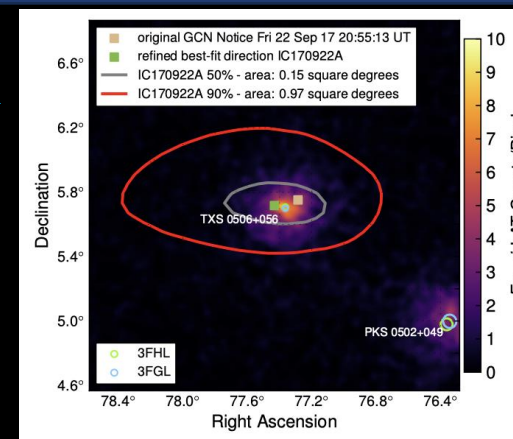
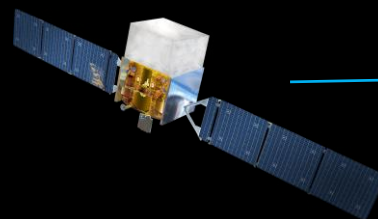


Probing a cosmogenic origin of astrophysical neutrinos and cosmic rays using gamma-ray observations of TXS 0506+056

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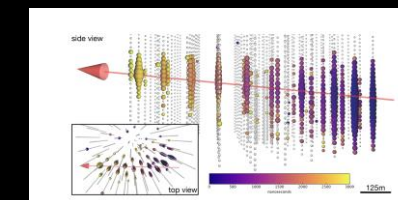


TXS 0506+056



<https://arxiv.org/pdf/1807.08816>

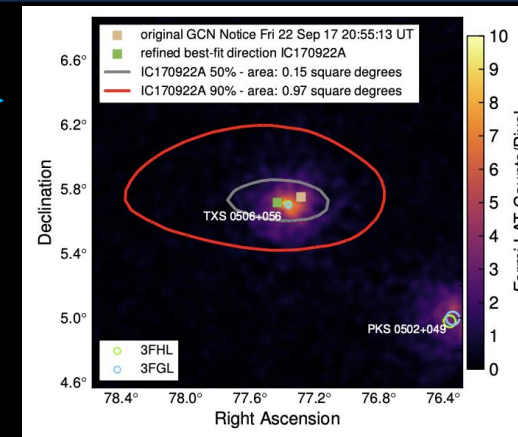
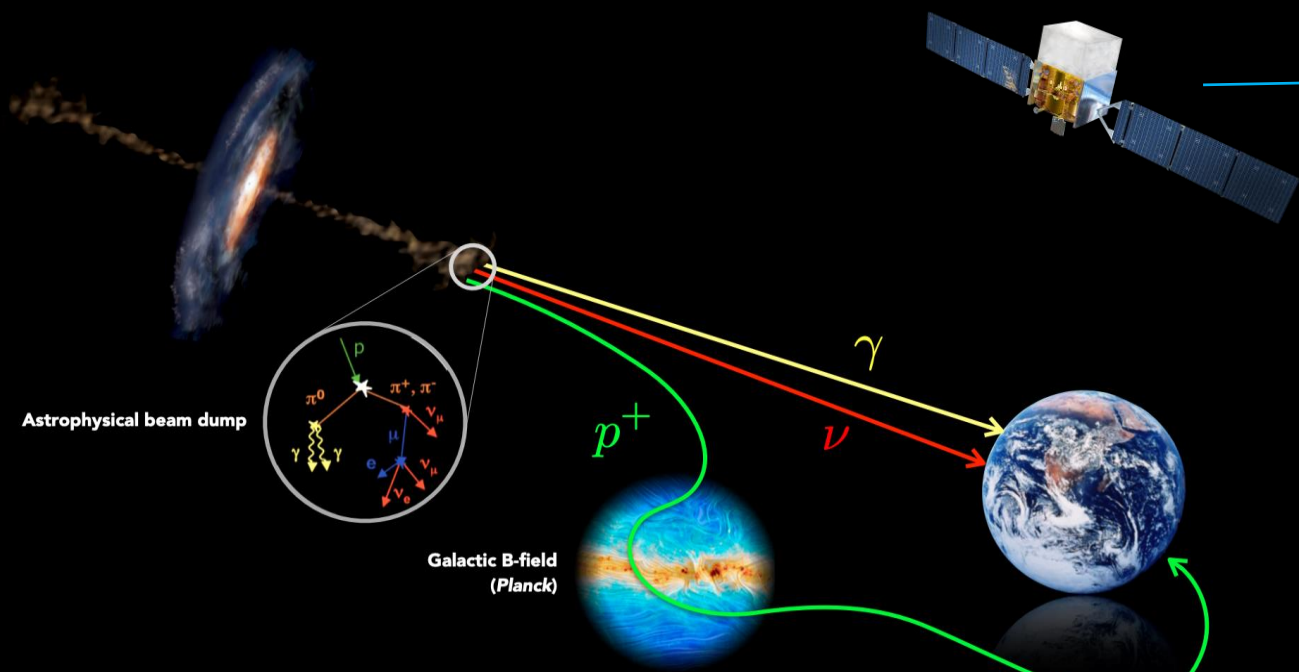
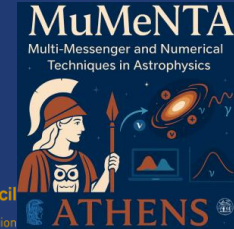
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- On Sept 22, 2017 IceCube reported the detection of a neutrino alert with a most probable energy of 290 TeV. This event was found to have a best-fit reconstructed direction to within 0.1° from the sky position of a blazar, TXS 0506+056 ($z=0.337$)

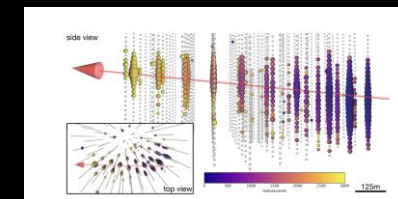


TXS 0506+056

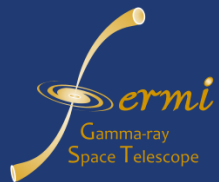


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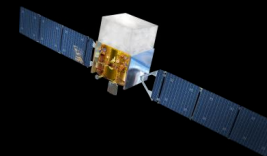
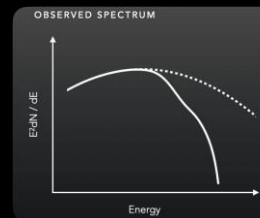
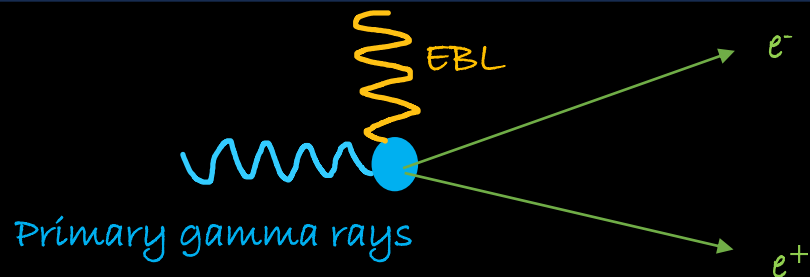
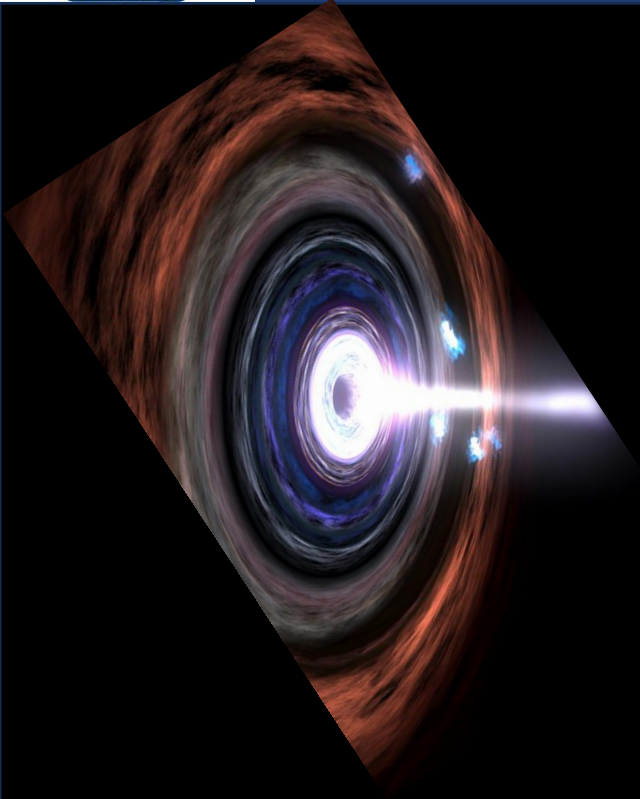
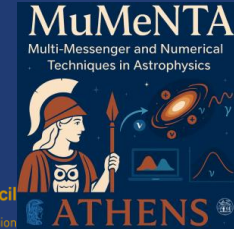
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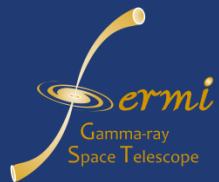


