Neutrino Astronomy with future neutrino telescopes

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University of Wisconsin-Madison

Neutrino Telescopes
Venice, October, 2023

"The past is the cause of the present, and the present will be the cause of the future. All these are links in the endless chain stretching from the finite to the infinite."
Abraham Lincoln

…, including the Neutrino telescopes workshops since1988

Abstract

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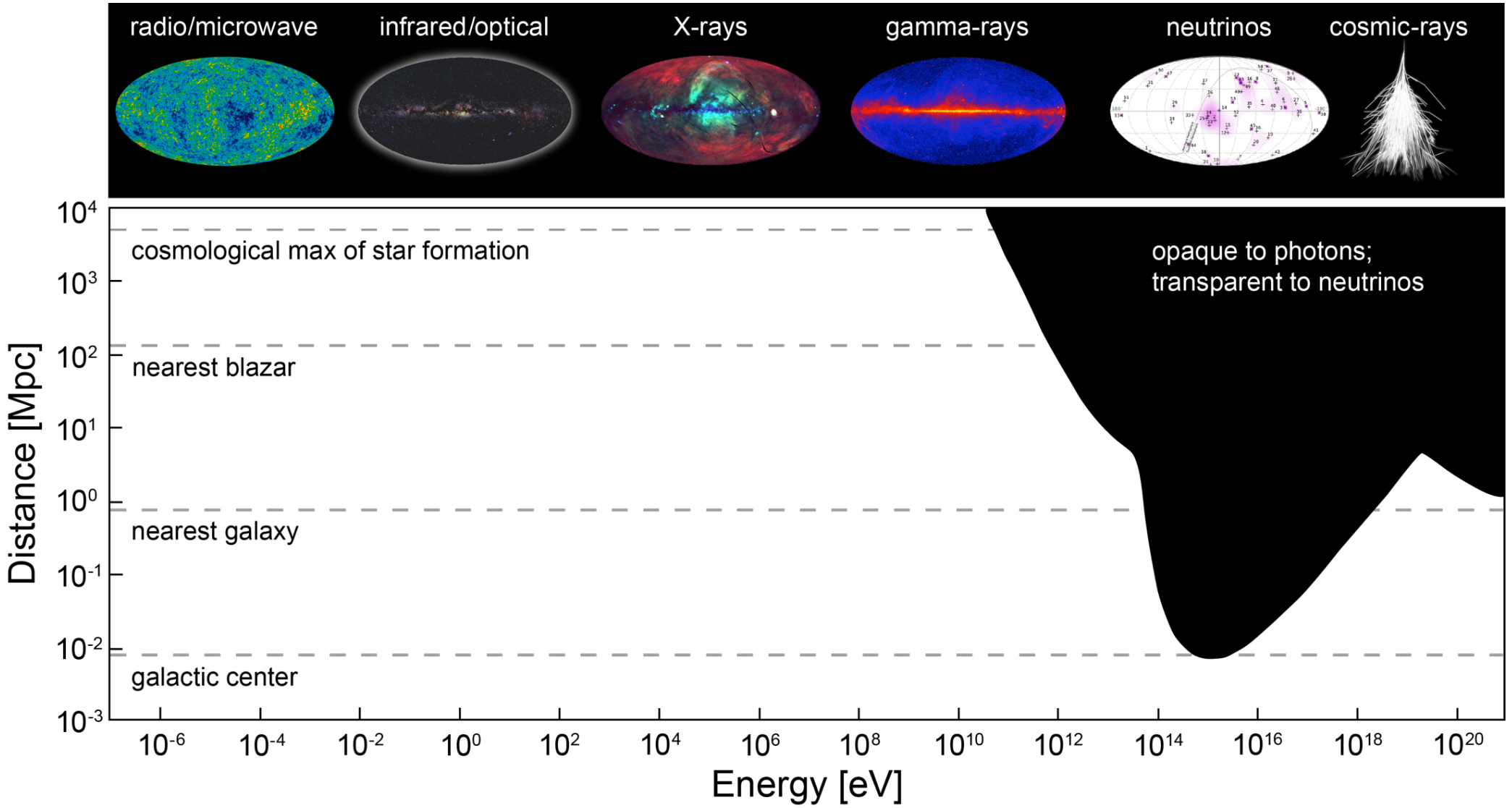
Key-words: Neutrino Telescopes, cosmic neutrinos

In the past decade, IceCube has established cosmic neutrino flux. IceCube has also observed neutrinos from the first extragalactic sources and the Milky Way. These observations set the stage for the next generations of neutrino telescopes worldwide. Multiple large water Cherenkov telescopes of kilometer-scale are being constructed or developed. Even more ambitious telescopes are being proposed and developed at the ten km scale. Multiple initiatives at the 1000km^3 target scale are proposed using radio and Earth-skimming nu_tau approaches at higher energies. I will review the current and future detectors. An order-of-magnitude increase within the next decade is realistic and urgently needed to obtain more sky coverage and increase the sensitivity by order of magnitude.

Outline

- Neutrino astronomy: Today's starting point
- IceCube, IceCube-Gen2
- Review of current and planned projects in optical
- Higher energies
- Outlook

Pushing the energy frontier in Astronomy with Neutrinos



At high energies: The Universe is opaque to the EM spectrum - ***and sometimes also at lower energies***

Detecting, discovering Cosmic Neutrinos
Event Rates are small.

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

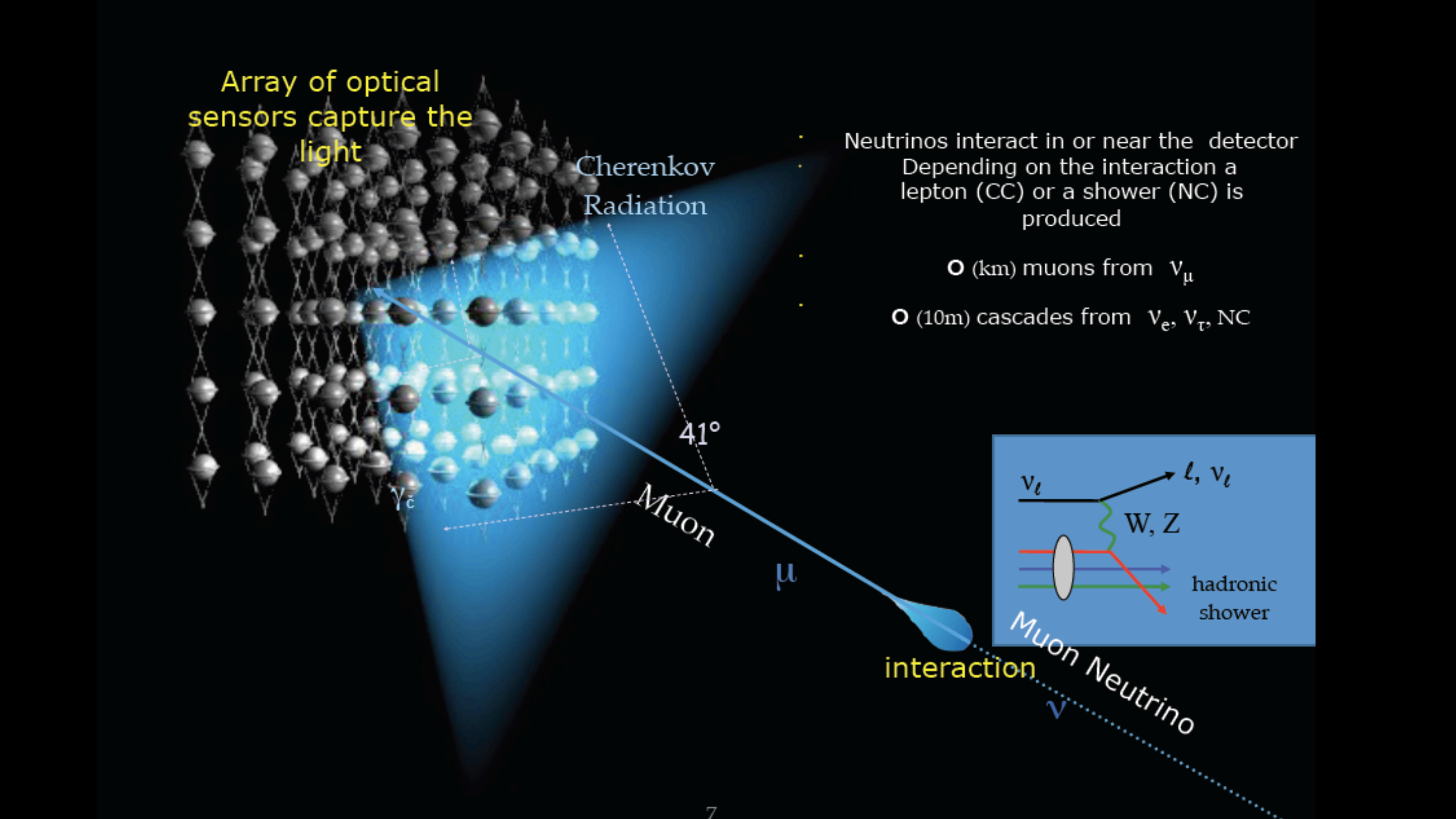
Optical Cherenkov method, proposed early in the 60ies using natural water, and then ice, as target is the pre-eminent method, from GeV to >10 PeV.

At higher energies: 10^18 Event rates are anticipated to be as much as ~1000 times smaller.

Need target of order 1000km^3

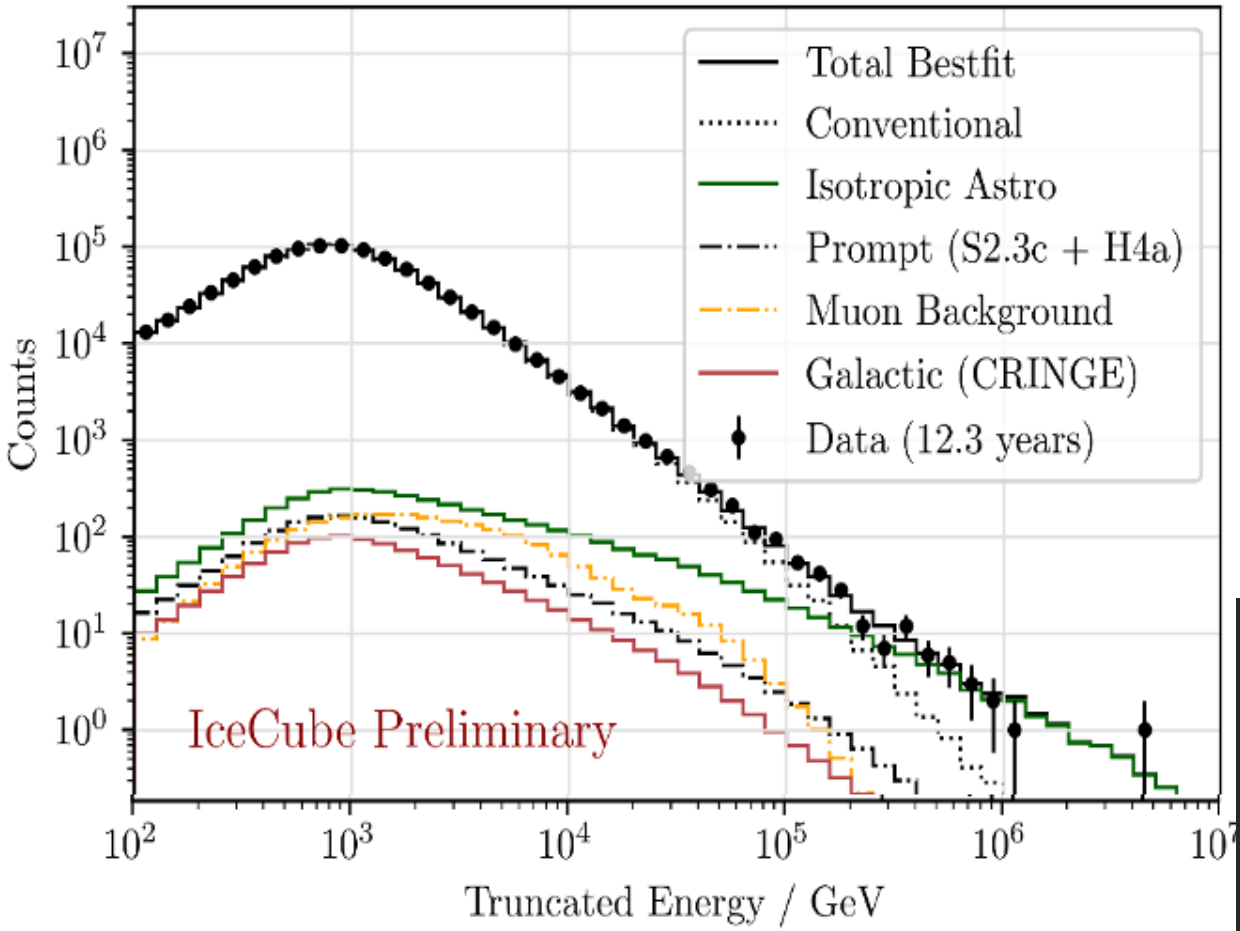
Radio detection of neutrinos is seen as primary method at 1E18eV.

In between, 10 PeV: room for **air Cherenkov**.


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

Today's starting point based on IceCube results

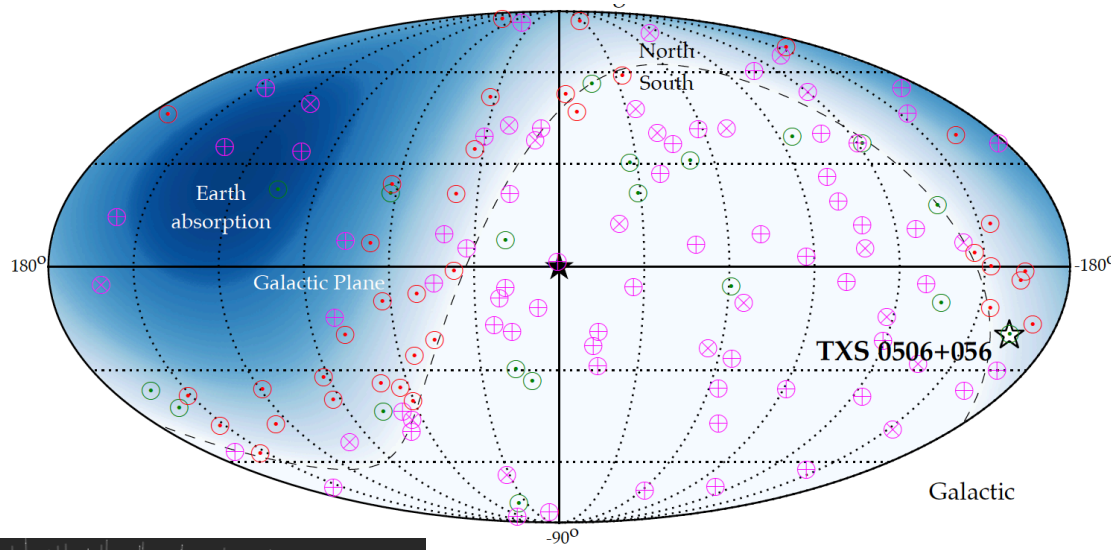
IceCube: Upgoing muons



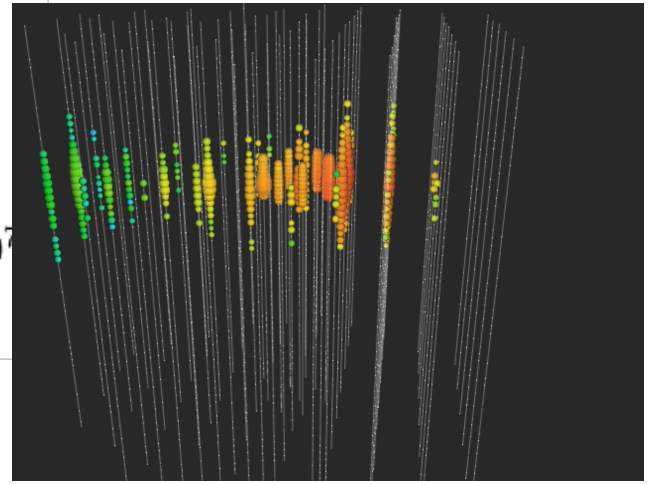
IceCube, ICRC 2023

https://arxiv.org/pdf/2308.08233.pdf

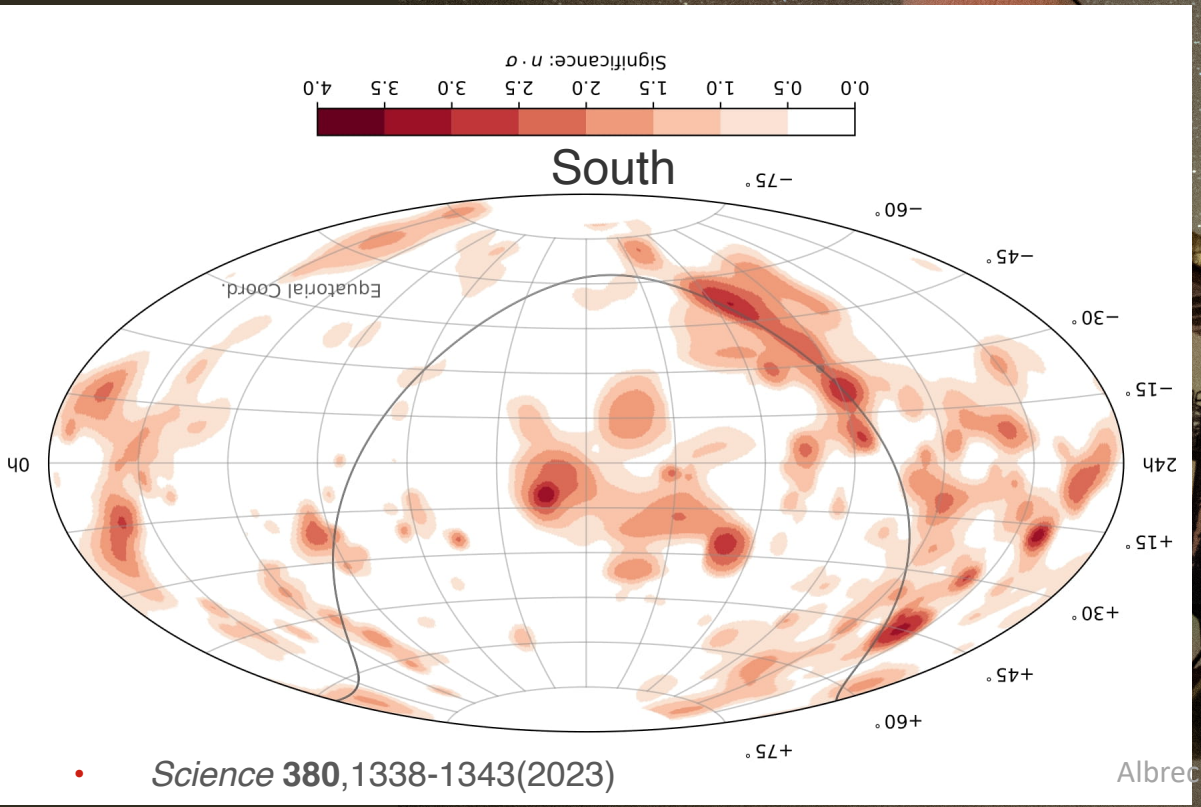
IceCube: HESE events
(selection of events with contained vertex)



https://arxiv.org/abs/2307.13878



Neutrinos from the Milky Way



- *Science* **380**,1338-1343(2023)

Albrecht Karle, UW-Madison

Credit: Yuya Makino, IceCube/NSF

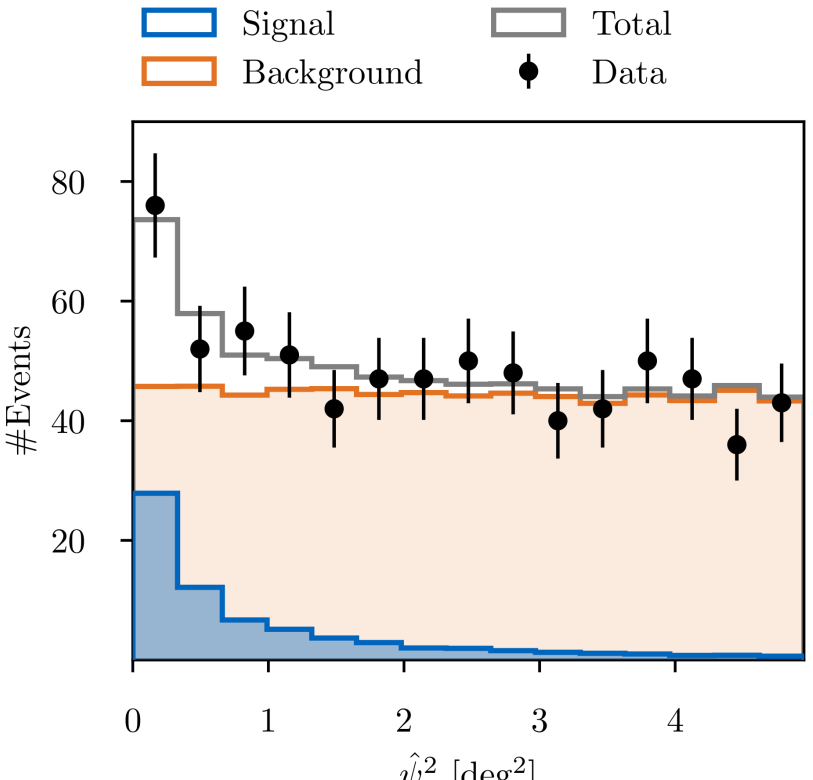
Neutrinos from the nearby galaxy NGC 1068

At the NGC 1068 location:

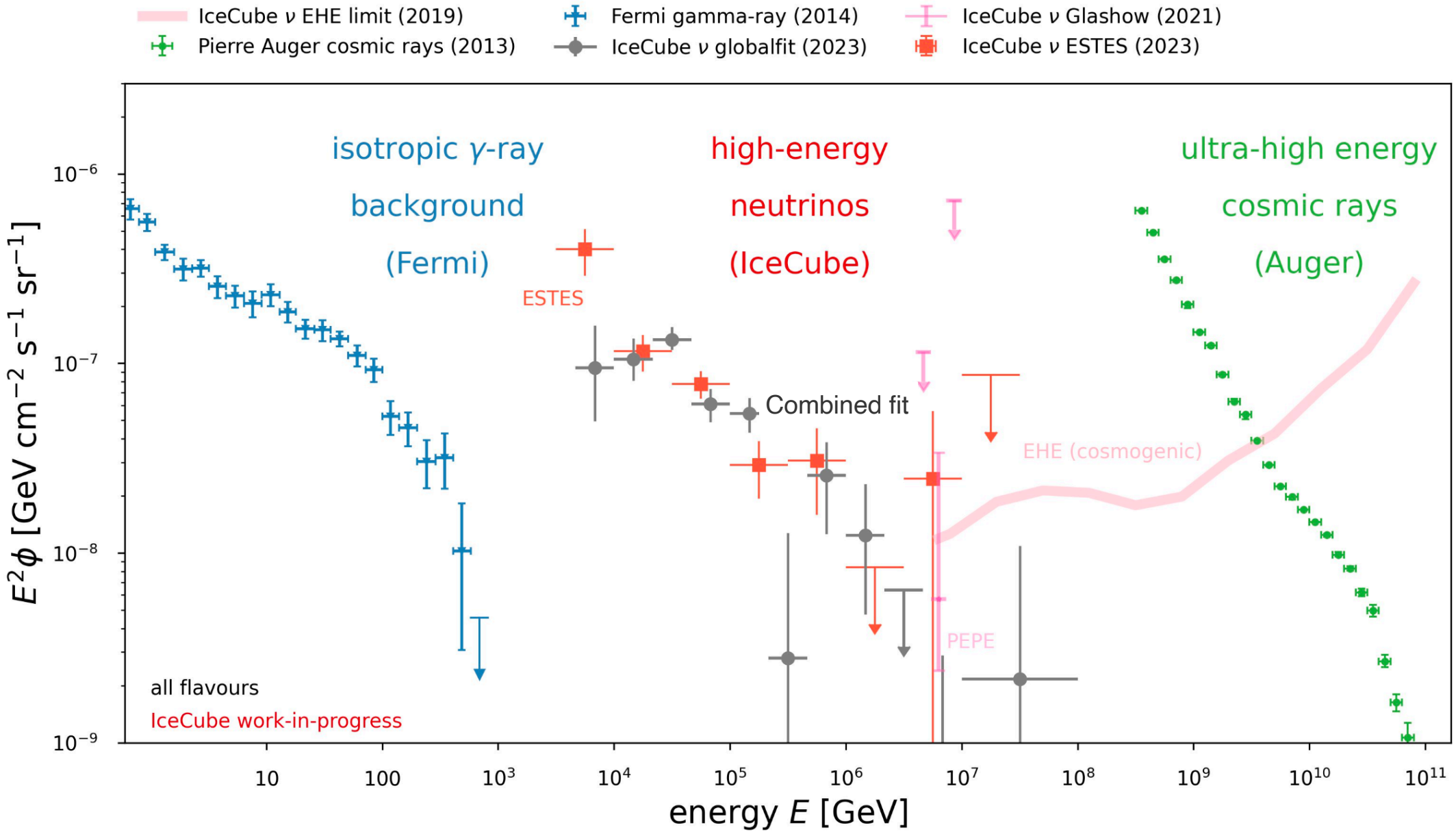
Astrophysical neutrino events = 79^{+22}_{-20}

Spectral index = 3.2 ± 0.2

Significance 4.2 sigma



Multimessenger Astrophysics - a wide energy range, especially for neutrinos



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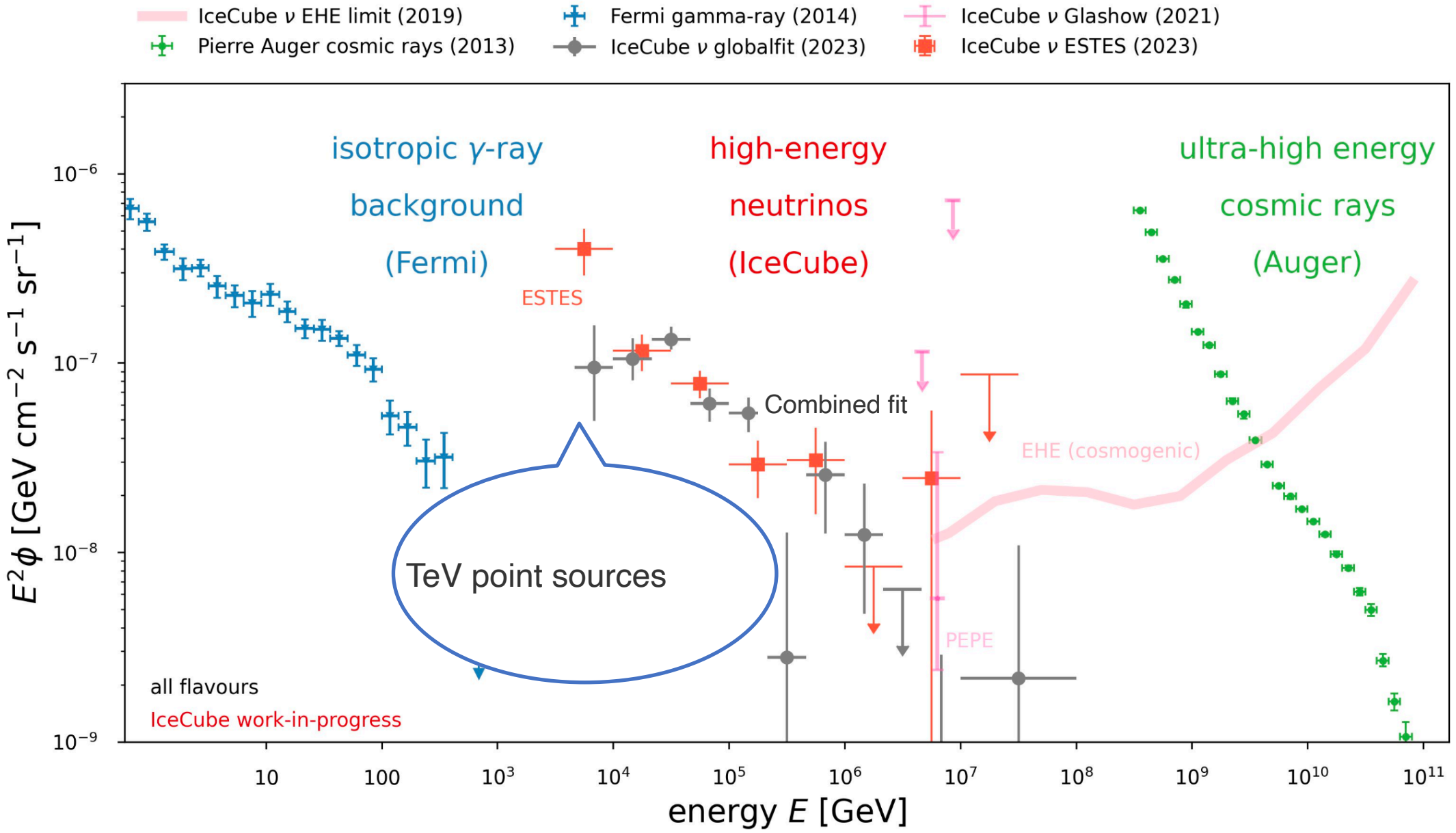

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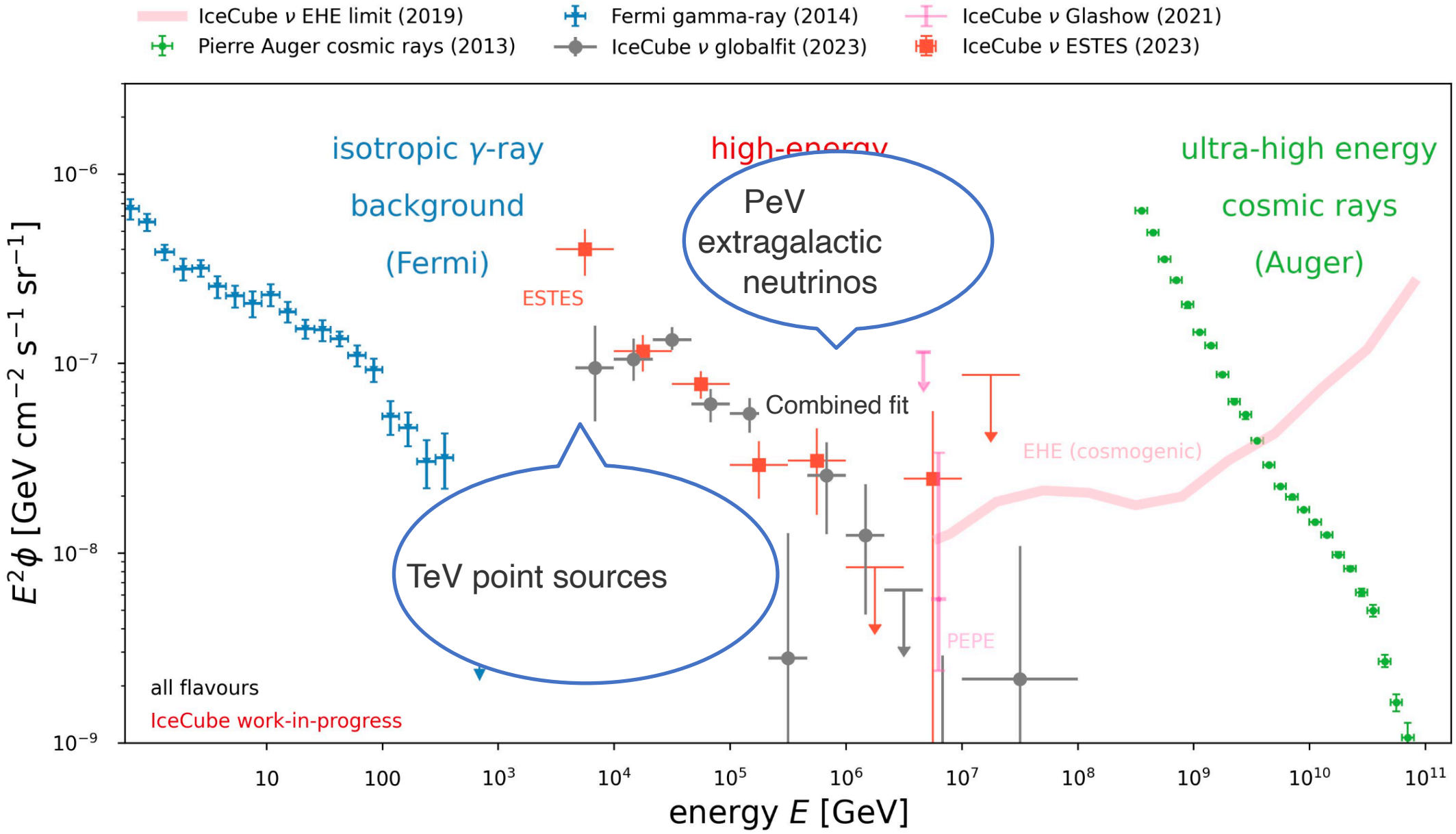

