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J. BOLMONT - LPNHE - PARIS

SOURCE-INTRINSIC ENERGY DEPENDENT TIME-DELAYS IN AGNS AND SEARCH FOR LORENTZ INVARIANCE VIOLATION

WORK DONE IN COLLABORATION WITH H. SOL (LUTH - MEUDON), C. LEVY (LPNHE/LUTH), U. PENSEC (LPNHE/LUTH), A. ROSALES DE LEON (LPNHE/LUTH)

SORBONNE UNIVERSITÉ

LPNHE PARIS

CNRS IN2P3 Les deux infinis

Rijeka - COST Conference
July 10-14, 2023

OUTLINE

- LIV searches and intrinsic time delays
- How we deal with source-intrinsic effects in LIV searches
- The most promising approaches
  - Population studies
  - Understanding the sources
    - A step towards discrimination between LIV and source intrinsic effects in blazar flares
- Conclusions

FOCUS ON HIGH AND VERY HIGH ENERGIES

DELAY DUE TO LORENTZ INVARIANCE VIOLATION

- **The delay is due to the quantum nature of spacetime at the Planck scale**
- Expression of the time-lag between two photons emitted at the same time at redshift z, for a linear LIV:

ΔE

$$\Delta t_{\rm LIV} = \frac{E_h - E_l}{E_{\rm QG}} \int_0^{z'} \frac{(1+z')dz'}{H(z')}$$

INCREASE WITH DISTANCE

with $H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$

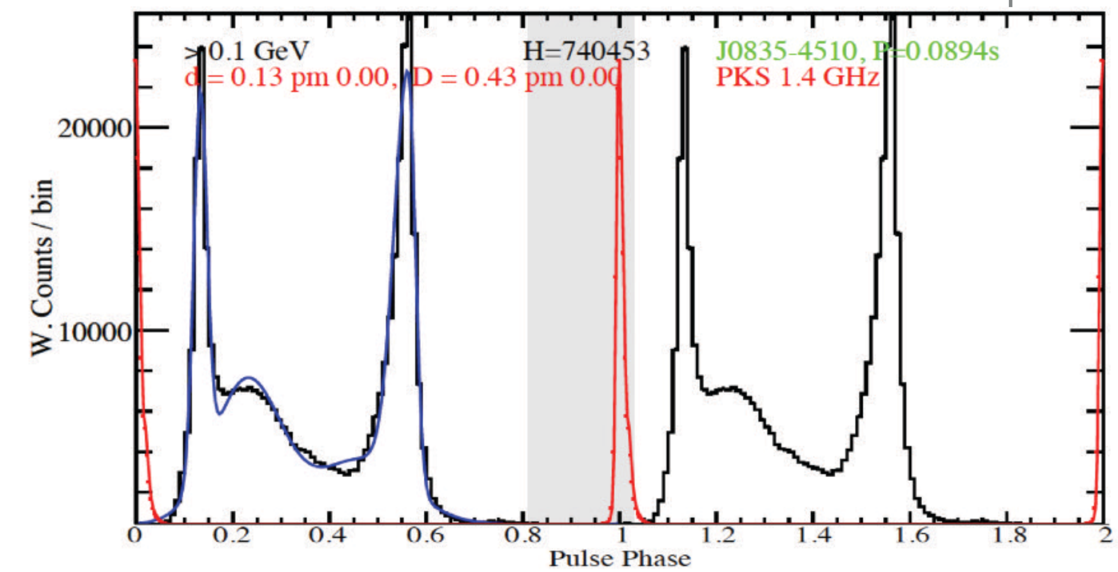
- Universe expansion is taken into account, here in the case of an explicit LIV (Jacob & Piran 2008)
  - Other models have a different redshift dependence (e.g. Rosati et al. 2015, Pfeifer 2018…)

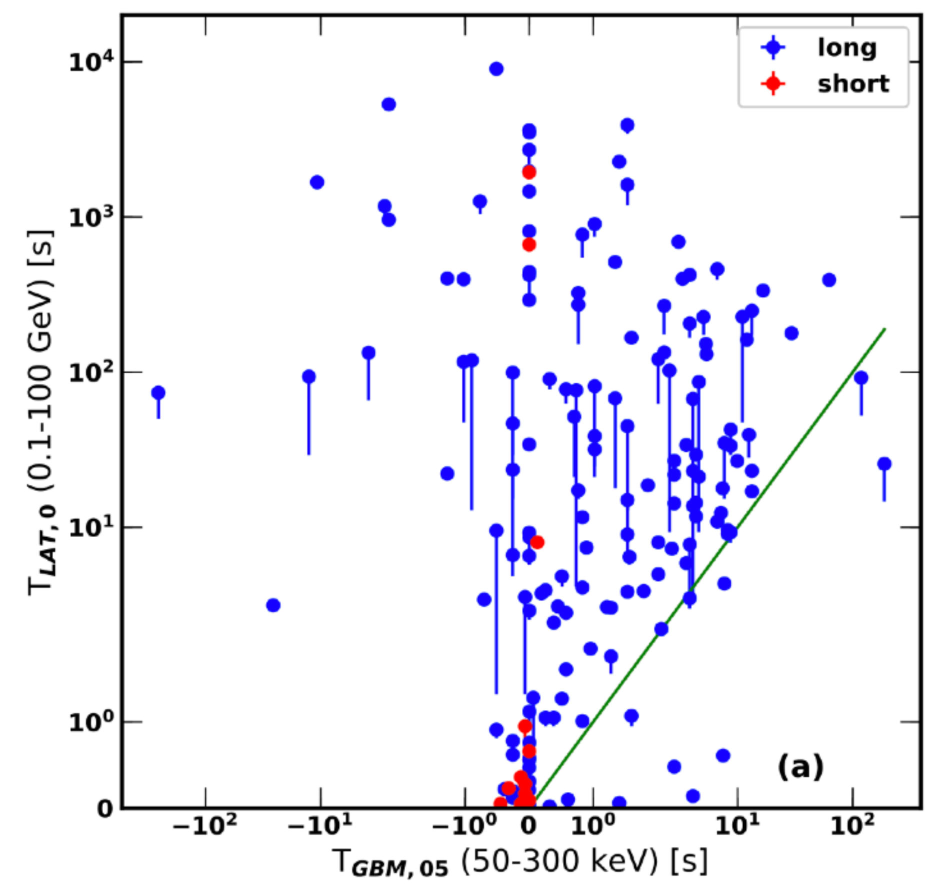
A KEY POINT: THE LAG DEPENDS ON THE DISTANCE

SOURCE INTRINSIC EFFECTS

- **Delays due to emission and acceleration mechanisms at the source**
- These effects show up for all types of sources used in LIV searches
  - Pulsars
  - Gamma-ray bursts
    - Ajello et al. 2019: « when high-energy emission is observed in GRBs, this emission is delayed and lasts longer compared to that in the low-energy band »
  - AGN Flares
    - Only one case with a significant lag measured at TeV energies

Vela pulsar



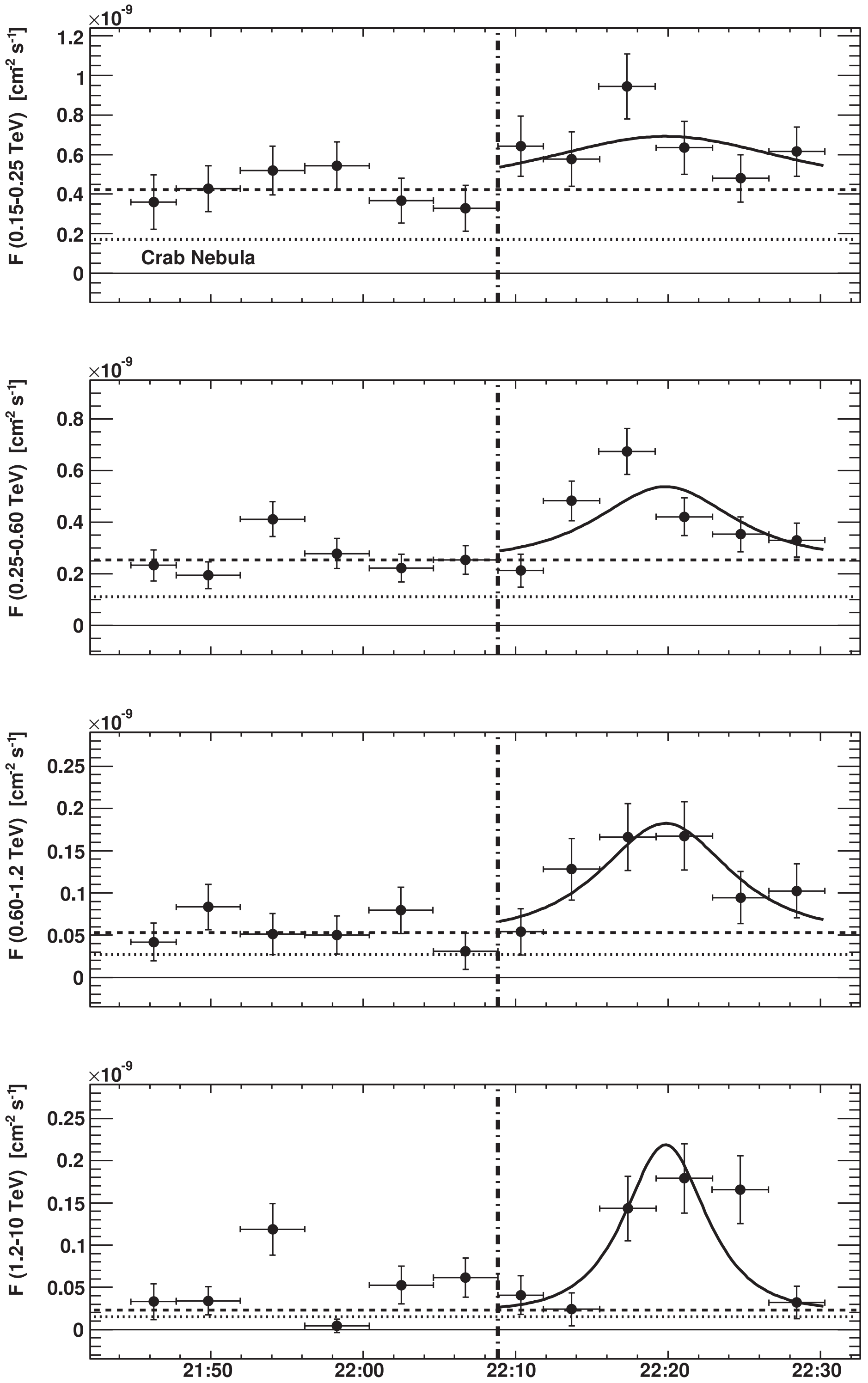


A KEY POINT: THE LAG SHOULD NOT DEPEND ON THE DISTANCE

MRK 501 FLARE SEEN BY MAGIC IN 2005

- ~20 minute long flare on July 9, ~1500 photons, z = 0.034
- Negligible background
- **Lag of 4±1 min** measured between < 250 GeV and >1.2 TeV
  - Confirmed with 2 methods: MAGIC 2008, Martinez & Errando 2009
- τ_1 = (0.030±0.012) s/GeV, and $E_{QG,1} = 0.30^{+0.24}_{-0.10} \times 10^{18}$ GeV
  - **Finally interpreted as a source intrinsic effect**

Flare of Mkn 501 (MAGIC), Albert et al. (2007)



Lag of 4±1 min (< 250 GeV, >1.2 TeV). Confirmed with two methods. Albert et al. 2008, Martinez & Errando 2009

HOW TO DEAL WITH SOURCE INTRINSIC EFFECTS IN LIV SEARCHES?

