Searching for Ultra-high Energy Neutrinos

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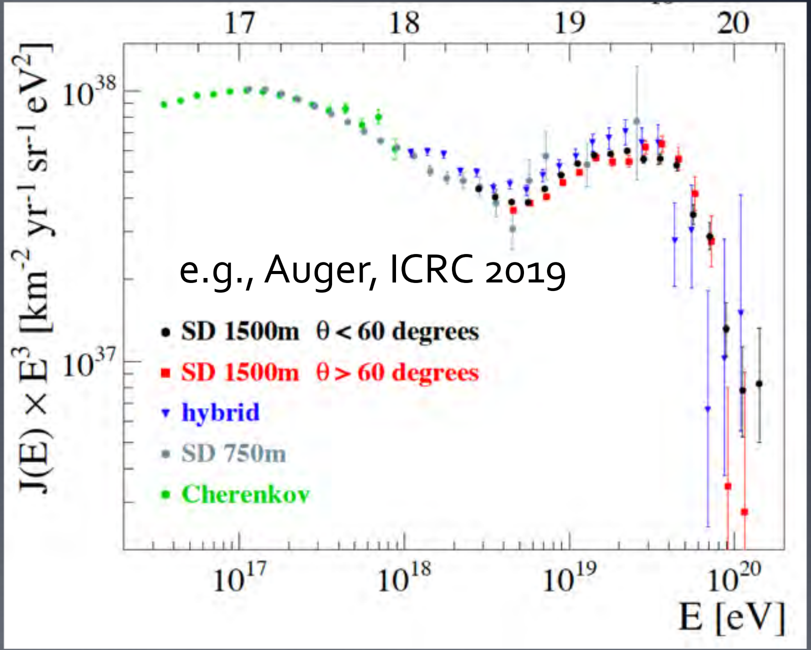
ICRC 2019

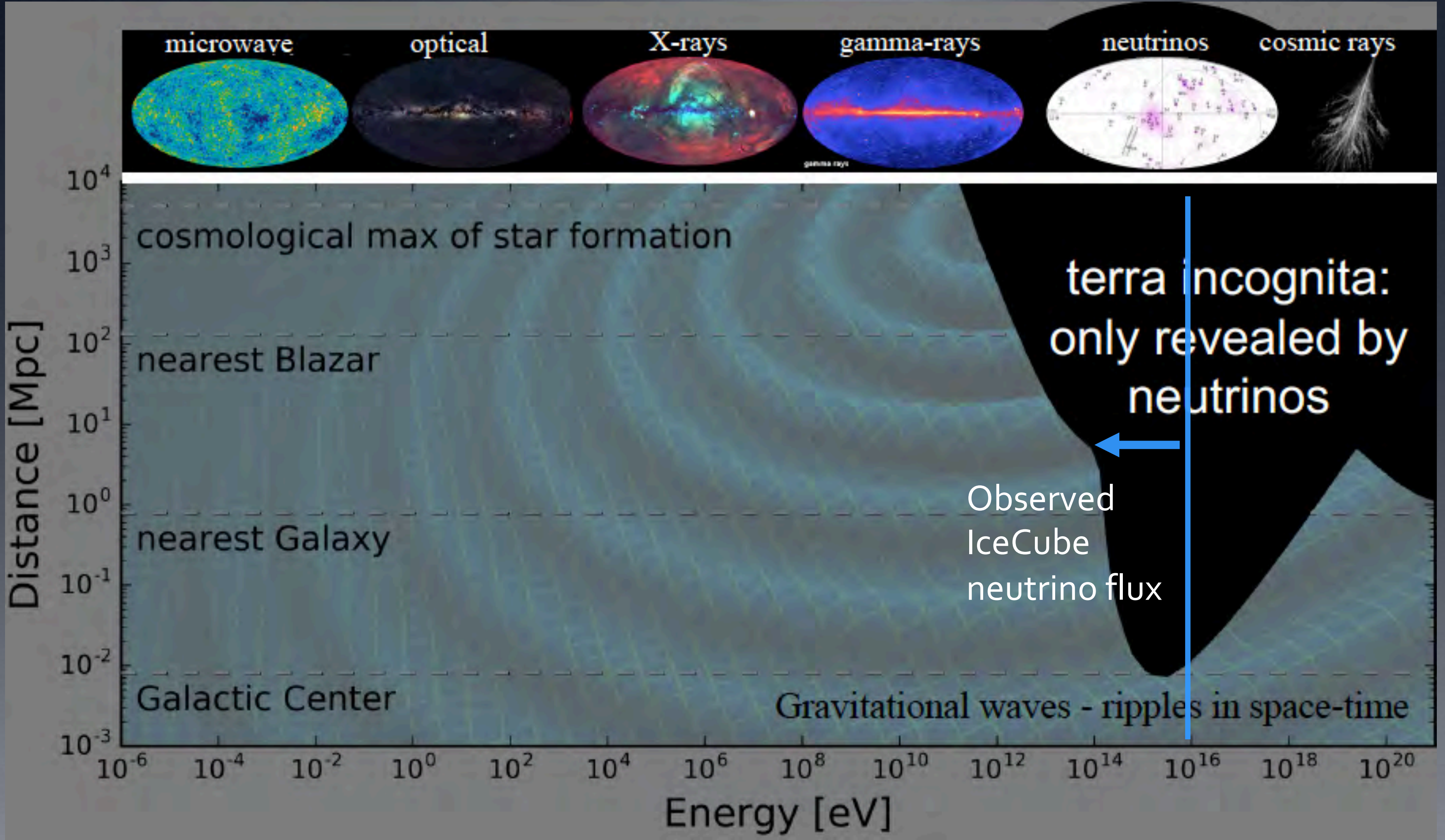
Neutrinos: The Ideal UHE Messenger

- Photons 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



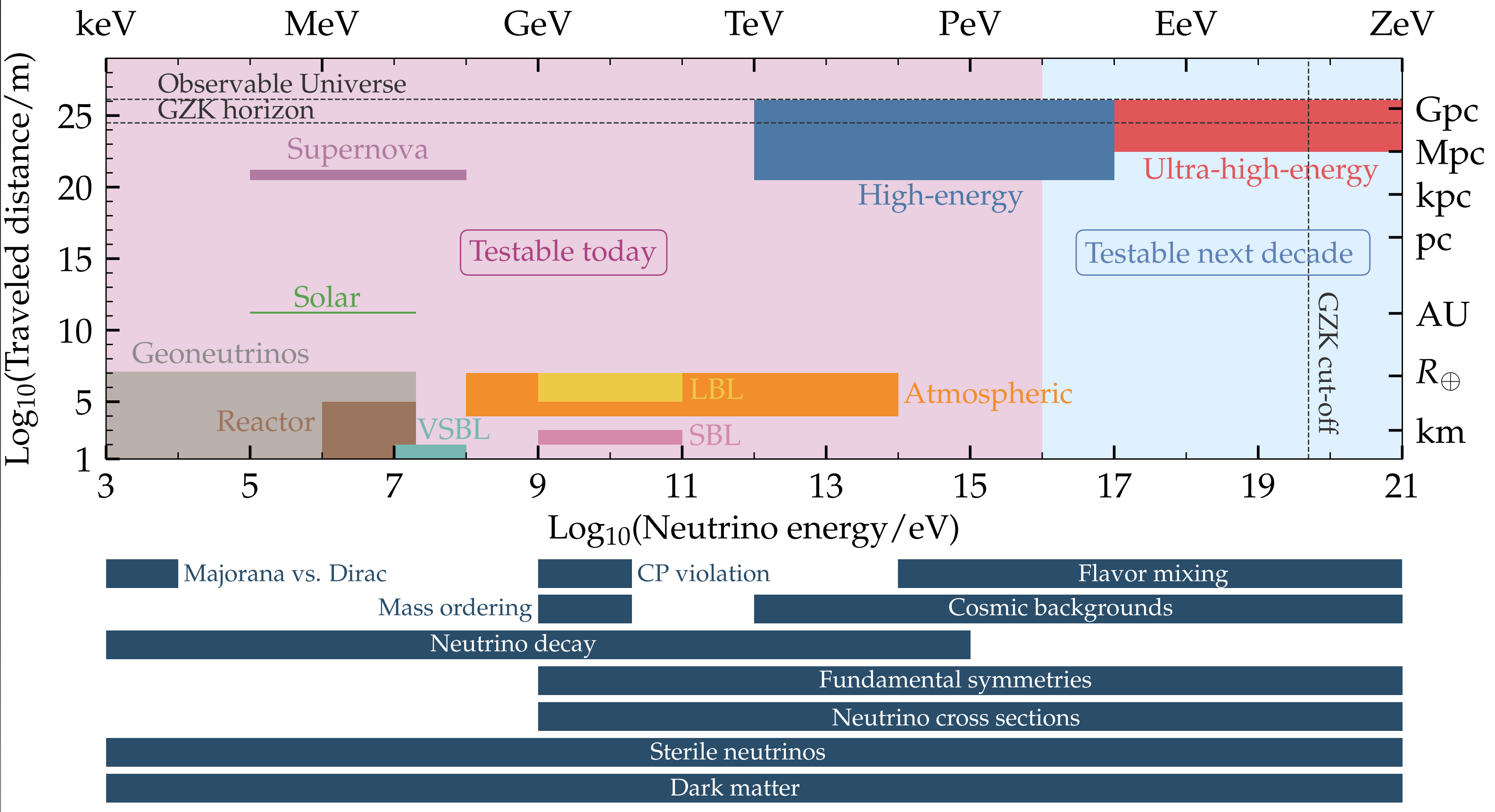
<u>UHE Neutrino Detectors:</u>

- 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?



microwave
optical
X-rays
gamma-rays
neutrinos
cosmic rays
cosmological max of star formation
nearest Blazar
nearest Galaxy
Galactic Center
terra incognita:
only revealed by
neutrinos
Observed
IceCube
neutrino flux
Gravitational waves - ripples in space-time
Distance [Mpc]
Energy [eV]

Probing a Wide Range of Fundamental Physics



M. Bustamante, from arXiv:1903.04333, Astro2020 Science Whitepaper

Neutrino Production: The GZK Process

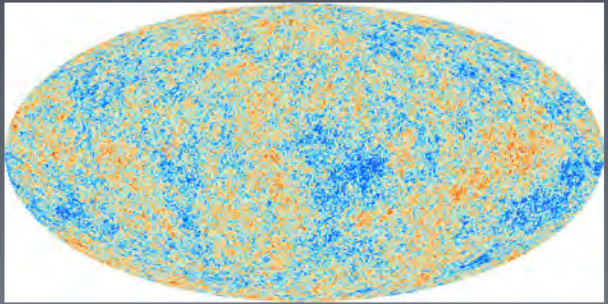
GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

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

Cosmic Rays

\+

CMB



= Neutrino Beam!

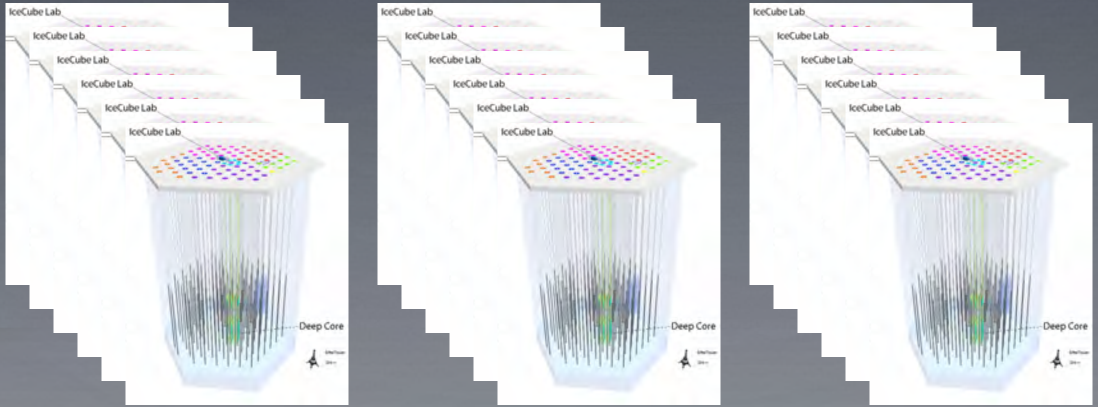
Discover the origin of high energy cosmic rays and neutrinos?

