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TeV gamma rays from blazars beyond z=1?

Felix Aharonian,[1,2] Warren Essey,[3] Alexander Kusenko,[3,4] and Anton Prosekin[2,*]

[1] *School of Cosmic Physics, Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland*

[2] *Max Planck Institute für Kernphysik, Heidelberg, Germany*

[3] *Department of Physics and Astronomy, University of California,Los Angeles, CA 90095-1547, USA*

[4] *Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*

At TeV energies, the gamma-ray horizon of the universe is limited to redshifts $z \ll 1$, and, therefore, any observation of TeV radiation from a source located beyond $z = 1$ would call for a revision of the standard paradigm. While robust observational evidence for TeV sources at redshifts $z \geq 1$ is lacking at present, the growing number of TeV blazars with redshifts as large as $z \simeq 0.5$ suggests the possibility that the standard blazar models may have to be reconsidered. We show that TeV gamma rays can be observed even from a source at $z \geq 1$, if the observed gamma rays are secondary photons produced in interactions of high-energy protons originating from the blazar jet and propagating over cosmological distances almost rectilinearly. This mechanism was initially proposed as a possible explanation for the TeV gamma rays observed from blazars with redshifts $z \sim 0.2$, for which some other explanations were possible. For TeV gamma-ray radiation detected from a blazar with $z \geq 1$, this model would provide the only viable interpretation consistent with conventional physics. It would also have far-reaching astronomical and cosmological ramifications. In particular, this interpretation would imply that extragalactic magnetic fields along the line of sight are very weak, in the range 10^{-17} G $< B < 10^{-14}$ G, assuming random fields with a correlation length of 1 Mpc, and that acceleration of $E \geq 10^{17}$ eV protons in the jets of active galactic nuclei can be very effective.

I. INTRODUCTION

Recent observations of active galactic nuclei with ground based gamma-ray detectors show growing evidence of very high energy (VHE) gamma-ray emission from blazars with redshifts well beyond $z = 0.1$. In this paper we examine the question of whether TeV blazars can be observed from even larger redshifts, $z \geq 1$. Although primary TeV gamma rays produced at the source are absorbed by extragalactic background light (EBL), we will show that it is possible to observe such distant blazars as point sources due to secondary photons generated along the line of sight by cosmic rays accelerated in the source.

To a large extent, the observations of blazars with $z > 0.1$ came as a surprise, in view of the severe absorption of such energetic gamma rays in the extragalactic background light (EBL). One of the obvious implications of these observations is the unusually hard (for gamma-ray sources) intrinsic gamma-ray spectra. Remarkably, the *observed* energy spectra of these objects in the very high energy band are, in fact, very steep, with photon indices $\Gamma \geq 3.5$. However, after the correction for the expected intergalactic absorption (i.e. multiplying the *observed* spectra to the factor of $\exp[\tau(z, E)]$, where $\tau(z, E)$ is the optical depth of gamma rays of energy E emitted by a source of redshift z), the intrinsic (source) spectra appear to be very hard with a photon index $\Gamma_s \leq 1.5$. Postulating that in standard scenarios the gamma-ray production spectra cannot be harder than $E^{-1.5}$, it was claimed that the EBL must be quite low, based on the observations of blazars H 2356–309 ($z = 0.165$) and 1ES 1101–232 ($z = 0.186$) by the HESS collaboration [1]. The derived upper limits appeared to be rather close to the lower limits on EBL set by the integrated light of resolved galaxies. Recent phenomenological and theoretical studies (e.g., Refs. [2, 3]) also favor the models of EBL which are close to the limit derived from the galaxy counts (for a recent review see Ref. [4]). This implies that further decrease in the level EBL is practically impossible, thus a detection of TeV gamma rays from more distant objects would call for new approaches to explain or avoid the extremely hard intrinsic gamma-ray spectra.

The proposed nonstandard astrophysical scenarios include models with very hard gamma-ray production spectra due to some specific shapes of energy distributions of the parent relativistic electrons – either a power law with a high low-energy cutoff or a narrow, e.g., Maxwellian type distribution. While the synchrotron-self-Compton (SSC) models allow the hardest possible gamma-ray spectrum with the photon index $\Gamma = 2/3$ [5, 6], the external Compton (EC) models can provide gamma-ray spectrum with $\Gamma = 1$ [6]. Within these models one can explain the gamma-ray emission of the blazar 1ES 229+200 at $z = 0.139$ with the spectrum extending up to several TeV [7] and sub-TeV gamma-ray emission from 3C 279 at $z = 0.536$ [8] ($\Gamma_s \sim 1$). Formally, much harder spectra can be expected in the case of Comptonization of an ultrarelativistic outflow [9], in analogy with the cold electron-positron winds in pulsars [10]. Although it is not

* Fellow of the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg (IMPRS-HD)

clear how the ultrarelativistic MHD outflows could form in AGN with a bulk motion Lorentz factor $\gamma \sim 10^6$, such a scenario, leading to the Klein-Nishina gamma-ray line-type emission [11], cannot be excluded *ab initio*. Further hardening of the initial (production) gamma-ray spectra can be realized due to the internal $\gamma - \gamma$ absorption inside the source [12, 13]. Under certain conditions, this process may lead to an arbitrary hardening of the original production spectrum of gamma rays.

