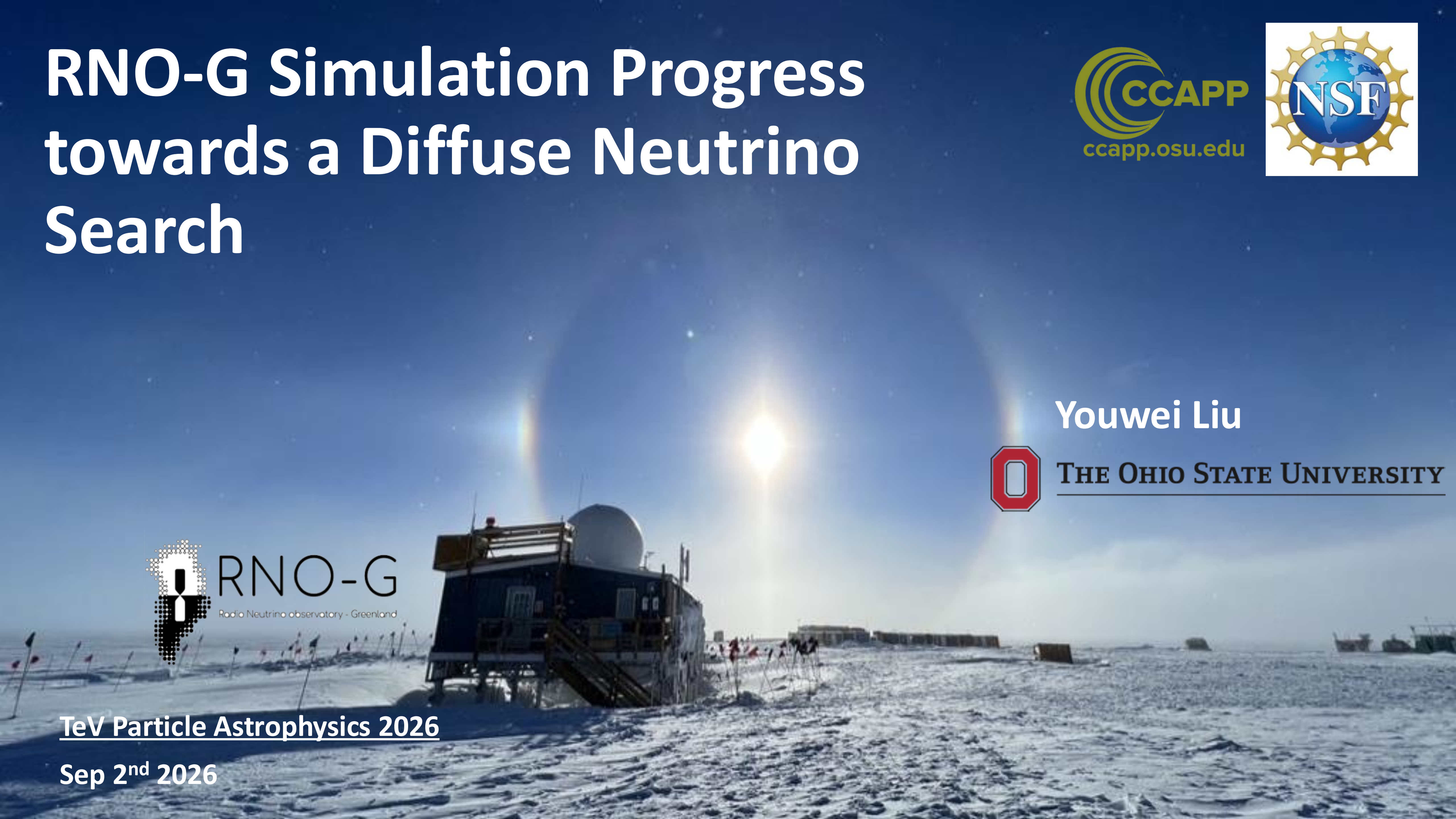
RNO-G Simulation Progress towards a Diffuse Neutrino Search



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TeV Particle Astrophysics 2026

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Outline:

- What we have:
  - 5 Years of Physics data
- What we want:
  - Ultra High Energy Neutrinos **(UHEN)**
- What we need:
  - Simulation to match the detector

This Presentation will cover:

- RNO-G simulation update
- Introduction on diffuse search
- Analysis Simulation plan

Simulation structure:
NuRadioMC

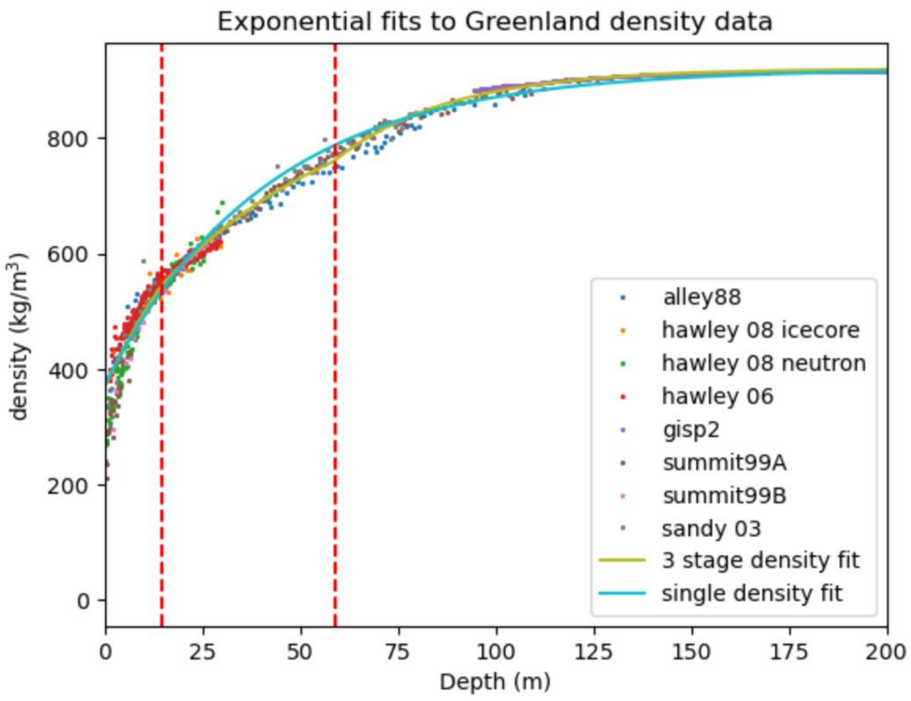
Event Generation	Signal Generation	Signal propagation	Detector simulation
Generate neutrino properties	Generate secondary showers and Radio Signal	Calculate signal path and amplitude based on Ice model	Readout signal based on Hardware response

