Snowmass2021 - Letter of Interest

The Radio Neutrino Observatory in Greenland (RNO-G)

Thematic Areas:
■ (CF7) Cosmic Frontier: Cosmic Probes of Fundamental Physics
■ (IF10) Instrumentation Frontier: Radio Detection
■ (NF04) Neutrino Frontier: Neutrinos from natural sources
■ (NF06) Neutrino Frontier: Neutrino Interaction Cross Sections
■ (NF10) Neutrino Frontier: Neutrino Detectors
■ (IF4) Instrumentation Frontier: Trigger and DAQ

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Abstract:

The highest energy neutrinos probe extreme astrophysical environments inaccessible via other messengers and weak interactions at the highest energies. Through unprecedented sensitivity to neutrinos above 100 PeV, the Radio Neutrino Observatory in Greenland (RNO-G) will be a powerful multi-messenger high-energy neutrino experiment. With construction of an array of several km^2 expected in 2021-2023, RNO-G will be the largest in-ice neutrino detector and the first ultra-high-energy neutrino observatory with a view of the Northern sky. RNO-G will also study the deployment and operation of dozens of stations of low-threshold in-ice neutrino detectors employing a hybrid design of deep and surface components, an important step for the development of the larger radio array planned for IceCube-Gen2.

1 Science Case

With the the discovery of a diffuse flux of astrophysical neutrinos [1–5] and the identification of the first candidate extra-galactic source of neutrinos [6;7], neutrinos have been established a powerful messenger in the exploration of the high-energy universe. The Radio Neutrino Observatory in Greenland (RNO-G) will extend the reach of multi-messenger neutrino experiments to energies above 100 PeV (ultra-high energies UHE), with a unique view of the Northern sky and the largest footprint of a radio neutrino experiment (see Fig. 1). It will provide several critical technological tests that will inform the design of the radio component of IceCube-Gen2.

Neutrinos are ideal messengers to study the sites of the highest energy particle acceleration in the universe. Because they only interact through the weak force, neutrinos point back to their sources, can reach Earth from the most distant corners of the universe, and provide a clear indication of hadronic, cosmic ray acceleration (see LoIs [8;9] for more detail). Above 100 PeV, astrophysical neutrinos can be generated through cosmic ray interactions with gas or radiation at (or near) some of the most energetic objects in the universe [10–16]. Cosmogenic neutrinos [17] expected due to interactions of cosmic rays with photon backgrounds [18;19] – and from observations of the cosmic ray spectrum [20;21] – are also expected at UHE [22–24]. The neutrino flux encodes information about the evolution and acceleration mechanisms at cosmological length scales.

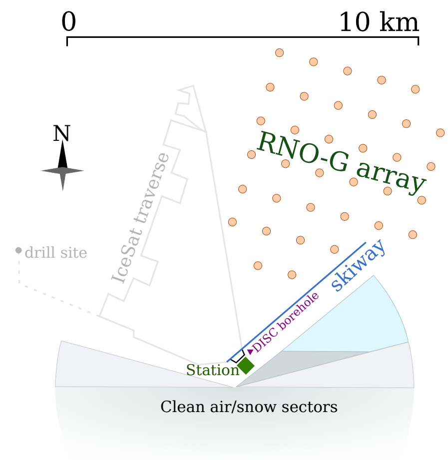

Figure 1: Planned array at Summit Station.

The first observation of a neutriono from a blazar, TXS 0506+056, coincident with a flare in γ-rays opened a new window into the non-thermal universe through multi-messenger observations [6;7]. However, the neutrino sky must be more complex; neutrinos from blazars cannot comprise the bulk of the diffuse neutrino spectrum [25–30] and many sources may extend to higher energies [10–16]. Bursts of neutrinos from the most explosive sources are expected to peak in flux at the EeV scale [11;12;31–61;61–76]. To fully understand the neutrino sky over cosmological distances, we must build a larger detector and extend observations up to EeV energies.

