Laboratoire d'Annecy de Physique des Particules

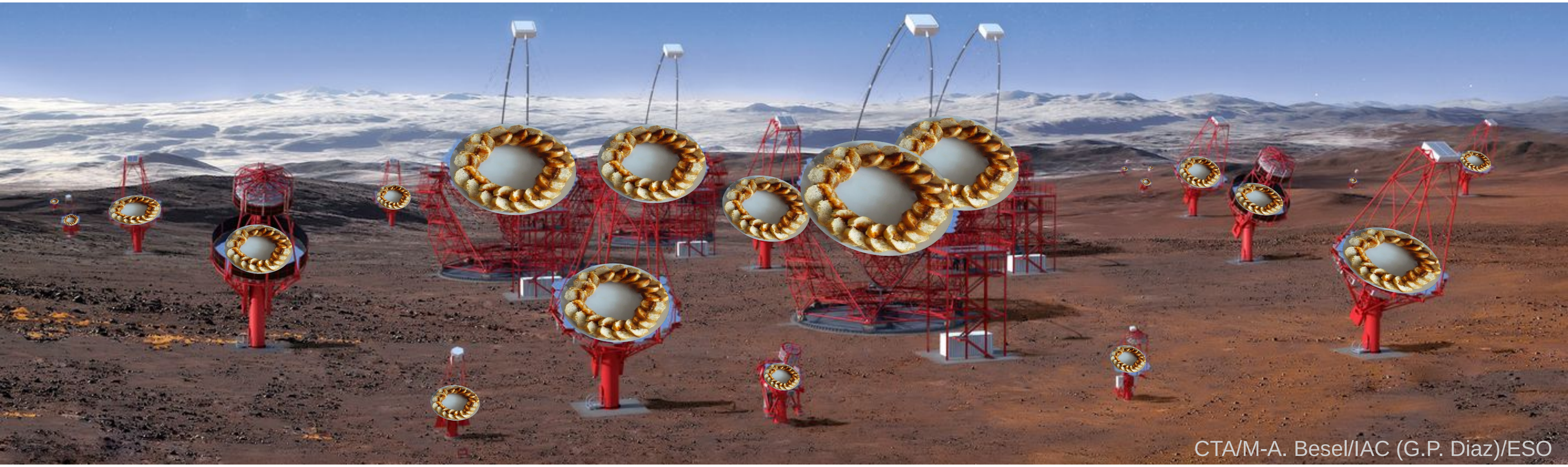
Lorentz invariance violation search with the Large-Sized Telescope-1 of CTA

Journées jeunes chercheurs 2023

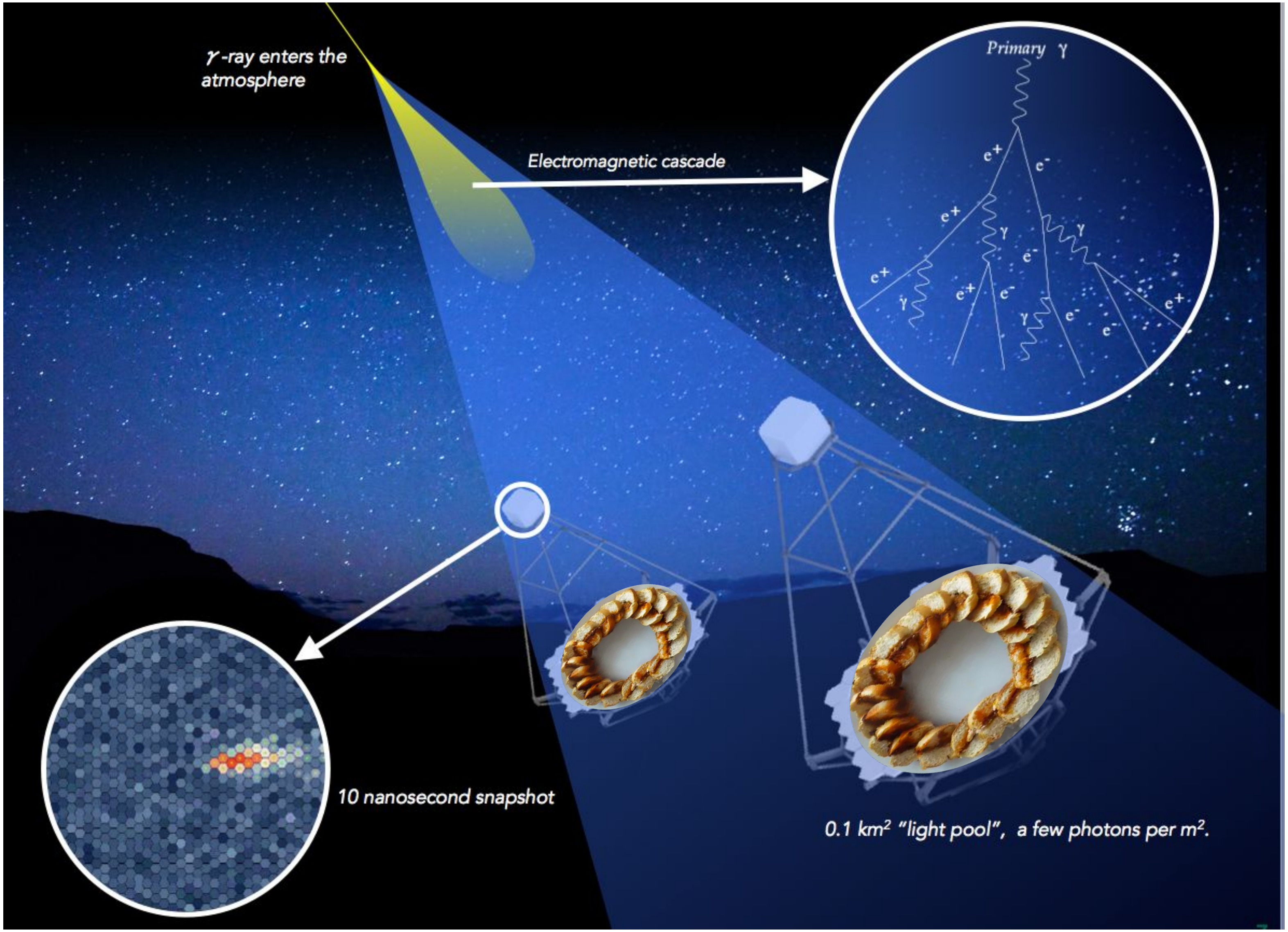
Cyann Plard, with Sami Caroff

Cherenkov préfous array

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

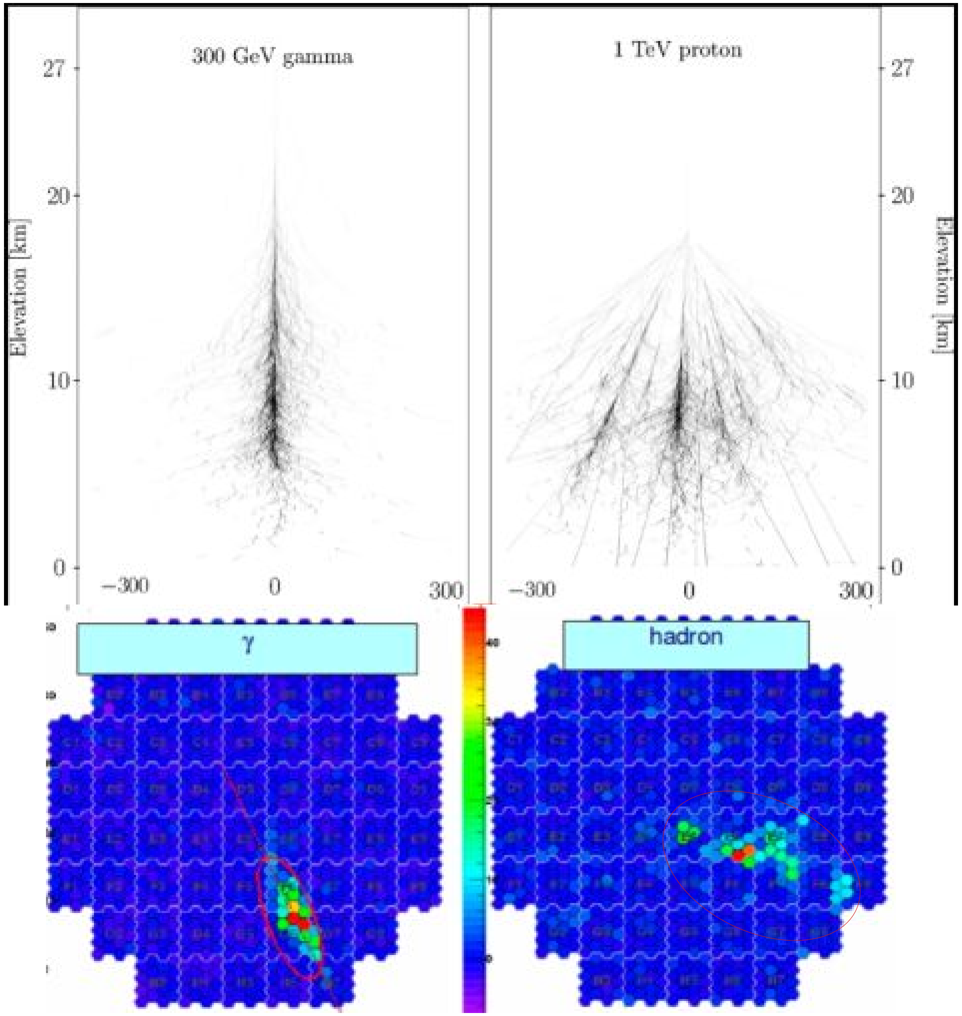

CTA/M-A. Besel/IAC (G.P. Diaz)/ESO

Indirect detection : Cherenkov astronomy



Cherenkov astronomy : hadronic background

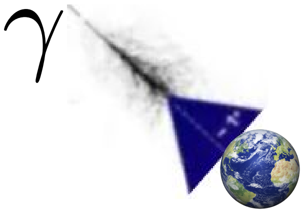
Gamma-ray Hadron (proton)



The data production chain

Cherenkov light

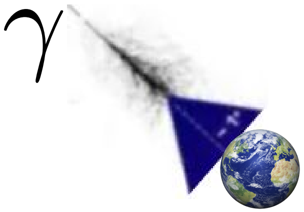
The data production chain



Cherenkov light

Raw data

The data production chain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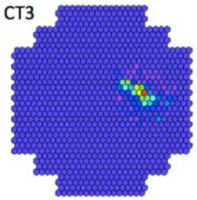
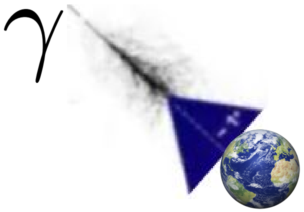


Calibration

The data production chain



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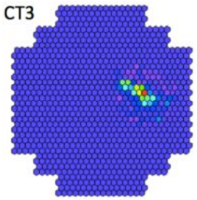