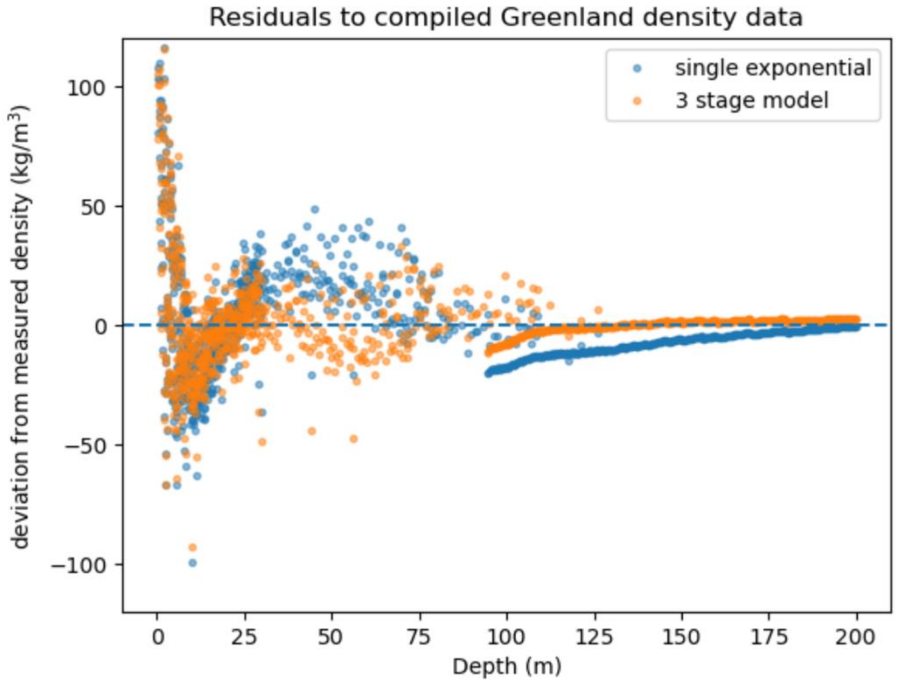
Glaser, Christian, Daniel García-Fernández, Anna Nelles, et al. "NuRadioMC: Simulating the Radio Emission of Neutrinos from Interaction to Detector." *The European Physical Journal C* 80, no. 2 (2020). https://doi.org/10.1140/epjc/s10052-020-7612-8.

Signal Propagation

3 Part Ice model adoption

- updated ice model to better match density measurements
- computation time of new method is reasonable
- only minor changes to effective volume of detector
- better ice model = decreased uncertainties on reconstruction





Ali, S., P. Allison, S. Archambault, et al. “Modeling the Refractive Index Profile n(z) of Polar Ice for Ultra-High Energy Neutrino Experiments.” arXiv:2406.00857. Preprint, arXiv, April 1, 2026. https://doi.org/10.48550/arXiv.2406.00857.

Credit: Ruben Camphyn, Felix Schlüter, Simona Toscano

Detector response
Gain Calibration

Extraordinary results require an extraordinary understanding of the detector

Example from ICECUBE:

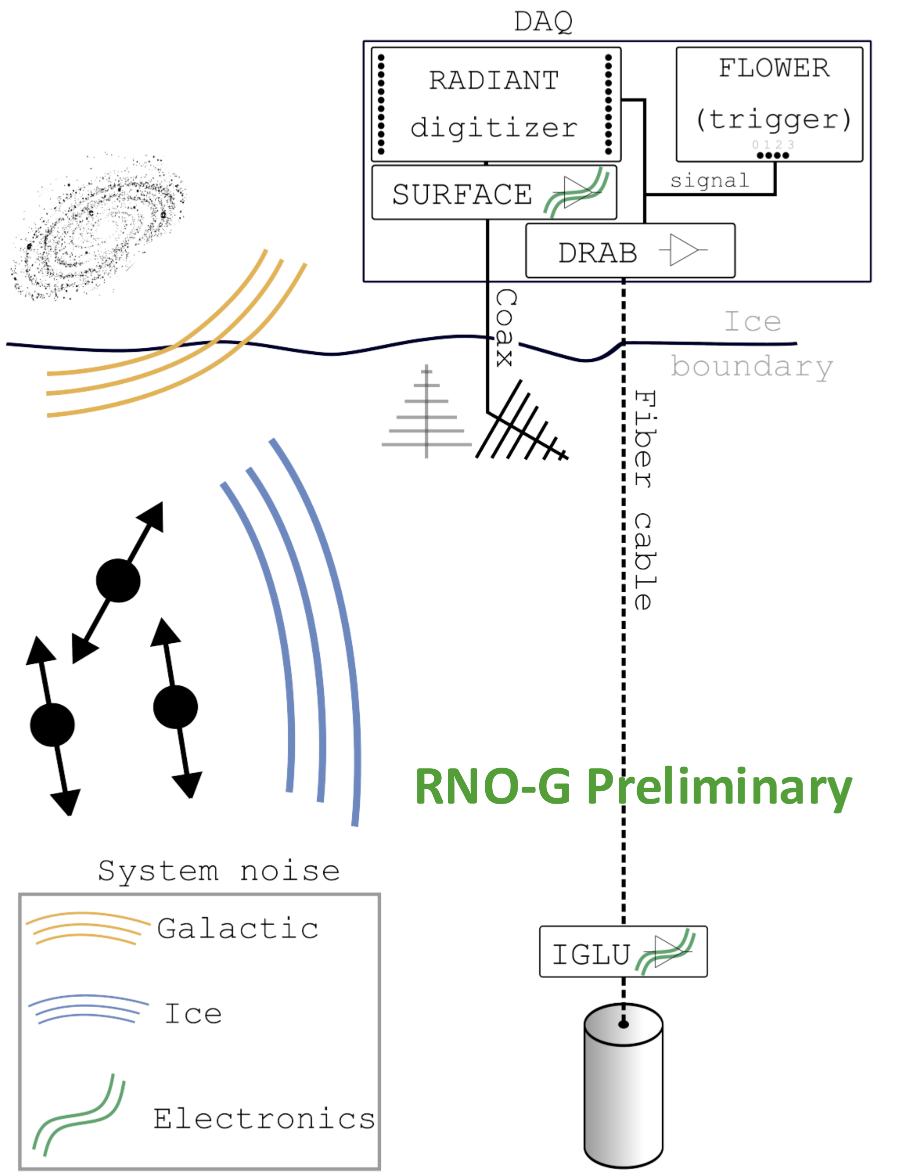
IceCube has only seen 3 nus with energy > 5 PeV over 12 years
very low expected flux at these energies!

