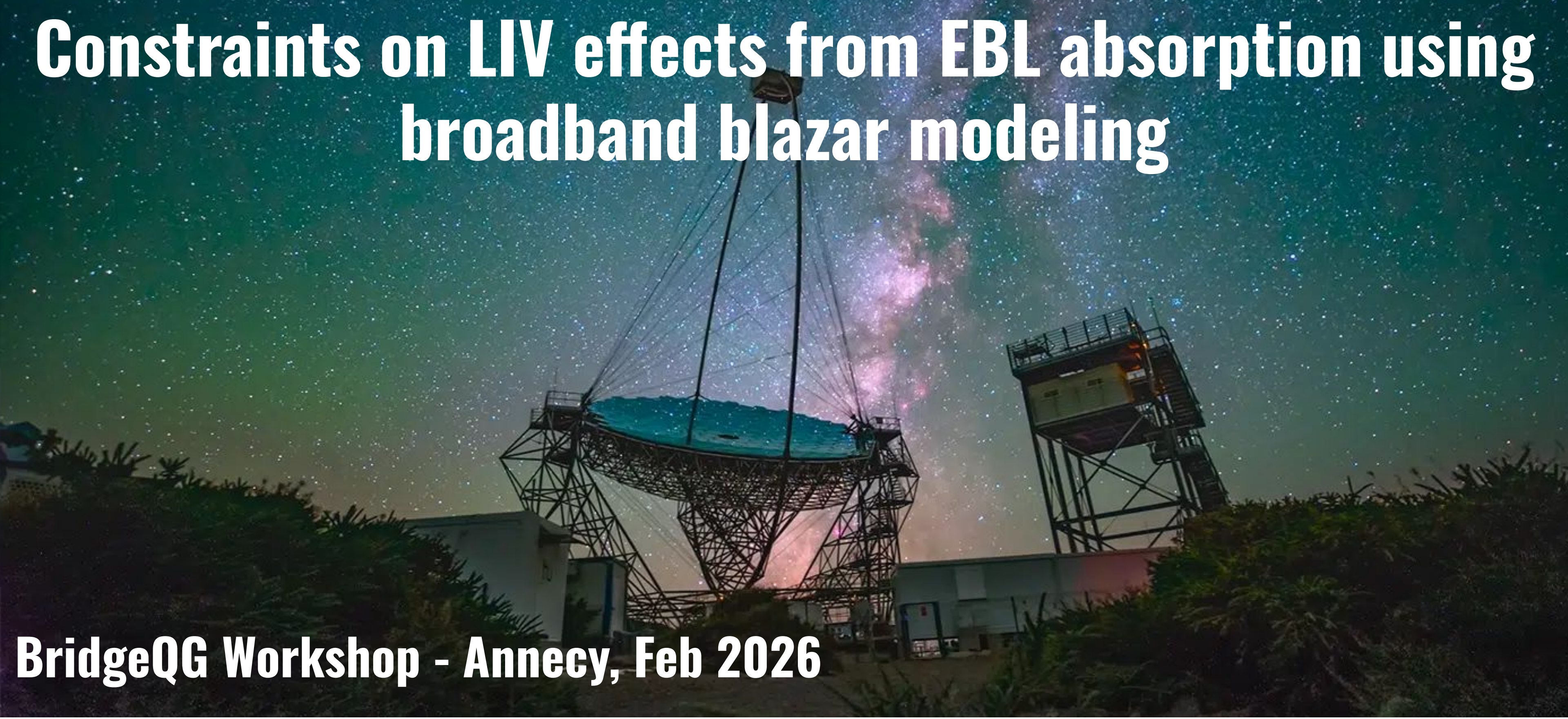
Constraints on LIV effects from EBL absorption using broadband blazar modeling



BridgeQG Workshop - Annecy, Feb 2026

CTAO | LST COLLABORATION

UNIVERSITY OF LODZ

A. Rosales de León on behalf the Łódź working group:
J. Sitarek, W. Bednarek & G. Borkowski

What is Lorentz Invariance Violation (LIV)?

