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Observable signatures of cosmic rays transport in Starburst Galaxies on gamma-ray and neutrino observations

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ABSTRACT

The gamma-ray emission from Starburst and Star-forming Galaxies (SBGs and SFGs) strongly suggests a correlation between star-forming activity and gamma-ray luminosity. However, the very nature of cosmic ray (CR) transport and the degree of their confinement within SBG cores are still open questions. We aim at probing the imprints left by CR transport on gamma-ray and neutrino observations of point-like SFGs and SBGs, looking into quantitative ways to discriminate among different transport models. We analyse the 10-yr Fermi-LAT spectral energy distributions of 13 nearby galaxies with two different CR transport models, taking into account the corresponding IR and UV observations. We also generate mock gamma-ray data to simulate the CTA performance in detecting these sources. In this way, we propose a test to discriminate between the two CR models, quantifying the statistical confidence at which one model can be preferred over the other. We point out that the current data already give a slight preference to CR models that are dominated by advection. Moreover, we show that CTA will allow us to firmly disfavour models dominated by diffusion over self-induced turbulence, compared to advection-dominated models, with Bayes factors, which can be as large as $10^7$ for some of the SBGs. Finally, we estimate the diffuse gamma-ray and neutrino fluxes of SFGs and SBGs, showing that they can explain 25% of the diffuse HESE data while remaining consistent with gamma-ray limits on non-blazar sources.

Key words: galaxies: starburst – galaxies: star formation – gamma rays: galaxies – Neutrinos.

1 INTRODUCTION

Starburst and Star-forming Galaxies (SBGs and SFGs) are astrophysical sources with a compact central region, called the starburst nucleus (SBN), where the star-forming activity is mostly concentrated. They are endowed with a large gas density ($n_{\text{ISM}} \sim 100–1000$ cm$^{-3}$), an enhanced supernova explosion rate $R_{\text{SN}} \sim 0.1–1$ yr$^{-1}$, and magnetic fields of the order of $10^{-5}$ μG (Thompson et al. 2006). The measurements by the Fermi-LAT (Ajello et al. 2020), VERITAS (VERITAS Collaboration et al. 2009), and H.E.S.S. (H.E.S.S. Collaboration et al. 2018) collaborations have shown their capability to produce gamma-rays (Ajello et al. 2020) with a luminosity correlated to their star formation rate (SFR). This suggests that the non-thermal emission of these galaxies can be strictly dependent on their star-forming activity (Ackermann et al. 2012; Ajello et al. 2020; Kornbeck et al. 2020, 2021). Indeed, supernova remnants (SNRs) shocks are supposed to accelerate protons up to PeV energies (Sveshnikova 2003; Murase, Ahlers & Lacki 2013; Tamborra, Ando & Murase 2014). Furthermore, if high-energy cosmic rays (CRs) are confined within the SBN by diffusion on magnetic inhomogeneities for long times, they have an enhanced chance to copiously produce gamma-rays and neutrinos through hadronic collisions. In fact, SBGs and SFGs are often considered to be astrophysical calorimeters or reservoirs, being able to confine high-energy CRs within their very core. The calorimetric condition requires the time-scale for energy loss of CRs to be shorter than their escape time from the SBN. However, although electron confinement is nowadays an established result (Peretti et al. 2019; Roth et al. 2021), the degree of high-energy proton calorimetry is still under debate. This is because it depends on the interplay between different phenomena like diffusion, wind advections, and energy losses, which are difficult to reliably model. Different CR transport scenarios have been used to describe the observed gamma-ray emission from nearby SFGs and SBGs, trying to disentangle a calorimetric behaviour from a diffusion-dominated regime ($\tau_{\text{diff}} \ll \tau_{\text{loss}}, \tau_{\text{adv}}$) (Sudoh, Totani & Kawana 2018; Peretti et al. 2019; Ha, Ryu & Kang 2020; Krumholz et al. 2020; Müller, Romero & Roth 2020; Kornbeck et al. 2020, 2021; Owen, Lee & Kong 2021a; Owen, Kong & Lee 2021b; Shimono, Totani & Sudoh 2021; Werhahn, Pfrommer & Girichidis 2021a; Werhahn et al. 2021b; Xiang, Jiang & Tang 2021). The major uncertainty factor is due to distinctive time-scale modelling. Different models suggest Kolmogorov-like diffusion from magnetic field turbulence (Yoast-Hull et al. 2013;}

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Peretti et al. 2019, 2020) as well as self-generated diffusion generated by the streaming instability (Krumholz et al. 2020; Roth et al. 2021). Uncertainty comes also from the fraction of ionized gas, which can vary from $10^{-4}$ to $10^{-1}$ (Peretti et al. 2019; Krumholz et al. 2020).

This, in turn, leads to a different role for the advection, which predominately affects the hot ionized gas in SBNs (Krumholz et al. 2020). Furthermore, a greater fraction of neutral gas would reduce Kolmogorov-like turbulence, supporting streaming instability as source of magnetic inhomogeneities.

In this framework, current measurements make it challenging to quantitatively discriminate between different scenarios, leading to a significant uncertainty in the gamma-ray and neutrino fluxes expectation from SBGs. A major limitation comes from the fact that only 13 SFGs are observed through gamma rays and just a few of them are observed at energies greater than 10 GeV (Ajello et al. 2020; Kornecki et al. 2020). This points out the importance for future gamma-ray experiments (Acharya et al. 2018; Albert et al. 2019; Hinton 2021) as well as possible neutrino point-like observations (Adrian-Martinez et al. 2016; Aiello et al. 2019; Aartsen et al. 2020; Ambrosone et al. 2021b) to better constrain the characteristics and the CR transport scenario for the nuclei of SBGs.

