Distinguishing between LIV and intrinsic spectral timelags in blazar flares

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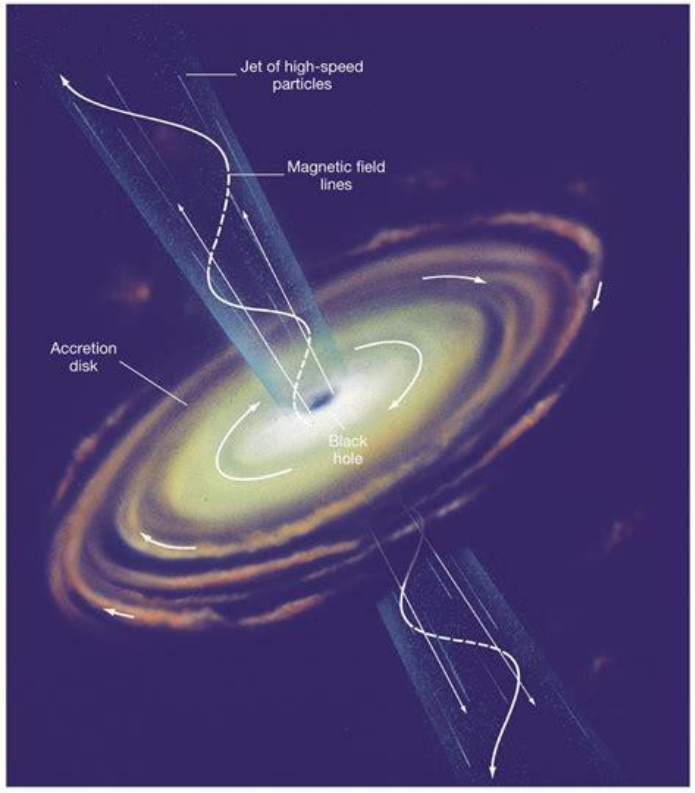
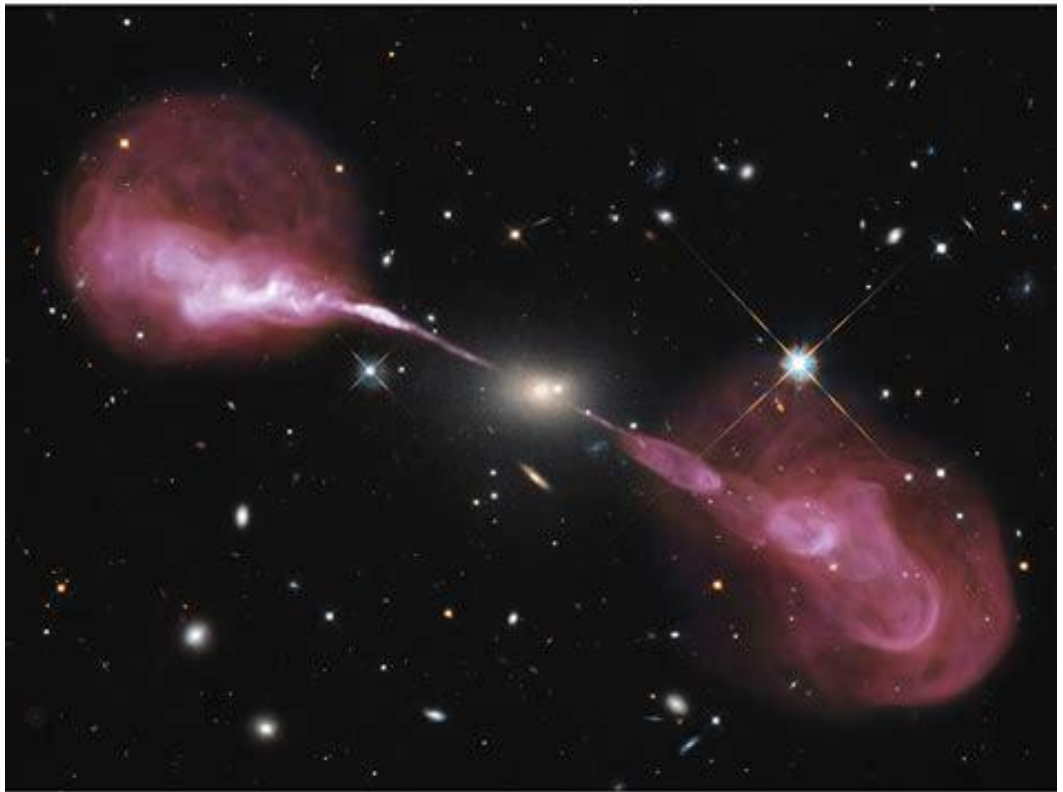
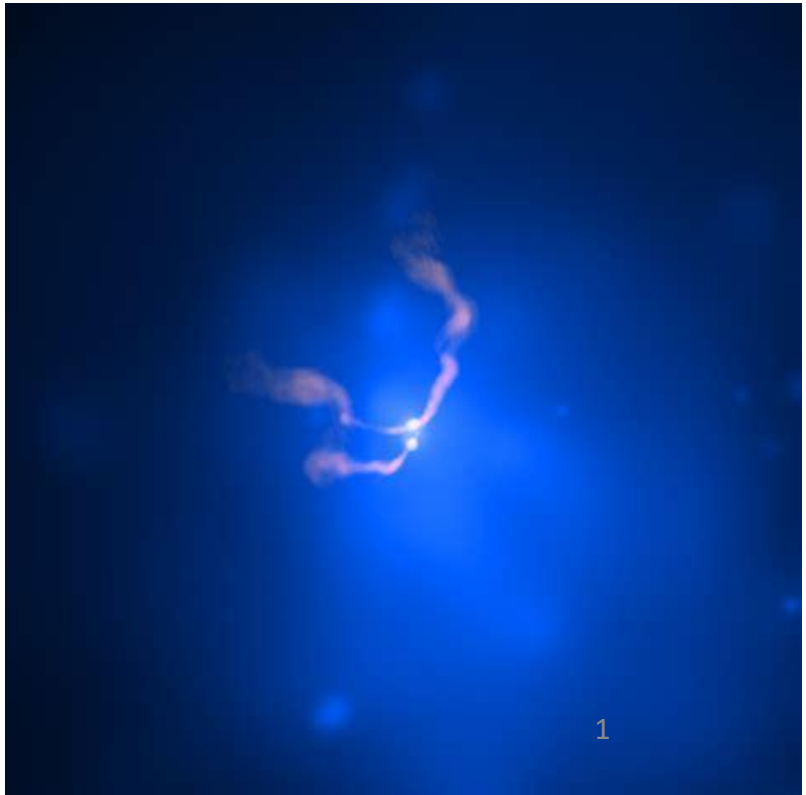
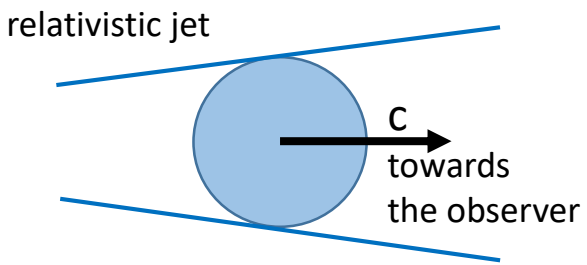
BridgeQG workshop: Bridging HE astrophysical modelling and LIV studies
Annecy, Feb 4-6, 2026







