Star-Forming Galaxies as TeV γ-ray sources: Prospects for Detection

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CSIC

VHEGA

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MOTIVATION AND GOAL

Motivation:

- Young stars and supernovae => Particle acceleration => CR => Non-thermal radiation.
- Reservoirs of high-energy CR, may act as **neutrino** factories.
- Origin of the SFGs gamma-ray emission remains enigmatic due to **limited observations** and the **low angular resolution** of current gamma-ray telescopes.
- Identifying best SFGs candidates for detection by Cherenkov telescopes is crucial to **validate or challenge existing models.**

Goal: to assemble the largest possible sample of SFGs with potential detectability by the new generation of gamma ray telescopes.

Methodology and Assumptions

We explored the prospect of discovering new **SFGs in the GeV** energy range and subsequently **assessed their potential detection at TeV** energies.

SFGs? presence of a clear IR - OP double peak

Simple emission Model:

* Diffuse emission p-p interactions ->
Spectral index ≈ 2.2 from GeV to TeV.

Sample of SFGs

***Fermi* - LAT**

- ASSOC1 and 2 in **4FGL-DR4** (gll_psc_v33.fit) SBG, GAL, SEY.
- We check one by one that the "SF" component exists by checking its SED at low energies (**opt - IR**).
- Excluded: Not SF => 14 SFGs to investigate.

MANGROVE sample: a flux-limited sample covering the entire sphere within 11 Mpc (Local Volume) and ~90% of the sphere out to 350 Mpc (d, SFR(Hα); Biteau 2021).

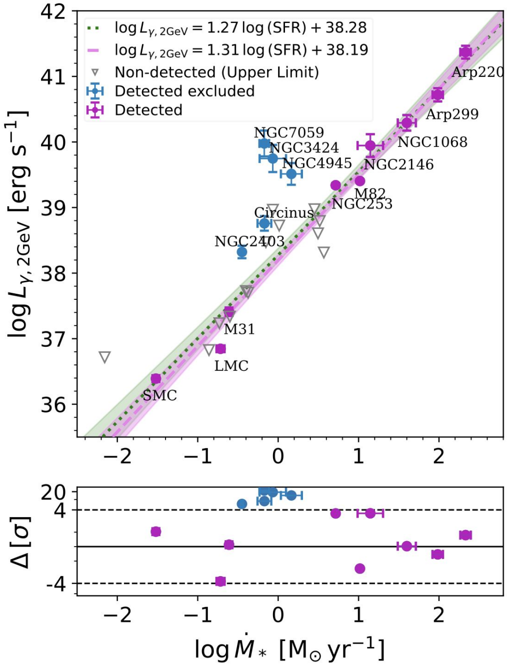
- $F \propto \frac{\mathrm{SFR}}{4\pi d^2} > \alpha \frac{\mathrm{SFR}_{\mathrm{NGC\ 253}}}{4\pi d^2_{\mathrm{NGC\ 253}}}$ α=1/3.5, ensuring galaxies with expected flux ≥ 1/3.5 of NGC253 are detectable by next-generation observatories (~1 mCrab in 50 h, vs. ~3.5 mCrab at 1 TeV for NGC 253).
- Excluded: Not SF => 13 SFGs to investigate.

4FGL catalog

Lγ-SFR relation at 2 GeV

Lγ,2 GeV: Fitted Spectra from the 4FGL.
2 GeV (Reduce uncertainty - **pivot energy**)

SFR: Kornecki et al. (2020) employed *multi- wavelength tracers* (in particular FUV+IR25μm or Hα+IR25μm and total IR emission in 8–1000μm, Kennicutt 1998; Kennicutt & Evans 2012). This take into account dust attenuation.



Residual

$$L_{\gamma,\,2\mathrm{GeV}} \propto (\mathrm{SFR})^{1.3}$$

+

NGC4945, NGC3424, NGC2403* (sbg), NGC7059 (gal), Circinus (sey).

AGN (Gavazzi et al. 2011; Lenc & Tingay 2009; Prieto et al. 2004) or **SFR mis-estimation** (Kornecki et al. 2020).

NGC 2403: possible **supernova** (Xi et al. 2020a) or **misidentified as blazar** (Bruzewski et al. 2023).
NGC 7059: greatest deviation, power-law index 1.8 ± 0.1. Misidentified ?

Evaluating GeV detection for SFGs NOT listed in 4FGL

- From the sample of 13 galaxies we explored their latest ***Fermi* data** and analyze their possible detection in the GeV band (binned likelihood analysis assuming a PL spectrum and a spectral index of 2.2 in all cases).

