

Can we constrain the extragalactic magnetic field from very high energy observations of GRB 190114C?

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Primary very high energy γ rays from γ -ray bursts (GRBs) are partially absorbed on extragalactic background light photons with subsequent formation of intergalactic electromagnetic cascades. Characteristics of the observable cascade γ -ray signal are sensitive to the strength and structure of the extragalactic magnetic field (EGMF). GRB 190114C was recently detected with the MAGIC imaging atmospheric Cherenkov telescopes, for the first time allowing us to estimate the observable cascade intensity. We inquire whether any constraints on the EGMF strength and structure could be obtained from publicly available γ -ray data on GRB 190114C. We present detailed calculations of the observable cascade signal for various EGMF configurations. We show that the sensitivity of the Fermi-LAT space γ -ray telescope is not sufficient to obtain such constraints on the EGMF parameters. However, next-generation space γ -ray observatories such as MAST would be able to detect pair echoes from GRBs similar to GRB 190114C for the EGMF strength below 10^{-17} – 10^{-18} G.

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I. INTRODUCTION

The recent detection of very high energy (VHE) ($E > 100$ GeV) γ rays from γ -ray bursts (GRBs) with imaging atmospheric Cherenkov telescopes (IACTs) MAGIC [1] and H.E.S.S. [2] have aroused great interest. Besides being important for the understanding of “intrinsic” physics of GRBs (e.g., Refs. [3–8]), these observations could in principle be used to constrain the spectrum of the extragalactic background light (EBL) as well as the strength and structure of the extragalactic magnetic field (EGMF). Primary VHE γ rays escaping from the source are partially absorbed on EBL photons by means of the pair production (PP) process ($\gamma\gamma \rightarrow e^+e^-$) [9,10]. This leads to a characteristic cutoff in the spectra of distant extragalactic sources [11]. The imprint of the EBL in the spectra of blazars was

robustly detected with the Fermi-LAT space γ -ray telescope [12,13] and IACTs (e.g., Ref. [14]). Secondary electrons and positrons (hereafter “electrons” for simplicity) get deflected in the EGMF and then produce cascade γ rays by means of the inverse Compton (IC) process $e^-\gamma \rightarrow e^-\gamma'$ or $e^+\gamma \rightarrow e^+\gamma'$. Parameters of the observable γ -ray flux are sensitive to the EGMF strength and structure [15–17].

The first lower limits on the EGMF strength ($B \geq 3 \times 10^{-16}$ G) obtained with Fermi-LAT [18] data on blazars using spectral information [17] were subsequently found to be subject to significant systematic effects including those related to the unknown duty cycle [19,20] and poorly constrained spectral properties of the source, uncertainties of the EBL spectrum, etc. [21,22]. In particular, Ref. [21] concluded that it is hard to rule out the zero-EGMF hypothesis. Under such circumstances, an independent channel of information is desirable such as that provided by GRB observations at high ($E > 100$ MeV) and very high energies [15,23–27].

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The observable signal from intergalactic electromagnetic cascades depends on many parameters, including the primary intensity, the duration of the flare, the shape of the intrinsic spectrum, and the redshift of the source. In the present paper, we perform detailed numerical calculations of the observable intergalactic cascade signal from GRB 190114C, taking into account statistical and systematic uncertainties of the intrinsic VHE γ -ray spectrum (i.e., the spectrum of γ rays that have escaped into the intergalactic medium). We also take into account the systematic uncertainty of the EBL intensity, which appears to be a major factor affecting the observable pair echo intensity. The inclusion of any other systematic effect is equivalent to the addition of a nuisance parameter, further increasing the uncertainty of the EGMF parameter measurement and thus reinforcing our conclusions.

This paper is organized as follows. In Sec. II, we describe the approach to constraining the EGMF parameters with pair echoes from GRBs, In Sec. III, we reconstruct the intrinsic γ -ray spectrum of GRB 190114C (the optimization procedure presented in this section is based on Ref. [28]). In Sec. IV, we describe our analysis of Fermi-LAT data in order to set experimental upper limits on the pair echo intensity from GRB 190114C. In Sec. V, we present our results for the expected observable intergalactic cascade signal assuming various values of B . We conclude that the sensitivity of the Fermi-LAT telescope is not sufficient to constrain the EGMF.

