

A Comprehensive Diffuse Neutrino Search Using the Full Askaryan Radio Array

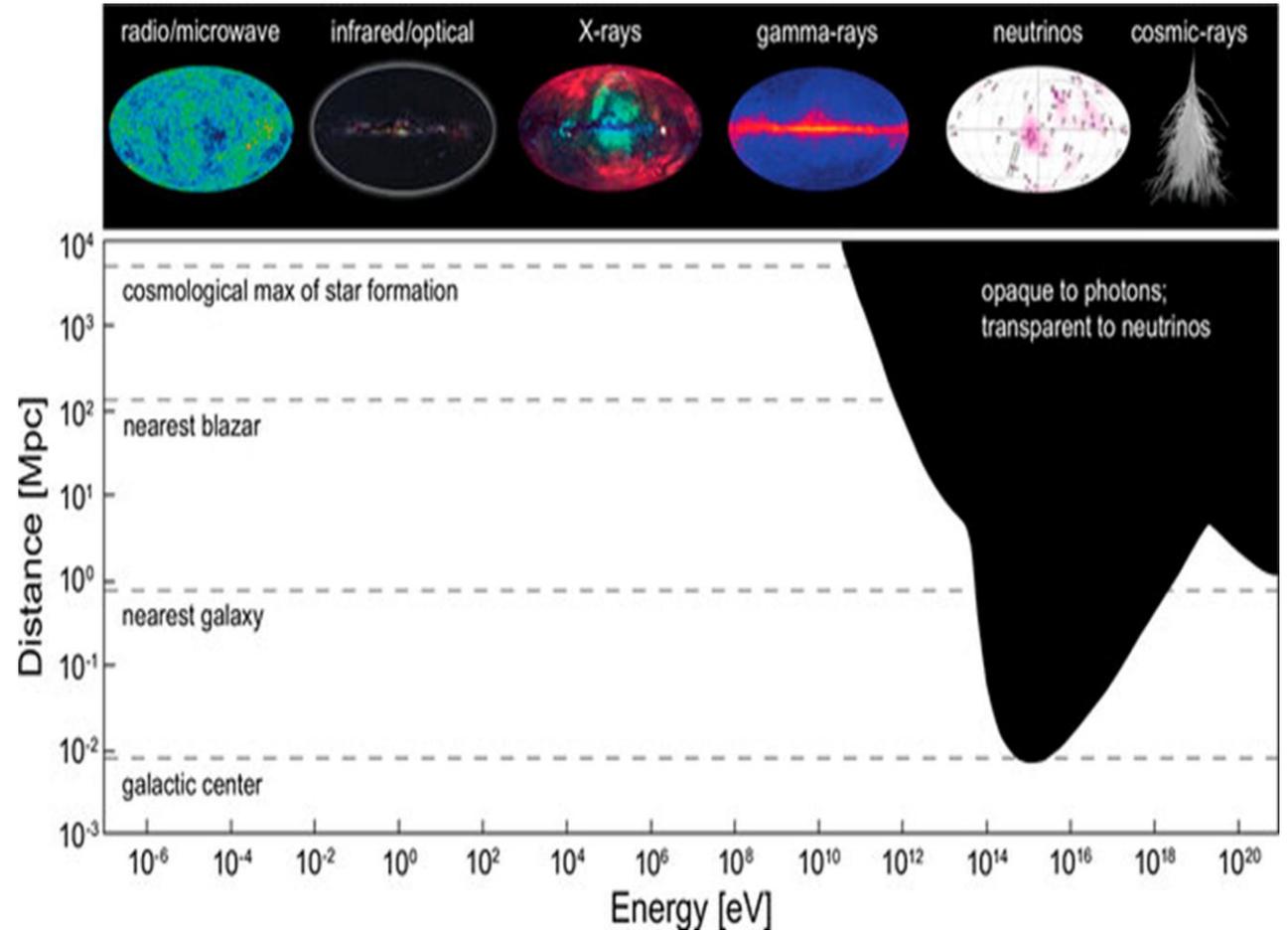
**Pawan Giri
For the ARA Collaboration**



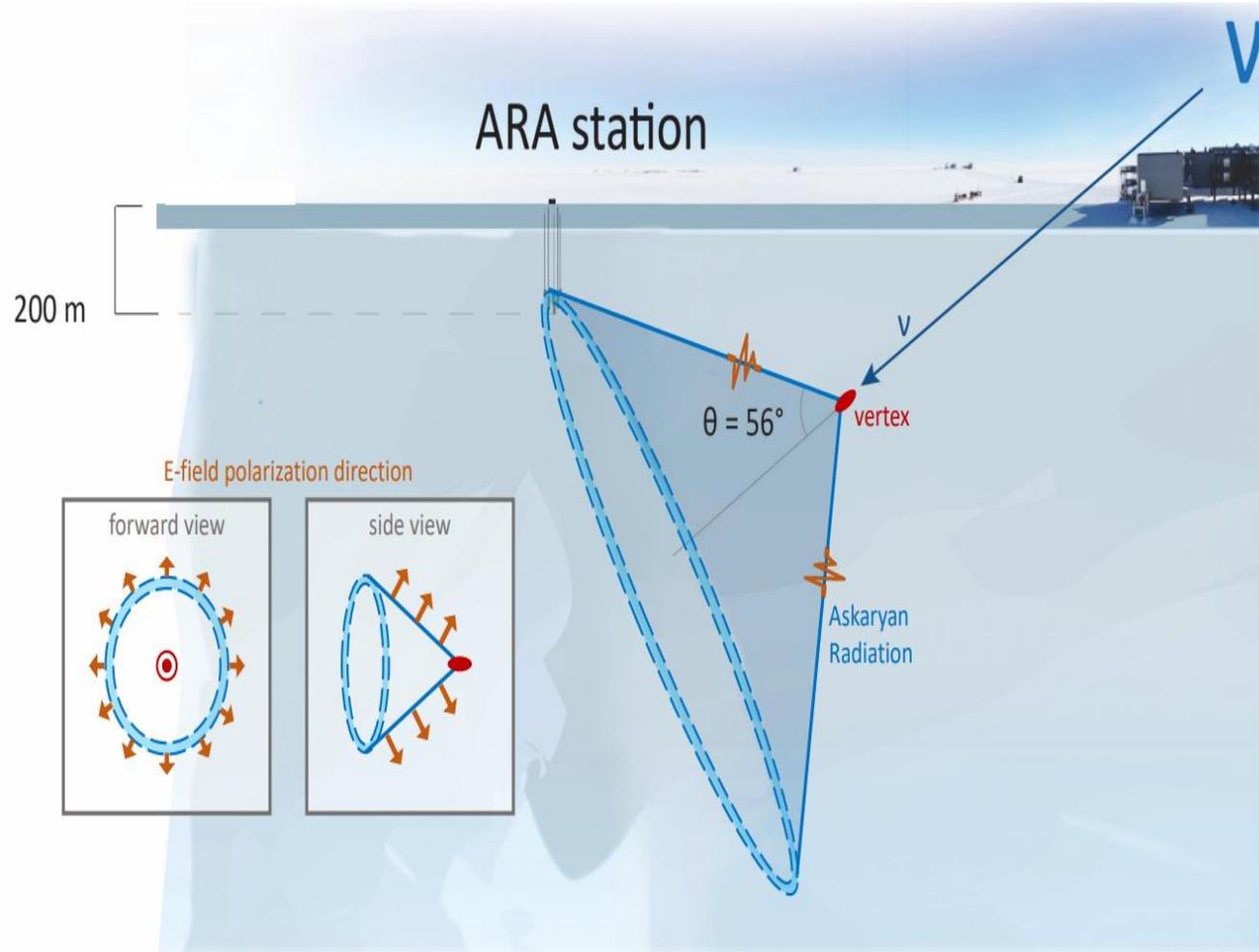
Lepton Photon 2025, Madison, Wisconsin, USA

