



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

Status of First Neutrino Search

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on behalf of the RNO-G Collaboration

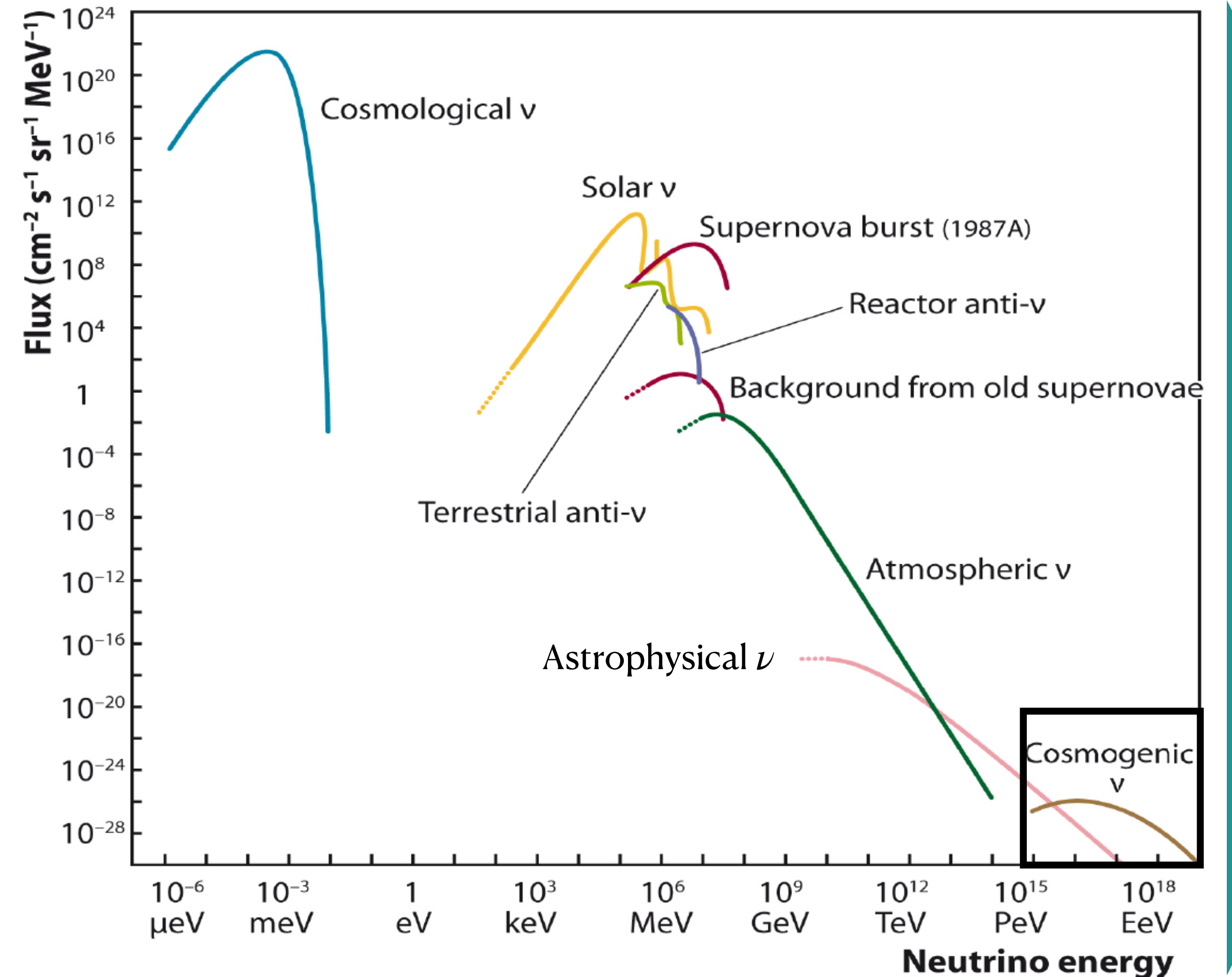


Overview

- RNO-G is designed to detect ultra-high energy (UHE) neutrinos above 100 PeV
- Partially completed detector has been collecting data since 2021, will be used for RNO-G's first neutrino search



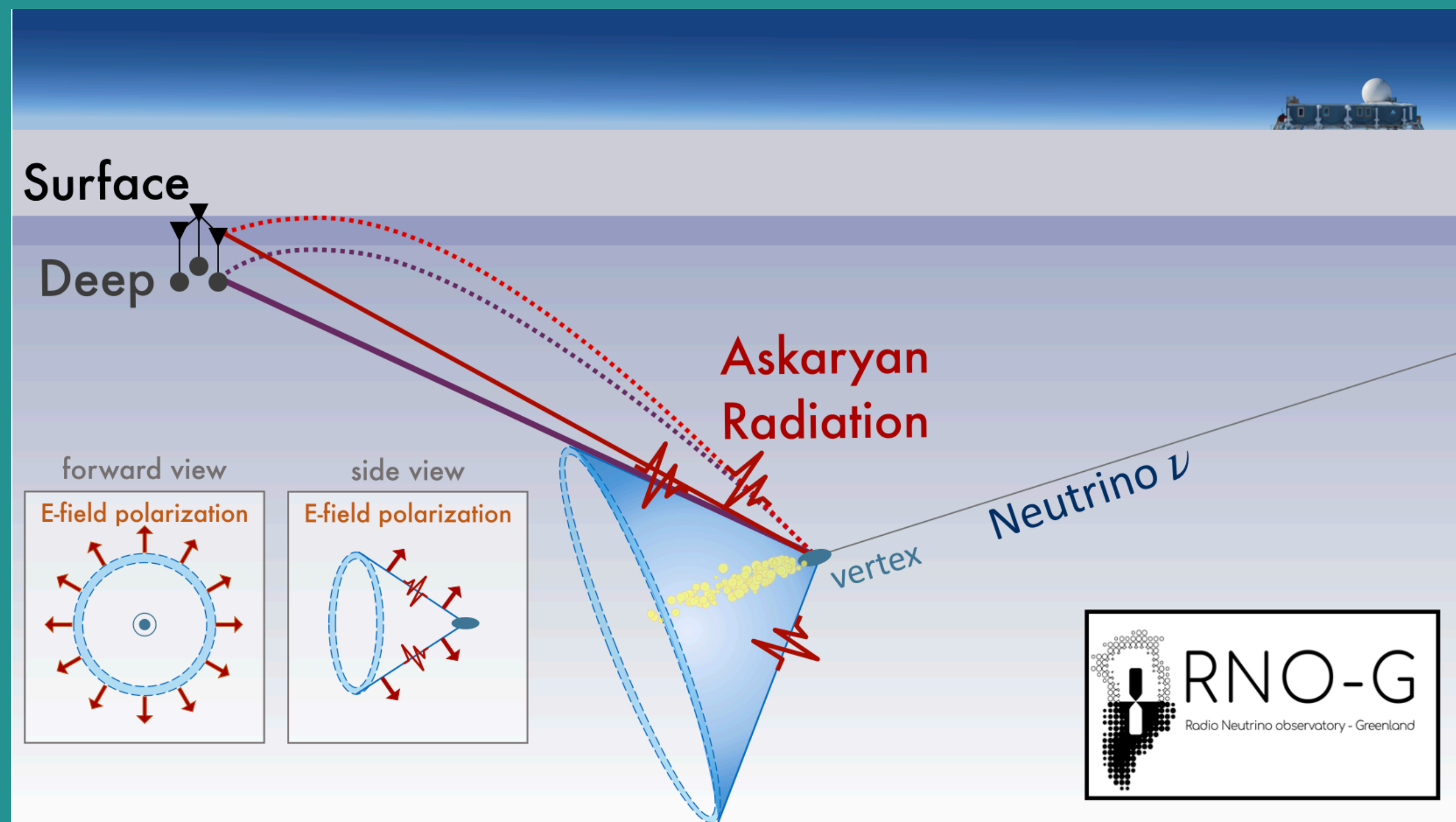
Summit Station, Greenland



Radio Neutrino Detection of UHE Neutrinos

Detection Mechanism: Askaryan Emission

UHE neutrinos interact with ice producing shower of relativistic secondary particle



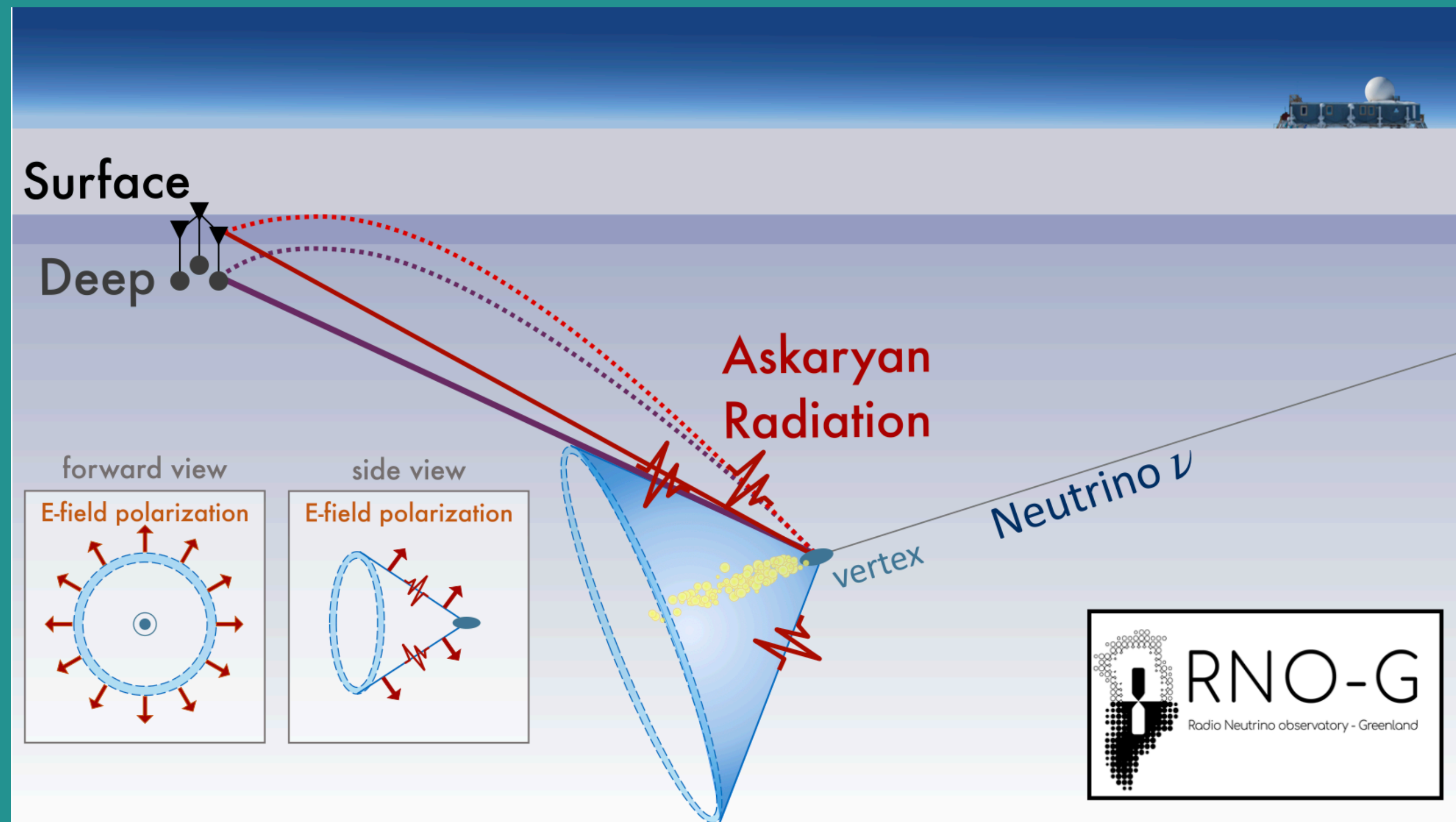
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Negative net charge of shower emits a cone of Cherenkov radiation



