Radio Detection of the Highest Energy Neutrinos

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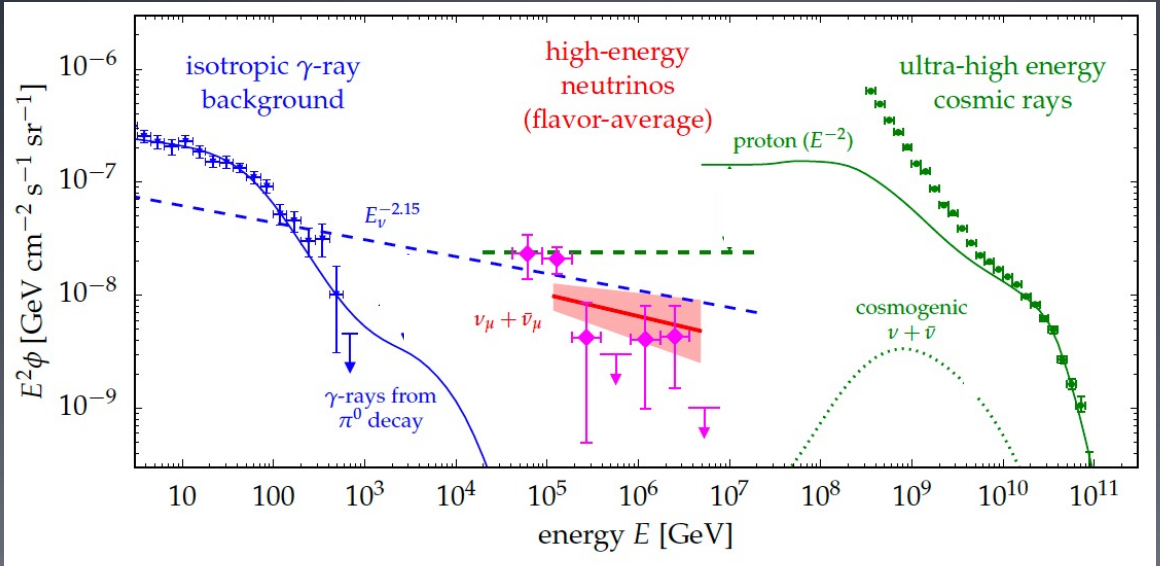
The Ultra-High Energy Universe

- There are sources making particles x 10⁴ more energetic than the neutrinos seen by IceCube (we've seen cosmic rays from them)



arXiv:1903.04334

- How are these particles accelerated?
  - Active Galactic Nuclei (black holes accreting mass)?
  - Blazars (Jets emitted in our direction by AGN)?
  - Gamma Ray Bursts (most luminous events in the universe)?

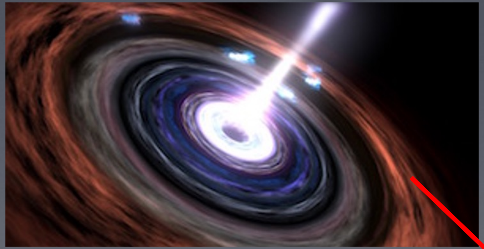
Neutrinos are the Best Way to View the Ultra-High Energy Universe!

Possible Messenger Particles:

- Photons are lost above 100 TeV (pair production on CMB & IR)
- Protons and Nuclei deflect in magnetic fields
- Neutrons decay
- Neutrinos: point back to sources, travel unimpeded through universe

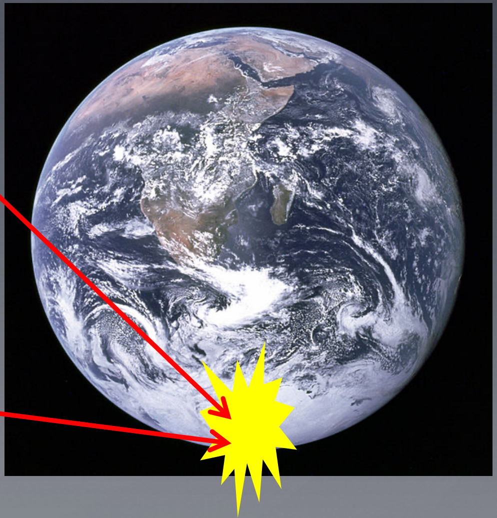
<u>Ultra-High Energy Neutrino Telescopes:</u>

- Open a unique window into the universe
  - Highest energy observation of extragalactic sources
  - Very distant sources
  - Deep into opaque sources
- How the high energy universe evolves?



Active Galactic Nucleus, Credit: NASA Goddard

Gamma Ray Burst, Credit: NASA, ESA, M. Kornmesser

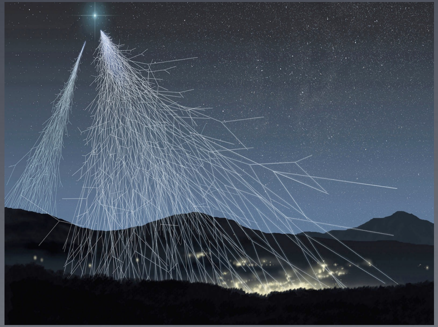


Neutrino Production: The GZK Process

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

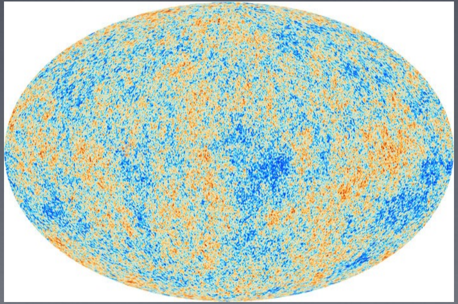
$$
\begin{aligned}
p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} & \\
\rightarrow \mu^{+} + \boxed{\nu_{\mu}} & \\
\rightarrow e^{+} + \boxed{\bar{\nu_{\mu}} + \nu_{e}} &
\end{aligned}
$$

Cosmic Rays



\+

CMB



= Neutrino Beam!

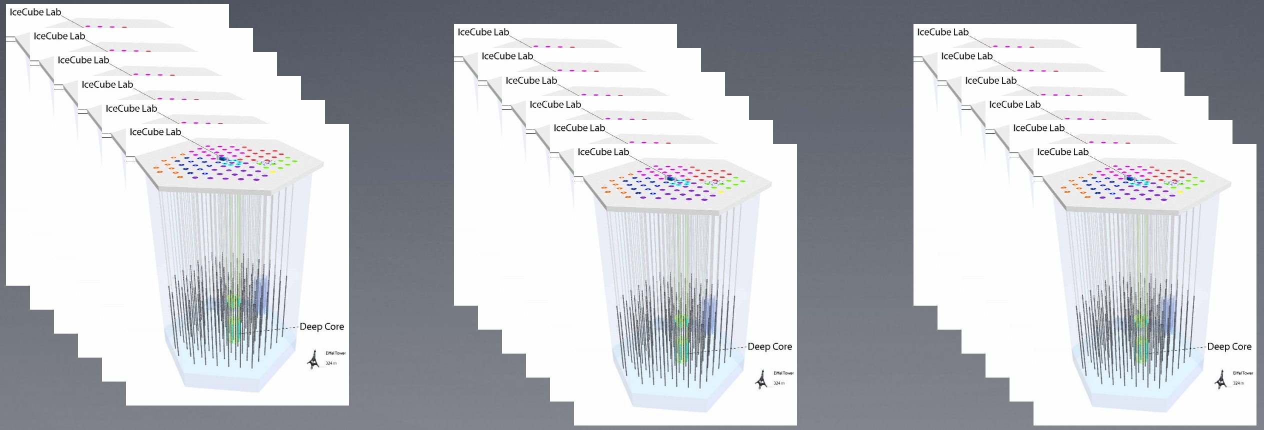
Discover the origin of high energy cosmic rays and neutrinos?

What is the high energy cutoff of our universe?

What is(are) the acceleration mechanism(s)?

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 (hence IceCube)
- The highest energy neutrinos are even more rare, so you need an even bigger detector
  - You have to get creative (that’s the fun part!)

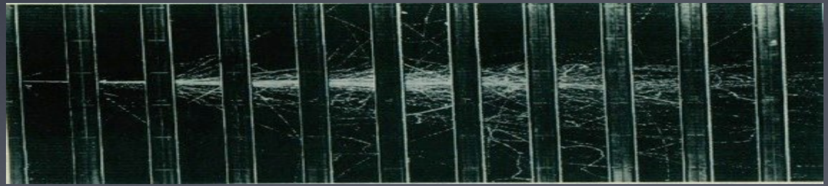


…?