Thus, the failure of "standard" models to reproduce the extremely hard intrinsic gamma-ray spectra is likely to be due to the lack of proper treatment of the complexity of nonthermal processes in blazars, rather than a need for new physics. However, the situation is dramatically different in the case of blazars with redshift $z \geq 1$. In this case the drastic increase in the optical depth for gamma rays with energy above several hundred GeV implies severe absorption (optical depth $\tau \gg 1$), which translates into unrealistic energy budget requirements (even after reduction of the intrinsic gamma-ray luminosity by many orders of magnitude due to the Doppler boosting). In this case, more dramatic proposals including violation of Lorentz invariance [14–16] or "exotic" interactions involving hypothetical axion-like particles [17, 18] are justified. Despite the very different nature of these approaches, their main objective is the same – to avoid severe intergalactic absorption of gamma rays due photon-photon pair production at interactions with EBL. This feat was accomplished either by means of big modifications in the cross-sections, or by assuming gamma-ray oscillations into some weakly interacting particles during their propagation through the intergalactic magnetic fields (IGMFs), e.g., via the photon mixing with an axion-like particle. Alternatively, the apparent transparency of the intergalactic medium to VHE gamma rays can be increased if the observed TeV radiation from blazars is secondary, i.e., if it is formed in the development of electron-photon cascades in the intergalactic medium initiated by primary gamma rays [9]. This assumption can, indeed, help us to increase the *effective* mean free path of VHE gamma rays, and thus weaken the absorption of gamma rays from nearby blazars, such as Mkn 501 [9, 19]. However, for cosmologically distant objects the effect is almost negligible because the "enhanced" mean free path of gamma rays is still much smaller than the distance to the source.

A modification of this scenario can explain TeV signals from objects beyond $z = 1$ if one assumes that the primary particles initiating the intergalactic cascades are not gamma rays, but protons with energies $10^{17} - 10^{19}$ eV [20–27]. AGN are likely source of very high energy cosmic rays [28, 29]. High-energy protons can travel cosmological distances and can effectively generate secondary gamma rays along their trajectories. Secondary gamma rays are produced in interactions of protons with 2.7 K cosmic microwave background radiation (CMBR) and with EBL.

II. RECTILINEAR PROPAGATION AND DEFLECTIONS

Secondary photons from proton induced cascades point back to the source if the the proton deflections are small [29]. Rectilinear propagation of protons is possible along a line of sight which does not cross any galaxies, clusters of galaxies, because their magnetic fields would cause a significant deflection. In addition, IGMFs can cause deflections in the voids, where the fields can be as low as 10^{-30} G [30, 31], but the analysis of blazar spectra including cosmic rays and secondary photons points to a range from 0.01 to 30 femtogauss [25]. As long as IGMFs are smaller than a femtogauss, they do not affect the point images of blazars. It remains to show that a typical line of sight does not cross a galaxy, cluster, etc. The mean rectilinear propagation length for protons reaching us from a distant source was discussed in Ref. [31]. Given homogeneity of the large-scale structure at large redshifts, this distance can be estimated as the mean free path of a proton in a volume filled with density n of uniformly distributed scatterers, each of which has a size R [31]. A typical distance the proton passes without encountering a scatterer is $L \sim 1/(\pi R^2 n)$. One can estimate this distance for galaxies, clusters, etc., and adopt a constraint based on the minimal distance $L_{\rm min}$. Sources at distances much larger than $L_{\rm min}$ should not be seen as point sources of secondary photons. It turns out that the strongest limit comes from galaxy clusters [31]:

$$L_{\rm min} \sim 1/(\pi R^2 n) \sim (1-5) \times 10^3 {\rm Mpc}. \qquad (1)$$

This distance is large enough for a random source at $z \geq 1$ to be seen with no obstruction by a cluster, or a galaxy [31]. Thus, the protons of relevant energies propagate rectilinearly, assuming the IGMFs are small.