In this paper, we assess the signatures of different cosmic ray transport mechanisms on point-like and diffuse gamma-ray and neutrino contributions of SFGs and SBGs, and exploit them to understand which model can better explain the data. In particular, we consider both an advective model adopted, e.g. by Peretti et al. (2020), and the model provided by Krumholz et al. (2020), which considers CR transport in the nucleus dominated by diffusion on self-induced turbulence. Following the analysis described in Ambrosone et al. (2021b), we compare the gamma-ray predictions of the two CR transport models with 10-yr Fermi-LAT data (Ajello et al. 2020) as well as H.E.S.S. (H.E.S.S. Collaboration et al. 2018) and VERITAS (VERITAS Collaboration et al. 2009) collaborations data for 13 known SBGs (VERITAS data are available only for M82 and H.E.S.S. data are only available for NGC 253). For Circinus Galaxy, we make use of data from Hayashi et al. (2013). As in Ambrosone et al. (2021b), for each source, we require the SFR to be in agreement with the one derived from infrared (IR) and ultraviolet observations (Kornecki et al. 2020). We show that current data are slightly better accommodated by the model developed by Peretti et al. (2019), suggesting advection to be important for high-energy CR transport in SBNs. Then, we investigate the ability of future gamma-ray telescopes sensitive to $\mathcal{O}(10\text{ TeV})$ photons, such as CTA (Acharya et al. 2018) and SWGO (Albert et al. 2019; Hinton 2021), to further discriminate between the different CR transport models. We perform a forecast analysis by means of mock data generation for the most promising sources using the public information of the CTA telescope. In particular, we determine the statistical confidence at which the diffuse-dominated model (Krumholz et al. 2020) might be excluded in the near future in favour of the advection-dominated one (Peretti et al. 2020).1 We report the $p$-values and the Bayesian factors obtained in the case of the Frequentist and Bayesian approaches, respectively. We hence emphasize the importance of future gamma-ray telescopes for constraining the SFGs and SBGs emission properties.

Finally, we calculate the diffuse neutrino and gamma-ray fluxes from the whole populations of SFGs and SBGs, making use of the approach put forward by Ambrosone et al. (2021a). We set the properties of all the sources, e.g. the distribution of the spectral indices, to be consistent with the ones previously inferred by the local point-like observations. Interestingly, such a comprehensive data-driven scenario may explain 25 per cent of the HESS neutrino flux (Abbari et al. 2021) when a cut-off energy of protons is of the order of 10 PeV, as well as 33 per cent of the Extra-galactic Gamma-ray Background (EBG) above 50 GeV (Ackermann et al. 2016; Lisanti et al. 2016; Bechtol et al. 2017; Yoshida & Murase 2020). Hence, it is in agreement with the independent multi-component fit provided by Ambrosone et al. (2021a), and it is consistent within 1$\sigma$ with the gamma-ray limits on non-blazar sources (Ackermann et al. 2016; Lisanti et al. 2016; Bechtol et al. 2017; Yoshida & Murase 2020). This result becomes crucial when compared to the one presented by Roth et al. (2021) since it shows that the use of a different CR transport model for the SBG class allows us to explain a greater portion of diffuse high-energy neutrino measurements without evading all the existing EGB bounds on non-blazar sources.

The paper is organized as follows: In Section 2, we describe in detail the two CR models we utilize for our analyses and how we calculate gamma-ray and neutrino spectra. In Section 3, we describe the analysis of current gamma-ray data, while in Section 4 we discuss the forecast analysis for the CTA telescope. In Section 5, we calculate the diffuse gamma-ray and neutrino fluxes. Finally, in Section 6, we draw our conclusions.

2 CRS TRANSPORT AND NON-THERMAL EMISSIONS IN AN SBG

In this section, we model the transport of CRs, with particular emphasis on the differences between the two approaches of Peretti et al. (2019) and Krumholz et al. (2020) (hereafter, model A and model B, respectively). The phenomenology arising from these differences in the gamma-ray and neutrino fluxes is the fundamental topic of this paper. Since the starburst activity lasts for long time ($\sim10^8$ yr, Peretti et al. 2021a), a steady state is reached between the cosmic ray cooling, transport, and injection phenomena. In particular, the distribution $F_p(E)$ of high-energy protons with energy $E$ can be written as

$$F_p(E) = Q(E) \cdot \tau_{\text{life}}(E) = Q(E) \cdot \tau_{\text{loss}}(E) \cdot F_{\text{cal}}(E),$$

where $Q(E)$ is the injection rate of protons, $\tau_{\text{life}}$ is the lifetime of protons inside the SBN, and $\tau_{\text{loss}}$ is the losses time-scale. In both models, the energy losses of protons are defined by the processes of p-p interactions, ionization and Coulomb interaction (Peretti et al. 2019; Schlickeiser 2002). However, the effects due to Coulomb and ionization interactions are negligible for $E > 1 \text{ GeV}$. Finally, $F_{\text{cal}}(E)$ is the so-called calorimetric fraction, which represents the fraction of high-energy protons which effectively lose their energy via proton-proton collisions inside the nucleus, thereby producing gamma-rays and neutrinos. If SBGs were efficient proton calorimeters at all energy ranges, we would have $F_{\text{cal}}(E) = 1$. Models A and B induce different calorimetric fractions because of different assumptions on CR transport and geometry. We are going to describe these separately in the following two subsections.

2.1 Model A for cosmic ray transport

Model A [see Peretti et al. (2019), for more details] considers the SBN as a spherical compact region and adopts a leaky-box model to

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1By diffusion or advection-dominated models, we mean that diffusion and advection are, respectively, the main escape processes for those particular models.
compute the proton distribution. In this case, the calorimetric fraction takes the following form:

\[ F_{\text{cal}}(E) = \frac{\tau_{\text{eff}}(E)}{\tau_{\text{adv}}(E) + 1}, \]  
(2)

where \( \tau_{\text{eff}}(E) \) is the dimensionless effective optical depth for protons, which represents the effective depth of the material through which a CR must pass on its way out of the SBN (Krumholz et al. 2020). It is given by the ratio between the escape time \( \tau_{\text{esc}} \) for protons and the energy losses time-scale \( \tau_{\text{loss}} \). The escape time is

\[ \tau_{\text{esc}} = \left( \frac{1}{\tau_{\text{adv}}} + \frac{1}{\tau_{\text{diff}}} \right)^{-1}, \]  
(3)

