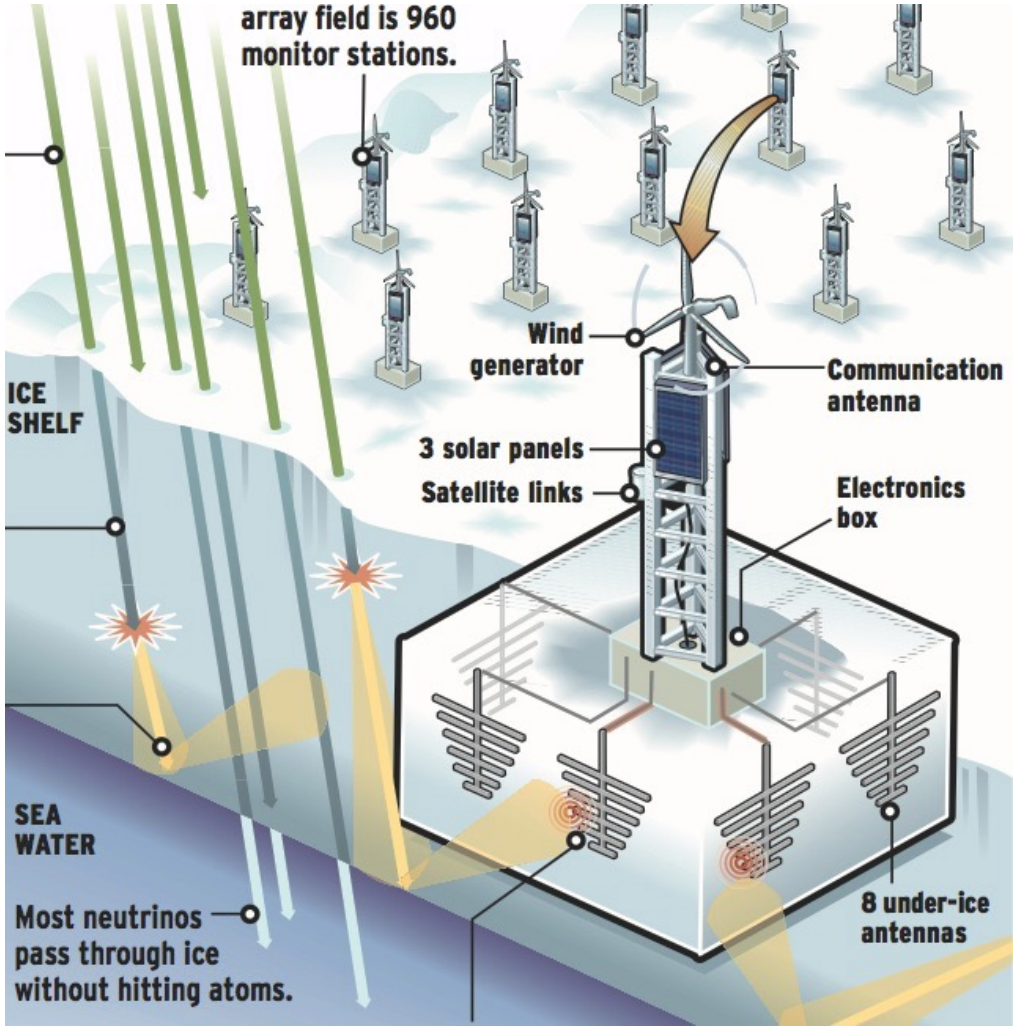
The development of near surface radio detectors for high energy neutrino astronomy - from ARIANNA to IceCube-Gen2

Credit: OC Register

ARIANNA Concept 2012



RENCONTRES DU VIETNAM

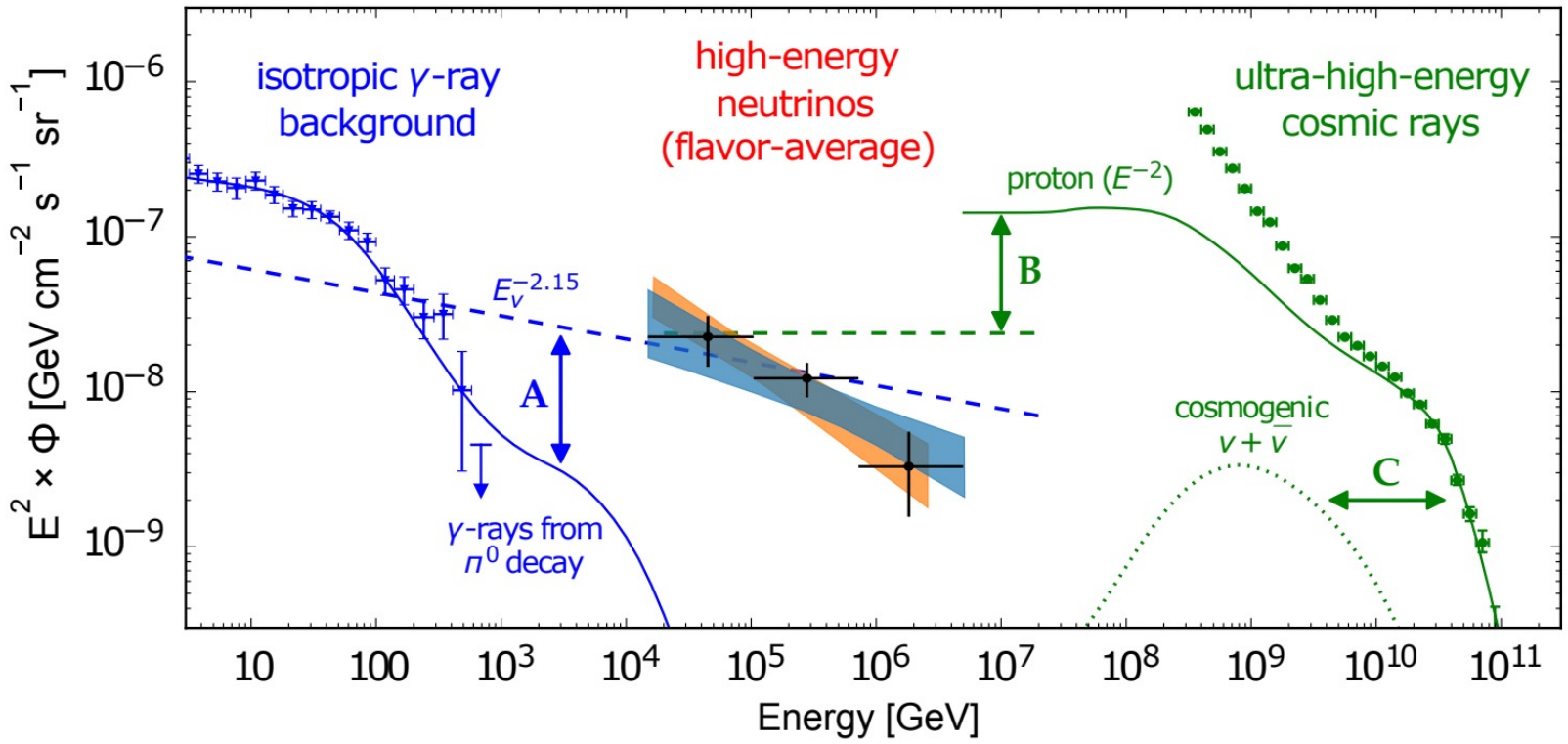
Jan 5, 2025

Steven W. Barwick

UCI University of California, Irvine

Why is radio needed in EeV=10^9 GeV neutrino astronomy?

A. Ishihara, ICRC2023



Cosmogenic EeV neutrinos required Order 10^3 times larger detection volumes than IceCube!

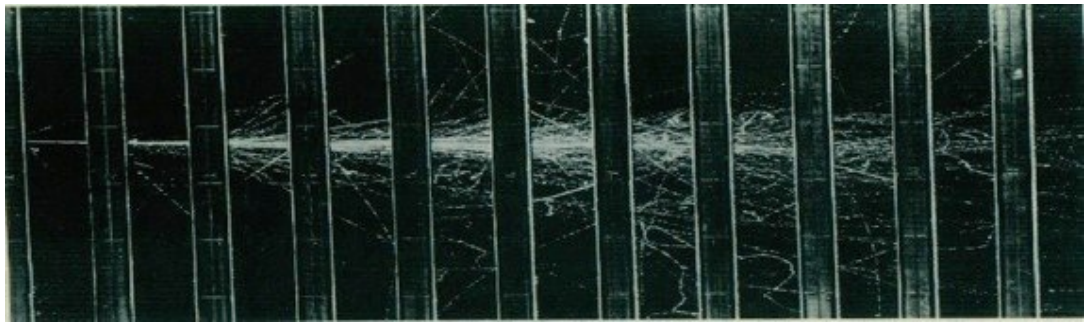
What is different about radio?

- Attenuation length for radio is 10x larger than for optical photons in cold Antarctic ice
  - Separate the sensors by 1000m instead of 100m
  - Factor of 100 decrease in area density
- Air bubbles do not affect radio wavelength
  - all ice can be used, not just below 1500m
  - sensor stations can be placed within meters of the surface, reducing costs (drilling is expensive)
- Straightforward to measure polarization, so a single station can measure energy and direction.

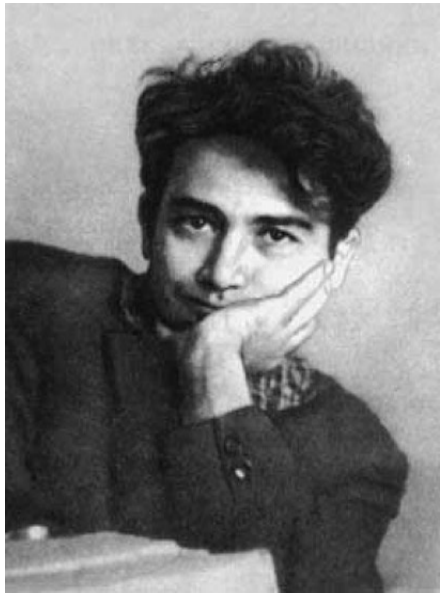
For overview: see Barwick and Glaser, Encyclopedia of Cosmology; arXiv:2208.04971

Radio Detectors: The Askaryan Effect

- EM, hadronic cascade in in dense, dielectric media (ice)
- Coherent radio Cherenkov radiation ($P \sim E^2$) if $\lambda >$ Moliere radius

