Modeling intrinsic time-lags in flaring blazars in the context of Lorentz Invariance Violation searches

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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.**

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

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

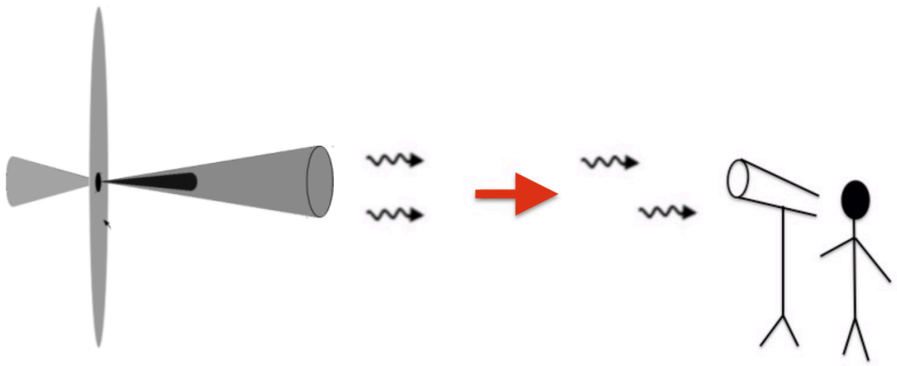
$$\Delta t \simeq \frac{n+1}{2}\frac{E_1^n - E_2^n}{E_P^n} f(z) \quad \rightarrow \quad \tau_n = \frac{\Delta t_n}{\Delta E_n} = \pm\frac{n+1}{2H_0 E_{QG}^n} f(z)$$

Sensitivity maximised for distant, variable and energetic source

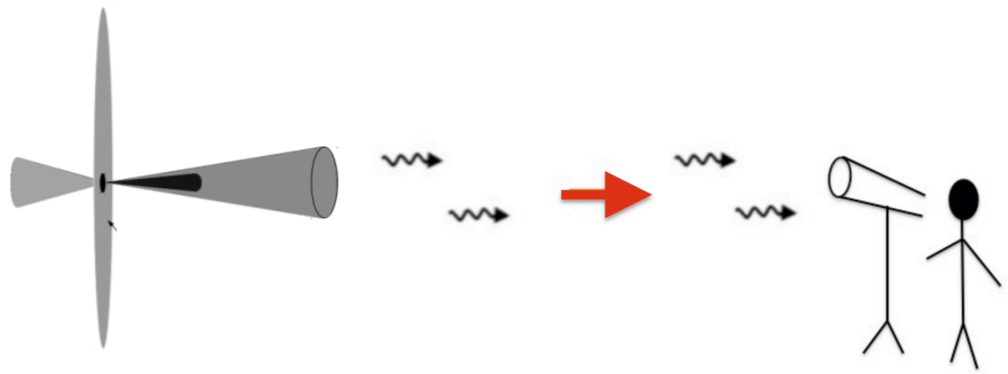
→ **Active Galactic Nuclei**

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

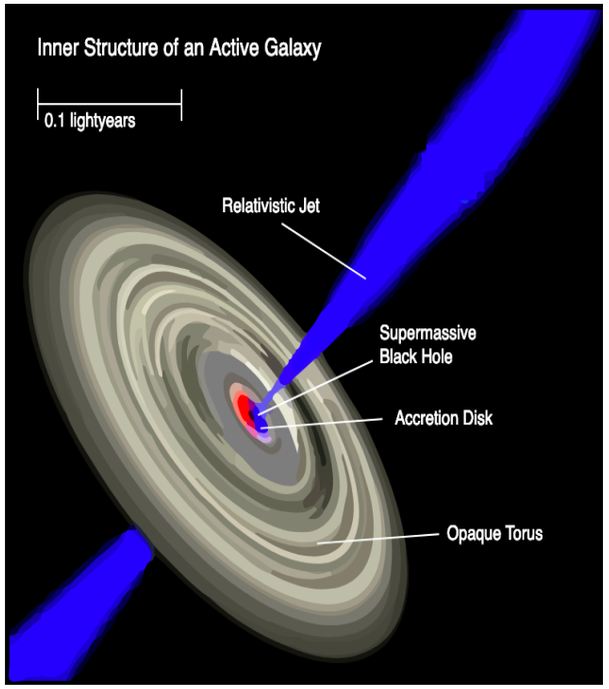
These intrinsic delays need to be characterized and **differentiated** from LIV-induced ones in order to provide a proper interpretation for observed delays

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.

Blazars

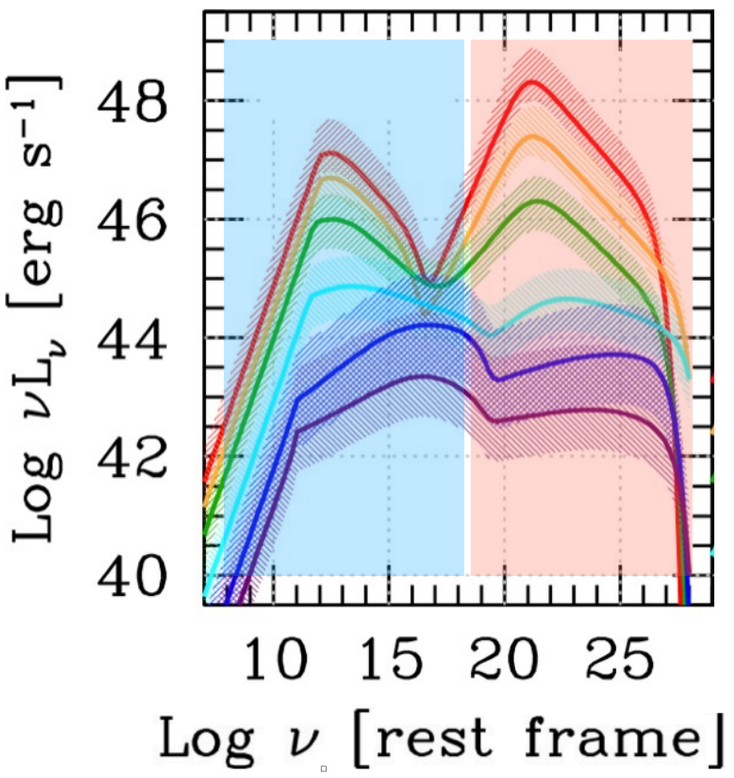
Active galactic nuclei (AGN) nominate **galaxies' core** hosting a super-massive blackhole fed by an accretion disk. They can display relativistic jets and are surrounded by dust clouds.

Blazars are a **sub-category of AGNs** where jets are oriented in the direction of our line of sight.