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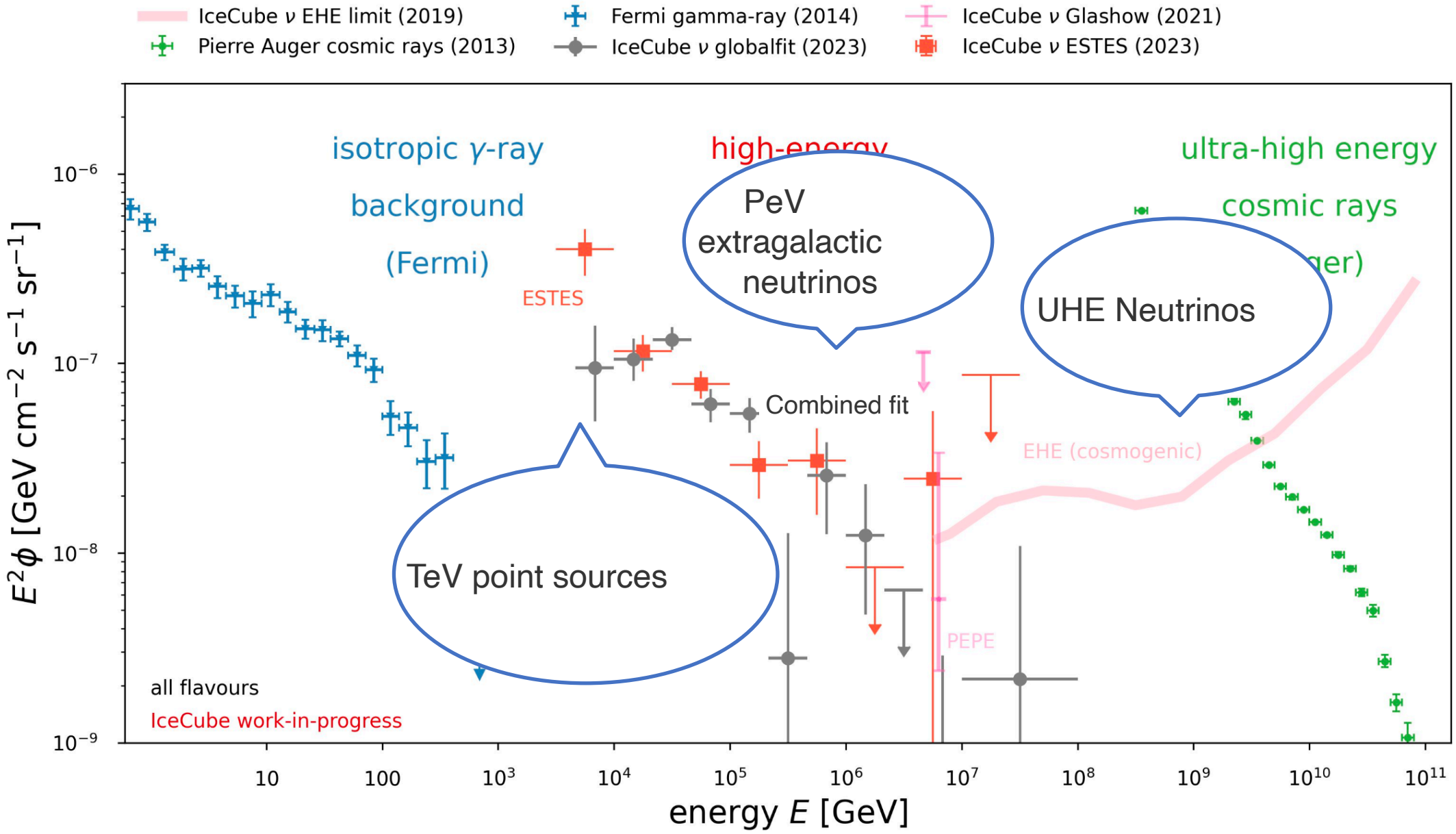

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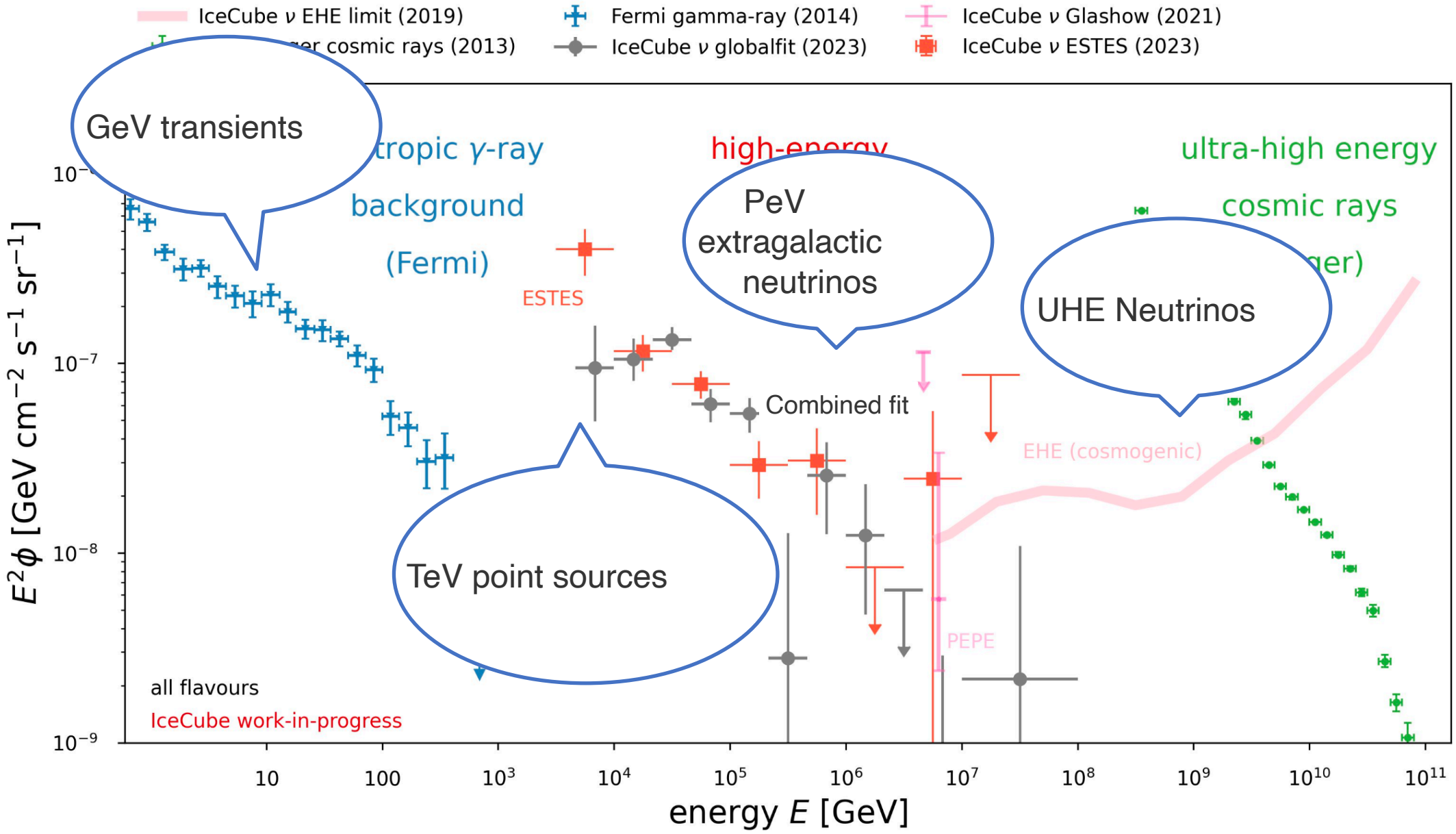
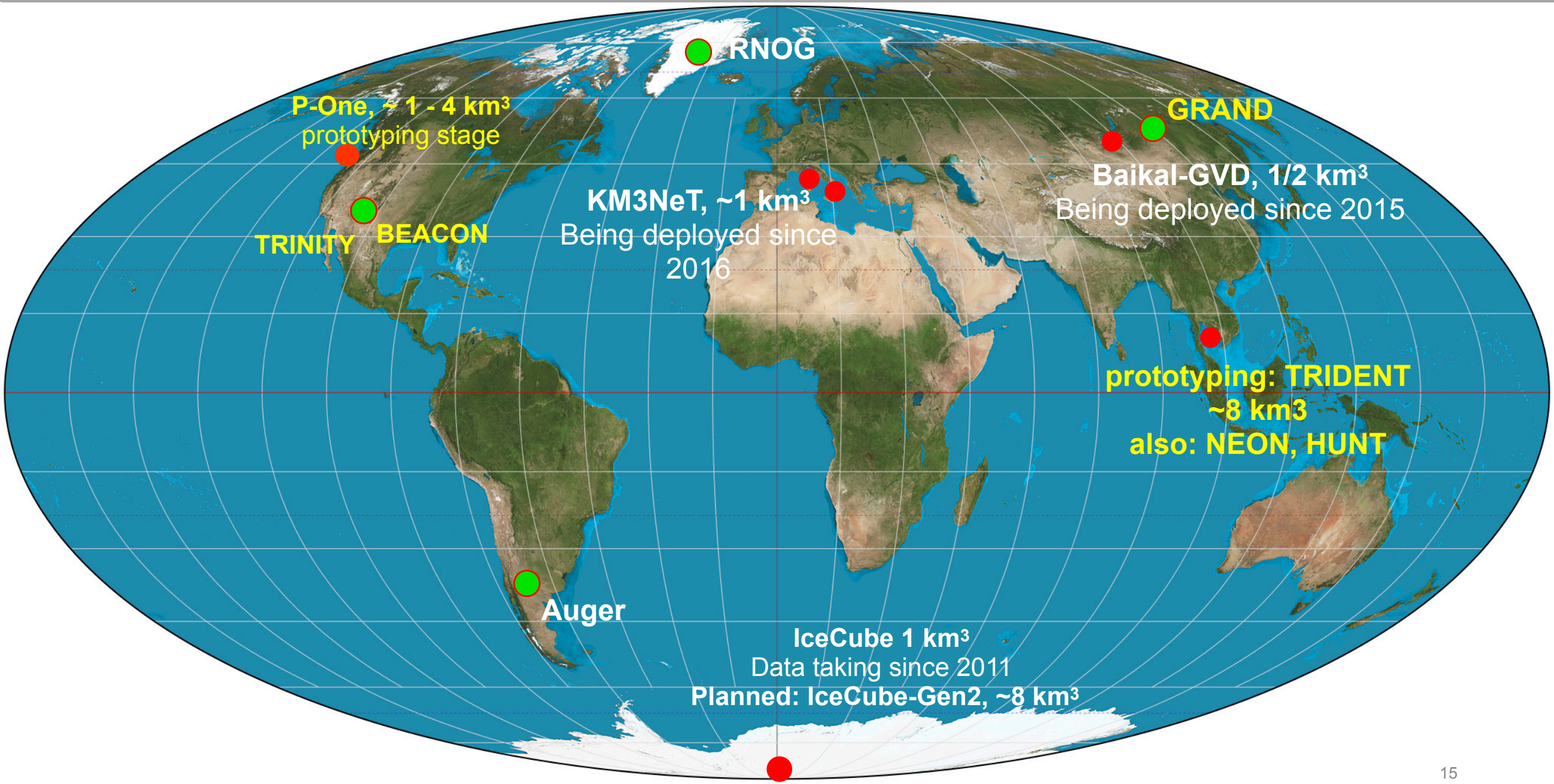


The Global Neutrino Telescope Landscape



Outline

- Neutrino astronomy: The starting point
- **IceCube, IceCube-Gen2**
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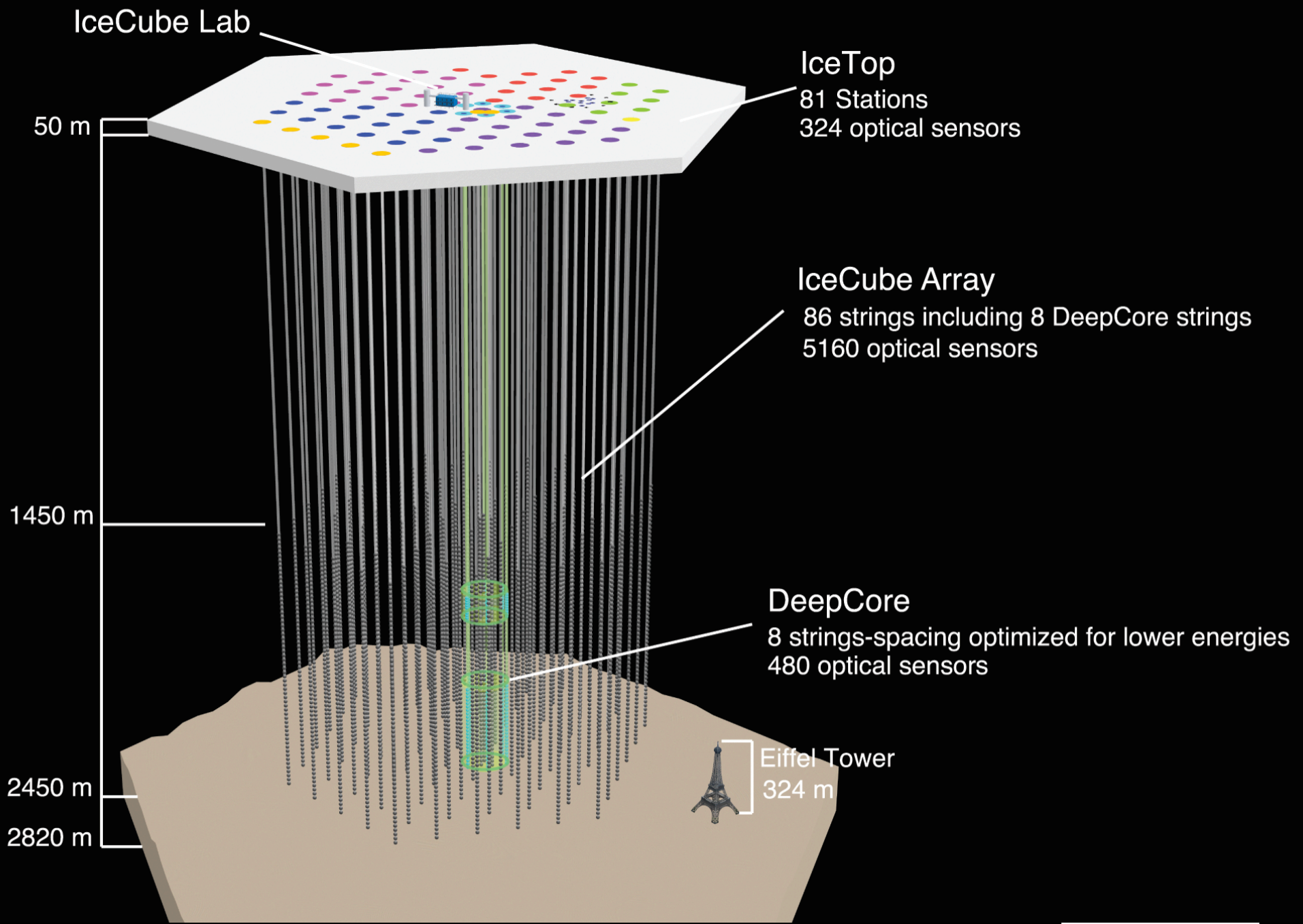
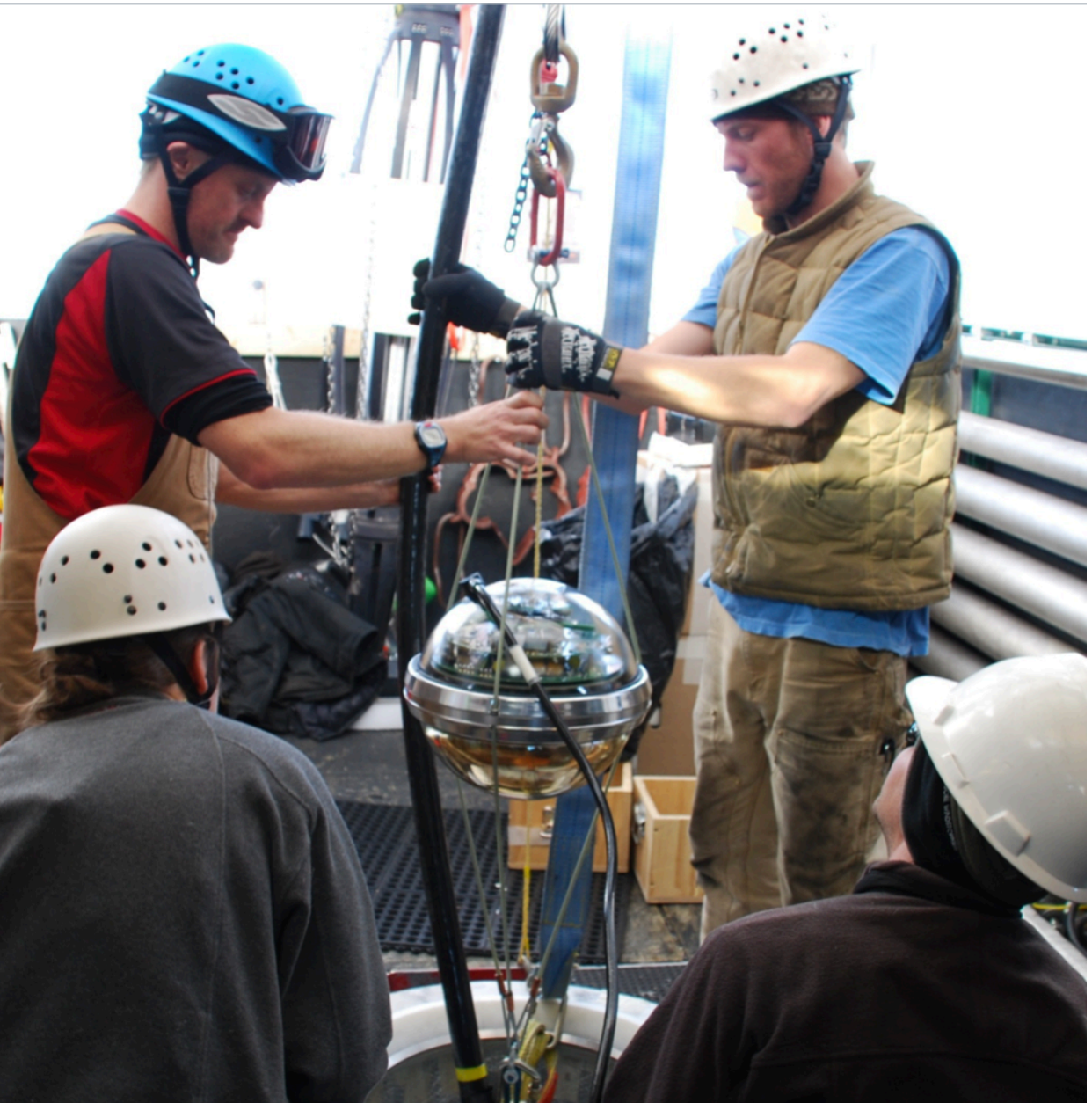
The IceCube Neutrino Observatory

Instrumented volume:
~1km^3



IceCube



Optical sensors are extremely stable

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

A good foundation for use in
—> IceCube-Upgrade and
—> IceCube-Gen2.

The IceCube-Upgrade

In progress

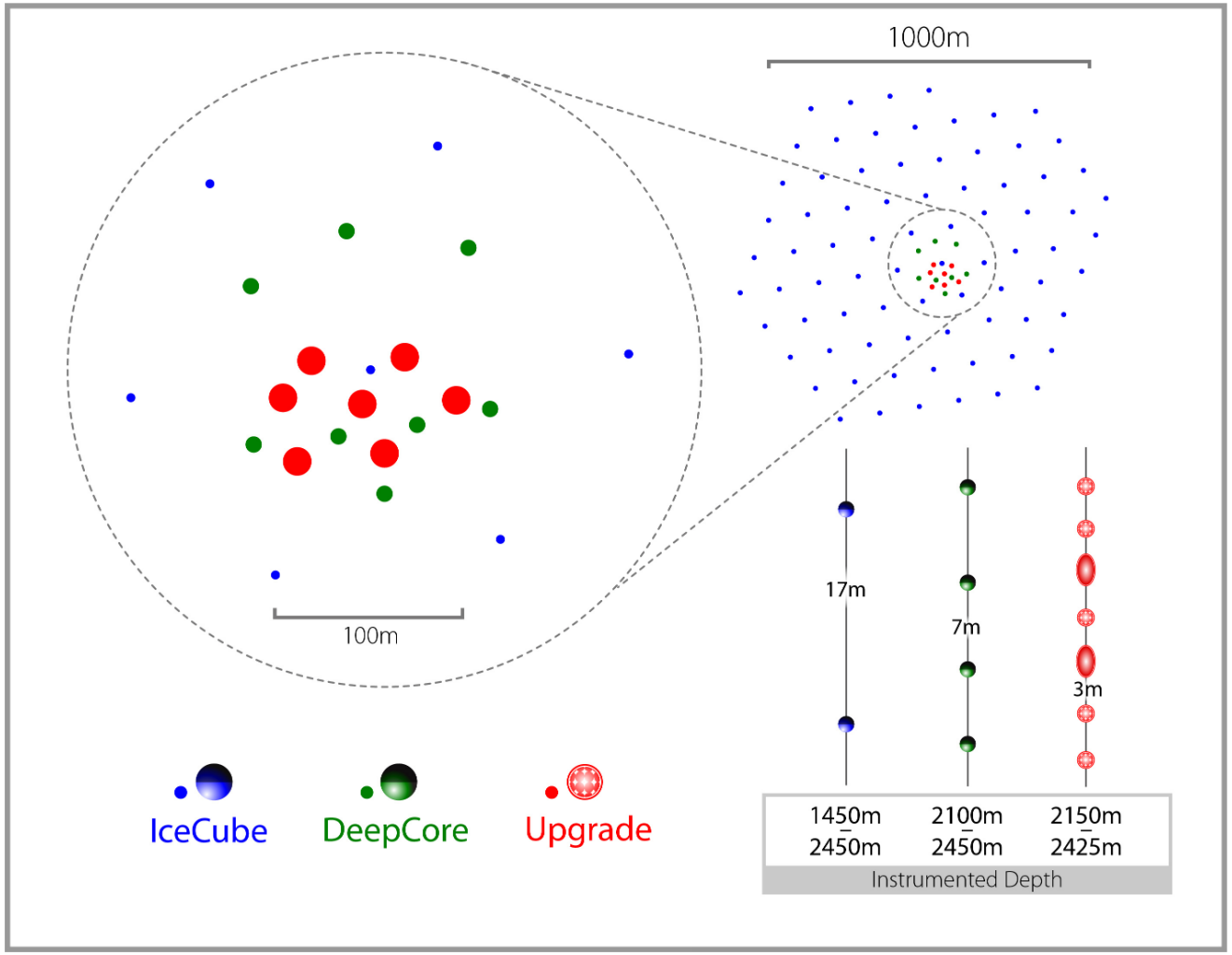
Scope:
Add 7 new strings, 700 sensors.
PMT coverage (density): 10x DeepCore

Instrumented volume: 2 Mt
Energy threshold: ~ 1 GeV

IceCube rejects muons to <1% of atmospheric neutrino rate.

Goals:

- Neutrino properties
- Improved calibration
- Phase 1 of Gen2

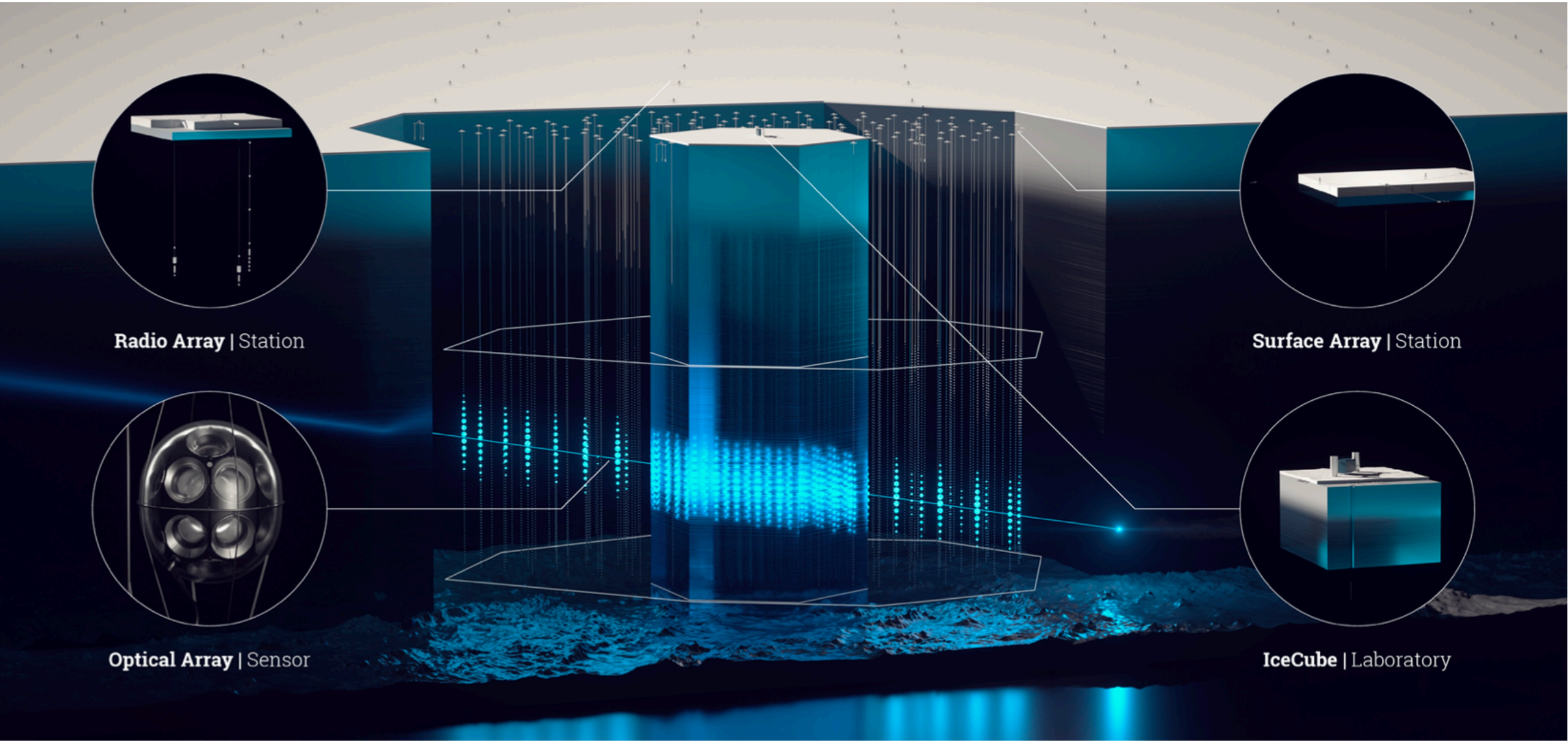


Installation: 2025/26 South Pole season.

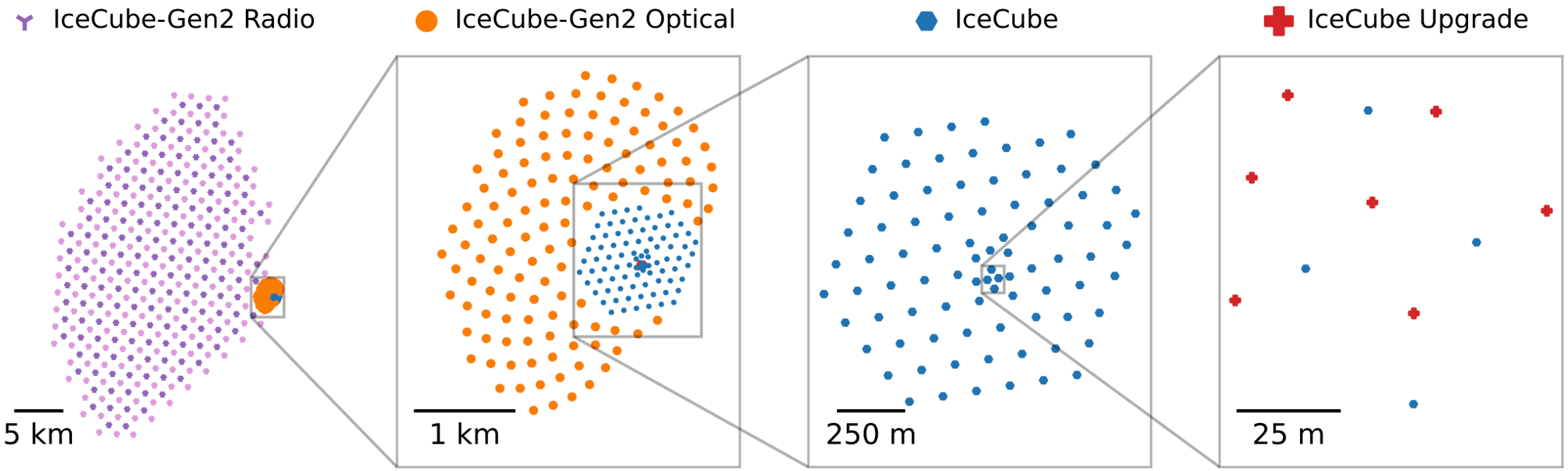
IceCube-Gen2

IceCube released a Technical Design Report

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



IceCube and IceCube-Gen2 — scales and energie ranges

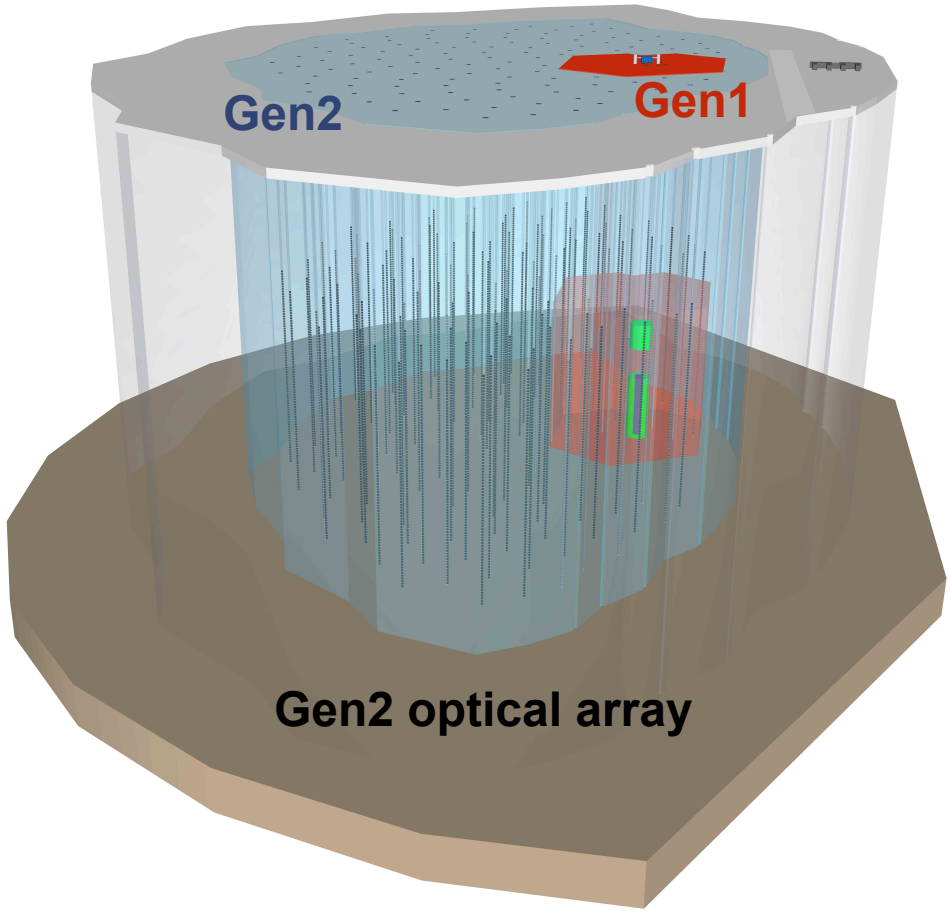


>10 PeV **> 3 TeV** **>0.5 TeV** **few GeV**

deployment in Dec. 2025

Scope: 1. The Optical Cherenkov Array

The main detector component.



