KM3NeT/ARCA Sensitivity for Constraining Starburst Galaxies

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Abstract.
The expectation for detecting with the KM3NeT/ARCA telescope, signals from Starburst Galaxies, both as diffuse signal and as point-like excess, is presented. A recent theoretical model was used for the diffused flux. The model, which has been developed by authors of this contribution, takes into account a "blending" of spectral indices to describe the spectral energy distribution. For the point-like search approach, the most promising local starburst galaxies to be observed as point-like neutrino excesses were considered: NGC 1068, the Small Magellanic Cloud and the Circinus Galaxy. For the diffuse analysis, the sensitivity for two ARCA building blocks is provided, considering both track and shower events, in the range of 100 GeV – 100 PeV. For the point-like analysis, the sensitivity for two ARCA building blocks is provided considering only track events. ARCA has the potential to constrain the selected phenomenological scenarios, showing the minimum of the sensitivity where the theoretical spectral energy distributions are expected to peak. This could provide evidence of the link between star-forming processes and hadronic emissions.

1. Introduction

Since the discovery of a flux of astrophysical neutrinos by the IceCube Neutrino Observatory, there has been a lot of effort to unveil their origin. In this framework, the upcoming KM3NeT/ARCA neutrino detector will be a fundamental tool to probe the Universe. ARCA is a deep-sea Cherenkov neutrino telescope under construction in the Mediterranean sea off-shore the Sicily coast (near Porto Palo, at a depth of 3500 m). When completed, ARCA will have a volume of about 1 . km^3 [1]. It is optimised for the detection of high-energy cosmic neutrinos, through the observation of the Cherenkov light induced in the medium by the secondary particles produced in the interaction of the incoming neutrino inside or surrounding the detector. Given its position at the medium latitudes, the detector will guarantee a view of the sky complementary to the one of IceCube. In this work, a sensitivity study is presented for the potential of the complete ARCA detector to constrain the flux of high energy neutrinos emitted by a particular astrophysical source class: Star-forming and Starburst Galaxies (SFGs and SBGs). These objects are able to steadily confine high-energy protons in their nucleus and thus are usually referred to as reservoirs of ultra high-energy cosmic rays. SFGs and SBGs are expected to copiously produce neutrinos and gamma-rays by hadronic collisions. The present analysis is divided in two parts: diffuse and point-like. For the diffuse analysis, the calculation of the all-sky integrated sensitivity (using track and cascade events) is presented and compared with the theoretical model provided by Ref. [2]. A Boosted Decision Tree (BDT) has been used for the selection of the signal and the background. The Monte Carlo production used for this analysis accounts for all neutrino flavours as well as both charged and neutral current interactions (see [3] for details). On the other hand, for the point-like analysis, the sensitivity was calculated for the Small Magellanic Cloud (SMC), Circinus and NGC 1068, which are the most promising sources for ARCA. In this case, for the signal, dedicated Monte Carlo simulation files were produced through gSeaGen code [4], considering only ν_μ and $\bar{\nu}_\mu$ in the charged current channel. Results indicate that KM3NeT/ ARCA will be able, after few years of operation, to discriminate such hadronic scenarios, potentially demonstrating how star forming processes can be traced by high-energy neutrino production.

2. Sensitivity Calculation

The sensitivity was calculated by using a frequentist approach. In particular, the Felmand and Cousins method was applied to evaluate the 90% C.L. upper limits (see [5] for details). Given a signal flux ϕ_s, the sensitivity can be calculated as:

$$\phi_{90} = \frac{n_{90}}{n_s} \cdot \phi_s \tag{1}$$

where n_s is the expected number of signal events induced by the astrophysical flux and n_{90} is the average upper limit, which only depends on the background events. n_{90}/n_s is defined as the Model Rejection Factor (MRF). The MRF is a tool to physically understand if the detector will be able to test a theoretical model. Indeed, if MRF < 1 the sensitivity constrains the theoretical flux. By contrast, if MRF > 1 the detector cannot discriminate the theoretical expectation. n_{90} analytically scales as $\sim 2.4(n_b + 1.04)^{0.43}$, where n_b is the expected number of background. This formulation sets two different regimes for the sensitivity: the very low background regime and the very high background regime. For the former case $n_b \ll 1$, $n_{90} = 2.44$, constant in time. This leads to a sensitivity scaling as T^{-1}, where T is the exposure time considered for the data-taking. On the contrary, for the latter case $n_b \gg 1$,$\phi_{90} \sim T^{-0.5}$, leading to a slower scaling with time for the sensitivity. For this contribution, only the integrated sensitivity was taken into account by looking into the whole energy range $100\,\mathrm{GeV} - 100\,\mathrm{PeV}$. In order to evaluate Eq. 1, it is fundamental to correctly estimate both the number of signal and background events, minimizing the MRF. The selection chains both for the diffuse and point-like analysis are described in the following sections.

