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

8th Heidelberg symposium on high-energy gamma-ray astronomy

Cyann Plard & Sami Caroff
on behalf on the LST collaboration

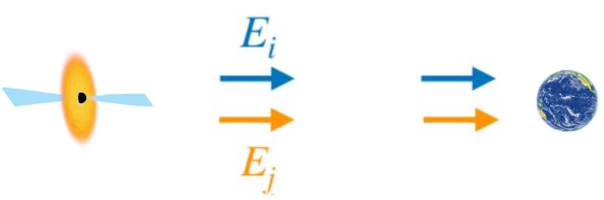
- Unification of general relativity and quantum field theory: quantum gravity
  - → effects of QG expected to appear at Planck scale $E_P \sim 10^{19} \mathrm{GeV}$
- Some quantum gravity models allow a violation of Lorentz invariance
  - → may be observable using high energetic gamma-rays

Lorentz invariance violation (LIV)

Lorentz invariance: speed of light c in vacuum is energy-independent

$$E^2 = p^2c^2$$

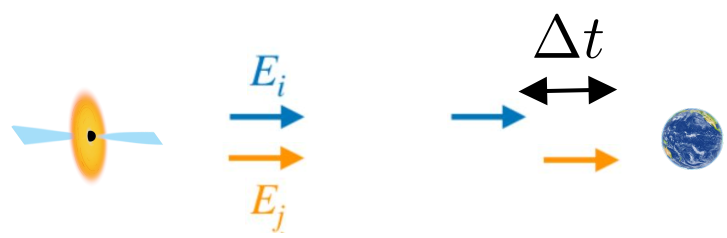
$$v_\gamma = c$$



$\longrightarrow$

$$E^2 = p^2c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

$$v_\gamma(E_\gamma^n, E_{QG,n}) \neq c$$



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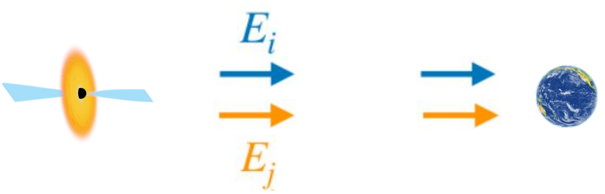

→

$$E^2 = p^2 c^2 \times \left[1 \pm \sum_{n=1}^{\infty} \left(\frac{E}{E_{QG,n}} \right)^n \right]$$

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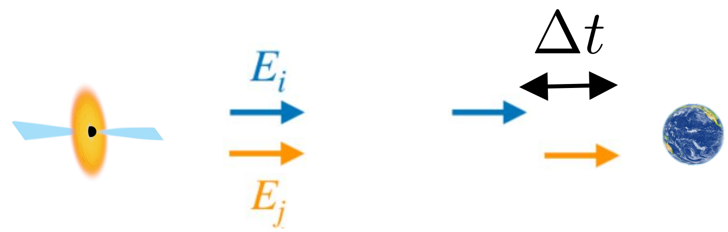


$$\lambda_n = \frac{\Delta t}{\Delta E^n \kappa_n(z)} = \pm \frac{n+1}{2 H_0 E_{QG,n}^n}$$

→

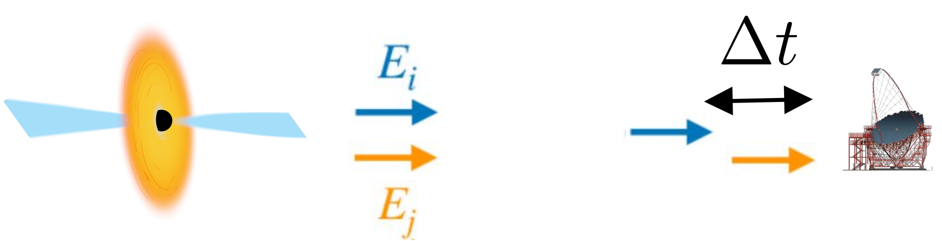
Search for a limit on $E_{QG,n}$ at the first order $n = 1$

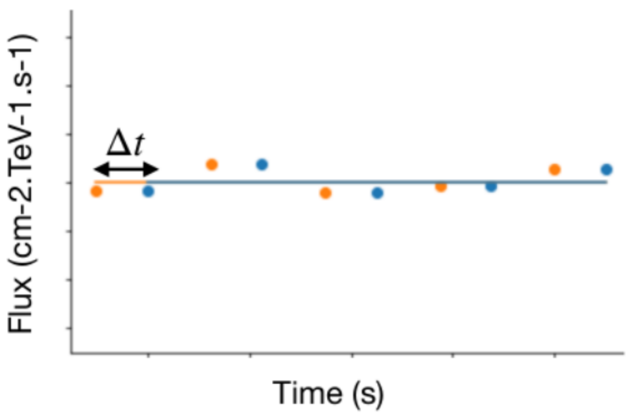
Sources

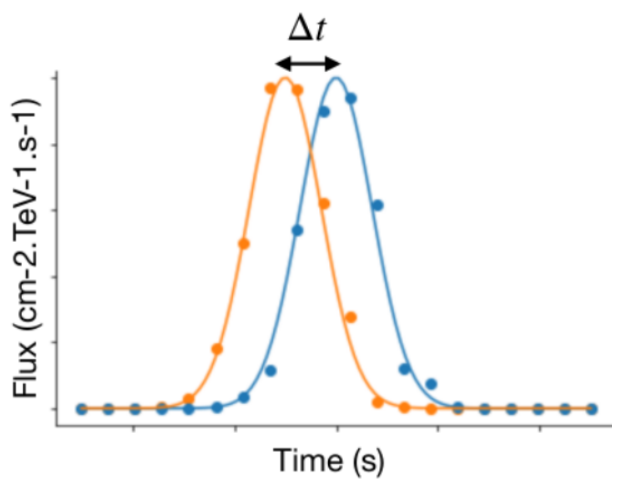
- Large range of energy
- Cosmological distance
- Highly variable and active source

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

→ blazars, gamma-ray bursts, pulsars



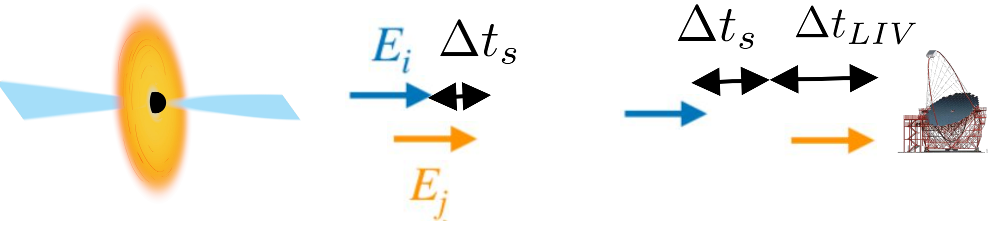




No guarantee that photons are emitted at the same time

→ Intrinsic source delay:

$$\Delta t = \Delta t_{LIV} + (1+z)\Delta t_{source}$$



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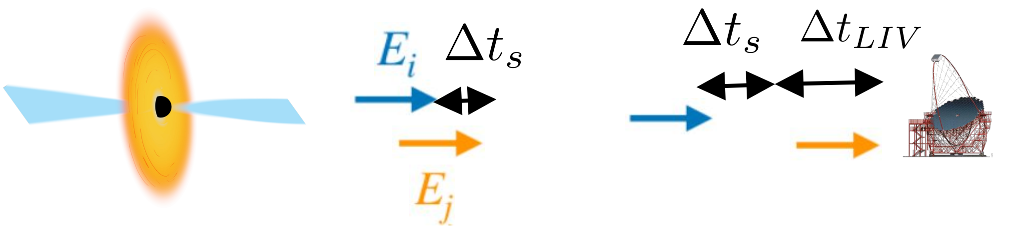


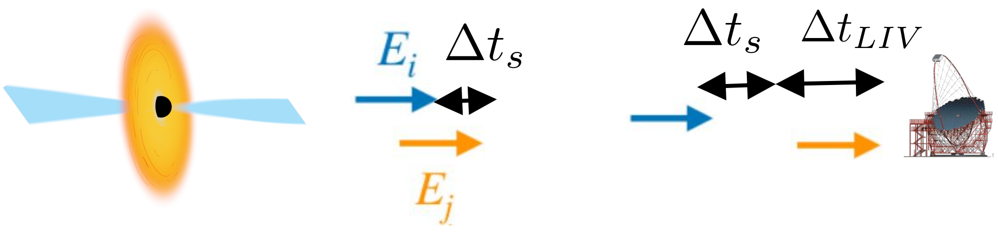
Δt_{source}	Δt_{LIV}
Redshift-independent	Redshift-dependent
Sources and flares -dependent	Sources and flares -independent

Intrinsic source delay

No guarantee that photons are emitted at the same time

→ Intrinsic source delay:

$$\Delta t = \Delta t_{LIV} + (1+z)\Delta t_{source}$$

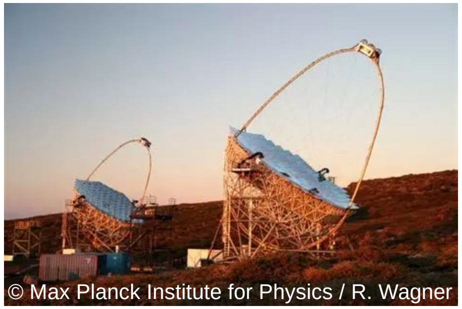


Δt_{source}	Δt_{LIV}
Redshift-independent	Redshift-dependent
Sources and flares -dependent	Sources and flares -independent

→ Combination of different flares and different (types of) sources

Combination of sources: γLIV WG

- Analysis already performed with various individual flares and/or sources observed with Cherenkov telescopes but **data were never combined**
- *Gamma-ray LIV Working Group (γLIV WG)* between H.E.S.S., MAGIC, VERITAS and LST to **combine** different types of sources and flares from various experiments
- Combination of **simulations** of data from experiments involved in the γLIV WG (without LST) already performed: *Bolmont et. al., 2022, ApJ 930 75*
- This work: prototype of a global and consistent analysis on all **blazar** data of **LST-1** then combine it with the *γLIV WG* data

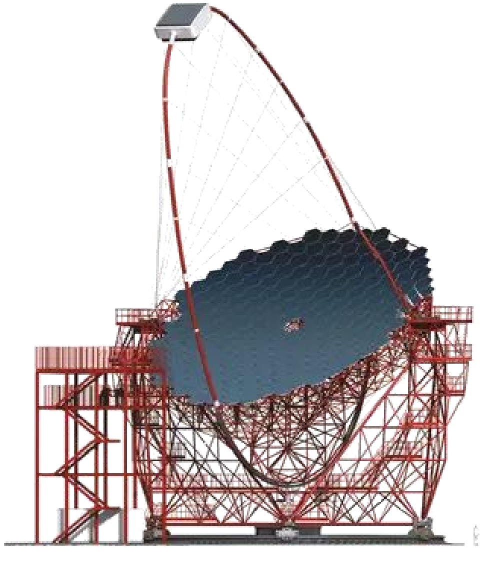


Analysis: step 1

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 z	0.069	0.0043	0.047	0.433 *(Jones et al. 2021)*	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

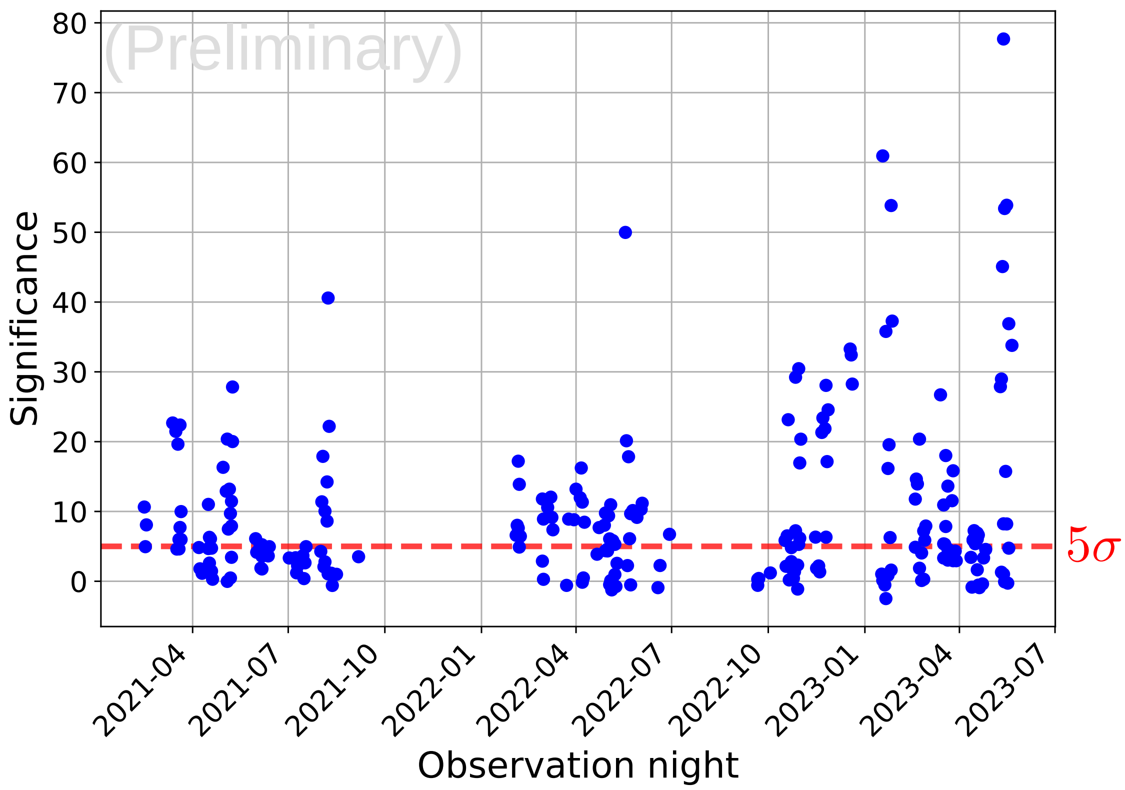
↓

Variability test on each significant observation night

Cyann Plard & Sami Caroff (LAPP, CNRS)

