Lorentz invariance violation search with the Cherenkov Telescope Array Observatory Large-Sized Telescope

Fourth Annual Conference of COST Action CA18108– July 2023

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Lorentz invariance violation (LIV)

Lorentz invariance : speed of light c in vacuum is a constant

- Quantization of space-time

↓

- Modification of the dispersion relation : $$E^2 = p^2c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \alpha_n \left(\frac{E}{E_{QG}}\right)^n\right]$$

↓ $v = \frac{\partial E}{\partial p}$

- Energy-dependency of the photon velocity $v(E)$: Lorentz invariance violation (LIV)

↓

- Two photons i and j with $E_j > E_i$ arrive with $\Delta t = t_j - t_i$

↓

- Measurement of $$\lambda_n = \frac{\Delta t_n}{\Delta E_n \kappa_n(z)} = \pm \frac{n+1}{2H_0 E_{QG}^n}$$

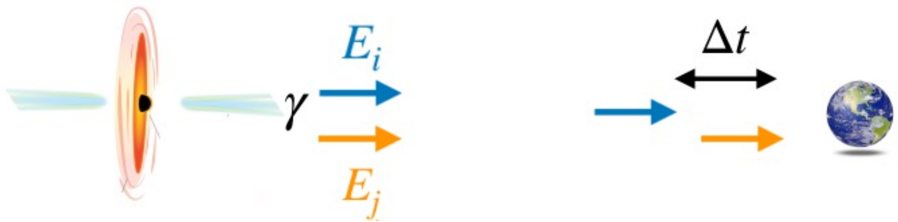
Search for $E_{QG,lim}^n$ for $n = 1$

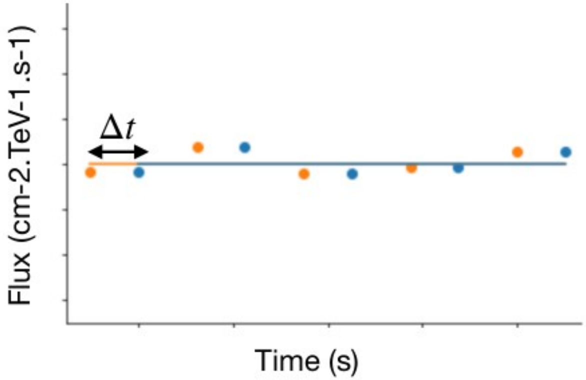
Astronomical sources

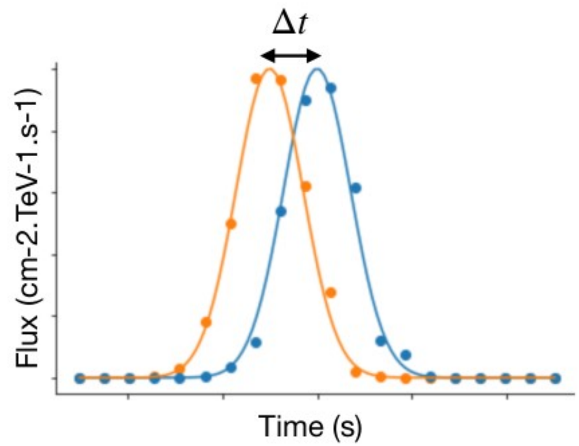
- Large range of energy
- Cosmological distance
- Highly variable and active source

→ Blazars, GRBs, pulsars

$$\Delta t = \pm \frac{n+1}{2} \frac{\Delta E^n}{E^n_{QG}} \times \kappa_n(z)$$

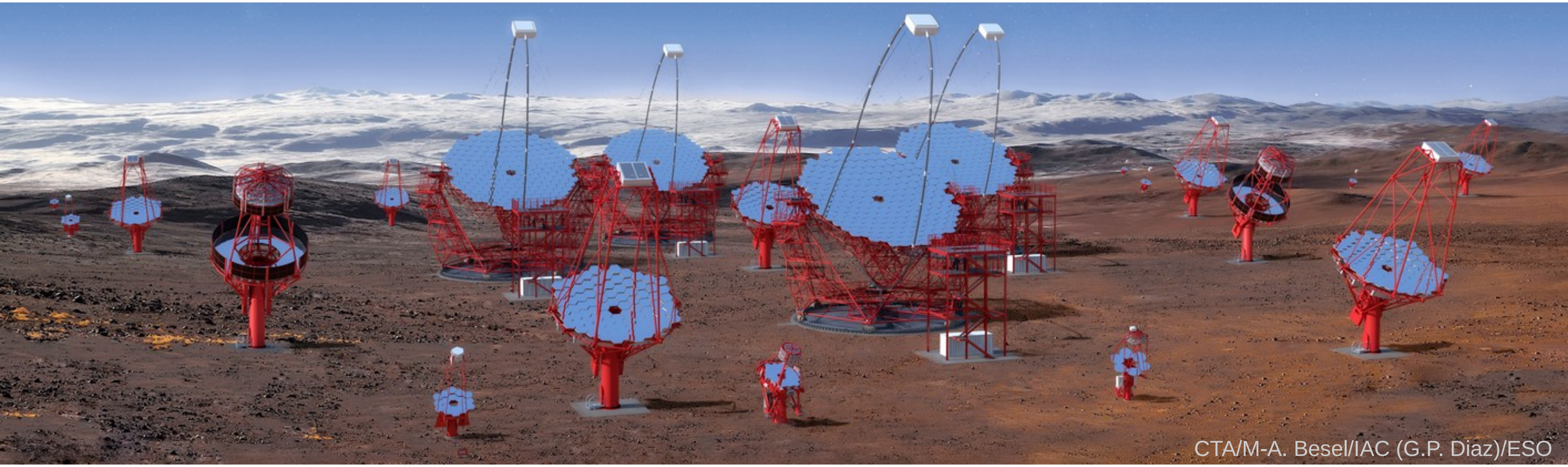




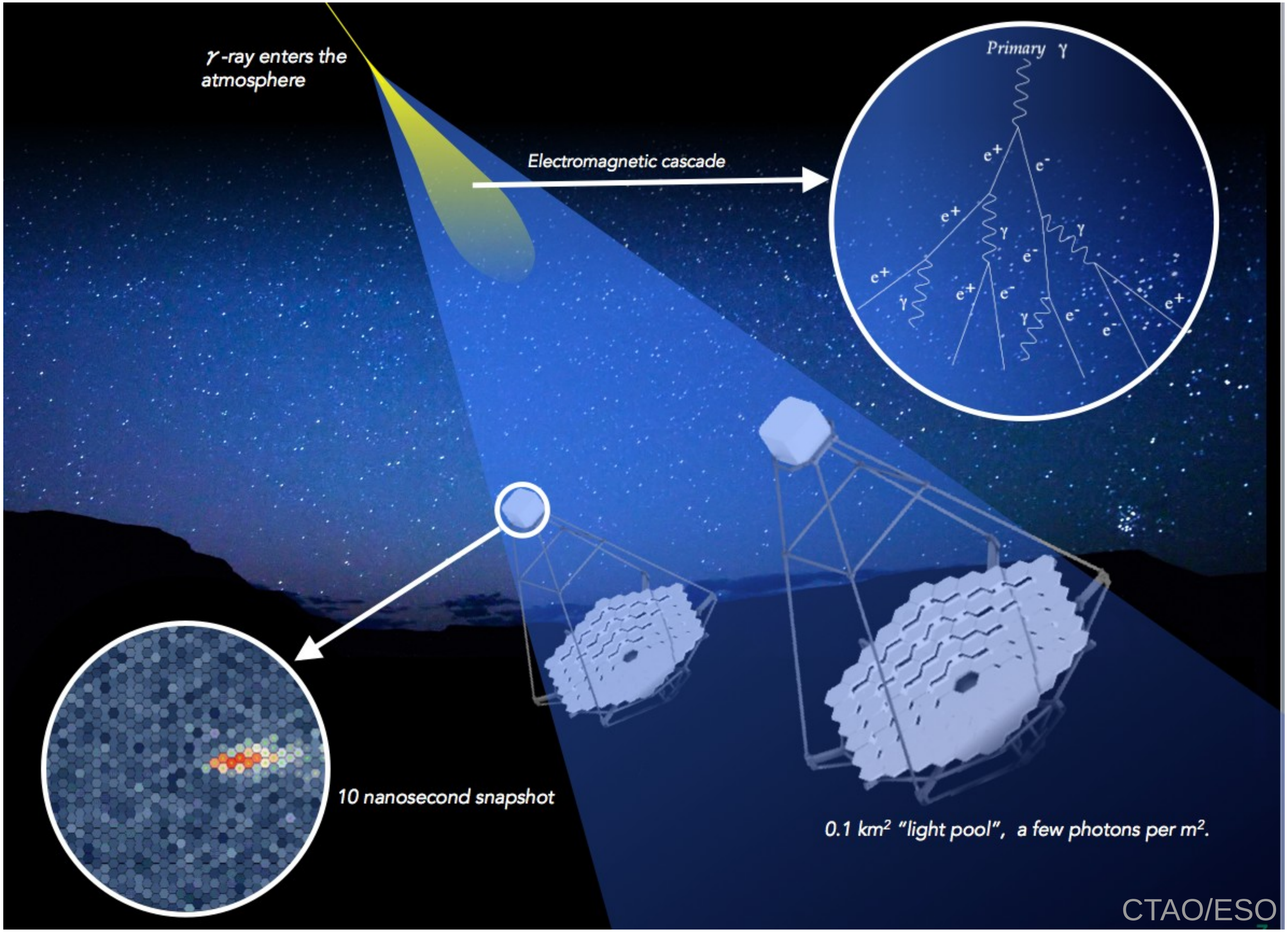


Cherenkov telescope array observatory

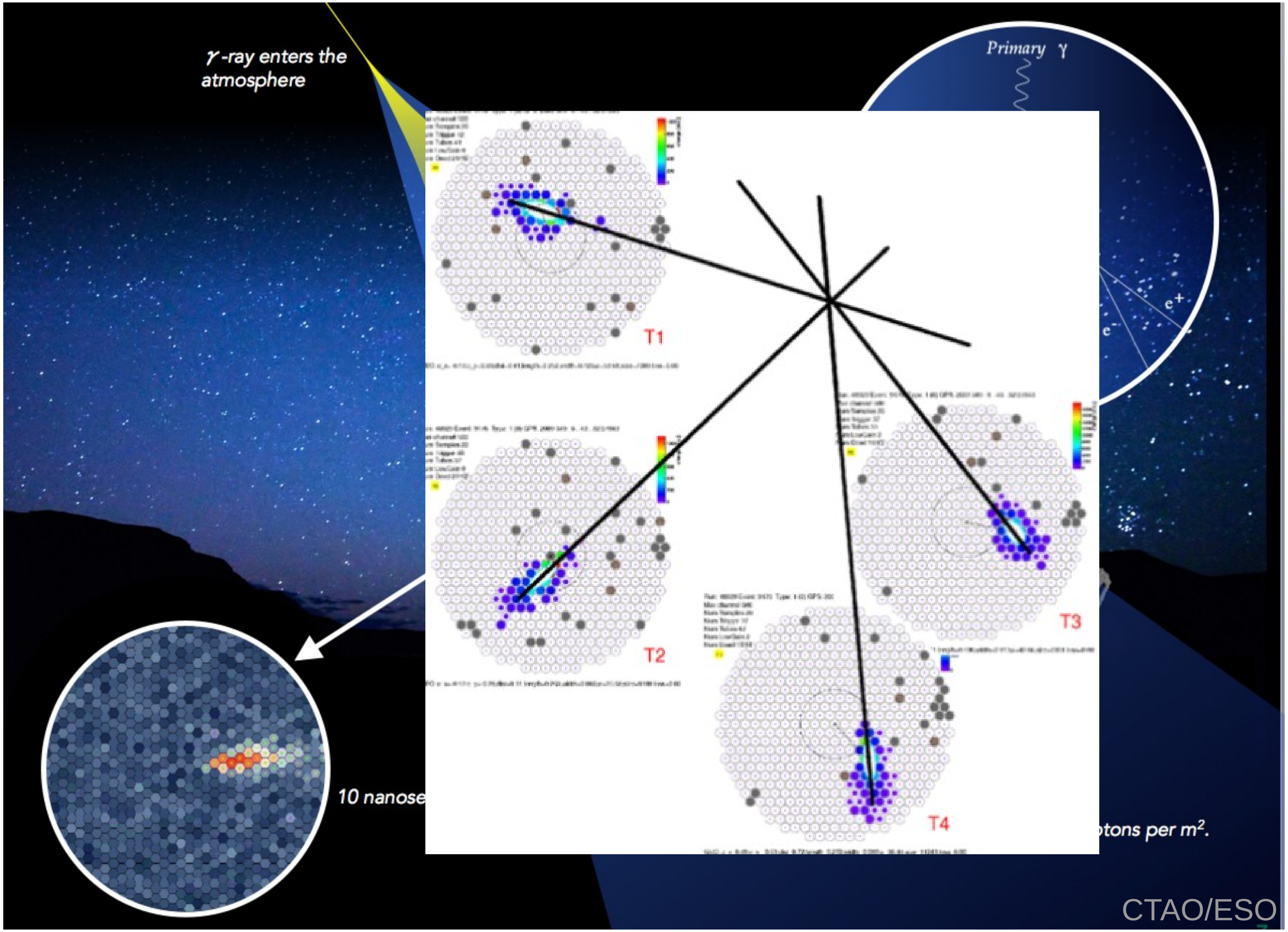
- Next generation of Cherenkov telescopes
- 2 geographic sites : North (La Palma, Spain) and South (Chile)
- 3 types of telescopes
- One telescope constructed so far : the Large-Sized Telescope-1 (LST-1)



