

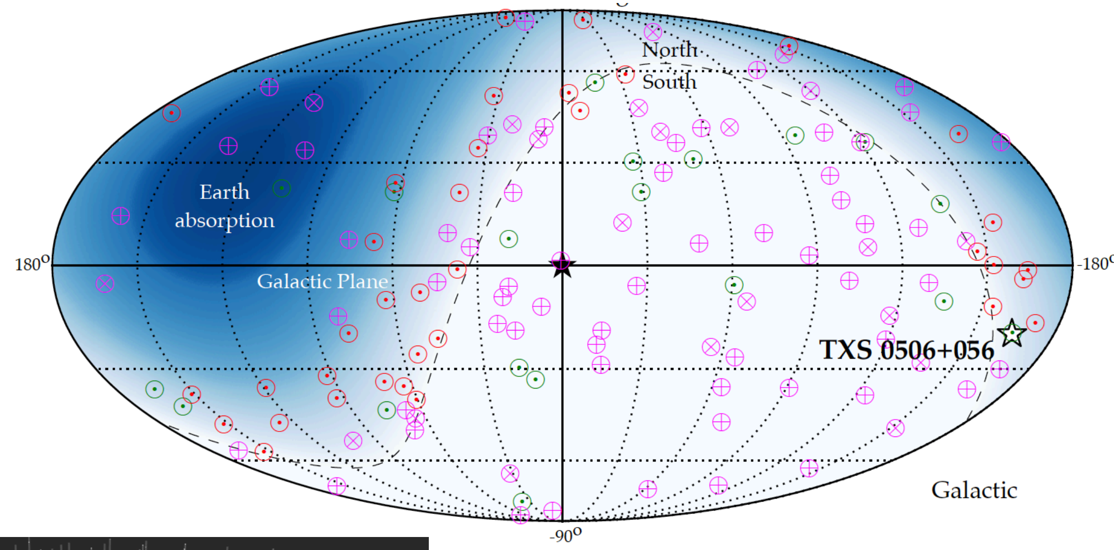


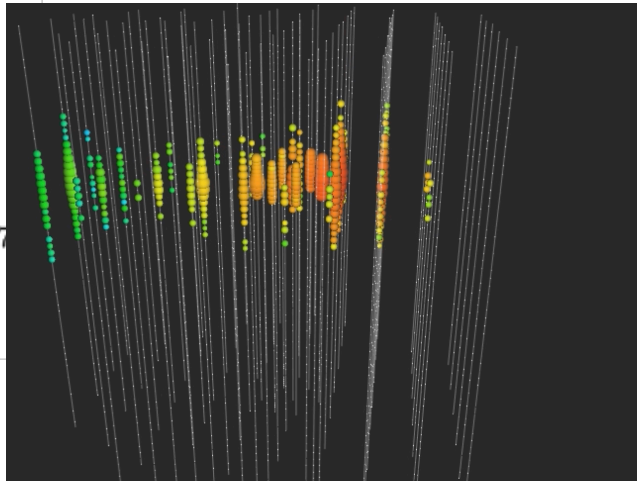
Today’s starting point based on IceCube results

IceCube: Upgoing muons



IceCube: HESE events
(selection of events with contained vertex)



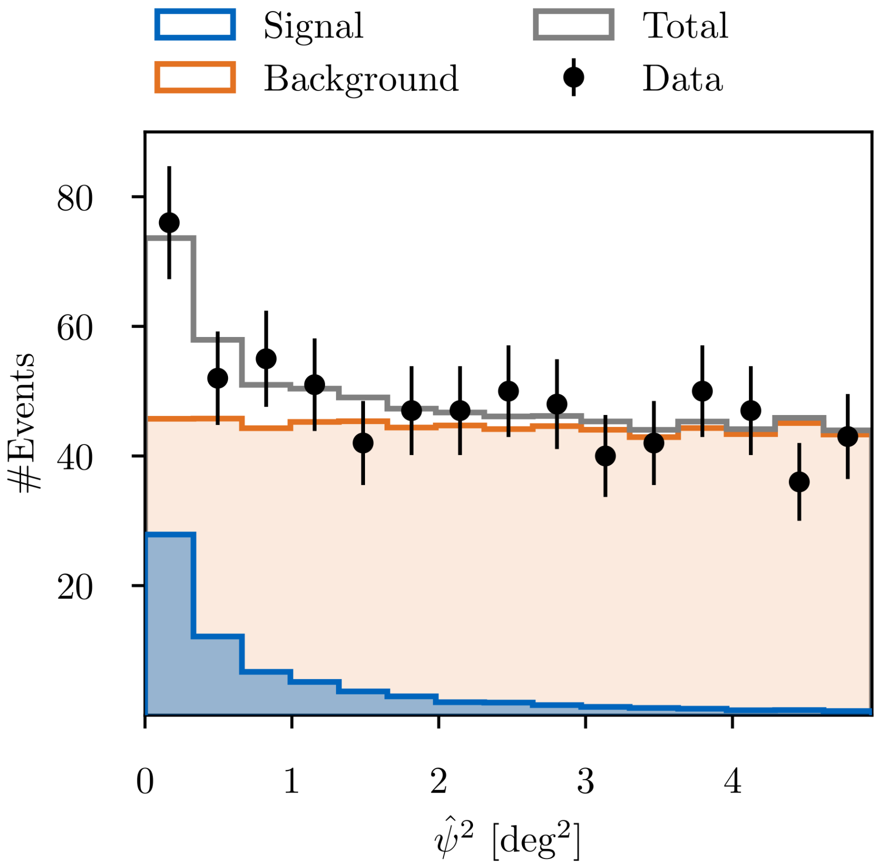


https://arxiv.org/abs/2307.13878

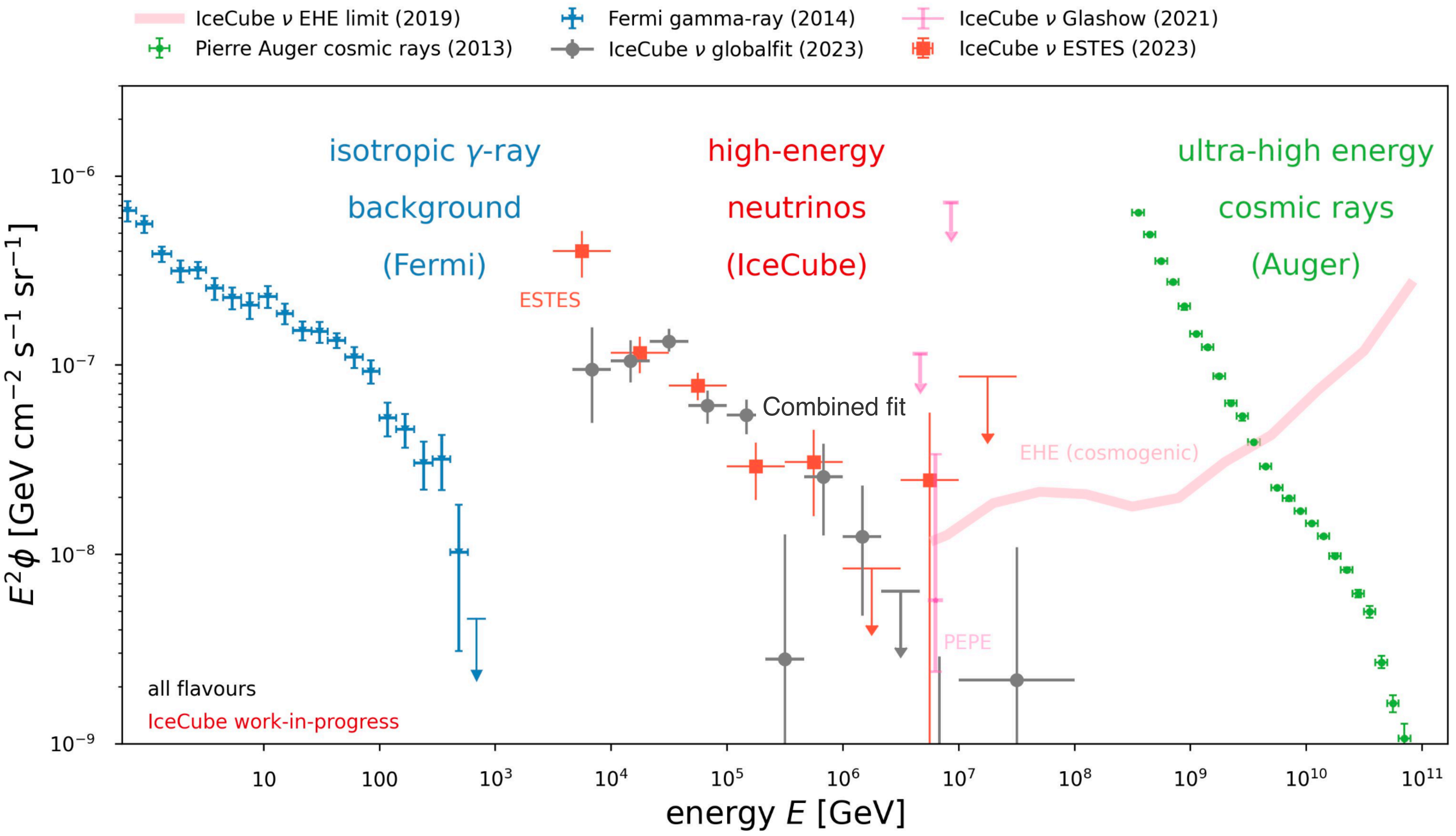
Neutrinos from the nearby galaxy NGC 1068

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

Significance 4.2 sigma



Multimessenger Astrophysics - a wide energy range, especially for neutrinos



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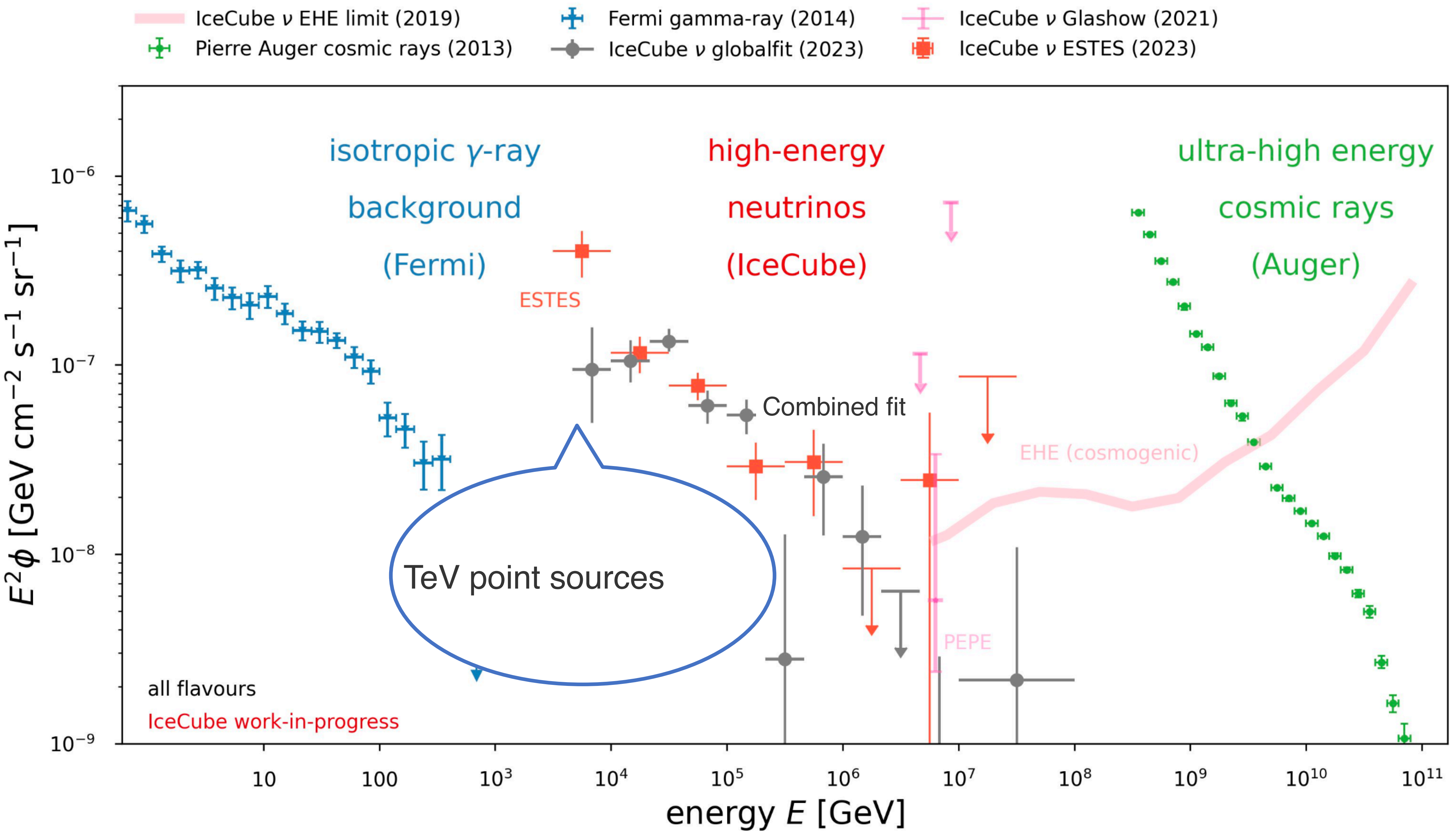

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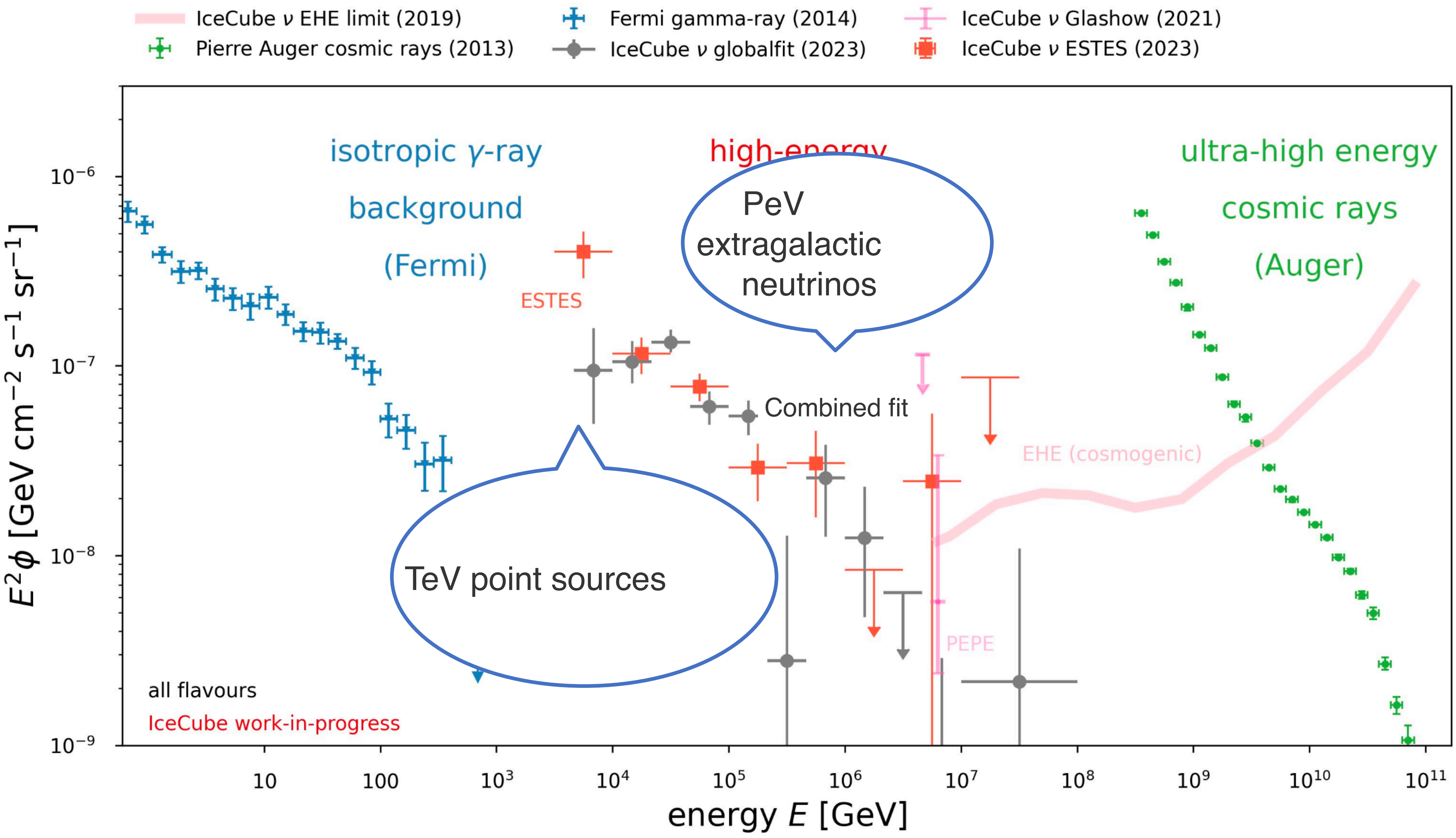

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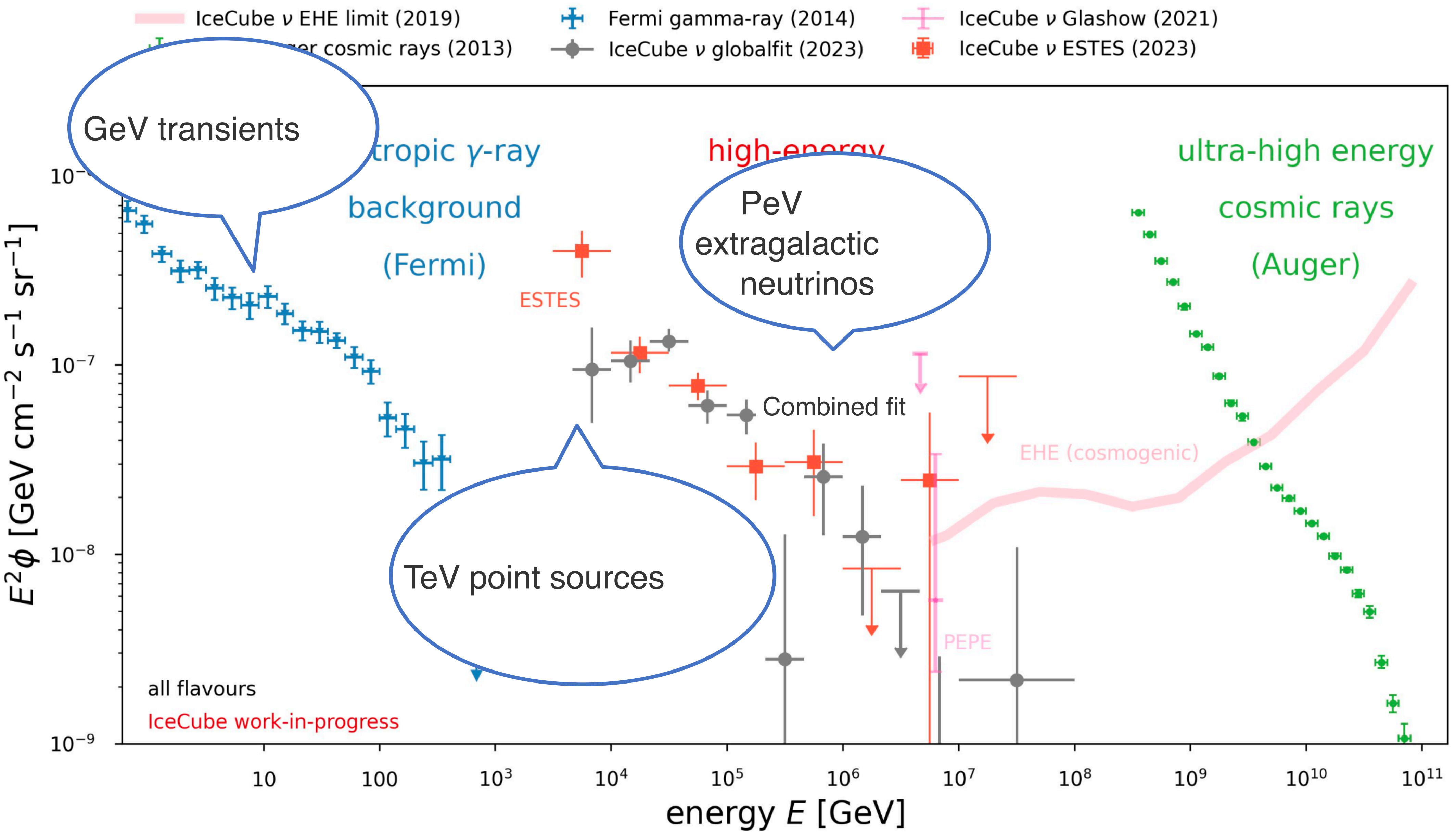
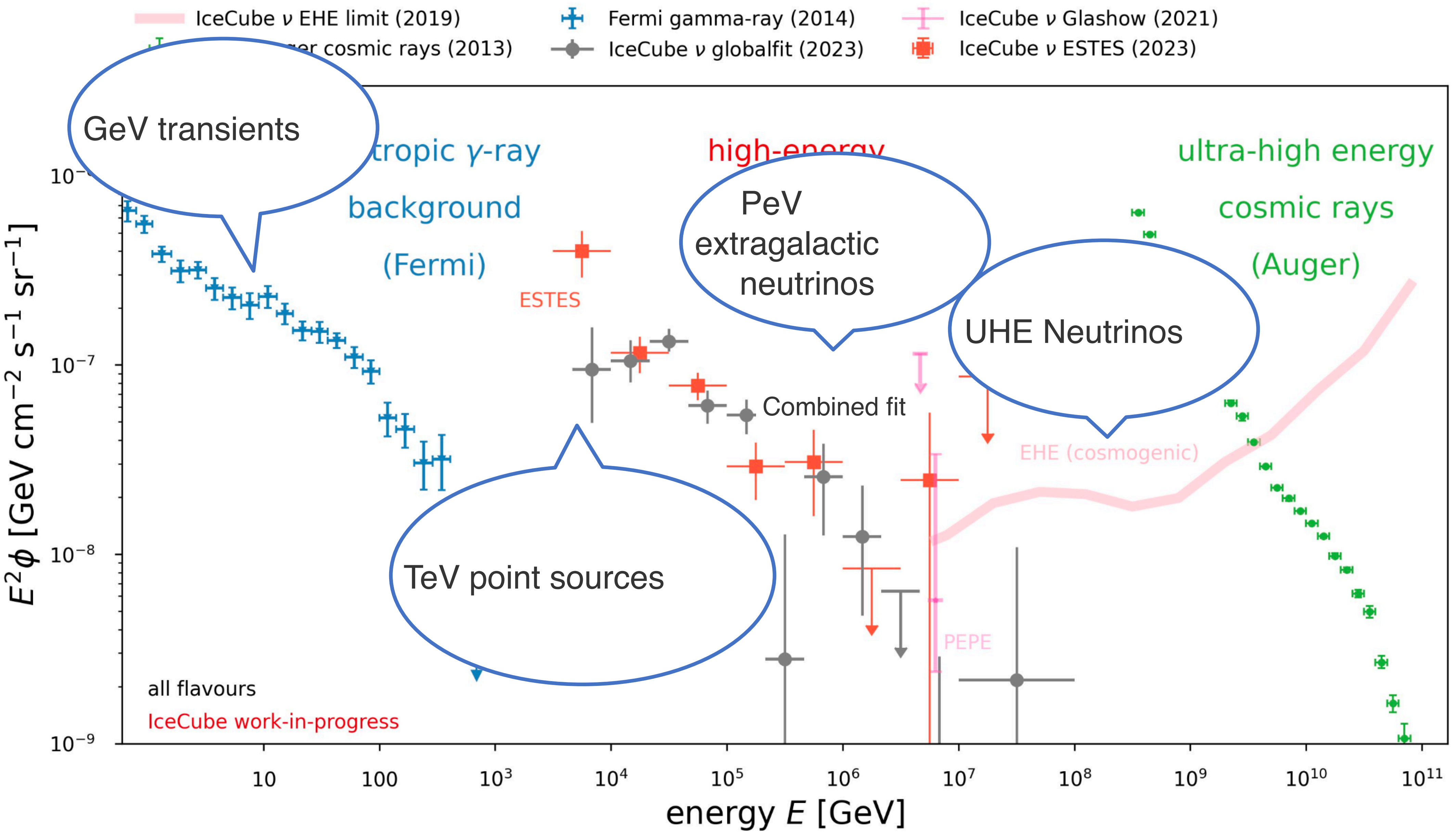
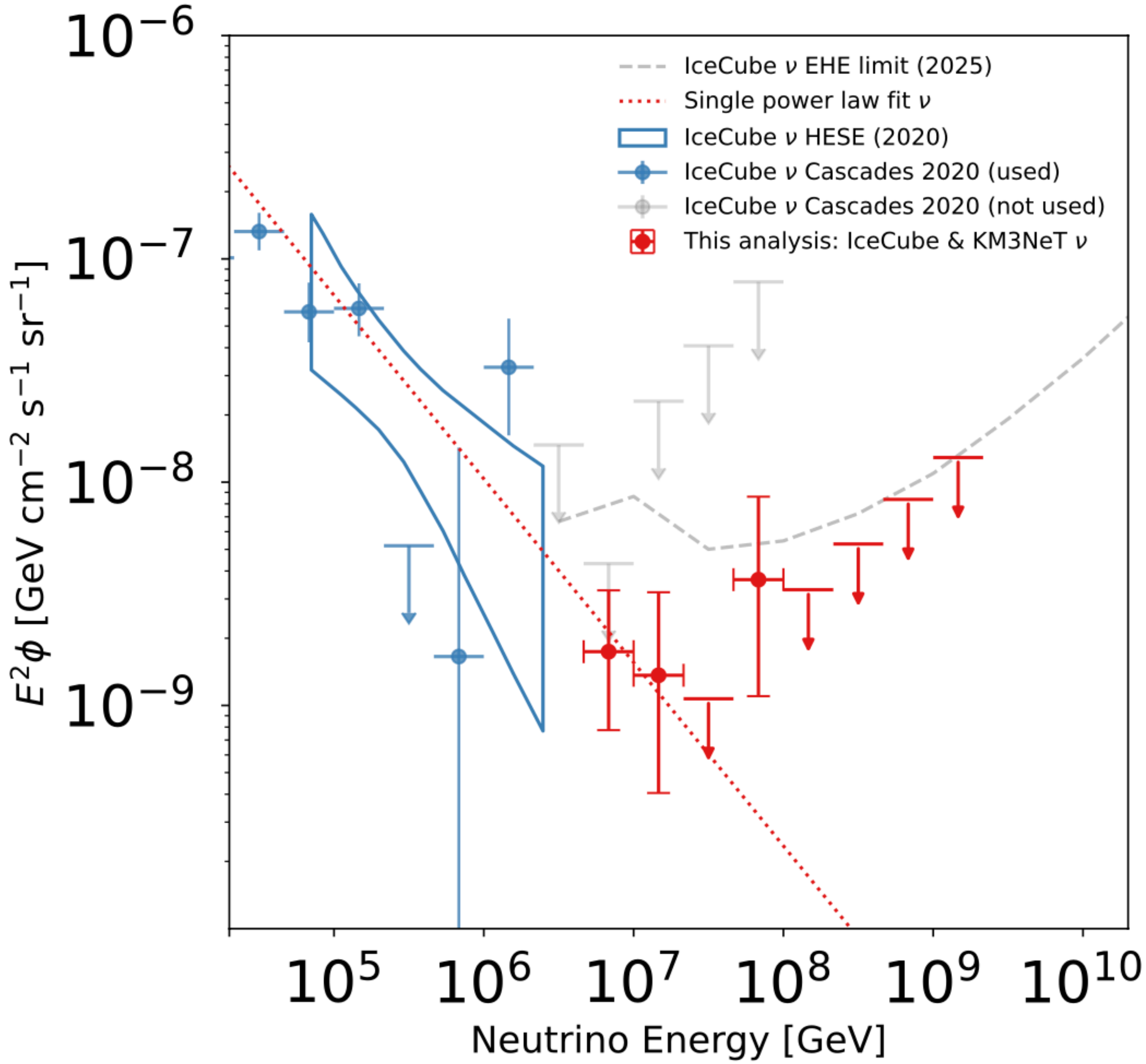


