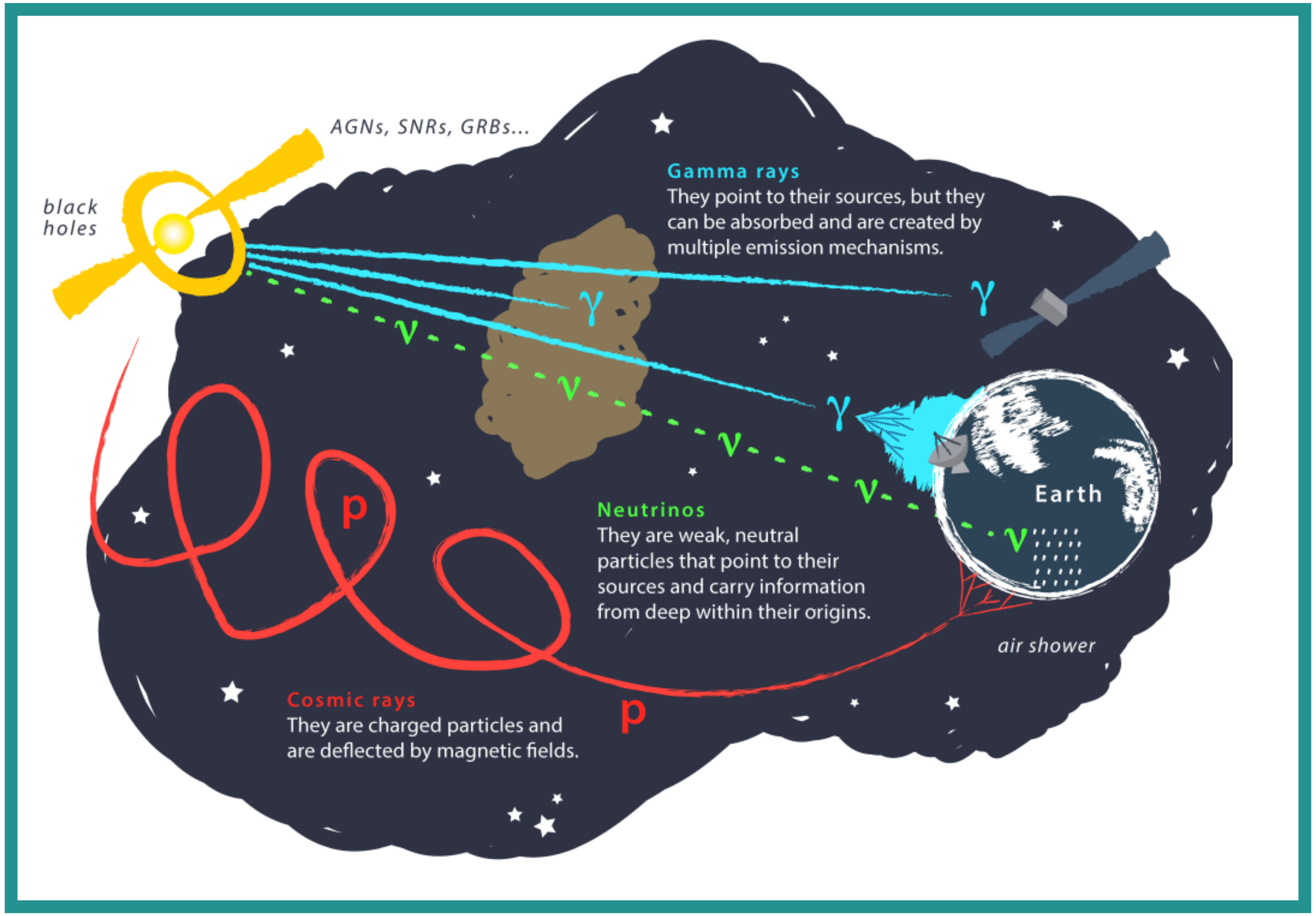
The Radio Neutrino Observatory in Greenland (RNO-G)

Instrumentation Overview

Aishwarya Vijai on behalf of RNO-G
PhD Student at the University of Maryland

Importance of Neutrinos



Cosmic Ray Interactions produce neutrinos

Cosmic Ray Acceleration

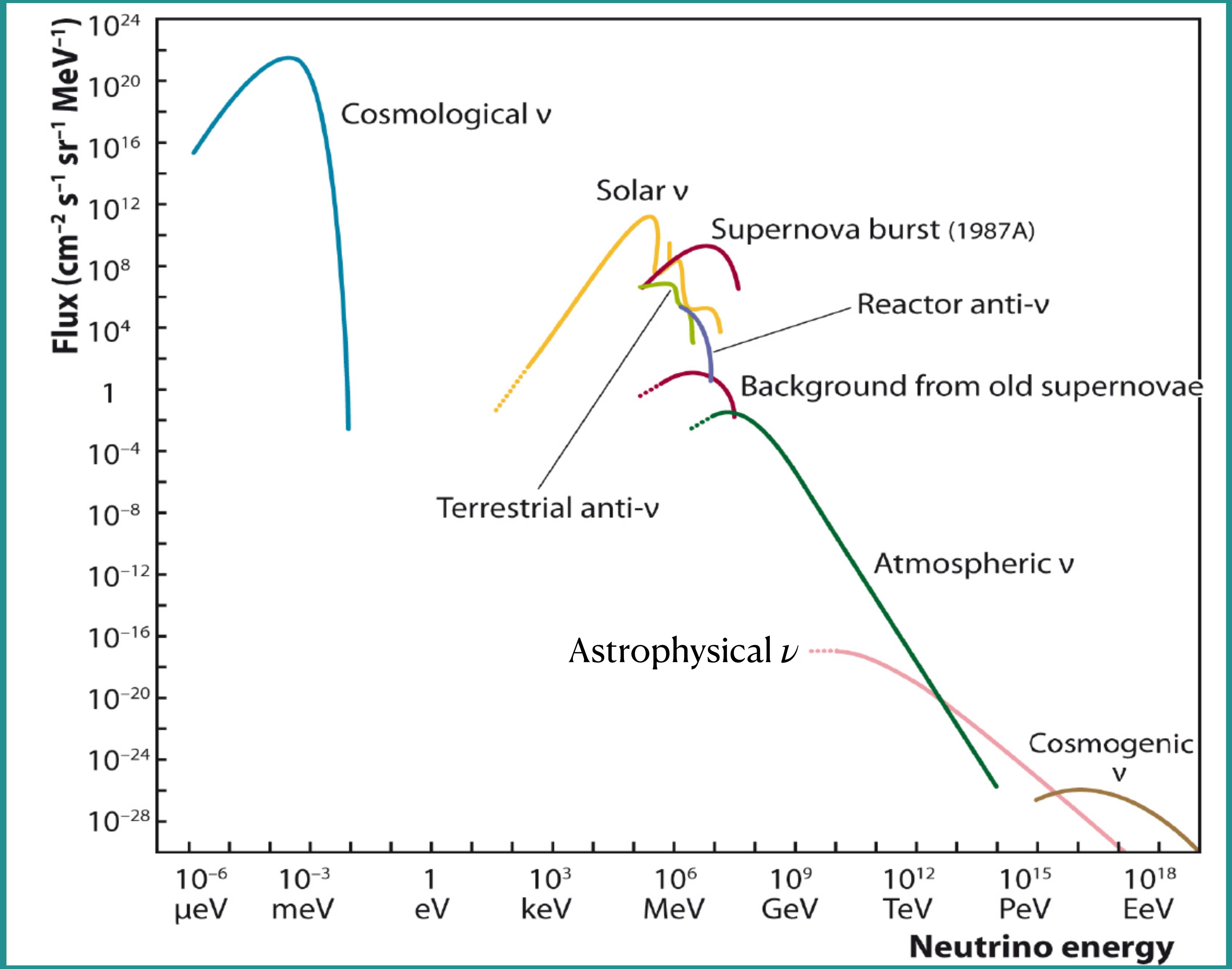
How are cosmic rays accelerated to energies as high as 10^{20} eV?

Cosmic Ray Composition

Are cosmic rays primarily made of protons?

Scientific Motivation

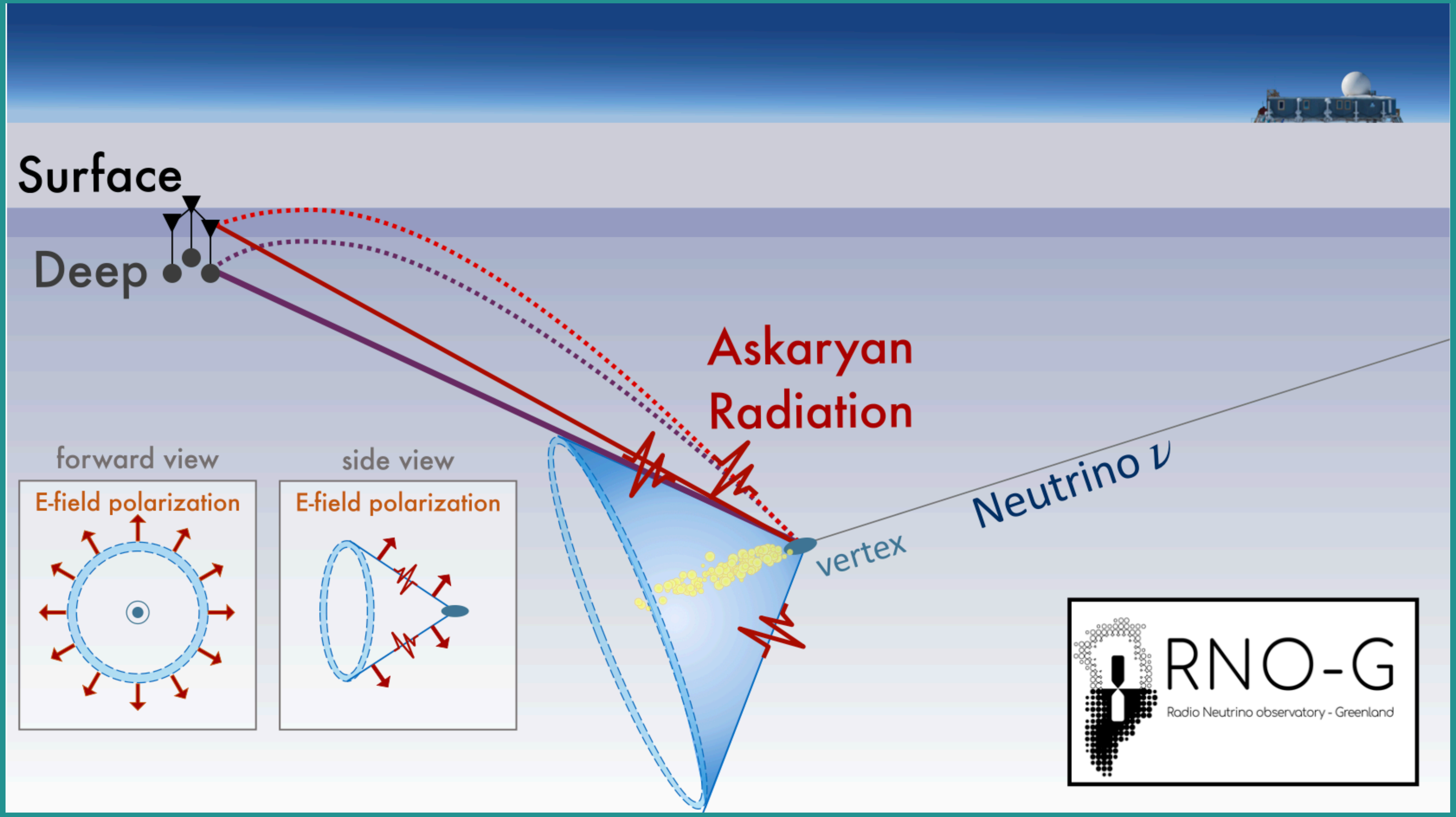
- Expect > 10 PeV Astrophysical and Cosmogenic neutrinos (ultra high energy, UHE)
- Mean Free path of PeV Neutrinos ~ 10^7 meters, <1/km^3/yr
- Need a large detector on the scale of tens of km^3 in the form of RNO-G



Radio Neutrino Detection of UHE Neutrinos

Detection Mechanism: Askaryan Emission

UHE (> 10 GeV) neutrinos interact with ice producing shower of relativistic secondary particle



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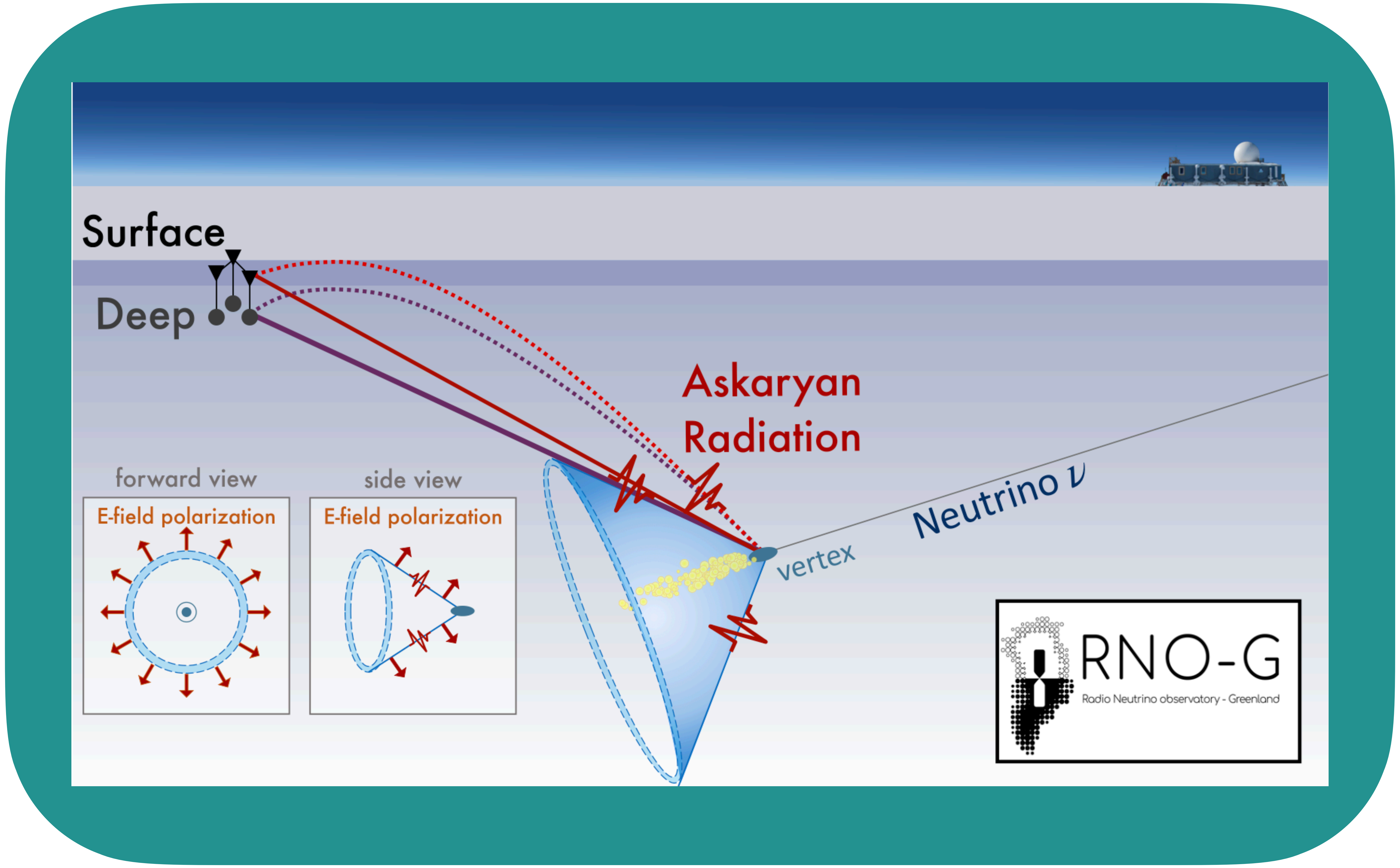

UHE (> 10 GeV) neutrinos interact with ice producing shower of relativistic secondary particle

↓

Negative net charge of shower emits a cone of Cherenkov radiation

Radio Neutrino Detection of UHE Neutrinos

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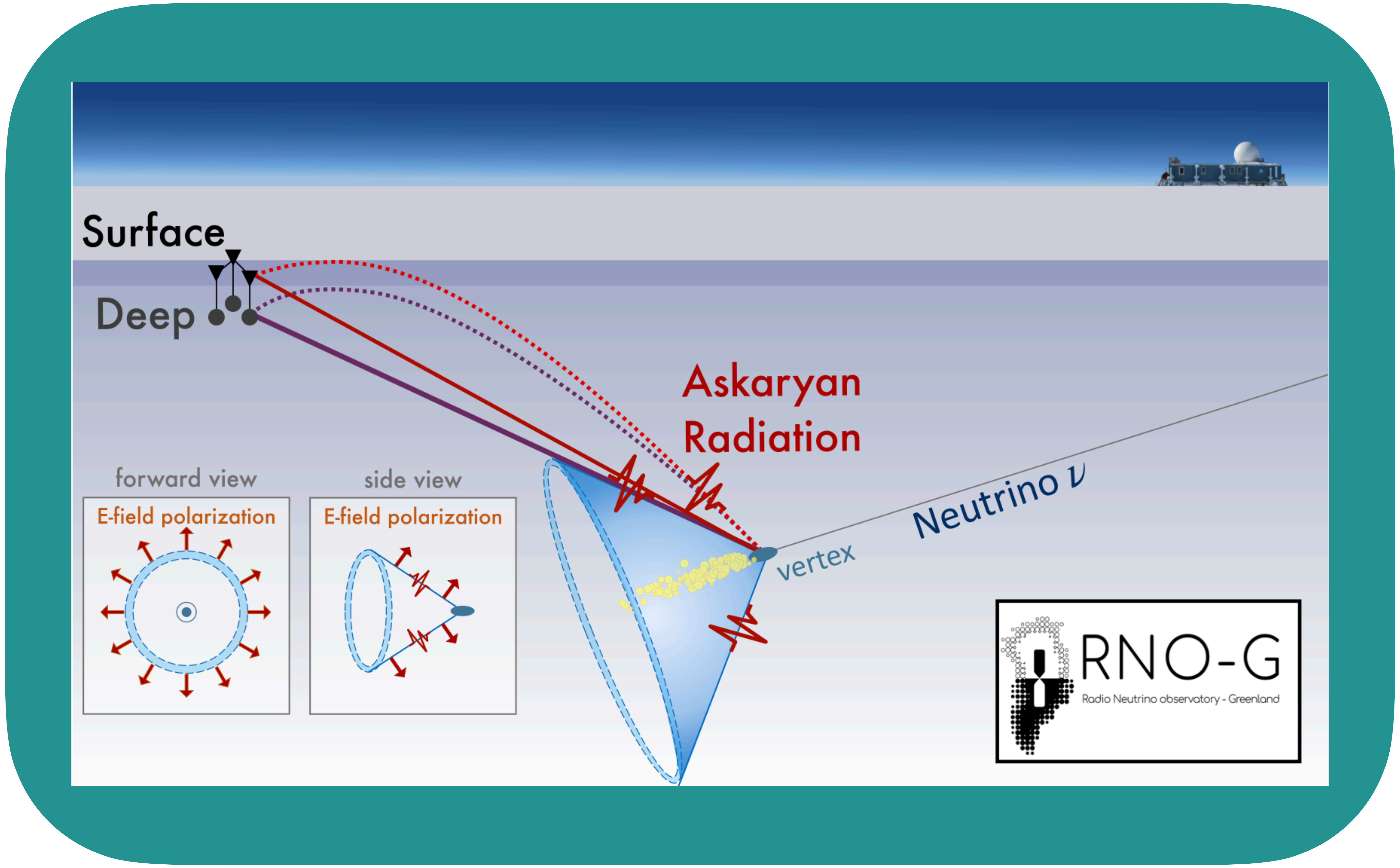

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Coherent amplification in radio

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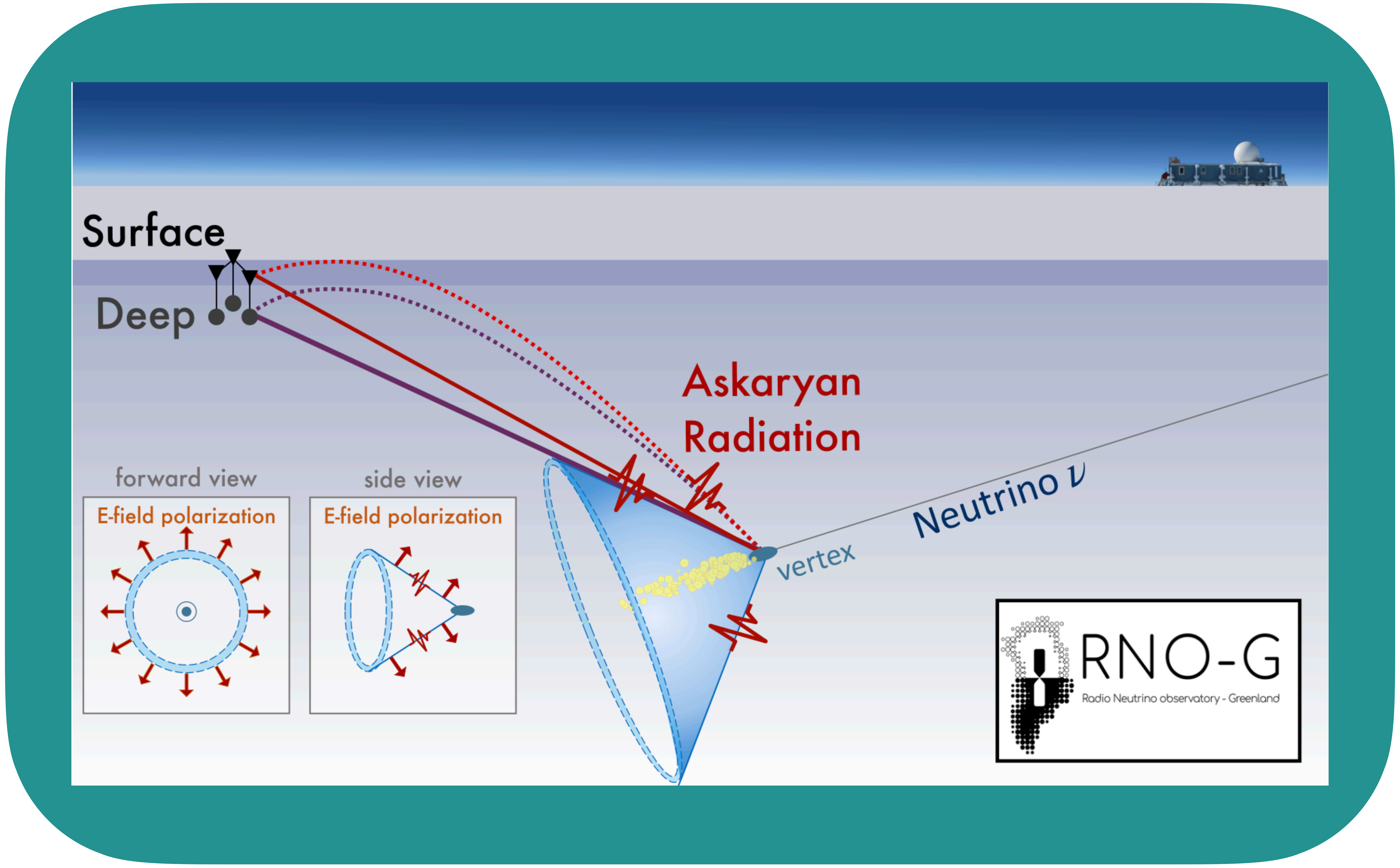


