SDU University of Southern Denmark

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Probing the origin of astrophysical neutrinos and ultra-high energy cosmic rays using Fermi-LAT VERITAS observations of TXS 0506+056

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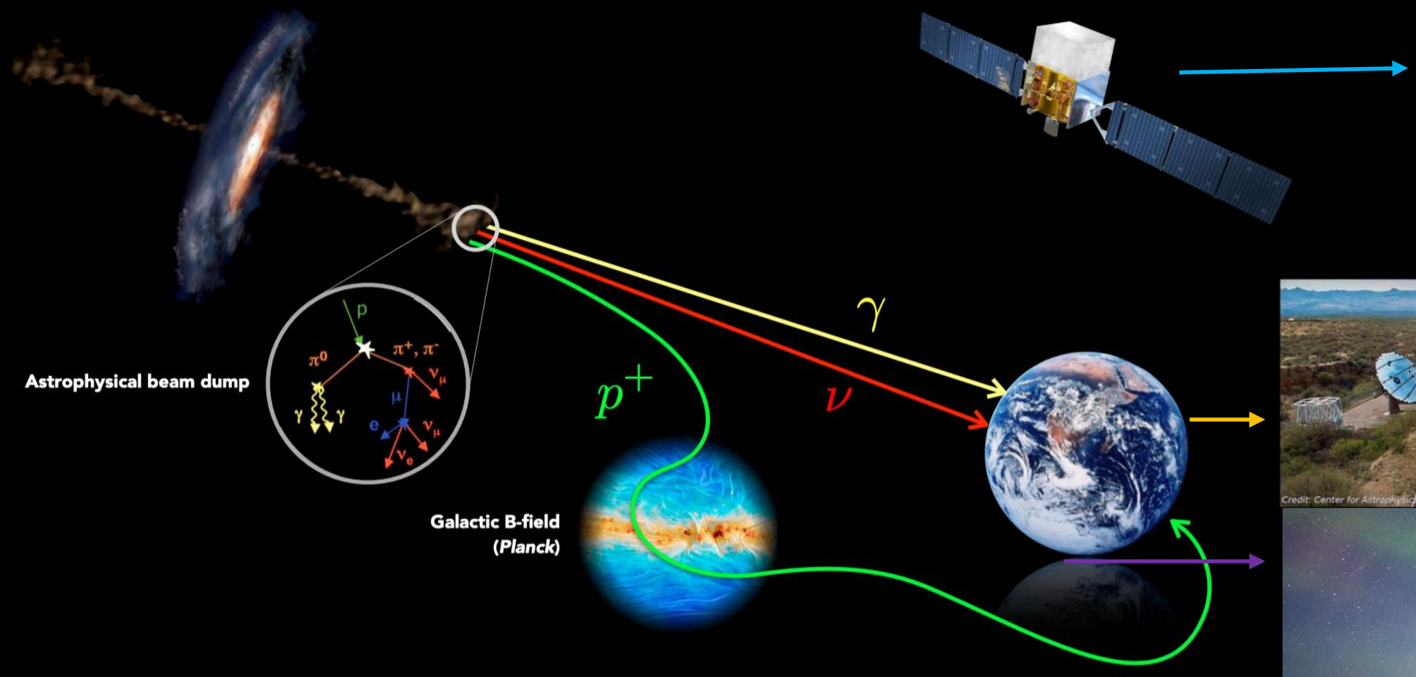
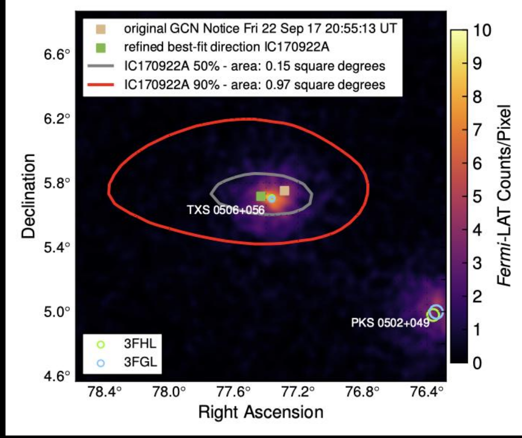
Fermi Gamma-ray Space Telescope