Very recently, Wang *et al.* [29] (hereafter W20) found that observations of GRB 190114C with MAGIC and Fermi-LAT allow one to rule out $B < 3 \times 10^{-20}$ G. These results were derived for a large-scale EGMF with the coherence length L_c much greater than the characteristic cascade electron energy loss length L_{E-e} . Our conclusions are significantly different from those of W20 (see Sec. VI for a more detailed discussion). Finally, we conclude in Sec. VII.

II. QUALITATIVE CONSIDERATIONS AND ANALYTIC ESTIMATES

Above the observable energy of approximately 200 GeV, γ rays from GRB 190114C (redshift $z = 0.4245$) are strongly absorbed on the EBL; i.e., the optical depth of the PP process becomes greater than unity. The secondary electrons are produced with the typical angular spread $\theta_p \approx 1/\gamma_e$, where $\gamma_e = E_e/(m_e c^2)$ is the electron Lorentz factor, E_e is the electron energy, m_e is the electron mass, and c is the speed of light. The electrons propagate through the EGMF, get deflected by the angle θ_B , and accumulate time delay, meanwhile producing cascade γ rays via the IC acts.

For the range of parameters considered in the present work, pair production occurs mainly on EBL photons, while IC scattering occurs mainly on cosmic microwave

background photons [30]. The contribution of IC scattering on EBL photons to the observable cascade spectrum is significant only in the cutoff region of this spectrum (see Ref. [31], Fig. 3). A very short and basic introduction to the physics of intergalactic electromagnetic cascades is available in Ref. [32]; much more detailed treatments could be found in Refs. [16,33]. The geometry of intergalactic electromagnetic cascades in the magnetized Universe was also considered in, e.g., Refs. [34,35].

Following Ref. [16] [see its Eq. (39)], the time delay of cascade γ rays for the typical conditions considered in the present work may be estimated as

$$\Delta T = \sqrt{\Delta T_B^2 + \Delta T_P^2}, \quad (1)$$

$$\Delta T_B = \frac{(1+z)L_\gamma}{2c} \left(1 - \frac{L_\gamma}{L_s}\right) \theta_B^2, \quad (2)$$

$$\Delta T_P = \frac{(1+z)L_\gamma}{2c} \left(1 - \frac{L_\gamma}{L_s}\right) \theta_P^2, \quad (3)$$

where L_γ is the distance traveled by the parent γ ray before interaction and L_s is the distance from the source to the observer. According to Ref. [16] [Eq. (30)] for a large-scale EGMF and $L_\gamma \ll L_s$

$$\theta_B \approx \frac{L_{E-e}}{R_L} \approx \frac{3 \times 10^{-6}}{(1+z)^2} \left(\frac{B}{10^{-18} \text{G}}\right) \left(\frac{E_e}{10 \text{ TeV}}\right)^{-2}, \quad (4)$$

where L_{E-e} is the characteristic cascade electron energy loss length, R_L is the electron Larmor radius, and z is the redshift. For the conditions of our work ($B > 10^{-20}$ G and $E_\gamma < 10$ GeV, where Fermi-LAT has the maximal sensitivity), as a rule, $\theta_B > \theta_P$ and thus $\Delta T_B > \Delta T_P$ [see Ref. [16], Eq. (41)]. Therefore, in this case, $\Delta T \sim \Delta T_B \propto B^2$. If the time delay exceeds the observation time of the Fermi-LAT instrument ($\Delta T > \Delta T_{\text{obs-LAT}}$), the observable cascade spectrum will exhibit a cutoff at low energies, since low energy cascade γ rays acquire a greater time delay. Given that the typical energy of cascade γ rays $E_{\gamma-c} \propto E_e^2$ [16], the energy of the cutoff $E_{br} \propto B$.