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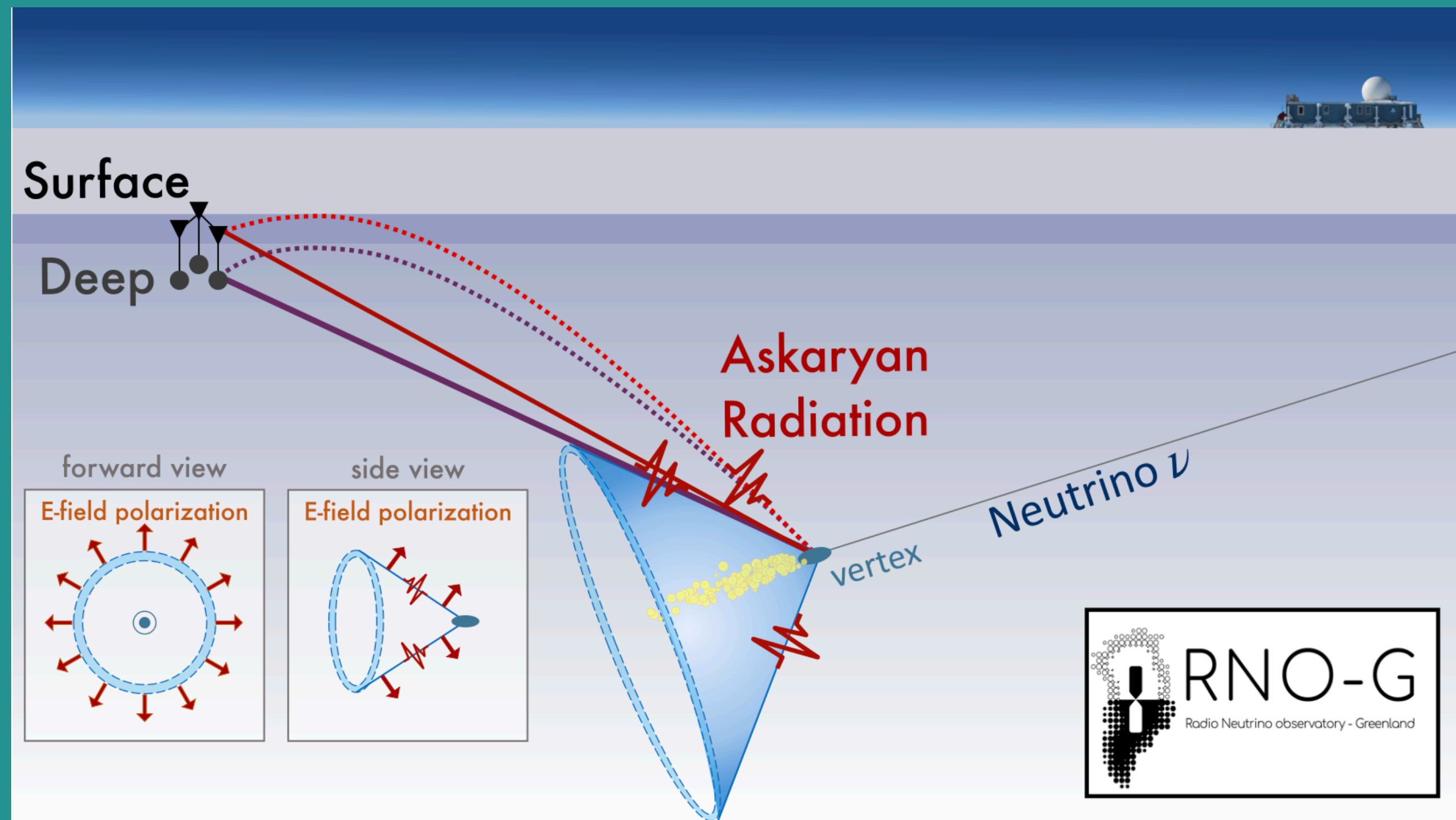
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Coherent amplification in radio



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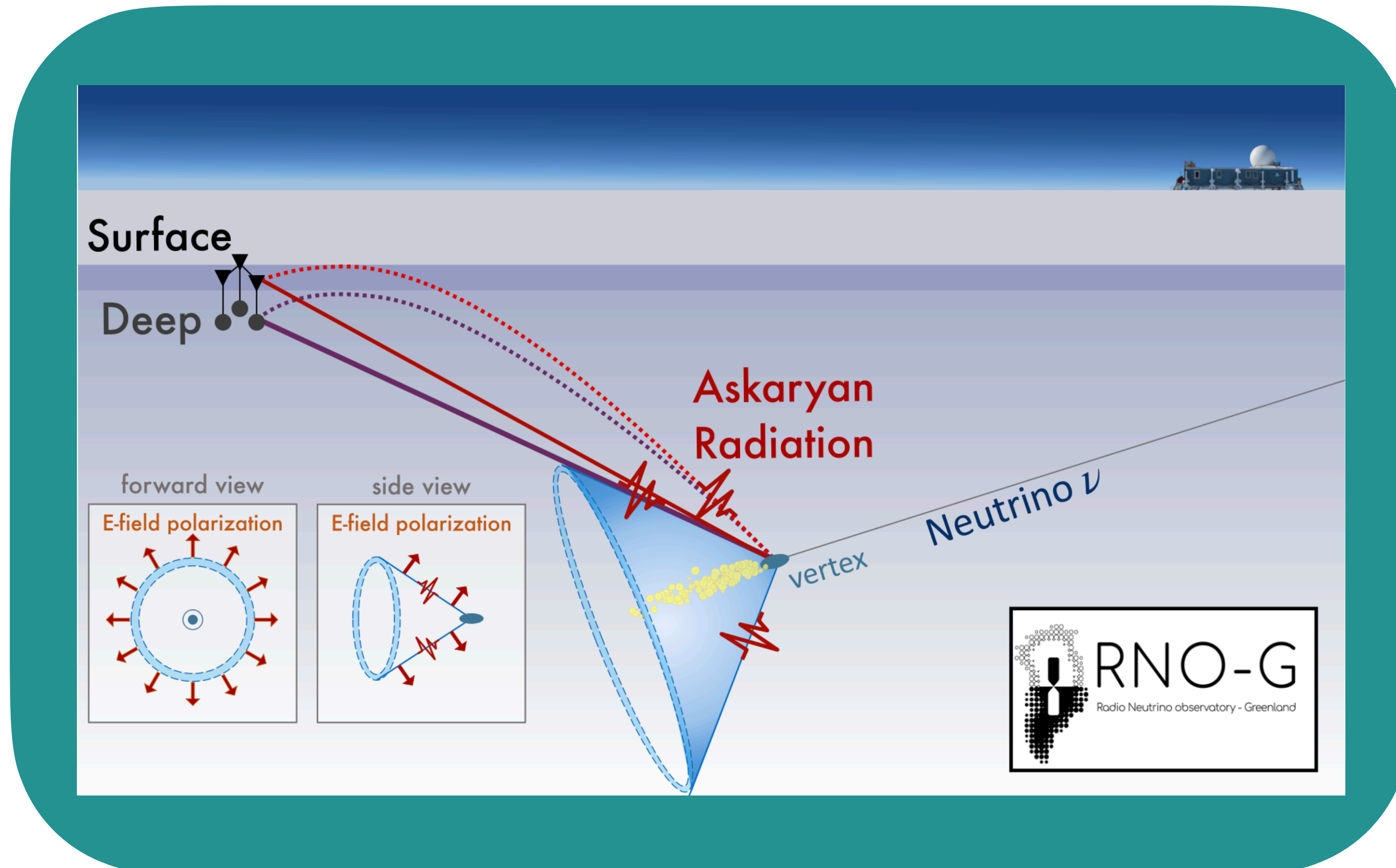
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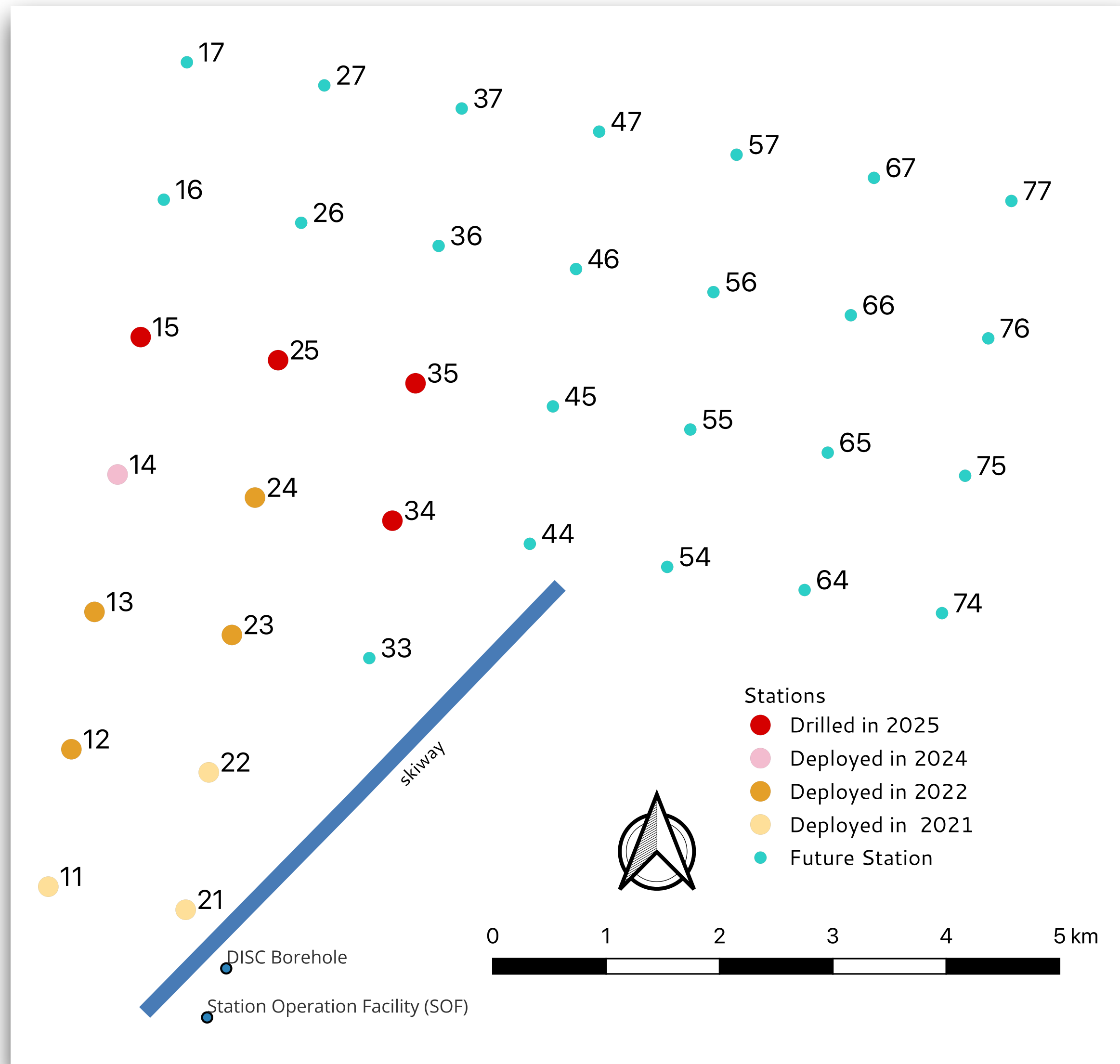
Coherent amplification in radio



Pulse (100-600 MHz) detected by antennas



RNO-G Detector

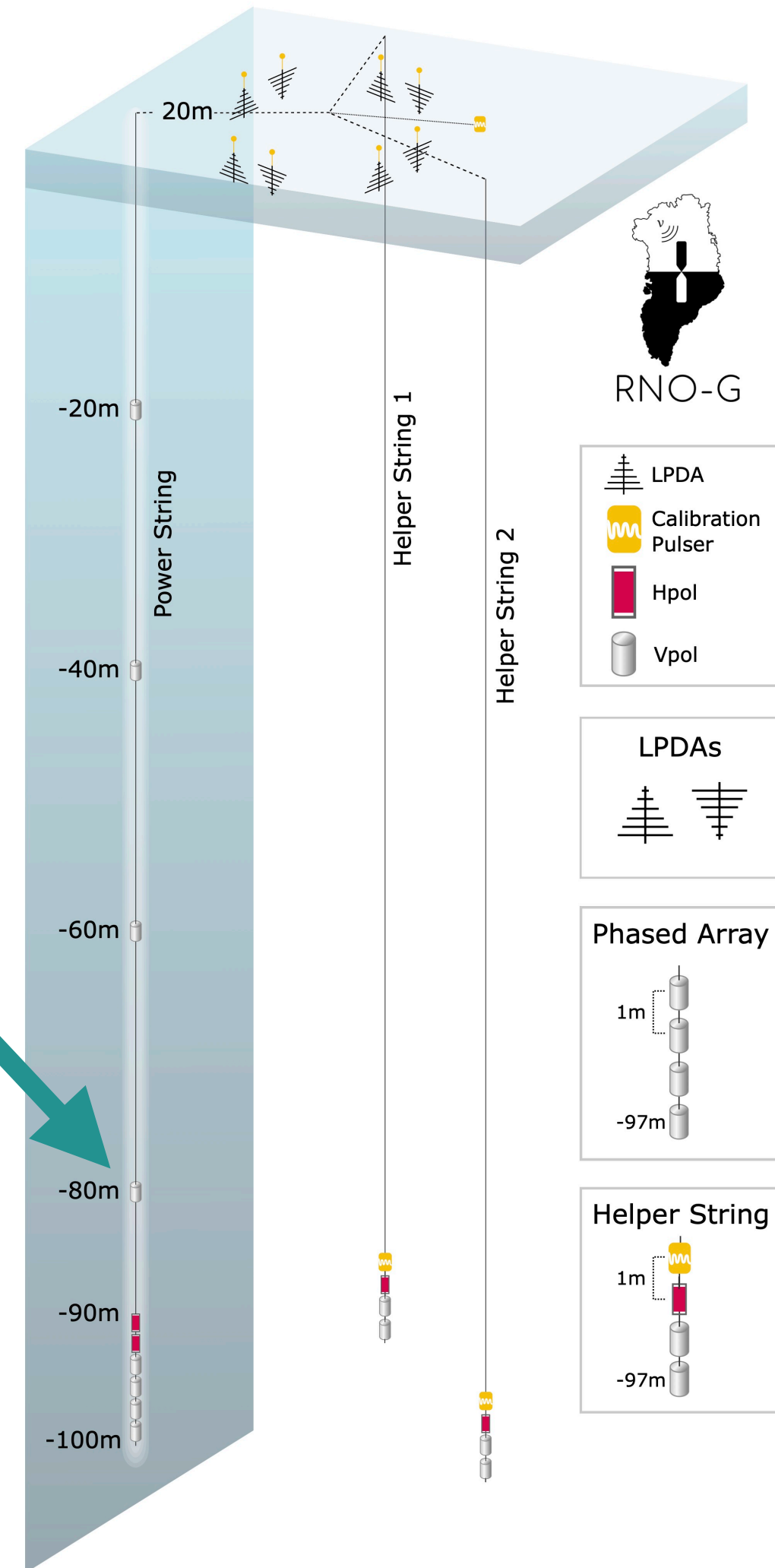


- Array of 35 stations of which 8 have been built so far
- 1.25 km spacing between stations to account for Greenland ice attenuation length $\sim O(1km)$
- Each station contains three vertical cables ("strings") carrying antennas embedded in ice to detect radio emission