Schematic of an AGN

Revised blazar sequence
(Ghisellini et al., 2017)



Synchrotron emission peak from the interaction between electrons in the jet and magnetic field

Inverse Compton emission peak:

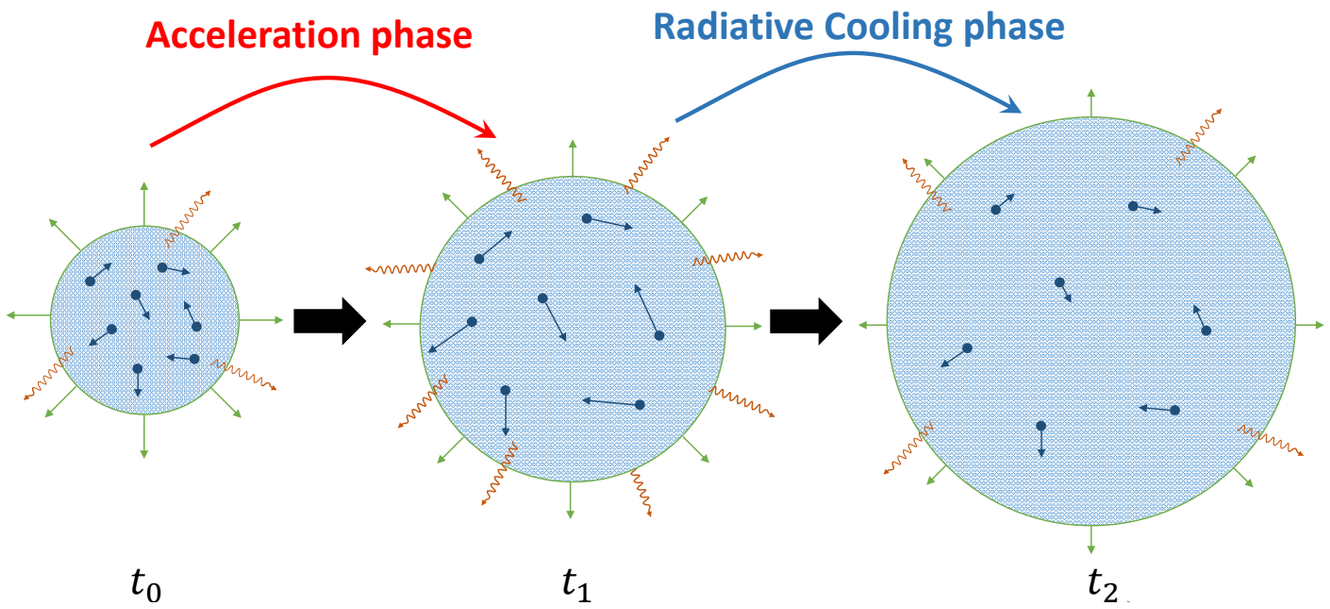
- between electrons and their synchrotron photon (synchrotron self Compton **SSC**)
- between electrons and photons from external field generated by the accretion disk (external inverse Compton EIC)

Time-dependent model

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

Synchrotron Self Compton

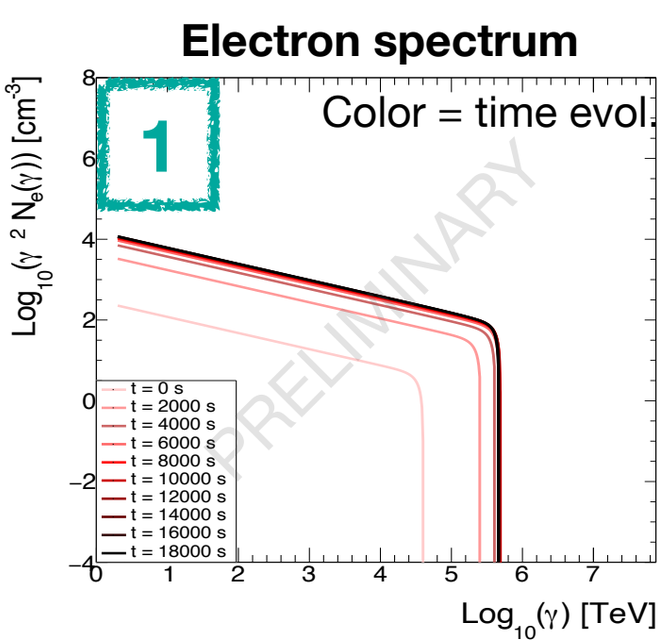
- Single bulk of leptonic plasma
- Evolution described with a differential equation (DE) solved analytically
- Most basic processes needed to generate a flare: acceleration & cooling
- Neglect injection and escape of particles.

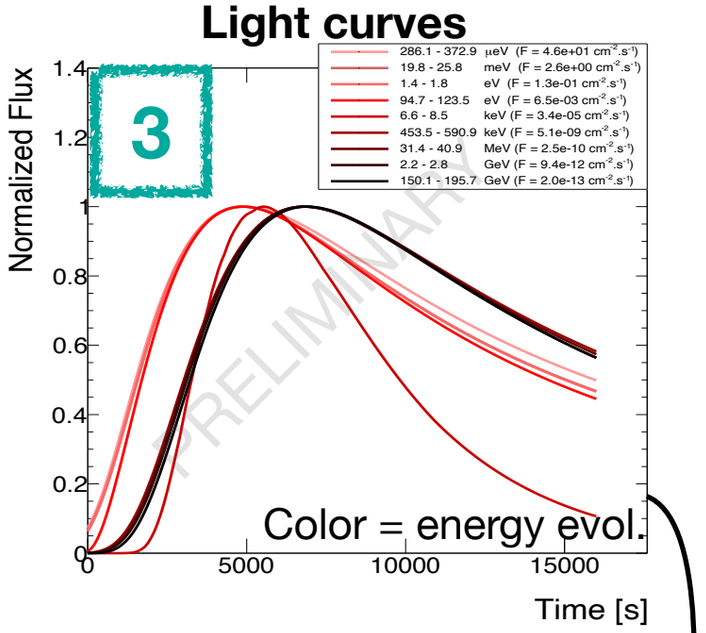


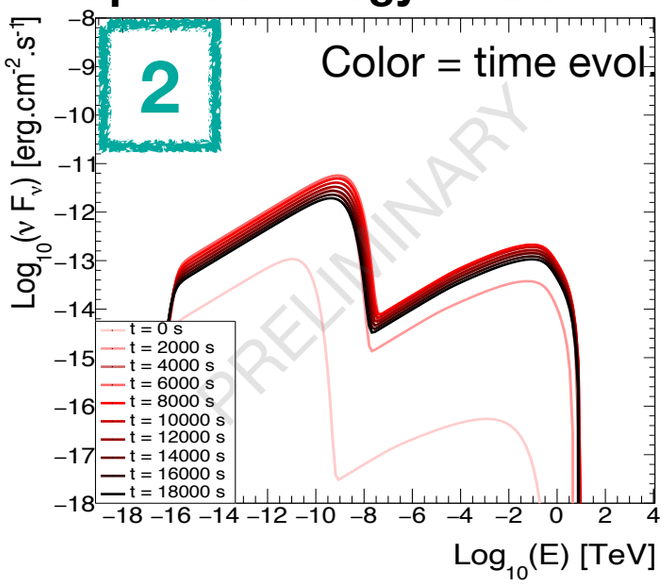
$$C^{acc} \propto A(t) = A_0 \left(\frac{t_0}{t}\right)^{m_a}$$

