DISCOVERY OF GeV EMISSION FROM THE CIRCUINS GALAXY WITH THE FERMI LARGE AREA TELESCOPE

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ABSTRACT

We report the discovery of γ-ray emission from the Circinus galaxy using the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope. Circinus is a nearby (~4 Mpc) starburst with a heavily obscured Seyfert-type active nucleus, bipolar radio lobes perpendicular to the spiral disk, and kpc-scale jet-like structures. Our analysis of 0.1–100 GeV events collected during 4 yr of LAT observations reveals a significant (>7.3σ) excess above the background. We find no indications of variability or spatial extension beyond the LAT point-spread function. A power-law model used to describe the 0.1–100 GeV γ-ray spectrum yields a flux of \((18.8 \pm 5.8) \times 10^{-9} \text{ photon cm}^{-2} \text{ s}^{-1}\) and photon index 2.19 ± 0.12, corresponding to an isotropic γ-ray luminosity of \(3 \times 10^{39} \text{ erg s}^{-1}\). This observed γ-ray luminosity exceeds the luminosity expected from cosmic-ray interactions in the interstellar medium and inverse Compton radiation from the radio lobes. Thus, the origin of the GeV excess requires further investigation.

Key words: galaxies: active – galaxies: individual (Circinus) – galaxies: jets – galaxies: Seyfert – radiation mechanisms: non-thermal

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1. INTRODUCTION

Active galactic nuclei (AGNs) often possess fast nuclear outflows and collimated radio-emitting jets powered by accretion onto supermassive black holes (e.g., Krolik 1999). Relativistic jets produced in radio-loud AGNs (such as blazars and radio galaxies), which are typically hosted by early-type galaxies, are well-established sources of Doppler-boosted γ-ray emission, dominating the extragalactic source population in the GeV range (Nolan et al. 2012). The bulk of the observed γ-ray jet emission in such systems is believed to originate within a few parsecs of the central black hole (e.g., Abdo et al. 2010a). However, Fermi Large Area Telescope (LAT) observations of nearby radio galaxies indicate that large-scale structures—hereafter “lobes” or “bubbles”—formed by jets outside their hosts due to interactions with the intergalactic medium, can also be bright GeV emitters (Abdo et al. 2010b; see also Katsuta et al. 2013).

Radio-quiet AGNs, the most luminous of which are classified as Seyferts by their optical spectra, are typically hosted by late-type galaxies. The “radio-quiet” label does not necessarily mean these sources are completely “radio-silent,” and the nuclear jets found in these systems are non-relativistic and comparatively low-powered (e.g., Lal et al. 2011), so that AGNs and starburst activities may both be equally important factors in the formation of kpc-scale outflows and lobes (e.g., Gallimore et al. 2006). Seyfert galaxies seem γ-ray quiet as a class (Teng et al. 2011; Ackermann et al. 2012a).

Besides radio-loud AGNs, another class of established extragalactic γ-ray sources consists of galaxies lacking any pronounced nuclear activity, but experiencing a burst of vigorous star formation. The observed GeV emission from these sources is most readily explained by interactions of galactic cosmic rays (CRs) with ambient matter and radiation fields of the interstellar medium (ISM; Ackermann et al. 2012b, and references therein). Starburst-driven outflows routinely found in such systems may lead to the formation of large-scale bipolar structures extending perpendicular to the galactic disks and somewhat resembling jet-driven AGN lobes (Veilleux et al. 2005).

Circinus is one of the nearest (distance \(D = 4.2 \pm 0.7 \text{ Mpc}\); Tully et al. 2009) and most extensively studied composite starburst/AGN systems, but its location behind the intense foreground of the Milky Way disk, \((l, b) = (311^\circ 3, -3^\circ 8)\), resulted in exclusion from several previous population studies using LAT data (Ackermann et al. 2012a, 2012b). Circinus exhibits a polarized broad Hα line with FWHM ~ 3000 km s\(^{-1}\) (Oliva et al. 1998), evidencing a heavily obscured Seyfert 2 nucleus that ranks as the third brightest Compton-thick AGN (Yang et al. 2009). Radio observations have mapped bipolar bubbles extending orthogonal to the spiral host, as well as kpc-scale jet-like structures likely responsible for the formation of the lobes (Elmouttie et al. 1998). The extended morphology of the system including the lobes has been recently resolved and studied in X-rays (Mingo et al. 2012). Here, we report the discovery of a significant γ-ray excess positionally coinciding with the Circinus galaxy using 4 yr of Fermi-LAT data and discuss possible origins for this emission.

