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TeV GAMMA RAYS: OBSERVATIONS VERSUS EXPECTATIONS & THEORY

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Abstract. The scope of this paper is to discuss two important questions relevant for TeV γ-ray astronomy; the pursuit to reveal the origin of cosmic rays in our galaxy, and the opacity of the universe in γ-rays. The origin of cosmic rays stipulated the field of TeV astronomy in the first place, and led to the development of the atmospheric Cherenkov technique; significant progress has been made in the last decade through the detection of several supernova remnants, the primary suspects for harboring the acceleration sites of cosmic rays. TeV γ-rays propagate mostly unhindered through the galactic plane, making them excellent probes of processes in SNRs and other galactic sources. Key results related to the SNR origin of cosmic rays are discussed. TeV γ-ray spectra from extragalactic sources experience significant absorption when traversing cosmological distances. The opacity of the universe to γ-rays above 10 GeV progressively increases with energy and redshift; the reason lies in their pair production with ambient soft photons from the extragalactic background light (EBL). While this limits the γ-ray horizon, it offers the opportunity to gain information about cosmology, i.e. the EBL intensity, physical conditions in intergalactic space, and potentially new interaction processes. Results and implications pertaining to the EBL are given.

Keywords: supernova remnants, starburst galaxies, blazars, gamma rays, extragalactic background light, individual: G120.1+1.4, RXJ1713, 3946, M82, NGC253.

1. Introduction

The field of TeV astronomy has undergone a revolution over the last decade as attested by the dramatic increase in the number of TeV γ-ray sources.

From a handful of sources in the late 1990s, TeV γ-ray astronomy has become a new discipline in high energy astrophysics with more than 150 objects across a wide range of source classes (see Fig. 1). Collectively these TeV emitters provide important constraints to the origin and propagation of cosmic particles ($e^{\pm}$, $p^{\pm}$, ions, …). This conference paper is not intended to cover the entire field of TeV γ-ray astronomy; for an overview, see [16, 20, 31]. Instead, two important current topics in TeV astronomy are discussed:

Origin of galactic cosmic rays Studies of particle acceleration in individual supernova remnants (SNRs) may hold the key to understanding the origin of cosmic rays. If SNRs are indeed the dominant acceleration sites of cosmic rays in our galaxy, and given certain reasonable assumptions, earlier predictions [10] suggested that SNRs up to distances of several kpc should be detectable in TeV γ-rays. With the operation of the current generation of atmospheric Cherenkov telescopes (ACTs), i.e., MAGIC, HESS and VERITAS, TeV astronomy has become a powerful and promising tool for pinning down the locations of cosmic-ray accelerators in our galaxy. SNRs in environments that contain sufficient amounts of target material for a cosmic beam dump, such as the compressed gas in shell-type SNRs or a nearby molecular cloud, are likely to reveal the presence of cosmic rays (protons, ions) through γ-rays from neutral pion decays ($p + p \to \pi^0 + \cdots \to \gamma + \gamma$).

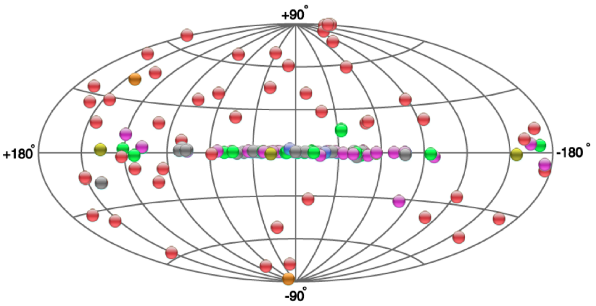

Figure 1. The TeV γ-ray sky as of May 2012 is shown (http://tevcat.uchicago.edu/), including AGNs (red), two SB galaxies (orange), pulsar wind nebulae (magenta), shell-type supernova remnants and a molecular cloud (green), γ-ray binaries (yellow), a globular cluster (blue), and unidentified γ-ray sources (grey).

However, an abundance of relativistic electrons, as indicated by non-thermal X-ray synchrotron radiation, provides an unwelcome background for the search for γ-ray emission of hadronic origin. Relativistic electrons boost soft photons to TeV energies (IC) and are able to produce γ-rays through electron bremsstrahlung. The excellent angular resolution of ACTs (0.1°) combined with broad spectral coverage (100 GeV ÷ 100 TeV) and sufficient energy resolution (10 ÷ 20 %) provides the best technique available for imaging and spectroscopic analysis of the γ-ray emission. Spatially resolved spectroscopy of the often complex regions surrounding supernova remnants are pivotal if hadronic emission from a cosmic-ray acceleration site is to be separated from contributors, such as pulsars and plerions. Equally important is the combination of data from GeV γ-ray telescopes, Fermi-LAT, AGILE with data from TeV telescopes; together they cover 5 ÷ 6 orders of magnitude in energy, allowing one to potentially distinguish spectra from hadronic and leptonic origin based on spectral curvature.

