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Sensitivity of the Cherenkov Telescope Array to the gamma-ray emission from neutrino sources detected by IceCube

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Gamma-ray observations of the astrophysical neutrino sources are fundamentally important for understanding the underlying neutrino production mechanism. We investigate the Cherenkov Telescope Array (CTA) ability to detect the very-high-energy (VHE) gamma-ray counterparts to the neutrino-emitting Active Galaxies. The CTA performance under different configurations and array layouts is computed based on the neutrino and gamma-ray simulations of steady and transient types of sources, assuming that the neutrino events are detected with the IceCube neutrino telescope. The CTA detection probability is calculated for both CTA sites taking into account the visibility constraints. We find that, under optimal observing conditions, CTA could observe the VHE gamma-ray emission from at least 3 neutrino events per year.

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1. Introduction

Astrophysical sources capable of hadronic acceleration to relativistic energies are the potential sources of astrophysical neutrinos. Unlike photons, neutrinos are able to travel through dense astrophysical environments and over cosmological distances without the Extragalactic Background Light (EBL) absorption to provide unambiguous tracers of hadronic acceleration.

In 2013 the IceCube Neutrino Observatory reported the presence of an all-sky, isotropic, high-energy neutrino flux of extraterrestrial origin [1]. The sources responsible for the measured astrophysical neutrino flux and their identification are topics still under discussion.

In April 2016 IceCube initiated the real-time alert program [2], in which neutrino events that are likely to be of astrophysical origin are reported via the General Coordinates Network (GCN; `https://gcn.nasa.gov`). The updated alert system was introduced on June 17, 2019 [3]. All alerts are now classified depending on the likelihood of being from astrophysical origin. For the *Gold* alerts the probability is at least 50% *signalness* and an expected incident rate is about 10 events per year, while for *Bronze* alerts it is 30% with around 20 additional expected events per year.

All the major operating Imaging Atmospheric Cherenkov Telescopes (IACTs) have implemented follow-up observation programs to search for VHE (E>100 GeV) gamma-ray emission associated with IceCube neutrino alerts.

The Cherenkov Telescope Array (CTA; [4]) will be the next generation ground-based IACT facility. With an array located in each hemisphere, CTA will provide gamma-ray observations from around 20 GeV up to 300 TeV with an unprecedented sensitivity, angular and energy resolution. The Northern array (CTA-N) will be located at Roque de los Muchachos Observatory on the island of La Palma, Spain; while the Southern array (CTA-S) will be located at the Paranal Observatory in the Atacama desert of Chile. CTA-N will operate in the energy range of 20 GeV to 50 TeV, while CTA-S will concentrate on Galactic targets and will operate in the energy range between 20 GeV and 300 TeV.

To achieve the performance goals, CTA will consist of 3 telescope types, each one optimised for a specific energy range. The Large-Sized Telescopes (LSTs) will be sensitive to the faint low-energy showers (below 200 GeV). The Medium-Sized Telescopes (MSTs) will operate in the core energy range of the array (between 100 GeV and 10 TeV). The Schwarzschild-Couder Telescope (SCT) is also being developed to work in the same energy range as the MSTs. The Small-Sized Telescopes (SSTs) are planned to be deployed only in South and cover the highest part of CTA energy range.

CTA telescopes are designed to rapidly re-position to any location in the sky: the LSTs can re-position to anywhere in the sky above the elevation of 30° in less than 30 seconds.

We present the results of simulations of the CTA Neutrino Target of Opportunity (NToO) program. The CTA performance under different configurations is computed based on neutrino and gamma-ray simulations of steady and transient types of sources. The CTA detection probability is calculated for both CTA sites taking into account visibility constraints and assuming an optimistic observation scenario.

2. IceCube and FIRESONG

2.1 IceCube

IceCube is the >TeV neutrino telescope operating at the South Pole [5]. It has observed the all-sky, all-flavor flux of neutrinos, compatible with the isotropic emission hypothesis. The isotropy is usually interpreted as being extragalactic in origin, an assumption that we make here.

We investigate 2 cases. First, we use the all-sky neutrino flux to determine the joint IceCube-CTA detectability of steady neutrino sources. Secondly, we consider the population of neutrino flaring blazars, using TXS 0506+056 as an example.

For the first case we follow the study of astrophysical muon neutrinos with 8 years of IceCube data which describes their spectrum as a power-law in energy [6]. The sensitivity to point sources with a matching spectral index has only been published for a spectral index of -2.19 [7].

