JOURNÉE DES ETUDIANTS

LORENTZ INVARIANCE VIOLATION RESEARCH WITH ACTIVE GALACTIC NUCLEI

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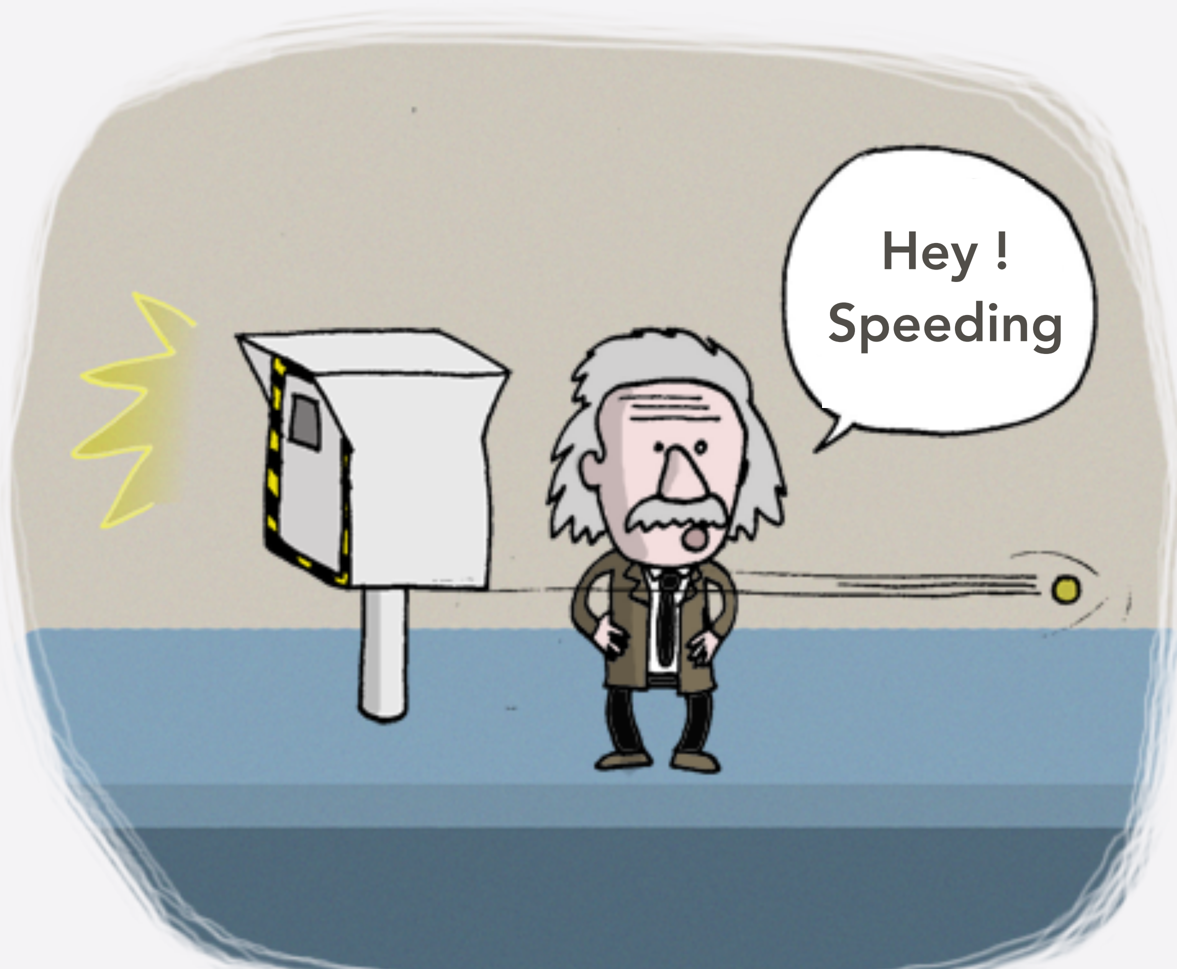
Theoretical framework



WHAT IS LORENTZ INVARIANCE VIOLATION ?

LIV appear in some **Quantum Gravity (QG) models** (string theory, loop quantum gravity . . .)

A **modified dispersion relation** for photon in void can appears, violating Lorentz Invariance. We can express it in a model independent way :

$$E = p^2c^2 \left[1 \pm \sum_n k_n \left(\frac{E}{E_P}\right)^n\right]$$

This lead to a **difference of time of flight** of photons with different energy during their propagation :

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

INTRODUCTION

Observation framework

WHICH SOURCE TO OBSERVE THIS EFFECT ?

$$\tau = \frac{\Delta t}{\Delta E} = \pm \frac{1+n}{H_0} \frac{1}{E_{QG}^n} f_n(z)$$

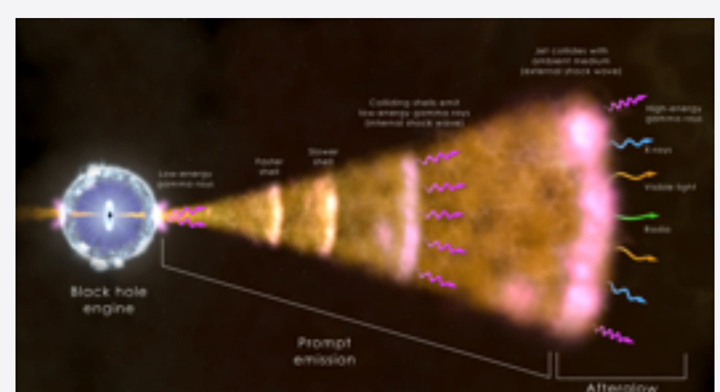
Three important criteria in order to be able to see this effect :

- **A variable source** in order to distinguish a time delay
- **A distant source** to maximize the propagation effect and so maximize $f_n(z)$
- A source which emit photons with **large energy range** to maximize ΔE

THREE KIND OF SOURCE FULFILL THOSE CRITERIA :

Active Galactic Nuclei

Pulsars

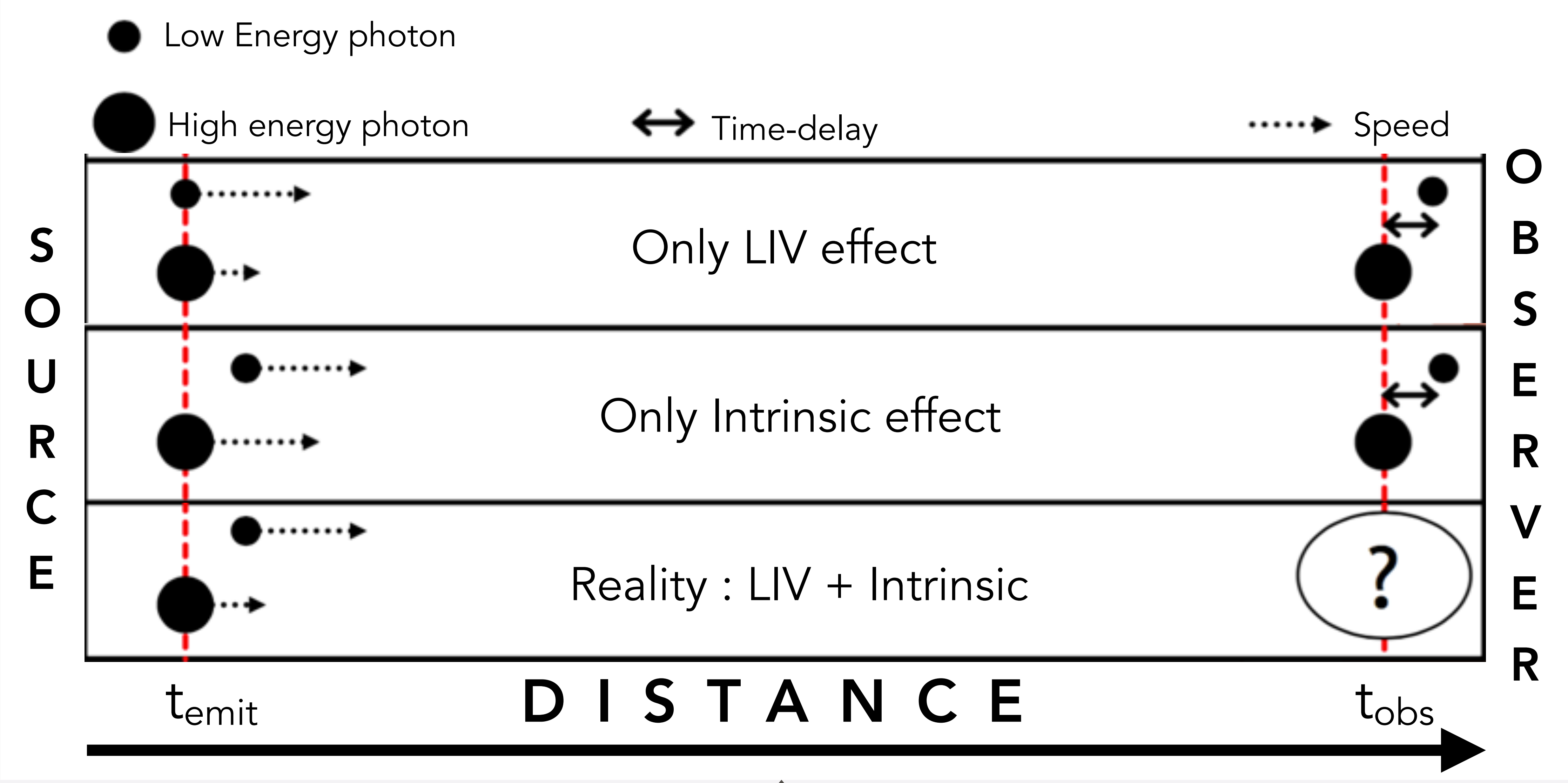


Gamma-Ray Burst

INTRODUCTION

Why modeling ?

Studying Active Galactic Nuclei is crucial for Lorentz Invariance Violation study in order to **constrain measured time-delay** :



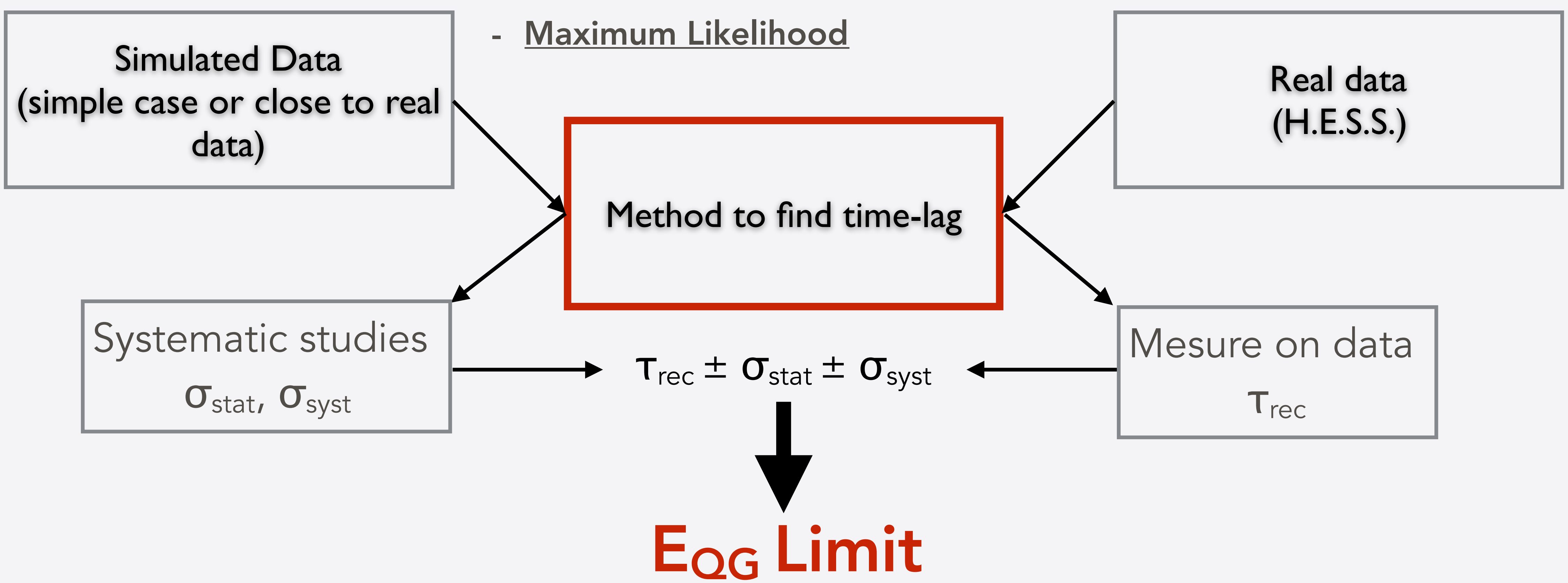
LIV

Goal of LIV study

We try to mesure **a time-lag τ_n**, sign of Lorentz Invariance Violation

Different methods exist :

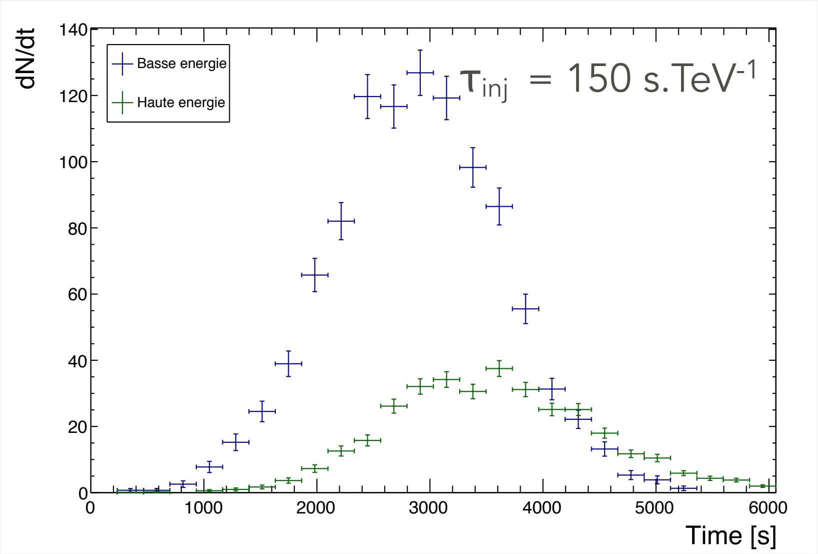
- *Pair view*
- *Sharpness Maximisation Method*
- *Cross-Correlation*
- **Maximum Likelihood**



