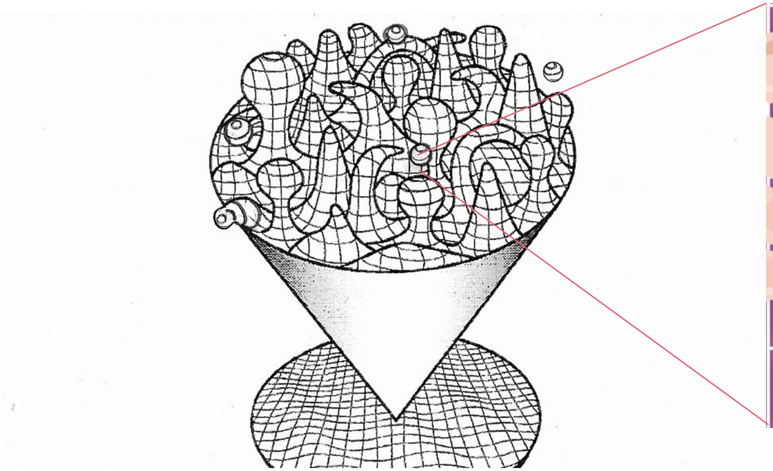
Disentangling intrinsic source effects from LIV ones in time-lag researches with VHE gamma-rays by combining data from various observatories

BrideQG Workshop – Feb. 2026

Cyann Plard for the γ-LIV working group

[See Julia’s and Tomislav’s contributions]



$(l_P \simeq 10^{-35}\ \mathrm{m})$

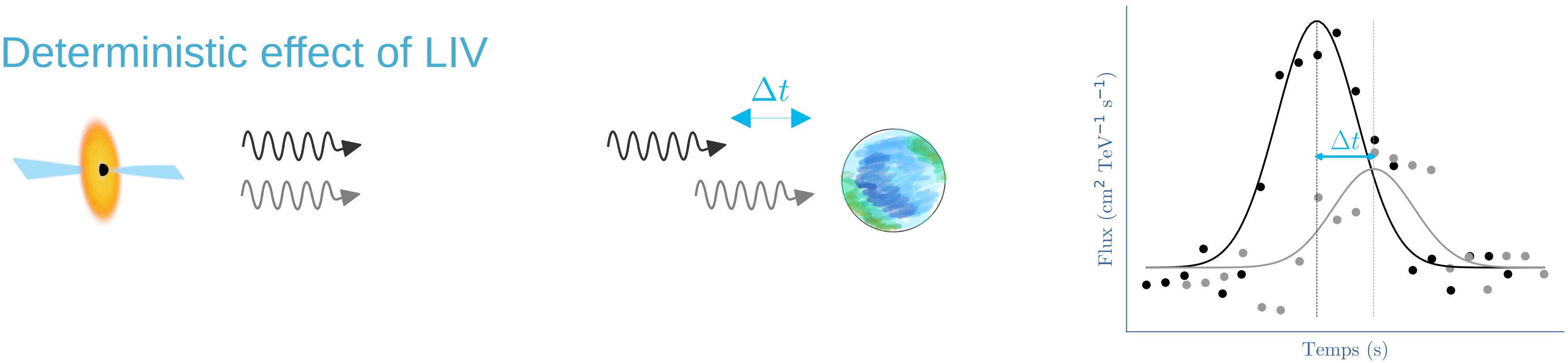
$(E_P \simeq 10^{19}\ \mathrm{GeV})$

$$E^2 = p^2c^2(1+\epsilon)$$

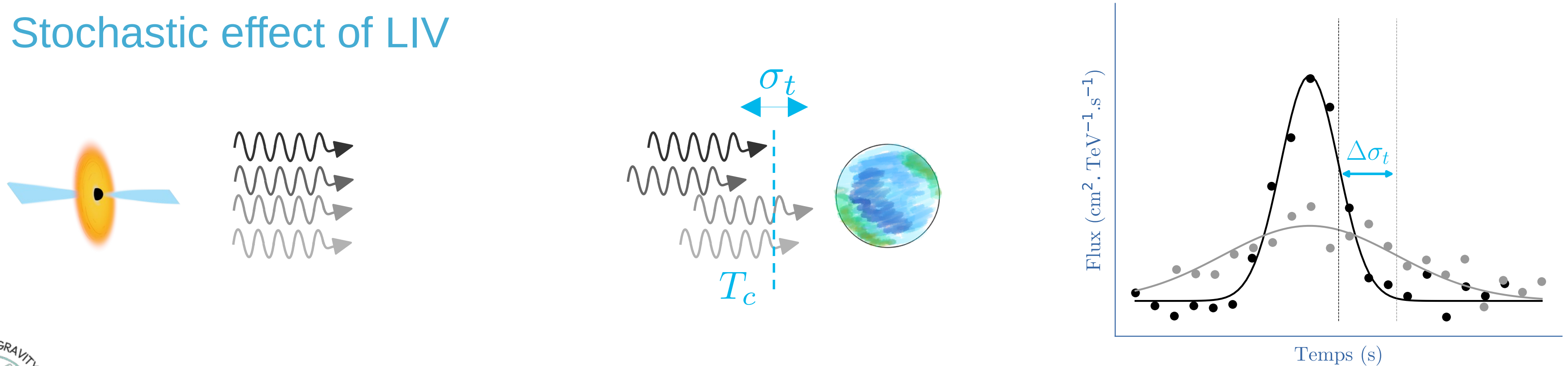
Modified dispersion relation of photons

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

Deterministic effect of LIV

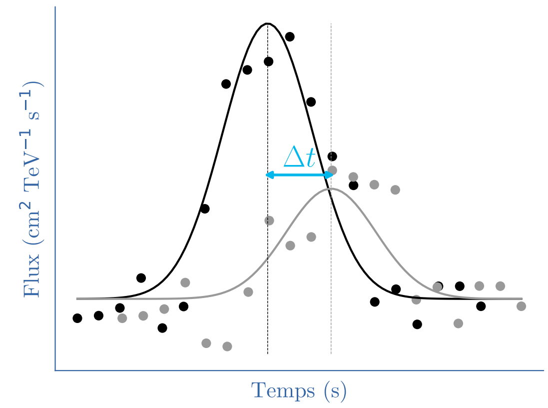


Stochastic effect of LIV



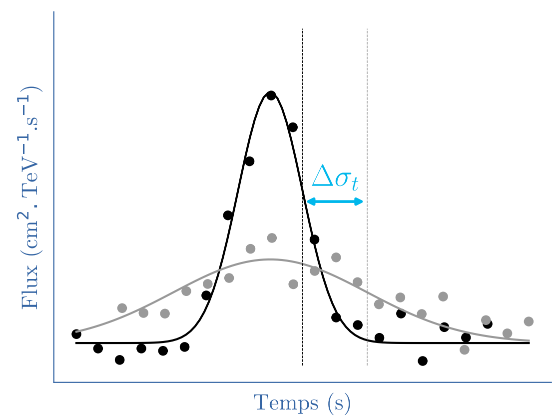
Time delays from LIV

Deterministic effect of LIV

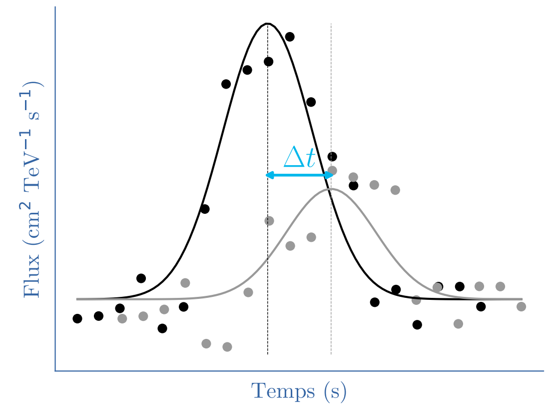


$$\Delta t_n \text{ or } \sigma_{t,n} = \pm \frac{n+1}{2} \frac{\Delta E^n}{{E_{\mathrm{LIV},n}}^n} \times \frac{\kappa_n(z)}{H_0}$$

Stochastic effect of LIV



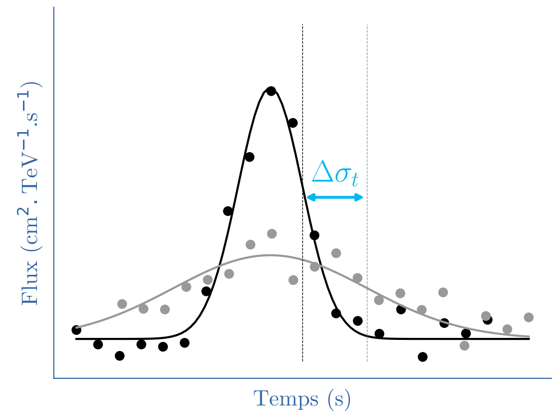
Deterministic effect of LIV



$$\Delta t_n \text{ or } \sigma_{t,n} = \pm \frac{n+1}{2} \frac{\Delta E^n}{{E_{\mathrm{LIV},n}}^n} \times \frac{\kappa_n(z)}{H_0}$$

No detection → constraint on minimal value of E_{LIV} at $n = 1$ and $n = 2$

Stochastic effect of LIV



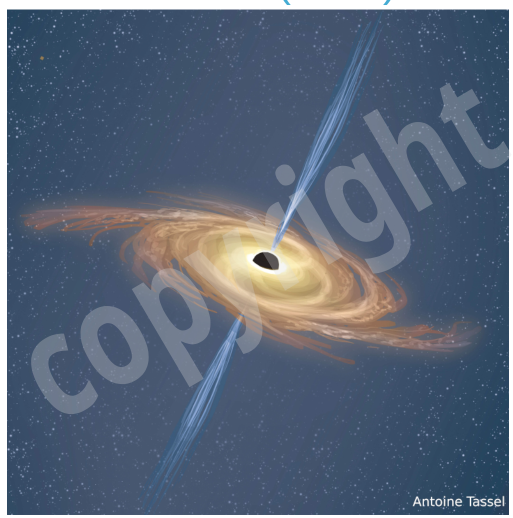
Choice of sources

Need:

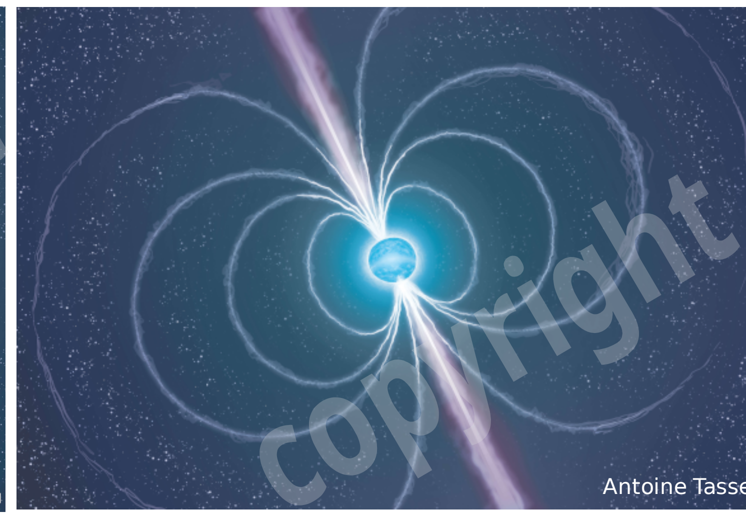
- VHE photons and large energy range
- Important flux
- Very high temporal variability of flux

Gamma-ray bursts

Blazars (AGN)

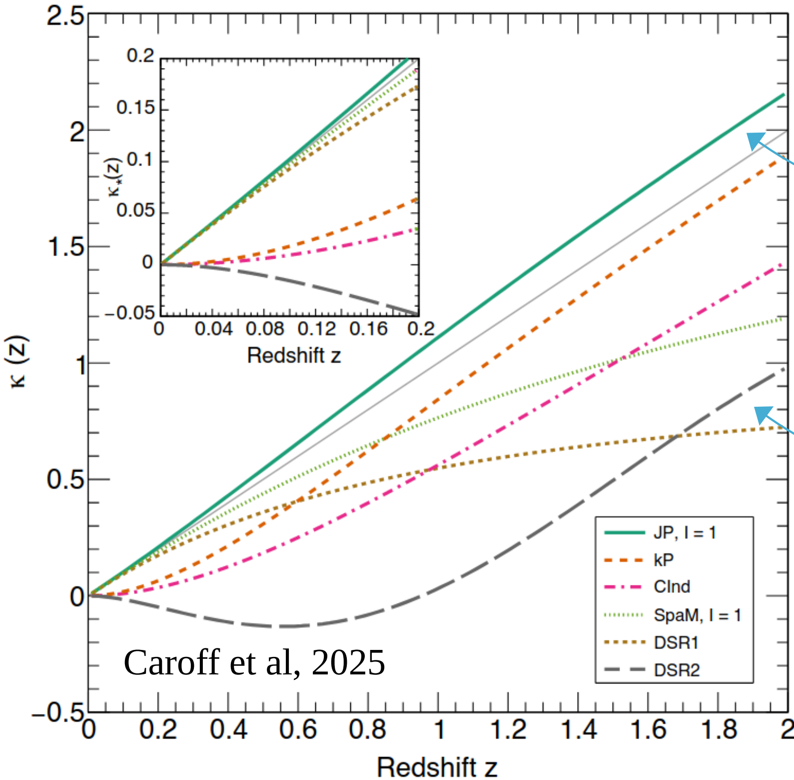


Pulsars



[See Julia’s and Tomislav’s contributions]

$$\Delta t_n \text{ or } \sigma_{t,n} = \pm \frac{n+1}{2} \frac{\Delta E^n}{E^n_{\mathrm{LIV},n}} \times \frac{\kappa_n(z)}{H_0}$$