Method 1: Radio emission from neutrino interactions in dense material

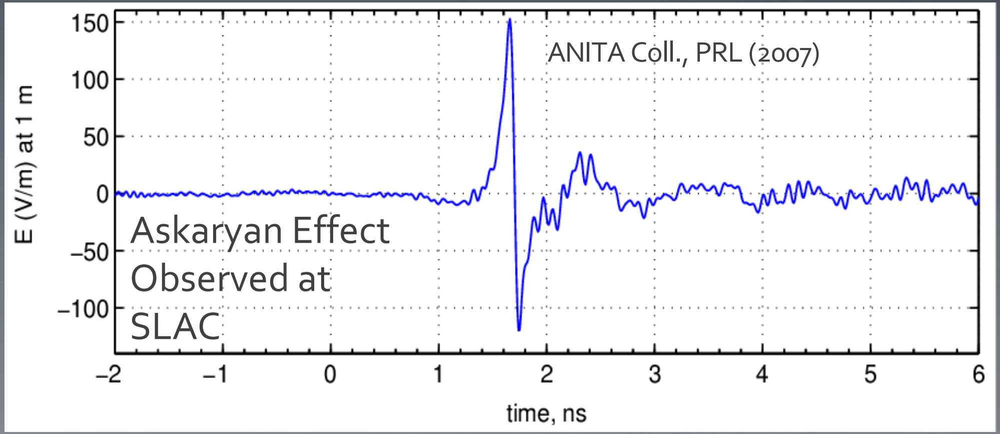
- EM shower in dielectric (ice, sand) → moving negative charge excess
- Coherent radio Cherenkov radiation (P ~ E²) if λ > Moliere radius

e^+, e^-, γ ⟶

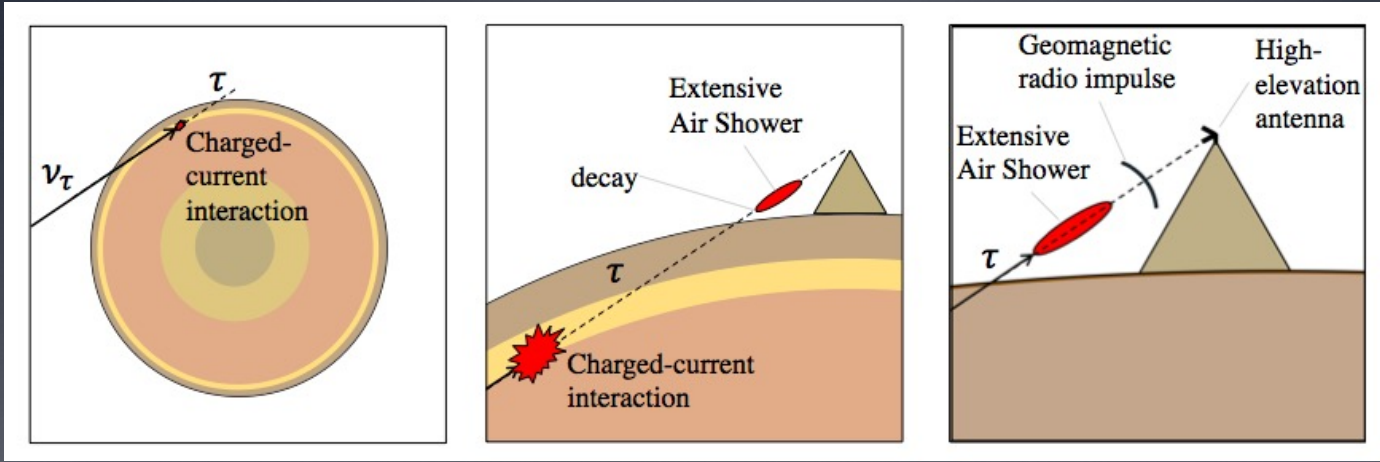


Typical Dimensions:
L ~ 10 m
$R_{moliere}$ ~ 10 cm

→ Radio Emission is stronger than optical for UHE showers



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



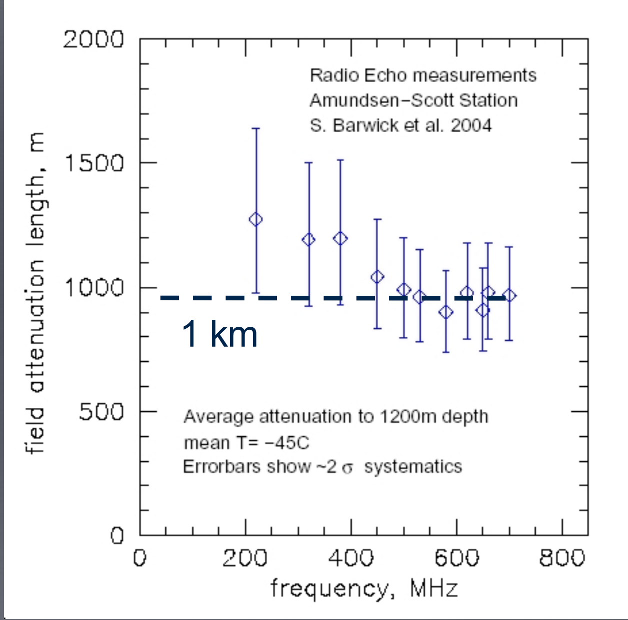
S. Wissel

- Looks like an upward going cosmic ray air shower
- Observe from surface, a mountain, balloon, or space
- Experimental concepts, e.g. GRAND, BEACON, TAROGE, POEMMA, TRINITY, Auger

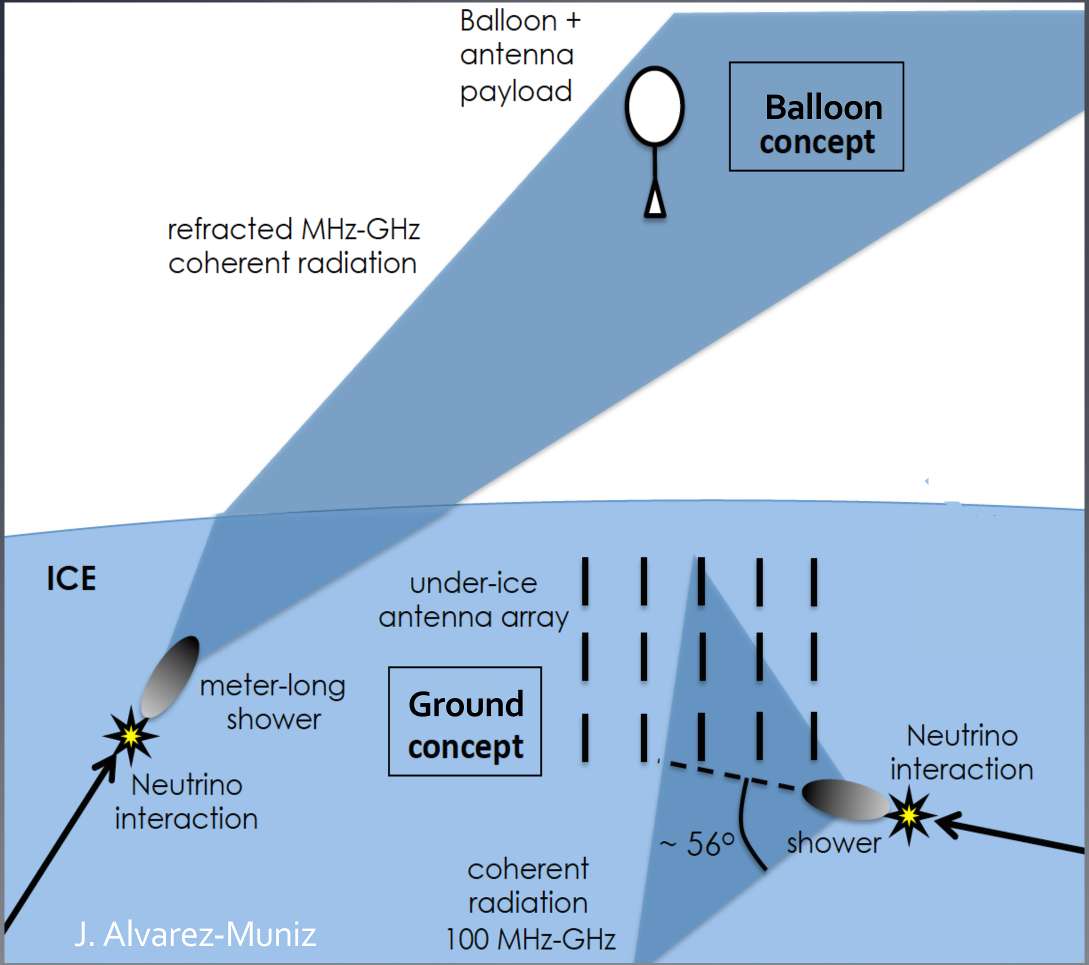
Askaryan Emission Detector Requirements

- ~1 GZK neutrino/km²/year
- L_{int} ~ 300 km
  → 0.01 neutrinos/km³/year
- Need a huge (~100 km³), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF (vs. ~100 m for optical signals used by IceCube)

→ Ice is good for radio detection of UHE neutrinos!



