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GAMMA–GAMMA ABSORPTION IN THE BROAD LINE REGION RADIATION FIELDS OF GAMMA-RAY BLAZARS

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ABSTRACT

The expected level of $\gamma\gamma$ absorption in the Broad Line Region (BLR) radiation field of γ-ray loud Flat Spectrum Radio Quasars (FSRQs) is evaluated as a function of the location of the γ-ray emission region. This is done self-consistently with parameters inferred from the shape of the spectral energy distribution (SED) in a single-zone leptonic EC-BLR model scenario. We take into account all geometrical effects both in the calculation of the $\gamma\gamma$ opacity and the normalization of the BLR radiation energy density. As specific examples, we study the FSRQs 3C279 and PKS 1510-089, keeping the BLR radiation energy density at the location of the emission region fixed at the values inferred from the SED. We confirm previous findings that the optical depth due to $\gamma\gamma$ absorption in the BLR radiation field exceeds unity for both 3C279 and PKS 1510-089 for locations of the γ-ray emission region inside the inner boundary of the BLR. It decreases monotonically, with distance from the central engine and drops below unity for locations within the BLR. For locations outside the BLR, the BLR radiation energy density required for the production of GeV γ-rays rapidly increases beyond observational constraints, thus making the EC-BLR mechanism implausible. Therefore, in order to avoid significant $\gamma\gamma$ absorption by the BLR radiation field, the γ-ray emission region must therefore be located near the outer boundary of the BLR.

Key words: galaxies: active – galaxies: jets – gamma rays: galaxies – radiation mechanisms: non-thermal – relativistic processes

1. INTRODUCTION

Blazars are a class of radio-loud, jet-dominated active galactic nuclei whose jets are oriented at a small angle with respect to our line of sight. Their broadband emission is characterized by two broad non-thermal radiation components, from radio to UV/X-rays, and from X-rays to γ-rays, respectively. The low energy emission is generally understood to be due to synchrotron radiation by relativistic electrons in a localized emission region in the jet. In leptonic models for the high-energy emission of blazars (see, e.g., Böttcher et al. 2013 for a discussion of the alternative, hadronic models), the γ-ray emission is due to Compton upscattering of soft target photon fields by the same ultrarelativistic electrons in the jet. In the case of low-frequency-peaked blazars (with synchrotron peak frequencies typically below $\sim 10^{14}$ Hz), such as Flat Spectrum Radio Quasars (FSRQ), which show strong optical—UV emission lines from a Broad Line Region (BLR), it is often argued that the target photons for γ-ray production are the external (to the jet) photons from the BLR (e.g., Madejski et al. 1999). This would naturally suggest that the γ-ray emission region is located inside the BLR, in order to experience a sufficiently high radiation energy density of this target photon field.

This picture, however, seems to be challenged by the detection of several FSRQs (including 3C279, PKS 1510-089: Albert et al. 2008; Abramowski et al. 2013) as sources of very-high-energy (VHE, $E > 100$ GeV) γ-rays: VHE γ-rays produced in the intense BLR radiation fields of these FSRQs are expected to be subject to $\gamma\gamma$ absorption (e.g., Donea & Protheroe 2003; Reimer 2007; Liu et al. 2008; Sitarek & Bednarek 2008; Böttcher et al. 2009). This has repeatedly been considered as evidence that the γ-ray emission region must be located near the outer edge of the BLR (e.g., Tavecchio et al. 2011), in order to avoid excess $\gamma\gamma$ absorption by the BLR radiation field, or that exotic processes, such as photon to Axion-Like Particle conversion, may act to suppress the impact of $\gamma\gamma$ absorption (e.g., Tavecchio et al. 2012).

The above referenced works on the $\gamma\gamma$ opacity due to the BLR radiation field, however, used generic parameters for the respective FSRQs, independent of parameters and emission scenarios actually required for the production of the observed γ-ray emission in those blazars. In this paper, we consider two VHE γ-ray detected FSRQs, namely 3C279 and PKS 1510-089. We start out with constraints on the BLR luminosity and energy density from direct observations, under the assumption that the MeV–GeV γ-ray emission is the result of Compton upscattering of the BLR radiation field (EC-BLR) by the same ultrarelativistic electrons responsible for the IR—optical—UV synchrotron emission. Within the observational constraints, we then self-consistently investigate the dependence of the $\gamma\gamma$ opacity due to the BLR radiation field on the location of the γ-ray emission region. This is done by re-normalizing the local emissivity in the BLR (within the observational constraints) for any given location of the γ-ray emission region to result in the required energy density experienced by the emission region, which is kept fixed in the process.