2. LAT DATA ANALYSIS AND RESULTS

The LAT is a pair-production telescope on board the Fermi satellite with large effective area (6500 cm\(^2\) on axis for >1 GeV...
which shows the Australia Telescope Compact Array (ATCA) 1.4 GHz radio contours at positional errors of the $\gamma$ significance of core position of Circinus, corresponding to a formal detection likelihood fit when placing a new candidate source at the sources were left free in the fitting procedure. within the 68% confidence region for the direction of the $\gamma$ of positions around the galaxy (TS map). Circinus is located TS value for the candidate source when evaluated over a grid sufficient angular resolution (see, e.g., Ackermann et al.2013b) a point-like feature, but we note that the LAT does not excess. The distribution of the $\gamma$ to spatially resolve the core, the radio lobes, or the galactic disk located 0.10′′ away from Circinus. Additionally, the model included the isotropic and Galactic diffuse emission components;10 flux normalizations for the diffuse and background included the isotropic and Galactic diffuse emission components10 flux normalizations for the diffuse and background which were left free in the fitting procedure. Our analysis yields a test statistic (TS) of 58 for the maximum likelihood fit when placing a new candidate source at the core position of Circinus, corresponding to a formal detection significance of $\sim 7.3\sigma$. Figure 1 shows the spatial variation in the TS value for the candidate source when evaluated over a grid of positions around the galaxy (TS map). Circinus is located within the 68% confidence region for the direction of the $\gamma$-ray excess. The distribution of the $\gamma$-ray excess is consistent with a point-like feature, but we note that the LAT does not have sufficient angular resolution (see, e.g., Ackermann et al. 2013b) to spatially resolve the core, the radio lobes, or the galactic disk (all shown in the right panel of Figure 1) of the system. Assuming that 2FGL J1415.7–6520 is an additional $\gamma$-ray source distinct from the Circinus galaxy, we repeat the analysis including 2FGL J1415.7–6520 in the background model. The $\gamma$-ray excess at the position of Circinus yields in such a case a TS of 52, while no significant excess can be seen at the formal position of 2FGL J1415.7–6520 (TS $\simeq$ 5.6). Our analysis confirms therefore a single point-like $\gamma$-ray excess positionally coinciding with Circinus, which may be identified with 2FGL J1415.7–6520 after the localization of the 2FGL source is refined using the 4 yr accumulation of LAT data. The 2FGL analysis flagged 2FGL J1415.7–6520 as a source with a low signal-to-background ratio (2FGL flag was set to ‘4’), meaning its position can be relatively strongly affected by systematic uncertainties in the Galactic diffuse emission model (see also Ackermann et al. 2012c), and the overall positional error of 2FGL J1415.7–6520 could be larger than indicated. Our analysis here of 4 yr of accumulated LAT data for the source allowed it to be detected at higher energies, thus decreasing the systematic uncertainty in the location. A simple power-law model (PL) adequately describes the $\gamma$-ray spectrum of the source, yielding a $\gamma$-ray flux $F_{\gamma,0.1\,\text{GeV}} = (18.8 \pm 5.8) \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$ and photon index $\Gamma = 2.19 \pm 0.12$, corresponding to an isotropic 0.1–100 GeV luminosity of $L_{\gamma} \simeq (2.9 \pm 0.5) \times 10^{40}$ erg s$^{-1}$. The best-fit model together with flux points of the spectral energy distribution (SED) are plotted in Figure 2. We also perform spectral fits using a broken PL model and a log-parabola model, but no significant improvement ($<1.2\sigma$) can be seen in the likelihood values when compared with the PL parameterization. The results of the spectral fits for Circinus are summarized in Table 1. For comparison, we also derived $\gamma$-ray fluxes and spectra for four LAT-detected starburst galaxies (Ackermann et al. 2012b) with 4 yr LAT data by performing the same analysis procedure described above, and we summarize the results in Table 1.