Cherenkov astronomy



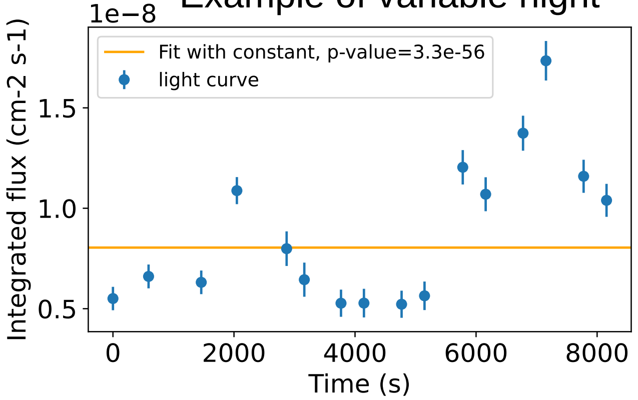
Cherenkov astronomy



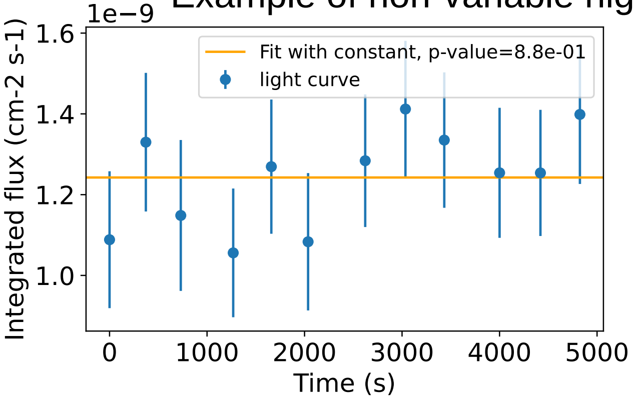
Looking for nights with variable flux in short time scale :

- fit of the light curve with constant function
- variable if pvalue < 5σ

Example of variable night



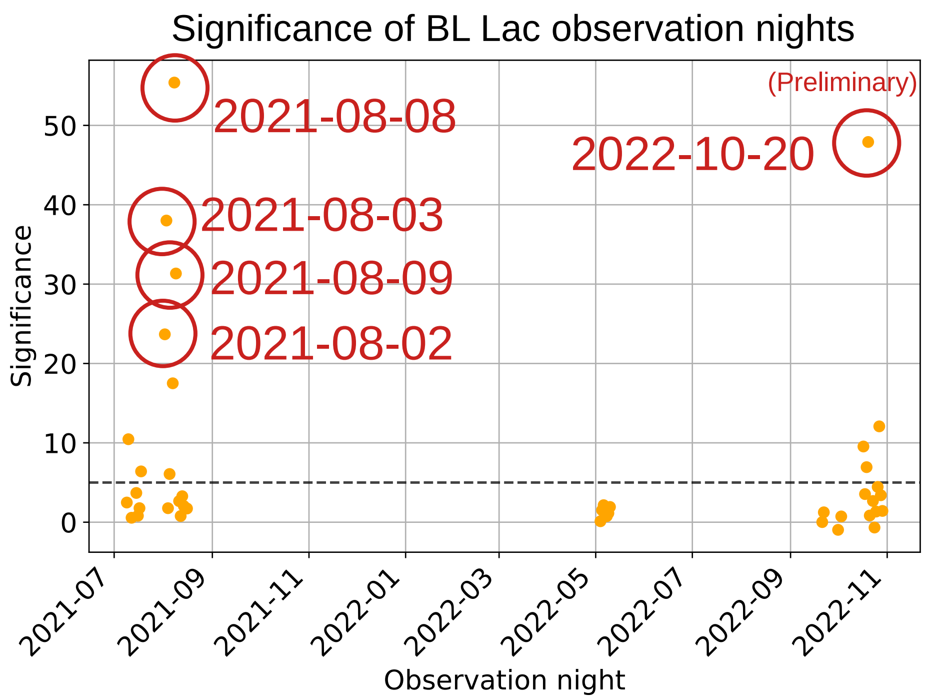
Example of non-variable night

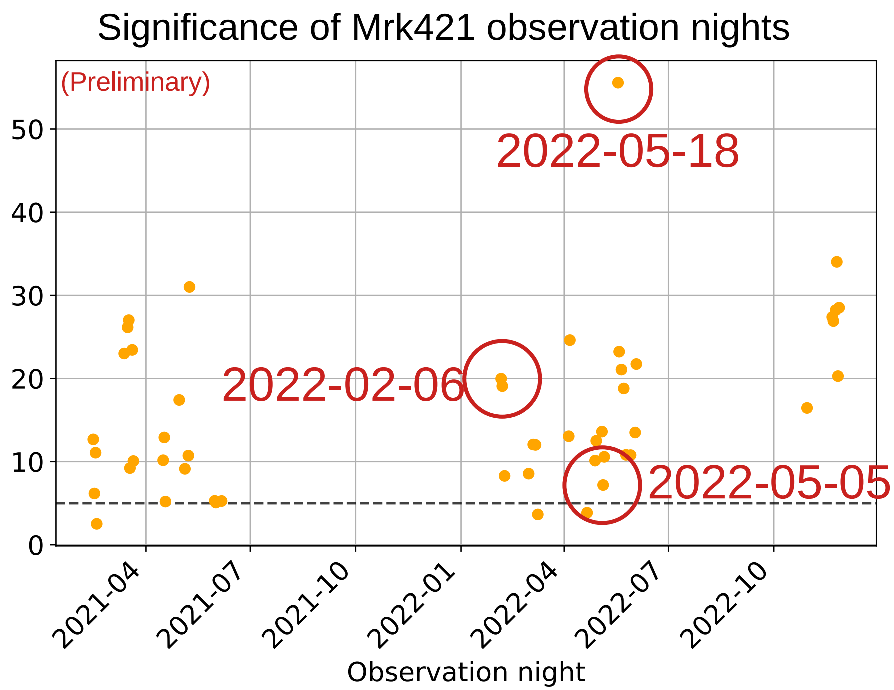


For the LIV analysis, we need to perform simulations of our dataset :

- Energetic characterisation : flux vs energy (spectra)
- Temporal characterisation : flux vs time (light curve)
  - LIV energy-dependency : low energy and high energy samples
  - Find a temporal pattern to « see » Δt : used if pvalue > 2σ
- Extraction of E_{QG} limit at 2σ

Variable nights

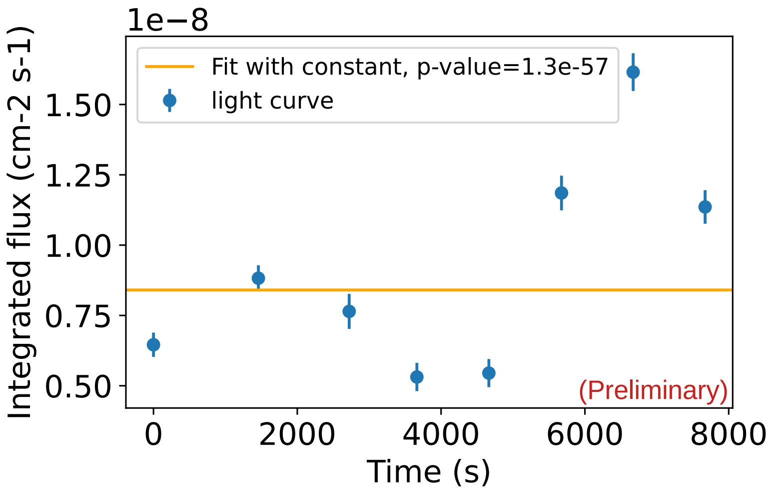




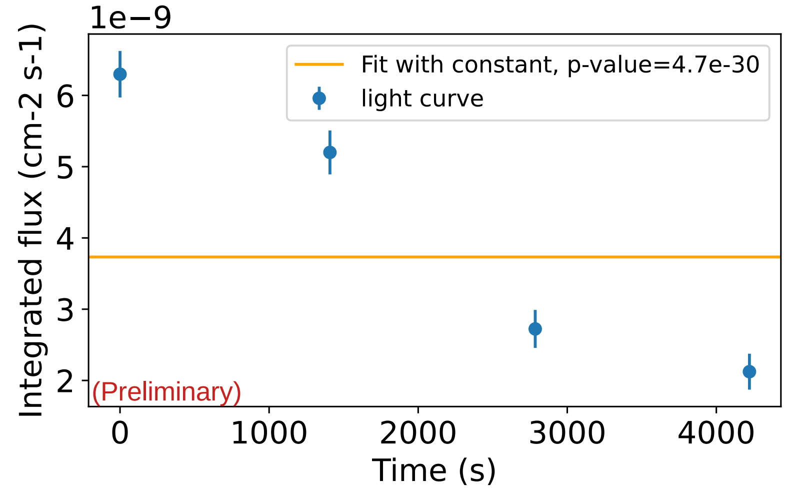
- Found 5 variable nights for BL Lac and 3 for Mrk421
- The following analysis is on BL Lac (Mrk421 analysis is on going)