If IGMFs on cosmological distance scales are smaller than 10^{-15}G, the protons propagate almost rectilinearly, and they carry some significant energy into the last, most important for us segment of their trajectory determined by the condition $l \leq \lambda_{\gamma,\rm eff}$, where $\lambda_{\gamma,\rm eff}$ is the *effective* mean free path of gamma rays. The secondary electron-positron pairs produced with an average energy of $(m_{\rm e}/m_{\rm p})E_{\rm p} \sim 10^{15}$eV initiate electromagnetic electron-photon cascades supported by the inverse Compton (IC) scattering of electrons on CMBR and photon-photon pair production of gamma rays interacting with EBL and CMBR. As long as the magnetic field is as small as is required to avoid the smearing of point sources, the cascade develops with an extremely high efficiency. Therefore, the gamma-ray zone is determined by the condition that $\lambda_{\gamma,\rm eff}$ be larger (typically, by a factor of 2 or 3) than the gamma-ray absorption mean free-path, $\lambda_{\gamma\gamma}$ shown in Fig.1.

Our analysis so far (and that of Berezinsky et al. [31]) left out the filaments between the clusters. Their size, volume filling factor, and geometry are uncertain, and observations provide only the upper limits. Models can accommodate a variety of field strengths in these fila-

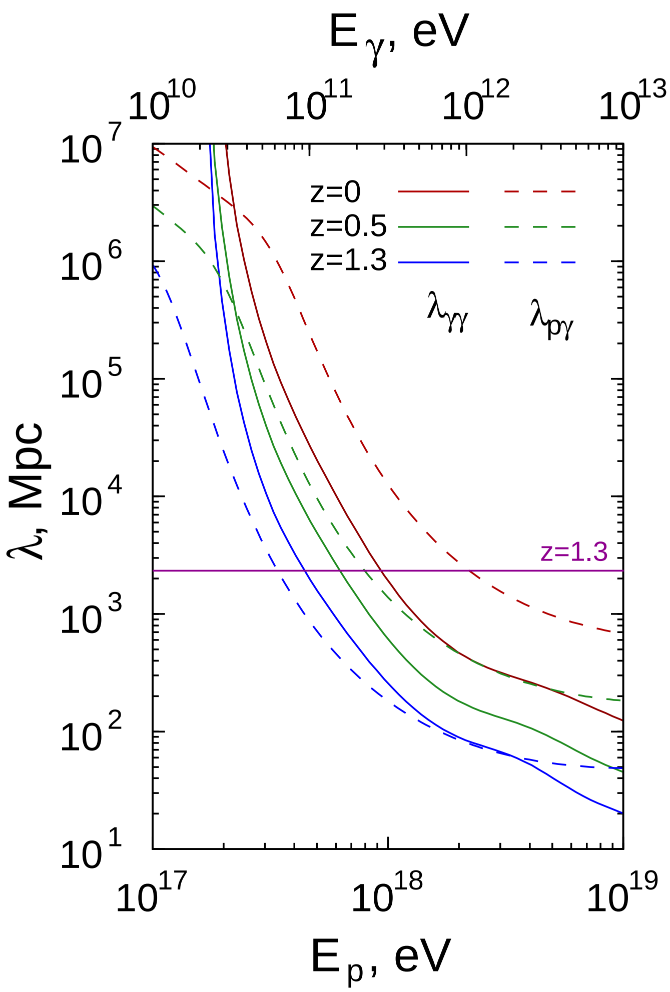

FIG. 1. The mean free paths of photons and protons as a function of energy and the source redshift. The calculations are based on the formalism developed in Ref. [33]. The gamma-ray absorption mean free path $\lambda_{\gamma\gamma}$ is shown for the EBL model of Ref. [2].

ments [32]. If nanogauss fields exist in large, numerous filaments, and if the line of sight passes through one or more filaments, the signal strength is reduced, as discussed in Ref. [23].

III. ENERGY REQUIREMENTS

The efficiency of this scenario depends on the energy of primary protons and the size of the *gamma-ray transparency zone*. It is approximately determined by the fraction of the proton energy released in e^+e^- pairs inside the gamma-ray transparency zone, at distances less than $\lambda_{\gamma,\mathrm{eff}}$ from the observer. Obviously, in the case of a broad energy distribution of protons, the main contribution to the gamma-ray flux comes from some energy range in which the proton mean free path is comparable to the distance to the source: $d = \lambda_{\mathrm{p}\gamma}(E, z = 0)$. In the case of nearby objects with $z \ll 1$, the corresponding energy E^* can be found from Fig. 1 as the point where the distance to the source is equal the mean free path of protons at the present epoch, $d = \lambda_{\mathrm{p}\gamma}(E^*, z = 0)$. The contributions of protons with lower or higher energies would be significantly smaller. For lower energies, the interaction probability is too small, while, for higher energies, the energy losses outside the gamma-ray transparency zone are too large. However, in the case of cosmologically distant objects, such a simple argument does not work because of very strong dependency of the proton's mean free path on both the energy and the redshift. It appears that, independent of the initial energy, only the low energy protons with $E \sim 10^{17}$ eV enter the *gamma-ray transparency zone*. This dramatically reduces the efficiency of production and transport of VHE gamma rays to the observer. At the same time, the efficiencies for gamma rays, the mean free paths of which are comparable to the distance to the source, remain high. This is the case for GeV gamma rays from cosmologically distant, $z \geq 1$, objects, and for VHE gamma rays from small-z objects. This can be seen from Fig.2, where we show the SED of gamma rays normalized to the initial energy of the proton. The curves are calculated for two redshifts, $z = 0.2$ and $z = 1.3$, and for several different proton energies.