Motivation for neutrino searches

- Origin of ultra-high energy cosmic rays is unknown
- Magnetic deflections in Galactic/extragalactic fields obscure arrival directions
- GZK photo-hadronic interactions with the CMB produce cosmogenic neutrinos
- Neutrinos are weakly interacting; cosmological attenuation is minimal; arrival directions are preserved



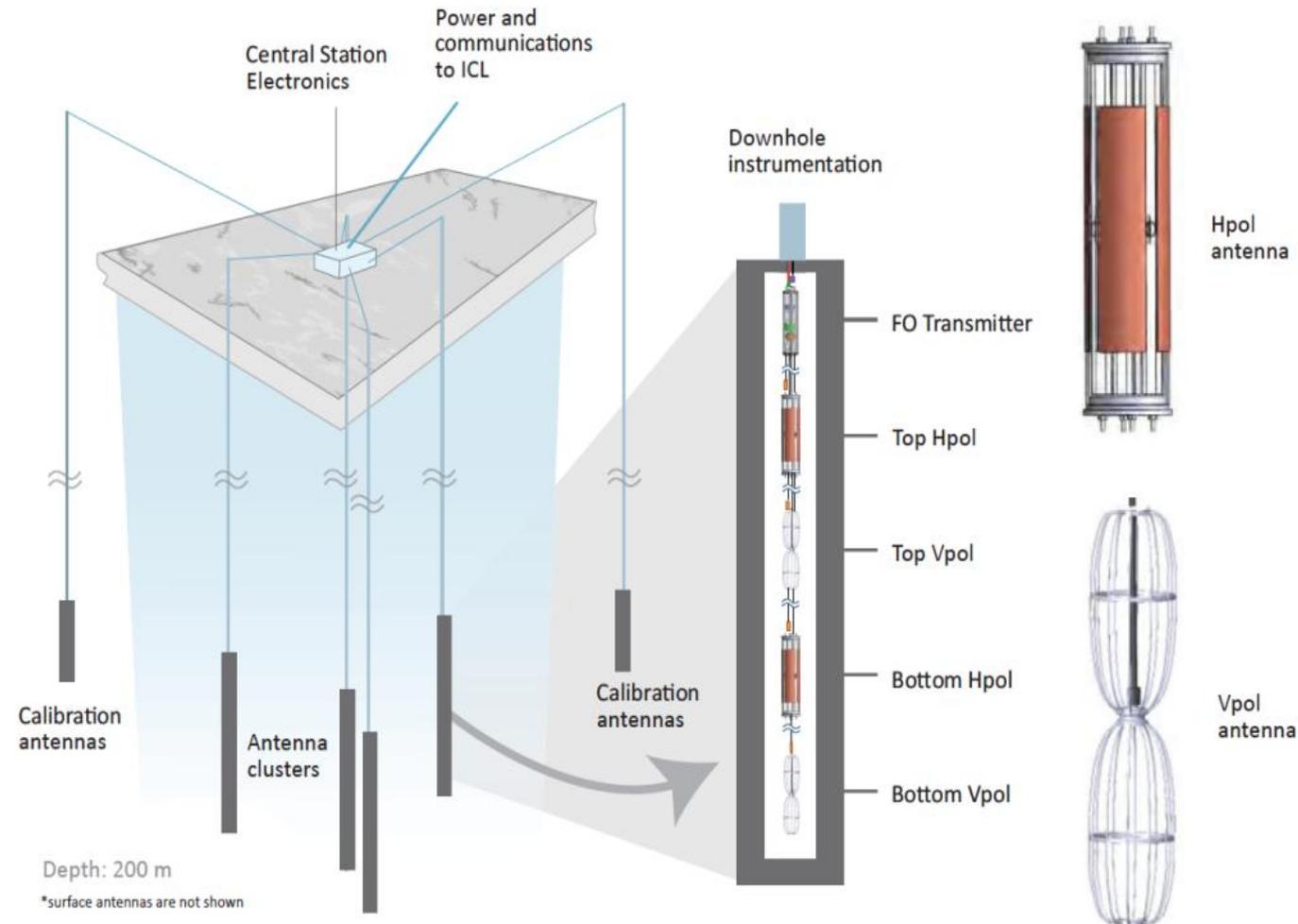
The Askaryan Radiation



- Neutrino interaction in ice produces a compact particle cascade
- The cascade develops a net negative charge excess
- The charge excess emits a short, coherent radio Cherenkov pulse
- Emission peaks on the **Cherenkov cone**, with angle set by refractive index
- The pulse is nanoseconds long and linearly polarized

The Askaryan Radio Array

- Designed to detect ultra-high energy neutrinos
- Five autonomous stations at the South Pole
- Each station: four in-ice strings with vertical and horizontal polarization antennas deployed to approximately 200 meters, plus calibration antennas
- Trigger: at least three of eight antennas of the same polarization (average rate about six hertz)
- A5 is unique with an additional phased array string (low SNR trigger)



Trigger Modes and Nominal Rates

➤ Calibration pulser triggers

Rate: 1 Hz

Purpose: monitor in-ice antenna response, ice propagation properties, and geometry calibration

