LST-1 analysis

Astrovibe workshop – july 2024

Cyann Plard & Sami Caroff

Credit : Me

Cherenkov telescope array observatory

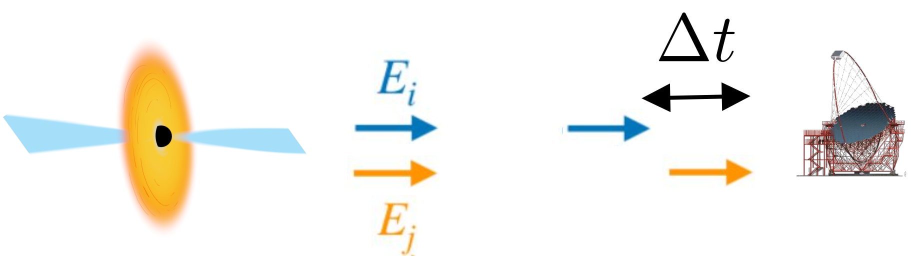
LST-1 in commisionning since 2019

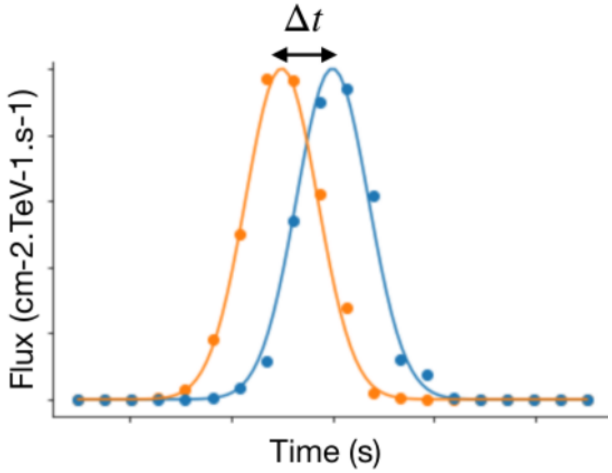
LST-4 construction site

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

→ blazars, GRBs, pulsars

$$\boxed{\lambda_{n=1}} = \frac{\Delta t_1}{\Delta E_1 \kappa_1(z)} = \pm \frac{1}{H_0 E_{QG,1}}$$





All **blazar** data of the LST-1 prototype of the Cherenkov telescope array observatory

Analysis : step 1

Several AGNs data of LST-1 from January 2021 to June 2023

	BL Lac	M87	1ES 1959+650	PG 1553+113	Mrk421	Mrk501	TON0599
Redshift	0.069	0.0043	0.047	0.49	0.03002	0.034	0.72
Observation time (hours)	44	9	13	24	72	66	9

237 hours of observations

Analysis : step 2

Several AGNs data of LST-1 from January 2021 to June 2023

↓

Variability test on each significant observation night

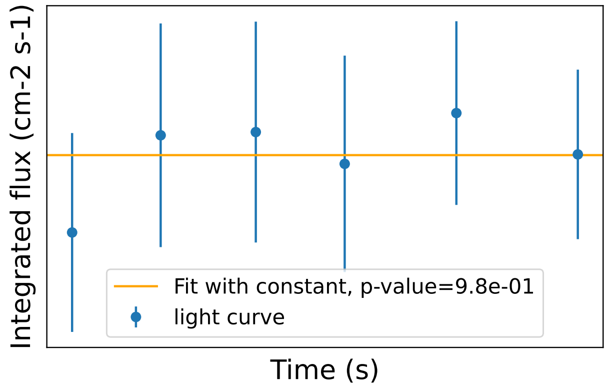
Analysis : step 2

Several AGNs data of LST-1 from January 2021 to June 2023

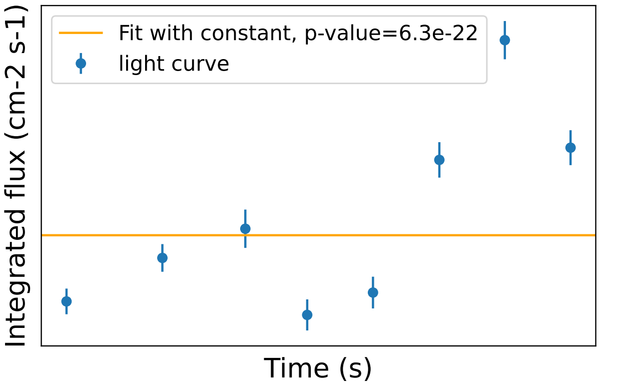
Variability test on each significant observation night

Constant fit
pvalue < 3×10^{-7}
(5σ)

Non-variable sample



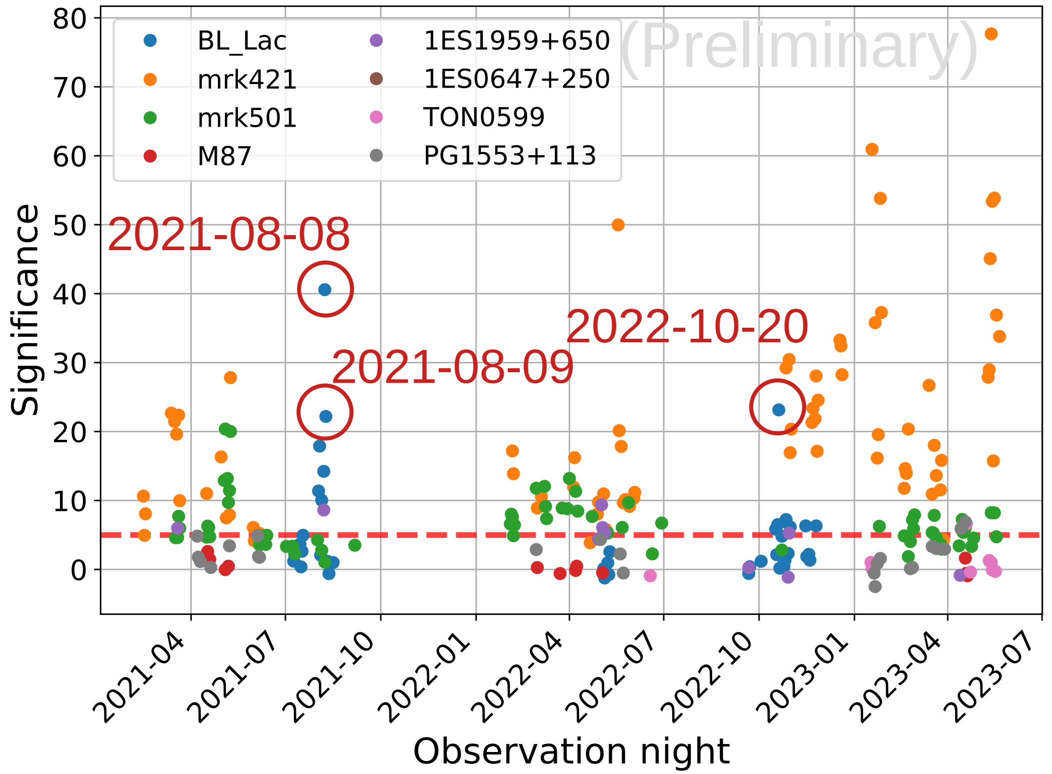
Variable sample



Step 2 : intra-night variability

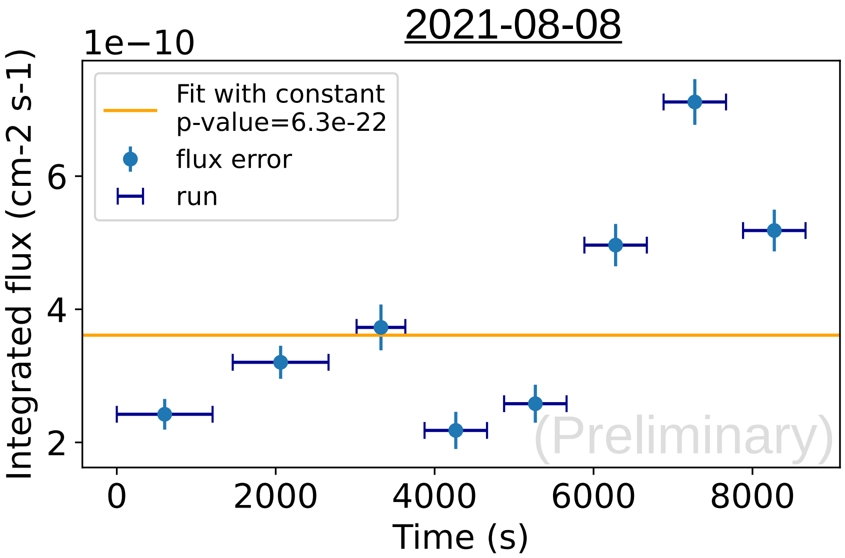
Several AGNs data of LST-1 from January 2021 to June 2023

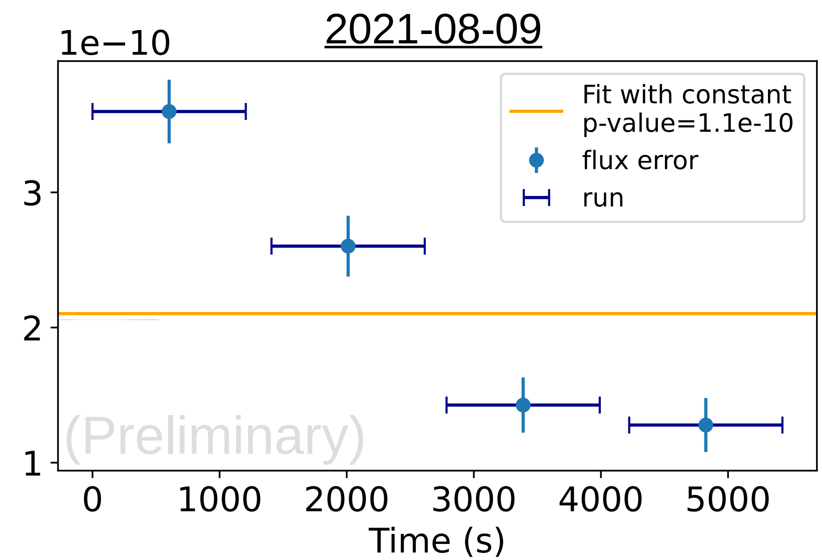
Significance vs observation nights for all sources