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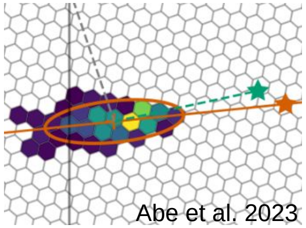
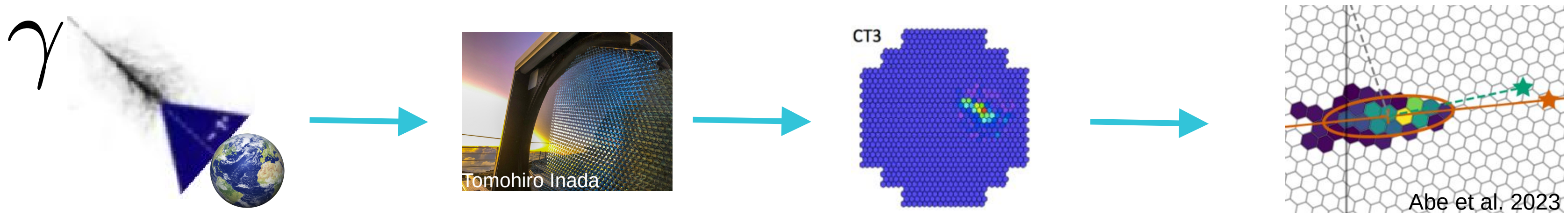
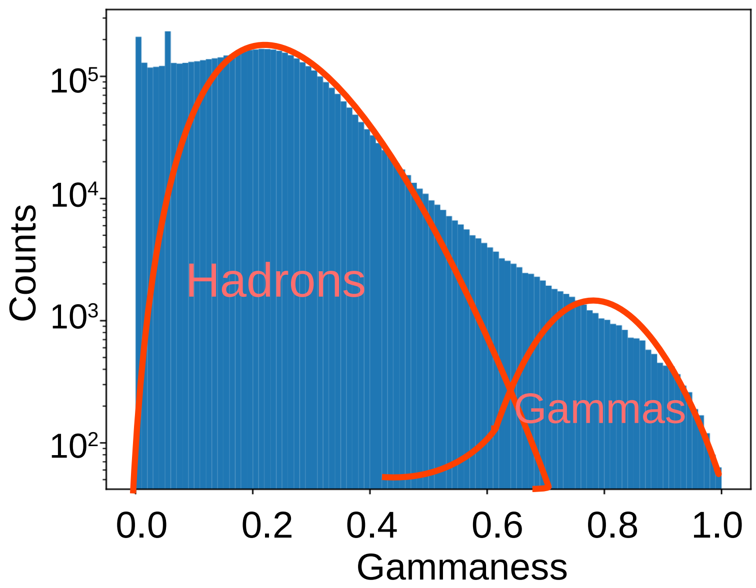


Reconstruction

The data production chain



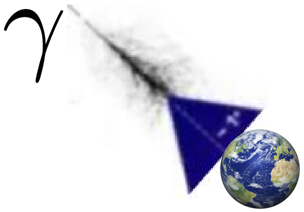
Cherenkov light → Raw data → Calibration → Reconstruction



Gammaness

score indicating how likely the primary event is a gamma ray

The data production chain



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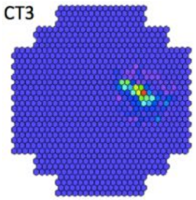

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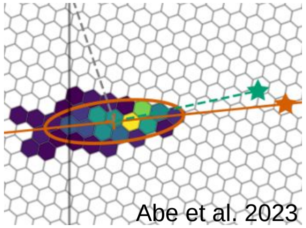

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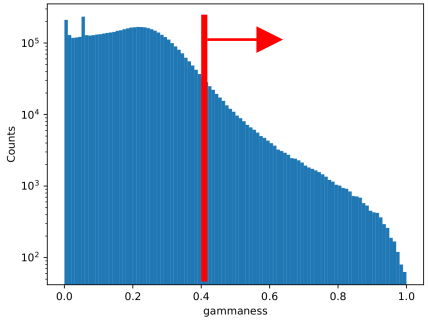
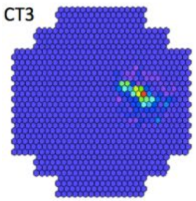


Gammaness cut +
Instrumental response functions

Cherenkov light

Raw data



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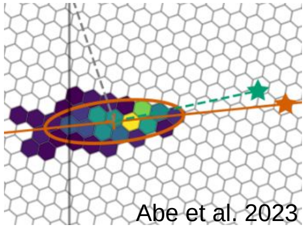

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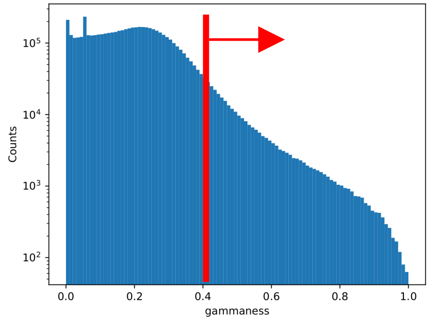

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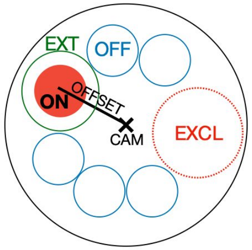
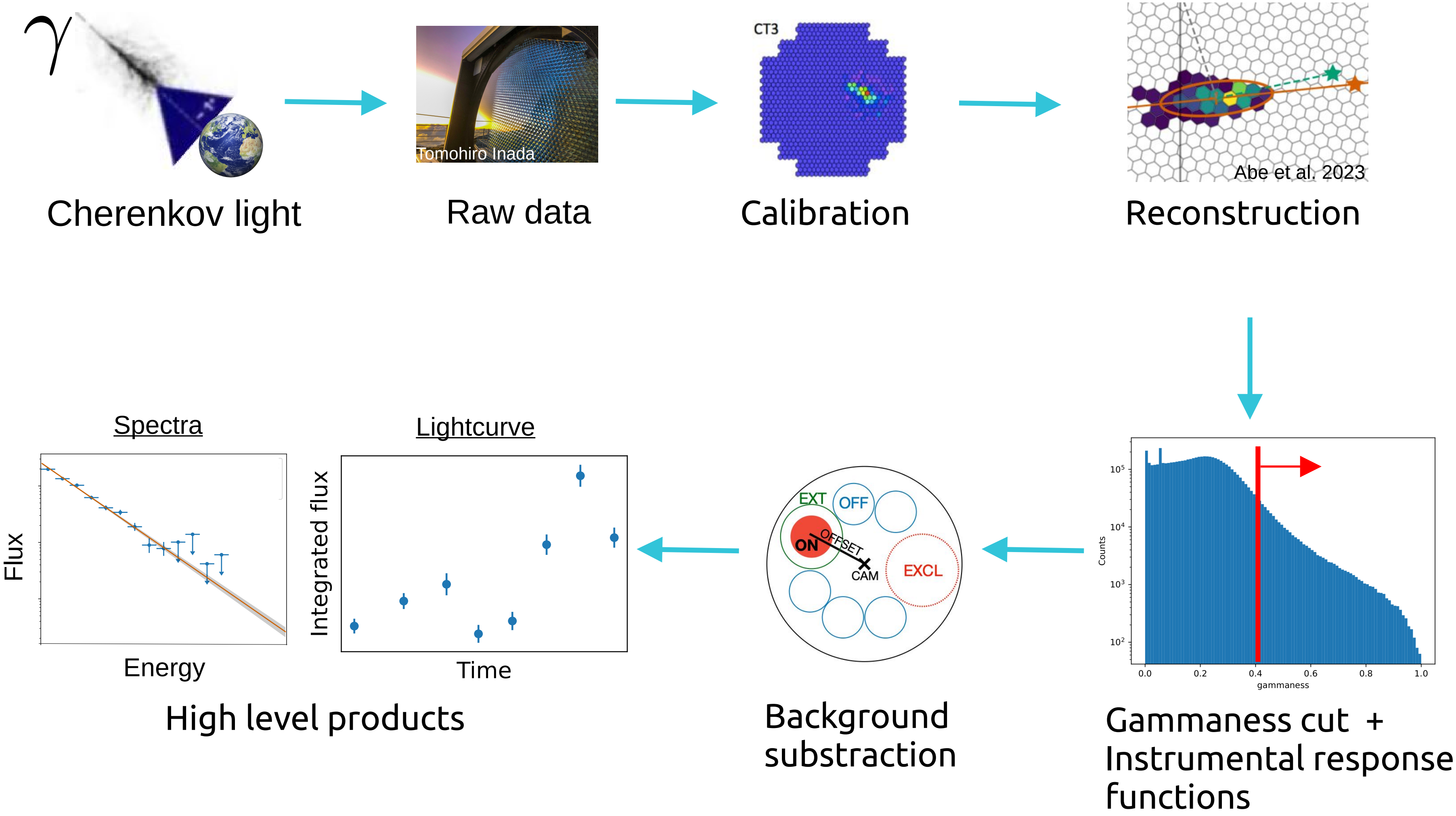


Background substraction

The data production chain



- Unification of general relativity and quantum field theory

  Difficulties at Planck scale $E_P \sim 10^{19}\mathrm{GeV}$

  → quantization of space-time

- Some quantum gravity theories allow a violation of Lorentz invariance

  → may be observable

Lorentz invariance violation (LIV)

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

- Quantization of space-time

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↓

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

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

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

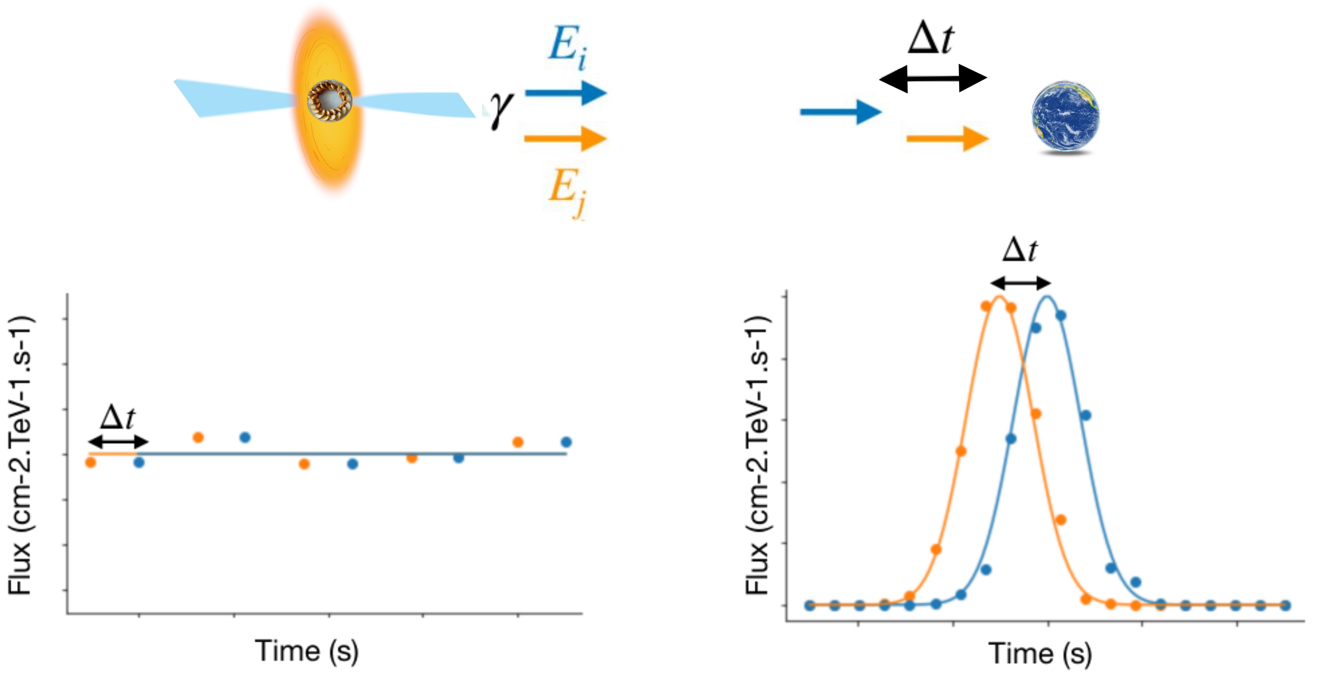
Search for $E_{QG,lim}^n$ for $n = 1$

- Large range of energy
- Cosmological distance

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

- Highly variable and active source

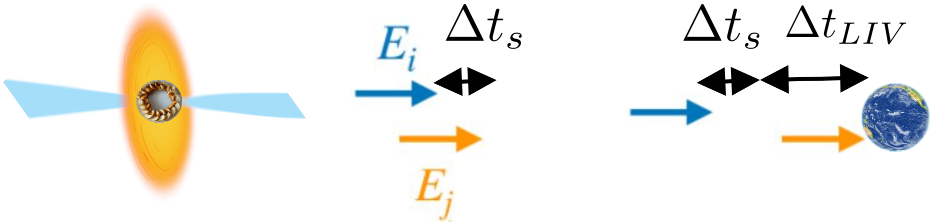
→ Blazars, gamma-ray bursts, pulsars



- No guarantee that photons are emitted at the same time

→ Intrinsic source delay :

$$\Delta t = \Delta t_{LIV} + \Delta t_{source}$$



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  - Intrinsic source delay : redshift-independent, source and flare-dependent (stochastic)
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→ Combination of different flares and different sources

