

# Radio Detection of the Highest Energy Neutrinos

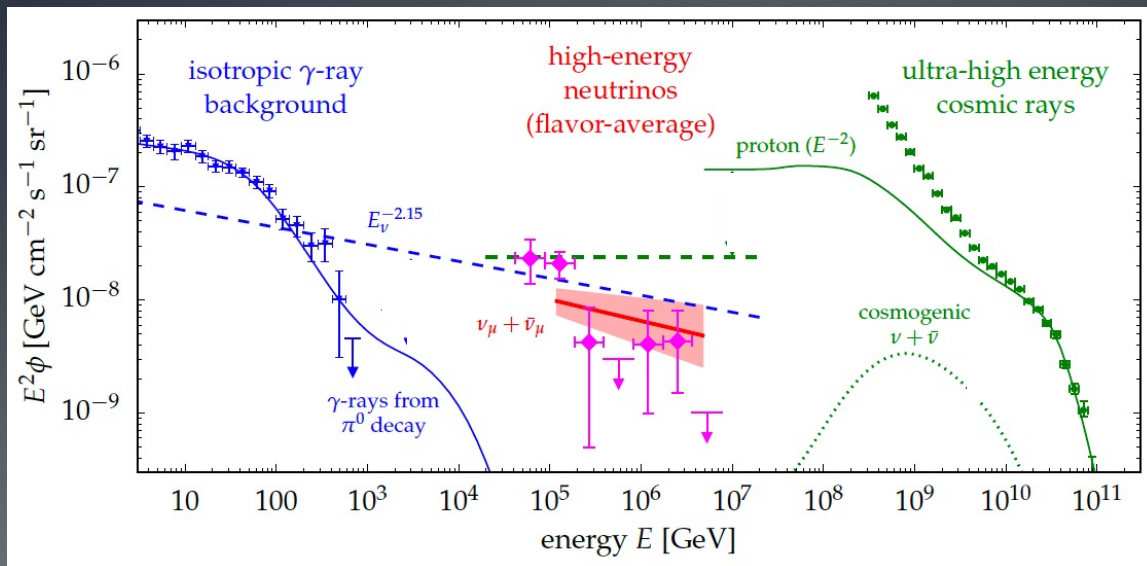


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University of Chicago  
9 June 2022



# The Ultra-High Energy Universe

- There are sources making particles  $\times 10^4$  more energetic than the neutrinos seen by IceCube (we've seen cosmic rays from them)



- 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)?

arXiv:1903.04334

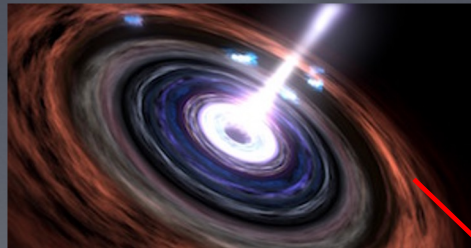
# Neutrinos are the Best Way to View the Ultra-High Energy Universe!

## 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**

## Ultra-High Energy Neutrino Telescopes:

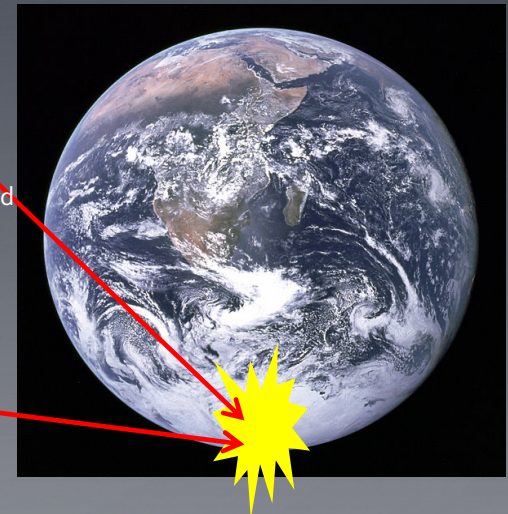
- Open a unique window into the universe
  - Highest energy observation of extragalactic sources
  - Very distant sources
  - Deep into opaque sources
- How the high energy universe evolves?



Active Galactic Nucleus, Credit: NASA Goddard



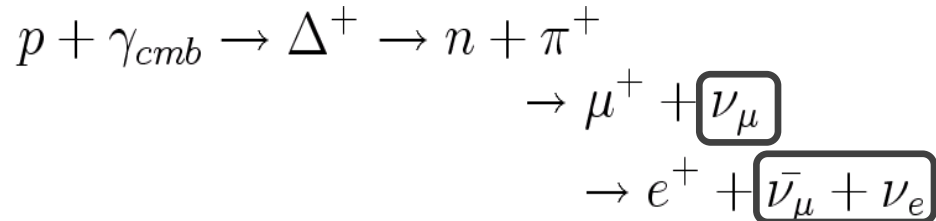
Gamma Ray Burst, Credit: NASA, ESA, M. Kornmesser





# Neutrino Production: The GZK Process

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

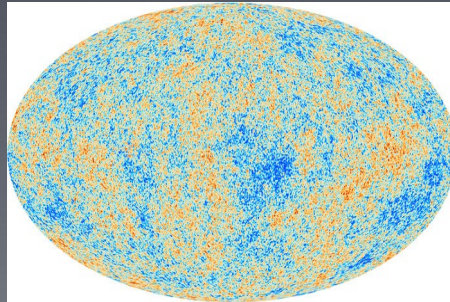


Cosmic Rays



Discover the origin of high energy cosmic rays and neutrinos?

CMB



What is the high energy cutoff of our universe?

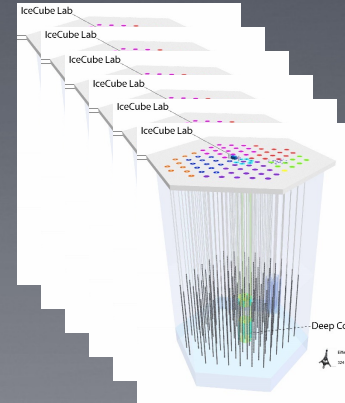
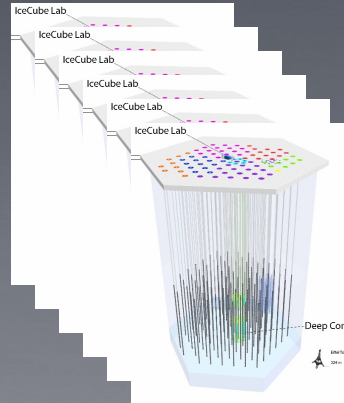
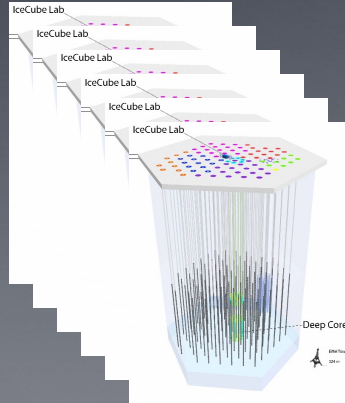
= Neutrino Beam!

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



# The Problem with Neutrino Astronomy

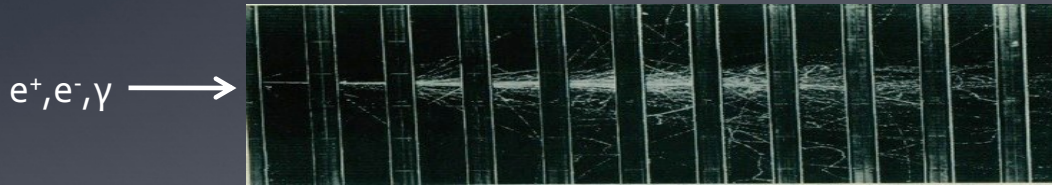
- Neutrinos don't interact very often, so it is hard to detect them!
  - Need a huge detector to have a chance to see them (hence IceCube)
- The highest energy neutrinos are even more rare, so you need an even bigger detector
  - You have to get creative (that's the fun part!)