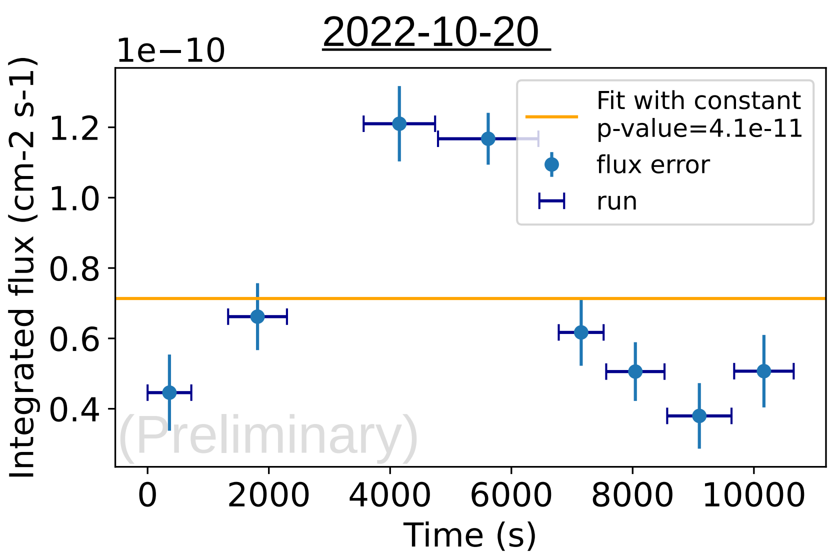


Found 1 source showing intra-night variability : **BL Lacertae** with 3 nights (~7h)

Variable lightcurves of BL Lac





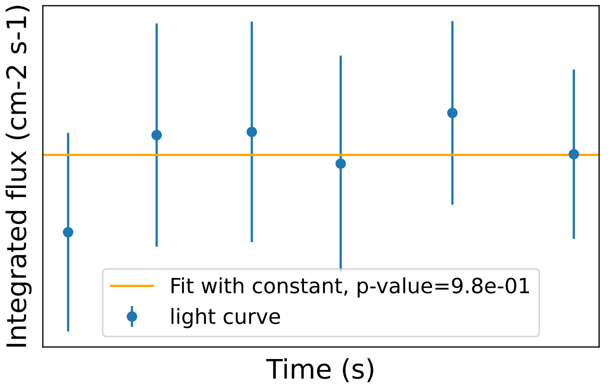


Analysis : step 2

Several AGNs data of LST-1 from January 2021 to June 2023

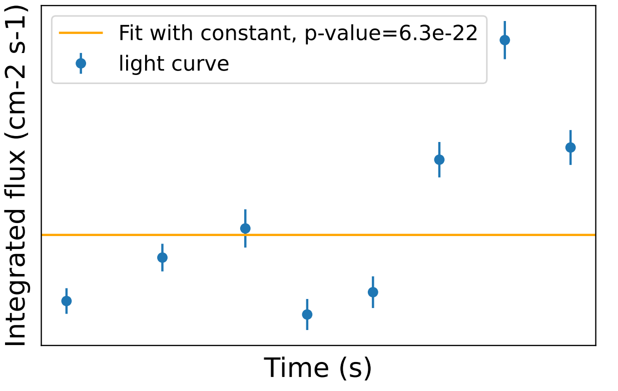
Variability test on each significant observation night

Non-variable sample



Constant fit
pvalue < 3×10^{-7}
(5σ)

Variable sample



Applied on Crab → no intra-night variability

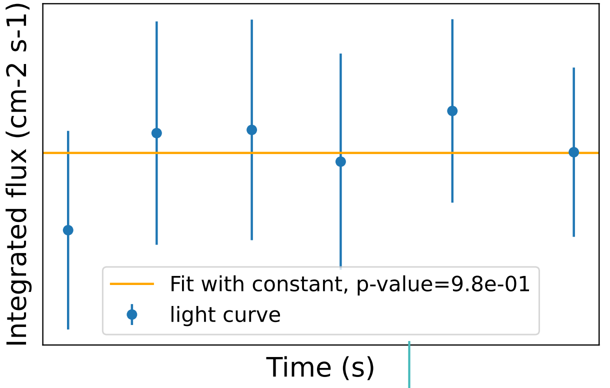
Analysis : step 3

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

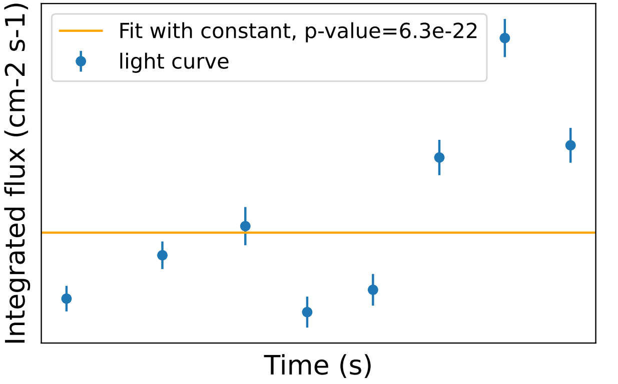
Constant fit
pvalue < 3×10^{-7}
(5σ)

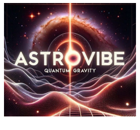
Non-variable sample



Optimization of gammaness cut

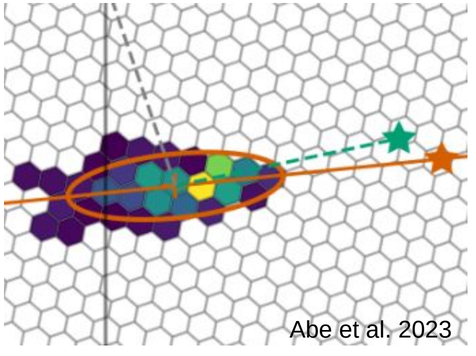
Variable sample

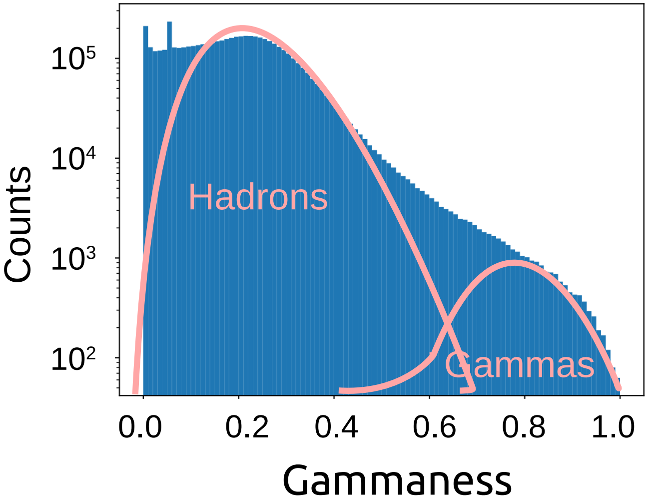




Non-variable sample

Optimization of analysis cut





Reconstruction of event properties

- direction
- energy
- type of particle (gamma, hadron, ...)

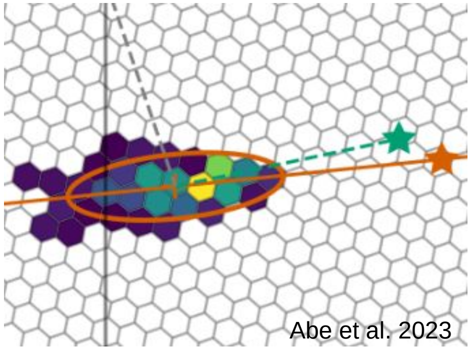
score of how likely an event is expected to be a gamma rather than background

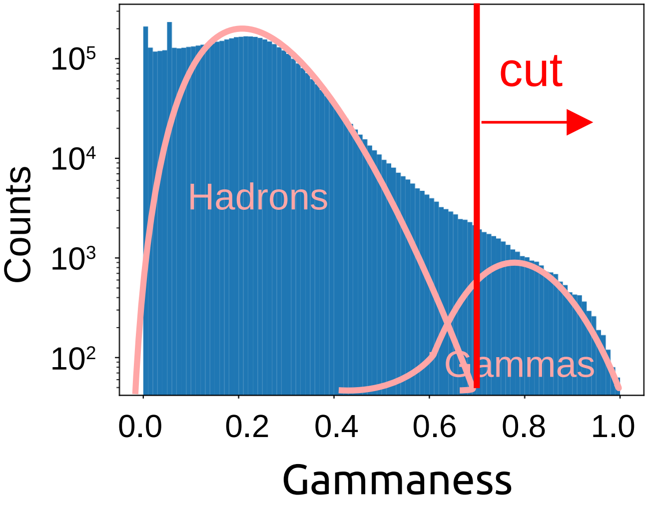
Step 3 : cut optimization

Non-variable sample

↓

Optimization of analysis cut





Reconstruction of event properties

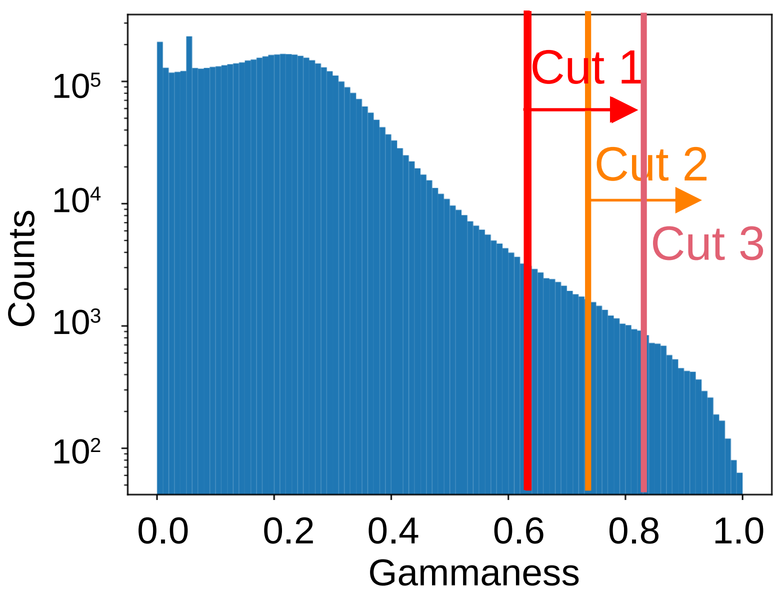
- direction
- energy
- type of particle (gamma, hadron, ...)

