Proton synchrotron, an explanation for possible extended VHE gamma-ray activity of TXS 0506 + 056 in 2017

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TXS 0506 + 056, source of the extreme energy neutrino event, IceCube-170922A, has an interesting environment to study the lepto-hadronic emissions. The Fermi-LAT detector reported high energy (HE) γ-ray flare between 100 MeV and 100 GeV starting from 15 September 2017 from this source. Several follow-ups to trace the very high energy (VHE) gamma-ray counterparts around the IceCube-170922A resulted in no success around 22 September 2022. Only after 28 September, the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) telescopes observed the first VHE gamma rays from the blazar above 100 GeV. The ~41 h survey resulted in VHE γ-ray activity until 31 October 2017, nearly 45 days after the HE flare. Here we propose the extended GeV γ rays can be explained by taking two production channels, electron synchrotron self Compton and proton synchrotron for HE and VHE emissions, respectively. The 45 days of VHE emission from the peak of the HE flare can be explained with $L'_p \simeq 10^{47}$ erg/sec in the jet frame and magnetic field of 2.4 G, consistent with the $L_{\rm Edd}$ for a blackhole mass 5×10^9 $M_\odot$. With the same luminosity of accelerated protons, we explained the observed neutrino flux with proton-varying-ambient interaction.

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I. INTRODUCTION

Observational correlation of a >290 TeV, extremely high energy (EHE) neutrino event from the flaring direction of TXS 0506 + 056 blazar on 22 September 2017 by IceCube (IceCube-170922A) offers a potential breakthrough in understanding blazars and their hadronic emissions. The follow-up multi-wavelength study for the neutrino event has enabled a deep understanding of the hadronic models for blazars. Such a synchronized observation over the broad energy range also has the potential to reassess the current understanding of different blazar emission models.

A follow-up study of IceCube-170922A by *Fermi* large area telescope (LAT) reported a gamma-ray (0.1–300 GeV) excess of $3.6 \pm 0.5 \times 10^{-7}$ photons $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ (statistical error only) within time period 15–27 September 2017 from TXS 0506 + 056 blazar, establishing the temporal correlation of the neutrino event [1]. AGILE also confirmed γ-ray activity above 100 MeV from the source [2] with the maximum emission occurring one or two days before the neutrino event. Subsequently, a multiwavelength campaign started for TXS 0506 + 056. An excess in the x-ray spectra from $2.32^{0.33}_{-0.29}$ to $2.5^{0.23}_{-0.12}$ was observed on 27 September with 5 ks observation by Swift-XRT. ASAS-SN reported a rise of 0.5 mag in V band [3]. Table I lists the details of the follow-up observations of the blazar by different detectors around the globe.

A sub-GeV and TeV gamma-ray search was also followed-up after the neutrino event. The high energy sterioscopic system (H.E.S.S) telescope searched around the region of the neutrino event for two consecutive nights and found no significant VHE emissions [9]. VERITAS conducted a similar search, and no VHE source was found within 3.5° of the neutrino event [8]. VERITAS also looked for VHE emission from the blazar TXS 0506 + 056 between 28 and 30 September, and a nondetection resulted in an upper limit of 6.8×10^{-12} $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$ at 99% C.L. above 160 GeV [8]. The High Altitude Cherenkov examined its observation from 15–19 September, then from 21–27 September, and 23–24 September, and found no evidence of emission above 1 TeV [12]. The major atmospheric gamma imaging Cherenkov (MAGIC) telescopes reported the first VHE observation from the blazar under good weather conditions with 374 ± 62 excess photons, up to energy 400 GeV marking a 6.2σ excess over expected background between 28 September and 3 October [10]. Afterwards, [11] reported VHE activity between 1.3 to 40 days after the neutrino event from the source by monitoring nearly 41 h with MAGIC telescope.

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TABLE I. Multiwavelength observations of TXS 0506 + 056 blazar during different epochs.