- On Sept 22, 2017 IceCube reported the detection of a neutrino alert with a most probable energy of 290 TeV. This event was found to have a best-fit reconstructed direction to within 0.1° from the sky position of a blazar, TXS 0506+056 ($z=0.337$)
- The correlation between the neutrino event and a gamma-ray flare of TXS 0506+056, measured with the Fermi-LAT, was found to be statistically significant at a level of 3σ . The first detection of this blazar in the VHE regime was with MAGIC at a significance level of 6.2σ in Oct 2017. VERITAS detected TXS 0506+056 at a significance of 5.8σ over a 35 hr dataset between Sept 2017 and Feb 2018
- Provides evidence that blazars accelerate cosmic rays that produce neutrinos and gamma rays

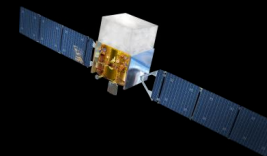
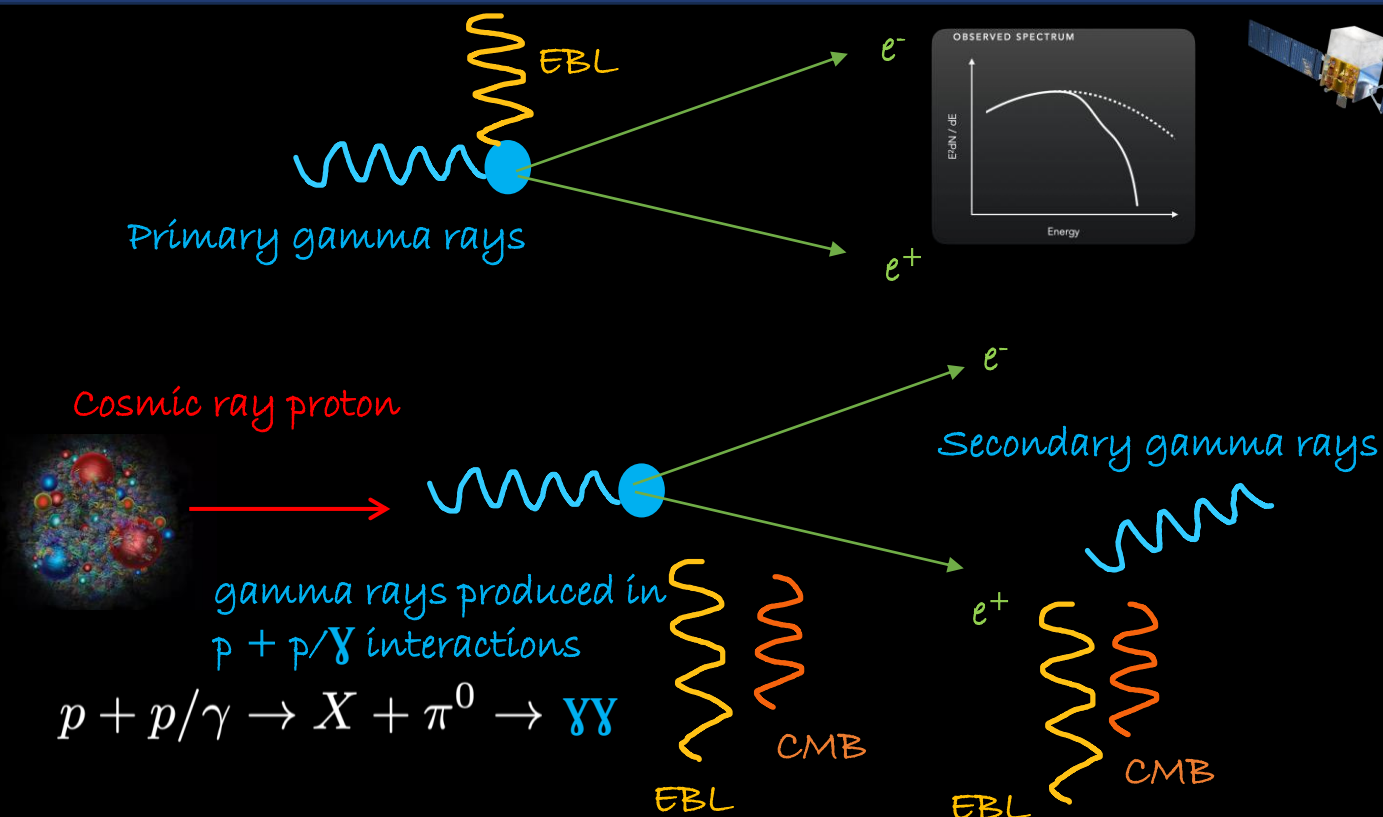
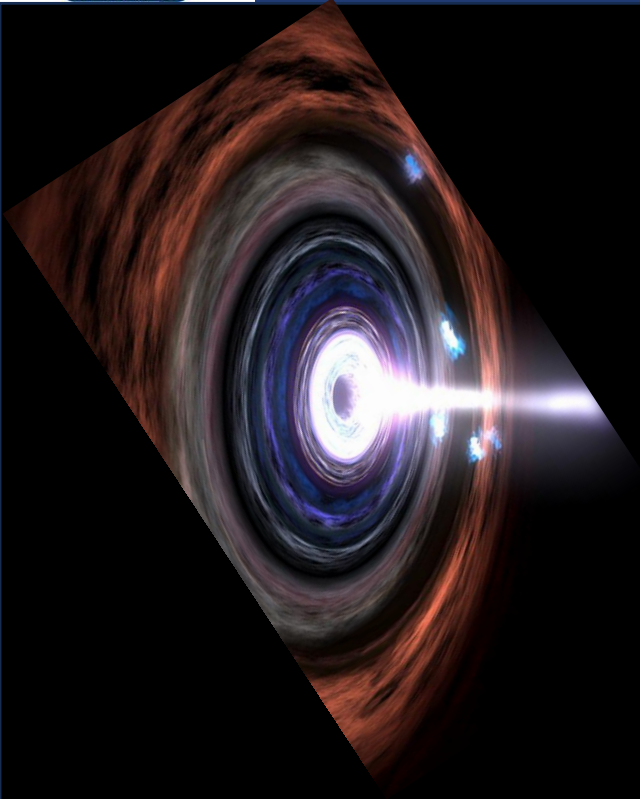
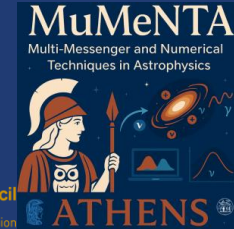