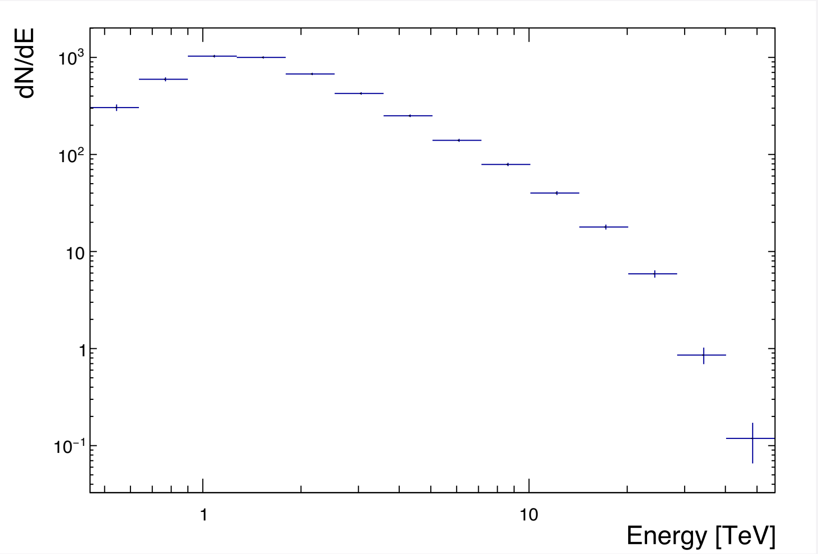
LIV

Results : Test of the method

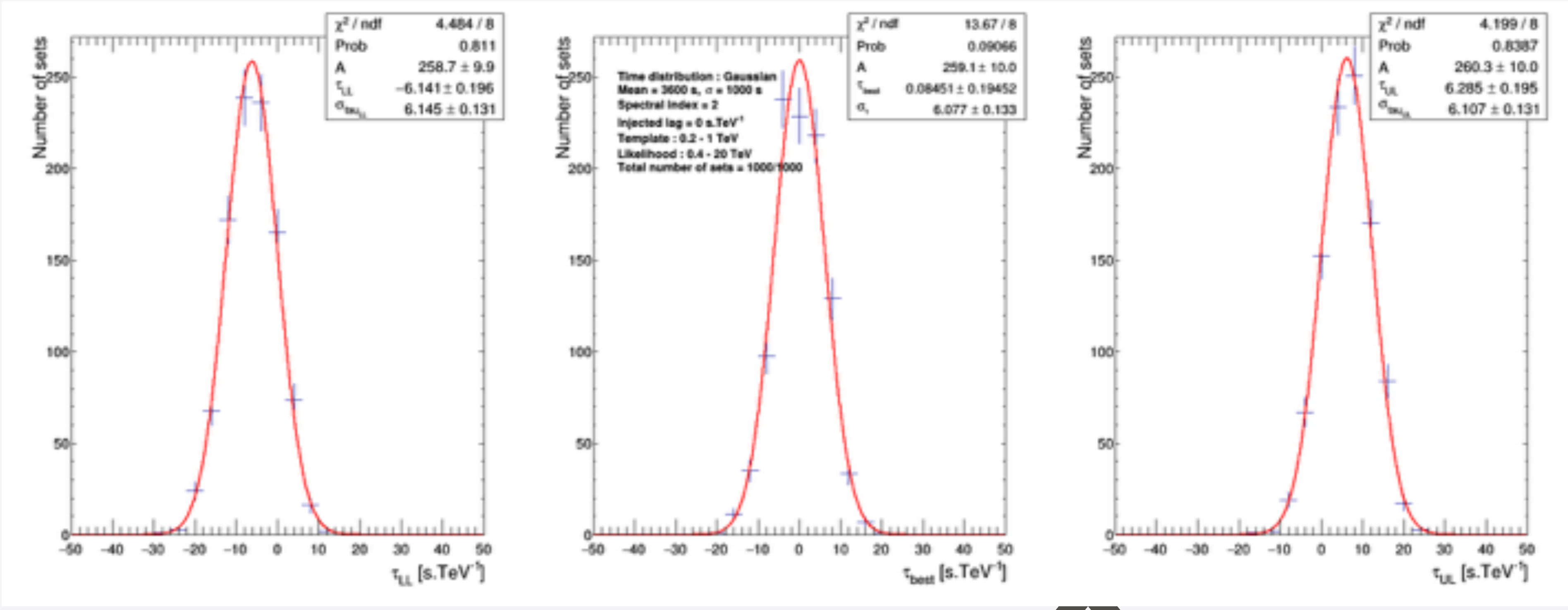
Time distribution : Gaussian



Energy distribution : (PowerLaw) x (Detector's Acceptance)



Simulation parameters



Injected lag :

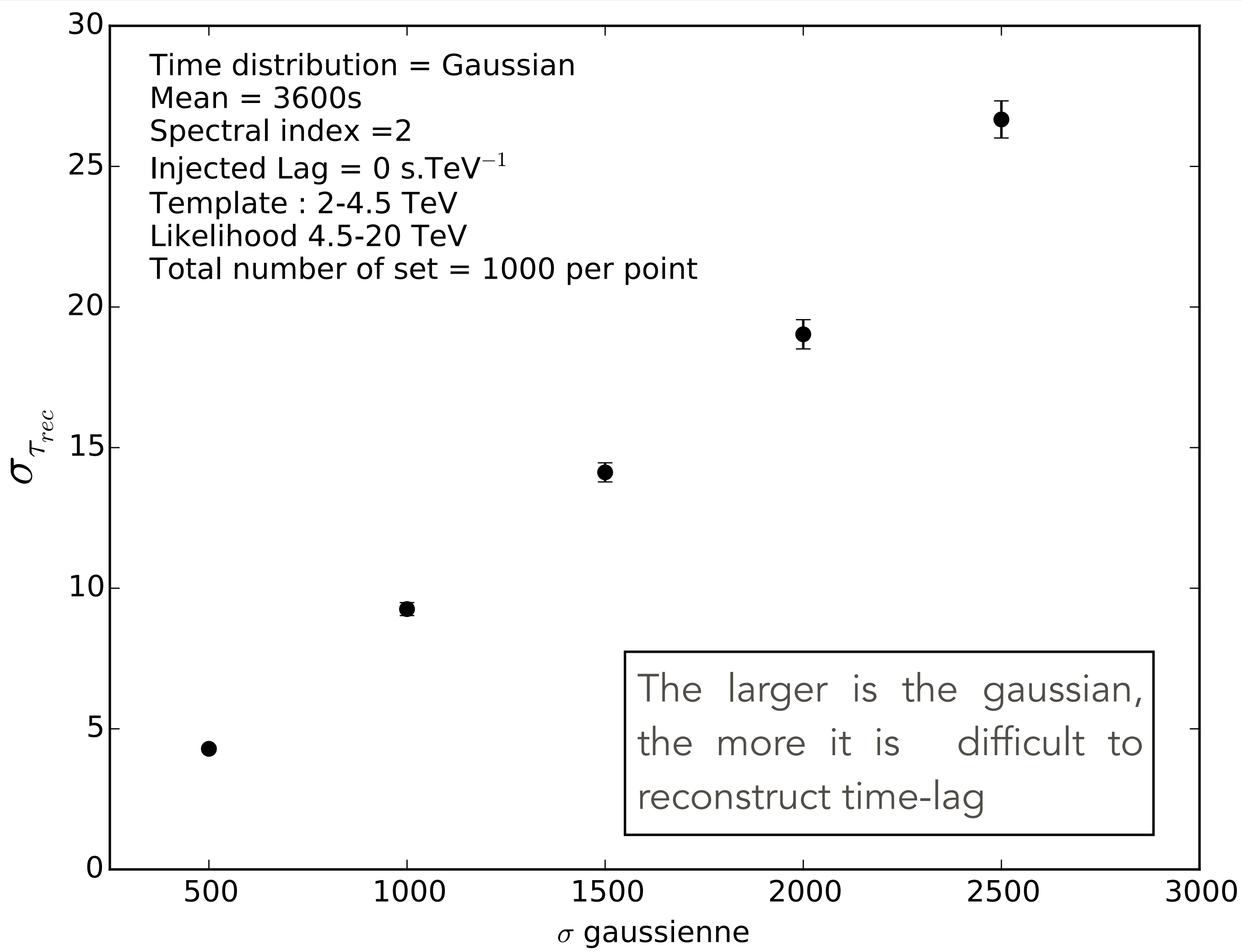
τ_{inj} = 0 s.TeV^{-1}

LIV

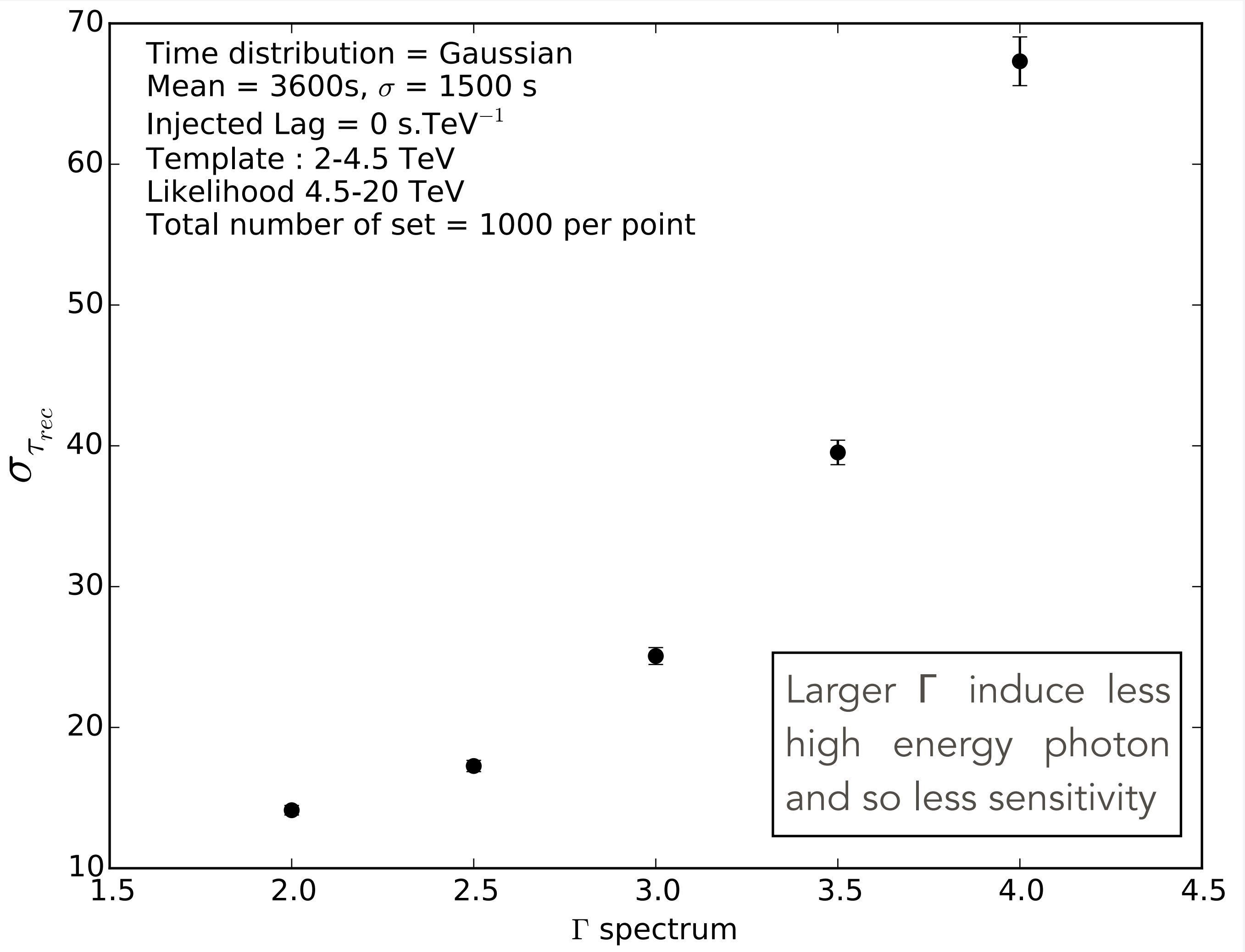
Results : Test of the method

We are looking **the impact of the source parameters on the errors** of the reconstruction of the time-lag parameter τ_n