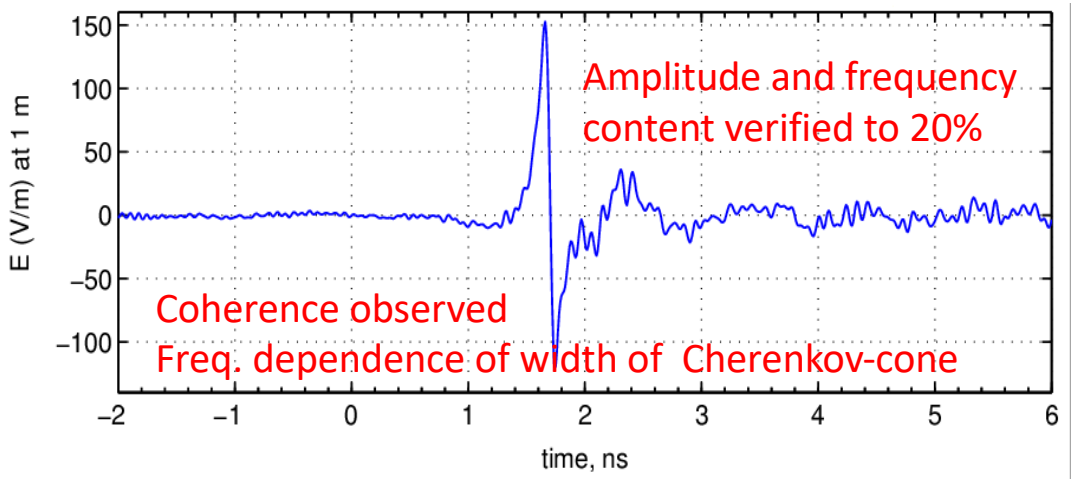


Typical Dimensions:
L ~ 10 m
$R_{moliere}$ ~ 10 cm



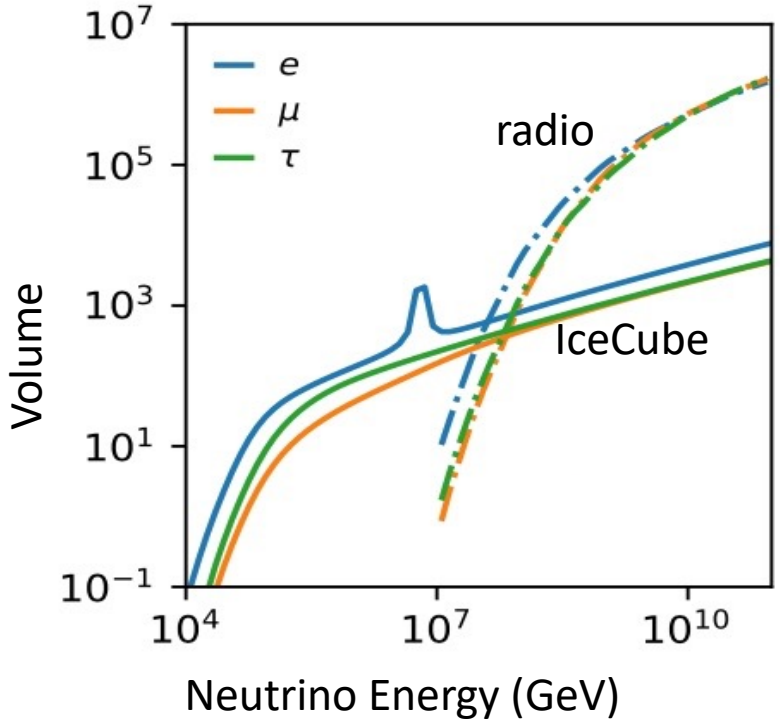
G. Askaryan

SLAC Tests confirmed expectation in ice



ANITA Coll., PRL (2007)

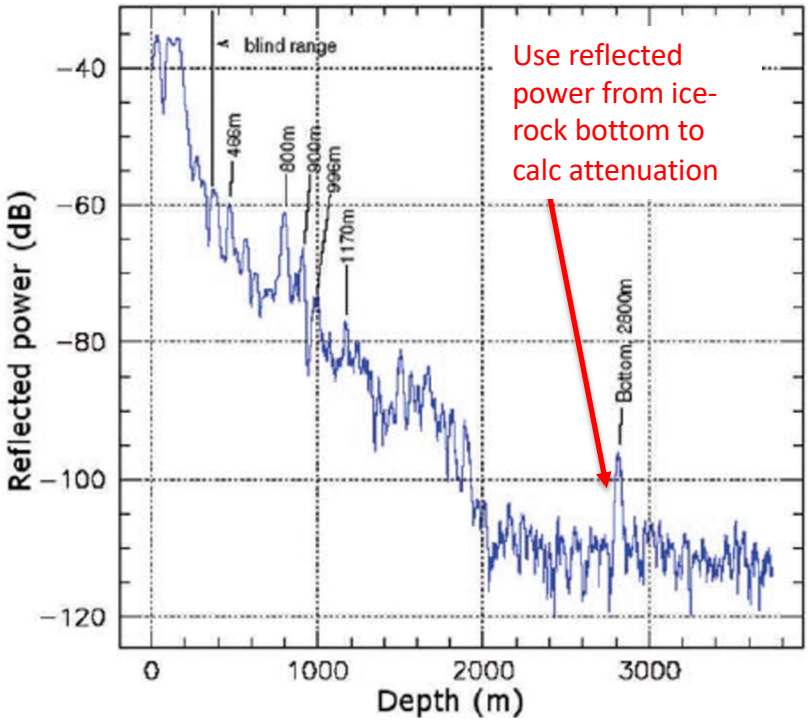
Upshot: Particle cascades with N ~10^9 produce measurable radio pulses, and radio power in coherent emission grows as neutrino Energy squared



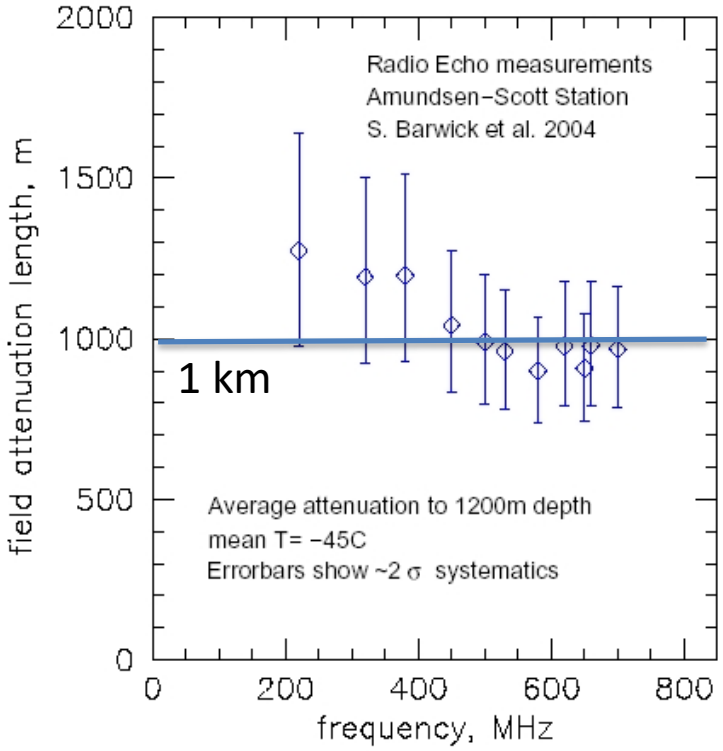
Book chapter intro to radio neutrino astronomy:
Barwick and Glaser (arXiv:2208.04971)

Field Attenuation Length in ice

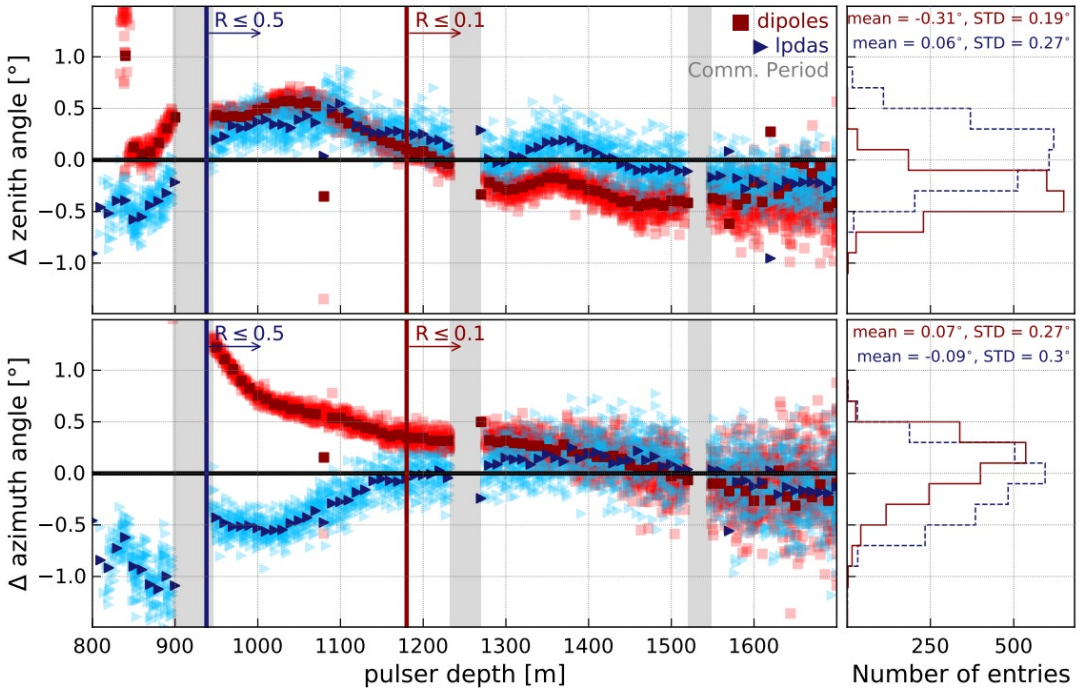
Barwick et al, J. Glaciology 51 (2005)231



S. Pole, Antarctica



Propagation Measurement by ARIANNA station in South Polar Ice



ARIANNA Collab, JINST 15 (2020) 09, P09039

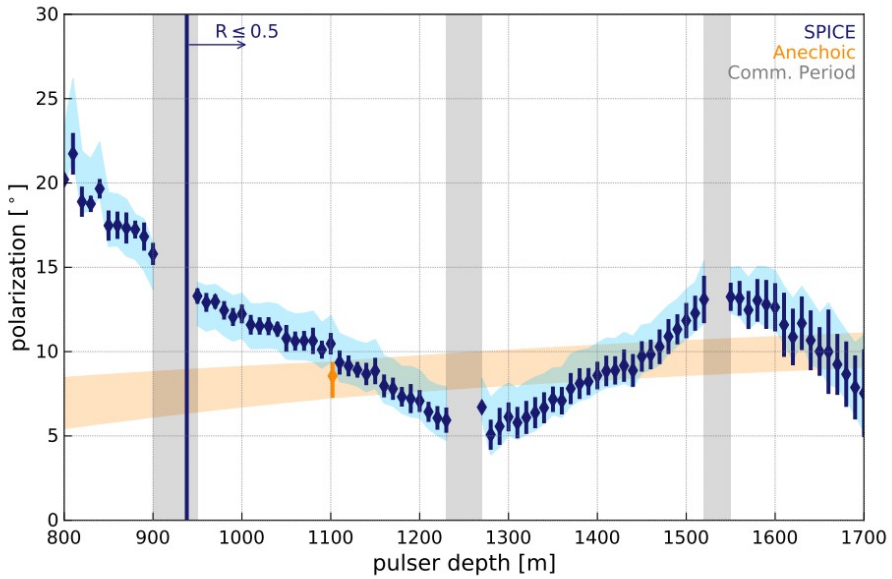
Lowered radio pulser to a depth of 1700m