3. Diffuse Analysis

For the diffuse analysis, the latest version KM3NeT-ARCA115 MC (full detector scenario) simulation was considered for the characterization of the background: atmospheric neutrinos and muons. Atmospheric neutrinos have been simulated by gSeaGen [4]. Atmospheric muons, on the contrary, have been simulated by the MUpage code [6]. By constrast, for the signal, we used the spectrum provided by Ref. [2], which could be parameterized by $E^{-2} \cdot e^{-E/500\,\mathrm{TeV}}$. A dedicated selection to reject the background has been performed, using two different selections for tracks and cascades.

Track Selection

As a first step of the selection, the events for which the reconstruction algorithm has failed were rejected (e.g. either negative reconstructed energy E_{rec} or negative likelihood $\mathscr{L}$). Only upgoing events $\theta < 100^\circ$ were considered, where θ is the zenith angle of the reconstruction event. Additional requirements were applied in order to reject poorly reconstructed tracks: *i)* $\beta_0 < 1^\circ$, where β_0 is the error on the reconstructed angle; *ii)* Len $> 300\,\mathrm{m}$, where Len is the reconstructed track-length; *iii)* $\mathscr{L}/n_{\mathrm{hits}} > 0.7$, where $n_{\rm hits}$ is the number of hits. Finally, a machine learning algorithm, in particular a boosted-decision-tree (BDT), was implemented to select "good" upgoing track-like events and reject atmospheric muons. The KM3NeT/ARCA115 Monte Carlo simulated events (atmospheric muons and neutrinos) have been used for the BDT training which was based on the main reconstruction variables (e.g. $\mathscr{L}, \beta_0, n_{\rm hits}$). The BDT score was further used for the final event selection: *i)* for $80^\circ < \theta < 100^\circ$, $\mathrm{BDT_{score}} > 0.9$. For $\theta < 80^\circ$, $\mathrm{BDT_{score}} > 0.4$.

Cascade Selection
For the shower-like events the whole sky has been considered. Events classified as tracks have been removed from the cascade selection. Cascade events were required to be contained inside the effective volume of the detector and to satisfy the following conditions: *i)* the containment inside the effective volume of the detector. *ii)* $n_{\rm hits} > 450$, $\mathscr{L} < -500$ and Len $< 300\,$m. Finally, as for the tracks, a dedicated BDT (called BDT cascades) for selecting "good" quality events has been developed. Different BDT score selections were applied depending on the direction of the events:

- If $\cos(\theta) > 0.6$, $\mathrm{BDT_{casc}} > -1.1$
- If $0.2 < \cos(\theta) < 0.6, \mathrm{BDT_{casc}} > -0.9$
- If $-0.2 < \cos(\theta) < 0.2, \mathrm{BDT_{casc}} > -0.8$
- If $-0.6 < \cos(\theta) < -0.2, \mathrm{BDT_{casc}} > 0.8$
- If $\cos(\theta) < -0.6$, $\mathrm{BDT_{casc}} > 1.1$

Results
The combined sensitivity was evaluated using both the signal and background events coming from the samples after the selection. The two considered samples for this analysis are spatially not homegenous. In Fig. 1, the sensitivity is shown for 10 years of data taking and compared with the result obtained by Ref. [2].This theoretical model takes into account a blending of spectral indexes, therefore potentially exploiting the variability of this crucial parameter along the source class. On the left, the sensitivity is compared with the SBG 1σ uncertainty band after taking into account both Fermi-LAT EGB and IceCube HESE data (see [2] for details). On the right, a similar comparison is presented, showing the $1-2\sigma$ uncertainty bands for the SBG SED, when considering Fermi-LAT and IceCube cascade observations. The comparison with the theoretical expectations indicates that with the sensitivity of the ARCA telescope it will be possible constrain this scenario after a few years of data taking.

