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Near-future discovery of point sources of ultra-high-energy neutrinos

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Upcoming neutrino telescopes may discover ultra-high-energy (UHE) cosmic neutrinos, with energies beyond 100 PeV, in the next 10–20 years. Their sources are guaranteed interactions sites of UHE cosmic rays. We propose to identify sources via search of multiplets of UHE neutrinos from similar directions. We provide state-of-the-art forecasts of their detection in the radio array of IceCube-Gen2. We find that sources at declination of $-45°$ to $0°$ will be easiest to discover. Discovering even one steady-state source in 10 years would imply that the source has an UHE neutrino luminosity at least larger than about 10^{43} erg s^{-1} (depending on the source redshift evolution). Discovering no transient source would disfavor transient sources brighter than 10^{53} erg as dominant.

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1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) is a long-standing open problem in astrophysics. They must be accelerated to energies higher than 10^{12} GeV, likely within extragalactic astrophysical sources. While several candidates have been proposed, none of them has been irrefutably identified. A crucial difficulty is that UHECRs are deflected in cosmic magnetic fields, and do not point back to their sources. This difficulty could be overcome via the detection of astrophysical neutrinos. These are expected to be produced in the interaction of UHECRs with dust and radiation in the sources in which they are accelerated, and subsequently reach the Earth. Differently from UHECRs, neutrinos are electrically neutral, and thus they point back to their sources.

A first step in this direction was the discovery of a diffuse flux of neutrinos of TeV–PeV energies, by the IceCube neutrino telescope. IceCube has identified candidate point sources for a few of these neutrinos, including the active galactic nucleus TXS 0506+056, the starburst galaxy NGC 1068, and the tidal disruption event AT 2017dsg. Since neutrinos typically carry an energy equal to 5% of their parent proton energy, these sources are guaranteed accelerators of UHECRs up to tens of PeV. However, there is no certainty that these sources are also the long-sought sources of EeV-scale UHECRs. The definitive answer to this question can be obtained by detecting point sources of ultra-high-energy (UHE) neutrinos, above 100 PeV.

Although their existence was proposed in the 1960s, UHE neutrinos remain undiscovered. The main challenge is the steep decrease of the astrophysical neutrino flux with energy, so that UHE neutrinos are rare and difficult to detect. However, in the coming decade a number of experiments are expected to start taking data, and should be sensitive enough to attain the detection of UHE neutrinos within the next 10–20 years. This will provide in principle the possibility of performing UHE neutrino astronomy via the detection of neutrino multiplets, i.e. clusters of neutrinos coming from similar positions in the sky. In Ref. [1], we provide state-of-the-art forecasts for this possibility. As a benchmark experiment, we focus on the radio array at IceCube-Gen2, which promises to be one of the most advanced and most sensitive ones, expected to start operations in the 2030s. However, our methods are of wider applicability and can be used in the more general context of UHE neutrino telescopes.

The possibility of discovering cosmic accelerators by using the angular distribution of UHE neutrinos was first pointed out in Ref. [2], which used the angular distribution of UHE neutrinos as a probe of the presence of point sources. However, due to the lack of realistic estimates of the experiment response at the time, Ref. [2] adopted simplifying assumptions on the experiment performance (e.g., a uniform detector effective area with a fixed fractional sky coverage). We provide the first prospects for point-source discovery, accounting for the angular-dependent response of the experiment and the crucial role of neutrino propagation through the Earth. We phrase our work in terms of two main questions: first, how large should a neutrino multiplet be in order to conclusively claim a point-source identification? Second, what information can we draw on UHE neutrino source populations if a source is detected or if no source is detected?

2. Prospects for UHE neutrino detection

In order to determine how large must a neutrino multiplet be to claim a point-source detection, we need an accurate modeling both of the detector response to a given neutrino flux, and of the background neutrino fluxes which may produce fictitious multiplets unrelated to astrophysical point sources. We discuss both these aspects in this section.