- LIV refers to the theoretical possibility that Lorentz invariance might not hold at extremely high energies or very small scales (Planck scale).
- LIV has been integrated successfully in special relativistic framework: Doubly Special Relativity (http://arXiv.org/abs/hep-th/0112090v2)

  and in Classical Quantum Mechanics: Generalized Uncertainty Principle (https://arxiv.org/abs/2308.13788)
- LIV is expected in some theories of Quantum Gravity (QG): String theory, spacetime foam, loop quantum gravity, etc…
- Quantization of space ~ the Planck distance 1.6x10^{-35} m
- Including LIV into the mathematical framework leads a modified dispersion relation for particles:

$$E^2 = p^2c^2 \times \left[1 + \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{QG,n}}\right)^n\right]$$

$$E_{QG,n} = \xi_n^{-1} \times E_{pl}$$

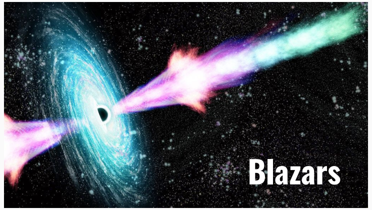
$$E_{pl} \sim 1.22 \times 10^{19} \quad \text{GeV}$$

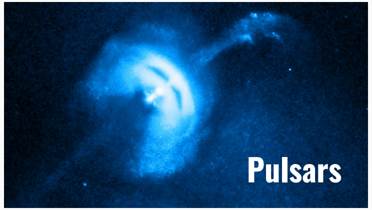
Subluminal scenario: $S_n = +1$
Superluminal scenario: $S_n = -1$

and n is the correction order

How to search for LIV signatures?

We need VERY HIGH ENERGY and DISTANT astrophysical sources to look for LIV effects





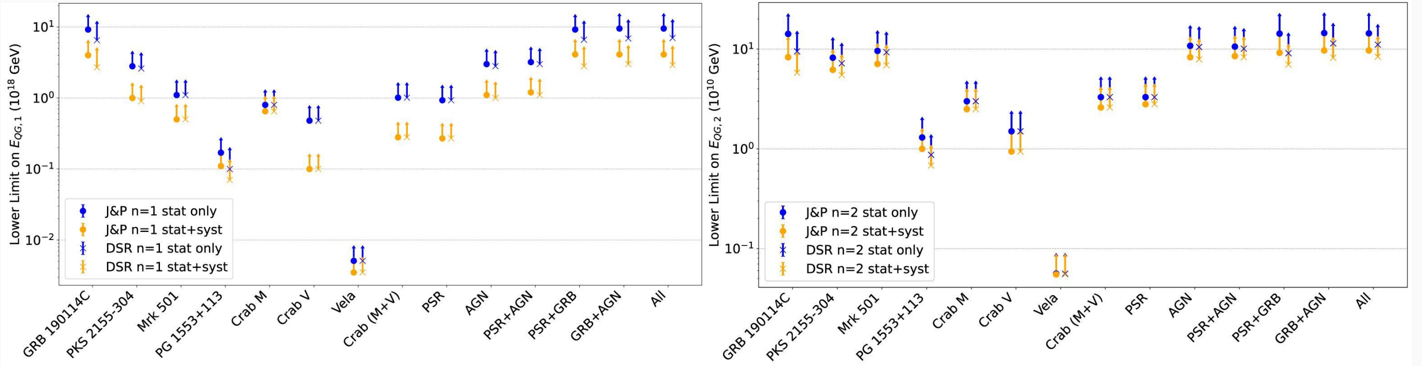


Image Credits: Bolmont et al. (2022)

"TIME-OF-FLIGHT" (TOF) PREVIOUS STUDIES:
Mrk 421 flare of 2014: Abe et al. JCAP07 (2024) 044 (MAGIC collaboration)
Mrk 501 flare of 2005: Albert et al. (2007) ApJ 669, 862 (MAGIC collaboration)
PKS 2155-304 flare of 2006: Abramowski at al. (2011) APh 34, 738 (H.E.S.S. Collaboration)
1st combined study on LIV: Bolmont et al. (2022) ApJ 930, 75 (H.E.S.S. + MAGIC + VERITAS) ... amongst others