4. Point-Like Analysis
KM3NeT/ARCA is expected to have an excellent angular resolution ($\sim 0.1^\circ$ for $\mathrm{E}_\nu > 10\,$TeV) [1], which is crucial for the determination of point-like excesses. For this analysis, the same Monte Carlo simulted sample as for the diffuse analysis were used for the background; for the signal, instead, dedicated Monte Carlo simulations file were made by the gSeaGen code [4]. Circinus and NGC 1068 were simulated without any extention, while SMC was considered as a 0.5° extended source, compatible with the expectations provided by Ref. [9]. Only ν_μ and $\bar{\nu}_\mu$ in charged current interactions (track-like events) were considered. Firstly, a a region of interest (RoI) was defined through the variable α which is set as the the angular distance between the nominal position of the source and the coordinates of the reconstructed track. For the signal selection, events with angular distance lower than α were taken into account ($\Omega_{\rm RoI} \simeq \pi\alpha^2$). The background was selected by considering the declination band centered at the source position and having a width consistent with the value of α ($\Omega_{\rm db} \simeq 2\pi 2\alpha$). The background was then rescaled for $\alpha/4 \simeq \Omega_{\rm RoI}/\Omega_{\rm db}$, the fraction of solid angle given by the RoI with respect to the declination band. This is justified by the fact that the background distribution is uniform in right ascension. Then, the MRF was minimized (using a cut and count approach) as a function of several parameters (e.g. α, $\mathscr{L}$, Len, β_0) in order to obtain dedicated optimized sensitivities for each source.

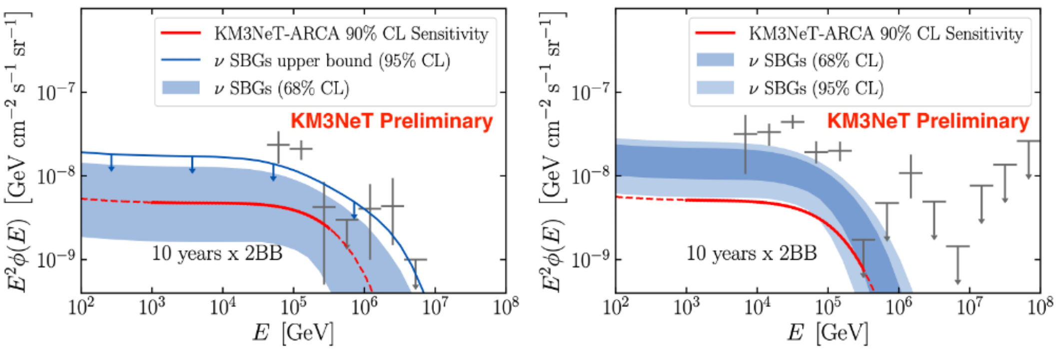

Figure 1: **Left**: The 90% C.L. sensitivity (red curve) is compared with the corresponding theoretical 1σ uncertainty band of the SBG spectral energy distribution according to the analysis of Ref. [2]. This band has been obtained by fitting the Fermi-LAT EGB and the IceCube HESE data. the IceCube HESE measurements [7] are also shown for reference. **Right:** The sensitivity is compared with the corresponding theoretical $1-2\sigma$ uncertainty band of the SBG spectral energy distribution according to the analysis of Ref. [2], considering EGB Fermi-lat and (6-year) of IceCube CASCADE samples. The IceCube cascades measurements ([8]) are shown for reference.

4.1. SMC

SMC is situated in the southern sky, where the visibility of ARCA is approximately 100%, therefore most of the background is composed by mis-reconstructed events. The cuts applied were: $\alpha = 0.7°$ and $\mathscr{L} > 80$. The main results are presented in Fig. 2. On the left, the sensitivity with the 1σ uncertainty band provided by the model of Ref. [9] is shown.