RNO-G Station Layout

VPols

Reconstruct vertical polarization of incoming signal



A Single RNO-G Station

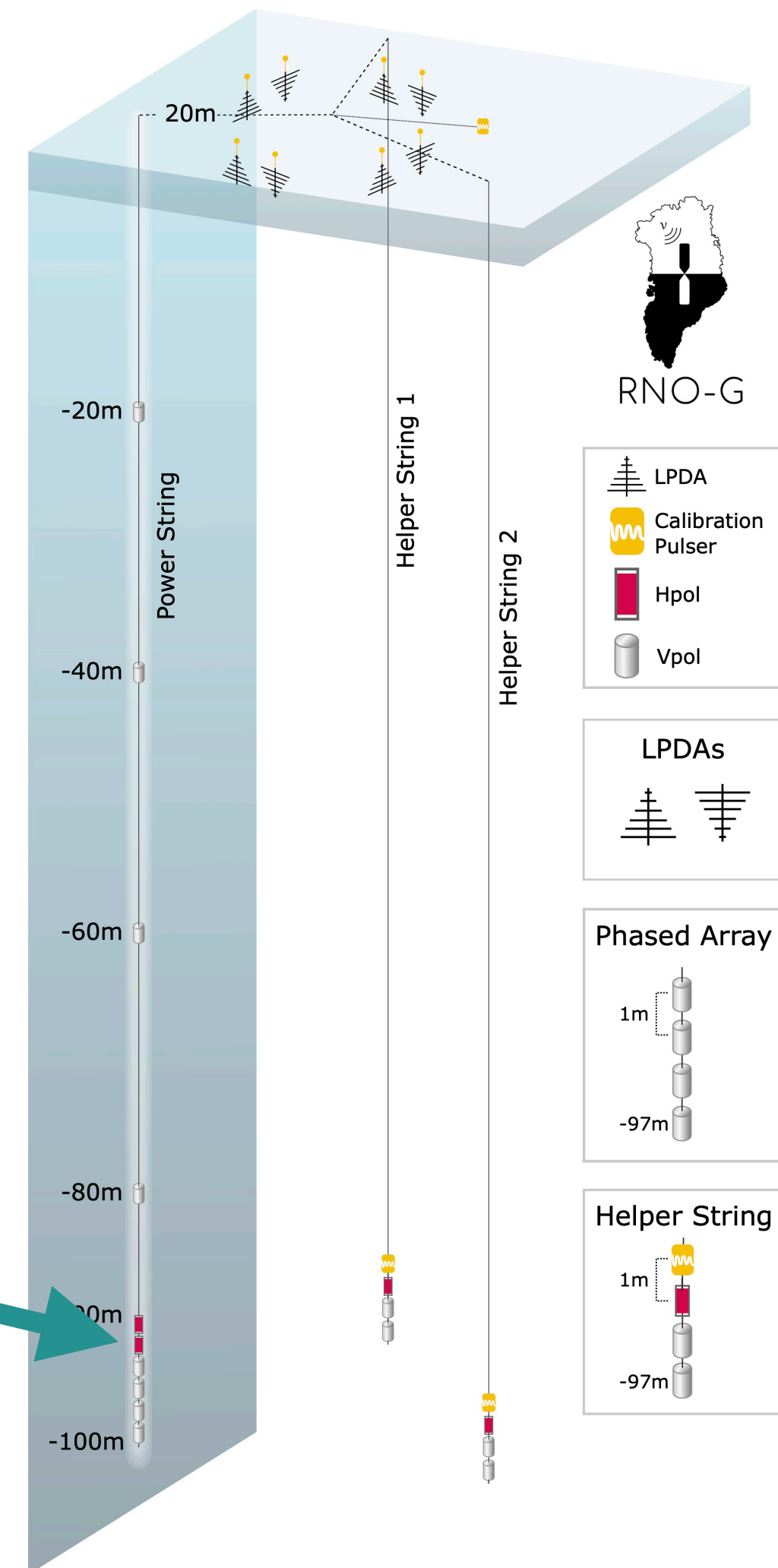
RNO-G Station Layout

VPols

Reconstruct vertical polarization of incoming signal

HPols

Reconstruct horizontal polarization of incoming signal



A Single RNO-G Station

RNO-G Station Layout

VPols

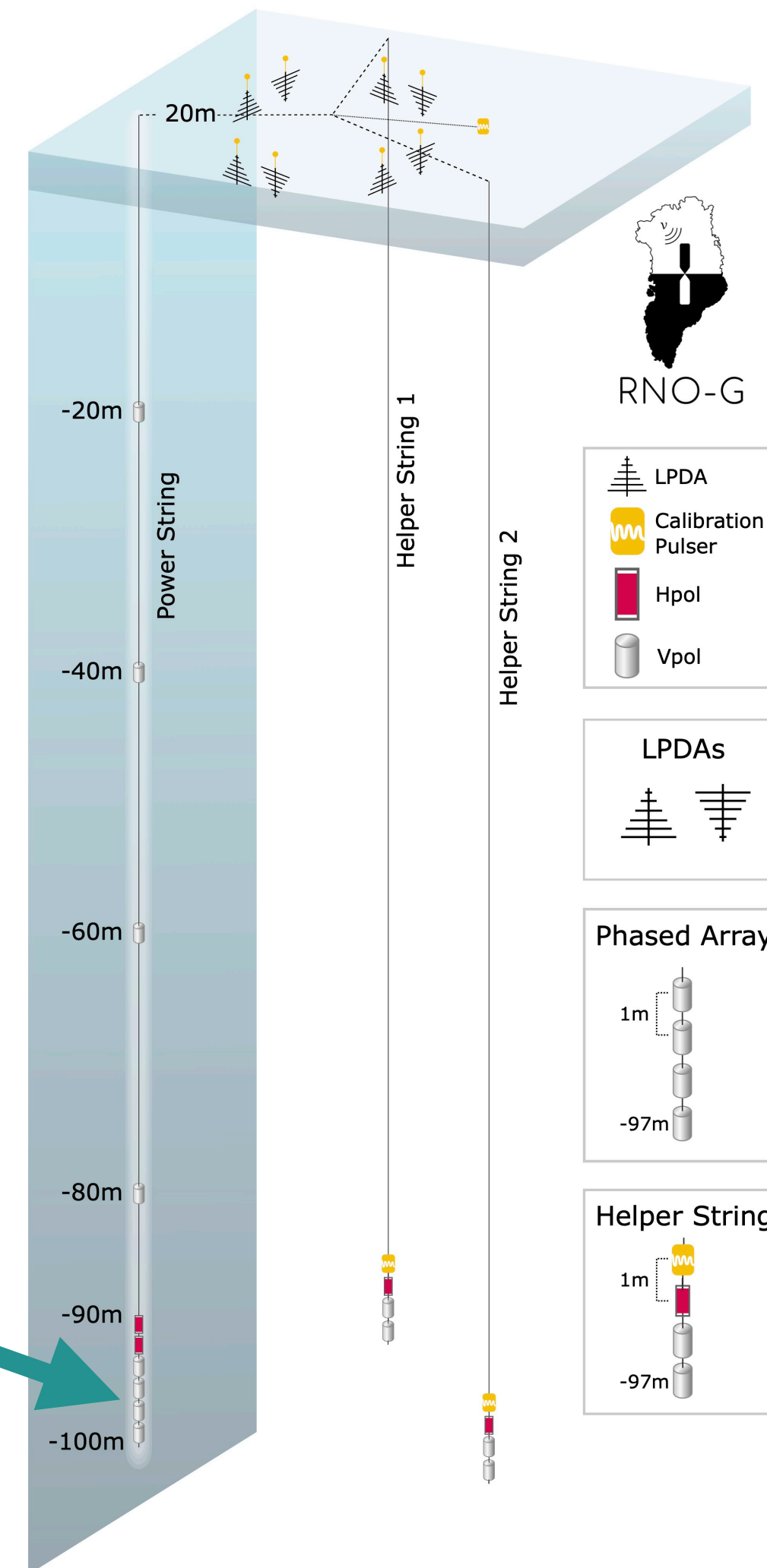
Reconstruct vertical polarization of incoming signal

HPols

Reconstruct horizontal polarization of incoming signal

Power String

Triggering on neutrino events



A Single RNO-G Station

RNO-G Station Layout

VPols

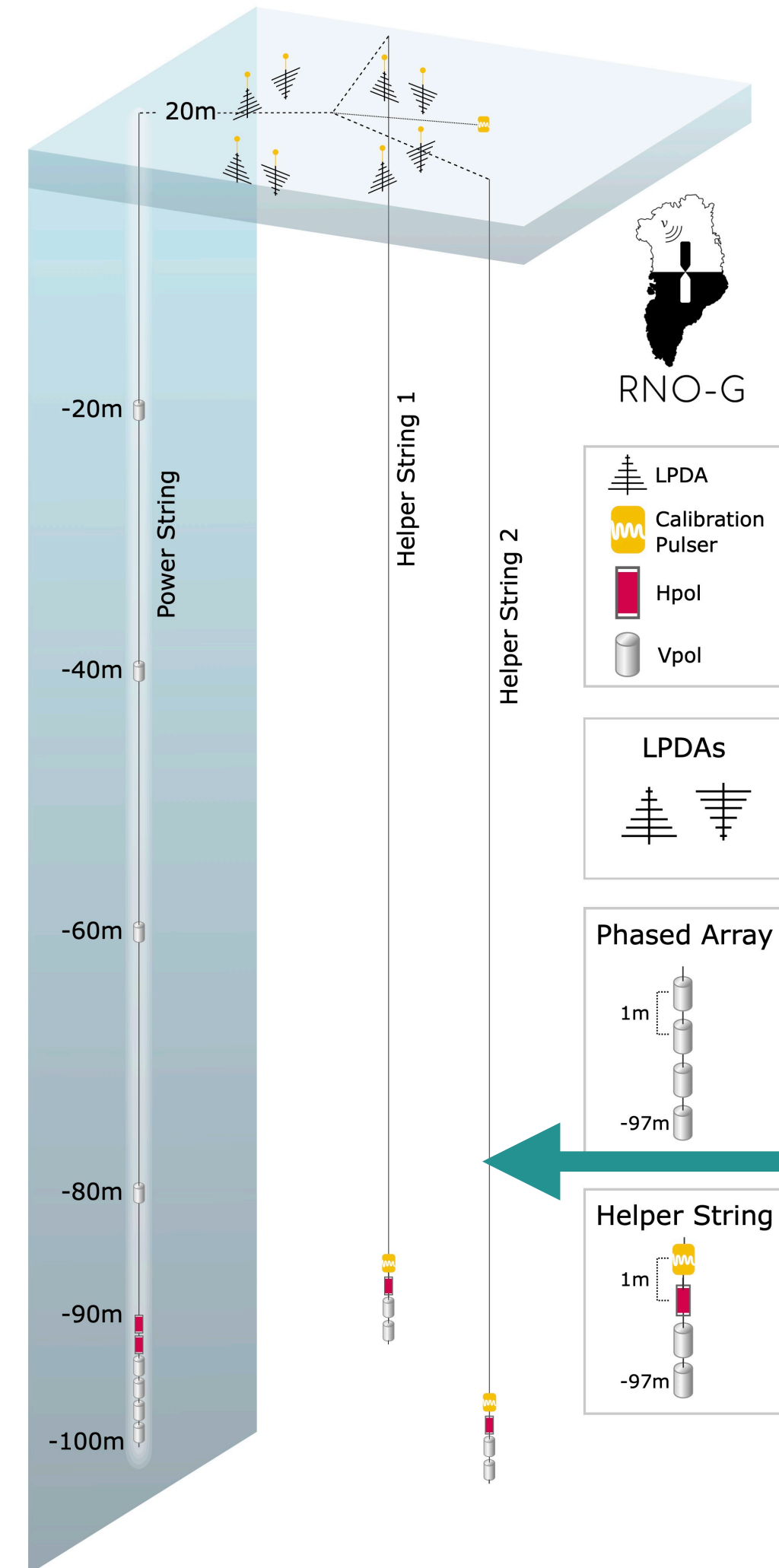
Reconstruct vertical polarization of incoming signal

