PROCEEDINGS OF SCIENCE

The Giant Radio Array for Neutrino Detection

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Ultra-high-energy cosmic neutrinos (UHE), with energies above 100 PeV, are unparalleled probes of the most energetic astrophysical sources and weak interactions at energies beyond the reach of accelerators. GRAND is an envisioned observatory of UHE particles - neutrinos, cosmic rays, and gamma rays - consisting of 200,000 radio antennas deployed in sub-arrays at different locations worldwide. GRAND aims to detect the radio emission from air showers induced by UHE particle interactions in the atmosphere and underground. For neutrinos, it aims to reach a flux sensitivity of $\sim 10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1}, with a sub-degree angular resolution, which would allow it to test the smallest predicted diffuse fluxes of UHE neutrinos and to discover point sources. The GRAND Collaboration operates three prototype detector arrays simultaneously: GRAND@Nançay in France, GRANDProto300 in China, and GRAND@Auger in Argentina. The primary purpose of GRAND@Nançay is to serve as a testbench for hardware and triggering systems. On the other hand, GRANDProto300 and GRAND@Auger are exploratory projects that pave the way for future stages of GRAND. GRANDProto300 is being built to demonstrate autonomous radio-detection of inclined air showers and study cosmic rays near the proposed transition between galactic and extragalactic sources. All three arrays are in the commissioning stages. It is expected that by 2028, the detector units of the final design could be produced and deployed, marking the establishment of two GRAND10k arrays. Strong candidates for the bases of GRAND-North and GRAND-South are China and Argentina, respectively. We will survey preliminary designs, simulation results, construction plans, and the extensive research program made possible by GRAND.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

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1. Introduction

Ultra-high-energy cosmic rays (UHECRs) are atomic nuclei with energies exceeding approximately 10^{18} electron volts (eV), and their origins remain a puzzle [1]. The mechanisms by which they attain such extreme energies are still poorly understood. Throughout their journey from the point of acceleration to their arrival at Earth, cosmic rays interact with matter and radiation fields along their trajectory, producing numerous secondary particles, including neutrinos and photons. This production establishes a significant multi-messenger connection. UHECRs can be deflected from their original paths by intervening magnetic fields and may undergo absorption during their propagation. Similarly, photons have the potential to be absorbed. However, neutrinos, being largely unaffected by obstacles, travel to Earth with minimal interference, making them a valuable messenger for exploring the vast reaches of the Universe.

The Giant Radio Array for Neutrino Detection (GRAND) [2] is a proposed large-scale observatory specifically designed to unravel and investigate the sources of UHECRs. One of its primary objectives is to discover and study UHE neutrinos. GRAND will detect the radio signals emitted when UHE cosmic rays, gamma rays, and neutrinos produce extensive air showers (EAS) in the Earth's atmosphere. Its configuration also enables comprehensive fundamental particle physics, cosmology, and radioastronomy studies. GRAND will also play a significant role in detecting neutrino emissions from transient astrophysical sources [3]. In the subsequent sections, we will delve into the concept of GRAND, its physics topics, simulated performance, the ongoing development of prototyping arrays, and the proposed phased implementation.

2. The GRAND project

2.1 Radio detection

When a cosmic particle interacts with the Earth's atmosphere, it initiates an EAS process. This cascade of particles, in turn, produces electromagnetic radiation primarily due to the deflection of charged particles within the shower by the Earth's magnetic field. This phenomenon, known as geomagnetic emission, exhibits coherence in the tens of MHz frequency range. Consequently, it generates short-duration ($< 1\mu$s), transient electromagnetic pulses with amplitudes significant enough to enable the detection of the EAS, given that the energy of the shower exceeds approximately $10^{16.5}$ eV [8, 9]. Radio detection of extensive showers is a mature technique that benefits from the valuable experience gained through numerous previous experiments, such as AERA, LOFAR, CODALEMA, Tunka-Rex, and TREND, that presented the proof of principle that an antenna array can detect EAS in a stand-alone mode [4].

