

GRAND, a Giant Radio Array for Neutrino Detection: Objectives, design and current status

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Abstract. The Giant Radio Array for Neutrino Detection (GRAND) aims to answer one of the most pressing open questions in astrophysics: what is the origin of ultra-high-energy cosmic rays (UHECRs)? It will do so indirectly: UHECRs make secondary UHE neutrinos which encode information about the properties of UHECRs and their sources. GRAND is designed to discover UHE neutrinos even under pessimistic predictions of their flux, reaching a sensitivity of $6 \times 10^{-9} \text{ GeV.cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$ around 10^9 GeV . It will do so by using 20 sub-arrays of 10 000 radio antennas forming a total detector area of 200 000 km^2 , making it the largest air-shower detector ever built. With this sensitivity, GRAND will discover cosmogenic neutrinos in 3 years of operation, even in unfavorable scenarios. Because of its subdegree angular resolution, GRAND will also search for point sources of UHE neutrinos, both steady and transient. Moreover, GRAND will be a valuable instrument for astronomy and cosmology, allowing for the discovery and follow-up of large numbers of radio transients - fast radio bursts, giant radio pulses - and studies of the epoch of reionization. In this contribution we will present briefly some of the science goals, detection strategy, construction plans and current status of the GRAND project.

1 The GRAND science case

Ultra-high-energy cosmic rays (UHECRs), with energies above 10^8 GeV , are the most energetic particles currently known. They are purportedly made in powerful cosmic accelerators, though none has been identified. The recent observation of neutron-star merger GW170814 has brilliantly shown that the challenges of high-energy astronomy will be solved by combining data from a large number of multi-messenger experiments. A complete picture of UHECR sources will come from jointly studying cosmic rays, neutrinos, and gamma rays across all available energies, but *EeV neutrinos are the most promising way to probe sources of UHECRs beyond 100 EeV*.

The Giant Radio Array for Neutrino Detection (GRAND) is a proposed detector primarily designed to discover and study the sources of UHECRs. It will achieve this directly, by collecting large numbers of UHECRs; and indirectly, by looking for UHE gamma rays and UHE neutrinos.

Presently, the most precise results on UHECRs come from the two largest cosmic-ray detectors, the Pierre Auger Observatory [1] and the Telescope Array (TA) [2]. GRAND is expected to have an

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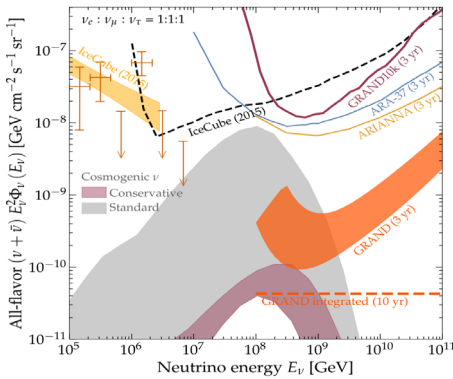


Figure 1. Predicted cosmogenic neutrino flux, compared to experimental upper limits and sensitivities. The gray shaded region brackets all “standard” parameters of UHECR models [3]. The darker shaded area show conservative, more pessimistic scenarios. The astrophysical neutrino signal below 3 PeV was reported by IceCube. Existing upper limits (90% C.L.) are from ANITA-II, Auger, and IceCube. Projected 3-year sensitivities of planned instruments are for ARA-37, ARIANNA, POEMMA, the partial configuration GRAND10k, and the full configuration GRAND200k. Plot taken from *Ke Fang et al.* (GRAND Collaboration) PoS(ICRC2017) 996. arXiv:1708.05128v1

UHECR event rate 20 times higher than Auger. In 1 year of operation, GRAND should detect 6 400 events above $10^{10.5}$ GeV, versus 320 in Auger; and 150 events above 10^{11} GeV, versus 8 in Auger. This would enable GRAND to make measurements with unprecedented statistics of the proton-nucleon cross-section, the distribution of arrival directions and the possible correlation with nearby sources.

But direct detection of UHECRs is not enough to find the sources. It has already been established that the Universe is opaque to UHECRs. During propagation, UHECRs interact with the cosmic microwave background (CMB) and the extragalactic background light (EBL) by photo-pion production. As a result, UHECRs above 40 EeV rarely survive for more than 100 Mpc. The range of predictions for the resulting cosmogenic neutrino flux is wide (see Fig. (1)), as we are uncertain about how UHECR sources evolve with redshift, how particle acceleration occurs, and what is the mass composition of UHECRs. Existing detectors will only be able to discover UHE neutrinos if the flux lies close to the current upper limits. Further, even if a discovery is made in these detectors, the event rate will likely be insufficient to characterize the spectra and extract from it information about UHECR sources. To find the origin of UHECRs beyond 100 EeV, there is need for a UHE neutrino detector capable of discovering and characterizing UHE neutrinos, even in unfavorable scenarios.