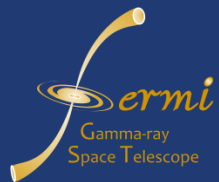
Secondary gamma rays from line-of-sight cosmic ray interactions



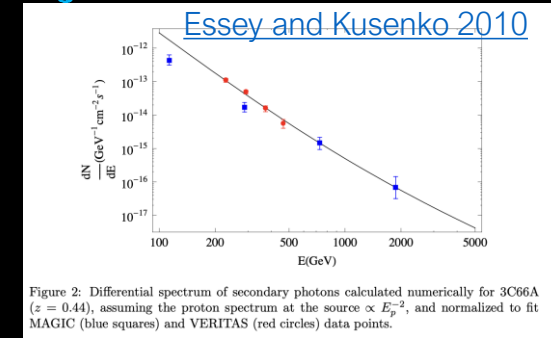
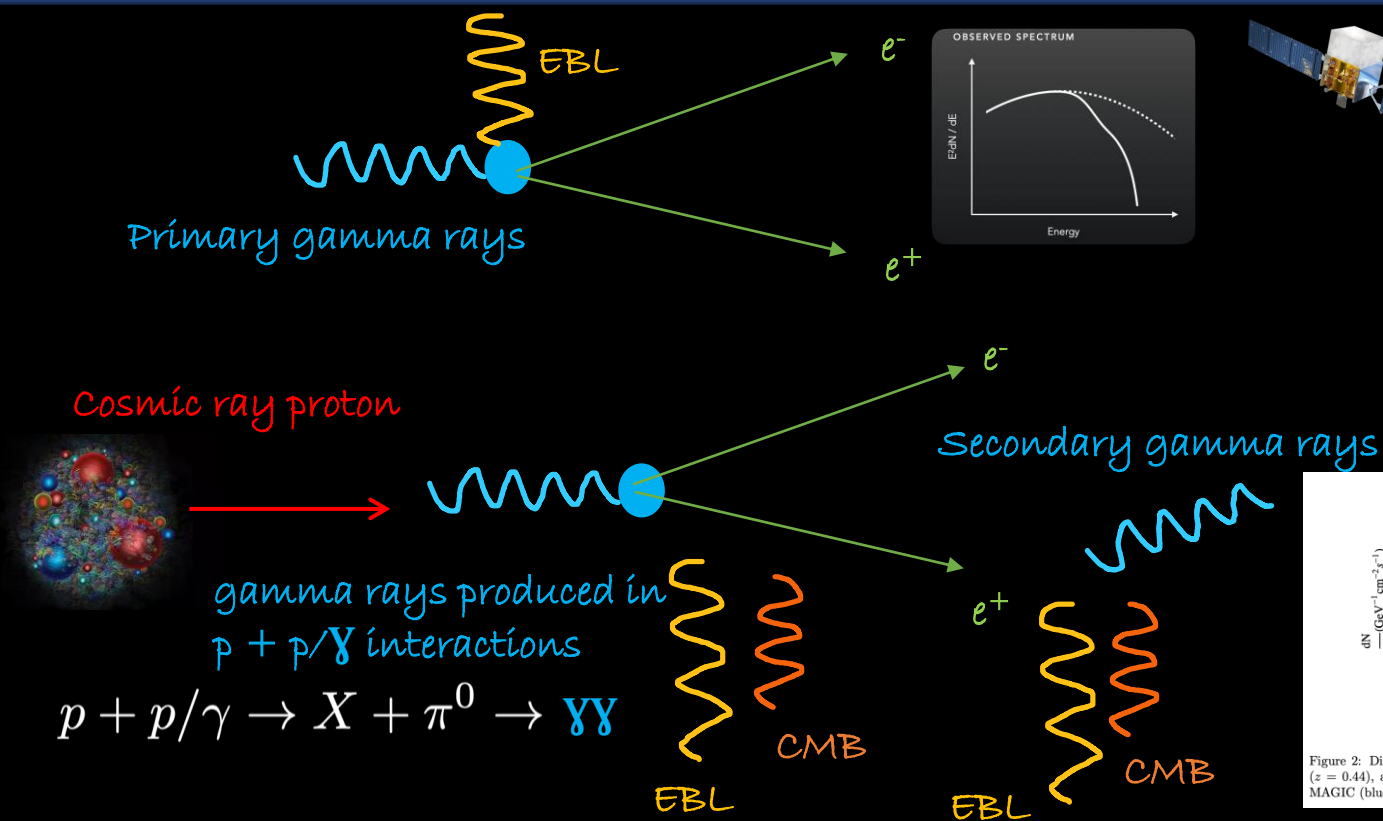
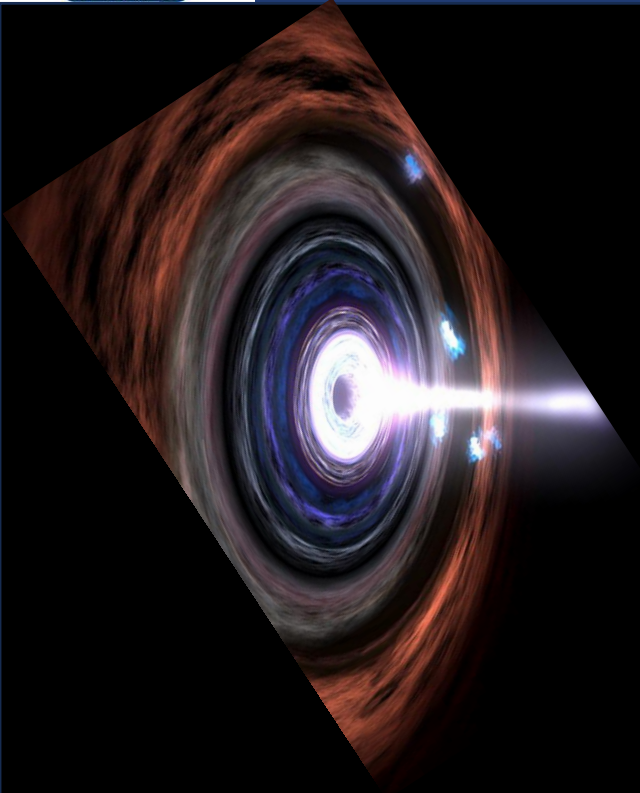
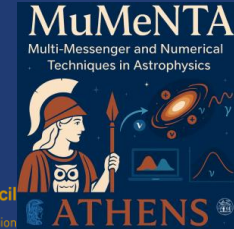


Secondary gamma rays from line-of-sight cosmic ray interactions





Secondary gamma rays from line-of-sight cosmic ray interactions



- In addition to the gamma rays and neutrinos produced at the source, there could be a contribution from the (so-called) cosmogenic neutrinos and gamma rays produced along the line-of-sight
- These result from the interactions between cosmic rays and the background photons, namely the extragalactic background light (EBL) and the cosmic microwave background (CMB), producing electron-positron pairs
- These pairs can inverse Compton scatter the CMB photons up to gamma-ray energies and subsequently initiate electromagnetic cascades



We report on a new search for cosmogenic proton cascade emission in TXS 0506+056, using a combined data set from the Fermi-Large Area Telescope and VERITAS



