The Radio Neutrino Observatory in Greenland (RNO-G): Towards the Radio Detection of Cosmic Rays In Greenland Ice

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The Ohio State University
Center for Cosmology and Astroparticle Physics

RNO-G
Radio Neutrino Observatory - Greenland

NSF

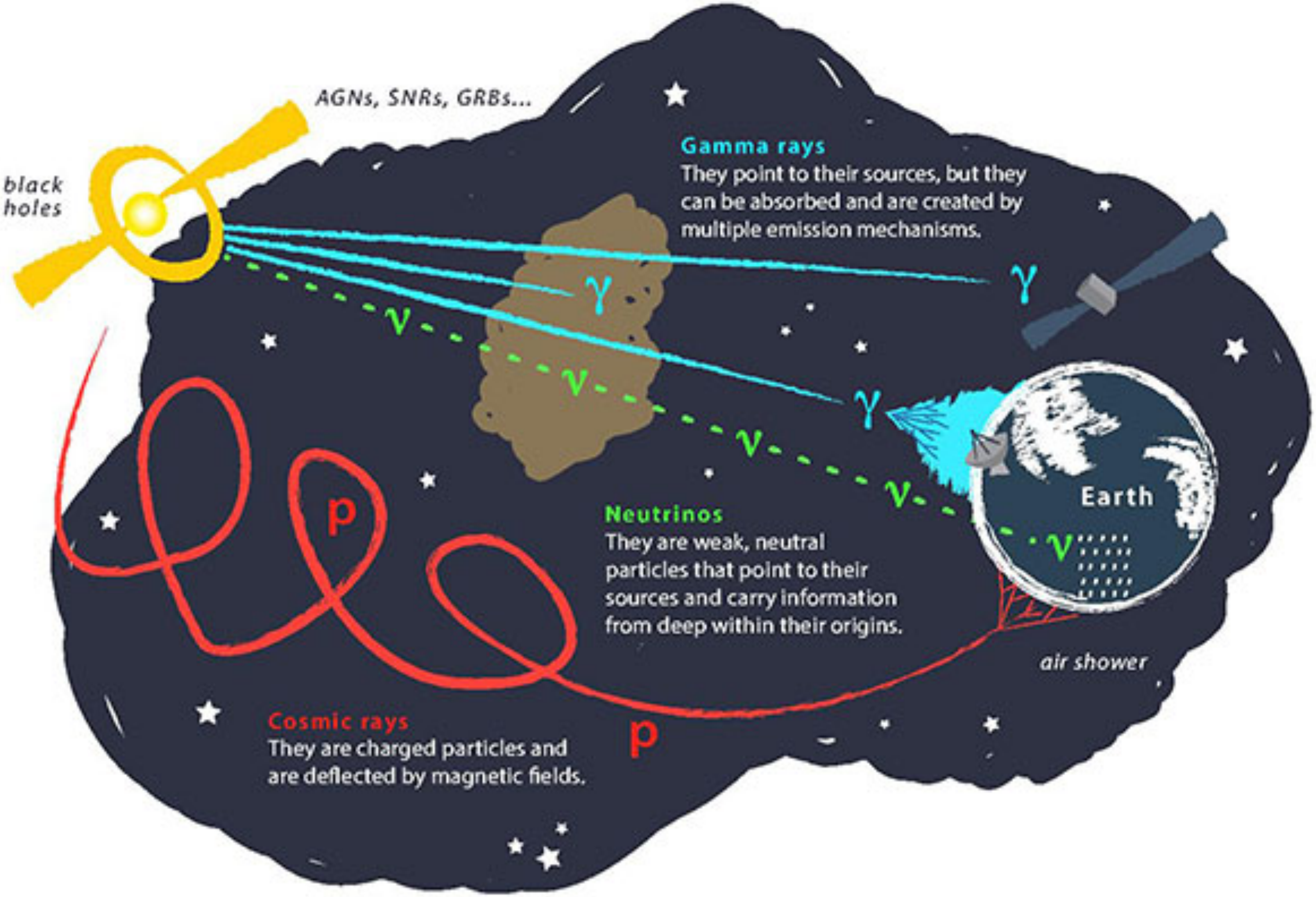


Figure 1: A study of the universe through light, neutrinos, cosmic rays, and gravitational waves, combining all messengers into one story. Credit for the image: Ice Cube Collaboration

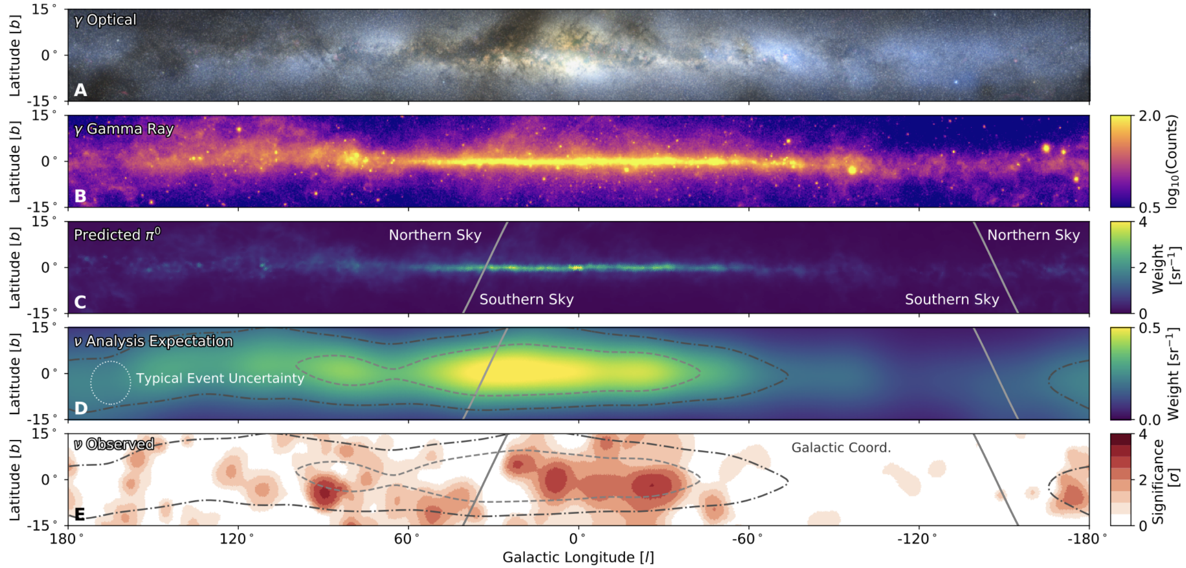


Figure 2: The plane of the Milky Way galaxy in photons and neutrinos [1]

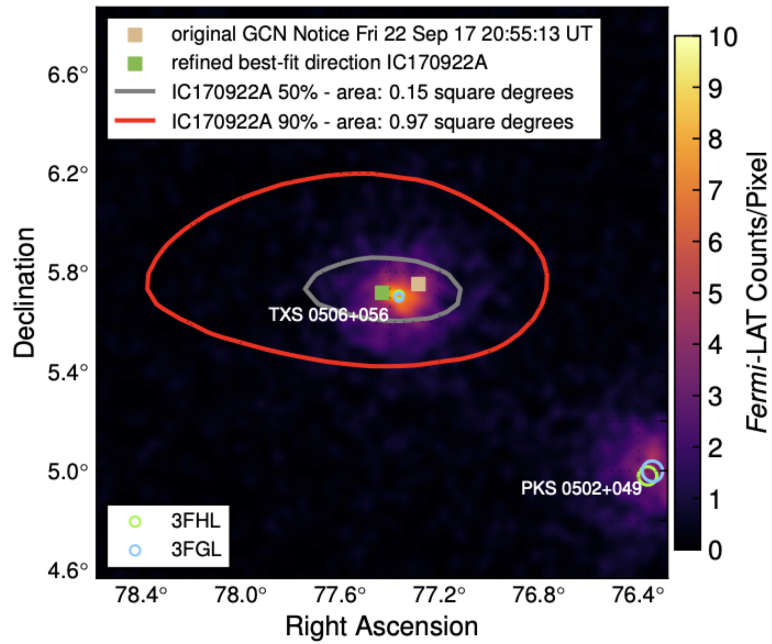


Figure 3: Fermi-LAT and MAGIC observations of IceCube-170922A's location [2].