What is the high energy cutoff of our universe?

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

The Problem with Ultra-high Energy 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
- 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!)

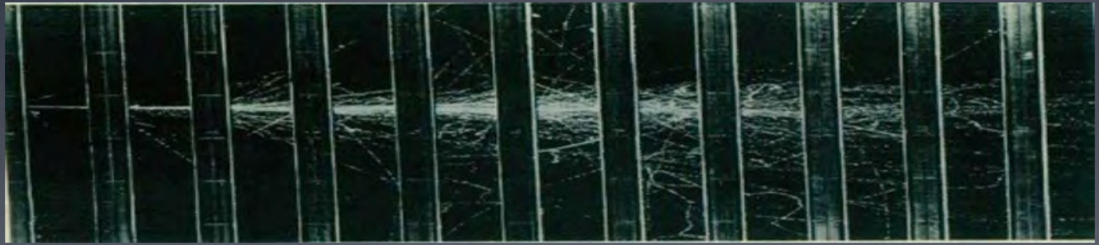


... ?

Method 1: Radio emission from neutrino interactions in dense material

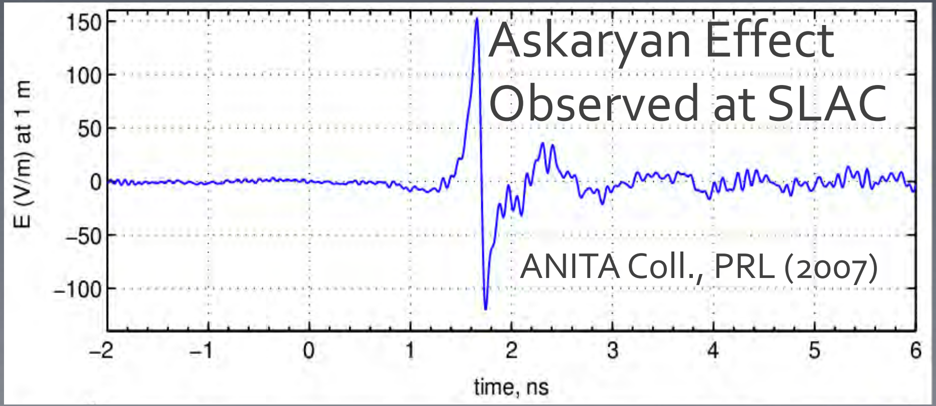
- EM shower in dielectric (ice, sand) → moving negative charge excess
- Coherent radio Cherenkov radiation (P ~ E^2) if λ > Moliere radius

e^+, e^-, γ ⟶

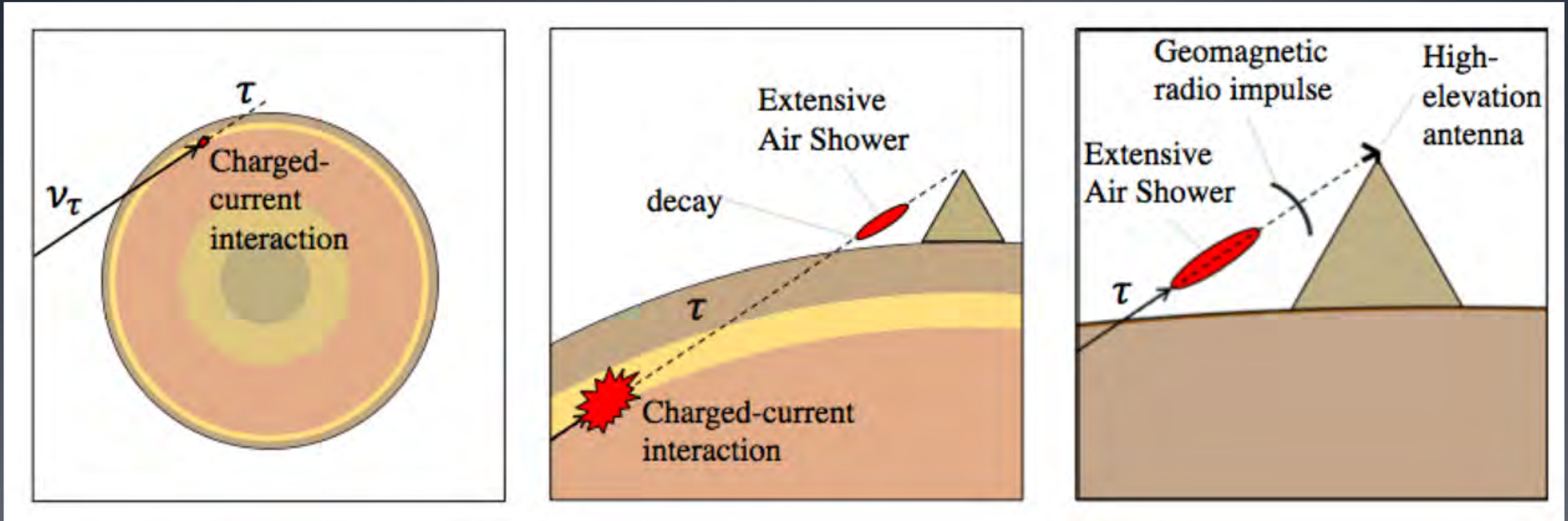


Typical Dimensions:
L ~ 10 m
$R_{moliere}$ ~ 10 cm

→ Radio Emission is stronger than optical for UHE showers



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

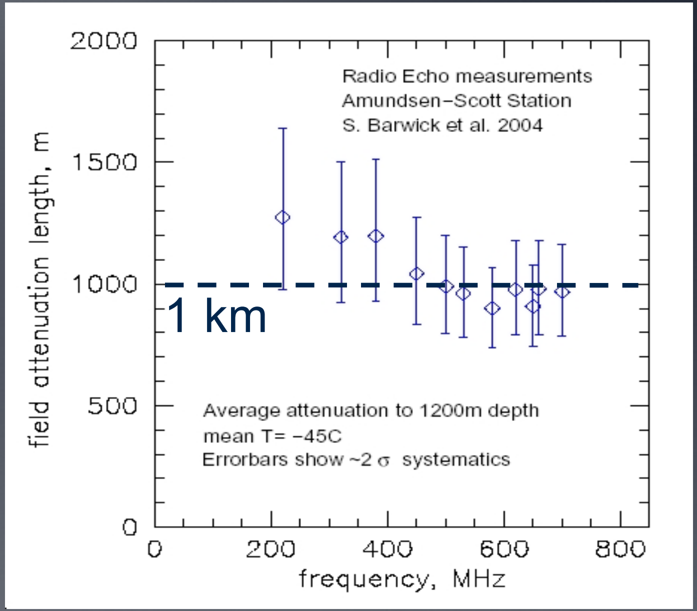


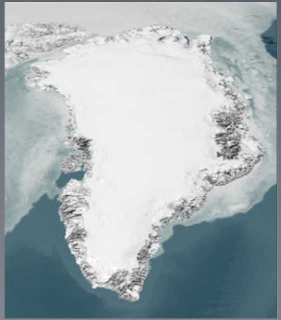
S. Wissel

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

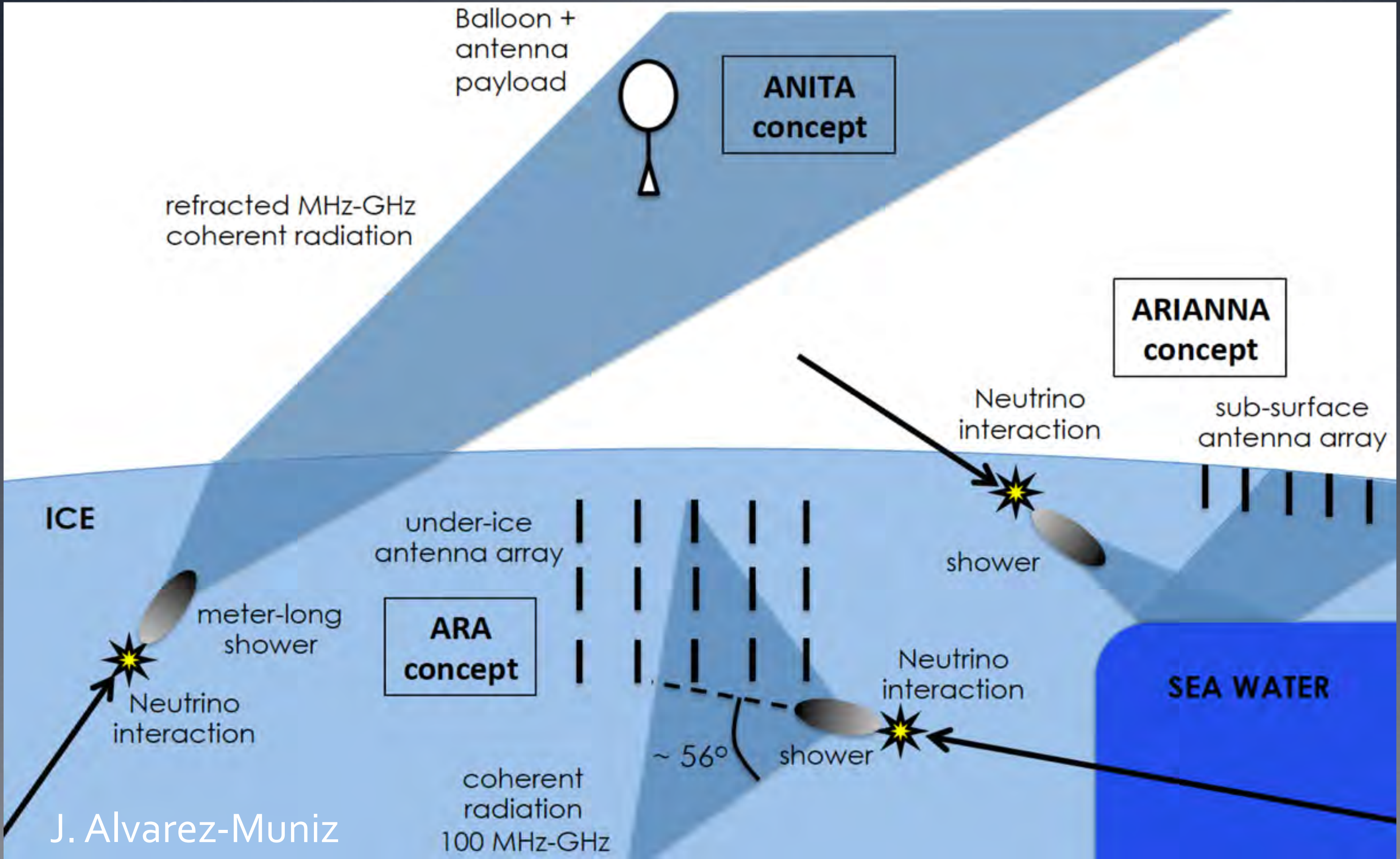
Askaryan Neutrino Detector Requirements

- 1 UHE neutrino/km²/year
- L_{int} ~ 300 km for ice
  → 0.003 neutrinos/km³/year
- Need a huge (> 1000 km³), radio-transparent detector
- Long radio attenuation lengths in ice
  - 1 km for RF
- → Ice is good for radio detection of UHE neutrinos!





