ENERGY DEPENDENT TIME DELAYS IN BLAZAR LIGHT CURVES

A FIRST LOOK AT MODELING OF SOURCE-INTRINSIC EFFECT IN THE MEV-TEV RANGE AND CONSTRAINTS ON LORENTZ INVARIANCE VIOLATION WITH H.E.S.S.

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H.E.S.S.

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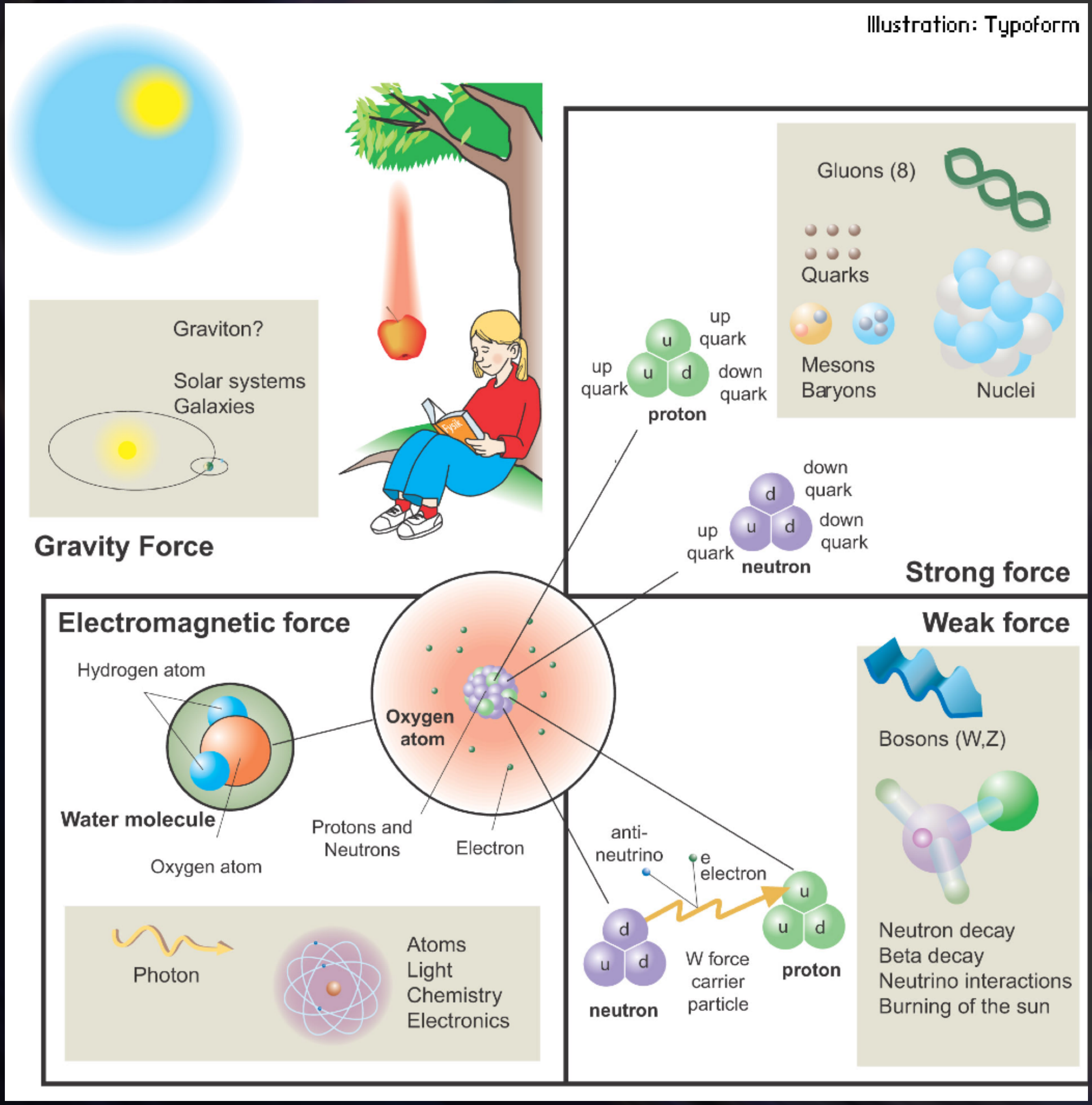
INTRODUCTION



4 fondamental interactions :

- 3 interactions are well described by the Standard Model (Particle physics)
- The gravitation is left alone and described by the General relativity (Gravitation, Cosmology . . .)

Theorists are trying to merge these 4 interactions in a common framework :

Quantum gravity

INTRODUCTION

Lorentz Invariance Violation (LIV) appears in some approches to Quantum Gravity

This LIV can appears due to a modification of the propagation of photon in vacuum which can be expressed with a simple toy model:

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

This relation leads to energy dependent velocities for photons:

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

Subluminal (+1) or Superluminal (-1)

2 mains cases :

- *n = 1 : Linear case*
- *n = 2 : Quadratic case*

INTRODUCTION

Energy-dependent velocities for the propagation of photons induce time delays

High energy photon

Low energy photon

Considering a LIV sub-luminal effect

(high energy photons slower than low energy photons)

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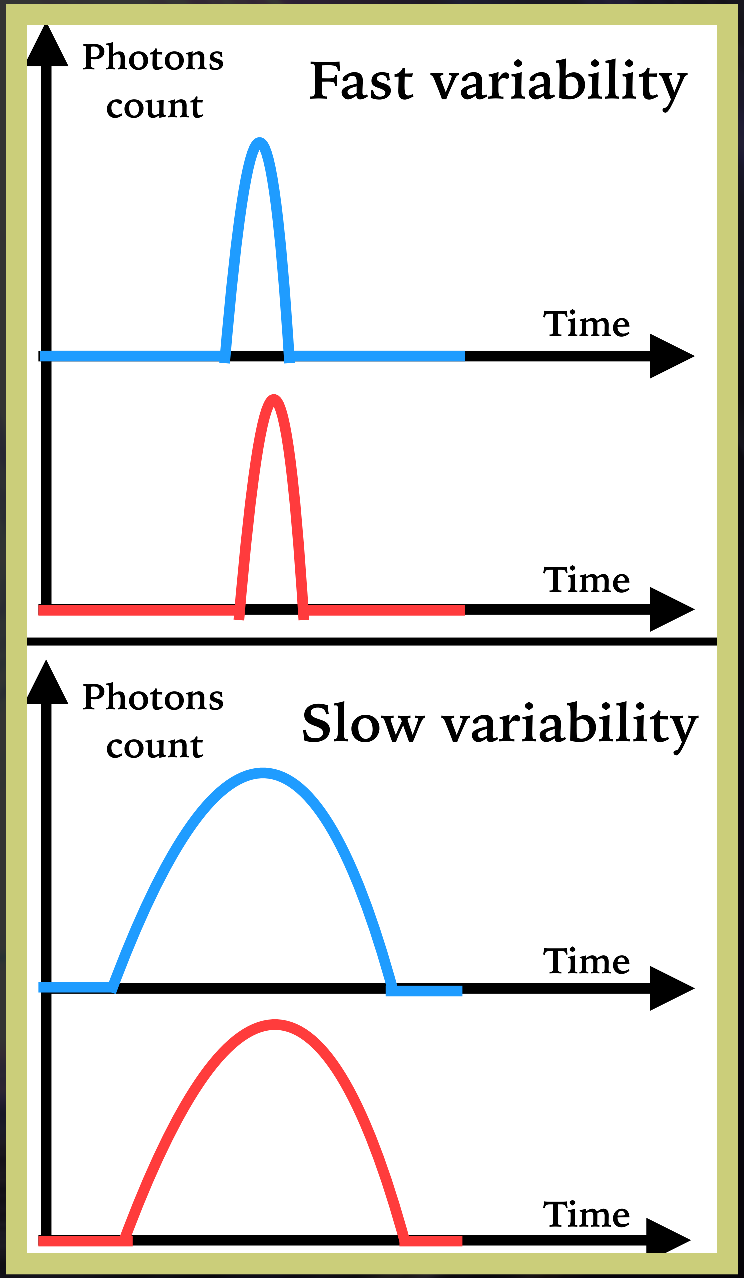
The time delay between 2 photons of different energies coming from an astrophysical source at redshift z:

$$\Delta t_n = \pm \frac{n+1}{2} \frac{E_1^n - E_0^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} \mathrm{d}z'$$

Which source to observe this effect ?

Three important criteria to be able to see this effect :

➡ A variable source in order to measure a time delay



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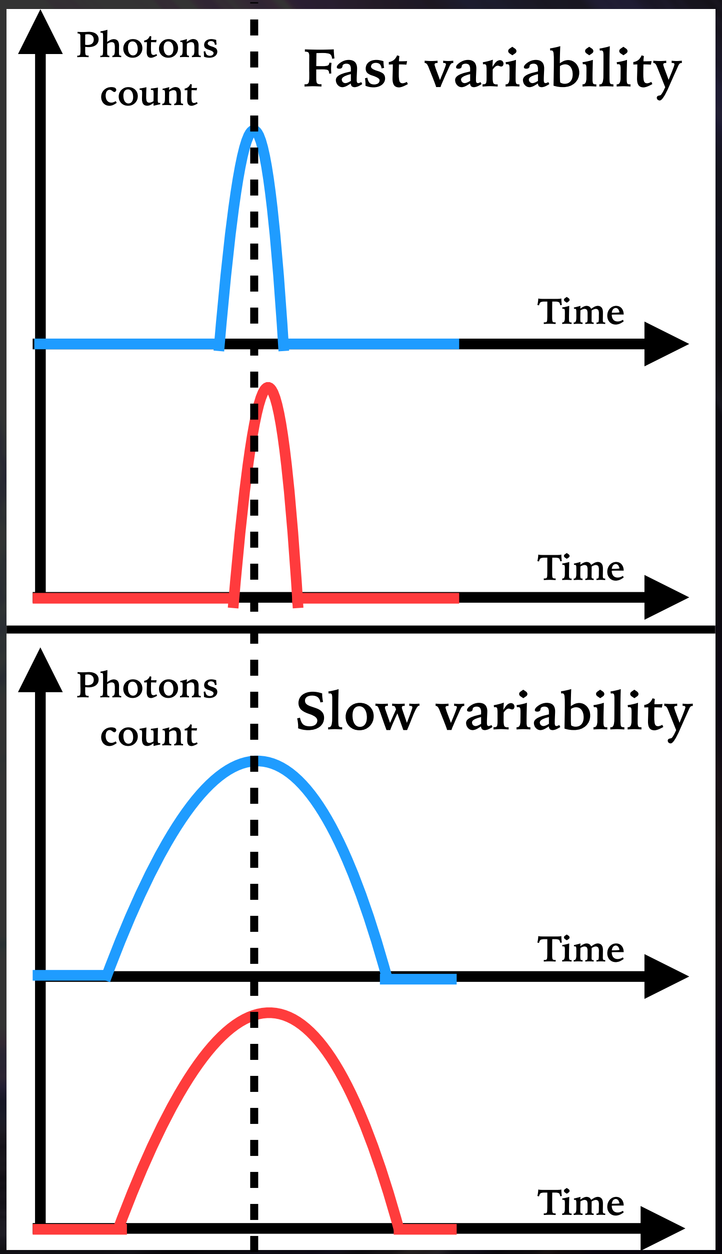

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Which source to observe this effect ?

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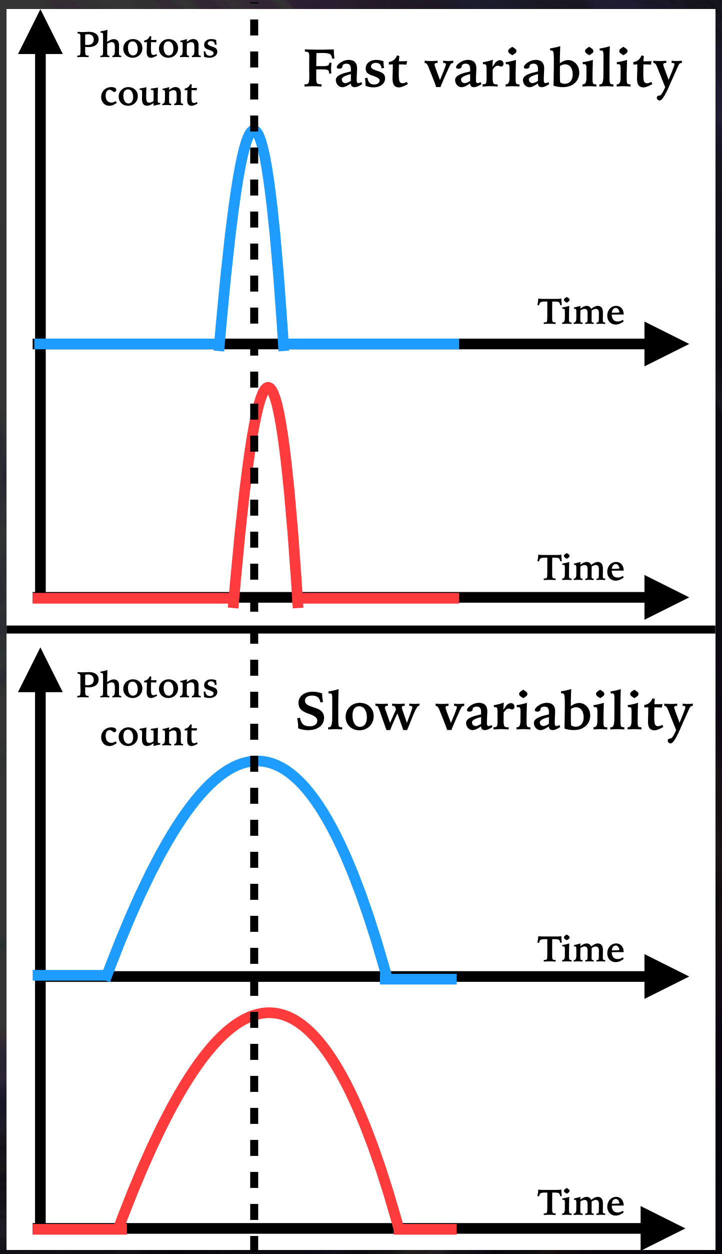
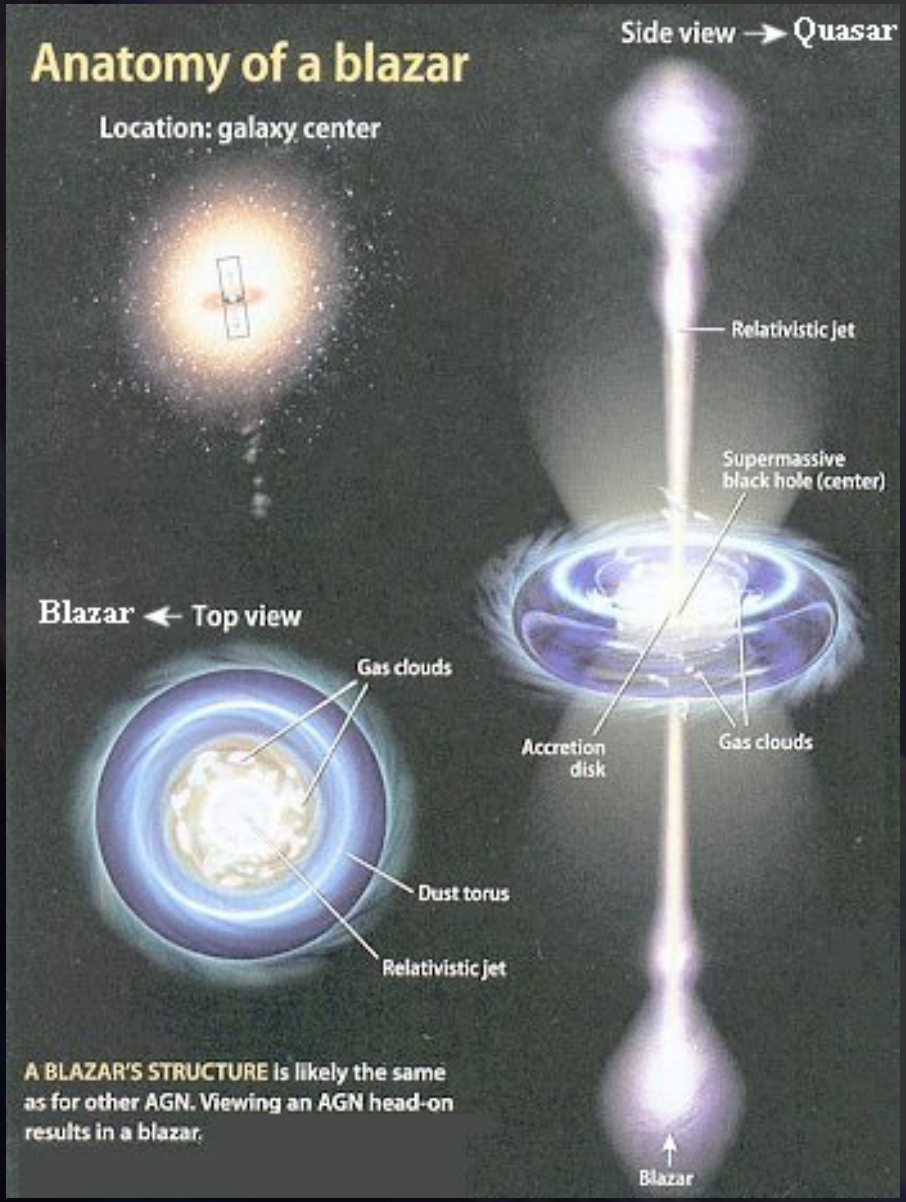
➡ A distant source to maximize the propagation effect

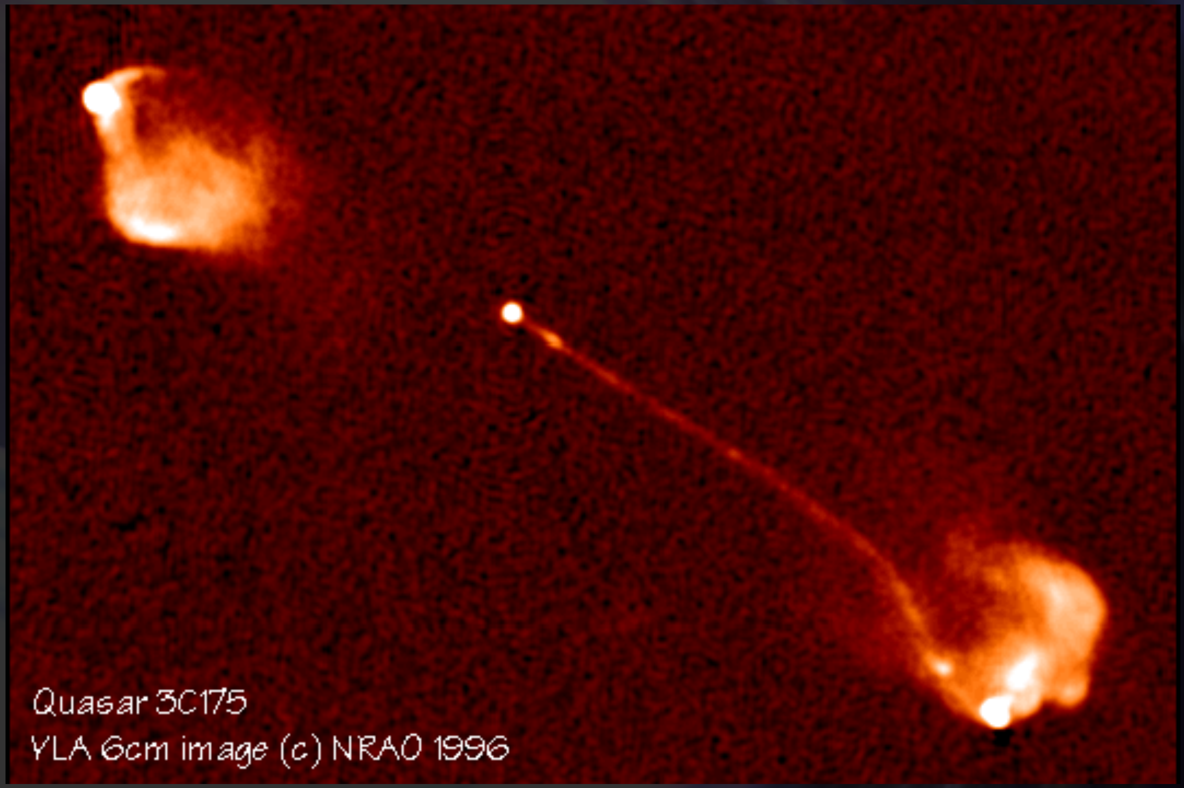
➡ A source which emits photons with large energy range to maximize the energy difference



INTRODUCTION

Active Galactic Nuclei





Doppler boosting : $t_{obs} = \frac{t_s}{\delta}$

$$\nu_{obs} = \delta \nu_s$$

$$F_{obs}\left(\nu_{obs}\right) = \delta^3 F_s\left(\nu_s\right)$$

INTRODUCTION

H.E.S.S. is an **hybrid array** of 5 imaging atmospheric Cherenkov telescopes

- CT1-4 : **13m telescopes**, designed for high energy (**100 GeV up to ~50 TeV**)
- CT5 : **28m telescope**, designed for low energy (**down to ~20 GeV**), good instrument to catch **transient event such as AGN flares**

To look for LIV signatures, we search for **energy-dependent time delays in** the **arrival time of γ-ray photons** coming from **blazar flares**

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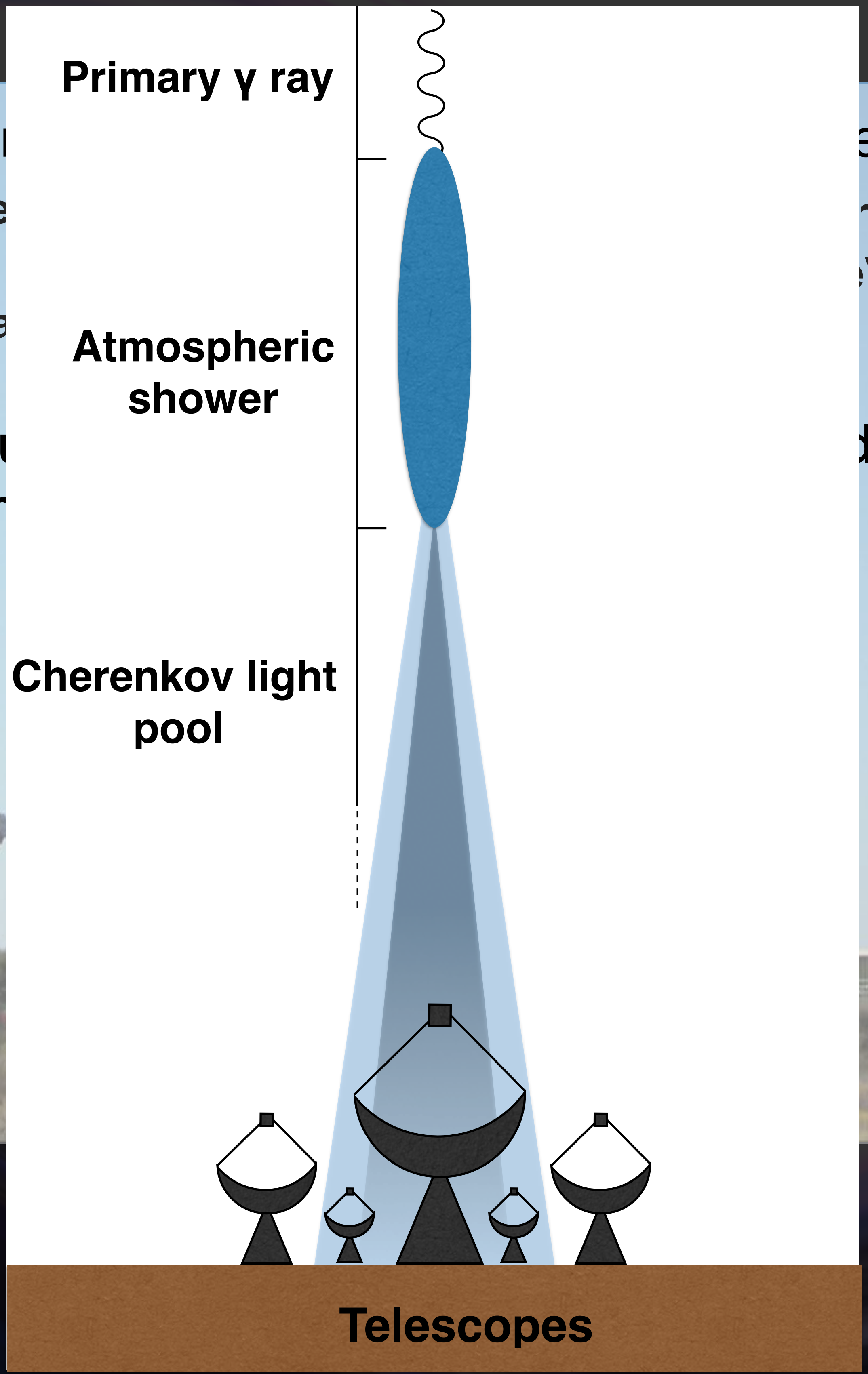

TESTING LORENTZ INVARIANCE

To search for LIV signatures, we define a parameter of interest

$$\tau_n = \frac{\Delta t}{E^n} \longrightarrow \Delta t_{LIV} = \tau_n E^n$$

With n = 1 or 2 for linear or quadratic LIV effect

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Real data
(H.E.S.S.)

Maximum Likelihood
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σ_{stat}, σ_{syst}

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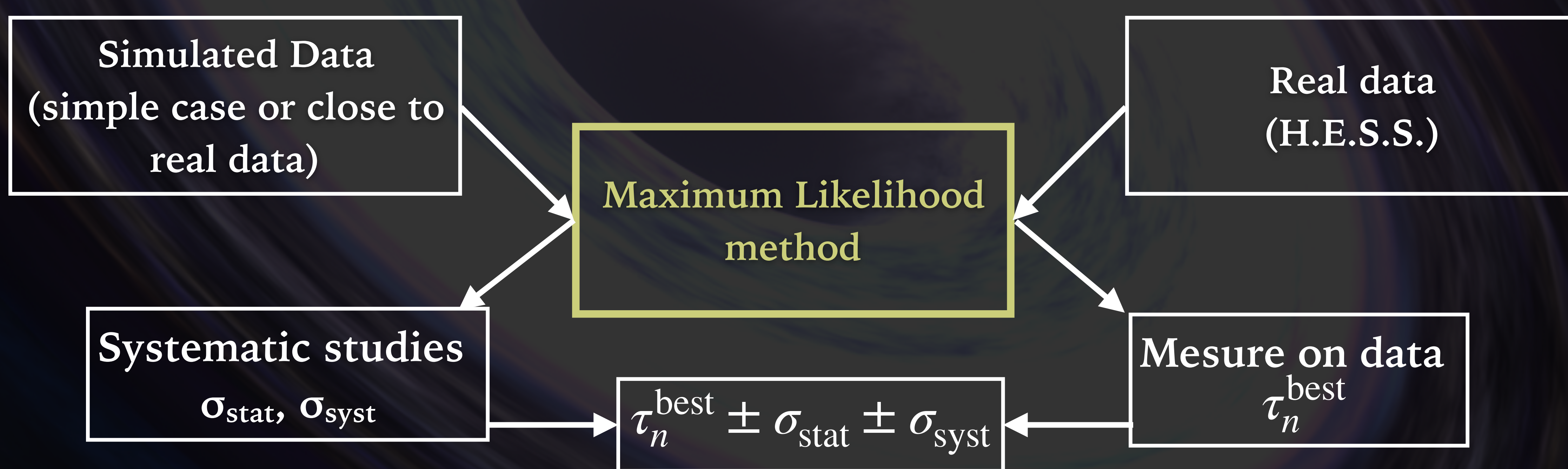

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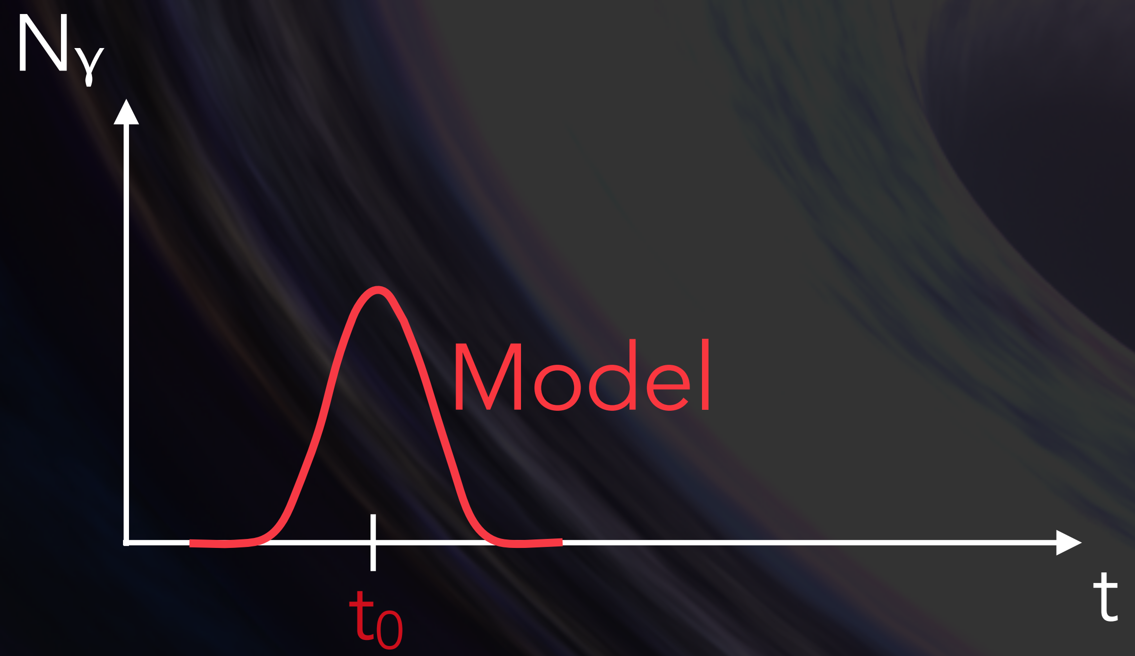
$\tau_n^{best} \pm \sigma_{stat} \pm \sigma_{syst}$

E_{QG} Limit

MAXIMUM LIKELIHOOD METHOD

The Likelihood function gives the probability of an event to match a model with respect to one or several parameters