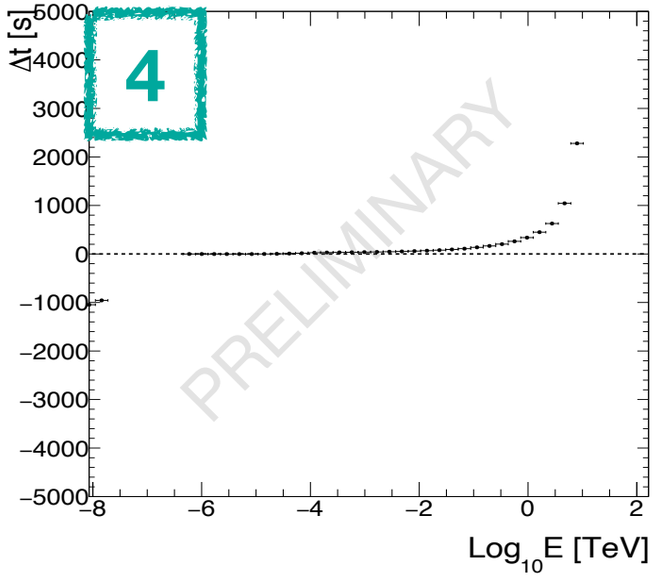
$$C^{cool} \propto B^2(t) = \left[B_0 \left(\frac{t_0}{t}\right)^{m_b}\right]^2$$

Generating a flare: intrinsic effects









LC maxima

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

The « typical » arrival time is taken at the **maximum.**

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

Injecting LIV: simultaneous treatment

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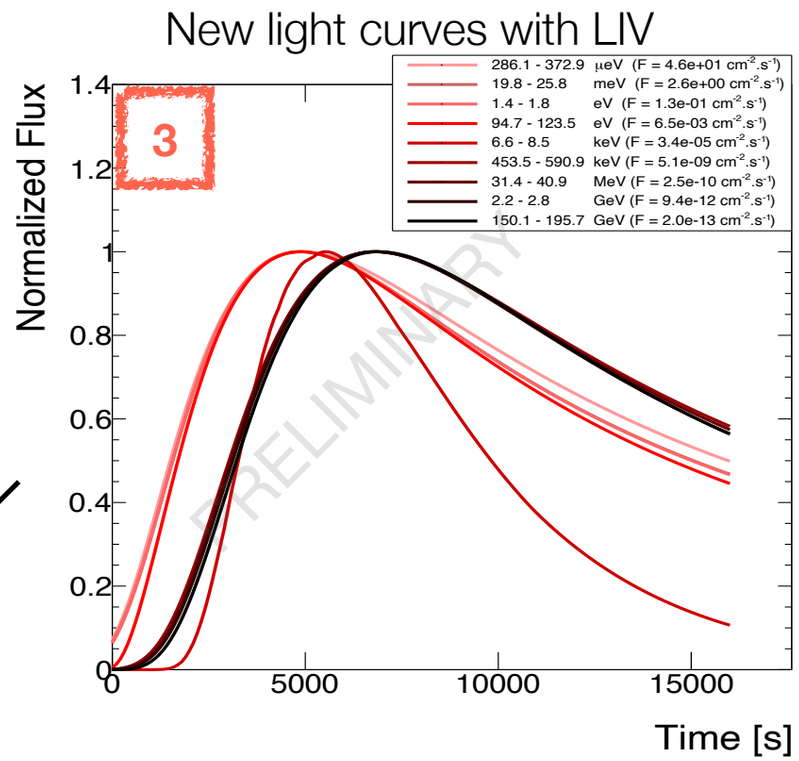
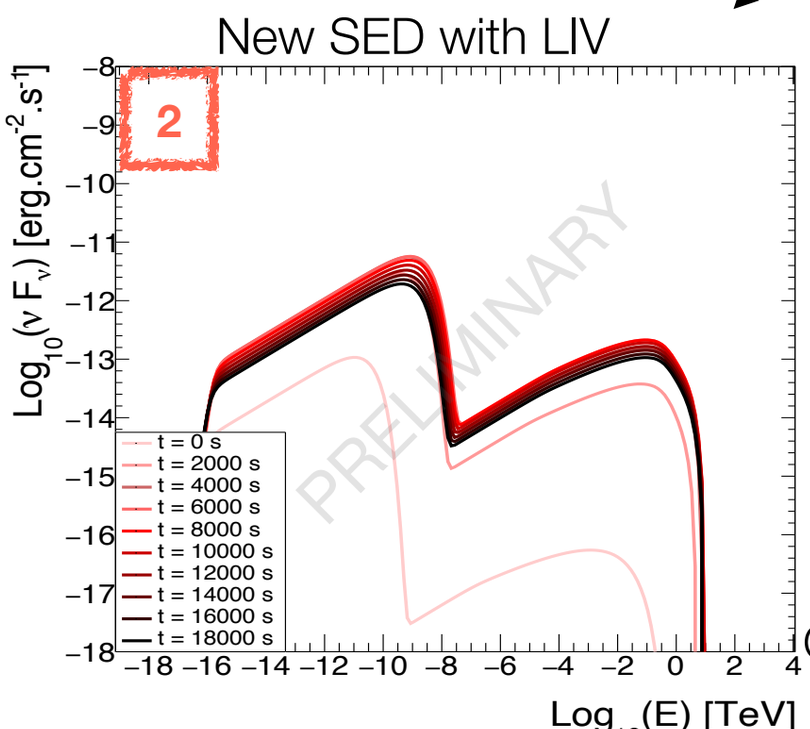
$$t_{LC} \rightarrow t_{LC} + \tau_n E_{LC}^n$$

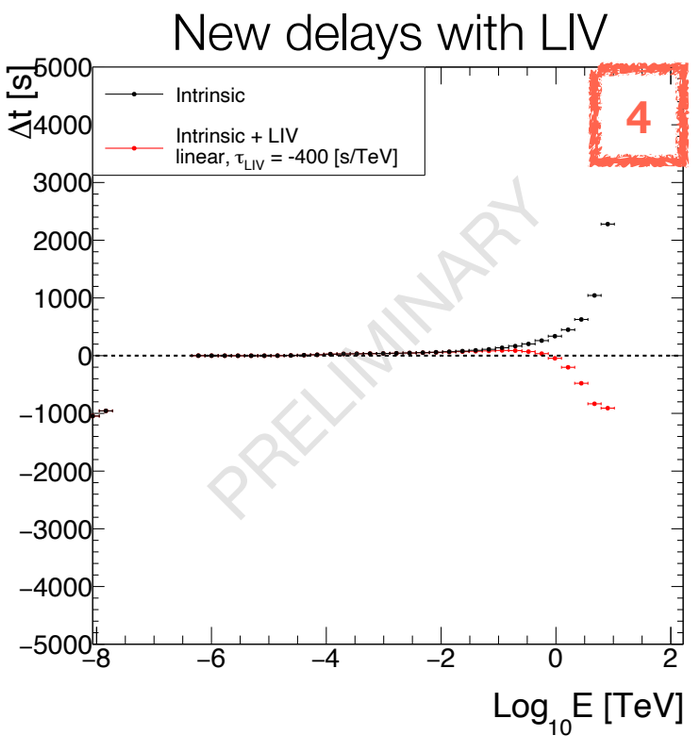
τ_n is the LIV term (input parameter)