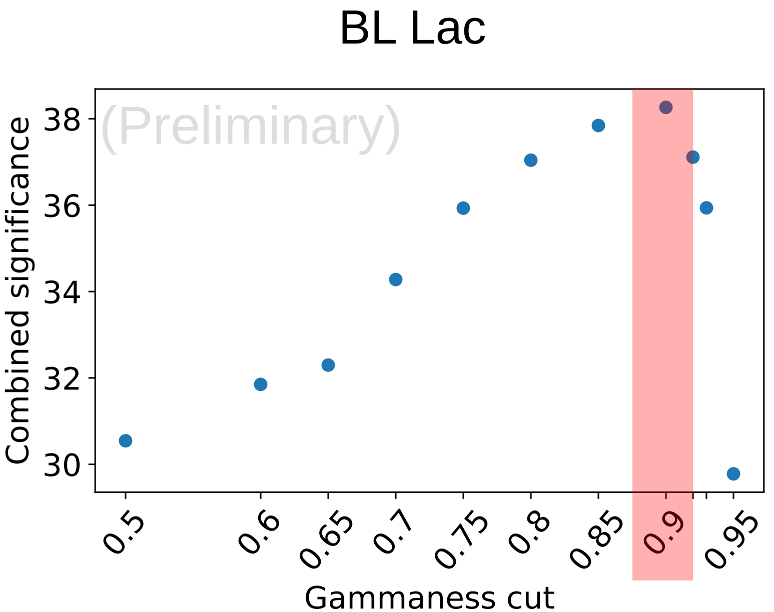
score of how likely an event is expected to be a gamma rather than background

Step 2 : cut optimization

Non-variable sample

Select different gammaness cuts and search for the significance





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

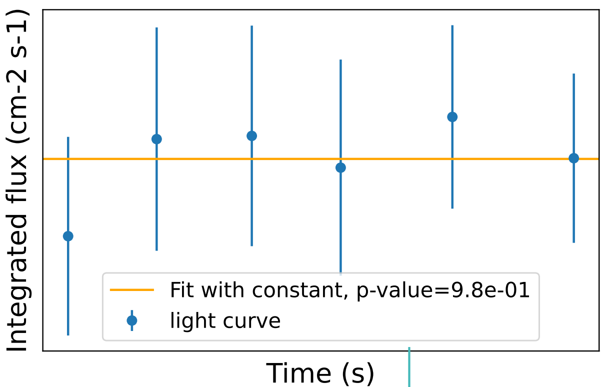
Analysis : step 3

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

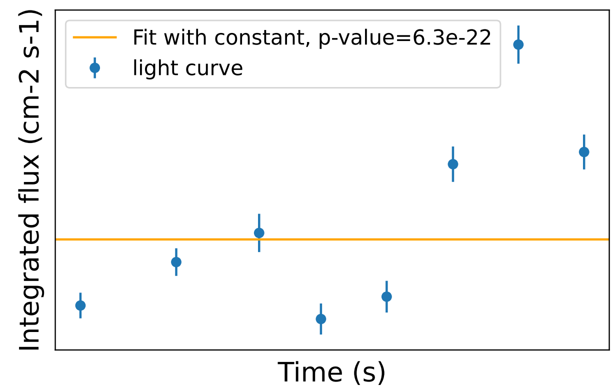
Constant fit pvalue < 5σ ?

Non-variable sample



Optimization of gammaness cut : **0.9** for BL Lac

Variable sample



Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

Constant fit pvalue < 5σ ?

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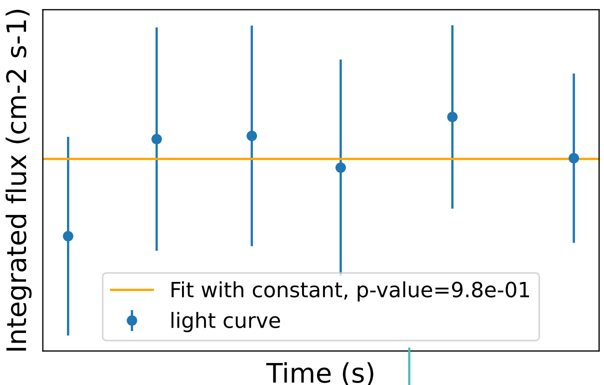

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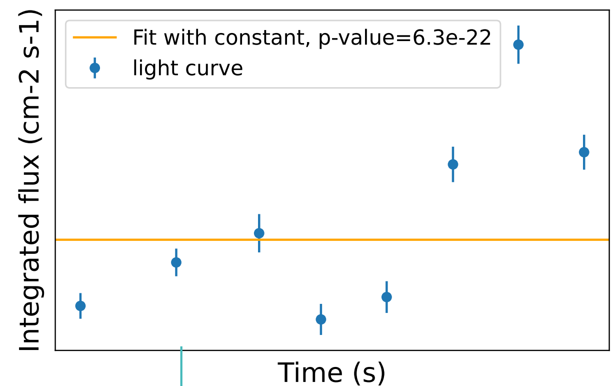
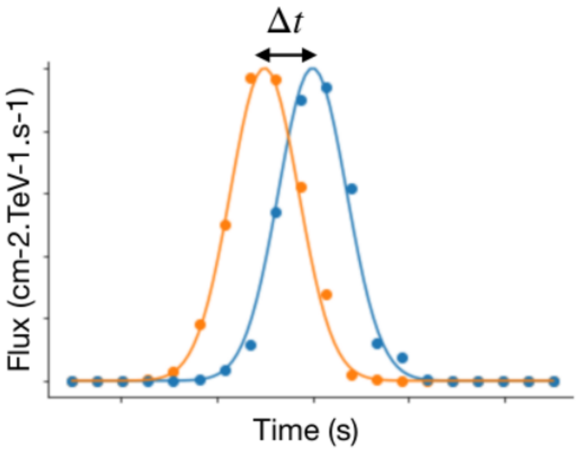


Search for a variability pattern and extract sample properties (energetic and temporal distributions)

Search for a variability pattern and extract sample properties (energetic and temporal distributions)

- Find a pattern (model) to describe the lightcurve variability : selected if p-value > 0.05 (2σ)

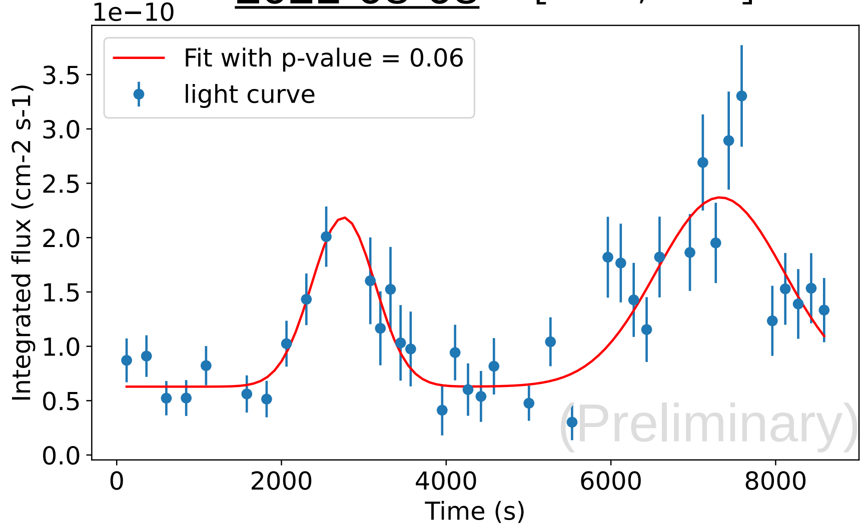


Step 4 : variability pattern

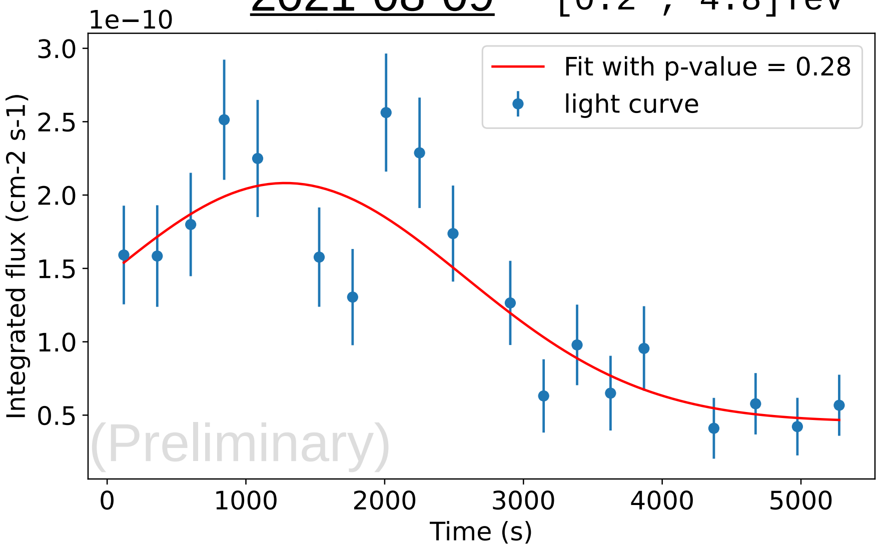
- $A_1 e^{\frac{(t-\mu_1)^2}{2\sigma_1^2}} + A_2 e^{\frac{(t-\mu_2)^2}{2\sigma_2^2}} + C_0$

- $A e^{\frac{(t-\mu)^2}{2\sigma^2}} + C$

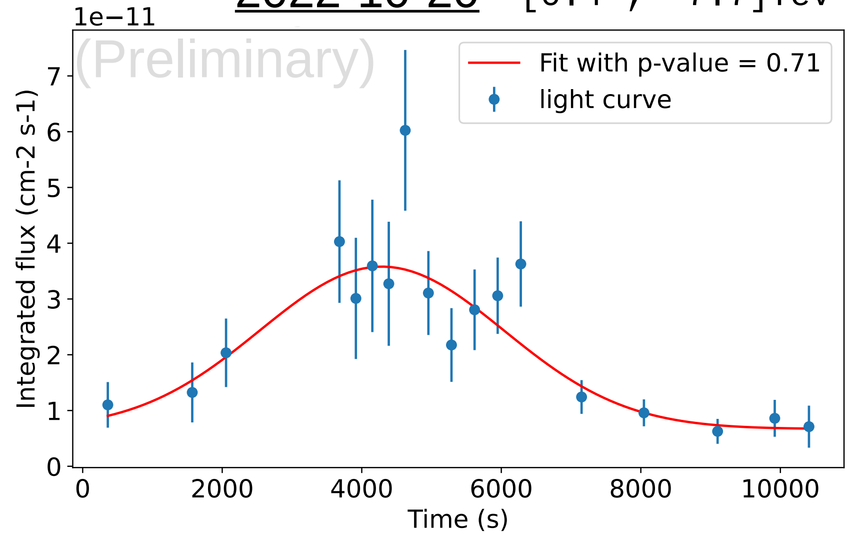
<u>2021-08-08</u> `[0.3 ; 4.8]TeV`



<u>2021-08-09</u> `[0.2 ; 4.8]TeV`



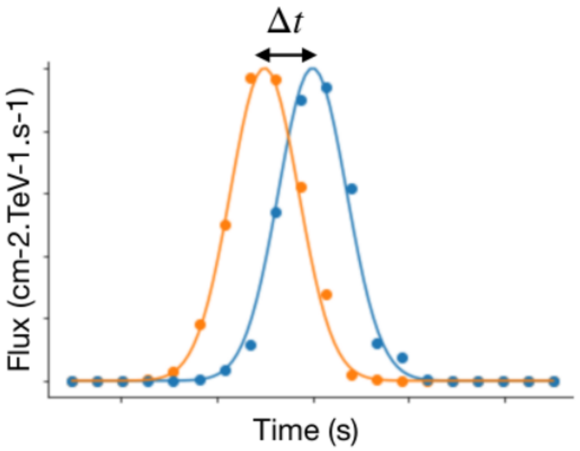
<u>2022-10-20</u> `[0.4 ;  7.7]TeV`



Step 4 : variability pattern

Search for a variability pattern and extract sample properties (energetic and temporal distributions)

