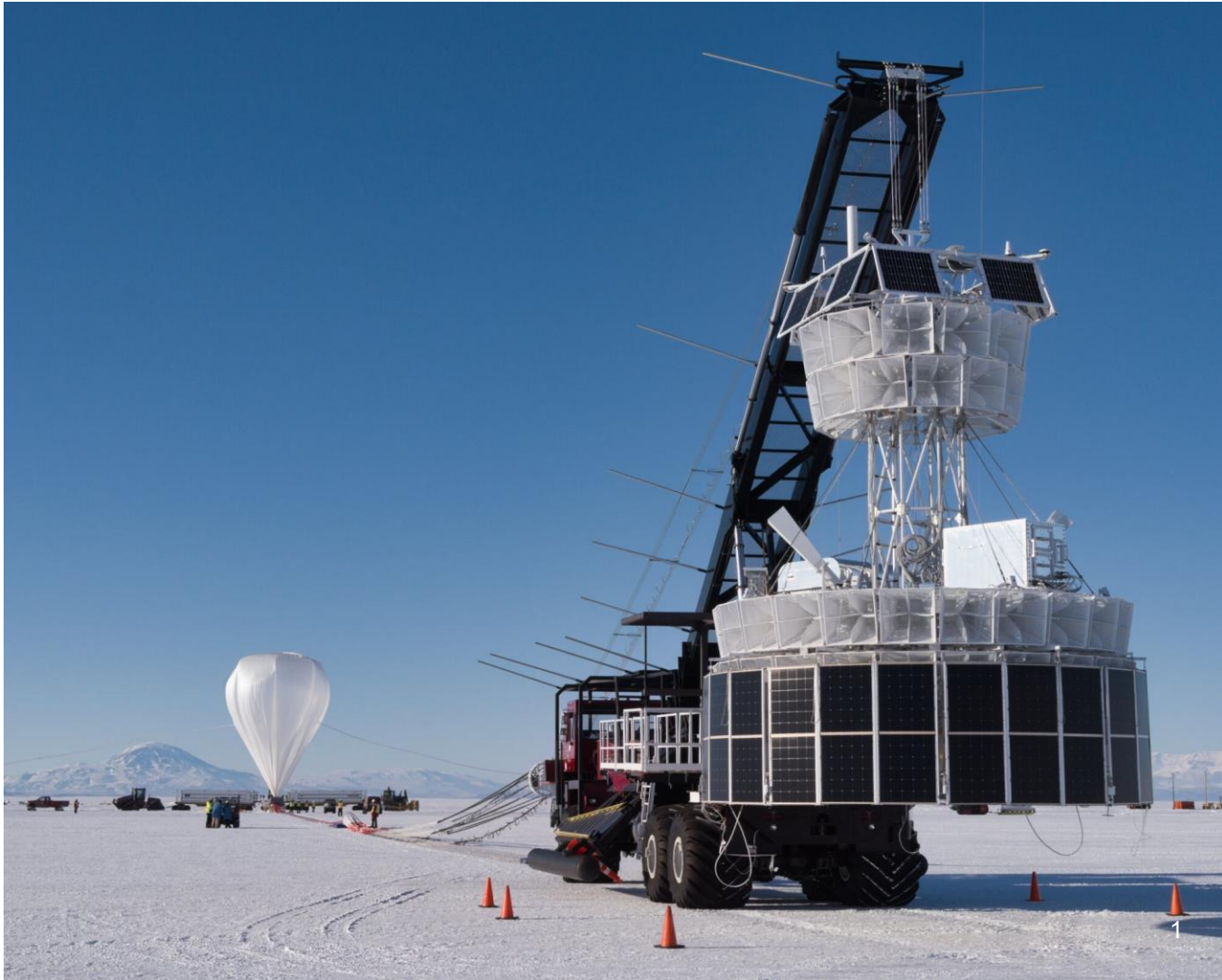
Using Radio Detectors to Measure the Highest Energy Neutrinos

Abigail Vieregg
University of Chicago
Neutrino 2026



Neutrinos: A Window to the Ultra-high Energy Universe

There are sources making particles x10^4 more energetic than the neutrinos seen by IceCube.

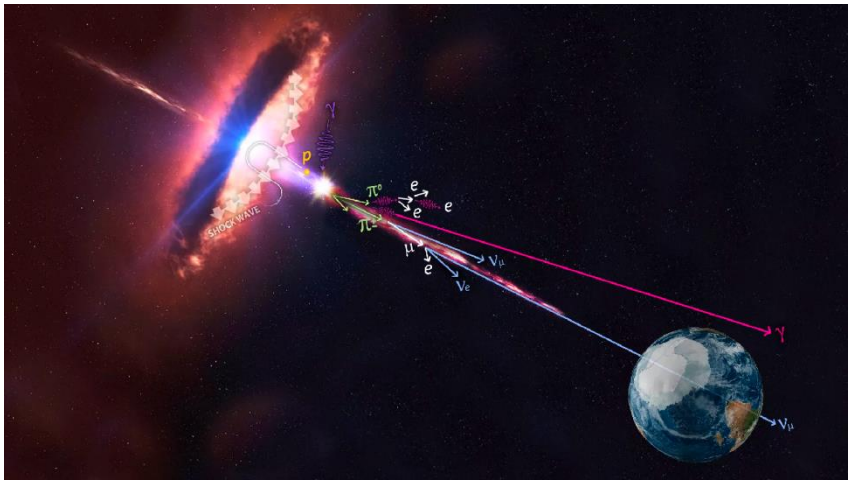
→ How are these particles accelerated?

Neutrinos are an ideal messenger:

- Propagate cosmological distances
- Not deflected by magnetic fields

Ultra-high energy (>100 PeV) neutrino telescopes open a unique window into the universe; complementary in the multi-messenger astrophysics landscape:

- Highest energy observation of extragalactic sources
- Very distant sources
- Deep into opaque sources
- Carry information about the production mechanisms

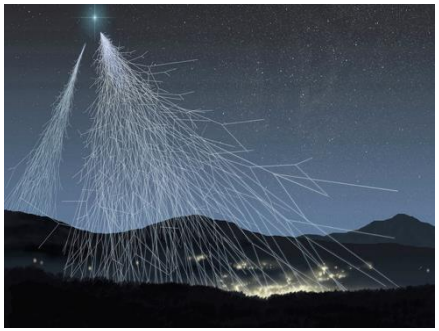


Neutrino Production: The GZK Process

GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

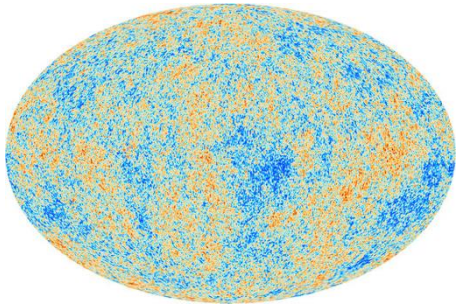
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Cosmic Rays



+

CMB

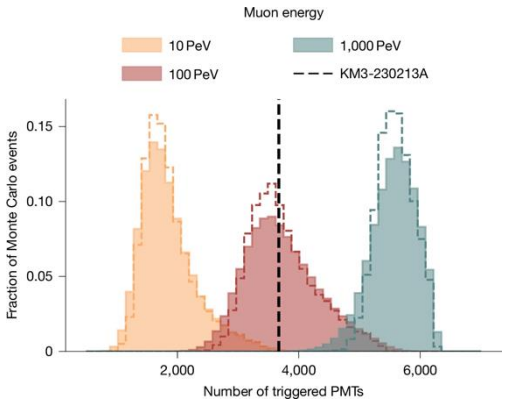


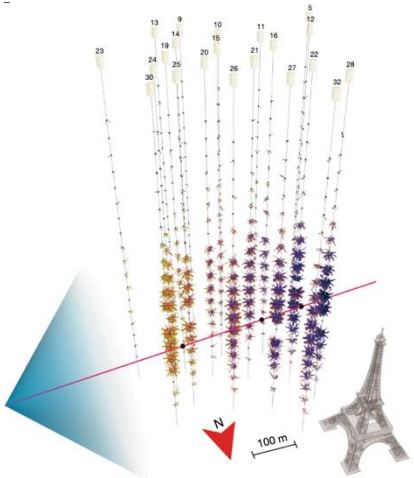
= Neutrino Beam!

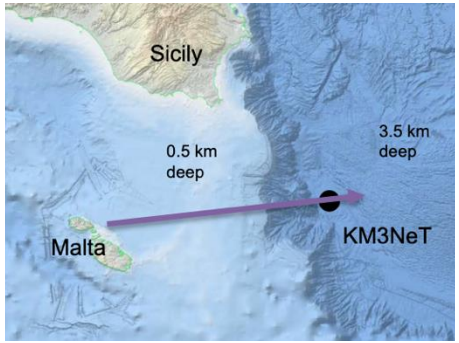
Can also ask: what is the high energy cutoff of our universe?

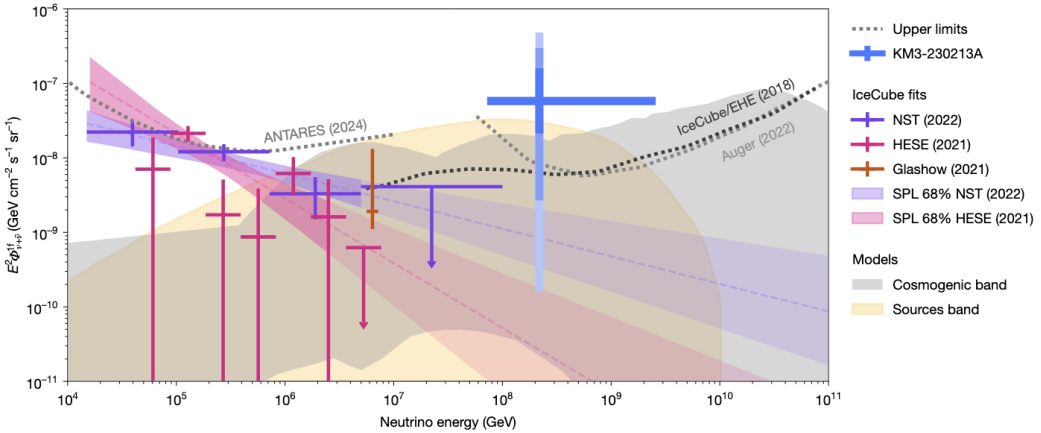
The Highest Energy Neutrino Ever Detected

- 10^{17} eV Neutrino Event seen with KM3Net
- A single UHE event was detected in Summer 2024
- Is this the first hint of cosmogenic neutrinos?
  (see S. Celli talk tomorrow)