The Concept: Radio Detection in Dense Media



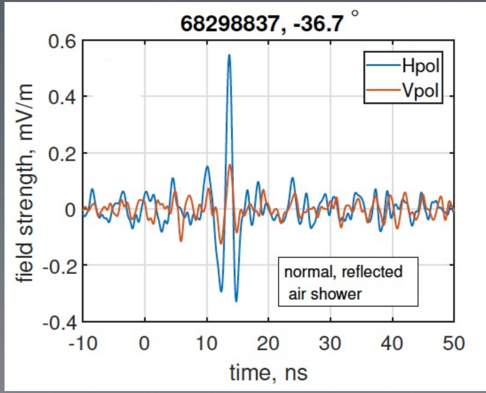
ANITA: Designed for the Highest Energies

NASA Long Duration Balloon launched from Antarctica, four flights (2006-2016)

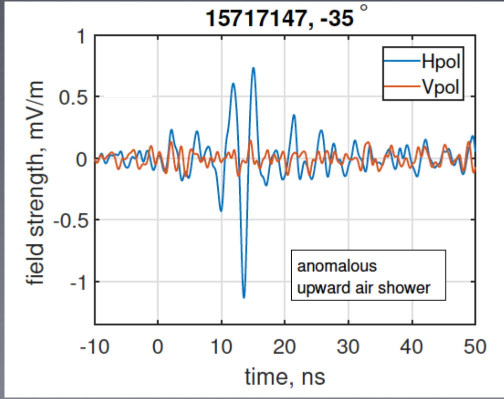
Instrument Overview:

- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas (interferometry)
- In-flight calibration from ground
- Threshold limited by thermal noise

Typical Cosmic Ray Event



Mystery Event



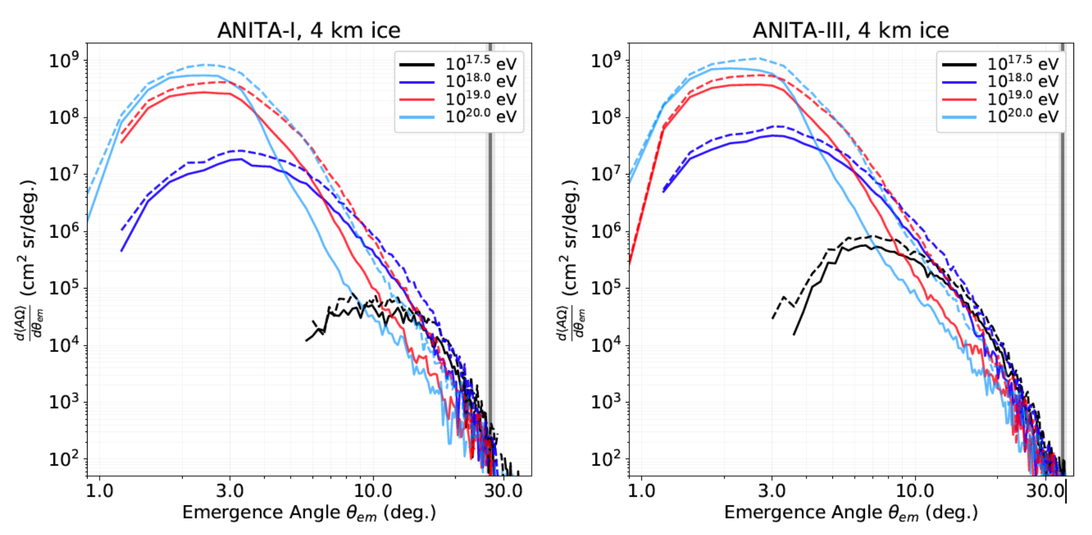
Results in a Nutshell:

- Askaryan channel: No excess seen above background (no discovery)
- ~100 UHE Cosmic Ray (>10^{18} eV) events detected over 4 flights
- Tau Air Shower Channel: Events seen??

ANITA Coll., PRL 2018

Mystery Events: The Problem with a Tau Neutrino Interpretation

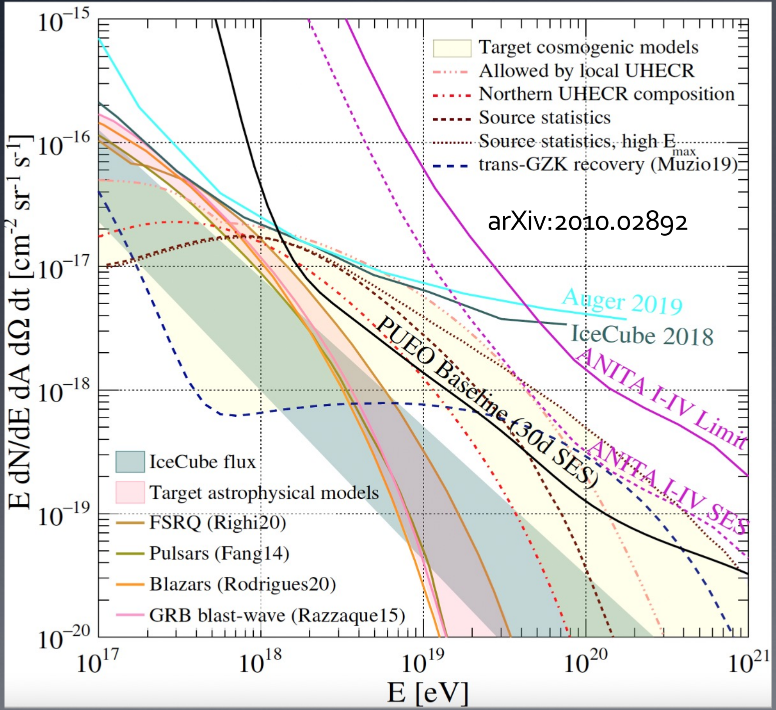
- The two observed "mystery events" are too steeply upgoing
- Transition Radiation? (Motloch et al. 2017, de Vries & Prohira 2019) from cosmic ray air showers?
- Or (more mundane) maybe there is some non-physics background we have not yet accounted for?
- Maybe it is beyond-standard-model physics? (e.g. Fox et al. 2019, and even I joined the fun: Hooper et al. 2019)



A. Romero-Wolf et al., 2018

PUEO: The Payload for Ultrahigh Energy Observations

PUEO Neutrino Sensitivity Projections



Much lower threshold than ANITA (x10 more sensitive across energies), takes over from IceCube at 10^{18} eV

What do Experimentalists do? Figure out a way to change the discovery space.

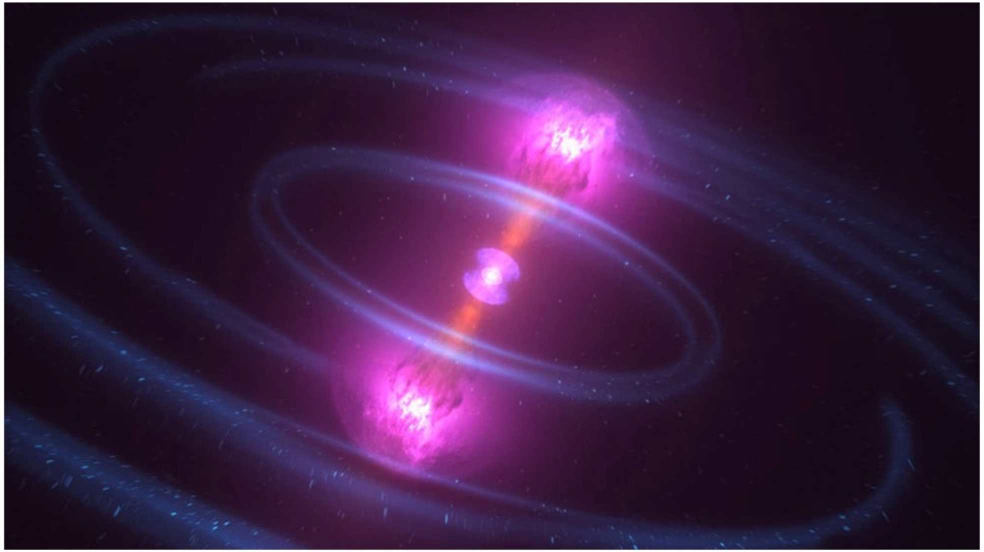
Especially large instantaneous effective volume, for transient, point source, and multi-messenger searches

PUEO Selected for Astrophysics Pioneers Mission by NASA

Jan. 7, 2021

NASA Selects 4 Concepts for Small Missions to Study Universe's Secrets

NASA has chosen four small-scale astrophysics missions for further concept development in a new program called Pioneers. Through small satellites and scientific balloons, these selections enable new platforms for exploring cosmic phenomena such as galaxy evolution, exoplanets, high-energy neutrinos, and neutron star mergers.



As neutron stars collide, some of the debris blasts away in particle jets moving at nearly the speed of light, producing a brief burst of gamma rays.
Credits: NASA's Goddard Space Flight Center/CI Lab

PUEO is a balloon mission designed to launch from Antarctica that will detect signals from ultra-high energy neutrinos, particles that contain valuable clues about the highest energy astrophysical processes, including the creation of black holes and neutron star mergers. Neutrinos travel across the universe undisturbed, carrying information about events billions of light years away. PUEO would be the most sensitive survey of cosmic ultra-high energy neutrinos ever conducted. The principal investigator is Abigail Vieregg of the University of Chicago.

- A new class of larger, more science capable balloon missions, small satellites, cubesats, rockets, or ISS payloads, up to $20M.
- Inaugural class is 4 missions: 3 small satellites and PUEO.
- All 4 missions passed the gate review and have been approved to proceed to implementation.
- PUEO is scheduled to fly in December 2024!!