where both the advection (\( \tau_{\text{adv}} \)) and the diffusion (\( \tau_{\text{diff}} \)) timescales do not depend on the position in the nucleus. The former is \( \tau_{\text{adv}} = R_{\text{SNB}}/v_{\text{wind}} \) where \( R_{\text{SNB}} = 200 \text{ pc} \) and \( v_{\text{wind}} = 500 \text{ km s}^{-1} \) are the radius of the SBN and the wind velocity, respectively (assumed equal for all the galaxies). The latter is \( \tau_{\text{diff}} \propto E^{-1/3} \) according to a Kolmogorov-like scenario with an energy density of the magnetic field \( F(k) \propto k^{-2/3} \) and a regime of strong turbulence inside the SBN (Peretti et al. 2019, 2020). Since the SBN extension is typically hundreds of parsecs, we neglect a possible radial dependence of the diffusion coefficient as it is instead observed in our Galaxy (Erlykin & Wolfendale 2013; Gaggero et al. 2015b, a). We adopt an average value of 200 \( \mu \text{G} \) for the magnetic field (Thompson et al. 2006). Under reasonable values for the parameters, model A predicts a high degree of calorimetric regime with a CR lifetime dominated by p-p loss time-scale. The Kolgomorov-like diffusion has only a marginal impact on CR transport, which is predominantly affected by p-p losses and advection as the main escape mechanism. As we will see, this is the main difference with model B.

### 2.2 Model B for cosmic ray transport

Model B (see Krumholz et al. 2020 for more details) considers the nucleus as a cylinder with a width of the order of 10^2 pc and neglects any advective phenomenon. In this case, the calorimetric fraction is given by

\[ F_{\text{cal}} = 1 - \left[ 0.25^2 \left( 1 \cdot 16 \cdot \tau_{\text{eff}} \right) + 3 \cdot \tau_{\text{eff}} \right]^{-1}, \]  
(4)

with \( M_A \approx 2 \). Equations (2) and (4) generally give different predictions for the calorimetric fraction. In particular, under the same \( \tau_{\text{eff}} \), equation (4) predicts a higher calorimetric fraction than equation (2). This is due to the difference in the SBN geometry of the two models. Furthermore, differently from model A, in model B CRs do not scatter off the strong large-scale turbulence of the magnetic field, but instead stream along field lines at a rate determined by the competition between streaming instability and ion-neutral damping, leading to transport via a process of field line random walk (Krumholz et al. 2020). In this case, the diffusion stems from the interaction with the Alfvén waves that CRs themselves generate via the streaming instability. We estimate the diffusive time-scale following Krumholz et al. (2020). First, we consider the velocity of the Alfvén waves as

\[ V_{\text{d}} = \frac{\sigma_{Z}}{\sqrt{2} \chi^{1/3} M_A}, \]  
(5)

where \( \chi = 10^{-4} \) is the ionisation fraction and \( \sigma_{Z} \) is the dispersion velocity for which we use the same scaling relation with the SFR reported by Roth et al. (2021). Then, we calculate the streaming velocity of CRs with energy \( E \) as

\[ V_{\text{d}} = \min \left[ c, \frac{(1 + 2.3 \times 10^{-3} \chi^{16/3}(E / m_p)^{-1/3}(n_{\text{ISM}} / 10^5 \text{ cm}^{-3})^{3/2}}{\left( \frac{\chi}{10^{-4}} \left( \frac{\sigma_{Z}}{\sqrt{2} \chi^{1/3} M_A} \right)^{1/2} \right)^{3/2}} \right]. \]  
(6)

where \( m_p \) and \( c \) are the proton mass and the speed of light, respectively. The factor \( c_1 \approx 1 \) is the ratio between the number density of CRs in the middle plane of the SBN and a thousand times the number density of CRs expected in the Milky Way near the Solar circle.\(^3\) Moreover, \( n_{\text{ISM}} \) denotes the interstellar medium density (for SBNs \( n_{\text{ISM}} \sim 10^2-3 \text{ cm}^{-3} \)) and \( \Gamma \) is the spectral index of the proton injection spectrum. It is worth mentioning that the diffusion mechanism breaks down at high energies, where the streaming velocity becomes equal to the speed of light. In this regime, the protons start to free-stream out of the SBN. From the streaming velocity the diffusive coefficient can be calculated as

\[ D = V_{\text{d}} \cdot L_A. \]  
(7)

where \( L_A = h/\text{min}[1, M_A^1] \) is the turbulence length scale with \( h \) being the height of the galactic disc. For the sake of simplicity, we consider \( h = 73 \text{ pc} \) for all the galaxies. Finally, the diffusion timescale is \( \tau_{\text{diff}} = h^2/D \).

### 2.3 Non-thermal emissions

In both models A and B, in order to calculate the gamma-ray and neutrino spectra, we assume that protons are injected with a power-law spectrum in momentum space with spectral index \( \Gamma + 2 \). The proton spectrum is directly proportional to the SFR \( \dot{M} \), normalized by requiring that each supernova releases into protons 10 per cent of its total explosion kinetic energy (\( \sim 10^{51} \) erg). Moreover, it is characterized by an exponential cutoff at 10 PeV, in agreement with the combined fit of IceCube and Fermi-LAT diffuse data (Ambrosone et al. 2021a). We also take into account the injection of primary electrons featuring a power-law spectrum in momentum space with spectral index \( \Gamma + 2 \), a normalization equal to 1/50 of one of the protons, and a Gaussian cutoff at 10 TeV similar to what is inferred for our Galaxy (Torres 2004; Peretti et al. 2019). The distribution of electrons can be computed in a similar way as in equation (1) where we take \( F_{\text{cal}} = 1 \) (Peretti et al. 2019, 2020; Roth et al. 2021).