BL Lac variable nights

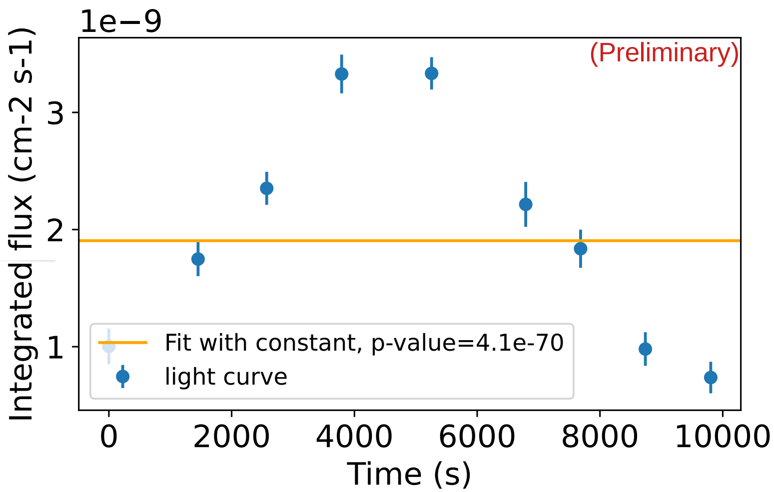
Lightcurve of the night 2021-08-08



Lightcurve of the night 2021-08-09



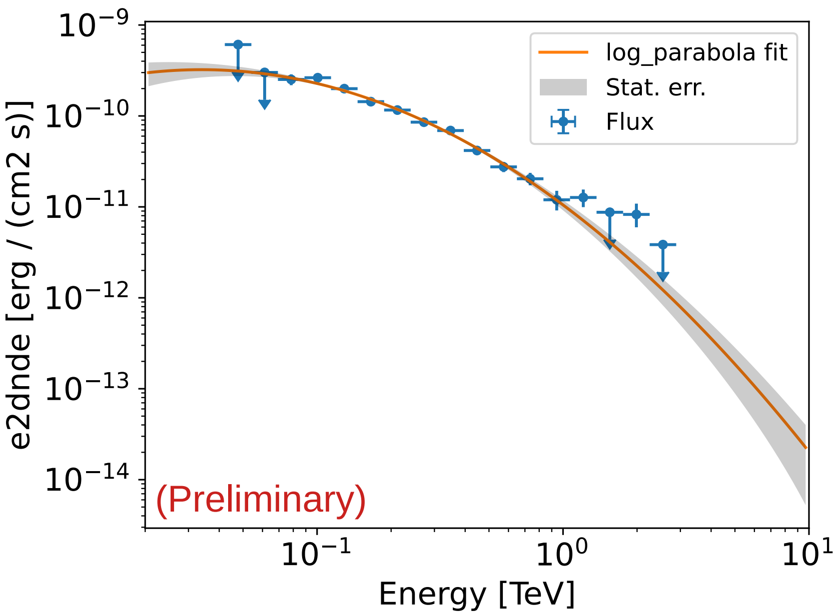
Lightcurve of the night 2022-10-20



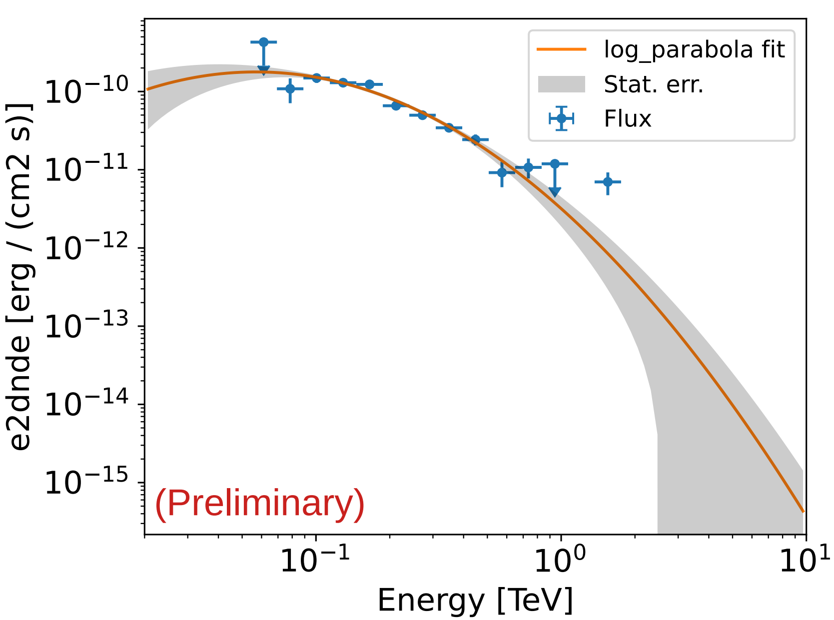
→ The following analysis is applied on 2021-08-08 and 2021-08-09

(analysis of 2022-10-20 on going)

Spectra of the night 2021-08-08



Spectra of the night 2021-08-09



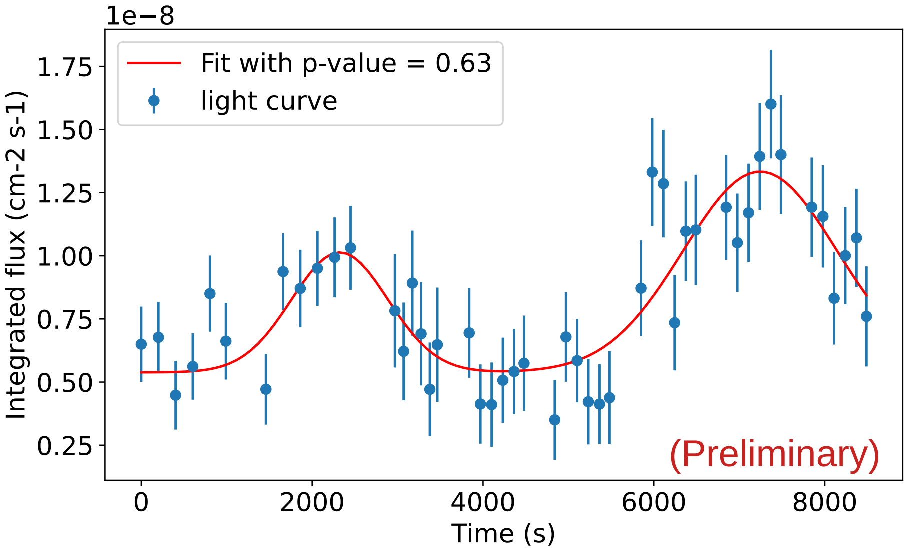
- 10 bins per decade, reconstructed energy : [20GeV , 10TeV]
- Select log parabola model instead of power law if p-value>5σ (equivalently)

BL Lac analysis : variability pattern

- Define two energy bins : lower and higher than median of counts E=0.19TeV
- Find a parametric model for the light curves : p-value > 0.05 (2σ)
- No significant disagreement between low and high energies

<u>August 8th 2021</u>

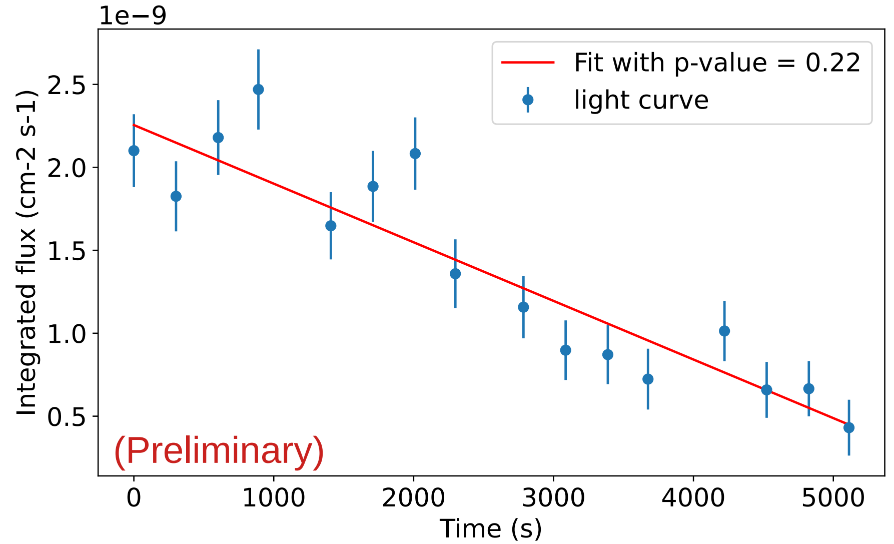
$$A_1 e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{-\frac{(x-\mu_2)^2}{2\sigma_1^2}} + C_0$$