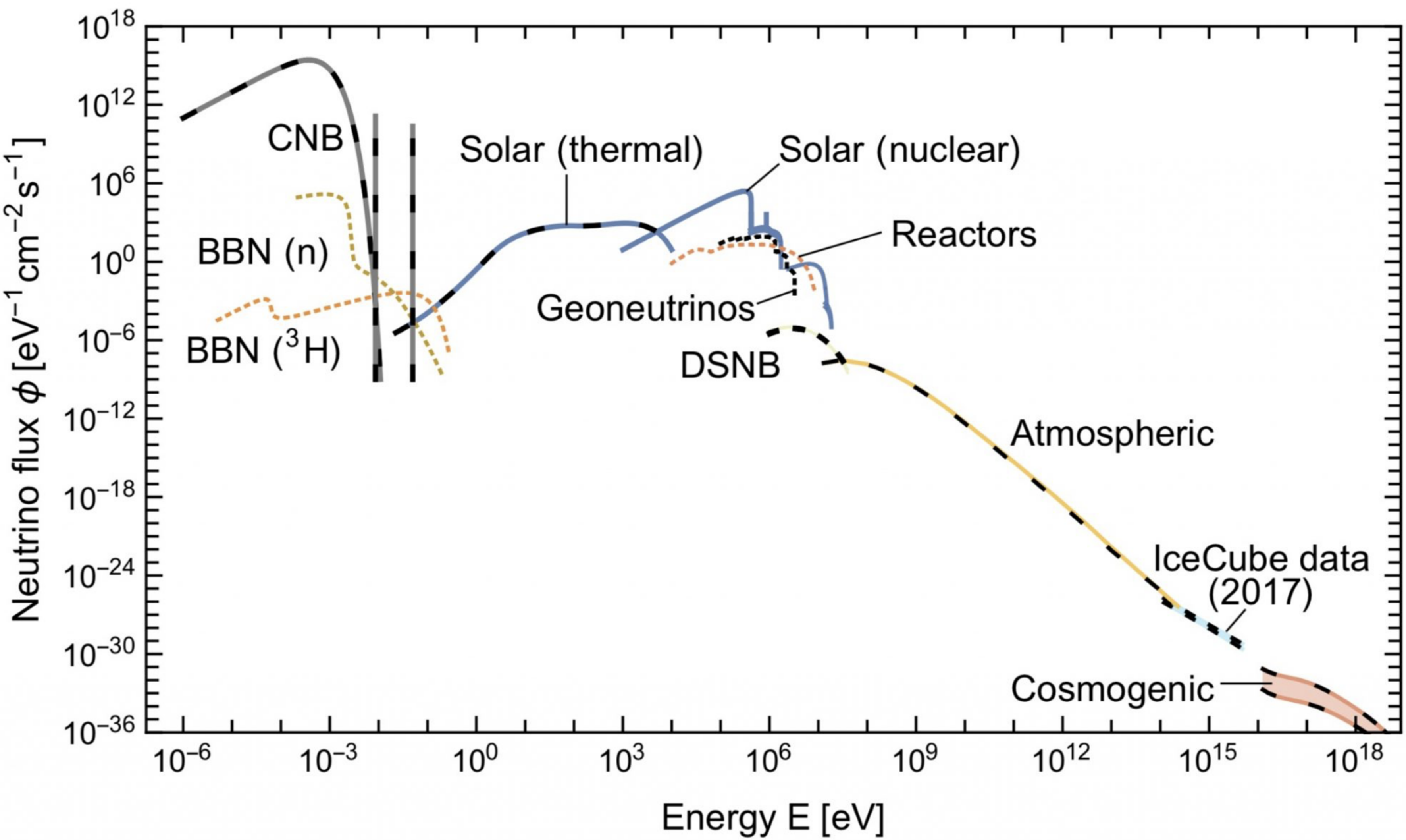


Figure 4: Grand Unified Neutrino Spectrum

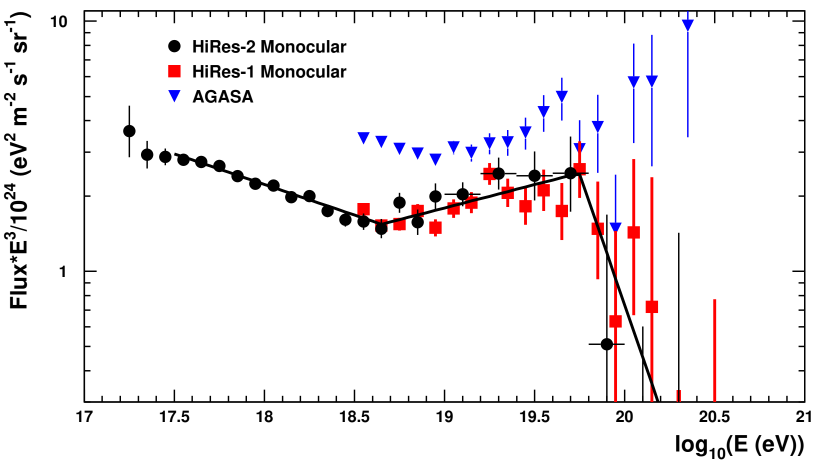


Figure 5: The GZK cut off of the UHE CR spectrum observed by HiRes [3].

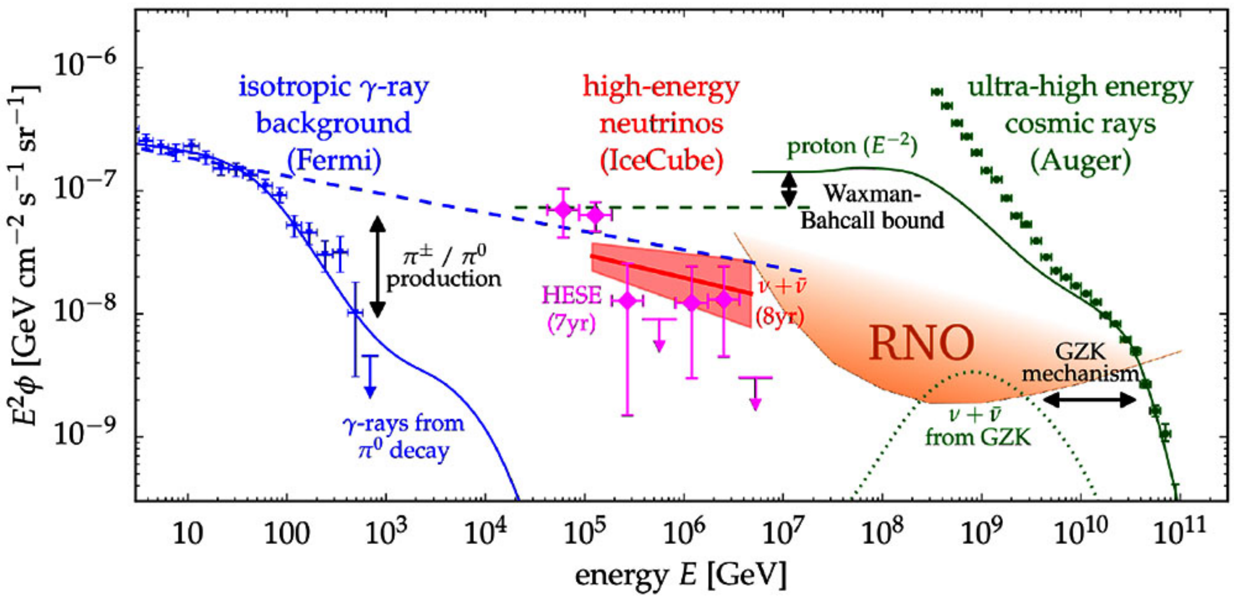


Figure 6: The high-energy diffuse fluxes of gamma rays, neutrinos, and cosmic rays [4].

Interactions of Ultra High Energy (UHE) CR with CMB photons produce a flux of secondary particles (GZK effect)

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \rightarrow \gamma + \gamma \\ n + \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} \end{cases}$$

- Pose upper limit on CR energy ($\geq 5{\cdot}10^{19}$ eV) observed on Earth
- Cosmogenic neutrino flux is **expected** at the highest energies from 10 PeV to 100 EeV

Detecting UHE neutrinos is challenging due to their extremely low flux (0.01 - 0.1 event/year/km^2 (!!)) and small interaction cross-section. Observation requires:

- Large detection volume O(100) km^3
- Dense medium

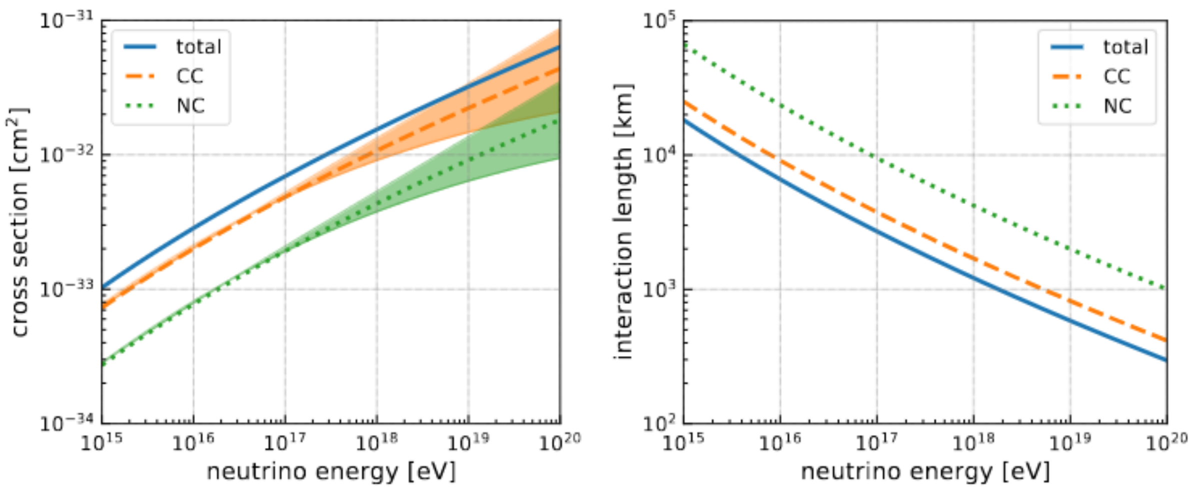


Figure 7: Neutrino interaction cross-section and interaction length in ice [5].

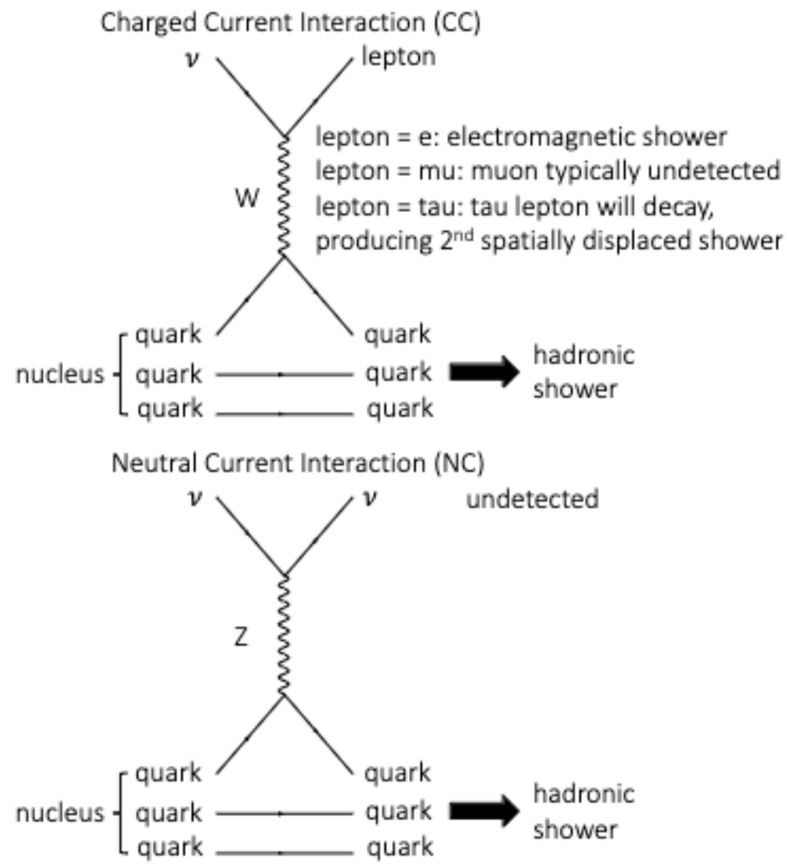


Figure 8: Feynman diagrams of a NC and CC neutrino interaction [6].

- In a dielectric medium, particle shower develops a charge asymmetry
- This moving charge imbalance emits coherent Cherenkov radiation in radio [7] (Askaryan effect)
- Strongest signal observed on Cherenkov cone $\theta_c = Cos^{-1}\frac{1}{\beta n}$
- Peak frequency for detectable signals: 100 MHz – 1 GHz

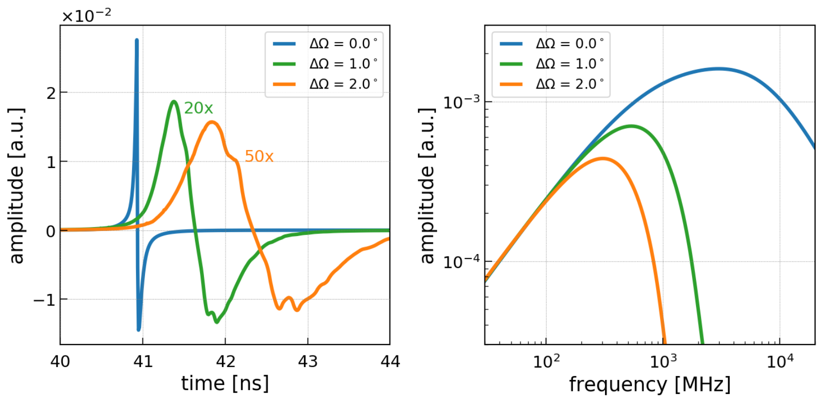


Figure 9: Short radio pulse - signature of UHE neutrino [6].