Detector	Epoch (MJD)	Reference
VLA	58031, 58032, 58035, 58038	[4]
Kanata	58019, 58020, 58021	[5]
Swit UVOT	58019	[6]
Nustar	58025	[7]
Swift XRT	58023, 58026	[6]
Fermi-LAT	58011 to 58023	[1]
VERITAS	58018, 58019, 58024, 58026	[8]
H.E.S.S	58019, 58020, 58021	[9]
MAGIC	58024 to 58051	[10,11]

During this time, two periods of enhanced VHE emission were observed, one between Modified Julian Date (MJD) 58029–58030 (2017 October 3–4) and the second on MJD 58057 (2017 October 31). A similar activity is also observed during 2018 December 1 and 3 (MJD 58453 and 58455) while monitoring the period between 2017 November and 2019 February with a total of nearly 79 h [13]. The light curve of HE observed by Fermi-LAT in [13] also reports a flare in the period 58087–58091 MJD.

Several groups have made dedicated attempts to explain the multiwavelength flare and the neutrino event from TXS 0506 + 056 with leptonic and photohadronic emission [14–18], and also proton-proton interactions [19–23]. Time-dependent modeling of the TXS 0506 + 056 multiwavelength flare has been done by [14] with synchrotron and synchrotron self-Compton emission (SSC), and the neutrino event with photohadronic interactions. This scenario requires super-Eddington jet power to explain the neutrino event. Additionally, the x-ray emission constrains the photohadronic model of neutrino production. Reference [15] considered synchrotron and external Compton emission of relativistic electrons to explain the multiwavelength spectrum of the flare and radiatively subdominant hadronic emission to explain the IceCube-170922A event.

The detailed follow-up observations suggest an approximately 45 days of extended VHE activity following the neutrino-correlated Fermi-LAT HE flare peak. We explain this extended period of VHE activity with proton synchrotron. We explain the multi-wavelength observation of TXS 0506 + 056 blazar with a standard single-zone leptohadronic model. Specifically, the several hundred MeV HE emissions with electron SSC and the MAGIC VHE events with proton synchrotron. We also explain the neutrino event with proton and varying-ambient interaction inside the blob.

Section II discusses the multiwavelength data collected for different detectors and the Fermi-LAT data analysis for TXS 0506 + 056. This section also details the leptohadronic modeling of the source. Section III is dedicated to the resulting time delay from the lepton and hadronic model.

II. MULTIWAVELENGTH MODELING OF TXS 0506 + 056

We collected the synchronized multiwavelength data for TXS 0506 + 056 with the IceCube-170922 neutrino event; details are listed in Table I. We analyzed the Fermi-LAT data for the time of the multiwavelength search of the source. We model the emissions until the HE gamma rays with electron synchrotron and SSC, whereas the VHE gamma-ray events with proton synchrotron in the jet of TXS 0506 + 056.

A. HE gamma-ray light curve of TXS 0506 + 056

Using the Fermi-LAT light curve repository[1] we generated the light curve for TXS 0506 + 056 (4FGL J0509.4 + 0542) for seven days time bin with a region of interest (ROI) 10° centering the source, using the Fermipy Tool[2] for MJD 57997–58253 (2017 September 01 to 2018 May 15). The light curve is shown in Fig. 1 for the energy bin 100 MeV to 300 GeV. We observed three different activities within this period.

To study the time of the flares, we fitted each of the first two activities by a sum of exponential functional form [24], which depicts the rising and decay time of the flare. The functional form of the fitted function is

$$F(t) = 2F_0\left[\frac{\exp(t_0 - t)}{T_r} + \frac{\exp(t - t_0)}{T_d}\right]^{-1}, \qquad (1)$$

where F_0 is photon flux at time t_0, T_r and T_d represent the rise and decay times of the peak, respectively.

We obtained the rising and decay time as 4.00 ± 2.41 and 3.58 ± 2.02 days, respectively, with peak time at $t_0 = 58014.02 \pm 3.17$ for the neutrino correlated HE-flare during period 58008–58021 MJD. The $2(T_d + T_r)$ resulted in a flare period of 14 days. Figure 2 shows this flare with 3-day bin events as observed by Fermi-LAT. The fitted function for the flare is shown with dashed lines. The time of the neutrino event IC170922-A, shown with a dotted line in Fig. 2. Similarly, the rise and decay time obtained for the subsequent HE flare in the period 58087–58091 MJD (30 November 2017 to 4 December 2017) is 1.28 ± 0.25 and 2.95 ± 0.25 days, respectively.

