Snowmass2021 - Letter of Interest

GRAND: Giant Radio Array for Neutrino Detection

Thematic Areas:

■ (NF4) Neutrinos from natural sources
■ (NF10) Neutrino detectors
■ (CF7) Cosmic probes of fundamental physics
■ (IF10) Radio detection
■ (TF11) Theory of neutrino physics

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Abstract: The Giant Radio Array for Neutrino Detection (GRAND) is a planned large-scale observatory of ultra-high energy (UHE) cosmic messengers (cosmic rays, gamma rays, and neutrinos) with energies exceeding 10^8 GeV. The ultimate goal is to solve the long-standing mystery of the origin of UHE cosmic rays. Three key features of GRAND will make this possible: its large exposure, sub-degree angular resolution, and sensitivity to the unique signals made by UHE particles. The strategy of GRAND is to detect the radio emission coming from the extensive air showers that develop in the terrestrial atmosphere as a result of the interaction of UHE cosmic rays, gamma rays, and neutrinos. GRAND will reach an unparalleled sensitivity to cosmogenic neutrino fluxes of $\sim 10^{-10}$ GeV cm^{-2} s-1 sr^{-1}. Because of its sub-degree angular resolution, GRAND will also search for point sources of UHE neutrinos, steady and transient.

Introduction.— Discovering the origin of ultra-high-energy cosmic rays (UHECRs), with energies of 10^9 GeV and above, is key to understanding the high-energy Universe. The origin of UHECRs remains an open question, due to the facts that they are deflected by extragalactic and Galactic magnetic fields—so they do not point back at their sources—and that, at the highest energies, above 50 EeV (1 EeV $\equiv 10^9$ GeV), they are unable to propagate for over 100 Mpc due to their losing energy on cosmic photon backgrounds.[1;2]

However, there is a way to circumvent these limitations: while propagating, the interaction of UHECRs with cosmic photons produce *cosmogenic* UHE gamma rays and neutrinos, with energies in the EeV scale.[3–7] While the gamma rays quickly cascade down to MeV–GeV, the neutrinos travel unstopped, without interaction or deflection, over distances of Mpc–Gpc, their ultra-high energies preserved except for the effect of cosmological expansion. The size and shape of the cosmogenic neutrino energy spectrum reflects the properties of their parent UHECRs—*i.e.*, their mass composition, maximum energy, and the shape of their emitted spectrum—and of their sources—*i.e.*, the evolution of their number density with redshift. In addition, UHE neutrinos may also be emitted directly from the sources if UHECRs interact with background matter and radiation in them, providing a way to reveal individual sources[8–19]

UHE neutrinos, long sought, remain undiscovered. Further, because the properties of UHECRs and their sources are largely uncertain, so is the predicted flux of UHE neutrinos; see Fig. 2, right. Recently, stronger limits on the flux of UHE neutrinos,[20;21] improved UHECR observations,[22–24] and improved computations of UHE neutrino production have lowered the predicted UHE neutrino flux significantly.[25–27] The Astro2020 Decadal Survey identified the need for UHE observatories if we are to discover UHE neutrinos.[28;29]

GRAND.— The Giant Radio Array for Neutrino Detection (GRAND) is a planned UHE multi-messenger observatory designed with the goal of discovering UHE neutrinos even in scenarios where their flux is low. GRAND will look for the radio emission coming from extensive air showers (EAS) in the atmosphere, initiated by the decay of tauons produced by Earth-skimming UHE ν_τ that interact underground, close to the surface.[30] To achieve sensitivity to low fluxes, GRAND will cover large areas with sparse arrays of antennas.

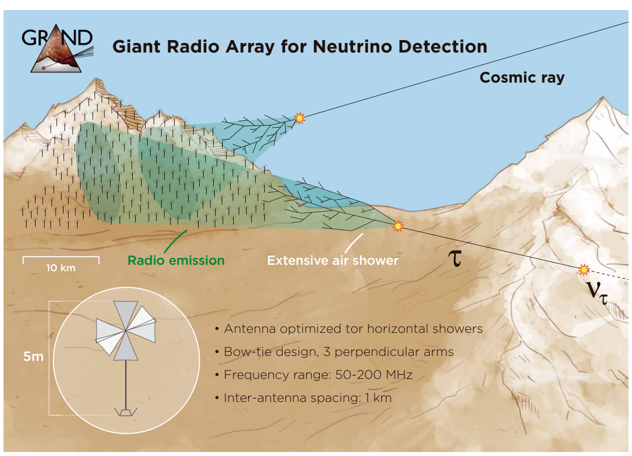

Figure 1: GRAND detection principle. Figure from[31].

GRAND will be especially sensitive to very inclined showers, *i.e.*, showers coming close to the horizon. The large size of the radio footprint for very inclined showers makes it possible to instrument a large area using a sparse array. We will implement a modular strategy for deploying GRAND. The final configuration will consist of $\sim$20 geographically separate and independent sub-arrays of $\sim$10000 km^2 each. Each sub-array will have about 10^4 antennas and will be able to explore a rich science program of its own. This modular strategy will allow us to build up sensitivity to progressively smaller fluxes of UHE particles, while distributing the construction efforts.