Our approach to simulation of the pair echo from GRB 190114C is illustrated in Fig. 1. The observable VHE γ -ray intensity dN_e/dE (the subscript e stands for ‘‘experimental’’) of GRB 190114C in the energy range of 0.2–1.1 TeV was measured with the MAGIC IACTs over the time period between $T_0 + T_1$ and $T_0 + T_2$ [1], where T_0 is the trigger time provided by the Burst Alert Telescope onboard the Neil Gehrels Swift Observatory [36] and the γ -ray Burst Monitor onboard the Fermi satellite [37], $T_1 = 62$ s, and $T_2 = 2454$ s. The corresponding spectral energy distribution (SED) (equal to $E^2 dN_e/dE$) is shown in Fig. 2 together with its statistical uncertainties as red circles with error bars. We use the MAGIC observations of GRB

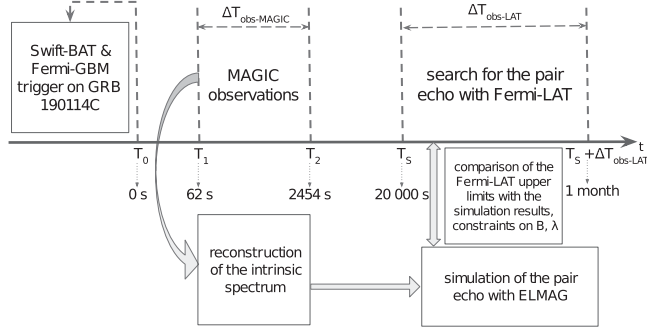
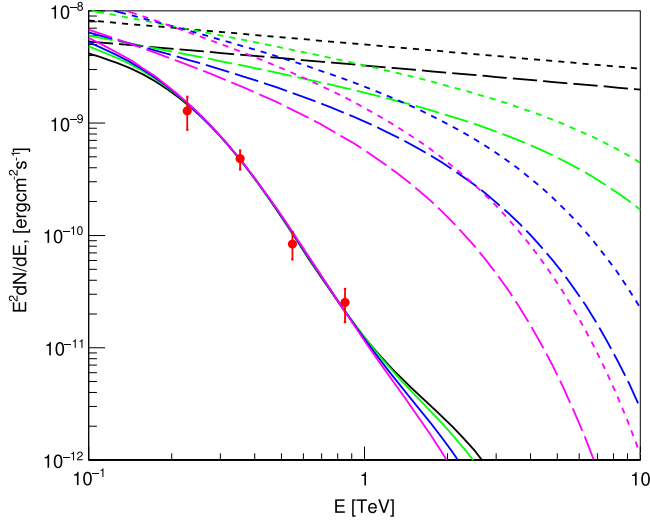


FIG. 1. A flow chart of the present work.

FIG. 2. SED of GRB 190114C measured with MAGIC (red circles with statistical uncertainties) together with best fits for various EBL model options (solid curves), the corresponding intrinsic SEDs (long-dashed curves), and the blueshifted intrinsic SEDs (short-dashed curves); the SEDs are averaged over the time period from T_1 to T_2 . See text for more details.

190114C to reconstruct the intrinsic spectrum of the source (see Sec. III). We search for the pair echo with Fermi-LAT starting at $T_0 + T_S$, where $T_S = 2 \times 10^4$ s, and derive upper limits on the pair echo SED (Sec. IV). The time shift T_S is needed in order to avoid the contamination from the afterglow γ rays. The reconstructed VHE spectrum is used as an input spectrum in our simulation of the pair echo from GRB 190114C (Sec. V), performed with the publicly available code ELMAG3 [38,39]. Finally, we compare the resulting model intensity of the observable cascade SED with the Fermi-LAT upper limits.

III. RECONSTRUCTION OF THE INTRINSIC SPECTRUM

In what follows, we characterize the intrinsic VHE γ -ray intensity with a simple form $\propto E^{-\gamma} \exp(-E/E_c)$.

This is a reasonable assumption, given the narrow energy range of the MAGIC spectrum (less than 1 order of magnitude). Assuming the EBL model of Gilmore *et al.* [40] (hereafter G12) and the redshift of the source $z = 0.4245$ [41,42], we estimate the spectral parameters γ and E_c as follows.