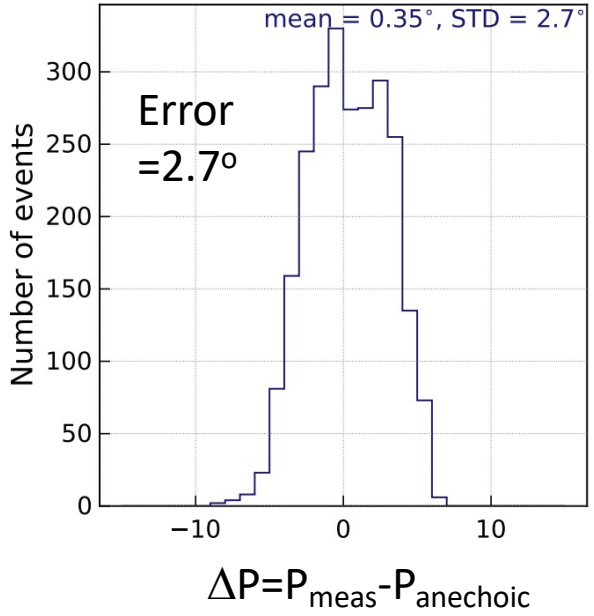
LPDA reconstruct the arrival angles to an accuracy of 0.3 degrees,

where

Δ= (angle measured) – (angle predicted from ray tracing)