$\kappa_n^{\mathrm{JP}}(z)$

Jacob & Piran, 2008

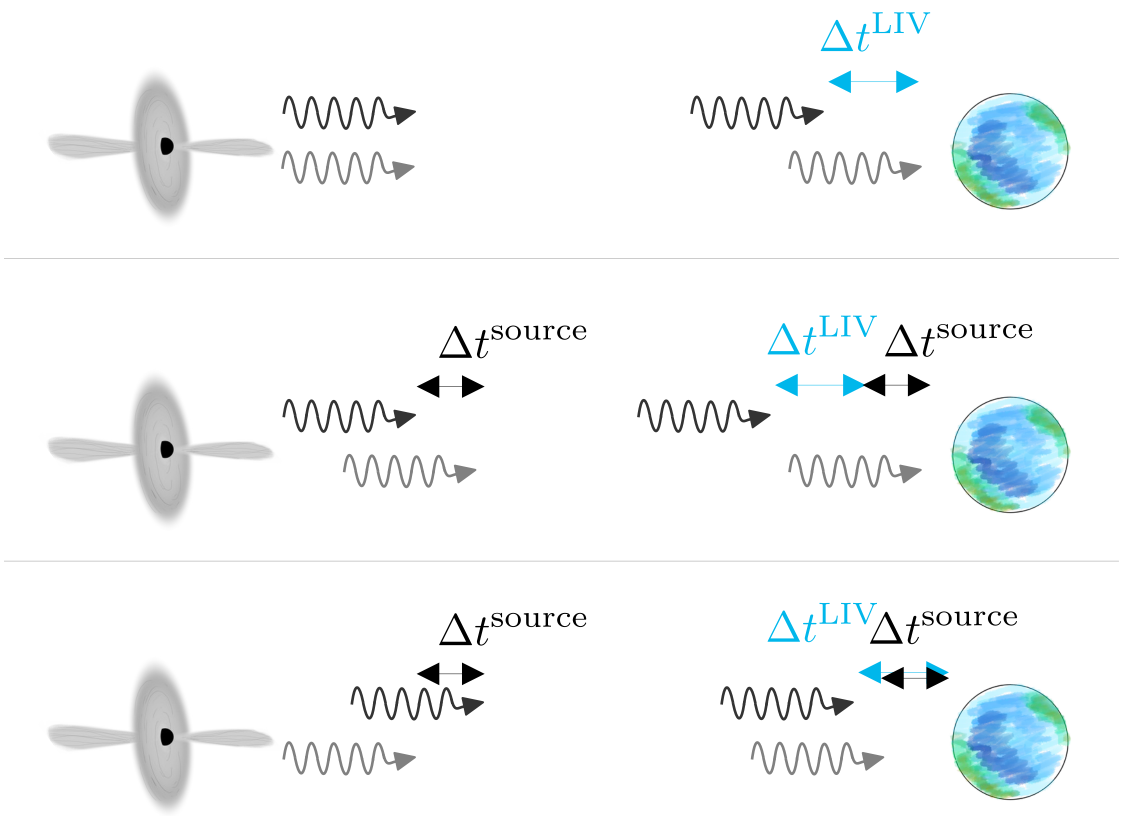
$\kappa_{n=1}^{\mathrm{DSR2}}(z, \alpha_1, \alpha_2, \alpha_3)$

Doubly special relativity
(3 free parameters)

Problem 1: Freedom of choice for propagation modelisation

→ need to combine data of sources distributed over a large range of redshift

No guarantee that photons are emitted at the same time



Problem 2: Intrinsic source delays may appear

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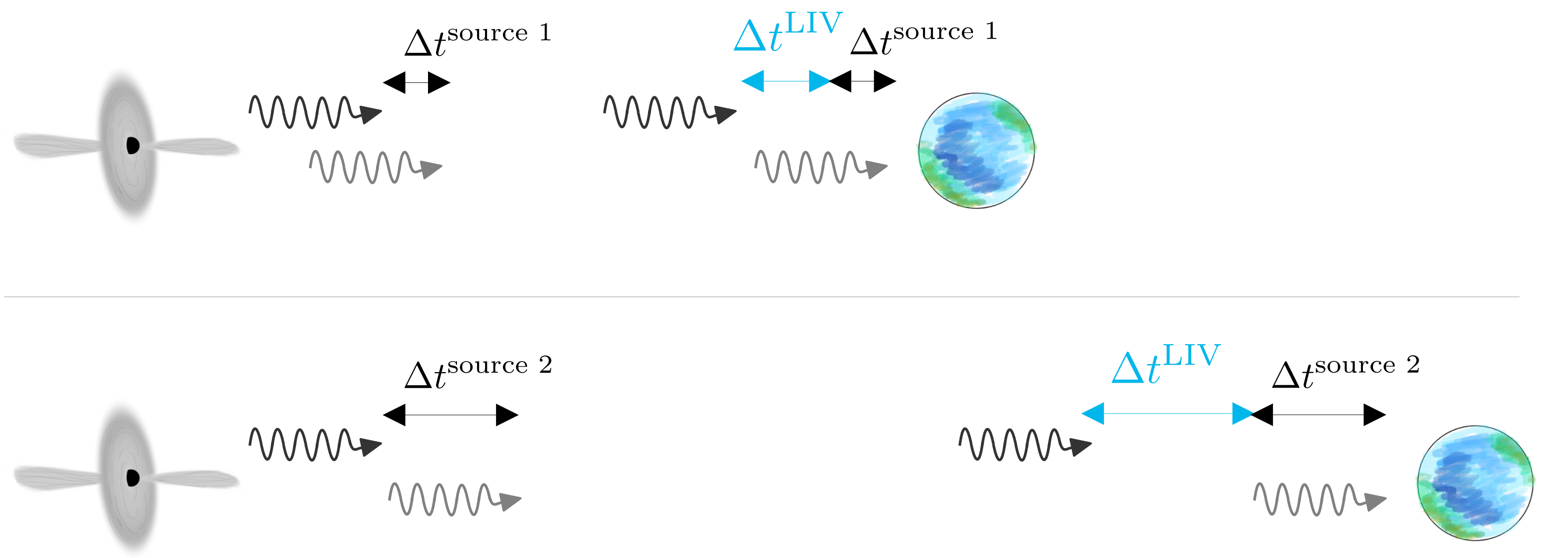


→ Source dependency: combination of various sources and various types of sources

→ Redshift dependency: combination of sources distributed over a large range of redshift

The γ-LIV working group

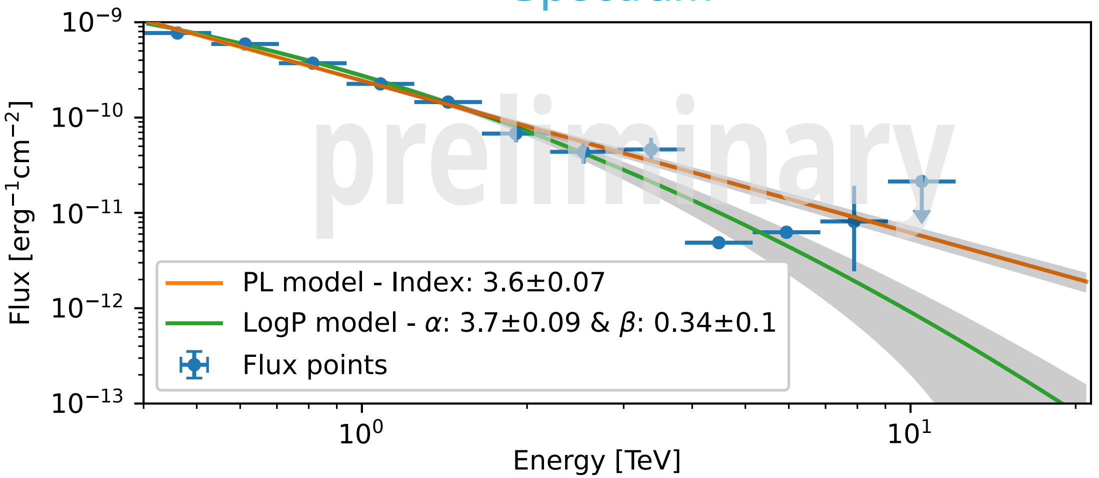
Problem 1: Freedom of choice for propagation modelisation

Problem 2: Intrinsic source delays may appear

Collaboration between 4 major
imaging atmospheric Cherenkov telescopes

[See Tomislav Terzic's contribution for IACT observation principle]

Spectrum

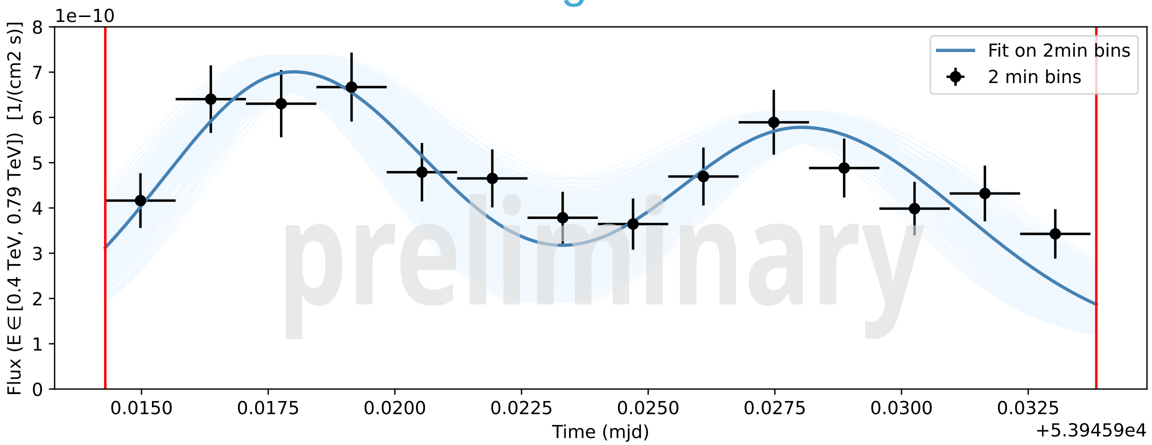


H.E.S.S. – 1 AGN flare

PKS 2155-304 (z=0,11610)

2006-07-29 – 0.5h

Lightcurve



[400 GeV ; 5 TeV]

Model: 2 gaussians

Ugo Pensec & Julien Bolmont, LPNHE – France (Ugo is now at univ. of Lodz – Poland)

MAGIC – 1 GRB

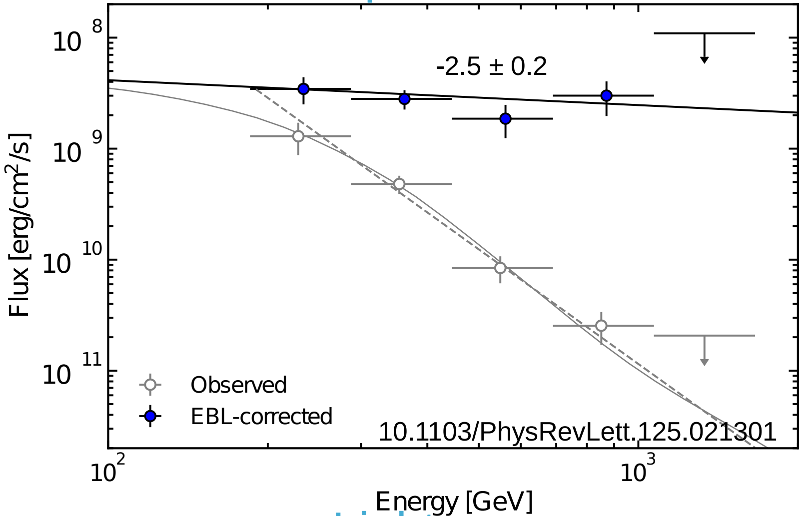
GRB 190114C (z=0,425)

2019-01-14 – 0.3h

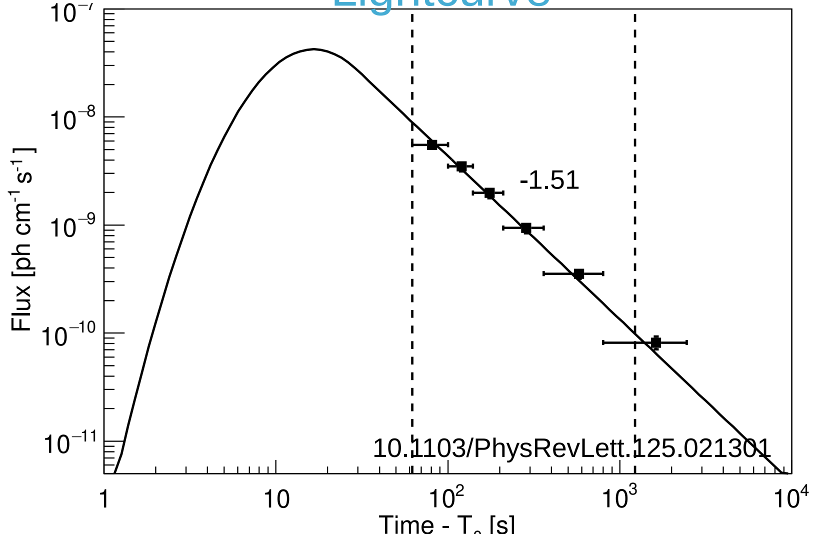
[300 GeV ; ~2 TeV]

