Students' day

Tests of Lorentz Invariance and intrinsic time delays in Active Galactic Nuclei with H.E.S.S./CTA

Christelle Levy

Hélène Sol (LUTh)
Julien Bolmont (LPNHE)

March 10, 2021

l'Observatoire de Paris | LUTH
Laboratoire de l'Univers et de ses Théories

SORBONNE UNIVERSITÉ

LPNHE PARIS

Lorentz Invariance Violation (LIV)

Some quantum gravity (QG) models predict a modified dispersion relation of photons in vacuum such that their **speed would be energy-dependent.**

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

$\longrightarrow$ **Constrain the QG energy scale** $E_{QG} \sim E_P = 1.22 \times 10^{19} GeV$

The LIV effect would translate, amongst others, into a **time-delay between the arrival time of photons with different energies.**

$$\Delta t \simeq \frac{n+1}{2} \frac{E_1^n - E_2^n}{E_P^n} f(z) \longrightarrow \tau_n = \frac{\Delta t_n}{\Delta E_n} = \pm \frac{n+1}{2H_0 E_{QG}^n} f(z)$$

Astrophysical sources

Measured delays maximized for sources:

- At large distances
- With large energy range

~~> Cosmological sources + TeV gamma-rays

\+ High variability for precision

◆ **Pulsars**

   + high variability, stable, large E spec.

   - very local

◆ **Gamma Ray Bursts (GRBs)**

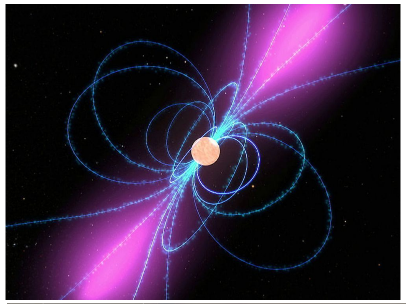
   + high variability, large z, large E spec.

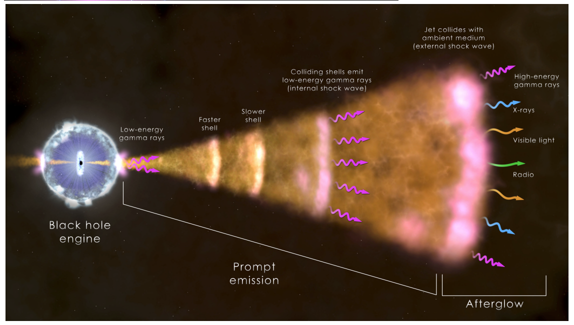
   - random and difficult to catch

◆ **Flaring Active Galactic Nuclei (AGNs)**

   + large z, large E spec, easier to catch

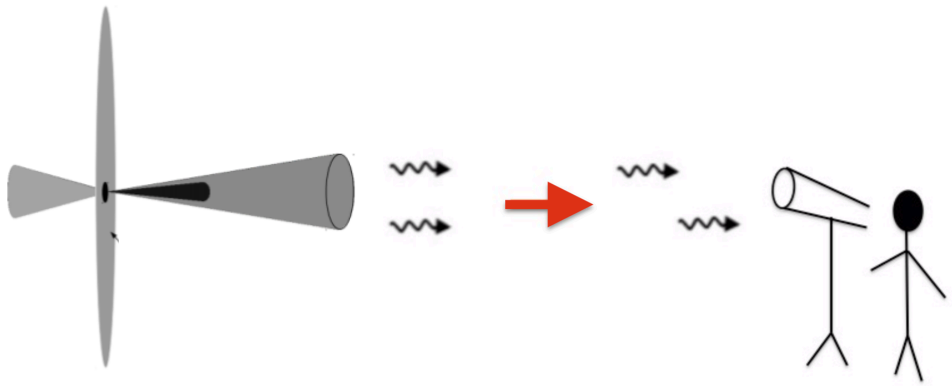
   - random, smaller variability



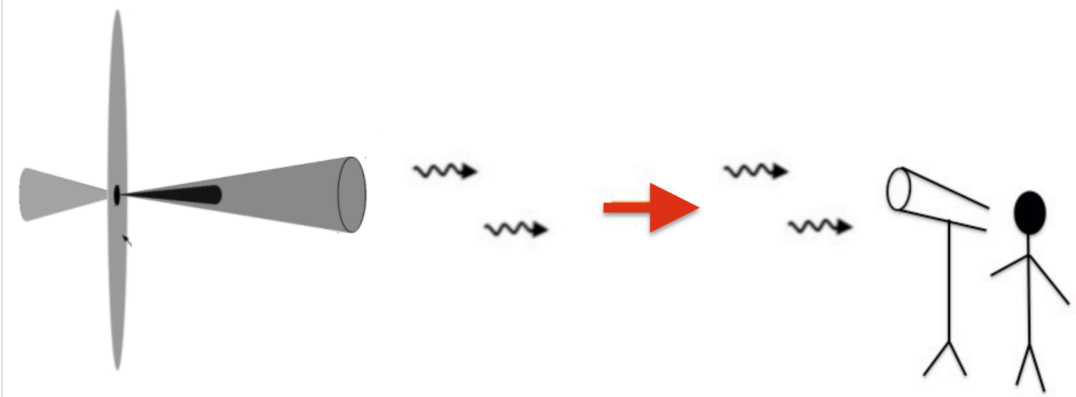


Intrinsic delays

In addition to LIV-induced delays, **intrinsic delays** can be generated by sources' emission mechanisms. **Neglected so far…**



LIV effect
Distance-dependent



Intrinsic effect
Distance-Independent

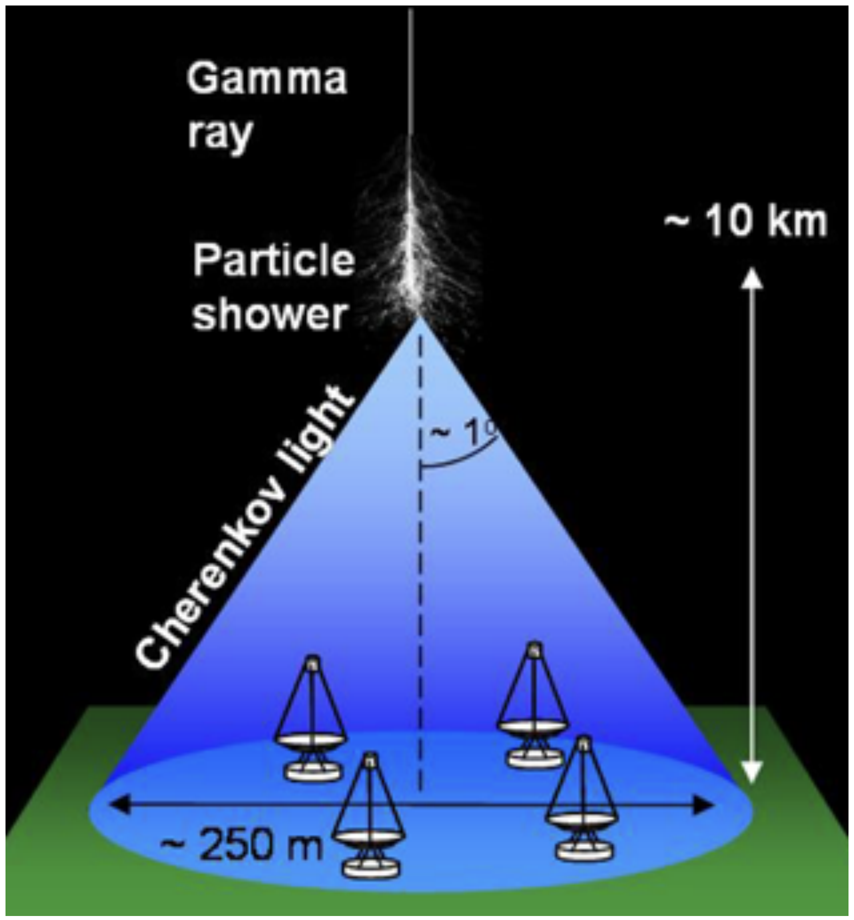
These intrinsic delays need to be characterized and **differentiated** from LIV-induced ones in order to provide a proper interpretation for observed delays

Such problem can be partly answered with either a ***data combination*** of different sources at different distances in the analysis, or the ***modelisation*** of the emission mechanisms of said sources.