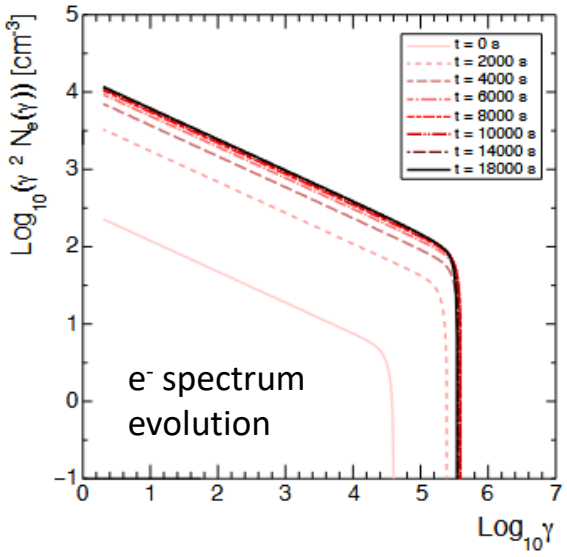
- Blazar flares : a large variety of scenarios --- > different possible origines for timelag in photon arrival times due to « in-situ » effects in the cosmic source
- Lags due to ‘macro’ physics: global geometry, extension of emitting TeV zone, multi-zones … (‘spatial shift’)
- Lags due to particle ‘micro’ physics: radiation mechanism in a compact zone (direct ‘time delay’) --- > typical flare triggered by in-situ particle acceleration and particle radiative cooling
- **Basic standard model**, rather successful at first order for many flares : Synchrotron-self Compton (SSC) [possibly + External-Compton (EC)] radiation from a compact single zone embedded in the jet - Widely used in literature

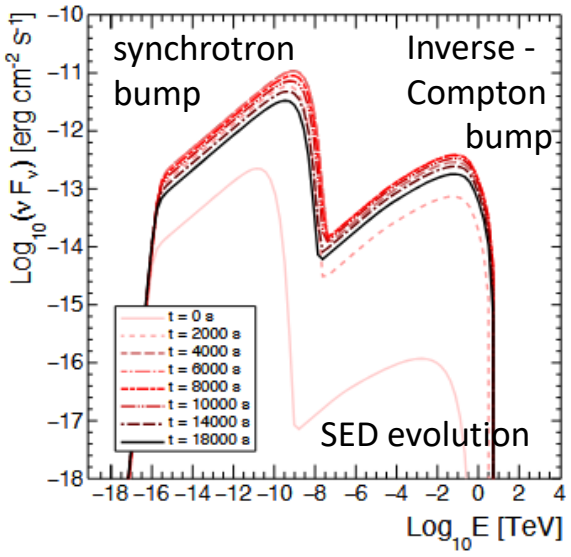


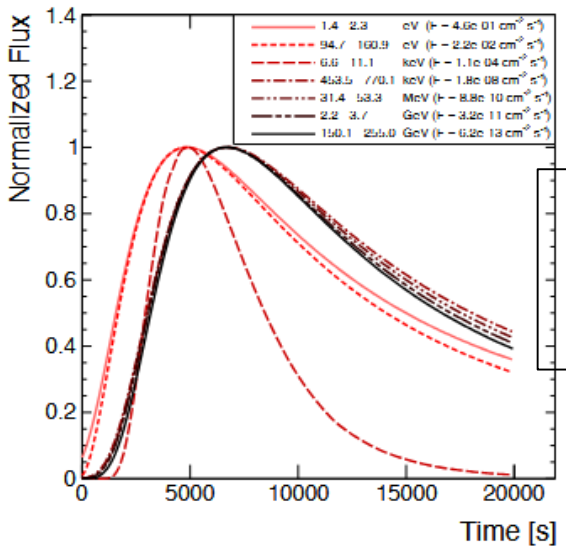
Kind of ‘minimal scenario’ for a flare : emitting zone, initial particle spectrum, acceleration and B evolution

- 3 ‘macro’ physics parameters: B magn field, R radius, δ Doppler factor (relativistic enhancement)
- 3 ‘micro’ physics parameters: N_0 density, γ_{cut_0} particle Lorentz factor, n index
- 3 ‘evolution’ parameters: amplitude and temporal evolution index of the acceleration process + temporal decay index of the B.