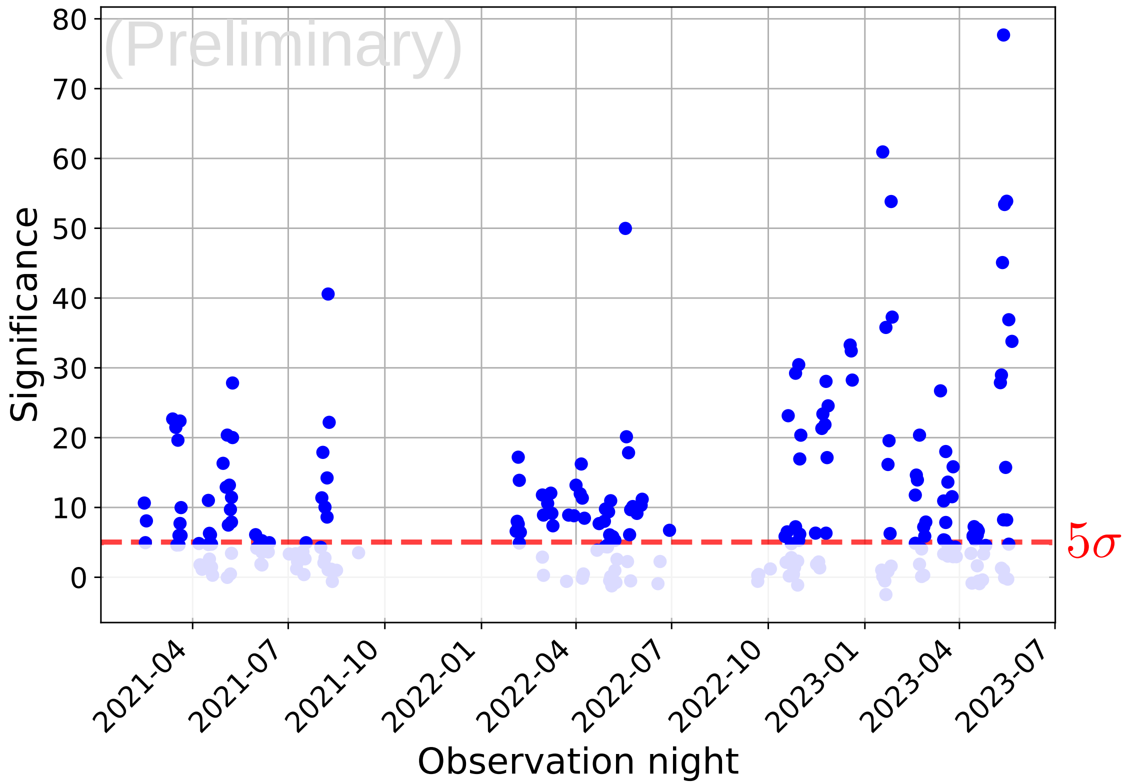
Step 2: intra-night variability

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



Step 2: intra-night variability

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



Analysis: step 2

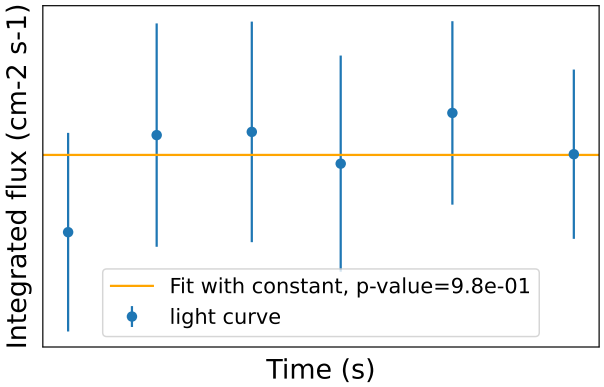
Several AGNs data of LST-1 from January 2021 to June 2023

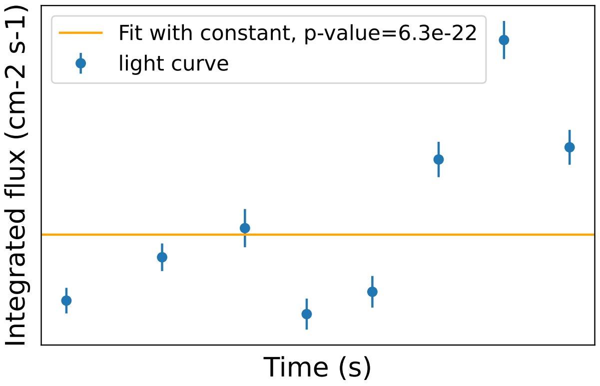
Variability test on each significant observation night

Non-variable sample

Constant fit
pvalue < $3x10^{-7}$
(5σ)

Variable sample





Step 2: intra-night variability

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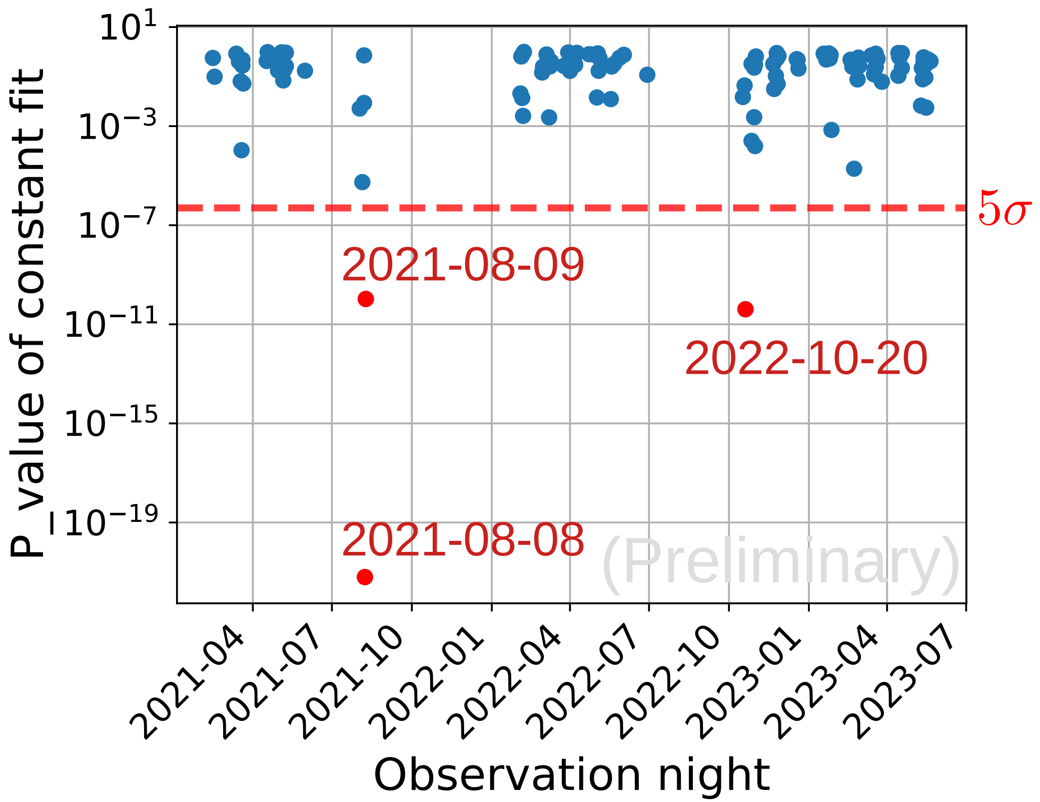
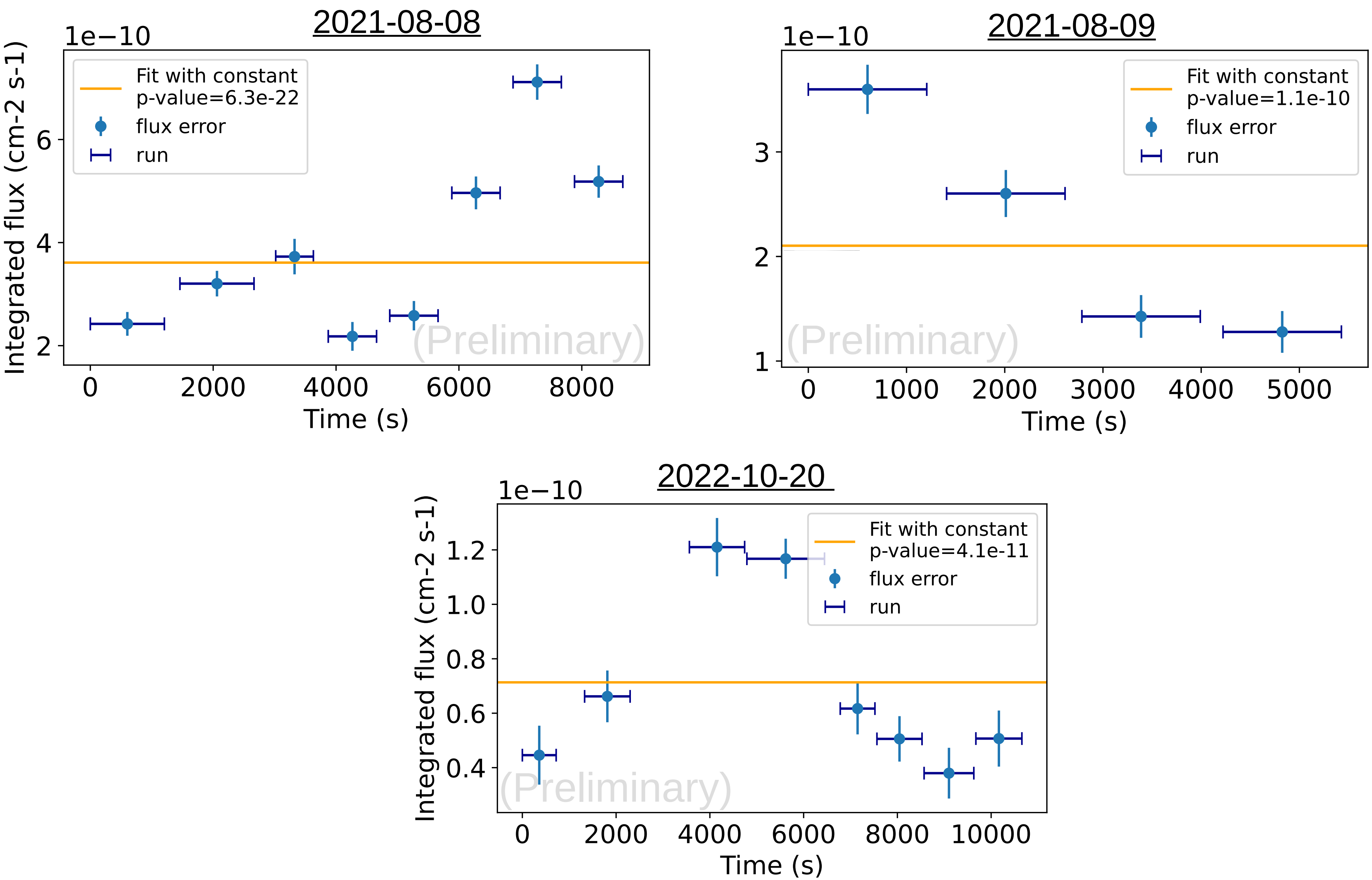


Found 1 source showing intra-night variability: **BL Lacertae** with 3 nights (~7h)

Variable lightcurves of BL Lac



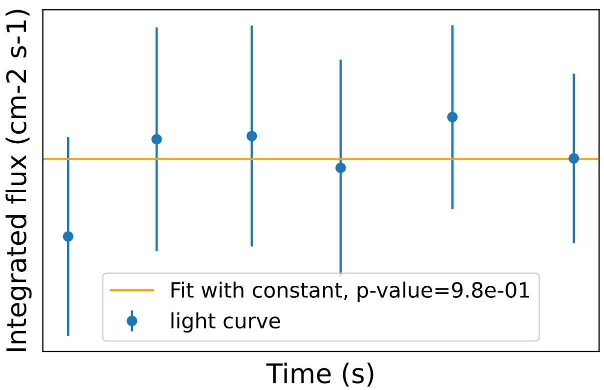
Analysis: step 3

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

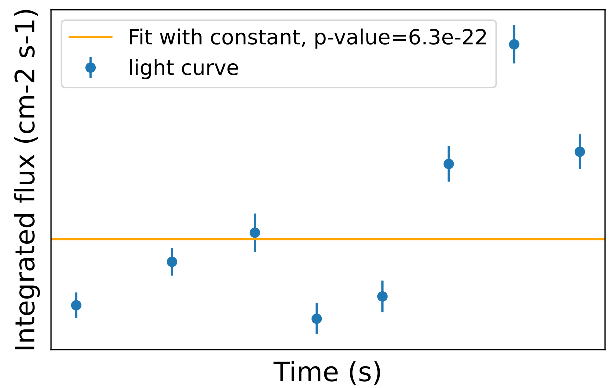
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample



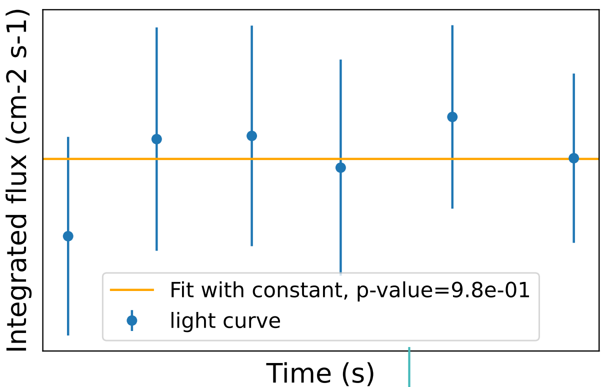
Analysis: step 4

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

Variability test on each significant observation night

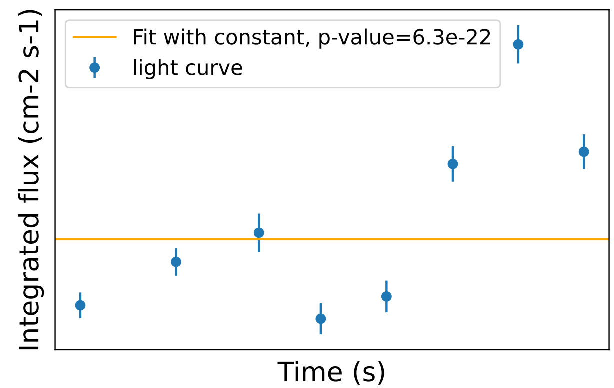
Constant fit
pvalue < 5σ

Non-variable sample



Optimization of analysis cut

Variable sample



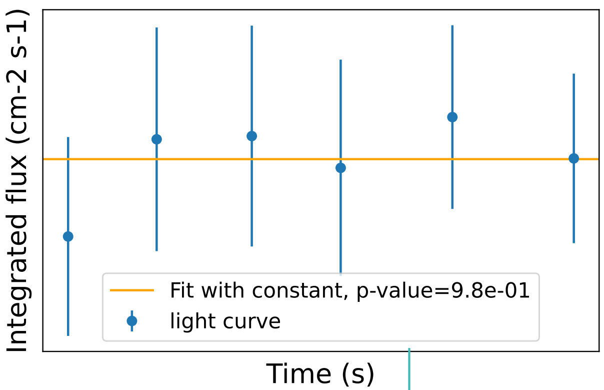
Analysis: step 5

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

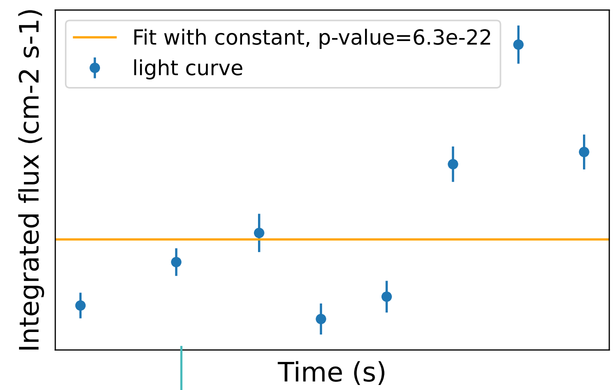
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample

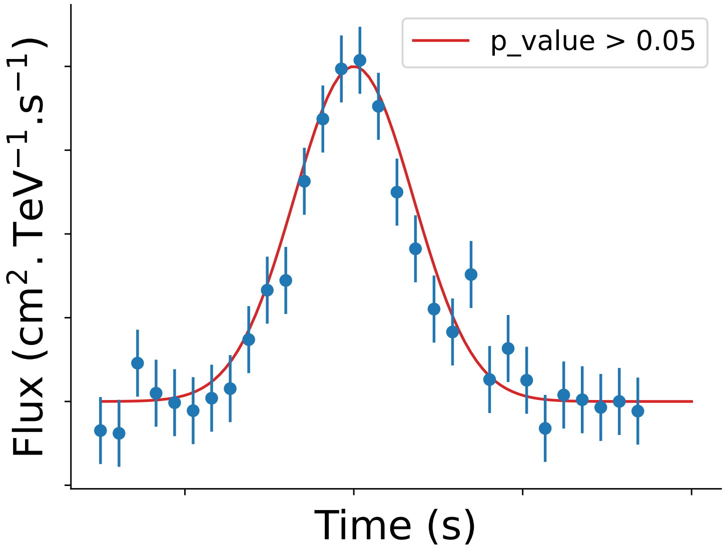


Optimization of analysis cut

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)

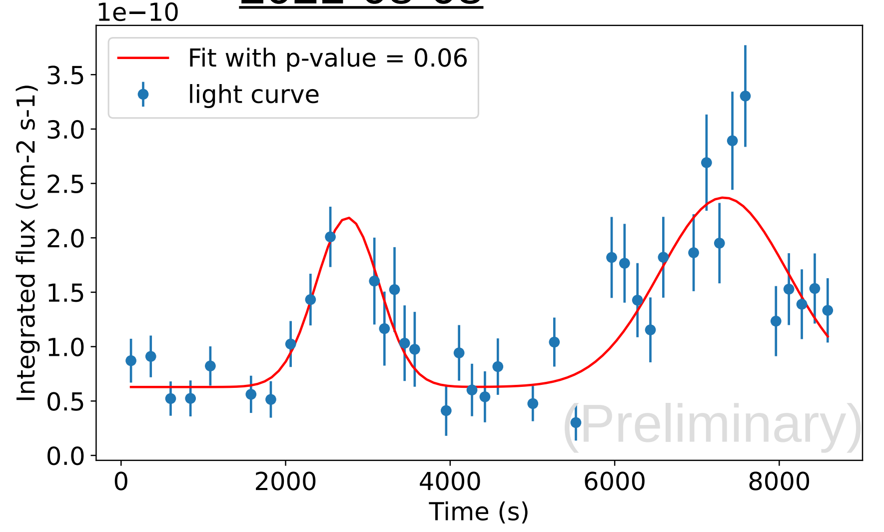
- Find a model to describe the lightcurve variability: non-rejected if p-value > 0.05 (2σ)



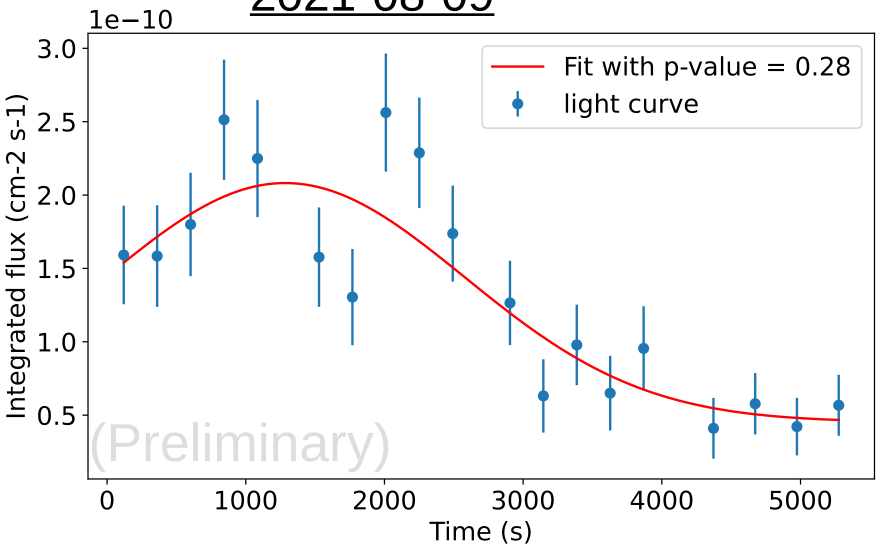
Step 5: variability pattern

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

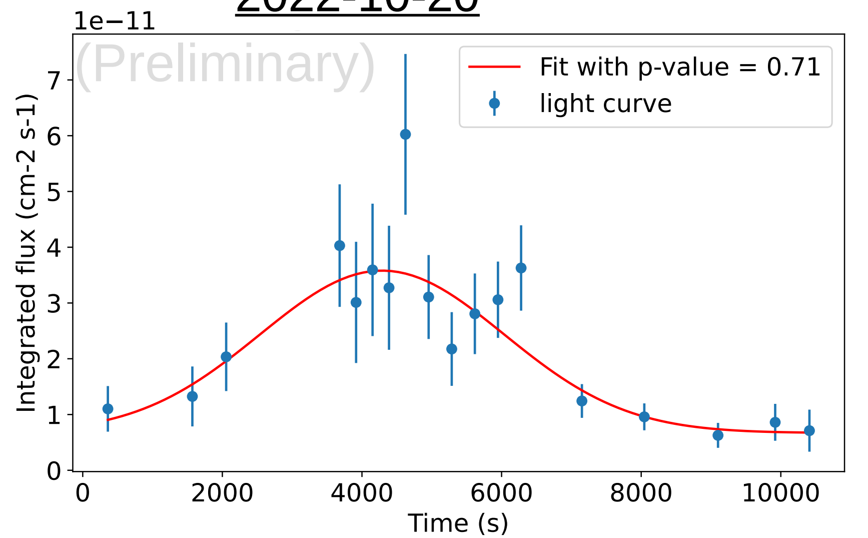
2021-08-08



2021-08-09



2022-10-20



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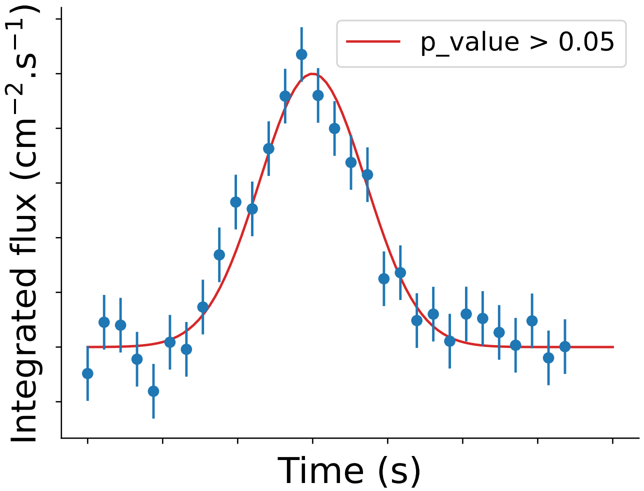
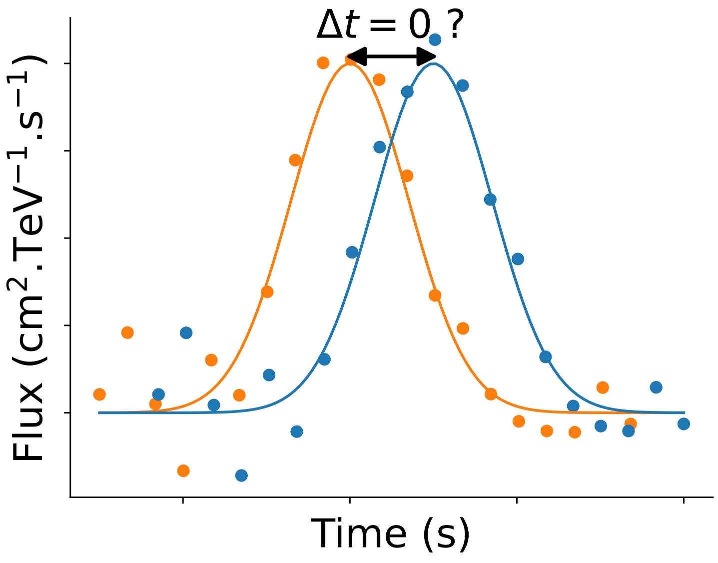


(Preliminary)	Lightcurve model (Gaussians)						
	C (cm-2.s-1)	A_1 (cm-2.s-1)	μ_1 (s)	σ_1 (s)	A_2 (cm-2.s-1)	μ_2 (s)	σ_2 (s)
2021-08-08	6.3e-11	1.6e-10	2752	386	1.8e-10	7326	778
2021-08-09	4.5e-11	1.7e-10	1284	1293			
2022-10-20	6.7e-12	2.9e-11	4288	1750			

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

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



Step 5: variability pattern

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

- Find a model to describe the lightcurve variability: non-rejected if p-value > 0.05 (2σ)
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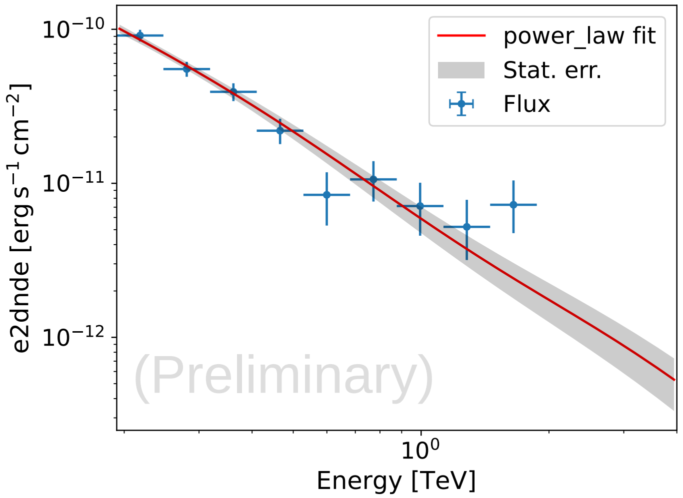
- Check: no significant time-variation of energetic distribution (spectra parameters)