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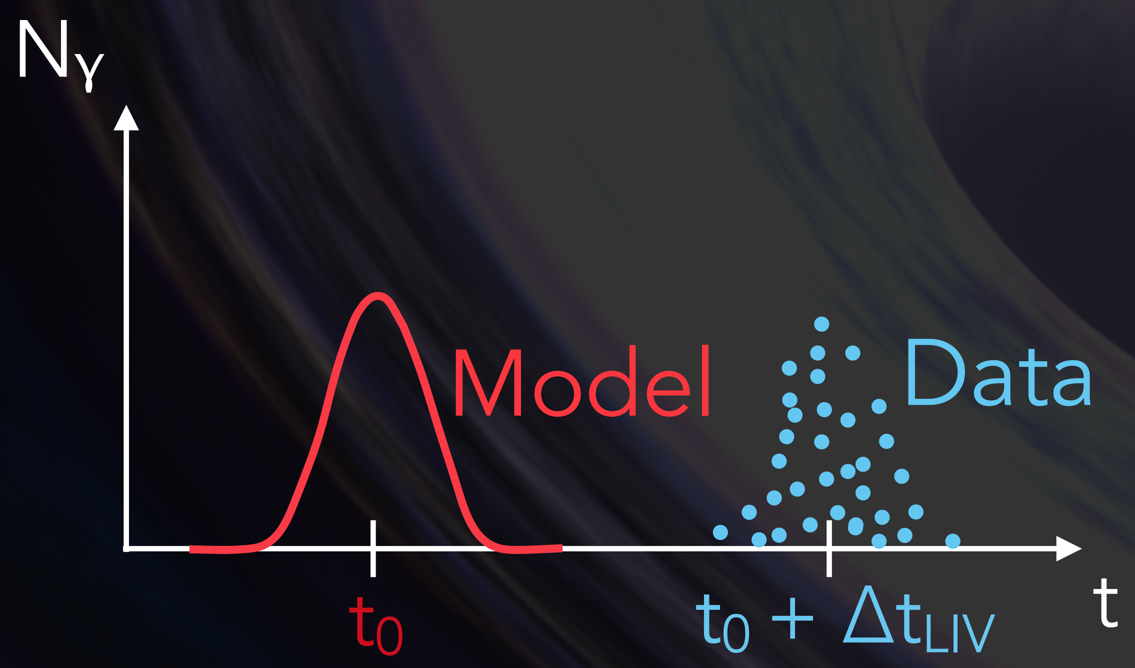

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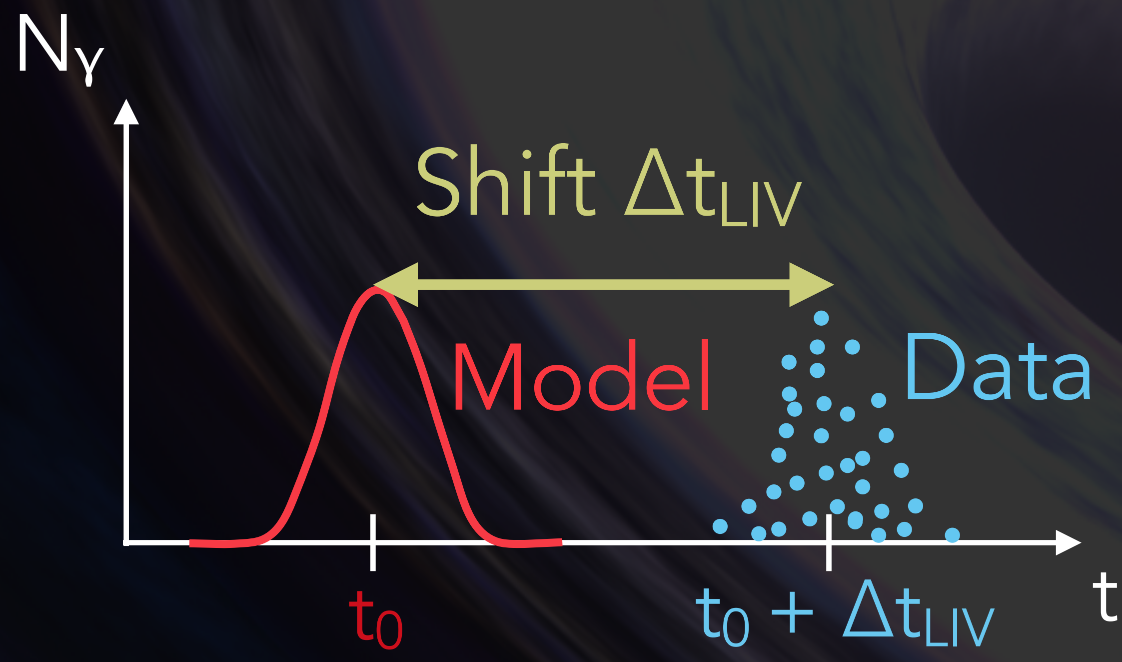

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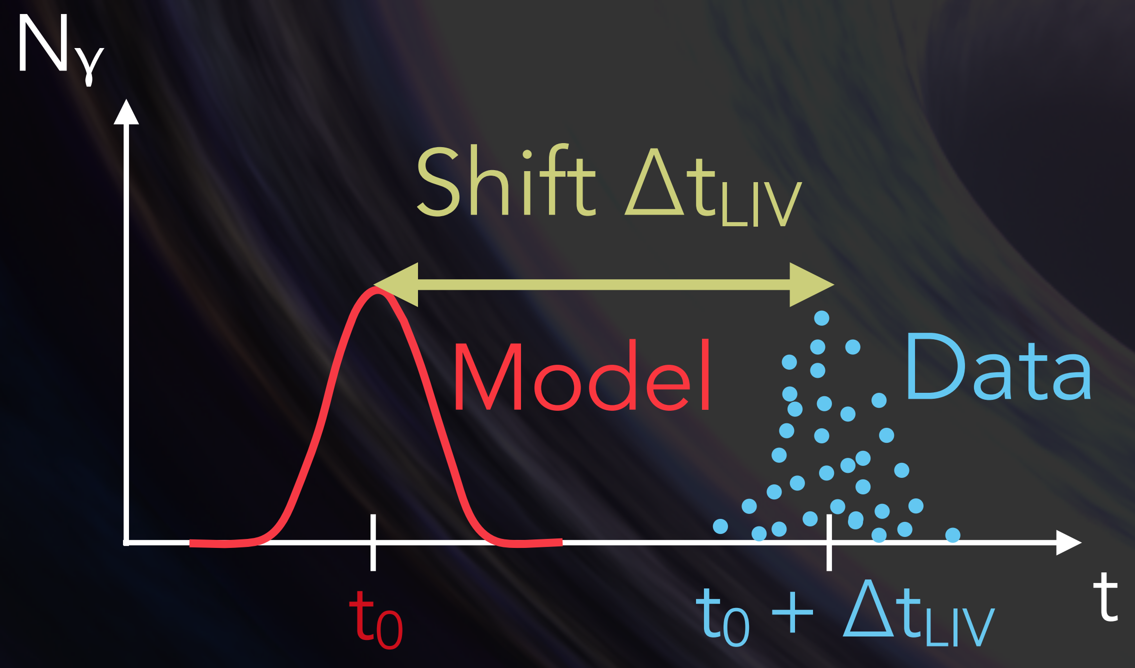

$$L(\Delta t) = \prod_{i=0}^{N_{points}} \mathrm{Model}(t_i - \Delta t)$$

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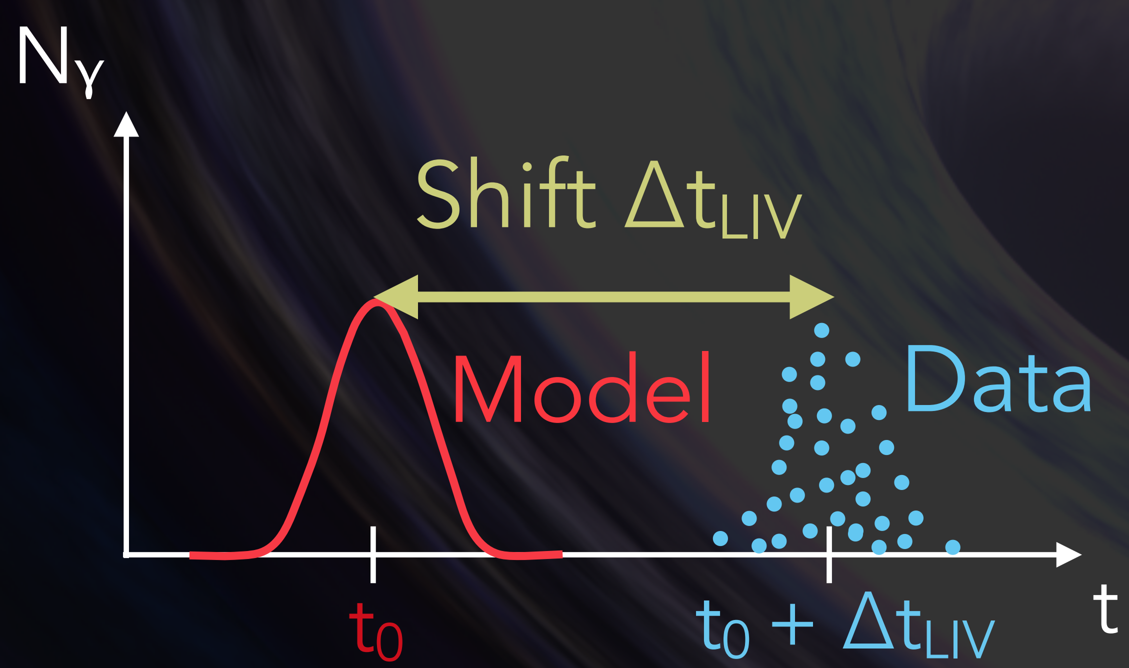

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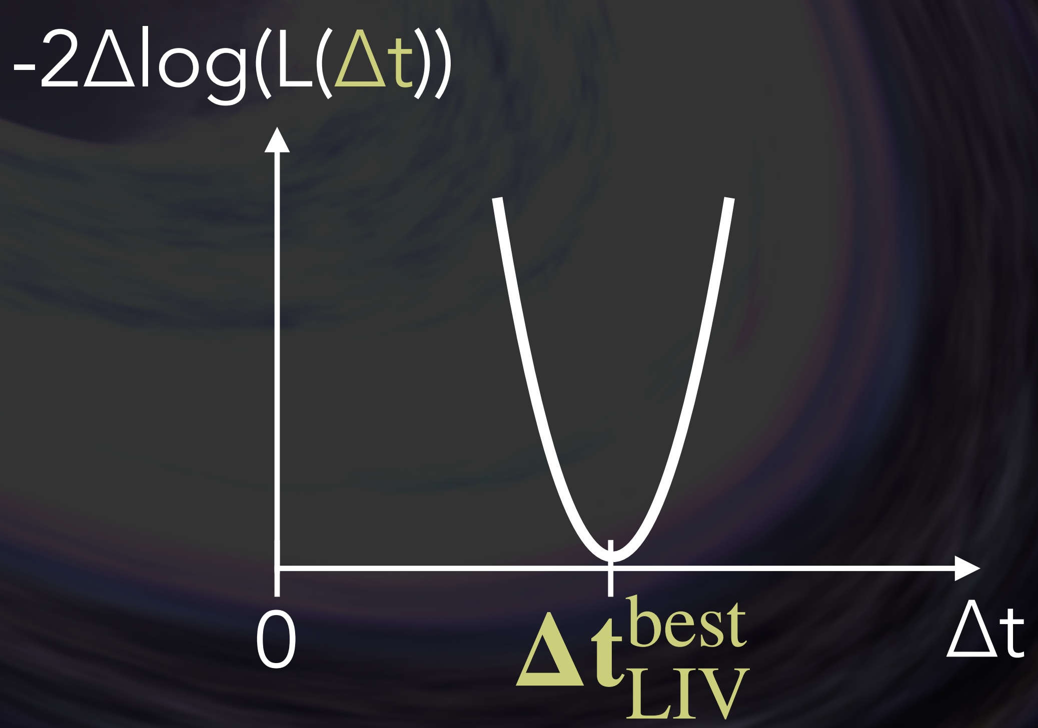

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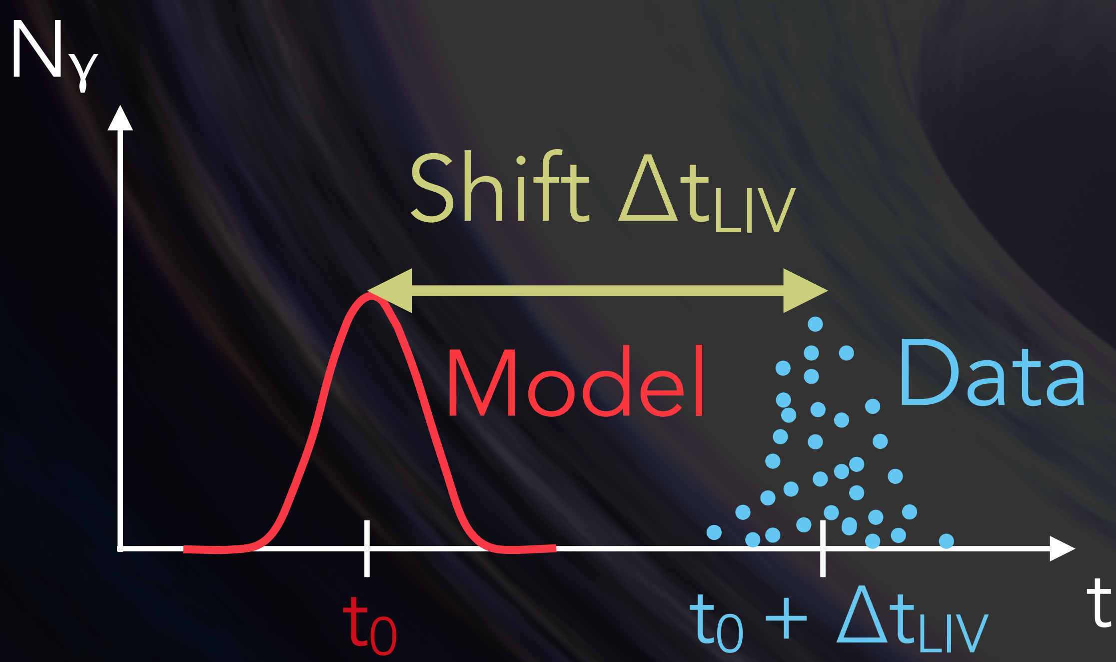

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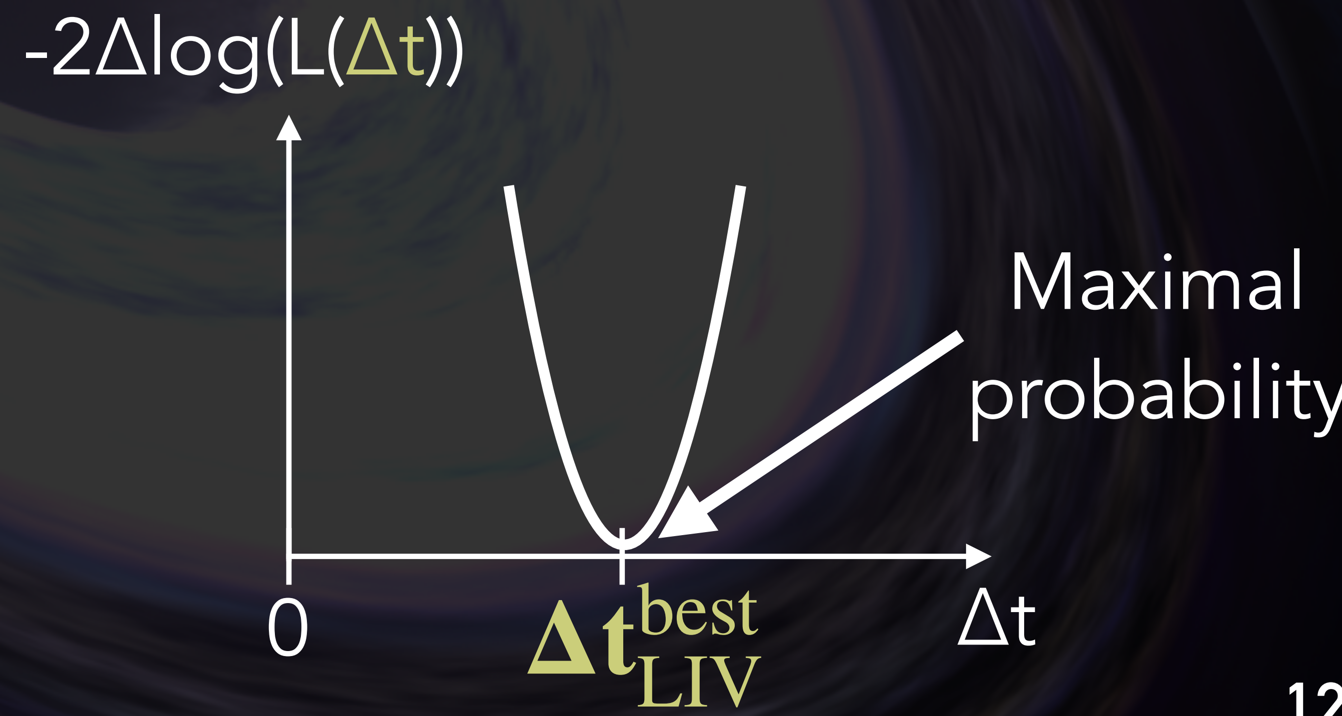

MAXIMUM LIKELIHOOD METHOD

The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with :

- Time function not delayed by LIV effect to take into account the variability

$$L\left(\tau_n\right) = \boxed{F\left(t - \tau_n E_i^n\right)}$$

Martinez & Errando (2009)

MAXIMUM LIKELIHOOD METHOD

The Likelihood function gives the probability of an event to match a model with respect to one or several parameters

The Likelihood function is built with :

- Time function not delayed by LIV effect to take into account the variability
- Energy function to give more strength to high energy events

$$L\left(\tau_n\right) = \boxed{\Gamma\left(E_i\right)} F\left(t - \tau_n E_i^n\right)$$

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The Likelihood function is built with :

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- Instrument response function to take care of the instrument uncertainties

$$L(\tau_n) = \boxed{\Lambda(E_i)}\,\Gamma(E_i)\,F(t - \tau_n E_i^n)$$

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- Instrument response function to take care of the instrument uncertainties
- Normalisation factor to get unbiased estimation of the parameter τ_n

$$L(\tau_n) = \boxed{N(\tau_n)}\, \Lambda(E_i)\, \Gamma(E_i)\, F(t - \tau_n E_i^n)$$

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- Energy function to give more strength to high energy events
- Instrument response function to take care of the instrument uncertainties
- Normalisation factor to get unbiased estimation of the parameter τn
- Multiplied over all high energy events

$$L\left(\tau_n\right) = \boxed{\prod_i} N\left(\tau_n\right)\,\Lambda\left(E_i\right)\,\Gamma\left(E_i\right)\,F\left(t - \tau_n E_i^n\right)$$

Martinez & Errando (2009)

MAXIMUM LIKELIHOOD METHOD

To apply the maximum likelihood method, events are split in two samples:

- Template region: The low energy part of the events where the LIV effect is neglected in order to estimate F(t)
- Likelihood region: The high energy part of the events used in the likelihood function for the estimation of τ_n

Using simulations, we can test the method and evaluate its performances

Gaussian shape time distribution

Power law energy distribution

500 template events (0.4 - 0.8 TeV)

500 likelihood events (0.8 - 4 TeV)

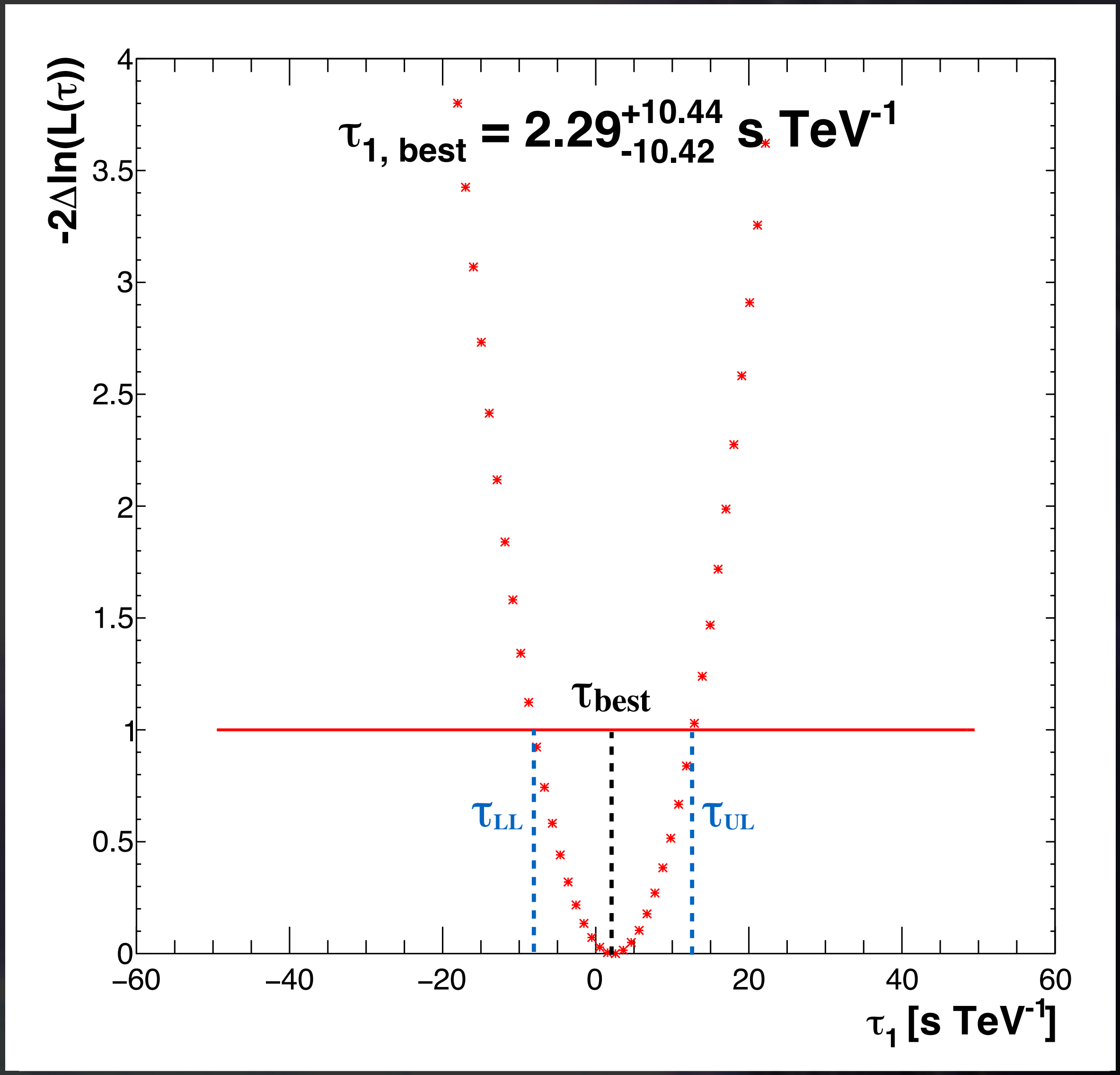
Energy resolution: 10%

Acceptance variations neglected

MONTE-CARLO SIMULATIONS

At first, F(t) is the true non-delayed function used for the simulations

With no injected LIV delay



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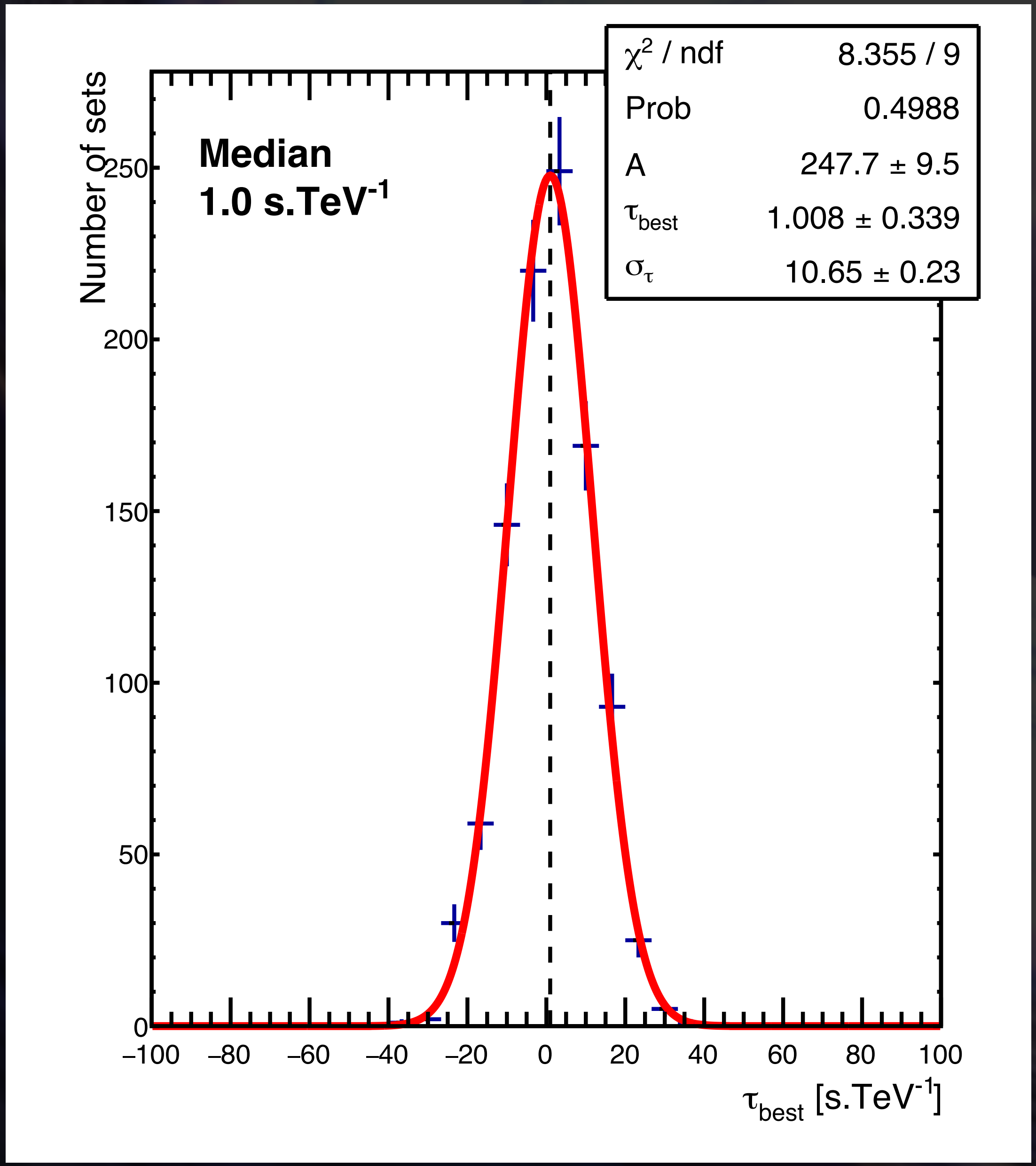
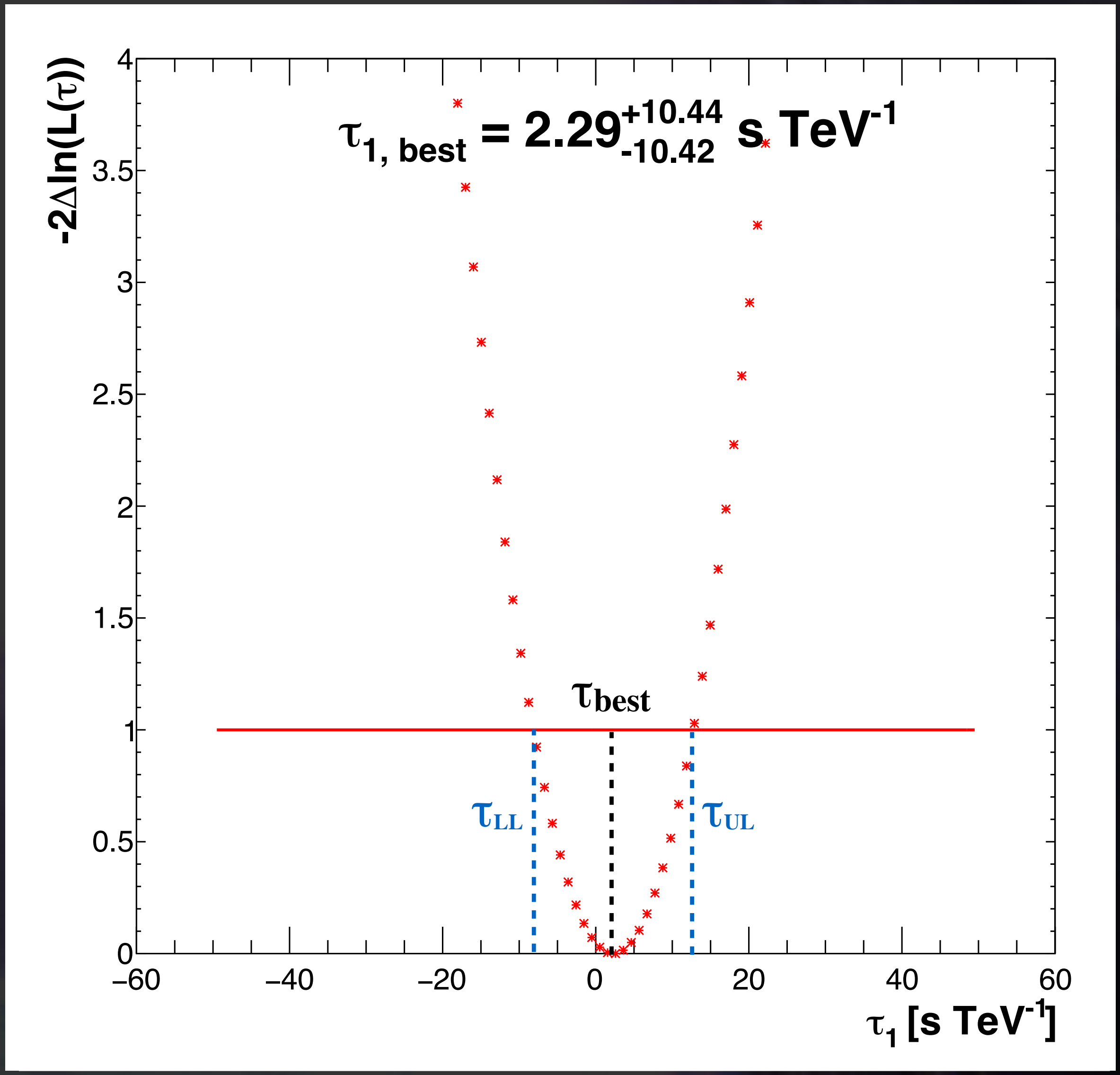
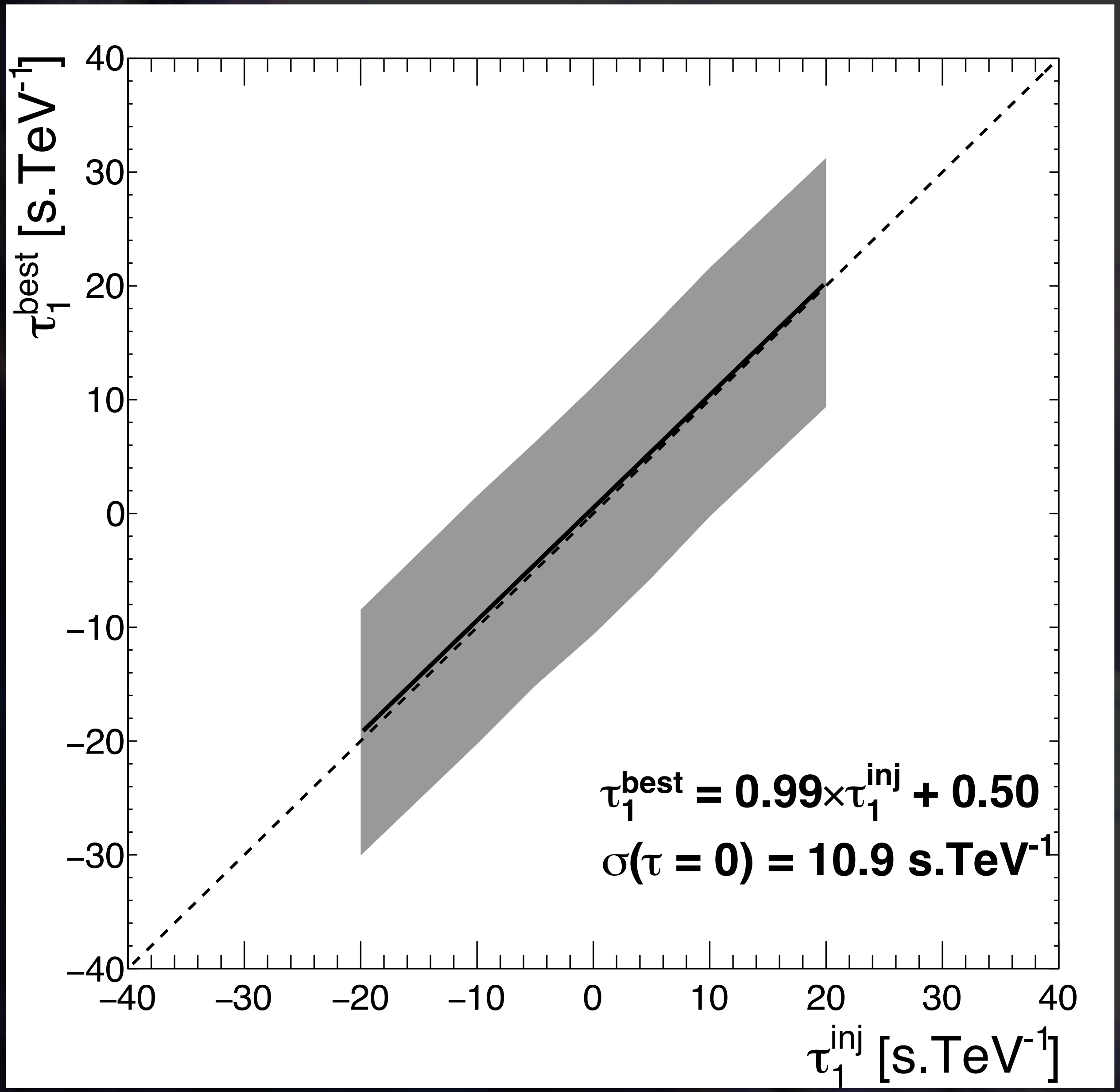