VERITAS

TXS 0506+056: A brief recap





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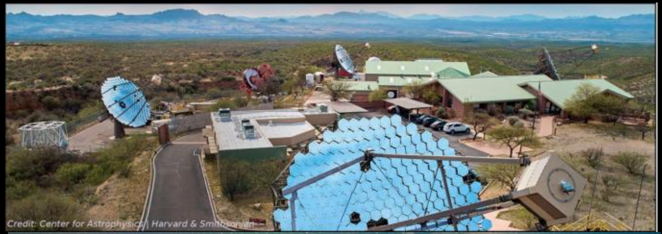
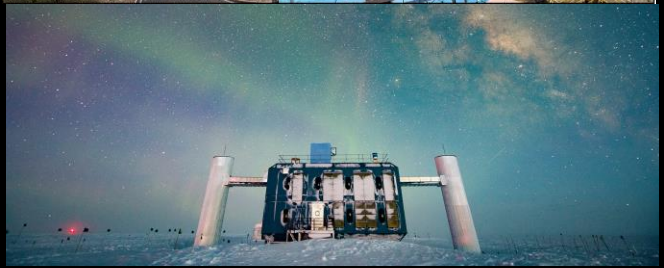
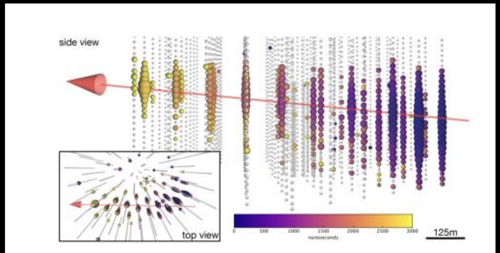
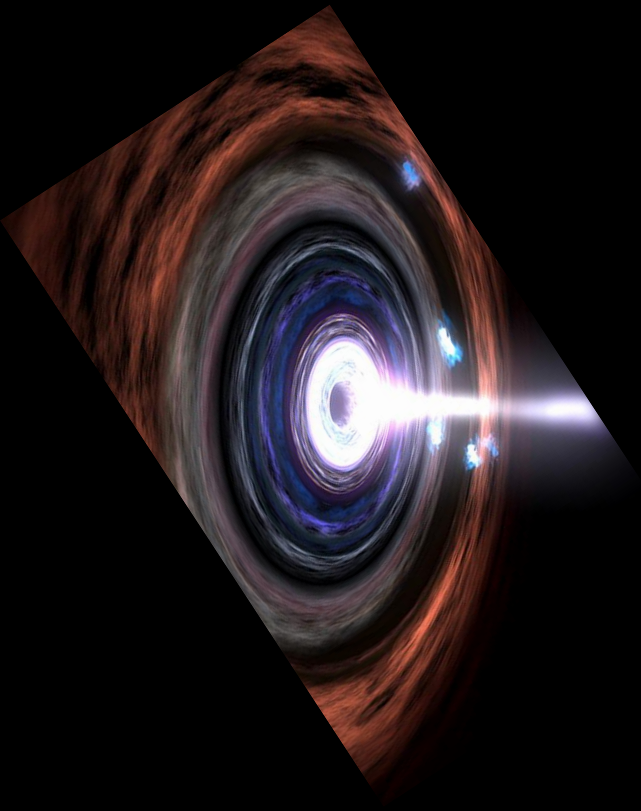


