A study of broadband variability in the context of hybrid leptohadronic models for TeV blazars

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UNTRAPHOB

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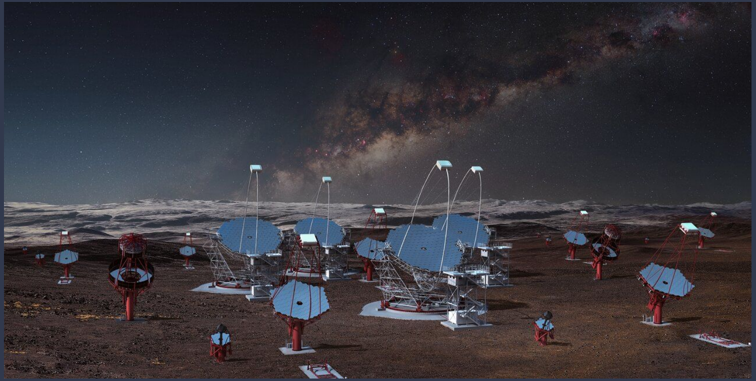
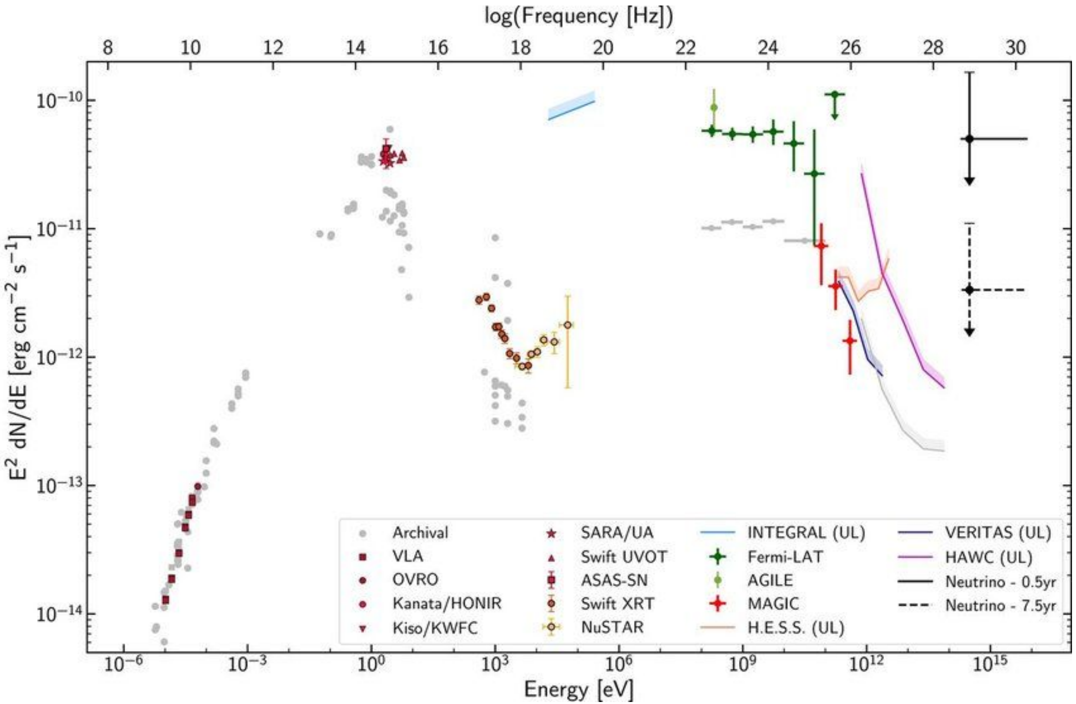
TeV Astronomy is Now !



(Credit: ESO)

TXS 0506+056

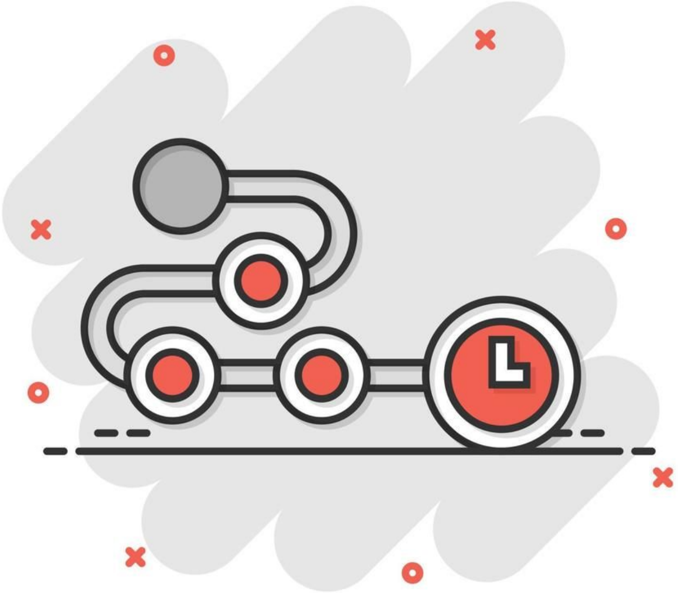


IceCube, F. L., MAGIC, A., ASAS-SN, H. A. W. C., HESS, I., Kanata, K., Kapteyn, L. T., & Subaru, S. N. (2018). VERITAS and VLA/17B-403 collaborations, Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. Science, 361. (https://doi.org/10.1126/science.aat1378)

Dedicated Variability Study for Hadronic Flares

Our Goals - Our Plan

- ➢ Model the average leptonic Blazar state
  - Data Preparation
  - LeHaMoC → Numerical Model
  - MCMC → Fitting Method
- ➢ Hadronic Loading
  - Determine the highest sub-dominant proton population possible
- ➢ Time Series Analysis
  - Use Gaussian methods to describe Fermi light curves
  - Translate Fermi curves to parameter variability
  - Vary 1 or more key parameters with time in LeHaMoC
- ➢ Simulated TeV ***light curves*** and ***spectra*** for the CTA