We set ($\gamma = 2$, $E_c = 10$ TeV) as the initial values of these parameters and calculate the observable intensity in all four bins of the MAGIC spectrum accounting for the effect of intergalactic absorption, dividing each of these bins to $N_{\text{div}} = 21$ parts in order to ensure small variation of the intergalactic $\gamma\gamma$ optical depth τ over any of these 84 new narrow bins. We define the χ^2 functional form as follows,

$$\chi^2(\gamma, E_c) = \sum_{i=1}^{N_{\text{bin}}} \frac{(F_{m;i}(\gamma, E_c) - F_{e;i})^2}{\Delta_i^2}, \quad (5)$$

where $N_{\text{bin}} = 4$ is the number of MAGIC energy bins and $F_{e;i}$ and $F_{m;i}$ are the measured (experimental) and model SEDs, respectively, normalized to their values at the decorrelation energy E_d ,

$$F_{e;i} = \frac{E_i^2 (dN_e/dE)_i}{E_d^2 (dN_e/dE)_d}, \quad (6)$$

$$F_{m;i}(\gamma, E_c) = \frac{F_m(E_{\text{min};i}, E_{\text{max};i}, \gamma, E_c)}{F_m(E_{\text{min};d}, E_{\text{max};d}, \gamma, E_c)}, \quad (7)$$

where

$$F_m(E_{\text{min};i}, E_{\text{max};i}, \gamma, E_c) = \frac{\sum_{j=0}^{N_{\text{div}}} E_j^{2-\gamma} e^{-E_j/E_c} e^{-\tau(E_j, z)}}{N_{\text{div}}}, \quad (8)$$

and

$$E_j = E_{\text{min};i} + (E_{\text{max};i} - E_{\text{min};i}) \frac{j}{N_{\text{div}}}. \quad (9)$$

$E_{\text{min};i}$ and $E_{\text{max};i}$ are the minimal and maximal energies of every MAGIC energy bin, respectively; decorrelation energy is defined as the central energy of the bin with the minimal statistical uncertainty of the measured spectrum; the minimal and maximal energies of this bin are denoted as $E_{\text{min};d}$ and $E_{\text{max};d}$, respectively. Finally, Δ_i is the statistical uncertainty of the measured SED in the i th energy bin; it was normalized in the same way as the measured SED.

Then, varying the fitting parameters (γ , E_c) and repeating the above-described procedure for every new set of these parameters, we minimize the χ^2 form with the MINUIT package [43] integrated into the ROOT framework and determine the best-fit values of γ and E_c .

The corresponding best-fit observable SED is shown in Fig. 2 as a black solid curve.

The intrinsic VHE γ -ray spectrum resulting from this procedure is also shown in Fig. 2 as a black long-dashed curve. Finally, we account for the effect of redshift [44]; the resulting intrinsic VHE γ -ray spectrum in the source rest frame is shown in Fig. 2 as black short-dashed curve. We note that for the G12 EBL model the best-fit value $E_c \rightarrow +\infty$; i.e., the intrinsic spectrum does not reveal a cutoff. On the other hand, the most natural models of GRB emission predict the existence of such a cutoff due to the PP process inside the source (see, e.g., Ref. [45]). This apparent slight tension between the reconstructed and predicted intrinsic spectral shapes could be relaxed if we assume a model of EBL with a slightly diminished intensity compared to the “nominal” G12 EBL model.

We repeat the whole procedure of the intrinsic spectrum reconstruction for three different normalizations of the EBL intensity, namely, those of 90%, 80%, and 70% of the original EBL intensity according to the G12 EBL model. The results for these three runs of the optimization procedure are shown in Fig. 2 as green, blue, and magenta curves, respectively.