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

(Preliminary)	Spectra model (power law)
	Index α
2021-08-08	3.44±0.2
2021-08-09	3.45±0.1
2022-10-20	3.48±0.2

Step 5: variability pattern

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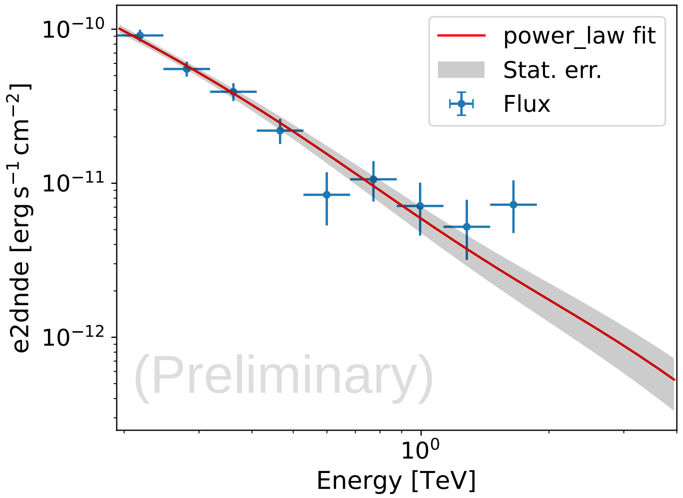
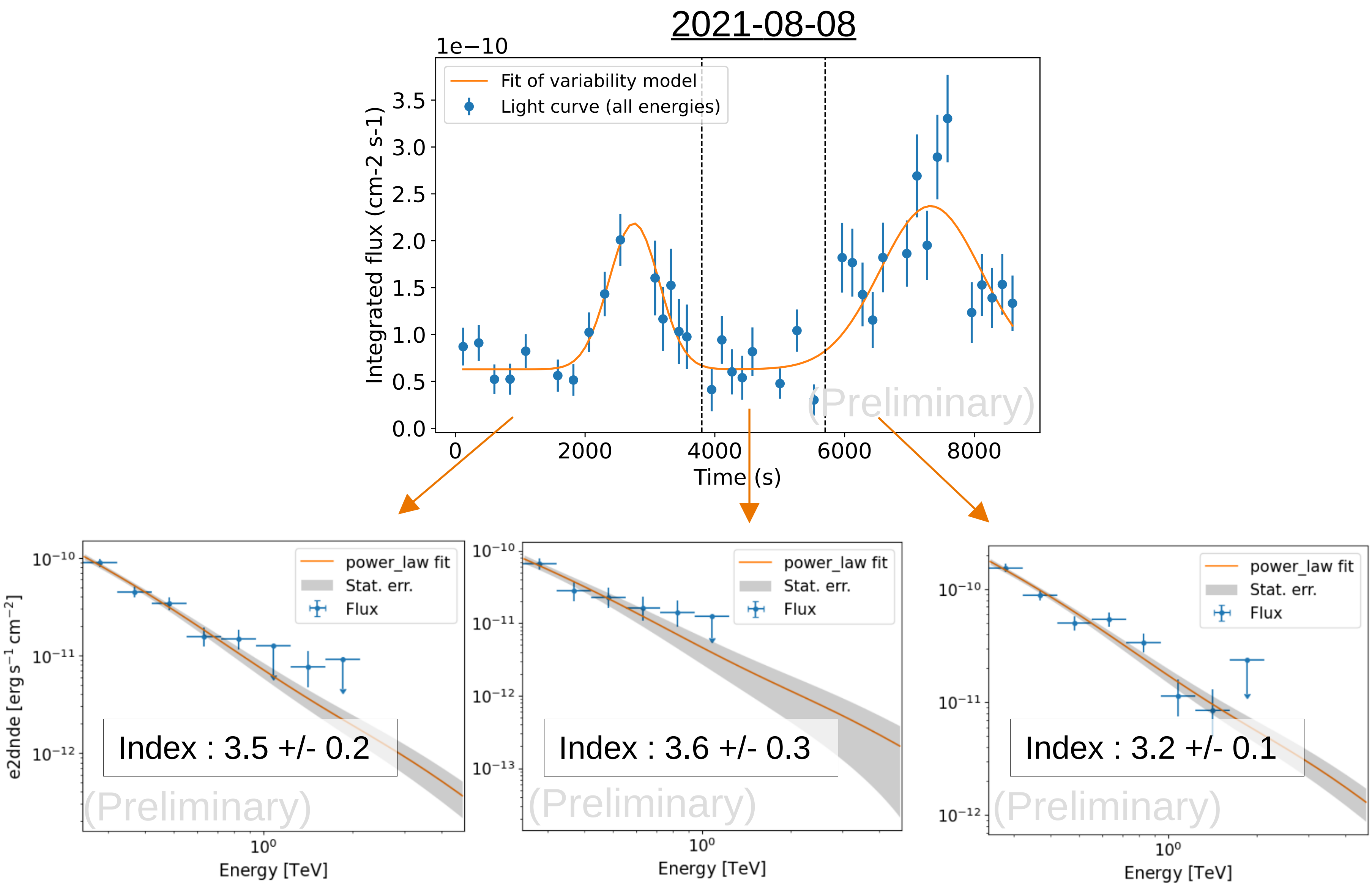


$$A_0\left(\frac{E}{E_0}\right)^{-\alpha}$$

time-independent index ?

Step 5: Time-independency of spectra

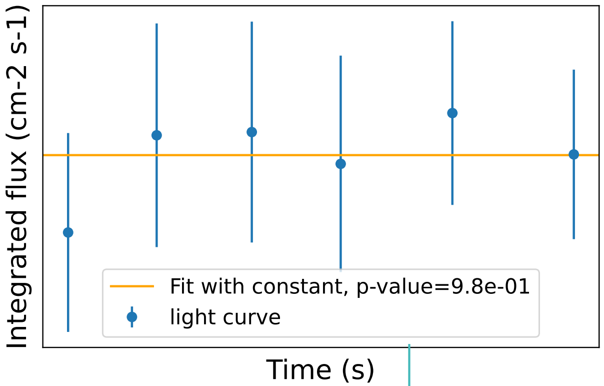


Several AGNs data of LST-1 from January 2021 to June 2023

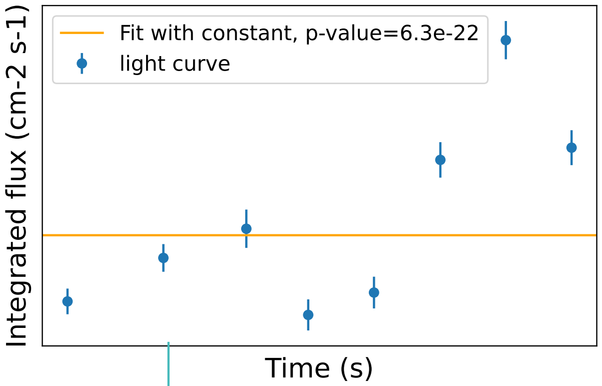
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample



Optimization of analysis cut

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

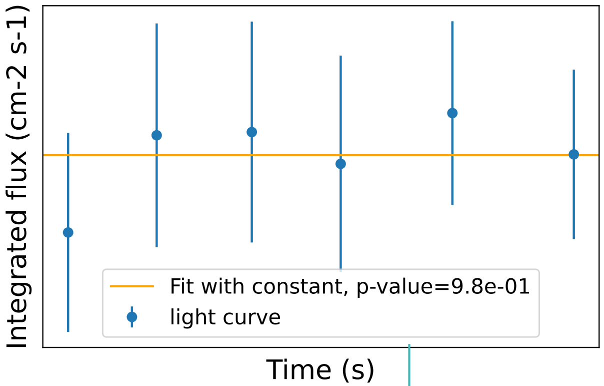
Analysis: step 6

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

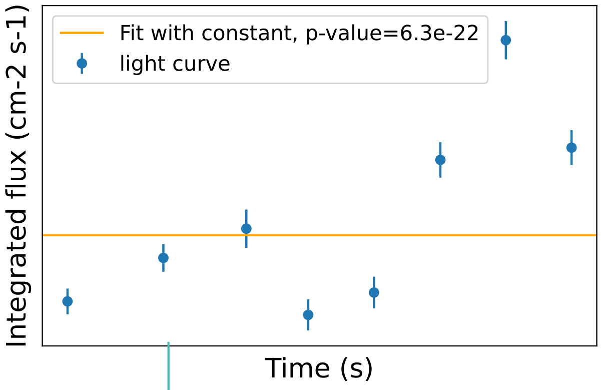
Variability test on each significant observation night

Constant fit pvalue < 5σ

Non-variable sample



Variable sample



Optimization of analysis cut

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

LIV analysis

LIV analysis

↓

LIVelihood software

- Created in the context of the γLIV working group
- Uses the **likelihood method**:
  λ_n is a free parameter that minimizes the likelihood function

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

for combination: $$\mathcal{L}_{\text{comb}}(\lambda_n) = \sum_{\text{source } S} \mathcal{L}_S(\lambda_n)$$

Analysis: step 6

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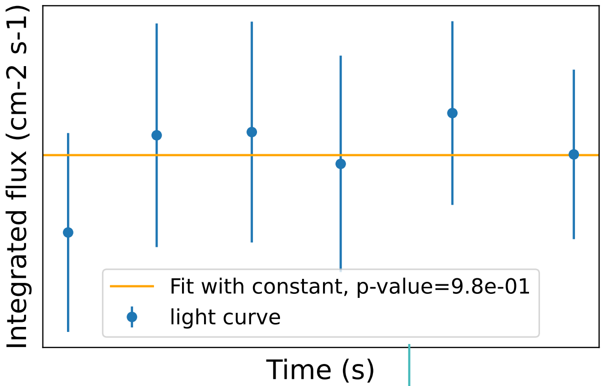
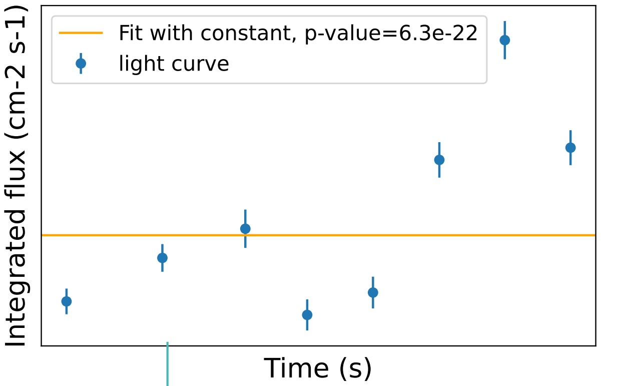
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample



Optimization of analysis cut

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

LIV analysis

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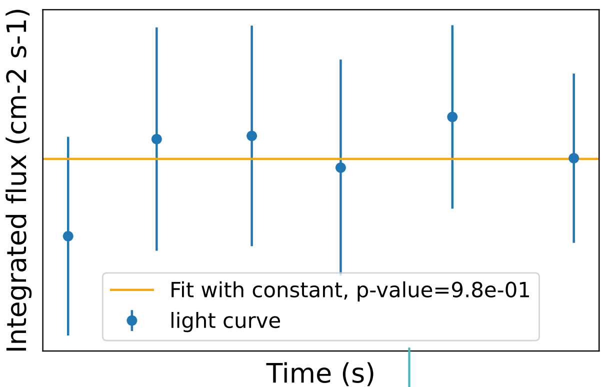

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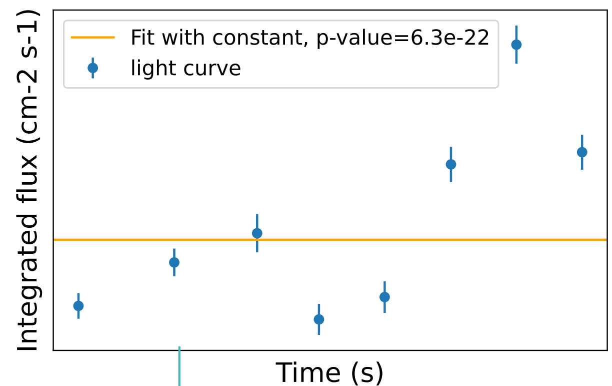

Optimization of analysis cut

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

LIV analysis

Sample of simulations for calibration

Step 7: Likelihood for calibration

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

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

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

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

Step 7: Likelihood for calibration

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

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

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Signal

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

Backgrounds k: baseline and hadrons

Step 7: Likelihood for calibration

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

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

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

Lightcurve * spectra

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

	Spectral model (power law)	Lightcurve model (Gaussians)						
	index α	C (cm-2.s-1) (baseline background)	A_1 (cm-2.s-1)	μ_1 (s)	σ_1 (s)	A_2 (cm-2.s-1)	μ_2 (s)	σ_2 (s)
2021-08-08	3.44	6.3e-11	1.6e-10	2752	386	1.8e-10	7326	778
2021-08-09	3.45	4.5e-11	1.7e-10	1284	1293			
2022-10-20	3.48	6.7e-12	2.9e-11	4288	1750			
hadronic background	2.7 (Aguilar et al, 2015)	C						

(Preliminary)