6 bins per run

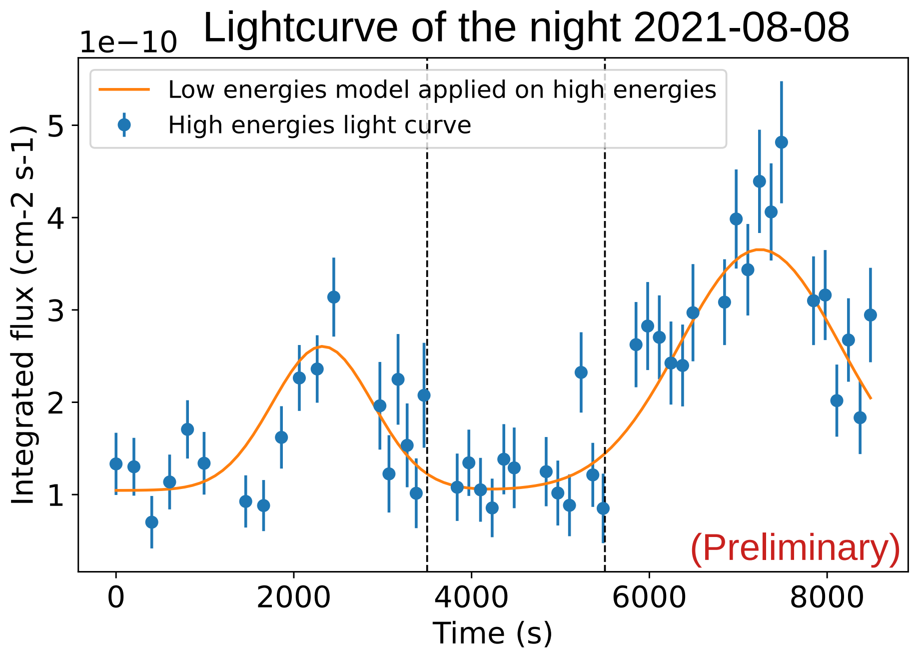
<u>August 9th 2021</u>

$$ax + b$$

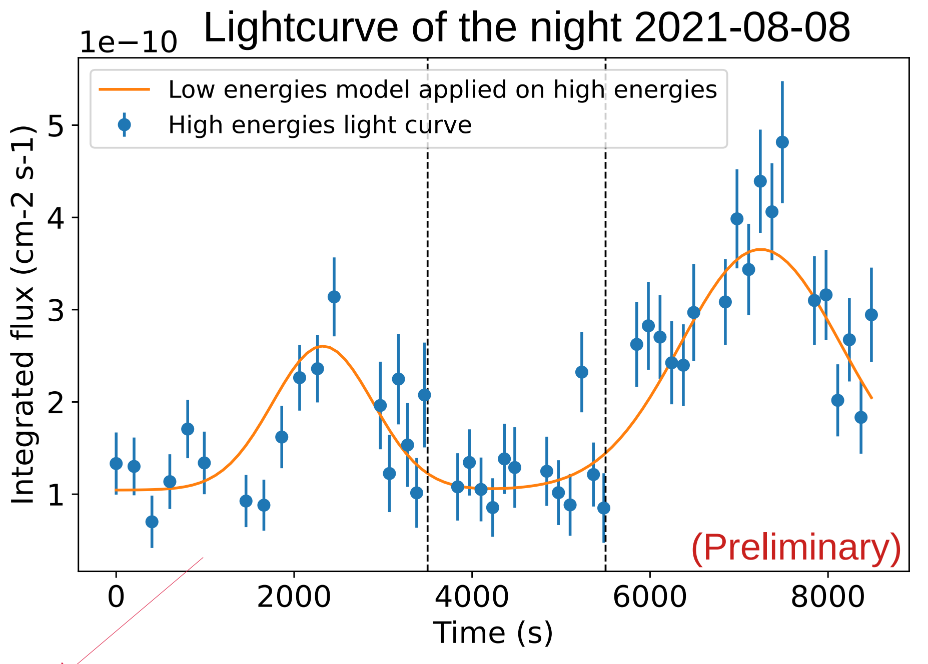


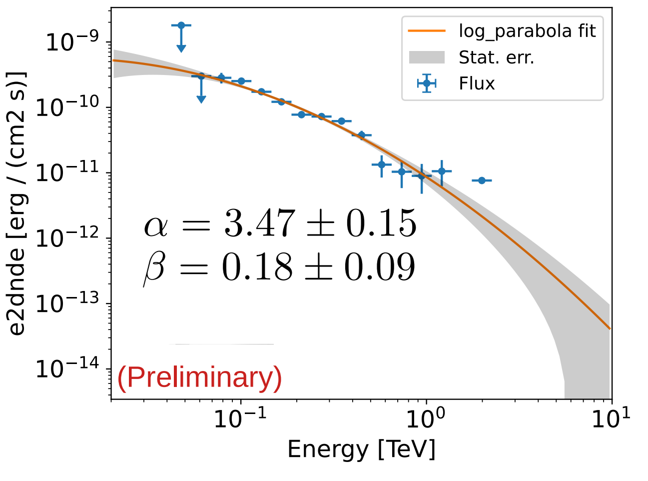
4 bins per run

Time-independency of the energetic distribution



Time-independency of the energetic distribution





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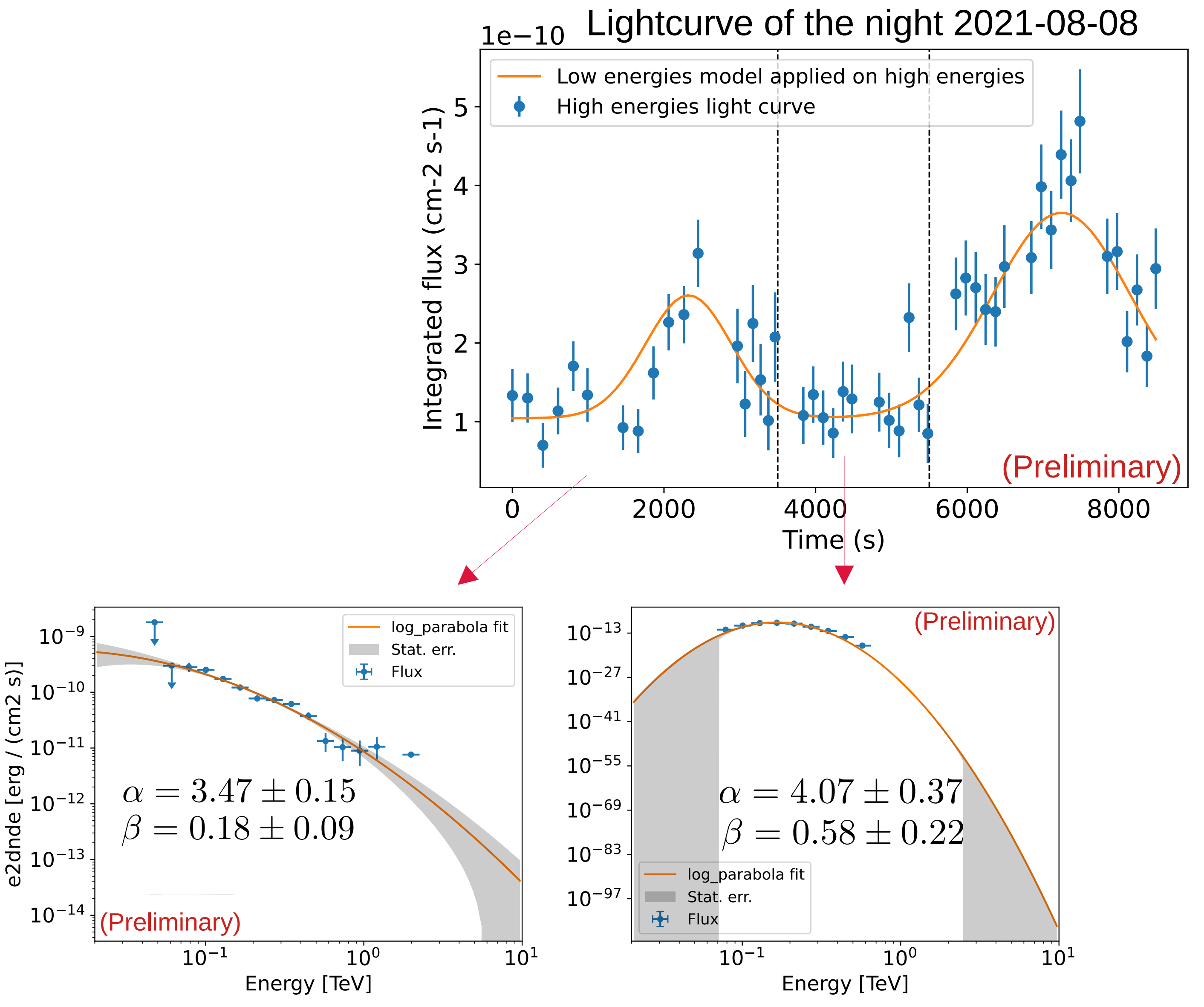

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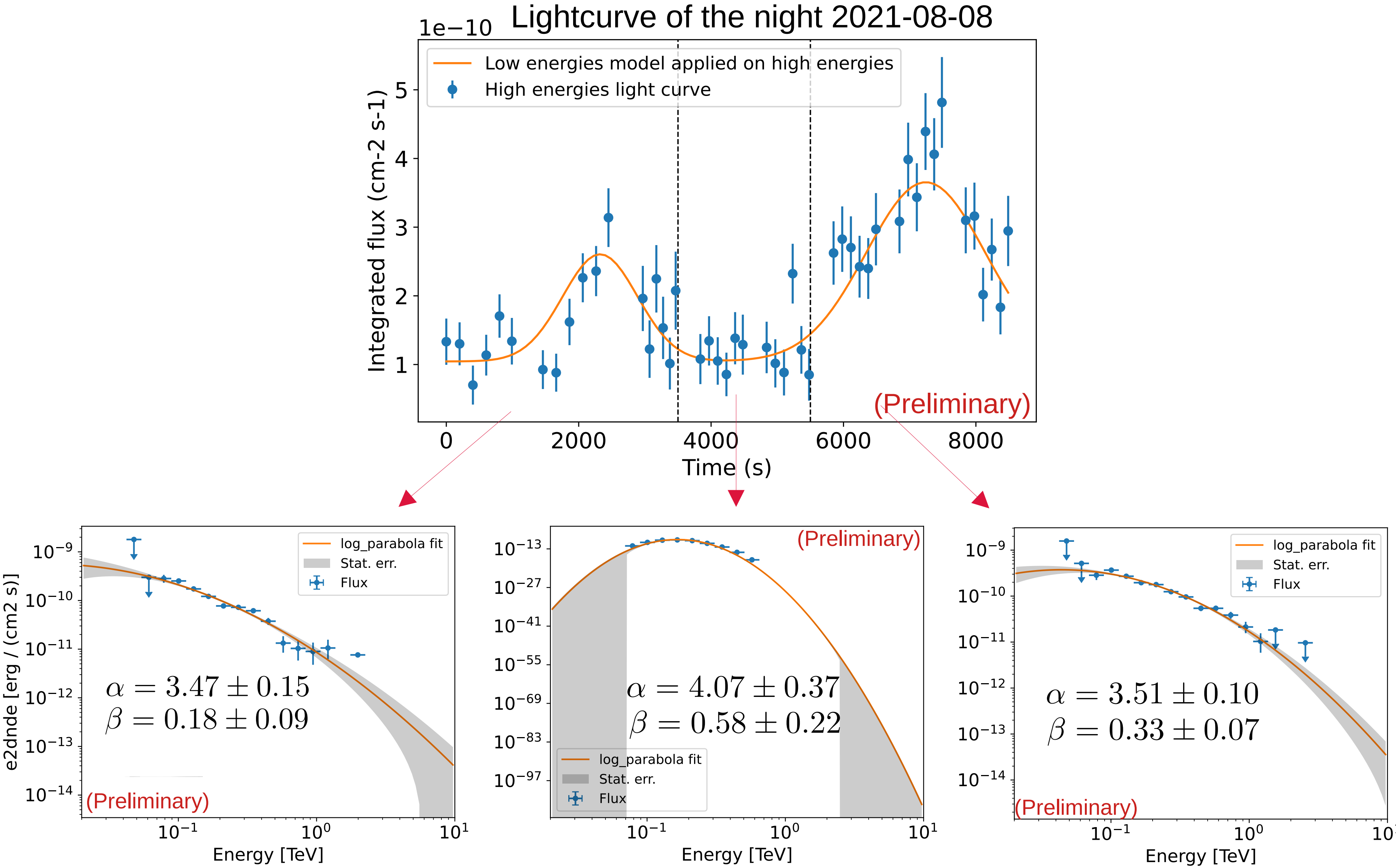

LIVelihood

- Code developped for time lag study and combination of different experiments data
- Based on ROOT C++
- Takes into account instrumental response and background
- Not yet public, created for the consortium between H.E.S.S., MAGIC, VERITAS, and now LST

H.E.S.S. MAGIC VERITAS

Likelihood method

Lag λ_n : free parameter, can be shared between sources with different redshifts

For one night :

$$\mathcal{L}(\lambda_n) = -\sum_i \log\Big(\frac{dP(E_{R,i}, t_i, \lambda_n)}{dE_R dt}\Big)$$

with

$$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_s(E_T, t; \lambda_n) dE_T}{N'_s}$$

$$+ \sum_k W_{b,k} \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

Lag λ_n : free parameter, can be shared between sources with different redshifts

For one night :

$$\mathcal{L}(\lambda_n) = -\sum_{\text{event } \mathbf{i}} \log\Big(\frac{dP(E_{R,\mathbf{i}}, t_{\mathbf{i}}, \lambda_n)}{dE_R dt}\Big)$$

with

$$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_s(E_T, t; \lambda_n) dE_T}{N'_s}$$

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Likelihood method

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Signal

$$+ \sum_{\mathbf{k}} W_{\mathbf{b,k}} \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{\mathbf{b,k}}(E_T) dE_T}{N'_{\mathbf{b,k}}}$$

Backgrounds k : hadrons and baseline

Lag λ_n : free parameter, can be shared between sources with different redshifts

For one night : $$\mathcal{L}(\lambda_n) = -\sum_i \log\left(\frac{dP(E_{R,i}, t_i, \lambda_n)}{dE_R dt}\right)$$

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W_s → proportion

N'_s → normalisation

$$+ \sum_k W_{b,k} \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

$W_{b,k}$ → proportion

$N'_{b,k}$ → normalisation

Lag λ_n : free parameter, can be shared between sources with different redshifts

For one night :
$$\mathcal{L}(\lambda_n) = -\sum_i \log\left(\frac{dP(E_{R,i}, t_i, \lambda_n)}{dE_R dt}\right)$$

with
$$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_s(E_T, t; \lambda_n) dE_T}{N'_s}$$

Instrumental response functions

$$+ \sum_k W_{b,k} \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

Lag λ_n : free parameter, can be shared between sources with different redshifts

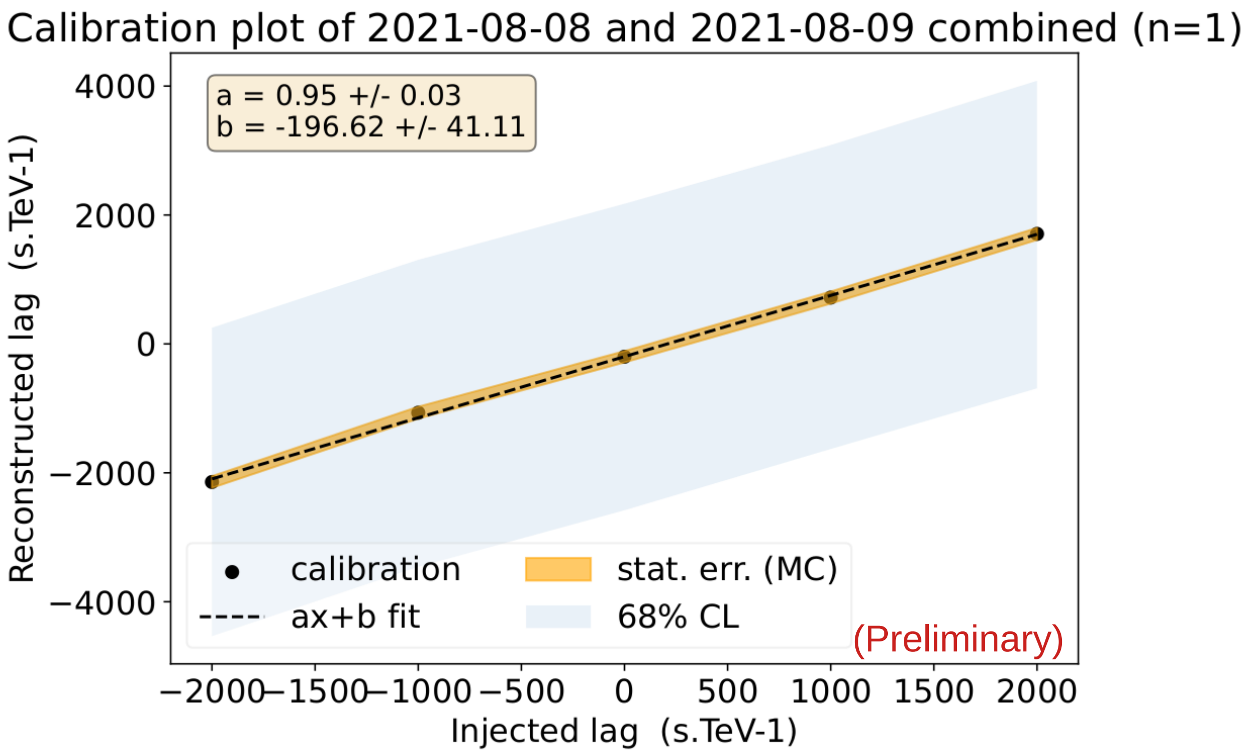
For one night : $$\mathcal{L}(\lambda_n) = -\sum_i \log\Big(\frac{dP(E_{R,i}, t_i, \lambda_n)}{dE_R dt}\Big)$$

