Progress towards an array-wide diffuse UHE neutrino search with the Askaryan Radio Array

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for the ARA Collaboration

PennState

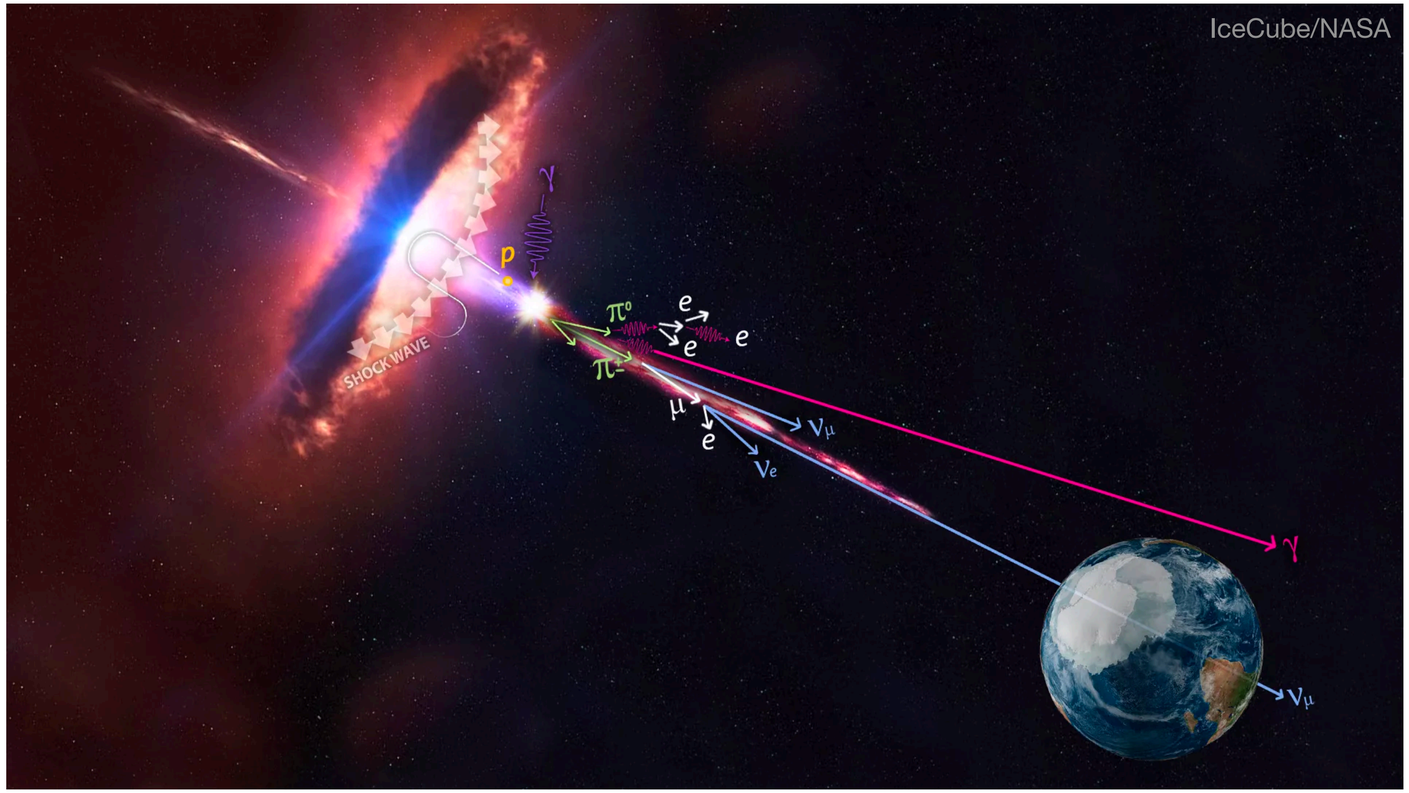
NSF

TeVPA
Chicago 2024

Image credit: Aman Chokshi, SPT/NSF

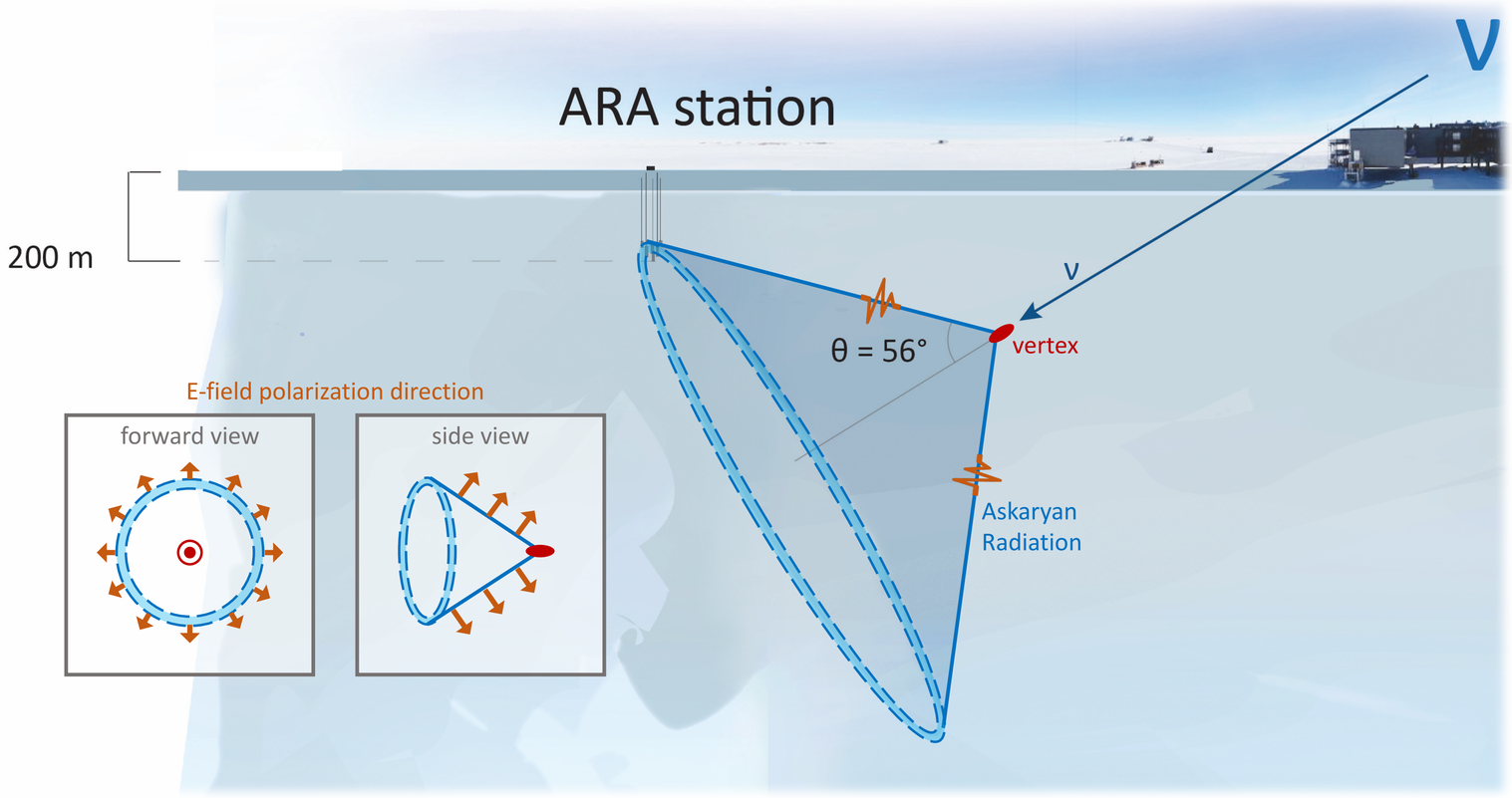
Windows into the UHE Universe

- Sources of UHE CRs remain unknown
- UHECRs themselves only probe the most local sources
  - GZK horizon
  - Extragalactic magnetic horizon
- UHE neutrinos = smoking gun signature of UHECRs
- Probe UHECR sources on cosmological scales
- Point back to sources (no magnetic field deflections)
- Probe particle physics beyond the LHC