Figure 1 also shows the VHE observations by MAGIC with square points. The two activities reported in [11] are shown within the shadow region for 28 September to 31 October. We associate these VHE activities with the neutrino correlated HE flare. Reference [13] reported another VHE activity from 1–3 December 2018. Our HE light curve analysis suggests another HE flare after the previously mentioned VHE activity. Hence we propose

[1] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/index.html.

[2] https://fermipy.readthedocs.io/en/0.14.1/_modules/fermipy/lightcurve.html.

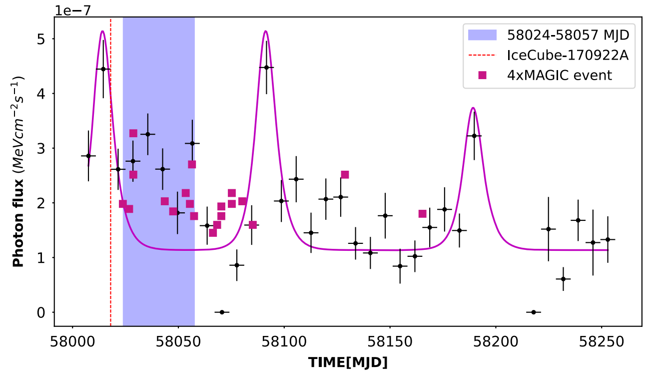

FIG. 1. The Fermi-LAT light curve of TXS 0506 + 056 blazar for energy range 1–300 GeV between MJD 57997-58253 with 7-day bin. The (red) dotted line shows the correlated IceCube-170922A neutrino event within the HE flaring episode 58008-58021 MJD. The shadow region indicates the period of VHE activity observed by MAGIC. The square points represent the MAGIC events reported in [13].

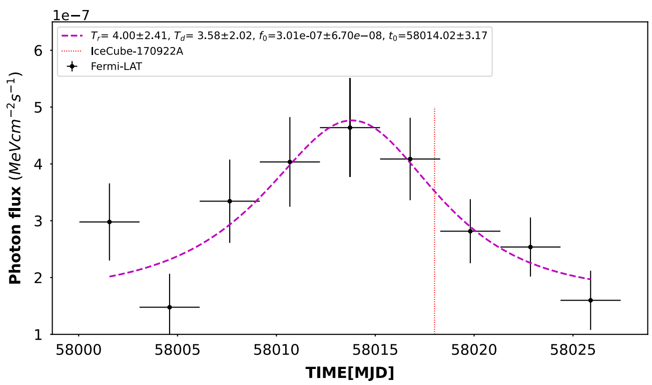

FIG. 2. The Fermi light curve of TXS 0506 + 056 for the flaring episodes 58008–58021 MJD in the energy range 0.1–300 GeV with 3 days time bin. The red line shows the correlated IceCube-170922A neutrino event falls in flaring episodes. The rising and decay time of the flare has been calculated by the fitting function(1).

this, more than one-year delayed VHE activity cannot be associated with the neutrino-correlated HE flare.

B. Fermi-LAT data analysis for SED

We have used the Fermi-LAT spectral energy distribution (SED) for MJD 58008 to MJD 58021, (from here onward, HE flare). We extract the SED using the Fermipy[3] tool. First, we collected the data from the LAT data server for the source TXS 0506 + 056 blazar within 1° radius ROI centered at the location of the source for the SED analysis. The point spread function (PSF) will be unaffected for low-energy photons, as there is no point source within the 1° region of the blazar listed in the fourth catalog (4FGL). The unbinned maximum-likelihood analysis was performed with the fermitool of version 2.2.0 and the instrument response function P8R3_SOURCE_V3. For our analysis, all the parameters of the Galactic diffuse model (gll_iem_v07.fits) and isotropic component iso_P8R3_SOURCE_V3_v1.txt are kept free within 1° of ROI. In the event section, Front + Back event type (evtype = 3), evclass = 128, and a zenith angle cut of 90° are applied based on 8 pass reprocessed source class. We have done the same analysis for MJD 58020 to MJD 58030 (24 September to 4 October). The SED points extracted are shown in Fig. 3 with circle (green) and up triangle (gray) points for the two periods, respectively.

[3]https://fermipy.readthedocs.io/en/latest/.