UHE (> 10 GeV) neutrinos interact with ice producing shower of relativistic secondary particle

Negative net charge of shower emits a cone of Cherenkov radiation

Coherent amplification in radio

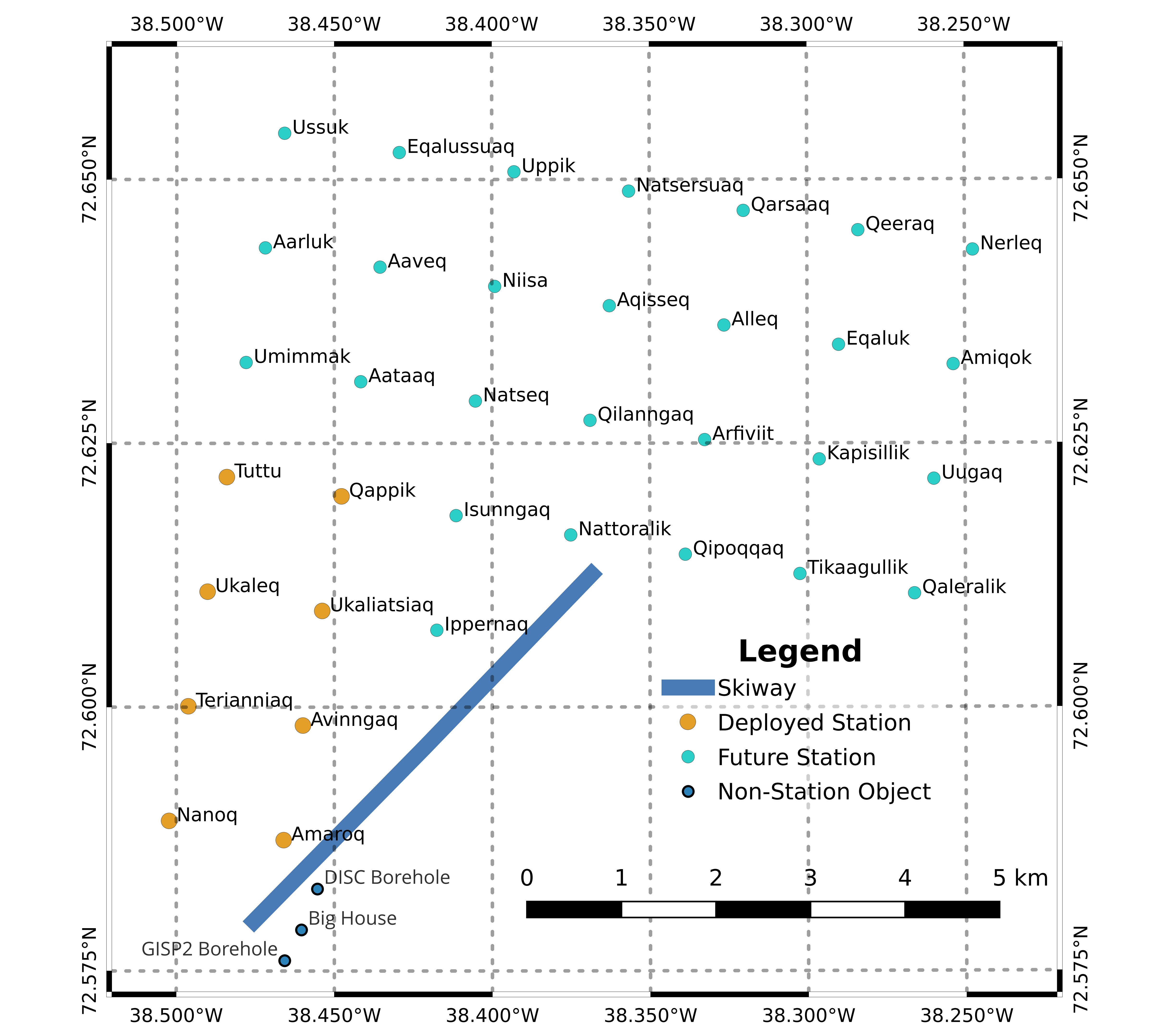
Few 100 MHz Pulse

Radio Neutrino Observatory in Greenland

Array of 35 stations, 8 built so far

Greenland Ice Attenuation length ~ $O(1km)$

Summit Station, Greenland

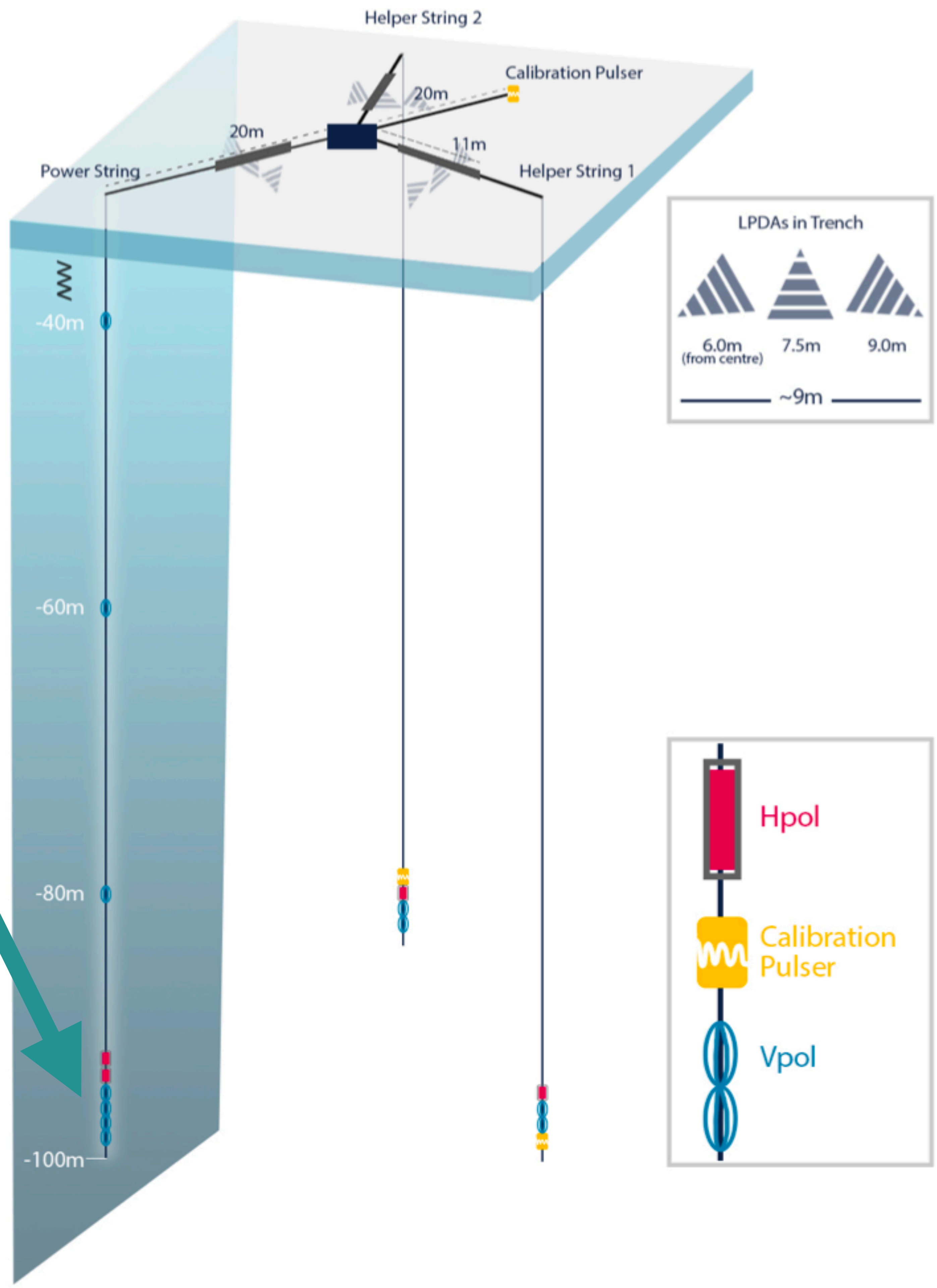


RNO-G Collaboration

RNO-G Station Layout

VPols

Reconstruct vertical polarization of incoming signal



A single RNO-G station

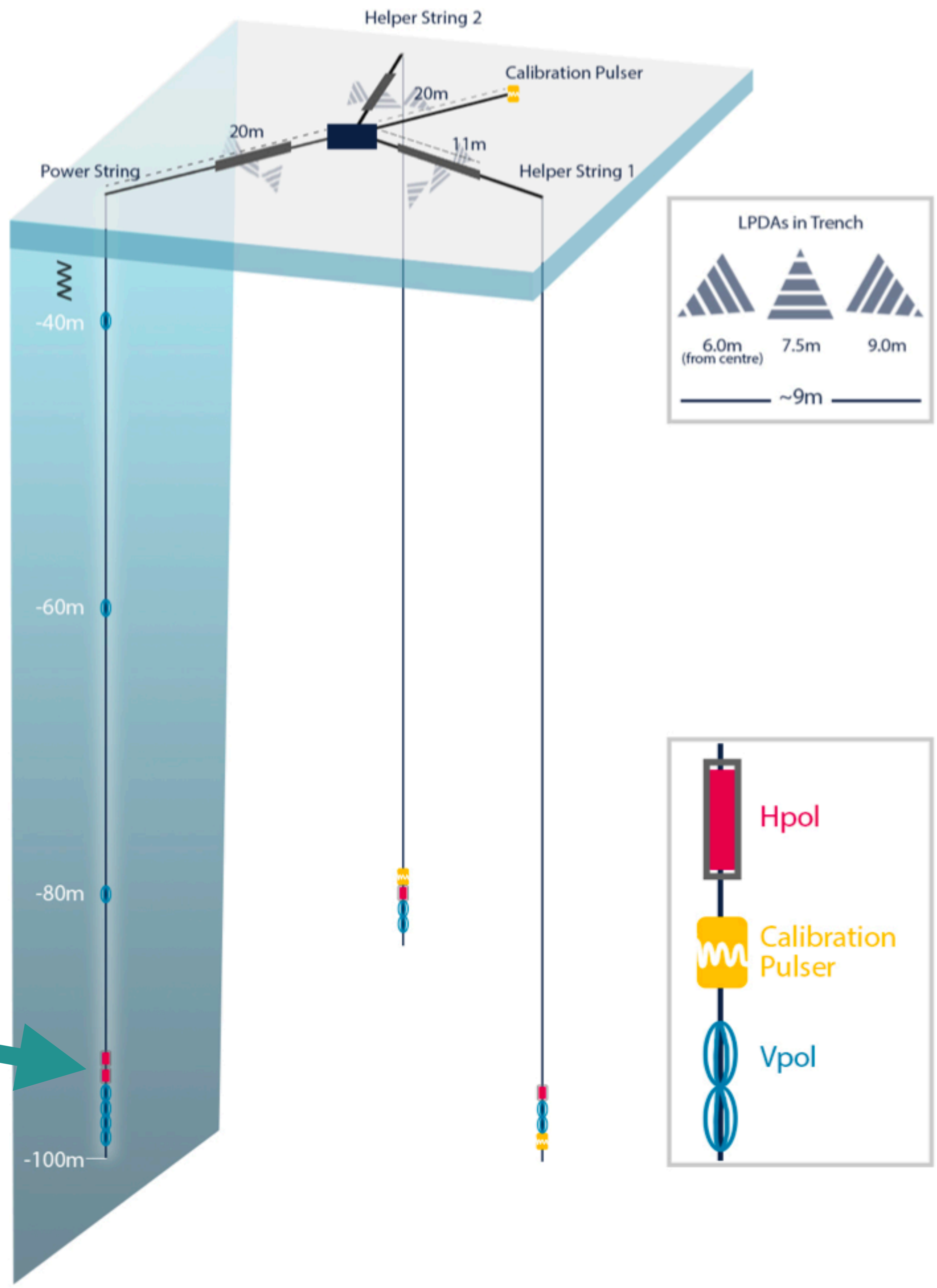
RNO-G Station Layout

VPols

Reconstruct vertical polarization of incoming signal

HPols

Reconstruct horizontal polarization of incoming signal



A single RNO-G station

RNO-G Station Layout

VPols

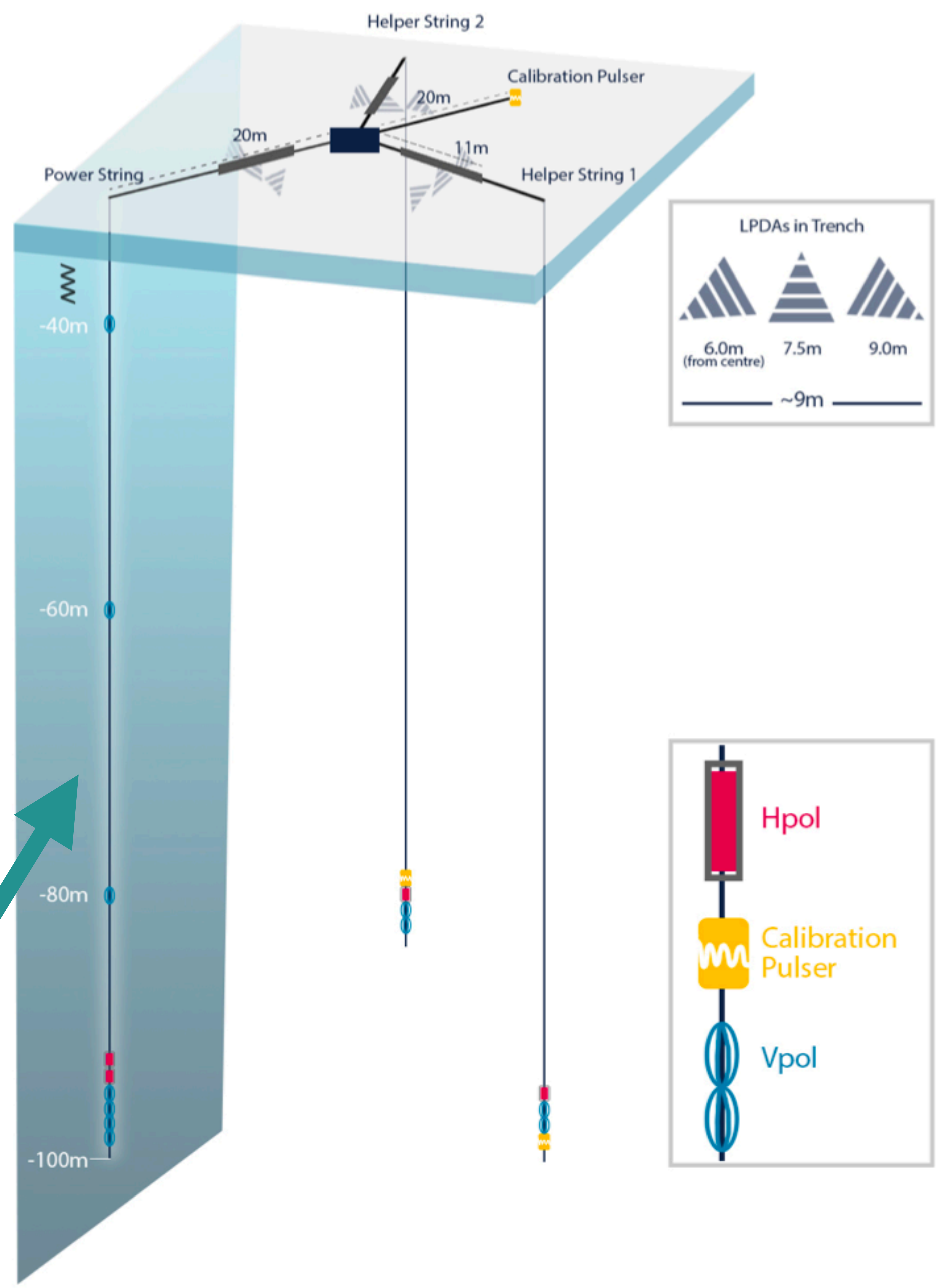
Reconstruct vertical polarization of incoming signal

HPols

Reconstruct horizontal polarization of incoming signal

Power String

Triggering on neutrino events



A single RNO-G station

RNO-G Station Layout

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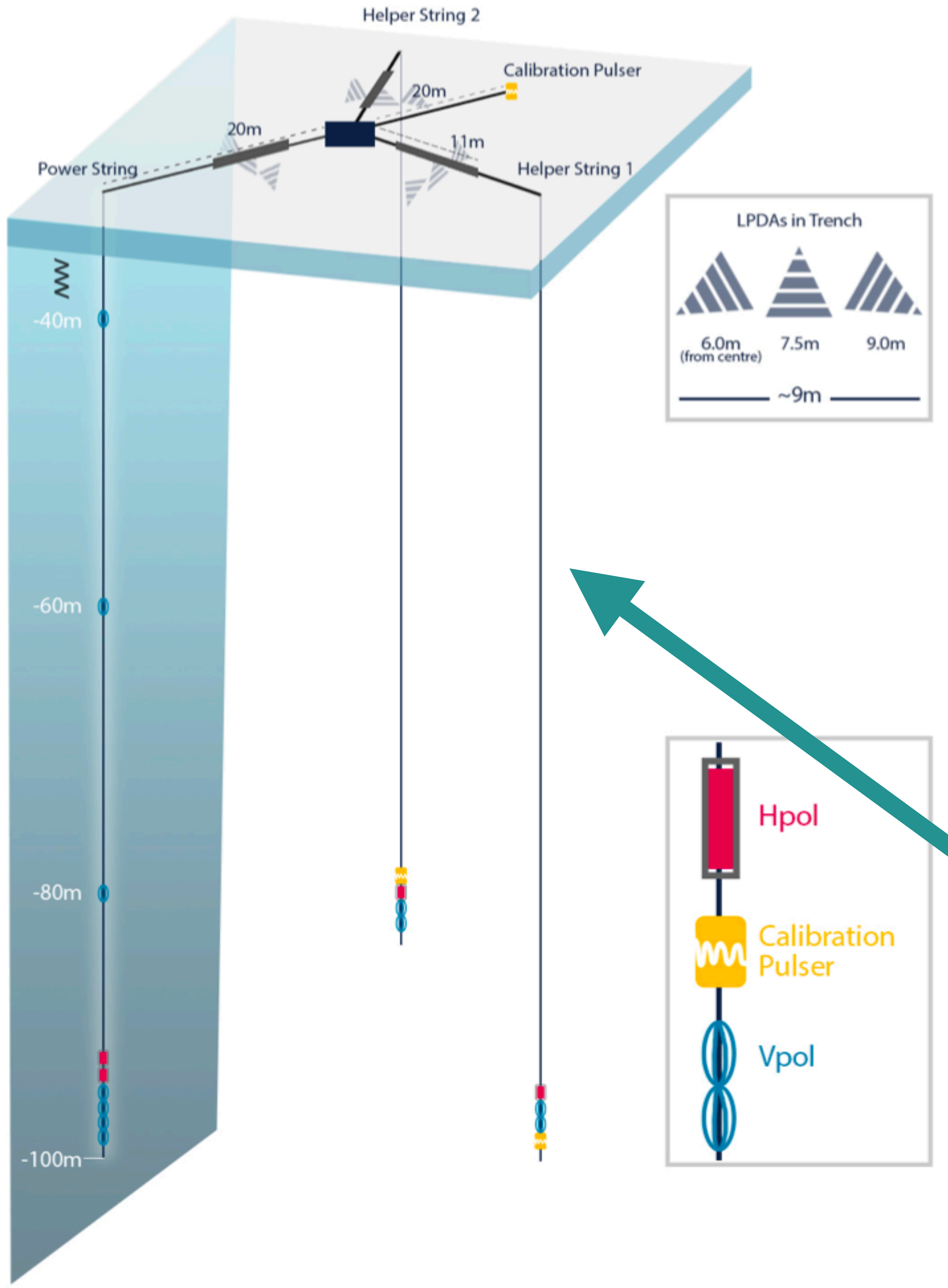