- Applying such SSC scenario *(Perennes, HS, Bolmont, 2020; Levy, HS, Bolmont, 2024)*







normalized light curves at different energies, showing 'peak-to-peak' Δt

First main results :

- Significant intrinsic Δt exist at TeV energies down to min scale for a rather large range of flare parameters *(Perennes et al, 2020)*
- Two regimes identified, with opposite signs of Δt
  - LE photons arriving first in the « acceleration-driven » regime
  - HE photons arriving first in the « cooling-driven » regime
- Feasibility studies of future detection with CTAO: such Δt appear to be detectable in bright flares, however this might not be very easy *(Rosales De Leon, Bolmont, HS, in preparation)*

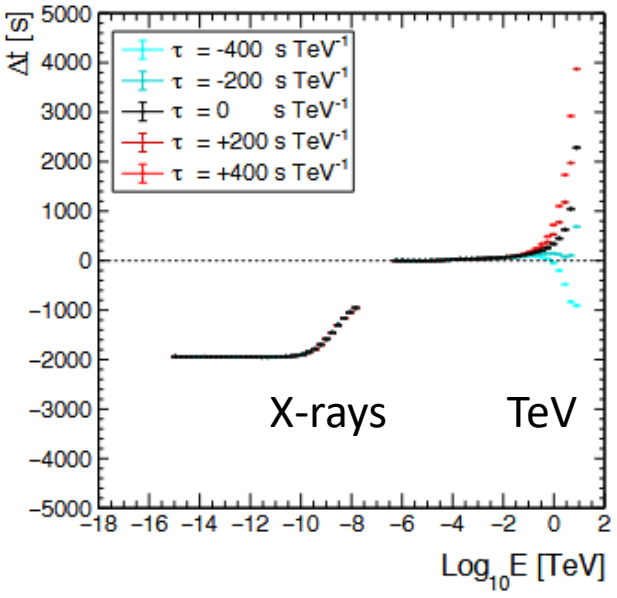
-- > could explain why no confirmed detection of Δt at VHE up to now (only 1 case in 2005, Mrk 501)

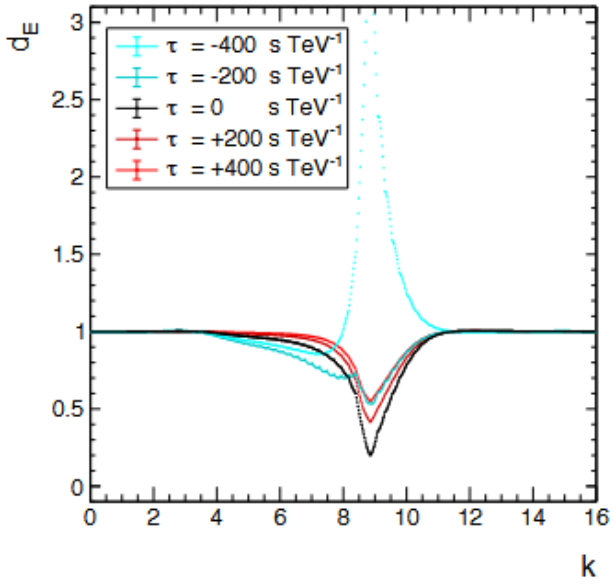
In case of Δt detection, how to distinguish between LIV and intrinsic SSC origin?

- **Proposal 1**: analyze the variation of Δt during the flare, since magnitude of intrinsic delays can vary in time along the flare, while LIV delays do not *(Perennes et al, 2020)*
  --- > interesting but not easy to achieve *(some hints in Ugo Pensec's PhD? 2025)*

- Explore other strategies, under various simplifying assumptions: standard physics without LIV to describe the flare « in situ », add LIV impacting only photon propagation along the line of sight, neglect Δt due to possible other propagation effects (dispersion by free e^-, non zero photon rest mass effects, gravitational potential integrated along the path …), explore a limited domain of flare parameters …

- Take advantage of an important property of SSC flare (+EC): high similarities between the two bumps of the SED (synchrotron bump and IC bump) and of their time evolution, and identify observables linked to such similarities, as for instance *(Levy et al, 2024)*:
- **Proposal 2**: Euclidian distance between the Δt (hopefully) detected in X-rays for the synchrotron bump, and in gamma-rays for the IC bump
- **Proposal 3**: hysteresis pattern during the flare, in the planes F_X- index and F_{gamma}-index





- Euclidean distance d_E quantifies the degree of similarity between the timelag versus energy curves at low (X-rays) and high (gamma-ray) energies

On figures: black = no LIV

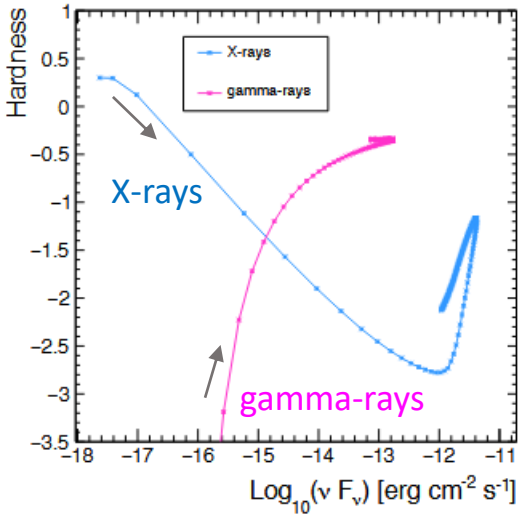
red = $\tau > 0$

blue = $\tau < 0$ (τ is the linear LIV term $\Delta t/\Delta E$)

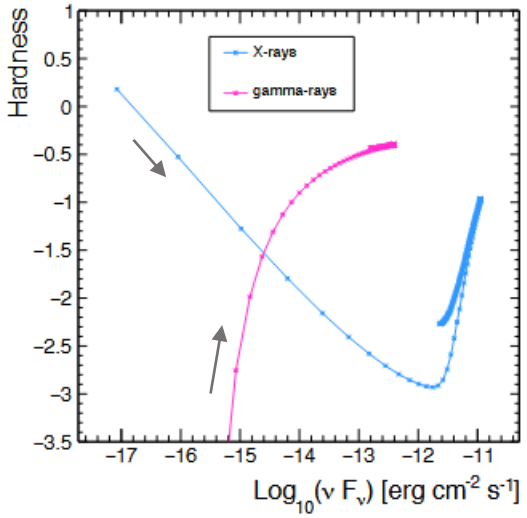
- The minimum of d_E as a function of the displacement k between the curves is always obtained for no LIV, for which the similarity is maximum. Simulations of several flares shows that pure SSC flares always have $d_{E,min} < 0.6$.

