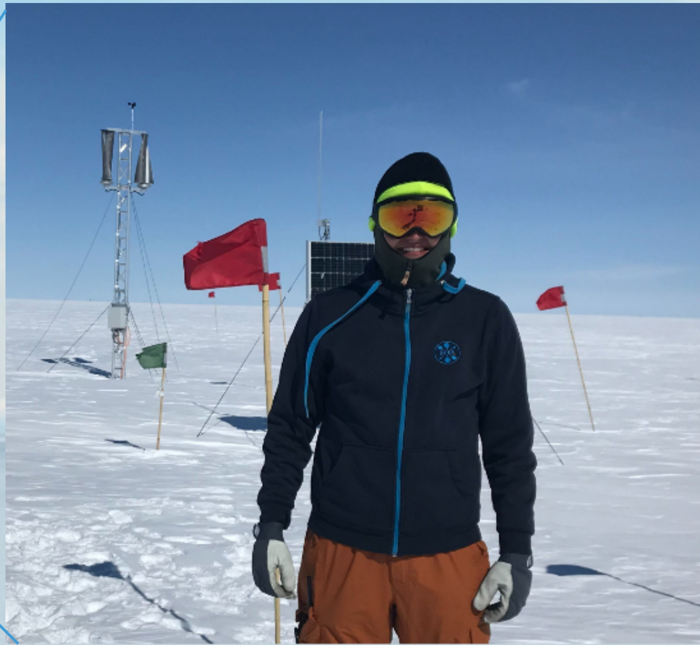
based on work by Jakob Henrichs and Bryan Hendricks

Cosmic Ray Detection with RNO-G



Anna Nelles

for

RNO-G

Radio Neutrino Observatory - Greenland

DESY.

HELMHOLTZ

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

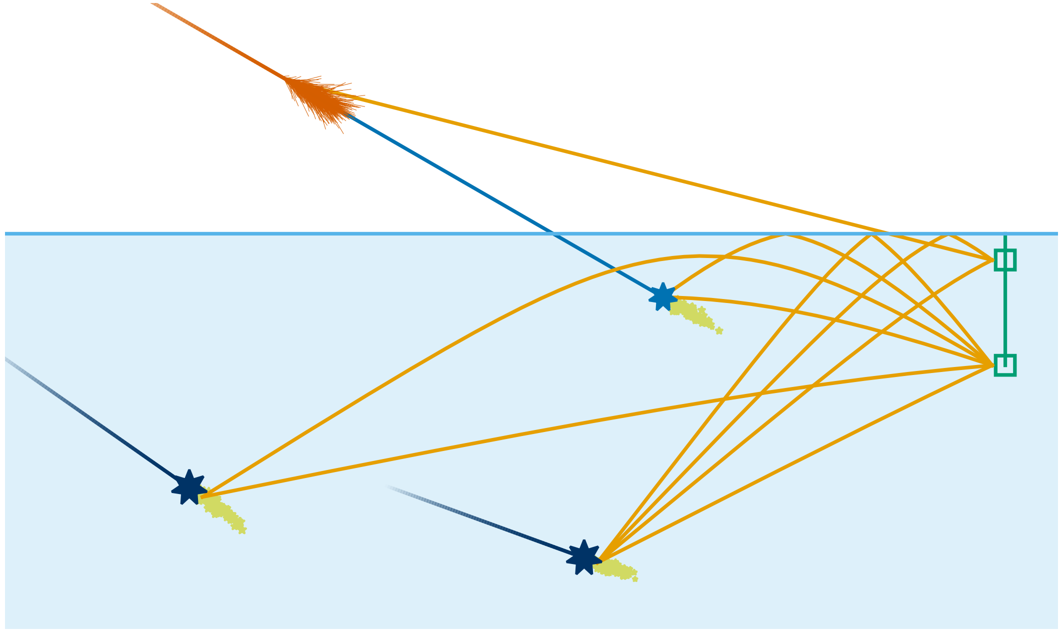
FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

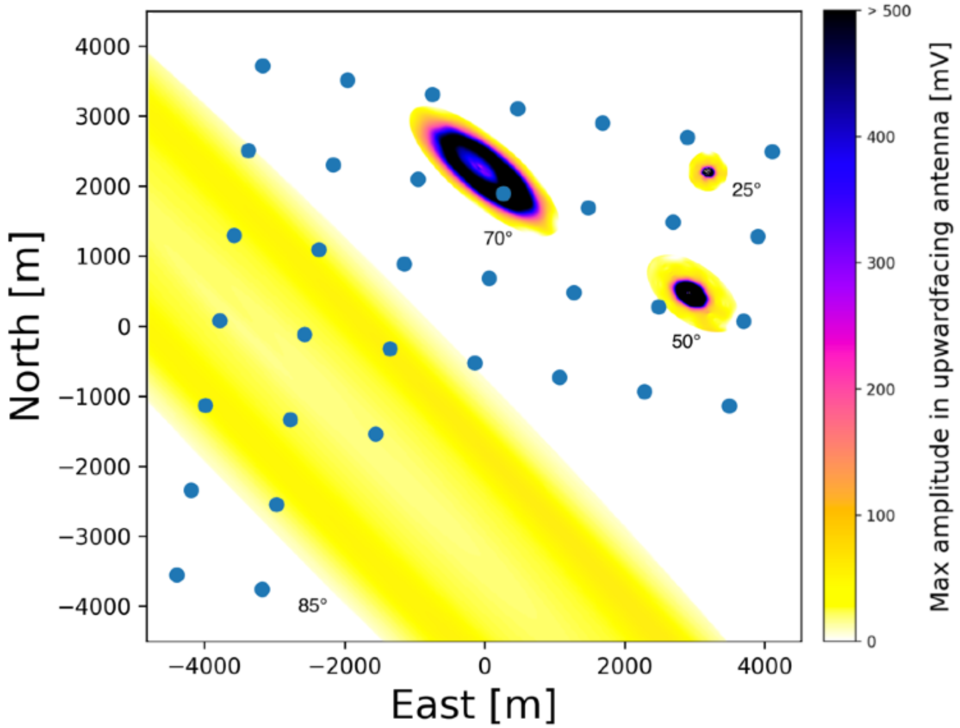
Co-funded by the European Union

Cosmic Rays in RNO-G

What parts of an air shower is RNO-G going to see?

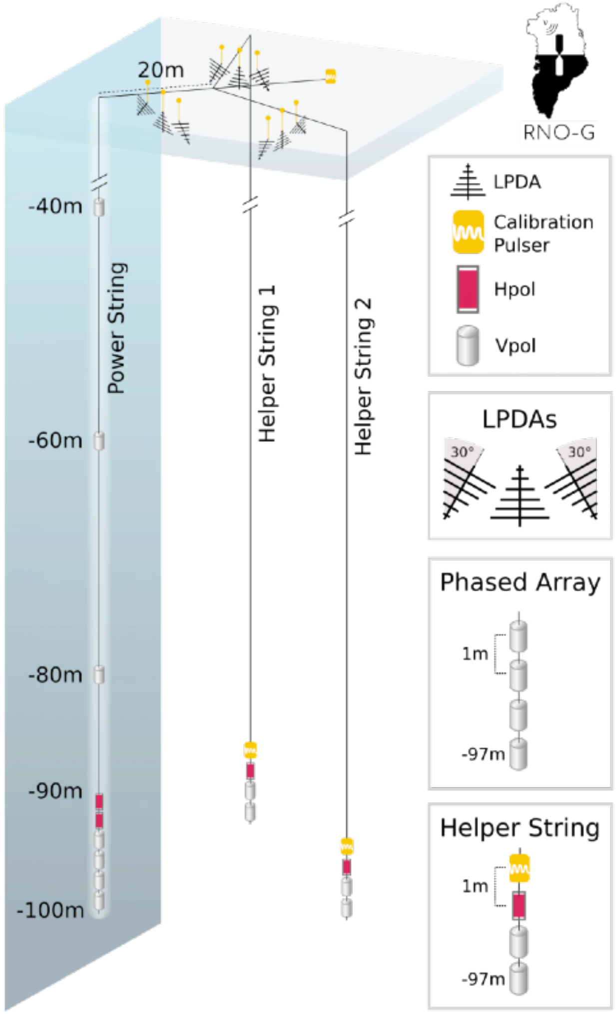
- Three types of air shower signals
  - In-air signal from air shower *(RNO-G data priority 1)*
  - In-ice signal from incomplete air shower
    see e.g. de Kockere et al. Phys. Rev. D 106, 043023 (2022)
  - PeV energy losses from muons
    see e.g. L. Pyras at al. JCAP10(2023)043
- In-air signal will be used to uniquely tag air showers
  - **Calibration source:** direction reconstruction, energy scale, proof-of-principle for analysis
  - **Background:** Show that predicted emission exists and can be vetoed





The Radio Neutrino Observatory in Greenland (RNO-G)