... ?

# Method 1: Radio emission from neutrino interactions in dense material

- EM shower in dielectric (ice, sand)  $\rightarrow$  moving negative charge excess
- Coherent radio Cherenkov radiation ( $P \sim E^2$ ) if  $\lambda > \text{Moliere radius}$

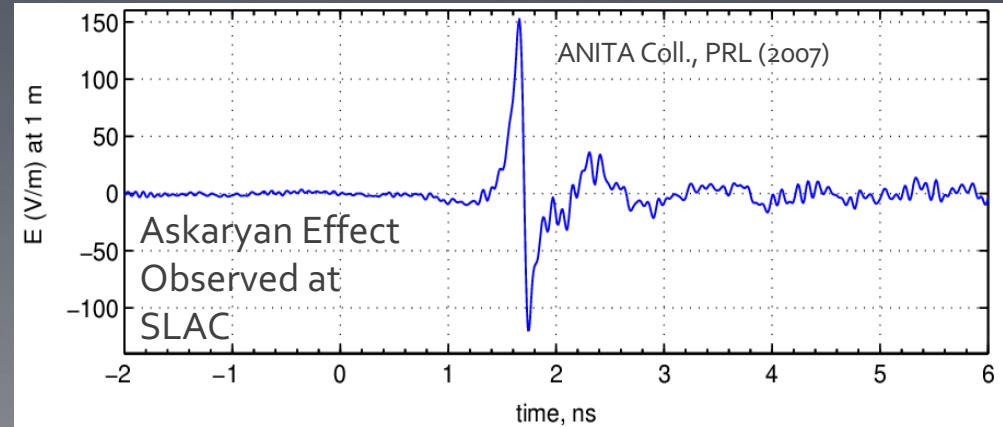


Typical Dimensions:

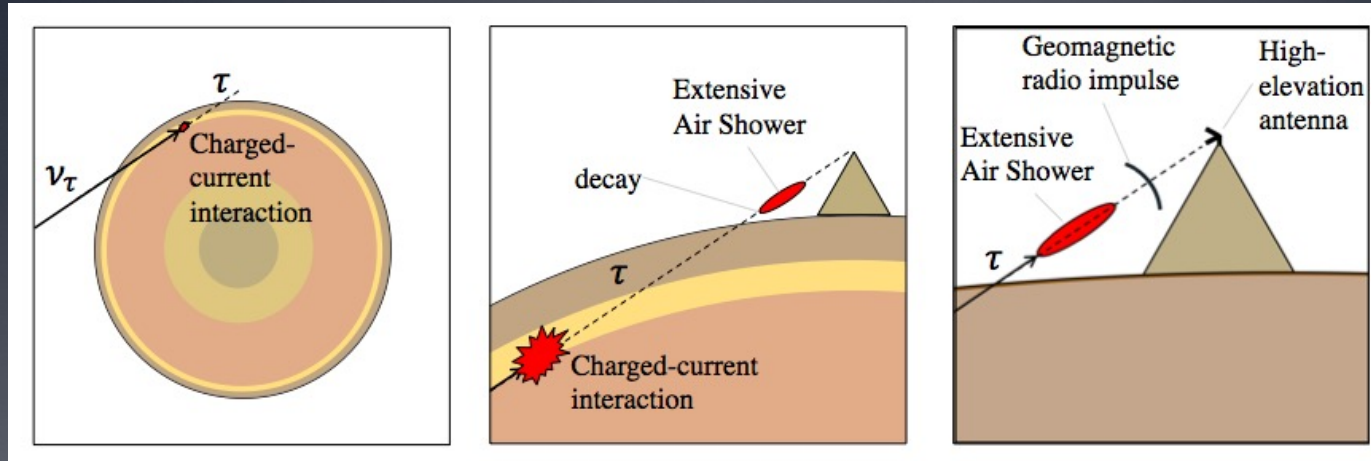
$L \sim 10 \text{ m}$

$R_{\text{moliere}} \sim 10 \text{ cm}$

$\rightarrow$  Radio Emission is stronger than optical for UHE showers



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



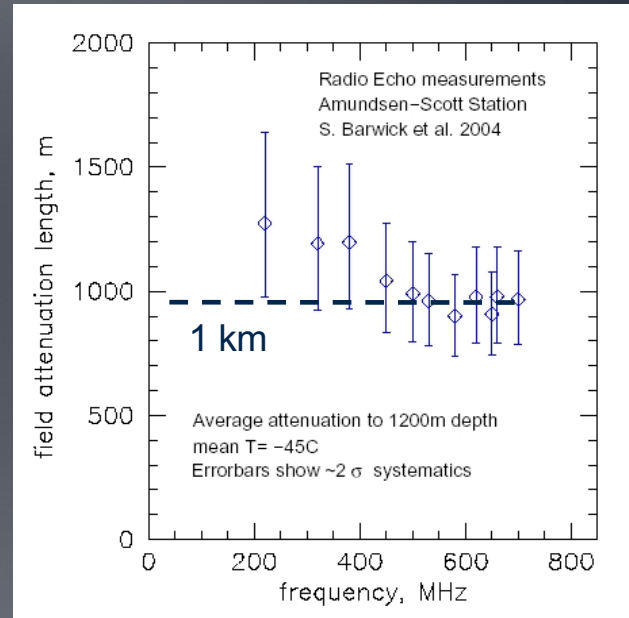
S. Wissel

- 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

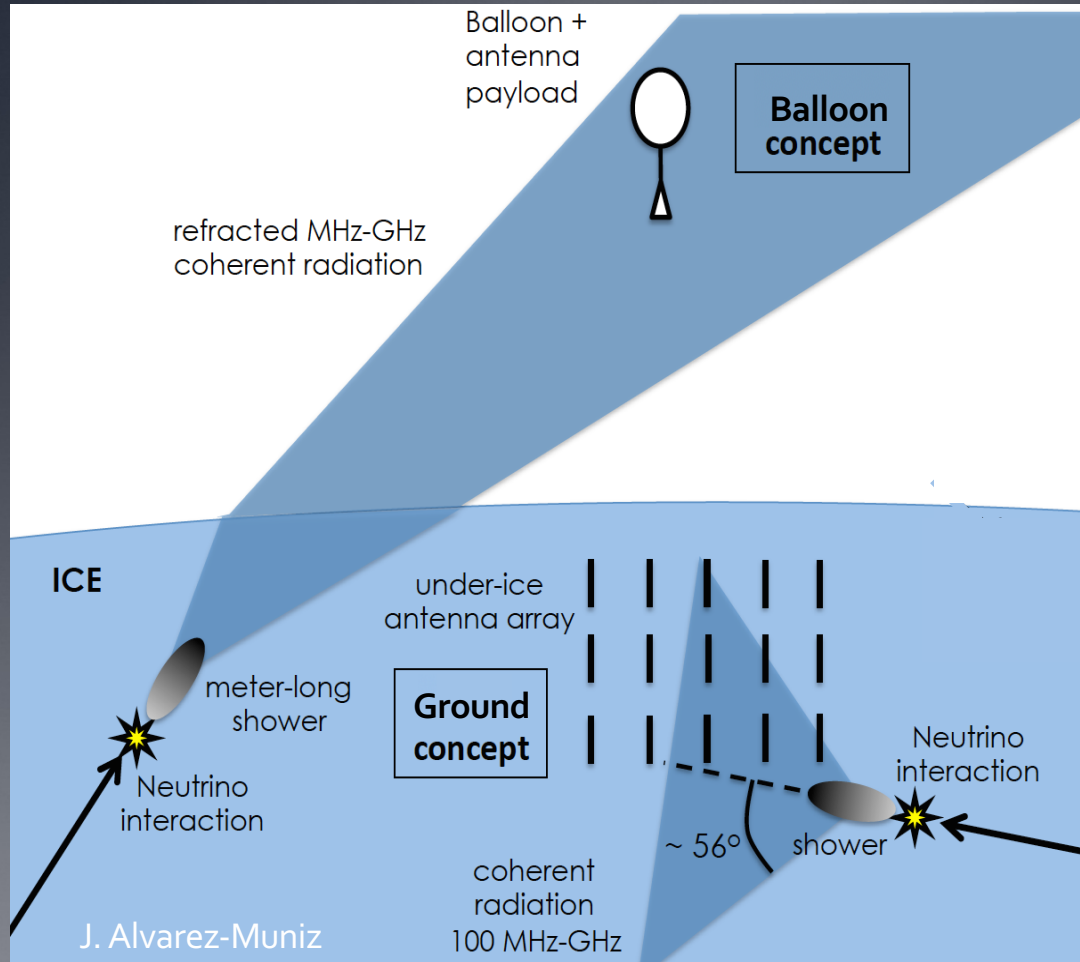


# Askaryan Emission Detector Requirements

- $\sim 1$  GZK neutrino/km<sup>2</sup>/year
- $L_{\text{int}} \sim 300$  km  
→ 0.01 neutrinos/km<sup>3</sup>/year
- Need a huge ( $\sim 100$  km<sup>3</sup>), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF (vs.  $\sim 100$  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:

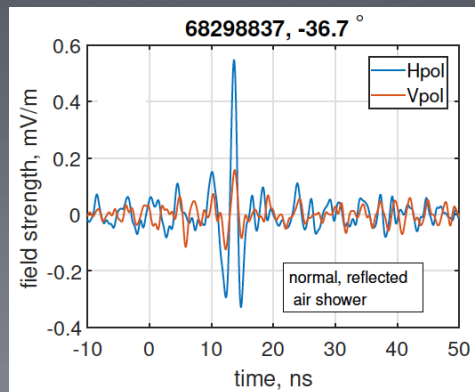
- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas (interferometry)
- In-flight calibration from ground
- Threshold limited by thermal noise

## Results in a Nutshell:

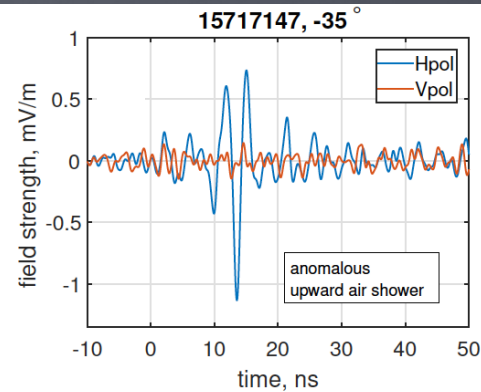
- Askaryan channel: No excess seen above background (no discovery)
- ~100 UHE Cosmic Ray ( $>10^{18}$  eV) events detected over 4 flights
- Tau Air Shower Channel: Events seen??



Typical Cosmic Ray Event



Mystery Event

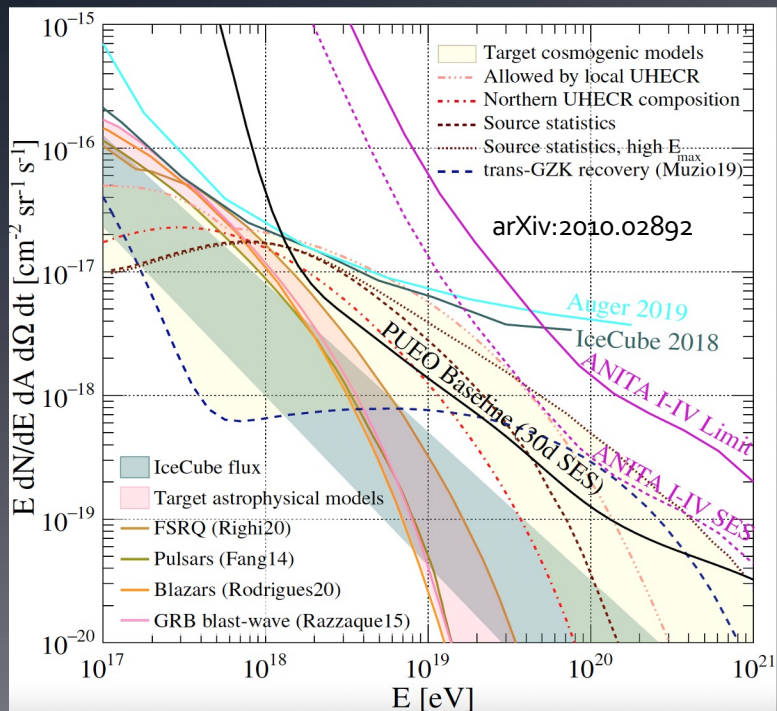




# PUEO: The Payload for Ultrahigh Energy Observations



## 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

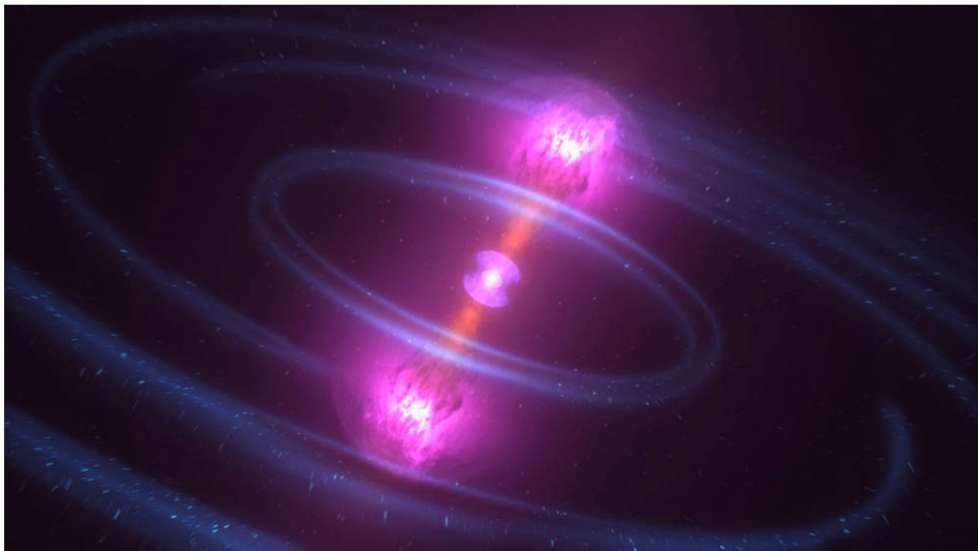
# PUEO Selected for Astrophysics Pioneers Mission by NASA

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

- 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!!

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 Vieregge of the University of Chicago.