However, cosmic neutrinos are less likely to be detected through interactions with the atmosphere due to their extremely small interaction cross-section with matter. Nevertheless, ν_τ neutrinos can produce τ leptons beneath the Earth's surface via charged-current interactions with rock. Thanks to their considerable range in rock (50 m per PeV of energy before decaying) and short lifetime (0.29 ps), τ leptons can emerge into the atmosphere and eventually decay, resulting in the initiation of a detectable EAS [10]. It is important to note that only Earth-skimming trajectories allow for such a scenario since the Earth acts as an effective barrier to neutrinos with energies surpassing 10^{17} eV.

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This characteristic proves to be advantageous for radiodetection purposes. Due to relativistic effects, the radio emission becomes highly focused in a forward-directed cone, with its opening defined by the Cherenkov angle $\theta_C \leq 1^\circ$. In the case of vertically incoming showers, this results in a radio footprint on the ground that spans only a few hundred meters in diameter. Consequently, a dense array of antennas is required to sample the signal in this scenario adequately. However, for an air shower with highly inclined trajectory, the increased distance between the antennas and the emission zone, coupled with the projection effect of the signal on the ground, leads to a few kilometers-long footprint [8, 9]. By targeting air showers with such inclined trajectories, it becomes feasible to detect them using a sparser and larger array, typically employing one antenna per square kilometer. This particular capability serves as a crucial feature of the GRAND detector.

GRAND also incorporates the strategy of selecting mountainous regions with advantageous topographies as deployment sites. An optimal topography involves two parallel mountain ranges spaced several tens of kilometers apart. One range serves as the target for neutrino interactions, while the other functions as a screen onto which the subsequent radio signal is projected. Simulations reveal that such configurations lead to an enhanced detection efficiency, approximately four times greater than that of a flat site [2].

2.2 Simulated performance

The end-to-end simulation pipeline used to determine GRAND's sensitivity incorporates the intricate topography of the array's site and the extensive instrumented area. Given the complexity of the task at hand, we ensure the inclusion of all relevant physics while striving to optimize computational performance. We individually validate each simulation part by comparing it with existing codes. The complete simulation chain is described in detail in [2].

The approach described in [12] has been applied in a preliminary analysis to reconstruct cosmic-ray-induced showers' maximum development ($X_{\max}$) on a GRAND-like array. This method achieves $X_{\max}$ resolutions of less than 40 g cm^{-2}, assuming knowledge of the shower energy and core position [13]. Another study, based on a spherical fit of the wavefront, even though it does not measure $X_{\max}$ directly, uses a figure of merit to estimate that the resolution will be slightly worse than 17 g cm^{-2} [5]. See figure 1, upper right.

Innovative reconstruction techniques performing fits to the strength of the radio signal as a function of the angle from the shower axis (angular distribution function - ADF) have showcased the potential to achieve angular resolutions of approximately 0.1° in determining the arrival direction of particles, as shown in figure 1, lower right [11]. Even though this result was developed and tested using simulated data only, this level of precision opens up the possibility of conducting neutrino and gamma-ray astronomy with the GRAND observatory.

The initial findings regarding energy resolution are promising. Using a preliminary reconstruction based on deep learning methods, an energy resolution of 15% was achieved without implementing an antenna response and in an idealized scenario for radio detection [6]. Another preliminary global reconstruction method that utilizes the angular distribution function also results in a 20% energy resolution [11]. Other machine learning and analytical methods are currently being developed within the collaboration. Consequently, a final energy resolution of 10% can likely be attained.