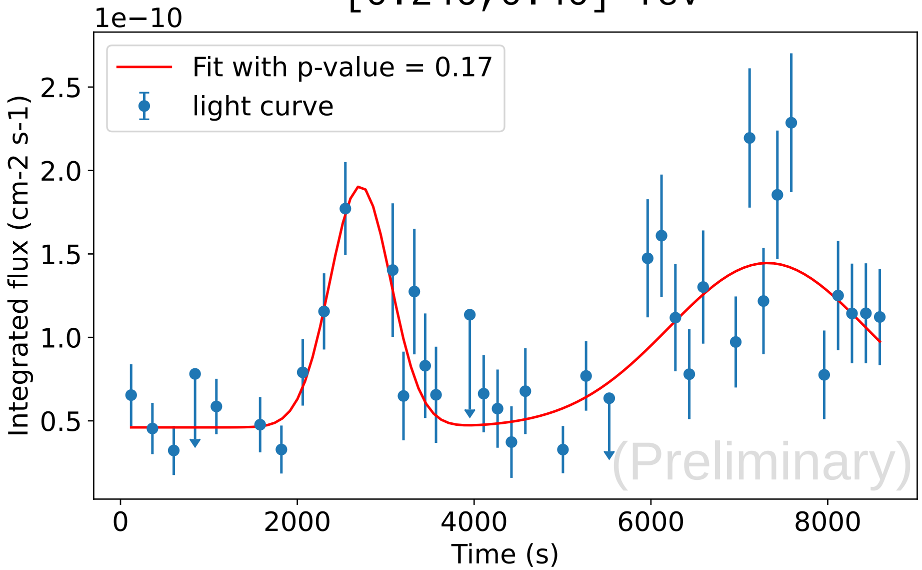
- Find a pattern (model) to describe the lightcurve variability : selected if p-value > 0.05 (2σ)
- Check : no significant disagreement between low and high energies (median of counts)



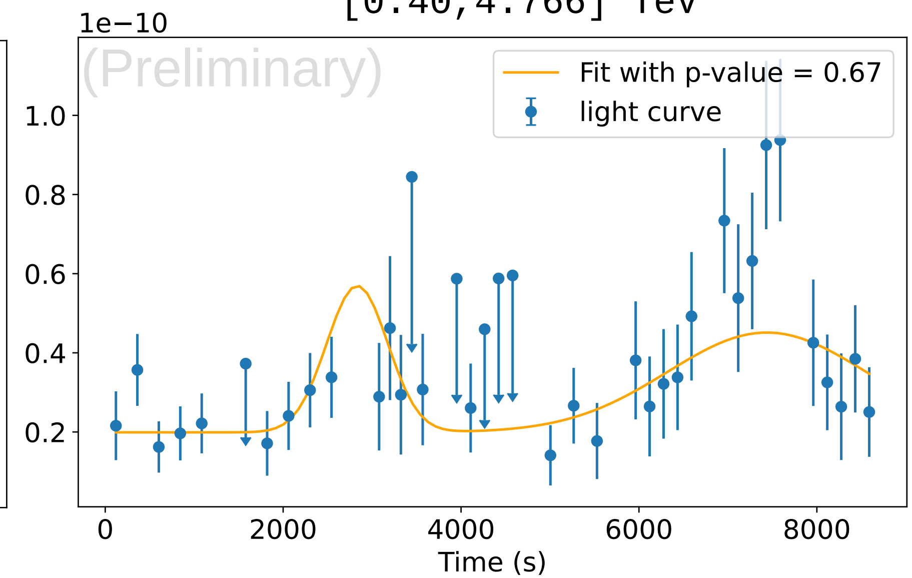
Step 4 : Band comparison method

2021-08-08 night

Low energies sample
[0.246,0.40] TeV



High energies sample
[0.40,4.766] TeV



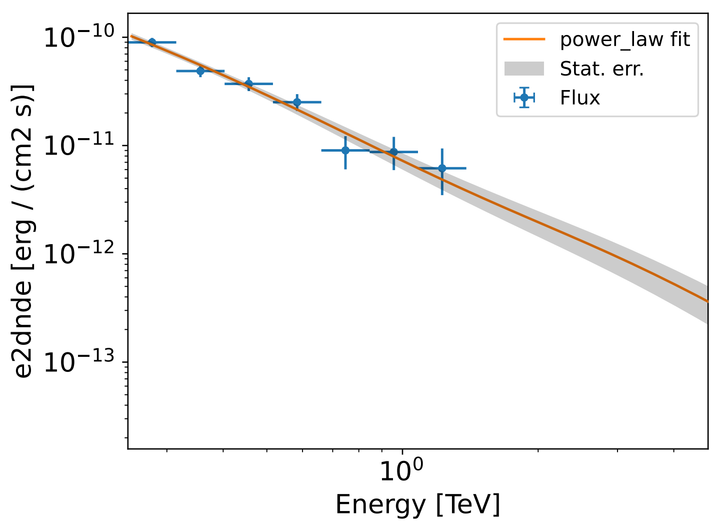
$$G_{LE}(t) = A_1 e^{\frac{(t-\mu_1)^2}{2\sigma_1{}^2}} + A_2 e^{\frac{(t-\mu_2)^2}{2\sigma_2{}^2}} + C_0 \qquad G_{HE}(t) = (G_{LE}(t-\Delta t) - C_0) \times A + C$$

→ Δt : (200 +/- 88)s

Step 4 : variability pattern

Search for a variability pattern and extract sample properties (energetic and temporal distributions)

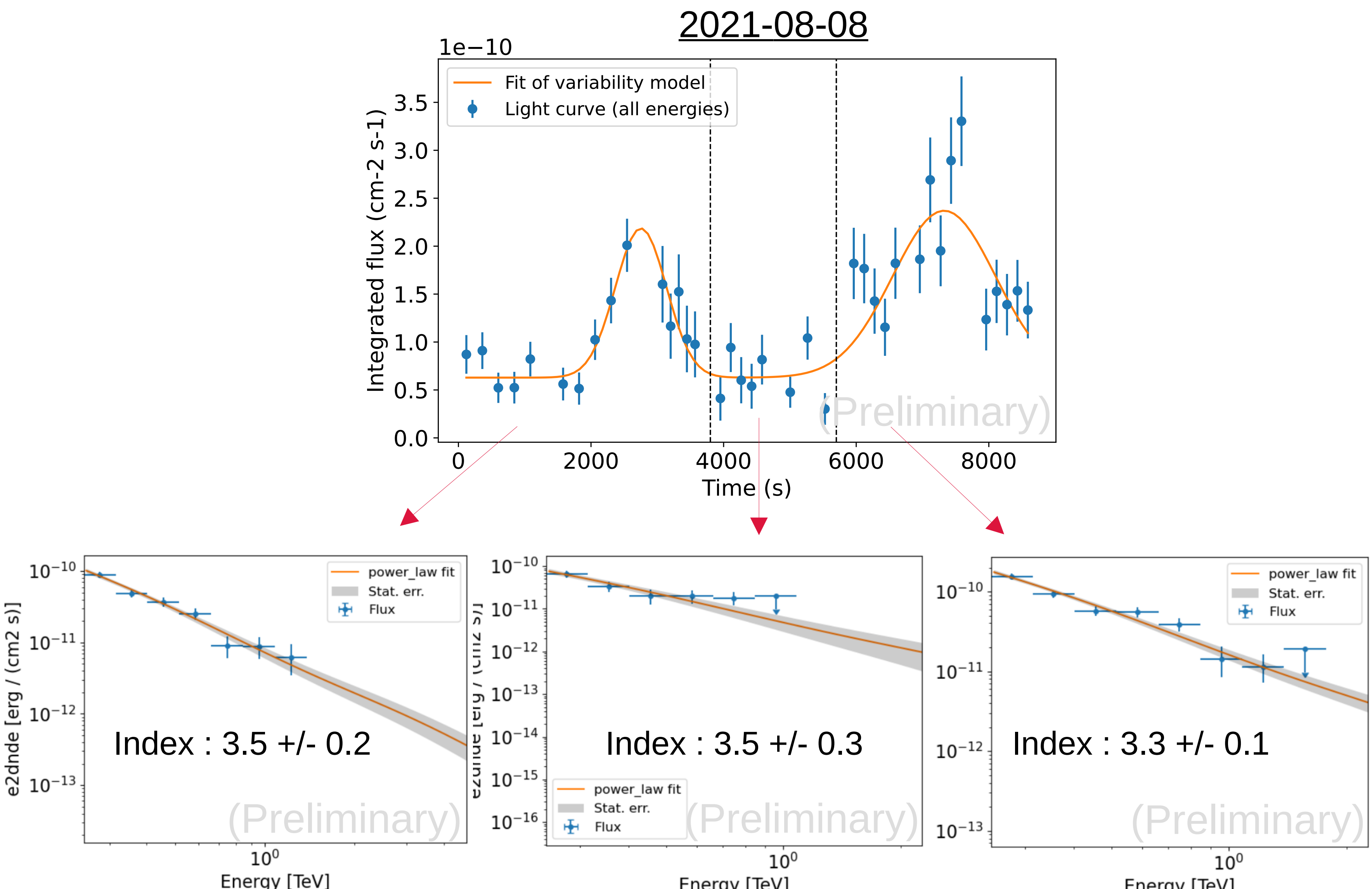
- Find a pattern (model) to describe the lightcurve variability : selected if p-value > 0.05 (2σ)
- Check : no significant disagreement between low and high energies (median of counts)
- Check : no significant time-variation of energetic distribution (spectra parameters)



$$A_0\left(\frac{E}{E_0}\right)^{-\alpha}$$

time-independent index ?

