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A new multimessenger study of Starburst galaxies: a closer look to expecting neutrinos

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Abstract. Considering the high star formation rate (up to 100 $M_\odot$/year) of starburst galaxies (SBGs), they are well posed between the guaranteed "factories" of high energy neutrinos, since they can contain accelerated cosmic rays in the central region where the high-density gas is present. A more accurate description of their possible hadronic emission could help to better explain the diffuse astrophysical flux measured by IceCube as well as the observed point-like excess, like the case of NGC1068. With this in mind we report here a multi-messenger study, looking at diffuse and resolved gamma-ray and neutrino measurements, that explain

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the very-high-energy (VHE) emission through a calorimetric scenario. For the analysis of the diffuse component we perform a blending of the available spectral indexes and produce a multi-component study of extragalactic background light (EGB), high energy starting events (HESE) and high-energy cascade IceCube data. In contrast to common prototype scenarios, the spectral index blending leads to a non negligible diffuse neutrino component from SBGs, accounting up to 40% of the HESE events, at 95.4% CL. This scenario privileges also a maximal energy within tens of PeV for the accelerated charge particles inside these galaxies. For the point-like study we report the proposed calorimetric description for the gamma-ray resolved SBGs within 100 Mpc, taking into account the star formation rate derived from their infrared emission. These neutrino expectations are then compared with the sensitivity of IceCube, IceCube/Gen2 and the incoming KM3NeT.

1. Introduction

Starburst galaxies (SBGs) are major candidates for the diffuse neutrino flux observed by IceCube, since they are "reservoirs" of very-high-energy cosmic rays and host enough interstellar gas to produce a considerable amount of hadronic interactions. Nonetheless, even though they are abundant in the local universe, just few of these galaxies are resolved by gamma-ray observations, showing a low VHE luminosity. This makes hard a detailed calorimetric description of their central regions and a corresponding calculation of the expected neutrino flux. Recent studies [1, 2] the well known M82 as a prototype and extrapolate the obtained scenario to the whole population of SBGs estimating the total neutrino and gamma-ray emission. Instead here we reported the new results considering all the gamma-ray data available for the resolved SBGs within 100 Mpc [3, 4] to better define the calorimetric model and extrapolate that one to the deep sky. In detail the gamma-ray spectral behavior of each of them is taken into account for this extrapolation. The correlated neutrino emission is obtained describing the VHE diffuse fluxes available with a multi-component approach.

The diffuse analysis is based on a recent observational report [5] that considered ten years of Fermi-LAT data for a catalog of 12 starforming galaxies. Our whole sky scenario started from a statistical study on the spectral properties of these galaxies. As we shown in this proceeding, this data-driven analysis resulted in a higher neutrino flux at 100 TeV respect to the prototype description without the need of a bigger gamma-ray flux below 1 TeV. This somehow alleviates the tension between the diffuse neutrino and gamma-ray observations. In addition to that, we used the extragalactic gamma-ray background (EBL) data of Fermi-LAT [6] and the diffuse flux measured by IceCube to obtain a multi-component and multi-messenger likelihood analysis of the VHE spectra. Apart the SBG contribution also a jetted AGN component is introduced following the description proposed by [7], where TXS0506+056 represent a prototype for the entire class of AGN without exceeding the IceCube stacking limit [8]. The diffuse and point studies reported included also the secondary gamma rays produced by electromagnetic cascades thanks to the public code γ-`Cascade`. The diffuse one comprised the latest 7.5-year HESE catalog [9], the 6-year high-energy cascade catalog [10] and the EGB available data [6]. The likelihood study considered as a free parameters the VHE flux normalization for SBGs, blazars and radio galaxies emission, as well as the maximal energy of the cosmic rays emitted by supernovae remnants (SNRs) inside the galaxies considered. The differences between the blending (distribution of observed spectral indexes) and the prototype (single power law as M82) scenarios are reported. The blending resulted to be better in agreement with data and a sizeable SBG neutrino component at 100 TeV is expected, differing from the prototype scenario where the neutrino contribution was negligible. In addition to that, the former approach prediliges a cut-off energy for cosmic rays smaller than few tens of PeV, leaving enough room in the spectrum measured by IceCube for a possible flux above hundreds of TeV related to blazars. As showed