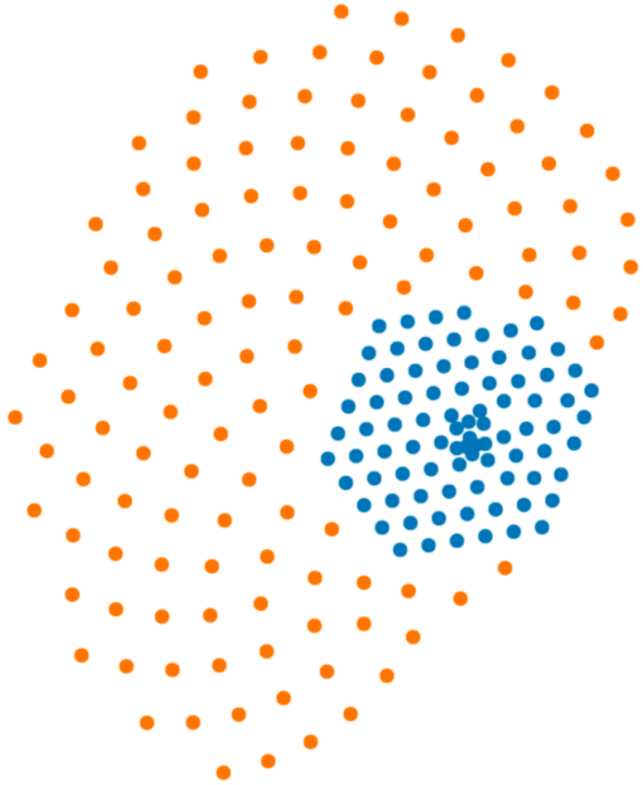
Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase

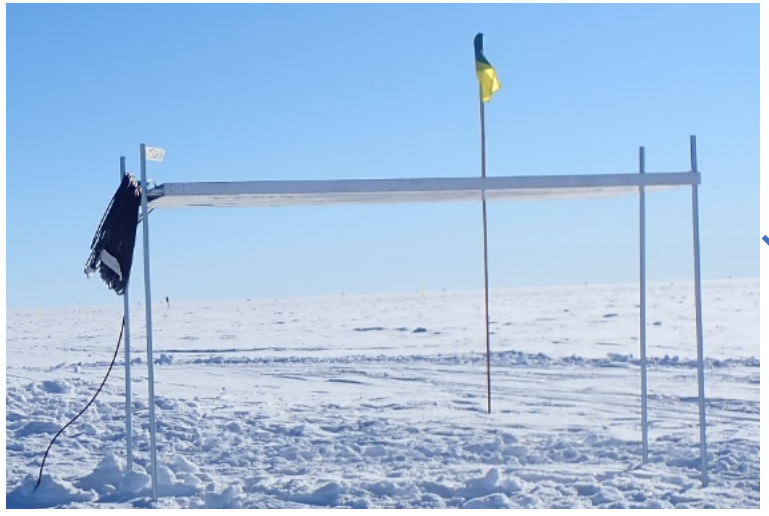
9600 optical sensors
—> 8 x Photon detection area

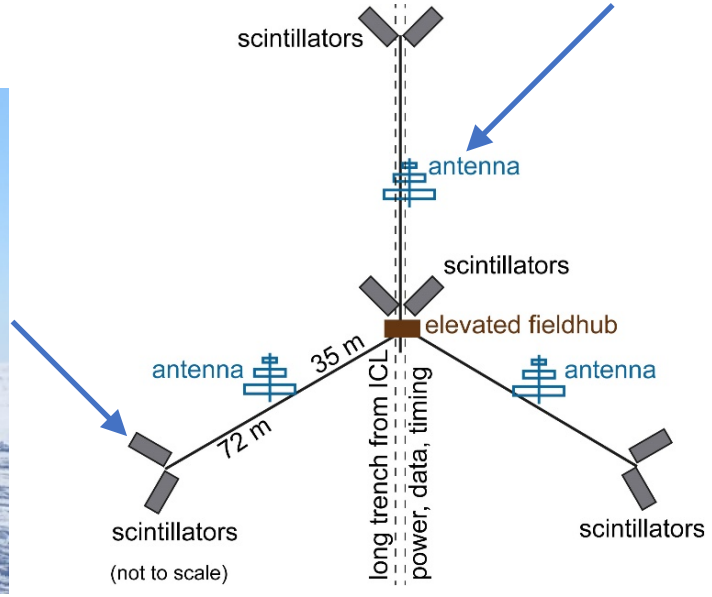
120 strings

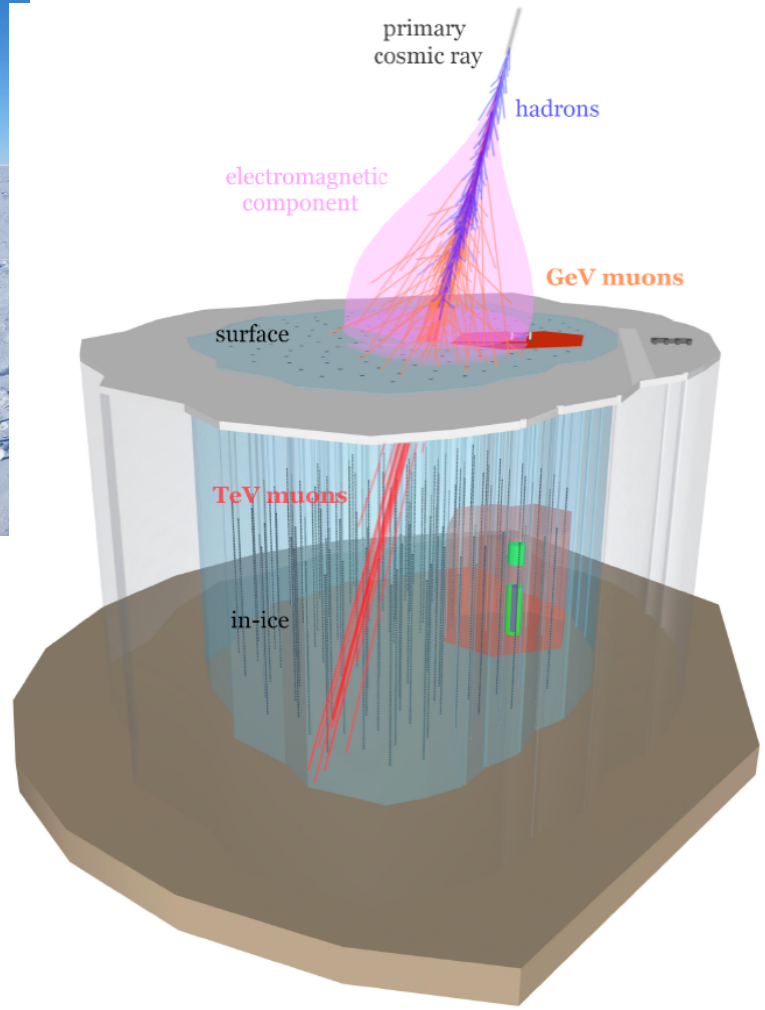


Scope: 2. The Surface Array

- 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



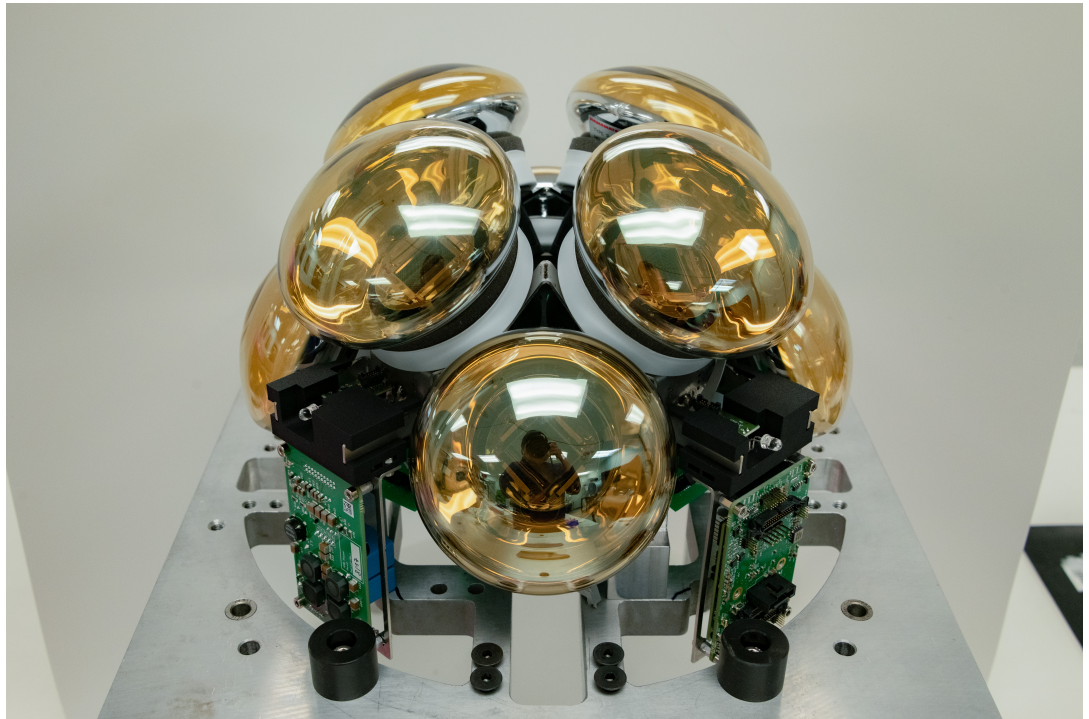


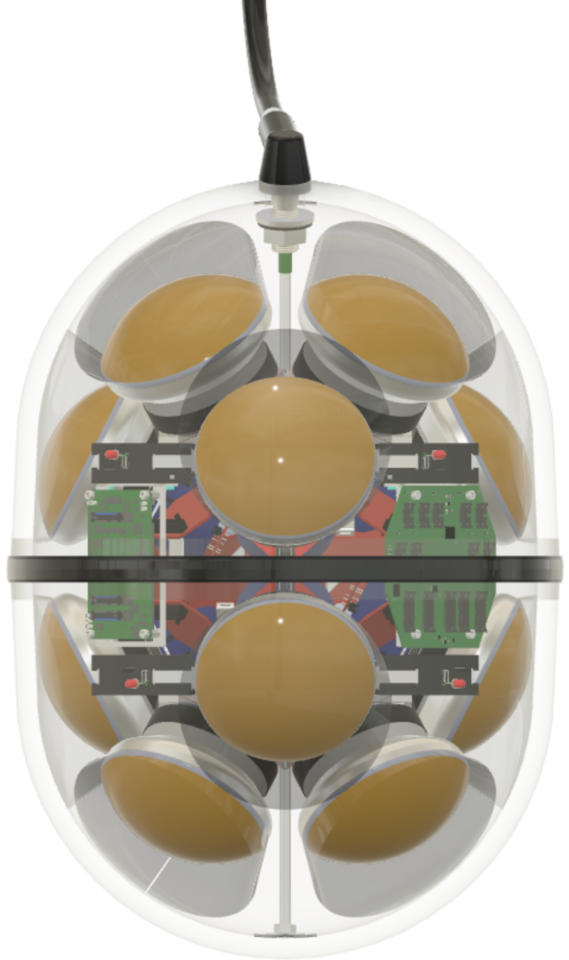


Sensor and Electronics

- **MDOM concept**
- **4-inch PMTs developed for IceCube-Gen2**

  (Hamamatsu and NNVT)
- **4 x sensitivity**
- **100 times dynamic range**
- **Less power (<5W/DOM)**





16 or 18 x 4 inch PMT
Diameter: 31 cm

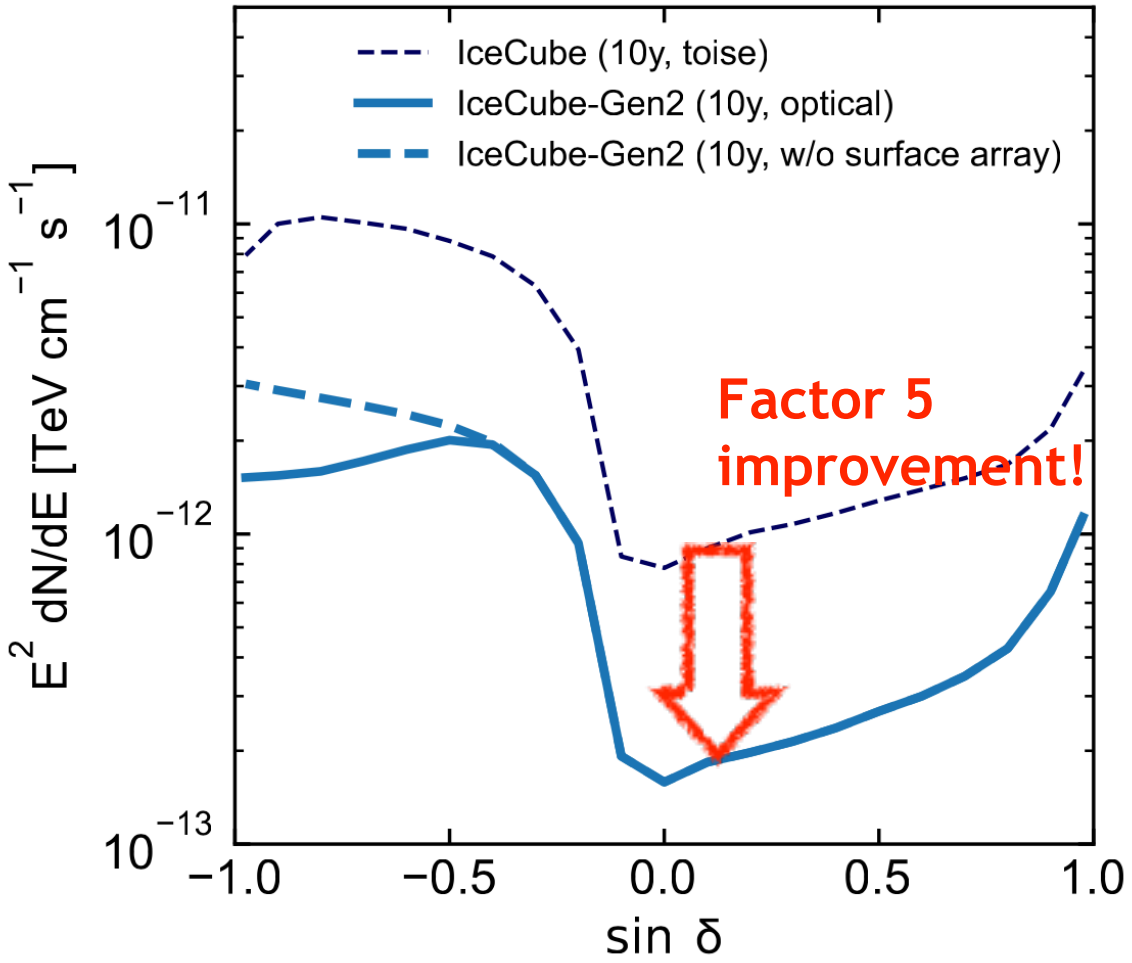
12 modules will be deployed with the Upgrade

IceCube-Gen2 sensitivity: Point sources

Angular resolution

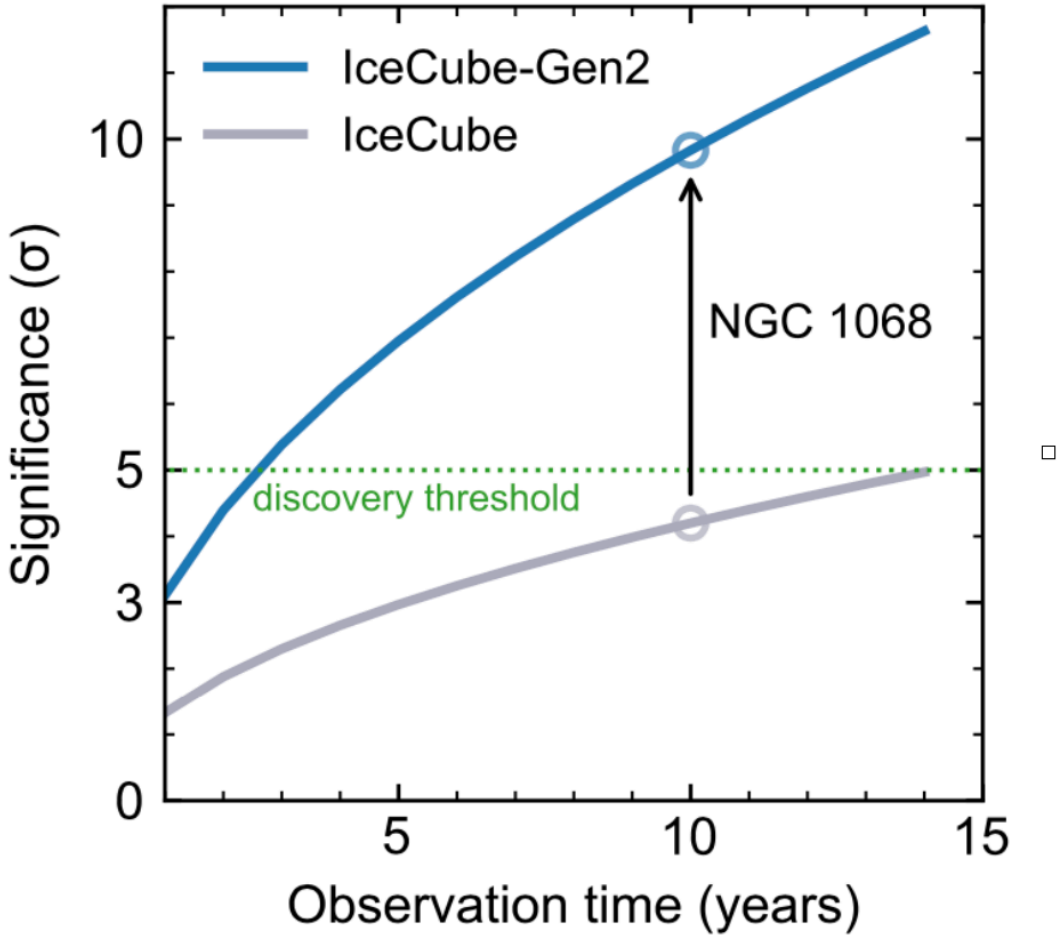
nu_mu: 0.2°
Cascades 100TeV: 3°

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

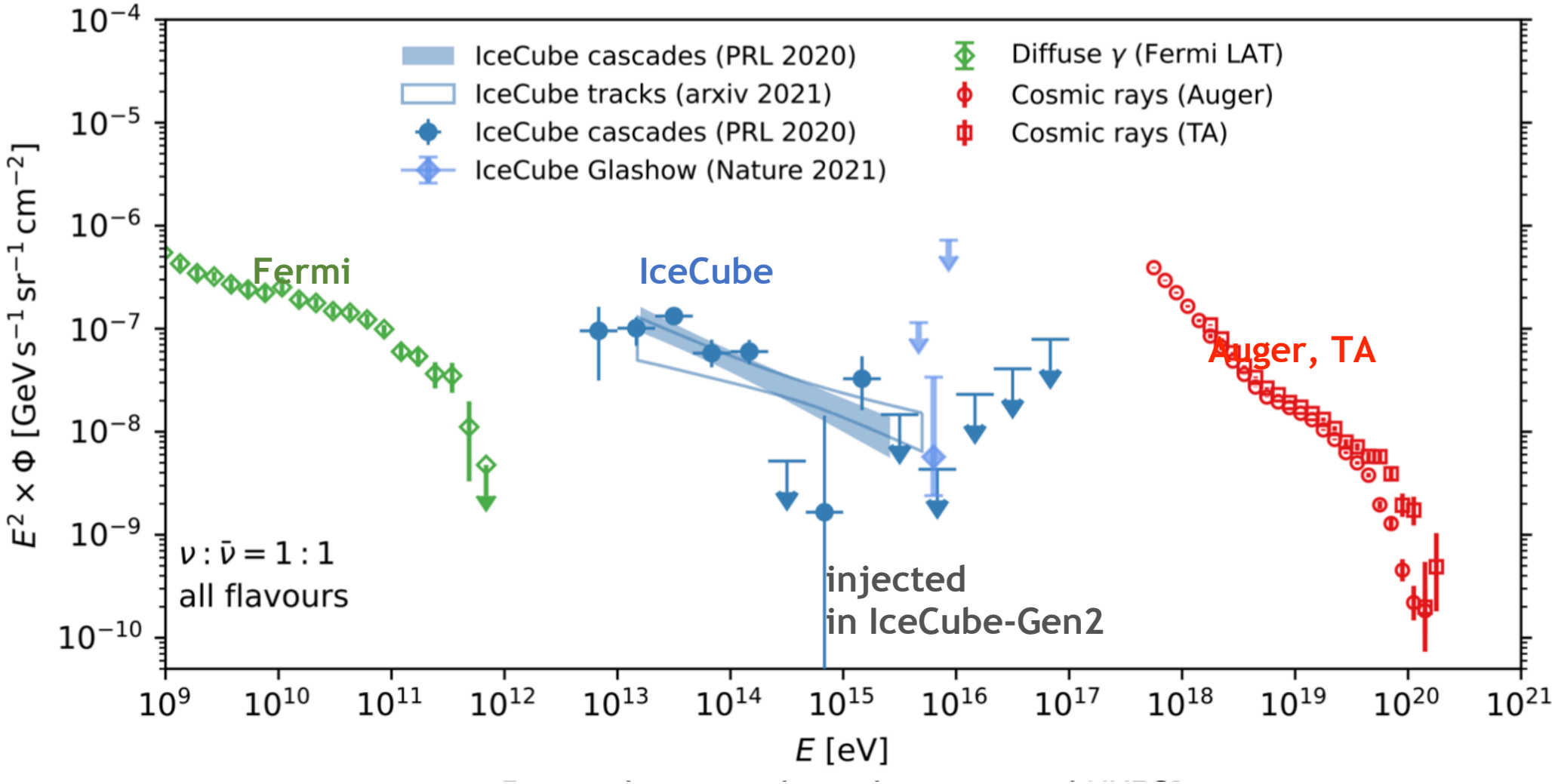


How would NGC 1068 look in IceCube-Gen2?

5 sigma in < 2 years
10 sigma in 10 years.



Understanding cosmic particle acceleration through multimessenger observation



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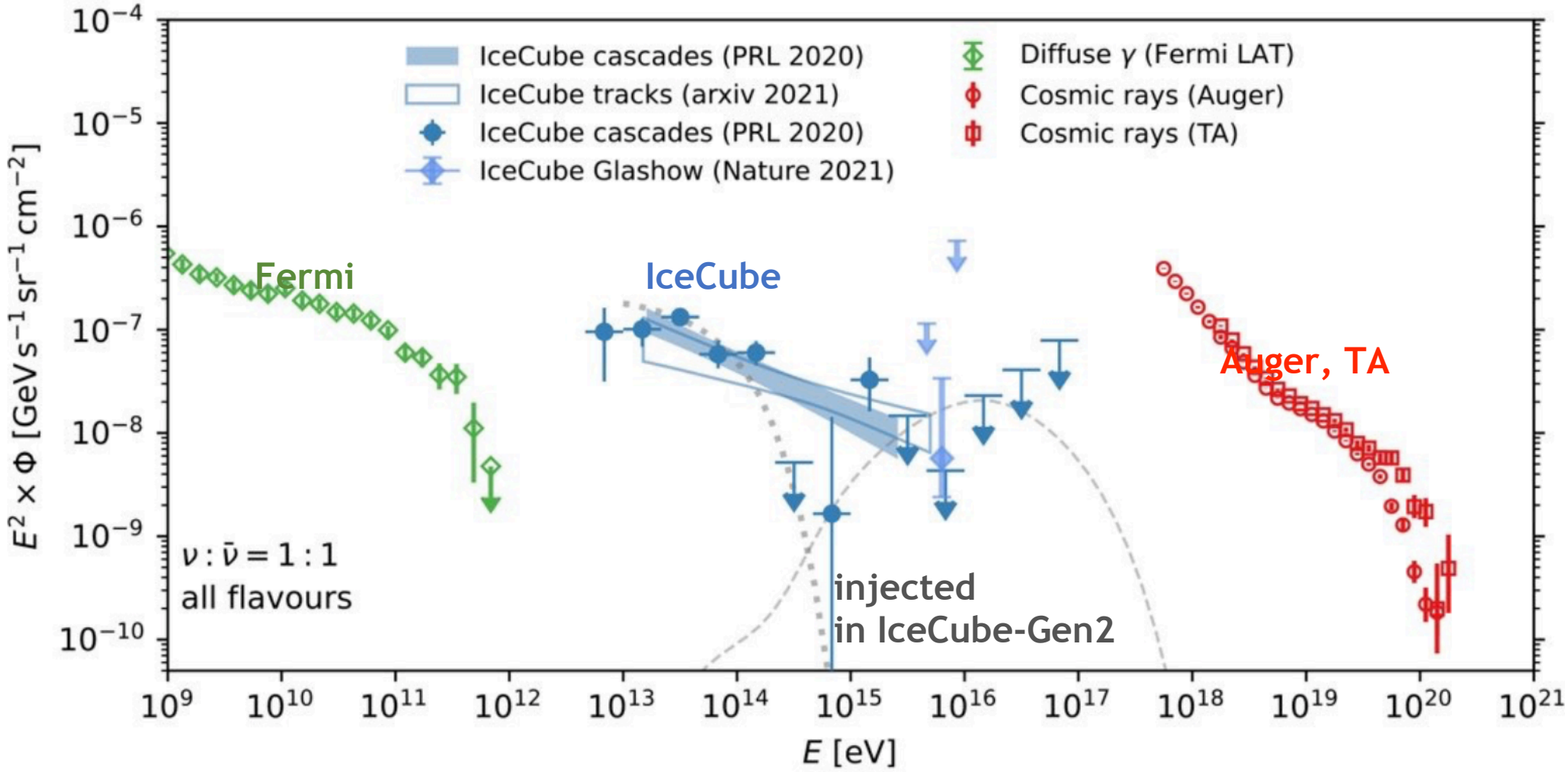
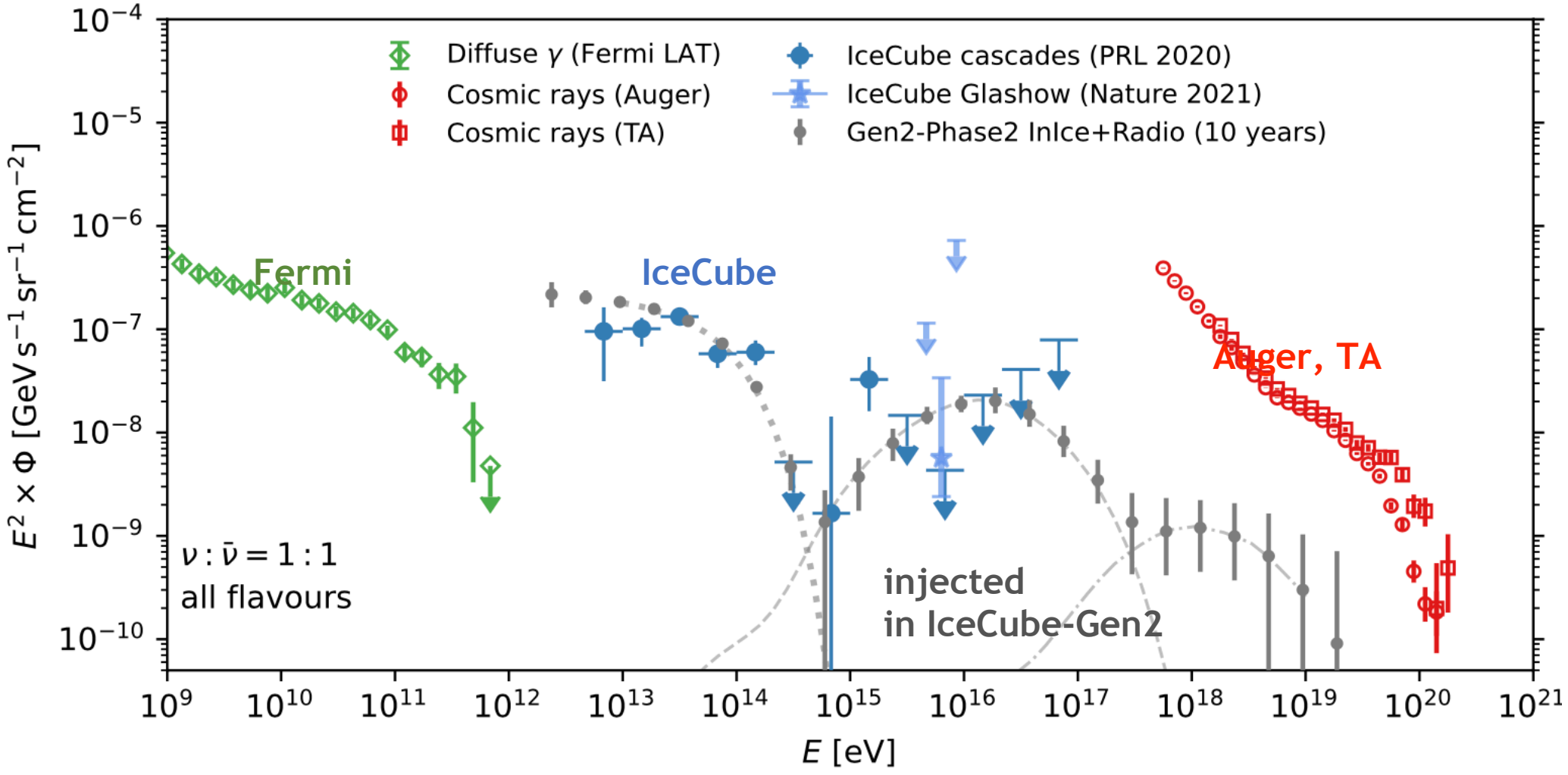
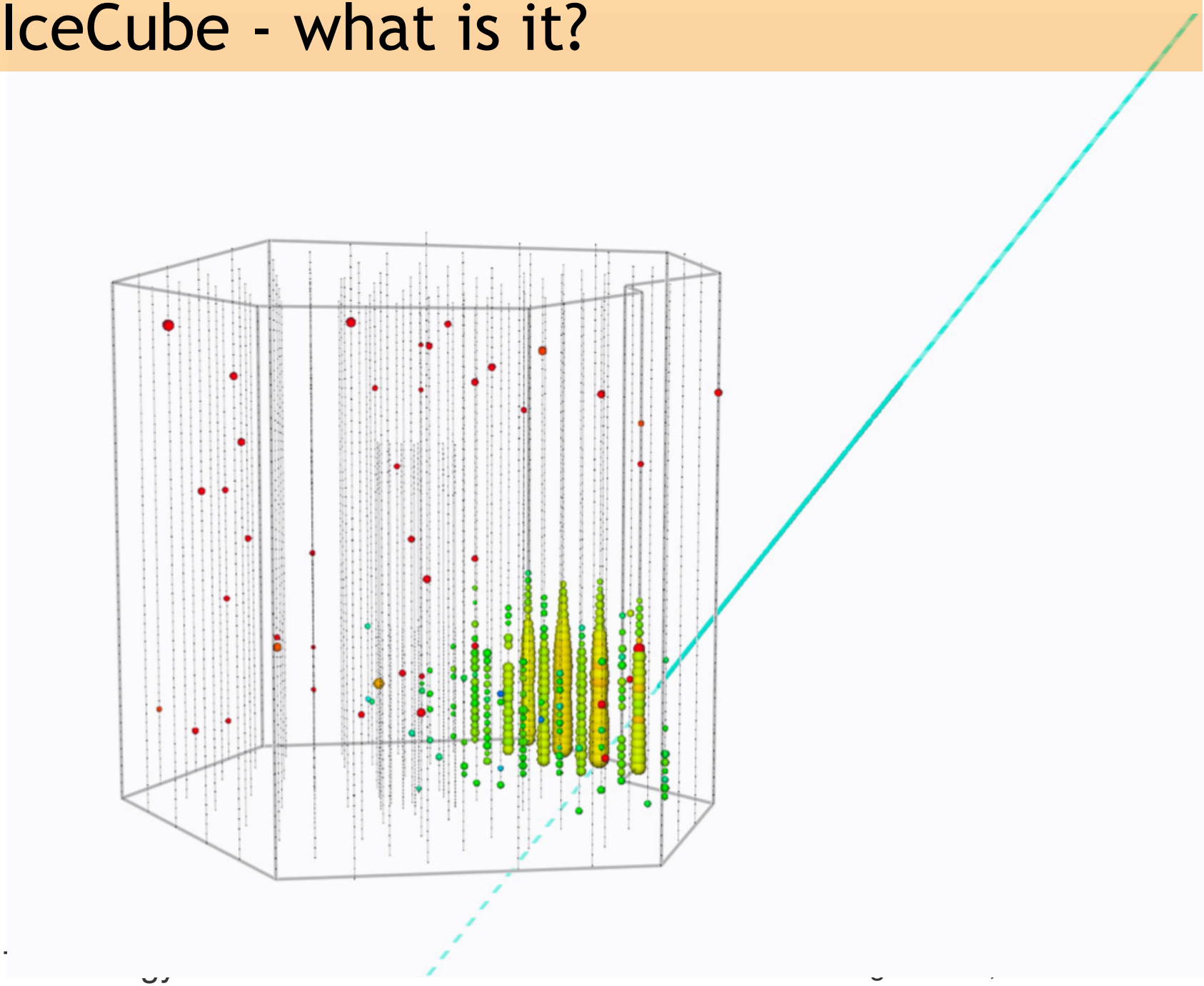


A common origin with UHECR?