A single RNO-G station

Helper String

Reconstructing neutrino energy/direction and calibration

RNO-G Station Layout

VPols

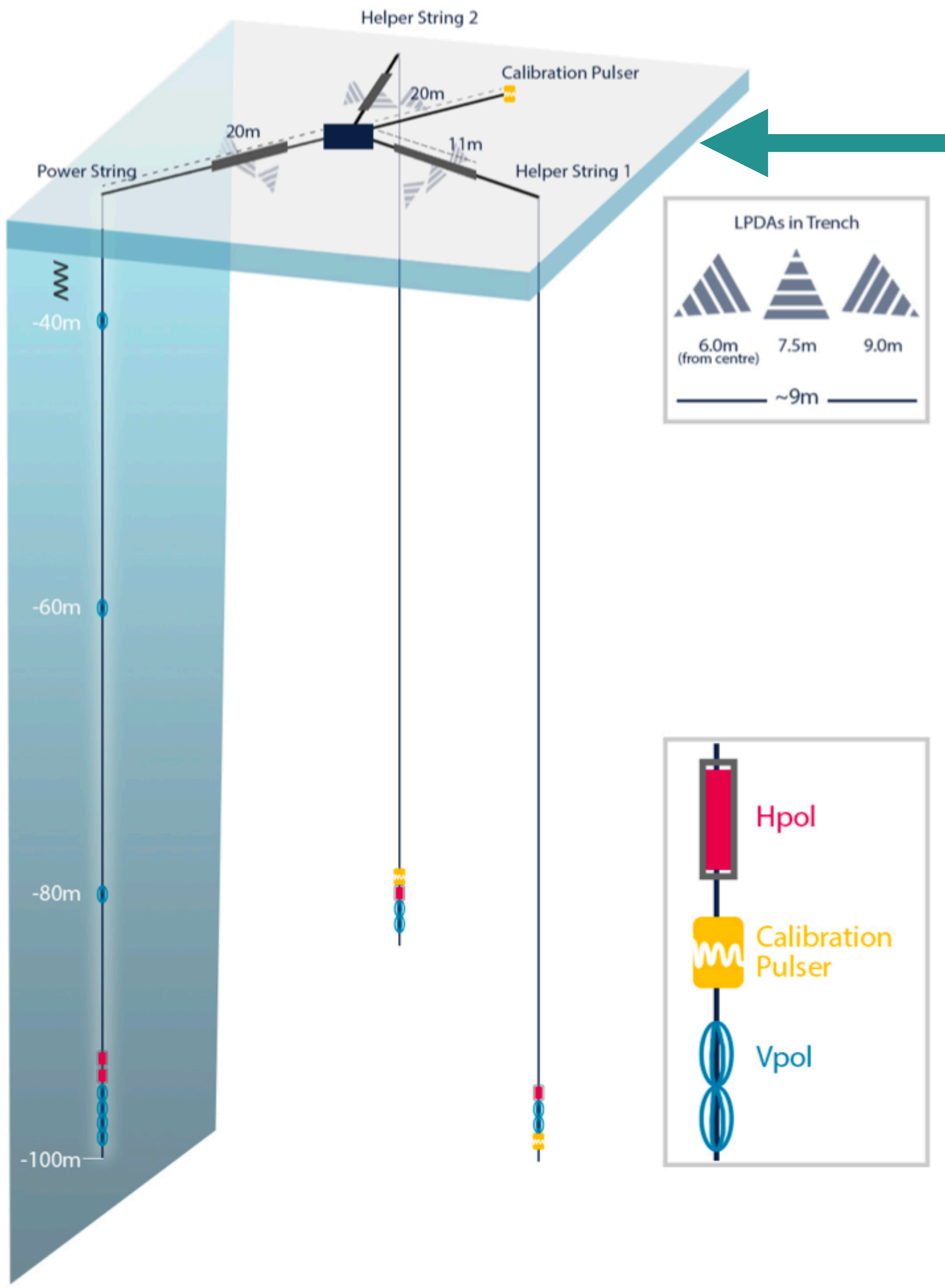
Reconstruct vertical polarization of incoming signal

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

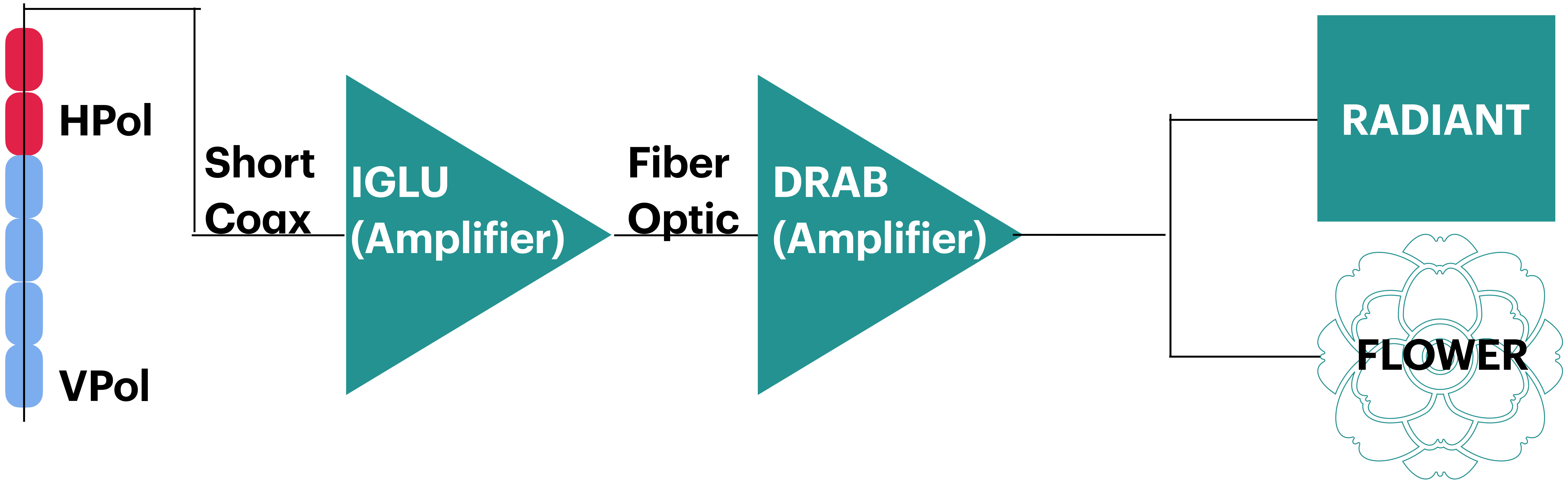
Reconstructing neutrino energy/direction and calibration

RNO-G Deployment

Stations run on solar power and each station draws ~ 25W

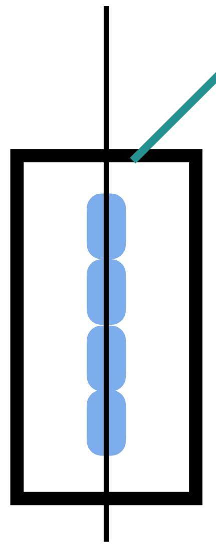
RNO-G Hardware Response

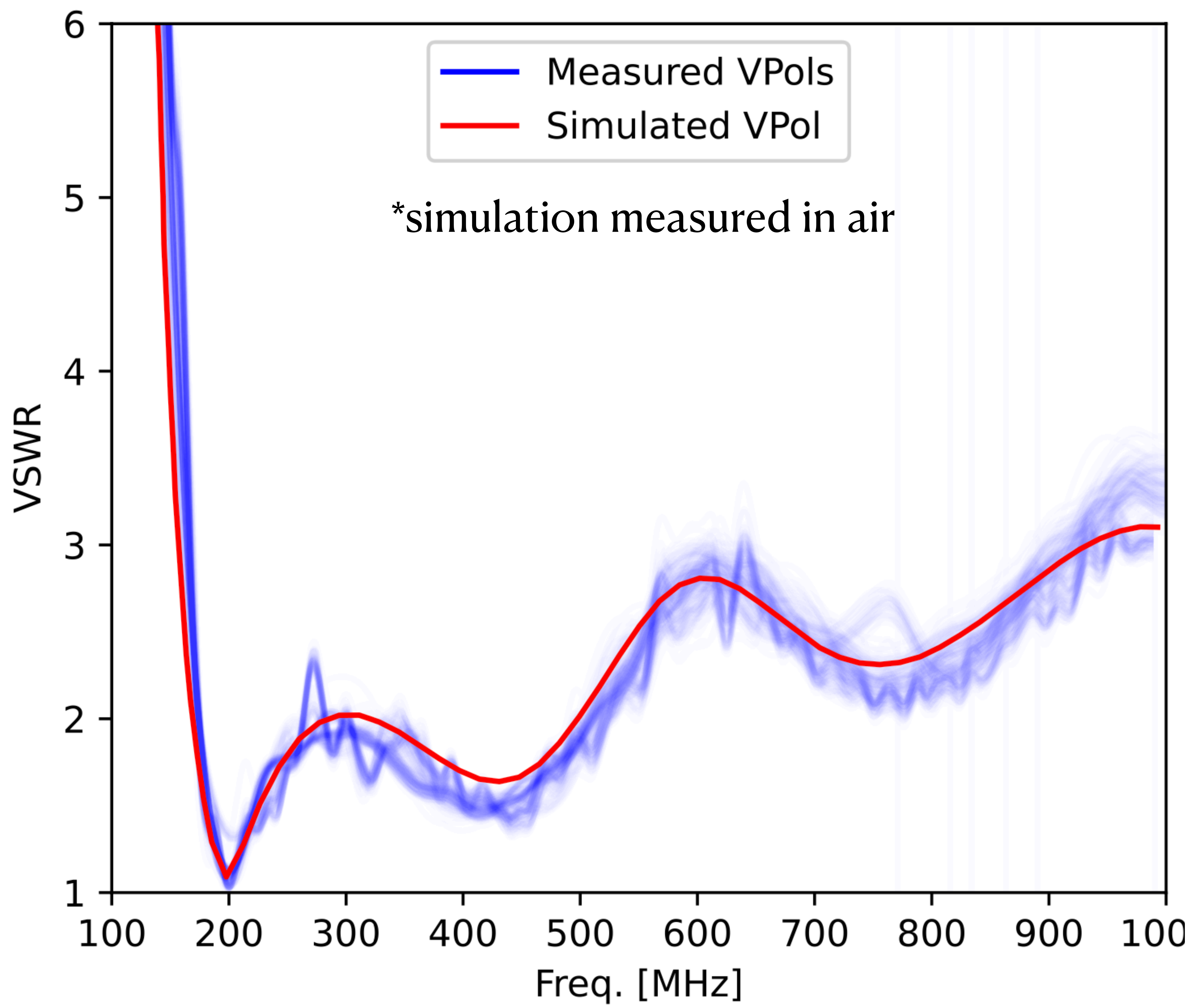
Overview



RNO-G Hardware Response

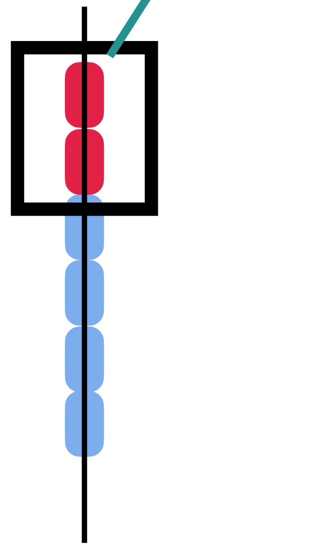
VPols: Broadband, highly reproducible antennas