Lightcurve's Gaussian width

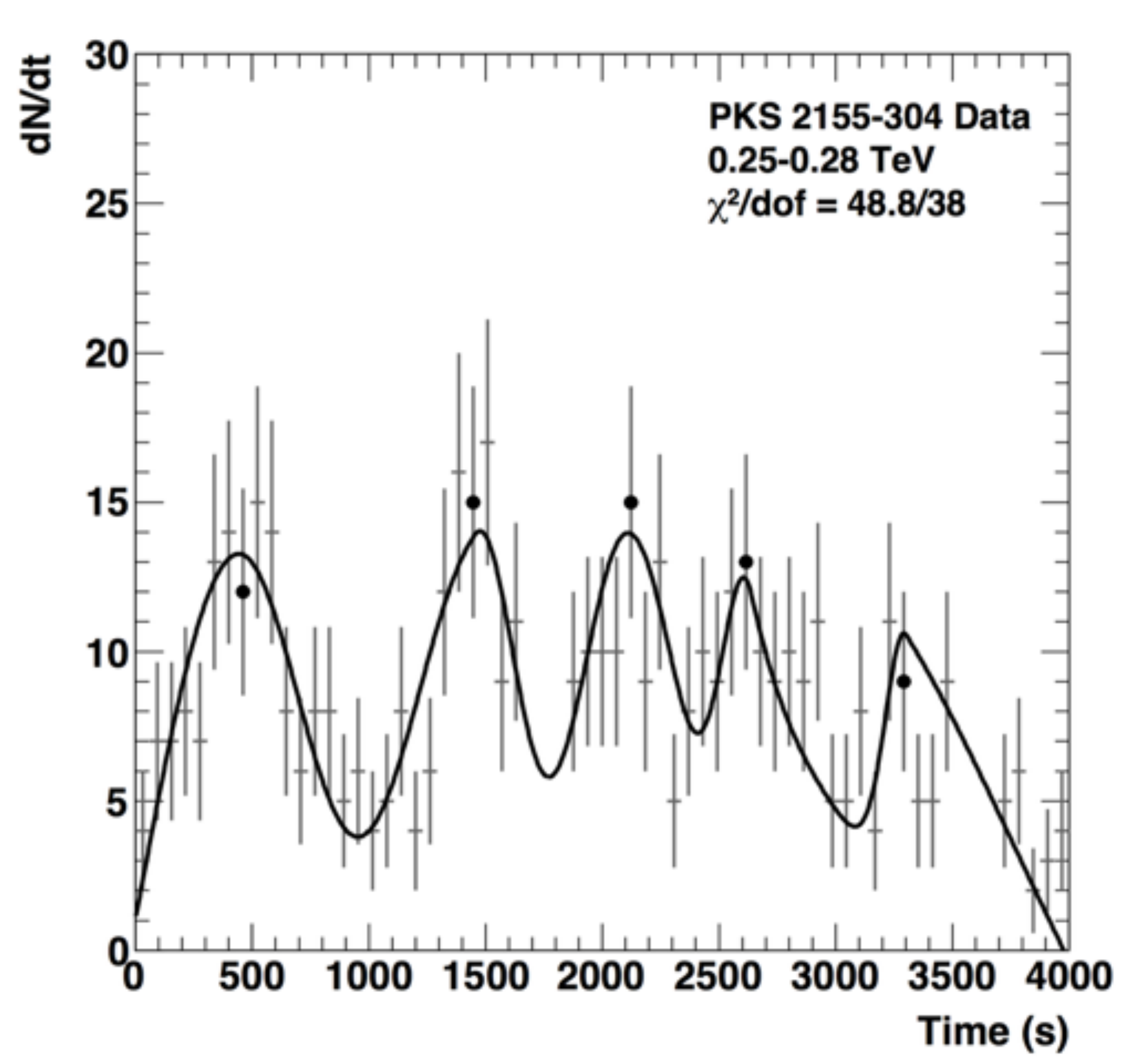


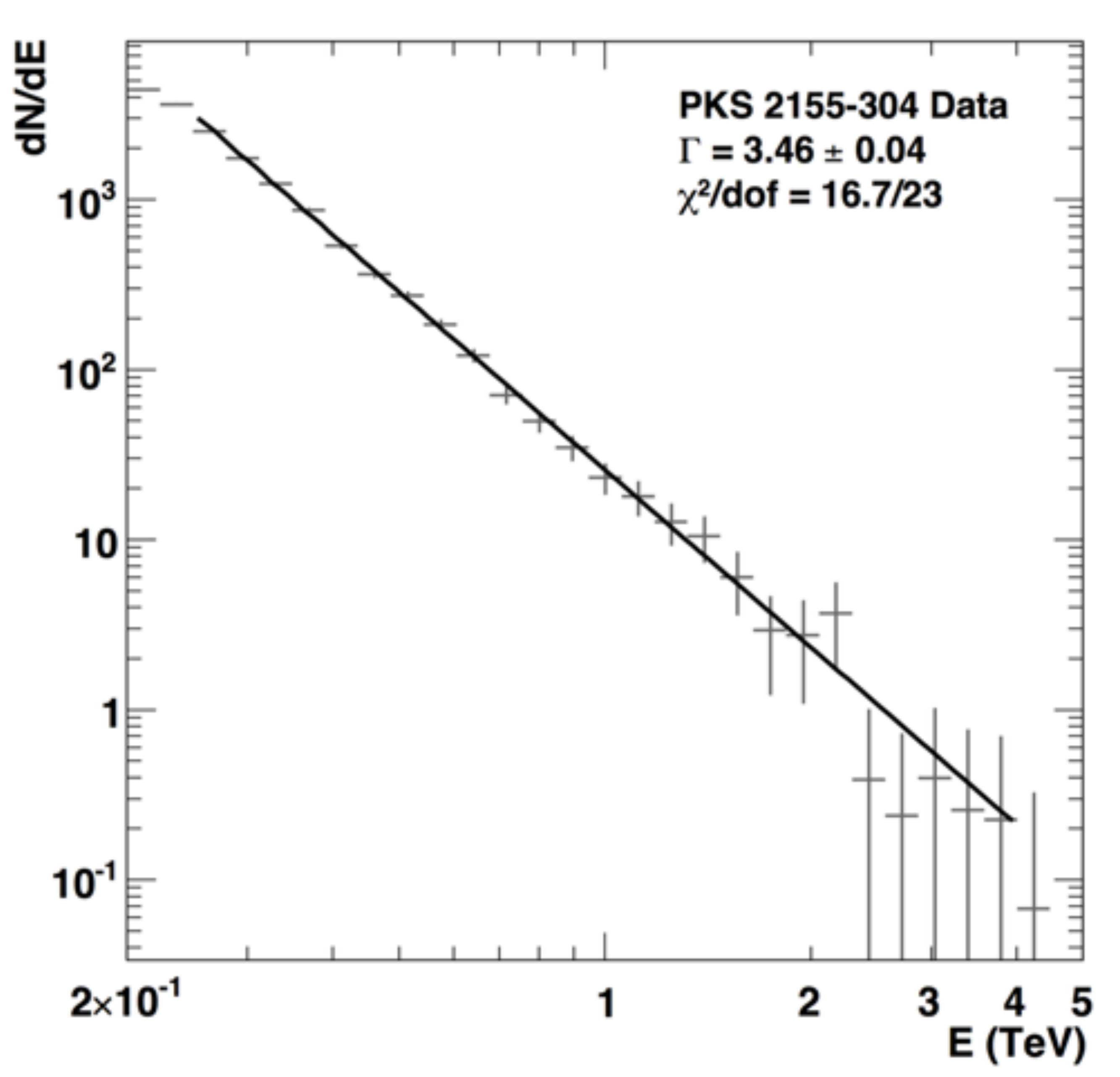
Spectral index Γ



LIV

Results : Re-doing PKS2155-304 analysis

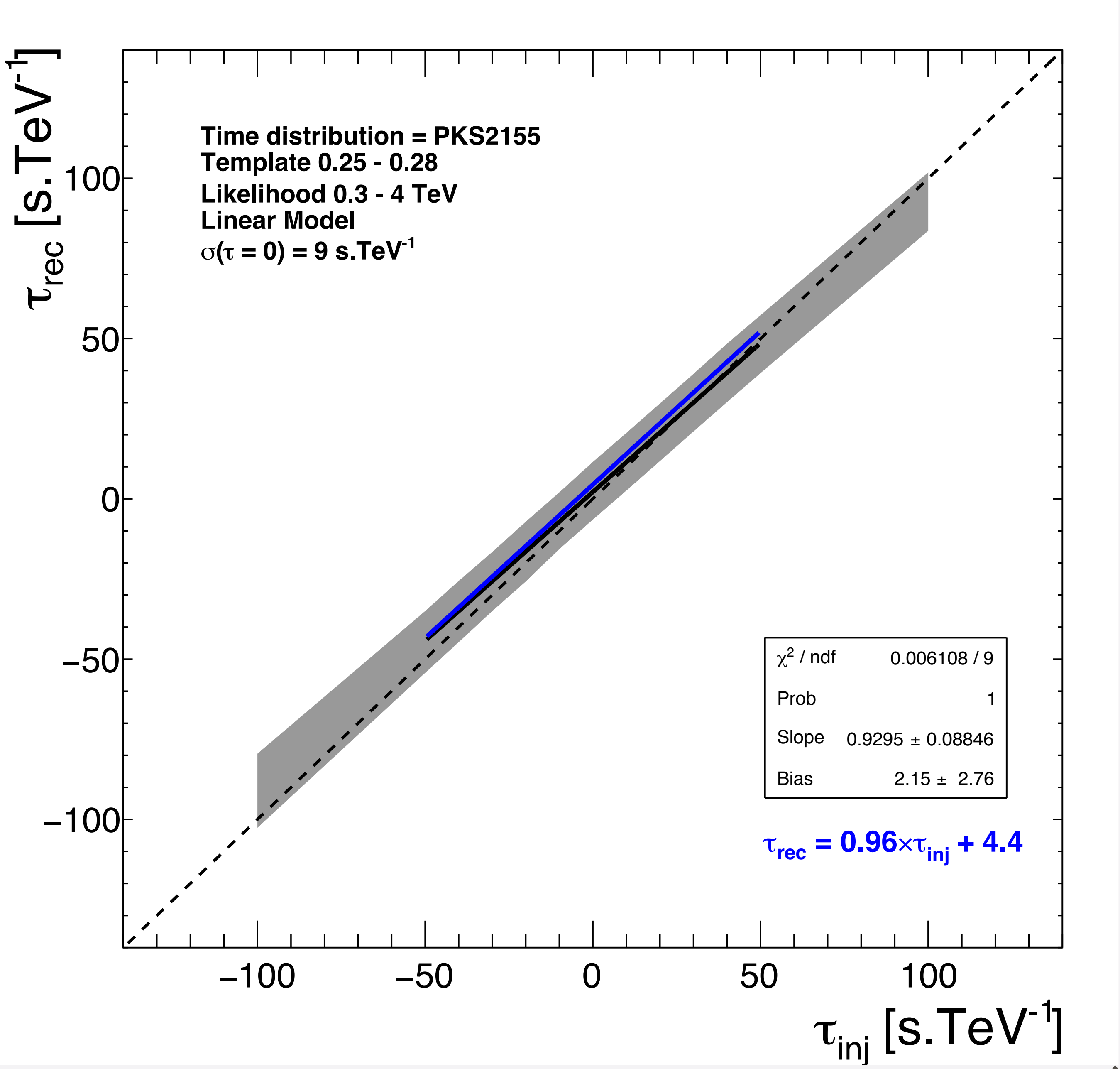


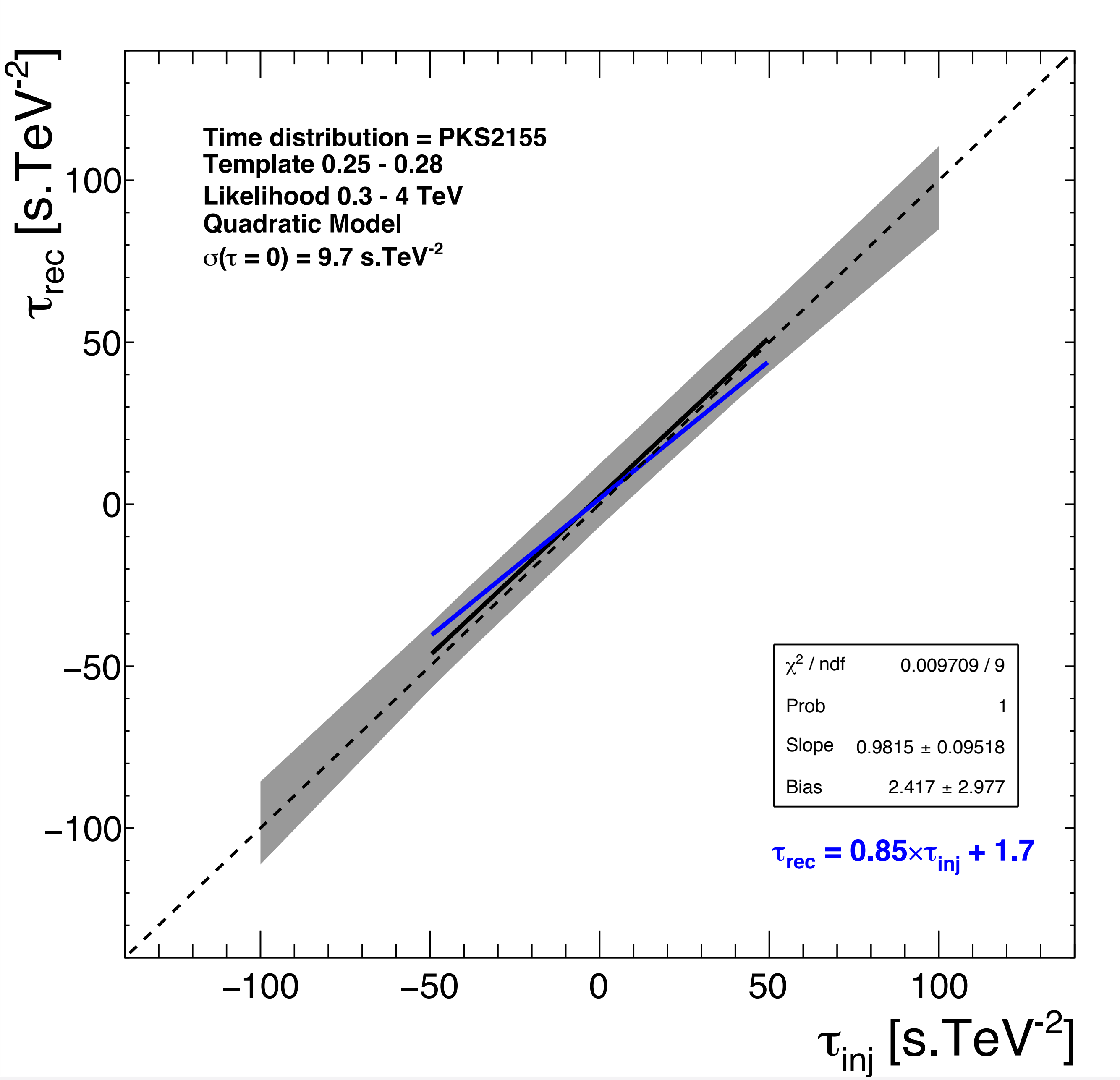


LIV

Results : Re-doing PKS2155-304 analysis

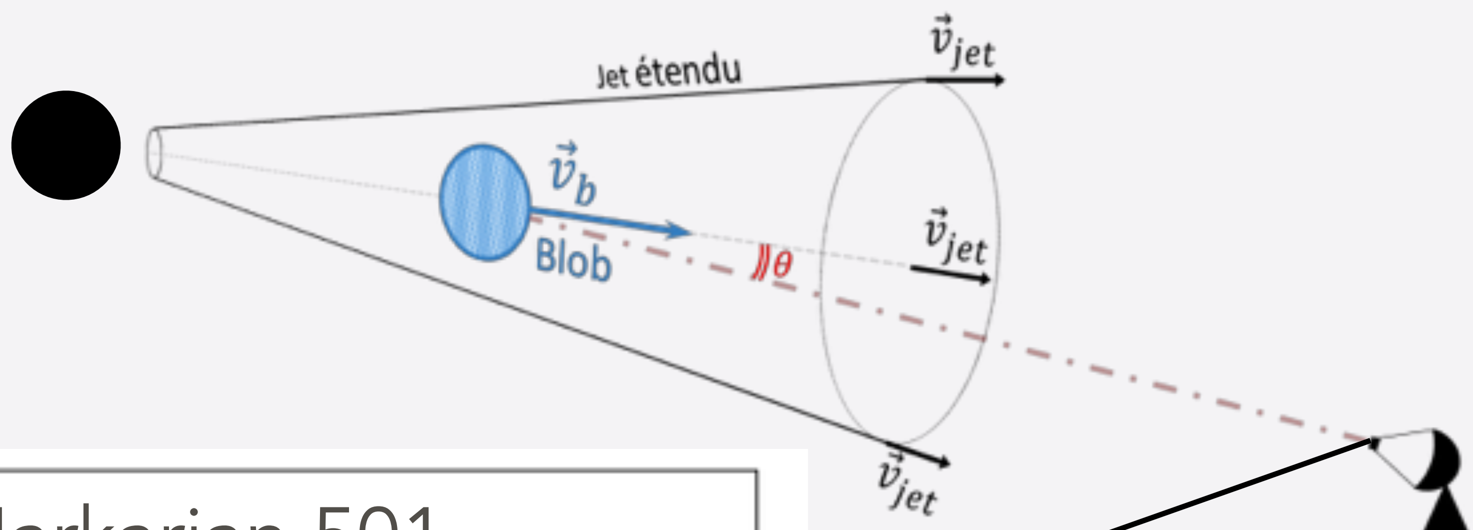
Blue curve from : arXiv:1101.3650v2

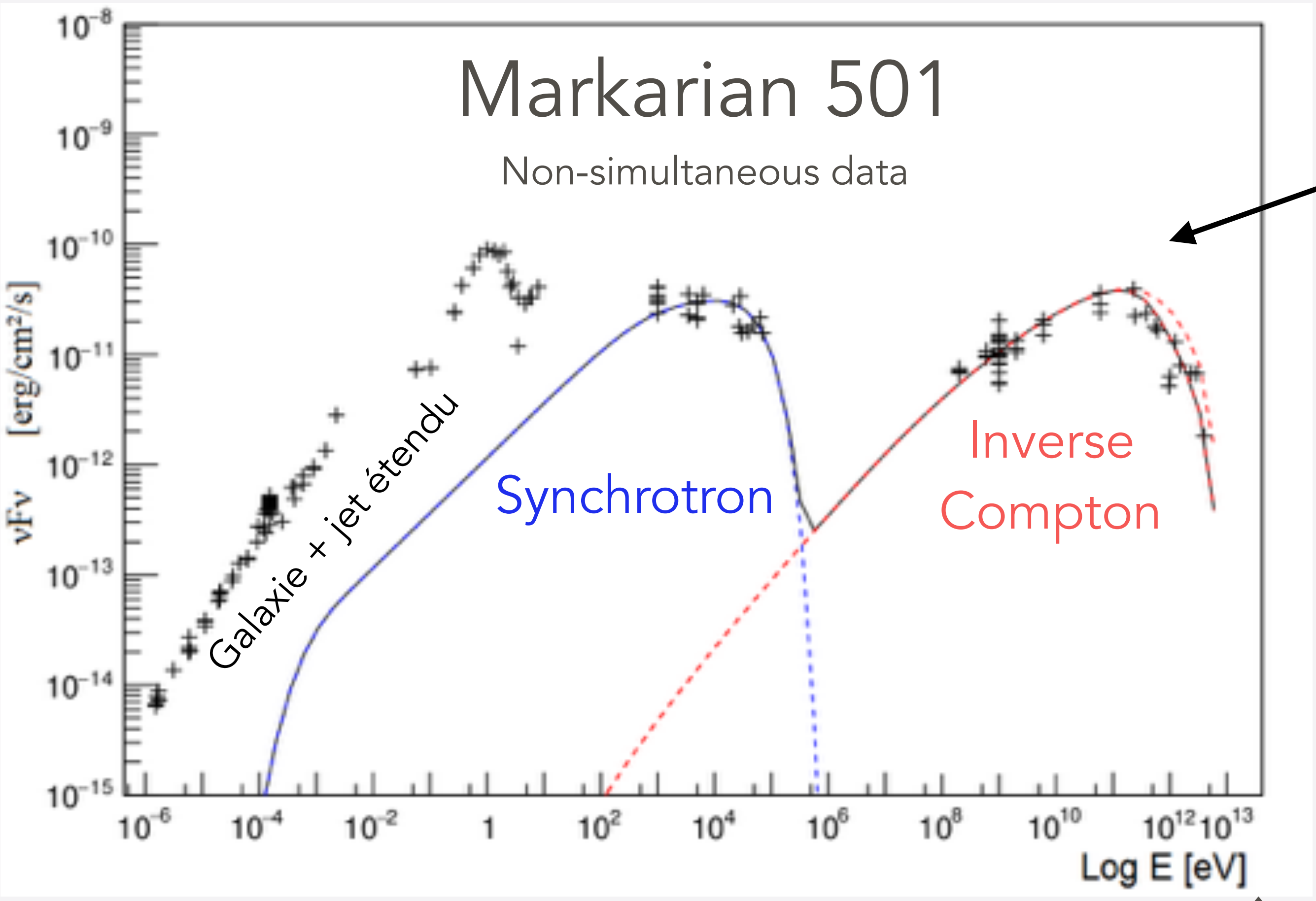


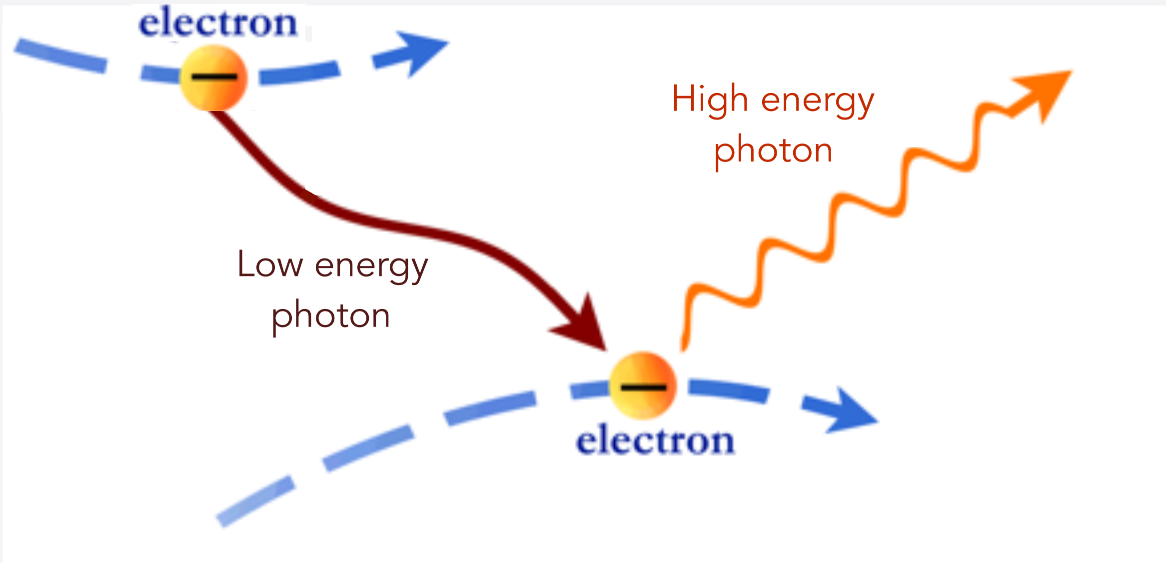