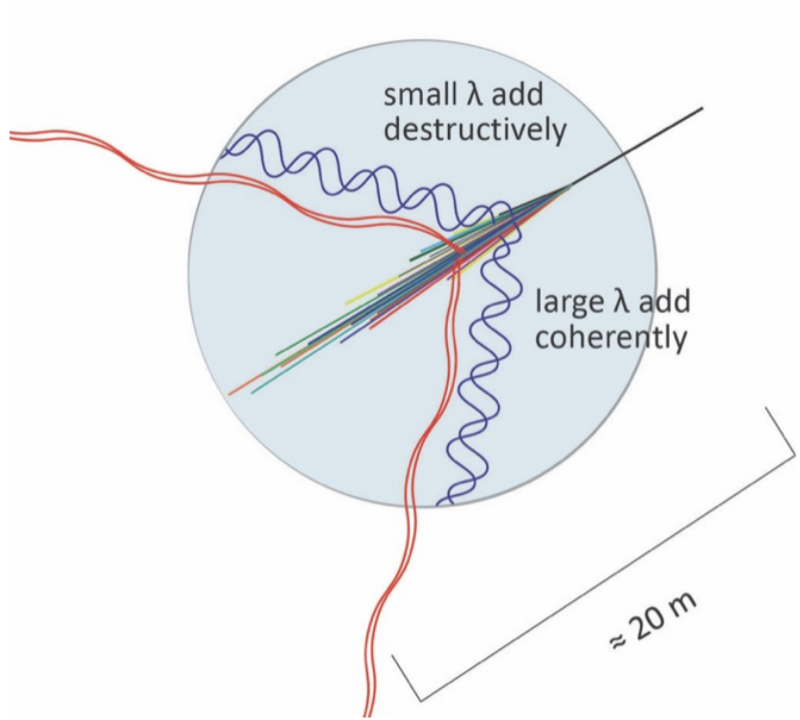


Figure 10: The Askaryan cone produced by particle shower.

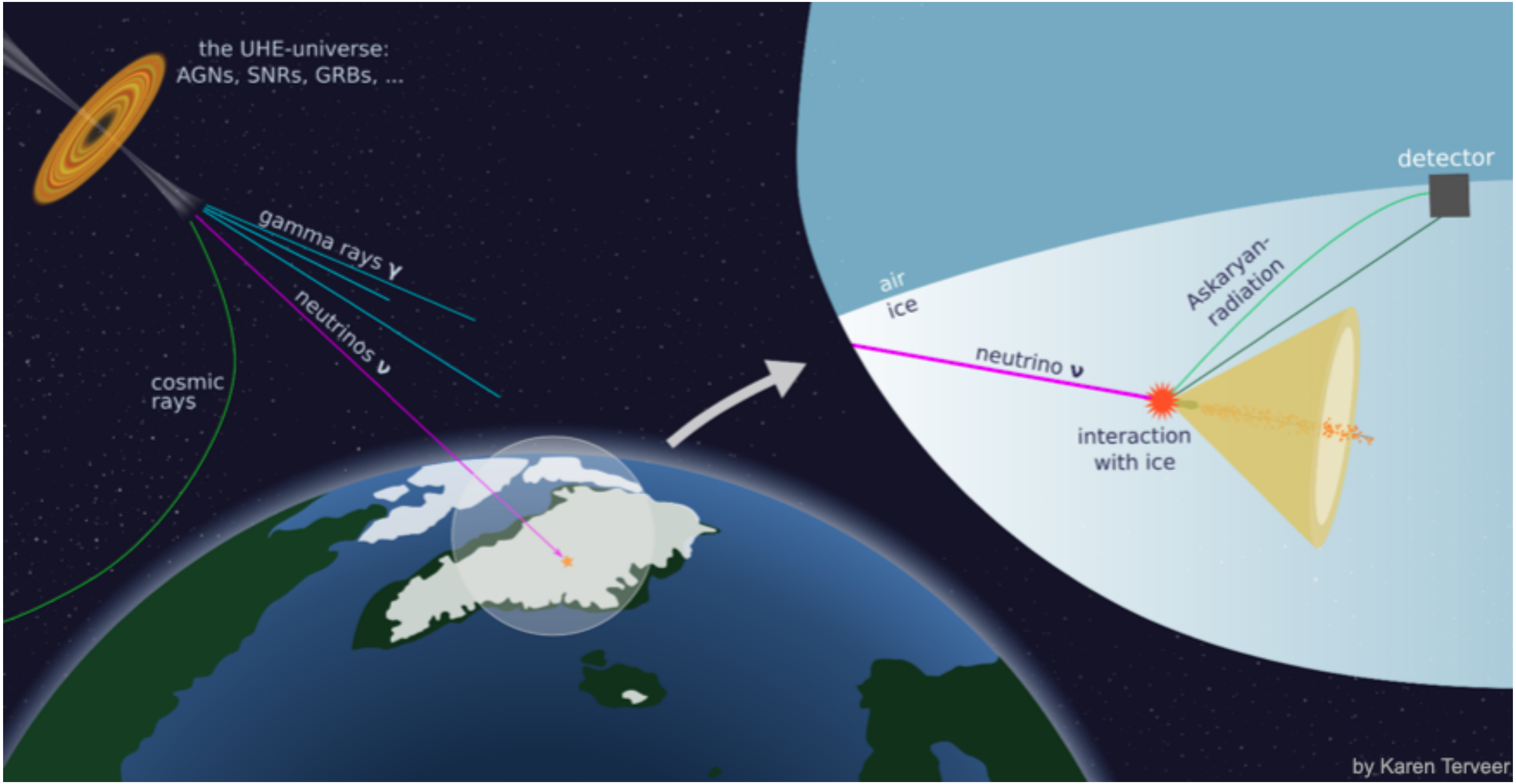


Figure 11: The RNO-g concept: detecting UHE neutrinos in Greenland's ice shelf via radio emission.

- Greenland ice sheet: up to 3 km thick at the Summit
- Radio attenuation length of cold polar ice: $\mathcal{O}$ 1 km [8],[6].
  — enabling neutrino detection over kilometer-scale volumes
- Changing index of refraction profile, causing "bending" of radio wave propagation trajectories in ice

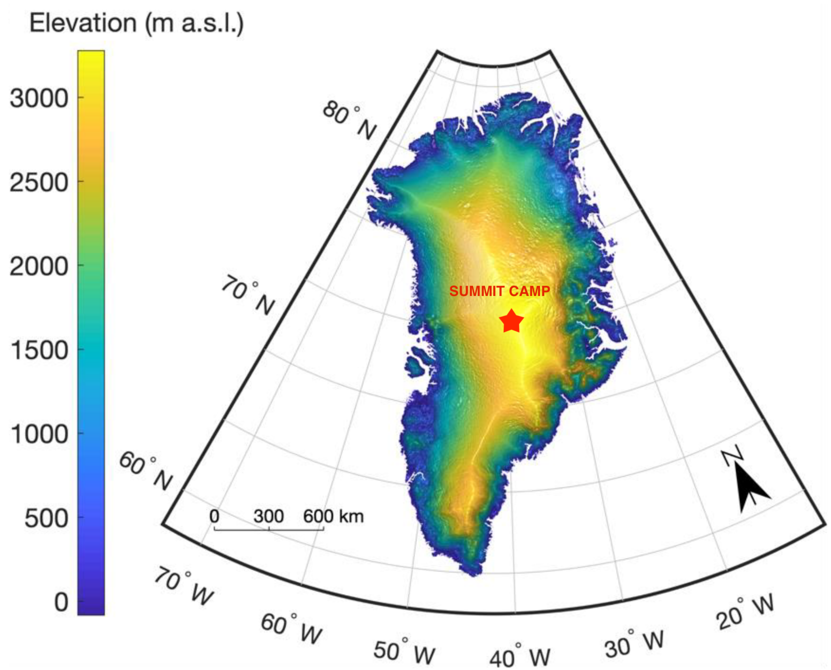
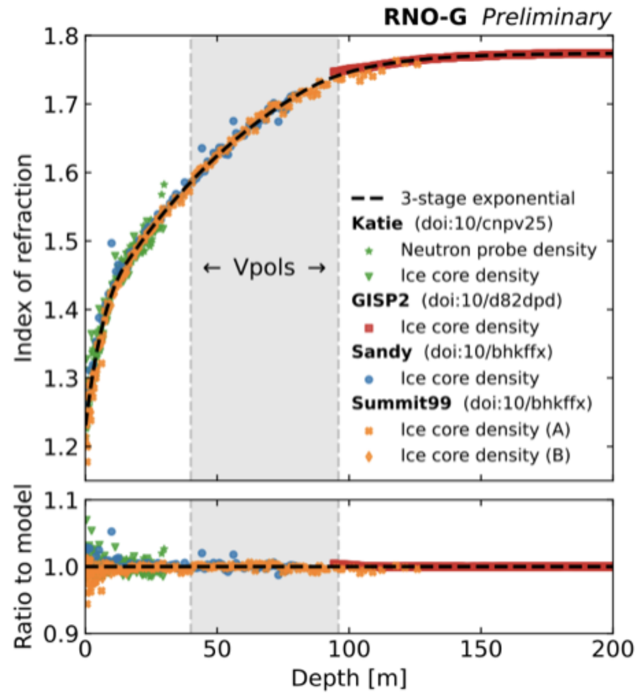
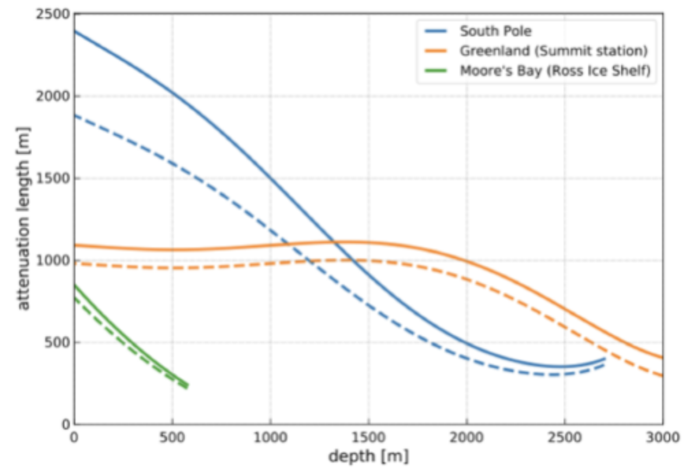


Figure 12: Greenland ice shelf elevation [9].