Sptem 4 : Time-independency of spectra



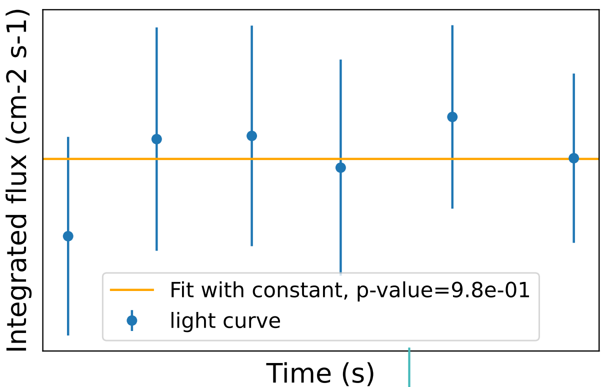
Analysis : step 4

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

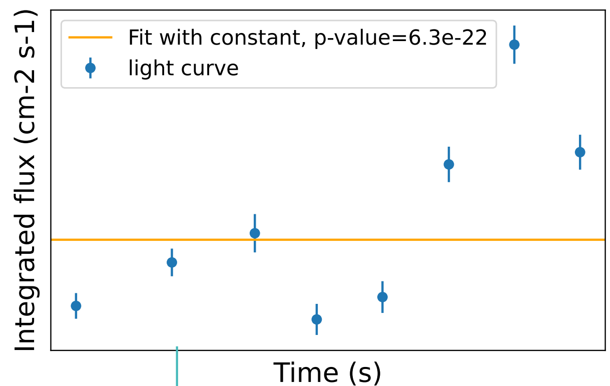
Constant fit pvalue < 5σ ?

Non-variable sample



Optimization of gammaness cut : 0.9

Variable sample



Search for a variability pattern and extract sample properties (energetic and temporal distributions)

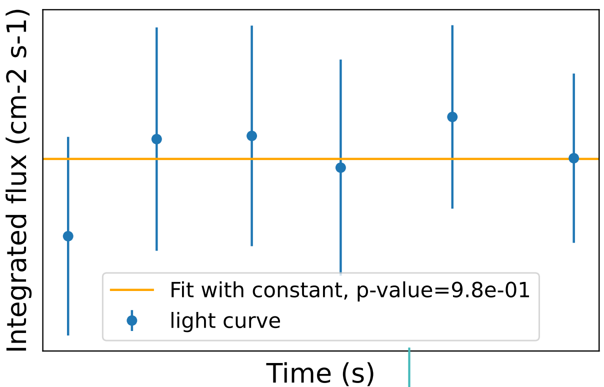
Analysis : step 5

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

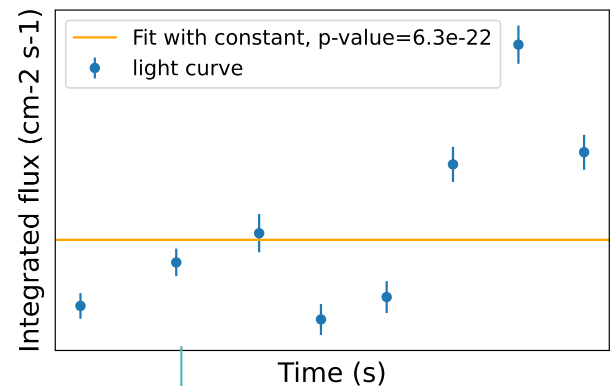
Constant fit pvalue < 5σ ?

Non-variable sample



Optimization of gammaness cut : 0.9

Variable sample



Search for a variability pattern and extract sample properties (energetic and temporal distributions)

LIV analysis

Step 5 : LIV analysis

LIV analysis

↓

LIVelihood

- Created for the consortium between H.E.S.S., MAGIC, VERITAS, and now LST
- Uses the **likelihood method**:
  λ_n is a free parameter that minimizes the likelihood function

for one source (or night): $$\mathcal{L}_S(\lambda_n) = -\sum_{\text{event } \mathbf{i}} \log\left(\frac{dP(E_{R,\mathbf{i}}, t_{\mathbf{i}}; \lambda_n)}{dE_R dt}\right)$$

$$\mathcal{L}_{\text{comb}}(\lambda_n) = \sum_{\text{all sources}} \mathcal{L}_S(\lambda_n)$$

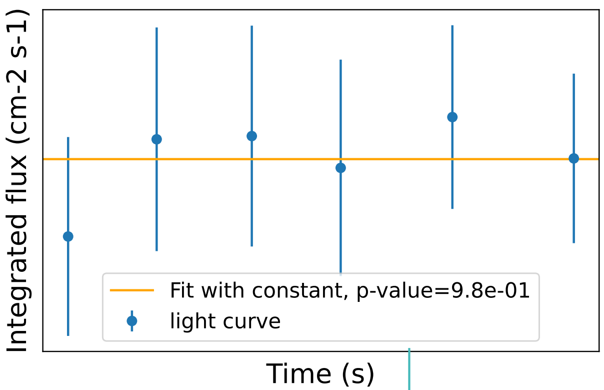
Analysis : step 6

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

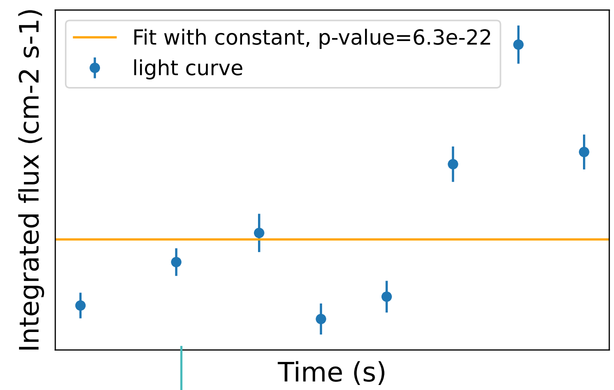
Constant fit pvalue < 5σ ?

Non-variable sample



Optimization of gammaness cut : 0.9

Variable sample



Search for a variability template and extract sample properties (energetic and temporal distributions)

LIV analysis

Sample of simulations for calibration

Step 6 : Likelihood for calibration

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

For one night :
$$\mathcal{L}(\lambda_n) = -\sum_{\text{event } \mathbf{i}} \log\left(\frac{dP(E_{R,\mathbf{i}}, t_{\mathbf{i}}; \lambda_n)}{dE_R dt}\right)$$

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

$$+ \sum_k W_{b,k} \frac{\int \mathrm{EffA}(E_T, t)\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

Step 6 : Likelihood for calibration

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Signal

$$+\sum_{\mathbf{k}} W_{\mathbf{b,k}} \frac{\int \mathrm{E_{ff}A}(E_T, t)\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{\mathbf{b,k}}(E_T) dE_T}{N'_{\mathbf{b,k}}}$$

Backgrounds k : hadrons and baseline

Step 6 : Likelihood for calibration

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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Instrumental response functions

$$+ \sum_k W_{b,k} \frac{\int \mathrm{E_{ff}A}(E_T, t)\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{b,k}(E_T) dE_T}{N'_{b,k}}$$

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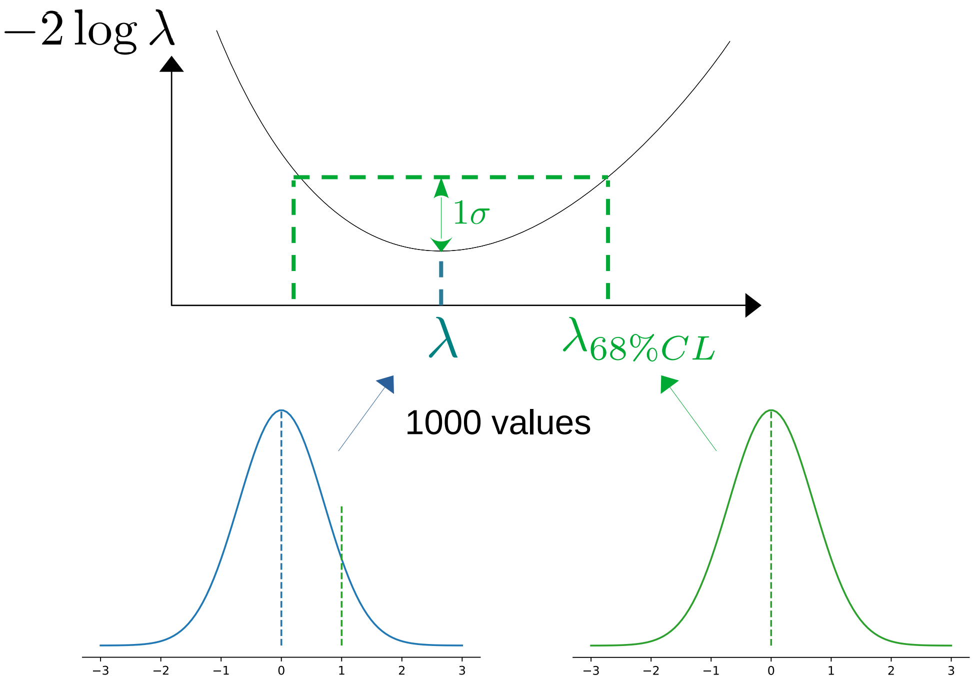
Lightcurve x spectra

Sample simulations for calibration

- Perform 1000 dataset simulations

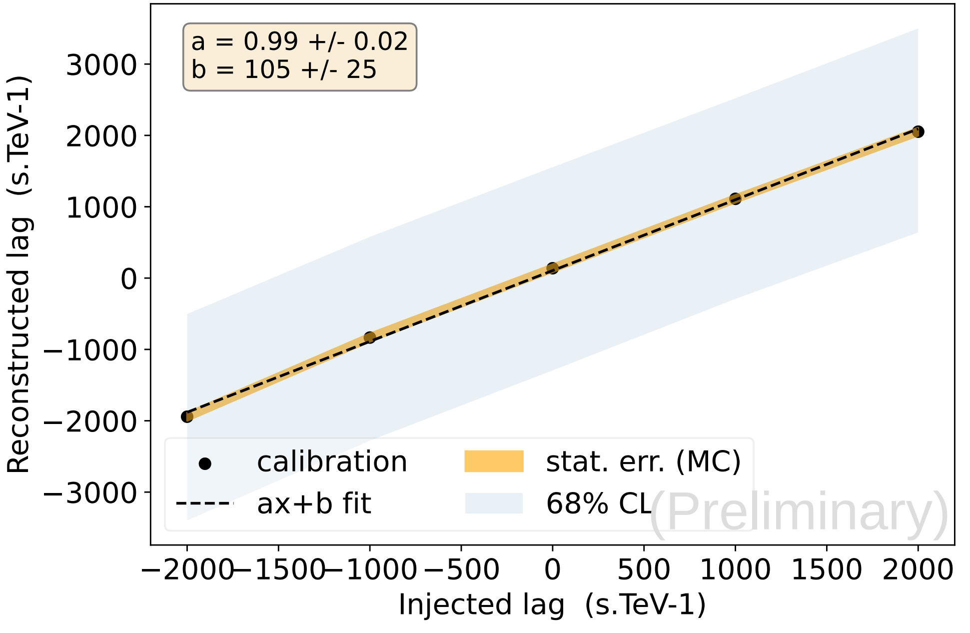


Step 6 : Calibration

Sample simulations for calibration

- Perform 1000 dataset simulations
- Calibration : inject lag to verify that LIVelihood reconstructs it well

BL Lac - 3 variable nights combined



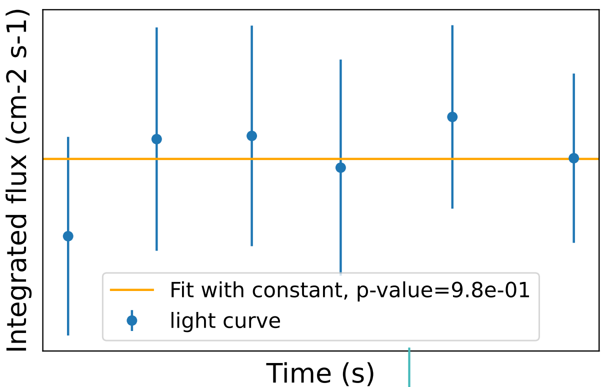
Analysis : step 6

Several AGNs data of LST-1 from January 2021 to June 2023

Variability test on each significant observation night

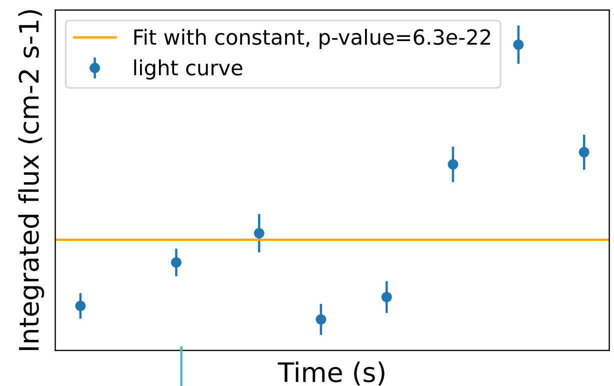
Constant fit pvalue < 5σ ?