in this proceeding, the resulting diffuse neutrino component possibly related to SBGs can be of the order of 40% (50%) of the total 7.5-year HESE neutrino events at 95.4%(99.7%) confidence level, without exceeding the known limits on the non-blazar EGB component [11], when the blending model is applied. The proposed whole sky high-energy neutrino emission from SBGs is calculated integrating this calorimetric description up to a redshift of $\sim$ 4–5, considering their dimness [2, 3].
The point-like analysis reported here comprises also a multi-messenger and multi-wavelength study to explore the possibility that present and future neutrino telescopes will resolve SBGs as neutrino point-like sources. This description followed [12] to model the transport of high-energy protons and electrons inside these galaxies. Also in this case 10-year Fermi-LAT data were accounted [5], looking at the spectral energy distributions (SEDs) of each of the 13 SFGs and SBGs observed. The gamma-ray emission of each SBG was used to set the hadronic and leptonic components and the related star formation rate (SFR) was verified to be consistent with the infra-red (IR) and ultra-violet (UV) observations [13]. Finally the expected neutrino flux normalization expected at 1 TeV for each SBG was compared with the expected sensitivity of IceCube, IceCube-Gen2, and KM3NeT (see Figure 2) in the same range of energy.

2. Emission from a Starburst galaxy

The high star formation rate (SFR) ($\psi \sim 10 - 100 M_{\odot} yr^{-1}$) observed in SBGs certifies the presence of possible accelerators of cosmic rays and a non negligible hadronic production due to their interaction with the high density interstellar gas present in the central regions. These observations are made thank to the absorption of star emission by the interstellar gas and re-emission in the infra-red (IR) band. These characteristics favors a hadronic emission component by the proton-proton interaction and somehow justify the linear relation between gamma-ray luminosity and infrared emission observed by [14]. The presence of a interstellar medium density of the order of $n_{\rm ISM} \sim 10^2 cm^{-3}$ and the existence of a strong magnetic field ($10^2 - 10^3 \mu G$) [15] favors CR confinement and interaction. For the presented analysis we imposed that the rate of supernovae events, and therefore SBG activity, are mostly confined within the starburst nucleus (SBN). Moreover we considered the motion and interaction of CR to be deeply affected by the supersonic wind flow [16] injected by SNRs and by related turbulence. Making high-energy CRs confined inside the SBN, the thickness can guarantee a seizable flux of neutrino emitted. The assumed calorimetric condition can be expressed through

$$T_{\rm loss} \leq T_{\rm esc} \,, \tag{1}$$

where $T_{\rm loss}$ is the typical CR timescale for interactions and $T_{\rm esc}$ is the timescale taken for a CR to escape from the source. This condition is strongly related to the ISM density and the wind flow velocity inside a SBG (see also [2]) instead of the CR spectral features SBGs [17] used to infer the confinement of CR electrons inside SBNs. The CR timescales reported here are obtained following [12] and the SBNs are described as spherical regions with the advection time $T_{\rm adv} = R/v_{\rm wind}$ depending on the radius (R) of this region and on the wind velocity ($v_{\rm wind}$). While for the time loss of CR we considered the proton- proton (p-p) interaction. CR diffusion is obtained using a Kolmogorov-like approach, with a density of the magnetic field $F(k) \propto k^{-d+1}$ with $d = 5/3$, with $k = 1/\lambda$ representing the wavenumber, and a regime of strong turbulence inside the SBN [2]. This description lead to a diffusion coefficient $D(p) \propto p^{1/3}$, with p representing the particles momentum, which implies $T_{\rm diff}(E) \propto E^{-1/3}$. A more detailed description of cosmic-ray transport used in this contribution can be found in [3, 4].