MODELING

Basics of Active Galactic Nuclei model



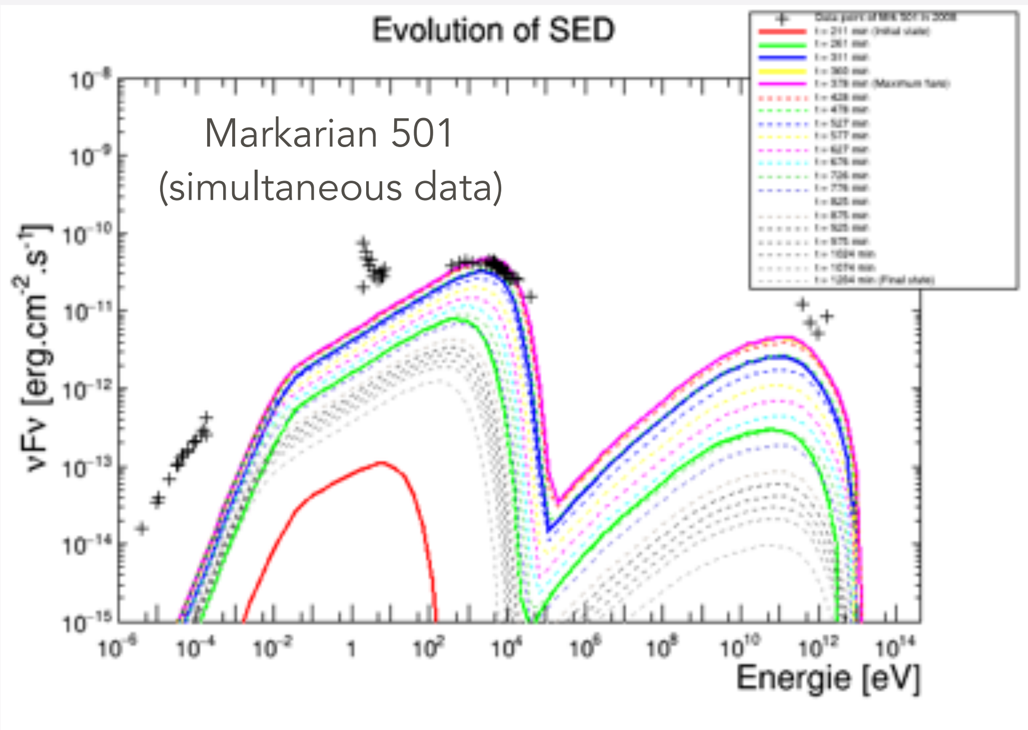


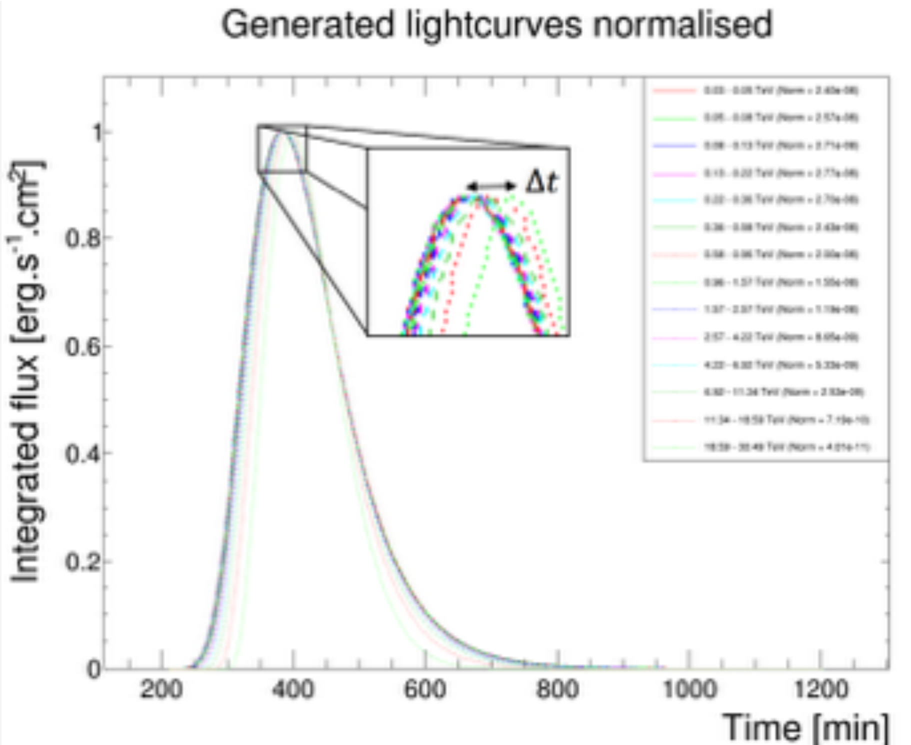


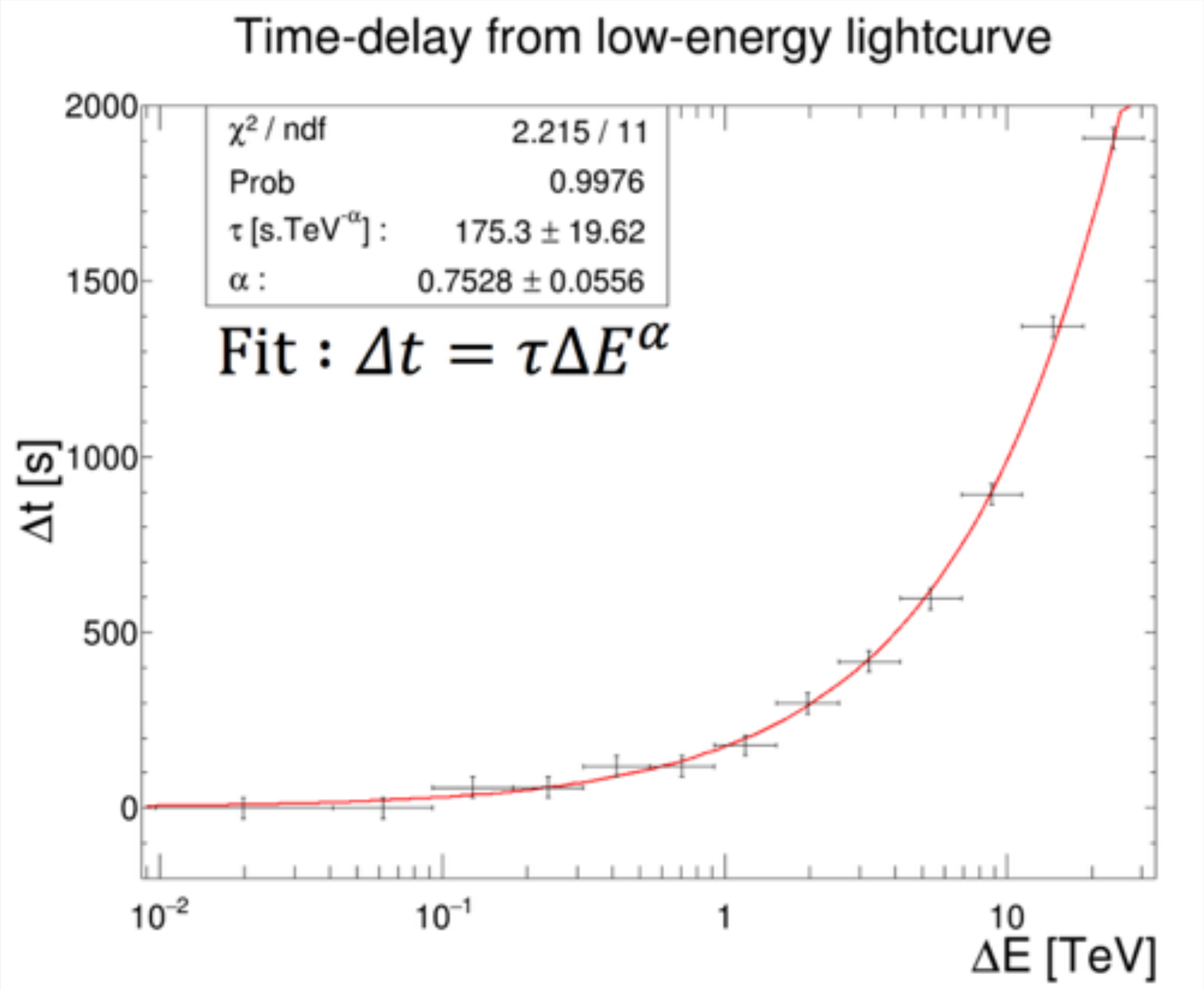
Synchrotron Self-Compton

MODELING

Preliminary work : M2 internship







In a simple model, we can see a time-delay which depend on the energy

MODELING

New time dependent model

The code used in M2 didn't allowed to **explore the whole parameters space**.