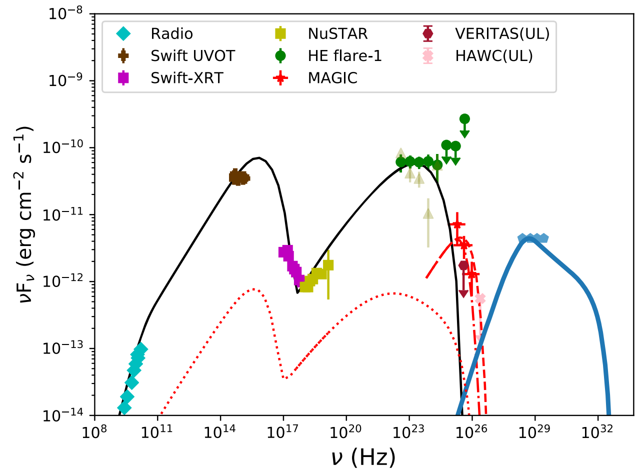

FIG. 3. Modeling of the multiwavelength observations of TXS 0506 + 056 blazar as a follow-up of IceCube-170922*A*. The (cyan) rectangle points represent radio observations by VLA, (brown) plus points show the optical, (purple) squares for Swift-XRT and (yellow) squares for hard x rays by Nustar. The (green) circles and (lemon) triangles represent HE γ rays by Fermi-LAT, and the (red) star shows the VHE γ rays by MAGIC. SED modeling: the electron synchrotron and SSC are shown with a (black) solid line and the proton synchrotron with a (red) dashed line. The gamma-ray emission after EBL contribution is shown with the (red) dot-dashed line. The thicker solid blue line represents the neutrino flux from $p-p$ interaction and the red dotted line is the cascade contribution.

C. Lepton modeling for HE gamma rays

We modeled the SED of the TXS 0506 + 056 source for the HE-flare period with the emissions from a single zone blob of radius, R. The accelerated electrons follow a spectral form $E_e^{\prime -\alpha_e}$ ($'$—represent jet frame) in the blob. The photon emissions in UV, optical, and soft x-ray energies from the source are explained with electron synchrotron in the blob magnetic field, B. The electron synchrotron cooling time is

$$t_{\mathrm{syn},e}^{\mathrm{obs}} \simeq 7.91\times 10^{-3}\delta_{16}^{-1}B_{2.4}^{-2}E_{e,10}^{\prime -1}\ \mathrm{days}, \qquad (2)$$

TABLE II. The parameters used in the lepto-hadronic model for the SEDs of TXS 0506 + 056 blazar.

Parameters	Values
z	0.336
d(pc)	1.79×10^9
δ	16
Γ_j	8
B(G)	2.4
R' (cm)	1.23×10^{16}
α_e	1.65
$\gamma'_{e,\min}$	4500
$\gamma'_{e,\max}$	2.1×10^4
α_p	2.01
$E'_{p,\min}$ (eV)	10^{14}
E'^{b}_{p} (eV)	2.95×10^{18}
$E'_{p,\max}$ (eV)	4.6×10^{19}
$L'_e(\mathrm{erg\,s^{-1}})$	2.9×10^{43}
$L'_p(\mathrm{erg\,s^{-1}})$	5.9×10^{47}

where $E'_{e,10} = E'_e/10^{10}$ eV. The hard x rays and HE gamma rays are modeled with time-dependent SSC by the relativistic electrons using GAMERA package [25]. The SED modeling to explain the data points is presented in Fig. 3. The modeling parameters details are listed in Table II.

D. Modeling proton synchrotron for VHE gamma rays

Relativistic protons in the blob also follow the nonthermal flux $E_p'^{-\alpha_p}$ with exponential cutoff. We consider the acceleration of relativistic protons in the same region up to the maximum energy $E'_{p,\max}$.

$$t_{\rm acc}^{\rm obs} \simeq 1.8 E'^{p}_{19} \delta_{16}^{-1} B_{2.4}^{-1} \eta_4 \text{ days}, \tag{3}$$

where gyro-factor $\eta_4 = \eta/4$.