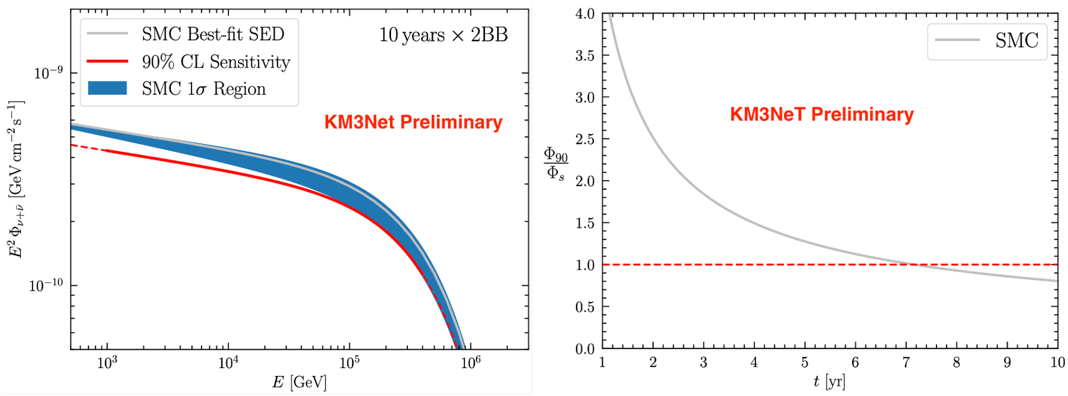

Figure 2: **Left** sensitivity compared with the theoretical 1σ uncertainty band of the source (according to the analysis of Ref [9]). **Right** Sensitivity as a function of time. The detector will be able to put strict constraints after 7 years of data taking.

On the right, the integrated sensitivity is shown as a function of time. The sensitivity has been evaluated considering the best-fit SED scenario ($\sim E^{-2.1} \cdot e^{-E/500\,\mathrm{TeV}}$). The hadronic scenario can be constrained with the complete/full ARCA detector after 7 years of operation.

4.2. Circinus

For Circinus, the following cuts were applied for the signal and the background: $\alpha = 0.5°$, $\mathscr{L} > 70$ and Len $> 120\,\mathrm{m}$. It is important to stress that also this source is situated where ARCA has full visibility. In Fig. 3, the results are presented for the Circinus Galaxy, in an analogous way as for SMC. On the left, the

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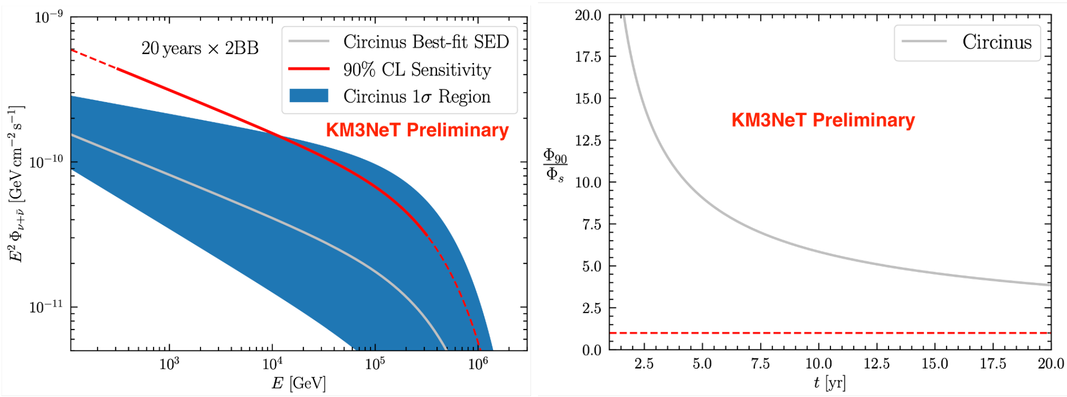

Figure 3: **Left** The integrated sensitivity compared with the theoretical 1σ uncertainty band of the source (according to the analysis of Ref. [9]). The plot refers to 20 years of data taking for 2 Building Blocks. **Right** The ARCA sensitivity as a function of time. The detector is not able to discriminate the SBG scenario.

1σ uncertainty band (according to Ref. [9]) is compared with the sensitivity after 20 years of data taking. Unfortunately, the detector will not be able to discriminate the SBG activity of the source. The sensitivity has been evaluated for the best-fit SED scenario ($\sim E^{-2.3} \cdot e^{-E/500\,\mathrm{TeV}}$). On the right, the sensitivity as a function of with time is shown. Even though the experiment cannot directly discriminate the potential neutrino production/yield from SBG activity, its potential neutrinos coming from AGN activity [10] can be characterised by a higher flux and, likely, be constrained by ARCA.