with $$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_s(E_T, t; \lambda_n) dE_T}{N'_s}$$

$$+ \sum_k W_{b,k} \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

Lightcurve x spectra

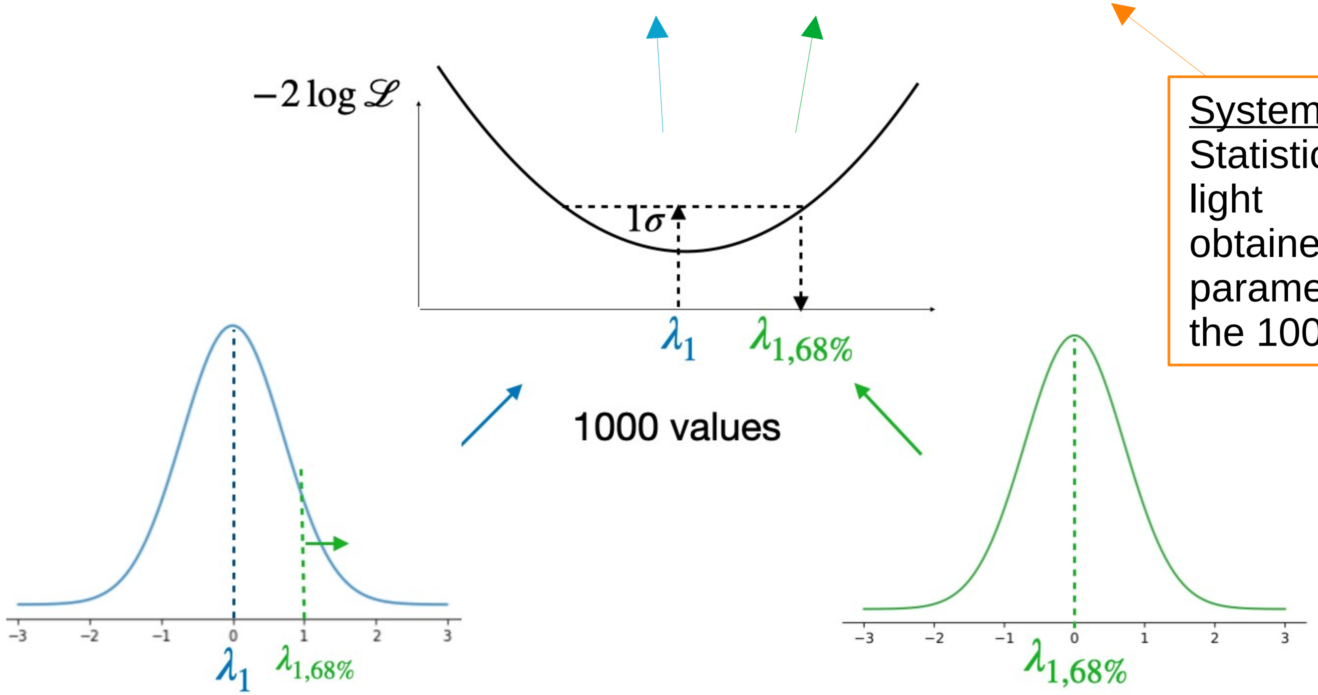
- Find the λ_1 that minimizes the likelihood
- Get the 95% uncertainty of λ_1
- Perform 1000 dataset simulations for calibration
- After calibration, if λ_1 compatible with 0 → $E^1_{QG,lim}$ on real data



Extraction of E_{QG} limit

On real data :

Time delay : $\lambda_1 = (3432\ ^{+2688}_{-2665}\ ^{+4482}_{-4221})\,\mathrm{s.TeV^{-1}}$

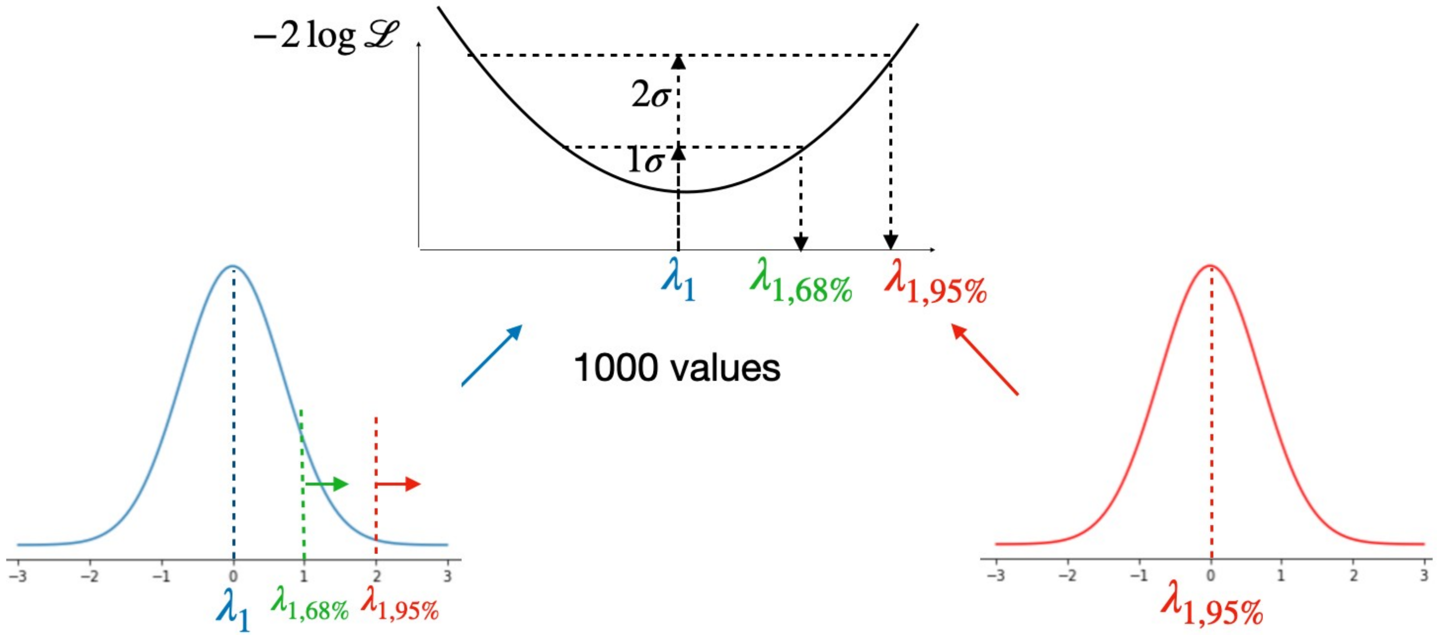


Systematics :
Statistical uncertainty of the light curve template : obtained by letting all parameters free in each of the 1000 simulations

Extraction of E_{QG} limit

On real data :

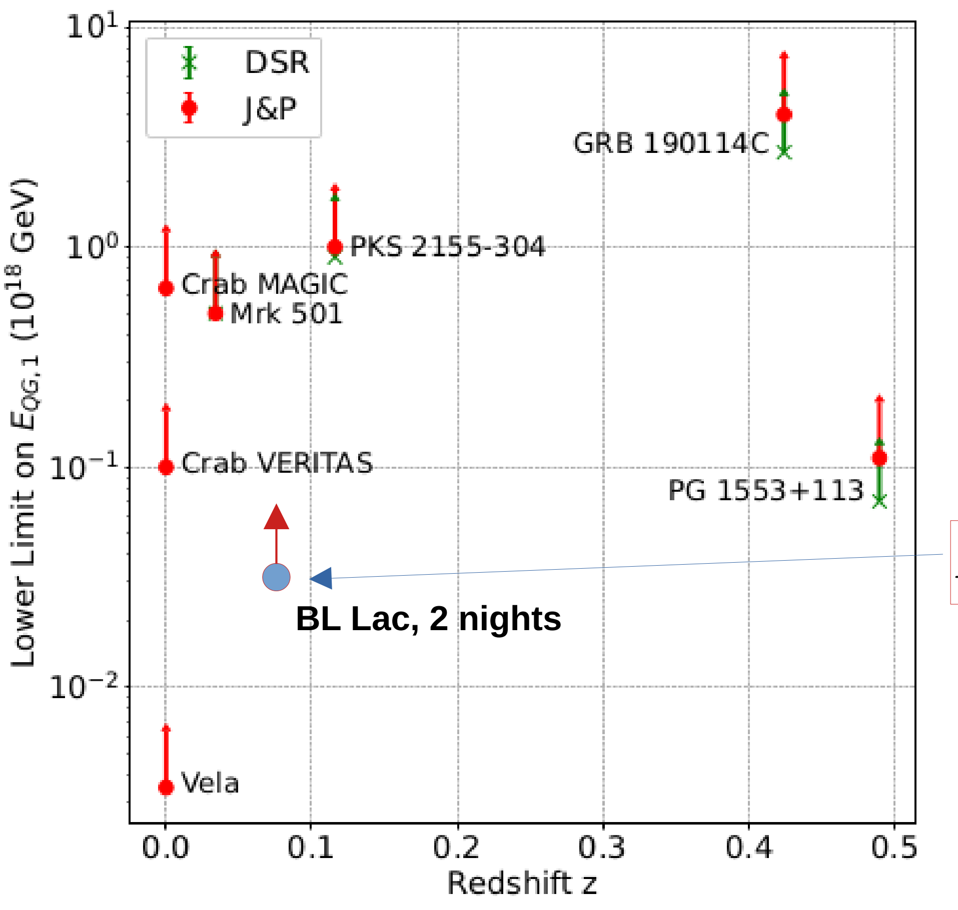
Time delay : $\lambda_1 = (3432\,^{+2688}_{-2665}\,^{+4482}_{-4221})\,\mathrm{s.TeV^{-1}}$



Use $\lambda_{1,95\%} = \pm\dfrac{n+1}{2H_0E^1_{QG,lim}}$ to extract : $E^1_{QG,lim} = 3.0\times10^{16}\,\mathrm{GeV}$

(subluminal case)

Comparison with other limits



$$E^{1}_{QG,lim} = 3.0 \times 10^{16}\text{GeV}$$

(subluminal case)