Gain Calibration is conducted

- per channel • per operation season

Gain calibration is done to extract:

- Background noise effective temperature
- Accurate per channel gain frequency response

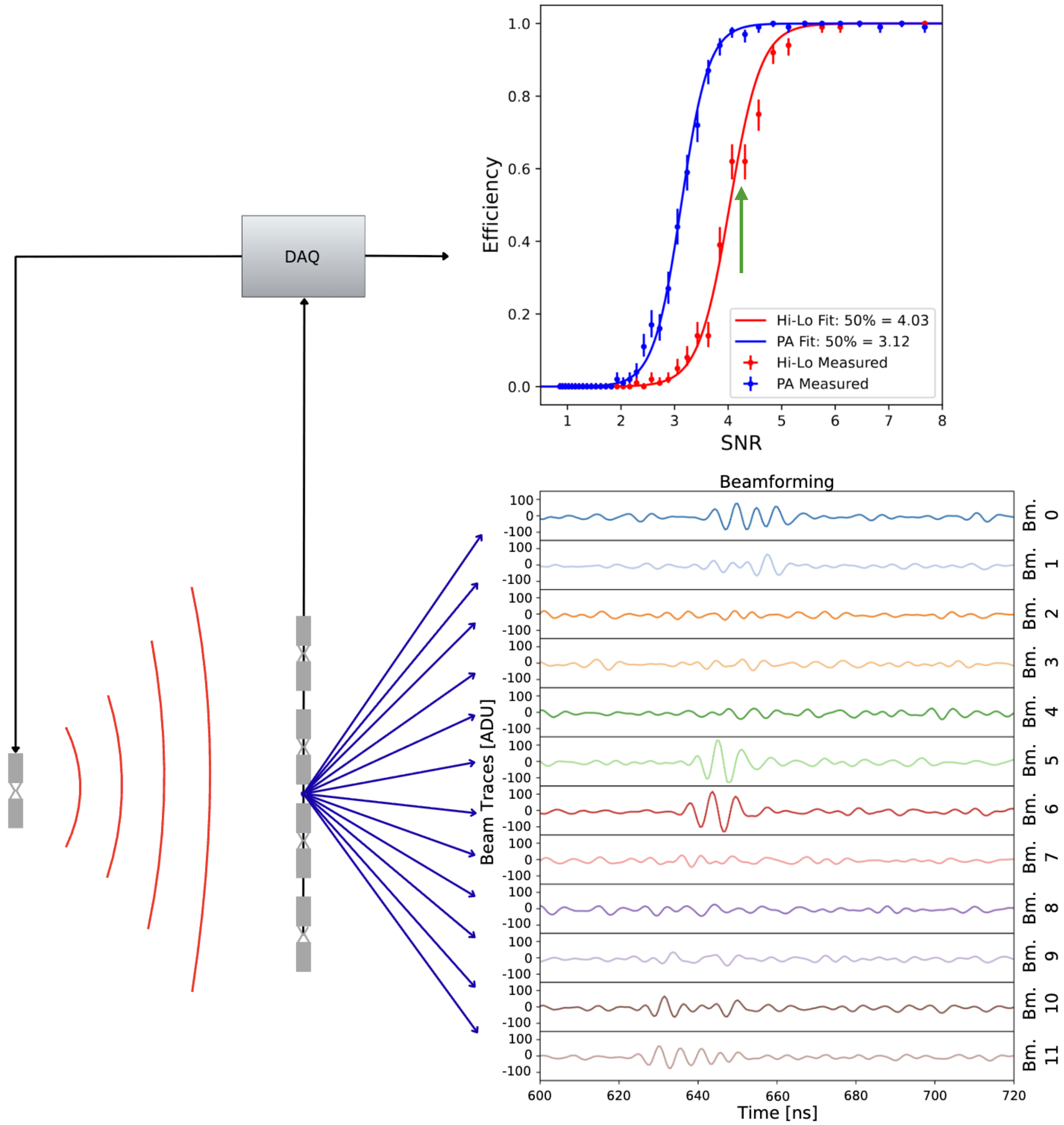


Trigger design:
Phased array

Beamforming:

- Linearly adds signals in specific directions
- Boosts SNR by $\sqrt{N}$

This trigger was deployed in the 2024 off-season



Collaboration, RNO-G., S. Agarwal, J. A. Aguilar, et al. “The Beamformed Trigger of RNO-G: Its Design and in-Field Performance.” arXiv:2607.24470. Preprint, arXiv, July 27, 2026. https://doi.org/10.48550/arXiv.2607.24470.