And its relation to previous (neutrino) air shower detections



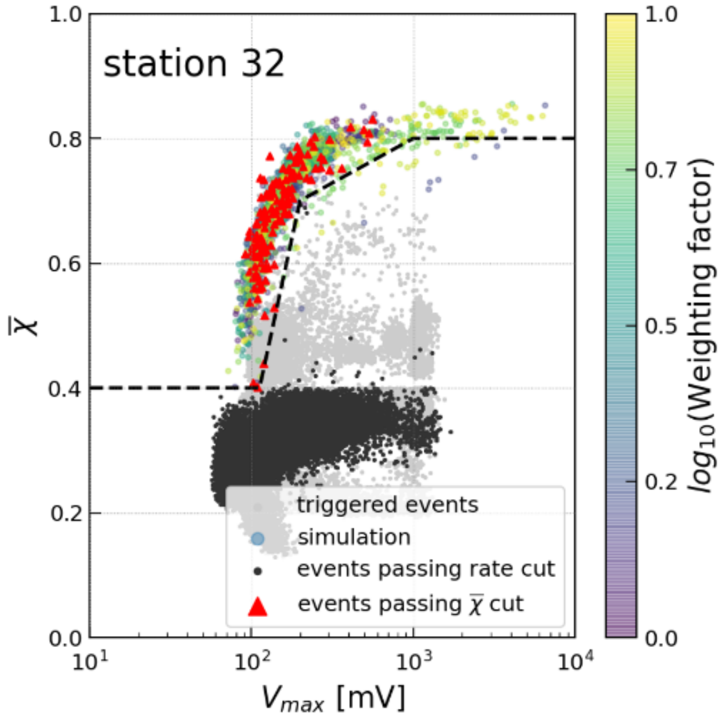
- **Shallow component:** 9 LPDAs, 3 pointing upwards
  - Very similar to **ARIANNA**, but different electronics, different trigger, different number of antennas
  - In principle sensitive to ‘regular’ air shower emission, only refraction into ice needed
- **Deep component:** 15 channels on three strings, combination of Vpols and Hpols
  - Closely related to **ARA**, but different electronics, different trigger, different type and number of antennas
- **Unique**: Combination of both
  - However, the firmware that can actually read out both signals for down-going signals at the same time is only being rolled out this year -> *See talk by Ryan Krebs for more details*

Cosmic-rays in in-ice neutrino detectors

Where are we at?

- **ARIANNA** collaboration has shown in several studies that ARIANNA detects air showers right where it is expected from simulations
- They also separate well from background noise
- Most challenging: Triboelectric signals measured during high-wind periods *(see Astropart.Phys. 145 (2023) 102790)*

ARIANNA collaboration JCAP04(2022)022



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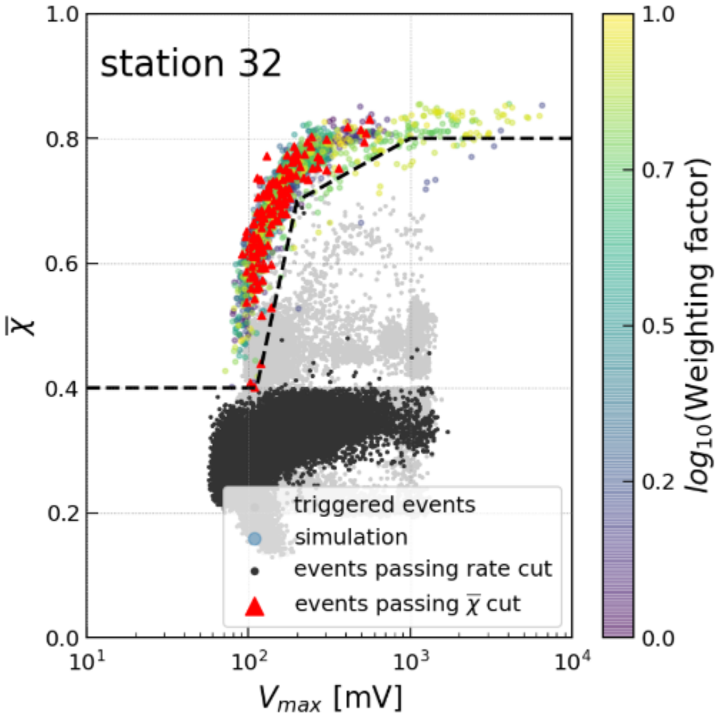

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- One event (found in neutrino search) hypothesized to stem from air shower core hitting the ice
- Cosmic ray candidates found in a deep analysis *(PhD thesis Latif)*

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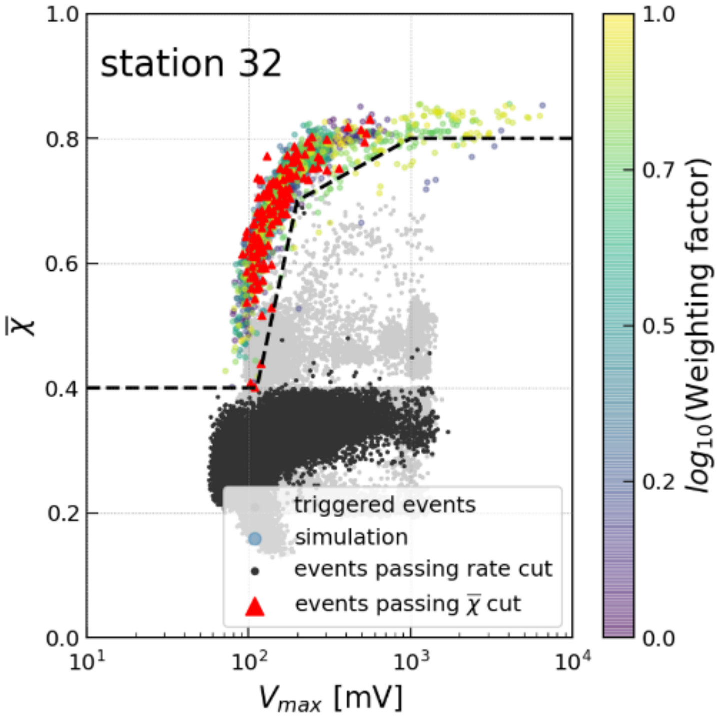

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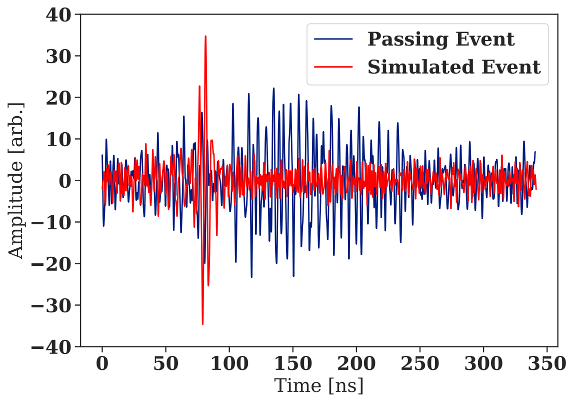

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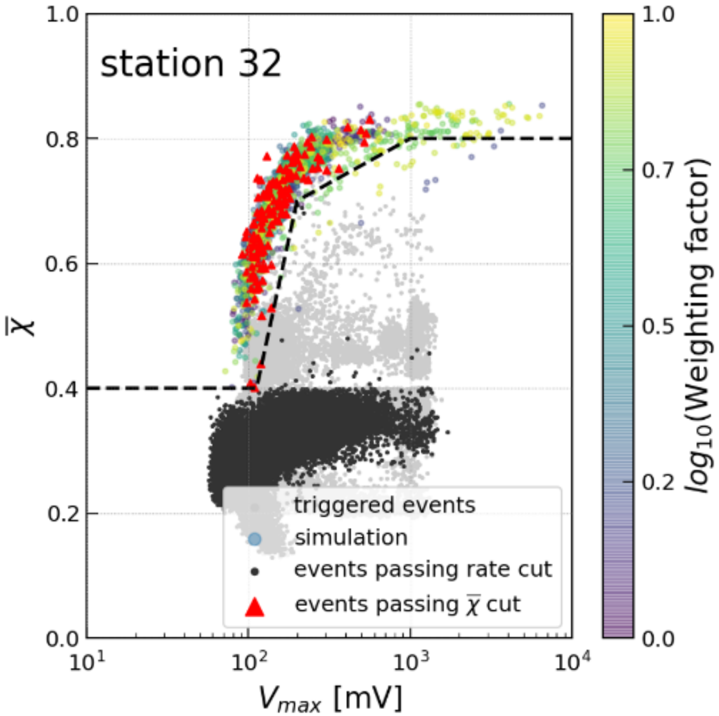

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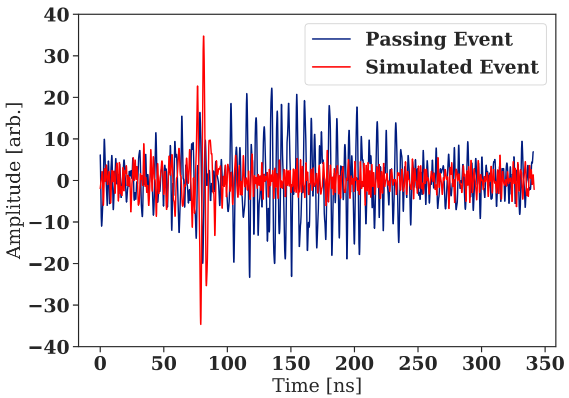
- No existing detector has a working air shower trigger on in-air signal that reads out also the corresponding in-ice signal
- Will be future Golden Channel for RNO-G

