Science Case for the
Giant Radio Antenna Neutrino Detector

Kumiko Kotera — Institut d'Astrophysique de Paris, UMR 7095 - CNRS, Université Pierre & Marie Curie, 98 bis boulevard Arago, 75014, Paris, France ; email: kotera@iap.fr

> "The title [of this book] is more of an expression of hope than a description of the book's contents [...]. As new ideas (theoretical and experimental) are explored, the observational horizon of neutrino astrophysics may grow and the successor to this book may take on a different character, perhaps in a time as short as one or two decades."
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> John N. Bahcall, *Neutrino Astrophysics*, Cambridge University Press, 1989

High-energy ($> 10^{15}$ eV) neutrino astronomy will probe the working of the most violent phenomena in the Universe. When most of the information we have on the Universe stems from the observation of light, one essential strategy to undertake is to diversify our messengers. The most energetic, mysterious and hardly understood astrophysical sources or events (fast-rotating neutron stars, supernova explosions and remnants, gamma-ray bursts, outflows and flares from active galactic nuclei, ...) are expected to be producers of high-energy non-thermal hadronic emission. Hence they should produce copious amounts of high-energy neutrinos. These signatures will be central to any future progress in the fields of high-energy astrophysics and astroparticle physics. Additionally, they should contribute to unveil fundamental neutrino properties.

1 Why neutrinos?

Neutrinos are unique messengers that let us see deeper in objects, further in distance, and pinpoint the exact location of their sources.

Neutrinos can escape much denser astrophysical environments than light, hence they enable us to explore processes in the deepest layers of objects that are invisible to traditional and gamma-ray astronomy. This can be illustrated through the example of MeV neutrinos detected from the Sun, which made possible the direct study of the nuclear interactions occurring at its very core. The detection of the MeV neutrinos emitted by the explosion of the local supernova 1987A also provided a direct observation of the core-collapse mechanism of massive stars. In both cases, stringent constraints were also derived on fundamental neutrino properties (masses, oscillation, etc.).

Neutrinos travel in geodesics unaffected by magnetic fields. Unlike cosmic-rays which are charged, they do not undergo deflections that induce a shift from the source position in the sky as well as time delays[1]. Neutrinos can thus be spotted in spatial and temporal coincidence with any type of source (steady or transient).

Cosmic rays and photons are also both absorbed by the cosmic backgrounds while propagating through cosmological scales in the Universe. Neutrinos on the contrary are not affected by such backgrounds and can easily probe cosmological distances.

These characteristics could help identify the origins of high-energy cosmic rays, that have remained a mystery for over a century.

2 Why high-energy neutrinos?

The small interaction cross-section of neutrinos makes it difficult to detect them on the Earth. A first experimental argument for going to high energies, is that the interaction probability for neutrinos roughly scales with energy. Above about PeV energies, the Earth becomes opaque to neutrinos. It is then possible to detect them either by looking at those coming downwards, or by using the Earth and/or its atmosphere as a target, and observe the produced up-going secondary showers (see, e.g., [1]).

From the astrophysical point of view, it should be pointed out that neutrinos with energies much greater than GeV can only be produced by very high-energy primary hadronic cosmic rays, via neutron decay or by interaction with radiation or matter. Note that neutrinos provide definite evidence for hadronic acceleration, while gamma-ray signatures are controversial, as they can also be generated through leptonic channels.

The main goal of the construction of high energy ($>$ PeV) neutrino telescopes is thus to explore the signatures of hadronic acceleration in the most powerful phenomena in the Universe. As detailed in the following sections, ultrahigh-energy cosmic ray (UHECR) observations tell us that the highest energy particles are most likely to be produced in extra-galactic sources, and the existence of PeV to EeV ($= 10^{15-18}$ eV) neutrinos is guaranteed. By going to high energies, we thus naturally move to *neutrino astronomy at cosmological scales.*

3 Neutrinos from ultrahigh energy cosmic rays: theoretical predictions

The cosmic-ray spectrum extends to energies above 10^{20} eV. The highest energy cosmic rays are likely to originate in extragalactic sources, given the (limited) strength of Galactic magnetic fields and the lack of correlations with the Galactic plane. Cosmic-ray anisotropy measurements with the Auger Observatory and the Telescope Array indicate that the Galactic-

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[1] a 1-degree deflection over 100 Mpc leads to 10^4 yrs of time delay compared to a rectilinear propagation.

extragalactic source transition likely happens around a few EeV [2, 3, 4].