Polarization Measurement by ARIANNA in South Polar Ice -1

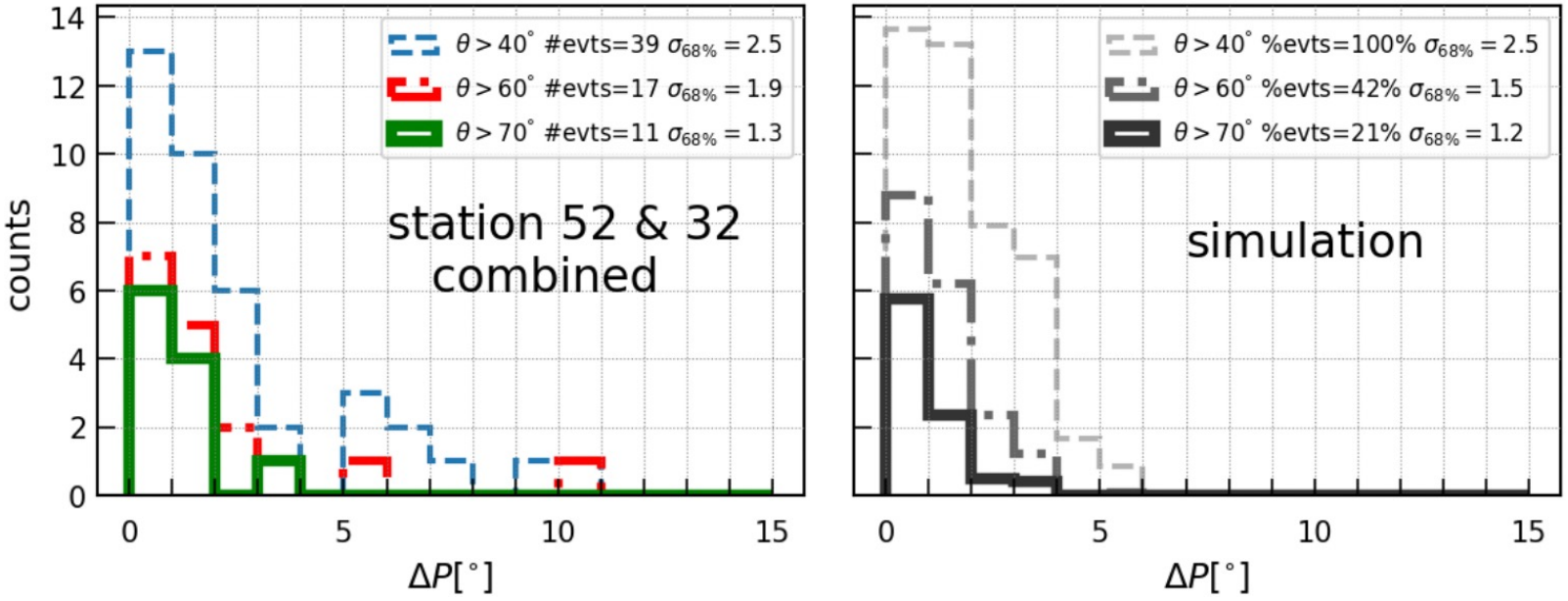




ARIANNA Collab, JINST 15 (2020) 09, P09039

Polarization measurement -2

Using Cosmic Ray radio signals to verify polarization reconstruction



Horizontal Polarization error, ΔP, is 2.5 deg

ARIANNA Collab, JCAP 04 (2022) 04, 022

ARIANNA “radio” neutrino detector

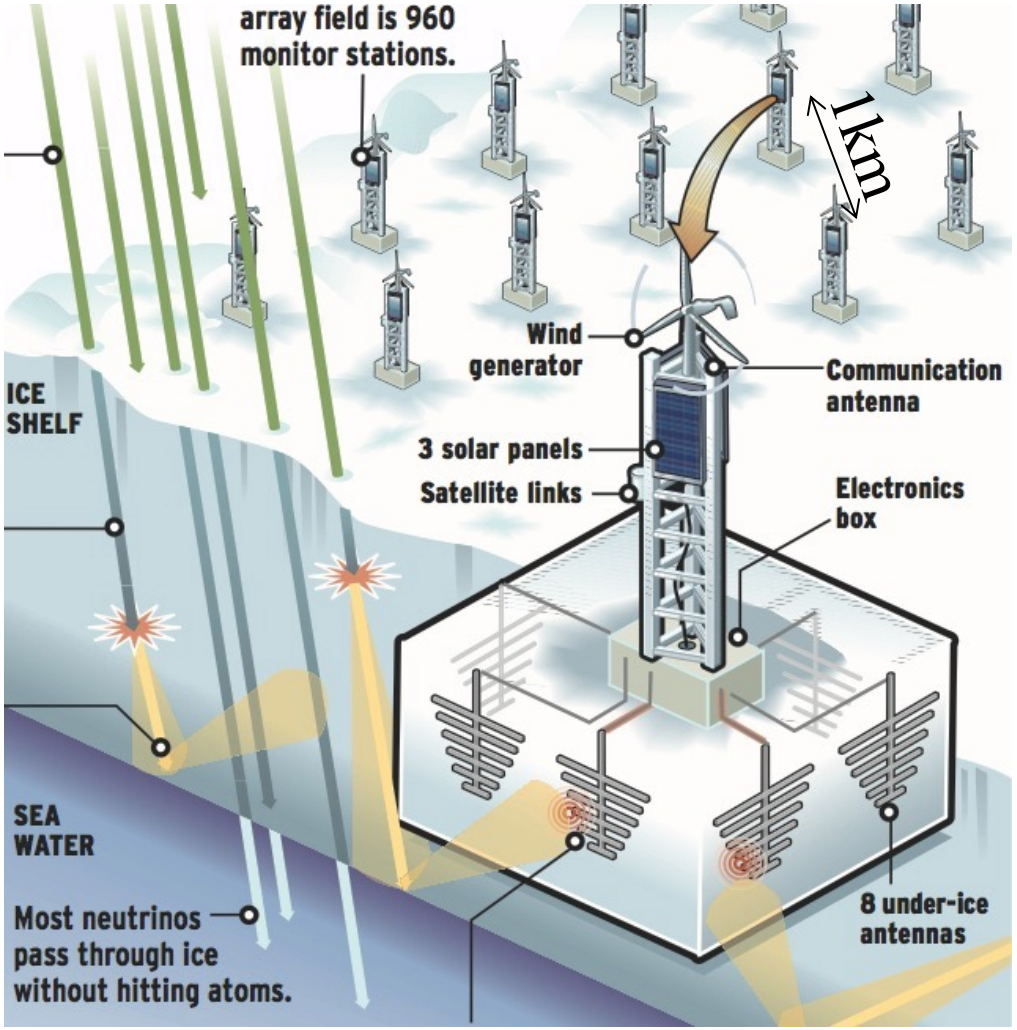
International ARIANNA collaboration

US

Sweden

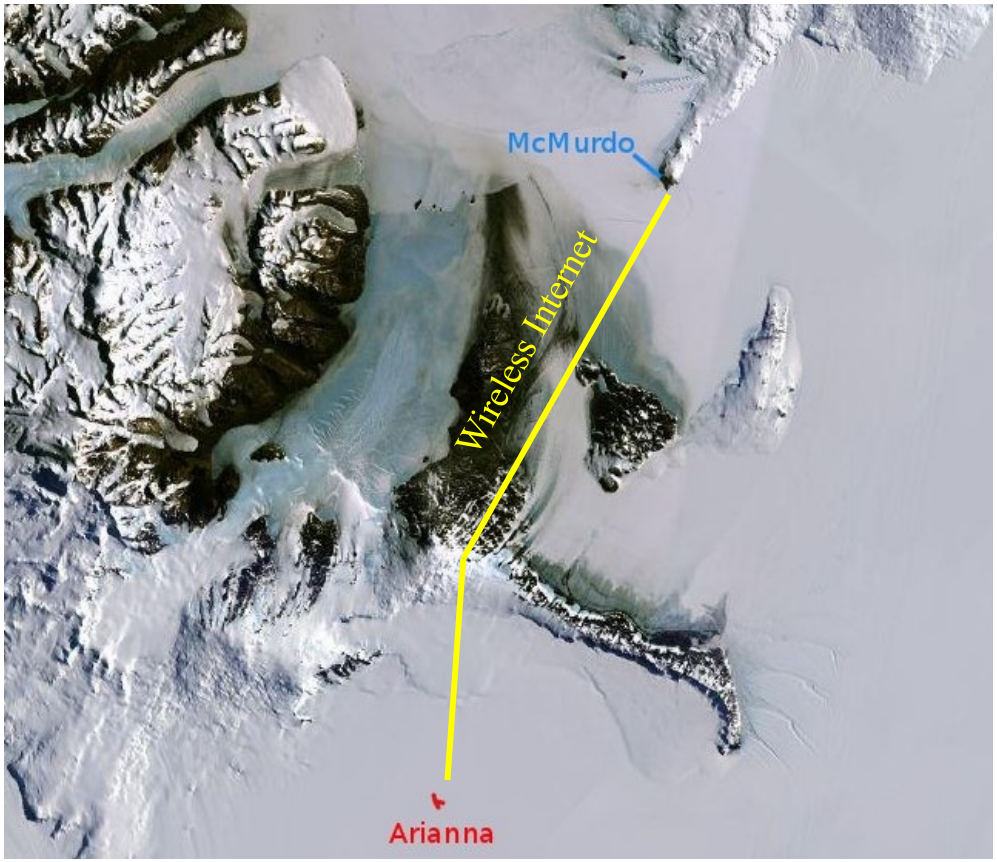
Germany

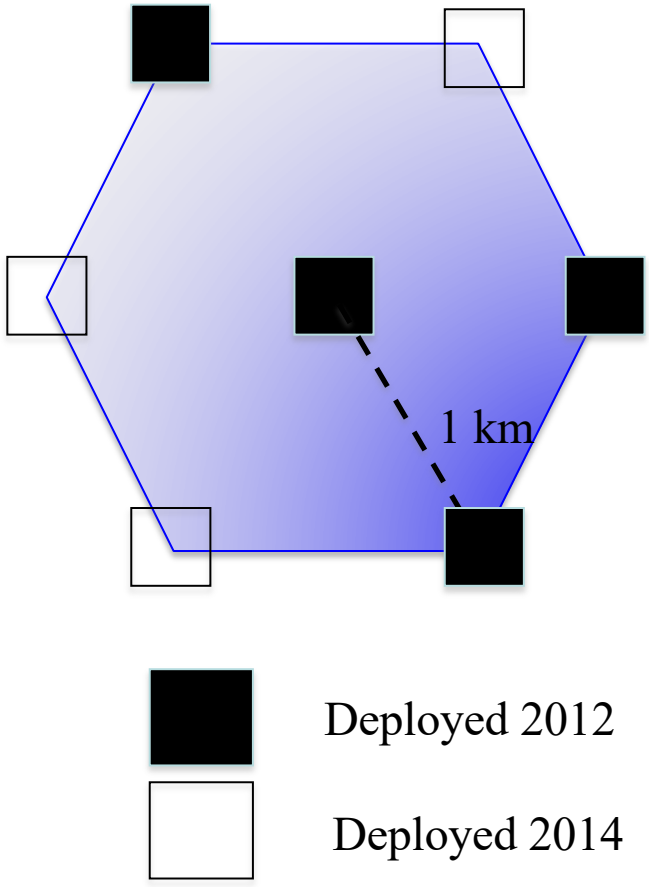
https://arianna.ps.uci.edu/



From OC Register 2012

ARIANNA Pilot Array
Completed: 2014

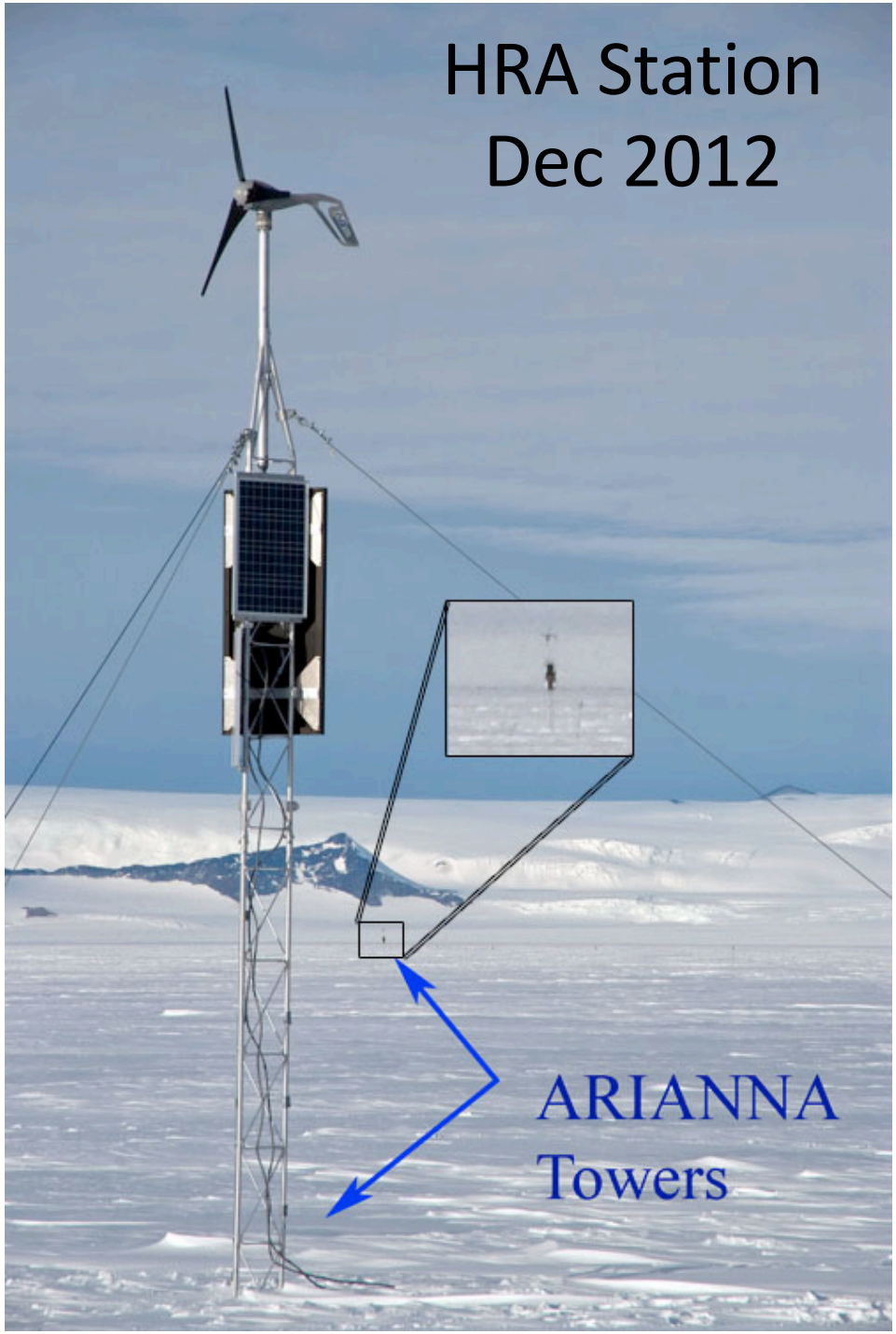




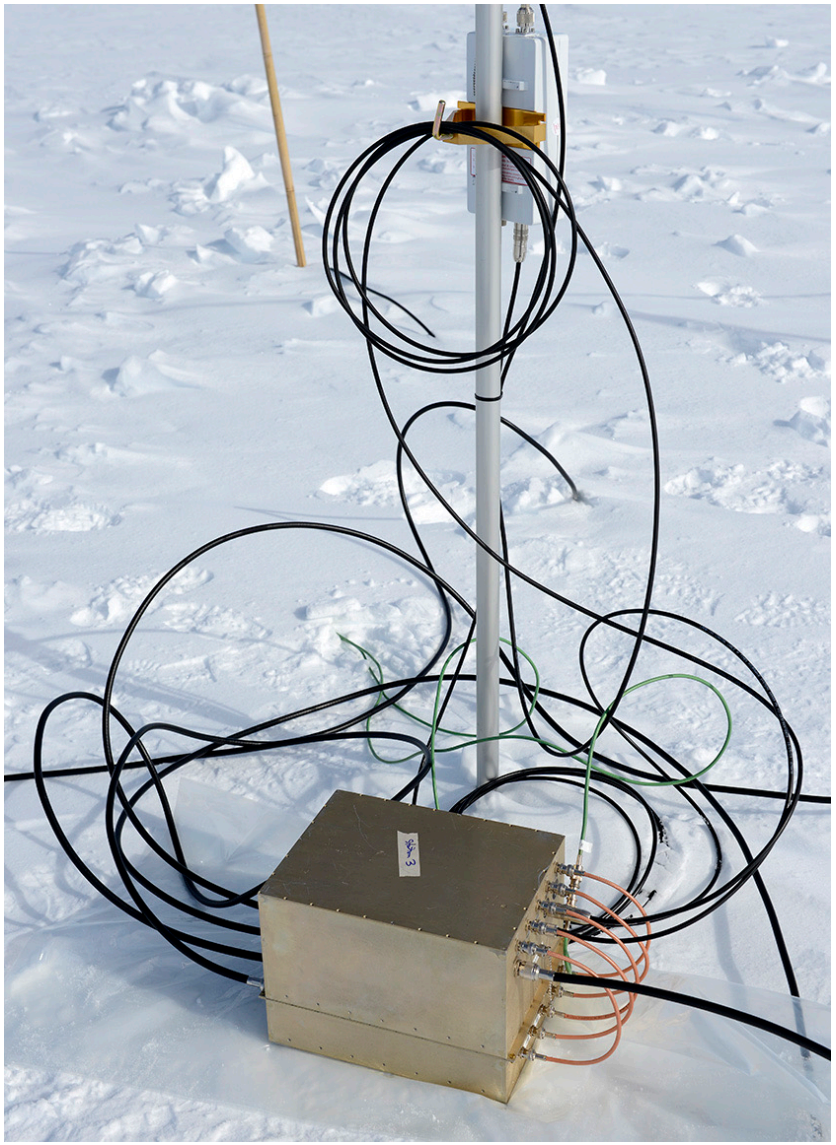
Decommissioned in 2021

Constructing ARIANNA Station

Installation: Each station required 2/3 day and 4 people; Gen2 radio will be even faster.

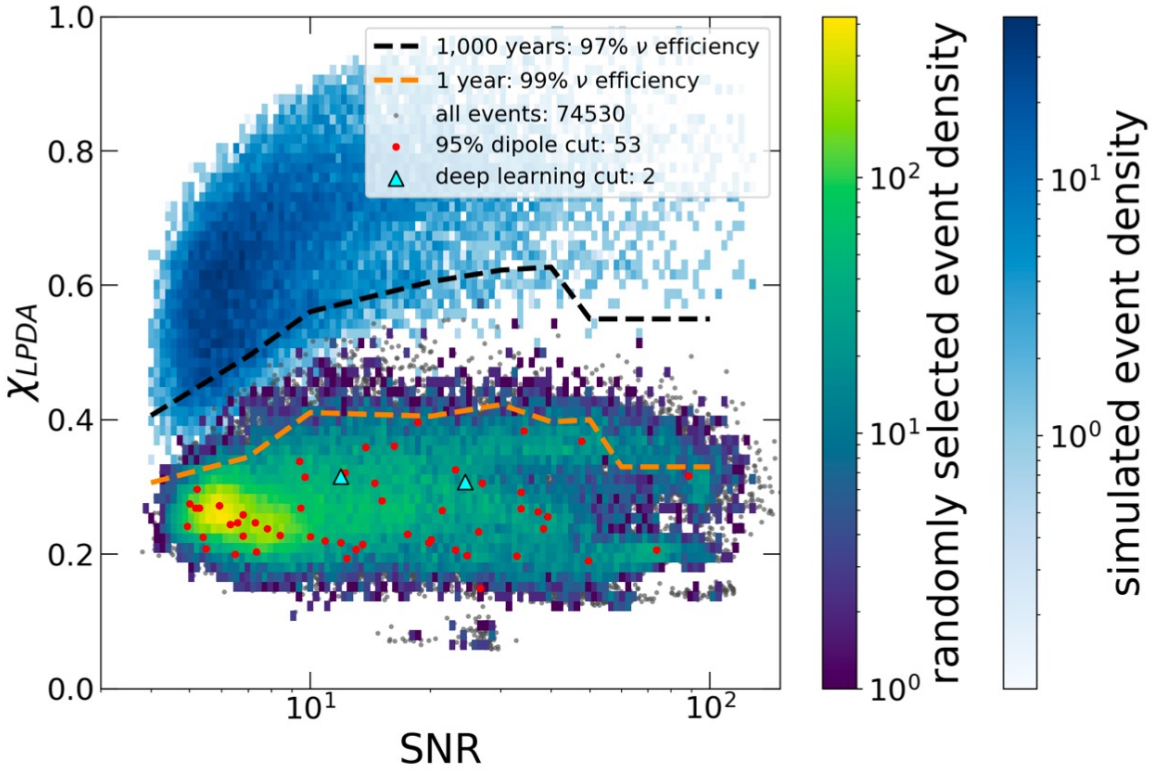


Electronics and base of comms tower
(transmission over Iridium Satellite)



It Works!

