Gamma-Ray Potential Detection of Star-Forming Galaxies in the TeV Range

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Introduction

Star-forming galaxies (SFGs) offer insights into cosmic-ray (CR) processes.; they are extragalactic γ-ray sources whose non-thermal emission is associated with their stellar populations rather than active galactic nuclei. The tight correlation between their star formation rate (SFR) and their observed radio/γ-ray luminosity [1] supports this idea. This non-thermal radiation provides critical information on CR transport.

Although γ-ray emissions in the GeV range are clearly connected to their SFR, the origins of higher-energy emissions are uncertain due to limited observational data.

To identify the most promising SFGs for future γ-ray observatories, we compiled a comprehensive sample. This includes those detected by *Fermi*-LAT in the GeV range and others catalogued in the near-infrared within the Local Volume. We used both empirical models and observations to predict their TeV spectra and evaluated their detectability with the latest ground-based instrument response functions. Our findings indicate that nearly a dozen SFGs could be detected by the next generation of Cherenkov telescopes, in particular Cherenkov Telescope Array Observatory (CTAO).

SFGs Sample

Currently, only two SFGs, M82 and NGC 253, have been detected in the TeV energy range by VERITAS and H.E.S.S., respectively. To explore the discovery of new galaxies in the GeV range and assess their potential for TeV detection, we first review galaxies detected in the GeV range by *Fermi*-LAT. We then analyse the potential for detecting, at TeV energies, galaxies not yet observed in the GeV range. For this, we use the Revised MANGROVE Sample from [2], which includes SFGs covering over 90% of the sky and extending up to 350 Mpc ($z < 0.08$), each with an SFR estimation.

Selection criteria:

- Galaxies must show a clear star-forming component in the optical and infrared spectrum, evaluated using the SSDC SED Builder.
- For the 4FGL catalogue, we include sources with class designations 1 and 2 that match normal galaxies ("GAL"), starburst galaxies ("SBG"), or Seyfert galaxies ("SEY").
- From the sample in [2], we initially select galaxies with an expected γ-ray flux greater than 1 mCrab at 1 TeV, based on their SFR and distance, using NGC 253 as a reference, and exclude galaxies with dwarf elliptical, lenticular, or elliptical morphology.

Applying these criteria, we identified 13 galaxies not yet detected by *Fermi*-LAT in the GeV range (the **Non-GeV detected sample**) and 14 galaxies that have been detected (the **GeV detected sample**) for further investigation.