The PUEO Team

PUEO

OHIO STATE

KU

UNIVERSITY OF HAWAI'I

WASHINGTON UNIVERSITY IN ST. LOUIS · 1853

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Queen Mary University of London

UNIVERSITY OF DELAWARE · 1743

THE UNIVERSITY OF CHICAGO

PennState

臺灣大學 National Taiwan University

UCL

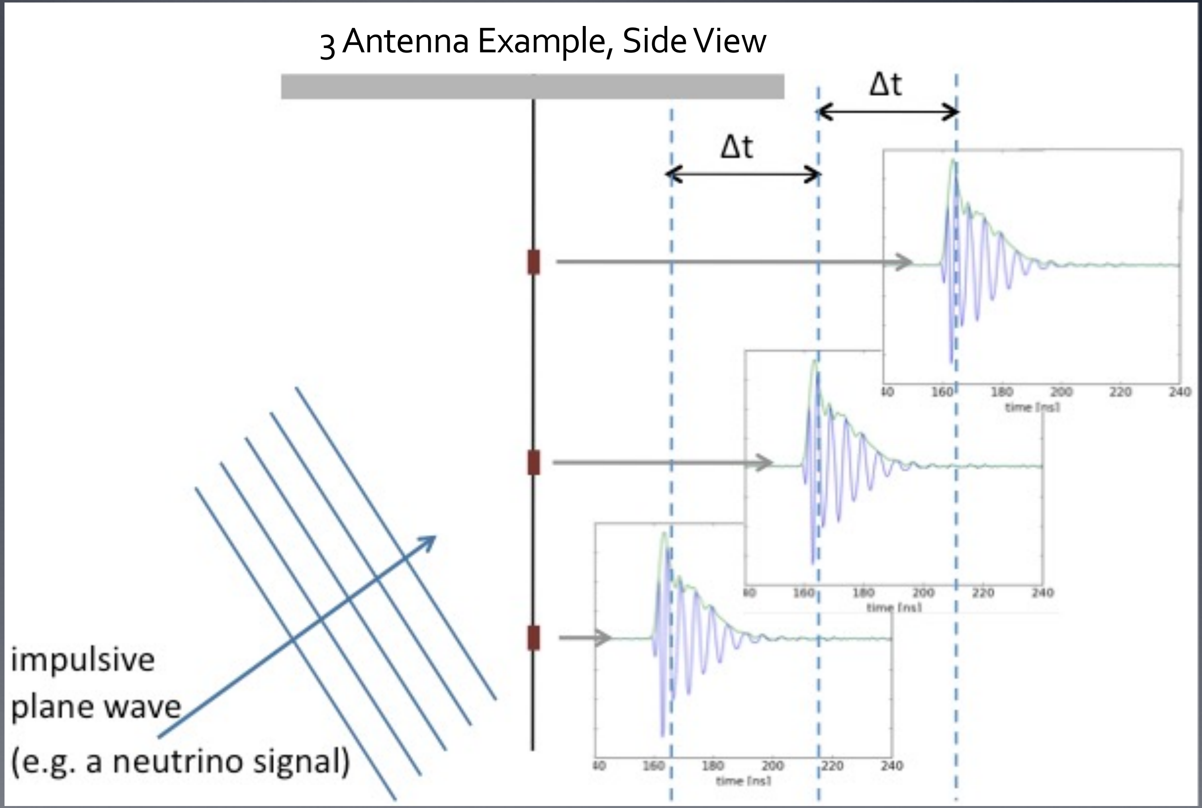
The PUEO Instrument

- 216-RF-Channel Main Instrument, with a 16-antenna, dual-polarization beamforming trigger
- 16-RF-Channel Low Frequency Instrument
- 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 HiCal payloads.

Pushing the Threshold Down and Increasing Sensitivity: A Phased Array

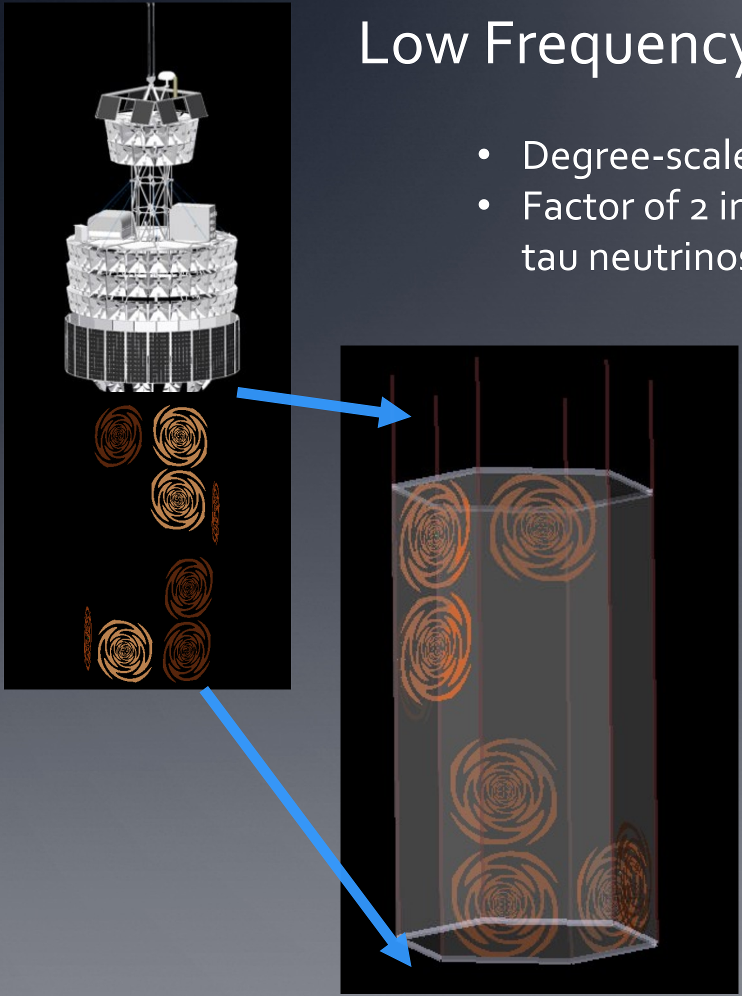
- You know Δt based on the antenna geometry and the speed of light in ice
- Line up signals according to the Δt you know, then sum
- For real neutrino events (plane waves), you a get a higher signal-to-noise sqrt(N) in voltage
- Do this all the time for all possible incoming angles

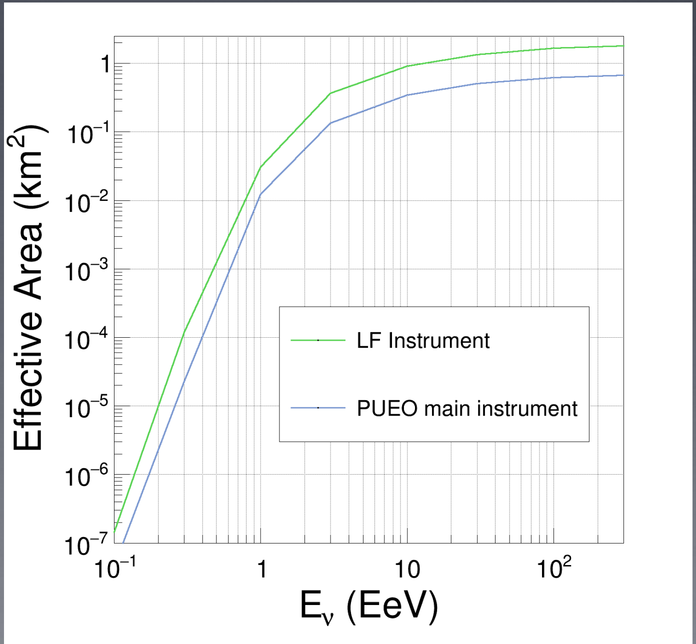
- This is the major technological advancement for PUEO; we're flying 24 RFSoC-based boards