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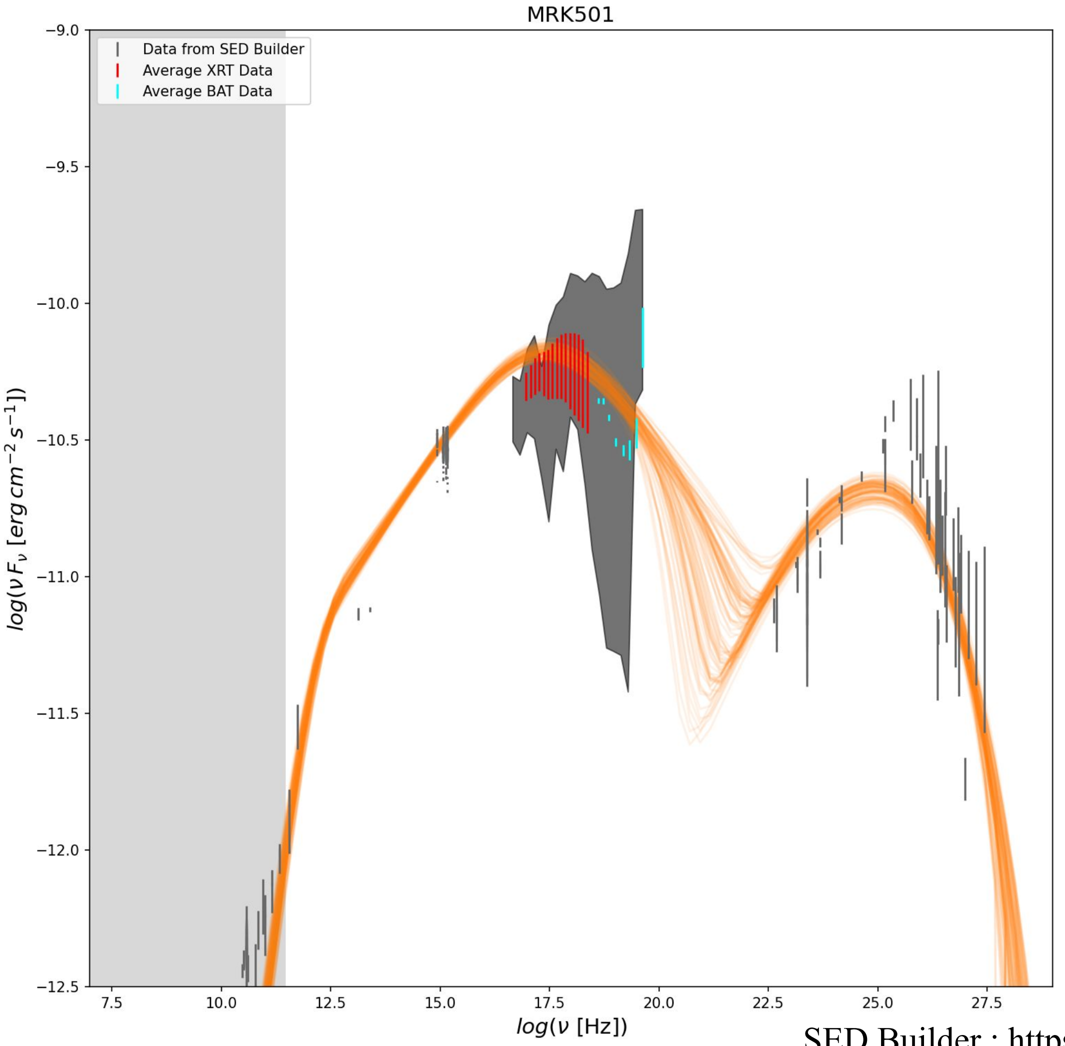
LeHaMoC

Leptonic Modelling



SED Builder : https://tools.ssdc.asi.it/SED/

The Parameters

log(R)

log(B)

log(γ_{min})

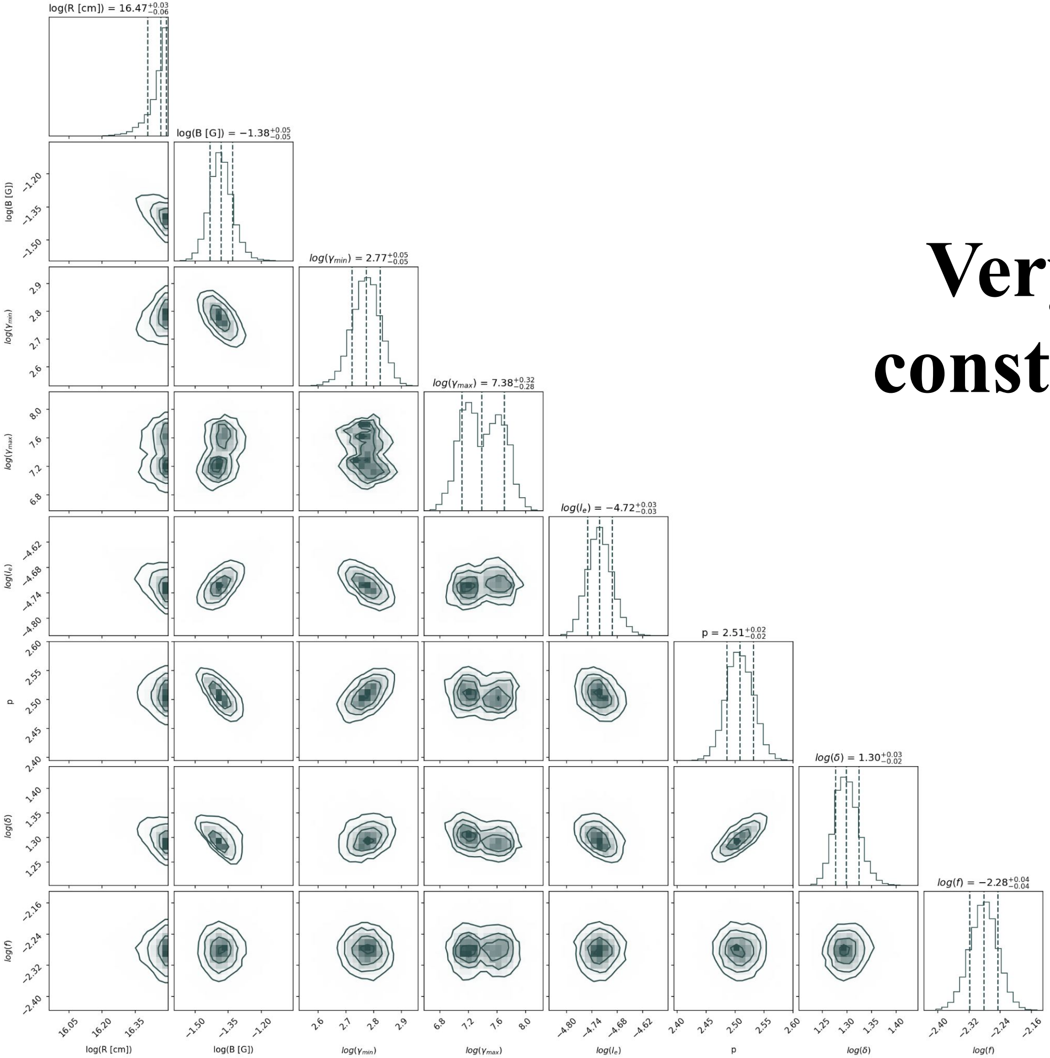
log(γ_{max})