Multimessenger Astrophysics - a wide energy range, especially for neutrinos



Ref: Lu, Muzio, Yuan
arXiv:2502.06944

Combined IceCube KM3NeT Flux



Example for possible explanations:

1: AGN P-Gamma bump (blue)

2: Cosmogenic neutrino flux from cosmic rays on CMB (only) photons (red)

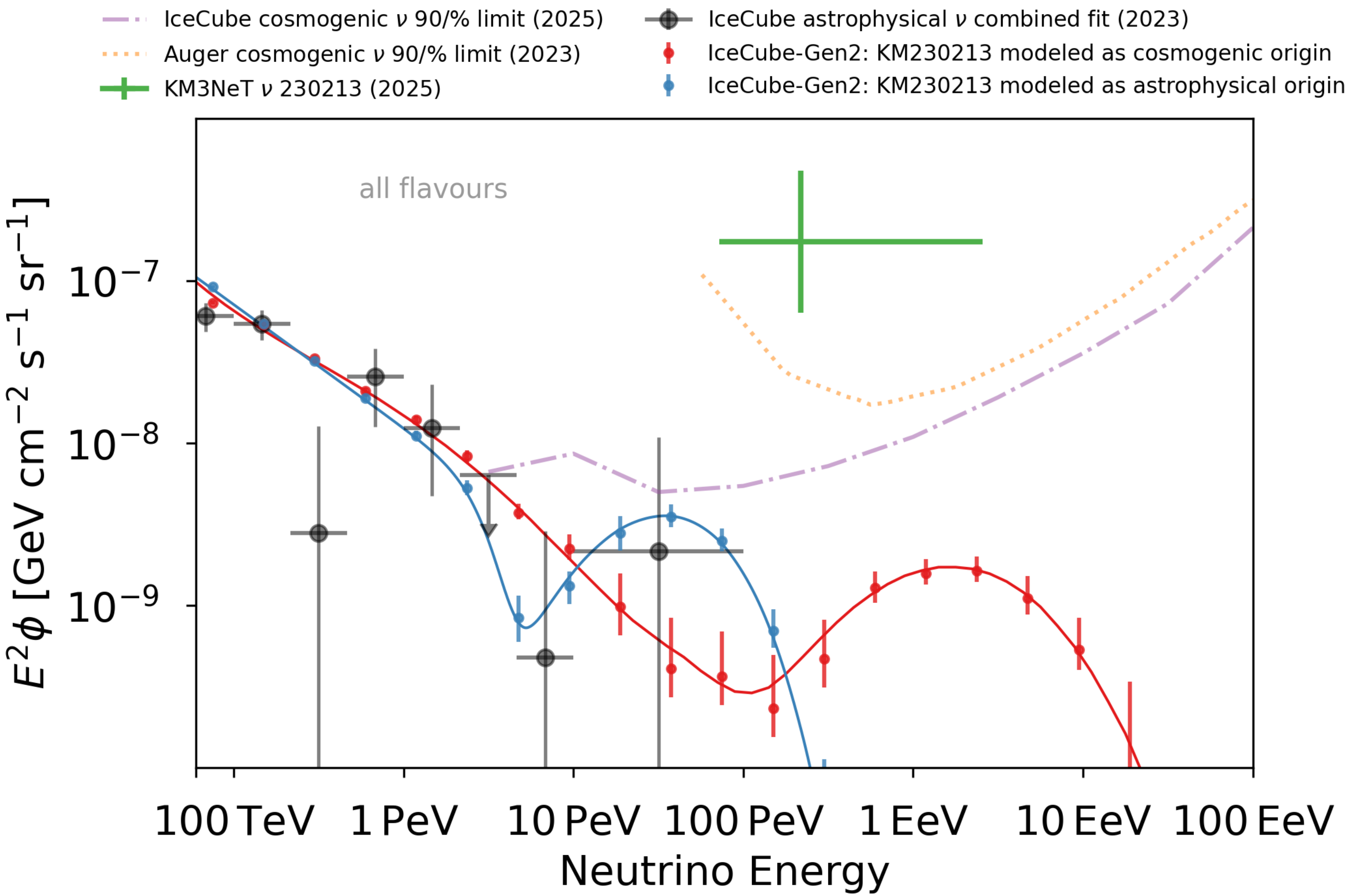
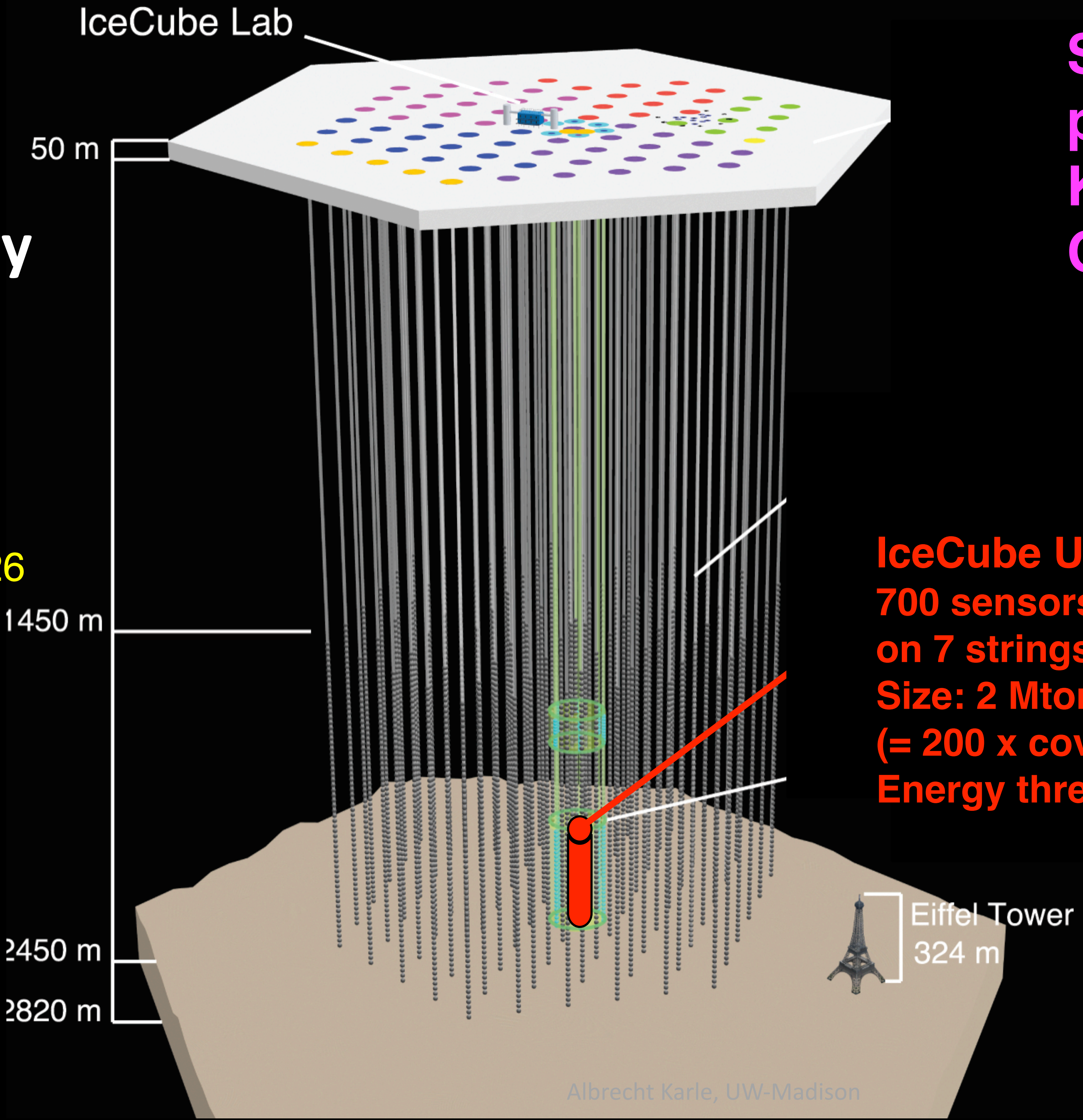


Figure courtesy of Lu Lu

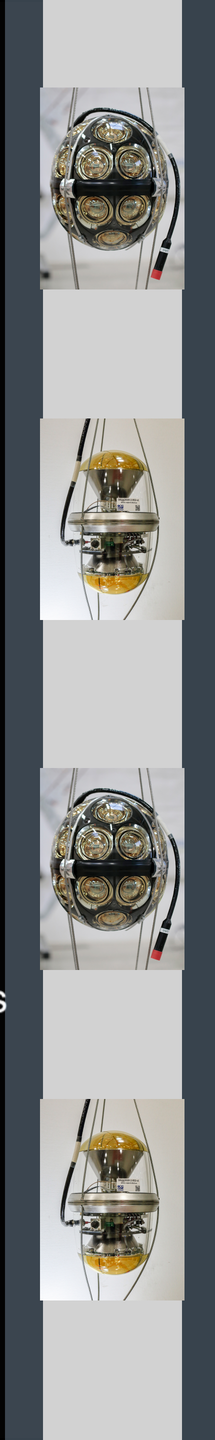
The IceCube Neutrino Observatory + IceCube Upgrade

Deploy in 2025/26



Similar performance: KM3NeT ORCA

IceCube Upgrade
700 sensors (3 x sensitivity IC DOM) on 7 strings.
Size: 2 Mtons
(= 200 x coverage/Mton)
Energy threshold: 3 GeV



IceCube Upgrade field work

South Pole

January 16, 2025

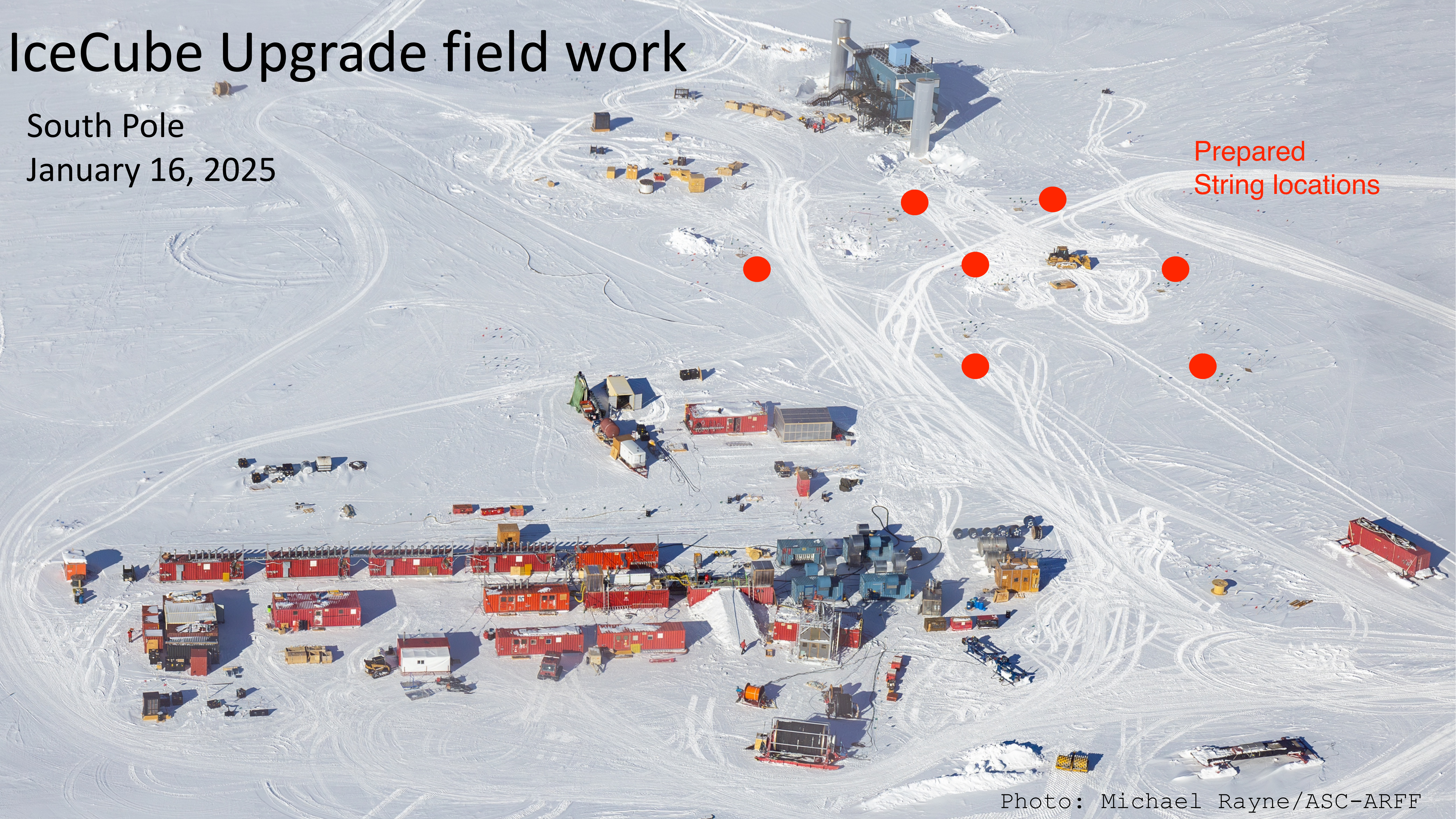
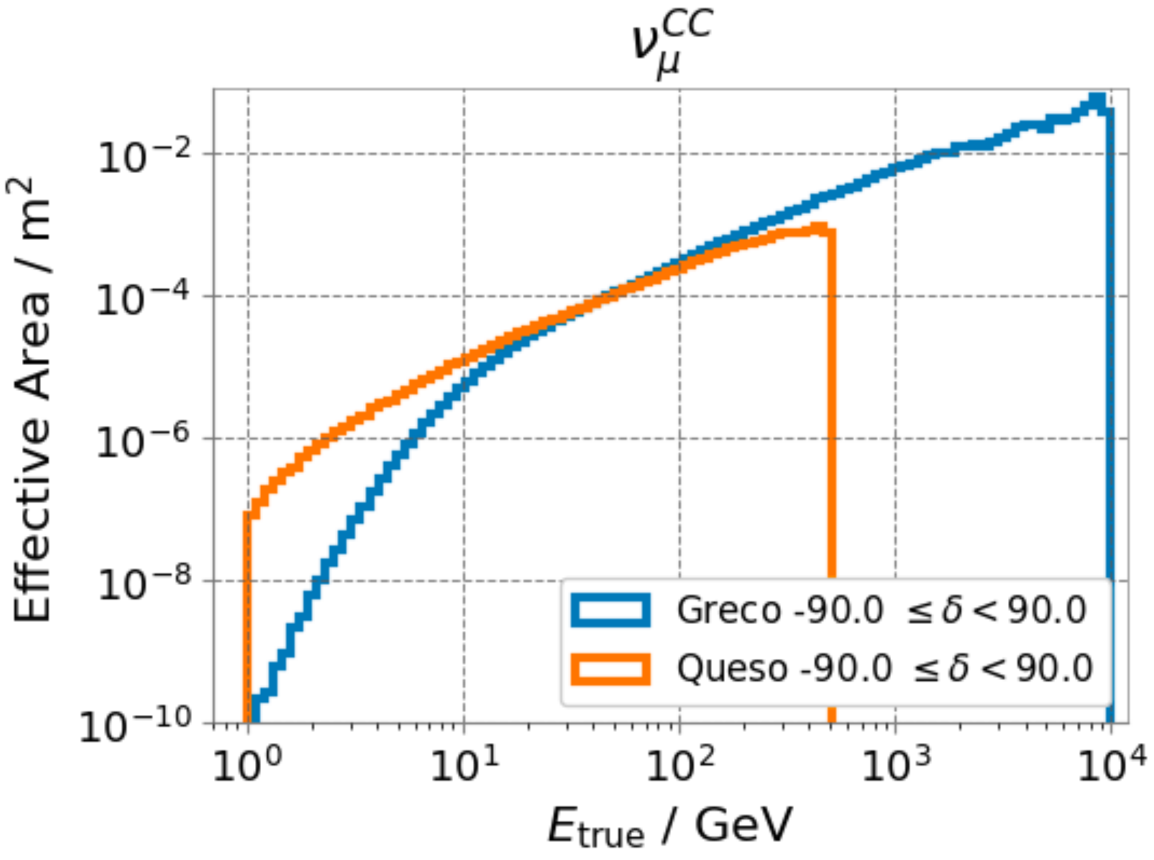
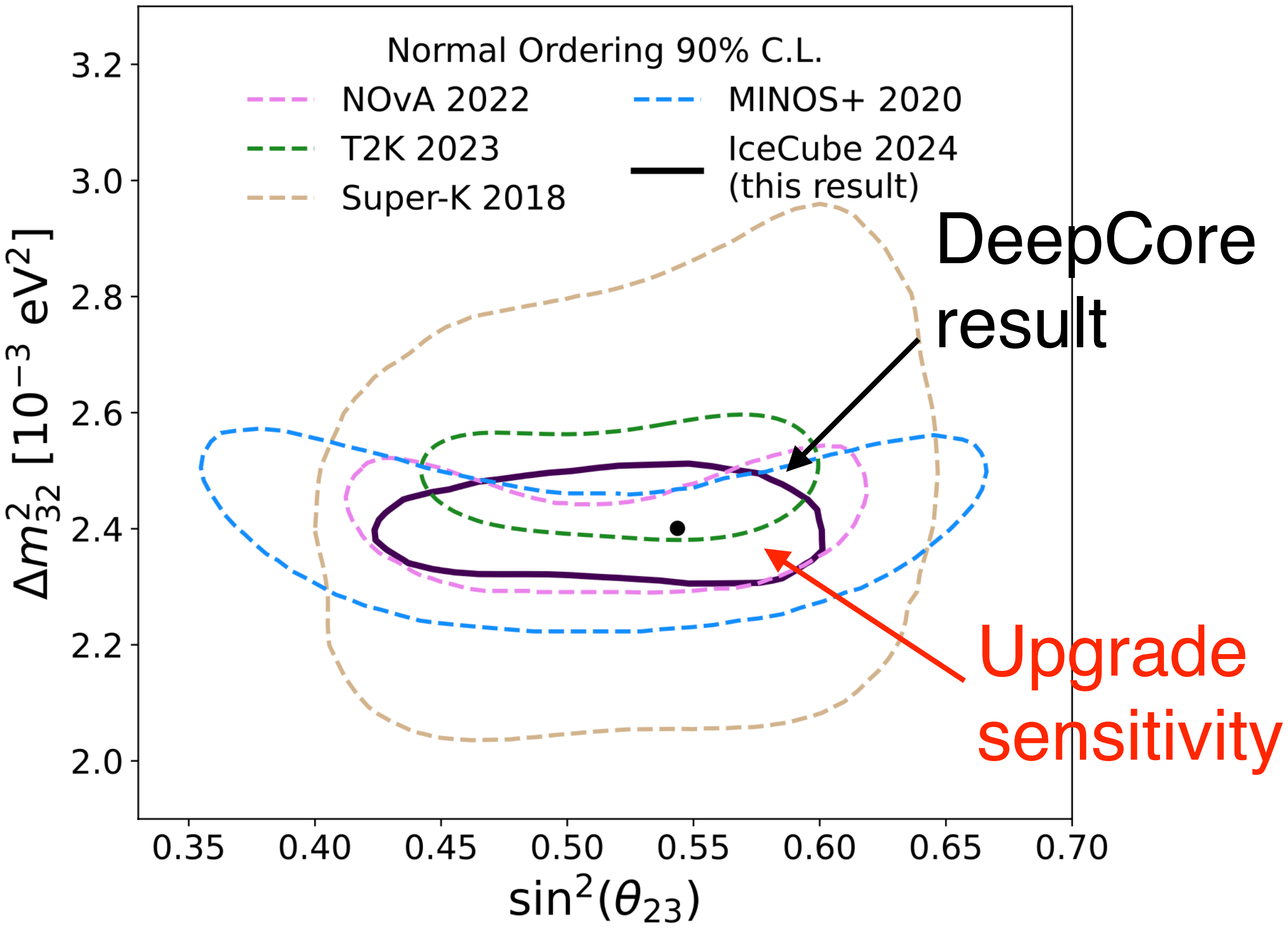