Inverse reconstruction

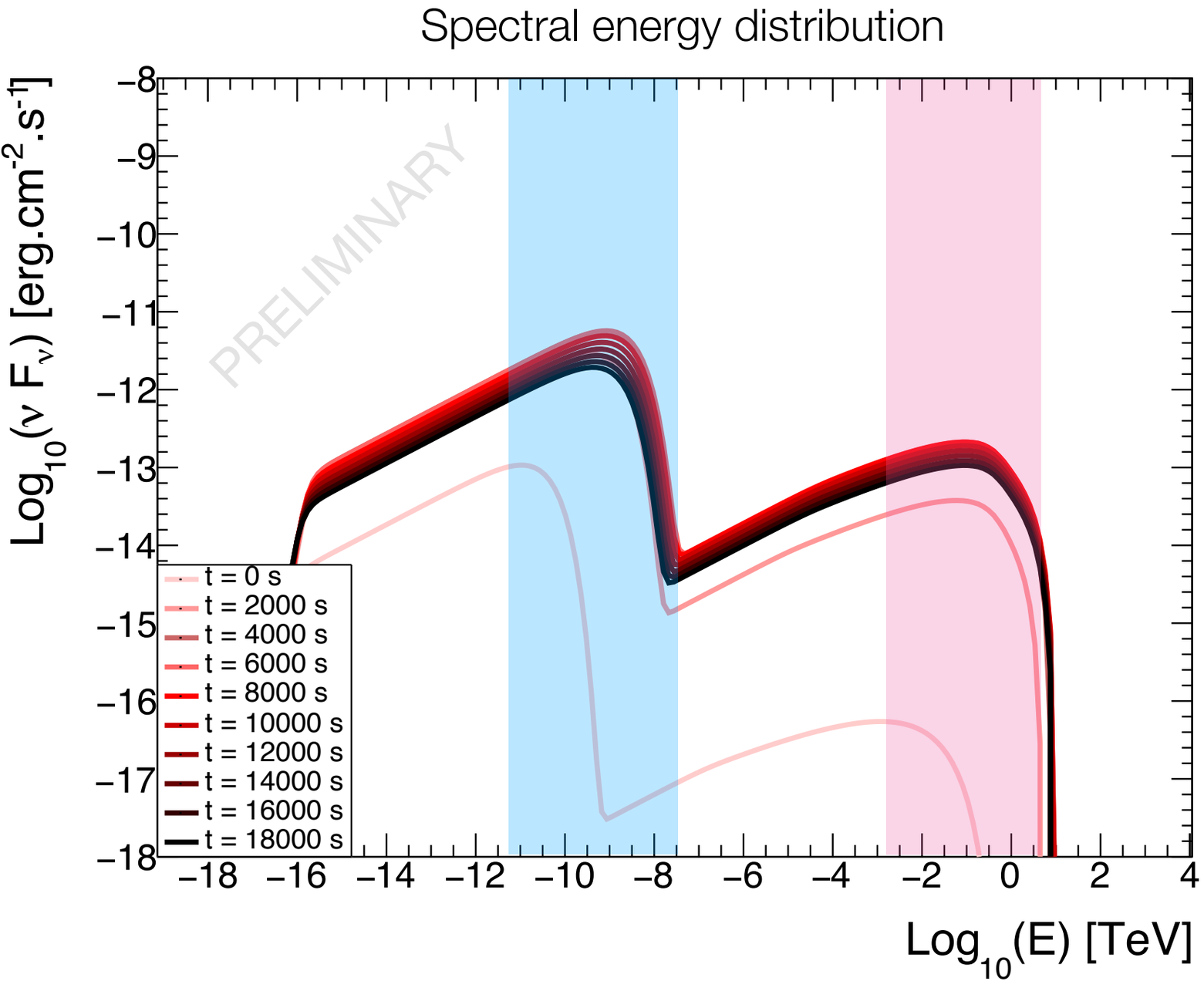


How to exploit these?



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 synchrotron (X-ray) and delays in the inverse Compton (gamma-ray) domains to evolve together.

==> Deduce intrinsic delays at gamma-ray energies from the observation of delays in the X-range.