Non-variable sample



Optimization of gammaness cut : 0.9

Variable sample



Search for a variability template and extract sample properties (energetic and temporal distributions)

LIV analysis

Sample of simulations for calibration

Several AGNs data of LST-1 from January 2021 to June 2023

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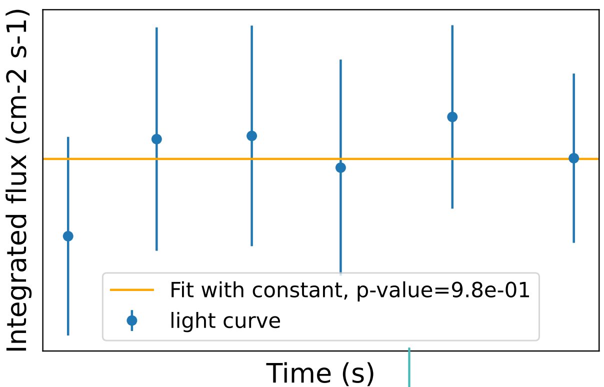

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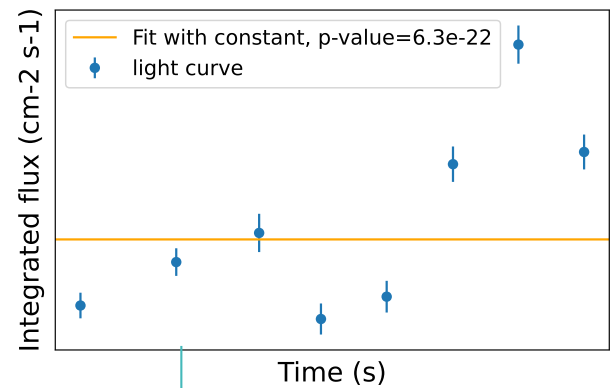


Search for a variability template and extract sample properties (energetic and temporal distributions)

LIV analysis

Sample of simulations for calibration

Application on real data

Step 7 : Likelihood for real data

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

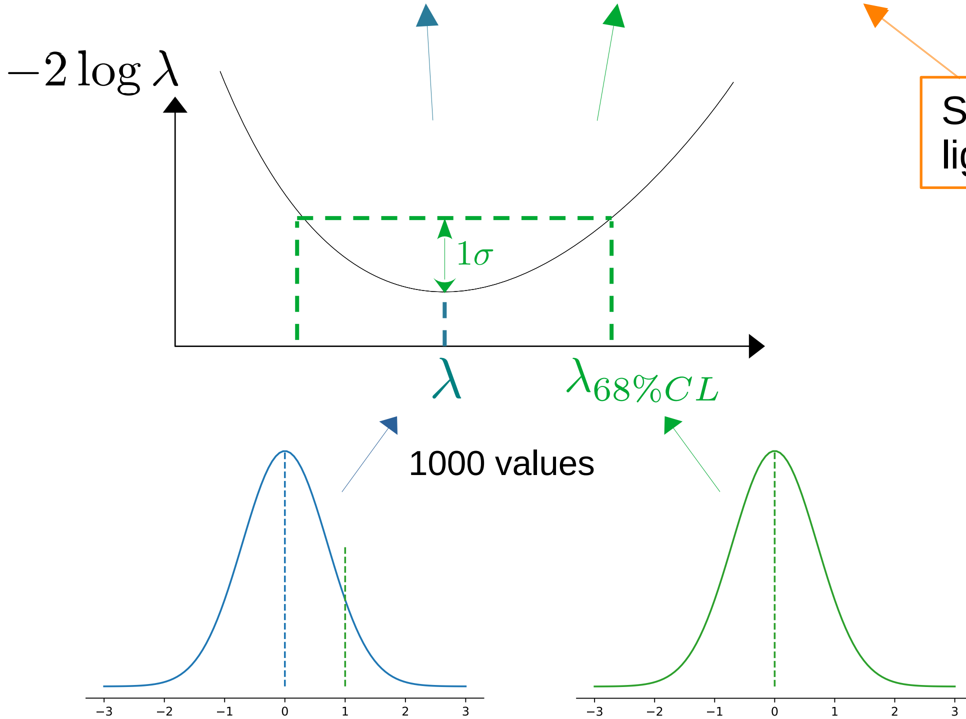
$$+W_b \frac{\int \mathrm{EffA}(E_T, t)\mathrm{MM}(E_T, E_R) \times \mathrm{F}_b(E_T) dE_T}{N'_b}$$

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

Step 7 : LIV analysis on real data

Application on real data

Time delay : $\lambda_1 = (3768\ {}^{+1475}_{-1466}\ {}^{+3433}_{-3414})\,\mathrm{s.TeV^{-1}}$