LIV working group: MAGIC H.E.S.S. VERITAS CTAO

Detection methods

	Spectral Method (EBL+LIV)	Time-of-Flight (ToF) Method
Main Observable	Deviations in gamma-ray spectra due to modified pair production	Energy-dependent arrival time delays of photons
Physical Effect Probed	Modified kinematics of interaction (energy thresholds, EBL)	Modified photon propagation velocity
Energy Sensitivity	multi-TeV	GeV – TeV range
Best Sources	Persistent emitters (e.g., blazars, radio galaxies)	Fast transients (e.g., GRBs, AGN flares)
Observational Requirement	High-statistics spectra at VHE	High time resolution and well-timed photon events
Main Limiting Factor	Uncertainties in EBL and source modelling, limited by VHE sensitivity	Unknown intrinsic source delays, limited by time resolution

BY APPLYING BOTH METHODS:

- ❑ Probe LIV across a broad energy range and redshift baseline.
- ❑ Cross-check results with independent observational techniques.
- ❑ Improving confidence in LIV constraints by mitigating model dependence.

LIV effects on EBL

VHE gamma-rays are absorbed through the interaction with the low-energy radiation photons of the extragalactic background light (EBL):

$$\gamma + \gamma_{EBL} \rightarrow e^{+} + e^{-}$$

LIV modifies the kinematics of high-energy photon interaction, the energy threshold is modified as:

$$\epsilon_{min} = \frac{m^2 c^4}{E_\gamma} + S_n \frac{E_\gamma^{n+1}}{4E_{QG,n}^n}$$

Subluminal scenario: $S_n = +1$
Superluminal scenario: $S_n = -1$ for n = 1, 2 ...

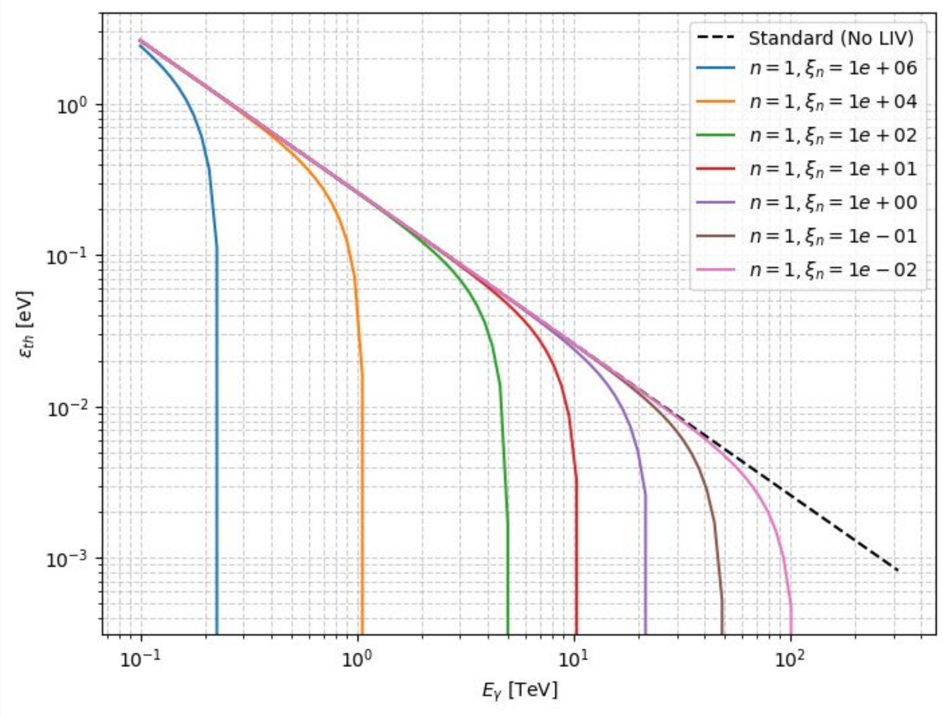
This deviation could lead to the reduction of cosmic opacity (subluminal LIV effect), affecting the gamma-ray spectra of sources at TeV energies.

Detecting anomalies in gamma-ray opacity remains challenging due to the limited sensitivity of current TeV observatories.

