Time delays in AGN flares - Disentangling intrinsic and LIV delays

From PhD theses
of C. Perennes and of C. Levy
and associated publications

Collaboration:
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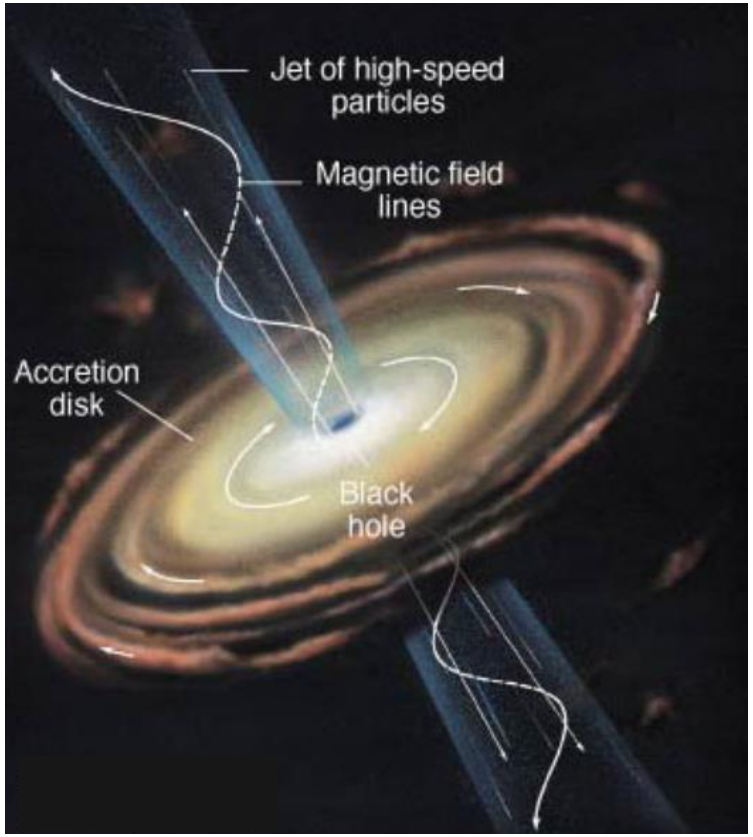
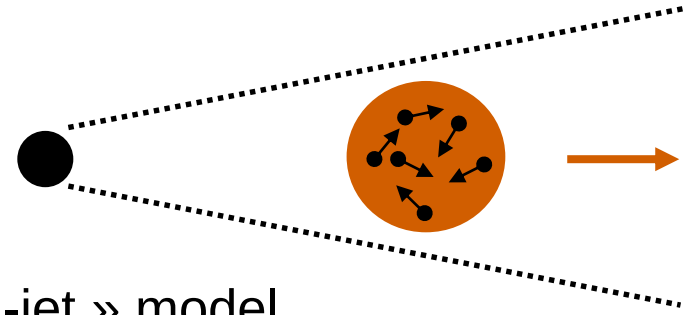


ASTROVIBE meeting, Paris, July 16-17 2024

One-zone leptonic blazar flare



« Blob-in-jet » model

Evolution of the particle distribution:

$$\frac{\partial N_e(t,\gamma)}{\partial t} = \frac{\partial}{\partial \gamma}\{[\gamma^2 C_{\rm cool}(t) - \gamma(C_{\rm acc}(t) - C_{adia}(t))]N_{\rm e}(t,\gamma)\}$$

SSC + EIC + adiabatic effects
Can be solved analytically for weak enough (SSC) IC losses

$$N(0,\gamma) = N_0 \gamma^{-n} \left[1 - \left(\frac{\gamma}{\gamma_{cut}}\right)^{n+2}\right]$$

Particle number density at t = 0

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

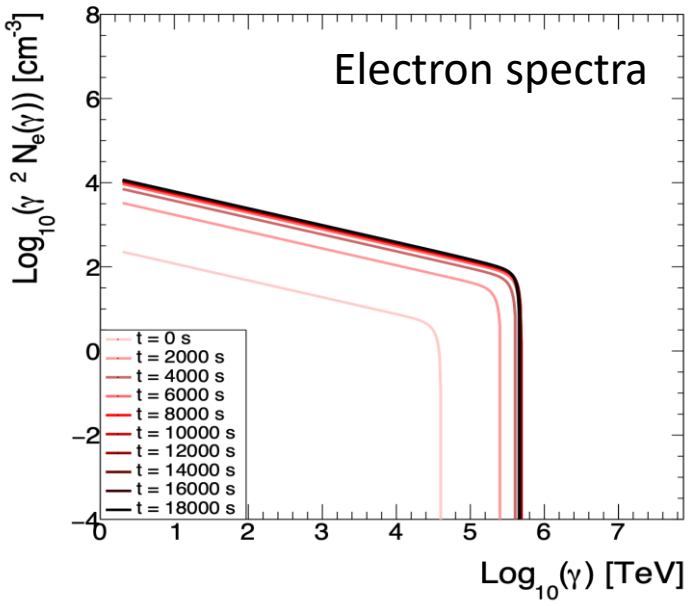
Radiative cooling term, SSC + EIC

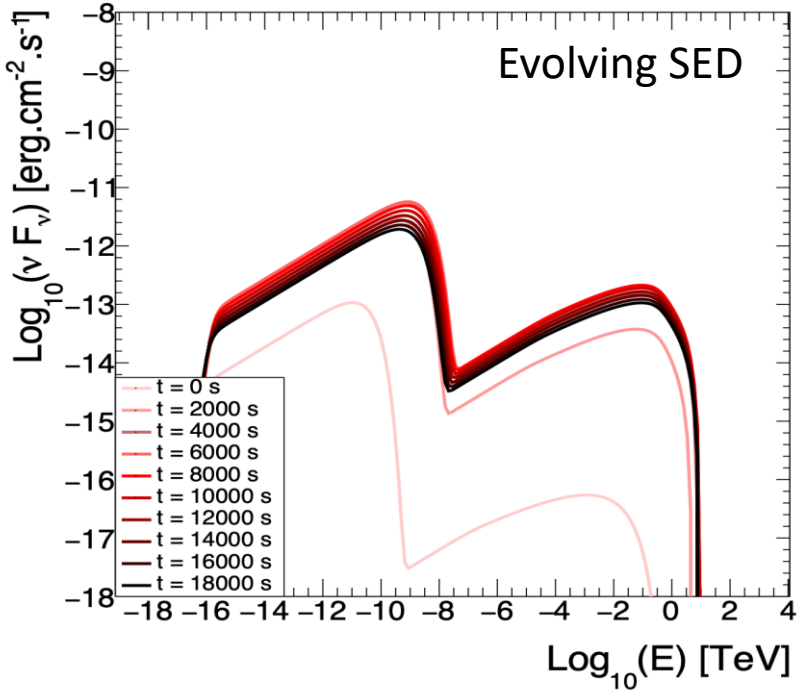
$$C^{acc} \propto A(t) = A_0 \left(\frac{t_0}{t}\right)^{m_a}$$

