Radio Detection of Ultra High Energy Neutrinos with Askaryan Radio Array at South Pole

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IC: Martin Wolf, IceCube/NSF

Goal of High Energy Neutrino Astrophysics

- **What is the nature and cosmic distribution of the astrophysical accelerators that produces highest energy particles in the Universe?**

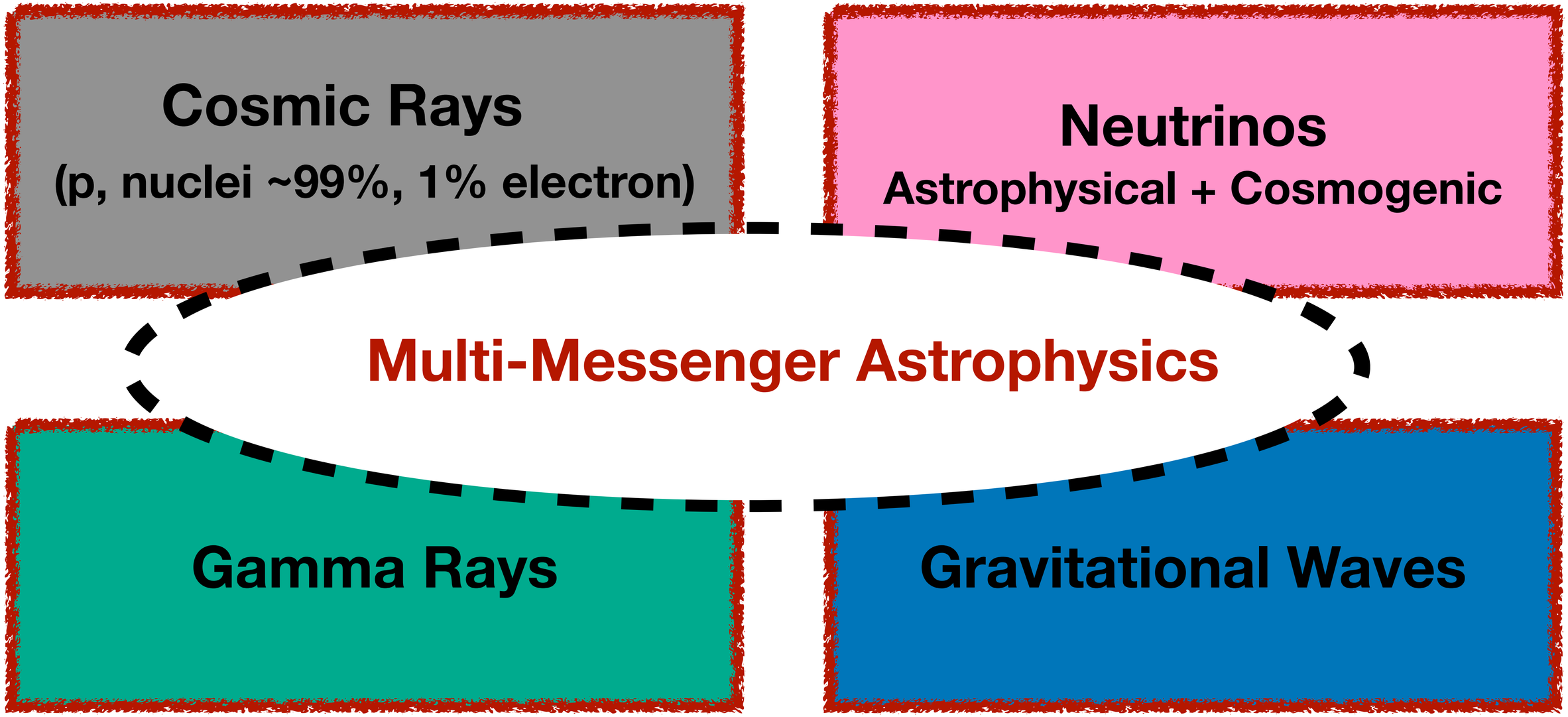
- **What are the fundamental particles & interactions of nature ?**


GRB, Credit NASA, ESA


AGN, Credit NASA

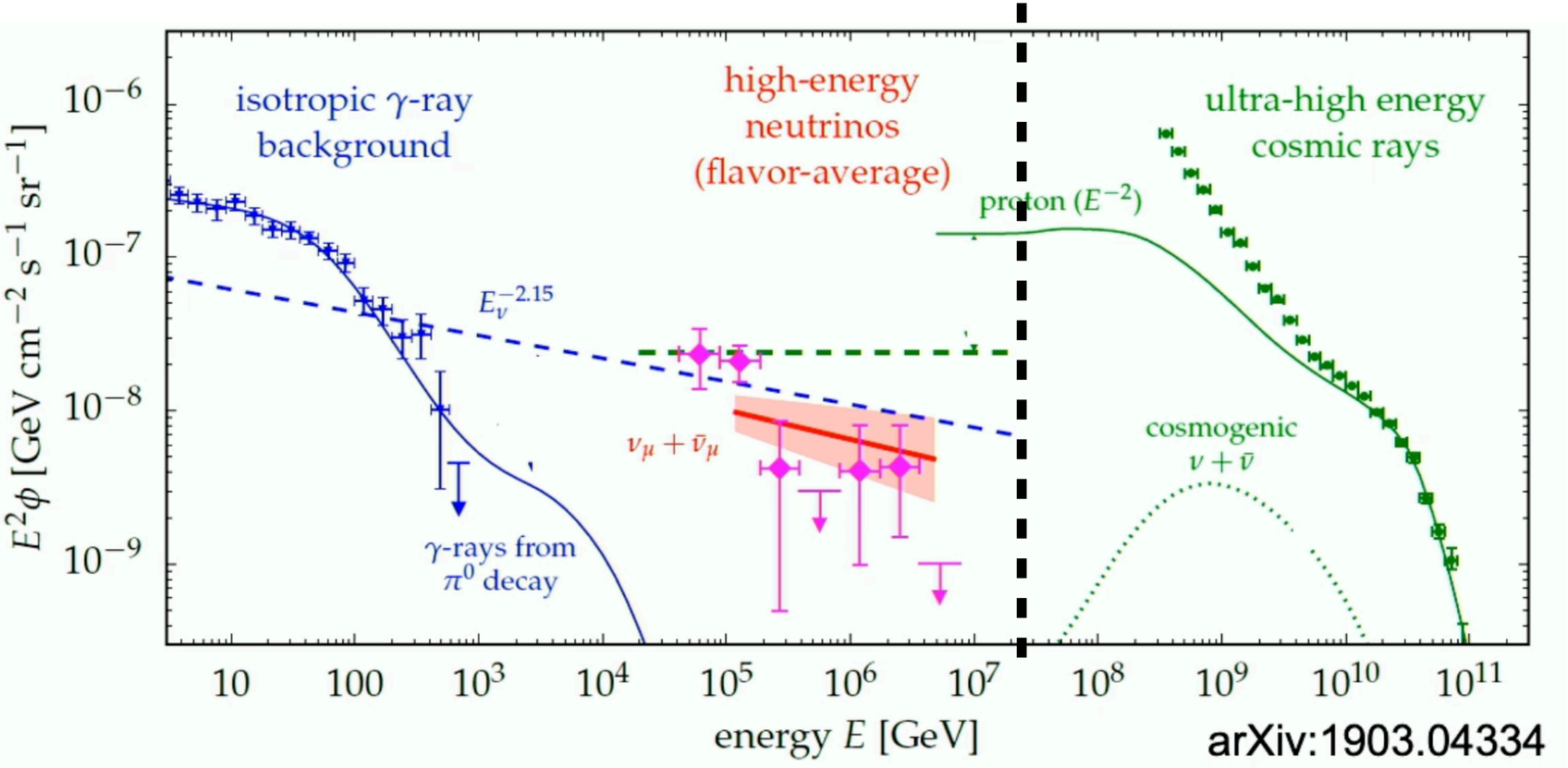

Neutron star Collision
Credit NASA

Exciting Era of Multi-Messenger Astrophysics



The Ultra High Energy Universe

By "UHE", I mean "$E\nu$ > 30 PeV"



Why Study Neutrinos ?

1. Cosmic rays

- **Bent by magnetic field**

2. **Gamma rays: absorbed by CMB, EBL, dust**

3. GW : Hard to point back to the source

4. Neutrinos open unique window to the high energy Universe.

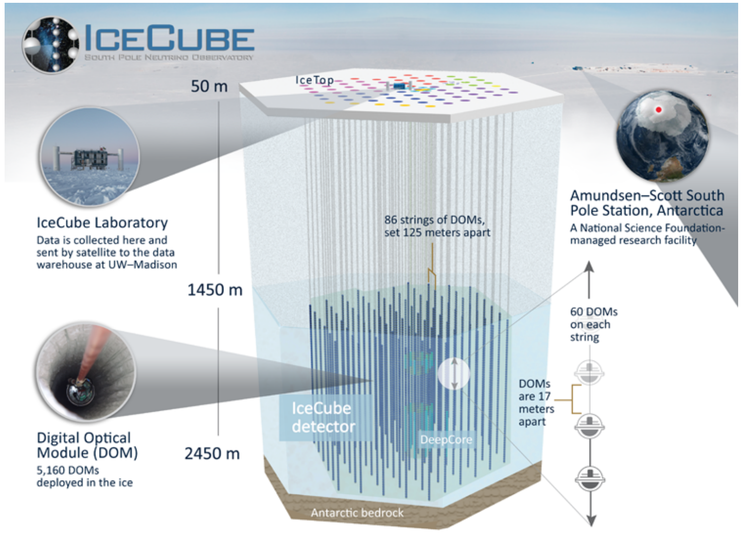
- ☑ **Highest energy observations of extragalactic sources**
- ☑ **Very distant sources**
- ☑ **Probe into opaque sources**
- ☑ **Carry information about the accelaration mechanism**

Astrophysical Neutrinos

Neutrinos born in (or near) the cosmic ray accelerators

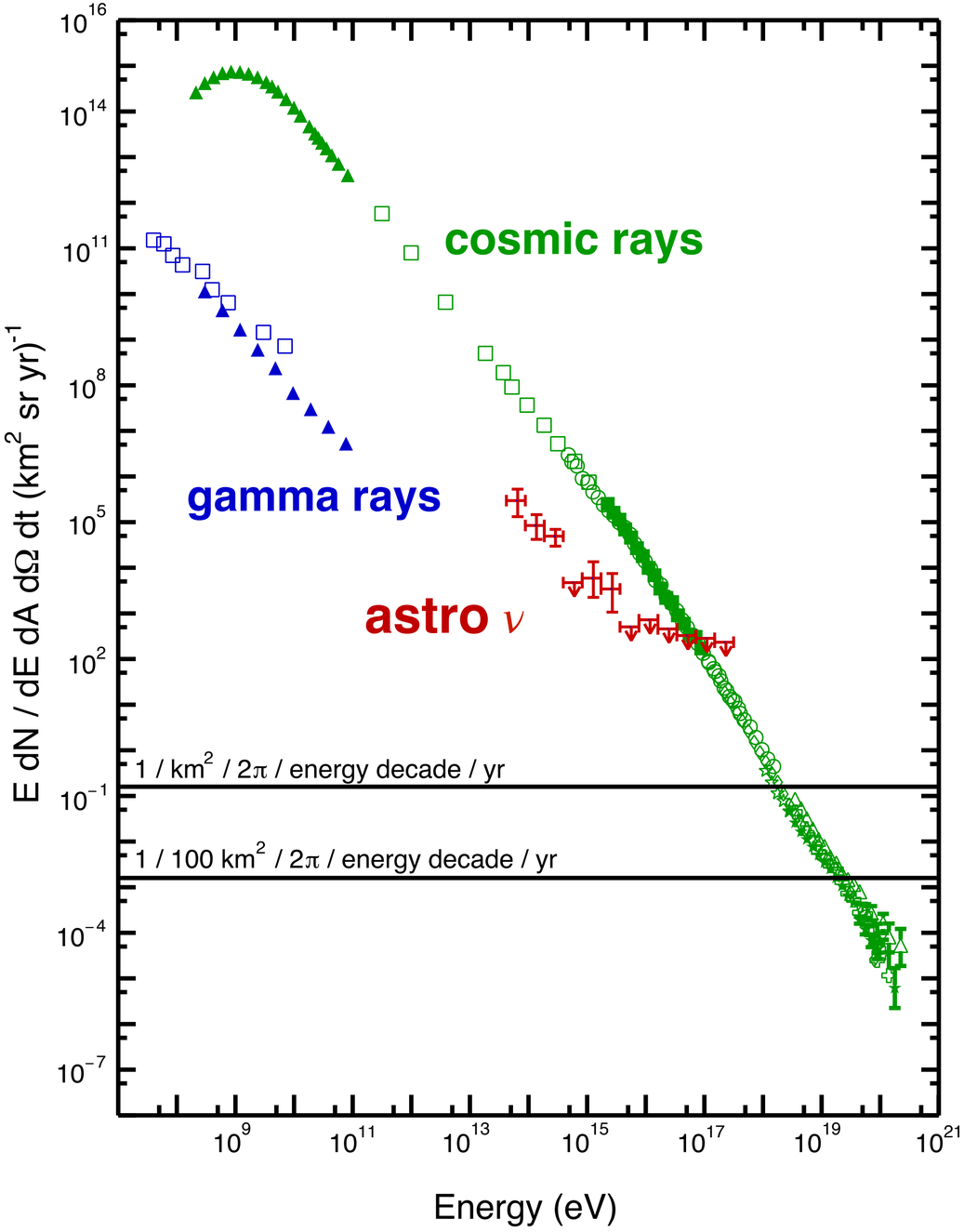
Unambiguous proof of hadronic acceleration

Neutrinos have been Detected in 2012 !
(Only hints of sources)



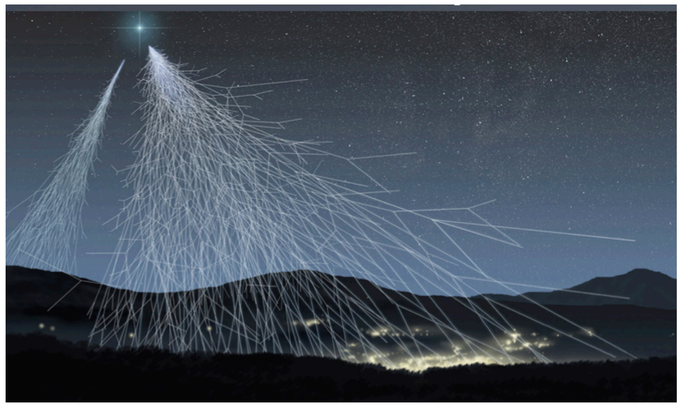
AGN, NGC 1068

first evidence of a neutrino source
4.2σ Significance



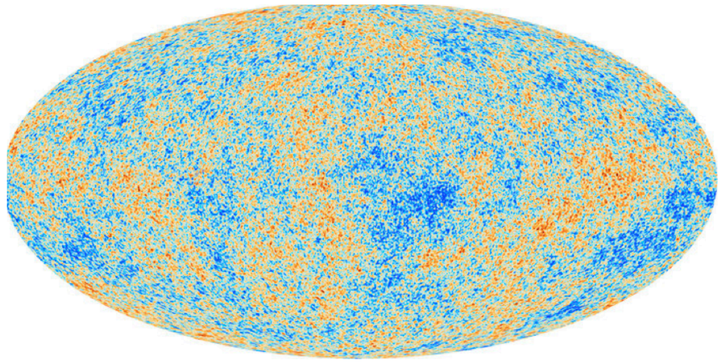
UHE Neutrino production: The GZK process

Cosmic Ray ($E_p > 10^{19.5}$ eV)



+

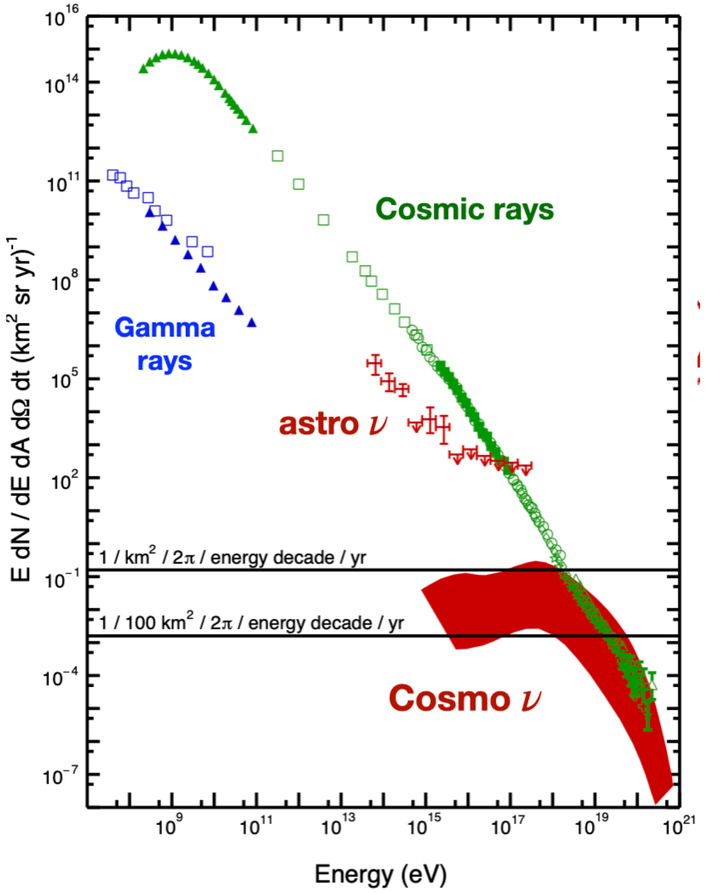
CMB photons



=

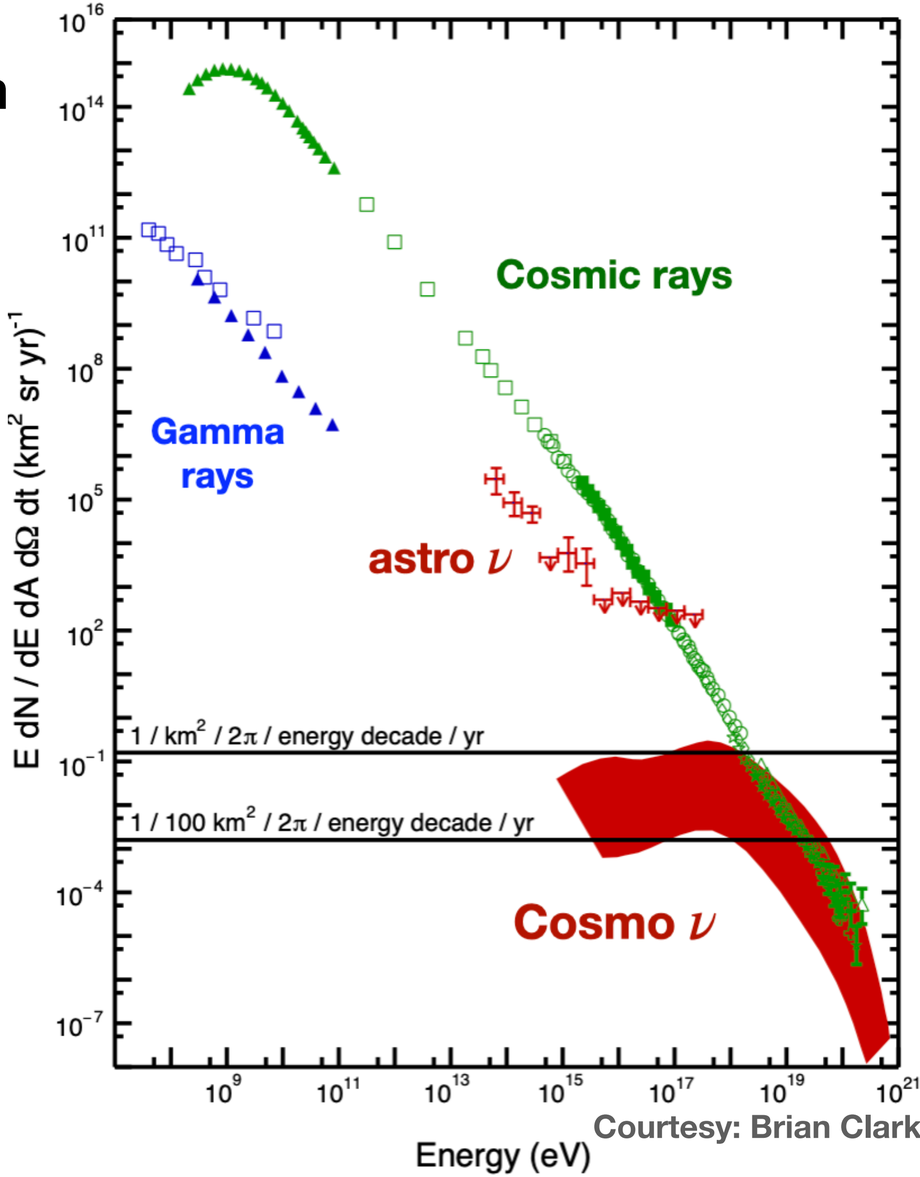
Neutrino beam !

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



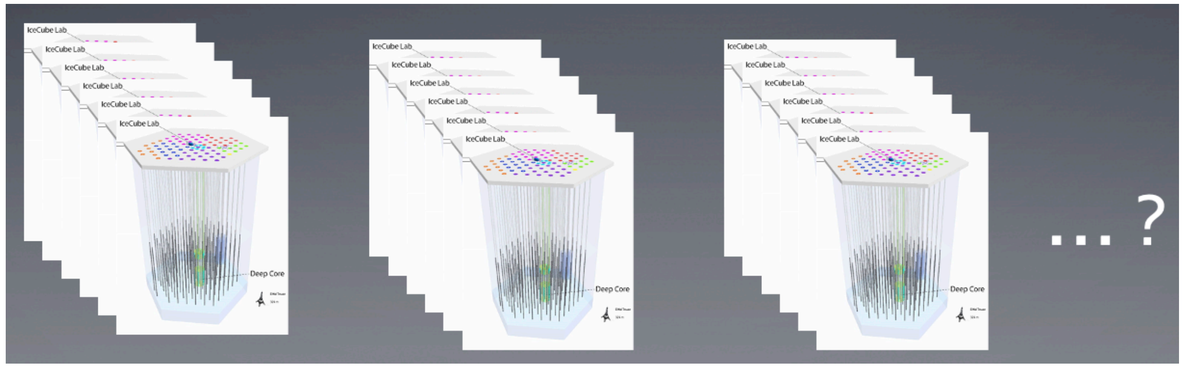
The Problem with Neutrino Astronomy

- **Neutrinos are weakly interacting, very hard to detect them**
- **0.003 GZK neutrinos/km^3/year**
- **To get 1 GZK neutrinos we need > 1000 km^3 of clean, dense dielectric medium**



Solutions?

1) Wait for many decades to detect 1 GZK Neutrino
2) Make many more IceCube

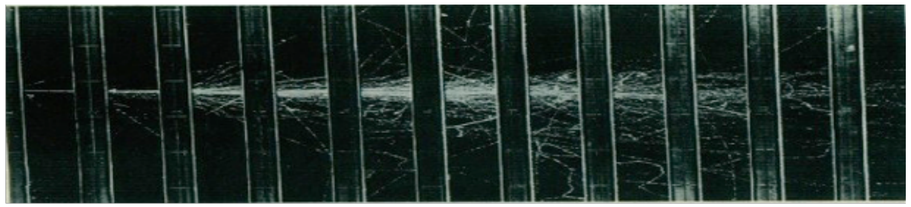


3) Try Something else (That's the fun part)

Instead of Optical, try Radio !!