We compare the gamma-ray spectrum and neutrino observations with the predictions of cosmic-ray induced cascades in intergalactic space



We determine the best-fit parameters of a proton emission spectrum describing the data by modeling the observed gamma-ray spectrum as a combination of the primary spectrum, whose origin we remain agnostic about, and the cascade spectrum



Our method has the advantage that the only assumption we make is that cosmic rays are accelerated in the source and subsequently escape



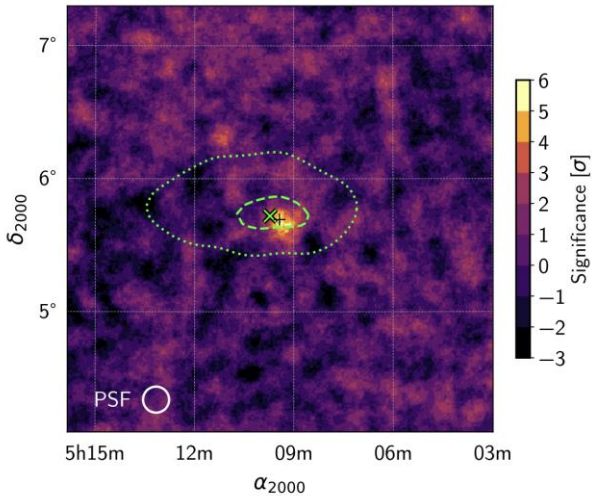
We also obtain constraints on the proton escape luminosity, using Monte Carlo simulations

- Located at the Fred Lawrence Whipple Observatory in southern Arizona at 1,268 m a.s.l.
 - CTAO prototype SCT telescope co-located
- Finished 18th year of full-array operations in Summer 2025
- VERITAS observations of TXS 0506+056:
 - VERITAS detected TXS 0506+056 at a significance of 5.8σ over a 35 hr dataset between Sept 2017 and Feb 2018. For the cascade study, we are using the published VERITAS dataset from the flare period (MJD 58019 – MJD 58155)

Field of view	3.5° diameter	Angular Resolution (r_{68})	$\sim 0.08^\circ$ @ 1 TeV
Energy Range	~ 85 GeV to ~ 30 TeV	Energy Resolution	$\sim 17\%$
Effective Area	$\sim 10^5$ m ² at 1 TeV	Sys. Errors: Flux	$\sim 20\%$
Sensitivity	1% Crab in <25 h	Sys. Errors: Spectral Index	~ 0.1

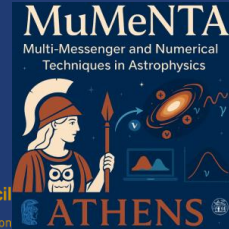


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Multiwavelength lightcurves

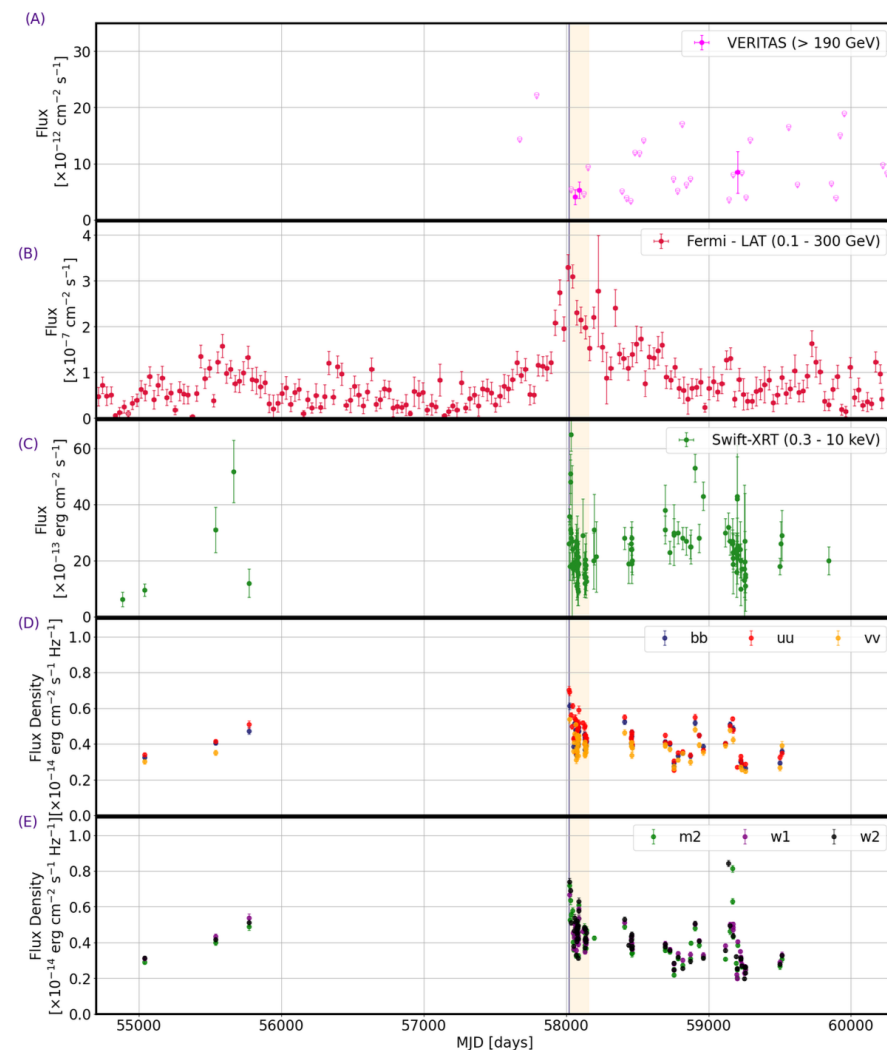


- Using Fermi-LAT spectrum contemporaneous with VERITAS data from the flare period (MJD 58019 – MJD 58155) . Significance: 45.4σ , Flux: $(2.3 \pm 0.2) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$
- Swift-XRT observations of TXS 0506+056 were taken for the time interval between 4th August 2008 and 1st October 2023 (MJD 54683 - 60218)
- We also have Swift-UVOT observations in the UW1, UW2, UM2, U, B, and V filters of the optical-UV band for the same time period
- Shown alongside is the final multi-wavelength lightcurve
- Note that only the time interval corresponding to the VERITAS flare period and the corresponding Fermi-LAT data is considered in the cascade study

Figure 1. Multiwavelength lightcurves of TXS 0506+056 between MJD 54683 and MJD 60218, which corresponds to midnight on 2008 August 4 until midnight on 2023 October 1. The blue narrow band corresponds to the IceCube alert, IceCube-170922A, observed on 2017 September 22 (MJD 58018). The orange shaded region corresponds to the time interval between 2017 September 23 and 2018 February 6, investigated in A. U. Abeysekara et al. (2018). (A) Monthly binned VHE lightcurve for VERITAS observations above an energy threshold of 190 GeV. Upper limits at a 95% confidence level are quoted for observations with a significance of lower than 2σ . (B) Fermi-LAT lightcurve in 30 day bins in the 0.1–300 GeV band. (C) Swift-XRT energy flux in the 0.3–10 keV band. (D) and (E) Optical/UV flux observations with the Swift-UVOT in the UW1-, UW2-, UM2-, U-, B-, and V-band filters, split into the UV and optical components for enhanced readability.