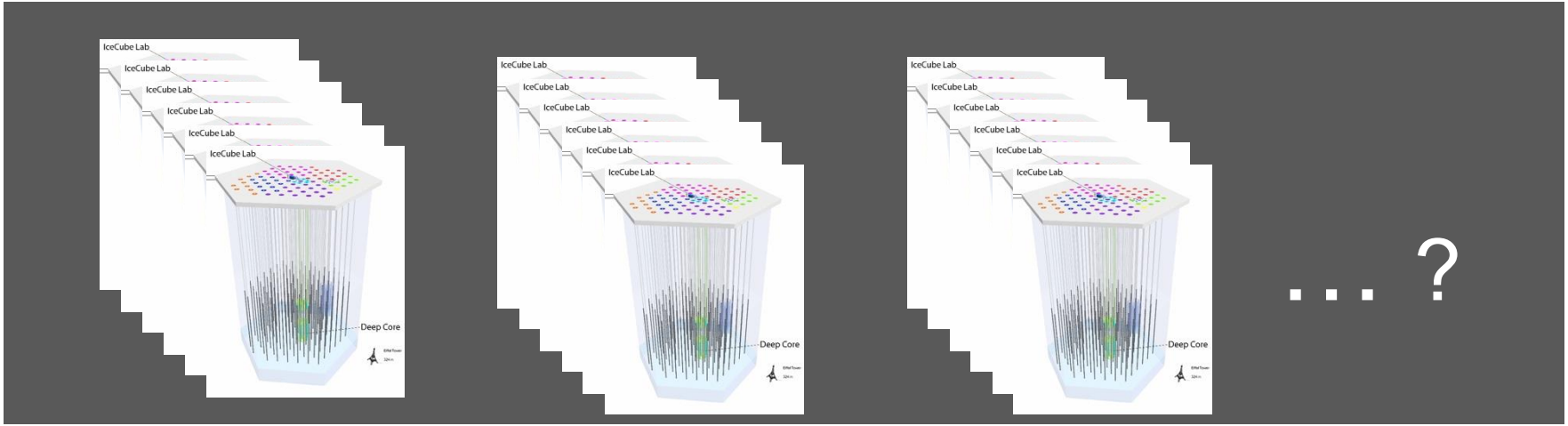




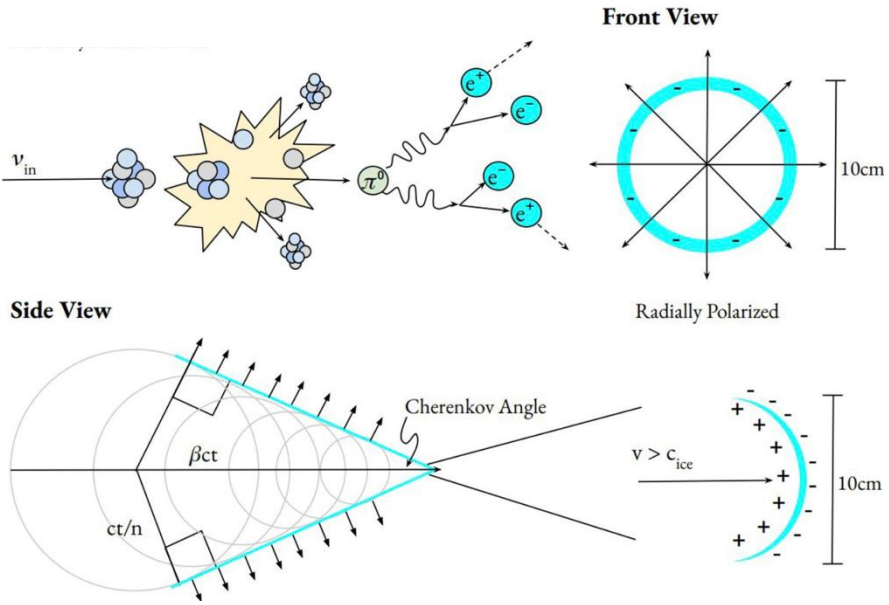
KM3NeT Coll., Nature 2025

The Problem with Neutrino Astronomy

- Neutrinos don’t interact very often, so it is hard to detect them!
  - Need a huge detector to have a chance to see them (IceCube/KM3NeT)
- The highest energy neutrinos are even more rare, so you need an even bigger detector – but how do you build that?

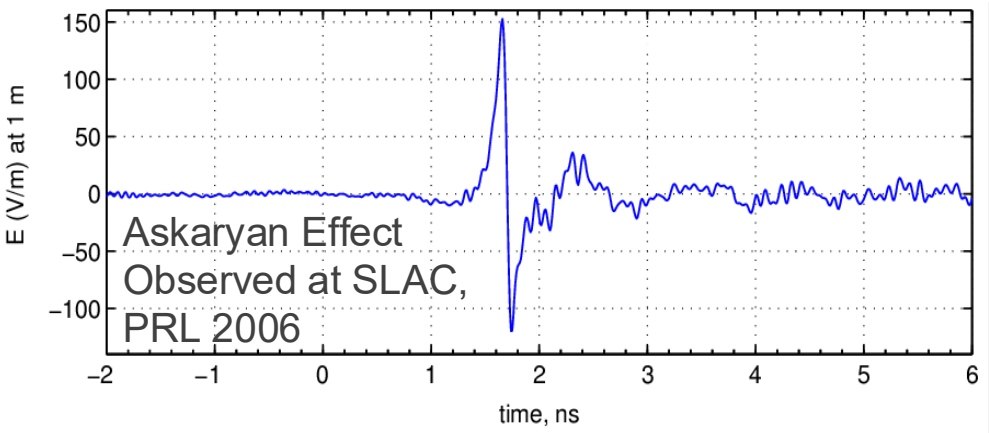


Method 1: Radio emission from neutrino interactions in a dielectric

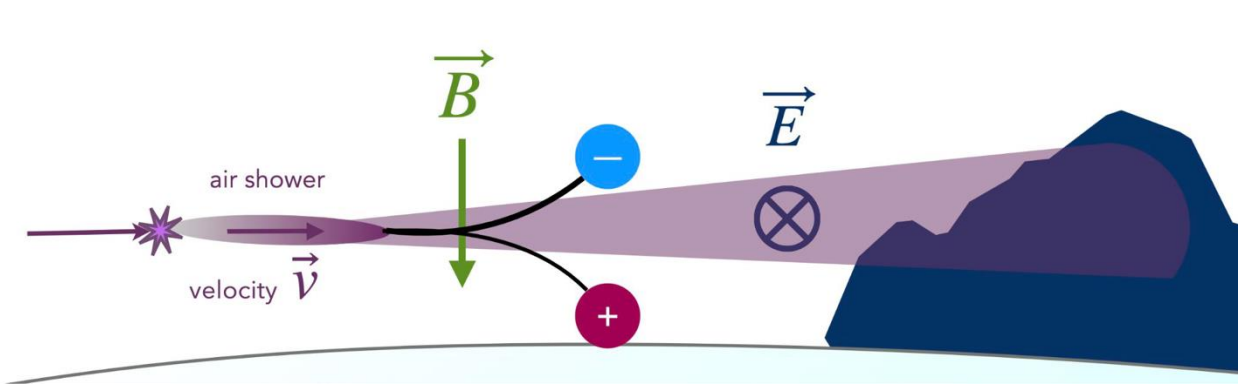


- EM shower in dielectric (ice, sand) → moving negative charge excess
- Coherent radio Cherenkov radiation (P ~ E^2) if λ > Moliere radius, called the **Askaryan Effect**

→ Radio Emission is stronger than optical for UHE showers



Method 2: Emission (Radio or Optical) from Tau Neutrino Induced Air Showers



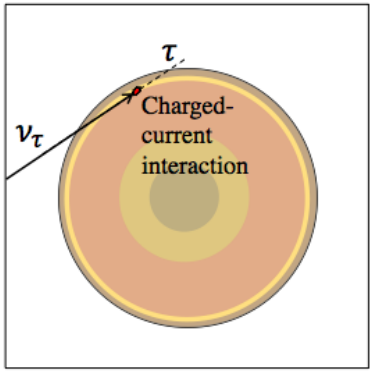
Extensive air showers initiated by high energy particles hitting the atmosphere make geomagnetic radio emission

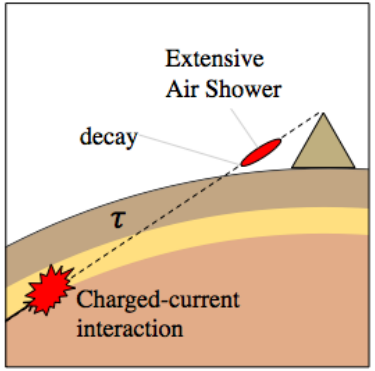
S. Wissel

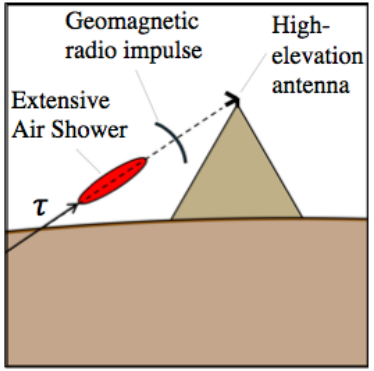
Neutrino-induced signals:

- Looks like an upward going cosmic ray air shower
- Observe from surface, a mountain, balloon, or space

(See posters from C. Trimarelli, R. Thong, K. Tran, C. Arguelles Delgado, A. Roy)

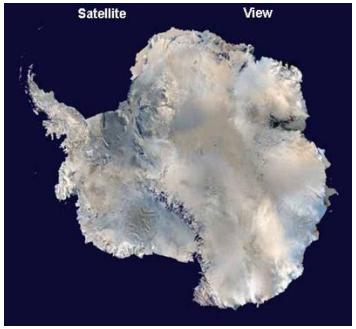






Radio Neutrino Astronomy Across Energy Scales

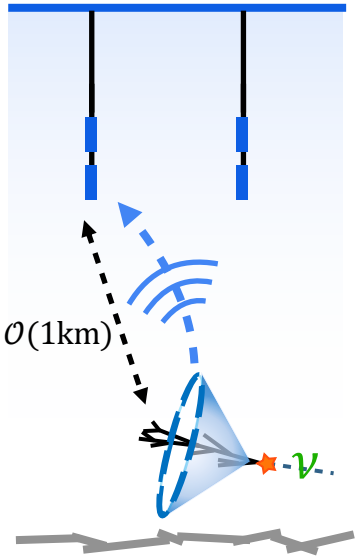
Need a huge (~100 km^3), radio-transparent detector: glacial ice



We need different instruments to cover the full energy range of expected cosmogenic neutrinos, above the energy range of IceCube and KM3NeT