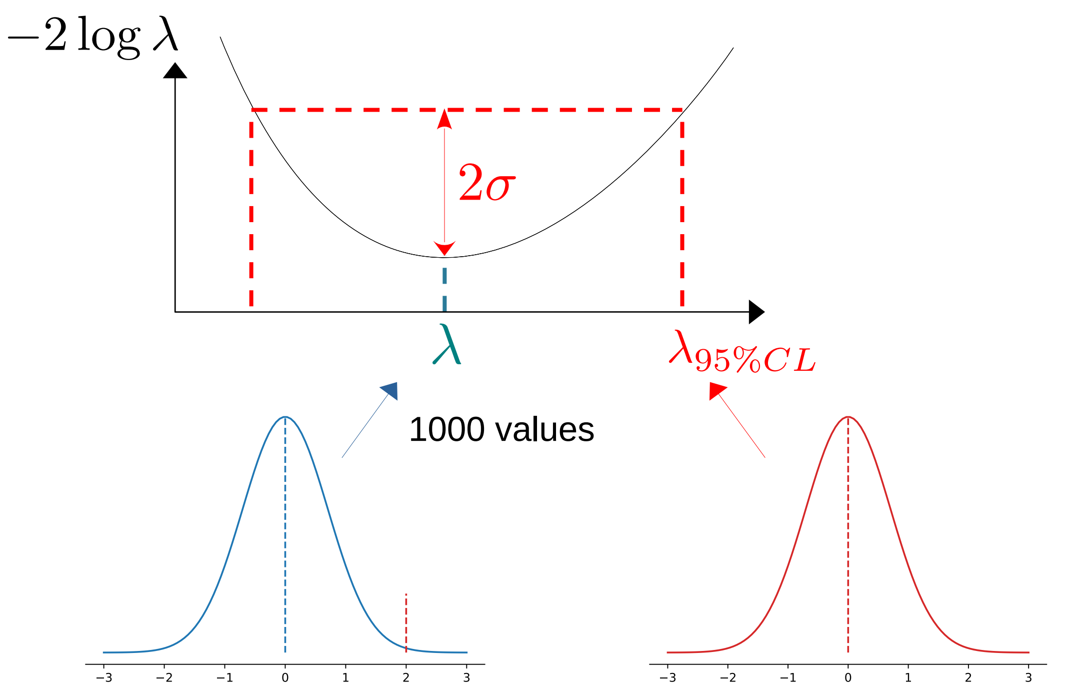


Statistical uncertainty of the light curve template

Step 7 : LIV analysis on real data

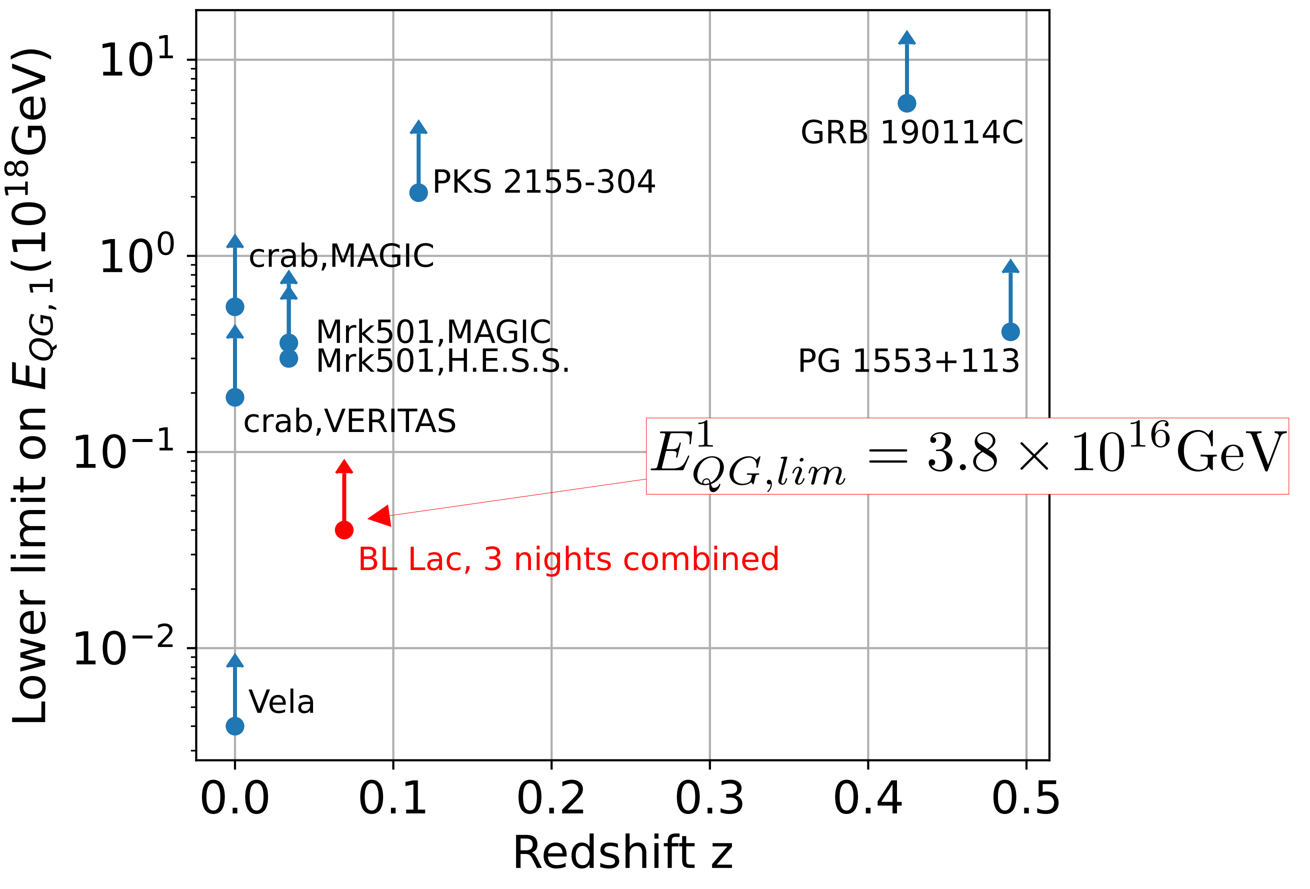
Application on real data

Time delay : $\lambda_1 = (3768 \ ^{+1475}_{-1466} \ ^{+3433}_{-3414})\,\mathrm{s.TeV^{-1}}$



Use $\lambda_{1,95\%CL} = \pm \frac{1}{H_0 E^1_{QG,lim}}$ to extract : $\boxed{E^1_{QG,lim} = 3.8 \times 10^{16}\,\mathrm{GeV}}$

Comparison with other limits

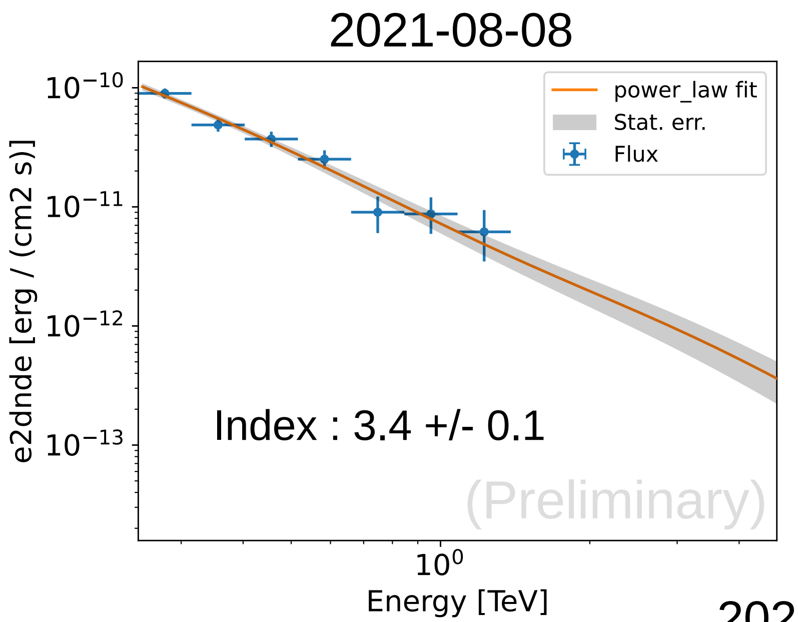


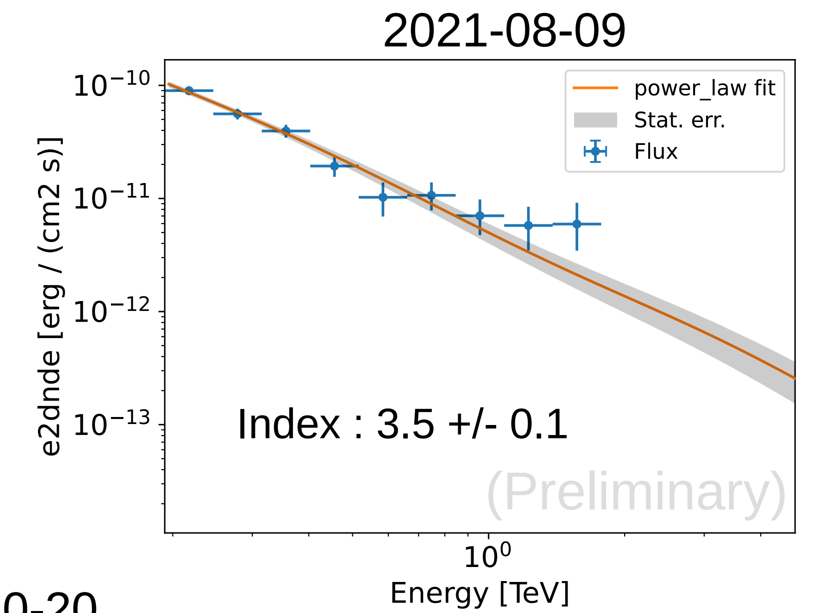
Bolmont et al., 2022

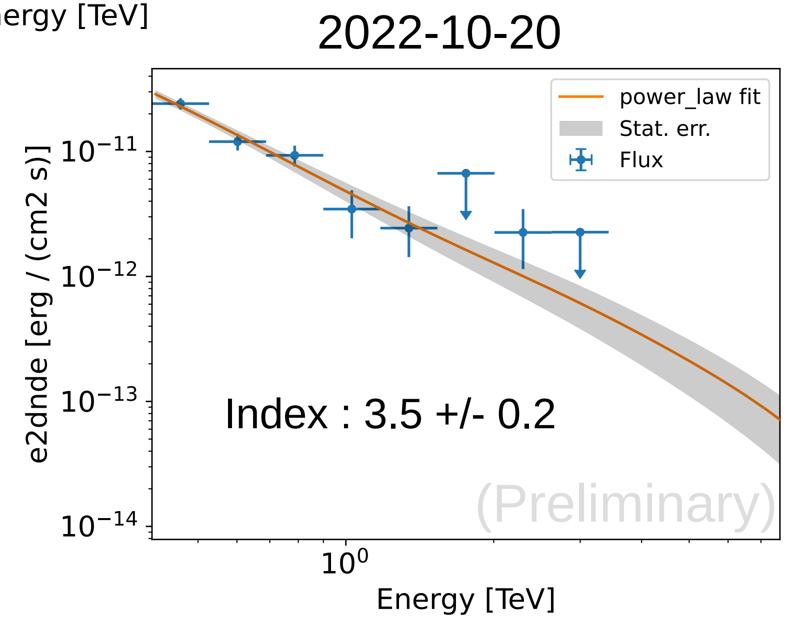
- Performed a systematic analysis of several AGN from LST data until June 2023, searching for variability in the lightcurve of a given night
- Found 3 nights showing intra-night variability (BL Lac)
- Combined these 3 nights to extract a limit on E_{QG} at the order n=1 using real data

Ongoing work :

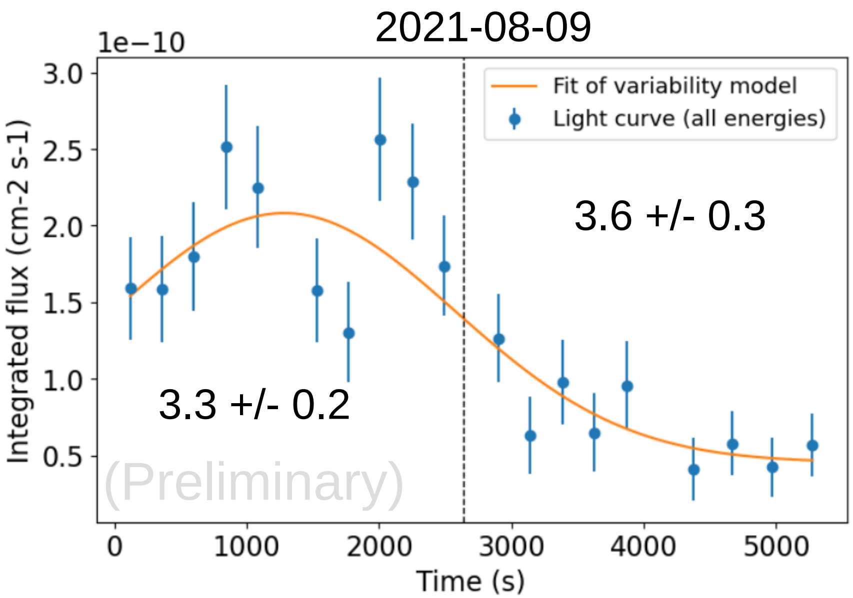
- Working on extended and most recent dataset
- Analysis with energy-dependent gammaness (and θ^2) and optimize the cuts also using the Crab
- Implementation of all systematics (template, spectral index, background, energy scale, distance)
- Order n=2 and other κ(z) models (used here Jacob & Piran 2008)
- Combination of LST data with the consortium data, in particular wih H.E.S.S. and VERITAS data in the following months

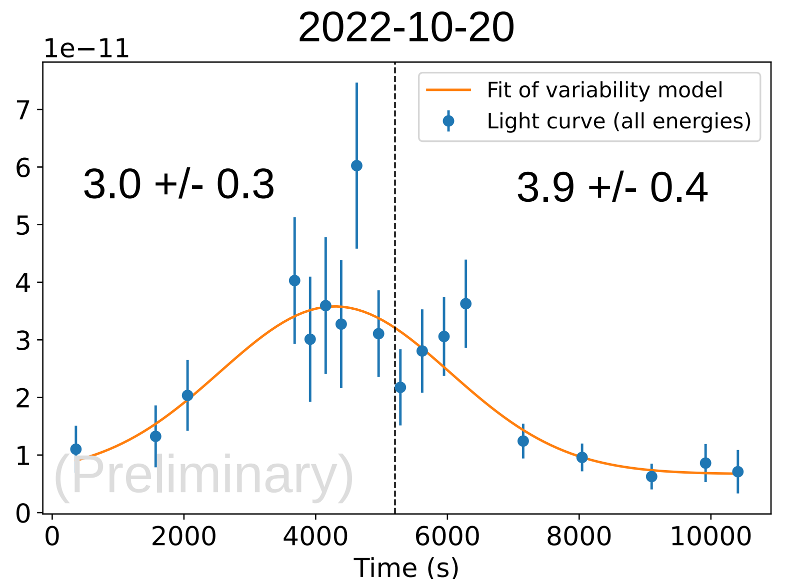

2021-08-08
power_law fit
Stat. err.
Flux
e2dnde [erg / (cm2 s)]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{0}
Energy [TeV]
Index : 3.4 +/- 0.1
(Preliminary)