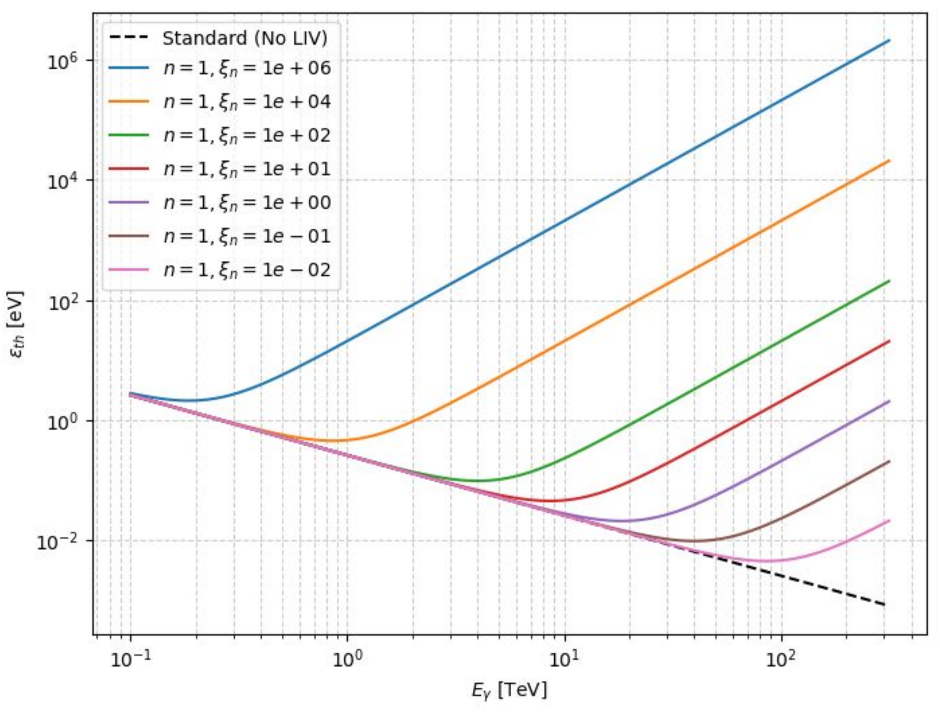
The CTAO greater sensitivity and effective area than previous experiments, would be ideal to search for LIV effects at multi-TeV energies.

LIV effects: Shift in energy threshold [n=1]

LIV - Superluminal effect (S=-1)

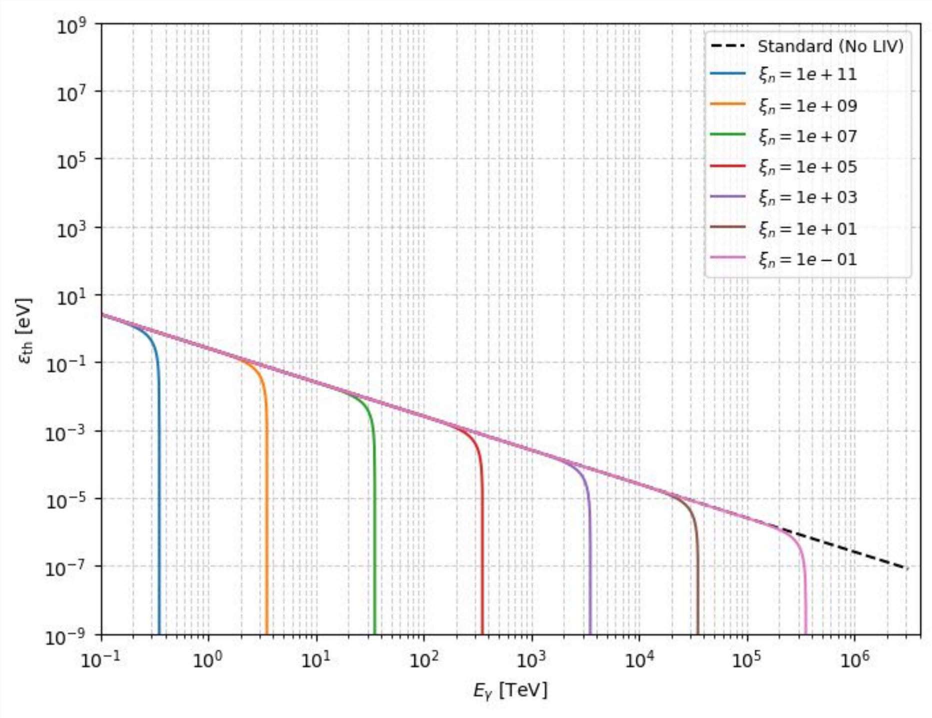


LIV - Subluminal effect (S=+1)