A fraction of the UHECR energy is expected to be converted to high energy neutrinos through the decay of charged pions produced by interactions with ambient matter and radiation[2]. These interactions may happen either in the source environment, or during the journey of the primary UHECR from the source to the Earth. The neutrinos produced in the latter scenario are called *cosmogenic neutrinos*.

3.1 Neutrinos from the source environments

For sources where proton are accelerated and undergo photo-pion interactions with optical depth equal to unity ($\tau_{p\gamma} = 1$), the neutrino luminosity derived from the observed cosmic-ray luminosity is of order $E_\nu^2\Phi_{\rm WB} \sim 3.4\times10^{-8}\,{\rm GeV\,cm^{-2}\,sr^{-1}\,s^{-1}}$ [9]. This reference estimate is called the Waxman-Bahcall bound. For optically thin sources, the overall level of neutrinos is expected to be lower, and for optically thick sources, cosmic rays are not accelerated to the highest energies and neutrinos above $E \sim$ EeV are sharply suppressed [10].

The magnetic field in the source environment, especially in clusters of galaxies, can play an important role by confining the charged UHECRs and thus leading to increased interaction probabilities [11, 12, 13, 14, 15, 5, 16, 17].

The normalization of these fluxes highly depends on assumptions about the opacity of the acceleration region and on the shape of the injection spectrum as well as on the phenomenological modeling of the acceleration ([18, 19, 9, 20, 21, 22, 5, 23, 24, 25, 10, 8, 26], see also [27, 28, 29, 30, 6, 31] for GRB-specific studies and [32, 7] for neutron stars). Example of flux estimates are presented in Fig. 1. Note that these estimates do not assume particularly optimistic parameters.

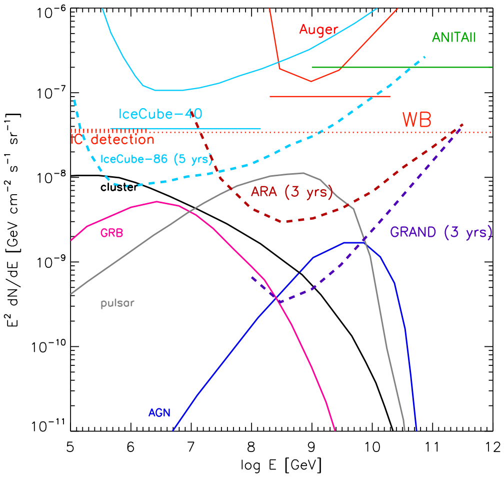

Figure 1: *Estimates for neutrino fluxes for all flavors produced at source environments, for clusters of galaxies [5], GRBs [6], pulsars [7], AGN [8]. The IceCube detection range and flux level is indicated in red hashes, and the Waxman-Bahcall bound in red dotted lines. Overlayed are experimental limits (current and projected). Details are given in caption of Fig. 2.*

Some source scenarios can however be tested with increased sensitivities. In particular, the sensitivity of IceCube is already highly constraining fireball-type UHECR acceleration models in GRBs. In such models, the amount of neutrino production in the internal shock regions where ions should be accelerated can be calculated consistently, once assumptions are

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[2] About 1/2 of $p\gamma$ photopion interactions (2/3 of pp hadronic interactions) produce charged pions, that carry a fraction of the parent cosmic-ray energy $E_\pi/E_p \sim 0.2$ ($E_\pi/E_p \sim 0.6$ for pp). Each neutrino takes up $E_\nu/E_\pi \sim 0.25$ of the parent pion.

made on a finite set of parameters such as the baryonic loading, the acceleration efficiency to ultrahigh energies, the jet Lorentz factor, etc. Studies show that the parameter space allowed for these quantities would be strongly reduced if no neutrinos are observed from the position of detected GRBs in the next decade [33, 34, 35, 36, 37]. Newly-born pulsar scenarios also predict a guaranteed level of EeV neutrinos by interaction of UHECRs in the surrounding supernova ejecta [32, 7]. A non-detection of neutrinos at EeV energies in the next decade would enable us to rule out this potential candidate source.