In Section 2, we describe the general model setup and methodology of our calculations. Section 3 presents the results, specifically for 3C279 (Section 3.1) and PKS 1510-089 (Section 3.2). Section 4 contains a brief summary and a discussion of our results.

2. MODEL SETUP

Our considerations are based on the frequently used model assumption that the γ-ray emission from FSRQ-type blazars is the result of the EC-BLR mechanism (e.g., Ghisellini et al. 2010; Böttcher et al. 2013). We represent the BLR as a spherical, homogeneous shell locally emitting with an

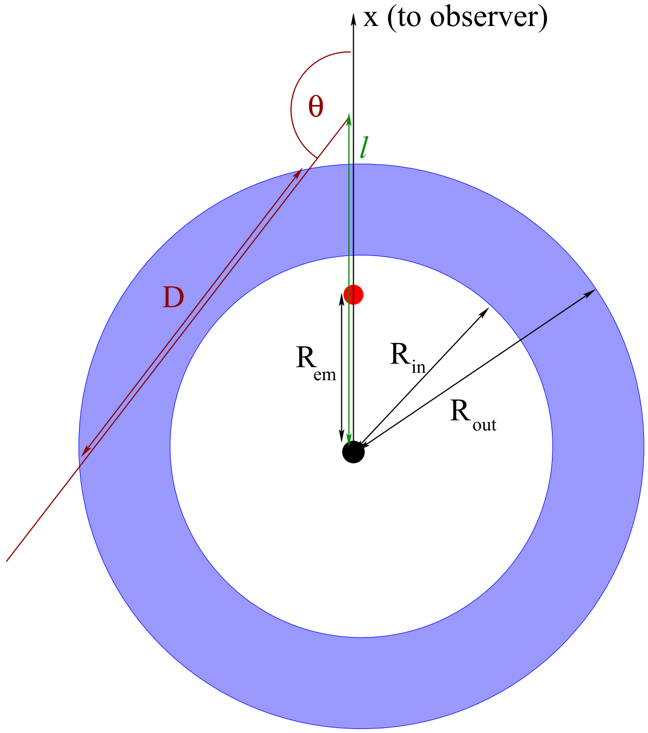

Figure 1. Illustration of the model geometry used for the BLR $\gamma\gamma$ opacity calculation.

emissivity j_ϵ^0 within an inner ($R_{\rm in}$) and outer ($R_{\rm out}$) boundary of the BLR. The geometry of our calculations is illustrated in Figure 1.

Under the single-zone leptonic model assumptions with the EC-BLR mechanism producing the MeV–GeV γ-ray emission, the energy density of the BLR can be uniquely determined solely based on the peak frequencies and νF_ν peak fluxes of the synchrotron and EC γ-ray components of the spectral energy distribution (SED). For this purpose, we make the simplifying assumption that the Doppler factor $\delta = (\Gamma[1 - \beta_\Gamma \cos\theta_{\rm obs}])^{-1}$ is equal to the bulk Lorentz factor Γ (corresponding to a normalized velocity $\beta_\Gamma = \sqrt{1 - 1/\Gamma^2}$) of the flow, which is true to within a factor of $\lesssim 2$ for blazars, in which we are viewing the jet at a small observing angle $\theta_{\rm obs} \lesssim 1/\Gamma$. We furthermore assume that the γ-ray peak in the SED is dominated by Compton upscattering of Lyα photons from the BLR in the Thomson regime. This latter assumption is valid for FSRQ-type blazars in which the γ-ray peak typically occurs at $E < 1$ GeV (and which we are considering in this paper), but may not hold for blazars of the intermediate- or high-frequency peaked classes. In the following, photon energies are expressed as dimensionless values $\epsilon = h\nu/(m_e c^2)$.