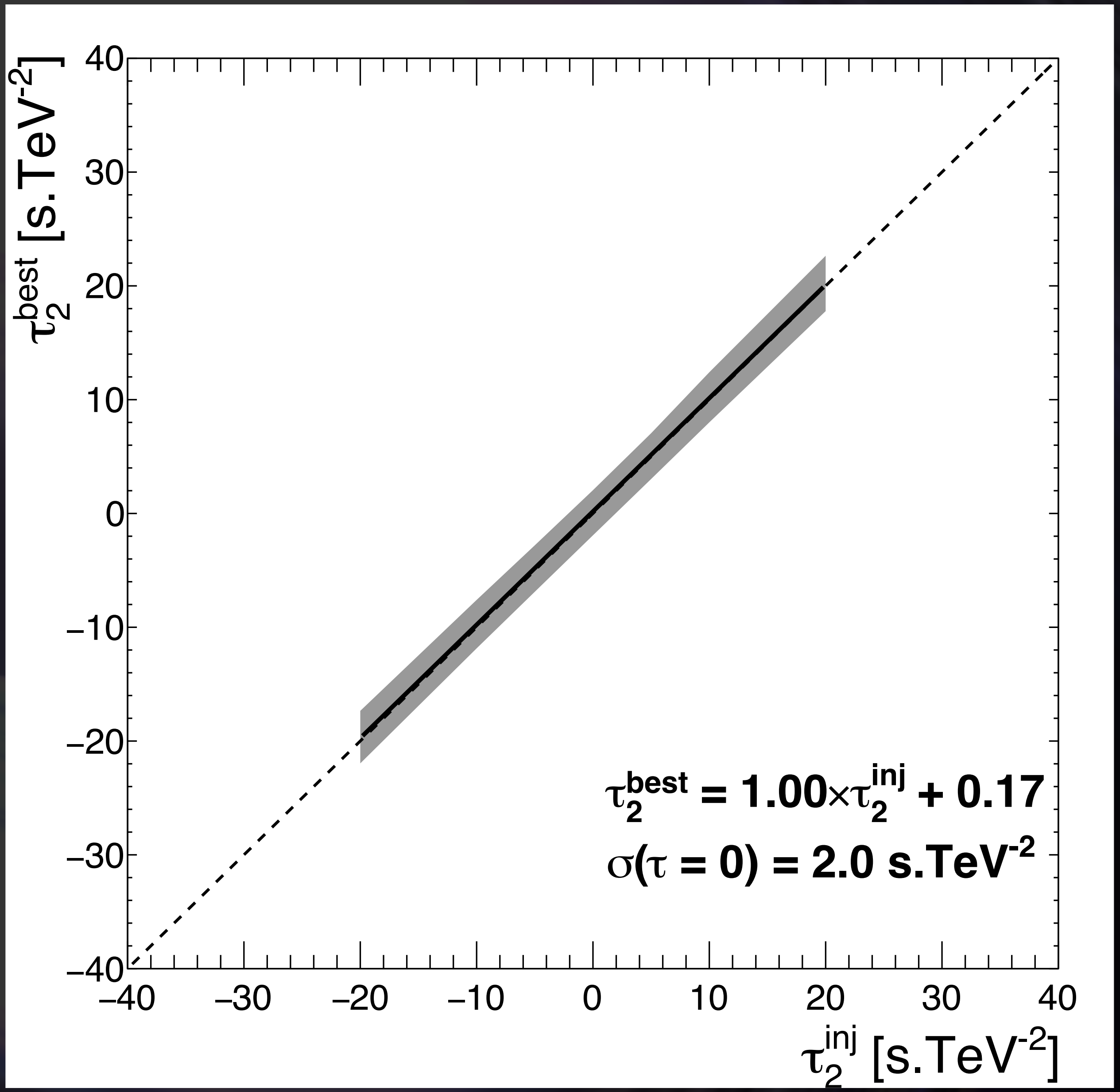
A 1000 realizations of the same data set allows to improve the evaluation of statistical uncertainties

MONTE-CARLO SIMULATIONS

Then, injecting multiple τ_n values, the calibration of the method can be deduced



Linear LIV effect

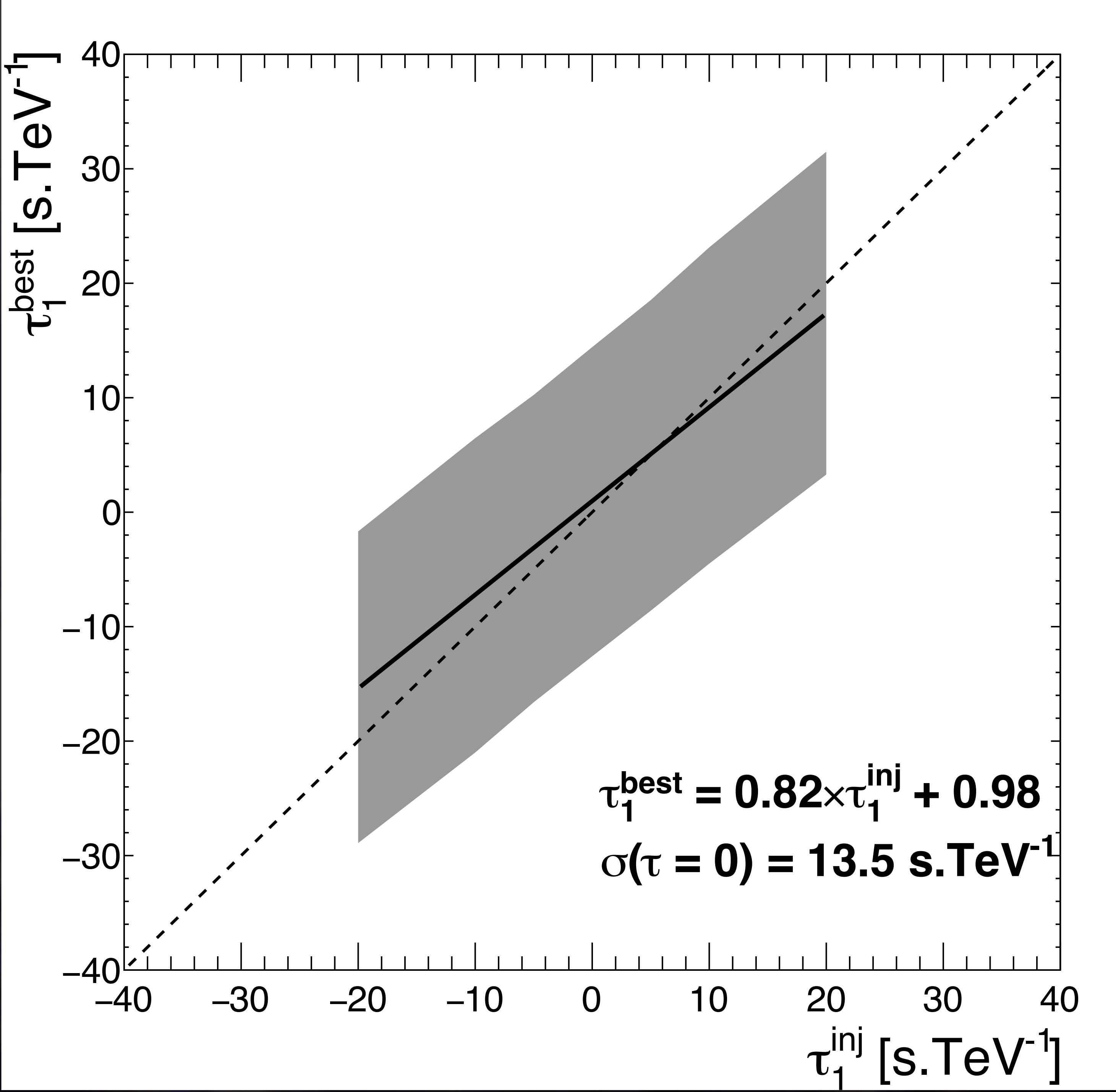


Quadratic LIV effect

MONTE-CARLO SIMULATIONS

However, in case of data F(t) has to be deduced from the template region where LIV effect can be non-negligible

Template : 400-800 GeV



Linear LIV effect

HIGH ENERGY TEMPLATE CORRECTION

To take into account this effect, we implement a template correction in the model used for the likelihood function

$$L\left(\tau_n\right) = \prod_i N\left(\tau_n\right)\,\Lambda\left(E_i\right)\,\Gamma\left(E_i\right)\,F\left(t - \tau_n E_i^n + \overline{E_T^n}\tau_n\right)$$

which takes into account that the template region can be affected by LIV effect

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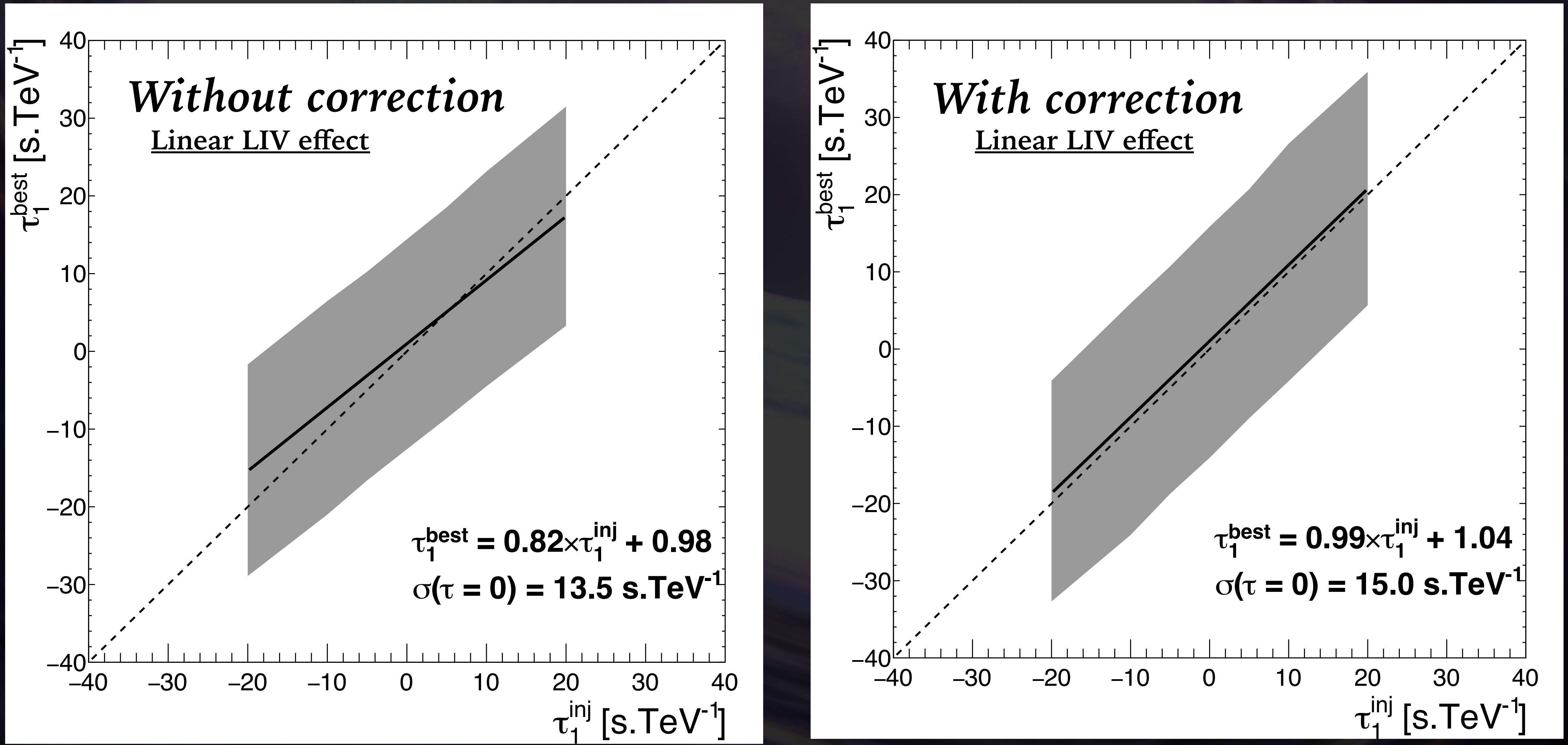
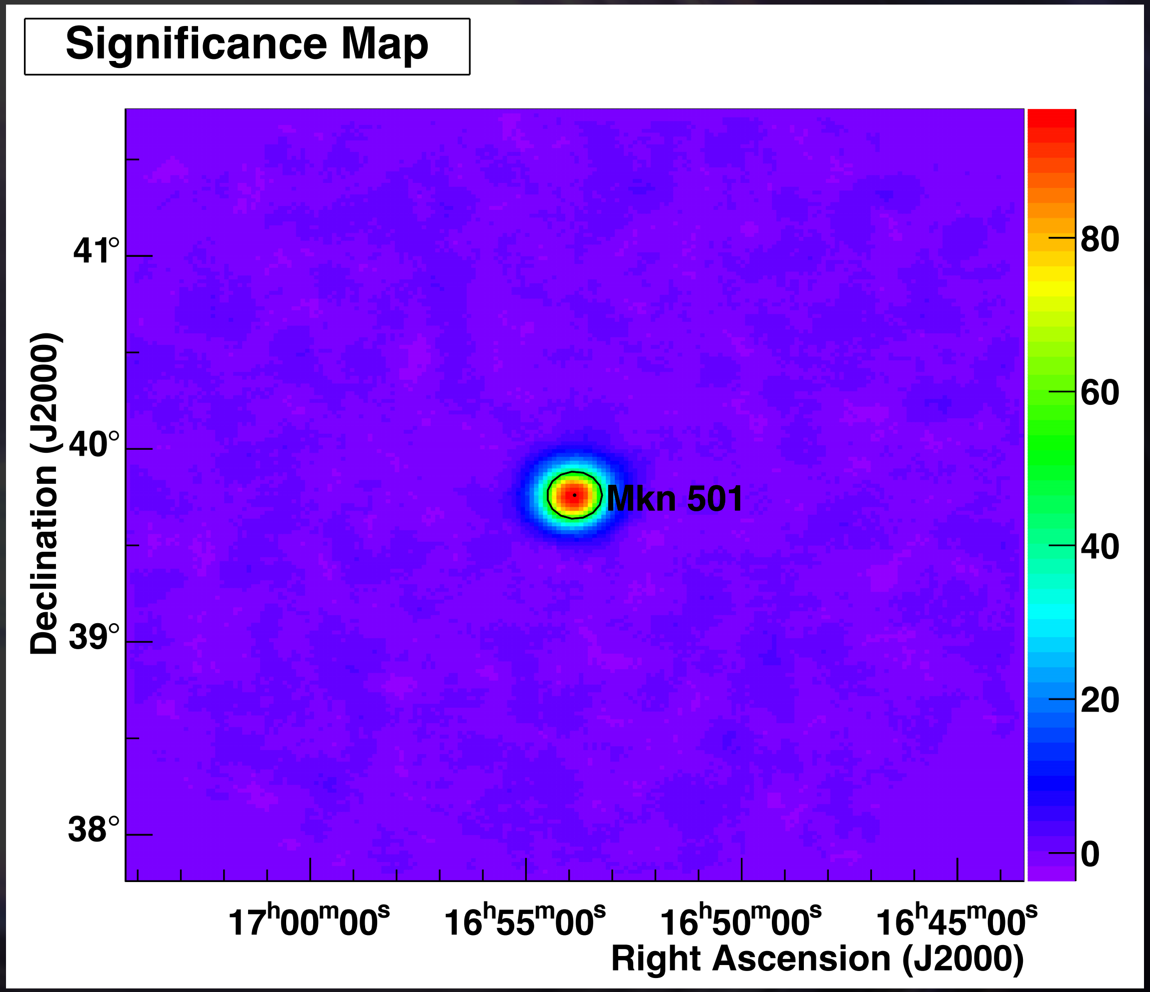


MARKARIAN 501 – FLARE ANALYSIS

A flare from Markarian 501 (z = 0.034) in 2014 was observed by H.E.S.S.

The source is detected with a high significance (> 60σ) but with a large zenith angle (>60°) involving a high energy threshold for this data set at 1.3 TeV

The data show 1435 events between 1.3 and 20 TeV

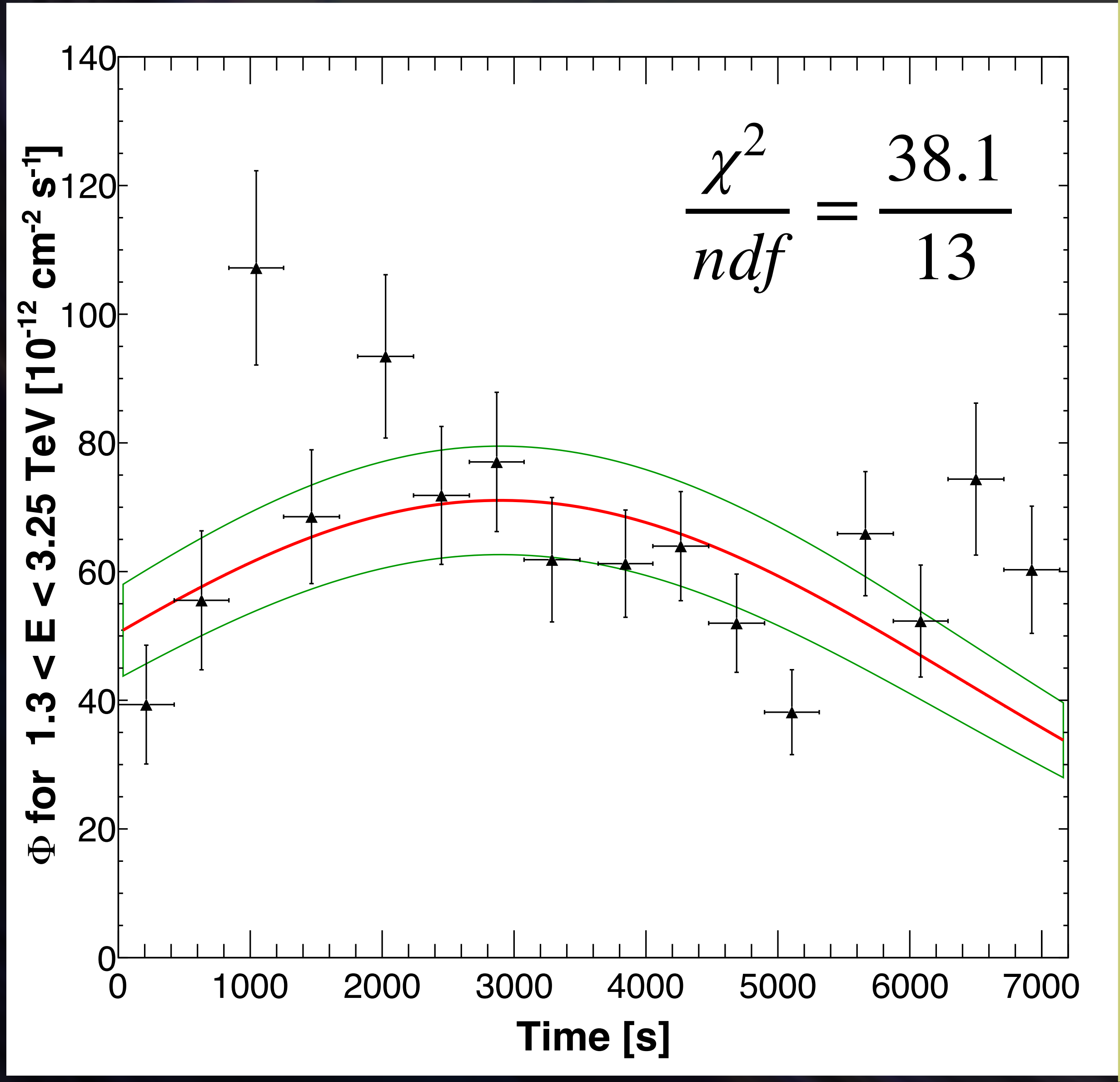


The two regions for the maximum likelihood are chosen between :

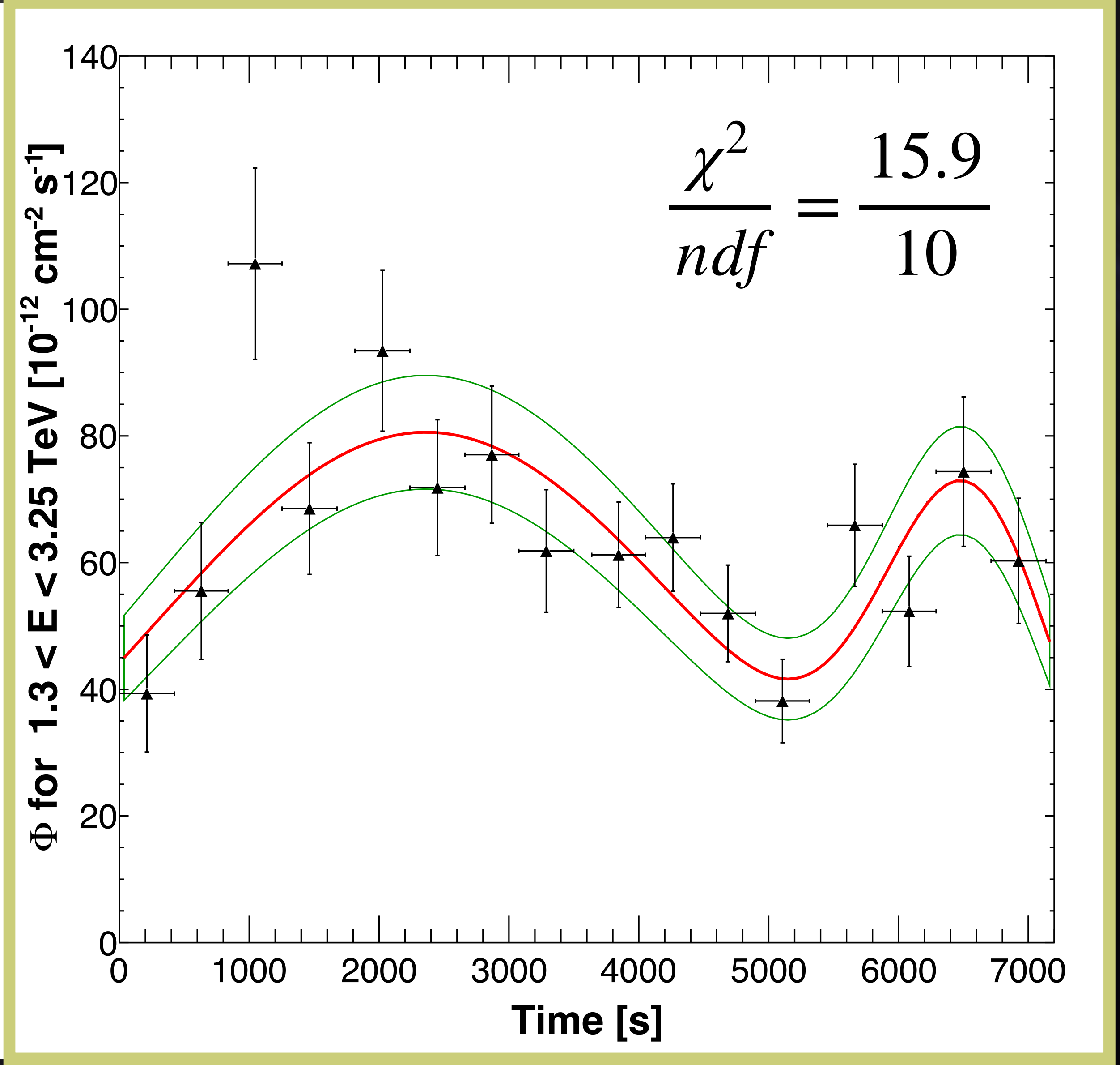
- 1.3 - 3.25 TeV for the template region (773 events)
- 3.25 - 20 TeV for the likelihood region (662 events)

MARKARIAN 501 – FLARE ANALYSIS

For the time function F(t), a double Gaussian function is preferred over a single Gaussian to parameterize the light curve in the template energy range



Simple Gaussian fit

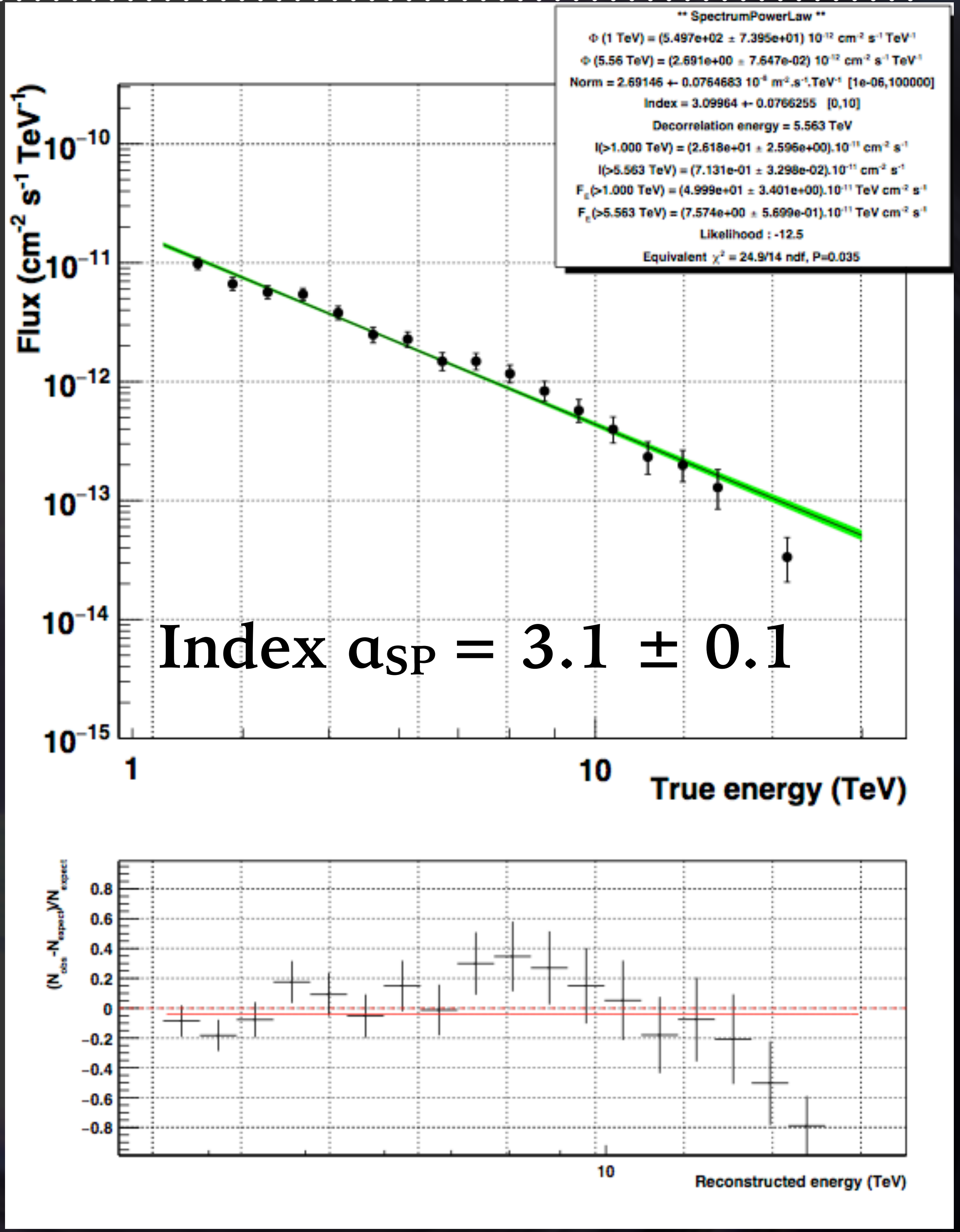


Double Gaussian fit

MARKARIAN 501 – FLARE ANALYSIS

The energy function Γ(E) is obtained by fitting the energy spectrum in the likelihood energy range