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Reconstruct horizontal polarization of incoming signal

Power String

Triggering on neutrino events



RNO-G

LPDA
Calibration Pulser
Hpol
Vpol

LPDAs

Phased Array

1m
-97m

Helper String

1m
-97m

Helper String

Reconstructing neutrino energy/
direction and calibration

A Single RNO-G Station

RNO-G Station Layout

VPols

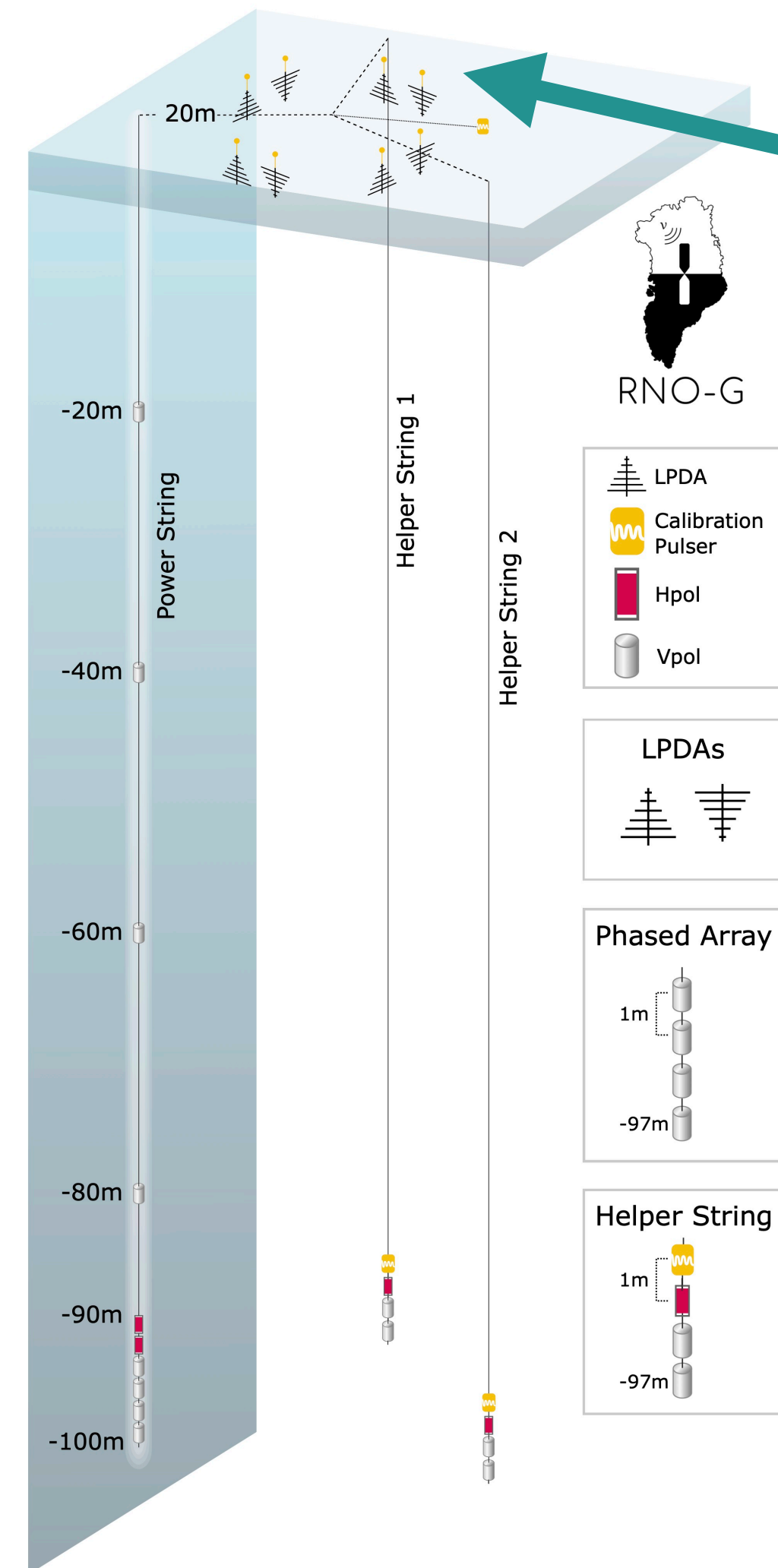
Reconstruct vertical polarization of incoming signal

HPols

Reconstruct horizontal polarization of incoming signal

Power String

Triggering on neutrino events



A Single RNO-G Station

LPDAs

Surface antennas to distinguish between signals going up through and down through detector

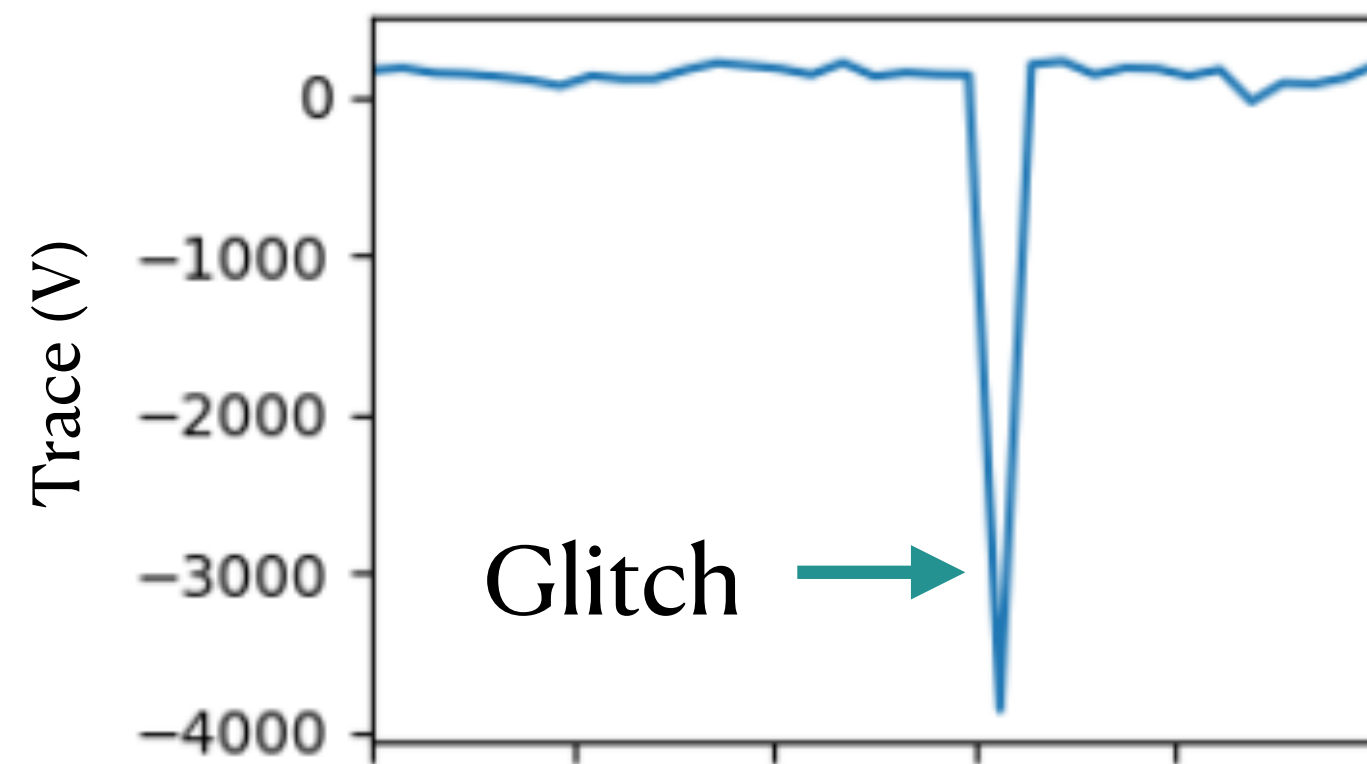
Air shower veto

Helper String

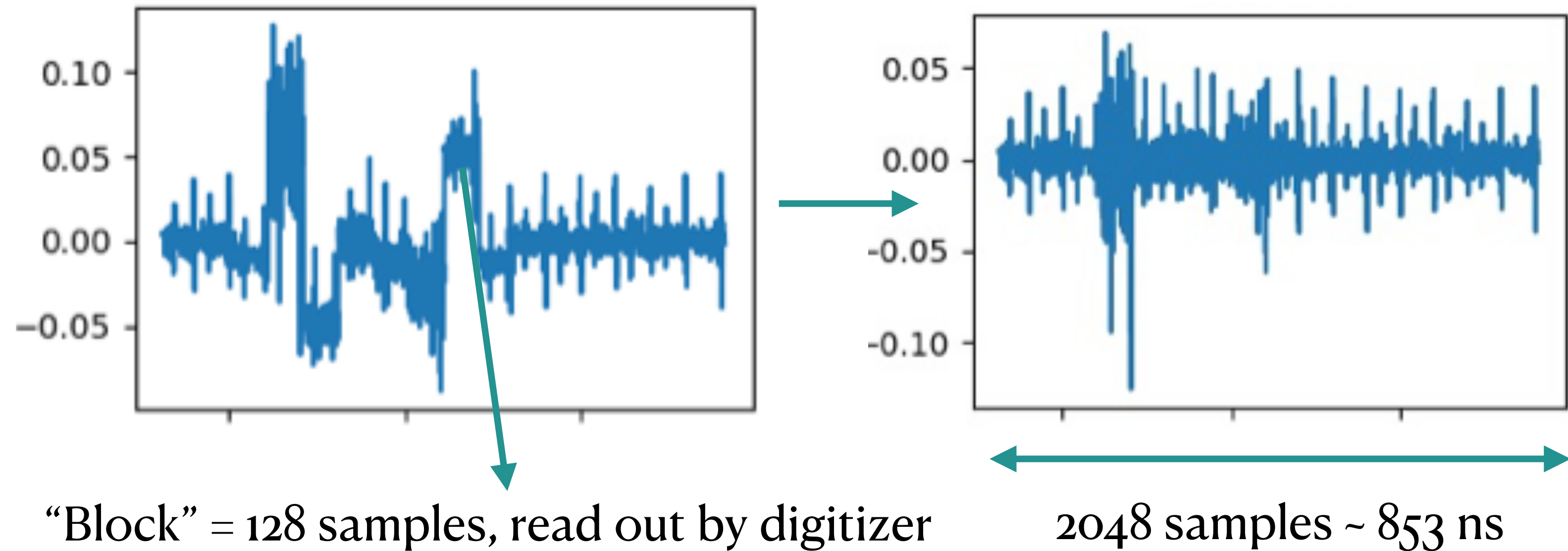
Reconstructing neutrino energy/direction and calibration