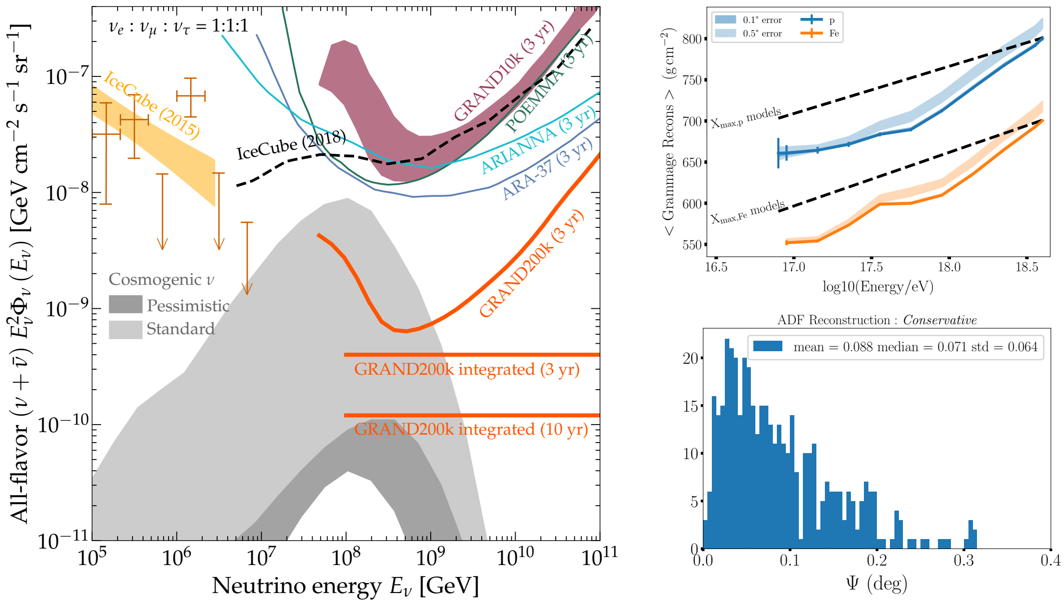

Figure 1: Left: Predicted cosmogenic neutrino flux, compared to experimental upper limits and sensitivities. Gray-shaded regions are generated by fitting UHECR simulations to Auger spectral and mass-composition data [2]. Upper right: Mean value of the radio grammage distribution per energy slices for Proton (blue line) and Iron (orange line). The error-bars show the statistical fluctuations, taken equal to $\sigma_{X_e}/\sqrt{N}$ where N is the number of simulated showers per energy slice. The shaded areas correspond to the additional uncertainties associated to error on the direction of origin of the showers for $1-\sigma$ values of 0.1° (dark) and 0.5° (light) [5]. Lower right: Distributions of the angular distances Ψ for the GRANDProto300-like layout (see section 4) [11].

3. GRAND science case

3.1 Ultra-high energy messengers

The interaction between UHECRs and the cosmic microwave background (CMB) and extra-galactic background light (EBL) gives rise to the generation of fluxes of photons and neutrinos with cosmogenic origins. Despite our limited understanding of the sources of UHECRs, the existence of these fluxes is assured. Even with pessimistic assumptions, GRAND has the potential to constrain the parameter space significantly. Alternatively, with more optimistic assumptions, GRAND may achieve the required sensitivity to detect cosmogenic neutrinos, as illustrated in the figure 1, left. GRAND's full sensitivity for cosmic neutrinos goes down to 4×10^{-10} GeV cm^{-2} s^{-1} sr^{-1} for $E > 10^{17}$ eV as shown in figure 1, left. Cosmogenic neutrino studies indicate that the outcomes of measurements conducted by GRAND will have significant implications for constraining the sources of UHECRs [15, 16]. Additionally, they will provide constraints on the proton fraction at UHE [17]. The remarkable sensitivity of GRAND, coupled with its sub-degree angular resolution, will unlock the potential for conducting UHE neutrino astronomy, enabling the identification of point sources [18]. Figure 2, left, shows the sensitivity limit of GRAND for point sources. It is worth noting that the sources of UHECRs and UHE neutrinos could be distinct. Therefore, even if a heavy composition is observed in UHECRs, it does not necessarily imply a suppression in the flux of neutrinos at EeV energies.

Similarly to UHE neutrinos, the cosmogenic flux of UHE photons is also guaranteed. They may be emitted by astrophysical sources, depending on their opacity. However, distant objects cannot be directly observed as they are absorbed by the CMB/EBL and reprocessed to lower energies. The most stringent upper limits on UHE photons can be improved by two orders of magnitude after three years of data-taking by GRAND. See figure 2, right [2].

3.2 Multimessenger astronomy

With its excellent angular resolution and extensive sky coverage, GRAND has the potential to detect UHE neutrinos associated with transient events in conjunction with electromagnetic emissions. While its instantaneous field of view covers approximately 5% of the sky, utilizing all azimuthal angles at any given moment allows for daily coverage of about 80% for one site only. In practice, the actual coverage will be even more significant as the final configuration of GRAND will consist of multiple sub-arrays distributed across different geographical locations.