We wanted to **create a new code of modeling** active galactic nuclei **focusing on intrinsic time-delay** at high energy.

Starting point : general equation describing the evolution of electrons in active galactic nuclei (*The Origin of Cosmic Rays*, V.L. Ginzburg) :

$$\frac{\partial N_e}{\partial t}+\frac{\partial}{\partial E}\left(b(E,t)N_e(E,t)\right)-\frac{1}{2}\frac{\partial^2}{\partial E^2}\left(d(E,t)N_e(E,t)\right)=Q(E,\mathbf{r},t)-p(E,t)N_e(E,t)$$

$$b(E,t)=\frac{dE}{dt}$$

Systematical energy variation (acceleration, SSC, adiabatic expansion . . .)

$$d(E,t)=\frac{d}{dt}\overline{(\Delta E)^2}$$

Fluctuation of systematical variation (second order terms)

Injection of particles

Loss of particles

MODELING

Numerical integration - Tests of the method

Numerical integration is used to solve the differential equation in order to get **a flexible model.**

A simple **finite difference method** was chosen in the first try :

$$\frac{dN_e(E,t)}{dE} = \frac{N_e(E+dE,t) - N_e(E,t)}{dE}$$

We applied it on a **simple case** to test the method :

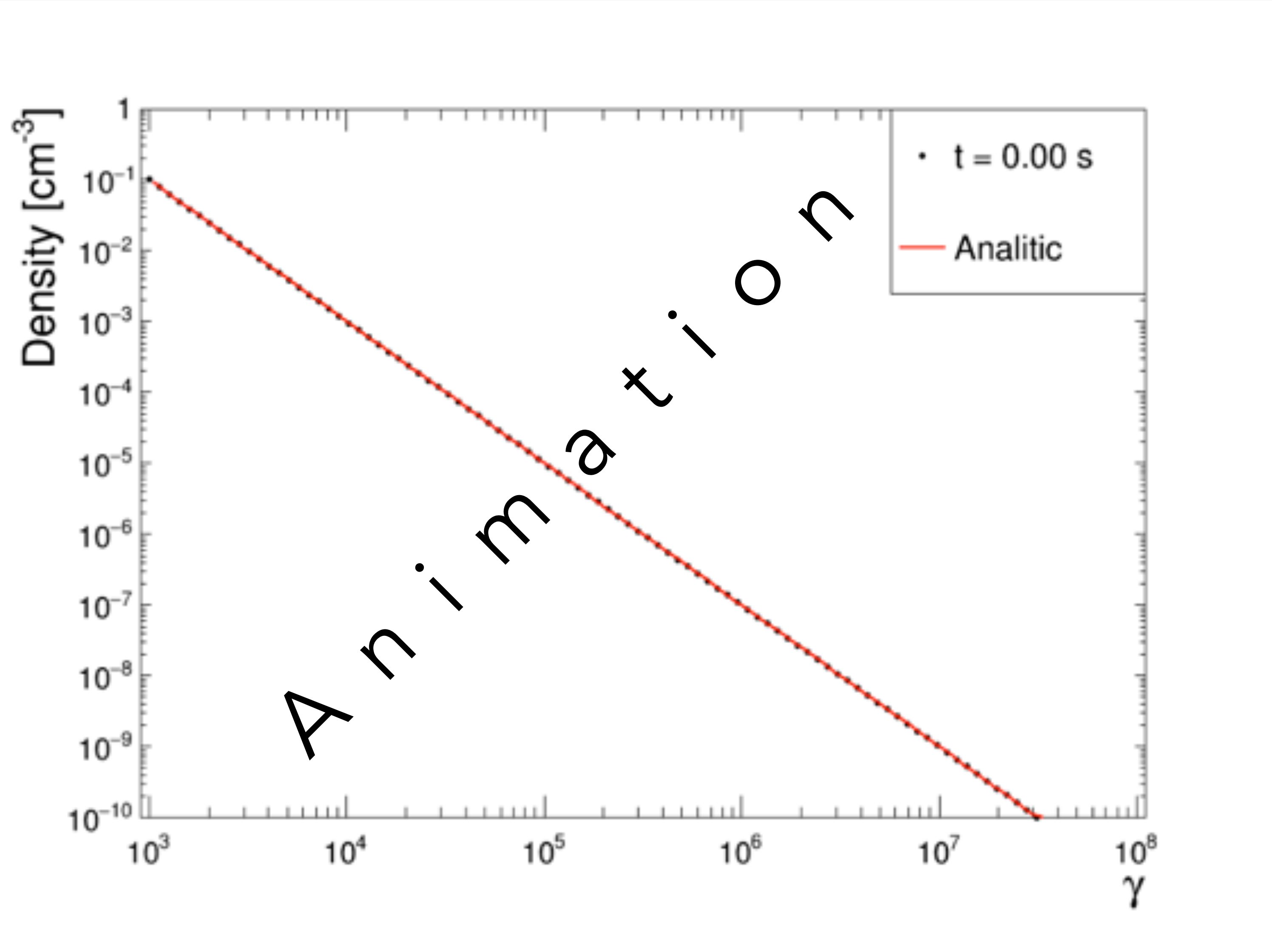
- Initial electron spectrum : $N_e(E,t_0) = K_0 E^{-\Gamma}$
- Only synchrotron losses is considerer : $\left(\frac{dE}{dt}\right)_{synch} = -\beta E^2$

This simple case give the following differential equation :

$$\frac{\partial N_e(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(\beta E^2 N_e(E,t)\right) = 0$$

MODELING

First results



Initial electron spectrum index Γ = 2

Comparison with an **analytic solution** (Kardashev 1981) :

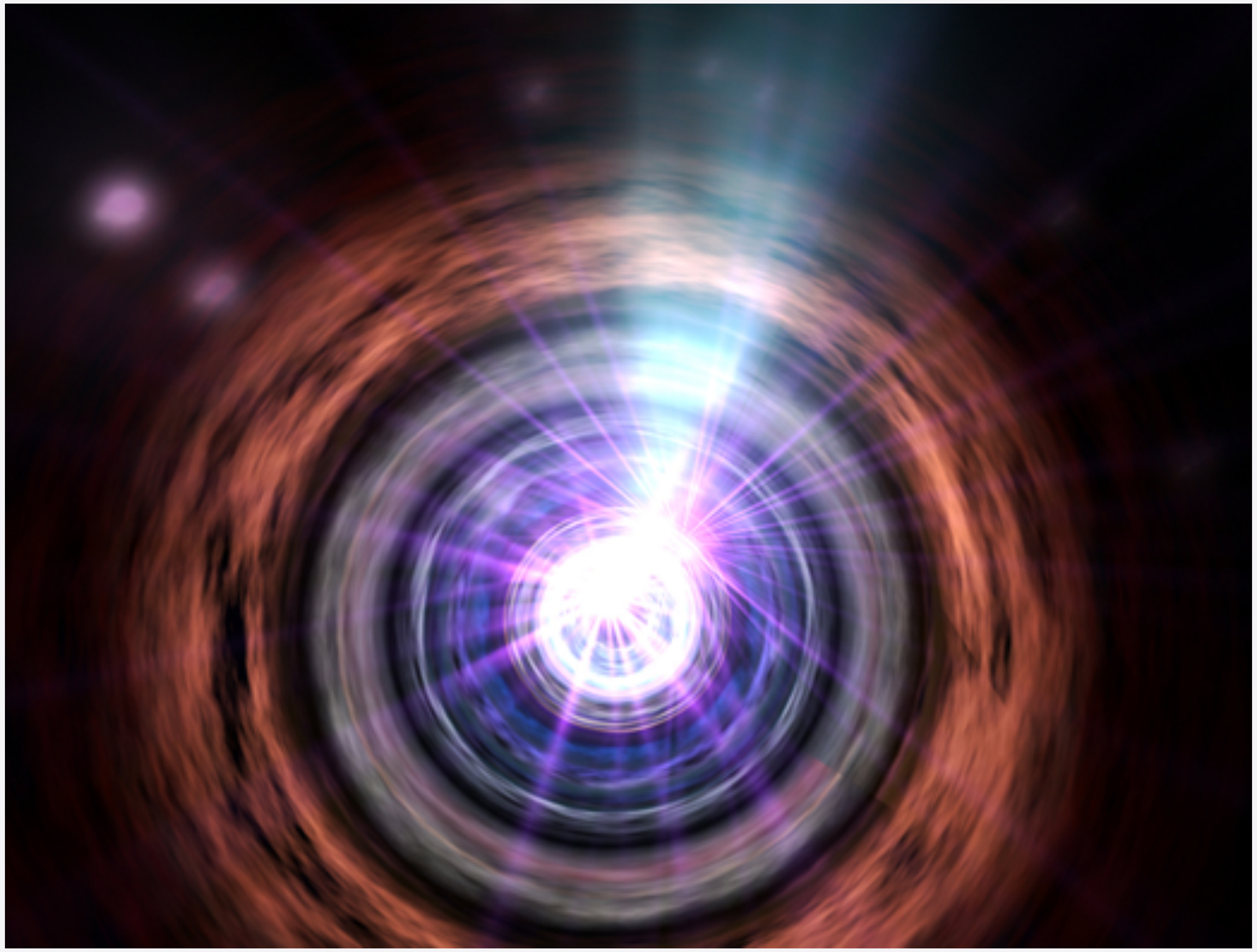
$$N_e(E,t) = \begin{cases} K_0 E^{-\Gamma}(1-\beta t E)^{\Gamma-2}, & E < \frac{1}{\beta t} \\ 0\ , & E > \frac{1}{\beta t} \end{cases}$$

If we check the **synchrotron cooling time** :

$$t_{synch} \propto \gamma^{-1}$$

MODELING

Prospectives pour la modélisation

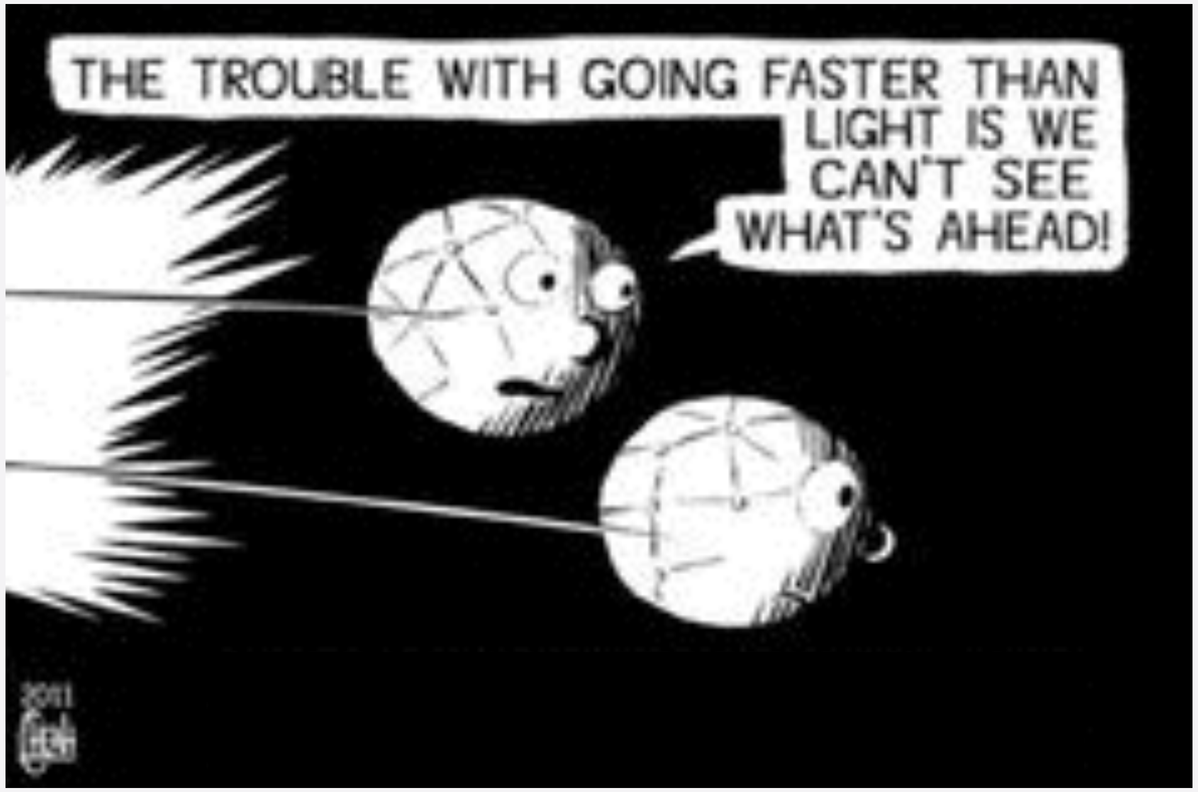


Next step for modeling :

- **Use a better method** for the numerical resolution
- **Add others physical effects** : Acceleration, particles injection, Inverse Compton losses . . .

