Search for Lorentz Invariance Violation with CTA/LST

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LIV general description

- Lorentz Invariance Violation (LIV) allowed by some Quantum Gravity candidate theories
- In brief, we expect energy dependent velocities for photons in vacuum

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

$$v_n(E) = c \left[1 \pm \frac{n+1}{2} \left(\frac{E}{E_{QG}} \right)^n \right]$$

- subluminal, + superluminal

- Delay of two photons emitted at the same time at a source with a redshift z :

$$\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{H_0 E_{QG}^n} \kappa_n(z),$$

with

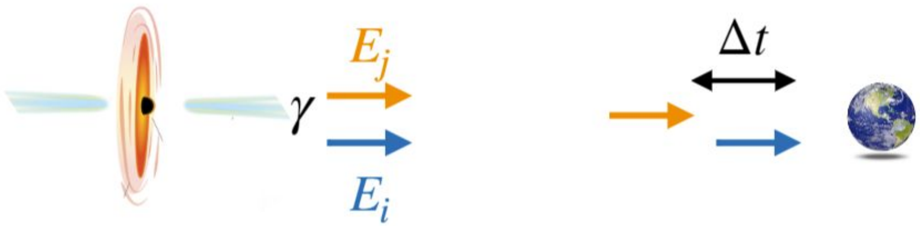
$$\kappa_n^{LIV}(z) \equiv \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz',$$

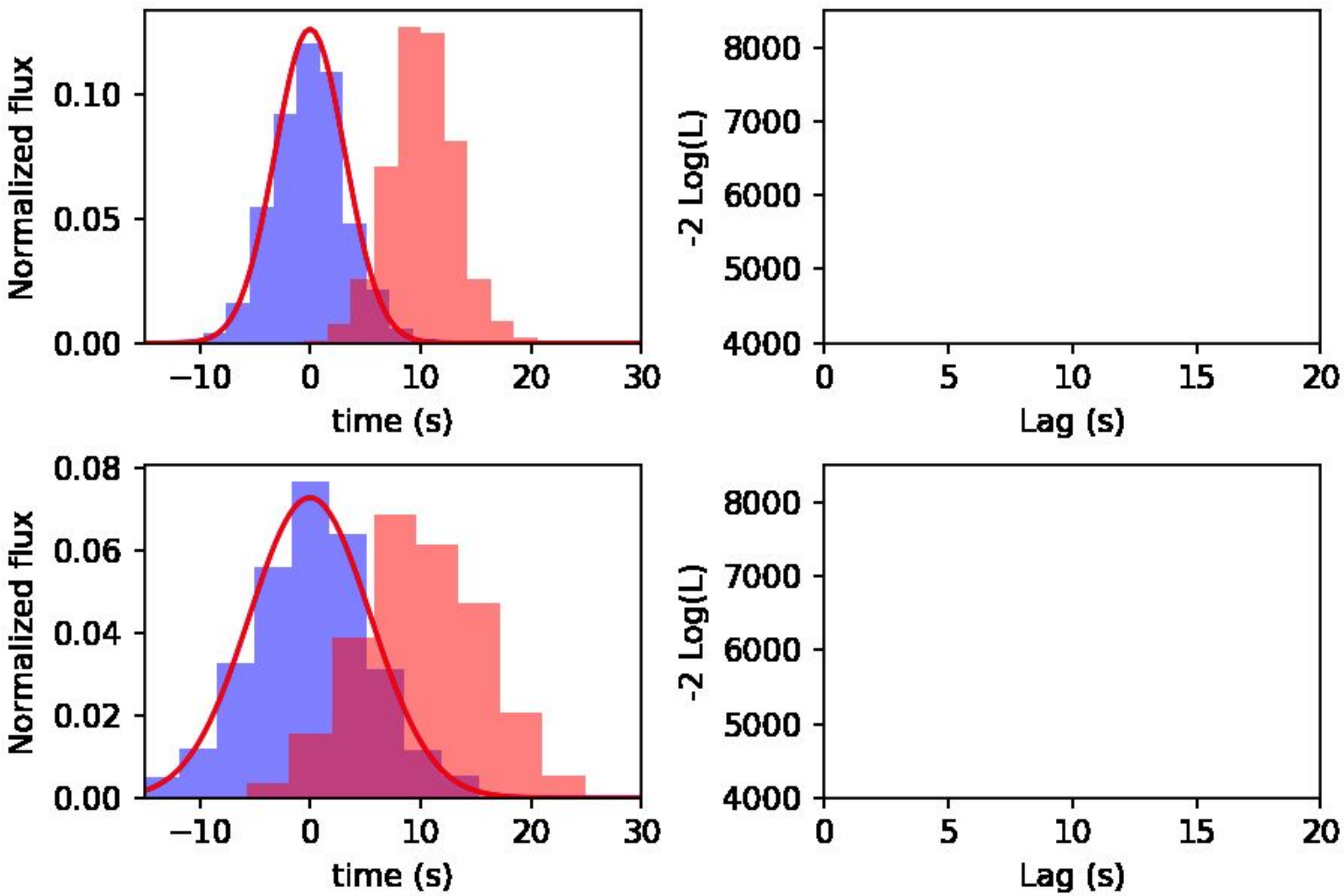
- Time delay per energy :

$$\tau_n = \frac{\Delta t_n}{\Delta E_n} = \pm \frac{n+1}{2H_0 E_{\mathrm{QG}}^n} K_n(z)$$

- To maximize sensitivity on LIV effects, we need distant, variable, and energetic sources

Time lag method





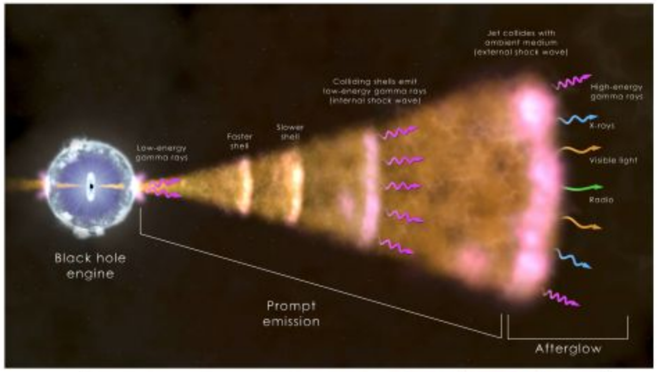
Astrophysical sources combination

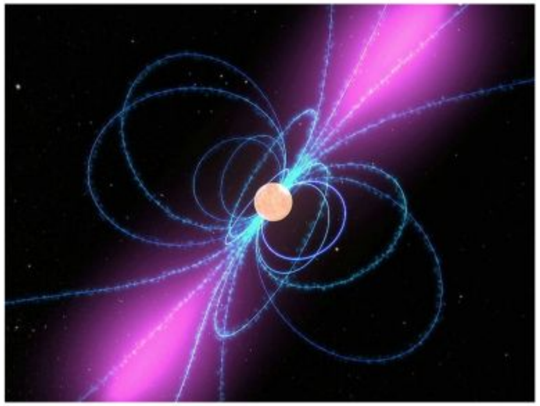
- Need distant, variable, energetic and important statistics

- Flaring AGNs → distant sources, short variability (~10 mins)
- Pulsar → local sources but high variability, need to accumulate years of data
- GRBs → Fast variability (prompt emission ~mins) and distance