In Fig. 3 we show the dependence of the efficiency of energy transfer on the redshift of the source. It is determined by the character of evolution of radiation fields with z. While the energy density of CMBR monotonically decreases with z, namely $w_{\mathrm{CMBR}} \propto (1 + z)^4$, the dependence of the density of EBL on z is more complex and uncertain. For small redshifts, the density of EBL increases with z, but at redshifts corresponding to the epochs before the maximum of the galaxy formation rate ($z \sim 2$), the density of EBL is contributed only by the first stars, therefore it drops at large redshifts. Correspondingly, the probability of gamma rays to reach the observer has a nonlinear dependence on the energy of protons and the source redshift. Depending on the energy of gamma rays, the efficiency reaches its maximum at intermediate redshifts, $z \sim 0.1 - 0.3$. We note that at $z \sim 0.1$, the efficiency could be rather high (greater than 1%) even at 10 TeV. Therefore, the contribution of this channel to the quiescent component of VHE radiation from nearby blazars can be quite significant. At large redshifts, $z \geq 1$, the efficiency at TeV energies drops dramatically, and it does not exceed 10^{-5} at $z = 1$. Yet, even with such a small efficiency, one can expect TeV gamma rays from sources with $z \sim 1$, provided that the parent protons leave the blazar in a narrow beam. In contrast, TeV gamma rays emitted directly by the source at $z \geq 1$ suffer severe absorption, thus only a negligible fraction can survive and reach the observer.

Indeed, for gamma rays with energy in excess of several hundred GeV arriving from a source at $z = 1$, the optical depth is very large, $\tau_{\gamma\gamma} \sim 10$, for any realistic model of EBL. VHE gamma rays cannot survive the se-

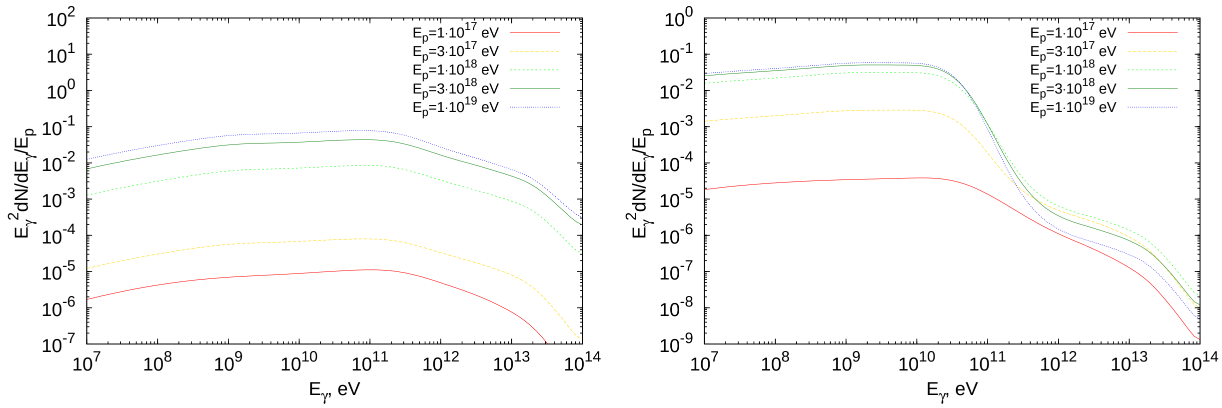

FIG. 2. The energy spectra of secondary gamma rays produced by protons of different energies emitted from a source at $z = 0.2$ (left panel) and $z = 1.3$ (right panel). The curves are normalized to the proton energy, hence, they show the differential efficiency of the energy transfer from protons to gamma rays. It is assumed that the intergalactic magnetic field $B = 0$.