# The PUEO Team





# The PUEO Instrument

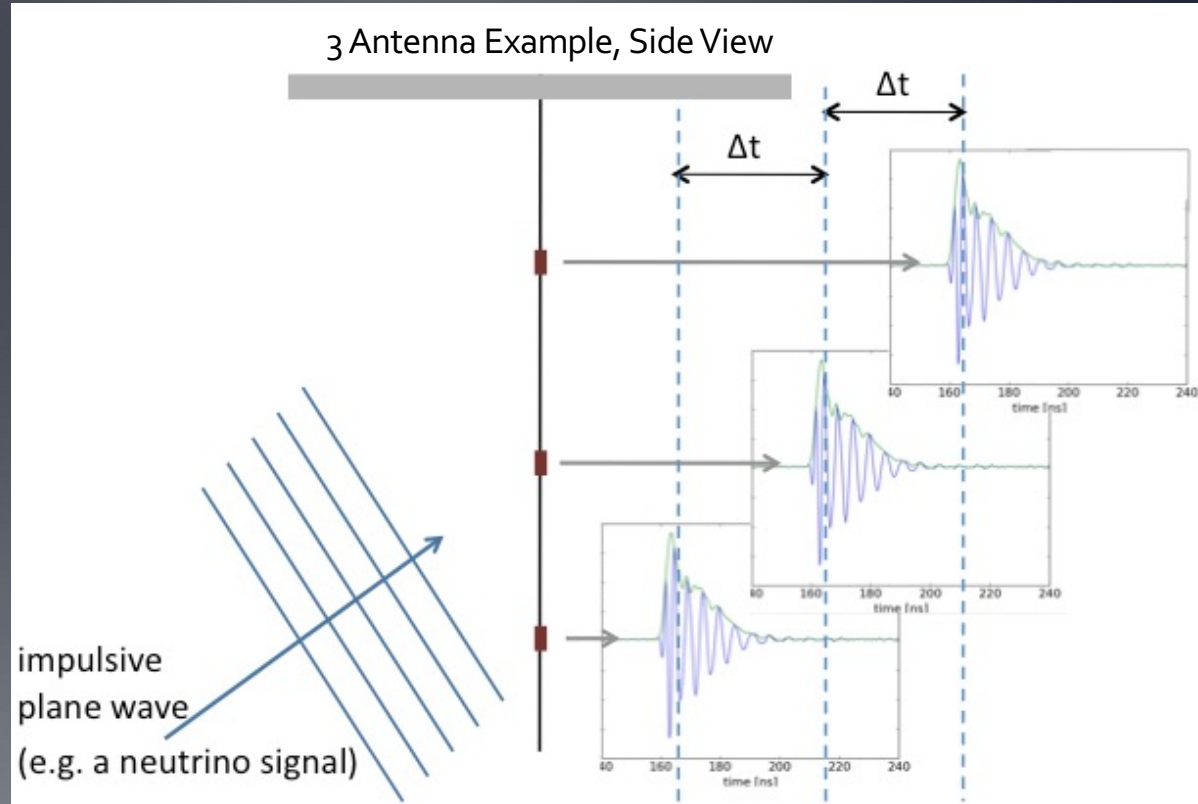


- 216-RF-Channel Main Instrument, with a 16-antenna, dual-polarization beamforming trigger
- 16-RF-Channel Low Frequency Instrument
- Triply redundant 128 TB onboard data storage
- Command and control, data transfer to the ground
- Suite of navigation instruments: heading, pitch, roll, location
- Housekeeping/environment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



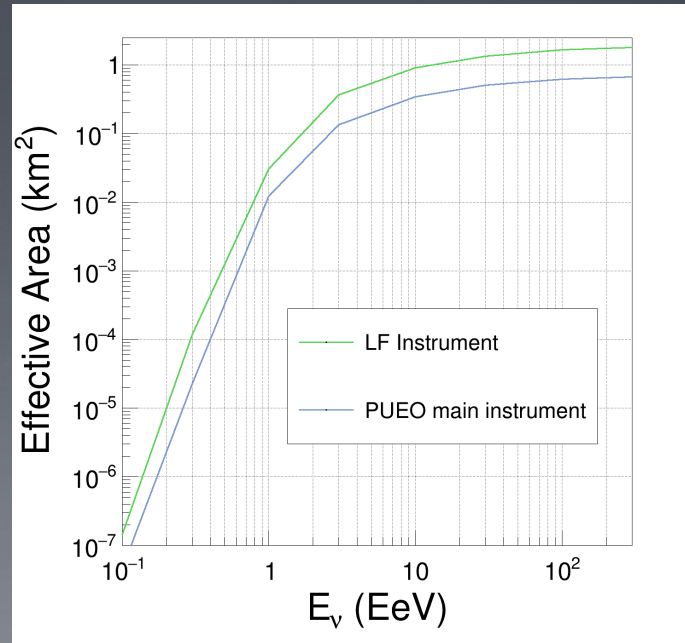
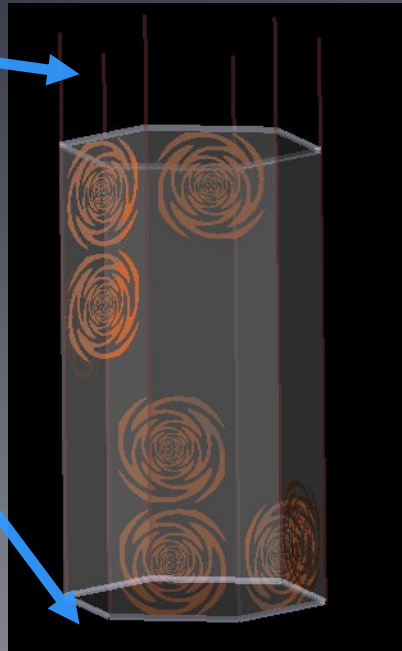
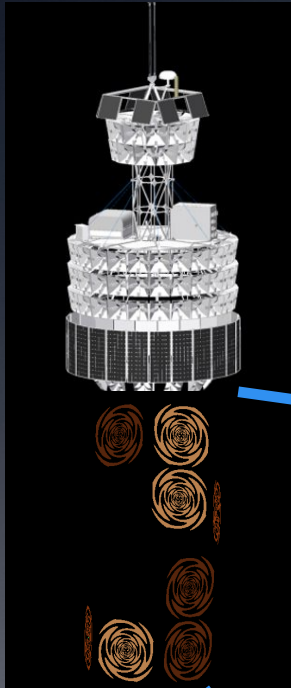
# Pushing the Threshold Down and Increasing Sensitivity: A Phased Array

- You know  $\Delta t$  based on the antenna geometry and the speed of light in ice
- Line up signals according to the  $\Delta t$  you know, then sum
- For real neutrino events (plane waves), you 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