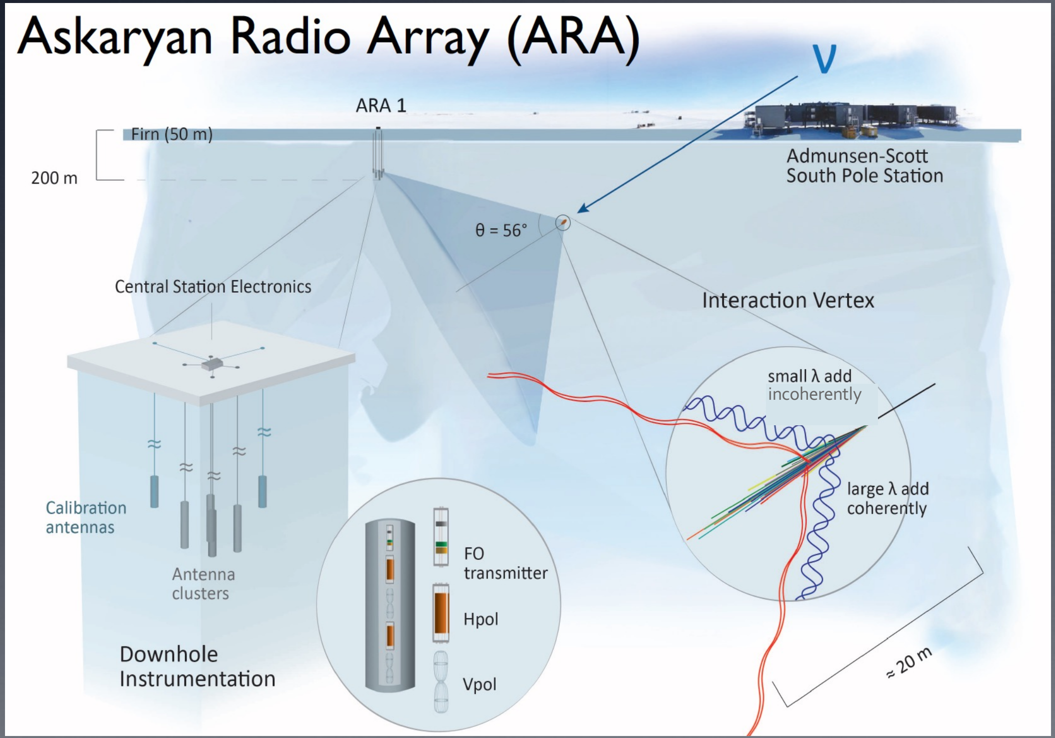
Low Frequency Instrument Performance

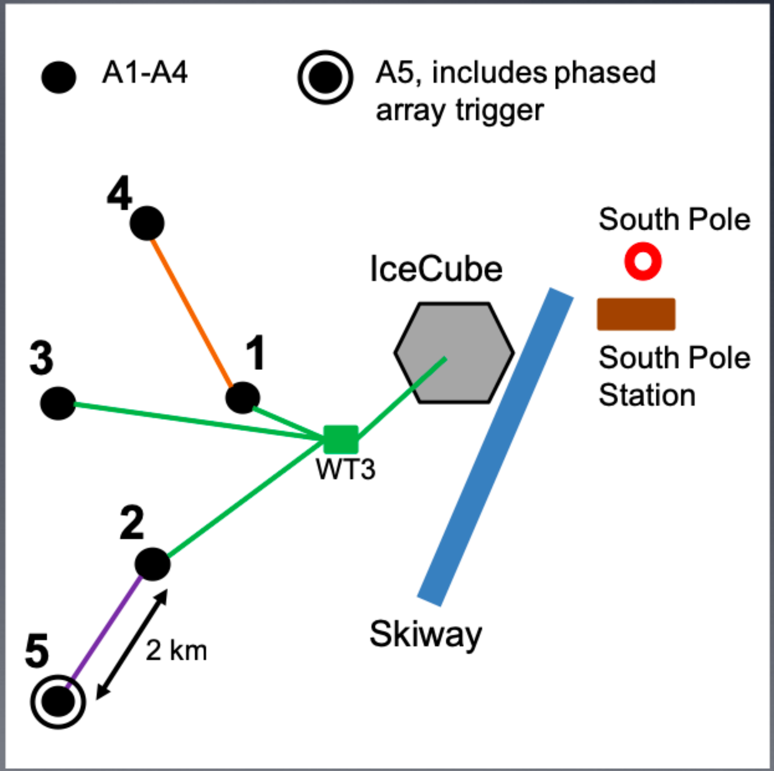
- Degree-scale angular resolution expected
- Factor of 2 improved sensitivity (effective area) to tau neutrinos compared with Main Instrument





ARA: In-Ice Radio Detector at South Pole

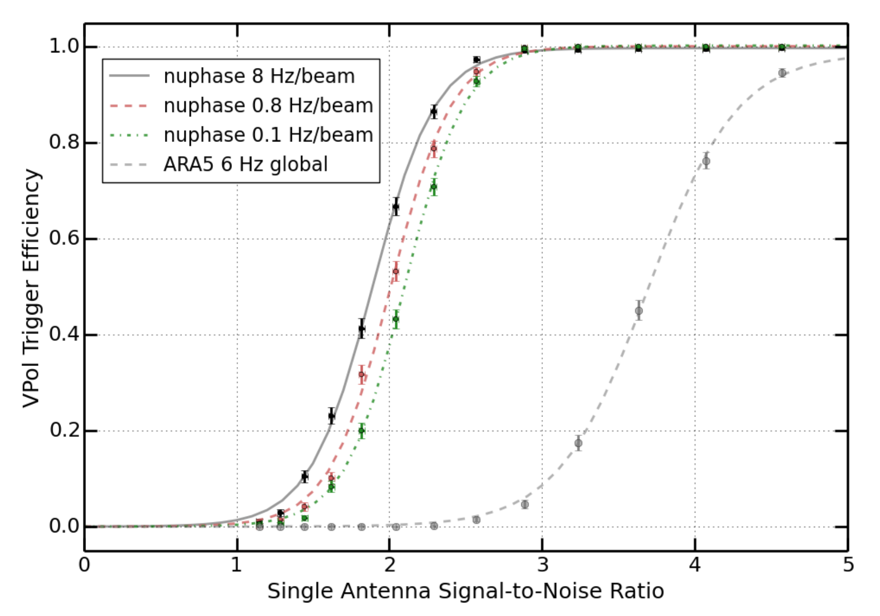


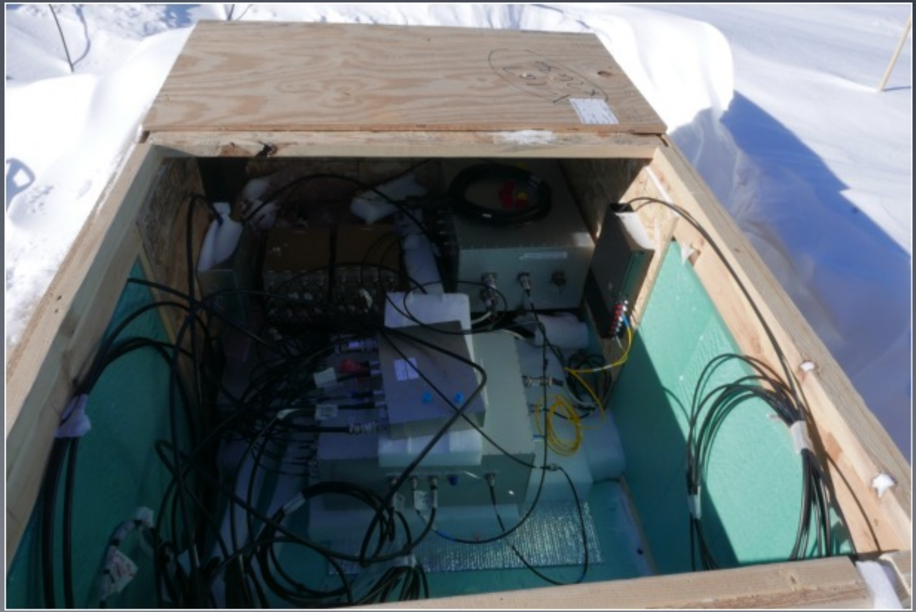


THE UNIVERSITY OF CHICAGO · University of Nebraska Lincoln · VUB VRIJE UNIVERSITEIT BRUSSEL · University of Delaware 1743 · University of Maryland 1856 · Ohio State · CHIBA UNIVERSITY · KU · WISCONSIN UNIVERSITY OF WISCONSIN–MADISON · 臺灣大學 National Taiwan University

ARA's Phased Array Trigger System

- A real-time interferometric phased array trigger system has been running since 2018
  - New DAQ – has been perfectly stable since deployment
  - Trigger performance matches simulations exactly
  - Improvement x2 effective volume achieved already

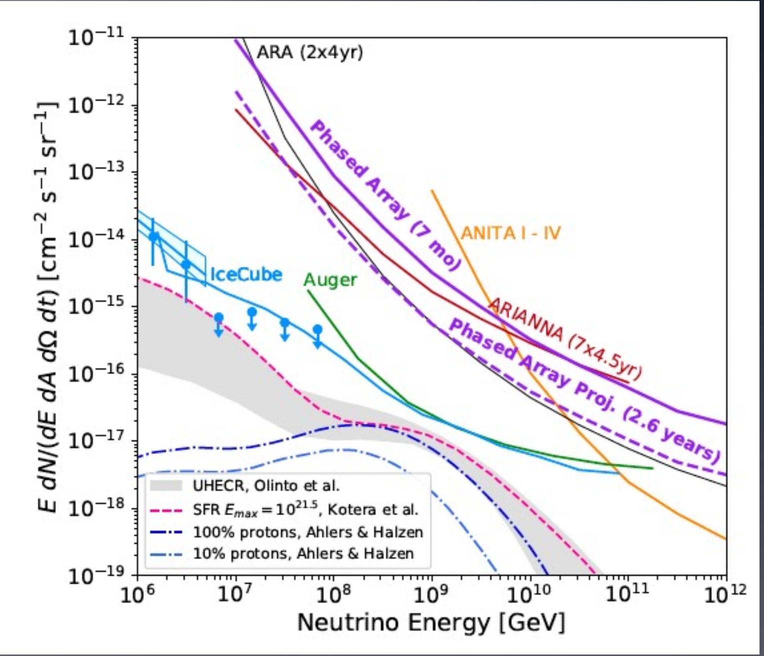


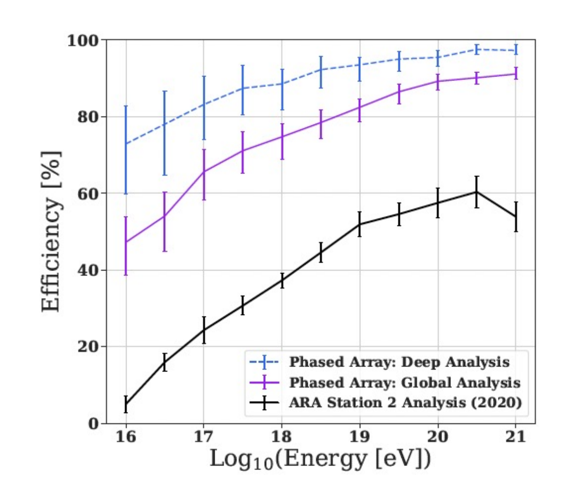


ARA Coll., NIM 2018

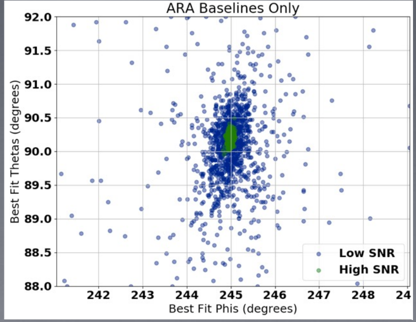
First Analysis of ARA Phased Array Data

- Its nice to get more sensitivity in hardware, but it only matters if you can analyze the data near threshold
- Turns out you can analyze the data down to threshold (see arXiv:2202.07080), and do it better than before.
- Points the way to building future detectors with the low-threshold phased array trigger design.
- Eyeballing: 50 station-years beats 10 years of IceCube @ 10^{18} eV. Another x 10 is a real ultra-high energy neutrino detector.