Population study: data combination

H.E.S.S. + MAGIC + VERITAS

Imaging Atmospheric Cherenkov Telescopes (IACTs)



- **Gamma-rays (GeV~TeV)** interact in the atmosphere and produce particle showers
- Emission of **Cherenkov (blue) light** due to charged particles going faster than light in the atmosphere.
- This light is **focused with mirrors and detected with a camera**.

H.E.S.S. + MAGIC + VERITAS - Goals

- **Combine all available data from H.E.S.S., MAGIC and VERITAS in a joint analysis**

  → **Better limits on QG energy scale** with increased statistics

- Use different types of sources with different intrinsic characteristics

  → **Prepare Cherenkov Telescope Array (CTA) era** with the combination of different arrays with different instrument response functions (IRFs)

Working group tasks

- **Development of a common software** in order to simulate, analyse and combine data-sets.
- For now we work on **simulations in order to calibrate and validate the method**
- List of sources (only published sources are studied) such that **all class are represented** with different characteristics:
  - AGN
    - Markarian 501 (MAGIC) flare of 2005
    - PG 1553+113 (H.E.S.S.) flare of 2012
    - PKS 2155-304 (H.E.S.S.) flare of 2006
  - Pulsar
    - Crab (MAGIC, VERITAS)
    - Vela (H.E.S.S.)
  - GRB
    - 190114C (MAGIC)

Combination method

- Separate photon list in 2 sub-sets $\longrightarrow$ low energy vs. high energy light curves (time distributions)
  - ✳ **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\mathrm{Sig}(E,t|\tau_n)}}{N_{\mathrm{Sig}(\tau_n)}}$$

- Incorporation of **background treatment:** hadrons (cosmic rays) and baseline photons
- Combination $\longrightarrow$ **Instrument Response Functions** vary for each source and instrument
  - ✳ Approximations were made on IRFs treatment for most of the previous studies
  - ✳ We developed a method to fully take into account IRFs without any simplification
- **Systematics estimation** $\longrightarrow$ via profile likelihood method (Sami Caroff):
  - ✳ Light curve parametrisation, spectral index (signal), signal and bkg proportions, energy scale, redshift

Results: Limits on E_{QG} Example: AGNs

So far only upper limits on E_{QG}.

Work in progress: results for the GRB and PSR currently being produced (long process)
==> illustration with 3 AGNs for the linear case (n=1).

Results shown with systematics, for 2 models of redshift dependency, at 95% CL:

PG 1553+113 (10^{18} GeV)	Mkn 501 (10^{18} GeV)	PKS 2155-304 (10^{18} GeV)	Combination (10^{18} GeV)
0.11	**0.52**	**1.00**	**1.12**

==> The best limit (individual source: PKS) is **improved by ~15%** by the combination!

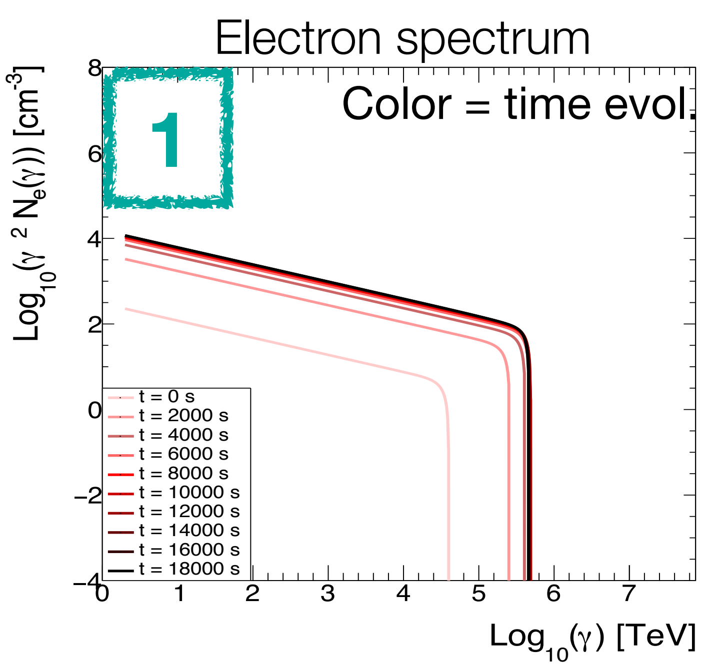
The combination is dominated by the source with the most stringent limit
==> Generally we have: GRB >> AGN >> PSR

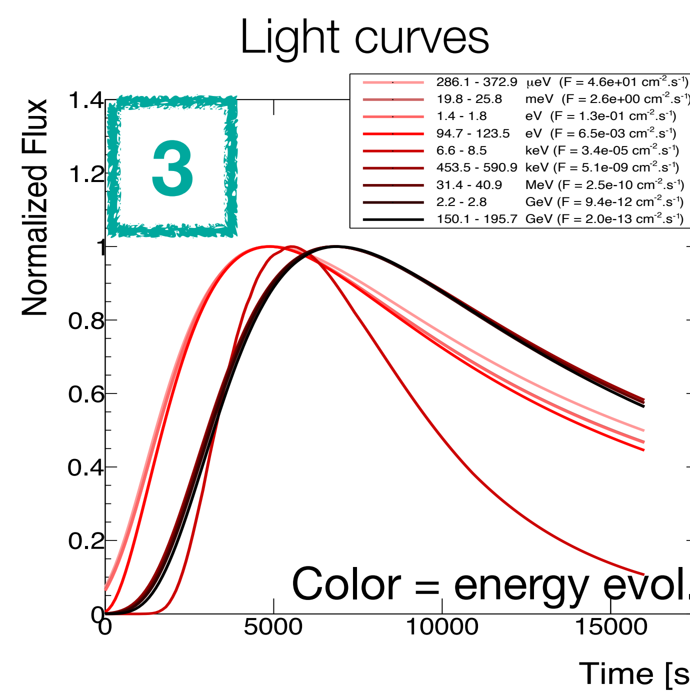
Modelisation:
intrinsic effects in blazars

Generating a flare: intrinsic effects

$$\frac{\partial N_e(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{ \left[\gamma^2 C_{\rm cool}(t) - \gamma C_{\rm acc}(t)\right] \; N_{\rm e}(t,\gamma) \right\} \quad : \; \text{SSC model}$$

