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The Giant Radio Array for Neutrino Detection

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The Giant Radio Array for Neutrino Detection (GRAND) is a proposal for a giant observatory of ultra-high energy cosmic particles (neutrinos, cosmic rays and gamma rays). It will be composed of twenty subarrays of 10 000 antennas each, to be deployed after 2030 at various locations around the world, totaling a detection area of 200 000 km^2. According to simulations, GRAND will reach unprecedented sensitivity to neutrinos of astrophysical origin with energies above 10^{17} eV, sufficient to guarantee their detection. GRAND's sub-degree angular resolution will also make it possible to hunt for point sources and possibly start neutrino astronomy. This, combined with the large instantaneous field of view expected from the location of the sub-arrays in different continents and hemispheres, will make GRAND a key instrument in the forth-coming era of multi-messenger transient astronomy, during which the century-long mystery of the nature and origin of the particles with highest energy in the Universe may be solved.

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1. Introduction

Ultra-high-energy neutrinos of astrophysical origin are unique probes of violent phenomena in the Universe [1]. We present here the Giant Radio Array for Neutrino Detection (GRAND), a proposal for a radio array which size —200 000 km^2— will guarantee the detection of these cosmic neutrinos. We first describe the GRAND detection concept, then detail its science case, which includes cosmic and gamma rays besides neutrinos. We finally describe GRAND experimental challenges and how we plan to tackle those.

2. The GRAND project

2.1 Detection concept

Principles of radio detection of air showers are detailed in [2, 3], and the GRAND detection concept is presented in [4]. It is briefly summarized here. When a cosmic particle interacs in Earth's atmosphere, it induces an extensive air shower (EAS), which in turn, generates electromagnetic radiation mainly through the deflection of the charged particles in the shower by Earth's magnetic field. This geomagnetic emission is coherent in the tens of MHz frequency range, generating short ($<1\,\mu$s), transient electromagnetic pulses, with amplitudes large enough to allow for the detection of the EAS [5–7] if the shower energy is above $\sim 10^{16.5}$ eV.

Cosmic neutrinos however have a very small probability of being detected through this process because of their tiny interaction cross-section with matter. Yet, ν_τ can produce τ leptons under Earth's surface through charged-current interactions with rock. Thanks to its large range in rock and short lifetime, the τ particle may emerge into the atmosphere and eventually decay to induce a detectable EAS [8]. Because the Earth is opaque to neutrinos of energies above 10^{17} eV, only Earth-skimming trajectories allow for such a scenario.

This peculiarity turns out to be an asset for radiodetection. Because of relativistic effects, the radio emission is strongly beamed forward in a cone whose opening is given by the Cherenkov angle $\theta_C \leq 1^\circ$. For vertically incoming showers, this induces a radio footprint on the ground of few hundred meters in diameter only, requiring a large density of antennas for a good sampling of the signal. For very inclined trajectories however, the larger distance of the antennas to the emission zone and the projection effect of the signal on ground combine to generate a much larger footprint [2]. Targeting air showers with very inclined trajectories make it possible to detect them with a sparse array (typically one antenna per km^2). This is a key feature of the GRAND detector.

Another feature of GRAND is to target mountainous areas with favorable topographies as deployment sites. An ideal topography consists of two opposing mountain ranges, separated by a few tens of kilometers. One range acts as a target for neutrino interactions, while the other acts as a screen on which the ensuing radio signal is projected. Simulations (see section 2.2) show that such configurations result in a detection efficiency improved by a factor ~ 4 compared to a flat site [4].

2.2 Detector performances

2.2.1 Neutrino sensitivity

In order to estimate the potential of GRAND for the detection of cosmic neutrinos, an end-to-end simulation chain was developed, composed mostly of computation-effective tools created