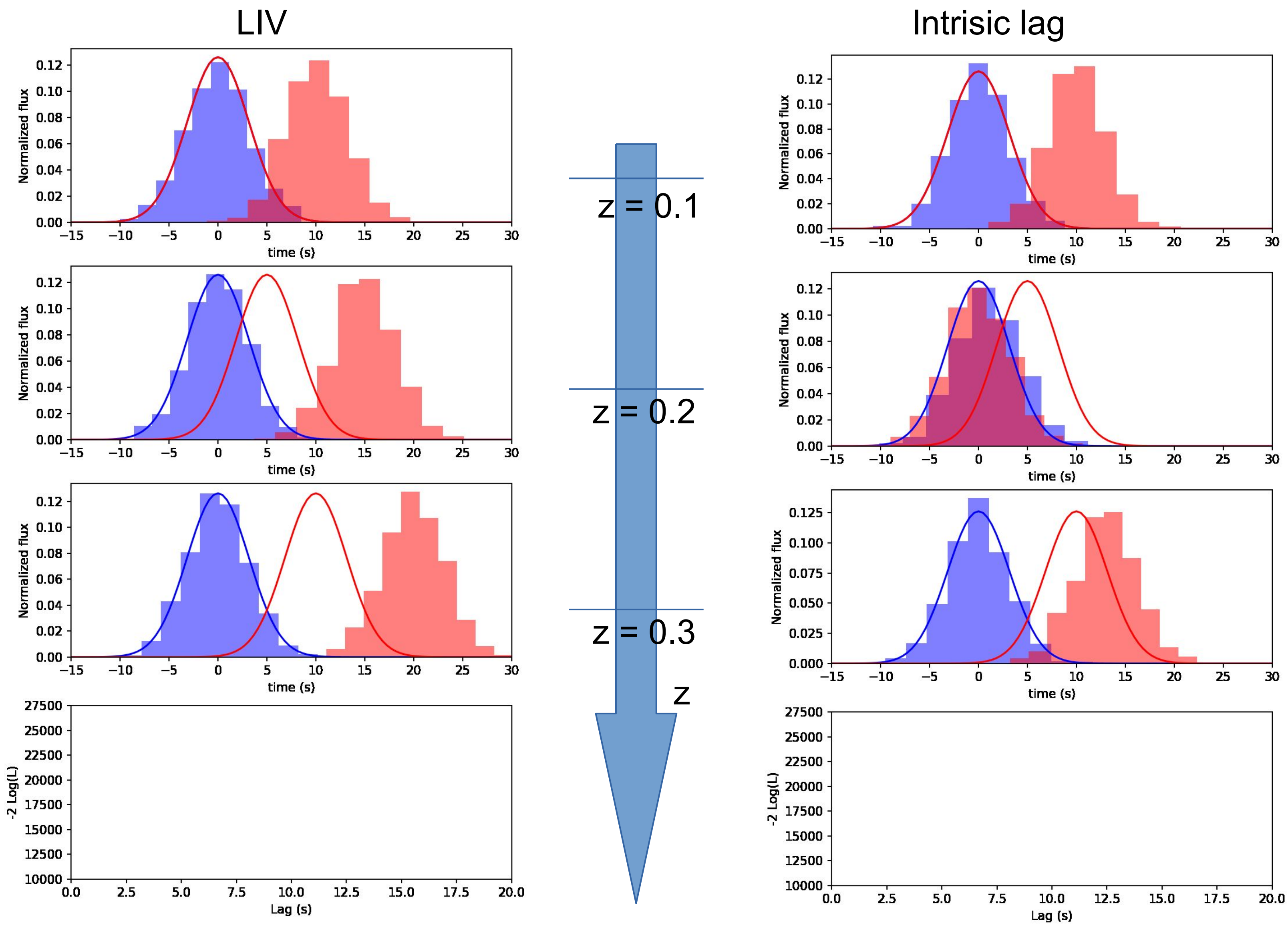
- LIV implies same effect to all these sources independently of the acceleration processes

- Why combination of different sources :
  - Source intrinsic effects
  - different redshifts (redshift dependence of LIV time lag)
  - Increase the statistics





Intrinsic lags versus LIV lag



Indirect detection of gamma-rays

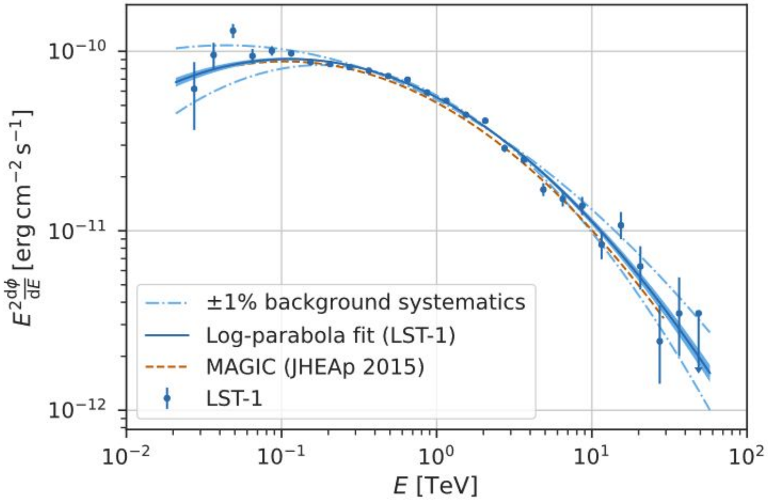
- **IACTs → Imaging Atmospheric Cherenkov Telescope**
- Cherenkov light produced by secondary particles
- **Pro :**
  - Good angular resolution (~0.1°) and **energy resolution (~10-15%)**
  - Good low **exposure time sensitivity**
- **Cons :**
  - Narrow field of view (~5°)
  - Low duty cycle (10-15%)

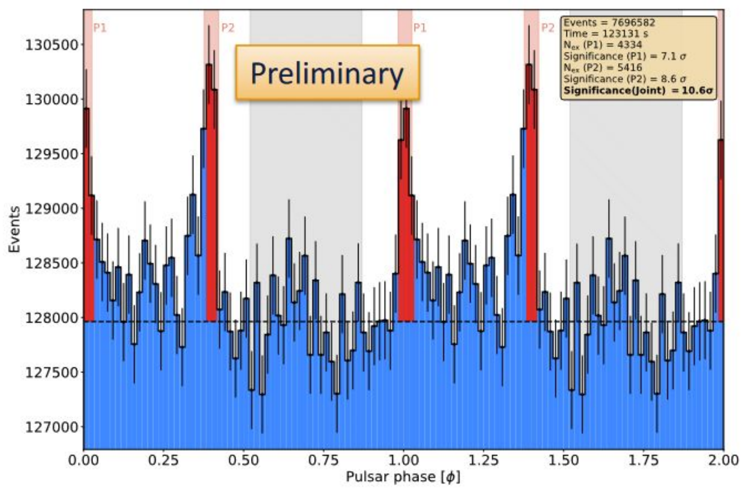
- **Water Cherenkov Array**
- Detection of secondary particles with Cherenkov in water tank
- **Pro :**
  - Big field of view (15% of sky)
  - High duty cycle (~100%)
- **Cons :**
  - Less precise for angular resolution (0.75° @ 1 TeV, 0.3° @ 10TeV) and energy resolution (95% @ 1TeV, 50% @ 10TeV)

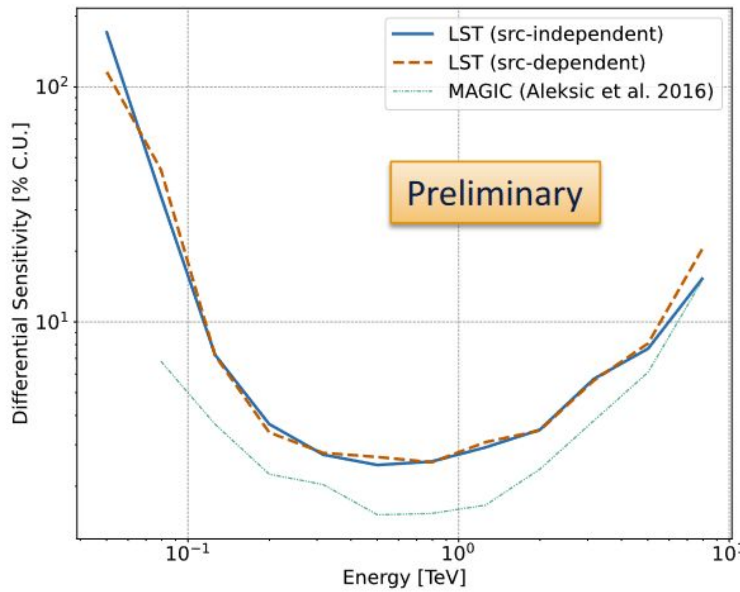
LST1 @ La Palma

- First telescope of North site installed in the la Palma island since 2018
- On-going commissioning and real data acquired
- 3 LST and MSTs will start to be built soon (2023)

LST1 @ La Palma







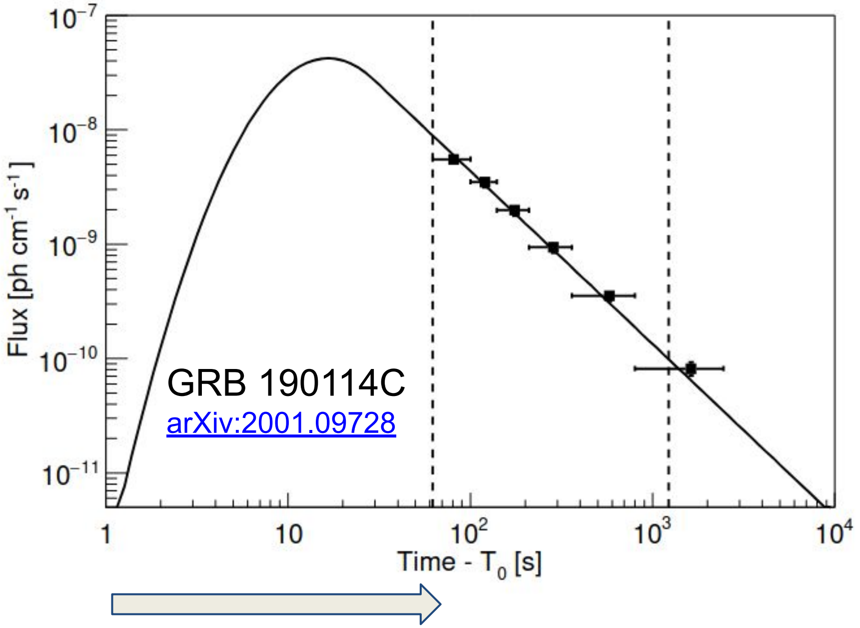
- First validation of the LST-1 with Crab Nebula
- Current sensitivity already comparable to MAGIC (Mono versus Stereo)

future observatories - CTA

- 3 types of telescopes :
  - LST (23 m)
  - MST (12 m)
  - SST (4.3 m)
- Optimized for different energies :
  - 20 GeV - 3 TeV
  - 80 GeV - 50 TeV
  - 1 TeV - 300 TeV
- ~100 telescopes in two sites :
  - La Palma (North hemisphere)
  - Paranal (South hemisphere)
- End of construction for 2025