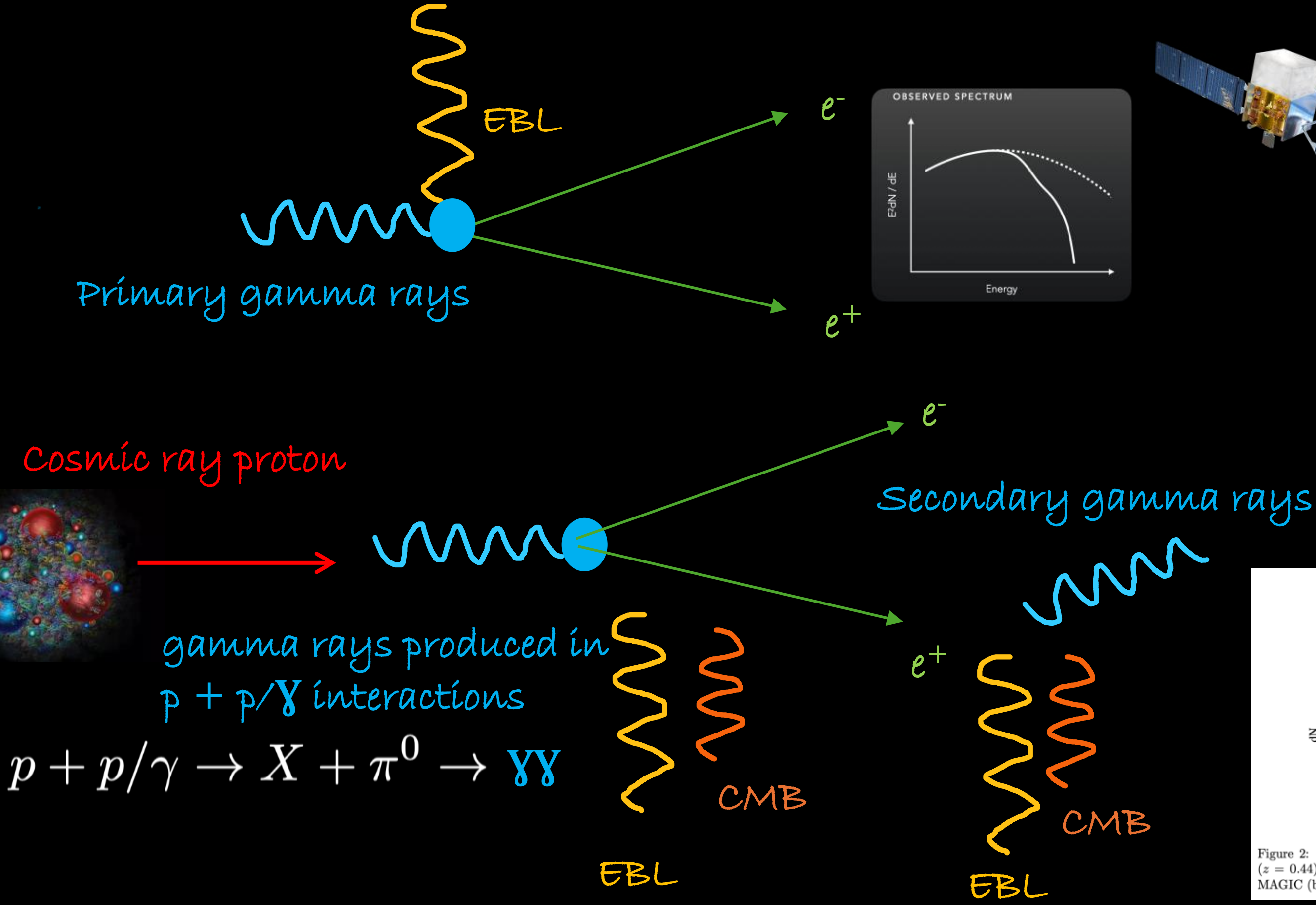


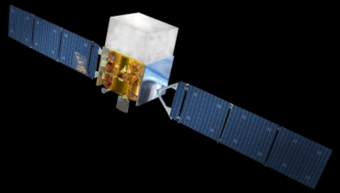


- On Sept 22, 2017 IceCube reported the detection of a neutrino alert with a most probable energy of 290 TeV
- This event was found to have a best-fit reconstructed direction to within 0.1° from the sky position of a blazar, TXS 0506+056 (z=0.337)
- The correlation between the neutrino event and a gamma-ray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







Essey and Kusenko 2010

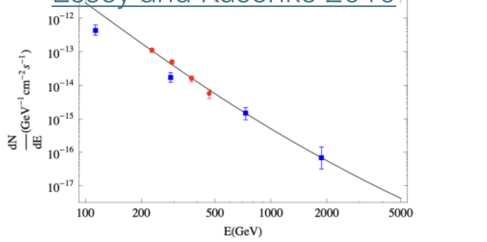


Figure 2: Differential spectrum of secondary photons calculated numerically for 3C66A ($z = 0.44$), assuming the proton spectrum at the source $\propto E_p^{-2}$, and normalized to fit MAGIC (blue squares) and VERITAS (red circles) data points.

- 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 IC scatter the CMB photons up to gamma-ray energies and subsequently initiate electromagnetic cascades

Methodology

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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

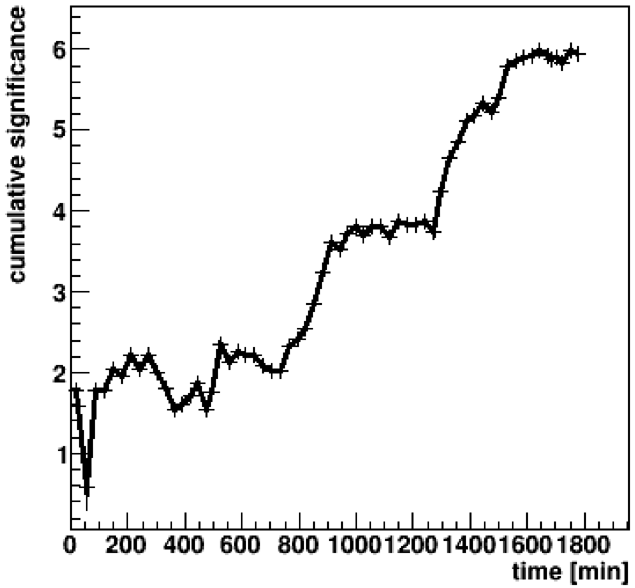
We compare the gamma-ray spectrum and neutrino observations with the predictions of cosmic-ray induced cascades in intergalactic space

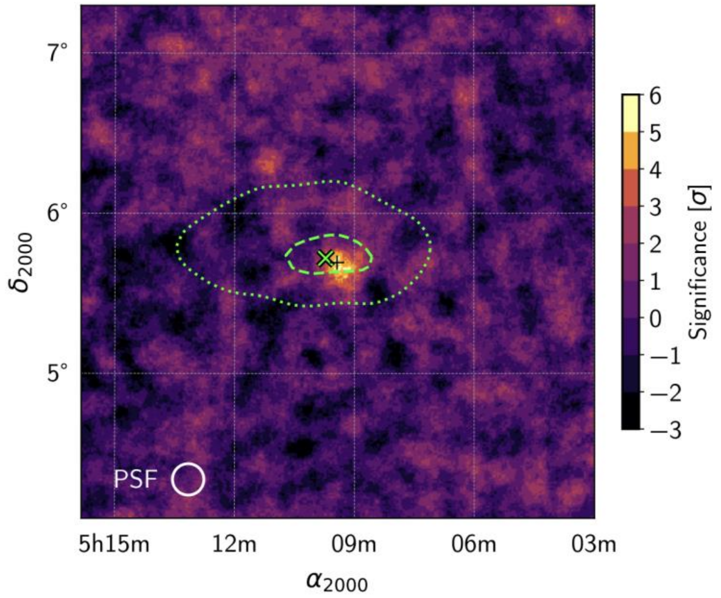
We perform a joint fit of the primary gamma-ray emission **(whose origin we stay agnostic about)** and the proton spectrum. Our method has the advantage that the only assumption we make is that cosmic rays are accelerated in the source and subsequently escape