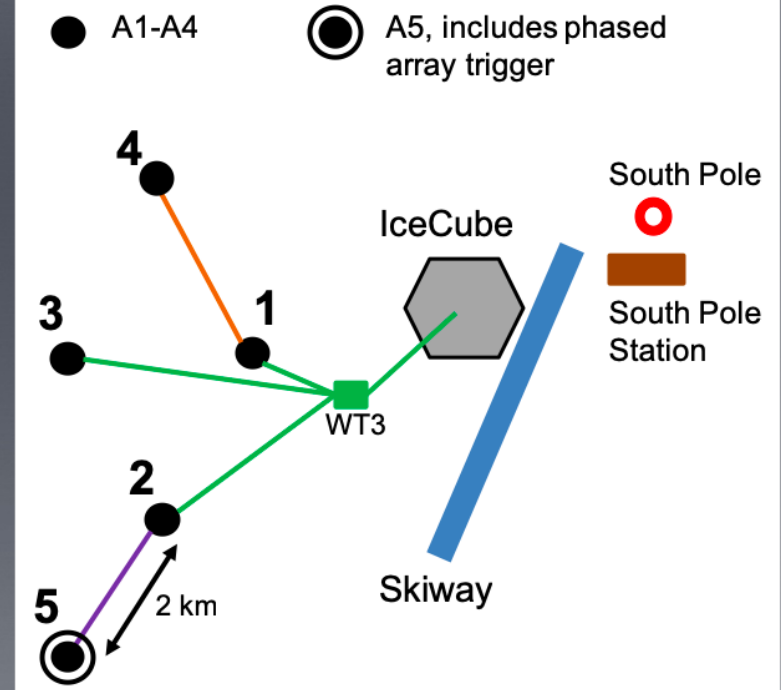
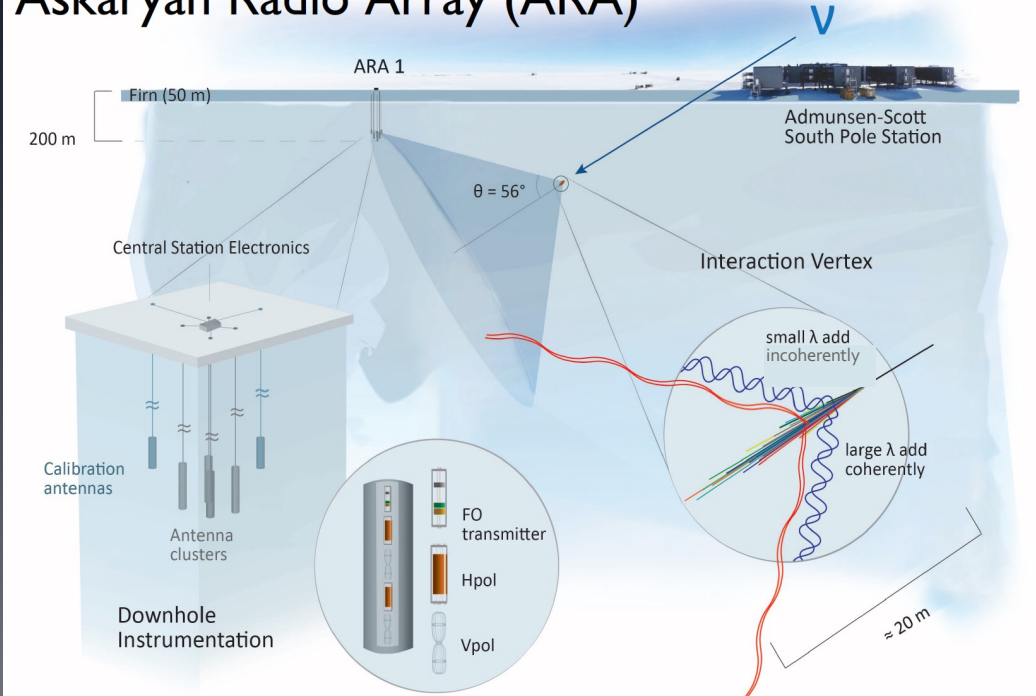
- Degree-scale angular resolution expected
- Factor of 2 improved sensitivity (effective area) to tau neutrinos compared with Main Instrument





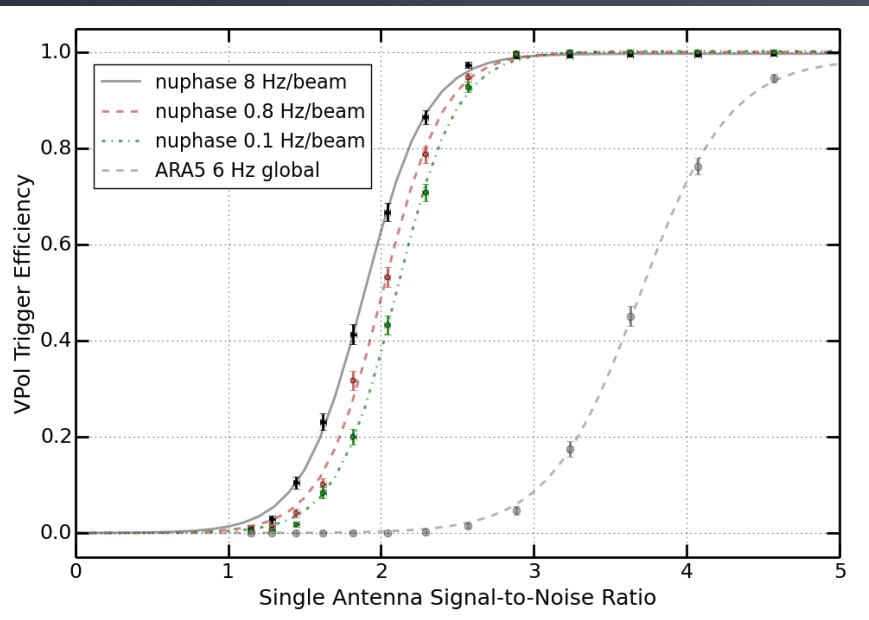
# ARA: In-Ice Radio Detector at South Pole

## Askaryan Radio Array (ARA)



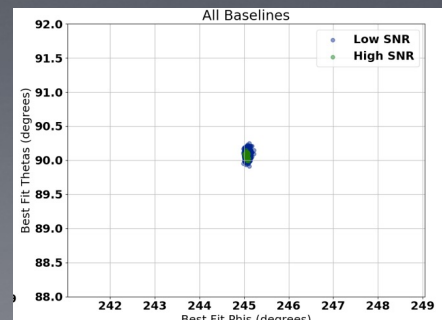
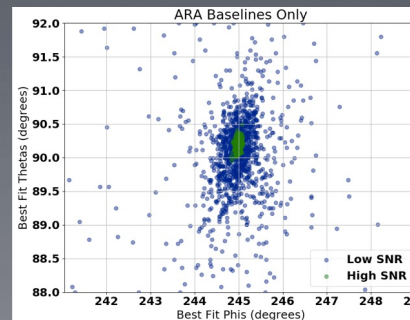
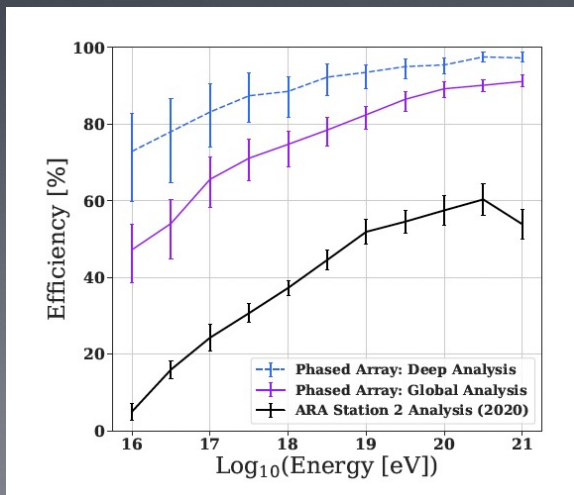
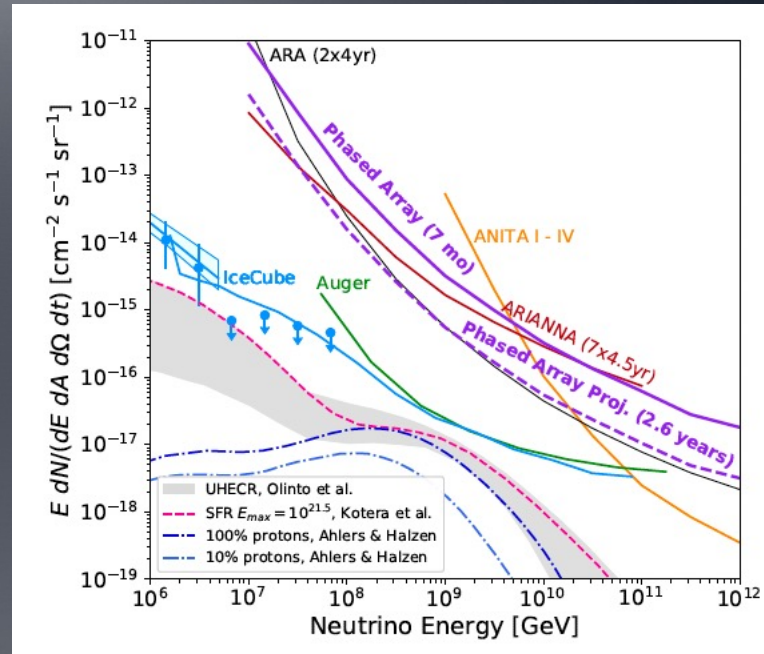
# ARA's Phased Array Trigger System