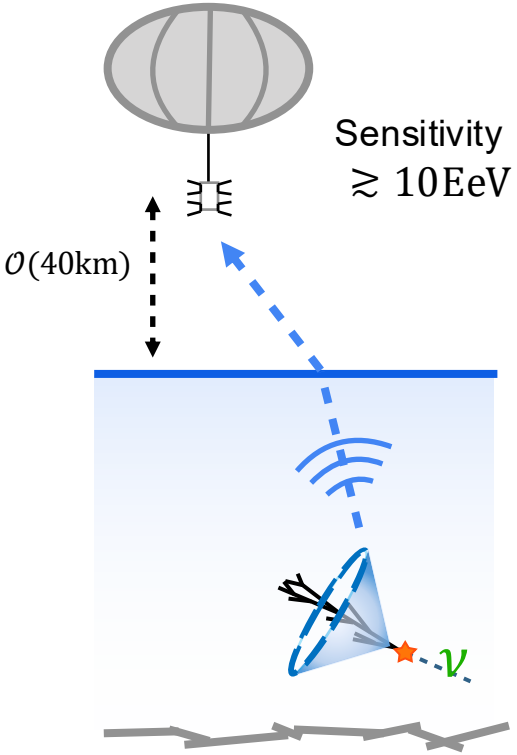
Ground-based

Sensitivity
$\gtrsim 100\mathrm{PeV}$



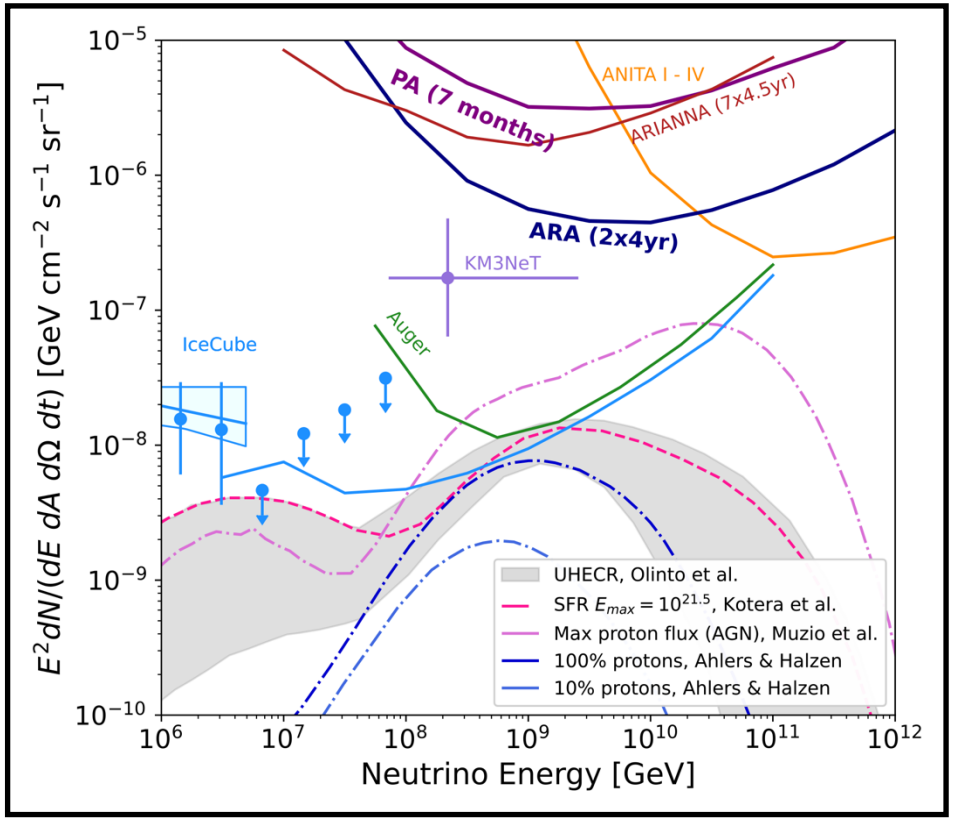
Balloon-based

Sensitivity
$\gtrsim 10\mathrm{EeV}$



Best Constraints at the Highest Energies

The best sensitivity up to $10^{19.8}$ eV is from IceCube.



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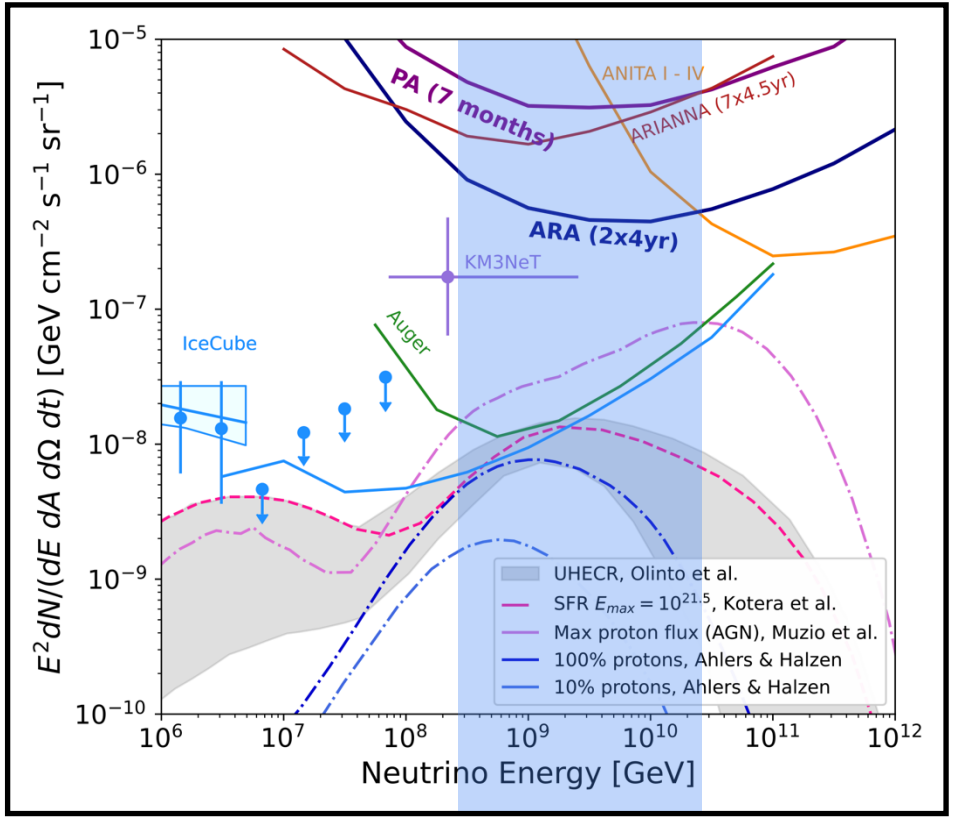
Small ground-based in-ice radio experiments have provided constraints (e.g. ARA, ARIANNA), and a larger array is currently under construction (RNO-G).



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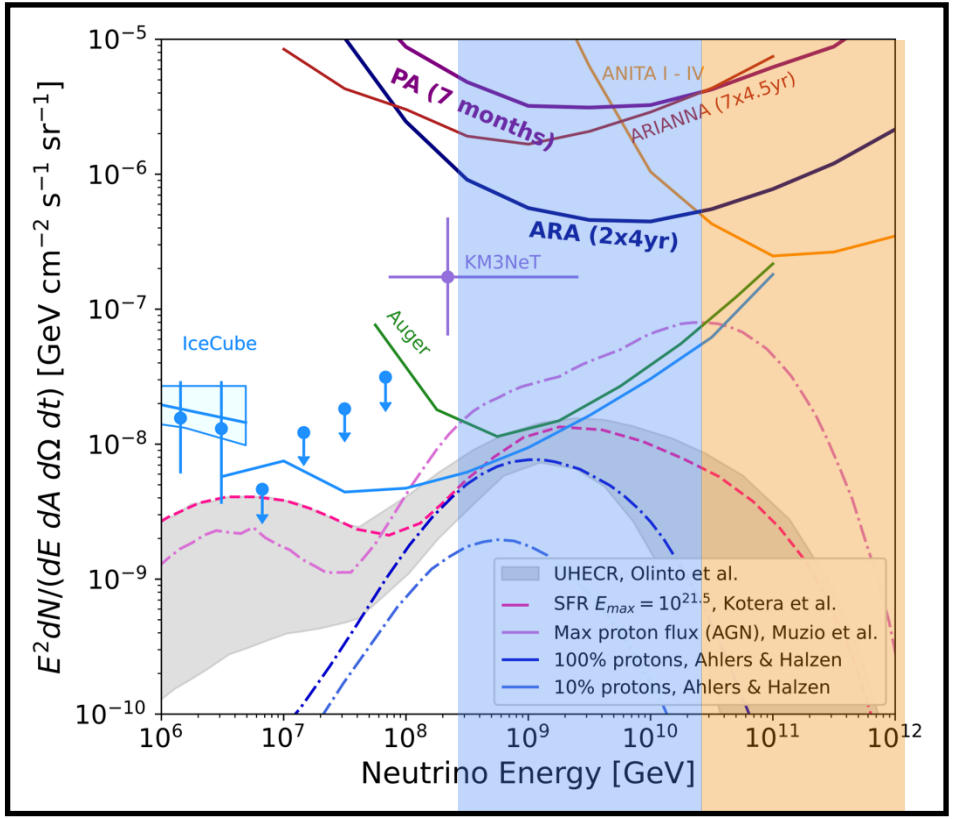
At the highest energies, the best constraints come from a balloon-borne experiment (ANITA), and the next-generation experiment just flew (PUEO)