Understanding cosmic particle acceleration through multimessenger observation



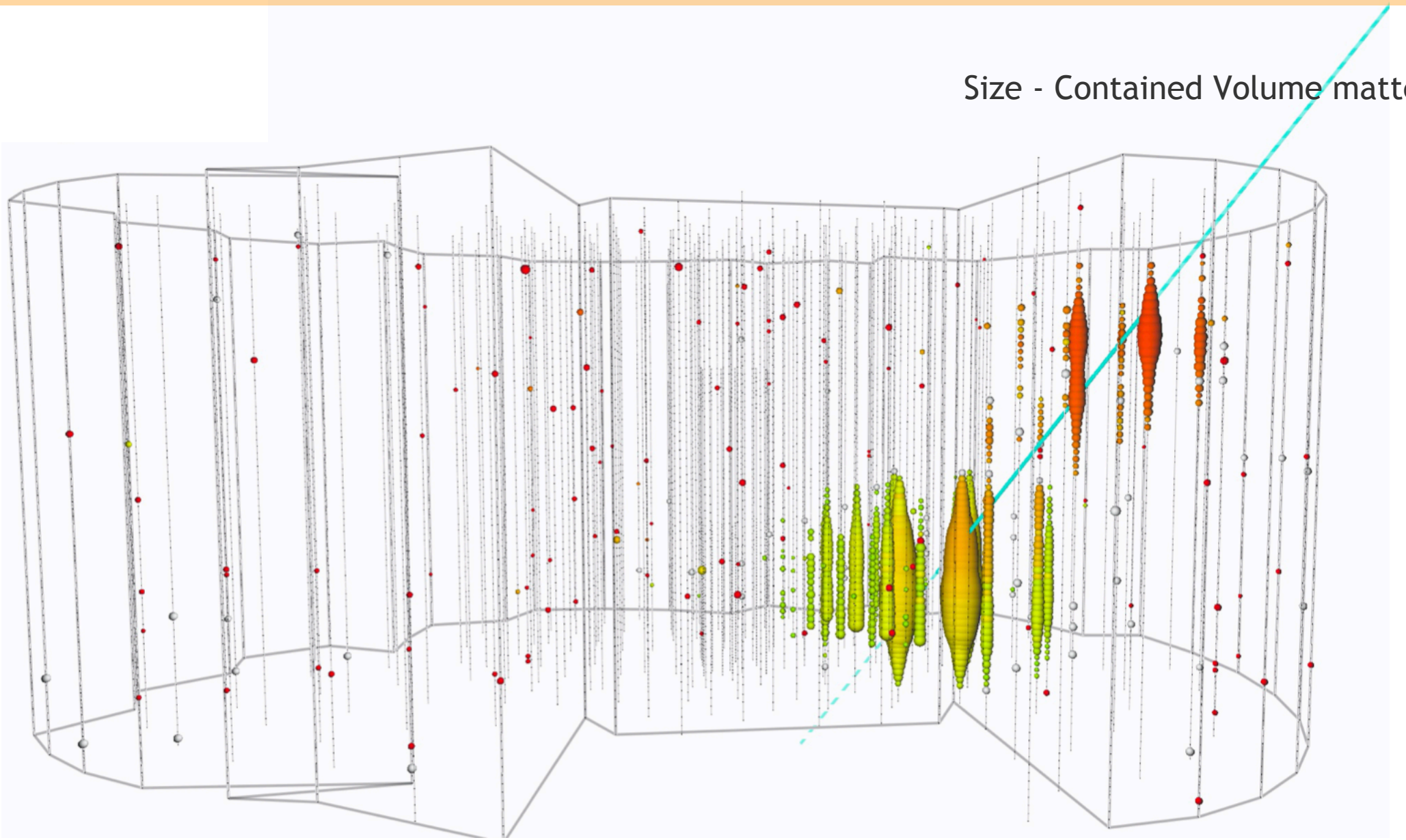
A simulated event in IceCube - what is it?



Currently: have ~2 events at the 100

The same event in IceCube-Gen2

Size - Contained Volume matters.



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

credit.: Lu Lu, IceCube

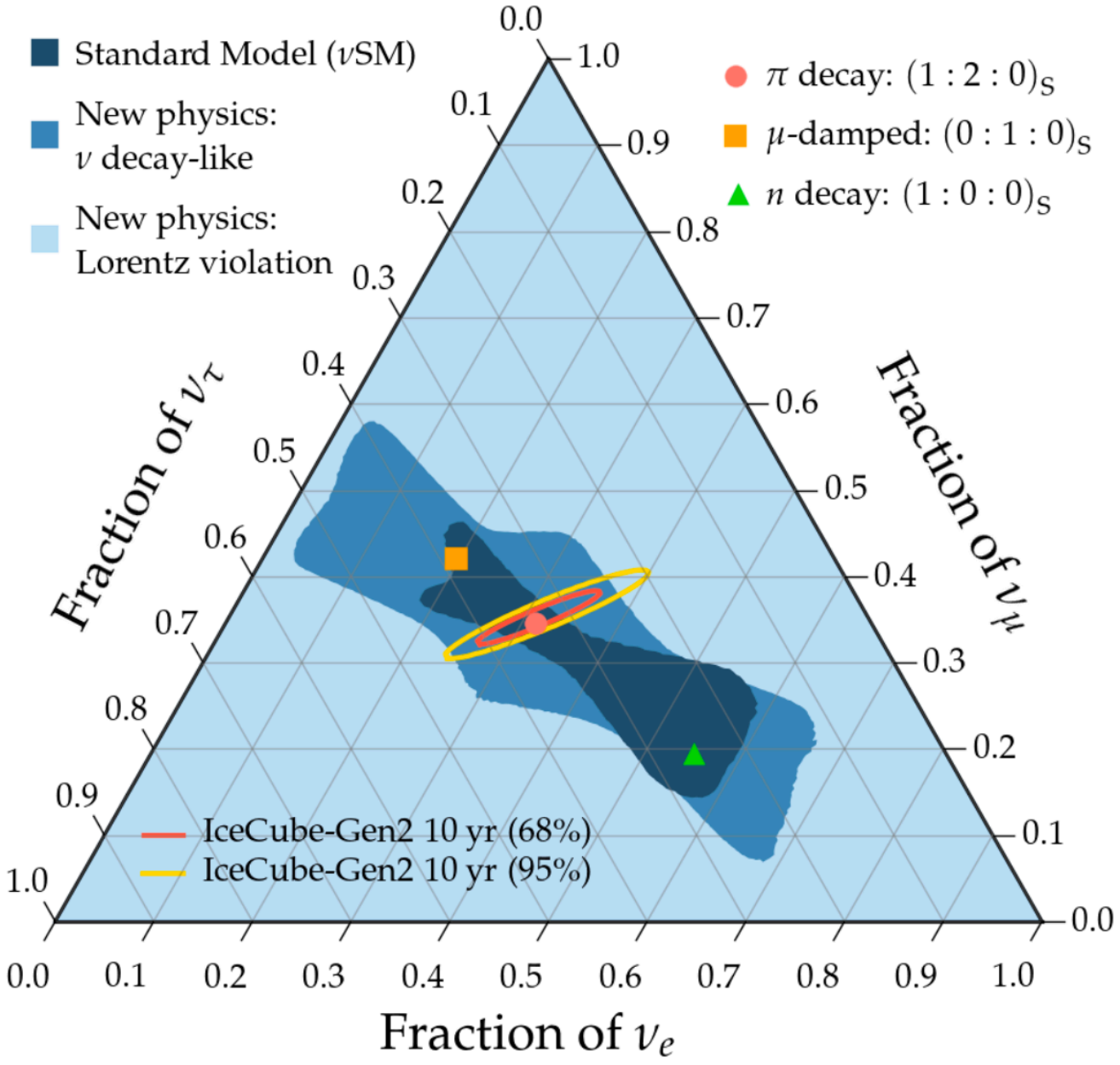
IceCube-Gen2: Flavor ratio <—> BSM

Particle ID

Oscillations of PeV neutrinos over cosmic distances:

- **understanding sources**
- **BSM Physics**

—> Mauricio Bustamante's talk.



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

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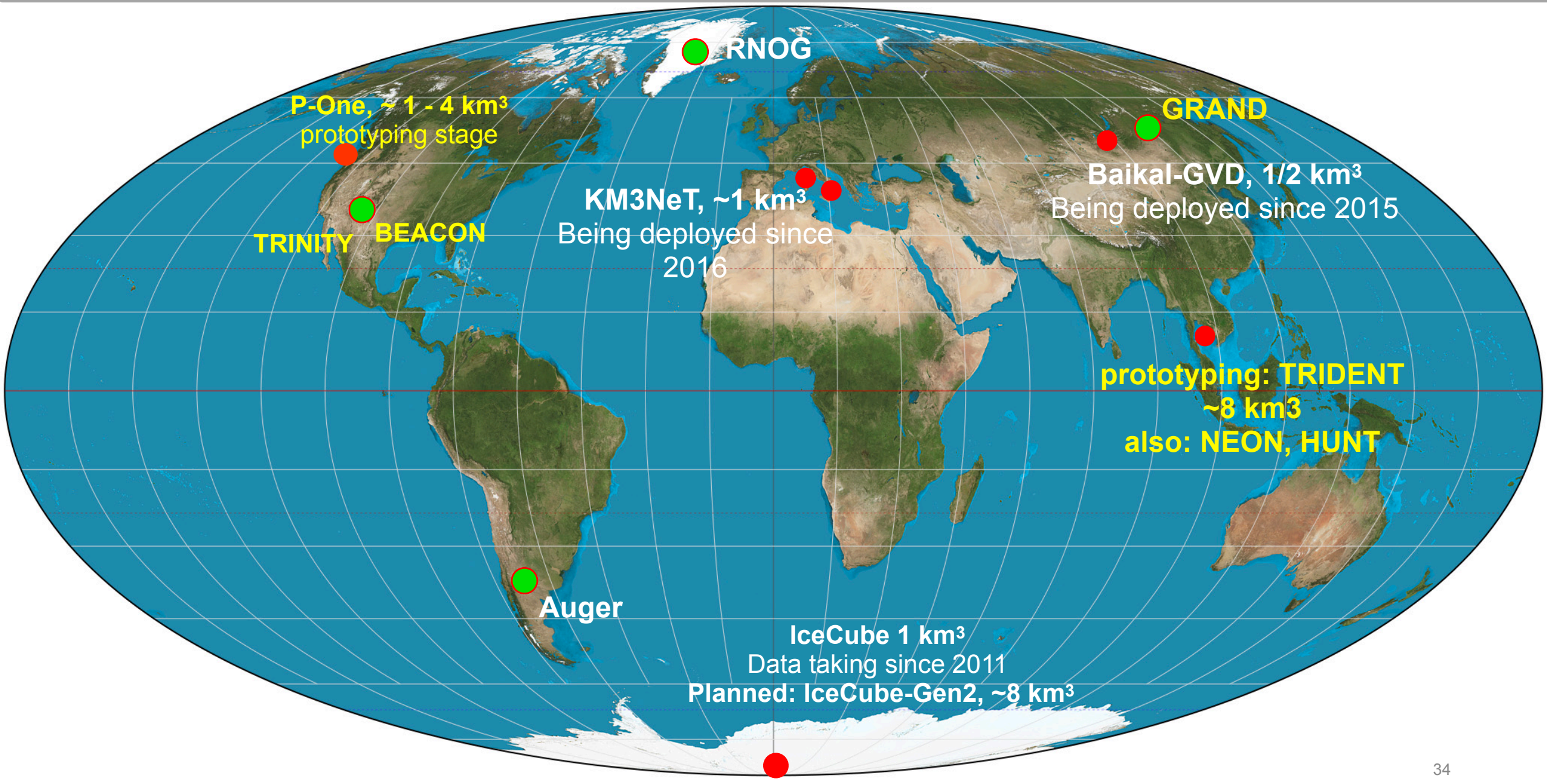
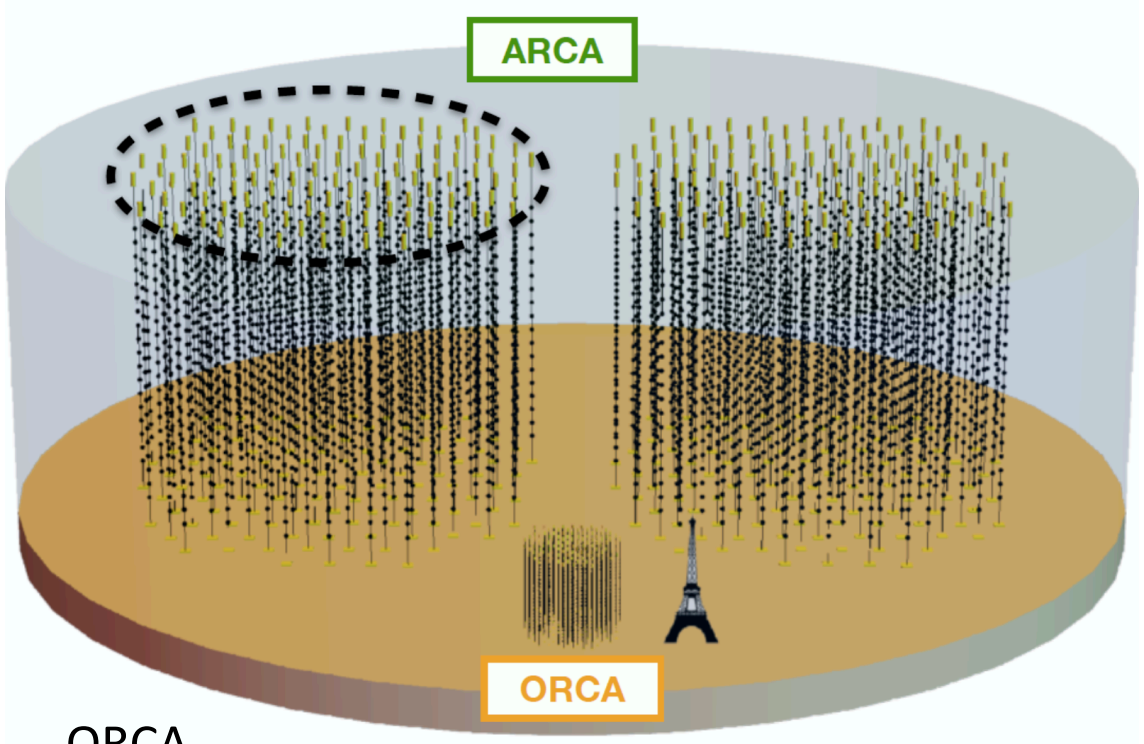


KM3NeT

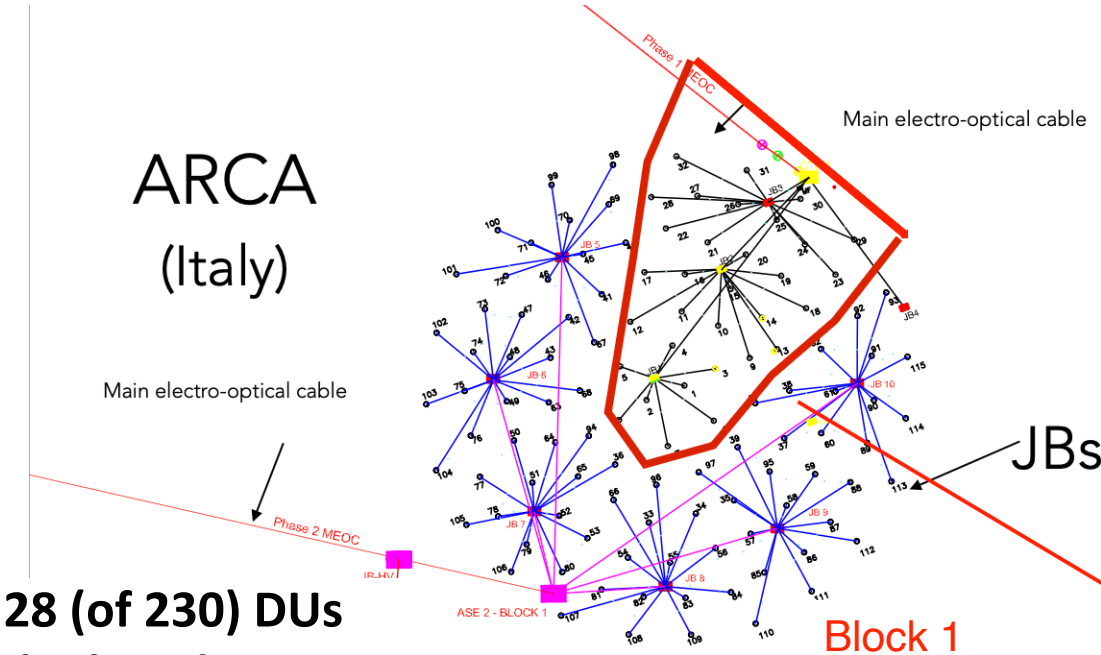
ARCA
100 km from Sicily
Instr. Mass: 2 × 0.5 Gt

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

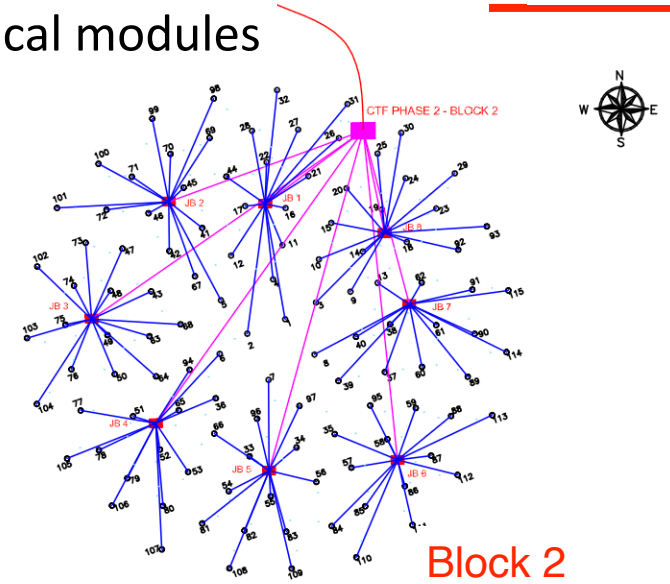


ORCA
40 km from Toulon, France
Instr. mass: 5-8 Mtons
status: 11 of 115 DUs deployed

ARCA
(Italy)



28 (of 230) DUs deployed
504 optical modules

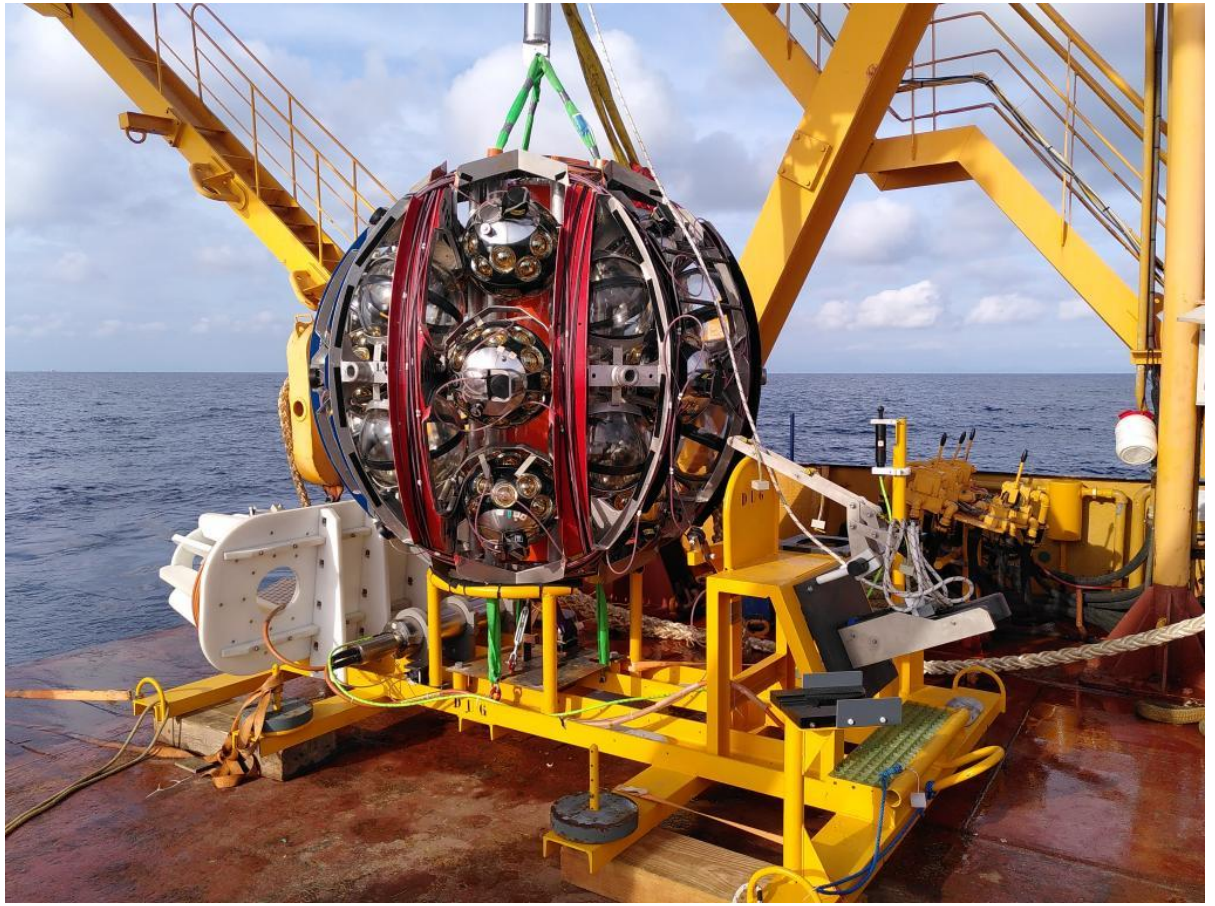


KM3NeT - Optical Sensor and construction

- 31 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:

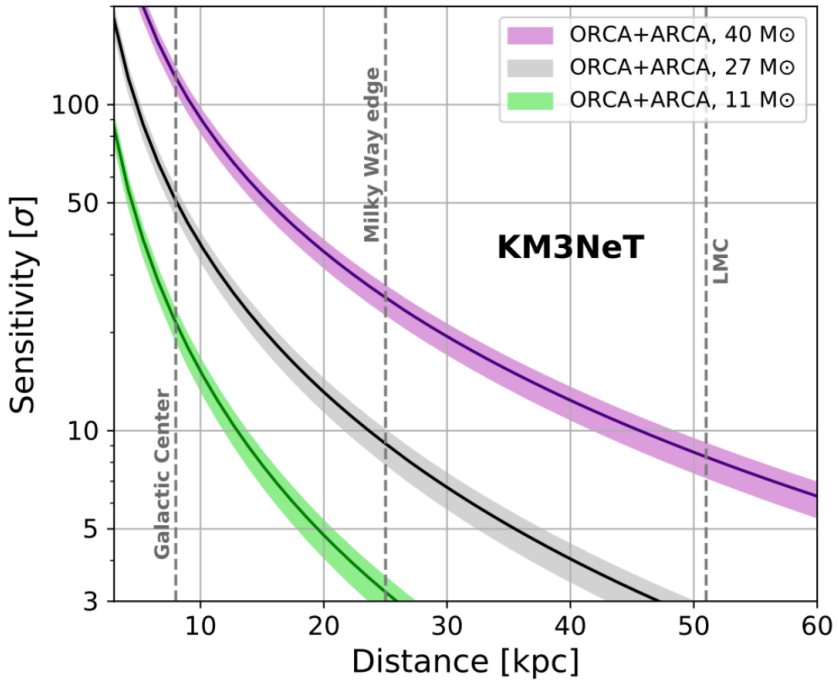
  A sphere of spheres.



KM3NeT - Optical Sensor and construction

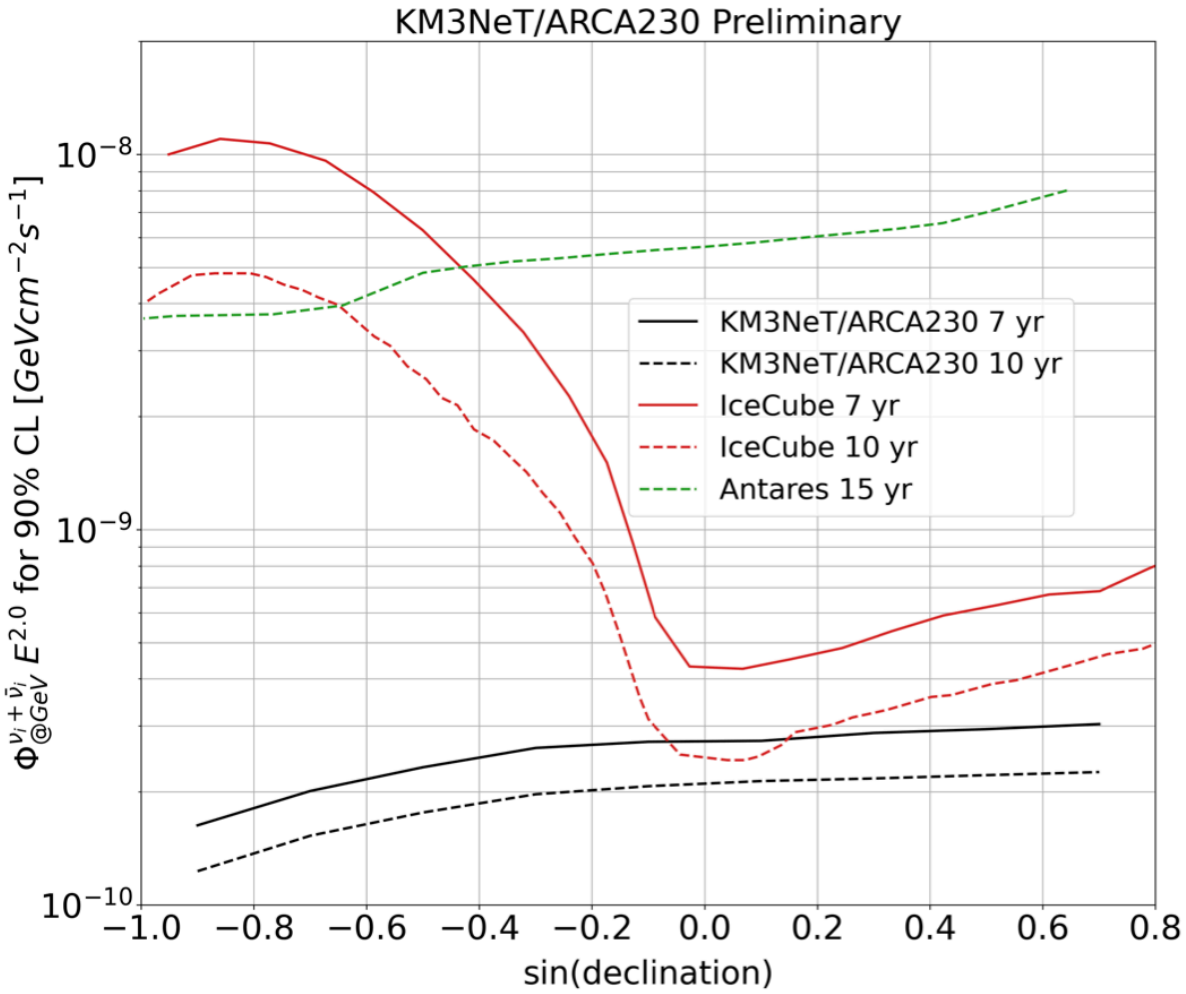
- A milestone on Supernova detection in water

Demonstration of multi-PMT potential to reject noise from sea water.



>5σ for ARCA+ORCA for 27M⊙ at a distance <35kpc

- Projected sensitivity to E^-2 point sources



Baikal GVD

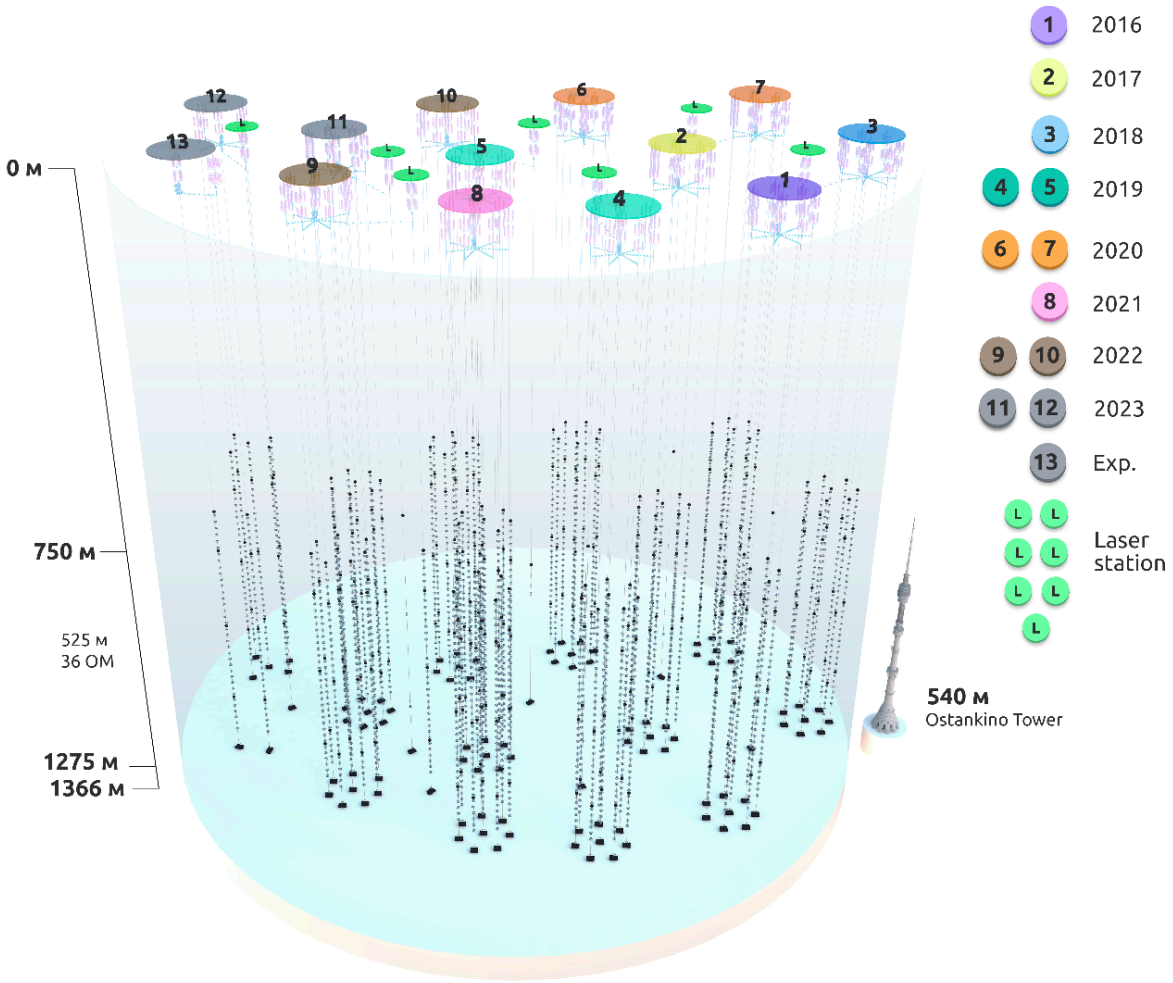
- Lake Baikal, Siberia
- Deployment in March/April from ice cover
- Clusters with 8 strings, each with 36 10“ PMTs

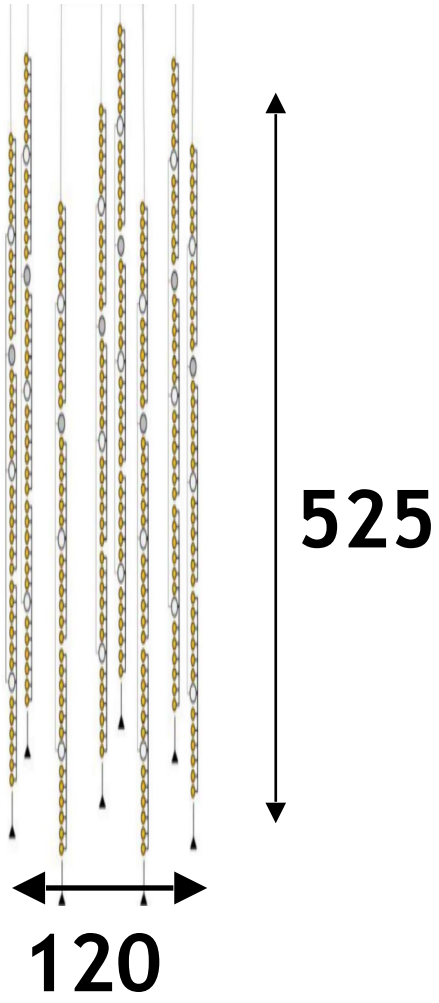
Baikal GVD - in construction

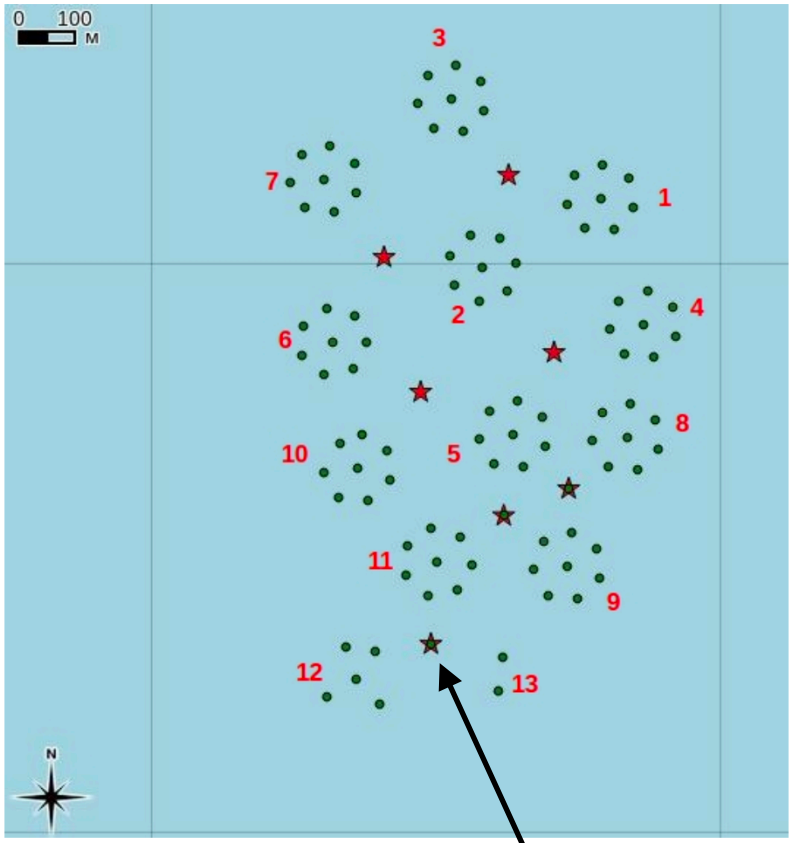
In construction since 2015.
Status fall 2022:
12 of 18 stations deployed