IV. FERMI-LAT DATA ANALYSIS

Here, we derive upper limits on the observable SED of GRB 190114C. We select Fermi-LAT data within 1 month of observation, starting at $T_0 + T_S$, where $T_S = 2 \times 10^4$ s. The region of interest (ROI) is a circle with the radius of 12° , centered at the position of the GRB ($\alpha_{J2000} = 54.507^\circ$, $\delta_{J2000} = -26.947^\circ$). We have applied the energy selection from 100 MeV to 100 GeV. For other selection parameters, we use standard recommendations for off-plane point source identification with Fermi-LAT.

We then perform unbinned likelihood analysis of the selected data with `FermiTools` [46]. We construct a model of observed emission including the following sources that could contribute to the detected γ -ray counts inside the ROI: 1) GRB 190114C itself, modeled as a pointlike source with power-law spectrum at the center of the ROI, 2) all sources from the Fermi 8-Year Point Source Catalog (4FGL) [47] located within 17° from the center of the ROI, and 3) galactic and isotropic diffuse γ -ray backgrounds using models provided by the Fermi-LAT Collaboration. For GRB 190114C, we set both spectral index and normalization as free parameters; for pointlike sources within 5° from the center of the ROI and the diffuse backgrounds, only the normalizations were left free, while the spectral shapes were fixed; for pointlike sources beyond 5° from the center of the ROI, both normalizations and shapes were fixed.

Using this model of the observed emission, we perform the maximization of the likelihood; i.e., we determine the values of parameters which yield the maximal probability of producing the observed γ -ray counts. We calculate the

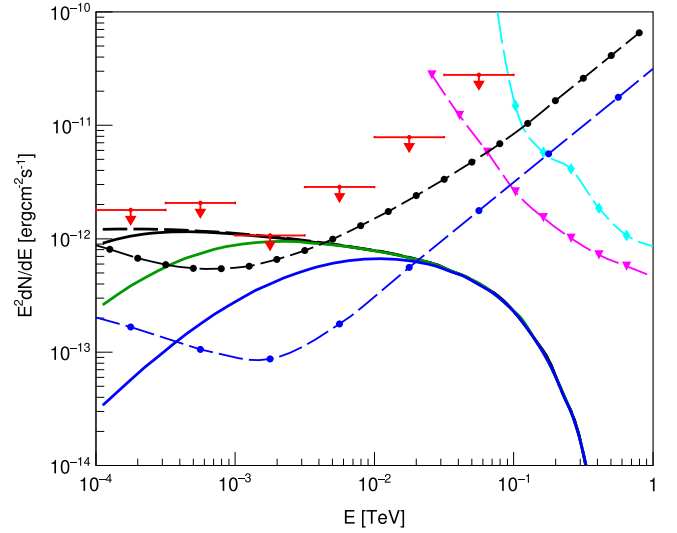


FIG. 3. Upper limits on the SED of GRB 190114C derived from Fermi-LAT data (red horizontal bars with downward arrows) together with model SEDs for various values of B (curves without symbols; see the text for more details). The SEDs are averaged over the Fermi-LAT observation time $\Delta T_{\text{obs-LAT}}$. Also shown are the differential sensitivity of the CTA IACT and the MAST γ -ray telescope (filled symbols connected with long-dashed lines; see the text for more details).

value of the test statistic corresponding to the hypothesis of the GRB 190114C emission being present in the dataset against the null hypothesis of it being absent. The resulting value of the test statistic $TS \ll 1$, which means that there is no significant γ -ray flux detected from this GRB.

Given that no signal from GRB 190114C was detected, we place upper limits on its SED. At this stage of our analysis, we reduce the emission model to only four sources: GRB 190114C, 4FGL J0348.5-2749 (the brightest pointlike source inside the ROI), and two diffuse backgrounds described above. These sources are responsible for almost all observed γ rays inside the ROI. Finally, we run the user-contributed PYTHON script `likeSED.py` [48] to calculate upper limits (95% C.L.) on the emission from GRB 190114C in six energy bins (two bins per decade of energy). These upper limits are shown in Fig. 3. They are slightly different from similar results of W20.