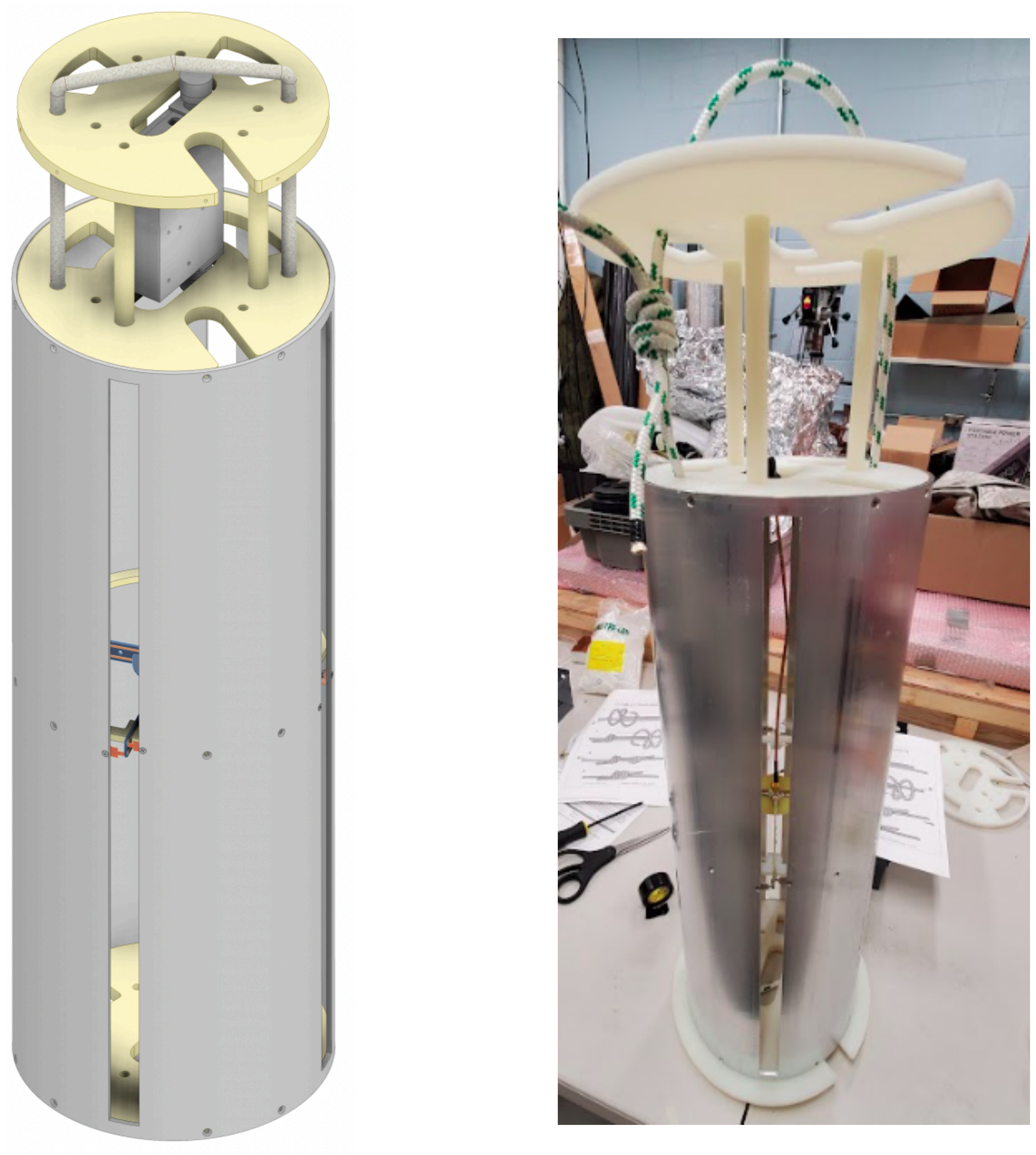




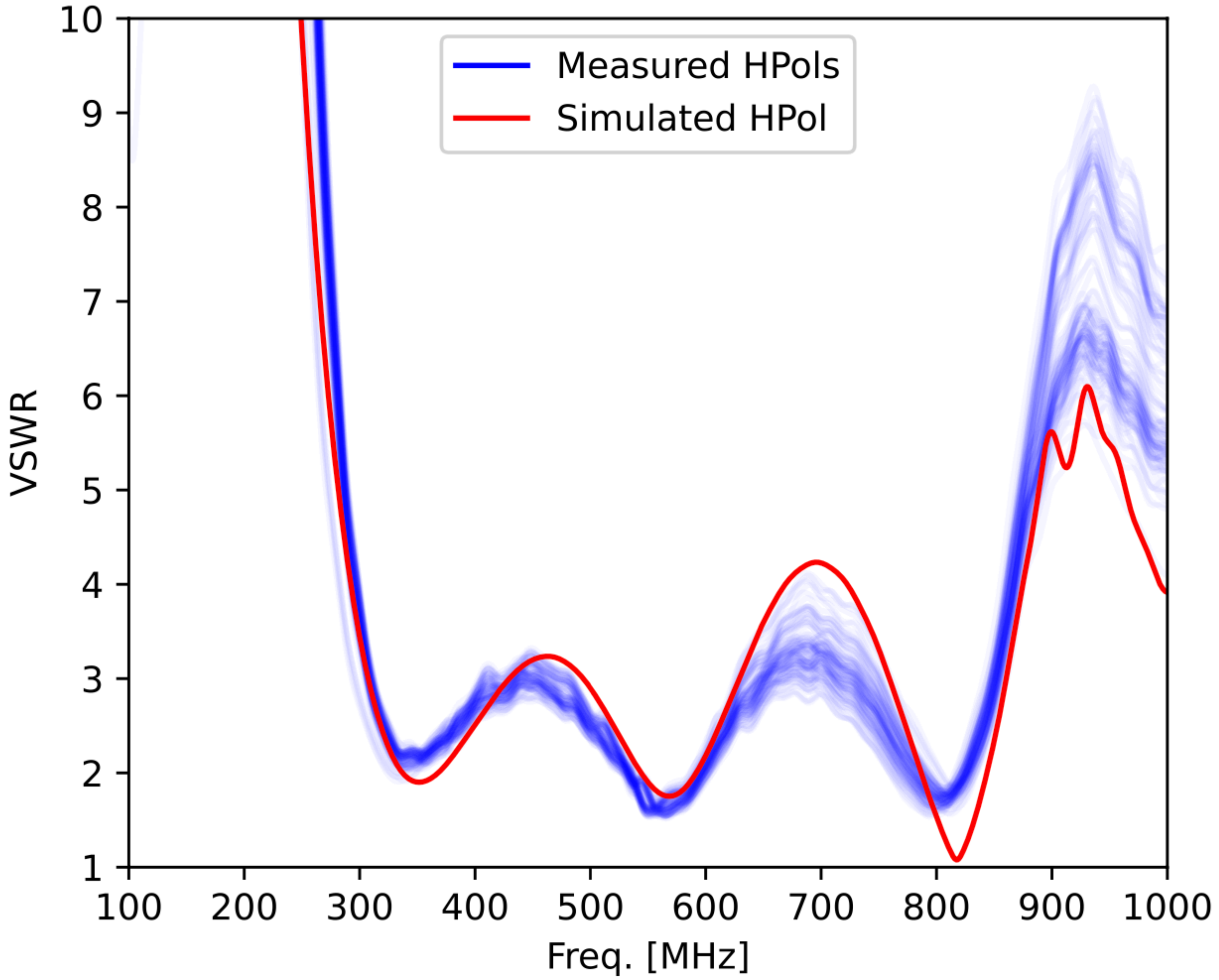
RNO-G Hardware Response

HPols: Good simulation-data agreement





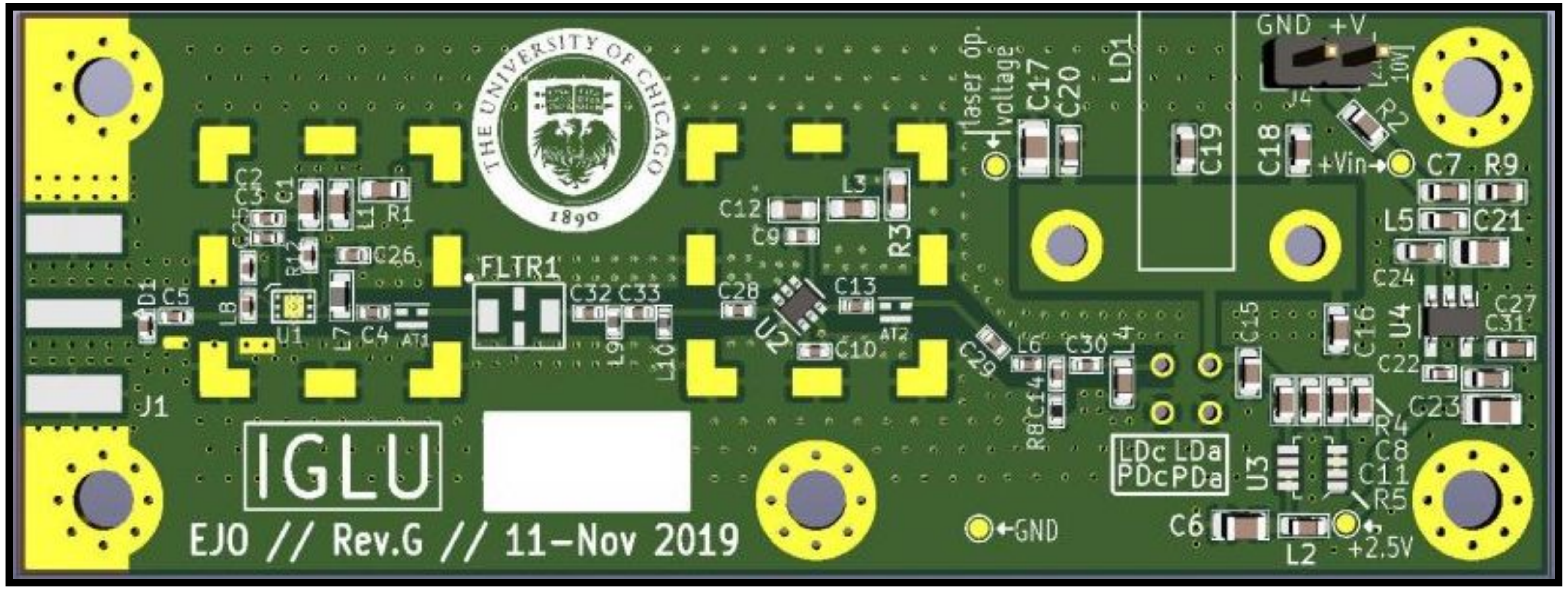
Tri-slot Antenna



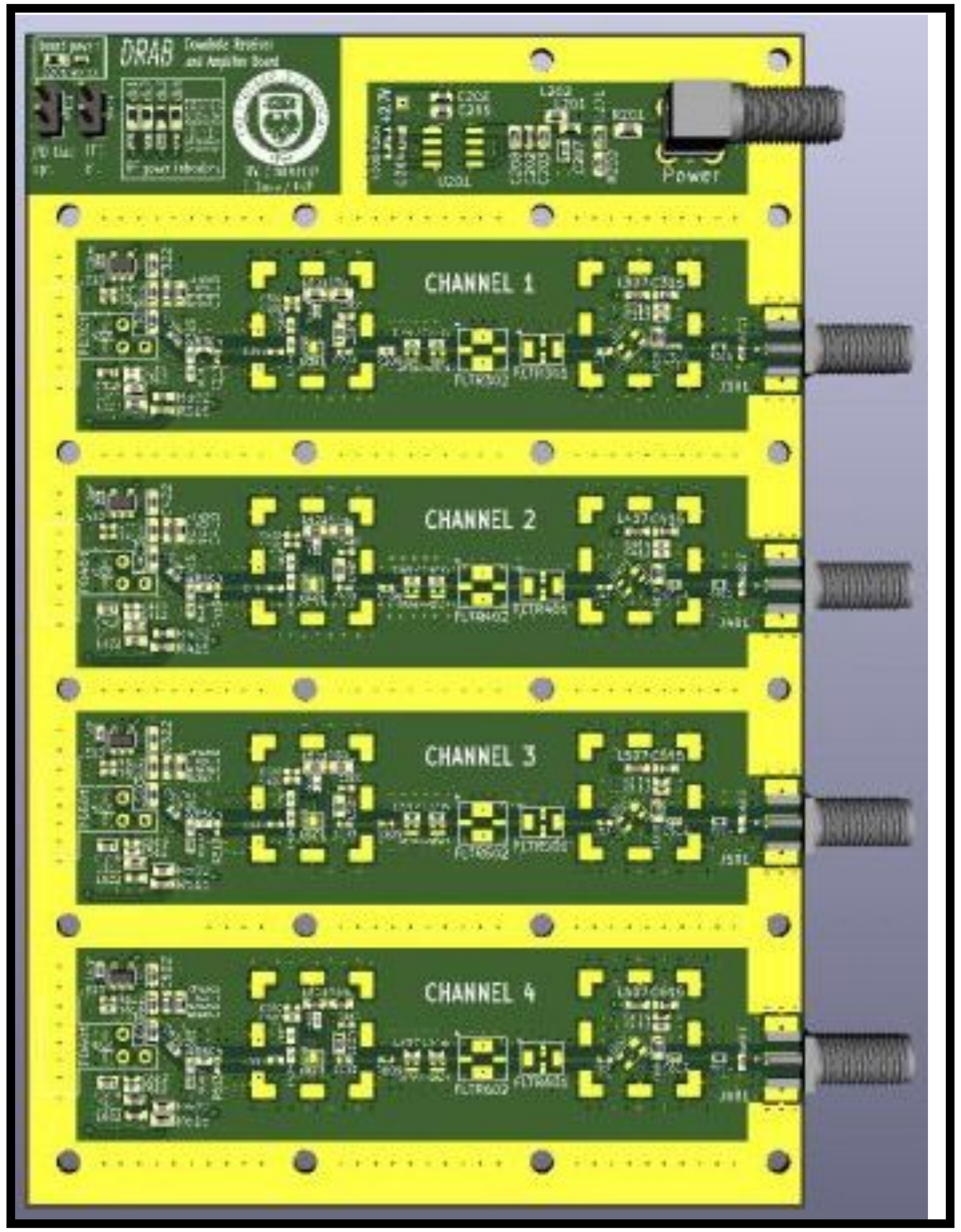
RNO-G Hardware Response

IGLU: In Ice Gain with Low Power Unit

DRAB: Downhole Reciever and Amplifier Board



IGLU



DRAB

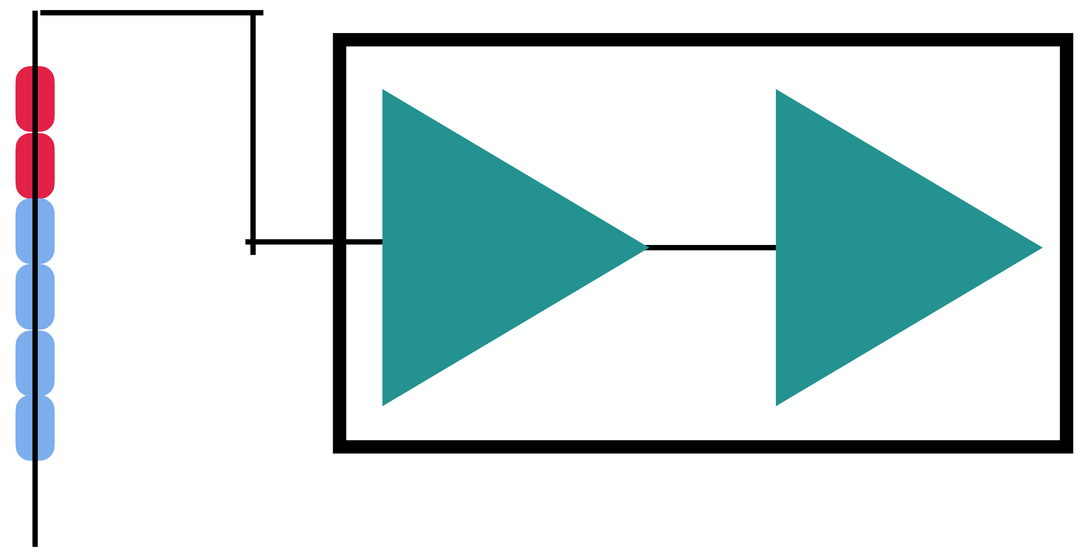
RNO-G Hardware Response

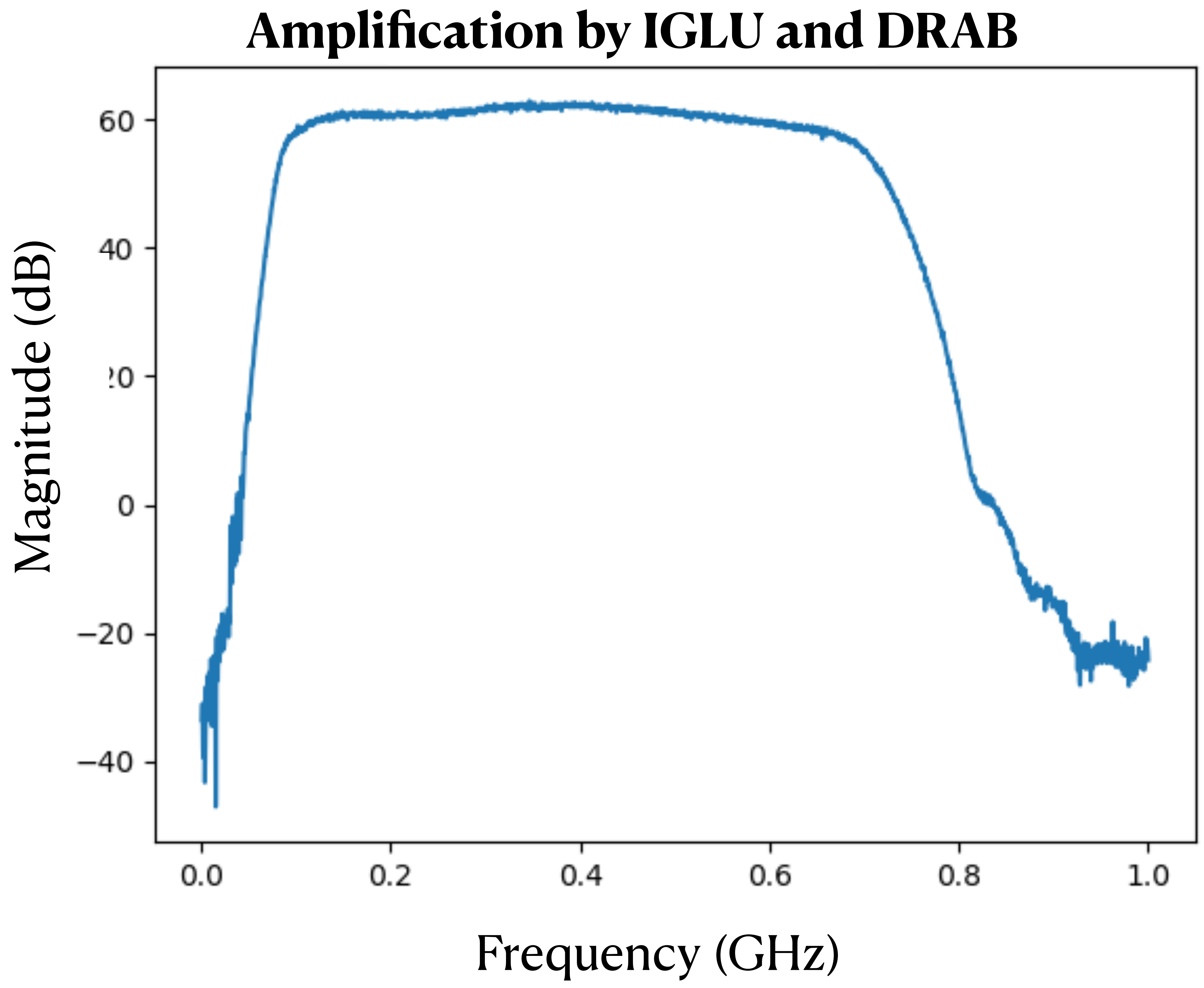
IGLU: In Ice Gain with Low Power Unit
DRAB: Downhole Reciever and Amplifier Board

Immediate analog to RFoF (radio frequency over fiber) signal conversion ensures uniform response for phasing and prevents attenuation during transmission to surface

Custom designed low power (~140 mW) and minimal noise temperature

(< 150 K)



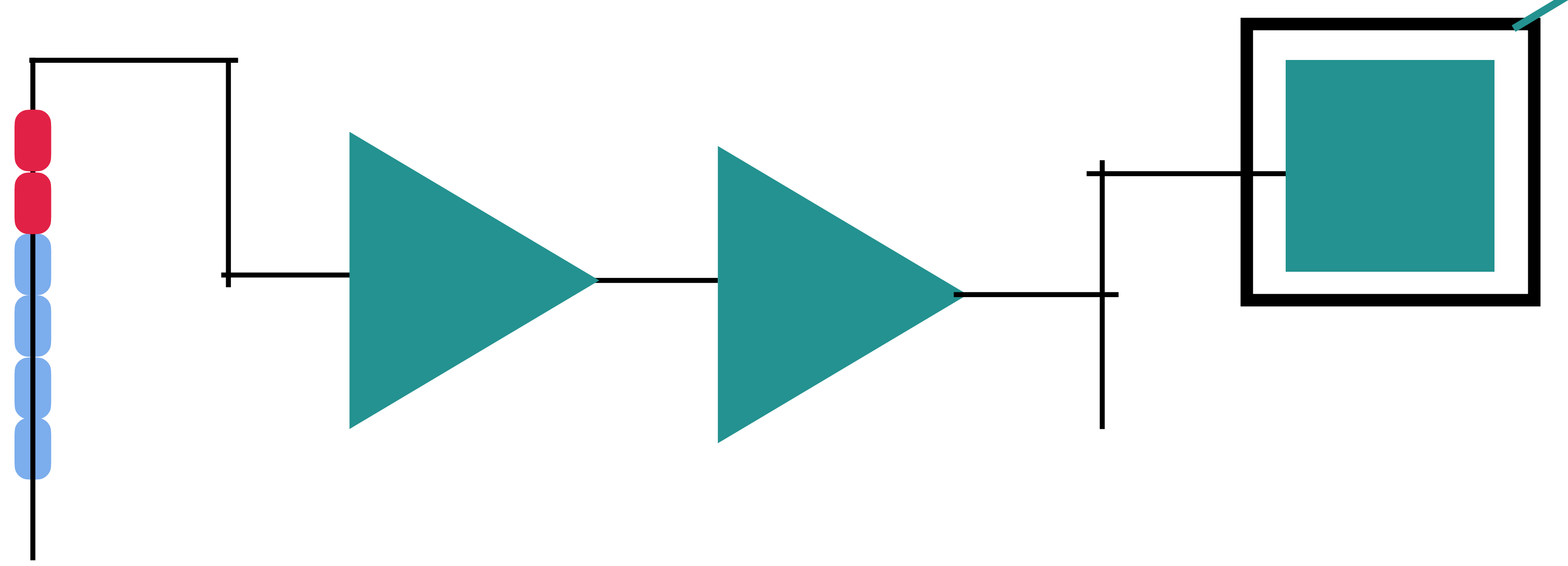


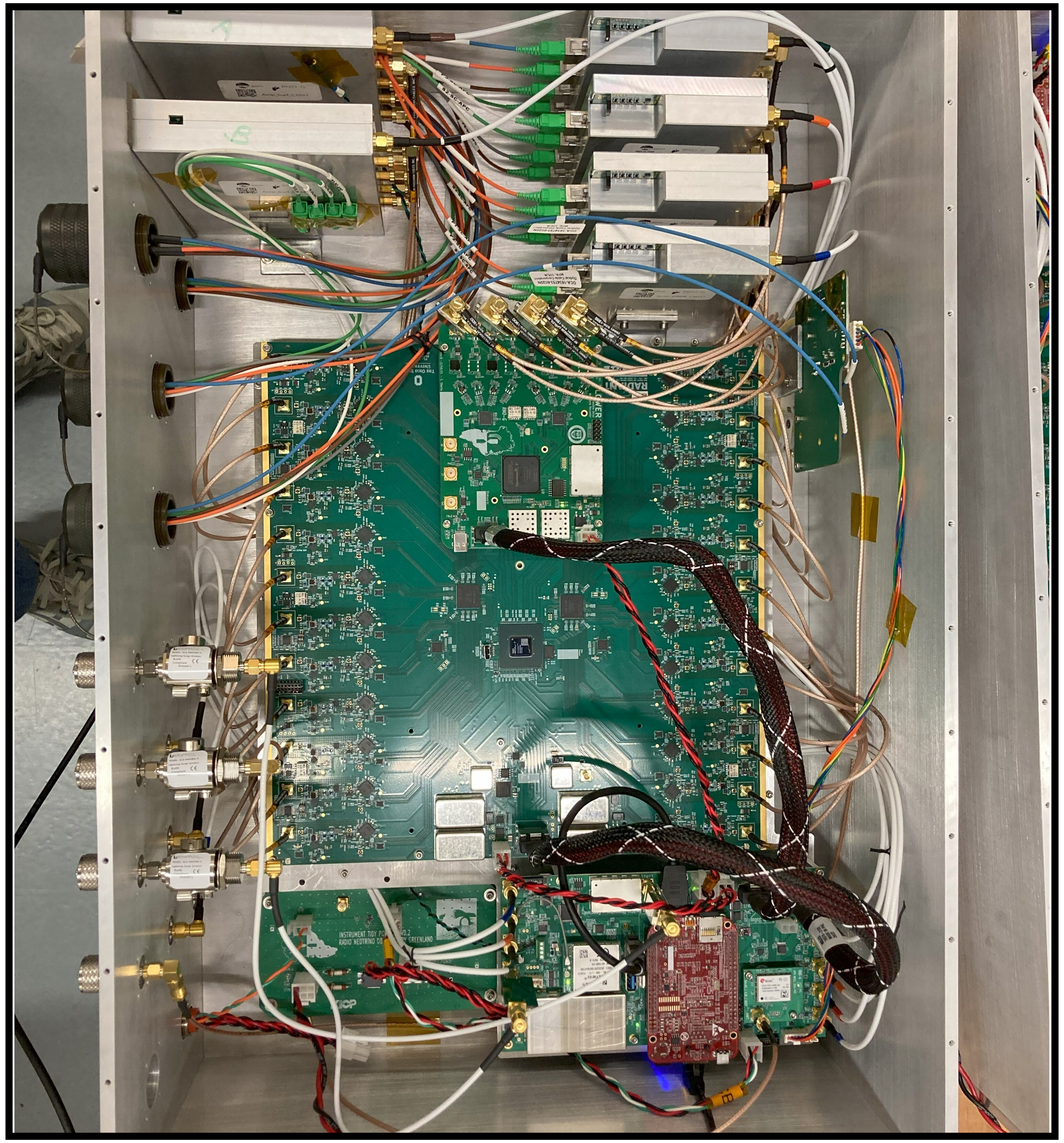
RNO-G Hardware Response

RADIANT: Radio Digitizer and Auxillary Neutrino Trigger

RADIANT

24 Channel digitizer at 2.4 GS/s capable of in-situ timing and calibration



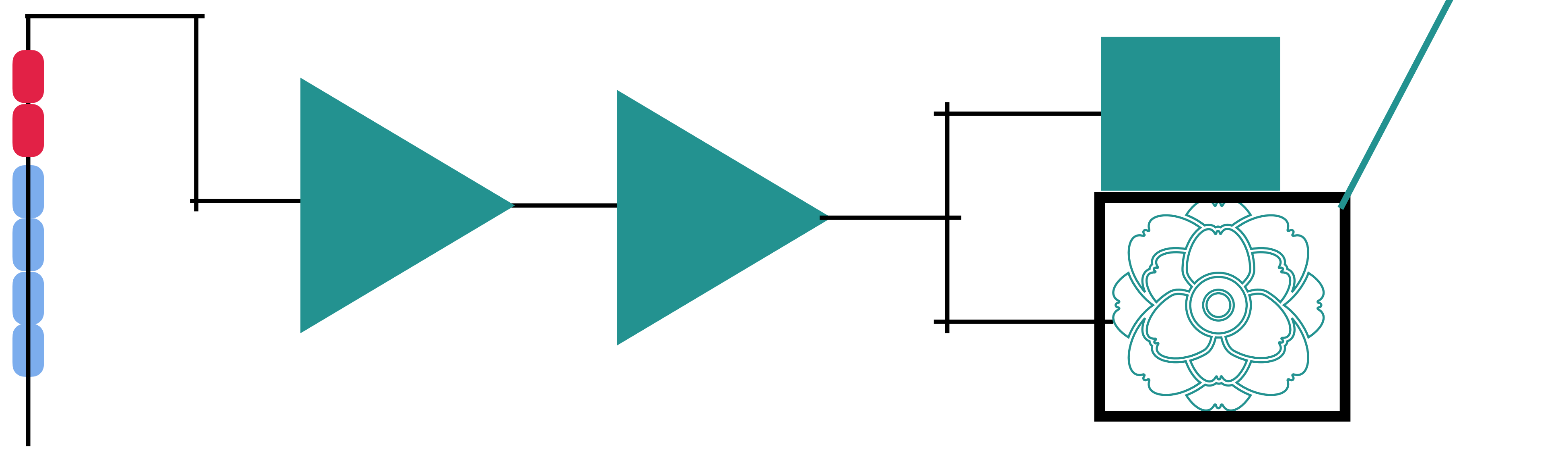


RNO-G Hardware Response

FLOWER: Flexible Octal Waveform Recorder

FLOWER

RNO-G Trigger Board



RNO-G Triggers

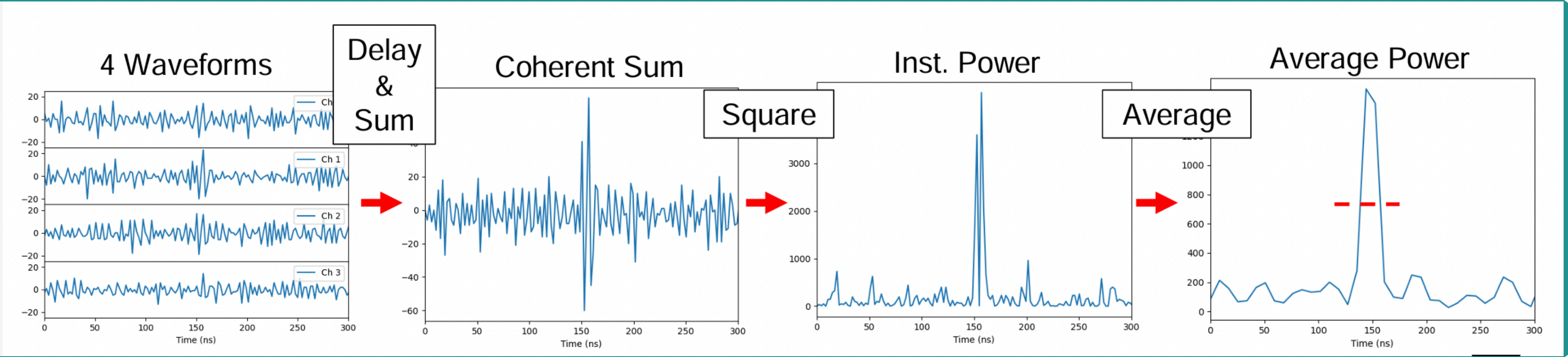
2/4 Hit Multiplicity Trigger

- 2/4 VPol channels on power string must trigger
- Looks for impulsive/"Askaryan-like" signal

Phased Array Trigger

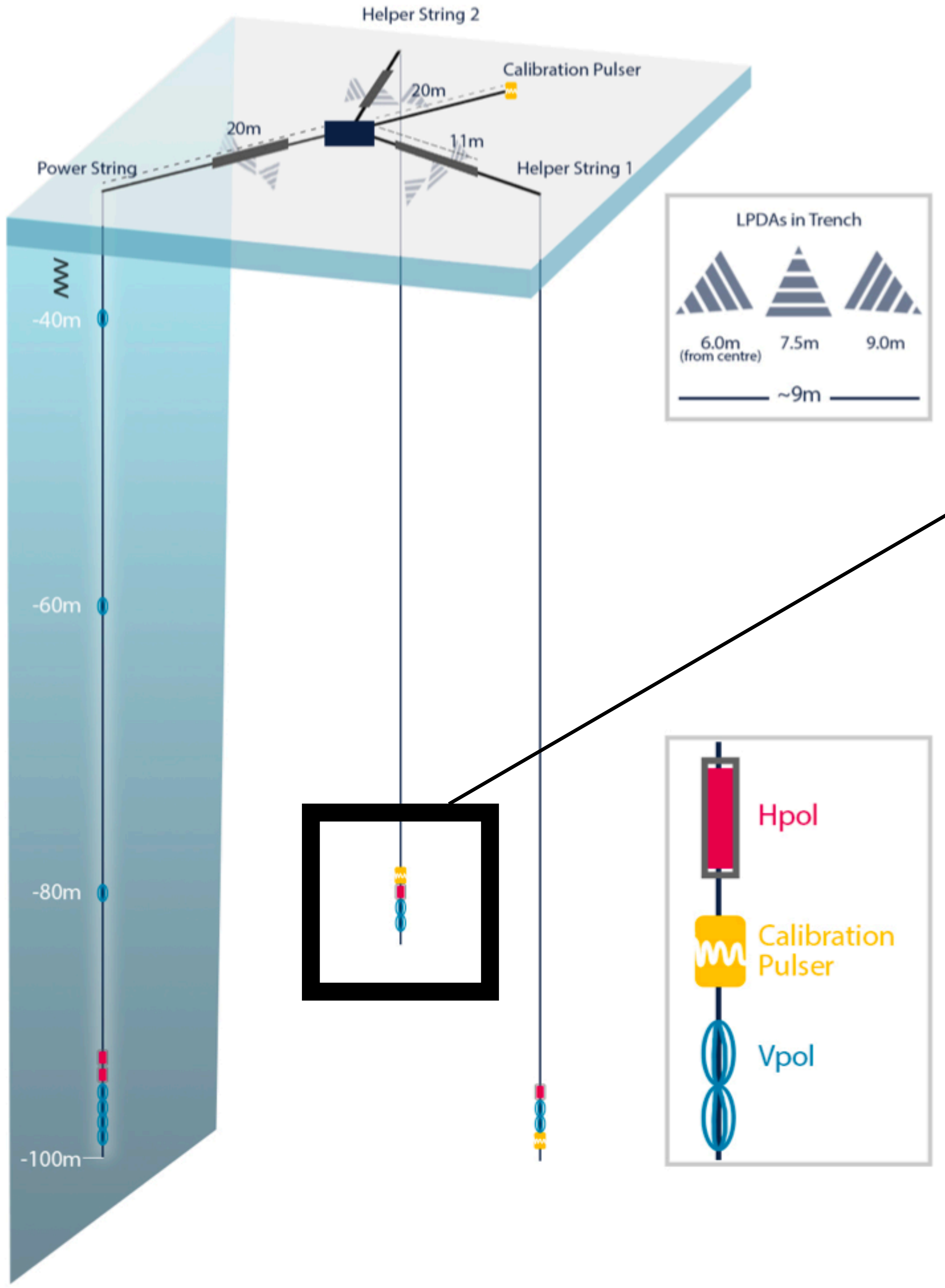
- Combine signals of multiple deep antennas with time delays corresponding to incident angle of radiation
- Designed to reduce trigger threshold to 2σ