The synchrotron peak frequency in the blazar SED is then given by $\nu_{\rm sy} \approx \nu_0\, B_{\rm G}\, \gamma_p^2\, \Gamma/(1 + z)$, where $\nu_0 \approx 4 \times 10^6$ Hz, $B_{\rm G}$ is the magnetic field in the emission region in units of Gauss, and γ_p is the Lorentz factor of electrons radiating at the peak of the SED (i.e., the peak of the electron energy spectrum in a $\gamma^2\, n(\gamma)$ representation). The EC-BLR peak frequency is located at $\epsilon_{\rm EC} \approx \epsilon_{\rm Ly\alpha}\, \gamma_p^2\, \Gamma^2/(1 + z)$, where $\epsilon_{\rm Ly\alpha} \approx 2 \times 10^{-5}$. These two observables can be used to constrain the magnetic field:

$$B_{\rm G} = \frac{\nu_{\rm sy}}{\nu_0}\, \frac{\epsilon_{\rm Ly\alpha}}{\epsilon_{\rm EC}} \Gamma. \tag{1}$$

Denoting $f_{\rm sy/EC}$ as the peak νF_ν flux values of the synchrotron and EC-BLR components, respectively, the ratio of EC-BLR to synchrotron peak νF_ν fluxes may then be used to constrain the BLR radiation energy density, since

$$\frac{f_{\rm EC}}{f_{\rm sy}} \approx \frac{8\pi\, u_{\rm BLR}\, \Gamma^2}{B^2} \tag{2}$$

which finally yields

$$u_{\rm BLR} \approx \frac{1}{8\pi}\, \frac{f_{\rm EC}}{f_{\rm sy}} \left(\frac{\nu_{\rm sy}}{\nu_0}\, \frac{\epsilon_{\rm Ly\alpha}}{\epsilon_{\rm EC}} \right)^2 \text{erg cm}^{-3}. \tag{3}$$

Notably, the dependence on the uncertain bulk Lorentz (and Doppler) factor cancels out in this derivation, so that Equation (3) provides a rather robust estimate of $u_{\rm BLR}$ in the framework of a single-zone leptonic EC-BLR interpretation of the blazar SED.

It has been shown (Tavecchio & Ghisellini 2008; Böttcher et al. 2013) that the γ-ray spectrum resulting from Compton upscattering of a thermal blackbody at a temperature of $T_{\rm BLR} = 2 \times 10^4$ K is an excellent approximation to the spectrum calculated with a detailed, line-dominated BLR spectrum. However, $\gamma\gamma$ absorption features are known to be much more sensitive to the exact shape of the target photon spectrum. Therefore, for our evaluation of the $\gamma\gamma$ opacity in the BLR radiation field, we use a detailed, line-dominated BLR spectrum including the 21 strongest optical and UV emission lines with wavelengths and relative fluxes as listed in Francis et al. (1991).

Based on the value of $u_{\rm BLR}$ estimated through Equation (3) and observational constraints on the BLR luminosity $L_{\rm BLR}$, we first estimate the approximate location of the BLR, $R_{\rm BLR}$ through

$$R_{\rm BLR} = \sqrt{\frac{L_{\rm BLR}}{4\pi\, u_{\rm BLR}\, c}}. \tag{4}$$

$L_{\rm BLR}$ is either directly measured or estimated to be a fraction ($f \sim 0.01 - 0.1$) of the accretion-disk luminosity. The boundaries of the BLR are then chosen as $R_1 = 0.9\ \ R_{\rm BLR}$ and $R_2 = 1.1\ \ R_{\rm BLR}$. We have done calculations with different widths of the BLR and verified that the choice of these boundary radii has a negligible influence on our final results.

For any given location of the emission region at a distance $R_{\rm em}$ from the central supermassive black hole of the AGN, the emissivity j_ϵ at any point within the BLR is then fixed through the normalization to the required energy density $u_{\rm BLR}$ as resulting from a proper angular integration, assuming azimuthal symmetry around the x axis:

$$\begin{aligned} u_{\rm BLR} &= \int_0^\infty d\epsilon \int_0^\infty dr\ 2\pi \int_{-1}^1 r^2\, d\mu\, \frac{j_\epsilon(\boldsymbol{r})}{4\pi\, r^2\, c} \\ &= \frac{1}{2c} \int_0^\infty d\epsilon\, j_\epsilon^0 \int_{-1}^1 d\mu\, D(\mu) \end{aligned} \tag{5}$$

where $j_\epsilon(\boldsymbol{r})$ is a Heaviside function equal to j_ϵ^0 for locations $\boldsymbol{r}$ inside the BLR (i.e., between $R_{\rm in}$ and $R_{\rm out}$), and 0 elsewhere, and $D(\mu)$ is the length of the light path through the BLR in any given direction $\mu = \cos\ \theta$ (see Figure 1). Once the normalization j_ϵ^0 of the BLR emissivity is known, the $\gamma\gamma$ opacity for γ-rays emitted at the location $R_{\rm em}$ along the x axis is calculated as