- We **only found marginal detection of M83 and M33** with a TS =18 and 22, respectively. For the **rest we obtained smaller TS values.**

- We calculated the corresponding 95 % confidence level UL in the whole energy range (0.1 GeV - 100 GeV) by fixing the spectral index to 2.2 and spectral points.

$$\int_{E_{\rm min}}^{E_{\rm max}} N_o E^{-\alpha} E \, dE \leq \mathrm{UL} \longrightarrow \mathbf{N_{o,max}}$$

$$E_{\rm min} = 0.1 \text{ GeV}$$
$$E_{\rm max} = 100 \text{ GeV}$$

$$dN_{max}/dE = N_{o,max} E^{-\alpha}$$

Candidate SFGs in the TeV energy range

- Extrapolation of the GeV spectrum measured by Fermi-LAT (+ EBL absorption)

- Physical model: Lγ,2GeV - SFR scaling with a power-law spectral index α = 2.2 + EBL absorption

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

- Estimated the 50 h 3σ CTAO sensitivity for a point-like IRF at a fixed zenith angle and fixed offset using ***Gammapyv1.1*** and the CTAO IRF version: ***prod5 v0.1***.

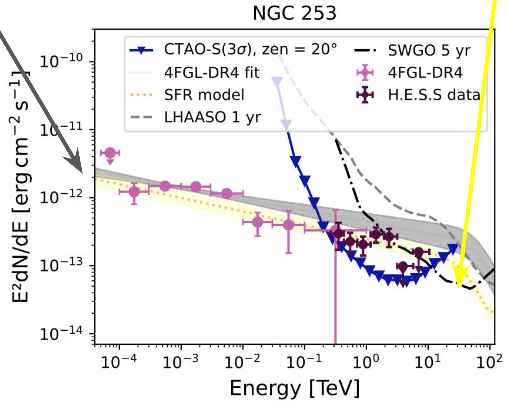
gammapy: https://docs.gammapy.org/
IRF: https://zenodo.org/record/5499840

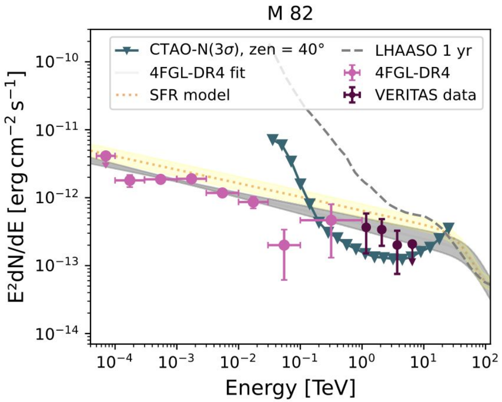
Results: Detectability in the TeV energy range

THE BEST CANDIDATES

4FGL extrapolation
its error band

Physical model

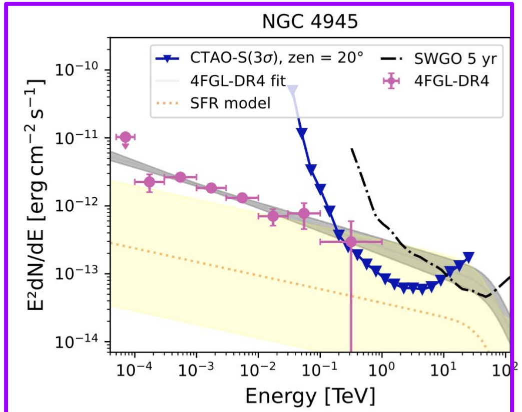


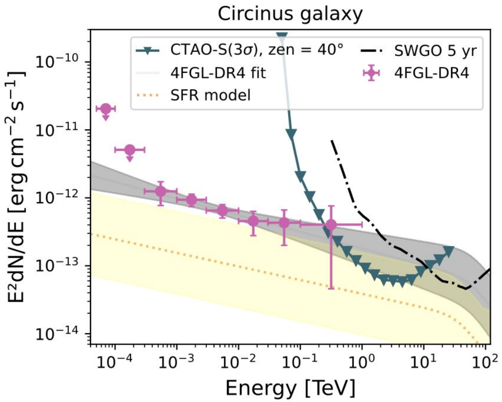


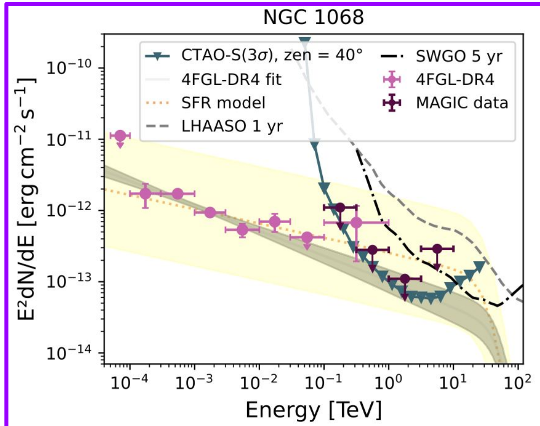
Sensitivities:

- 50 h 3σ CTAO
- LHAASO (N)
- SWGO (S)

3 new! (NGC1068, NGC4945, Circinus)