Performances

- Performance for time-lag measurement depend of many factors
    - Angular resolution (improve detectability of point sources)
    - Gamma/Hadron separation (less background, better detectability)
    - Field of view size (permits to catch more easily transient events)
        - 5° for LSTs, 8° for MSTs
    - Time resolution (almost ~ ns for IACTs, only limited by statistics)
    - Repointing speed (Help to catch prompt phase of transients)
        - 20 sec for LST, current generation is 60-120 sec



- Depends of external alert convoluted with **repointing speed** and **luck**
- The lower observation delay, the better variability and statistics

- Combination of all available data from the three leading Imaging Atmospheric Cherenkov Array
- Preparing the CTA era (combination of sources and observatories North and South)
- Joined analysis of different type of sources (AGNs, pulsars, GRB)
- Signed MoU between experiments to share data for LIV study + LST collaboration included soon
- First step done, production of a common software for LIV analysis : LIVelihood

LIVelihood code general description

- Code made for time-lag study and combination of different data of experiments
- Code based on ROOT C++
- Not yet public code, but plan to be public after CTA DL3 data format support implemented (in order to support the CTA era, and evaluation of outside MoU observatories)
- Several functionnalities
  - Unbinned likelihood taking into account IRFs
  - Simulations of lightcurve with or without injected lag
  - Systematics uncertainties treatment with profiled likelihood
  - Different model of redshift distance term implemented (J&P and DSR)
  - Able to run on both lightcurves (GRBs and AGNs) and phasograms (pulsars)
- Made by design to be easily used for diverse experiments, designed for HESS+MAGIC+VERITAS but easily tunable for other IACTs or other experiments (Fermi)
- Definition of a new experiment needs some ingredients :
  - Systematics (Energy scale, Signal/Background uncertainty, Spectral Index)
  - IRFs (Migration Matrix, Effective Area)

Likelihood

Spectra — Light curve

$$F_s(E_t, t; \lambda_n) = \frac{\Gamma_s(E_t)\, C_s\left(t - D(E_t, \lambda_n, z)\right)}{N_s}, \quad (7)$$

Lag corrected by redshift

$$D(E_t, \lambda_n, z) = \lambda_n \times \kappa_n(z) \times E_t^n, \quad (8)$$

- Simple likelihood with a « perfect » instrument (no Emig and flat acceptance)
- Lag corrected by redshift used as a free parameter
- Can be shared as free parameter between sources at different redshift

Likelihood

Background/Signal proportion — IRFs — Light curve * spectra

$$\frac{dP}{dE_m dt} = w_s \frac{\int A(E_t,\vec{\varepsilon})M(E_t,E_m) \times F_s(E_t,t;\lambda_n) dE_t}{N'_s} + \sum_k w_{b,k} \frac{\int A(E_t,\vec{\varepsilon})M(E_t,E_m) \times F_{b,k}(E_t,t) dE_t}{N'_{b,k}}, \quad (12)$$

Normalisation

$$L_S(\lambda_n) = -\sum_{\mathrm{i}} \log\left(\frac{dP}{dE_m dt}(E_{m,i},t_i);\lambda_n\right). \quad (13)$$

- Likelihood takes into account IRFs and background
- Several types of background can be added (so far, quiescent state + gamma-like hadrons)
- Should be generic enough for every type of gamma-ray observatory
- Very time consuming (1D + 3D integral for each event !), using precomputation and tabulation of likelihood, and interpolation for the minimization
- Can handle time dependent IRFs

Combination and systematics

$$L_{comb}(\lambda_n) = \sum_{\text{all sources}} L_S(\lambda_n).$$

- Combination done by summing log-likelihood over sources and/or observation nights
- Systematic error terms added to each source log-likelihood

$$L(\lambda_n, \vec{\theta}) = L_{\mathrm{S}}(\lambda_n, \vec{\theta}) + L_{\mathrm{template}}(\vec{\theta}_{\mathrm{C}}) + L_{\gamma}(\theta_{\gamma}) + L_{\mathrm{B}}(\vec{\theta}_{\mathrm{B}}) + L_{\mathrm{ES}}(\theta_{\mathrm{ES}}) + L_{\mathrm{z}}(\theta_{\mathrm{z}}), \quad (15)$$

a. $\vec{\theta}_{\mathrm{C}}$, the parameters of the light curve analytic parameterization,

b. θ_{γ}, the power law index of signal events spectrum,

c. $\vec{\theta}_{\mathrm{B}}$, the ratio of signal and of background event numbers to the total number of events,

d. θ_{ES}, the energy scale,

e. θ_{z}, the distance or redshift.

→ Some parameters depend of the instrument used for the observation

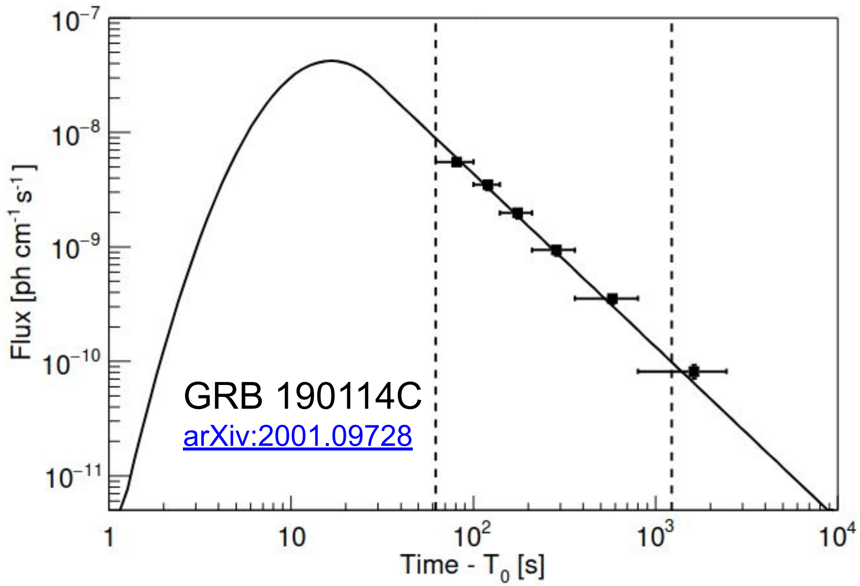
Simulated sources

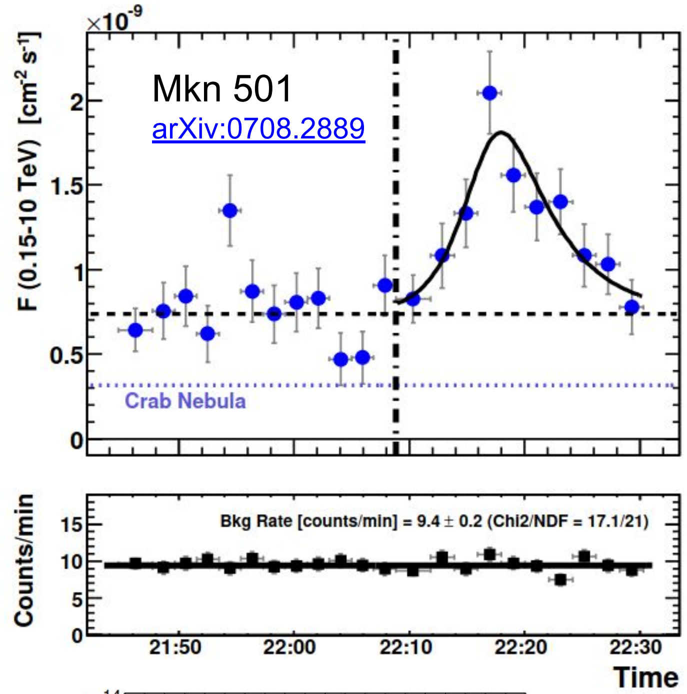
- Tested on 6 different sources already published by consortium collaborations :
  - Different types AGNs, GRB and pulsar phasograms
  - Some of them observed by two different observatories and combined (Crab pulsar)
- Simulation done using the instruments IRFs for these particular observations
- Light curve simulation code included in the LIVelihood code
  - Again modular code, IRFs can be tuned to study other observatories and sources