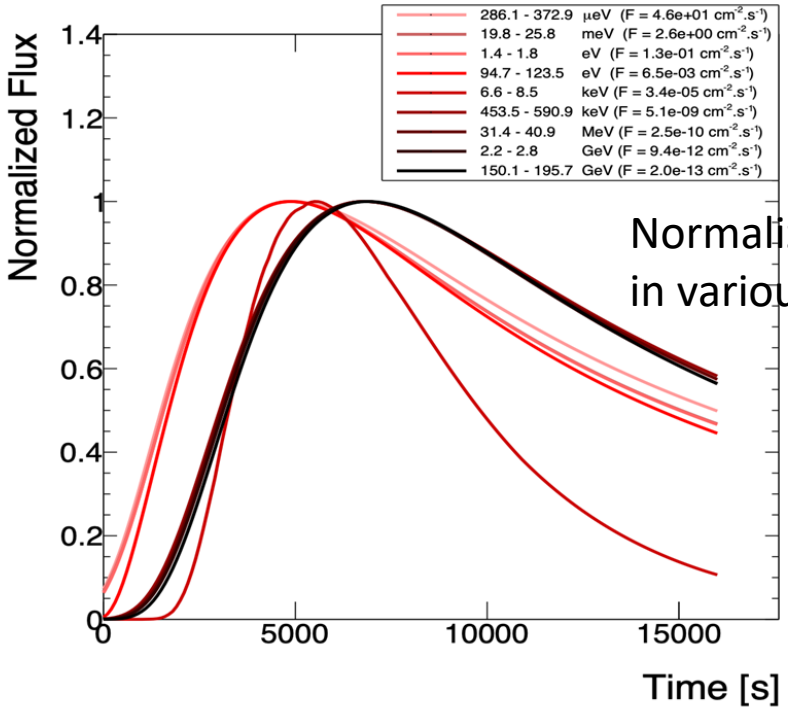
Acceleration term (parametrized)

$$C^{adia} = -\frac{m_r}{t}$$

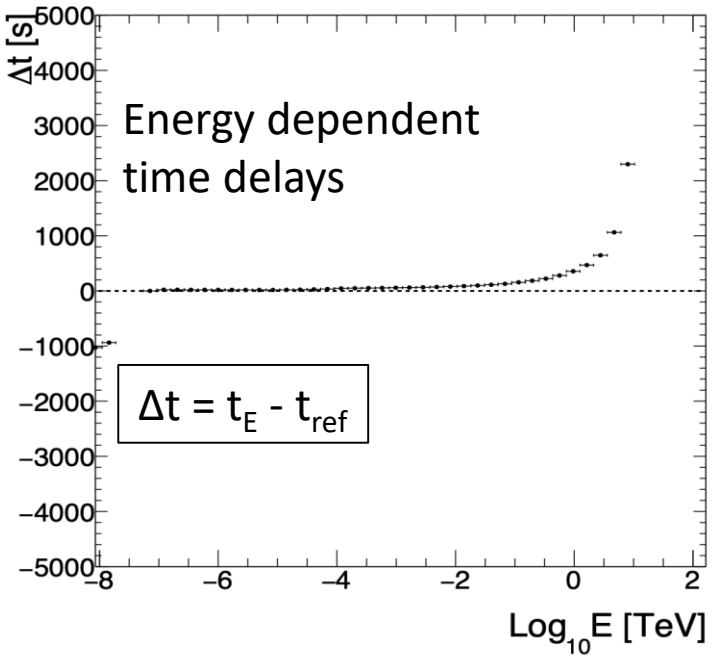
Adiabatic effect (expansion or compression of the blob of radius $R(t) = R_0 (t_0/t)^{-m_r}$)