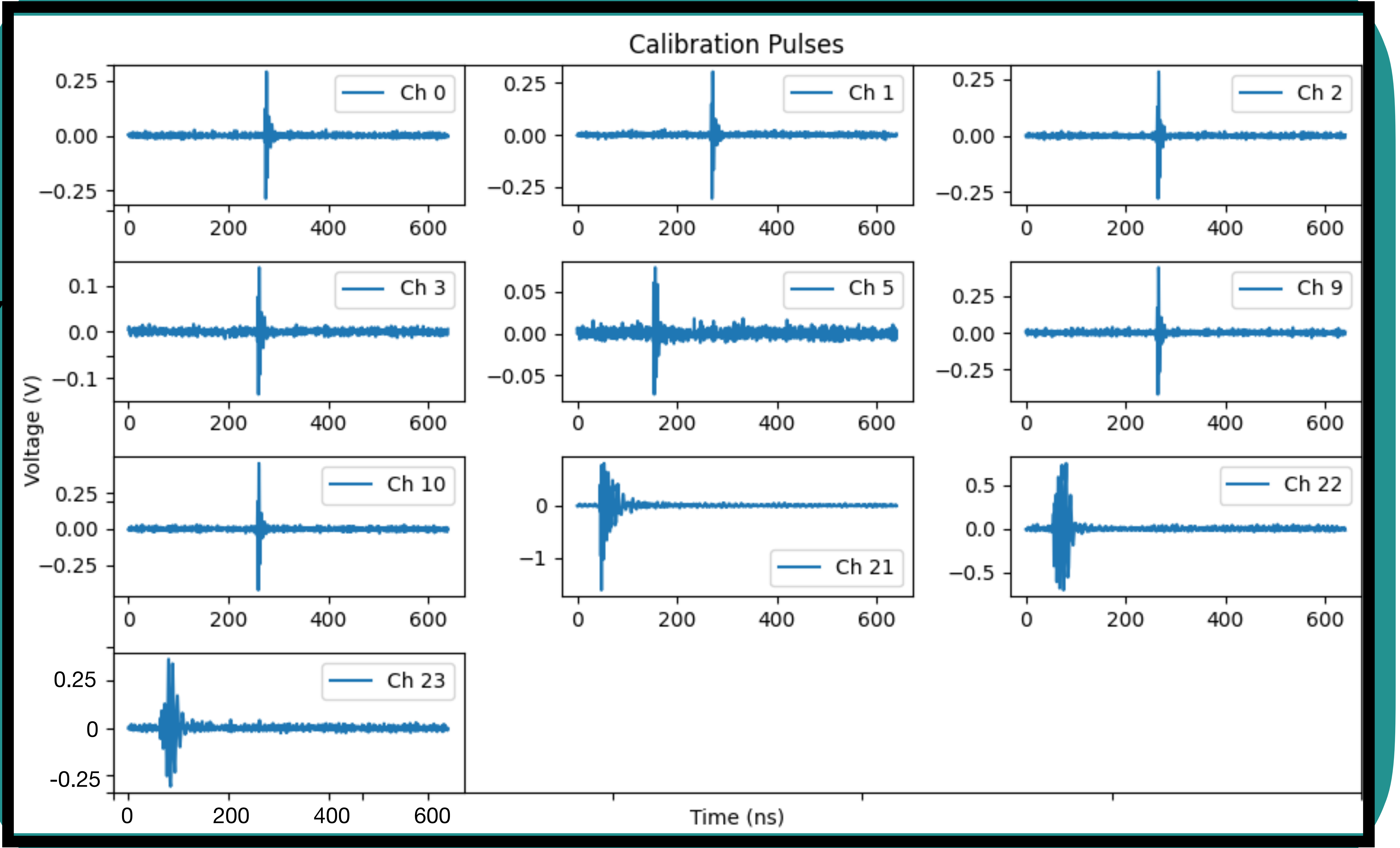
Phased Array Trigger



Trigger Efficiency Study

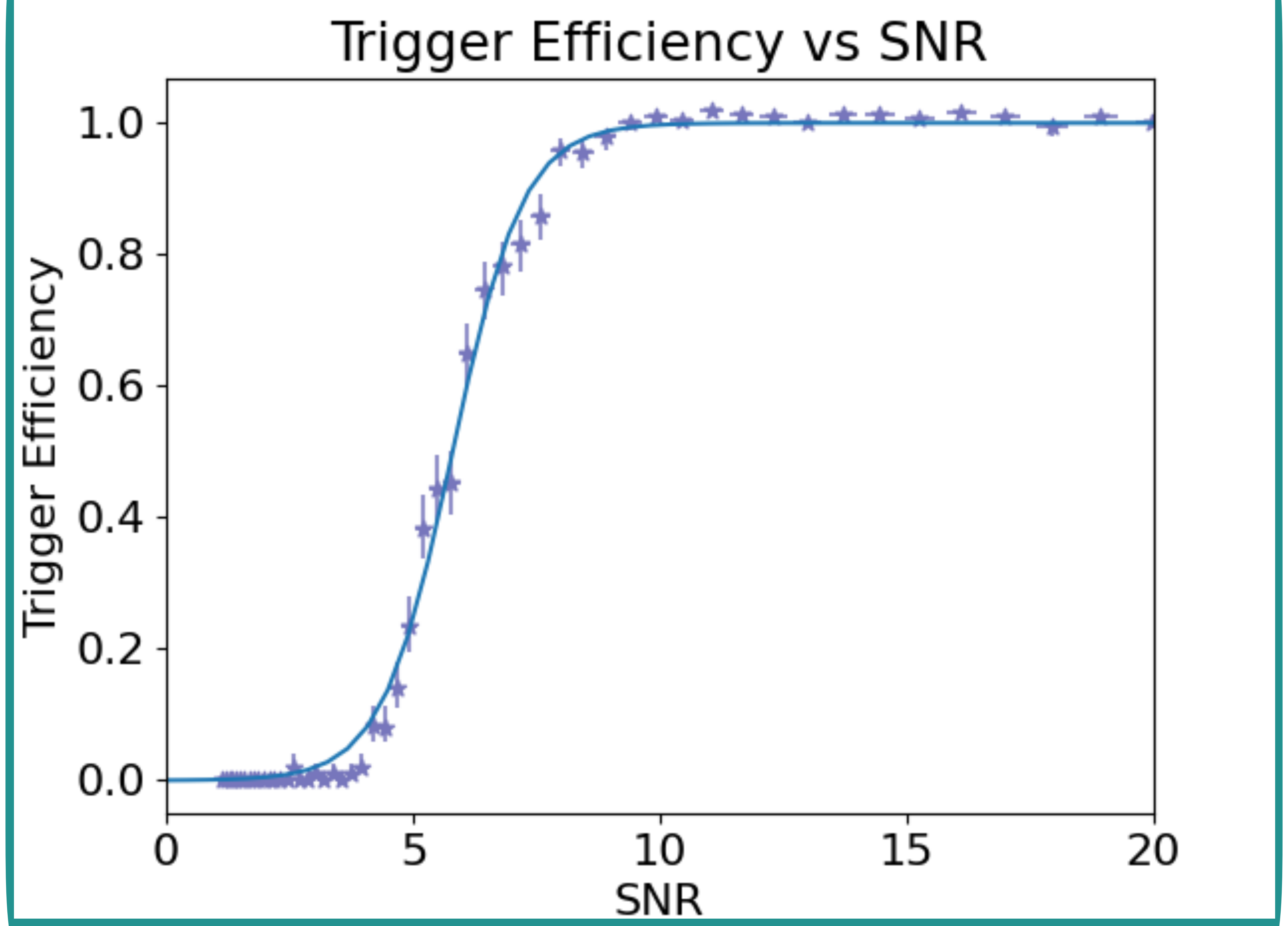
Efficiency of the 2/4 multiplicity trigger as a function of SNR using calibration pulses





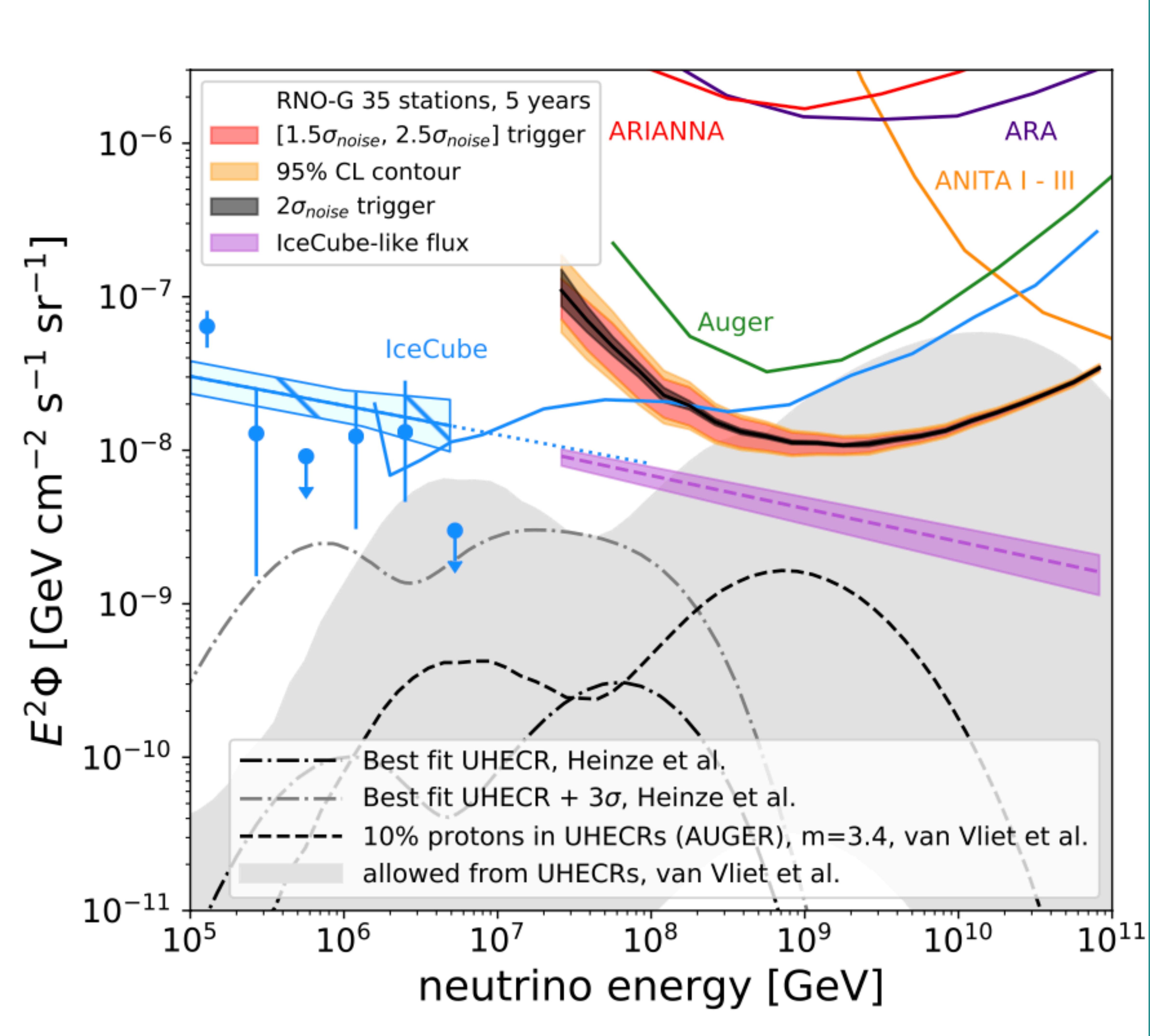
*STUDY IS STILL IN PROGRESS

Trigger Efficiency Study



- Current in-situ 50% efficiency point ~ 5.8
- With the phased array trigger, lower this to ~ 2

Scope of RNO-G



- RNO-G will probe new parameter space/higher energies
- Unique northern hemisphere location provides complimentary sky coverage
- Opportunities for technological development

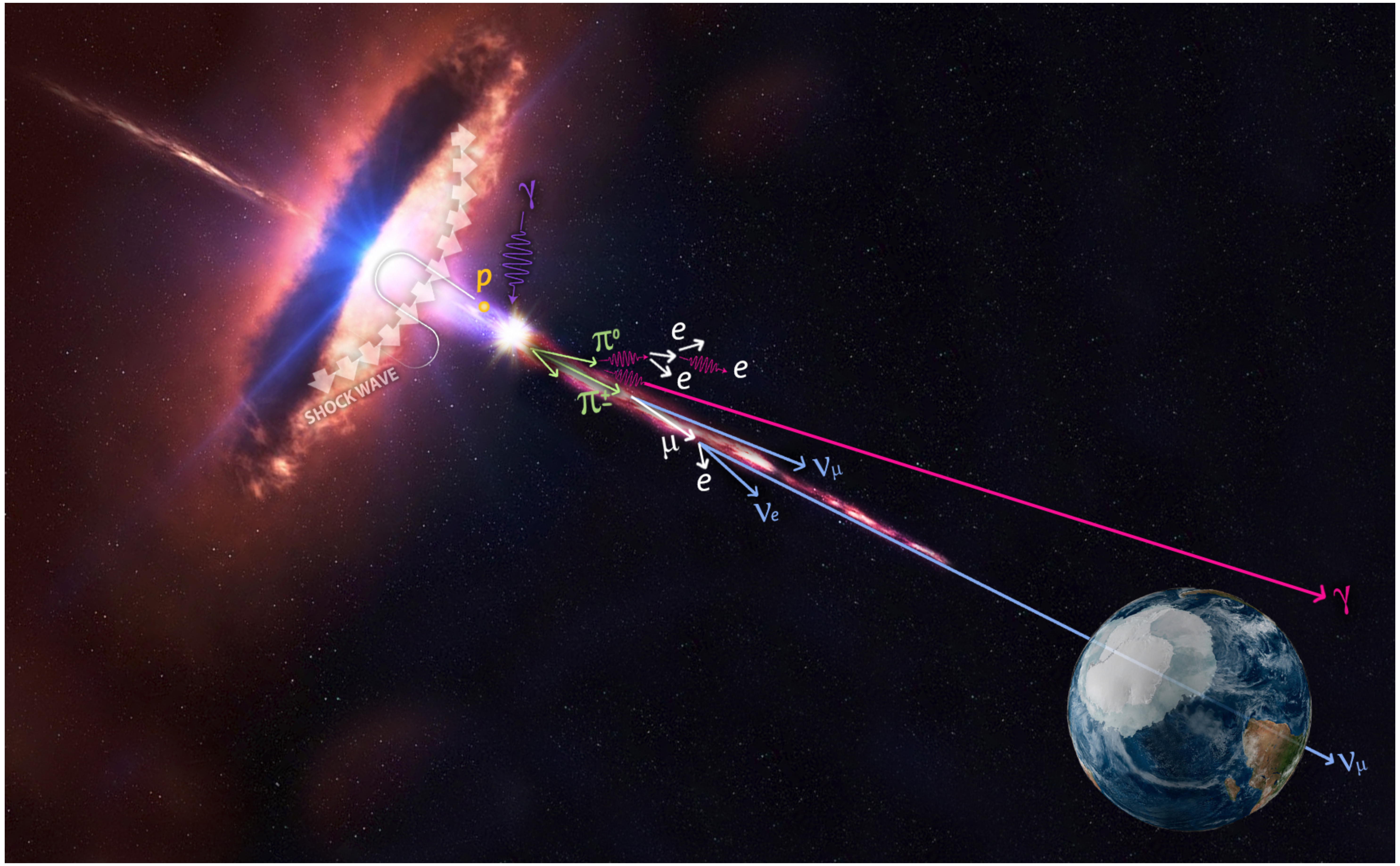
Conclusion

- Radio neutrino detection **optimizes chances of >10 PeV neutrino detection**
- Low power RF system allows for **increased livetime**
- Good **simulation-data agreement** and **reproducibility** among antennas
- In-situ trigger efficiency studies reflect the **current trigger threshold** that will be improved upon with the **phased array trigger**
- Phased array trigger will give **lowest signal trigger threshold** in the field

Backup Slides

Astrophysical Neutrinos

Produced through interactions of cosmic rays at sources



Proton-Photon ($p\gamma$) Interaction

$$p + \gamma \rightarrow p + \pi^0$$

Proton-Proton (pp) Interaction

$$p + p \rightarrow D + e^+ + \nu_e$$

Beta Plus Decay

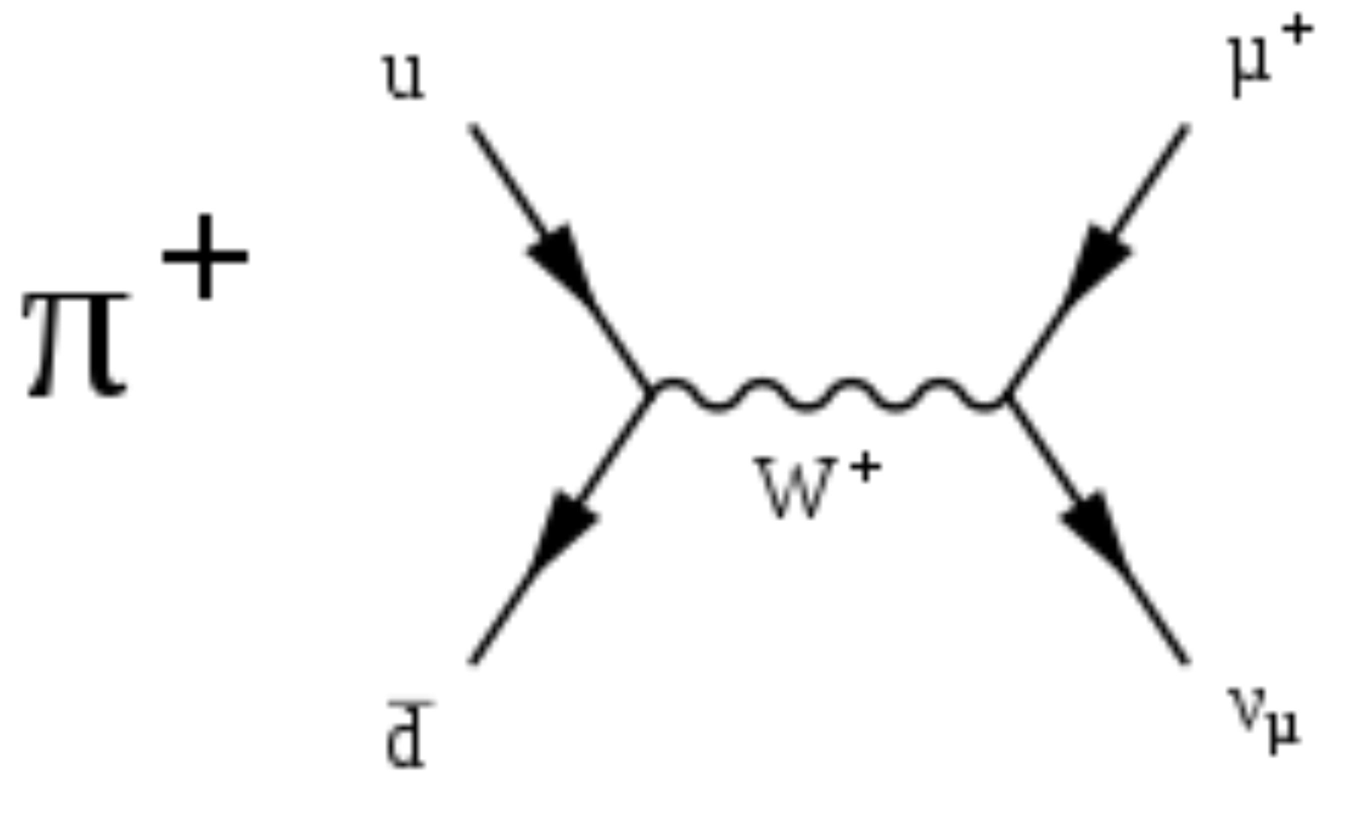
$$p \rightarrow n + e^+ + \nu_e$$

Cosmogenic Neutrinos

Cosmic ray interactions produce unstable particles that decay

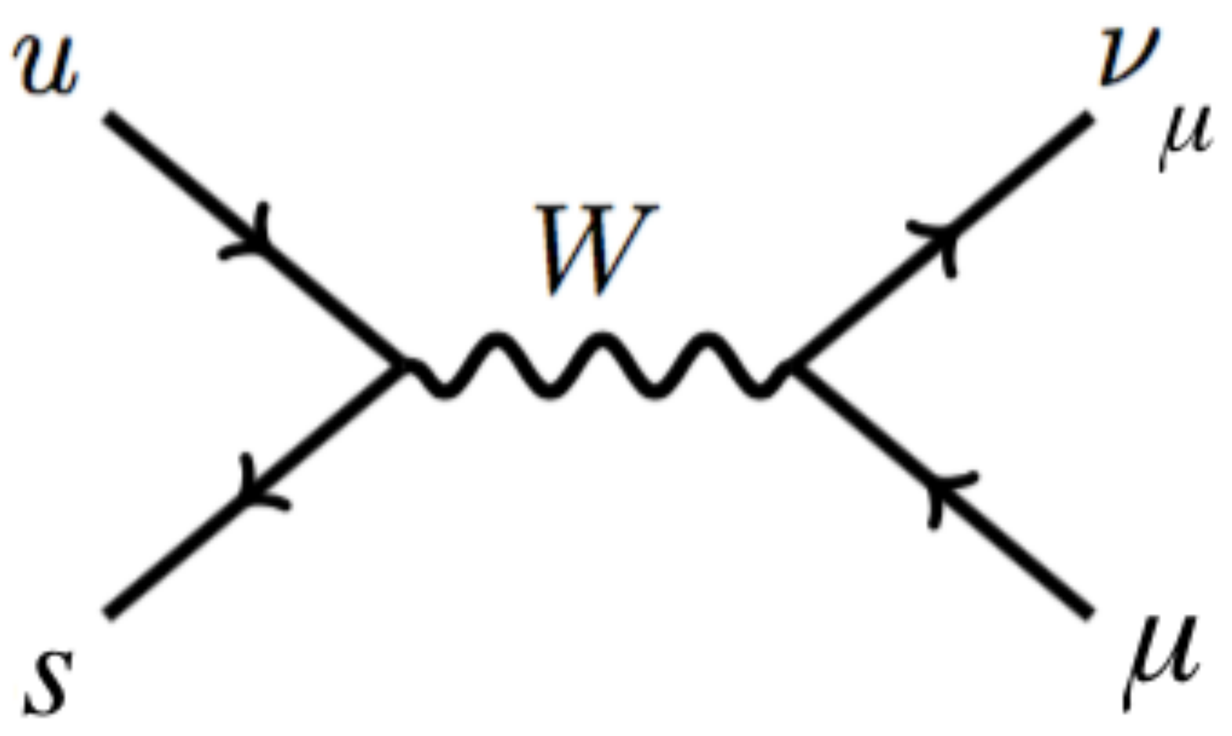
Pion (π) Decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