EM shower in dielectric (ice, sand) ⟶ **moving negative charge excess**

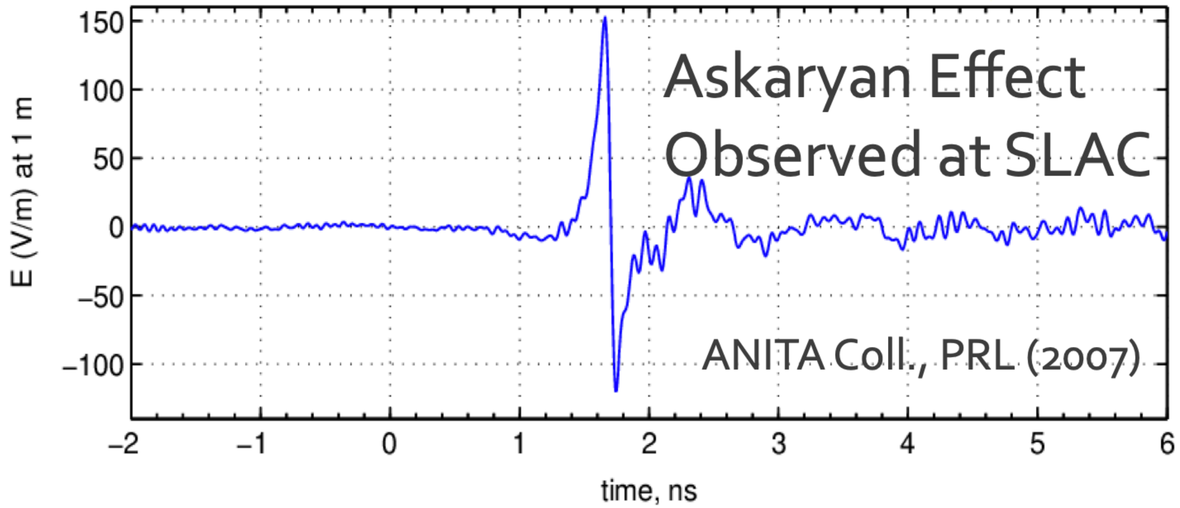
e^+, e^-, γ ⟶



Typical Dimensions
L ~ 10 m
$R_{Moliere}$ ~ 10 cm

Radio Emission is stronger than optical for UHE showers
Coherent radio Cherenkov radiation ($P \sim E^2$)
if $\lambda >$ Moliere radius

$E > 10^{18}$ eV
E^2 >>>>>>>> E



The Need

Extremely large volume

(1 to 10^3 km^3) of radio transparent medium

Ice is an excellent radio transparent medium

Ice is Dense !

Good target material for weakly-interacting particles

Ice is clean and cold!

Very transparent to electromagnetic radiation in the MHz - GHz band!

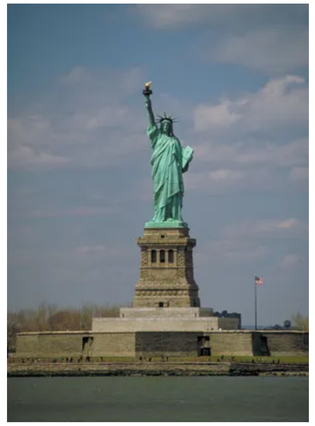
Long attenuation length of Radio signals in ice (~ 1 km) vs. ~ 100 meter for optical signal, used by IceCube

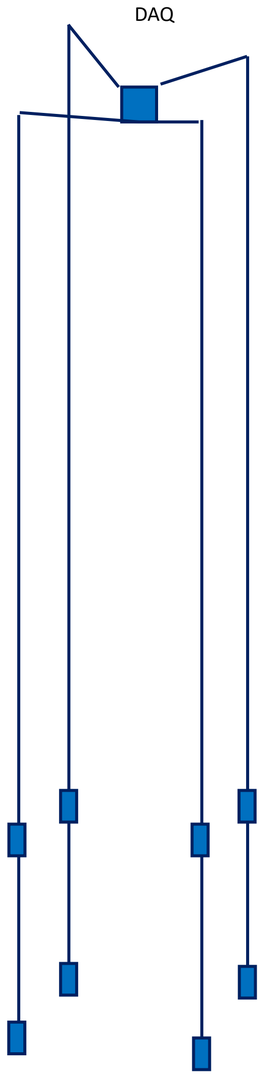
Antarctica

Enormous Volume to detect neutrinos

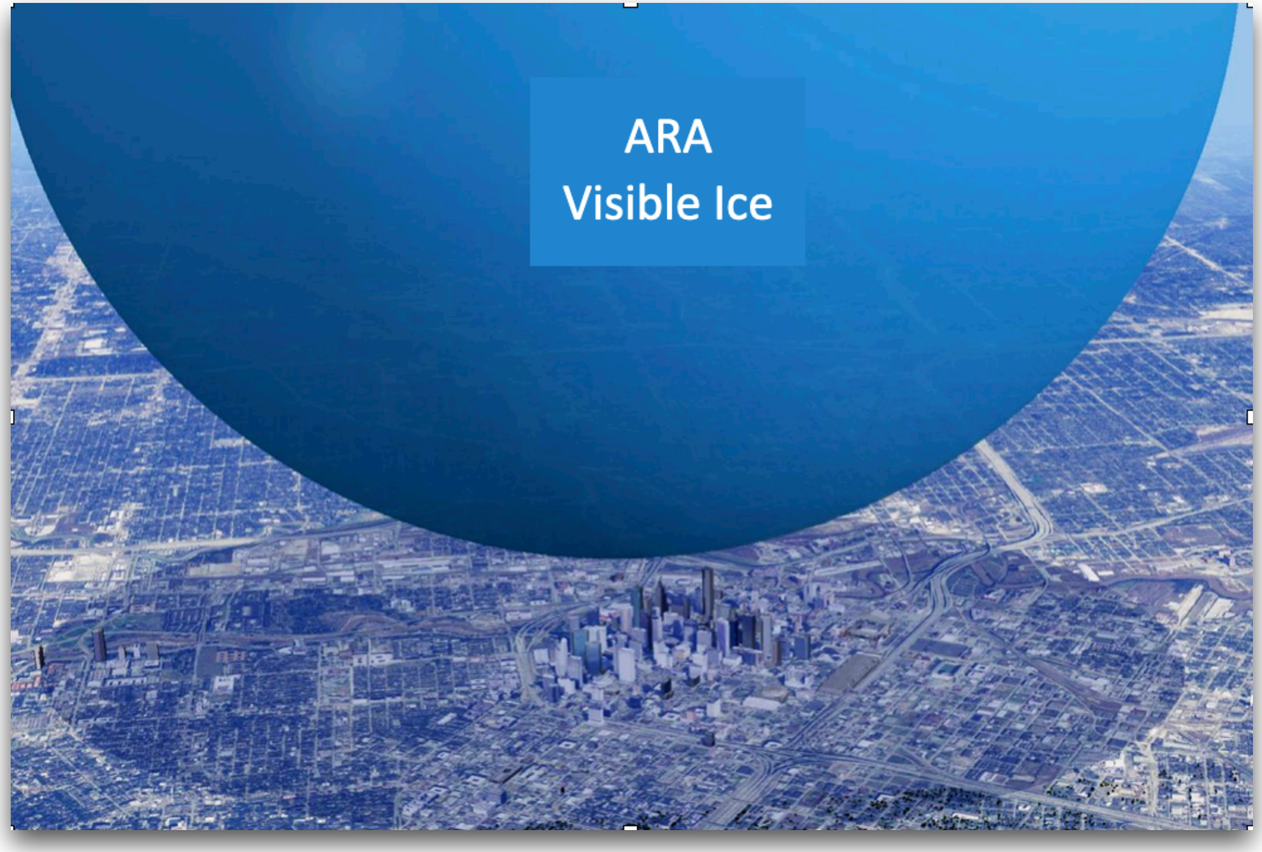
Depth of ARA antennas ~ 2.2 times the height of the Statue of Liberty

93 meter





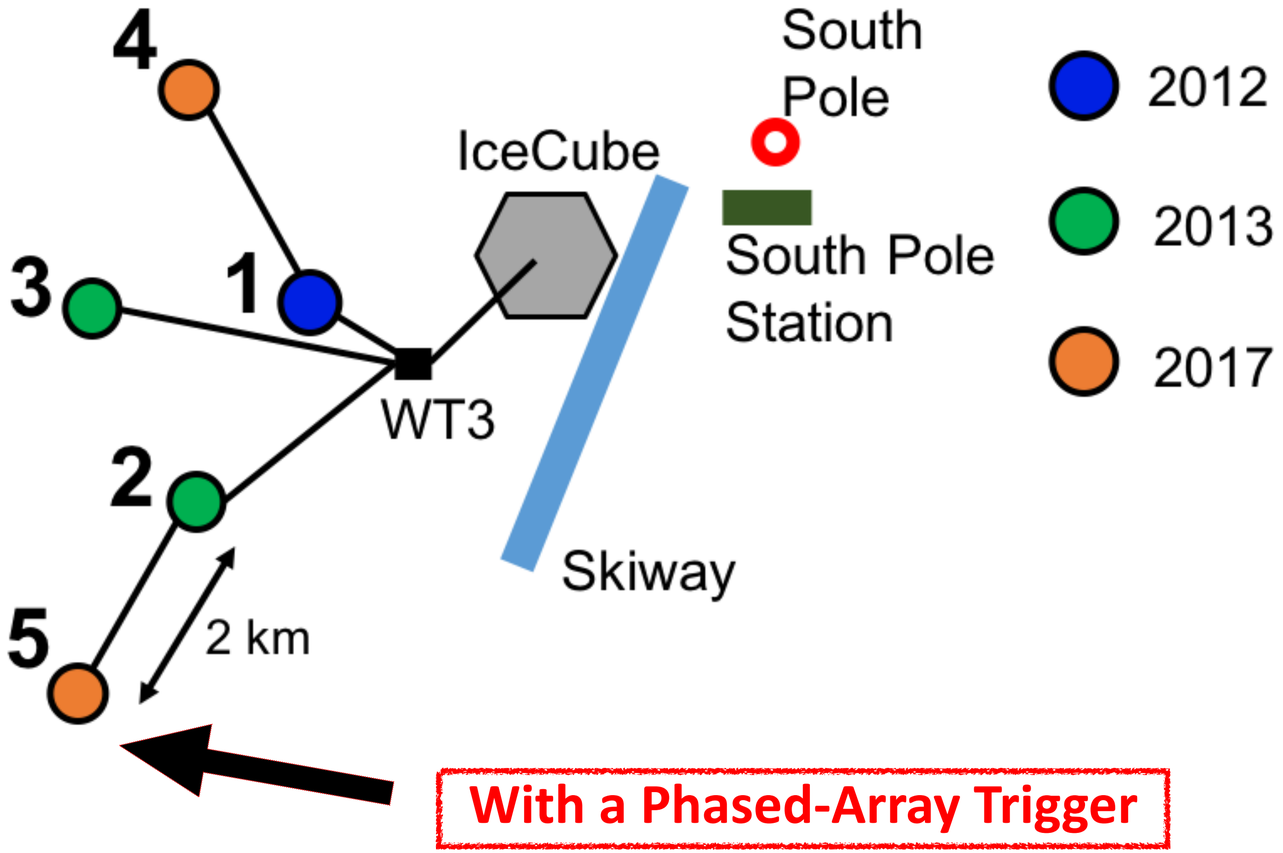
200 meter



1 ARA station ~ 20 km^3 ice

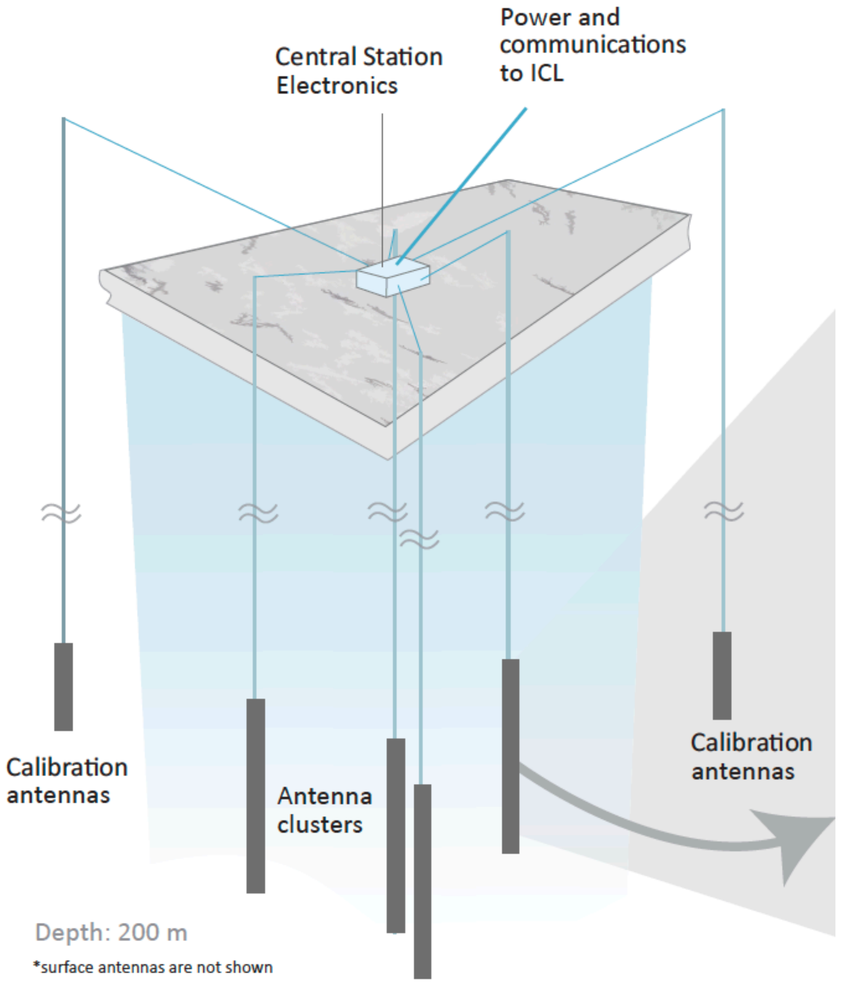
The Askaryan Radio Array (ARA)

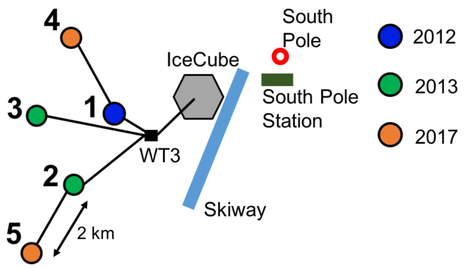
Five independent stations have been collecting data for ~ a decade



ARA's 5th station is special

A1 - A4

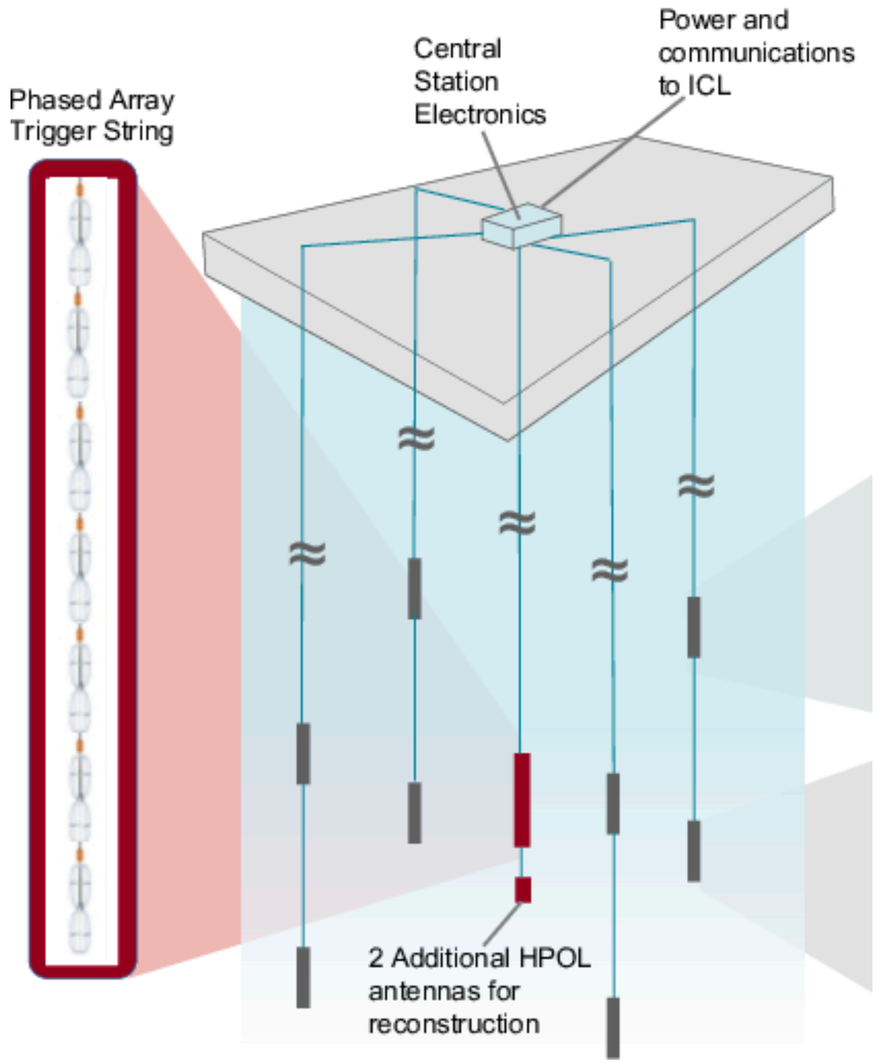




HPol

VPol

A5 + PA system



ARA Station Deployment

Courtesy: Brian Clark

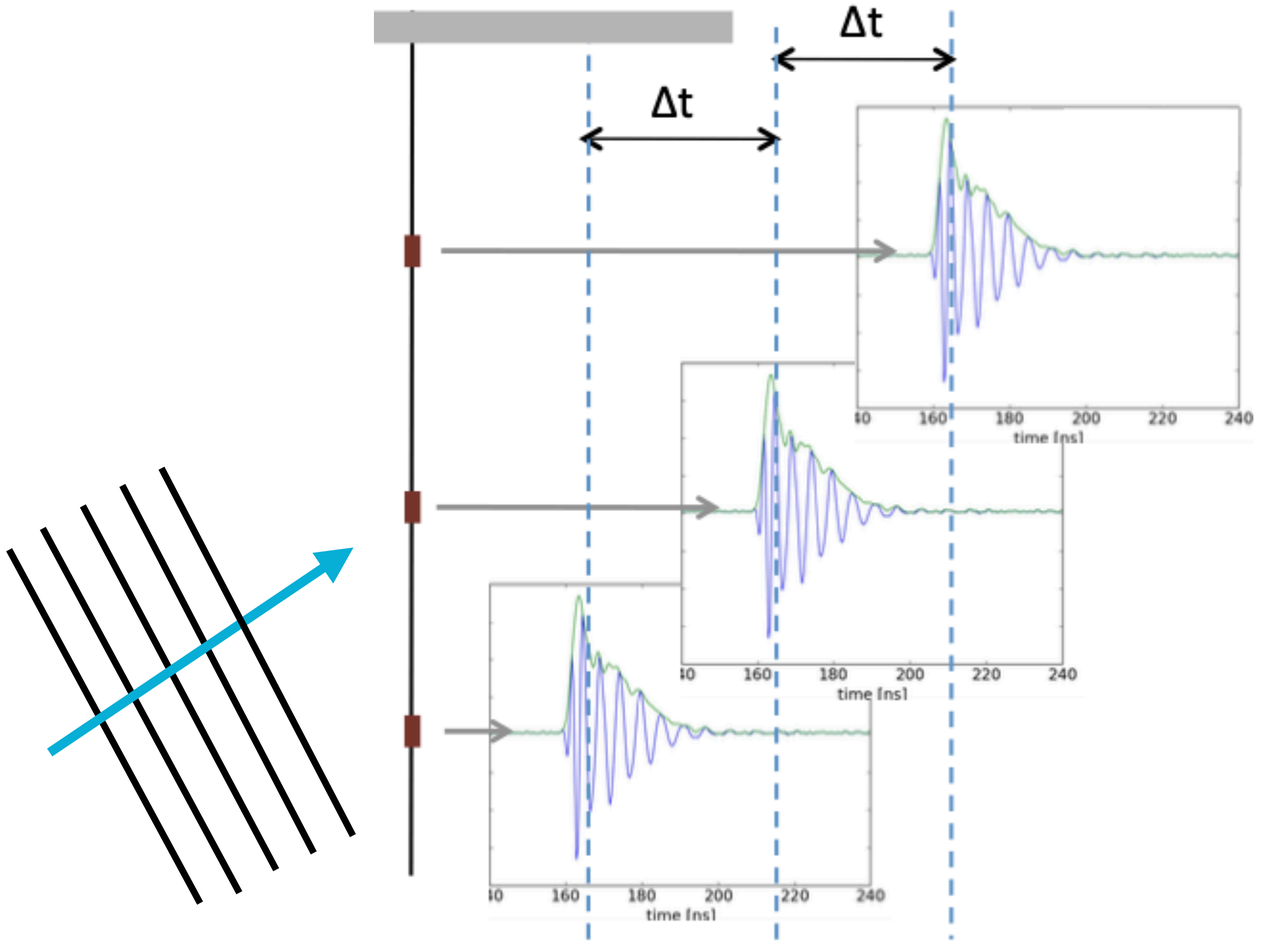
A Phased Array Trigger Design

- **Phased Array demonstrated capabilities of triggering on low SNR signals which are otherwise buried in noise**

- **Phased Array improves signal strength by combining multiple signals together before the signals are fed into the trigger system**

- **Adds signals together in predetermined directions (“beams”) through delay-and-sum method.**

- **Plane wave signals add coherently, noise likely does not. This effectively lowers trigger threshold**



Impulsive plane wave (eg., neutrino signal)