Neutrinos are emitted through the decay of charged pions (\( \pi \to \mu \nu_\mu, \mu \to e \nu_e \nu_\mu \)) that are produced in hadronic interactions of the injected protons with the interstellar gas with density \( n_{\text{ISM}} \). We determine the neutrino production rate by assuming that pions always carry 17 per cent of their parent proton kinetic energy (Kelner, Aharonian & Bugayev 2006). For each galaxy, the density \( n_{\text{ISM}} \) is obtained by means of the same scaling relation with the SFR reported by Amyrose et al. (2021b), in agreement with the Kennicutt relation (Kennicutt 1998; Kennicutt & Evans 2012; Kennicutt & De Los Reyes 2021). Such a relation connects the surface density of SFR, \( \Sigma_{\text{SFR}} \), and the gas surface density, \( \Sigma_{\text{gas}} \). In particular, we have

\[ n_{\text{ISM}} = 175 \left( \frac{M_*}{5 \times 10^7 \text{ M}_\odot \text{yr}^{-1}} \right)^{2/3} \text{ cm}^{-3}. \]  
(8)

Gamma-rays are principally emitted by hadronic processes through neutral pion decays (\( \pi^0 \to \gamma \gamma \)). Nonetheless, we also take

\(^3\)We have verified that a slightly different value for \( c_1 \) does not significantly affect our results.
into account the gamma-ray emission from bremsstrahlung and inverse Compton scatterings of primary electrons as well as secondary ones [see Peretti et al. (2019) and Ambrosone et al. (2021b) for details]. The gamma-ray emission from inverse Compton scattering depends on the density of background (low energy) photons acting as a target. We consider all sources to have a similar spectral shape for the background photons equal to the M82 best-fitting background spectrum reported by Peretti et al. (2019). The normalization for the different sources is self-consistently determined by the radiation energy density $U_{\text{rad}}$ of each source. For such a quantity, we assume a direct proportionality to the SFR, which is expected to be steadily linked to the IR luminosity (Kennicutt 1998; Inoue, Hirashita & Kamaya 2000; Hirashita, Buat & Inoue 2003; Yuan et al. 2011; Kennicutt & Evans 2012; Kennicutt & De Los Reyes 2021).

$$U_{\text{rad}} = 2500 \frac{M_{*}}{5 M_{\odot} \, \text{yr}^{-1}} \text{ eV cm}^{-3}.$$

We emphasize that both the hadronic and secondary leptonic components are dictated by the SFR and the calorimetric fraction, namely by the CR transport mechanisms assumed in the SBNs. Finally, we account for both internal and external gamma-ray absorption due to pair-production processes with background photons. For the latter, we consider as targets both CMB photons and the extragalactic background light model reported in Franceschini & Rodighiero (2017).

### 3 IMPRINTS OF THE COSMIC RAY TRANSPORT ON CURRENT GAMMA-RAYS DATA

The models A and B, outlined in the previous section, are based on different assumptions on CRs transport, and this gives rise to differences in the gamma-ray and neutrino spectra. This is highly significant because for nearby SBGs we have both gamma-ray data and estimates of their SFR through IR and UV data. Therefore, the comparison of the theoretical predicted gamma-ray spectra with data allows us to scrutinize whether there are observable features characterizing the CR transport inside SBGs. We here discuss such a comparison for models A and B with actual data.

We study the gamma-ray spectral energy distributions (SEDs) of 13 galaxies observed by Fermi-LAT in 10 yr of observations (Ajello et al. 2020). For Circinus Galaxy, we make use of data from Hayashida et al. (2013). For M82 and NGC 253, we also use the data provided by VERITAS (VERITAS Collaboration et al. 2009) and H.E.S.S. (H.E.S.S. Collaboration et al. 2018), respectively. For each galaxy, as performed by Ambrosone et al. (2021b), we determine the most-likely values for the two free parameters of the two models: the SFR $M_*$ and the spectral index $\Gamma$ of injected protons and electrons. We adopt a Bayesian approach, using as a posterior distribution, 3

$$p(M_*, \Gamma | \text{SED}) \propto \mathcal{L}(\text{SED}|M_*, \Gamma) \cdot p(M_*) \cdot p(\Gamma),$$

with a Gaussian likelihood function,

$$\mathcal{L}(\text{SED}|M_*, \Gamma) = \exp \left[ -\frac{1}{2} \sum_i \left( \frac{\text{SED}_i - E_i^2 \Phi_i(E_i|M_*, \Gamma)}{\sigma_i} \right)^2 \right]$$

<table>
<thead>
<tr>
<th>Source</th>
<th>Model A $(M_*, \Gamma)$</th>
<th>$\chi^2/\text{dof}$</th>
<th>Model B $(M_*, \Gamma)$</th>
<th>$\chi^2/\text{dof}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>(4.5, 2.30)</td>
<td>1.24</td>
<td>(3.0, 2.30)</td>
<td>1.88</td>
</tr>
<tr>
<td>NGC 253</td>
<td>(3.3, 2.30)</td>
<td>1.32</td>
<td>(2.1, 2.20)</td>
<td>1.95</td>
</tr>
<tr>
<td>ARP 220</td>
<td>(740, 2.66)</td>
<td>1.52</td>
<td>(740, 2.65)</td>
<td>1.53</td>
</tr>
<tr>
<td>NGC 4945</td>
<td>(4.15, 2.30)</td>
<td>1.52</td>
<td>(3.45, 2.40)</td>
<td>1.07</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>(16, 2.52)</td>
<td>0.65</td>
<td>(12, 2.50)</td>
<td>0.71</td>
</tr>
<tr>
<td>NGC 2146</td>
<td>(15, 2.50)</td>
<td>0.50</td>
<td>(12, 2.50)</td>
<td>0.52</td>
</tr>
<tr>
<td>ARP 299</td>
<td>(28, 2.15)</td>
<td>0.18</td>
<td>(28, 2.05)</td>
<td>0.19</td>
</tr>
<tr>
<td>M31</td>
<td>(0.34, 2.40)</td>
<td>0.52</td>
<td>(0.19, 2.55)</td>
<td>0.46</td>
</tr>
<tr>
<td>M33</td>
<td>(0.44, 2.76)</td>
<td>0.44</td>
<td>(0.25, 2.89)</td>
<td>0.48</td>
</tr>
<tr>
<td>NGC 3424</td>
<td>(5.4, 2.22)</td>
<td>1.63</td>
<td>(5.4, 2.20)</td>
<td>1.51</td>
</tr>
<tr>
<td>NGC 2403</td>
<td>(0.75, 2.12)</td>
<td>0.38</td>
<td>(0.37, 2.15)</td>
<td>0.37</td>
</tr>
<tr>
<td>SMC</td>
<td>(0.038, 2.14)</td>
<td>1.90</td>
<td>(0.0149, 2.25)</td>
<td>5.50</td>
</tr>
<tr>
<td>Circinus</td>
<td>(6.6, 2.32)</td>
<td>0.92</td>
<td>(4.6, 2.30)</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Here, SED, is the measured data, where $i$ runs over the energy bins centred around the energy $E_i$, and $\sigma_i$ are the observational uncertainties. We compare the data with the gamma-ray flux $\Phi_i(E_i|M_*, \Gamma)$ predicted by the models considered in each energy bin. We assume the source distances given in Kornecki et al. (2020). Following the analysis of Ambrosone et al. (2021b), for all the galaxies we consider the same uniform prior $p(\Gamma)$ on the spectral index in the range 1.0–3.0. For $M_*$, we account for prior information driven by the current measurements of the SFR, assuming a prior distribution $p(M_*)$ uniform in an interval of a factor of 3 from the SFR values given in Kornecki et al. (2020). This choice is only representative of the wide variety of SFR estimates present in the literature (Groves et al. 2008; Bolatto et al. 2011; For, Koriulski & Jarrett 2012; Rahmani, Lianou & Barnby 2016; Yoast-Hull et al. 2017; Ajello et al. 2020; Peretti et al. 2020).