ARA collaboration Phys.Rev.D 105 (2022) 12, 122006

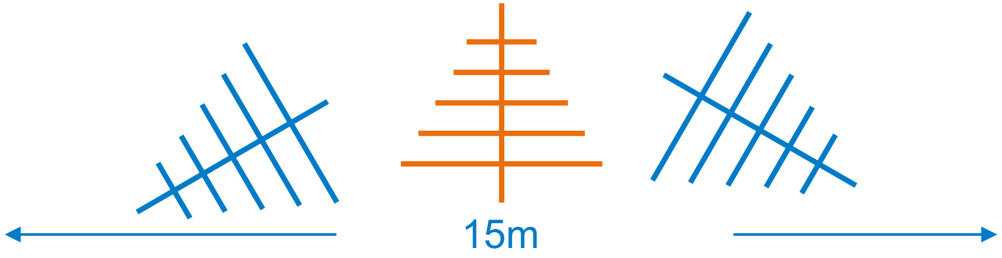


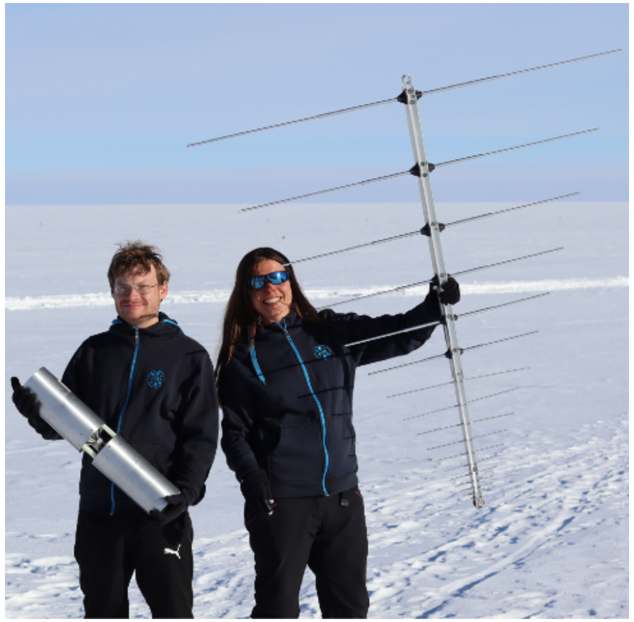
Cosmic rays in shallow component of RNO-G

Basic parameters of RNO-G targeting air showers

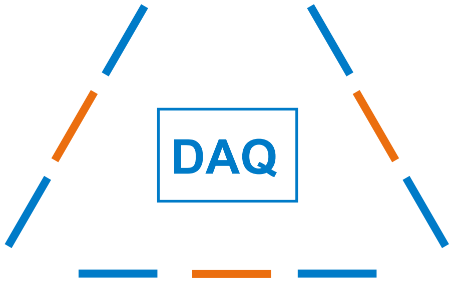
- 35 RNO-G stations will be installed until 2026 (more likely after that)
  - Radio-only cosmic-ray detector of 70 km^2 at a height of 3000m above sea-level, station spacing 1.25 km
  - Large Bandwidth: 80 MHz - 600 MHz, dedicated cosmic-ray trigger
  - Uptime planned at 90% (currently wind-power for winter still under active development)

Side view (first 7 stations), below the ice surface:





Top view:



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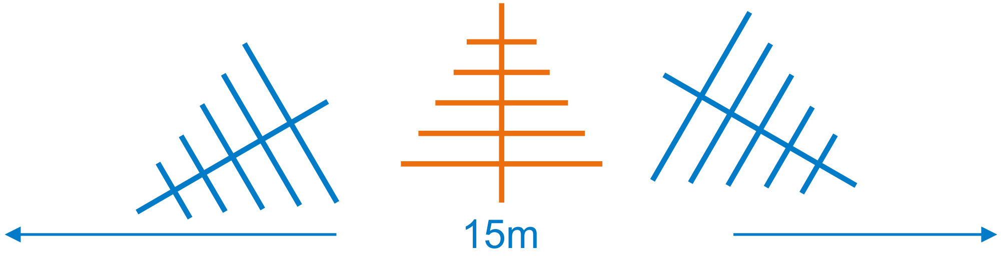
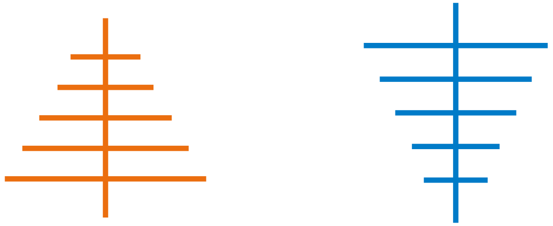
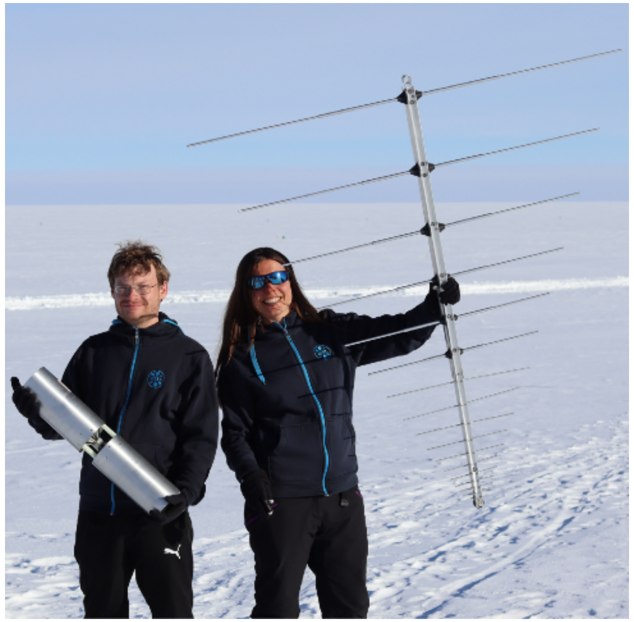


Planned for future stations:





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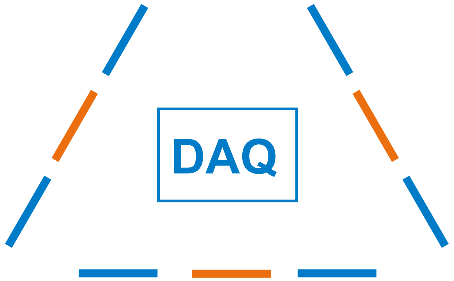
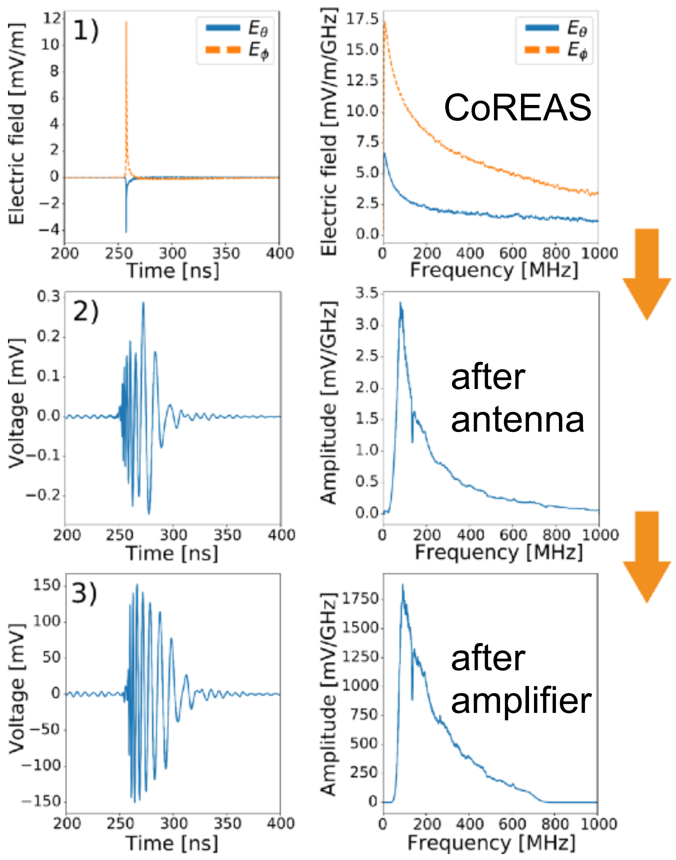


Top view future stations:

Finding cosmic rays in RNO-G

All information in self-triggered data



- Analysis strategy: following *ARIANNA Coll., Astropart. Phys. 90 (2017) 50*
  Correlate all recorded triggers with signal templates
- **Improvement**: more efficient, less brute-force approach: 3 templates based on Gaussian pulses convolved with hardware response have been found sufficient to retrieve all pulses (in simulations)
- Possible future improvement: Matched filter / likelihood, *see talk Martin Ravn*