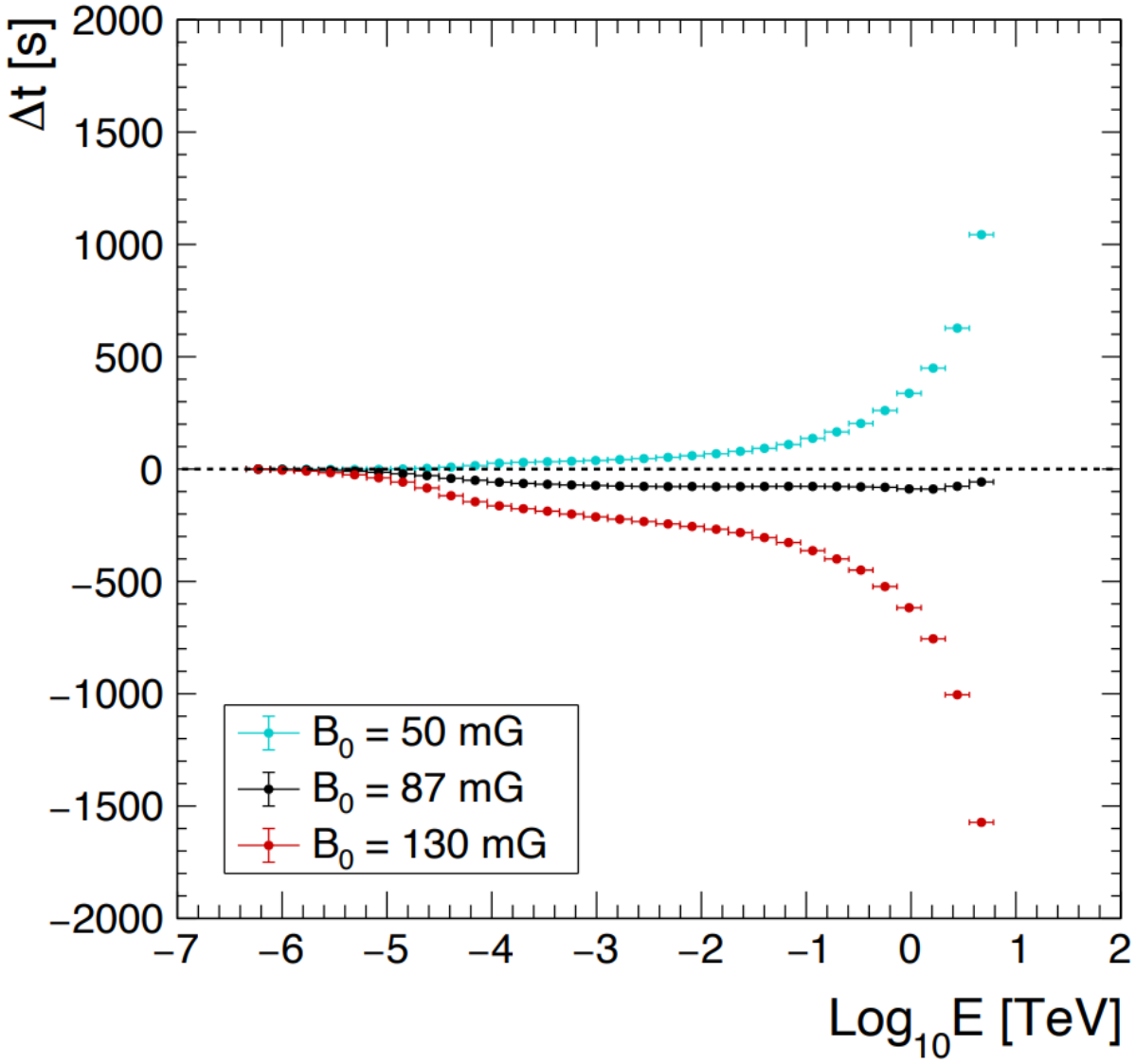






Normalized light curves
in various spectral ranges





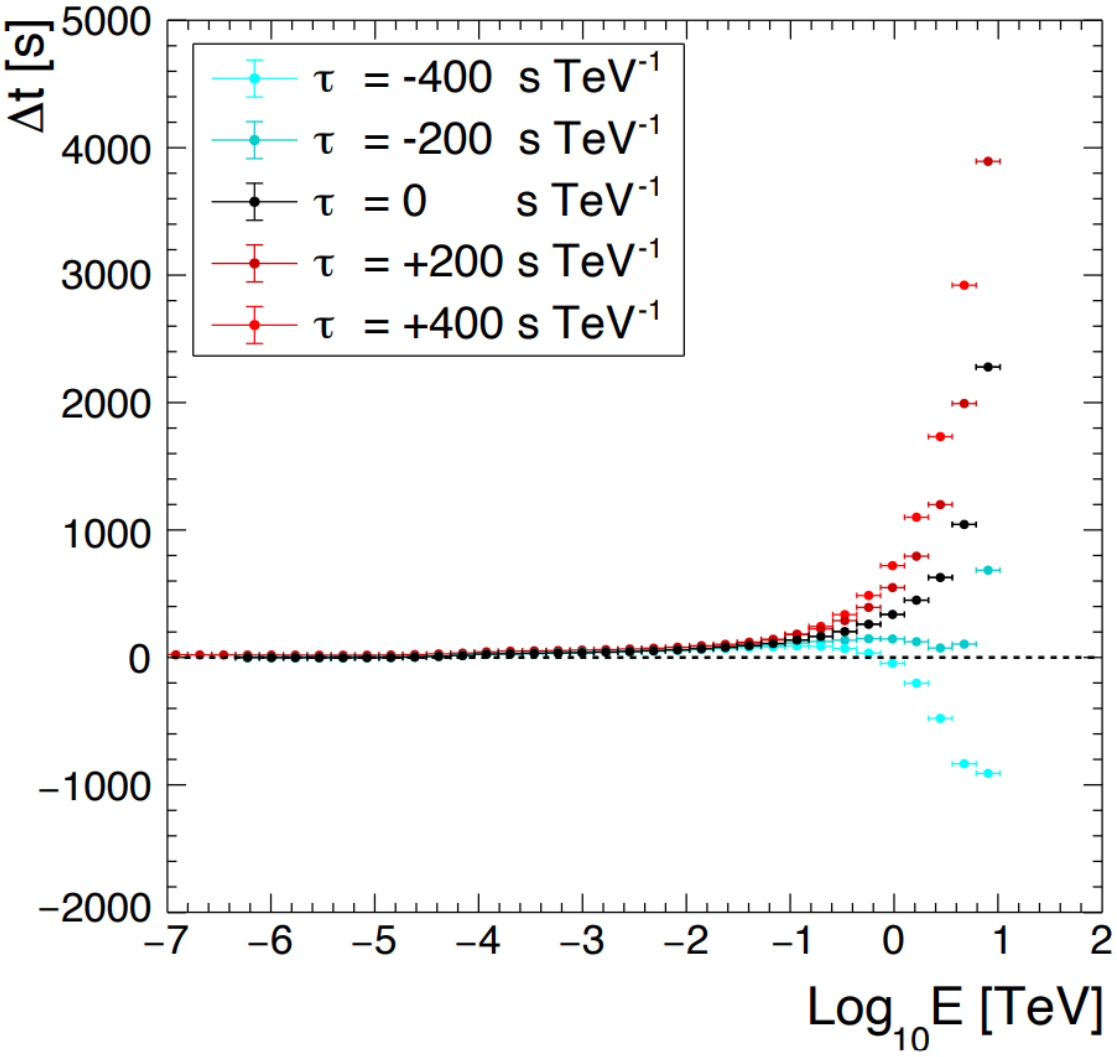
Significant intrinsic time delays at VHE!