Opacity of the universe in gamma rays Since the 1960s, it has been known that the propagation of γ-rays on cosmological distance scales is affected through their interaction with the extragalactic background light (EBL) via the process of pair production [18]. With more than 3 dozen extragalactic sources detected at TeV energies up to a redshift of ∼ 0.5, this paradigm can now be tested and used to strongly constrain the intensity of the EBL. Direct EBL detection in the near-IR to mid-IR is hampered by overwhelming local foregrounds from zodiacal light in the solar system and galactic starlight.

While still speculative, suggestions were made that the propagation length of γ-rays could be substantially increased through photon mixing with axion-like particles [26]. Those require new physical processes not yet established experimentally or observationally. Another possibility is given by blazar jets co-accelerating cosmic-ray hadrons along with electrons in appreciable amounts; protons subsequently interact with diffuse photons from intergalactic radiation fields resulting in secondary photons. Due to the smaller cross-section of the hadron-photon interactions compared to $\gamma\gamma \rightarrow e^+e^-$, this process would increase the γ-ray horizon of blazars to substantially larger distance scales compared to primary TeV photons [13]. Such a scenario is attractive in the context of attributing cosmic-ray acceleration beyond the "knee" in the cosmic-ray spectrum to relativistic jets. Both such processes could in principle alter/invalidate current EBL constraints from γ-ray observations. However, neither scenario – photon mixing with an axion-like particle nor the presence of intergalactic hadron induced – cascades has been firmly established.

2. Cosmic ray origin

2.1. Individual supernova remnants

TeV sources that coincide with a supernova shell and/or a molecular cloud include RXJ1713-3946, a prominent medium age (1,000–several thousand years) supernova remnant, possibly associated with SN393 AD and the object G120.1+1.4, the remnant from SN1572 (also known as Tycho's supernova). The latter was identified as a Type Ia SN; in the absence of any pulsar or neutron star, this identification favors a relatively pristine environment for Tycho. Both SNRs exhibit a supernova shell in X-rays, and both appear to be interacting with a molecular cloud. Thus they are prime candidates for probing cosmic-ray acceleration and the fixed-target model for cosmic-rays producing γ-rays.

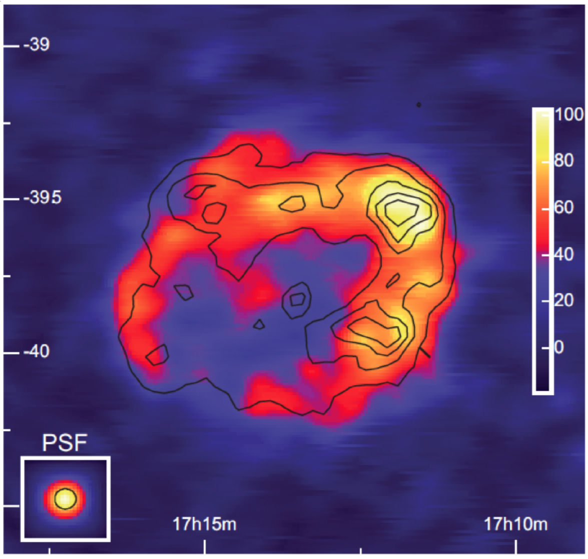

Figure 2. The skymap of the region around supernova remnant RXJ-1713-3946 is shown [7]. The contour lines indicate X-ray emission at 1 ÷ 3 keV [28].

The skymap of RXJ1713-3946 in TeV γ-rays (Fig. 2) shows a characteristic bright shell (∼ 1° across) with a similar morphology to the X-ray contour lines (black). The X-ray emission is dominated by a non-thermal continuum suggesting synchrotron radiation of 100 TeV electrons as its origin [28]. These electrons make a guaranteed contribution to the TeV γ flux through inverse Compton scattering of soft photons from the Cosmic Microwave Background (CMB).