Some Results

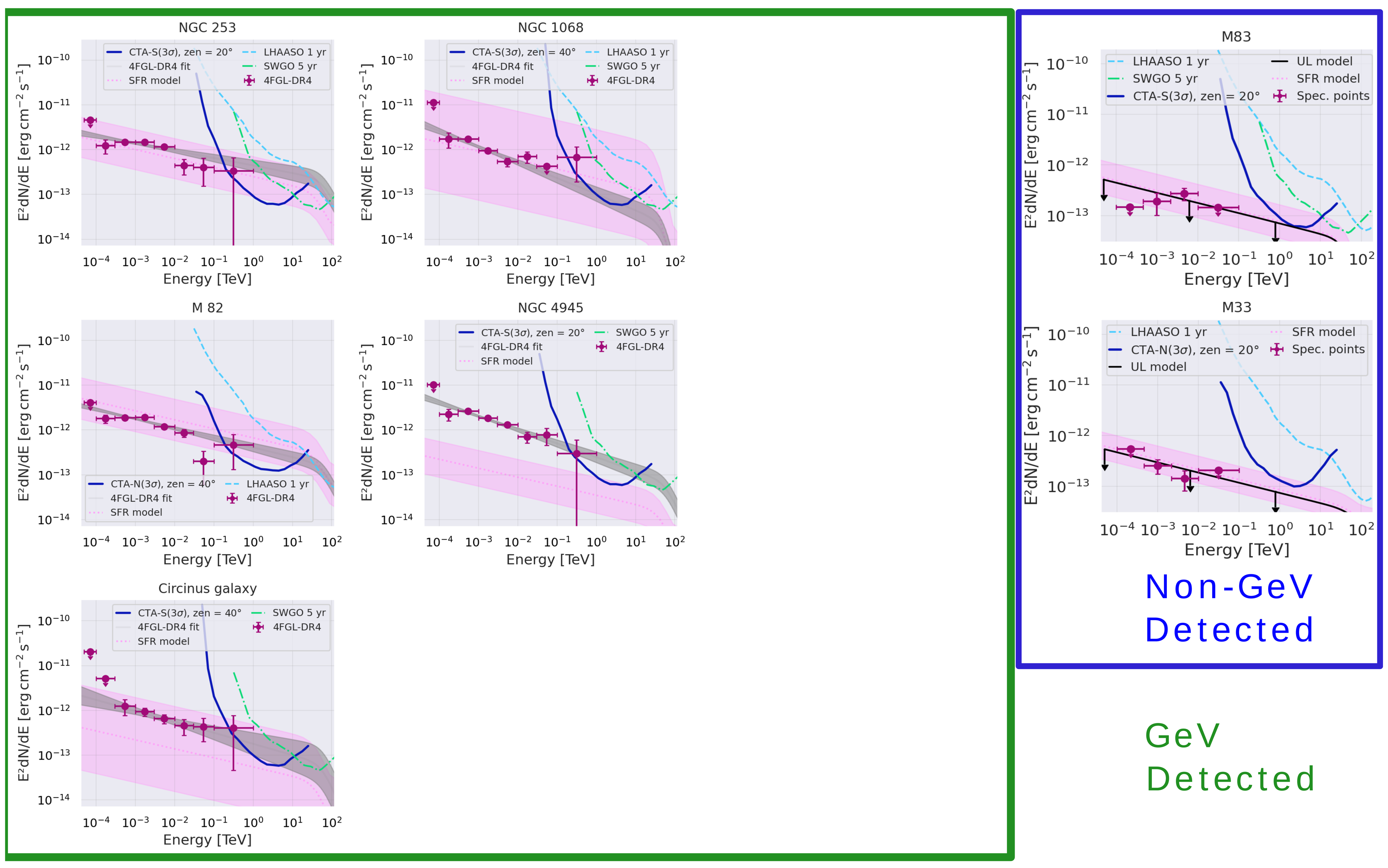

Figure 1: SEDs of the top candidates selected from GeV detected (left panel) and Non-GeV Detected (right panel). In each panel, violet dots denote spectral points from *Fermi*-LAT data. The pink dotted line and associated shaded region depict the empirical model scaled to the SFR of the galaxy along with its associated uncertainty. The blue solid line indicates the 3σ-level point source sensitivity of CTAO in 50 h. Light blue dashed line and green dotted-dashed line show the LHAASO and SWGO sensitivity respectively. In left panel the grey line and grey shaded region represent the best power-law fit to the γ-ray data, as provided in the 4FGL-DR4 catalogue, including absorption on the EBL at multi-TeV energies. In right panel the black solid line with arrows represents the upper bound on the expected γ-ray emission of each galaxy including the absorption on the EBL.

Conclusions

We identified three new candidates (NGC 1068, NGC 4945, and Circinus) for very high-energy observations, alongside M82, NGC 253, and the Magellanic Clouds. Six additional galaxies (NGC 2403, Arp 299, Arp 220, NGC 3424, M83 and M33) are near the CTAO sensitivity limit. NGC 253 and M82 were highlighted as promising targets for LHAASO, while NGC 253, NGC 4945, and Circinus are of interest for SWGO. This study underscores the need for refined models to better predict γ-ray spectra. Observing these galaxies in the TeV range is key for insights into CR acceleration, transport, and absorption, advancing our grasp of CRs physics.

The L_γ - SFR correlation

We revisit the L_γ–SFR correlation from [3] for the GeV detected sample. We focus on the luminosity at 2 GeV, close to the pivot energy where the γ-ray flux uncertainty is minimised, rather than using the integrated *Fermi*-LAT energy range. To estimate the SFR, we use multiwavelength tracers to account for dust attenuation. A fit was initially performed including the 14 galaxies. Then to provide an estimation of the γ-ray luminosity of a galaxy given its SFR, we performed another fit with only those that follow a tight correlation, excluding galaxies that are more than 4 sigma from their best-fit.

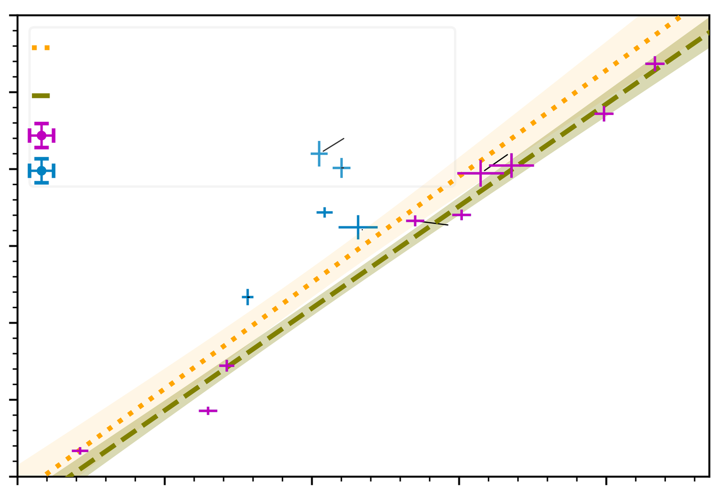

Figure 2: $L_{\gamma,2\,\mathrm{GeV}}$ – SFR observed correlation. The dashed green line and associated shaded region shows the best-fit model excluding blue markers and the shaded region represents the 68% confidence-level band.

TeV γ-Ray Spectra and Sensitivity

We developed an empirical model for the non-thermal emission of SFGs, assuming that γ-ray emission is produced by CR interactions with the interstellar medium, which scales with the SFR. The spectrum is modelled as a PL with a fixed slope of 2.2, normalised using the L_γ-SFR correlation and accounting for γγ absorption by the Extragalactic Background light (EBL) as:

$$F\,[\mathrm{erg\,s^{-1}\,cm^{-2}}] = \frac{L_{2\,\mathrm{GeV}}(\mathrm{SFR})}{4\pi d^2}\left(\frac{E}{2\,\mathrm{GeV}}\right)^{-\Gamma+2} e^{-\tau(E;z)}, \quad (1)$$

where $\tau(E;z)$ is the optical depth from [4], tabulated as a function of redshift z.

For galaxies not detected in the GeV range, we reanalysed GeV observations using Fermi-LAT PASS 8 archival data (from August 4, 2008, to July 12, 2023) to calculate upper limits (ULs) and spectral points. We also built an UL model which is similar to the empirical model but with the energy flux at 2 GeV normalised from the ULs. We also computed the sensitivity for an azimuth-averaged pointing with *Gammapy* using the latest version of the CTAO instrument response functions (IRFs): prod5 v0.1.7. Additionally, we compared the expected γ-ray flux of SFGs with the differential sensitivities of LHAASO (with 20" PMT configuration) and SWGO.

References

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