Cosmogenic UHE Gamma Rays are also a guaranteed by-product of photo-pion production of UHECRs with the CMB, and they are also generated through inverse-Compton scattering of CMB photons by electrons or positrons produced by UHECRs scattering off the CMB. Furthermore, if UHE photons are produced inside astrophysical sources, they would point back to them. The detection of astrophysical UHE photons would be possible with GRAND for nearby sources (≤ 10 Mpc). The detection of UHE photons, either astrophysical or cosmogenic, would present an opportunity to probe the little-known distribution of the diffuse cosmic radio background (CRB). The energy range from 10^{10} to 10^{11} GeV, where GRAND will reach full efficiency for photon detection, is optimal to constrain the impact of the CRB on UHE photon propagation.

EeV neutrinos can also be produced when UHECRs interact with photons and hadrons inside the sources themselves. Fig. (2) summarizes predictions of the fluxes of EeV neutrinos produced in the most powerful astrophysical sources. The intermediate 10 000-antenna GRAND10k array could detect neutrinos from newborn pulsars with 3 years of operation, and characterize their spectrum. The full 200 000-antenna GRAND200k array could achieve the same for all source models shown.

Since GRAND will detect particle cascades with the radio technique, it will be a unique instrument for detecting the cosmological radio signal at 21 cm. This would open up a window to previously unexplored epochs of the Universe, between redshifts $z = 1000$ — the surface of last scattering — and $z = 6$ — the end of the epoch of reionization (EoR). Measuring the properties of the 21cm radio signal would reveal how the Universe transitioned from a dark phase to a bright phase, were baryonic matter

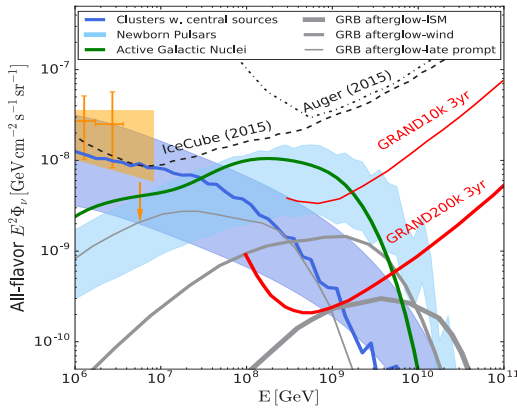


Figure 2. Predicted neutrino flux from different classes of astrophysical sources, compared to upper limits on UHE neutrinos from IceCube and Auger, and projected 3-year sensitivity of GRAND10k and GRAND200k (see Section 3). Several source classes can account for the observed UHECR spectrum: galaxy clusters with central sources, fast-spinning newborn pulsars, active galactic nuclei, and afterglows of gamma-ray bursts. Plot taken from *Ke Fang et al.* (GRAND Collaboration) PoS(ICRC2017)996. arXiv:1708.05128v1

became pre-eminent in the formation and evolution of cosmic structures [4–6]. GRAND frequency range fits optimally to search for the global EoR signal, and we will be able to explore the potential to carry out this measurement already in the GRANDProto300 construction stage (see Section 3).

Due to its sensibility to transient radio signals, GRAND is also capable of detecting Fast radio bursts (FRBs) and Giant Radio Pulses (GP): single, short electromagnetic pulses coming from outer space, typically lasting a few ms, emitted in a broad frequency band, and dispersed in arrival times. The brevity and large dispersion of these pulses suggest that FRBs are associated to compact sources with characteristic sizes of a few thousand kilometers, located at extragalactic distances while GP are associated to compact objects in our galaxy, like the pulsar in the Crab Nebula.

Extrapolations from present-day small-number statistics suggests that a few thousand FRBs occur every day. Many theories have been proposed to explain FRBs, but their origin remains a mystery; see [7] for a review. With potentially orders of magnitude more FRBs detected than the currently available sample, GRAND could bring important clues in answering fundamental questions including what the space density of FRBs in the local Universe is, how do their radio spectra in the low-frequency range evolve, whether the spectra at low frequencies is as dispersed as at high frequencies, whether there is a low-frequency cut-off in the spectrum, and how common FRB repeaters are.