log(l_e)

p

log(δ)

log(f)



Very well constrained!

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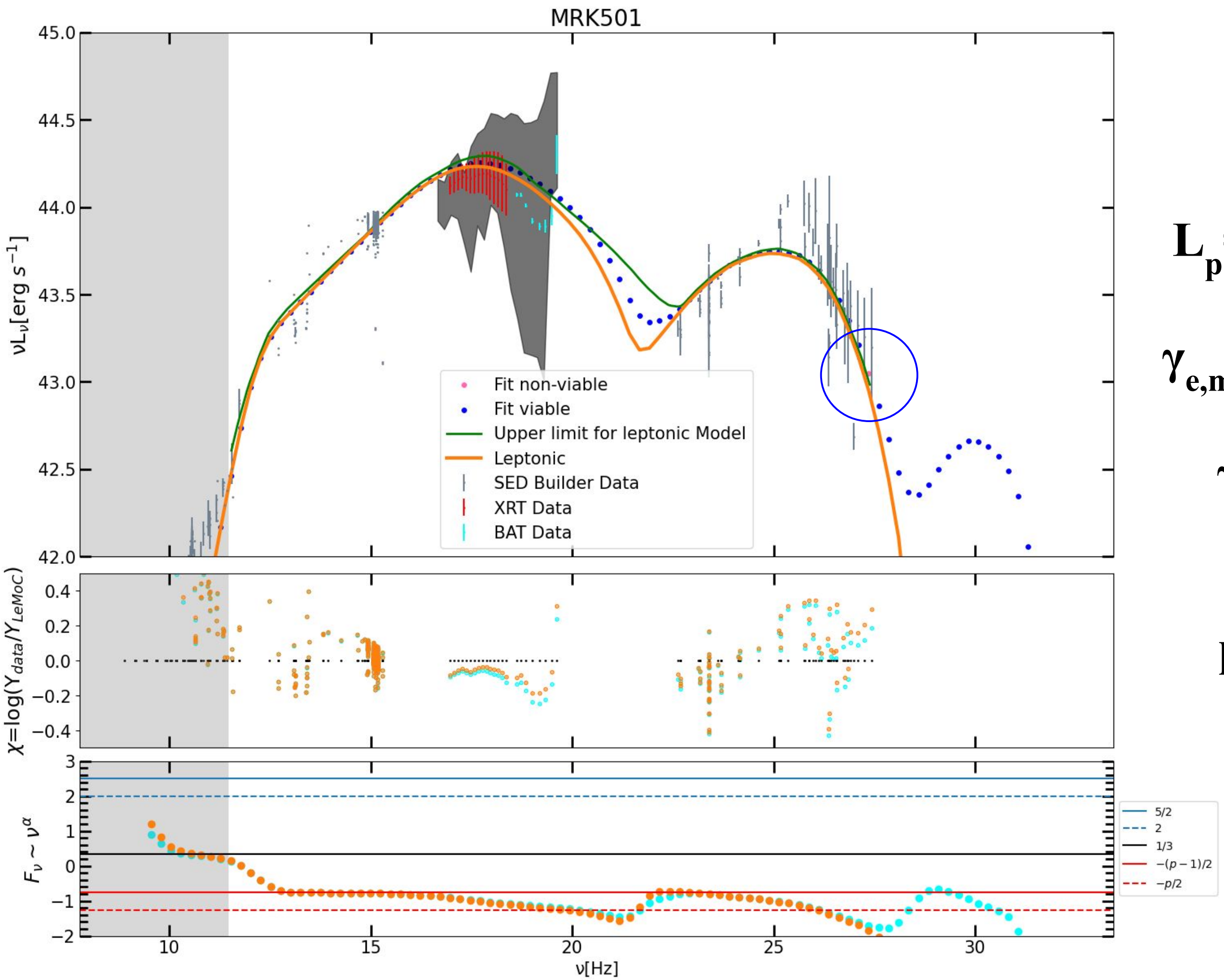
Who Let the Protons out