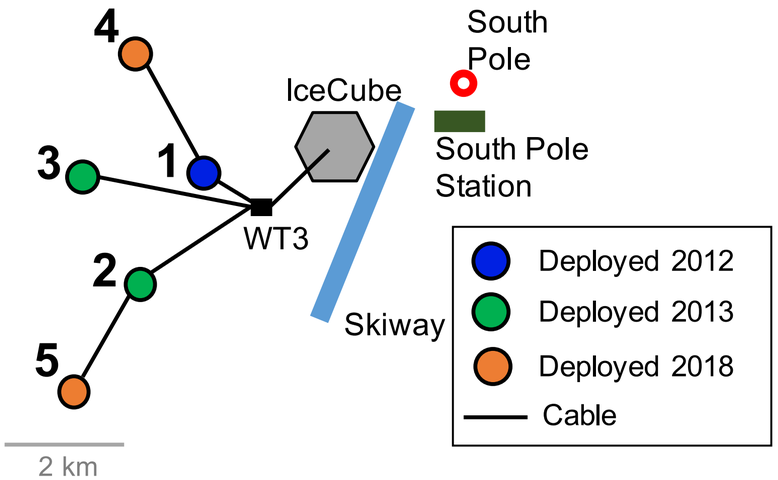
Askaryan Radiation

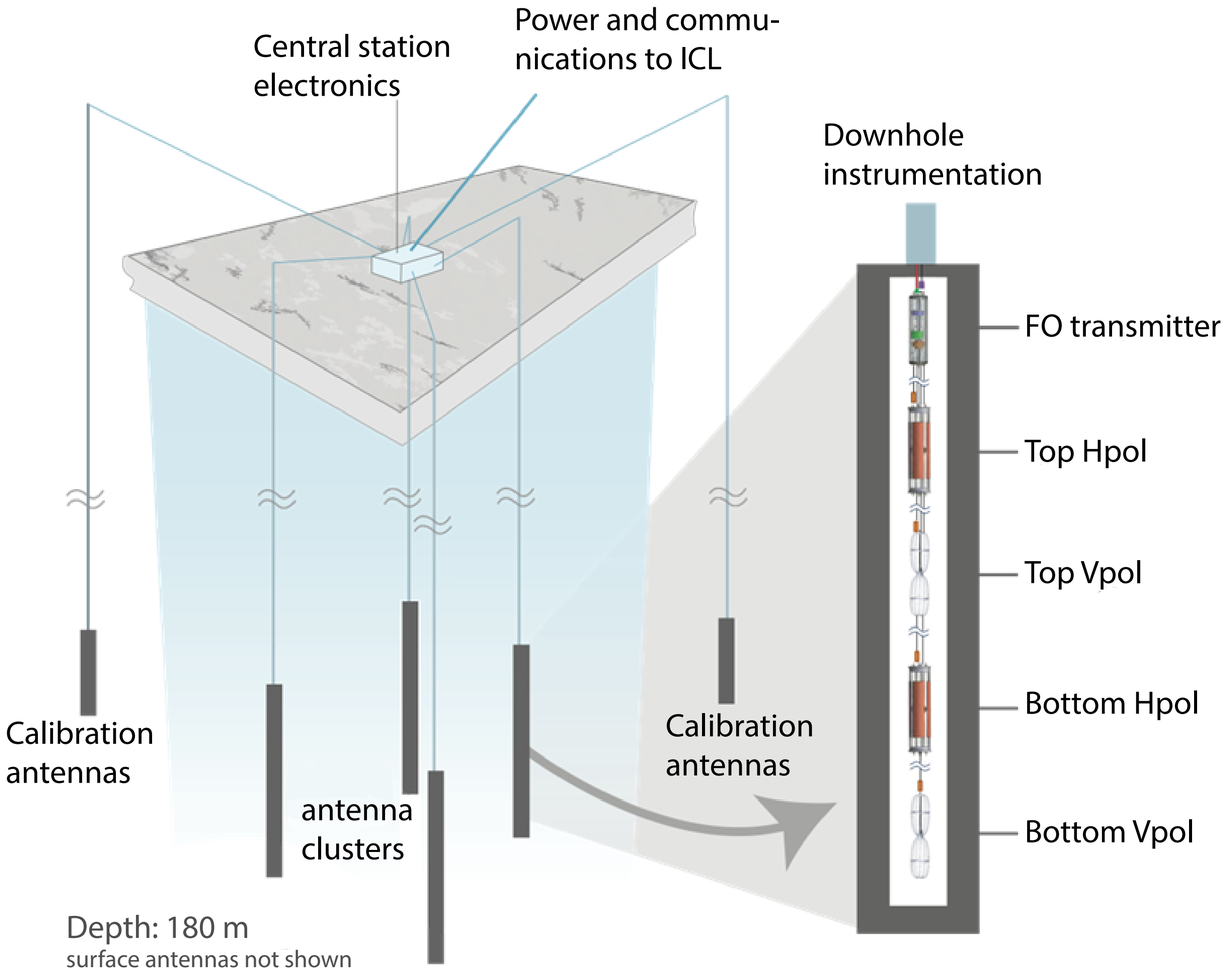
- Neutrino interaction in dense medium initiates particle cascade
- Particle cascade emits pulse of coherent radio emission along Cherenkov cone — Askaryan radiation
- Radio has ~1 km attenuation length in ice
- Radio antenna embedded in ice = efficient monitor of enormous volume



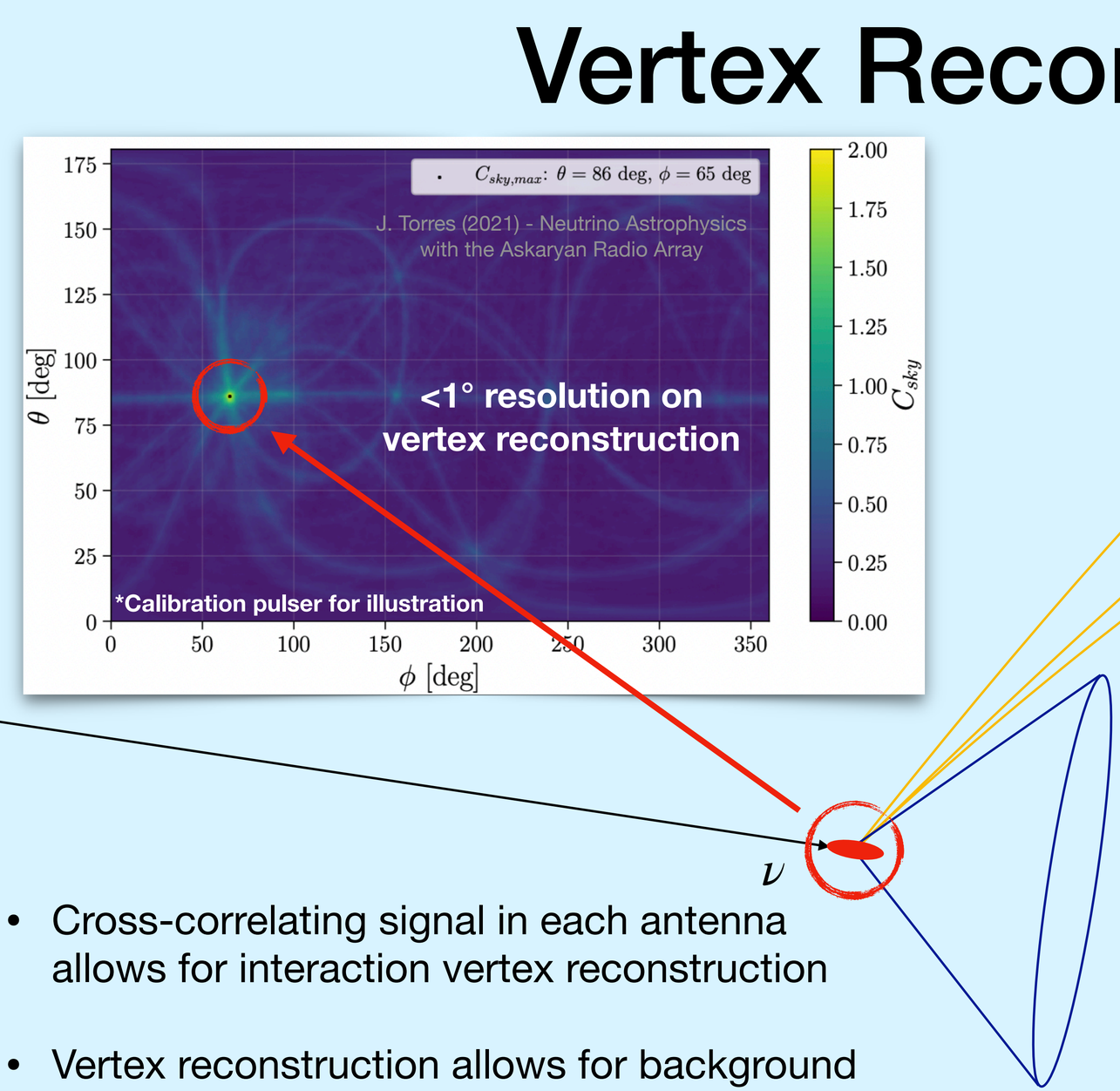
ARA Detector Overview

- 5 independent stations on hexagonal grid at South Pole
- Each station has 4 strings embedded in ice
- Each string has 4 radio antennas (2 VPols & 2 HPols) at ~200 m depth
- Trigger condition:
  - 3 like-polarization antennas with integrated power 5x ambient noise within 170 ns coincidence
- ~6 Hz trigger (+1 Hz software trigger)