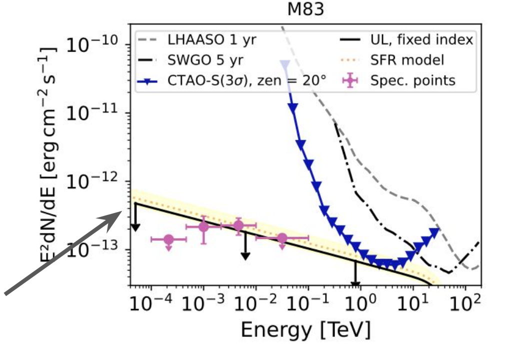


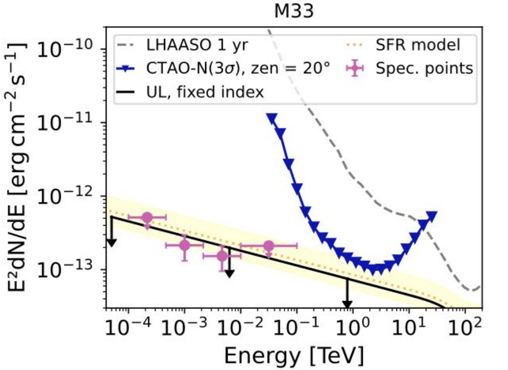




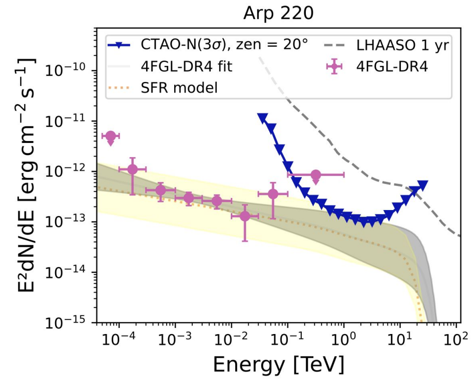
More interesting candidates

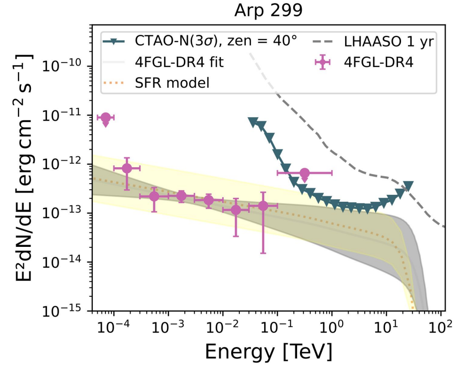
Empirical model
No,max UL





NOT IN THE 4FGL CATALOG





PROTON CALORIMETERS ?

A few takeaways

- We have identified **3 candidates** worthy of recommendation for observation in the VHE domain.

  NGC 1068, NGC 4945 and Circinus Galaxy.

- We should definitely put an eye on:

  M83, M33, ARP 220 and ARP 299 (near the detection limit).

Thank you !!!

Table B.1. Sample of SFGs studied in this work.

Name	d Mpc	R.A. deg	Dec deg	Revised MANGROVE	IRAS RBGS	Ackermann 2012 sample	$\dot{M}_*$ $M_\odot$ yr^{-1}	4FGL Name	$\mathcal{F}_{2\,\mathrm{GeV}}$ 10^{-13} erg s^{-1} cm^{-2}	CTAO	LHAASO, SWGO
LMC	0.049 ± 0.002	80.00	-68.75	✓	✓	✓	0.192 ± 0.022	J0519.9-6845e	240.0 ± 5.9	?	?
SMC	0.064 ± 0.001	14.50	-72.75	✓	✓	✓	0.030 ± 0.003	J0058.0-7245e	50.3 ± 2.5	?	?
NGC 6822	0.4603 ± 0.0040	296.24	-14.80	✓			0.0070 ± 0.0006	-	< 2.05	-	-
M31	0.74 ± 0.02	10.82	41.24	✓	✓	✓	0.245 ± 0.023	J0043.2+4114	3.91 ± 0.55	?	-
M33	0.853 ± 0.016	23.46	30.66	✓	✓	✓	0.251 ± 0.013	-	< 2.49	+	-
NGC 300	1.944 ± 0.040	13.72	-37.68	✓			0.138 ± 0.005	-	< 0.15	-	-
NGC 55	1.981 ± 0.020	3.79	-39.22	✓			0.186 ± 0.010	-	< 0.37	-	-
IC 342	2.24 ± 0.10	56.70	68.10	✓		✓	0.40 ± 0.03	-	< 0.89	-	-
Circinus	2.41 ± 0.26	213.29	-65.33	✓			0.68 ± 0.13	J1413.1-6519	8.3 ± 1.2	++	+
NGC 2403	3.13 ± 0.06	114.37	65.59	✓			0.355 ± 0.012	J0737.4+6535	1.79 ± 0.39	o	o
NGC 1569	3.25 ± 0.24	67.70	64.85	✓			0.70 ± 0.08	-	< 2.34	-	-
M81	3.61 ± 0.20	148.89	69.07	✓			0.42 ± 0.04	-	< 0.32	-	-
M82	3.53 ± 0.03	148.95	69.67	✓	✓	✓	10.41 ± 0.19	J0955.7+6940	17.0 ± 1.0	++	+
NGC 253	3.61 ± 0.03	11.90	-25.29	✓	✓	✓	5.19 ± 0.09	J0047.5-2517	14.0 ± 1.0	++	+
NGC 4945	4.06 ± 0.77	196.36	-49.47	✓	✓	✓	1.46 ± 0.44	J1305.4-4928	16.5 ± 0.9	++	+
M83	4.79 ± 0.09	204.25	-29.87	✓	✓	✓	3.29 ± 0.10	-	< 2.27	+	-
NGC 3621	6.70 ± 0.37	169.57	-32.81	✓			0.86 ± 0.07	-	< 1.72	-	-
M101	6.76 ± 0.11	210.80	54.35	✓			3.13 ± 0.22	-	< 0.74	-	-
NGC 6946	6.95 ± 0.38	308.71	60.15	✓		✓	3.70 ± 0.33	-	< 0.36	-	-
M106	7.54 ± 0.09	184.74	47.30	✓			1.03 ± 0.08	-	< 0.78	-	-
M51	8.34 ± 0.30	202.47	47.23	✓			2.83 ± 0.15	-	< 1.13	-	-
NGC1068	13.4 ± 1.8	40.67	-0.01		✓	✓	40 ± 10	J0242.6-0000	9.12 ± 0.68	++	o
NGC 2146	17.2 ± 3.2	94.53	78.33				14.0 ± 5.1	J0618.1+7819	2.49 ± 0.38	o	-
NGC 3424	18.8 ± 3.7	162.91	32.89				0.86 ± 0.32	J1051.6+3253	1.32 ± 0.35	o	-
NGC 7059	24.7 ± 4.6	321.84	-60.01				0.67 ± 0.09	J2127.6-5959	1.30 ± 0.34	?	?
Arp 299	46.8 ± 3.3	172.07	58.52				97 ± 14	J1128.2+5831	2.00 ± 0.37	o	-
Arp 220	80.9 ± 5.7	233.70	23.53				214 ± 32	J1534.7+2331	2.99 ± 0.53	o	-