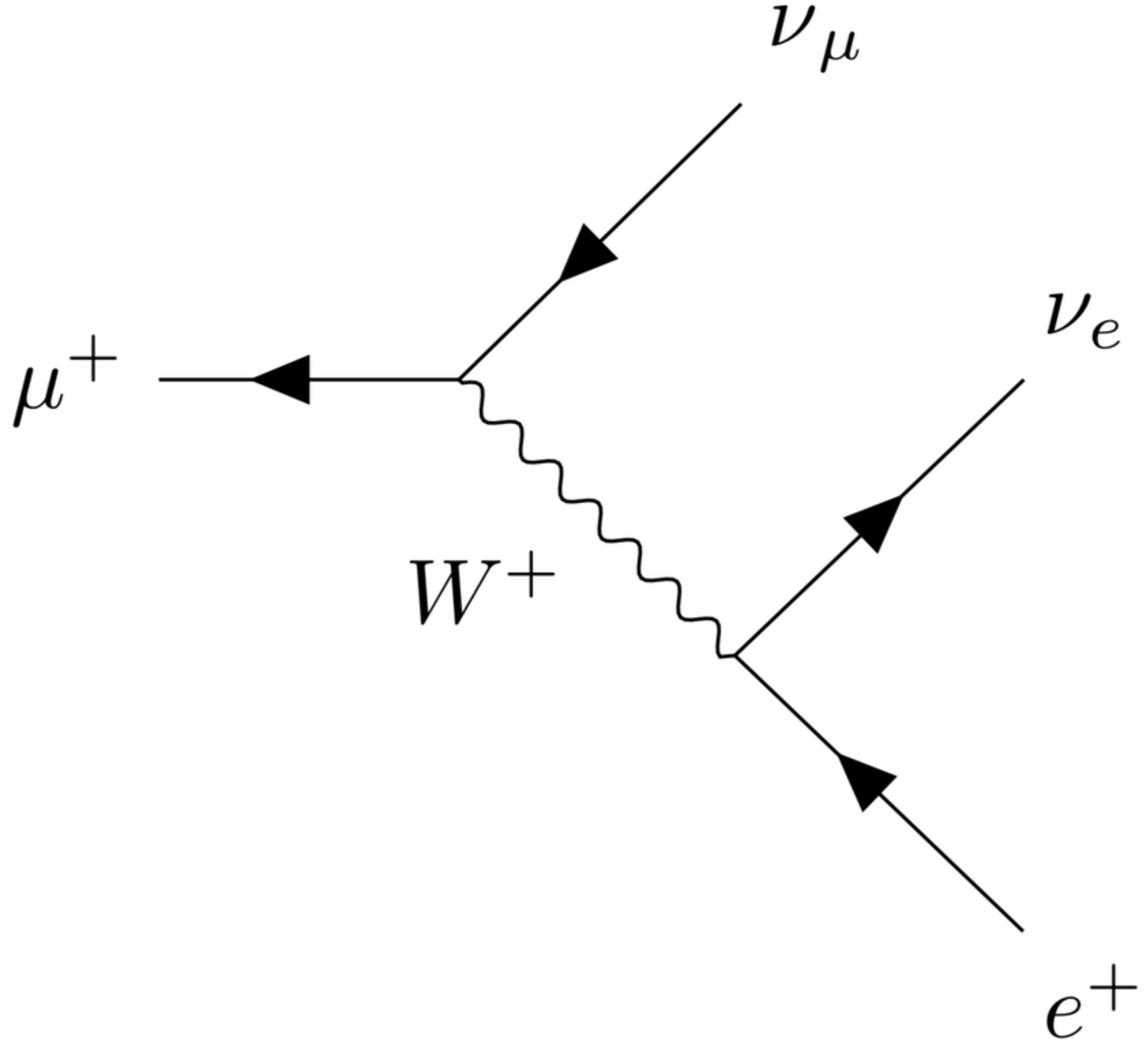
Kaon (K) Decay

$$K^+ \rightarrow \mu^+ + \nu_\mu$$



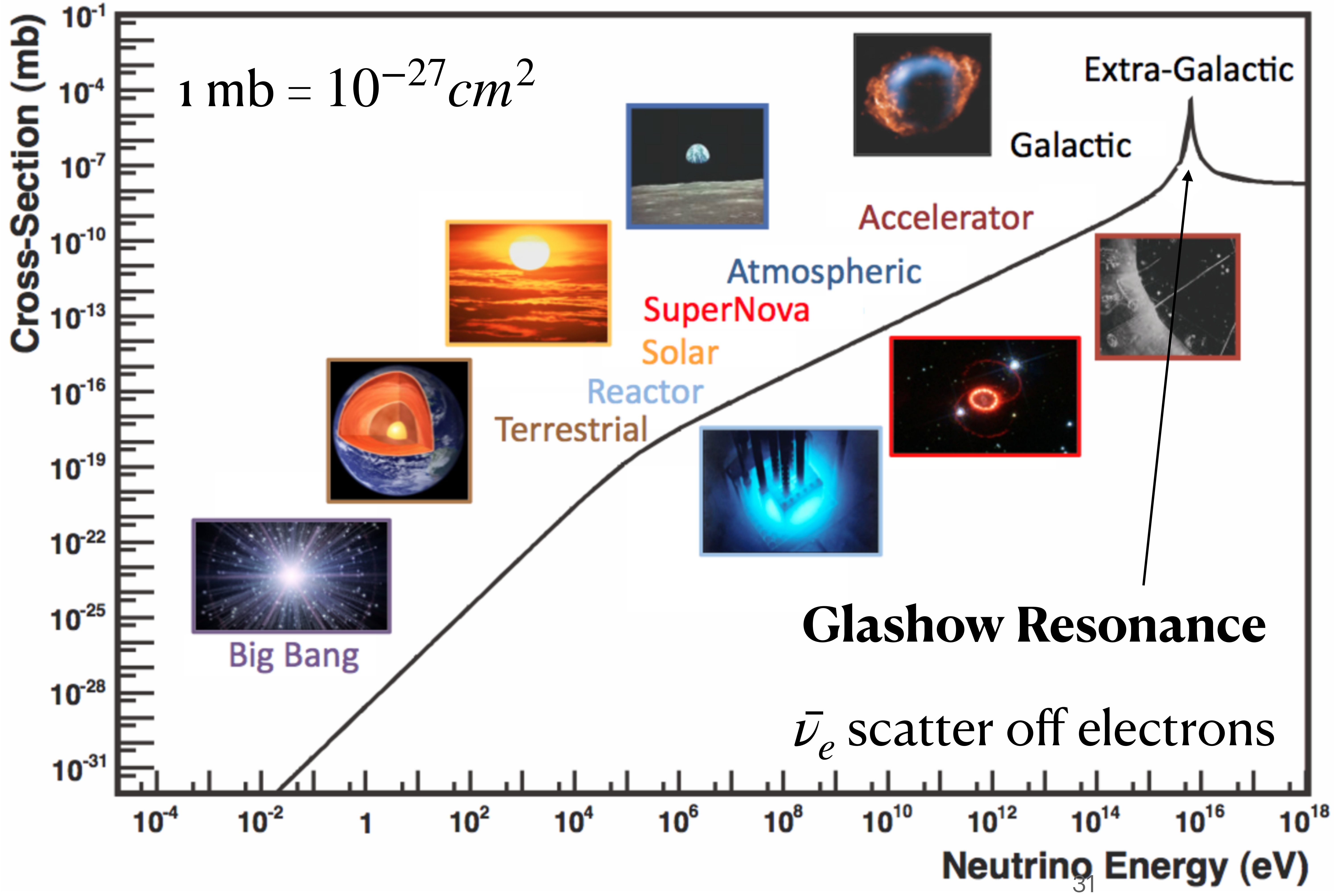
Muon (μ) Decay

$$\mu^+ \rightarrow e^+ + \nu_\mu^- + \nu_e$$



Neutrino Interactions

Neutrinos interact very rarely and need large detectors



Deeply Inelastic

> 10 GeV neutrinos pry apart nucleons

Mean Free Path

1 PeV neutrinos -> 10^7 m

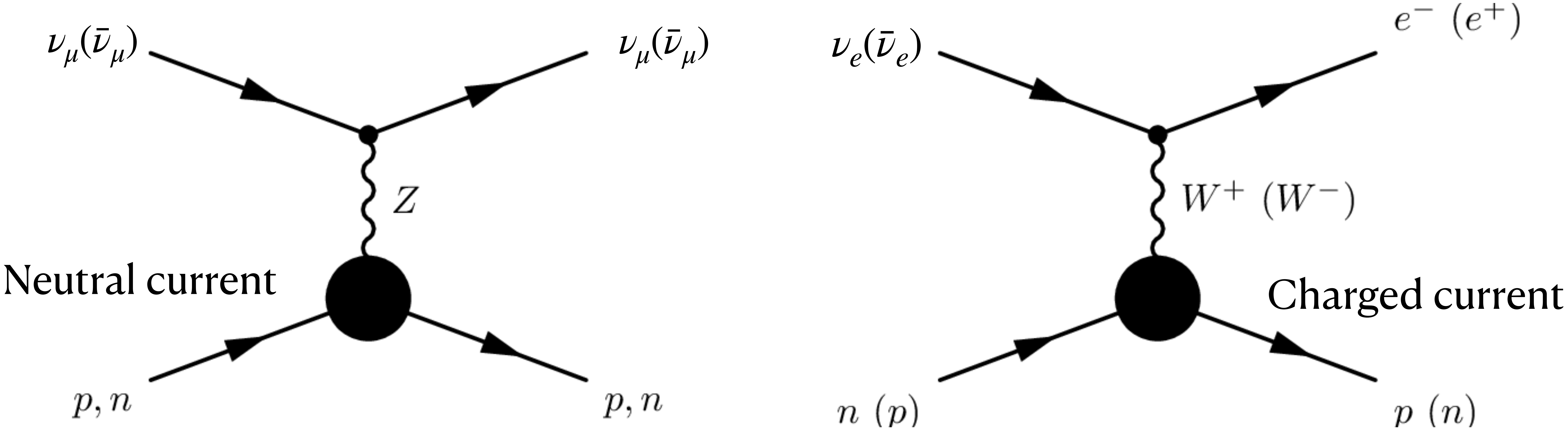
Interaction Cross Section

$10^{-58} cm^2$ to $10^{-31} cm^2$ for neutrino energies from 10^{-2} to 10^{18} eV

Detection Mechanism

Detect (> 10 GeV) neutrinos through deep inelastic neutrino-nucleon interactions

Deep Inelastic Neutrino-Nucleon Interactions



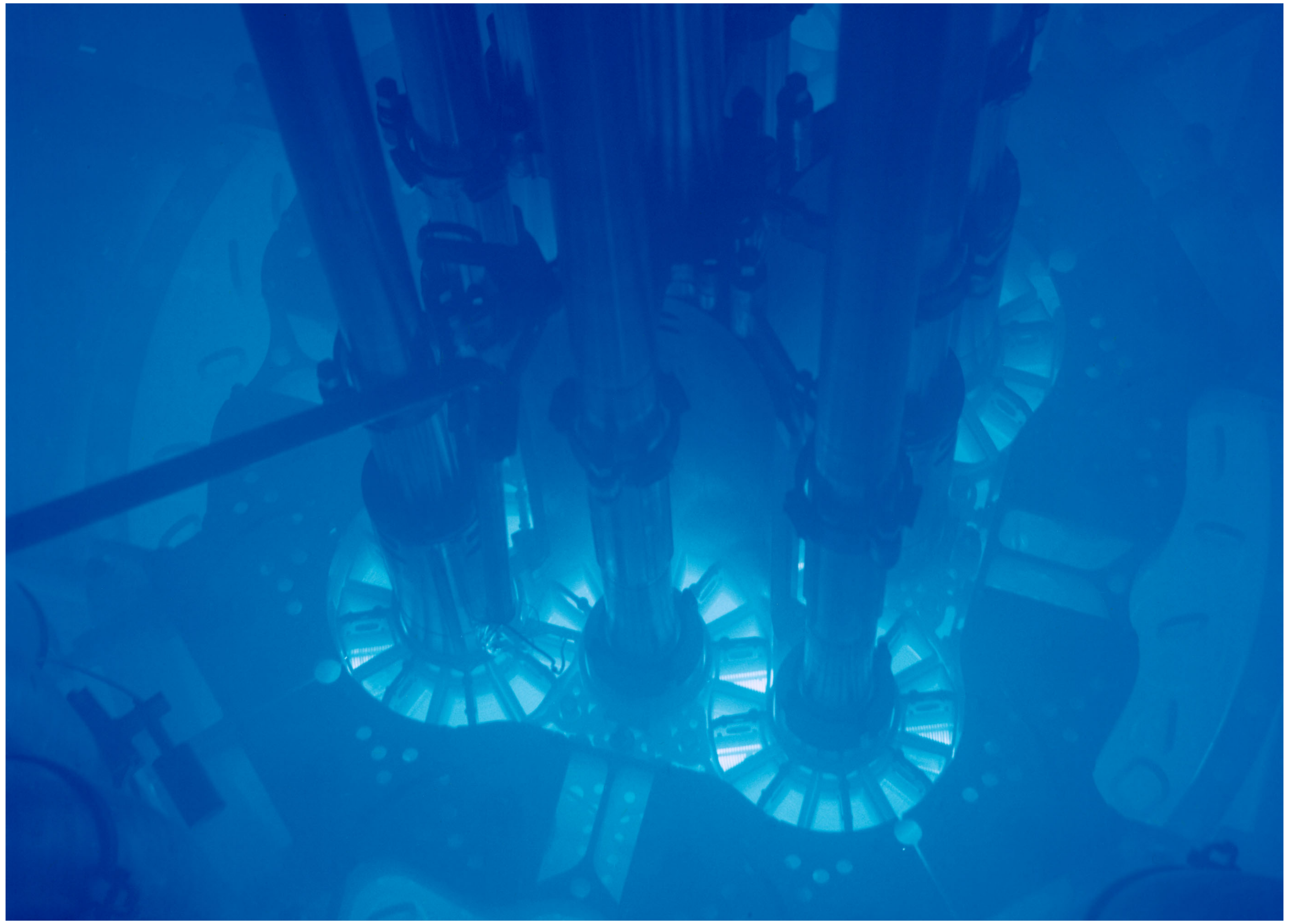
Nucleon Decay

$n \rightarrow p^+ + e^- + \nu_e^-$ (neutron decay)

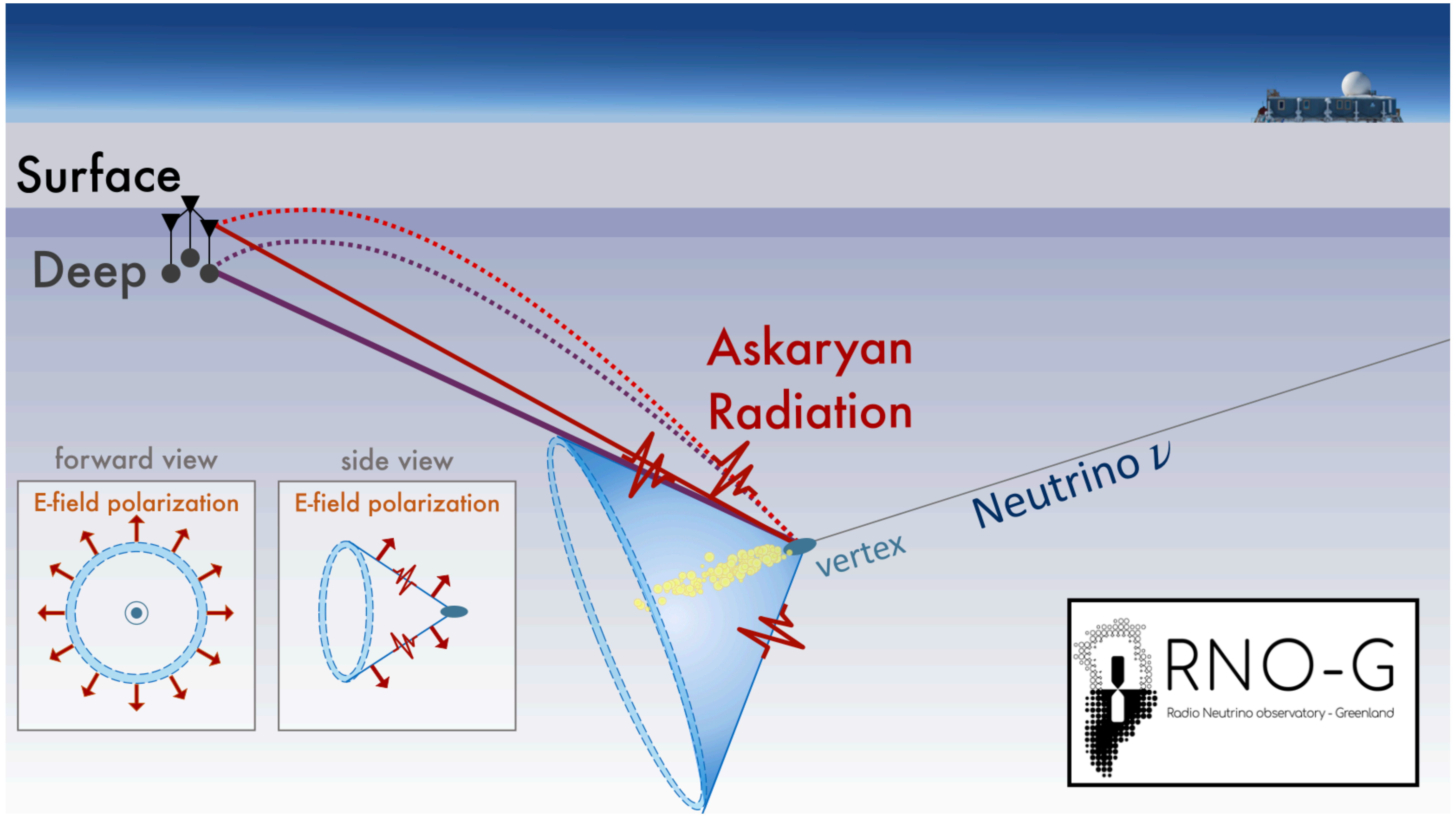
$p^+ \rightarrow n + e^+ + \nu_e$ (beta plus decay)

Cherenkov Emission

Particles in cascade that travel faster than speed of light in medium release blue (“optical”) light

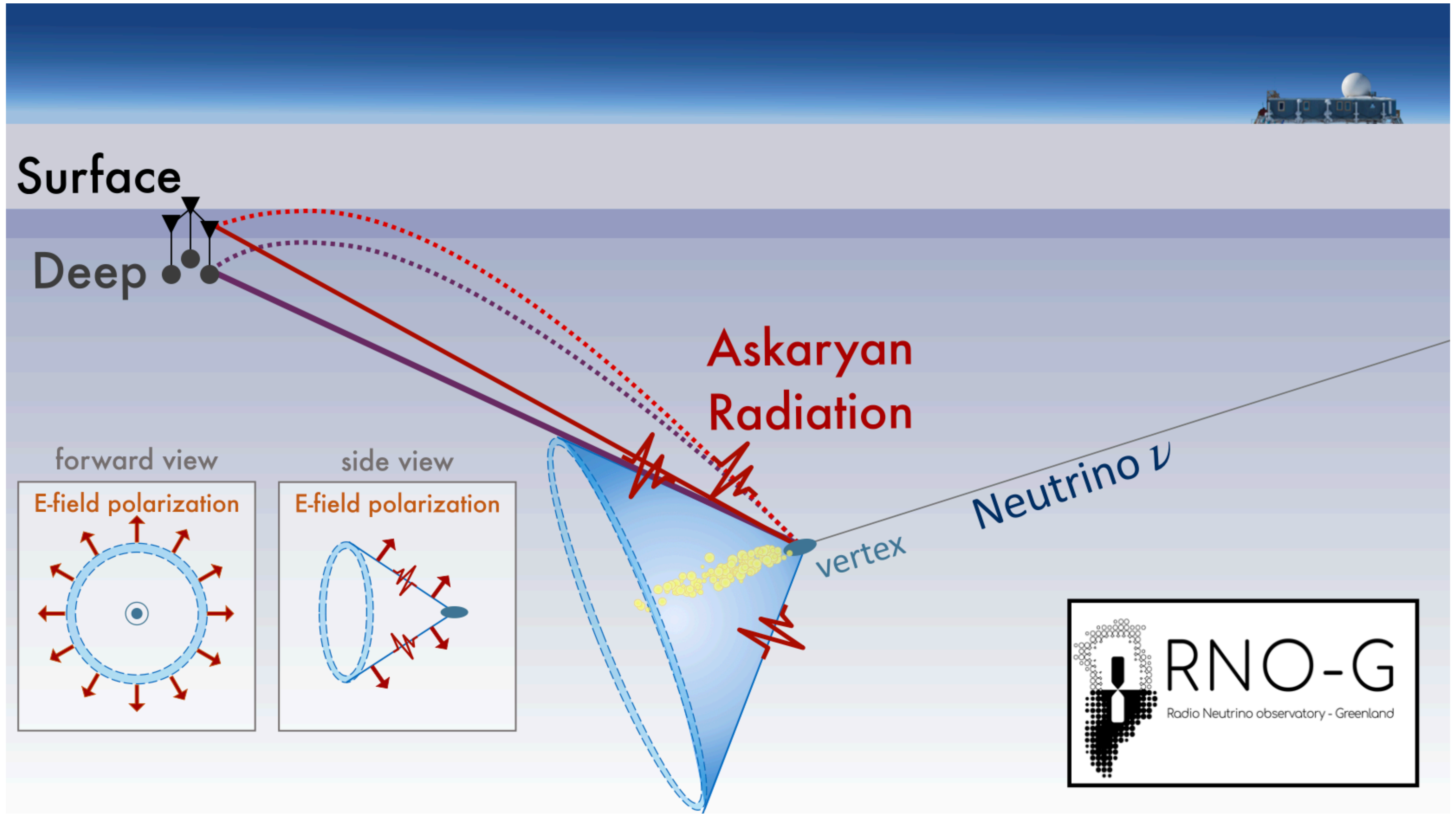


Askaryan Emission



- $e^+ + e^- -> 2\gamma$
- Photons ionize atoms to release free e^- or knock out loosely bound electrons
- Excess negative charge radiates
- Radiation at ~10 cm constructively interferes (coherent amplification in radio)
- Constructive interference at lengths > cascade size (~ 10 cm)