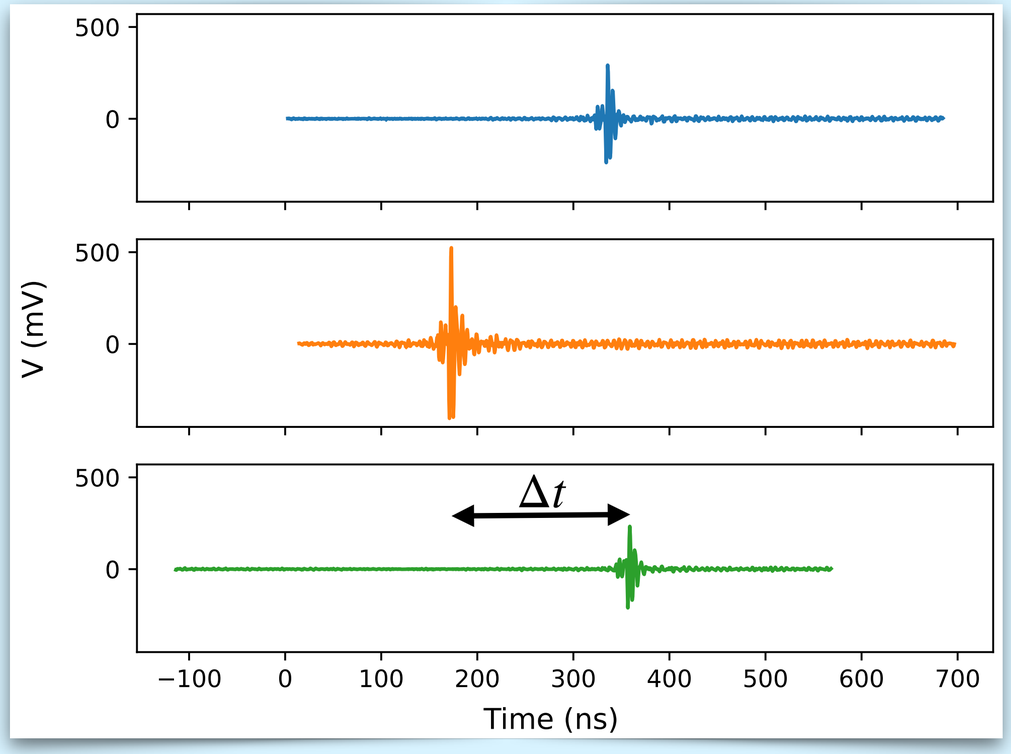
Vertex Reconstruction



- Cross-correlating signal in each antenna allows for interaction vertex reconstruction
- Vertex reconstruction allows for background CR and anthropogenic signals to be discarded

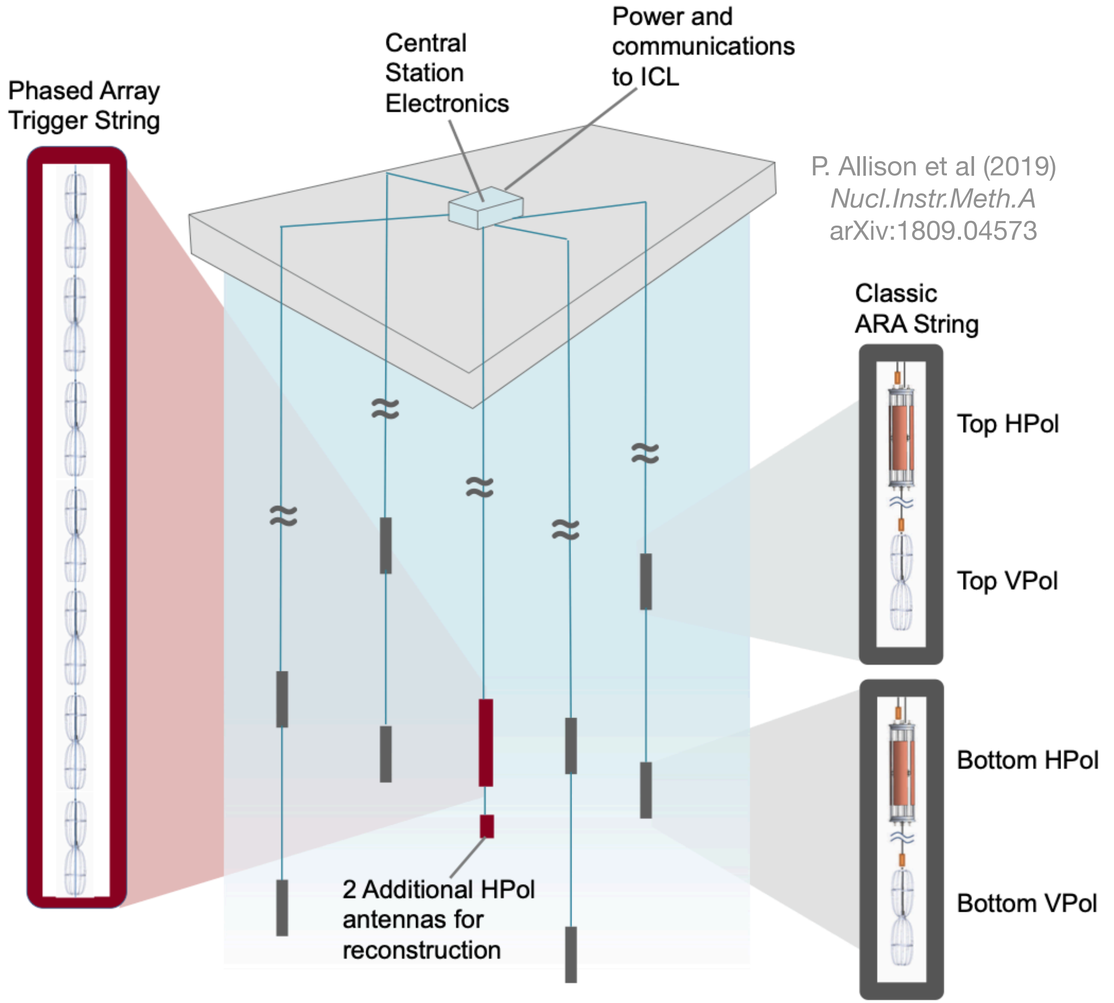
See talk from Alan Salcedo Gomez Wednesday 5:15PM

See talk from Kenny Couberly Wednesday 3:30PM



Phased Array Detector

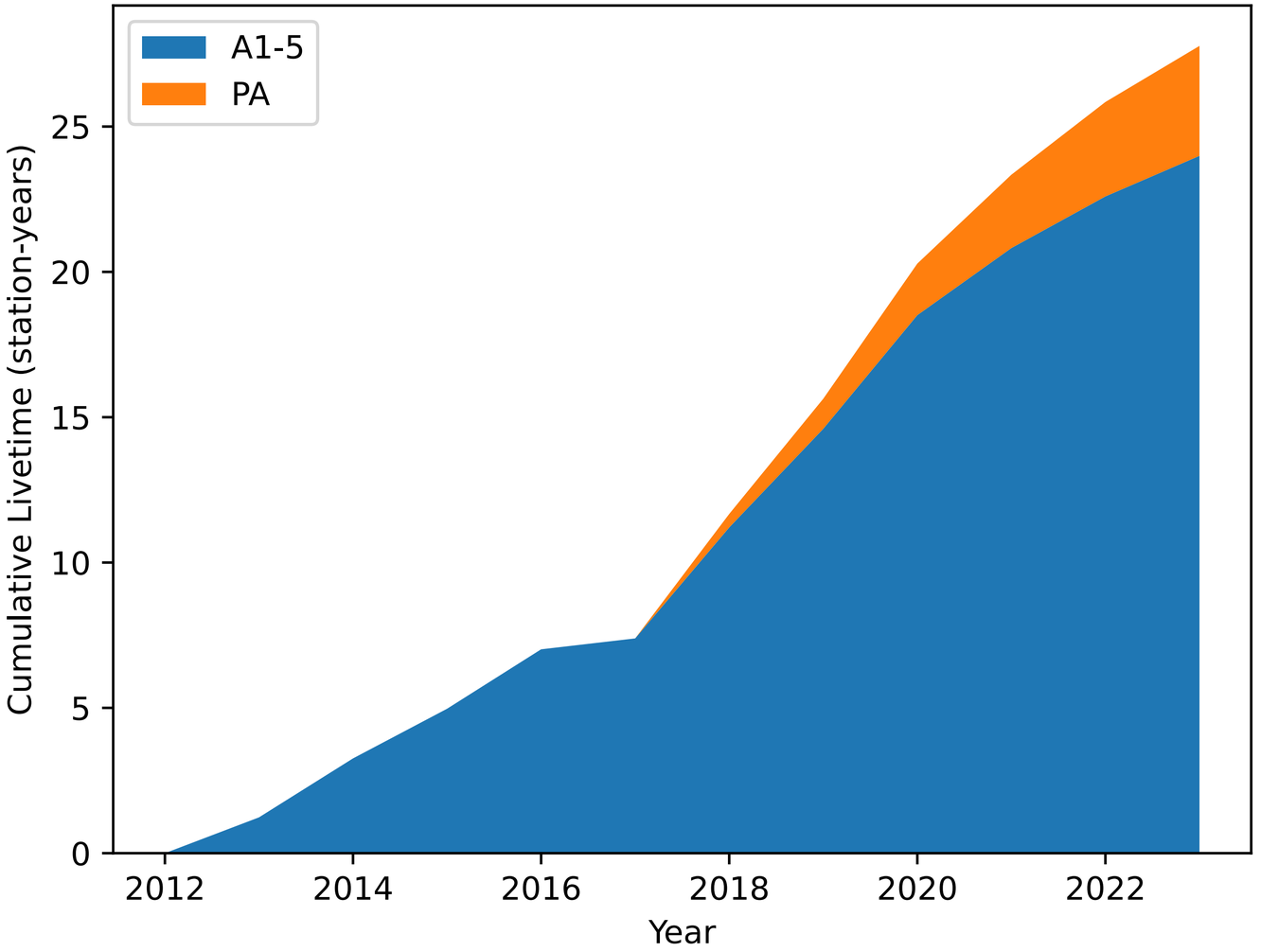
- Fifth ARA station (A5) has two subdetectors:
  - Traditional ARA strings
  - Additional central string: **the Phased Array (PA)**
- PA string has 9 closely packed antennas (7 VPols & 2 HPols) at ~180 m depth
- **More efficiently triggers** on low signal-to-noise ratio (SNR) signals by adding VPol signals in preset directions (beams)
  - Signals add coherently, noise does not
- Triggers when a beam has excess power in 10 ns window
- ~11 Hz trigger rate