Notes. The first two columns provide the common name of the galaxy, d is the luminosity distance, R.A. and Dec are the right ascension and declination in the ICRS reference system of the center of the associated 4FGL source. The next three columns indicate whether the source meets the selection criterion described in section 2.1 (flux relative to that of NGC 253 > 1/3.5) in the Revised MANGROVE Sample (Biteau 2021), the IRAS Revised Bright Galaxy Sample (Sanders et al. 2003), and the sample proposed by Ackermann et al. (2012). $\dot{M}_*$ is the SFR. 4FGL Name is the name of the associated γ-ray source in 4FGL-DR4. $\mathcal{F}_{2\,\mathrm{GeV}}$ is the energy flux at 2 GeV. The last two columns qualify the reliability of detection by the new γ-ray observatories, whether pointed (CTAO) or wide field (LHAASO, SWGO): "++", "+", "o", "-", "?" indicate, respectively, a high degree of reliability, a good degree of reliability, a possibility of detection, an unlikely detection, and that a detailed study is needed before concluding.

BACKUP

GeV-detected

Table 2. Sample of SFGs included in the 4FGL that satisfy the selection criteria defined in Sect. 2.3.

Name	4FGL Name	d Mpc	RA deg	Dec deg	$\dot{M}_*$ $M_\odot\,yr^{-1}$	$\mathcal{F}_{2\,GeV}$ 10^{-13} erg s^{-1} cm^{-2}
LMC	J0519.9−6845e	0.049 ± 0.002	80.00	−68.75	0.192 ± 0.022	240.0 ± 5.9
SMC	J0058.0−7245e	0.064 ± 0.001	14.50	−72.75	0.030 ± 0.003	50.3 ± 2.5
M31	J0043.2+4114	0.74 ± 0.02	10.82	41.24	0.245 ± 0.023	3.91 ± 0.55
Circinus	J1413.1−6519	2.41 ± 0.26	213.29	−65.33	0.68 ± 0.13	8.3 ± 1.2
NGC 2403	J0737.4+6535	3.13 ± 0.06	114.37	65.59	0.355 ± 0.012	1.79 ± 0.39
M82	J0955.7+6940	3.53 ± 0.03	148.95	69.67	10.41 ± 0.19	17.00 ± 0.98
NGC 253	J0047.5−2517	3.61 ± 0.03	11.90	−25.29	5.19 ± 0.09	14.0 ± 1.0
NGC 4945	J1305.4−4928	4.06 ± 0.77	196.36	−49.47	1.46 ± 0.44	16.50 ± 0.90
NGC 1068	J0242.6−0000	13.4 ± 1.8	40.67	−0.01	40 ± 10	9.12 ± 0.68
NGC 2146	J0618.1+7819	17.2 ± 3.2	94.53	78.33	14.0 ± 5.1	2.49 ± 0.38
NGC 3424	J1051.6+3253	18.8 ± 3.7	162.91	32.89	0.86 ± 0.32	1.32 ± 0.35
NGC 7059	J2127.6−5959	24.7 ± 4.6	321.84	−60.01	0.67 ± 0.09	1.30 ± 0.34
Arp 299	J1128.2+5831	46.8 ± 3.3	172.07	58.52	97 ± 14	2.00 ± 0.37
Arp 220	J1534.7+2331	80.9 ± 5.7	233.70	23.53	214 ± 32	2.99 ± 0.53