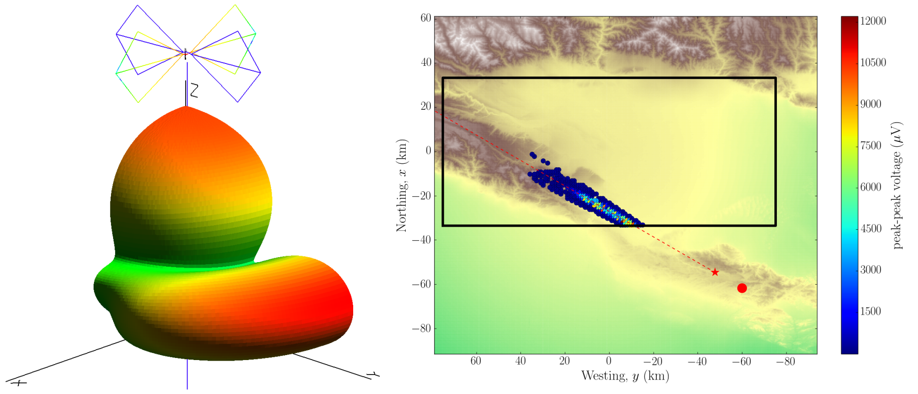

Figure 1: Left: NEC4 simulation of the HorizonAntenna gain as a function of direction. Right: One simulated neutrino event displayed over the ground topography of the simulated area. The large red circle shows the position of the τ production and the red star, its decay. The dotted line indicates the shower trajectory. Circles mark the positions of triggered antennas. The color code represents the peak-to-peak voltage amplitude of the antennas. The limits of the simulated detector are indicated with a black line.

within the GRAND Collaboration to take into account the very large size of the detector and its complex topography.

The first element of the simulation chain is DANTON [9], a 3-D Monte-Carlo sampler of τ leptons generated by ν_τ interactions underground. Simulations of neutrino interactions, τ energy losses in various materials (rock, air, etc) and decays are embeded in a realistic implementation of the topography, which also allows one to take into account the shadowing effect of the mountains on the propagating radiation in a satisfying manner. A back-tracking mode (i.e. simulation from the decay point upwards, with appropriate probability weighting) is also implemented in DANTON, reducing the computation time by several orders of magnitude compared to a forward mode for neutrino with energies below 10^{18} eV.

The radio emission induced by each simulated τ decay is then computed through a semi-analytical treatment called *radio morphing*, which computes the radio signal of any air shower at any position in space by simple mathematical operations applied to a single shower used as a reference [10]. Radio morphing enables one to reduce the required CPU computation time by two orders of magnitude at least compared to standard microscopic simulation codes, while reproducing their results within $\sim 10\%$ in signal amplitude.

A specific design was developed for the GRAND antenna. This *HorizonAntenna* [4] is composed of 3 arms, allowing for a complete measurement of the polarization of the signal. Placed 5 m above ground, with a design optimized for the 50-200 MHz frequency range, its sensitivity to near-horizontal signals is optimal. The HorizonAntenna response to EAS radio signals was simulated using the NEC4 code (see figure 1) and integrated in our simulation chain.

The final step of the simulation chain is the trigger simulation. It requires that, for at least 5 units in one 9-antenna square cell, the peak-to-peak amplitude of the voltage signal at the output of the antennas is larger than 30 μV (twice the expected stationary background noise in the 50-200 MHz frequency range) in an agressive scenario, or 75 μV in a more conservative one .

This simulation chain was run over a 10 000 km^2 area, with 10 000 antennas deployed along a square grid of 1 km step size in an basin surrounded by high peaks of the TianShan mountain range in China (see figure 1). The simulation area will be extended to the full Earth surface (excluding non-accessible areas) in a near future and will be used to identify twenty similar subarrays at locations associated with optimal neutrino sensitivity, thus forming the proposed 200 000 km^2 GRAND detector. For now, the 3-year 90% C.L. GRAND sensitivity limit is derived from the simulated 10 000 km^2 region by direct scaling. It is presented in Figure 2 and the implications on the science goals achievable by GRAND are detailed in section 2.3.

2.2.2 Reconstruction performance

A precision better than 0.1°will be needed for neutrino astronomy, while resolutions of $\sim$10% on shower energy and 20 $\mathrm{g\cdot cm^{-2}}$ on the position of the shower maximum of development X_{max} are required for cosmic rays and gamma rays (see section 2.3). Reconstruction of these parameters from radio data have now reached performances comparable to standard techniques [11–13], but it is not yet demonstrated that GRAND will achieve similar results for nearly horizontal air showers detected with radio antennas only. For such inclined geometries, it is nearly as if the detector performs a sampling of the shower along its longitudinal axis, while standard trajectories correspond to a lateral cut. Shower aging thus has to be taken into account in the reconstruction procedure. Work on this topic is ongoing within GRAND with simulated data, and will be tested in real conditions with GRANDProto300 [14] (GP300), the prototype for GRAND to be started in 2021.