18 Clusters of 8 strings with 36 sensors each

Instrumented volume: ~1/2 km3



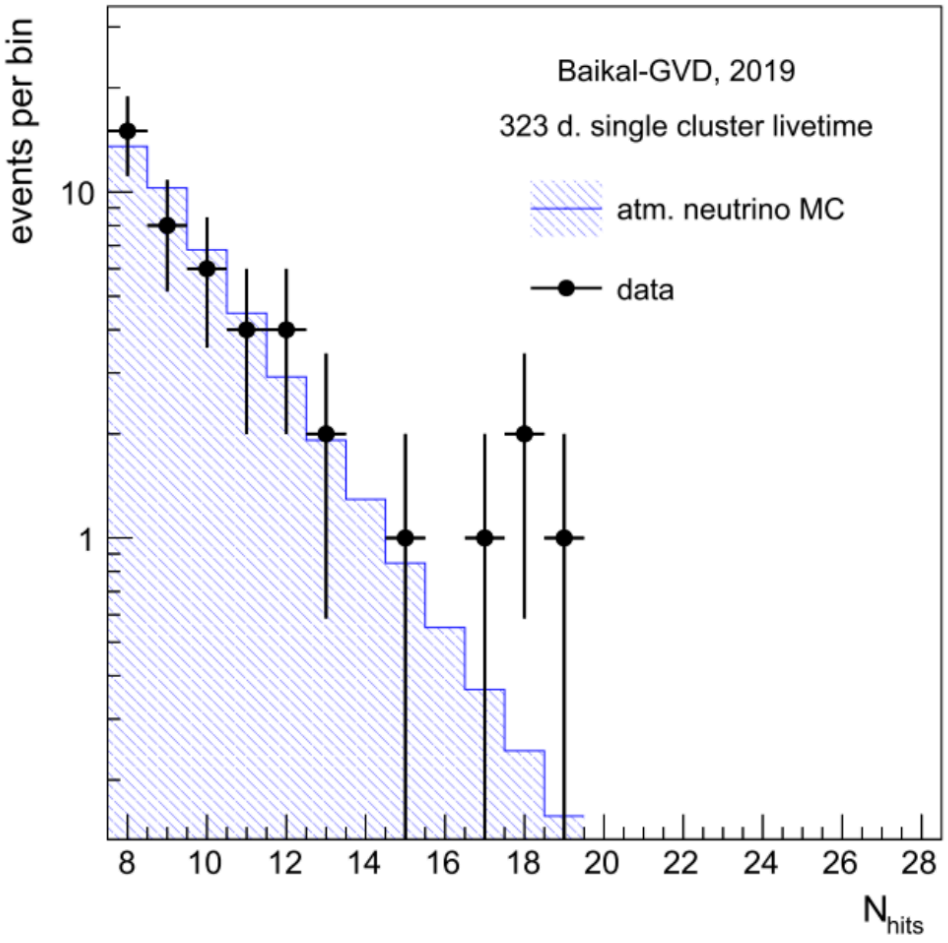




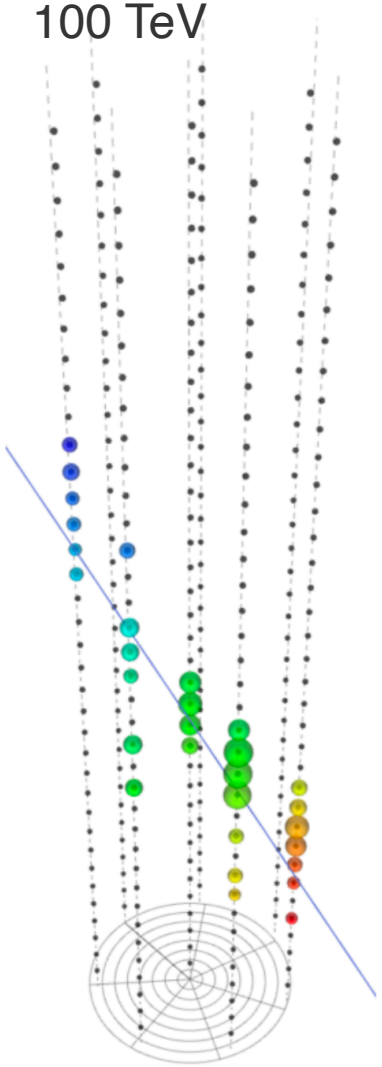
Baikal GVD - data

Reject background at 3 sigma

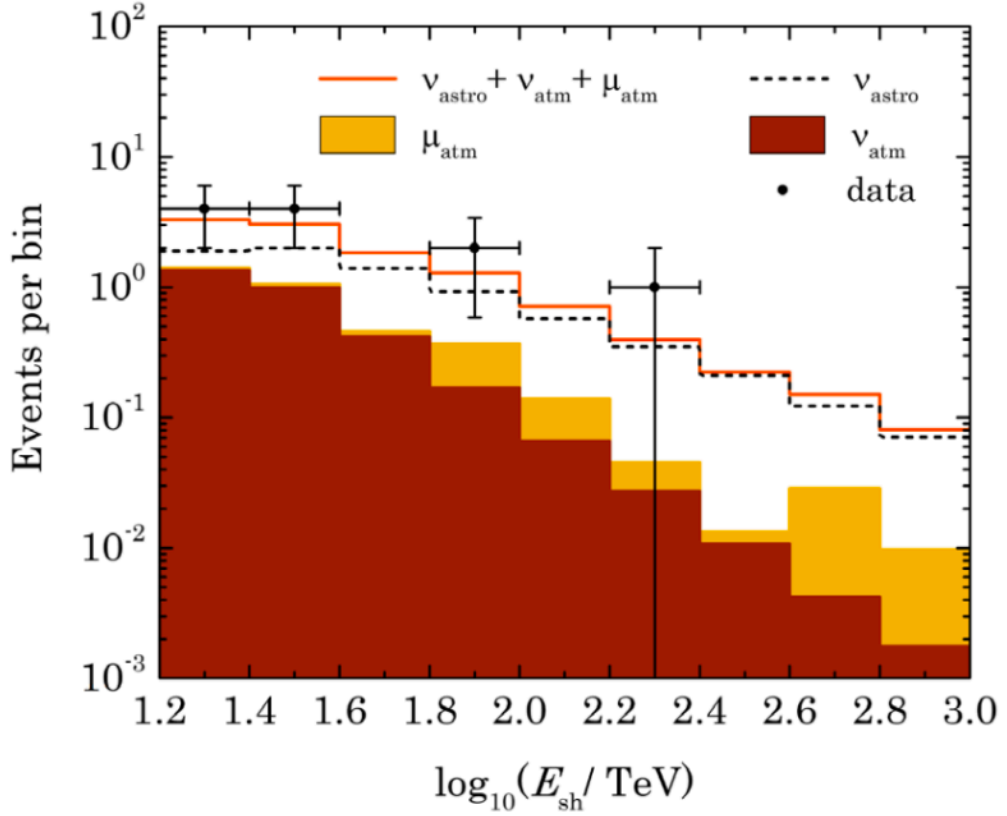
Upgoing muon distribution vs MC



Upgoing muon, 100 TeV

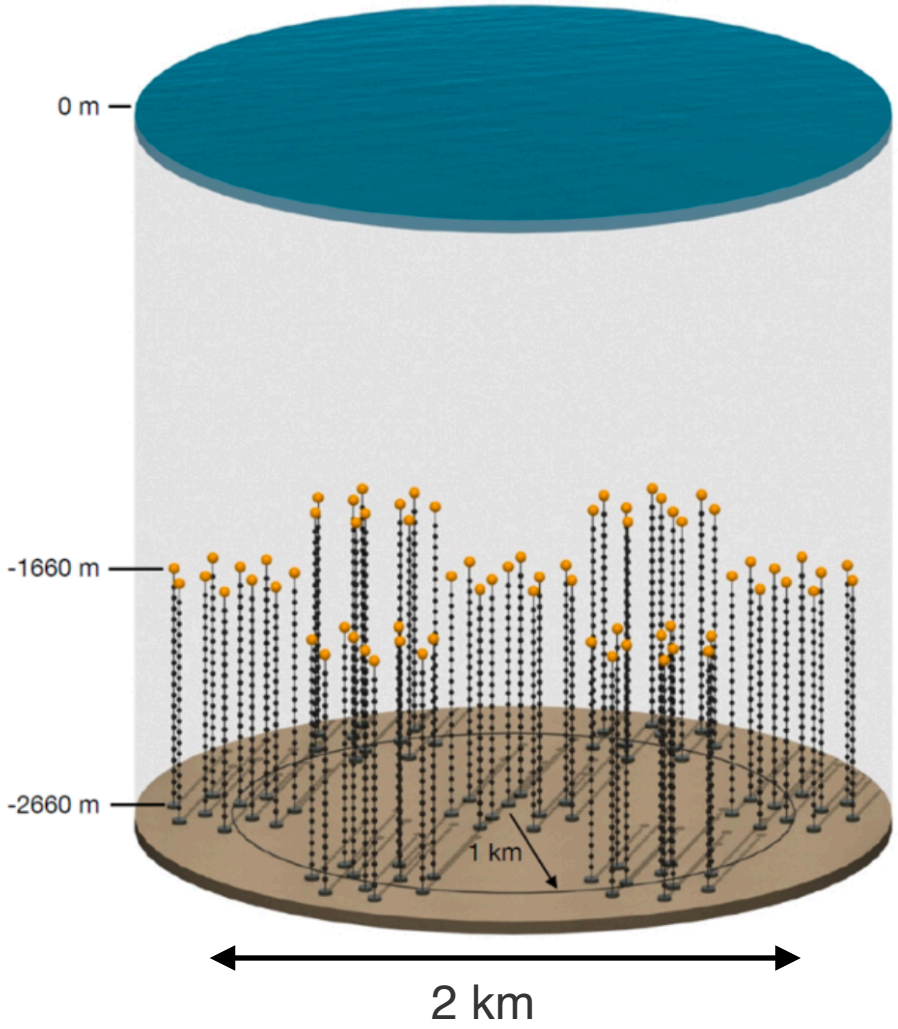


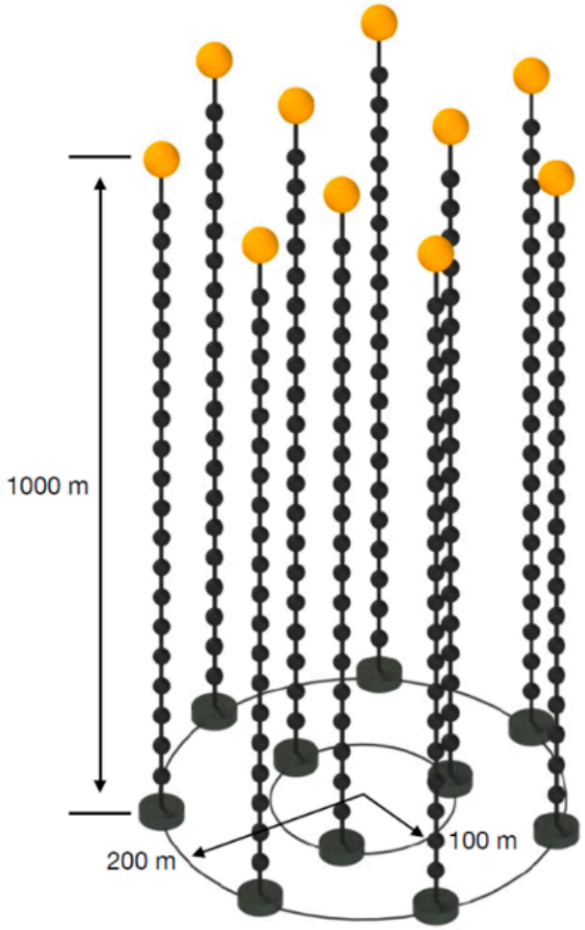
Upgoing cascade events with astrophysical component.



P-ONE (Pacific Ocean Neutrino Experiment)

Proposed project in R&D and prototyping phase

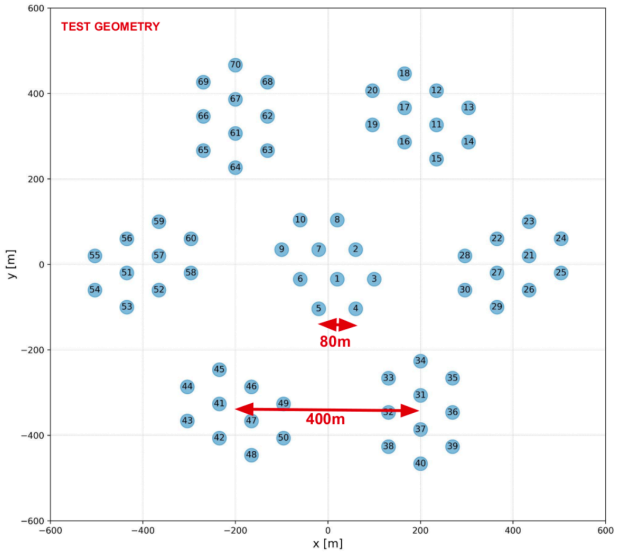




Conceptual Design:
7 clusters x 10 strings x 20 DOMs
total: 70 strings, 1400 sensors

diameter, height
(prel.): 400m, 1 km

Targeted energy range:
> 10 TeV



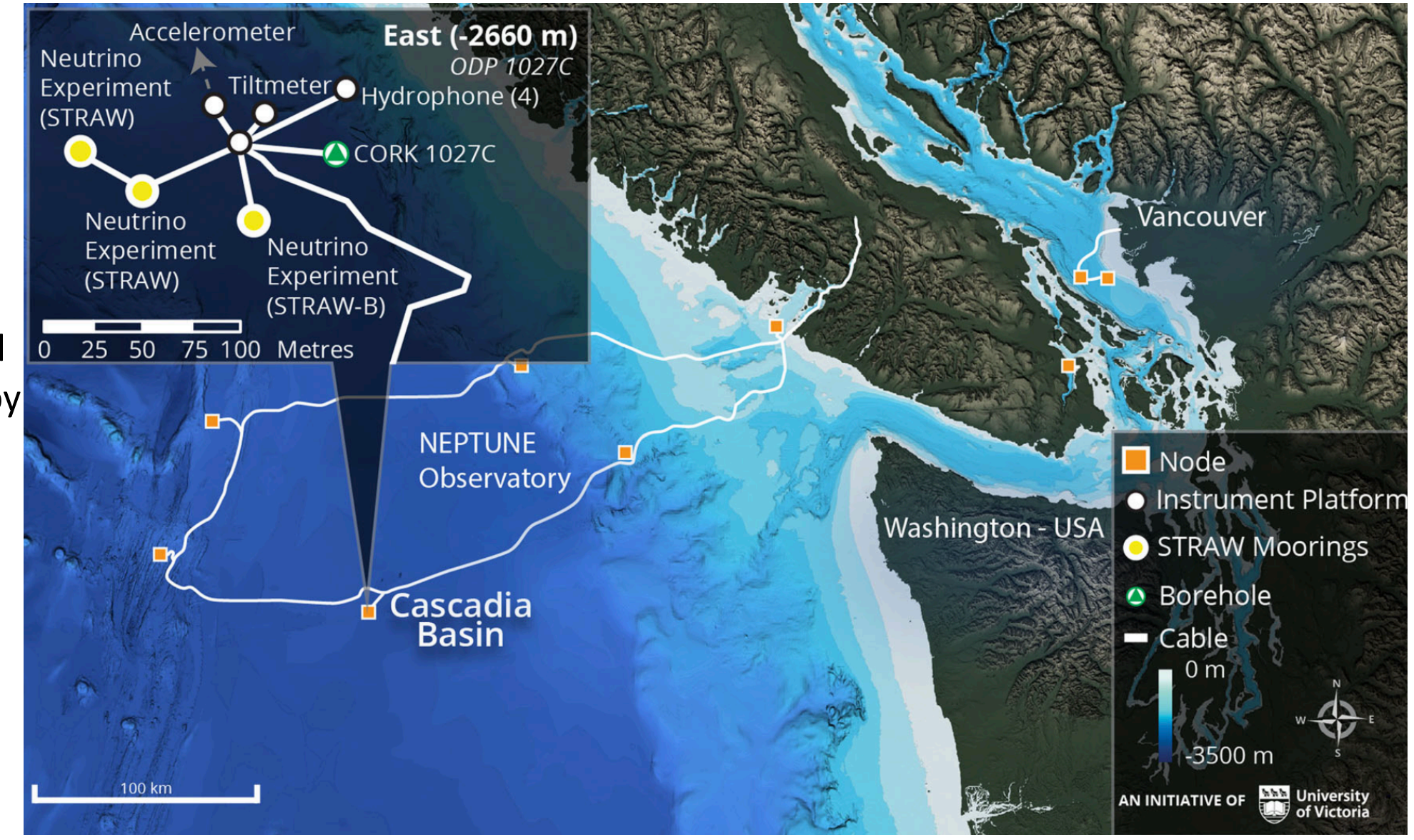
P-ONE

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)

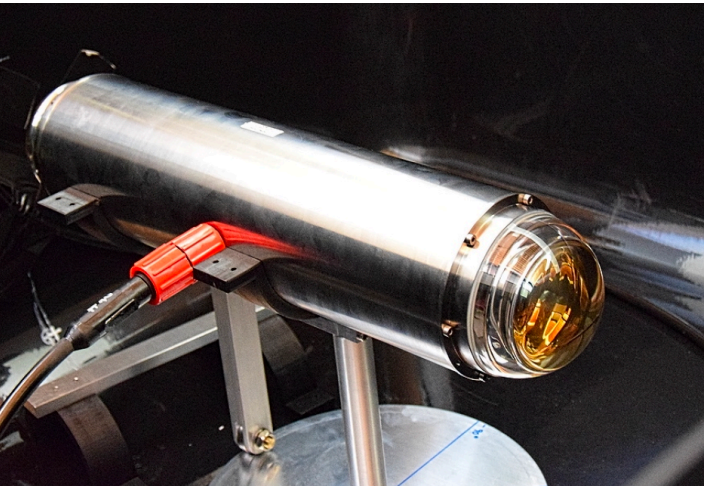


P-ONE

- Completed 2 pathfinder missions (STRAW)
- P-ONE-1 - one string - in 2024
- P-ONE demonstration cluster 2024-2027 (funded)

Elise Resconi writes:
“We are progressing on the hardware and will be ready in 2025 with a first deployment (this is realistic).”

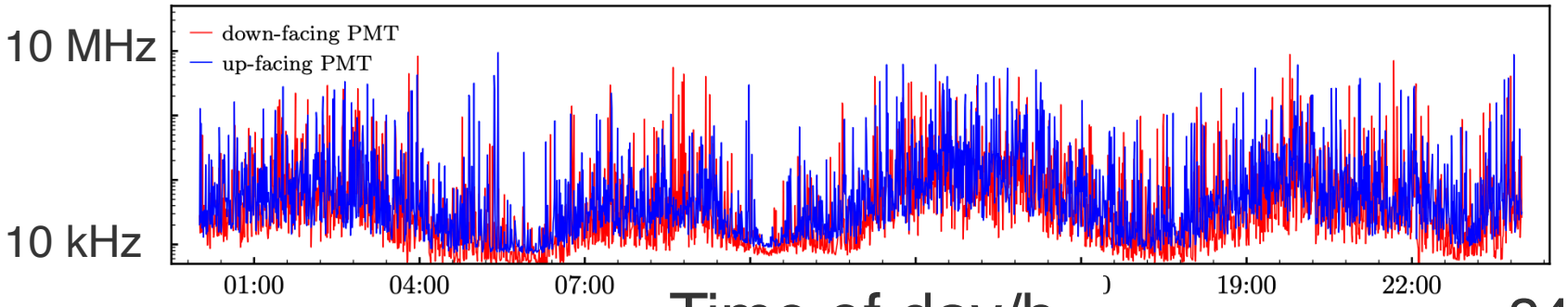
Attenuation length reported as **~28m** (at 450nm) comparable to other sites.



The European Physical Journal C

volume 81, Article number: 1071 (2021)

Noise rate in a 3 inch PMT



M. Boehmer *et al* 2019 *JINST* **14** P02013

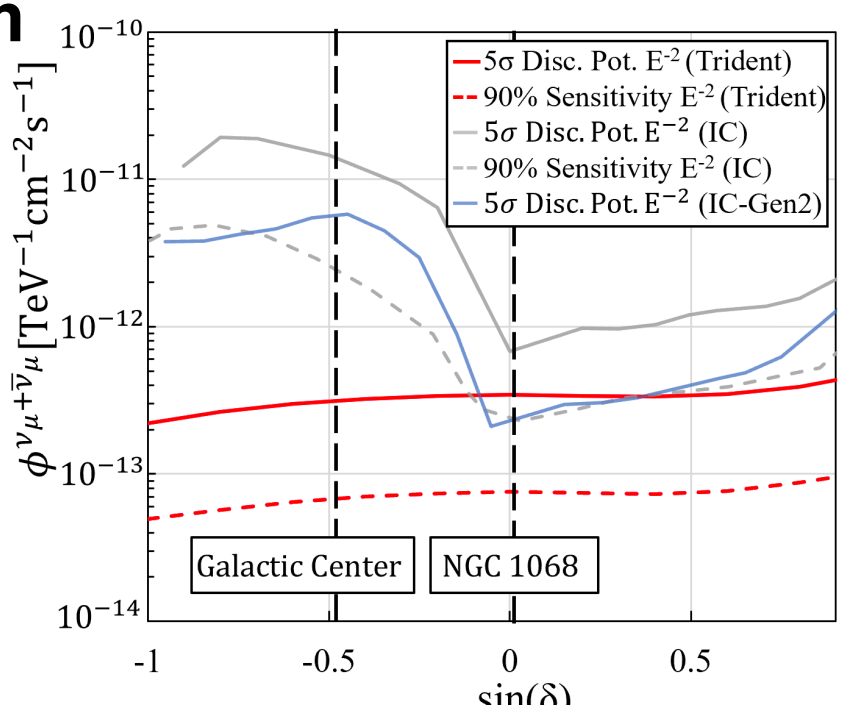
TRIDENT

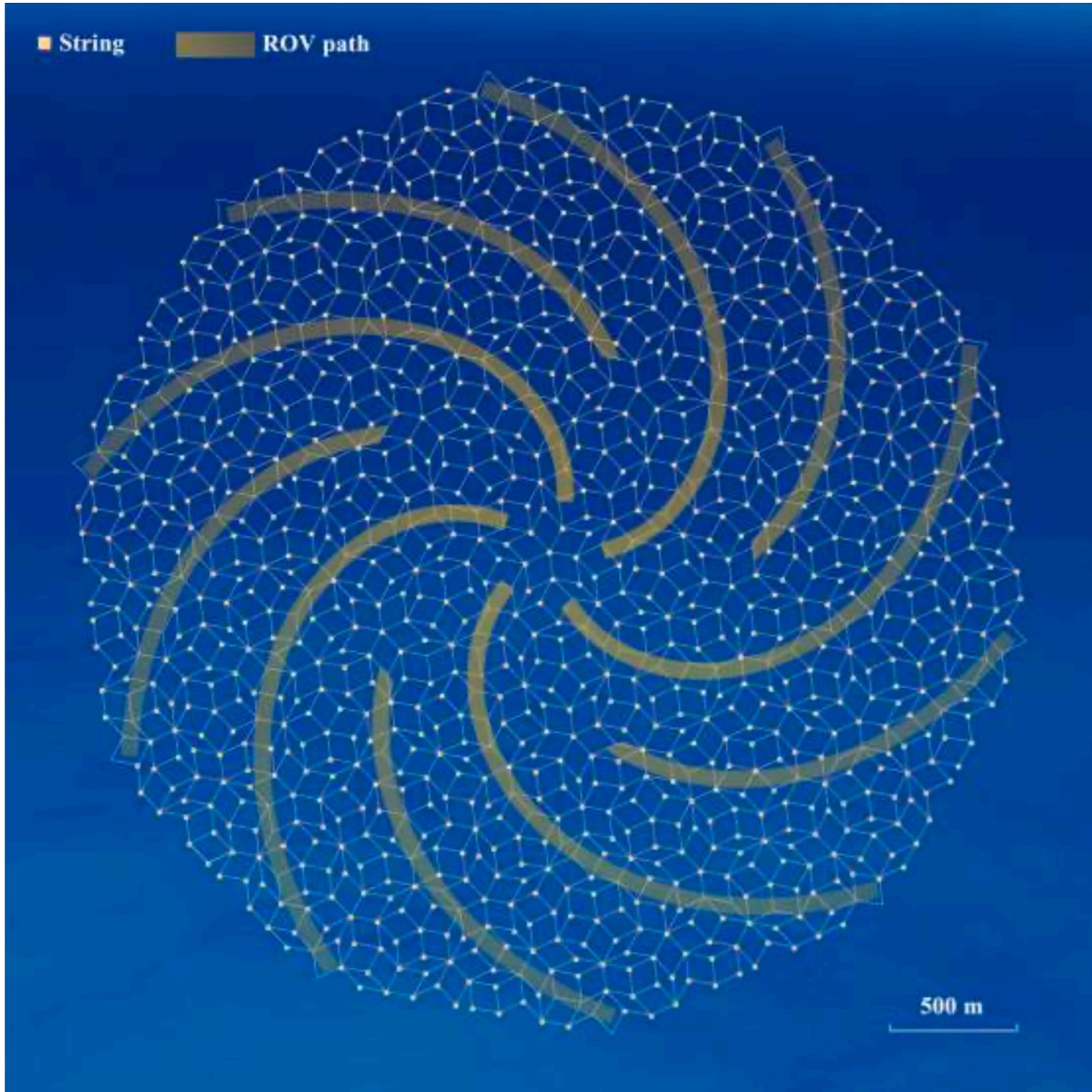
Proposed project in R&D and prototyping phase

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

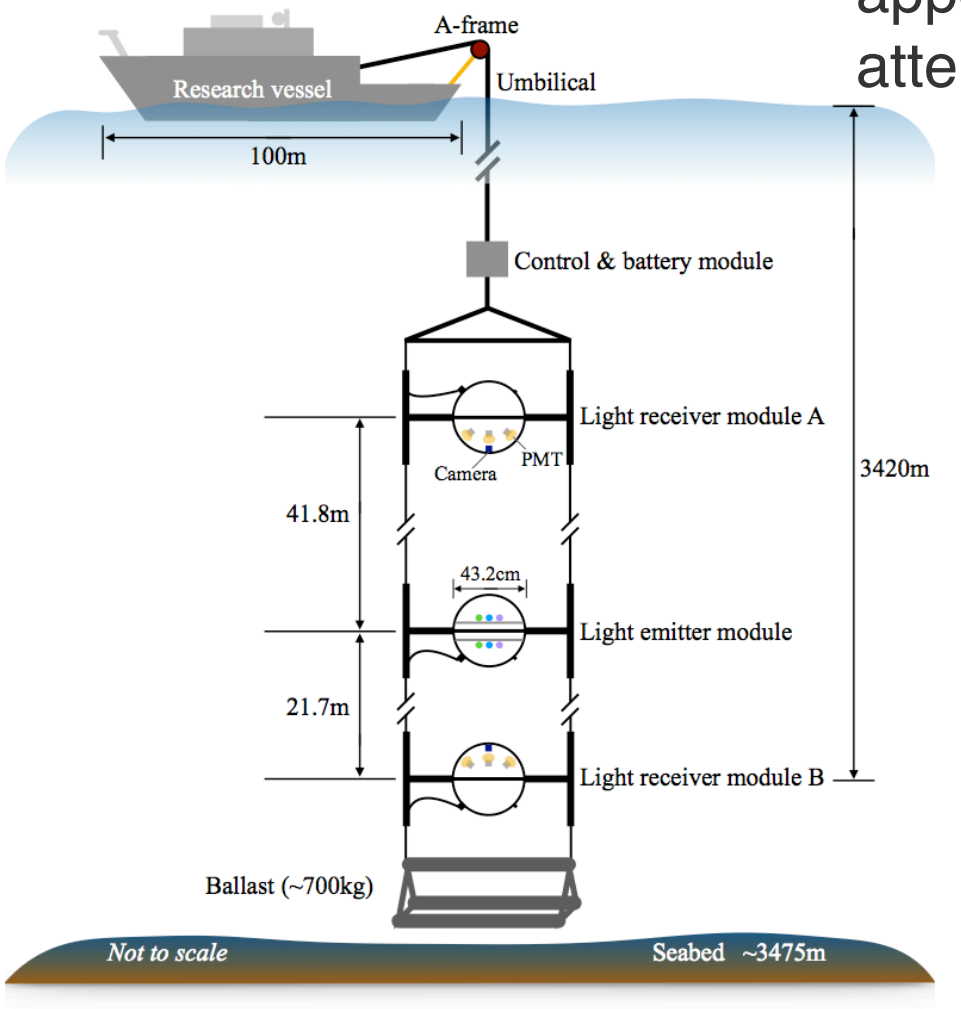
Scope:

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





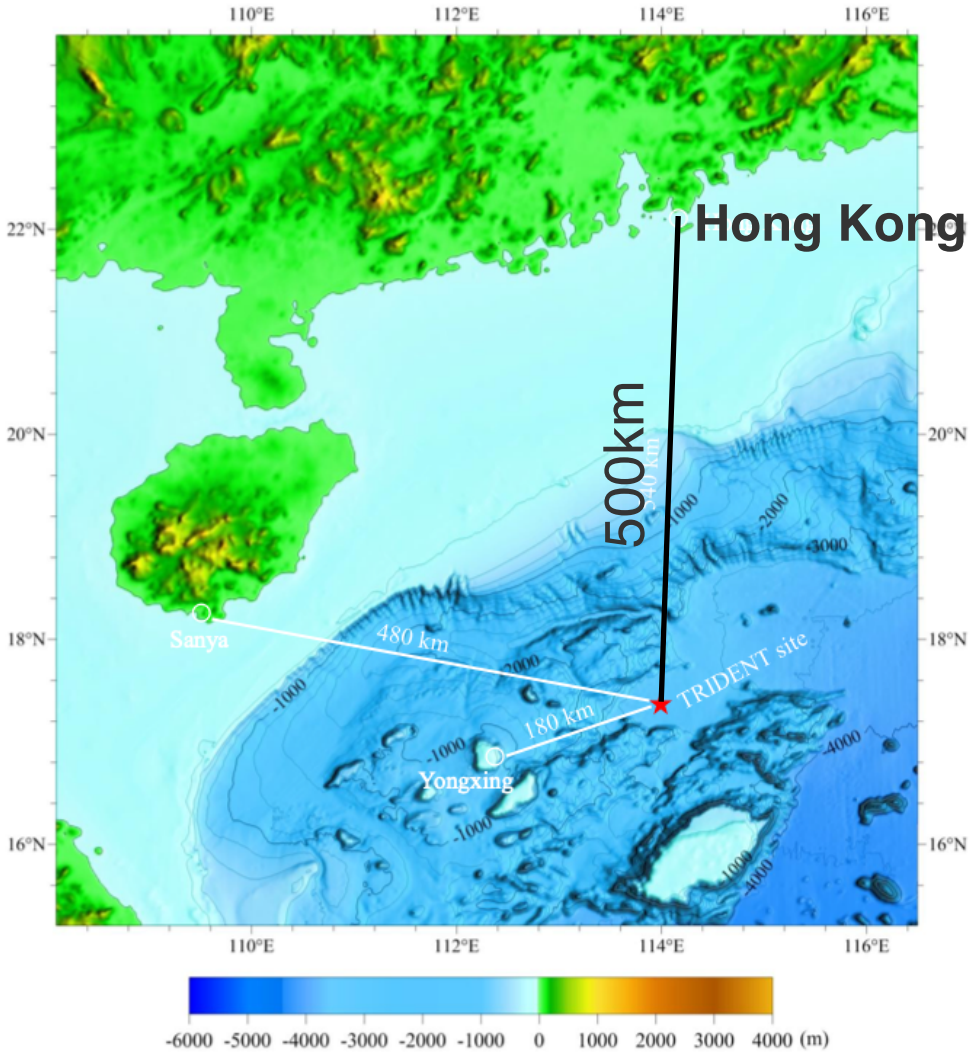
TRIDENT: Exploration



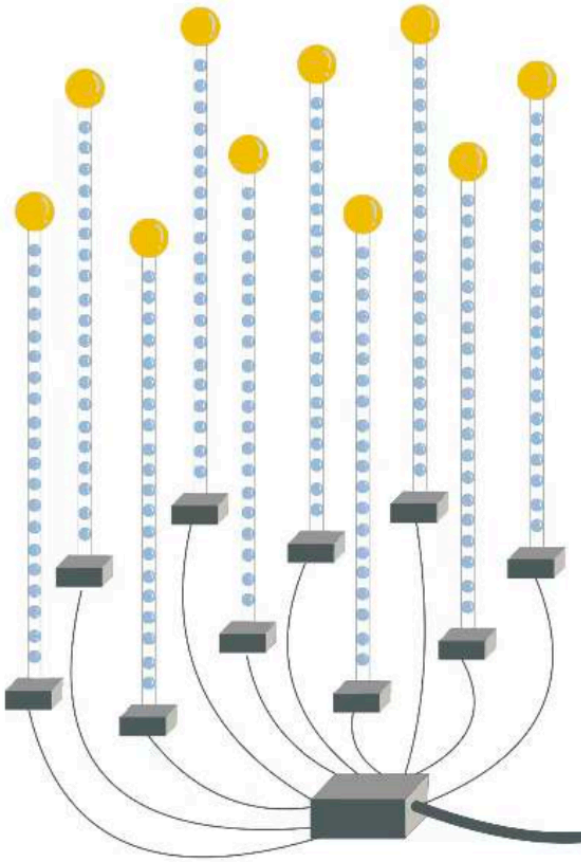
Optical properties, appear reasonable: attenuation: 20 - 30 m