Consortium between different experiments : H.E.S.S., MAGIC, VERITAS, LST-1

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→ None of these delays have been observed at TeV scale

Analysis : step 1

All blazar data of LST-1 until June 2023

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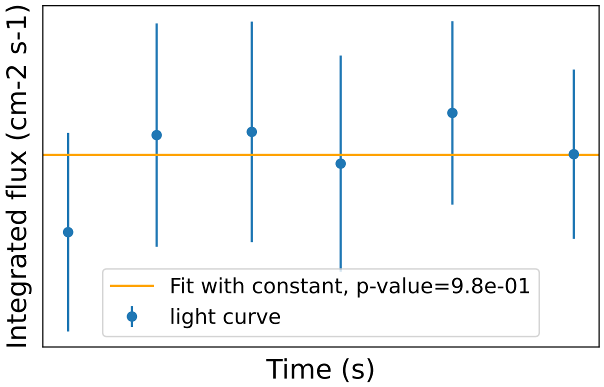
Variability test on each significant observation night

All blazar data of LST-1 until June 2023

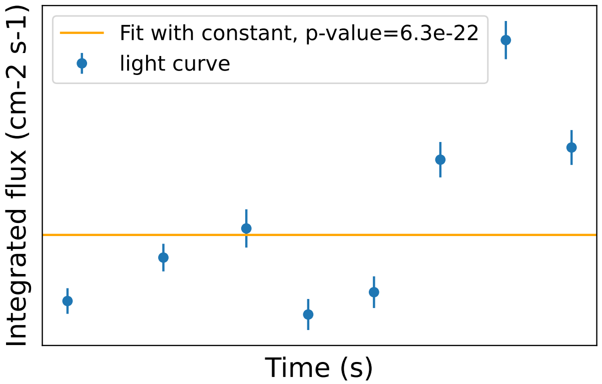
Variability test on each significant observation night

Constant fit : pvalue < 5σ ?

Non-variable sample



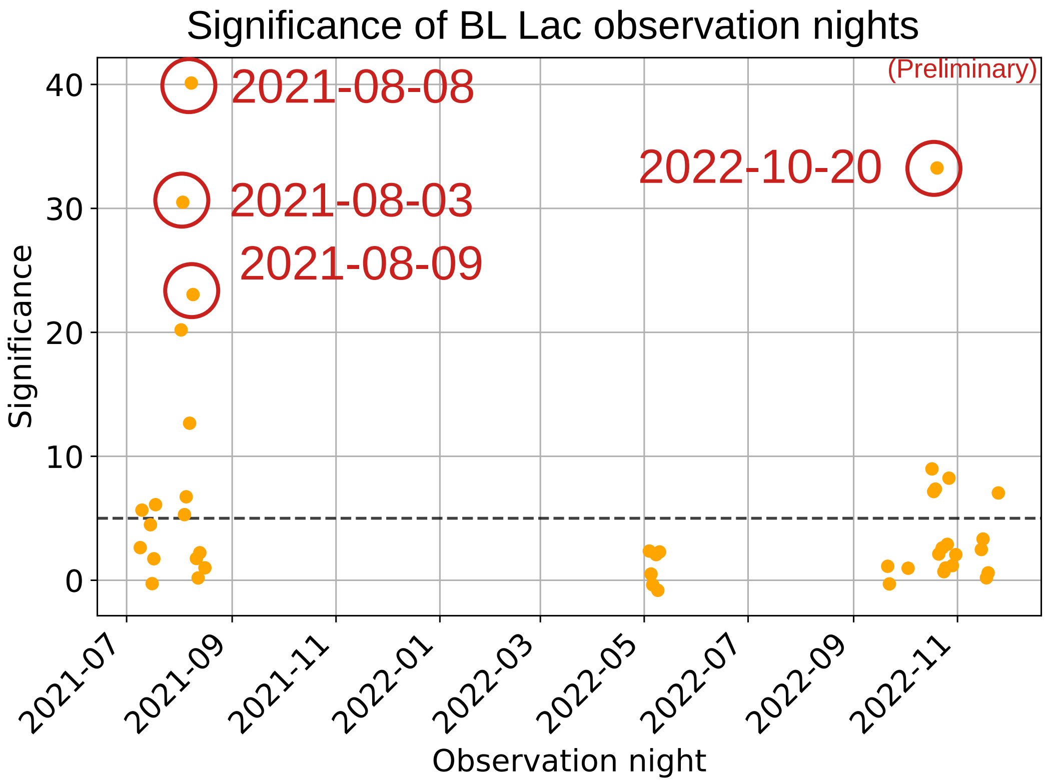
Variable sample



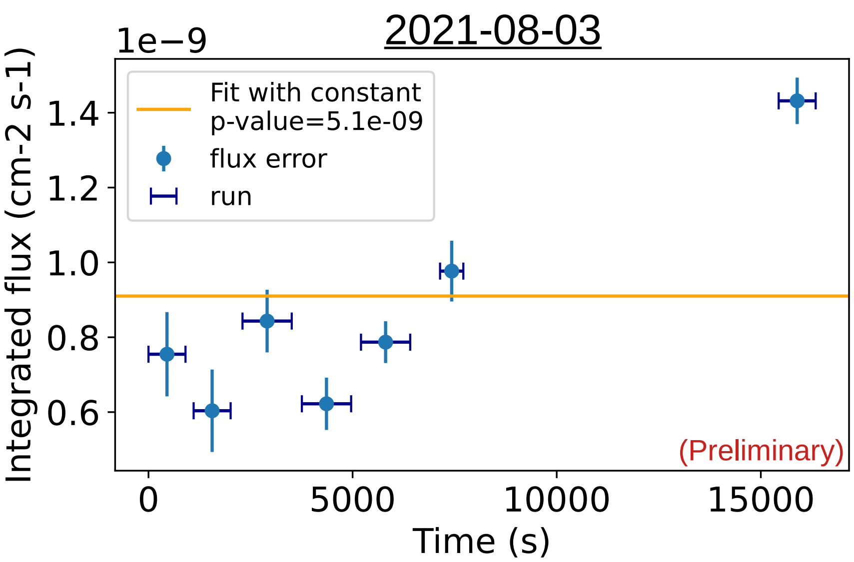
Step 1 : variable nights

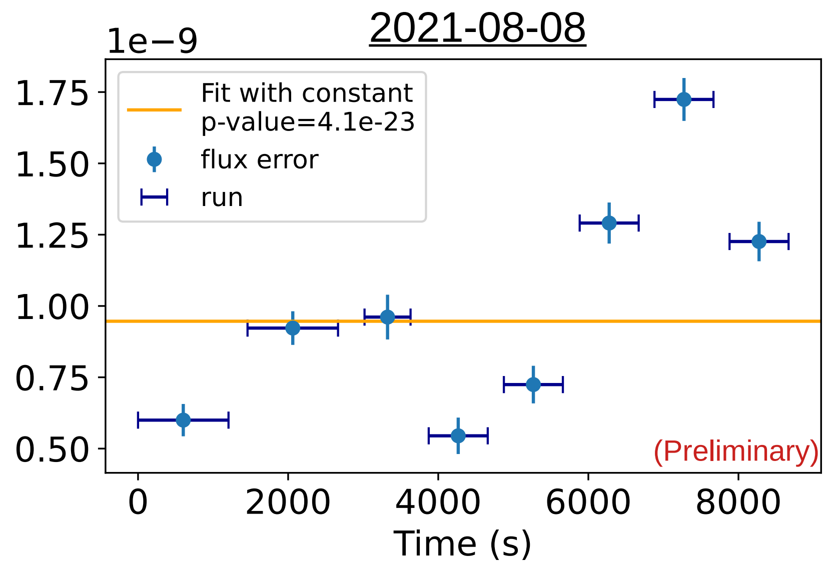
All blazar data of LST-1 until June 2023

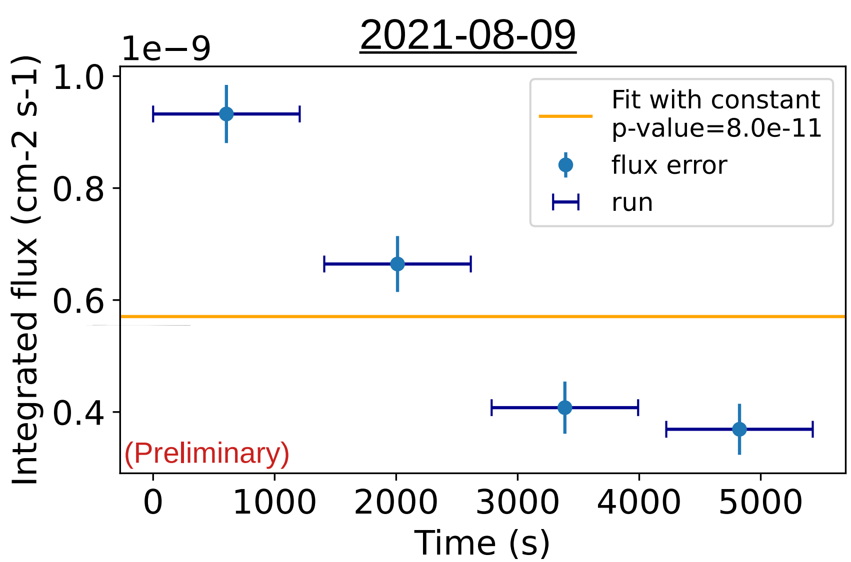
Found 1 variable source : BL Lacertae, redshift 0.069 with 4 variable nights

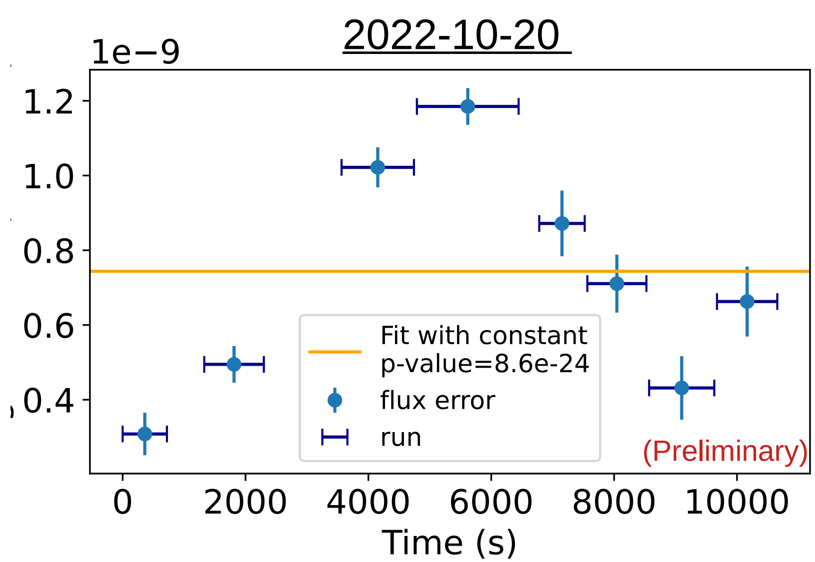


Lightcurves of BL Lac variable nights









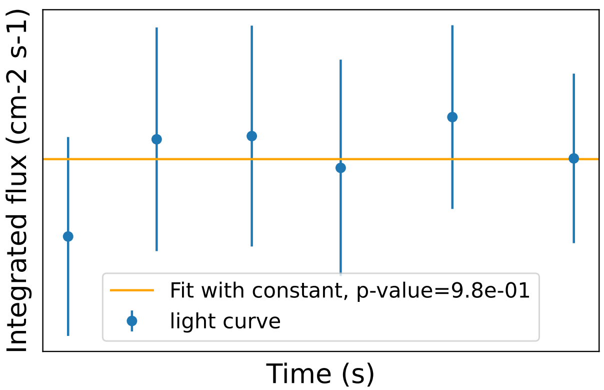
Analysis : step 2

All blazar data of LST-1 until June 2023

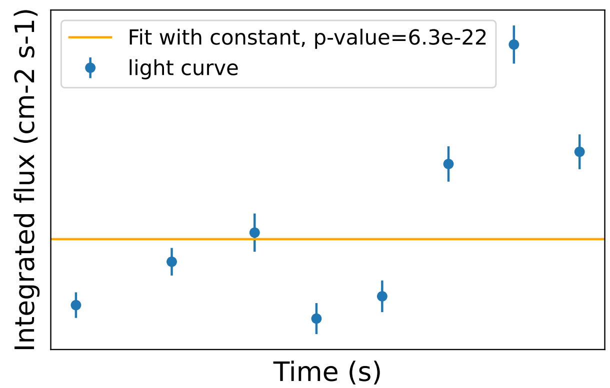
Variability test on each significant observation night

Constant fit pvalue < 5σ ?