$$\tau_{\gamma\gamma}(\epsilon_\gamma) = \frac{1}{2c}\int_{R_{\rm em}}^{\infty} dl \int_{-1}^{1} d\mu \int_0^\infty d\epsilon \, \frac{j_\epsilon^0 \, D(\mu)}{\epsilon \, m_e c^2} \times (1-\mu_i)\,\sigma_{\gamma\gamma}(\epsilon_\gamma, \epsilon, \mu_i) \quad (6)$$

where $\mu_i = -\mu$ is the cosine of the interaction angle between the γ-ray and the BLR photon, and $\sigma_{\gamma\gamma}$ is the polarization-averaged $\gamma\gamma$ absorption cross section:

$$\sigma_{\gamma\gamma}(\epsilon_\gamma, \epsilon, \mu_i) = \frac{3}{16}\sigma_T\,(1-\beta_{\rm cm}^2)\left([3-\beta_{\rm cm}^4] \times \ln\left[\frac{1+\beta_{\rm cm}}{1-\beta_{\rm cm}}\right] - 2\beta_{\rm cm}[2-\beta_{\rm cm}^2]\right) \quad (7)$$

(Jauch & Rohrlich 1976) where $\beta_{\rm cm} = \sqrt{1 - 2/(\epsilon_\gamma \epsilon\,[1-\mu_i])}$.

It is obvious that the re-normalization of the local emissivith j_ϵ^0 depending on the location of the γ-ray emission region (according to Equation (5)), implies that the inferred BLR luminosity,

$$L_{\rm BLR}^{\rm requ} = \frac{4}{3}\pi(R_{\rm out}^3 - R_{\rm in}^3)\int_0^\infty j_\epsilon^0 \, d\epsilon \quad (8)$$

may deviate from the observationally determined value. In particular, $L_{\rm BLR}^{\rm requ}$ will increase rapidly for locations of the γ-ray emission region outside of $R_{\rm out}$ (in order to keep $u_{\rm BLR}$ constant). We consequently restrict our considerations to a range of $R_{\rm em}$ within which $L_{\rm BLR}^{\rm requ}$ is within plausible observational uncertainties of the reference value.

3. RESULTS

3.1. 3C279

The BLR luminosity of 3C279 was estimated by Pian et al. (2005) to be $L_{\rm BLR}^{\rm obs} = 2 \times 10^{44}$ erg s^{-1}. Representative SEDs of 3C279 (e.g., Abdo et al. 2010) show a synchrotron peak frequency of $\nu_{\rm sy} \sim 10^{13}$ Hz and a γ-ray (EC-BLR) peak energy of $\epsilon_{\rm EC} \sim 10^2$, while the γ-ray to synchrotron flux ratio is characteristically $f_{\rm EC}/f_{\rm sy} \sim 5$. This yields an estimate of the BLR radiation energy density of $u_{\rm BLR} = 1 \times 10^{-2}$ erg cm^{-3}, implying an average radius of the BLR (according to Equation (4)) of $R_{\rm BLR} = 2.3 \times 10^{17}$ cm.

Figure 2 illustrates the resulting $\gamma\gamma$ optical depth due to the BLR radiation field for various γ-ray photon energies (lower panel) and the required BLR luminosity (upper panel) as a function of the location of the γ-ray emission region. For most photons in the VHE γ-ray regime, the $\gamma\gamma$ opacity exceeds one for locations far inside the inner boundary of the BLR, and gradually drops to values slightly below one when approaching the BLR.

It is well known (e.g., Böttcher & Dermer 1998) that, for a fixed emissivity (and, hence, luminosity) of the BLR, the BLR photon energy density slowly increases when approaching the inner boundary of the BLR. Consequently, as we keep $u_{\rm BLR}$ fixed in our procedure, the inferred BLR luminosity has to decrease as we consider locations of the emission region closer to $R_{\rm in}$, which adds to the effect of a decreasing optical depth simply due to the decreasing path length of the γ-ray photons through the BLR radiation field. The opacity continues to