Ongoing Efforts in Radio Detection in Dense Media



J. Alvarez-Muniz

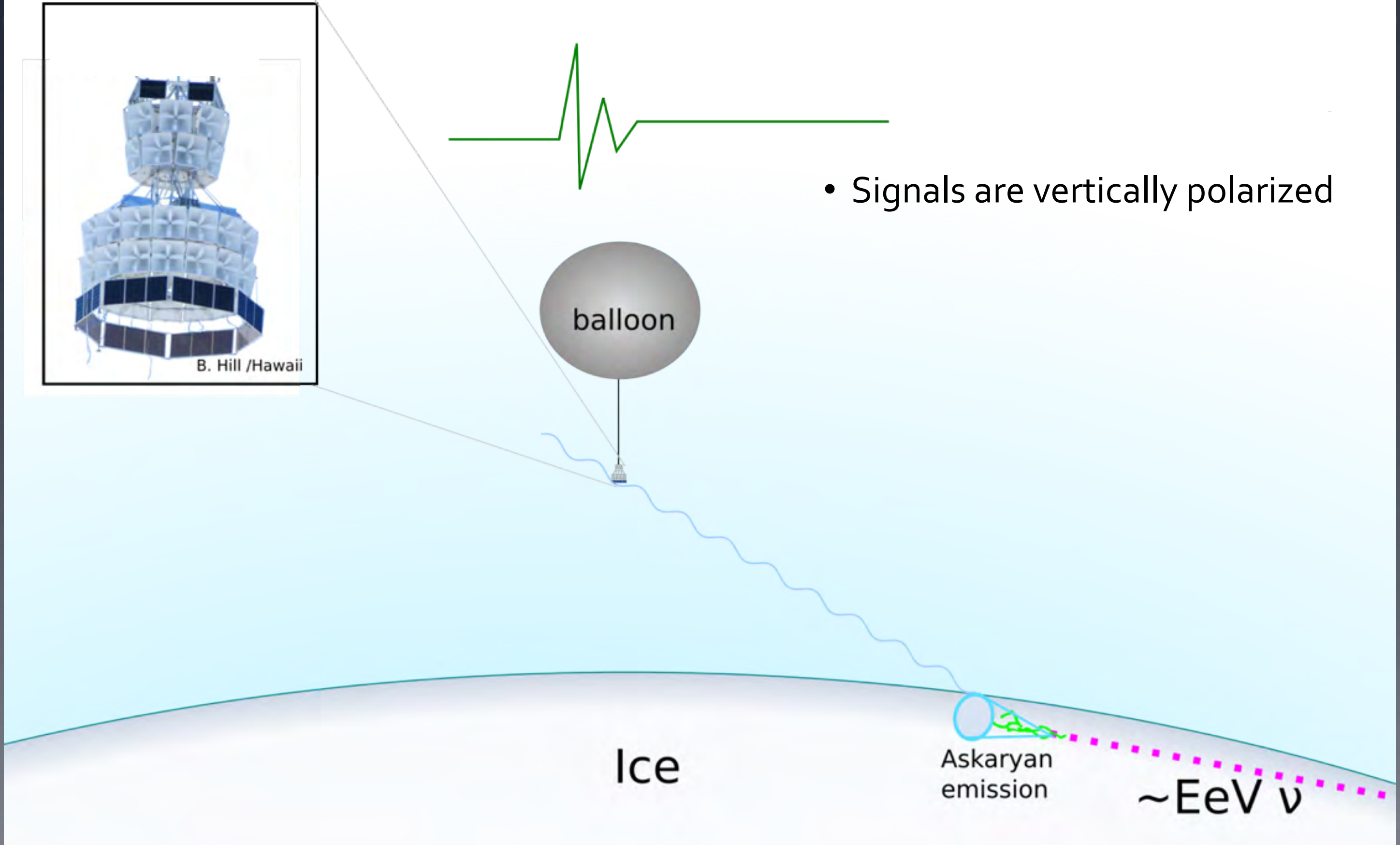
ANITA: Designed for Energies > $10^{19.5}$

NASA Long Duration Balloon launched from Antarctica, four flights thus far

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

1) Neutrino-Induced Askaryan Emission in Ice

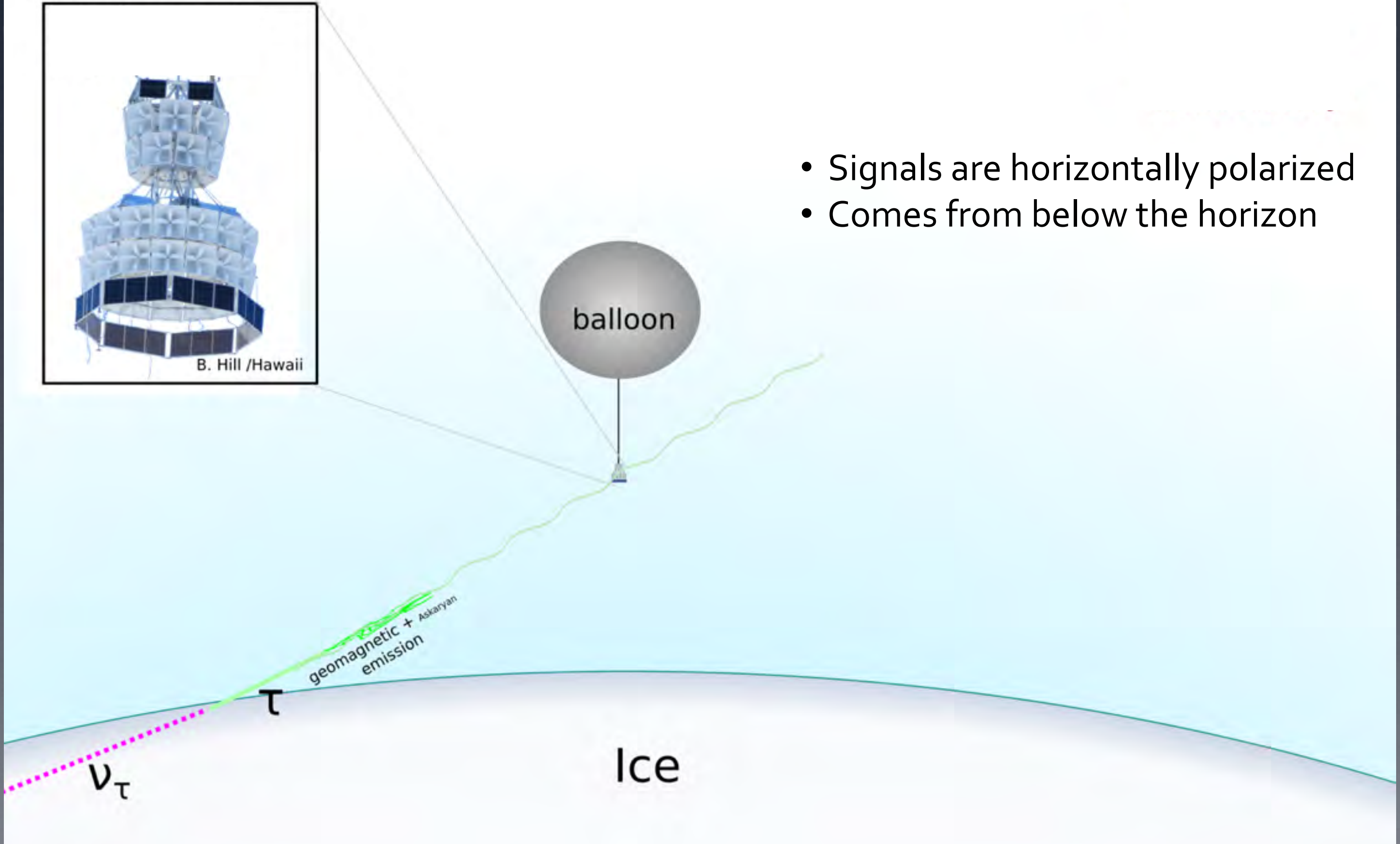


- Signals are vertically polarized

C. Deaconu

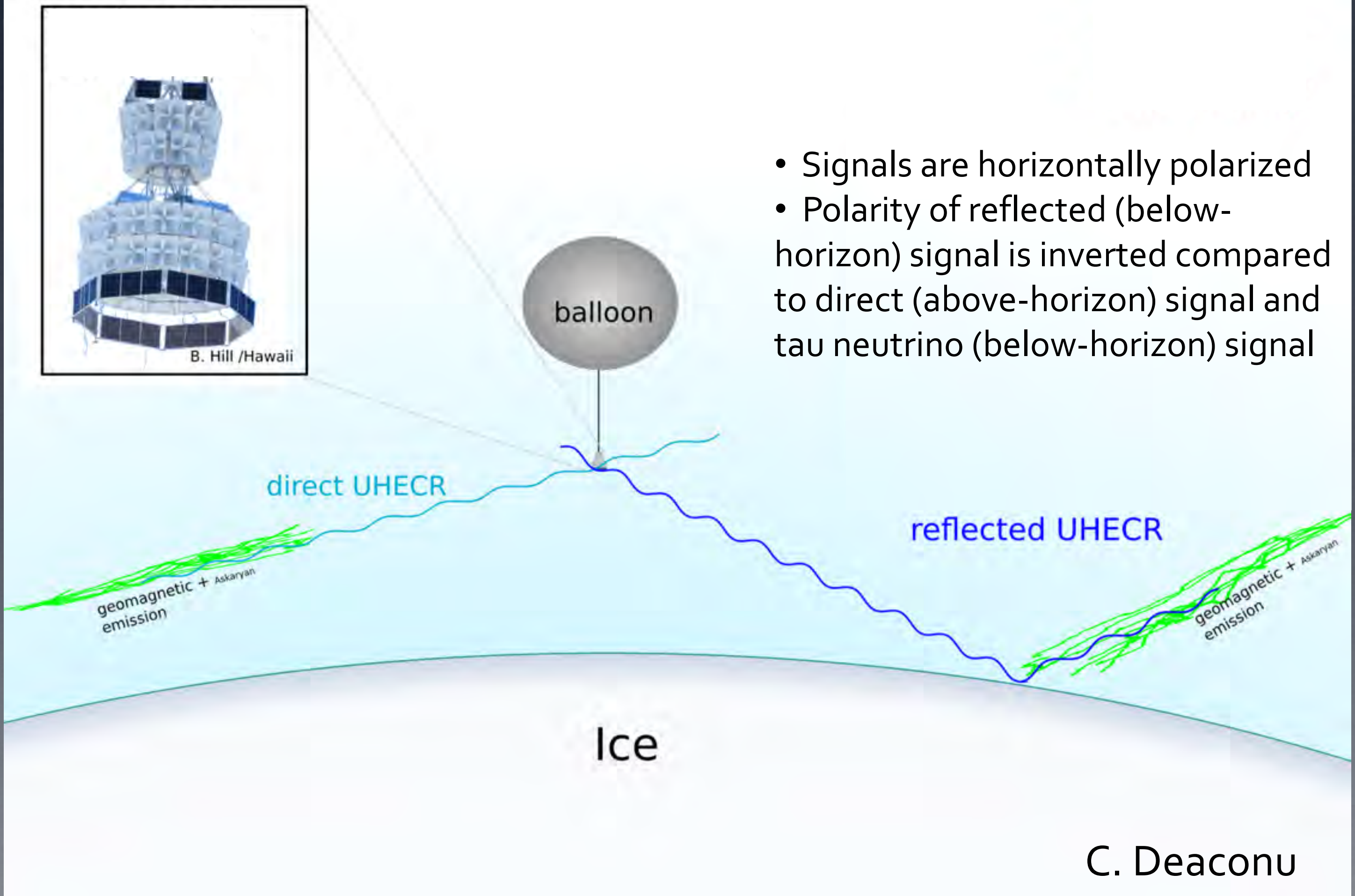
2) Radio Emission from Tau-Neutrino-Induced Air Showers

- Signals are horizontally polarized
- Comes from below the horizon



C. Deaconu

3) Radio Emission from Cosmic-Ray-Induced Air Showers



- Signals are horizontally polarized
- Polarity of reflected (below-horizon) signal is inverted compared to direct (above-horizon) signal and tau neutrino (below-horizon) signal