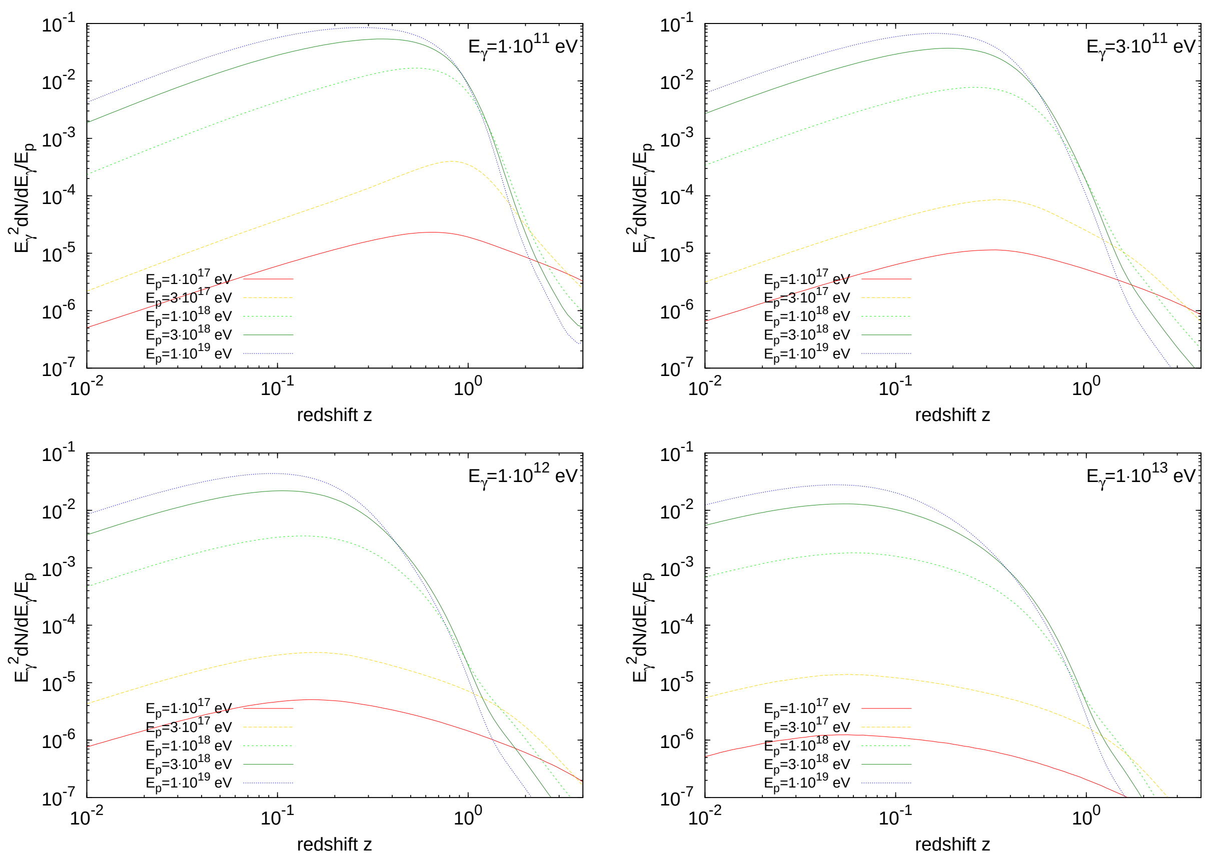

FIG. 3. The differential efficiency of the energy transfer from protons to gamma rays as a function of the redshift of the cosmic-rays source for different initial energies E_p of the monoenergetic proton beam.

vere intergalactic absorption (see Fig. 4). This could be relevant for TeV gamma-ray emission from the blazar PKS 0447-439 [34], given the large redshift of the source $z \geq 1.126$, as claimed in Ref. [35]. However, recently two independent groups [36] challenged the interpretation of the redshift measurements of Ref. [35]. Thus, the redshift of PKS 0447-439 remains uncertain.

