Observing the UHE Universe with GRAND

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1 Introduction

Despite decades of experimental and theoretical efforts, the origin of the particles with the highest energies in the Universe remains unknown. The recent detection of new types of cosmic messengers —neutrinos [1] and gravitational waves [2]— and the performances of the present generation of γ and UHECR detectors [3, 4, 5] have however enabled the rise of multimessenger astronomy, which yielded remarkable results in the very last years. Following arguments developed in [6, 7], we show in section 2 how the detection of UHE neutrinos could provide a decisive contribution to this effort. In section 3, we explain why the Giant Radio for Neutrino Detection (GRAND) could be the instrument which will achieve the detection of these particles when it will be fully deployed, around 2030. We also present GRANDProto300, the pathfinder for GRAND.

2 UHE cosmic messengers

2.1 The case for multimessenger astronomy

The combined analysis of signals from different cosmic messengers has resulted in significant progress in our understanding of violent phenomena in the Universe. The most striking example is obviously the event GW170817 [8], which generated —and still does— a wide range of scientific outputs.

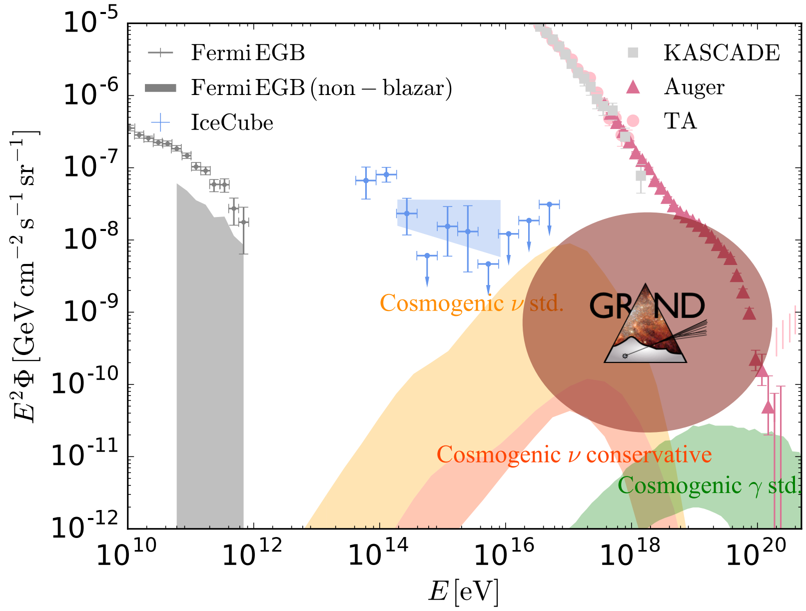

Figure 1: Energy density spectra of cosmic messengers. For γ rays, we show the extragalactic gamma-ray background measured by Fermi-LAT [3, 10] and, shaded, the contribution due to unresolved, non-blazar sources. For neutrinos, we show the all-flavor 6-year measurements by IceCube [11, 12]. For cosmic rays, we show measurements by KASCADE-Grande [13], Auger [14], and Telescope Array [15]. We show the predicted ranges of cosmogenic neutrino flux from [16] and of cosmogenic γ-rays from [3]. The GRAND target sensitivity zone is overlaid. Figure extracted from [6].

But detection of point sources —such as this one or the detection by IceCube of neutrinos coming from the direction of the blazar TXS0506+056 [9]— were not the only noticeable results in the field: measurements of diffuse fluxes from γ-rays, neutrinos and UHECRs also show that energy densities of these messengers are within a similar range (see Fig. 1), stressing their strong connection and providing excellent motivation for further multimessenger observations.

2.2 UHE neutrinos

Among all cosmic messengers, neutrinos are often presented as the cleanest probe of the Universe: due to their low cross sections, they can escape dense astrophysical environments opaque to photons and travel unimpeded over cosmological distances, allowing direct observation of their sources at high redshifts. Unlike cosmic rays, they are not deflected in magnetic fields and can be observed in spatial and temporal coincidence with photons and gravitational waves.

Neutrinos of energies above 10^{17}eV present additional attractive features for the understanding of violent phenomena in the Universe:

First, UHECRs of hadronic nature may interact with photon fields (CMB or infrared) during their cosmic journey if their energy is larger than a given threshold ($\sim 10^{19.5}$ eV for proton). This interaction produces *cosmogenic* neutrinos, which energy density peaks above 10^{17} eV (see Fig. 1). As the hadronic nature of UHECRs is now established [14], this flux is guaranteed. Its intensity however notably depends on the chemical composition of UHECRs and the cosmologic evolution of their sources. The detection of cosmogenic neutrinos —or strong limits on their flux— would therefore provide a powerful handle on these parameters, which are not precisely known and of great scientific value.