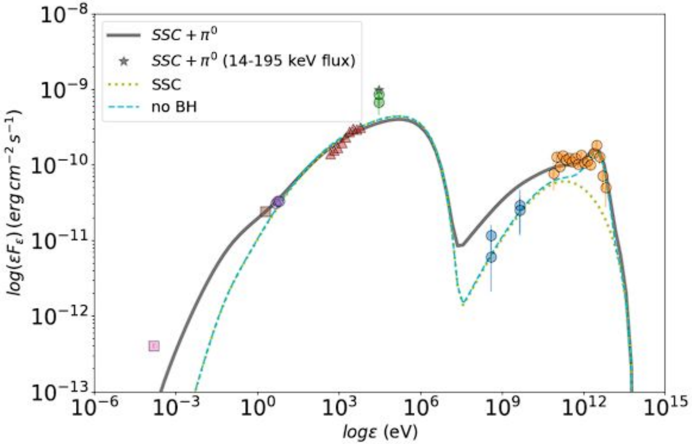
$L_p = 10^{5.95} L_e$

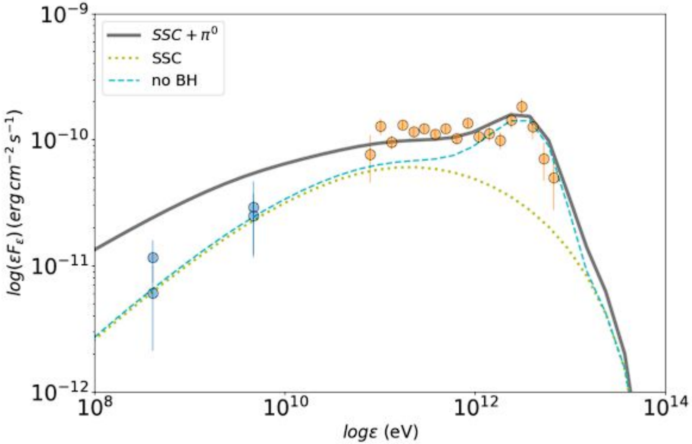
$\gamma_{e,min} = \gamma_{p,min}$

$\gamma_{e,max} = \gamma_{p,max}$

$p_p = p_e$

Comparison to Petropoulou et al. 2023
π^0ump up the Jam!





Parameter	Value
δ	13
R' (cm)	1.5×10^{16}
B' (cm)	0.16
ℓ_e	$10^{-4.2}$
s_e	1.7
$\gamma'_{e,min}$	$\leq 10^4$
$\gamma'_{e,max}$	10^7
ℓ_p	1.6
s_p	1.7
$\gamma'_{p,min}$	10^3
$\gamma'_{p,max}$	$10^{3.2}$

Petropoulou, M., Mastichiadis, A., Vasilopoulos, G., Paneque, D., González, J. B., & Zanias, F. (2023). TeV pion bumps in the gamma-ray spectra of flaring blazars. *arXiv preprint arXiv:2308.14184*, accepted in A&A