Since Circinus is located near the Galactic plane, it is important to consider systematic errors caused by uncertainties
in the Galactic diffuse emission model. We test eight alternative diffuse models (following Ackermann et al. 2013a; de Palma et al. 2013) and find that the derived source flux above 0.1 GeV shifts by no more than 3%, which is much smaller than the statistical uncertainty. The detection significance at the source position remains stable for the different alternative diffuse models (TS $\simeq$ 58–60).

We also analyze a limited event sample with an energy range 1–100 GeV within a $10^4 \times 10^4$ RoI. In this energy range, reduced systematic effects related to diffuse emission modeling are expected, owing in part to the improved spatial resolution of the LAT. The PL character of the $\gamma$-ray continuum is confirmed with $\Gamma = 2.19 \pm 0.41$, and we find that much of the statistical power of our search comes from photons above 1 GeV (TS = 42). The extrapolated flux above 0.1 GeV from the higher energy analysis corresponds to $(16.4 \pm 5.6) \times 10^{-9}$ photon cm$^{-2}$ s$^{-1}$, in good agreement with the result obtained using events from 0.1 GeV.

Figure 3 shows a TS map created using events with this energy band, and we have confirmed that Circinus is located at the edge of the 68% confidence contour of the $\gamma$-ray source. We also produced an observed counts profile of Circinus and compared it with the best-fit point-like source model as shown in Figure 4.

The observed counts profile is consistent with the model shape of a point-like source, indicating no significant spatial extension of the $\gamma$-ray excess.

In order to search for variability in the $\gamma$-ray flux, we divided the 4 yr observation window into half-year intervals and derived $\gamma$-ray fluxes above 0.1 GeV for each time interval using a PL model with photon index fixed at the best-fit value obtained for the 4 yr data set. No significant variability is found in the

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### Table 1

| Name       | $D$  (Mpc) | $L_{\gamma}/10^{44}$ (erg s$^{-1}$) | $L_{\gamma}/10^{38}$ (erg s$^{-1}$) | TS  | $F_{\gamma,0.1}(\text{GeV})$ (erg s$^{-1}$ cm$^{-2}$) | $\Gamma$ | $L_{\gamma}/10^{40}$ (erg s$^{-1}$) $\times 10^{-4}$ | $L_{\gamma}/L_{\text{IR}}$ $\times 10^{-2}$ |
|------------|----------|-------------------------------------|-------------------------------------|-----|-----------------------------------------------|--------|-----------------------------|-------------------------------|
| Circinus   | 4.2      | 0.60                               | 0.45                                | 58  | $18.8 \pm 5.8$                                | 2.19   | 2.9 $\pm 0.5$                | 4.9 $\pm 0.9$                 |
| NGC 253    | 2.5      | 0.69                               | 0.59                                | 135 | $10.7 \pm 2.1$                                | 2.18   | 0.60 $\pm 0.07$             | 0.87 $\pm 0.10$               |
| M 82       | 3.4      | 2.0                                | 1.5                                 | 205 | $16.2 \pm 2.3$                                | 2.25   | 1.47 $\pm 0.14$             | 0.74 $\pm 0.07$               |
| NGC 4945   | 3.7      | 1.0                                | 1.5                                 | 42  | $7.2 \pm 2.4$                                 | 2.05   | 1.17 $\pm 0.23$             | 1.13 $\pm 0.22$               |
| NGC 1068   | 16.7     | 11                                 | 23                                  | 46  | $7.3 \pm 2.9$                                 | 2.29   | 15.0 $\pm 2.9$              | 1.41 $\pm 0.27$               |
| NGC 253    | 2.5      | 0.69                               | 0.59                                | 135 | $10.7 \pm 2.1$                                | 2.18   | 0.60 $\pm 0.07$             | 0.87 $\pm 0.10$               |
| M 82       | 3.4      | 2.0                                | 1.5                                 | 205 | $16.2 \pm 2.3$                                | 2.25   | 1.47 $\pm 0.14$             | 0.74 $\pm 0.07$               |
| NGC 4945   | 3.7      | 1.0                                | 1.5                                 | 42  | $7.2 \pm 2.4$                                 | 2.05   | 1.17 $\pm 0.23$             | 1.13 $\pm 0.22$               |
| NGC 1068   | 16.7     | 11                                 | 23                                  | 46  | $7.3 \pm 2.9$                                 | 2.29   | 15.0 $\pm 2.9$              | 1.41 $\pm 0.27$               |
γ-ray flux ($\chi^2$/dof $= 5.2/7$). We also checked the cumulative significance of the γ-ray excess at the source position during the 4 yr observation; the TS showed a gradual increase, as expected for a steady source. Both the source light curve and the cumulative TS are presented in Figure 5.