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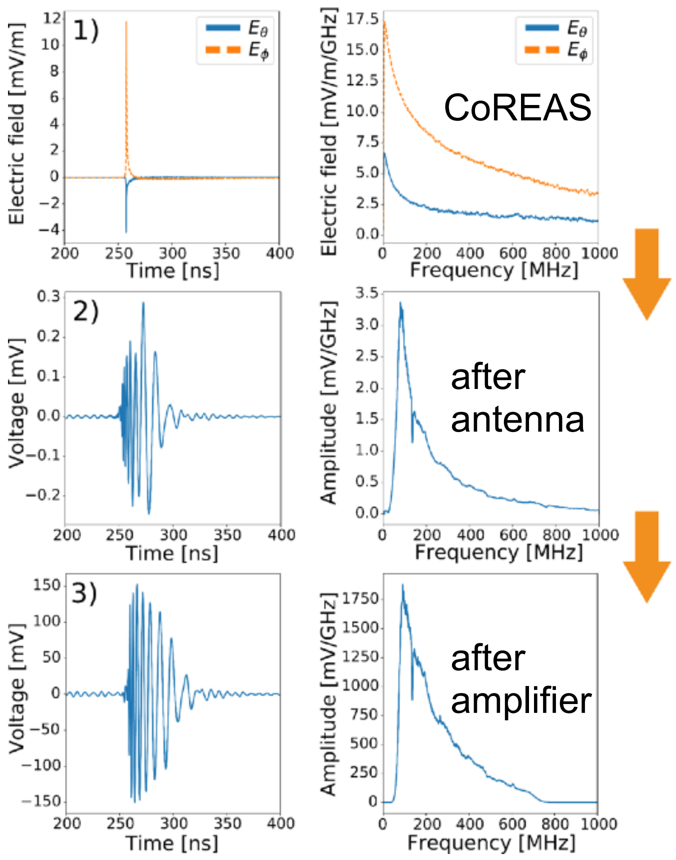

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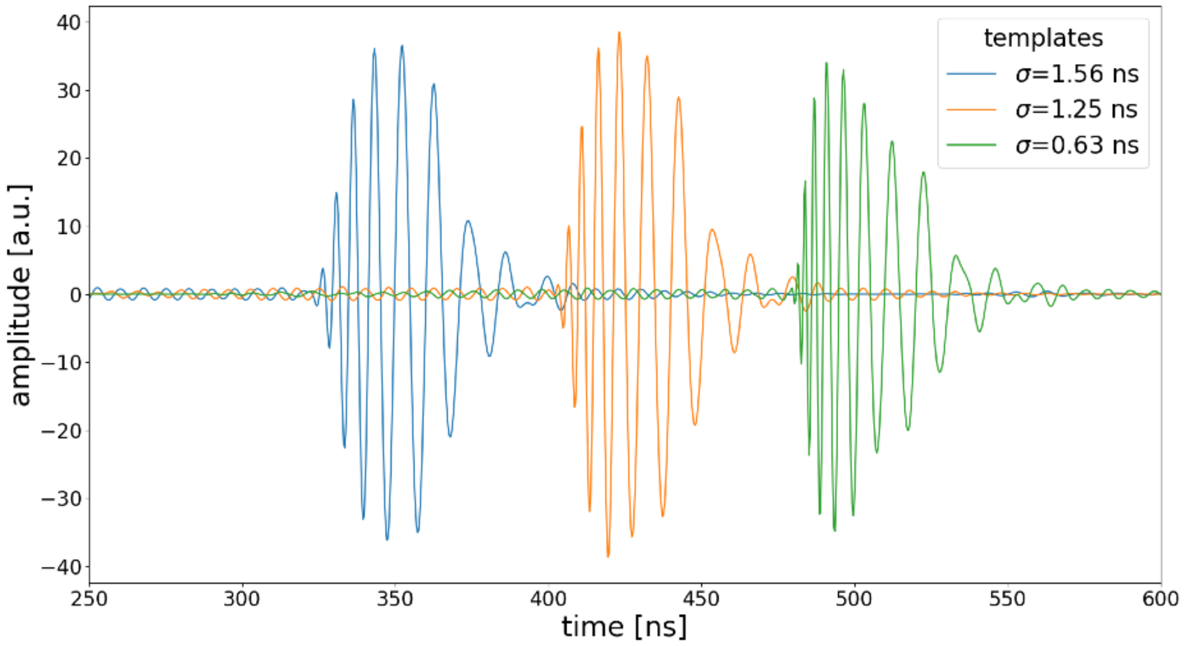
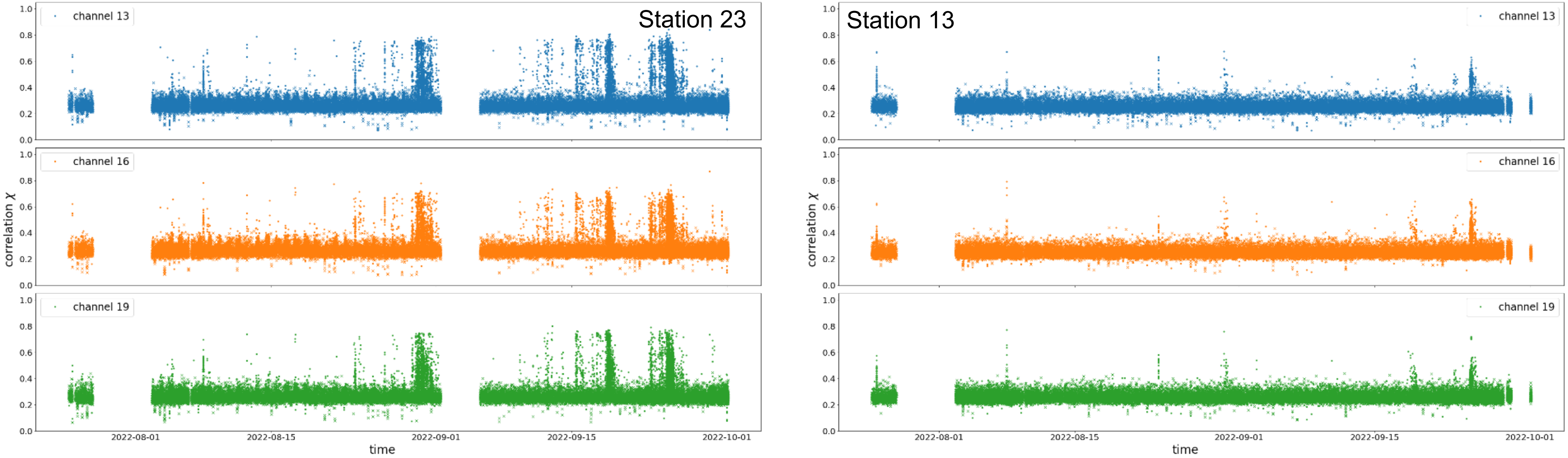


Finding cosmic rays in RNO-G data

Analysis strategy: shallow component

- RNO-G has a blinding policy; 3% of the data are free to do any analysis on, data transferred in real-time
- Here: analysis on 3% of LPDA data from 3 stations between August 2022 and October 2022; very early data
- Indicative ‘signal region’ above 0.8 in correlation value



raw data, not corrected for trigger threshold: still signal region very clean!

Simulations of shallow component

Analysis strategy: where should they be?

Data

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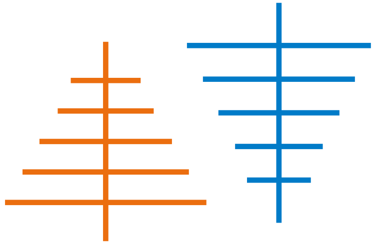
Data

up-vs-down cut[(1)]



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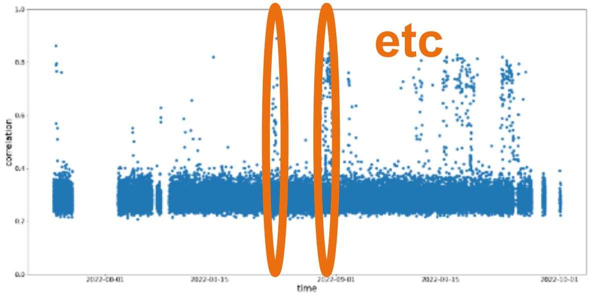

Data

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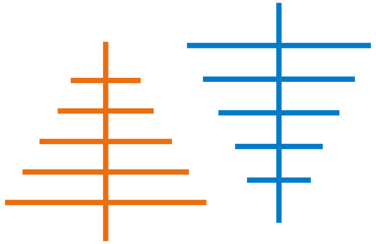

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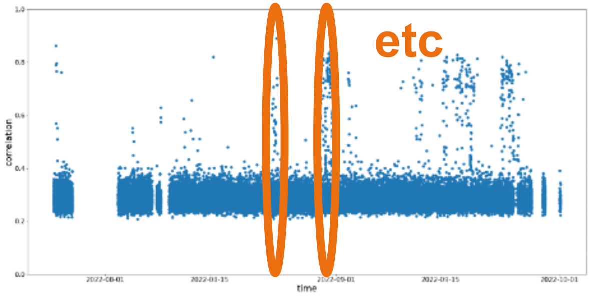