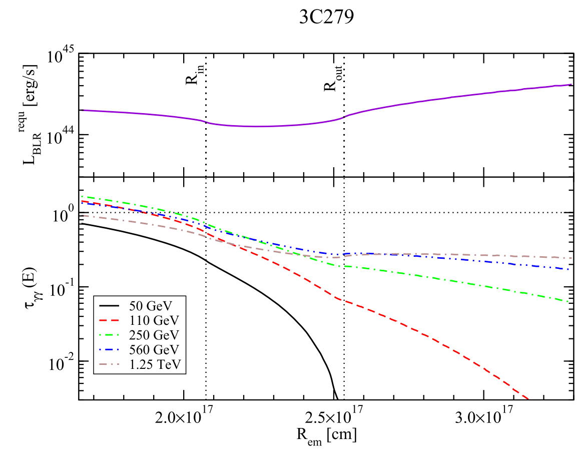

Figure 2. Results for 3C279. Lower panel: $\gamma\gamma$ absorption optical depth as a function of location of the emission region, $R_{\rm em}$, for a fixed value of $u_{\rm BLR}$ as encountered by the emission region at the respective location (see the text), for several γ-ray photon energies. Upper panel: required luminosity of the BLR, according to the re-normalization of the local BLR emissivity (Equation (8)).

decrease as the emission region is located inside the BLR. Notably, the decrease of $\tau_{\gamma\gamma}$ for locations outside the BLR is very shallow, at least for photons at $E \gg 100$ GeV, because the fixed value of $u_{\rm BLR}$ requires a rapidly increasing local emissivity j_ϵ^0 (and, thus, BLR luminosity). For this reason, we quickly reach values of $L_{\rm BLR}^{\rm requ.} \sim 2\,L_{\rm BLR}^{\rm obs}$ which we consider excessive compared to the observationally determined value. Thus, if the γ-ray emission region is located beyond the distance range considered in Figure 2, the GeV γ-ray emission can no longer be produced by EC scattering of BLR photons with plausible parameter choices, and would, instead, have to be produced by a different mechanism, such as EC scattering of IR photons from a dusty torus.

3.2. PKS 1510-089

In the case of PKS 1510-089, to our knowledge, no value of the total luminosity of the BLR has been published. We therefore parameterize the luminosity of the BLR as a fraction $f = 0.1\,f_{-1}$ of the accretion disk, $L_{\rm BLR} = f\,L_d$. The accretion disk luminosity was determined by Pucella et al. (2008) to be $L_d = 1.0 \times 10^{46}$ erg s^{-1}. Characteristic SEDs of PKS 1510-089 (e.g., Abdo et al. 2010) indicate $\nu_{\rm sy} \sim 3 \times 10^{12}$ Hz, $\epsilon_{\rm EC} \sim 10^2$, and $f_{\rm EC}/f_{\rm sy} \sim 20$, for which Equation (3) yields $u_{\rm BLR} = 4.5 \times 10^{-3}$ erg cm^{-3}, yielding a BLR radius of $R_{\rm BLR} = 7.7 \times 10^{17} f_{-1}^{1/2}$ cm.

The results for a fiducial value of $f = 0.1$ (i.e., BLR luminosity = 10% of the accretion disk luminosity) are illustrated in Figure 3. The general trends are the same as found for 3C279, with slightly larger values of $\tau_{\gamma\gamma}$ due to the larger BLR luminosity (assuming $f = 0.1$) and larger BLR size. Still, the same conclusion holds: If the GeV γ-rays are produced by the EC-BLR mechanism, the γ-ray emission region must be located near the outer boundary of the BLR, whereas for locations far beyond the outer boundary, the EC-BLR mechanism becomes implausible for the production of the observed GeV γ-ray flux.

Figure 4 illustrates that this general result is is only weakly dependent on the value of f, with $\gamma\gamma$ opacities being smaller for

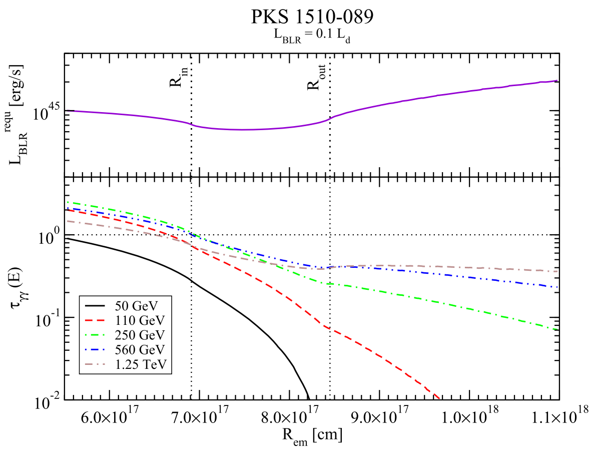

Figure 3. Results for PKS 1510-089, assuming $L_{\mathrm{BLR}} = 0.1\,L_d$. Panels and symbols as in Figure 2.