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

- **Several methods were used in the past**:
  - Neglect intrinsic effects
  - Population studies (at low energies + GRBs only)
  - Conservative modeling (see Vasileiou et al. 2013)
- In the future, **we need to focus on**:
  - Multi-source population studies at TeV energies (see Bolmont et al. 2022)
  - Full modeling of the sources, with a focus on studying source intrinsic effects (for AGNs: Perennes et al. 2020, Levy et al. in prep.)

NEGLECTING SOURCE INTRINSIC EFFECTS

- **Done in all LIV studies using only one source**
- It sounds bad, but…
  - All LIV studies were performed in a « small » energy range
    - Only one acceleration mechanism at play at the source (e.g. blazars in the TeV range → Inverse Compton)
  - No significant lag was measured in any LIV analysis. (Except for Mkn 501 flare of 2005)

- But reducing the energy range results in a decrease of sensitivity to LIV…

POPULATION STUDIES (GRBS ONLY)

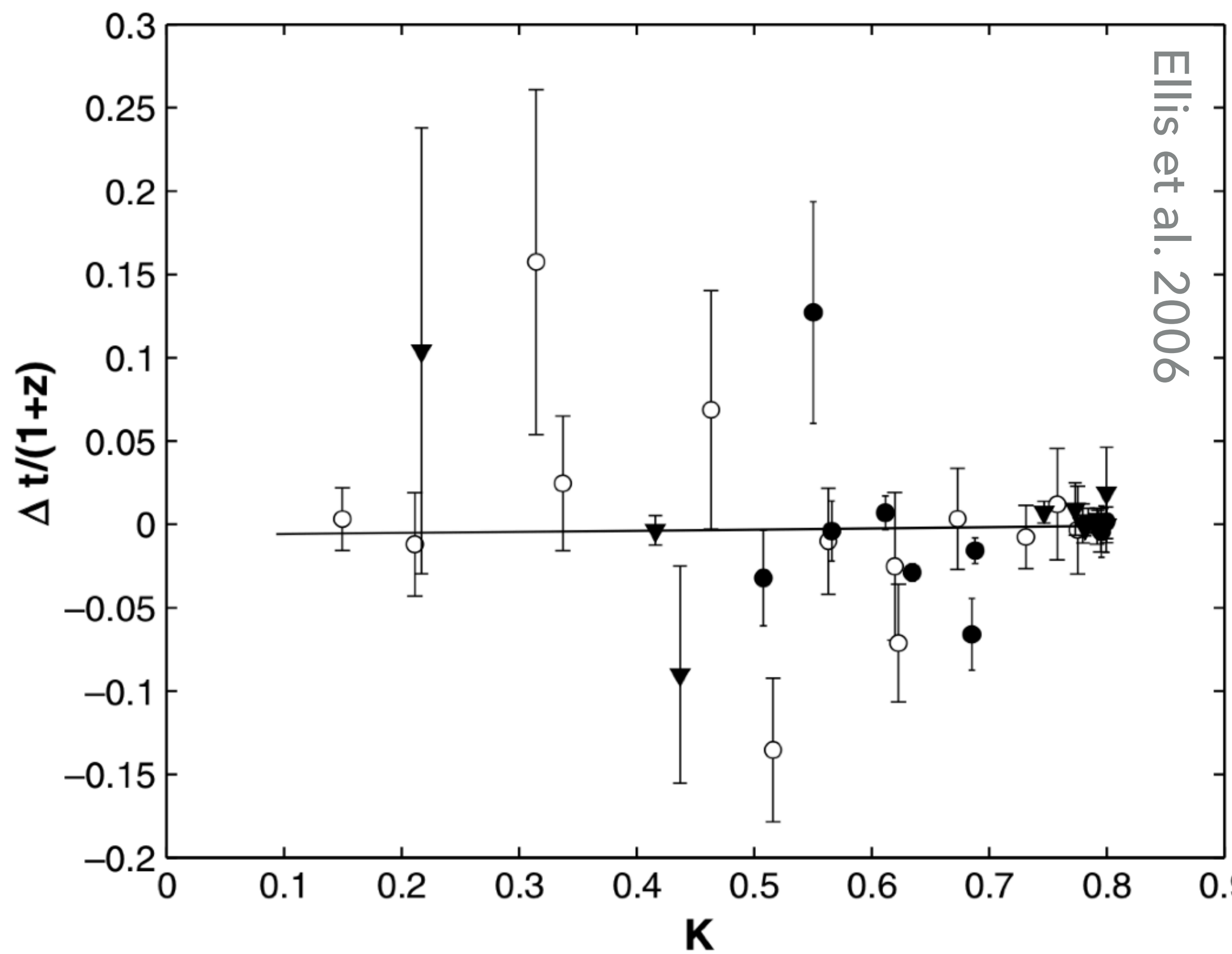
- The delay is parameterized as

$$\frac{\Delta t_{\mathrm{meas}}}{1+z} = a_{\mathrm{LIV}}\,\kappa(z) + b_{\mathrm{int}}$$

  where a_{LIV} accounts for the LIV effect and b_{int} for the intrinsic delay

- Most of these studies use both long and short bursts

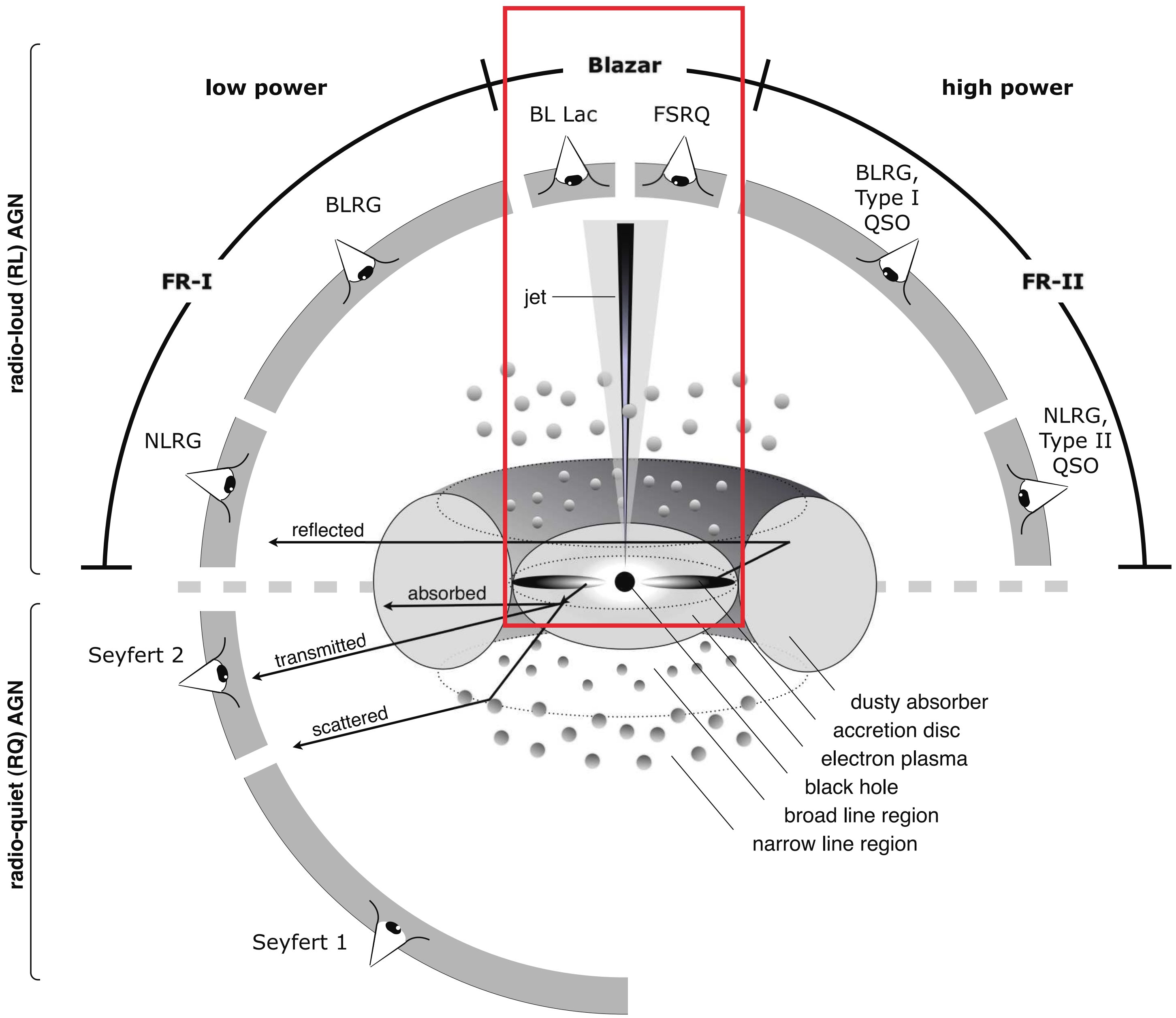
- **Intrinsic delays are assumed to be identical for all bursts**