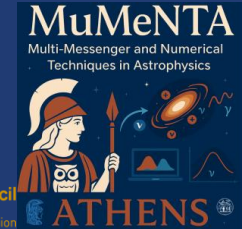
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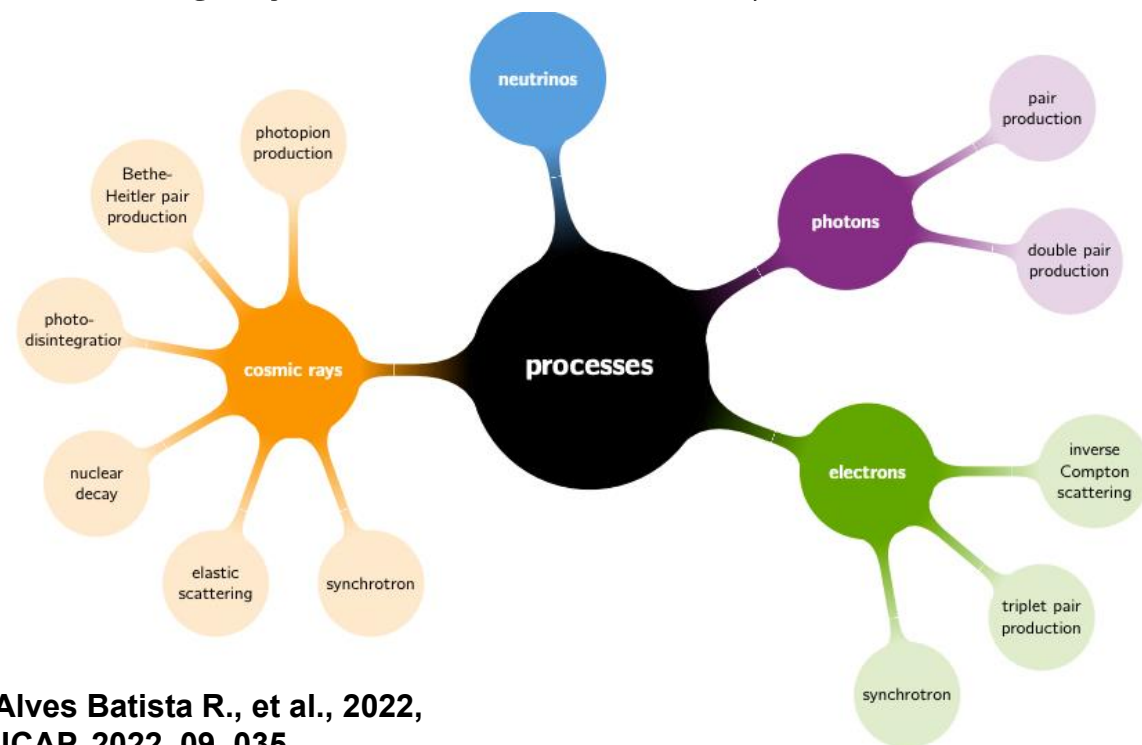


Modeling the proton cascade contribution



Simulate full development of cosmic-ray cascades using CRPropa v3.1.6, including all relevant interactions and energy losses (pion production, pair production, IC scattering, synchrotron, adiabatic)

- Consider only cascade photons arriving with a time delay shorter than 6 months, matching the blazar's active phase during the 2017 flare
- Simulations are reweighted to produce energy-dependent sky maps for arbitrary input spectra; assume jet axis aligned with the line of sight
- For each magnetic field, 1000 independent simulations are combined into a single spectrum
- Results shown correspond to a magnetic field $B=10^{-16}$ G, consistent with lower-limit estimates for IGMF in cosmic voids



Alves Batista R., et al., 2022,
JCAP, 2022, 09, 035

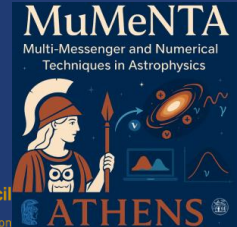
Figure 4. Schematic view of the interactions and energy-loss processes implemented in CRPropa 3.2 for different types of particles.



Modeling the proton cascade contribution



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- We inject protons in energies between 10^{12} eV and 10^{18} eV
- We choose a proton injection that follows a power law function with a high-energy exponential cut-off:

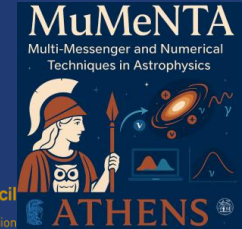
$$\frac{dN_{\text{inj}}}{dE_p} = \kappa E_p^{-\alpha_p} \exp\left(-\frac{E_p}{E_{p, \text{max}}}\right)$$

where the subscripts represent cascade emission and proton energies

- Spectral index $\alpha_p \in [1.8, 2.6]$; cut-off energy $E_{p, \text{max}} \in [10^{15}, 10^{19}]$ eV
- Fewer particles are injected at higher energies to reduce computation time
- All secondaries are tracked; tracking ends below 0.1 GeV or beyond 4 Gpc
- Minimum rigidity at injection: 50 GV (to avoid producing sub-Fermi photons)
- Cosmology: standard Λ CDM



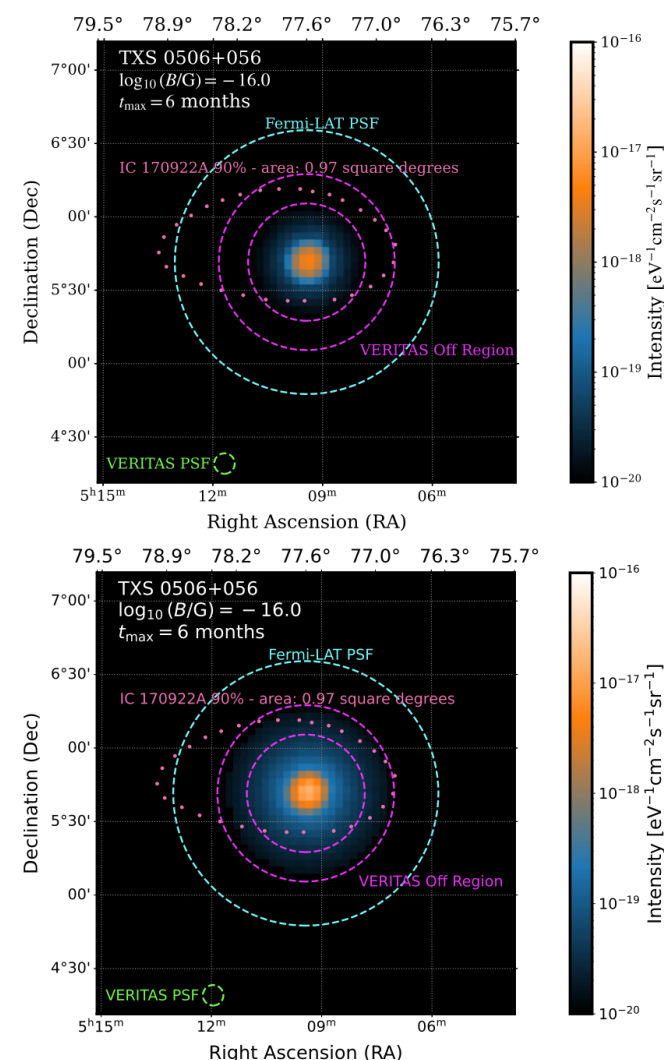
Modeling the proton cascade contribution



- Show simulated cascade photon flux per solid angle for $B = 10^{-16}$ G
- PSF of Fermi-LAT and VERITAS shown for comparison
- When analyzing VERITAS data, include only cascade photons arriving within the ON region
- Contamination of the VERITAS OFF region by cascade photons is later found to be $\leq$ few % for injection parameters within the 2σ exclusion region (e.g., 0.004 expected cascade photons in OFF region for best-fit case vs. 16,174 total OFF events)

Figure 2. The simulated photon cascade flux per solid angle for the best-fit spectrum, i.e., the subdominant cascade, assuming an LP $\times$ EBL primary photon spectrum (top) and a PLE $\times$ EBL primary photon spectrum (bottom). The values assumed for the maximum blazar activity time and magnetic field are $t_{\text{max}} = 6$ months and $B = 10^{-16}$ G, respectively. The pink dotted line indicates the 90% confidence level region for the neutrino event IceCube-170922A (from IceCube Collaboration et al. 2018b). The green, cyan, and purple dashed lines represent the PSFs of the VERITAS and Fermi-LAT observations and the VERITAS OFF region, respectively.