Photo: Michael Rayne/ASC-ARFF

The IceCube-Upgrade





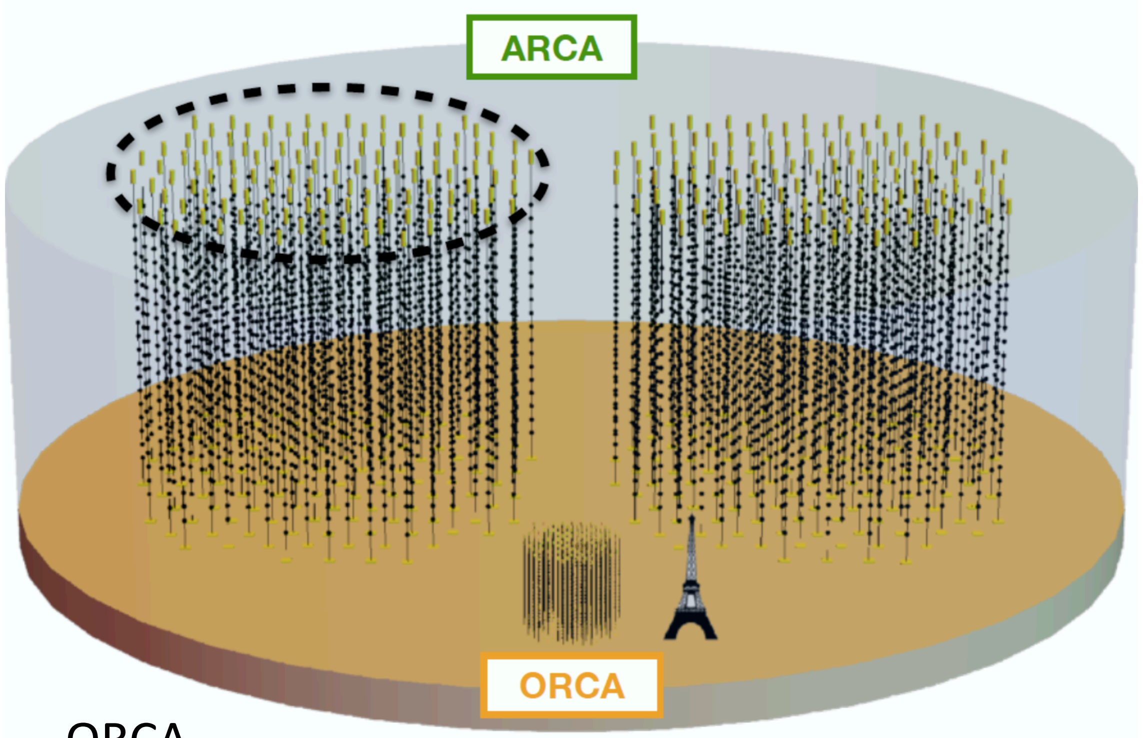
KM3NeT

ARCA

100 km from Sicily

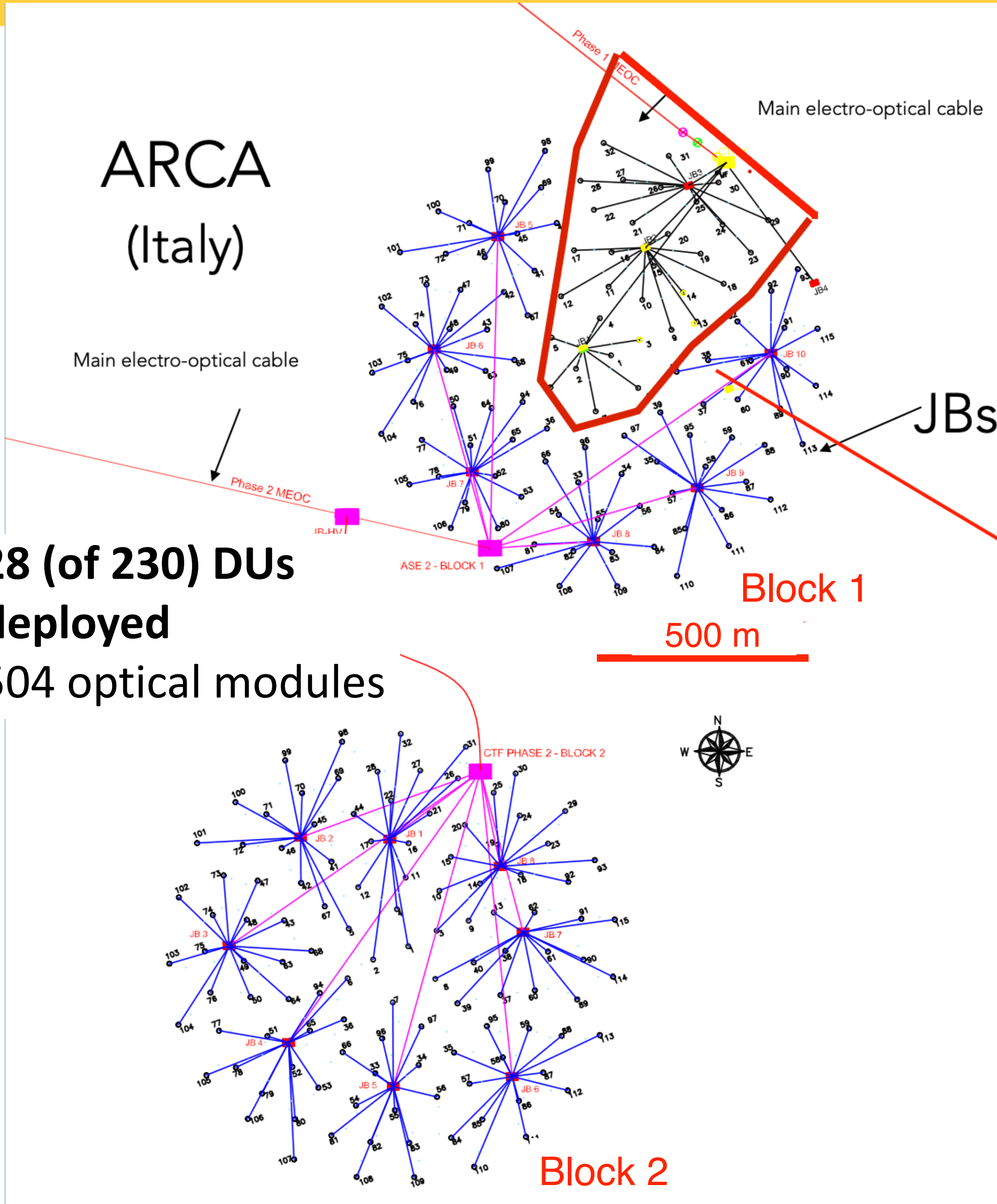
Instr. Mass: 2 × 0.5 Gt

1 Block:
115 strings (detection units)
each with **18 optical sensors**

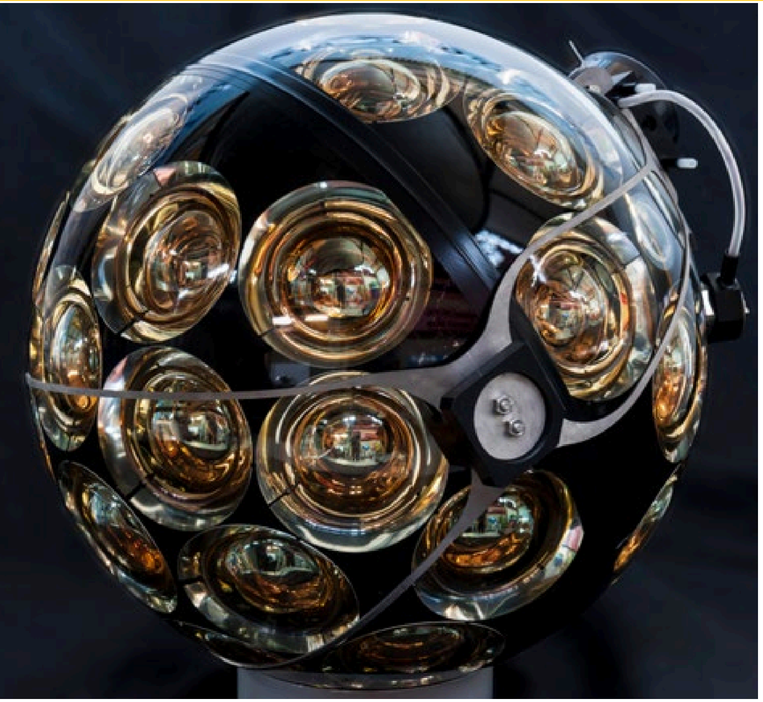


ORCA
40 km from Toulon, France
Instr. mass: 5-8 Mtons
status: 11 of 115 DUs deployed

28 (of 230) DUs deployed
504 optical modules

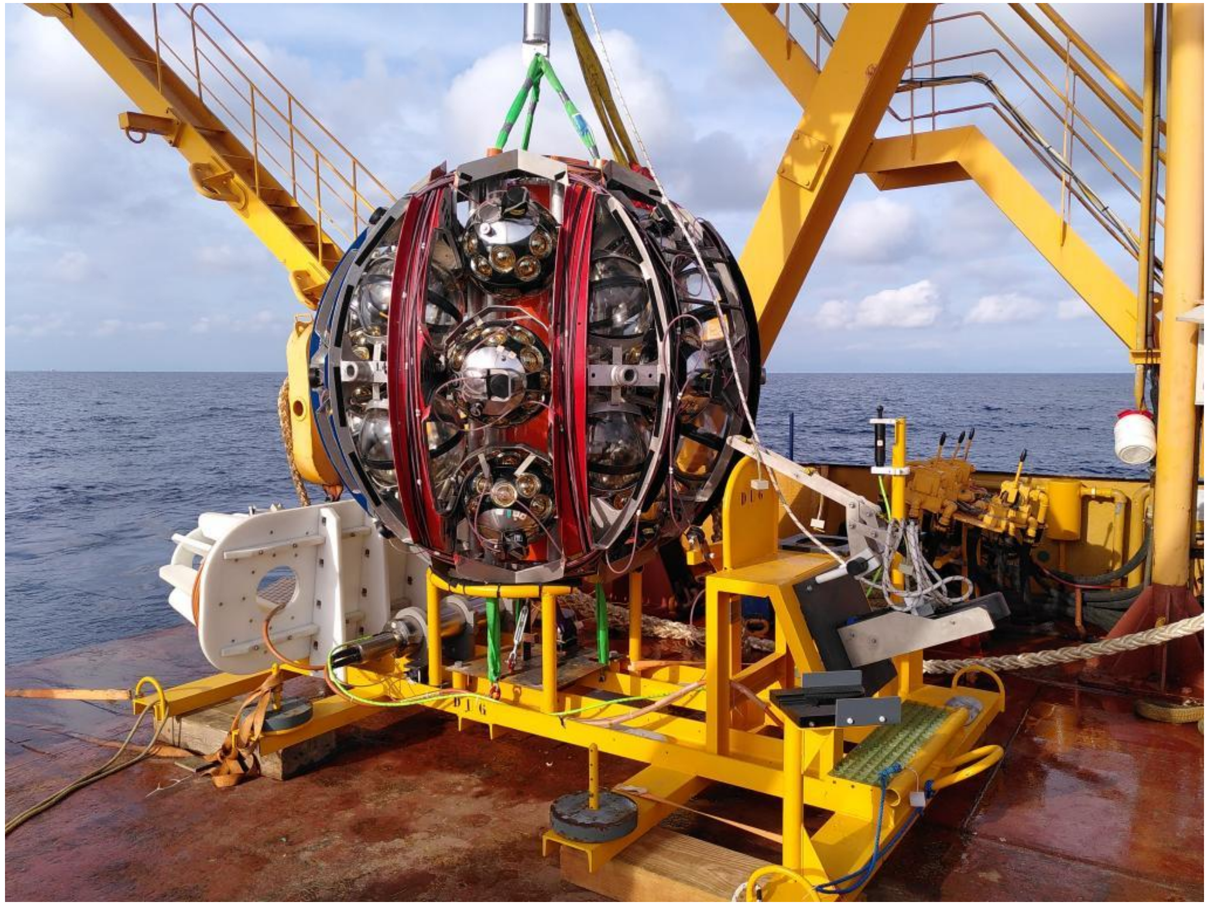


KM3NeT - Optical Sensor and construction



- 31 x 3-inch PMTs in 17-inch glass sphere (cathode area ~3x10-inch PMTs)
- Pioneered the concept of multi-PMT modules, with directional information: directionality, cost.

- Unique deployment scheme from a vessel:
  A sphere of spheres.



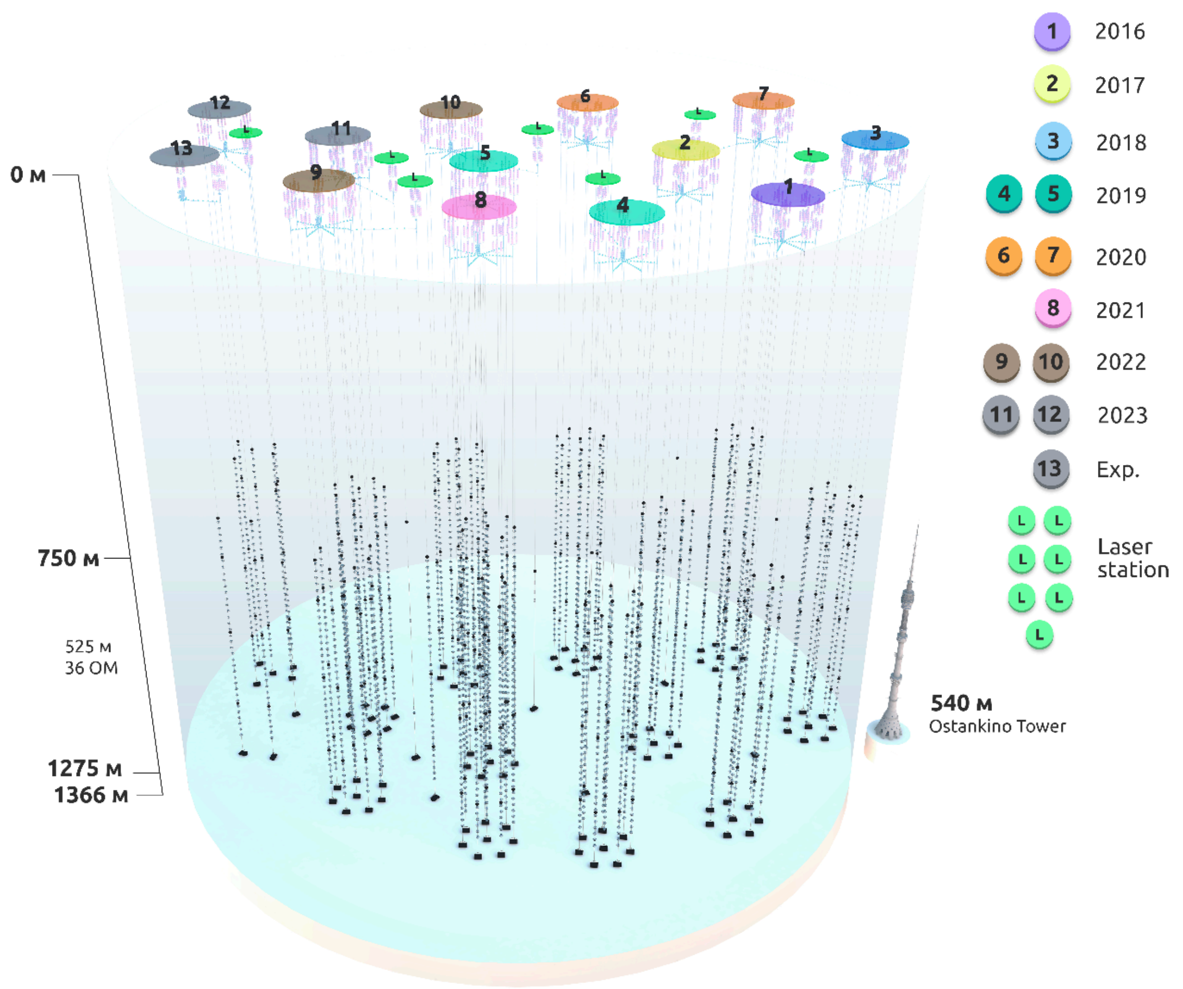
Baikal GVD (1/2 km3 scale detector in construction)

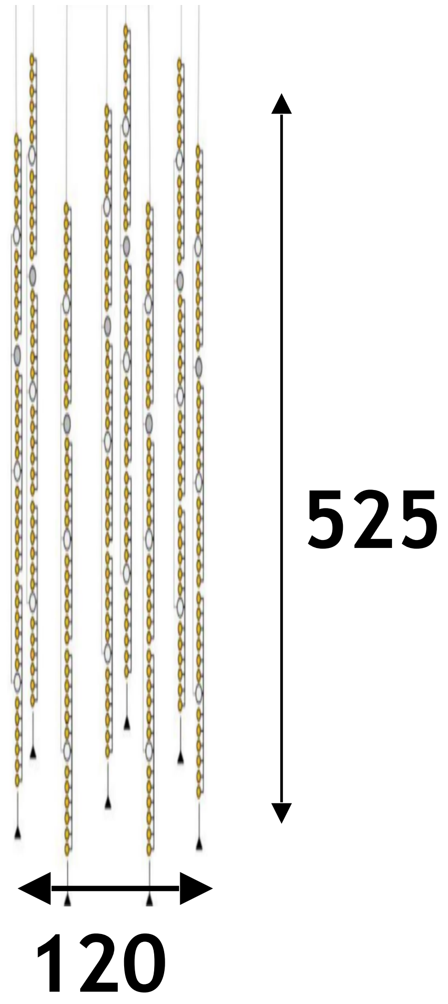
- Lake Baikal, Siberia
- Deployment in March/April from ice cover
- Clusters with 8 strings, each with 36 10“ PMTs

Baikal GVD - in construction

18 Clusters of 8 strings with 36 sensors each

Instrumented volume: ~1/2 km3





Baikal GVD - in construction

March 2025. (GNN News letter)

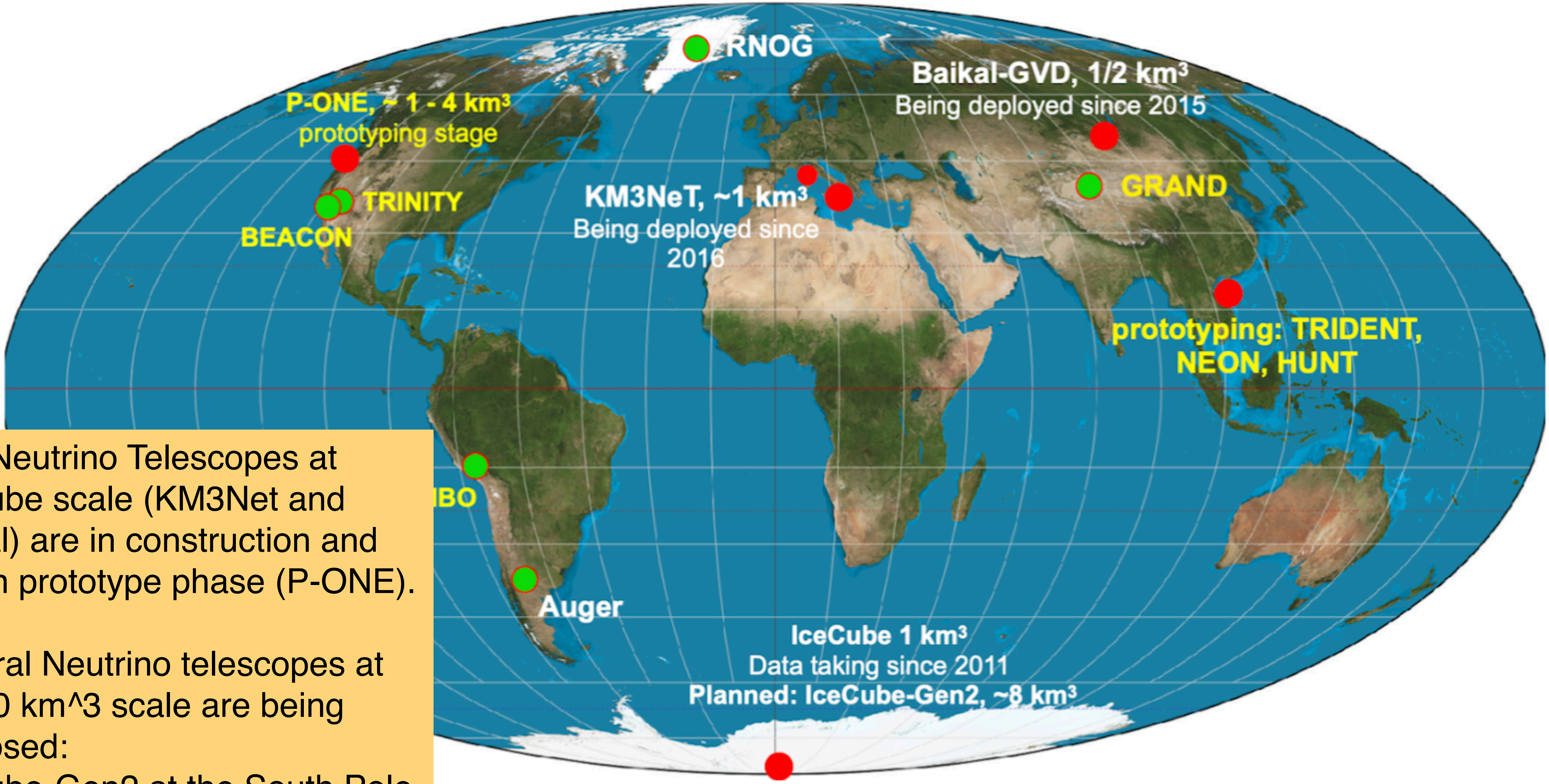
Deploying the "Chinese string"

Neutrino astronomy

- from discovery: Cosmic neutrino flux from TeV to PeV energies, first sources, Milky Way

- to astronomy and astrophysics

—> The next generation neutrino telescopes

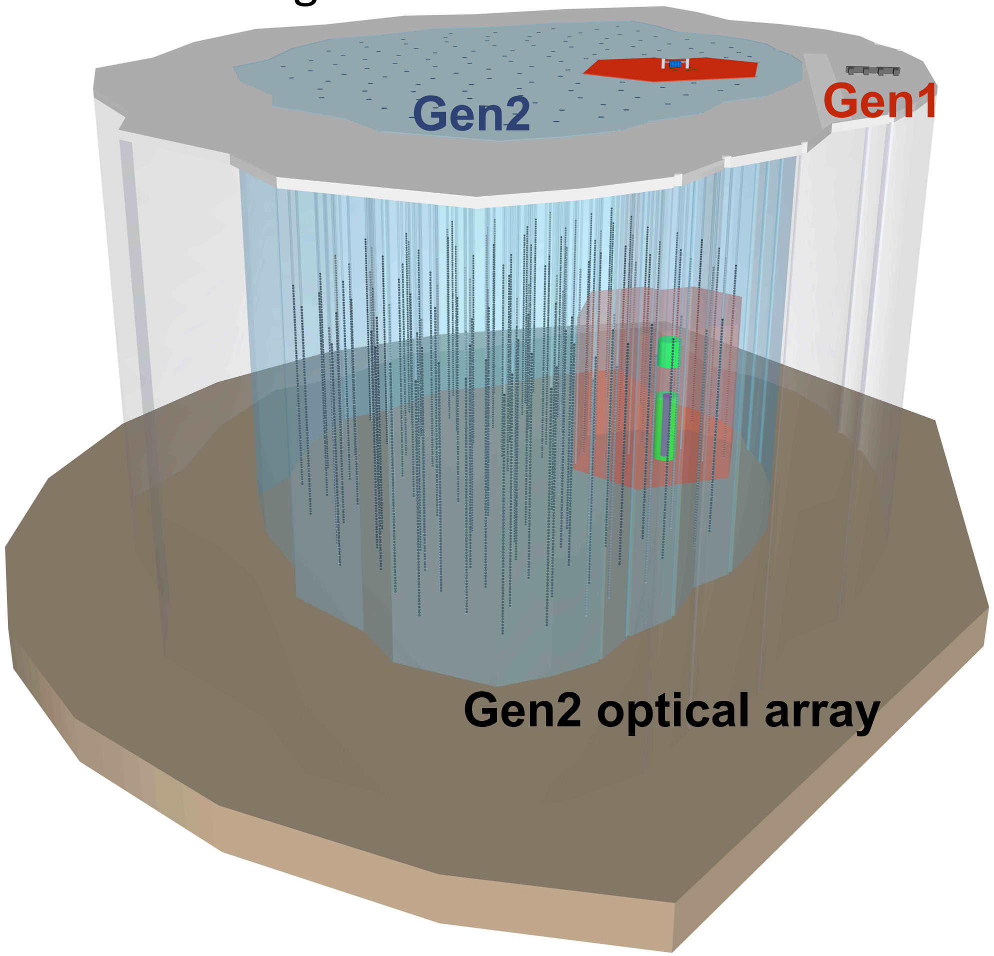


Two Neutrino Telescopes at IceCube scale (KM3Net and Baikal) are in construction and one in prototype phase (P-ONE).