A significant effort was made to reconstruct the direction of origin of neutrino-induced air showers simulated with the ZHAireS code over a GRAND-like array deployed on a toy-model topography, corresponding to a plane detector area facing the shower with a variable slope [15]. A hyperbolic fit to the radio wavefront [16] has been implemented, and yielded an angular resolution better than 0.2°for ground slopes larger than a few degrees, as the different antenna elevations provide an excellent lever arm for the reconstruction of the zenith angle. This method will be tested over realistic topographies.

The method of [17] has been implemented to reconstruct the maximum of development of cosmic-ray induced showers on a GRAND-like array in a preliminary treatment. It yields resolutions on X_{max} better than 40 $\mathrm{g\cdot cm^{-2}}$ provided that the shower energy and core position are known.

These two results are encouraging signs that for large zenith angles the broad footprint of GRAND events compensate its low density of unit detectors, but reconstruction methods dedicated to GRAND still need to be optimized.

2.3 GRAND science case

2.3.1 Ultra-high-energy neutrinos

The sources, production, and nature of the particles with the highest energies in the Universe are still a mystery, despite decades-long experimental efforts. Ultra-high-energy neutrinos could be an extremely valuable tool to approach this mystery: thanks to their very low interaction probability and neutral charge, these particles travel unimpeded from their sources over cosmological distances. Besides, their production is intrisically linked to that of ultra-high-energy cosmic rays (UHECRs), be it inside the sources or along the propoagation of UHECRs.

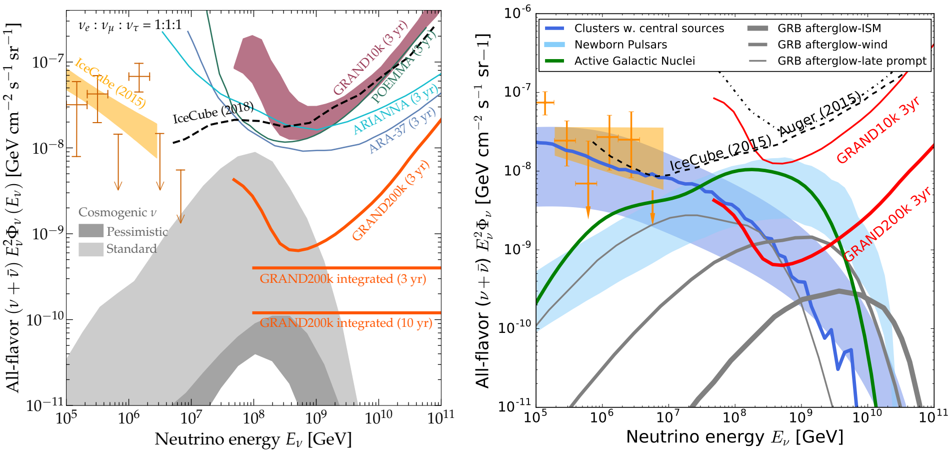

Figure 2: Left: all-flavor cosmogenic neutrinos flux expectations derived from the results of the Pierre Auger Observatory [18] superimposed to the differential sensitivity limit derived from the 10 000 antennas simulation presented in section 2.2 ("GRAND10k", purple area) and the extrapolation for the 20-times larger GRAND array ("GRAND200k", orange line). Right: expected neutrino fluxes produced at the source for different types of sources superimposed to the GRAND10k and GRAND200k 3-years sensitivity limit. Taken from [4].

In the latter case, interactions between UHECRs and the cosmic microwave background produce *cosmogenic* neutrinos whose differential flux depends on the astronomical evolution of the sources and the UHECRs composition and energy spectrum. A collection of 20 subarrays such as the one used in the simulation presented in section 2.2 yields a neutrino sensitivity for GRAND that allows us to probe the full range of expected fluxes of cosmogenic neutrinos [18] within 10 years (see figure 2).

For several UHECR source candidates, models predict fluxes of neutrinos larger than those of cosmogenic origin (see figure 2). GRAND will also probe neutrino production at the sources while its expected excellent angular resolution (see section 2.2.2) will open the path for ultra-high-energy neutrino astronomy and multi-messenger studies of transient phenomena with instruments like CTA [19] or next-generation gravitational-waves detectors [20].

2.3.2 UHECRs and gamma rays

According to preliminary simulations, GRAND will have full detection efficiency for cosmic rays with zenith angles larger than 70° and energies above 10^{18} eV [4]. This will yield an exposure 15 times larger than the Pierre Auger Observatory. Further, it will cover both Northern and Southern hemispheres, rendering GRAND an excellent tool to study the end of the UHECRs spectrum.