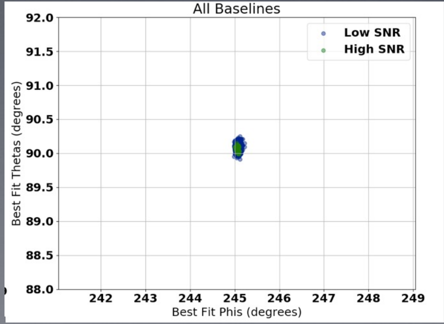




ARA Collaboration: arXiv:2202.07080



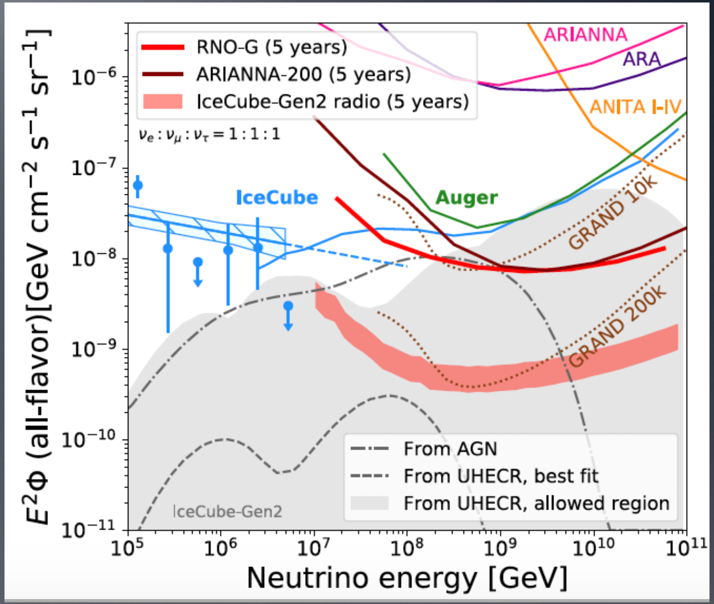
OLD



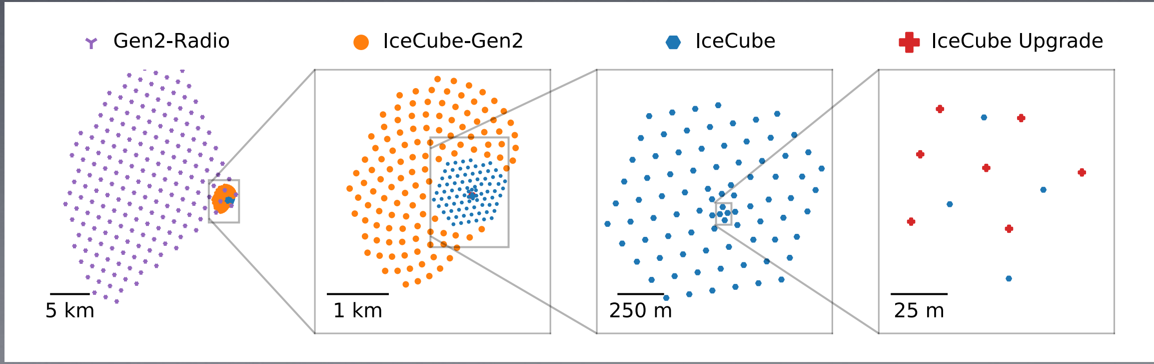
NEW

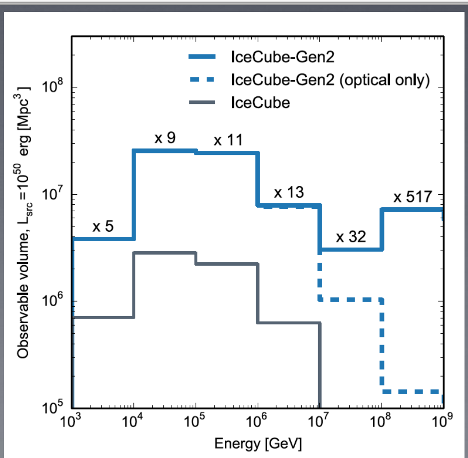
Toward IceCube-Gen2

- IceCube Gen2: a multi-component facility to reach the broadest range of energies.
- Radio component required to reach the science goals at the highest energies (e.g. revealing the sources and propagation of the highest energy particles)



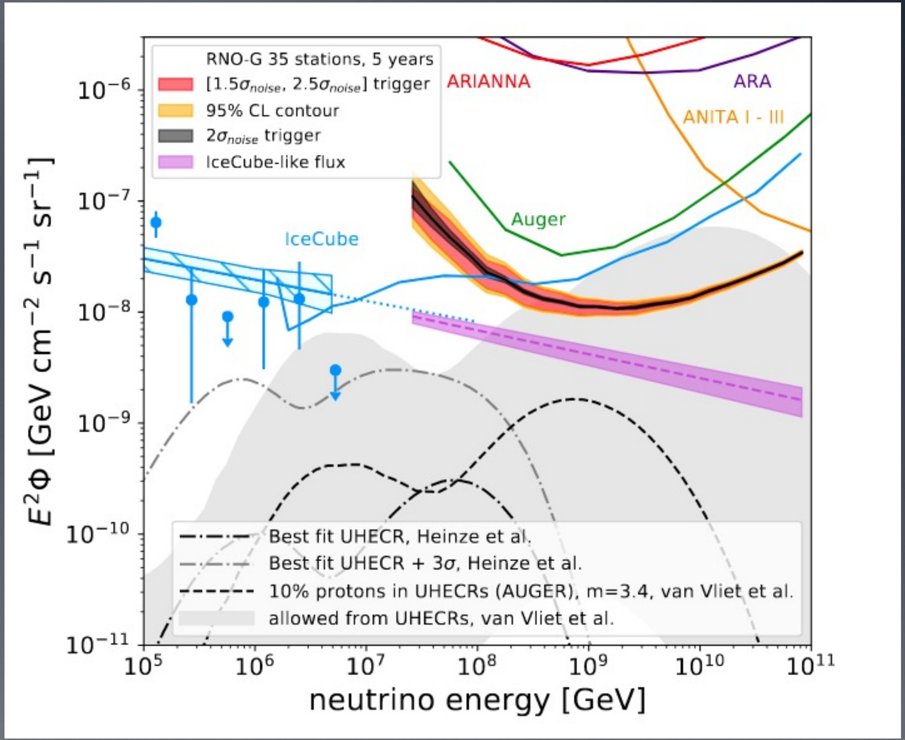
IceCube Gen2 Whitepaper: arXiv: 2008.04323





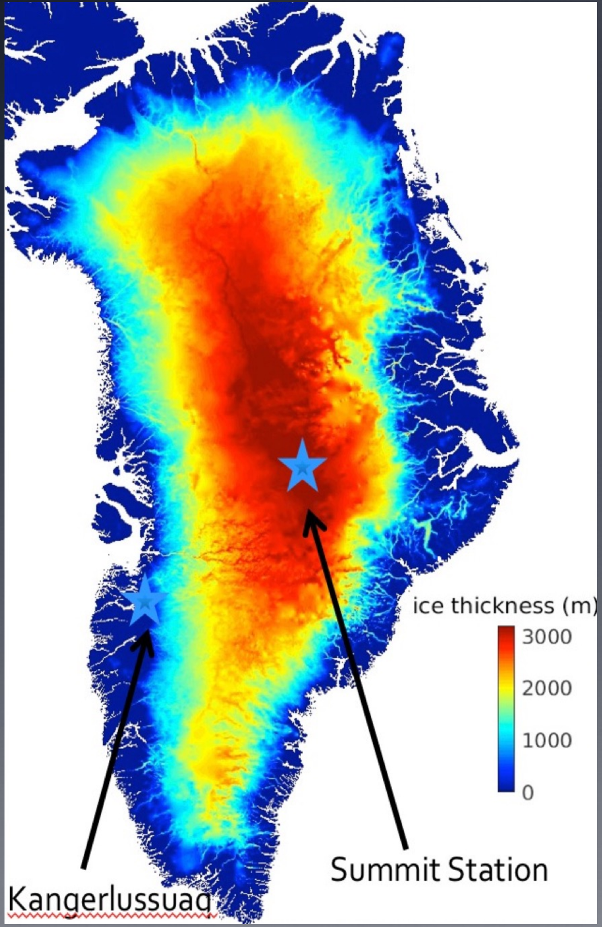
Radio Neutrino Observatory in Greenland (RNO-G)