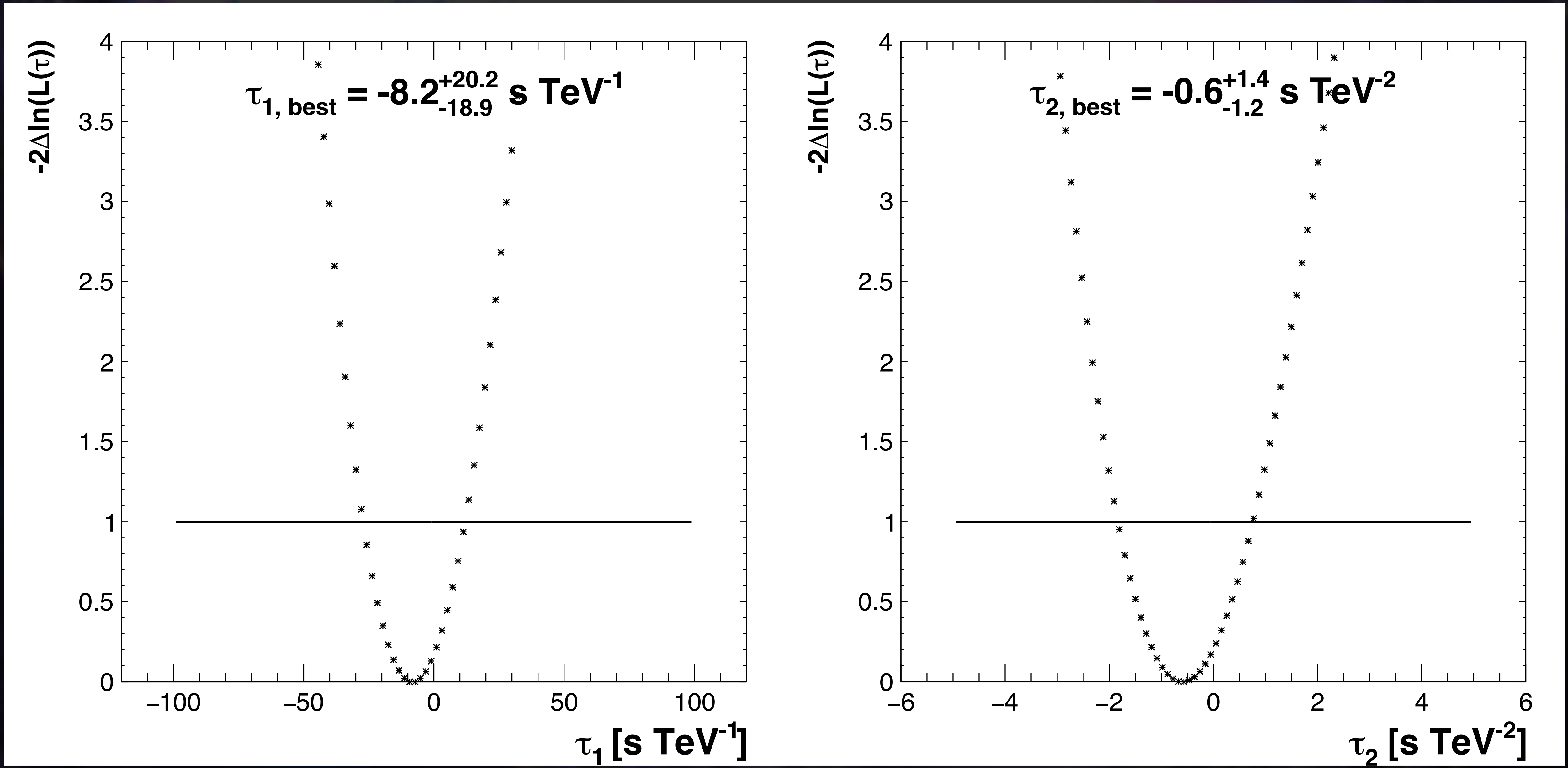
A simple power law function represents fairly the energy spectrum and allows a simple computation of the Likelihood function



MARKARIAN 501 – LIKELIHOOD ESTIMATION

The likelihood function provides the best estimations of τ_n

No significant time delay is found for both linear and quadratic LIV effect

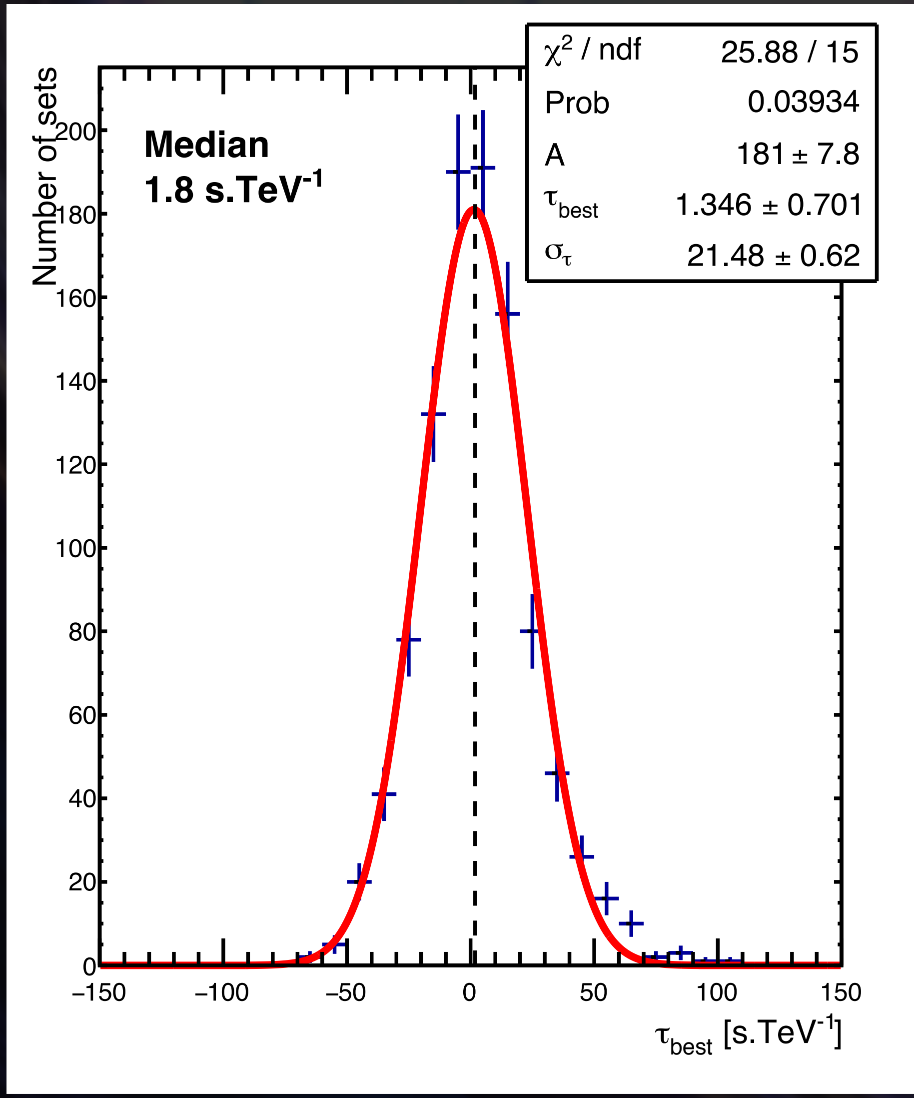


Linear LIV effect　　Quadratic LIV effect

MARKARIAN 501 – STATISTICAL UNCERTAINTIES

To improve the estimation of statistical uncertainties, simulations are done which reproduce the flare data.

From a 1000 realizations of the flare data set with no LIV delay, the dispersion of the reconstructed τ_n is used to deduce the statistical uncertainties



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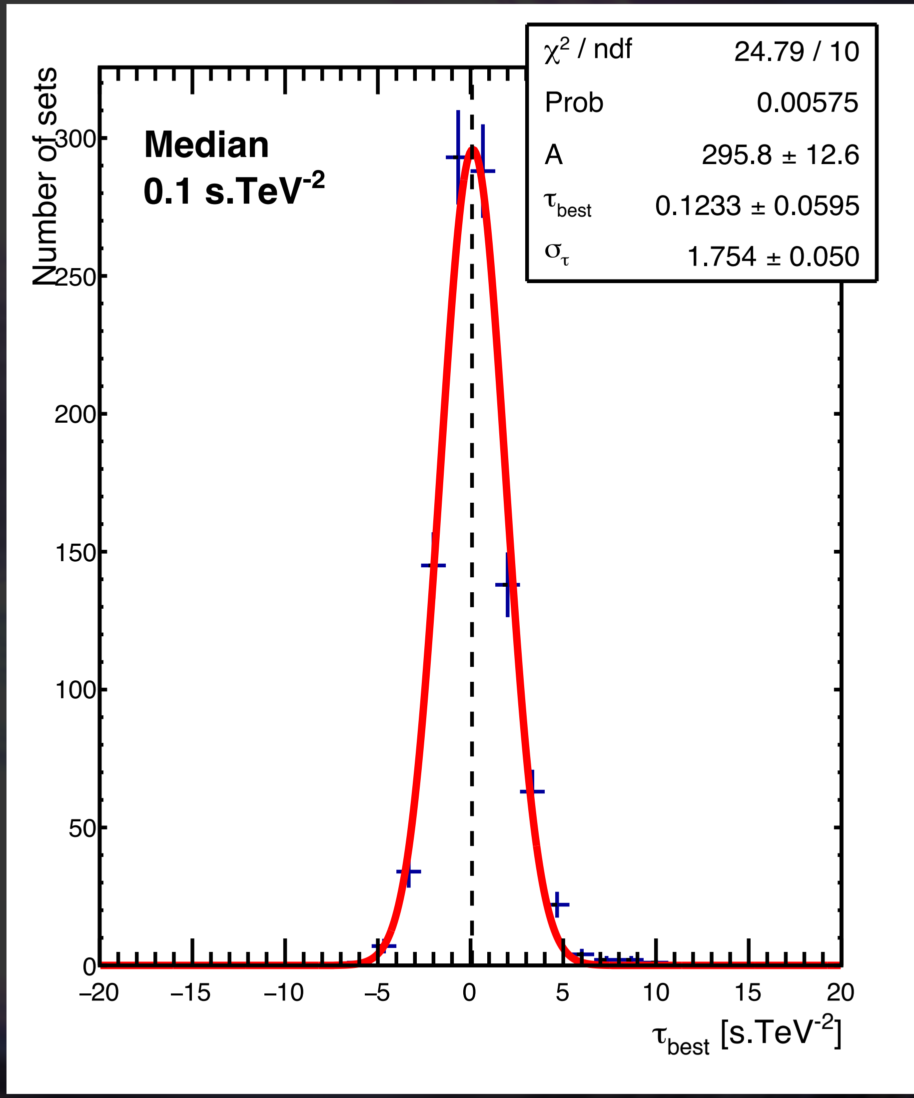


Quadratic LIV effect

MARKARIAN 501 – SYSTEMATIC STUDIES

Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics

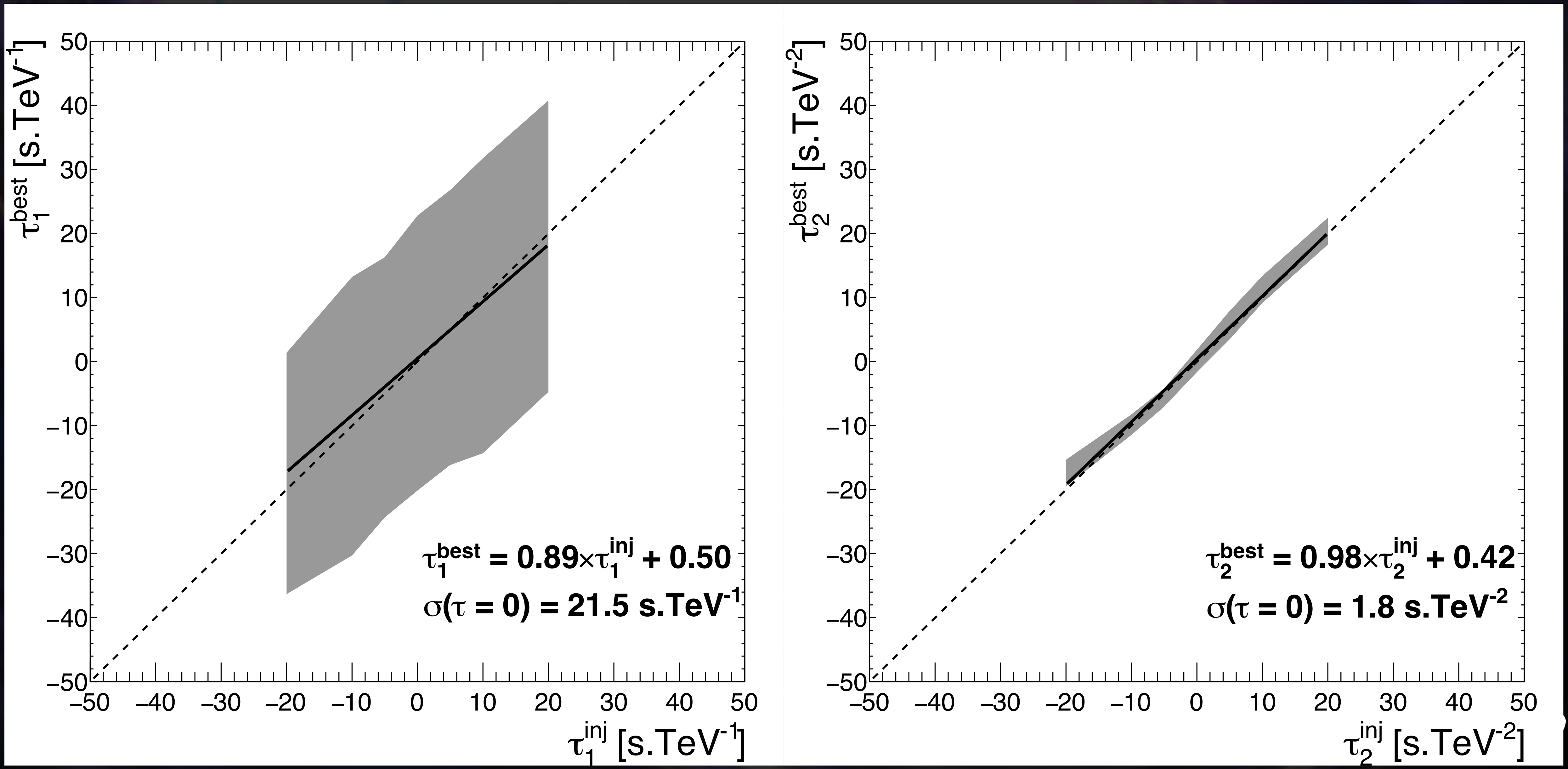
Source of systematic errors
Likelihood calibration
$F(t)$ and $\Gamma(E)$ determination
Analysis selection cut
Energy bias
Background contribution

MARKARIAN 501 – SYSTEMATIC STUDIES

Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics

Maximum likelihood calibration

From a 1000 realization reproducing Mrk 501 flare, injecting different τ_n values



MARKARIAN 501 – SYSTEMATIC STUDIES

Systematic uncertainties are estimated using simulations and investigating individual contribution of each source of systematics

Source of systematic errors	Linear effect	Quadratic effect
Likelihood calibration	$^{+5.5}_{-2.8}$	$^{+0.4}_{-0.5}$
F(t) and Γ(E) determination	$^{+4.6}_{-3.5}$	$^{+0.4}_{-0.2}$
Analysis selection cut	$^{+10.6}_{-8.2}$	$^{+0.7}_{-0.6}$
Energy bias	$^{+2.3}_{-5.2}$	$^{+0.1}_{-0.6}$
Background contribution	$^{+0.8}_{-0.1}$	$^{+0.1}_{-0.1}$
Total	$^{+13}_{-11}$	$^{+0.9}_{-1.0}$

MARKARIAN 501 – RESULTS

Combining statistical and systematic uncertainties:

$$\tau_1^{\text{best}} = -8.2 \pm \binom{+22}{-20}_{(stat)} \pm \binom{+13}{-11}_{(syst)} \ \text{s}\,.\,\text{TeV}^{-1}$$

$$\tau_2^{\text{best}} = -0.6 \pm \binom{+1.6}{-1.4}_{(stat)} \pm \binom{+0.9}{-1.0}_{(syst)} \ \text{s}\,.\,\text{TeV}^{-2}$$

Which allows to derive 95% confidence level lower limits on $E_{QG,\,n}$ for subluminal and superluminal LIV effect

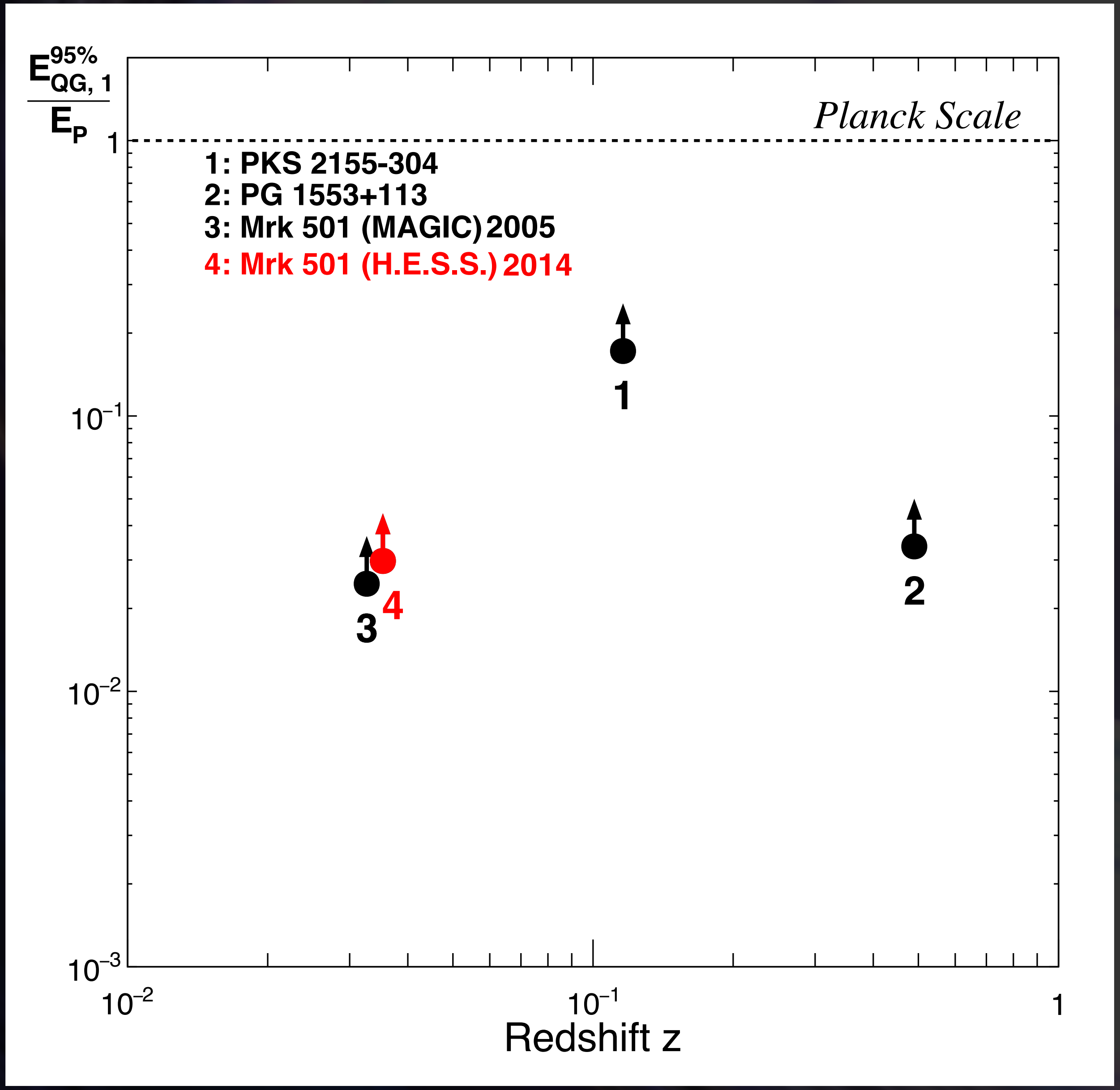
$$E_{QG,1}^{95\%} = \begin{cases} 3.63 \times 10^{17}\ \text{GeV}, & \text{subluminal case} \\ 2.89 \times 10^{17}\ \text{GeV}, & \text{superluminal case} \end{cases} \qquad E_{QG,1}^{95\%} \sim 0.03 E_P$$

$$E_{QG,2}^{95\%} = \begin{cases} 8.79 \times 10^{10}\ \text{GeV}, & \text{subluminal case} \\ 7.66 \times 10^{10}\ \text{GeV}, & \text{superluminal case} \end{cases} \qquad E_{QG,2}^{95\%} \ll E_P$$

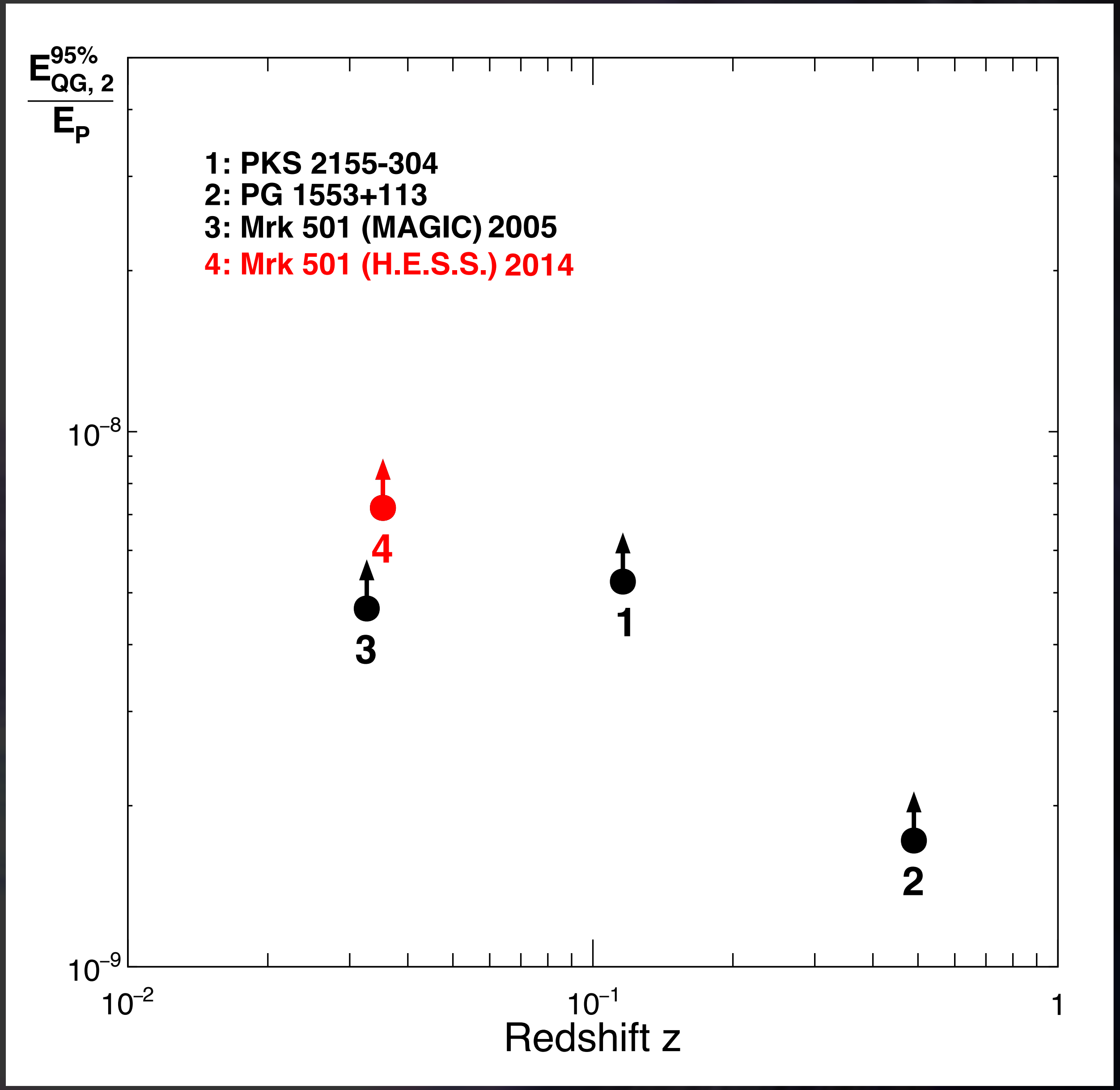
Paper will be submitted soon

MARKARIAN 501 – RESULTS

The 95% lower limits on the Quantum Gravity energy scale obtained with Mrk 501 can be compared to the results obtained with other AGN flares



Linear LIV effect



Quadratic LIV effect

BLAZAR MODELING

Why modeling the source ?

High energy photon

Low energy photon

What happens if there is a source-intrinsic time delay ?

BLAZAR MODELING

Why modeling the source ?

High energy photon

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BLAZAR MODELING

Why modeling the source ?

High energy photon

Low energy photon

What happens if there is a source-intrinsic time delay ?

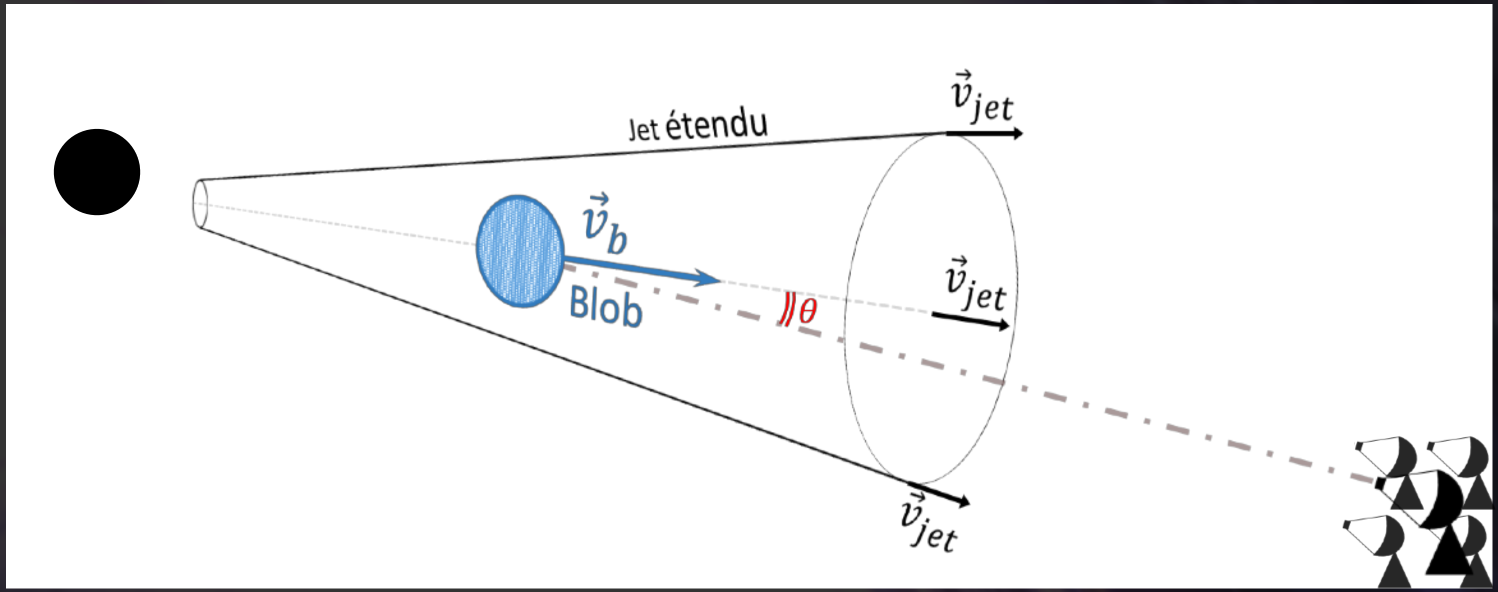
Modeling is crucial in order to understand time delays and get more robust constraints for Quantum Gravity models

MODELING BLAZAR FLARE

A "Blob" is responsible of high energy emissions

We consider only electrons as the main emitters:

Leptonic models



MODELING BLAZAR FLARE

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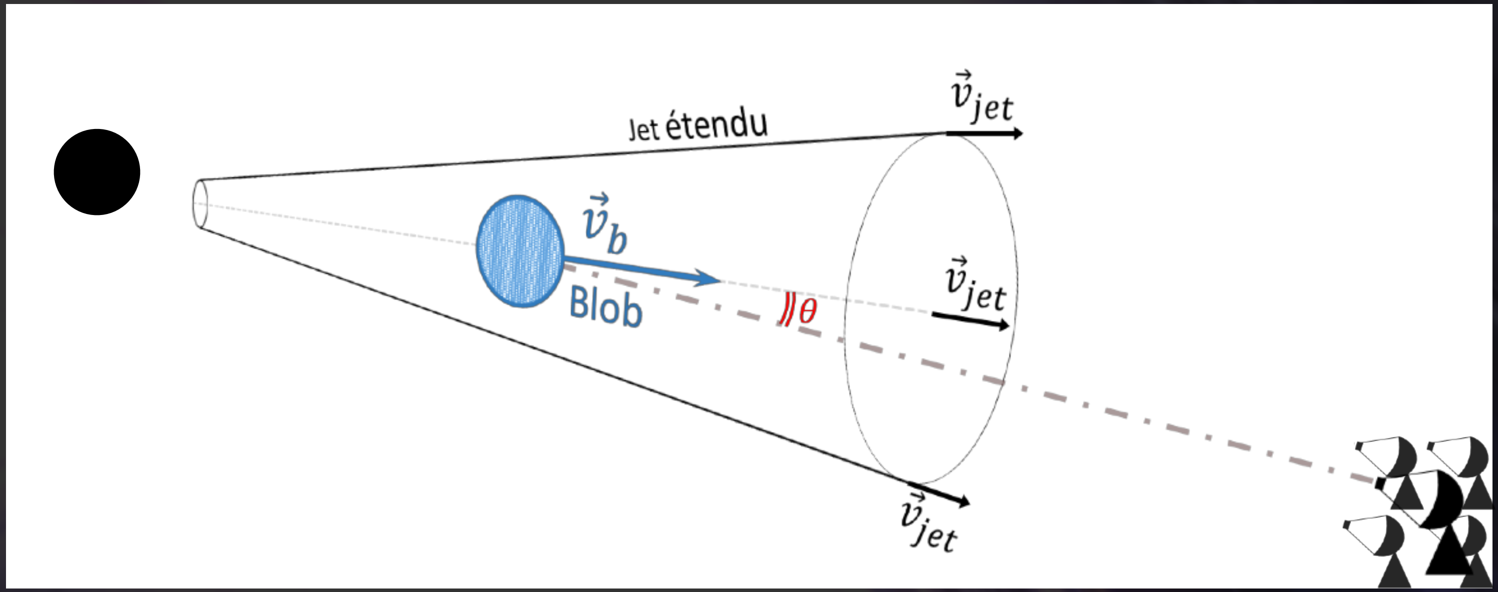

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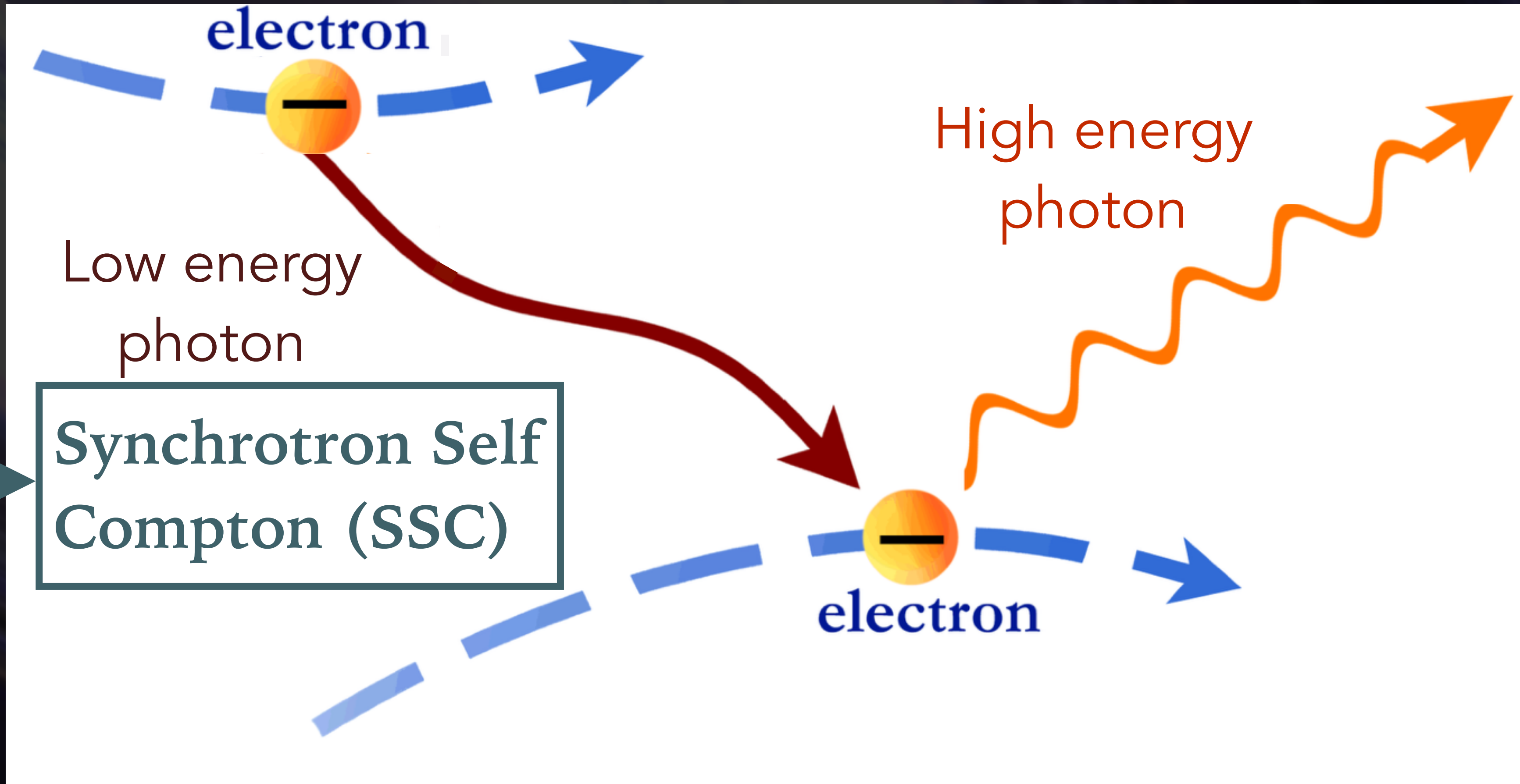
2 main processes responsible of photons emissions :