The results of such an analysis are reported in Table 1. For most SBGs, current data are not able to statistically discriminate between the two models, although model A generally provides slightly smaller chi-squared values. On the other hand, for M82 and NGC 253, model B is disfavoured at $\sim 2\sigma$ level. A tension at $\sim 1\sigma$ between model B and the case of SMC, which, however, is mainly driven by low-energy data. Thus, we do not consider this as conclusive evidence in favour of model A. We emphasize that SMC is a particular case of bona fide SFG (Ajello et al. 2020), because of its low SFR. In fact, its low supernova explosion rate makes it more similar to a quiescent galaxy (Milky Way like) than an SBG. This source is supposed to be dominated by Kolmogorov-like diffusion rather than self-induced diffusion or advection (Kornecki et al. 2021), making model B quite inapplicable to this source and the prediction of model A less optimistic. Furthermore, being a nearby source ($D = 60$ kpc) (Kornecki et al. 2020), the details of the modelling might be somewhat influential on the results, thereby making the comparison between model A and model B less robust. Nonetheless, we report the results of our analyses even for this galaxy for the sake of completeness. Moreover, it is interesting to remark, once again, the differences between the two scenarios, even though the more robust results are the ones derived for the other sources, which are characterized by more intense star-forming activity. The importance of data above 100 GeV resides in the fact that the calorimetric fraction of model B rapidly drops to zero. This makes it highly difficult to accommodate high-energy data. In order to highlight this behaviour,
Figure 1. Best-fitting SEDs for model A (dashed blue line) and model B (solid orange line) as inferred by Fermi-LAT data Ajello et al. (2020) and VERITAS data (VERITAS Collaboration et al. 2009).

Figure 2. Comparison between the integrated luminosity between (0.1–100) GeV for model A (solid blue line) and model B (dashed orange line), with the corresponding measurements of the 13 galaxies analysed (Kornecki et al. 2020).

In Fig. 1, we show the SED for M82 predicted by the two models in their best-fitting scenario. This result is highly significant since, differently from the analysis in Krumholz et al. (2020), we find that model B is not able to accommodate high-energy data for this source (VERITAS Collaboration et al. 2009). This suggests that the diffuse model B cannot provide a full explanation of SFGs and SBGs emissions above 1 TeV. On the other hand, it is worth noticing that model B provides a higher calorimetric fraction for energies below 100 GeV with respect to model A. This implies that a smaller value of the SFR is required to fit the data. Therefore, sources like NGC 4945 get to be better fitted by this model because their emission can be better described while satisfying the prior on the SFR deduced by IR and UV observations.

However, concerning the source NGC 4945, Ajello et al. (2020) point out that the star-forming activity may not be responsible for the totality of its emissions due to the presence of an AGN activity. Indeed, model A cannot fully explain its gamma-ray data even with the highest value for the SFR (4.15 M⊙ yr⁻¹) as allowed by the prior, leaving room for a possible AGN component. On the contrary, this is not the case for model B, which requires $M_s = 3.45$ M⊙ yr⁻¹.

The different dependence on the SFR in the two models is highlighted in Fig. 2, where we compare the gamma-ray luminosity $L_\gamma$ (integrated between 0.1 and 100 GeV) as a function of $M_s$. In the plot, the integrated luminosity is computed assuming a reference value of the spectral index ($\Gamma = 2.2$) for all the galaxies as in Kornecki et al. (2021) and Roth et al. (2021). However, it is worth noticing that $L_\gamma$ depends only marginally on $\Gamma$. This allows for the comparison with the measurements of the individual sources even though the experimental SEDs are explained by different values for the spectral index (see Table 1). As can be clearly seen in the plot, at low SFR, the luminosity predicted by model B (dashed orange line) is higher than the one by model A. This just mirrors the higher calorimetric fraction of model B with respect to model A. On the contrary, for high values of the SFR, the two models predict the sources to be efficient calorimeters ($F_{\text{cal}} = 1$), leading to the same scaling of the luminosity with the SFR.

The weak preference of current gamma-ray data for model A might already suggest that advection plays a key role as an escape mechanism in SFGs and SBGs. However, more definitive conclusions might be drawn only with more gamma-ray data, especially at energies higher than 1 TeV. As will be discussed in the next subsection, the CR transport mechanism will be crucially probed by future gamma-ray telescopes.