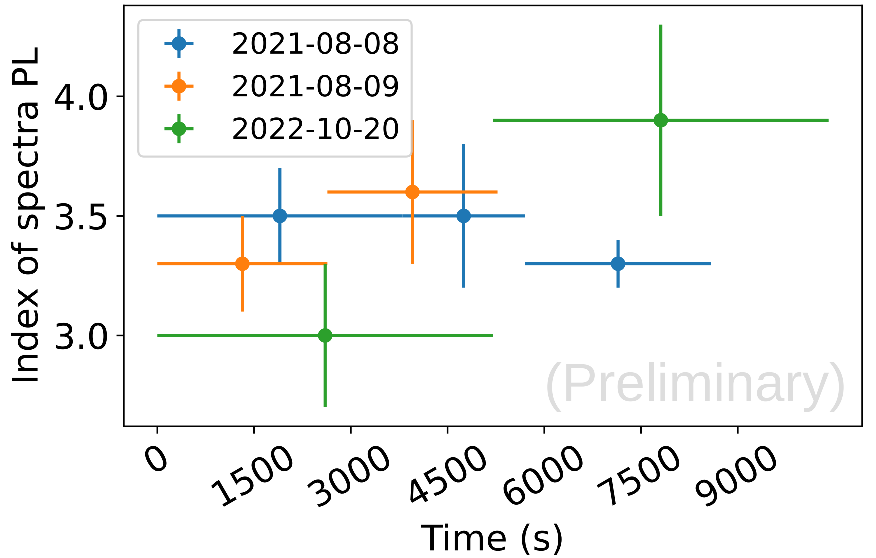

2021-08-09
power_law fit
Stat. err.
Flux
e2dnde [erg / (cm2 s)]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{0}
Energy [TeV]
Index : 3.5 +/- 0.1
(Preliminary)


2022-10-20
power_law fit
Stat. err.
Flux
e2dnde [erg / (cm2 s)]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{0}
Energy [TeV]
Index : 3.5 +/- 0.2
(Preliminary)

Time-independency of the energetic distribution

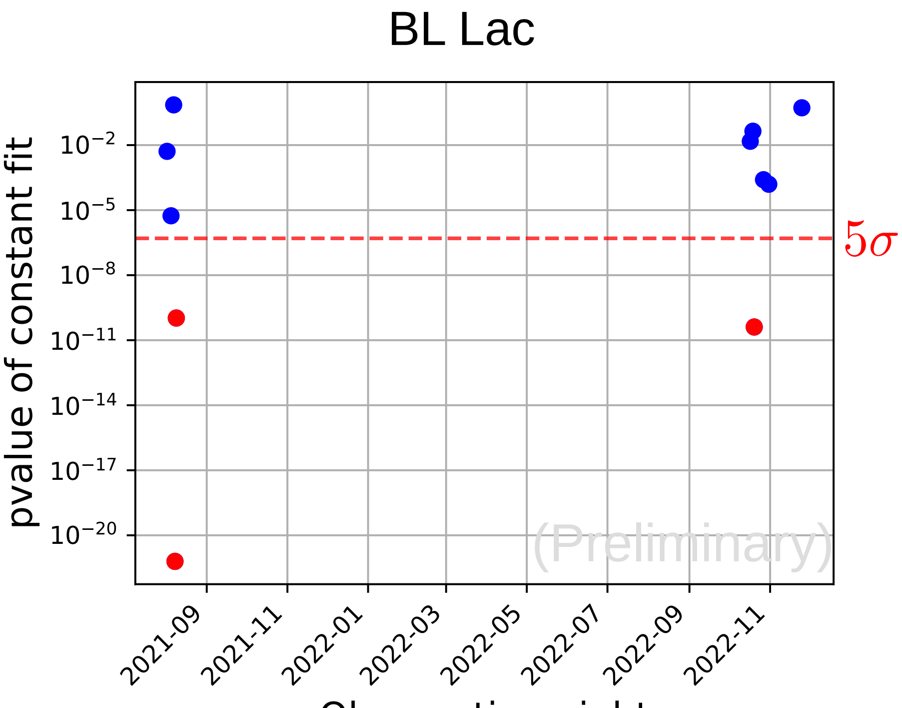


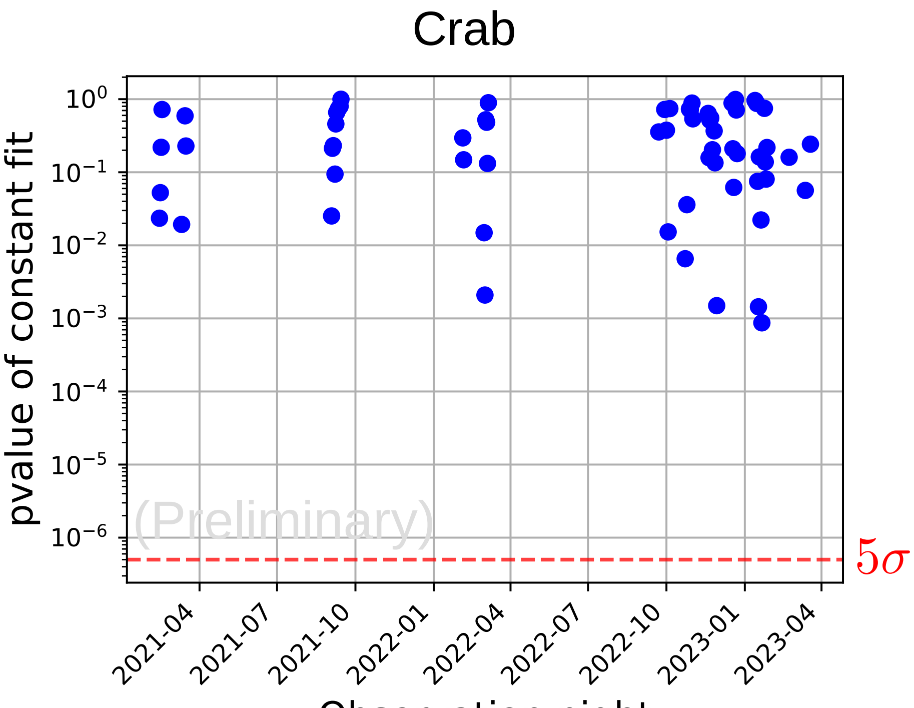


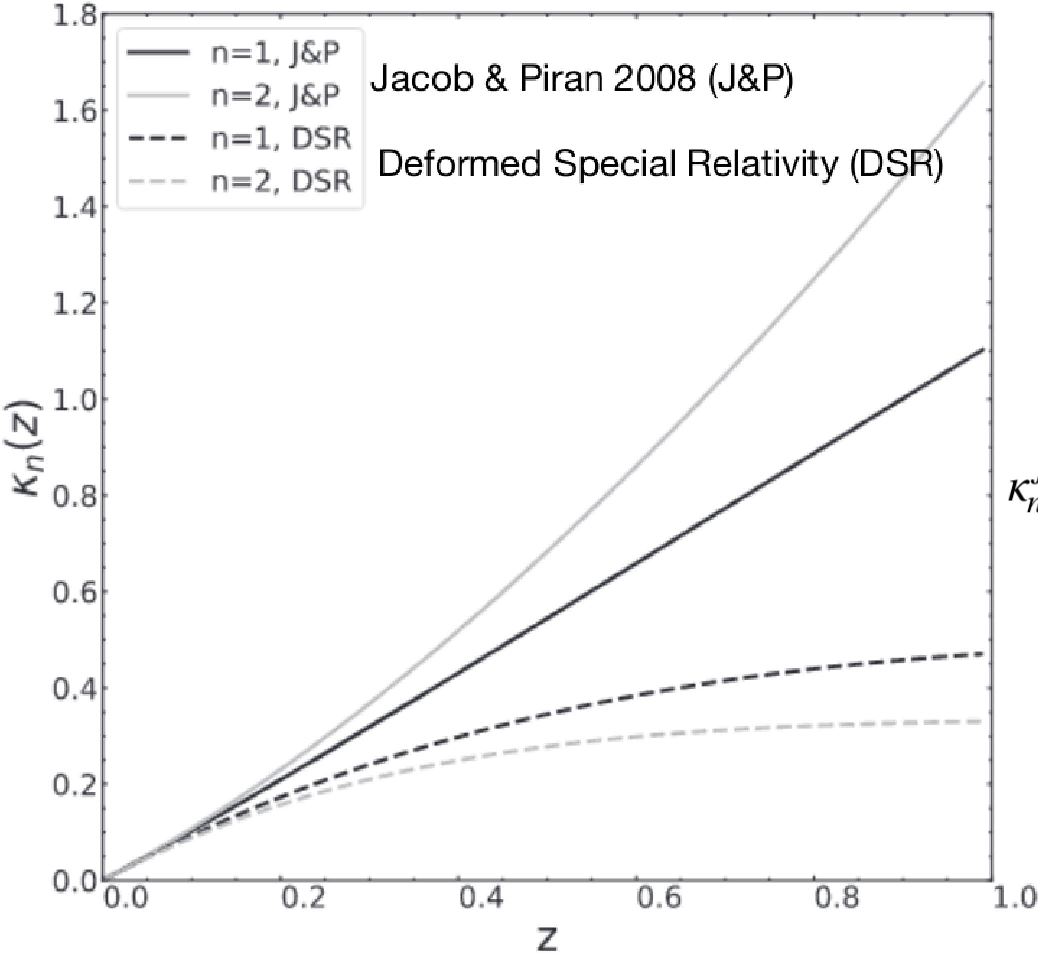


Intra-night variability test on crab

crab is a stable source $\leftrightarrow$ expecting 0 night with intra-night variability







Bolmont et al 2022

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

Systematics

$$\mathcal{L}(\lambda_n, \vec{\theta}) = \mathcal{L}_S(\lambda_n, \vec{\theta}) +$$

$$+\mathcal{L}_{\text{template}}(\vec{\theta}_C) + \mathcal{L}_\gamma(\vec{\theta}_\gamma) + \mathcal{L}_B(\vec{\theta}_B) + \mathcal{L}_{ES}(\vec{\theta}_{ES}) + \mathcal{L}_z(\vec{\theta}_z)$$

- $\vec{\theta}_C$: parameters of lightcurve analytic parametrization → dominant (Bolmont et al. 2022)
- $\vec{\theta}_\gamma$: power-law index of signal events spectrum
- $\vec{\theta}_B$: $\frac{\text{signal}}{\text{total events}}$ & $\frac{\text{hadrons}}{\text{total background}}$
- $\vec{\theta}_{ES}$: energy scale → can increase when n=2
- $\vec{\theta}_z$: distance (redshift) → ~ 0