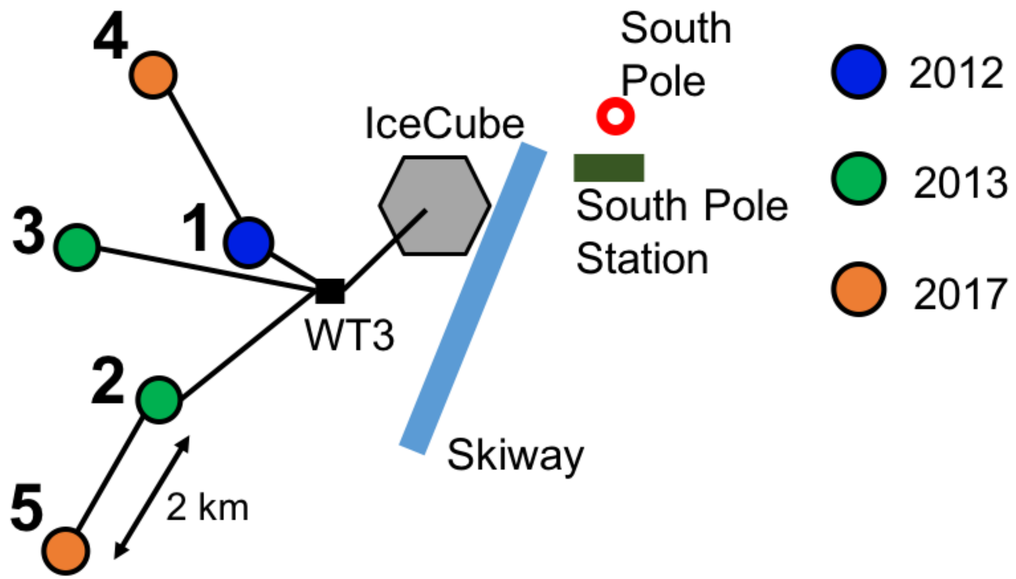
Pic Courtesy: Kaeli Hughes

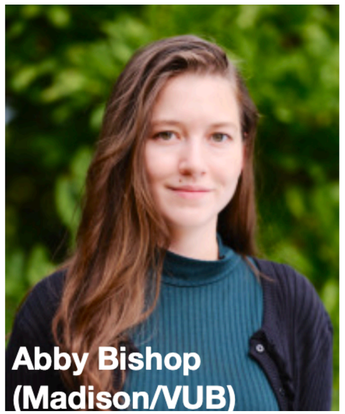
ARA’s Ongoing UHE Neutrino Searches

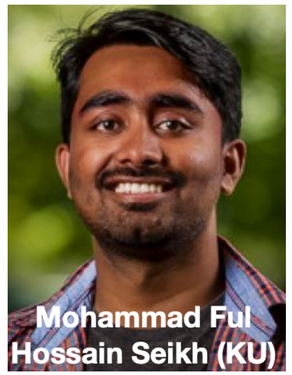
Towards a Five Station Analysis

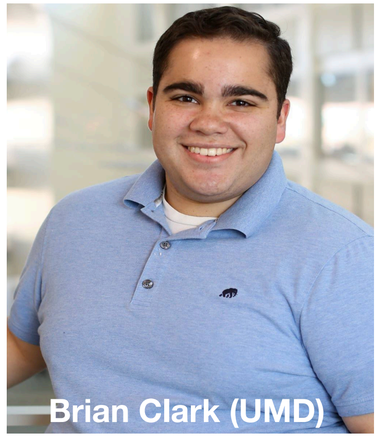
- **Goal: Conduct diffuse neutrino search in livetime through 2023 leveraging the entire Askaryan Radio Array**

- **Roughly 379 TB of data on disk**









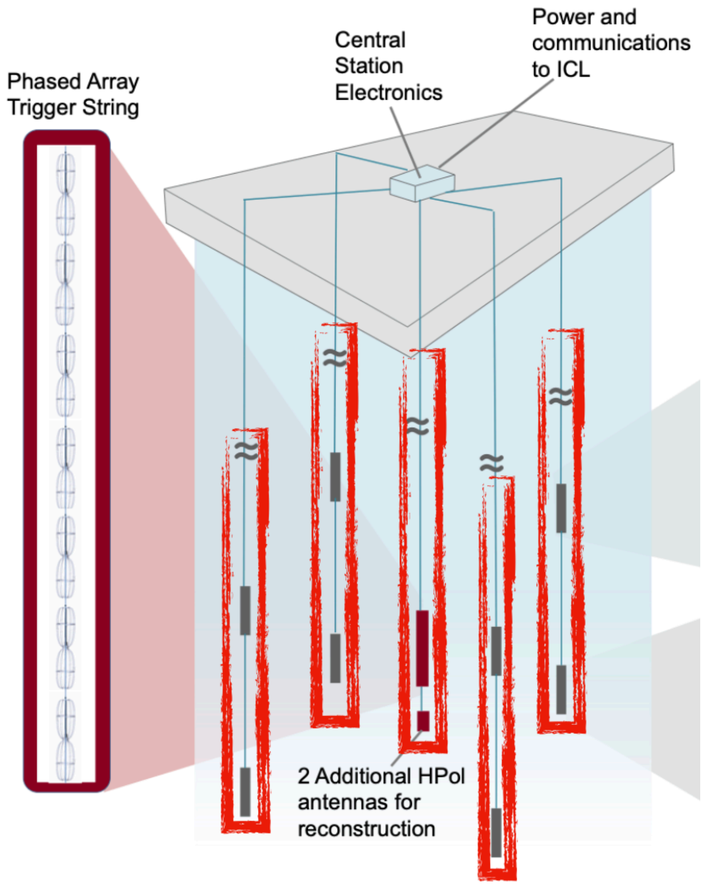
First array-wide search in deep stations

A Pioneering Hybrid Analysis

Combine PA & ARA subdetectors to maximize background rejection & analysis efficiency

- **Hybrid design = Phased array + 7 A5 Vpols** readout through the Phased Array DAQ
- **Unique detector, representative of next generation of detectors like RNO-G & IceCube-Gen2**
- **Livetime : 2020 + 2021 data from hybrid system**
- Optimize cuts for 5σ discovery potential

ARA station 5

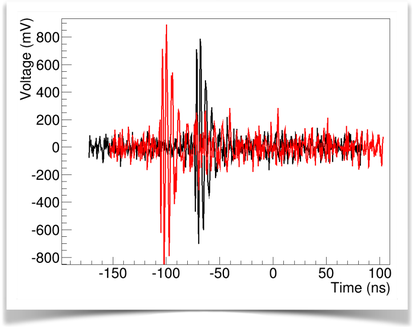


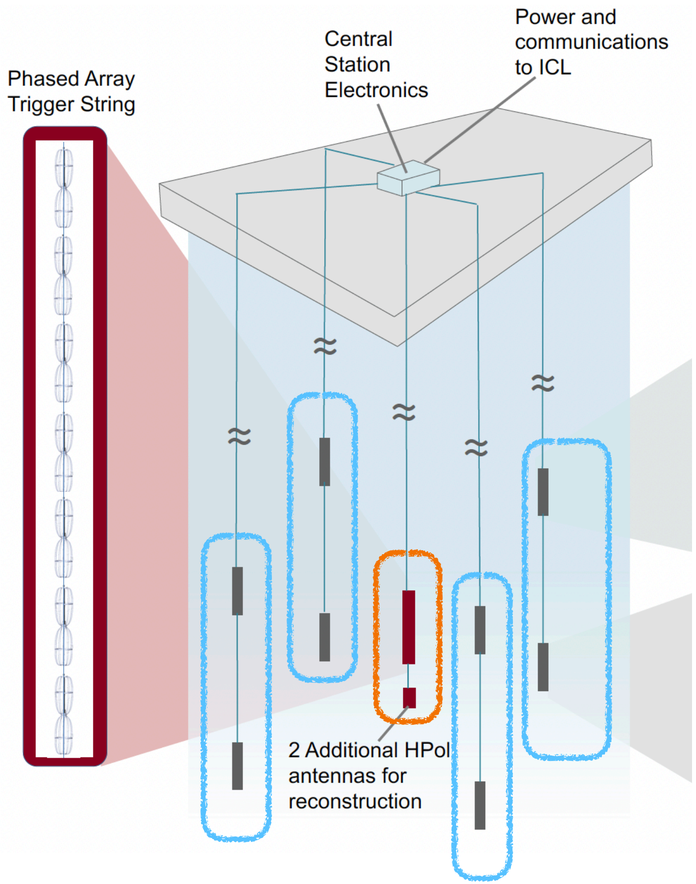
Paramita Dasgupta, Ohio State

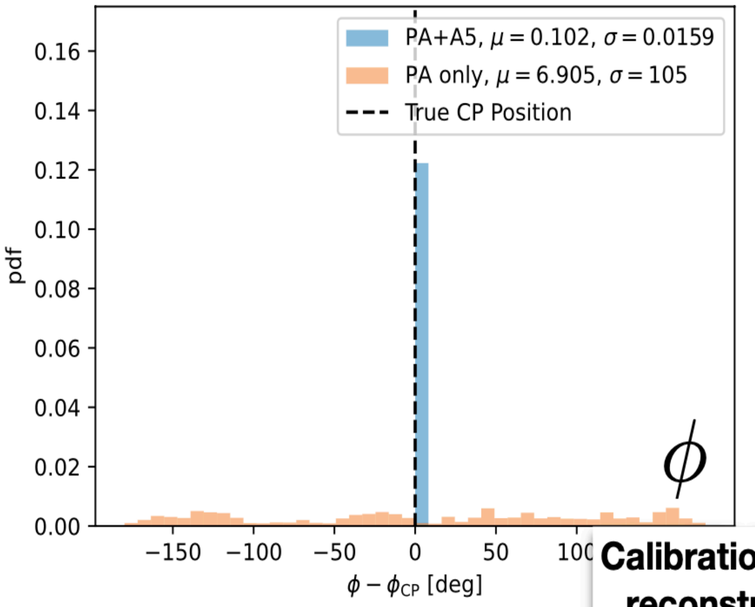
Marco Muzio, UW Madison

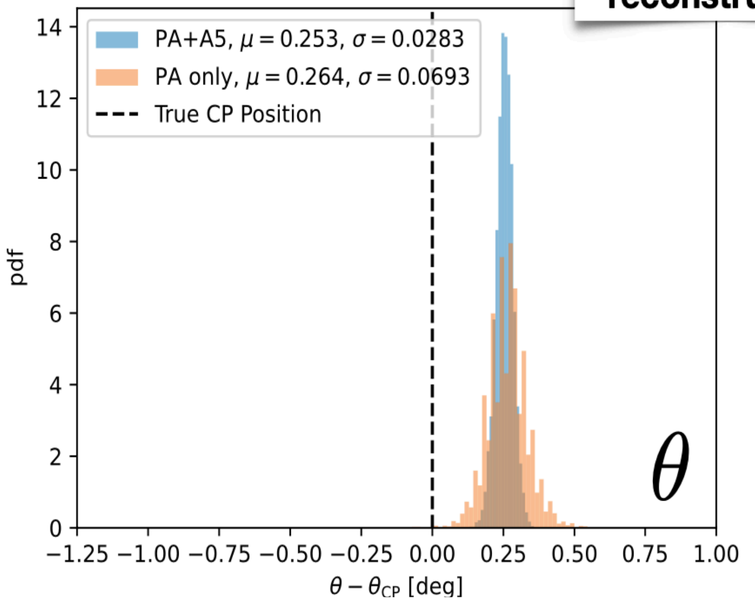
Advantages of a Hybrid detector

- **Excellent amizuth sensitivity with hybrid antennas**
- **~2x zenith sensitivity to vertex position**
- **Precise in-ice reconstruction of events**
- **High background rejection based on direction and timing information**









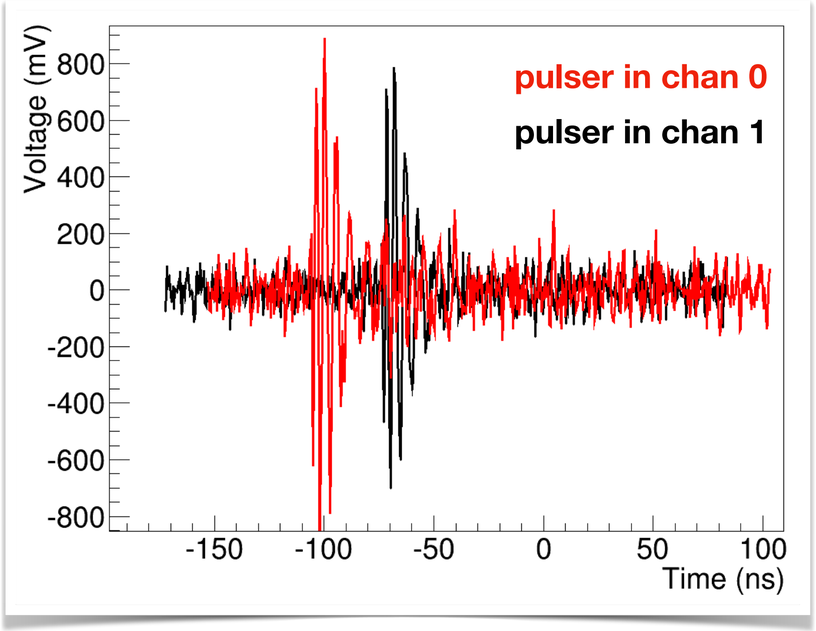
Calibration pulse reconstruction

Reconstruction of Source location with A5-PA hybrid system

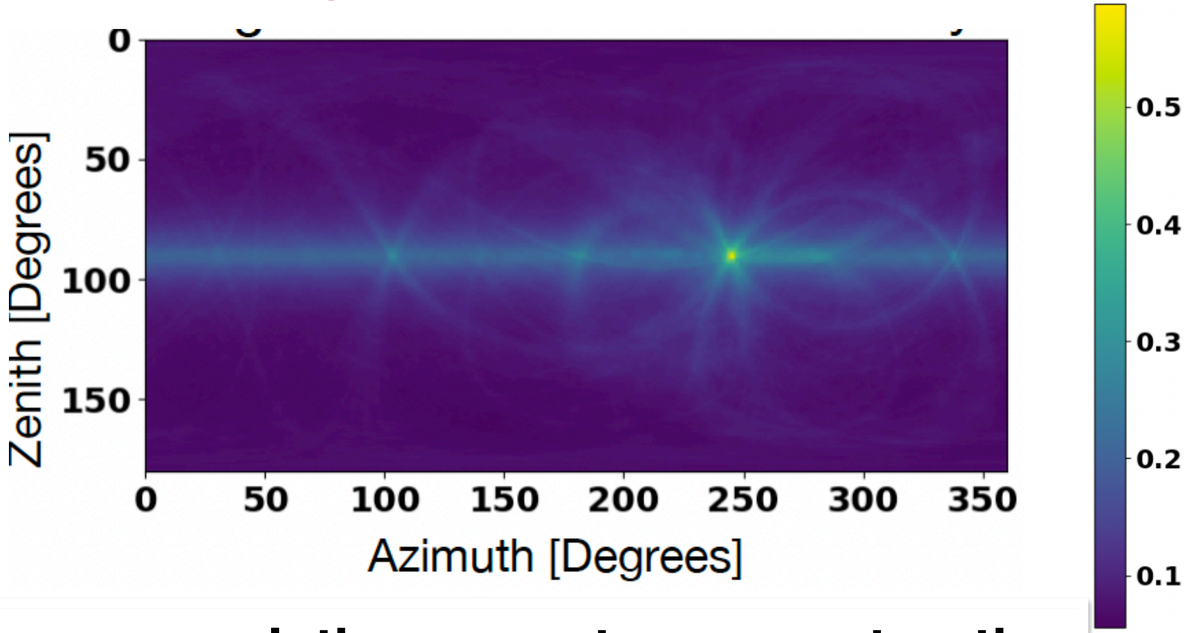
- **Excellent pointing accuracy with A5-PA antennas, improved vertex reconstruction would lead to improved analysis efficiency**

- **Improved surface background removal using correlation map**

Pulser signal in a pair of channels

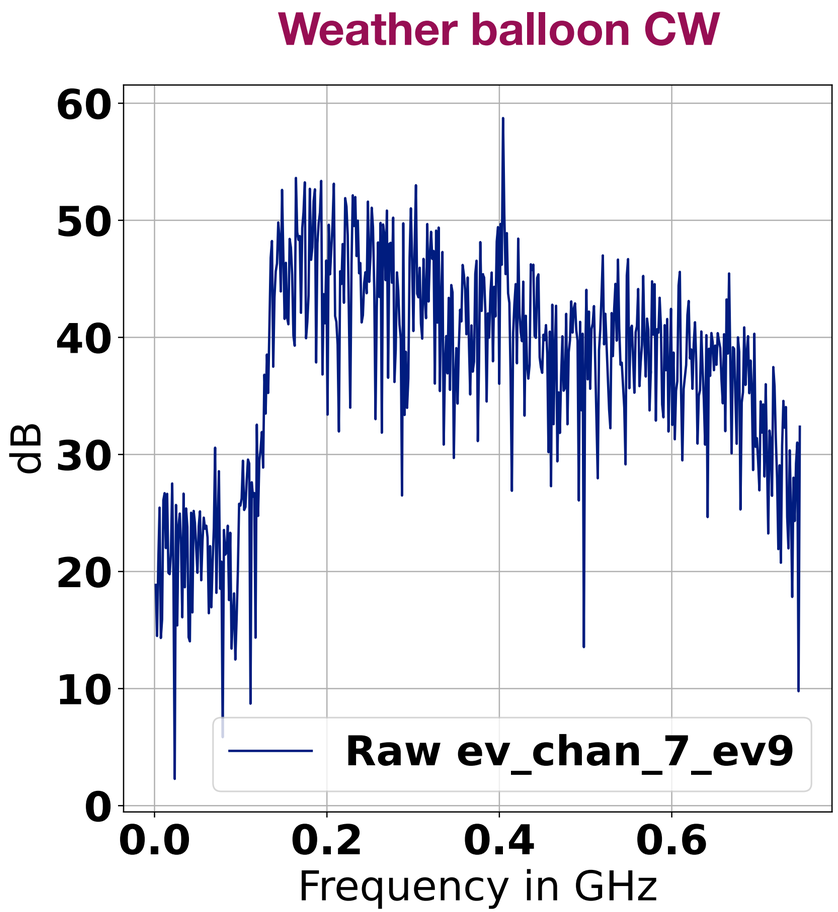


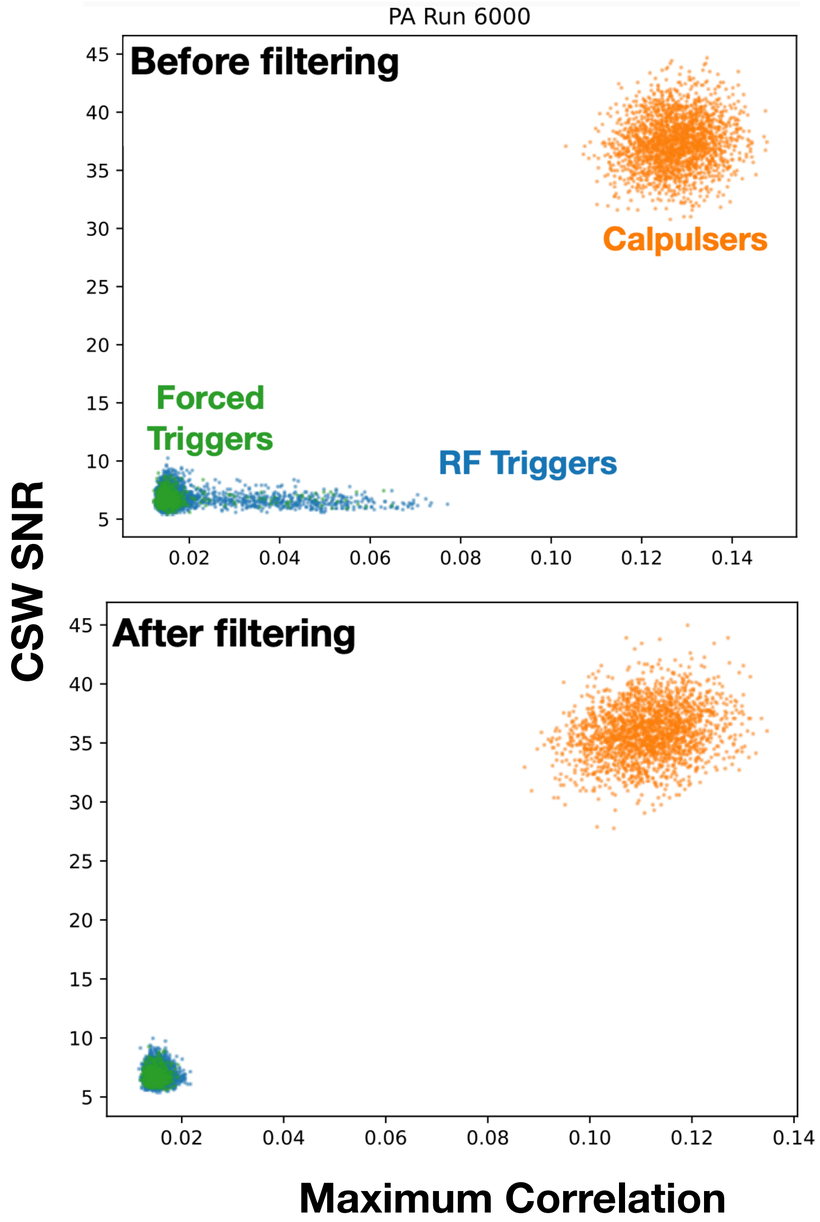
Reconstructed pulser source location using A5-PA hybrid antennas



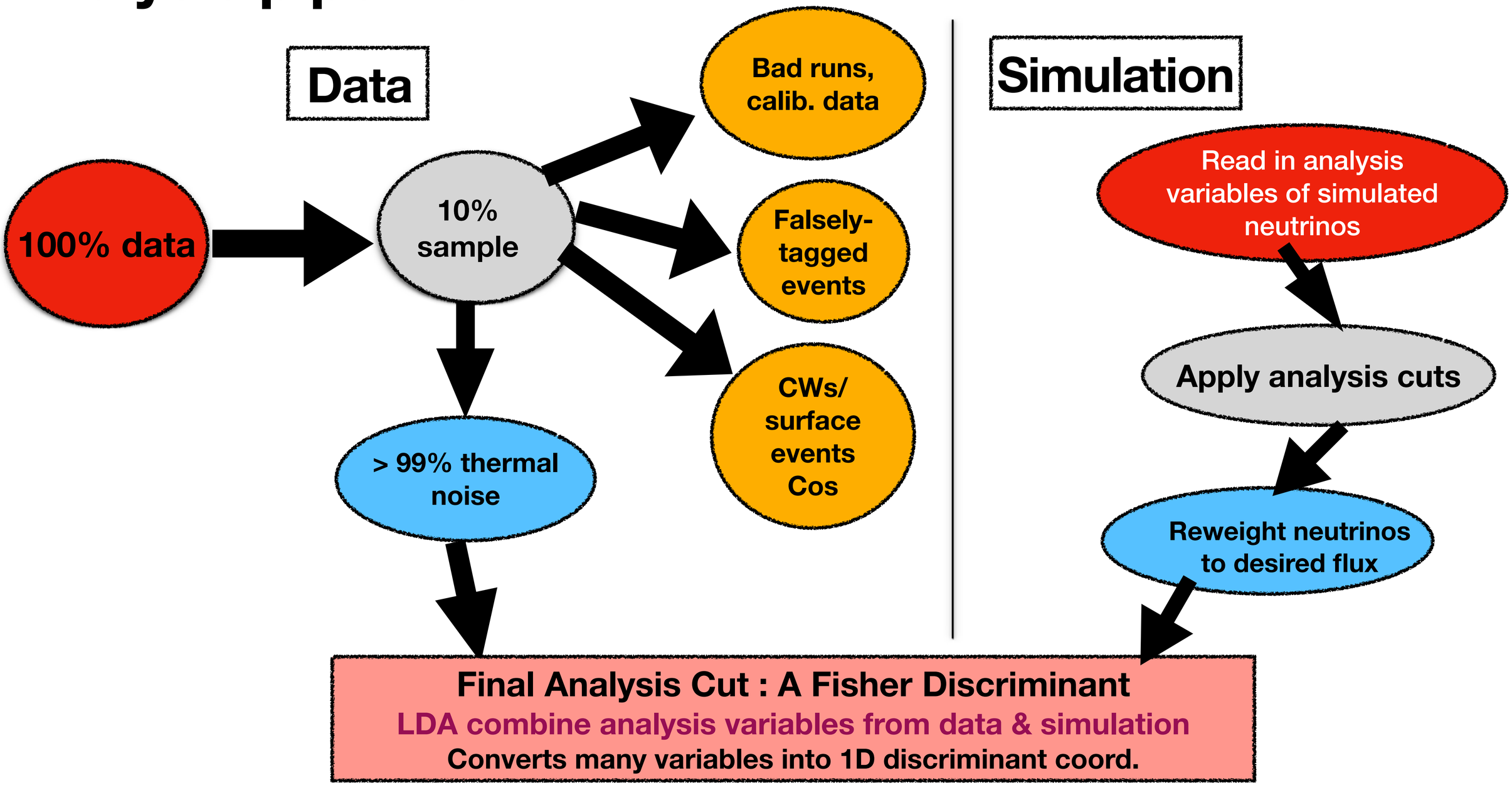
< 0.6 degree resolution on vertex reconstruction