We modeled the VHE emissions observed by MAGIC with proton synchrotron in the blob with the magnetic field, B. The synchrotron cooling time for the proton is

$$t_{{\rm syn},p}^{\rm obs} \simeq 7.52 B_{2.4}^{-2} \delta_{16}^{-1} E'^{-1}_{p,19} \text{ days}, \tag{4}$$

where $E'_{p,19} = E'_p/10^{19}$ eV.

E. Neutrinos from proton-proton interaction

We modeled the neutrino flux observed by IceCube from TXS 0506 + 056 with pp interaction following [22]. The gas density required to model the neutrino flux associated with IC170922-A obtained by [22] is $n_H = 1.68 \times 10^6$ cm^{-3}. The time required for pp interaction in the observer frame is

$$t_{pp}^{\rm obs} \simeq 3.52 \delta_{16}^{-1} n_{H,10^8}^{-1} \sigma_{pp}(E'_{p,16}) \text{ days}, \tag{5}$$

where $n_{H,10^8} = n_H/(10^8 \text{ cm}^{-3})$, $\delta_{16} = \delta/16$, $E'_{p,16} = E'_p/(10^{16} \text{ eV})$. We calculated the neutrino flux during the HE-flaring period only. We considered the ambient to be decreasing with time with index α_a,

$$n_H = n_{H,0} t^{-\alpha_a} \text{ cm}^{-3}. \tag{6}$$

One can expect such a variation due to the dynamics of the jet. We emphasize that accelerated protons interact with the ambient. Hence for fitting, we consider the evolution of the ambient over accelerated time. Hence, the ambient density becomes,

$$n_H \simeq (1.8 \times 10^6)^{-\alpha_d} n_{H,0} \eta_4^{-\alpha_d} B_{2.4}^{\alpha_d} E'^{p-\alpha_d}_{19} \text{ cm}^{-3}. \tag{7}$$

The parameter α_a and $n_{H,0}$ values are obtained from fitting the proposed model.

III. RESULTS AND DISCUSSION

The light curve of TXS 0506 + 056 at a redshift $z = 0.336$ observed by Fermi-LAT within the energy range 0.1–300 GeV suggests a HE flare from MJD 58008 to MJD 58021. IceCube-170922A neutrino event occurred at this flaring episode. Follow-up observations by ground-based imaging atmospheric Cherenkov telescopes (IACTs) like VERITAS, H.E.S.S reported nondetection with upper limits 1.2×10^{-11} cm^{-2} s^{-1} and 7.5×10^{-12} cm^{-2} s^{-1} respectively above >175 GeV. A total of 5 h of observations centring TXS 0506 + 056 between September 28 and 30 by VERITAS also reports no evidence of gamma-ray emission at the blazar location [8]. Whereas MAGIC reported VHE activity starting its observation from 28 September to 31 October 2017. Hence the multiwavelength model should incorporate and extend VHE emission for 45 days from the peak of the HE flare. We explain this extended time of VHE emission with the proton synchrotron.

Details of the model fitting parameters are listed in Table II, and the SED model is shown in Fig. 3. The lepton modeling for the HE flare requires a magnetic field of B = 2.4 Gauss in a R$'$ = 1.23×10^{16} cm blob with doppler $\delta = 16$ and Lorentz factor $\Gamma = 8$. The observed HE-flare time, 14 days, is more than the light crossing time, $\frac{R'(1+z)}{c\delta}$. The electron spectra follows a spectral index $\alpha_e = 1.65$ within energies $\gamma'_{e,\min} = 4500$ to $\gamma'_{e,\max} = 2 \times 10^4$. This results in a jet frame electron luminosity, $L'_e = 2.9 \times 10^{43}$ erg/sec. The electron synchrotron and SSC model are shown in Fig. 3 with a solid (black) line.