3. DISCUSSION

In Figure 6, we plot the γ-ray luminosity of Circinus, $L_\gamma$, normalized by the total IR (8–1000 μm) luminosity, $L_{\text{IR}}$, as a function of $L_{\text{IR}}$. For comparison, the plot includes γ-ray upper limits (95% confidence level) derived for a large sample of starbursts selected from the HCN survey, together with eight γ-ray-detected star-forming galaxies (the four Local Group galaxies and four starbursts). These all follow Ackermann et al. (2012b), with the exception of the four starbursts where the results are from our updated 4 yr LAT analysis (Table 1). In addition, we also show the γ-ray upper limits for the sample of hard X-ray selected Seyferts (Ackermann et al. 2012a). The IR luminosities are derived from the fluxes measured by the Infrared Astronomical Satellite (IRAS) in four bands, following Sanders & Mirabel (1996).

As shown in Figure 6 and discussed quantitatively in Ackermann et al. (2012b), the γ-ray emission related to CRs in the ISM scales with the total IR luminosity, which serves as a proxy for the injected CR power within the supernova remnant paradigm for galactic CR origin. Circinus is more than five times overluminous in the γ-ray band when compared with this scaling relation (see also Table 1). In fact, the $L_\gamma/L_{\text{IR}}$ luminosity ratio for Circinus exceeds the so-called ‘calorimetric limit’ expected to hold when CRs interact faster than they can escape the galactic disk, and as much as $\eta \simeq 10\%$ energy per supernova explosion goes into CR acceleration, $\eta E_{\text{SN}} \simeq 10^{50}$ erg (see, e.g., Lacki et al. 2011; Ackermann et al. 2012b). Circinus also does not follow the correlation found for star-forming galaxies between $L_\gamma$ and total monochromatic 1.4 GHz radio luminosity $\nu L_\nu$, by a factor of six (see Table 1 and the right panel of Figure 6). Following the approach of Ackermann et al. (2012b), and assuming that star-forming galaxies do follow a simple PL scaling between γ-ray and total-IR luminosity, we find that adjusting either the normalization of this relation or the intrinsic scatter to accommodate Circinus would tend to overpredict the total number of galaxies that have been actually detected by LAT.

Let us consider the possibility that the total IR and radio luminosities listed in Table 1 underestimate the star formation rate (SFR). Whereas standard scaling relations using IRAS fluxes yield $\text{SFR} \simeq 2 M_\odot \text{yr}^{-1}$, the most recent mid-IR studies of Circinus with Spitzer presented by For et al. (2012) suggest $\text{SFR} \simeq (3–8) M_\odot \text{yr}^{-1}$ (depending on the particular calibration method). The differences between SFRs derived from...
mid-IR and total-IR (IRAS) measurements might be explained if Circinus is a relatively dust-poor system for which the far-IR luminosity is not a reliable indicator of the SFR. The SFR converted from the observed total 1.4 GHz fluxes (Yun et al. 2001) is only \( \gtrsim 1.5 M_\odot \) yr\(^{-1}\), but the radio luminosity could also underestimate the actual CR injection power if the interstellar magnetic field strength were below average. On the other hand, the total flux density ratio \( \log \left( \frac{F_{\nu,\text{radio}}}{F_{\nu,\text{1.4 GHz}}} \right) \) = 2.40 demonstrates that Circinus obeys the “far-IR/radio” correlation established for local star-forming and starburst systems (e.g., Seymour et al. 2009). The luminosities of NGC 1068 and NGC 4945, which are similar starburst/Seyfert composite galaxies, are consistent with the \( \gamma \)-ray-to-total-IR and \( \gamma \)-ray-to-radio correlations (Ackermann et al. 2012b; see also Figure 6). These complexities in the Circinus system make a firm conclusion regarding the attribution of \( \gamma \)-rays to CR interactions difficult.