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

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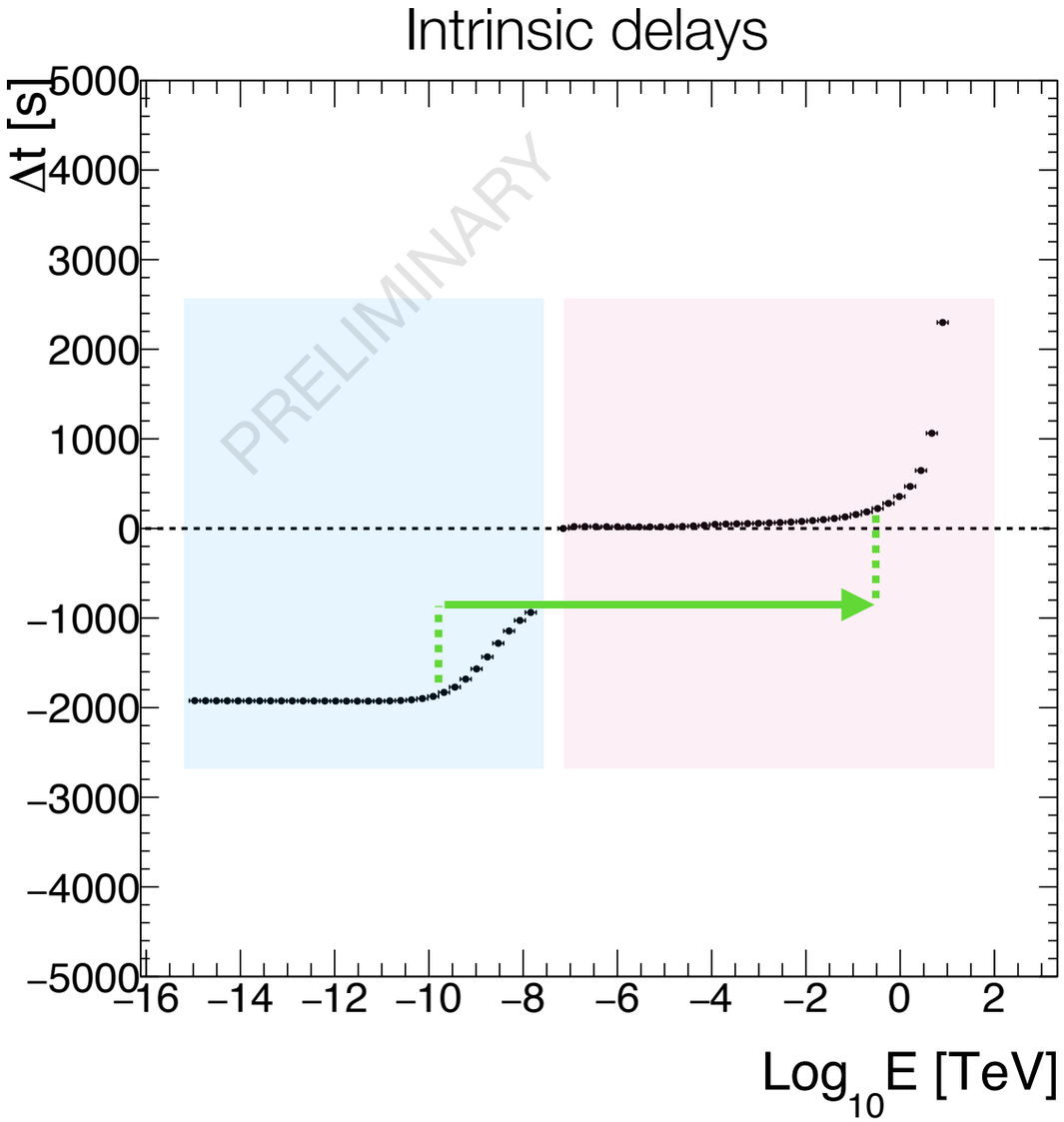
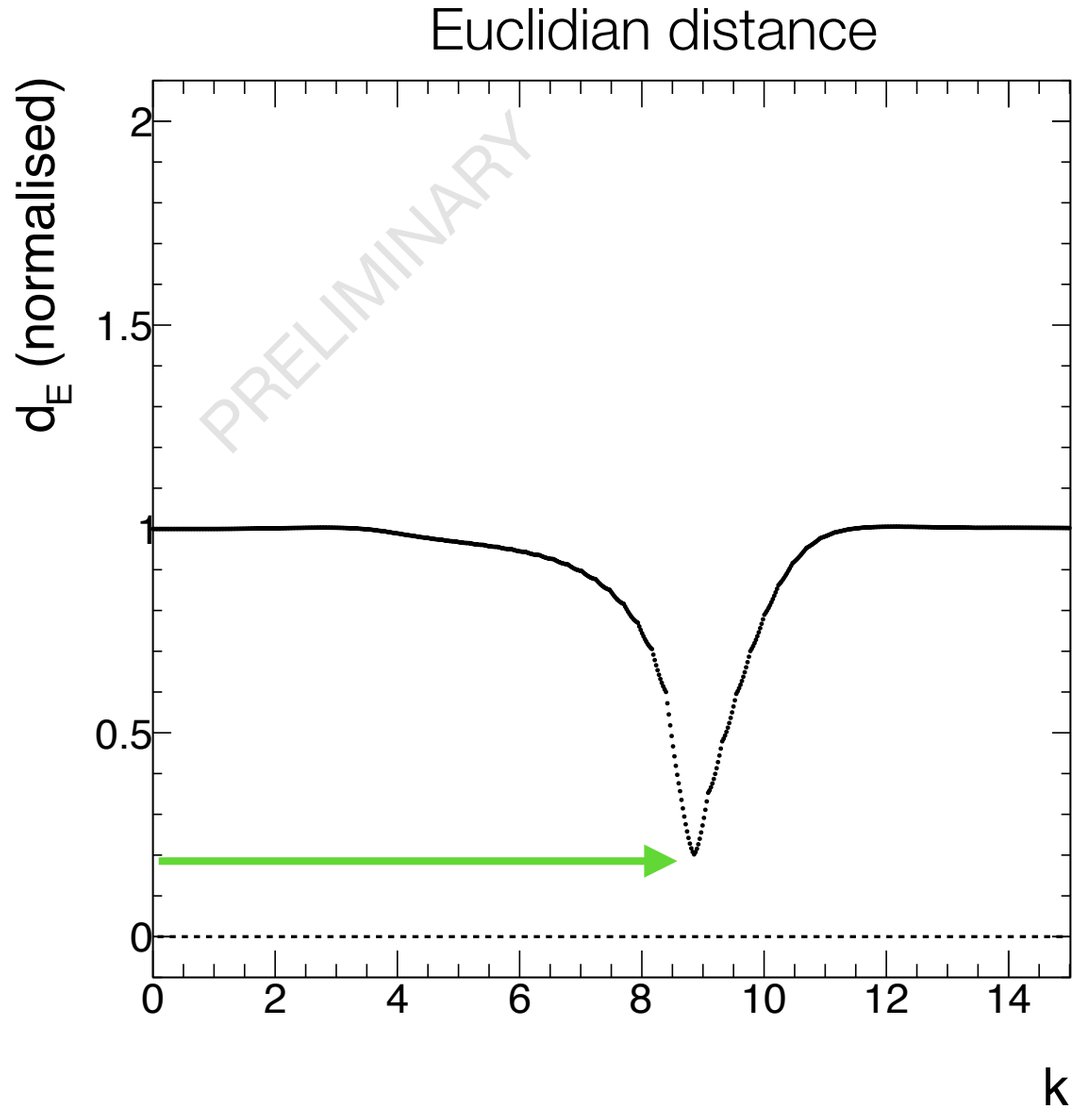
Euclidian distance
Intrinsic only





Euclidian distance performed btw X-range and gamma-range data-sets.

X-range and gamma-range systematically follow the **same trend.**
Good agreement between the 2 datasets (EBL & Klein-Nishina effects have small impact on delays).