Likelihood-based reconstruction

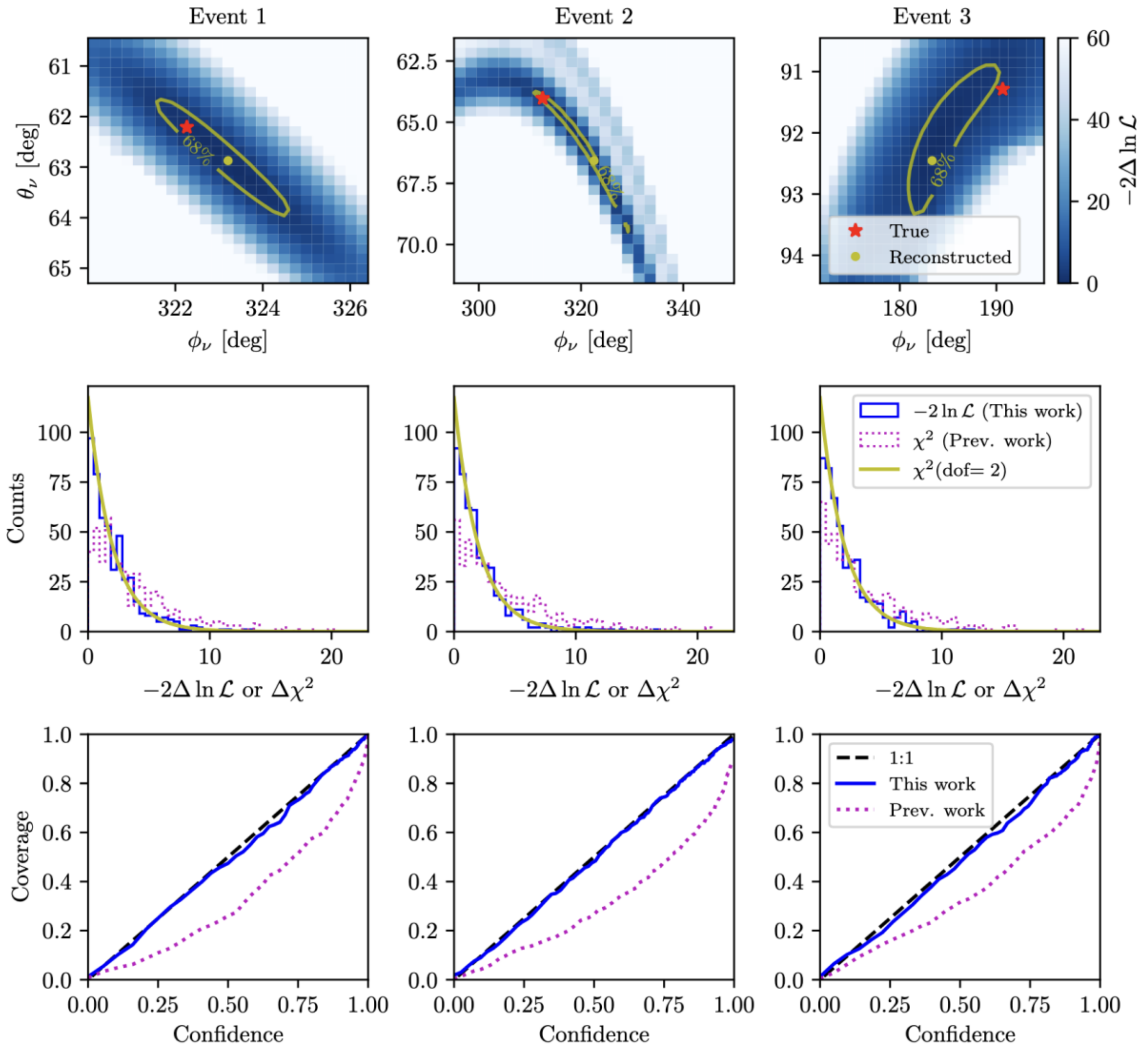
Find best fit by minimizing $-2\ln\mathcal{L}$

$\mathcal{L}$: Likelihood

Neutrino reconstruction result based on new method

- Improve reconstruction precision
- Fast reliable uncertainty estimates
- Improve signal efficiency for future detectors

New feature, Currently not used in diffuse search



Ravn, Martin, Christian Glaser, Thorsten Glüsenkamp, Ayca Özcelikkale, and Alan Coleman. “Likelihood Reconstruction for Radio Detectors of Neutrinos and Cosmic Rays.” *Physical Review D* 114, no. 4 (2026): 043025. https://doi.org/10.1103/m22t-cbgw.

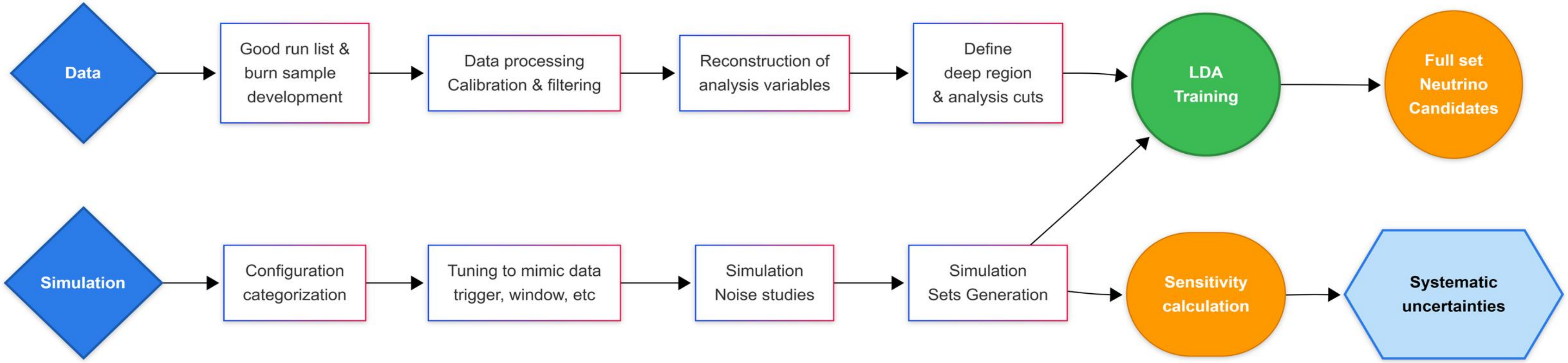
Neutrino diffuse search strategy

Definition of “diffuse”:

Search for neutrinos from any direction, staying agnostic to specific sources

Objective:

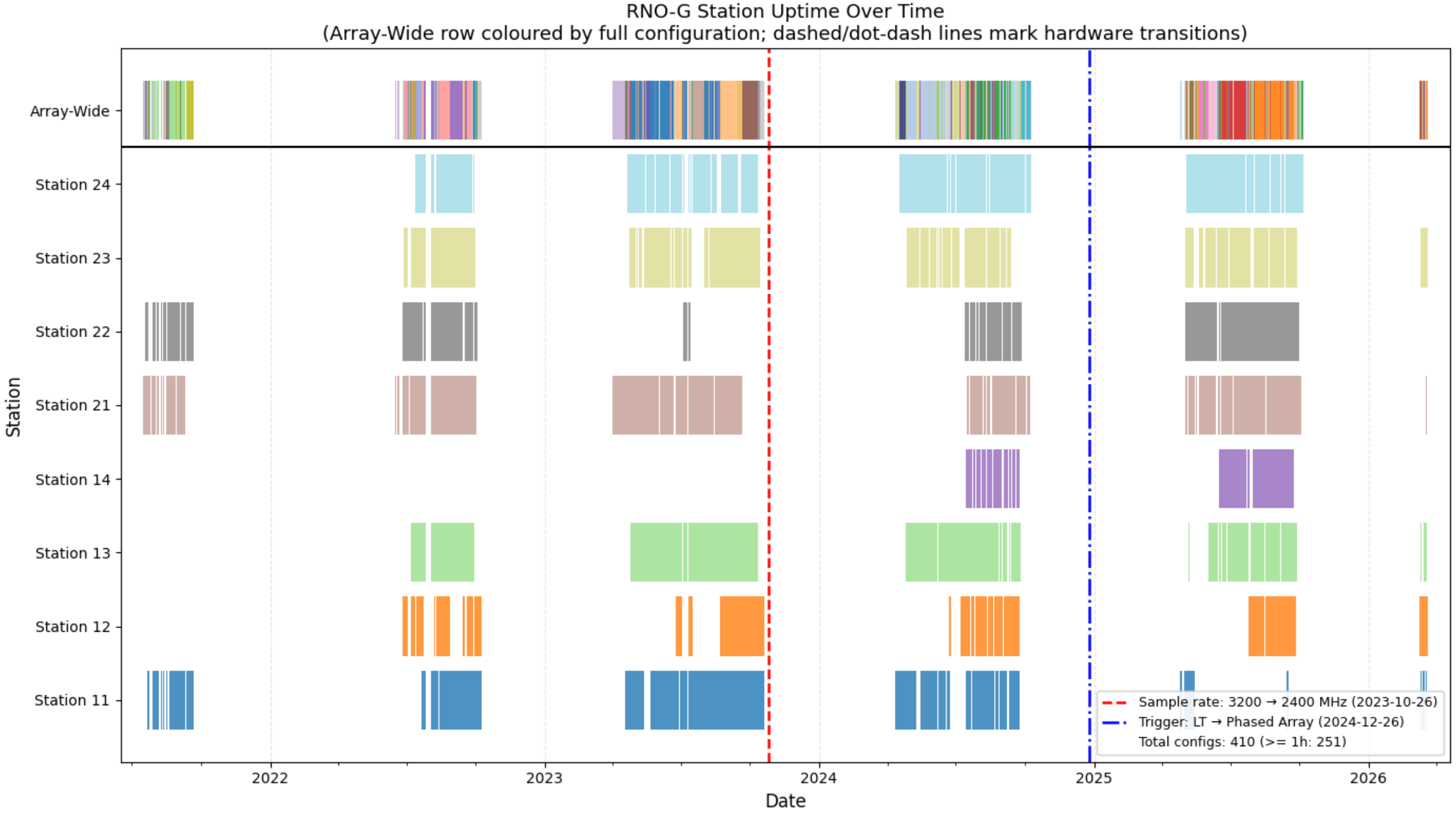
Generate possible neutrino candidates and provide a limit on the astrophysical neutrino flux



Simulation Plan

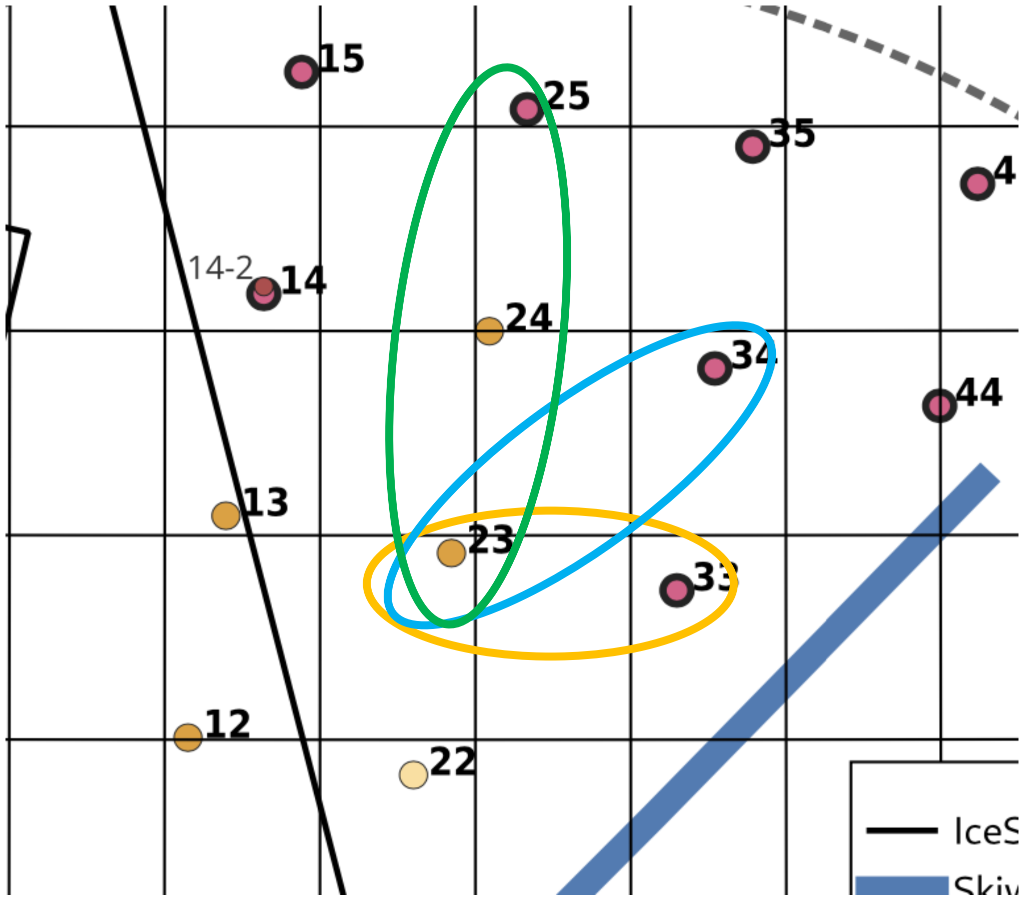
- RNO-G has run in many configurations as stations have come online
- this will only continue as RNO-G grows to 35 total stations
- need to carefully consider a simulation strategy to reflect this