V. SIMULATION OF PAIR ECHO FROM GRB 190114C

Using the publicly available code `ELMAG3` [38,39], we calculate the observable SED of intergalactic cascades over $\Delta T_{\text{obs-LAT}} = 1$ month assuming the “original” G12 EBL model (the corresponding intrinsic VHE γ -ray SED over the time period $\Delta T_{\text{obs-MAGIC}} = T_2 - T_1$ is shown as short-dashed black line in Fig. 2). The EGMF was modeled following the approach of Refs. [49,50] (see Sec. 2.1 of Ref. [38]) as isotropic random nonhelical turbulent

field with a Kolmogorov spectrum and Gaussian variance B_{RMS} (hereafter simply B). In total, 200 field modes were simulated with the minimal and maximal spatial scales $L_{\text{min}} = 5 \times 10^{-4}$ Mpc and $L_{\text{max}} = 5$ Mpc, respectively. In this case, the coherence length $L_c = 1$ Mpc [38]. The cascade electrons were propagated through the EGMF as described in Sec. 2.2 of Ref. [38] (i.e., using the full three-dimensional simulation).

For simplicity, we chose to calculate models of pair echo emission over the time period from T_0 to $T_0 + 1$ month rather than starting at $T_0 + T_S$. Subtracting γ rays that have time delay less than T_S would decrease the observable intensity and thus would reinforce our conclusions. The ELMAG3 code includes two terms of time delay arising from the deflection of cascade electrons in the EGMF and from the angular spread of electrons in PP acts, but it does not account for another two terms, namely, the one arising from the angular spread of cascade γ rays in IC acts, as well as the accumulated deflection of cascade electrons in IC acts (“cascade electron recoil”). A more detailed account of these effects is underway and will be published elsewhere. Given the difference of $\Delta T_{\text{obs-MAGIC}}$ and $\Delta T_{\text{obs-LAT}}$, an additional factor $K_{\text{Corr}} = \Delta T_{\text{obs-MAGIC}}/\Delta T_{\text{obs-LAT}}$ was introduced in order to obtain the observable SED in the Fermi-LAT energy band.

The resulting observable cascade SEDs are shown in Fig. 3 for four different values of $B = 10^{-20}$ G (black solid curve), 10^{-19} G (green solid curve), 10^{-18} G (blue solid curve), and $B = 0$ (black dashed curve). All these curves are below the Fermi-LAT upper limits. Therefore, no constraints on the EGMF strength and/or structure could be set using these data. The account of the MAGIC systematics on the intrinsic spectrum normalization (about 50%) would introduce an additional source of uncertainty [1]. We note that all four model curves practically coincide at $E > 40$ GeV, while at lower energies, three of these curves successively branch down from the zero-field curve at an energy $E_{br} \approx 40 \text{ GeV} \cdot B/(10^{-18} \text{ G})$. This behavior of observable SEDs is in full agreement with analytic estimates presented in Sec. II.

The sensitivity of the Cherenkov Telescope Array (CTA) IACT [51,52] for five hours of observation, the statistical significance $Z = 5\sigma$, and five energy bins per decade of energy is also shown in Fig. 3 for the zenith angle of 20° (magenta triangles connected with magenta dashed curve) and of 60° (cyan diamonds connected with cyan dashed curve). The energy threshold of CTA is too high to detect the cascade signal.

Finally, in Fig. 3, we present the sensitivity of the MAST projected space γ -ray telescope [53] for one month of observation in the survey mode and two following options: 1) five energy bins per decade of energy and $Z = 5\sigma$ (black circles connected with black dashed curve) and 2) two energy bins per decade of energy and $Z = 2\sigma$ (blue circles connected with blue dashed curve). For both options, we