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

Lightcurve * spectra

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

Step 7: Likelihood for calibration

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

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

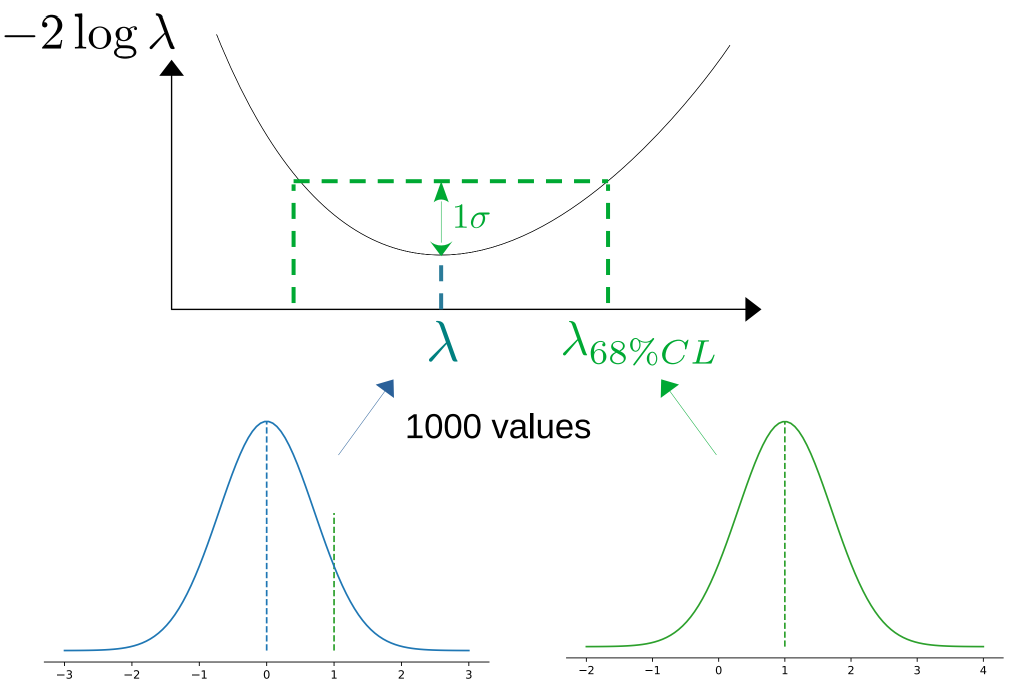
with
$$\frac{dP}{dE_R dt} = W_{\mathbf{s}} \frac{\int \mathrm{E_{ff}A}(E_T, t)\mathrm{MM}(E_T, E_R) \times \mathrm{F}_{\mathbf{s}}(E_T, t; \lambda_n) dE_T}{N'_{\mathbf{s}}}$$

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

Instrumental response functions

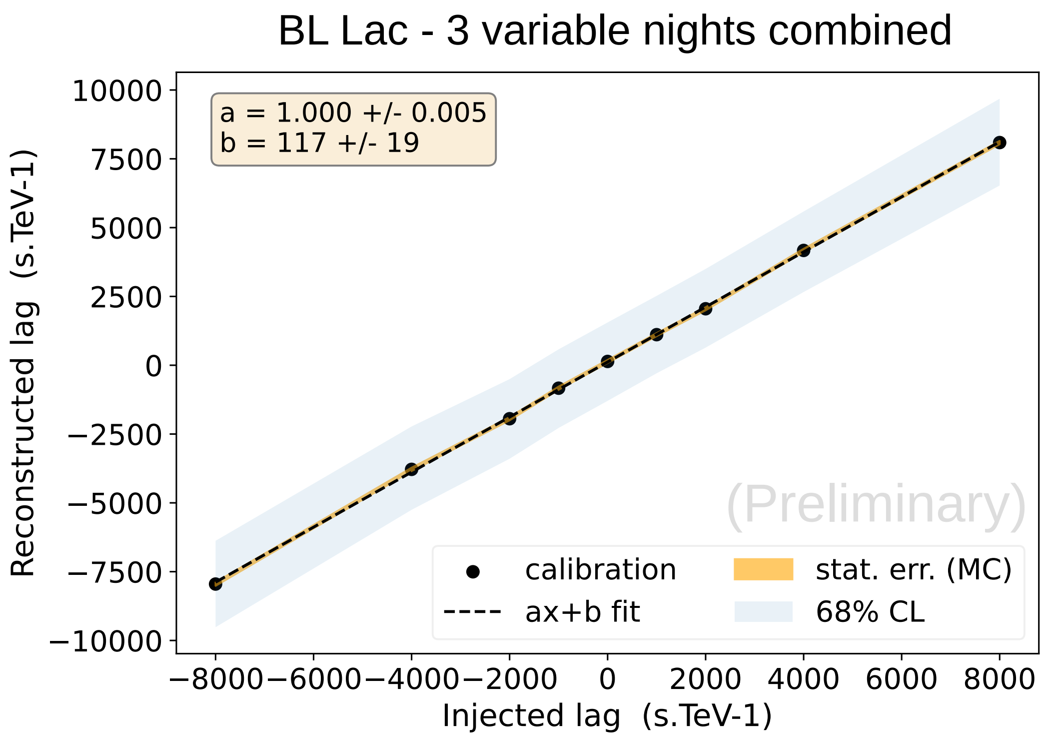
Simulations sample for calibration

- Perform 1000 dataset simulations



Simulations sample for calibration

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

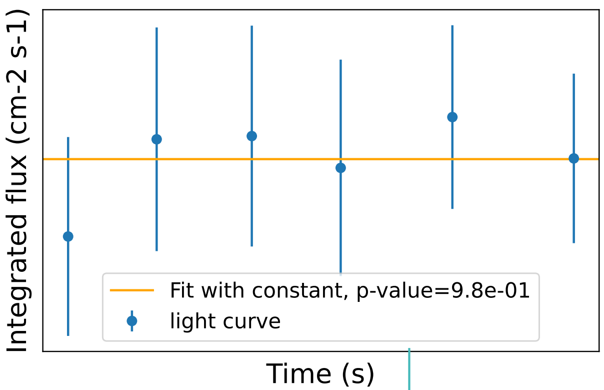


Several AGNs data of LST-1 from January 2021 to June 2023

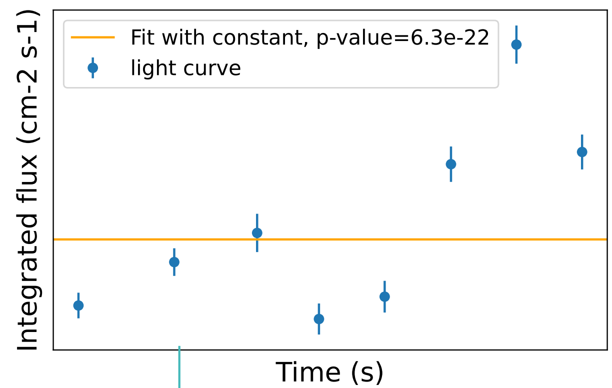
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample



Optimization of analysis cut

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

LIV analysis

Sample of simulations for calibration

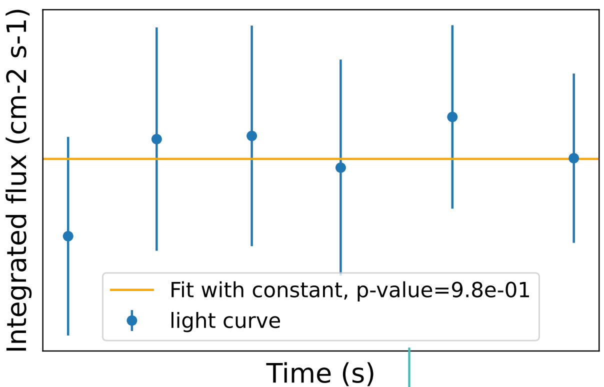
Analysis: step 8

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

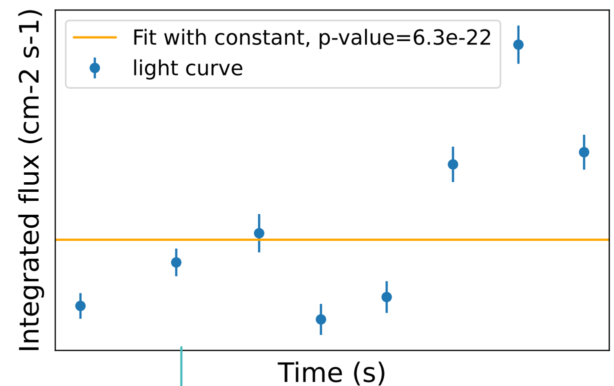
Variability test on each significant observation night

Constant fit
pvalue < 5σ

Non-variable sample



Variable sample



Optimization of analysis cut

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

LIV analysis

Sample of simulations for calibration

Application on real data

Step 8: Likelihood for real data

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

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

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

signal

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

baseline background

$$+W_\mathbf{h} \frac{dN_\mathbf{off}}{dE_R} \times \frac{1}{T} \times \frac{1}{N'_\mathbf{h}}$$

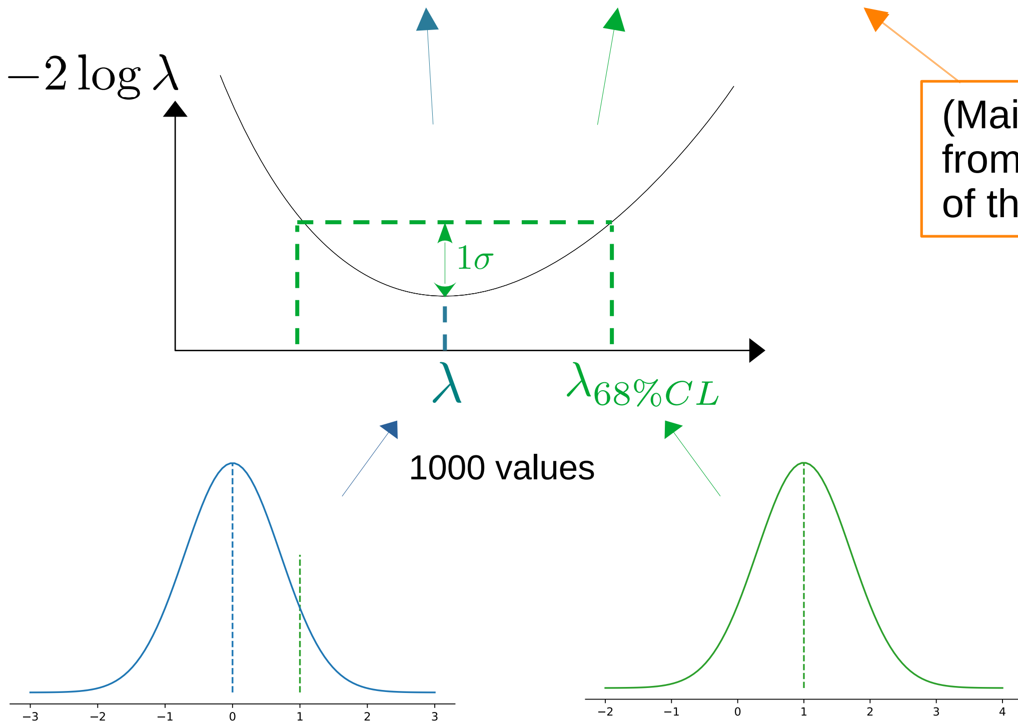
hadronic background

from reflected region background technique applied on real data

Step 8: LIV analysis on real data

Application on real data

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

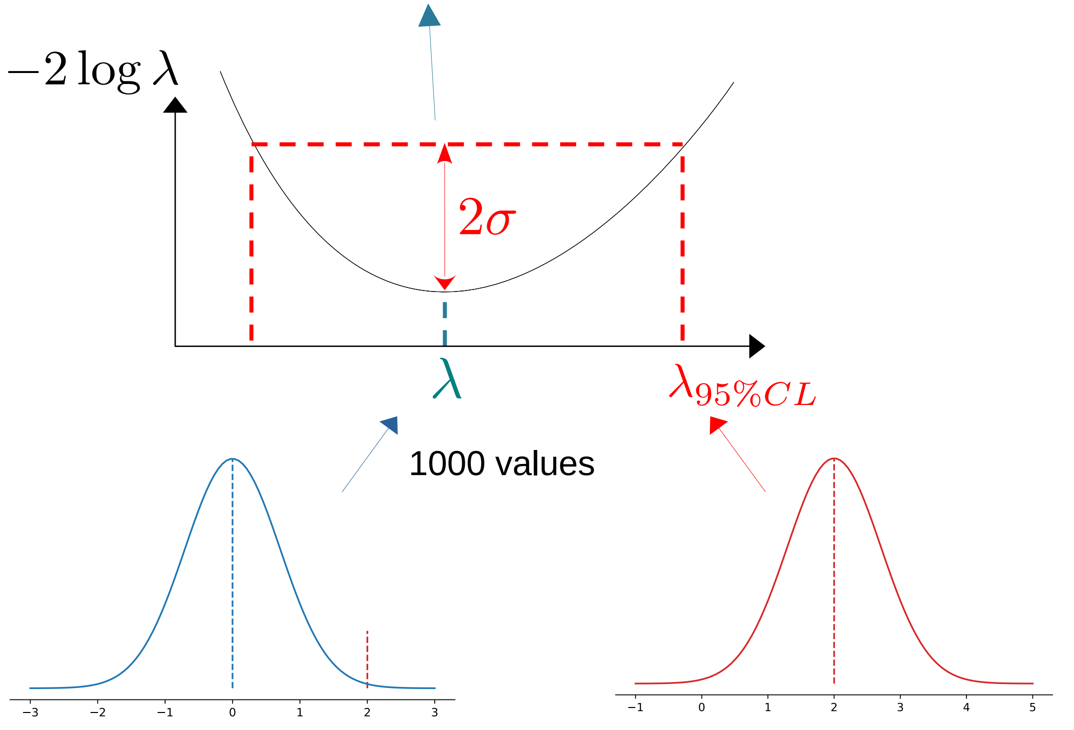


(Main) systematic error arising from the statistical uncertainty of the light curve template