Model: power law

Spectrum



Lightcurve

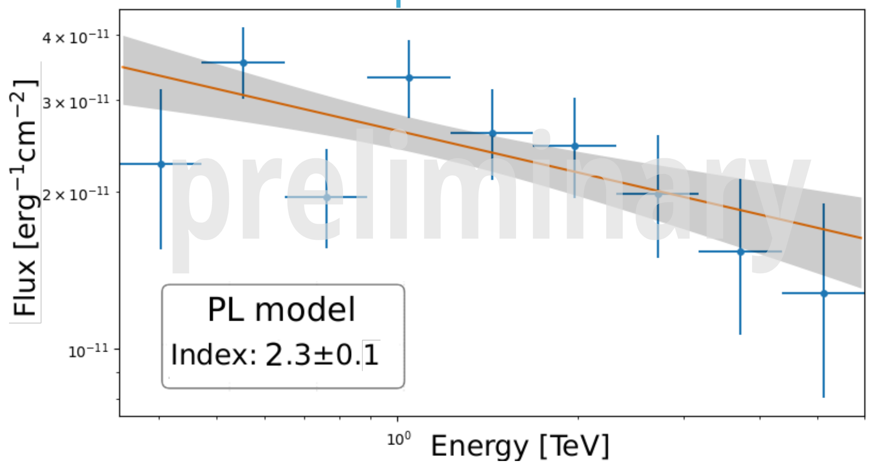


Data sample for LIV study

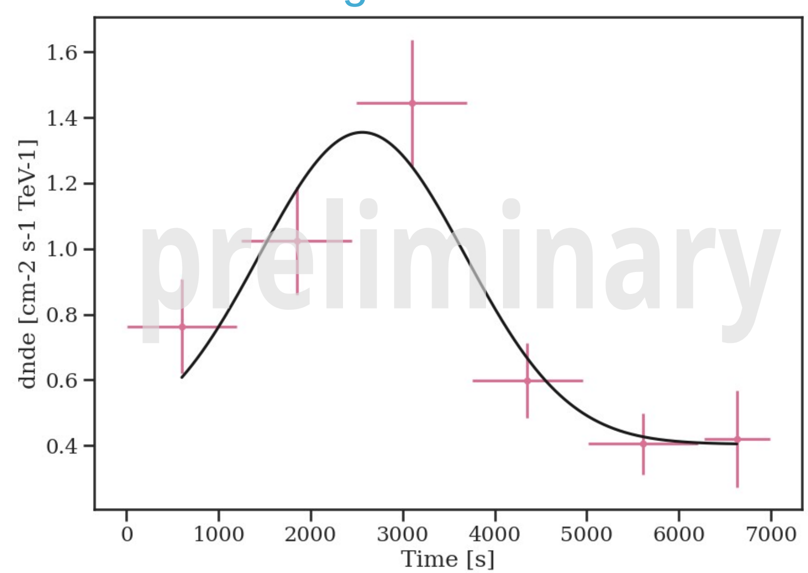
VERITAS – 1 AGN flare
1ES 1959+65 (z=0,047)
2021-05-20 – 1.8h

[250 GeV ; ~6 TeV]
Model: 1 gaussian

Spectrum



Lightcurve



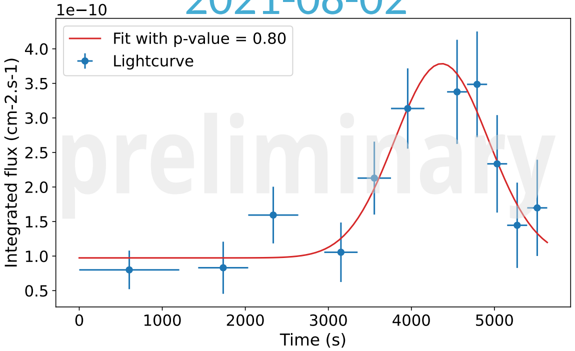
Samantha Wong, McGill univ. – Canada

LST-1 (CTAO) – 5 AGN flares
(from scan of all AGN data of LST-1)
BL Lacertae (z=0,069) – 10.6h

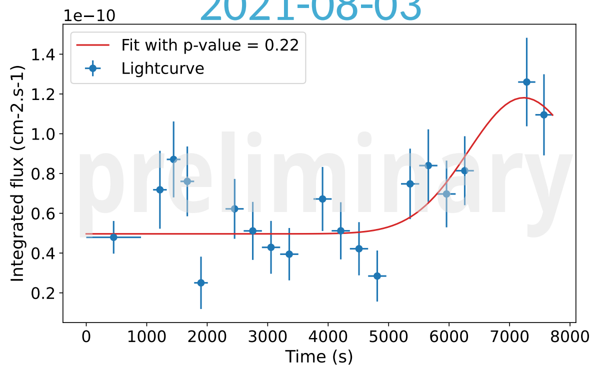
[only lightcurves are shown]

From 119 GeV to 3 TeV
Model: n gaussians

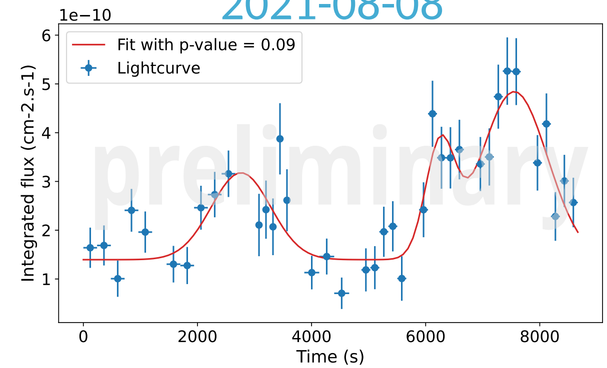
2021-08-02



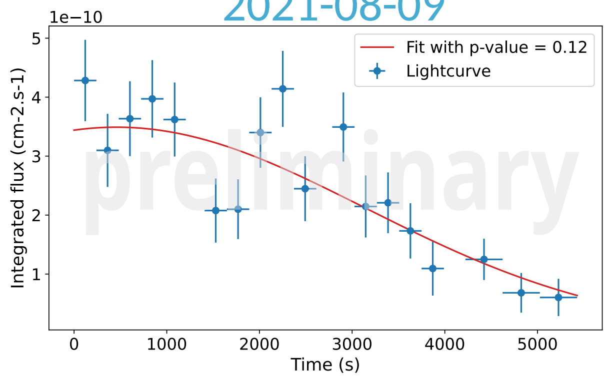
2021-08-03



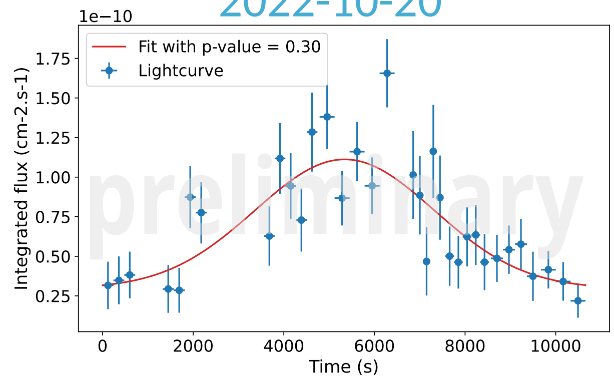
2021-08-08



2021-08-09



2022-10-20

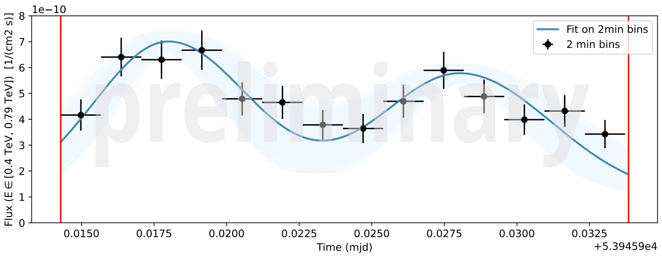


Cyann Plard & Sami Caroff – LAPP, France

Data sample for LIV study

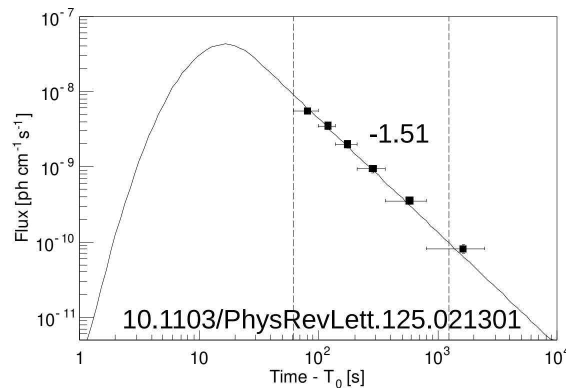
H.E.S.S.

1 AGN flare (z=0.11610)



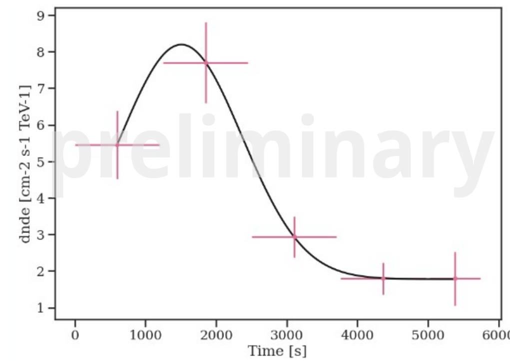
MAGIC

1 GRB (z=0.425)



VERITAS

1 AGN flare (z=0.047)

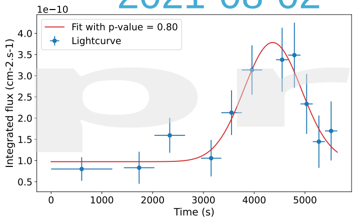


γ-LIV WG sample: 1 GRB + 7 AGN flares (4 different z)

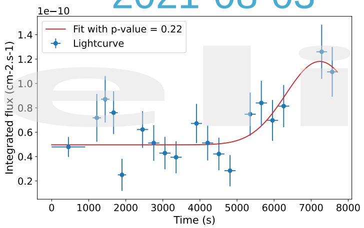
LST-1 (CTAO)

5 AGN flares (z=0.069)

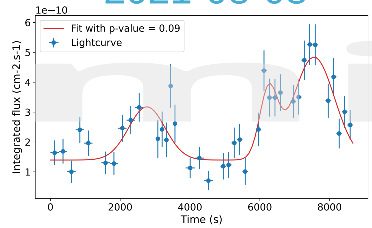
2021-08-02



2021-08-03



2021-08-08



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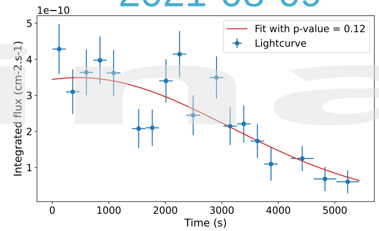
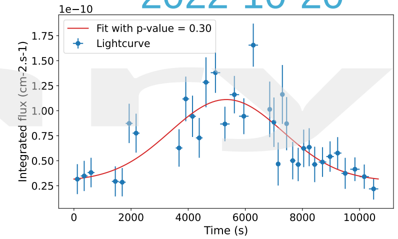


2022-10-20



Method: maximum likelihood

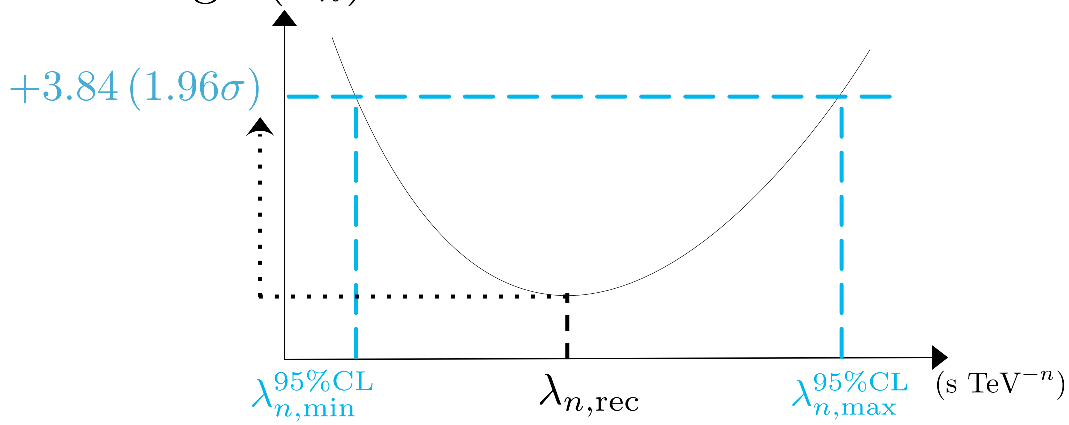
- Root C++
- Can analyse data of various observatories
- Maximisation of likelihood $\mathcal{L}(\lambda_n)$ by the *lateshift* λ_n
- Various types of simulations and analysis
- Takes into account:
  - Instrumental response functions (IRF)
  - Systematics

Method: maximum likelihood

Likelihood built from the PDF of detecting an event i at time t_i and energy E_i:

$$\mathcal{L}(\lambda_n) = \prod_i \frac{1}{\mathcal{L}_{i,0}} \times \frac{d^2 P}{dE_R dt}(E_{R,i}, t_i; \lambda_n)$$

$$L(\lambda_n) = -2 \log \mathcal{L}(\lambda_n)$$



$$\begin{array}{c}\lambda_{t,n} \\ \text{or} \\ \lambda_{\sigma,n}\end{array} = \frac{\Delta t_n \text{ ou } \sigma_{t,n}}{\Delta E^n \kappa_n(z)} = \pm \frac{n+1}{2H_0} \frac{1}{E_{\mathrm{LIV},n}{}^n}$$