Synchrotron Self Compton

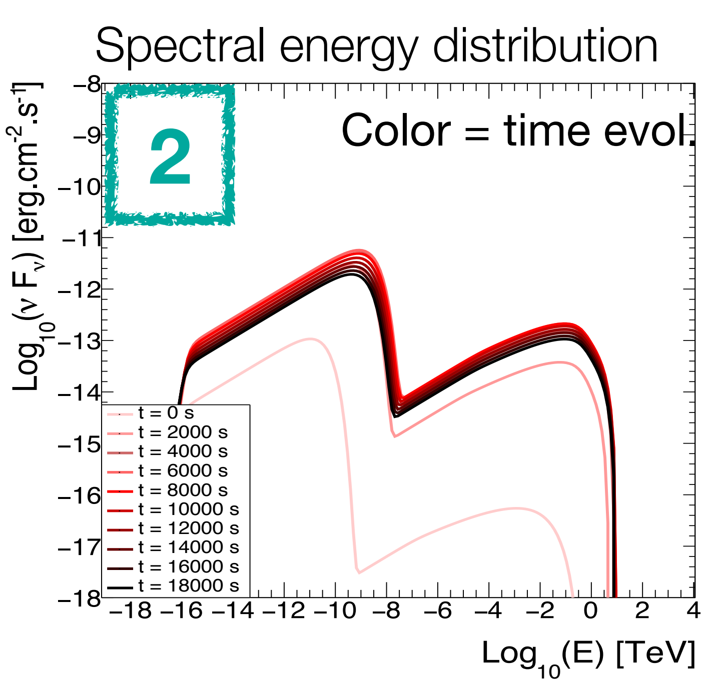


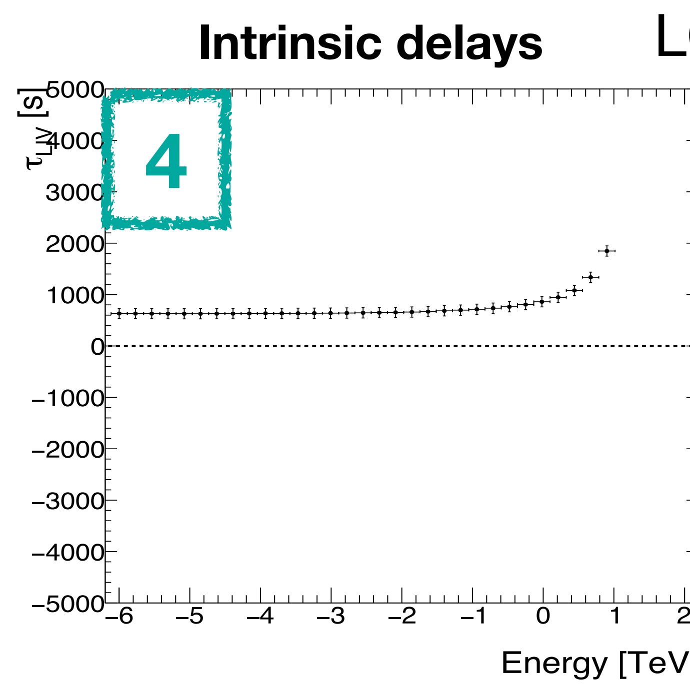


Light curves computed on a given energy band E_{LC}.

« Typical » arrival time taken at the maximum.

LC maxima



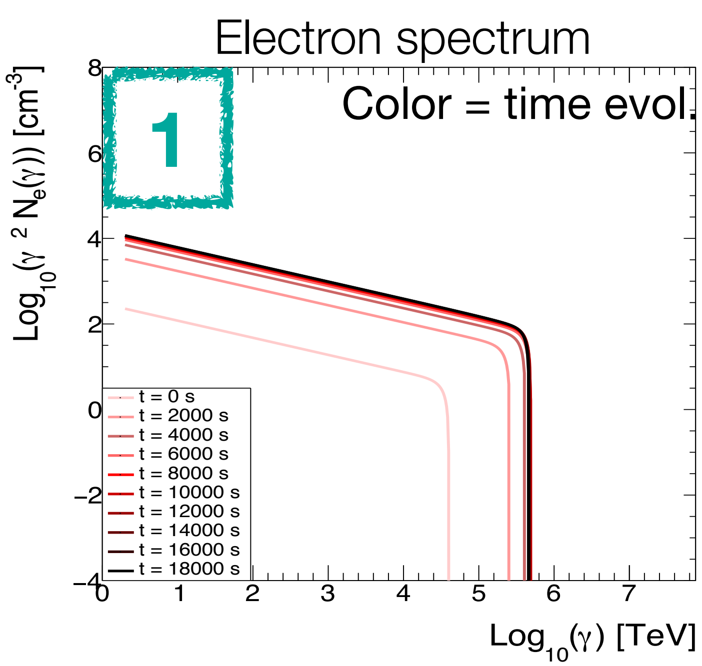


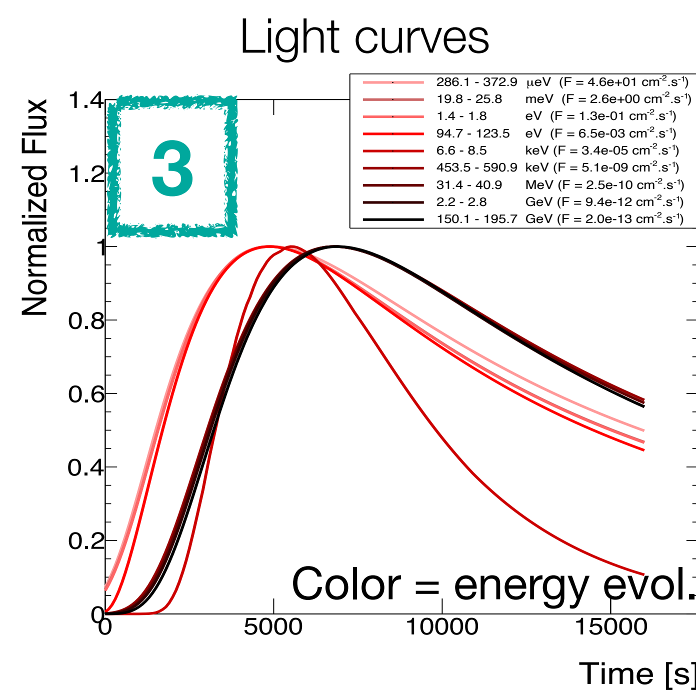
Delays are computed with respect to a reference light curve / typical arrival time.

Generating a flare: injecting LIV

$$\frac{\partial N_e(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\left\{ \left[\gamma^2 C_{\mathrm{cool}}(t) - \gamma C_{\mathrm{acc}}(t)\right] \; N_{\mathrm{e}}(t,\gamma) \right\} \quad : \;\; \text{SSC model}$$