--- > measurement of large values of $d_{E,min}$ would indicate the influence of non-intrinsic delays (non zero LIV)

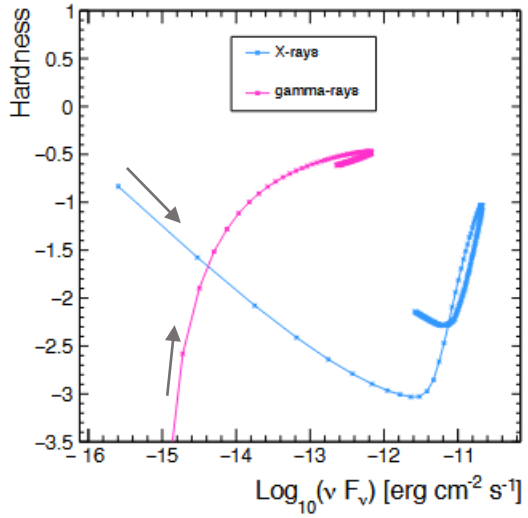
Hysteresis pattern: rising phase and decay phase of flares can follow different paths in the planes « flux » versus « spectral index » (or « hardness »)



SSC flare in acceleration-driven regime



SSC flare in « transition zone » with no significant intrinsic Δt



SSC flare in cooling-driven regime

For SSC flares with no LIV, the direction of rotation at the flare peak is always the same in X-rays and γ-rays

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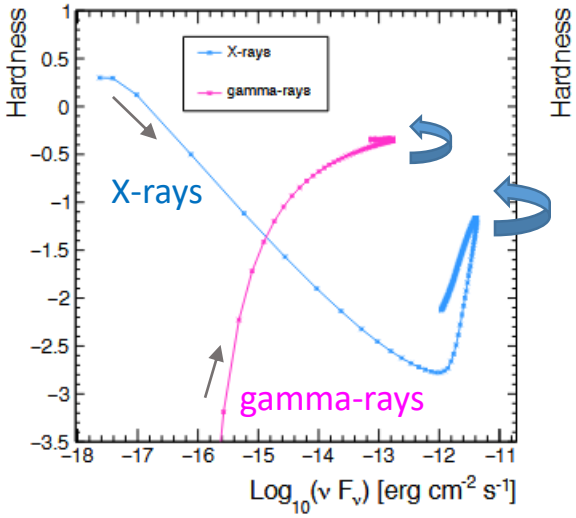
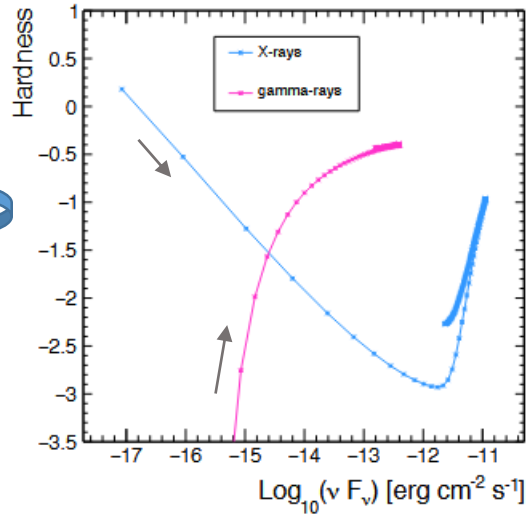


SSC flare in acceleration-driven regime



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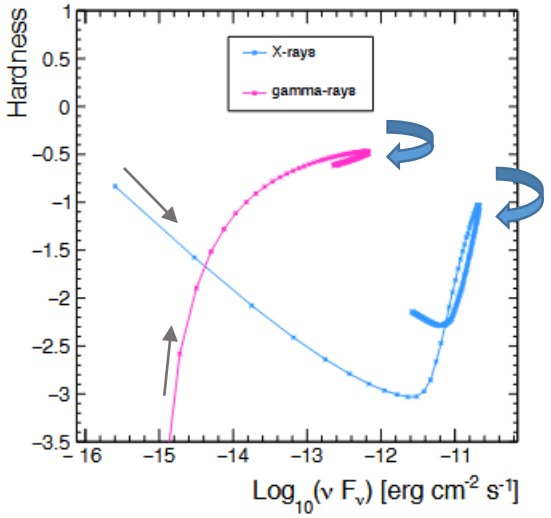