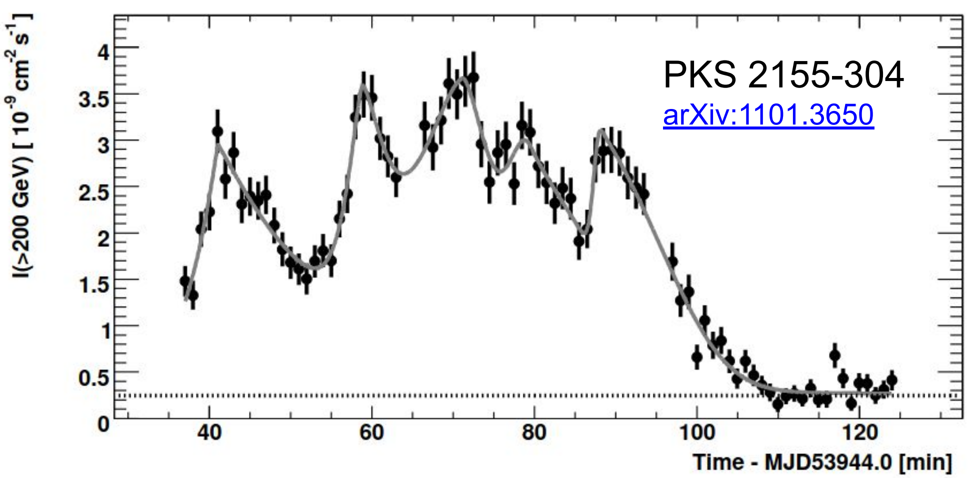
Table 3. Simulation settings for the individual sources.

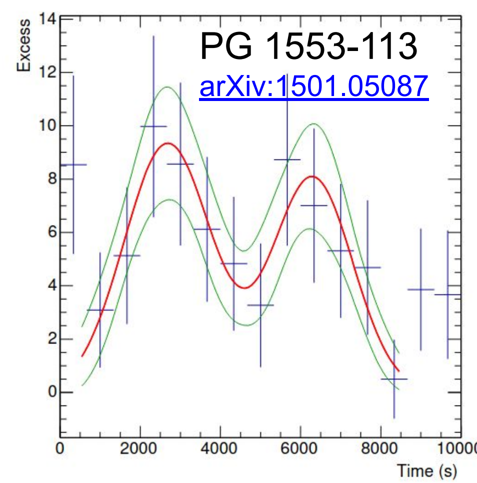
Source	Energy Range (TeV)	Time Range[a]	Spectral index Γ_s, Γ_b	Lightcurve shape	Number of events likelihood[b], template[c]	Background proportion hadronic, baseline
GRB 190114C	0.3 - 2	60 - 1200 s	5.43, -	curved power law	726, -	0.055, 0.
PG 1553+113	0.4 - 0.8	0 - 8000 s	4.8, 4.8	double Gauss	72, 82	0.29, 0.15
Mrk 501	0.25 - 11	0 - 1531 s	2.2, 2.2	single Gauss	1800, -	0.39, 0.
PKS 2155-304	0.28 - 4	0 - 4000 s	3.46, 3.32	5 asymmetric Gauss	2965, 561	0., 0.02
Crab (M)	0.4 - 7	0.36 - 0.45	2.81, 2.47	single Gauss + Baseline	14869, -	0., 0.961
Crab (V)	0.2 - 10	0.37 - 0.43	3.25, 2.47	single Gauss + Baseline	22764, -	0., 0.964
Vela	0.06 - 0.15	0.50 - 0.60	3.9, 1.75	asymmetric Lorentzian	330820, -	0., 0.998