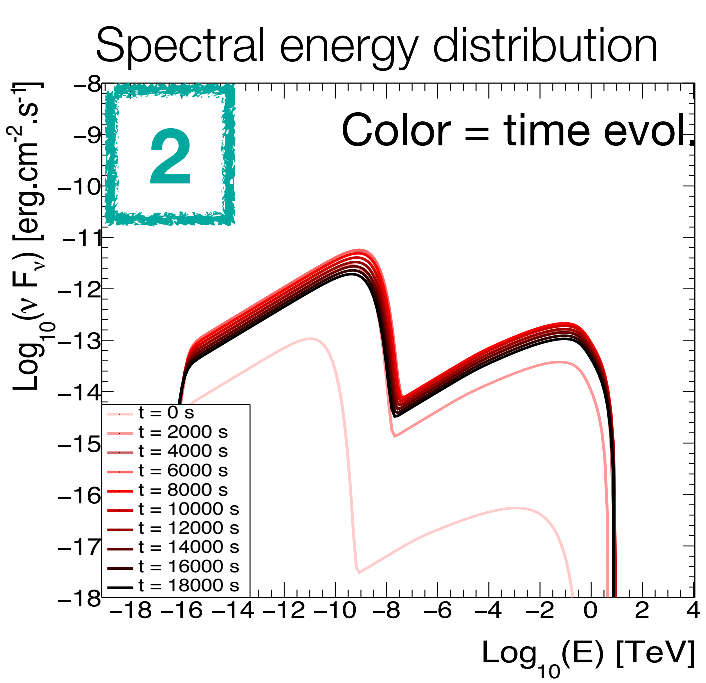
Synchrotron Self Compton

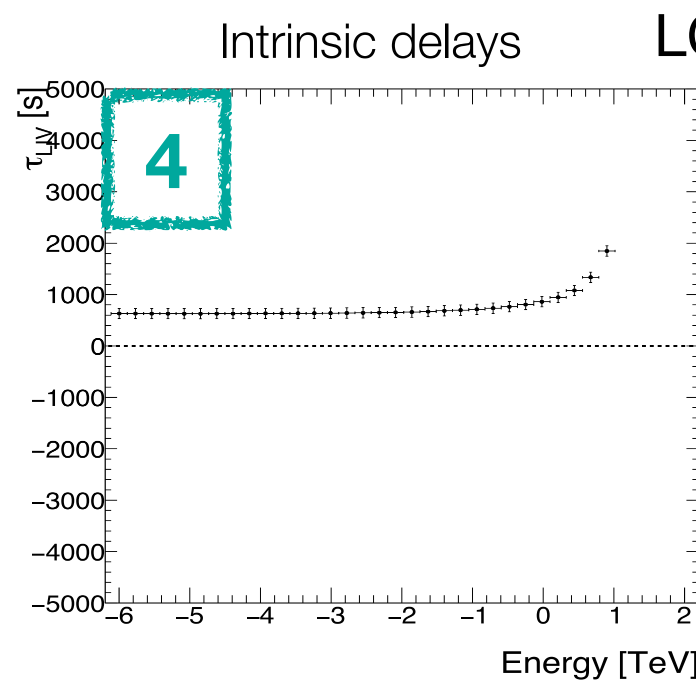




5 **LIV lag injection**

LC maxima



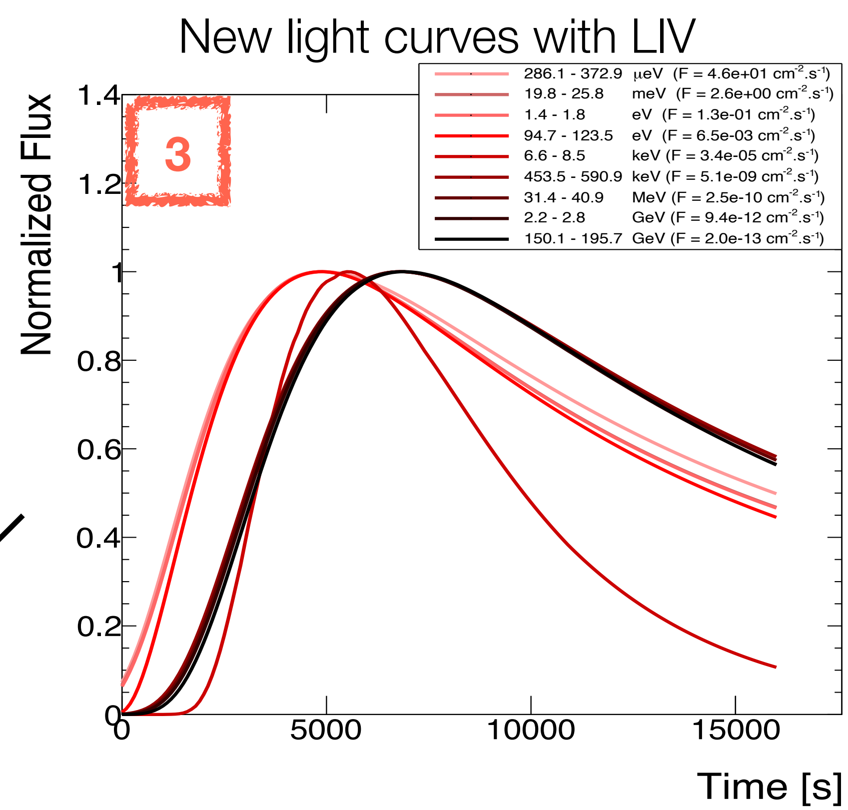


Injecting LIV: simultaneous treatment

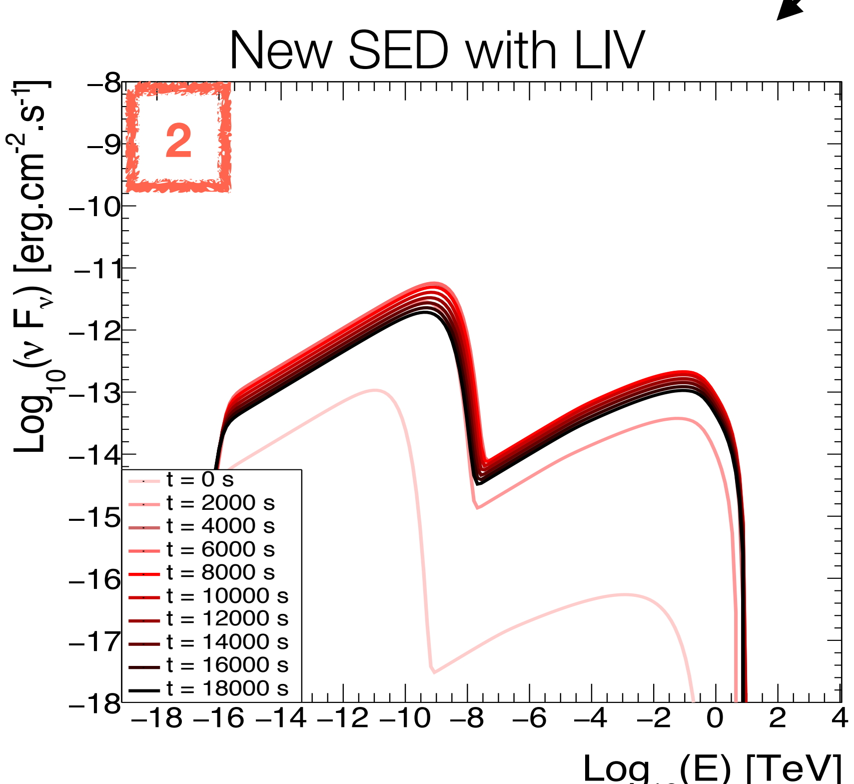
5

$$t_{LC} \rightarrow t_{LC} + \tau E_{LC}^{n}$$

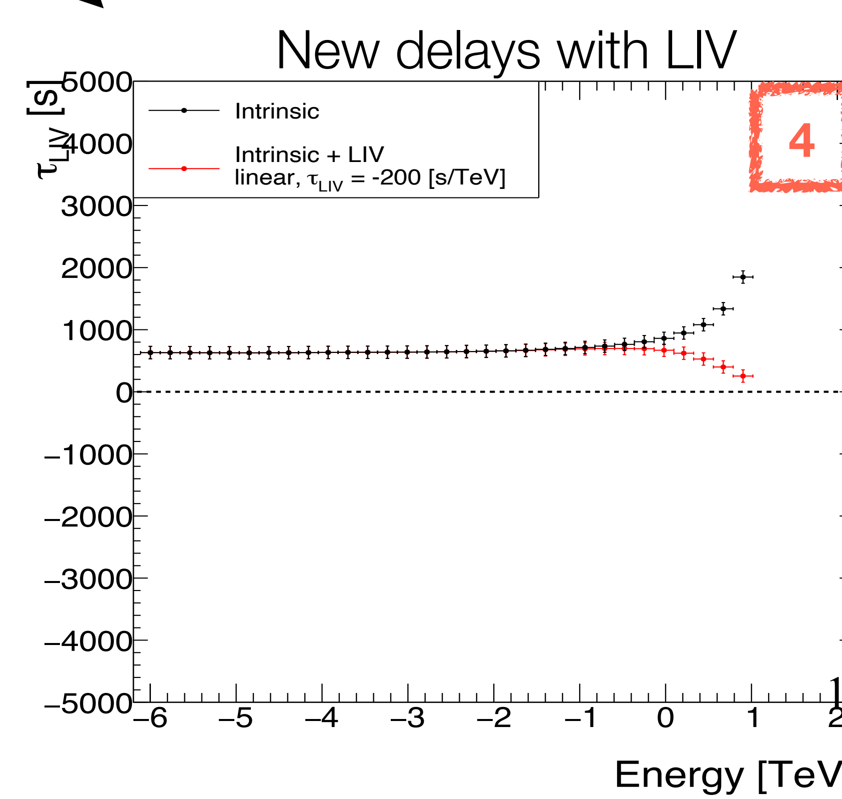
τ is the LIV term (input parameter)