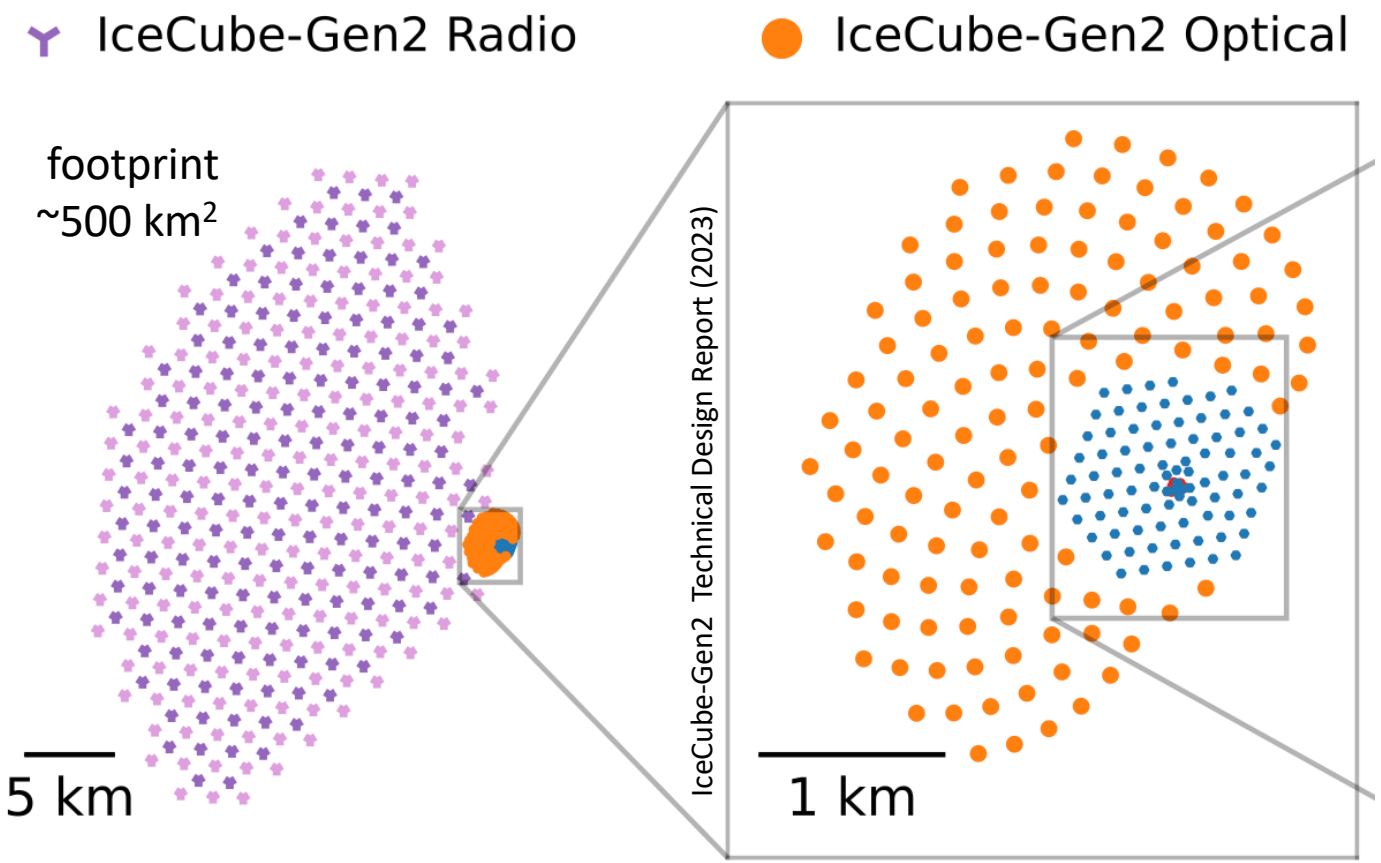
ARIANNA: A. Anker, et al, JCAP 10(2023)060



Blue shows where a neutrino would be if ARIANNA did find one (it didn't)

Triangles are only ARIANNA data events surviving from search.

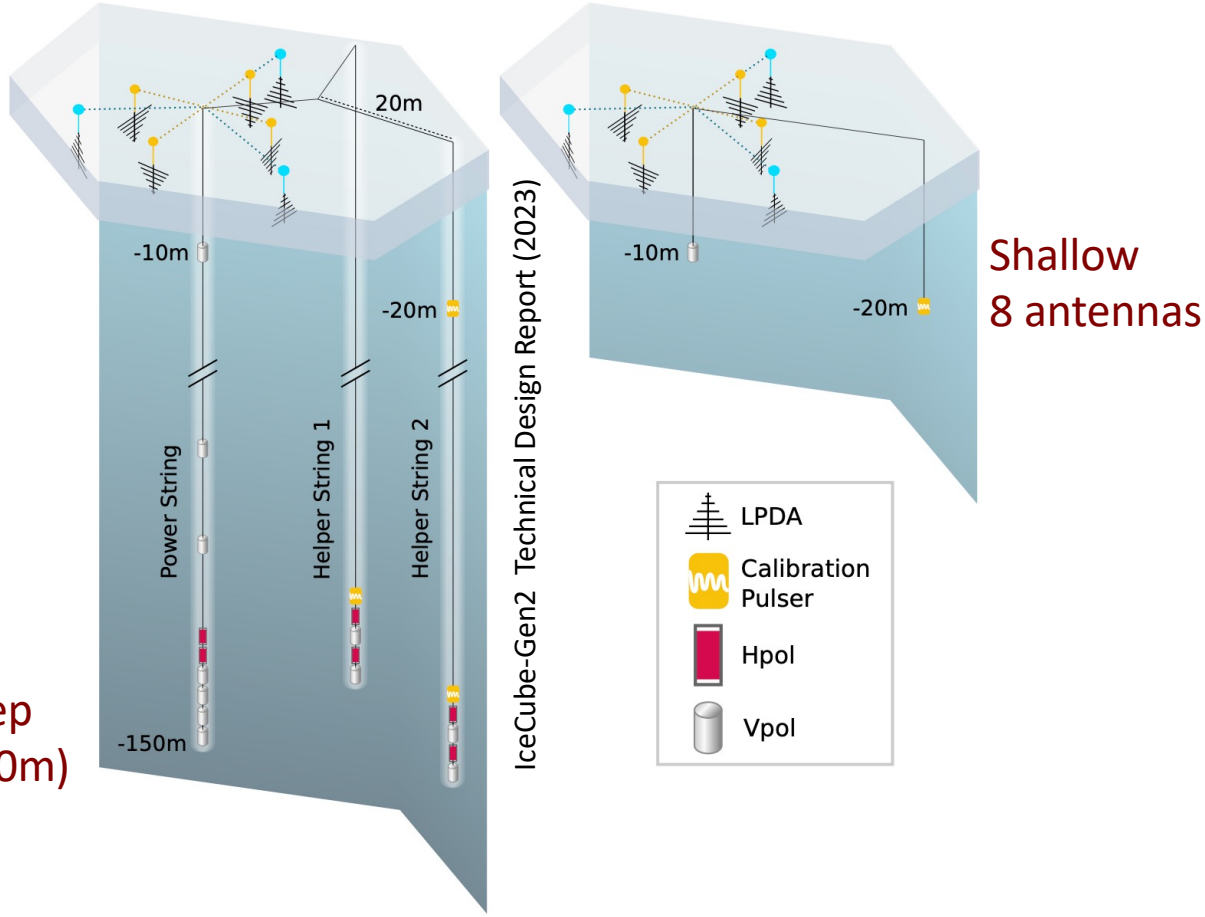
IceCube-Gen2 Station Grid Layout



shallow:hybrid ratios between 2:1 and 4:1
compatible with science goals

IceCube Gen2 Radio Detector

Hybrid
24 antennas



Shallow
8 antennas

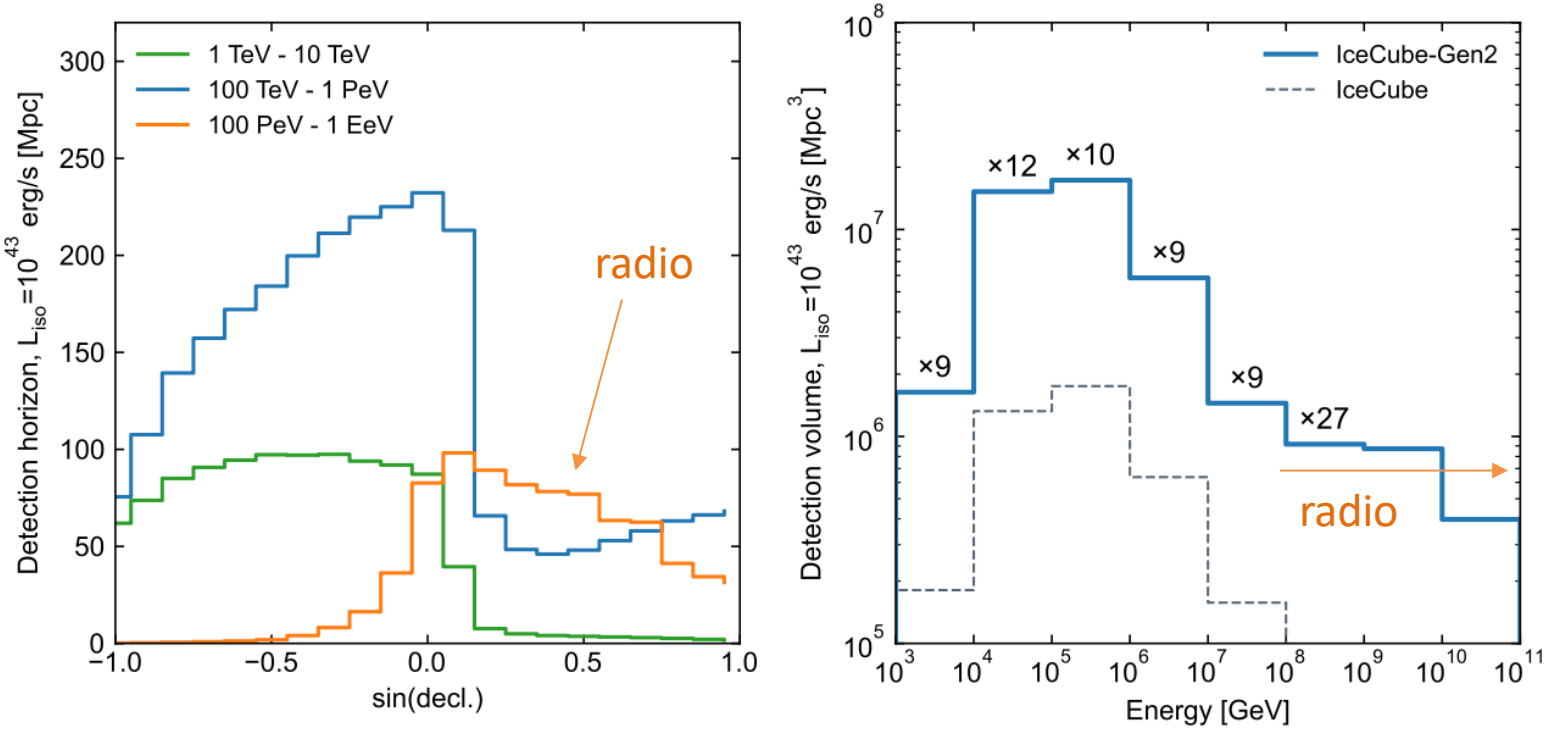
Deep
(150m)