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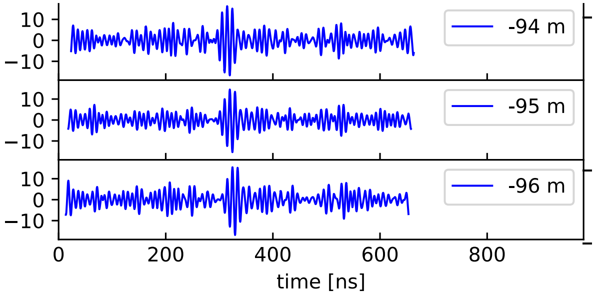
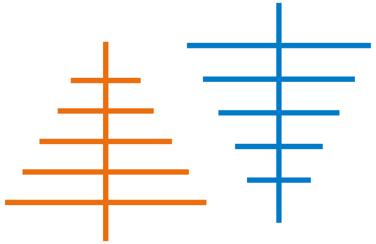


half trace RMS cut(2)



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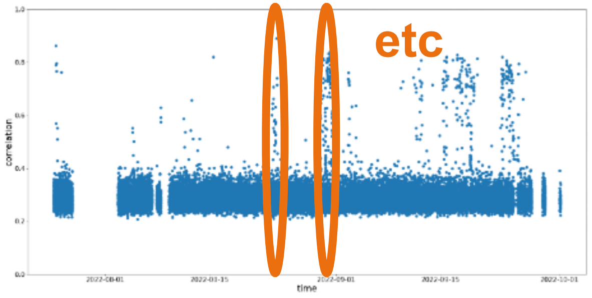
(1)High-wind periods *(Astropart.Phys. 145 (2023) 102790)* largest source of background, most visible in LPDAs at surface

(2)Solar flares show impulsive structure but elevate full waveform *arXiv:2404.14995*



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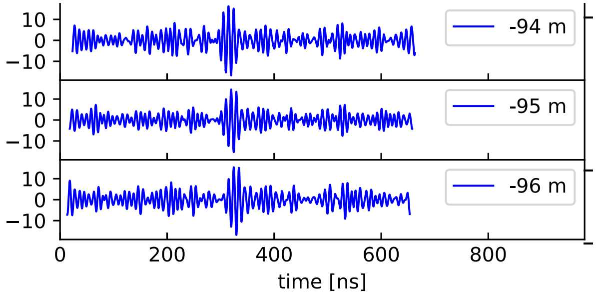

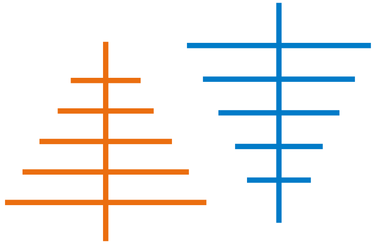

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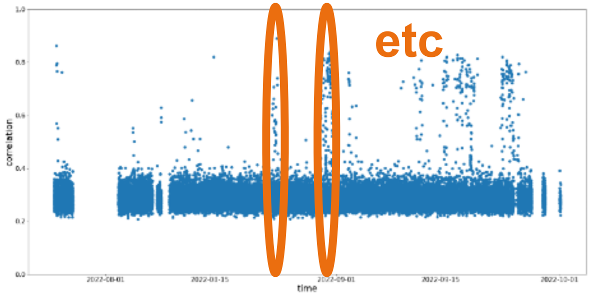

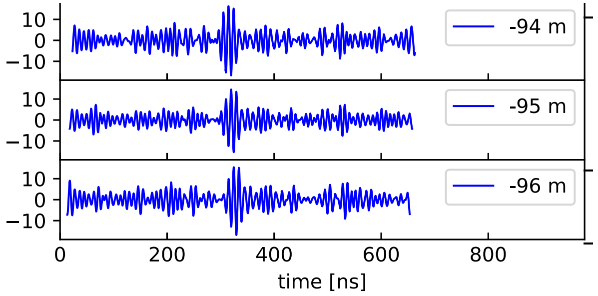

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up-vs-down cut[1]

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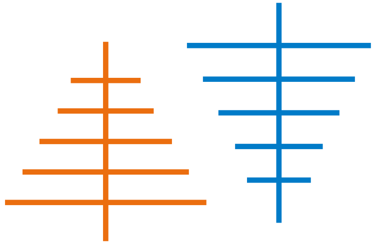
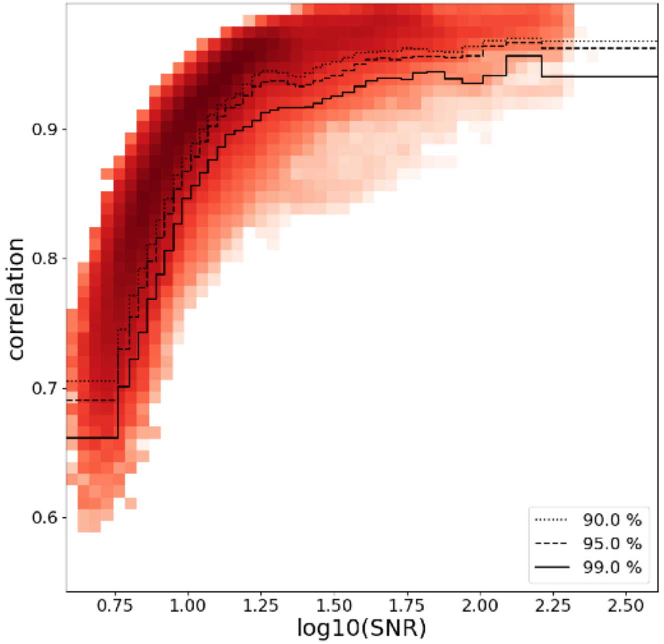
half trace RMS cut[2]

template cut



RNO-G CoREAS simulations



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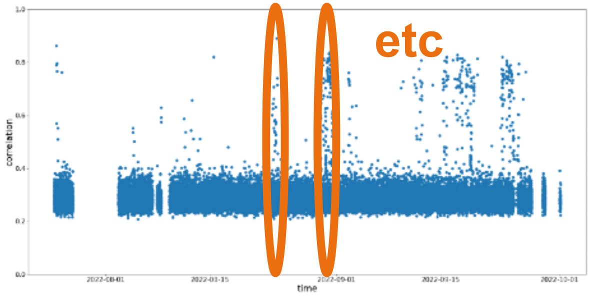

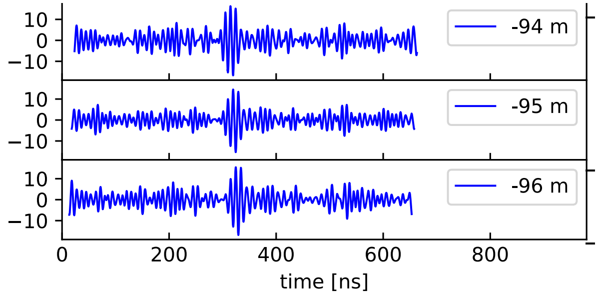

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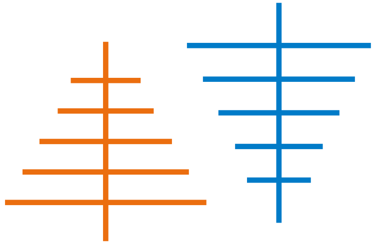