While not shown in Fig. 2, a molecular cloud located in the northwestern part of the SNR shell [14] is suggestive of the possibility that a substantial part of the TeV emission might originate from neutral pion decays. Spectroscopy could yield unequivocal evidence for a hadronic component: the γ-ray spectrum from pion decays with a cutoff at 70 MeV, along with a hard spectrum up to the maximum energy (which depends on age) of the accelerator.

Detailed models generally find that the curvature of a γ-ray spectrum of hadronic origin is quite distinct from an inverse Compton spectrum. The γ-ray spectrum of RXJ1713-3946 is shown in Fig. 3. Several models based on inverse Compton scattering of electrons are shown, indicating that the data are es-

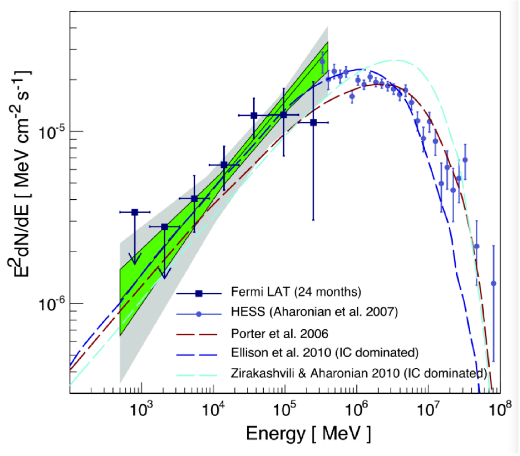

Figure 3. The combined energy spectra of RXJ-1713-3946 from Fermi-LAT and HESS [1, 7] along with inverse Compton emission models are shown. As can be seen, the spectrum of RXJ-1713-3946 can be fitted by a leptonic scenario.

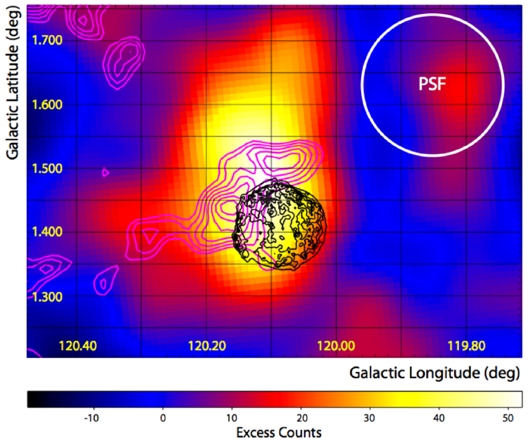

Figure 4. The skymap [3] of the region around Tycho is shown. The black cross marks the centroid of the TeV emission. The black contour lines show the X-ray emission from a Chandra ACIS exposure (thin black lines). Radio contour lines are shown in magenta and are based on ^{12}CO emission from the FCRAO Survey.

sentially in agreement with the observed spectrum. While some hadronic contribution to the γ-ray spectrum is possible, inverse Compton radiation seems be sufficient to explain the data.

Long considered that Tycho's SNR is a prime candidate for hadron acceleration [30]. While distance estimates of Tycho's SNR range from $2.5 \div 5$ kpc, its age 440 years and its type (Type Ia) are well established. A TeV γ-ray image of Tycho [3] is shown in Fig. 4; the color scale indicates the number of excess γ-ray events per bin, the black lines represent the X-ray contours (Chandra ACIS) [21] and the magenta contour lines correspond to ^{12}CO emission from a high resolution radio survey [19].

The TeV emission appears to be spatially coincident with the molecular cloud, rather than the centroid of the X-ray shell. This is what one would expect if the γ-rays were hadronic in origin. However, note that the shell-type structure of Tycho is just 0.15° in diameter, comparable to the point spread function of current generation TeV telescopes. Further observations are required to unambiguously correlate the TeV emission with the molecular cloud. The flux above 1 TeV is just 1 % of the Crab Nebula flux (standard candle in TeV γ-rays), therefore much improved measurements with current and/or next generation ACTs are expected and promise to resolve the source of TeV emission.

The multi-wavelength spectrum of Tycho including radio, X-ray, Fermi-LAT and VERITAS data is shown in Fig. 5 along with several emission models. The synchrotron spectrum in the radio – X-ray provides an important constraint on the inverse Compton flux in γ-rays. For a given synchrotron flux, a strong magnetic field requires a low electron number density n_e and thus a low inverse Compton emission component in GeV $\div$ TeV γ-rays.