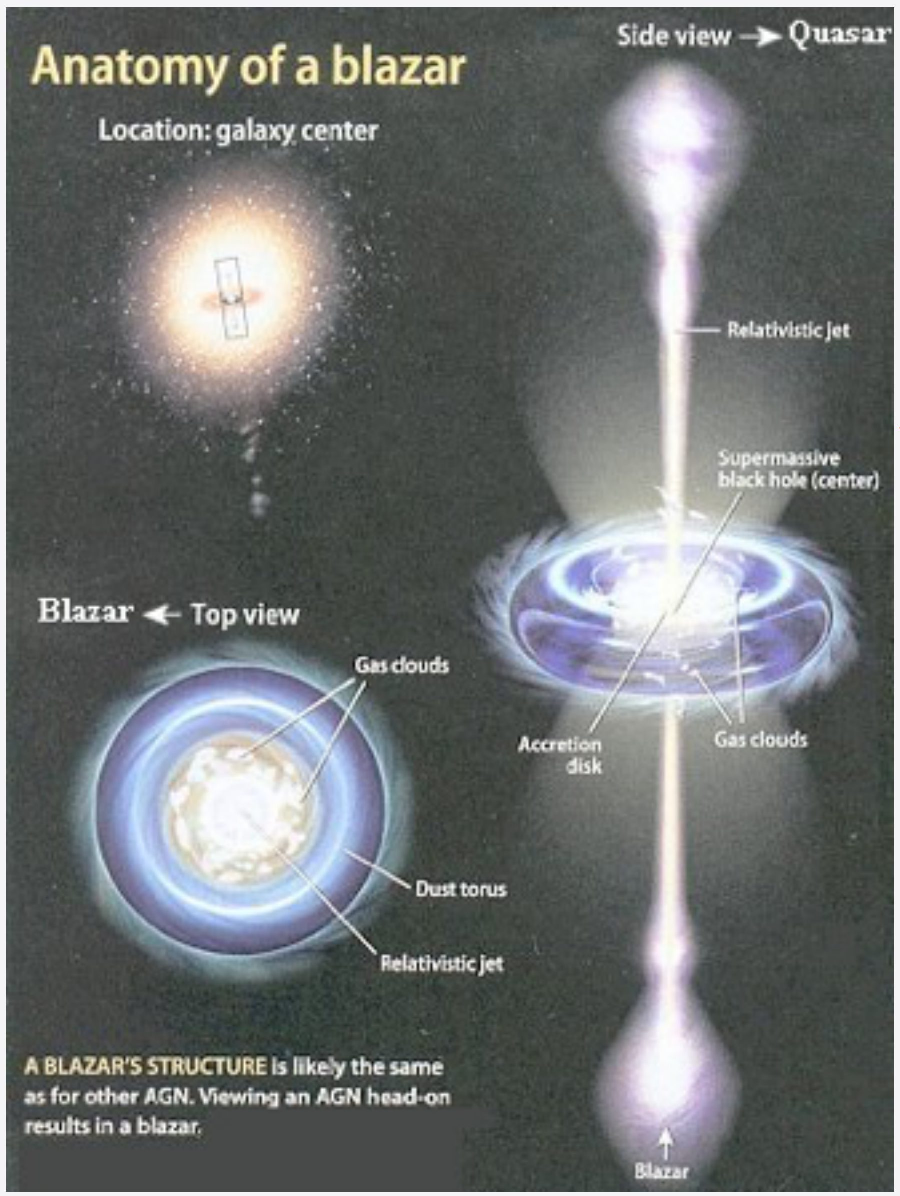
And when the **code will be ready**, we will be able to use the output of the model to **compute lightcurves** which will be **injected directly in the LIV analyse** to reconstruct **time-lag from source.**

Thank you for your attention



INTRODUCTION

Observation framework



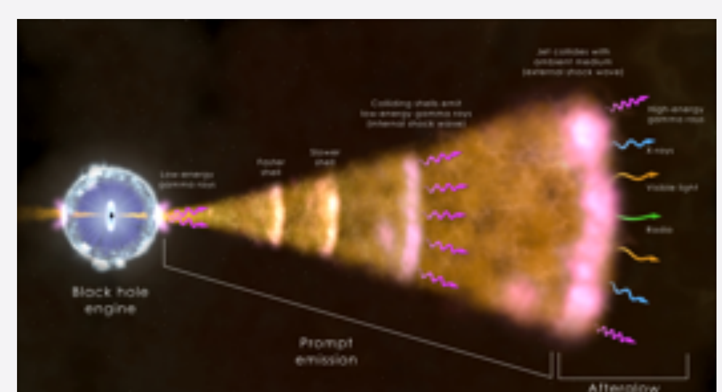
Doppler boosting effect : $\nu_{obs} = \delta \nu_{source}$

$$F_{obs} = \delta^4 F_{source}$$

THREE KIND OF SOURCE FULFILL THOSE CRITERIA :

Active Galactic Nuclei

Pulsars



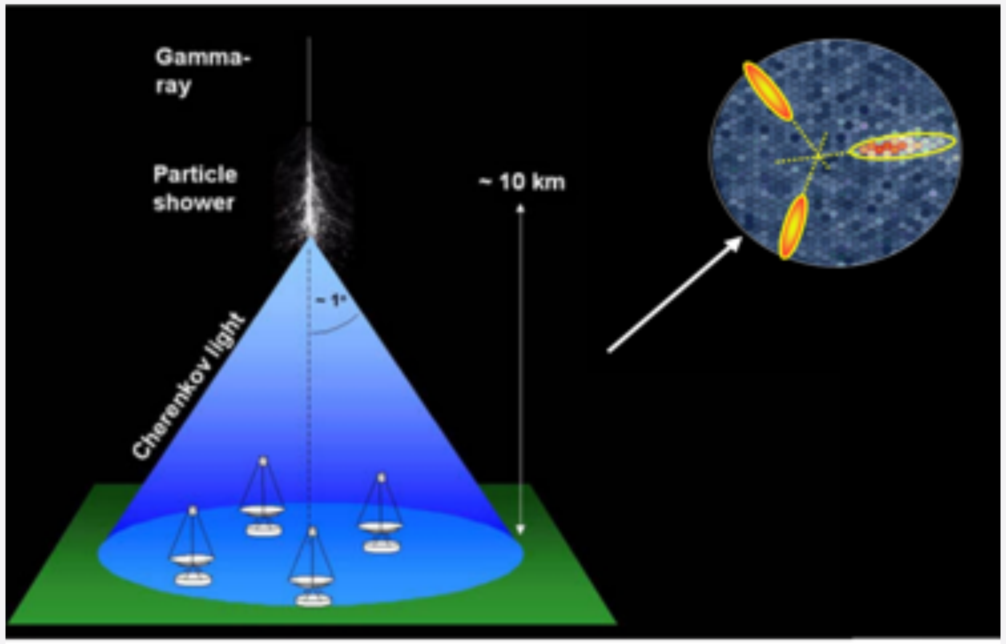
Gamma-Ray Burst

ANNEXE

Observation Instrument

Datas are from H.E.S.S. (High Energy Stereoscopic System) experiment located in Namibia.

H.E.S.S. is a hybride network of 5 Cherenkov telescope (4 small telescopes and one big) observing photons from dozen of GeV to a dozen of TeV



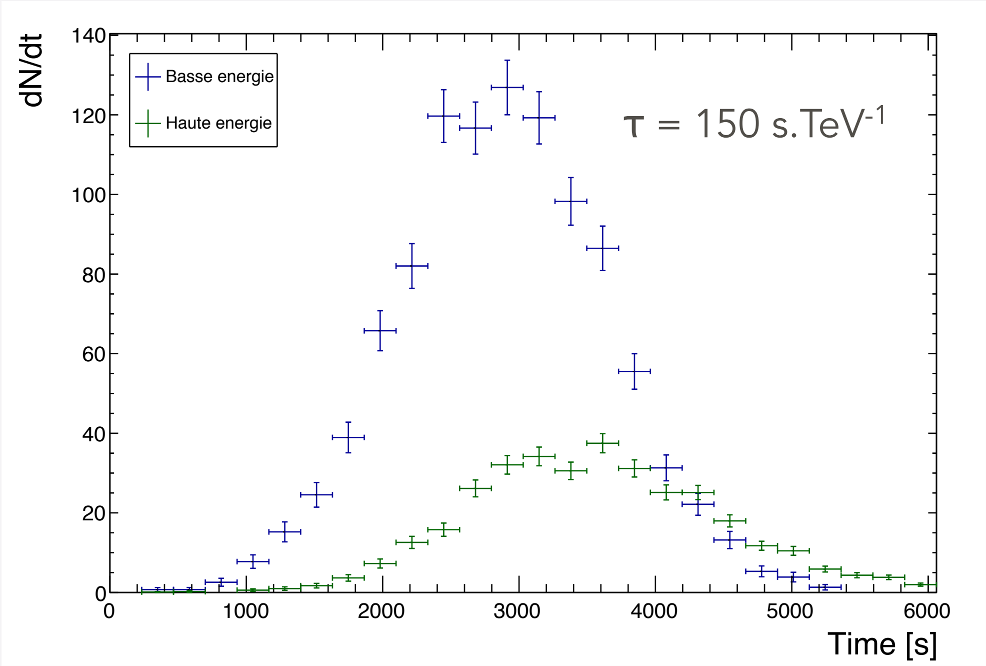
LIV

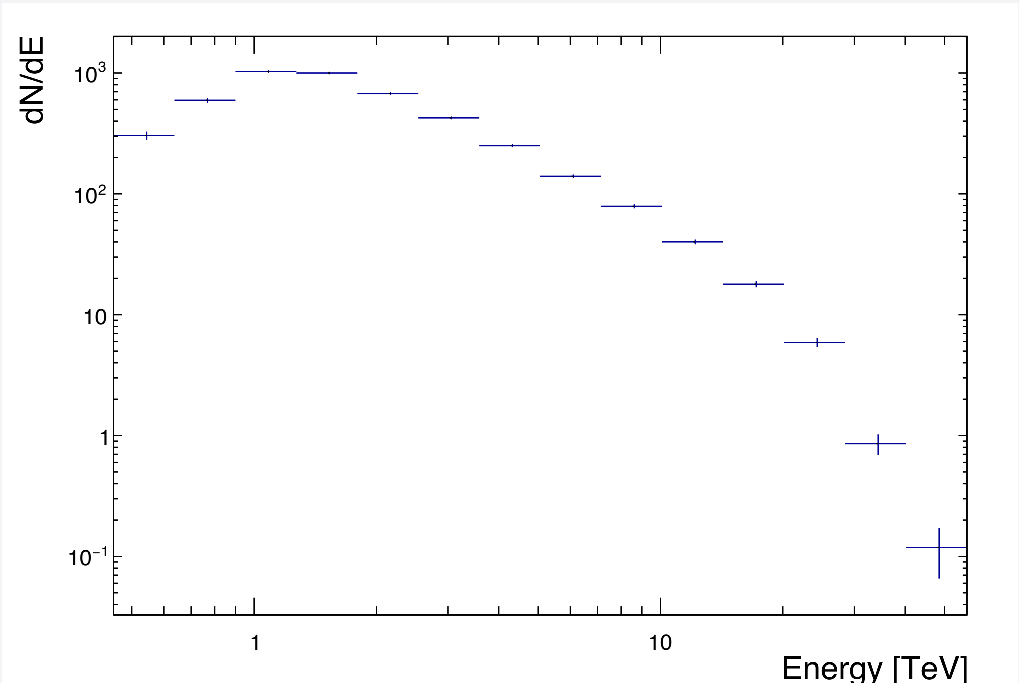
Simulation of LIV research

To simulate data, we need **three input** :

- ✦ A **spectral shape**
- ✦ A **lightcurve shape**
- ✦ **I.R.F.** from the experience we consider : Acceptance and Energy resolution

We can then inject the time-lag : $t_{rec} = t_{true} + \tau_n E^n$





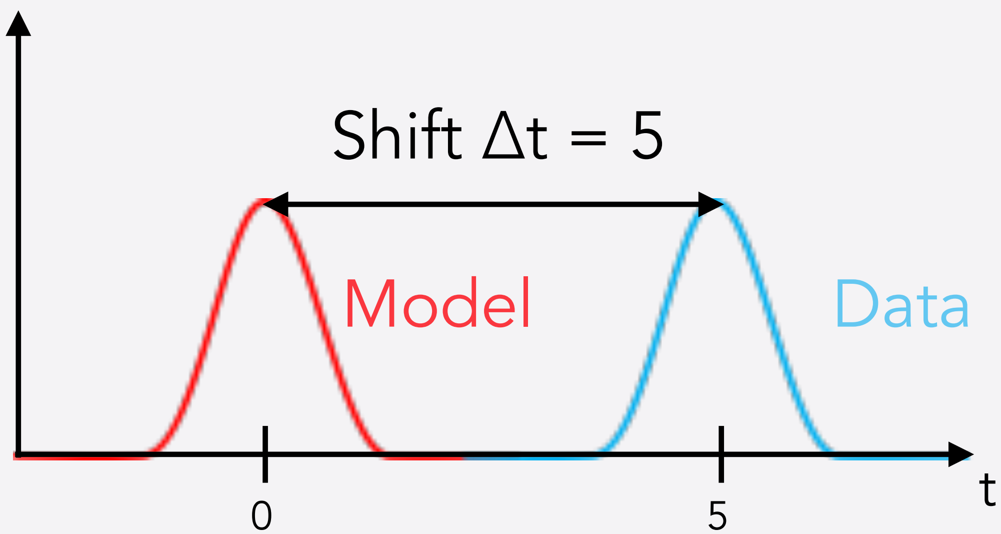
LIV

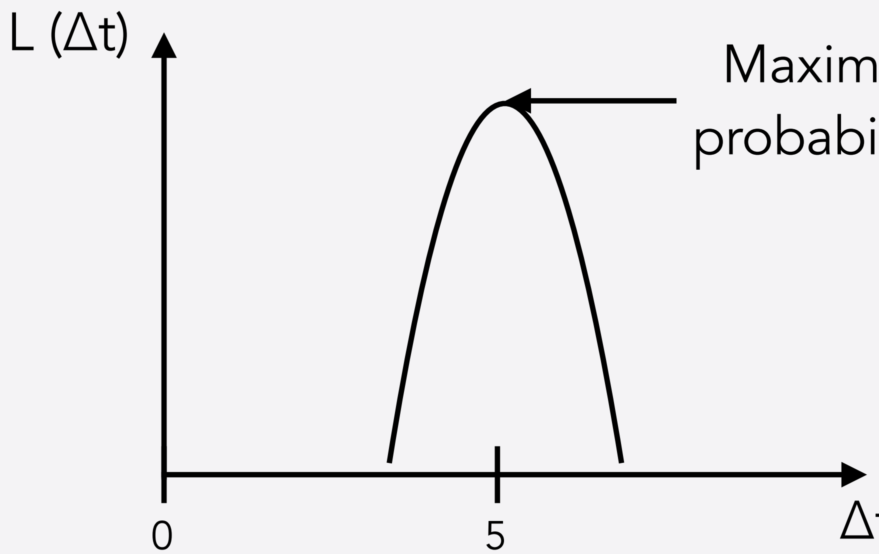
Maximum Likelihood Method

We use a **maximum likelihood method**, which is the more sensitive to reconstruct τ_n, sign of Lorentz Invariance Violation