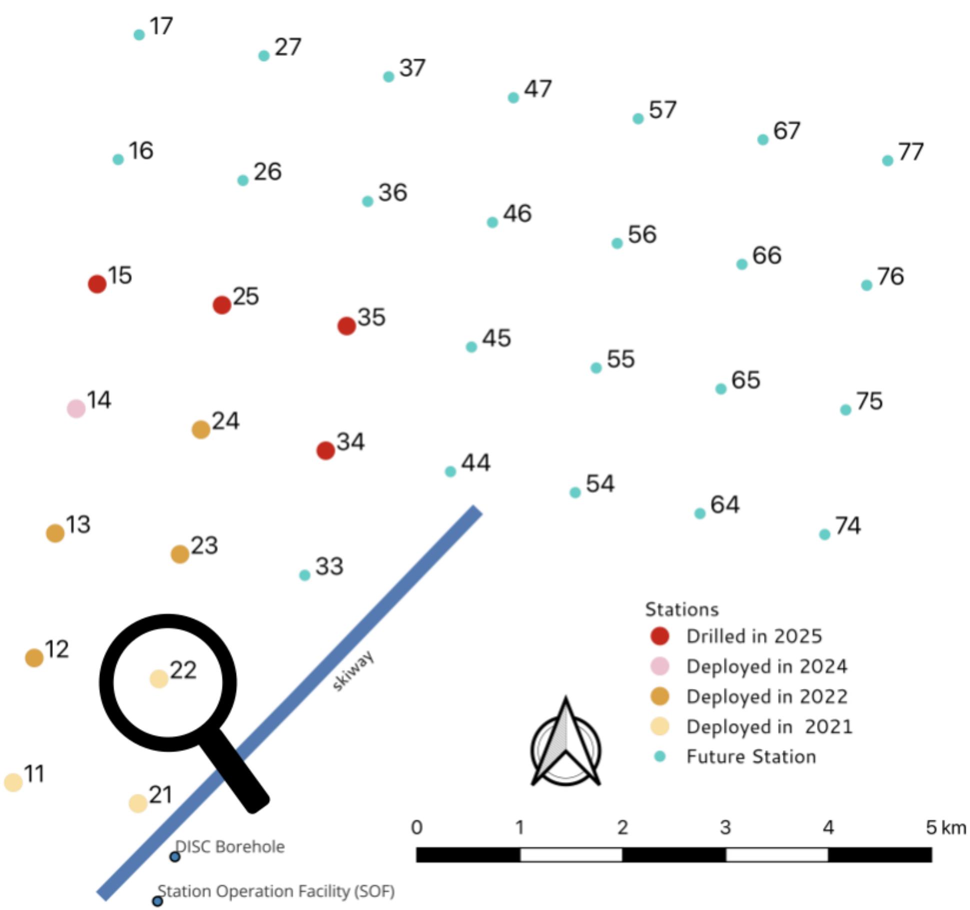


Figure 13: RNO-g site layout. Array of independent detector stations.

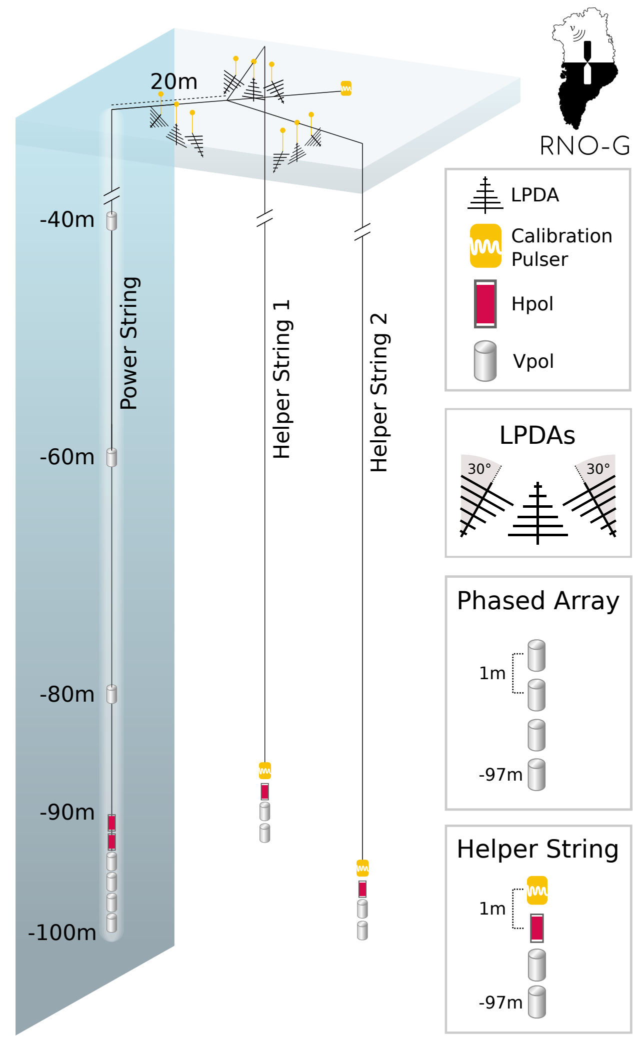


Figure 14: RNO-g station detail [4]. ©RNO-g Collaboration.

RNO-G: Design and Sensitivity, arXiv:2010.12279

RNO-g Antennas And In-situ Calibration Sources

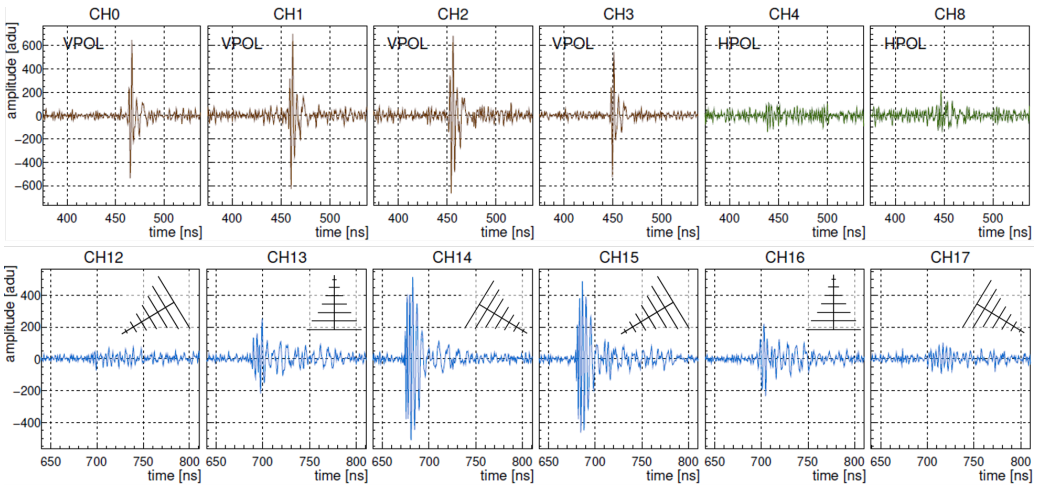


Figure 15: Calibration pulser waveforms [10]

RNO-G: Instrument Performance, arXiv:2411.12922

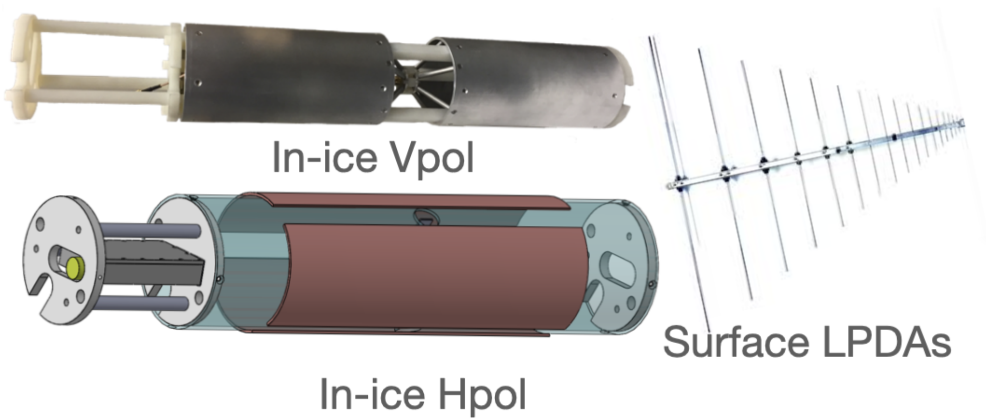


Figure 16: RNO-g antennas.

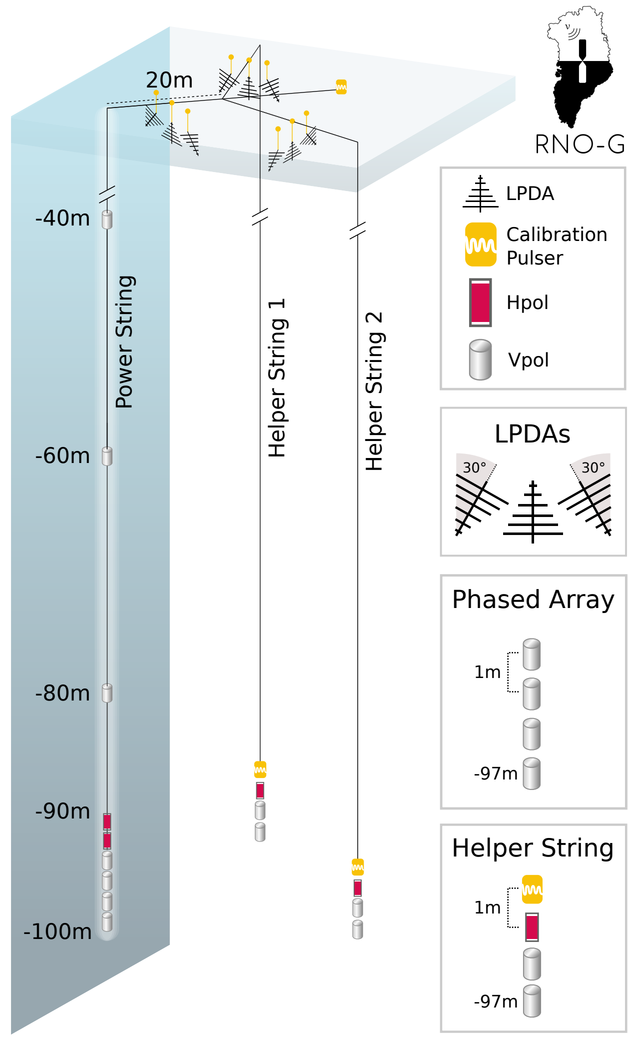


Figure 17: RNO-g station detail. ©RNO-g Collaboration.