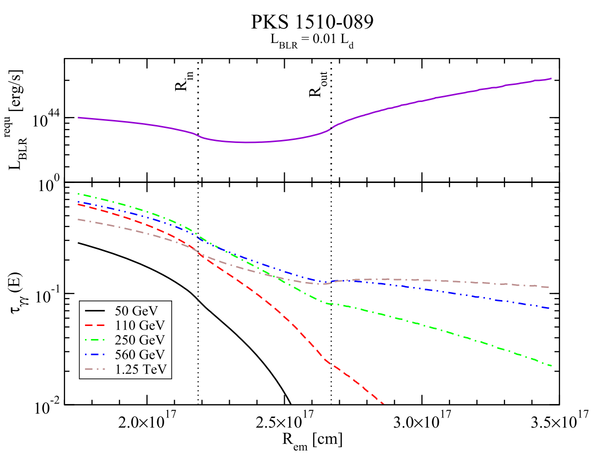

Figure 4. Results for PKS 1510-089, assuming $L_{\mathrm{BLR}} = 0.01\ \ L_d$. Panels and symbols as in Figure 2.

smaller values of f (i.e., smaller values of L_{BLR}, but keeping u_{BLR} fixed). This is expected as a smaller value of L_{BLR} implies a smaller size of the BLR and, thus, a smaller effective path length of γ-ray photons through the BLR radiation field. Consequently, an approximate scaling $\tau_{\gamma\gamma} \propto f^{1/2}$ holds.

4. SUMMARY AND DISCUSSION

We have re-evaluated the $\gamma\gamma$ opacity for VHE γ-rays in the BLR radiation fields of VHE-detected FSRQ-type γ-ray blazars. Our method started from a fixed value of the radiation energy density u_{BLR} and inferred average radius of the BLR, based on the observationally constrained BLR luminosity. Keeping the value of u_{BLR} fixed, we calculated $\tau_{\gamma\gamma}$ for a range of locations of the γ-ray emission region, from inside the inner boundary to outside the outer boundary of the BLR. For the specific examples of 3C279 and PKS 1510-089, we found that the resulting $\gamma\gamma$ opacities for VHE γ-ray photons exceed unity for locations of the γ-ray emission region inside the inner boundary of the BLR (in the case of PKS 1510-089, this is true for $L_{\mathrm{BLR}} \gtrsim 0.1\,L_d$), in agreement with previous studies (e.g., Liu et al. 2008; Sitarek & Bednarek 2008; Böttcher et al. 2009). We find that, under the assumption of the GeV γ-ray emission being produced by the EC-BLR mechanism, the $\gamma\gamma$ opacity gradually drops for locations of the γ-ray emission region approaching the BLR and within the boundary radii of the BLR, reaching values far below unity when approaching the outer boundary. For locations outside the BLR, the BLR luminosity required to still be able to produce the observed GeV γ-ray flux through the EC-BLR mechanism, quickly exceeds observational constraints, thus requiring alternative γ-ray production mechanisms, such as EC scattering of IR photons from a dusty torus. Alternative radiation mechanisms/target photon fields are required in any case for the production of VHE γ-rays, since Compton scattering of the optical/UV target photons from the BLR to >100 GeV energies would occur in the Klein-Nishina regime, in which this process is strongly suppressed.

In the case of PKS 1510-089, the uncertain BLR luminosity allows for configurations of the VHE γ-ray emission region even within the inner boundary of the BLR if the BLR luminosity is $L_{\mathrm{BLR}} \lesssim 10^{-2}\,L_d$, i.e., in the case of a very small covering factor of the BLR.

The generic estimates of the BLR radiation energy density and inferred radius of the BLR based on the SED characteristics and the assumption of γ-ray production dominated by EC scattering of BLR photons, are in reasonable agreement with independent methods of determining R_{BLR} (and, thus, u_{BLR}). Specifically, Pian et al. (2005) estimated the size of the BLR of 3C279 to be $R_{\mathrm{BLR}} \sim 9 \times 10^{16}$ cm. Bentz et al. (2009) provided a general scaling of the size of the BLR with the continuum luminosity of the accretion disk, $L_d = 10^{45}\,L_{d,45}$ erg s^{-1}, of $R_{\mathrm{BLR}} \sim 3 \times 10^{17}\,L_{d,45}^{1/2}$ cm, where the continuum lumonisity λL_λ at $\lambda = 5100$ Å is used as a proxy for the disk luminosity. This implies a universal value of $u_{\mathrm{BLR}} \sim 3 \times 10^{-2} f$ erg cm^{-3}, in reasonable agreement with our SED-based estimates.