TRIDENT:

Location: South China Sea



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



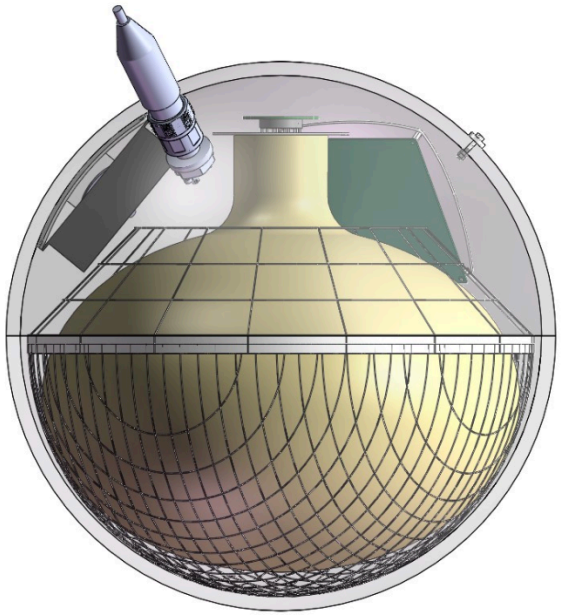
HUNT - **H** stands for Huge

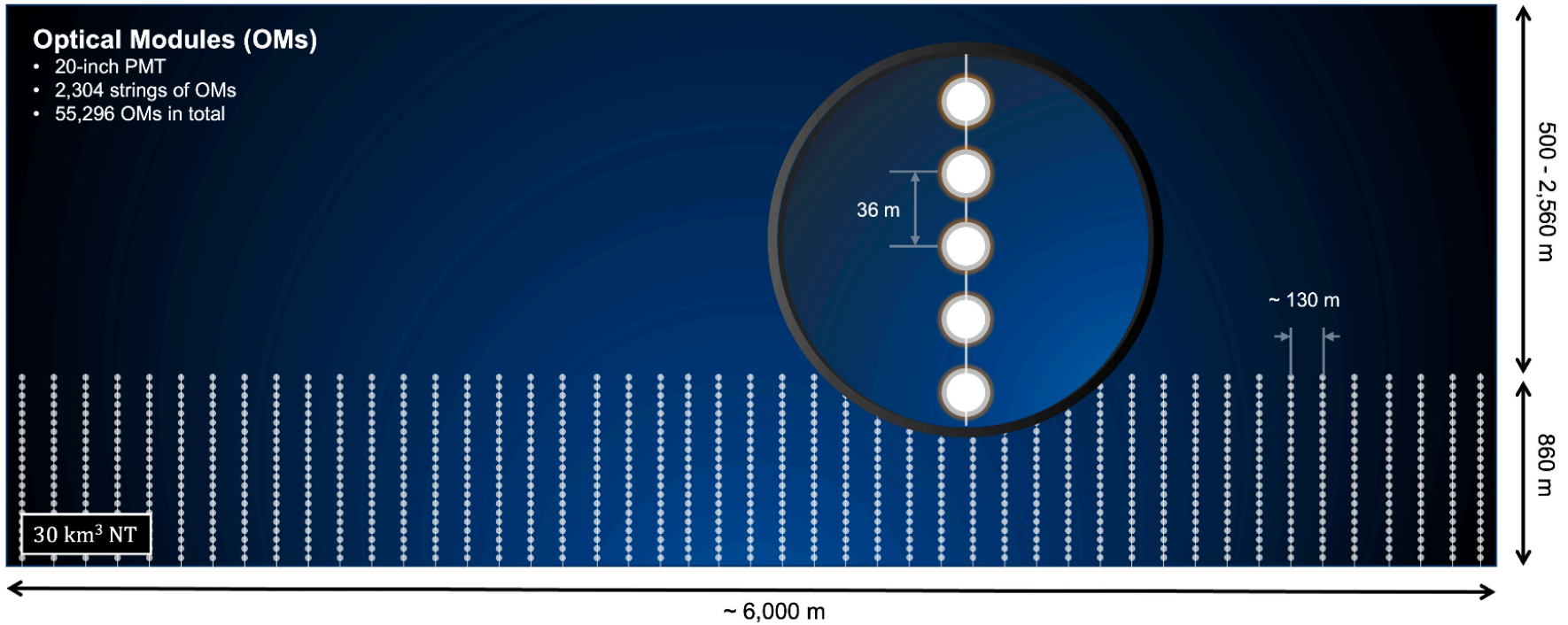
Huge underwater NT

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





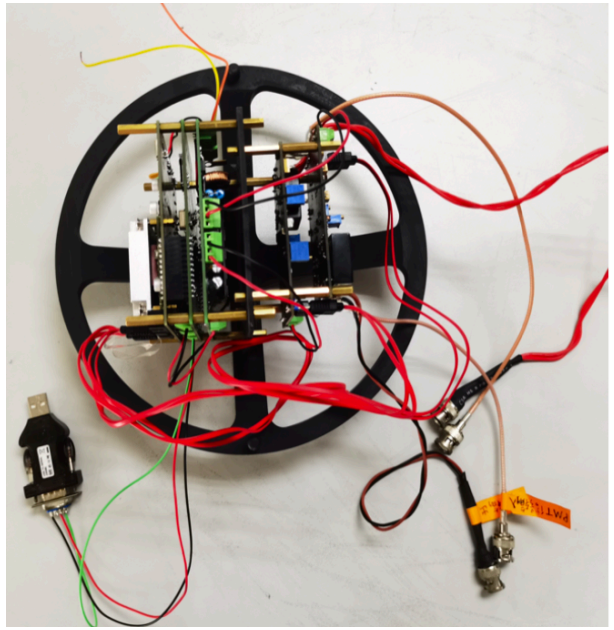
NEON

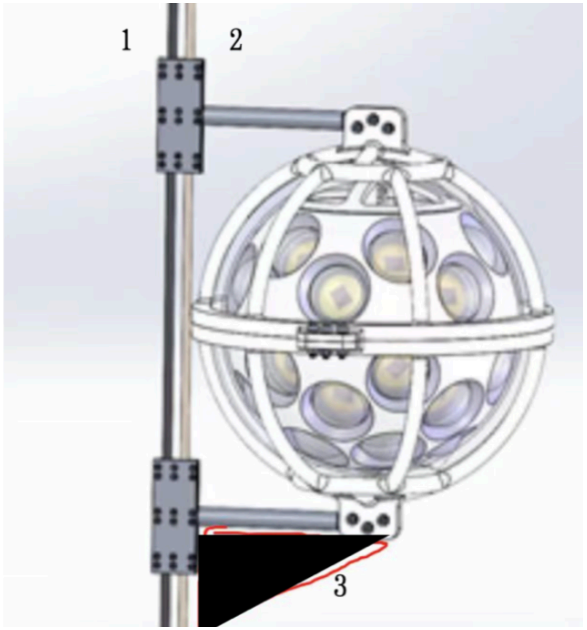
Several contributions to ICRC

South China Sea
Instrumented volume: ~1 km^3

Location:
South China Sea TBD

Simulation studies
Hardware R&D
presented at ICRC





Neutrino telescopes at various stages

There is a lot going on!

Snapshot at 100 TeV energy

(proposed) Detector	Instr. Volume / km^3	Modules /#PMT x size (inch) (DOM size*)	Effective area nu-mu [m^2]	Ang. resolution [deg]	Status
IceCube	1	80*60=5000 (1ref)	100	~0.3	2011 comp.
Baikal GVD	~0.4	144*36=5184 (1)		~0.1	60%
KM3NeT ARCA	~1	230*18=4140 (3p)	100	~0.1	12% (accel)
P-ONE	1 (cluster volume) 3 (envelope vol.)	70*20=1400 (3p)		~0.1	prototype
IceCube Gen2	8	120*80=9600 (4p)	~300	~0.2	design
TRIDENT	7.5	1200*30=3600 (~3p)	~700	~0.1	prototype
NEON	1	TBD			R&D
HUNT	30	2300*24=55000* (4)			R&D

References: ICRC

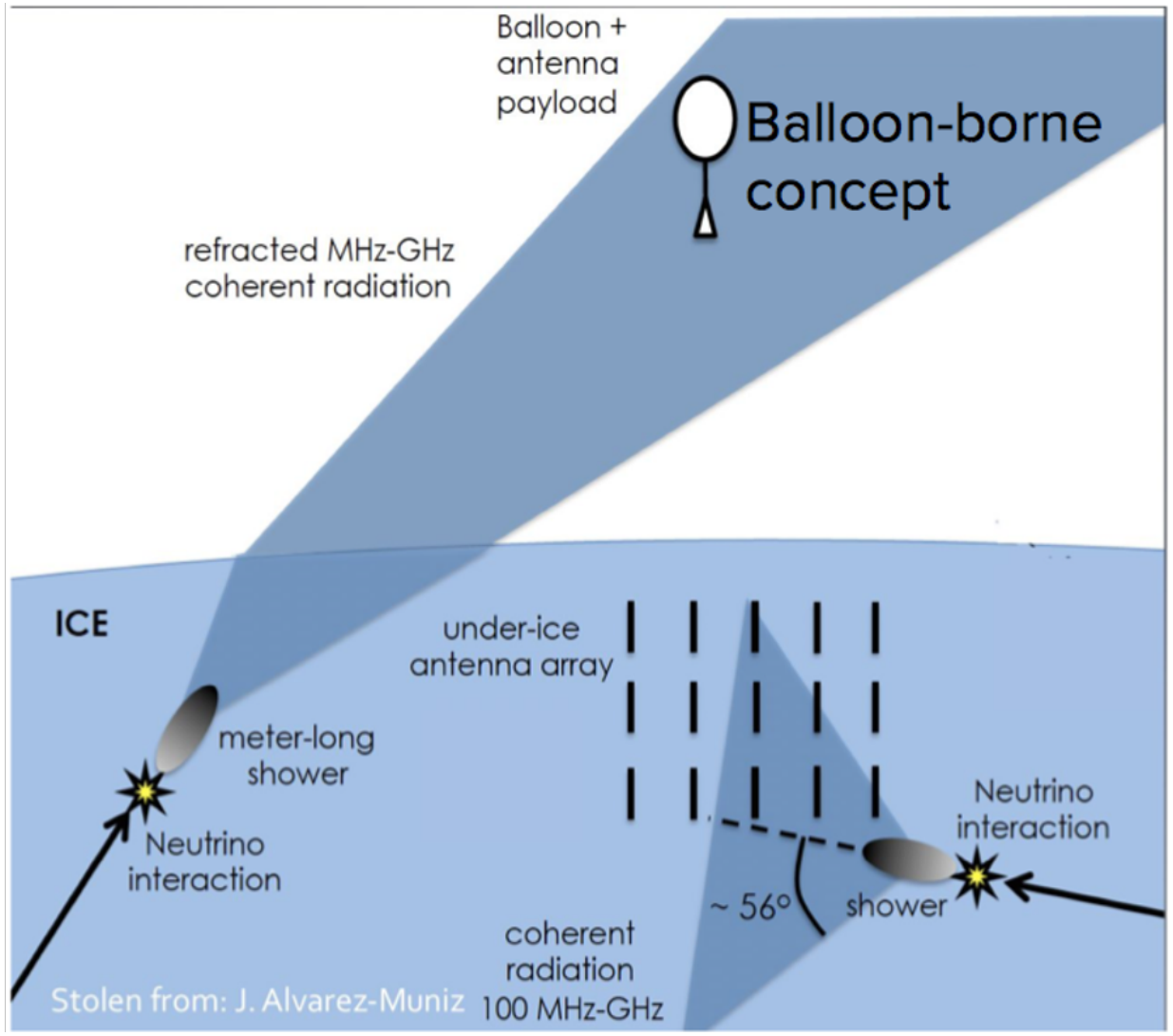
*sensor eff. area / IceCube 10 inch, p= pixelized

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



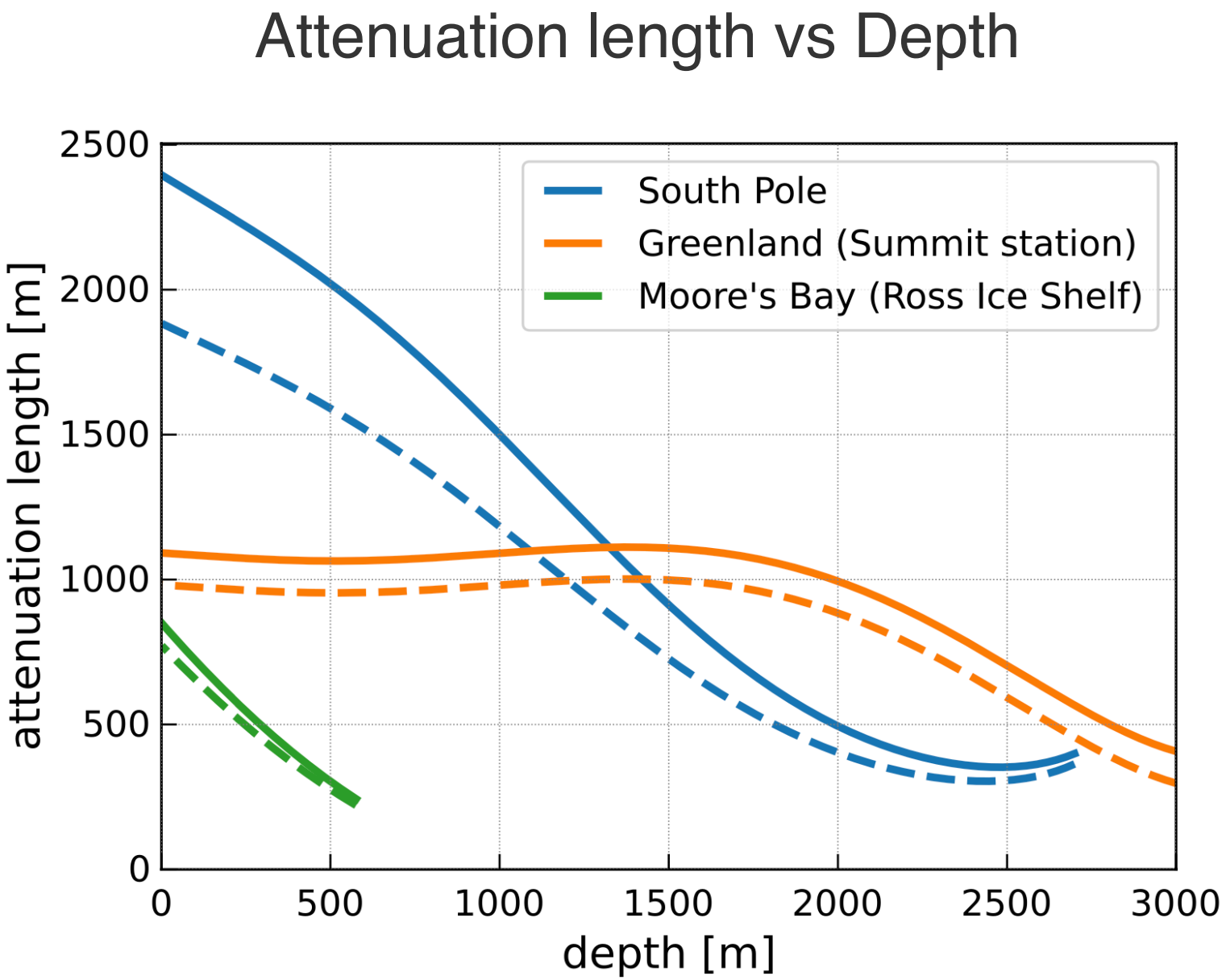
ANITA:
Higher energy threshold due to larger distance
to interaction
next —> PUEO
impressive improvement by phased array triggering
Threshold ~ 1000 PeV

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

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

Using massive ice sheets as target for radio detection



Strong function of temperature.

South Pole is the coldest ice (-55degC at the top)

Using massive ice sheets as target for radio detection

Requirement: a lot of ice

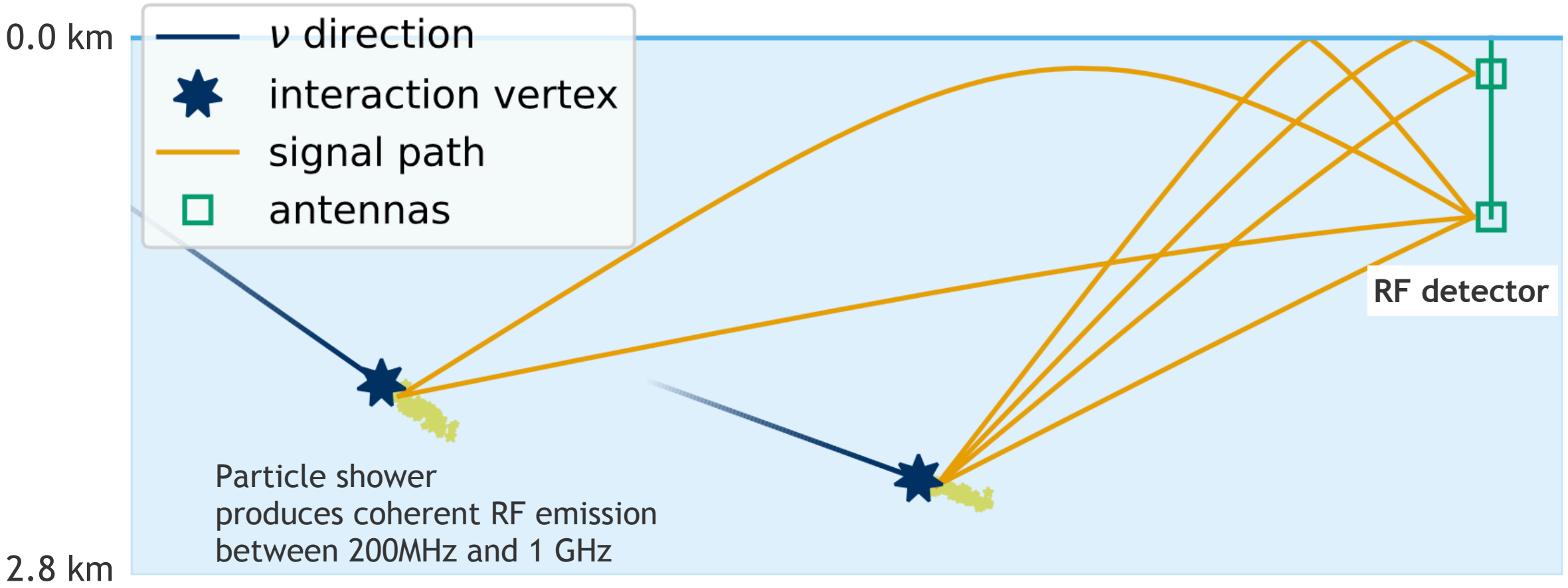
- South Pole
- Ross Ice Shelf (coast of Antarctica)
- Greenland

Antarctica

Greenland

Using massive ice sheets as target

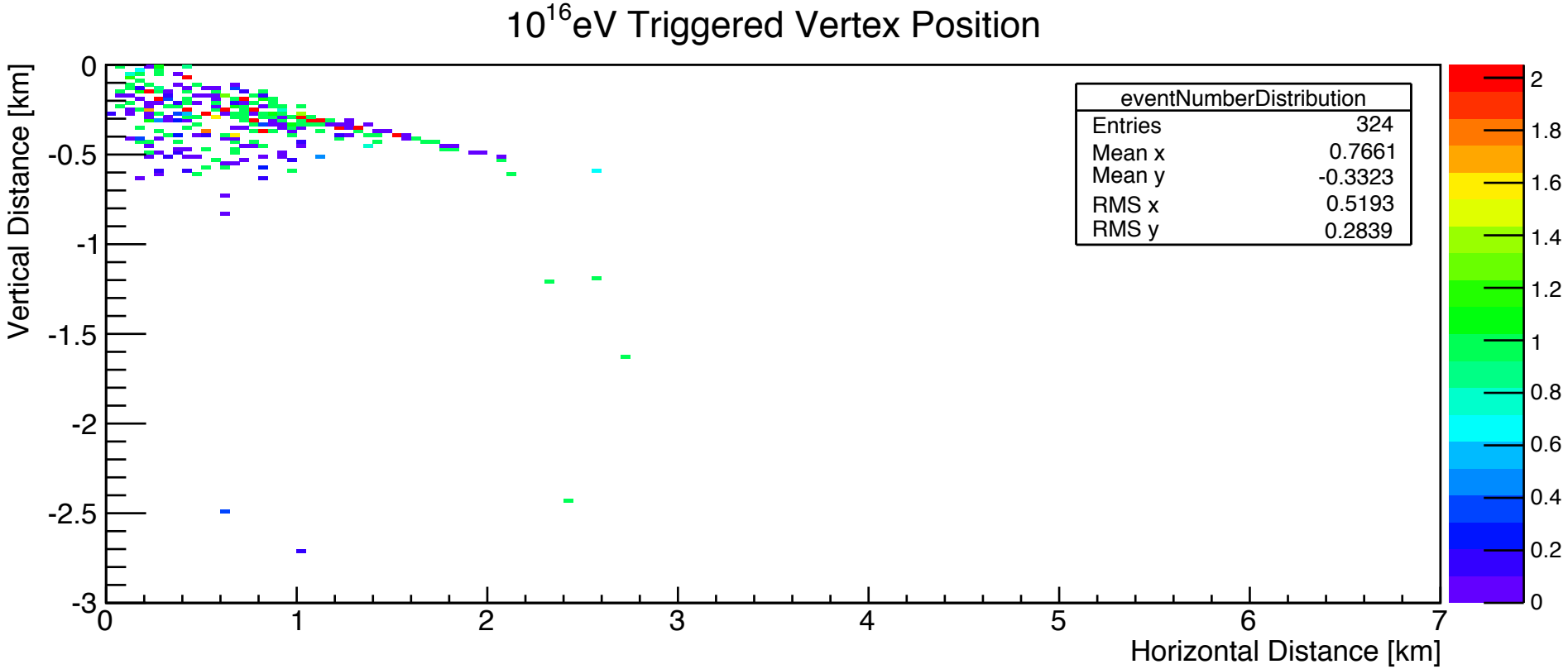
Askaryan: coherent radio transient from high energy cascade at Cherenkov angle
Signal grows with energy^2



Radio detection: Visibility of neutrinos with ARA station.

Simulated events triggering
ARA station at 200m

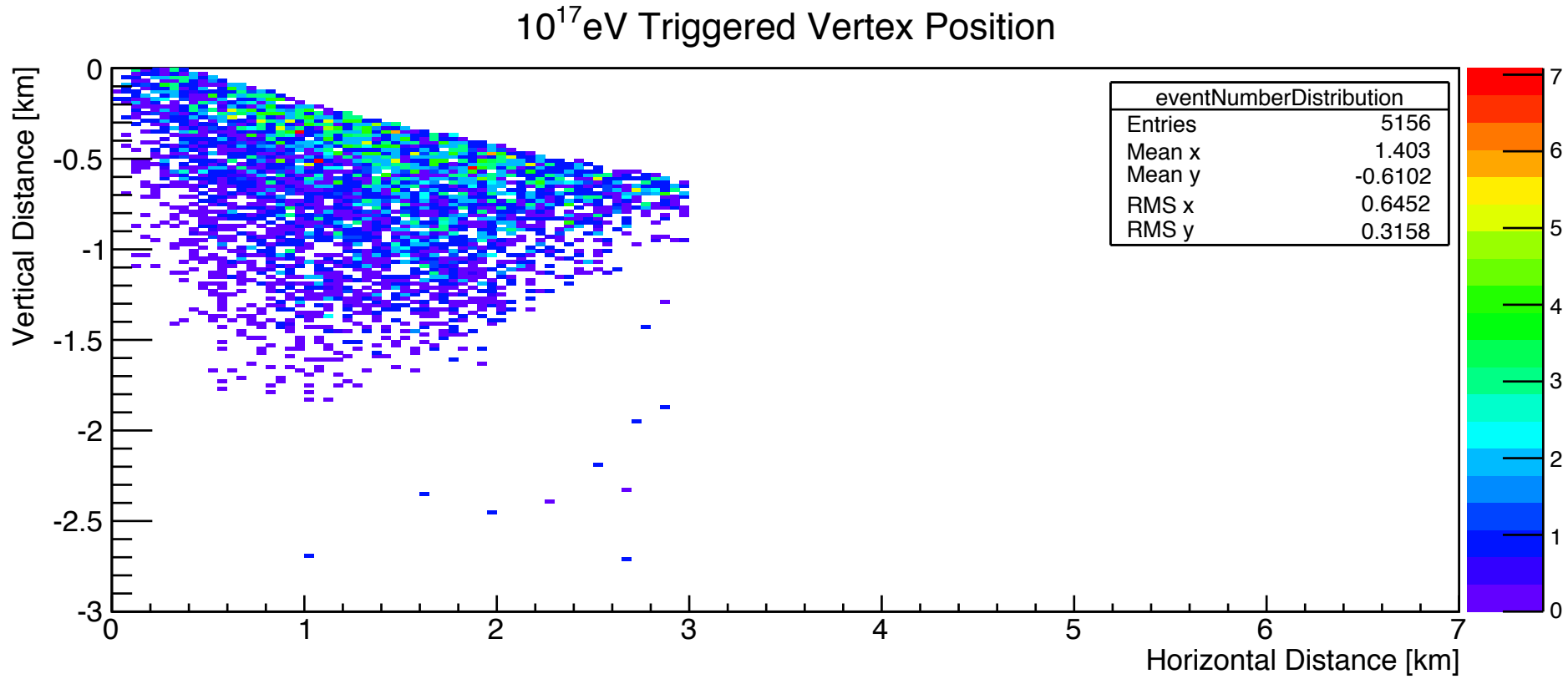
10^16 eV



Depth and effective volume at South Pole.

Simulated neutrino events triggering
ARA station at 200m

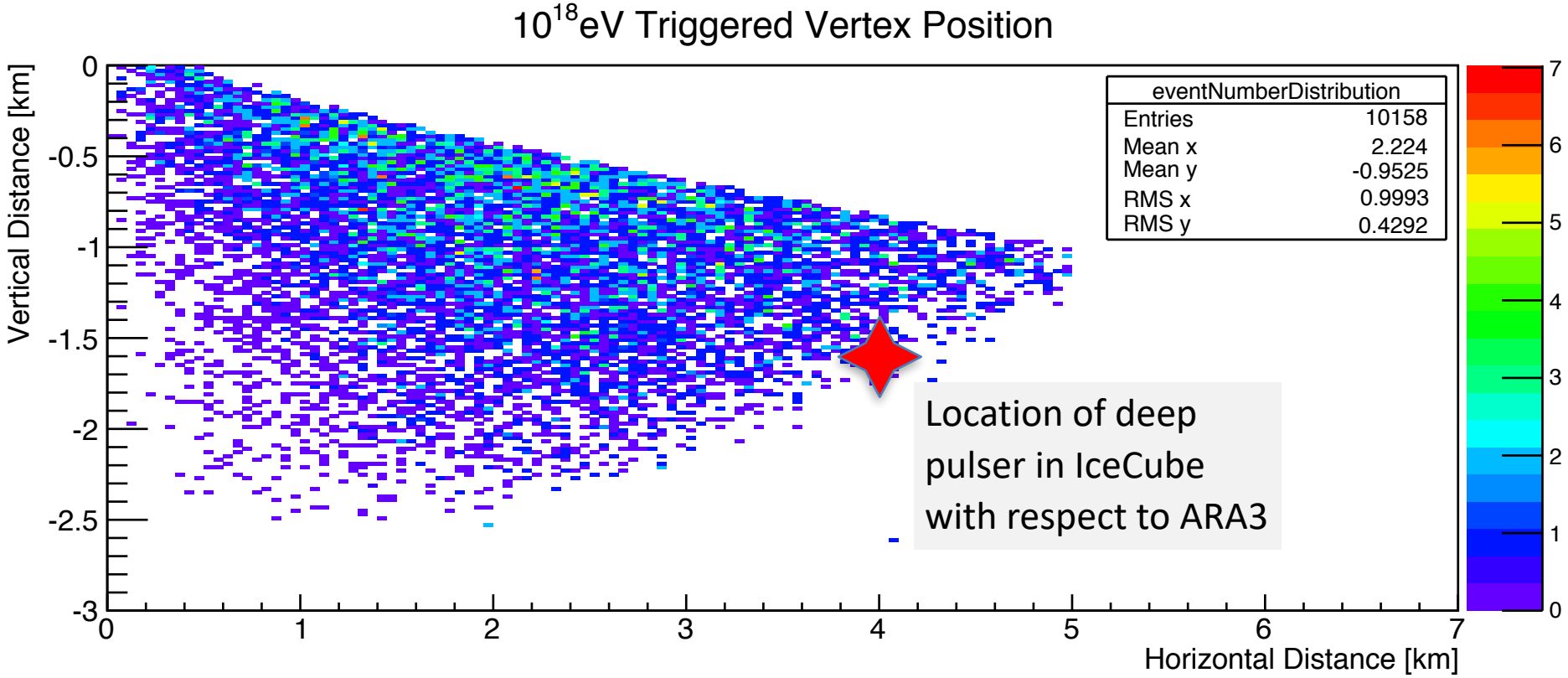
10^17 eV



Depth and effective volume at South Pole.

Simulated neutrino events triggering
ARA station at 200m

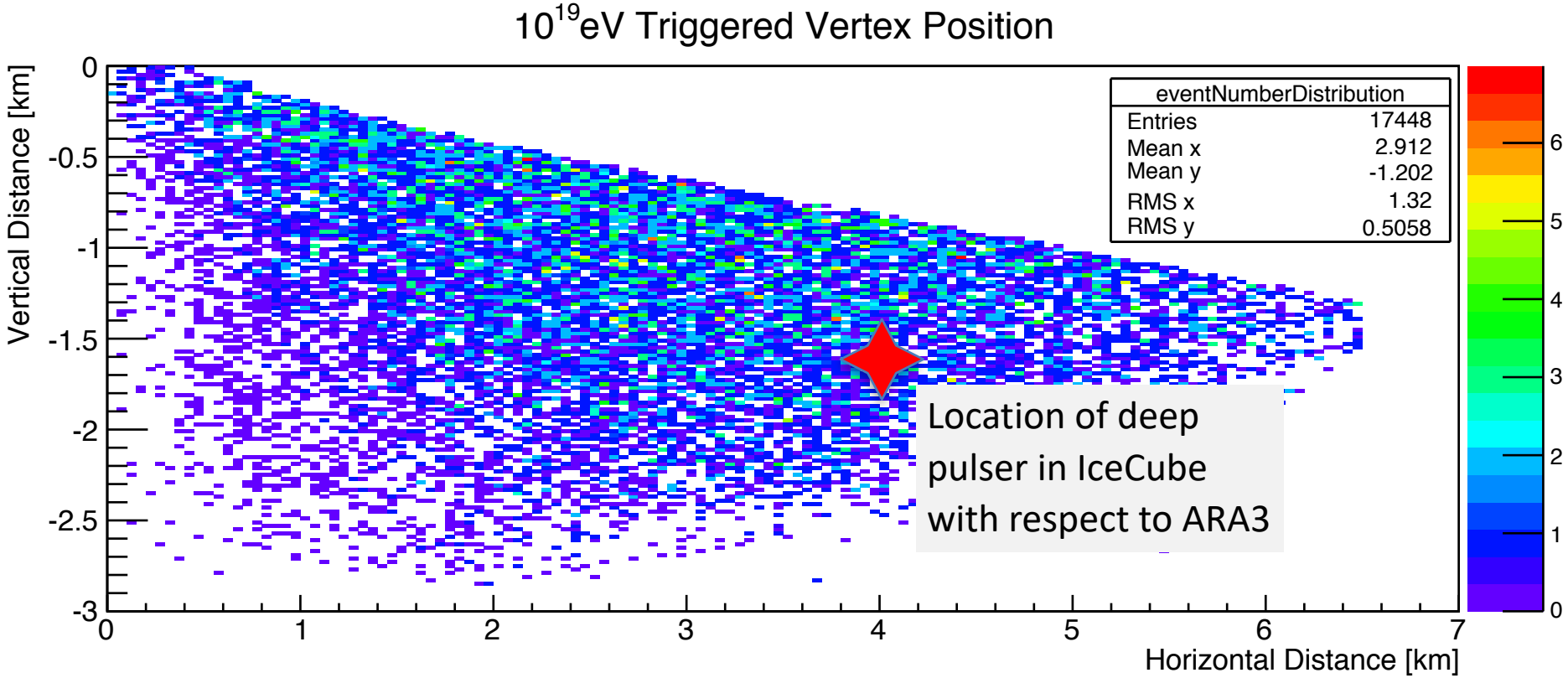
10^18 eV



Depth and effective volume at South Pole.