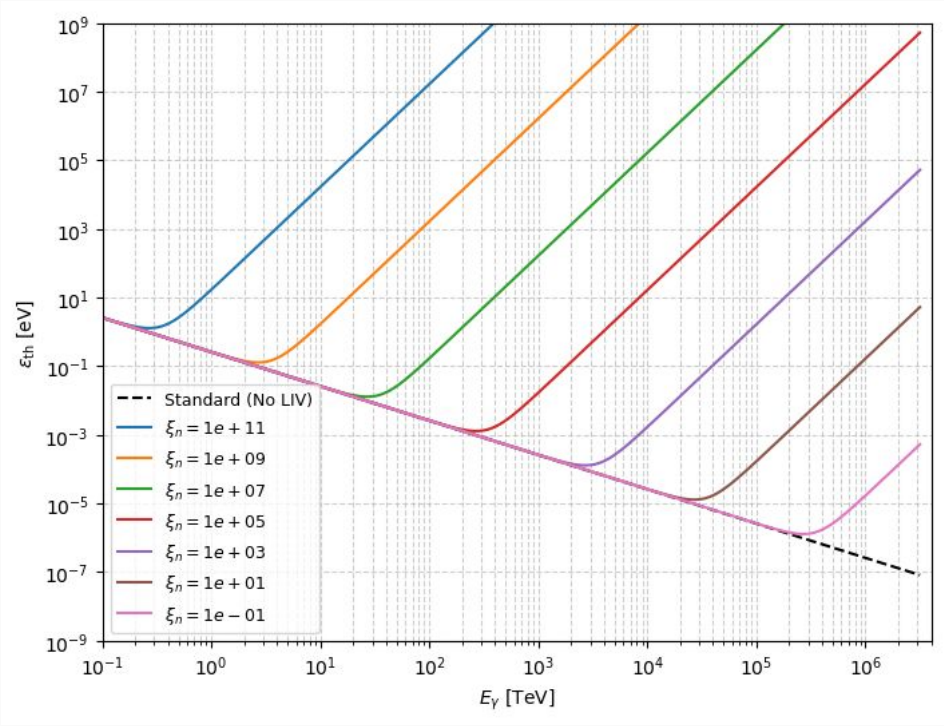


LIV effects: Shift in energy threshold [n=2]

LIV - Superluminal effect (S=-1)



LIV - Subluminal effect (S=+1)



LIV effects: EBL opacity computation [n=1]

Abdalla & Böttcher (2018)

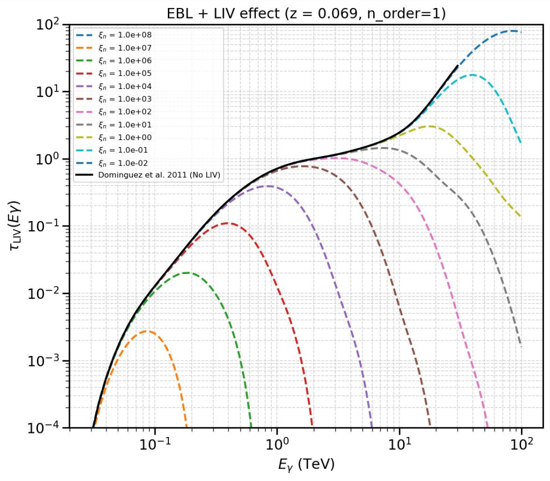
$$s(z)_{max} = 4\epsilon E_\gamma (1+z) + (m_\gamma c^2)^2$$

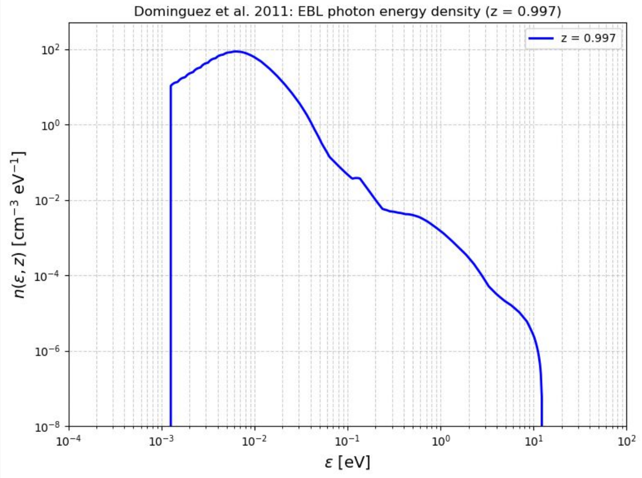
$$\tau_{\gamma\gamma}(E_\gamma, z_s) = \frac{c}{8E_\gamma^2} \int_0^{z_s} \frac{dz}{H(z)(1+z)^3} \int_{\epsilon_{min}}^{\infty} \frac{n(\epsilon, z)}{\epsilon^2} \int_{s_{min}}^{s(z)_{max}} [s - (m_\gamma c^2)^2] \sigma_{\gamma\gamma}(s) ds$$