The second case is based on the evidence of neutrino emission from the blazar TXS 0506+056 first reported as an outcome of the IceCube real-time alert program. On September 22, 2017 the event IceCube-170922A with energy of 290 TeV and probability of astrophysical origin 0.565 was detected and triggered a large number of multi-wavelength observations. Both *Fermi*-LAT and MAGIC found that the spatially coincident blazar TXS 0506+056 was flaring in gamma rays at that time. The accidental coincidence was ruled out with 3σ confidence [8]. Archival study of IceCube data in the direction of TXS 0506+056 revealed an additional $\sim$110 day neutrino flare from October 2014 to March 2015 [9]. In *Fermi*-LAT, there is no evidence for a gamma-ray flare [10] during the 2014-2015 period.

It remains unclear whether all gamma-ray bright blazars are neutrino sources, furthermore they cannot be responsible for most of the astrophysical neutrino flux [11].

2.2 FIRESONG

FIRESONG [12] is the code that enables the simulation of neutrino source populations with detailed calculation that includes ΛCDM cosmology, chosen source evolution, arbitrary luminosity functions, arbitrary neutrino spectra, flexibility in saturating or not the astrophysical neutrino all-sky flux, etc. FIRESONG can simulate both steady or transient/flaring populations.

The luminosity function and evolution of neutrino sources are not known. Following [13] we parameterize the populations of neutrino sources by a characteristic luminosity and an effective local density and assume a standard candle luminosity. We explore both *no evolution* and SFR evolution following [14]. We adopt the ΛCDM parameters reported by Planck in 2015 [15] to set up the simulations of FIRESONG: $\Omega_{M_0} = 0.308$, $\Omega_{\Lambda_0} = 0.692$ and $h = 0.678$.

2.2.1 Steady sources

We have simulated the standard candle neutrino sources with local densities between 10^{-5} Mpc^{-3} and 10^{-12} Mpc^{-3} for the SFR evolution scenario and between 10^{-6} Mpc^{-3} and 10^{-12} Mpc^{-3} for the no evolution scenario. The luminosity is in the range between over-saturating the all-sky neutrino flux by one-to-two orders of magnitude and under-saturating it by one order of magnitude ($10^{50} < L_\nu < 10^{57}$ erg/yr).

2.2.2 Flaring sources

To test the joint sensitivity of IceCube and CTA to saturation of the diffuse flux by neutrino flares we consider the model of [16], in which the diffuse neutrino flux is saturated by a special class of blazars producing neutrino flares similar to TXS 0506+056. Assuming these neutrino-flaring blazars show the same redshift distribution as all blazars, we approximate their ρ_o as fractions (10%, 5%, 1%) of the local blazar density. For the value of local blazar density from [17] these fractions are converted to ρ_o of 1.5×10^{-9}, 7.5×10^{-10} and 1.5×10^{-10} Mpc^{-3} respectively. We assume that they have the same flare duration in the source frame and use the best-fit flare duration of TXS 0506+056, which was 110 days in the Earth frame [9] which translates to 82 days in the source frame.

We have used FIRESONG to simulate the distribution of neutrino-flaring blazars for each value of ρ_o, assuming one year of operation and flat cosmological evolution. The neutrino fluxes from the flares have been normalized by matching the sum of their time-integrated flux to the time-integrated diffuse neutrino flux from [7]. To estimate the number of IceCube realtime alert events from each flare we used the *Gold* events effective areas from [3]. Only sources producing one or more such events have been considered for further simulations of CTA observations.

3. Simulation of CTA observations

To simulate the CTA follow-up observations of the neutrino sources we used the `ctools` and `gammalib` packages [18]. Each simulated neutrino source is characterised by a redshift (z), a spectrum normalisation (A_ν) and a declination (δ). The right ascension (α) is assigned randomly. For calculation of the gamma-ray flux emitted together with neutrinos in the steady source scenario we assume that they could be produced in proton interactions with the surrounding photon ($p\gamma$ interactions). The secondary pions and other particles decay to neutrinos or gamma rays and in the simplest case the relation between the gamma ray and neutrino production rates is:

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 A_{\nu_\alpha}(E_\nu) = \frac{K_\pi}{4} E_\gamma^2 A_\gamma(E_\gamma) \tag{1}$$

where $\mathrm{E}_\gamma = 2\mathrm{E}_\nu$ and K_π is a factor which accounts for the ratio of charged to neutral pions: $\mathrm{K}_\pi = 1$ for $p\gamma$ interactions [19]. We do not consider any additional absorption or cascading of gamma rays inside the source.

For the neutrino flaring blazars simulations we adopt the phenomenological model of [16] describing the gamma-ray emission during the 2014-2015 neutrino flare of TXS-0506+056. This model includes the absorption of gamma rays in the source. The gamma-ray spectrum is given by:

$$\frac{dN_\gamma}{dE} = A_\nu E^{-2} e^{-E_L/E - E/E_H} \ , \tag{2}$$

where A_ν is a neutrino flux normalisation, and E_L and E_H are the low and high energy cutoffs respectively. For the simulated sources located at different redshifts the values of these parameters were scaled accordingly from the ones given in [16] for the blazar TXS 0506+056: z=0.335, $E_L = 0.1$ TeV, $E_H = 20$ TeV.