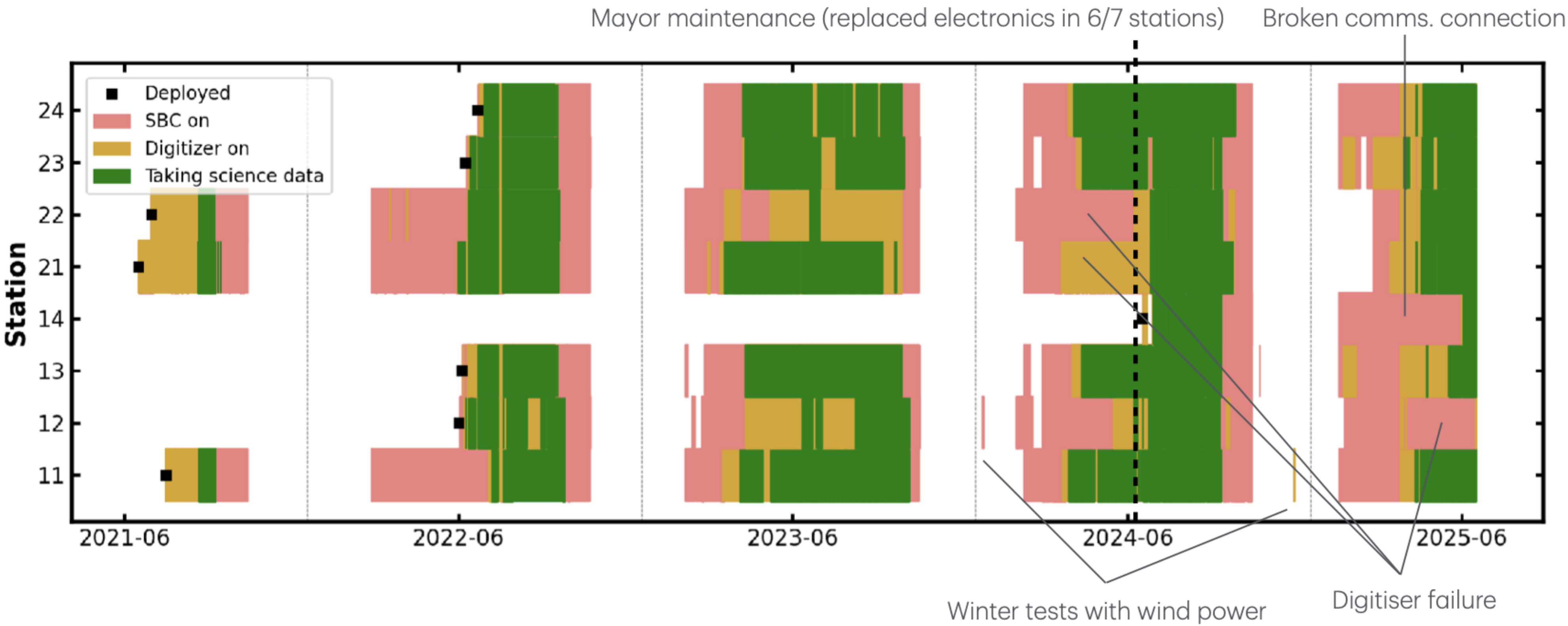


Figure 18: Uptime of the first eight RNO-G stations. Credit: F. Schlüter et al (RNO-G), ICRC 2025

- Data collection has been running since 2021 with existing stations
- Science data taken are restricted to the arctic summer (for now, wind turbines are under tesing!)

- The signal excesses were recorded during solar flares in coincidence with the Callisto network
- Observed flares show strong time-domain impulsivity
- Solar flares reconstructed on-sky enable absolute pointing calibration to subdegree resolution

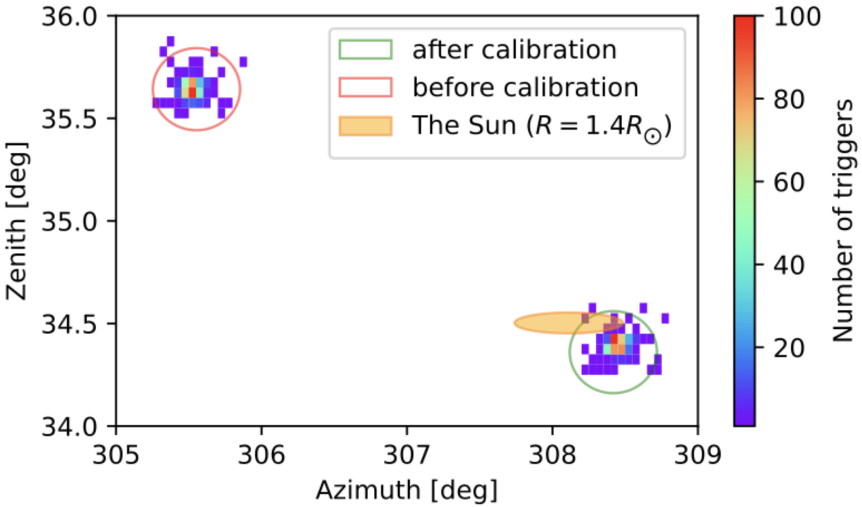


Figure 19: Reconstructed source location for the solar flare; [11].

M. Mikhailova et al (RNO-G), arXiv:2404.14995

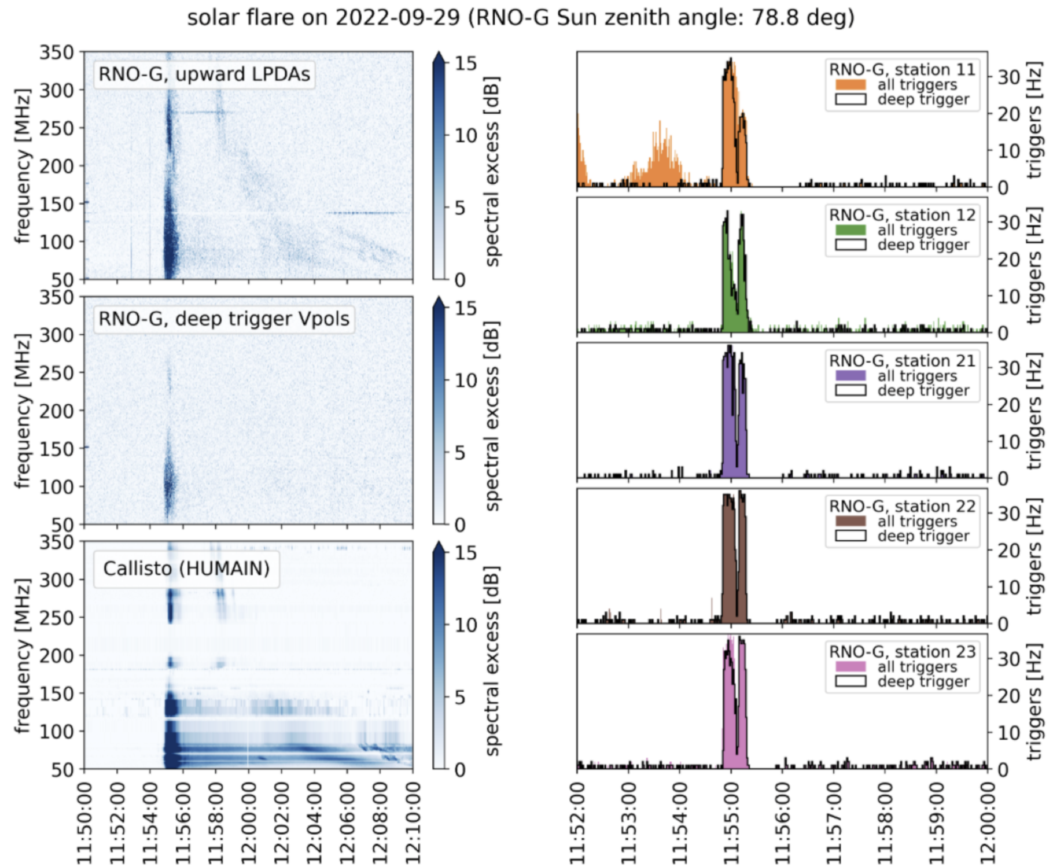
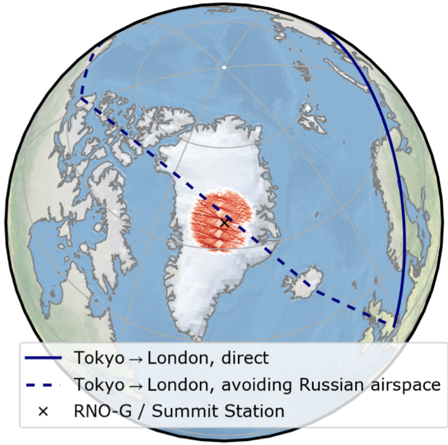


Figure 20: Left: Frequency spectra from RNO-G stations and Callisto during 2022-09-29 solar flare; Right: Deep & shallow trigger rates [11].



S. Hallmann et al (RNO-G), arXiv:2506.17522

- Multiple flights daily over RNO-G array
- Tag backgrounds in neutrino searches
- Strong far-field calibration, seen by many stations
- Test station timing and pointing accuracy

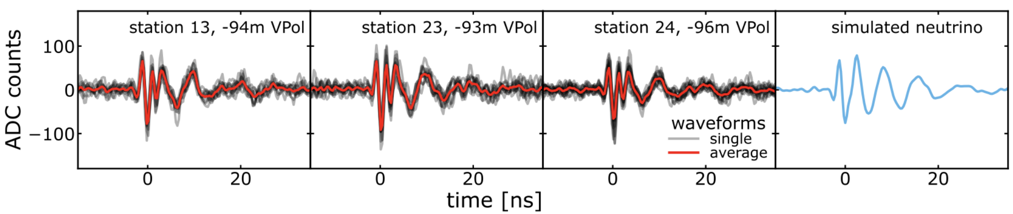


Figure 21: Impulsive event from a passing aircraft [12].

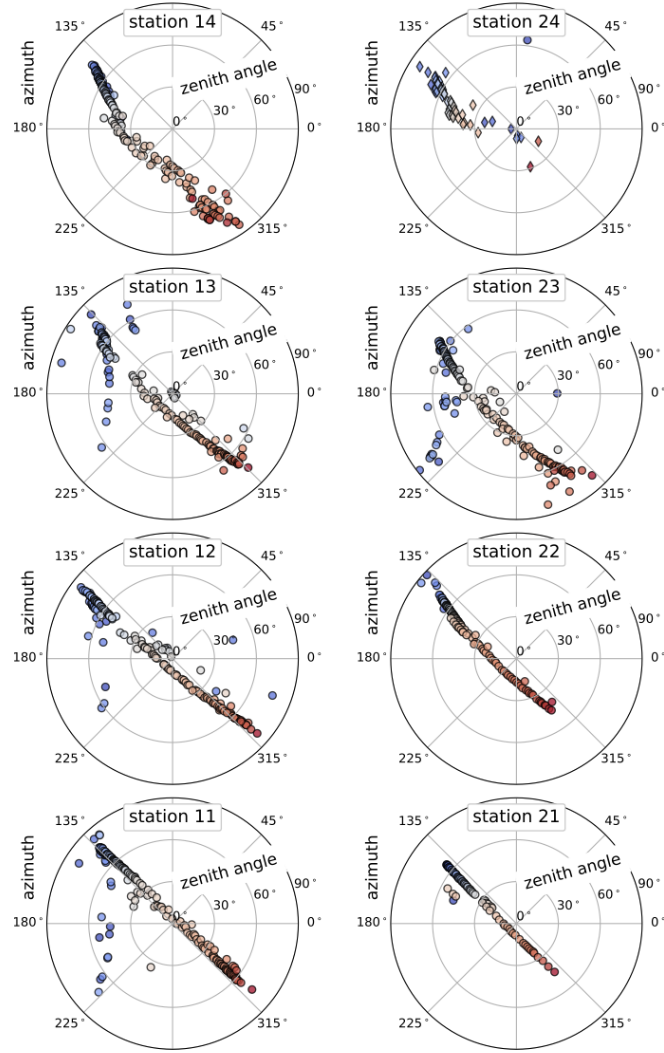
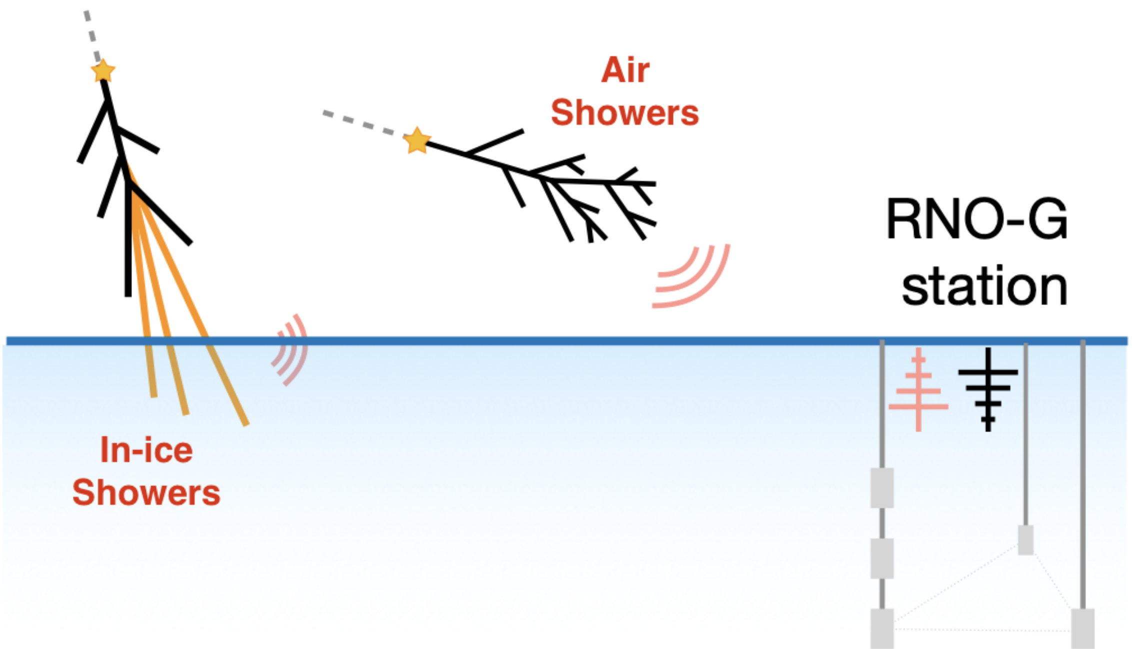