2 Detection strategy

For neutrinos at EeV energies, the interaction length is too long for the atmosphere to represent a relevant target, except at nearly horizontal directions. In rock, the interaction length is a few hundred km, making the Earth opaque to neutrinos. However, if the interacting neutrino is a ν_τ , the heavy mass of the tau generated in the interaction suppresses its radiative losses and its short lifetime (0.29 ps) gives it a range of 50 meters per PeV of energy before decaying. As a result, a tau born from an UHE ν_τ underground could exit the rock and decay above the antenna array, triggering a particle shower that emits a radio signal detectable by the antennas, as sketched in Fig. (3).

The radio emission mechanisms from air showers, combined with the Cherenkov effect, result in complex emission signals in terms of amplitude, frequencies, and polarization, which are well understood and can be modeled in great detail for a given shower geometry. The radio-detection of an air shower at different locations inside the radio footprint allows to reconstruct the shower geometry from data and to infer the properties of the primary by means of best-fit procedures. GRAND will profit from the momentum experienced by the field of radio detection of extensive air showers thanks

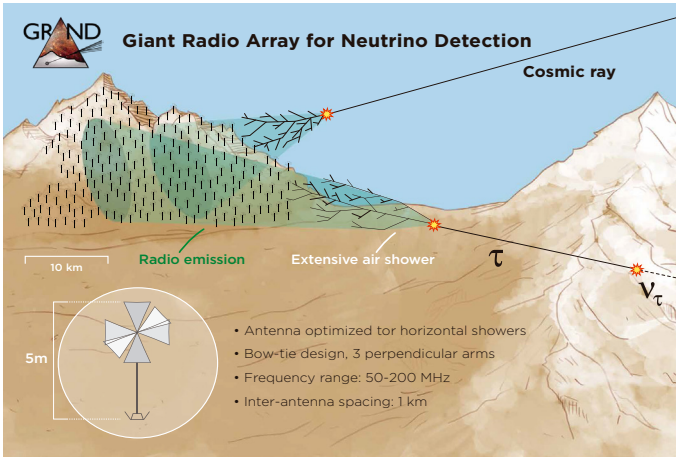


Figure 3. Sketch depicting the GRAND detection strategy: extensive air showers generated by the decay of a τ lepton originated in the interaction of a ν_τ , are detected by an array of antennas on a mountainous topography. These events come within a few degrees from the horizon as Earth-skimming events and horizontal atmospheric events. Cosmic rays also generate extensive air showers and can be detected, in general with a much steeper incoming direction, which makes them easier to differentiate.

to drastic technological, theoretical and numerical advances done in the last decade. Radio detection has become a mature and autonomous technique rivaling with standard techniques, as demonstrated by AERA, CODALEMA, LOFAR, Tunka-Rex, and TREND; see [8–10] for recent reviews. The technique is particularly well-adapted for the detection of inclined showers, as induced by neutrinos: radio waves are not attenuated in the atmosphere, leading to 100-km² radio footprints on the ground, tens of kilometers away from the shower source (see for example Fig. (4)). Furthermore, radio antennas are cheap and robust and thus ideal for the deployment of giant arrays.

GRAND will thus focus on detecting extensive air showers with incoming directions within a few degrees from the horizon: Earth-skimming events and horizontal atmospheric events. We have designed the GRAND detection units to have a high detection efficiency along the horizon — we call the design HORIZONANTENNA. Since the severity of ground-reflection effects decreases with h/λ , where h is the detector height above ground and λ is the radio wavelength, we set the HORIZONANTENNA at $h = 5$ m and the frequency range to $f > 50$ MHz ($\lambda < 6$ m). Because we would like to detect radio Cherenkov rings — which could help background rejection and signal reconstruction — we set the upper limit of the frequency range to $f = 200$ MHz. Recent studies confirm that extending the frequency band to an upper limit around 200 MHz significantly improves the signal-to-noise ratio and lowers the detection threshold compared to the traditional band [11].

The HORIZONANTENNA is a bow-tie antenna, which offers a relatively flat response as a function of azimuthal direction and frequency. Its design is inspired by the GRANDProto35 antennas [12], with 3 perpendicular arms (X, Y, Z) oriented along two horizontal directions and a vertical one. Its size is half GRANDProto35 antennas, as the frequency range for GRAND is 50–200 MHz while for GRANDProto35 it is 30–100 MHz. A prototype of the HORIZONANTENNA will be tested in the GRANDProto35 setup in 2018.

3 construction plans and current status of the GRAND project

A staged construction approach will allow us to validate the key steps required for the final configuration, while also achieving important science milestones with the partial configurations, commensurate with other, smaller-scale neutrino detectors.