Assuming a 20 g·cm^{-2} resolution is achieved in X_{max} — a realistic goal given present experimental results [11, 12] and preliminary simulations results (see section 2.2.2)— GRAND will be able to distinguish between showers made by UHECRs and UHE cosmogenic gamma rays. Non-detection of cosmogenic gamma rays within 3 years of operation of GRAND would then exclude a light composition of UHECRs, while detection of UHE gamma rays from nearby sources would probe the diffuse cosmic radio background [21].

2.3.3 Fast radio bursts

By incoherently adding the signals from the large number antennas in a subarray, GRAND will also be able to detect a 30-Jy fast radio burst (FRB) with a flat frequency spectrum [4]. Moreover, as incoherent summing preserves the wide field of view of a single antenna, GRAND may be able to detect several hundreds of FRBs per day. In addition, detection of a single FRB by several subarrays would allow to reconstruct the direction of origin of the signal.

2.4 The path to GRAND

GRAND will perform standalone radio detection of air showers. This is a challenge, as measurements have shown that, outside polar areas, the rate of transient radio signals due to background sources (high voltage power lines or transformers, planes, thunderstorms, etc.) dominates that of EAS in the tens-of-MHz frequency range by several orders of magnitude [22], a statement that will hold even truer for neutrino-induced showers. Two questions naturally arise from this observation: how to collect and identify EAS events, and how to single out neutrino-induced events among them. Below we explain how we expect to tackle these two issues.

2.4.1 Identification of neutrino events

At energies above 10^{16} eV, cosmic rays are expected to induce air showers at a higher rate than neutrinos by several orders of magnitude. Yet, selecting events with trajectories reconstructed below the horizon will allow to reject most cosmic rays. Further, measuring the $X_{\max}$ position (further than 100 km from the shower core position for a cosmic ray with zenith angle larger than $\sim$85°) will provide another very powerful discrimination tool.

2.4.2 Standalone radio-detection of air showers

We believe that achieving a $\sim$100% detection efficiency of EAS combined with a rejection of background close to 100% is possible, because of the following:

- Excellent quality of the radio environment of the experiment site —and, in particular, a low rate of transient radio pulses— is extremely important. The protocol used in the site survey for the GP300 phase of GRAND [14] will be extended and optimized when validating the locations of the GRAND subarrays.
- It has been shown already that EAS radio signatures clearly differ from background events: their time traces are usually much shorter [23], while their amplitude [24] and polarization patterns at ground [25] are very specific. Taking advantage of these unique features has already made it possible to perform a very efficent rejection of the background signals using radio data only [22]. EAS identification is thus not a physics issue, but a technical one.
- Digital radio-detection of EAS has been an active field of research for two decades now, but no large-scale effort of autonomous radio detection has been initiated: trigger algorithms very often remain limited to basic signal-over-threshold logics, DAQ is often not adequately dimensioned for the data rate, and self-triggered radio data remain scarce. Given the ongoing progress on hardware (fast electronics, large-band data transfer protocols) and software tools

(*e.g.* machine learning methods [26, 27]) instrumental to this topic, we believe much better can be done. A dedicated effort has been initated in GRAND to provide an efficient, cost- and power-effective system of autonomous radio detection of EAS. The GP300 setup will be used as a testbench to test and validate solutions for the next stages of GRAND.

2.5 GRAND timeline

The path towards GRAND is the following: between 2020 and 2025, we will run GP300. Besides its appealing science program [14], GP300 will allow to validate the GRAND detection principle, but also to test and optimize the detection units' design, autonomous trigger and data transfer. Ten thousand units of the final design will be produced and deployed in 2025 to create GRAND10k, the first GRAND subarray, which will launch GRAND's neutrino hunt. When GRAND10k operates as expected, its design will be frozen. The replication of GRAND10k in the twenty subarrays forming GRAND will commence around 2030. Producing units at industrial scale will allow to switch to a fully integrated ASIC design for the front-end electronics and reduce costs, while improving reliability and reproductability of individual units. The design of each subarray may be adapted, depending on location and topography, or to address specific science cases.

3. Conclusion

A detailed, robust, and reliable simulation chain demonstrates that the $200\,000\,\mathrm{km}^2$ GRAND detector will reach sensitivity to ultra-high-energy neutrinos, either cosmogenic or astrophysical in origin. This, combined with its exposure to UHECRs and UHE gamma rays, will make GRAND a powerful tool to study the origin of UHECRs. A staged plan has been defined to bring GRAND to life. Its first step is the soon-to-be-deployed GRANDProto300, which will allow to validate the GRAND design and reconstruction tools.

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