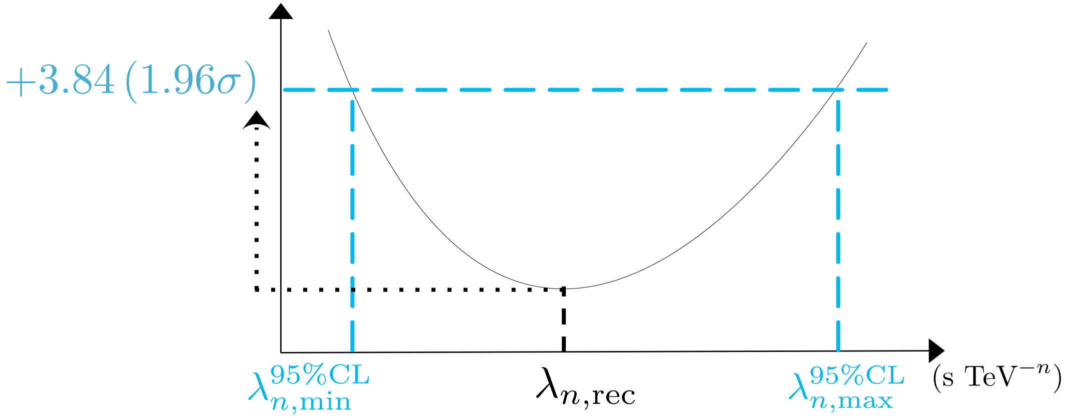
The log-likelihood $L(\lambda_n)$ is minimised by the *lateshift* λ_n

Method: maximum likelihood

Likelihood built from the PDF of detecting an event i at time t_i and energy E_i:

$$\mathcal{L}(\lambda_n) = \prod_i \frac{1}{\mathcal{L}_{i,0}} \times \frac{d^2P}{dE_R dt}(E_{R,i}, t_i; \lambda_n)$$

$$L(\lambda_n) = -2\log \mathcal{L}(\lambda_n)$$



Combination of N_s sources:

$$L_{\mathrm{comb}}(\lambda_n) = \sum_{n_s=1}^{N_s} L_{n_s}(\lambda_n)$$

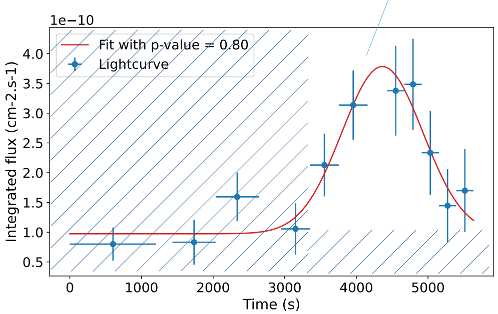
Method: building the likelihood

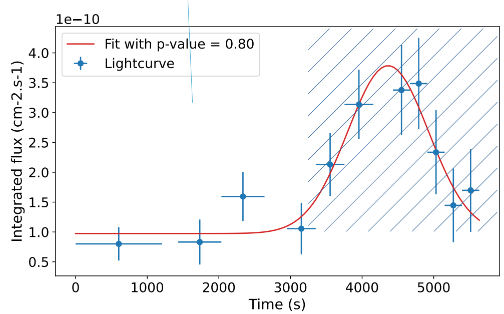
Likelihood built from the PDF of detecting an event i at time t_i and energy E_i:

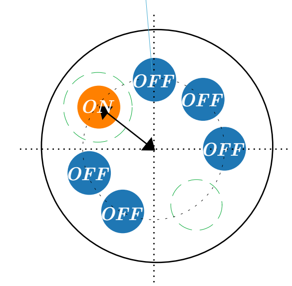
$$\mathcal{L}(\lambda_n) = \prod_i \frac{1}{\mathcal{L}_{i,0}} \times \frac{d^2P}{dE_R dt}(E_{R,i}, t_i; \lambda_n)$$

$$\frac{d^2P}{dE_R dt} = w_S \frac{d^2P_S}{dE_R dt}(E_{R,i}, t_i; \lambda_n) + w_B \frac{d^2P_B}{dE_R dt}(E_{R,i}, t_i) + w_H \frac{d^2P_H}{dE_R dt}(E_{R,i}, t_i)$$

Signal — Baseline background — Hadronic background







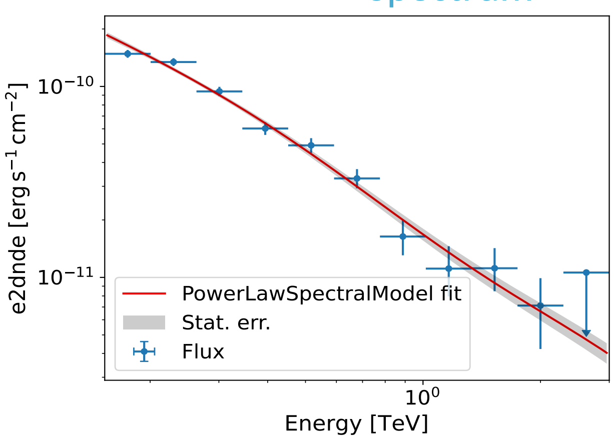
[estimated from specific regions in the field of view]

$$\frac{d^2P}{dE_Rdt} = \underbrace{w_S\frac{d^2P_S}{dE_Rdt}(E_{R,i},t_i;\lambda_n)}_{\text{Signal}} + w_B\frac{d^2P_B}{dE_Rdt}(E_{R,i},t_i) + w_H\frac{d^2P_H}{dE_Rdt}(E_{R,i},t_i)$$

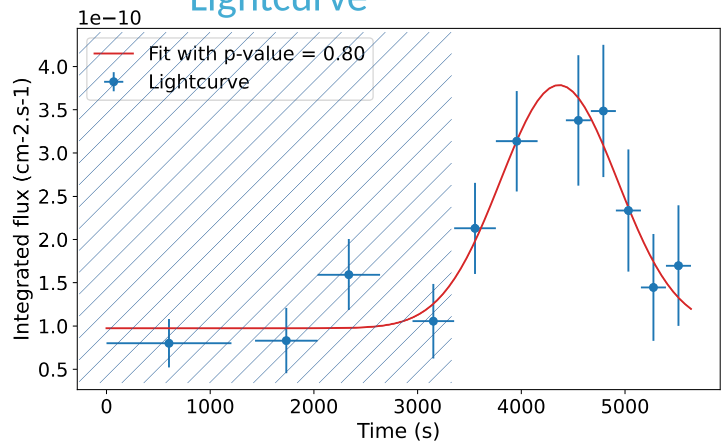
$$\int \Gamma_S^*(E_T)C_S^*(t)\mathcal{P}_{\text{LIV}}(t\rightarrow t')dt$$

Temporal propagator of LIV effects

Spectrum



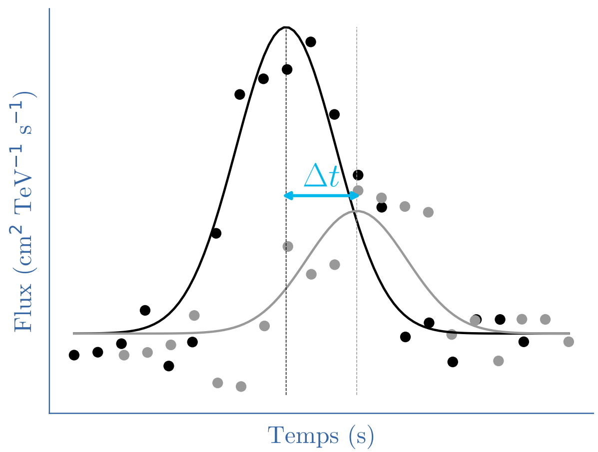
Lightcurve



LIVelihood

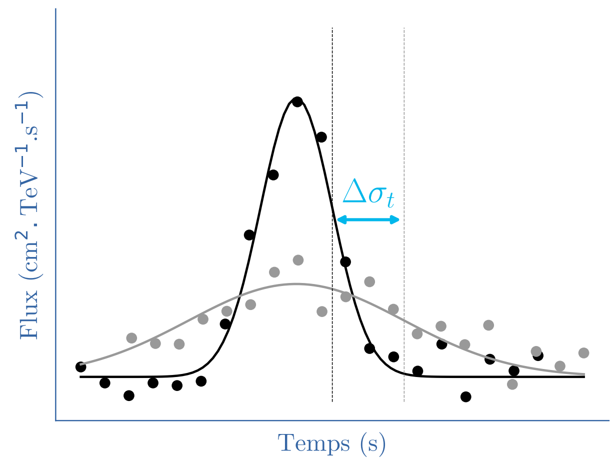
$$\int \Gamma_S^*(E_T) C_S^*(t) \mathcal{P}_{\mathrm{LIV}}(t \to t')dt$$

Temporal propagation of LIV effects results in:



"Deterministic" effect

$$C_S(t - \Delta t_n)$$



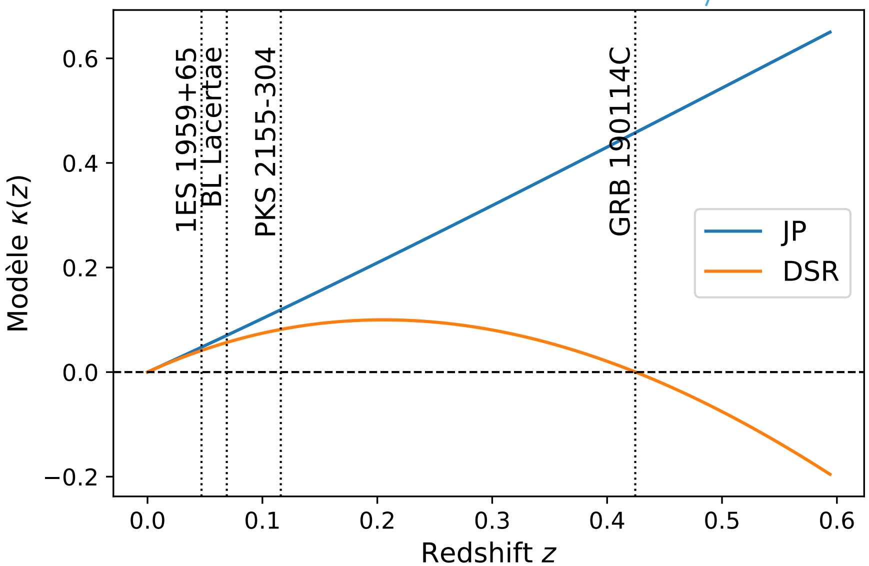
"Stochastic" effect

$$C_S(t; \lambda_{\sigma,n}) = \mathrm{Gauss}\left(\mu_S, \sqrt{\sigma_S^2 + {\sigma_t}^2}, A_S A_{\mathrm{LIV}}\right)$$

$$\lambda_n \times \kappa_n(z) \times E_T^n$$

Method: choice of $\kappa_n(z)$

$$\begin{matrix}\Delta t_n \\ \text{or} \\ \sigma_t\end{matrix} = \lambda_n \times \kappa_n(z) \times E_T^n$$



$\kappa_n^{\mathrm{JP}}(z)$

Jacob & Piran, 2008

$\kappa_{n=1}^{\mathrm{DSR2}}(z, \alpha_1, \alpha_2, \alpha_3)$

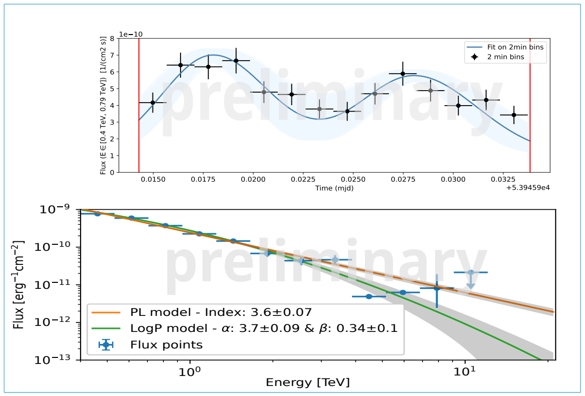
Doubly special relativity

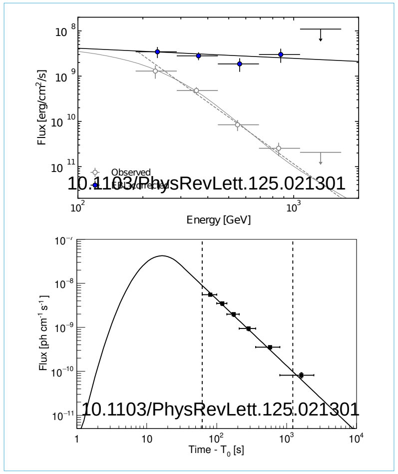
- Deterministic LIV: JP and DSR with choice of α to illustrate the impact of the modelisation
- Stochastic LIV: only JP and only with LST-1 data

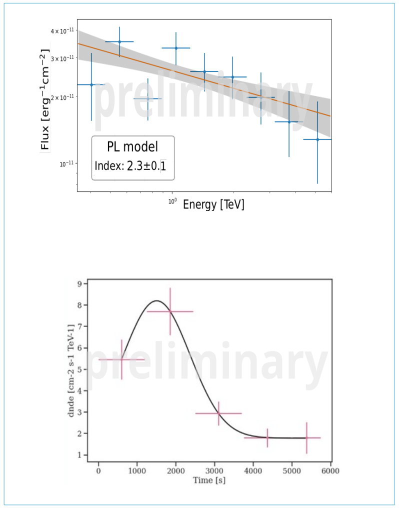
Method: simulations

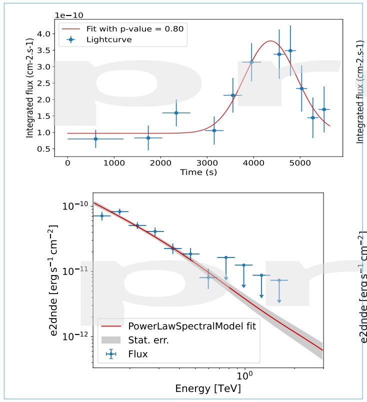
LIVelihood

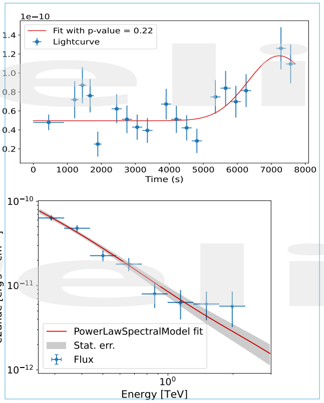
1000 simulations (of different types) of the dataset