2 regimes depending on physical parameters of the flare :

- « acceleration-driven » (increasing trend)
- « cooling-driven » (decreasing trend)

Resulting from the 'competition' between cooling and acceleration processes

	SSC parameters	Value	Unit
Redshift	z	0.03	-
Doppler boost	δ_b	40	-
Magnetic field strength	B_0	87	mG
Bulk radius	R_0	5×10^{15}	cm
Lepton density	N_0	300	cm^{-3}
Lorentz boost min	γ_{min}	2	-
Lorentz boost cut-off	γ_{cut}	4×10^4	-
Power law index	n	2.4	-
	Evolution parameters		
Acceleration strength	A_0	4.5×10^{-5}	s^{-1}
Acceleration evolution rate	m_a	5.6	-
Magnetic field evolution rate	m_b	1	-
Bulk radius evolution rate	m_r	0	-



Injection of LIV :

$t \rightarrow t + \tau E_{LC}$

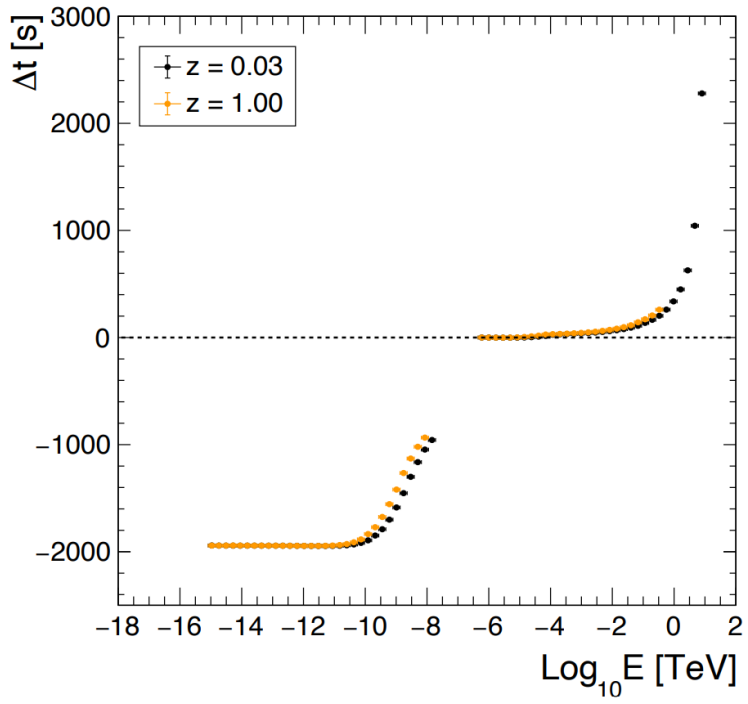
For the same intrinsic flare (in black), the resulting Δt then depends on the LIV value.

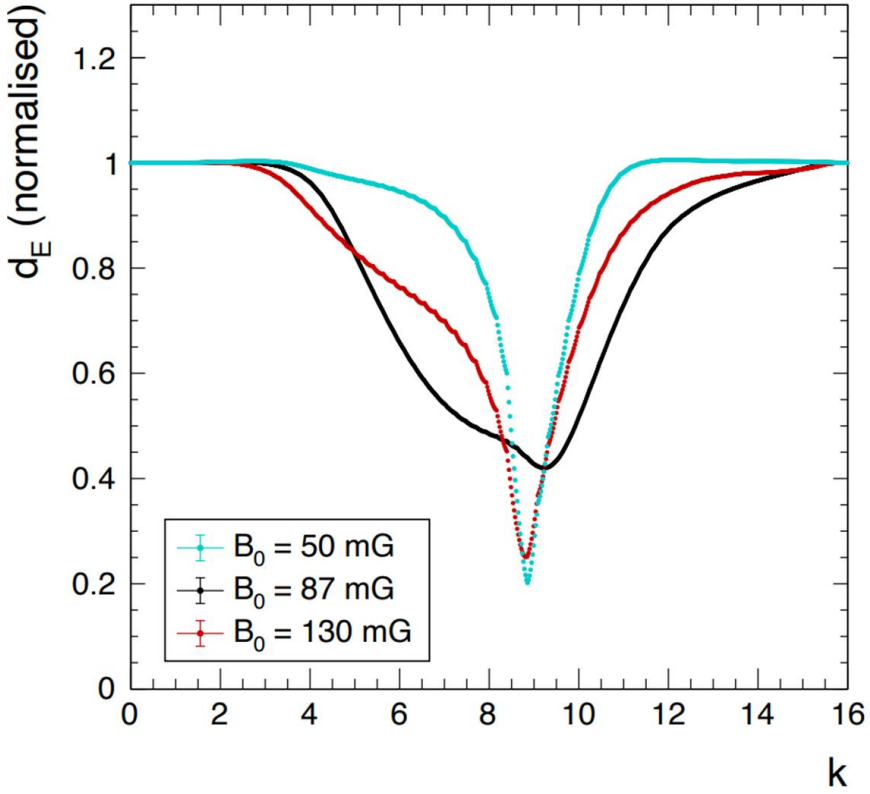
LIV can even change the observed trend of the delay, pushing it towards increasing or decreasing trend.