2.1 Detector response

A key improvement of our work over the preceding literature is to provide a detailed description of the response of the radio array at IceCube-Gen2 to an astrophysical neutrino flux. This includes accounting for neutrino propagation through the Earth, and a full simulation of the detector response.

When astrophysical neutrinos arrive at the Earth, they reach the detector, located at the South Pole, from different directions. Neutrinos passing through the Earth are attenuated and shifted to lower energies because of the scattering with nuclei in matter. This induces a peculiar anisotropy in the response of the detector. Downgoing neutrinos arrive at the detector from above, and are largely unattenuated. Upgoing neutrinos arrive at the detector from below, and are strongly attenuated. Earth-skimming neutrinos arrive at the detector from directions close to the horizon, so that they are mildly attenuated. We compute neutrino in-Earth propagation using the state-of-the-art tool NuPropEarth [3].

Inside the detector, a neutrino interacts with a proton or neutron of the Antarctic ice, via neutrino-nucleon deep inelastic scattering, triggering a high-energy particle shower that receives a fraction of the neutrino energy. The charged particles in the shower emit a coherent radio signal—Askaryan radiation, which is then detected by the radio array. A complete modeling of the detector must account both for the geometry of the detector, and for the neutrino-nucleon scattering. For this work, we adopt the IceCube-Gen2 effective volumes from Ref. [4], computed via simulations using the same tools as the IceCube-Gen2 Collaboration.

2.2 Backgrounds

The main challenge to multiplet searches is that, underlying the UHE neutrinos from point sources, we expect a diffuse background of UHE neutrinos and atmospheric muons whose random over-fluctuations may mimic multiplets from point sources.

The diffuse flux of UHE neutrinos is likely composed of cosmogenic neutrinos, made in UHECR interactions en route to Earth, and of neutrinos from unresolved sources. While this flux has never been measured, upper bounds have been obtained on it mainly from IceCube [5] and Auger [6]. Rather than adopting a particular prediction, we set the diffuse UHE neutrino flux to benchmark levels representative of current and future detector sensitivity: the current IceCube upper limit on the energy flux $E_\nu^2 \Phi_\nu$ (*high*) [5], and versions of it shifted down to 10^{-8} (*intermediate*) and 10^{-9} GeV cm^{-2} s^{-1} sr^{-1} (*low*). We also account for a background of atmospheric muons, which is, however, negligible.

2.3 Discovering sources

The first question that we address is how large should a detected multiplet be to claim that it is due to a point source, and not to an over-fluctuation of the background. We outline our strategy