Non-variable sample



Variable sample



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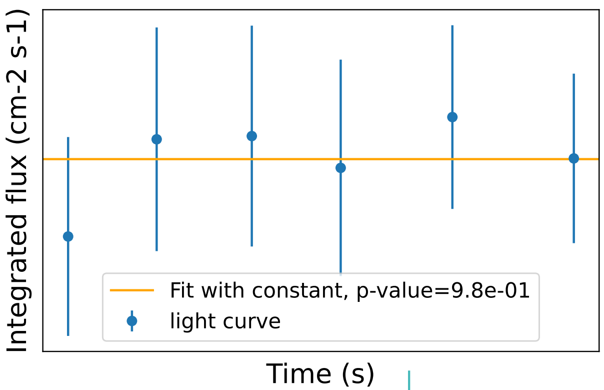
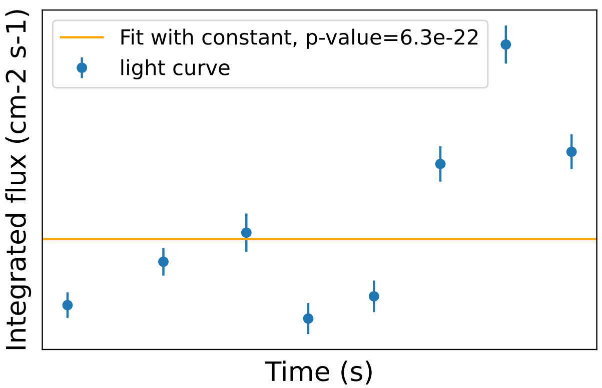
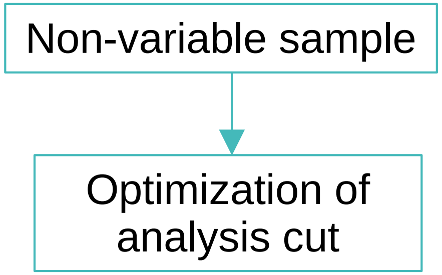


Optimization of analysis cut

Variable sample

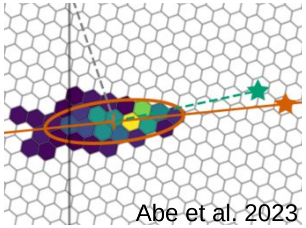


Step 2 : cut optimization

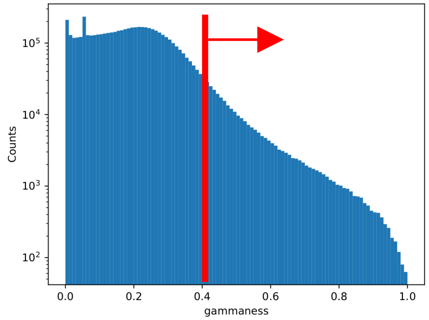


Non-variable sample

Optimization of analysis cut



Reconstruction

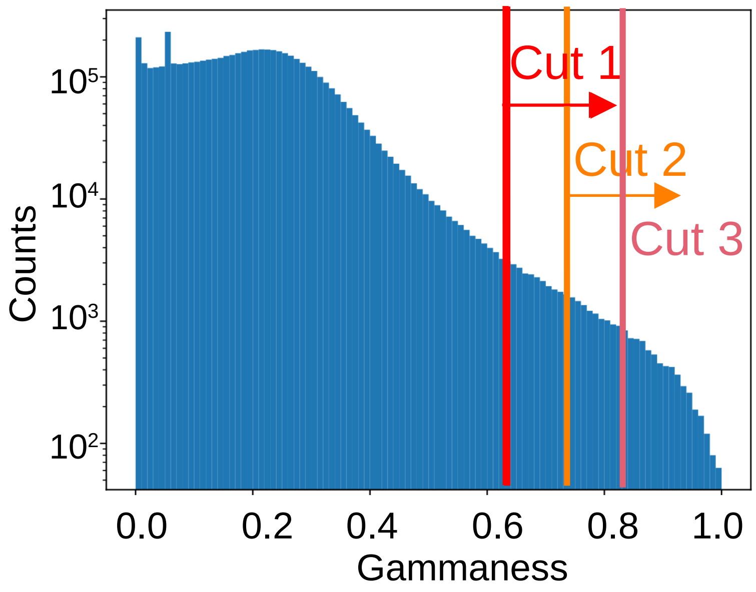


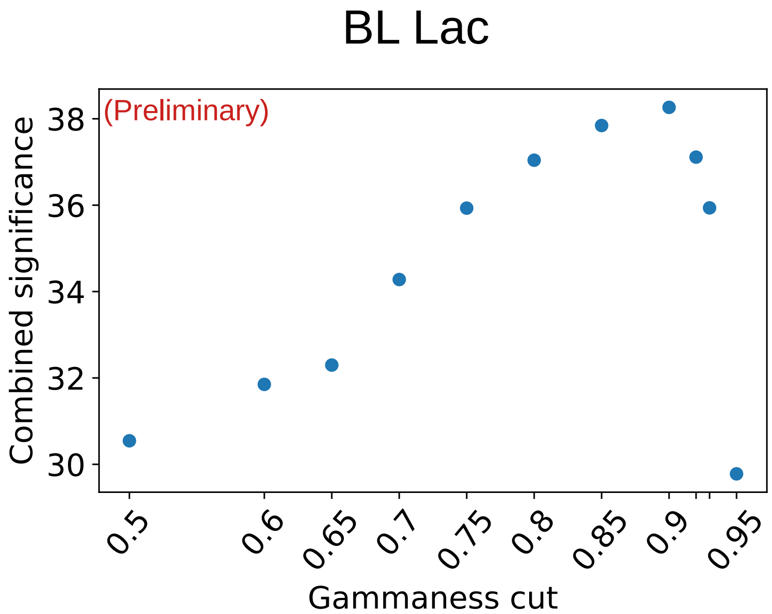
Gammaness cut

Step 2 : cut optimization

Non-variable sample

Select different gammaness cuts and search for the significance





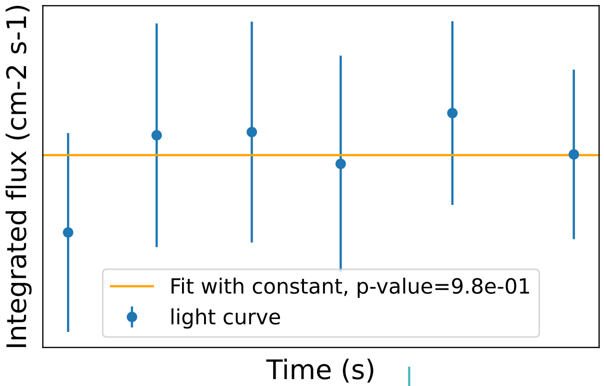
$$S_{cut} = \sqrt{\sum_{non-var\,night} S_n^2}$$

All blazar data of LST-1 until June 2023

Variability test on each significant observation night

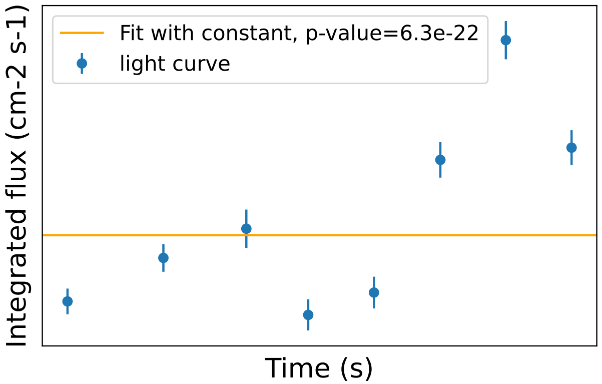
Constant fit
pvalue < 5σ ?

Non variable sample



Optimization of
analysis cut : 0.9

Variable sample



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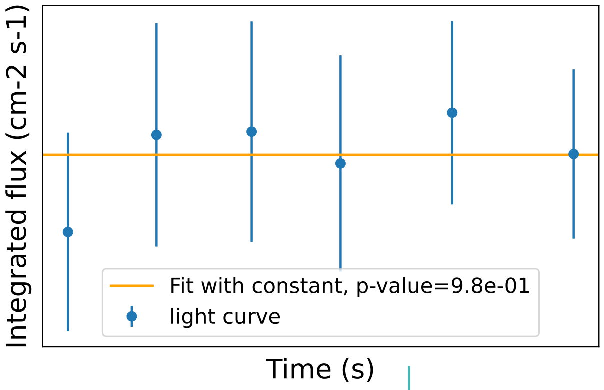

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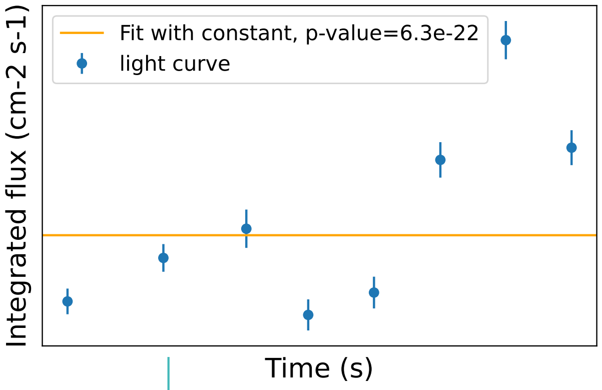

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Search for a variability template and extract sample properties (energetic and temporal distributions)