To account for the gamma-ray flux attenuation during their propagation we used the EBL model of [20] in all of our simulations.

We test the performance of CTA with the `prod3b-v2` CTA Instrument Response Functions (IRFs) for the Omega configuration and `prod5-v0.1`.

Using `ctobssim` for each source we simulated photon events lists, arriving within 30 min of observations and the Region of Interest (RoI) of 5° centered at the source coordinates. Then, we employed `ctlike` to perform a maximum likelihood fitting to the unbinned data. A source was considered detected if the Test Statistic (TS) value was equal or higher than 25.

The Omega configuration corresponds to the final CTA arrays configuration: 4 LSTs and 15 MSTs for CTA-N and 4 LSTs, 25 MSTs and 70 SSTs for CTA-S [4]. The IRF set contains 3 zenith angle observation options at 20°, 40° and 60°, assumed to be valid in the following zenith bins: $[0°,\ 33°]$, $[33°,\ 54°]$, and $[54°,\ 66°]$ respectively. It also accounts for the azimuth dependence coming from the geomagnetic field configurations at each site (depending on the pointing direction: North, South or an average over the azimuth direction). All site, zenith and azimuth combinations total to 18 IRFs.

The Alpha configuration is the initial configuration of CTA arrays to be built with the lower number of operational telescopes (consisting of 15 MSTs and 50 SSTs for CTA-S and 4 LSTs and 5 MSTs for CTA-N). The Alpha configuration IRFs have the same zenith angles and azimuth pointing direction combinations as the Omega ones.

4. Results

4.1 Steady neutrino sources

As steady neutrino sources we consider the "*hot-spots*" emerging in the time-integrated IceCube sky map with the flux equal or higher than the 5σ discovery potential (pre-trial). Assuming that their neutrino and γ-ray emission is constant in time, the observations with CTA do not have to be performed immediately after their detection. In the most optimistic case, the data was taken under the optimal conditions: the lowest zenith angle (achieved at the source culmination, hence the azimuth direction – North or South – is defined automatically) and dark night. These assumptions allow us to assign the "best" IRF for each source, count how many sources were detected in those optimal conditions and derive the detection probability for each type of cosmological evolution and array separately.

Our results (Fig. 1) show that in the low-to-mid-luminosity range the discovery potential of joint IceCube and CTA Omega observations is limited by the IceCube capabilities. All hot-spots visible to CTA down to density 10^{-9} Mpc^{-3} would be detected. On the other hand, in the low density-high luminosity regime, where the sources are located at large redshifts ($z > 1$), the EBL absorption impedes CTA detection probability reaching 100%. This trend is more pronounced for the flat redshift evolution.

The comparison of the Omega and Alpha arrays performance revealed almost no impact for CTA-N, independent of the assumed source evolution. On the other hand, CTA-S Alpha array shows a dramatic performance loss due to the absence of LSTs. Therefore, whenever possible we recommend observations with the CTA-N Alpha array, unless the source is located at a low redshift ($z < 0.1$) and visible for CTA-S at low zenith angles.

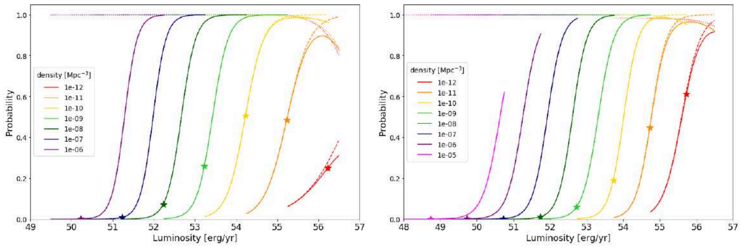

Figure 1: Detection probability as a function of source luminosity (L_ν) for sources following the flat redshift evolution (left) and the SFR evolution (right) for 30 min observations with CTA-N Omega, including visibility constraints. The colored lines represent different local densities (ρ_o) from 10^{-12} to 10^{-5} Mpc^{-3}. Dashed lines show the IceCube detection probability, dotted lines – the CTA detection probability and solid lines – the combined one. The stars mark the source populations saturating the neutrino diffuse flux, as measured by IceCube [6].

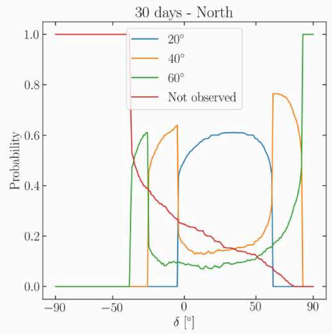

Figure 2: Probability of observation of the alert at CTA-N Omega in different zenith bins as a function of the alert declination.