Simulated sources

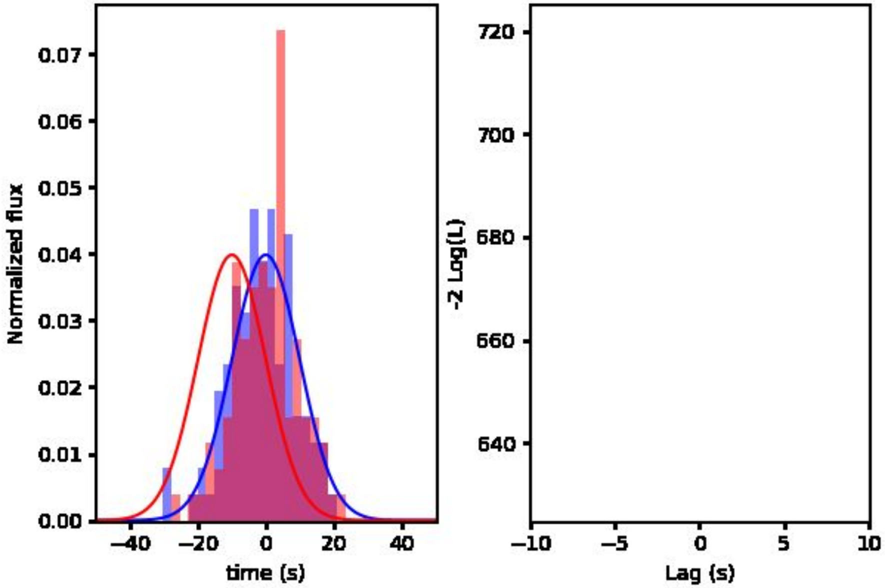


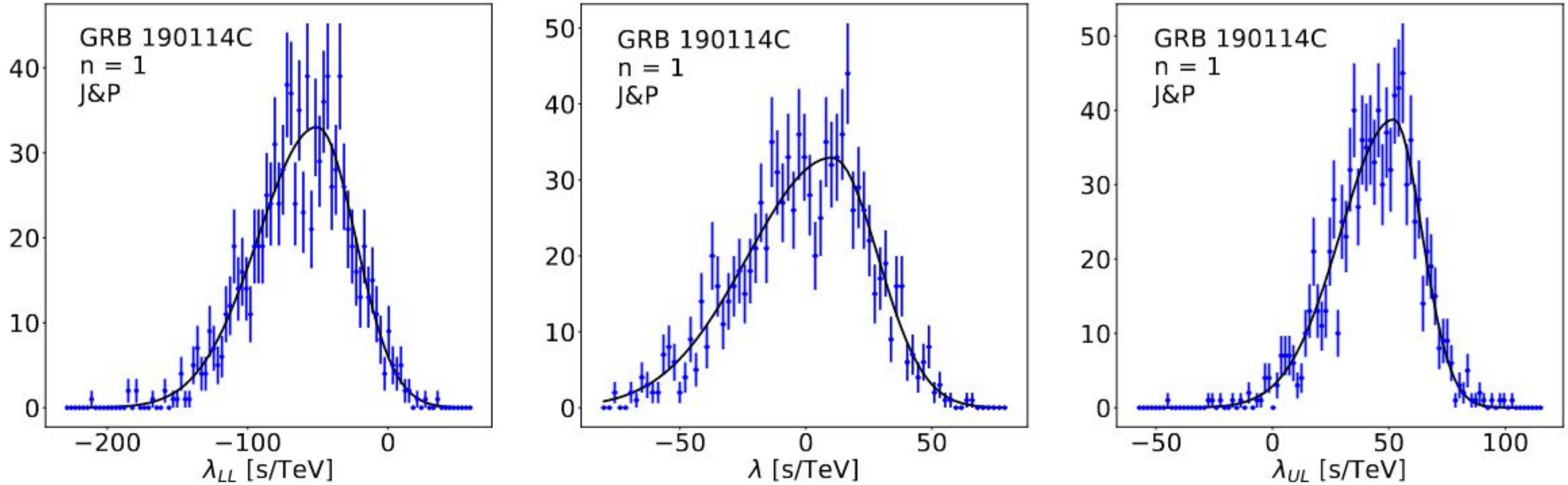






Code validation





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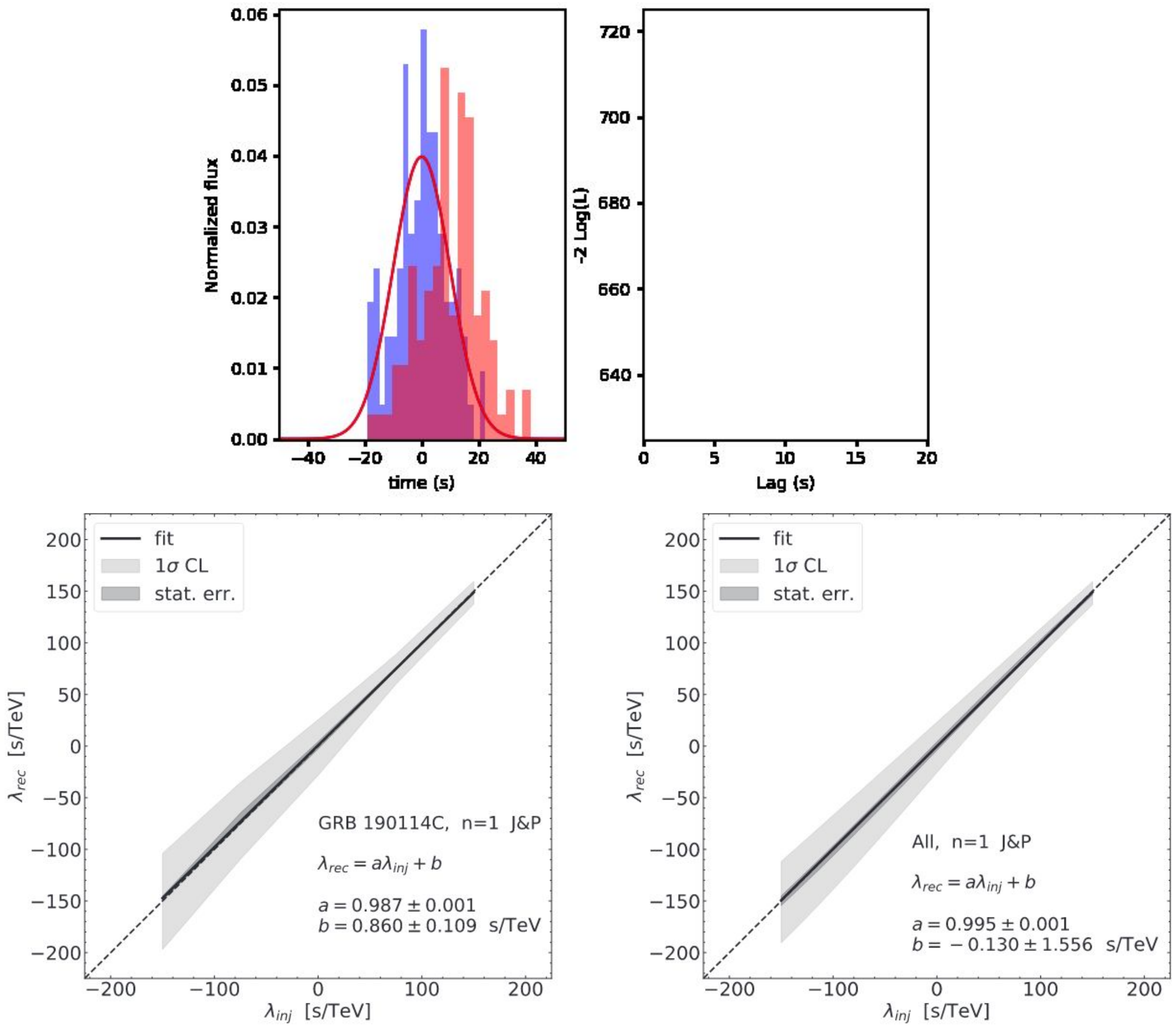
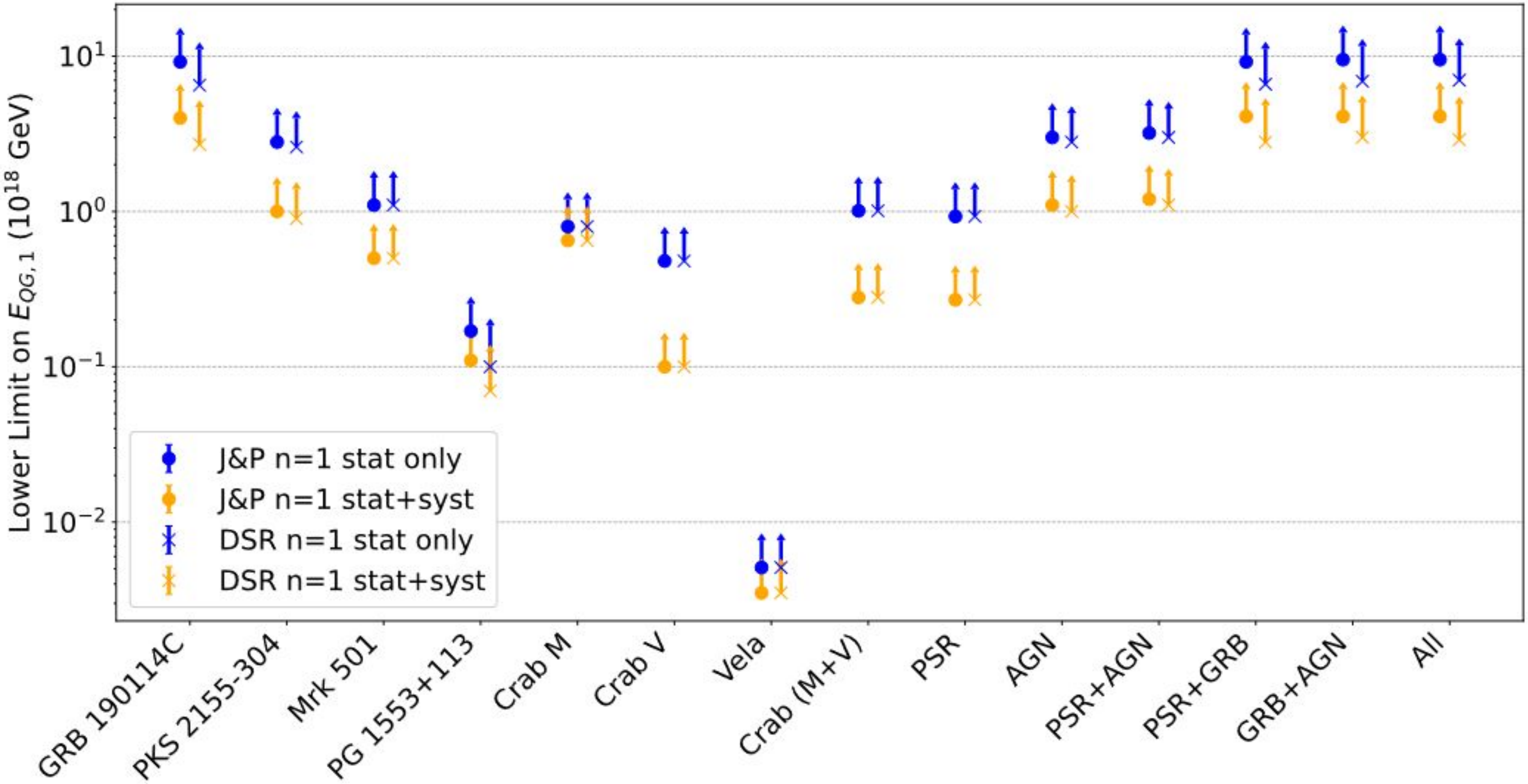


Limits



Lower Limit on $E_{QG,1}$ (10^{18} GeV)
10^{1}
10^{0}
10^{-1}
10^{-2}
J&P n=1 stat only
J&P n=1 stat+syst
DSR n=1 stat only
DSR n=1 stat+syst
GRB 190114C
PKS 2155-304
Mrk 501
PG 1553+113
Crab M
Crab V
Vela
Crab (M+V)
PSR
AGN
PSR+AGN
PSR+GRB
GRB+AGN
All

Conclusions and outlook

- **LIVelihood** implement all the needed component to add various experiments and source for LIV searches
  - IRFs treatment
  - Observatory dependent systematics
  - Tunable level of background and background energy distribution
- **CTA data DL3 format** support implemented, code to be provided to community as open-source code
- **Code ready to handle real data** from HESS+MAGIC+VERITAS+LST, new publication on population study with real data on-going
- On-going work to **support Fermi-LAT** data, can be added to the next population study
- On-going discussions with **LST collaboration** to join the MoU in order to add more transient to the population study and support the **CTA science** (MoU ready to be signed, signature next week)

Outlook Cyann thesis

- Support of HESS+MAGIC+VERITAS+LST consortium study : LST data responsible

- Support transient and variable sources search and analysis in LST Collaboration

- Study of LIV in LST data :
  - BL Lac flare
  - Crab pulsar phasogram
  - new GRB ? new AGN Flare ?