GRAND will be a crucial triggering partner, enabling the precise reconstruction of the arrival direction of neutrino-induced air showers near the horizon with sub-degree accuracy and minimal latency. This capability allows GRAND to issue alerts to other experiments or coordinated systems promptly. Additionally, as a follow-up partner, GRAND can swiftly validate alerts generated by other experiments as well as gravitational-wave detectors. If the target directions fall within GRAND's instantaneous field of view, it becomes possible to establish constraints on UHE neutrino emissions originating from the observed transient.

3.3 Radioastronomy and cosmology

With its wide field of view and broad frequency range, GRAND will be a potent instrument for exploring millisecond-scale phenomena in radio wavelengths. It will enable the comprehensive measurement of astrophysical transients such as fast radio bursts (FRBs) and Giant Radio Pulses (GRPs) at low frequencies, offering unprecedented statistical data [2, 22]. Additionally, by accurately mapping the sky temperature with millikelvin precision, GRAND has the potential to observe the overall signature of the Epoch of Reionisation and study the Cosmic Dawn. These significant measurements will be achievable even during the intermediate construction stages of GRAND (GRANDProto300 and GRAND10k).

4. Experimental setups for prototyping

A dedicated design was formulated for the antenna used in the GRAND project, known as the HorizonAntenna [2]. This antenna features three perpendicular arms, enabling comprehensive polarization measurements of the signal. Positioned at a height of 3.2 m above the ground and optimized for the frequency range of 50-200 MHz, it exhibits optimal sensitivity to near-horizontal signals. It was tested in the field from August to December 2018.

Thirteen detection units (GRANDProto13), consisting of antennas and associated electronics, were deployed in the Gobi desert, Gansu Province, China, in February 2023. Data is being collected and analyzed from this initial setup, which serves as the foundation for the GRANDProto300 array

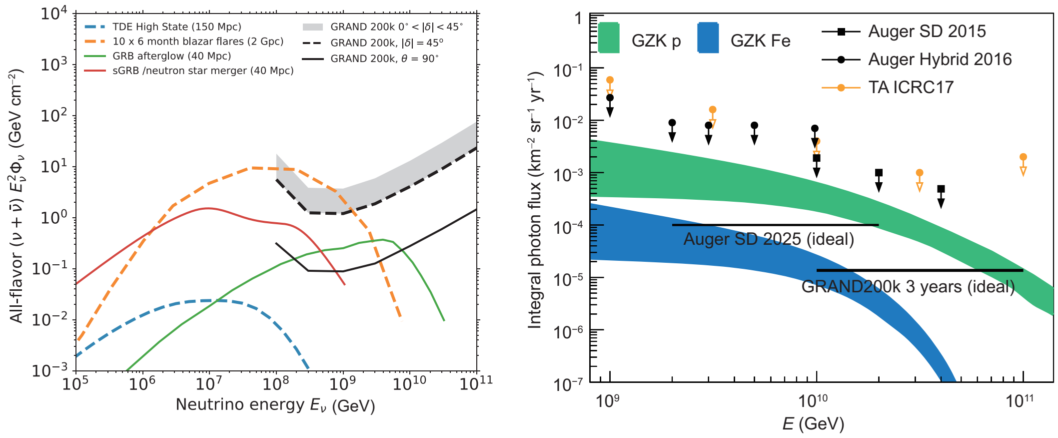

Figure 2: Left: The sensitivity limits of GRAND for point sources [2]. It is important to note that these GRAND limits assume the deployment of 200k antennas at a single location. Right: The projected upper limits of GRAND on the sensitivity to UHE photons after three years of operation are presented. For comparison, we also include the current upper limits from Auger and TA and the projected capabilities of Auger by 2025. Additionally, we overlay the predicted cosmogenic UHE photon flux resulting from pure-proton and pure-iron UHECRs, as estimated in [14].

[21]. One transient event is shown in figure 3, right. We are validating the detector unit design with the ones already deployed, and once this is done, we will deploy the remaining 70 units already built. This array will already be enough to detect cosmic rays. Then in a couple of years, we will build and deploy the remaining 200 units to form GRANDProto300.