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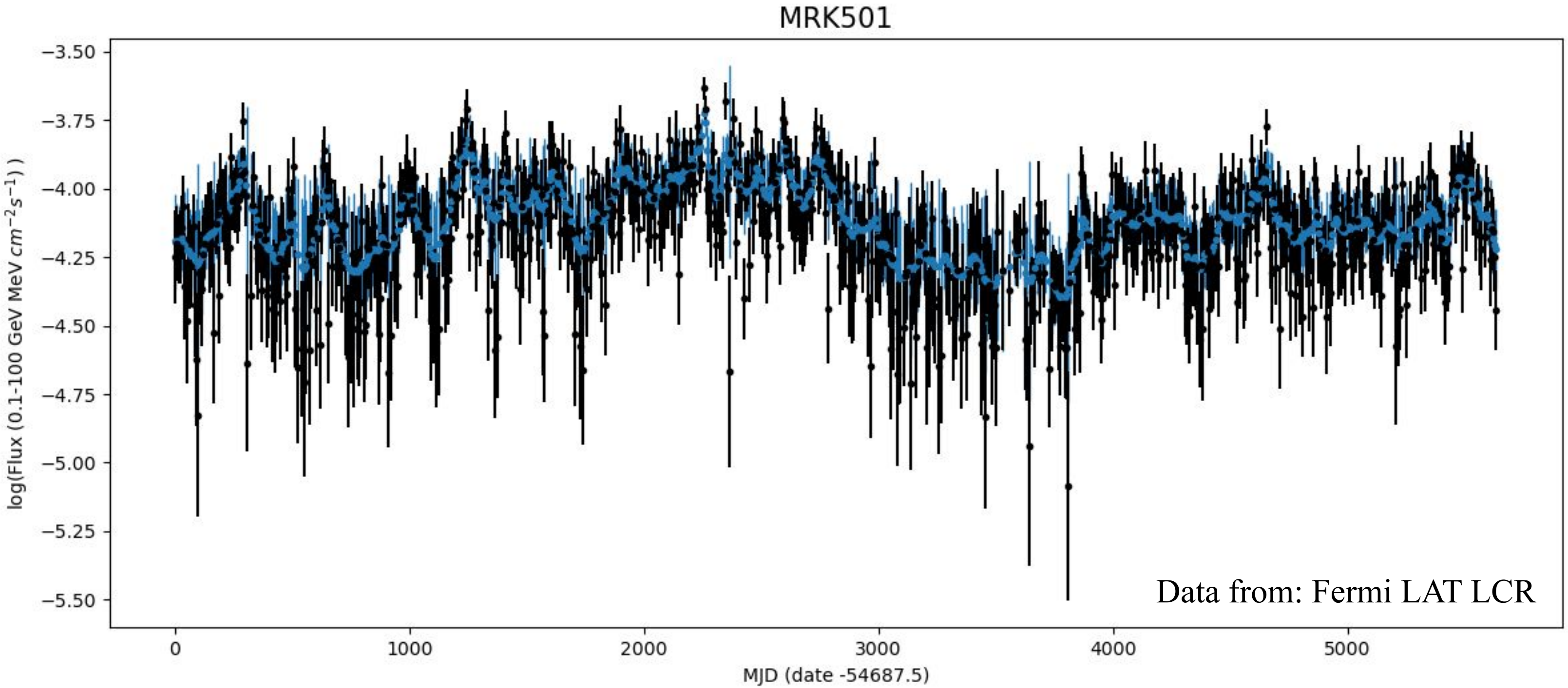
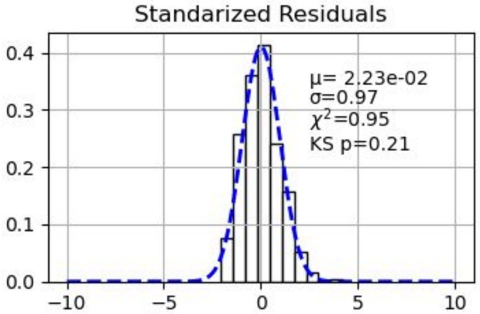
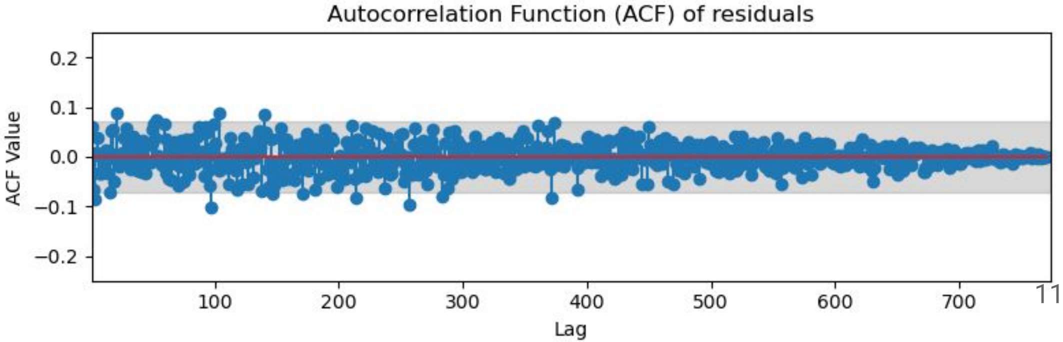
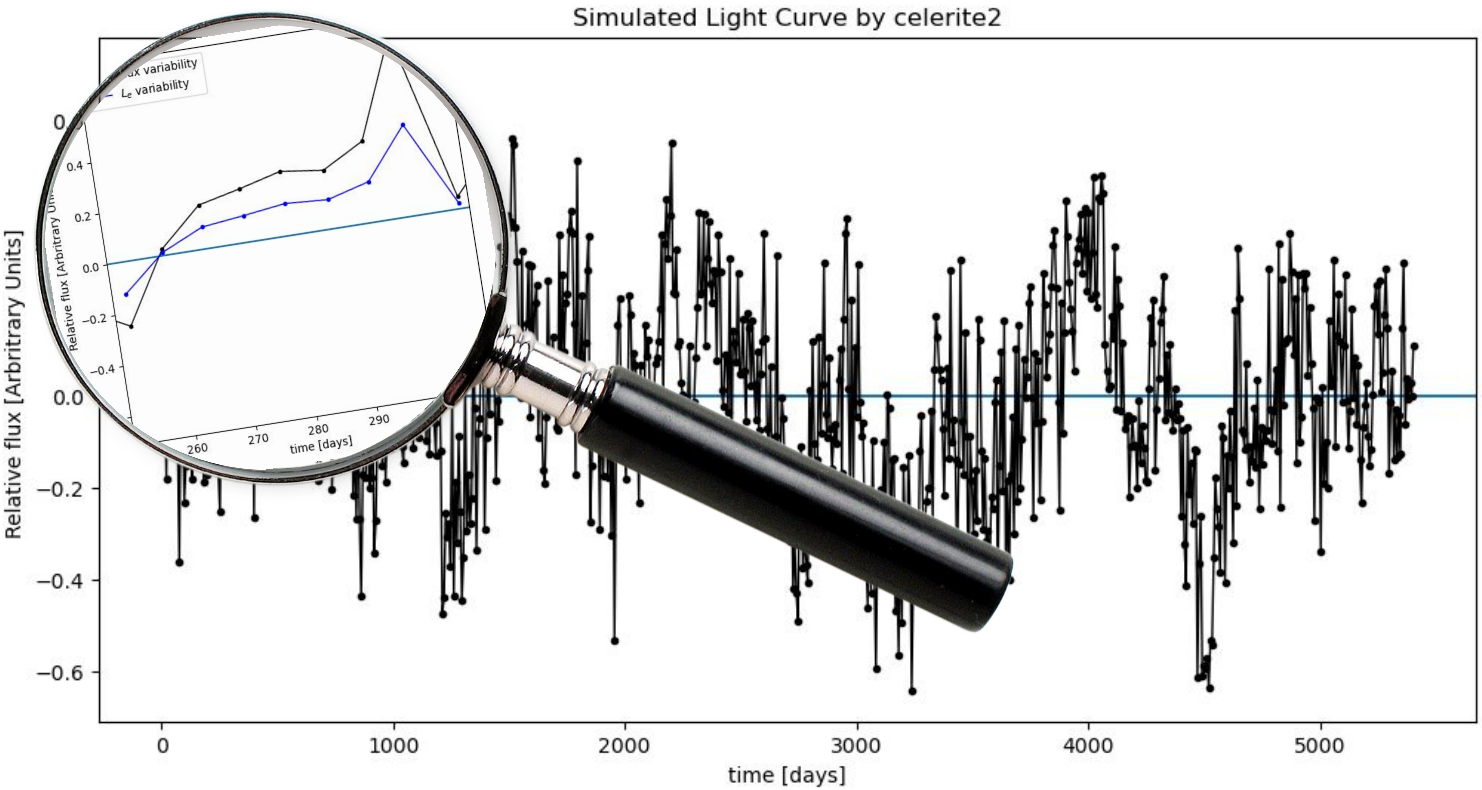
Fermi LAT fitting - 7day binning