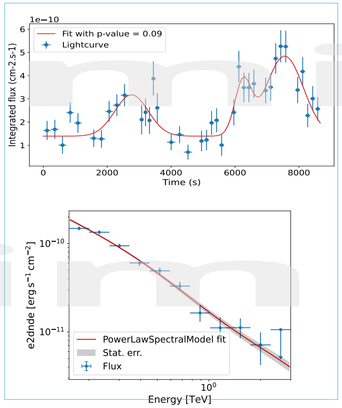


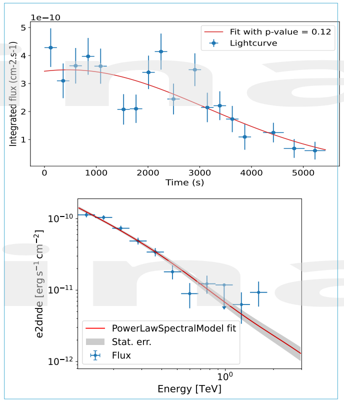


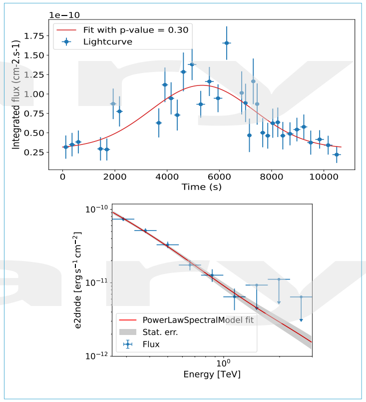








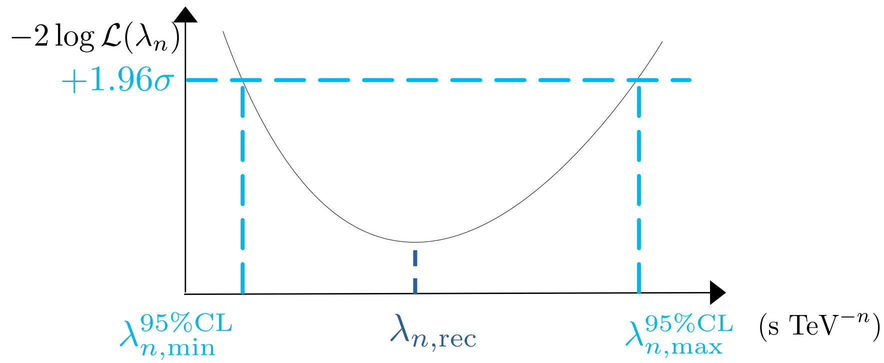




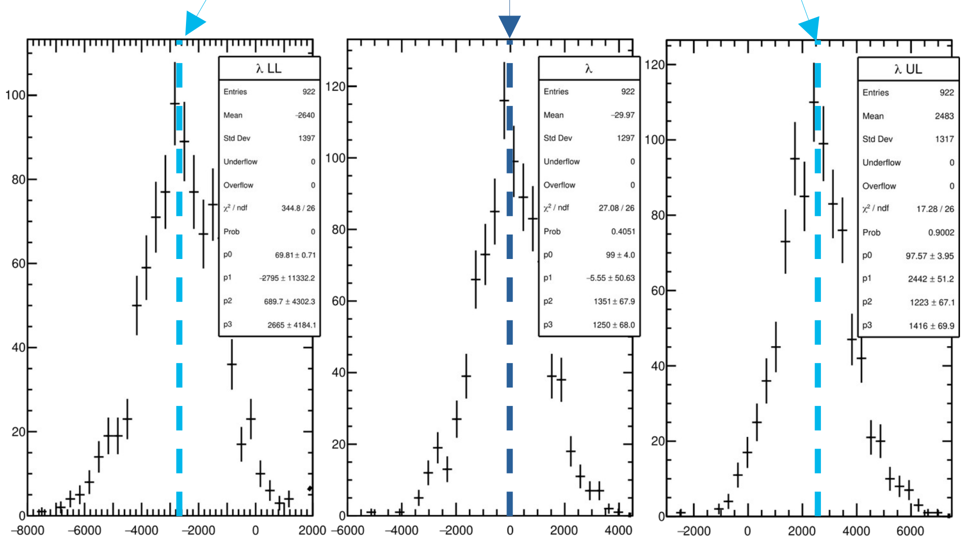
Method: simulations

1000 simulations (of different types) of the dataset

One log-likelihood minimisation per simulation

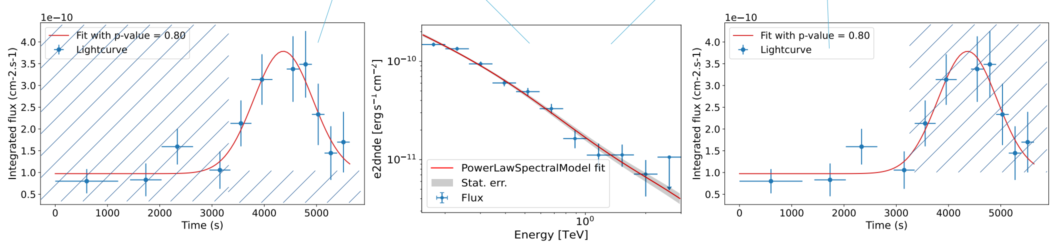


distribution of 1000 reconstructed lateshifts



1. Calibration – synthetic simulations with IRF

Simulations: Signal + Baseline background + Hadronic background



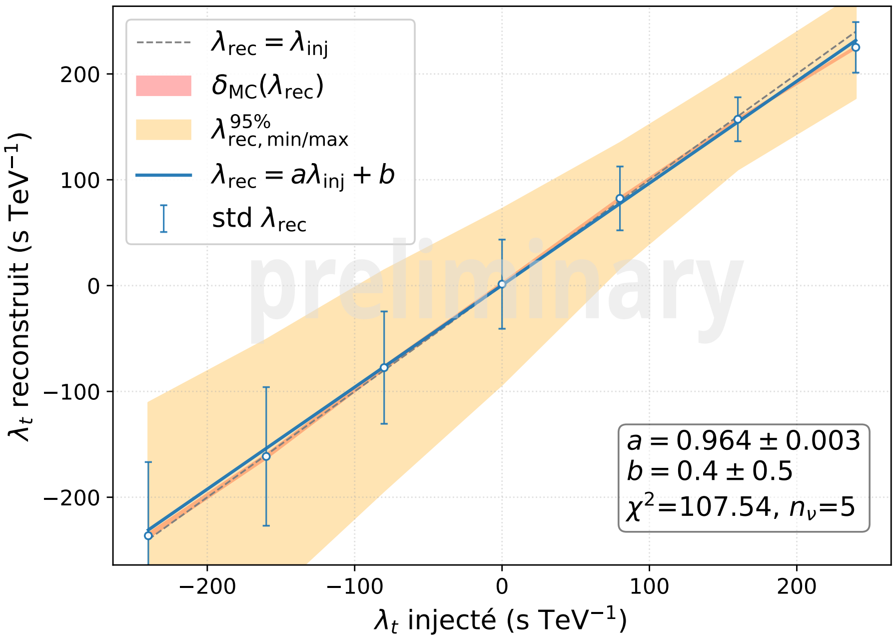
Power law with photon index $\alpha = 2.7$ (PhysRevLett.114.171103)

- Signal and baseline from data parametrisation
- "Theoretical" hadronic background
- IRF taken into account by convolution

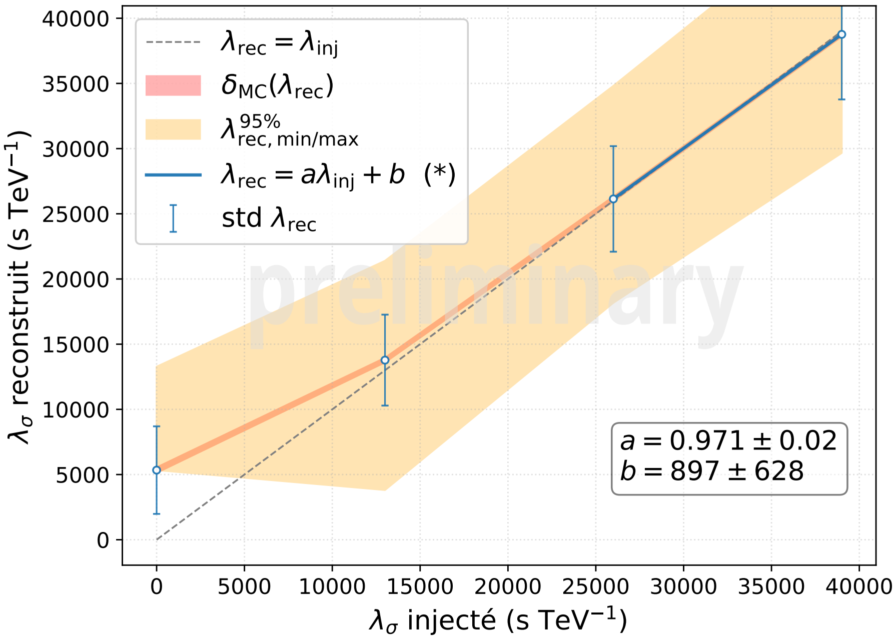
Artificial injection of lateshift

1. Calibration – synthetic simulations with IRF

Deterministic effect – γ-LIV WG data – $\kappa_{n=1}^{\mathrm{JP}}$



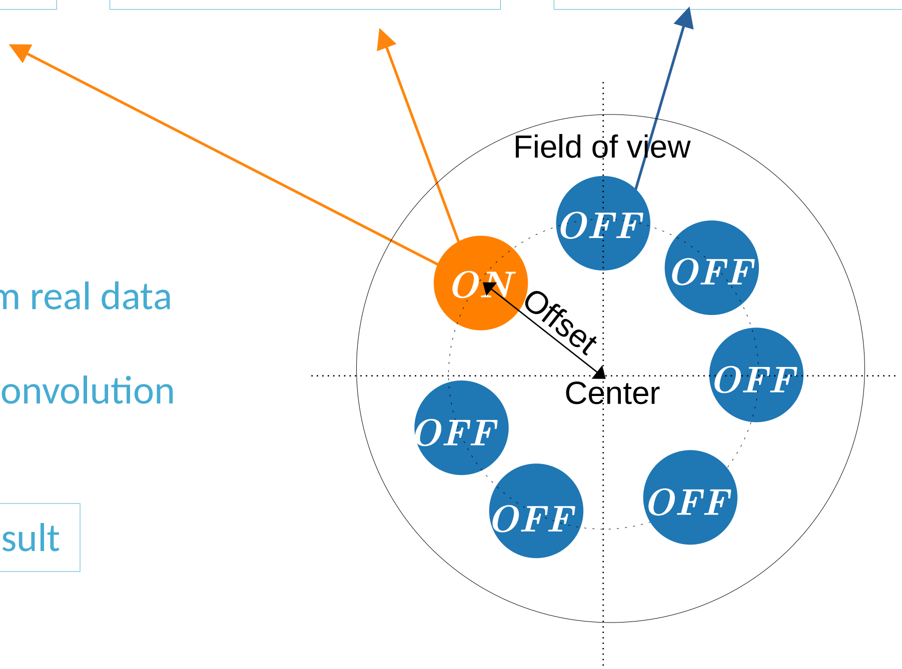
Stochastic effect – LST-1 data – $\kappa_{n=1}^{\mathrm{JP}}$



Method: simulations 2

1. Calibration – synthetic simulations with IRF
2. Lateshift extraction – Toy MC simulations

Simulations: Signal + Baseline background + Hadronic background



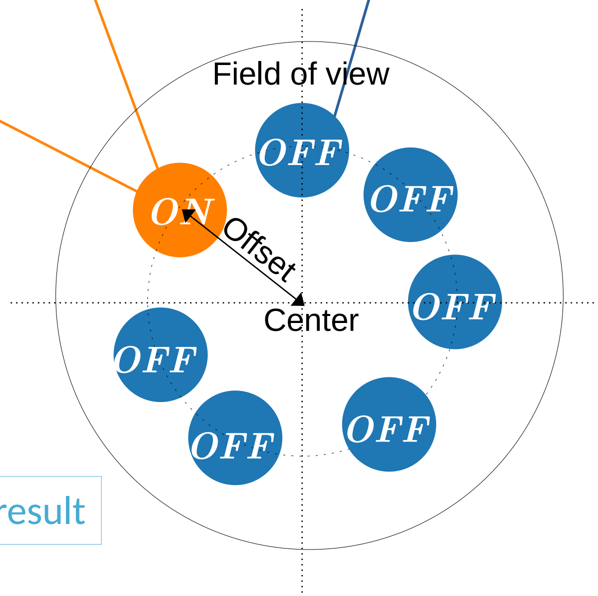
- Signal and background from real data
- IRF taken into account by convolution

Extraction of the result

Method: simulations 3

1. Calibration – synthetic simulations with IRF
2. Lateshift extraction – Toy MC simulations
3. Bias test – Toy MC boostrap simulations