Inverse reconstruction

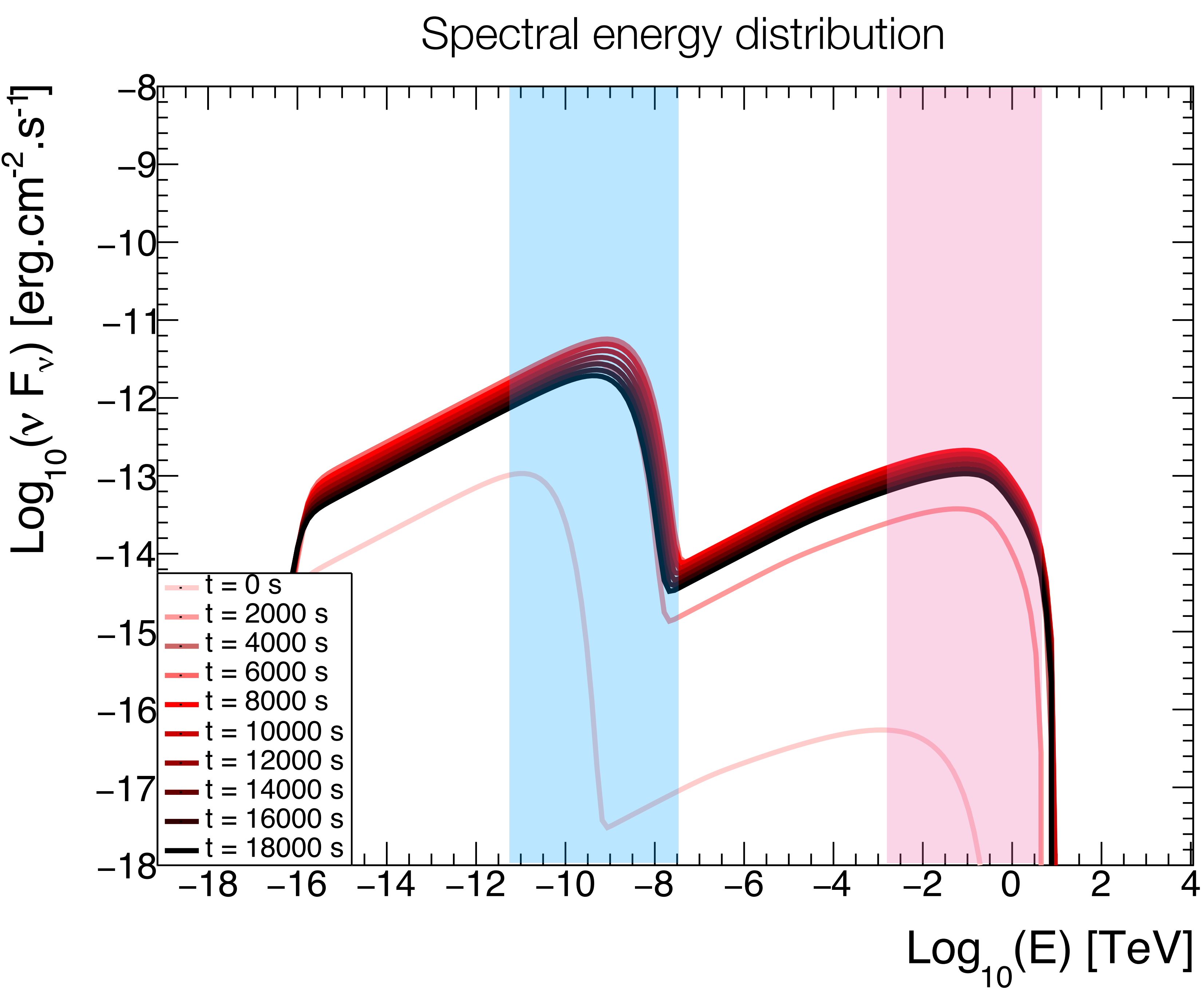


How to exploit these?



Multi-wavelength study

How to distinguish intrinsic and LIV effects?



The 2 bumps evolve together (SSC model excluding EBL, Klein-Nishina and LIV effects):

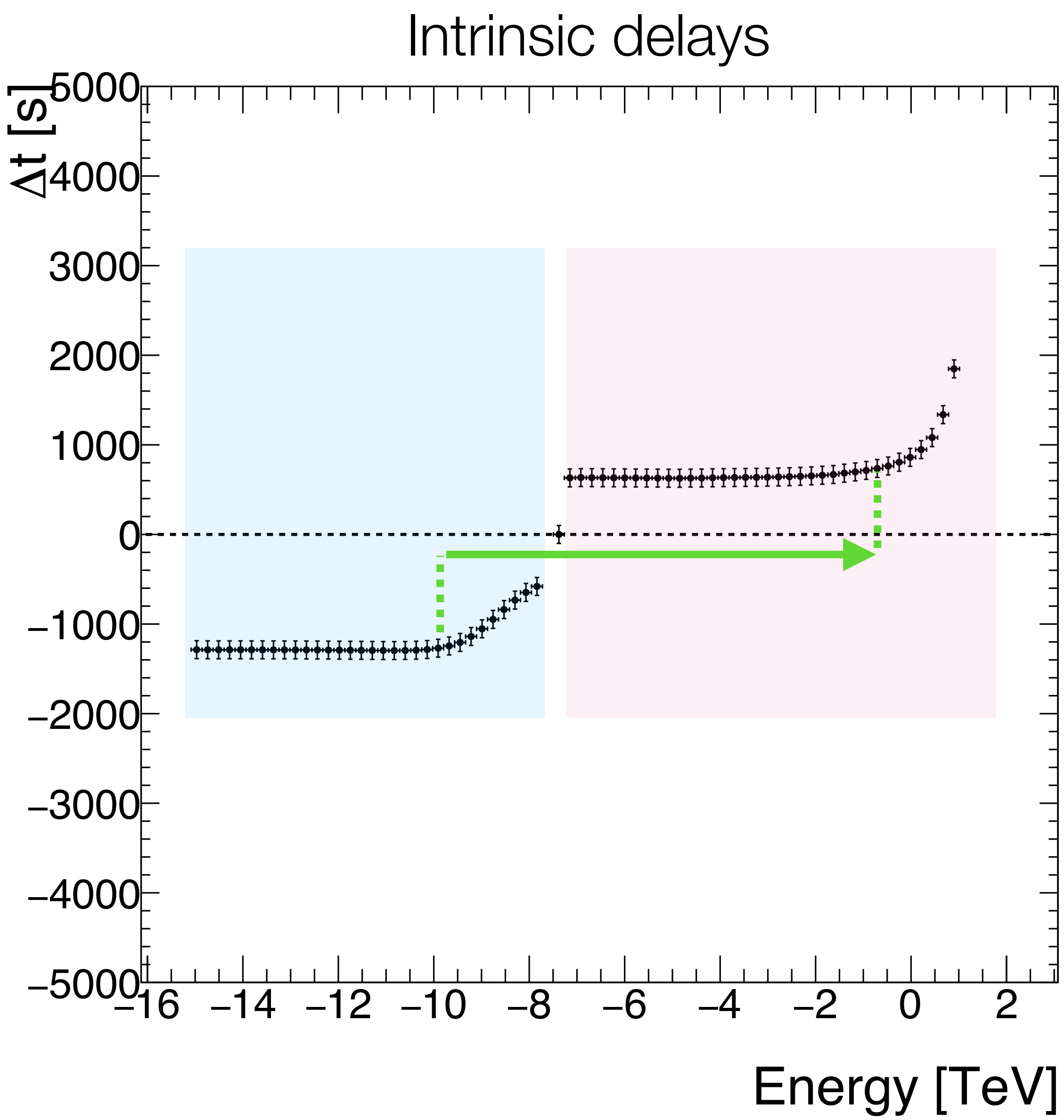
We expect delays in the soft X-range and delays in the gamma-range to evolve together.