The method compares datas to a model, event by event. It returns the **probability function** of datas fitting the model depending one or several parameters

$$L(\Delta t) = \prod_{Data} \text{Model}(t_{data} - \Delta t)$$





LIV

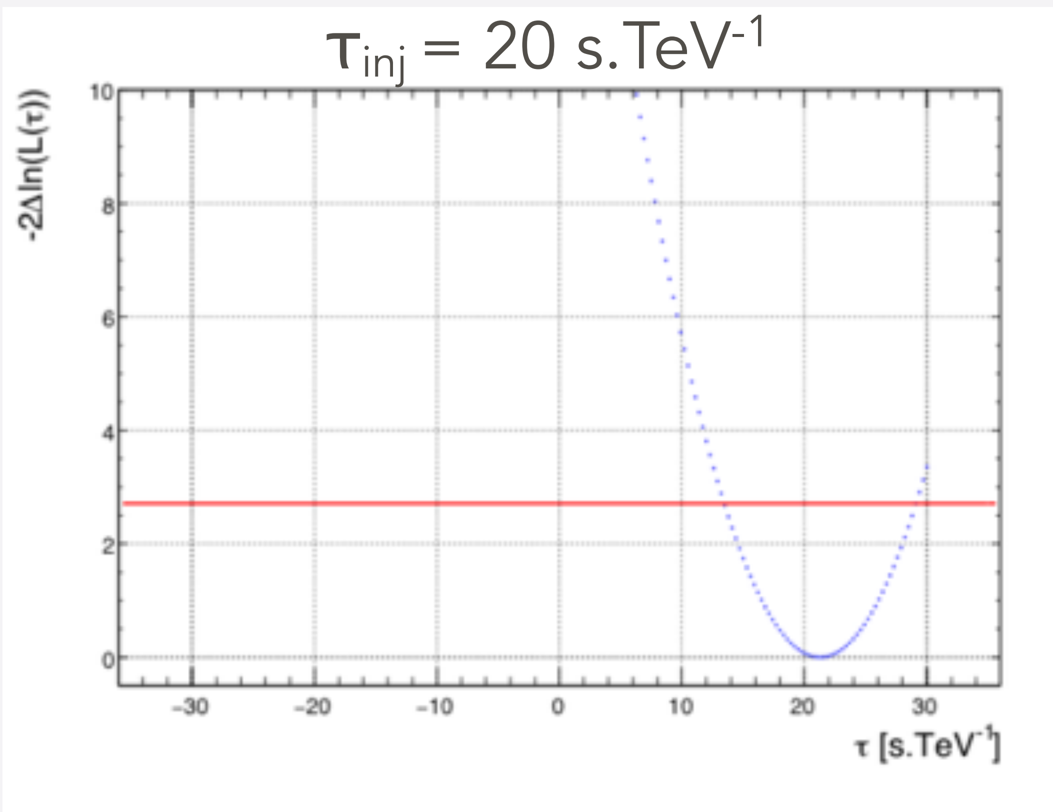
Analyse of data to find LIV effect

The model, used for likelihood, is built from **low energy photons** which are supposed **not delayed** by LIV effect

Then, we compare the model to **high energy photon which are strongly delayed**

$$L(\tau) = \prod_{i=1}^{n_{HE}} \frac{1}{N(\tau)} A_{eff}(E_i)\Lambda(E_i) f(t_i - \tau_n E_i^n)$$

- $\frac{1}{N(\tau)}$: Normalisation Factor
- $A_{eff}(E_i)$: Acceptance
- $\Lambda(E_i)$: Energy distribution
- $f(t_i - \tau_n E_i^n)$: Time distribution not delayed



ANNEXE

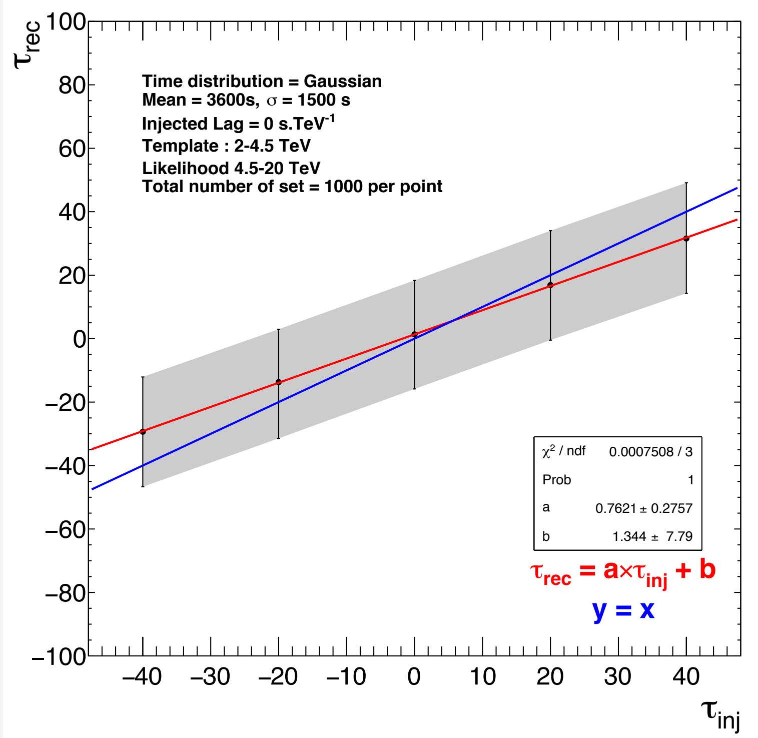
LIV Results : Improvement of model

Low energy photons in model are still delayed by LIV effect, but supposed not to be.

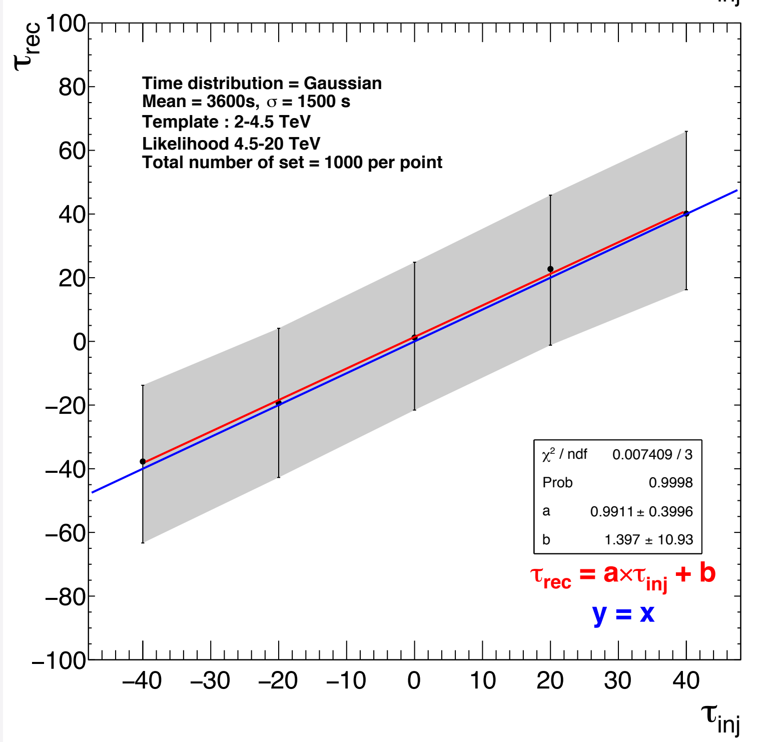
If the model energy range is too high, the effect is not negligible anymore and the time-lag reconstruction is not accurate.

We need to correct the maximum likelihood formula :

$$L(\tau) = \prod_{i=1}^{n_{HE}} \frac{1}{N(\tau)} A_{eff}(E_i)\Lambda(E_i) f(t_i - \tau_n E_i^n + \tau_n < E_t >^n)$$



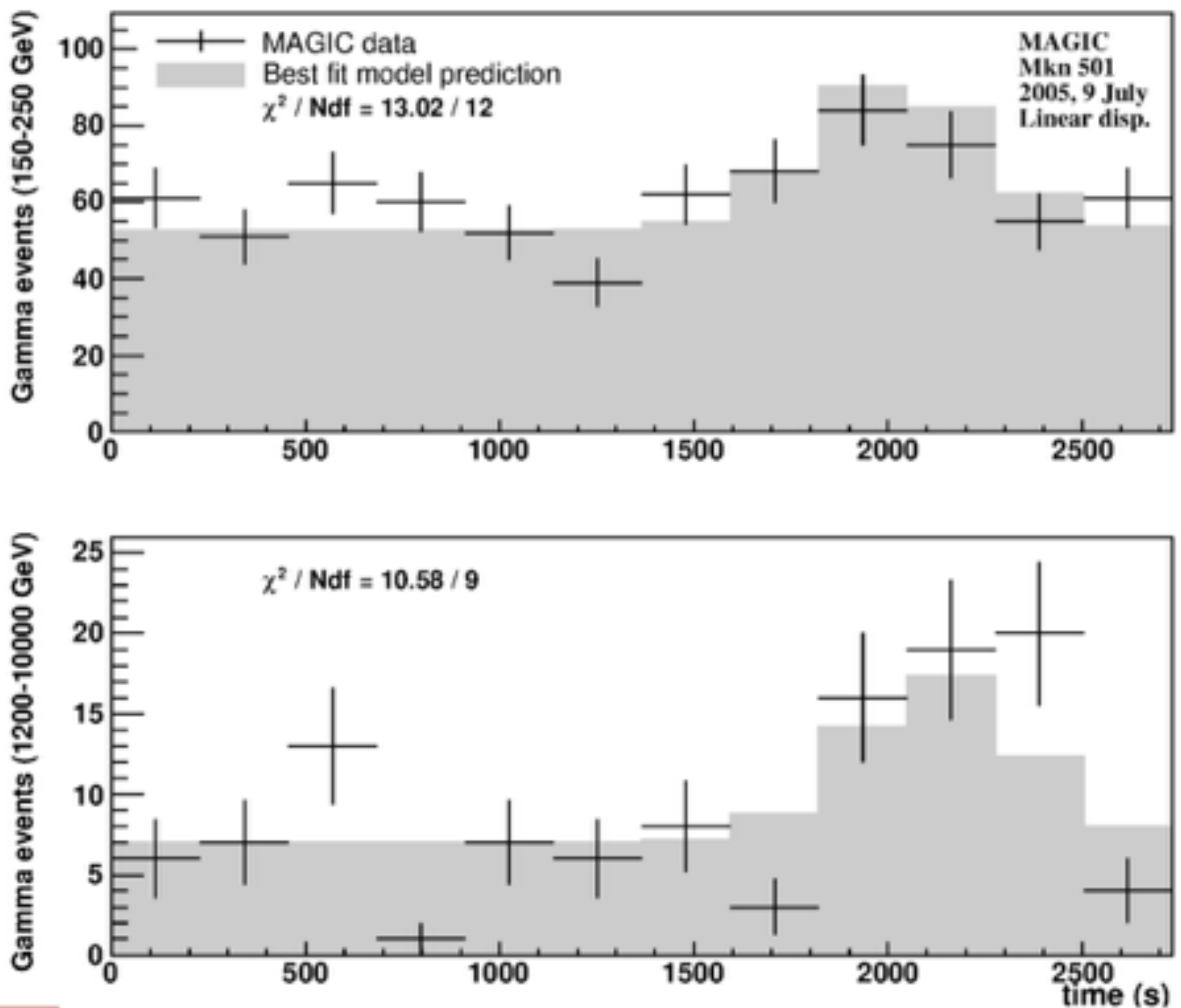
Not corrected



Corrected

ANNEXE

Results from MAGIC



From Albert et al. 2008

From MAGIC data :

Time-lag between
0.15 - 0.25 TeV and 1.2-10 TeV

$$\tau = 48 \pm 21\ s.TeV^{-1}$$

$$\Delta t > 0$$

LIV

Collaboration H.E.S.S., MAGIC, VERITAS

H.E.S.S.