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Modeling the combined spectrum

- The primary spectrum is modeled as:

$$\frac{dN_{\text{prim}}}{dE_{\gamma}} = N_0 \left(\frac{E_{\gamma}}{E_0} \right)^{-\Gamma_{\text{LP}} - \beta \ln \left(\frac{E_{\gamma}}{E_0} \right)} \exp(-\tau_{\gamma\gamma})$$

Log parabola (LP) x EBL

$$\frac{dN_{\text{prim}}}{dE_{\gamma}} = N_0 \left(\frac{E_{\gamma}}{E_0} \right)^{-\Gamma_{\text{PLE}}} \exp \left(-\frac{E_{\gamma}}{E_{\gamma, \text{cut}}} \right) \exp(-\tau_{\gamma\gamma})$$

Power law with exponential cutoff (PLE) x EBL

- The combined spectrum is expressed as a sum of the primary gamma-ray spectrum and the contribution of the proton cascade component to the spectrum
- The combined Fermi-LAT and VERITAS spectrum is used to obtain the χ^2 values over a grid of proton injection parameters (α_p and $E_{p, \text{max}}$) for fixed values of magnetic field ($B = 10^{-16}$ G in the following example) and the [Dominguez 2011](#) EBL model throughout

Table 1

A Combination of Best-fit Spectral Parameters Obtained from the Joint Fit to the Combined Gamma-Ray Spectrum for TXS 0506+056

Fit Function	N_0 ($10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$)	Γ_{LP}	β	E_0 (TeV)	Γ_{PLE}	$E_{\gamma, \text{cut}}^{-1}$ (TeV^{-1})	α_p	$E_{p, \text{max}}$ (eV)	κ ($\text{cm}^{-2} \text{ s}^{-1} \text{ eV}^{-1}$)	$\chi^2/\text{n.d.f.}$
LP $\times$ EBL	3.3 ± 0.5	3.14 ± 0.02	0.08 ± 0.05	1	...	...	...	...	...	1.62
(LP $\times$ EBL) + cascade	3.3 ± 0.5	3.14 ± 0.02	0.08 ± 0.05	1	...	...	2.0	1.3×10^{16}	6.24×10^{-20}	1.77
PLE $\times$ EBL	143.7 ± 35.4	...	...	1	2.06 ± 0.03	12.03 ± 1.57	...	...	...	2.53
(PLE $\times$ EBL) + cascade	147.6 ± 36.3	...	...	1	2.06 ± 0.03	12.74 ± 1.68	2.0	7.5×10^{15}	6.24×10^{-19}	2.75

Note. Observed with Fermi-LAT and VERITAS. The final column states the $\chi^2/\text{n.d.f.}$ values obtained for each model.

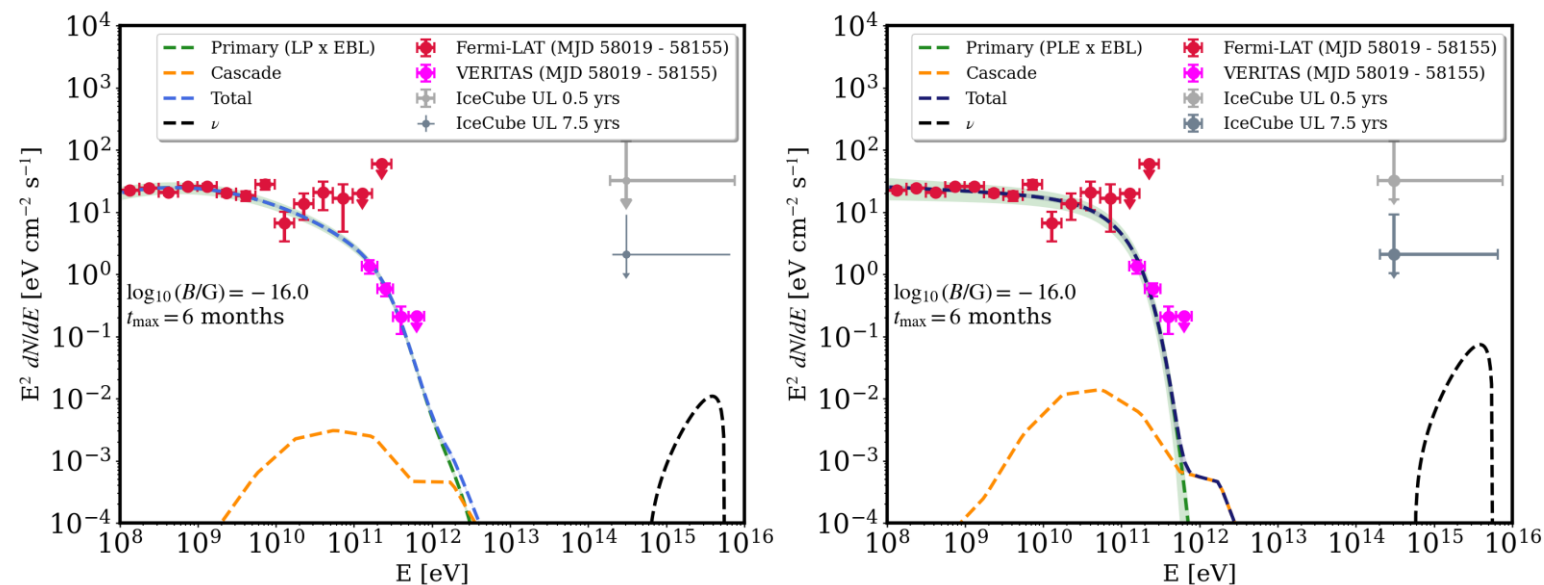
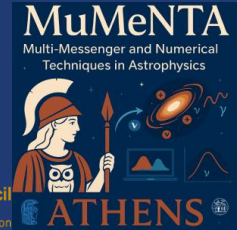


Figure 3. The observed Fermi-LAT and VERITAS spectra of TXS 0506+056 (red and magenta markers, respectively), together with the total best-fit spectrum (dashed blue line, including uncertainties). This is the sum of the primary photon spectra LP $\times$ EBL (top) and PLE $\times$ EBL (bottom) (dashed green lines, including uncertainties) and the cascade components (dashed orange lines, including uncertainties), respectively. Spectral points are shown as upper limits if the detection significance is below 2σ . The SEDs of the predicted cosmogenic neutrinos are shown in black. The spectral curves for the proton cascades and the neutrino spectrum correspond to the best-fit proton injection spectral parameters when considering an LP $\times$ EBL primary photon spectrum and a PLE $\times$ EBL primary photon spectrum, respectively (see Table 1). The values assumed for the maximum blazar activity time and magnetic field are $t_{\text{max}} = 6$ months and $B = 10^{-16}$ G, respectively. Also shown are the representative neutrino flux upper limits that produce, on average, one detection like IceCube-170922A over a period of 0.5–7.5 yr assuming an injection spectrum of $dN/dE \propto E^{-2}$ at the most probable neutrino energy, $E_\nu = 311$ TeV (IceCube Collaboration et al. 2018b).