Simulated neutrino events triggering
ARA station at 200m

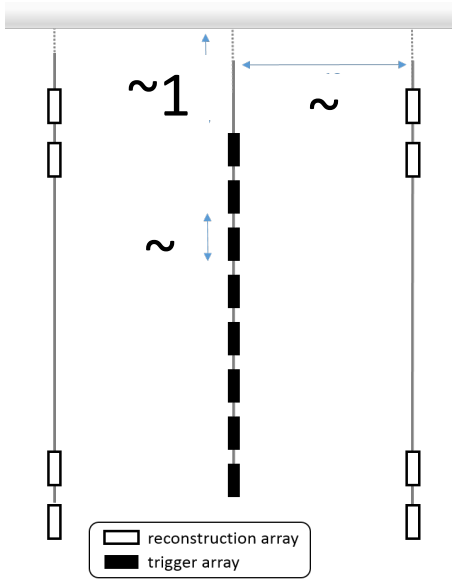
10^19 eV

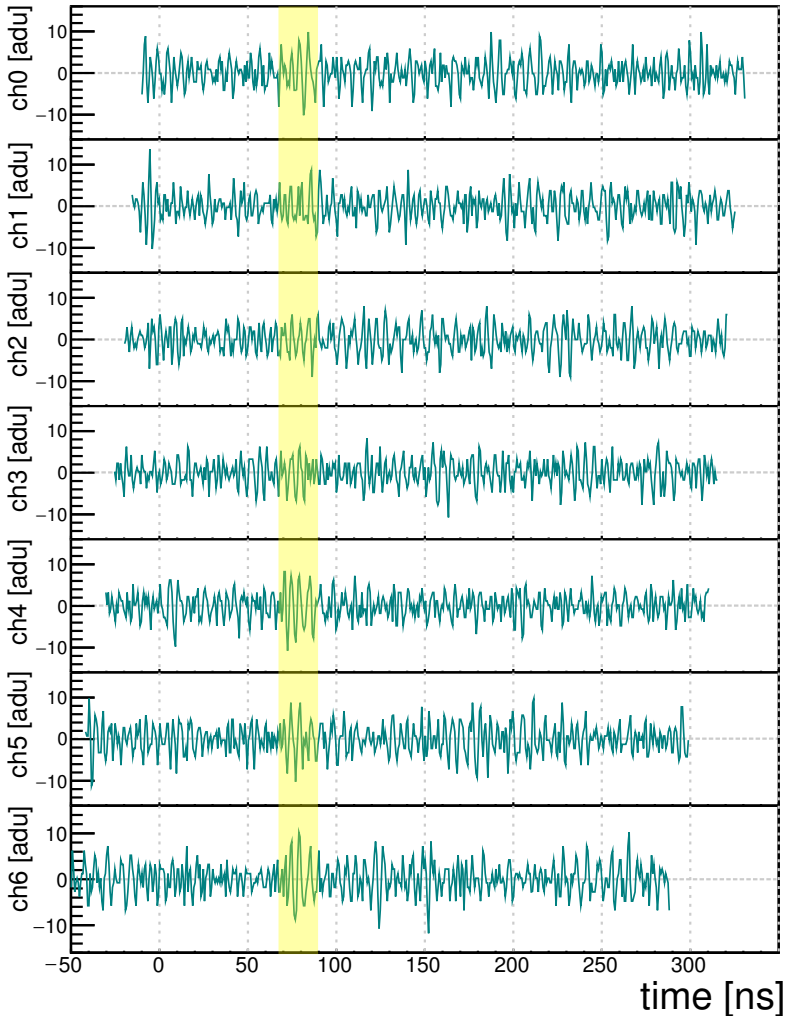


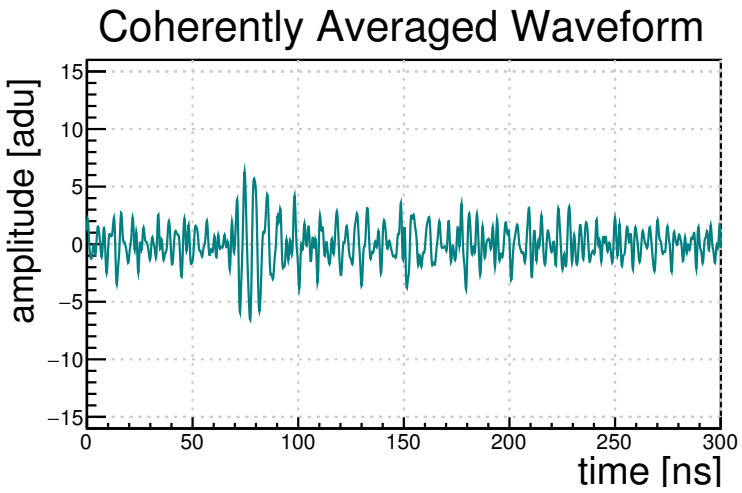
ARA station 5:
Lowering trigger threshold with Phased Array of Antennas

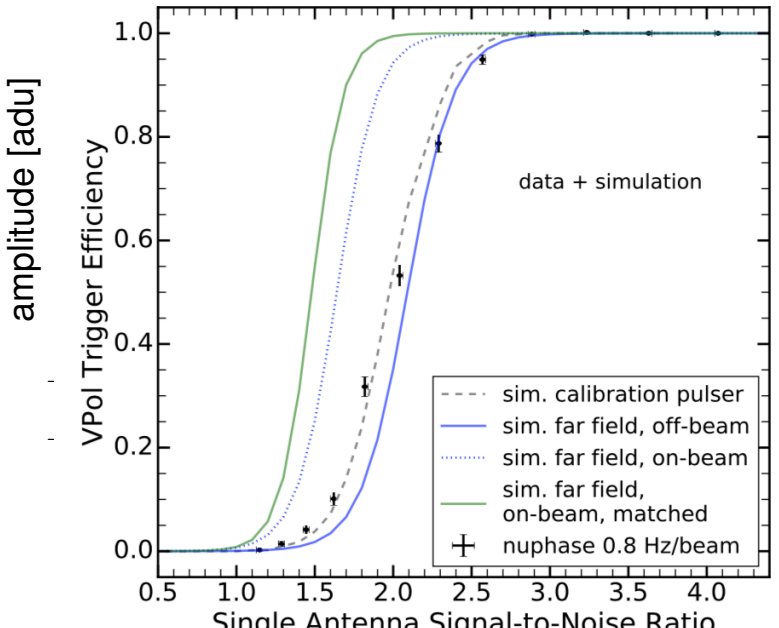
Spearheaded by Abby Vieregg et al.

Factor of ~2 increase in effective volume, event rates.

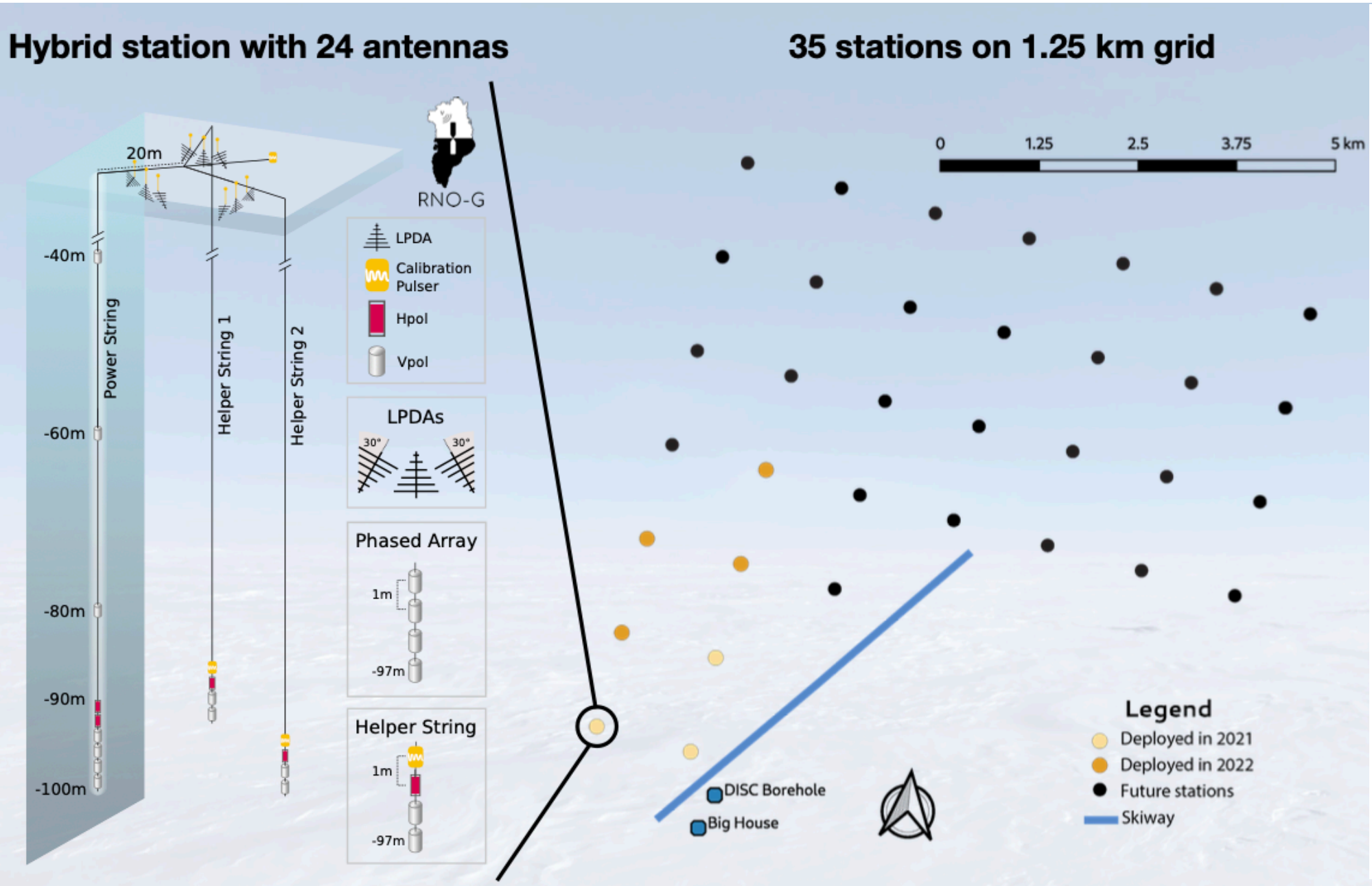








RNO-G: Radio Neutrino Observatory - Greenland



—>. Talks by Delia Tosi and Felix Schlüter

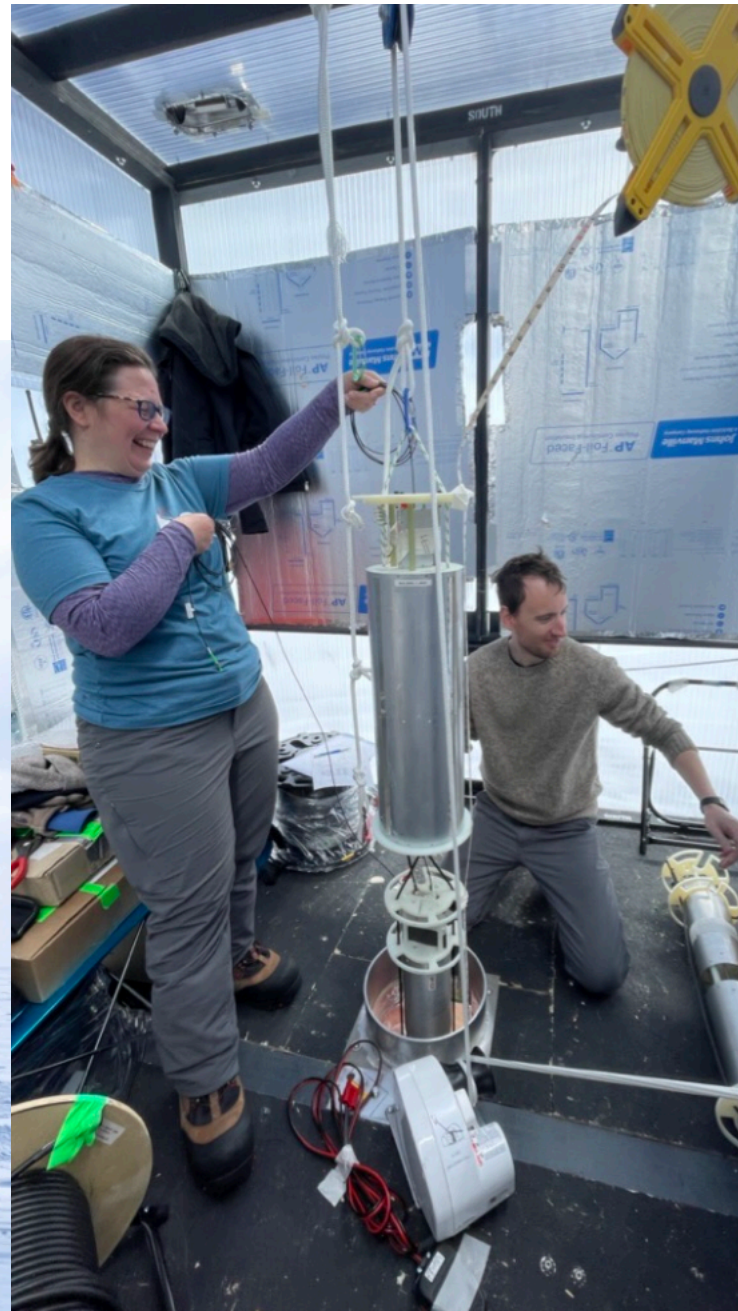
RNO-G: implements lessons learned from ARA, ARIANNA, Phased Array.

7 stations built,

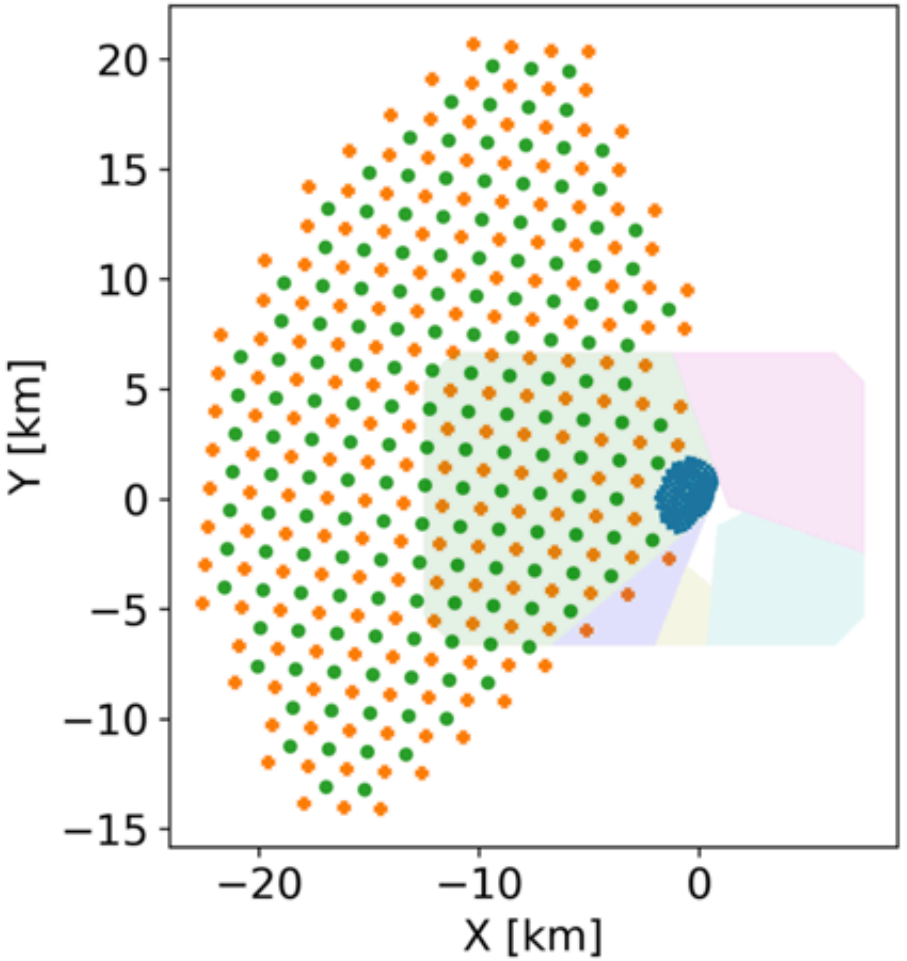
continued construction in the next several years.

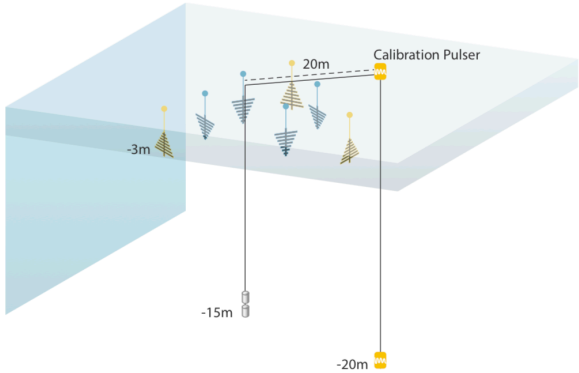
RNO-G: Radio Neutrino Observatory - Greenland

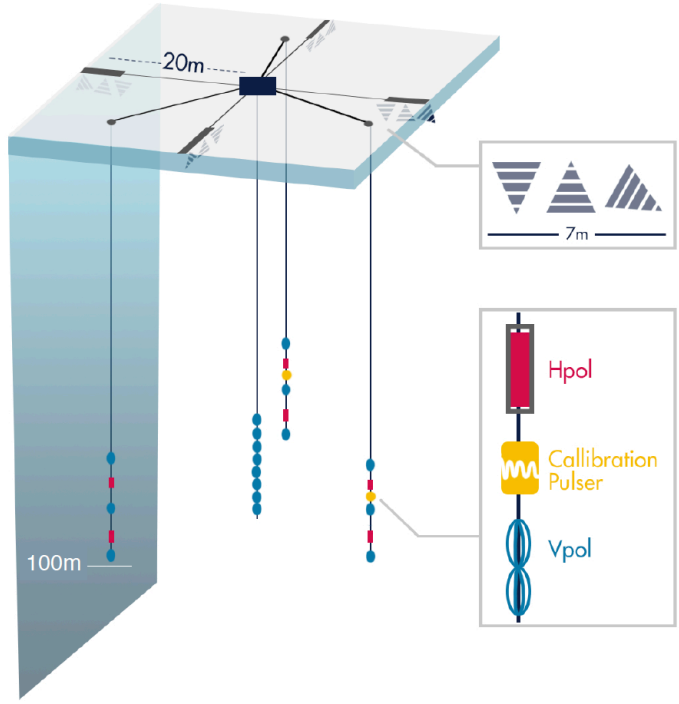
Challenge: Reliable and fast drilling
Drilling determines the schedule
Deployed 3 and 4 stations in past seasons (3 holes,100m, per season)
Team is hoping build one station in 3 days.
Sometimes bad weather.
RNO-G will provide important input for Gen2 Radio.



The IceCube-Gen2: the radio array



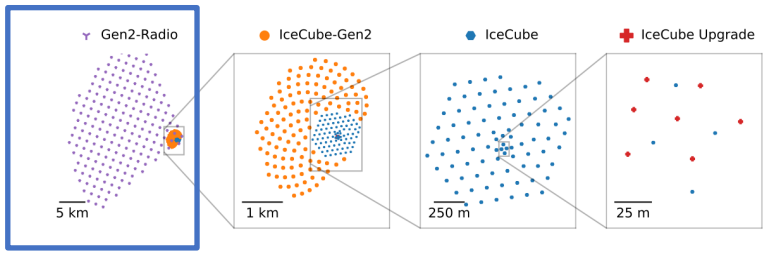




Area: 500 km^2

300 stations

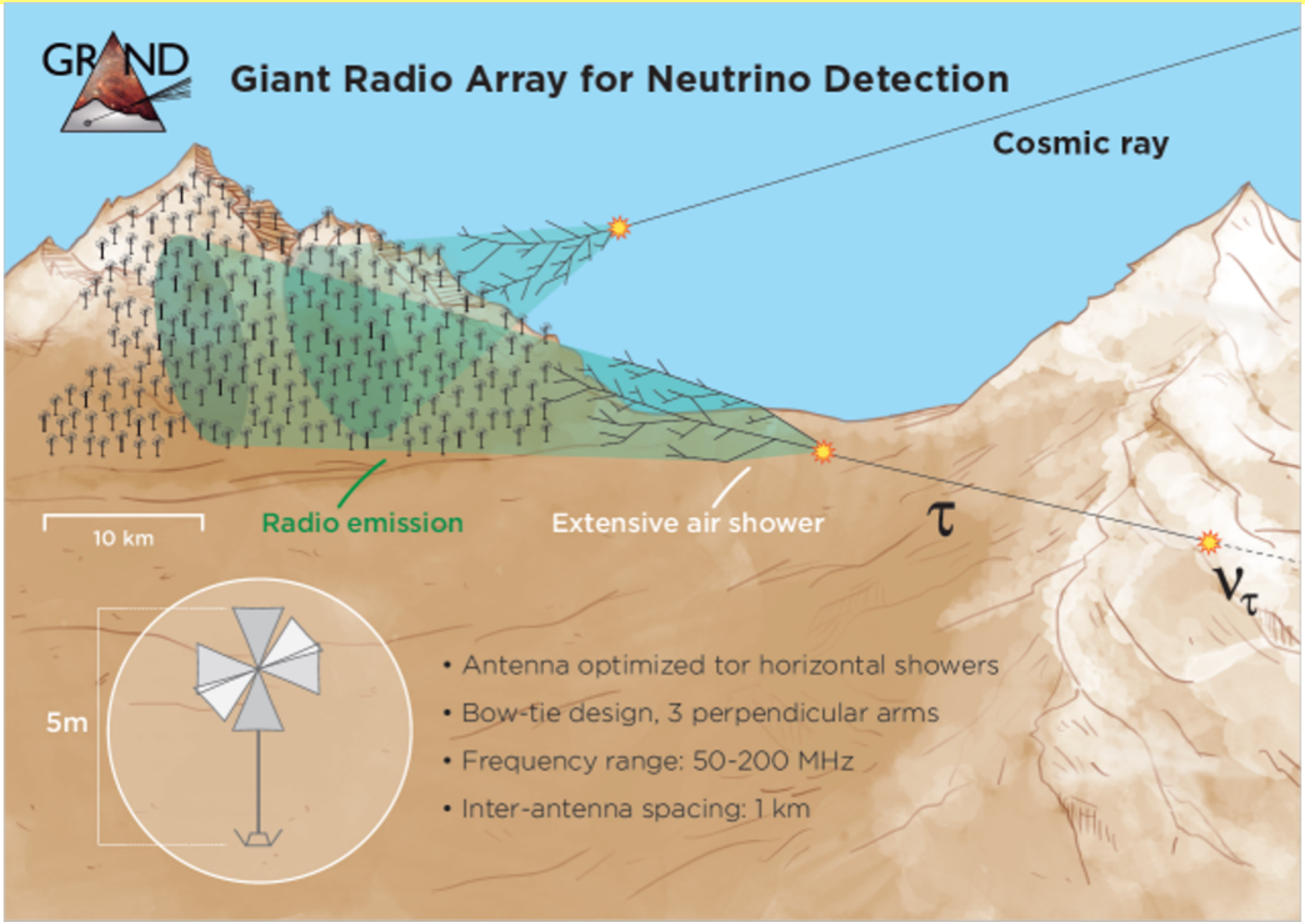
1000 km^3 of ice volume



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

GRAND: 200,000 antennas for horizontal taus

proposed



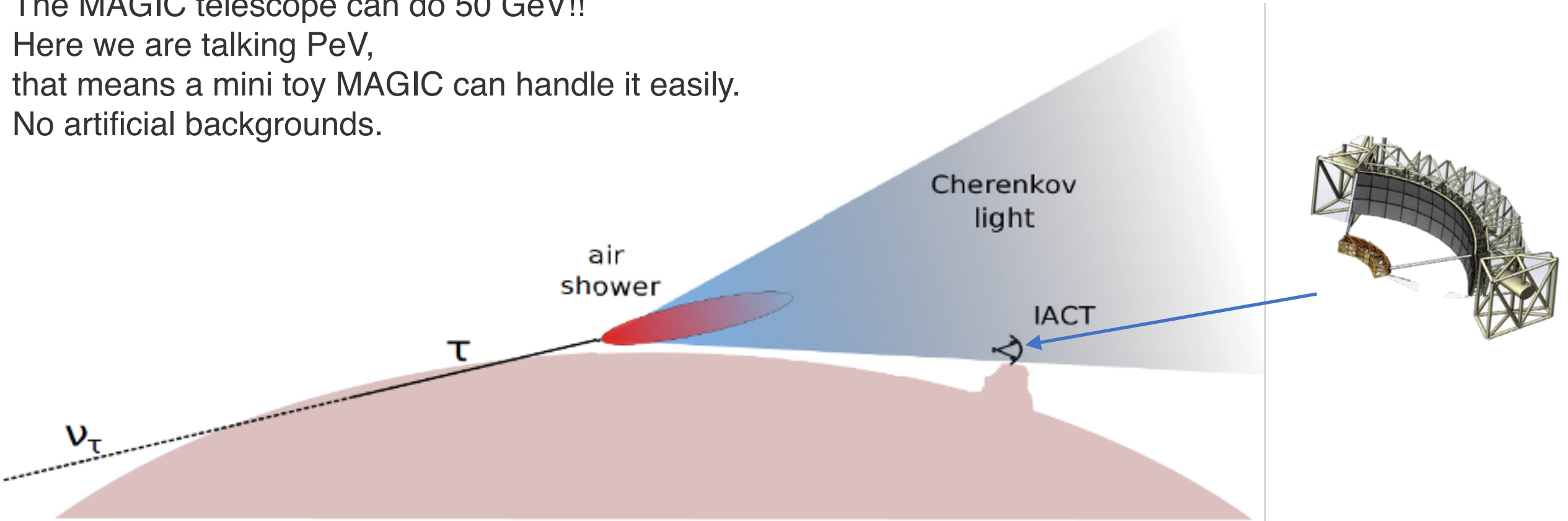
Trinity: View upward taus mountain with Cherenkov telescope

see talk by Michele Doro

Nepomuk Otte

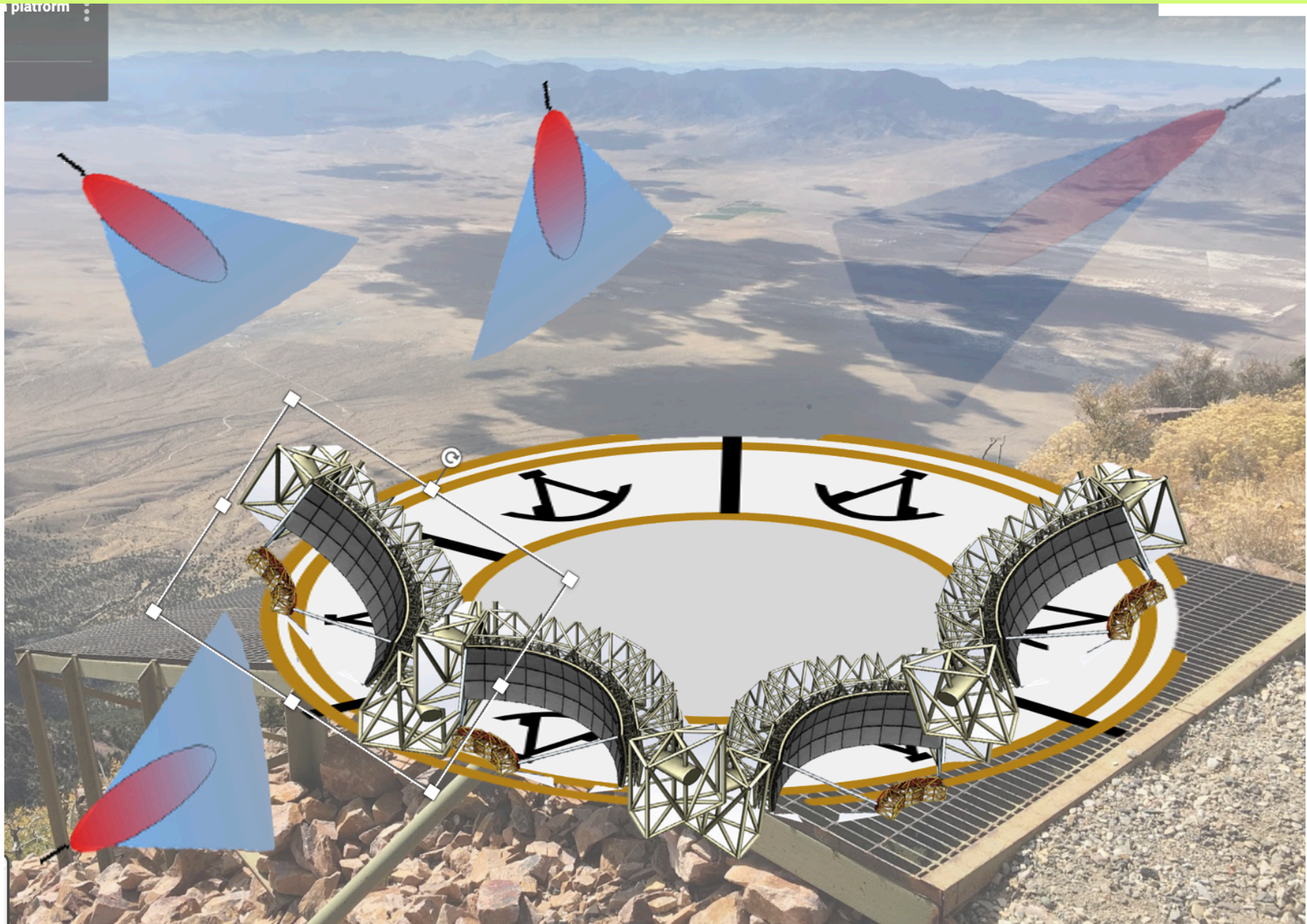
Advantage:
Low Energy threshold for emerging tau neutrinos

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.