==> **Deduce** gamma-range delays from the X-range ones

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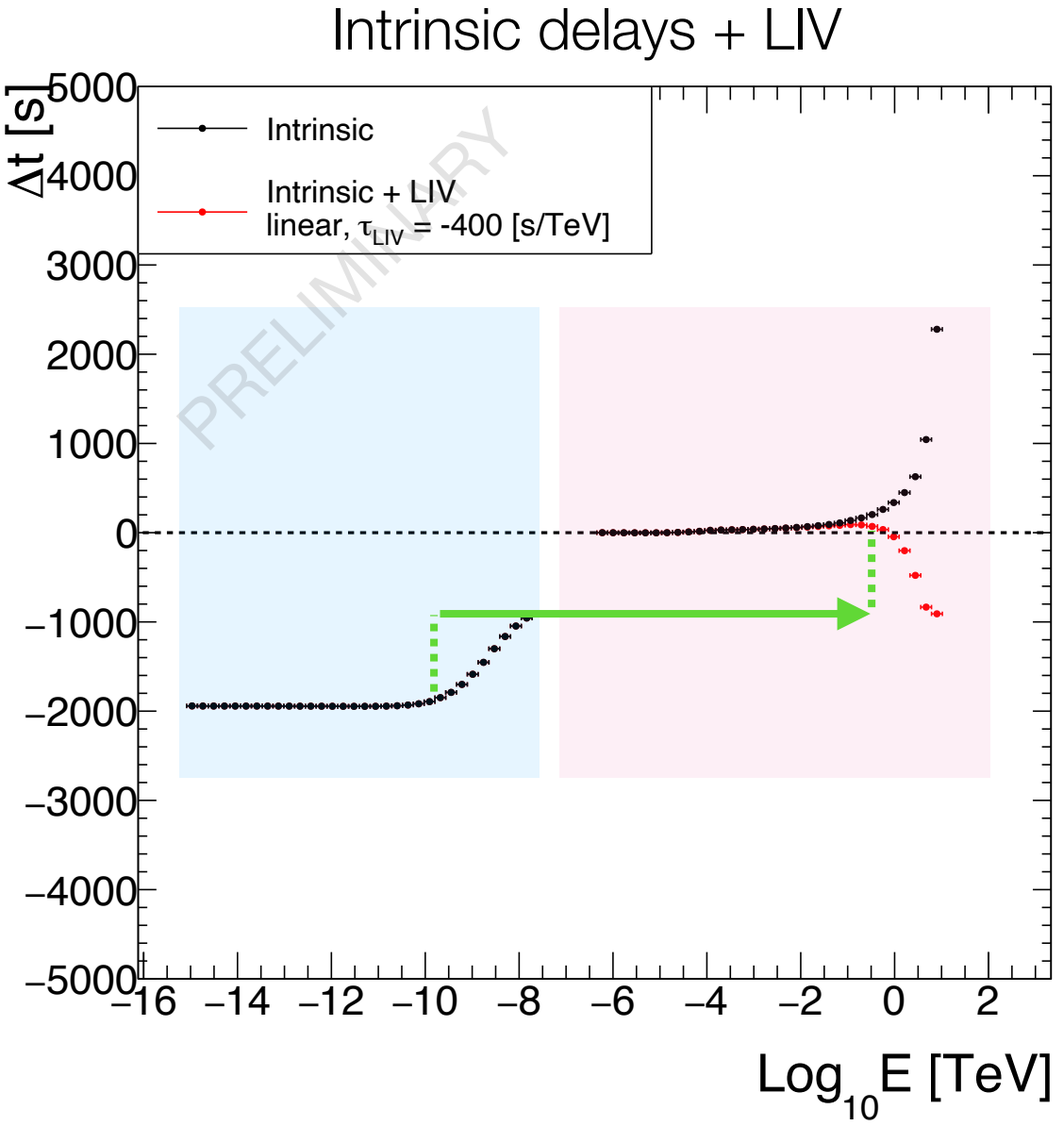
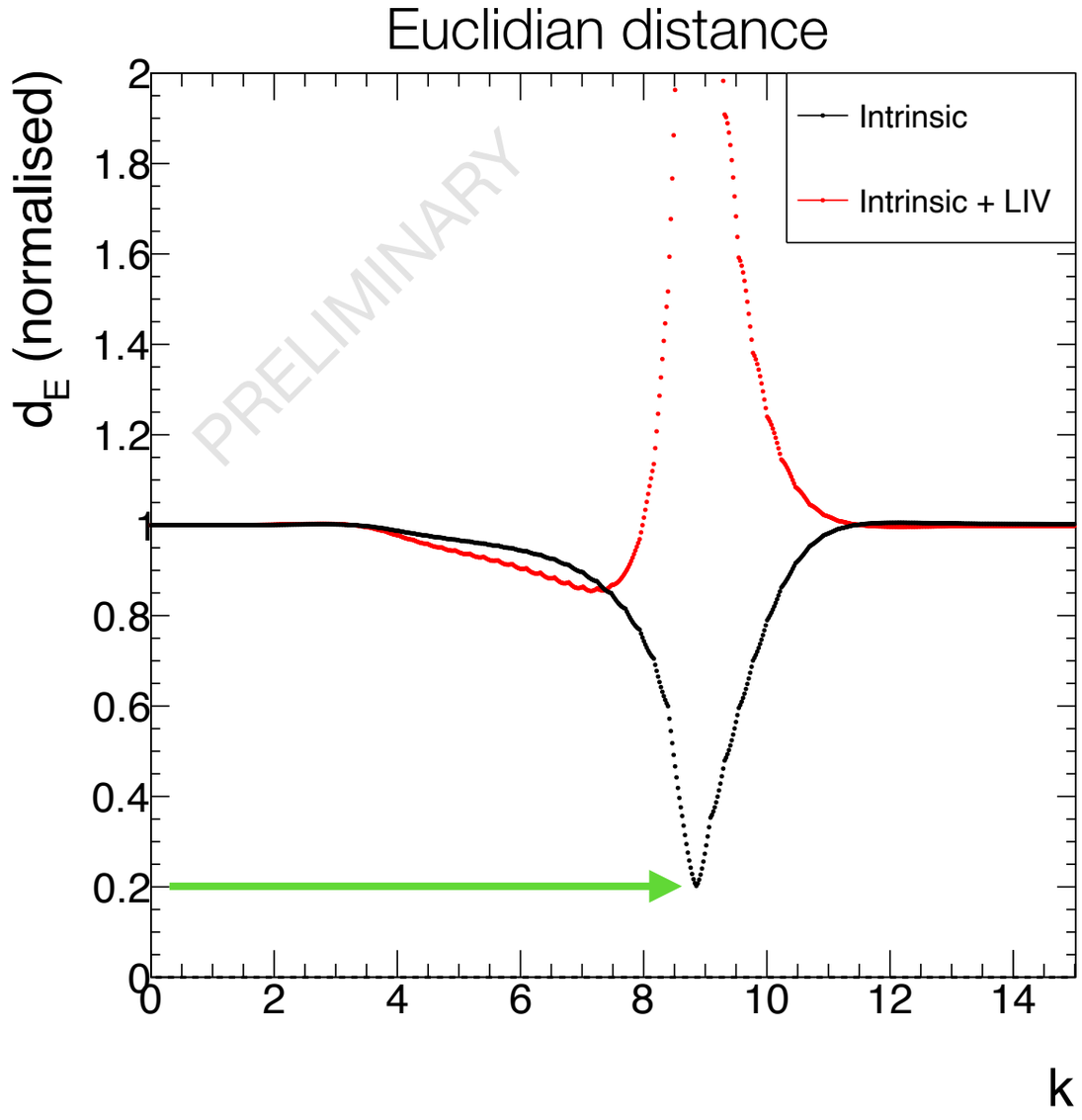
Euclidian distance
Intrinsic + LIV





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

==> argue delays can no longer be explained by intrinsic effects only when the distance is above a given **threshold** under the SSC hypothesis: **another effect is necessarily contributing** (here LIV)