Background removal: Continuous Wave (CW) Signals





Analysis pipeline

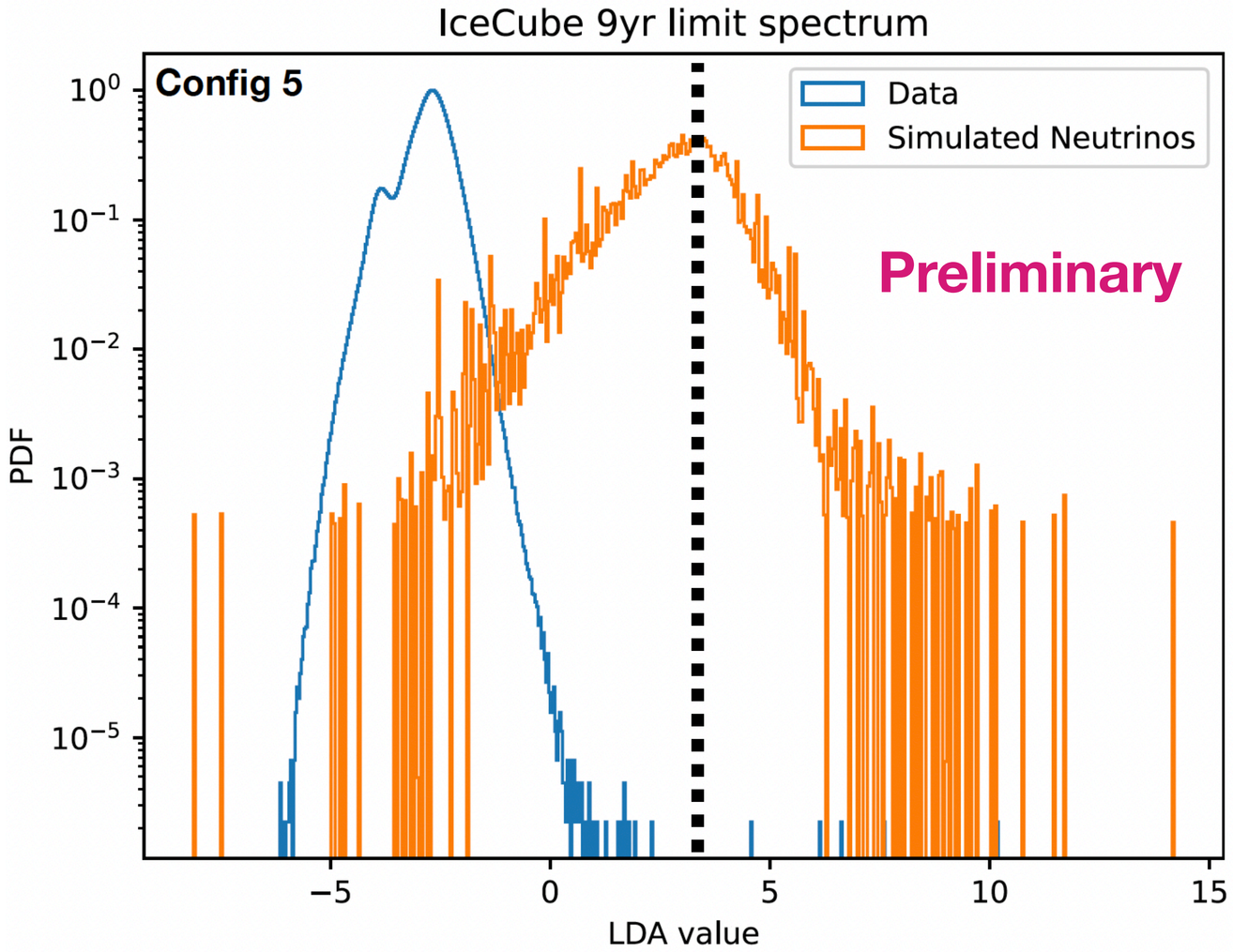


Separating Thermal Noise from Signal: Fisher Discriminant

LDA is a supervised Machine learning algorithm primarily used for classification tasks.

We are setting a cut for the best expected sensitivity.

Cut will be optimized for 5σ discovery using IceCube 2018 flux limit



*** Large fluctuations in simulated neutrino distribution due to limited statistics at low energies**
additional simulations underway

Conclusion

Exciting times ahead!

- In 3-5 years, we will have the sensitivity to detect neutrinos at the highest energies with ARA experiment
- First UHE neutrino candidates !!
- This will inform us on the sources of the highest energy particles.
- Non-detection will also help us constraint source models !
- The hardware, simulation, and technology we are developing now for radio experiments will directly feed in to future projects like IceCube-Gen2

Thank you

Additional Slides

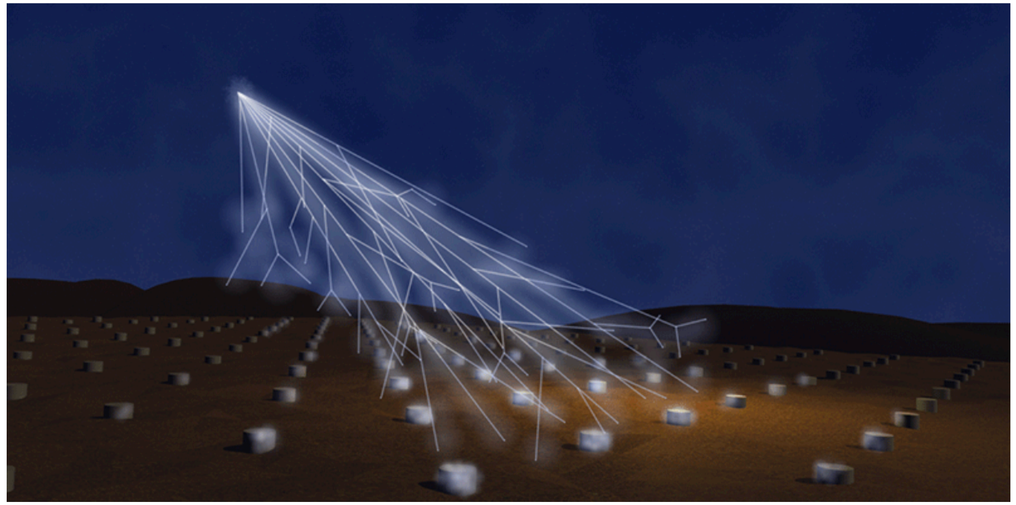
Cosmic Origin of Radiation

Cosmic Rays (1911)

Ionizing radiation detected in the atmosphere

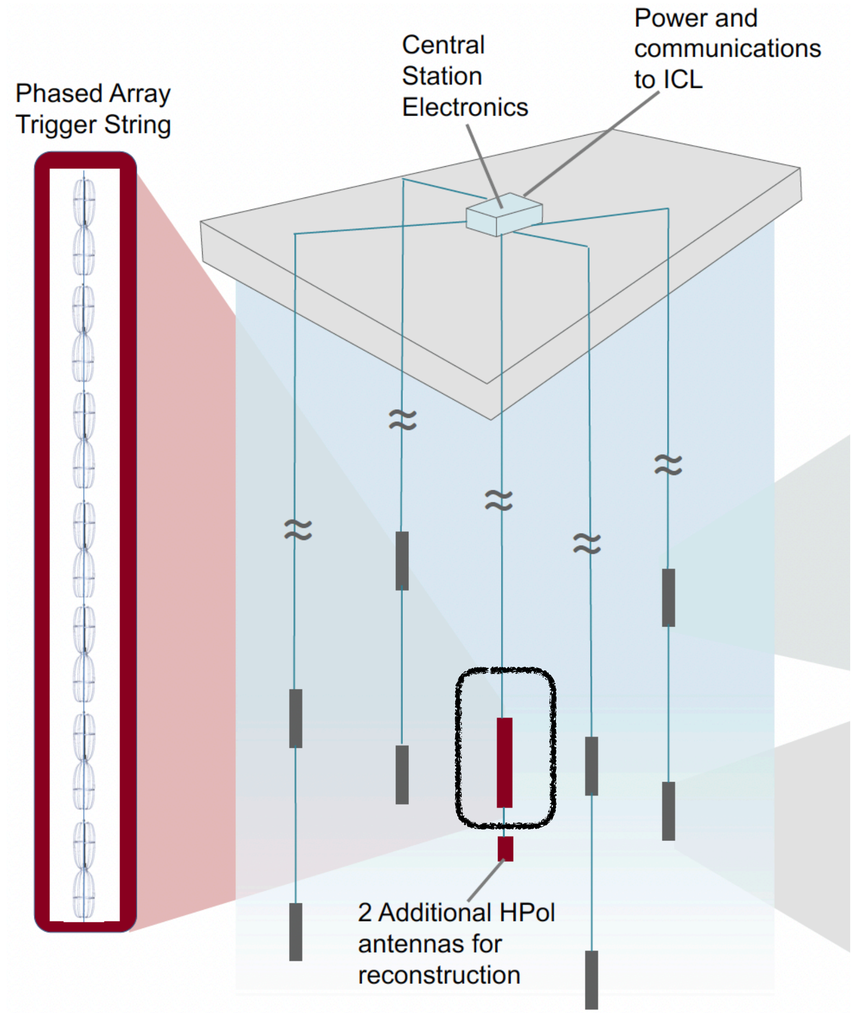
Fly's Eye (Utah) [1981–1992]

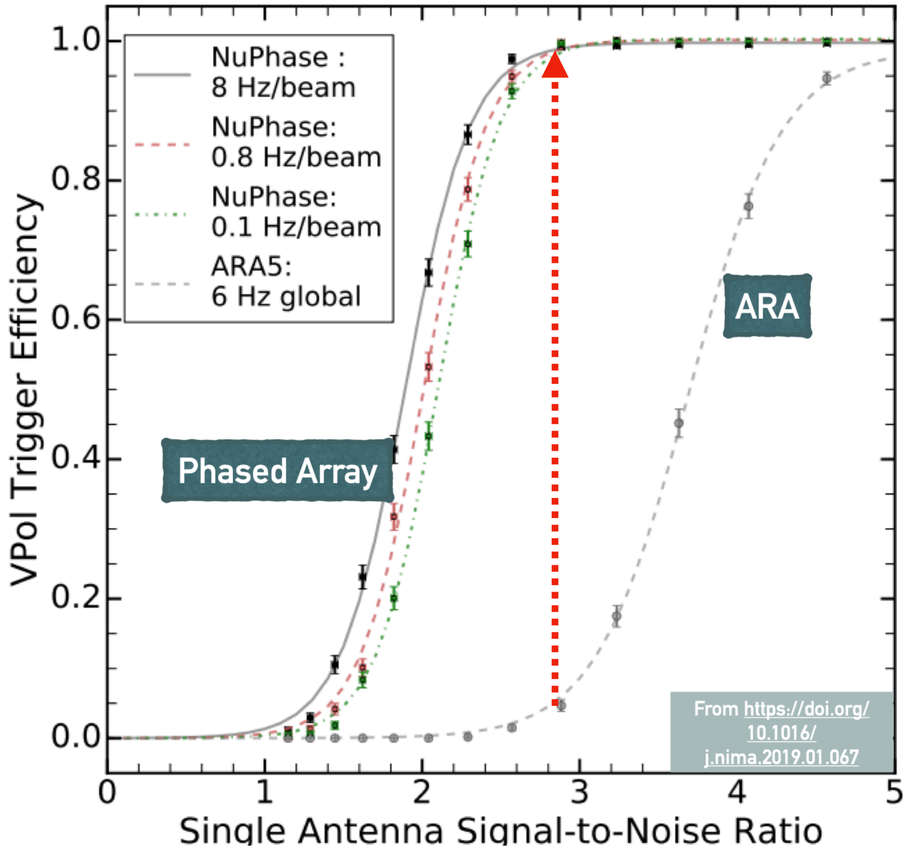
Pierre Auger Observatory, Argentina [2004 - Present]



The phased array detector

Analysis with *PA antennas alone* significantly improves trigger efficiency



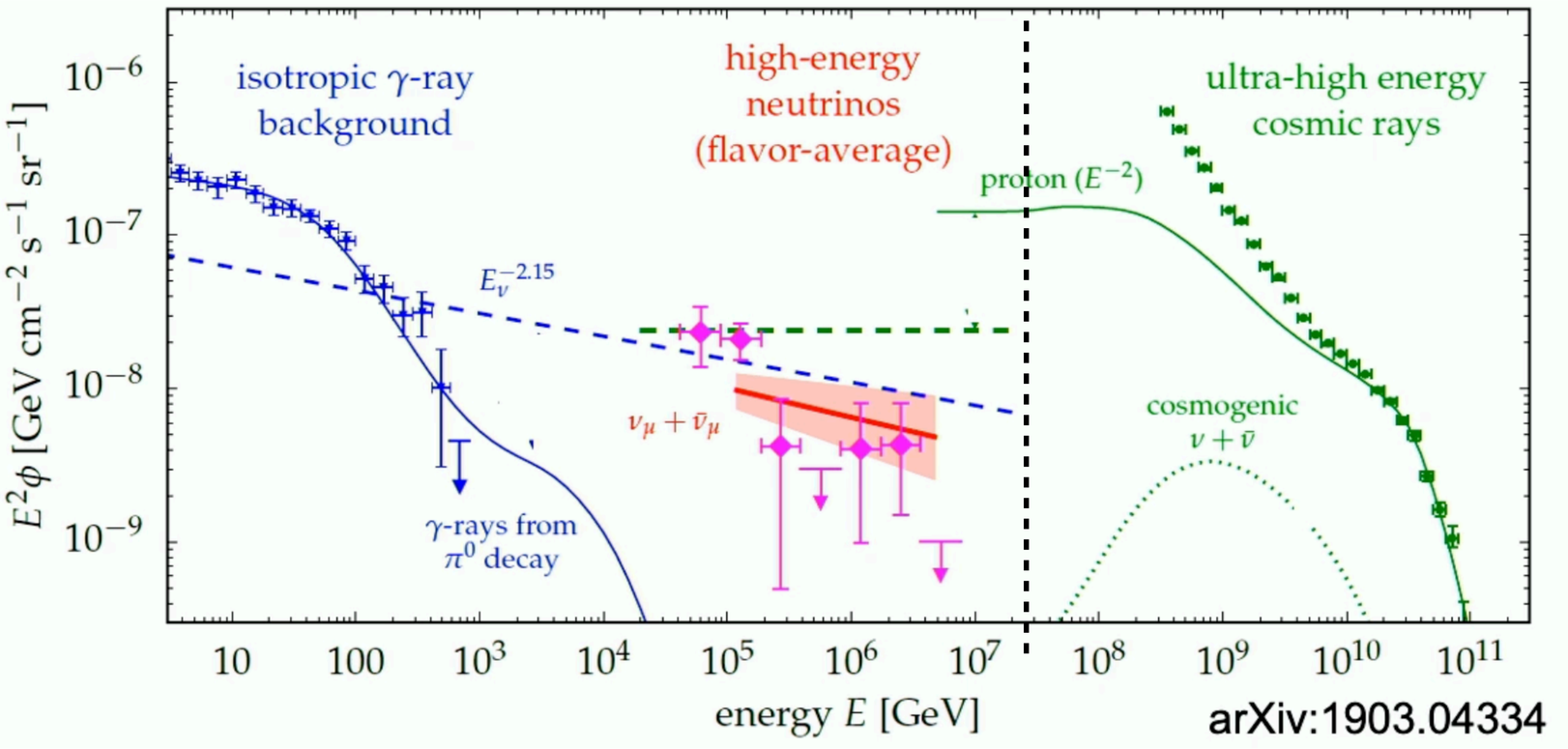


Improved Trigger efficiency

The Ultra High Energy Universe

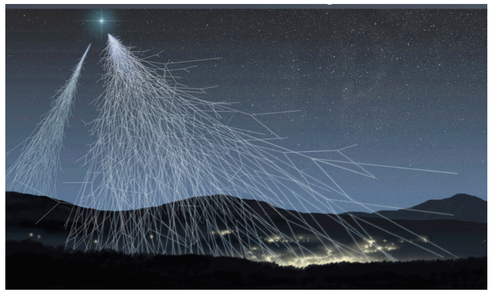
By "UHE", I mean "$E\nu$ > 30 PeV "

There are sources that make x 10^4 more energetic than the neutrinos seen by IceCube (we've seen cosmic rays from them)

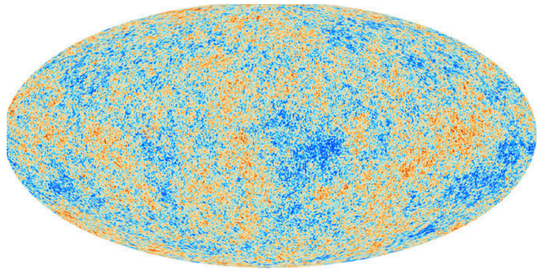


Types of Neutrinos We Aim to Detect

Cosmic Ray ($E_p > 10^{19.5}$ eV)

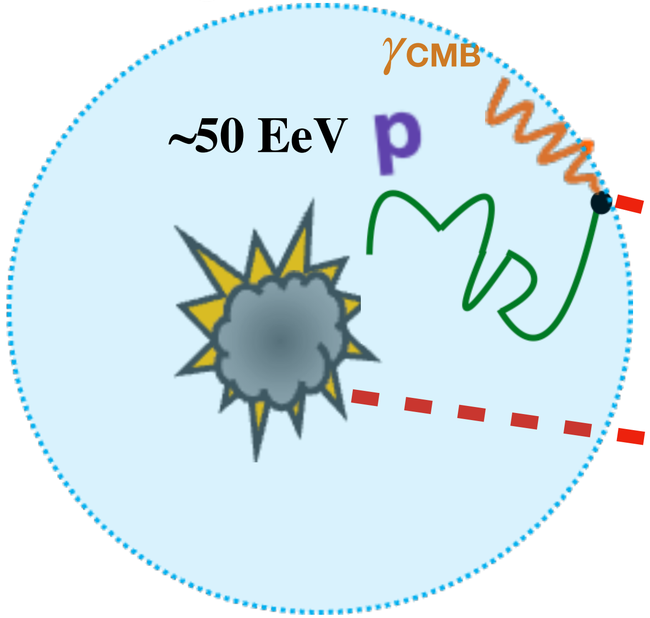


CMB photons



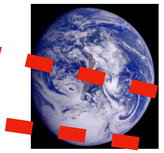
= Neutrino beam !

GZK Horizon
~ 50 Mpc



Cosmogenic Neutrinos

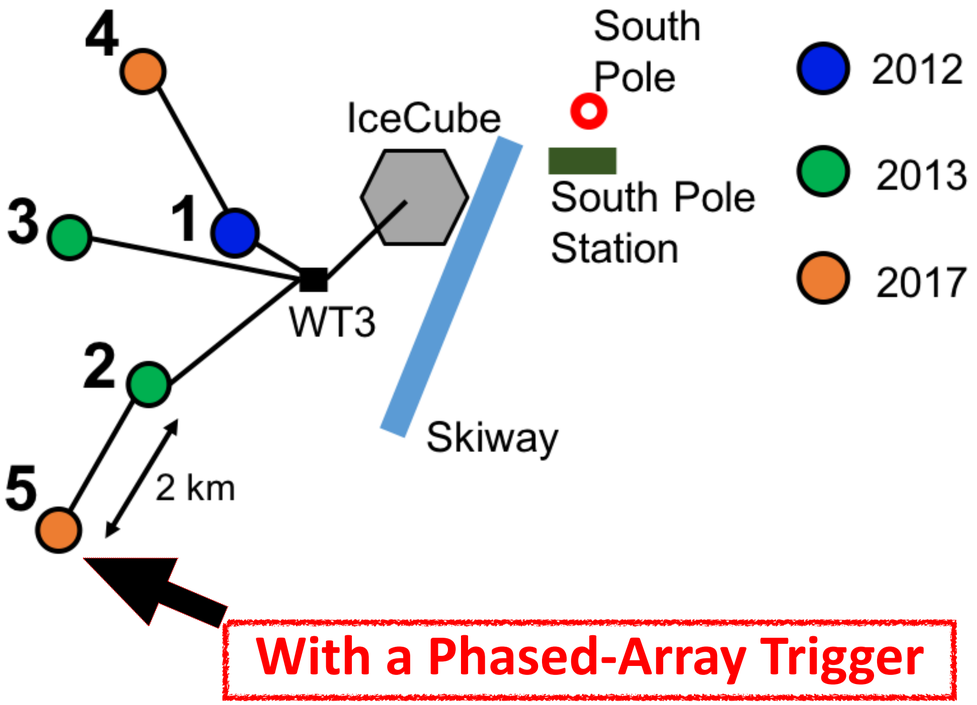
Astrophysical Neutrinos

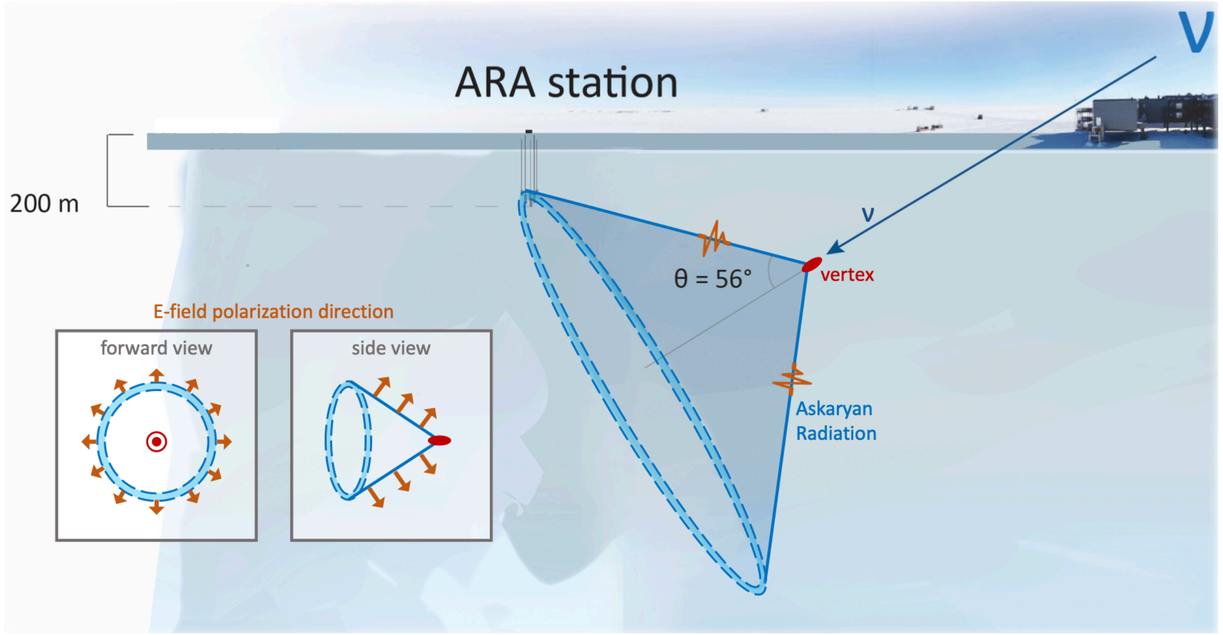


$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\rightarrow e^+ + \boxed{\bar{\nu_\mu} + \nu_e}$$