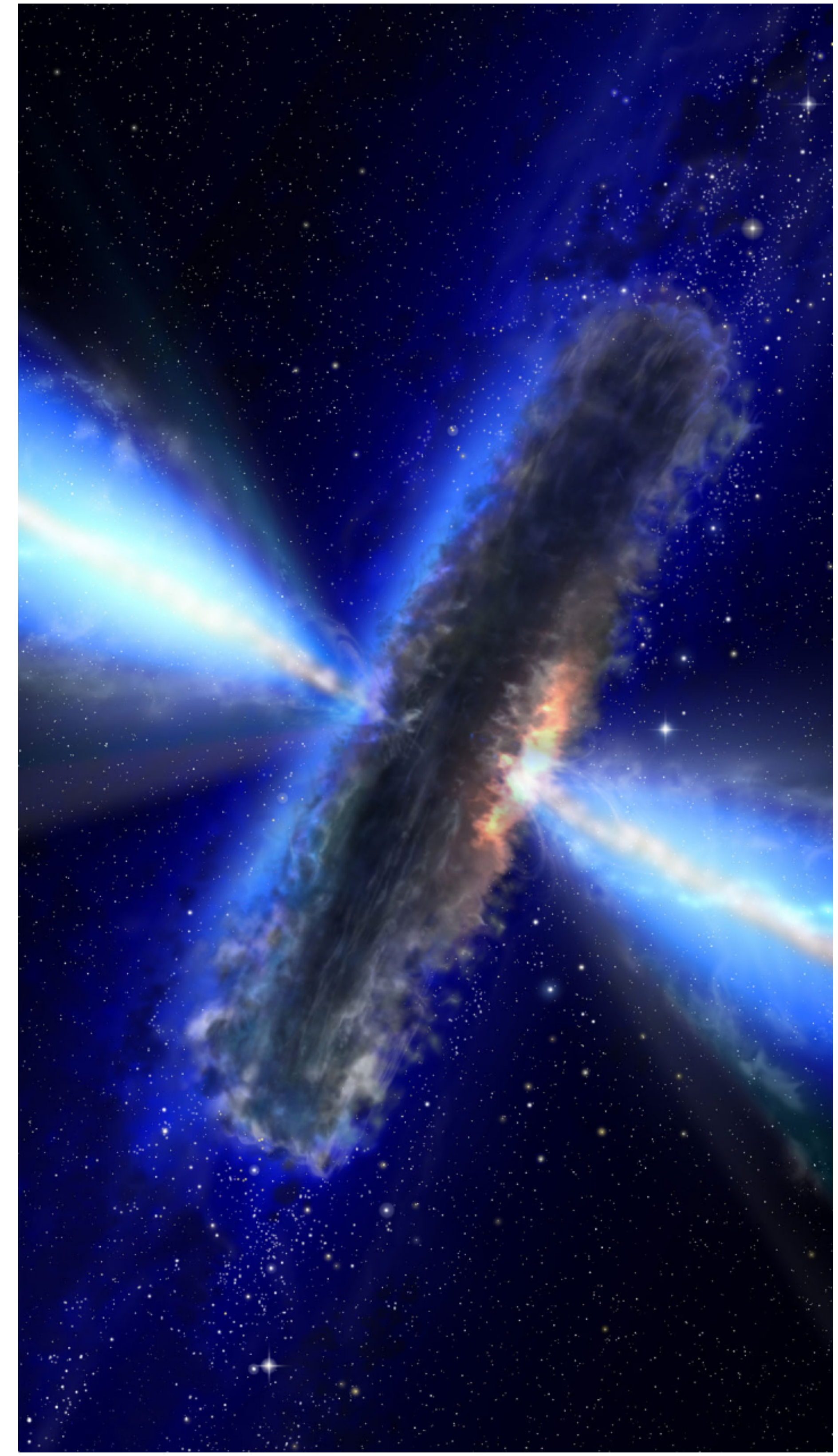
See also Bernardini et al. 2018, Bolmont et al. 2008, Ellis et al. 2000, 2003, 2006, 2019, …

UNDERSTANDING INTRINSIC EFFECTS

- **Focusing on blazars… at HE and VHE energies**
- The jet is the main contributor for the observed HE emission



Beckmann & Shrader 2012



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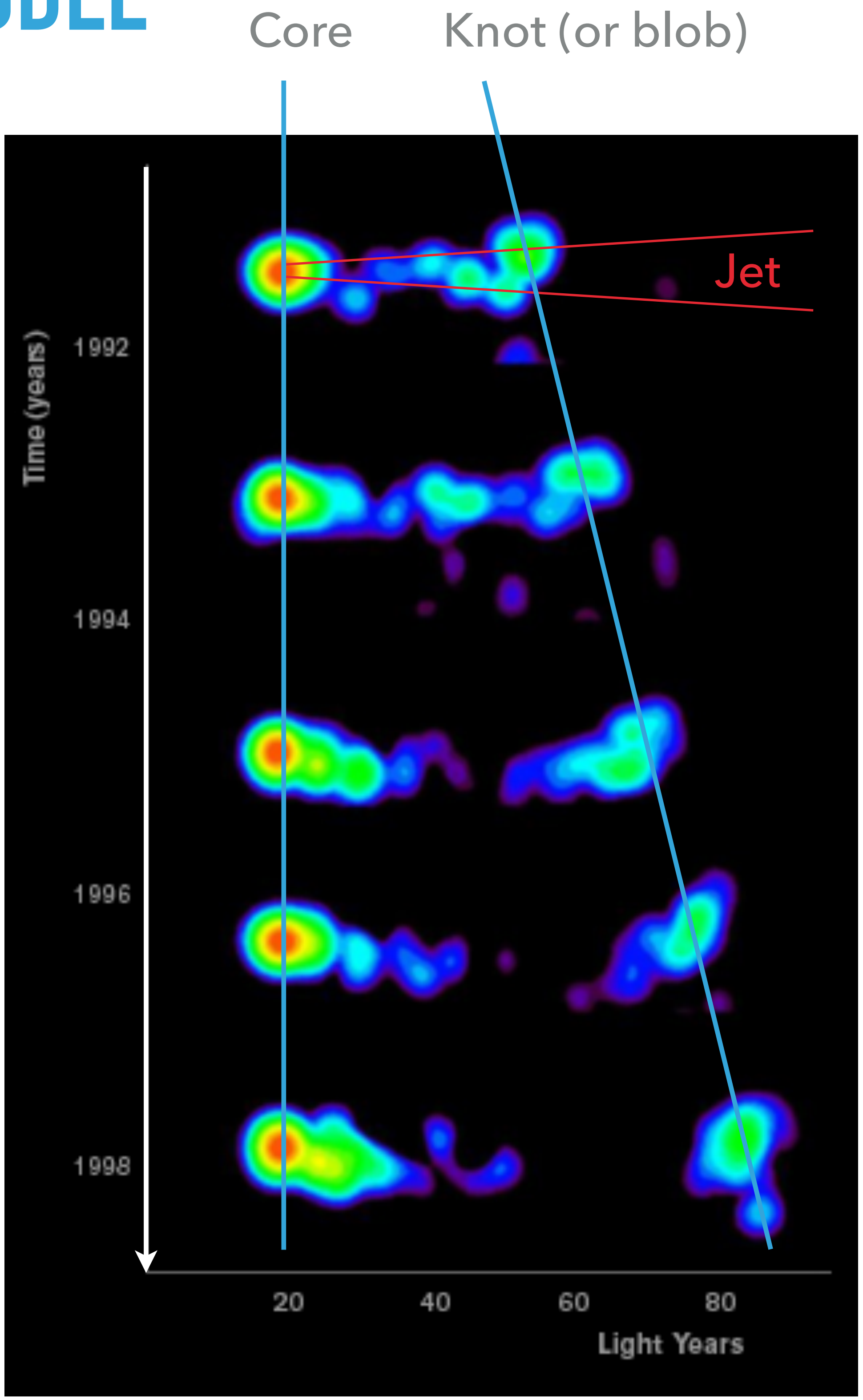
A SIMPLE « BLOB-IN-JET » LEPTONIC MODEL

- **Purely leptonic « blob-in-jet » model**
- A hotter and denser plasmoid of e^-/e^+ moving along the jet: the blob
- The VHE emission is entirely governed by the blob
- Strong magnetic fields
  - Synchrotron radiation
- Synchrotron photons can interact with the electrons in the blob
  - Inverse Compton
- Synchrotron Self-Compton (SSC)
- Inverse Compton of photon fields external to the jet or the AGN itself → External Inverse Compton (EIC)



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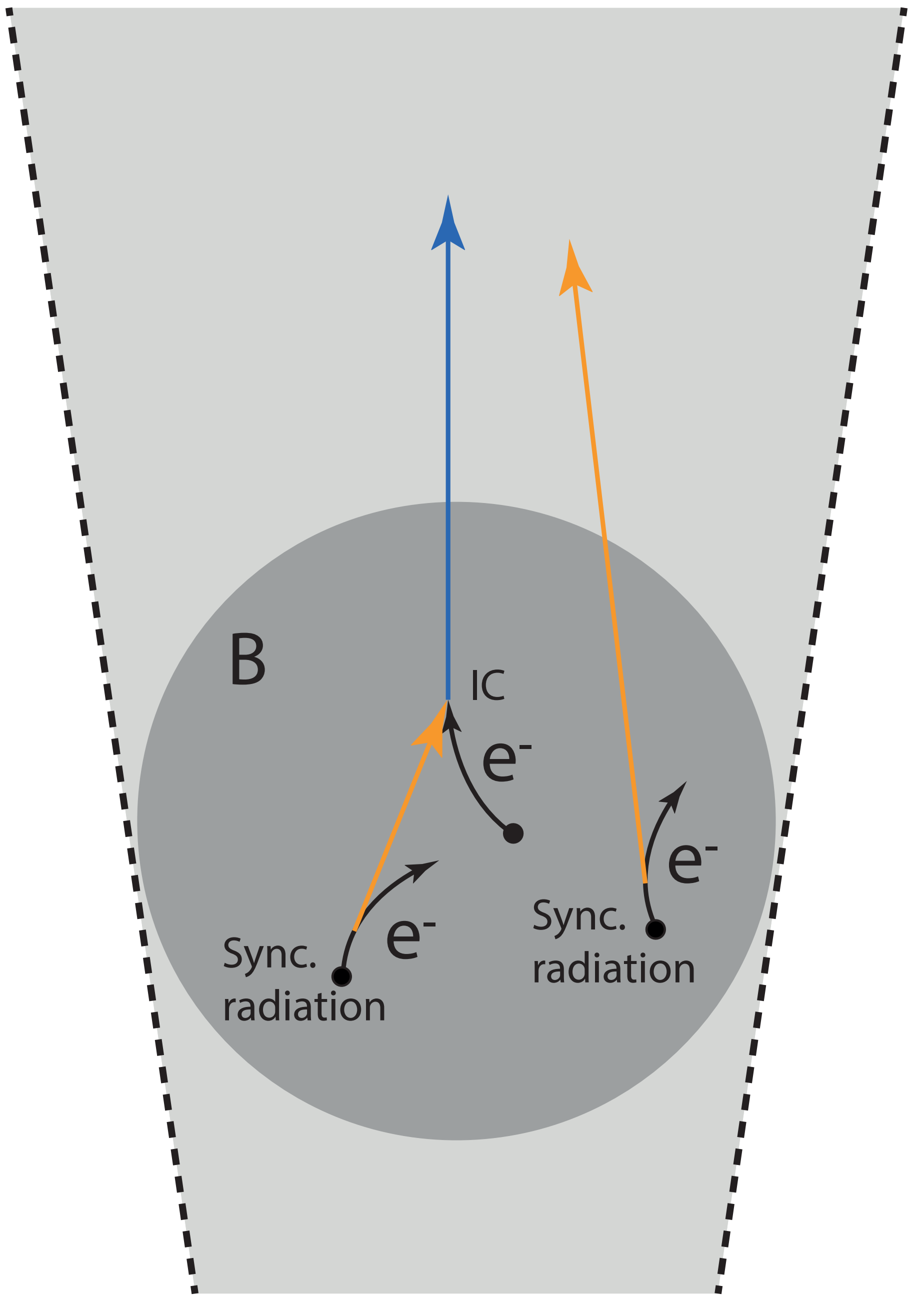