Data Processing Part 1

Glitch Removal



Block Offset Filtering

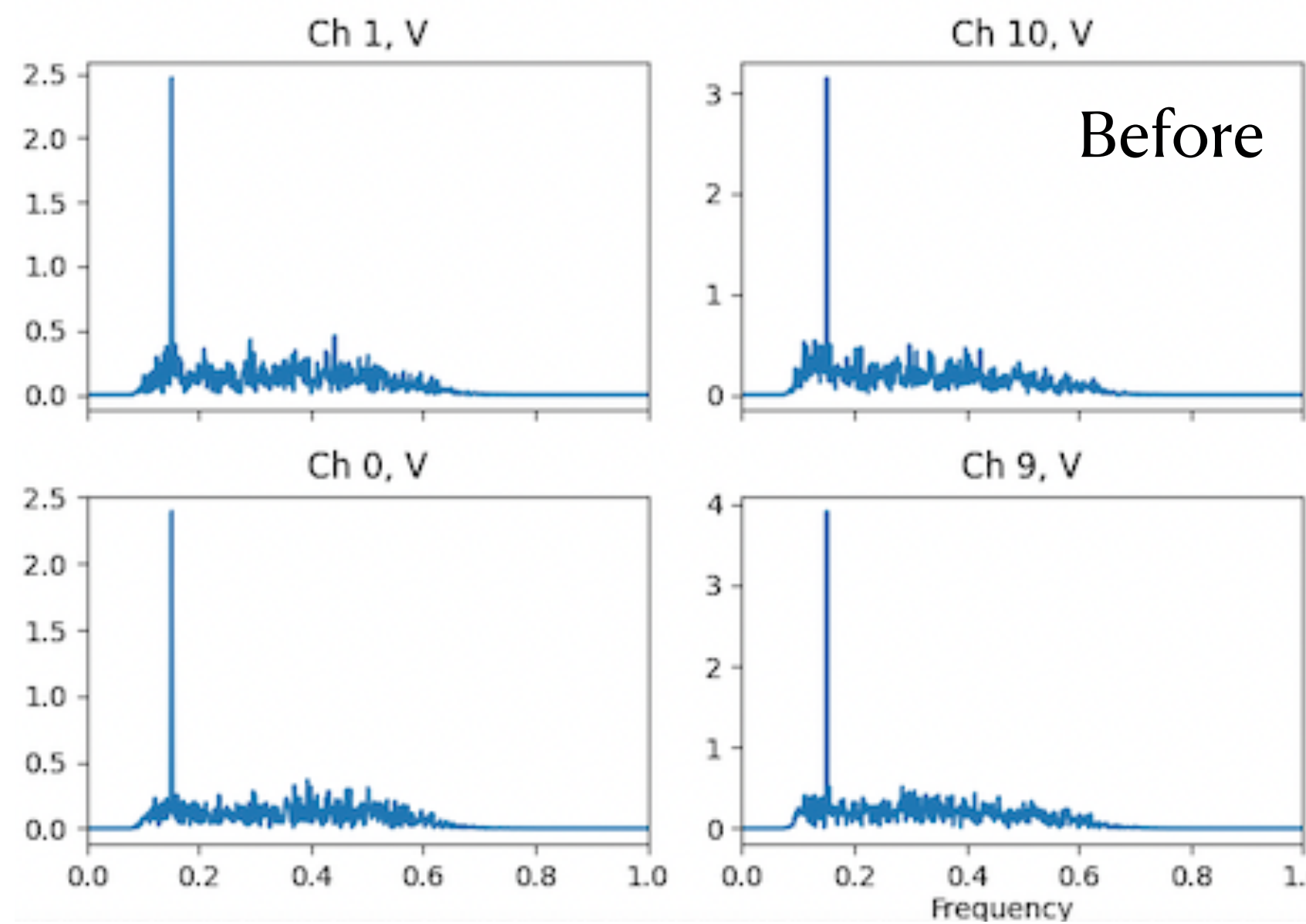


Subtract time delays from cables and readout chain

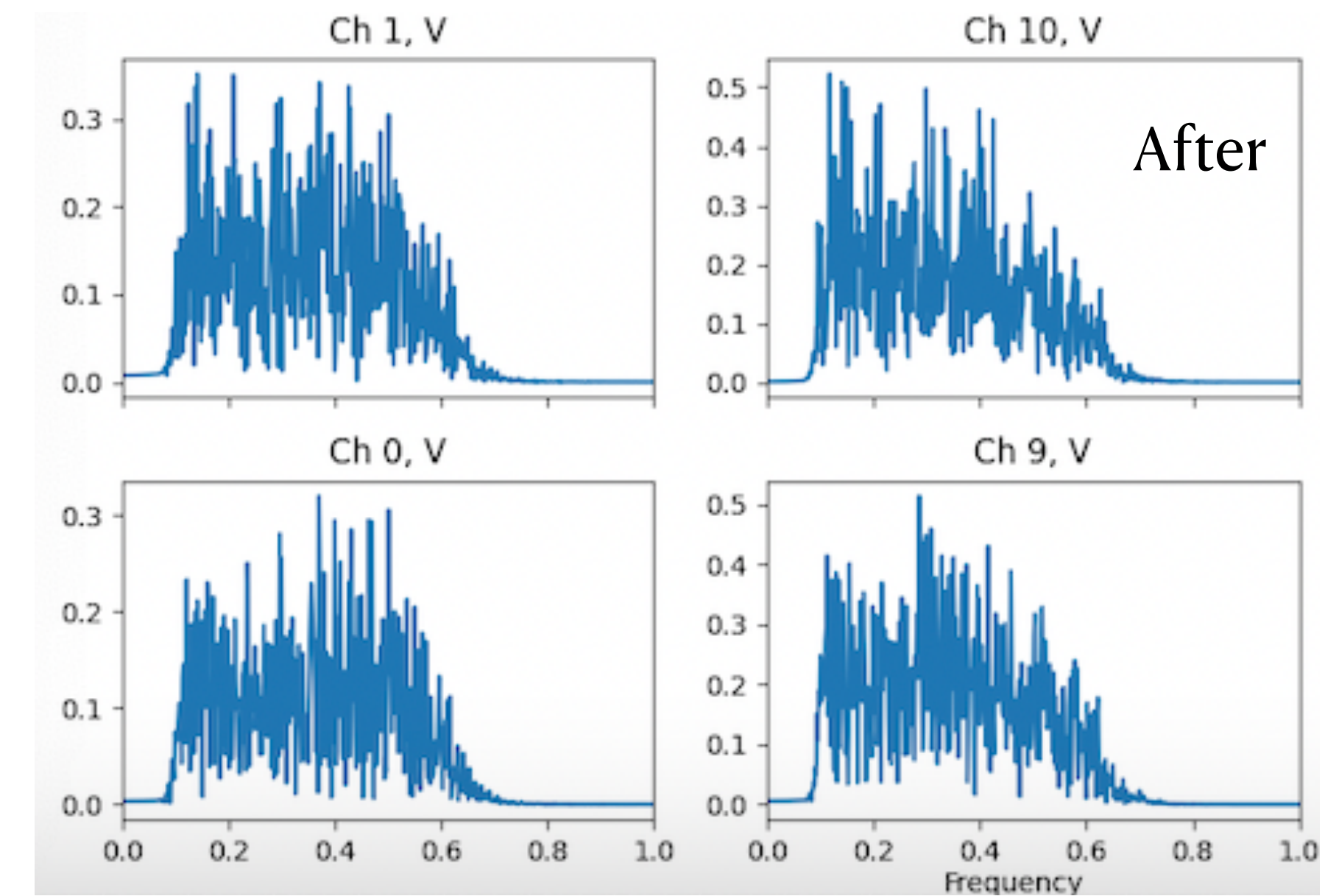
Upsampling to 5GHz

Data Processing Part 2

- Applying bandpass filter, 0.1 to 0.6 GHz
- Removing dispersion from signal chain



CW Filtering



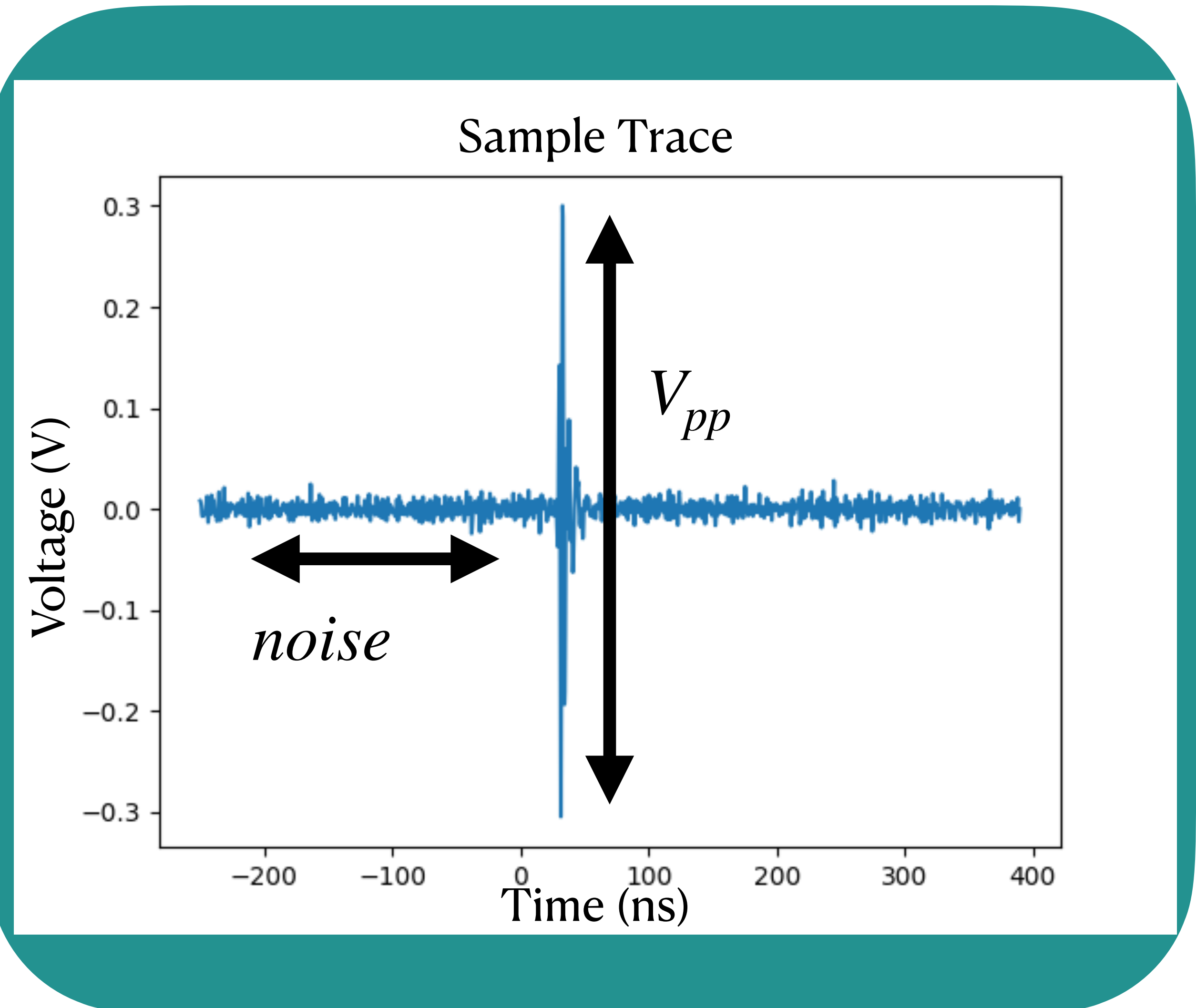
Frequency (GHz)

Frequency (GHz)

Analysis Variables

Event-level variables extracted from cleaned, processed data

- **SNR (Signal to Noise Ratio)**
 - Ratio between the peak to peak voltage and the RMS noise
- **RPR (Root Power Ratio)**
 - Ratio of the power of the trace to the RMS noise.
- Impulsive neutrino-like signals are expected to have a high SNR and RPR



Analysis Variables

Reconstruction: Determine vertex location of an event

Step 1: Generate travel time maps

- Time taken to travel from potential source location to antenna
- Accounts for signal propagation through ice layers and transition from ice to air
- Solve Eikonal equation at each potential source location using Python's Pykonal Eikonal Solver, implemented by P. Windischhofer

Eikonal Equation

$x = \text{depth}$

$$\nabla T = \frac{dT}{dx} = \frac{1}{v(x)} = n(x)$$

Travel Time (dependent on potential source location)

Analysis Variables

Reconstruction: Determine vertex location of an event

Step 2: Obtain Correlation as a function of lag

- Calculate correlation for pairs of traces (x, y) for multiple lags (k)
- N_k = number of overlapping values between traces at lag k
- Value diverges as N_k becomes small, Hanning window is applied to taper edges of correlation function to zero