4 FORECAST FOR THE CTA TELESCOPE

We perform a forecast analysis to quantitatively assess the ability of the future CTA telescope to discriminate between the two models of CR transport. In particular, we simulate future gamma-ray measurements using the public CTA information (Acharya et al. 2018). Motivated by the previous results, we assume the best-fitting model A to generate CTA mock data and we determine the statistical power with which they favour model A over model B. We focus only on the local sources for which the expected SED is higher than the differential CTA sensitivity. According to model A, which typically provides high gamma-ray spectra, we expect that the CTA telescope will observe at least four sources (Ambrosone et al. 2021b): SMC, M82, NGC 253, and Circinus galaxy. For each of these sources, we pursue the following procedure: First, we bin the energetic range (10²–10⁵ GeV), with the same binning provided by the CTA consortium. Secondly, for each source, we only consider the energetic bins for which the SED is higher than the CTA sensitivity. Hence, we calculate the expected number of signal events as

$$n_{\text{signal}} = T_{\text{obs}} \int_{\Delta E} A_{\text{eff}}(E) \Phi_{\gamma,A}(E) dE,$$

where $\Phi_{\gamma,A}$ is the gamma-ray flux predicted by the best-fitting model A according to present data, $A_{\text{eff}}$ is the CTA effective area, $\Delta E$ is the size of the energy bin, and $T_{\text{obs}} = 50$ h is the time of observation. We also take into account the number $n_{\text{bg}}$ of background events associated with misidentified CRs. We remark that $n_{\text{bg}}$ only depends on the declination of the source and the opening angle $\Delta \Omega$ of the observation. Considering that we expect gamma-rays to be mostly emitted by SBNs, we take $\Delta \Omega = \max(\Delta \Omega_{\text{res}}, \Delta \Omega_{\text{SBN}})$ where $\Delta \Omega_{\text{res}}$ is the CTA energy-dependent angular resolution function and $\Delta \Omega_{\text{SBN}}$ represents the angular dimension of the source SBN. For all the sources except SMC (the nearest source), we have $\Delta \Omega_{\text{SBN}} < \Delta \Omega_{\text{res}}$. For SMC, we consider the intrinsic extension of its SBN $\Delta \Omega_{\text{SBN}} = 0.38^\circ$.

For each energy bin, we randomly generate $10^4$ numbers of events $n_{\text{bg}}$ by means of a Poisson distribution with a mean value of $n_{\text{cal}} = n_{\text{signal}} + n_{\text{bg}}$, namely $n_{\text{obs}} \sim \text{Poiss}(n_{\text{obs}})$. Then, we estimate the empirical number of signal events simply as $\tilde{n}_{\text{signal}} = n_{\text{obs}} - n_{\text{background}}$. From this quantity, we can calculate the empirical SED assuming a
generic power-law flux $E^{-2}$. In particular, we have

$$\text{SED}_i = \frac{n_{\text{signal,}i}}{T_{\text{obs}} \int_{\Delta E} A_{\text{eff}}(E) \left( \frac{E}{1 \text{ GeV}} \right)^{-2} dE},$$

where $i$ runs over energy bins. The reconstructed SEDs are affected by an uncertainty that can be directly estimated through the Poisson uncertainty on $n_{\text{obs}}$ as

$$\Delta SED_i = \sqrt{\frac{n_{\text{obs,}i}}{n_{\text{signal,}i}}}.$$

We emphasize that in this generation of mock data, we simply consider the best-fitting gamma-ray flux $\Phi_{\gamma, A}$ provided by model A with current data. Hence, we neglect the intrinsic uncertainty on the expected gamma-ray flux as provided by the posterior distribution in equation (10). We show the impact of the intrinsic uncertainty in Appendix A. Accounting for the intrinsic uncertainty generally leads to larger Bayes factors and smaller $p$-values for SMC, M82, and NGC 253. Therefore, the results we obtain in the text are reasonably conservative.

For each of the 10^4 mock data sets, we again perform the statistical analysis described in the previous section, including this time the mock data SED as well. In Fig. 3, we show the updated best-fitting scenarios for the four sources according to one realization of the CTA mock data. In particular, the solid blue (dashed orange) lines represent the best-fitting SEDs according to model A (B). For M82, SMC, and NGC 253, they coincide with the one obtained with current data only. This stems from the fact that these sources have not only ~GeV data, which constrain their normalization (SFR), but also data above 100 GeV, which constrain their shape (i.e. the spectral index). The only exception is the Circinus Galaxy (bottom right-hand panel), for which the current absence of data above 10 GeV leads to a different best-fitting SED for model B (dot-dashed orange line referred to with ‘model B’). In the plots, we also show the expected 1 yr sensitivity of the SWGO experiment (Albert et al. 2019; Hinton 2021). We emphasize that this future telescope is also expected to observe the brightest sources located in the Southern hemisphere in the 1–10 TeV energy range.

We can then quantify the statistical confidence with which model B can be excluded by computing the $p$-value in a Frequentist approach as well as the Bayes factor $B$ for the two models. The $p$-value is simply given by

$$p = \int_{\chi_{\text{min}}^2}^{\chi_{\text{max}}^2} f_k(k) \, dk,$$

where $\chi_{\text{max}}^2 = -2 \ln \left[ \max \mathcal{L}_k(M, \Gamma) \right]$ and $f_k(k)$ is the probability distribution function of a chi-square with $k$ degree of freedom. For each source, $k$ is given by the total number of data points (current and mock data) minus two (number of free parameters). On the other hand, the Bayes factor is computed as

$$B = \frac{\int_{\mathcal{L}_A} \mathcal{L}_A(SED|M, \Gamma) \, dM \, d\Gamma}{\int_{\mathcal{L}_B} \mathcal{L}_B(SED|M, \Gamma) \, dM \, d\Gamma},$$

where $\mathcal{L}_A$ and $\mathcal{L}_B$ are the likelihood functions for model A and B, respectively. We note that the two integrals are performed over the same two-dimensional (2D) phase space given by the uniform priors on $M$ and $\Gamma$. For each source, we therefore obtain a distribution of expected $p$-values and Bayes factors given the different mock data sets.