The $\gamma\gamma$ opacity constraints derived here can, of course, be circumvented if (a) the GeV γ-ray emission is not produced by the EC-BLR mechanism, or (b) the GeV and TeV γ-ray emissions are not produced co-spatially. In case (a) the energy density of the BLR radiation field at the location of the γ-ray emission region can be arbitrarily small, i.e., the γ-rays can be produced at distances far beyond the BLR. Evidence for γ-ray production at distances of tens of pc from the central engine has been found in a few cases, based on correlated γ-ray and mm-wave radio variability (e.g., Agudo et al. 2011). In this case, GeV γ-rays can still be produced in a leptonic single-zone EC scenario by Compton scattering external infrared radiation from a dusty torus. However, it is often found that, in order to provide a satisfactory representation of the SEDs of FSRQ-type blazars, both the BLR and the torus-IR radiation fields are required as targets for γ-ray production (e.g., Finke & Dermer 2010). In case (b), one would need to resort to multi-zone models, in which the GeV emission could be produced within the BLR at sub-pc distances, but the VHE γ-rays are produced at distances of at least several parsecs. In such a scenario, one would not expect a strong correlation between the variability patterns at GeV and VHE γ-rays. This appears to be in conflict with the correlated GeV (*Fermi*-LAT) and VHE variability of PKS 1510-089 (Abramowski et al. 2013) and PKS 1222+21 (Aleksić et al. 2011), while the VHE γ-ray detections of 3C279 by MAGIC (Albert et al. 2008) occurred before the launch of *Fermi*, so no statements concerning correlated GeV and VHE γ-ray variability can be made in this case.

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[3] Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors, and the NRF does not accept any liability in this regard.

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Erratum: "Gamma–Gamma Absorption in the Broad Line Region Radiation Fields of Gamma-Ray Blazars" (2016, ApJ, 821, 102)

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In the published article, our code to evaluate the $\gamma\gamma$ opacity due to the BLR radiation field contained a numerical error, due to which all opacities are a factor of 2π too low. The corrected Figures 2-4 are shown below. The conclusions of the paper do not change qualitatively, but the constraints on the location of the γ-ray emission region become tighter. In particular, in the case of 3C279, VHE photons beyond ~300 GeV, must be emitted significantly beyond the BLR, if produced by Compton scattering of BLR photons.

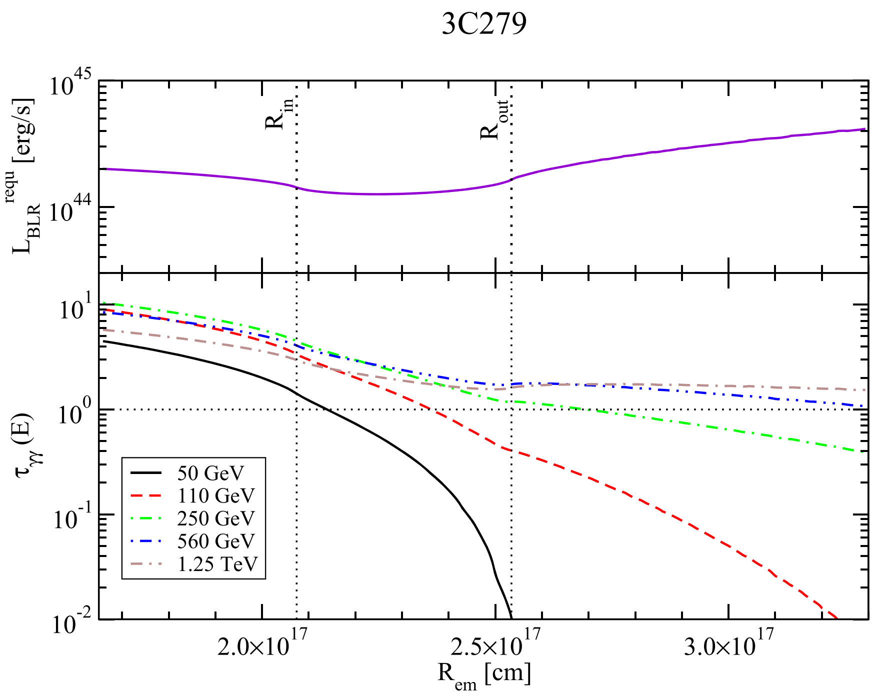

Figure 2. Corrected results for 3C279. Lower panel: $\gamma\gamma$ absorption optical depth as a function of location of the emission region, R_{em}, for a fixed value of u_{BLR} as encountered by the emission region at the respective location (see the text), for several γ-ray photon energies. Upper panel: required luminosity of the BLR, according to the renormalization of the local BLR emissivity (Equation (8) in the published article).