Step 8: LIV analysis on real data

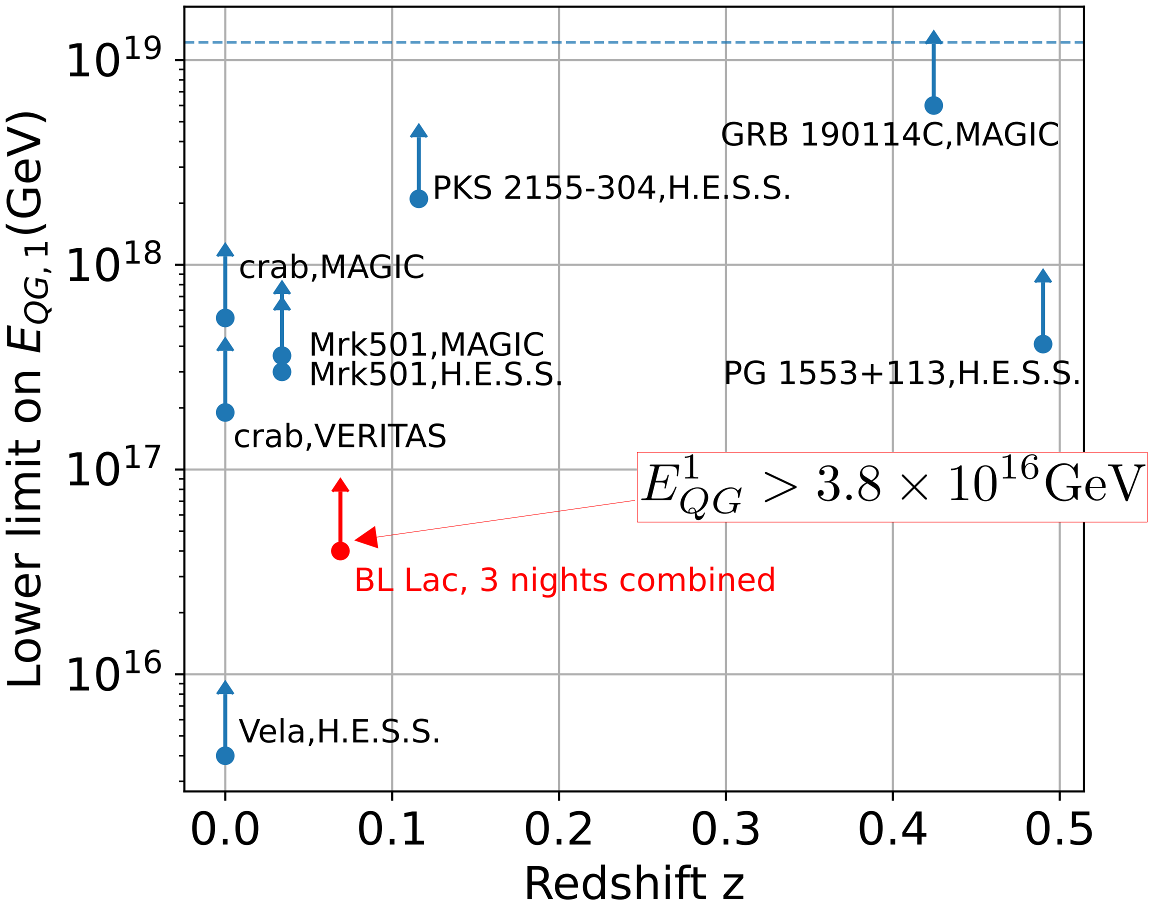
Application on real data

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



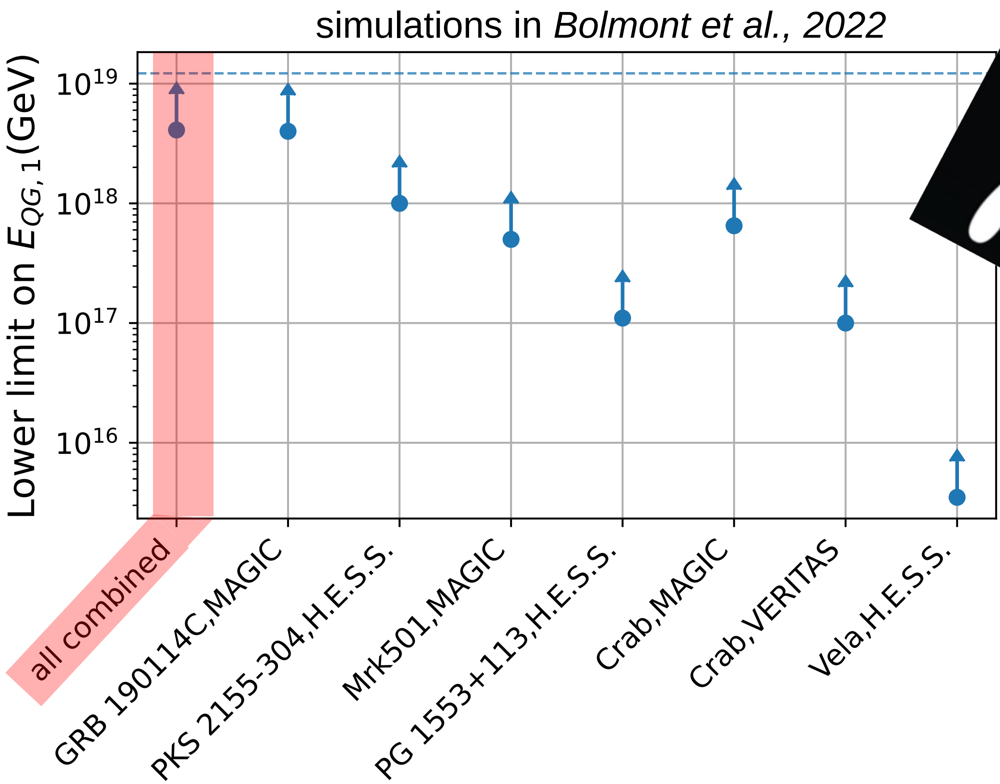
Use $\lambda_{1,95\%CL} = \pm \frac{n+1}{2H_0 E^1_{QG,lim}}$ to extract: $E^1_{QG} > 3.8 \times 10^{16}\,\mathrm{GeV}$

Comparison with other limits



Bolmont et al., 2022

$$\mathcal{L}_{\text{comb}}(\lambda_n) = \mathcal{L}_{H.E.S.S.}(\lambda_n) + \mathcal{L}_{MAGIC}(\lambda_n) + \mathcal{L}_{VERITAS}(\lambda_n)$$

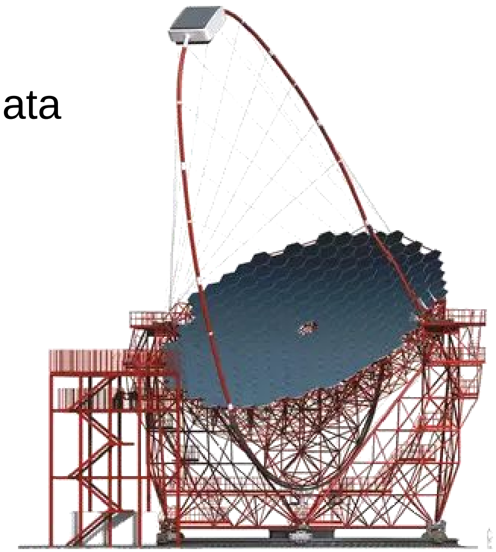


LIVelihood is ready for real data combination, including LST-1 data !

$$\mathcal{L}_{\text{comb}} = \mathcal{L}_{H.E.S.S.} + \mathcal{L}_{MAGIC} + \mathcal{L}_{VERITAS} + \mathcal{L}_{LST-1}$$

Conclusion

- Systematic analysis of several AGN from LST-1 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}^{1} using real data
- First analysis performing a combination of flares with Cherenkov telescope data



Ongoing work:

- Working on extended dataset and most recent data
- Implementation of all systematics (template, spectral index, background, energy scale, distance)
- $E_{QG,lim}$ for n=2 and various κ(z) models (used here *Jacob & Piran, 2008*)
- **Combination of LST-1 analysis with the γLIV WG data**

H.E.S.S. MAGIC VERITAS CTAO LST COLLABORATION

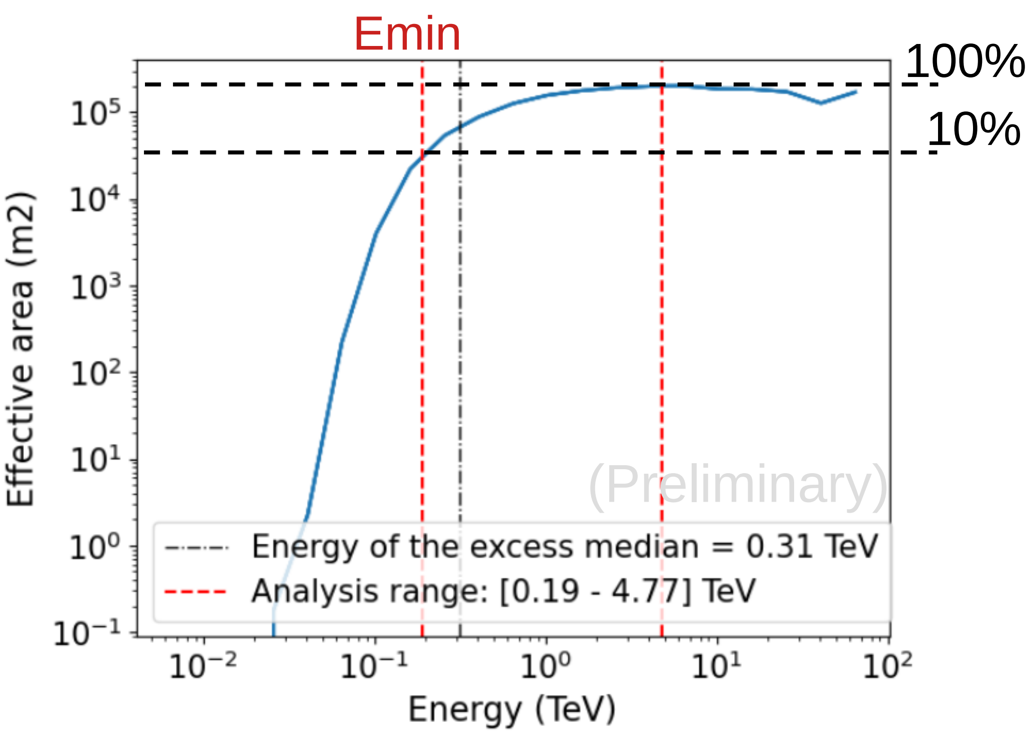
Backup

Step 1: Analysis energy ranges

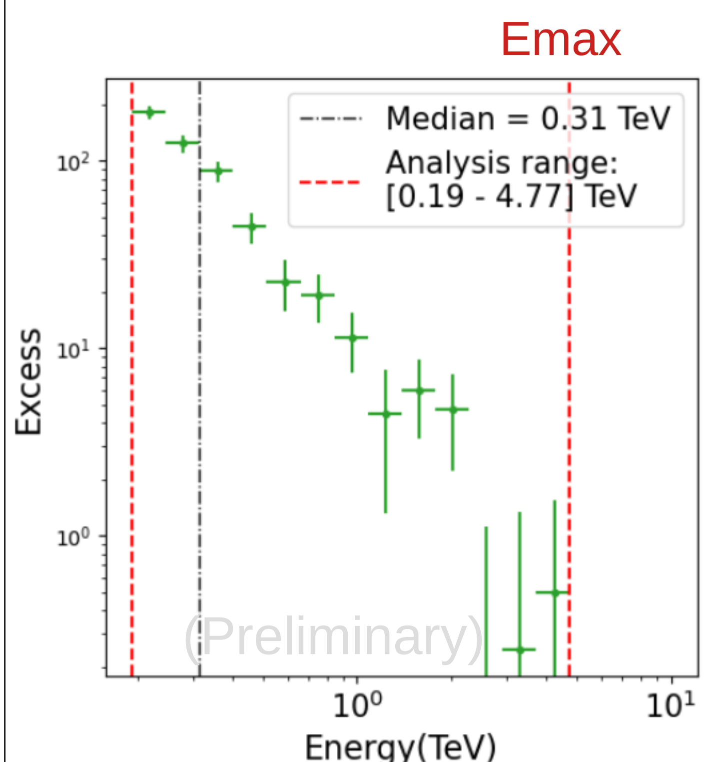
Night-wise energy ranges:

2021-08-08	2021-08-09	2022-10-20
[0.25 ; 4.8] TeV	[0.19 ; 4.8] TeV	[0.40 ; 7.7] TeV