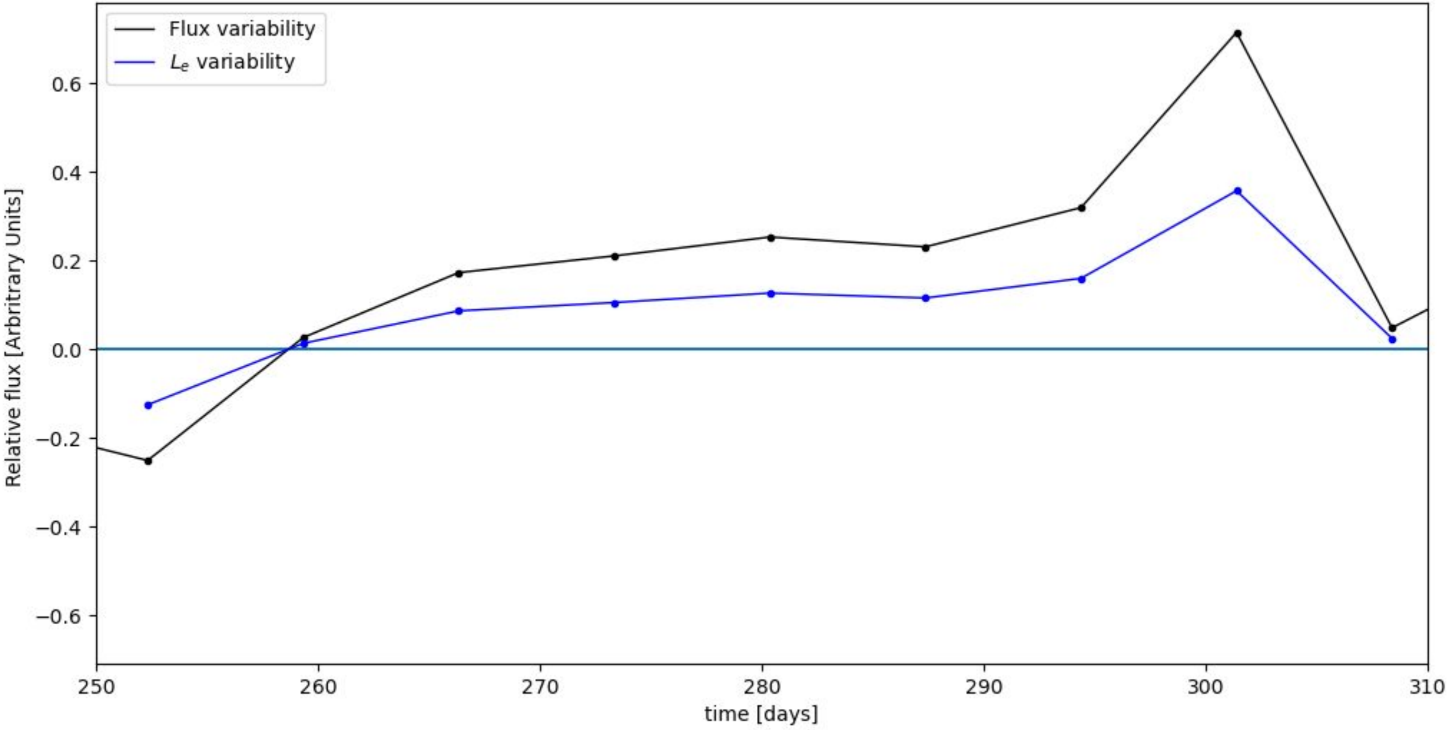




Creating the variability



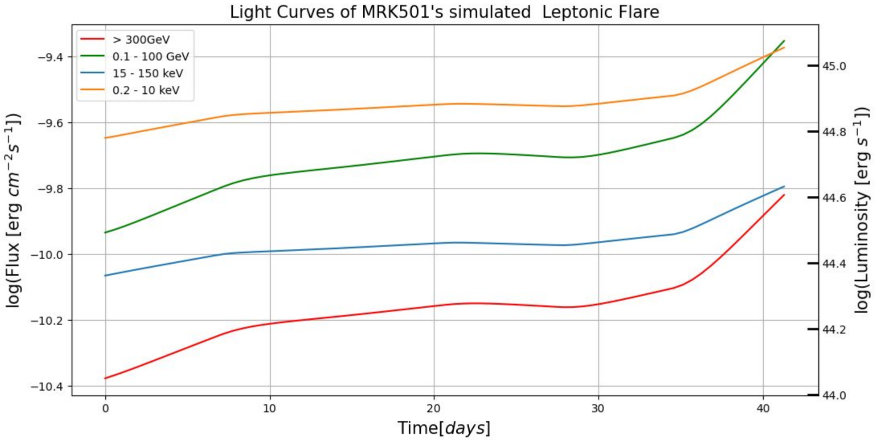
Translating Flux to parameter variability