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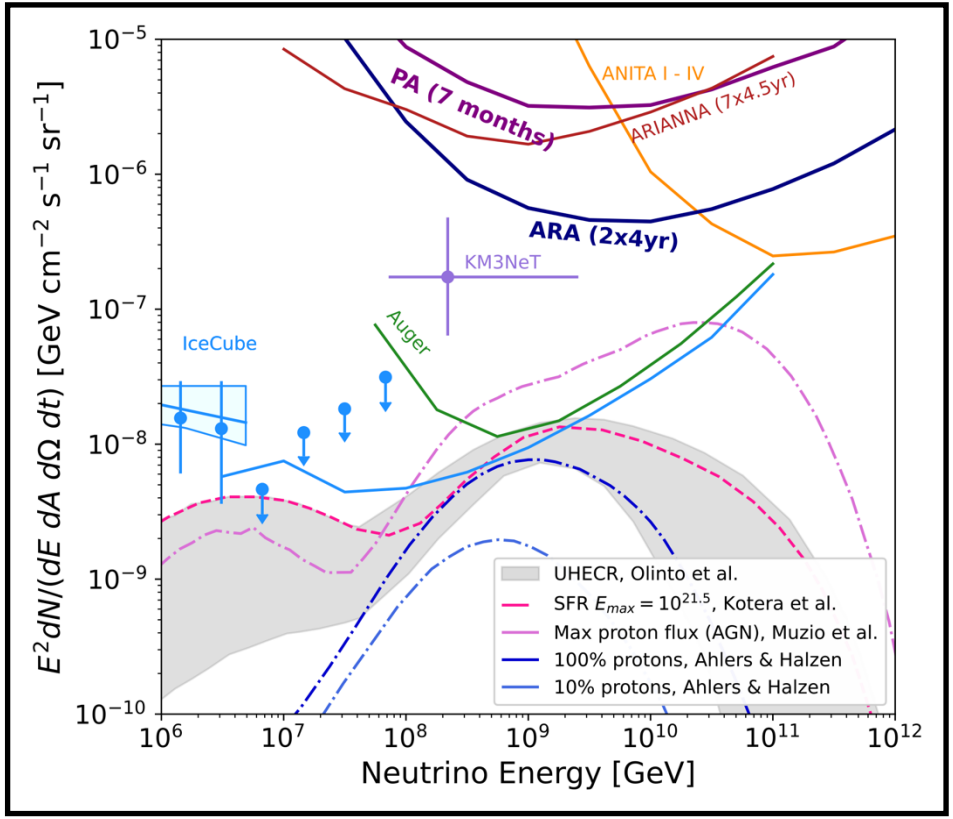
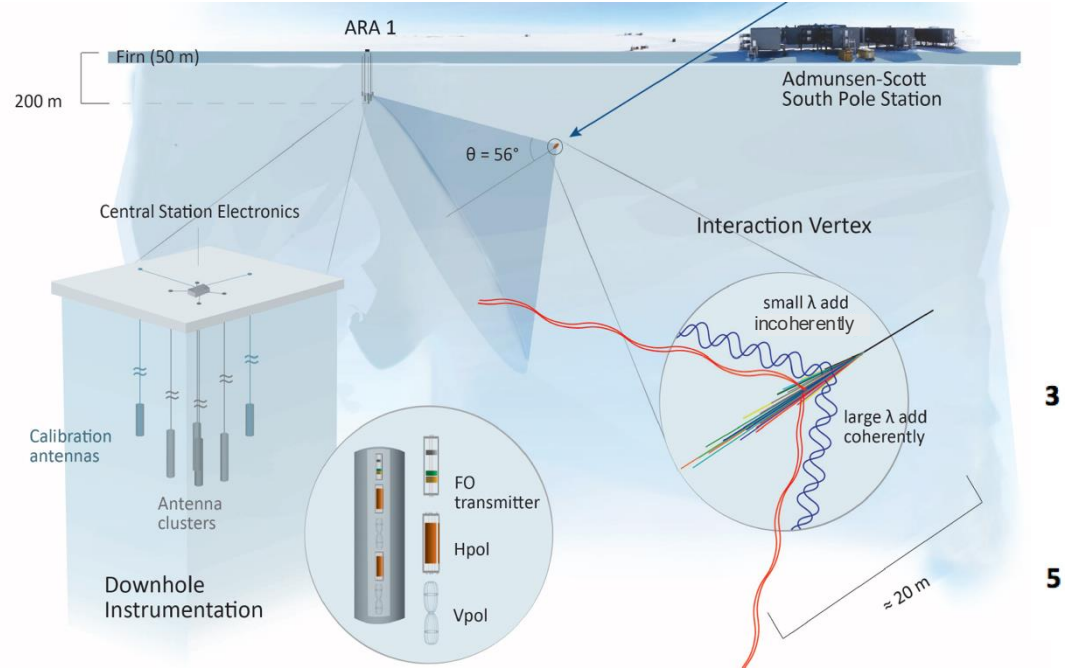
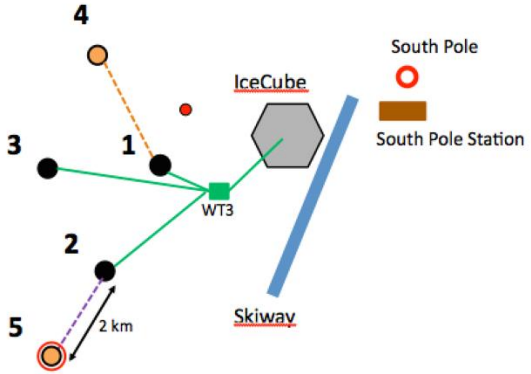
So, how do you do better than this?



The Askaryan Radio Array (ARA)



- 5 Stations of Ground-Based Radio Detectors at the South Pole
- Most recent instrumentation install was 2017/18

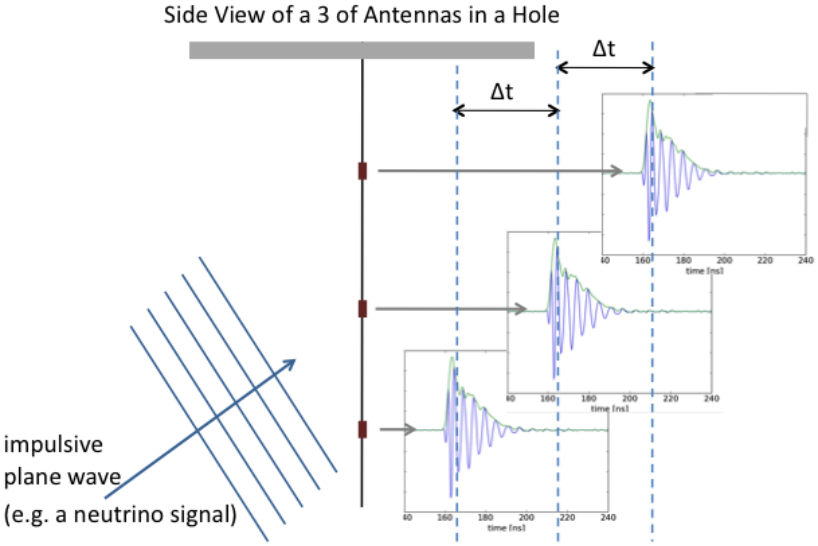


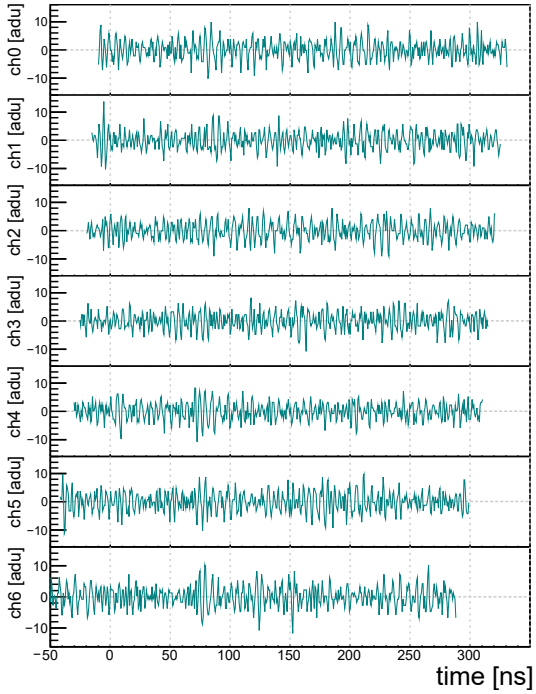
ARA Beamforming Trigger

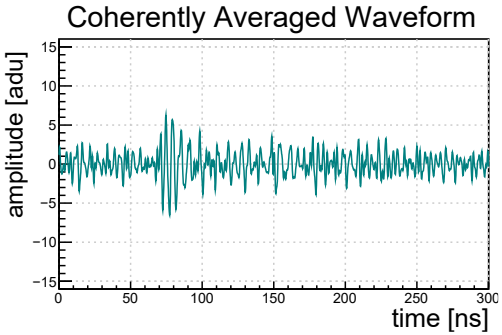
ASKARYAN RADIO ARRAY

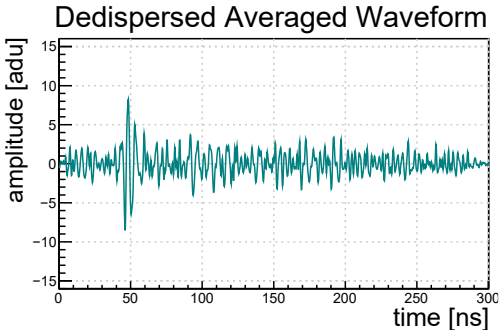
Beamforming at the trigger level increases SNR to trigger on by sqrt(N).

Create many beams simultaneously to cover the entire solid angle of interest.









ARA Coll. NIM 2019

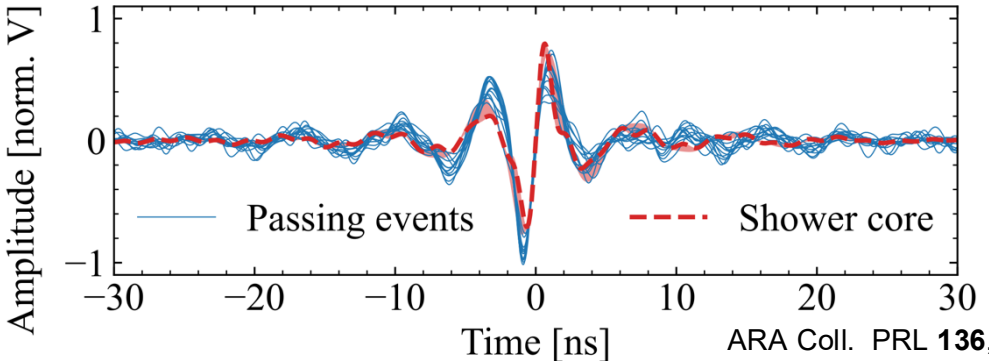
New Results This Year: Observation of Askaryan Emission

Observation of Askaryan Emission from Ultrahigh Energy Cosmic Rays in Ice

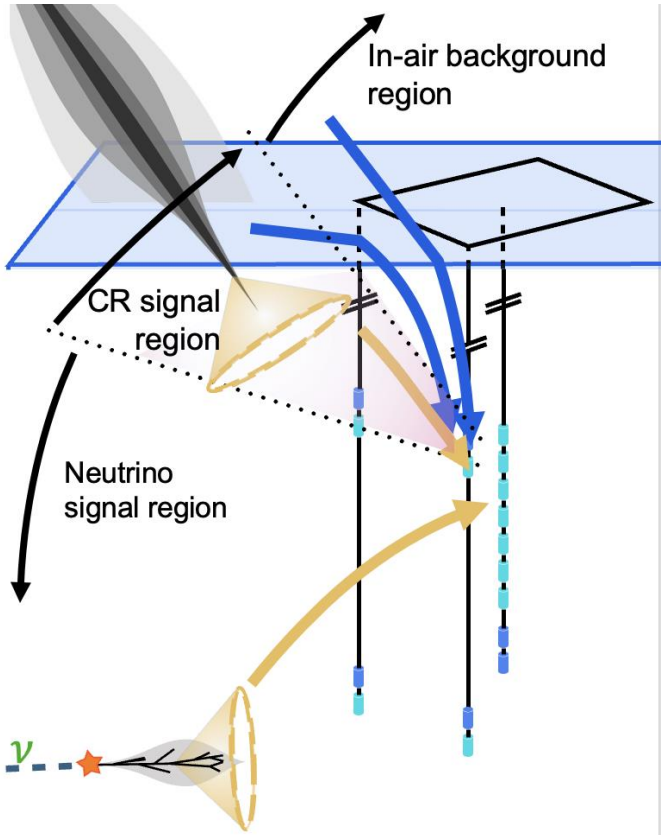
- 13 events observed (5.1σ above background)
- Similar event shape, frequency content, the same electric field polarity, and match simulations (signal shape as well as expected event rates) well.

Why is this important?