A magnetic field of $\sim 200\,\mu$G in regions of the shell was derived by Cassam-Chenai et al. [9], suggesting that the rapid cooling of electrons in the narrow X-ray filaments of Tycho is due to a strong magnetic field. Although much larger than what is typically found in the galaxy ($\sim \mu$G), it is plausible since magnetic field amplification in shocks has been long considered inevitable for cosmic-ray acceleration. Similarly, an analysis by Acciari et al. [3] suggests significant magnetic field amplification; again the large synchrotron luminosity compared to the γ-ray luminosity requires significant magnetic field amplification; a lower bound of $\sim 78\,\mu$G arises, even if γ-rays were mostly due to inverse Compton emission. In any case, the large magnetic field leads Giordano et al. [17] to conclude a low contribution to the γ-ray spectrum assuming a one-zone model.

Fitting bremstrahlung to the data results in a significant problem, as its magnitude depends on the electron number density n_e and the ambient gas density; increasing n_e overproduces inverse Compton emission, while increasing the gas density leads to un-typically high gas densities. Thus the authors suggest that the GeV $\div$ TeV γ-ray spectrum is most likely due to pion decay.

However, a recent model brought forward by Atoyan & Dermer [8] deems single-zone models for Tycho unrealistic. They propose a two-zone model that can well accommodate the measured spectrum with a combination of an inverse Compton and a bremsstrahlung component. Further observations are necessary to address these objections and to pinpoint the exact location of the GeV $\div$ TeV emission, and spectral measurements to improve upon statistical uncertainties of the energy spectrum between 400 MeV and 10 TeV. The γ-ray emission from Tycho's SNR appears to have all the signs of a hadronic accelerator; a smoking gun

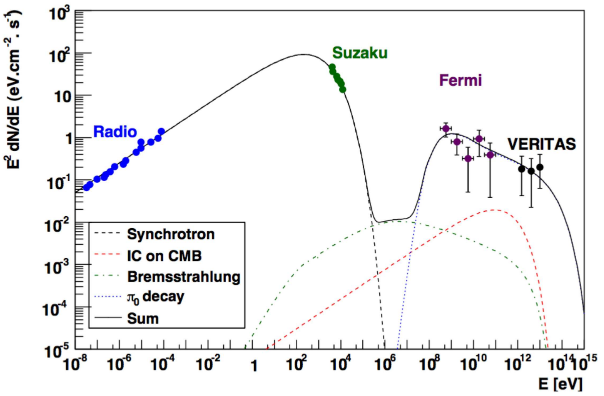

Figure 5. The broadband energy spectrum of Tycho is shown including radio data, X-ray data (Suzaku) and γ-data from the Fermi-LAT and from VERITAS, for details and references see [17].

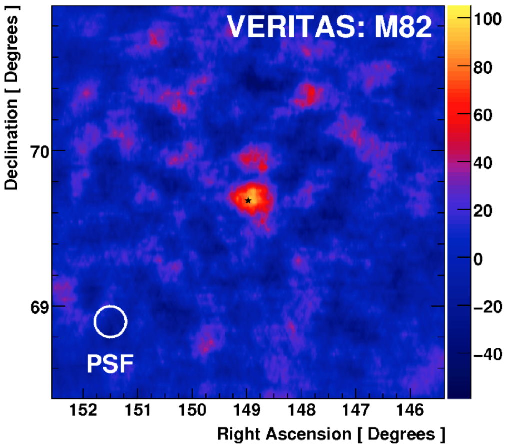

Figure 6. The γ-ray image of the M82 region is shown at energies above 700 GeV. The sky map shows the measured excess (colour-scale) of γ-ray-like events above the estimated background.

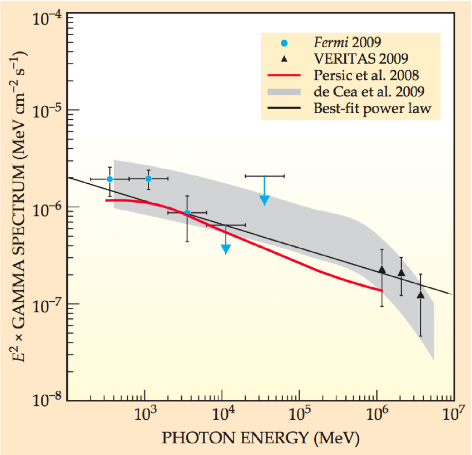

Figure 7. The γ-ray spectrum [27] of the starburst galaxy M82 region is shown as measured by the Fermi-LAT and VERITAS observatory and are compared to theoretical predictions.

signature would be the detection of a characteristic cutoff at 70 MeV, which might be possible with the Fermi-LAT and/or with the AGILE satellite.