Current results in configuration categorization



Simulation Strategy

- Major RNO-G station updates always applied off-season across all stations
- Reduce overcounting effect by computing neighboring pairs of single station sim by γ
- $Neighbor\ relationship$: γ
  - Orange: $\gamma = 1st$ Nearest
  - Blue: $\gamma = 2nd$ Nearest
  - Green: $\gamma =\ 3rd$ Nearest



Scalable! Reusable!

No multi-station configuration required!

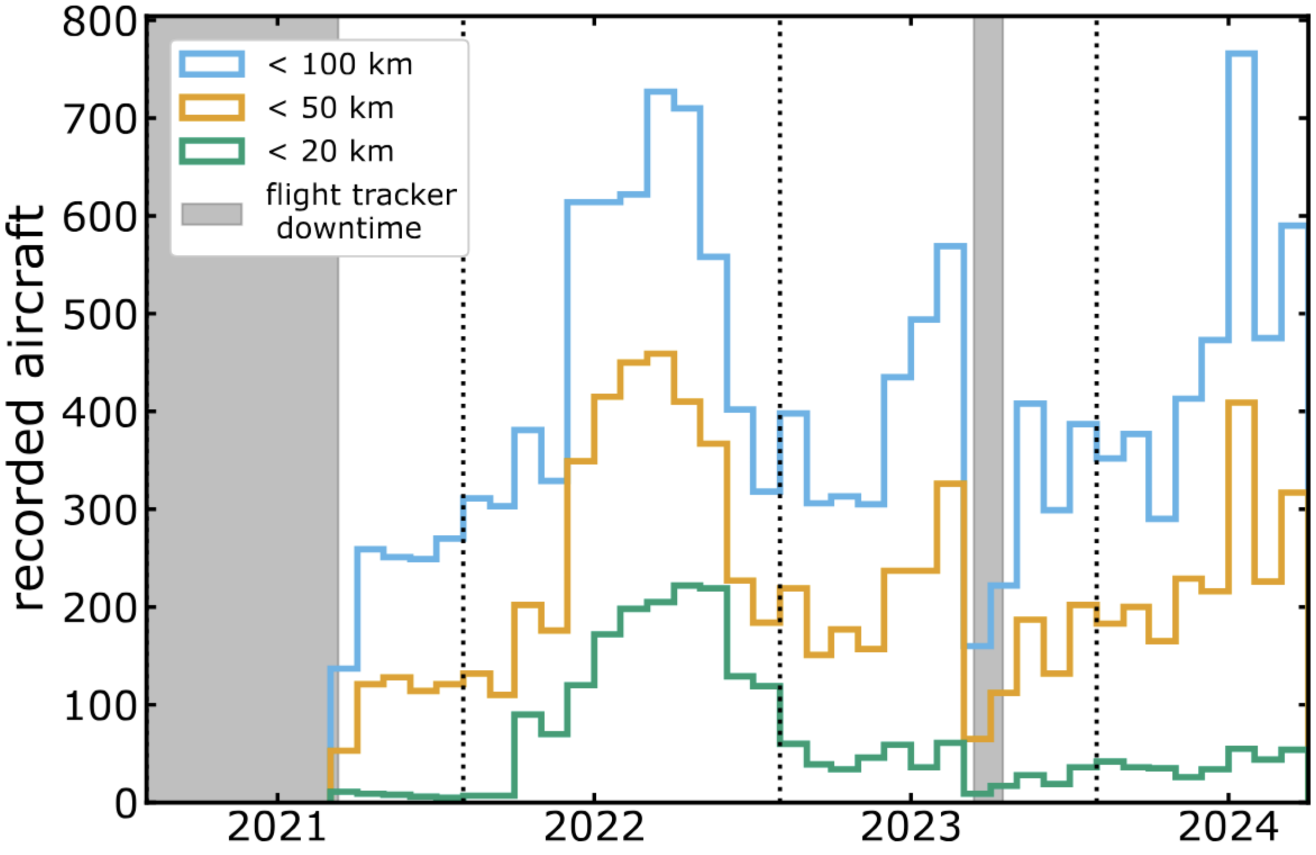
Data Cleaning

Known background sources based Cuts:

- Airplane Cut
- Spatiotemporal Cut
- Wind Cut
- Direction Cut
- Intra-run Rate Cut
- Glitches event cut

Example:

Airplane flying near the station picked up by station plane tracker



Agarwal, S., J. A. Aguilar, N. Alden, et al. "Radio Emission from Airplanes as Observed with RNO-G." *Journal of Instrumentation* 20, no. 11 (2025): P11015. https://doi.org/10.1088/1748-0221/20/11/P11015.