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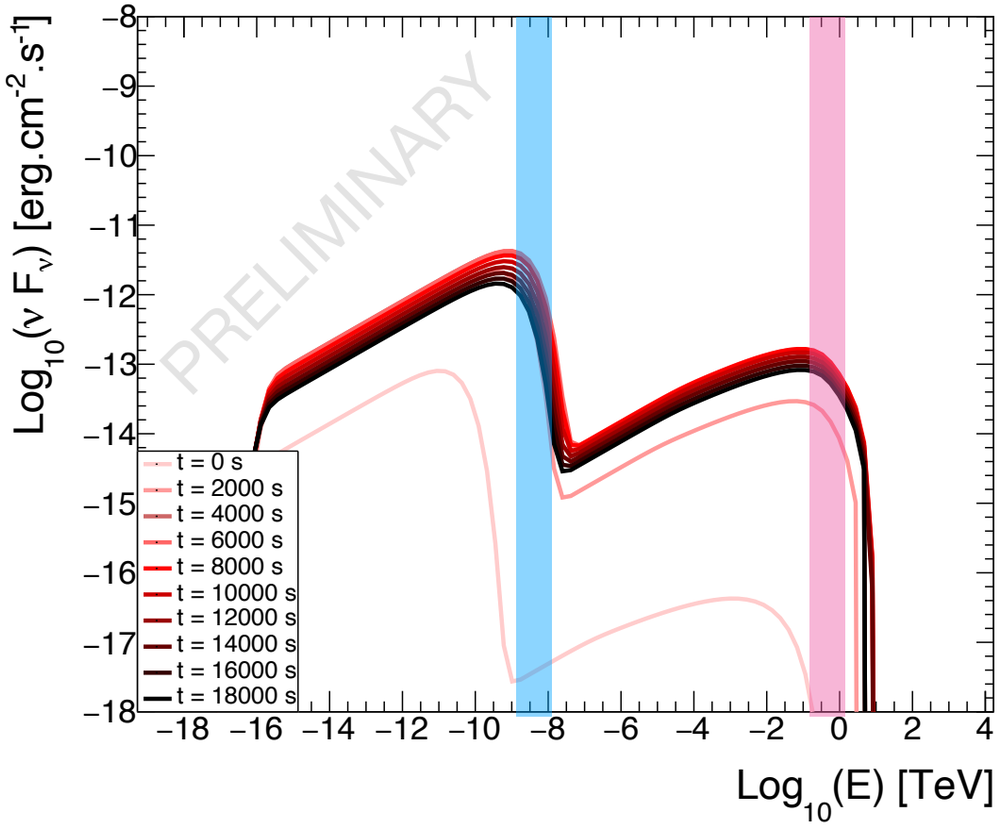
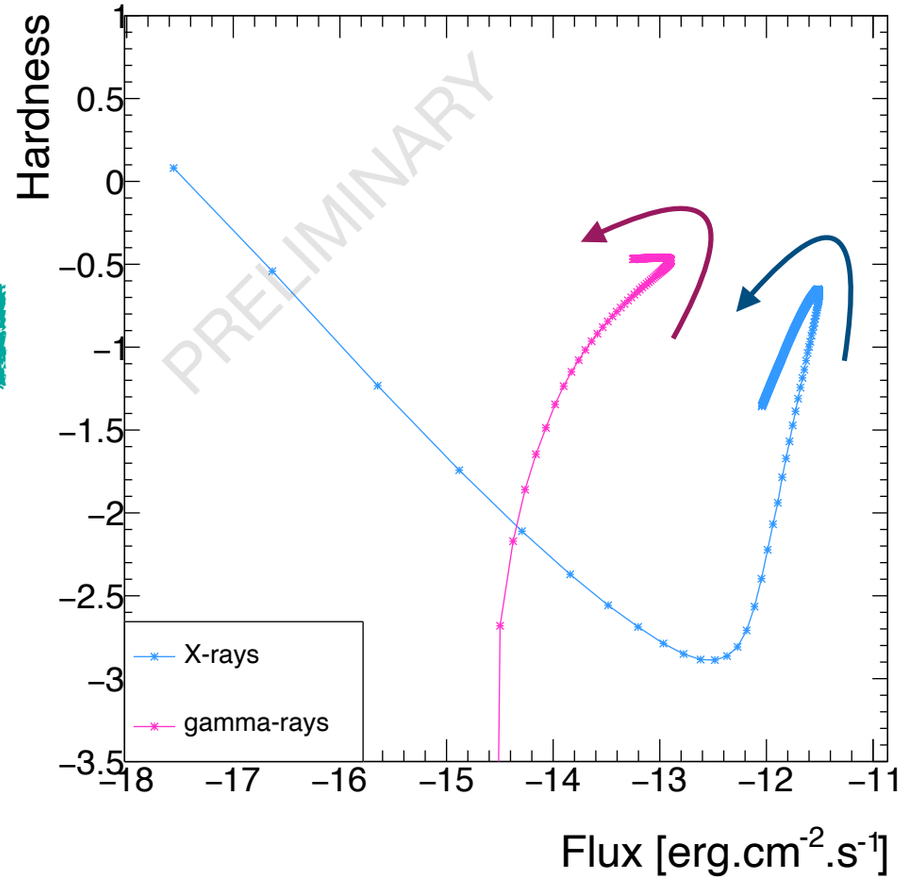
HID: intrinsic only

SED



Intrinsic

HID



Hardness-intensity diagrams (HID): slope of the SED competed on a small energy band as a function of the mean SED flux in that band.