3.2 The guaranteed cosmogenic neutrinos

The constraints derived on UHECRs (energy, nature, ...) from their detection necessarly implies that their propagation in the intergalactic medium leads to the production of cosmogenic neutrinos and gamma-rays by interactions on the cosmic radiation backgrounds (so-called GZK effect). The expected cosmogenic neutrino and gamma-ray fluxes depend mostly on parameters inherent to cosmic-rays themselves (their composition and overall flux), but also on the injection index at the source and the source emissivity evolution history for diffuse fluxes. Figure 2 summarizes the effects of different assumptions on these parameters [46]. It is striking from this plot that the parameter space is currently poorly constrained, with uncertainties of several orders of magnitude in the predicted flux. The good news however is that there is a guaranteed minimum flux, even in the case when UHECRs are composed of heavy nuclei, with low maximum acceleration energies, and no source evolution (blue lines).

UHECR models with large proton maximum acceleration energy ($E_{\max} > 100$ EeV), source evolution corresponding to the star formation history or the GRB rate evolution and pure proton or mixed 'Galactic' compositions, are shaded in grey in Figure 2 and give detectable fluxes in the EeV range with $0.06 - 0.2$ neutrino per year at IceCube and $2 - 5$ neutrino per year for GRAND. This energy range should be also soon explored by projected radio instruments such as the Askaryan Radio Array (ARA, [45]) and ARIANNA [47].

The sensitivity of GRAND nearly reaches the lowest predicted limits: either a large number of cosmogenic neutrinos will be detected, under standard assumptions on sources, or extremely severe constraints will be derived for the most pessimistic scenarios.

4 Why now? — the multi-messenger and time-domain era

We stand today at the threshold of a *multi-messenger era*, where neutrinos will play a central role.

The construction of gamma-ray telescopes such as MAGIC, VERITAS and HESS on the ground, as well as the launch of the AGILE and Fermi satellites have open the way for the exploration a vast panel of astrophysical objects over a new range of wavelengths. Recently, gamma-ray observations of supernova remnants W44 and IC443 by the AGILE and Fermi telescopes [48, 49, 50] have confirmed that relativistic protons are present in these two supernovae. Such observations will help shaping up the theories of hadronic acceleration. A significant increase in sensitivities and angular/time resolution will be ob-

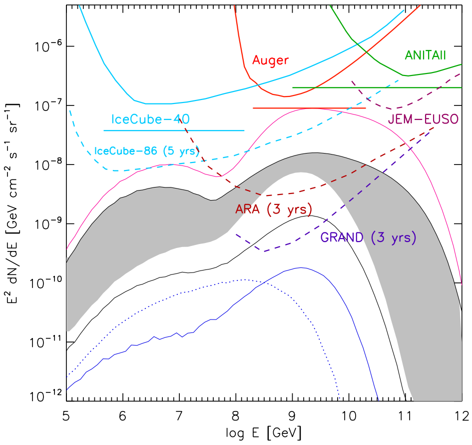

Figure 2: *Cosmogenic neutrino flux for all flavors, for different UHECR parameters compared to instrument sensitivities. Pink solid line: strong cosmological source evolution case [38] with a pure proton composition, Galactic-extragalactic transition below the ankle [39], and maximum acceleration energy* $E_{\rm max} = 3 \times 10^{21}$ *eV. This model is already ruled out by the Fermi diffuse gamma-ray background measurements [26]. Blue lines: no source evolution with: iron-rich (30%) composition and* $E_{Z,\rm max} < Z$ *10 EeV (dotted line) and pure iron injection and* $E_{Z,\rm max} = Z$ *100 EeV (solid), with Z the charge number of nuclei. Grey shaded range brackets all Galactic-extragalactic transition models, with source evolution following the star formation history for* $z < 4$*, pure proton and mixed 'Galactic' compositions, and large proton* $E_{\rm max}(> 100\,EeV)$*. Including the uniform source evolution would broaden the shaded area down to the black solid line. Current experimental limits (solid lines) assume 90% confidence level and full mixing neutrino oscillation. The differential limit and the integral flux limit on a pure* E^{-2} *spectrum (straight line) are presented for IceCube-40 (pale blue, 40), ANITA-II (green, 41) and Auger (red, 42). For future instruments, we present the projected instrument sensitivities (dashed lines) for IceCube-86 after 5 yrs (pale blue, 43), JEM-EUSO [44], ARA-37 for 3 years [45], GRAND for 3 years.The limit for GRAND is only preliminary, as it is based on approximative (but realistic) estimations of the air showers radio emission.*