- First validation of Askaryan emission models and dense shower physics at these energies
- Calibration and validation of neutrino sensitivity for Askaryan detectors



ARA Coll. PRL **136**, 151003



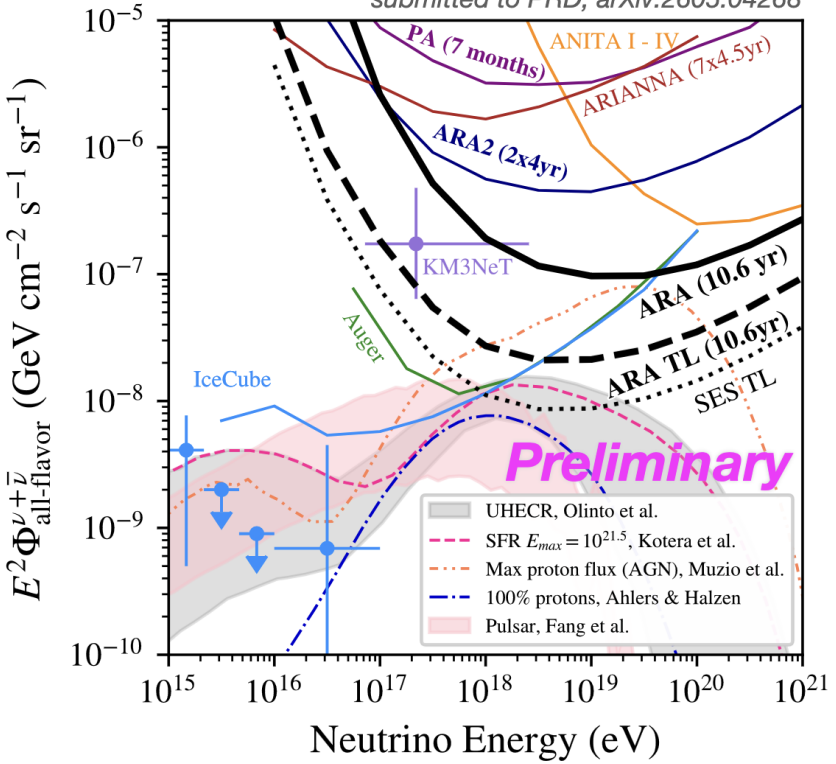
New Results This Year: New Constraints on Diffuse Flux

New Constraints on the UHE Diffuse Neutrino Flux (Unblinded Last Month!)

- Analyzed 10 Years of ARA Data from all 5 ARA stations: 2013-2023
- Best sensitivity to date above $10^{19.5}$ eV
- Background estimate across 10 years and 5 stations is: 0.13 +/- 0.01
- Unblinding: 1 event observed (further inspection of the event indicates it is likely to be background from the detector itself)

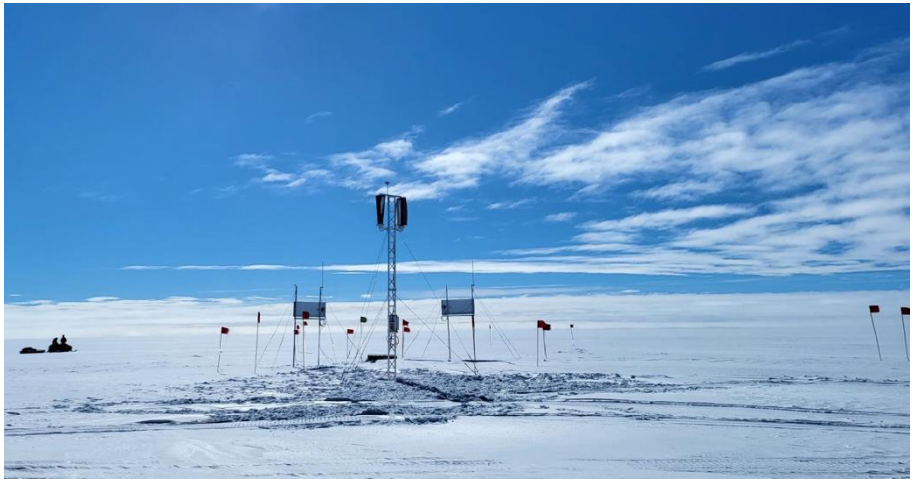
See poster from M. Seikh!

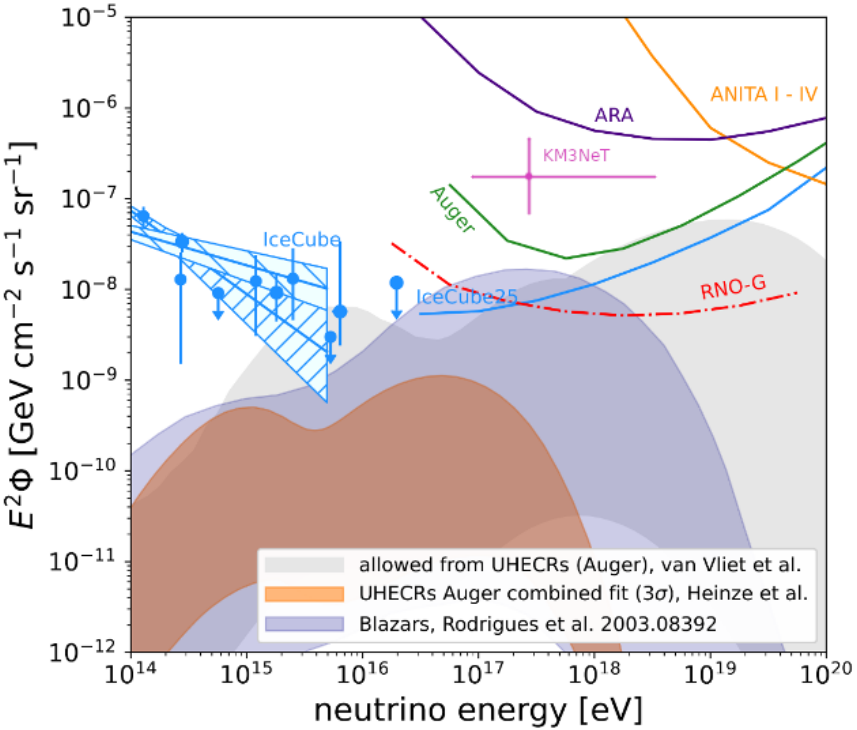
Alden et al. (ARA Collaboration), submitted to PRD, arXiv:2605.04268



Radio Neutrino Observatory in Greenland (RNO-G)

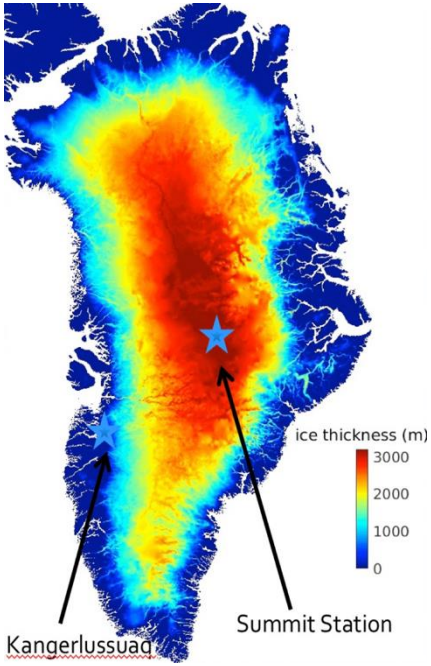
- RNO-G is currently being installed at Summit Station in Greenland (first hardware deployed in 2021).
- RNO-G is designed to be scalable to even larger arrays (IceCube-Gen2 Radio Array)





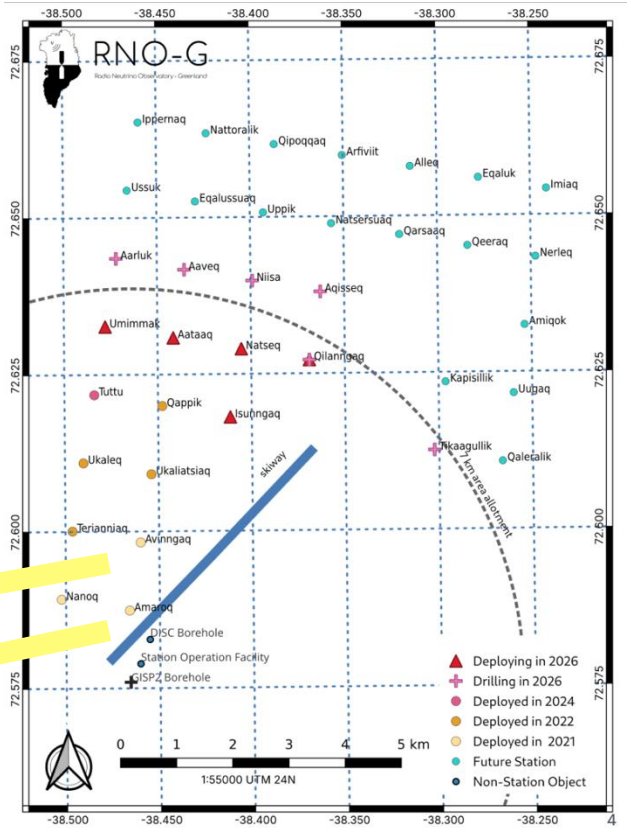
See Poster from A. Nozdrina

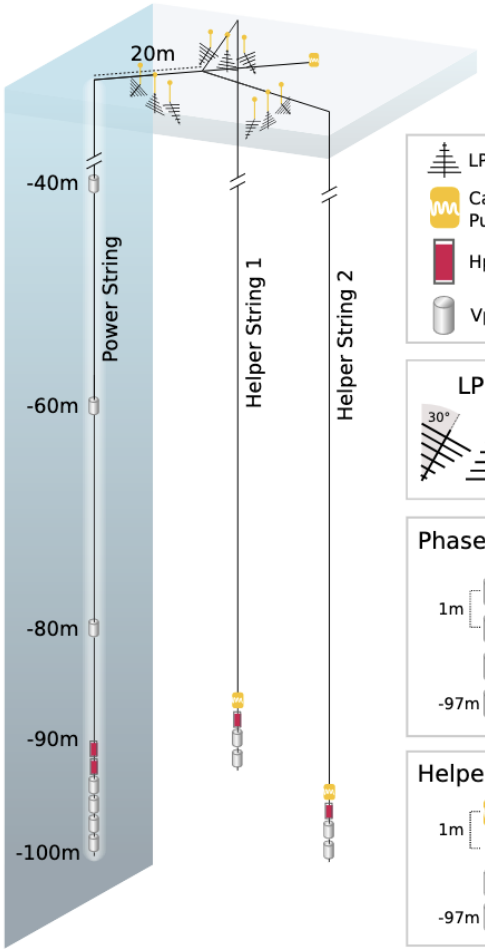
Radio Neutrino Observatory in Greenland (RNO-G)



Already the most sensitive UHE neutrino detector operating at 10^{17} eV!