- 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



# 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

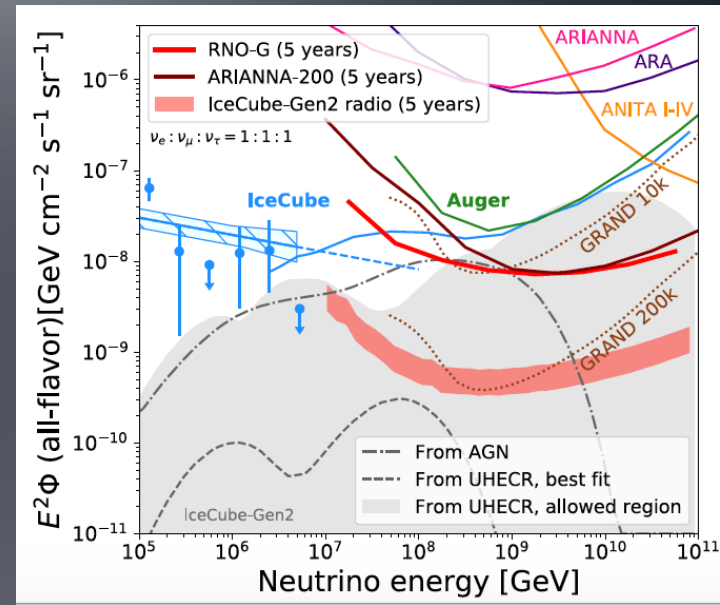
OLD

NEW

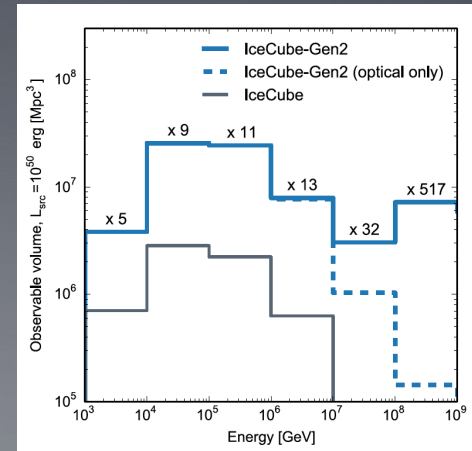
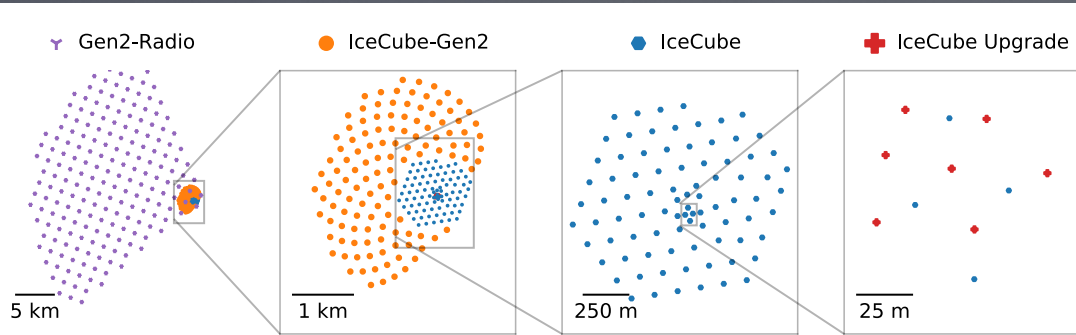


# Toward IceCube-Gen2

- 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)