We also apply a full statistical analysis to jointly determine the best-fit parameters of a proton emission spectrum describing the data and derive constraints on the proton escape luminosity, using state-of-the-art Monte Carlo simulations

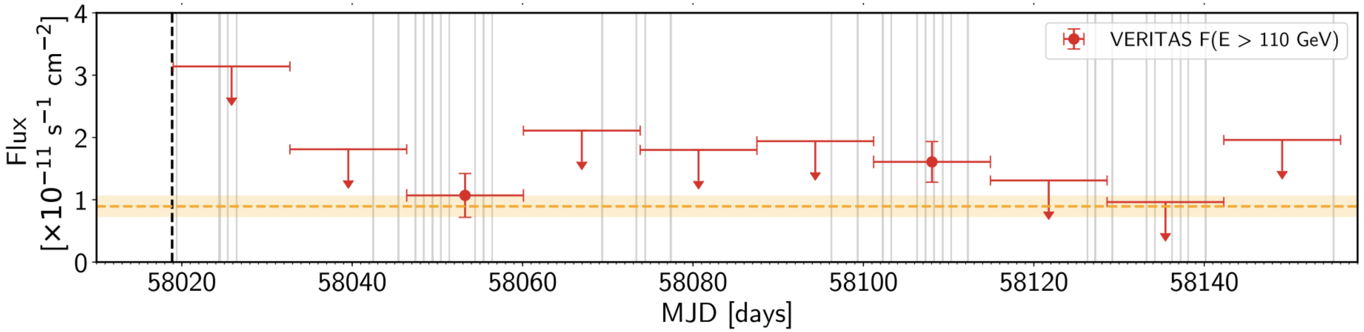
VERITAS analysis

- VERITAS detected TXS 0506+056 at a significance of 5.8σ over a 35 hr dataset between Sept 2017 and Feb 2018



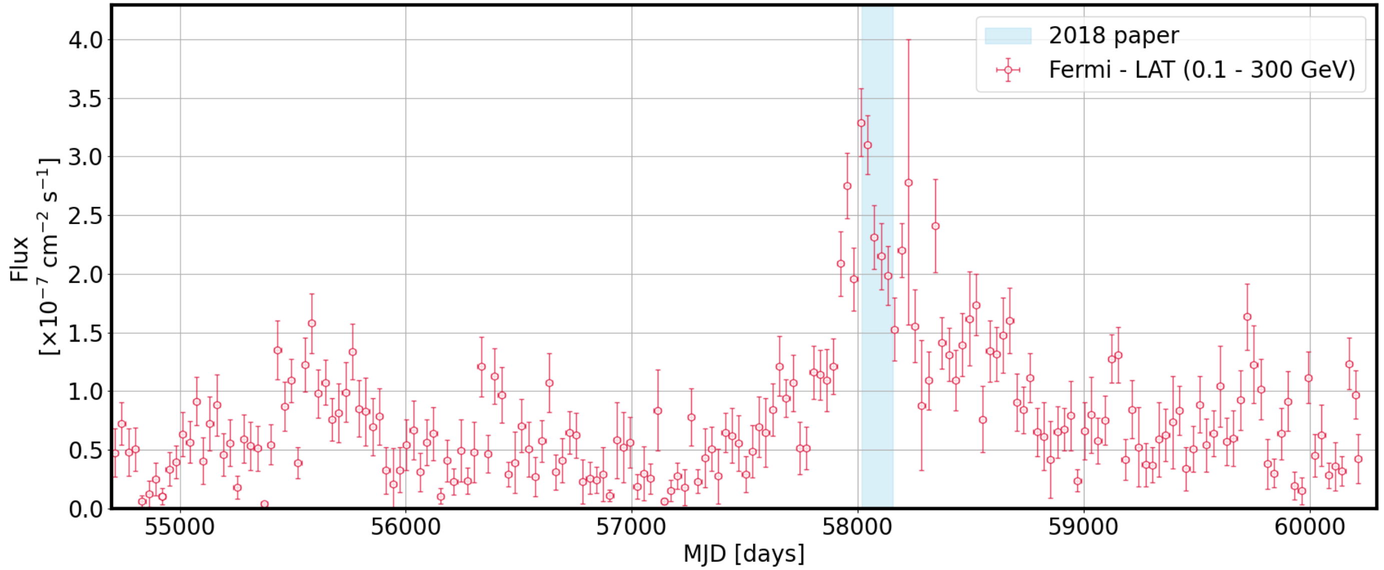


For now, we are using the published VERITAS data from the flare period (MJD 58019 – MJD 58155)