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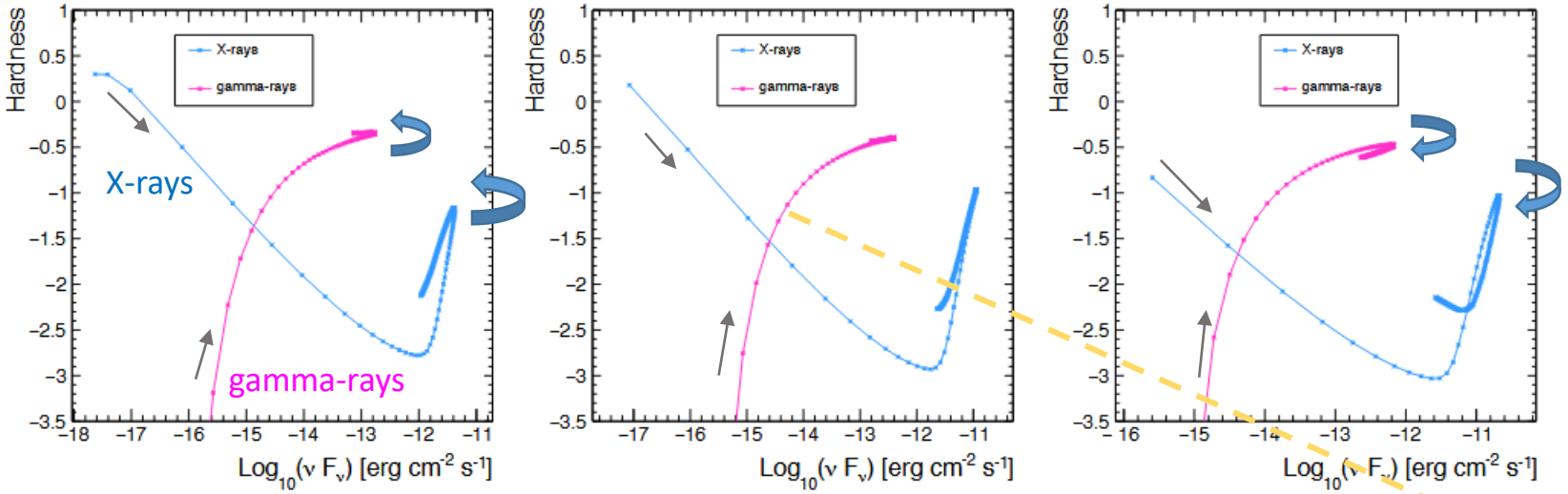
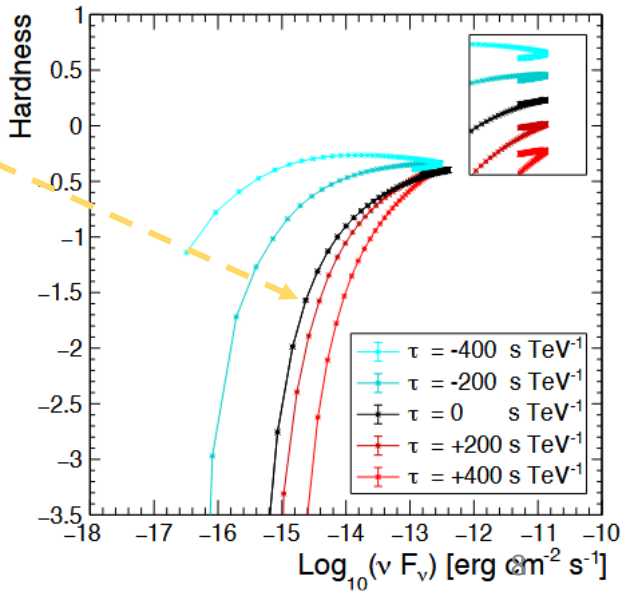


SSC flare in acceleration-driven regime

SSC flare in « transition zone » with no significant intrinsic Δt

SSC flare in cooling-driven regime

Adding non–zero LIV completely modifies the direction of rotation in γ-rays, while X-rays remain the same



For SSC flares with no LIV, the direction of rotation at the flare peak is always the same in X-rays and γ-rays

- Large values of Euclidean distances and opposite direction of rotation in hysteresis pattern for simultaneous X-rays and gamma-ray flare data appear as rather strong signatures for the presence of non-intrinsic delay, namely non-zero LIV under our various symplifying assumptions

- These two techniques are complementary: d_E analyses mostly light curves and could apply to flares with multiple peaks, while hysteresis requires *measurement of spectral index* and applies mainly to bright single flares
- However, both methods require *very high quality and simultaneous data* to achieve such deep analysis ; and also require to *catch the rising phase!* (alert strategies or monitoring?)
- Need to know by other means (optical data, soft γ-rays, polarisation, multi-messenger …) that the intrinsic flare is really SSC (+EC) - Best hope: BL Lac flares (HBL)

- **Proposal 4**: given the above difficulties and uncertainties, large samples of flares needed to confirm any potential first detection hints

  --- > increase statistics, examine redshift dependency !...

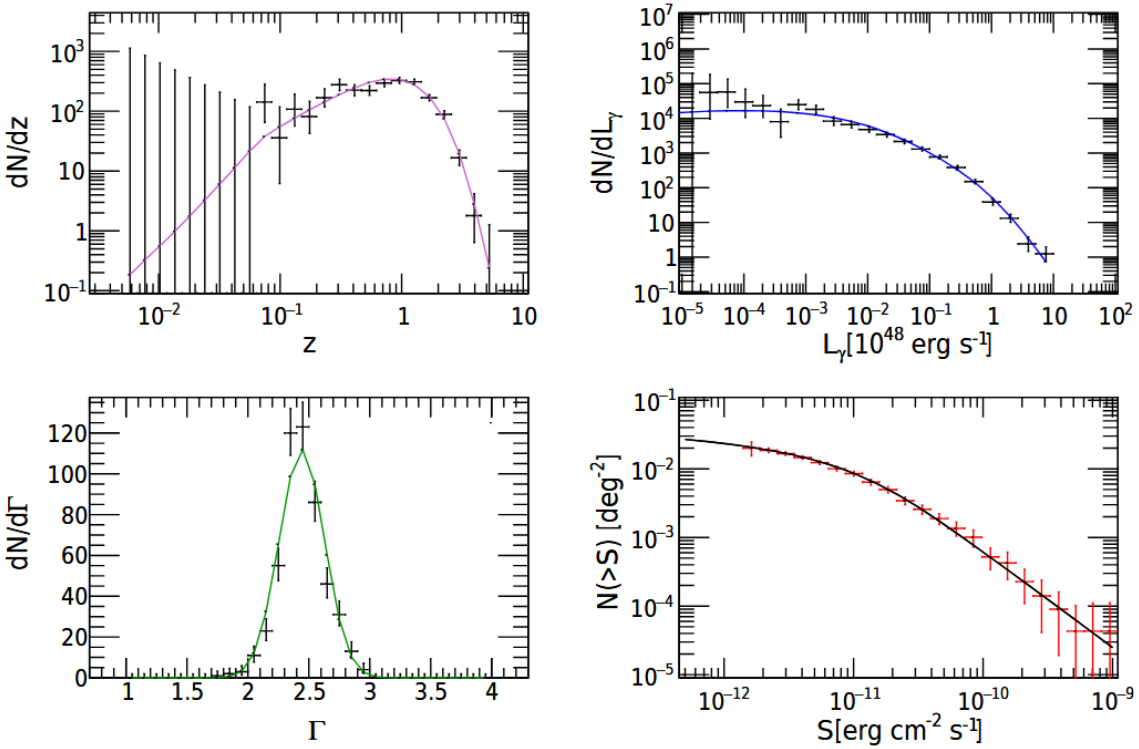
Some caveats

- The ‘flare data set’ still very poor, but a majority of well observed flares appears to be in the « cooling-driven » regime ---> possible systematic trend not cancelled by increasing statistics
- Redshift dependency: interesting in the frame of Jacob-Piran model, but quite complex with the variety of alternative models
- Moreover, populations of quasars and blazars show a cosmological evolution:

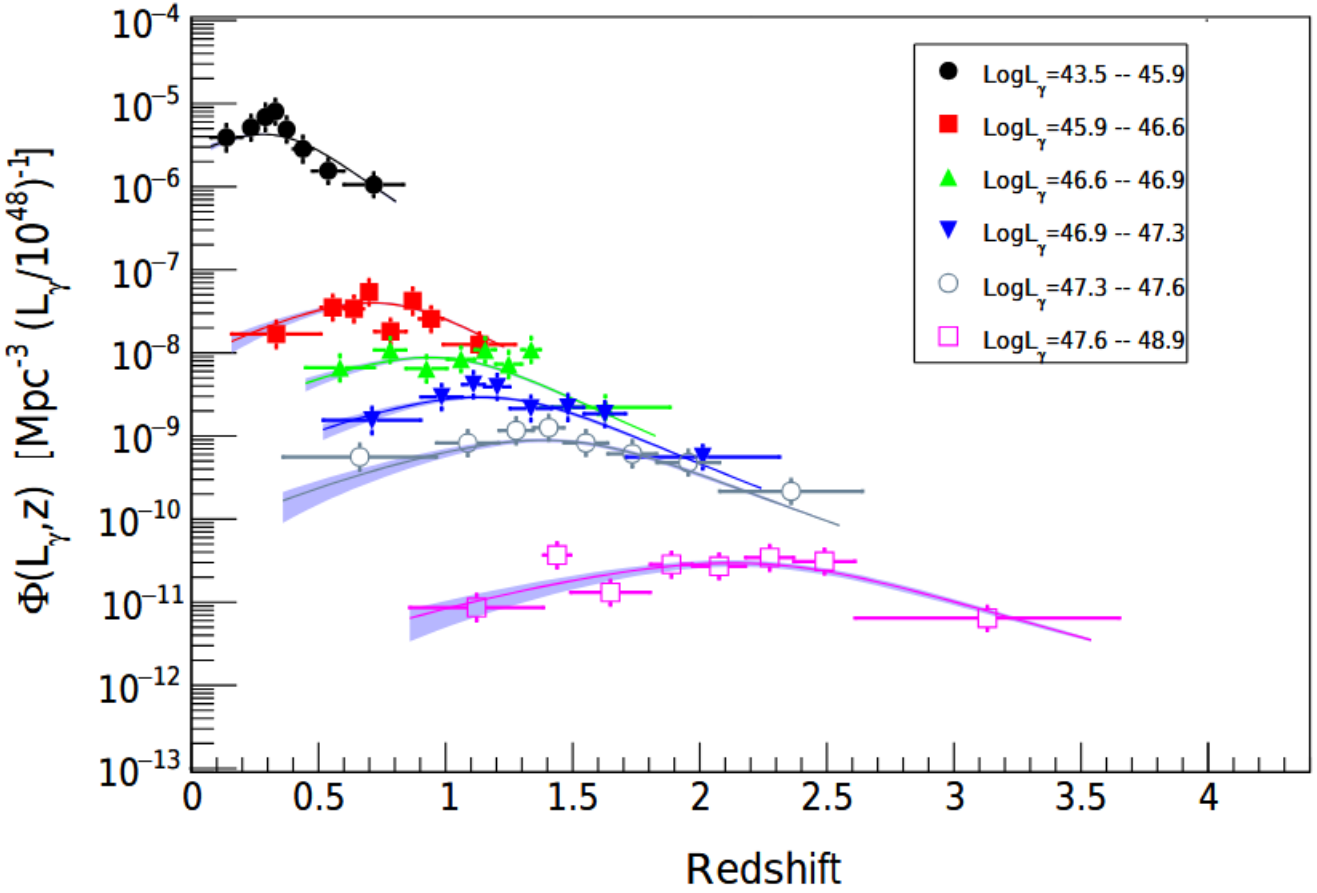
  - formation of SMBH at high z,
  - then at lower z quasars appear more active in dense environments (clusters of galaxies, interaction of galaxies, merger of galaxies …), i.e. for higher accretion rate,
  - feedback effects of AGN on their environment (heating, outflow: reduce star formation…) --- > self-regulation of activity

  --- > Existence of a peak in z of quasar and blazar space densities

Observed redhift, luminosity, photon index, + cumulative source count distribution of 519 Fermi/LAT FSRQs: *(Rajguru et al, ApJ, 2025)*



Number density of FSRQs as a function of z in L_γ intervals:

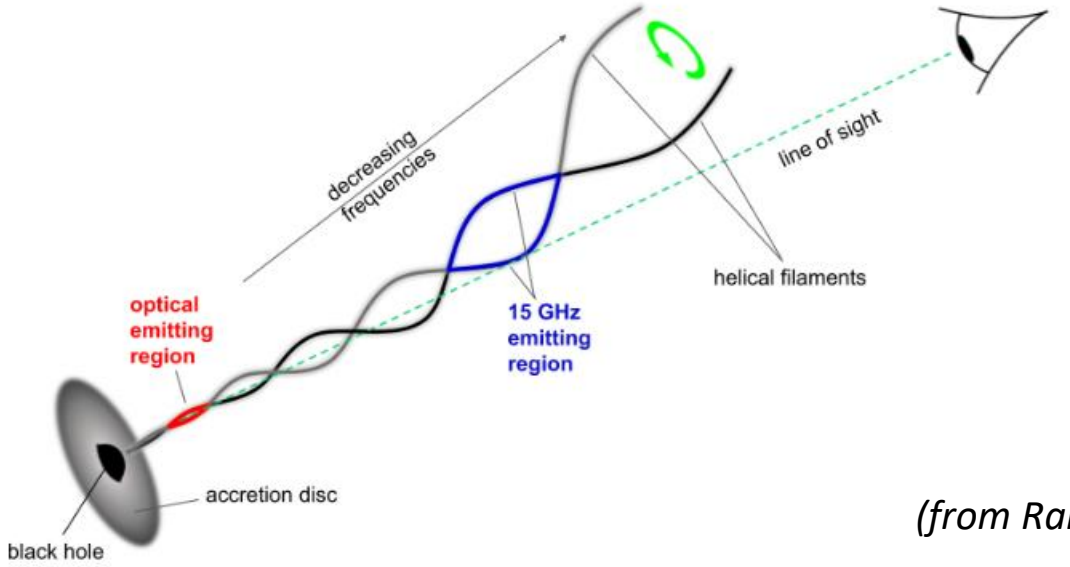


- Variation of number of sources with redshift, also dependent on gamma-ray luminosity
- Cosmological evolution of FSRQs with z (similar trend also for BL Lacs)
- Such global activity evolution might as well induce some evolution with z of flare properties !

Some wayout from such complexity?

- Back to the variety of flare scenarios?
- **Proposal 5**: consider an alternative purely geometric/kinematic scenario for flares based on a lighthouse effect, perhaps even simpler than standard SSC models
- Specific models: primalery proposed for AGN showing quasi-periodicities in their fluxes, quasi-periodicities attributed to a helical jet or a wiggling 'blob' trajectory

--- > variation in viewing angle and Doppler factor δ, which directly induces the flares by enhanced Doppler boosting as $F_\nu(t)$ varies as $\approx \delta^{2+\alpha}(t)$ *(α, spectral index ≈ 2 in optical and γ)*

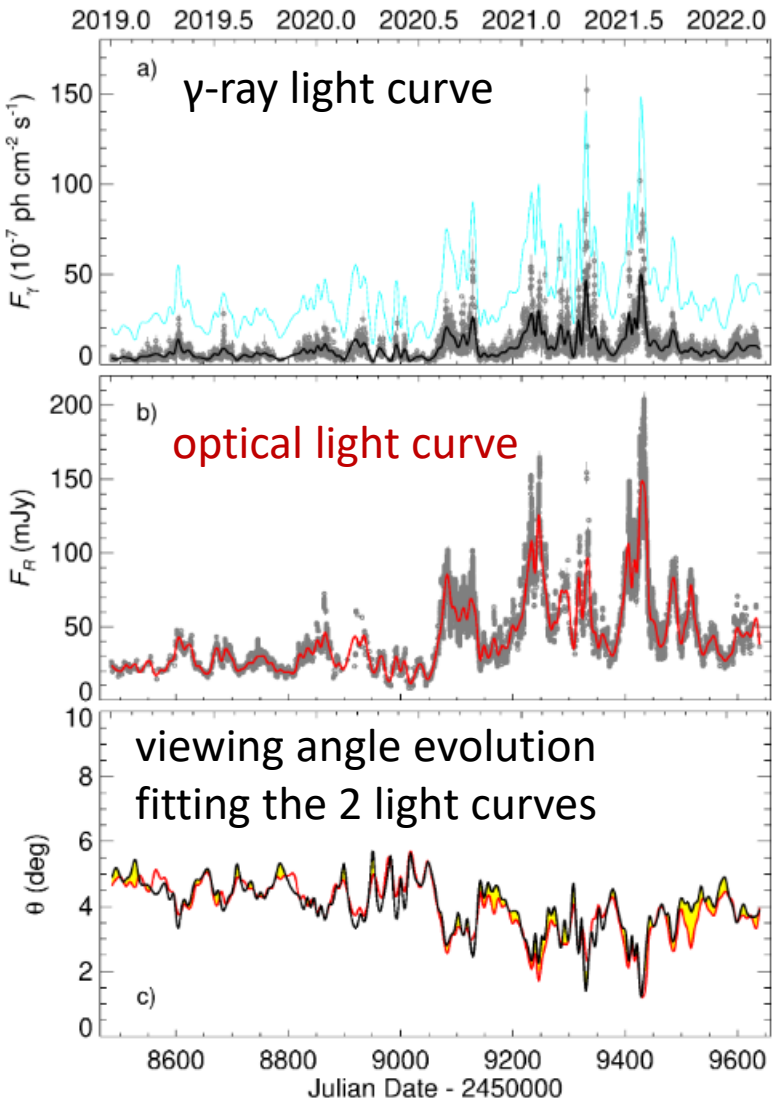


$$\delta = [\Gamma(1 - \beta \cos\theta)]^{-1}$$

θ = viewing angle

(from Raiteri et al, A&A, 2024)