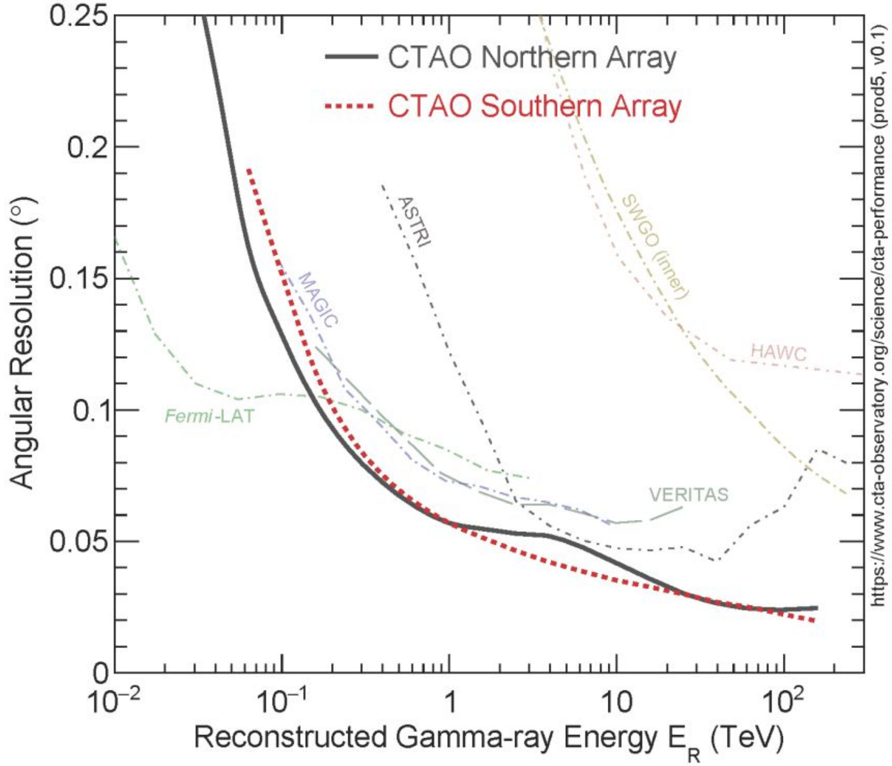
- Study of more generalized of new type dispersion relation (spatial momentum, stochastic LIV, …)

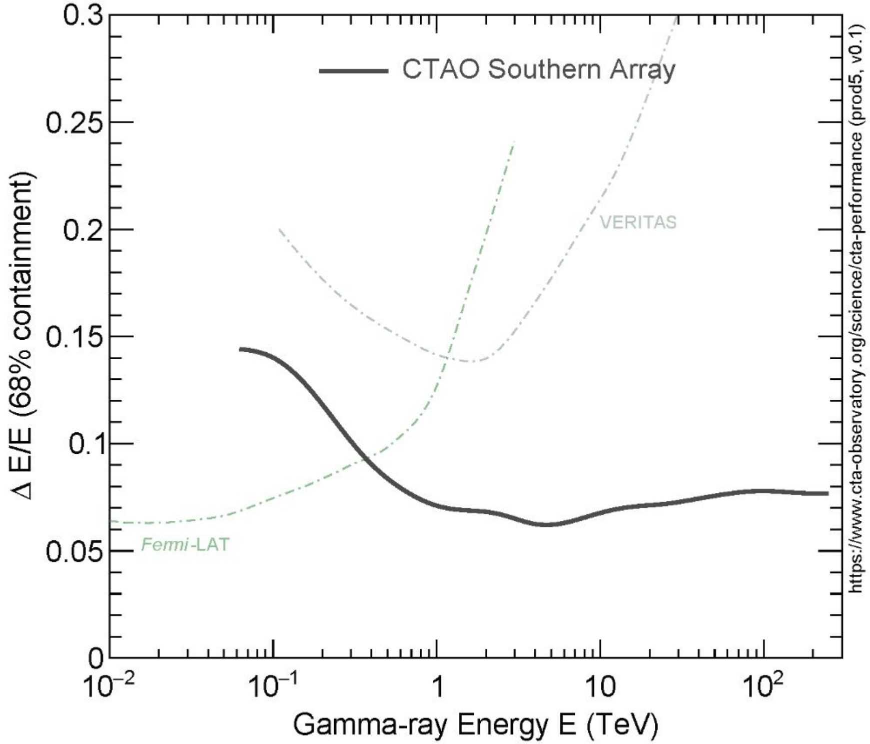
- Prospective for LIV in CTA era :
  - GRB population study
  - AGN monitoring program
  - Combination of EBL effect + time lag effect

Back-up slides

Performances

https://pos.sissa.it/395/005/pdf



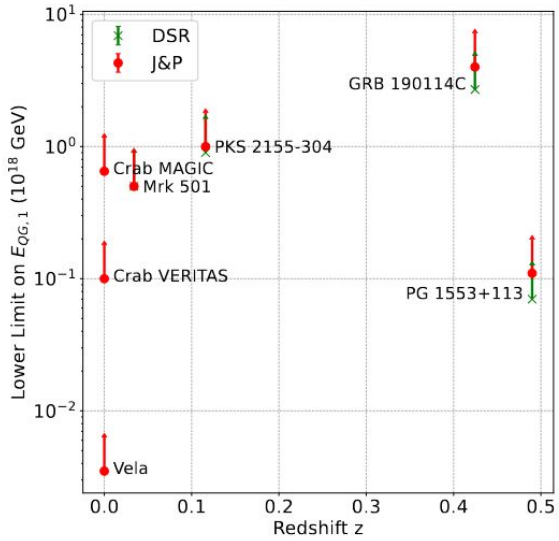


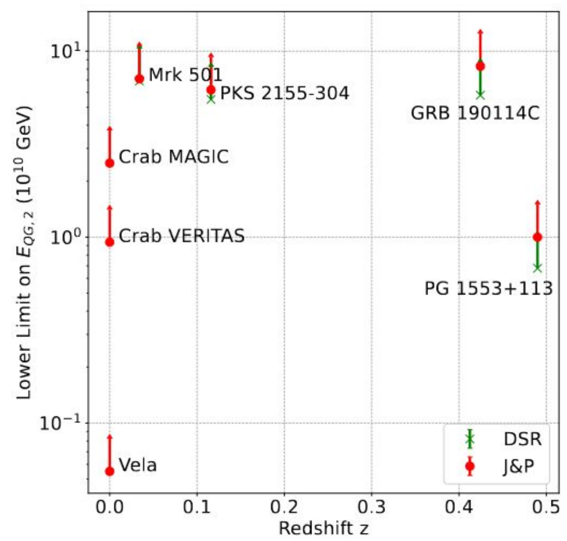
- Only marginally impact LIV analysis (a better resolution reduce the background)

- Key for LIV analysis, directly impact the measurement

Redshift variability of the limit

- Redshift variability of the limit is ruled by three processes :
  - **Distance** (reduce events by D_L^2)
  - **EBL absorption** (high energy events absorbed)
  - **Delay increase with redshift**