Fermi-LAT analysis

- Using Fermi-LAT spectrum contemporaneous with VERITAS data from the flare period (MJD 58019 – MJD 58155)
- Significance: 45.4σ, Flux: $(2.3\pm0.2)\times10^{-7}$ cm^{-2} s^{-1}



- ROI radius = 15°
- Spatial bin size = 0.1°/pixel
- 4 energy bins/ decade (100MeV to 300 GeV)
- Sources within 20° included in model with fixed spectral
- Sources within 3° Spectral parameters left free to vary

Modeling the proton cascade contribution

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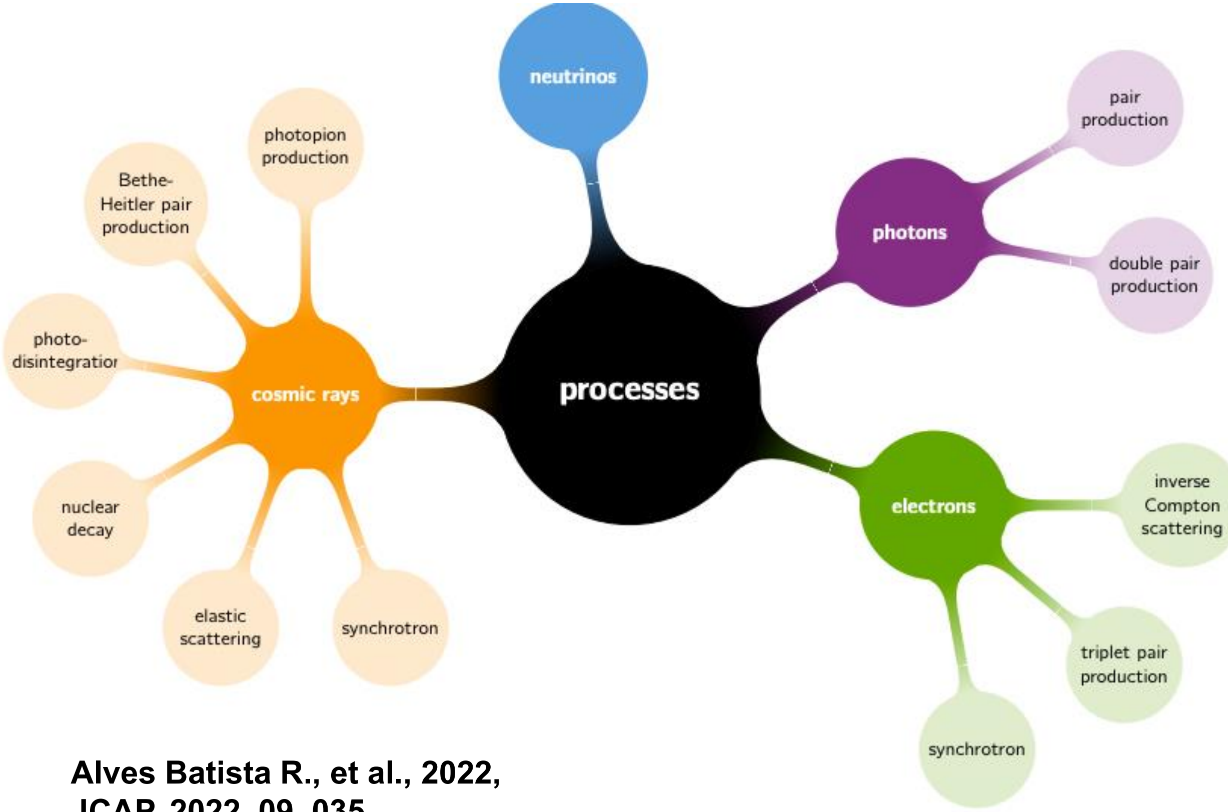
Model the development of proton cascades in the intergalactic medium using the **CRPropa** Monte Carlo simulation package, using all the relevant interactions

- Consider all cascade photons arriving with a time delay shorter than a maximum blazar activity time, 6 months
- The simulations are converted into energy-dependent sky maps for arbitrary input spectra, assuming the jet axis is along line-of-sight. The spectra serve as the input templates for the data analysis
- For each magnetic field, 1000 independent simulations were performed that were then combined into a single spectrum.
- In the following discussions, we show the results obtained for a magnetic field B = 10^{-16} G



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 with delta functions in energy between 10^{12} eV and 10^{18} eV
- We choose a proton injection that follows a power law with low and high energy exponential cut-offs:

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

where the subscripts represents cascade emission and proton energies

- The low energy cut-off is fixed to $E_{p,\ min} = 10^{13}$ eV, motivated from constraints on the total proton luminosity of TXS 0506+056 (Petropolou et al. 2020)
- The proton injection spectral slope parameter considered is in the interval $\alpha_p \in [1.8, 2.6]$ and the high energy cut-off interval is $E_{p,max} \in [10^{14}, 10^{19}]$ eV

Modeling the primary spectrum

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- The primary spectrum is modeled as:

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

Log parabola (LP) + EBL

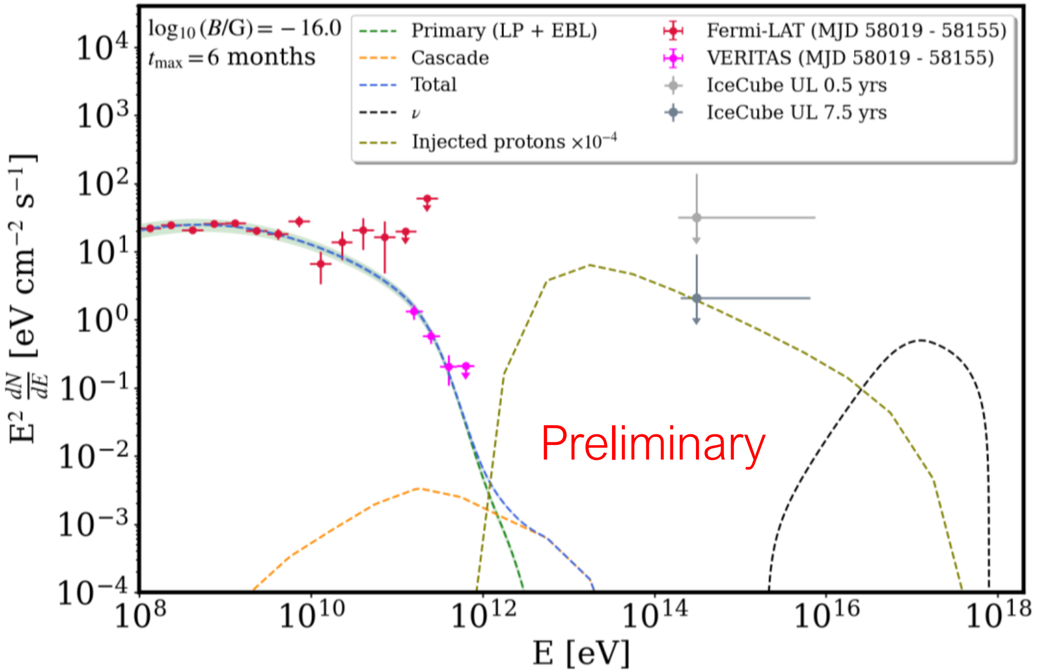
$$\frac{dN_{\mathrm{prim}}}{dE_\gamma} = N_0 \left(\frac{E_\gamma}{E_0}\right)^{-\Gamma_{\mathrm{PLE}}} \exp\left(-\frac{E_\gamma}{E_{\gamma,\mathrm{cut}}}\right) \exp(-\tau_{\gamma\gamma})$$

Power law with exponential cutoff (PLE) + EBL

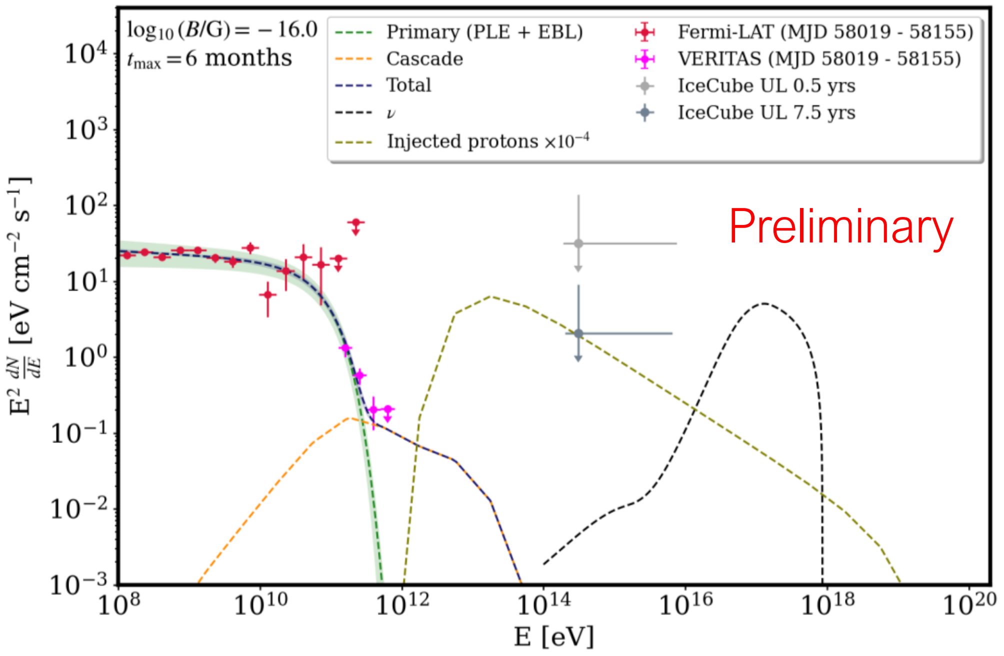
- The combined spectrum is expressed as a sum of the primary gamma-ray spectrum and the contribution of the proton cascade component to the spectrum