- Synchrotron process
- Inverse Compton process



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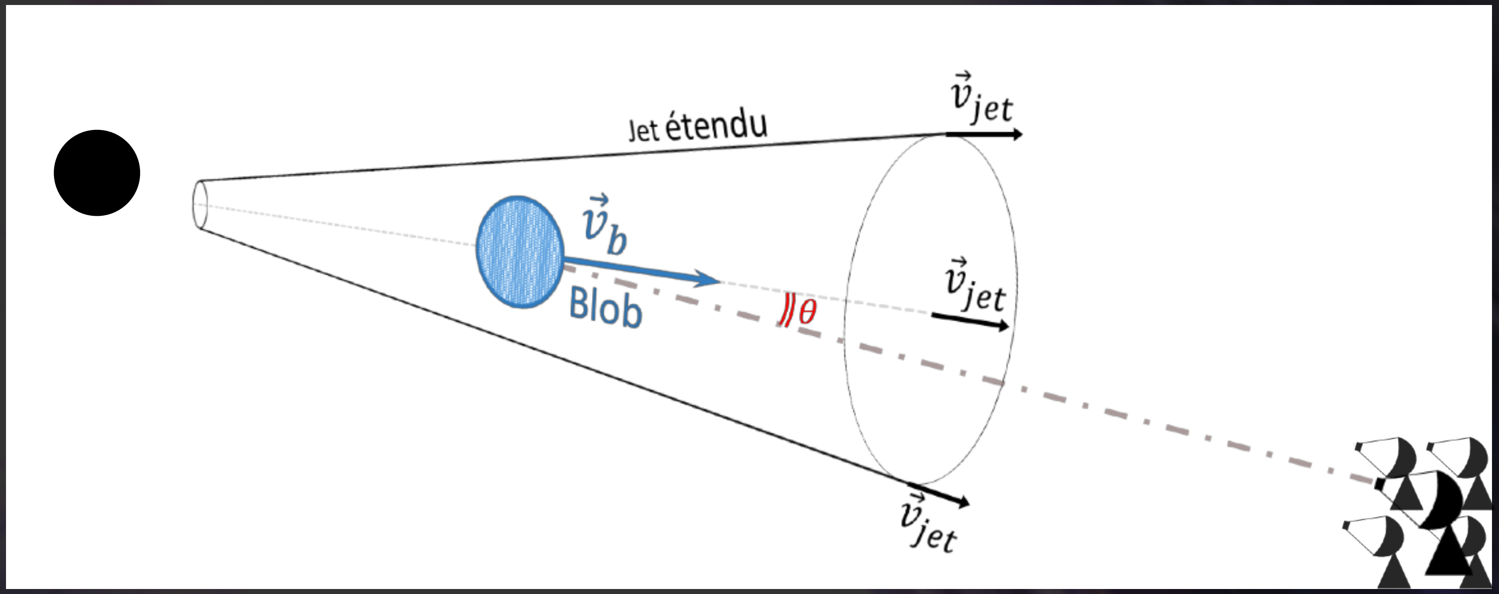

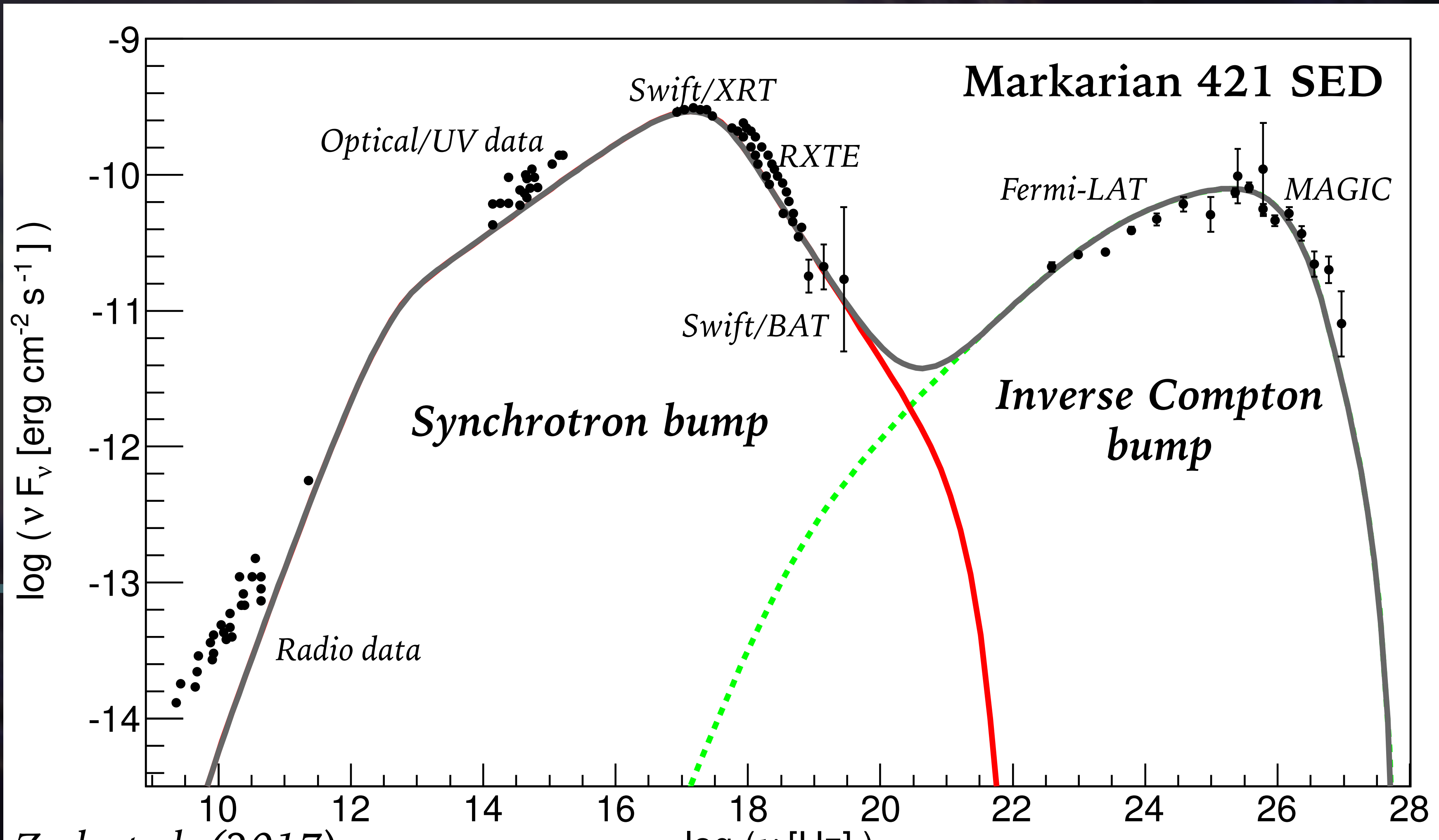

Zech et al. (2017)

ELECTRONS EVOLUTION

A time-dependent blazar flare model was developed describing the evolution of electrons responsible for the high energy emissions:

<u>Starting point</u> : A general transfer equation which describes the evolution of electrons in plasma *(The Origin of Cosmic Rays, V.L. Ginzburg, 1964)* :

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

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

Fluctuation of systematical variation (second order terms)

Injection of particles

Loss of particles

35

ELECTRONS EVOLUTION

Katarzynski et al (2003)

A simplified differential equation is used to provide a minimal time dependent model, with an analytic solution (under some assumptions):

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

The initial electron spectrum follows a power law function with a high energy cut-off:

$$N_e(0,\,\gamma) = K_0\,\gamma^{-n}\left[1 - \left(\frac{\gamma}{\gamma_{c,0}} \right)^{n+2} \right]$$

ELECTRONS EVOLUTION

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Electrons cooling effect: energy losses via SSC emissions

$$C_{cool}(t) = \frac{4\sigma_T c}{3 m_e c} U_B(t)\left(1 + \frac{1}{\eta}\right)$$

$$U_B = \frac{B(t)^2}{8\pi}$$

$$\boxed{\eta = \frac{U_B(t)}{U_{rad}(t)}}$$

Has to be large

Synchrotron dominated

$$B(t) = B_0 \left(\frac{t_0}{t}\right)^{m_b}$$

ELECTRONS EVOLUTION

Katarzynski et al (2003)

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Electron acceleration: Energy gain from acceleration processes (generic one)

$$C_{acc} = A_0 \left(\frac{t_0}{t}\right)^{m_a}$$

Acceleration term allows to initiate the flare

ELECTRONS EVOLUTION

Katarzynski et al (2003)

A simplified differential equation is used to provide a minimal time dependent model, with an analytic solution (under some assumptions):

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

Adiabatic expansion: Energy losses from the evolution of the emission zone radius

$$R(t) = R_0 \left(\frac{t_0}{t}\right)^{-m_r} \qquad V_{exp} \approx \frac{c}{\sqrt{3}}$$

Speed of sound in relativistic plasma

$$C_{adiab} = \frac{m_r}{t} \qquad t_0 = \frac{R_0}{V_{exp}}$$

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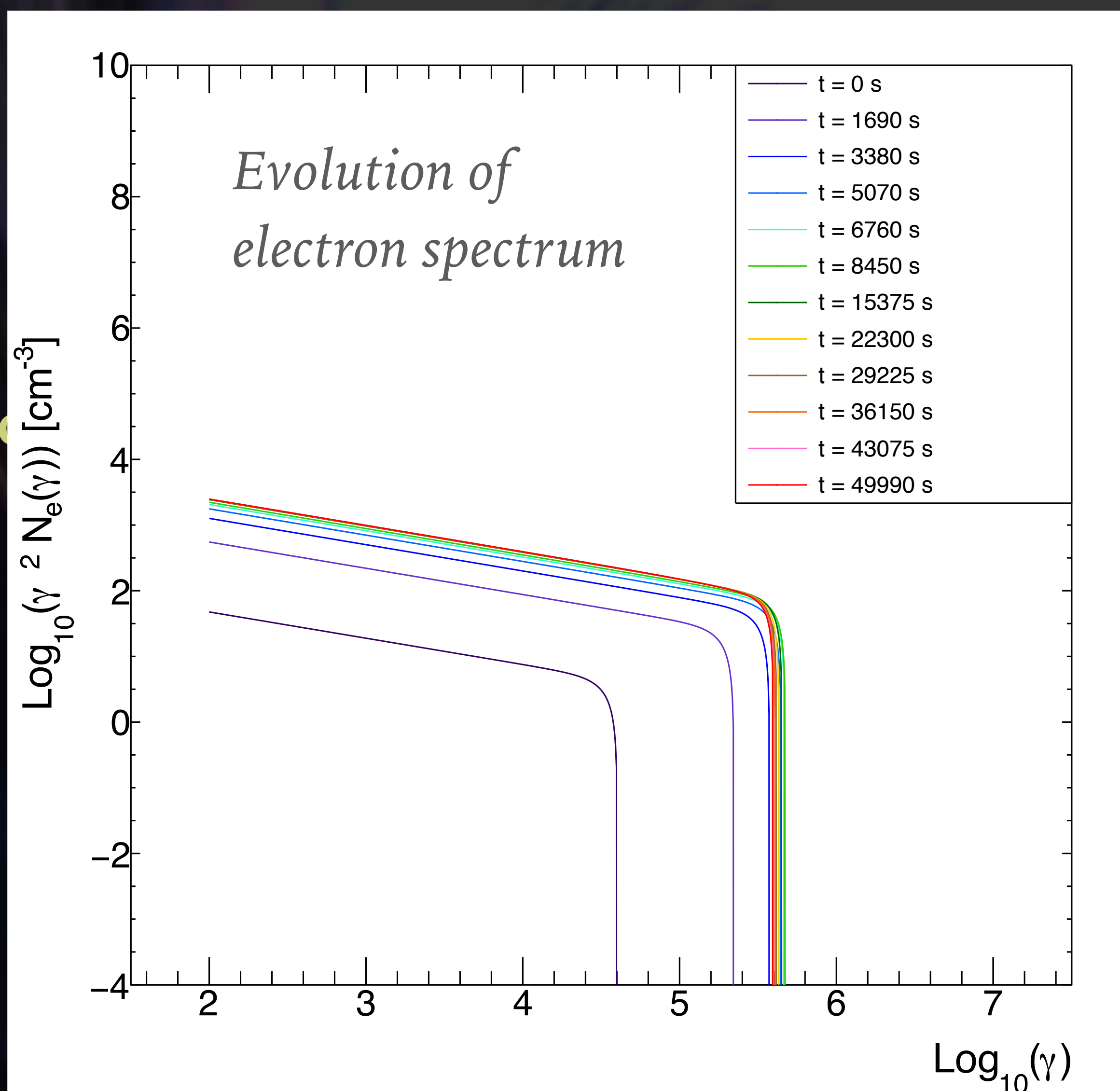
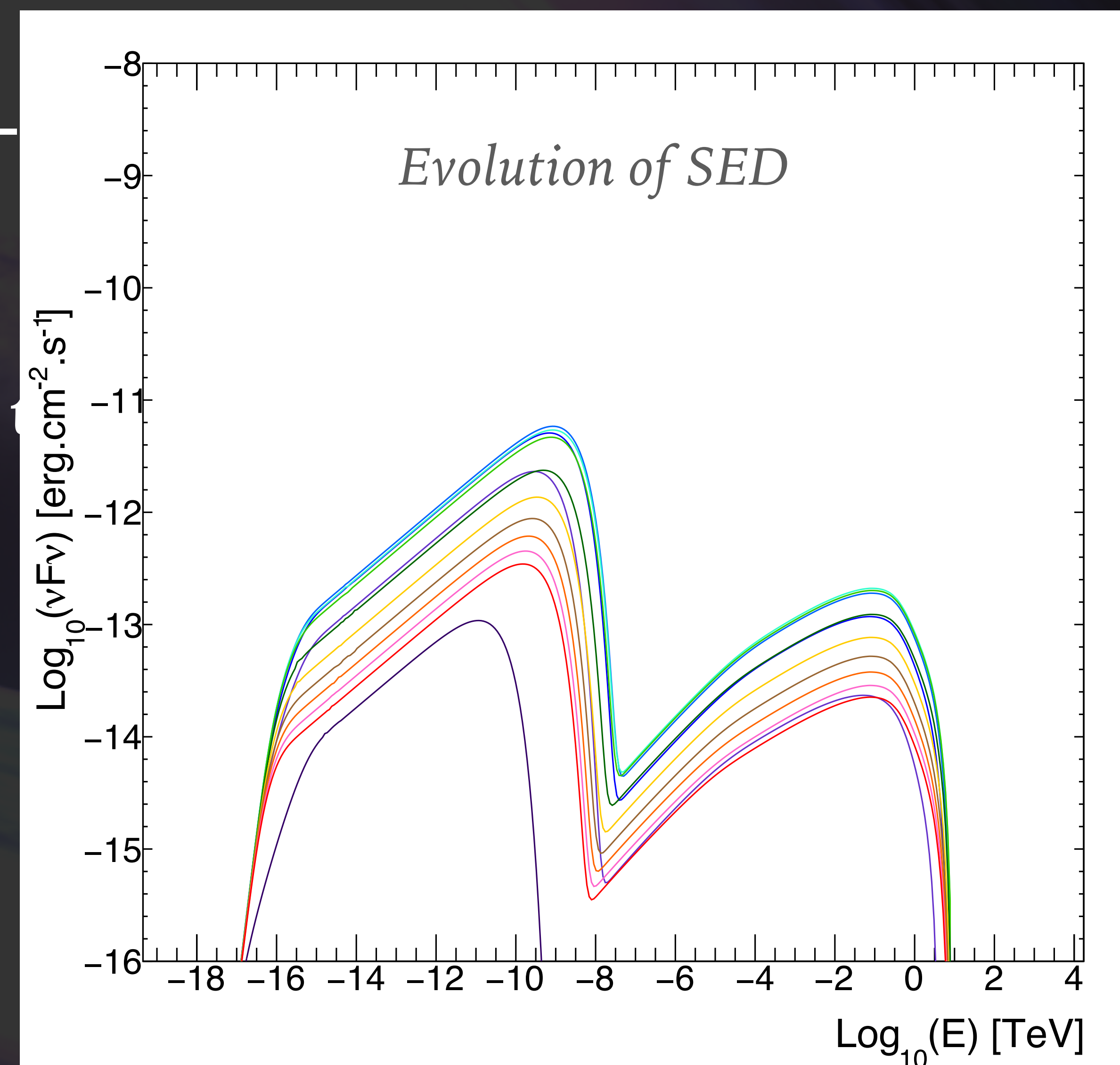




At first, adiabatic expansion is not considered to simplify the scenario

INVESTIGATING INTRINSIC TIME DELAY

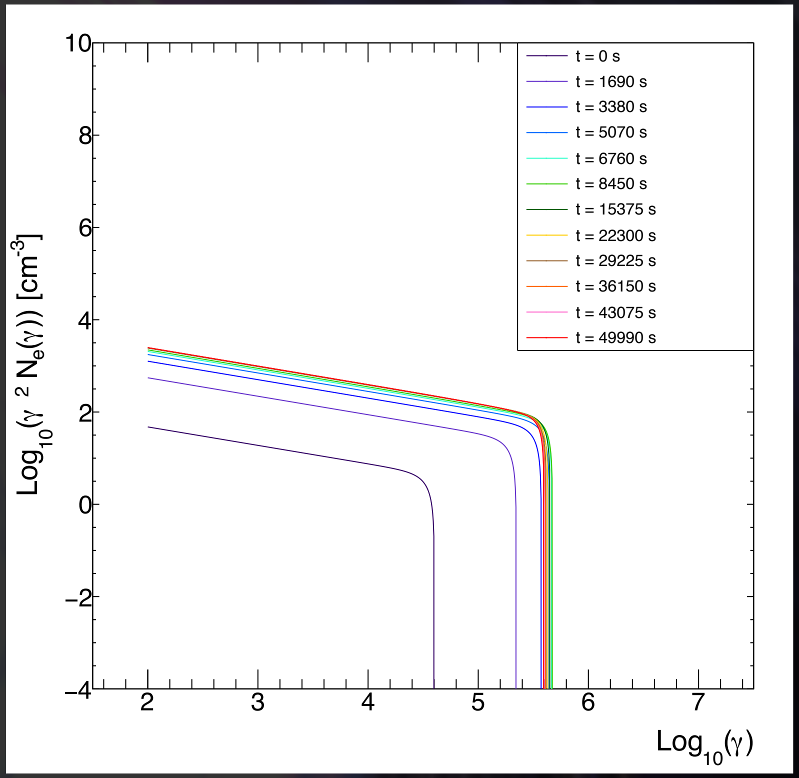
Two different cases were identified which depend on the time t_{max} when the electrons highest energy $\gamma_c(t)$ is reached and starts to decrease with time

Case 1

The time t_{max} happens after all the light curves peak

Case 2

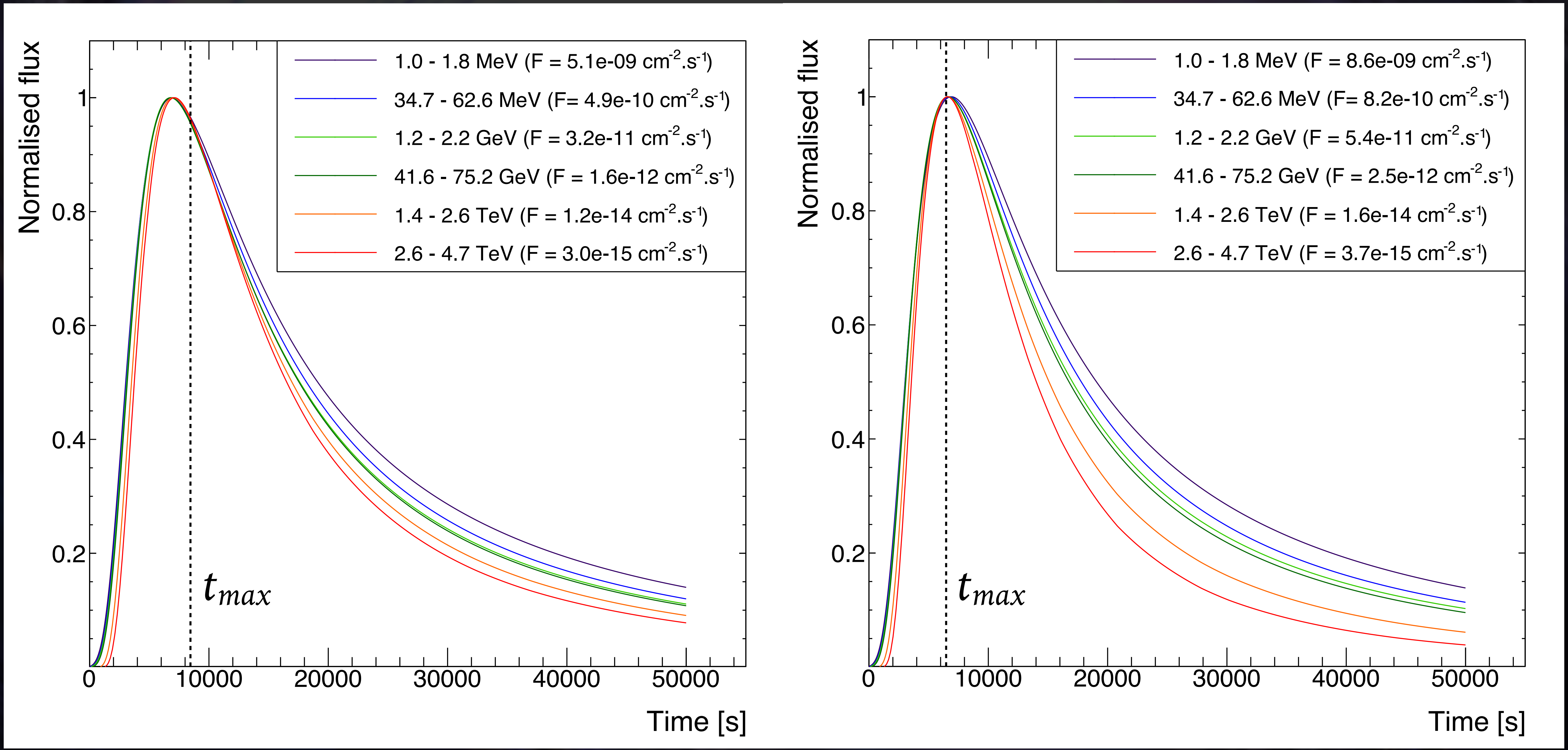
The time t_{max} happens before all the light curves peak



The difference between the 2 cases is related to the process which initiates the flux decrease for the highest energy light curves

INVESTIGATING INTRINSIC TIME DELAY

The light curves at different energies show the presence of time delays



Case 1 Case 2

INVESTIGATING INTRINSIC TIME DELAY

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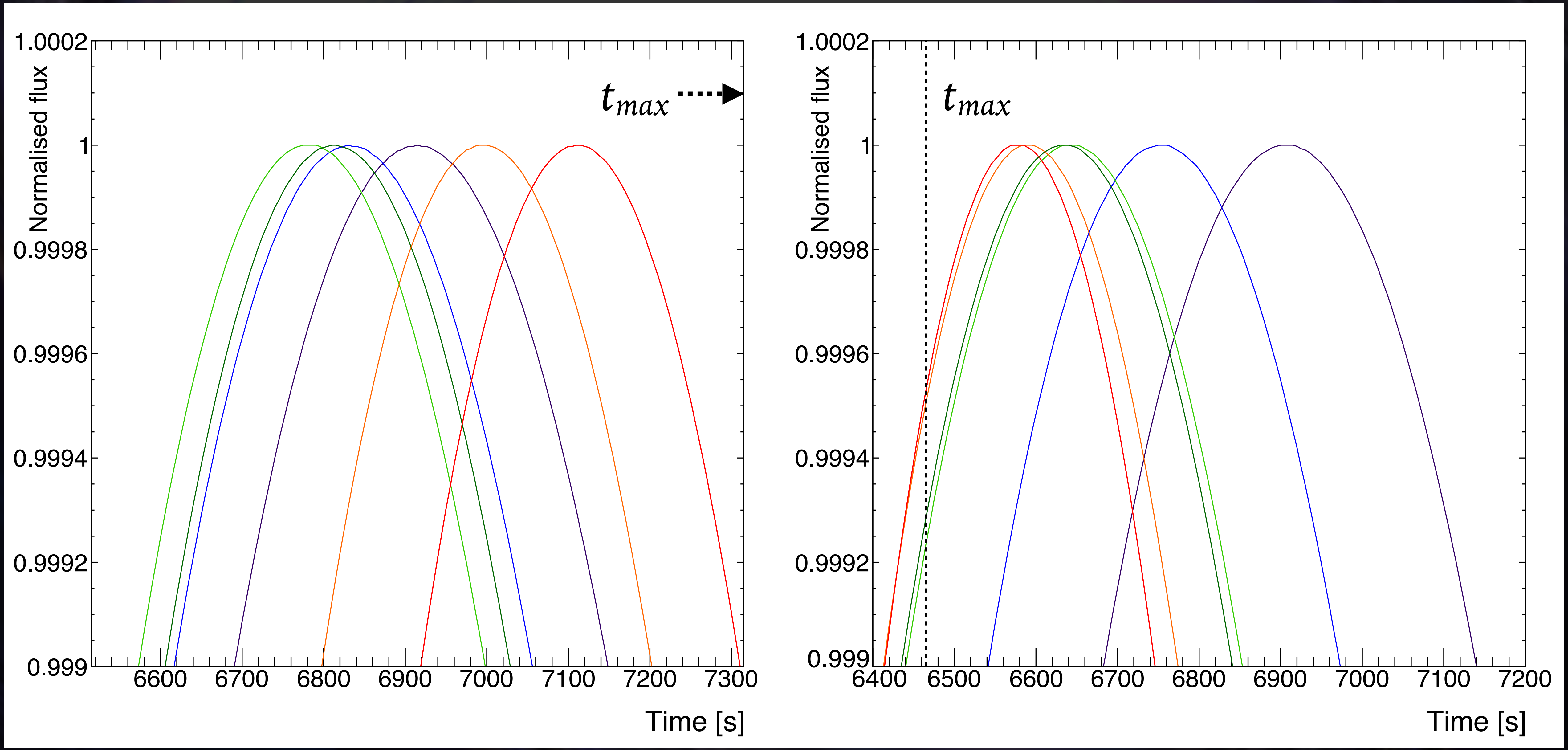
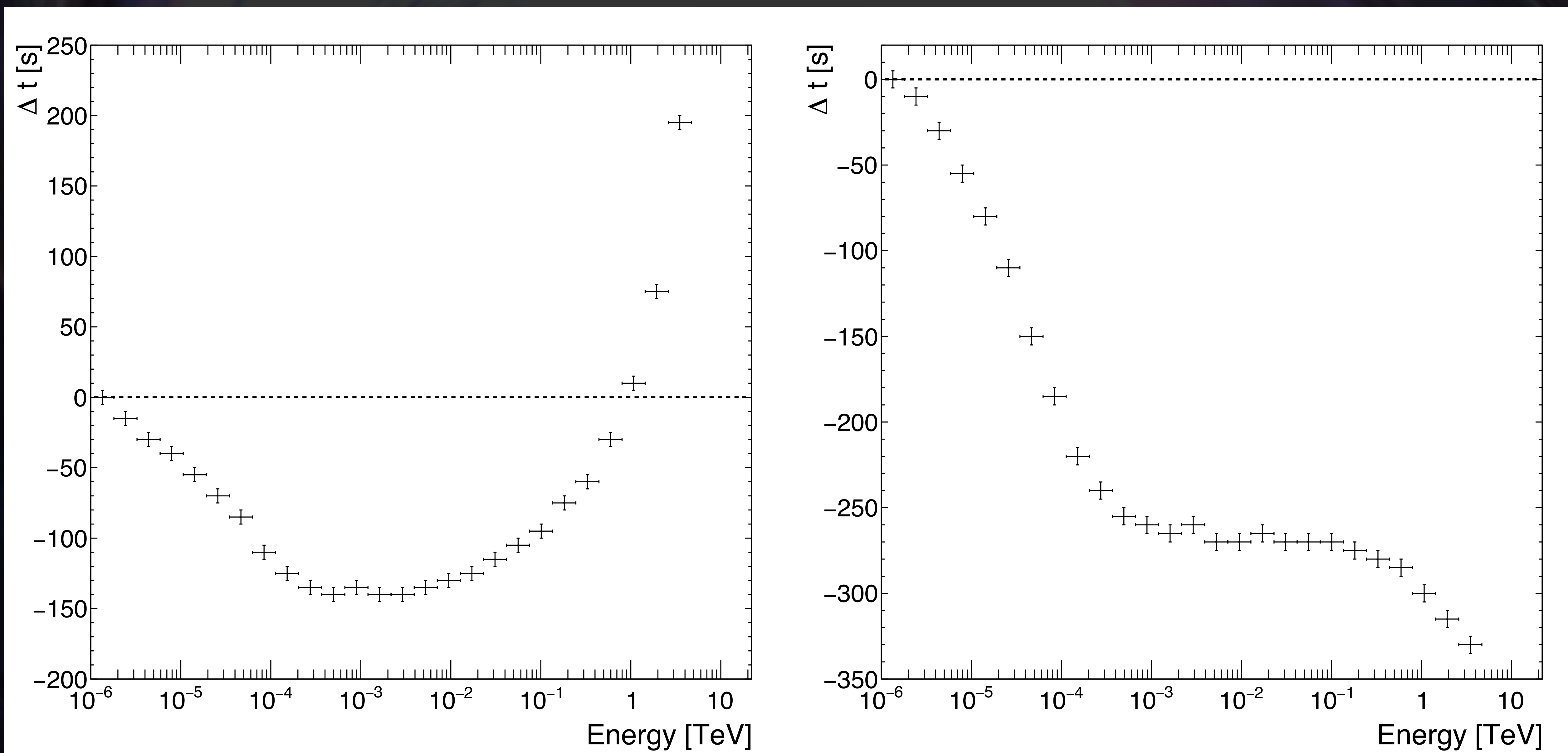