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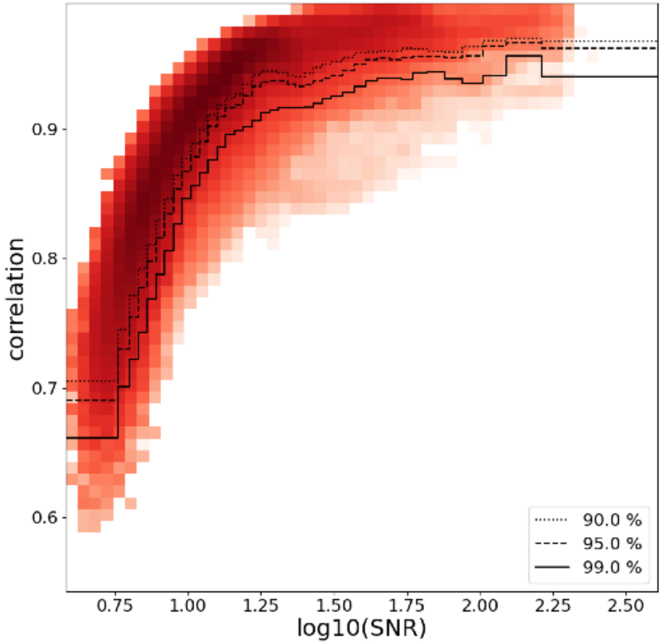
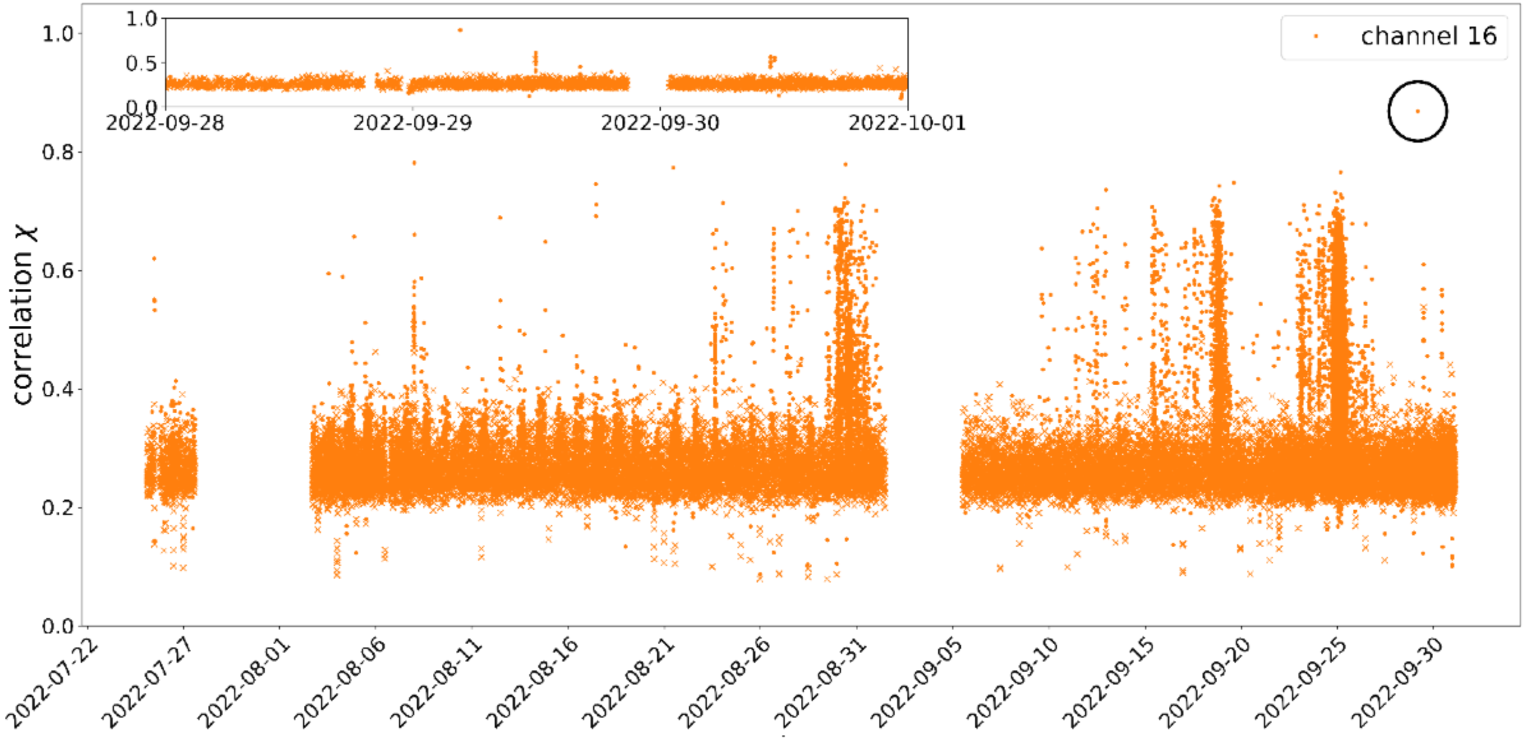


From simulations (including the detector), cosmic rays of 'useful' signal-to-noise ratio should be above 0.7 up to 0.95 for high SNR

Cosmic ray candidate(s)?

What the data tells us

- Using un-blinded data only
- Region above 0.9 essentially empty, but isolated high correlating signals



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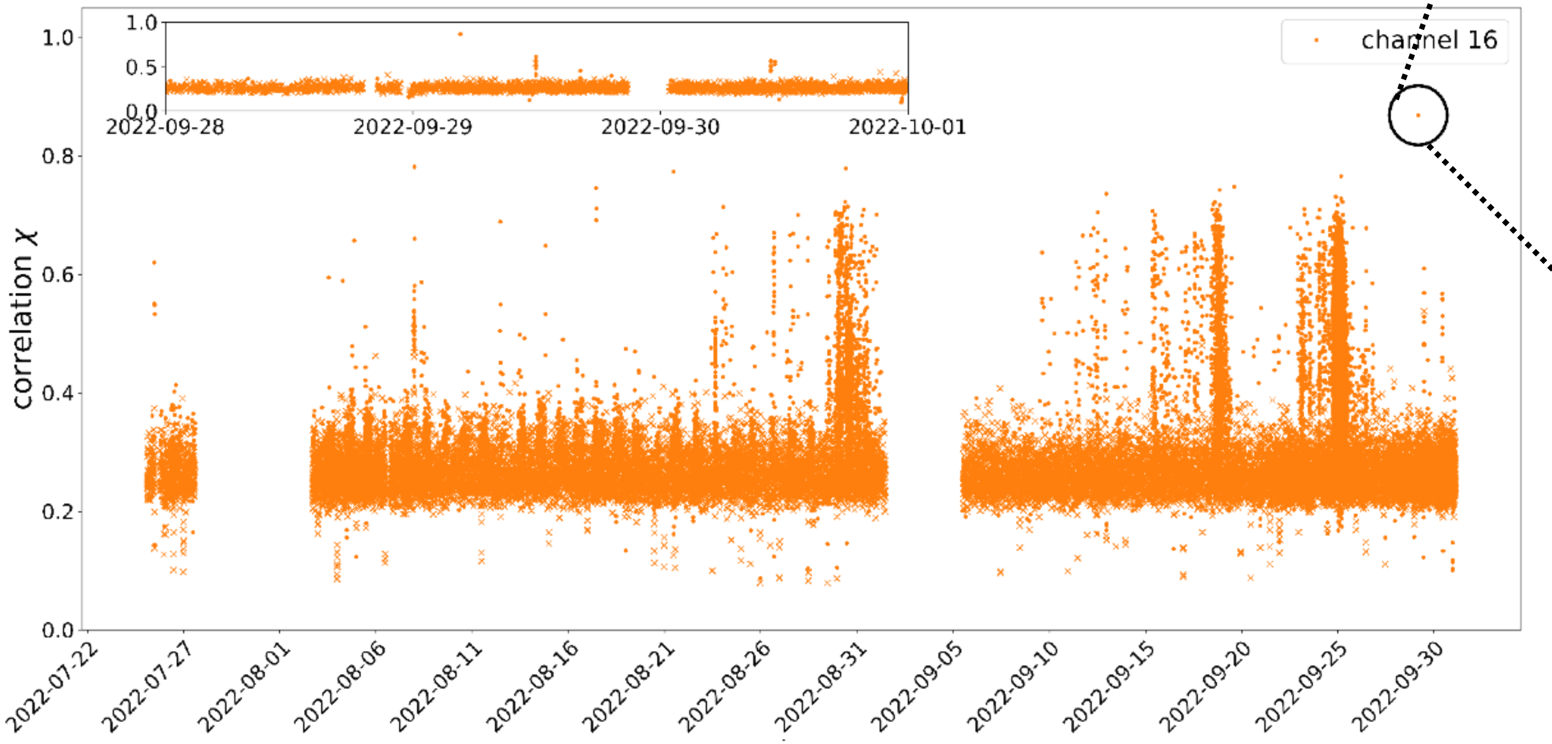
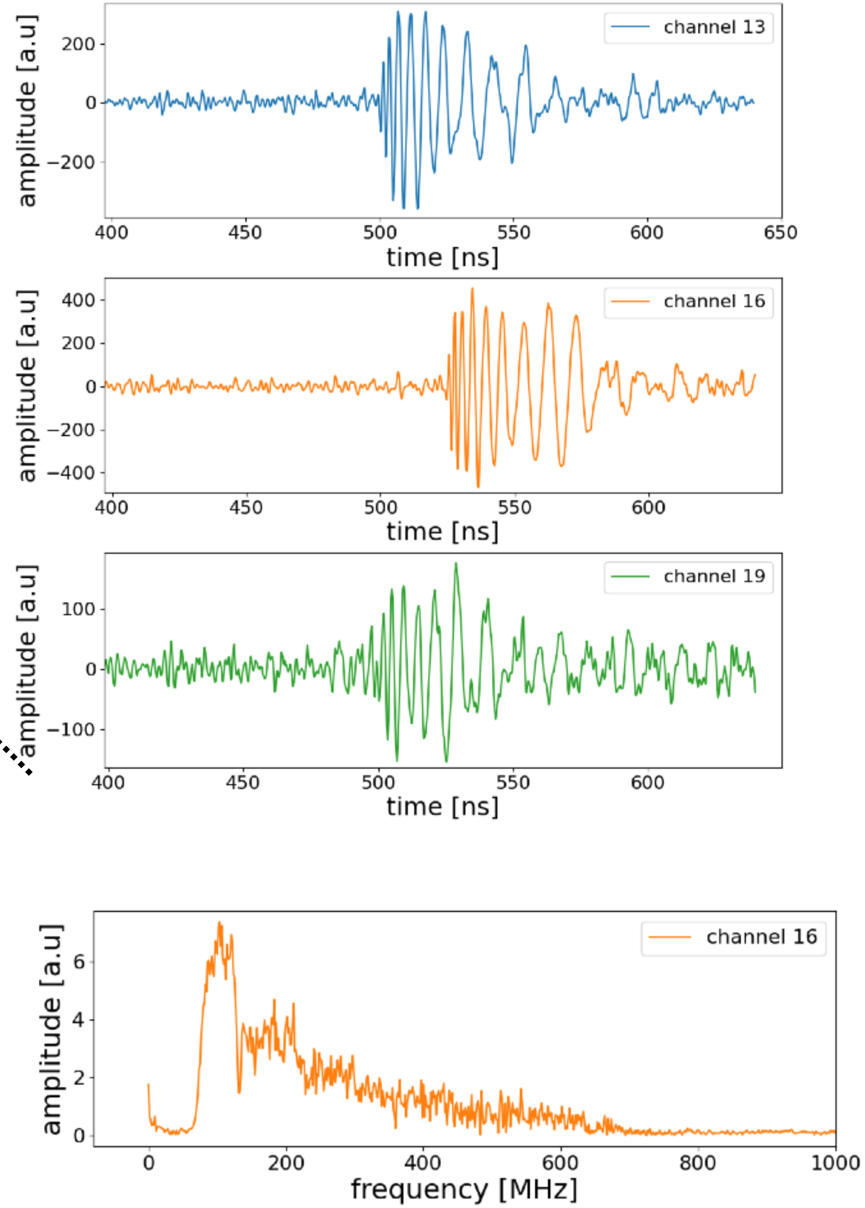