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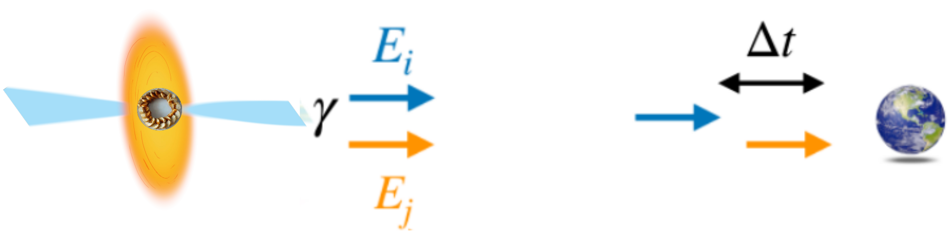
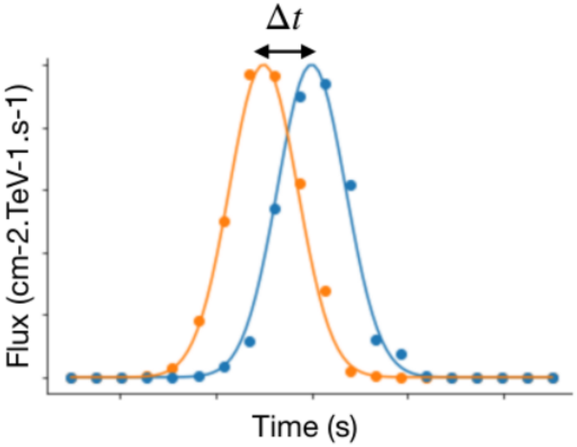
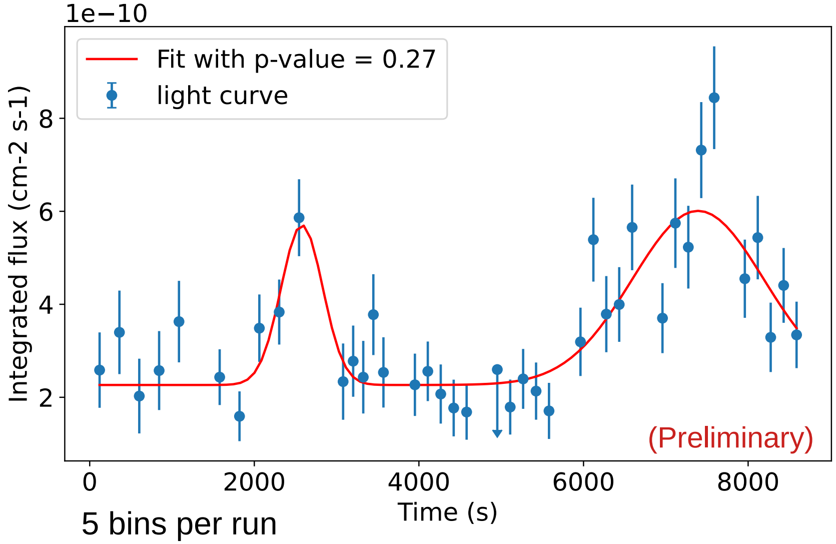
- Define two energy bins : **lower** and **higher** than median of counts
- Find a parametric model for the lightcurve of the low energies sample : selected if p-value > 0.05 (2σ)
- No significant disagreement between low and high energies
- No significant time-variation of spectra (flux vs energy) parameters





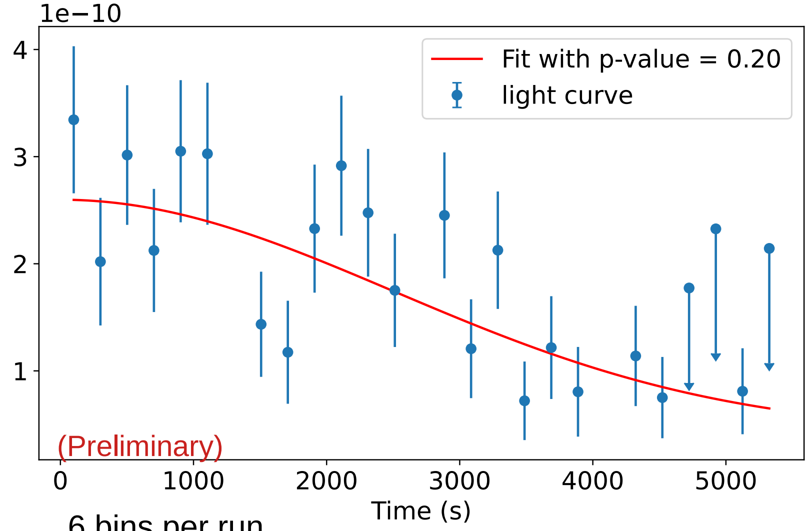
Parametric models of the low energies variability

BL Lac 2021-08-08



5 bins per run

BL Lac 2021-08-09



6 bins per run

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

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

p-value > 0.05 (2σ)

All blazar data of LST-1 until June 2023

Variability test on each significant observation night

Constant fit
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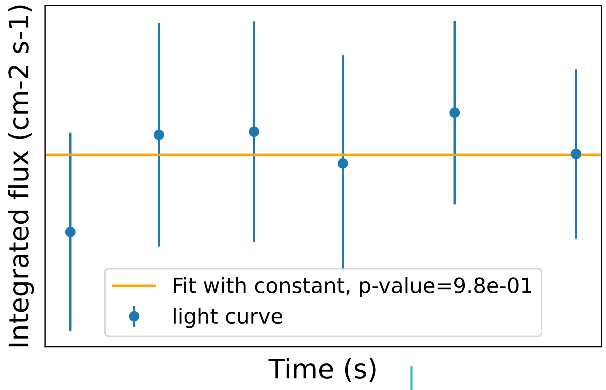
Non-variable sample



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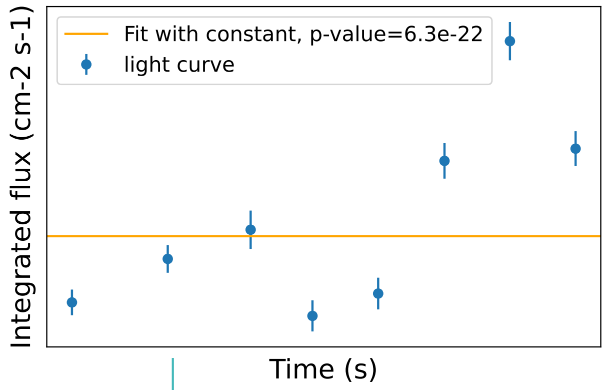
Variable sample



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

All blazar data of LST-1 until June 2023

Variability test on each significant observation night

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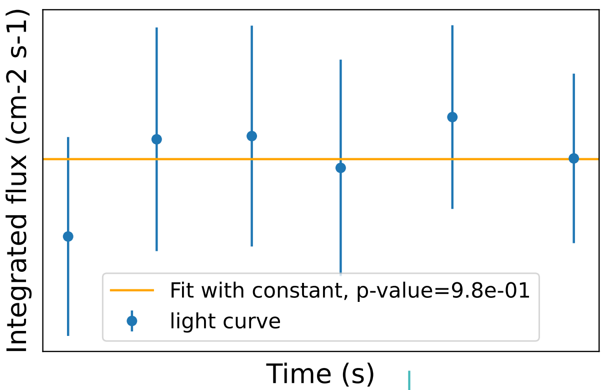

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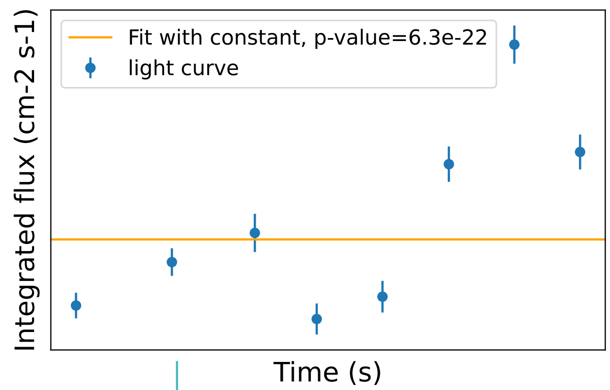

Search for a variability template and extract sample properties (energetic and temporal distributions)

Sample simulations to validate LIV analysis

All blazar data of LST-1 until June 2023

Variability test on each significant observation night

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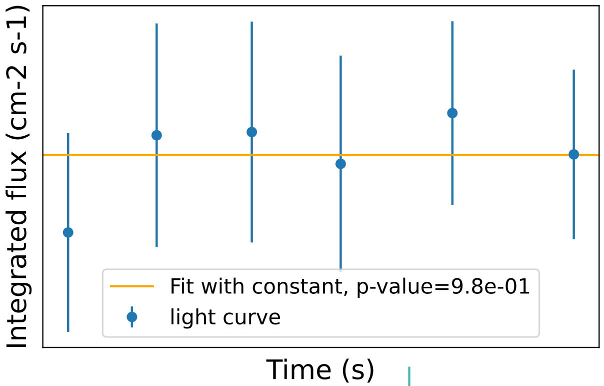

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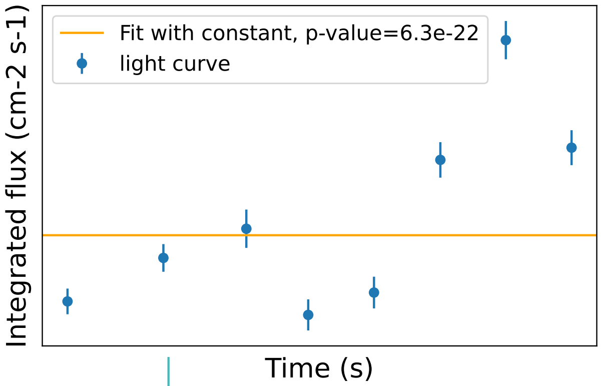

Search for a variability template and extract sample properties (energetic and temporal distributions)

Sample simulations to validate LIV analysis

LIV analysis on real data with the variability template

Sample simulations to validate LIV analysis

LIV analysis on real data with the variability template

↓

LIVelihood

- Code developped for time lag study and combination of different experiments data
- Uses the likelihood method :
  the time lag is a free parameter that can be shared between sources with different redshift and that minimizes the likelihood function :

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

Step 4 : Likelihood method

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

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

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

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

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

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Signal

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

Backgrounds k : hadrons and baseline

Step 4 : Likelihood method

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

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

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

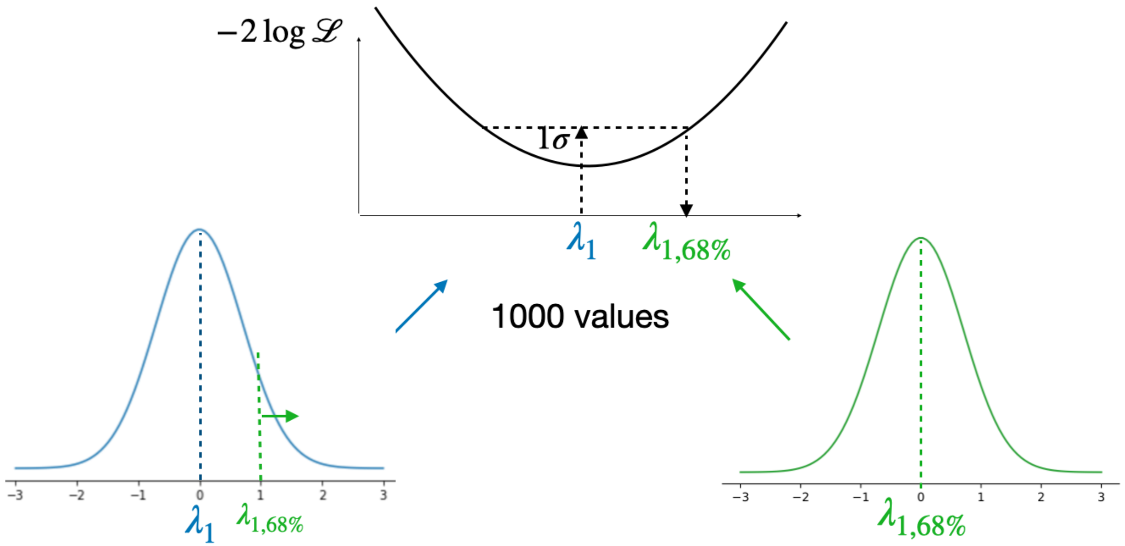
with $$\frac{dP}{dE_R dt} = W_s \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_s(E_T, t; \lambda_n) dE_T}{N'_s}$$