It therefore deeply modifies the expected VHE signal of SSC flares

How to discriminate between intrinsic and LIV delays?
Hereafter d_E and HID

Without LIV: High similarity between delays in X-rays and gamma-rays of SSC flares, quantified by values of the minimum of the **Euclidian distance d_E** between the two sets of points



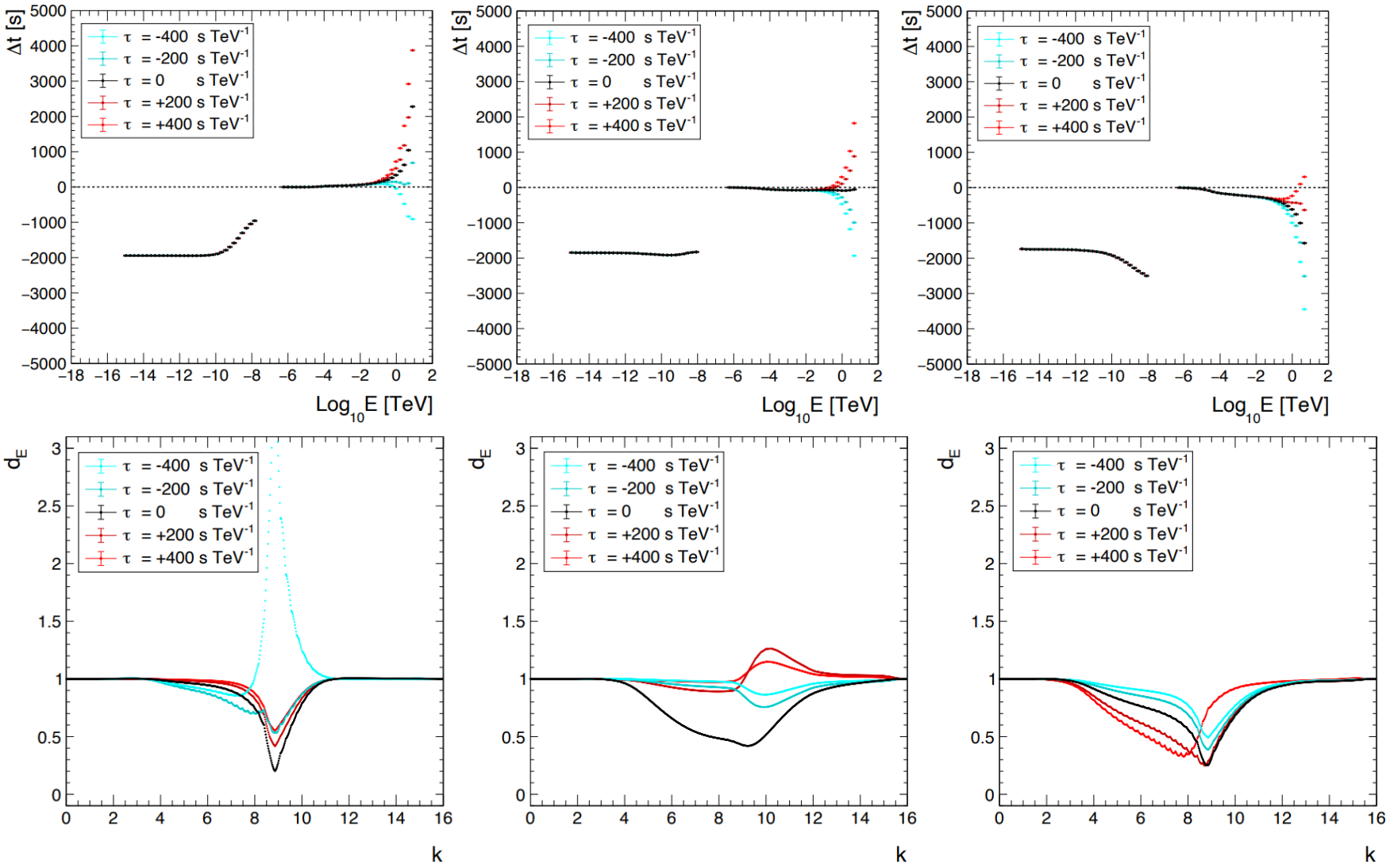


The d_E remains small for SSC flares, despite KN and EBL effects
For a large space of flare parameters, optimal k is always found between 8 and 10, and **minimum of d_E is always < 0.6**

$$d_E(k) = \frac{\sqrt{\sum_i (A[i-k] - B[i])^2}}{\sqrt{\sum_i (A[i-k] + B[i])^2}}$$

(10^k = displacement along E)

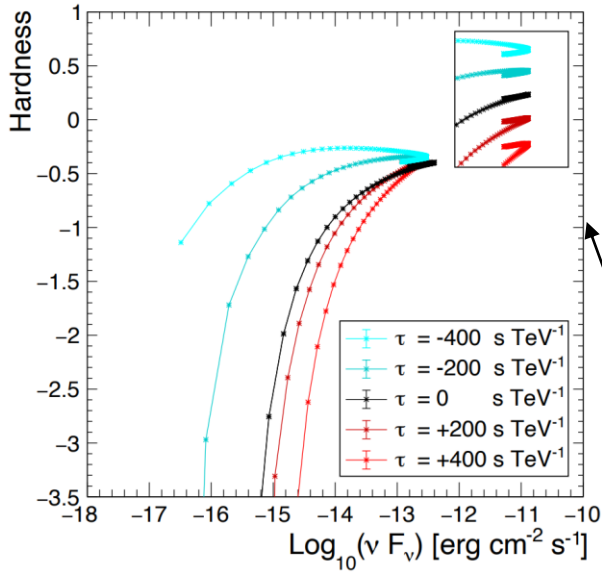
With LIV: the picture can be completely modified (for the 3 trends, increasing, flat and decreasing)



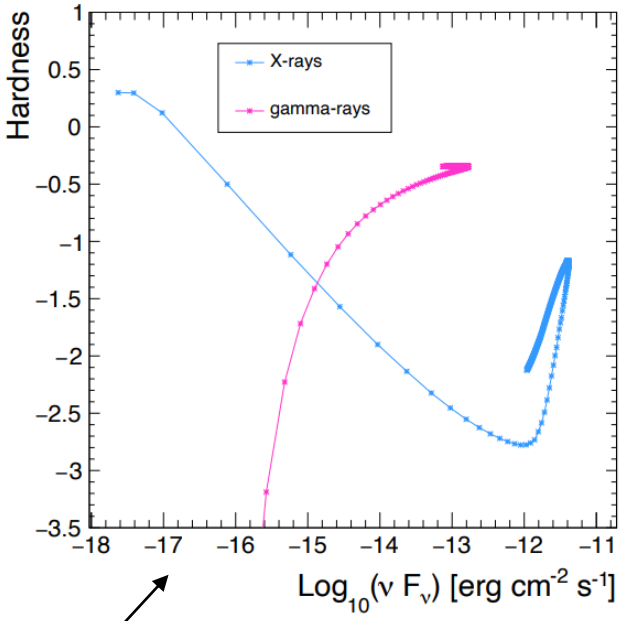
→ Detecting minimum of $d_E > 0.6$, or optimal $k < 8$ or > 10, would emphasize the presence of non-intrinsic effects possibly due to LIV.