P. Allison et al (2019)
Nucl.Instr.Meth.A
arXiv:1809.04573

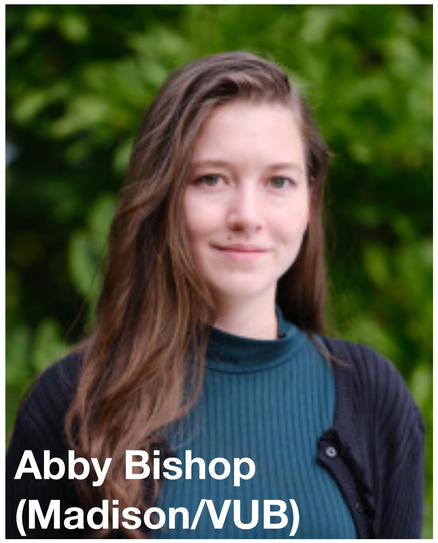
Towards a Five Station Analysis

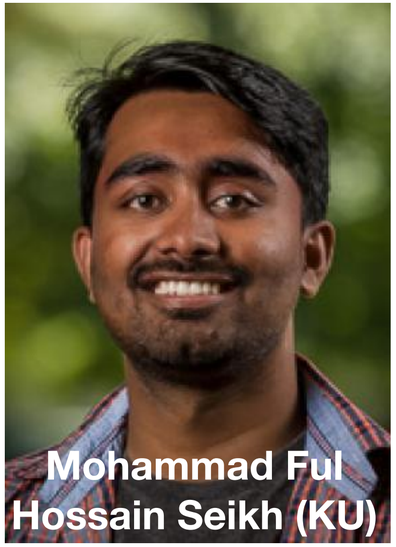
- ARA has been taking data for more than a decade
- Through 2023, accumulated ~28 station-years across 5 stations
  - Roughly 379 TB of data on disk
- **Goal: Conduct diffuse neutrino search in livetime through 2023 leveraging the entire Askaryan Radio Array**
  - Perform global optimization to maximize discovery potential
- First array-wide search in deep stations

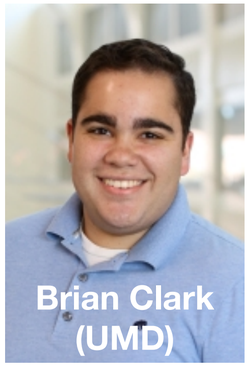


Station-Level Analyses

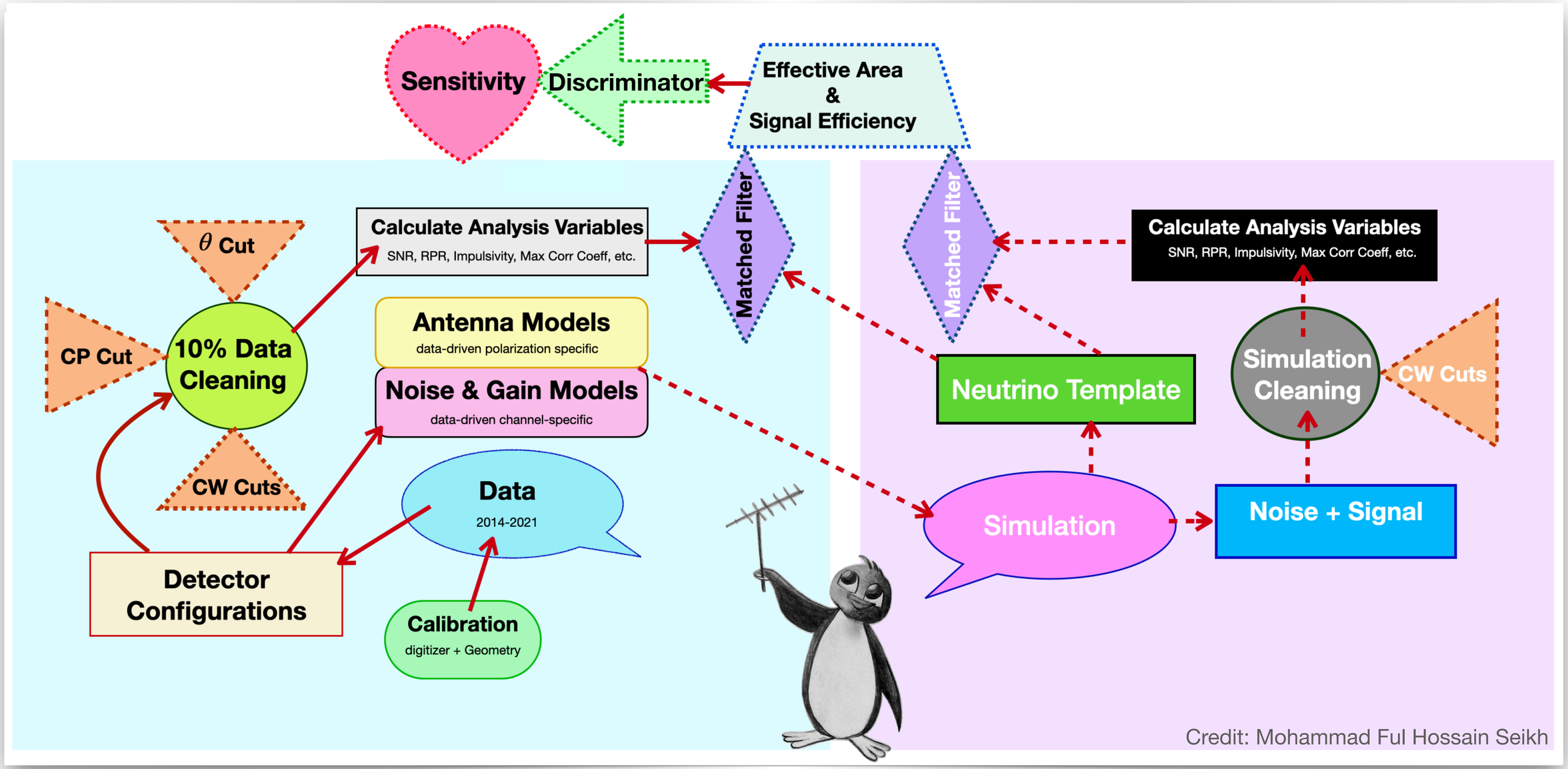
- Enormous amount of data to analyze!
- Highly-coordinated effort across 9 institutions
- Core team of 7 analyzers