Case 1

Case 2

INVESTIGATING INTRINSIC TIME DELAY

The time delay is computed using time difference between the maximum of the light curve at 1 MeV to the maximum of the light curve at energy E



Case 1 *Perennes et al. ICRC 2017* *Paper in preparation* Case 2

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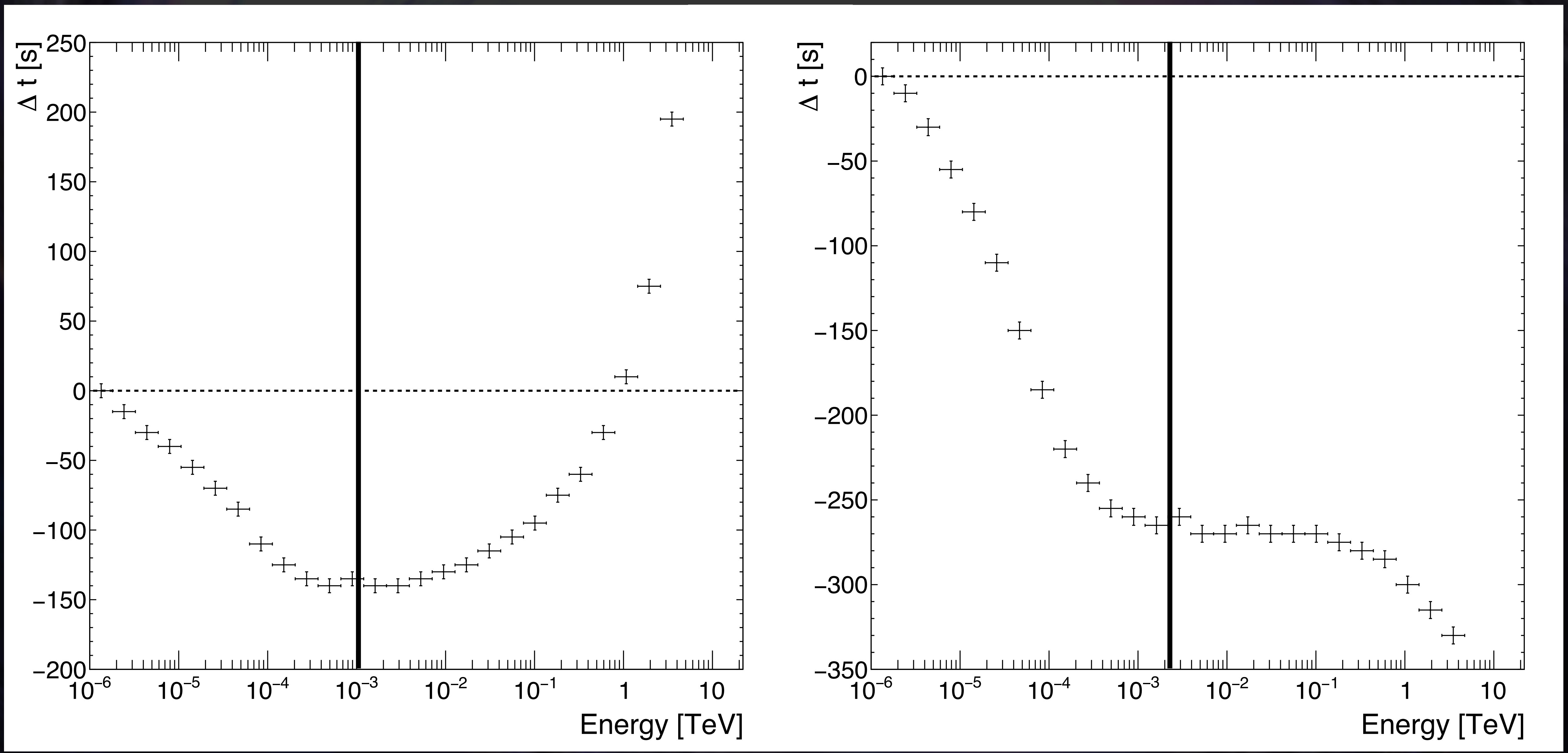

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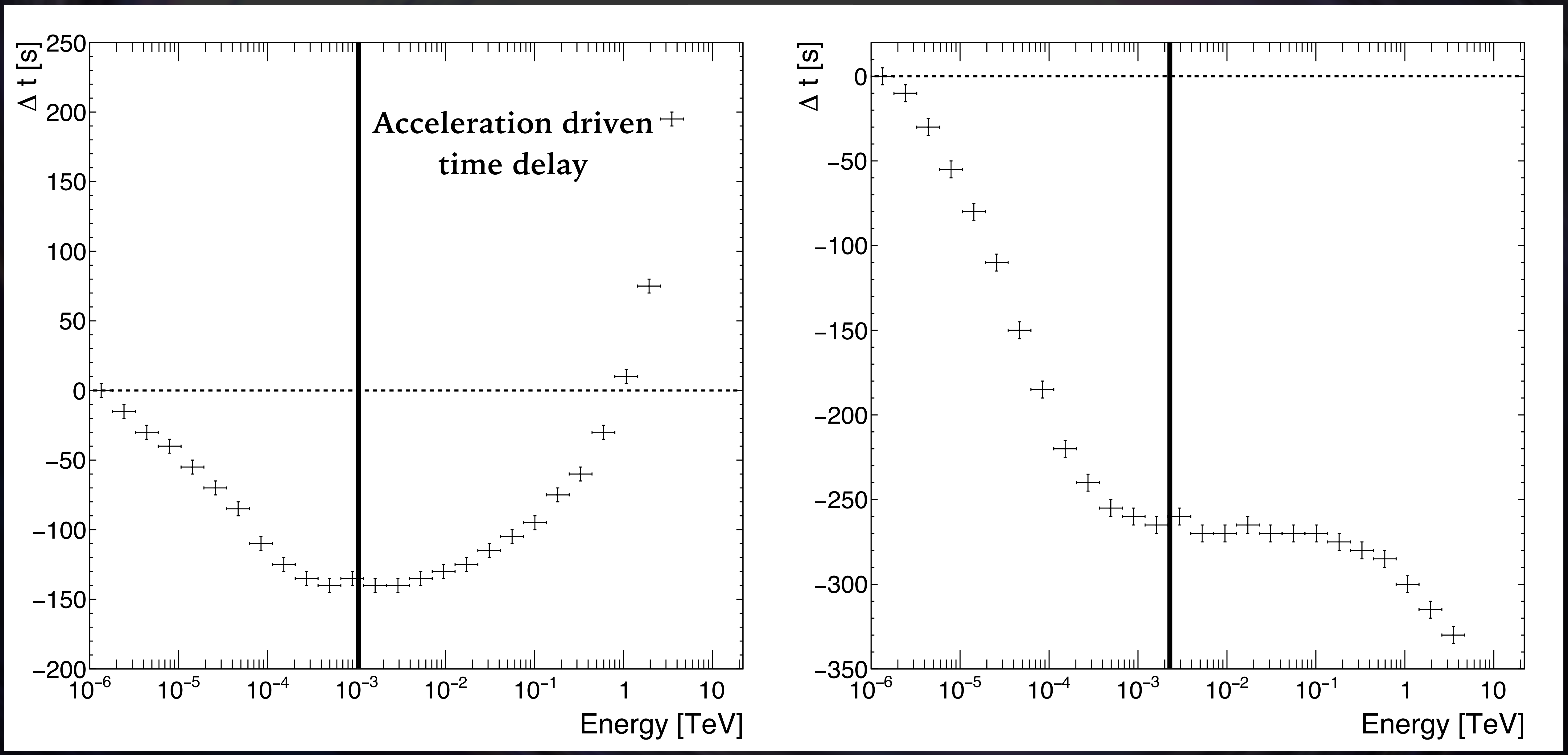

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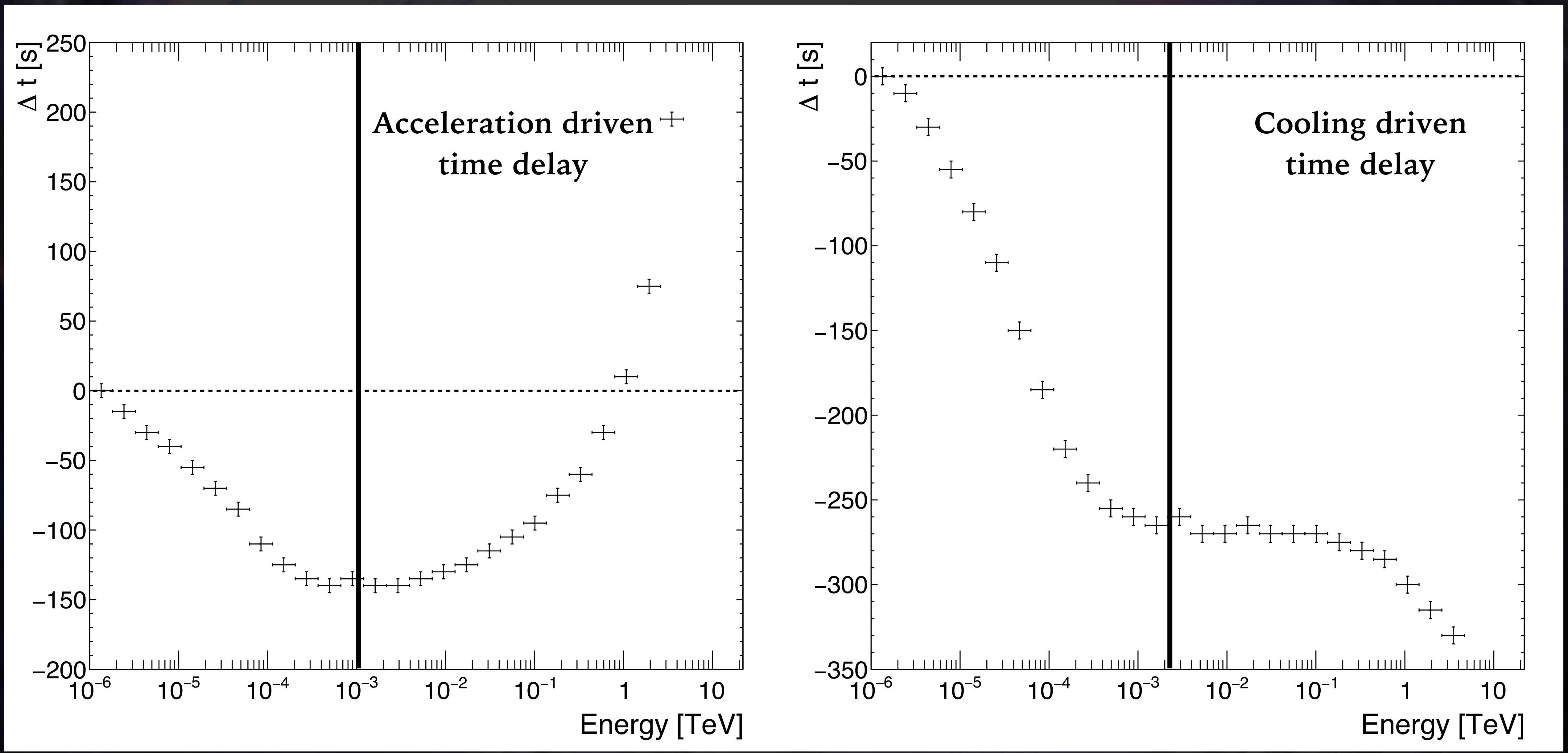

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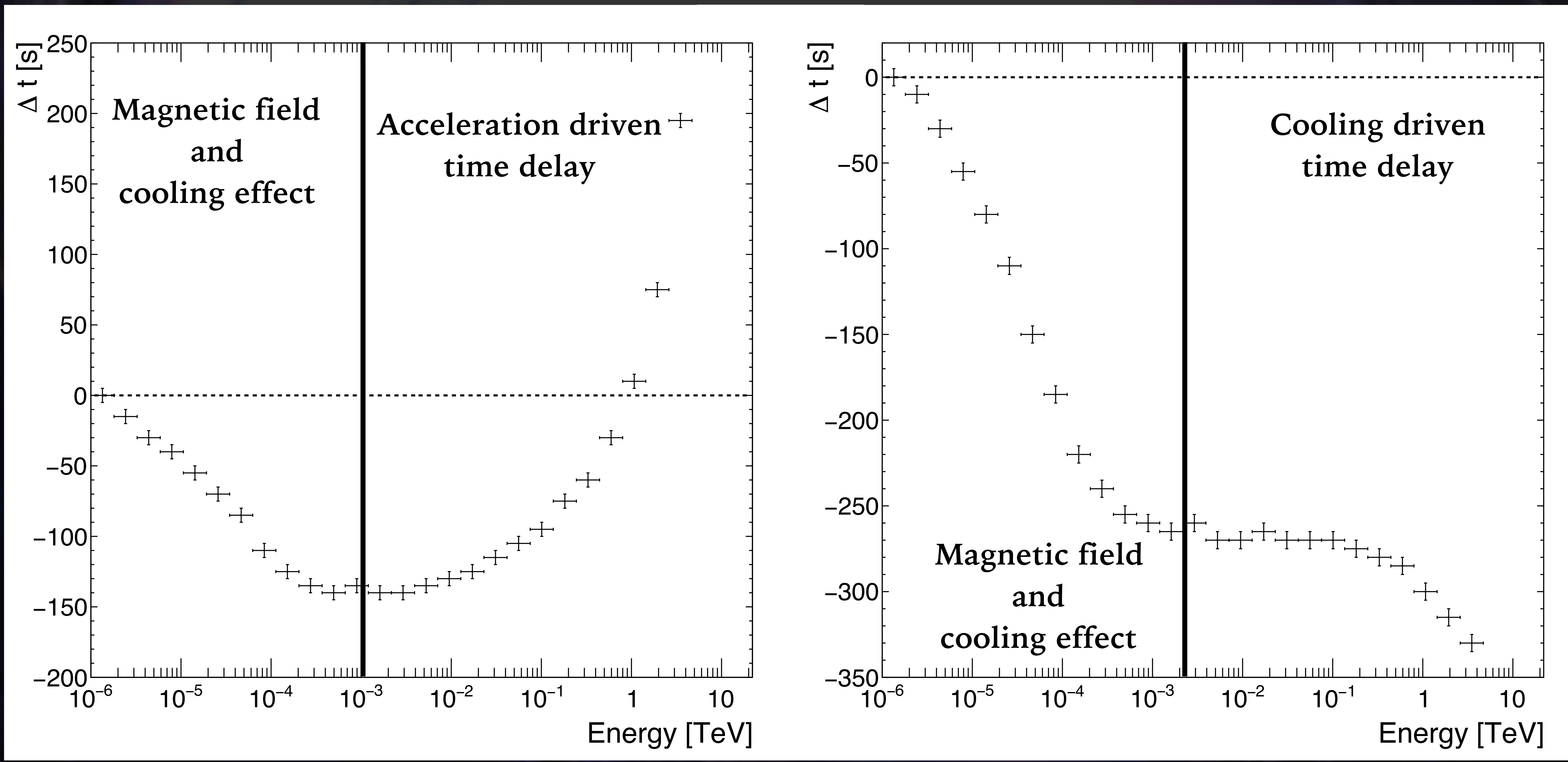


Case 1

Perennes et al. ICRC 2017
Paper in preparation

Case 2

INVESTIGATING INTRINSIC TIME DELAY

The MeV-GeV time delays are explained by the combined action of the magnetic field decrease and the energy depend cooling effect

Above GeV energies, we identify two distinct regimes depending on the process driving the delay:

Acceleration driven regime (Case 1)

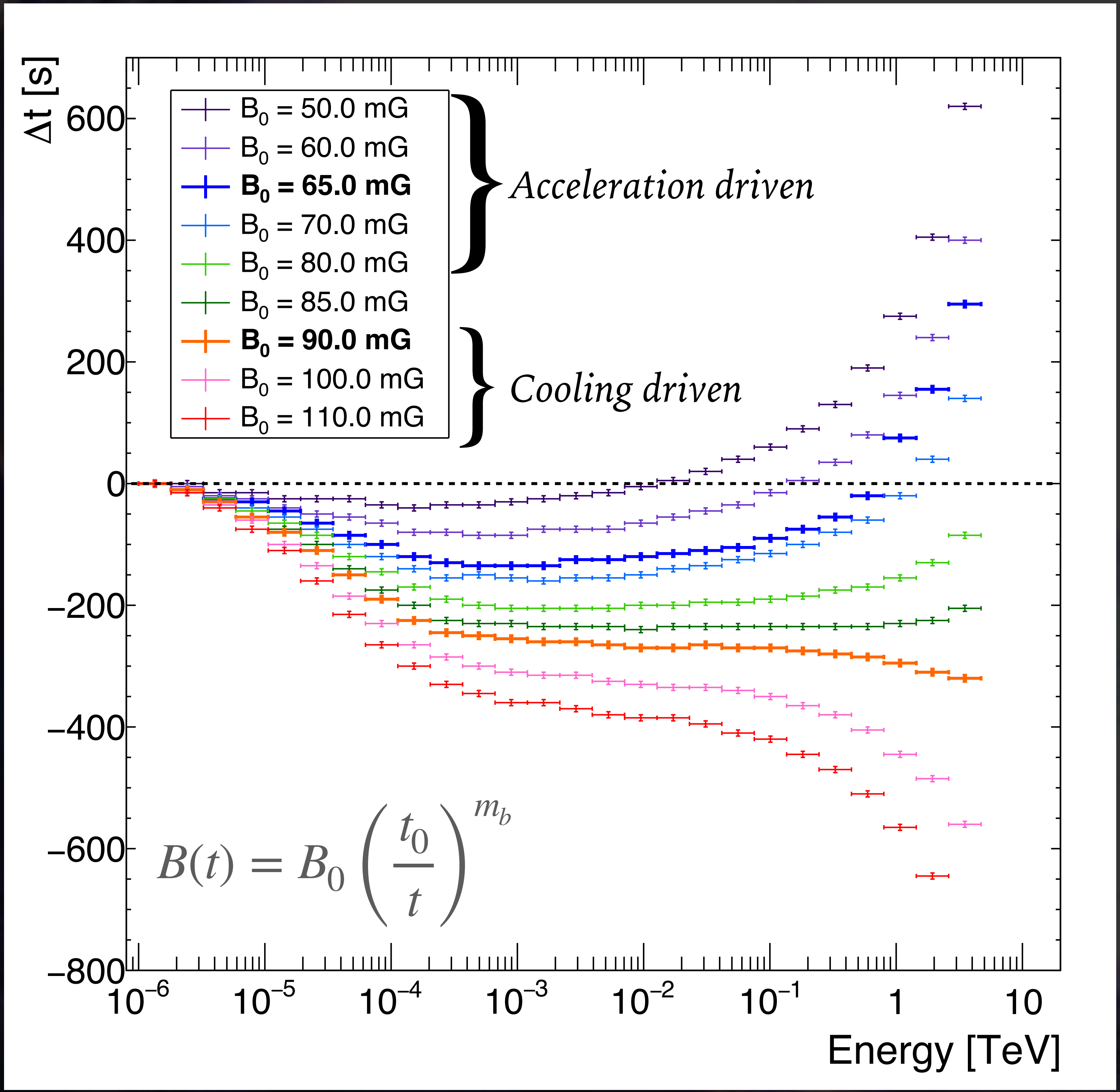
The increasing time delay comes from a long-lasting acceleration where electrons need time to be accelerated

Cooling driven regime (Case 2)

The decreasing time delay comes from a strong radiative cooling affecting high energy electrons

The influence of the model parameters is investigated by varying individually each of them

INVESTIGATING INTRINSIC TIME DELAY



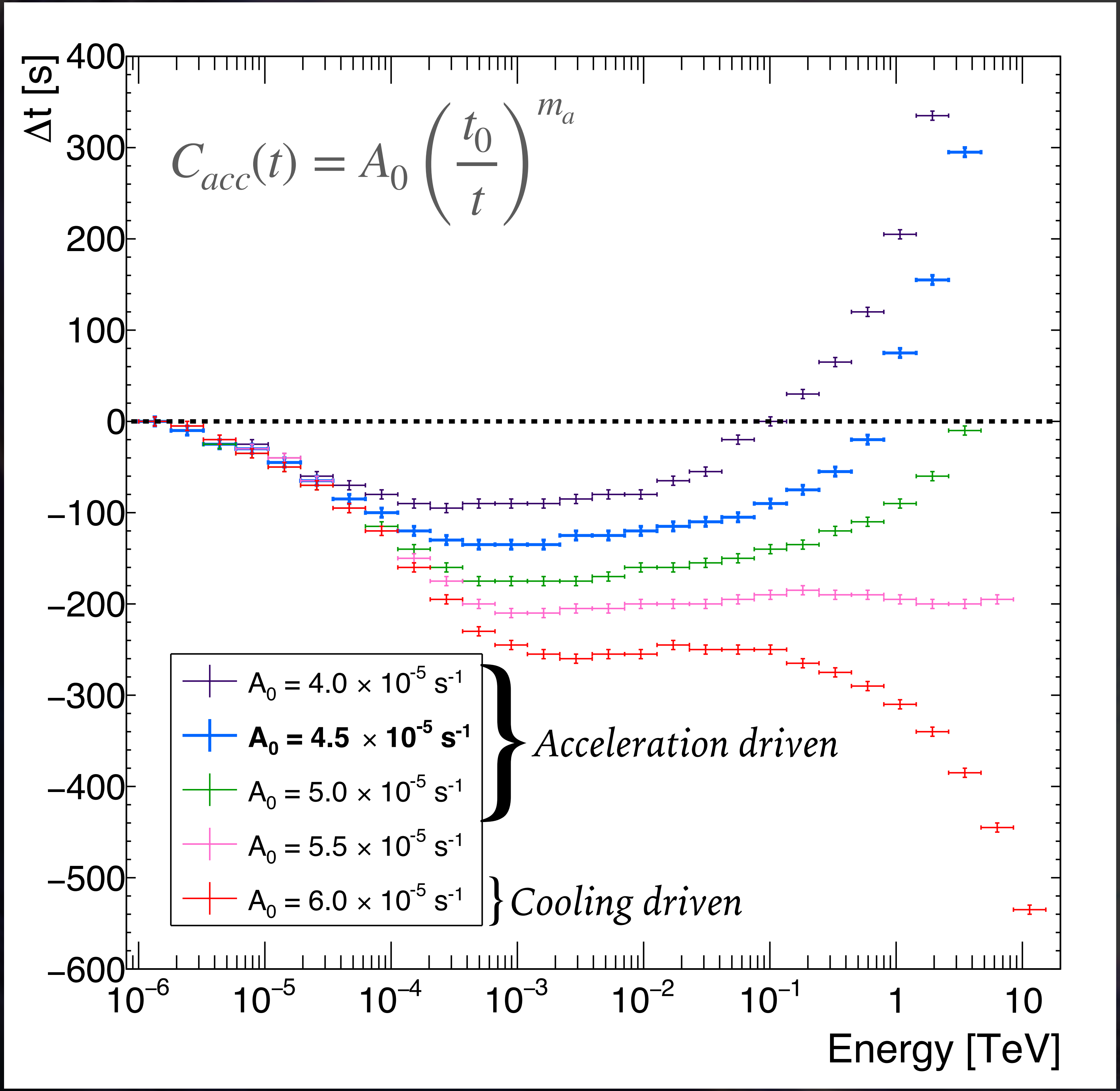
A small B_0 allows the acceleration to last long and leads to an acceleration driven regime

At the transition, a constant delay is produced at GeV energy leading to no delay in this range

A large B_0 induces a strong radiative cooling leading to a cooling driven regime

Paper in preparation

INVESTIGATING INTRINSIC TIME DELAY



A small A_0 provides a weak acceleration which lasts long due to small radiative cooling leading to an acceleration driven regime

At the transition, a constant delay is produced at GeV energy leading to no delay in this range

A large A_0 induces a strong acceleration leading to a cooling driven regime

Paper in preparation

ADIABATIC EXPANSION

From the variations of all the model parameters, the two regimes are found when the parameter influences the electron evolution

The transition from one regime to the other is related to the relative strength between acceleration and radiative cooling

Between the two regimes, a transition area is found producing no delay at GeV-TeV energies

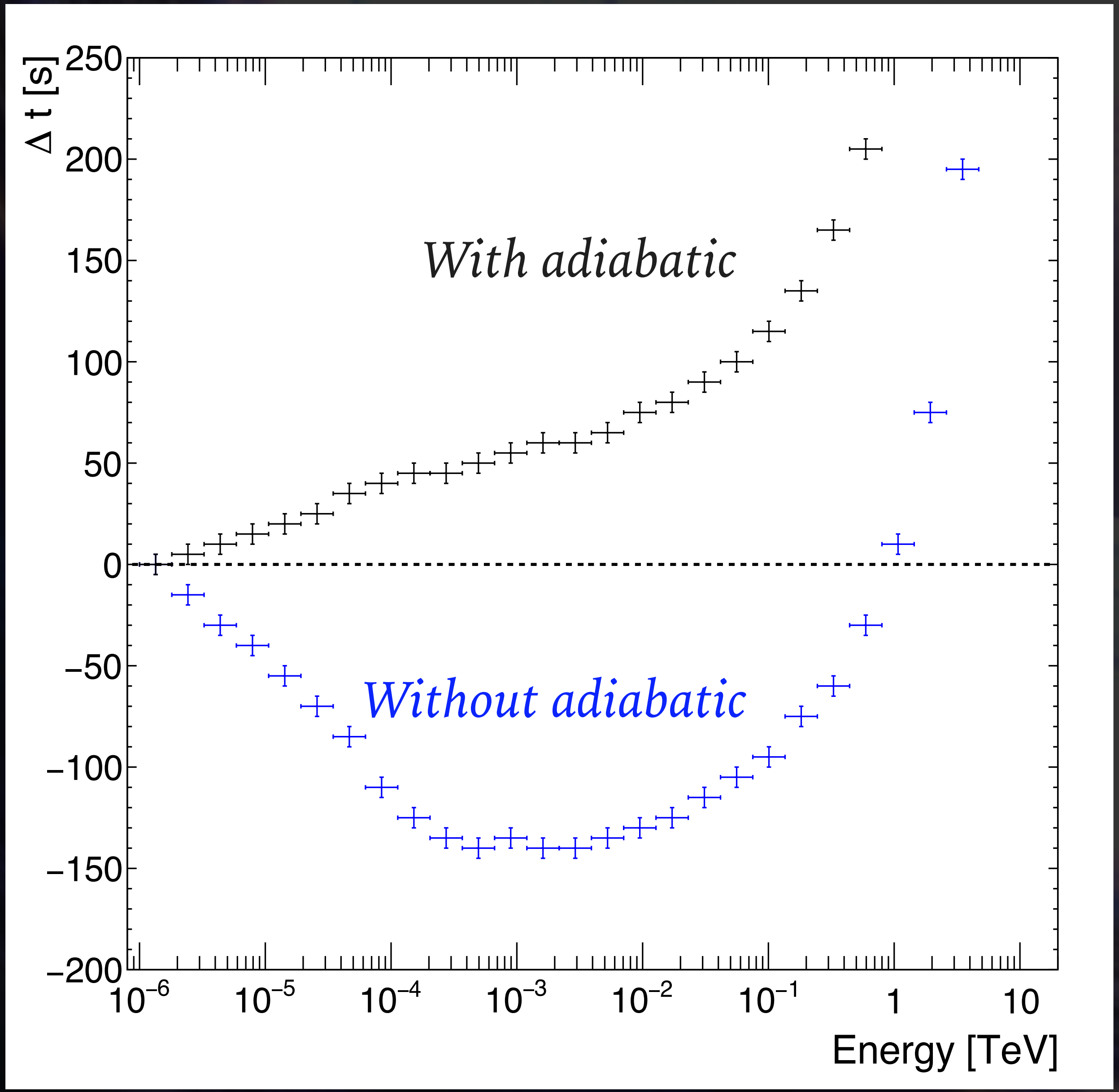
Until now, adiabatic expansion was removed from the scenario to simplify the interpretation about the time delay origin

We propose now to study the addition of adiabatic expansion

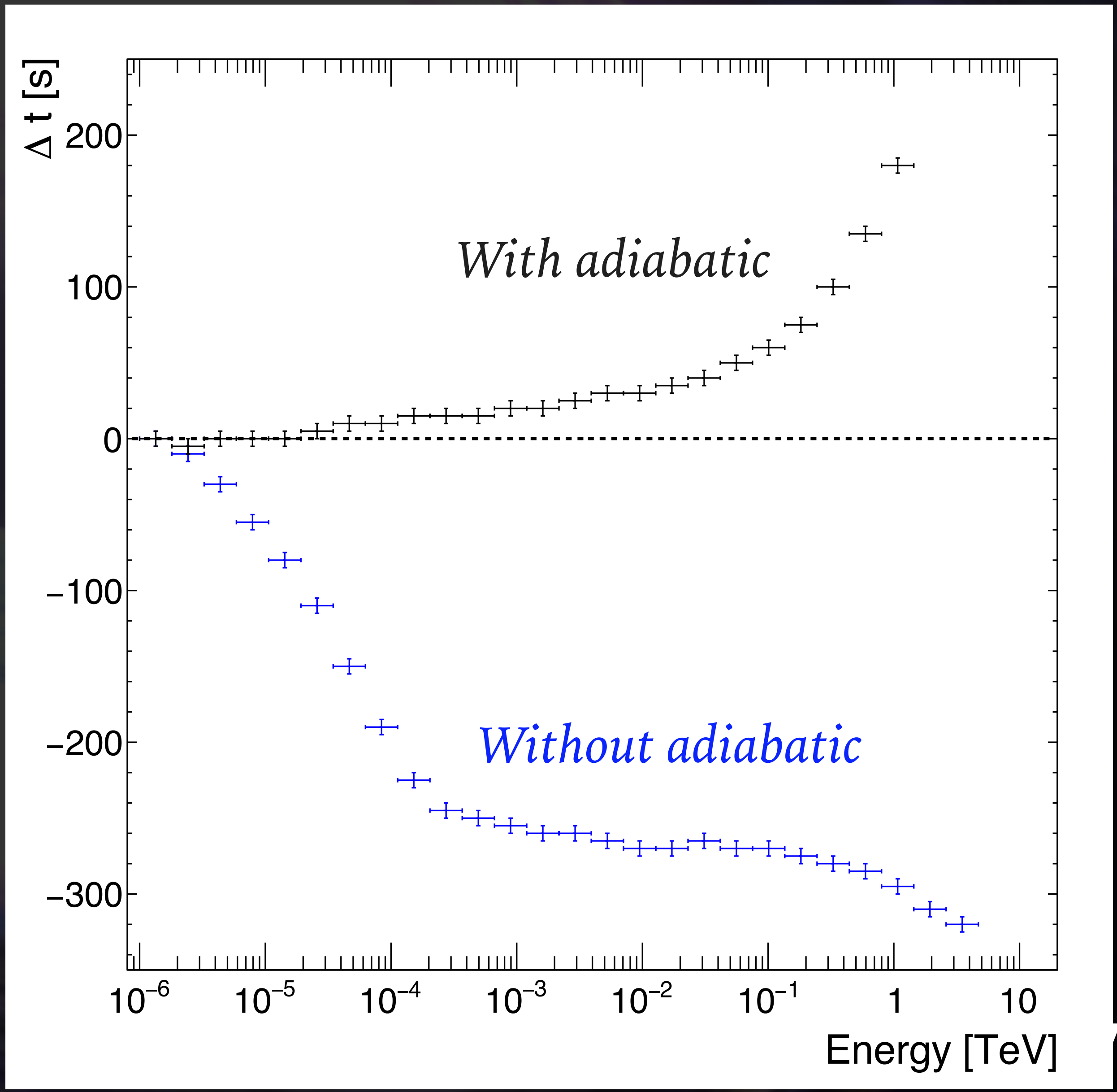
ADIABATIC EXPANSION

The adiabatic expansion brings an additional source of energy loss for electrons leading to a shorter flare as well as a dilution of the electron density due to R(t)

Acceleration driven case



Cooling driven case



CONSTRAINTS FROM TIME DELAY INFORMATION

The time delay information can provide some constraints on either blazar modeling or time delay studies such as the search of LIV signatures.