2.2. Starburst galaxies

Particle acceleration up to 100 TeV has been demonstrated in galactic SNRs. However, observations have so far failed to provide unambiguous proof for hadronic cosmic-ray acceleration in any single γ-ray source. Despite the tremendous observational progress made over the last decade, the question as to whether or not SNRs produce the bulk of cosmic rays in our galaxy remains open. In fact, a path towards solving this question requires a census of the large galactic population of SNRs, to establish their dominance in accelerating cosmic rays. This will only become possible with a next generation observatory such as CTA [5].

Starburst (SB) galaxies offer a complementary “laboratory” for probing the role of SNRs as cosmic-ray accelerators; γ-ray emission from an SB galaxy provides a calorimetric measure of the cosmic-ray density in the star-forming region and can be used to establish the connection between star formation (e.g., SNRs) and cosmic-ray origin. A high star formation rate in SB galaxies results in a large population of massive young stars and consequently high SN rate (30 times higher than in the Milky Way). Combined with a relatively high gas density, the swath of young SNRs provides a promising opportunity to detect γ-rays from pion decays. Despite its large distance (3.6 Mpc), M82, with a 10 times higher star formation rate and higher gas density compared to the Milky Way, was deemed detectable [29] in γ-rays with current generation of ACTs.

The starburst region in M82 extends several 100 pc across, therefore the actual region from which γ-ray emission is expected is below the angular resolution of ACTs. Figure 6 shows a γ-ray point source from the direction of M82,discovered by VERITAS [2]. A weak flux of 0.9 % of the Crab at 700 GeV is close to the predicted flux. Similarly, the SB galaxy NGC253 detected by HESS [4] shows a small flux close to the expected level of emission.

The GeV ÷ TeV spectrum of M82 is shown in Fig. 7. The Fermi spectrum between 0.1 ÷ 3 GeV is described by a power law with $\mathrm{d}N/\mathrm{d}E \propto E^{-2.2\pm0.2}$ and the VERITAS spectrum fits a power law $\propto E^{-2.5\pm0.6}$. Similarly, the Fermi and HESS spectra of NGC253 ($\propto E^{-1.94\pm0.4}$ and $\propto E^{-2.14\pm0.18}$) are consistent with the spectral index of 2 that arises in the model of diffusive shock acceleration. A caveat is that the currently available γ-ray spectra at GeV and TeV energies are not sufficient to claim single component spectra.

Assuming that the energy spectra of M82 and NGC253 are indeed power laws from sub-GeV to multi-TeV energies, these data provide strong evidence for a connection between star formation and cosmic-ray production. This is consistent with shock acceleration of hadrons in SNRs. Following Lacki et al. [22], the spectra of M82 and NGC253 indicate that energy losses of cosmic rays from pion production and advective losses from a galactic wind dominate over any diffusive losses, which would steepen the measured spectrum. In summary, the discovery of TeV γ-ray emission from SB galaxies at the flux level that is expected from cosmic-ray interactions with gas in the star forming region, and a measured spectral slope that is consistent with shock acceleration in SNRs, provides strong evidence for SNR origin of cosmic rays.

3. THE OPACITY OF THE UNIVERSE IN GAMMA-RAYS

The universe is more transparent to γ-rays than expected; this notion arises from the fact that several blazars have been detected at a redshift of ≥ 0.3, with 3C279 being the most distant[1] object with redshift $z = 0.536$. While the universe is transparent to γ-rays below 10 GeV, the opacity increases with energy and redshift, making it opaque to TeV photons en route to Earth when traveling from redshifts ≥ 0.5.

Thus, Fermi-LAT spectra combined with spectra from ACTs should contain pertinent information on γ-ray absorption. Figure 8 shows the difference between the GeV spectra and the TeV spectra $\Delta\Gamma = \Gamma_{\text{GeV}} - \Gamma_{\text{TeV}}$ for 3 dozen extragalactic sources versus redshift (source list, see review by Dwek & Krennrich 2012 [12]). If EBL absorption were to affect the spectra, a gradual softening of the energy spectra with redshift is expected, while the exact functional form depends on the EBL spectrum itself. This is due to a higher proper number density of EBL photons and a shift of the EBL spectrum towards shorter wavelengths as is the case with any cosmological radiation field at larger redshifts.