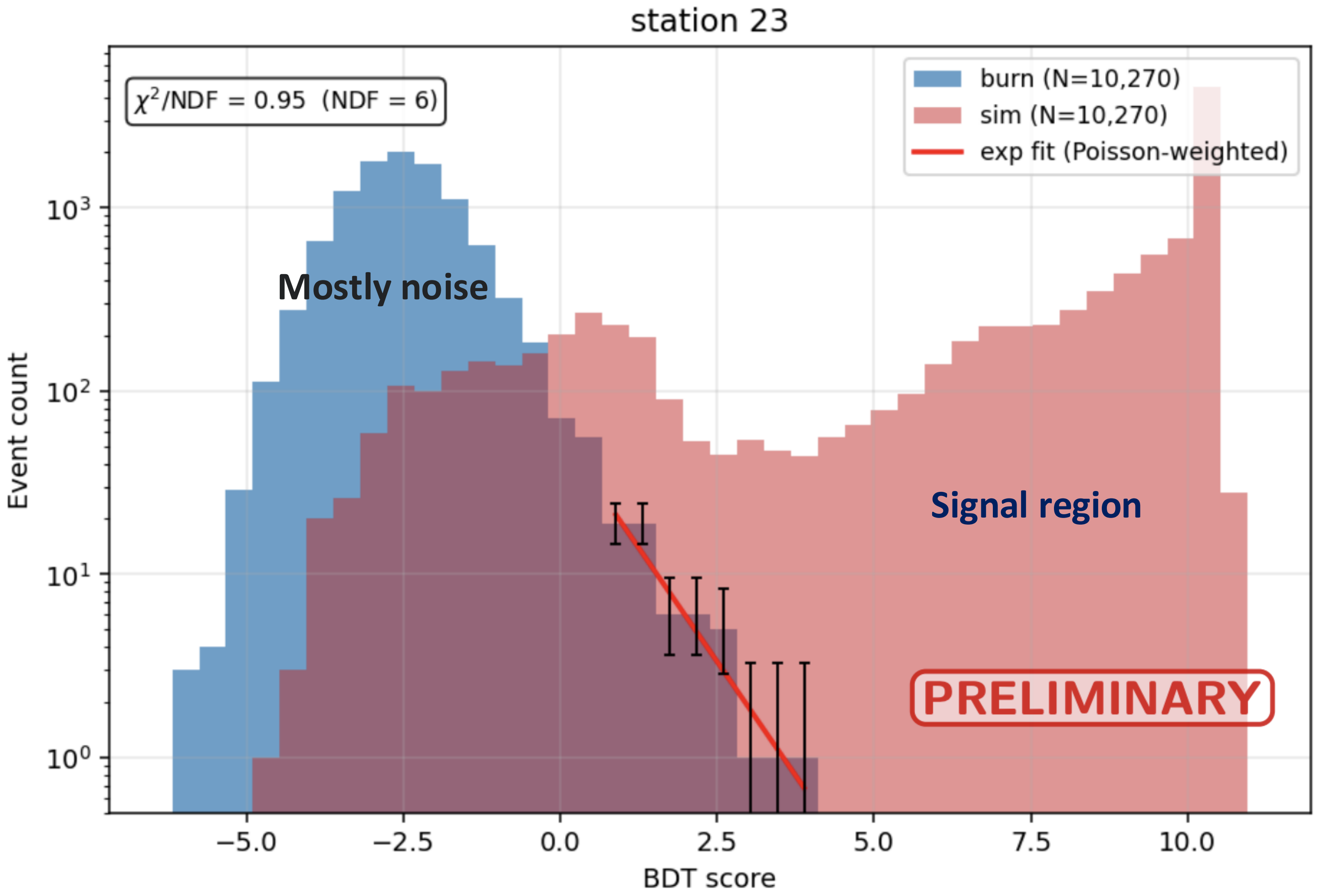
Machine learning (ML)

various ML techniques are informing our cut strategy

(Deep CR as an example)

here, a boosted decision tree is distinguishing detector noise from simulated impulses

next step is to integrate this method into full neutrino search pipeline



Bryan Hendricks, Searching for Cosmic Rays in the Deep Antennas of RNO-G
https://indico.kit.edu/event/5380/contributions/22589/attachments/10498/17994/05-arena-hendricks.pdf

Future plan of RNO-G

- RNO-G is currently drilling for more stations in Greenland right now
- Deep CR Analysis and diffuse neutrino search is on-going

Thanks for Every RNO-G member's contribution!

Hope RNO-G can bring us more physics on UHEN in the near future

Detector response

Gain Calibration

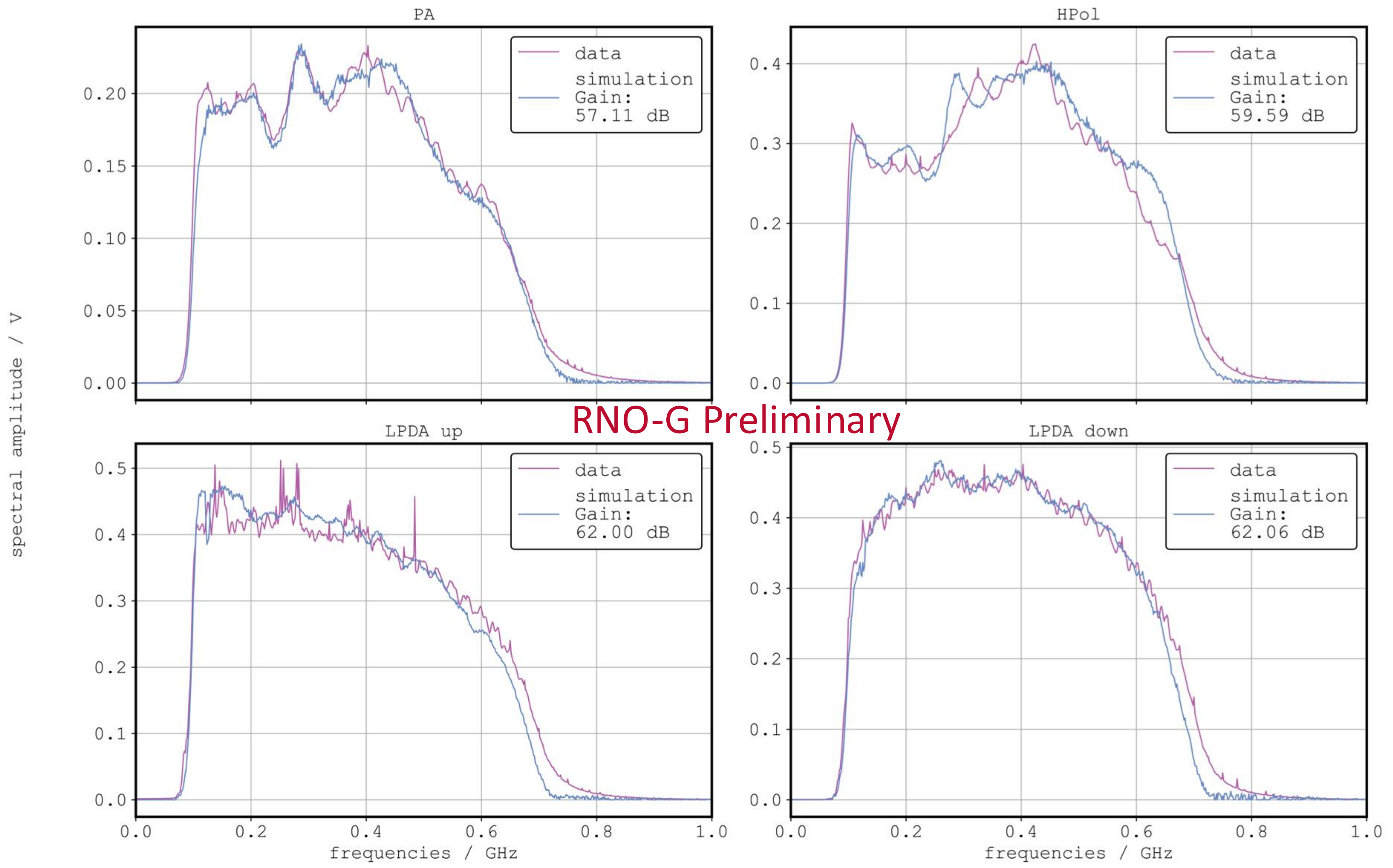
Credit: Ruben Camphyn, Felix Schlüter, Simona Toscano