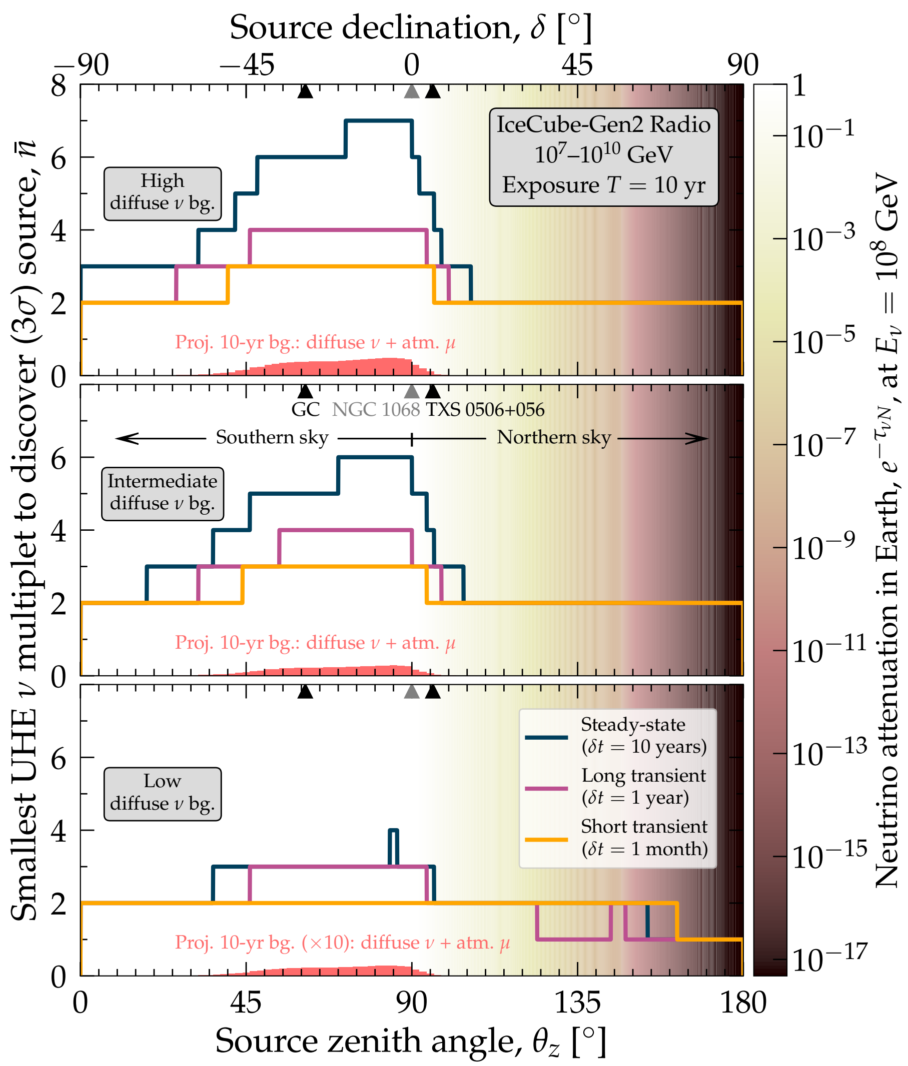

Figure 1: Smallest UHE multiplet needed for the IceCube-Gen2 radio array to discover an UHE neutrino source, steady-state or transient, with global significance of 3σ, for three choices of the unknown background diffuse UHE neutrino flux: high (*top*), intermediate (*center*), and low (*bottom*). For each, we show the projected 10-year rate of background events with reconstructed shower energy of 10^7–10^{10} GeV. The shading shows the in-Earth attenuation coefficient $e^{-\tau_{\nu N}}$ for 100-PeV neutrinos, where $\tau_{\nu N}$ is the optical depth to neutrino-nucleon (νN) scattering; smaller values of it represent stronger attenuation. For this plot, we use a detector angular resolution of $\sigma_{\theta_z} = 2°$ and our baseline radio array design. Figure taken from Ref. [1].

here, and refer to Ref. [1] for details.

We tessellate the sky in pixels, with a size equal to the angular resolution of the detector, namely $\sigma_{\theta_z} = 2°$ (see, e.g., Ref. [7]). In the i-th pixel, we compute the expected number of events due to the background μ_i after the exposure time T. To exclude the possibility that a neutrino multiplet was background-induced, rather than source-induced, we need the probability that the background alone produced a multiplet.

The *local* p-value p of detecting a multiplet of more than n_i events in the i-th pixel, i.e., the probability that a multiplet is due to background alone, is $p(\mu_i, n_i) = \sum_{k=n_i}^{+\infty} (\mu_i^k/k!)e^{-\mu_i}$. But this does not account for the look-elsewhere effect: even if p is small—so that a background fluctuation is unlikely—the probability that an excess with this p-value occurs anywhere in the sky may be large. Therefore, following Ref. [1], in our forecasts we use instead the *global* p-value $P(p)$, i.e., the probability that a multiplet with local p-value p occurs in any of the pixels.

Figure 1 shows the smallest multiplet needed to claim source discovery at 3σ, i.e., with $\bar{P} = 0.003$, in $T = 10$ yr of exposure time, for our three background neutrino diffuse fluxes. In all cases, sources located above IceCube-Gen2 ($\theta_z \lesssim 45°$), where the background is smallest, may be discovered by detecting a doublet or triplet, regardless of the choice of benchmark. However, detection is unlikely in these directions because the detector effective volume is small. In contrast, sources located closer to the horizon ($45° \lesssim \theta_z \lesssim 95°$), where the background is largest, require larger multiplets, as large as a heptaplet for the high background benchmark. Yet, detection is promising in these directions because the effective volume is larger and in-Earth attenuation is mild.