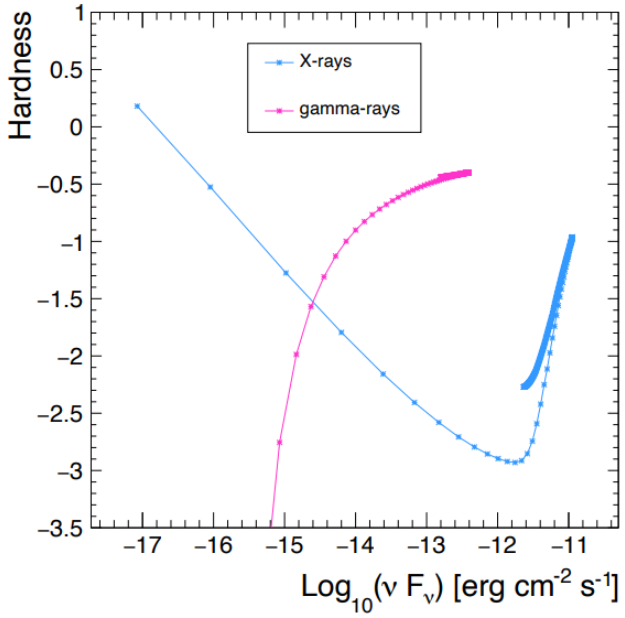
HID, Hardness-Intensity diagrams, explore hysteresis patterns during the flare evolution (rising and decreasing phases)

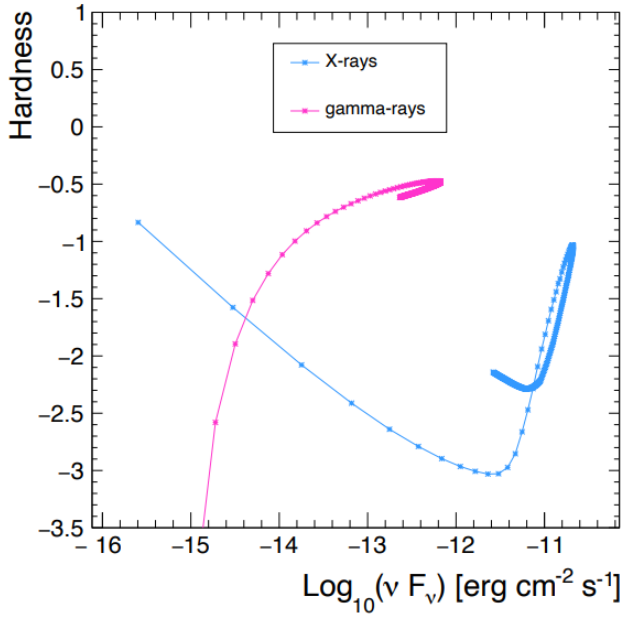
Allows us to analyze the degree of similarity between the two SED bumps in X-rays and VHE: shows the evolution of the SED index (hardness) as a function of the SED flux (intensity), computed over 2 windows with lower boundary at the position of the peak at the highest energies reached during the flare (with a width of 1 decade in energy)



Non-zero LIV:
modify the apparent evolution at VHE
Can change the direction of rotation