Simulations: Signal + Baseline background + Hadronic background



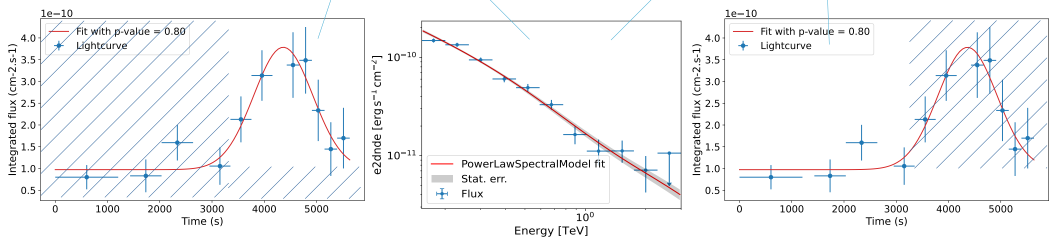
- Signal and background from real data
- IRF taken into account by convolution
- Shuffling of arrival time between events

Substraction of this reconstructed lateshift to the final result

LIVelihood

1. Calibration – synthetic simulations with IRF
2. Lateshift extraction – Toy MC simulations
3. Bias test – Toy MC boostrap simulations
4. Extraction of systematics – synthetic simulations "template free"

Simulations: Signal + Baseline background + Hadronic background



Power law with photon index
$\alpha = 2.7$ (PhysRevLett.114.171103)

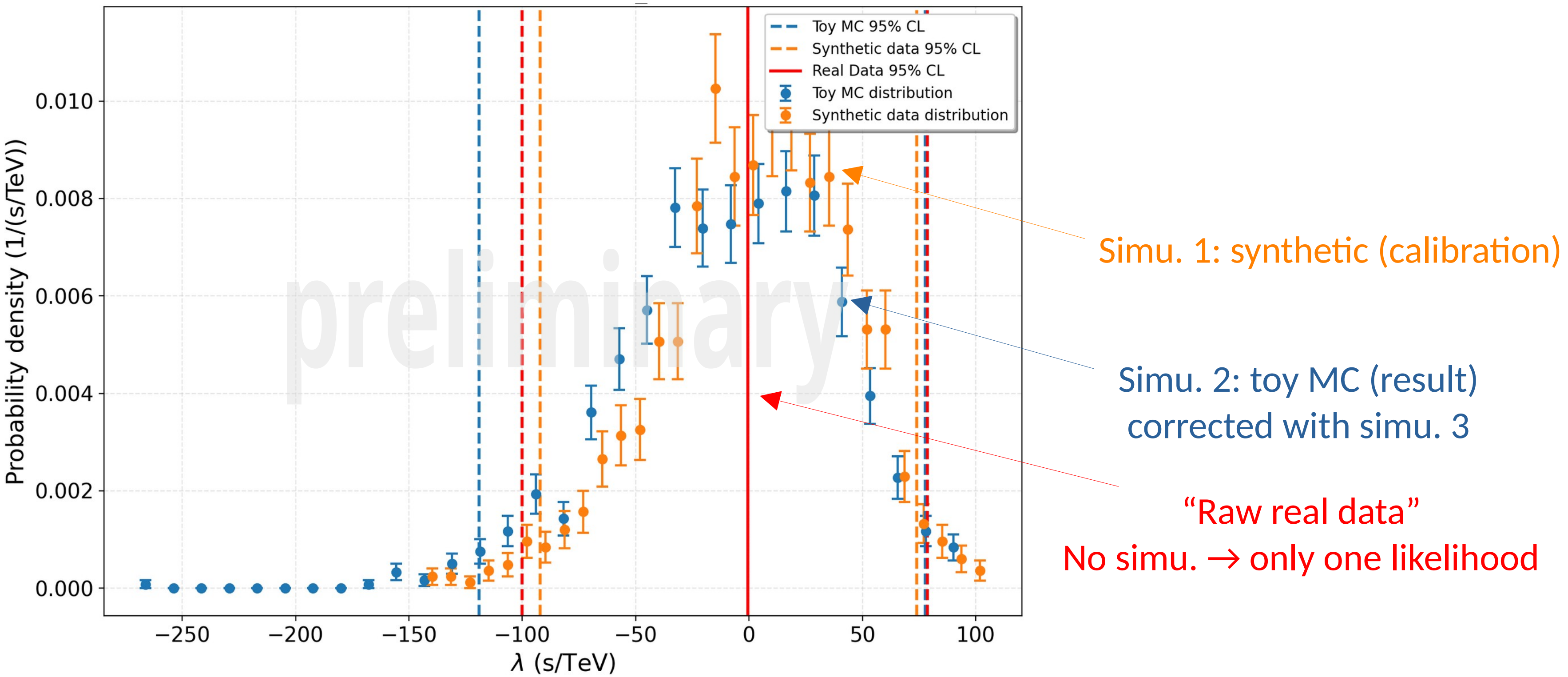
- Signal and baseline from data parametrisation
- "Theoretical" hadronic background
- No IRF
- Spectra and lightcurve parameters are free for likelihood minimisation

Extraction of systematical uncertainties

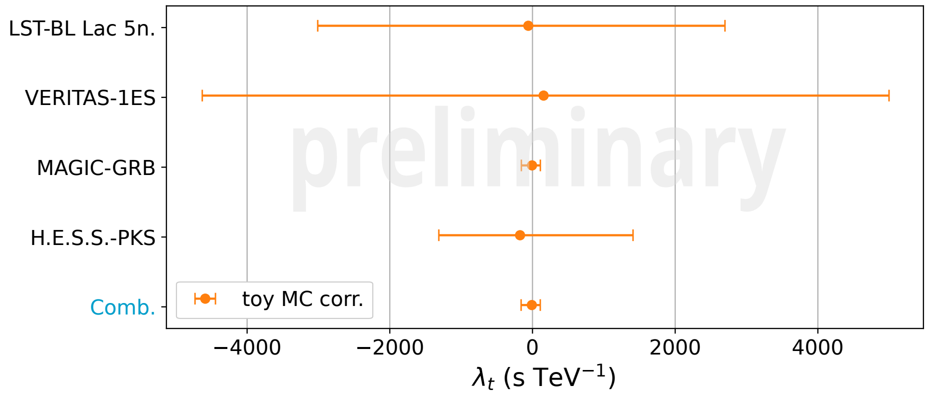
Method: simulations 4

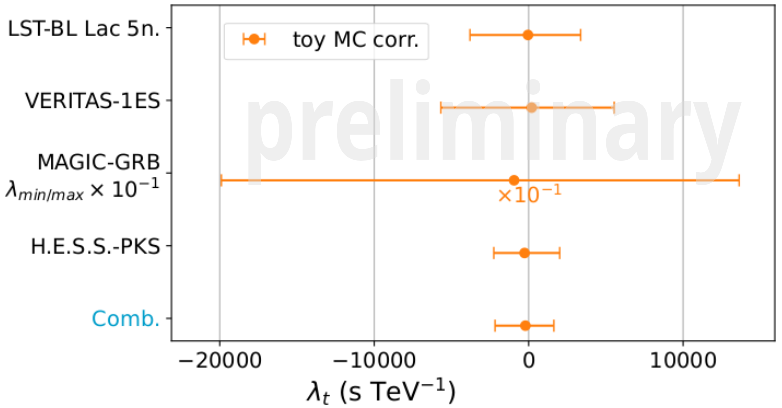
1. Calibration – synthetic simulations with IRF
2. Lateshift extraction – Toy MC simulations
3. Bias test – Toy MC boostrap simulations
4. Extraction of systematics – synthetic simulations “template free”

Deterministic effect – γ-LIV WG data – $\kappa_{n=1}^{\mathrm{JP}}$



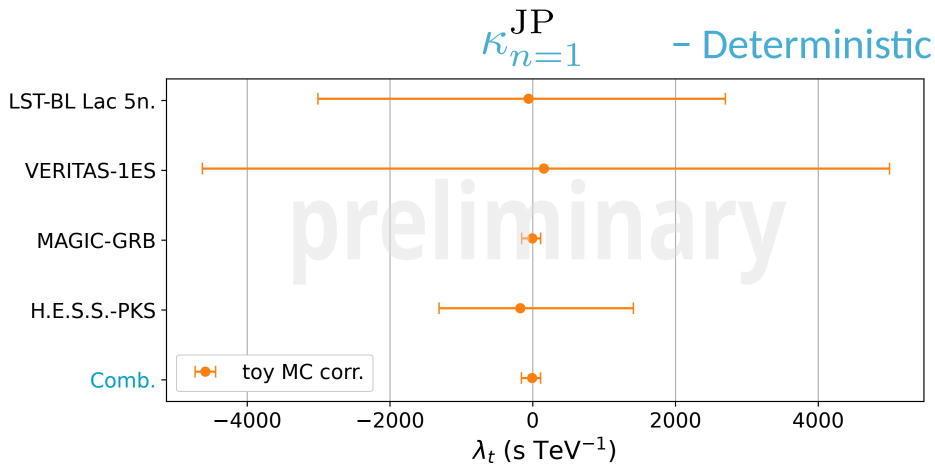
$\kappa_{n=1}^{\mathrm{JP}}$ – Deterministic effect – γ-LIV WG data – $\kappa_{n=1}^{\mathrm{DSR2}}$

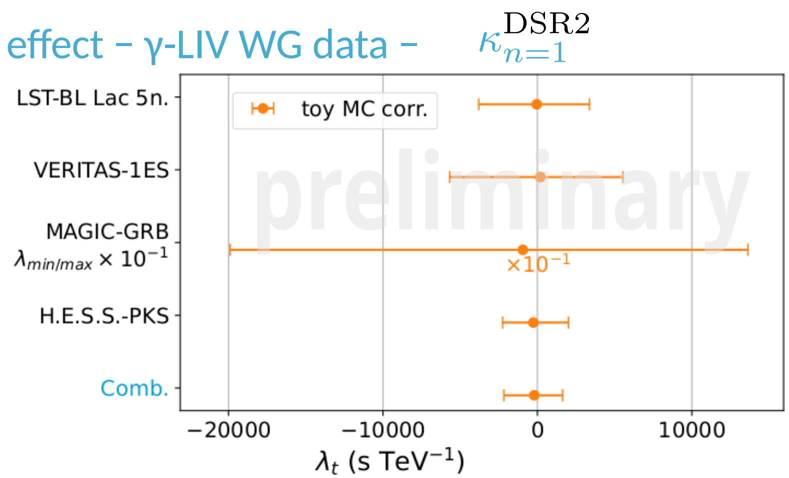




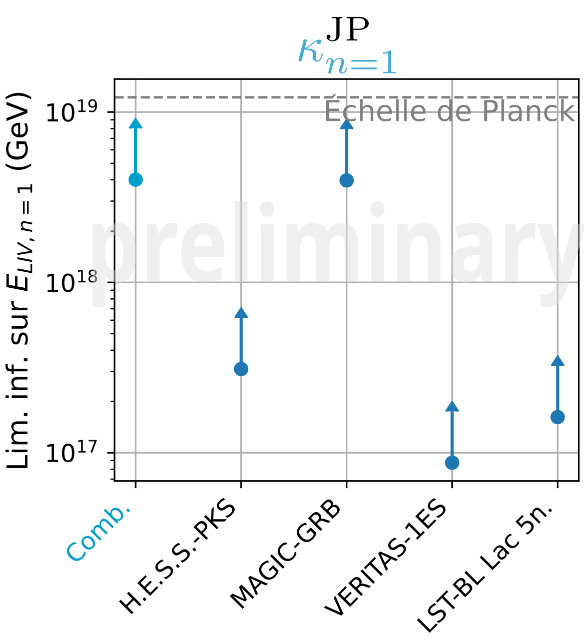
Constraint on deterministic LIV

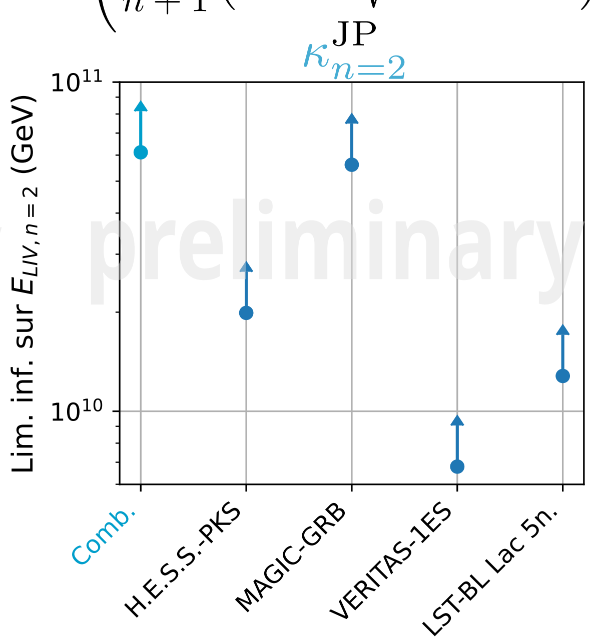
– Deterministic effect – γ-LIV WG data –