Bolmont et al., 2022

Conclusion

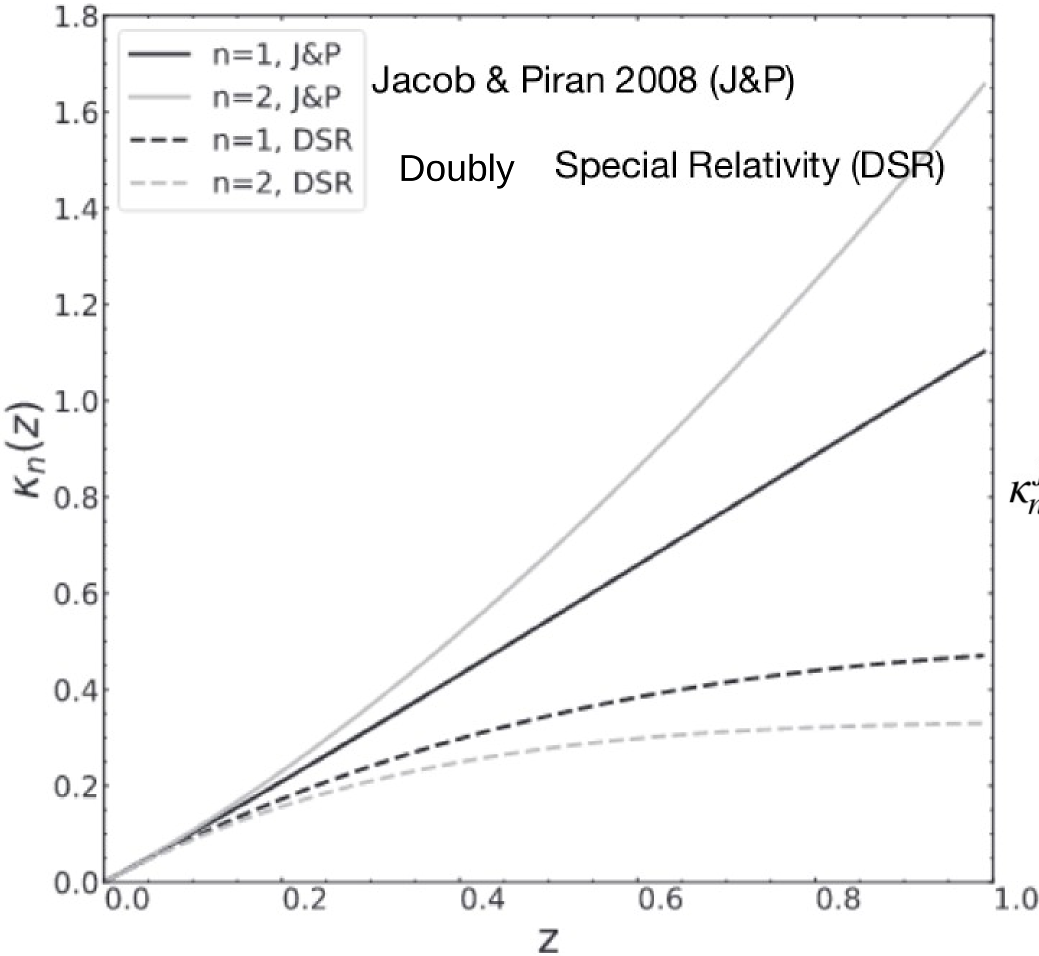
- LIV analysis of 2 variable nights of BL Lac
- Combined them to extract a limit on E_{QG} at the order n=1 on real data

Ongoing work :

- Combine with other flares (2022-10-20) and other sources (Mrk421)
- Derive LST systematics and integrate them to LIVelihood
- Limit on E_{QG} for n=2

Backup

Redshift correction

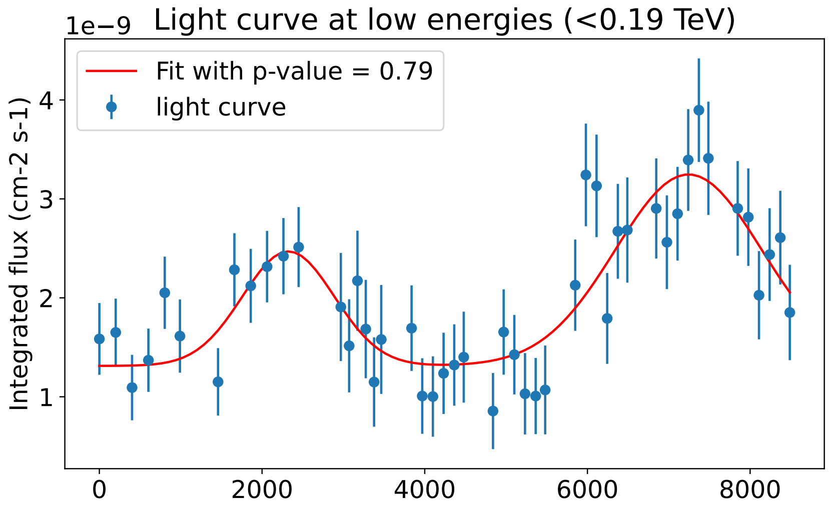


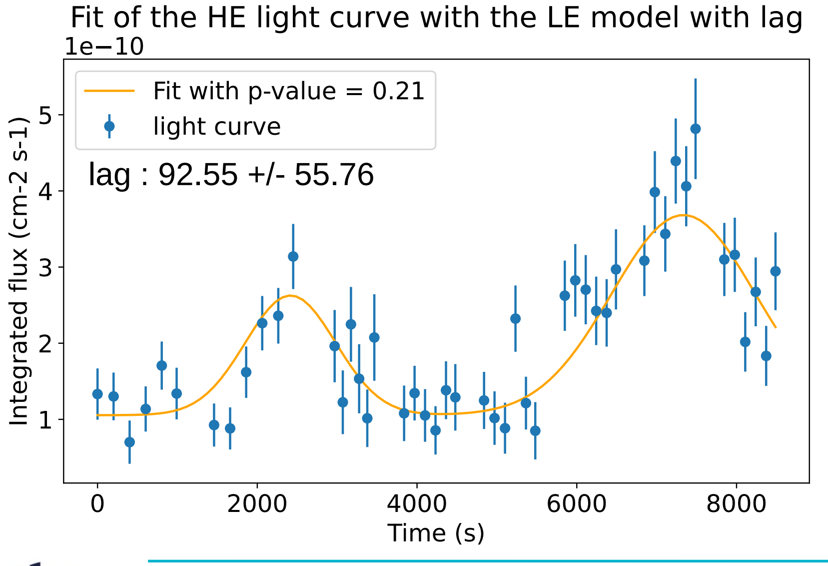
Bolmont et al 2022

$$\kappa_n^{J\&P}(z) = \frac{1}{z_0}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}dz'$$