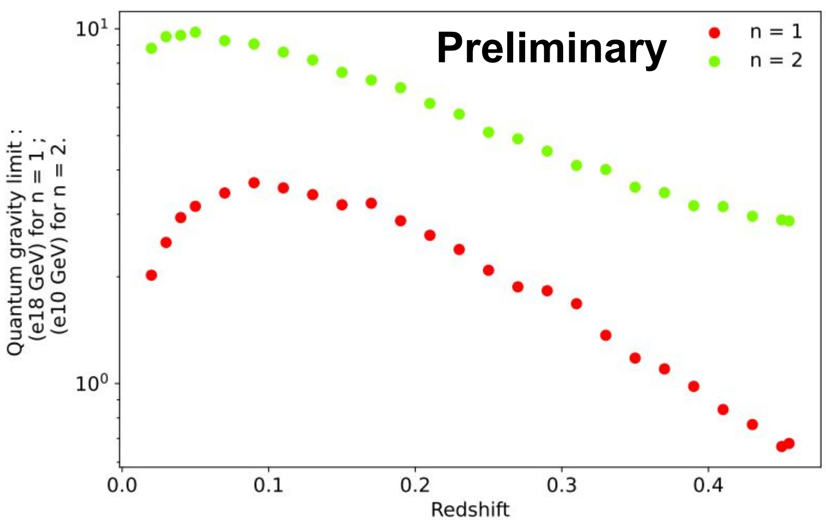


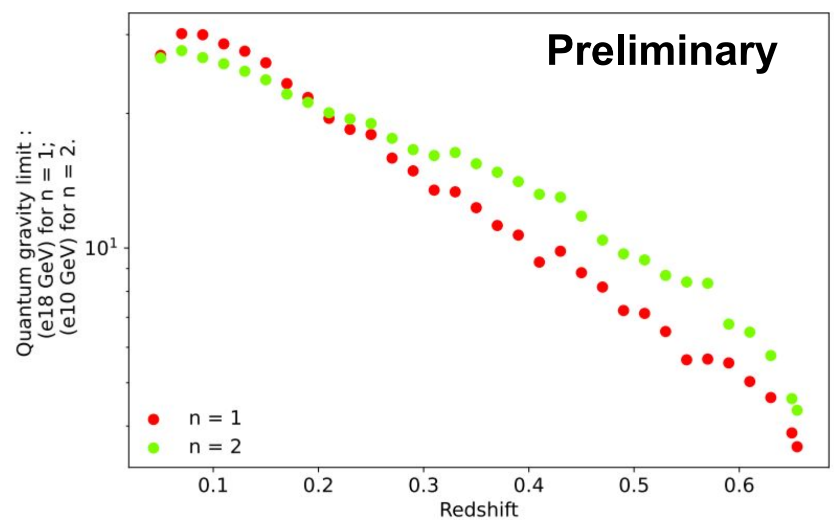


PKS 2155-137

M1 thesis : Amélie Nigou

GRB 190114C





Compared Sensitivity

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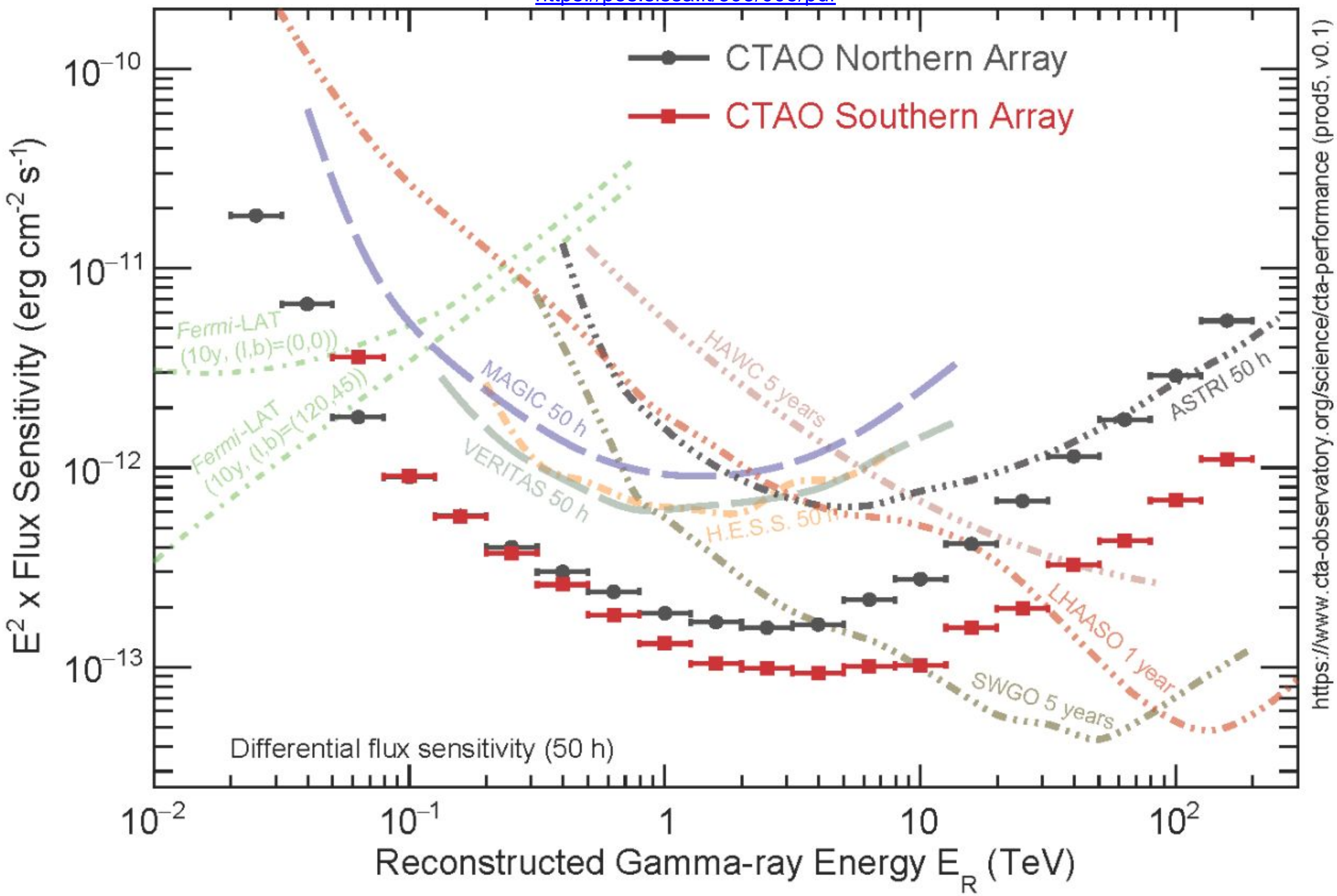
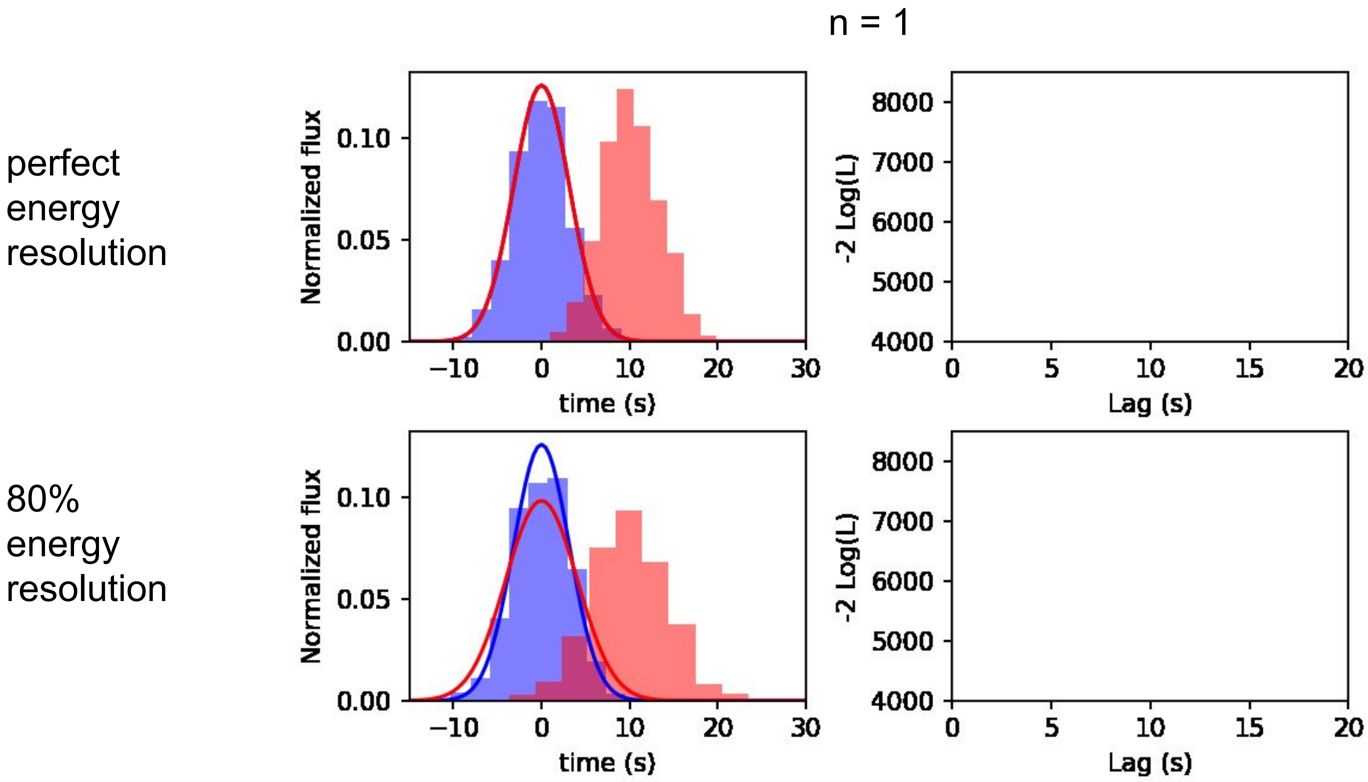


- The lower the more transient sources we can catch
- Mostly the low energy that are important for catching transients

Energy resolution impact on time lag

- Energy resolution effect is similar to add stochasticity in the time lag
- Better energy resolution increases the detectability of the lag