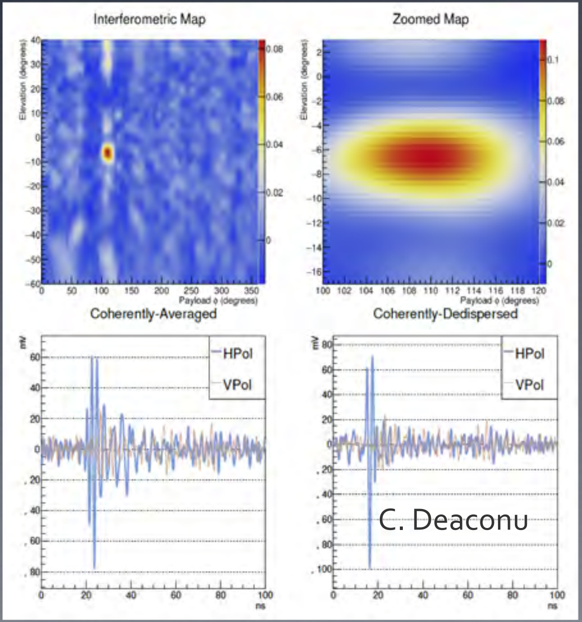
C. Deaconu

ANITA3 and ANITA4 Askaryan Neutrino Search Results

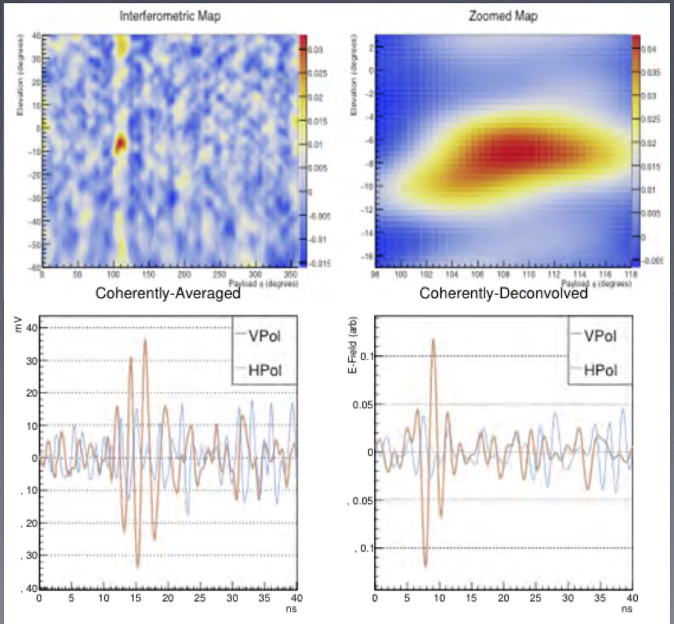
	Number of Events in Signal Region	Background Estimate
ANITA3	1	$0.7^{+0.5}_{-0.3}$ events
ANITA4	1	$0.6^{+0.7}_{-0.5}$ events

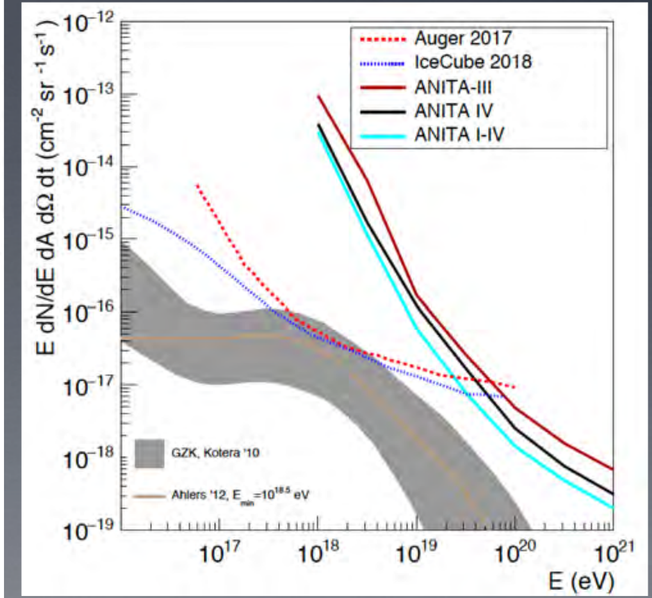
ANITA Coll. PRD 2018, PRD 2019

Simulated Neutrino Event



Candidate Event



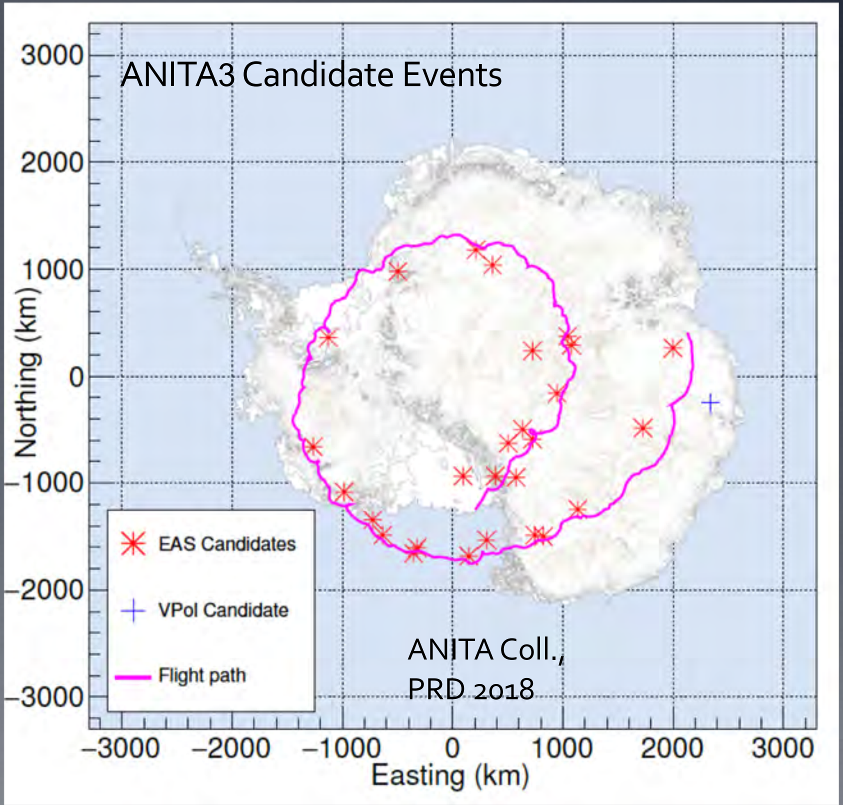


See C. Deaconu Talk

ANITA Also Sees Air Showers

(Cosmic Rays + Tau Neutrinos + Anything Else That Might Make Air Showers)

- Signals are distinguishable from in-ice neutrinos via polarization
- Energy > 10^{18} eV
- ANITA1: 16 Air Showers
- ANITA3: 28 Air Showers
- ANITA4: 24 Air Showers

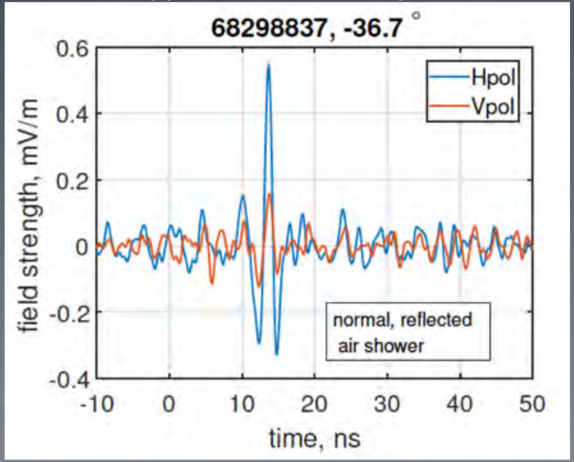


ANITA Coll., PRL 2016
ANITA Coll., Astroparticle Phys. 2016
ANITA Coll., PRD 2018

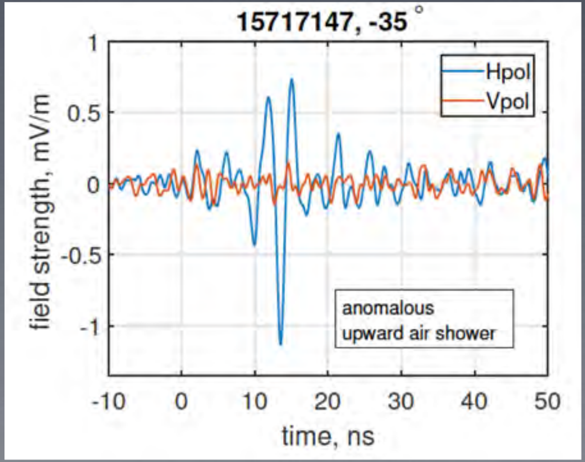
Polarity Flipping and Tau Neutrinos

- Polarity should be the same for all reflected cosmic ray events
- One of the 28 air showers in ANITA3 is not the same polarity as the rest
  - There was another one of these in ANITA1
- Each of these two observations is 1 event on a background of ~0.01
- Sign of an upgoing (tau neutrino?) air shower?

Typical Cosmic Ray Event



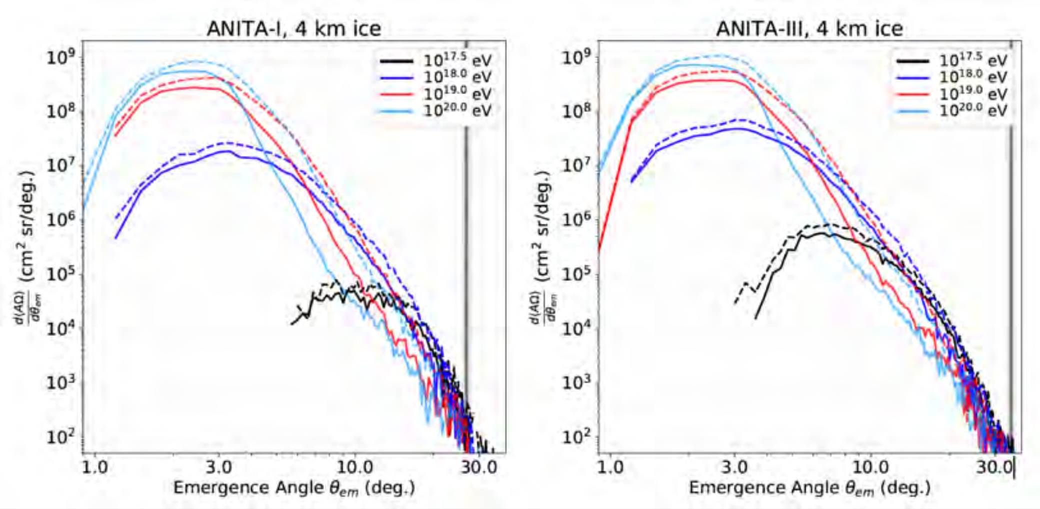
Mystery Event



ANITA Coll., PRL 2018

Problem with a Tau Neutrino Interpretation

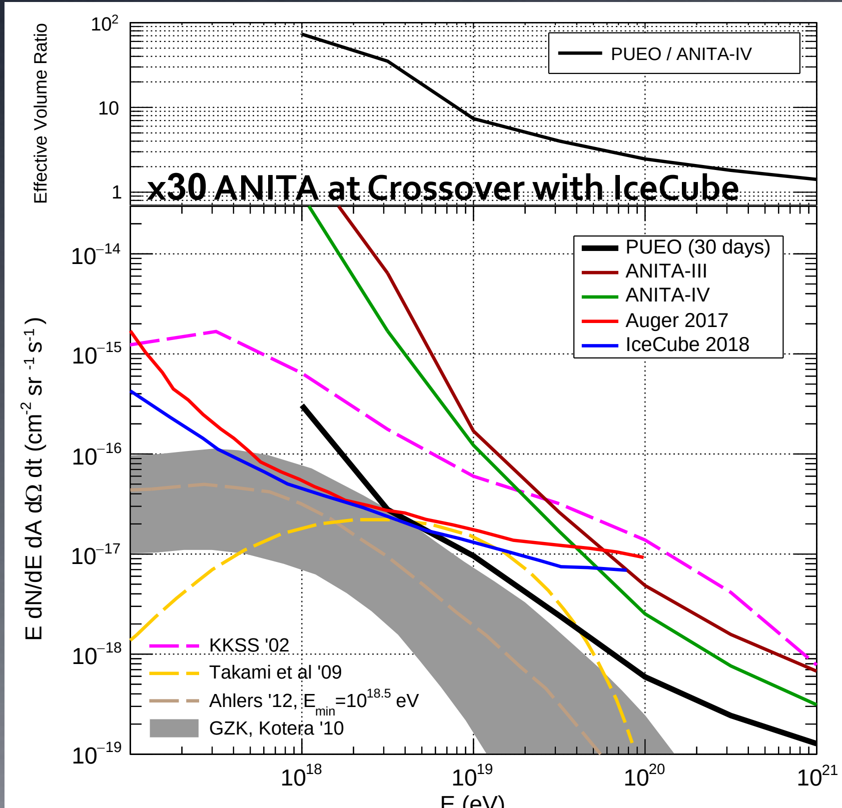
- Both events are too steeply upgoing to nicely fit the standard model for a diffuse flux of tau neutrinos.
- Maybe it is Transition Radiation (Motloch et al. 2017, de Vries & Prohira 2019) from cosmic ray air showers?
- Or (more mundane) maybe there is some non-physics background we have not yet accounted for?
- Maybe it is beyond-standard-model physics? (e.g. Fox et al. 2019)