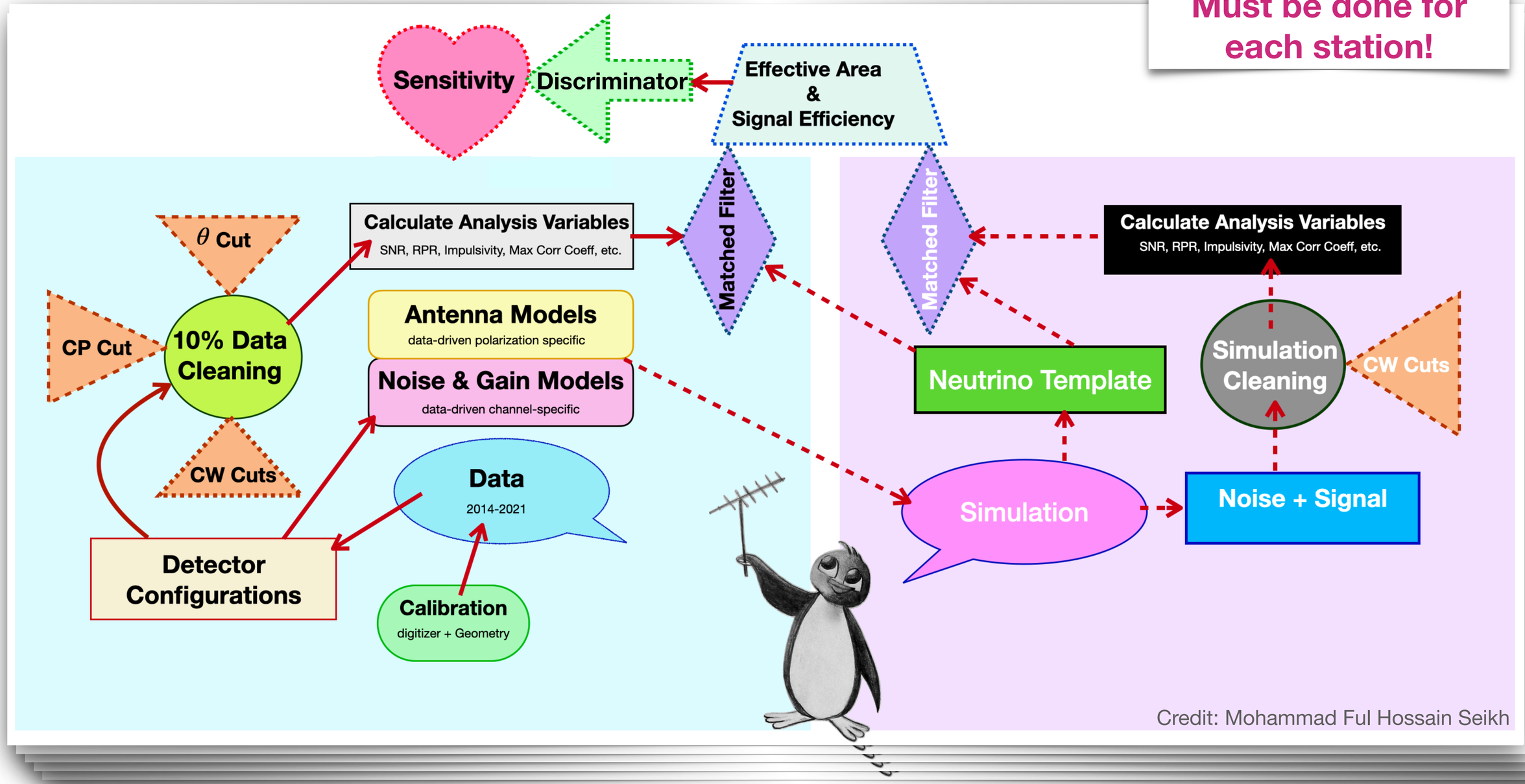


Station-Level Analyses



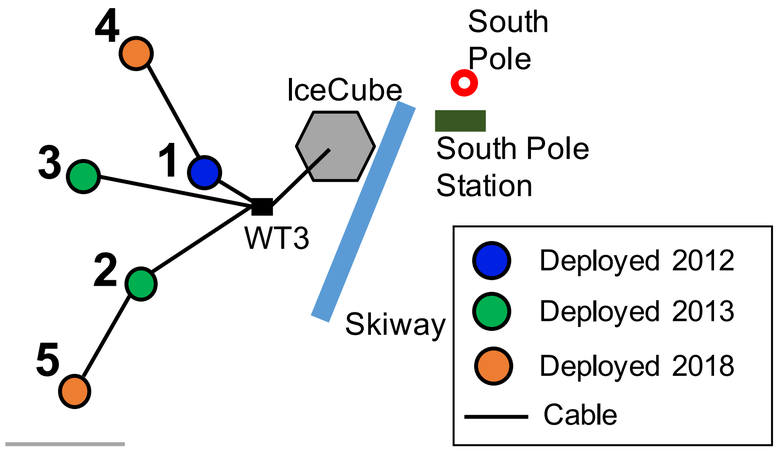
Station-Level Analyses

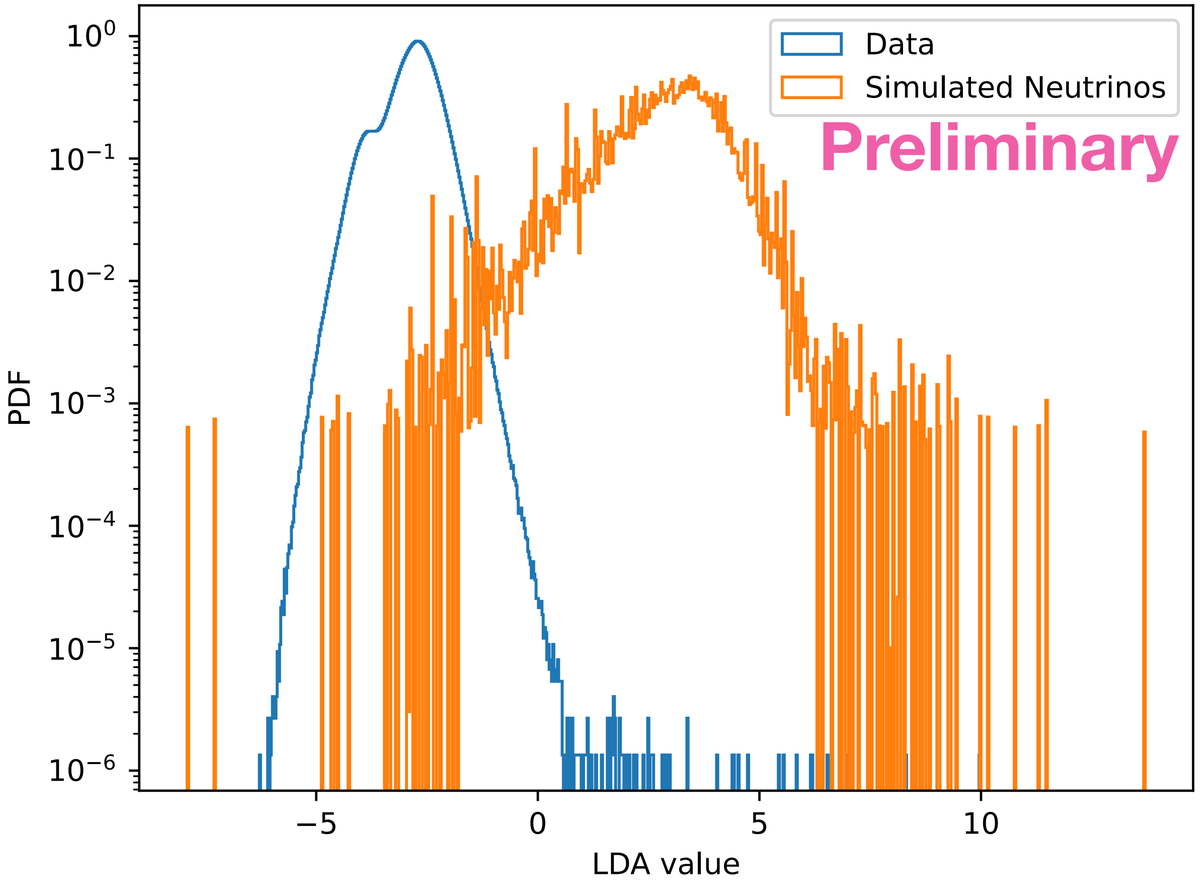
Must be done for each station!



