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Detector optimization figures-of-merit for IceCube's high-energy extension

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ABSTRACT

With the design and development of next-generation high-energy neutrino detectors, it is important to compare different detector designs to optimize detection probability and science reach. These comparisons are nevertheless difficult due to large uncertainties in current neutrino source model parameters. We examine the role of the most important characteristics of high-energy neutrino searches in the probability of discovering different source types. We derive scaling relations for each considered source and search scenario, which can be used to compare different detector designs with respect to their utility in discovering different source populations. The recovered scaling relations are independent of source strengths, providing a model-independent comparison.

1. Introduction

IceCube's recent discovery of cosmic high-energy neutrinos [1–4] represents an important step in studying high-energy astrophysical processes with neutrinos. Nevertheless, the origin of the observed neutrinos is currently unknown. Multimessenger searches have not recovered electromagnetic [5,6] or gravitational wave [7] counterparts, and the neutrinos' directional distribution so far is consistent with diffuse emission [8]. The observed neutrino energy distribution is also so far consistent with multiple possible source types [9–13].

Some high-energy neutrino observatories are planned to be substantially expanded in the near future. IceCube's planned upgrade, IceCube-Gen2 [14], aims to instrument 10 km^3 volume, essentially increasing sensitivity by a factor of 10. The KM3NeT detector is planned to be constructed in the Mediterranean with comparable volume [15]. There are also plans to expand the Baikal neutrino detector at lake Baikal to km^3 volume [16].

The specifics of how a neutrino observatory is built or expanded given a fixed cost depend on the relative importance of several factors. For example, a part of the detector can be dedicated to help reject the atmospheric background. This part then, however, is not used in direct detection, therefore reducing the overall sensitivity. Such tradeoffs can be made by aiming to optimize the science reach of the detector.

The goal of this paper is to assess how detector characteristics affect the science reach of a high-energy neutrino detector. Given the limited resources for construction, the optimization of the detector's ability to probe the high-energy universe is essential. We will focus on the discovery of the astrophysical sources of origin of cosmic neutrinos. For numerical values, we will consider IceCube's Gen2 extension, but the results are generally valid for other detectors as well.

While there are numerous critical aspects of detector construction, here we approach this question from the perspective of some of the fundamental detector characteristics, such as (i) sensitivity, (ii) directional uncertainty, and (iii) background rejection ability. While these quantities can vary with source direction, time, etc., here we consider them as characteristic overall values and describe the detector's capability with them. While local variations of these parameters may affect search sensitivity, they are unlikely to change the general relations that we derive below. There are also other important parameters, such as the reconstructed energy uncertainty, which can play an important role in, e.g., spectral analysis. The search method we consider in the following takes advantage of directional and temporal correlation, and therefore energy reconstruction will not be of primary importance. Our aim is to derive scaling relations between the above three characteristic parameters that determine the detector's sensitivity for different source types. Such a relation can then help establish a detector design that maximizes the chance of discovery within the available resources. In other words, it is likely that the design process requires compromises between achieving greater sensitivity, directional uncertainty or background rejection capability. This work tries to help make the best compromise.

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There are different source types for which detector design optimization may be different. We will consider

1. continuous point sources
2. transient sources
3. an extended galactic source

Further, we will examine searches for TeV neutrinos for which a large number of events are detected with IceCube, as well as ultra-high energy neutrinos with a significantly lower number of detections and better signal-to-noise ratio.

We are interested in the connection between the probability of discovering a given source type, and the following parameters:

- N_{ast}: number of astrophysical neutrinos detected during the considered observation period.
- ψ: angular uncertainty of the reconstructed neutrino direction.
- N_{atm}: number of atmospherical background events detected during the considered observation period.

We will derive a scaling relation between these three quantities for each of the considered source type.

The paper is structured as follows. Section 2 introduces a search strategy that will be assumed in deriving detection probabilities. Sections 3, 4.2 and 5 describe results for continuous point sources, transients and extended galactic sources, respectively. Section 6 summarizes and discusses the results.

2. Search strategy

There are a large number of possible search strategies for high-energy neutrinos for a variety of source types. Here we adopt a simple strategy that captures the important features of efficient multimessenger searches, while allowing for the analytical evaluation of the sensitivity.