- RNO-G is currently being installed at Summit Station in Greenland (first hardware deployed in 2021, 2022 deployment season just started).
- RNO-G is designed to be scalable to large arrays (IceCube-Gen2)

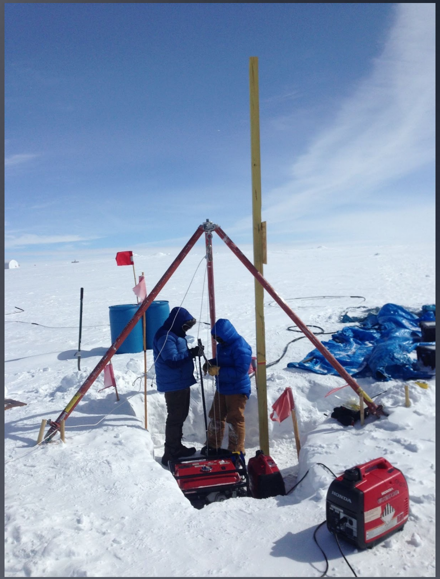


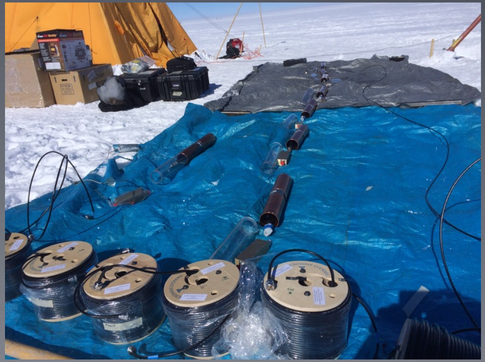
DESY. FAU Friedrich-Alexander Universität Erlangen-Nürnberg | ULB Université Libre de Bruxelles | VUB Vrije Universiteit Brussel | Ghent University | The University of Chicago | PennState | Wisconsin University of Wisconsin–Madison | Whittier College 1887 | KU | University of Delaware | The Ohio State University | Uppsala Universitet | Berkeley Lab | Michigan State University | Cal Poly

Summit Station Site

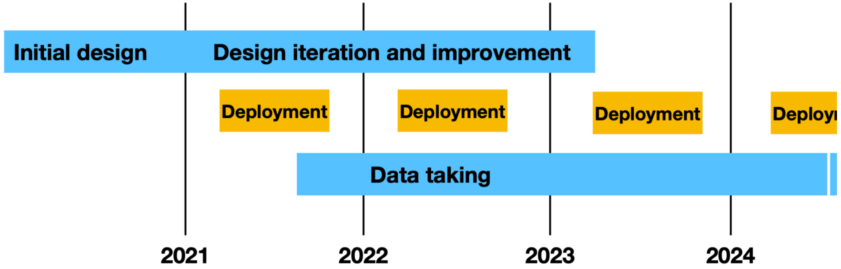


- 3 km deep ice; attenuation length shorter than South Pole.
- NSF-run station, LC-130 access during the summer (May-August)
- Site is good for solar & wind power
- Early studies in 2013 and 2015: measurements of ice attenuation length, and first in-situ test of a phased array trigger

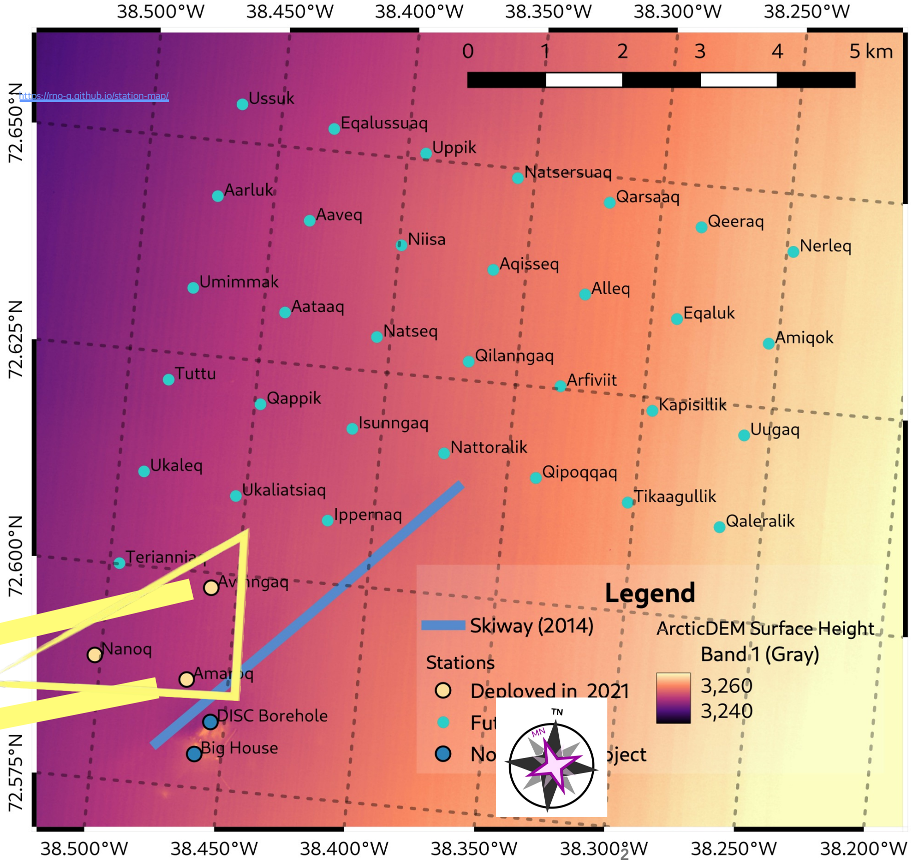




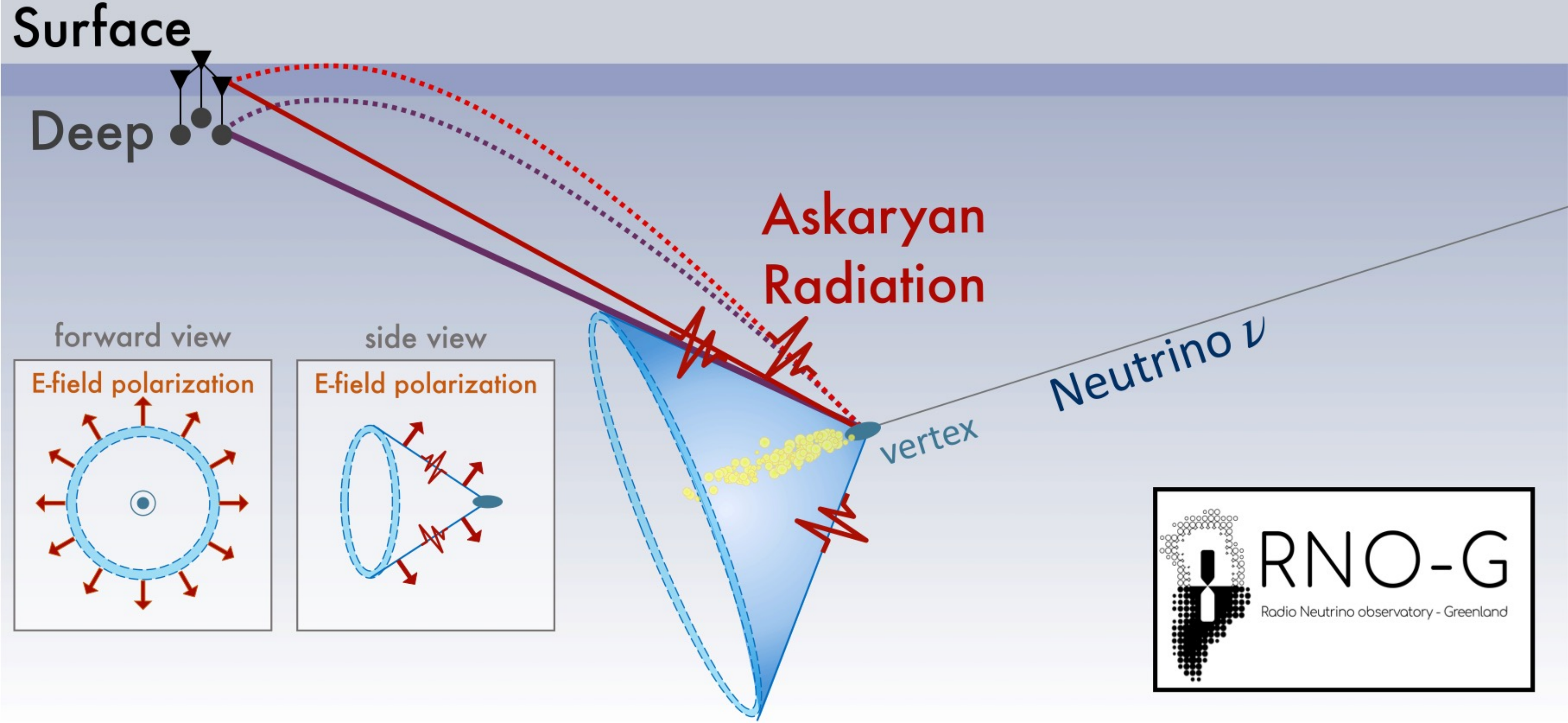
- 35 stations, 1.25 km spacing
- LTE Comms, Solar/Wind Power (due to site constraints)
- First deployment season in 2021, 3 stations installed.
- 2022 deployment season is underway. (7 stations currently deployed and operating!)
- 2 more seasons (2023 and 2024) of instrumentation deployment worked out with NSF as of now.