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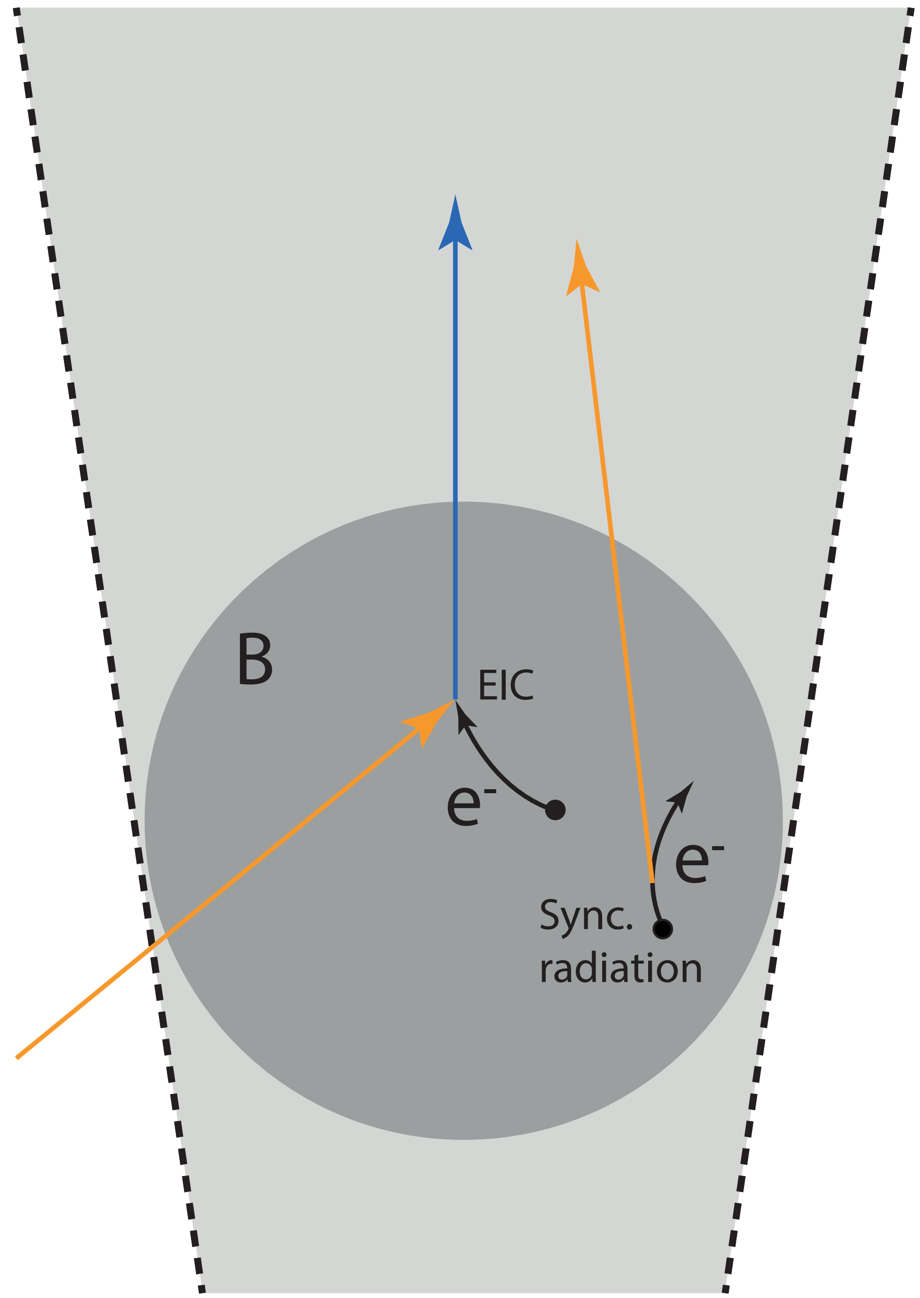
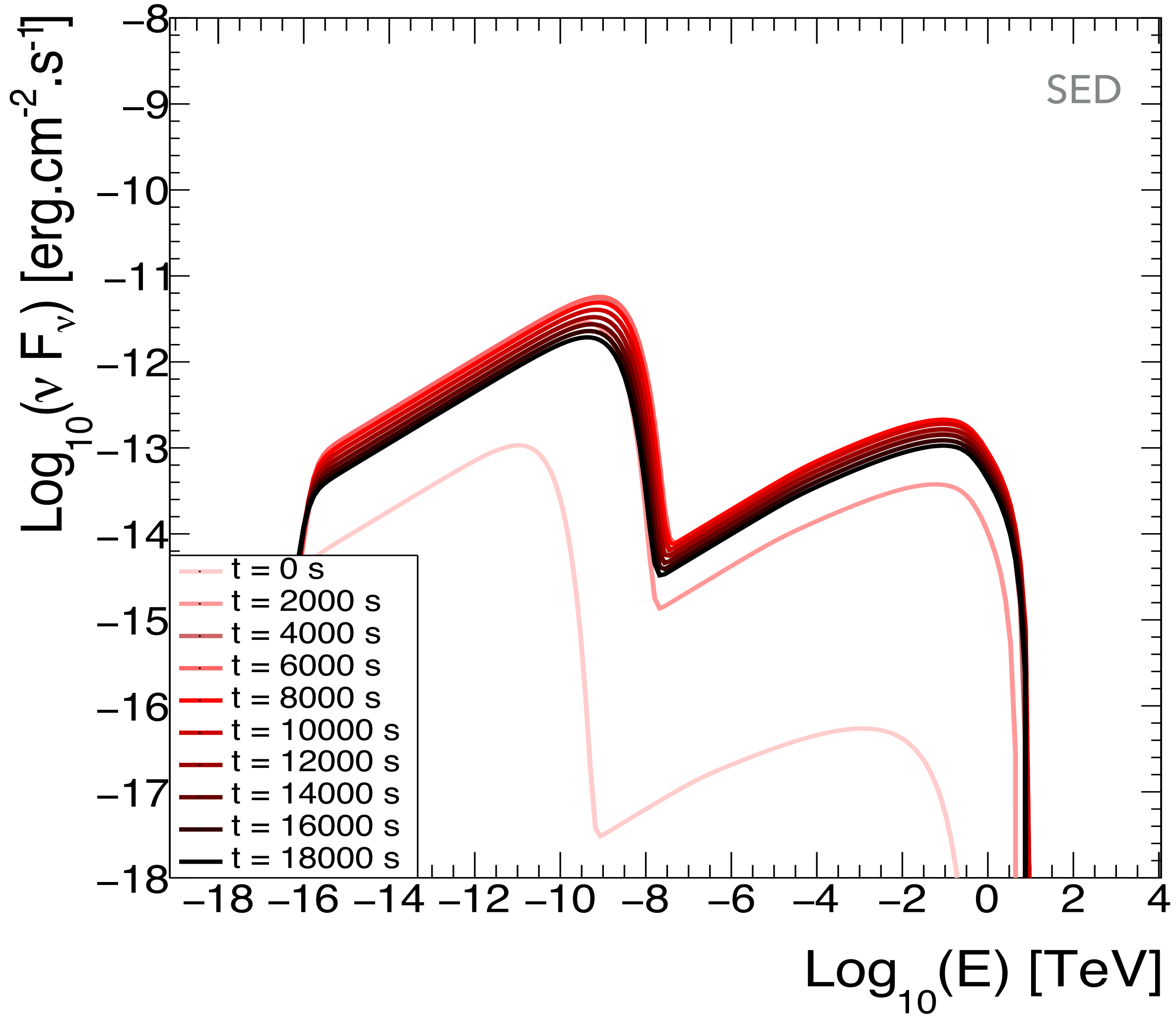


QUANTIFYING INTRINSIC LAGS

C. Levy, H. Sol, A. Rosales, JB
Plots from C. Levy

- **First attempts to characterize intrinsic effects in blazar flares in connexion to LIV searches**
- SED and light curves produced from a simple SSC model (Katarzyński et al. 2001)
- Temporal evolution due to
  - Electron acceleration (↗)
  - Electron energy losses and decrease of magnetic field (↘)
- $\Delta t = t_E - t_{ref}$ computed from a reference light curve (lowest energy)



Perennes et al. (w JB) 2020,
Levy et al. (w JB) in prep. + ICRC 2021

NEGATIVE LAG: HIGH ENERGY PEAK BEFORE LOW ENERGY PEAK

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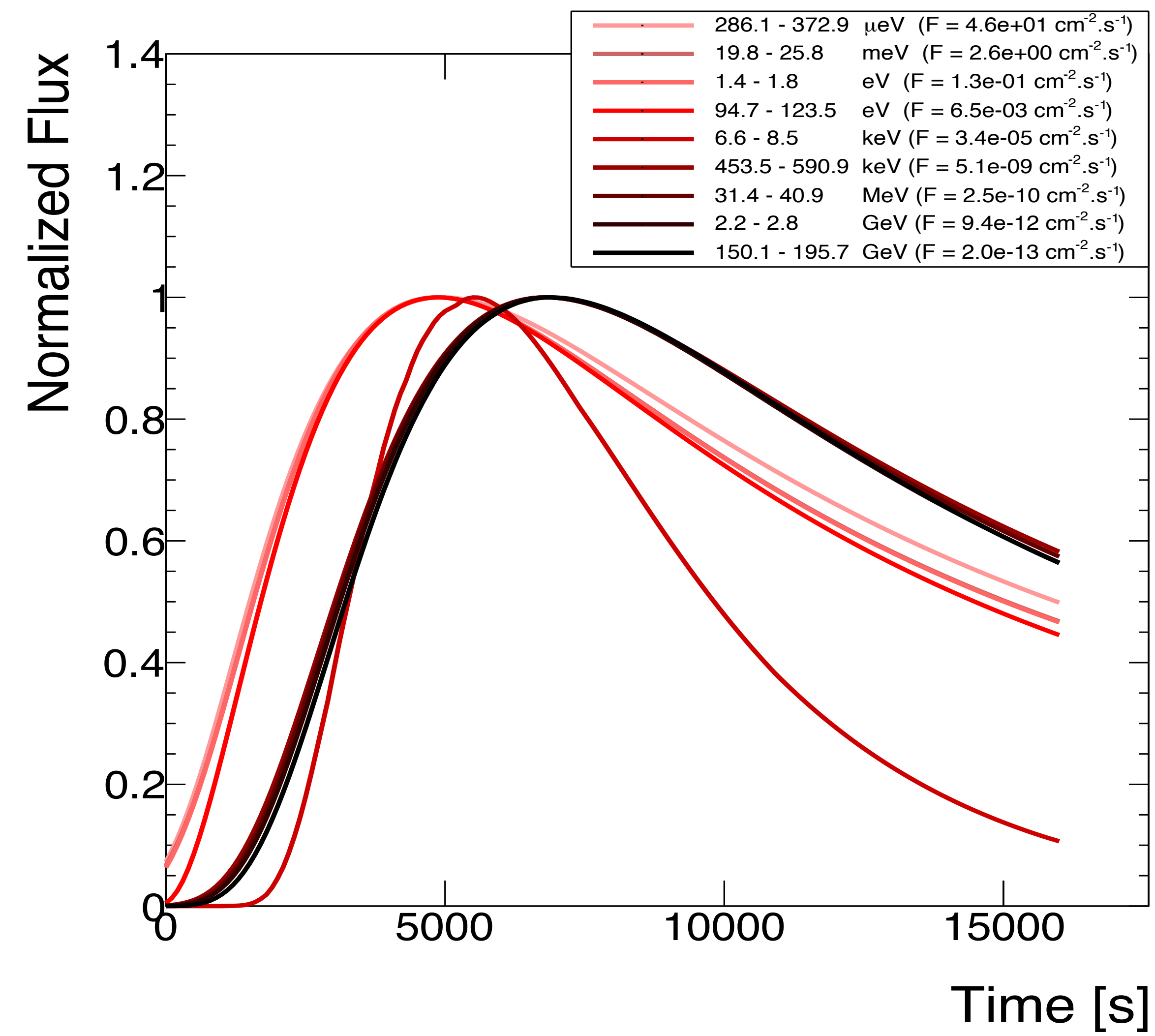