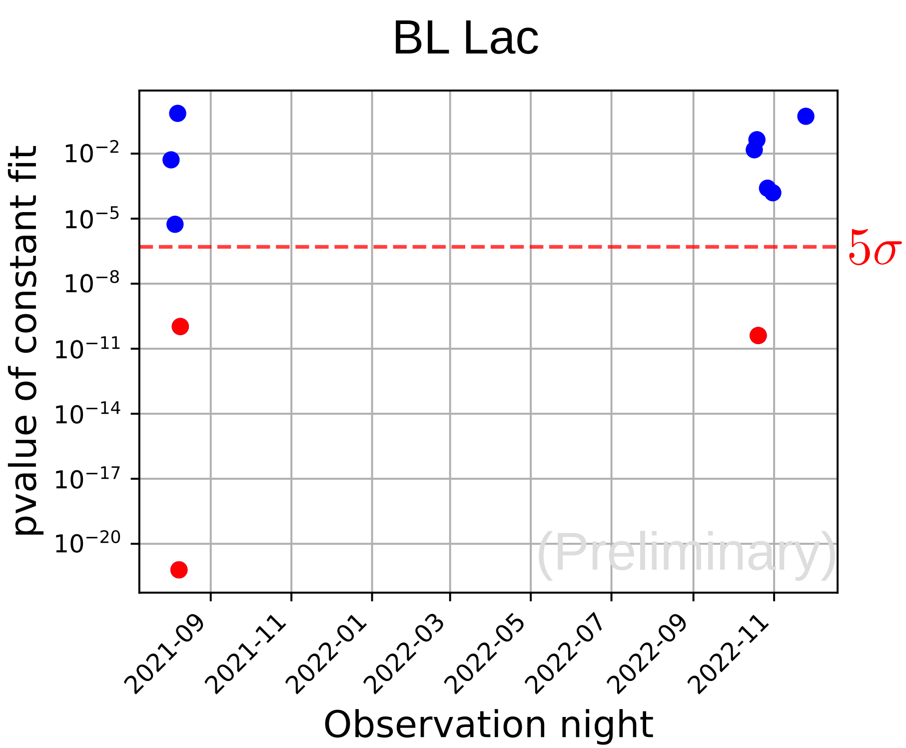
1. Apply a safe mask threshold of 10% of effective area for each run and keep most conservative values for the whole night

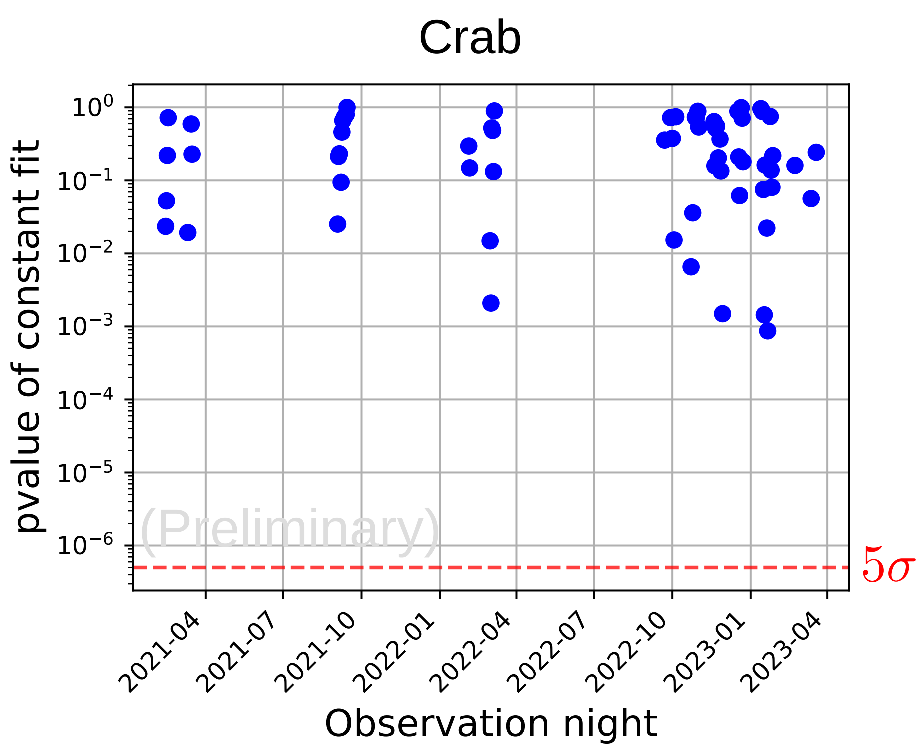


2. Keep the extrema non-zero energy bins of excess



crab is a stable source ↔ expecting 0 night with intra-night variability

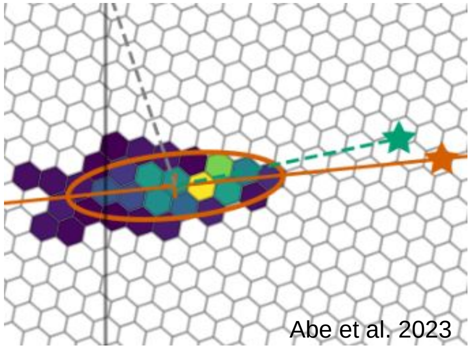


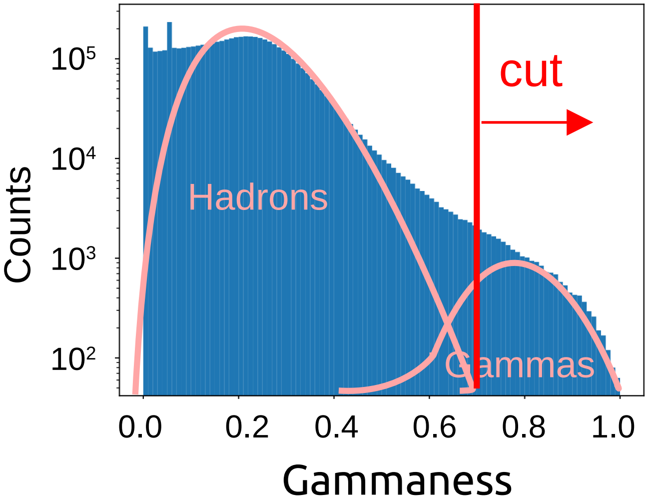


Non-variable sample

→

Optimization of gammaness cut





Reconstruction of event properties

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

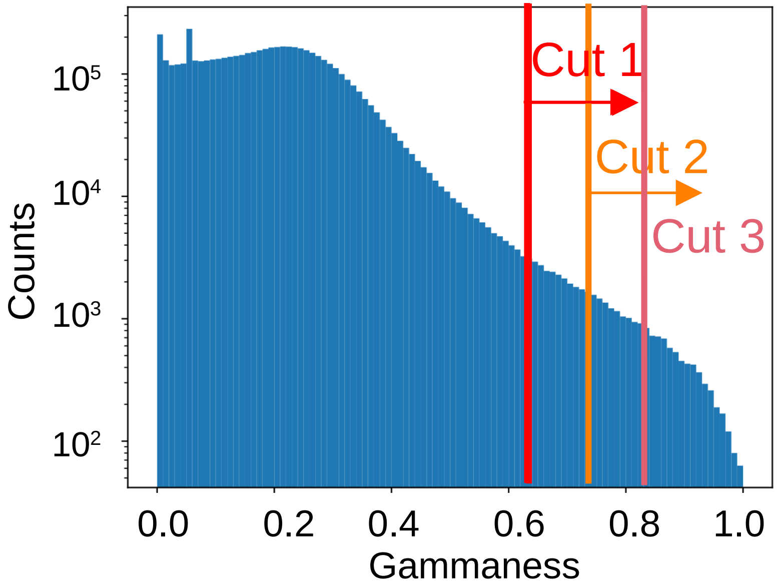
score of how likely an event is expected to be a gamma rather than background

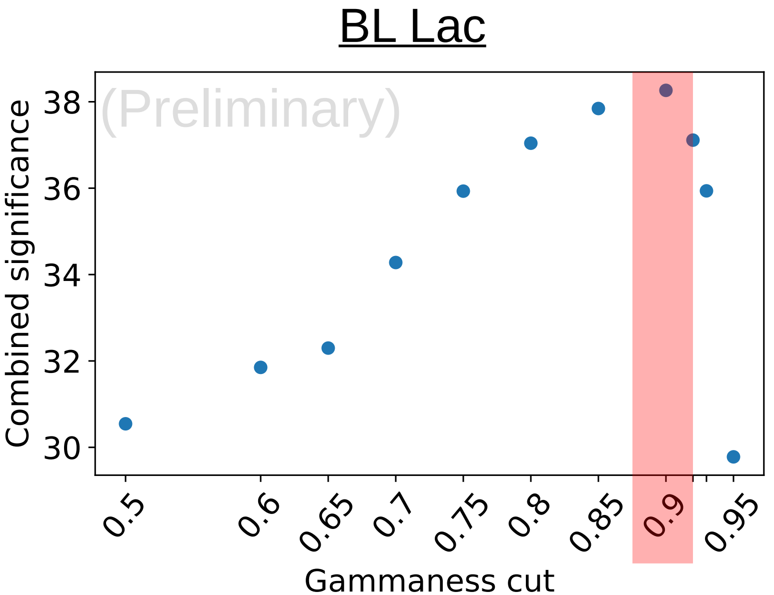
Step 3: cut optimization

Non-variable sample

↓

Select different gammaness cuts and search for the significance

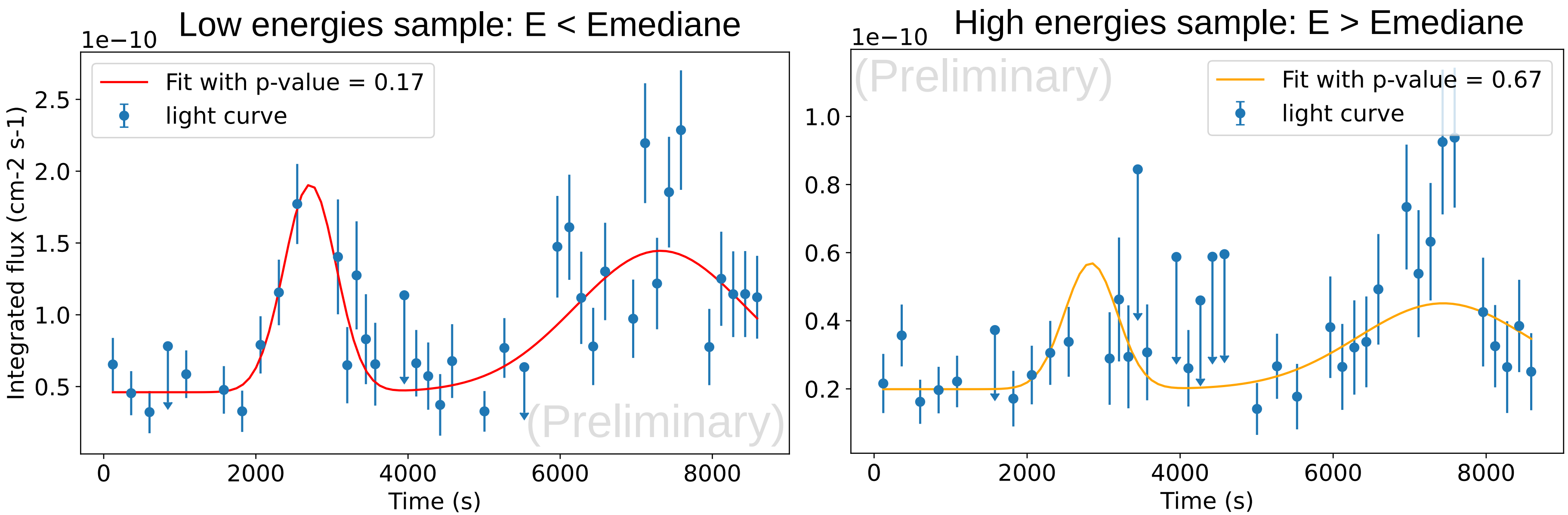




Given a source s and its sample of non-variable nights N_s: $S_{\text{s, cut}} = \sqrt{\sum_{n \in N_s} S_n^2}$