MAGIC

VERITAS

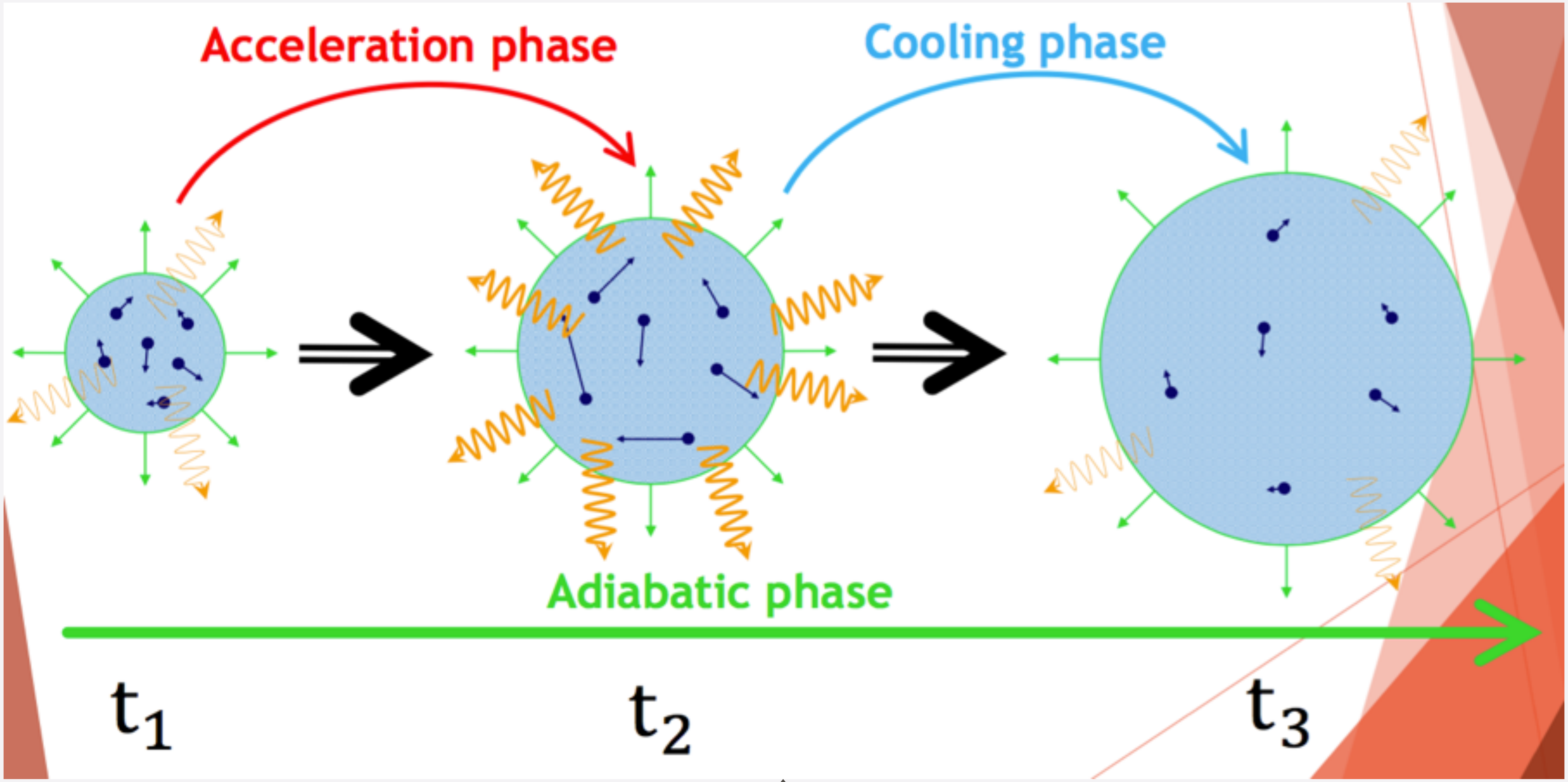
Motivations : **Combining all available data** for time-lag study in order to **improve current limits** on Lorentz Invariance Violation

Work : Develop a **join analysis** which will allow to use many sources. Currently we analyse source one by one. One of the **goals** will be to **combine different kind of sources** : Active Galactic Nuclei, Pulsars and Gamma-ray Burst

This is a way to avoid intrinsic time-delay

ANNEXE

Evolution of emission zone

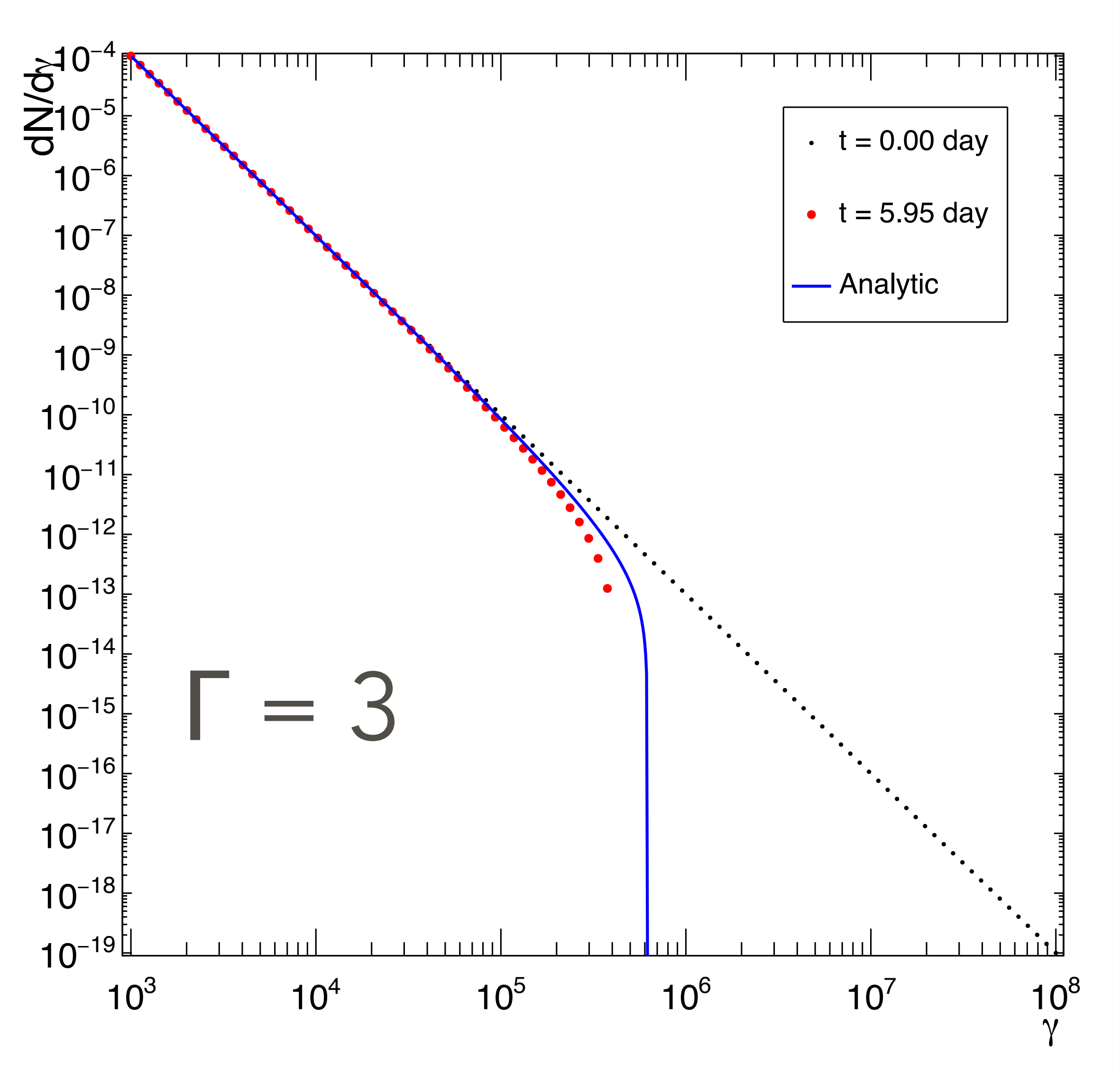


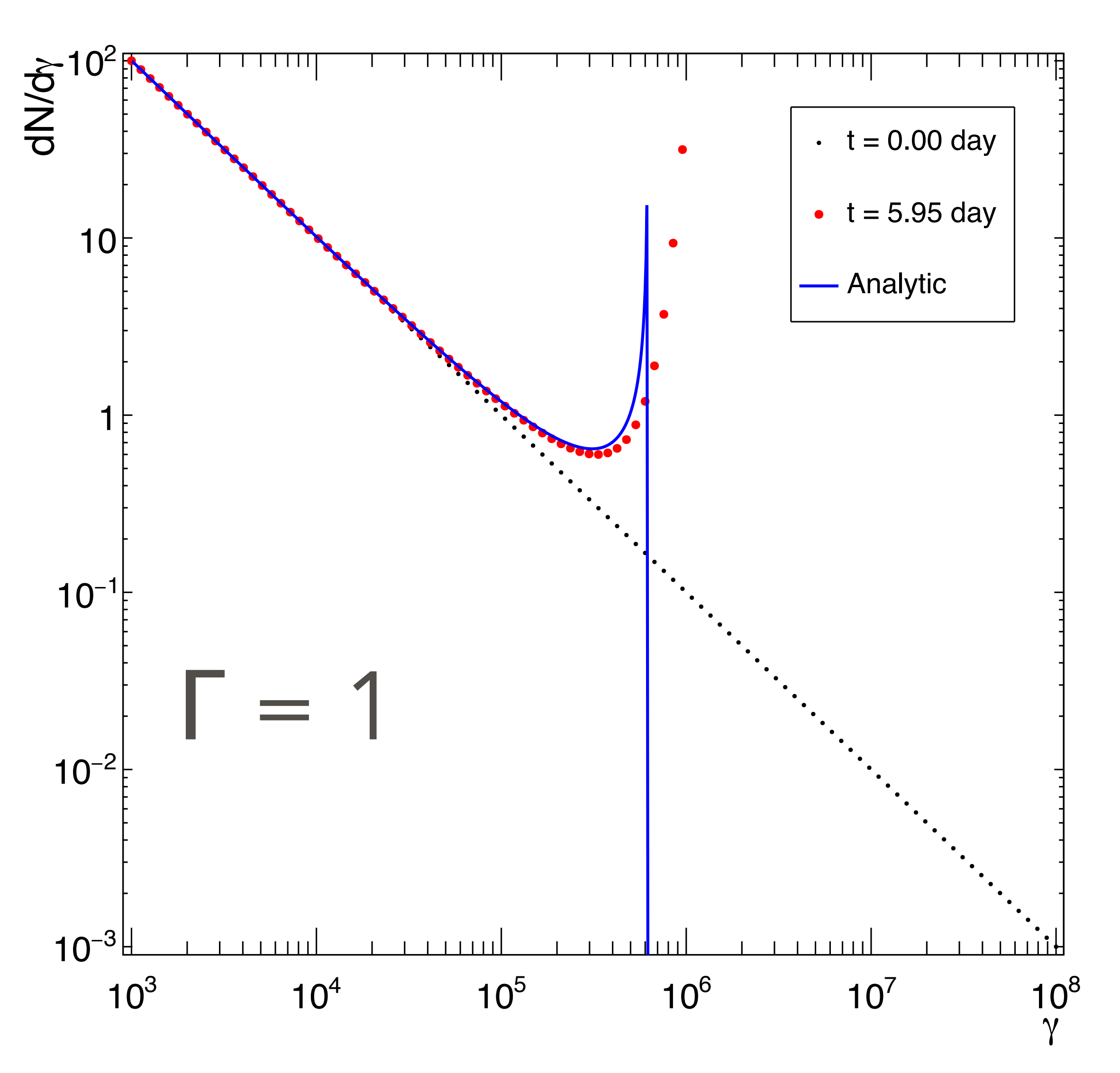
ANNEXE

First results

For initial electron spectrum index Γ ≥ 2 the **result is close to the analytic solution**

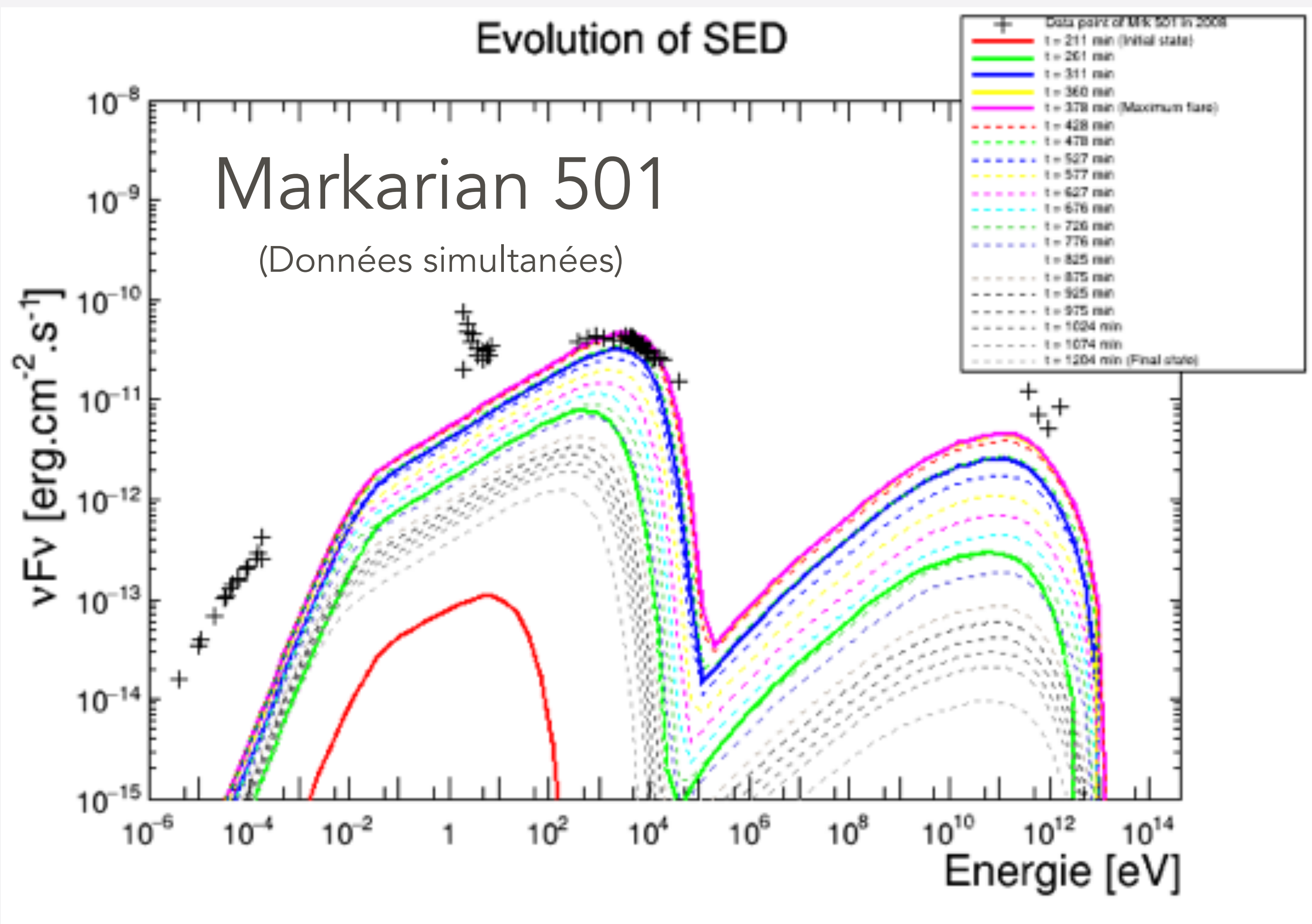
But when Γ < 2, the finite difference method doesn't success to describe well the problem due to the hard slope of the solution





MODELING

Preliminary work : M2 internship



DEVELOPMENT OF TIME DEPENDENT MODEL

We use existing code and we simplified them to consider only high energy process for our model, what we are interested for LIV

The variations of photons flux observed are due to the variation of the electron spectrum at the source :

$$\frac{\partial N_e(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{\left[C^{cool}(t)\gamma^2 - \left(C^{acc}(t) - C^{adia}(t)\right)\gamma\right] N_e(t,\gamma)\right\}$$