- The combined Fermi-LAT and VERITAS spectrum is used to obtain the χ^2 values over a grid of protons injection parameters (α_p and $E_{p,\,max}$) for fixed values of magnetic field ($B = 10^{-16}$ G in the following example and the Dominguez 2011 EBL model throughout), using the MINUIT fit routine in gammapy

Constraints on spectrum of protons escaping source



LP + EBL



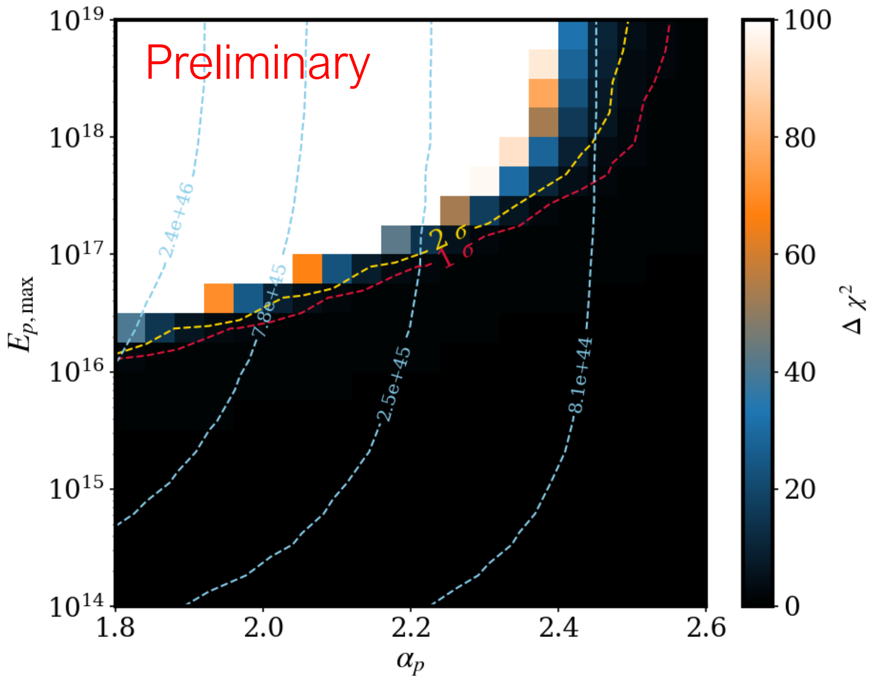
PLE + EBL

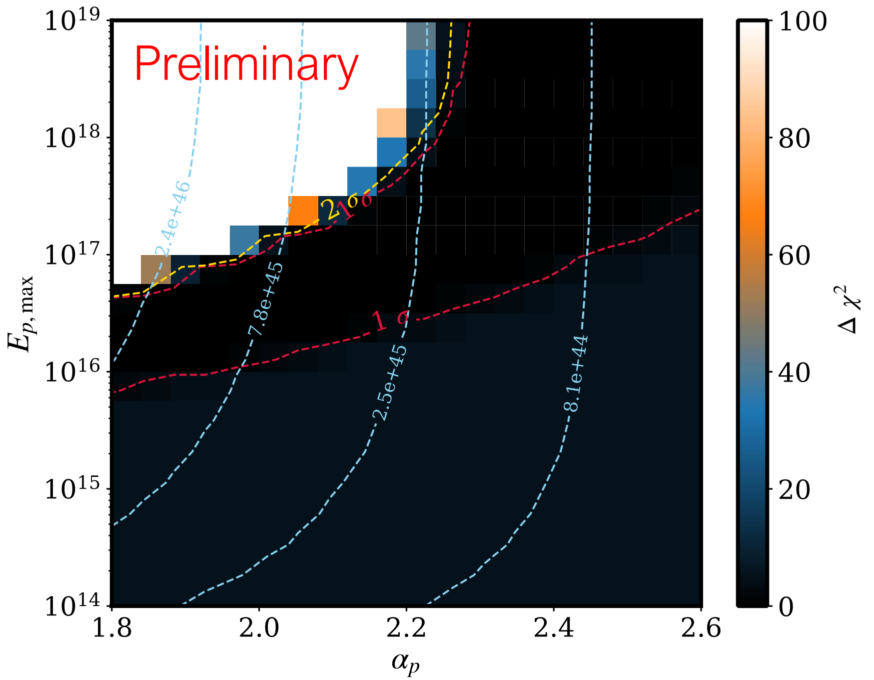
Model	χ^2
LP+EBL	16.1
LP+EBL+cascade	16.6
PLE+EBL	47.6
PLE+EBL +cascade	39.2