➤ Forced/software triggers

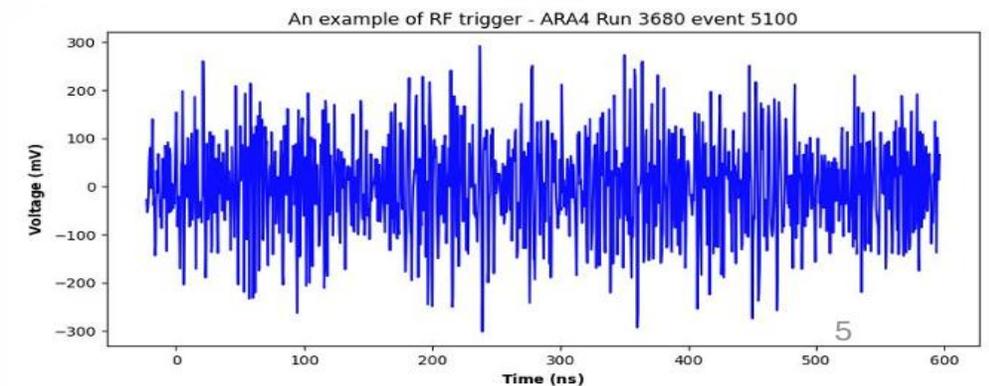
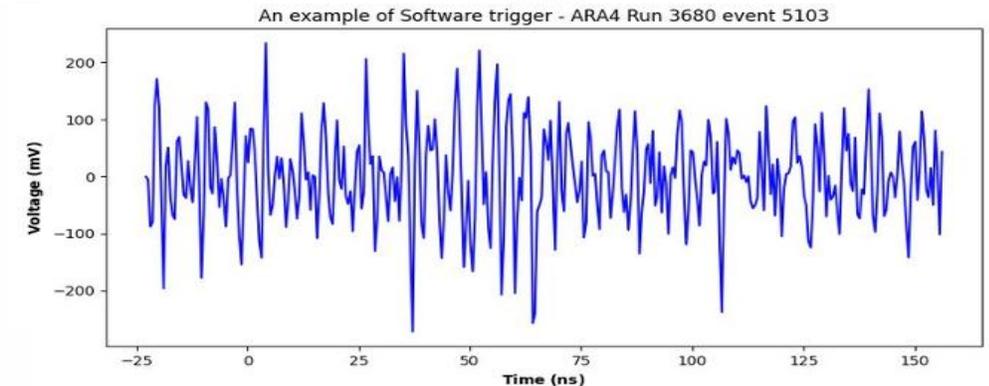
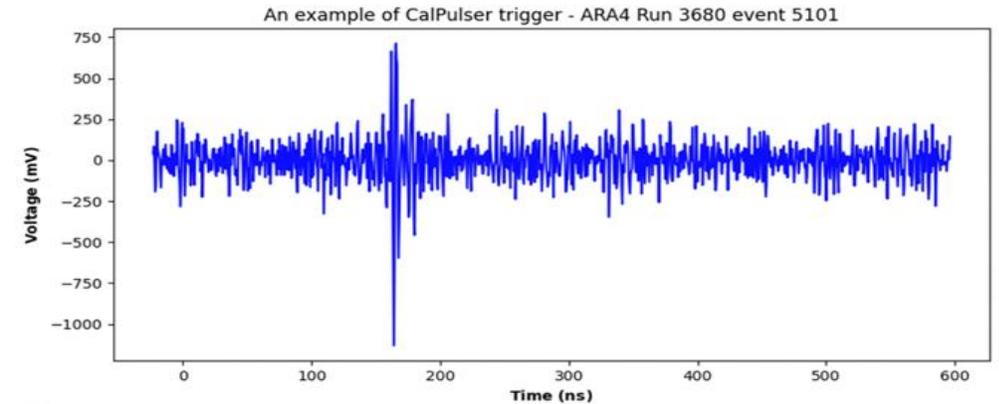
Rate: 1 Hz

Purpose: monitor ambient thermal noise; acquired without a trigger condition

➤ Radio frequency (RF) triggers

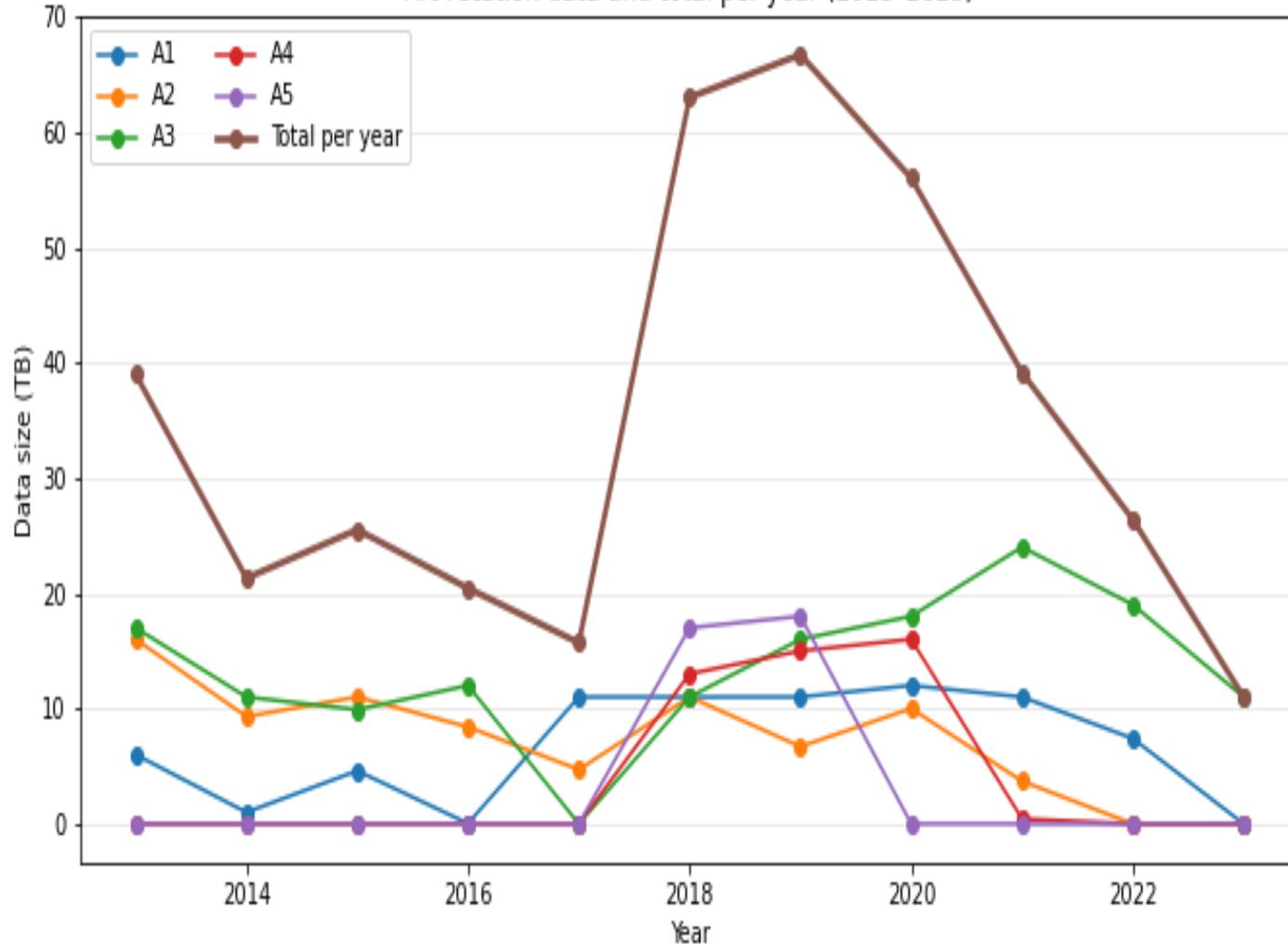
Rate: 4 Hz

Purpose: neutrino events search



The array wide neutrino search

ARA station data and total per year (2013-2023)



➤ More than a decade of successful run

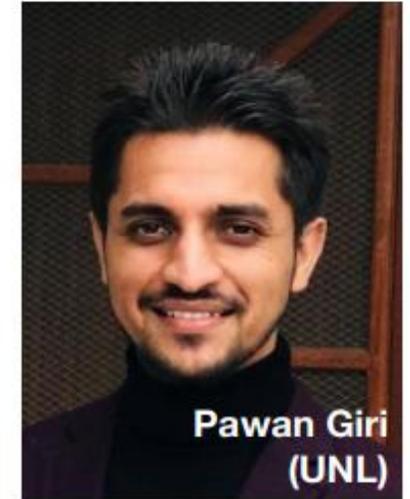
➤ Largest data analysis ever with radio-antennas based neutrino detector