Correlation

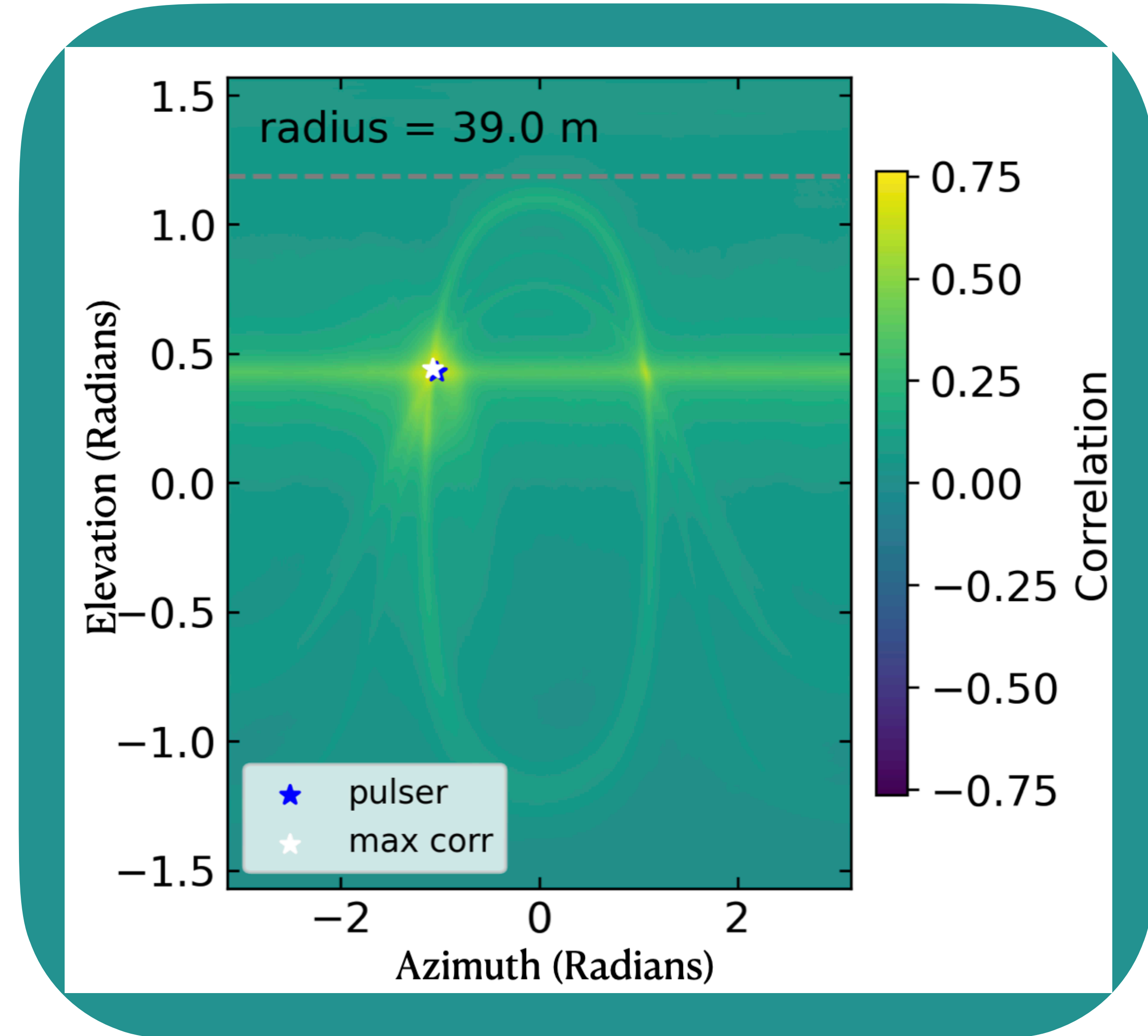
$$\sum_{i=0}^{i=n} \frac{x(i) * y(i - k)}{N_k}$$

Lag in unit of samples

Number of samples in traces (x, y)

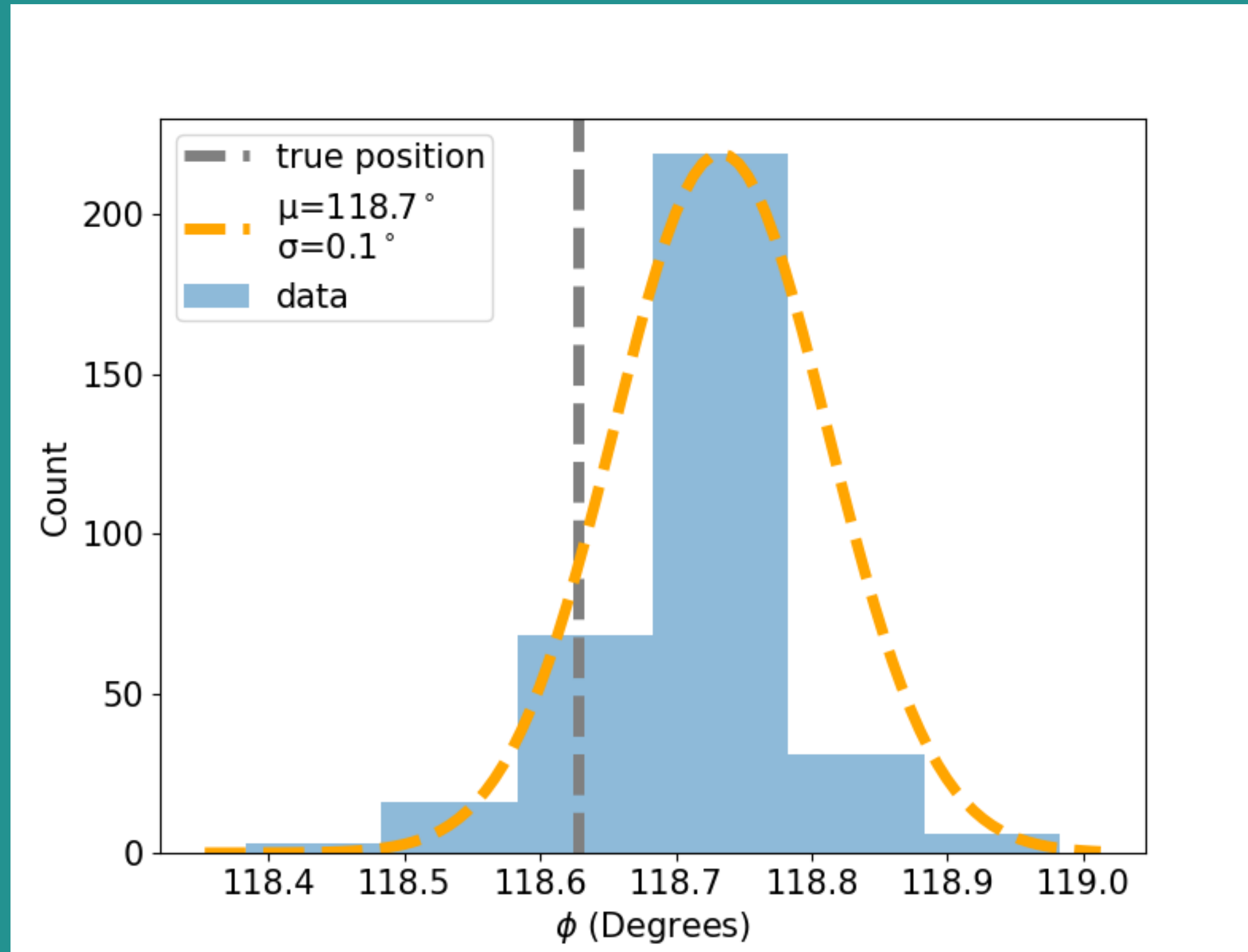
Correlation Map

- ⦿ Point on the sky provides a *lag*
- ⦿ A *lag* provides a *correlation*
- ⦿ Sum correlation values are over all antenna pairs