Constraints on spectrum of protons escaping source



- The stat-surfaces obtained over the parameter space investigated for the proton injection parameters are shown
- The color scale denotes the difference in χ^2 values obtained at each point and the minimum χ^2 obtained over the entire parameter space
- The proton injection parameters corresponding to the minimum χ^2 value obtained over the entire parameter space are shown with a blue star
- Also shown are the 2σ uncertainty contours, depicting regions of the parameter space not compatible with the gamma ray data. The dashed green curves represent points in the parameter space that correspond to the same proton escape luminosity

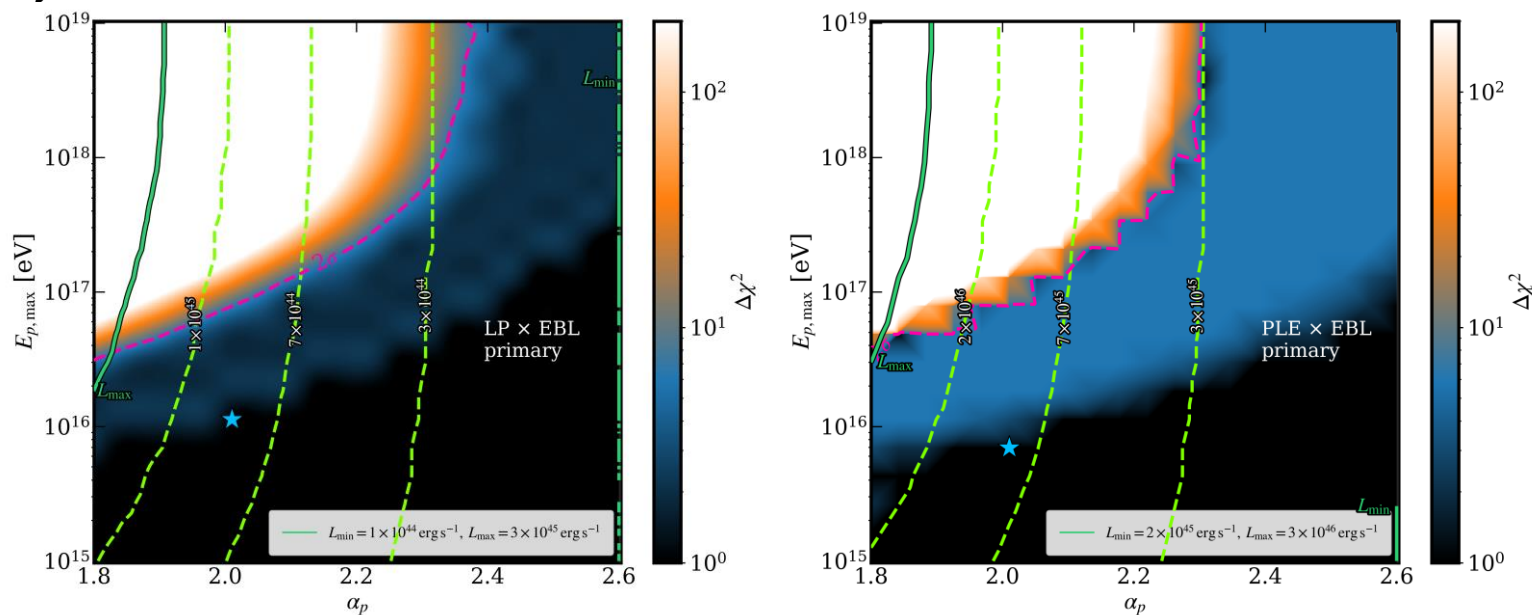
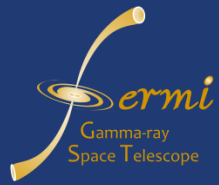
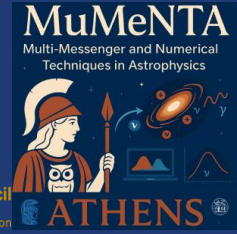


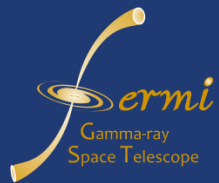
Figure 4. The stats-surfaces obtained over the investigated parameter space of the proton spectrum, $E_{p,max}$ and α_p , assuming an LP $\times$ EBL primary photon spectrum (top) and a PLE $\times$ EBL primary photon spectrum (bottom). The values assumed for the maximum blazar activity time and magnetic field are $t_{max} = 6$ months and $B = 10^{-16}$ G, respectively. The color scale denotes the $\Delta\chi^2$, the difference between the χ^2 values at each point, and the minimum χ^2 value obtained over the entire parameter space. The blue stars mark the best-fit parameter combination corresponding to the global minimum χ^2 and listed in Table 1. The dashed purple curves show 2σ uncertainty contours. The dashed green curves represent points in the parameter space that correspond to the same proton escape luminosity, as labeled. The dark green curves mark the lower and upper bounds on the proton escape luminosity, denoted as L_{min} and L_{max} , respectively, and shown in the legend.



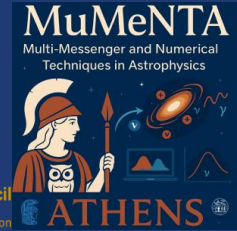
Constraints on fraction of escaped protons



- We have derived constraints on the spectrum of the protons escaping the source (and therefore on the luminosity of escaped protons)
- This was found to be dependent on the assumed gamma-ray spectrum



Constraints on fraction of escaped protons



- We have derived constraints on the spectrum of the protons escaping the source (and therefore on the luminosity of escaped protons)
- This was found to be dependent on the assumed gamma-ray spectrum
- We now flip this by fixing the proton spectral parameters and derive constraints on the fraction of escaped protons
- We consider the parameters from [Keivani et al. \(2018\)](#), $\delta=24.2$, $L_{p,max} = 1.9 \times 10^{50}$ erg/sec, keep proton parameters, $\alpha_p \in [1.8, 2.6]$ and $E_{p,max}=3.6 \times 10^{17}$ eV, and vary just the cascade emission normalization, κ , and hence the proton escape luminosity