$$\epsilon_{min} = \frac{m^2 c^4}{E_\gamma} + S \frac{E_\gamma^2}{4E_{LIV}}$$

$$s_{min} = 4(m_e c^2)^2$$

$$(m_\gamma c^2)^2 \equiv S \frac{E^3 (1+z)^3}{E_{LIV}}$$





LIV effects: EBL opacity computation [n=2]

$$s_{max}(z) = 4\epsilon_\gamma E_\gamma (1+z) + \delta_{(n=2)}$$

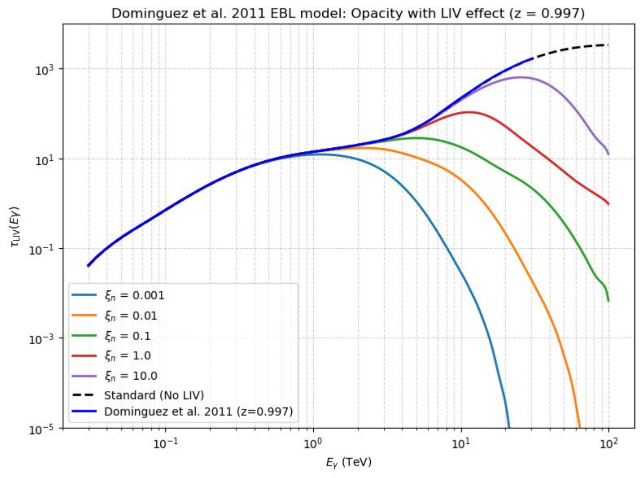
Abdalla & Böttcher (2018)

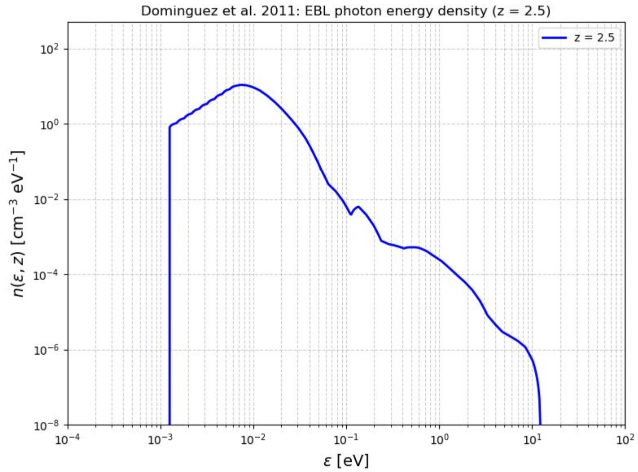
$$\tau_{\gamma\gamma}(E_\gamma, z_s) = \frac{c}{8E_\gamma^2}\int_0^{z_s} \frac{dz}{H(z)(1+z)^3}\int_{\epsilon_{min}}^{\infty} \frac{n(\epsilon, z)d\epsilon}{\epsilon^2}\int_{s_{min}}^{s_{max}} [s - \delta_{(n=2)}]\sigma_{\gamma\gamma}(s)ds$$