Second, if UHE neutrinos are detected from a given point source, then this is also a source of UHECRs. Such a smoking-gun event would be a gigantic step towards solving the mystery of UHECR origin. It is not out of reach: the limits set by Auger on the UHE neutrino flux associated with the GW170817 event for instance are within one order of magnitude of some models of emission [17].

Third, the neutrino spectrum is not measured for energies above a few PeV (see Fig. 1). Pushing this energy frontier would be natural, in particular in the context of multimessenger astronomy, where only the combined information of several messengers over the largest energy range will allow to tackle the mystery of UHECRs origin. UHE neutrinos is uncharted territory, and it is the essence of fundamental research to go for the unknown.

2.3 UHE γ-rays and UHECRs

Alike neutrinos, UHE γ-rays can be produced by UHECRs of sufficient energy through photo-hadronic interactions during their propagation, and their flux strongly depends on the nature of UHECRs. Search for these cosmogenic photons thus provides a handle on this parameter. UHE γ-rays would also allow to measure the (very poorly known) Radio Cosmic Background [18] or perform tests of Lorentz Invariance Violation [19], which predicts photons arrival time depending linearly or quadratically on their energy.

Auger allowed for significant progress in our knowledge of UHECRs [14]. However the limited statistics at the highest energies, despite 15 years of data taking, does not allow for a firm statement on the main reason why the UHECR spectrum drops above 10^{19} eV: is it due to the photo-hadronic interactions mentioned already, or do UHECRs sources simply run out of steam? Precise measurements of the energy and composition of UHECRs, combined with significantly larger statistics, are needed to answer this question, key to the understanding of the origin of UHECRs. In addition to this, tensions exist between the results of Auger and Telescope Array. Combined effort is being carried out to understand this, but these discrepancies could simply be explained by the fact that the two detectors are observing different regions of the sky [5].

3 GRAND contribution

3.1 Strategies for the detection of UHE neutrinos

The arguments presented in section 2 have motivated several prospective efforts working towards a viable detection concept which could eventually achieve a sensitivity to UHE neutrinos better than Auger by one order of magnitude. The combination of very low neutrino fluxes at ultra-high energies with small interaction cross-sections require gigantic volumes of a dense target material, making this detection very challenging. Three main strategies have emerged:

- One possibility consists in searching for the electromagnetic emission of a particle cascade initiated by a neutrino interaction in the ice. This emission is coherent in the 200-1200 MHz range, frequencies for which cheap detectors —radio antennas— have been developed, while the ice has excellent propagation properties in this range. Several projects have been proposed in Antarctica [20, 21, 22] with significant experimental achievements already, but the limited neutrino field of view at South Pole [22] and the poor angular resolution [21] inherent to this technique significantly impede its potential for transient point-source astronomy, and thus mainly restrict it to the search for cosmogenic neutrinos.

- Neutrinos may also undergo charged-current interactions with the Earth target. For a tau neutrino, the produced tau lepton may emerge and decay in the atmosphere, hence initiating an upward-going air shower. Probability of such an event is non-negligible [23] provided in particular that the path underground is not too long (typically $< 1000\,\mathrm{km}$). Auger mostly bases its neutrino analysis on the search for such Earth-skimming events [24], but observation from space of the Cerenkov light produced by neutrino-induced showers would allow for significantly larger exposure. Proposals for neutrino detection from satellites have been formulated [25, 26]. The expected performances are attractive.

- Air showers generate coherent radio emissions in the 10s to 100s of MHz. Neutrinos inducing air showers through the above-mentioned process may therefore be detected thanks to these radio signatures. The Giant Radio Array for Neutrino Detection (GRAND) proposes to take advantage of the very low price, robustness, response stability and easiness of deployment of radio antennas to instrument very large surfaces of mountain terrain. GRAND would be composed of 10 to 20 arrays of 20 to 10 000 antennas each, with antenna density around $1\,\mathrm{km}^{-2}$ and deployed between 2025 and the early 2030s at favorable locations around the Earth, forming a total detector area of $200\,000\,\mathrm{km}^2$. The GRAND proposal is detailed in [6]. Below we summarize its expected performances in the perspective of the detection of UHE cosmic messengers.

3.2 GRAND detection of UHE neutrinos

Simulations based on tools developed by the GRAND collaboration [27, 28] conclude that GRAND could be sensitive to neutrino energy density as low as $4 \cdot 10^{-11}\,\mathrm{GeV{\cdot}cm^{-2}{\cdot}s^{-1}{\cdot}sr^{-1}}$ at 90% C.L., for energies above $10^{17}\,\mathrm{eV}$ and 10 years of observation with the complete layout [6]. This would allow a deep scan of the expected cosmogenic neutrinos fluxes (see Fig. 1), thus providing a very powerful insight on the composition of UHECRs, some even claiming that the proton/iron fraction could be measured down to a 5% precision [29]. Only for the most pessimistic projections [30] would cosmogenic neutrinos not be detected, but GRAND would then put stringent limits on the fraction of protons in the UHECRs flux [31].