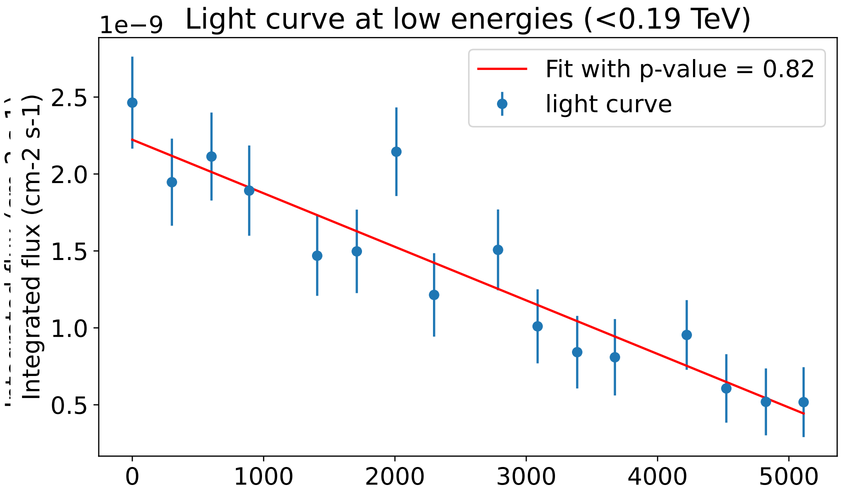
Model comparison

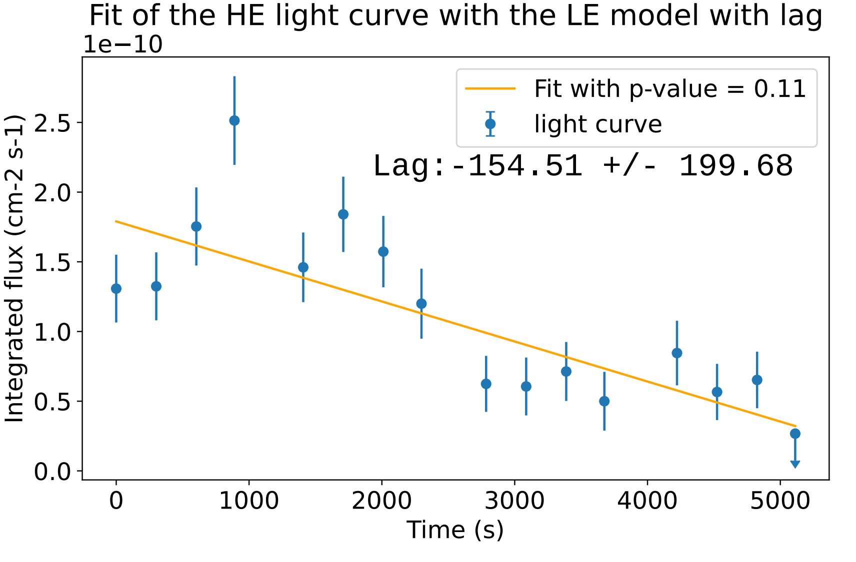
August 8th 2021





August 9th 2021

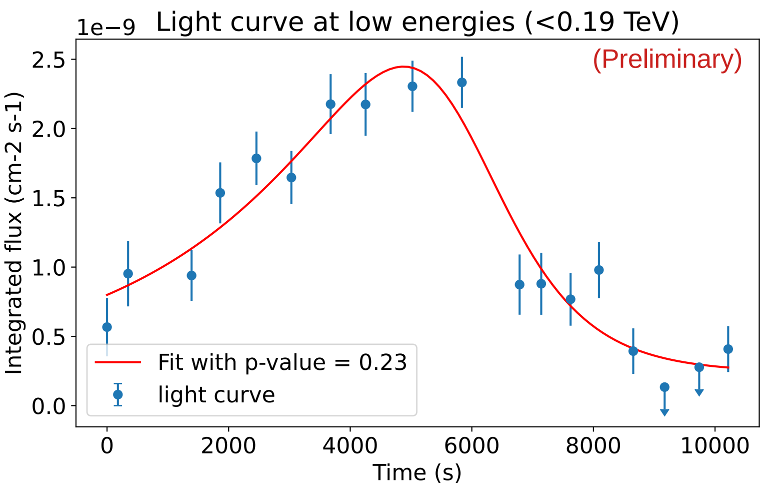


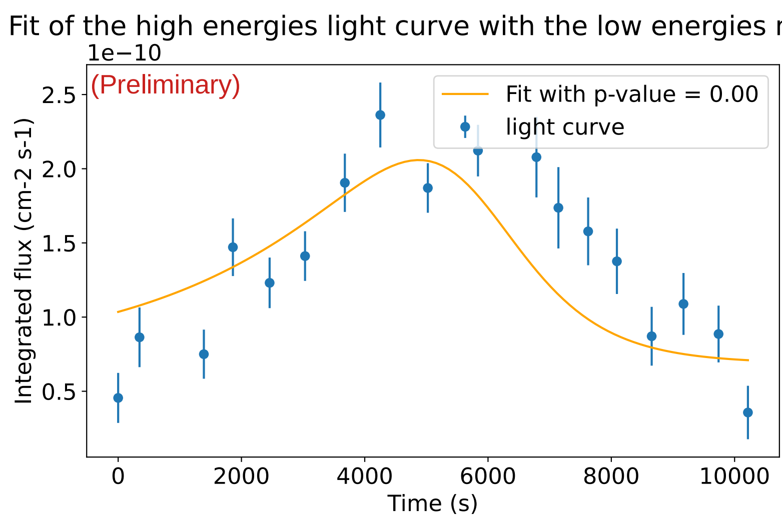


BL Lac 2022-10-20 variable night

Asymmetric gaussian

$$F_{c,0} + \frac{F_0}{e^{\frac{t_1 - t}{T_r}} + e^{\frac{t - t_1}{T_d}}}$$

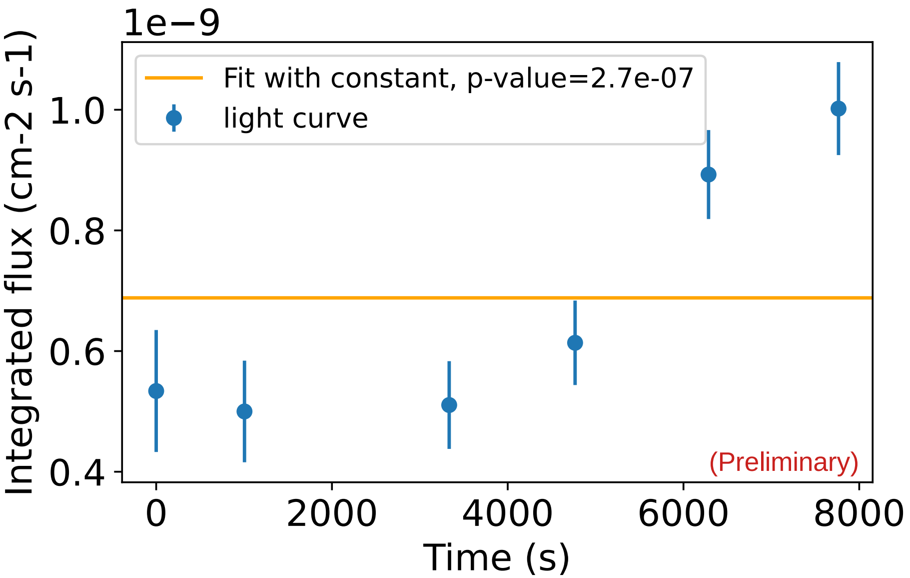




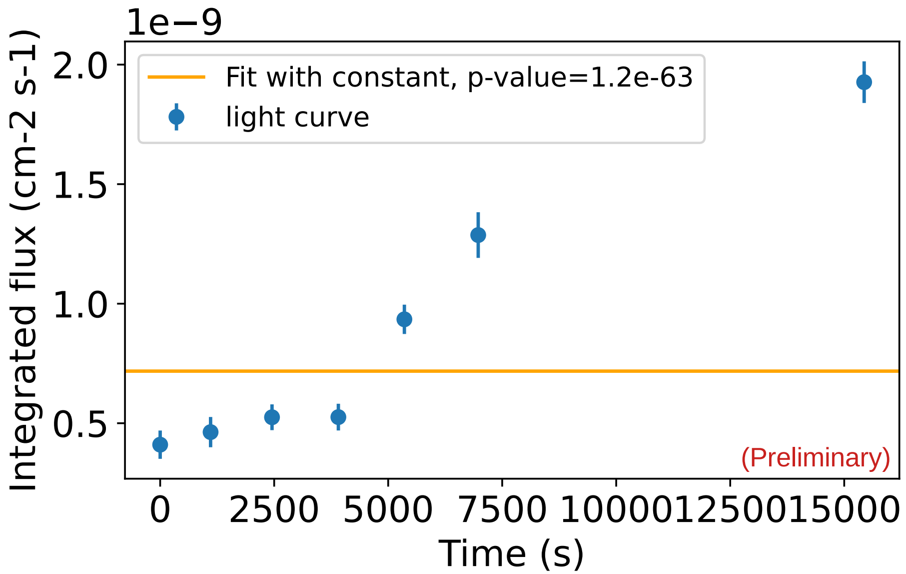
P-value= 0.000016 < 0.05 (2σ)

BL Lac variable nights

Lightcurve of the night 2021-08-02



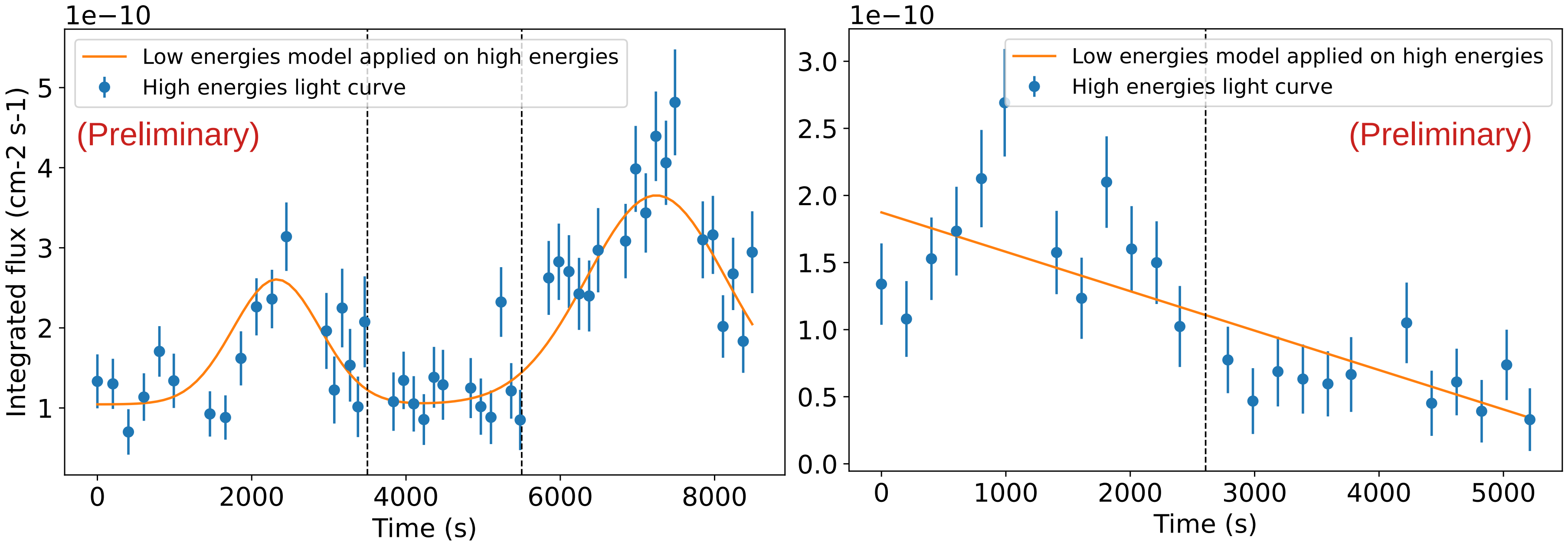
Lightcurve of the night 2021-08-03



Time-independency of the log parabola parameters

August 8th 2021

August 9th 2021

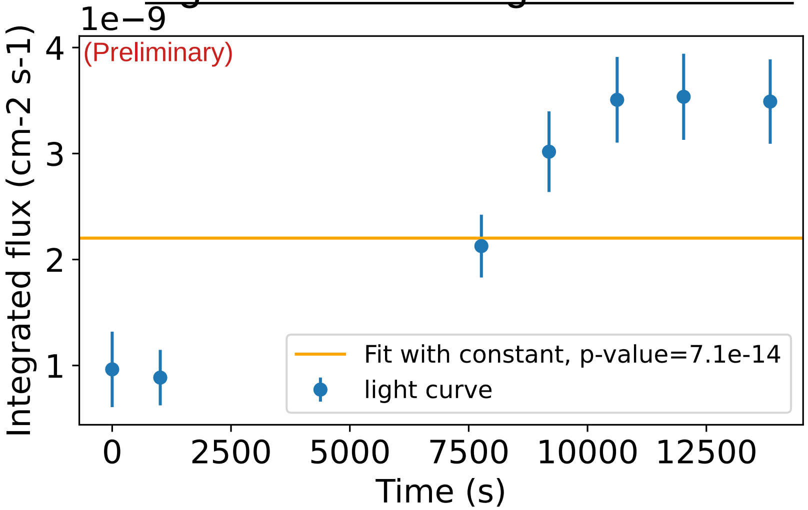


August 8th 2021: $\alpha = 3.47 \pm 0.15$, $\beta = 0.18 \pm 0.09$; 4.07 ± 0.37, 0.58 ± 0.22; 3.51 ± 0.10, 0.33 ± 0.07

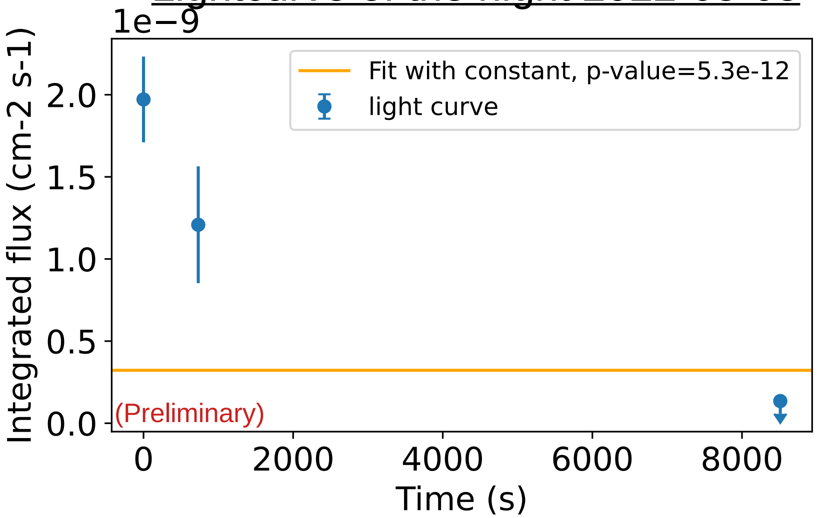
August 9th 2021: $\alpha = 3.72 \pm 0.20$, $\beta = 0.36 \pm 0.12$; 5.28 ± 1.13, 1.06 ± 0.57