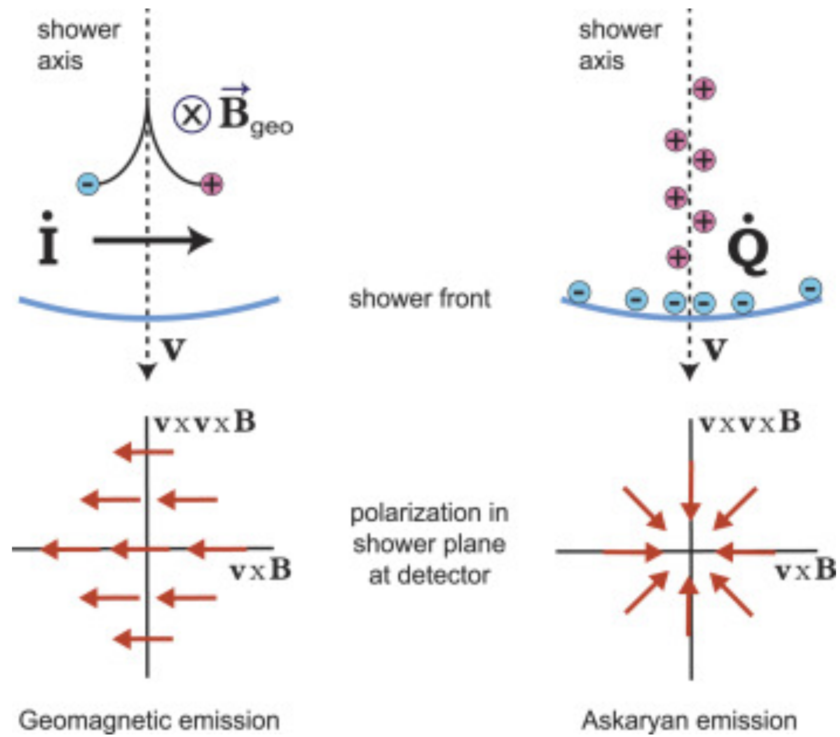
Figure 22: Direction reconstruction from individual stations.

Search For Comic-Rays

RNO-G detects cosmic rays through two channels:

- Geomagnetic radio emission from air showers, captured by the surface antenna array
- Air showers that reach the ice surface (thanks to Summit station elevation!) and propagate into the ice, producing Askaryan radio pulses detected by in-ice antennas





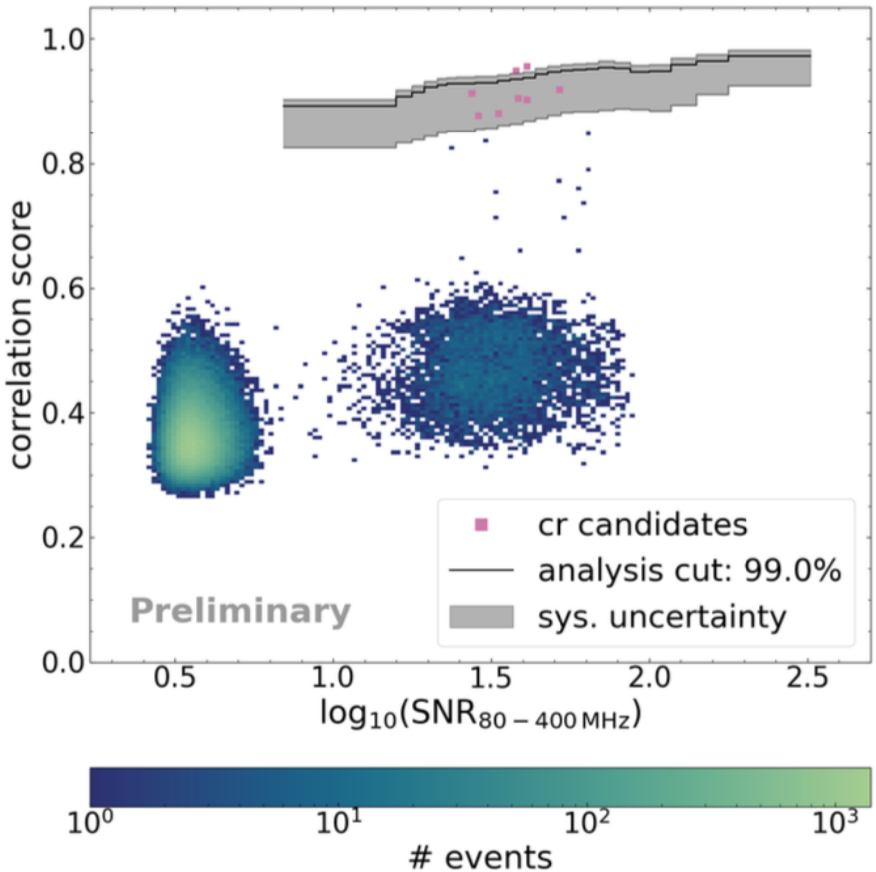


Figure 23: Events surviving analysis cuts from one of the RNO-g station, with highlighted CR candidates.

J. Henrichs et al (RNO-G), PoS(ICRC2025)288

- Using LPDAs to detect radio emission from cosmic-ray air showers.
- A template search inspired by an ARIANNA experiment analysis [13]
- Several CR-candidates have been found, in agreement with expected number of events
- Verifies a good understanding of the RNO-G system response. The shape of the signal matches expectations

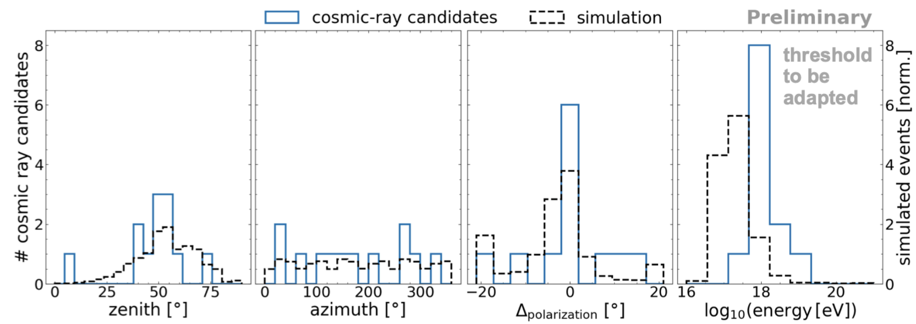


Figure 24: CR candidates features in compare with simulations.

In-Ice Cosmic Rays as Neutrino Background

- Surface CRs vetoed by antenna array
- In-ice CRs mimic neutrino signals — harder to reject
- Zenith cut helps, but reduces volume
- Tagging in-ice CRs validates detection methods