Global Optimization

- Final signal cut will be made in discriminator value
  - Maximize signal-background separation
- Cut will be optimized for 5σ discovery potential *across the full array*
  - Enables more sensitive result than simply combining 5 single-station optimized limits
- Will optimize assuming the IceCube 2018 limit [PRD 98, 062003 (2018)] as flux model



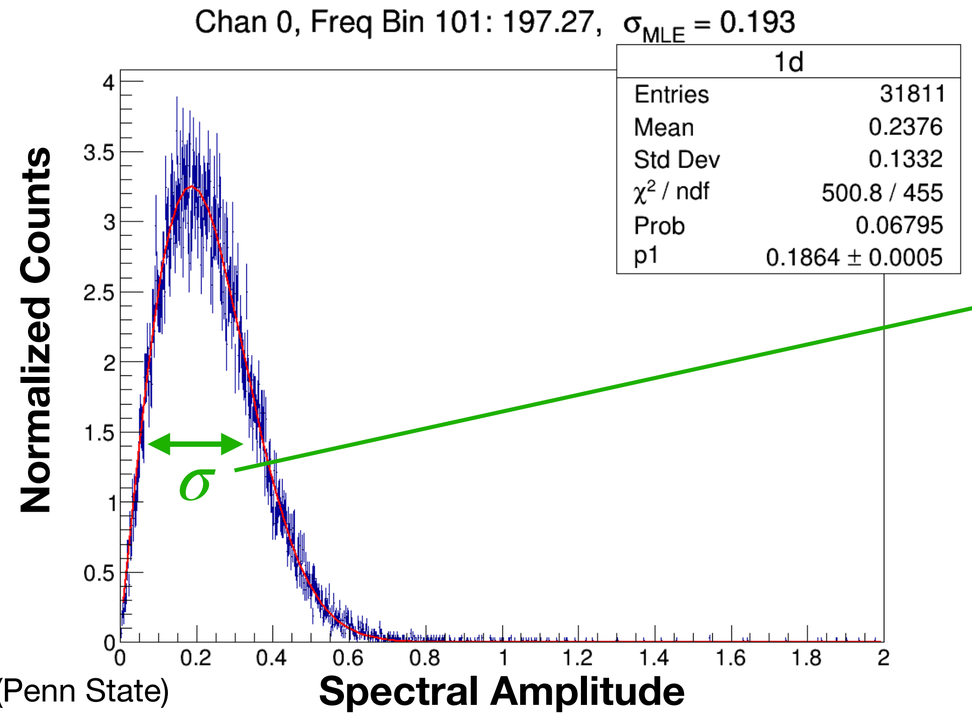


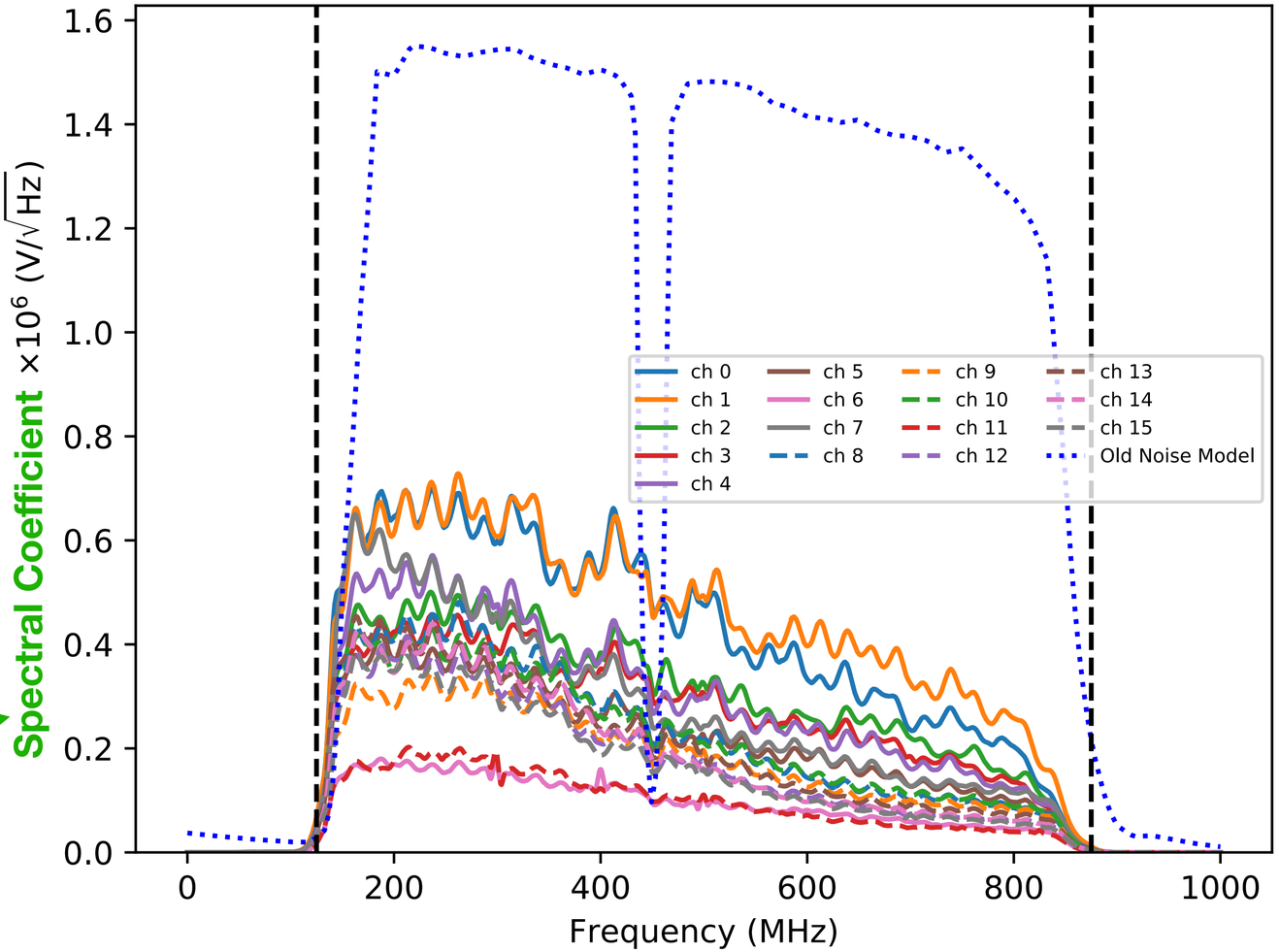
$$\phi_{\mathrm{up}} = \frac{\mathrm{FC}(\sum_s b_s)}{\sum_s A_{\mathrm{eff},s} T_s \epsilon_s}$$

Depend on signal cut value

Detector Characterization: Noise Models

- Data-driven noise models now implemented in simulation
- Extracted Rayleigh distribution parameters for each frequency, channel, & station configuration
  - Based on forced trigger data
- Includes noise contributions from environment and signal chain