3. Diffuse analysis

In this proceeding we quantified the astrophysical neutrinos possibly associated to starburst galaxy population using a statistical multi-messenger analysis which considers both neutrino

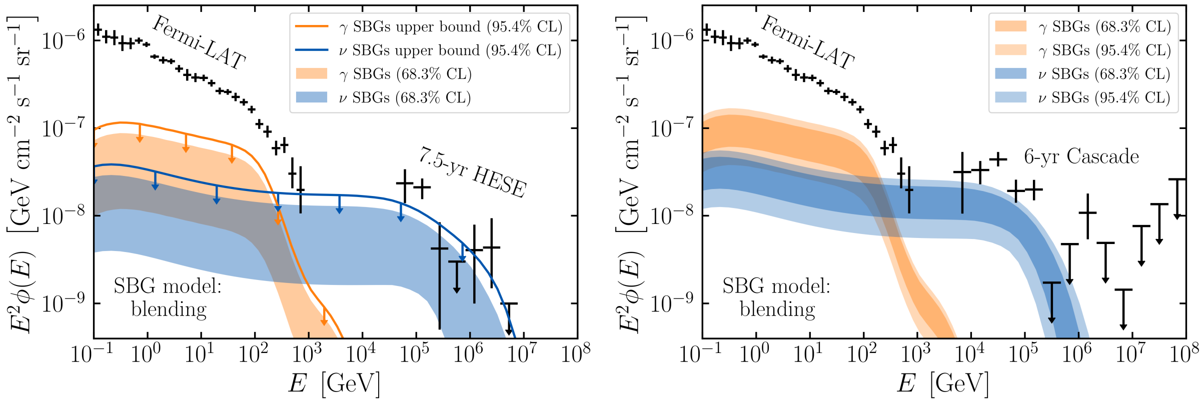

Figure 1. Gamma-ray (orange) and single-flavour neutrino (blue) uncertainty bands at 68.3% CL (dark colors) and 95.4% CL (light colors) for the diffuse SBG emission calculated with the multi-messenger analysis when considering of the blending of spectral indexes. The left (right) plot corresponds to the multi-messenger analysis with IceCube 7.5-year HESE (6-year cascade) neutrino data. In the left plot, the solid lines indicate the upper bounds at 95.4% CL.

and gamma-ray observed data. As already introduced this analysis is based on two neutrino IceCube data samples: the 7.5-year HESE data (track and shower topologies above 60 TeV) and the 6-year high-energy cascade data (only includes shower-like events, mostly electron and tau neutrino flavours) and the extragalactic gamma-ray background (EGB) measured by Fermi-LAT [6]. Taking into account the gamma-ray limit obtained for non resolved sources [18], we performed this multi-component analysis for diffuse neutrino and gamma rays considering SBGs, blazars and radio galaxies.
For both the neutrino and the gamma-ray components, we perform a maximum likelihood study using a chi-squared likelihood. For the neutrino data, we use the following chi-squared function:

$$\chi^2_\nu = \sum_i \left(\frac{\Phi^{\rm IC}_{\nu,i} - N_{\rm Blazars}\Phi^{\rm Blazars}_{\nu,i} - N_{\rm SBG}\Phi^{\rm SBG}_{\nu,i}(p^{\rm max})}{\sigma^{\rm IC}_{\nu,i}} \right)^2 , \tag{2}$$

where $\Phi^{\rm IC}_{\nu,i}$ is the diffuse single-flavour flux observed by IceCube in each energy interval i with uncertainties $\sigma^{\rm IC}_{\nu,i}$, whereas $\Phi^{\rm Blazars}_{\nu,i}$ and $\Phi^{\rm SBG}_{\nu,i}$ are the neutrino flux of blazars and SBG sources, respectively. The obtained neutrino spectra considering EGB, HESE and cascade data are reported in Fig. 1.

4. Point-like analysis

With the reported point-like analysis we calculated the expected VHE neutrino emission from SFGs and SBGs using a likelihood analysis of gamma-ray data of each single source. The neutrino flux id obtained implying that the observed gamma-ray SEDs are saturated with emission related to star-forming activity. For this purpose we performed the analysis taking into account the gamma-ray SEDs of 13 galaxies observed by Fermi-LAT with 10 years of observation [5].[1] For M82 and NGC 253 we also consider the data provided by VERITAS [19] and H.E.S.S. [20], respectively. For each SBG we followed a Bayesian approach to assess the most-likely values for two free parameters: the star formation rate $\dot{M}_*$ and the spectral index Γ

[1] The data reported in [5] are normalized to a constant value of 10^{-9} GeV cm^{-2} s^{-1} at an energy of 1 GeV. We have suitably rescaled them using the reported best-fit parameters of the power-law model.