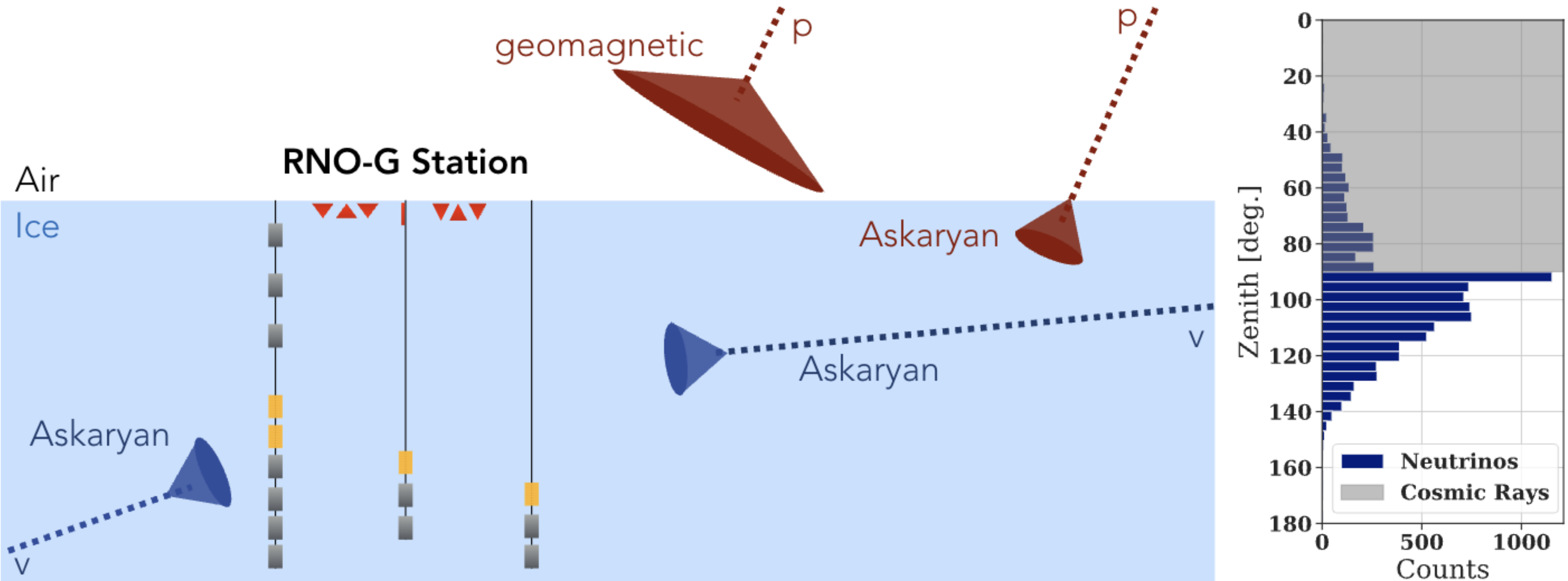
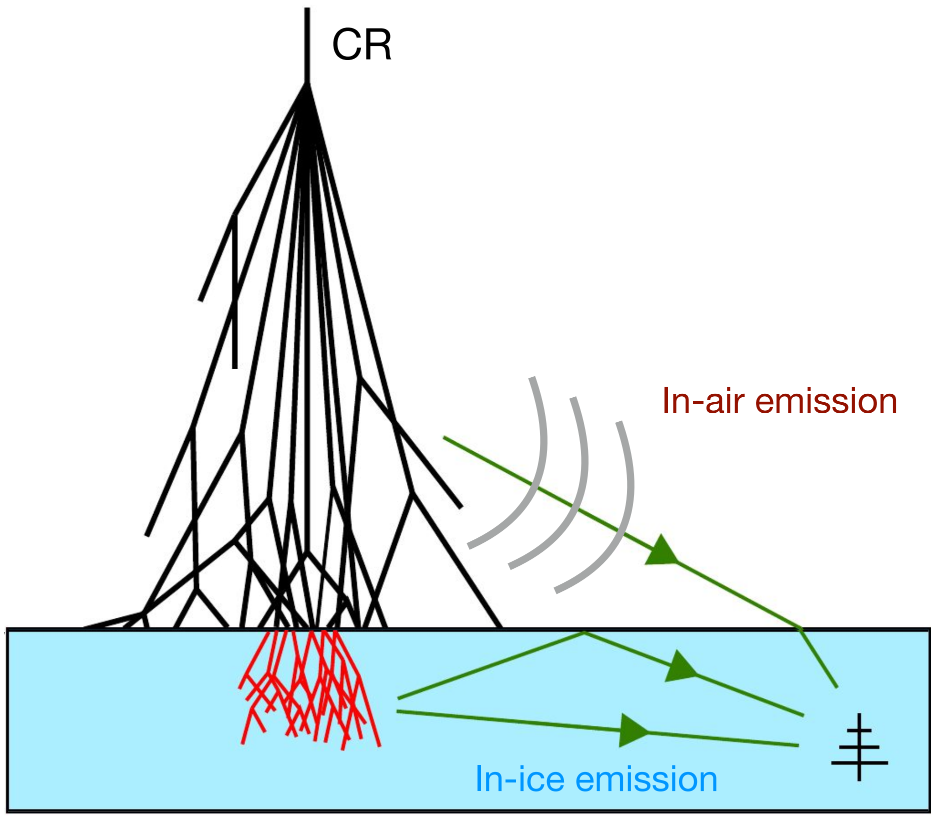
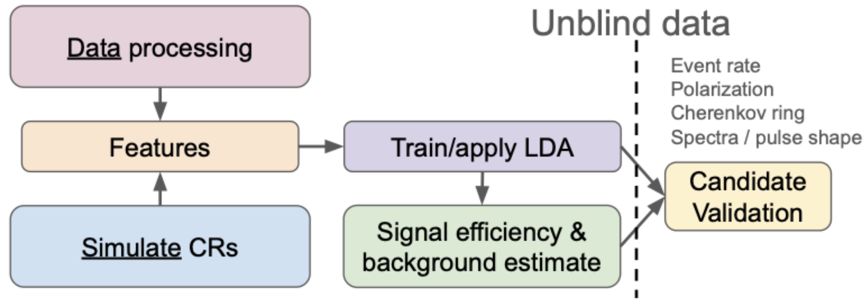


Figure 25: Cartoon of CR shower core entering the ice and emitting radio signal which mimics radiation from neutrino-induced showers in the ice.

- Ongoing analysis using machine learning (LDA discriminant analysis) searching for CR induced Askaryan signals
- Developing comprehensive simulations of radio emission within the **FAERIE** framework [14]:
  - **CORSIKA7** for simulating in-air particle cascades
  - **GEANT4** for simulating in-ice particle cascades
- Developing tools for future neutrino search





B. Hendricks et al (RNO-G), PoS(ICRC2025)1057

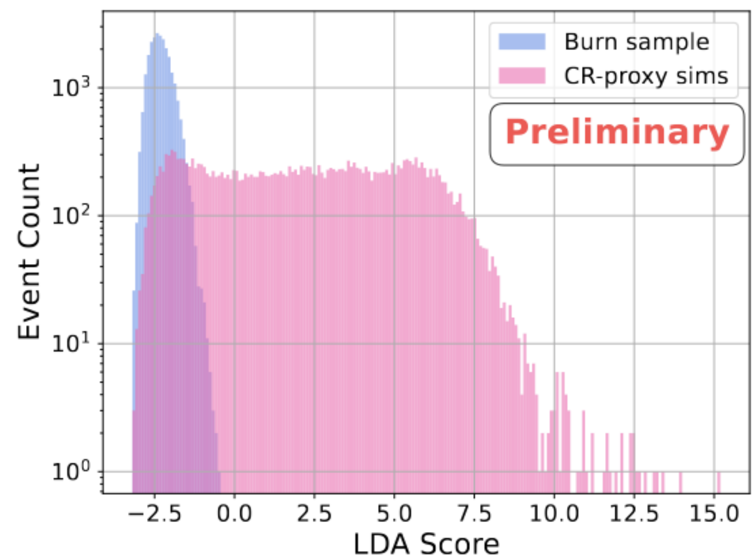


Figure 26: LDA scores for the RNO-g CR burn sample and simulated CR-proxie for one of the stations.

- RNO-G: UHE neutrino detector in Greenland, 50 km^2 coverage
- 8/35 stations deployed, already largest in-ice radio array by area
- Experience informs IceCube-Gen2 radio component design.
- Early results: cosmic-ray searches, calibration campaigns, tools for first neutrino search
- 35 stations $\times$ 5 years $\rightarrow$ sensitive to optimistic cosmogenic flux models

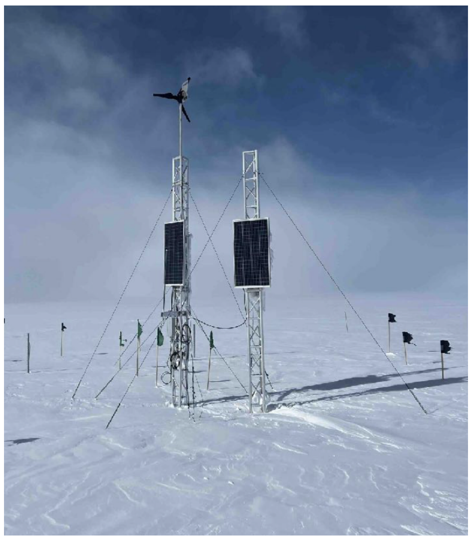


Figure 27: View on a RNO-g station.

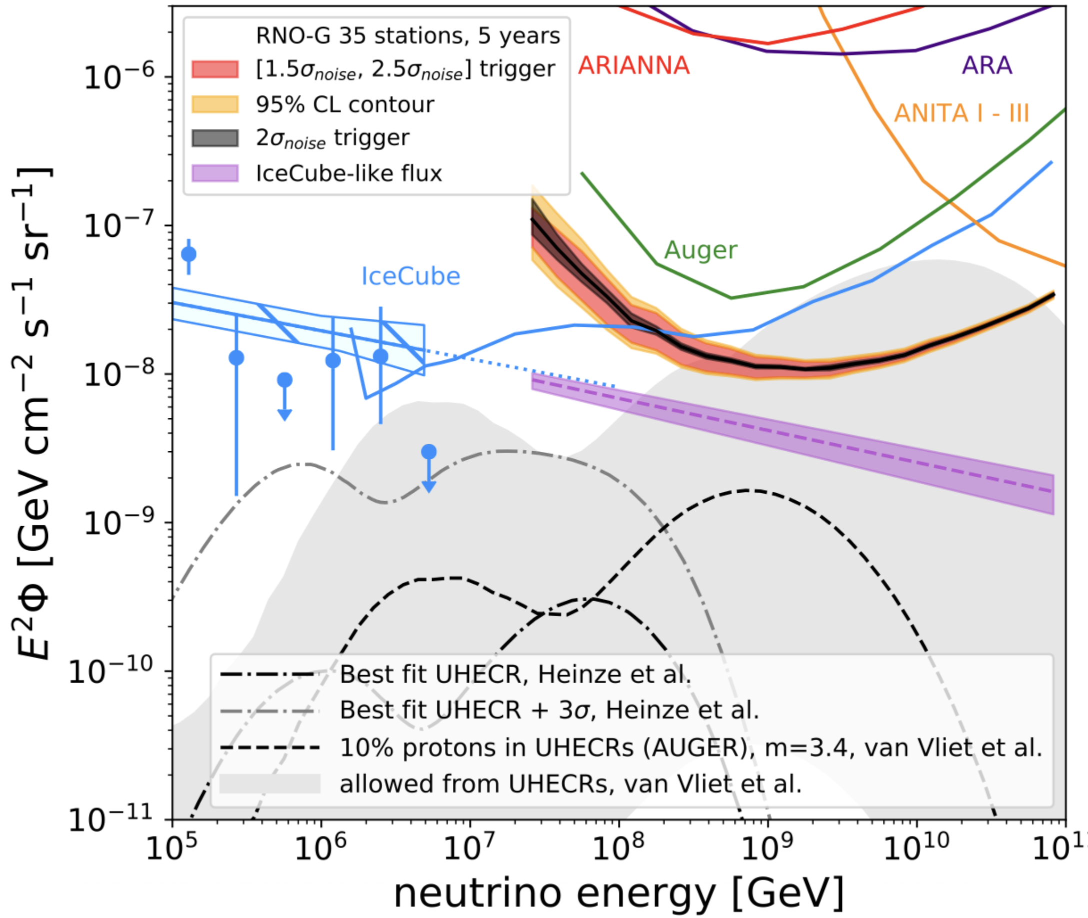


Figure 28: The five-year sensitivity (90% CL upper limits) of RNO-G to the all-flavor diffuse flux for 35 stations [4].