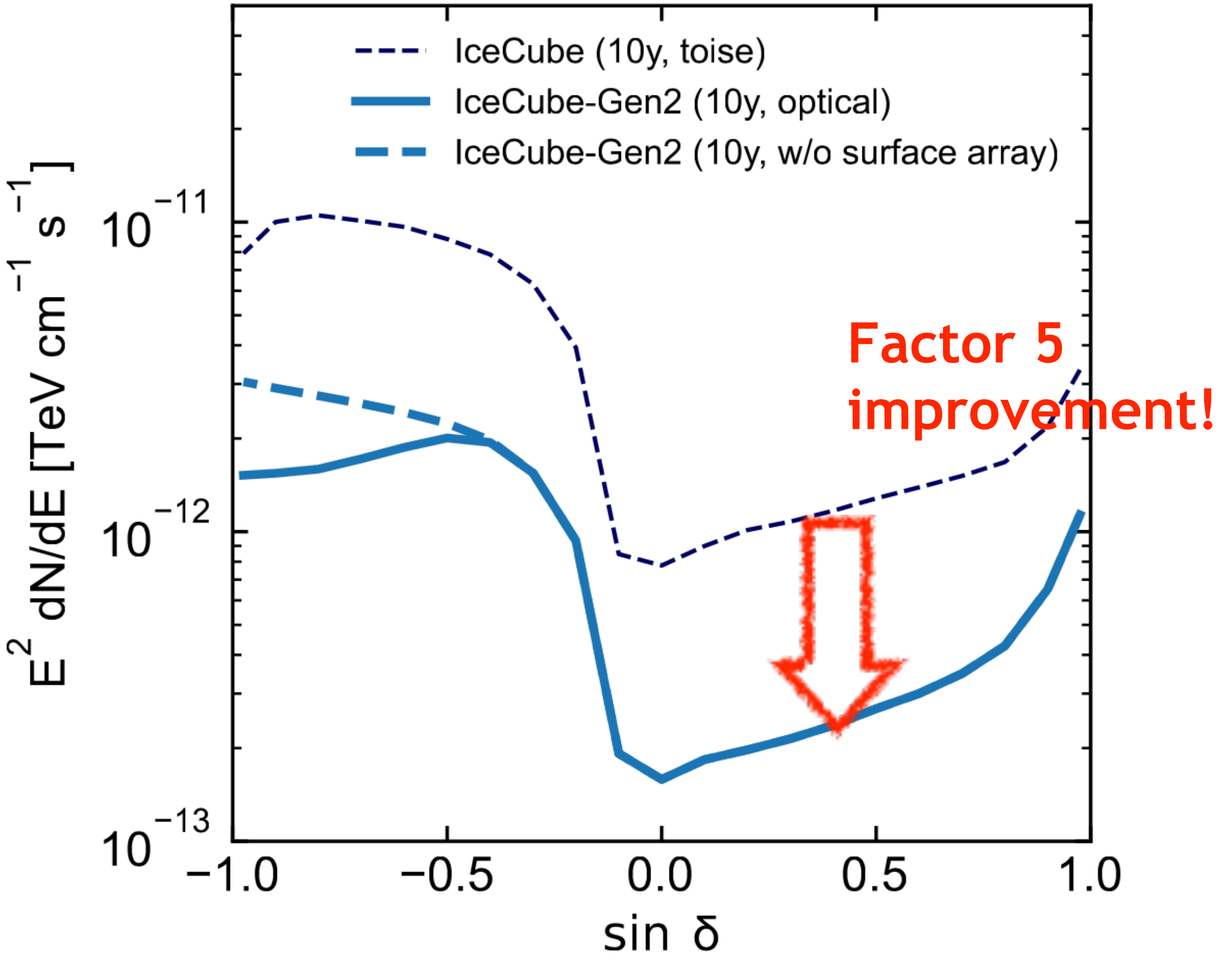
Several Neutrino telescopes at the 10 km^3 scale are being proposed:
IceCube-Gen2 at the South Pole and 2 in China.

IceCube-Gen2 Optical Cherenkov Array

Instrumented Volume: 8 km³
9600 optical sensors
120 strings



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

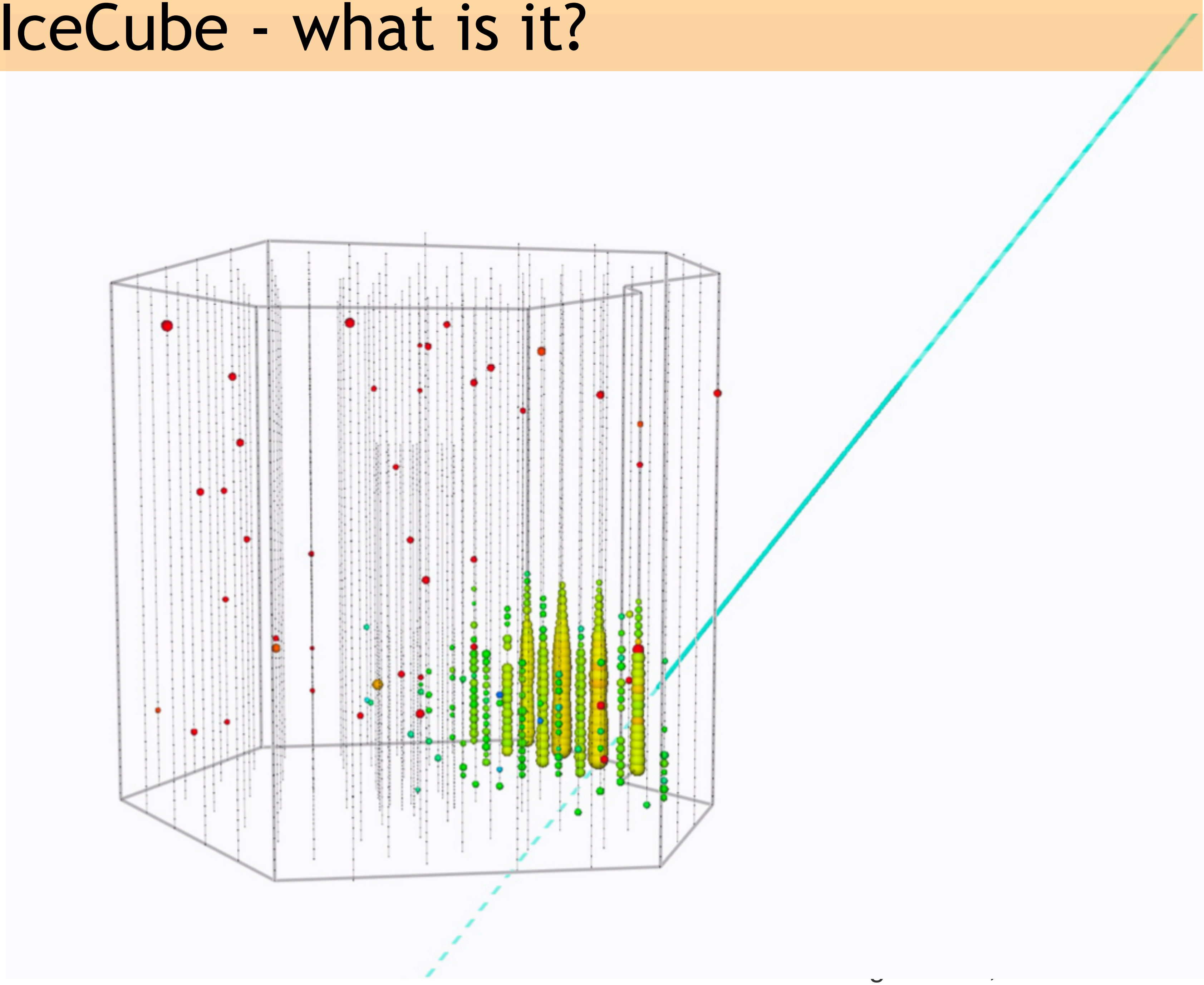


The Gen2 Digital Optical Module

- 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.

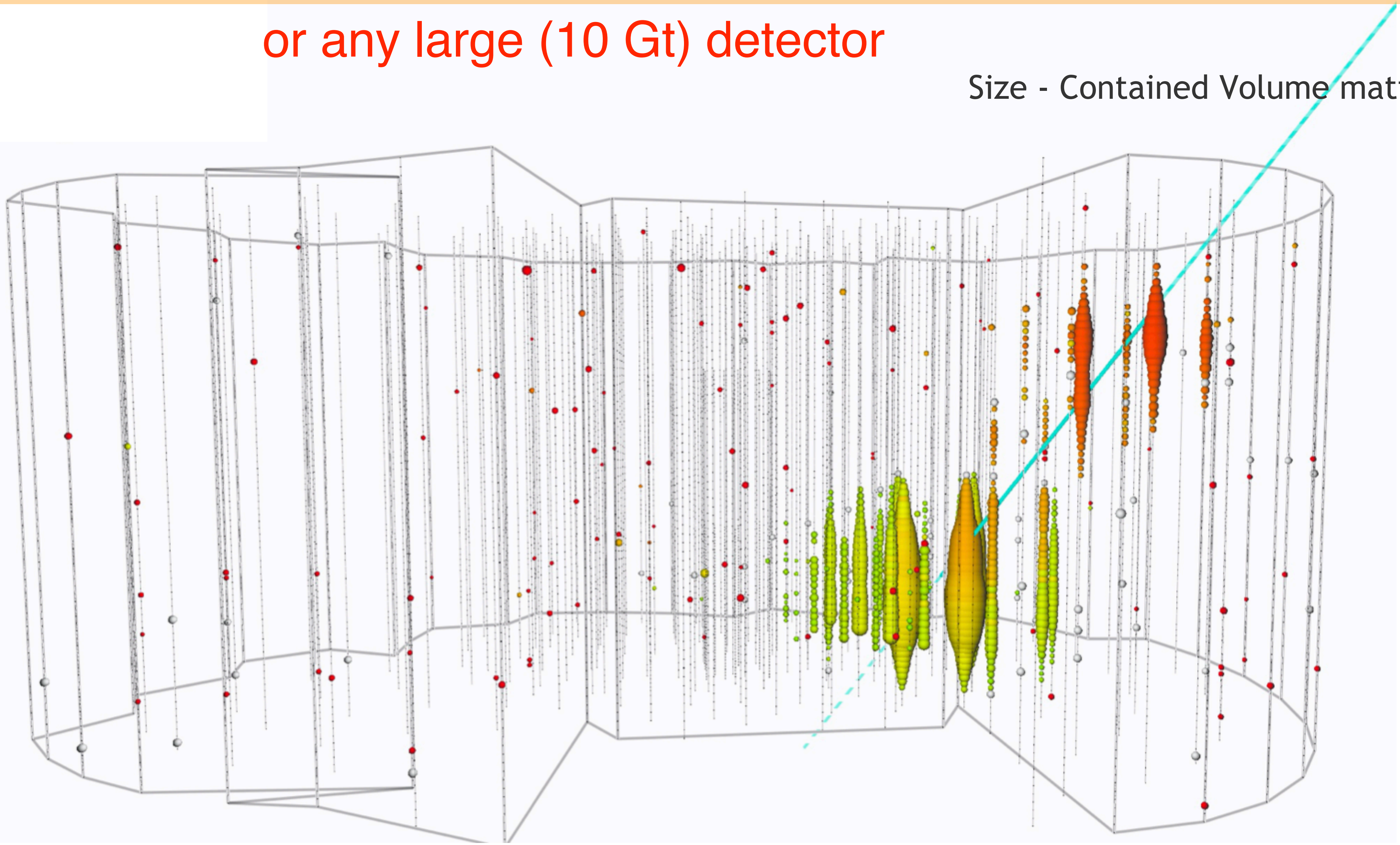
A simulated event in IceCube - what is it?



The same event in IceCube-Gen2

or any large (10 Gt) detector

Size - Contained Volume matters.



Currently: have ~2 events at the 100 TeV energy scale

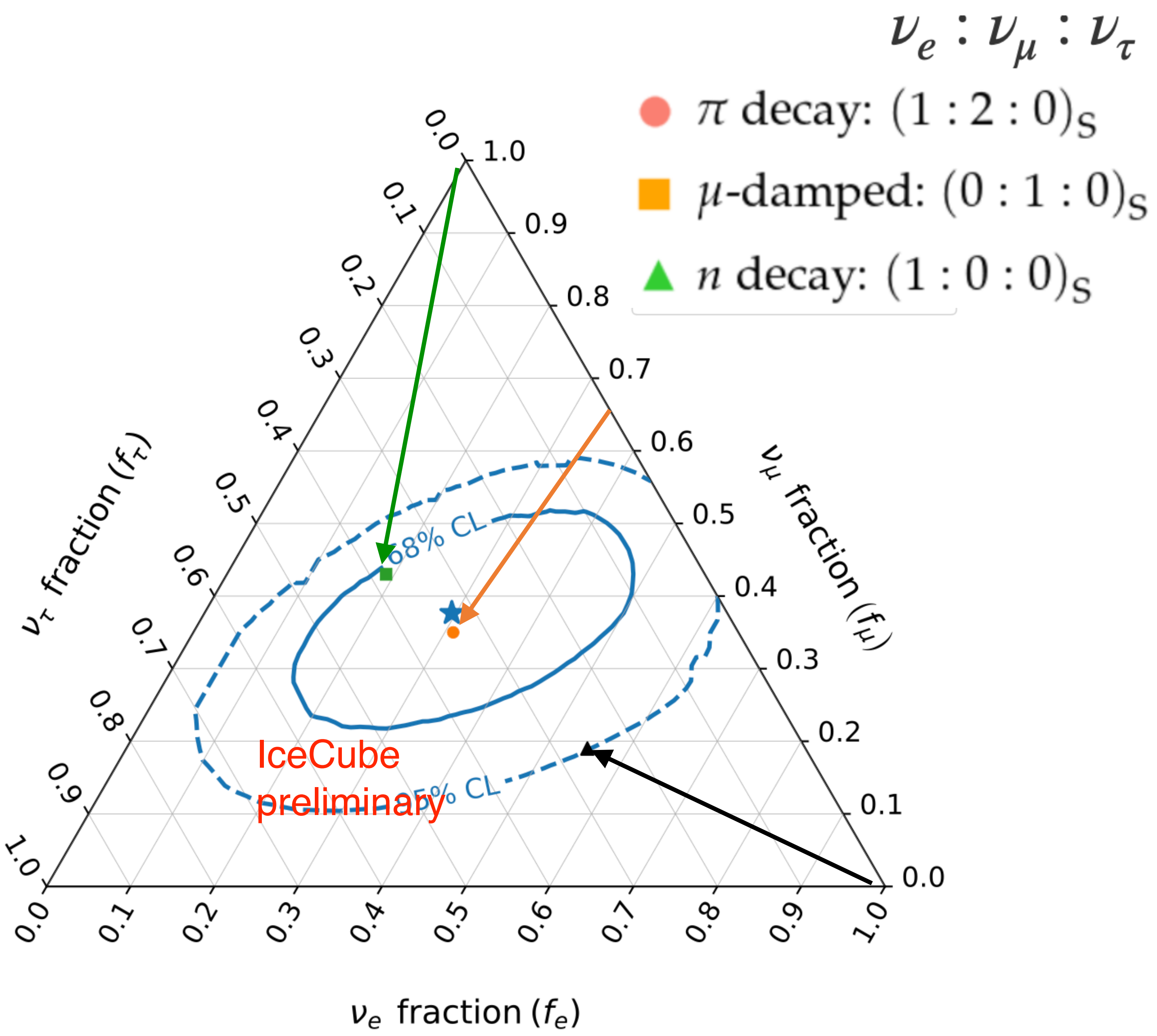
credit.: Lu Lu, IceCube

Flavor Composition

The flavor composition at Earth traces back to the composition at the source.

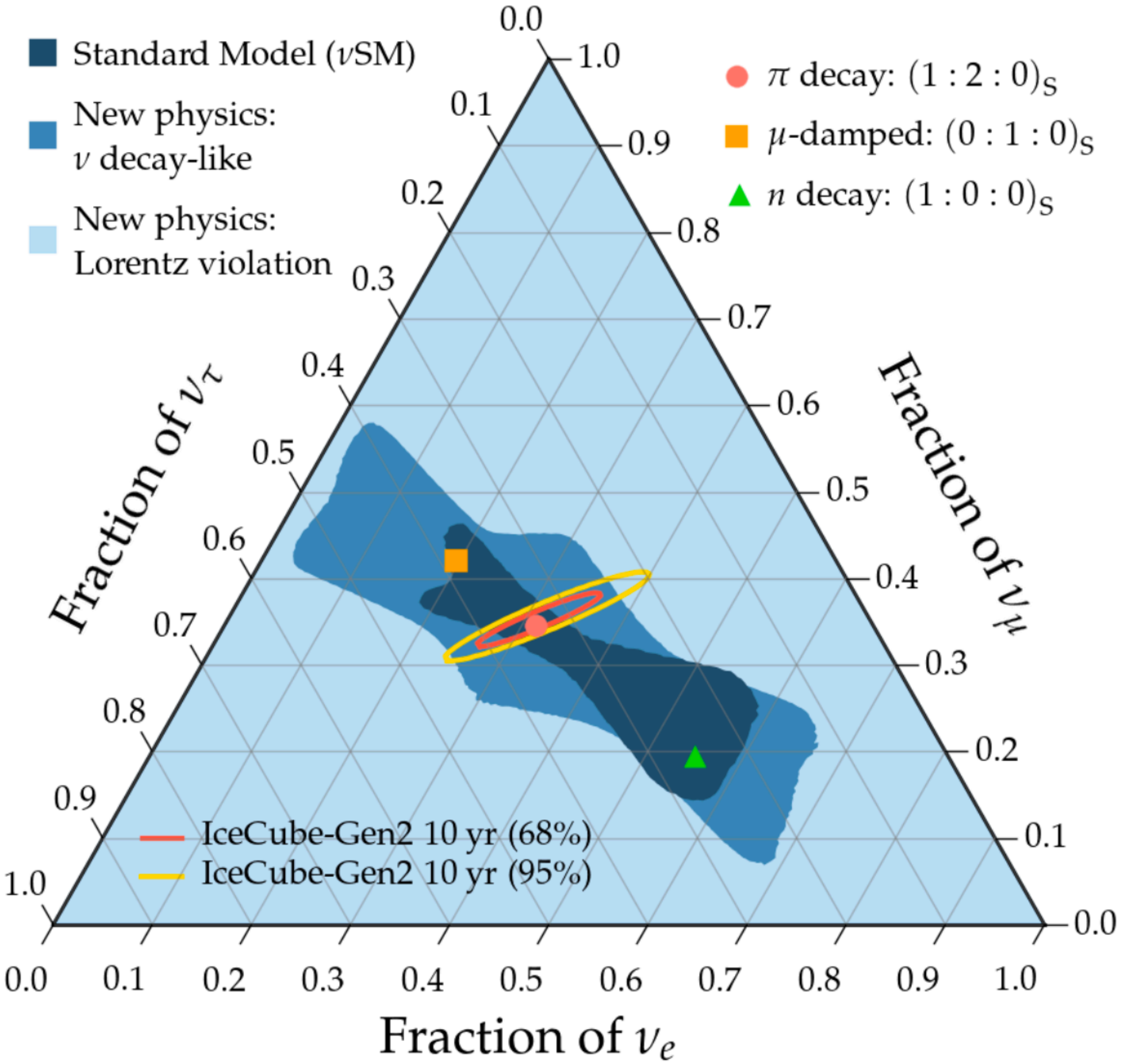
This is the first closed contour we observed.

Mauricia Bustamante sees already a future where we analyse the flavor composition of individual sources.