tained in the coming years with HAWC, LHAASO and CTA.

After many decades of efforts to discover the origin of cosmic rays, current observatories are now reaching the necessary exposure to begin unveiling this long-standing mystery. By mid-2014, the Pierre Auger Observatory and the Telescope Array have collected about 120 and 50 events above 5.7×10^{19} eV respectively. The measurement of a flux suppression at the highest energies [51], reminiscent of the "GZK cutoff" [52, 53] produced by the interaction of particles with the cosmic microwave background photons for propagations over intergalactic scales, and the absence of striking anisotropy in the arrival directions has appeased the debate concerning the extragalactic provenance of UHECRs. These features not only suggests that UHECRs would originate outside of our Galaxy, but also that the sources of the highest energy particles should be located within $\sim 100\,\mathrm{Mpc}$ distance, in our local Universe. However, the sources remain unknown and results from the Auger Observatory on the arrival directions and chemical composition of UHECRs make the picture even more puzzling ([54, 55] for recent reviews).

IceCube has just opened the breach for high-energy neutrino astronomy, by detecting two PeV energy neutrinos, followed by 35 others from $30\,\mathrm{TeV}-2\,\mathrm{PeV}$ energies [56, 57, 58]. The measured flux is of order $E_\nu^2\Phi \sim 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ per flavor, close to the Waxman-Bahcall flux level that instruments are finally able to probe. It represents a $5.7\,\sigma$ excess above the atmospheric background (neutrinos produced by cosmic ray interactions with the atmosphere). The three main messengers (cosmic rays, neutrinos and gamma-rays) are now being detected together, and it is time to collect more neutrinos, span the whole energy range up to $>\mathrm{EeV}$ energies, and move to a point-source analysis.

We are also entering an epoch where *time domain astronomy* is booming in all wavelengths, rendered possible by the high sensitivity and timing precision achieved by the recent instruments. Neutrinos can participate fully in this field, as they do not experience time delays due to magnetic deflections. In particular, those generated close to the source should be observed nearly in coincidence with electromagnetic (possibly transient – e.g., for blazar flares, gamma-ray bursts, etc.) signals. Cosmogenic neutrinos on the other hand would be spread out in time, as they can have been produced anywhere during the propagation of the primary cosmic rays, which experience deflections.

A high-sensitivity high-energy neutrino detector with very good angular resolution, that would collect enough neutrinos to be able to achieve time-domain neutrino astronomy would be a dream tool today for the whole high-energy astrophysics and astroparticle communities. The construction of a powerful array such as GRAND would fulfill this dream.

5 Objectives of High-Energy Neutrino Astronomy

A) Detect the diffuse cosmogenic neutrinos

As we saw in Section 3, the diffuse cosmogenic neutrino flux is guaranteed by the observation of UHECRs, and the sensitivity of GRAND will cover the flux uncertainty range almost to the lowest limit.

It is therefore highly likely that this signature will be observed by GRAND. Its level will then constrain the major cosmic-ray injection and source properties. Because of the wide energy span of GRAND ($\sim\ 3\times10^{16} - 3\times10^{20}\,\mathrm{eV}$), it will be possible to measure accurately and consistently the shape of the neutrino spectrum, and overcome most degeneracies in parameters. If EeV neutrinos are detected, PeV information can help select between competing models of cosmic ray composition at the highest energy and the Galactic to extragalactic transition at ankle energies. The flux at ZeV ($=10^{21}\,\mathrm{eV}$) energies will also constrain the maximum acceleration energy.