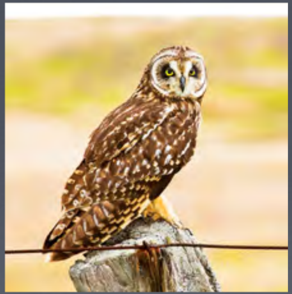


A. Romero-Wolf et al., 2018

PUEO: The Payload for Ultrahigh Energy Observations

PUEO Neutrino Sensitivity Projections





Follow up on ANITA observations with greatly improved sensitivity

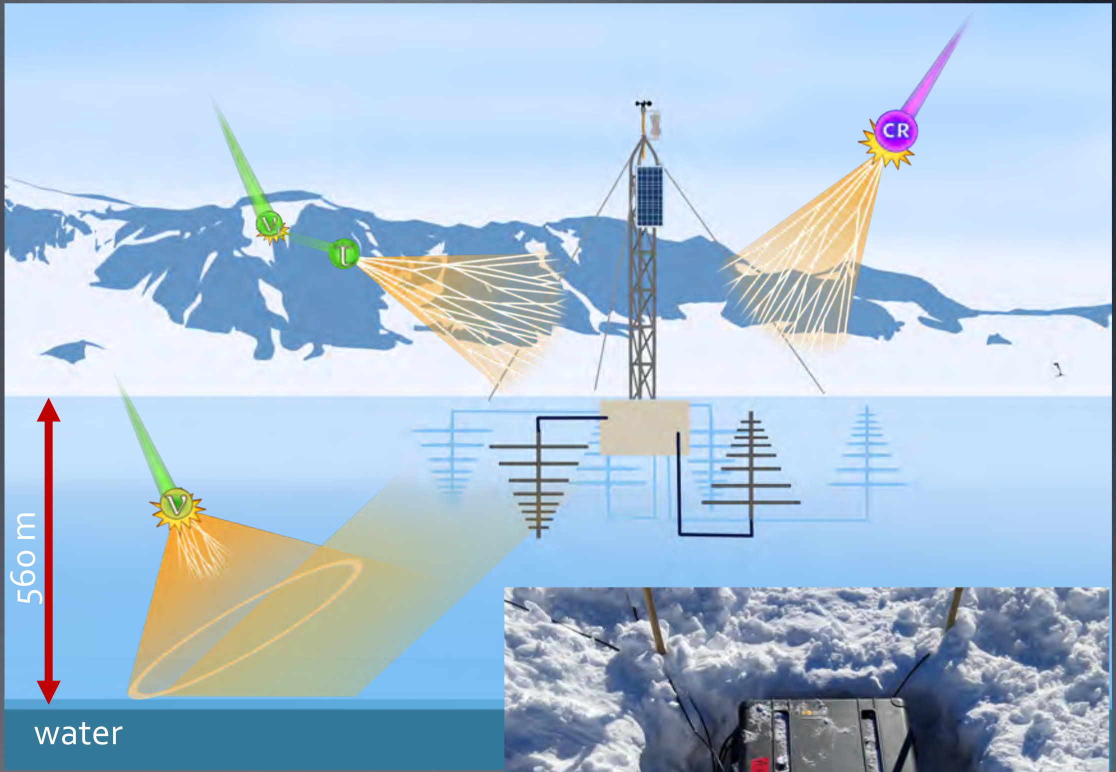
Especially large instantaneous effective volume, for transient, point source, and multi-messenger searches

PUEO's Improvements Over ANITA

- Order-of-magnitude improvement enabled by:
  - interferometric phased array trigger
  - real-time digital filtering
  - x2 more antenna collecting area above 300 MHz
  - Improved pointing resolution

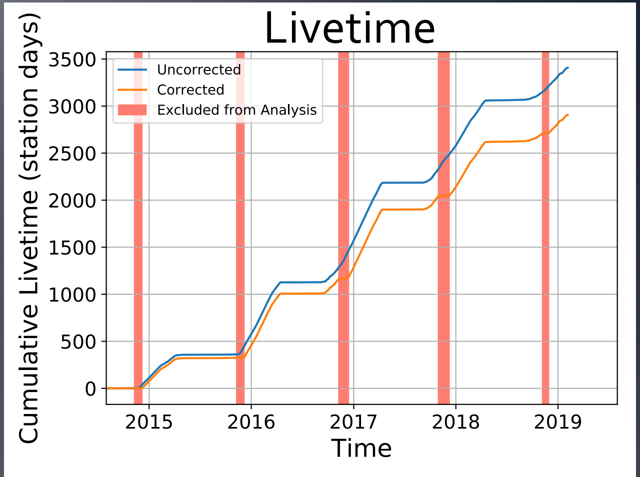
ARIANNA: Ross Ice Shelf, Antarctica

- Reliable, low power ~5W
- Autonomously powered: solar power + wind
  - current prototype survives harsh Antarctic conditions and powers station for ~40% of the time
- Iridium satellite + WiFi communication
- Can be used at any location (Moore's Bay, South Pole, Greenland, etc.)

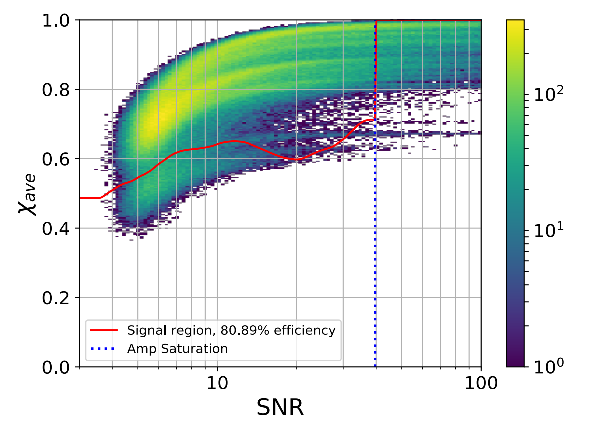


ARIANNA Neutrino Search: 8 Station-Years of Data

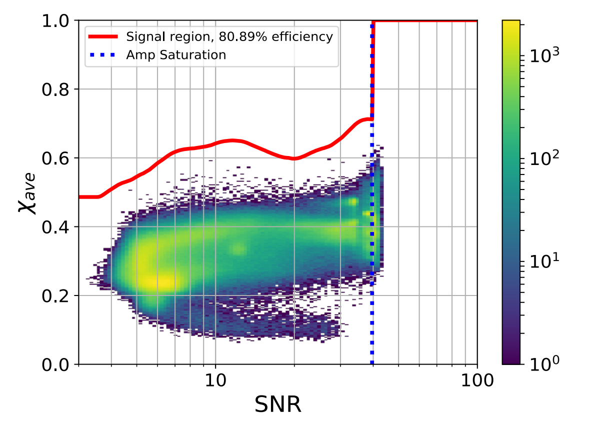
- Uses Askaryan template matching search