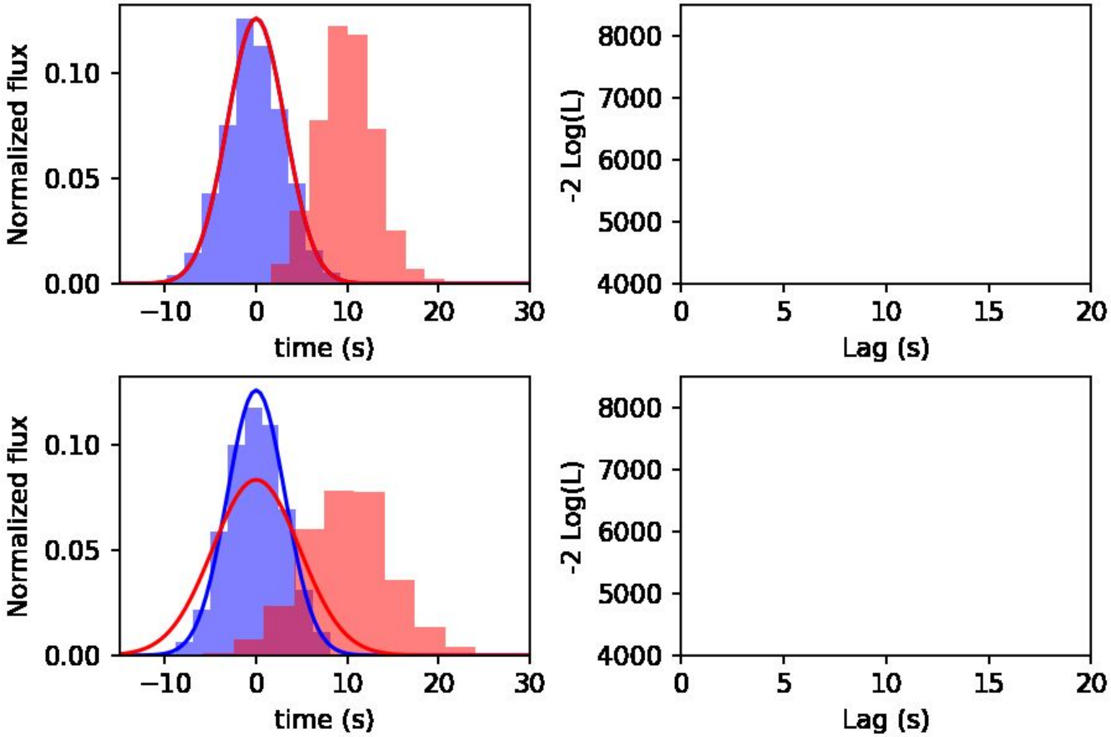
Energy resolution impact on time lag

- Energy resolution effect is similar to add stochasticity in the time lag
- Better energy resolution increases the detectability of the lag
- Worsen for higher LIV order !

n = 2

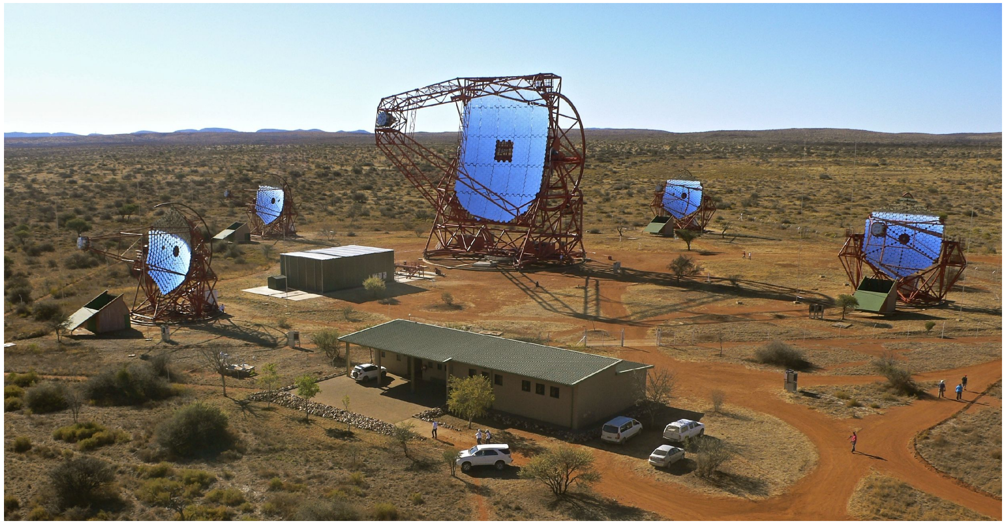
perfect energy resolution

80% energy resolution



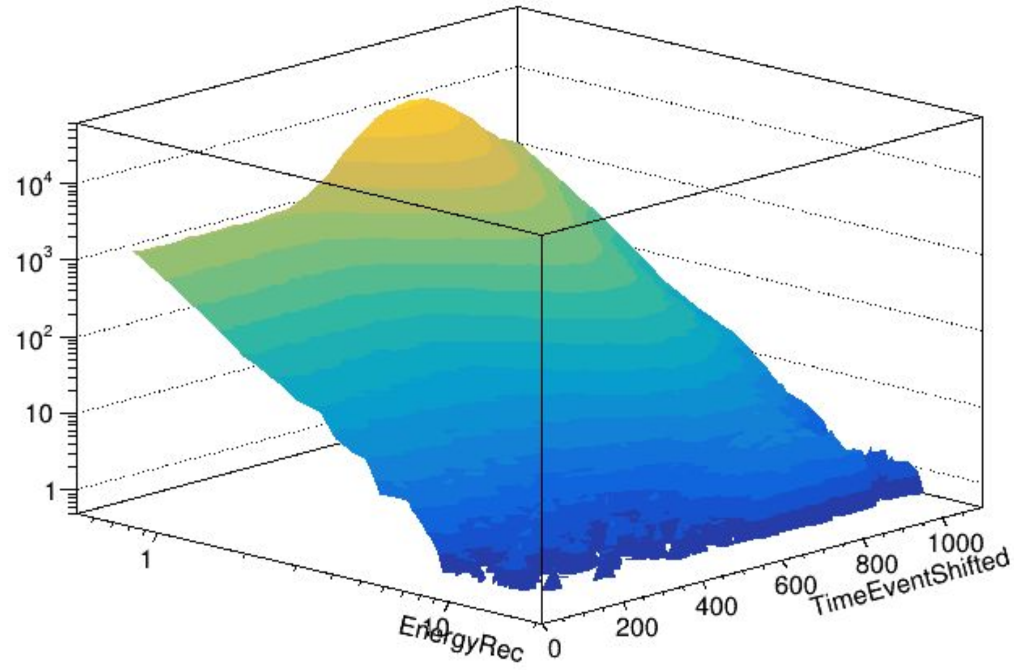
IACTs versus HAWC

- HAWC dedicated for high energy (large surface collection), but not optimal for transient because of “bad” short time sensitivity
- But :
  - 100% duty cycle (can’t miss a transient because of full moon or weather or day light)
  - Big field of view (15% of the sky !!)
- But :
  - No detection of sub-day AGN variability so far…
  - …if any in future, would be interesting to add HAWC in the consortium



Simulations

- Light curve simulation code included in the LIVelihood code
- Able to run simulations for light curve and phasograms (pulsar)
- Parameters needed :
  - Light curve shape (or phasogram shape)
  - PL index of signal and bakground
  - IRFs (Acceptance, Energy Migration) can handle time dependent IRFs
  - Redshift
  - Injected Time lag per energy
  - N_signal and N_background



Time Lag redshift corrected

$$\lambda_n \equiv \frac{\Delta t_n}{\Delta E_n \ \kappa_n(z)} = \pm \frac{n+1}{2\mathrm{H}_0 \ E_{QG}^n},$$

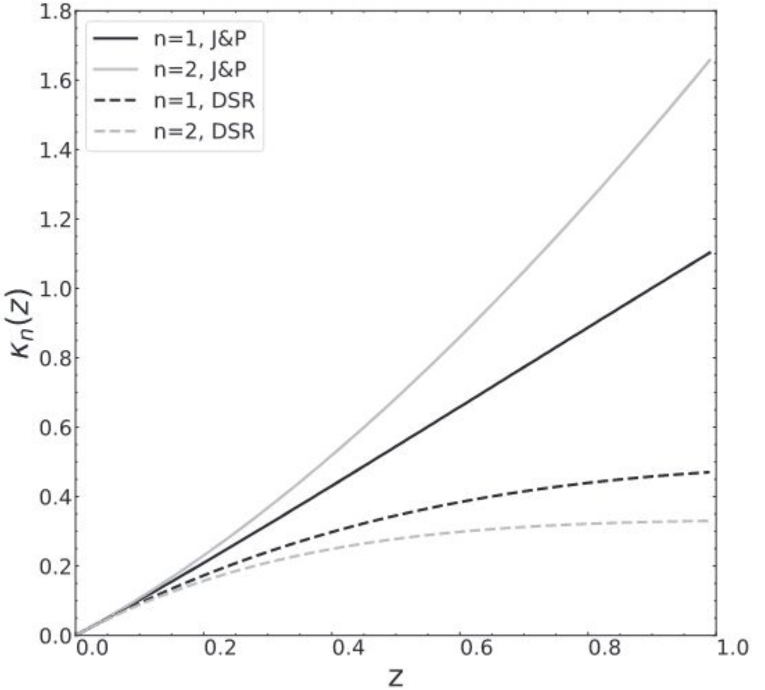
- Constrained parameter, redshift independent (can be easily combined between sources/experiments)
- Distance Lag parameter can be computed with two different models assumptions (J&P, DSR)
- Other models can be easily implemented

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

$$\kappa_n^{\mathrm{DSR}}(z) \equiv \int_0^z \frac{h^{2n}(z')dz'}{(1+z')^n \sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}},$$

with

$$h(z') \equiv 1 + z' - \sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda} \times \int_0^{z'} \frac{dz''}{\sqrt{\Omega_m (1+z'')^3 + \Omega_\Lambda}}$$



Detection principle