4.2 Neutrino flaring blazars

For the blazar flares an additional feature to account for is the transient nature of the source. The follow-up strategy of present IACTs involves either immediate observation of the source, if it is visible, or at most observation a few days after the alert. However, as emphasized in [21], the length of the 2014 - 2015 flare of TXS 0506+056 encourages one to take up a longer follow-up for transient sources. Therefore, we consider a maximum follow-up time $T_{\max}$ of about 30 days.

Within this time window we assume that the follow-up is performed at the time when the zenith angle of the alert is minimal, the center of the Sun is at least 18° below the horizon and the center of the Moon is 0.25° below the horizon. This choice maximizes the performances of the detector during the measurement.

We show this probability for all 3 zenith angle bins, as well as the complementary probability that the zenith angle is larger than 66°, in Fig. 2 for the case of CTA-N Omega. The wide range of declination angles are visible with CTA-N alone. The probability that observations cannot be performed at all is equal to 1 only for sources from the Southern hemisphere with declinations lower than about −45° and it rapidly decreases below 0.5 for sources with larger declinations. Similar results are obtained for CTA-S, which is most sensitive in the Southern hemisphere.

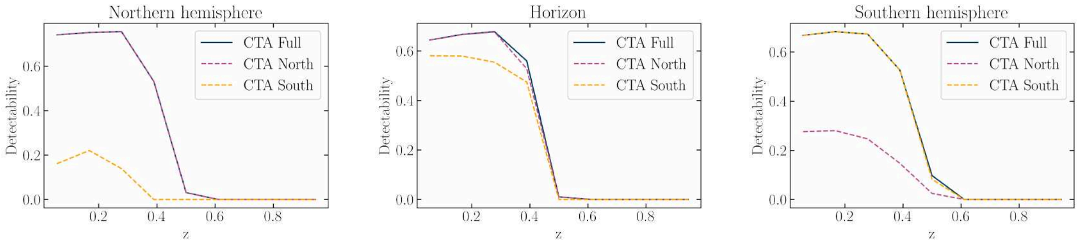

Figure 3: Fraction of detected alerts at CTA-N Alpha, CTA-S Alpha, and either of 2 arrays as a function of redshift for alerts originating from the Northern hemisphere, horizon and Southern hemisphere. The source number density is 1.5×10^{-9} Mpc^{-3}.

Local source density (Mpc^{-3})	Fraction of detected alerts North	Horizon	South	Detected alert rate (yr^{-1}) North	Horizon	South	Total alert rate (yr^{-1})
1.5×10^{-10}	0.32	0.28	0.28	0.61	2.17	0.57	3.35
7.5×10^{-10}	0.27	0.23	0.26	0.51	1.78	0.52	2.81
1.5×10^{-9}	0.22	0.18	0.22	0.42	1.38	0.45	2.25

Table 1: Fraction of alerts from different declination regions detected by CTA Alpha defined as the ratio between detected alerts and all *Gold* alerts, including the background ones. The last column is the rate of detected astrophysical alerts, obtained using the rate of non-background *Gold* alerts.

We also account for the possibility that the measurement is performed after the flare has ended. For a random initial alert time, the probability that the source is observed is

$$P_{\text{meas}}(z) = 1 - \frac{T_{\max}}{2T'_{\text{flare}}(1+z)}, \tag{3}$$

where $T'_{\text{flare}} = 82$ days is flare duration in the source rest frame. We weight the result over 3 zenith bins using the probabilities shown in Fig. 2 for CTA-N to account for the alert visibility. The final result is the probability that an alert with a given declination and redshift is detected as a gamma-ray source at CTA (both CTA-N and CTA-S) for a random initial alert time.

In Fig. 3 we show the fraction of alerts detected by the CTA Alpha configuration as a function of redshift for 3 different regions of declination: Northern hemisphere ($\delta > 5°$), horizon ($-30° < \delta < 5°$) and Southern hemisphere ($\delta < -30°$). The detectability has a decrease for redshifts larger than about 0.5 which is mainly driven by the EBL absorption. As expected, in the Northern (Southern) hemisphere detection is mainly performed by CTA-N (CTA-S). At the horizon the performance of 2 arrays is comparable.

The fractions of detected alerts from all declination regions for the Alpha configuration of CTA are summarized in Table 1. We also show the total rate of detected astrophysical alerts, both separated for declination region and for the full sky (obtained using the rate of astrophysical alerts: 0.95 per year from the Northern hemisphere, 3.89 per year from the horizon, and 1 per year from the Southern hemisphere [3]). The probability of alert detection is smaller than for the Omega array by a few percent, but even in this case, a significant number of IceCube alerts are expected to be detected by CTA every year.

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