In Table 2, we summarize the results of the above-described forecast analysis. In particular, we report the mean values of the distributions of $p$-value and Bayes factor along with the corresponding values deduced with current data only. Moreover, we report the 68 percent and 95 percent one-sided intervals of the two distributions. As can be seen in the table, current data strongly disfavour model B for the SMC source. For other sources, we find that with future CTA observations, model B might be excluded at more than $2\sigma$ according to the expected small $p$-values. Furthermore, large Bayes factors are expected in favour of model A. This trend is robust against possible uncertainties on the astrophysical parameters of the sources. This is discussed in Appendix B, where we investigate how the fit for model B depends on other parameters such as the height of the disc $h$, the dispersion velocity $\sigma_v$ and the gas density $n_{\text{ISM}}$ without assuming any scaling relation with the SFR for the latter two. Even in this case, we find $p$-values $<0.1$ (Bayes factor $>10$) for 95 per cent of the mock data sets generated under model A. Therefore, our results point out that CTA will be able to firmly discriminate between the two models of CR transport within the SFGs and SBGs. We conclude this section by pointing out that CTA and SWGO will also quantitatively test the hadronic production of SMC, giving more indirect constraints on cosmic ray transport mechanisms, assessing if the hadronic production from SMC is as optimistic as predicted by model A considered in this article.

5 FROM POINT SOURCES TO DIFFUSE FLUXES

The observation of nearby galaxies provides valuable constraints on the parameters that define their point-like emissions. Equipped with such information, we can now calculate the cumulative diffuse gamma-ray and neutrino fluxes correlated to unresolved SFGs and SBGs emissions. As pointed out by Roth et al. (2021), model B (Krumholz et al. 2020) is inadequate at ultra-high energies, thereby making unreliable the comparison with IceCube neutrino observations. For this reason, hereafter we only consider model A, with the aim of refining our previous calculations for the diffuse flux (Ambrosone et al. 2021a), taking into account the spectral variability of SBGs as obtained in the present source-by-source analysis.

We carry this calculation out by adopting a similar approach to the one described by Ambrosone et al. (2021a). In particular, this approach exploits the fact that, in model A, for good reservoirs, the neutrino and gamma-ray fluxes do not depend on the structural details of the SBN (e.g. the dimension of the starburst region $R_{\text{SBN}}$ or the interstellar medium density $n_{\text{ISM}}$), but rather on the SFR $M_\star$, and the spectral index $\Gamma$. Therefore, we can consider a prototype galaxy (M82) to set the astrophysical parameters and then linearly scale with the SFR the fluxes of a generic source, which take the expression (Peretti et al. 2020)

$$\Phi_{\gamma, \nu}(E, z| M_\star, \Gamma) = \frac{M_\star}{M_{\star, 0}} \Phi_{\gamma, \nu}(E, z| M_{\star, 0}^{M82}, \Gamma),$$

with $M_{\star, 0}^{M82} = 4.5 M_\odot$ yr$^{-1}$. Then, the diffuse gamma-ray and neutrino flux can be obtained as

$$\Phi_{\gamma, \nu}^{\text{diff}}(E) = \int_0^{4.2} \frac{dz}{d^2 J} \int_{M_{\text{min}}}^{M_{\text{max}}} dM_\star \frac{d\nu}{H(z)} S_{\text{SFR}}(z, M_\star) \Phi_{\gamma, \nu}(E, z| M_\star, \Gamma),$$

where we integrate over the whole SFG and SBG population in redshift $z$ and SFR $M_\star$, for which we consider the modified Schechter function $S_{\text{SFR}}(z, M_\star)$ reported by Peretti et al. (2020). Such a quantity has been obtained by fitting in the redshift interval $0 \leq z \leq 4.2$ the
IR + UV data of a Herschel Source sample (Gruppioni et al. 2013) after subtracting the AGN contamination (Delvecchio et al. 2014). For the cosmological Hubble parameter \( H(z) = H_0 \sqrt{\Omega_M (1 + z)^3 + \Omega_L} \) we take \( H_0 = 67.74 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_M = 0.31 \), and \( \Omega_L = 0.69 \), and \( d_L(z) \) denotes the comoving distance. Finally, \( \Phi(z) \) is the emitted neutrino and gamma-ray fluxes averaged over the distribution of allowed spectral indexes, namely

\[
\left\langle \Phi(E, \nu) \right\rangle = \int \Phi(E, \nu) \ dE
\]

The main differences between the present calculation and the one in Ambrosone et al. (2021a) are threefold. First, we take a different spectral index distribution \( p_{\nu}(\Gamma) \), directly stemming from the \( \Gamma \) values inferred by gamma-ray point-like data and reported in Table 1. This makes our estimates highly consistent with each other since the same CR transport model is used for point-like and diffuse analysis. In particular, we consider the spectral index distribution to be a Gaussian distribution with a mean value of 4.36 and a standard deviation standard 0.2. Secondly, we do not set by hand a lower limit for the SFR above which SBGs and SFGs are considered as good calorimeters. Indeed, as summarized by equation (1), the sources which are dominated by either advection or diffusion losses naturally have their calorimetric fraction approaching zero, thus giving a negligible contribution to the diffuse fluxes. Therefore, we integrate from a minimum SFR \( M_{s, \text{min}} \approx 0.038 M_{\odot} \text{yr}^{-1} \) according to our point-like analysis. Thirdly, we do not consider a free normalization for the diffuse flux, which is instead directly predicted under the aforementioned assumptions. Before showing our main results, we would like to stress that the plausibility of this method resides in the fact that, as demonstrated also by Roth et al. (2021), the majority of the contribution comes from sources that have a high SFR \( M_s \gtrsim 1 M_{\odot} \text{yr}^{-1} \), for which the calorimetric approach is reasonably...
The potential to firmly discriminate between model A and model B, providing the latter a highly suppressed emission above a few TeV. We emphasize that in the Southern hemisphere a crucial role will also be played by the upcoming SWGO telescope thanks to a larger field of view and a longer duty cycle compared to CTA. The comparison between the two models depends crucially on the hadronic production above ~1 TeV, which is present in model A and suppressed in model B due to diffusion. Since this hadronic production generally follows a power-law spectrum, the results we obtain are roughly independent of the details of the models (e.g. choice of the astrophysical parameters) and are mainly determined by the spectral index, normalization, and maximal cosmic ray energy, which we obtain from current gamma-ray data on SFGs. Finally, we have employed the information inferred by the local gamma-ray observations to consistently and robustly estimate the diffuse gamma-ray and neutrino emission from the whole population of SFGs and SBGs. We have found that model A predicts a 25 per cent contribution of these sources to the IceCube HESE data, in agreement with the gamma-ray limits on the non-blazar component. This result confirms that cosmic reservoirs are of paramount importance for the description of high-energy neutrino observations, even though they cannot explain the whole astrophysical flux observed.