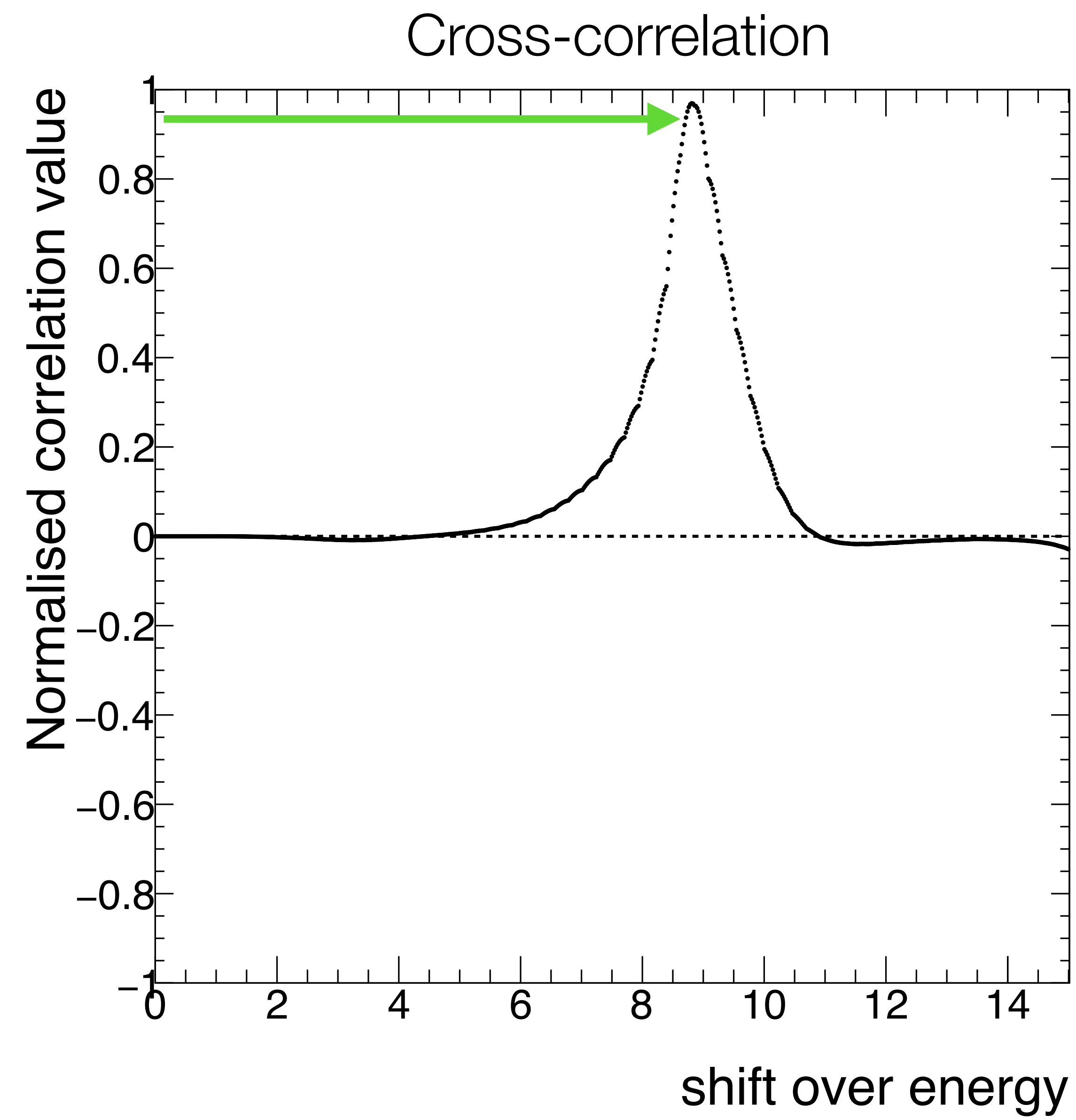
==> Predict intrinsic delays in the gamma range from the observation of delays in the soft X-range.

LIV is observable in gamma range only.
==> Any difference between observed and predicted delays would hint at another contribution (here LIV).

4

Cross-correlation Intrinsic only





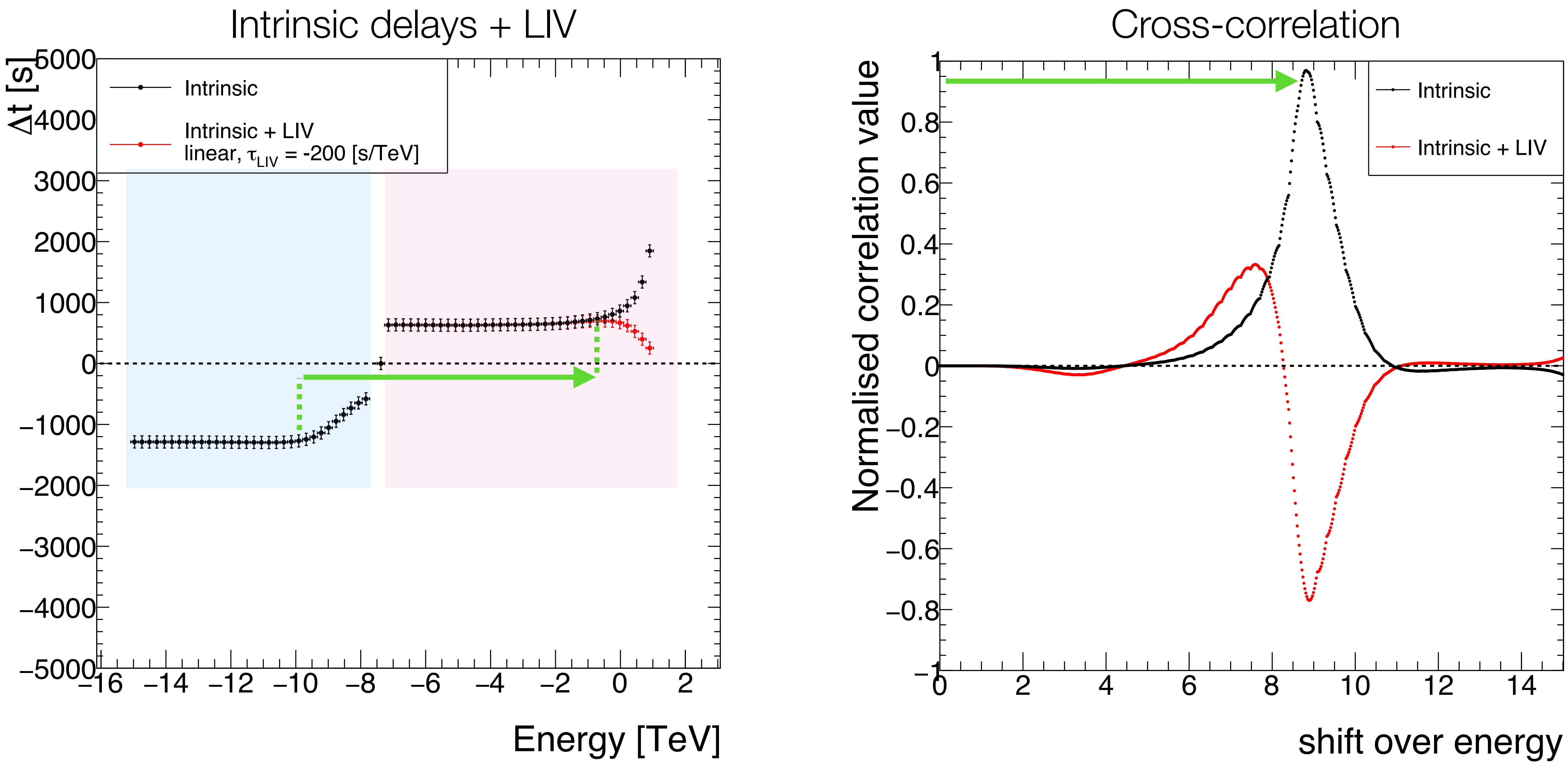
Cross-correlation performed btw soft X-range and gamma-range data-sets.

X-range and gamma-range systematically follow the same trend.
Almost perfect (100%) correlation (EBL and Klein-Nishina effects have small impact on delays).