- The combined spectrum seems to be already well described by the LP+EBL model and the additional cascade component does not improve the fit
- For the PLE+EBL model primary spectrum, the additional cascade component produces a significantly better fit than without the cascade component
- The corresponding simulated neutrino spectra for the proton injection parameters are compatible with the neutrino flux upper limits

Constraints on spectrum of protons escaping source

LP + EBL



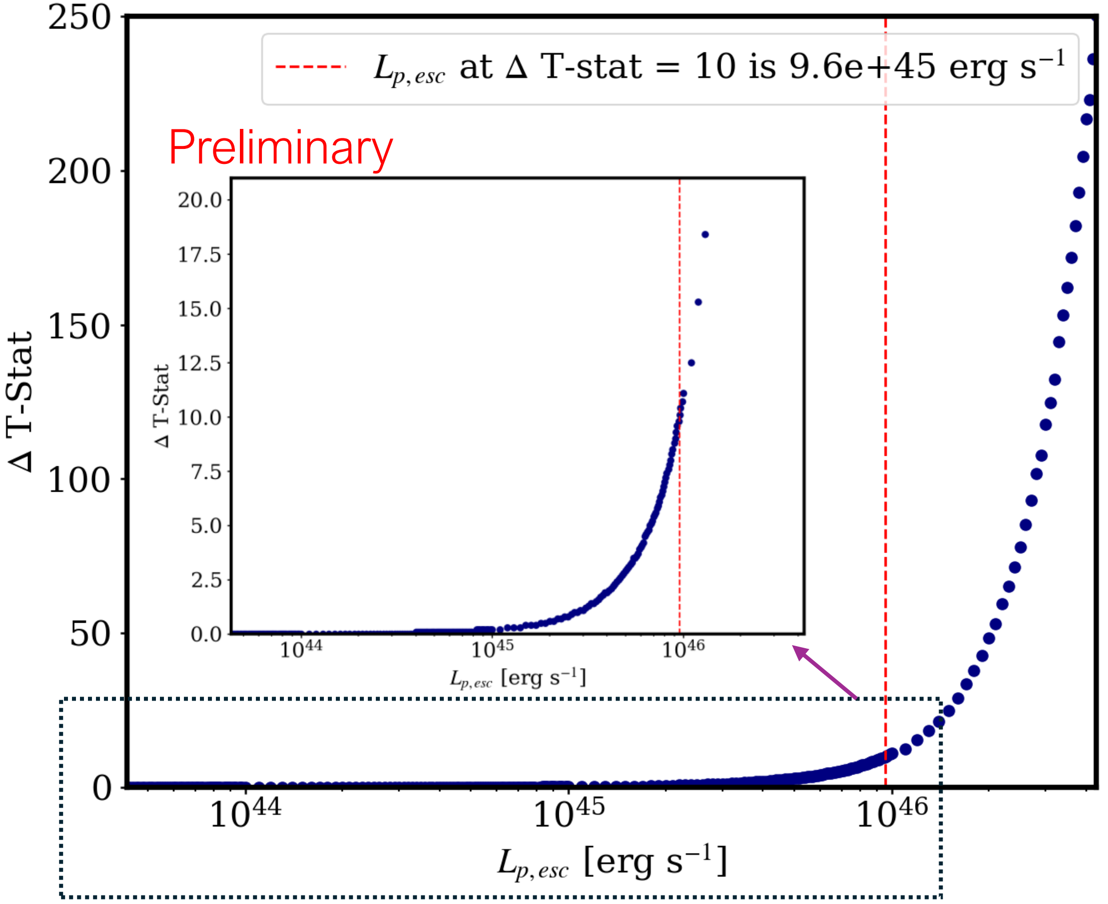


PLE + EBL

- The stat-surfaces obtained over the parameter space investigated for the proton injection parameters are shown above
- 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
- Also shown are the 1σ and 2σ uncertainty contours, depicting regions of the parameter space not compatible with the gamma ray data
- The dashed blue curves represent points in the parameter space which correspond to the same proton escape luminosity

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), δ=24.2, $L_{p,max}$ = 1.9 x 10^{50} erg/sec (in observes frame) , and keep proton parameters, α_p=2 and $E_{p,\ max}$=3.6 x 10^{17} eV, and vary just the cascade emission normalization, **κ**, and hence the proton escape luminosity
- Our preliminary value is ~10^{-4} which is reasonable given the extreme environment within AGNs, where many protons would interact with surrounding matter and magnetic fields, losing energy or being deflected before they can escape



Summary

- 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 model the development of proton cascades in the intergalactic medium using CRPropa
- The combined Fermi-LAT and VERITAS spectrum is used to obtain the χ^2 values over a grid of protons injection parameters (α_p and $E_{p,\,max}$) for fixed values of magnetic field and we derive constraints on the spectrum of the protons escaping the source
- We then fix the proton spectral parameters to derive constraints on the fraction of escaped protons

https://veritas.sao.arizona.edu/wiki/VPOD#/media/File:T1_Milky_May_20230513.jpg