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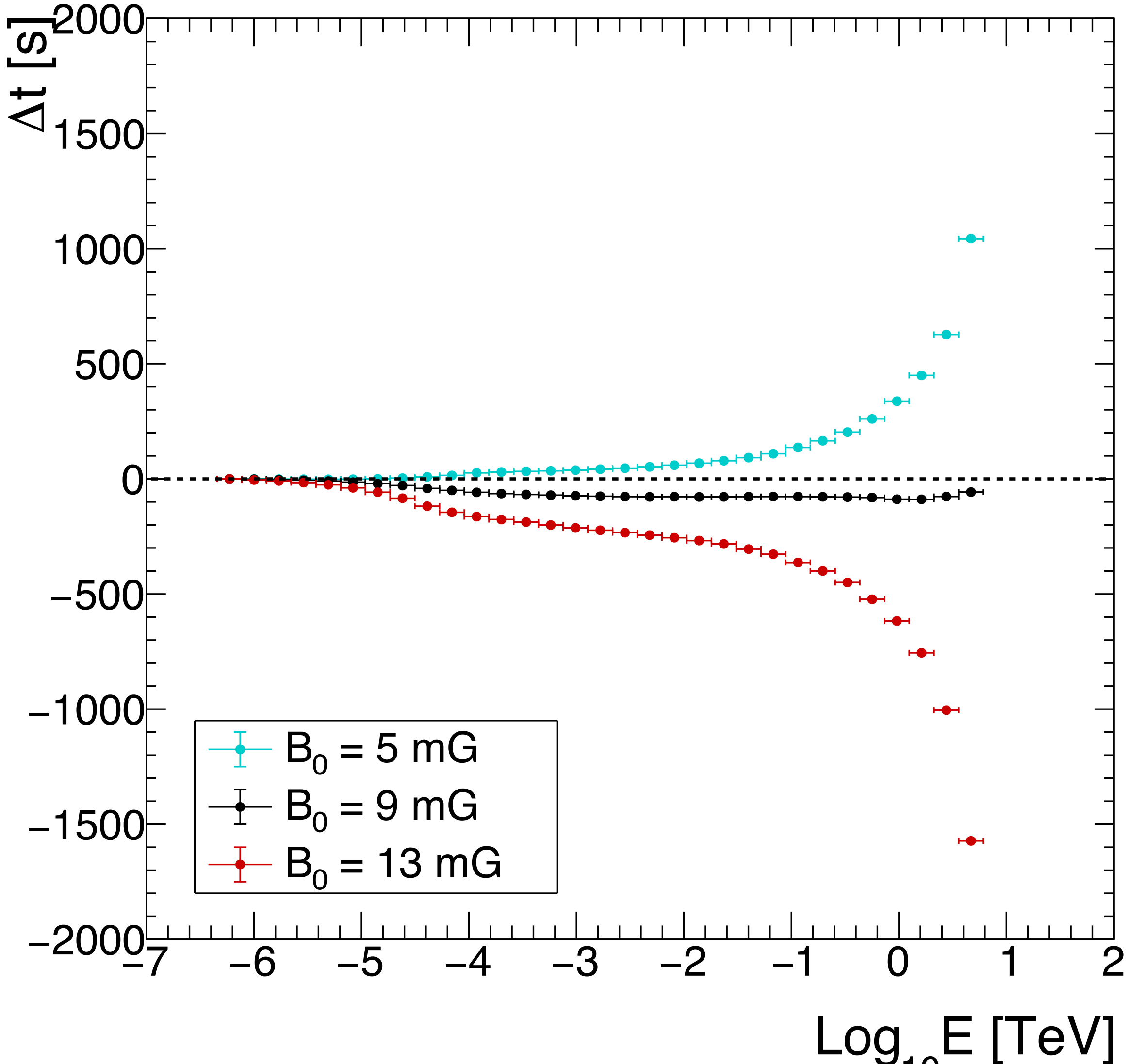
QUANTIFYING INTRINSIC LAGS

- **Time delays show three types of regimes due to the competition between acceleration and cooling processes**
  - Increasing trend: slow acceleration
  - Decreasing trend: fast acceleration
  - « Flat » regime: acceleration and cooling are balanced
- **Changing the model parameters in their validity ranges allows to retrieve the different trends**

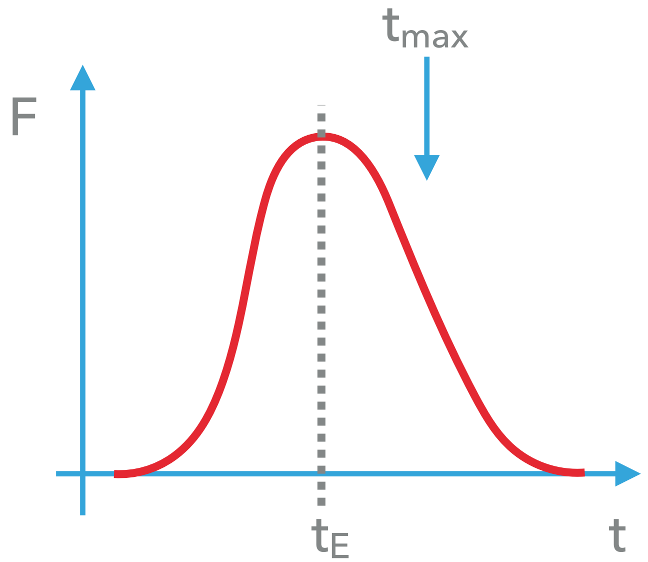
INCREASE: SLOW ACCELERATION WRT COOLING PROCESSES
LE PEAK BEFORE HE

DECREASE: FAST ACCELERATION WRT COOLING PROCESSES
HE PEAK BEFORE LE

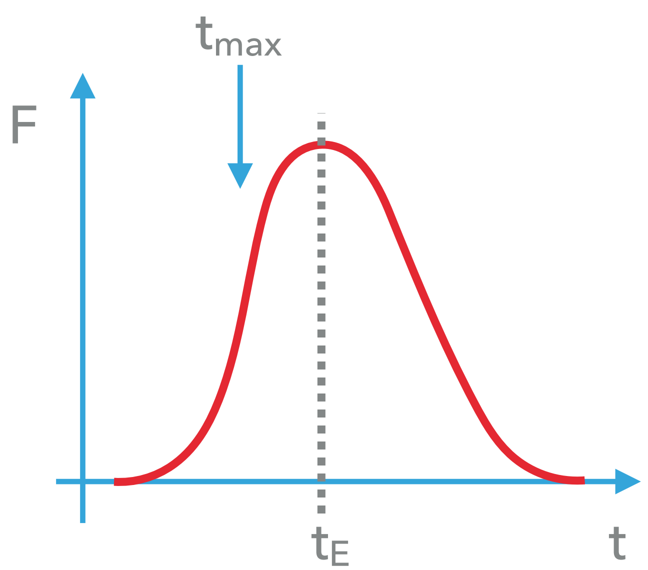


TWO DELAY REGIMES

- **Two delay regimes due to imbalance between acceleration and cooling processes**
  - The two processes happen at the same time, but with different efficiencies
- **Increasing delays - slow acceleration**
  - Max Lorentz factor reached after lightcurves start to decay ($t_{max} > t_E$)
    → slow acceleration wrt decay processes
    → HE photons emitted later
    → HE peak after LE



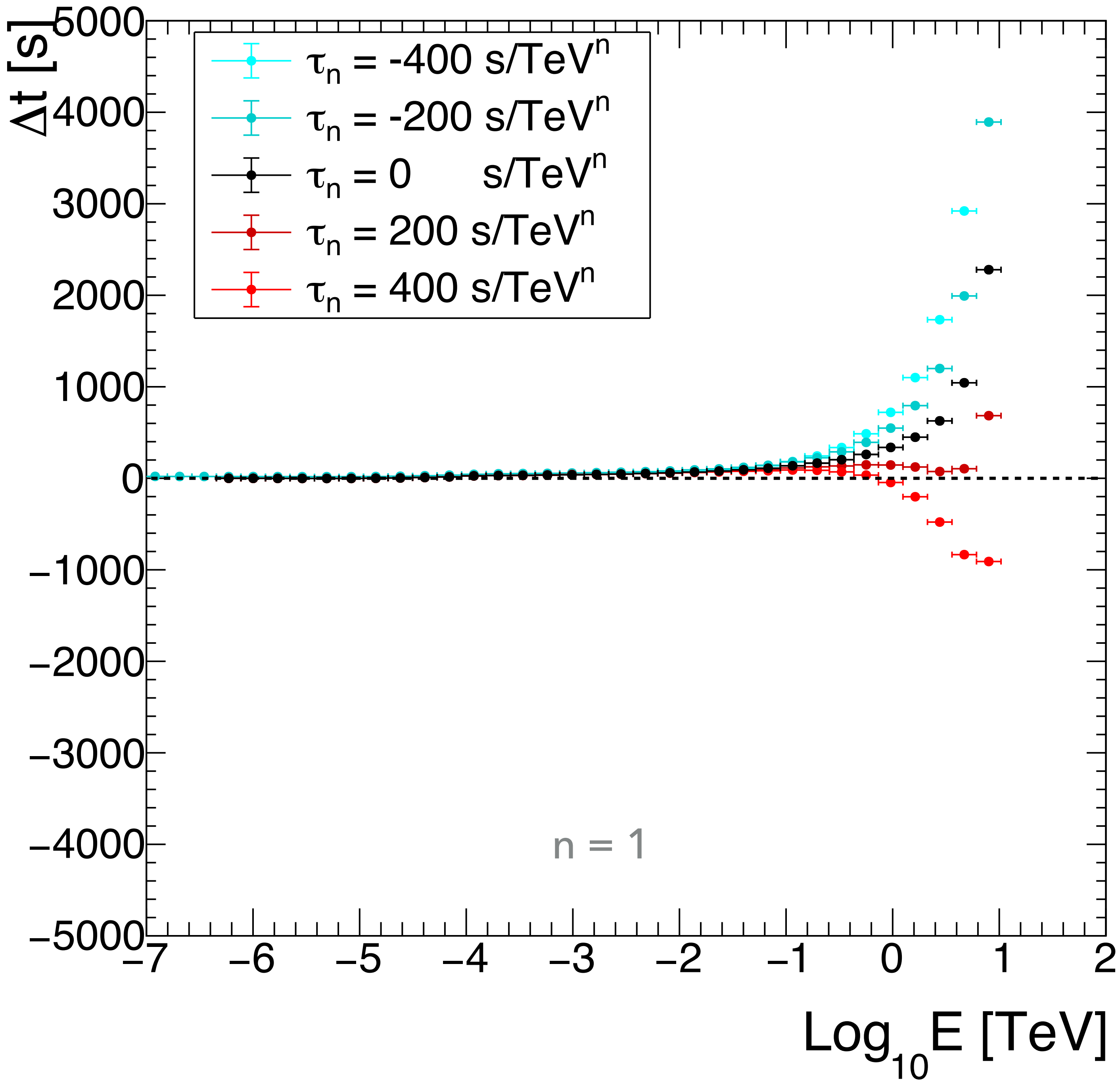
- **Decreasing delay - fast acceleration**
  - Max Lorentz factor reached before lightcurves start to decay ($t_{max} < t_E$)
    → fast acceleration wrt decay processes
    → HE photons emitted sooner
    → HE peak before LE