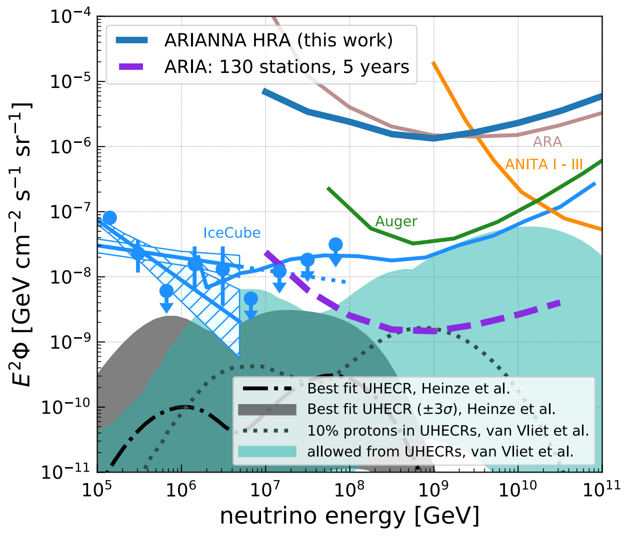


simulated neutrino signals



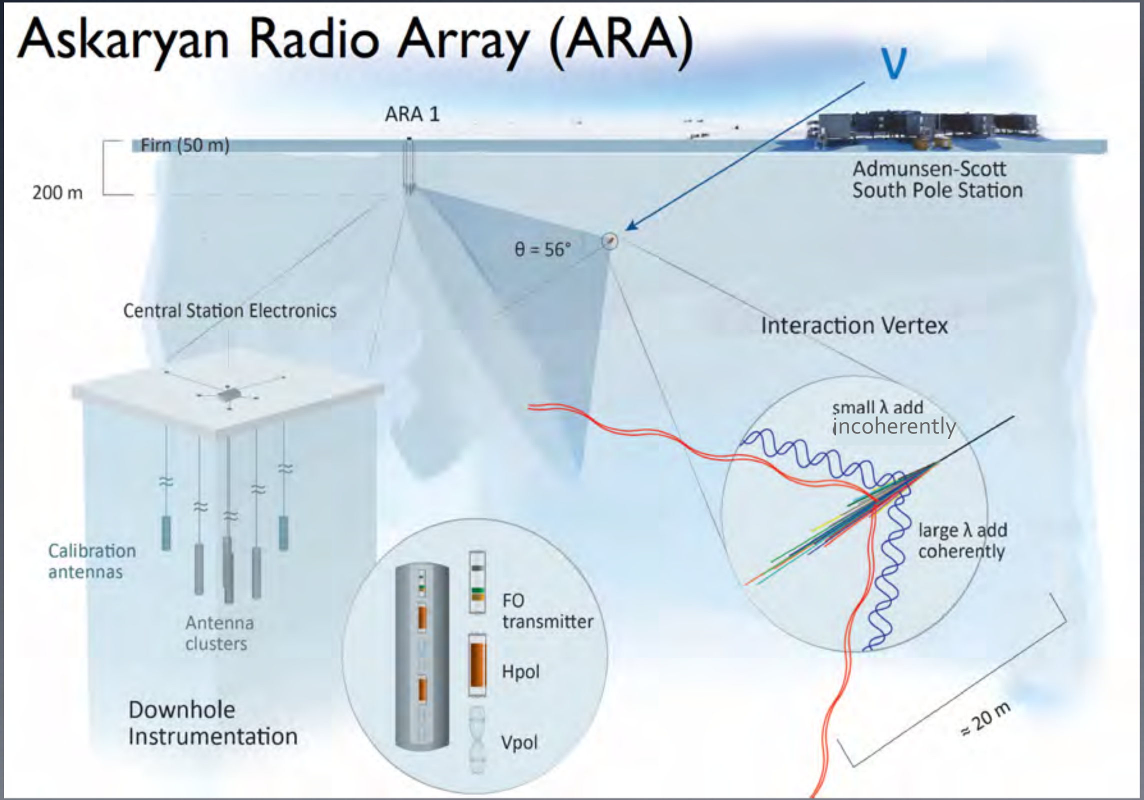
data

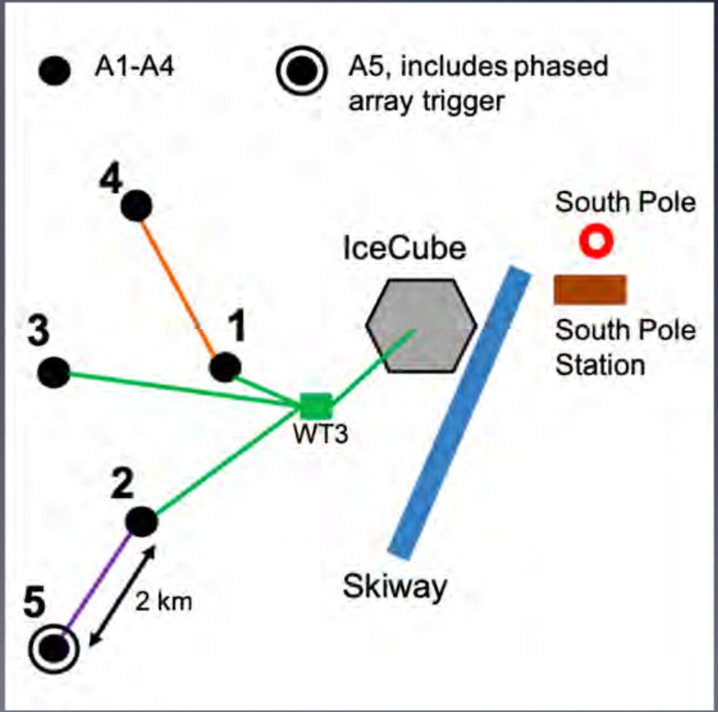




ICRC 2019, see C. Glasier Talk

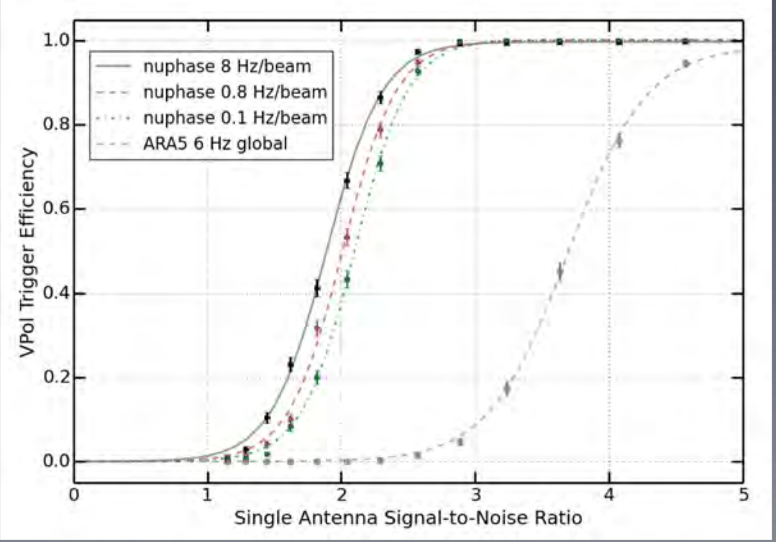
ARA: In-Ice Radio Detector at South Pole

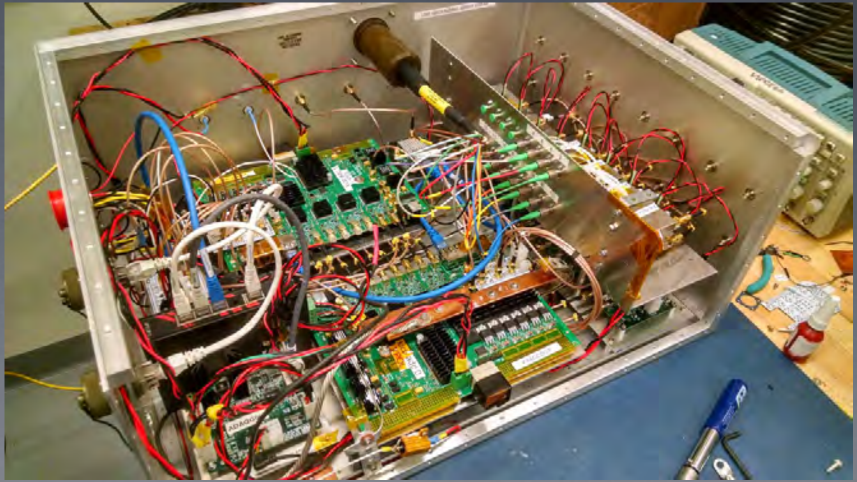




An Upgrade for ARA in 2017/2018

- Installed 2 new stations (bringing the total to 5)
- One with a real-time interferometric phased array trigger system
  - New DAQ – has been perfectly stable since deployment
  - Trigger performance matches simulations exactly
  - Improvement x2 effective volume achieved already

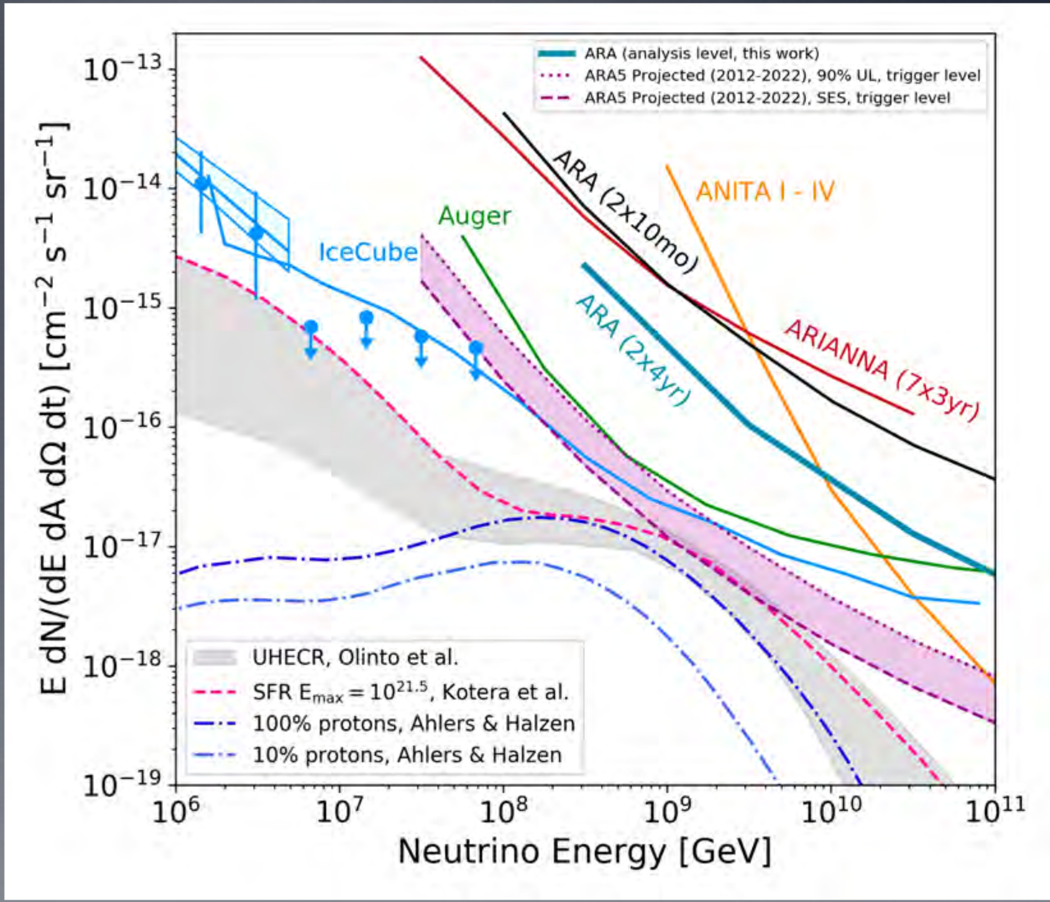




ARA Coll., NIM 2018, See E. Oberla Talk

ARA Sensitivity and Analysis Status

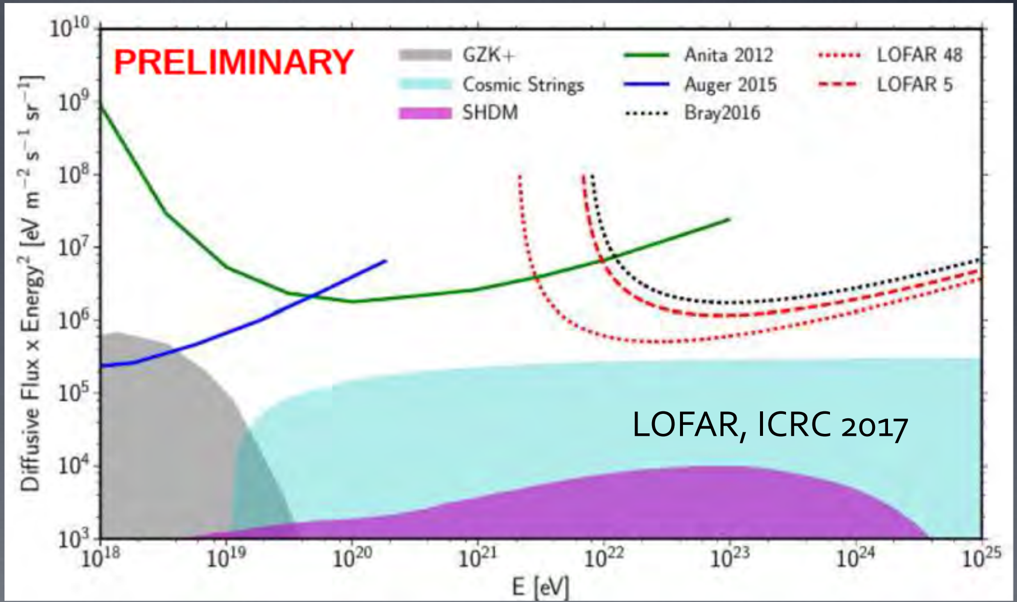
- 8 station-year analysis nearing unblinding
- 5 stations are now running, all with high livetimes over the last few years
- Projected sensitivity of data in the can by 2022 is shown in pink



See A. Connolly Talk

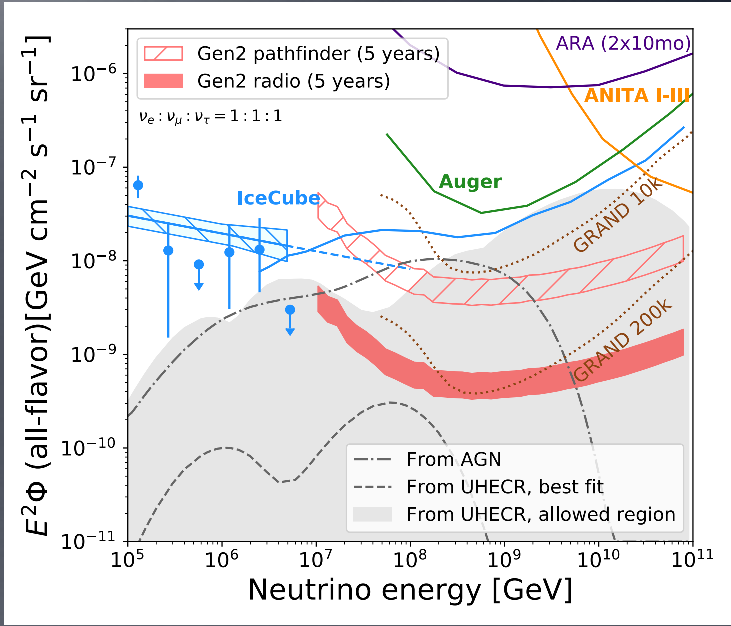
Lunar Detection (e.g. LOFAR)

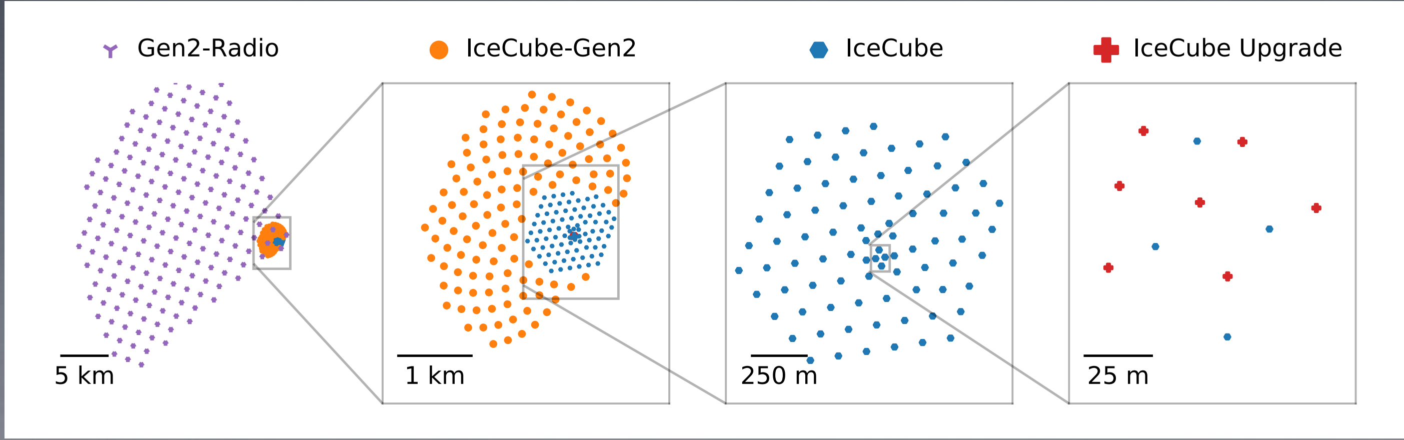
- Sensitive at highest energies, beyond GZK
- Multiple radio telescopes have done this search (GLUE, Parkes, etc.)