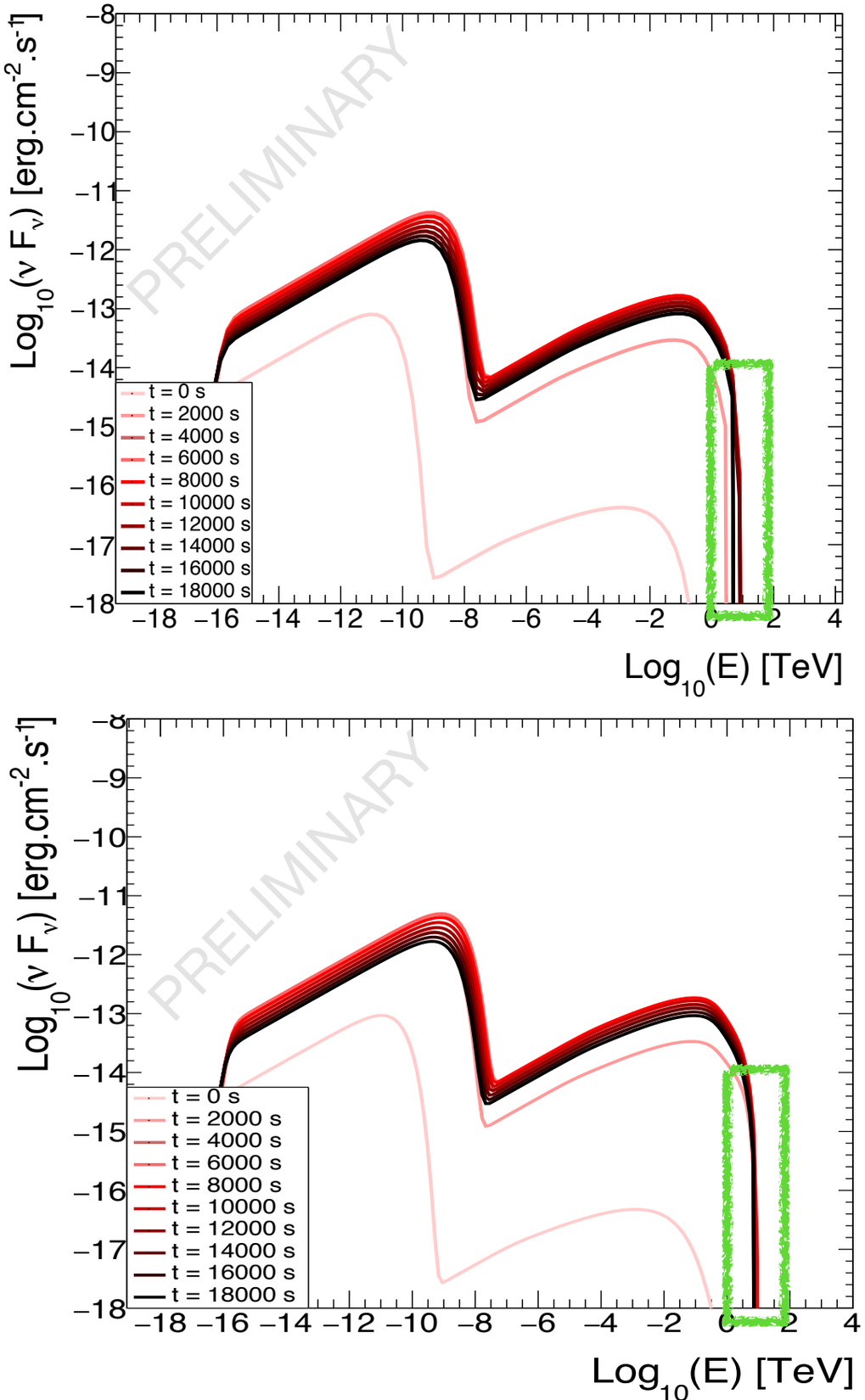
X-range & gamma-range systematically follow the **same loop orientation:** clockwise or anti-clockwise

LIV can change delays trend in the gamma-range
==> could **expect LIV to change gamma-range hysteresis loop orientation** as well.

2

HID: intrinsic + LIV

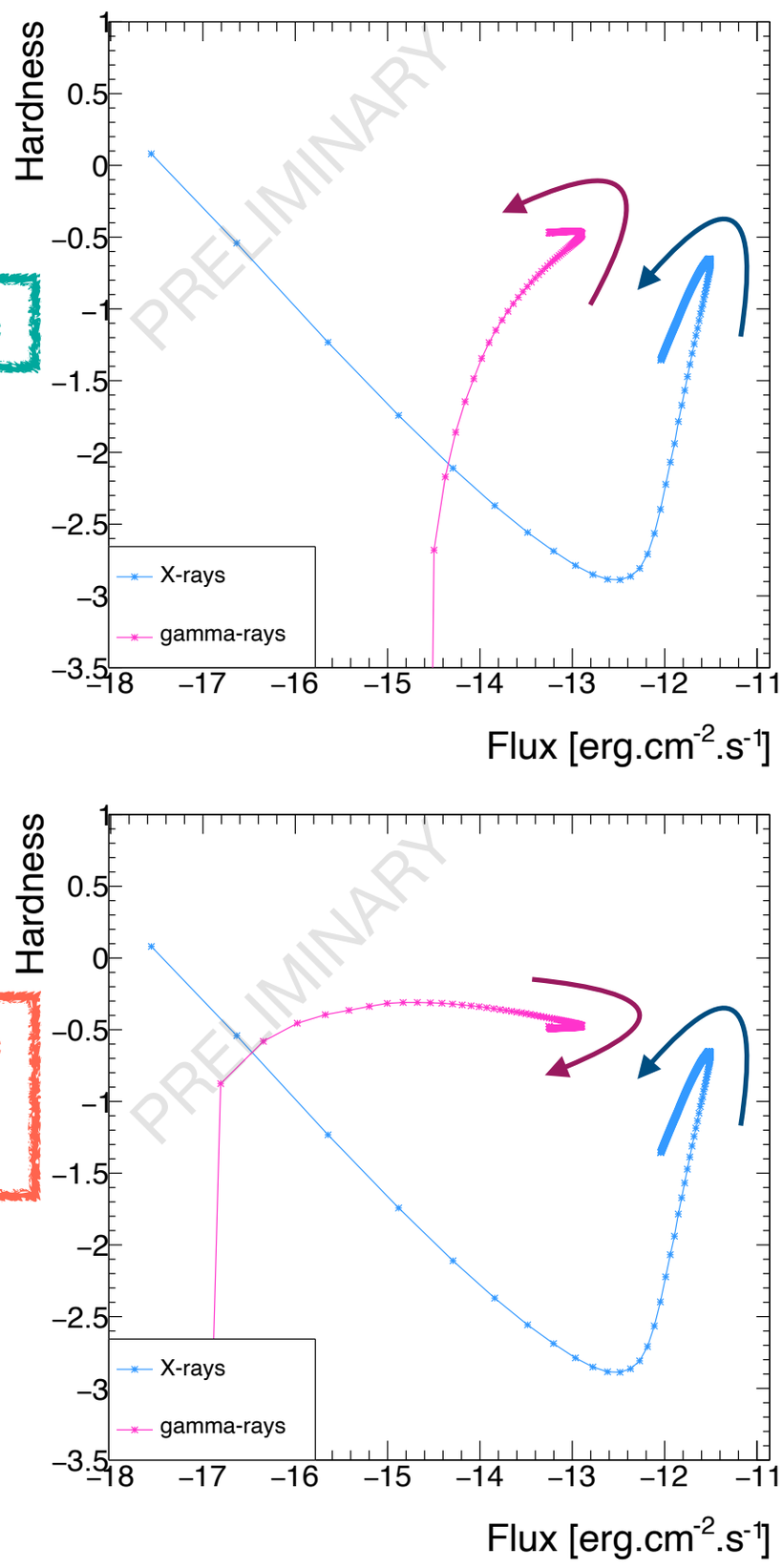
SED



Intrinsic

Intrinsic + LIV

HID



Prospects

- **Better characterise the prediction power** of the euclidian distance study
- Improve it with a Dynamic Time Warping (DTW) method
- Study the dependence between the euclidian distance and the source parameters —> evolution law?

- **Estimate capability of future instruments like CTA to resolve hysteresis patterns**
- Perform a fit on real or simulated data?

- **Multi-wavelength campaigns** providing effective time delay measurements should allow for a distinction between LIV and intrinsic effects.