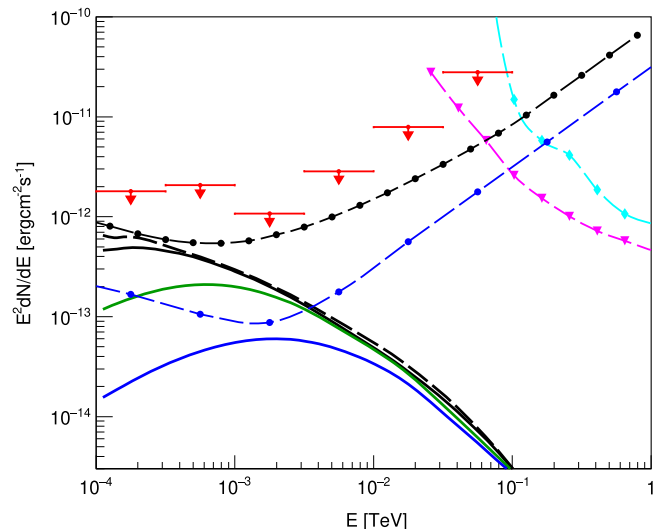


FIG. 4. Same as in Fig. 3, but model curves are for the modified EBL with $K_{\text{EBL}} = 0.7$.

have imposed an additional condition that the expected number of counts from the pair echo in every energy bin is greater than unity. We note that observations with MAST would allow us to probe the EGMF $B < 10^{-17}$ G using the pair echo method. Stronger values of $B = 10^{-14}$ – 10^{-17} G could be probed if a “magnetically broadened cascade pattern” [54] could be detected [16,53,55].

We have also performed similar calculations for a modified EBL model with the normalization factor $K_{\text{EBL}} = 0.7$ (see Fig. 4). The corresponding intrinsic VHE γ -ray SED over the time period $\Delta T_{\text{obs-MAGIC}} = T_2 - T_1$ for this EBL model is shown as short-dashed magenta line in Fig. 2. The residual difference between four model curves in Fig. 4 at high energies is mainly due to statistical fluctuations. Figure 4 demonstrates that for $K_{\text{EBL}} = 0.7$ the model pair echo intensity is well below the Fermi-LAT upper limits even for $B = 0$. However, observations with MAST would still allow us to probe the range of $B < 10^{-18}$ G using the pair echo method.

Qualitatively similar results to those presented in Figs. 3 and 4 could be obtained with the publicly available code of Ref. [35]. We note that our results apply directly to a large-scale EGMF. For a small-scale EGMF with $L_c < L_{E-e}$, a stronger magnetic field is required in order to achieve the same deflection of cascade electrons: $B \propto \sqrt{L_{E-e}/L_c}$ (e.g., Ref. [16]). The dependence of L_{E-e} on the electron energy E_e for $z = 0$ was presented in Ref. [56] in Fig. 2 (left); this figure was produced assuming the approximation for the IC process obtained in Ref. [57]. At $E_e < 10$ TeV, the Thomson approximation of Ref. [16] is applicable [see that reference’s Eq. (28)]. At $z = 0$, $L_{E-e} \approx 3$ Mpc for $E_e = 100$ GeV, and $L_{E-e} \approx 80$ kpc for $E_e = 5$ TeV; $L_{E-e}(E_e, z)/L_{E-e}(E_e, 0) \propto (1+z)^{-4}$.

In the present work, we have neglected the emission from primary afterglow after T_S . Preliminary estimates

show that the inclusion of this emission does not change our conclusions. A more detailed account of the primary afterglow is underway and will be published elsewhere. We note that our results are not sensitive to the time distribution of very high energy γ rays inside the MAGIC time window because this time window is much narrower than the Fermi-LAT time window.

VI. DISCUSSION

A. Influence of the EBL normalization on the pair echo intensity

The typical energy of cascade γ rays $E_{\gamma-c} \approx (4/3)\gamma_c^2 \epsilon$, where $\epsilon \approx 6.3 \times 10^{-4}$ eV is the characteristic energy of background photons [33,58]. Under the conditions of our analysis, Fermi-LAT is most sensitive to the pair echo emission at $E \approx 1$ GeV corresponding to the primary γ -ray energy $E_\gamma \approx 1.2$ TeV. The primary γ -ray intensity at such energies is about five times greater for $K_{\text{EBL}} = 1$ than for $K_{\text{EBL}} = 0.7$, explaining a decrease in intensity of cascade γ rays at $E = 1$ GeV by a comparable factor [59].