BL Lac 2019-2022

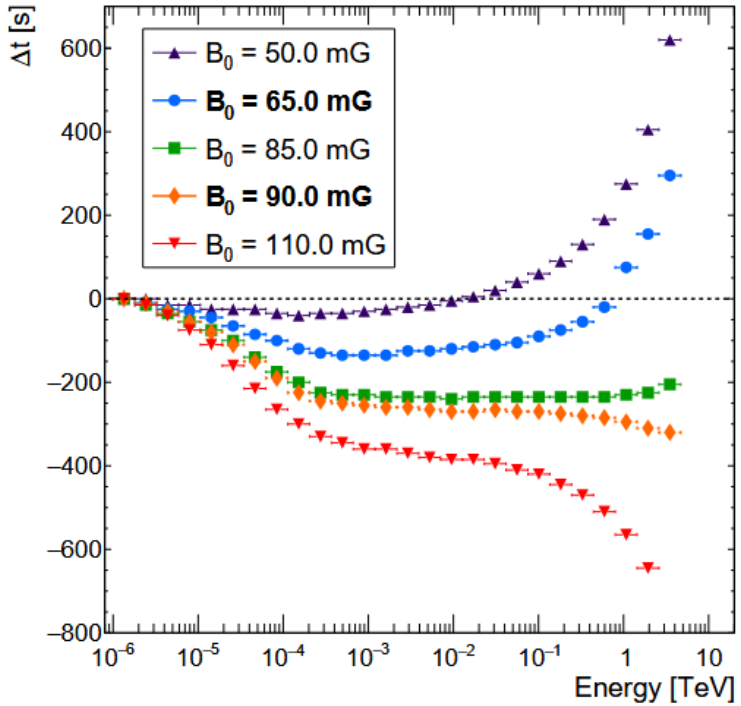


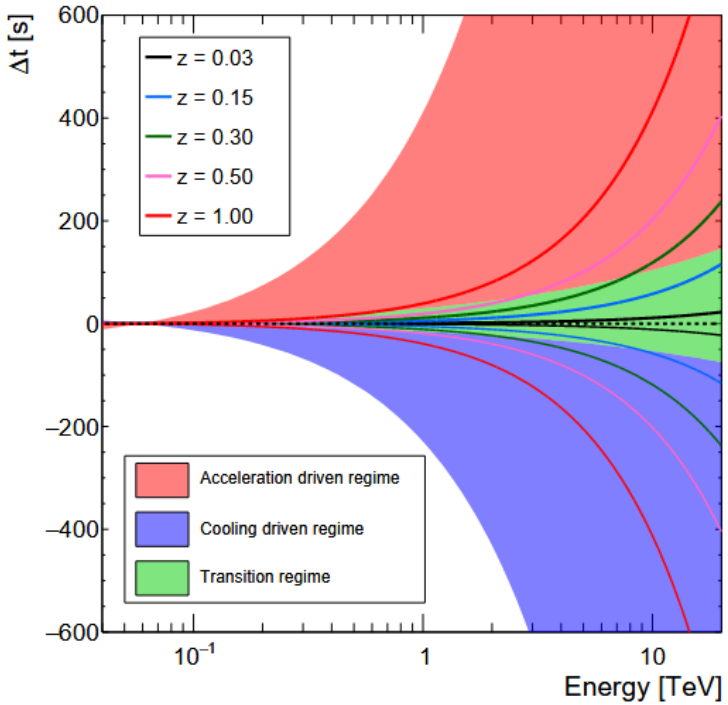
(Raiteri et al, 2024)

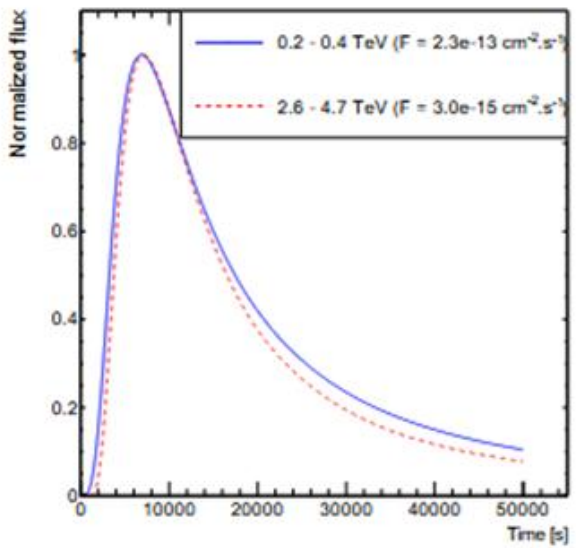
- Helicity and/or twisting can be triggered by several phenomena:
  - binary central BH and their orbital motion,
  - precession of BH axis *(BH behave like a gyroscope)*,
  - magnetic structure,
  - growth of instabilities along jet …
- Various timescales, depending on the origin of the twisting
- Periodicities or quasi periodicities might help to catch flares, because alerts become partially predictible!
- Pure kinematic description at 1st order: avoid having to treat complex time dependent micro plasma physics, and especially the need to describe flare generation with LIV effects included for self-consistency

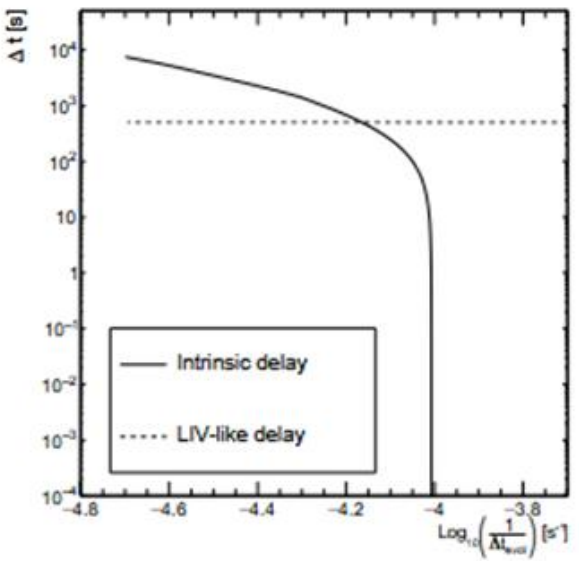
Could be a promising strategy at a first glance, despite the limited number of quasiperiodic blazars at VHE. But requires further investigation on relative importance of related intrinsic Δt.

(Conversely, including LIV effects in SSC flare generation modifies charged particles and photon production in sources: can generate additional VHE and UHE components in spectra, which could provide new contraints on LIV – cf Duarte & de Souza, 2025)


Δt [s]
B0 = 50.0 mG
B0 = 65.0 mG
B0 = 85.0 mG
B0 = 90.0 mG
B0 = 110.0 mG
Energy [TeV]


Δt [s]
z = 0.03
z = 0.15
z = 0.30
z = 0.50
z = 1.00
Acceleration driven regime
Cooling driven regime
Transition regime
Energy [TeV]


Normalized flux
0.2 - 0.4 TeV (F = 2.3e-13 cm⁻².s⁻¹)
2.6 - 4.7 TeV (F = 3.0e-15 cm⁻².s⁻¹)
Time [s]


Δ t [s]
Intrinsic delay
LIV-like delay