This looks very much like a cosmic ray!

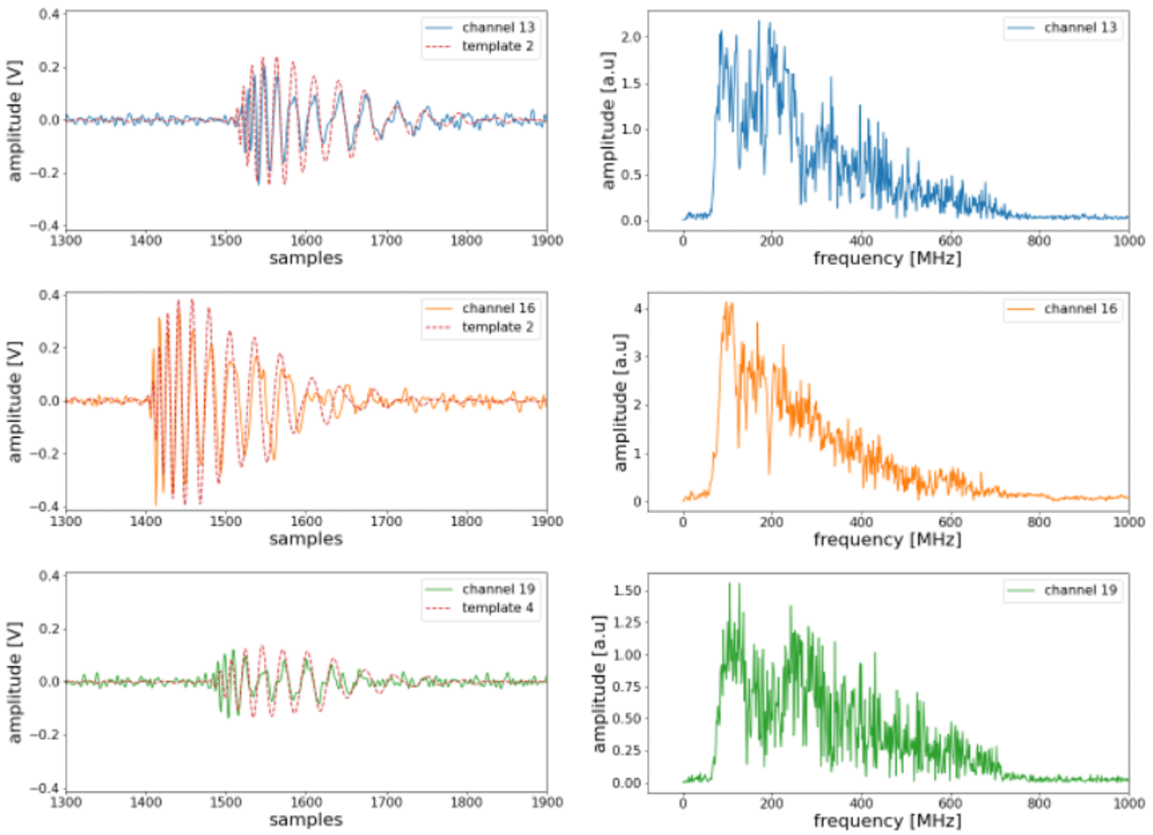


No cosmic rays?

Yes, but our modeling still off

- Question of systematics?
- Station is a complex system, fully modeled in simulations: this is first verification
- **Checks ongoing:** refractive index, digitizer artifacts and calibration, temperature dependence, faulty timing calibration, antenna VEL, amplifier non-linearity, …
- Probably some group delay still unaccounted for
- Work in progress

Candidate measured: $\chi = 0.82$; expected: $\chi > 0.95$



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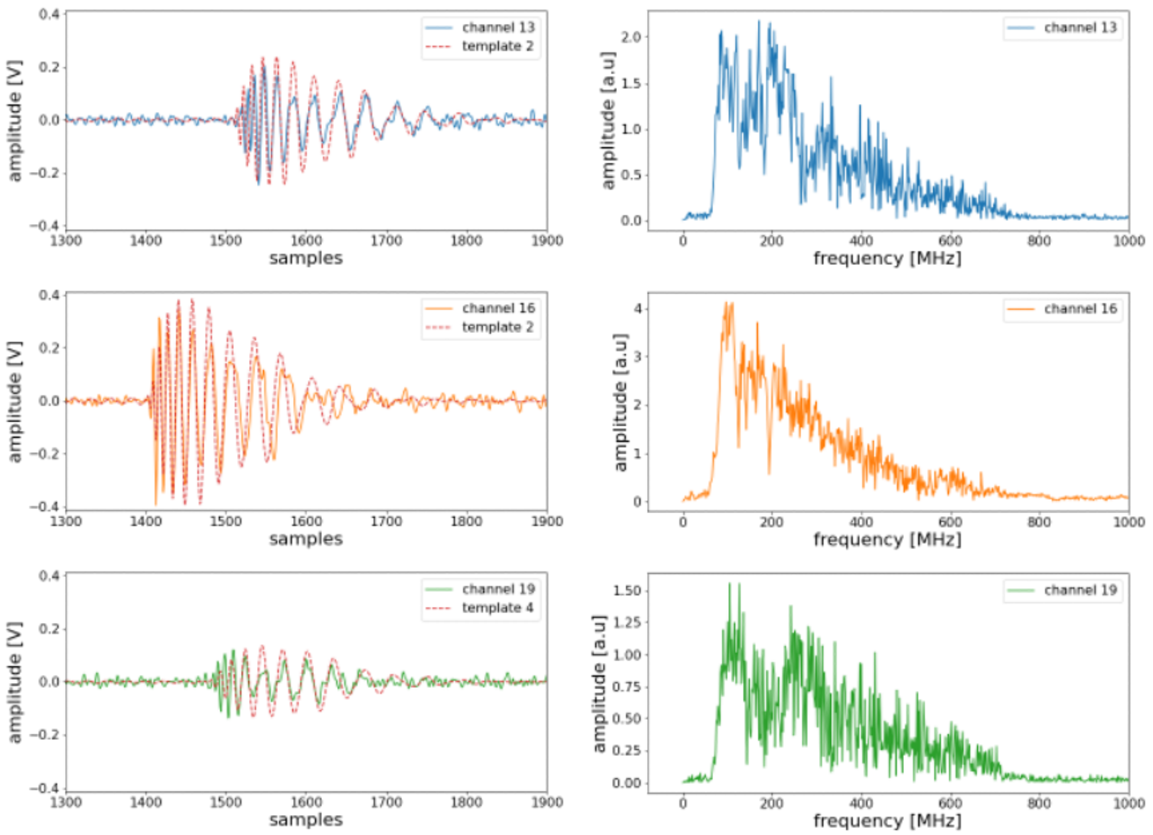

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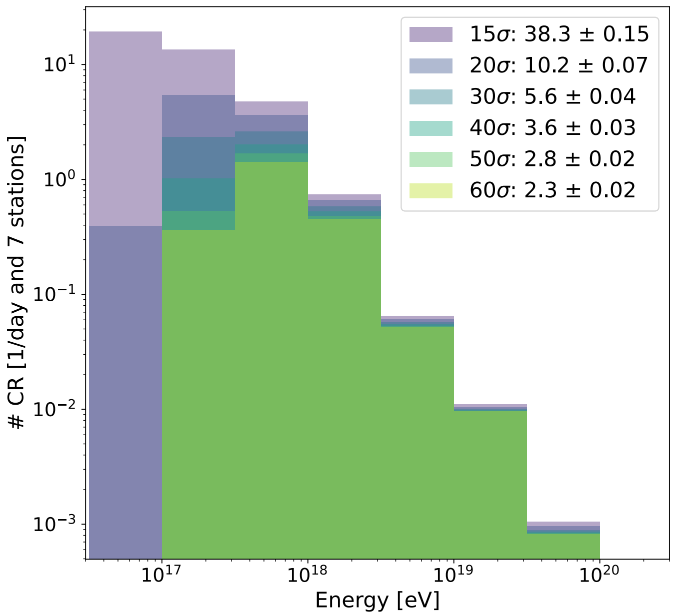
- RNO-G system very low noise, but also very complex (many channels, RF over fibre, new chips, new power system, new experimental site, very large bandwidth, …)
- Sensitive to details that may not have been investigated before
- Important to build trust in our understanding of the instrument before claiming: Neutrinos!