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DATA AVAILABILITY

The data underlying this article are available in the article and in its online supplementary material.

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APPENDIX A: IMPACT OF SOURCE UNCERTAINTIES ON MOCK DATA GENERATION

We here investigate how the mock data generation for the CTA telescope is affected by the current uncertainties on the source parameters. Such uncertainties are simply defined by the posterior distribution in equation (10) that is obtained with current gamma-ray data. Differently from the analysis presented in Section 4, for each source we produce mock data by sampling the SFR and the spectral index from the posterior distribution of model A, namely \((M_\star, \Gamma) \sim p(M_\star, \Gamma | \text{SED})\). These parameters determine the gamma-ray flux \(\Phi_{\gamma, \nu}\), which is then employed to compute the expected number of signal events \(n_{\text{signal}}\) according to equation (12). This time, we consider the observed number of events simply as \(n_{\text{obs}} = n_{\text{signal}} + n_{\text{bg}}\) and estimate the empirical SED directly from \(n_{\text{signal}}\) (see equation 13). As before, the uncertainty on the reconstructed SEDs is deduced from the Poisson uncertainty on the mock measurements \(n_{\text{obs}}\). In this way, for each source, we produce \(10^3\) mock data sets, which are analysed assuming model A and model B. As described in Section 4, we compute the \(p\)-values to test model B and the Bayes factors to compare the two models.

The results of this analysis are reported in Table A1. These results are quite more stringent than the one given by the previous case because for M82, NGC 253, and SMC the variability of the fit given by model A is pretty small and therefore the prediction of this model are quite in disagreement with the one predicted by model B. In particular, for M82 and NGC 253, the mean Bayes factors are respectively of the order of \(10^2\) and \(10^3\), which are much greater than the values obtained through the Poisson generation in Section 4. Correspondingly, the rejection \(p\)-values are lower than the Poissonian mock data. In fact, for SMC, the average \(p\)-value is given by \(2.0 \times 10^{-38}\), which is 2 order of magnitudes lower than the one provided by Poissonian mock data. The only exception is Circinus

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**Figure A1.** Distributions of \(p\)-values (top panel) and Bayes factors (bottom panel) obtained by generating CTA mock data according to a Poisson distribution (blue colour) and to the posterior distribution of source parameters (yellow colour). The vertical lines show both the current value (solid lines) with collected data, the mean (dotted lines), and 95 percent (dot–dashed) values corresponding to the mock distributions.
for which we just, currently, have six data points, making its posterior distribution quite unconstrained. In this case, we obtain similar results for the two different approaches to mock data generation. We show this in Fig. A1, where in the top and bottom panels we compare the distributions of \( p \)-values and Bayes factors, respectively, for the two mock data sets. We also highlight the mean and the 95 per cent C.L. values with dashed and dot–dashed lines, respectively, as well as the current values with collected gamma-ray data (solid lines). Even though the width of the distributions for the Poisson uncertainty and the source uncertainty are similar in this case, the distribution for the latter case is peaked at higher values of Bayes factor. Therefore, it is conservative to consider only the Poisson uncertainty, as we do in the main text.

### APPENDIX B: IMPACT OF THE UNCERTAINTY OF ASTROPHYSICAL PARAMETERS

Here, we scrutinize the impact on the results of the analysis presented in the main text coming from the uncertainties on the source structural parameters. These might play a key role in model B, which features a non-trivial calorimetric fraction \( F_{\text{cal}}(E) \) as a function of the energy. Therefore, it is reasonable to check whether our results depend on the assumptions that the structural parameters of local sources (e.g. \( h \), \( n_{\text{ISM}} \), and \( \sigma_g \)) are known and scale in a precise way with the SFR. In particular, equation (8) might not be exactly representative for all sources. For these reasons, for the four brightest sources, we perform a similar analysis on current and mock data by taking 5 free and independent parameters for model B: \( \Gamma, M_*, n_{\text{ISM}}, \sigma_g, \) and \( h \). For all the parameters, we consider uniform priors. For \( \Gamma \) and \( M_* \), we make use of the same priors as in the main text. For the SBN height \( h \), we consider the range 70–150 pc (an uncertainty of a factor of 2), being consistent with Krumholz et al. (2020) and Roth et al. (2021). For the velocity dispersion \( \sigma_g \), we take 25–50 km s\(^{-1}\) (an uncertainty of a factor of 2). Finally, for the gas density \( n_{\text{ISM}} \), we consider \( \mathcal{O}(10) \) variations: for Circinus and NGC 253 in the range 10–200 cm\(^{-3}\), for M82 in the range 30–300 cm\(^{-3}\), and for SMC in the range 1–20 cm\(^{-3}\). We summarize the main results in Table B1. These are obtained for only 100 mock data sets since the 5-parameter fitting procedure is highly time consuming. As can been seen by comparing with Table 2, the \( p \)-values (Bayes factors) increase (reduce) by a few orders of magnitudes. None the less, as discussed in the main text, our conclusions remain basically unaltered. This is a crucial point that, from one hand, underlines once again the importance for future measurements (despite all the possible uncertainties) and, from the other, remarks the intrinsic difference from the calorimetric fractions of models A and B.
Table B1. Results of the forecast analysis for the CTA telescope, considering the uncertainty on the structural parameters of the sources for model B.

<table>
<thead>
<tr>
<th>Source</th>
<th>Current data</th>
<th>95 per cent</th>
<th>68 per cent</th>
<th>Mean</th>
<th>Current data</th>
<th>95 per cent</th>
<th>68 per cent</th>
<th>Mean</th>
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<td>SMC</td>
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<td>$2.7 \times 10^{-21}$</td>
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<tr>
<td>M82</td>
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<td>$1.1 \times 10^{-4}$</td>
<td>$1.3 \times 10^{3}$</td>
<td>$2.0 \times 10^{4}$</td>
<td>$6.5 \times 10^{7}$</td>
<td>$1.6 \times 10^{7}$</td>
</tr>
<tr>
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<tr>
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<td>$1.2 \times 10^{-2}$</td>
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