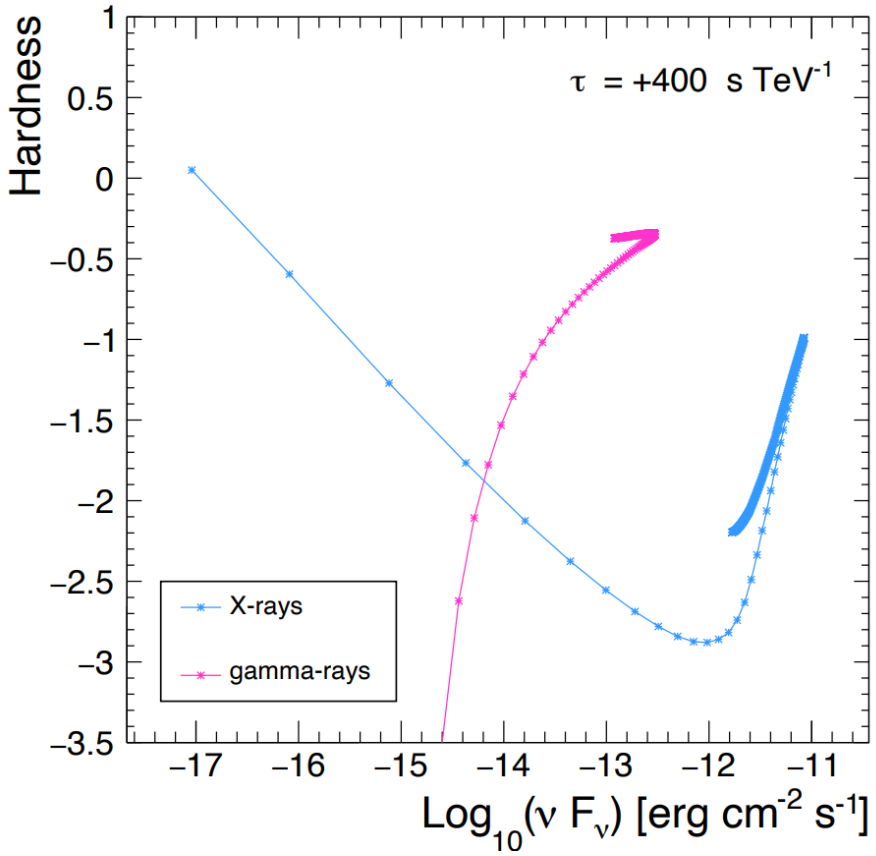


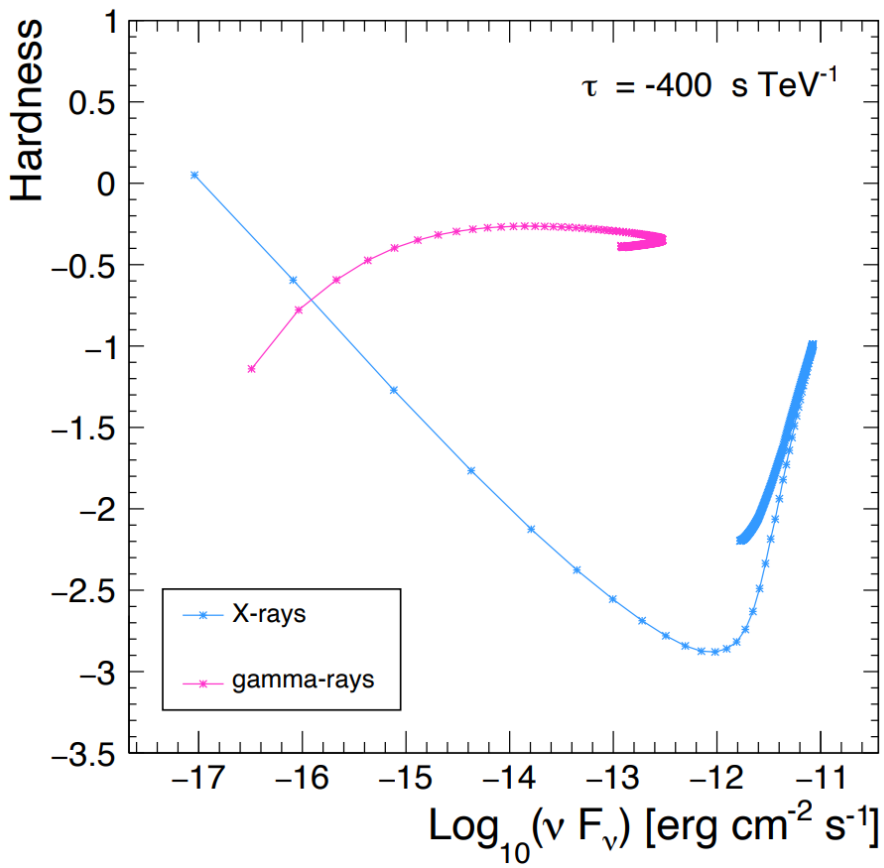




Without LIV: same direction of rotation at high fluxes in X-rays and VHE in the 2 regimes (and no hysteresis for flat trend)

With LIV: the previous SSC flare with « flat trend » and no hysteresis, now seen with two high values of LIV





The HID is unchanged by the LIV in X-rays as expected, but deeply modified at VHE!
In particular, the direction of rotation is reversed relatively to the X-rays for -400 s/TeV.

SSC flares without LIV can not show such opposite direction of rotation of their hysteresis

- For ‘basic’ AGN flare models with cooling and acceleration processes, two regimes appear for intrinsic delays at VHE:

  - « acceleration-driven » (increasing trend for Δt versus E)

  - and « cooling-driven » (decreasing trend for Δt versus E).

- For one-zone leptonic SSC scenarios: strong correlation and symmetry between intrinsic delays in X-rays (unaffected by LIV) and gamma-ray (where LIV effects could arise)

- ---> Euclidian distance d_E between delays in X-rays and in VHE, and hardness intensity diagrams (HID) in the two domains can inform on non-intrinsic delays possibly due to LIV, when such correlation is reduced or even lost.

- LIV can even change the apparent regime/trend of the flare and the direction of the hysteresis pattern shown by HID in gamma-rays

- ---> Detection of opposite direction of hysteresis patterns in X-rays and gamma-rays and/or measurements of $d_{E,min}$ values > 0.6 in SSC flares would sign the presence of non-intrinsic delays possibly due to LIV

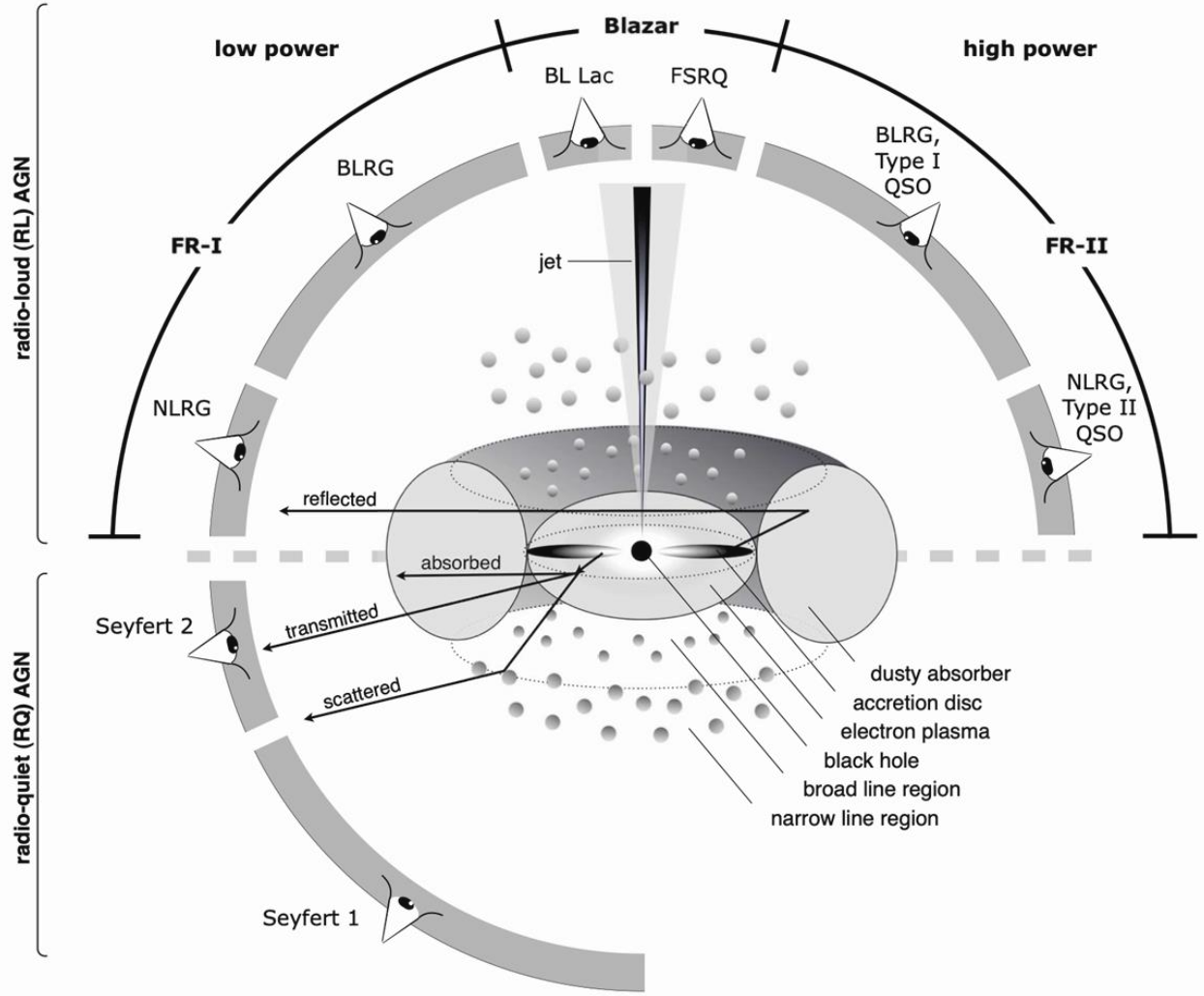
- No strong statistics on AGN flares up to now. However a majority of blazars flares (not all) seems to be in the « cooling-driven » regime. Then subluminal LIV effects with $\tau > 0$ (possibly the most « expected » ones from some theoretical points of view) oppose to the intrinsic trend of such flares, pushing them towards opposite « increasing trend », which can induce a significantly different observed signal