RNO-G Planned Layout

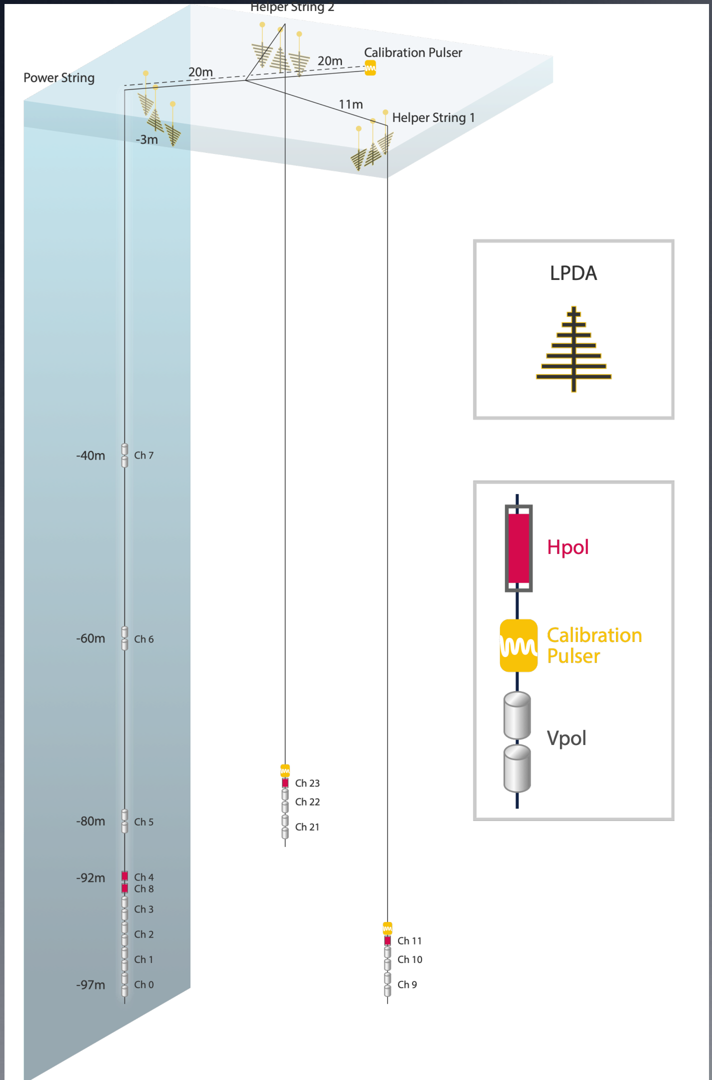


RNO-G Station Layout



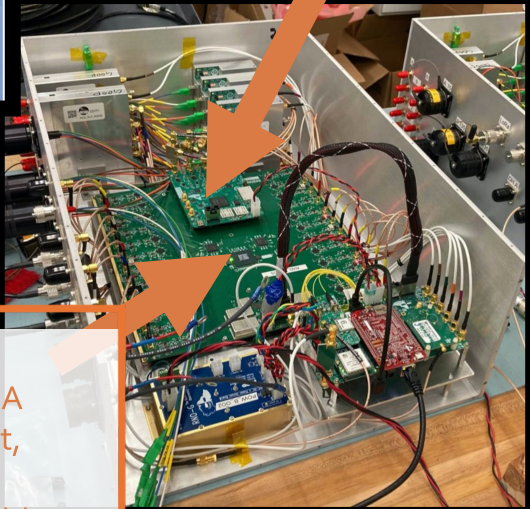
RNO-G

Radio Neutrino observatory - Greenland



RNO-G Station Design

Low threshold trigger board
Low bandwidth phased trigger (80-236 MHz) optimized for broad range of view angles



RADIANT DAQ Board
24 channel ADC using LAB4D SCA
>850 ns (2048 samples) per event, dual-buffered,
3.2 GSa/s, 1.3 GHz analog bandwidth
Low power envelope trigger

Station Deployment

Warm deployment sled movable by snowmobile

...or people!

Shallow antennas deployed in trenches

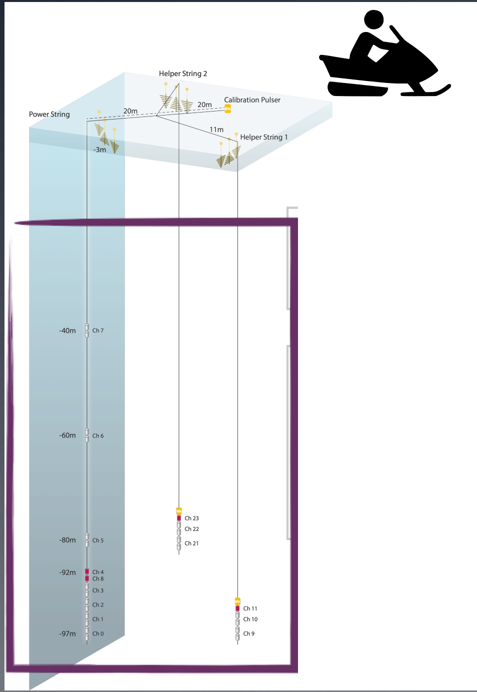
Shallow:
LPDAs

Deep channels lowered by hand

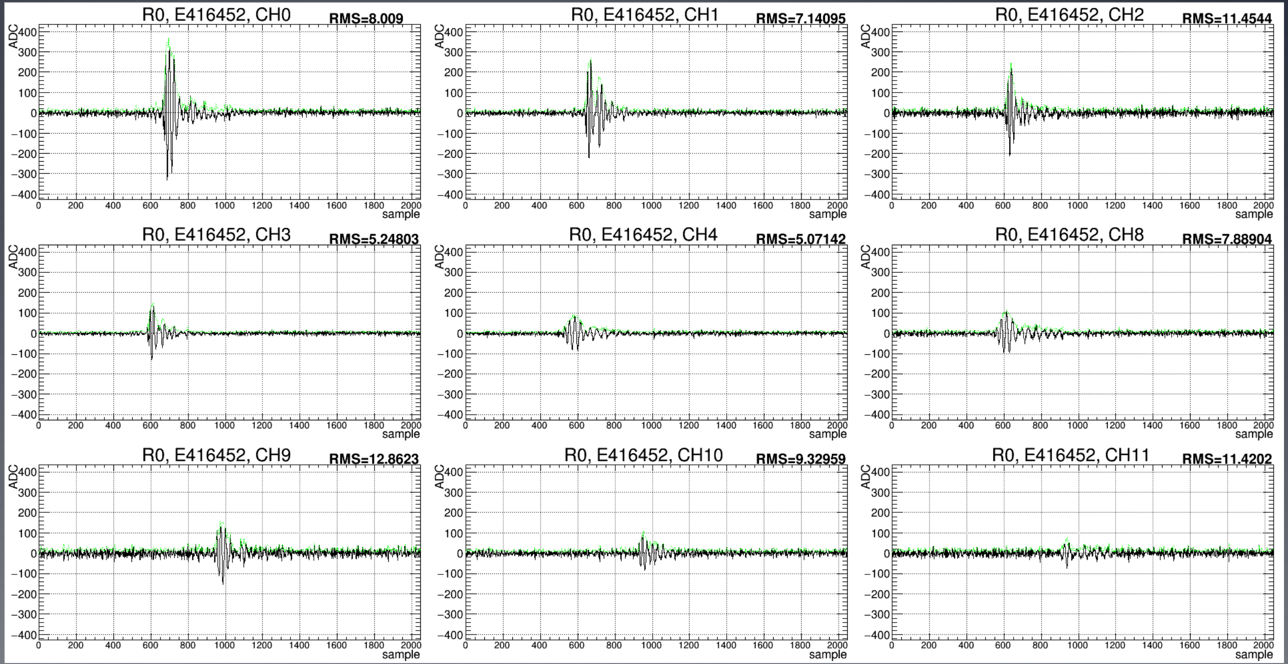
Vpol:
Fat dipoles

Hpol:
Wide quad-slots

We Can Trigger On Stuff!



Snowmobile lights up the deep channels



Summary

- The groundwork for a new generation of detectors has been laid with new technology development.
- PUEO & RNO-G are both under construction, and the discovery of ultra-high energy neutrinos is in sight.
- PUEO will open up discovery space at the highest energies, and will launch in 2024.
- RNO-G covers the energy range between IceCube and PUEO where astrophysical neutrinos should be, and is under construction!
- IceCube-Gen2 will incorporate a large radio array in the future.