Askaryan Emission Signal Strength



- Signal strongest at Cherenkov angle (56°)
- Coherence lost at higher frequencies first due to destructive interference
- Signal amplitude ∝ number of e^-
- Signal amplitude $\propto \dfrac{1}{R}$, R = distance from vertex
- Attenuation length in ice for 75 MHz signal was ~900 meters (temperature dependent)
- 0.1-1 GHz radio pulse detected by antennas

Radio and Optical Neutrino Detection

	Radio	Optical
Detection Mechanism	Askaryan Emission	Cherenkov Emission
Detection Instrument	Radio Antennas	PMTs (Photomultiplier Tubes)
What is detected?	0.1 - 1 GHz radio pulse	Blue light ("optical")
Suitable Energy Range	> 1 PeV	< 1 PeV
Scattering and Absorption Length	15-60 m (scattering) 60-200 m (absorption)	10-20 m (scattering) 50-100 m (absorption)
Instrumentation Density	Lower for same effective volume	Higher for same effective volume

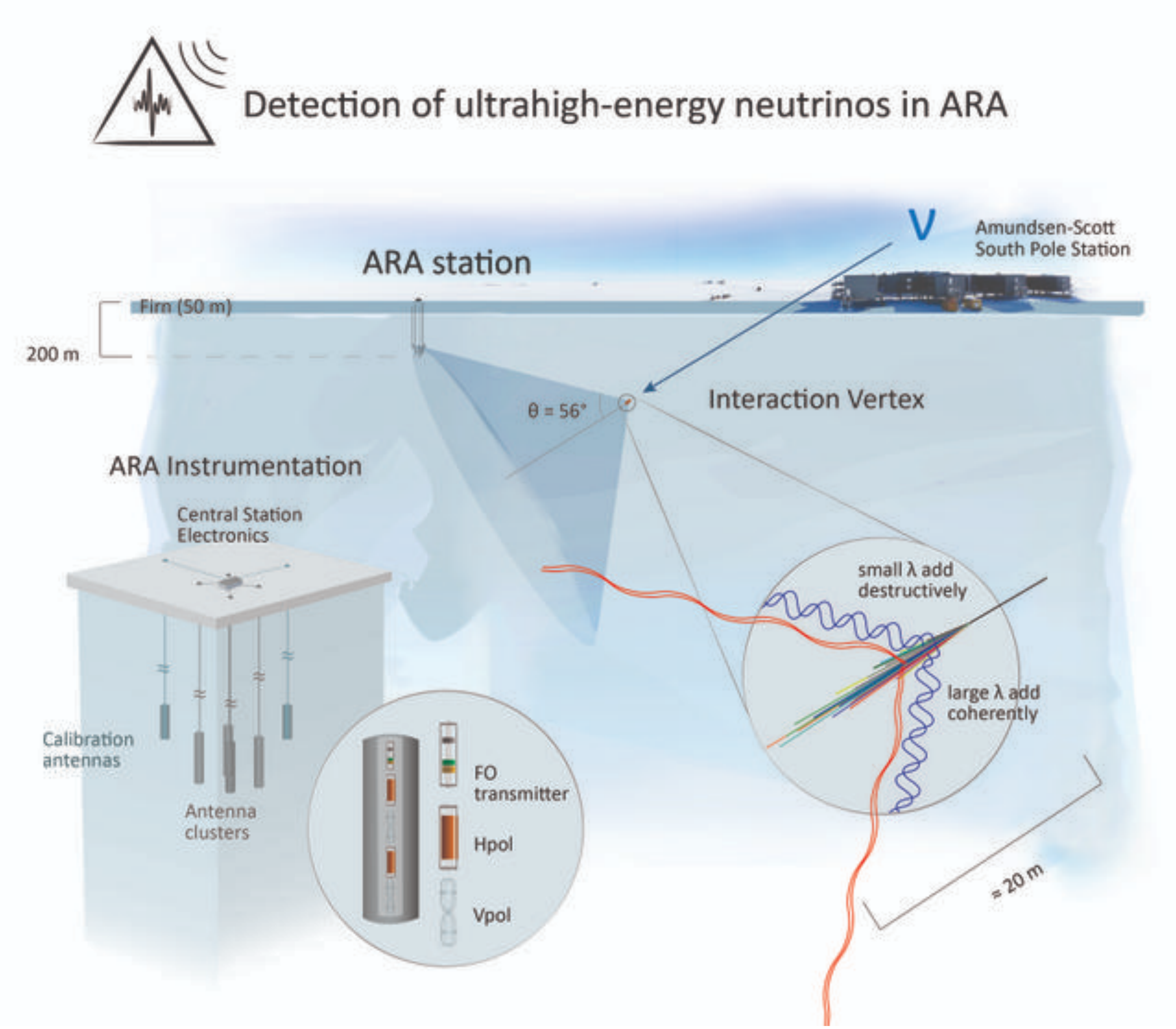
History of Radio Neutrino Detection

Radio Ice Cherenkov Experiment (RICE)

- 1995-2010, located at South Pole
- Place first limit on UHE neutrino flux and insight to radio frequency ice properties

Askaryan Radio Array (ARA)

- RICE direct successor at South Pole
- Developed interferometric trigger array improving radio neutrino detection efficiency by factor of 1.8



History of Radio Neutrino Detection

Antarctic Ross Ice-Shelf Antenna Neutrino Array (ARIANNA)

- Deployed antenna below snow surface (7 shallow/surface stations with 4 antennas each)
- Used solar power and wind turbines for 90% detector uptime

VPol Construction and Testing at UMD

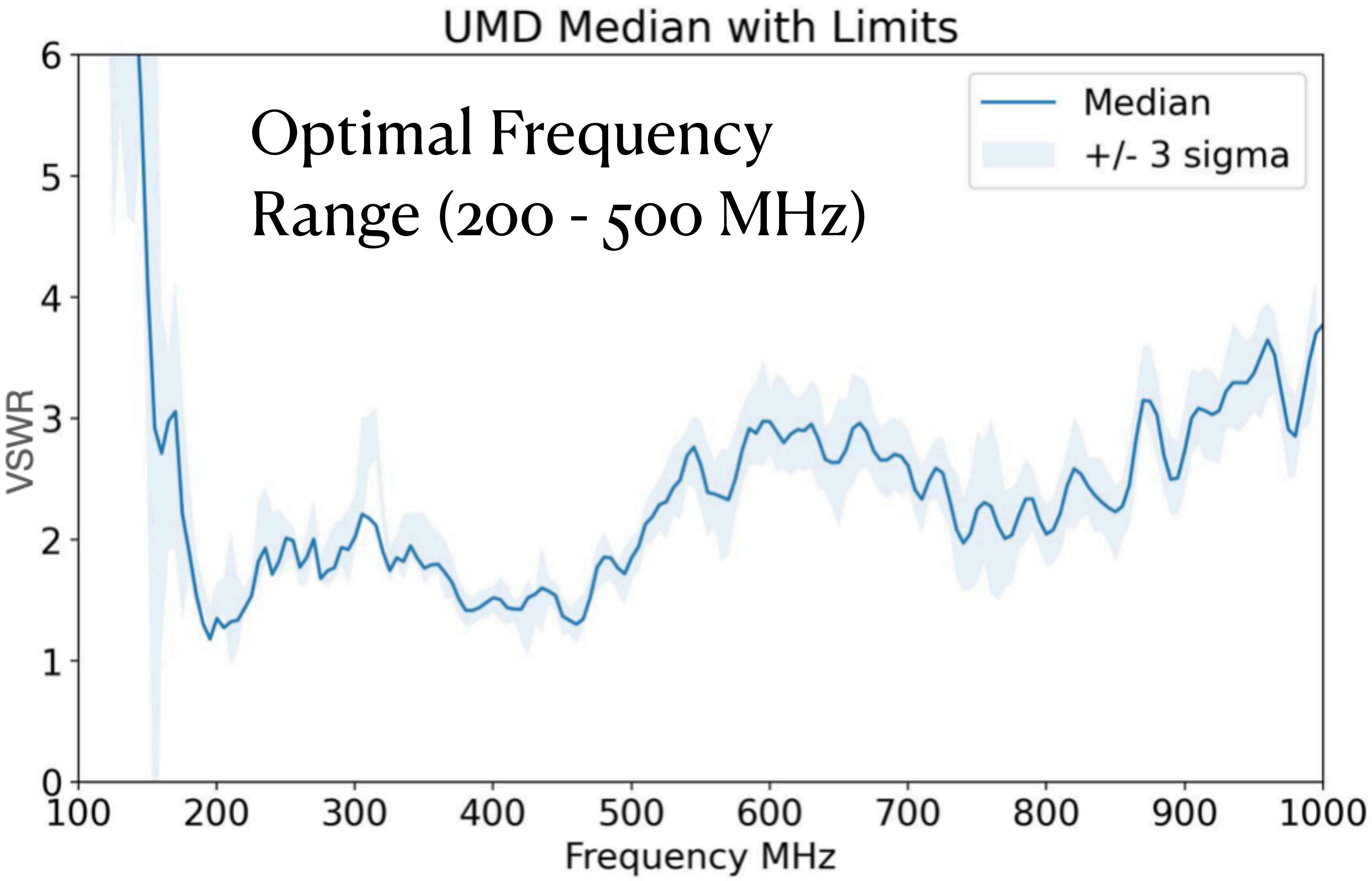
Purpose: Need good antennas to detect small signals

S11

Ratio of recieved to reflected power at antenna input

VSWR

$$VSWR = \frac{1 + S11}{1 - S11}$$



VSWR ~ 1 => S11 ~ 0

Very little power reflected from input indicating better performace

Repeatability across 100 antennas

RNO-G Backgrounds

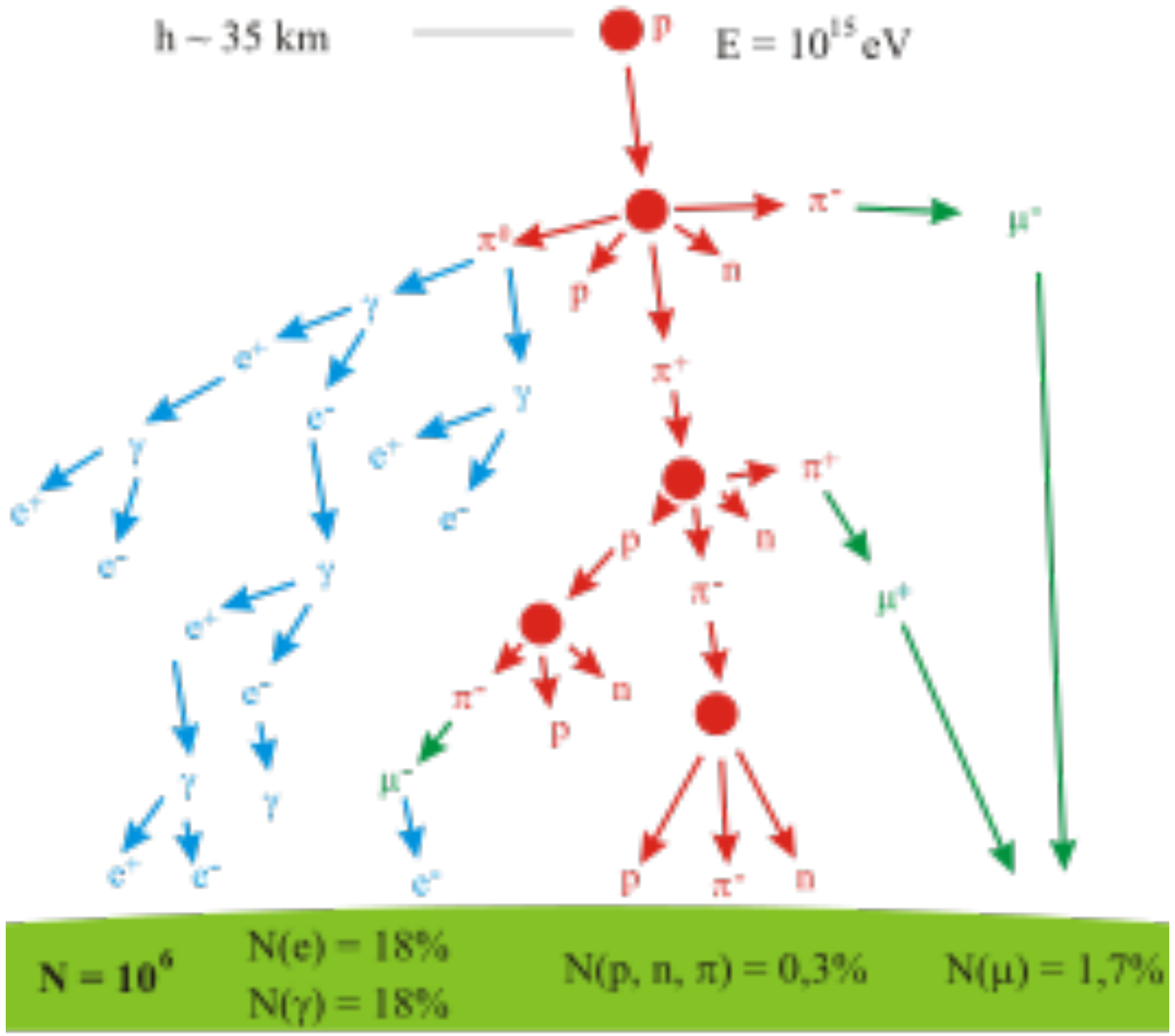
Major Hurdle: Separating Neutrino-Induced Signals from Background

Thermal Noise

- Noise in ice due to random motion of electrons
- Uncorrelated across antennas

Anthropogenic Noise

- Human-made noise identifed through reconstruction



Air Showers

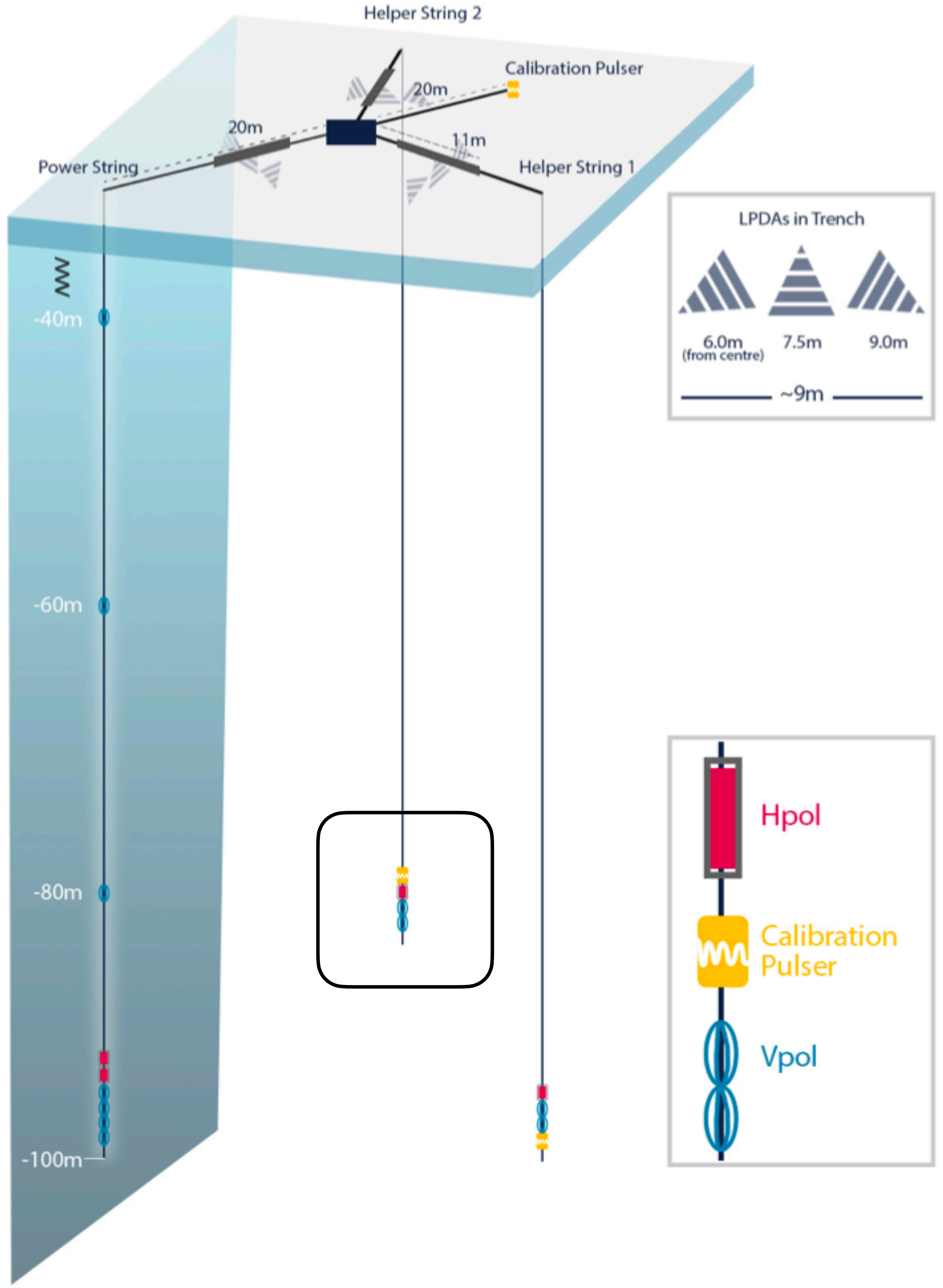
- Cosmic rays interact with atoms in atmosphere
- LPDA surface array to separate this background

RNO-G In-Situ Trigger Efficiency Studies

Motivation: Obtain instrument's sensitivity with current trigger

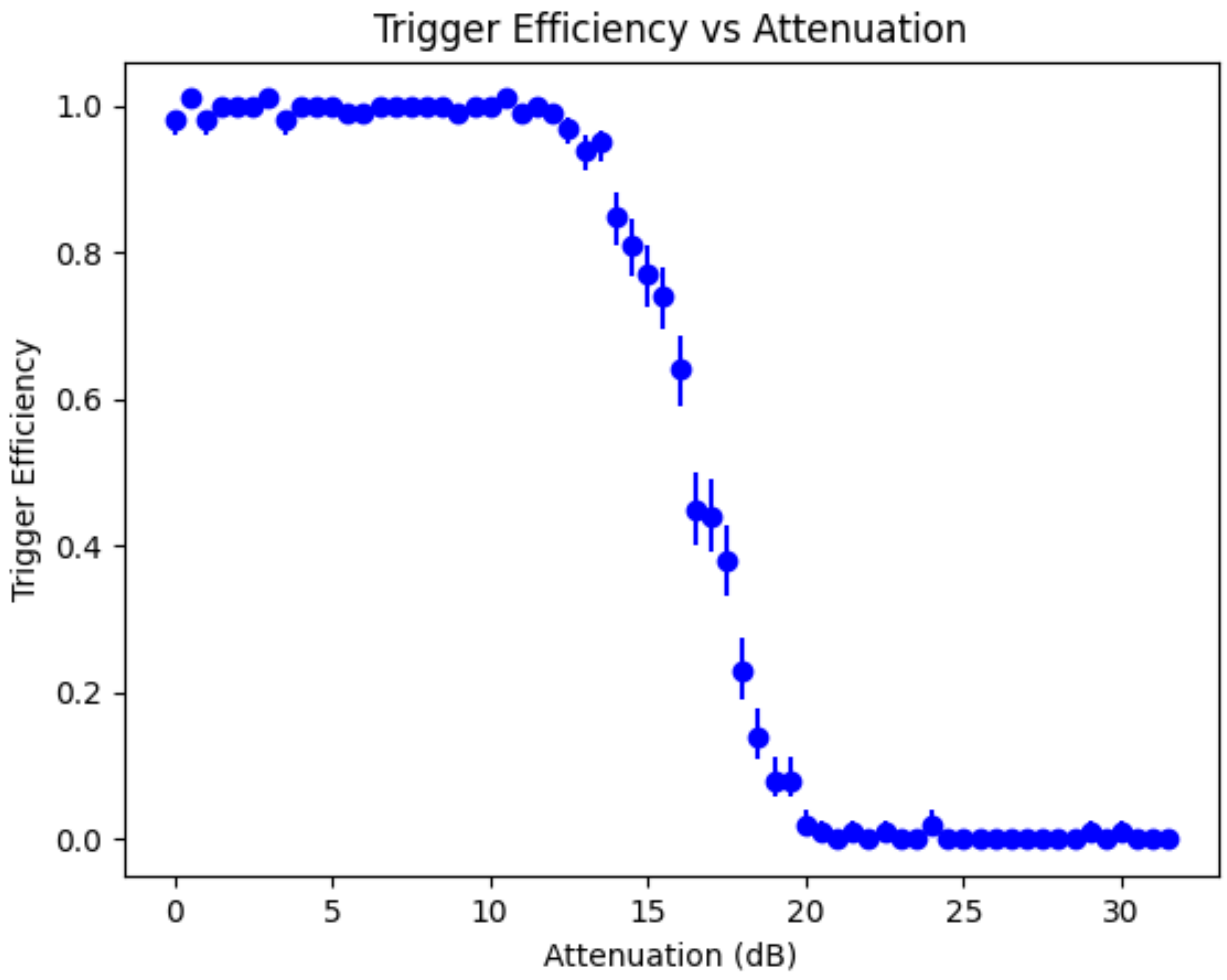
Methodology

- Calibration pulses that mimic neutrino signal and trigger 2/4 hit multiplicity
  - Pulses emitted at range of attenuations (0-32 dB) (pulse goes through attenuator)
- Find efficiency of 2/4 hit multiplicity trigger as a function of SNR
- Trigger efficiency and SNR first mapped to attenuation
- Utilizing data from station 23 run 3400