➤ Goal :

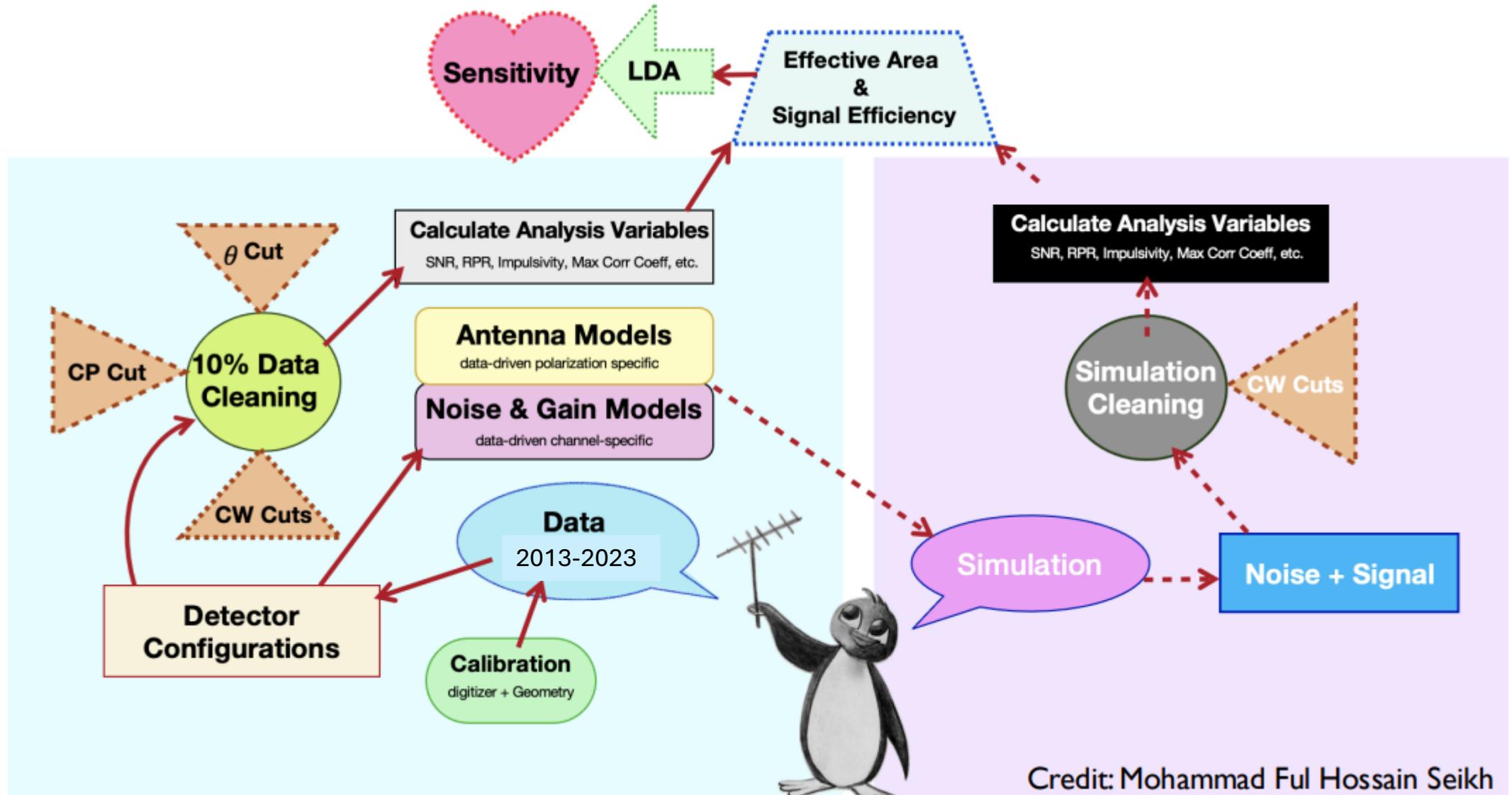
- Array-wide diffuse neutrino search with data through 2023.
- Perform global optimization to maximize discovery potential

The multi-institutional analysis team

- Large data analysis needs enormous effort
- A hard-working team of 8 analysts from 6 different institutions