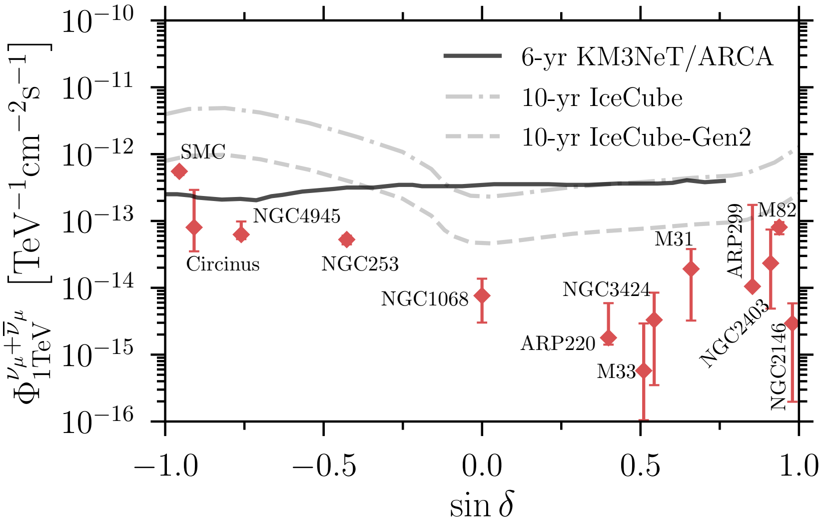

Figure 2. Muon neutrino flux normalizations at 1 TeV, obtained considering the star-forming activity of each source, as a function of source declination. The diamonds correspond to the most-likely values of neutrino emission deduced by current gamma-ray data [5], while the bands represent the 68% credible intervals of the marginal flux distributions. The reported lines shown the point-like sensitivity of different neutrino telescopes: 6-year KM3NeT/ARCA [21], 10-year IceCube [22], and 10-year IceCube-Gen2 according to [23].

of injected protons and electrons. We calculated the posterior distribution as

$$p(\dot{M}_*,\, \Gamma|\mathrm{SED}) \propto p(\mathrm{SED}|\dot{M}_*,\, \Gamma)\, p(\dot{M}_*)\, p(\Gamma)\,, \tag{3}$$

with a Gaussian likelihood function

$$p(\mathrm{SED}|\dot{M}_*,\, \Gamma) = e^{-\frac{1}{2}\sum_i \left(\frac{\mathrm{SED}_i - E_i^2 \Phi_\gamma(E_i|\dot{M}_*,\, \Gamma)}{\sigma_i}\right)^2}\,. \tag{4}$$

Here, SED_i are the measured data, where i runs over the energy bins centered around the energy E_i, and σ_i are the observational uncertainties. The data are also compared to the gamma-ray emission $\Phi_\gamma(E_i|\dot{M}_*,\, \Gamma)$ predicted by our model. In this study we adopted the distance of the SBGd reported by [13] without introducing any uncertainty for these values. A uniform prior of the spectral index ranging in 1.0–3.0 is considered for all the SBGs, while a different prior for each source is adopted for the SFR. Additionally we verified that the obtained $\dot{M}_*$ were consistent within 3 times with the corresponding values reported in [13]. The comparison of obtained $\dot{M}_*$ with the ones measured is based on the relation between $\dot{M}_*$ and the radiation density reported in [4]. The results of the analysis are summarized in Fig. 2.

5. Results and conclusions

Despite the fact that nearby known SBGs can contribute at the level of $\sim$ % to the total extraterrestrial neutrino flux measured by IceCube, the upcoming neutrino telescopes can potentially resolve some nearby starburst galaxies as point-like sources. In particular, they could constrain their hadronic emission and link their GeV-TeV gamma-ray emission with the expected intense star-forming activity. Moreover, we showed here that, when considering SBG neutrino emission up to a redshift $z \sim 4$, the total diffuse contribution of this class of sources to IceCube measurements can rise up to 20% $-$ 40% of the full sky astrophysical neutrino flux.

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