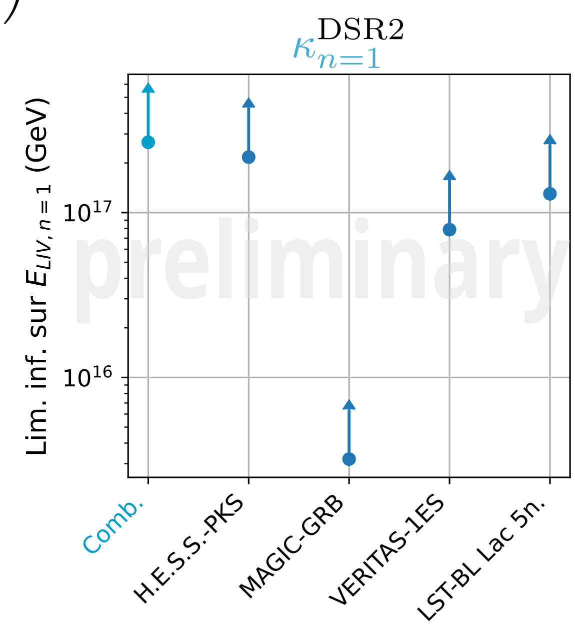




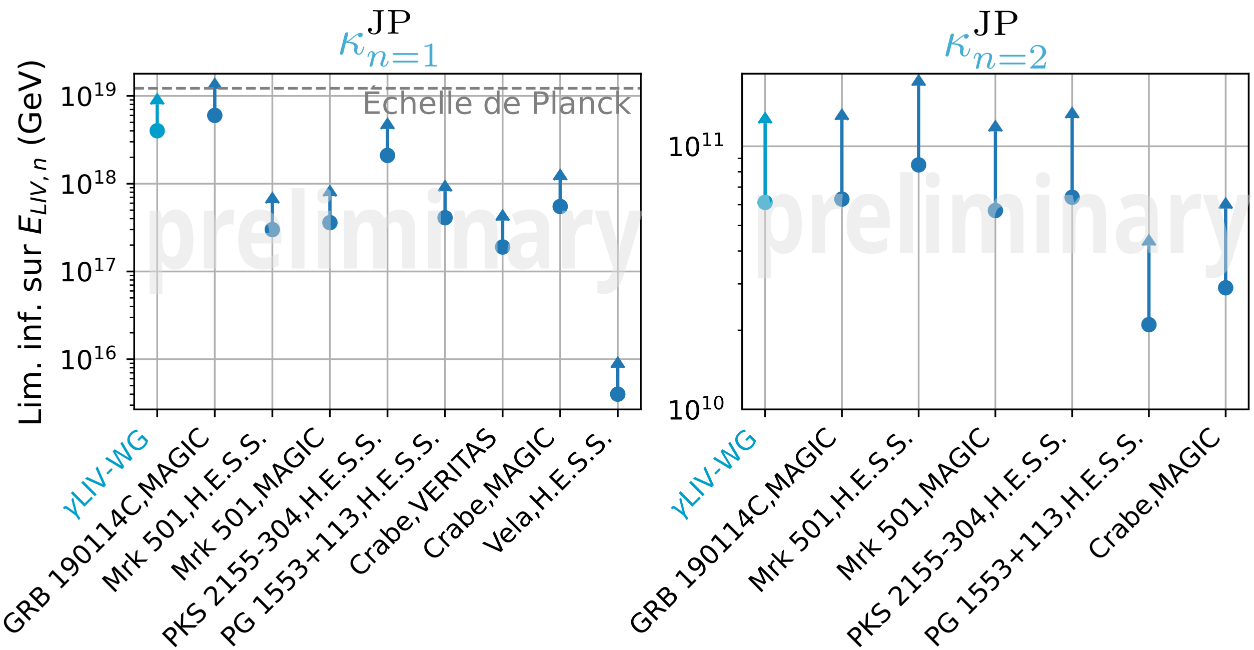
$$E_{\mathrm{LIV},n} = \left(\frac{2}{n+1} \left(\lambda_{n,\pm} + \sqrt{\delta_{\mathrm{stat}}^2 + \delta_{\mathrm{syst}}^2} \right) H_0 \right)$$







Deterministic effect – γ-LIV WG data



- Strongest constraint by Fermi GRB 090510 (doi:10.1103/PhysRevD.87.122001): $E_{\mathrm{LIV},1} > 9.3 \times 10^{19}$ GeV and $E_{\mathrm{LIV},2} > 1.3 \times 10^{11}$ GeV

  as suggested by doi:10.1103/PhysRevD.111.083021, need to reprocess these data

- 1st combination of different types of sources

- Includes a larger set of systematic effects and uncertainties than earlier analyses

Constraint on stochastic LIV

Stochastic effect – LST-1 data – κ_n^{JP}

$\lambda_{\sigma,n=1} = 446.07^{+7798.69}_{-N/A}\,\mathrm{s\,TeV}^{-1}$	$\lambda_{\sigma,n=2} = 1516.58^{+13557.86}_{-N/A}\,\mathrm{s\,TeV}^{-2}$
$E_{\mathrm{LIV},1} > 5.3\times10^{16}\ \mathrm{GeV}$	$E_{\mathrm{LIV},2} > 6.6\times10^{9}\ \mathrm{GeV}$

Only other study (doi:10.1038/nphys3270) at n=1: $E_{\mathrm{LIV},1} > 3.2\times10^{19}\ \mathrm{GeV}$

- Data from Fermi GRB 090510
- No systematics
- Unique source (no combination)
- We plan to reproduce this analysis with LIVelihood

Conclusion of a LIV search with photons time-of-flight

2 problems:
intrinsic source effects & freedom of propagation modelisation

“solution”:
combination of data from various sources & different types of sources & at different redshifts

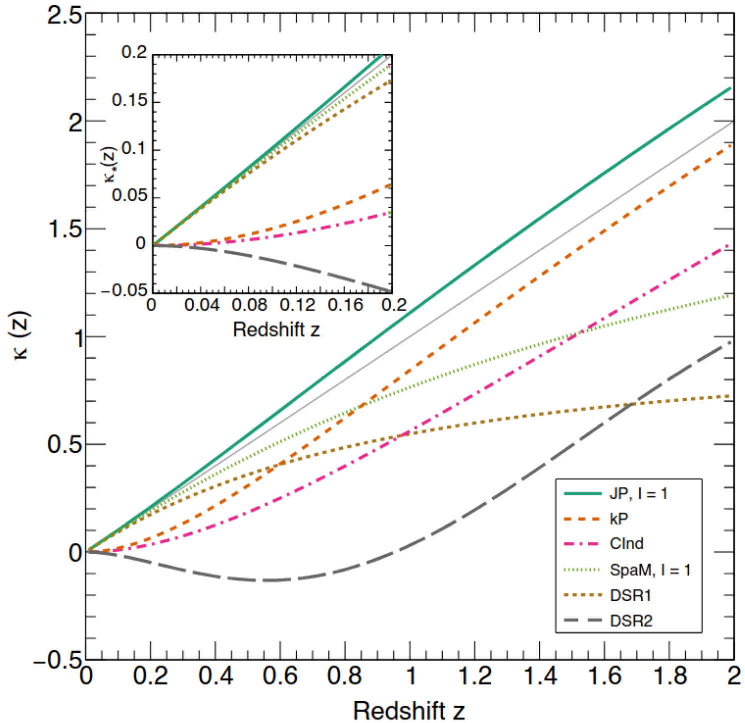
Collaboration between:

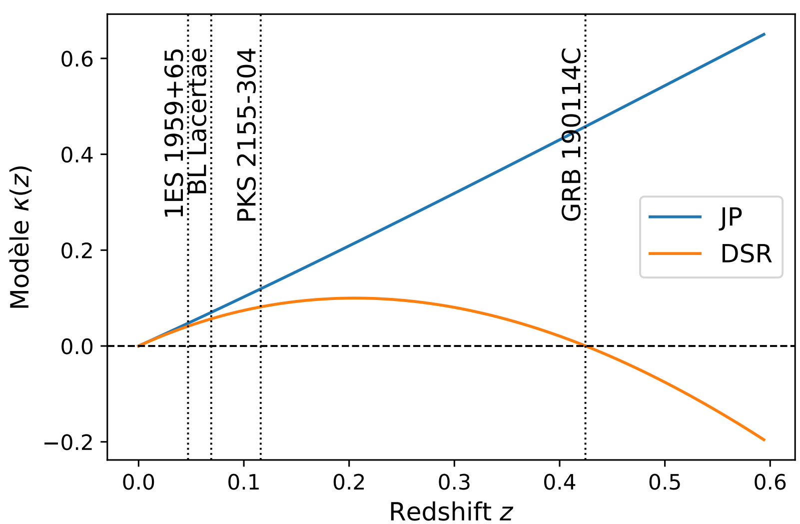
→ 1st constraint on LIV from a combination of different types of sources
→ analysis that includes the largest set of systematic effects and uncertainties

In the future:

- More sources!
  - More AGN flares from LST-1 (lower variability, lower energy threshold)
  - AGN population study in data of H.E.S.S., MAGIC, VERITAS like in LST-1 data
  - Pulsars!
  - GRB (Fermi)
- LST-2 to 4 and CTAO

Method: choice of $\kappa_n(z)$





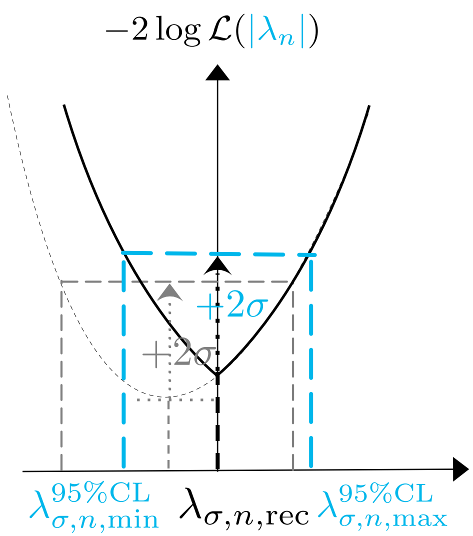
$$\kappa_n^{\mathrm{JP}} = \int_0^z dz' \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

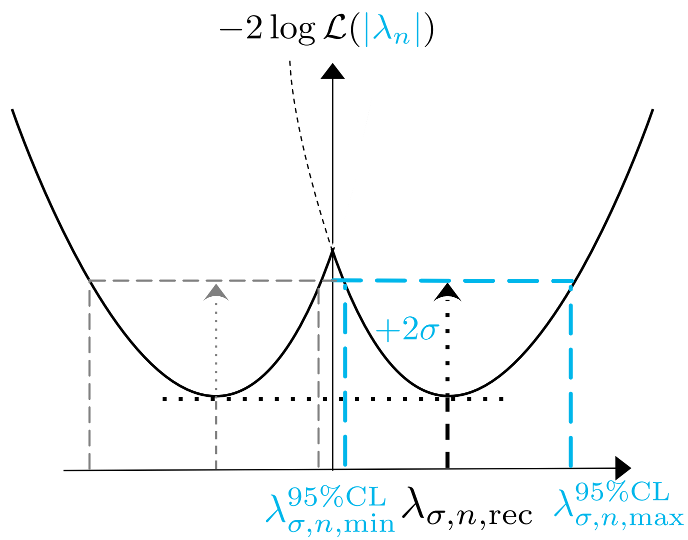
$$\kappa_{n=1}^{\mathrm{DSR2}} = H_0 \int_0^z dz' \frac{1+z'}{H(z')} \left[\alpha_1 + \alpha_2 \left(1 - \left(1 - \frac{H(z')I(z')}{1+z'} \right)^2 \right) + \alpha_3 \left(1 - \left(1 - \frac{H(z')I(z')}{1+z'} \right)^4 \right) \right]$$

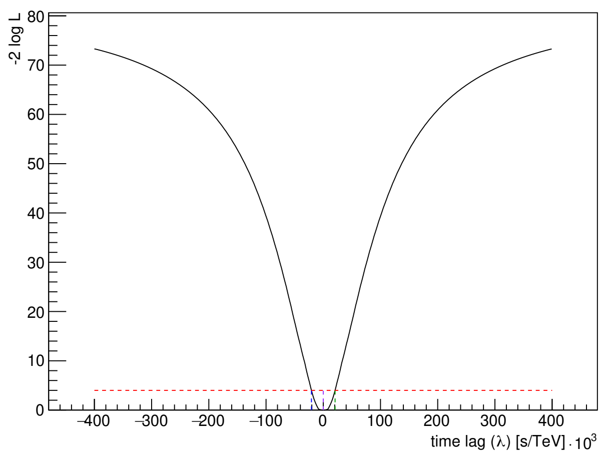
$\alpha_1 = 1 \quad \alpha_2 = -3.888 \quad \alpha_3 = 0.5$