Notes. The first two columns provide the common name of the galaxy and the name of the associated γ-ray source in 4FGL-DR4, d is the luminosity distance, RA and Dec are the right ascension and declination in the ICRS reference system of the center of the associated 4FGL source. $\dot{M}_*$ is the SFR. $\mathcal{F}_{2\,GeV}$ is the energy flux at 2 GeV calculated using the best-fit power-law parameters from the 4FGL-DR4.

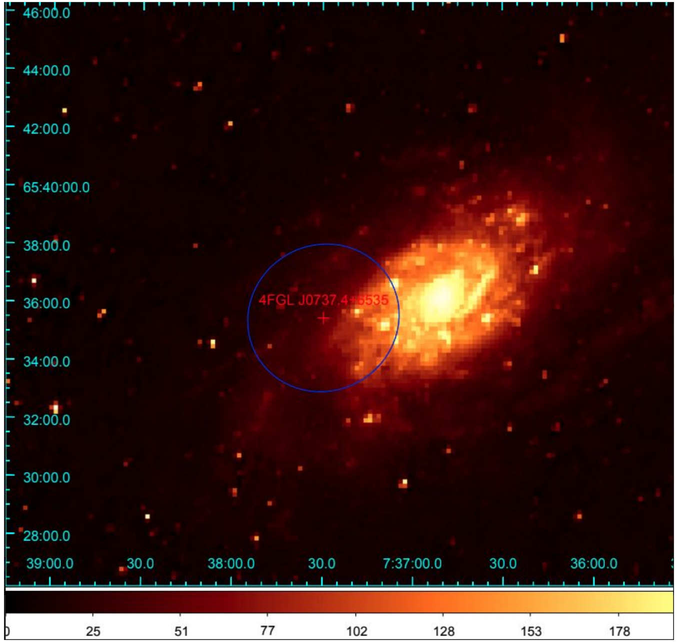
Non-GeV Detected

Table 1. Sample of SFGs not included in the 4FGL-DR4 that satisfy the selection criteria defined in Sect. 2.1.

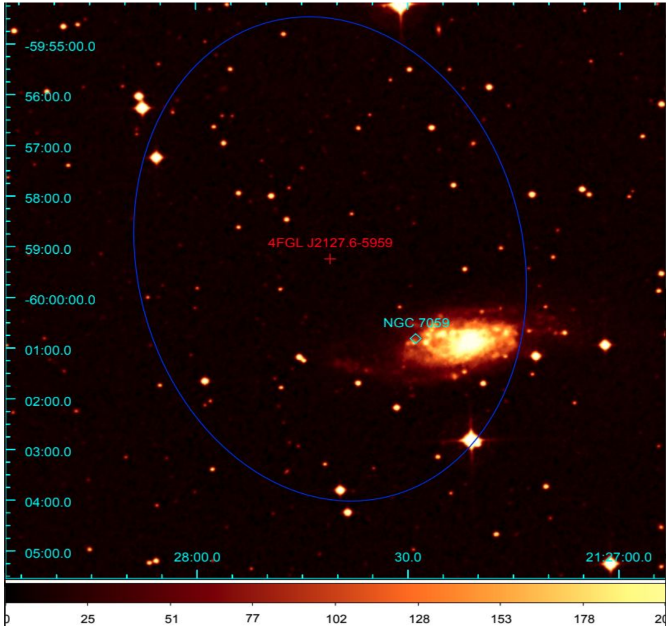
Name	d Mpc	RA deg	Dec deg	$\dot{M}_*$ $M_\odot\,\mathrm{yr}^{-1}$	TS	$\mathcal{F}^{\mathrm{UL}}_{0.1-100\,\mathrm{GeV}}$ $10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$	$\mathcal{F}^{\mathrm{UL}}_{2\,\mathrm{GeV}}$ $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$
NGC 6822	0.4603 ± 0.0040	296.24	−14.80	0.0070 ± 0.0006^d	8	8.72	20.5
M33	0.853 ± 0.016	23.46	30.66	0.251 ± 0.013^b	22	10.6	24.9
NGC 300	1.944 ± 0.040	13.72	−37.68	0.138 ± 0.005^a	0	0.63	1.48
NGC 55	1.981 ± 0.020	3.79	−39.22	0.186 ± 0.010^b	0	1.56	3.66
IC 342	2.24 ± 0.10	56.70	68.10	0.40 ± 0.03^c	3	3.77	8.86
NGC 1569	3.25 ± 0.24	67.70	64.85	0.70 ± 0.08^a	10	9.93	23.4
M81	3.61 ± 0.20	148.89	69.07	0.42 ± 0.04^b	0	1.37	3.21
M83	4.79 ± 0.09	204.25	−29.87	3.29 ± 0.10^a	18	9.66	22.7
NGC 3621	6.70 ± 0.37	169.57	−32.81	0.86 ± 0.07^a	7	7.31	17.2
M101	6.76 ± 0.11	210.80	54.35	3.13 ± 0.22^b	3	3.13	7.37
NGC 6946	6.95 ± 0.38	308.71	60.15	3.70 ± 0.33^c	0	1.52	3.56
M106	7.54 ± 0.09	184.74	47.30	1.03 ± 0.08^d	13	3.32	7.80
M51	8.34 ± 0.30	202.47	47.23	2.83 ± 0.15^a	7	4.82	11.3