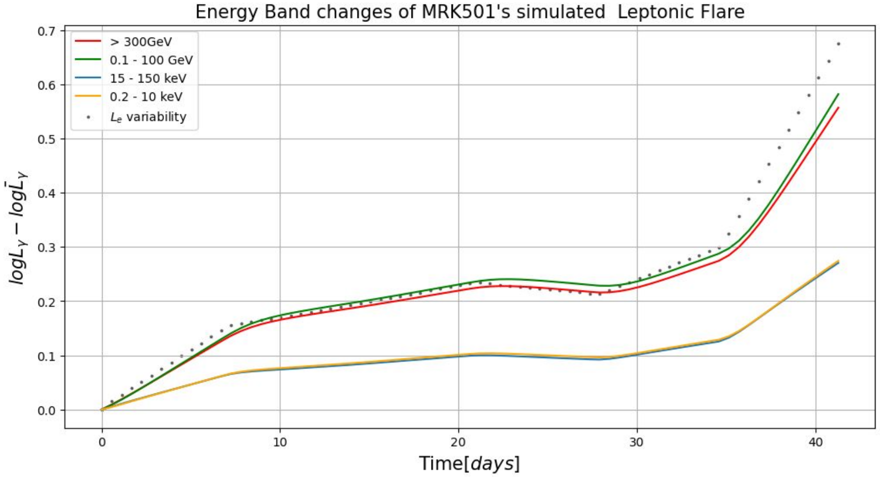


$L_{\gamma,SSC} \sim L^2_e$

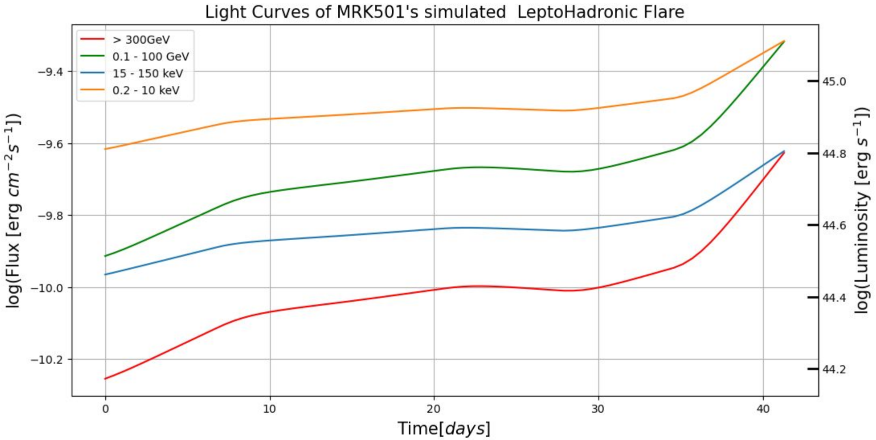
$\log L_{\gamma,SSC} \sim 2\log L_e$

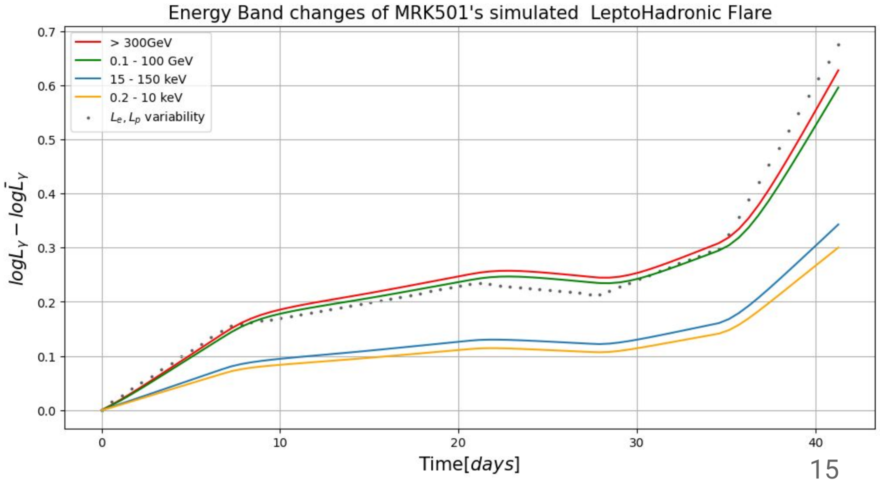
A Leptonic Flare !