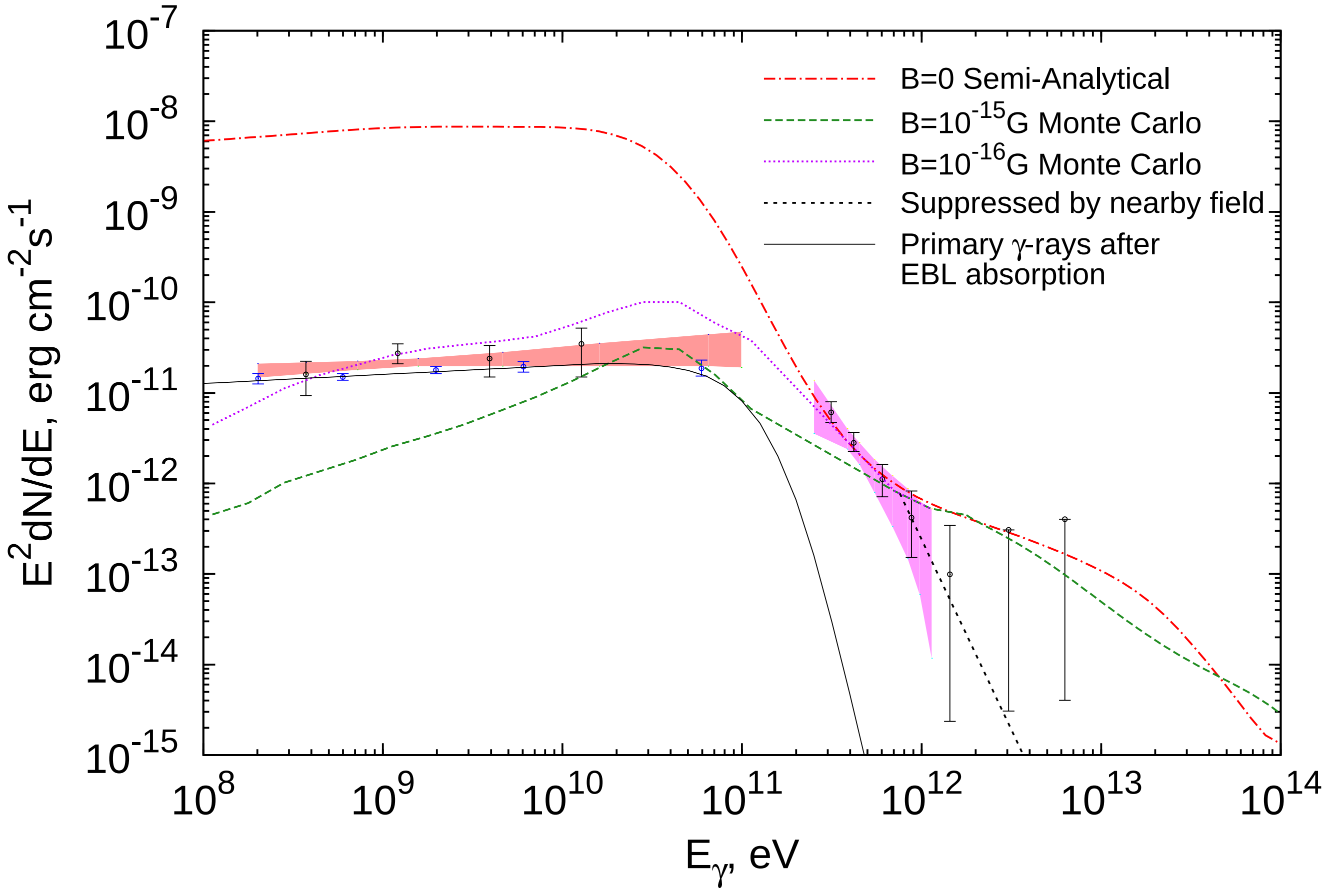

FIG. 4. Spectra of secondary gamma rays produced by protons from a source at $z = 1.3$, calculated using semi-analytical and Monte Carlo techniques. All theoretical curves are normalized to the observed flux around 1 TeV. The *Fermi* LAT data are shown according to 1LAC catalog [37] (smaller error bars), and according to Ref. [38] (large error bars). The data above 0.1 TeV are from HESS [34]. The semi-analytical calculations correspond to the magnetic field $B = 0$ and protons injected with E_p^{-2} type energy spectrum in the energy interval $E_p = 10^{17} - 10^{18}$ eV. Monte Carlo results for the secondary spectrum from protons with a high energy cutoff of 10^{19} eV are shown for IGMF $B = 10^{-16}$ G and $B = 10^{-15}$ G. The effect of significantly enhanced magnetic field within $D \lesssim 100$ Mpc of the observer is shown for illustration of a possible suppression of the spectrum above 1 TeV. Also shown is the spectrum from a pure-gamma (no cosmic rays) source with injection spectrum E_γ^{-2}, after intergalactic absorption for EBL model of Ref. [2].

IV. CASE STUDY: A BLAZAR AT $z = 1.3$

Regardless of the observational status of PKS 0447-439 redshift, it is important to understand whether secondary gamma rays can be detected from a source at a large redshift. Therefore, we use PKS 0447-439 as a case study for this more general question, assuming it has a redshift $z \approx 1.3$, as claimed in Ref. [35]. The analysis presented below should be viewed as a methodological study whose goal is to demonstrate that the model does allow TeV blazars at redshifts $z \geq 1$ to be observed, and that neither a dramatic revision of high-energy processes in blazars, nor new non-standard interactions of gamma rays are necessary.