Figure 8 shows a decrease of $\Delta\Gamma$ with redshift, which is could be due to EBL absorption. There is also significant scatter in $\Delta\Gamma$, which is a result of spectral changes between GeV and TeV energies related to the γ-ray source itself. The key problem in deriving EBL constraints from γ-ray absorption is our trusted knowledge of the intrinsic source spectra. In particular HBLs (empty circles) exhibit a wide spread in $\Delta\Gamma$; while hard spectra HBLs extend to several TeV (Mrk 501, Mrk 421, H 1426+428, 1ES 0229+200, etc.), others exhibit strong intrinsic curvature between GeV and TeV energies to the point where they are undetectable at TeV energies. Multi-wavelength modeling of the different sub-classes of blazars (FSRQs, LBLs, IBLs, HBLs) will be required to correct for source-intrinsic softening.

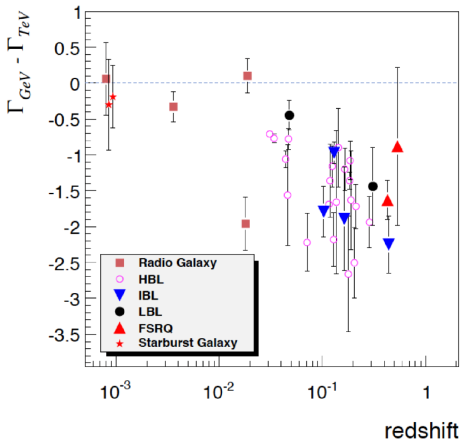

FIGURE 8. The difference between the spectral index measured by Fermi-LAT and ACTs ($\Delta\Gamma$) is plotted versus redshift for extragalactic sources [12].

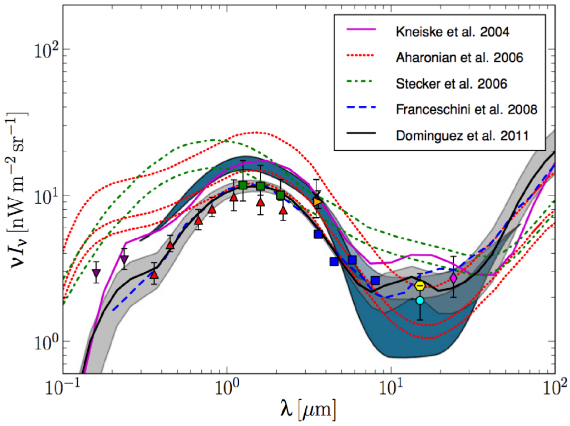

FIGURE 9. The blue shaded confidence region (2σ) of EBL constraints from [25] are shown and compared with galaxy count lower limits (filled symbols). Also shown are EBL models (lines). While these constraints are in good agreement with other works such as [6] in the near-IR, they are quite low in the mid-IR, but compatible with lower limits from galaxy counts.

Other approaches to provide limits and constraints on the EBL intensity in the near- to mid-IR are based on assumptions made on the intrinsic blazar spectra, guided by theoretical principles, i.e., the "no exponential-rise" principle [11] and the "no harder than $\Gamma \geq 1.5$" principle [6, 24], the latter based on the theory of diffusive shock acceleration.

A more recently developed method uses the fact the EBL spectrum exhibits a trough in the mid-IR between the stellar peak ($\sim 1\,\mu$m) and the dust emission peak ($\sim 100\,\mu$m). The depth of this feature of the EBL can also be expressed as a near/mid-IR ratio and determine the γ-ray absorption imprinted onto the γ-ray spectra, with the possibility of a spectral hardening or softening around 1 TeV, while the non-observations provide an unambiguous constraint on

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[1] A recent paper by Landt [23], claimed a redshift of ≥ 1.2 for TeV γ-ray detected BL Lac PKS 0447-439, but was shown to be invalid [15] as the absorption line found is a known telluric line.

the near/mid-IR ratio. The result from this analysis combined with Fermi ACT spectra has resulted in the limits and EBL constraints shown in Fig. 9.

In summary, EBL limits derived from γ-ray observations suggest a low intensity in the near to mid-IR and are compatible with lower limits from galaxy counts. These γ-ray limits are based on known physical processes. i.e., primary γ-rays traveling from the source to the observer and primarily affected by pair production as suggested by Gould & Schréder [18]. They are valid unless, indeed new physical processes, e.g., the development of intergalactic cascades or new physics such as photon mixing with axion-like particles – are demonstrated to occur.

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