- Currently: 8 stations installed and operating.
- 2026: Plan to deploy up to 5 more stations
- Planned configuration: 35 stations (hardware is fully funded from European funds)





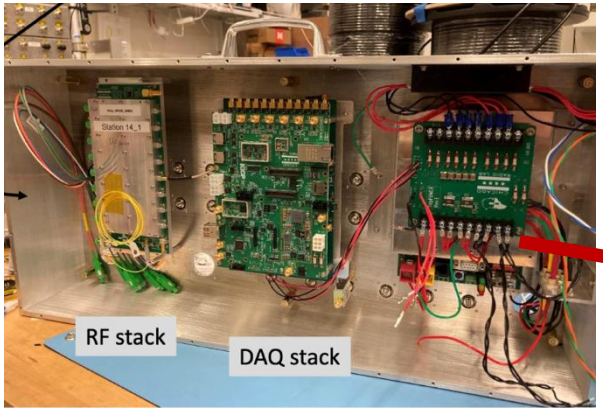
RNO-G

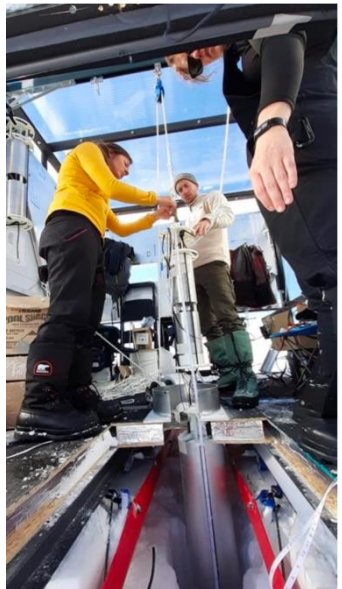
LPDA
Calibration Pulser
Hpol
Vpol

LPDAs
30°
30°

Phased Array
1m
-97m

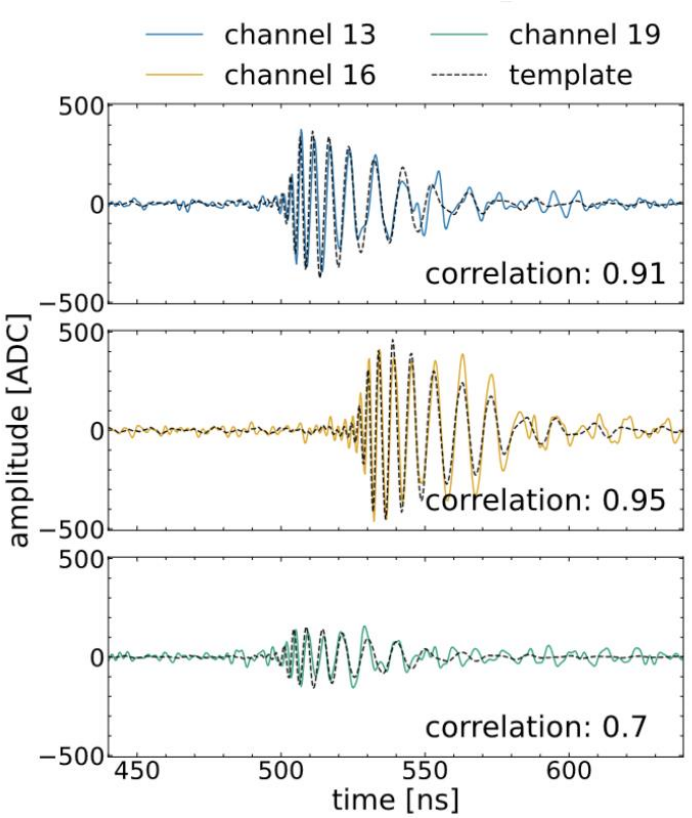
Helper String
1m
-97m



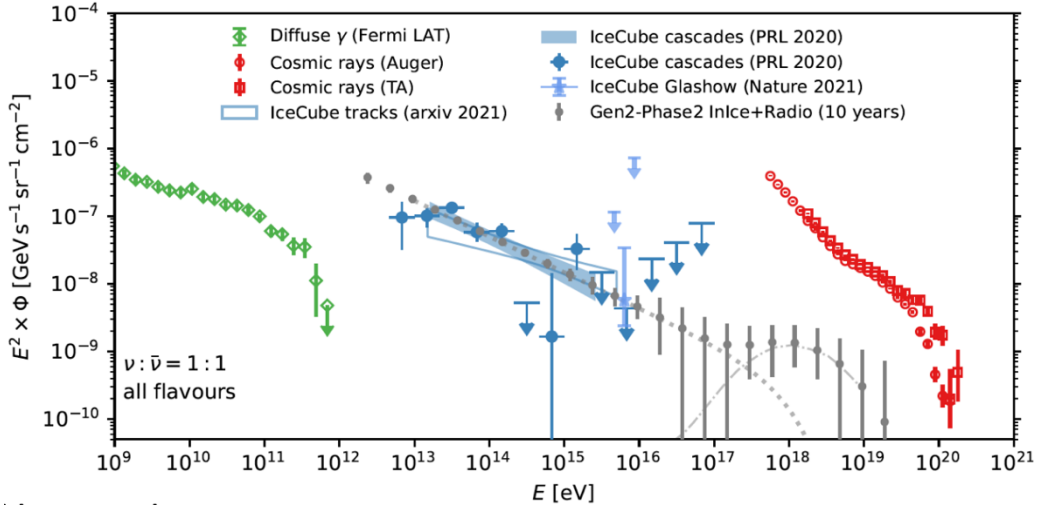


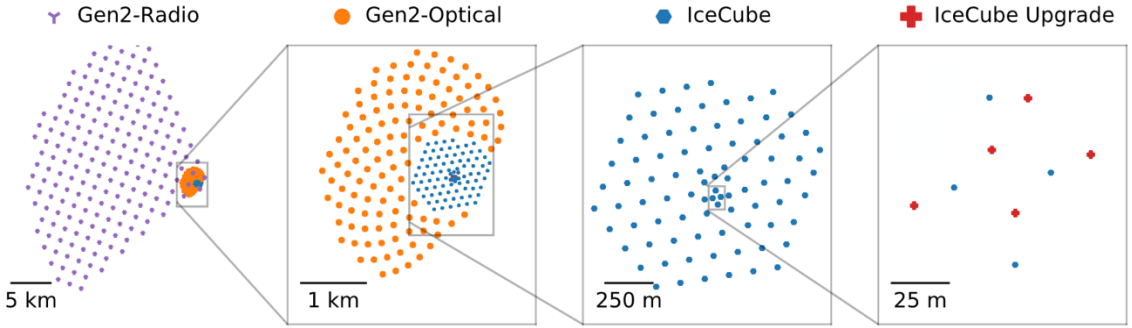
Cosmic Ray Air Showers in RNO-G

- Calibrating detector sensitivity to a (known) flux of cosmic ray air showers validates neutrino sensitivity. There is also cosmic ray air shower science to do.
- See likely cosmic rays air shower events in the three upward-pointing near-surface antennas in RNO-G.
- The signals match simulation well.

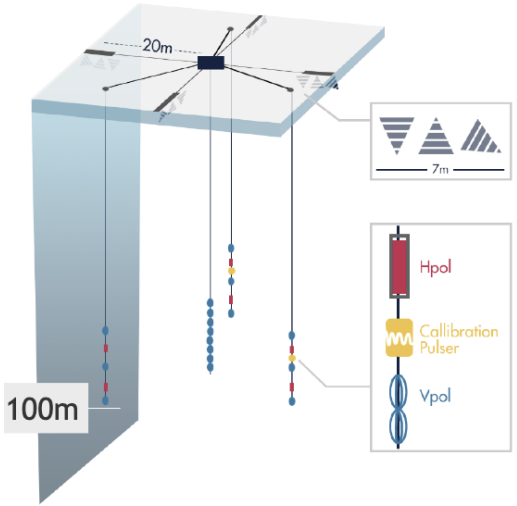


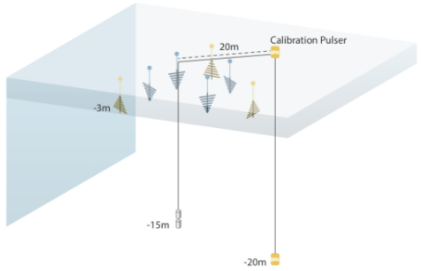
IceCube-Gen2: A Future Optical + Radio Observatory at the South Pole