Other than CR interactions, the disk coronae or accretion disks of Seyfert galaxies can be considered as possible \( \gamma \)-ray emission sites (e.g., Niedźwiecki et al. 2013). However, LAT studies of a large sample of hard X-ray-selected Seyferts devoid of prominent jets revealed that such sources are \( \gamma \)-ray quiet as a class, down to the level of 1\%–10\% of the hard X-ray fluxes (Ackermann et al. 2012a).

One of the striking characteristics of the Circinus system is the presence of well-defined radio lobes and kpc-scale jet-like features, the “plumes” (Elmouttie et al. 1998), which are also resolved at X-ray frequencies with Chandra (Mingo et al. 2012). Both of these might be relevant \( \gamma \)-ray emission sites. To investigate this idea quantitatively, we apply standard leptonic synchrotron and inverse-Compton (IC) modeling to the radio spectra of the lobes, investigating whether the extrapolation of the high-energy emission continuum may account for the GeV flux from the system. In the IC calculations we consider seed photons provided by the cosmic background radiation, the observed IR–to–optical emission of the galactic disk, and the UV–to–hard X-ray photon field due to the active nucleus, corrected for obscuration (assuming the intrinsic UV emission of the accretion disk \( \lesssim 3 \times 10^{33} \text{ erg s}^{-1} \); Prieto et al. 2010).

Figure 7 presents the broadband, multi-component SED of Circinus, including new LAT measurements. Integrated far-IR–to–optical measurements represent the dominant starlight and the dust emission of the galaxy, with a negligible contribution from a heavily obscured AGN. In the X-ray regime, the hard X-ray fluxes are dominated by the heavily absorbed emission of the accretion disk and disk coronae. As demonstrated in Elmouttie et al. (1998), the total radio fluxes of the source in the 0.4–8.6 GHz range are due to a superposition of various emission components characterized by different spectral properties. Using their published Australia Telescope Compact Array (ATCA) 1.4, 2.4, 4.8, and 8.6 GHz maps, we measured fluxes for each distinct component separately, namely, for the nucleus (circle with radius \( r = 1'' \approx 20 \text{ pc} \)), galaxy core including the central starburst region (\( r = 35'' \) circle), the outer parts of the galaxy disk, NW lobe (\( r = 44'' \) circle), NW plume (50'' \( \times \) 25'' box centered 68''15' from the nucleus), SE lobe (ellipsoid with radii of 70'' and 55''), and SE plume (62''5 \( \times \) 25'' box centered 89''30' from the nucleus). The total radio emission of the Circinus system at GHz frequencies is dominated by the central starburst region, and at lower frequencies by the outer parts of the galaxy disk; lobes and plumes contribute to the observed emission at the level of 10%; radio emission of the unresolved nucleus is negligible.

We fit the radio spectra of the lobes and plumes, assuming energy equipartition between the radiating electrons and the magnetic field (energy density ratio \( u_e/u_B \approx 1 \)), and a standard form of the electron energy distribution consisting of a PL \( dN_e/d\gamma \sim \gamma^{-2} \) between electron energies \( \gamma_{\text{min}} \approx 1 \) and \( \gamma_{\text{br}} \), breaking to \( dN_e/d\gamma \sim \gamma^{-3} \) between \( \gamma_{\text{br}} \) and \( \gamma_{\text{max}} \approx 10^6 \). We adjust both the electron normalization and break Lorentz factors \( \gamma_{\text{br}} \) to obtain satisfactory fits to the radio data for each region separately, and then evaluate the expected IC emission. The results of the modeling are given as blue curves in Figure 7, where we show in addition the modeled emission of the accretion disk and the disk coronae using the MyTÖRUS model (red curves; Murphy & Yaqoob 2009). For comparison, the figure presents also the interstellar radiation field/GALPROP models (Porter et al. 2008; Strong et al. 2010) placed at the distance of Circinus. Red curves denote the modeled emission of the accretion disk and the disk coronae using the MyTÖRUS model. Blue curves represent the modeled synchrotron and IC emission of the lobes and plumes. The thick gray dotted line represents the \( \gamma \)-ray spectrum of a star-forming system (assumed \( \Gamma = 2.2 \)) corresponding to the IR luminosity of Circinus and IR–\( \gamma \) correlation found in Ackermann et al. (2012b).