INTRINSIC EFFECTS VS LIV EFFECTS

Plots from C. Levy

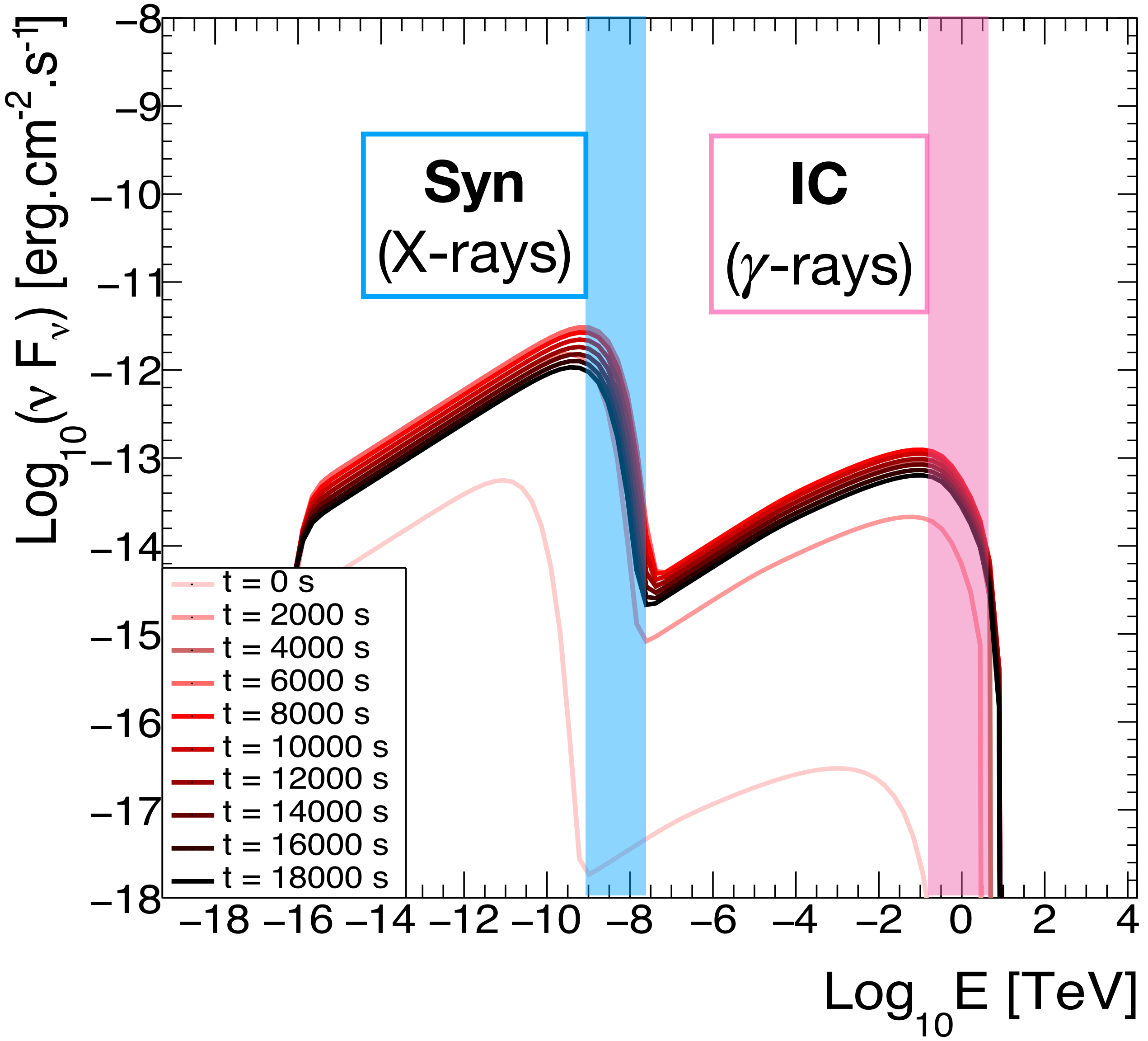
- When introducing LIV effects, here for z = 0.03, we see that
  - **LIV can result in a change of regime**
  - **LIV can cancel intrinsic effects out**
- Here we show only the MeV-TeV range
- What happens when the energy range is extended to lower energies?



DISCRIMINATING LIV AND INTRINSIC EFFECTS

Plots from C. Levy

- A very interesting outcome:
  - **The same trend is observed in both X-ray and gamma-ray domains**
  - **A remarkably stable and robust feature**
  - External Inverse Compton tend to decrease the correlation, but it's still there
  - EBL absorption and Klein-Nishina effects do not change this trend
- A key point for intrinsic vs. LIV effects discrimination



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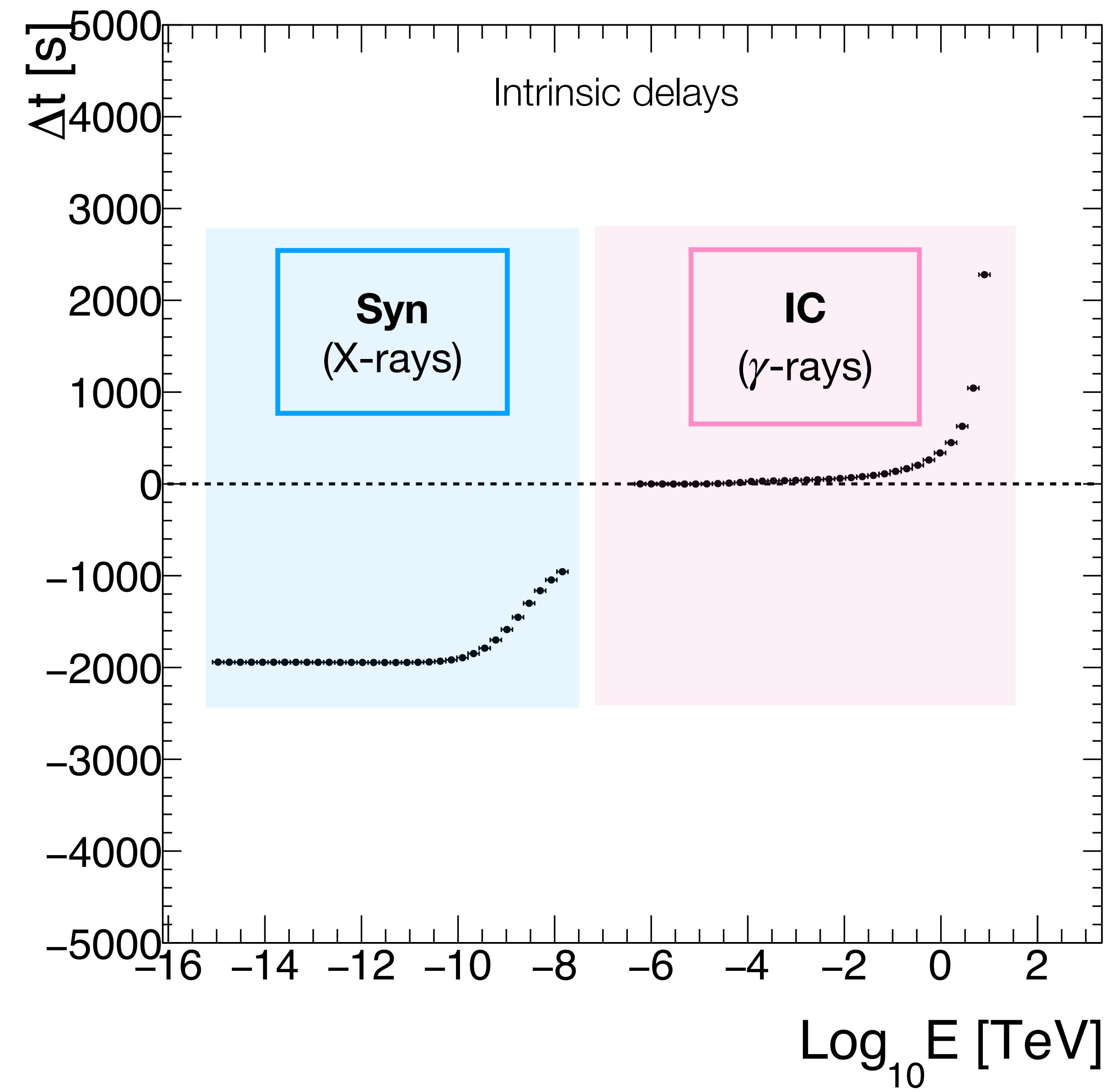
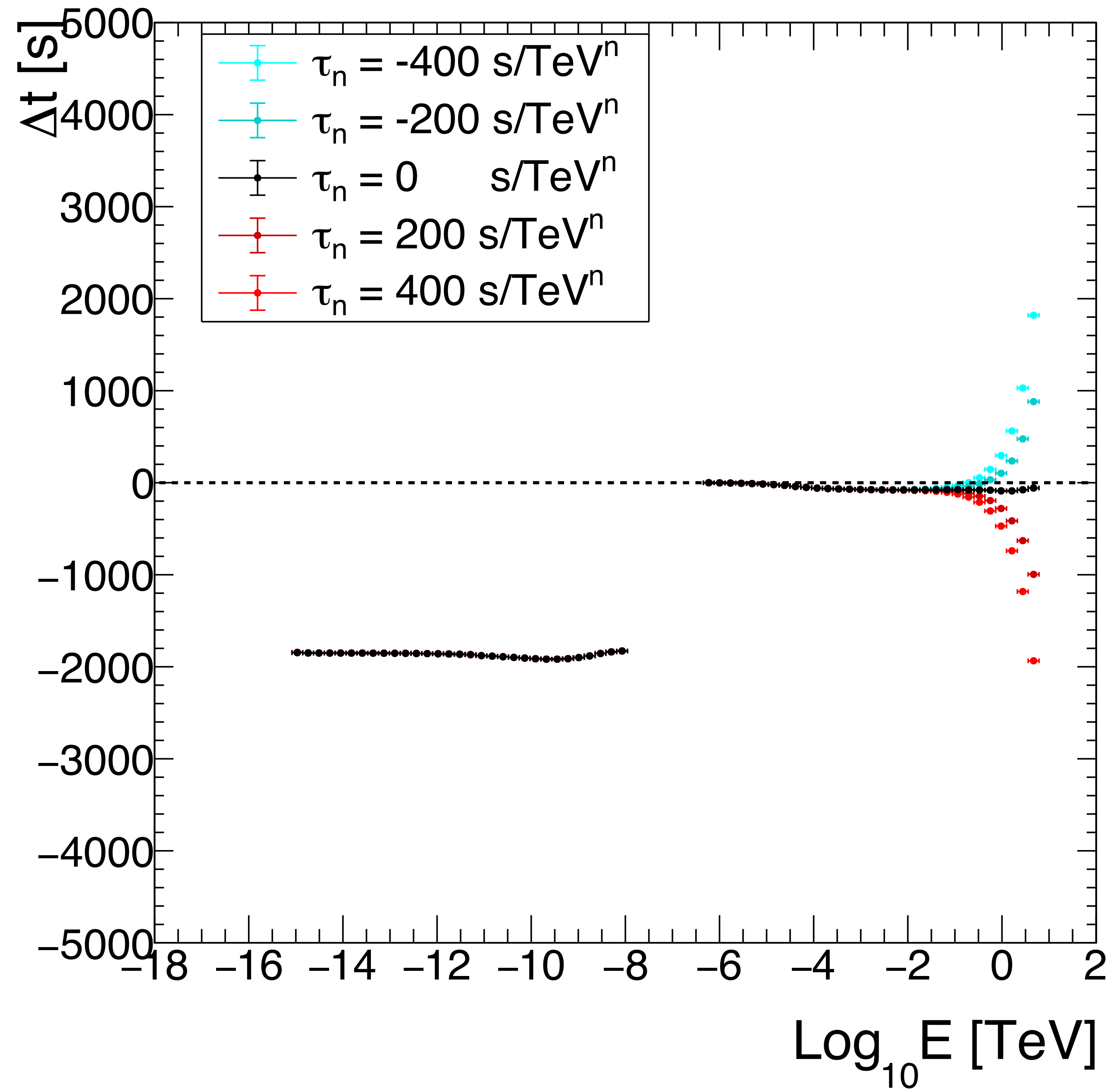