IceCube-Gen2: Flavor ratio <—> BSM

Particle ID

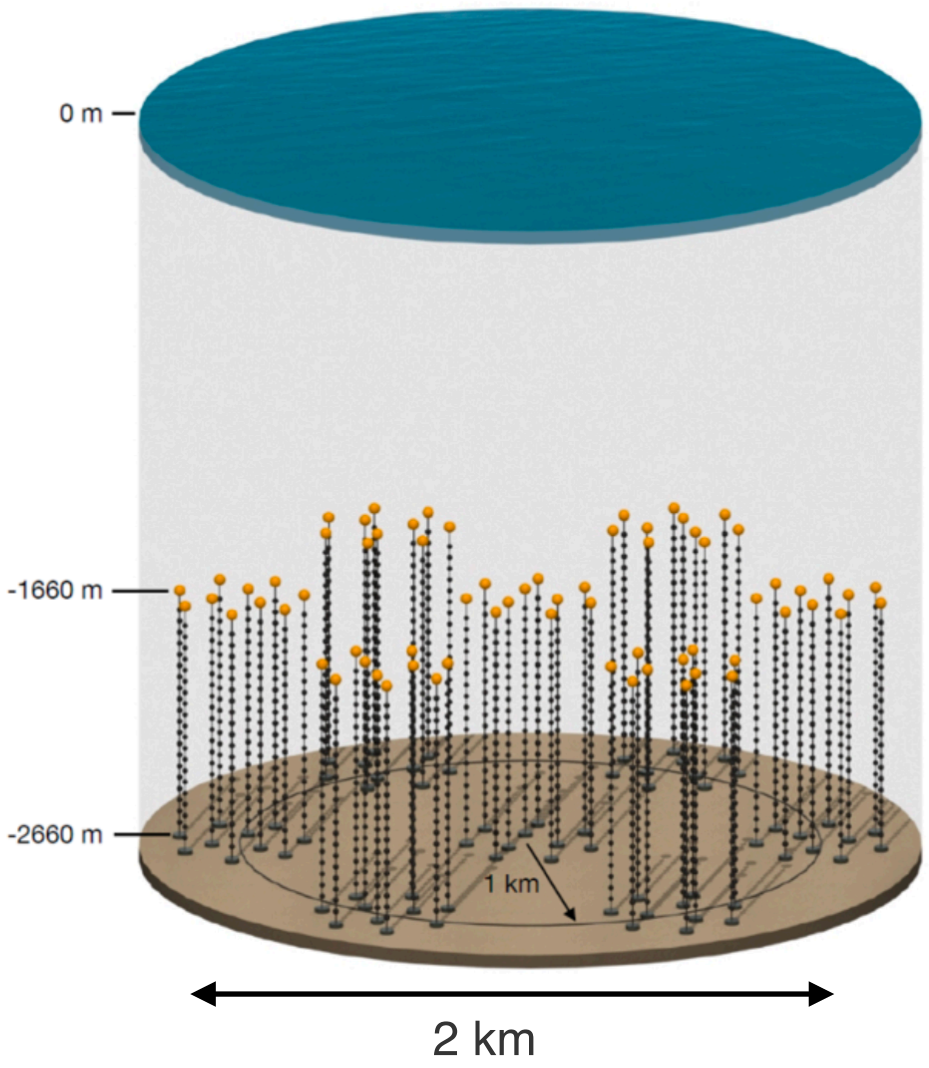


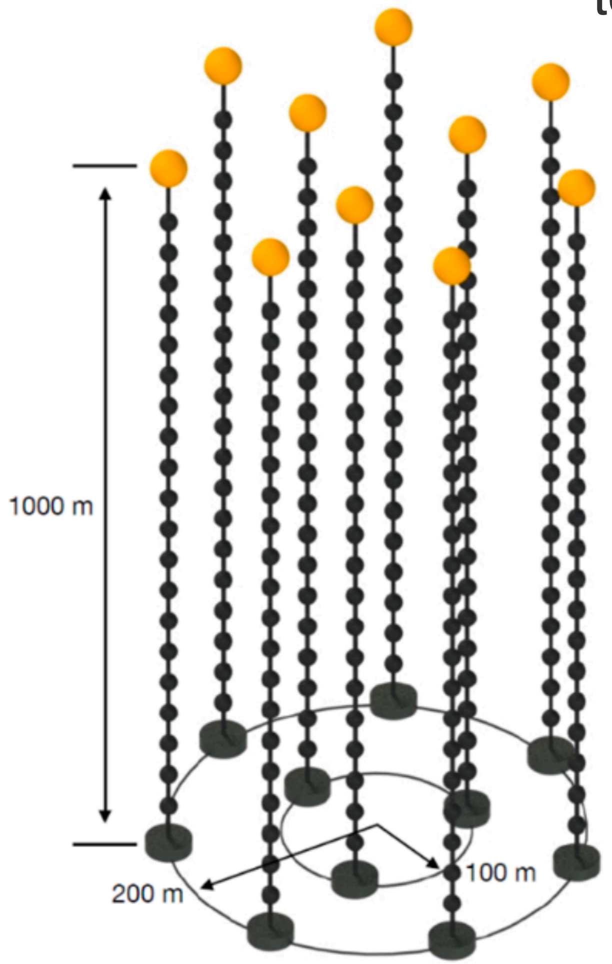
Mauricia Bustamante sees already a future where we analyse the flavor composition of individual sources.

P-ONE (Pacific Ocean Neutrino Experiment)

Proposed project in R&D and prototyping phase

Conceptual Design:
7 clusters x 10 strings x 20 DOMs
total: 70 strings, 1400 sensors





Targeted energy range:
> 100 TeV

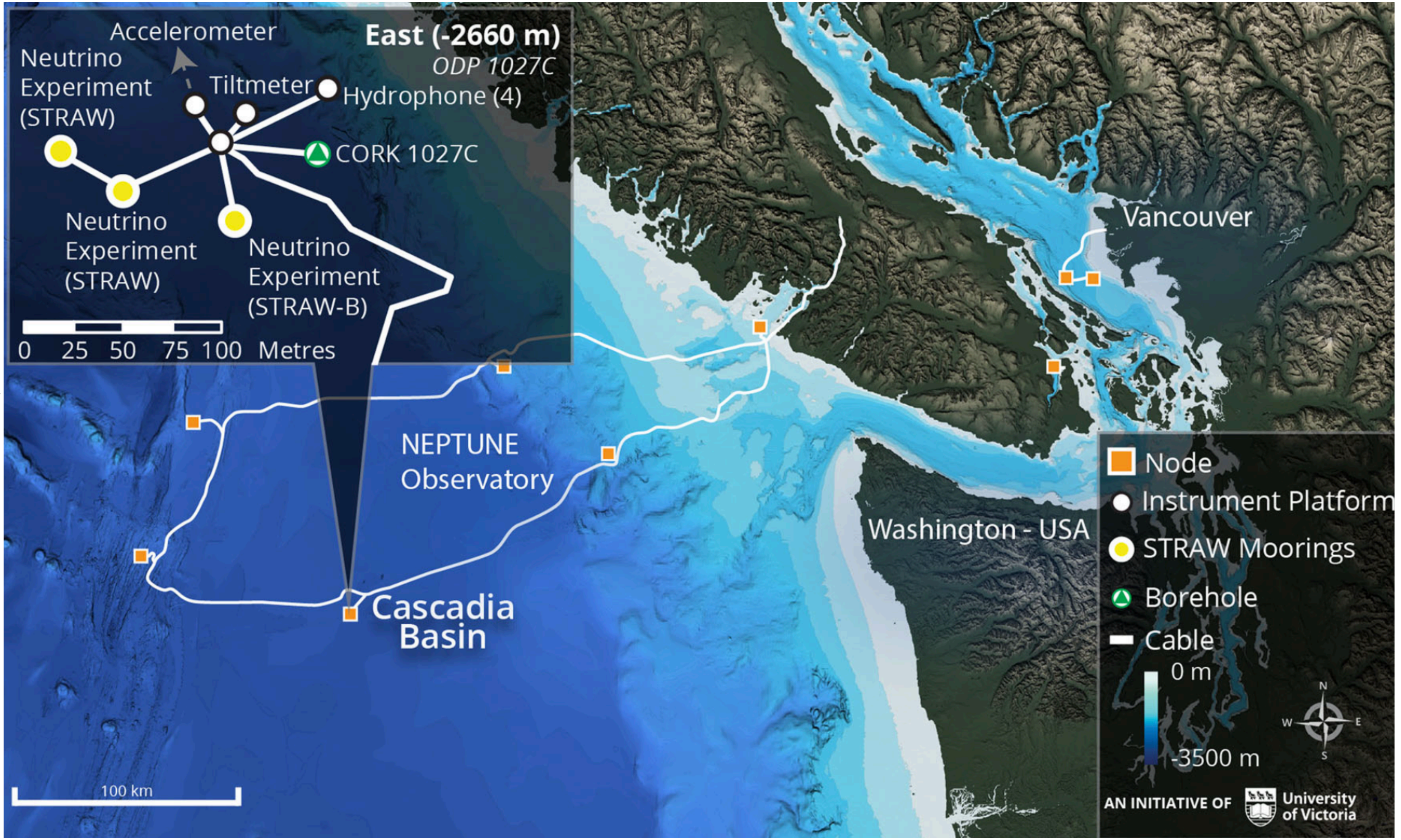
P-ONE

Proposed project in R&D and prototyping phase

Location: Pacific Ocean near Vancouver

Depth: 2600m

Logistical support infrastructure: Interface, anchoring and deployment operation by ONC (Ocean Network Canada)



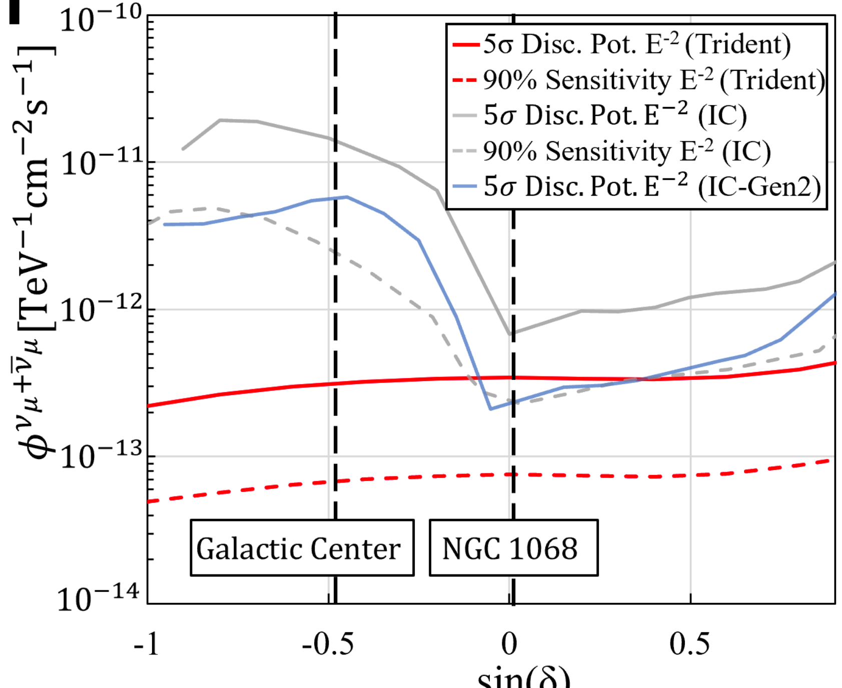
TRIDENT (China)

Proposed project in R&D and prototyping phase

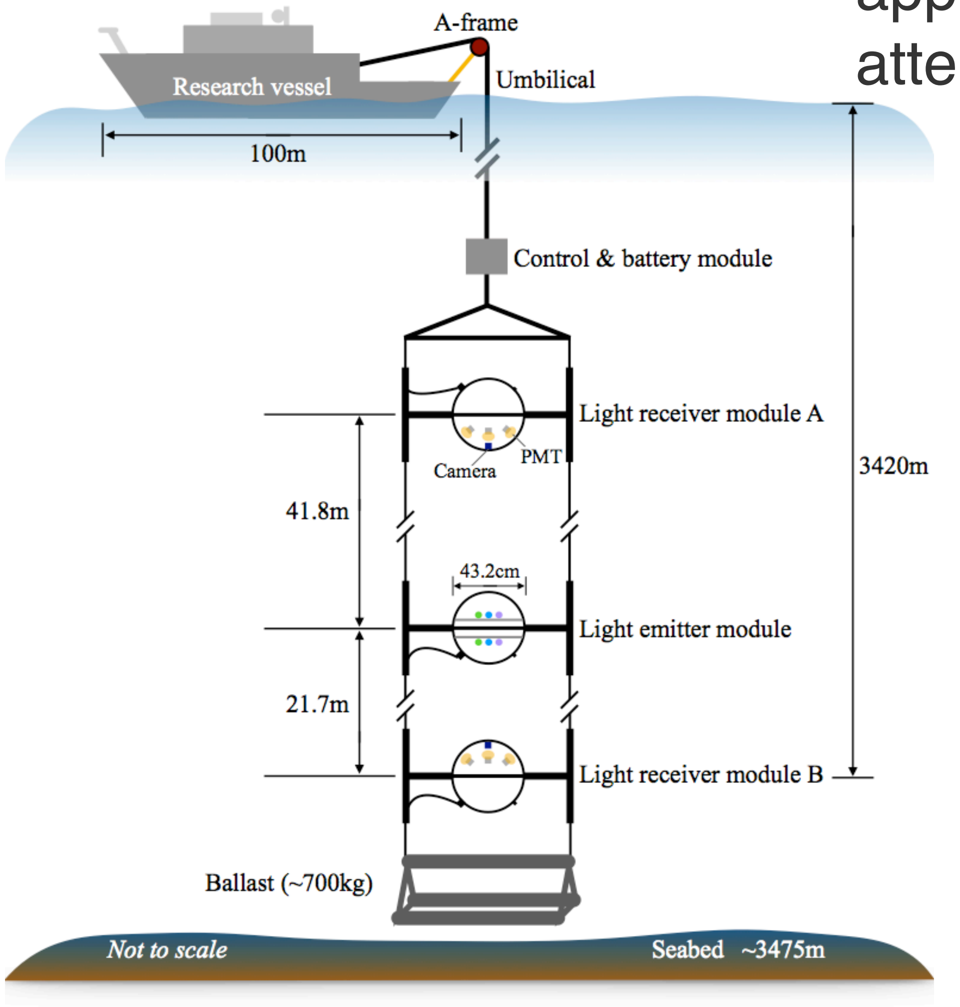
Nature Astronomy (2023). 10.1038/s41550-023-02087-6

Scope:
- **1211 strings**
- 30 hDOMs per string
- **7.5 km^3** (=10 km^2 x 750m)
- Location: South China Sea
- Depth: **3475m**

1200 strings - like DUMAND!!



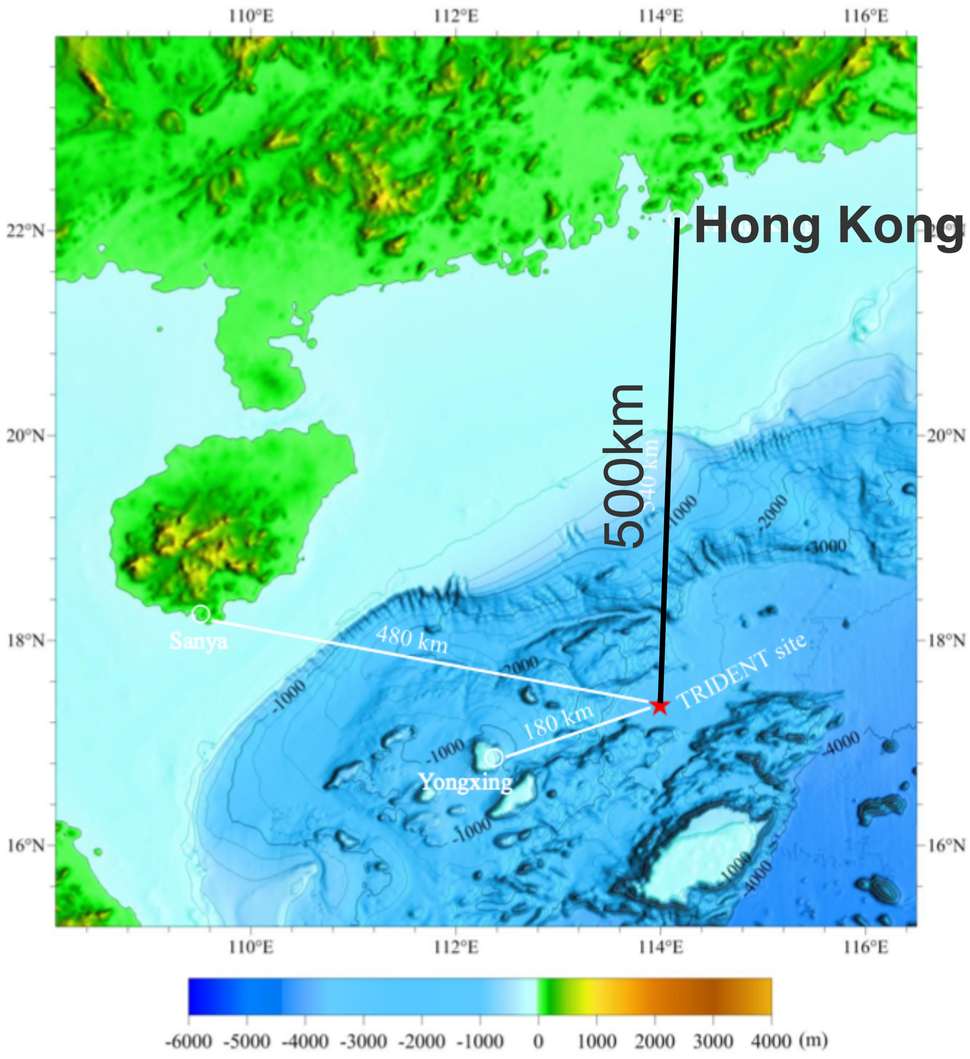
TRIDENT: Exploration



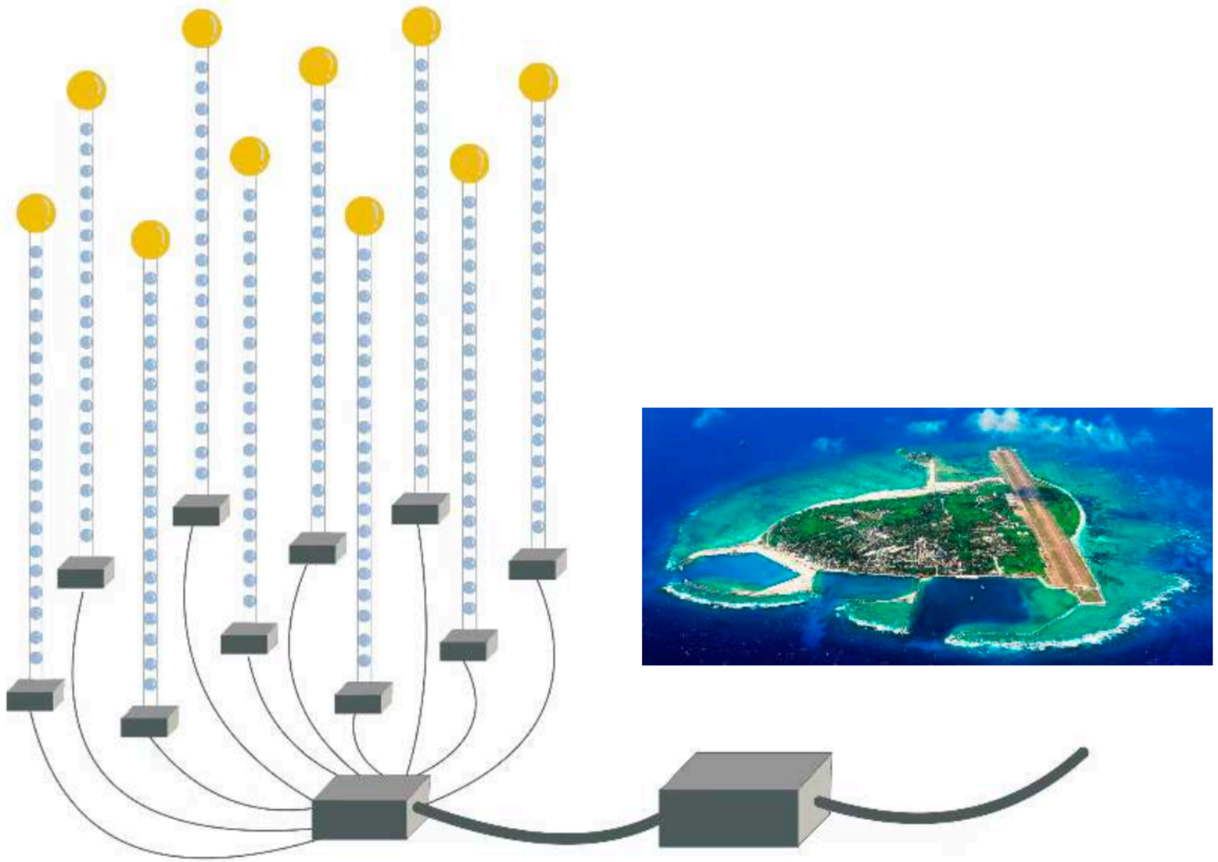
Optical properties, appear reasonable: attenuation: 20 - 30 m

TRIDENT:

Location: South China Sea



Phase 1 project 2022-2026: in progress
10 strings + deep sea cable



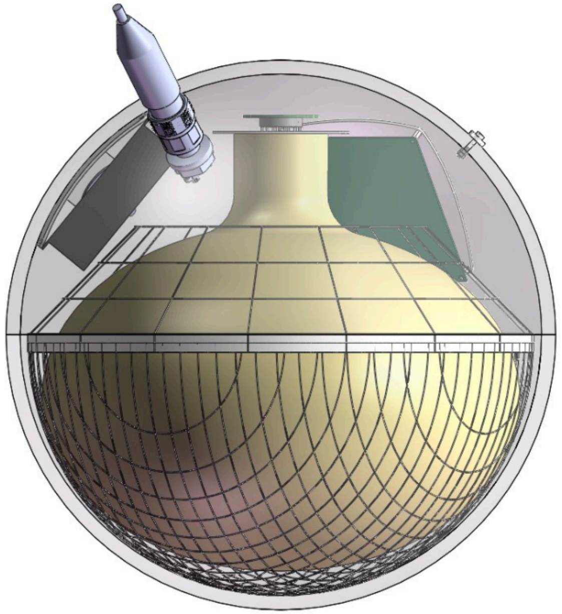
HUNT - **H** stands for Huge

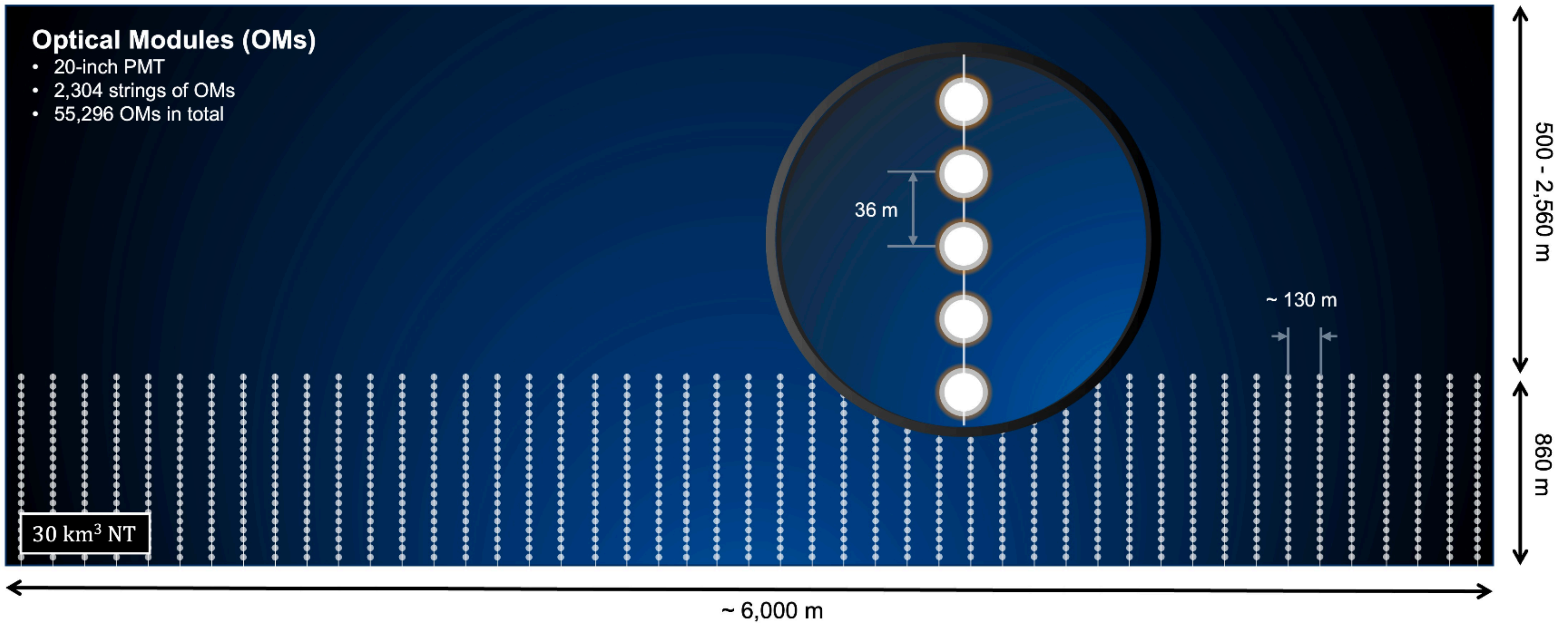
Huge Underwater NT

Outline presented at the ICRC

55,000 PMT of 50 cm diameter
2304 strings of 24 PMTs, 860m long
Instrumented volume 30 km^2