Deployed in 2025

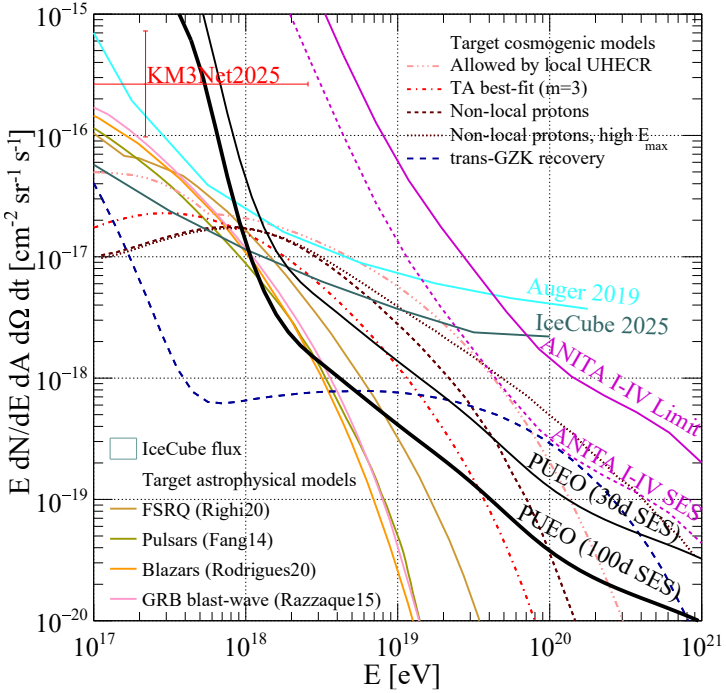




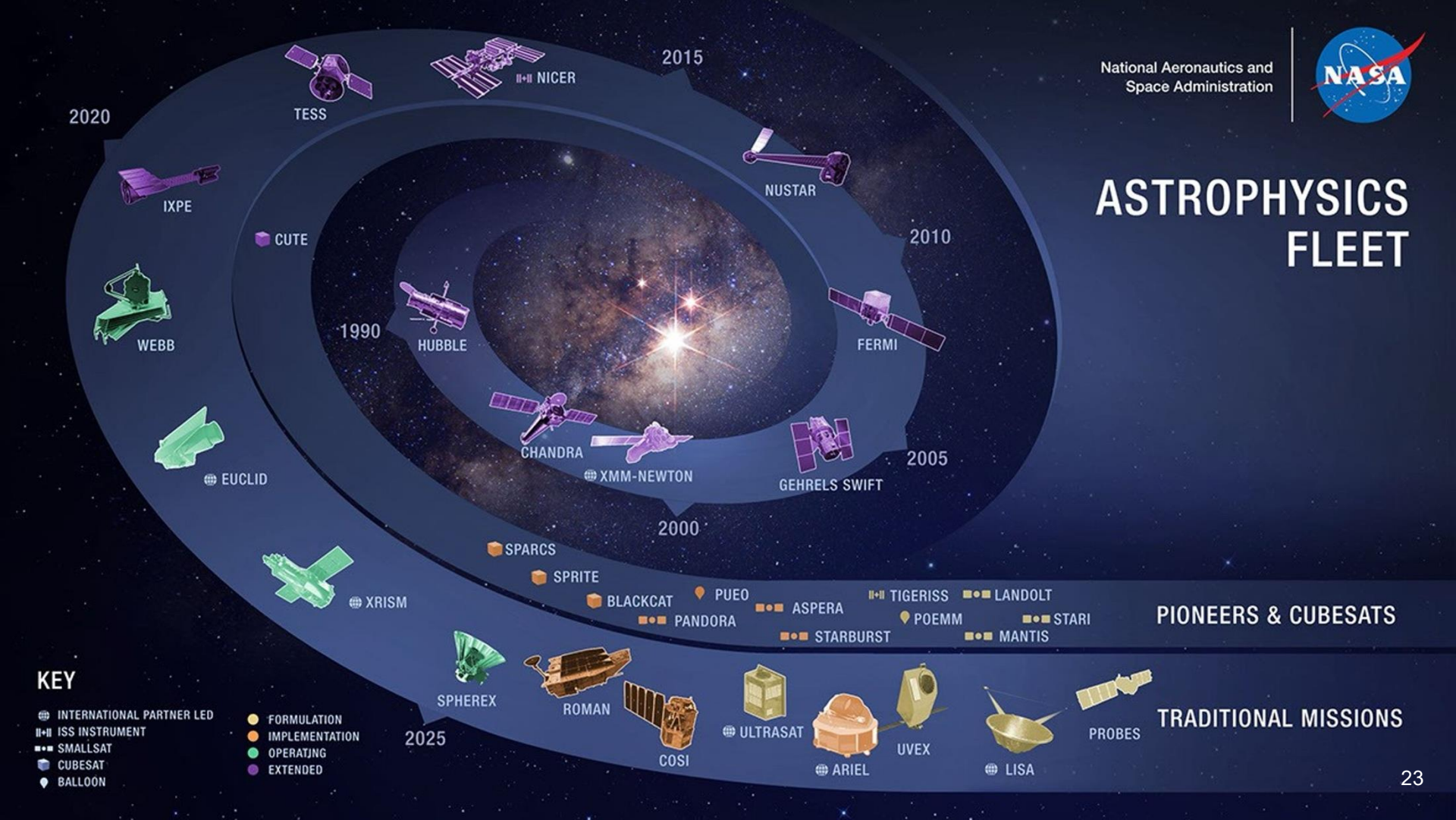
See A. Kheirandish Talk Yesterday

PUEO: The Payload for Ultrahigh Energy Observations

PUEO Neutrino Sensitivity Projections



See Posters from R. Scrandis and T. Coakley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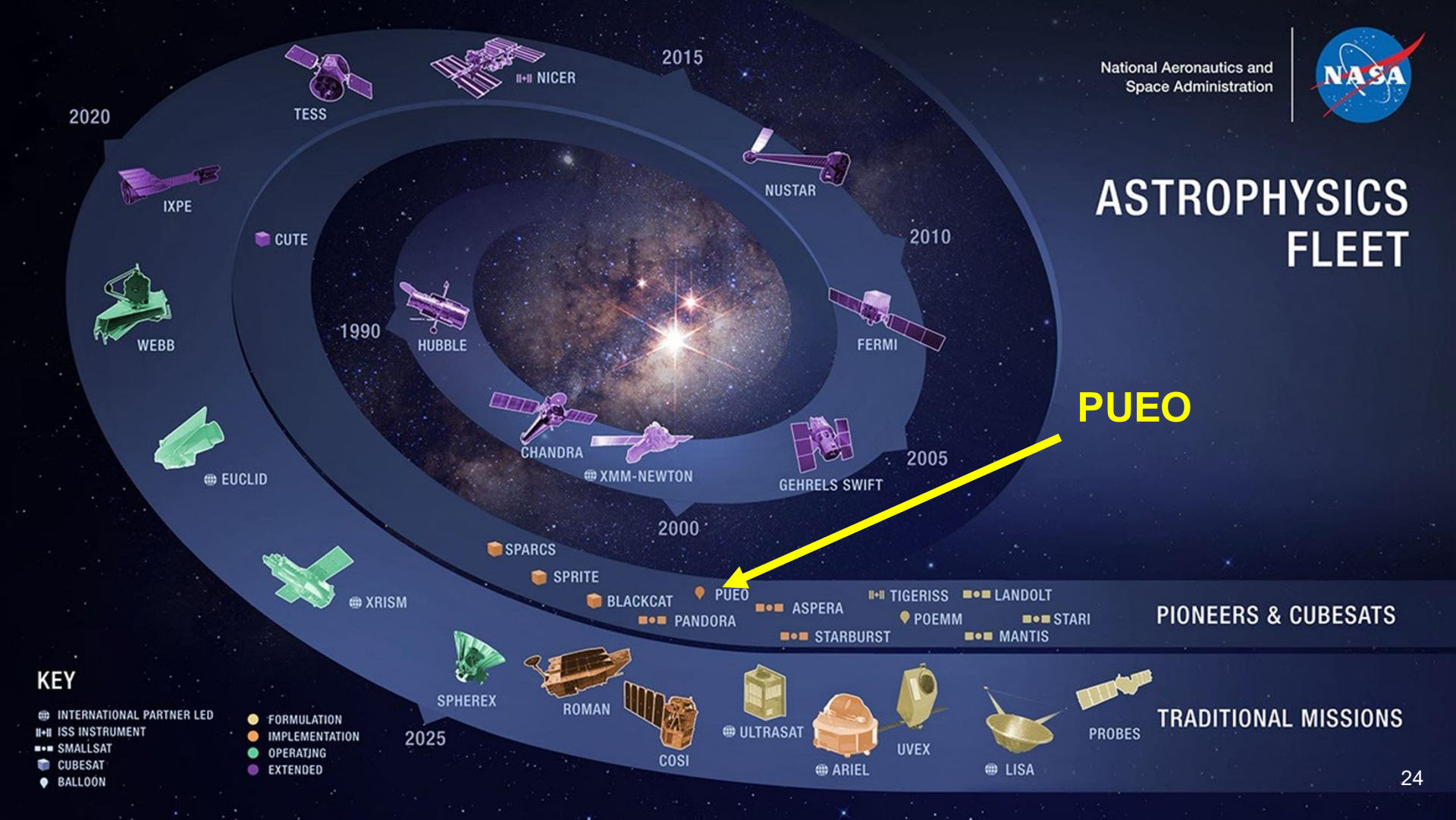
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GEHRELS SWIFT
EUCLID
PUEO
SPARCS
SPRITE
XRISM
BLACKCAT
PUEO
ASPERA
TIGERISS
LANDOLT
PANDORA
POEMM
STARI
STARBURST
MANTIS
PIONEERS & CUBESATS
SPHEREX
ROMAN
COSI
ULTRASAT
ARIEL
UVEX
LISA
PROBES
TRADITIONAL MISSIONS
KEY
INTERNATIONAL PARTNER LED
ISS INSTRUMENT
SMALLSAT
CUBESAT
BALLOON
FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED

The PUEO Instrument

- 192-RF-Channel Main Instrument
- 16-antenna, dual-polarization beamforming trigger.
- 16-RF-Channel Low Frequency Instrument (deployed after launch).
- Triply redundant 128 TB onboard data storage
- Command and control, data transfer to the ground
- Suite of navigation instruments: heading, pitch, roll, location
- Housekeeping/environment sensor system
- In-flight calibration from the ground and from a suite of hand-launched small payloads

Built on heritage from ANITA

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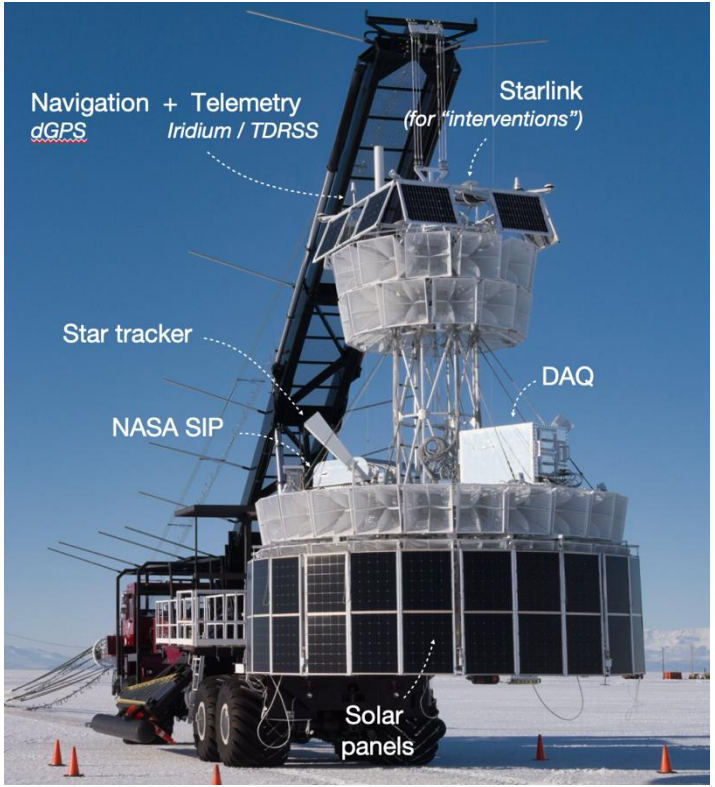
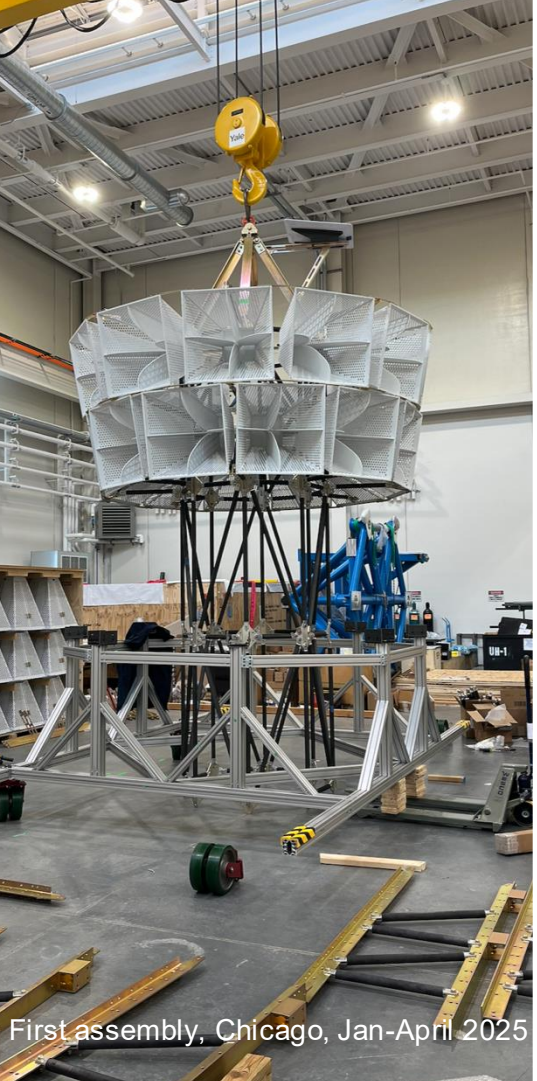
Built on heritage from ANITA