Thus, a modest (30%) change of the EBL normalization corresponds to a strong (an order of magnitude) decrease of the observable intensity in the energy region where Fermi-LAT has the maximal sensitivity (1–3 GeV under the conditions of the present work). Dedicated studies of the EBL indeed suggest that the total uncertainty of K_{EBL} may be around 30% [60] or even greater [61]. Theoretical models of the [40,62–69] also reveal a significant spread of the predicted intensity amounting to dozens of percent (see Fig. 7 in Ref. [67]).

B. Possible influence of plasma energy losses and other effects on the pair echo intensity

Pair beams resulting from the development of intergalactic electromagnetic cascades may be subject to plasma instabilities that may cause additional energy losses [70]. At present, it is unclear whether these “plasma losses” are considerable or subdominant with respect to IC losses (e.g., Refs. [71–78]). Therefore, in the present work, we have accounted for only the IC losses. We note, however, that the inclusion of the plasma losses would decrease the pair echo intensity and thus would reinforce our conclusions. Finally, we note that the inclusion of any additional effect such as $\gamma \rightarrow \text{ALP}$ oscillations, Lorentz invariance violation, or an account for the possibility that a part of VHE γ rays observed with MAGIC are in fact not primary, but cascade ones, is tantamount to the inclusion of a new nuisance parameter, further increasing the uncertainty of the EGMF parameter measurement and thus reinforcing our conclusions.

C. Comparison with the work of W20

The present study has a number of differences with respect to the work of W20 in both model assumptions and calculation techniques. From the text by W20, it transpires

that they did not perform a detailed reconstruction of the intrinsic γ -ray spectrum in the TeV energy range, as was done in the present work (see our Sec. III). Instead, W20 assumed that this primary spectrum had the power-law index $\gamma = -2$ and that a power-law decay of intensity starts at 6 s. The latter assumption is not supported with the model developed in Ref. [45] (see their Extended Data Fig. 7) where the maximum at the 300 GeV–1 TeV light curve (dark green curve) is situated at ≈ 20 s and not at 6 s. Additionally, the observable intensity of cascade γ rays significantly depends on the shape of the primary spectrum even if the total energy of primary γ rays is fixed.

Furthermore, we found that according to this model the total energy radiated in the afterglow phase of GRB 190114C in the 300 GeV–1 TeV energy range exceeds the energy output in the same energy range inside the time window from $T_0 + T_1$ to $T_0 + T_2$ by the factor of only $K_T = 2.4$ and not by $K_T = 5$ as was claimed by W20 [79]. Therefore, we argue that W20 have significantly overestimated the normalization of the observable pair echo intensity. They also did not account the EBL uncertainty that could decrease the observable pair echo flux at $E = 1$ GeV by the factor of 5 (see the discussion above). Some additional very high energy γ rays could in principle come from the prompt emission phase of GRB 190114C. However, the internal opacity for these prompt γ rays is expected to be high. Indeed, the authors of Ref. [45] demonstrate that the optical depth for TeV γ rays is significant even in the time interval 68–110 s after the trigger time (see their Fig. 3). Much stronger absorption is expected for the prompt emission phase γ rays. For this reason, we did not include these prompt γ rays in our calculations.

Finally, we note that W20 did not calculate arrival time for individual observable γ rays but introduced a normalization factor t_{dur} in order to compute the observable flux [see their Eq. (4)]. This procedure is not directly comparable to Monte Carlo approach utilized in the present paper.

VII. CONCLUSIONS

The sensitivity of the Fermi-LAT γ -ray telescope is not sufficient to detect the intergalactic electromagnetic cascade signal from GRB 190114C over the time period of one month. The calculations for different values of $\Delta T_{\text{obs-LAT}}$ are straightforward; the results of these calculations will be reported elsewhere. CTA will not be able to detect pair echo from GRBs similar to GRB 190114C due to a relatively high energy threshold of this γ -ray detector compared to space γ -ray telescopes. However, observations with CTA would be crucial for constraining the shape of the intrinsic spectrum. Hopefully, future γ -ray detectors such as MAST [53] with much improved sensitivity will be able to probe the EGMF strength and structure for $B < 10^{-17}$ – 10^{-18} G using the pair echo method.

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