How many cosmic rays does RNO-G expect?

Another challenge: the question of the trigger

- The number of cosmic rays that RNO-G expects to see crucially depends on the trigger threshold
  - Optimistic: 38 per day and 7 stations
  - Conservative: 2 per day and 7 stations
- Current best estimate (V2 DAQ trigger): 30σ



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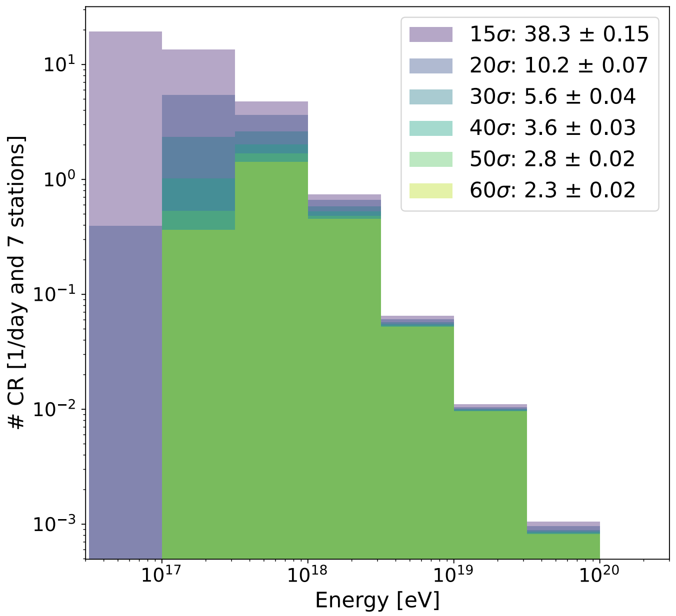
    - Sensitive to pulse shapes
    - Channel-to-channel variations large
    - Some temperature variations
- Modeling challenging and may need after-the-fact tuning with in-field data

PhD thesis, Lilly Pyras



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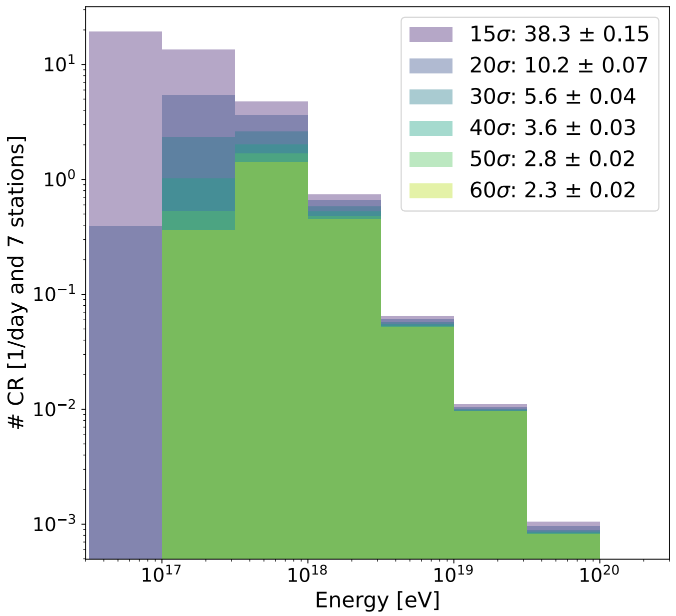

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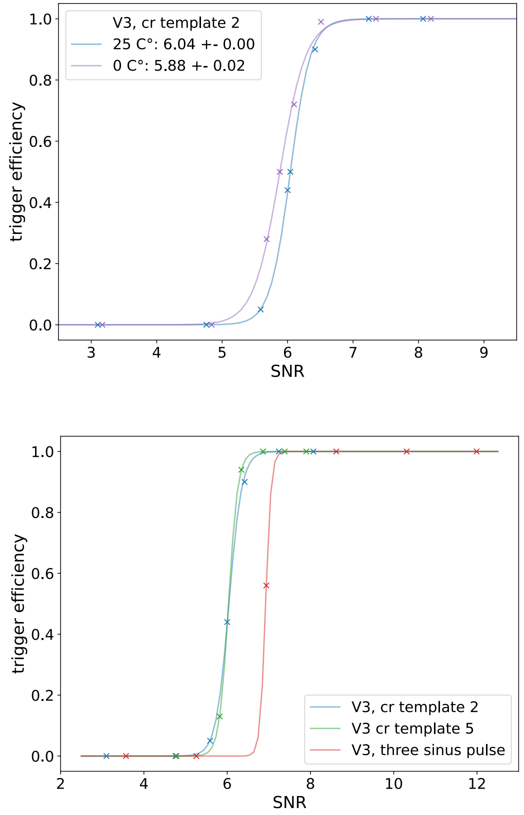

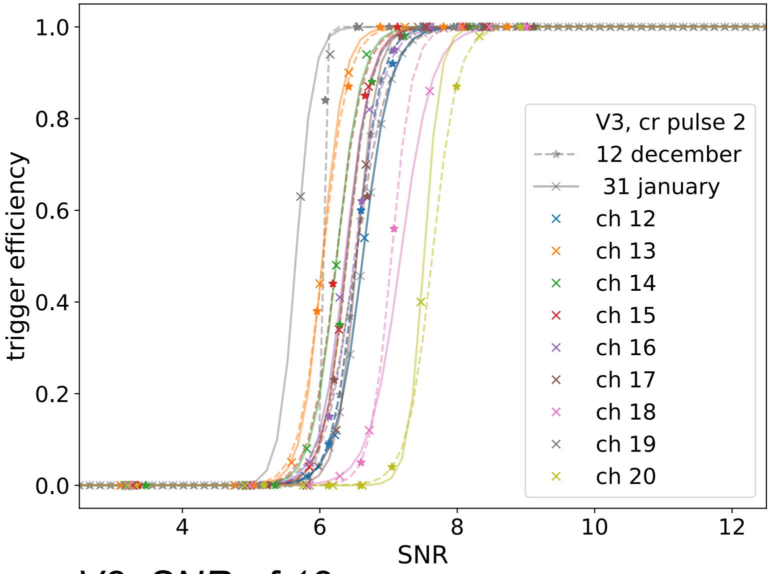

V2: SNR of 12 (in these units)

Cosmic rays in deep component of RNO-G

Work starting: first search for deep-only events and tested with deep & shallow from after 2024

- Derive an analysis of several features that are expected to separate relevant signals from noise
- Relies on prior experience with other analyses
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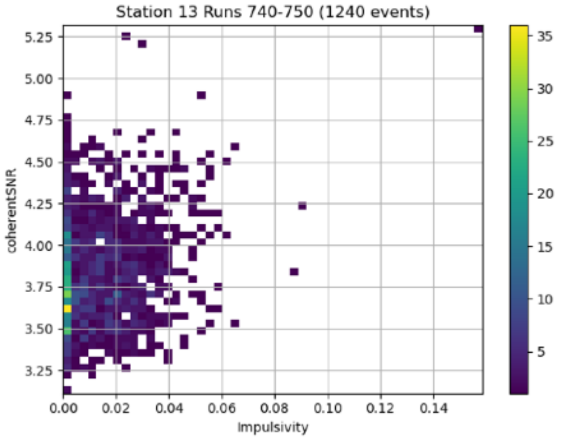
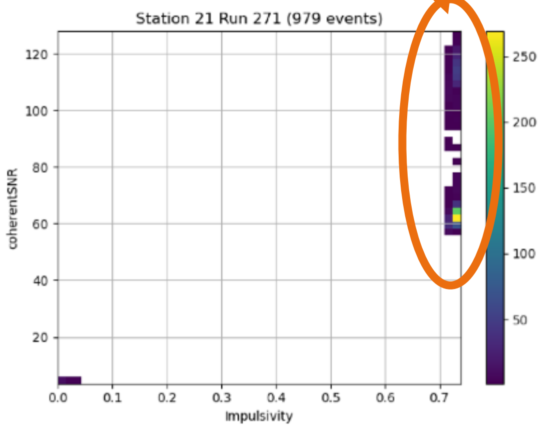
Noise in deep stations



Bermtop Pulsing



Conclusions

RNO-G as cosmic ray detector

- RNO-G will be a very large neutrino detector, but is also a reasonably cosmic-ray detector
- RNO-G uses cosmic-rays
  - to validate detector
  - to calibrate detector
  - to understand backgrounds
- First cosmic-ray candidates identified
- Self-trigger works, but will be improved for more cosmic rays
- Detailed studies on-going in the lab and field to get hardware understand to < 10% level still ongoing