Several characteristics of intrinsic delays can be used:

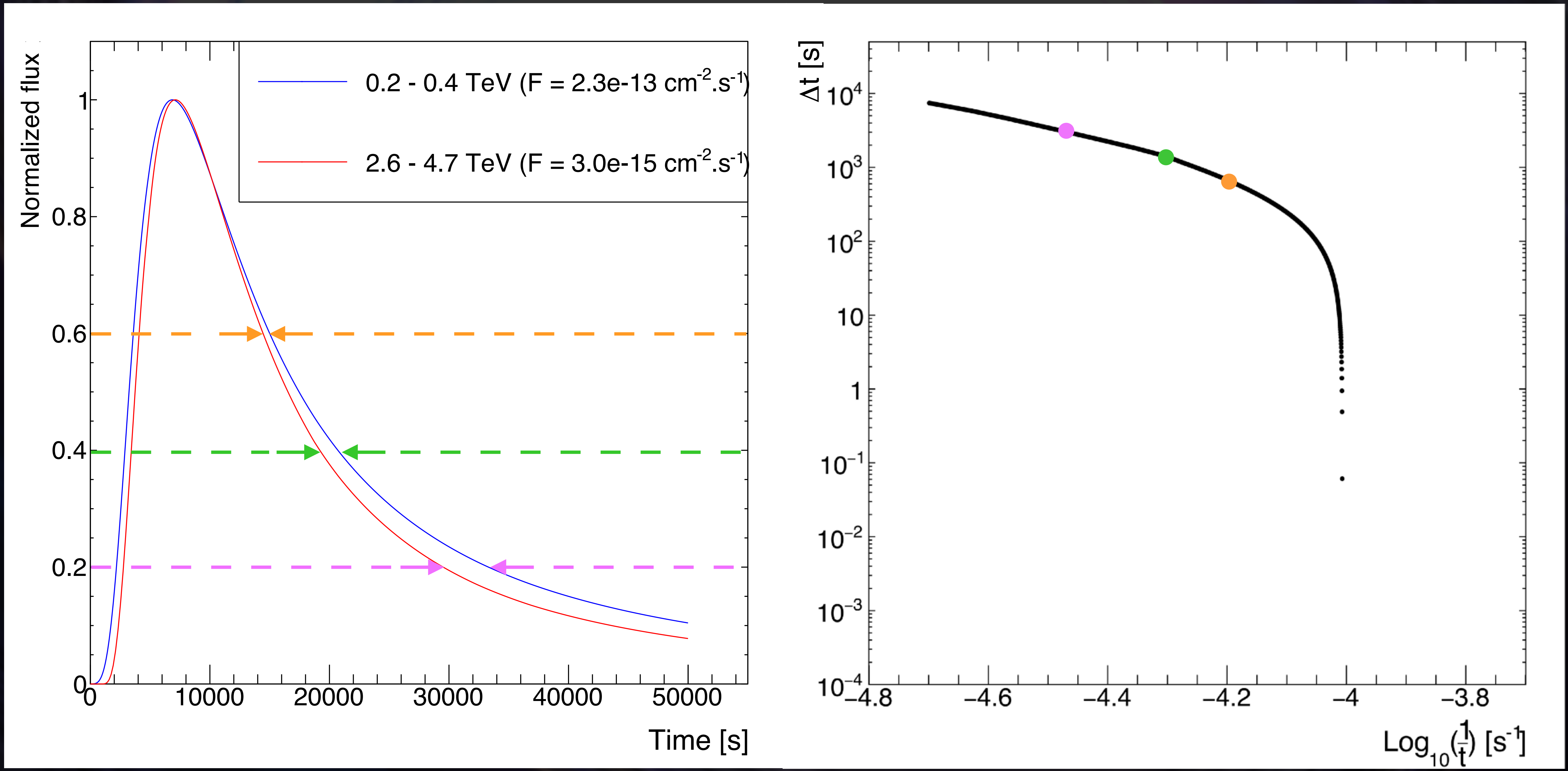
- The temporal evolution of time delay
- The energy evolution of time delay at GeV-TeV energies
- The presence of one of the time delay regimes

In addition, the redshift dependency of LIV delays can be used with multiple sources in order to minimize the impact of intrinsic effect

CONSTRAINTS FROM TIME DELAY INFORMATION

The temporal evolution of the time delay can reveal the presence of intrinsic delays

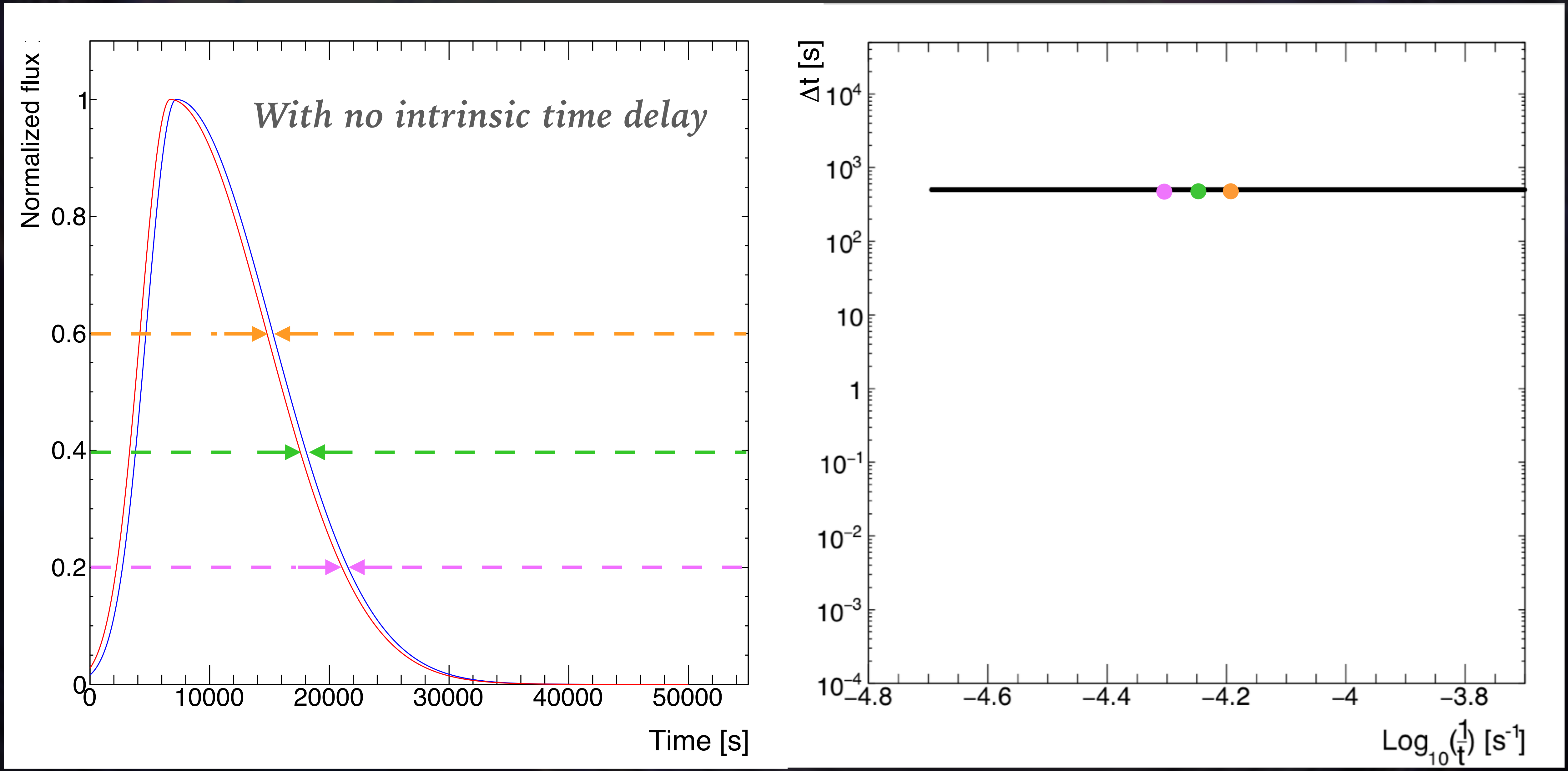
It is a consequence of the electrons acceleration and radiative cooling



From an acceleration driven case

CONSTRAINTS FROM TIME DELAY INFORMATION

In opposition, the LIV delay is not expected to produce such a signature as it affects all photons during their propagation

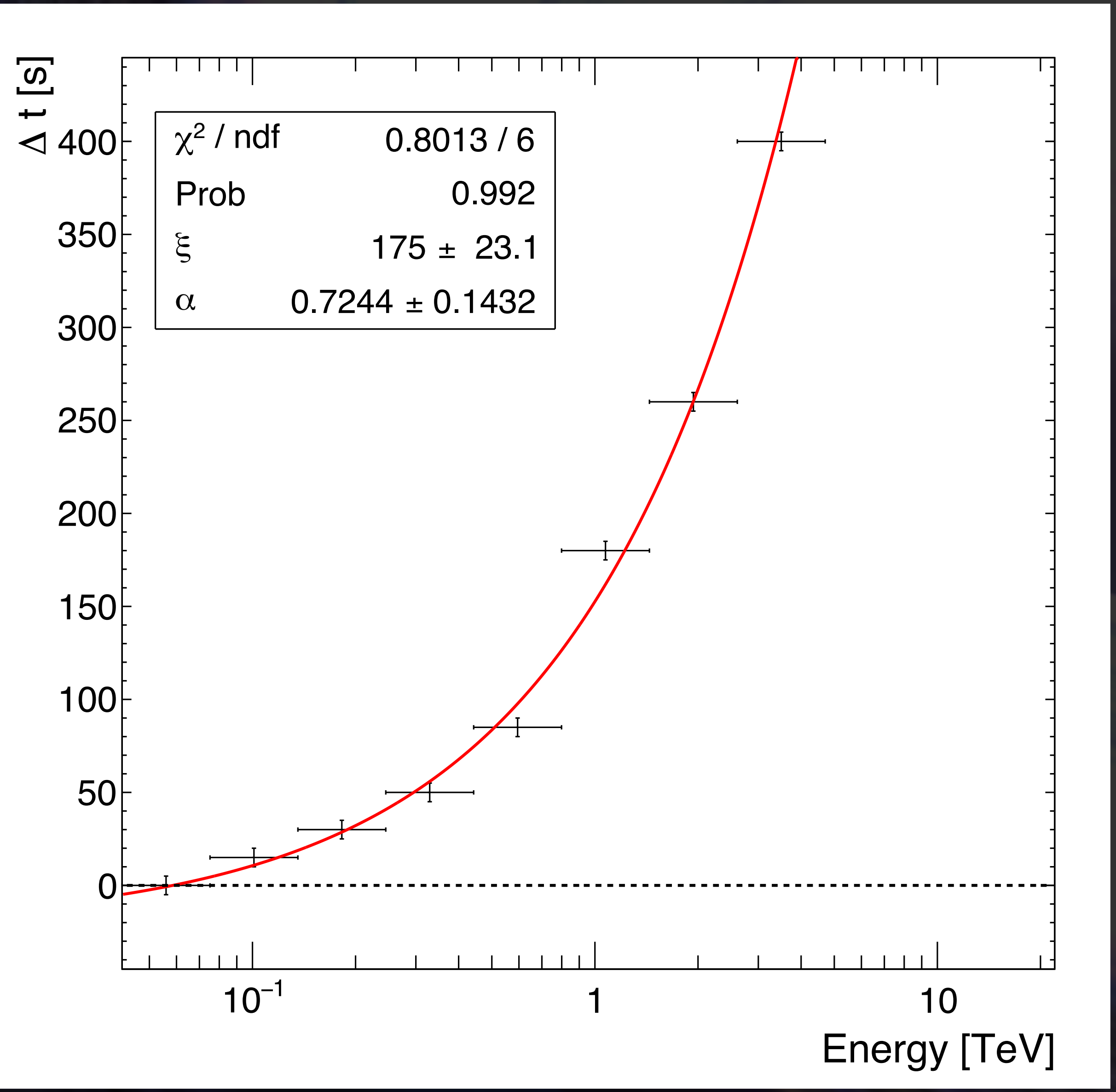


From simulated LIV delayed light curves

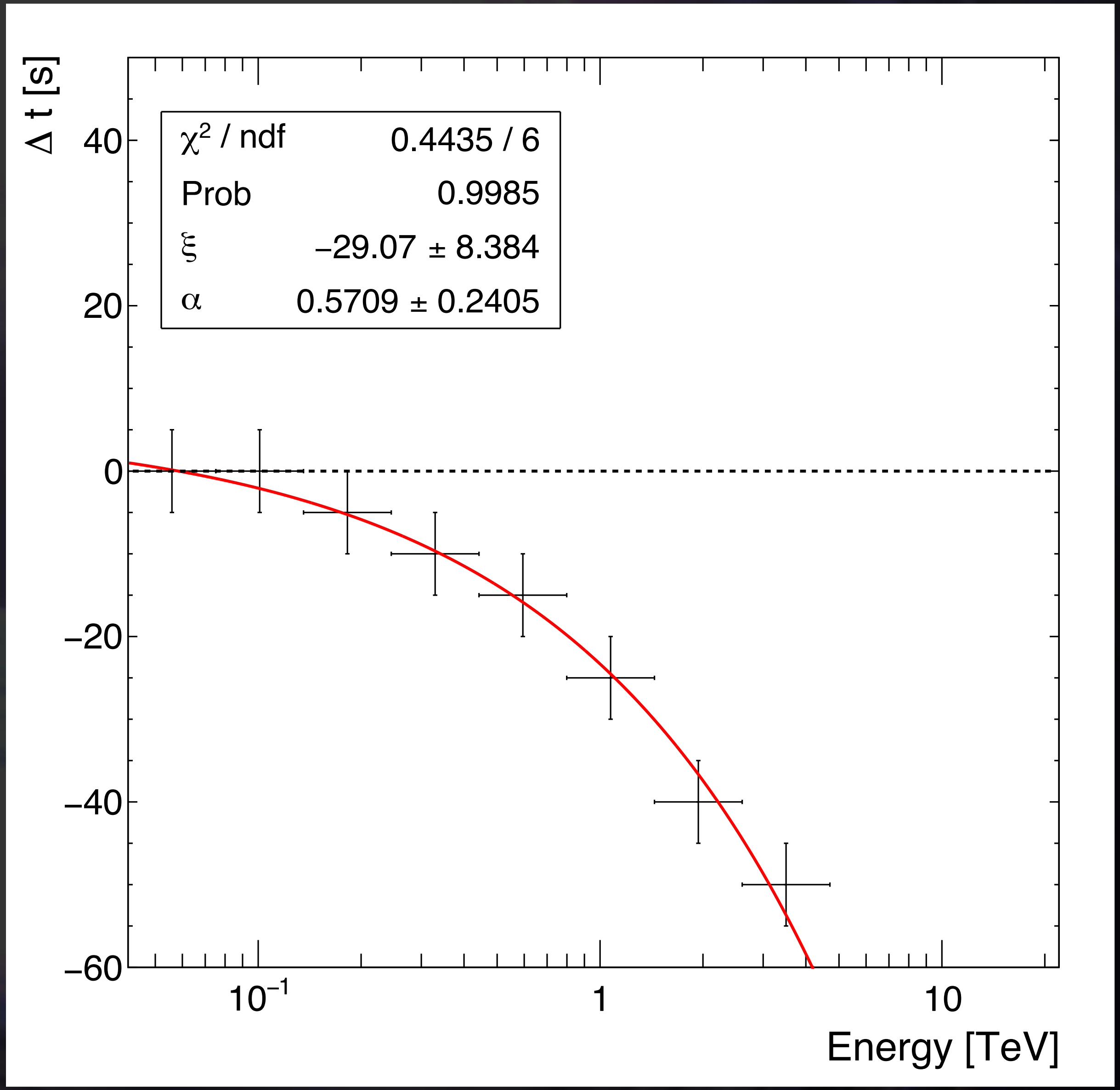
CONSTRAINTS FROM TIME DELAY INFORMATION

The energy evolution of the time delay at GeV-TeV energies can be used to try disentangle intrinsic delay from another source of delay

$$\Delta t = \xi \left(E^{\alpha} - E_0^{\alpha} \right)$$



Acceleration driven case



Cooling driven case

CONSTRAINTS FROM TIME DELAY INFORMATION

The energy evolution of the time delay can be used to try disentangle intrinsic delay from another source of delay

$$\Delta t = \xi \left(E^{\alpha} - E_0^{\alpha} \right)$$

From all the parameter space investigated with the model presenting significative time delays above GeV energies, we found:

$$\boxed{\alpha \in \left[0.4; 0.8\right]}$$

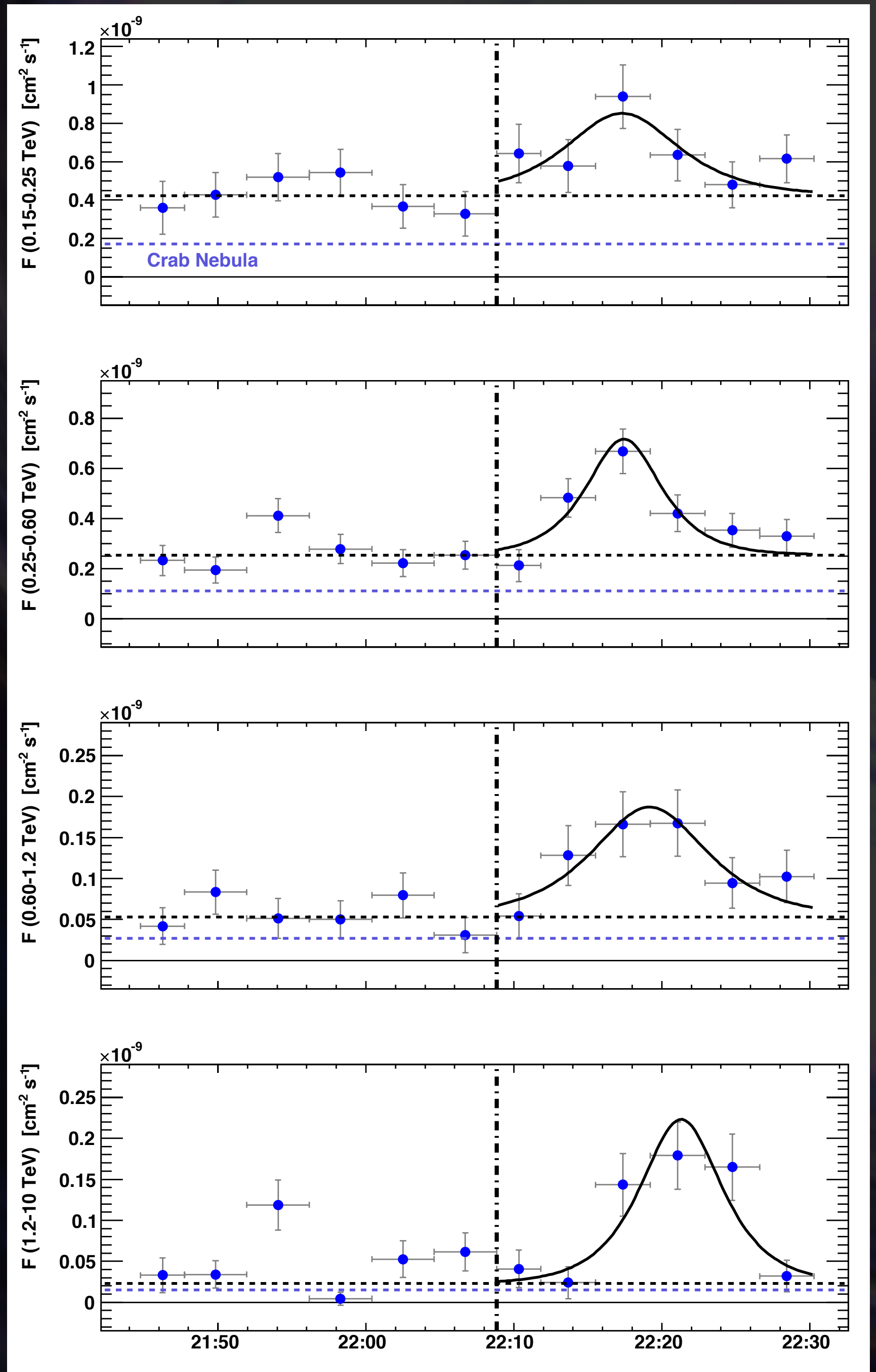
LIV delays are generally expressed with an energy dependence n = 1 or 2

How accurate are these descriptions ?

We need more theoretical insight on the energy dependency of the LIV delays in order to try disentangle them from intrinsic effect

CONSTRAINTS FROM TIME DELAY INFORMATION

The presence of one the regime gives information about the relative strength between acceleration and radiative cooling



Mrk 501 flare in 2005 observed by MAGIC

An increasing delay was reported with respect to the energy

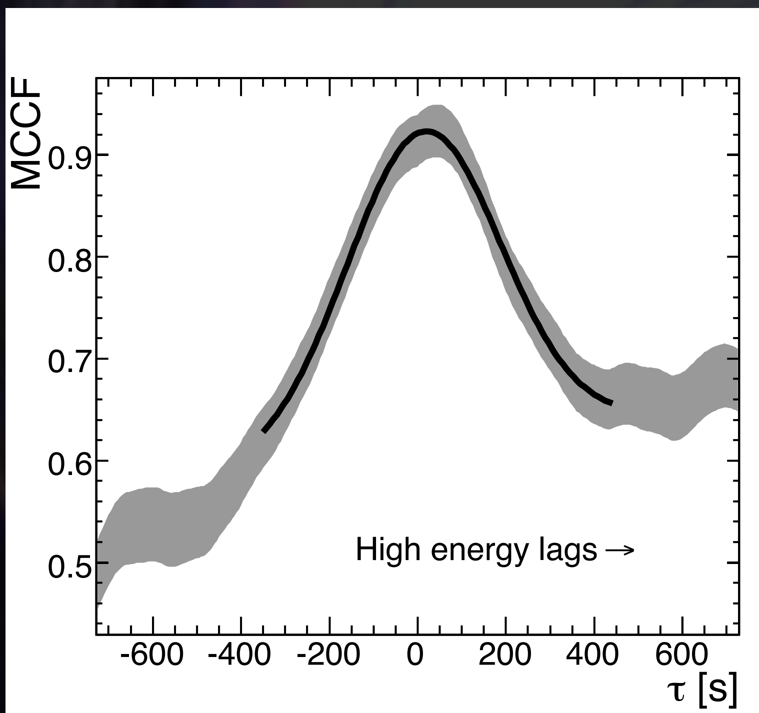
This corresponds to an acceleration driven regime

The modeling of the source requires a long-lasting acceleration to reproduce this flare

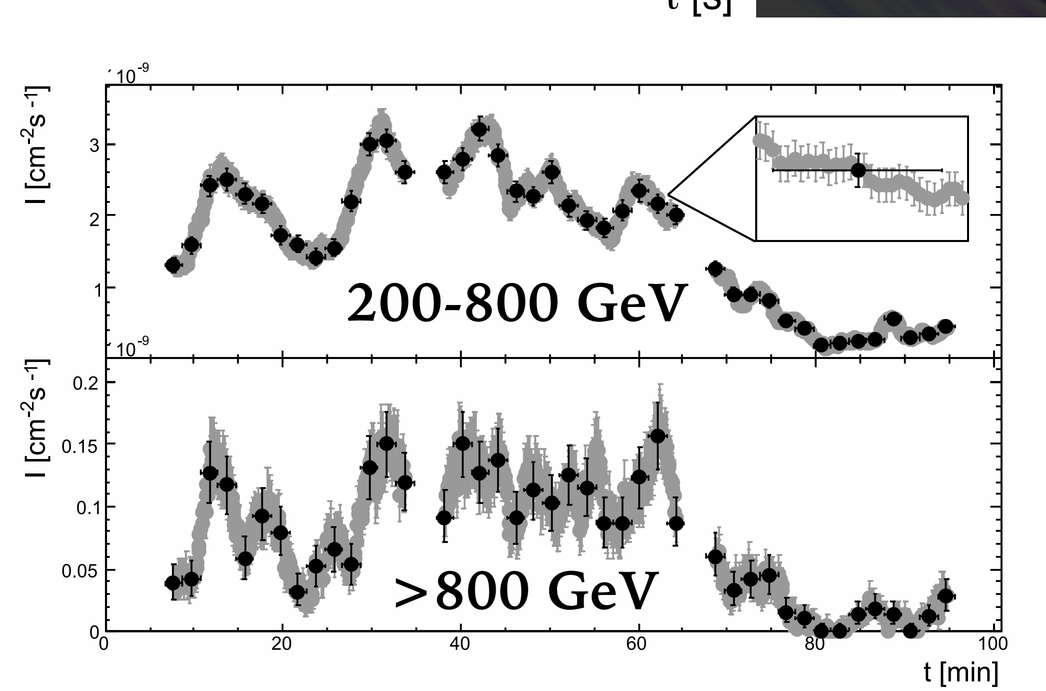
Albert et al. (2007)

CONSTRAINTS FROM TIME DELAY INFORMATION

The presence of one the regime gives information about the relative strength between acceleration and radiative cooling



$$\boxed{\tau = 20 \pm 28\ \mathrm{s}}$$



Aharonian et al. (2008)

PKS 2155-304 flare in 2006 observed by H.E.S.S.

A Cross-correlation function reported no significant time delay

This delay could correspond to the transition zone between the two regimes

Thus strong constraints on the flare modeling can be made in order to produce no delay

SUMMARY

I have developed a time dependent blazar flare model focused on γ-ray emission to study intrinsic time delays

Using the model, I have found the presence of intrinsic delays and determined their origins and specific characteristics which can provide new constraints using the time delays information

I have presented the maximum likelihood method used to search for LIV signatures and I have implemented a template correction for high energy threshold data set

I have analyzed the flare of Markarian 501 observed by H.E.S.S. and found no significant delay allowing to derive lower limits on the Quantum Gravity energy scale

CONCLUSIONS (1/2)

The linear lower limits obtained on $E_{QG,\,1}$ from the 2014 flare of Mrk 501 are similar compared to the limits from the 2005 flare of Mrk 501 observed by MAGIC

The quadratic lower limits provide the best constraint on $E_{QG,\,2}$ using an AGN flare

In addition, the implementation of the template correction in the maximum likelihood method will improve the analysis of future flares presenting a high energy threshold

CONCLUSIONS (2/2)

The intrinsic delays produced with our minimal model are found to be quite important, within the sensitivity of current instruments for some cases and would be detected by CTA

These delays present some specific characteristics that can already be used for blazar modeling or the search for fundamental physics such as LIV

However, some theoretical progress on energy dependency of LIV delays may be necessary to use the energy dependency information from intrinsic delays

This work combining modeling and the search of LIV signatures provides a new insight for LIV searches which should be more focused on time delays in a general way

PERSPECTIVE

From the modeling results on time delays, new investigations emerge within H.E.S.S. to search for any energy dependent time delays from all the data available

The time dependent blazar flare model provides the simplest scenario to generate a flare but only allows to investigate a limited parameter space

However, the model can be extended including for instance external inverse Compton emission

A more general and flexible model can also be investigated using the general transfer equation (*Ginzburg, 1964*) but requires a numerical resolution of the equation

Also, a joint effort on LIV studies from the H.E.S.S., MAGIC and VERITAS Collaboration tries to combine all available data (AGN, Pulsars, GRB?) to improve current limits on $E_{QG,n}$ with population studies

The limits deduced from the Mrk 501 flare will be included for this combination study as well as for future flares with the goal to prepare the science for CTA

Thanks for your attention

BACK-UP

LIV appears in some approches to quantum gravity

String Theory

Tentative to describe the 4 fundamental forces in a unified description

One type of particule: Strings. All known particles are vibrational mode of strings

The particle of gravity (graviton) can only be represented by relativistic strings

In some String Theory models LIV can emerge from the interaction between high energy photons and *compactified* extra-dimension (D-branes)