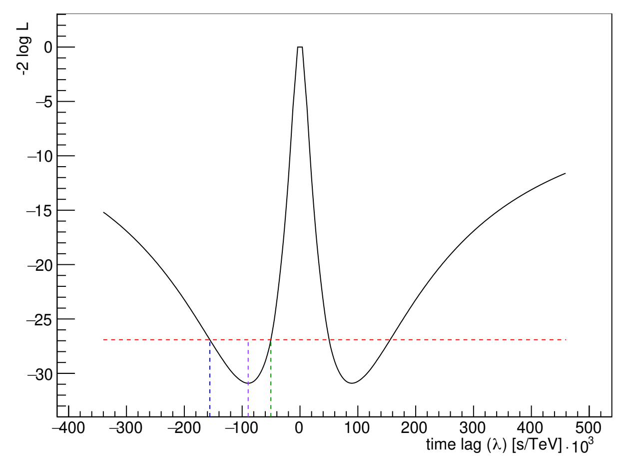
Stochastic effect and likelihood

Log-likelihood maximisation: $L(\lambda_n) = -2\log\mathcal{L}(|\lambda_n|)$





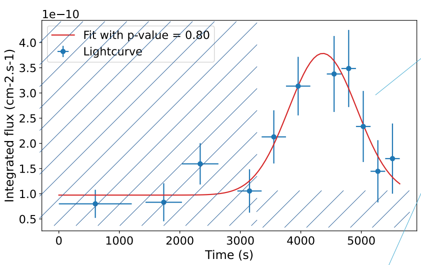




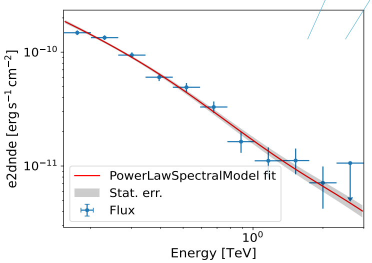
Method

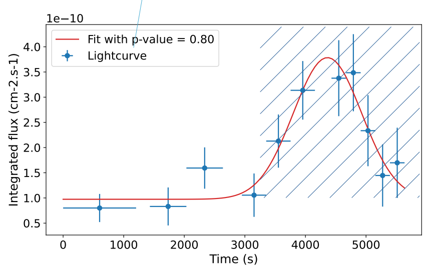
1. Calibration – synthetic simulations with IRF
2. Lateshift extraction – Toy MC simulations
3. Bias test – Toy MC boostrap simulations
4. Extraction of systematics – synthetic simulations “template free”

$$\frac{d^2P}{dE_R dt}(E_{R,i}, t_i; \lambda_n) = \frac{w_S}{N_S}\int \mathrm{M}(E_{T,i}, E_{R,i})\mathrm{A}(E_{T,i}, t_i)\Gamma_S(E_{T,i})C_S(t_i; \lambda_n \kappa_n(z) E^n_{T,i})dE_T$$
$$+\frac{w_B}{N_B}\int \mathrm{M}(E_{T,i}, E_{R,i})\mathrm{A}(E_{T,i}, t_i)\Gamma_S(E_{T,i})C_B dE_T$$
$$+\frac{w_H}{N_H}\int \mathrm{M}(E_{T,i}, E_{R,i})\mathrm{A}(E_{T,i}, t_i)\Gamma_H(E_{T,i})C_H dE_T,$$



indice de photon $\alpha = 2.7$ (PhysRevLett.114.171103)





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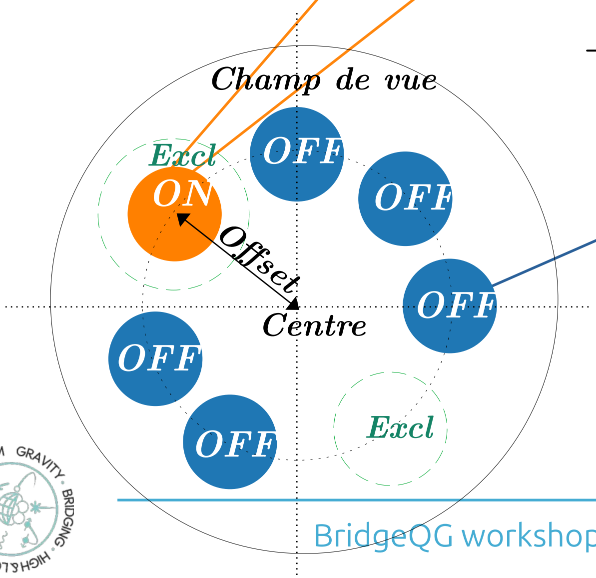
$$+\frac{w_B}{N_B}\int \mathrm{M}(E_{T,i}, E_{R,i})\mathrm{A}(E_{T,i}, t_i)\Gamma_S(E_{T,i})C_B dE_T$$
$$+\frac{w_H}{N_H}\times\frac{1}{T_{\mathrm{obs}}}\times\frac{dN_{\mathrm{OFF}}}{dE_R}(E_{R,i}, t_i)$$



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Minimisation of profile log-likelihood: $L_{n_s}(\lambda_n) = \sup_{\vec{\theta}_{n_s}} L^*_{n_s}(\lambda_n, \vec{\theta}_{n_s})$

Nuisance parameter

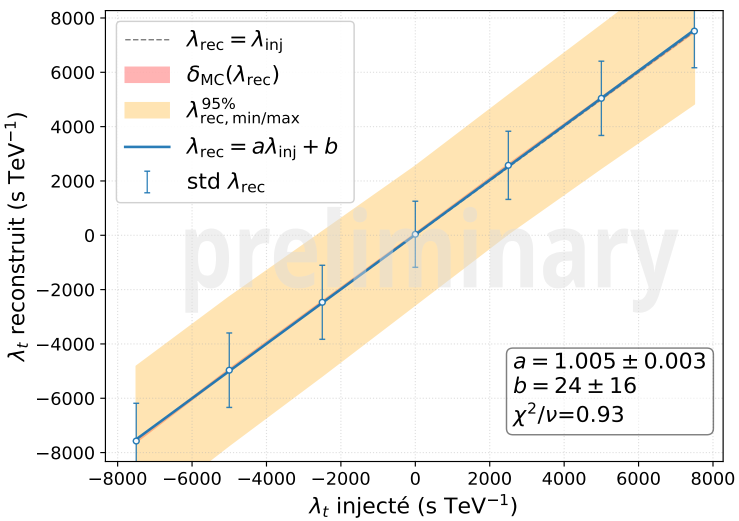
$$L^*_{n_s}(\lambda_n, \vec{\theta}_{n_s}) = L^*(\lambda_n, \vec{\theta}_{n_s}) + L^*_\alpha(\vec{\theta}_\alpha) + L^*_w(\vec{\theta}_w) + L^*_{\mathrm{ES}}(\theta_{\mathrm{ES}}) + L^*_z(\theta_z)$$

Spectral index | weight signal vs bkg | Energetic bias | redshift

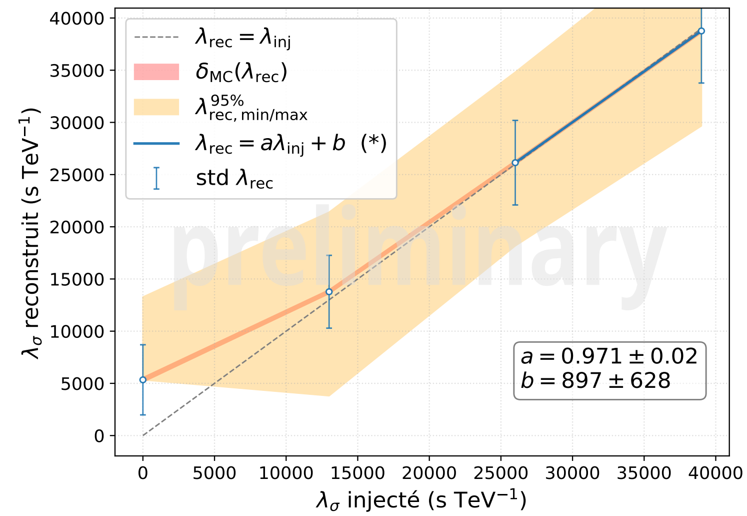
$$\frac{d^2P}{dE_R dt}(E_{R,i}, t_i; \lambda_n, \vec{\theta}_{n_s}) = \frac{\theta_{w,S}}{N_S}\Gamma_S(E_{R,i} \times \theta_{\mathrm{ES}}, \theta_\alpha) C_S(t_i; \lambda_n \kappa_n(\theta_z) \times (E_{R,i} \times \theta_{\mathrm{ES}})^n; \vec{\theta}_C)$$
$$+ \frac{\theta_{w,B}}{N_B}\Gamma_S(E_{R,i}, \theta_\alpha) C_B$$
$$+ \frac{\theta_{w,H}}{N_H}\Gamma_H(E_{R,i}) C_H,$$

Calibration plots – LST-1 data

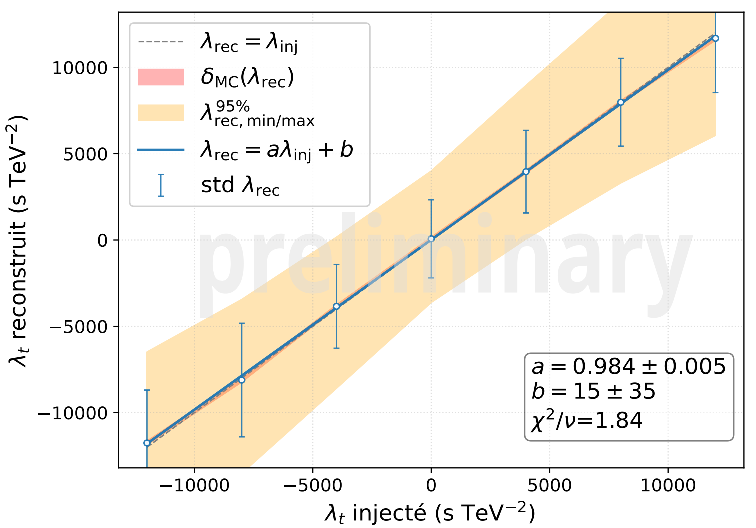
determ. - n=1



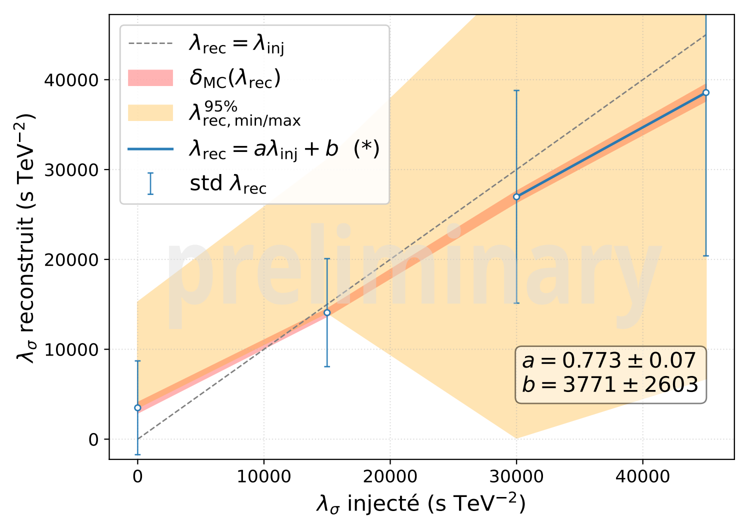
stoch. - n=1



determ. - n=2



stoch. - n=2



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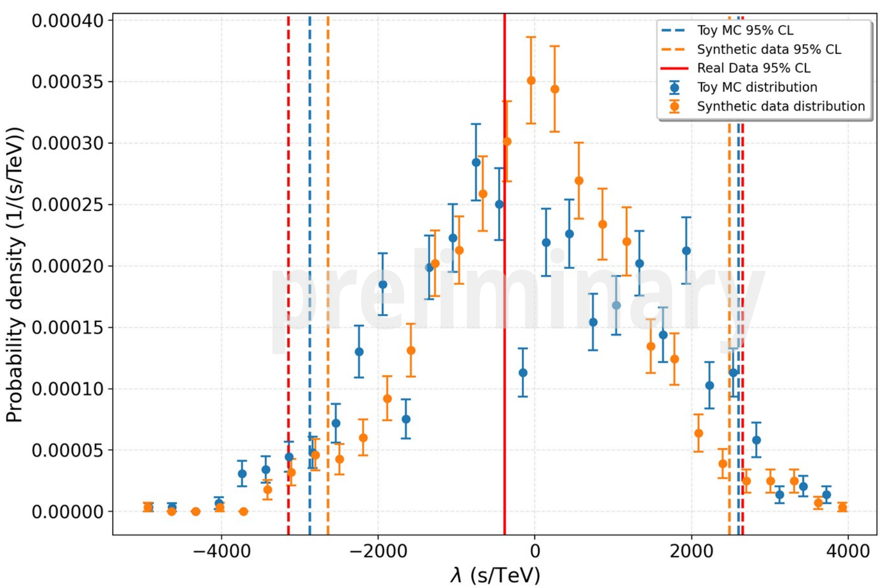
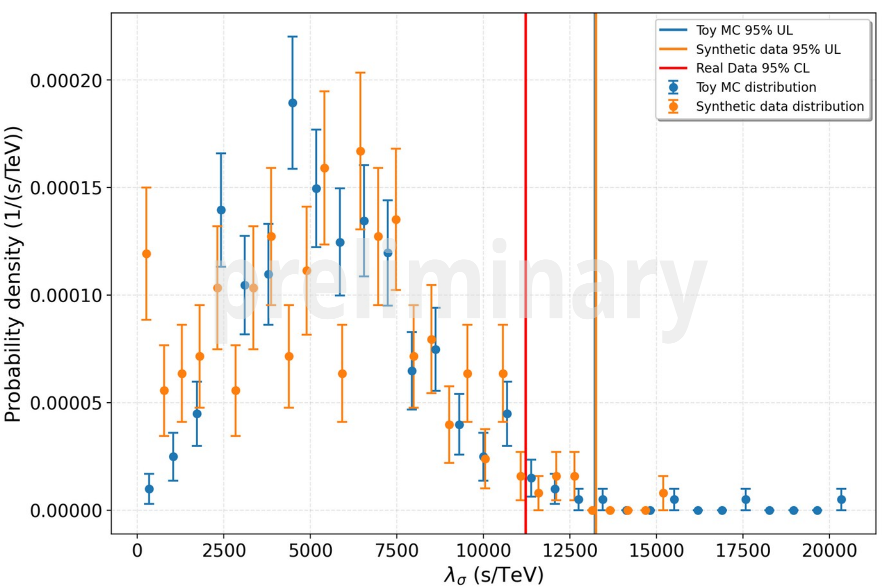
Deterministic effect – LST-1 data – $\kappa_{n=1}^{\mathrm{JP}}$



Stochastic effect – LST-1 data – $\kappa_{n=1}^{\mathrm{JP}}$



LST-1 data – BL Lacertae spectra