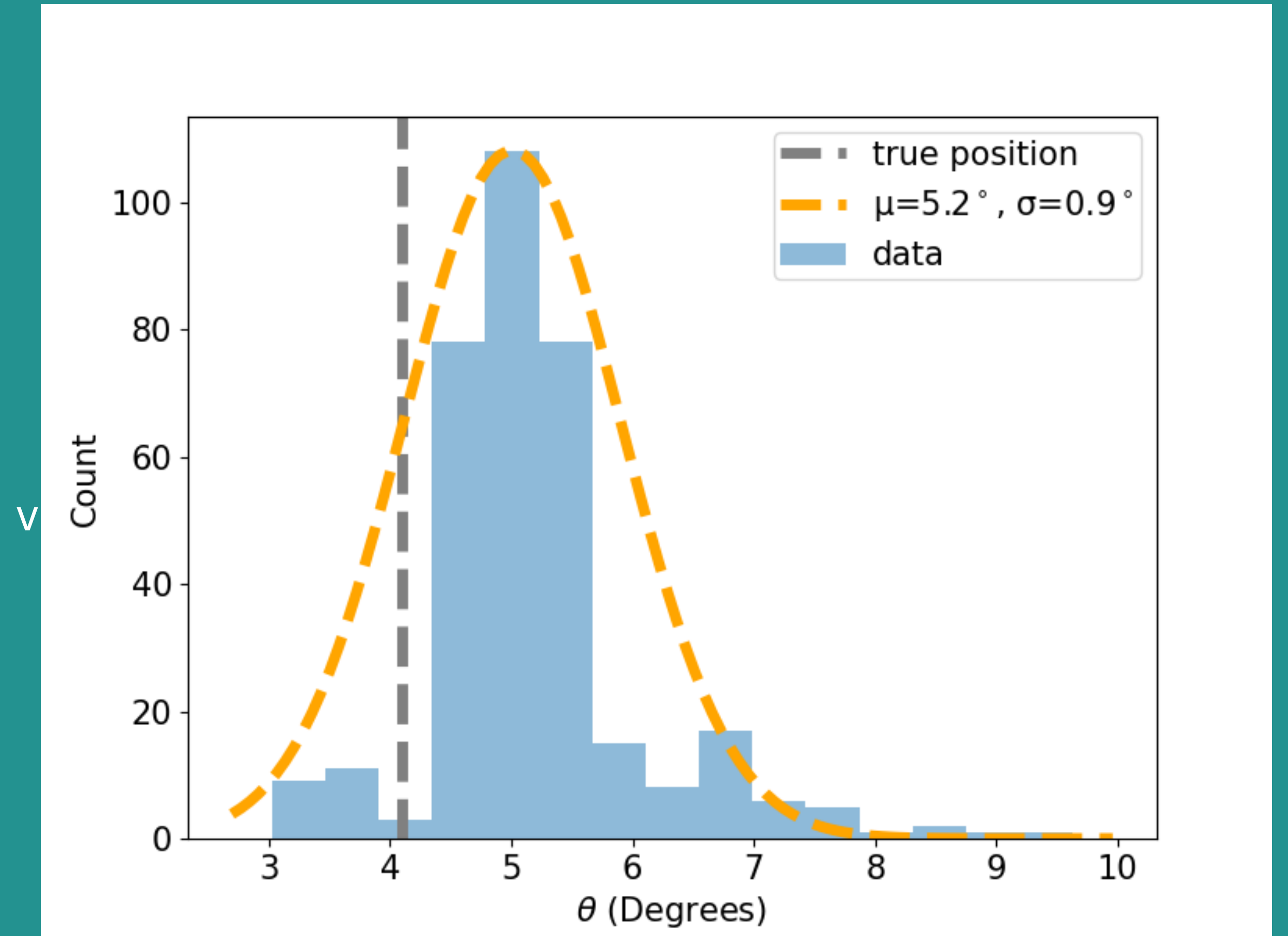


Testing Reconstruction

Calibration Pulses: Impulsive signals emitted by antenna on helper string



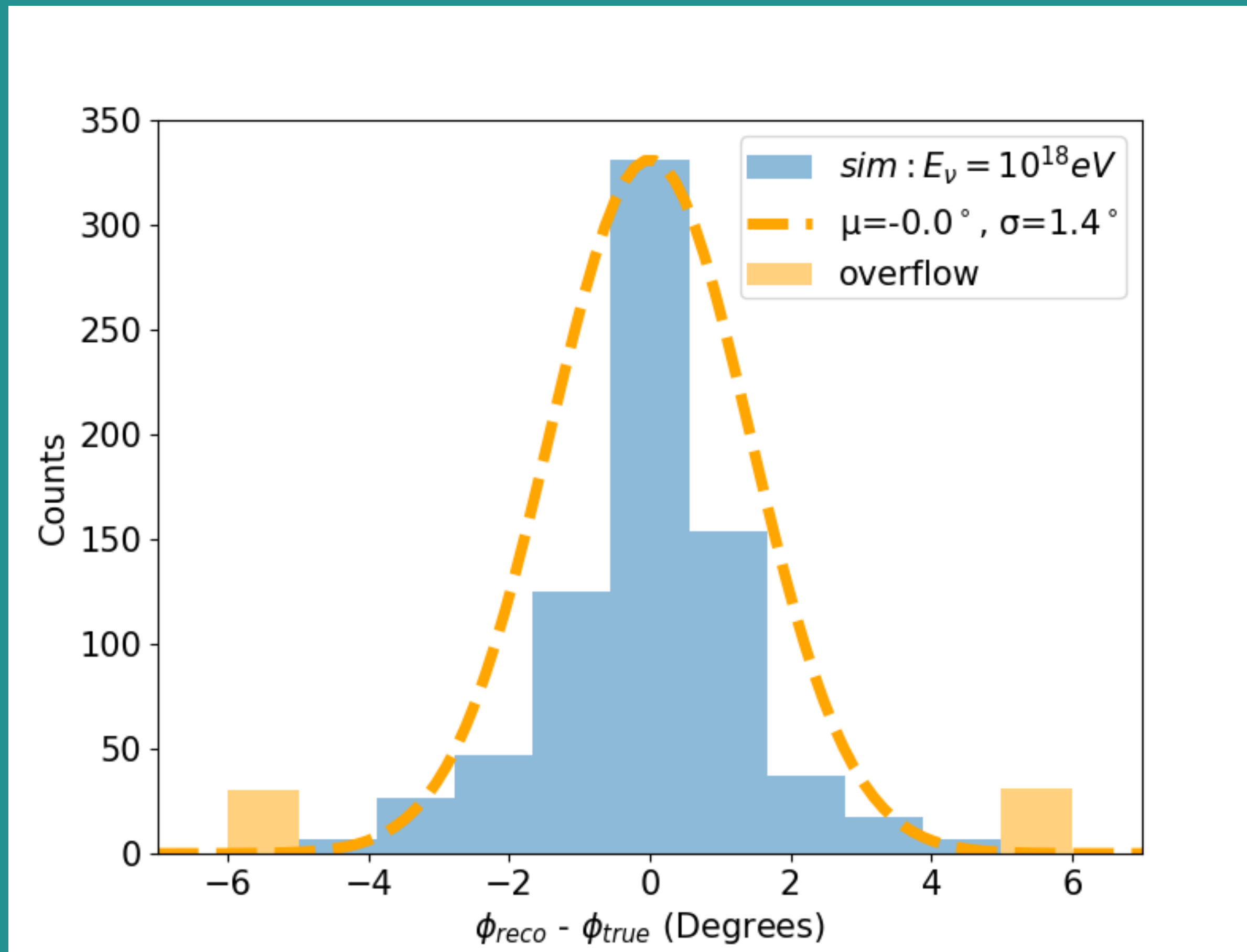
Reconstructed Azimuth



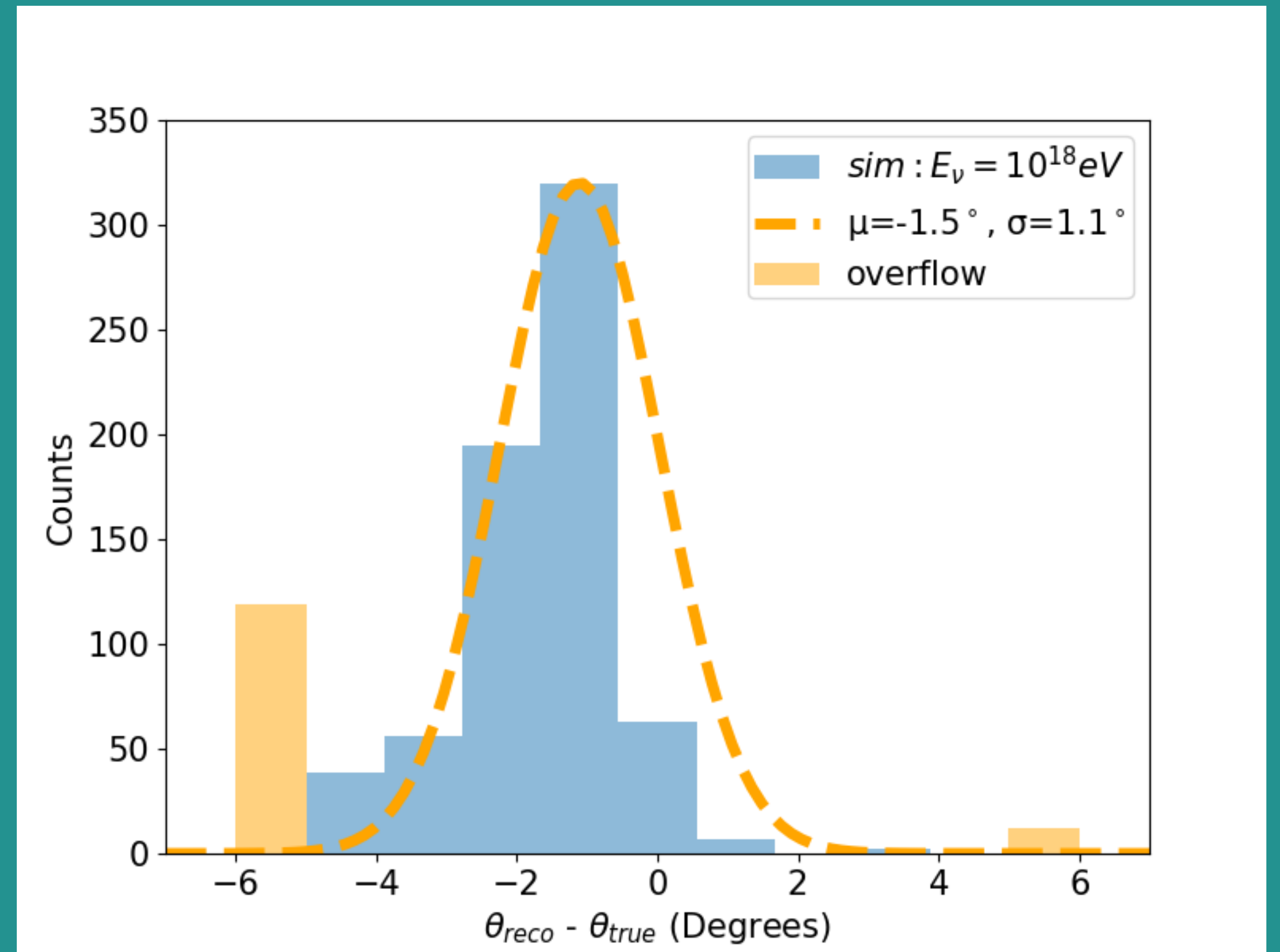
Reconstructed Elevation

Testing Reconstruction

Simulated Electron Neutrinos (ν) of energy $10^{18} eV$



Difference between true and reconstructed azimuth



Difference between true and reconstructed elevation

Analysis Variables

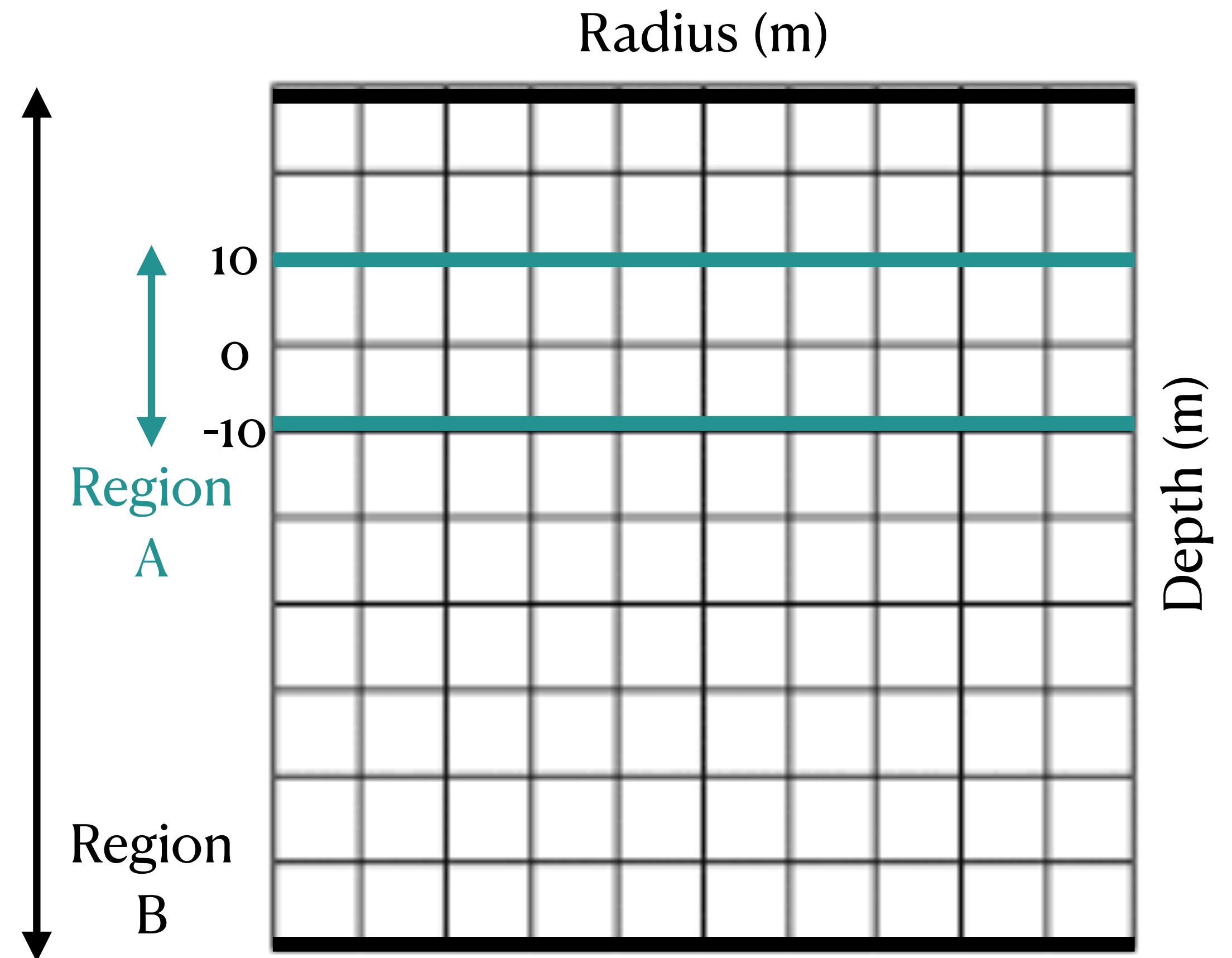
Surface Correlation Ratio (SCR)

- Determine if the event originates from surface or within ice (like neutrino interactions)

- $$SCR = \frac{CORR_{surf}}{CORR_{all}}$$

- $CORR_{surf}$ = max correlation in region A

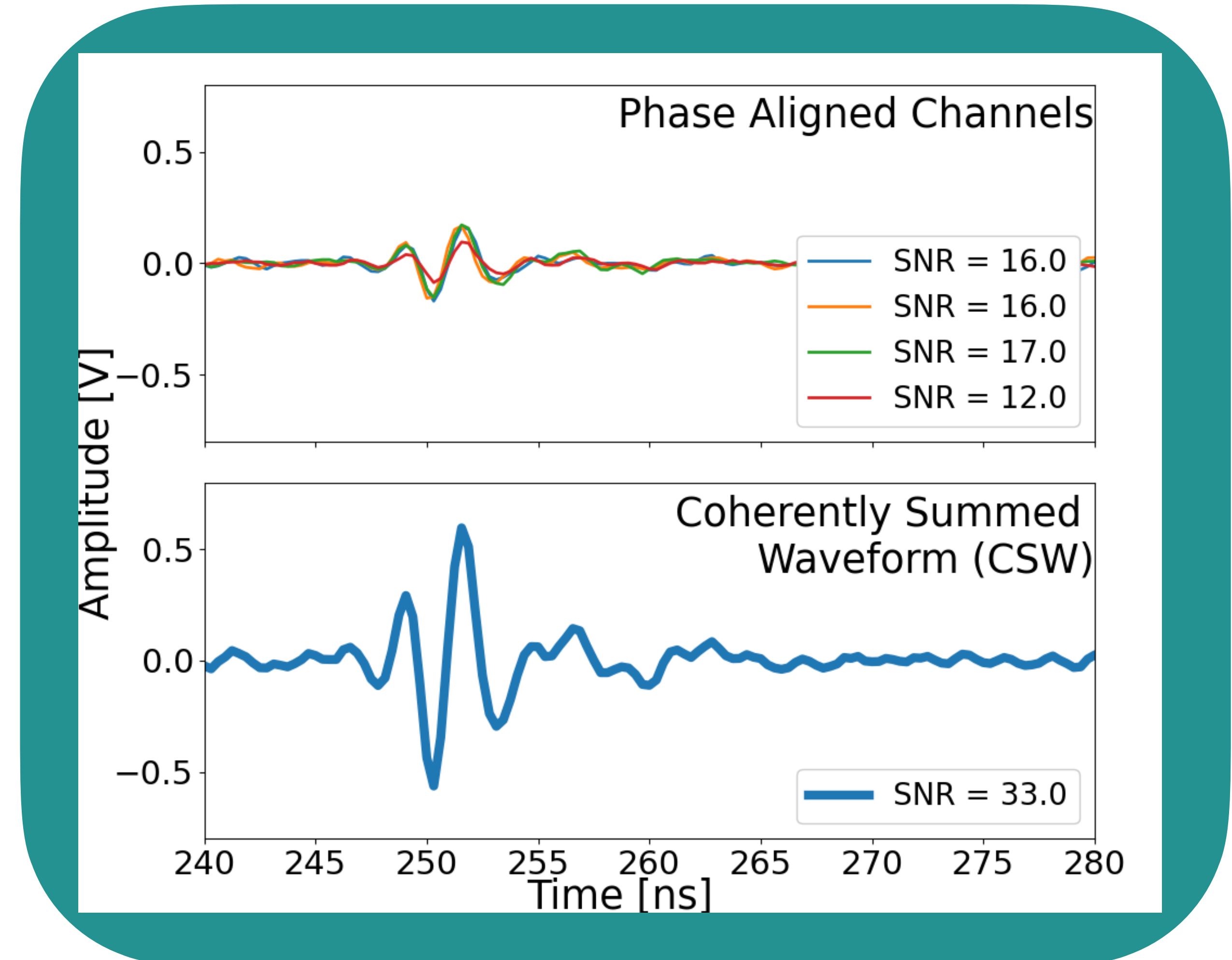
- $CORR_{all}$ = max correlation in region B



Analysis Variables

Coherently Summed Waveform (CSW)