Cosmic-ray protons with energies $E \leq 10^{18}$ eV do not lose a significant part of their energy to interactions with the background photons, and, as long as the IGMFs are very weak, the protons can provide an effective transport of the energy over a large (cosmological) distance toward the observer. Cosmic ray interactions with CMBR and EBL, via the Bethe-Heitler pair production $p\gamma \to pe^+e^-$ and the photomeson reactions $p + \gamma_b \to p + \pi^0$, initiate electromagnetic cascades. The resulting secondary VHE gamma rays are observed as arriving from a point source, provided that the broadening of both the proton beam and the cascade electrons due to the deflections in IGMFs does not exceed the point spread function of the detector. In the case of detection of VHE gamma rays from PKS 0447-439 by the HESS telescope array [34], $\theta_{\rm p}, \theta_{\rm cas} \leq 3$ arcmin. While the broadening of the proton beam takes place over the entire path of protons from the source to the observer (zone 1), the diffusion of electrons in the *transparency zone* (zone 2) is the most important factor for the broadening of the cascade emission. Therefore, strictly speaking, one should distinguish between the magnetic fields in these two zones, B_1 and B_2, respectively. The corresponding deflection angles are [39]

$$\theta_{\rm p} \approx 0.05\,\mathrm{arcmin}\,\left(\frac{10^{18}\mathrm{eV}}{E_p}\right)\left(\frac{B_1}{10^{-15}\mathrm{G}}\right)\left(\frac{L}{\mathrm{Mpc}}\frac{d}{\mathrm{Gpc}}\right)^{1/2} \tag{2}$$

and

$$\theta_{\rm cas} \approx 3.8\ \mathrm{arcmin}\,\left(\frac{10^{12}\mathrm{eV}}{E_\gamma}\right)\left(\frac{B_2}{10^{-15}\mathrm{G}}\right), \tag{3}$$

where L is the coherence length, and d is luminosity distance. One can see that, for comparable strengths of magnetic fields in two zones, the angular broadening is mainly due to the electron deflections in the *transparency zone*. Remarkably, such a deflection depends only on the magnetic field B_2 and the gamma-ray energy E_γ. Thus, a detection of an energy-dependent angular broadening of gamma-ray emission from blazars can provide a direct measurements of IGMF in a given direction [40].

The deflections of protons and cascade electrons result in delays of the arrival times of the signal. In the two zones defined above,

$$\Delta\tau_{\rm p} \approx 1.5\cdot 10^6\,\mathrm{s}\,\left(\frac{E_{\rm p}}{10^{18}\mathrm{eV}}\right)^{-2}\left(\frac{B}{10^{-15}\mathrm{G}}\right)^2\times \times\left(\frac{L}{1\,\mathrm{Mpc}}\right)\left(\frac{d}{1\mathrm{Gpc}}\right)^2 \tag{4}$$

and

$$\Delta\tau_\gamma \approx 1.3\cdot 10^6\mathrm{s}\left(\frac{E_\gamma}{10^{12}\ \mathrm{eV}}\right)^{-5/2}\left(\frac{B}{10^{-15}\mathrm{G}}\right)^2. \tag{5}$$

One can see that, for $B_1 \sim B_2 \sim 10^{-15}$ G, any time structure in the initial signal of 10^{18}eV protons on time scales of the order of a month or shorter are smeared out. Conversely, the interpretation of a variable VHE gamma-ray signal on timescales less than 1 month, in the framework of this model, would require magnetic field in both zones to be significantly weaker than 10^{-15} G. On the other hand, even for such small magnetic fields, the gamma-ray signals at GeV energies should be stable on timescales of tens of years.

Finally, a distinct feature of the proposed model is the spectral shape of gamma radiation. For relatively nearby sources, $z \ll 1$, the gamma-ray spectrum is flat, with a modest maximum around 10^{11} eV. For cosmologically distant sources with $z \geq 1$, the spectrum is steep in the sub-TeV part of the spectrum (down to 10 GeV), with a tendency of noticeable hardening above 1 TeV (see Fig. 2). Remarkably, the spectrum effectively extends to 10 TeV and higher energies even for cosmologically distant objects. However, a cutoff in the spectrum below a TeV energy cannot be excluded if the magnetic field in the ≈ 100 Mpc vicinity of the observer significantly exceeds 10^{-15} G.