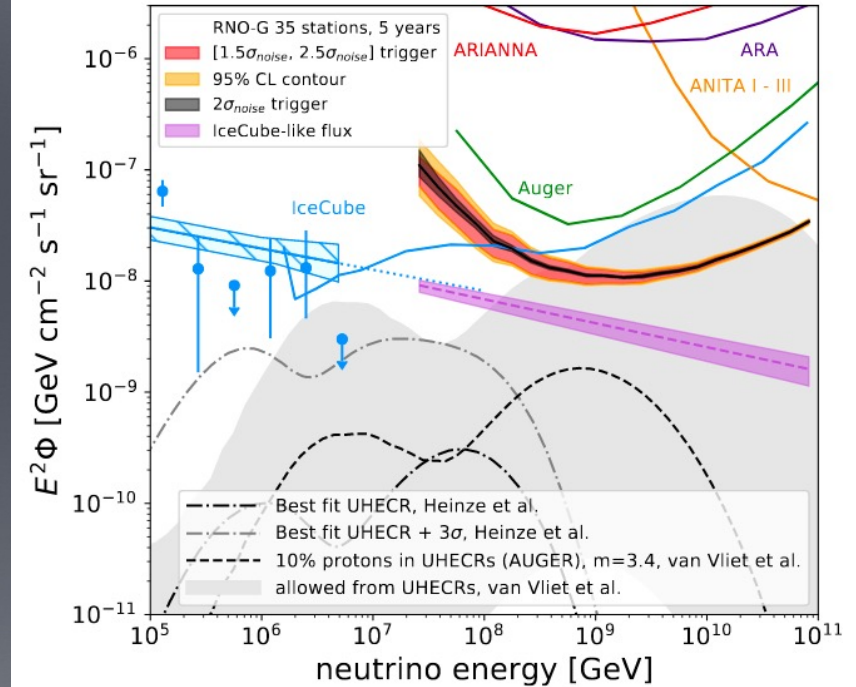


IceCube Gen2 Whitepaper: arXiv: 2008.04323

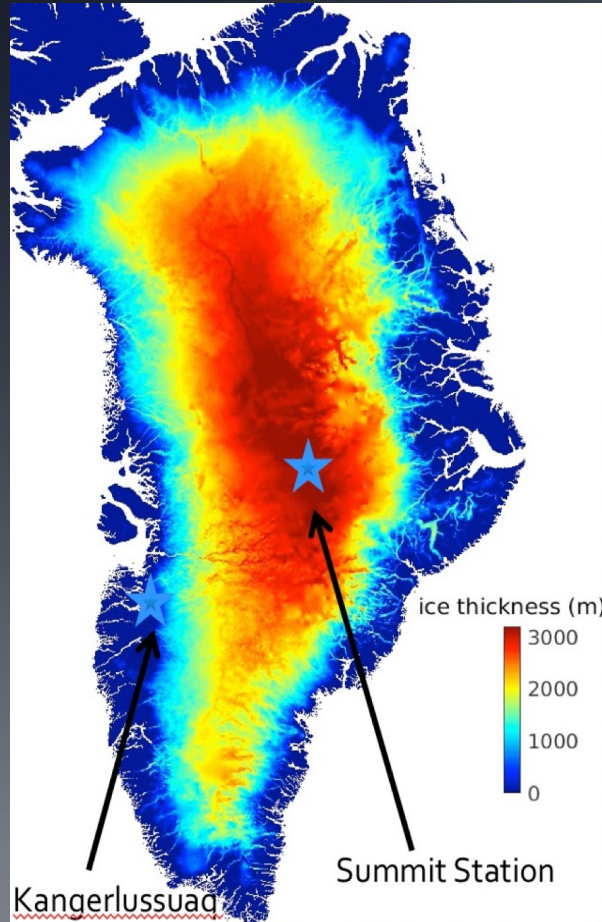


# Radio Neutrino Observatory in Greenland (RNO-G)

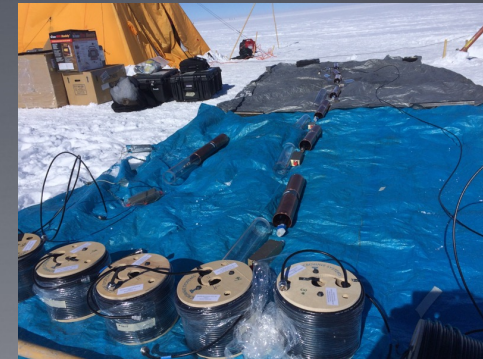
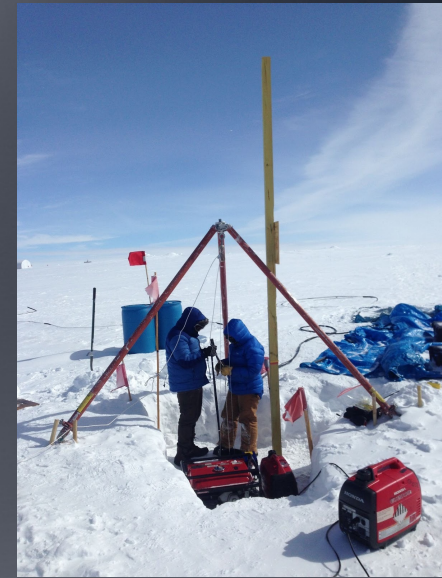
- RNO-G is currently being installed at Summit Station in Greenland (first hardware deployed in 2021, 2022 deployment season just started).
- RNO-G is designed to be scalable to large arrays (IceCube-Gen2)



# Summit Station Site

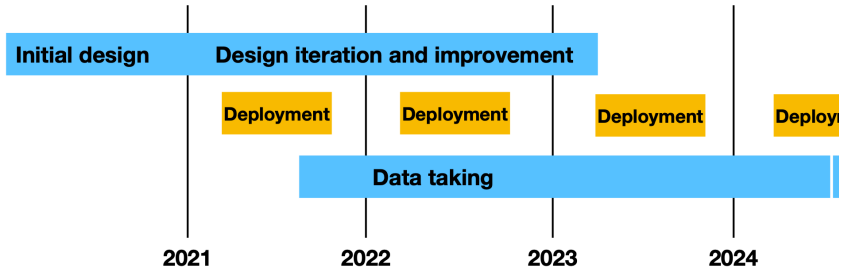


- 3 km deep ice; attenuation length shorter than South Pole.
- NSF-run station, LC-130 access during the summer (May-August)
- Site is good for solar & wind power
- Early studies in 2013 and 2015: measurements of ice attenuation length, and first in-situ test of a phased array trigger

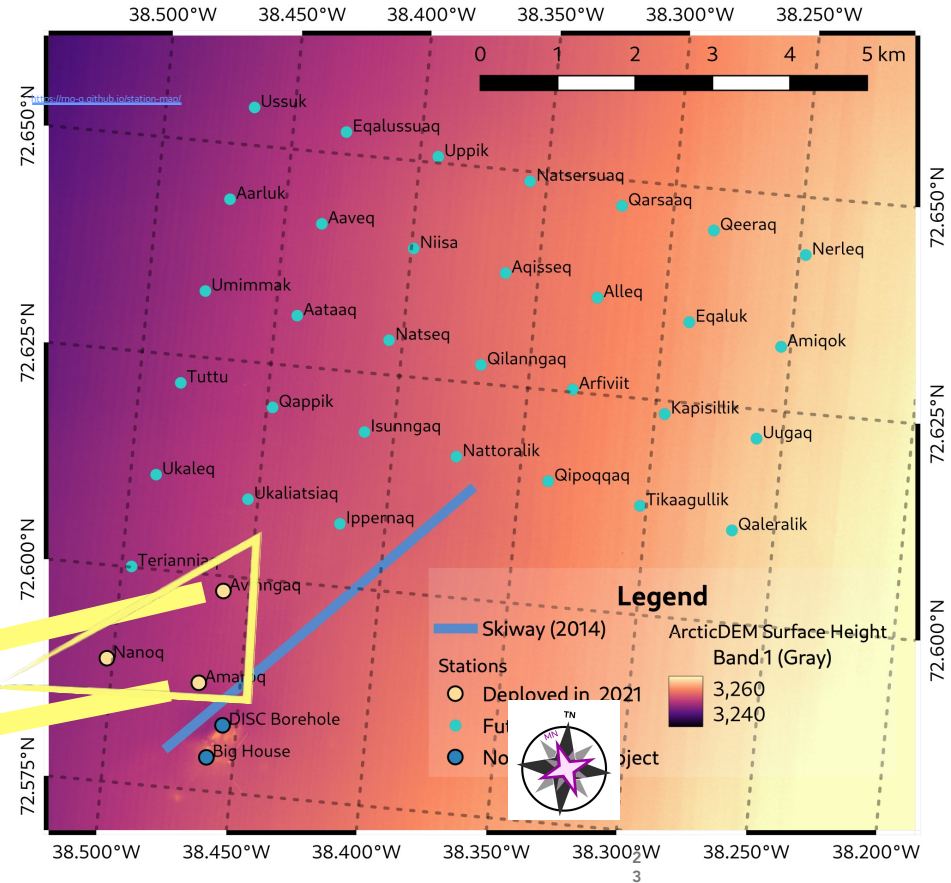




- ▶ 35 stations, 1.25 km spacing
- ▶ LTE Comms, Solar/Wind Power (due to site constraints)
- ▶ First deployment season in 2021, 3 stations installed.
- ▶ 2022 deployment season just began! Goal to install 6 stations
- ▶ 2 more seasons (2023 and 2024) of instrumentation deployment worked out with NSF as of now.