B) Constrain UHECR source candidates by stacking analysis

As mentioned in Section 3.1, some source scenarios can be strongly constrained by the non-observation of high-energy neutrinos with IceCube in the next decade. The high sensitivity of GRAND would enable to directly eliminate all the parameter-space for fireball models in GRBs [33, 34, 35, 36, 37] or neutron-star scenarios [32, 7].

If neutrinos are detected on the other hand, more dedicated searches are needed. A measurement of the precise shape of the spectrum would first help distinguish cosmogenic neutrinos from those produced at the source (a double bump structure as in Fig. 2 is indeed expected for cosmogenic neutrinos, due to the interactions with the CMB and UV/IR/optical photon backgrounds).

Stacking analysis, as already performed for GRBs, can then be performed at the position of potential sources. For newborn neutron-star scenarios for instance [59, 60, 7], searches at the location of nearby supernovae, especially hypernovae or ultra-luminous supernovae [61] should be promising.

The contribution of nearby sources, within $\sim 150\,\mathrm{Mpc}$ (a range where most steady and transient candidate sources for UHECRs can be spotted by gamma-ray instruments) is expected to be larger than the background diffuse flux, which makes the stacking analysis powerful. Note that a good angular resolution is required to make this analysis pertinent.

C) Neutrino and electromagnetic counterpart association for single transients

The detection of several neutrinos from a single UHECR source is the ultimate goal of high-energy neutrino astronomy. The probability of such a detection depends upon the overall number density of sources. If cosmic rays are protons, the absence of multiple UHECR events from single sources strongly disfavor models with source density $\bar{n} < 10^{-5}\,\mathrm{Mpc}^{-3}$ [62, 63, 64]. The low density of steady candidates (clusters of galaxies :$10^{-6}\,\mathrm{Mpc}^{-3}$), FRI-type : $10^{-5}\,\mathrm{Mpc}^{-3}$), FRII-type radio-galaxies : $10^{-8}\,\mathrm{Mpc}^{-3}$) might not be compatible with the anisotropy data in the case of proton composition. In all cases, and also for heavier composition models, multiple neutrinos are unlikely to be detected unless the neutrino luminosity of the sources exceeds their UHECR luminosity by three orders of magnitude.

For transient sources, the apparent n_0 and real ρ_0 number densities of proton UHECR sources are related via the cosmic ray arrival time spread δt due to magnetic fields: $\rho_0 \sim n_0/\delta t$ [65]. Bright transient events such as AGN flares, GRBs and pulsars can all accommodate these constraints and provide for the observed energy budget $\mathcal{E}_{\rm UHECR} \sim 10^{44.5}$ erg Mpc^{-3} yr^{-1}. For these anisotropy/source density reasons, it is likely that the actual sources of UHECRs are bright transient sources with rates at least comparable to long-duration GRBs ($n_{\rm GRB} \sim 5$ Gpc^{-3} yr^{-1} at $z = 1$) for the brightest sources able to supply UHECR energy $E_{\rm UHECR} \gtrsim 10^{52}\,\mathrm{ergs}$ each. Note that the associated UHECRs will not be observed in coincidence with these sources, as they will experience significant time delay due to magnetic deflection.

The correlation of a neutrino event with an electromagnetic event would most certainly identify the source, provided that the angular resolution is sufficiently good to explore the cosmological scales where the transient events would be located. At least a fraction of a degree resolution is required for such purposes. A wide multi-wavelength transient monitoring will be necessary to increase the chances of observing a coincident event.

D) Understand the origin of the IceCube neutrinos

The IceCube data are consistent with expectations for equal fluxes of all three neutrino flavors and with isotropic arrival directions, suggesting either numerous or spatially extended sources. It is envisaged that the observed flux level might either result from the superposition of discrete sources or be truly diffuse on some scale. The spectrum is well described by a power-law with index ~ -2, and the current statistics do not enable us to conclude on the apparent suppression of the neutrino flux between $\sim 0.3 - 1\,\mathrm{PeV}$.

Galactic and extragalactic scenarios have been proposed to explain the observed flux, with a tendency to favor extragalactic models (in particular, starburst galaxies as in the model predicted by [66], see also [67]). Galactic models mostly involve a connection with the Fermi bubble structures (relatively large-scale structures recently detected in gamma-rays and radio, 68, 69) or the Galactic halo [70, 71, 72, 73].