IceCube-Gen2 Technical Design Report (2023)

Upward facing LPDA near surface primarily designed to veto downging backgrounds an identify cosmic rays that generate radio pulses in the atmosphere

Radio in IceCube-Gen2

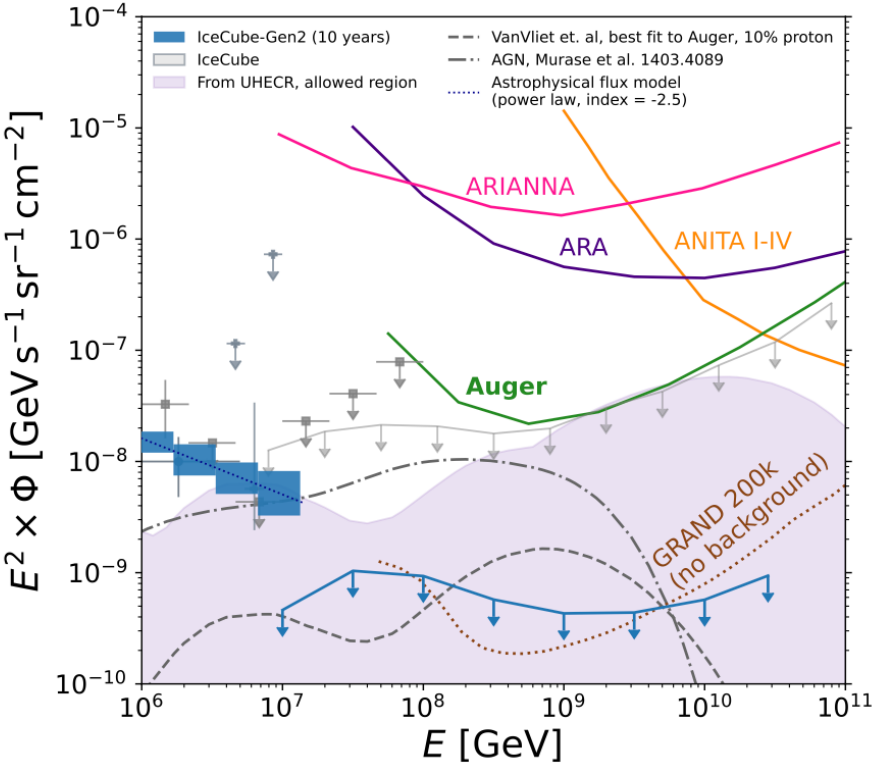
Steady sources outputting 10^{43} erg/s, E^{-2} spectrum



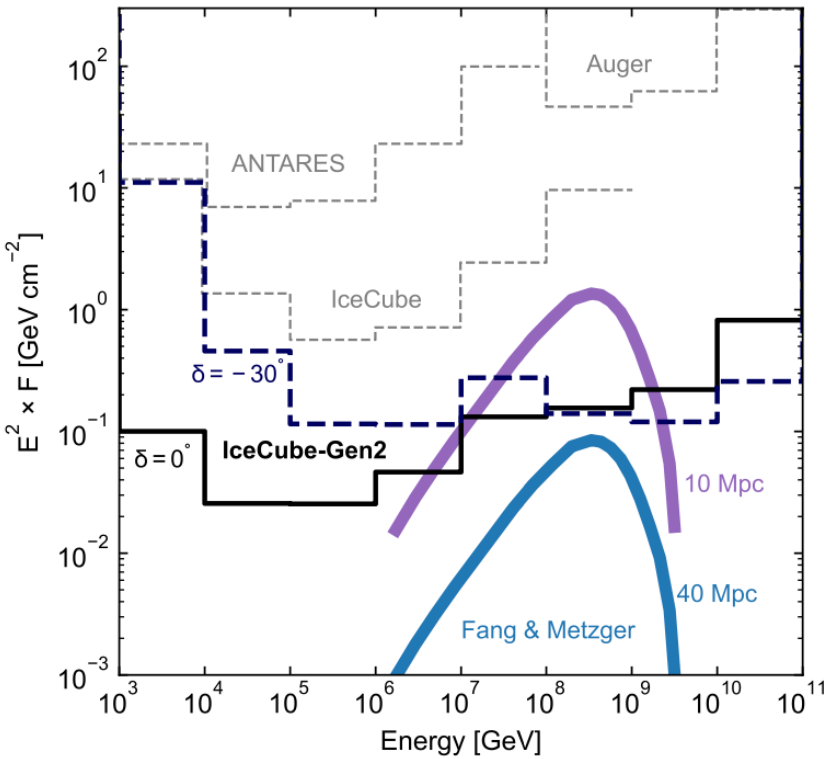
IceCube-Gen2 Technical Design Report (2023)

IceCube-Gen2 Science

Diffuse Flux

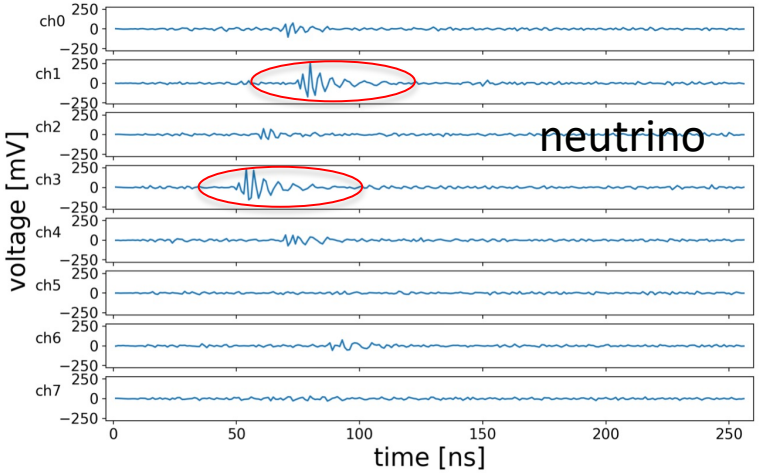


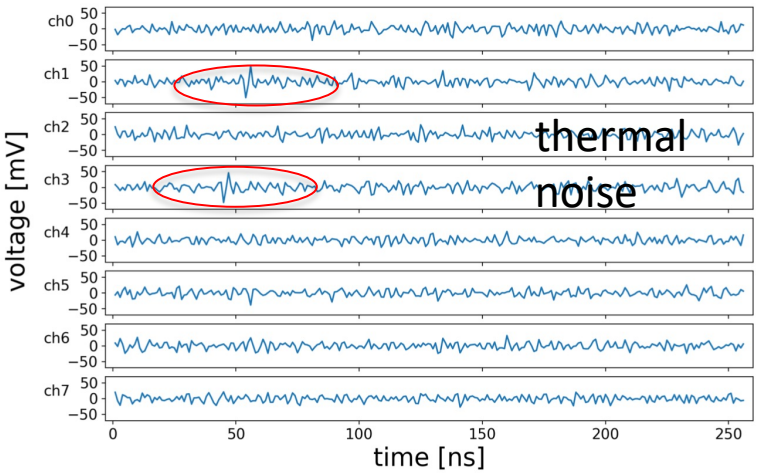
NS-NS mergers (Transient)

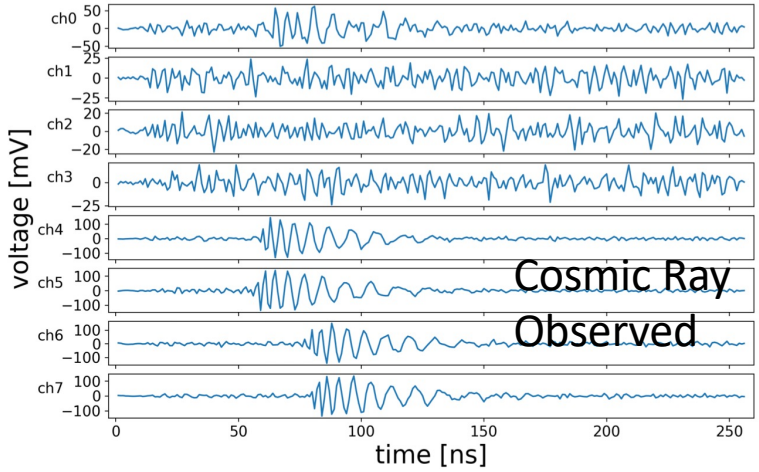


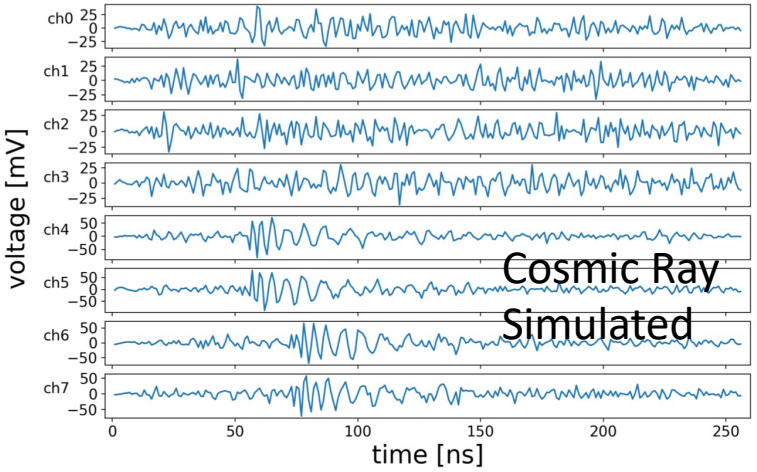
IceCube-Gen2 Technical Design Report (2023)

Gen2: Improve the radio trigger!