Location: in consideration: Baikal or somewhere South China Sea
prototype string in Lake Baikal planned



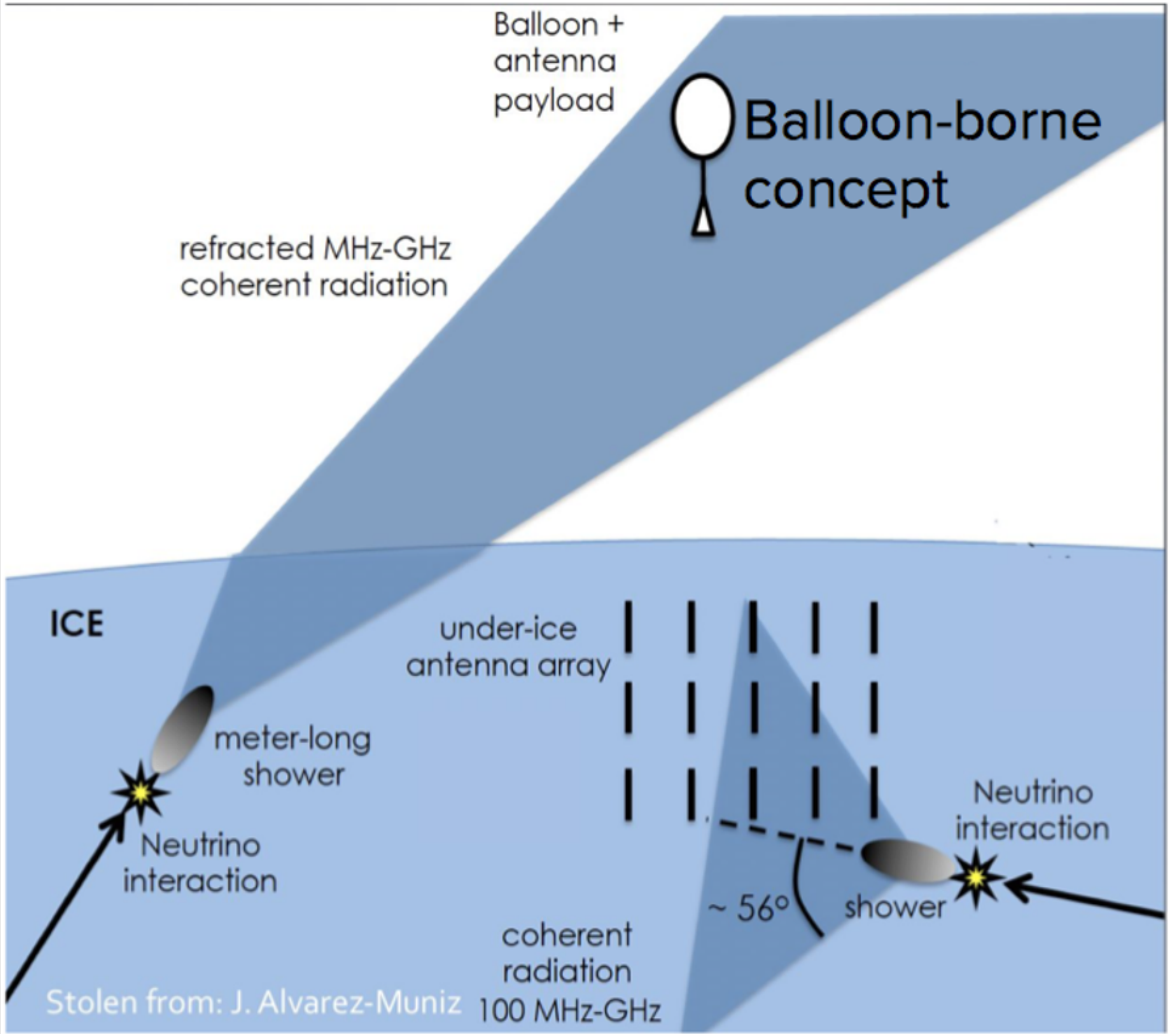


Outline

- Neutrino astronomy: The starting point
- IceCube, IceCube-Gen2
- Review of (other) current and planned projects
  optical
- **Ultra High Energies**
- Outlook

Using massive ice sheets as target for radio detection

Askaryan: coherent radio transient from high energy cascade at Cherenkov angle
Signal grows with energy^2



ANITA:
Higher energy threshold due to larger distance to interaction
next —> PUEO
impressive improvement by phased array triggering
High threshold ~ 1000 PeV

In-ice, Lower energy threshold: 30 PeV

Pioneering:
RICE: South Pole (coldest —> best ice)
ARIANNA: Moore's Bay
Askaryan Radio Array: South Pole - still running, new result this year.

RNO-G: Greenland
seen also as 'Phase 1' for Gen2 Radio

Using massive ice sheets as target for radio detection

Requirement: a lot of ice

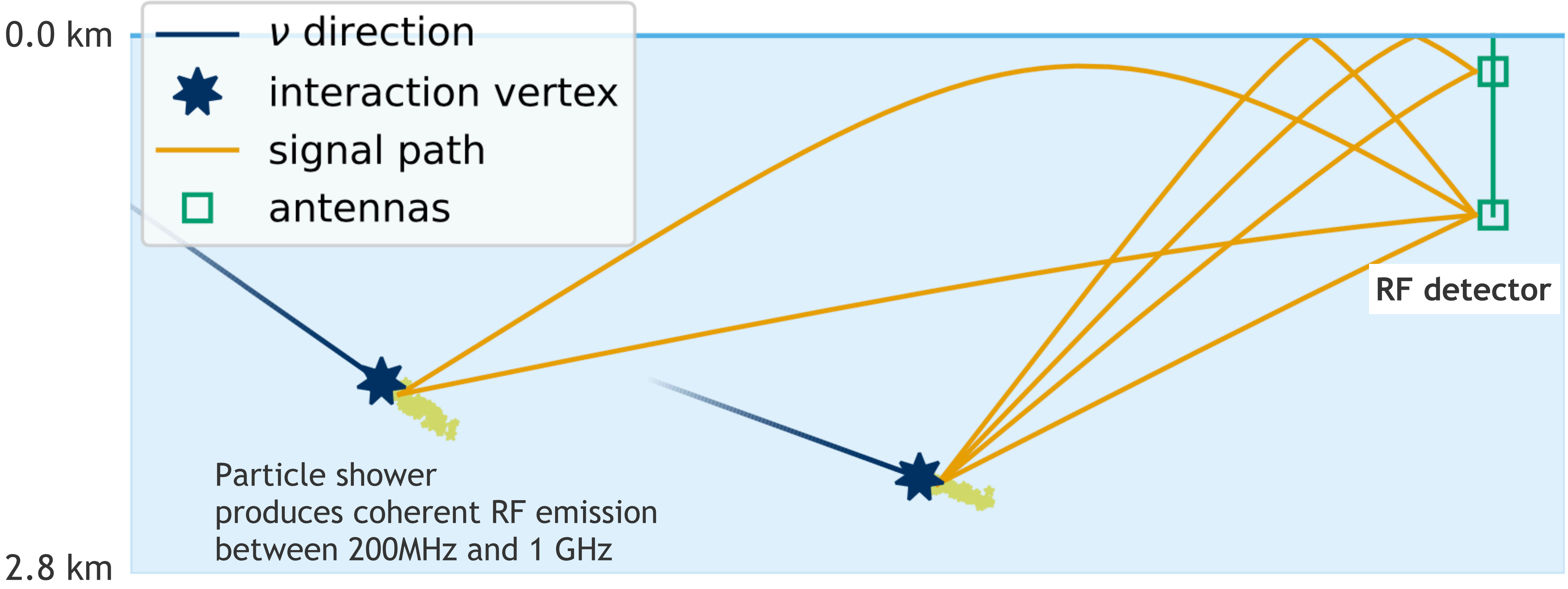
- South Pole
- Ross Ice Shelf (coast of Antarctica)
- Greenland

Antarctica

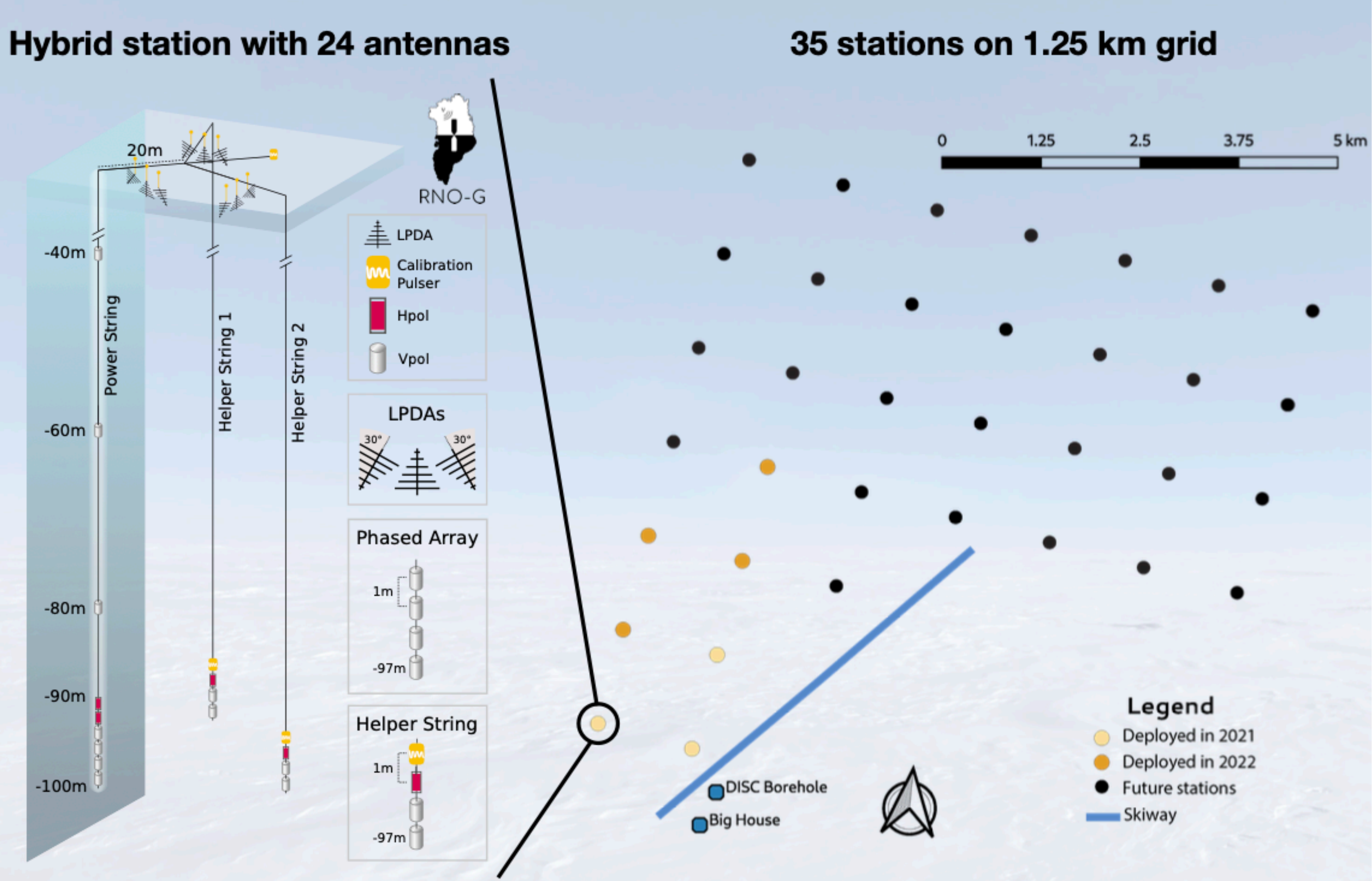
Greenland

Using massive ice sheets as target

Askaryan: coherent radio transient from high energy cascade at Cherenkov angle
Signal grows with energy^2



RNO-G: Radio Neutrino Observatory - Greenland



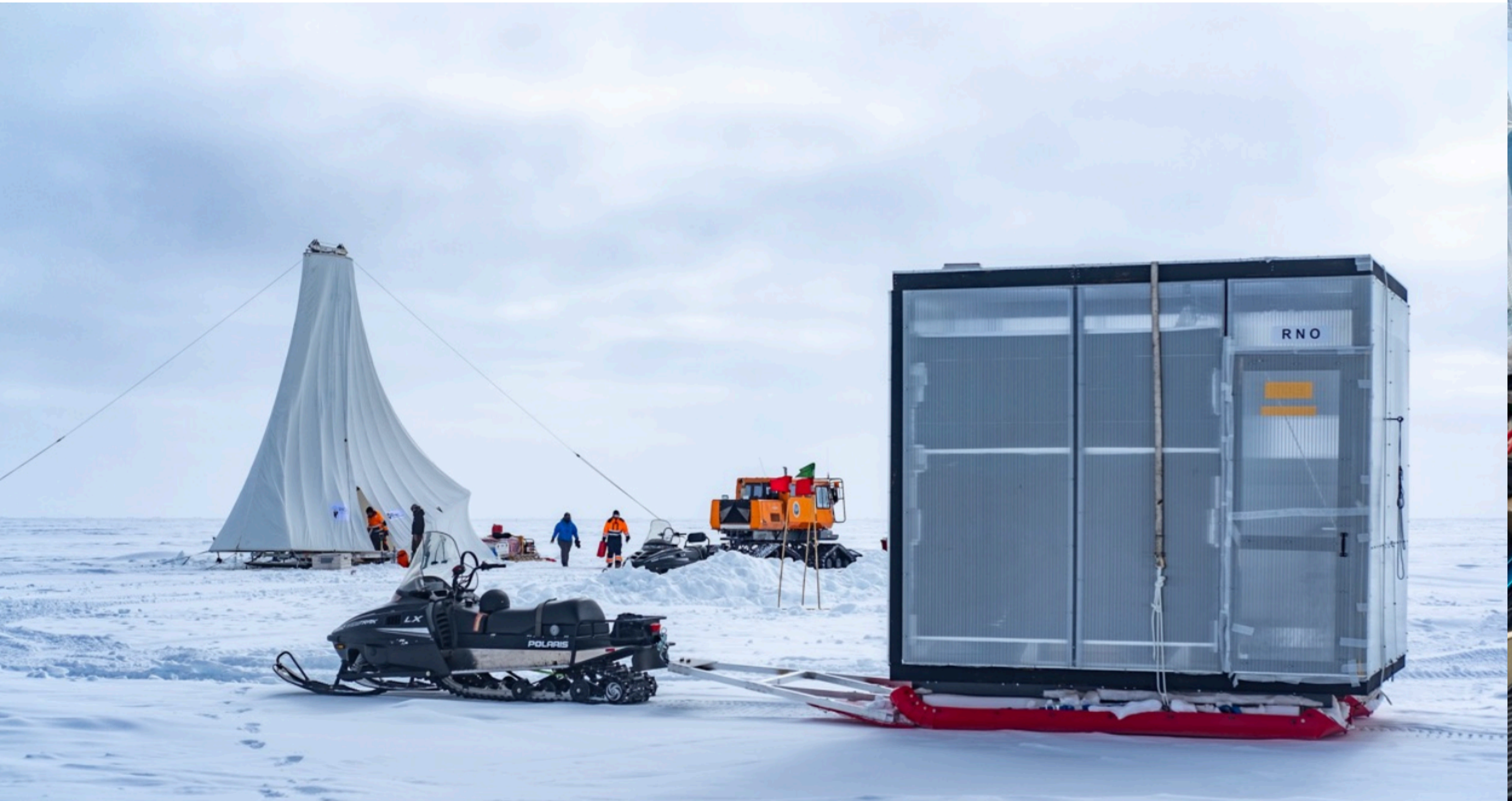
—>. Talks by Delia Tosi and Felix Schlüter

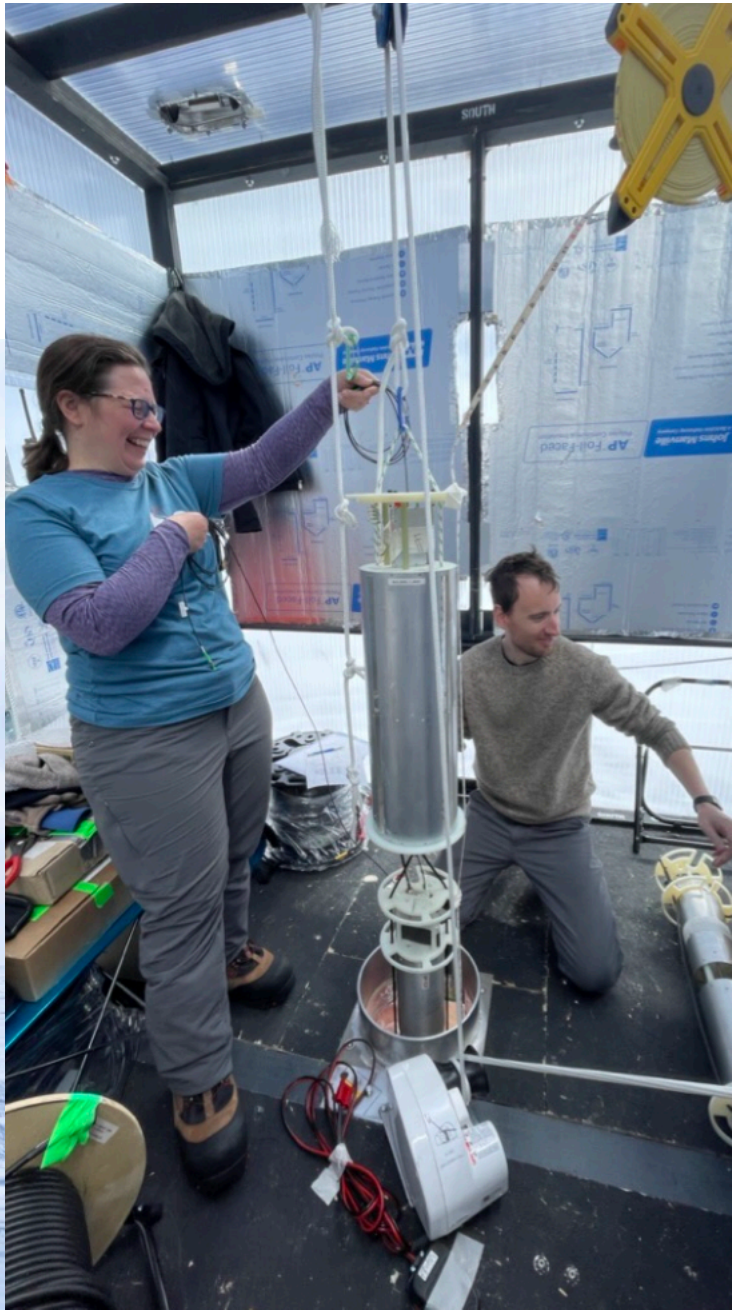
RNO-G: implements lessons learned from ARA, ARIANNA, Phased Array.

7 stations built,

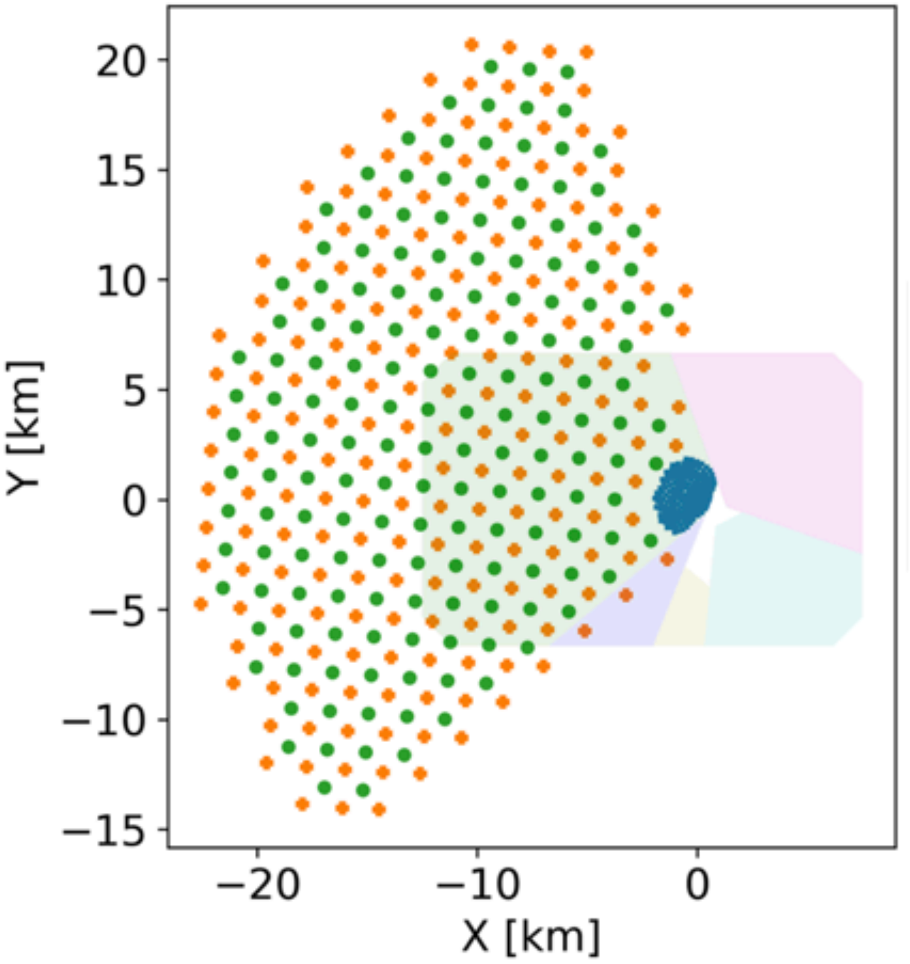
continued construction in the next several years.