Since we are interested in discovering the sources of origin, we consider a known astrophysical population of potential sources. Accordingly, the search relies on a catalog of potential neutrino sources observed with electromagnetic telescopes/detectors, with precisely known directions and distances, and if applicable, times and durations. For simplicity, we assume that the sources are uniformly distributed in the universe.

The strategy is the following. We count directional coincidences between the detected events and the source catalog. The significance of the search is determined based on the number of observed coincidences compared to the number expected assuming no correlation between neutrino and catalog directions. Since a too large number of sources in the catalog render the search not sufficiently sensitive, we exclude the farthest sources in the catalog such that the expected p-value from background-only neutrino events equals the p-value p_{disc} determined by the required false alarm rate. This ensures that, having a neutrino that originates from one of the sources within the (reduced) catalog will be a discovery. Note that the downside of the reduced catalog is that the detected astrophysical neutrinos that originate from the sources that are excluded from the reduced catalog are now part of the background.

We quantify the sensitivity of the above search strategy by the probability $P(p_{disc})$ that neutrinos from a source population are discovered with p-value $\leq p_{disc}$. This probability will also depend on the detector parameters.

We note that, while this search is relatively simple and does not take into account all information available in the source catalog, we find that its scaling is similar to that of a more complete search strategy, with comparable sensitivity. The reason is that at larger distances, sources are more uniformly distributed, therefore directional correlation gradually loses significance.

The derivation of the scaling is different for different scenarios. In the following, we organize the discussion along source types and neutrino energy ranges of interest, pointing out where the derivations overlap.

3. Continuous point sources

Continuous point sources are expected to continuously emit neutrinos, from within an angular size much smaller than the angular uncertainty of reconstructed neutrino directions. This class includes some of the most promising neutrino source candidates, such as starburst galaxies, active galactic nuclei (AGN), and quasars. We will discuss extended galactic sources in a separate section.

In the following we will separately consider the cases of ultra-high-energy ($\gtrsim$100 TeV) neutrino and TeV neutrino searches. These two cases have different signal and background detection rates that require separate treatment. Since we are interested in directional coincidence, for both cases we will focus on track events that have much better reconstructed directions than cascade events.

3.1. Ultra-high-energy search for continuous point sources

3.1.1. Number of detected signal and background neutrinos

It is useful to introduce N_s and N_b, the numbers of detected signal and background neutrinos, respectively. Signal neutrinos will be defined as those that originate from one of the sources in the reduced catalog. All other detected events, including atmospheric events as well as astrophysical neutrinos originating from sources not in the catalog, will be considered background, and their number will be denoted with N_b. Since the search is limited to sources within d_{th}, only a fraction

$$f_d \propto d_{th} \tag{1}$$

of astrophysical neutrinos will be included in N_s. This scaling comes from the fact that the neutrino contribution of a volume shell within $[d_{th}, d_{th} + \epsilon]$ is independent of d_{th}, where ϵ is a small distance. We therefore have

$$N_s = f_d N_{ast} \tag{2}$$

$$N_b = N_{atm} + (1 - f_d)N_{ast} \tag{3}$$

$$N_{total} = N_s + N_b \tag{4}$$

3.1.2. Discovery probability

We take advantage of the fact that ultra-high-energy searches have relatively few detections by optimizing for the detection of one signal neutrino. Since we focus on only the nearby sources (say within a few hundred Mpc) within which directional correlation can be significant, the fraction of astrophysical neutrinos originating from these nearby sources is small. Even with a ~10 times increased detection rate, the number of astrophysical neutrinos originating from a source within ~100 Mpc from a uniform source population over ~1 yr observation is $N_s \ll 1$.

In the limit of $N_s \ll 1$ the probability of discovery is

$$P(p_{disc}) \approx 1 - \mathrm{Pois}(0, N_s) \approx N_s, \tag{5}$$

where $\mathrm{Pois}(k, \lambda)$ is the Poisson distribution for k with parameter λ.

3.1.3. Threshold distance

With ψ directional uncertainty for the neutrino events and precise (i.e. $\ll \psi$) directional uncertainty for the source catalog, the chance of random directional coincidence between a neutrino and a source is $\propto\psi^2$. Let ρ_{source} be the number density of the astrophysical sources in the catalog, and d_{th} a threshold distance such that we