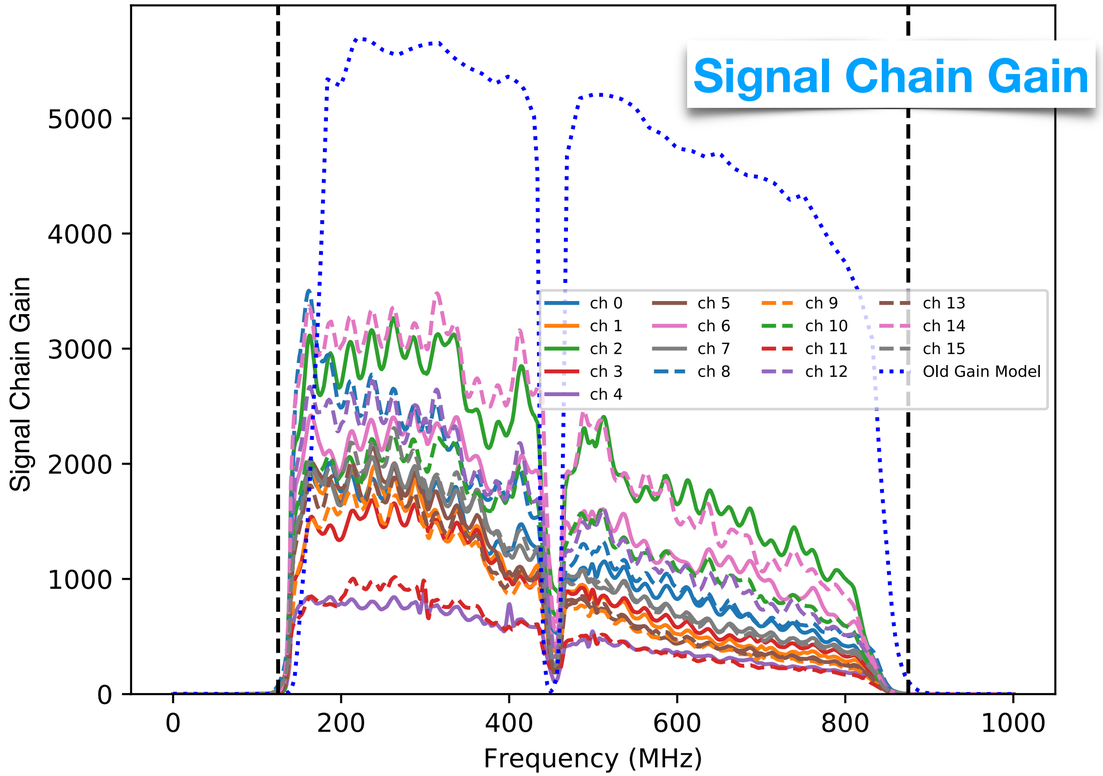


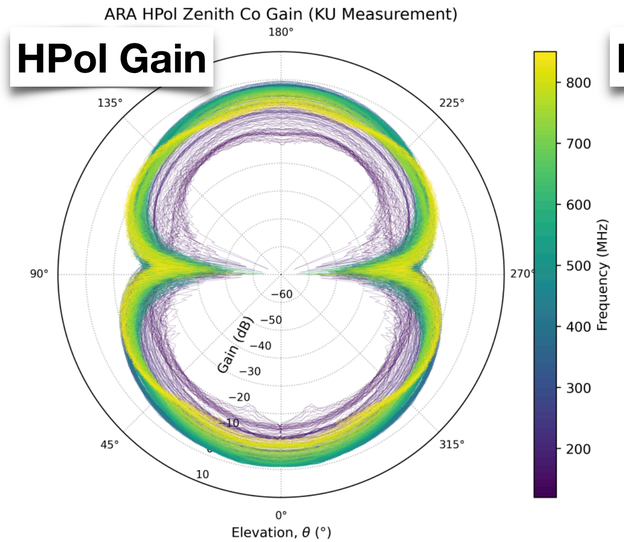


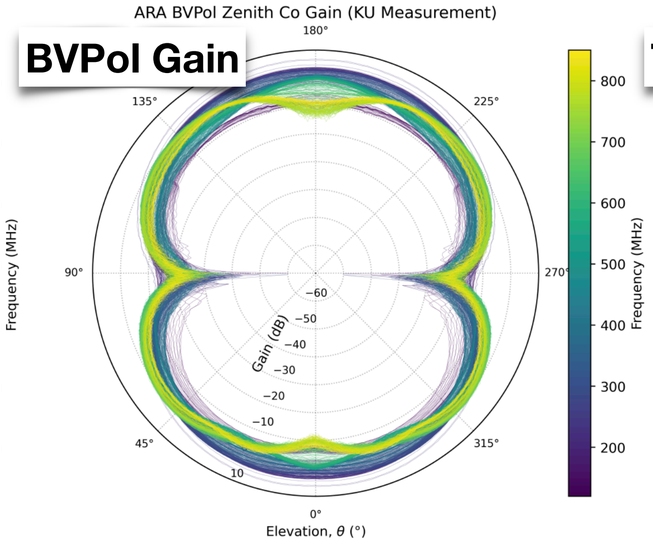
***Old noise model amplified by gain model, new models include system gain directly**

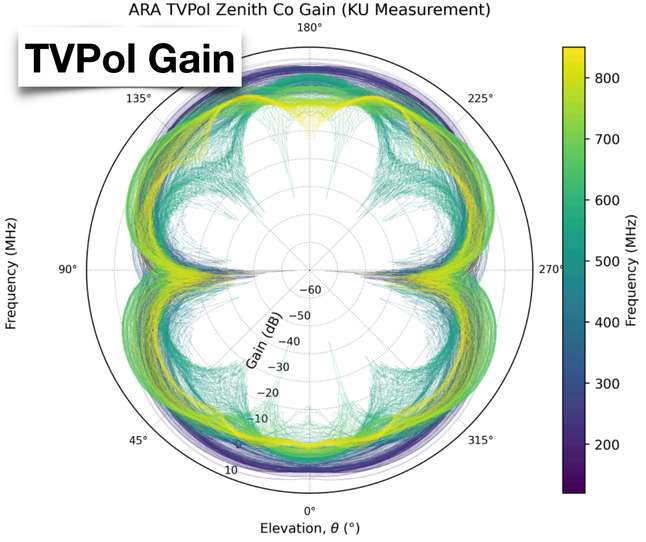
Detector Characterization: Antenna & Signal Chain Gain

- New anechoic chamber antenna measurements from University of Kansas
- Three antenna types:
  - Top & bottom VPols (dipoles)
  - HPol (quadslot)
- Data-driven gain models now implemented in simulation
  - Ratio of observed noise to theoretical expectation signal chain, accounting for antenna & amplifier properties



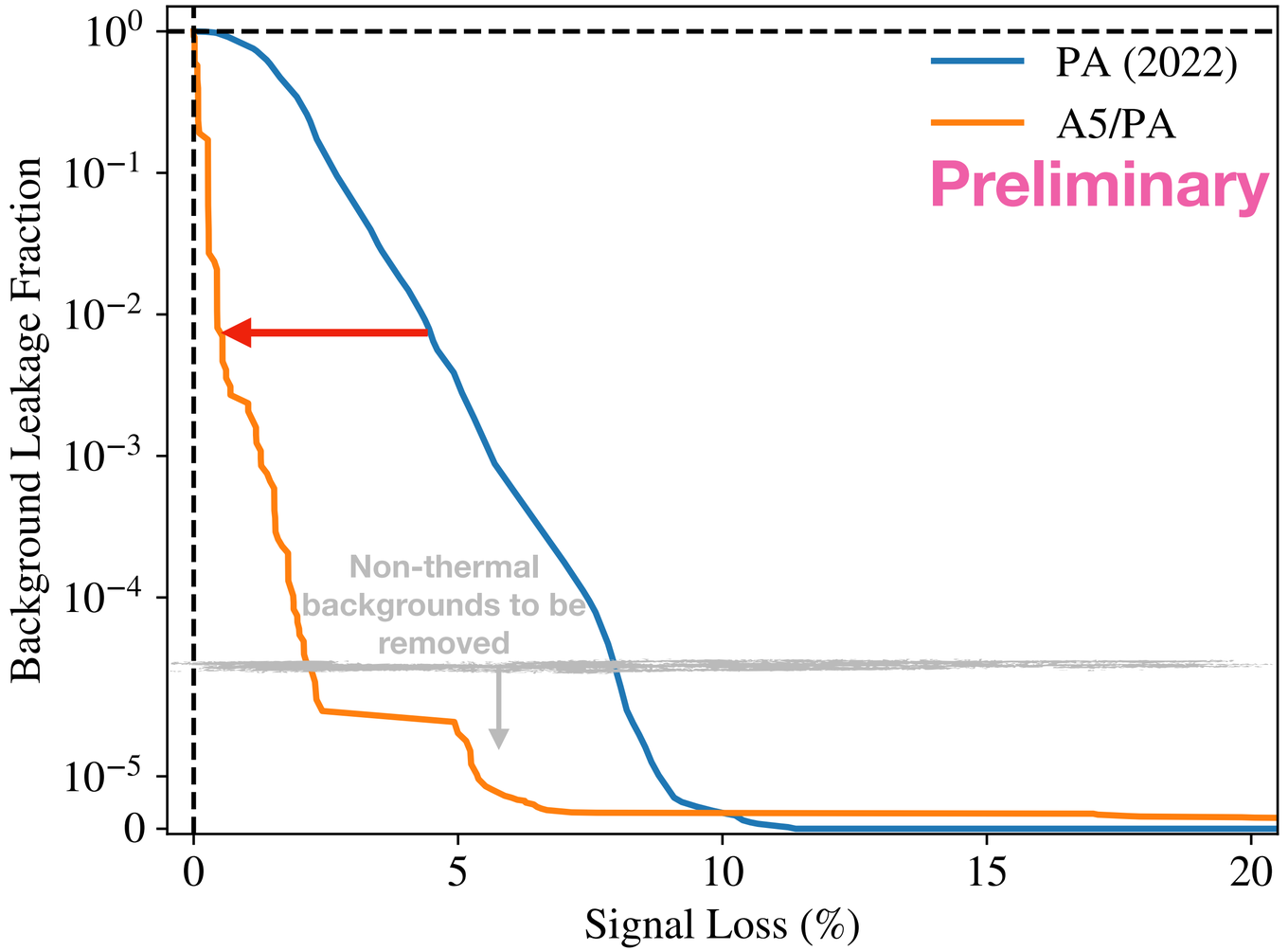






Improved Background Rejection

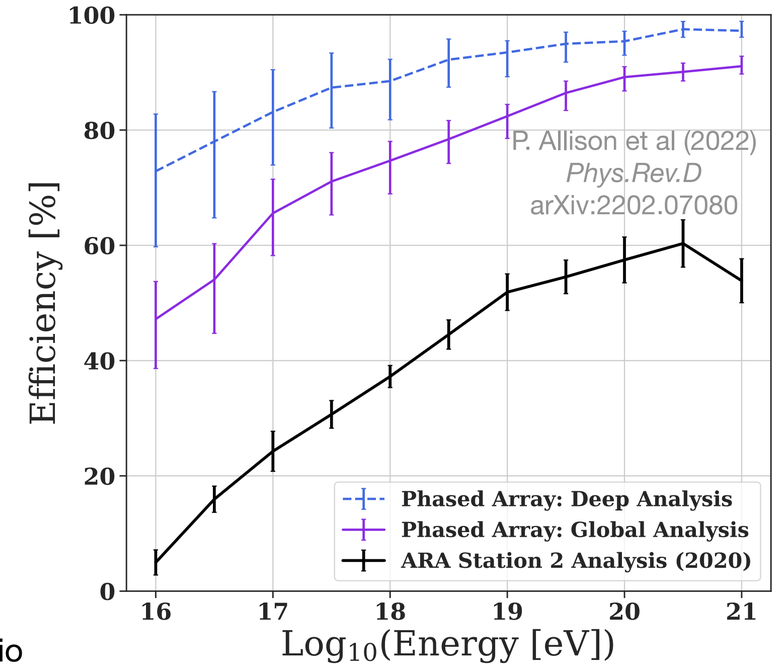
- Improved event characterizations have improved signal discrimination from thermal backgrounds
  - Implementation of waveform de-dispersion & coherent sums in all stations
  - Improved to analysis efficiency
- Significant improvements to reducing non-thermal backgrounds, especially for PA