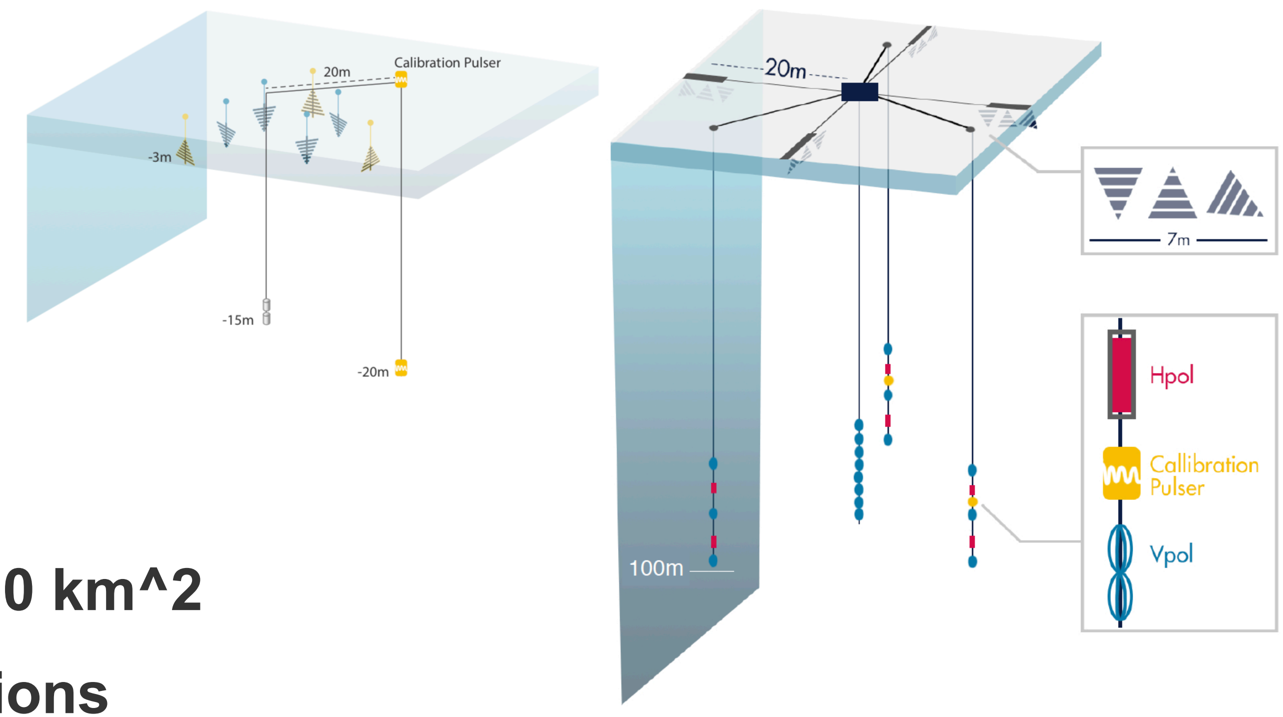
RNO-G: Radio Neutrino Observatory - Greenland





The IceCube-Gen2: the radio array





Area: 500 km^2

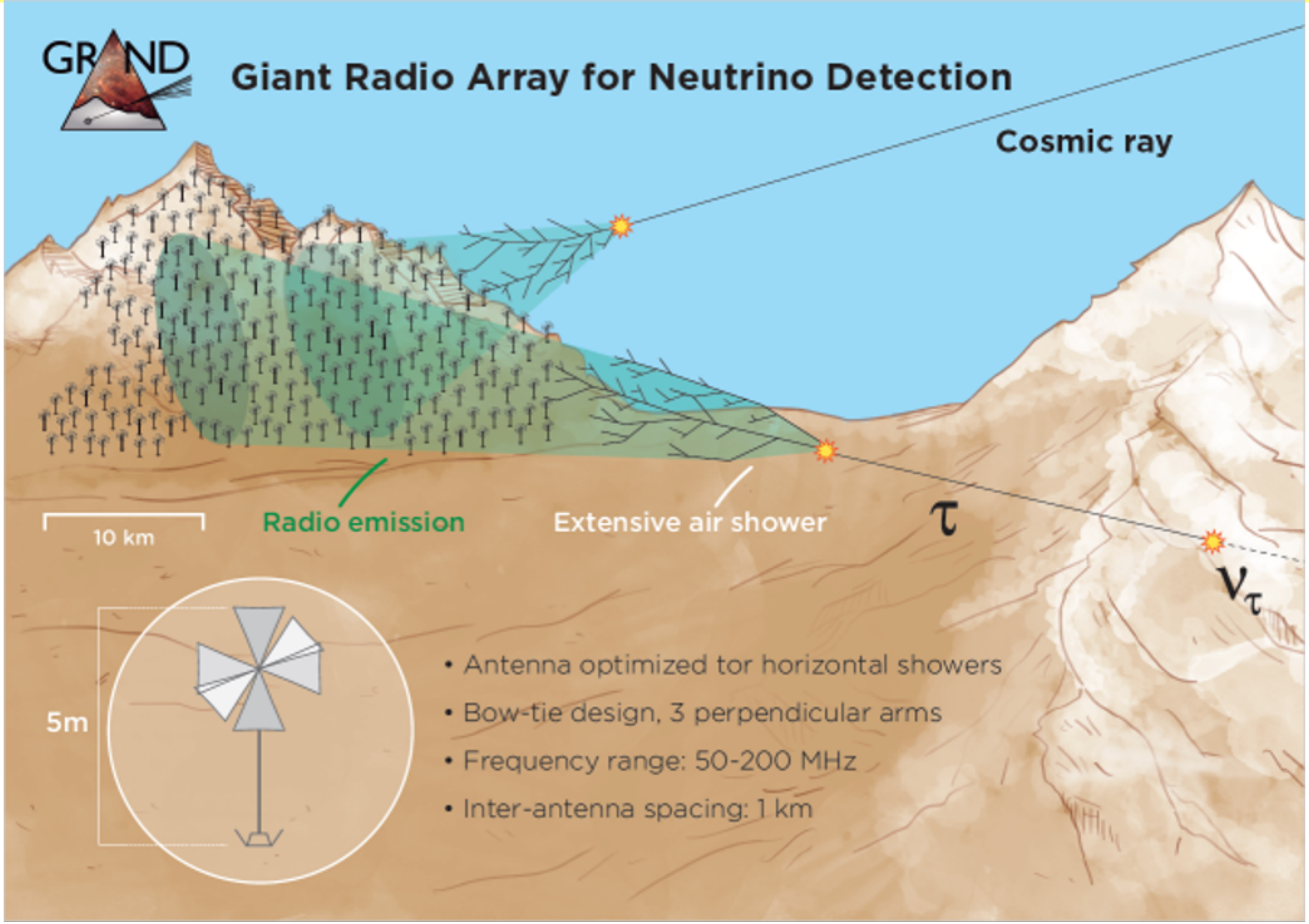
300 stations

1000 km^3 of ice volume

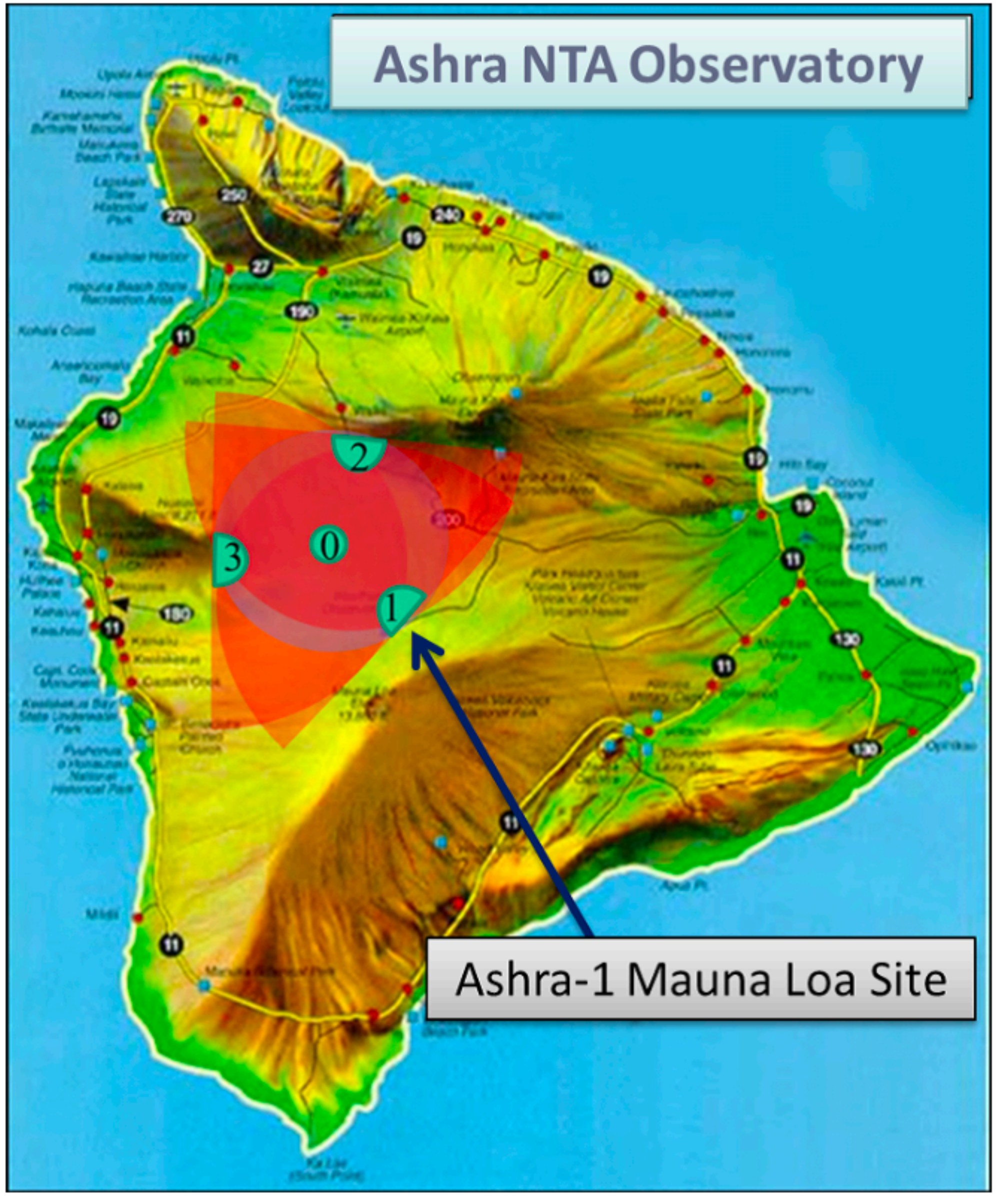
Heritage: ANITA (Antarctica from balloon), ARA (South Pole), RNO-G (Greenland)

GRAND: 200,000 antennas for horizontal taus

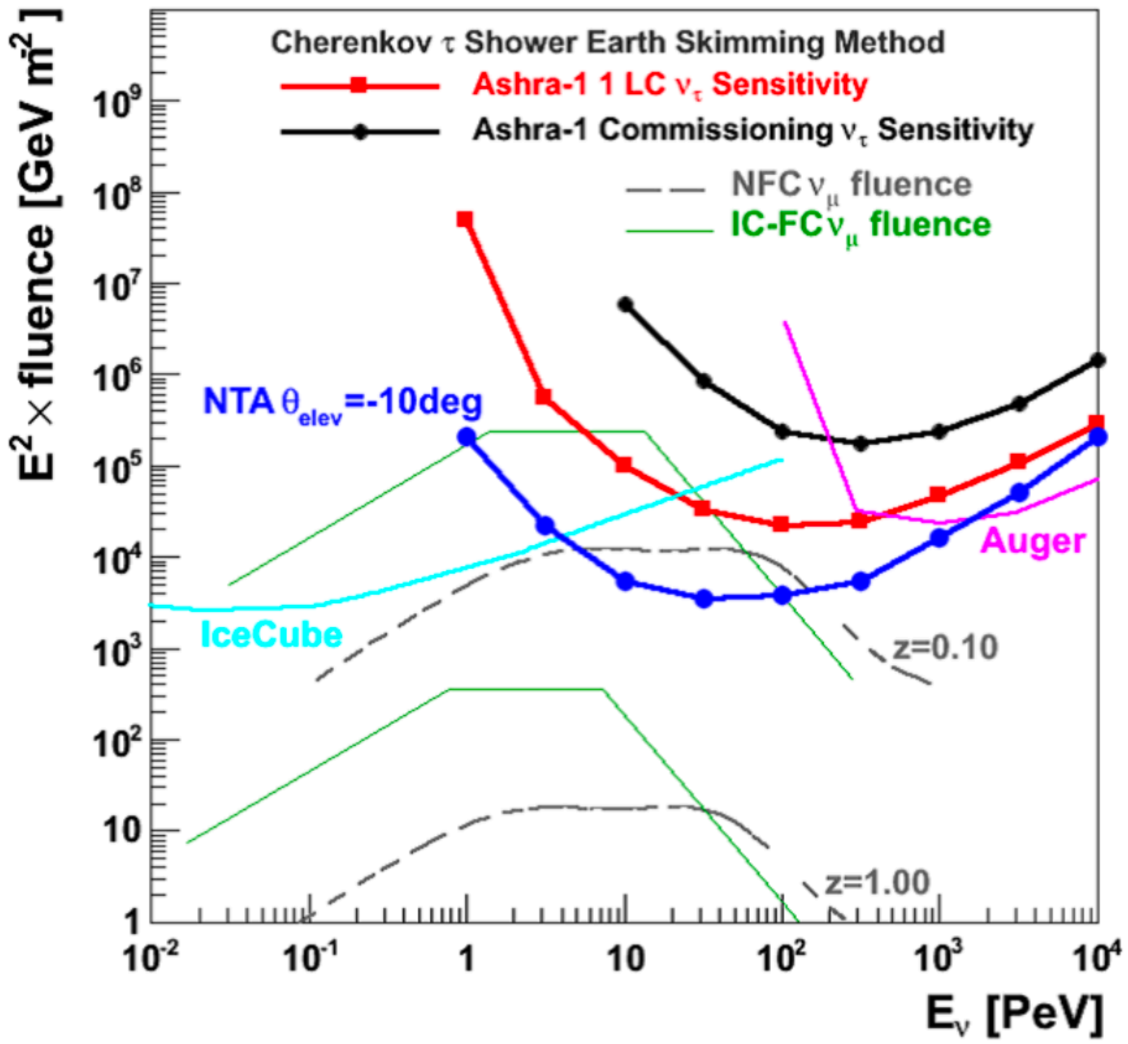
proposed



ASHRA, NTA: View taus on Big Island with optical



ASHRA NTA Collaboration
ICRC 2013



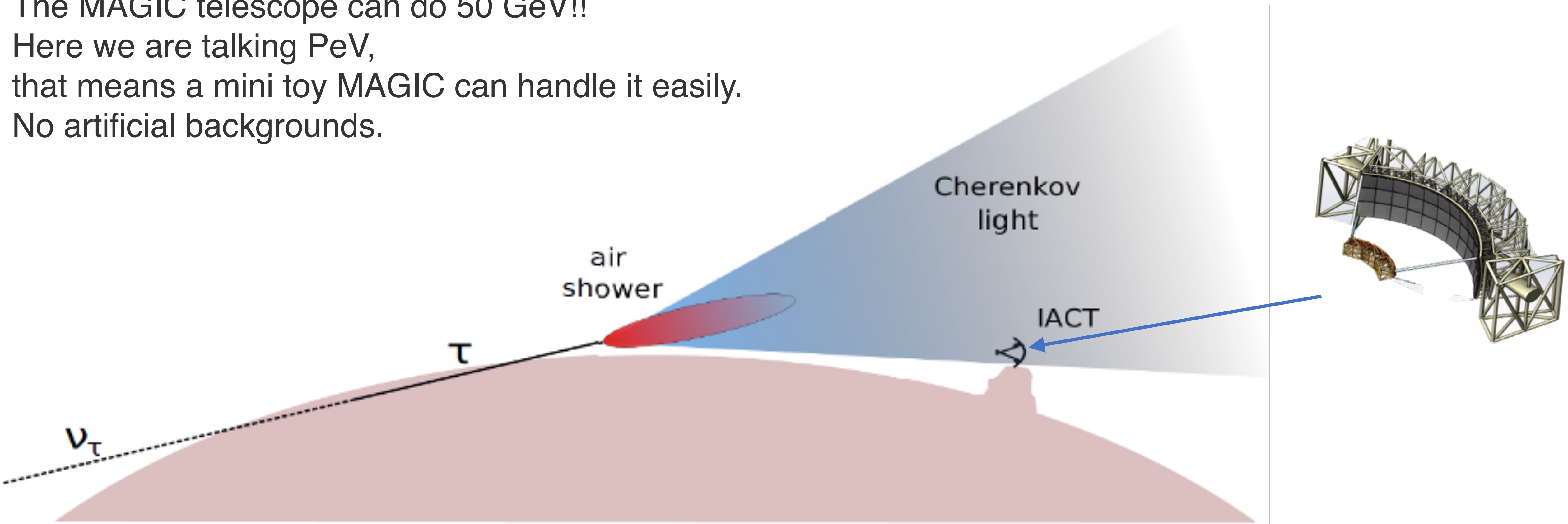
Trinity: View upward taus mountain with Cherenkov telescope

see talk by Michele Doro

Nepomuk Otte

Advantage:
Low Energy threshold for emerging tau neutrinos

For ref.:
The MAGIC telescope can do 50 GeV!!
Here we are talking PeV,
that means a mini toy MAGIC can handle it easily.
No artificial backgrounds.



Trinity: View upward taus mountain with Cherenkov telescope

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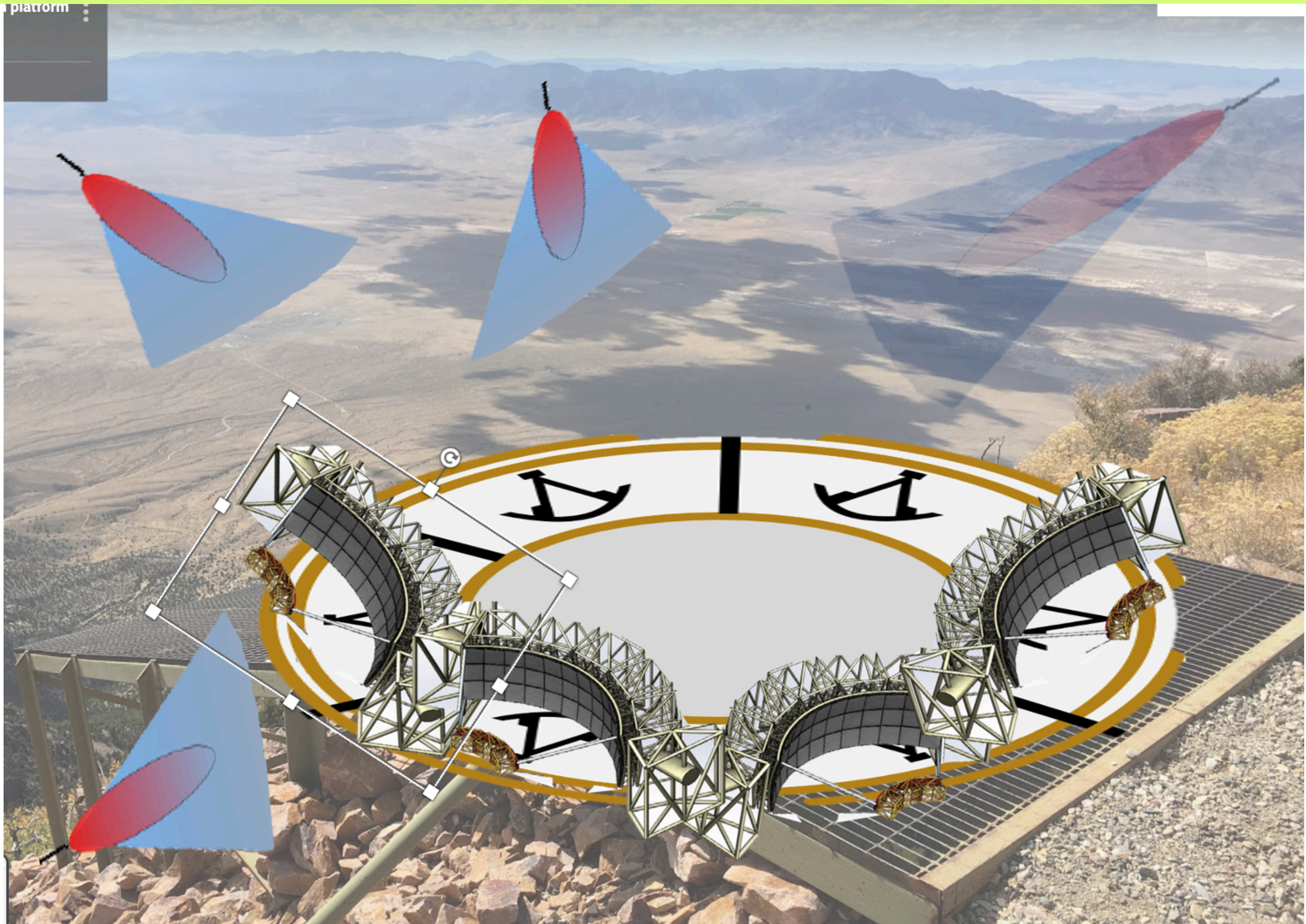
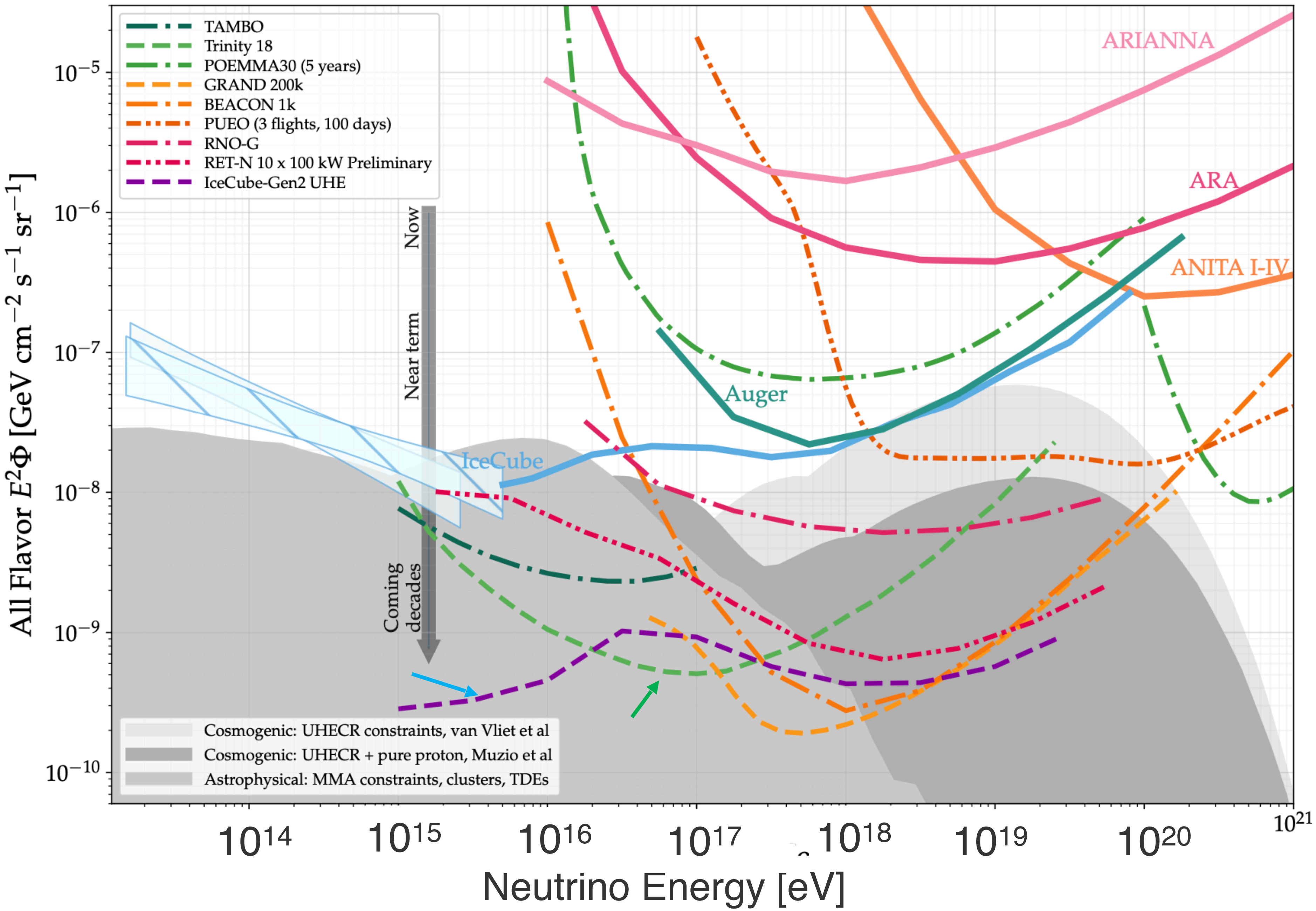