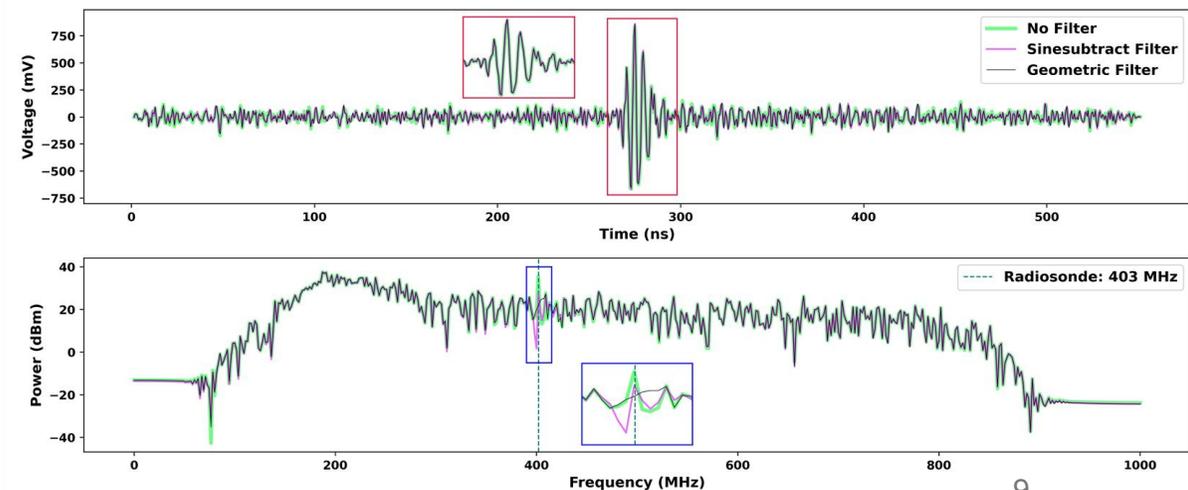
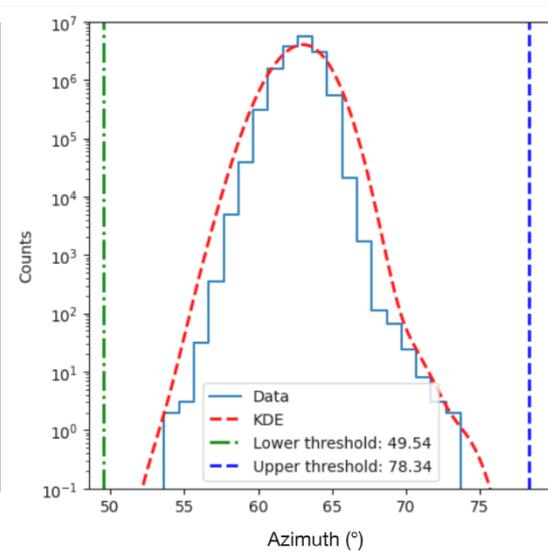
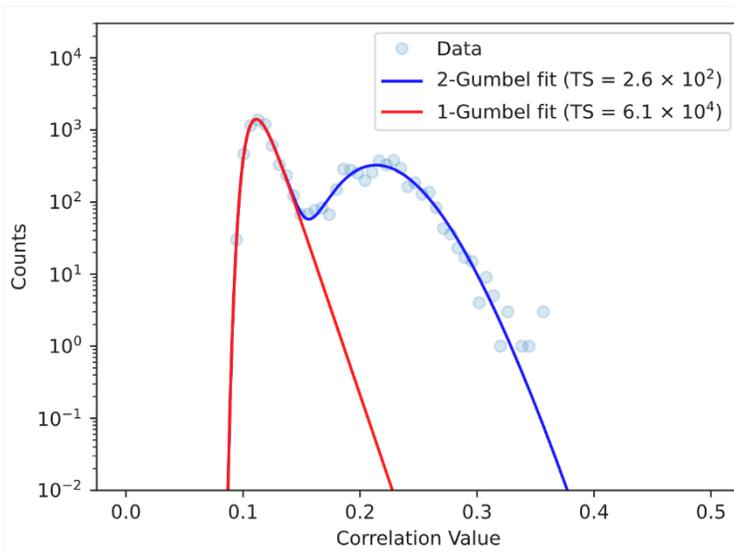
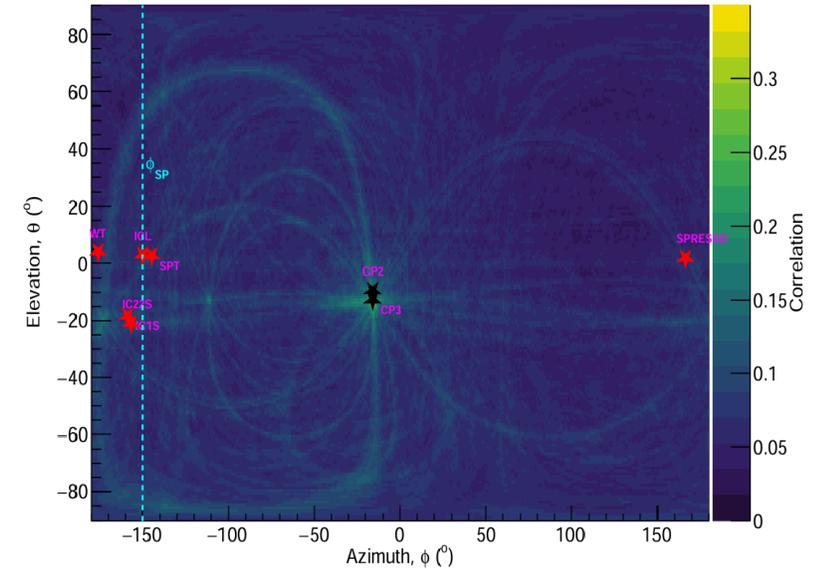
Station Level Analyses



(Data cleaning) Robust Background Mitigation

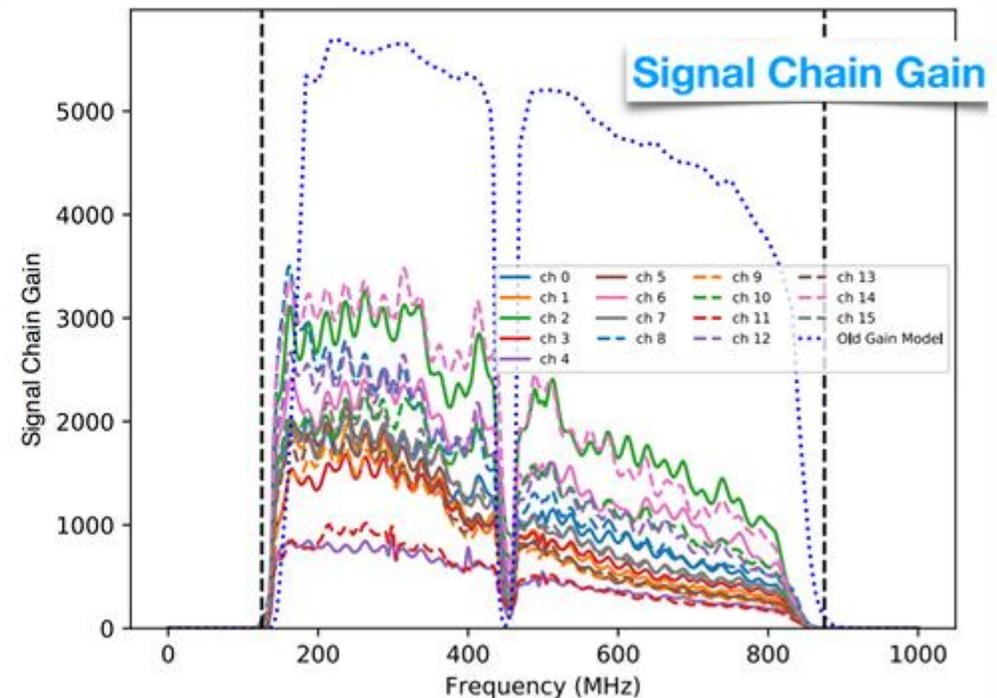
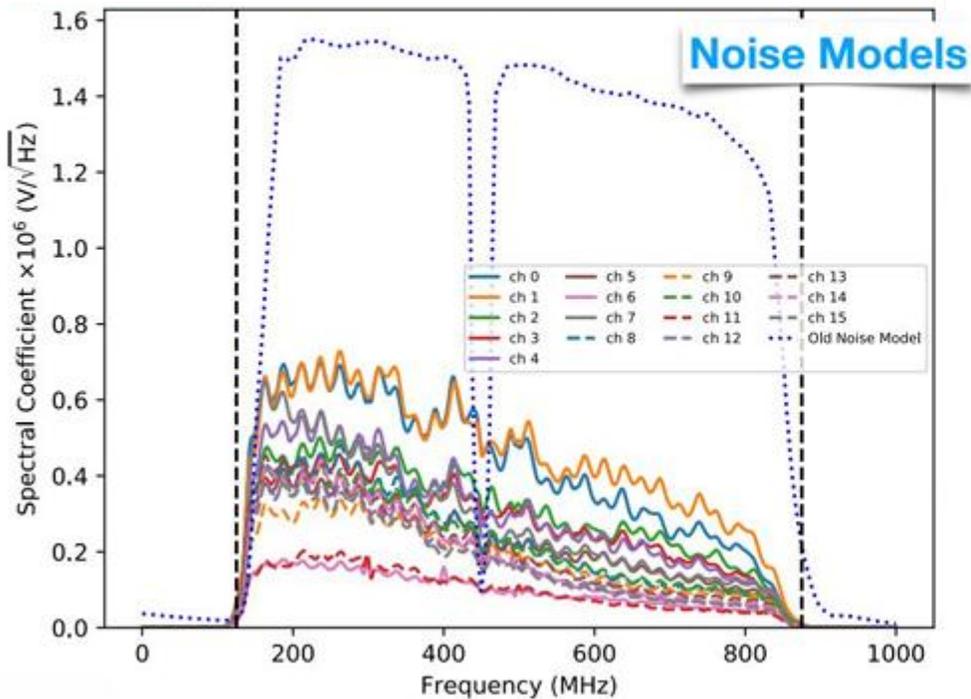
- Impulsive backgrounds from calibration pulsers, cosmic ray events, spark events, and surface activities
- Geometric cuts, spatial-temporal cuts, surface cut
- The persistent Continuous Wave (CW) interference