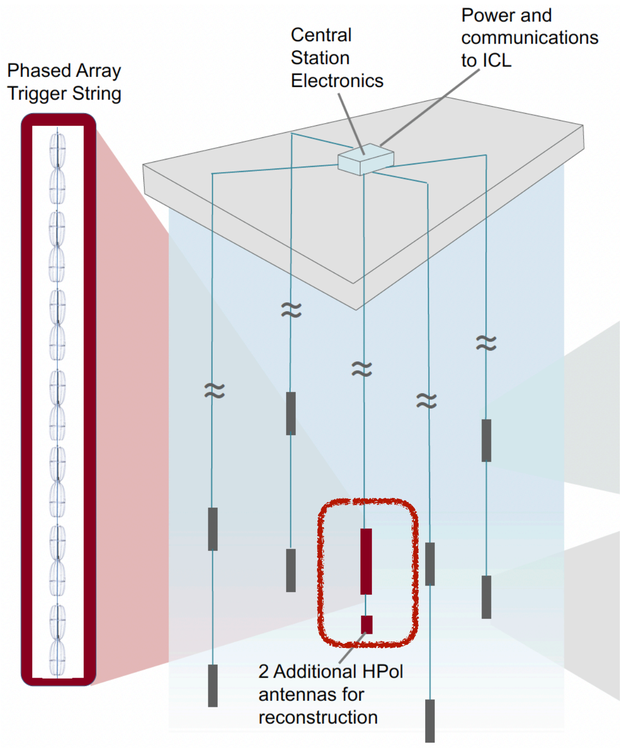
The Askaryan Radio Array (ARA)

Five independent stations have been collecting data for ~ a decade

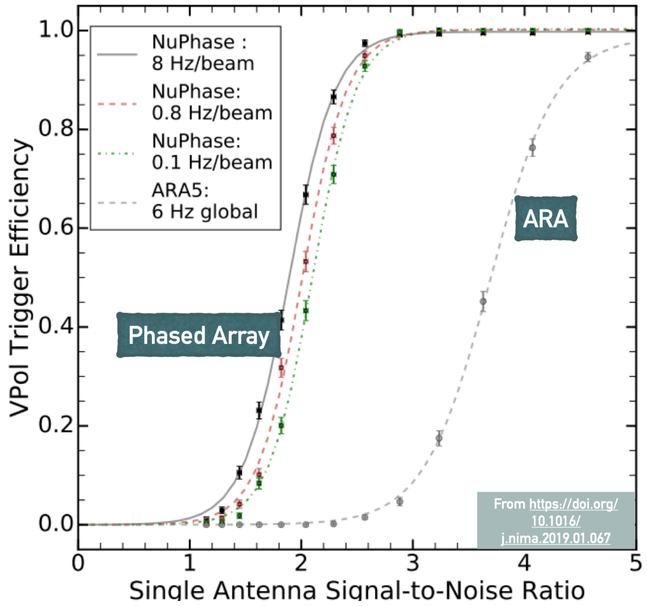




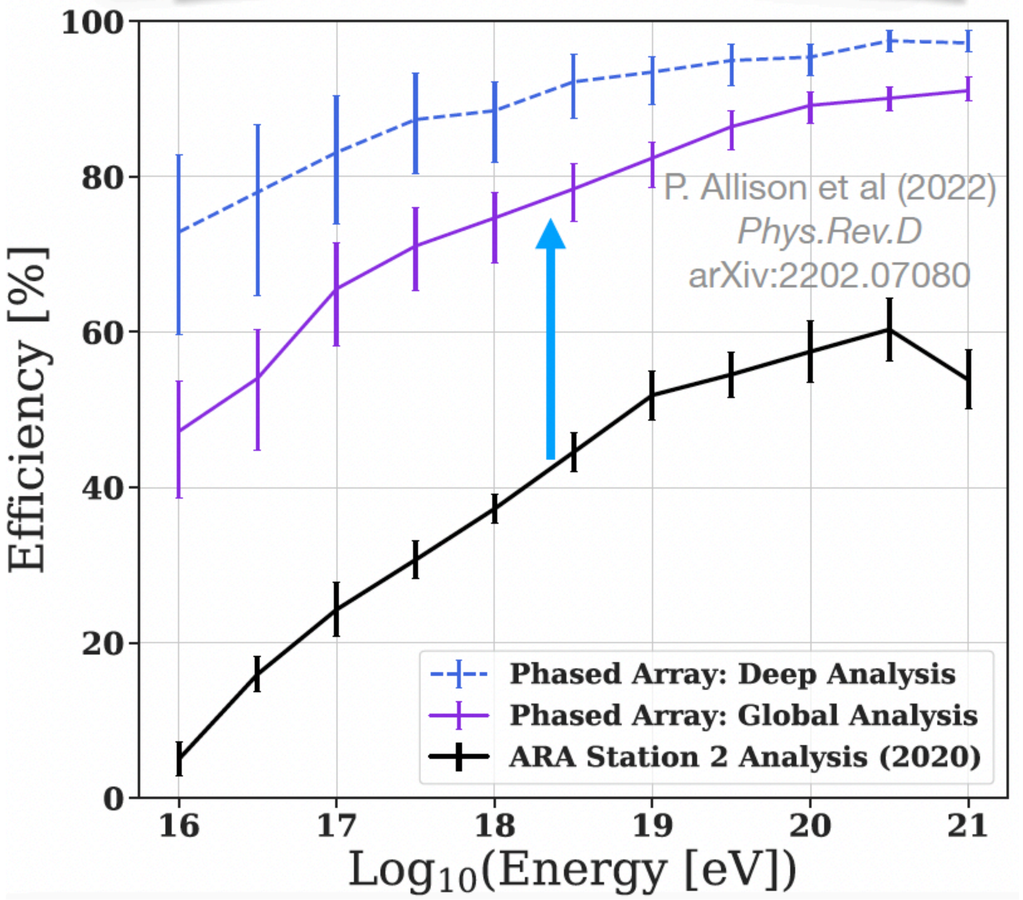
The Phased Array detector



Improved Trigger efficiency



Improved analysis efficiency



Fraction of triggered ν events in signal region

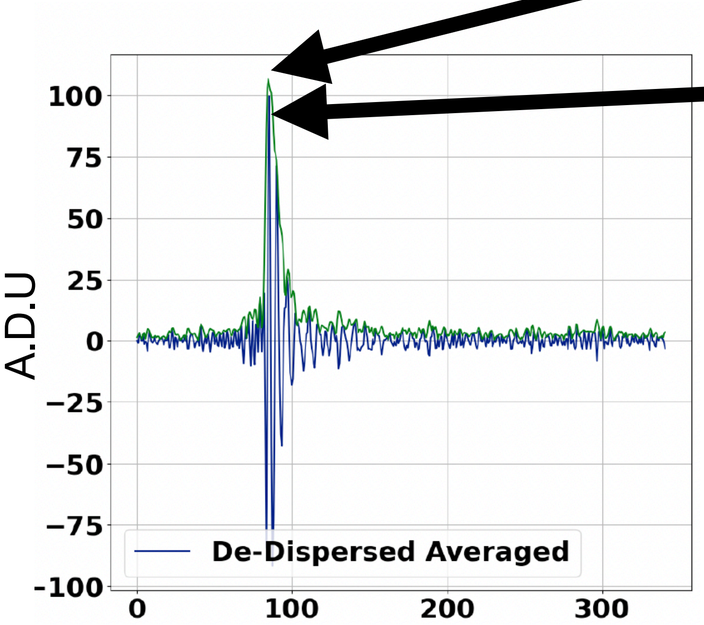
Status of UHE neutrino searches with ARA data

- **ARA collaboration is performing two analyses:**
  - **Highly-coordinated, multi-institution analysis with full array**
  - **A pioneering analysis that will lead next-generation of experiments.**

Example analysis variables

Hilbert Envelope peak power

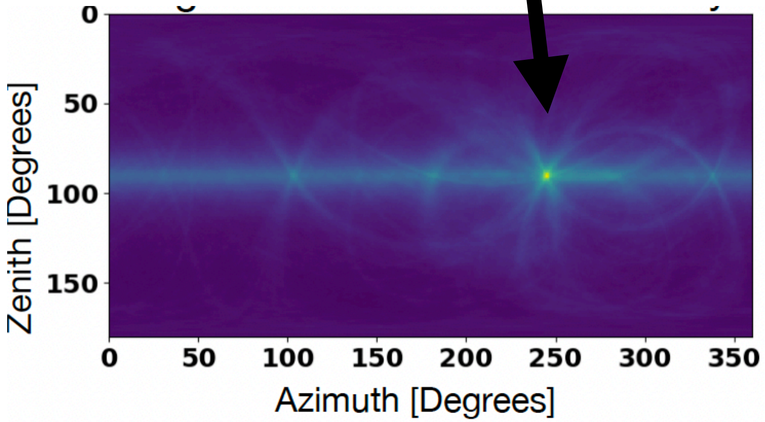
De-dispersed Av. wf peak power



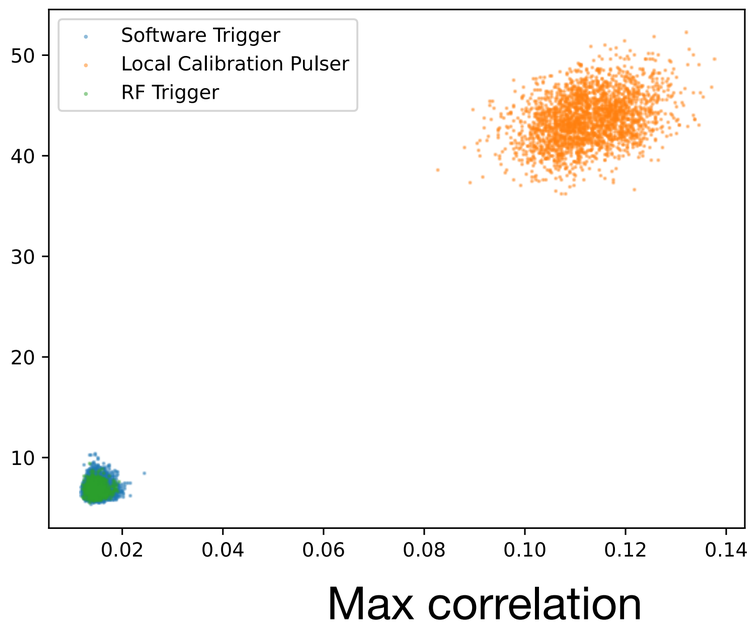
Maximum Corr. Value

CSW SNR = SNR of Coherently-Summed Waveform

Location of peak Reconstructed (θ, ϕ)



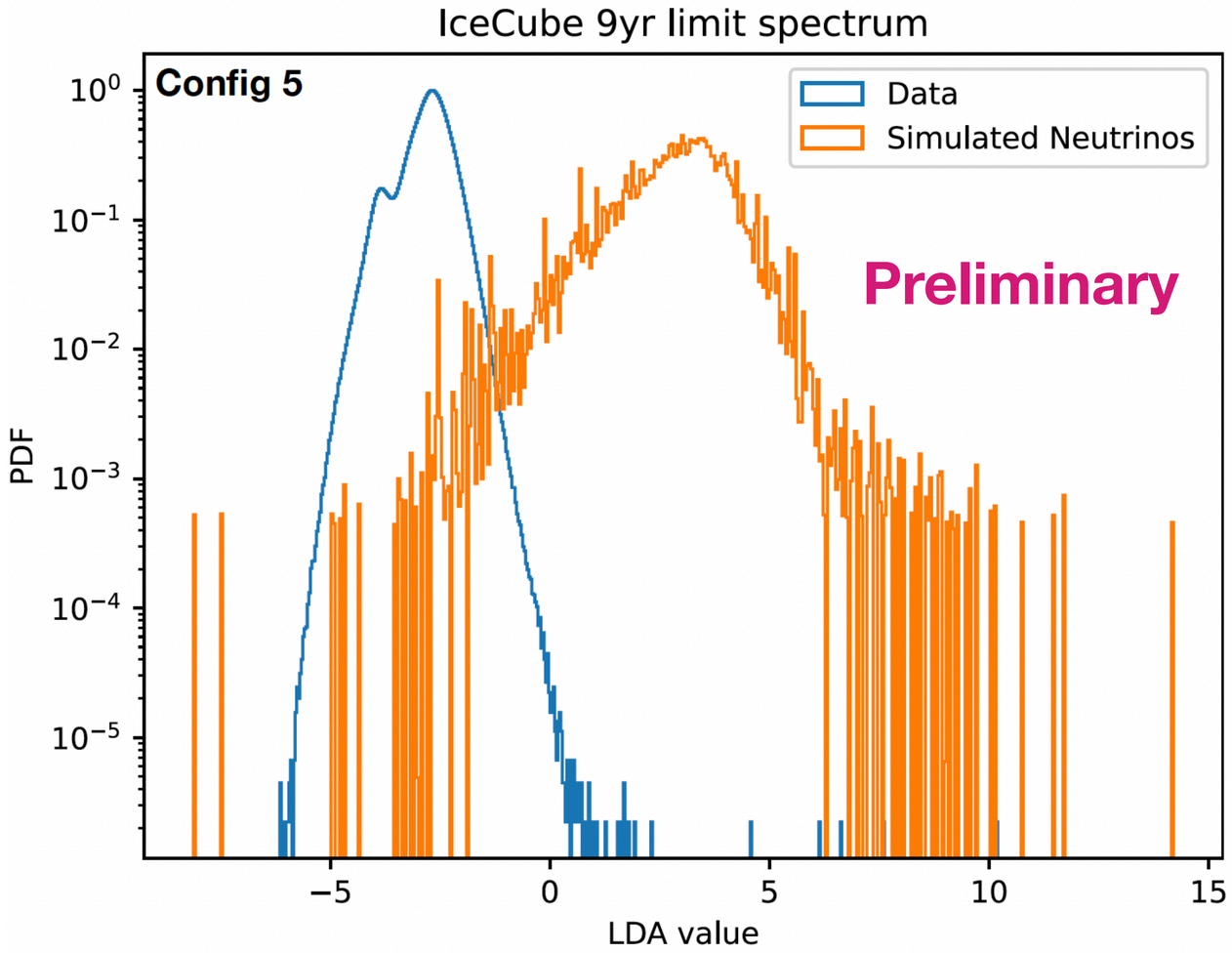
CSW SNR



Separating Thermal Noise from Signal: Fisher Discriminant

LDA is a supervised Machine learning algorithm primarily used for classification tasks.

- **We train linear discriminant to maximize separation in our selection variable space.**
- **Final variable is LDA value from data and simulation**

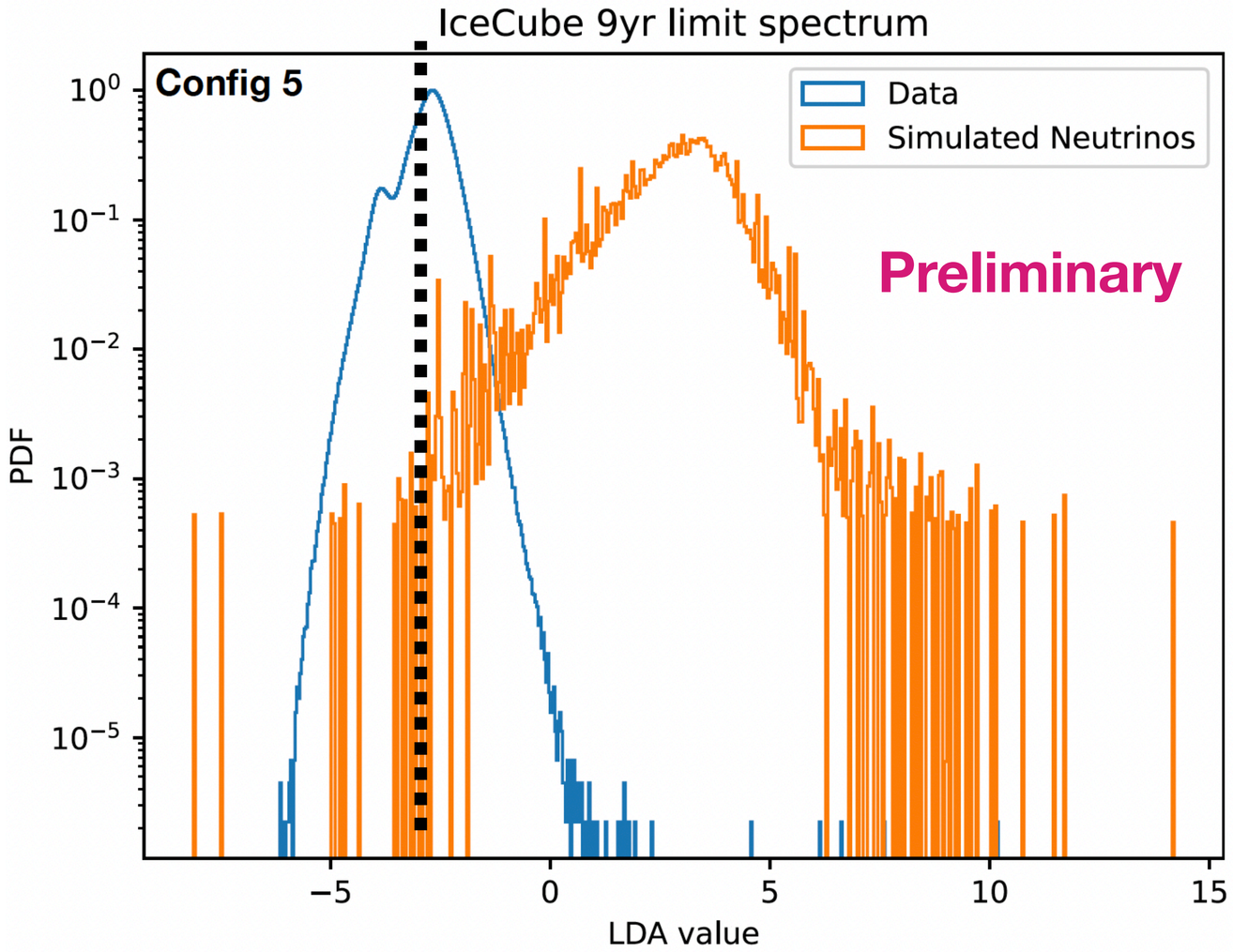


*** Large fluctuations in simulated neutrino distribution due to limited statistics at low energies**
additional simulations underway

Separating Thermal Noise from Signal: Fisher Discriminant

We are setting a cut for the best expected sensitivity.

Cut will be optimized for 5σ discovery using IceCube 2018 flux limit



*** Large fluctuations in simulated neutrino distribution due to limited statistics at low energies**
additional simulations underway

Interesting results from ARA in a few months !

We are conducting 2 analyses with ARA data

1. **Pioneering analysis with a hybrid detector system : PA antennas + traditional antennas**
   - Proof of concept for next-generation large in-ice radio array RNO-G (35 stations) & IceCube-Gen2 Radio (361 stations)
2. **Highly-coordinated, multi-institution analysis with all 5 ARA stations' data**

These 2 analyses will yield either:

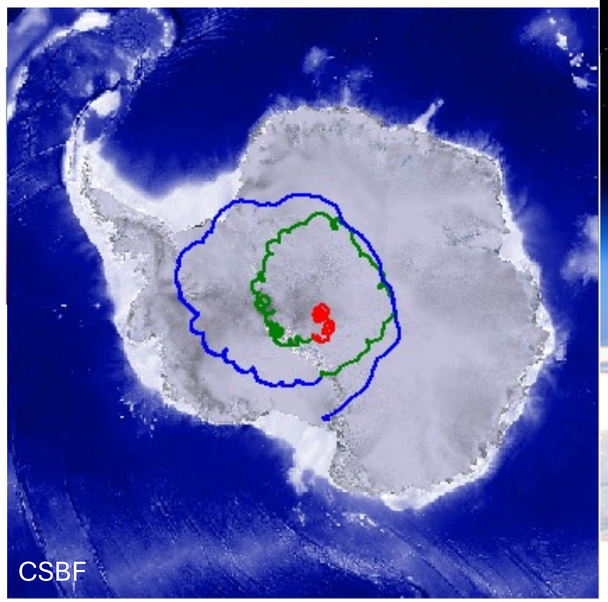
- **First UHE neutrino candidates !!**
- **Strongest flux limit up to 10^3 EeV (10^{21} eV) from any radio experiment to date !**

PUEO Experiment: Brief Introduction

cost cap $20M, 5-year missions

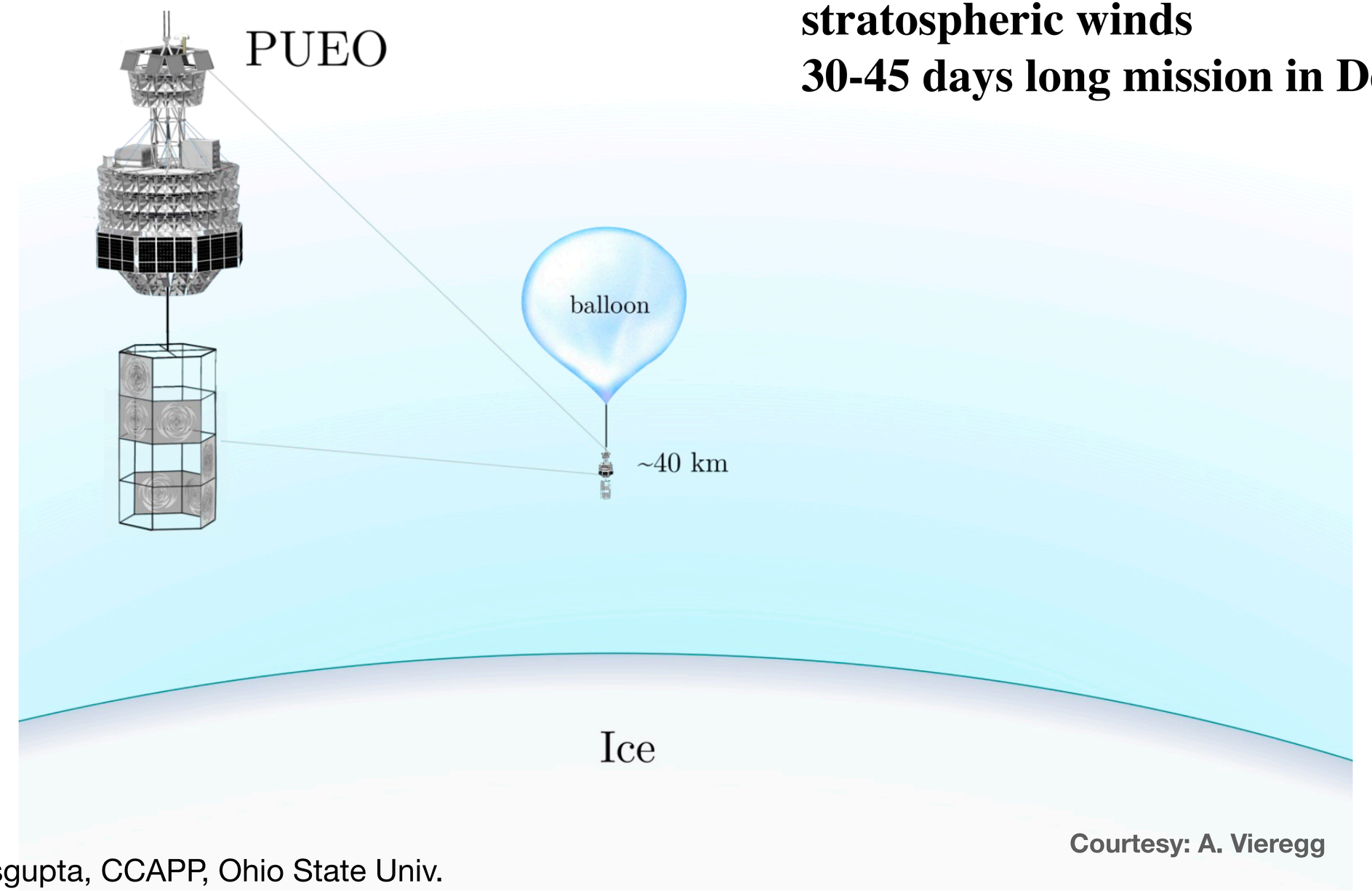
Payload for **U**ltrahigh **E**nergy **O**bservations

- Radio detection experiment
- NASA Long Duration Balloon flight over Antarctica
- Will measure the ultrahigh energy neutrinos' interactions with the Earth
  - >1 EeV (10^{18} eV)!