RNO-G builds on the experience and technical expertise of the Askaryan Radio Array (ARA) [77;78], the Antarctic Ross Ice-Shelf ANtenna Neutrino Array (ARIANNA) [79;80], and the Antarctic Impulsive Transient Antenna (ANITA) [81;82], and is an intermediate-scale discovery instrument for astrophysical and cosmogenic neutrinos at the highest energies. RNO-G will also serve inform the design for the for the radio component of the larger IceCube-Gen2. Together with the enlarged optical component, IceCube-Gen2 will be the ultimate neutrino observatory measuring the diffuse neutrino flux with an unprecedented sensitivity in a broadened energy range where both astrophysical and cosmogenic neutrinos are expected to reside [83]. The radio component will drive the sensitivity at the highest energies.

The Earth is opaque to neutrinos at PeV to EeV energies, such that UHE neutrino observatories are most sensitive to Earth-skimming neutrinos. Therefore, follow-up of TeV-scale IceCube events at higher energies requires a Northern detector. RNO-G will provide a unique view of the UHE Northern sky that is broad in declination and overlaps with the region of the sky where IceCube is most sensitive to lower-energy neutrinos. A single event observed with RNO-G will define the flux in a new energy regime, and even a non-detection will constrain the allowed flux through *multi-wavelength neutrino* observations. The overlap in sky coverage with IceCube will enable studies of several interesting flaring, transient sources over a broad energy band, as well as studies of point sources of high-energy neutrinos.

In case of detection of neutrinos, RNO-G will open the window to a new energy range for fundamental physics with neutrinos, allowing access to neutrino-nucleon cross-section measurements at EeV energies, as well as tests of the standard model validity (see[84;85] for details).

2 Technical Approach

RNO-G is designed to demonstrate the scalability of the radio detection technology, important for the design of IceCube-Gen2, while enabling the world's best UHE neutrino sensitivity through low thresholds and high efficiency.

Radio detection of neutrinos is possible through the Askaryan effect[86], where particle showers in dense media (in this case polar ice) cause nanosecond-scale radio pulses in the frequency range between 30 MHz and 1 GHz. Consequently, fast, broad-band and low-noise receivers and systems are needed to efficiently detect the rare signals. Multiple autonomous stations are combined into a detector array, covering several km^2, which requires the system to also be extremely robust and low-power, running fully on renewable energies, including for example custom RF-over fiber links and specialized broad-band antennas and amplifiers. As shown in Fig. 1, thirty-five stations on a 1 km spaced grid are planned to be deployed at Summit Station in Greenland by 2023.

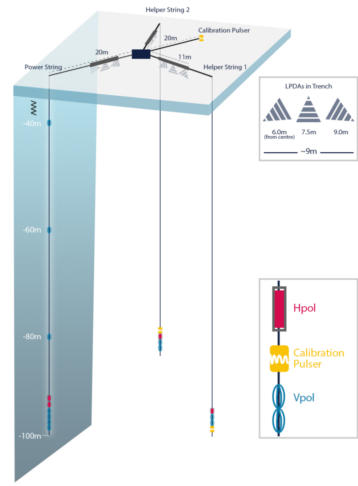

Figure 2: The RNO-G station design incorporates surface and deep antennas to search for ultra-high energy neutrinos with an efficient detector.

The RNO-G station design shown in Fig. 2 integrates a surface component and a deep component to each station. There are 9 surface channels per station and 15 deep channels, which span a depth of 100 m below the surface. The main trigger for the instrument is provided by the deep antennas to maximize effective volume, and the combination of the surface and deep antennas are critical for reconstruction and background rejection.

We will use an interferometric phased array to trigger RNO-G, similar to what has been demonstrated *in situ* at the South Pole on the ARA experiment[87;88] and has achieved the lowest demonstrated trigger threshold in the field. We expect to achieve the an elevation-averaged 50% trigger efficiency point at a 2σ threshold in voltage, comparable to the world leading performance of the existing ARA system. RNO-G stations are designed to be low-power and fully autonomous, relying on solar power for operations (while still considering options for wind power), and LTE communications for data transfer, command, and control. The design has been optimized for large-scale deployment, such as utilizing fast mechanical drilling.

3 Summary

RNO-G will be the first ultra-high-energy neutrino experiment with a view of the Northern Sky. With a total of 35 stations expected to be deployed within the next three years, it will also achieve the largest effective volume at EeV energies. The design builds on experiences from the last decade and the light-weight design is readily scalable to the $\mathcal{O}(100)$ km^2 needed to reveal the sources of both astrophysical and cosmogenic neutrinos.

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