==> predict gamma-range delays from the soft X-range ones

4

Cross-correlation Intrinsic + LIV



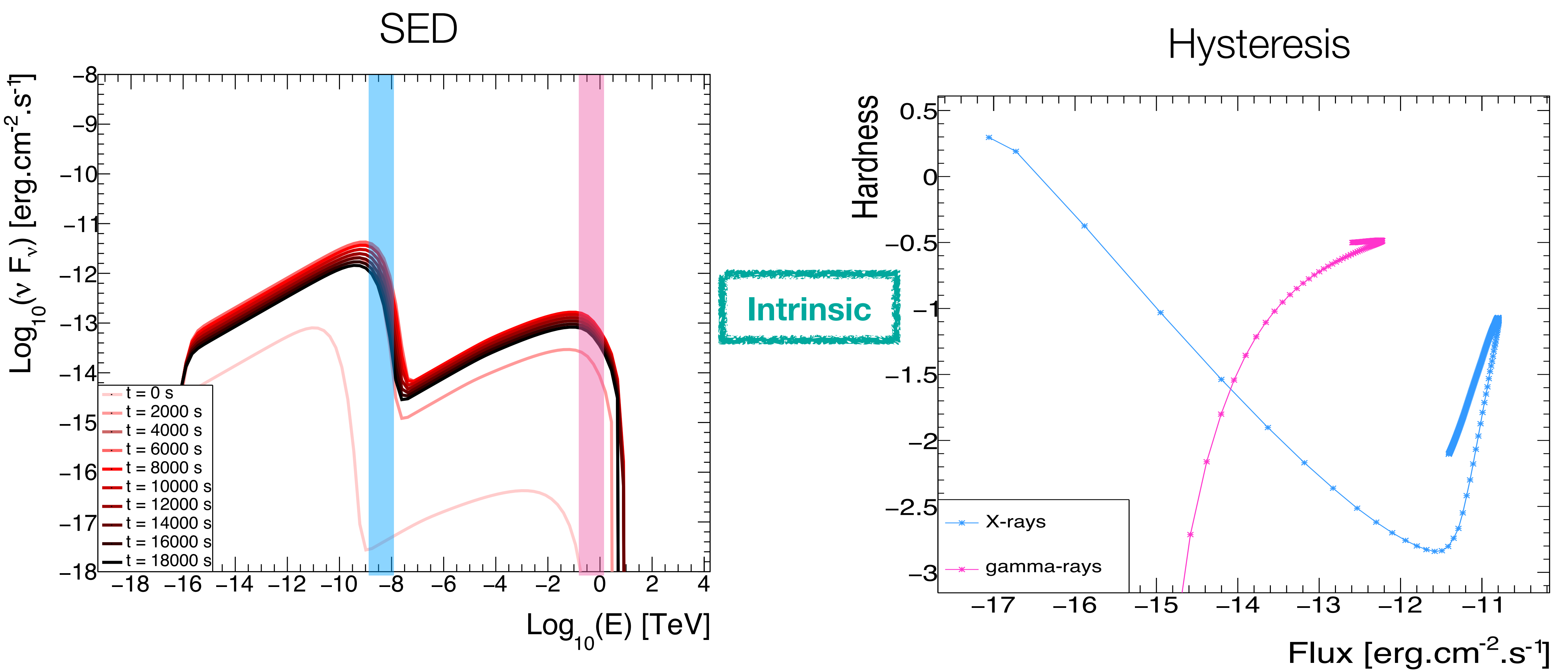
LIV (red) can have a strong impact on the delays and thus the correlation.

==> argue another effect is contributing (here LIV) when correlation is far from +1.

==> **Potentially a strong predicting or rejection tool under the SSC hypothesis!**

2

Hysteresis



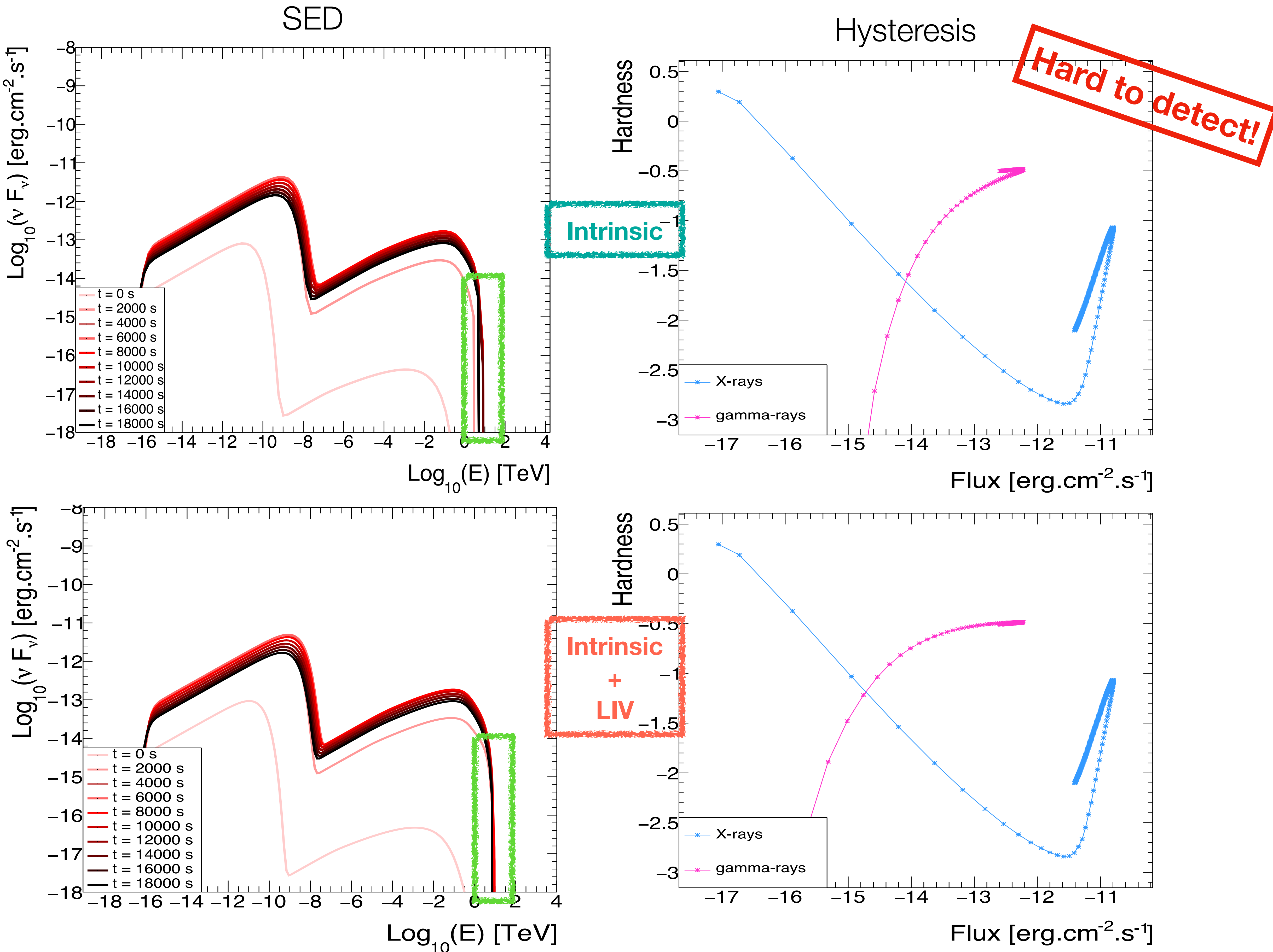
We compute the slope (hardness) of the SED on a small energy band close to the bumps' peak as a function of the mean SED flux in that band.

X-range and gamma-range systematically follow the same trend (clockwise or anti-clockwise).

LIV can change delays trend in the gamma-range
==> could expect LIV to change gamma-range hysteresis (pink) trends as well