Toward IceCube Gen2

- IceCube Gen2: a multi-component facility to reach the broadest range of energies.



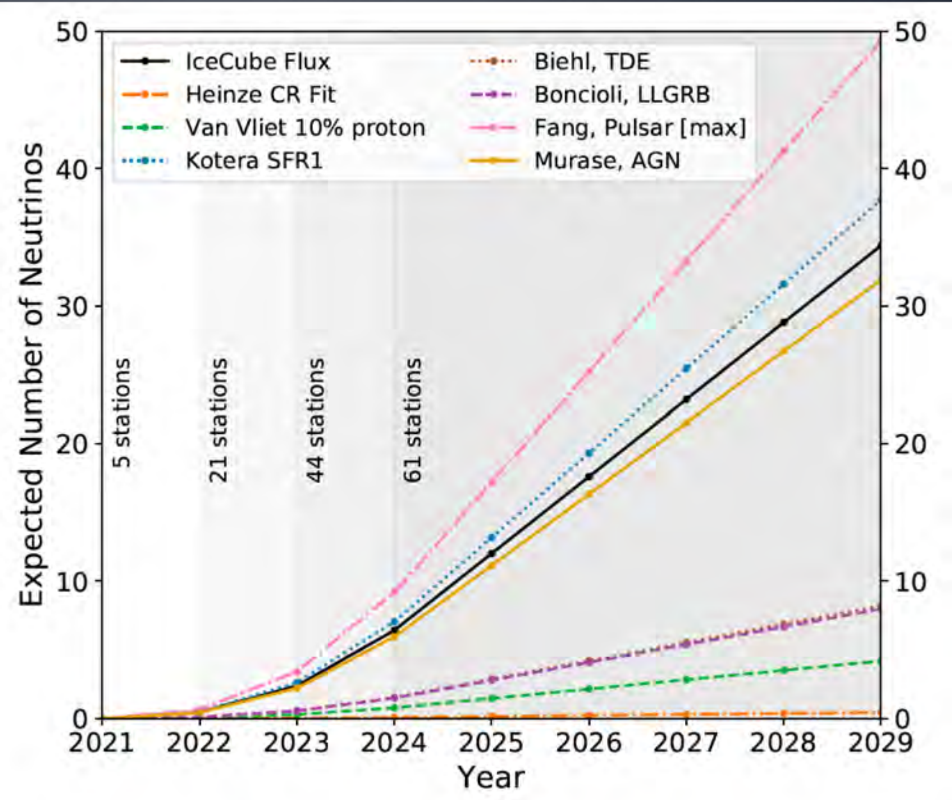


A. Nelles, from Astro2020 Whitepaper

The Path to a UHE Neutrino Observatory: What Is Needed Now?

- Demonstrated scaling of technology to the many 10's of stations level, with a path forward to 100's of stations for IceCube Gen2
- Continued analysis technique development to match improving trigger techniques
- Continued simulation development (a field-wide joint effort has been remarkably successful)
- With a detector of this scale, we'll also discover ultra-high energy neutrinos!

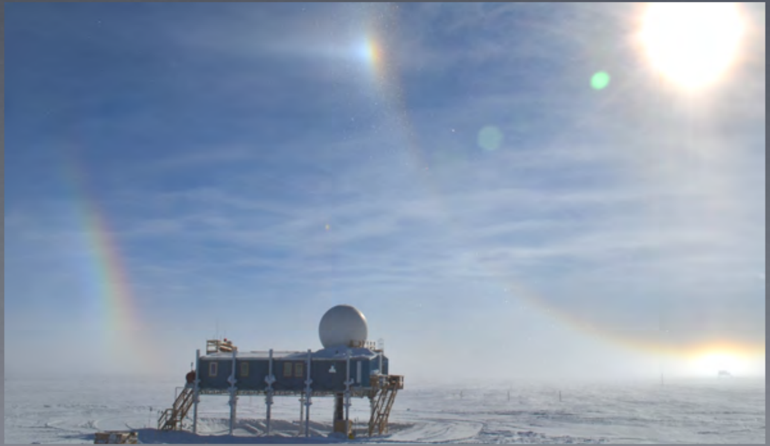
RNO Proposal: 61 Stations at South Pole

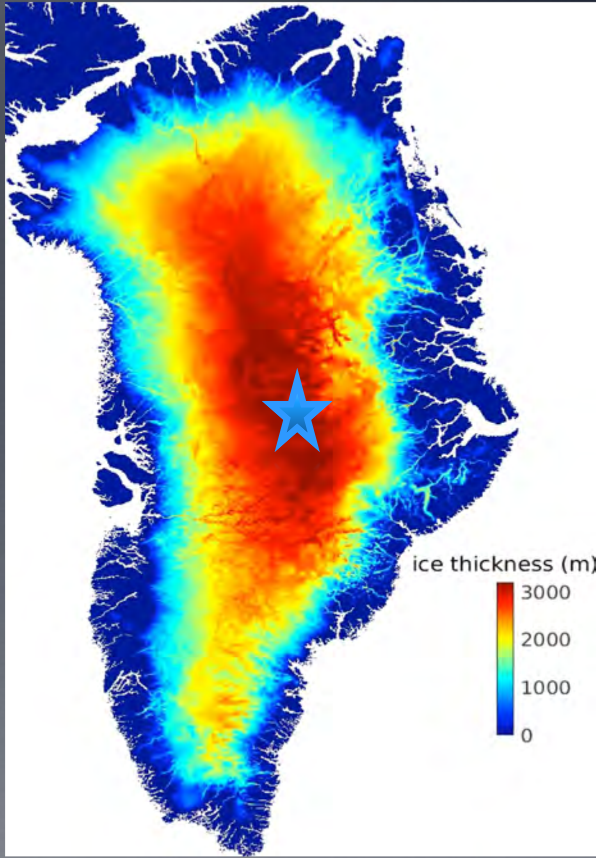


RNO Astro2020 Whitepaper

A Near-Term R&D Path Toward IceCube Gen2: Greenland

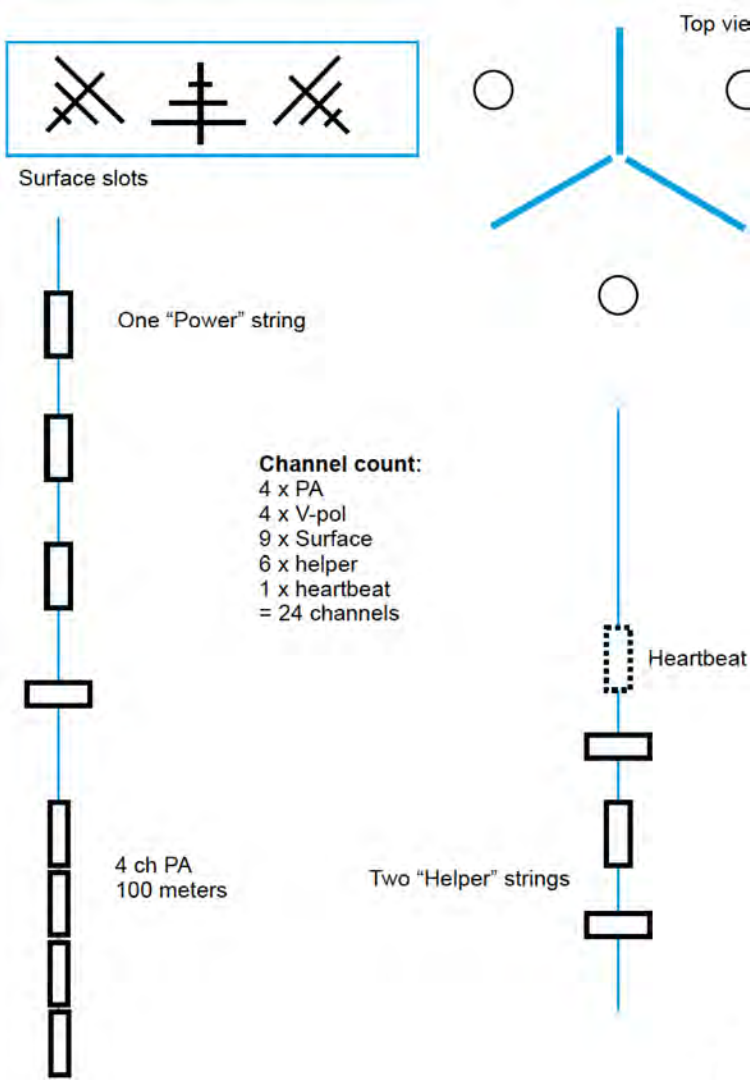
- NSF-Operated Year-round Summit Station
- 3km thick glacial ice
- Site is good for Solar/Wind generation
- 2013: Attenuation Length Measurement 2015: Prototype of phased array system 2020: First deployment of stations with scalable design