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

Lightcurve x spectra

Sample simulations to validate LIV analysis

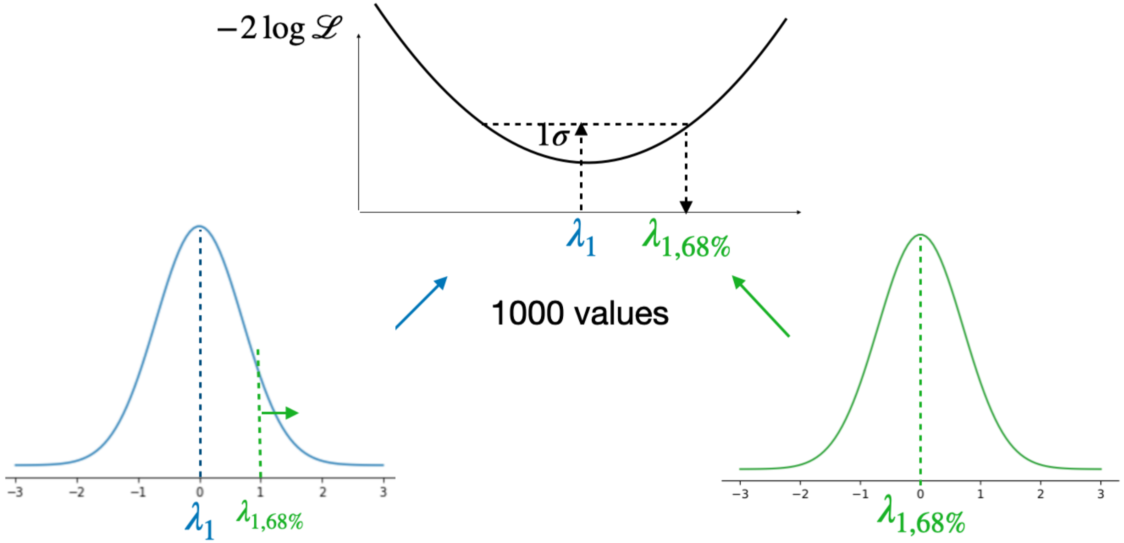
- Perform 1000 dataset simulations



Step 4 : simulations for calibration

Sample simulations to validate LIV analysis

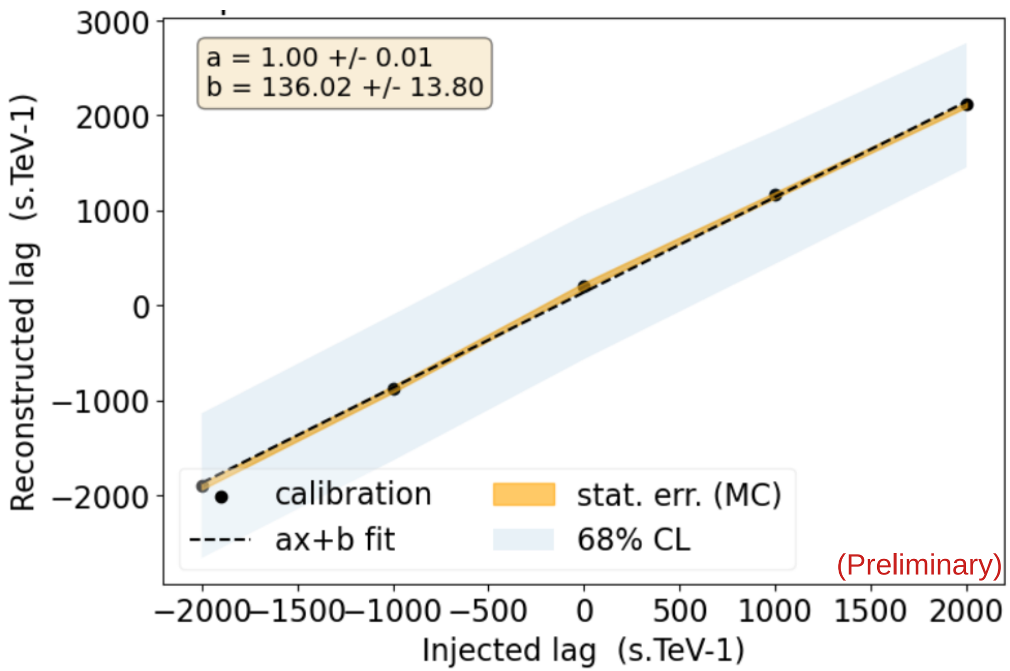
- Perform 1000 dataset simulations
- Calibration : inject lag to verify that LIVelihood reconstructs it well



Sample simulations to validate LIV analysis

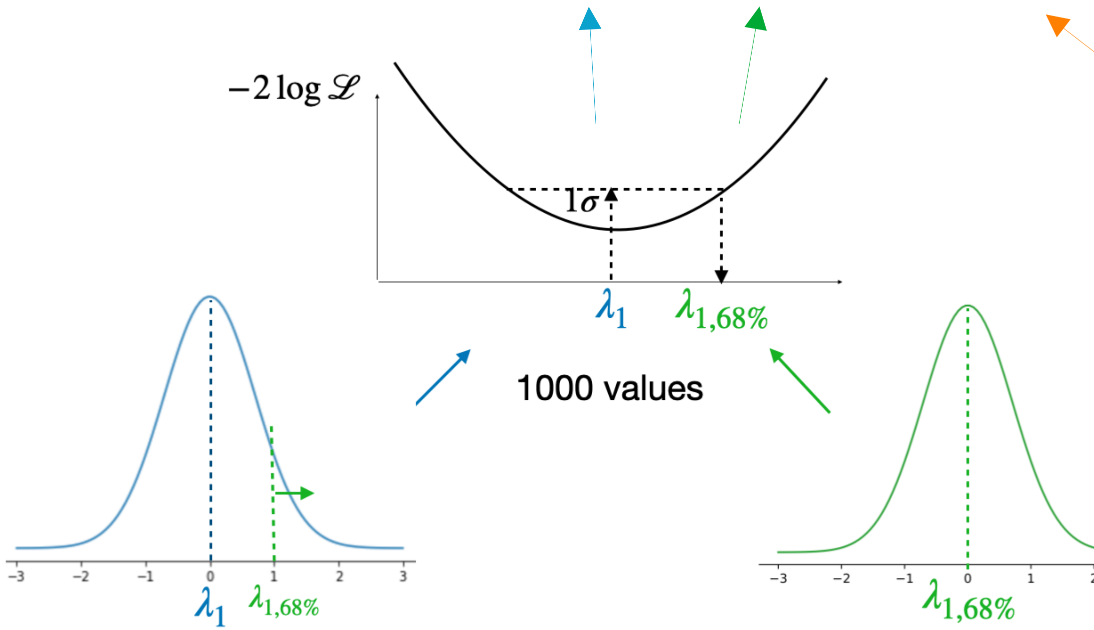
- Perform 1000 dataset simulations
- Calibration : inject lag to verify that LIVelihood reconstructs it well

BL Lac 2021-08-08 and 08-09 combined



LIV analysis on real data

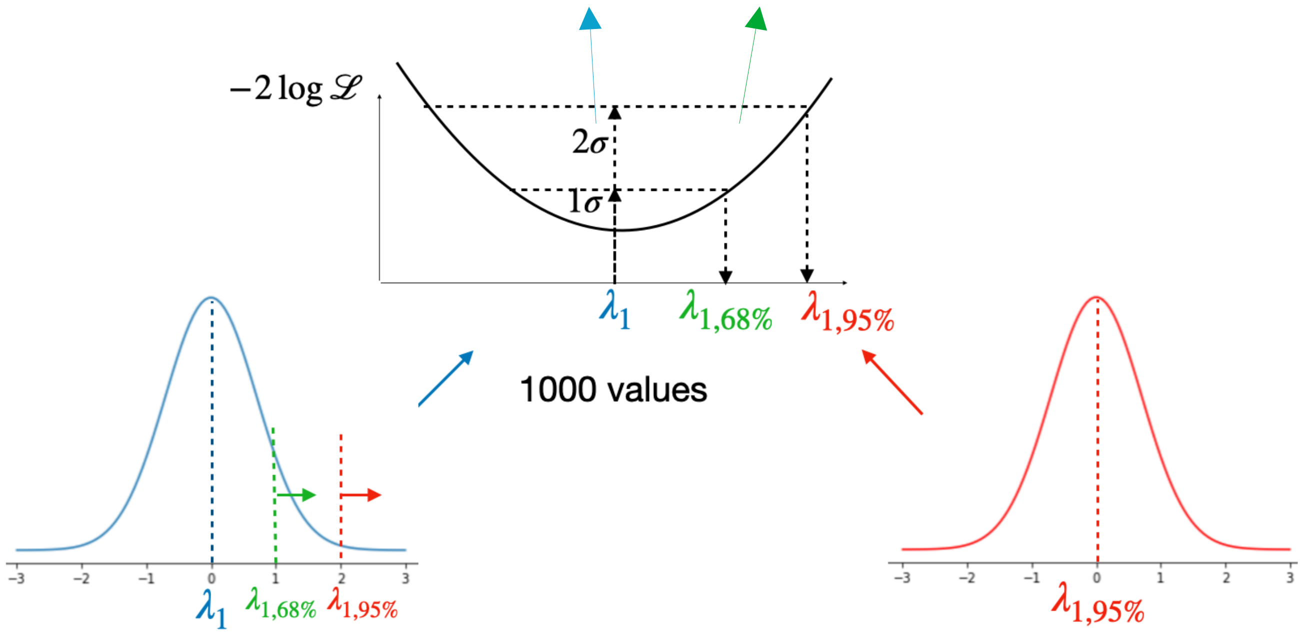
Time delay : $\lambda_1 = (2060\ ^{+2811}_{-2899}\ ^{+2479}_{-2143})\ \mathrm{s.TeV}^{-1}$



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

LIV analysis on real data

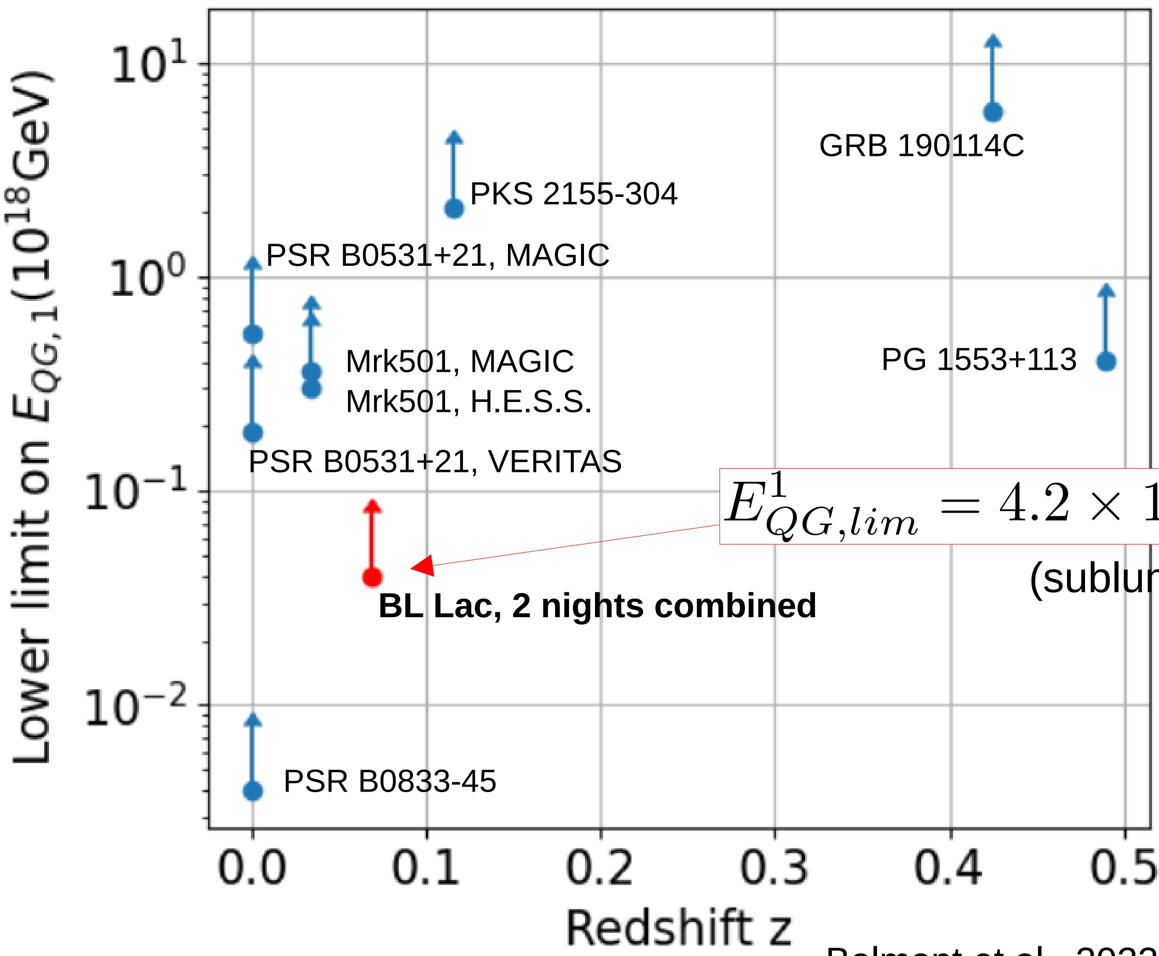
Time delay : $\lambda_1 = (2060 \, ^{+2811}_{-2899} \, ^{+2479}_{-2143})\,\mathrm{s.TeV^{-1}}$