## RNO-G Planned Layout



# RNO-G STATION LAYOUT



Surface

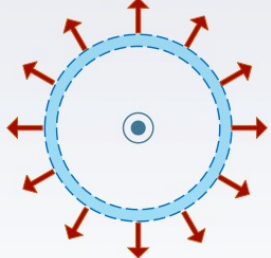
Deep

Askaryan  
Radiation

Neutrino  $\nu$

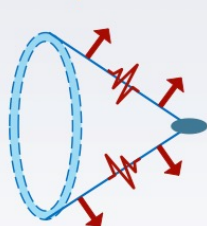
forward view

E-field polarization

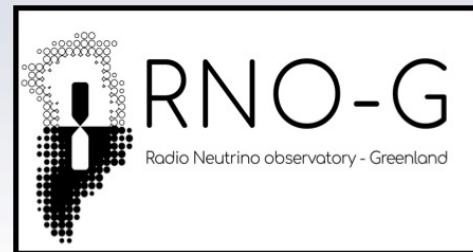


side view

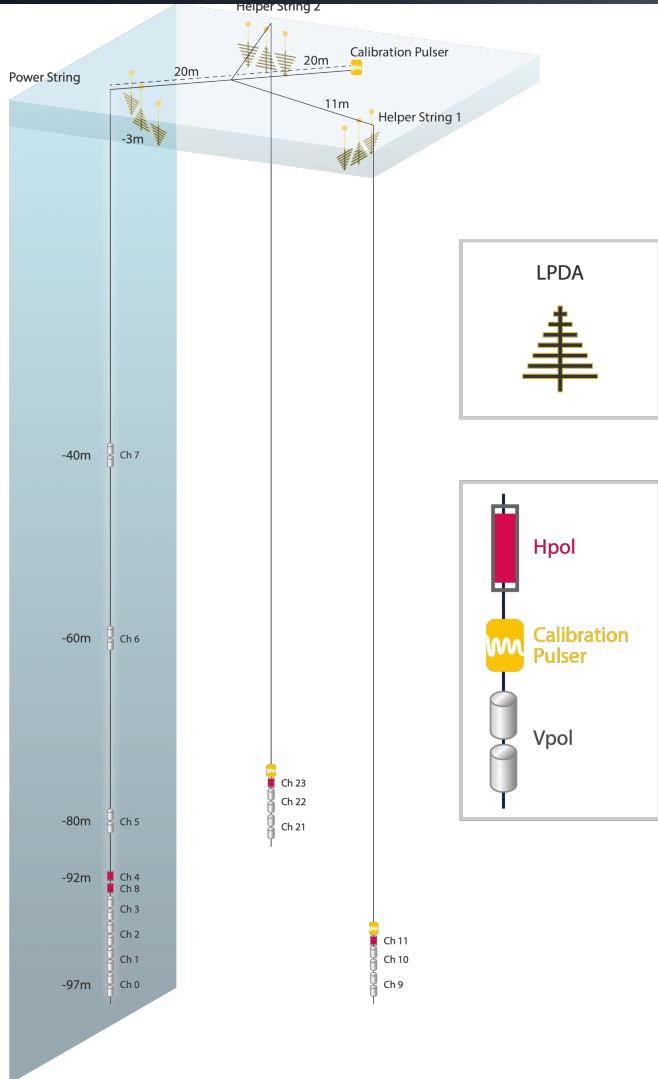
E-field polarization



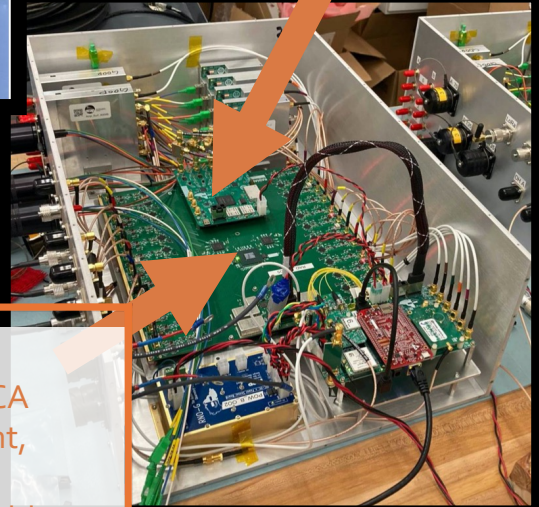
vertex



# 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

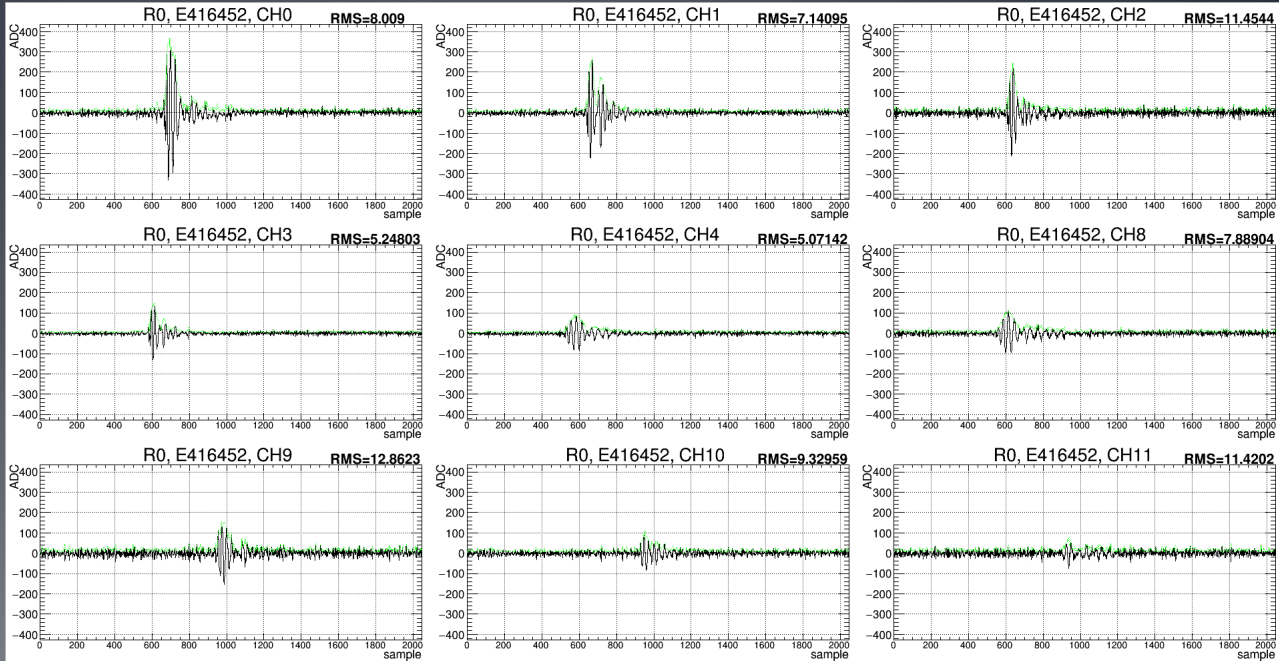
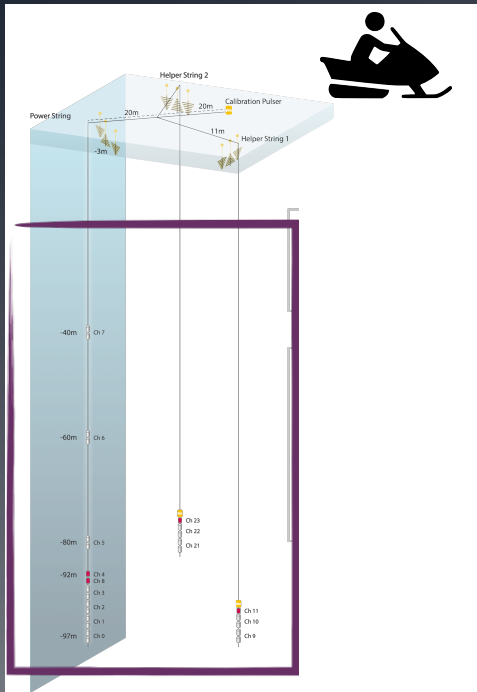


Vpol:  
Fat dipoles

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.