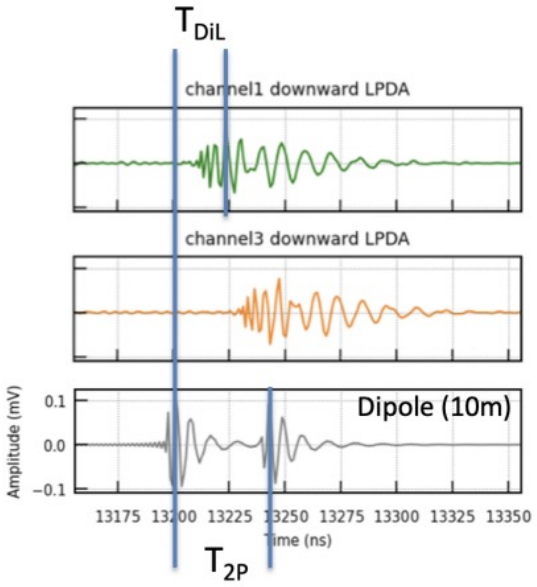


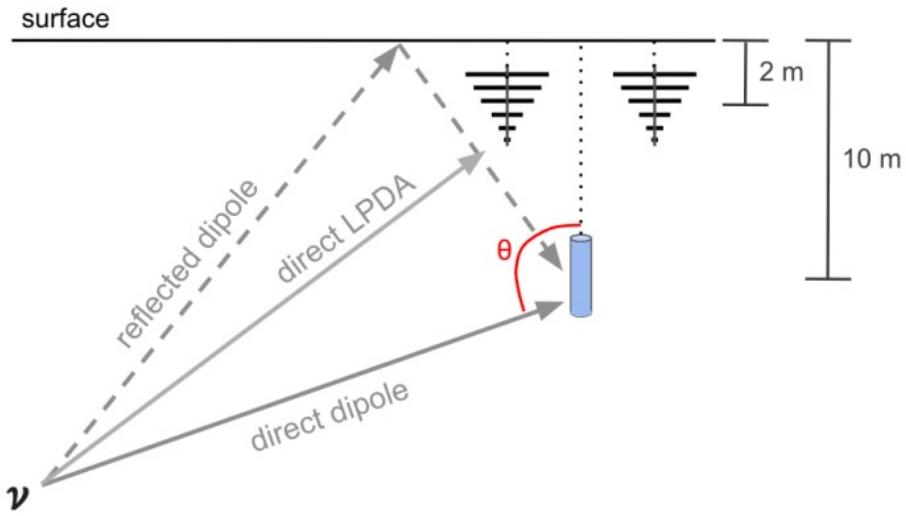




ARIANNA: JCAP 10 (2023) 060; and C.Glaser, et al. J. Inst 145(2023)102781

Another trigger improvement: Use dipole information

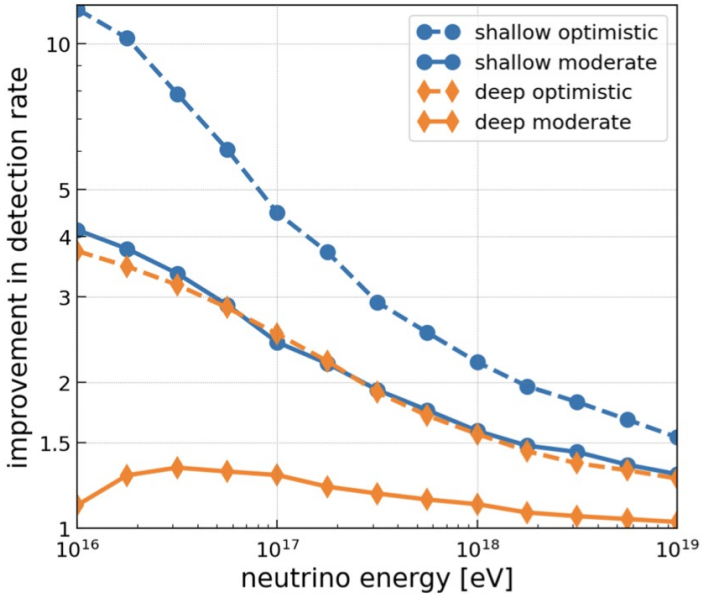


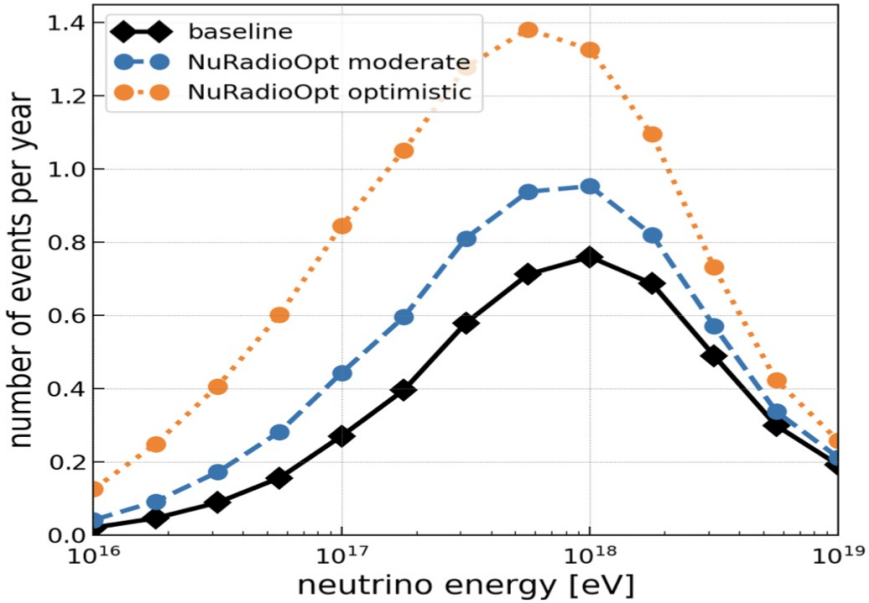


ARIANNA Collaboration JCAP 10 (2023) 060

Double pulse is unique to upward propagation, and provides distance to interaction vertex

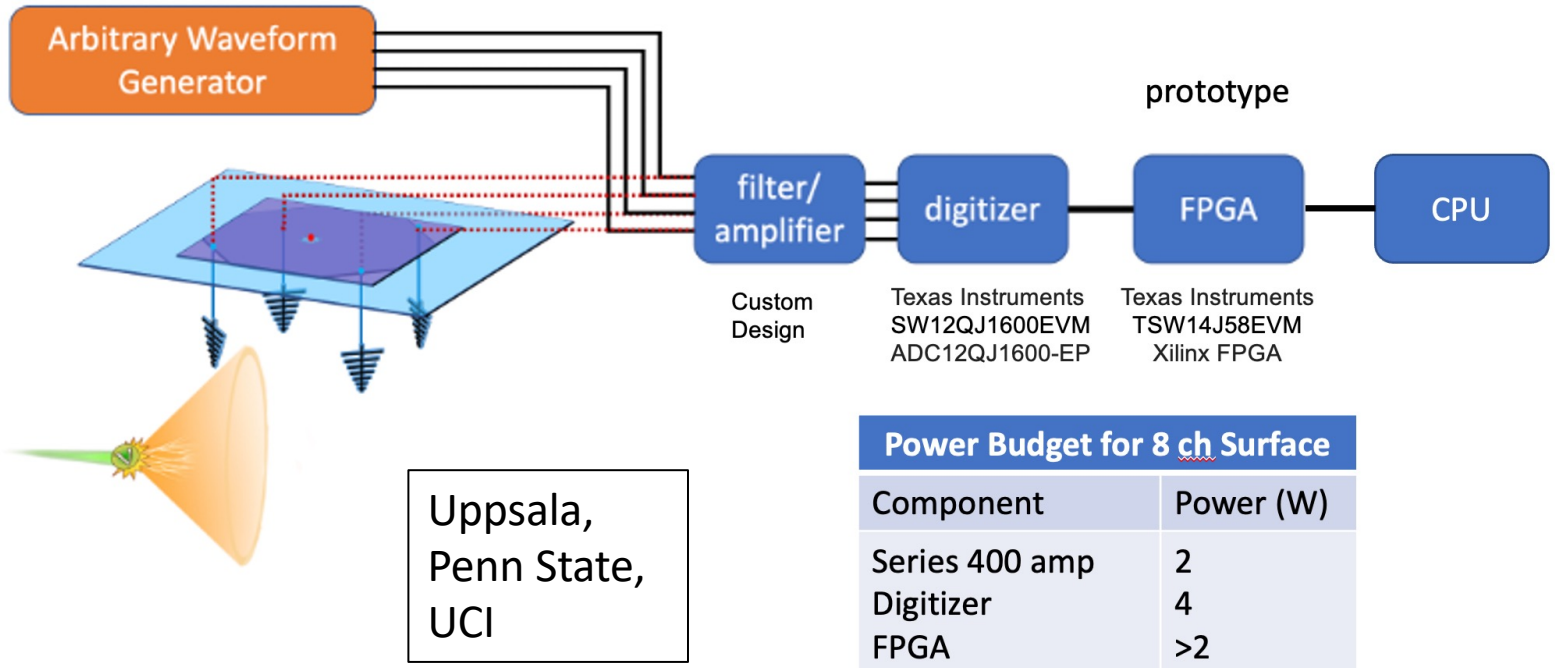
Expected Increase in Sensitivity due to AI trigger





C. Glaser

Ongoing Work-
AI assisted real time trigger in FPGA

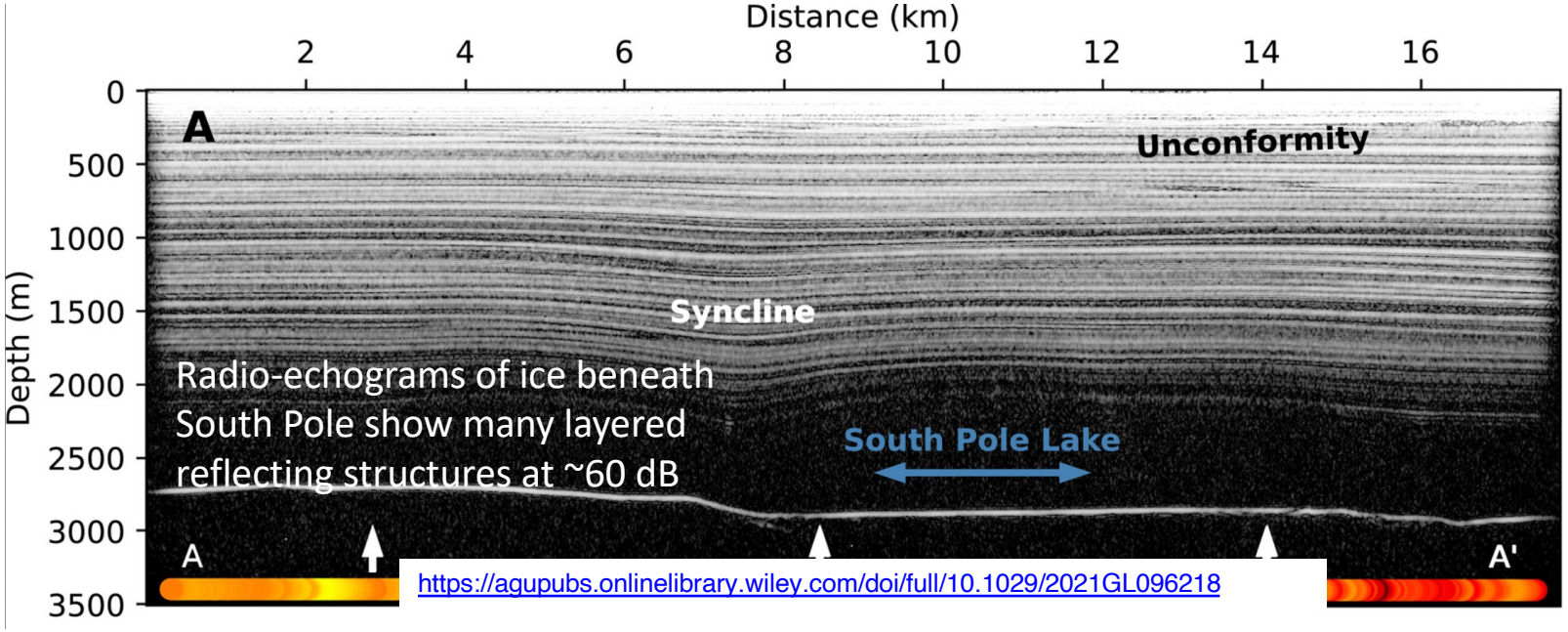


Uppsala,
Penn State,
UCI

Power Budget for 8 ch Surface	
Component	Power (W)
Series 400 amp Digitizer FPGA CPU (RaspPi0)	2 4 >2 2
Total	> 10