The measurements of the spectral features, spatial anisotropy and flavor content should become more accurate with increased IceCube exposure and improved analysis. The highest energy end of the observed spectrum can be probed simultaneously by GRAND, whose sensitivity and angular resolution will highly improve the quality of the data. It will then be possible to explore the different source scenarios in depth and work out associations with electromagnetic observations.

E) Explore fundamental neutrino properties

In addition to probing UHECR sources and acceleration, the detection of high energy neutrinos in association with an electromagnetic signal could help us study fundamental neutrino properties. In some bright transient sources, such as GRBs, the time delay between the arrival of the neutrinos and the photons could allow to test for Lorentz invariance violation due to quantum gravity effects [74, 75].

As was done for supernova 1987A, the ratio between photon and neutrino velocity could be measured to test the weak equivalence principle (which stipulates that both should suffer the same time delay while passing through a gravitational potential) [76]. With a time resolution of ~ 1 s, a GRB located at $1\,\mathrm{Gpc}$ distance would enable to set a fractional difference in photon and neutrino velocity of $\sim 10^{17}$ and in gravitational time delay of $\sim 10^{6}$ (implying improvements of 10^{9} and 10^{4} orders of magnitudes respectively).

The measurement of astrophysical neutrinos will also probe neutrino oscillation, mixing parameters, mass hierarchy, and possibly new physics [77]. In particular, if neutrinos are produced in astrophysical objects via pion production, no τ neutrinos are expected to be produced. Neutrino oscillations would however lead to the production of ν_τ in equal quantity as the other flavors at cosmological distances. GRAND, which is essentially designed to measure the up-going ν_τ would thus probe these oscillations. The measurements of other flavors via other instruments will be important to test the flavor ratios.

6 Advantages of GRAND over other existing or planned instruments

Several instruments have been built to search for high energy neutrinos, at the

Lake Baikal [78], in the Mediterranean Sea (ANTARES [79]), and the Antarctic ice (AMANDA, [80], IceCube [81]). All these experiments look for the Cherenkov light emission of secondary charged particles produced in weak interactions of neutrinos with nuclei, in optically transparent media. Coherent radio Cherenkov emission can also be used for detection, and this technique has been applied or will be applied from the regolith of the Moon (GLUE [82], NuMoon [83]), in the Greenland ice sheet (FORTE [84]) and in the Antarctic ice (RICE [85] and ANITA [41]). Planned instruments for high-energy neutrino detection via these same techniques include DecaCube, the ten-times larger successor to IceCube, KM3Net in the Mediterranean, the Askaryan Radio Array (ARA, 45), and ARIANNA [47]. These instruments will be able to reach sensitivities about ten times better than IceCube at EeV energies, but their angular resolution will be poor (more than a degree) due to the spatially broad Cherenkov signal.

UHECR observatories such as the Auger Observatory, Telescope Array and the planned JEM-EUSO satellite can set upper limits to the neutrino fluxes [3, 44], by searching the signals of neutrino-induced air-showers. This technique should enable a better reconstruction of the arrival direction. The exposure reached by these instruments is however not highly constraining for a large panel of source models.

GRAND will measure the geomagnetic synchrotron radio signal of up-going neutrino-induced air-showers. Thanks to its immense coverage (90k antennas over $60\,000\,\mathrm{km}^2$), it should reach a sensitivity ten times better than the planned ARA, and cover a wide energy range ($3\times10^{16} - 3\times10^{20}$ eV). It will also allow for a accurate angular resolution of less than 0.1 degree, a crucial parameter to point towards cosmological sources. All in all, GRAND proposes a cheap, scalable, easily maintainable and powerful detector, and can be deployed in any deserted region (preferably with mountains which would help screen out cosmic-ray induced air-showers) with very low radio background noise. Its technique has mostly been tested by the TREND array [86] and the background discrimination will further be tested in the summer 2015 with a prototype array of 35 antennas.

The construction of GRAND, with its high-sensitivity and very good angular resolution, has fully the potential to open the new field of time-domain high-energy neutrino astronomy.

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