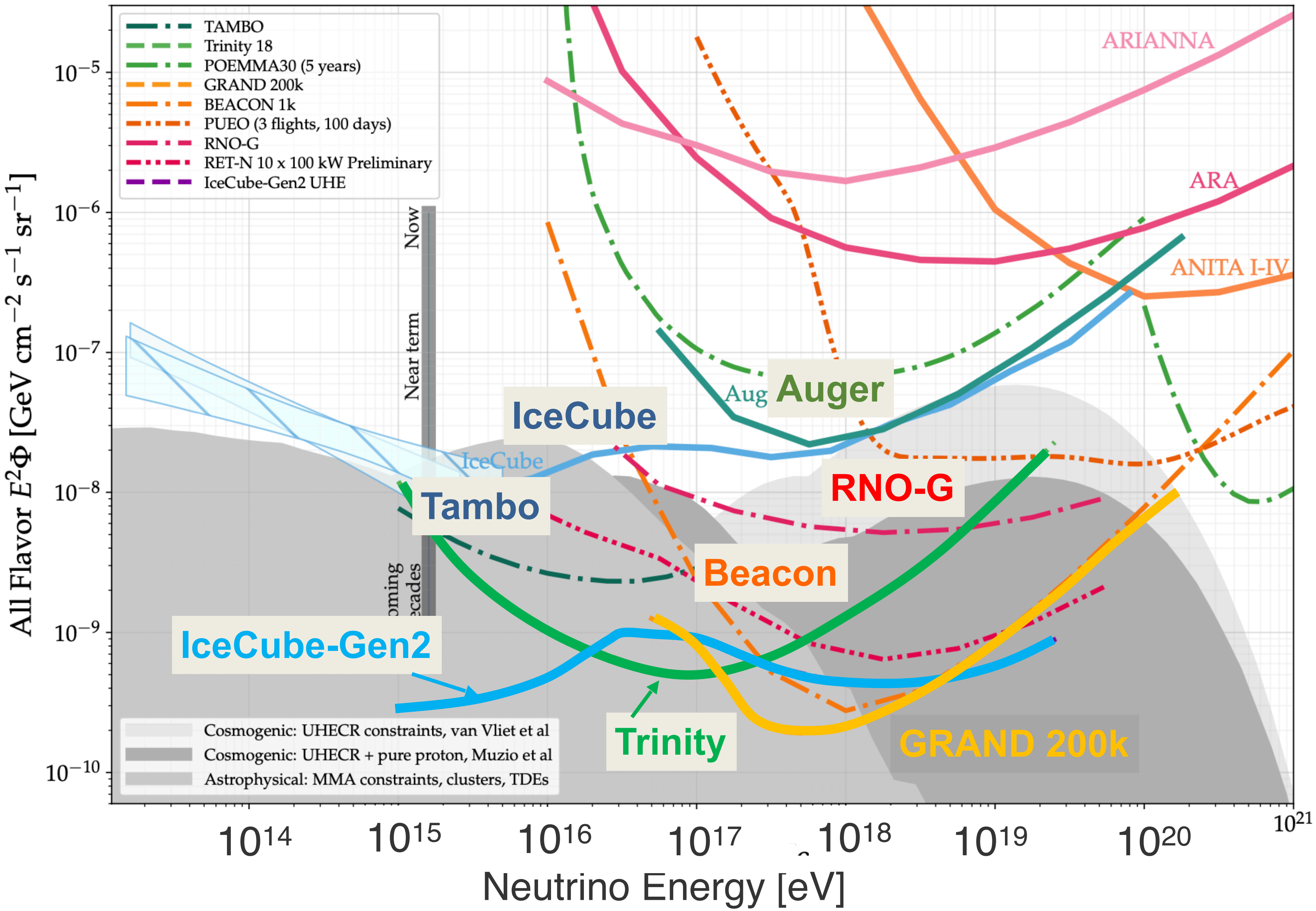
Ultra High Energies: Sensitivities



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

https://arxiv.org/abs/2203.08096

Ultra High Energies: Sensitivities



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

https://arxiv.org/abs/2203.08096

Neutrino astronomy in numbers:

Number of

- **Neutrino events above 1 TeV: > 1.2 Million**
- **Neutrino events above 1(100) PeV: 8 (1)**
- **Combined world detection volume: ~ 2 km^3**
- **Proposed water/ice Cherenkov detection volume in the next decade: 40 km^3**

- **Authors in current collaborations: > ~800 (IceCube and KM3Net 650)**
- **HE Neutrino papers at the largest recent cosmic ray conference (ICRC): ~200**

John Learned, 1993:
High Energy Neutrino Astronomy, Past, Present, and Future.

It took a little longer, but your wish has become a reality.

6. Conclusion: On the Threshold

As one sees from the number of proposals and actual programs underway, the field of neutrino astronomy seems to be heading for an active future. This author would believes that 4 major detectors may operate before the turn of the century. With the best calculations indicating that we are not far from detecting astrophysical objects, it would indeed be surprising if we do not see the birth of high energy neutrino astronomy before the end of the millenium. It will certainly be pleasant to go to neutrino meetings like this one and talk about physics results instead of history, theoretical speculations and plans!

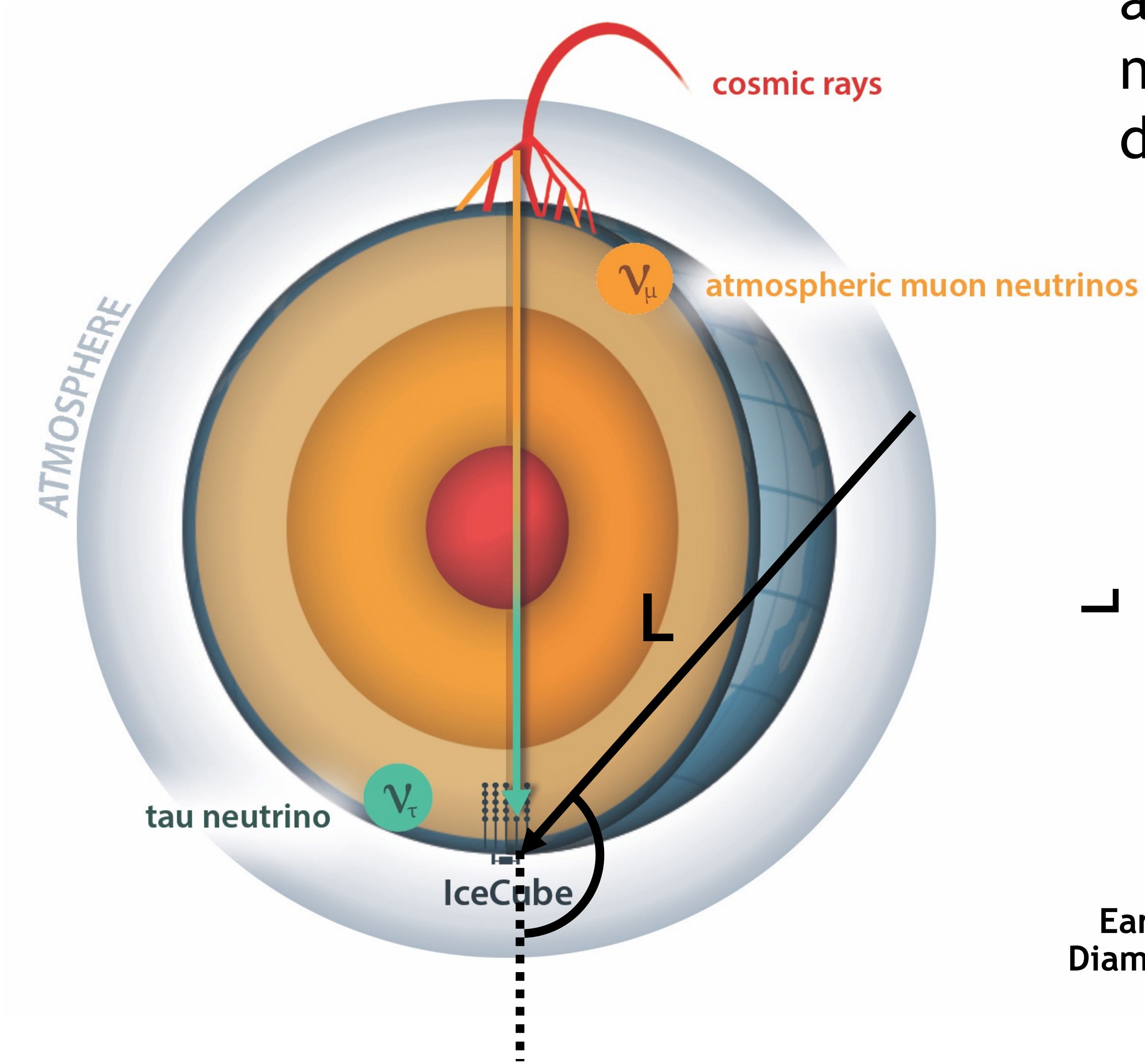
2023 Venice Neutrino telescope meeting.
John gave the first review talk on neutrino telescopes and their future in 1991 in Venice.

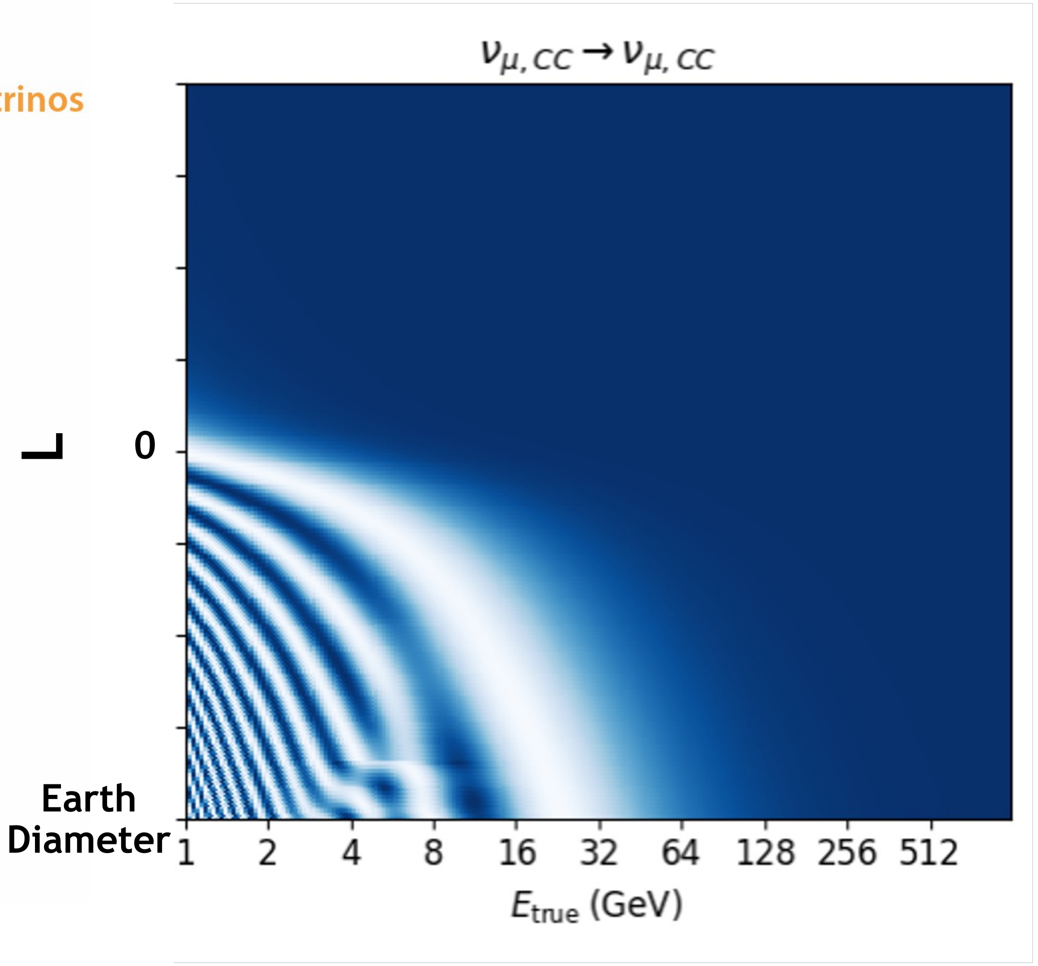
Happy Birthday!

Venice 2023

Backups

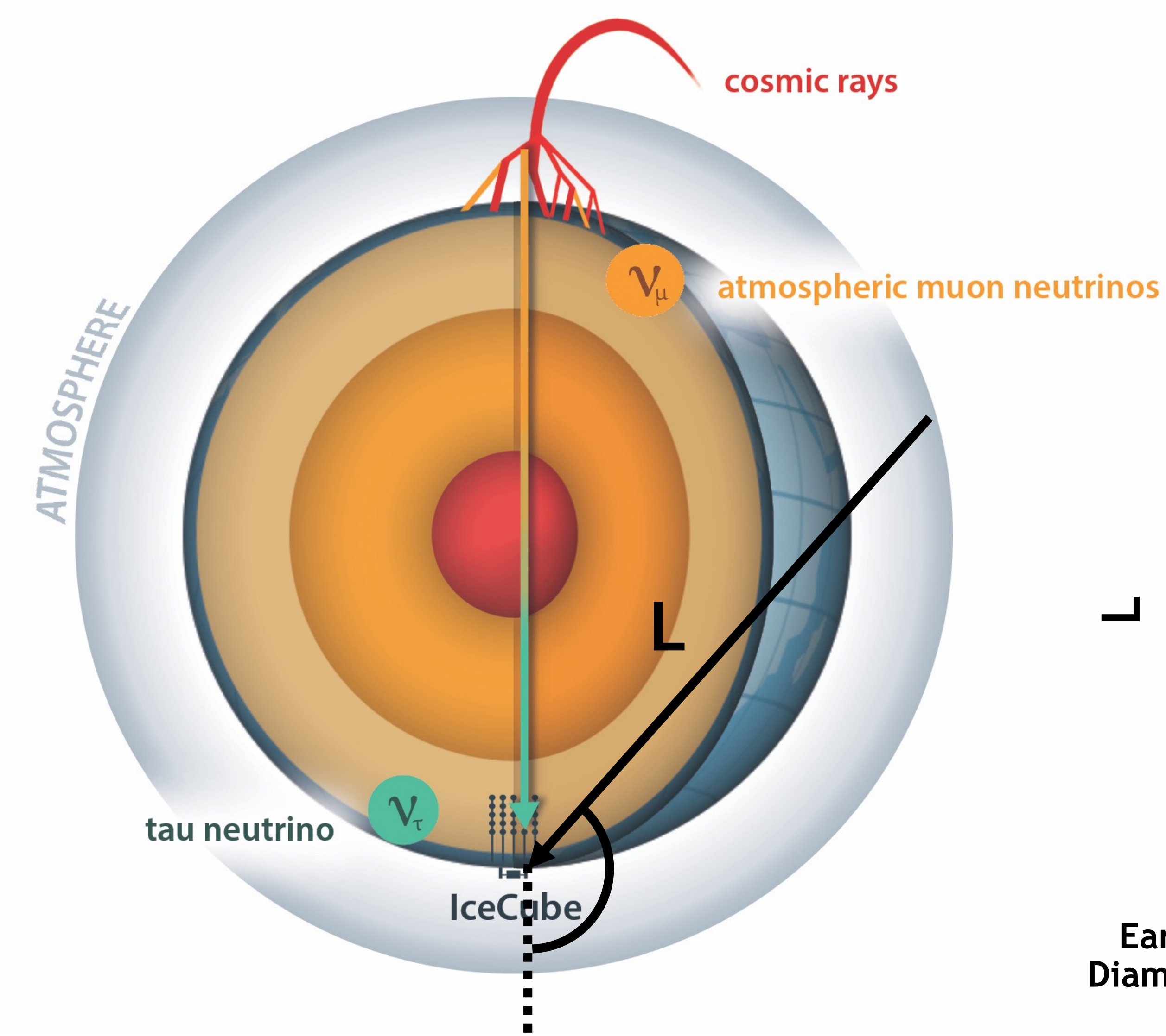
But we don't just have 1 energy and 1 distance, IceCube detects neutrinos of many energies and distances

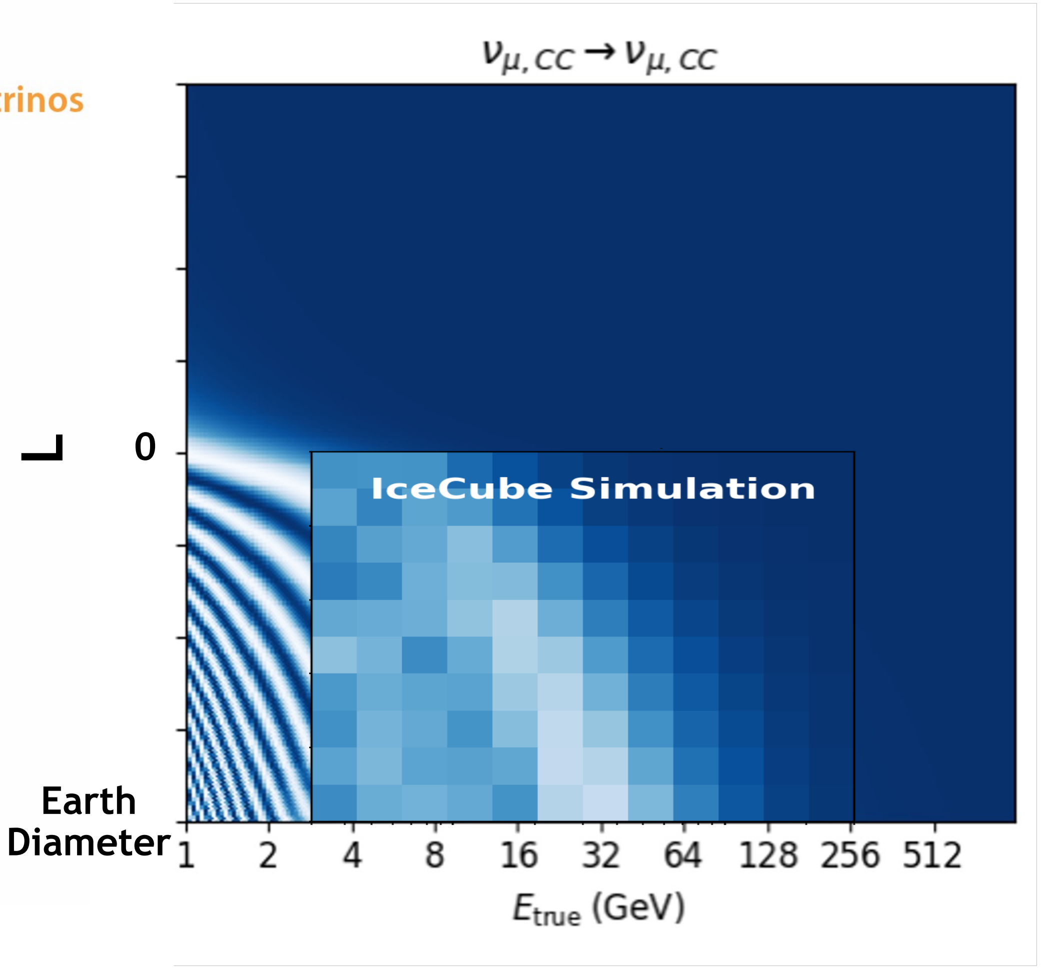




But the reality is more blurry

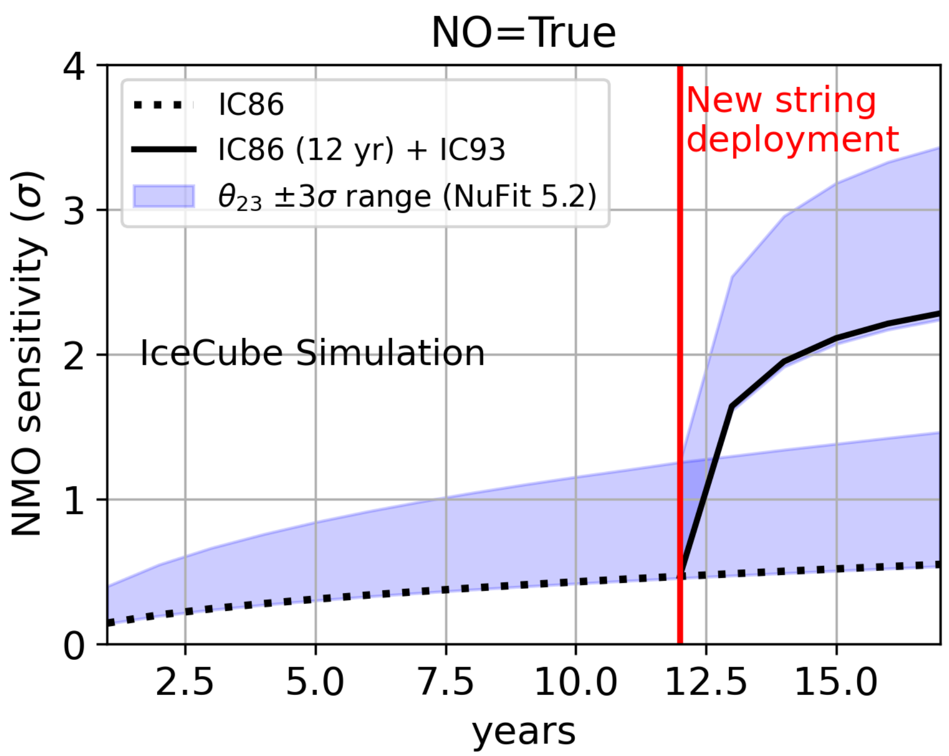
(Will look better with 200,000 events)





A fundamental question:
What is the mass hierarchy of neutrinos?

IceCube + Upgrade: 3 sigma/3 yrs



IceCube Upgrade+JUNO: 5 sigma/3 yrs