How It Works?

Balloon + payload will drift with stratospheric winds
30-45 days long mission in Dec 2025

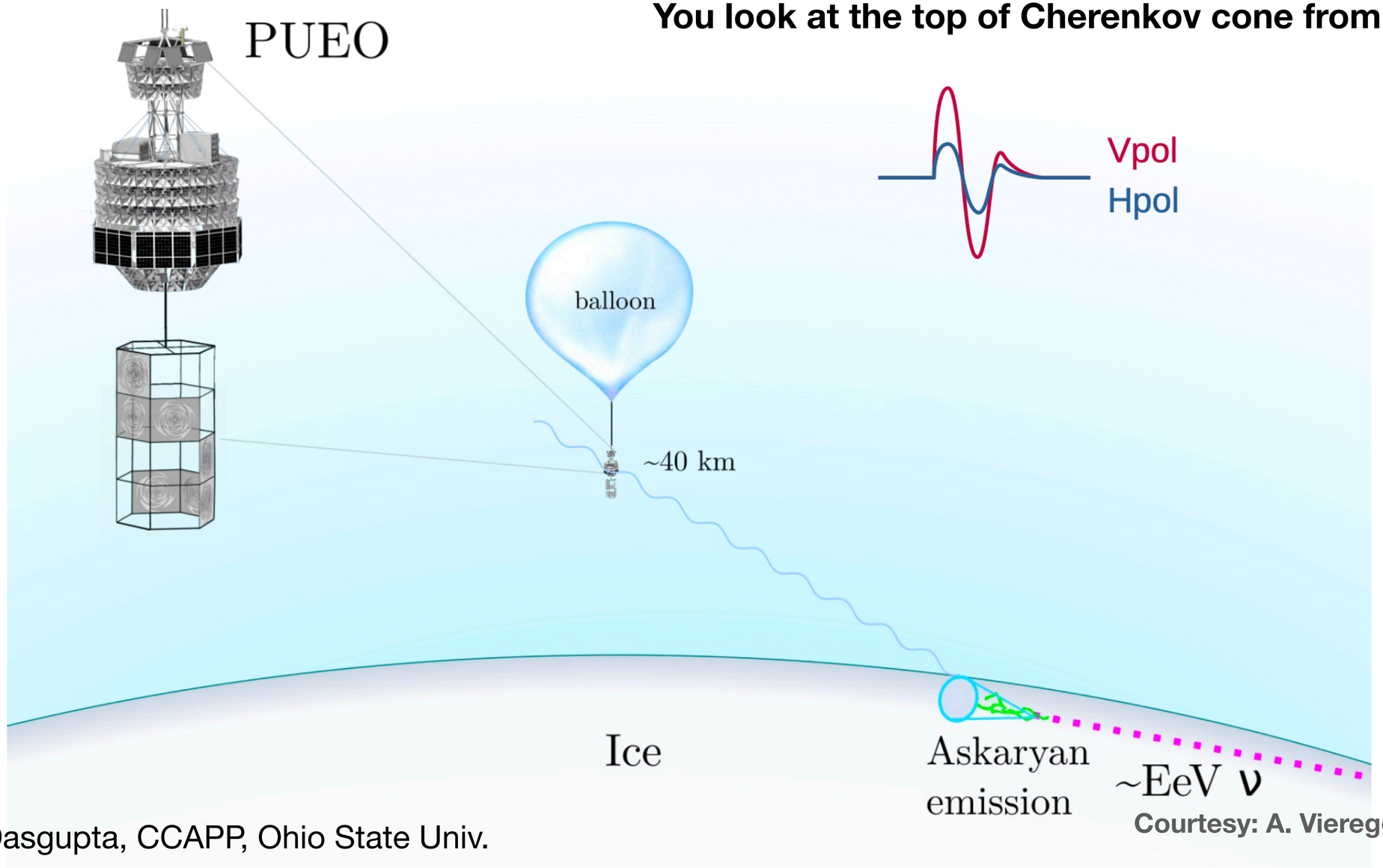


Courtesy: A. Vieregg

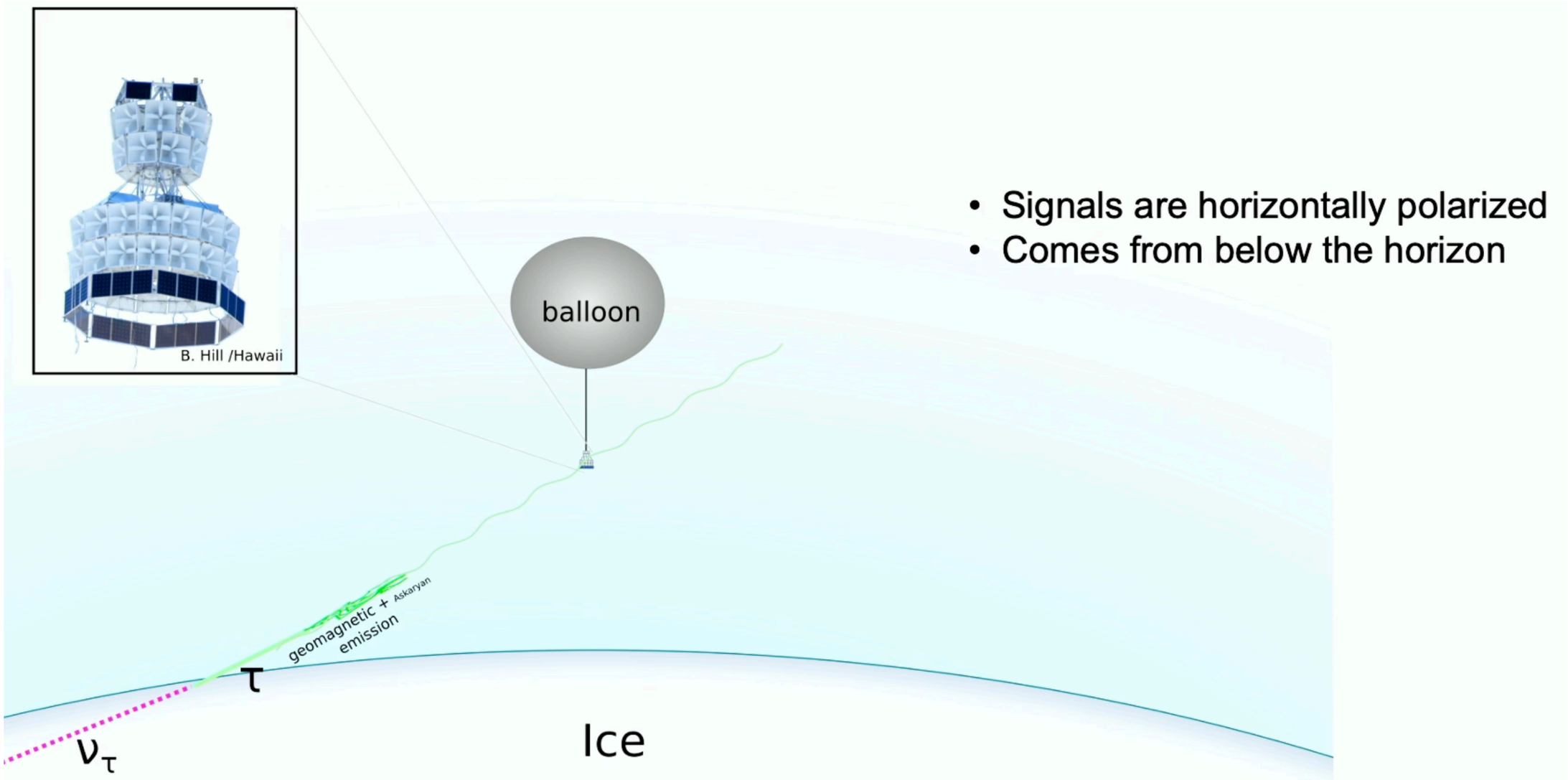
How It Works?

Signals are Vertically polarized

You look at the top of Cherenkov cone from the balloon



Courtesy: A. Vieregg

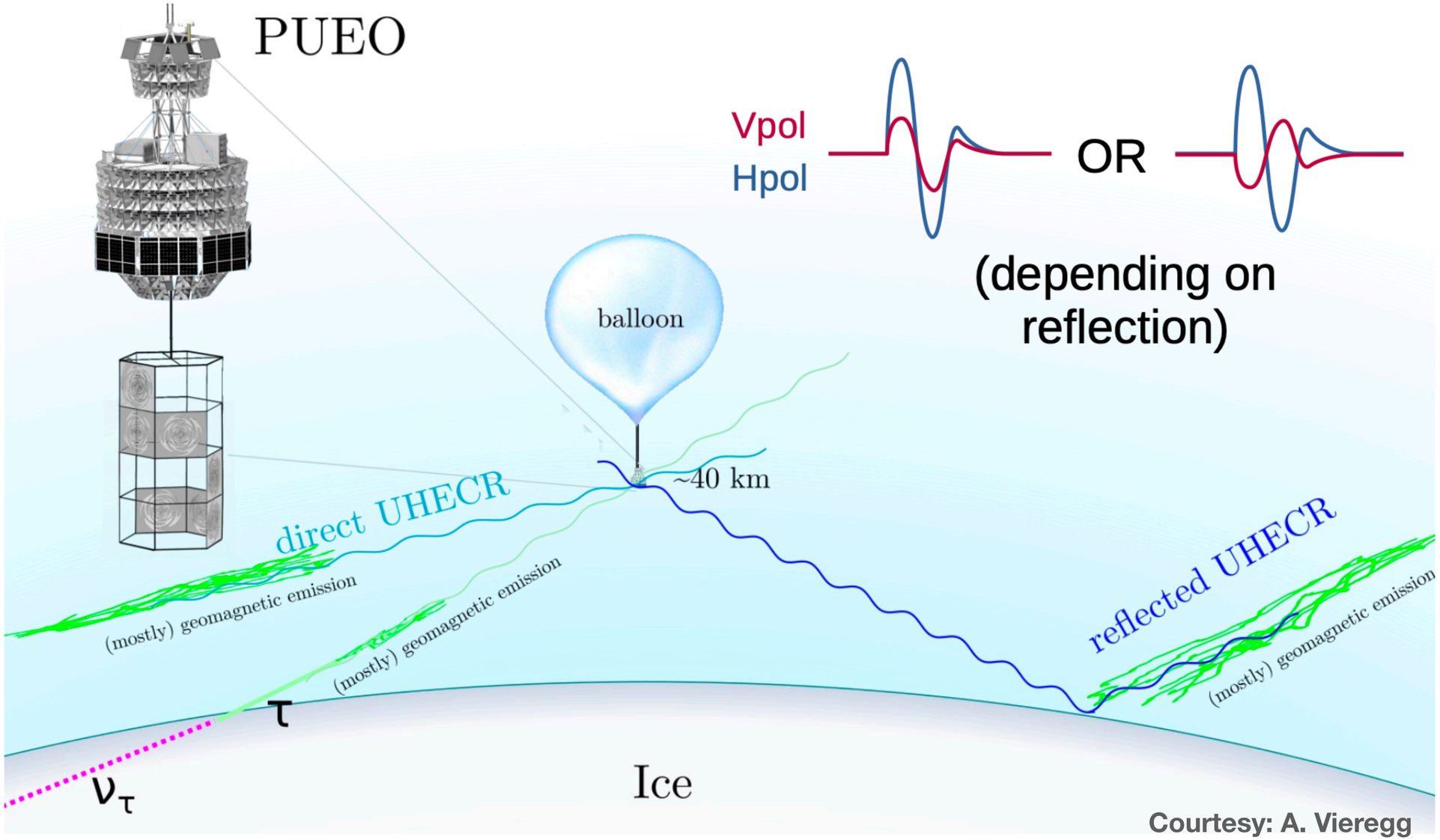


- Signals are horizontally polarized
- Comes from below the horizon

Courtesy: A. Vieregg

How It Works?

Signals are Horizontally polarized



Courtesy: A. Vieregg

Our work at IIT Kanpur (under the guidance of Prof. Pankaj Jain)

ELSEVIER

Astroparticle Physics
Volume 128, March 2021, 102530

General treatment of reflection of spherical electromagnetic waves from a spherical surface and its implications for the ANITA anomalous polarity events

Paramita Dasgupta, Pankaj Jain

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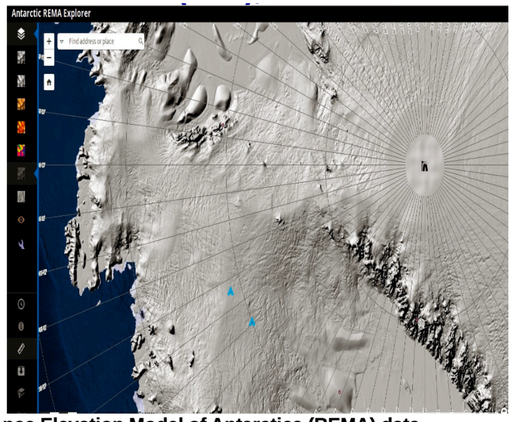
https://doi.org/10.1016/j.astropartphys.2020.102530 Get rights and content

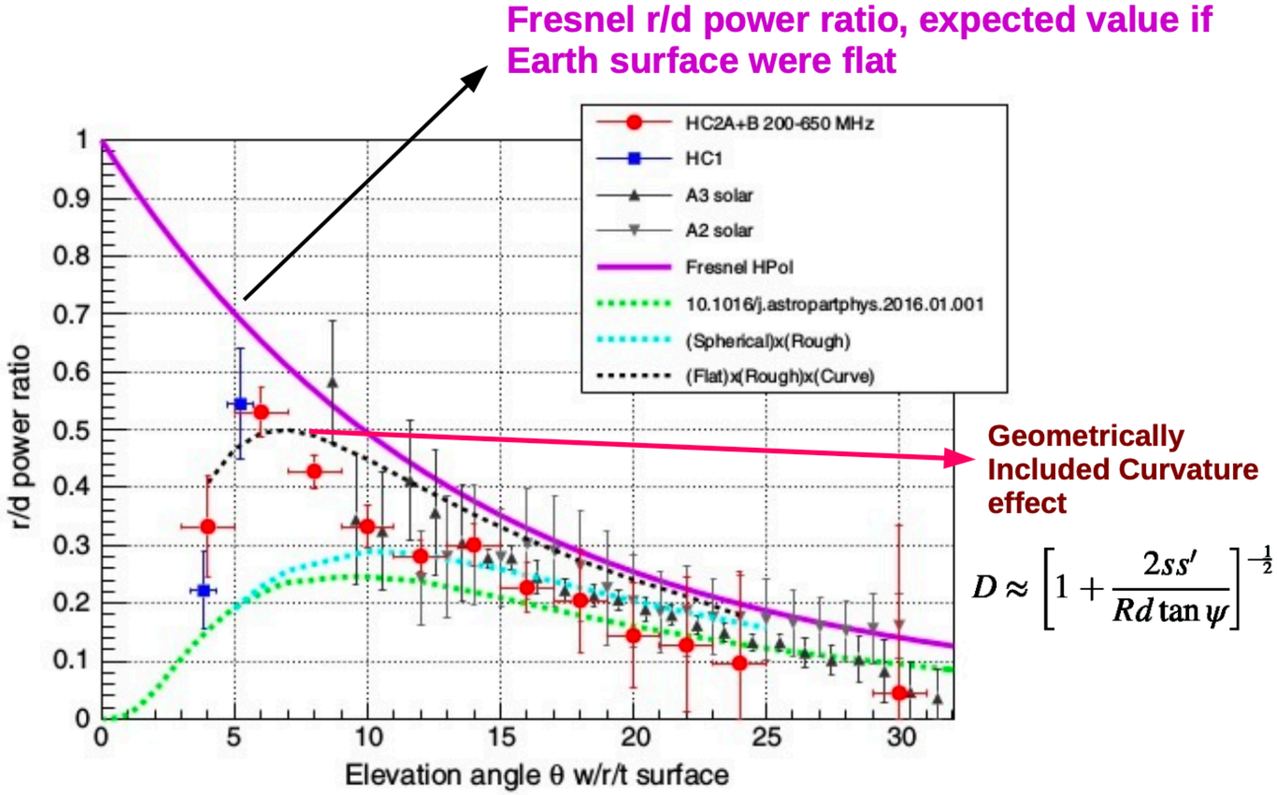
Abstract

We develop a general formalism to treat reflection of spherical electromagnetic waves or, more precisely, dipole radiation from a spherical surface. Our main objective is interpretation of radio wave signals produced by cosmic ray interactions with Earth's atmosphere which are observed by the Antarctica based ANITA detector after reflection



nce Elevation Model of Antarctica (REMA) data

r/d power ratio compared with HiCal data



$$D \approx \left[1 + \frac{2ss'}{Rd\tan\psi}\right]^{-\frac{1}{2}}$$

S. Prohira, A. Novikov, P. Dasgupta, P. Jain et al (ANITA collaboration)

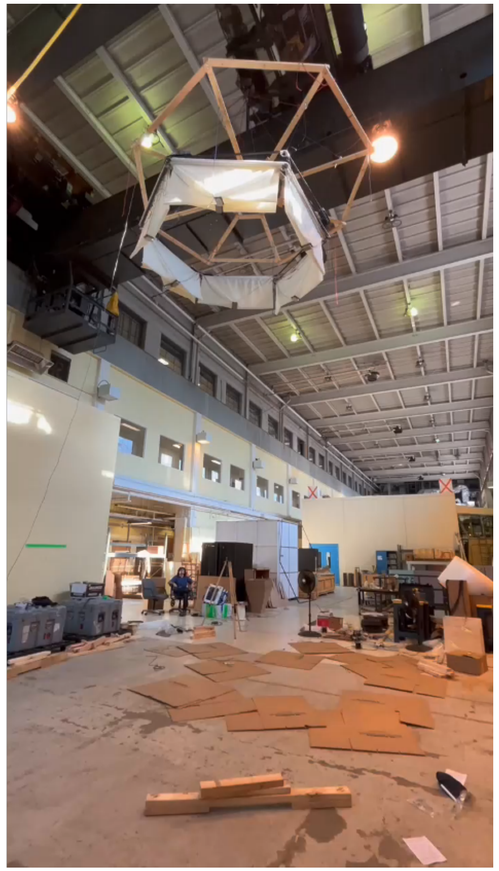
P. Dasgupta and P. Jain https://doi.org/10.1016/j.astropartphys.2020.102530

Status of PUEO

Now	Jan 2025	April 2025	July 2025	Winter 2025
Fabricating individual systems	Instrument Integration In Chicago	Thermal Vacuum Test at CSBF	Instrument Hang Test at CSBF	Antarctic Flight

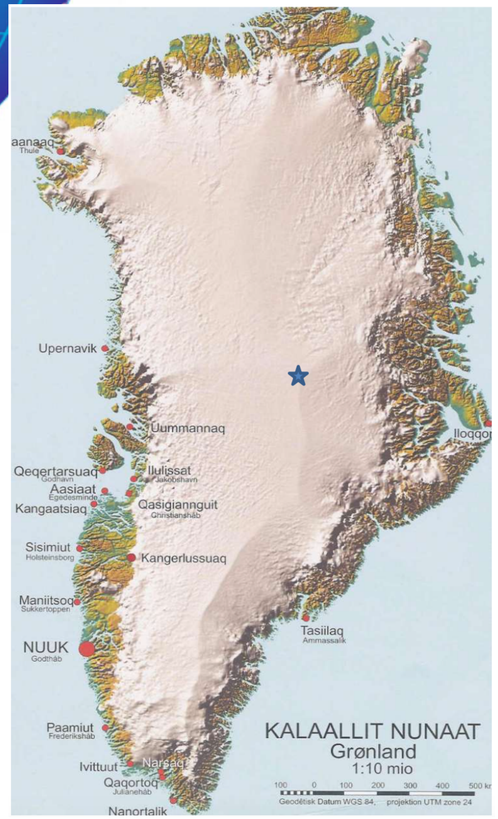
PUEO Collaboration Meeting, April 2024, Ohio State Univ