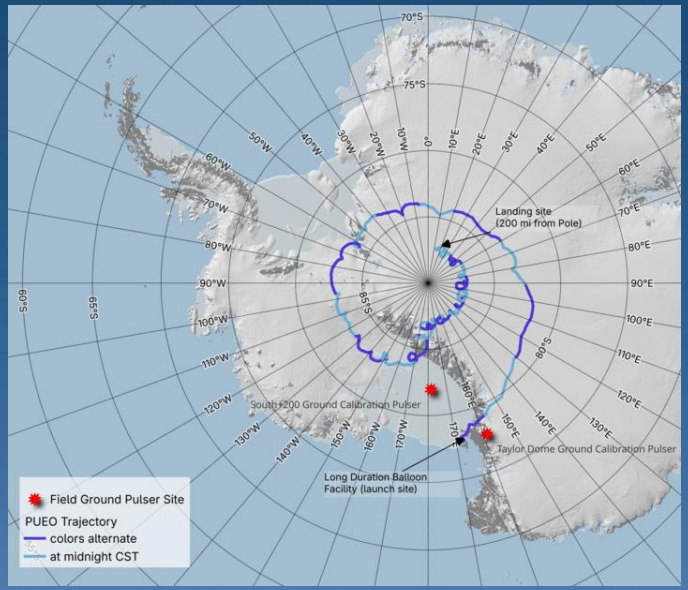


First assembly, Chicago, Jan-April 2025

Integration, Palestine TX, April-July 2025

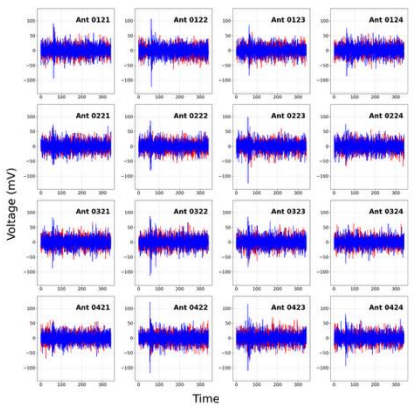
Final Integration and Launch, McMurdo, November- December 2025

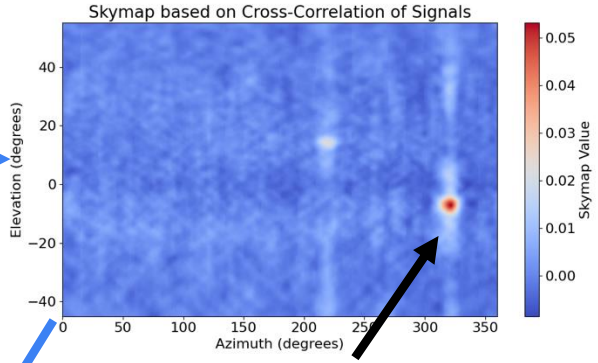
Launch: December 20, 2025
23 Day Flight



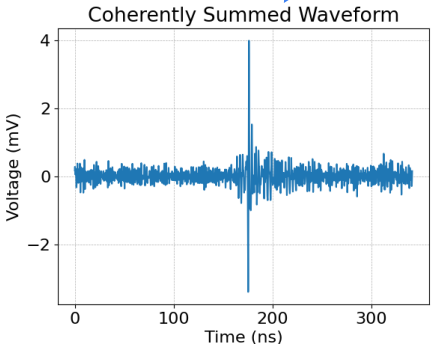
First Look At the Flight

Calibration Event from the Ground



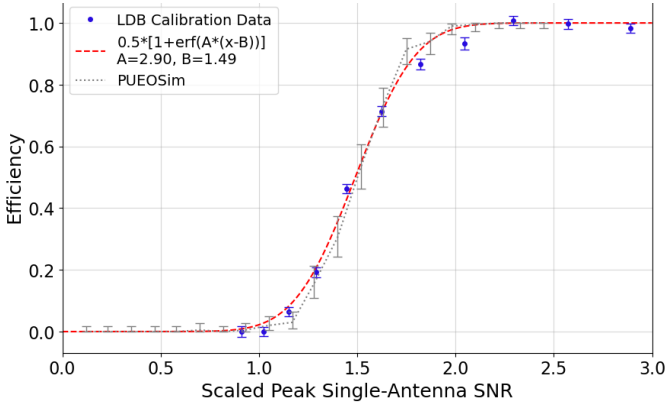


Location of calibration source



R. Scrandis

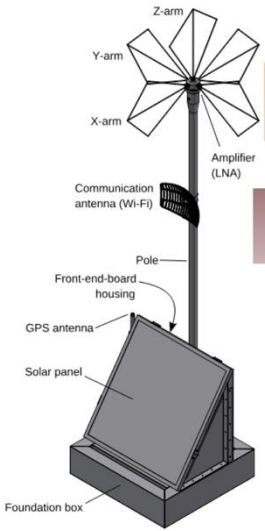
Achieved Trigger Efficiency



L. Beaufore

GRAND: Giant Radio Array for Neutrino Detection

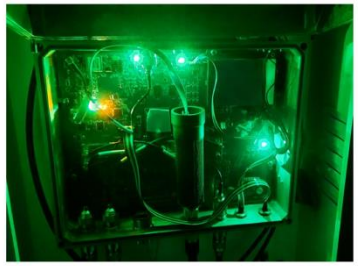
GRANDProto300 & other prototypes: experimental setup



Deployment of 13 antennas in Gansu (China) 65 in 2025 and 200 more later — Deployed Feb 2023

Deployment of 10 antennas on the Auger site in Malargüe, Argentina (cross-calibration) — Deployed Aug 2023

Deployment of 4 antennas in Nançay radio observatory (France) for trigger test (LPNHE) — Deployed Oct 2022

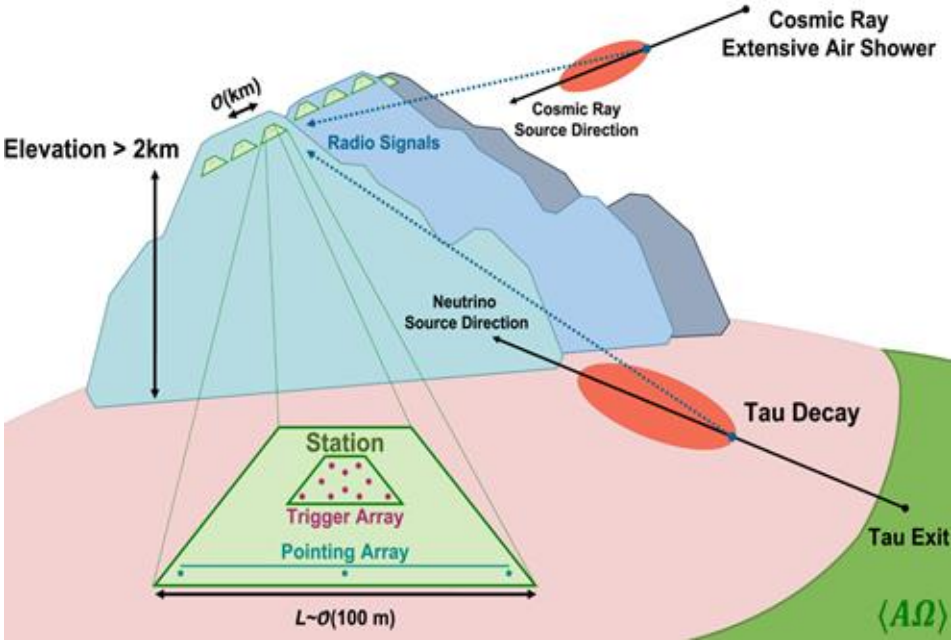


Full GRAND: 200,000 antennas, on a plateau, looking for skimming air showers induced by tau neutrino interactions in the Earth

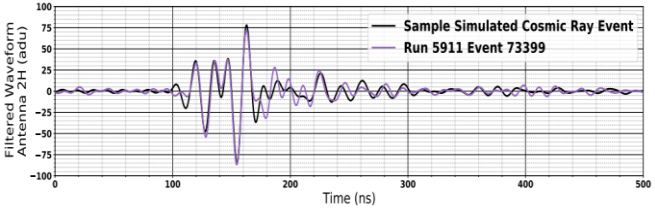
GRAND Coll. ICRC 2025
GRAND Coll. Moriond 2025 (Ferrière, Guelfand, Lavoisier)

BEACON: The Beamforming Elevated Array for Cosmic Neutrinos

Concept: $\mathcal{O}(1000)$ antennas, in beamforming stations on high mountaintops, designed to detect the radio emission of upgoing air showers created by earth-skimming ν_τ. Being on a mountain helps.



Cosmic-ray candidates event identified with prototype



S. Wissel et al. JCAP11(2020)065, D. Southall et al NIM-A 2022

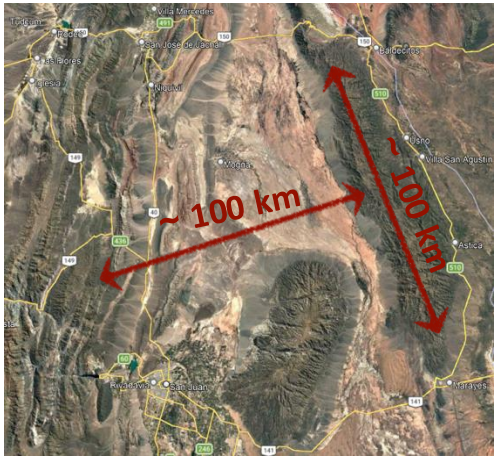
HERON: Hybrid Elevated Radio Observatory for Neutrinos

HERON=BEACON+GRAND

- 24 compact beamforming stations, of 24 antennas each, are embedded within a large sparse array of 360 standalone antennas
- Elevated 1-2 km above a valley floor
- Each beamforming station triggers the 15 nearest standalone antennas
- Sparse array provides offline event reconstruction and background rejection, and a separate veto trigger.

Site: San Juan Province, Argentina.

Full construction (936 antennas) was funded recently by an ERC grant; plan is to construct and calibrate the full array in the coming 5 years.



Summary

This field is moving forward fast, and there are lots of ideas!

New results in the last year include the first detection of Askaryan emission from ultra-high energy particles in dense media, and new world's best constraints on the neutrino flux at the highest energies.

New, science-scale (not prototypes!) experiments are being constructed and are operating (e.g. RNO-G and HERON).

PUEO launched this year, and results will come in the next year. First results from RNO-G, and then from HERON will follow.

IceCube-Gen2-Radio would be a major advancement for radio detection of UHE neutrinos.