The prospects are also excellent for the search of point sources [32] and transient astronomy, thanks again to GRAND's excellent sensitivity, but also its large field of view [1] and an expected resolution on the reconstructed neutrinos direction of origin down to 0.1° [6].

3.3 GRAND detection of UHE γ-rays and UHECRs

Judging from performances of radio arrays on the reconstruction of shower maximum [33] and preliminary studies within the collaboration [6], an excellent discrimination of showers induced by γ-ray and hadronic primaries may be achievable with GRAND, even though the reconstruction of X_{max} is challenging for the inclined showers targeted by GRAND. Its gigantic effective area would then allow to probe, within few years only, a vast part of the parameter space of the expected cosmogenic photon flux (see Fig. 2) or acquire large statistics, should they already be detected by Auger.

Similarly, the very large effective area of GRAND (20 times that of Auger) should allow to determine with much better statistical precision the high-energy end of the UHECR spectrum. Moreover, its very large field of view, covering both Northern and Southern part of the sky (see Fig. 2), will allow to study if the UHECRs properties change with direction, as possibly suggested by the comparison of Auger and TA results [5].

3.4 GRANDProto300

The detection principle of GRAND still has to be demonstrated. This is the main goal of GRANDProto300 [37] (GP300), a detector of 300 antennas covering 200 km^2. GP300 is planned to run in 2021. It will in particular aim at proving that very inclined ($\theta \geq 70°$) air showers induced by cosmic rays can trigger the detector with excellent efficiency, be discriminated from background transient events with very limited contamination, and eventually be reconstructed with the resolutions targeted for GRAND: $\sigma_\psi \sim 0.2°$ for direction, $\sigma_E/E \sim$20% for energy, and $\sigma_{Xmax} \sim$20 g/cm^2 for shower maximum.

The GP300 radio array may be complemented by an autonomous array of particle detectors in 2022. As for inclined trajectories only the muonic component of the showers reaches ground [38], and since the electromagnetic compo-

[1] While detection is possible for neutrino trajectories a few degrees below the horizon only —which implies that the instantaneous field of view at one given location is a few % of the sky only—, the 2π azimuth acceptance of the detector translates into a nearly full sky coverage over 24 hours.

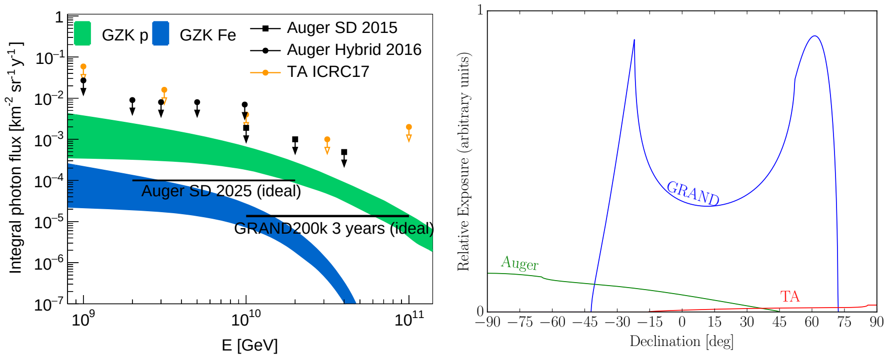

Figure 2: Left: Predicted cosmogenic UHE photon flux from pure-proton and pure-iron UHECRs [34]. Also plotted are the upper limits from Auger [35] and TA [36], the projected reach of Auger by 2025 and of GRAND after 3 years of operation [6]. Right: The relative annual geometric exposure to UHECRs of GRAND, Auger, and TA. Here we assume that the full GRAND array is deployed in one single location at 43°N. Exposure will cover an even larger declination range if subarrays are set at different locations in the world, as foreseen. Figures extracted from [6].

nent is solely responsible for the radio emission, this hybrid detector would allow a direct, unbiased measurement of both components on a shower-to-shower basis. This would be very useful to better study air shower physics, and contribute in particular to the understanding of the deficit of the number of muons in simulations [39]. The combined information of the two detectors would also provide the most efficient proxy for the nature of the primary [40]. This should allow an insight on the transition between the Galactic and extragalactic origin of the cosmic rays, expected to take place in the $10^{16.5} - 10^{18}$ eV energy range where GP300 will be sensitive.

4 Conclusion

Cosmic messengers with energies above 10^{17} eV —and primarily, neutrinos— are keys to understand how the particles with the highest energies in the Universe are generated. GRAND, a network of 10-20 radio arrays placed at different locations in the world and covering a total area of 200 000 km^2 after 2030, will detect and study these particles. GRANDProto300, its pathfinder —but also an experiment with appealing science program— will start in 2021.

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