Courtesy: A. Vieregg

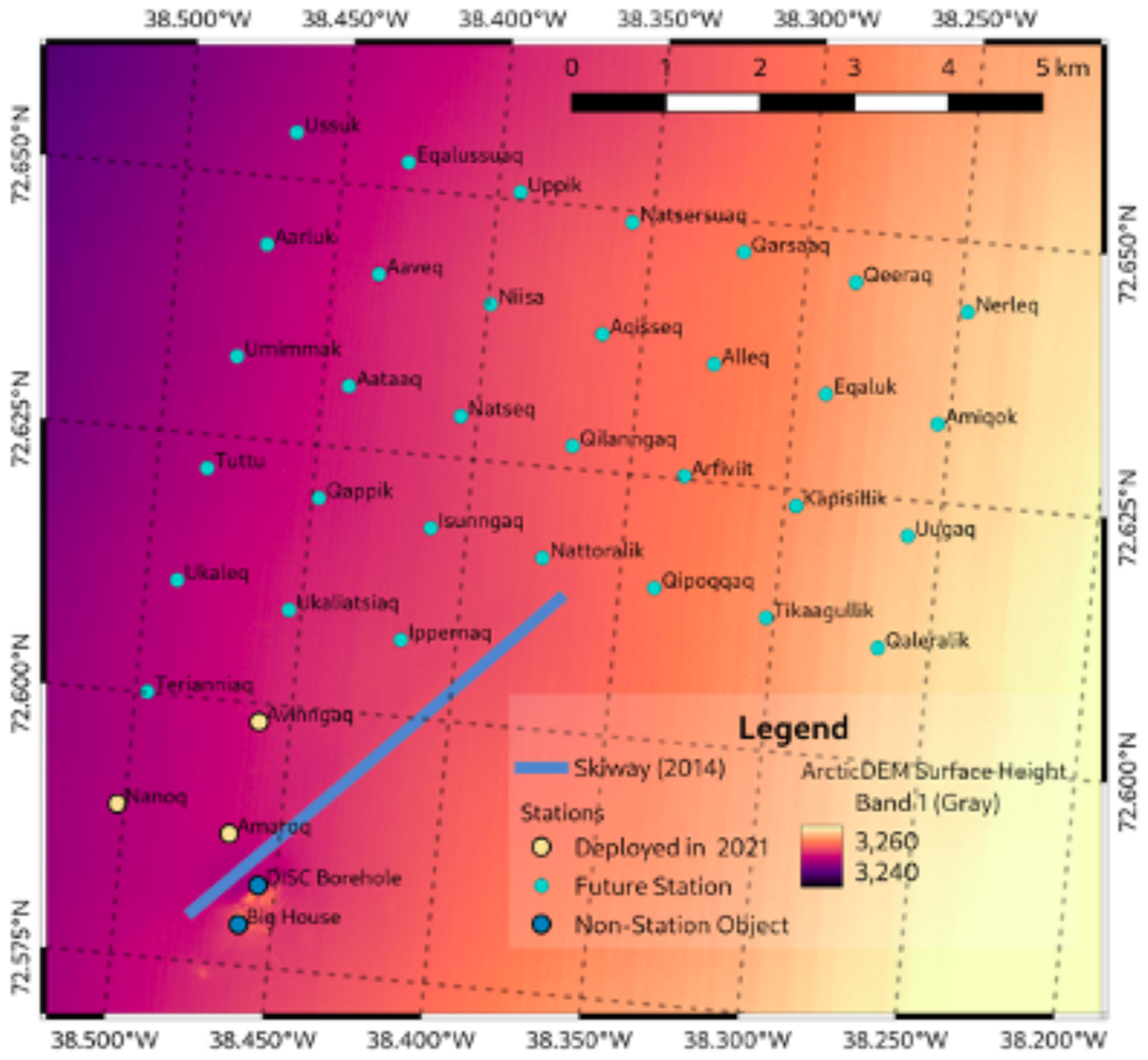


Courtesy: A. Vieregg

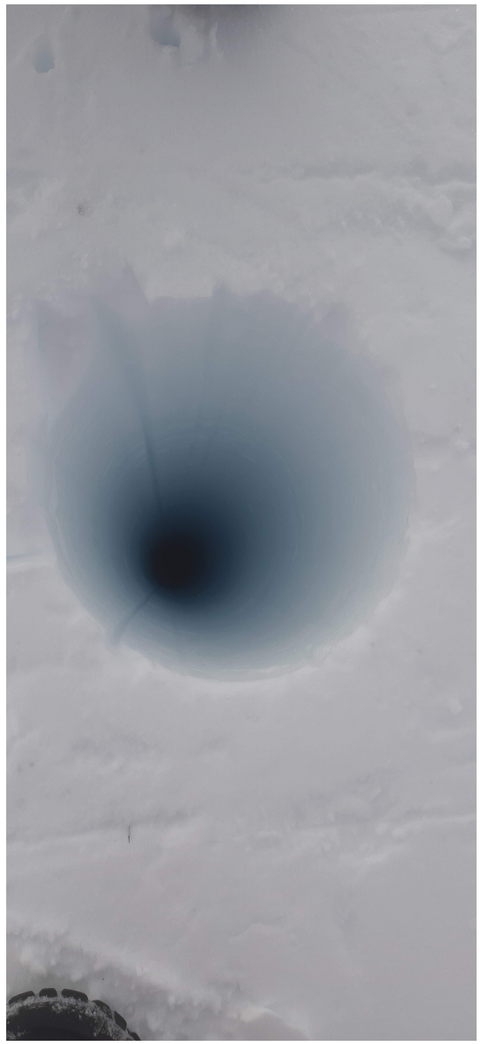
A Sun Dog and myself at midnight



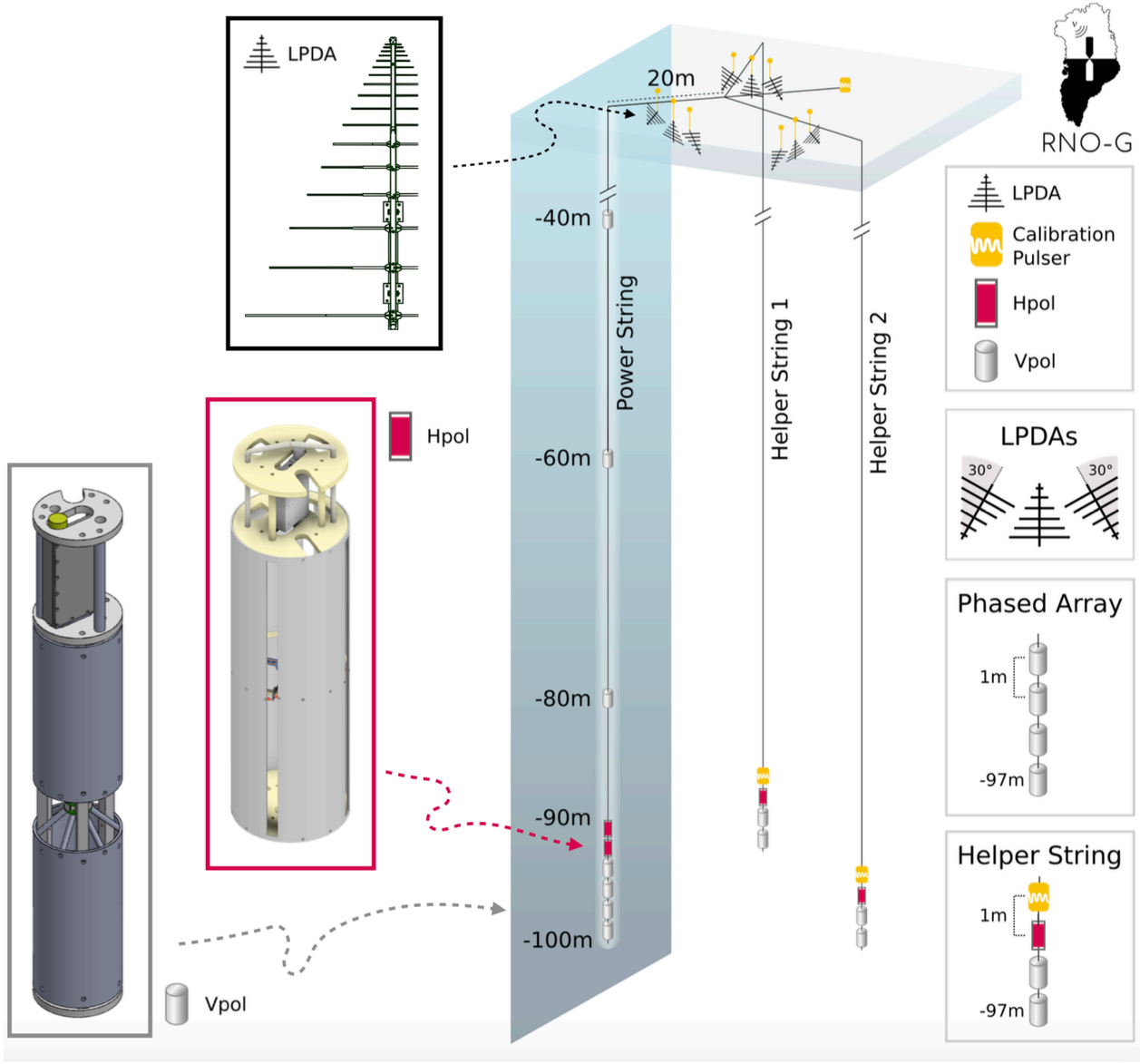
The Radio Neutrino Observatory (RNO-G) Experiment in Greenland



Drilling of deep holes in the Greenland Ice

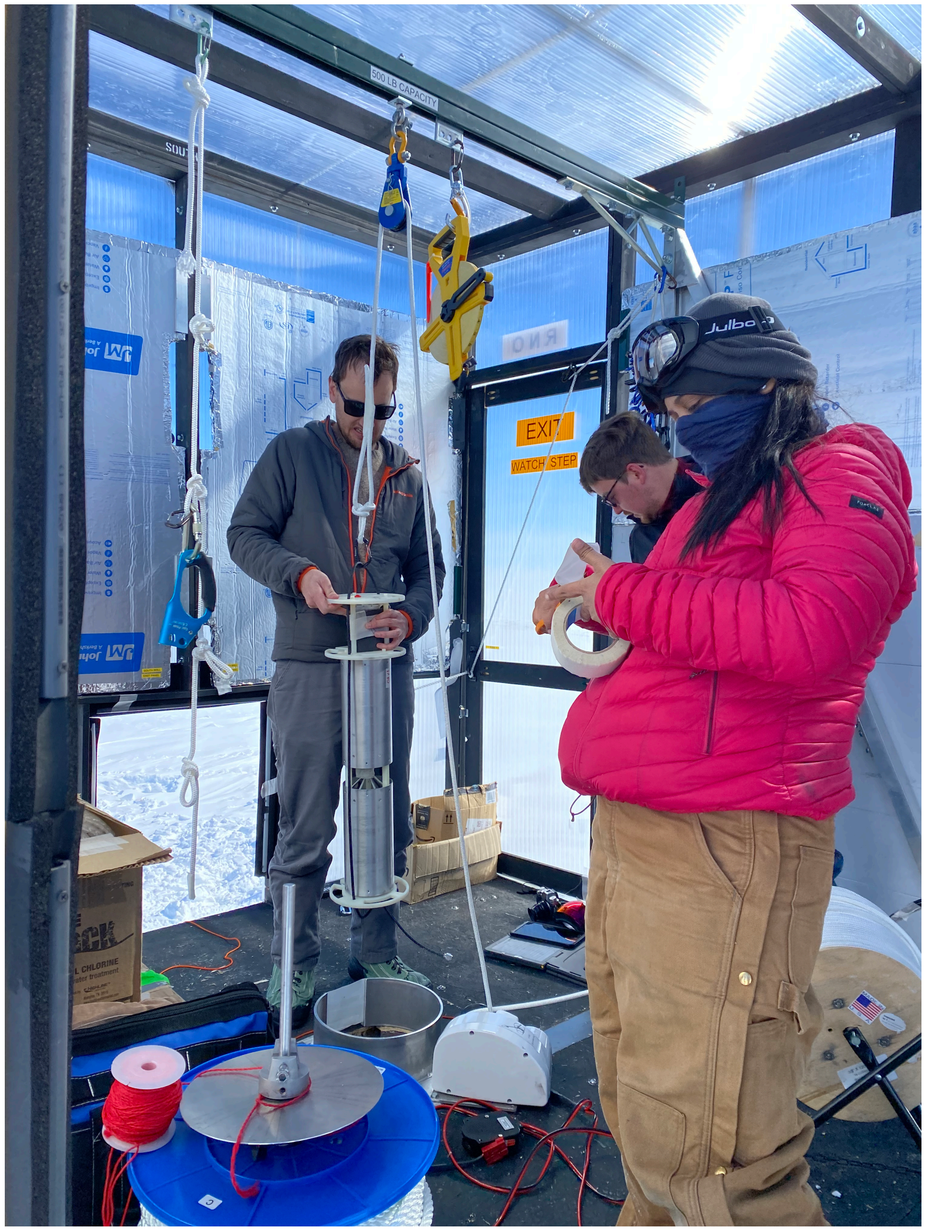


RNO-G Station Layout



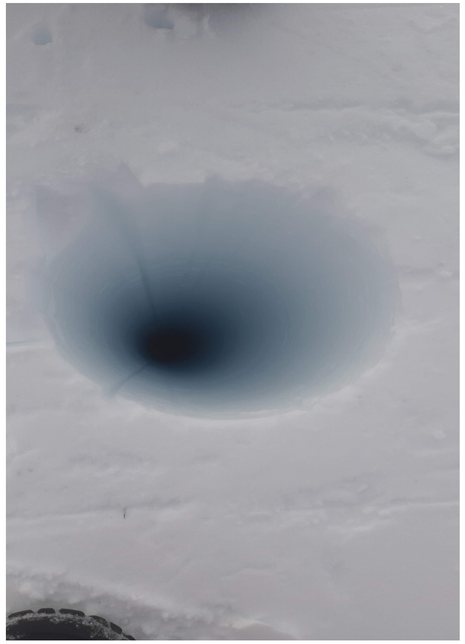
Paramita Dasgupta, CCAPP, Ohio State Univ.

RNO-G Deployment 2022 : My time on the Greenland Icesheet



RNO-G Deployment 2022 : My time on the Greenlandic Icesheet

RNO-G Deployment 2022 : My time on the Greenland Icesheet



SUMMIT STATION

72.58°N, 38.46°W, 3256 M

OCTOBER 2017

POLAR FIELD

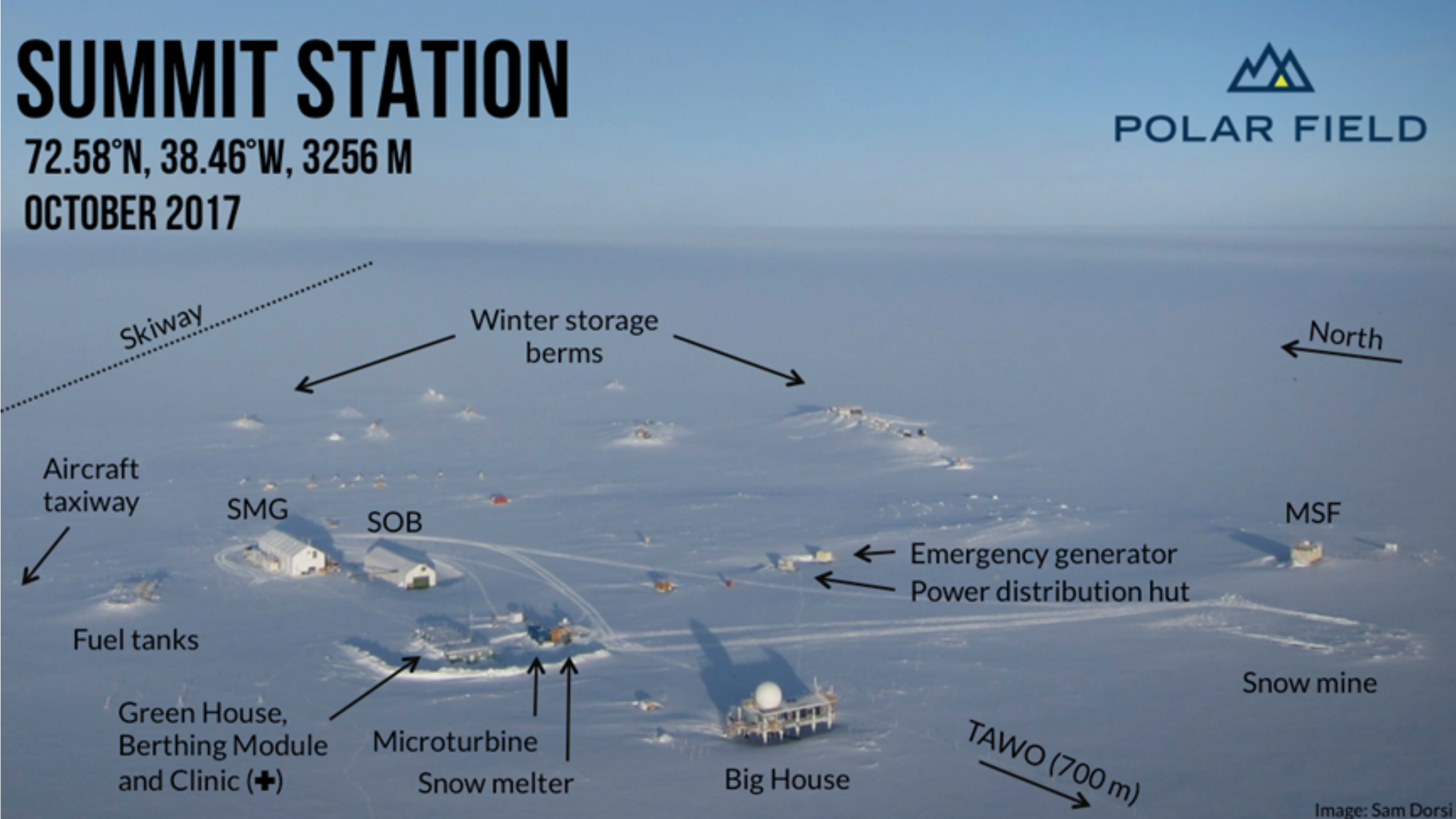


Image: Sam Dorsi


SUMMIT
STATION

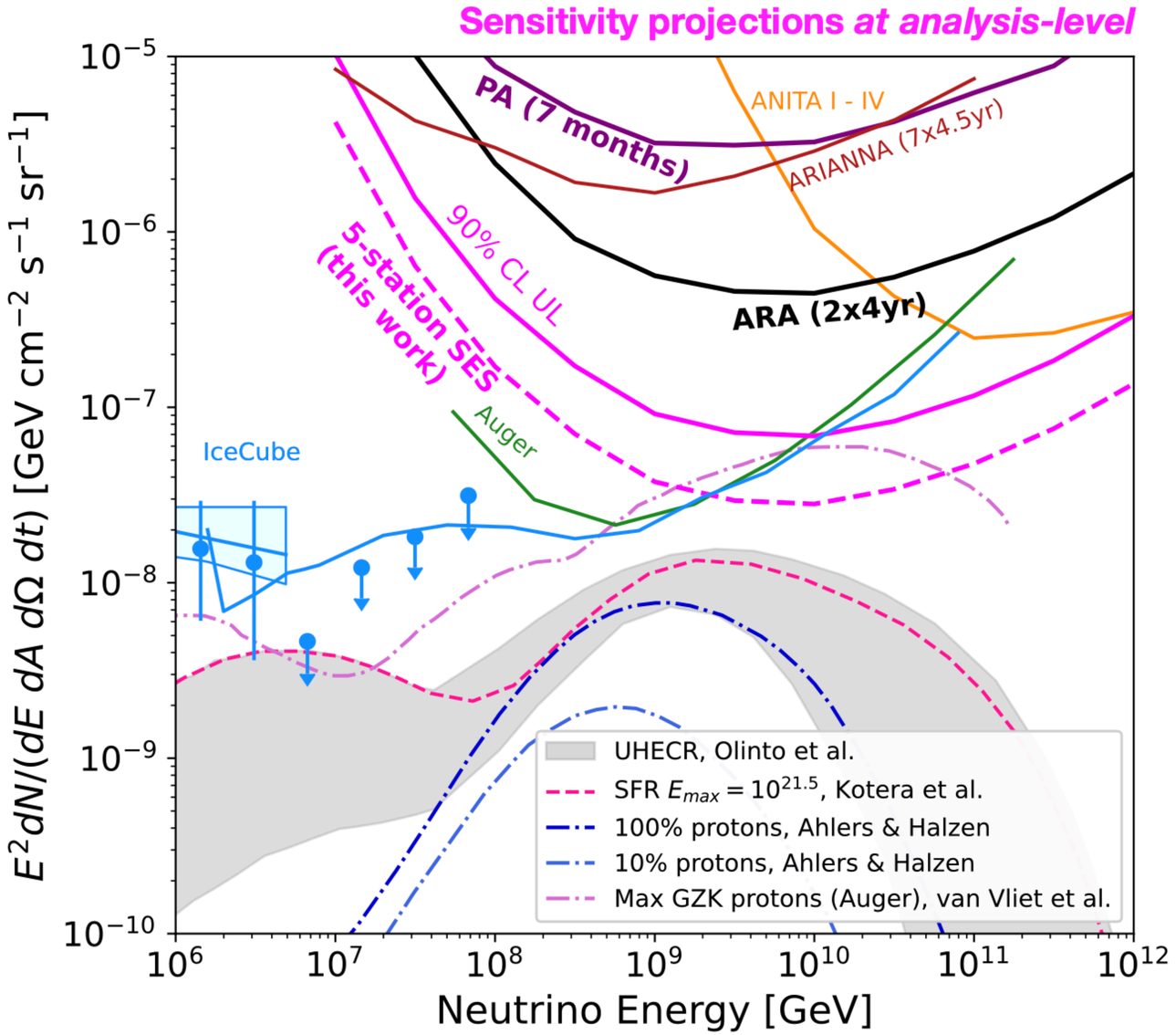
Surveying of RNO-G stations post deployment

Picture Courtesy Stephanie Wissel

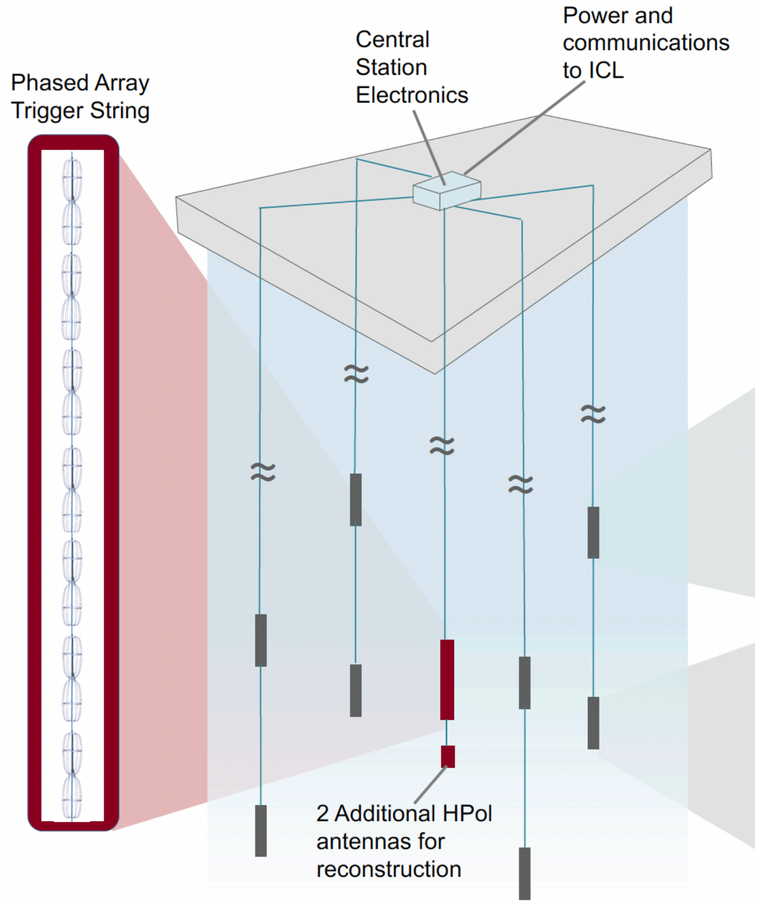
First ever UHE neutrino search with Decade long livetime

- Kotera et al. flux: ~ 3.1 events
- van Vliet et al. (Auger) flux: ~ 14.4 events
- IceCube 2018 limit flux: ~ 18.5 events

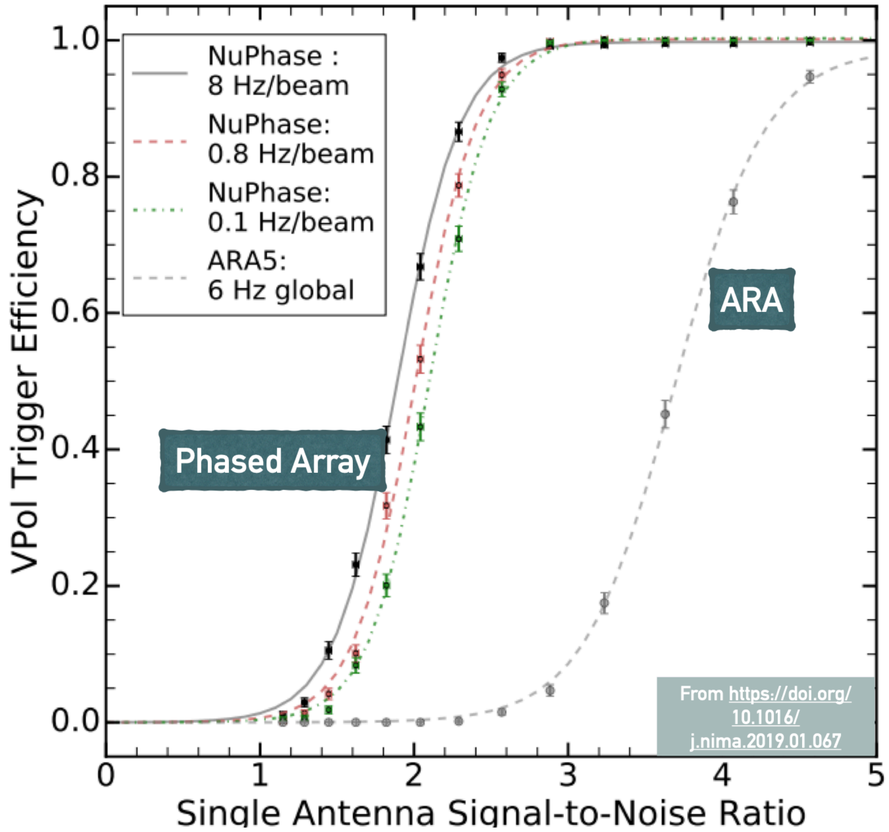
Stay tuned !!