Gain Calibration is conducted

- per channel
- per operation season

Currently calibrated:

Season: 2022 - 2024



Likelihood-based reconstruction

Find best fit by minimizing $-2\ln\mathcal{L}$

$$-2\ln\mathcal{L}(\boldsymbol{\mu}(\boldsymbol{\theta});\boldsymbol{x},\boldsymbol{\Sigma}) = n_t\ln(2\pi) + n_t\ln(|\boldsymbol{\Sigma}|) + \big(\boldsymbol{x}-\boldsymbol{\mu}(\boldsymbol{\theta})\big)^{\mathrm{T}}\boldsymbol{\Sigma}^{-1}\big(\boldsymbol{x}-\boldsymbol{\mu}(\boldsymbol{\theta})\big).$$

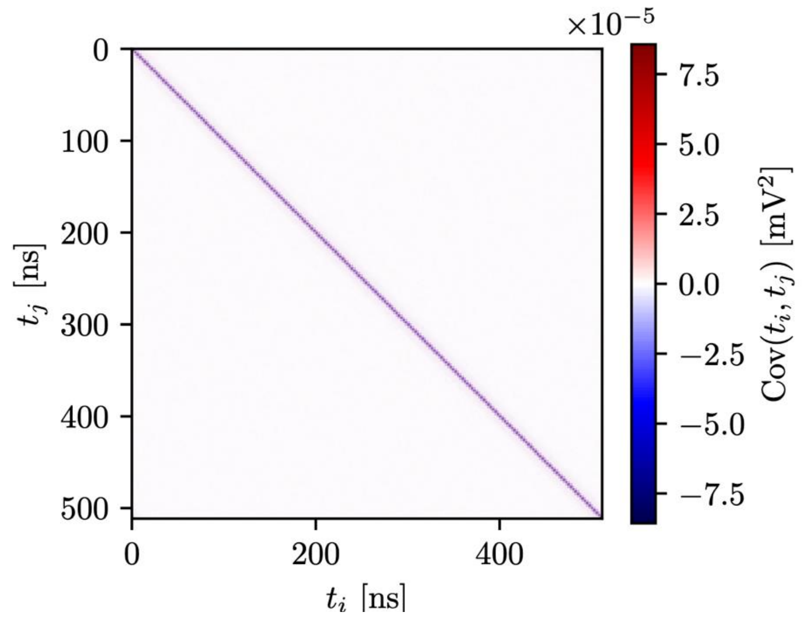
$\mathcal{L}(\mu(\theta); x, \Sigma)$: likelihood

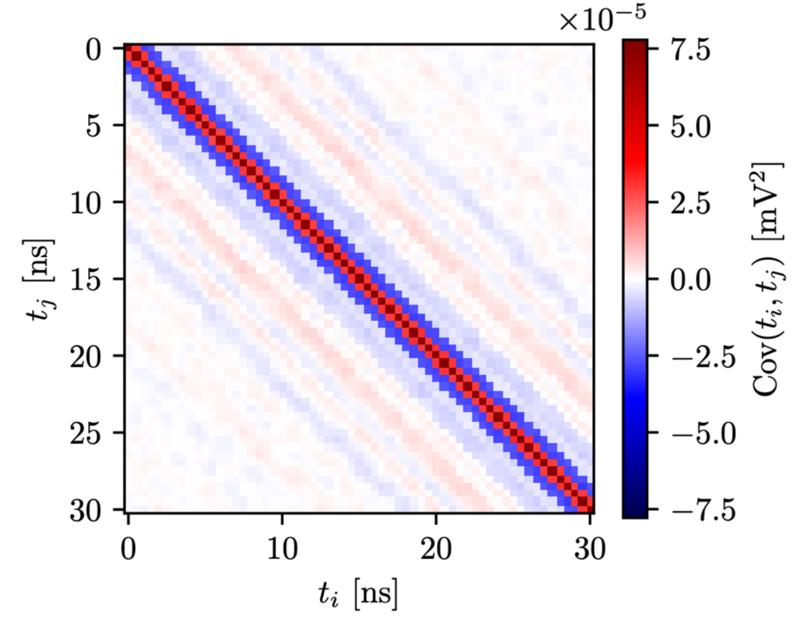
x : trace

μ : signal

Σ : covariance matrix

$\theta = (E_{shower}, \theta_v, \phi_v, r_{vertex}, \theta_{vertex}, \phi_{vertex}, t_0)$





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