For a nearby source, the spectral shape of secondary photons is remarkably independent of the details of the proton energy spectrum [21, 22], although the efficiency decreases dramatically for the proton energy below 10^{18} eV. For cosmologically distant sources, the shape of the gamma-ray spectrum does depend on the proton energy, especially at $E \leq 10^{18}$ eV. For a source at $z \geq 1$, the proton energy is transferred to gamma rays with a maximal efficiency if $E \approx 10^{18}$eV. Therefore, for an arbitrary spectrum of cosmic rays, the main contribution to secondary gamma rays comes from a relatively narrow energy interval of protons around 10^{18} eV. On the other hand, the gamma-ray spectrum produced by these protons in extremely low IGMF ($B \leq 10^{-17}$ G) disagrees with the broad band SED of gamma rays detected by *Fermi* LAT and HESS as shown in Fig. 4. This suggests the presence of magnetic fields stronger than 10^{-17} G. In a stronger magnetic field, deflections of the cascade electrons make the gamma-ray beam at low energies broader. The deflected flux does not contribute to a point source, but rather to the diffuse extragalactic background radiation. Meanwhile, VHE gamma rays may be confined in the initial narrow beam. This effect is demonstrated in Fig. 4 which is produced using the method described in Ref. [22]. For the IGMF $B \geq 10^{-17}$ G, the GeV gamma-ray flux within an angle corresponding to the PSF of HESS, drops by two orders of magnitude to the level detected by *Fermi* LAT. The impact on the spectrum of VHE gamma rays is less pronounced, unless the magnetic field exceeds 10^{-14} G.

The results presented in Fig. 4 show that secondary gamma rays can describe correctly the spectrum of PKS 0447-439, as long as IGMFs are in the range 10^{-17}G $< B < 10^{-14}$G, assuming random fields with a correlation length of 1 Mpc. This range of IGMF can be narrowed significantly in the future angular and temporal studies, leading to a more precise measurement of the magnetic field strengths along the line of sight. For example, detection of variability of VHE emission on timescales less than a few days would imply the values of magnetic fields close to 10^{-17} G. It is also important to search for an unavoidable (in the framework of this model) broadening of the angular extent of gamma-ray signals from cosmologically distant blazars. The choice of the gamma ray energy for such studies depends on the magnetic field. The detection of such an effect would be another strong argument in favor of the proposed scenario, and it would allow an accurate measurements of IGMFs in different directions.

V. DISCUSSION

One can see from Fig. 4 that the energy spectrum of gamma rays is quite stable from several hundred GeV to 10 TeV and beyond. Although the current statistics of the results reported by HESS does not allow robust conclusions regarding the energy spectrum above 1 TeV, the detection of multi-TeV gamma rays from PKS 0447-439 as well as from other cosmologically distant blazars would not be a surprise, but rather a natural consequence of the proposed scenario. However, we note that, if the magnetic field is enhanced in the *transparency zone*, i.e. in the vicinity of the observer, it could cause a strong suppression of the gamma-ray flux above some energy which can be found from the condition $\lambda_{\gamma\gamma}(E) = D$. The impact of this effect on the gamma-ray spectrum detected by an observer strongly depends on the linear scale of the enhanced magnetic field, D, but not much on the magnetic field itself (as long as the latter is significantly larger than 10^{-15}G). For example, for $D \sim 300$ Mpc, the steepening of the gamma-ray spectrum starts effectively around 1 TeV. This effect is illustrated qualitatively in Fig. 4.

The isotropic luminosity of the source in protons required to explain the data [34], is in the range $(1-3) \times 10^{50}$ erg/s, depending on the spectrum of protons. This is an enormous, but not an unreasonable power, given that the actual (intrinsic) luminosity can be smaller by several orders of magnitude if the protons are emitted in a small angle. In particular, for $\Theta = 3°$, the intrinsic luminosity is comparable to the Eddington luminosity of a black hole with a mass $M \sim 10^9 M_\odot$. Assuming that only a fraction of the blazar jet energy is transferred to high-energy particles, the jet must operate at a super-Eddington luminosity. While it may seem extreme, this suggestion does not contradict the basic principles of accretion, provided that most of the accretion energy is converted to the kinetic energy of an outflow/jet, rather than to thermal radiation of the accretion flow. Moreover, there is growing evidence of super-Eddington luminosities characterizing relativistic outflows in GRBs and in very powerful blazars [41].

Finally, we note that the protons emitted by cosmologically distant objects are potential contributors to the diffuse gamma-ray background. The total energy deposited into the cascades through secondary Bethe-Heitler pair production does not depend on the orientation of the jet or the beaming angle, but only on the injection power of $\geq 10^{18}$eV protons and on the number of such objects in the universe. Generally, the total energy flux of gamma rays is fairly independent of the strength of the intergalactic magnetic fields, except for the highest energy part of the gamma-ray spectrum. If the contribution of these sources to the diffuse gamma-ray background is dominated by cosmologically distant objects, then the development of the proton-induced electron-photon cascades is saturated at large redshifts. One should, therefore, expect a rather steep (strongly attenuated) spectrum of diffuse gamma rays above 100 GeV. However, in the case of very small intergalactic magnetic fields, the 10^{18}eV protons can bring significant amount of non-thermal energy to the nearby universe, and thus enhance the diffuse background by TeV photons. Perhaps, this can explain the unexpected excess of VHE photons in the spectrum of the diffuse gamma-ray background as revealed recently by the *Fermi* LAT data [42].

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