Use $\lambda_{1,95\%} = \pm \frac{n+1}{2H_0 E^1_{QG,lim}}$ to extract : $E^1_{QG,lim} = 4.2 \times 10^{16}\,\mathrm{GeV}$

(subluminal case)

Comparison with other limits



$$E^1_{QG,lim} = 4.2 \times 10^{16}\mathrm{GeV}$$

(subluminal case)

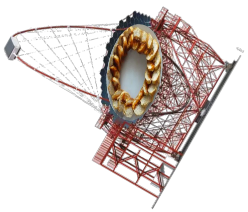
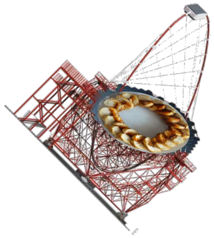
Bolmont et al., 2022

- Analysed all LST database on blazars, searching for variability
- Combined 2 variable nights of BL Lac to extract a limit on E_{QG} at the order n=1 on real data

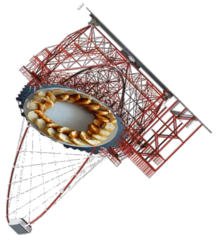
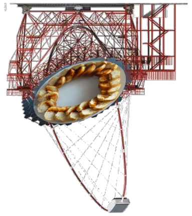
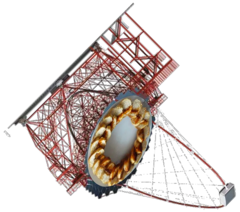
Ongoing work :

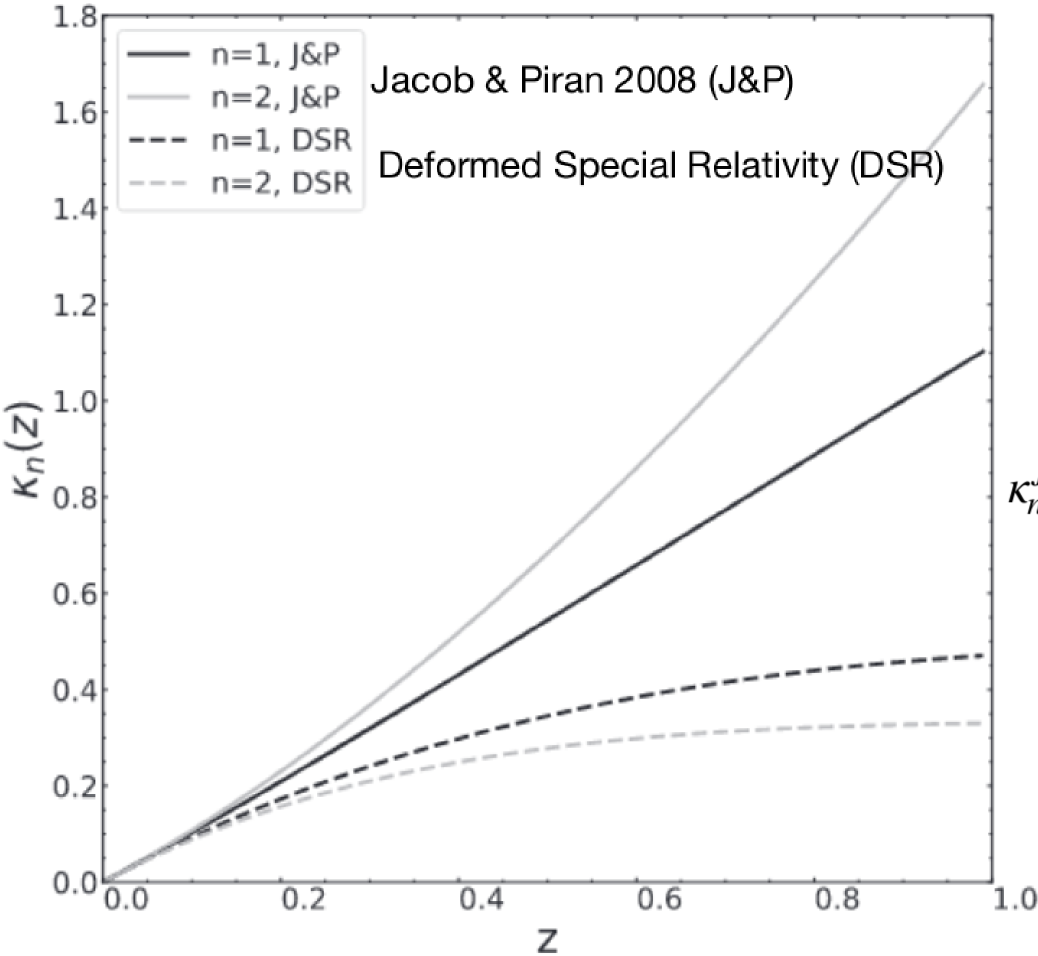
- Combine with the BL Lac 2022-10-20 night
- Combination of LST data with the consortium data



Thank you !



Bolmont et al 2022

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

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
$$\frac{dP}{dE_R dt} = W_{\mathbf{s}} \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{\mathbf{s}}(E_T, t; \lambda_n) dE_T}{N'_{\mathbf{s}}} + \sum_{\mathbf{k}} W_{\mathbf{b,k}} \frac{\int \mathrm{E_{ff}A}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{\mathbf{b,k}}(E_T) dE_T}{N'_{\mathbf{b,k}}}$$

IRFs

Signal

Lightcurve x spectra

Backgrounds k : hadrons and baseline

Likelihood for real data

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

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

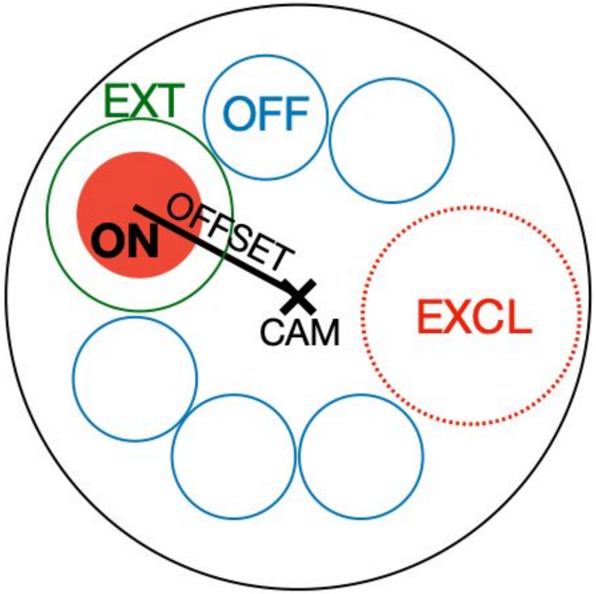
$$+ W_b \frac{\int \mathrm{EffA}(E_T, \vec{\epsilon})\mathrm{MM}(E_T, E_R) \times \mathrm{F}_b(E_T) dE_T}{N'_b}$$

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

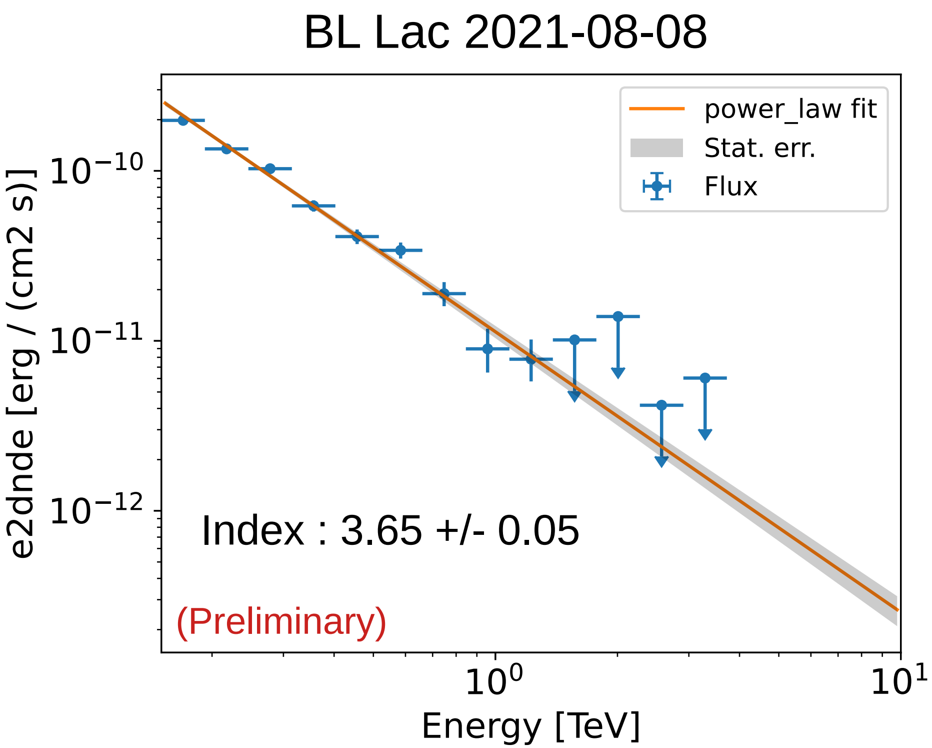
Reflected region background method

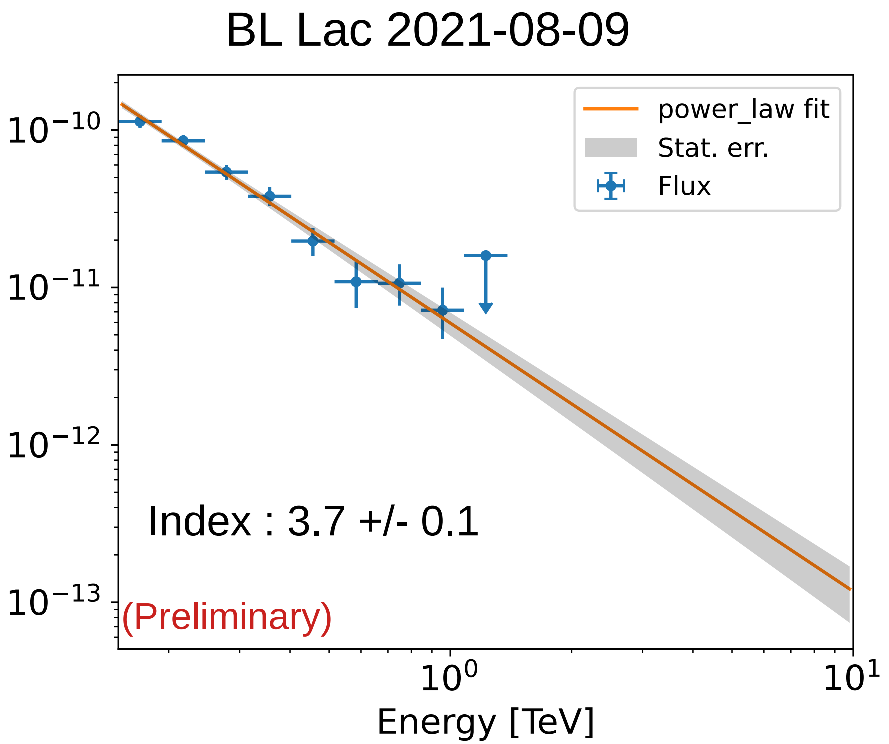
Hypothesis : background is purely radial in the field-of-view.