4.3. NGC 1068

The IceCube collaboration has inferred an excess of 50.4 above the background coming from the direction of NGC 1068 [11]. Therefore, Also this source was analyzed with the intention of understanding if KM3NeT/ARCA can put constraints on this scenario. Indeed, as already emphasised by Ref. [9], the SBG activity cannot explain the ICeCube excess. The excess could be explained by Seyfert activity characterised by a hot corona activity [10]. The sensitivity has been evaluated for a $E^{-3.2}$ spectrum, which is the best-fit scenario provided by the IceCube collaboration [11]. This source

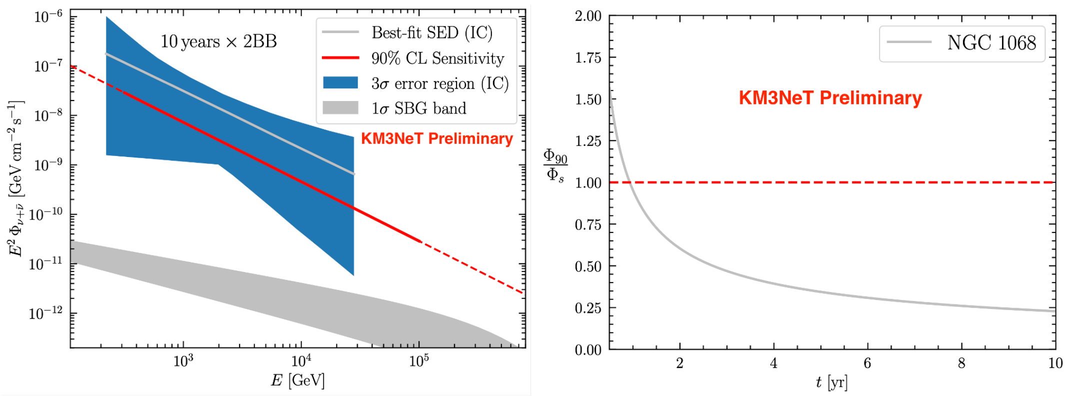

Figure 4: **Left** The sensitivity compared with the theoretical 1σ uncertainty band of the source (according to the analysis of Ref. [9]) as well as IceCube error region [11]. **Right** The ARCA sensitivity as a function of time. The detector will be able in 1 year to constrain the scenario inferred by IceCube.

is situated at the equatorial latitudes, therefore, only upgoing cut $\theta < 100°$ were considered in order to suppress the number of atmospheric muons. Then, we applied the following cuts: $\alpha = 0.7°$, $\beta_0 < 0.002$, $\mathscr{L} > 70$ and Len > 120 m. The selection chain is necessary as the input spectrum is almost as soft as the expected atmospheric neutrino flux. The results for NGC 1068 are shown in Fig. 4. The sensitivity (left) is compared both with the IceCube error region ([11]) and the SBG 1σ uncertainty [9]. It will be possible for KM3NeT/ARCA (or ARCA) to provide a strong constraints on the scenario inferred by IceCube in less than 1 year of operation (Fig. 4. right).

5. Discussion and Conclusions

KM3NeT/ARCA is a fundamental tool to unveil the origin of the astrophysical neutrino mystery. In this contribution, the expecations of ARCA to constrain the properties of an important source class, the Starburst Galaxies, have been revised. Looking at the whole sky, the integrated sensitivity has been estimated for a typical SBG signal $(E^{-2} \times Exp[-E/500\,\mathrm{TeV}])$ using upgoing tracks and all-sky cascade events as well as considering all neutrino flavours $(\nu_\mu, \nu_e, \nu_\tau)$ and interaction channels (NC and CC). For each selected sample, a dedicated BDT was used to reject the background. The ARCA detector, once completed, will be able to constrain the model considered here. From the point-like perspective, the sensitivity for the most promising SBG sources, SMC, Circinus and NGC 1068 are also provided. For the point source analysis, only ν_μ CC track events have been considered. For SMC, ARCA will be able to test the hadronic SBG production, indirectly providing invaluable information on the cosmic-ray transport inside this source as well as on the hadronic budget in this source. This exhibits the potential of neutrino astronomy to trace star-forming activity. For Circinus and NGC 1068, even though ARCA is not expected to test the SBG activity, it will be possible to discriminate the Seyfert activity shedding light on such scenarios as well.

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