Neutrino physics with GRAND

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1 Introduction

Cosmic neutrinos of ultra-high energies (E> 10^{17} eV) are unique probes of fundamental physics in an uncharted and otherwise unreachable energy and distance regime. Provided they can be detected in sufficient number, they would allow us to explore the cosmic and energy frontiers of particle physics, complementing current and future colliders. This is detailed in section 2, following arguments developed in [1] and [2]. Then in section 3 we discuss how the Giant Radio Array for Neutrino Array (GRAND), a proposal for a $200\,000^2$ radio antenna array to be deployed after 2030, could contribute to this exciting objective.

2 Fundamental physics with UHE cosmic neutrinos

Cross-section
The neutrino-nucleon cross section was measured using astrophysical and atmospheric neutrinos detected with IceCube [3, 4]. These results agree with Standard Model predictions within statistical errors (see Fig. 1). Measurements in the EeV range would probe the cross section at center-of-momentum energies of 100 TeV, where Beyond-Standard Models (BSM) may induce significant deviation from Standard-Model predictions [5].

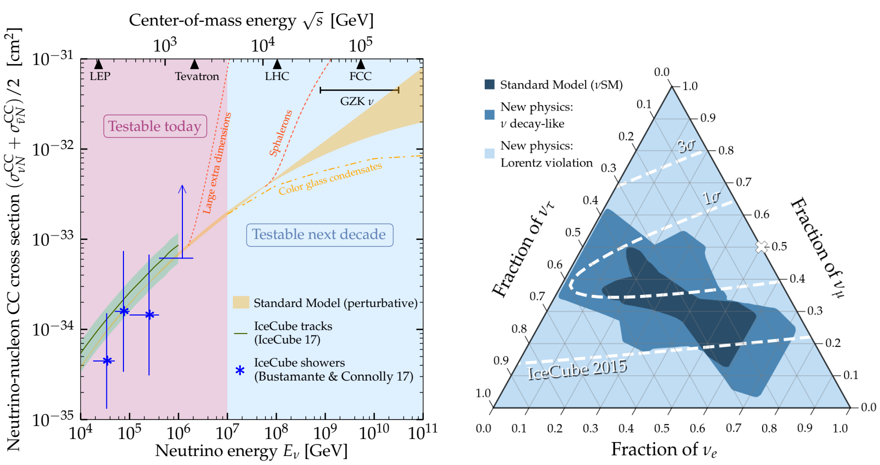

Figure 1: Left: Measurements and predictions of the high-energy neutrino-nucleon cross section using IceCube data [4]. Right: Flavor composition at Earth of high-energy cosmic neutrinos, indicating the "theoretically palatable" [6] regions accessible with the Standard Model with massive neutrinos (SM), with new physics similar to neutrino decay, and with new physics similar to Lorentz-invariance violation. The neutrino mixing parameters are generously varied within their uncertainties at 3σ. The tilt of the tick marks indicates the orientation along which to read the flavor content. Figures extracted from [2].

Flavor ratio

The recent detection of tau neutrinos by IceCube [7] is an indication that high-energy cosmic neutrinos en route to Earth oscillate. The predicted allowed region of the ratios of each flavor to the total flux is however small according to the Standard Model, even after accounting for uncertainties in the parameters that drive the oscillations and in the neutrino production process [6]. However, mixing is untested at ultra high energies and over cosmological propagation baselines, while BSM effects could affect oscillations, vastly expanding the allowed region of flavor ratios and making them sensitive probes of BSM [6], as shown in Fig. 1. It should also be stressed that measurements of the flavor ratio are free from uncertainties on the flux normalization. UHE cosmic neutrinos would therefore provide a powerful test for the nature of neutrinos and new physics.