Skymap of a Cal Pulsar event with all known landmarks

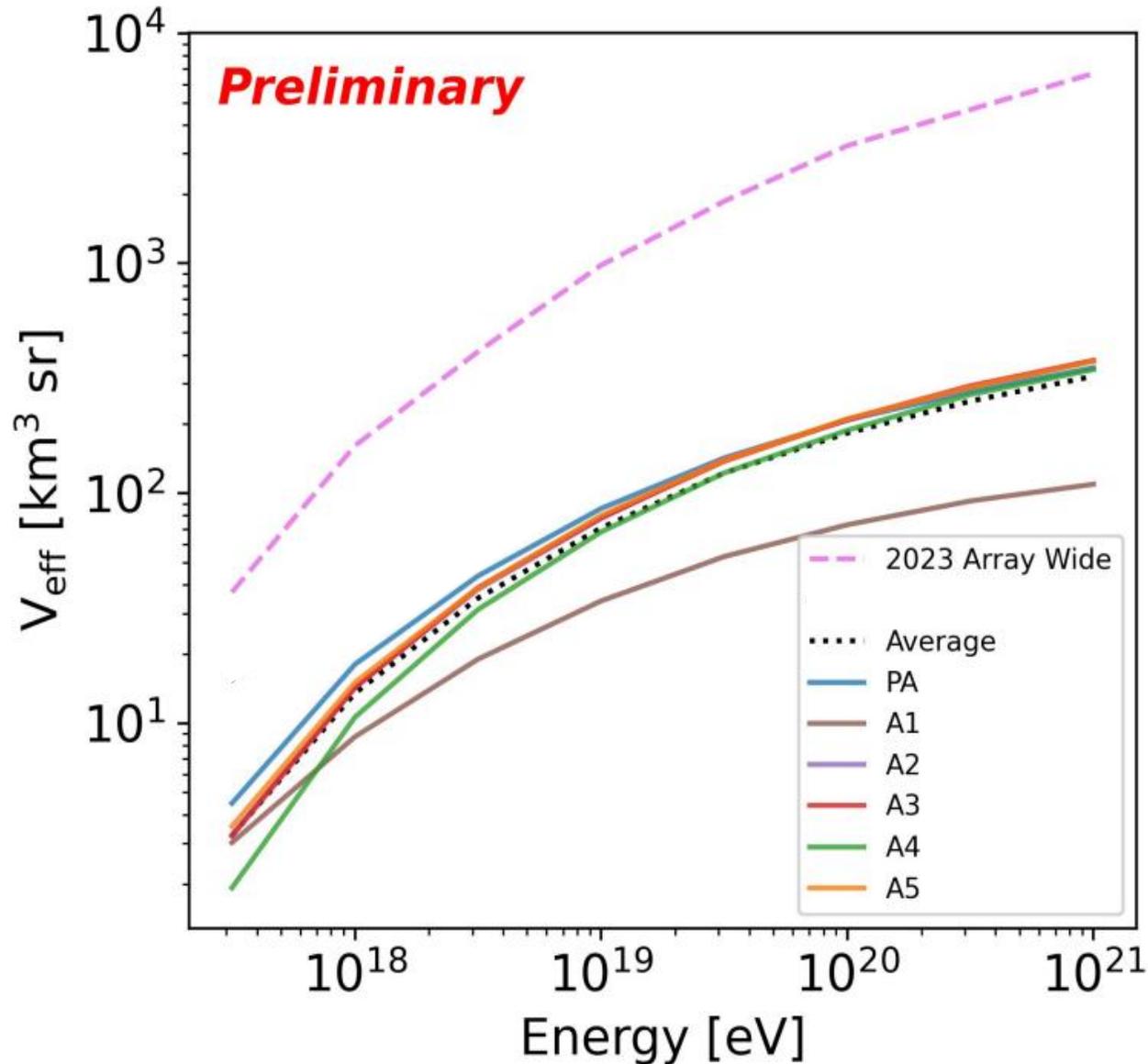


Data Driven Noise and Gain Models

- New antenna characteristics measurements at the University of Kansas
- Empirical modeling of noise and gain for individual antennas
- Rayleigh noise parameters estimated from forced-trigger data
- Gain models incorporate detector noise and antenna properties



Effective Volume simulation

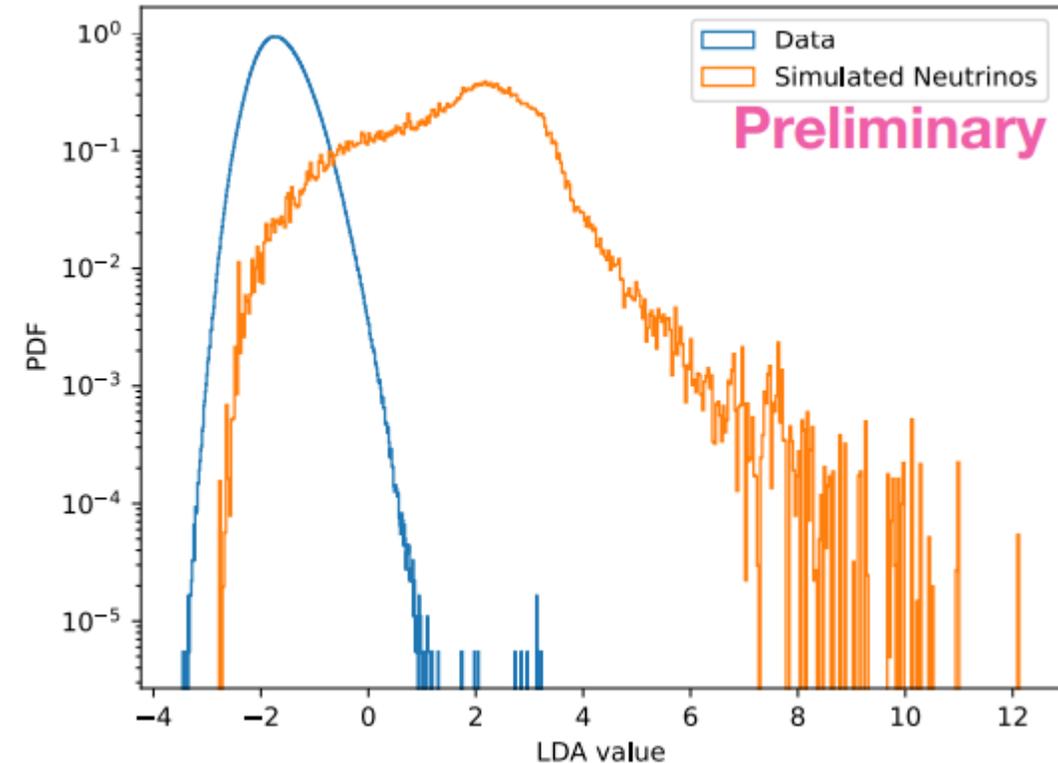


$$(V\Omega)_{\text{eff}}(E) \approx 4\pi V_{\text{gen}} \times \frac{N_{\text{det}}}{N_{\text{throw}}}$$