The Phased Array



Improved Trigger efficiency



?

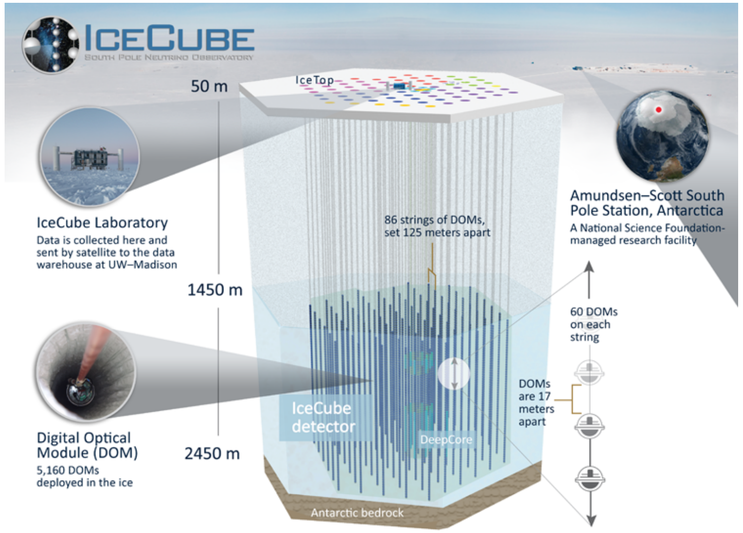
Analysis Efficiency

Astrophysical Neutrinos

Neutrinos born in (or near) the cosmic ray accelerators

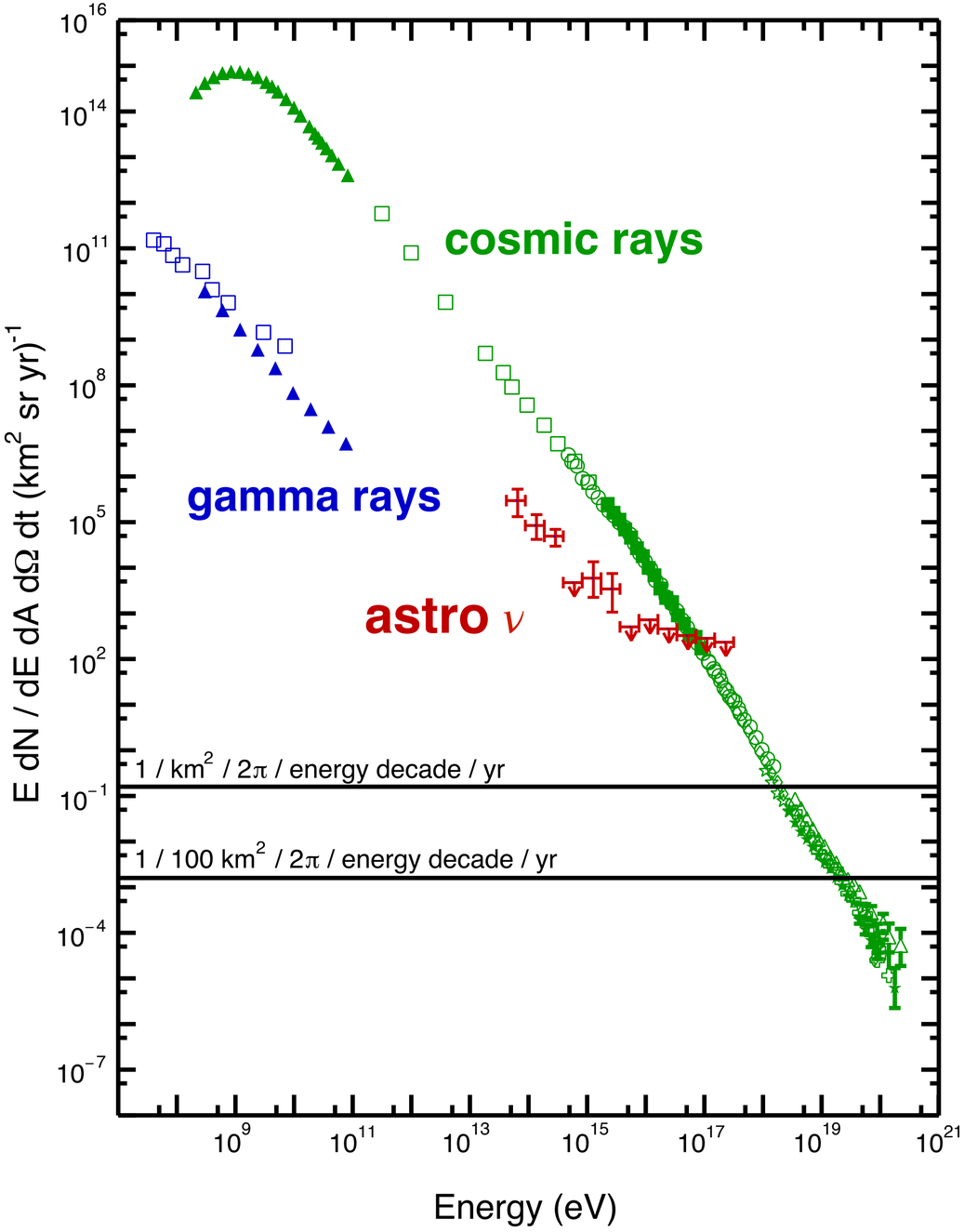
Unambiguous proof of hadronic acceleration

Neutrinos have been Detected in 2012 !
(Only hints of sources)



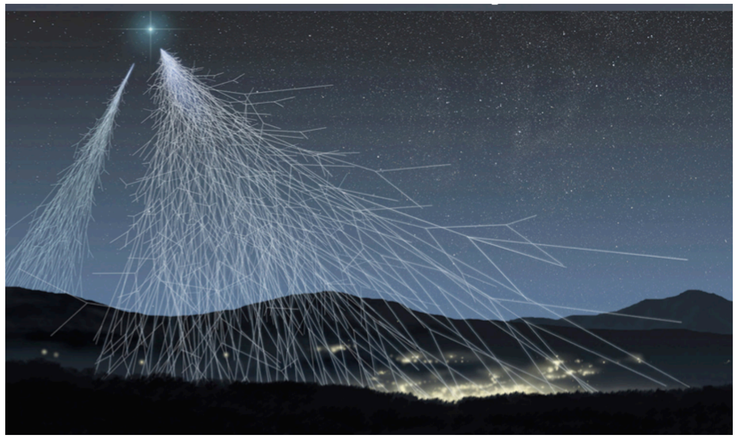
AGN, NGC 1068

first evidence of a neutrino source
4.2σ Significance

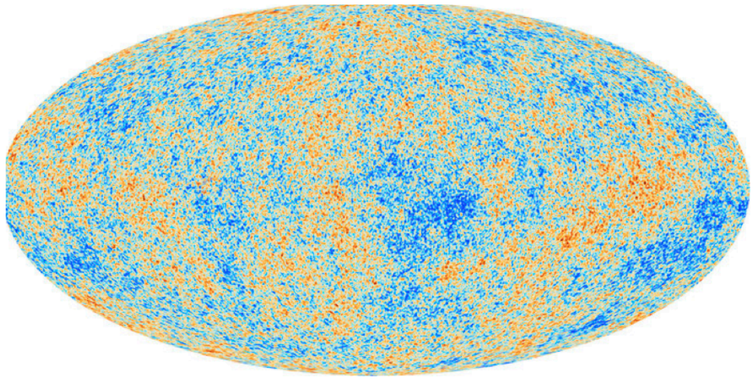


UHE Neutrino production: The GZK process

Cosmic Ray

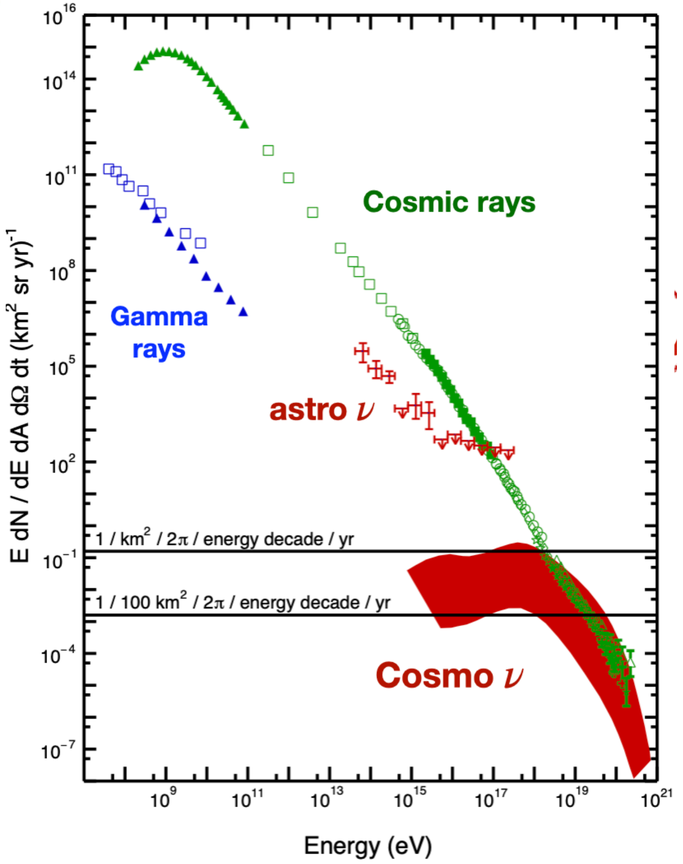


CMB photons



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

= **Neutrino beam !**

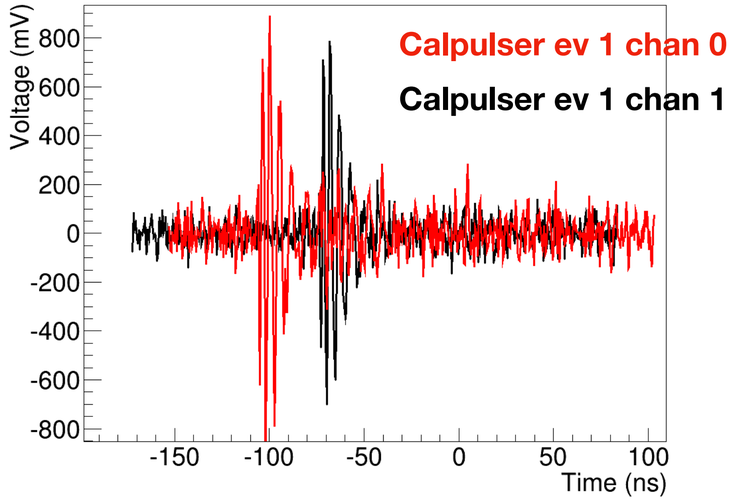


Classification of ARA data

1. Calibration Pulser Events

Recoded every second for in-situ calibration

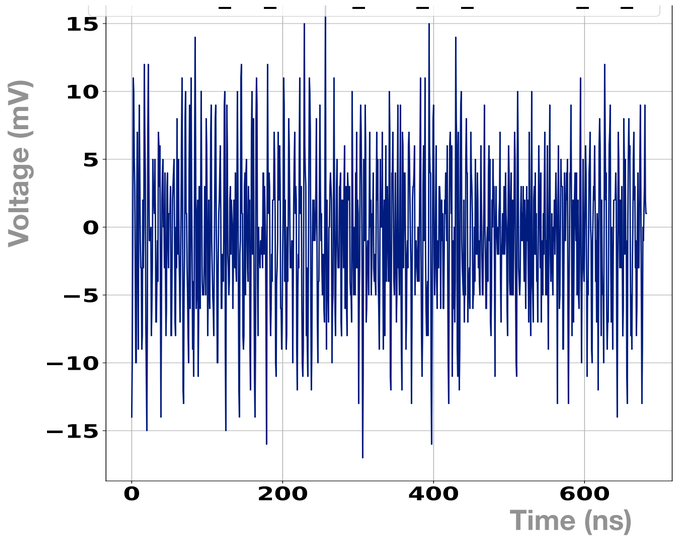
Calibration pulser event



2. Software Trigger Events (Forced Triggers)

Recorded every second to monitor the detector performance, sample the noise environment

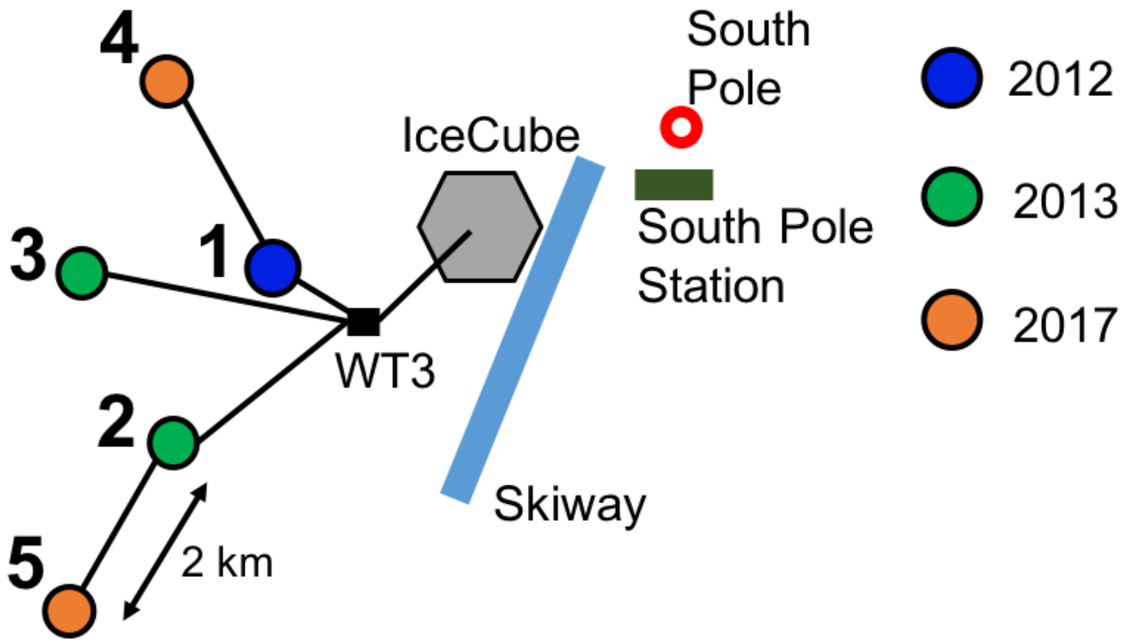
Thermal noise event



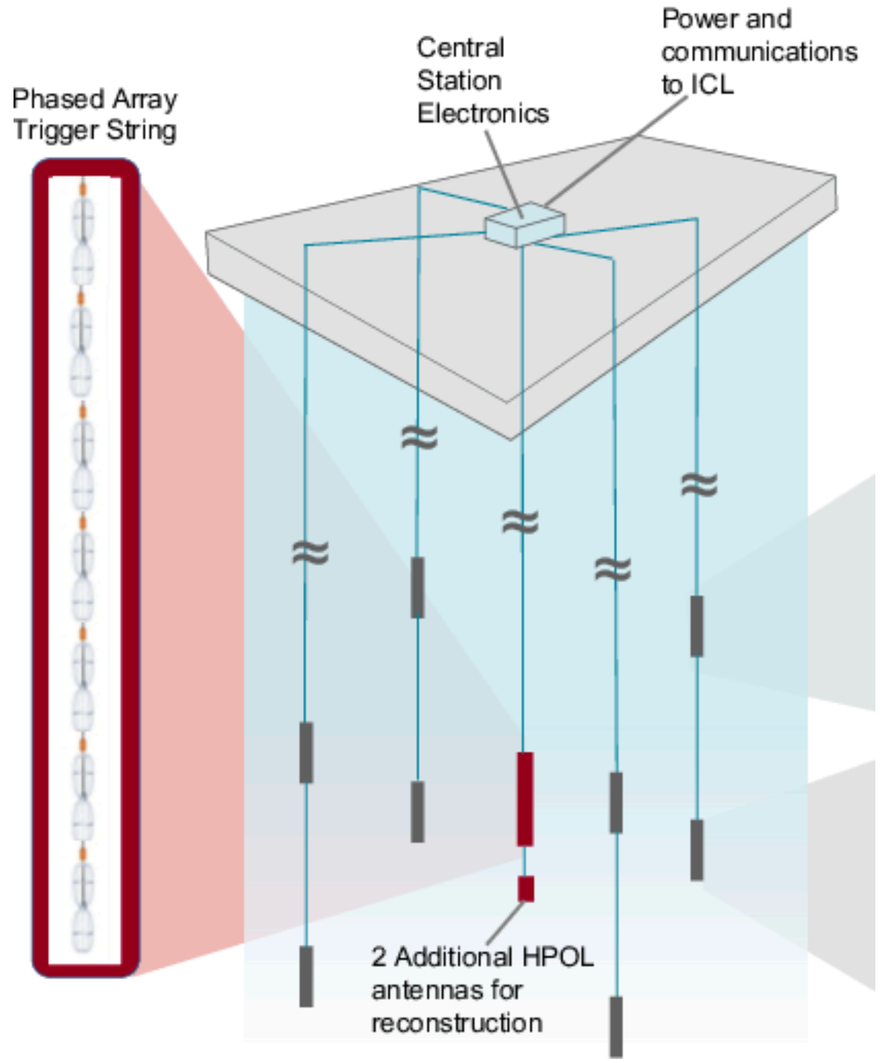
3. RF Trigger Events

Mostly thermal events + non-thermal background (eg, CR, CW, anthropogenic events, ….) + non-thermal ν-induced signal events

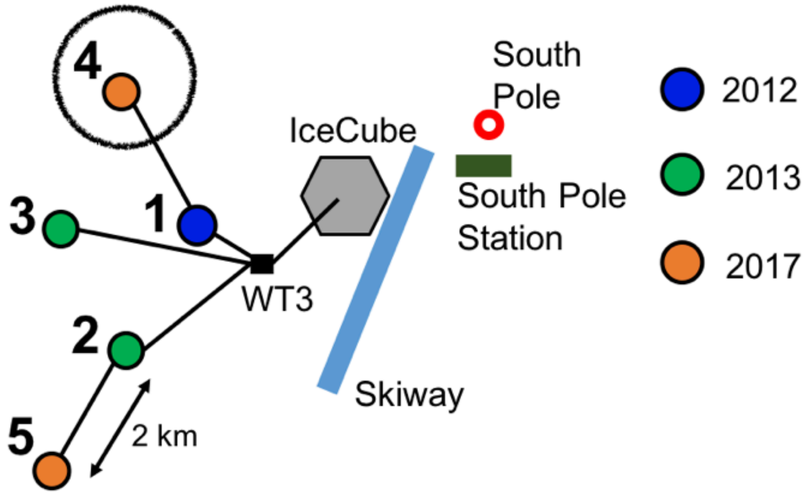
The 5th Station of ARA



A5 + PA system



Calibration for ARA stations

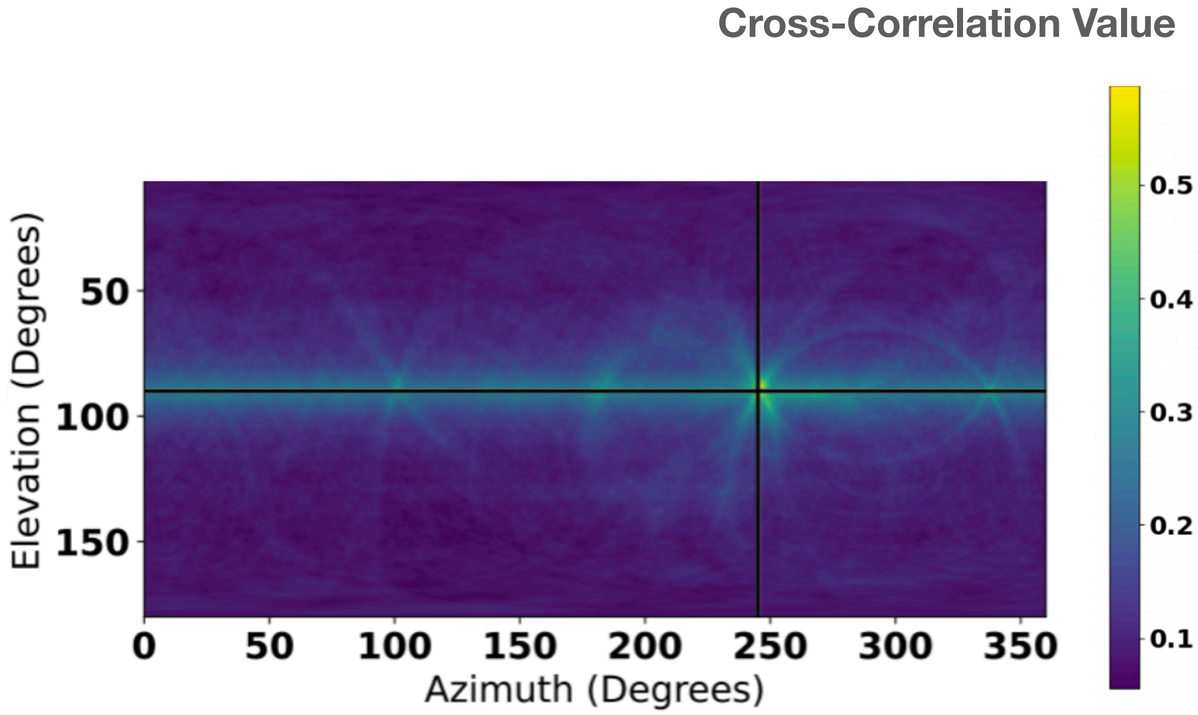


PROCEEDINGS OF SCIENCE
ONLINE ICRC 2021

The Calibration of the Geometry and Antenna delay in Askaryan Radio Array Station 4 and 5

Paramita Dasgupta[a,*] **Kaeli Hughes**[b] **on behalf of the ARA Collaboration**
(a complete list of authors can be found at the end of the proceedings)

[a] *Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium*
[b] *Dept. of Physics, Enrico Fermi Inst., Kavli Inst. for Cosmological Physics, University of Chicago, Chicago, IL 60637, U.S.A.*
E-mail: paramita.dasgupta@ulb.be, kahuges@uchicago.edu



< 0.5 degree resolution on vertex reconstruction