GRANDProto35 [12], the first construction stage of GRAND, will lay the groundwork for the next stages. It consists of 35 radio stations deployed at the same site as TREND [14–16], in the Tian Shan mountains, in the XinJiang province of China. It will test whether radio detection of air showers

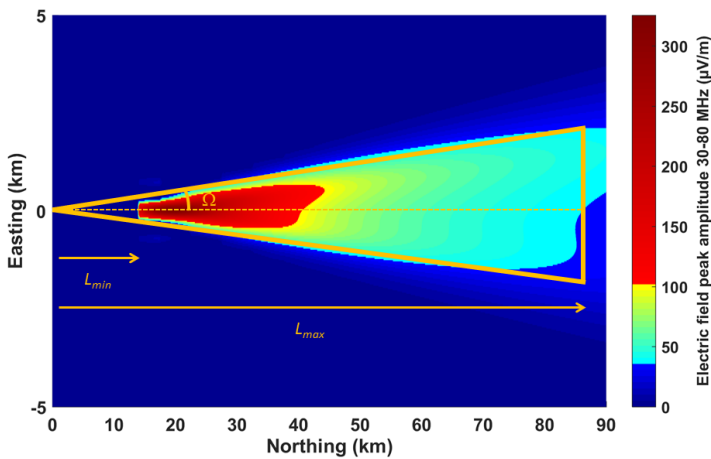


Figure 4. Expected distribution of the 30–80 MHz electric-field peak value on the ground for a ZHAireS [13] simulation of a shower with energy $3 \cdot 10^8$ GeV induced by a tau decaying at position (0, 0), at a height of 50 m above ground, with an angle of elevation of 0.5° above the horizontal, and flying North. Overlaid is the truncated triangular area defining the zone inside which the electric field is above $30 \mu\text{V m}^{-1}$.

is possible with an efficiency higher than 80% above threshold and a background rejection that keeps the ratio of false positives to true positives below 10%. At the moment of writing, GRANDProto35 is being deployed and the first stations are taking data.

GRANDProto300, the engineering stage of GRAND, will provide experimental validation of our simulations of radio-detection of horizontal showers. GRANDProto300 will span an area of 100–300 km². Funding for this stage has already been secured and several candidate sites have been identified in China. In order to finalize deployment of the array in 2020, the final site will be selected before end of 2018.

When completed, GRANDProto300 will be the largest self-triggered radio array for air-shower detection. While it will not be large enough to detect UHE neutrinos, it will be perfectly suited to study UHECRs in the range 10^8 – 10^9 GeV, on account of its large aperture for cosmic rays with zenith angles larger than 65° . Up to 10^5 cosmic-ray events are expected in the first two years of operation. The spectrum and mass composition of cosmic rays obtained with GRANDProto300 will be compared to results from previous experiments in order to confirm that very inclined air showers can be detected and accurately reconstructed using radio.

GRAND10k, the first large element of the full GRAND array, will be the first radio array that is sensitive to UHE neutrinos. It will consist of 10 000 antennas deployed over an area selected for its suitability for the detection of neutrino-initiated air showers — a *hotspot*. The design of GRAND10k will be based on that of GRANDProto300, after optimization of power consumption, triggers, and data transfer. Simulations show that GRAND10k will be able to probe flux models of cosmogenic neutrinos made by light UHECRs, with a sensitivity comparable to the planned final configuration of ARA. GRAND10k will be the largest UHECR detector, with an area 3 times larger than Auger or of the planned extension TAX4 [17], and a similar aperture to Auger — around 6 000 km² sr for energies above 10^{10} GeV. The field of view of GRAND10k overlaps with Auger and TAX4, which allows for cross-correlating with both. GRAND10k will also be large enough to detect giant radio pulses.

GRAND200k will be the full planned configuration of GRAND that will address the physics goals set out in Section 1. The completion and operation of the final configuration of GRAND — an array of 200 000 radio-detection units deployed over 200 000 km² — is a significant undertaking. GRAND200k will be deployed in separate sub-arrays, each containing $\sim 10^4$ detection units deployed on sites with topographies favorable to neutrino detection, making GRAND200k a replication of GRAND10k several times over with the added advantage of providing a better sky coverage. We do

not expect important design changes from GRAND10k; the antennas, electronics, triggers, and data collection will have been validated in the GRAND10k stage or earlier.

Several sites in China present favorable conditions, along with favorable logistics and other practical considerations, making it the leading candidates to host GRAND. In parallel, we are evaluating the deployment of GRAND sub-arrays in several other locations in the world that would enlarge the instantaneous field of view of GRAND, at the cost of a reduced flux sensitivity. Following this strategy would improve the prospects of detection of transient events and may allow to reconstruct the direction of origin of FRBs, provided they are simultaneously detected by multiple sub-arrays.

Acknowledgments

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