A. Proton synchrotron as a probe for the extended VHE events

We calculated the neutrino flux and the VHE energy photons with the proton-proton interaction and proton synchrotron in the same magnetic field of 2.4 G, respectively. The modeling resulted with a proton spectrum index, $\alpha_p = 2.01$ within energy $E'_{p,\min} = 10^{14}$ eV to

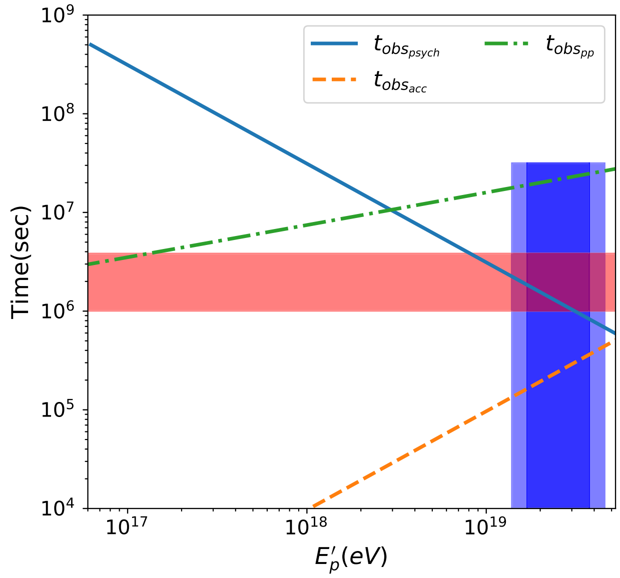

FIG. 4. The orange dashed line is the proton synchrotron cooling time, and the blue shaded region marks the proton energy region for which proton synchrotron cooling time is between 11 to 44 days in the observer frame.

$E'_{p,\max} = 5 \times 10^{19}$ eV. The $E'_{p,\max}$ is a few times more than the Hillas criterion, $E_{p,\max} = qRB$, q charge of an electron. However, as suggested by [26], the maximal energy of the particles in the jet of a blazar is determined by radiation losses rather than by the Hillas condition following

$$E'_{p,\max} = 3.7 \times 10^{19}\ \mathrm{eV}\left(\frac{M_{\mathrm{BH}}}{10^8\ \mathrm{M}_\odot}\right)^{3/8}. \qquad (8)$$

The observer frame proton synchrotron (solid), and the proton-proton interaction (dash-dot) timescale over the energy range $E'_{p,\min}$ to $E'_{p,\max}$ in the blob magnetic field of 2.4 G, are shown in Fig. 4. The energy where the synchrotron will dominate over the pp interaction, $E'^{b}_{p} = 2.95 \times 10^{18}$ eV. We obtained this for the ambient parameters, $n_{H,0} = 3.8 \times 10^{10}$ and $\alpha_d = 0.4$. These values are obtained such that we could explain both neutrino flux as well as VHE events. We calculated the neutrino flux within energy range $E'_{p,\min}$ to E'^{b}_{p}, shown with a thicker solid line in Fig. 3. The secondary cascade radiations produced by pp interaction using [27,28] are shown with the dotted line in the same figure. The typical proton energy required for producing synchrotron photons of critical frequency, ν_c in the observer frame is

$$E'_p = 4.38 \times 10^{19}\ \mathrm{eV}\left(\frac{\nu_{c,25}}{B_3}\right)^{1/2}\frac{(1+z)}{\delta}, \qquad (9)$$

where $\nu_{c,25} = \frac{\nu_c}{10^{25}}$.

By considering the M_{BH} of TXS 0506 + 056 as, $5 \times 10^9\ \mathrm{M}_\odot$ [14], our $E'_{p,\max}$ is consistent with Eq. (8). The total fitted jet frame proton luminosity is $L'_p = 5.9 \times 10^{47}$ ergs/ sec, which is again consistent with the Eddington luminosity of black-hole mass taken for TXS 0506 + 056. The proton synchrotron gamma-ray emission is shown in Fig. 3 with dashed (red) lines. The VHE γ-ray emissions from the source are attenuated due to interaction with extragalactic background light (EBL). We calculated this suppression using[4] for the source at a distance $d = 1.79 \times 10^9$ pc. The gamma-ray emission after this contribution is shown with dot-dashed (red) lines in Fig. 3.

The blue-shaded region shows the energy range of the protons in the jet frame corresponding to the observed VHE γ-ray event range. The $t_{\mathrm{obs}_{\mathrm{psync}}}$ for the energy range $E'_p = 1.38 \times 10^{19}$ to 4.57×10^{19} eV is 44 to 11 days, as shown with the horizontal (red) shaded region. The emissions above the mentioned E'_p get suppressed by the EBL. Our model gives a possible explanation for the extended VHE emission from the source with the varying ambient profile.

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