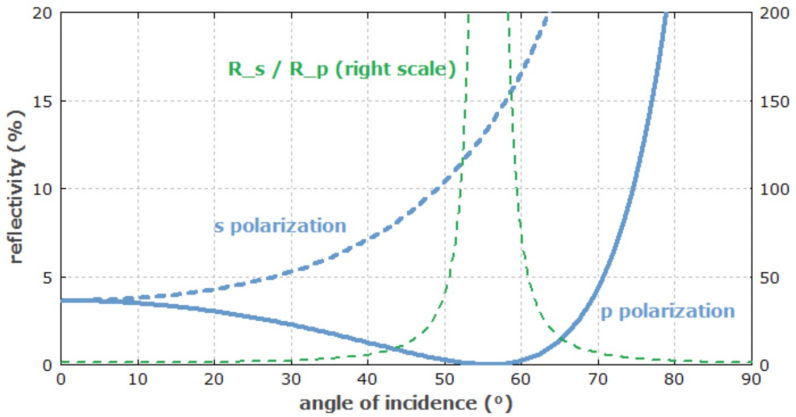
AI in FPGA uses full-band waveforms from all channels

Issue: In-ice scattering



Radio-echograms of ice beneath South Pole show many layered reflecting structures at ~60 dB

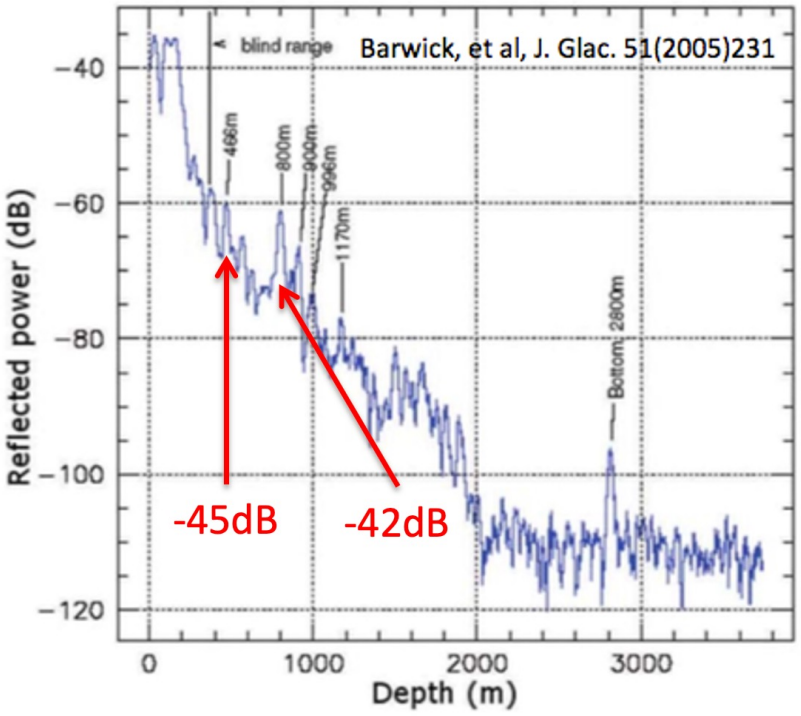
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GL096218



Reflection Coefficients increase nonlinearly as angle of incidence increases to near 90 deg

Issue: Back reflection

- Can back-reflection of cosmic ray initiated radio pulses mimic neutrino signals?

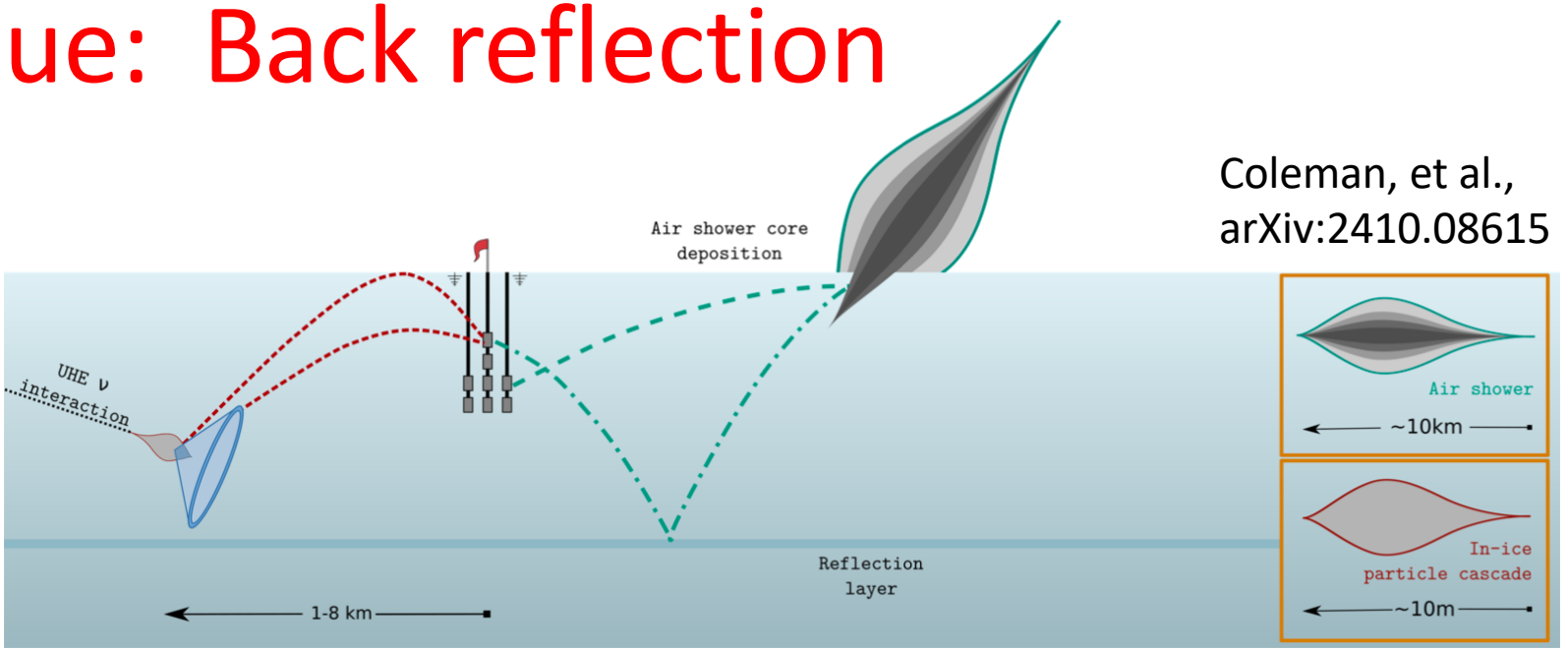


Recall primary purpose of study – measured attenuation length of ice

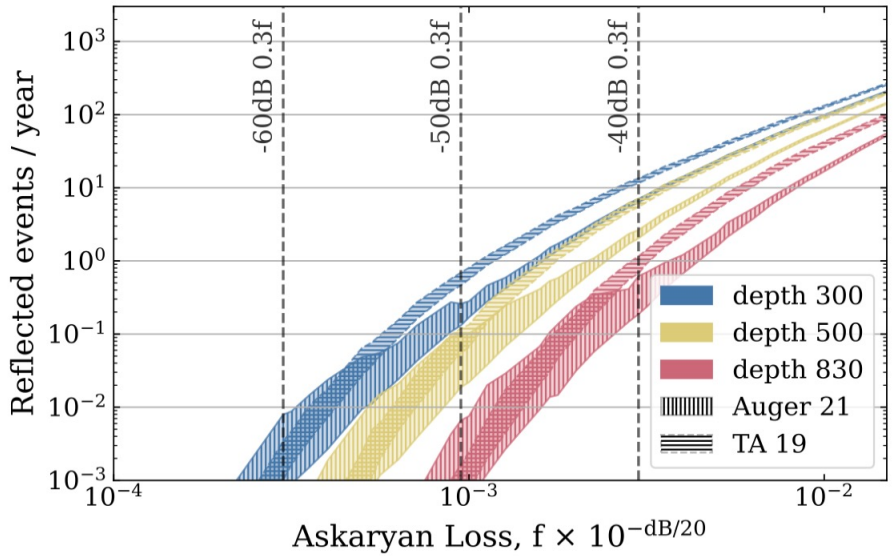
But data reveals significant variation in backscattered power from within the ice. Strong reflectors at depths of ~500m and 800m

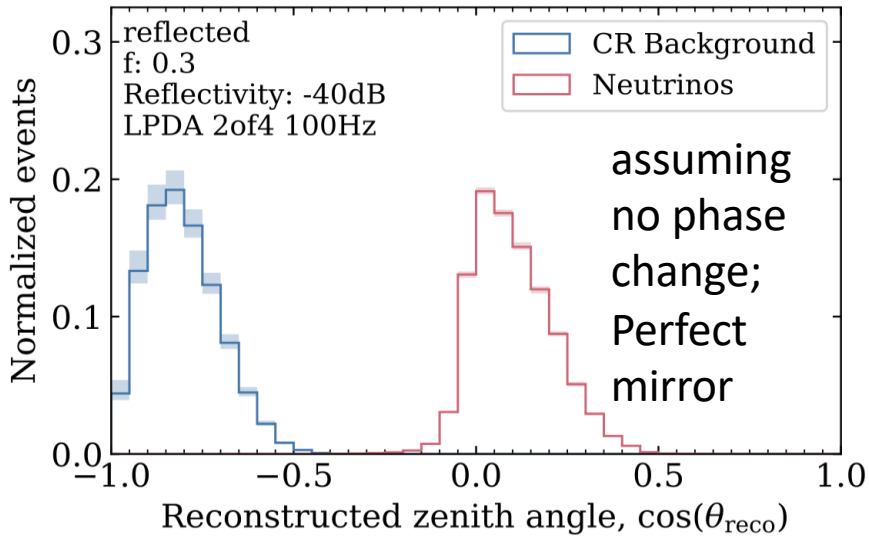
Suggestive, but need more data!

Issue: Back reflection



Coleman, et al., arXiv:2410.08615





0 deg is down direction

Commentary

- We need a comprehensive campaign to measure ice properties at South Pole
  - Reflection layers
    - depth, reflection strength vs incidence angle, scattering properties, phase change
  - Assess propagation in more detail, especially change of polarization and signal amplitude for grazing incidence propagation
  - Confirm birefringence models

Take-away Message

- Icecube astonishingly successful
  - collaboration planning for IceCube-Gen2
- Need to build bigger detector for higher energy neutrinos -> go radio!
- ARIANNA demonstration project complete
  - Near surface design based on ARIANNA in plan for IceCube-Gen2
- Gearing up to address next gen issues in radio
  - AI enhanced Trigger
  - Ice Propagation
  - Small, but not negligible background processes -> calibration tool?

Special thanks to UCI ARIANNA team members:

Stuart Kleinfelder (EE),Corey Reed, Joulien Tatar, Jordan Hanson, Geoffrey Gaswint, Chris Persichilli, Mahshid Roumi (EE), Liang Zhou (EE),Lee Moritz, Jeff Griskevich, Anna Nelles, Christian Glaser, Astrid Anker, Manuel Paul, Ryan Rice-Smith, AJ Nielsen, Leshan Zhao, and many undergrads

1993

Shown: (Left to right) Joulien Tatar, Chris Persichilli, James Walker, Corey Reed