Spectrum shape

Numerous new-physics models have effects whose intensities are proportional to some power of the neutrino energy E_ν and to the source-detector baseline L, i.e., $\alpha \kappa_n E_\nu^n L$, where the energy dependence coefficient n and the proportionality constant κ_n are model-dependent [62-66]. For instance, for CPT-odd

Lorentz violation or coupling to a torsion field, n = 0; and for CPT-even Lorentz violation or violation of the equivalence principle, n = 1. If GRAND were to detect neutrinos of energy E_ν coming from sources located at a distance L then, nominally, it could probe new physics with exquisite sensitivities of $\kappa_n \sim 4 \cdot 10^{-50}(E_\nu/EeV)^n(L/Gpc)^{-1}EeV^{1-n}$. This is an enormous improvement over current limits of $\kappa_0 \leq 10^{-32}$ EeV and $\kappa_1 \leq 10^{-33}$, obtained with atmospheric and solar neutrinos [8, 9]. This holds even if the diffuse neutrino flux is used instead, since most of the contributing sources are expected to be at distances of Gpc.

As mentioned before, BSM could affect flavor or cross section, but also the spectral shape of detected neutrinos. Indeed neutrino energy spectra are expected to be power laws. New physics could introduce additional spectral features, like peaks, troughs, and varying slopes. New physics models include neutrino decay [10], secret neutrino interactions [11], and scattering of dark matter [12].

Direction of arrivals

The distribution of the direction of arrivals of measured neutrinos allows to measure the cross-section, following for instance the method detailed in [4]. It is also a way to test the presence of dark matter: interactions of neutrinos with high-density regions of dark matter would indeed modify the distribution of neutrinos' directions of arrival: a DM clump around the Galactic Center may for instance imply a deficit of neutrinos in this direction [13].

3 GRAND contribution

GRAND is a proposal for a network of $\mathcal{O}(10-20)$ radio arrays to be deployed at various location around the world after 2025. Each of these arrays would be composed of 20-10 10^3 radio antennas with a unit density of $1\,\mathrm{km}^{-2}$. The GRAND detection principles and proposed design are explained in [1], and will also be presented in more details in a separate contribution to GT04 *Physique des Astroparticules*. Let us simply stress here that UHE ν_τ of cosmic origin are detected in GRAND through the showers induced in the atmosphere by the decay of the tau lepton produced by ν_τ interaction under the Earth surface.

Rate of neutrino events

Recent results of the Pierre Auger Observatory can be best fitted by a model with a predominant intermediate mass composition for Ultra High Energy Cosmic Rays (UHECRs) and a cut-off energy of the UHECR spectrum at source below $10^{19.5}$ eV [14]. Prediction of *cosmogenic* neutrinos fluxes —neutrinos produced by the interaction of UHECRs with photon targets during their journey through their Universe— based on these results [15, 16] are therefore significantly lower than earlier estimates, determined from a lighter mass composition. Yet, thanks to its gigantic area (200 000 km2 in total), simulations indicate that GRAND will reach a neutrino sensitivity improved by a factor ~20 compared to