- Effective volume quantifies the detector-sensitive ice volume at a given energy
- Derived from Monte Carlo with Earth survival, interaction probability, directional weighting, and station trigger/quality
- Used to calculate expected event counts from flux, interaction length, and livetime
- Latest simulations also include secondary contributions (NuLeptonSim)

Optimizing the Discriminator Cut

- Final event selection uses a cut on the discriminator value
- The cut maximizes separation between signal and background
- Optimization targets discovery potential across the full array and the available livetime
- This yields higher sensitivity than simply combining five single-station optimized limits
- The optimization assumes the global neutrino limits from IceCube 2025 and ANITA as the flux model

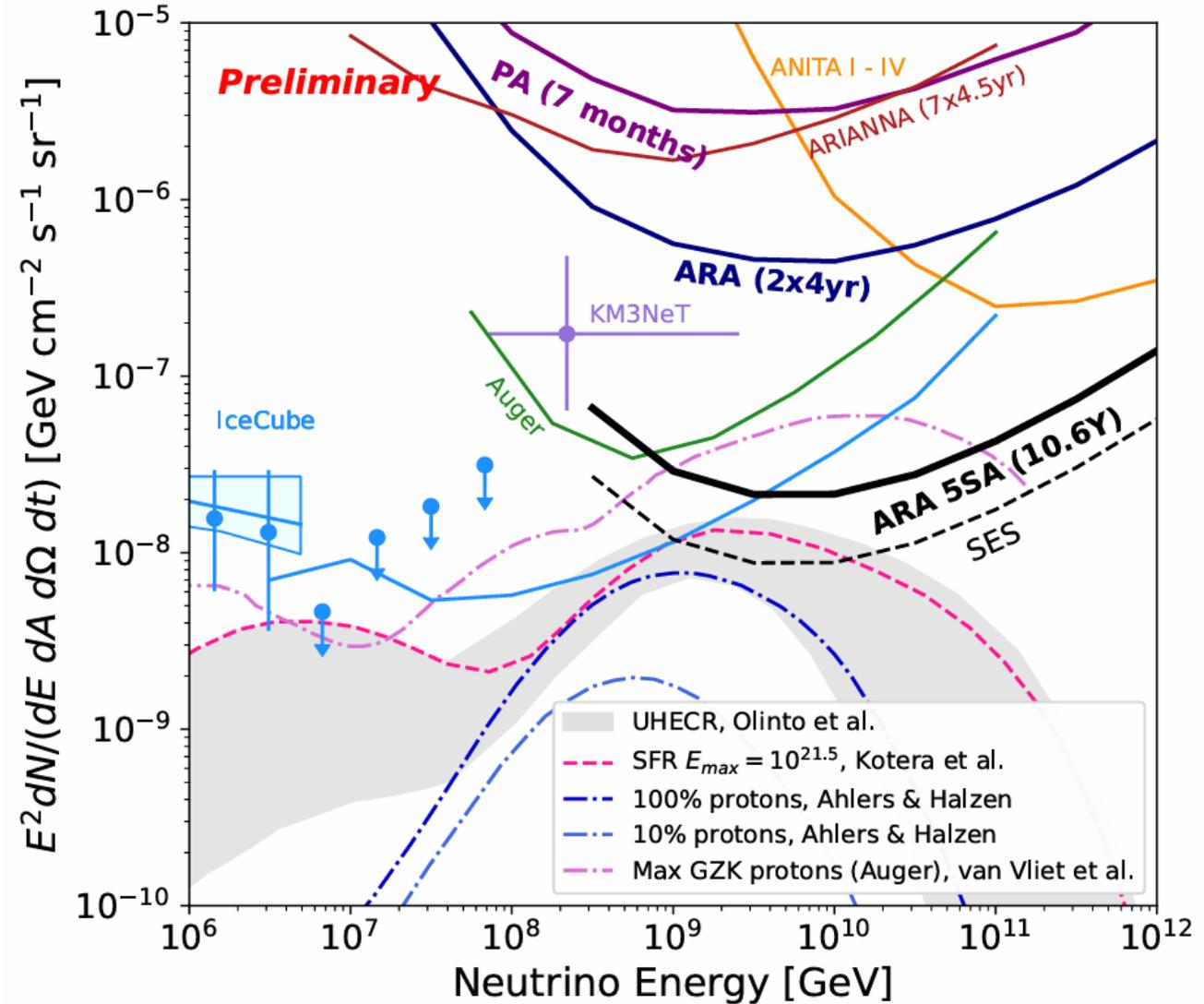


$$\phi_{\text{up}} = \frac{\text{FC}(\sum_s b_s)}{\sum_s \frac{(V\Omega)_{\text{eff},s}(E)}{L_{\text{int}}(E)} T_s \varepsilon_s}$$