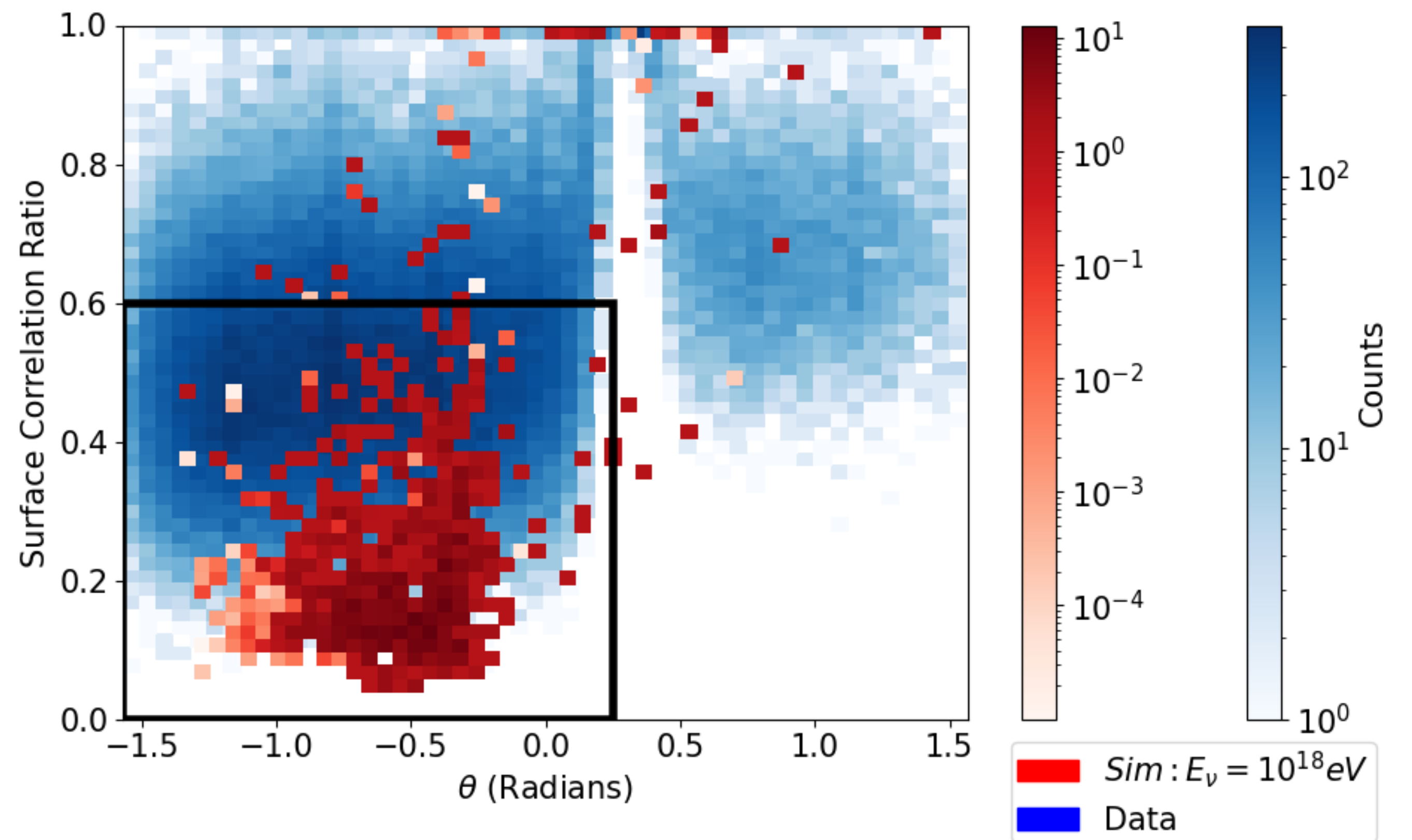
- Phase align traces and sum to create CSW with boosted $SNR \propto \sqrt{N_{ant}}$
- Extract variables describing the CSW like SNR and RPR



Results

SCR vs Elevation

- Made using all events from the good run list in 2021 for station 11
- Investigating a box-like cut that will be optimized in the future

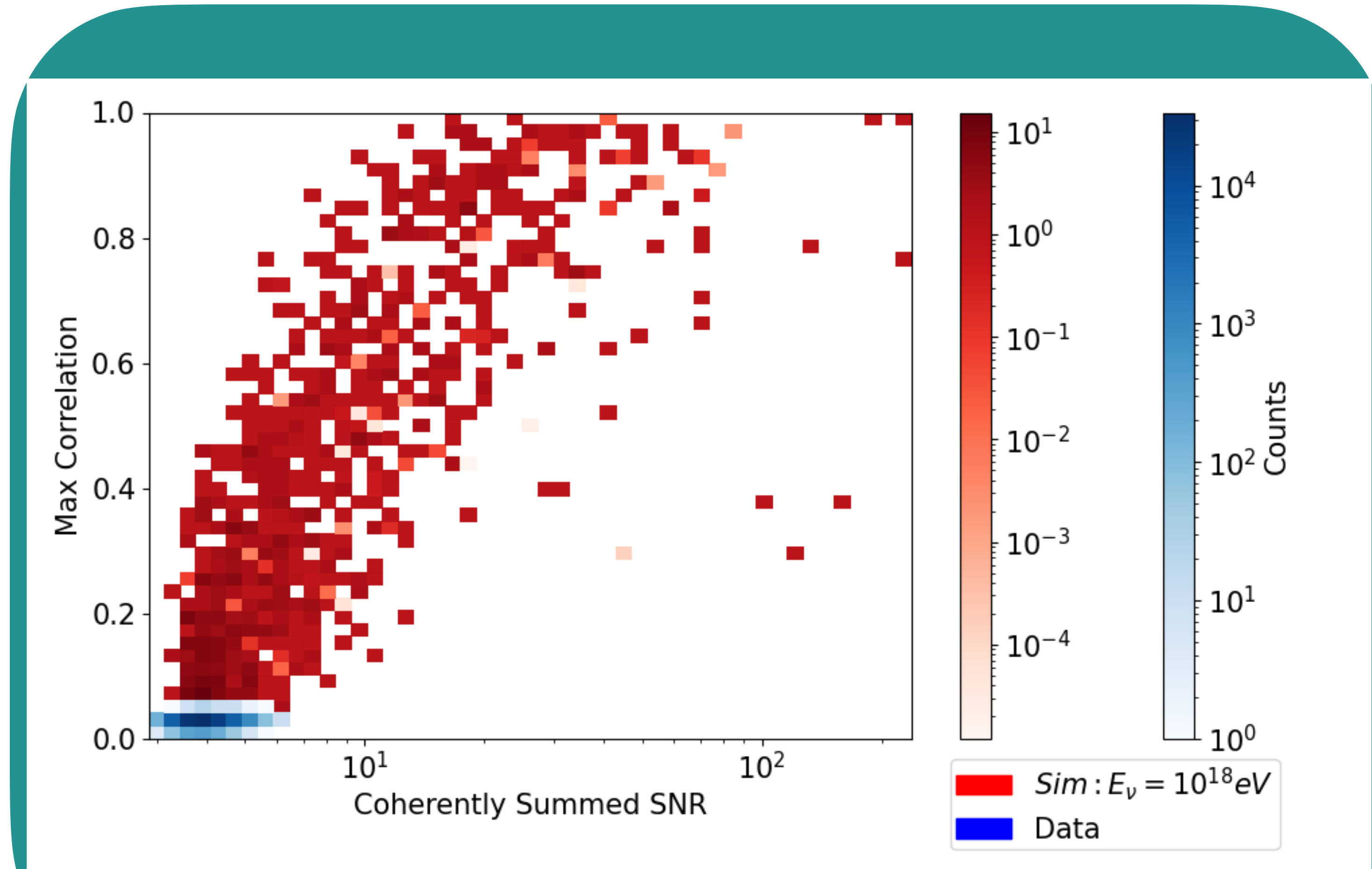


2D Histogram of SCR as a function of Elevation

Results

Maximum Correlation vs CSW SNR

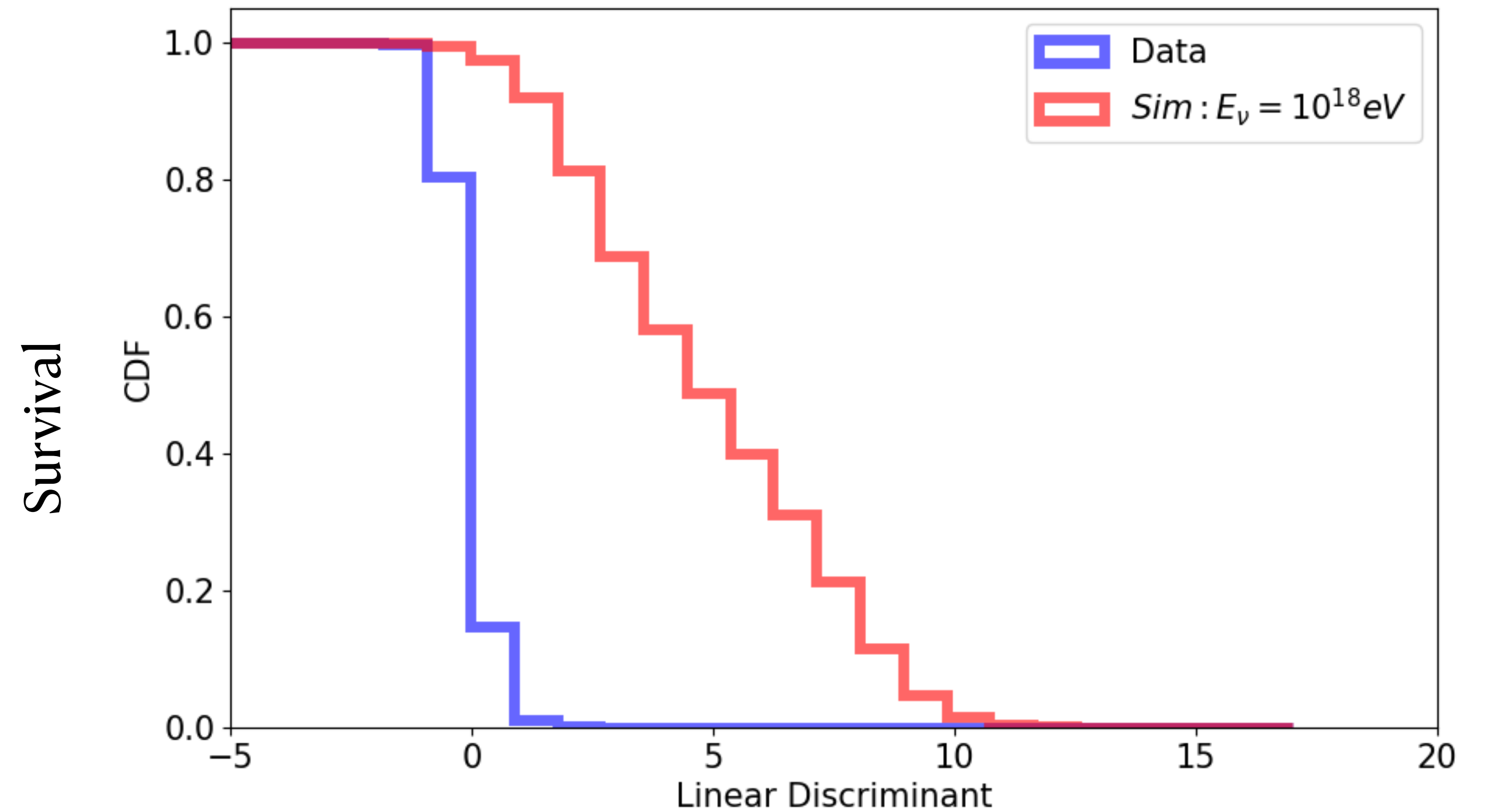
- Cut was applied to 2021 data
- Clear separation between simulated neutrinos and data, with data clustering at low SNR and low maximum correlation
- Can be used to separate data from neutrino-like signals.



2D Histogram of Max Correlation as a function of CSW SNR

Linear Discriminant Analysis (LDA)

- Developed to separate noise (2021 processed data) from neutrino-like signals
- Linear discriminant value of ~ 3 would remove all noise and preserve neutrinos.
- Determination of a precise cut is ongoing work



LDA projection of data and simulated neutrinos

Conclusion



- Significant progress has been made towards RNO-G's first neutrino search.
- Data processing pipeline has been set up, analysis variables have been calculated for processed data from Station 11 in 2021
- An LDA has been trained to maximize separation between background data and simulated neutrinos, will be used to create a cut
- Analysis will be applied to additional stations and years of data to set a limit on the diffuse neutrino flux.



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RMNOG

Radio Network - Greenland

Backup

Good Run List

Quality checks applied to create a clean dataset to be used for the neutrino search

Quality Checks

- Exclude runs (data) that are not classified as "Physics" runs, such as calibration runs
- Exclude runs with a high trigger rate, primarily composed of anthropogenic noise
- Exclude runs with a high root mean square (RMS) noise

Checks collectively remove ~1.4 % of total data collected

These runs undergo further processing

Projected Sensitivity