Step 5: Band comparison method

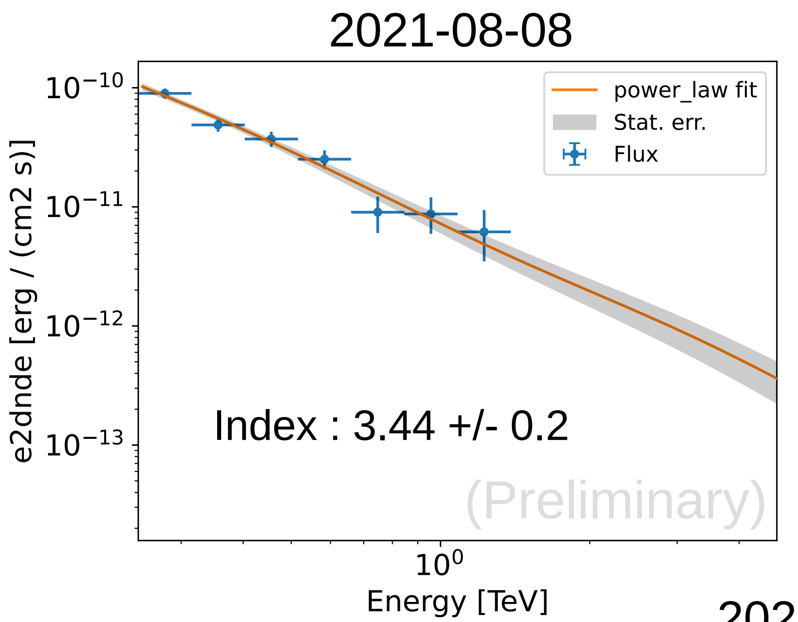
Example of 2021-08-08 night

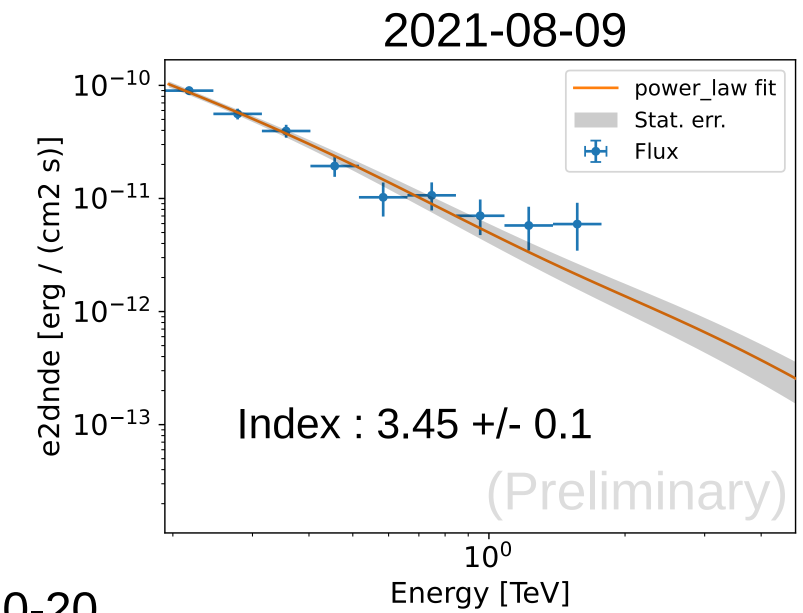


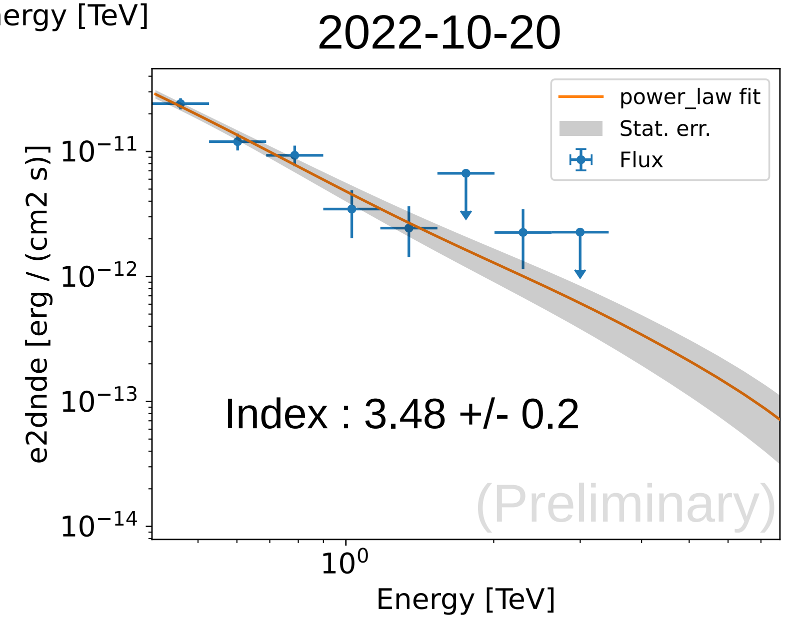
$$G_{LE}(t) = A_1 e^{\frac{(t-\mu_1)^2}{2\sigma_1{}^2}} + A_2 e^{\frac{(t-\mu_2)^2}{2\sigma_2{}^2}} + C_0 \quad G_{HE}(t) = (G_{LE}(t-\Delta t) - C_0) \times A + C$$

(Preliminary)	Energy range (TeV)	Median (TeV)	Delay Δt (s)	Delay significance (σ)
2021-08-08	[0.25 ; 4.8]	0.40	79±69	1.1
2021-08-09	[0.19 ; 4.8]	0.31	-136±397	0.3
2022-10-20	[0.40 ; 7.7]	0.69	-953±526	1.8

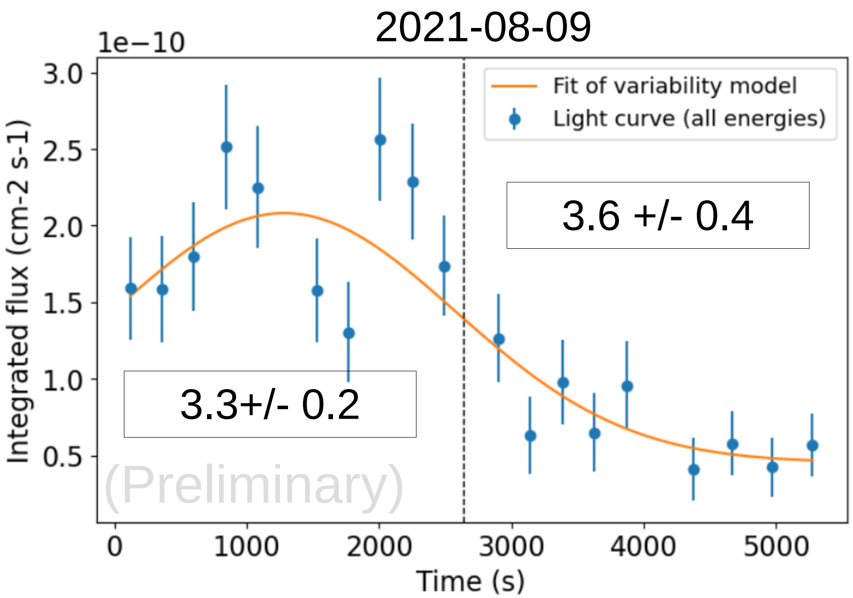
Step 5: Spectra fit

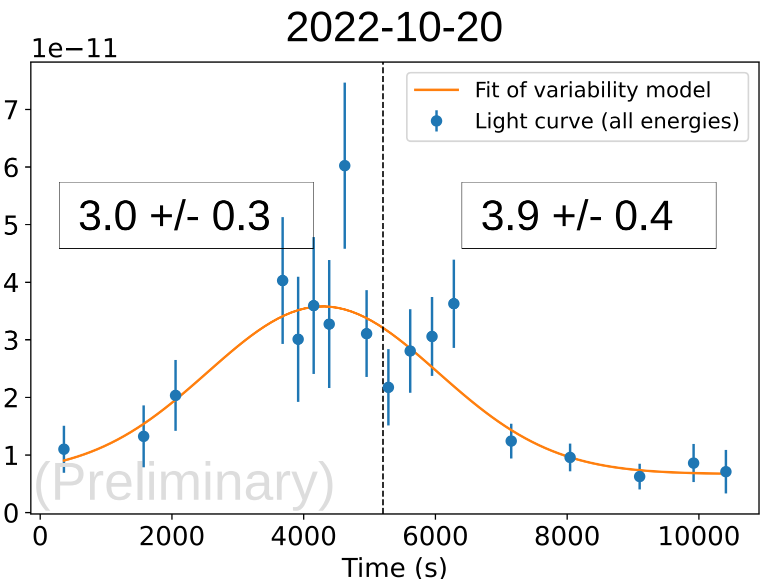


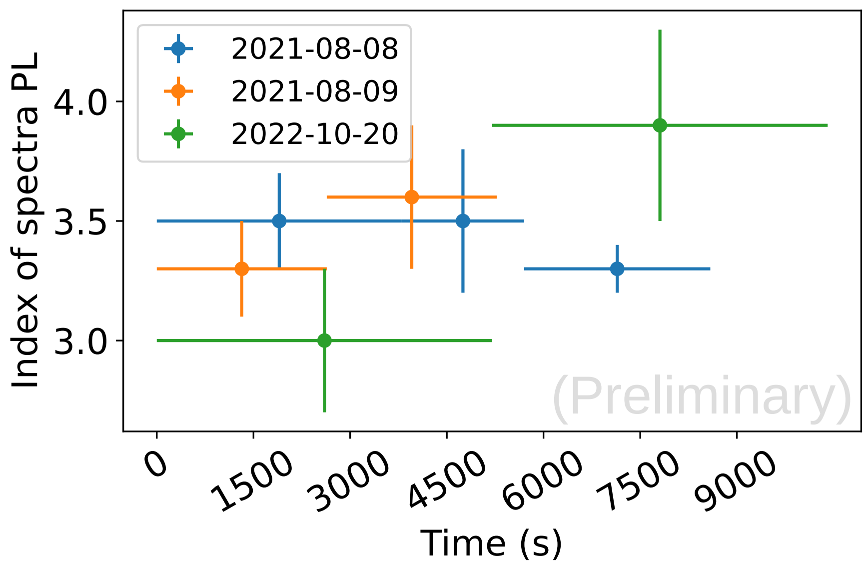




Step 5: Time-independency of spectra







for 2 given time bins j and k:

$$S = \frac{|\mathrm{index}_j - \mathrm{index}_k|}{\sqrt{\sigma_j^2 + \sigma_k^2}}$$

2021-08-08	2021-08-09	2022-10-20
1st - 2nd: 0.3σ 2nd - 3rd: 1.1σ 1st - 3rd: 1.0σ	0.9σ	2.2σ

(Preliminary)

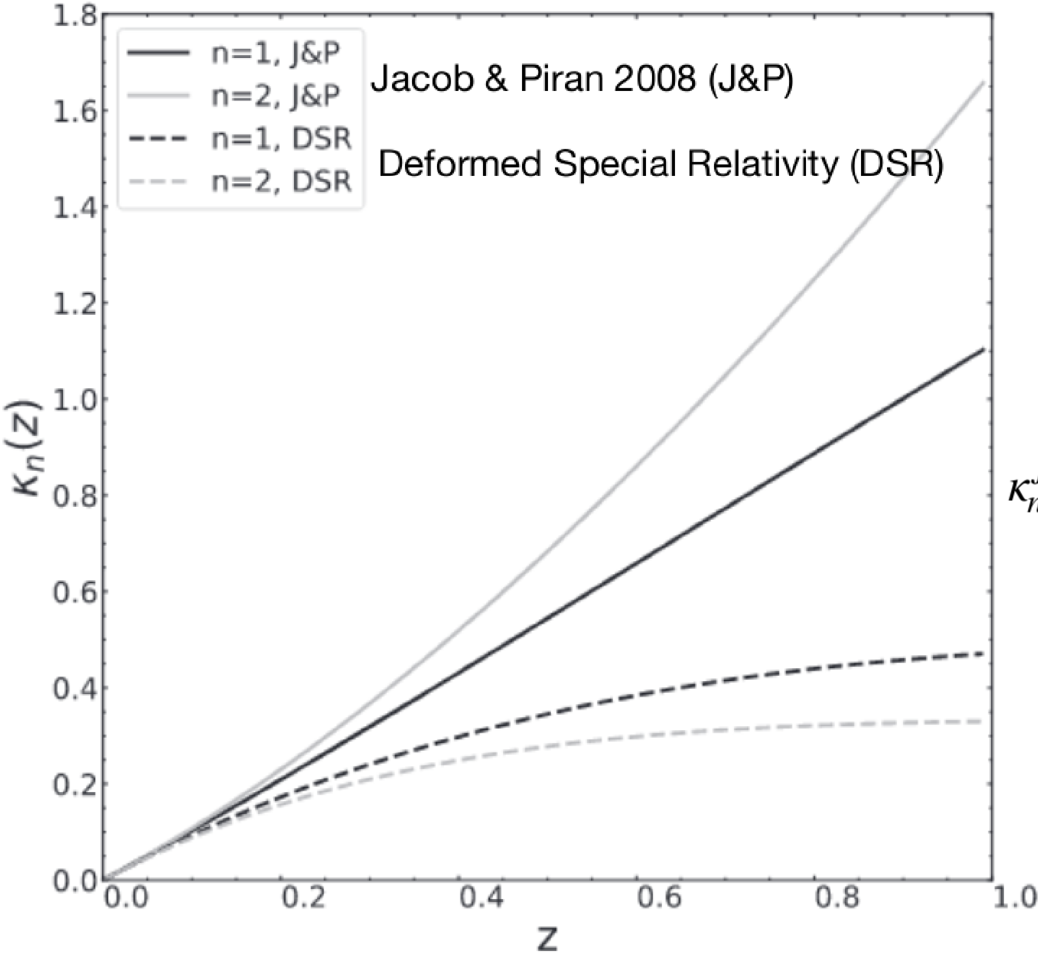
Ongoing: systematics

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

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

- $\vec{\theta}_C$: 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

Redshift correction



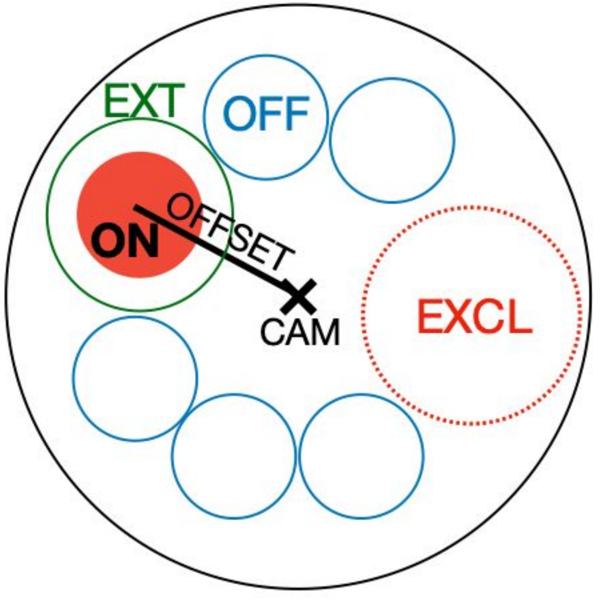
Bolmont et al 2022

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

Reflected region background technique

Hypothesis: radial symmetry of background 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



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