BACK UP

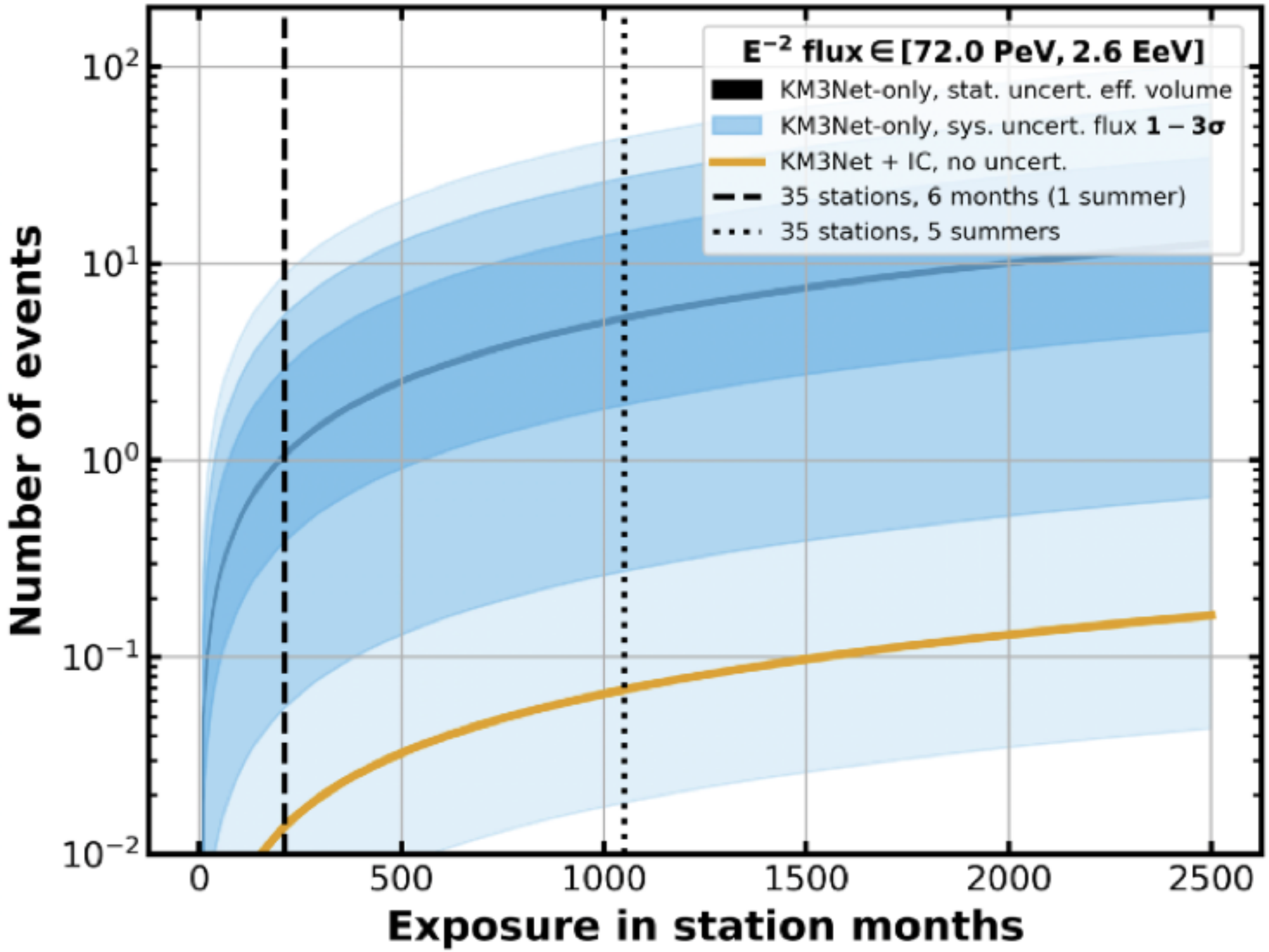


Figure 29: One summer of RNO-G35 → 1 neutrino for KM3NeT only E⁻2 flux.

A. Nelles et al (RNO-G), PoS(ICRC2025)1129

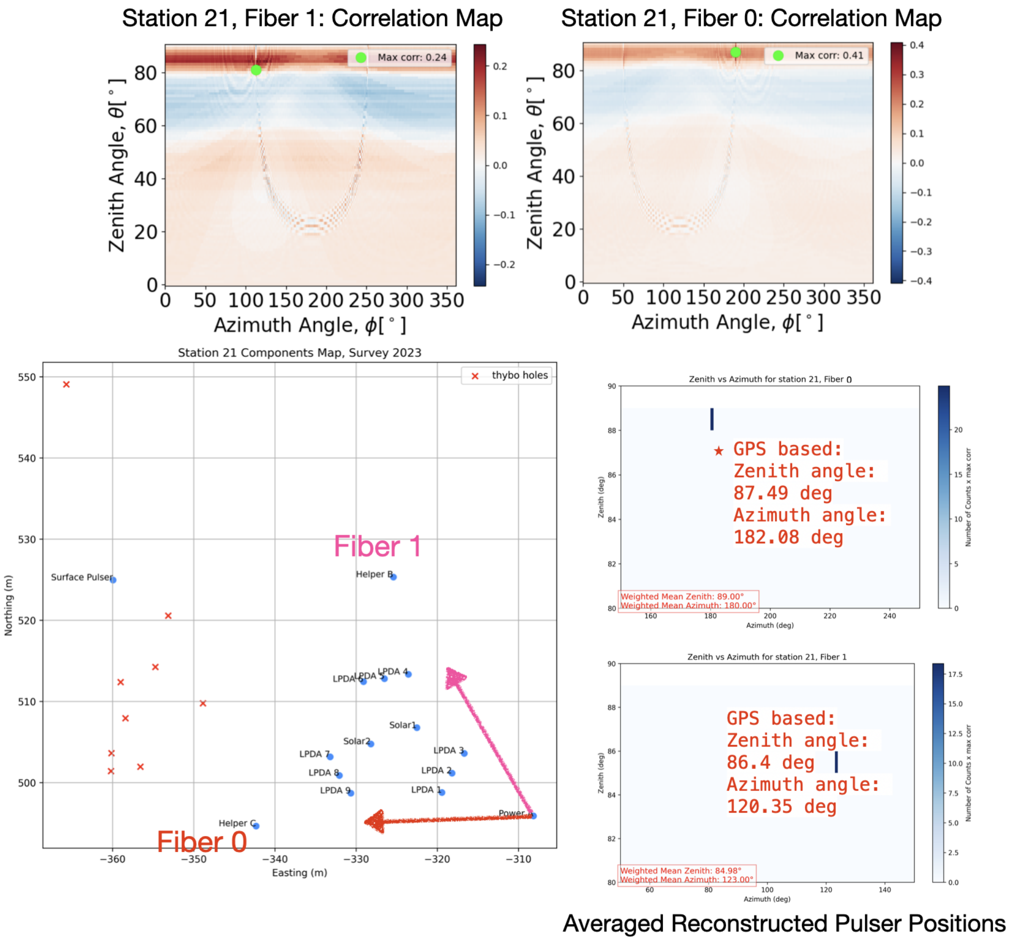


Figure 30: Interferometric reconstruction finds a signal's arrival direction by cross-correlating antenna waveforms and using their time delays to triangulate the source.

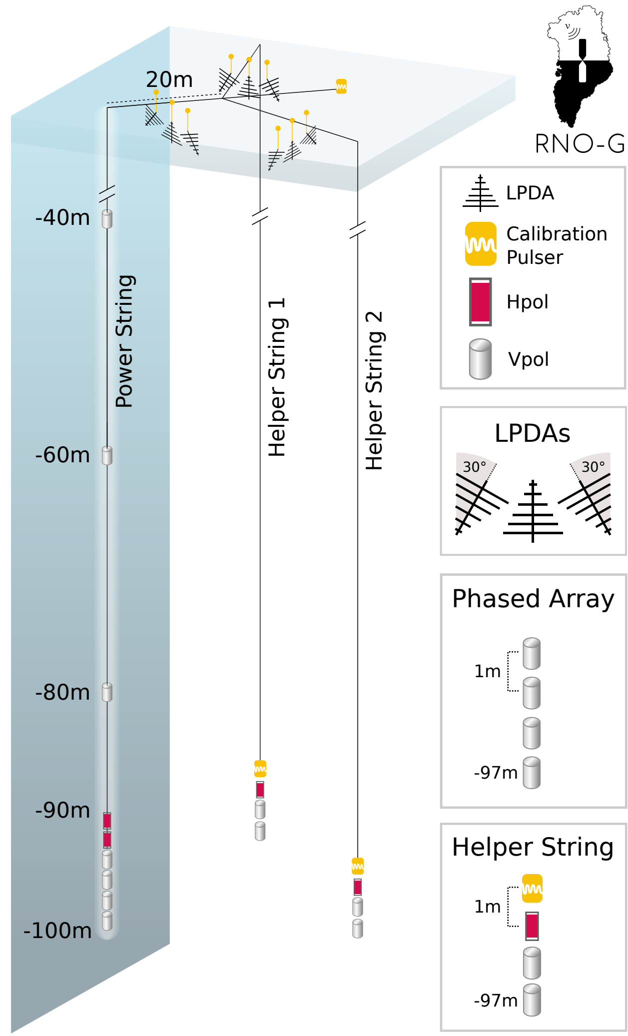


Figure 31: RNO-g station detail. ©RNO-g Collaboration.

The Askaryan electric field $\vec{\varepsilon}(f)$ as a function of frequency at the antenna can be expressed as:

$$\vec{\varepsilon}(f) = \vec{e}_p(\vec{\vartheta}_\nu, \vec{r}, R) \times |\vec{\varepsilon}_0(f)| \times \frac{e^{-R/L_\alpha(f)}}{R} \times exp\left[\frac{-(\theta-\theta_c)^2}{2\sigma_\theta(f)^2}\right]. \quad (1)$$

where parts of the eq. 1 depends on:

- **Signal polarization** $\vec{p} = \vec{l} \times (\vec{\vartheta}_\nu \times \vec{l})$
- **Inelasticity** $|\vec{\varepsilon}_0(f)|$ represents the dependence of the Askaryan signal amplitude on the neutrino energy, which scales linearly with the shower energy
- **Signal attenuation** L_α describes the attenuation of the radio signal during propagation.
- **Launch angle** - the angle θ between the neutrino direction and the launch vector

In-ice radio detector needs to be sensitive to are the incoming signal direction, the signal polarization, and the signal launch angle.

To reconstruct of the electric-field pulse, the following system of equations needs to be solved:

$$\begin{bmatrix} V_1(f) \\ V_2(f) \\ \vdots \\ V_n(f) \end{bmatrix} = \begin{bmatrix} H_1^\theta(f) & H_1^\phi(f) \\ H_2^\theta(f) & H_2^\phi(f) \\ \vdots & \vdots \\ H_n^\theta(f) & H_n^\phi(f) \end{bmatrix} \begin{bmatrix} \epsilon_1^\theta(f) \\ \epsilon_2^\phi(f) \end{bmatrix},$$

where $V_i(f)$ is a measured voltage trace of antenna i in frequency domain and H describes response.

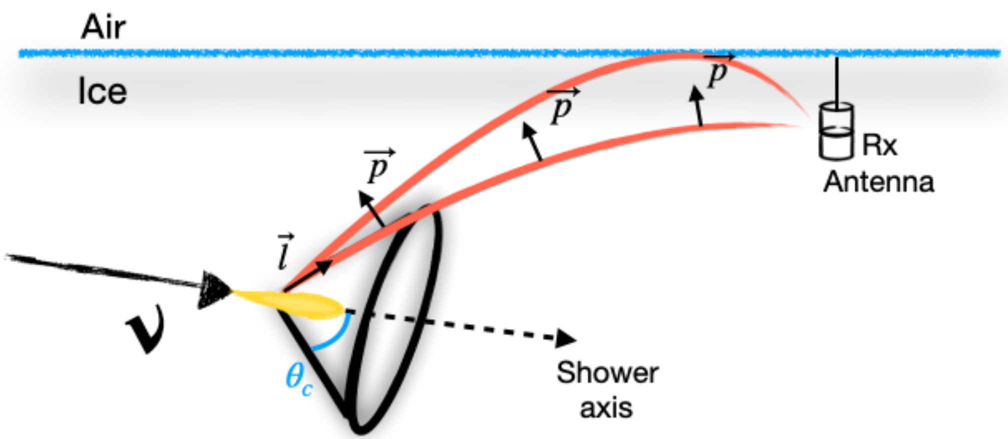


Figure 32: 2D projection of the event geometry.

Outline

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