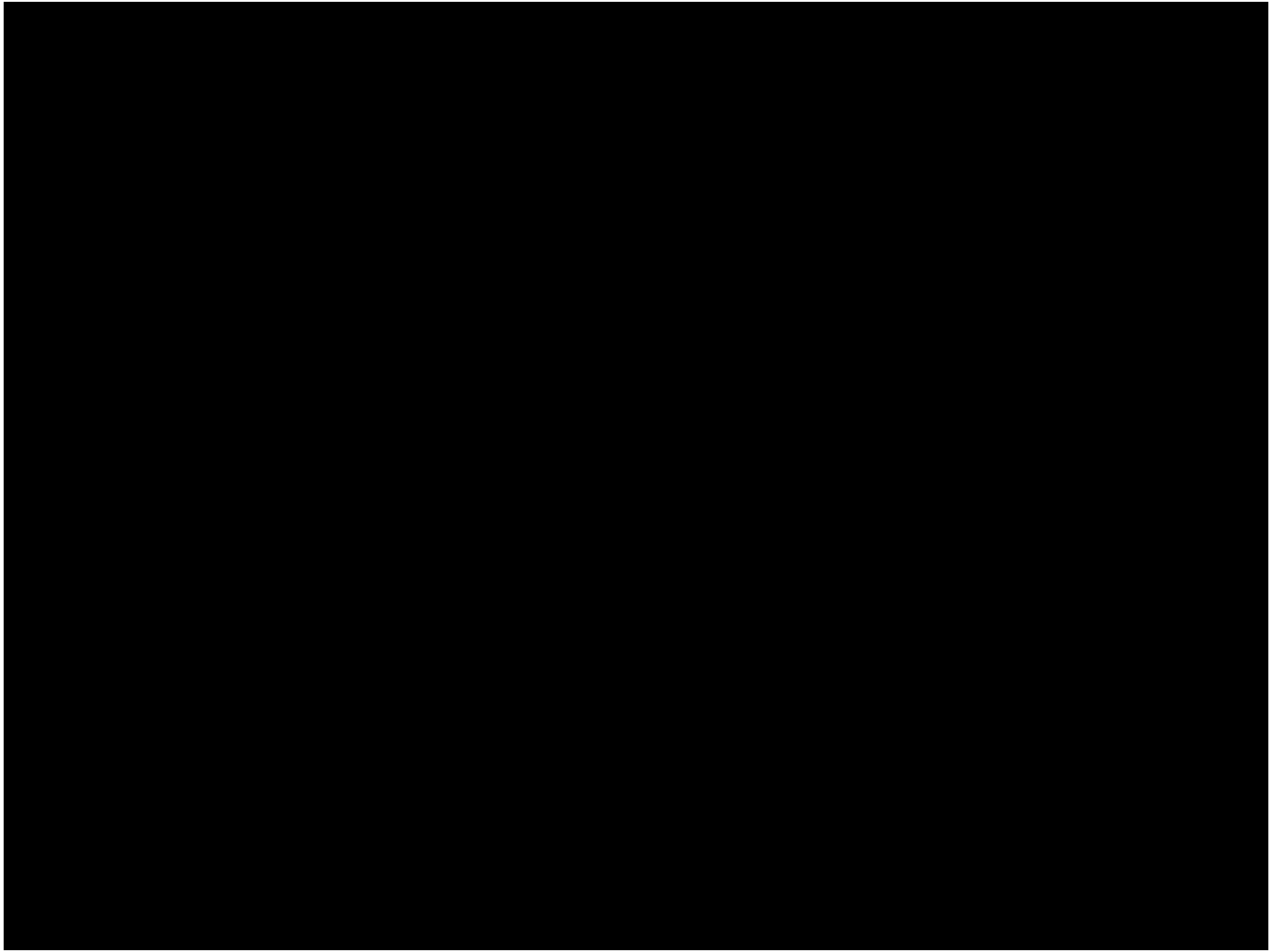


And it's LeptoHadronic Cousin

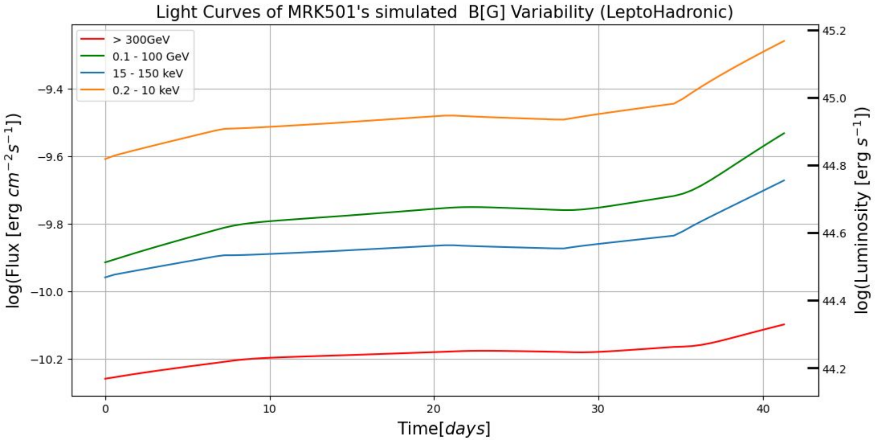


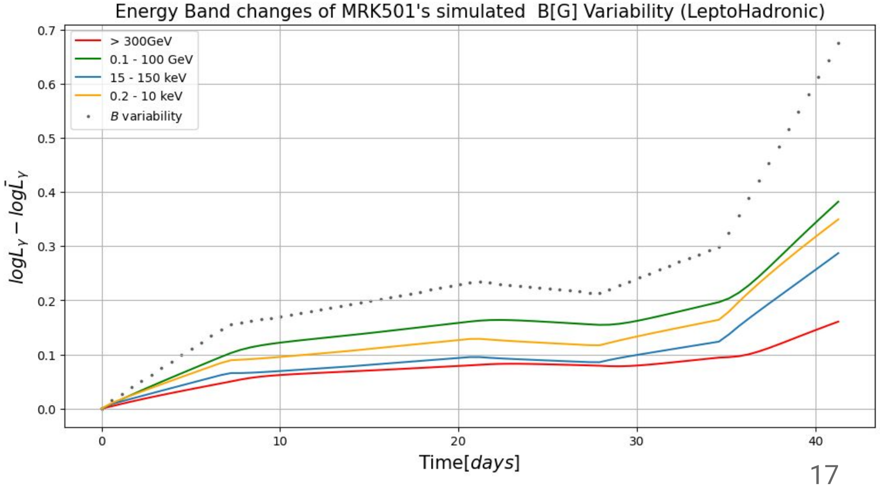


Long-Term LeptoHadronic Variability



Another Day Another Key Parameter - B [G]





First Dedicated Variability Study for Hadronic Flares

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Thank You!

Backup Stuff

Gaussian Process

$$\boldsymbol{y} = \begin{pmatrix} y_1 & \cdots & y_N \end{pmatrix}^{\mathrm{T}}$$

Data

$$X = \begin{pmatrix} \boldsymbol{x}_1 & \cdots & \boldsymbol{x}_N \end{pmatrix}^{\mathrm{T}}$$

Coordinates

$$\ln \mathcal{L}(\boldsymbol{\theta},\, \boldsymbol{\alpha}) = \ln p(\boldsymbol{y} \,|\, X,\, \boldsymbol{\theta},\, \boldsymbol{\alpha}) = -\frac{1}{2} \boldsymbol{r_\theta}^{\mathrm{T}} K_{\boldsymbol{\alpha}}{}^{-1} \boldsymbol{r_\theta} - \frac{1}{2} \ln \det K_{\boldsymbol{\alpha}} - \frac{N}{2} \ln (2\pi)$$

$$\boldsymbol{r_\theta} = \begin{pmatrix} y_1 - \mu_{\boldsymbol{\theta}}(\boldsymbol{x}_1) & \cdots & y_N - \mu_{\boldsymbol{\theta}}(\boldsymbol{x}_N) \end{pmatrix}^{\mathrm{T}} \qquad [K_{\boldsymbol{\alpha}}]_{nm} = k_{\boldsymbol{\alpha}}(\boldsymbol{x}_n,\, \boldsymbol{x}_m)$$

Gaussian Process - celerite

$$k_{\boldsymbol{\alpha}}(\tau_{nm}) = \sigma_n^2\,\delta_{nm} + \sum_{j=1}^{J} a_j \exp(-c_j\,\tau_{nm}) \quad .$$

Kernel Function

$$\left[\frac{\mathrm{d}^2}{\mathrm{d}t^2} + \frac{\omega_0}{Q}\frac{\mathrm{d}}{\mathrm{d}t} + \omega_0^2\right] y(t) = \epsilon(t)$$

Stochastically accelerated damped SHO

$$S(\omega) = \sqrt{\frac{2}{\pi}} \frac{S_0\,\omega_0^4}{(\omega^2 - \omega_0^2)^2 + \omega_0^2\omega^2/Q^2}$$

PSD

$$S(\omega_0) = \sqrt{2/\pi}\,S_0\,Q^2 .$$

$$\mathbf{y}* = \mathrm{chol}\,(\mathbf{K})^\top\,\mathbf{w}$$

(Shenbang Yang *et al* 2021 *ApJ* 907 105)