BACK-UP

LIV appears in some approches to quantum gravity

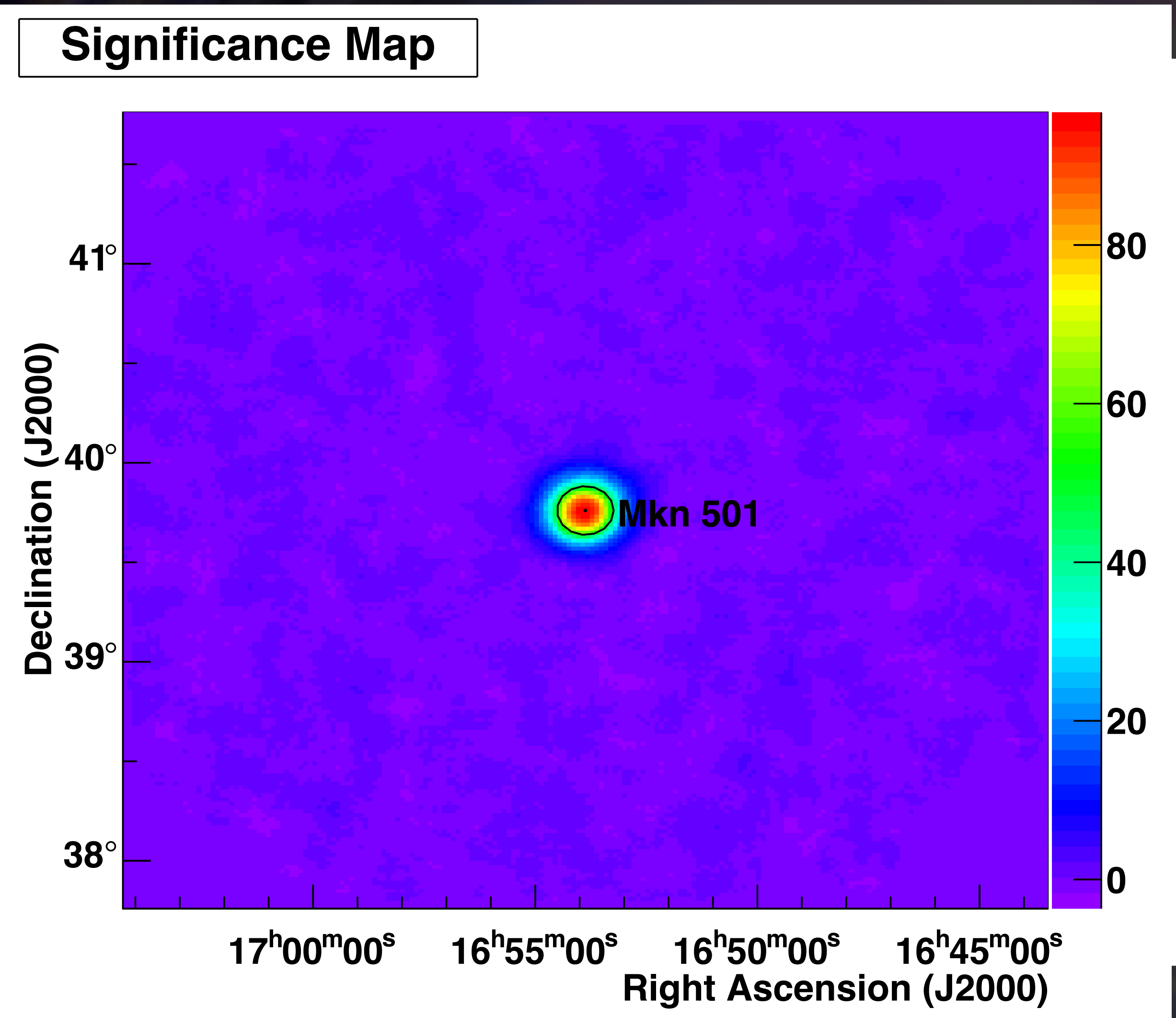
Loop Quantum Gravity

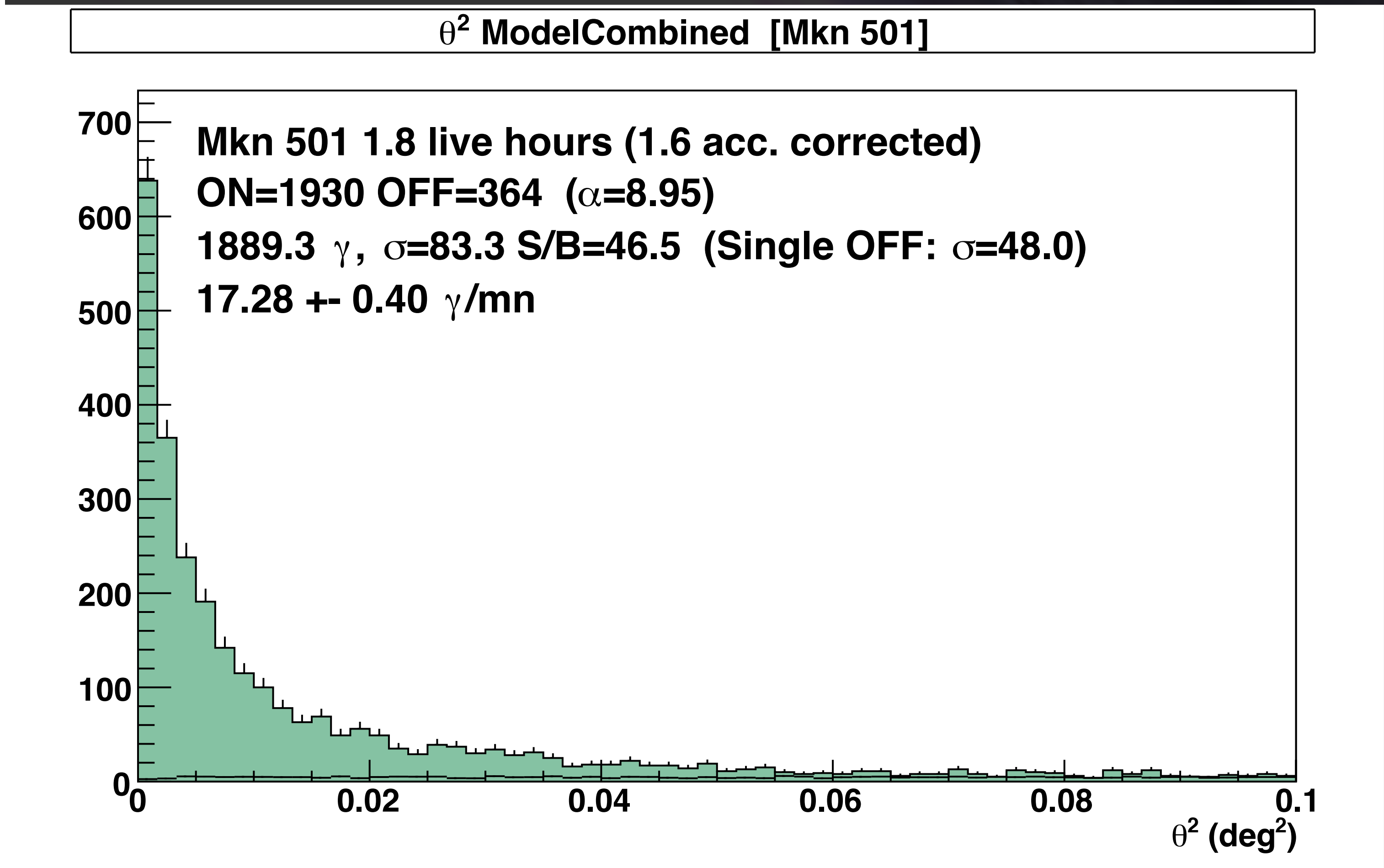
Tentative to quantize gravity as the other fundamental interactions

A new formalism is used based on loop instead of field

The space time becomes discrete and lead to an energy-dependent birefringence effect for the propagation of high energy photon in vacuum.

BACK-UP

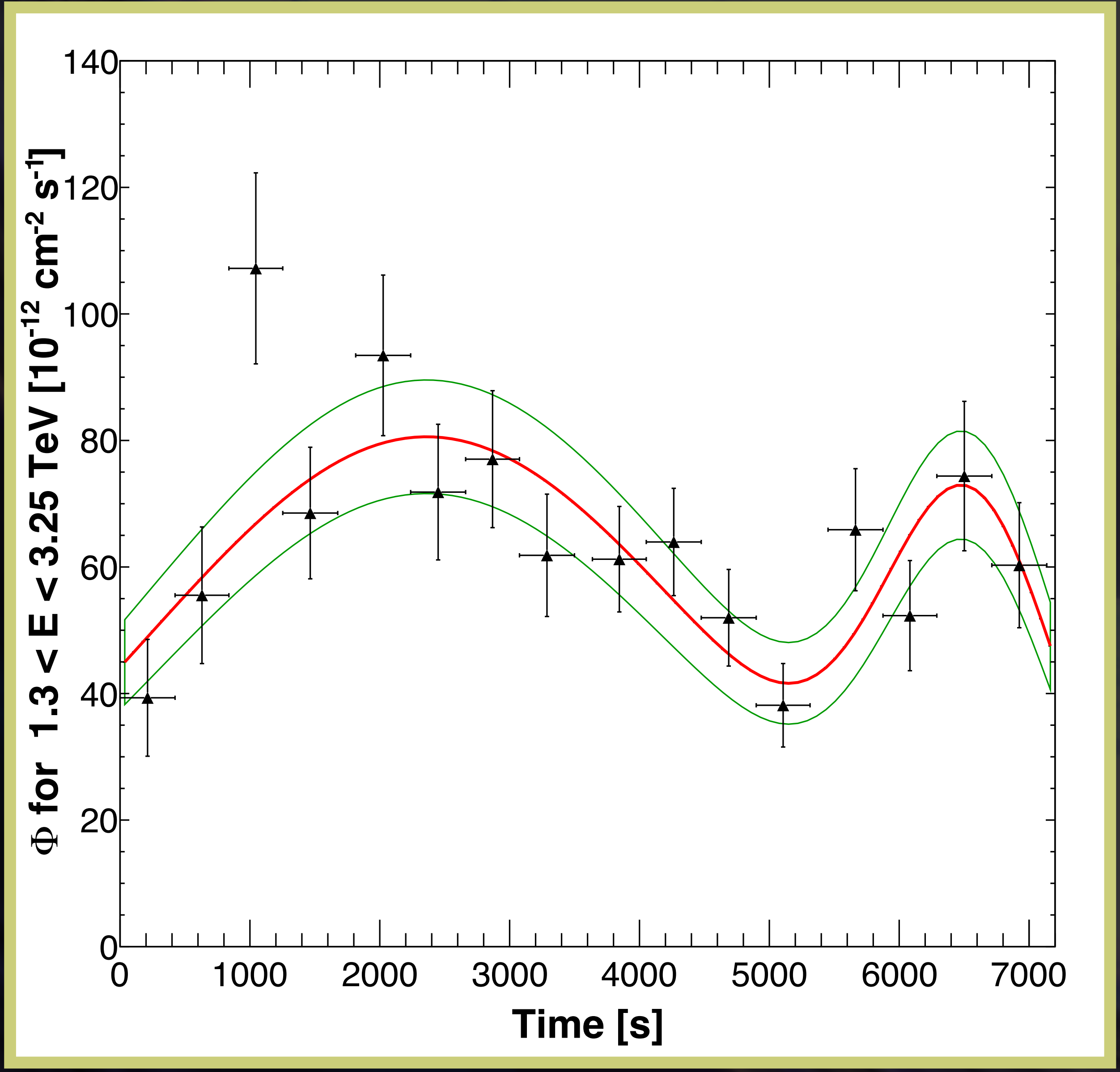




	N_{ON}	N_{OFF}	N_{excess}	S/B	Average Zenith angle
Run 1	424	82	415	45.5	64.2
Run 2	543	87	533	55.1	63.8
Run3	531	101	520	46.3	62.2
Run4	432	94	422	40.4	63.5
Total	1930	364	1890	46.5	63.4

BACK-UP

For the time function F(t), a double Gaussian function is preferred over a single Gaussian to parameterize the light curve in the template energy range



$X^2/ndf = 15.9/10$

First peak:

$A_1 = (80.6 \pm 5.6) \times 10^{-12}\ cm^{-2}\ s^{-1}$

$\mu_1 = (2361 \pm 185)\ s$

$\sigma_1 = (2153 \pm 302)\ s$

Second peak:

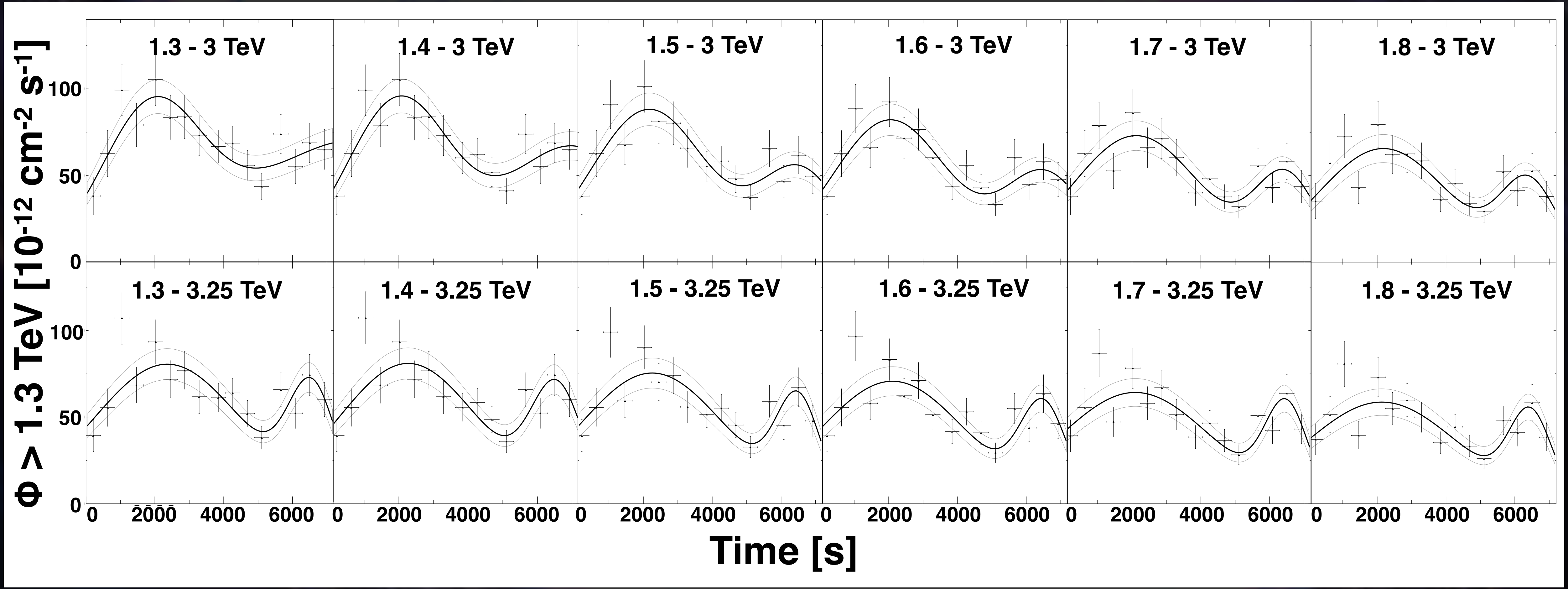
$A_2 = (61.5 \pm 11.1) \times 10^{-12}\ cm^{-2}\ s^{-1}$

$\mu_2 = (6564 \pm 220)\ s$

$\sigma_2 = (676 \pm 283)\ s$

BACK-UP

Actually, the template and likelihood energy ranges were chosen for the maximum likelihood method to ensure a robust estimation of F(t)



Such a behavior indicates a possible intrinsic effect close to the energy threshold of the data analysis

BACK-UP

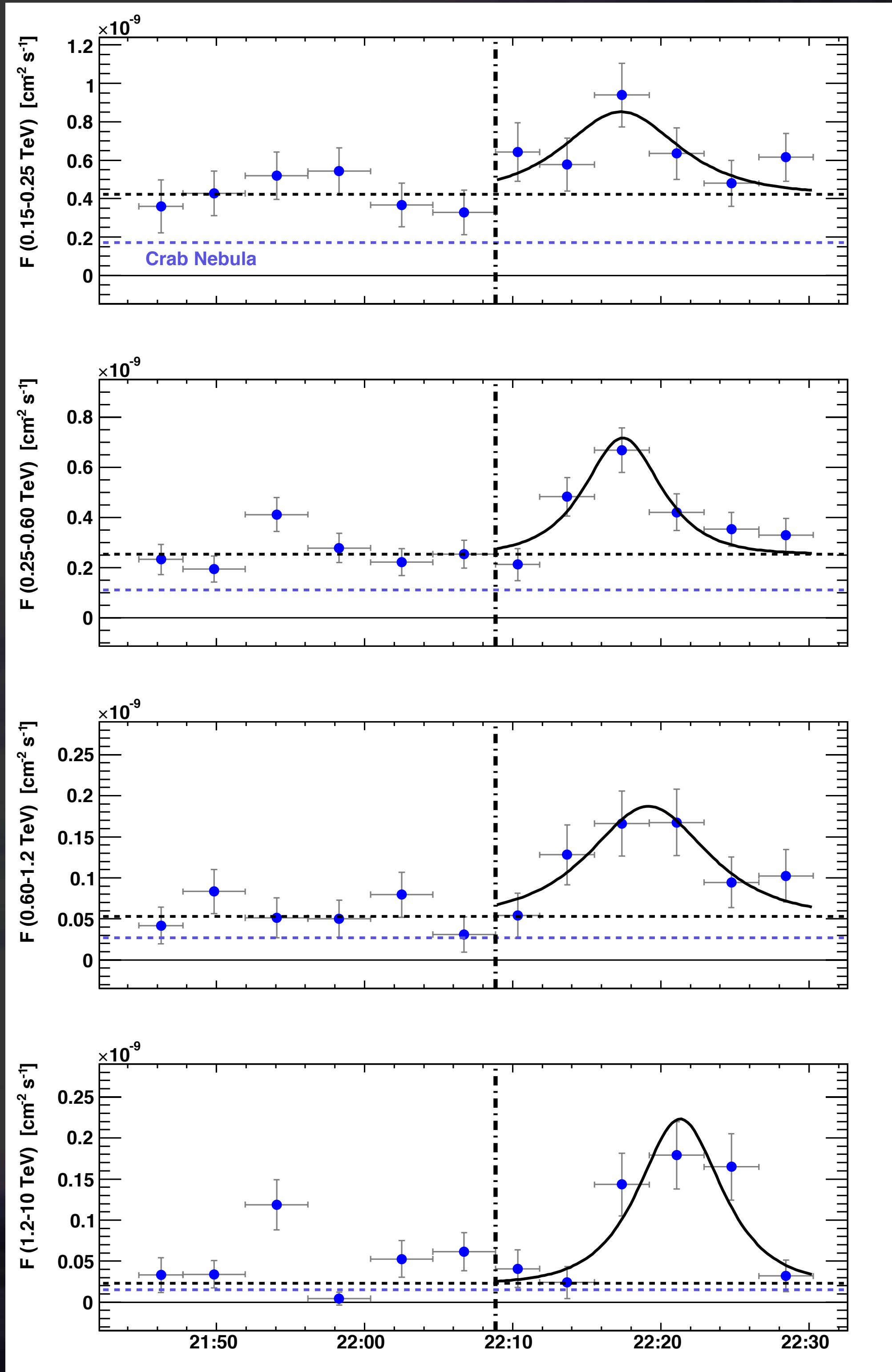
Some published models shows intrinsic time delays

A time delay was observed in the light curves from a flare of Markarian 501 in 2006 (*Albert et al., 2007*)

Bednarek & Wagner (2008) proposed a model to explain this delay with an increase of the Doppler factor of the emitting zone

$$\delta \propto A \times t$$

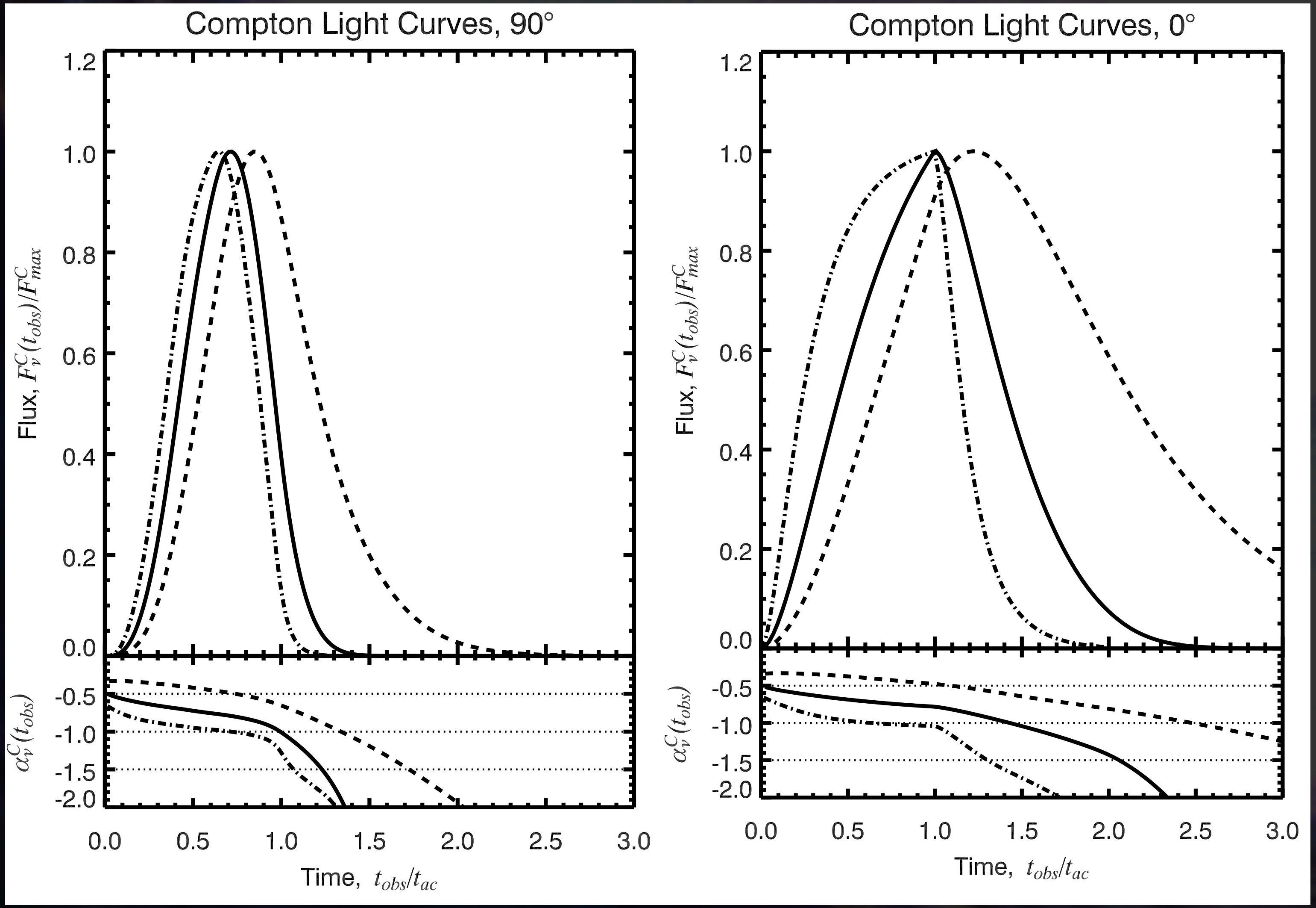
The Doppler boosting effect increasing with time produces high energy at later time



BACK-UP

Some published models show some intrinsic time delays

A model from *Sokolov et al. (2004)* describes the emission with a complex jet structure and considering shocks accelerating particles and photon internal travel time in the jet.



Time delays arise from the spatial distribution of particle in the jet

In addition, variation of the viewing angle leads to a modification of the photon travel time for an observer and so time delays

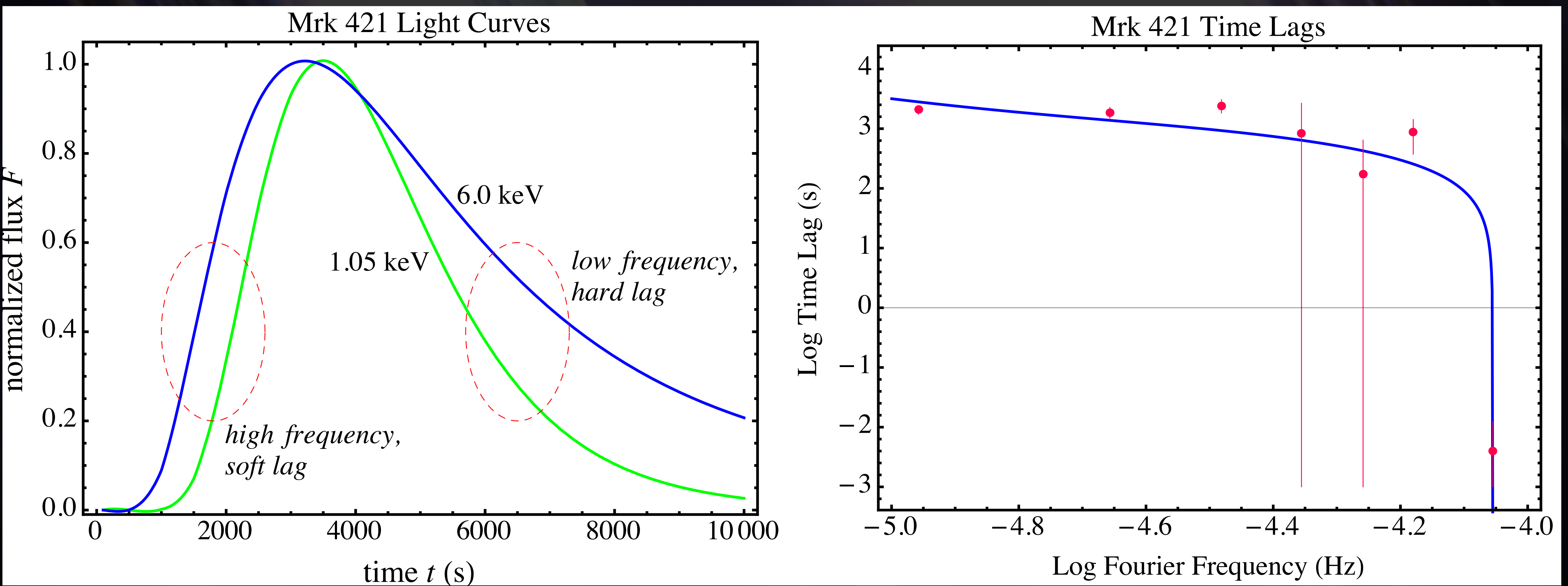
BACK-UP

Time dependent model based on a differential equation to describe the evolution of electrons

They attempt to model a flare from Mrk 421 at X-ray energies

From the Fourier transform of the time delay they obtain an temporal evolution of the time delay which match the data

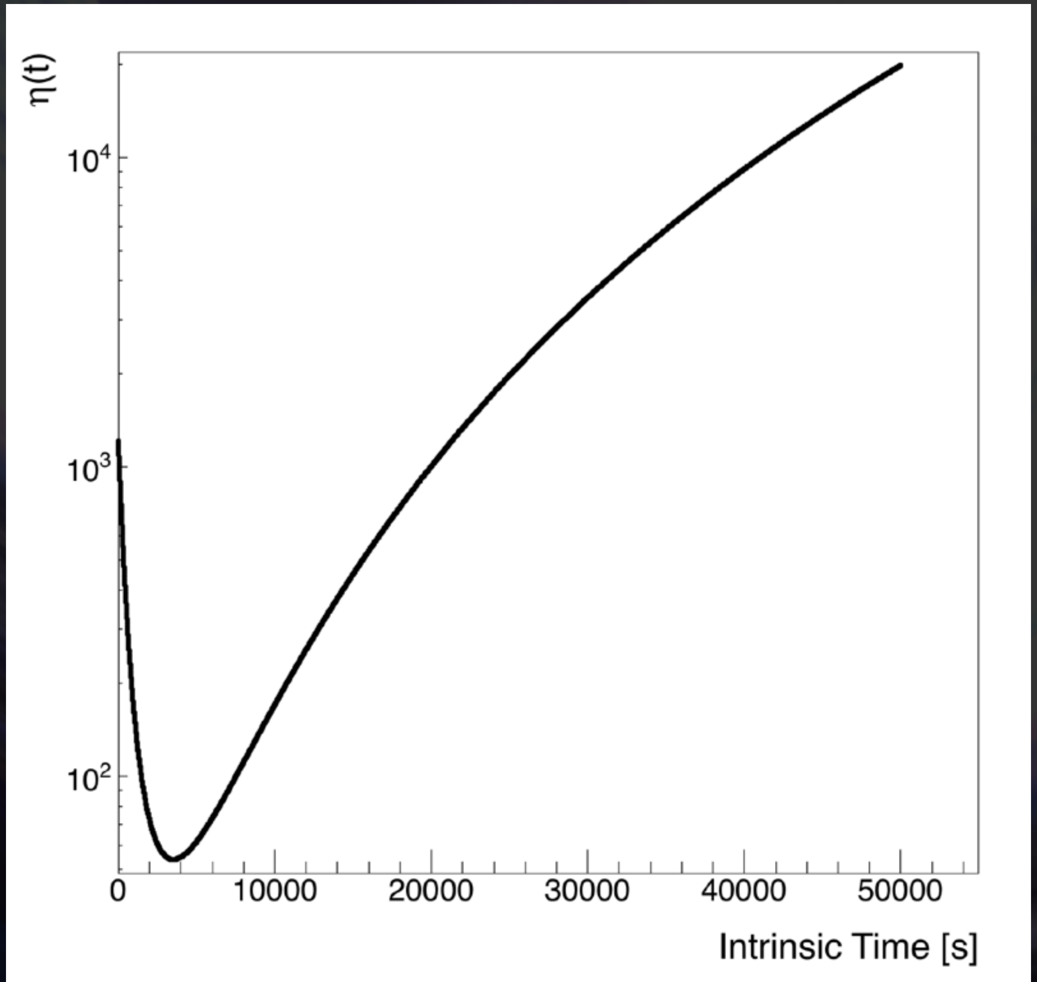
Lewis et al 2016



BACK-UP

Inversion Compton energy losses in the differential equation

$$\frac{\partial N_e(t,\gamma)}{\partial t} + \frac{\partial}{\partial \gamma}\left[\left(1 + \underbrace{\boxed{\int_0^\infty \gamma'^2 N_e(t,\gamma')d\gamma'}}_{\eta^{-1}}\right) C_{cool}(t)\gamma^2 N_e(t,\gamma)\right] = 0$$



BACK-UP

__H.E.S.S., MAGIC, VERITAS__

__LIV Consortium__

__Motivations:__ Combine all available data for the search of LIV signatures in order to improve current limits on LIV

__Work:__ Develop a joined analysis which will allow to use many sources and different kinds of sources

This is another way to try to separate source and propagation effects

BACK-UP

Simulation were done to evaluate the performances of such a combination

Source used for the combination:

- Mrk 501 flare in 2005 from MAGIC
- PKS 2155-304 "Big flare" in 2006 from H.E.S.S.
- PG 1553+113 flare in 2012 from H.E.S.S.
- Crab Pulsar with 194 hours of data from of VERITAS

Simulations include:

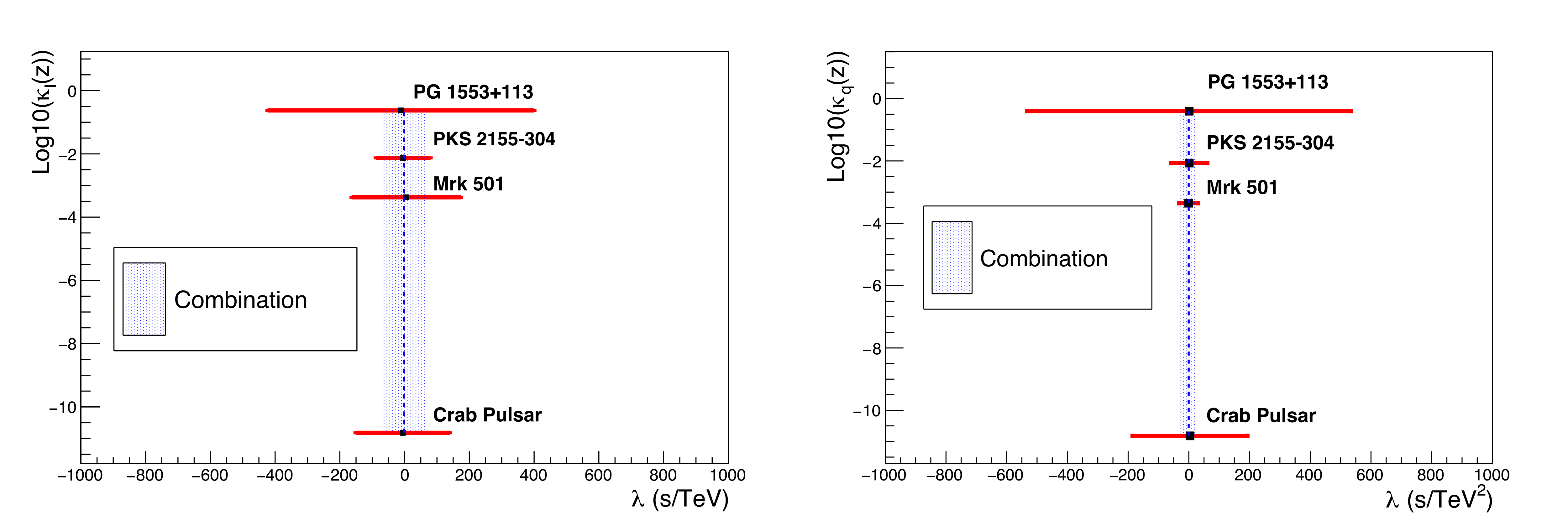
- 990 simulations of each data set
- True energy and time generated from public data only
- Application of the IRFs to obtaine measured values

BACK-UP

The LIV parameter is scaled for all sources as

$$\Lambda = \frac{\Delta t_n}{\Delta E^n \kappa_n(z)} = \frac{1}{E_{QG} H_0}$$

$$\Lambda = \tau\kappa(z)$$



BACK-UP

Combinaison results on the E_{QG} lower limits