DISCRIMINATING LIV AND INTRINSIC EFFECTS

Plots from C. Levy

- LIV effects are negligible in the X-ray regime
- **Comparing gamma and x-ray data will help disentangling LIV and intrinsic effects**
- **A strong case for simultaneous multi-lambda observations!**



- More details will be available the article in preparation

CONCLUSIONS (1/2)

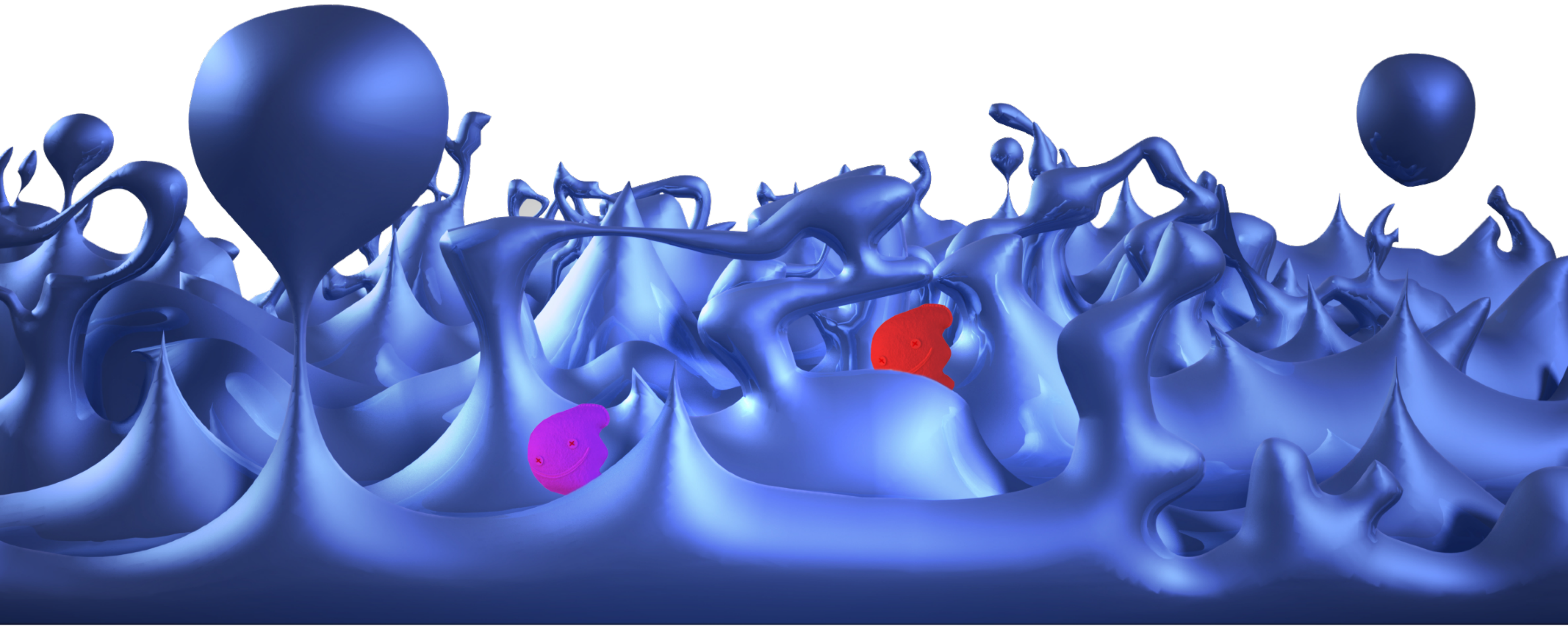
- Source-intrinsic spectral lags must be carefully considered in LIV searches
- They can be neglected in some conditions
- They can't be ignored when increasing the energy range
- In case of a positive lag detection, they will have to be separated from LIV effects
  - Population studies → using LIV effect dependance on z
  - Source modeling
- Both are developed and will be extended in the future

CONCLUSIONS (2/2)

- Intrinsic delay non-detection can also help to constrain models!
- Next developments for AGN jet modeling:
    - Investigate lepto-hadronic scenarios (A. Rosales)
    - Investigate CTA performance to detect the lags in the purely leptonic scenario (U. Pensec, A. Rosales)
- Intrinsic effects are certainly not universal
- Dedicated studies will be needed to interpret future positive lag detections

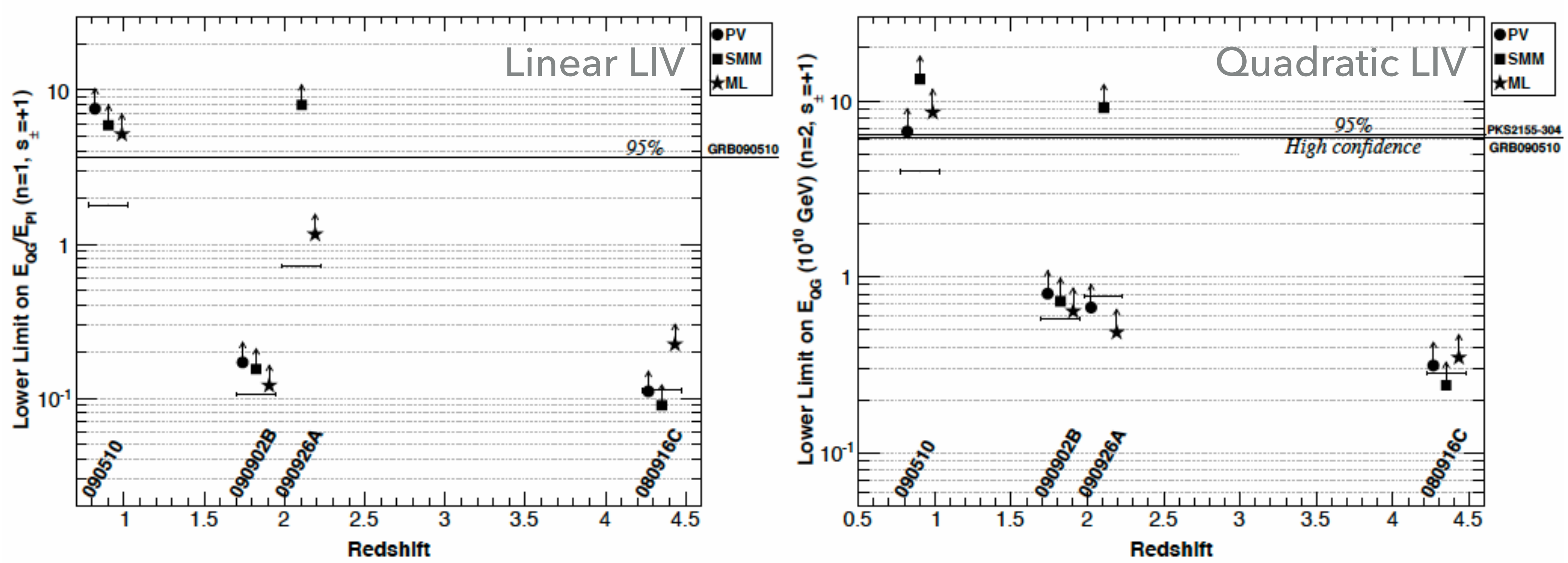
MERCI !

THANKS !



« CONSERVATIVE MODELING » OF SOURCE EFFECTS

Vasileiou et al. 2013



- Measure the Confidence Interval on $\Delta t_{n\ \mathrm{total}}$ from data
- Assume the range of $\Delta t_{\mathrm{source}}$
  - is as wide as the CI on $\Delta t_{n\ \mathrm{total}}$
  - is zero on average (bright bursts, no significant lag measured)
- Deduce the allowed range for $\Delta t_{n\ \mathrm{LIV}}$
- Take the value of $\Delta t_{n\ \mathrm{LIV}}$ which gives the least stringent constraint

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (95%CL)

	Source(s)	Experiment	Method	Results	
Individual GRB	GRB 021206	RHESSI	Fit + mean arrival time in a spike	$E_{QG,1} > 1.8 \times 10^{17}$ GeV	
	GRB 080916C	Fermi GBM + LAT	associating a 13 GeV photon with the trigger time	$E_{QG,1} > 1.3 \times 10^{18}$ GeV	$E_{QG,2} > 0.8 \times 10^{10}$ GeV
	GRB 090510	Fermi GBM + LAT	associating a 31 GeV photon with the start of any observed emission, DisCan	$E_{QG,1} > 1.5 \times 10^{19}$ GeV	$E_{QG,2} > 3.0 \times 10^{10}$ GeV
		Fermi LAT	PairView, SMM, likelihood	$E_{QG,1} > 9.3 \times 10^{19}$ GeV	$E_{QG,2} > 1.3 \times 10^{11}$ GeV
	GRB 190114C	MAGIC	Likelihood	$E_{QG,1} > 0.6 \times 10^{19}$ GeV	$E_{QG,2} > 6.3 \times 10^{10}$ GeV
Several GRB	9 GRBs	BATSE + OSSE	Fit	$E_{QG,1} > 10^{15}$ GeV	
	9 GRBs	BATSE + OSSE	wavelets	$E_{QG,1} > 0.7 \times 10^{16}$ GeV	$E_{QG,2} > 2.9 \times 10^{6}$ GeV
	15 GRBs	HETE-2	wavelets	$E_{QG,1} > 0.4 \times 10^{16}$ GeV	
	17 GRBs	INTEGRAL	likelihood	$E_{QG,1} > 3.2 \times 10^{11}$ GeV	
	35 GRBs	BATSE + HETE-2 + Swift	wavelets	$E_{QG,1} > 1.4 \times 10^{16}$ GeV	
	15 GRBs	SWIFT	CCF (50-100 keV, 150-200 keV)	$E_{QG,1} > 1.48 \times 10^{16}$ GeV	
	8 GRBs	Fermi LAT	irregularity, kurtosis, skewness estimators	$E_{QG,1} > 10^{17}$ GeV	
Individual PSR	Crab pulsar	EGRET	average time of the main pulse in different energy bands, fit of main pulse	$E_{QG,1} > 0.2 \times 10^{16}$ GeV	
		VERITAS	DisCan	$E_{QG,1} > 1.9 \times 10^{17}$ GeV	
		MAGIC	likelihood	$E_{QG,1} > 7 \times 10^{17}$ GeV	$E_{QG,2} > 4.6 \times 10^{10}$ GeV
	Vela pulsar	H.E.S.S.	likelihood	$E_{QG,1} > 3.5 \times 10^{15}$ GeV	$E_{QG,2} > 6.4 \times 10^{8}$ GeV