Steady-state sources, like starburst galaxies, are active during the full exposure time, T. Searches for them accumulate larger background and require larger multiplets to claim discovery. Long- and short-duration transient sources, like blazar flares and tidal disruption events, respectively, are active for a fraction of that time, δt. Searches for them require smaller multiplets. In Ref. [1] we show detection prospects for very-short-duration transients, which can always be discovered with doublets or triplets alone.

A crucial parameter for our prospects is of course the angular resolution. Using a resolution of 5° roughly doubles the size of the multiplets needed to claim discovery, as shown in Ref. [1]. On the other hand, our results are tentatively robust to the choice of the design of the IceCube-Gen2 radio array. Figure 1 uses our baseline design described above. We have tested two alternative designs in Ref. [1], finding comparable results.

3. Constraints on source population

The detection of point sources implies that the neutrino sky is populated with bright neutrino emitters. On the contrary, if no point source is observed, an upper bound can be set on the neutrino luminosity of individual neutrino sources. Here we quantify these statements. A population of steady sources can be described in terms of its local number density n_0 and the individual neutrino luminosity L_ν. For transient sources, one can use the local burst rate $\mathcal{R}_0$ and the energy emitted in neutrinos in a burst E_ν. We assume that sources are distributed according to the star formation rate in redshift. The entire source population produces a diffuse neutrino flux proportional to the product $n_0 L_\nu$, or $\mathcal{R}_0 E_\nu$. Such a diffuse flux cannot exceed the assumed background models. Therefore, for each background model, a first constraint can be drawn by this requirement.

We consider the scenario in which UHE neutrinos are produced by this population of sources, candidate for detection, and by an unresolved background of neutrinos. The latter can mimic either a cosmogenic neutrino flux or a flux from dim astrophysical sources, and is determined so that the total diffuse neutrino background equals the background flux assumed in each of the three models adopted. For each background model, we can now determine the probability of observing in at least one pixel in the sky a multiplet larger than the threshold value of Fig. 1 in an exposure time of 10 years. We use an exact analytical approach detailed in Ref. [1] for computing this probability as a function of n_0 and L_ν for steady sources, and of $\mathcal{R}_0$ and E_ν for transient sources. If at least one