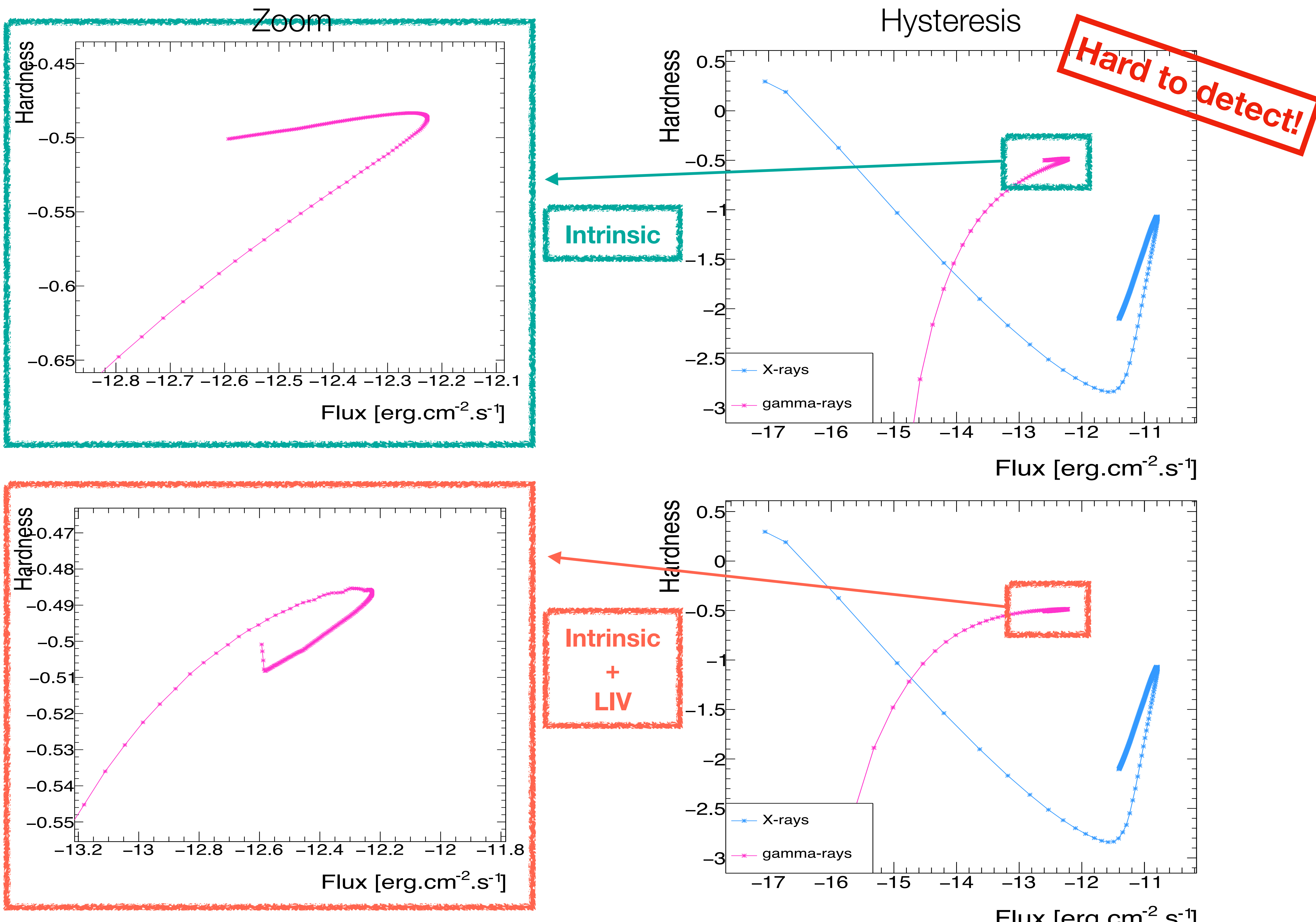
2

Hysteresis



2

Hysteresis zoom



What's left?

Population study: data combination

- Results on their way **—>** First technical paper about this method should be submitted soon
- Use this code for real new data analysis
- Inject a « fake » intrinsic lag : comparison btw individual sources and combinations

Modelisation: intrinsic delays + LIV

- Better characterise the prediction power of the cross-correlation
- Study the dependence between the correlation and the source parameters —> evolution law?
- Estimate CTA capability to resolve hysteresis
- Perform a fit on real or simulated data?

Back up

Combination method

- Separate photon list in 2 sub-sets $\longrightarrow$ low energy vs. high energy light curves (time distributions)
  - **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\text{Sig}(E,t|\tau_n)}}{N_{\text{Sig}(\tau_n)}}$$

$$R_{\text{Sig}}(E,t|\tau_n) = \int_{E_{true}=0}^{\infty} \underbrace{\boxed{D(E,E_{true})A_{\text{eff}}(E_{true},t)}}_{\text{Telescopes IRFs}} \underbrace{\boxed{\Lambda_{\text{Sig}}(E_{true})}}_{\text{Spectrum}} \underbrace{\boxed{F_{\text{Sig}}(t-\tau_n \cdot E_{true}^n)}}_{\text{Light curve}} dE_{true}$$

$$N_{\text{Sig}}(\tau_n) = \int_{t=t_{min}}^{t_{max}} \int_{E=E_{cut}}^{E_{max}} R_{\text{Sig}}(E,t|\tau_n) dEdt$$

Combination method

- Separate photon list in 2 sub-sets $\longrightarrow$ low energy vs. high energy light curves (time distributions)
  - **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\mathrm{Sig}(E,t|\tau_n)}}{N_{\mathrm{Sig}(\tau_n)}}$$

- Incorporation of **background treatment:** hardons (cosmic rays) and baseline photons

$$R_{\mathrm{Sig}}(E,t|\tau_n) = \int_{E_{true}=0}^{\infty} \overset{\text{Telescopes IRFs}}{\boxed{D(E,E_{true})A_{\mathrm{eff}}(E_{true},t)}}\,\overset{\text{Spectrum}}{\boxed{\Lambda_{\mathrm{Sig}}(E_{true})}}\,\overset{\text{Light curve}}{\boxed{F_{\mathrm{Sig}}(t-\tau_n\cdot E^n_{true})}}\,dE_{true}$$

$$\downarrow$$

$$F_{\mathrm{bck}}(t) = \mathrm{cst}$$

$$\downarrow$$

$$\mathcal{L}(\tau_n) = \prod^{N}(1-w_s)\left(w_\gamma \frac{R_{\mathrm{bck},\gamma}(E,t)}{N_{\mathrm{bck}}} + (1-w_\gamma)\frac{R_{\mathrm{bck,hadron}}(E,t)}{N_{\mathrm{bck}}}\right) + w_s \frac{R_{\mathrm{sig},\gamma}(E,t|\tau_n)}{N_{\mathrm{sig}(\tau_n)}}$$

Combination method

- Separate photon list in 2 sub-sets $\longrightarrow$ low energy vs. high energy light curves (time distributions)
  - **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\mathrm{Sig}(E,t|\tau_n)}}{N_{\mathrm{Sig}(\tau_n)}}$$

- Incorporation of **background treatment:** hardons (cosmic rays) and baseline photons
- Combination $\longrightarrow$ **Instrument Response Functions** vary for each source and instrument
  - Approximations were made on IRFs treatment for most of the previous studies

$$R_{\mathrm{Sig}}(E,t|\tau_n) = \cancel{\int_{E_{true}=0}^{\infty}} \overset{\cancel{\text{Telescopes IRFs}}}{\cancel{\boxed{D(E,E_{true})A_{\mathrm{eff}}(E_{true},t)}}} \overset{\text{Spectrum}}{\boxed{\Lambda_{\mathrm{Sig}}(E_{true})}} \overset{\text{Light curve}}{\boxed{F_{\mathrm{Sig}}(t-\tau_n \cdot E_{true}^{n})}} \cancel{dE_{true}}$$

$$\downarrow$$

$$R_{sig}\left(t \mid \tau_n\right) = \Lambda_{sig}\left(E\right) \cdot F_{sig}\left(t - \tau_n \cdot \overline{E}^{n}\right), \quad E = E_{true}$$

Combination method

- Separate photon list in 2 sub-sets $\longrightarrow$ low energy vs. high energy light curves (time distributions)
  - **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets

$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\mathrm{Sig}(E,t|\tau_n)}}{N_{\mathrm{Sig}(\tau_n)}}$$

- Incorporation of **background treatment:** hardons (cosmic rays) and baseline photons
- Combination $\longrightarrow$ **Instrument Response Functions** vary for each source and instrument
  - Approximations were made on IRFs treatment for most of the previous studies

$$N_{\mathrm{Sig}}(\tau_n) = \int_{t=t_{min}}^{t_{max}} \int_{E=E_{cut}}^{E_{max}} R_{\mathrm{Sig}}(E,t|\tau_n) dE dt$$ = 1 triple integral

$$\downarrow$$

$$N_{sig}(\tau_n) = \left[\int_{t_{min}}^{t_{max}} F_{sig}\left(t - \tau_n \cdot \overline{E}^n\right) dt\right] \times \left[\int_{E=0}^{\infty} \Lambda_{sig}(E)\, dE\right]$$ = 2 simple integral