- X CAM : camera pointing direction
- OFFSET : regions dispersion radius
- ON : source (gammas) + background
- EXT : exclusion of potential remaining source events
- EXCL : exclusion of a potential other source
- OFF : background



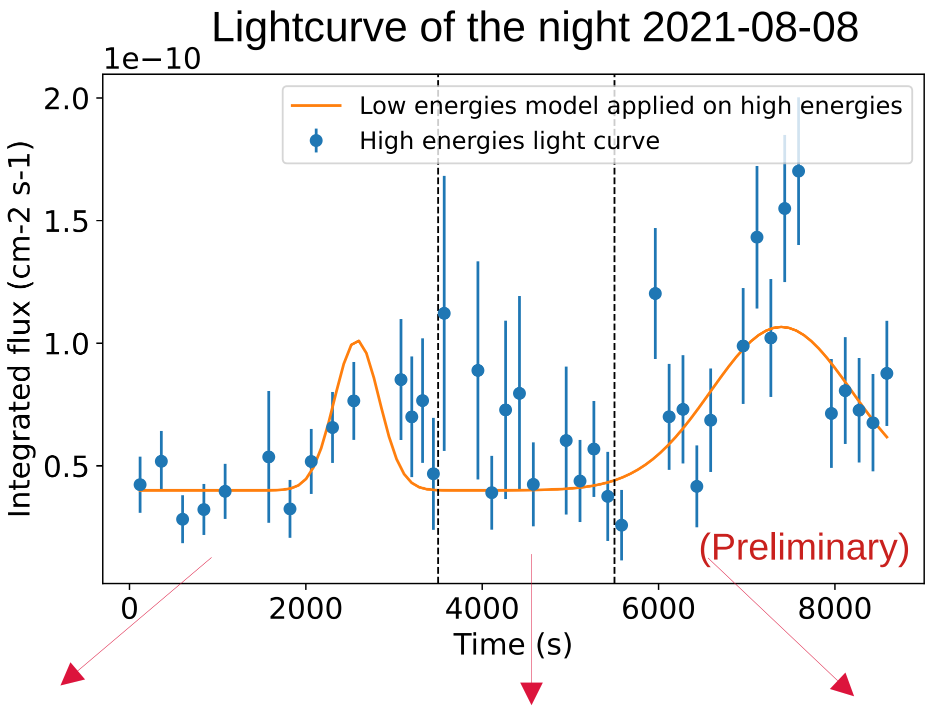
$$N_\gamma = N_{excess} = N_{on} - \frac{1}{n}\sum_n N_{n,off}$$

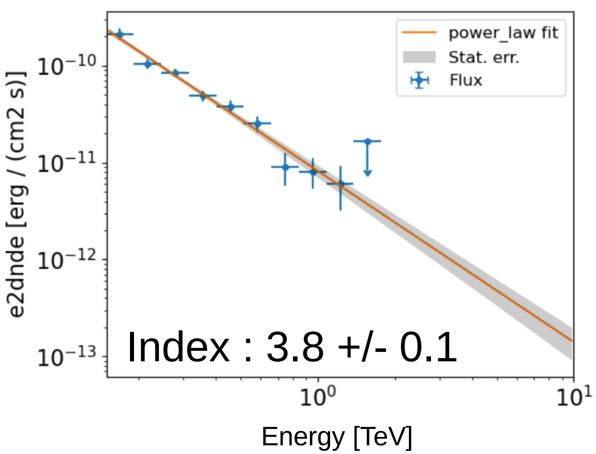


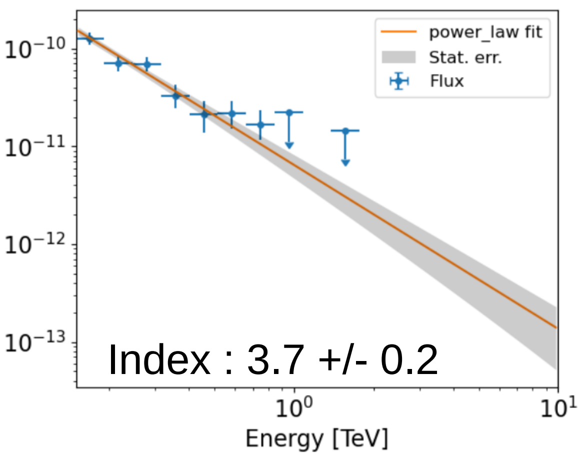


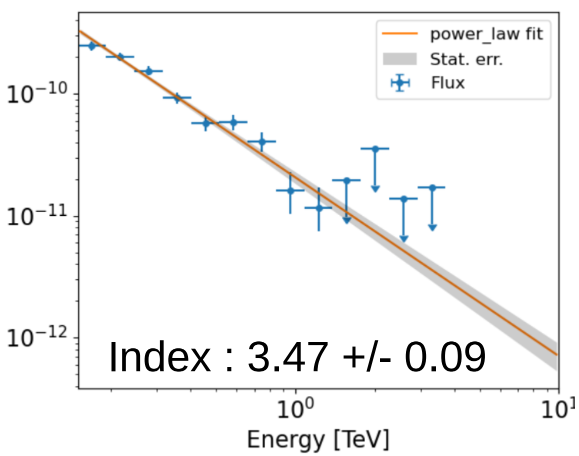
10 bins per decade, ON radius = 0.2°, energy reco : [150GeV , 10TeV]

Time-independency of the energetic distribution



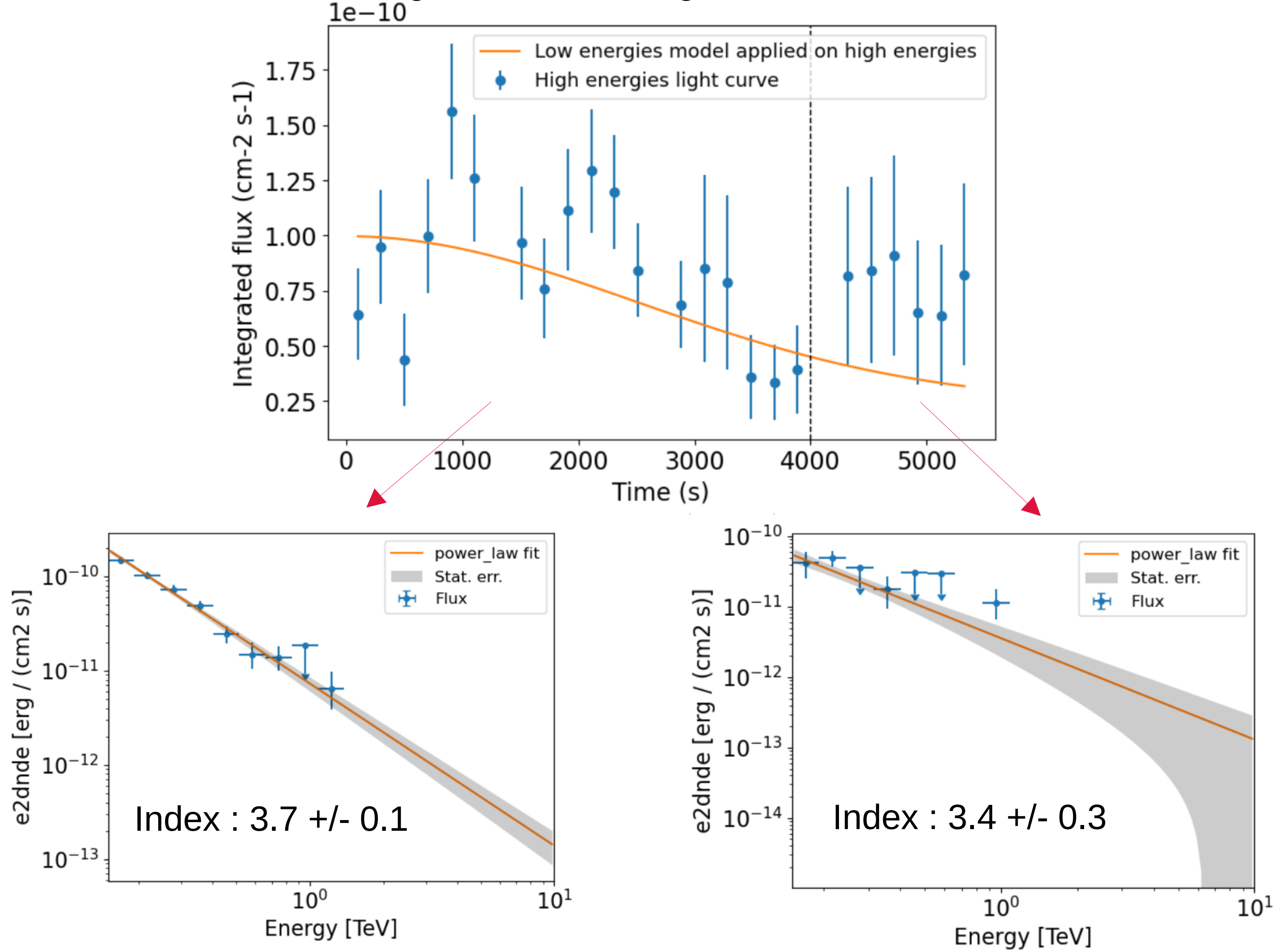




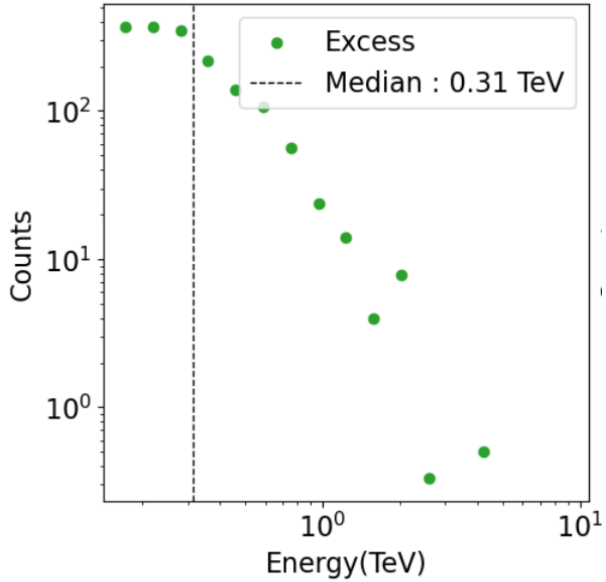


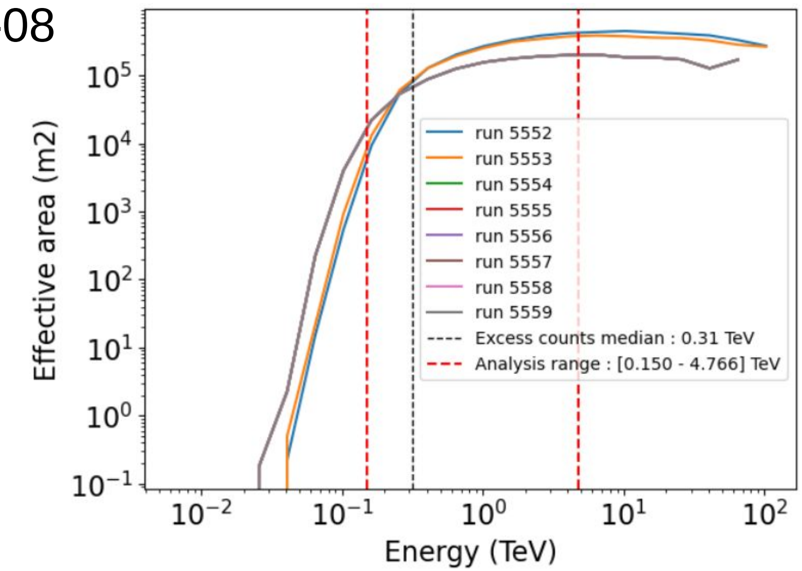
Time-independency of the energetic distribution

Lightcurve of the night 2021-08-09



2021-08-08





2021-08-09