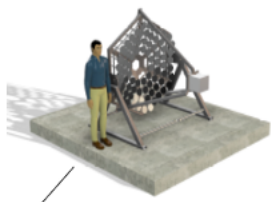
Trinity: View upward taus mountain with Cherenkov telescope

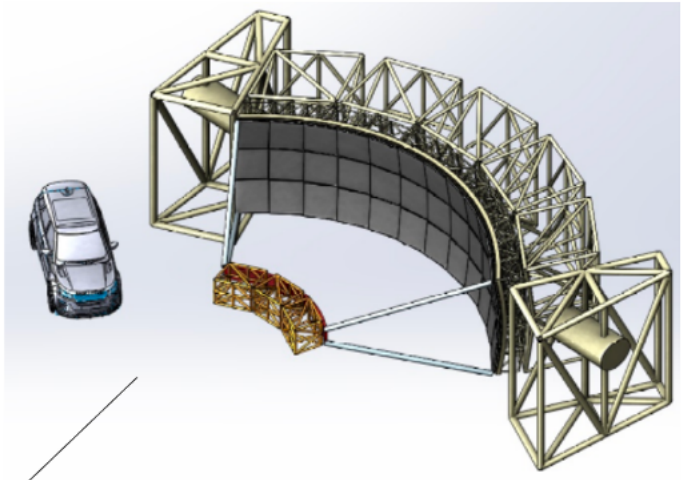
proposed



Trinity: View upward taus mountain with Cherenkov telescope

In early R&D phase



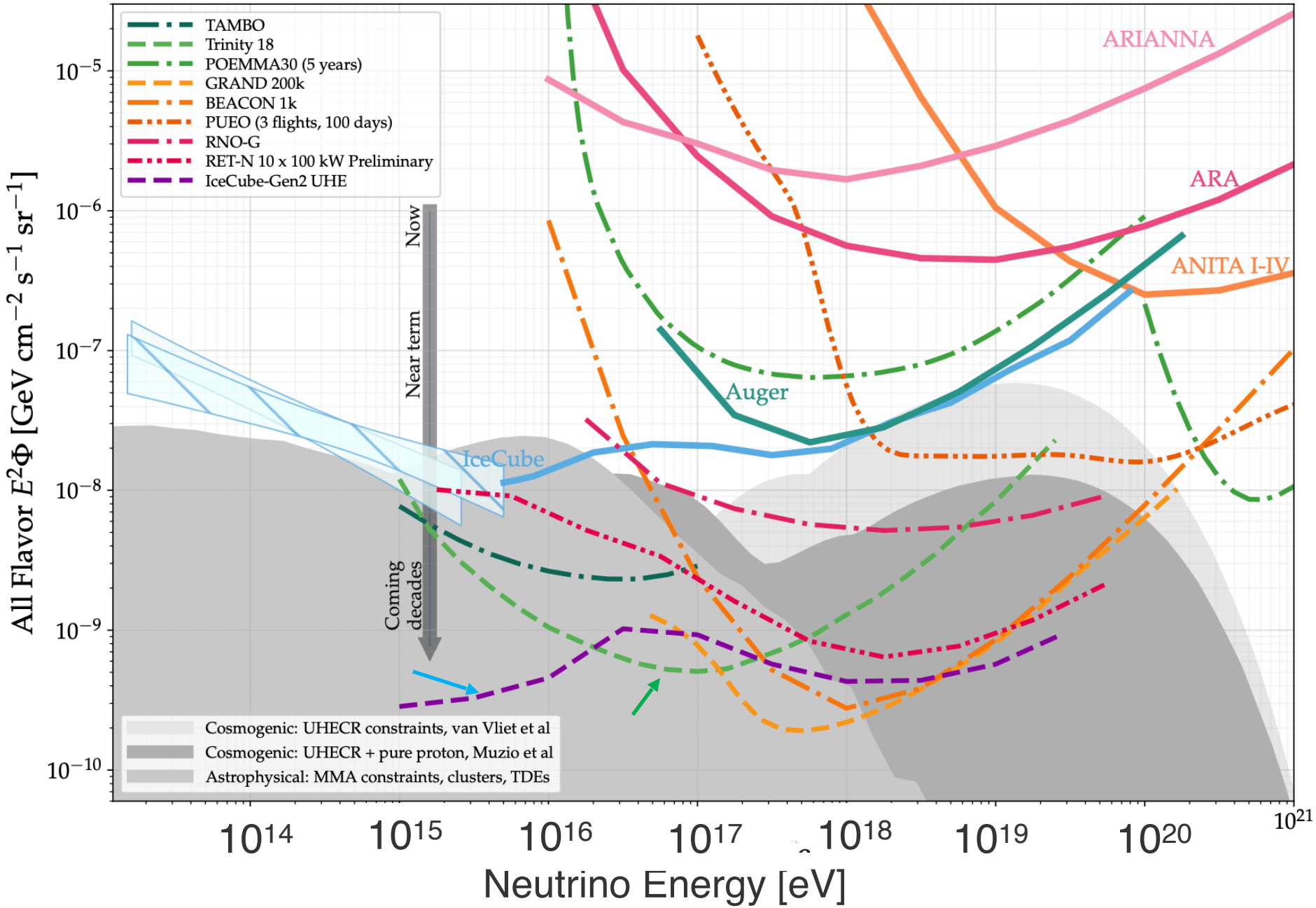


2021
Demonstrator

2025
Prototype

2030
Trinity construction

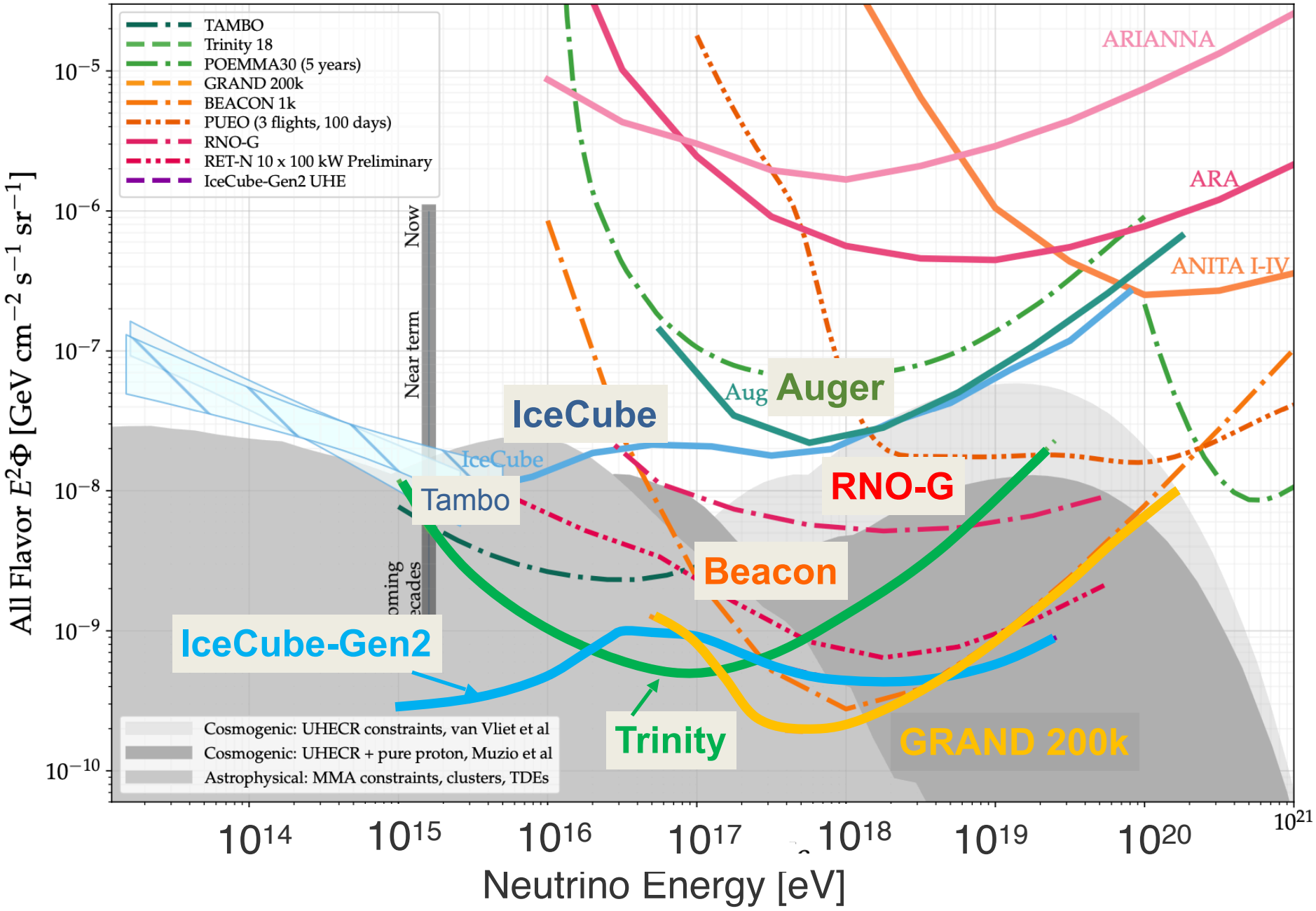
Ultra High Energies: Sensitivities



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

https://arxiv.org/abs/2203.08096

Ultra High Energies: Sensitivities



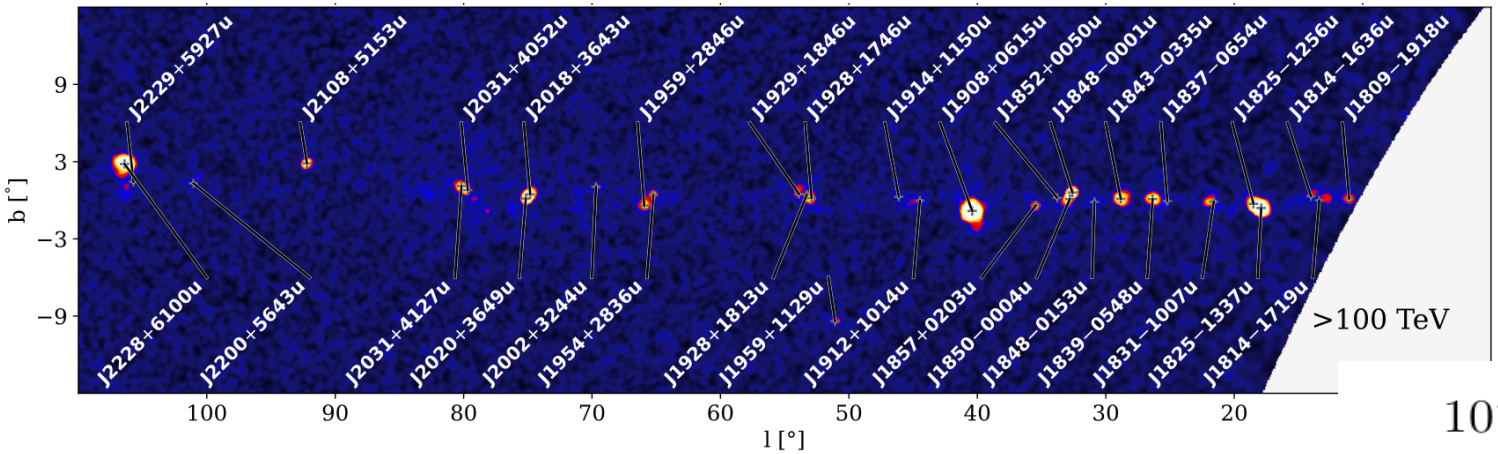
High-Energy and Ultra-High-Energy Neutrinos: A **Snowmass White Paper**

https://arxiv.org/abs/2203.08096

Outline

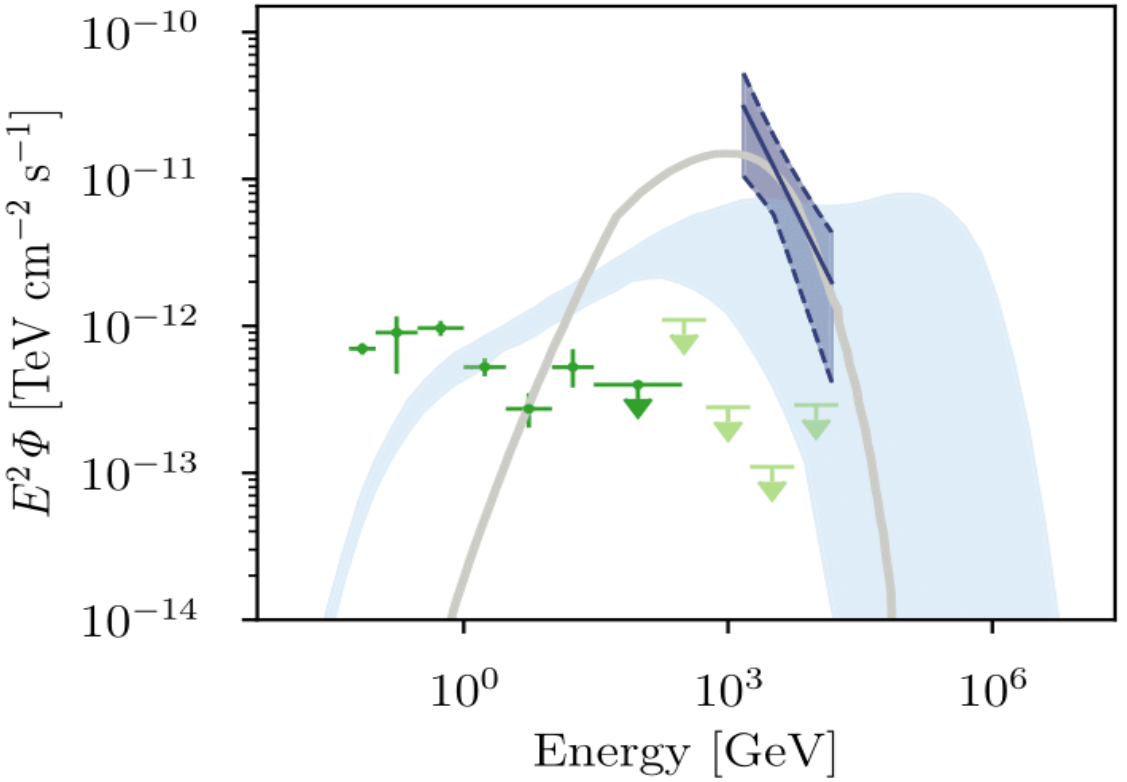
- Neutrino astronomy: The starting point
- IceCube, IceCube-Gen2
- Review of (other) current and planned projects optical
- Ultra High Energies
- **Outlook**

Outlook



LHAASO: 43 sources exhibit clear UHE emission, with a significance above 4σ at E > 100 TeV

NGC 1068 not seen in high energy Gamma Rays.



—> We need Neutrinos to access cosmic ray accelerators!

Outlook

- High energy Neutrino astronomy has entered a new era

  From discovery to astroparticle physics and astronomy

  ICRC had more than 150 papers on neutrino telescopes

- Several detectors are advancing in construction:
  - Baikal and KM3Net, RNO-G, …
- New and ambitious projects:

  P-ONE, IceCube-Gen2, TRIDENT, HUNT

Order of magnitude increase in discovery potential.

Will also allow to characterize the energy spectrum of NGC 1068

(Low energies as important as high energies)

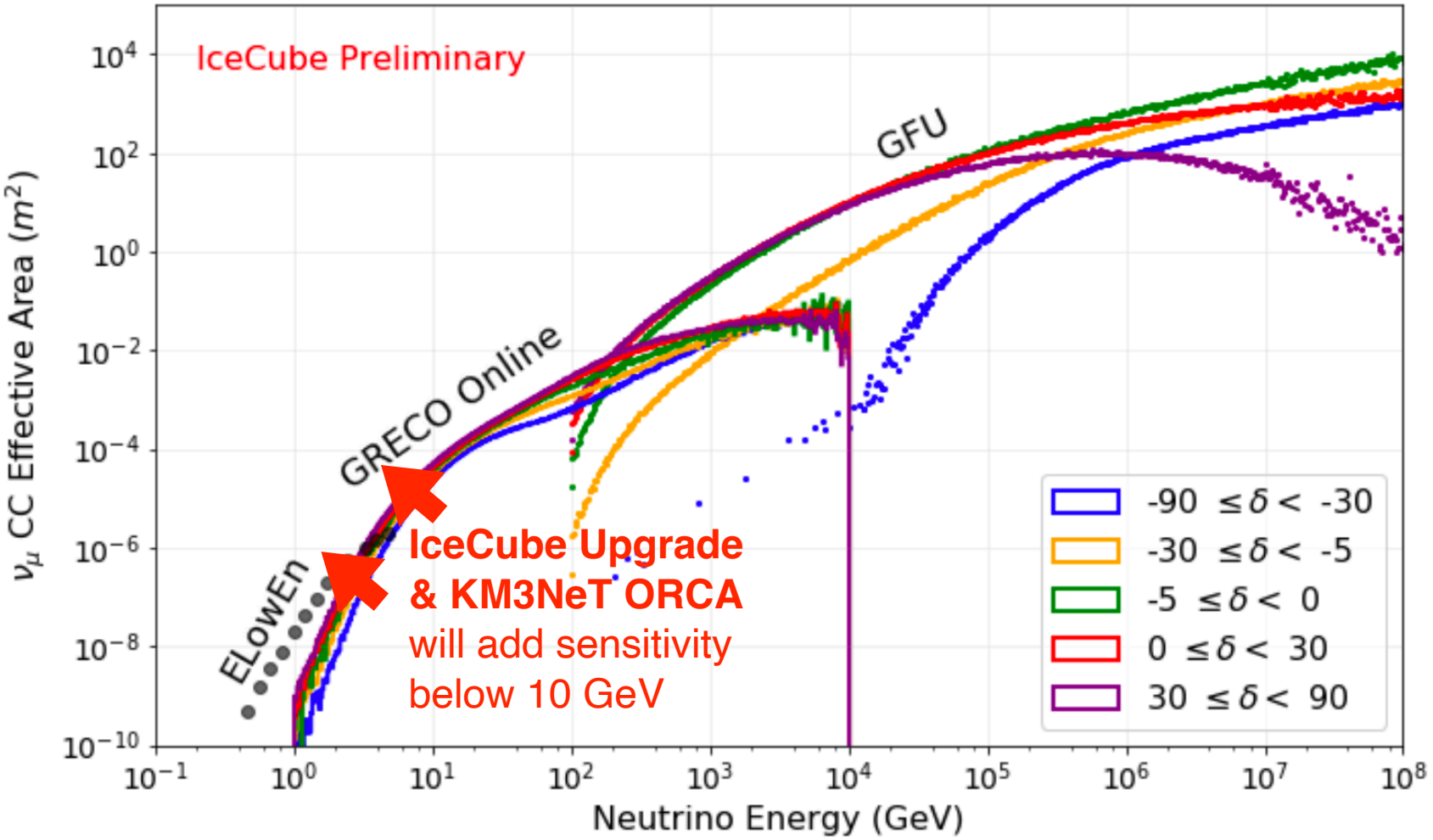
Neutrinos play growing role in Multimessenger Astrophysics

Can’t rely on gamma rays to find cosmic ray accelerators.

Backups

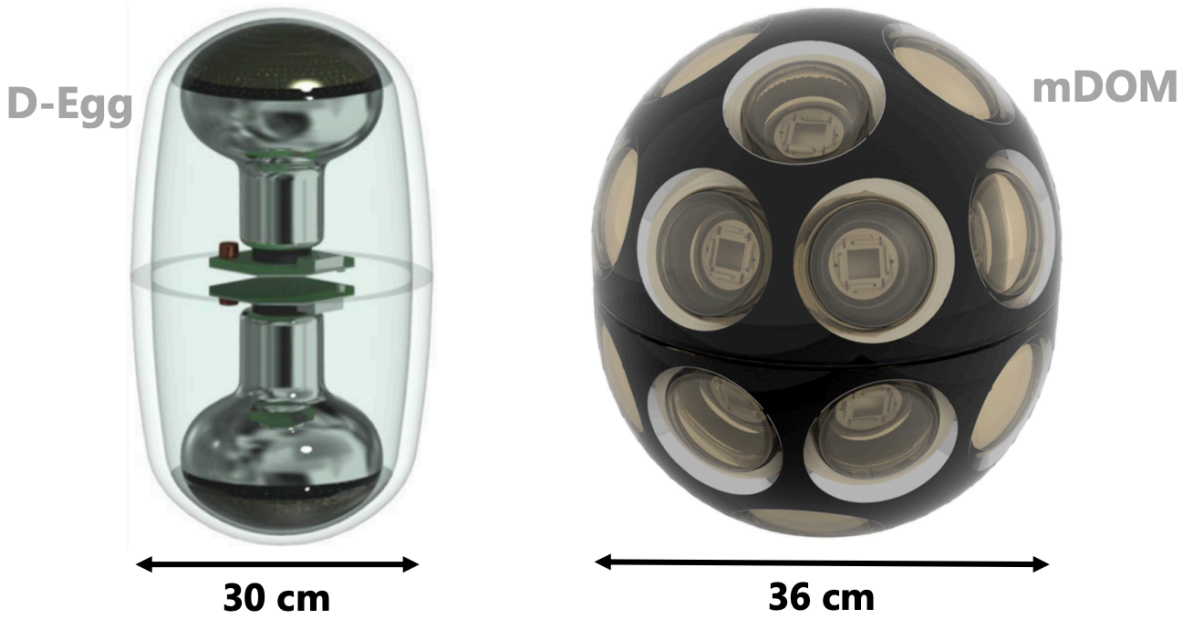
Lowest energies: GeV Neutrinos for transient sources MMA

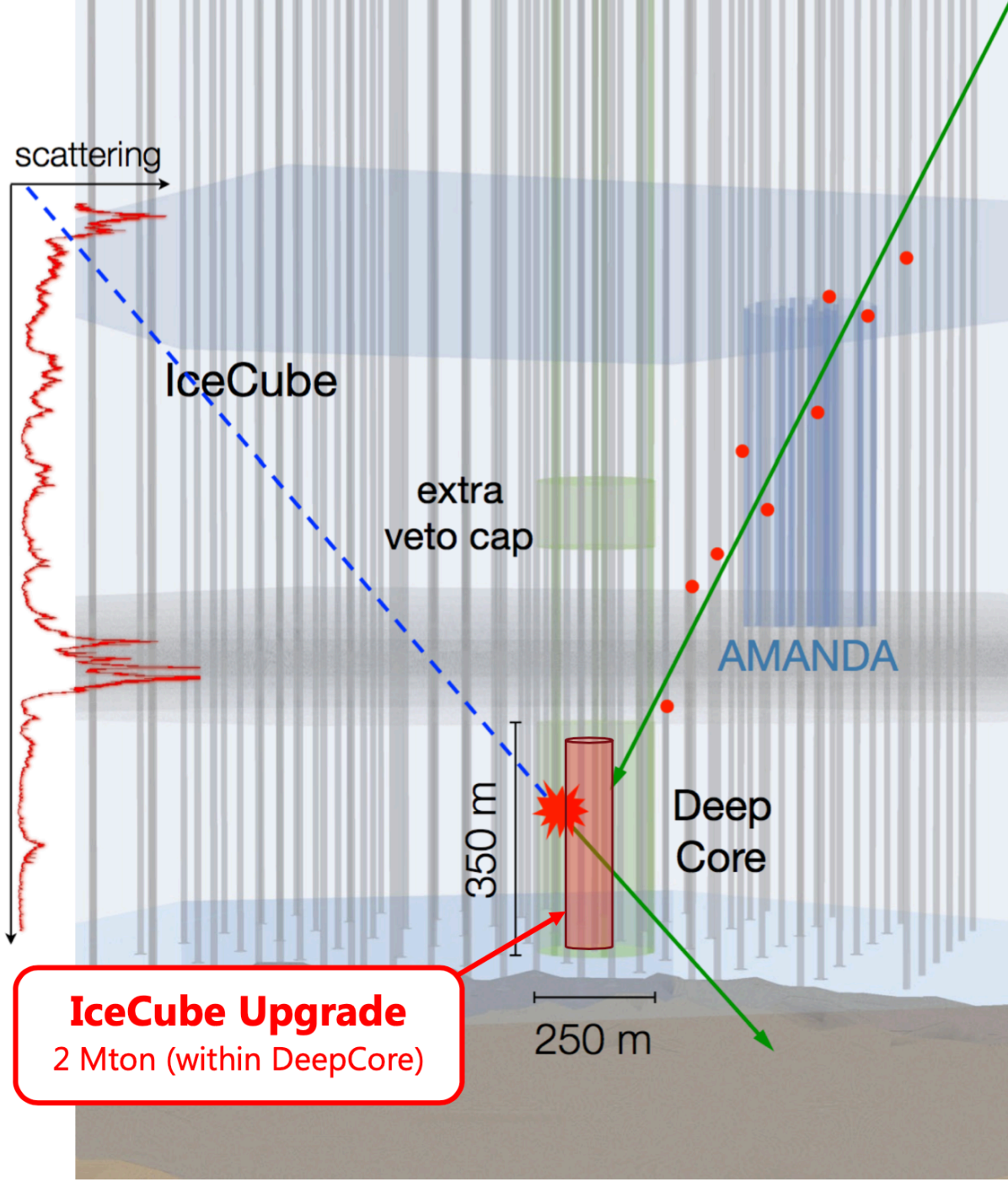
IceCube Upgrade and KM3NeT ORCA
will dramatically improve sensitivity from 1 - 30 GeV
(essentially BG free for short transients.)



The IceCube Upgrade

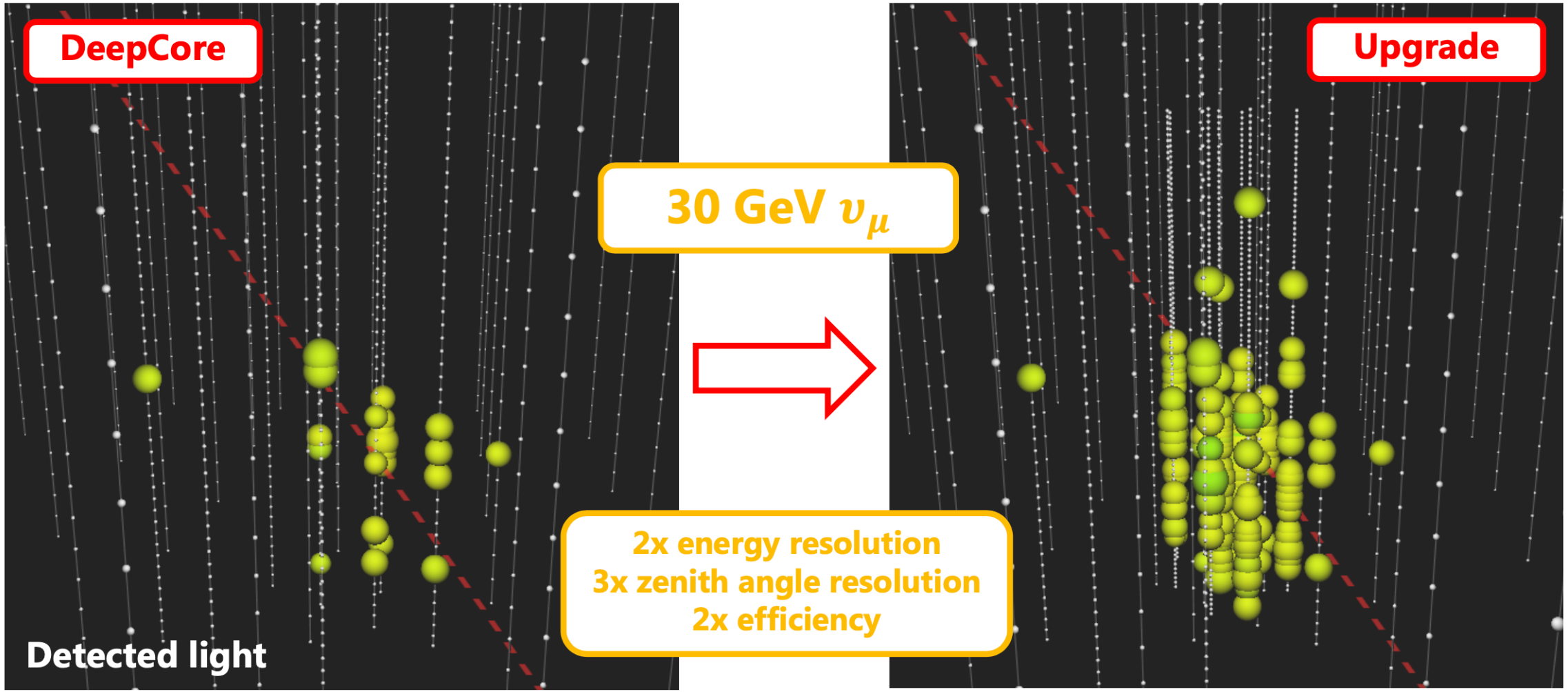
- **Low-energy extension to IceCube**
  - Deployment in **2025/6**
  - **Drop threshold to 1 GeV**
- 700 multi-PMT sensors
- Improved detector/ice calibration





IceCube Upgrade: Increased photocathode density

- **Dense instrumentation** in 2 Mton core
  - Large increase in photocathode density → sensitive down to ~**1 GeV neutrinos**



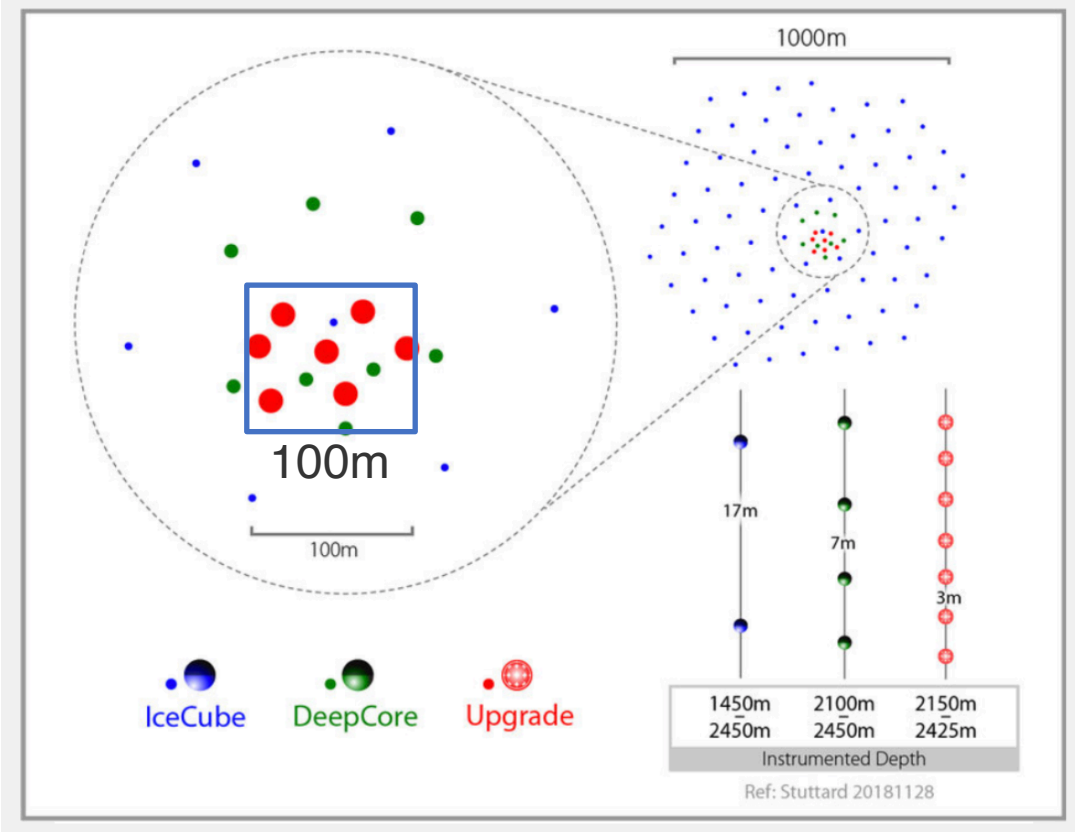
Slide: Tom Stuttard, Neutrino 2022

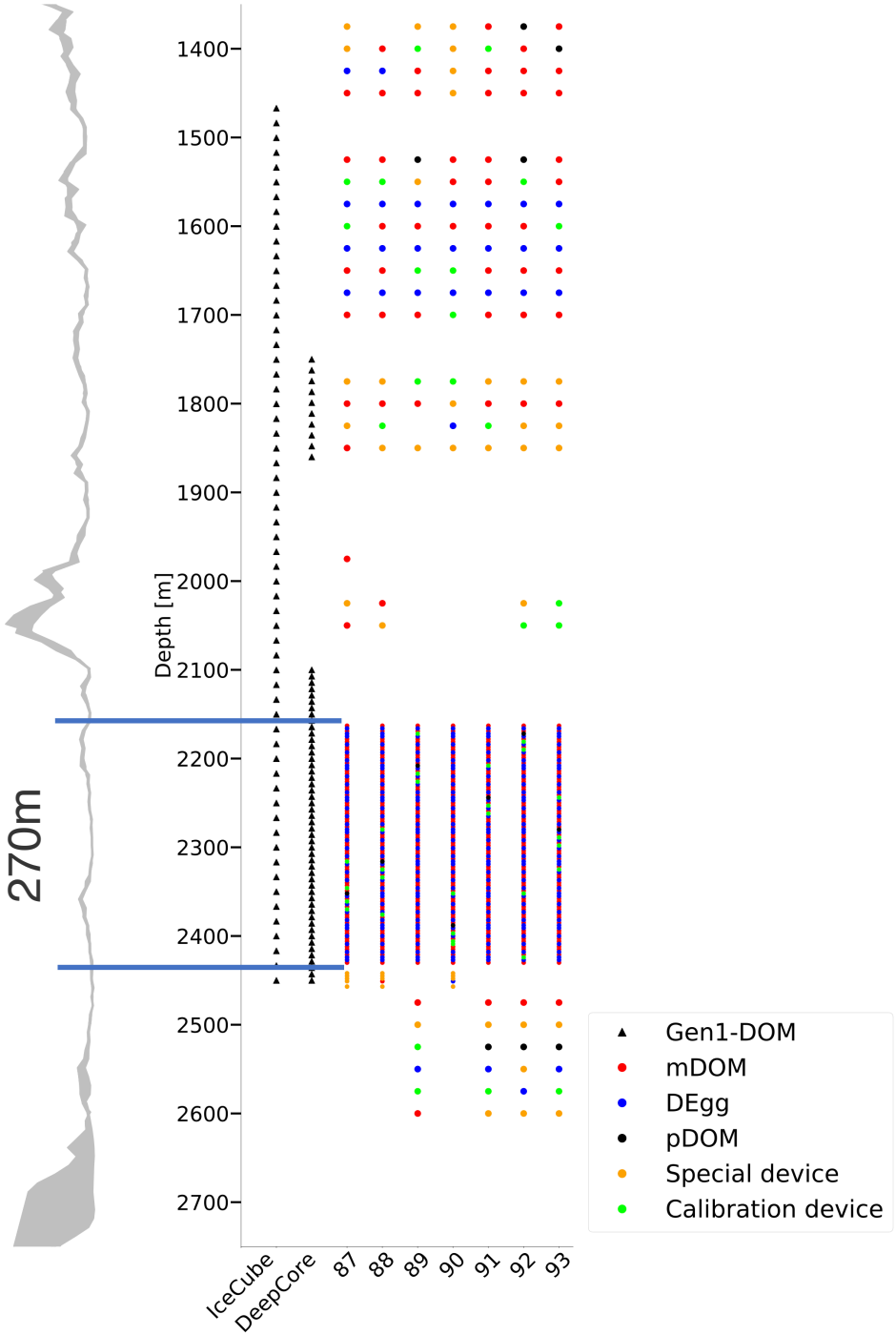
The IceCube Upgrade

Seven strings, densely instrumented.

Instrumented volume: 2.7 Mt

700 DOMs in clearest ice.





IceCube-Gen2 sensitivity: Point sources