- Warning: EIC and adiabatic effects do not modify the general picture of intrinsic delays (with 2 regimes) but can reduce the intrinsic correlation between X-rays and gamma-rays

- --- > The cases of pure SSC flares from BL Lac intrinsically in the cooling regime presently appear as the best opportunity to catch a clue for a LIV signal in a blazar flare.

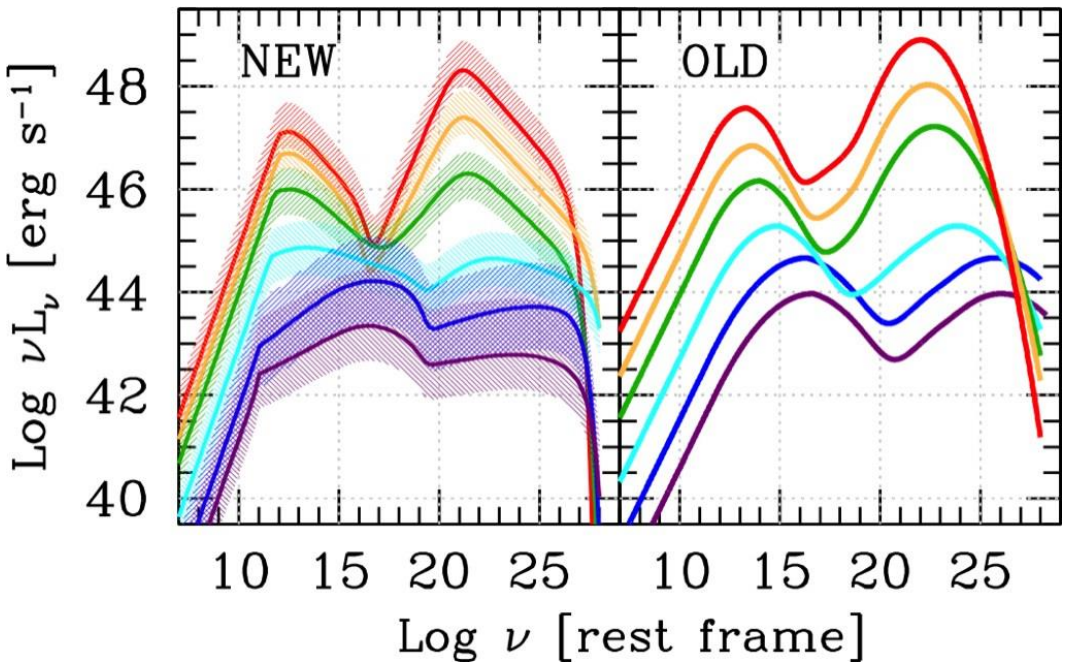
  (hopefully future MWL, polarized, and MM data should make it possible to identify cases of pure SSC flares quite well)

- *NB: another significant difference between intrinsic and LIV delays is that intrinsic ones vary during flares while LIV ones remain constant. But is that detectable?*



Blazar sequence

(average SED for gamma and radio groups)



- Several limitations of our current analysis - Extend to more complex/sophisticated leptonic scenarios (acceleration mechanisms), multi-zones, hadronic, lepto-hadronic, flares due to pure geometrical effects (with possibly small/negligible intrinsic delays), etc.

- Reconsider how to analyze data: remove the degeneracy between LIV and intrinsic delays by identifying the scenario (with and without LIV) which fits best the whole set of observable quantities, taking then also into account Δt, d_E and HID in X-rays and gamma-rays, in addition to spectra and light curves ...

- However, **first, check the feasibility of detection of intrinsic and possible LIV time delays and of the obtention of detailed data on flares in VHE!!** *(see Alberto's talk)*

- Plan simultaneous observations of blazar flares in X-rays and gamma-rays, with good spectral and temporal resolutions and coverage, at different redshifts to obtain a significant sample of blazar flare with high quality data. Several flares from the same source might be interesting (possibly different flare parameters but same LIV effect)

- Development of efficient alert networks, realtime analysis, data-driven detection techniques (deep learning, anomaly detection …) will play an important role for this research field

- Closely related to AGN flares studies … No future detection of delays could strongly constrain flare models ;)