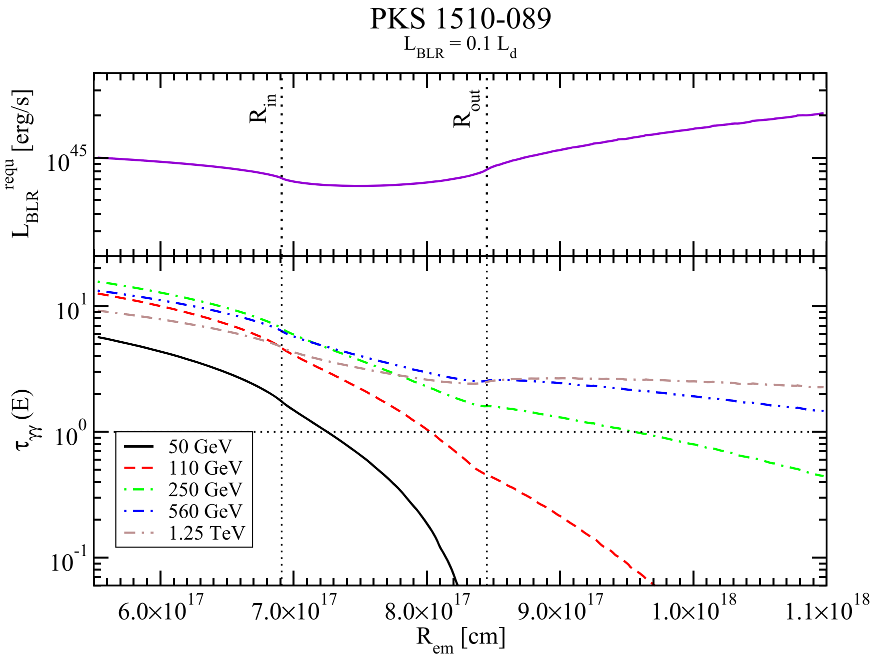

Figure 3. Corrected results for PKS 1510-089, assuming $L_{\rm BLR} = 0.1\ \ L_d$. Panels and symbols are the same as in Figure 2.

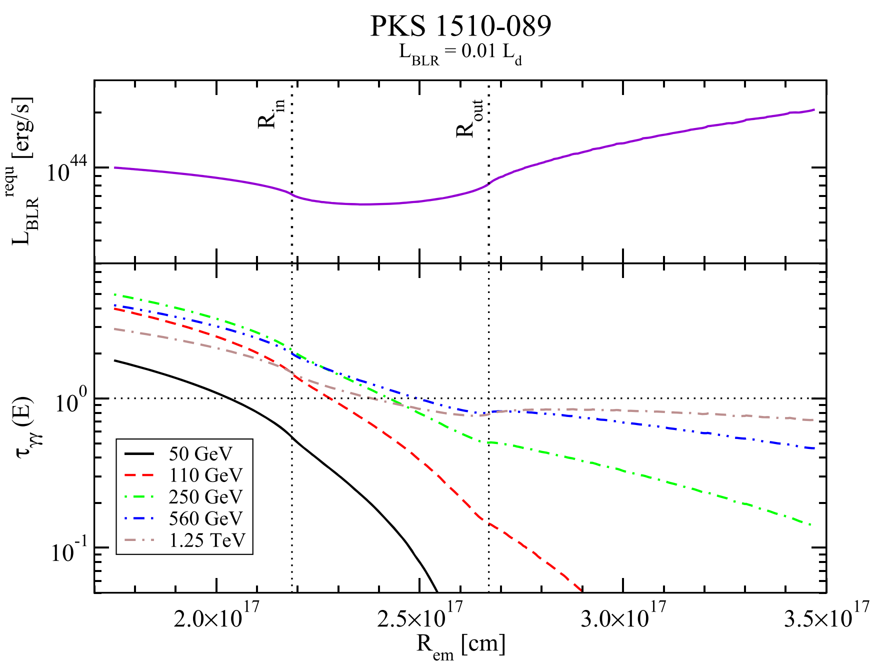

Figure 4. Corrected results for PKS 1510-089, assuming $L_{\rm BLR} = 0.01\ \ L_d$. Panels and symbols are the same as in Figure 2.

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Reference

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