Notes. The columns d, RA, and Dec are the distance, right ascension, and declination in the ICRS reference system of the galaxy center taken from the SIMBAD astronomical database. $\dot{M}_*$ is the SFR. TS is the obtained test statistic for detection in the GeV energy range. $\mathcal{F}^{\mathrm{UL}}_{0.1-100\,\mathrm{GeV}}$ and $\mathcal{F}^{\mathrm{UL}}_{2\,\mathrm{GeV}}$ are the 95% confidence level upper limits on the energy flux integrated over 0.1–100 GeV and at 2 GeV, respectively, assuming a fixed spectral index of 2.2. [(a)]Computed from FUV (Gil de Paz et al. 2007) plus IRAS 25 μm (Sanders et al. 2003) fluxes. [(b)]Computed from FUV (Gil de Paz et al. 2007) plus IRAS 25 μm (Rice et al. 1988) fluxes. [(c)]Computed from Hα (Kennicutt et al. 2008) plus IRAS 25 μm (Sanders et al. 2003) fluxes. [(d)]Computed from Hα (Kennicutt et al. 2008) plus IRAS 25 μm (Rice et al. 1988) fluxes.

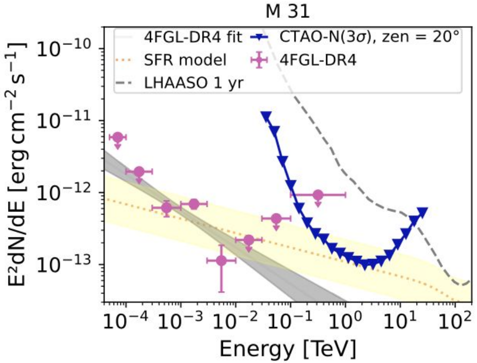
NGC 2403 FIELD

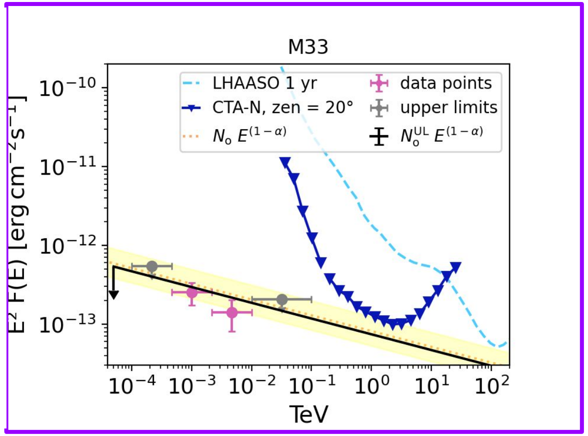


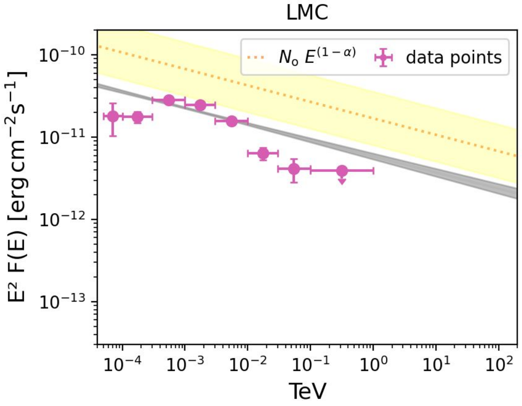
NGC 7059 FIELD

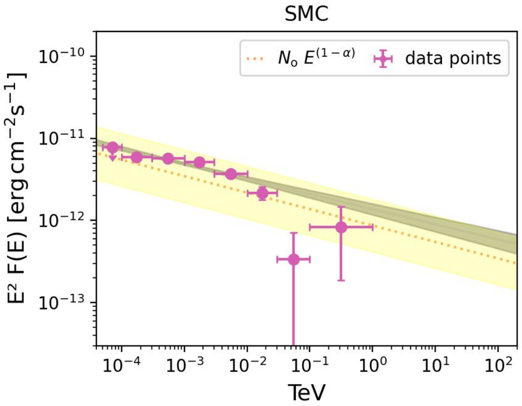


Extended sources





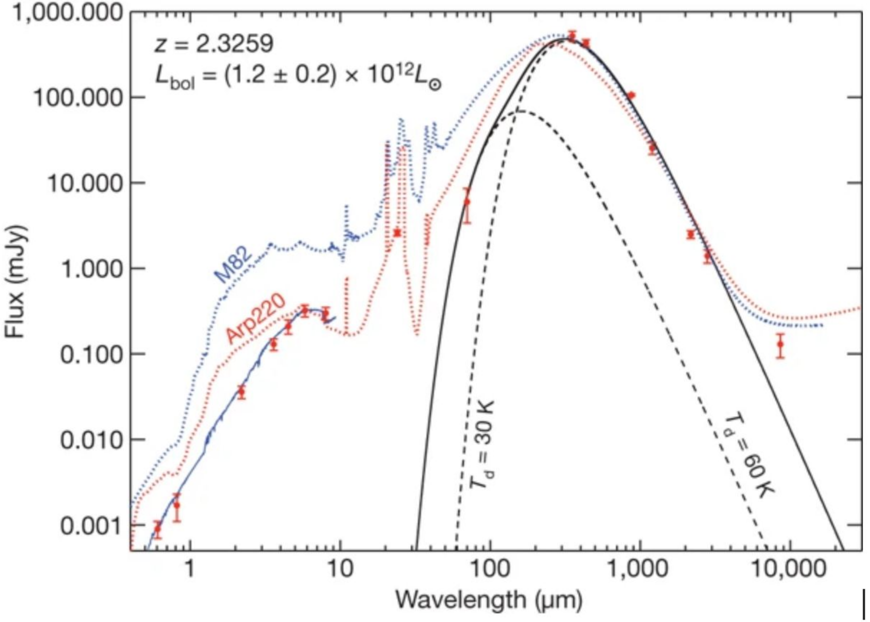


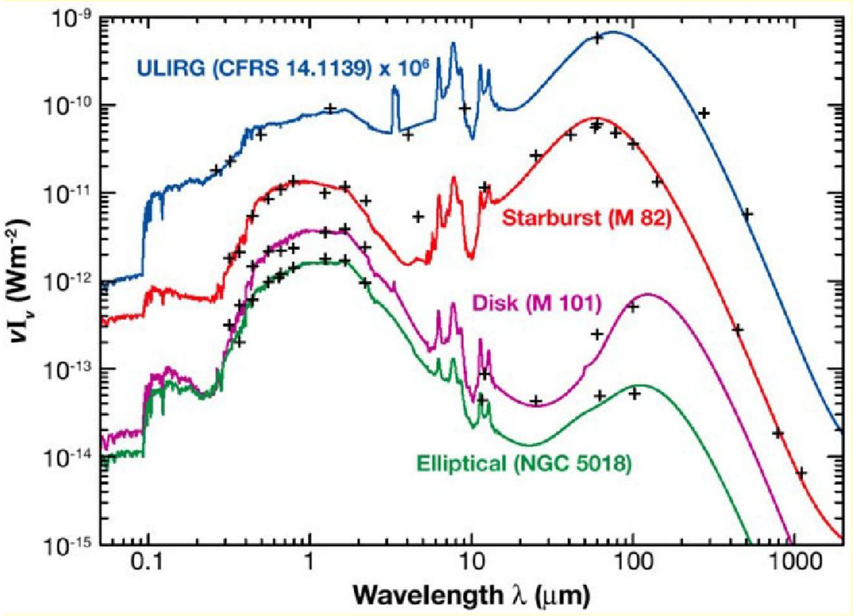


Assuming most of the emission is located in the SBG nucleus / central molecular zone of radius **R < 1 kpc and angular resolution at 1 TeV ~ 5'**

Then, the nucleus would be "point like" for **R/d < 5'**

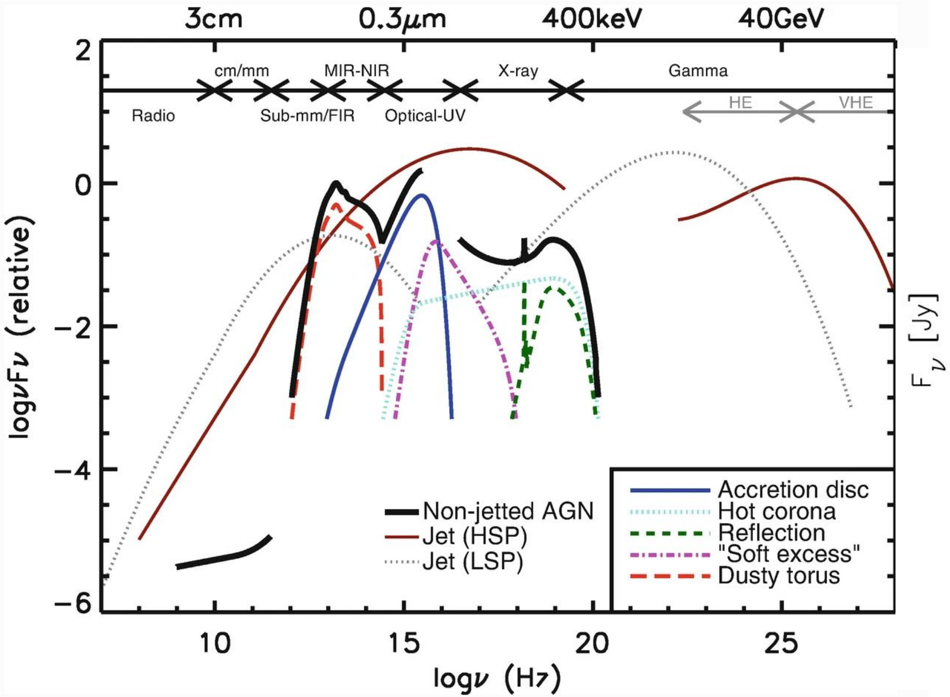
- d(LMC / SMC) ~ 50-60 kpc => extended emission requiring dedicated studies (cf. LMC work by CTA).
- d(M31/33) ~ 700 - 900 kpc => potential to detect a point-like emission.