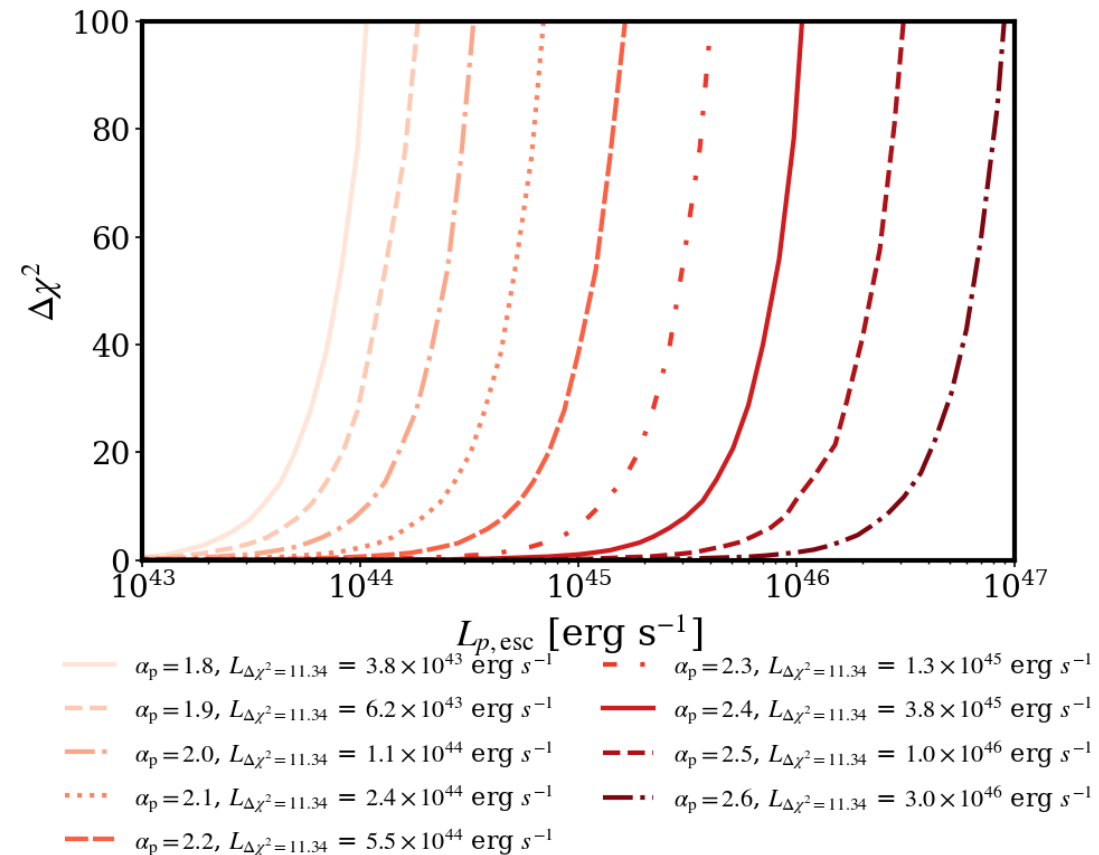
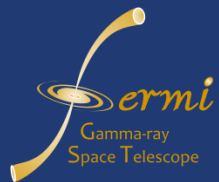
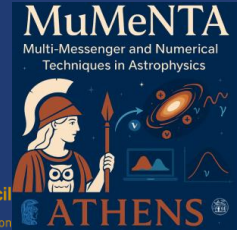


Figure 5. The $\Delta\chi^2$ values obtained as a function of the proton escape luminosity $L_{p,esc}$. The high-energy cutoff is fixed at $E_{p,max} = 3.6 \times 10^{17}$ eV, and the proton spectral index is fixed in the interval $\alpha_p \in [1.8, 2.6]$ at intervals of 0.1.



Constraints on fraction of escaped protons



- Our value for the proton-escape fraction is $\sim 10^{-4}$ which is reasonable given the extreme environment within AGN, where many protons would interact with surrounding matter and magnetic fields, losing energy or being deflected before they can escape
- This fraction represents a lower limit, as it is derived from a specific maximum proton luminosity model
- Consequently, while it indicates that only a small portion of protons injected into the AGN jet escape into intergalactic space under this particular assumption, the actual escape fraction could be higher depending on the true proton luminosity of the source

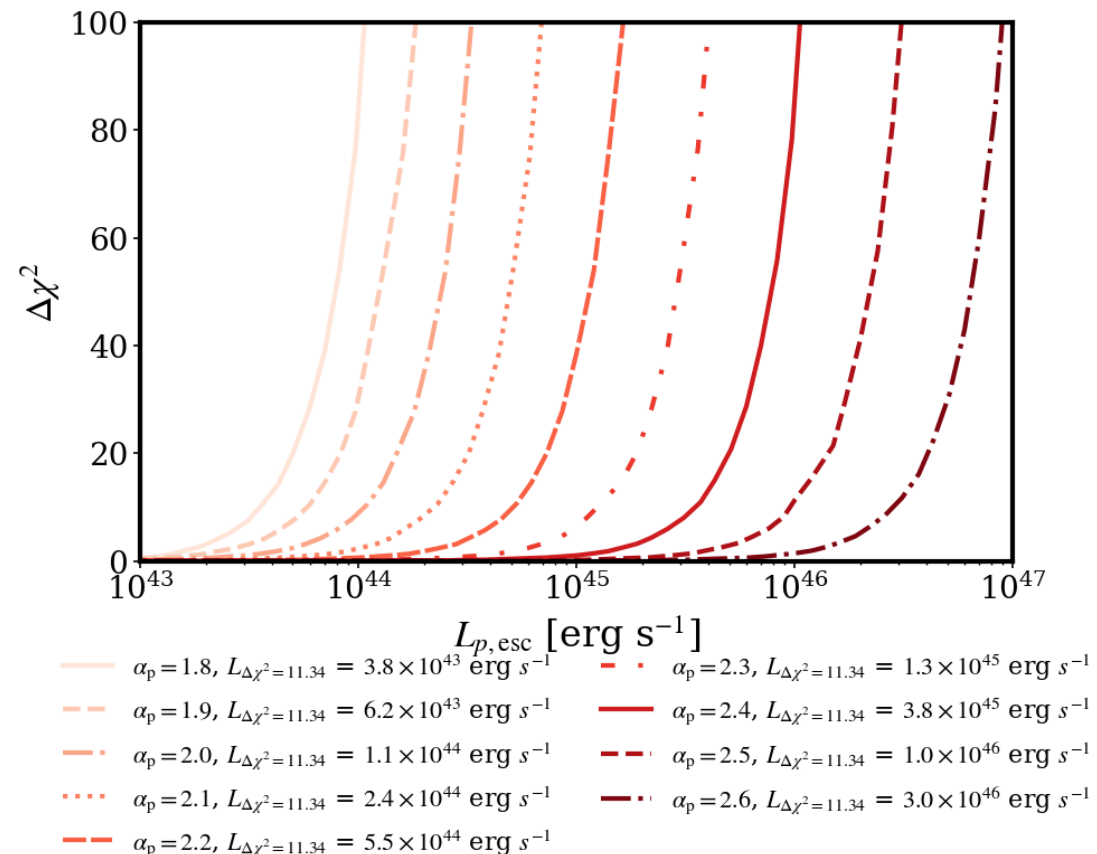


Figure 5. The $\Delta\chi^2$ values obtained as a function of the proton escape luminosity $L_{p,esc}$. The high-energy cutoff is fixed at $E_{p,max} = 3.6 \times 10^{17} \text{ eV}$, and the proton spectral index is fixed in the interval $\alpha_p \in [1.8, 2.6]$ at intervals of 0.1.



Conclusions

We report on a new search for proton cascade emission in TXS 0506+056, using a combined data set from the Fermi Large Area Telescope and VERITAS

We also present the upper limits obtained in over 5 years of follow-up of TXS 0506+056, as well as contemporaneous multiwavelength data

We model the development of proton cascades in the intergalactic medium using CRPropa

We find no evidence for cascade emission in the combined Fermi-LAT and VERITAS data. Nevertheless, we use our results to derive constraints on the spectrum of the protons escaping the source

The combined Fermi-LAT and VERITAS spectrum is used to obtain the χ^2 values over a grid of proton injection parameters (a_p and $E_{p, \max}$) for fixed values of magnetic field

We then fix the proton spectral parameters to derive constraints on the fraction of escaped protons. This represents a lower limit based on a specific maximum proton luminosity model and suggests only a small fraction of protons escape the AGN jet under this assumption

Special thanks to:

- Connor Mooney for leading the VERITAS primary analysis, as well as Swift analysis
- Manuel Meyer for help with the CRPropa simulations and discussion
- The VERITAS and Fermi-LAT Collaborations, especially the working group conveners and reviewers

If you want to learn more, please check out our work at:
<https://iopscience.iop.org/article/10.3847/1538-4357/ae1d72>

Photo credit: The VERITAS Collaboration

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Probing a Cosmogenic Origin of Astrophysical Neutrinos and Cosmic Rays Using Gamma-Ray Observations of TXS 0506+056

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On behalf of my new Greek friends
“Thank you for listening!”