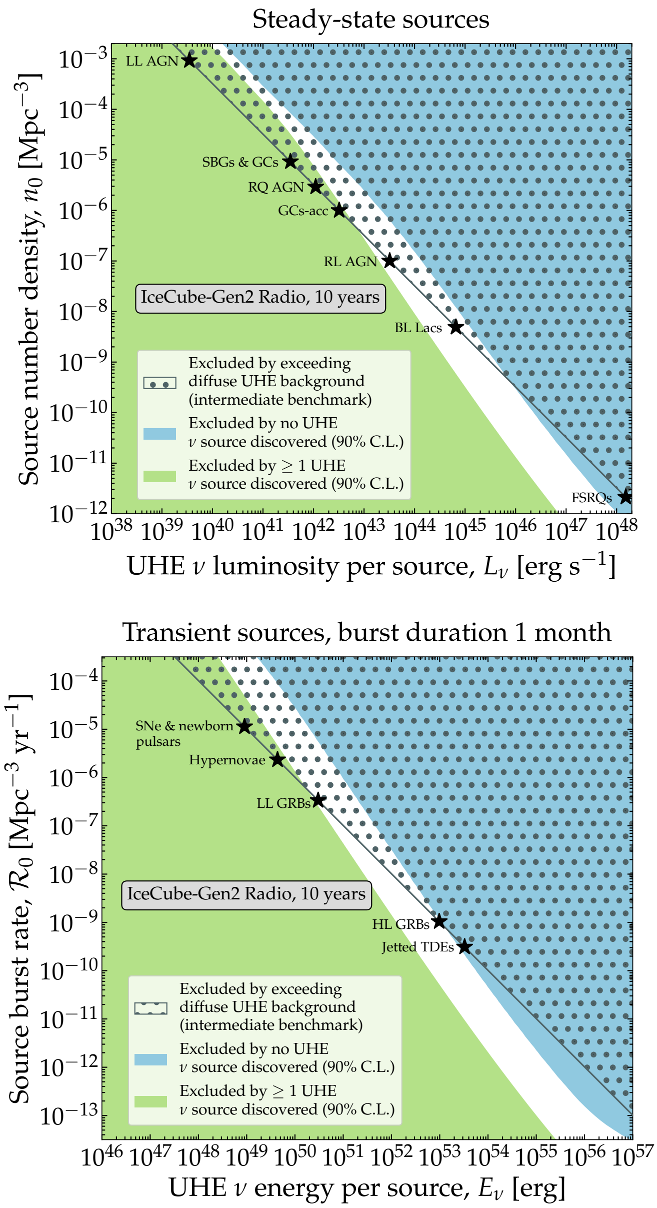

Figure 2: Constraints on candidate classes of steady-state (*top*) and transient (*bottom*) UHE neutrino sources, from the discovery or absence of UHE multiplets, i.e., of UHE neutrino sources, in the radio array of IceCube-Gen2 after 10 years of exposure. We showcase promising candidate source classes; for each, the value of L_ν or E_ν is chosen to saturate the background UHE neutrino diffuse flux; for this plot, we fix it to our intermediate benchmark. In the hatched region, the flux from the source population exceeds the background diffuse flux. Figure taken from Ref. [1].

source is discovered after 10 years, we require this probability to be larger than 10%; if no source is discovered, it should be larger than 90%.

Figure 2 shows the constraints that we set on UHE source populations based on this approach, assuming our intermediate benchmark UHE diffuse background. If no steady-state source is discovered after 10 years, rare source classes would be disfavored as individually dominant. No source class is really rare enough to be disfavored. Conversely, if even one source is discovered, most known steady-state candidates would be excluded. For transient sources, the situation is reversed. If none is discovered, the brightest transients, with total energy emitted per source larger than 10^{53} erg, would be disfavored: these include GRBs and TDEs, which are known candidates for UHECR acceleration. Conversely, if even one transient source is discovered, it would be a strong indication in favor of these source classes.

4. Discussion

We have shown that multiplet identification is a promising technique to discover point sources of neutrinos in the ultra-high-energy range. Our prospects are the first ones that adopt a realistic, state-of-the-art modeling of the IceCube-Gen2 radio array, accounting both for angular-dependent effective volumes and effects of neutrino absorption in Earth. We identify the minimum size of the multiplets that are needed to conclusively claim a discovery on top of an otherwise diffuse neutrino flux. Furthermore, we adapt our results to obtain projected constraints on the properties of the source populations generating the diffuse flux if no multiplet is discovered or, vice versa, if at least one multiplet is discovered. No source discovery excludes bright, mostly transient candidates, whereas at least one source discovery would exclude dim sources as the dominant contributors to the diffuse flux.

We have explored the robustness of our results against different detector designs, finding that the main parameter which can actually impact them is the angular resolution. Therefore, our work provides a target for the required resolution of about 2°, needed for efficient multiplet identification, that can inform the design of the upcoming detectors.

Our projected constraints on source populations are based on the assumption of all sources having the same luminosity and distributed according to the star formation rate. In our main paper [1], for the two selected, promising populations of TDEs and FSRQs, we have considered the full luminosity and redshift distribution to infer what the expected number of multiplets would be. For both, we find that, if they produce a diffuse signal of tens to a hundred events in 10 years at IceCube-Gen2 radio array, they would be expected to be detected based on their distribution.

Finally, we emphasize that multiplet identification does not require any associated electromagnetic signal, so it is an efficient strategy even for gamma-ray dark sources. On the other hand, if the sources do have a comparable electromagnetic signal, much more powerful detection prospects could be obtained by association with catalogs of known sources.

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