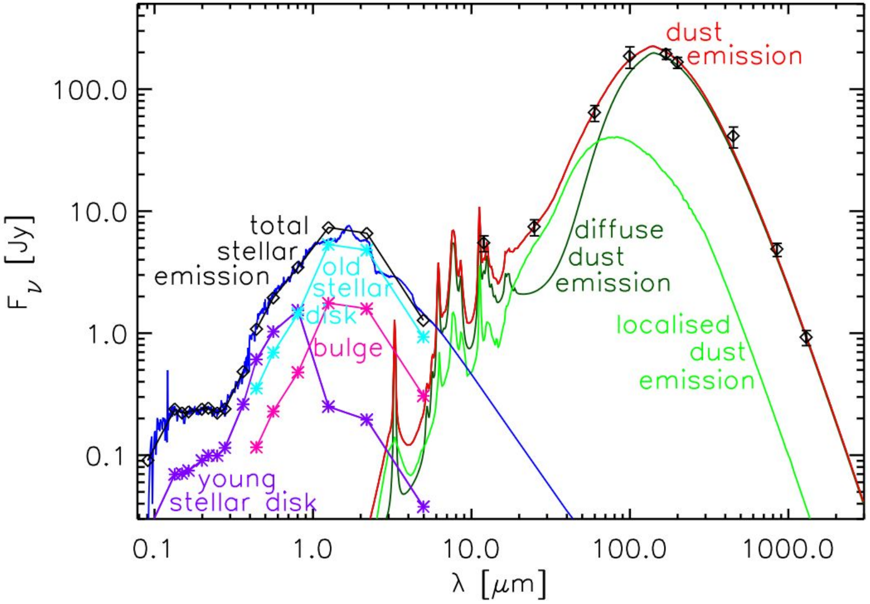


To illustrate how the spectral energy distribution of the galaxy compares to local starbursts, we overlaid the spectral energy distributions from M82 (blue dashed line) and Arp220 (red dashed line), both scaled to equal flux at 1.2 mm. The solid black line denotes the best-fit spectrum, a two-component dust model with temperatures fixed at T_d = 30 K and 60 K and a dust emissivity of β = 1.8 in a modified black-body function. We also overlaid the best-fit stellar spectral energy distribution to the optical to mid-infrared photometry (solid blue line) from which we estimate stellar age, extinction, luminosity and mass through population synthesis. The vertical error bars denote root-mean-square uncertainties in the measurements at each wavelength.

From http://elte.prompt.hu/sites/default/files/tananyagok/InfraredAstronomy/ch10s02.html wavelength.



A schematic representation of the spectral energy distribution (SED) of radiatively efficient AGN, loosely based on the observed SEDs of non-jetted quasars (e.g., Elvis et al., 1994; Richards et al., 2006). The black solid curve represents the total emission and the various colored curves (shifted down for clarity) represent the individual components. The jet SED is also shown for a high synchrotron peaked blazar (HBL; based on the SED of Mrk 421) and a low synchrotron peaked blazar (LBL; based on the SED of 3C 454.3). The various AGN components and classes are described in details later in the text. (Figure reproduced from Padovani et al. (2017), Fig. 1, with permission. Image credit: C. M. Harrison)



Cristina C. Popescu et al 2010

https://link.springer.com/referenceworkentry/10.1007/978-981-16-4544-0_113-1/figures/1

To ensure the relevance of the subsample to be examined, we first selected galaxies that are a priori bright enough to be detectable by next-generation TeV γ-ray observatories, using the criterion

$$\frac{\mathrm{SFR}}{4\pi d^2} > \alpha \frac{\mathrm{SFR}_{\mathrm{NGC\ 253}}}{4\pi d^2_{\mathrm{NGC\ 253}}},$$

where $\alpha = 1/3.5$. This condition ensures that a galaxy with an expected flux ≥ 1/3.5 of NGC 253 would be detectable by the new-generation observatories, which can reach fluxes of ~1 mCrab in ~50 hours, compared to ~3.5 mCrab at 1 TeV for NGC 253 measured with previous-generation telescopes in 160 hours.