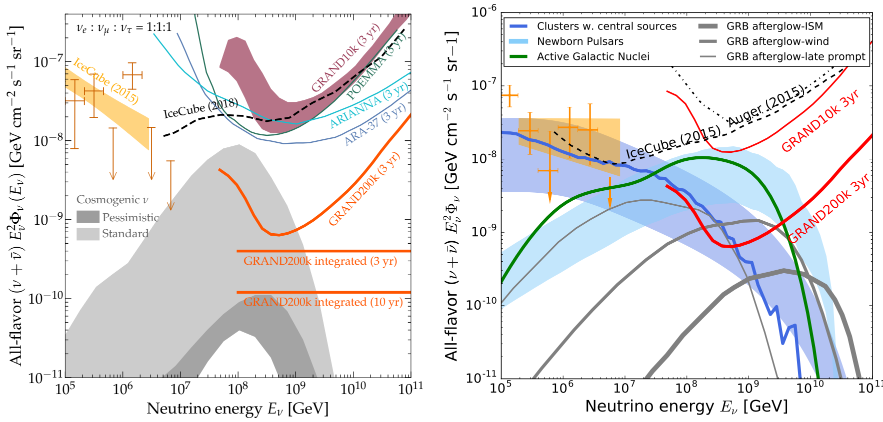

Figure 2: Left: Predicted cosmogenic neutrino flux, compared to experimental upper limits and sensitivities. Gray-shaded regions are generated by fitting UHECR simulations to Auger spectral and mass-composition data [15]. Right: Predicted neutrino flux from different classes of astrophysical sources (galaxy clusters with central sources [20], fast spinning newborn pulsars [21], active galactic nuclei [22], and afterglows of gamma-ray bursts [23], compared to upper limits on UHE neutrinos from IceCube [17] and Auger [18], and projected 3-year sensitivity of GRAND10k (first array of 10000 antennas, in 2025) and GRAND200k (full layout, after 2030). Figures extracted from [1].

the present best limits [17, 18] (see Fig. 2). This should allow to detect cosmogenic neutrinos with GRAND, especially if a fraction of UHECRs are protons [19].

Besides, GRAND sensitivity should also allow to detect neutrinos directly directly produced by various sources, as shown in Fig. 2. Under optimistic —though not unlikely— hypothesis, the rate of detected neutrinos in GRAND would then amount up to several tens of events per year. We'll see below that in this case, GRAND could indeed contribute to the physics of neutrinos.

Angular direction

Thanks to the mountainous topography where the antenna arrays will be deployed, a $\sim 0.1^o$ resolution is expected on the direction of origin of the neutrino [1]. It should therefore be possible to determine with good precision the differential rate of neutrino events as a function of distance traveled underground. From this can be extracted the neutrino cross section, following a method detailed in [6].

Flavor ratio

Electrons are absorbed within few meters of rock, while muons fly across the atmosphere with a marginal probability of decaying: only tau neutrinos are thus likely to induce a detectable signal in GRAND induced by the underground neutrino interaction mechanism above mentioned.

However, direct neutrinos interactions in the atmosphere may also induce air showers which could be detected by GRAND and discriminated from UHECRs thanks to a much deeper development in the atmosphere. Obviously neutrinos of any flavor would induce such events, thus providing a handle on neutrino-flavor study within GRAND. Even though the probability of such events increases with energy [18], they remain however much more seldom than events induced by underground neutrino interactions. Such a study may thus remain limited by statistics, even though a handful of events would already provide valuable insight on this topic.

Besides, if other experiments —such as POEMMA [24] or RNO [25]— are able to detect neutrinos of different flavor in a same energy range, it would be possible to compute a flavor ratio from the combined cosmic UHE neutrino sample.

Neutrino spectrum

It is possible to reconstruct the shower energy from the radio with a precision of the order of 20% [26]. However, in the case of GRAND, it is impossible to determine what fraction of the initial neutrino energy E_ν was actually transferred to the tau lepton or the amount of energy lost by the tau before it emerged in the atmosphere. An event-by-event reconstruction of the neutrino energy is therefore impossible and only a lower bound on E_ν can be computed.

However a neutrino spectrum can be inferred through an unfolding approach [27] if a sufficient number of events are detected. Saying if this treatment would be precise enough to infer physics properties of UHE neutrinos is highly speculative at this stage, and requires a more thorough and quantitative study.

4 Conclusion

Ultra-high energy neutrinos of cosmic origin would be an extremely valuable tool to study neutrino properties and fundamental laws of the Universe in an energy domain beyond reach otherwise.

Given the large uncertainties on the expected fluxes, it is however not possible to guarantee that sufficient statistics will be achieved with next-generation neutrino observatories to actually perform this study.

Provided the neutrino fluxes are above the most pessimistic expectations, we can however say that GRAND would be in an excellent position to compute the neutrino interaction cross-section at energies above 10^{18}eV. It would also certainly contribute to flavor ratios studies, especially if another experiment is able to detect neutrinos in the same energy range. Other studies are more speculative.

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