Mrk421 variable nights

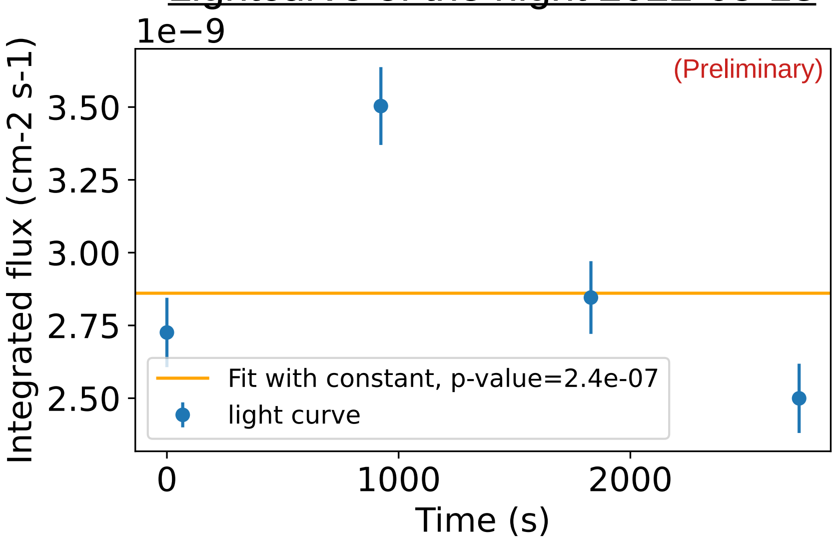
Lightcurve of the night 2022-02-06



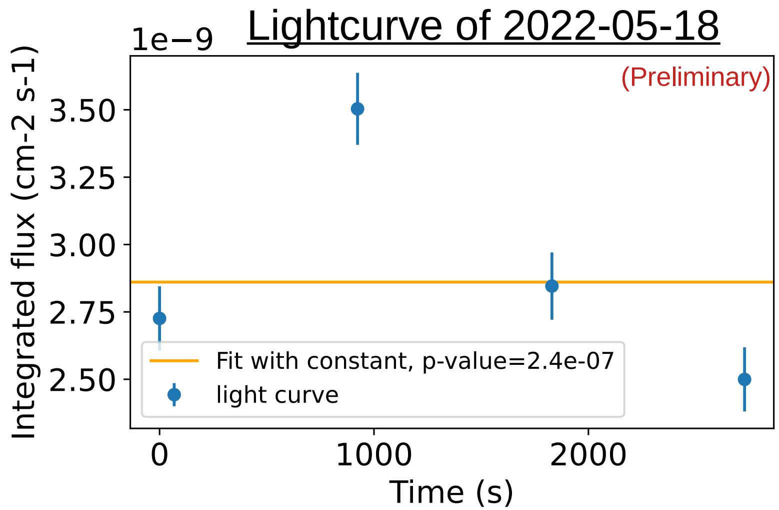
Lightcurve of the night 2022-05-05

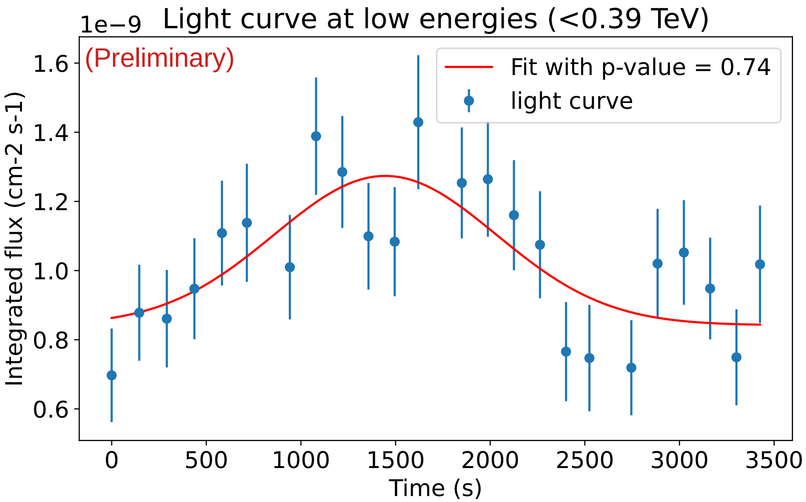


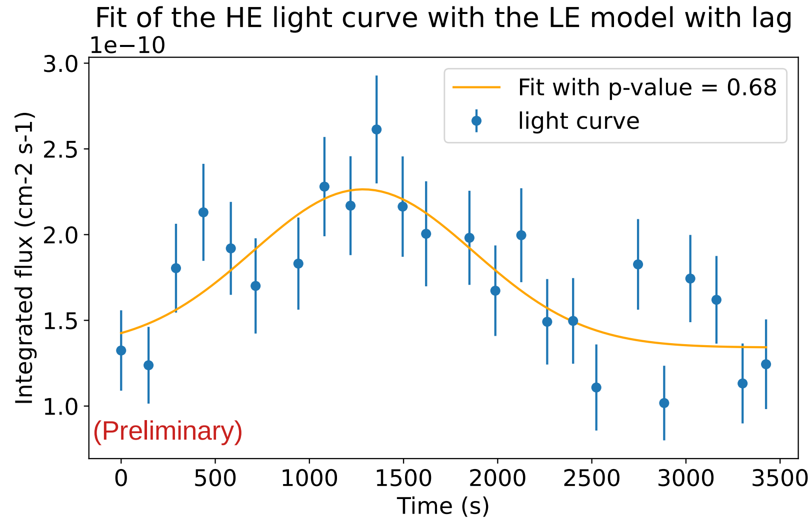
Lightcurve of the night 2022-05-18



Mrk421 2022-05-18 variable night







6 bins per run

Lag : -160 +/- 95 compatible with 0

→ LIVelihood analysis on going

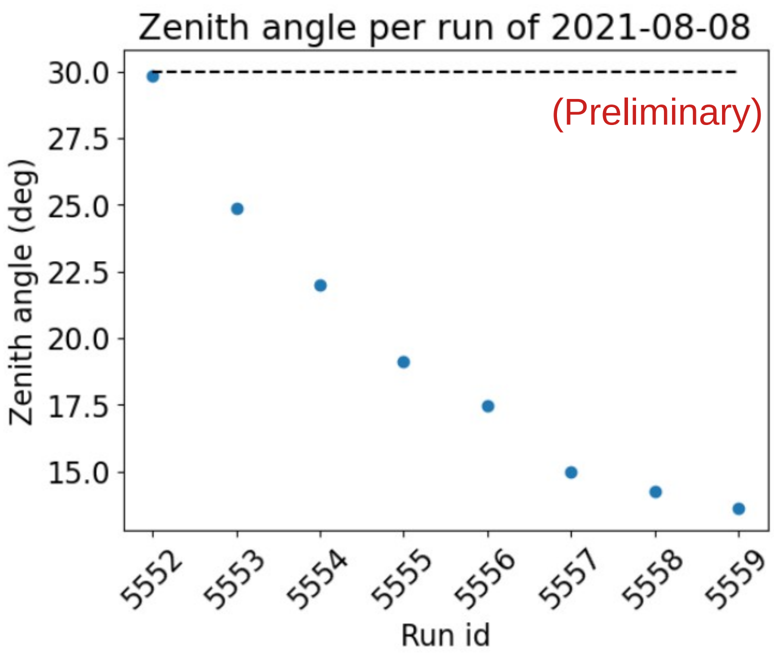
$$\mathcal{L}(\lambda_n) = -\sum_i \log\Big(\frac{dP(E_{R,i}, t_i, \lambda_n)}{dE_R dt}\Big)$$

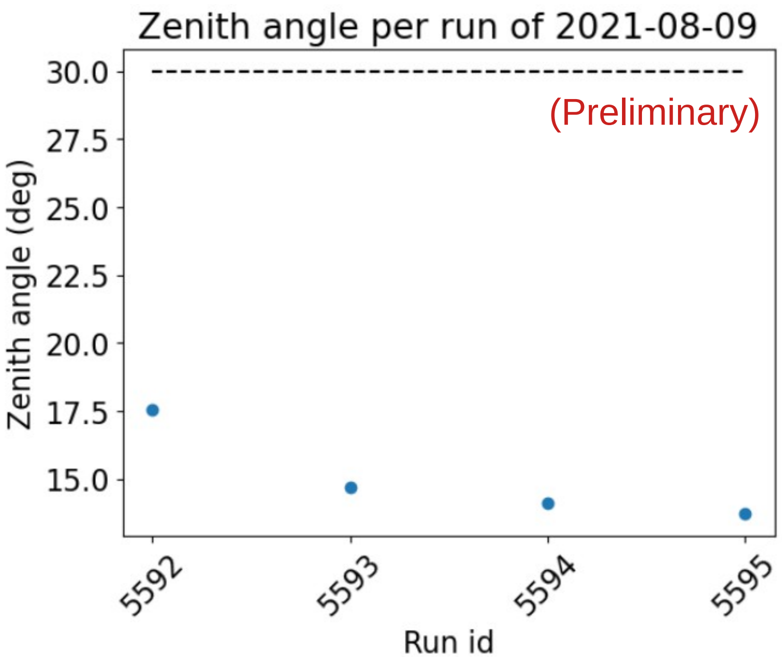
$$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_S(E_T, t; \lambda_n) dE_T}{N'_s}$$

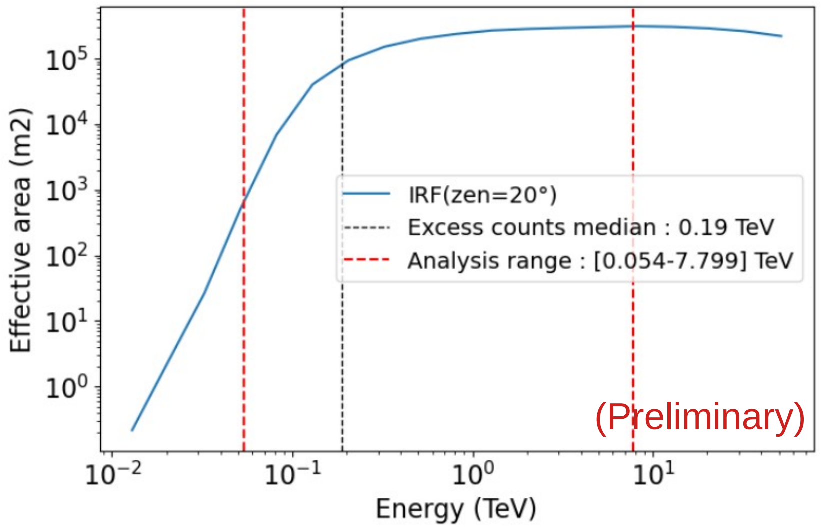
$$+W_b \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_b(E_T) dE_T}{N'_b}$$

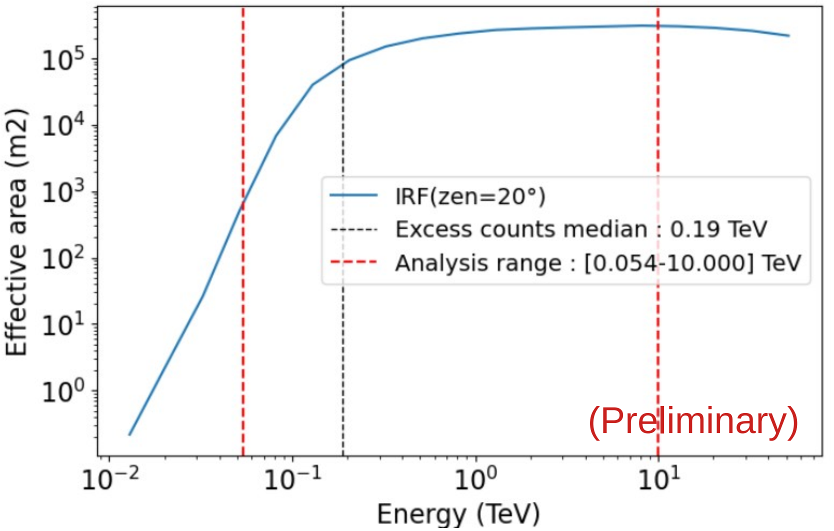
$$+W_h \frac{dN_{off}}{dE_R} \times \frac{1}{T} \times \frac{1}{N'_h}$$

IRFs and zenith angle







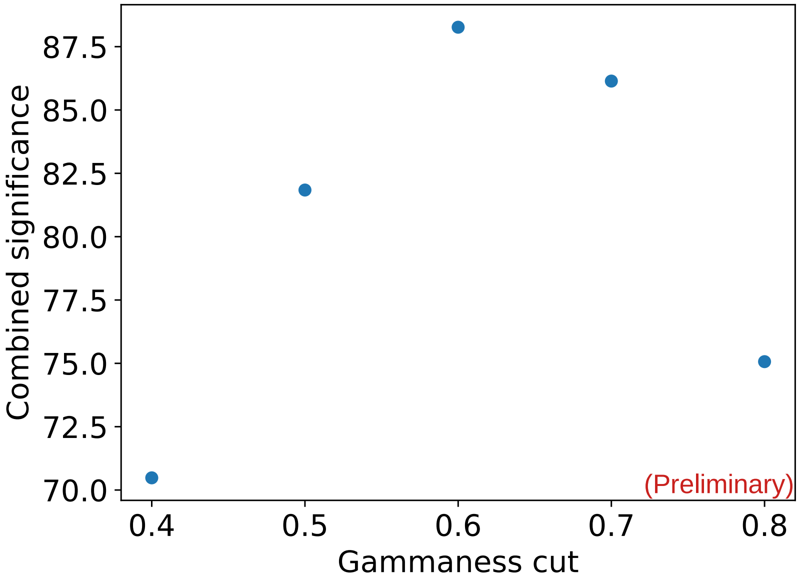


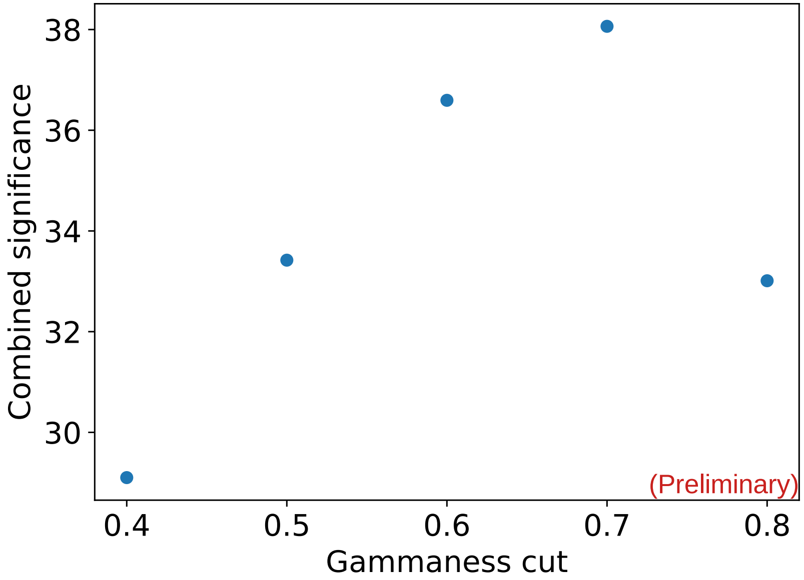
Tuned gammaness cut for BL Lac DL3

Search for the gammaness cut that maximizes the combined significance of all variable nights and all non-variable nights.

$$S_{cut} = \sqrt{\sum_{var\,night} S_n^2}$$

$$S_{cut} = \sqrt{\sum_{non-var\,night} S_n^2}$$





- All the analysis has been done with cut of 0.6 ; cut of 0.7 is on going
- Tuned cut search for Mrk421 on going