For cross-calibration and scientific purposes, the addition of particle detectors to the prototype array is still under consideration. By utilizing the GRANDProto300 array, we will have the capability to investigate cosmic rays within the energy range of $10^{16.5}$ to 10^{18} eV, which encompasses the transitional region between galactic and extragalactic origins. The array will also allow for the detection of radio transients. Moreover, if particle detectors are used, they will address the discrepancies observed between simulations and measurements of muons [19].

Four detection units were deployed at the Nançay Radio Observatory in France in the autumn of 2022 [20]. The primary objective of the GRAND@Nançay test array is to conduct hardware and trigger testing. A preliminary spectrum obtained on-site is shown in figure 3, upper left.

Additionally, ten detection units are being deployed at the Pierre Auger Observatory site from March to August 2023. The main goal is to perform cross-calibration and validation of reconstruction using coincident events with Auger. By taking an average spectrum we could verify the presence of FM radio and TV stations in Malargue, as shown in the preliminary spectrum of figure 3, lower left.

The GRAND collaboration will complete the deployment and continue the operation of prototype arrays: GRAND@Nançay, GRANDProto300, and GRAND@Auger. Meanwhile, it will also focus on characterizing the radio background and exploring the features of autonomous detection of inclined extensive air showers.

Furthermore the GRAND collaboration is committed to minimizing its carbon footprint throughout its operations. By implementing sustainable practices and utilizing energy-efficient technologies, the project aims to reduce its environmental impact. Efforts are made to optimize the use of resources, reduce waste generation, and promote recycling and reuse. The collaboration strives to minimize travel-related emissions by employing remote collaboration tools and promoting virtual meetings whenever possible [23].

5. Future GRAND timeline

It is expected that by 2028, the detector units of the final design could be produced and deployed, marking the establishment of two GRAND10k arrays. Strong candidates for the bases of GRAND-North and GRAND-South are China and Argentina, respectively, which will assure a good sky coverage. Subsequently, around 2030, the replication of GRAND10k will commence, resulting in twenty subarrays comprising the entire GRAND project. By scaling up production to an industrial level, the front-end electronics can be transitioned to a fully integrated ASIC design, leading to cost reduction, improved reliability, and greater reproducibility of individual units. Furthermore, the design of each subarray can be customized based on location, topography, or specific scientific objectives.

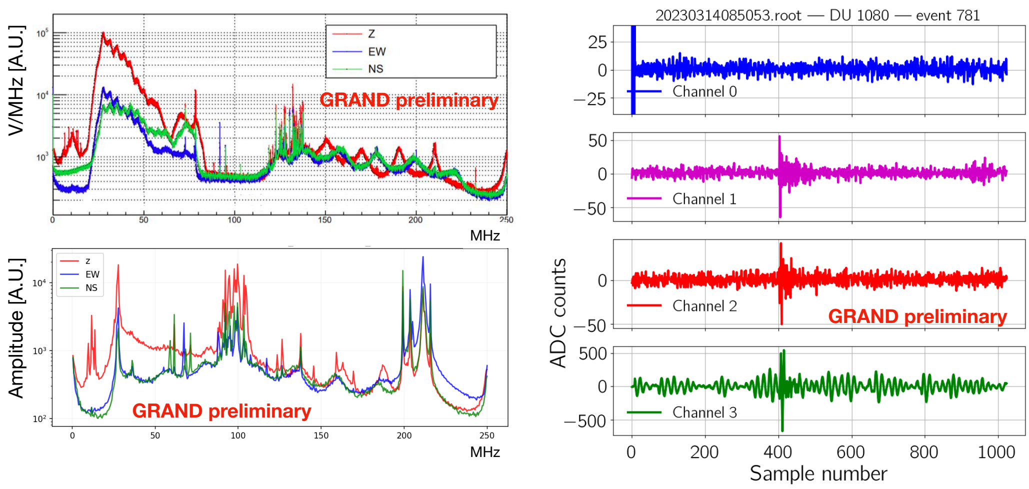

Figure 3: Upper left: Spectrum measured at GRAND@Nançay. Lower left: Average spectrum of one detector unit at GRAND@AUGER. Right: Transient event measured in GRANDProto13. Channel 1=X, 2=Y, 3=Z and channel 0 is free floating.

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