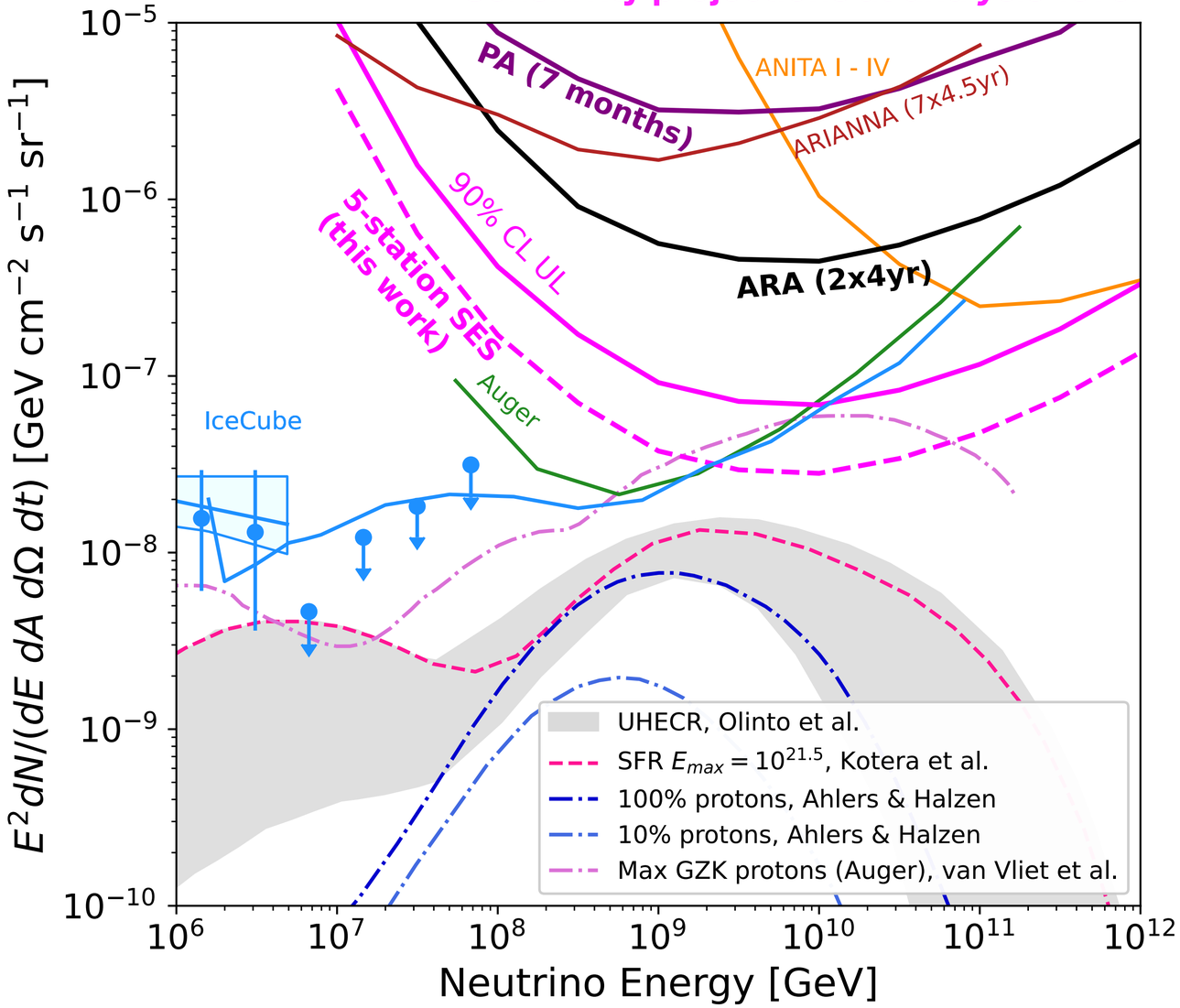
See talk from Paramita Dasgupta Wednesday 5:30PM

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 2018 limit flux: ~18.5 events



Sensitivity projections *at analysis-level*



***Projected assuming same analysis efficiency as 2019 A2/3 analysis & 2019 PA analysis**

Summary

- ARA has accumulated ~28 station-years of livetime through 2023
- **Conducting first-ever array-wide neutrino search in deep stations**
  - Highly-coordinated, multi-institution analysis
  - Improved analysis methods & detector characterization
- Proof of concept for next-generation large in-ice radio arrays
  - e.g. RNO-G (35 stations)
    & IceCube-Gen2 Radio (361 stations)
- **Will yield either:**
  - **First UHE neutrino candidates**
  - **Strongest flux limit up to 1000 EeV from any radio experiment**

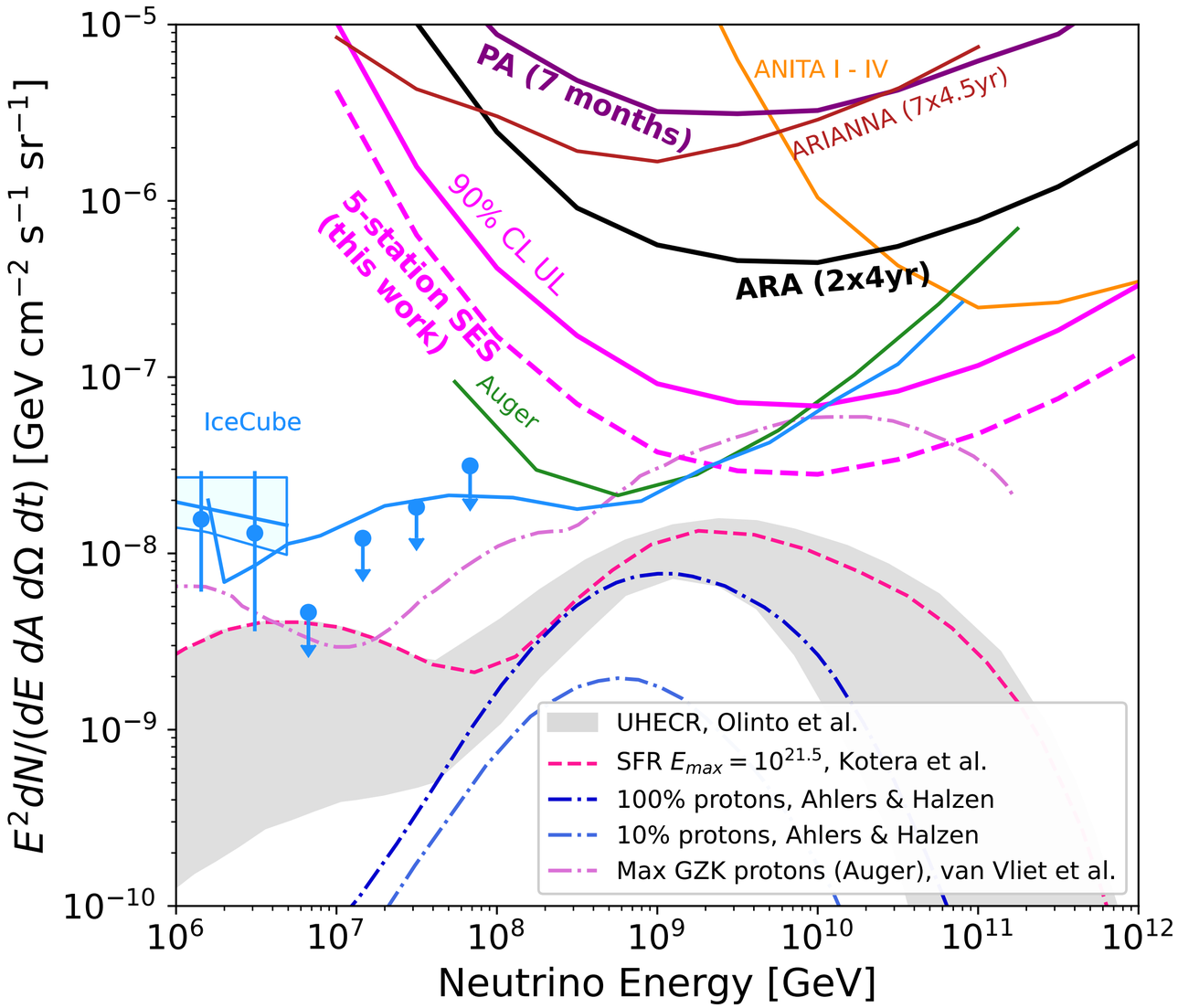


Image credit: Aman Chokshi, SPT/NSF