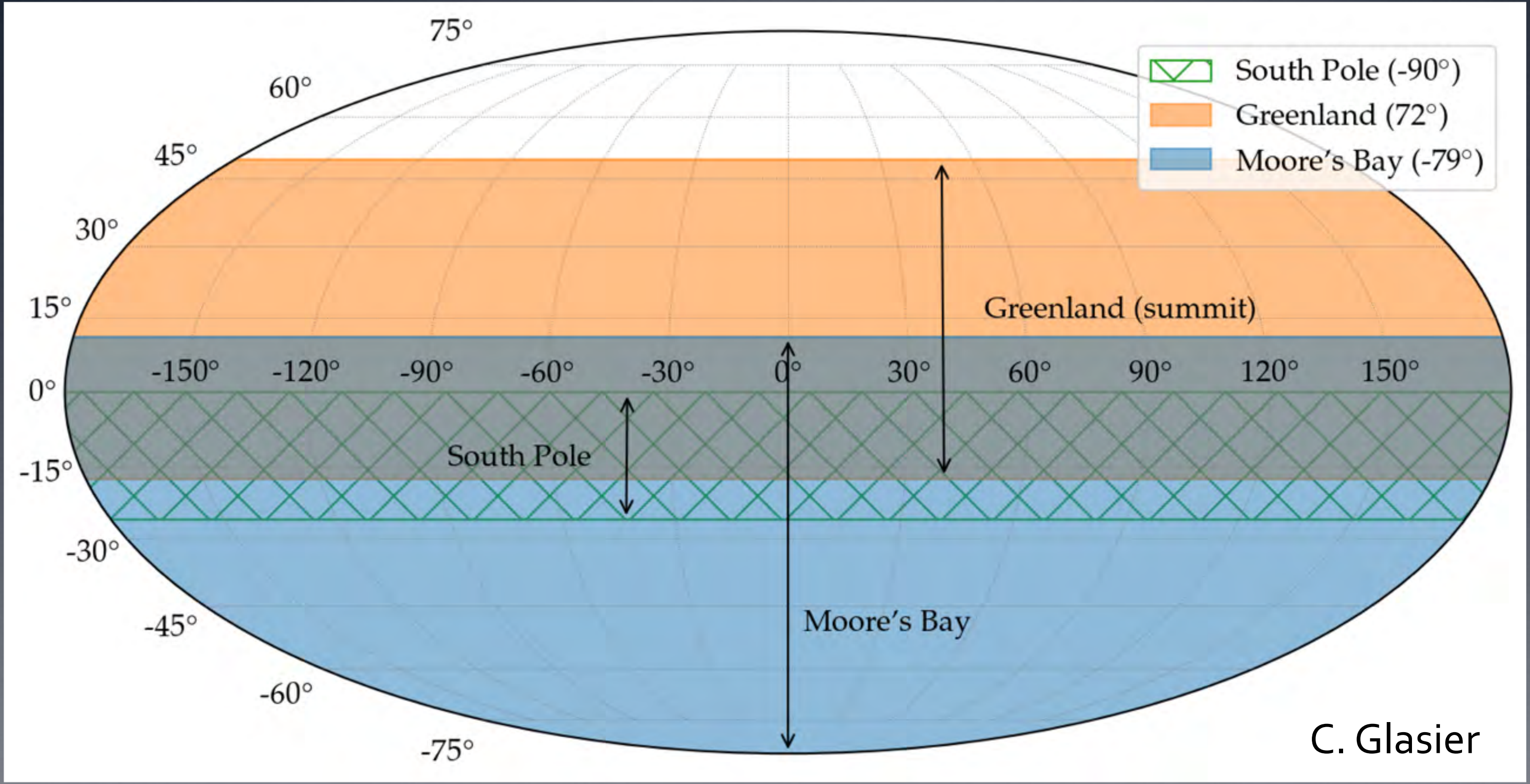


Station Design for Greenland

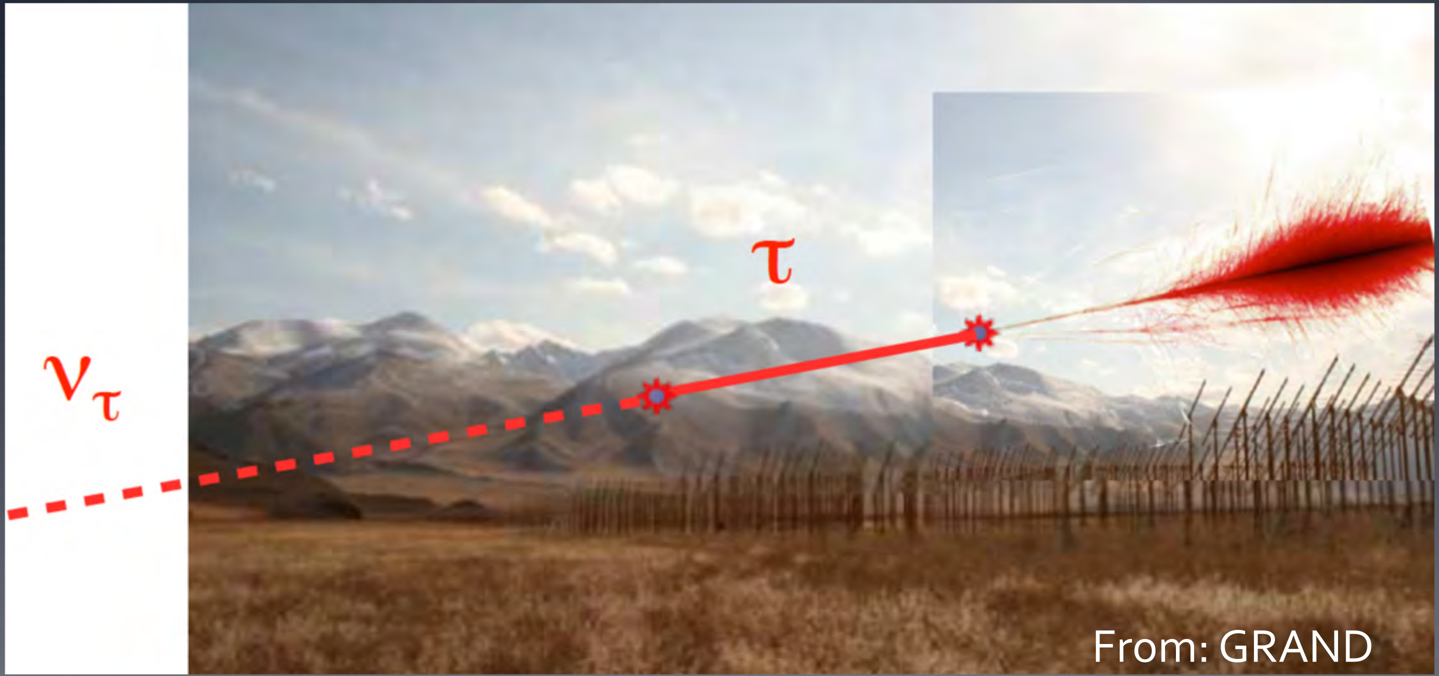
- A lightweight version of the proposed RNO design, which is suitable for the Summit Station site
- Deep detector with phased array trigger (100m deep) to maximize effective volume and sensitivity
- Surface detector with cosmic-ray detection and veto
- Antennas at multiple depths and on multiple strings to optimize reconstruction



Sky Coverage for Multi-Messenger Astronomy



Emission from Tau Neutrinos

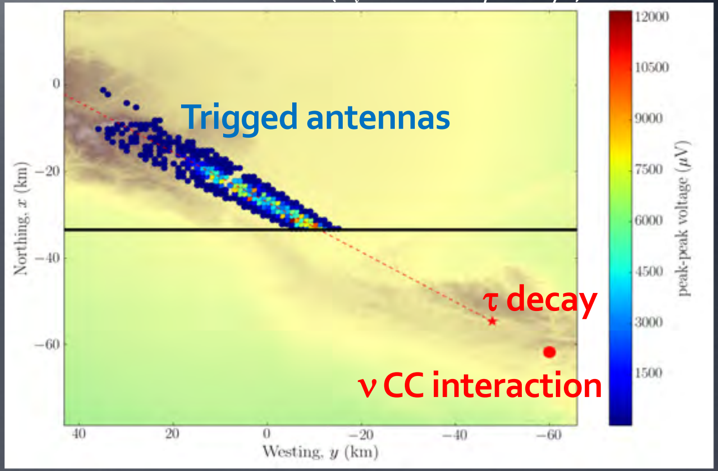


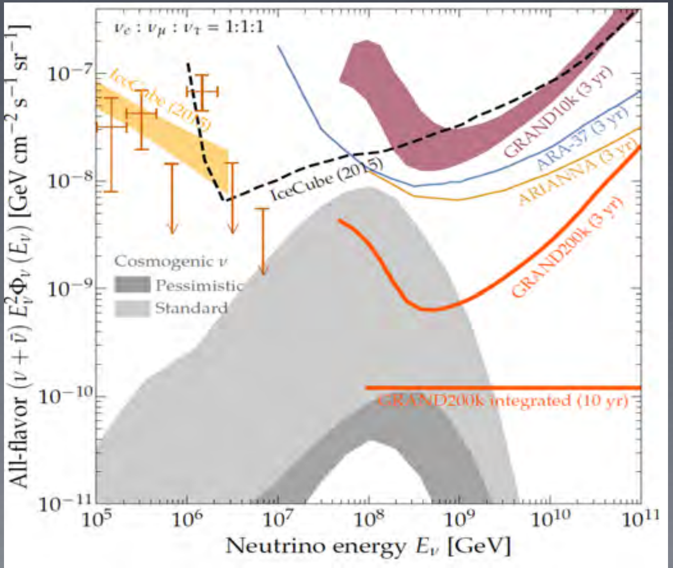
- Observe from the surface (Auger, GRAND, ARIANNA, etc.), a mountain (TAROGE, BEACON, etc.), balloon (ANITA), space (POEMMA)

GRAND

- Giant network of 20x10'000 radio antennas to be deployed at different locations in the world in 203x.
- Simulations indicate sensitivity to neutrinos, FoV (~full sky) & angular resolution (~0.2°) sufficient to do **UHE neutrino astronomy**.
- Details of design to be informed by GRANDProto300 (+ other experiments)
- See O. Martineau Talk

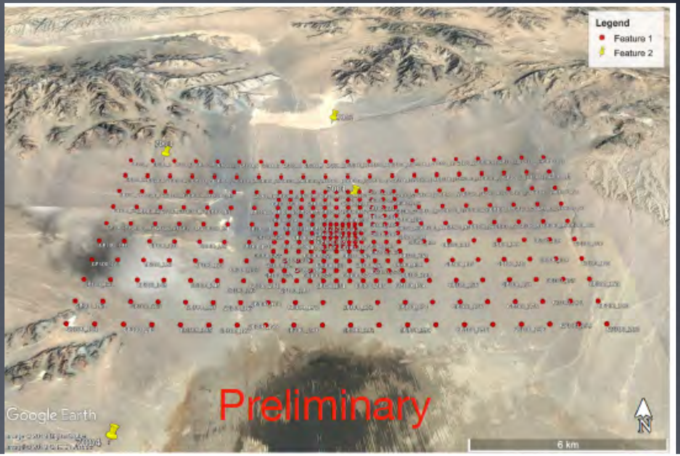
Simulated event (E_ν = 2 10^{19}eV; θ = 87°)

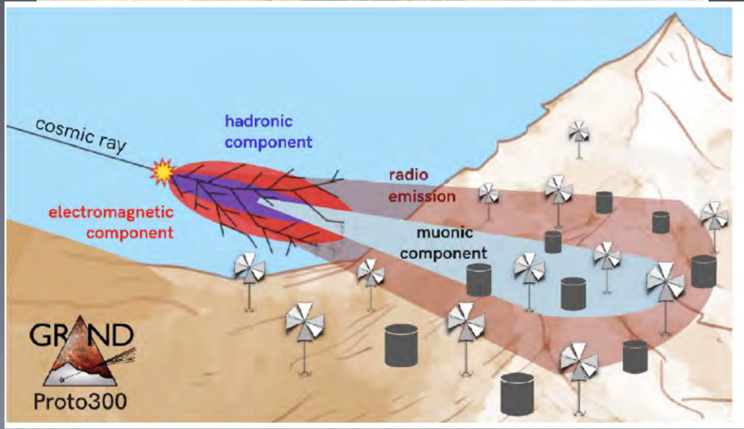




GRANDProto300

- 300 self-triggered antennas to be deployed in LengHu, QingHai, China in 2020-2021.
- Designed for very inclined showers (>70°) and ~100% data collection.
- Demonstrate GRAND detection principle thru reconstruction of CR properties in 30PeV-1EeV.
- Testbench for further stages of GRAND
- See V. Decoene talk



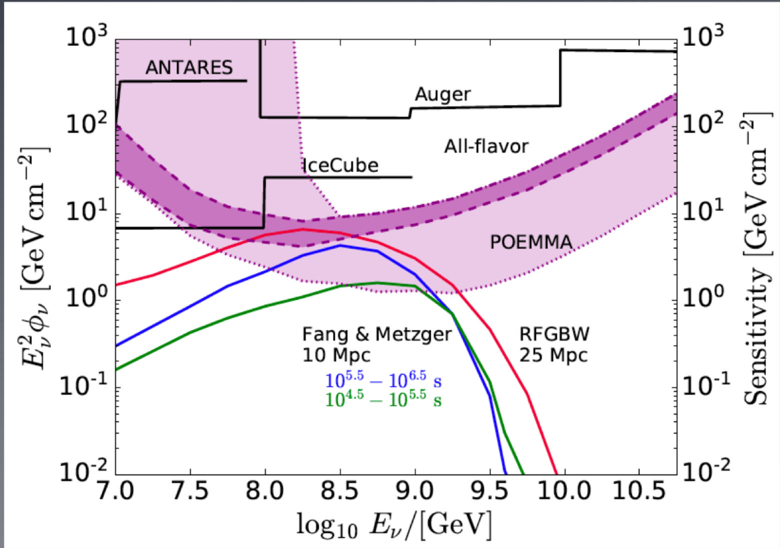


POEMMA

Detecting optical Cherenkov signal from upward-going tau neutrinos

- A satellite mission to detect UHECRs and UHE Neutrinos

Transient Source Sensitivity



arXiv:1906.07209 See A. Olinto Talk, M. Reno Talk

Summary

- Observation of UHE neutrinos would open a new window onto the universe
- The Askaryan radio technique can probe a new energy regime – from the highest energies down to (hopefully) PeV energies, and a mid-scale detector is needed now.
- The tau neutrino EAS channel is promising, and is accessible from a balloon, mountain, or surface configuration