The sub-arrays will be deployed on sites with topographies favorable to the radio detection of UHE neutrinos. We take several site features into account to maximize the collection efficiency, optimize the antenna sensitivity, and improve the reconstruction. For example, a mountain slope with an elevation of 1000–2000 m acts as an efficient projection screen for the forward-beamed radio signal of a neutrino-initiated shower that emerges from the ground, while antennas lying in a valley would fail to detect the signal. The difference in antenna altitudes on a slope also provides an improved reconstruction of the zenith angle for very inclined showers. The sub-arrays will be ideally deployed on a mountain slope facing another

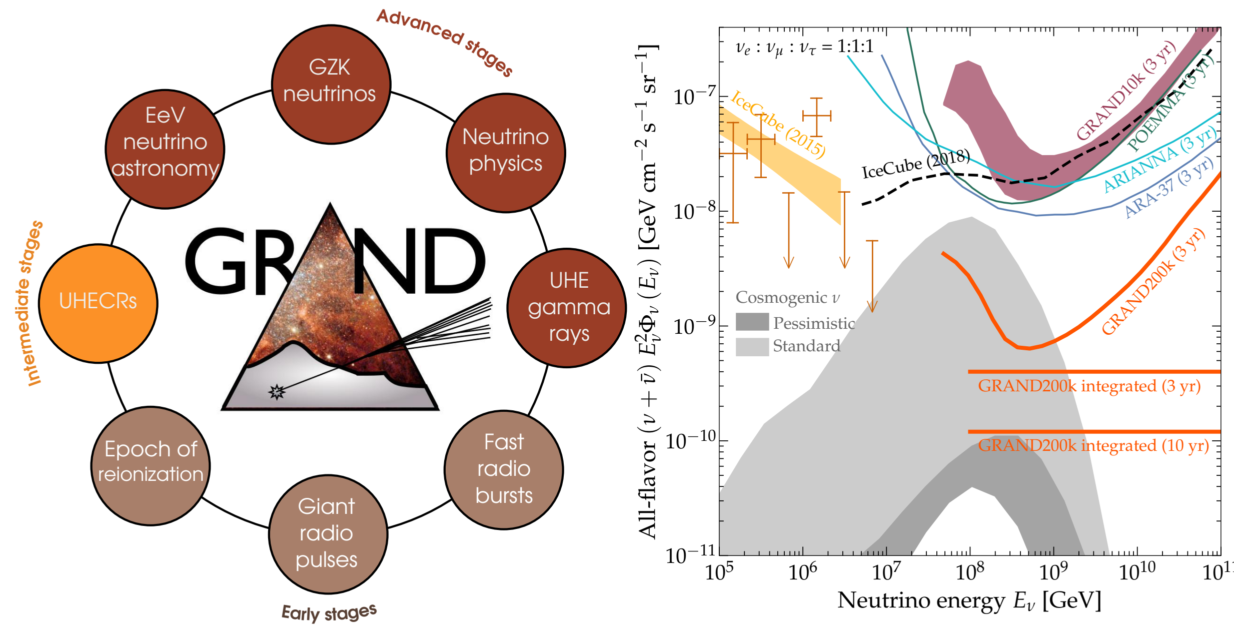

Figure 2: *Left:* GRAND science program. *Right:* The sensitivity of GRAND to a diffuse flux of UHE neutrinos. Figures from [31].

mountain that would serve as a target for the interaction of downward-going neutrinos. Simulations indicate that, for specific topographies, these downward-going "mountain" events could be as frequent as the upward-going Earth-skimming events. The opposing mountain will also act as a natural screen to stop very inclined UHECRs, improving the background rejection.

Science program and neutrino sensitivity.— Figure 1, left, shows that GRAND has a rich science program that includes not only UHE neutrinos, but also UHECRs, UHE gamma rays, tests of fundamental physics,[32;33] and studies of radio-emittng astrophysical sources. We refer to the GRAND white paper[31] for details and focus here only on UHE neutrinos. Figure 1, right, shows a representative range of cosmogenic neutrino flux predictions based on the measured UHECR spectrum and mass composition[26]. GRAND has a design differential sensitivity that covers a large part of the standard flux range, reaching sensitivities of a few times 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}. Further, due to large area coverage and the leverage provided by the inclination of the mountain slopes, GRAND should be able to achieve sub-degree angular resolution, making it also sensitive to searches of UHE point sources and transient neutrino events.[34]

Antenna design.— The radio signals from EAS initiated by Earth-skimming neutrinos will arrive with zenith angles close to 90° and a polarization that is mostly horizontal. This introduces a serious challenge for radio-detection, as the diffraction of radio waves off the ground severely alters the antenna response. We have designed an antenna with a high detection efficiency along the horizon to address this problem: the HorizonAntenna, an active bow-tie antenna with a relatively flat response with azimuthal direction and frequency, inspired by the designs in CODALEMA,[35] and AERA.[36]. We operate it in the frequency range of 50–200 MHz (instead of the maximum 80–100 MHz used in most existing arrays) to be able to detect radio Cherenkov rings. Extending the frequency band to 200 MHz significantly reduces the radio background, improves the signal-to-noise ratio, and lowers the detection threshold[37].

The GRAND Collaboration has surveyed radio conditions at potential construction sites and is currently in the process of deciding on the construction site of the 300-antenna engineering array, GRANDProto300[31].

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