(A color version of this figure is available in the online journal.)
The departures from the minimum energy condition \( u_e/u_B \gg 1 \), which may enhance the expected IC radiation for a given synchrotron (radio) flux, are often claimed for lobes in radio galaxies and quasars (see Takeuchi et al. 2012, and references therein). In the particular case of Circinus, however, the effect would have to be extreme in order to account for the flux detected with the LAT, \( u_e/u_B \sim 10^4 \). Although we cannot exclude this possibility, we consider it rather unlikely. Deep, high-resolution X-ray observations could in principle be used in the near future to validate the \( u_e/u_B \gg 1 \) hypothesis for the Circinus lobes, but at this moment the very limited photon statistics of the available Chandra maps precludes any robust detection of a non-thermal lobe-related emission component at keV photon energies. We note, however, that the IC model curve calculated for \( u_e/u_B = 1 \) and shown in Figure 7 is below the corresponding upper limits.

Yet another possibility is the presence of an energetically significant population of CR protons associated with the radio lobes. Relativistic protons injected by the kpc-scale jets/plumes, or accelerated at the bow shocks of the expanding lobes (see Mingo et al. 2012), may generate a non-negligible \( \gamma \)-ray emission due to the decay of pions produced during CR interactions with surrounding matter. However, due to the sparseness of thermal gas within the galactic halo (gas number density \( \lesssim 10^{-4} \) cm\(^{-3} \)), implying a low efficiency for this process, the resulting GeV fluxes are likely below the \( \gamma \)-ray output of the galactic disk.

It is interesting to comment in this context on the similarities between the Circinus lobes and the Fermi-LAT discovered giant “Fermi Bubbles” in our Galaxy (Dobler et al. 2010; Su et al. 2010). Even though the origin of both structures is still under debate, the jet activity of their central supermassive black holes—which are of comparable masses, namely, \( M_{BH} \sim (1.7 \pm 0.3) \times 10^6 \) M\(_\odot\) for Circinus (Greenhill et al. 2003) and \( (4.5 \pm 0.4) \times 10^6 \) M\(_\odot\) for the Milky Way (e.g., Ghez et al. 2008)—is the widely considered scenario. In the case of Circinus, the jet scenario is evidenced directly by the presence of collimated outflows supplying the lobes with energetic magnetized plasma (see the discussion in Elmonti et al. 1998; Mingo et al. 2012), while in the case of our Galaxy, it is supported by general energetic arguments and numerical simulations reproducing well the observed properties of bubbles (e.g., Guo & Mathews 2012; Yang et al. 2012). In both systems, the lobes extend to kpc scales across the galactic disks and are characterized by magnetic field strengths of the order of \( \sim 10 \) \( \mu \)G (see Su et al. 2010; Mertsch & Sarkar 2011 for Fermi Bubbles). Thus, it seems that structures analogous to the Fermi Bubbles and Circinus lobes may not be uncommon in late-type galaxies undergoing episodic outbursts of AGN (jet) activity, but their contributions to the total \( \gamma \)-ray outputs of the systems do not exceed \( \sim 10\% \).

4. CONCLUSIONS

Here we report the detection of a steady and spatially unresolved \( \gamma \)-ray source at the position of Circinus, consistent with 2FGL J1415.7–6520 based on a refined analysis using 4 yr of LAT data. Although the observed PL spectrum (\( \Gamma = 2.19 \pm 0.12 \)) is similar to that of other LAT-detected starburst systems, Circinus is \( \gamma \)-ray overluminous by a factor of \( 5–6 \) relative to what is expected for emission from the ISM, based on multiwavelength correlations observed for nearby star-forming galaxies. However, the range of SFRs estimated from radio, mid-IR, and far-IR luminosities span a factor of \( \lesssim 4 \), indicating large uncertainties in the expected CR power delivered to the ISM. We presented several alternative possibilities for the origin of the GeV excess, including emission from the extended radio lobes, but found no conclusive answer to fully account for the GeV emission. This issue may be resolved by future studies, as Circinus is a compelling target for observations in the very high energy \( \gamma \)-ray regime with ground-based Cerenkov telescopes; the TeV-detected starburst systems NGC 253 and M82 (Acero et al. 2009; Acciari et al. 2009) are actually fainter in the GeV range.

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