- Best limit so far: $E_{QG,1} > 9.3 \times 10^{19}$ GeV with GRB 090510
- Population studies lead to $E_{QG,1} > 10^{17}$ GeV
- Competitive results possible for pulsars on $E_{QG,2}$

References available on a back-up slide

LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (AGN)

	Source(s)	Experiment	Method	Results	
Individual flaring AGN	Mrk 421	Whipple	average time of the main pulse in different energy bands	$E_{QG,1} > 0.4 \times 10^{17}$ GeV	
	Mrk 421	MAGIC	likelihood	$E_{QG,1} > 5.4 \times 10^{18}$ GeV	$E_{QG,2} > 1.4 \times 10^{11}$ GeV
	Mrk 501	MAGIC	ECF, likelihood	$E_{QG,1} > 0.2 \times 10^{18}$ GeV	$E_{QG,2} > 2.6 \times 10^{10}$ GeV
			likelihood	$E_{QG,1} > 0.3 \times 10^{18}$ GeV	$E_{QG,2} > 5.7 \times 10^{10}$ GeV
	Mrk 501	H.E.S.S.	likelihood	$E_{QG,1} > 3.6 \times 10^{17}$ GeV	$E_{QG,2} > 8.5 \times 10^{10}$ GeV
	PKS 2155-304	H.E.S.S.	MCCF	$E_{QG,1} > 7.2 \times 10^{17}$ GeV	$E_{QG,2} > 0.1 \times 10^{10}$ GeV
			wavelets	$E_{QG,1} > 5.2 \times 10^{17}$ GeV	
			likelihood	$E_{QG,1} > 2.1 \times 10^{18}$ GeV	$E_{QG,2} > 6.4 \times 10^{10}$ GeV
	PG 1553+113	H.E.S.S.	likelihood	$E_{QG,1} > 4.1 \times 10^{17}$ GeV	$E_{QG,2} > 2.1 \times 10^{10}$ GeV
	3C279	H.E.S.S.	likelihood	$E_{QG,1} > 1.6 \times 10^{17}$ GeV	$E_{QG,2} > 1.5 \times 10^{10}$ GeV

- 5 different objects
- Redshift ranging from 0.03 (Mrk 421) to 0.54 (3C279)
- Best limits for $E_{QG,1}$ and $E_{QG,2}$: Mrk 421

References available on a back-up slide

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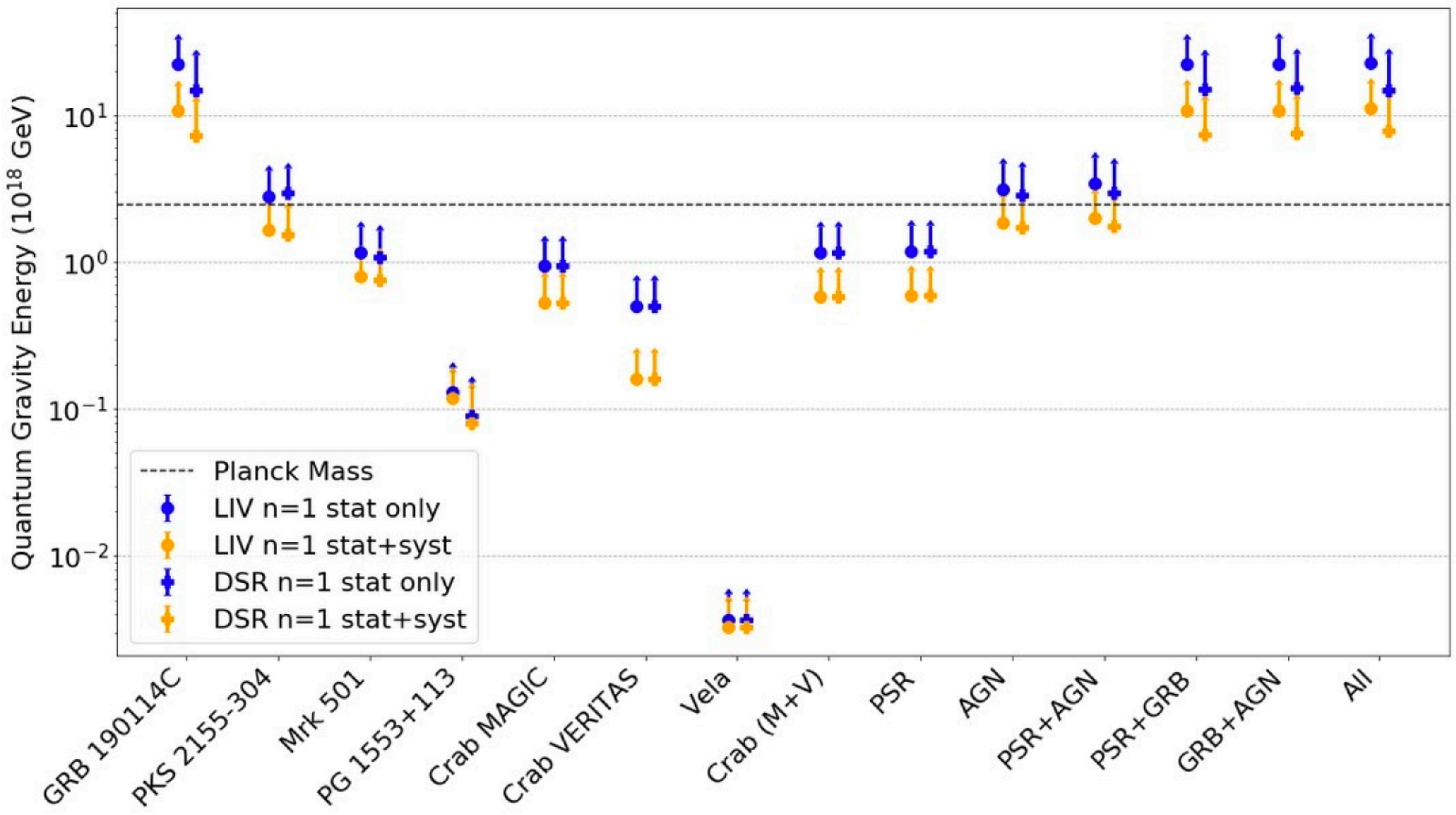
References available on a back-up slide

PREPARING POPULATION STUDIES

- Simulated data from published spectra and light curves
  - GRB 190111C detected by MAGIC
  - Three AGN flares detected by MAGIC and H.E.S.S.
  - Two VHE Pulsars detected by H.E.S.S., VERITAS and MAGIC



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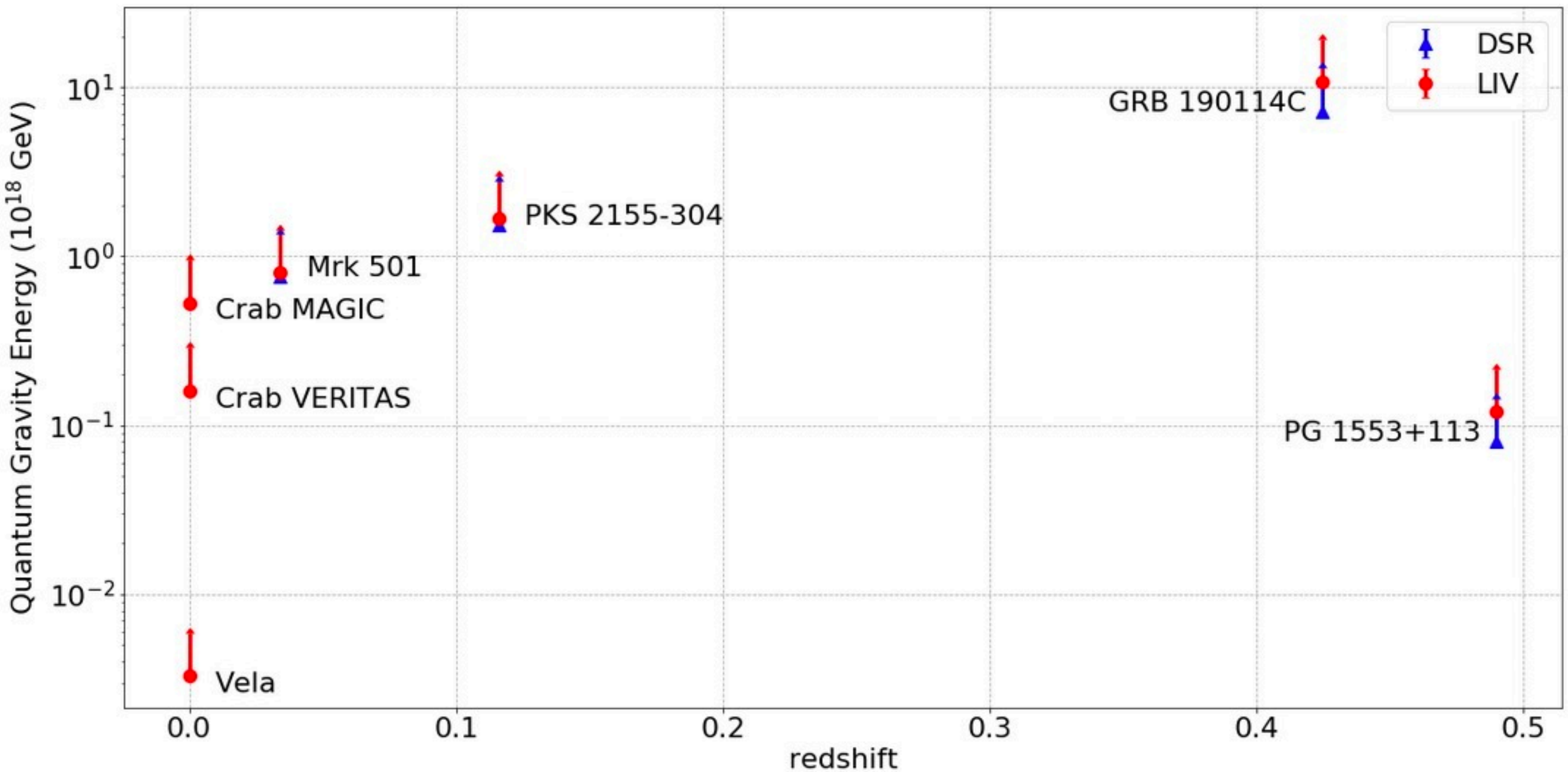

- Technical paper on the method to appear in early 2021
- Final paper with all available sources to follow