Depend on signal cut value

Projected Sensitivity

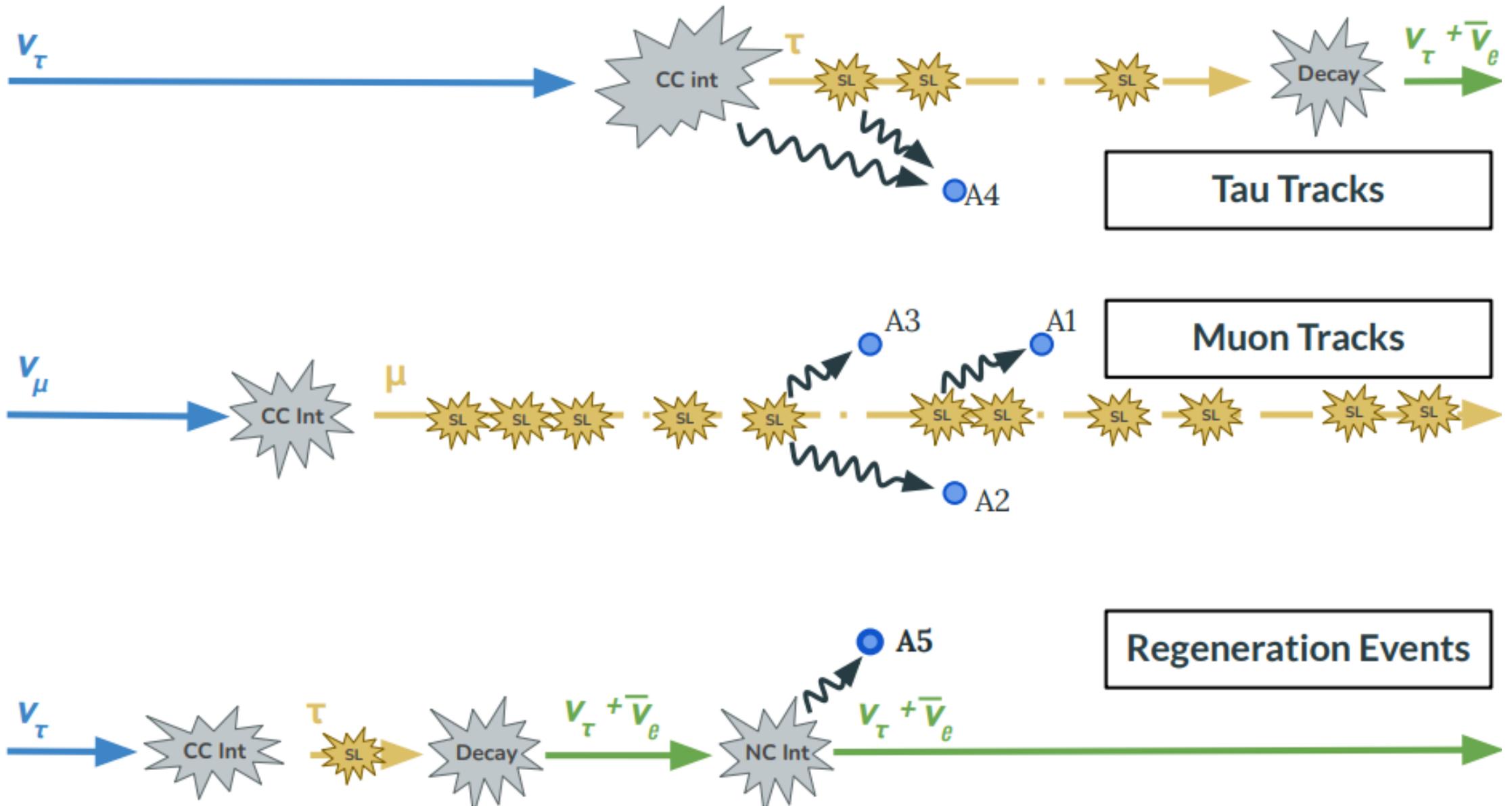
- Expected number of events at trigger-level for analyzed livetime:
 - Kotera et al. flux: ~ 3.1 events
 - van Vliet et al. (Auger) flux: ~ 14.4 events
 - IceCube 2025+ANITA limit flux: ~ 23.5 events



Summary

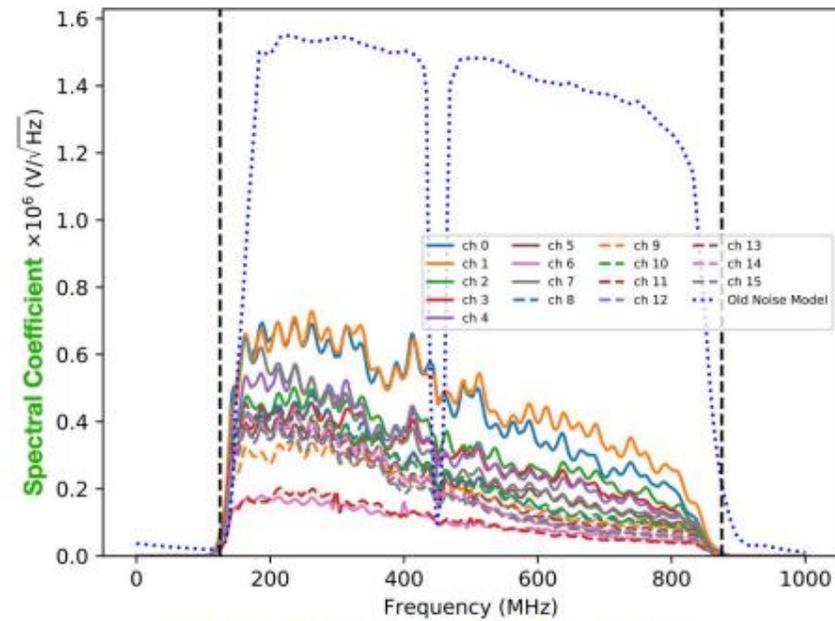
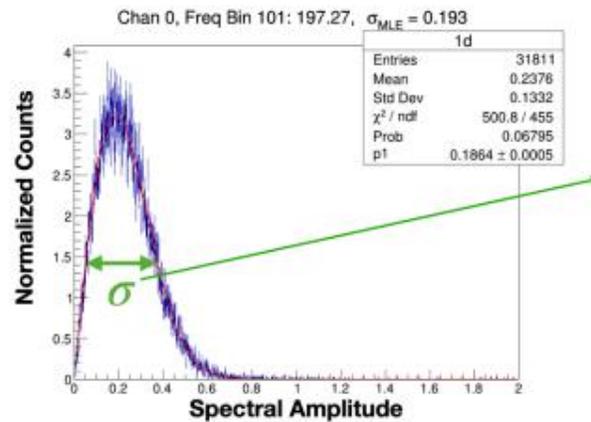
- ARA has recorded about 28 station-years of livetime through 2023
- The first array-wide neutrino search in the deep stations
- This analysis incorporates new analysis methods and detector characterization compared to previous ARA analyses
- Establishes a basis for next-generation, large in-ice radio arrays RNO-G and IceCube-Gen2 Radio
- Outcome will be either:
 - Ultra high energy neutrino candidates
 - The strongest flux limit from any radio experiment

BackUp slides

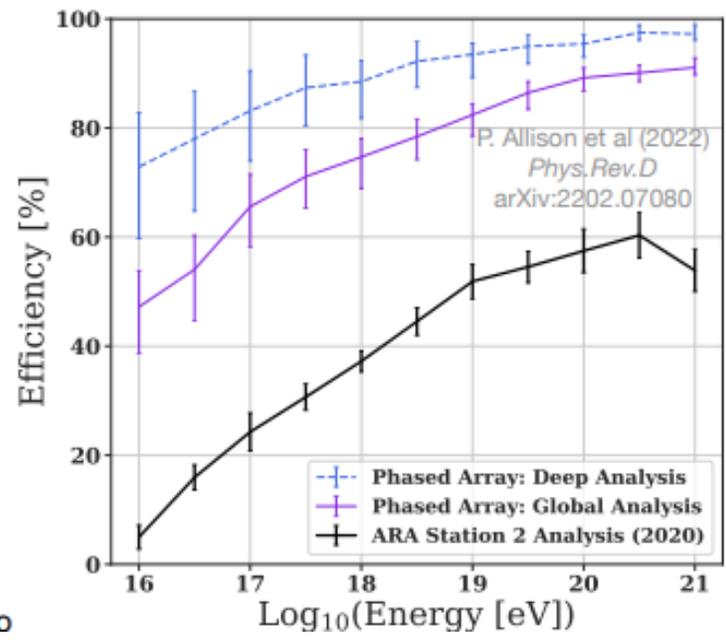


Data-driven noise models now implemented in simulation

- Rayleigh distribution parameters extracted from forced-trigger data
 - Per-frequency & per-channel modeling captures amplifier + environmental noise
- Includes noise contributions from environment and signal chain



***Old noise model amplified by gain model,
new models include system gain directly**



Iarco Muzio