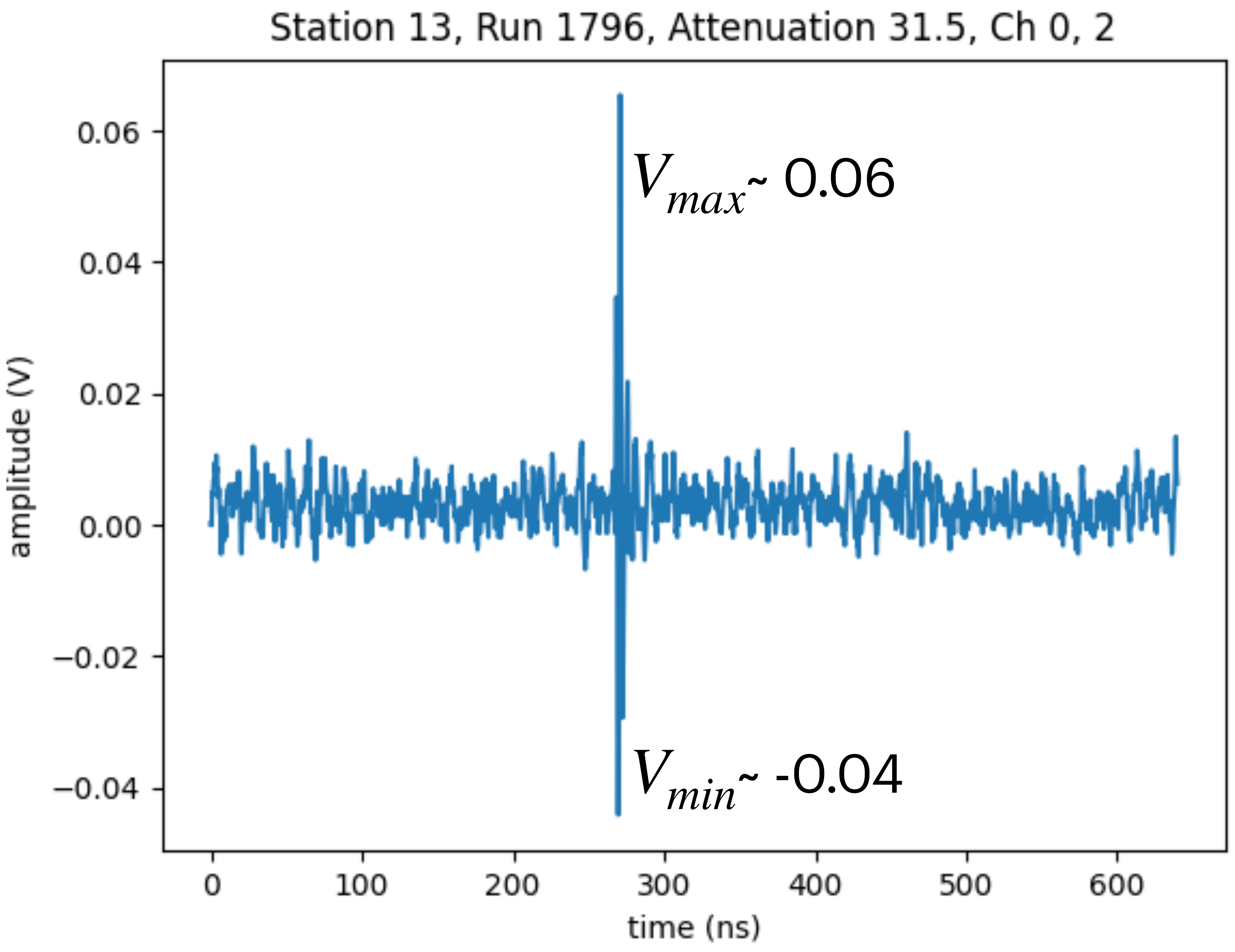
Trigger Efficiency

- $Trigger\ Efficiency_{att} = \frac{pulses\ triggered_{att}}{pulses\ emitted_{att}}$
- 100 pulses at each attenuation
- Error bars: Wilson Confidence interval
    - Asymmetrical error bounds contained between 0 and 1 (no overshoot)



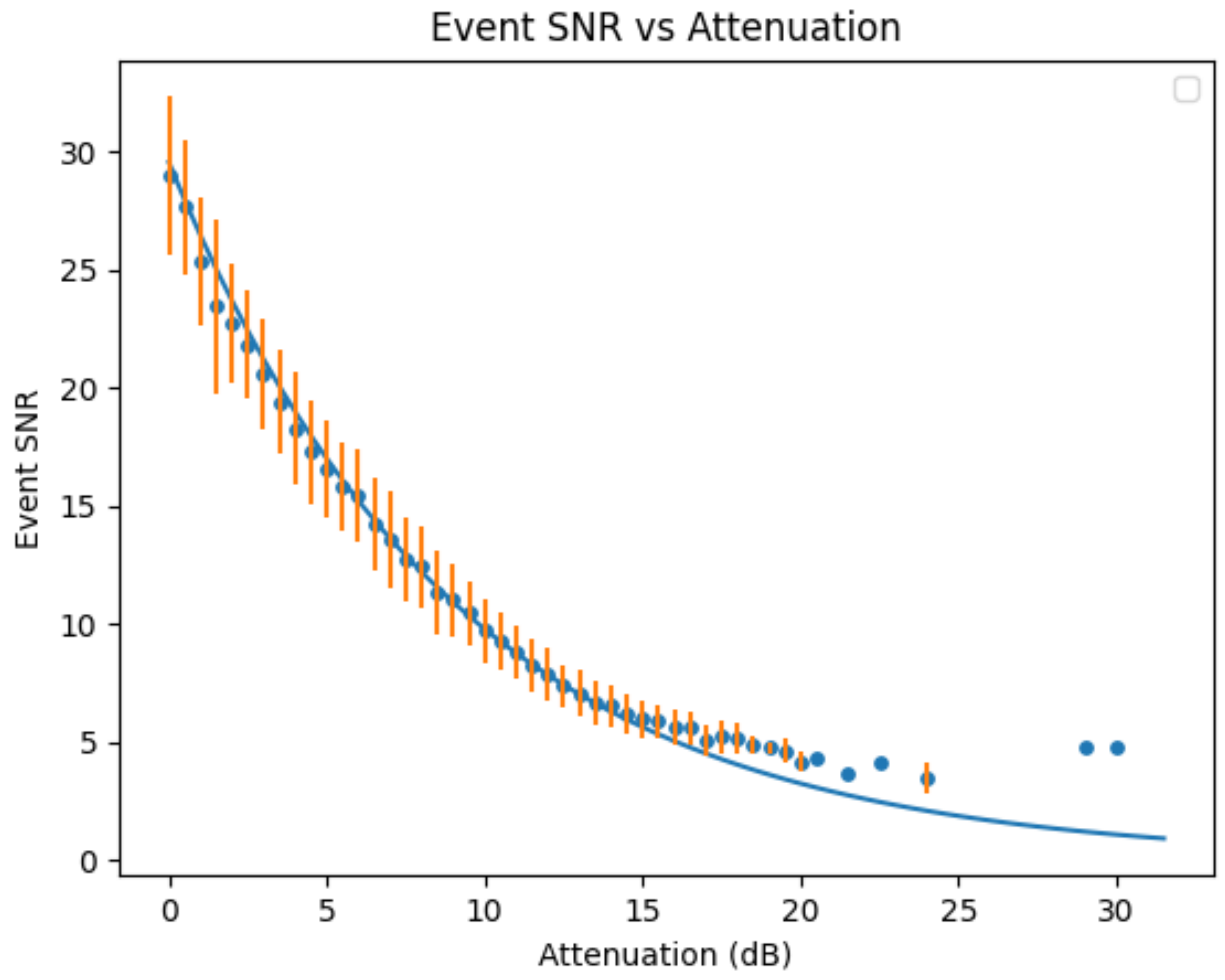
Signal to Noise Ratio (SNR)

- $SNR = \dfrac{V_{max} - V_{min}}{2 \times RMS_{noise}}$
- RMS_{noise}
  - Noise identified by force trigger (triggers at regular intervals (0.1 Hz)
  - Unique for each channel
- Used 2nd higher SNR across 4 channels for each event
  - Higher SNR = more likely to trigger

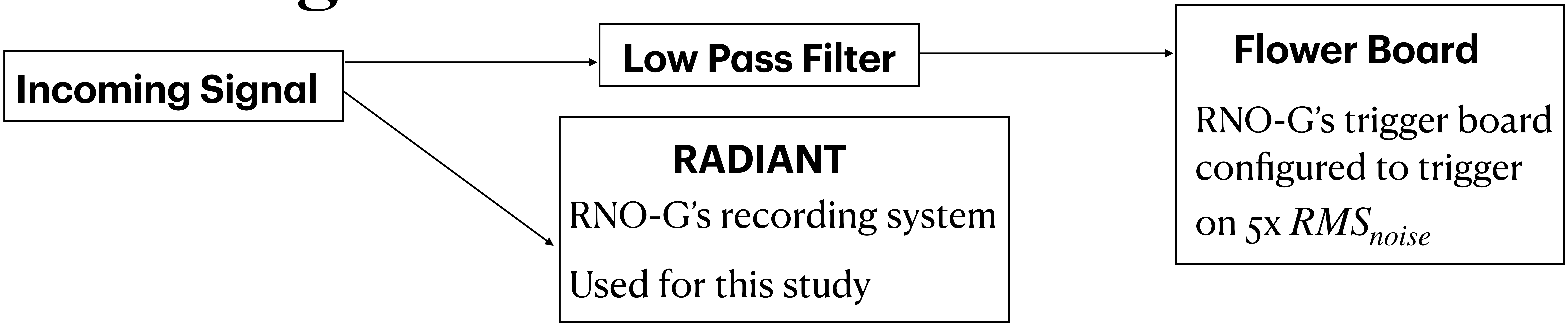


SNR vs Attenuation

- Average SNR at each attenuation
- Error bars = standard deviation of SNR
- Exponential fit from 6-15 dB
- Low attenuation: pulses saturate fiber optic
- High attenuation: not enough events
- Used exponential fit parameters to calculate SNR over 0-32 dB

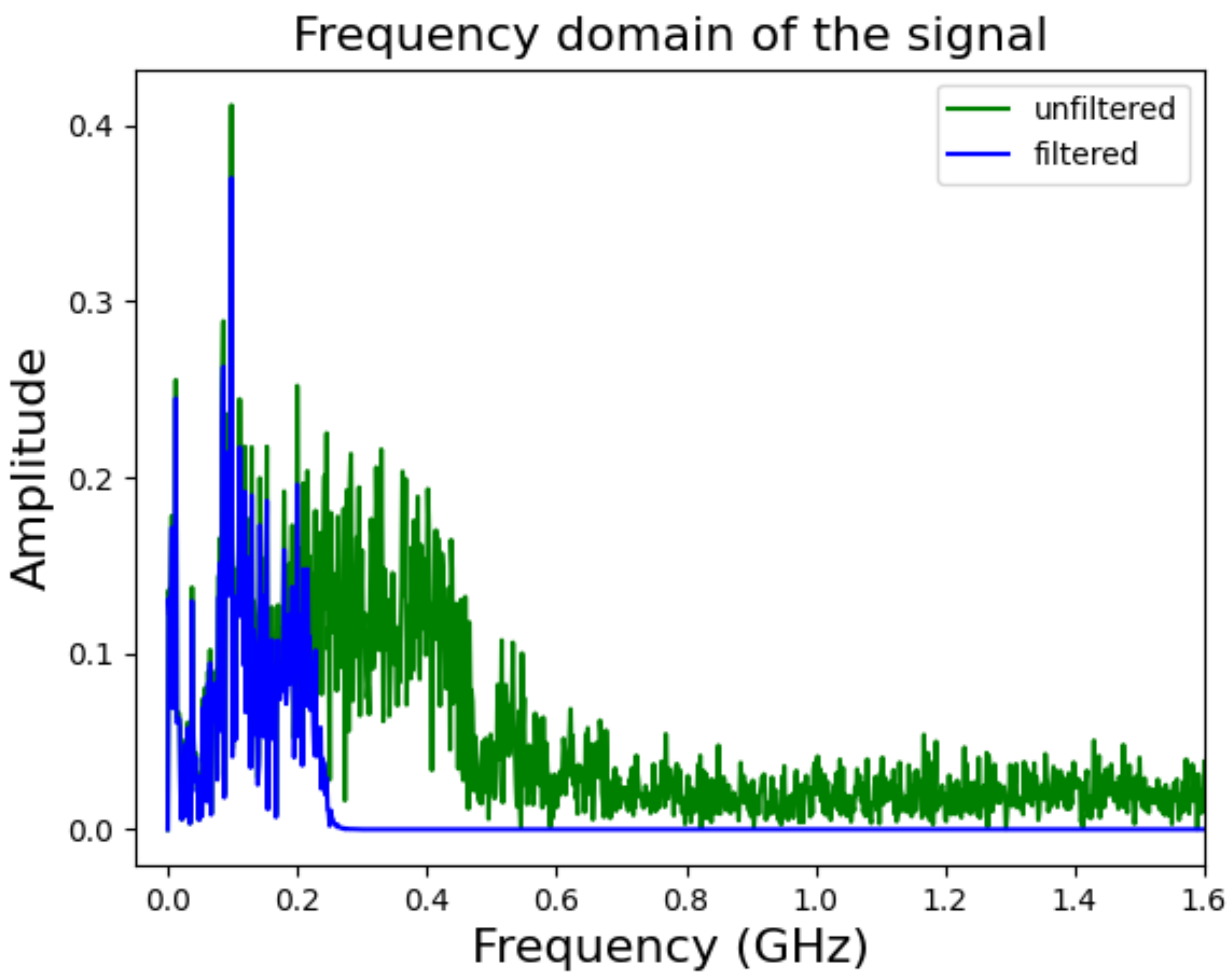


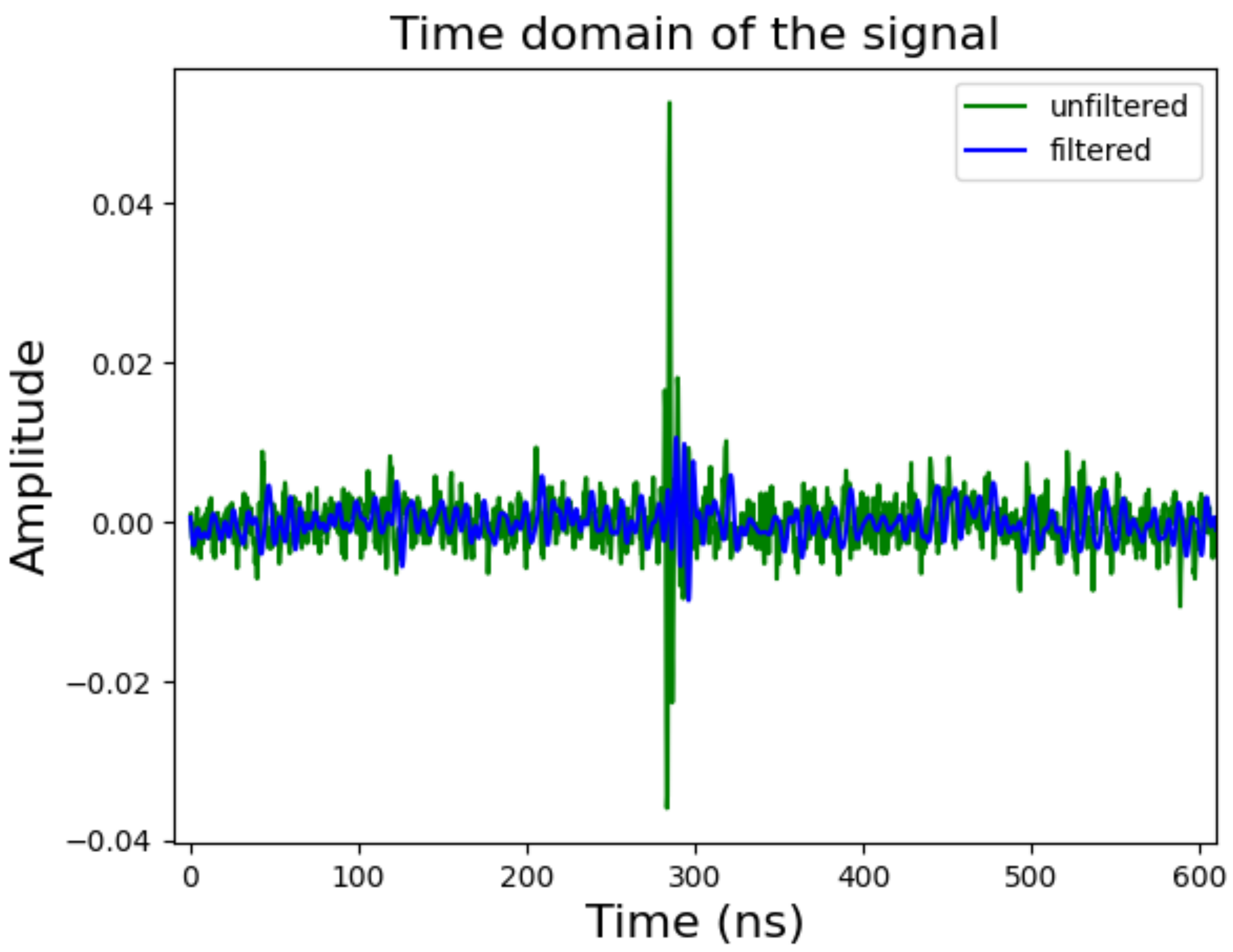
Filtering



- Applied additional low pass filter to RADIANT data to compare to Flower Board
- Applied additional high pass filter (Butterworth filter, order 8, cutoff frequency 0.05 MHz) to reduce out of band noise
- Filtering cuts high frequency power of pulse, reducing peak-to-peak voltage and SNR

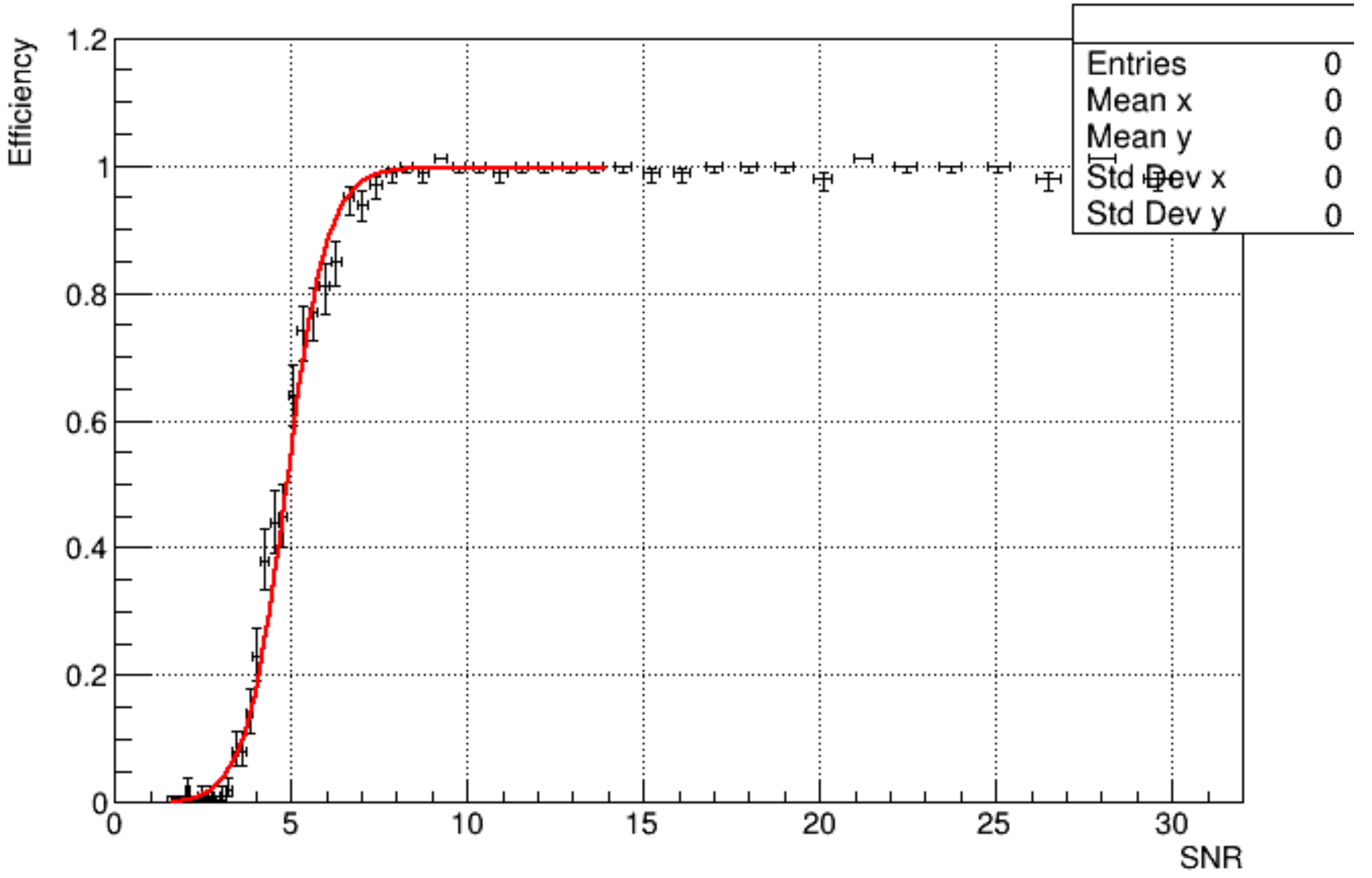
Effect of Low Pass Filter





Trigger Efficiency vs SNR

- Logistic Function Fit
  - $f = \dfrac{1}{1 + e^{-k(x - x_0)}}$
- k = steepness/growth rate
- $x_0 = 4.89 \pm 0.05$, agrees with flower board (50% efficiency point)
- $\dfrac{\chi^2}{dof} = 1.06$, p-value = 0.37



1st measurement of RNO-G's in-situ trigger efficiency