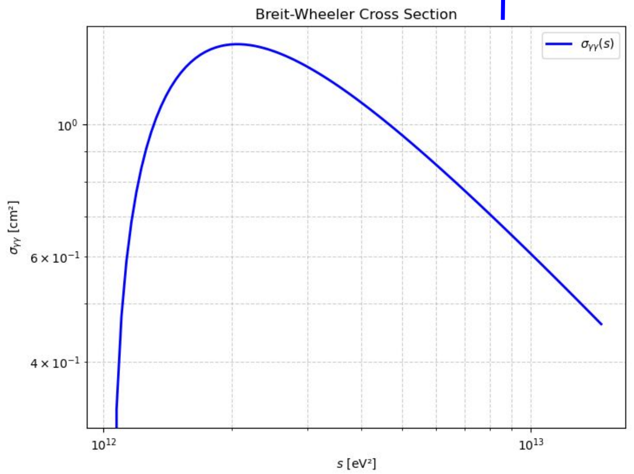
$$\epsilon_{min} = \frac{m_e^2 c^4}{E_\gamma} + S\frac{E_\gamma^3}{4E_{LIV}^2}$$

$$s_{min} = 4(m_e c^2)^2$$

$$\delta_{(n=2)} = S\frac{E_\gamma^4 (1+z)^4}{E_{LIV}^2}$$

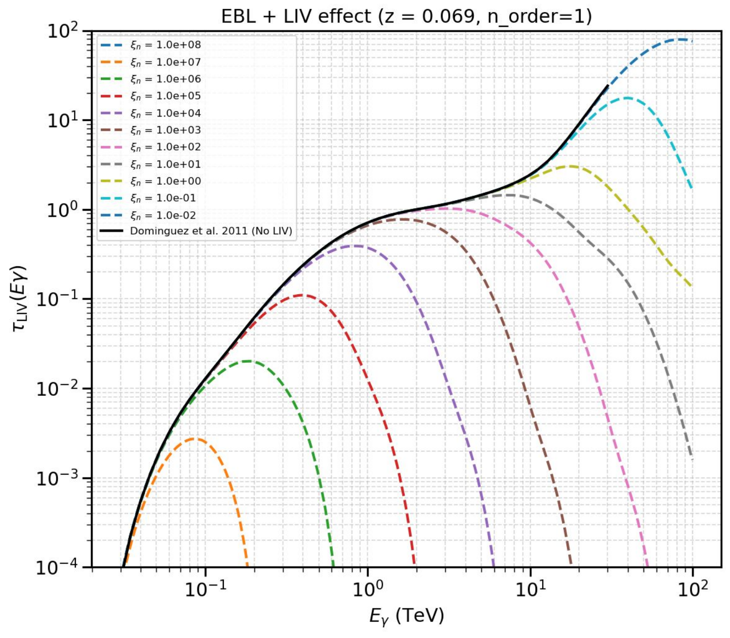


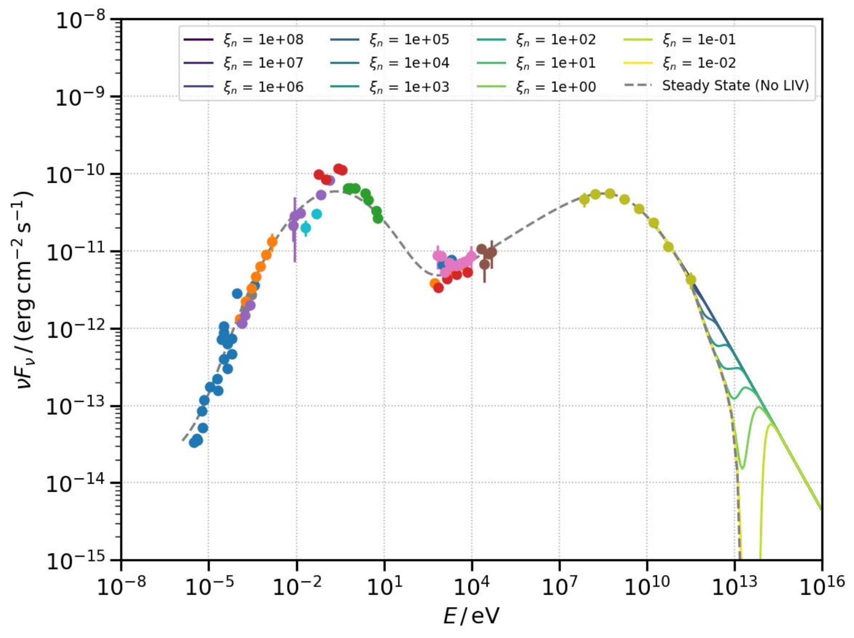




LIV effects: Absorption features in gamma-ray spectra

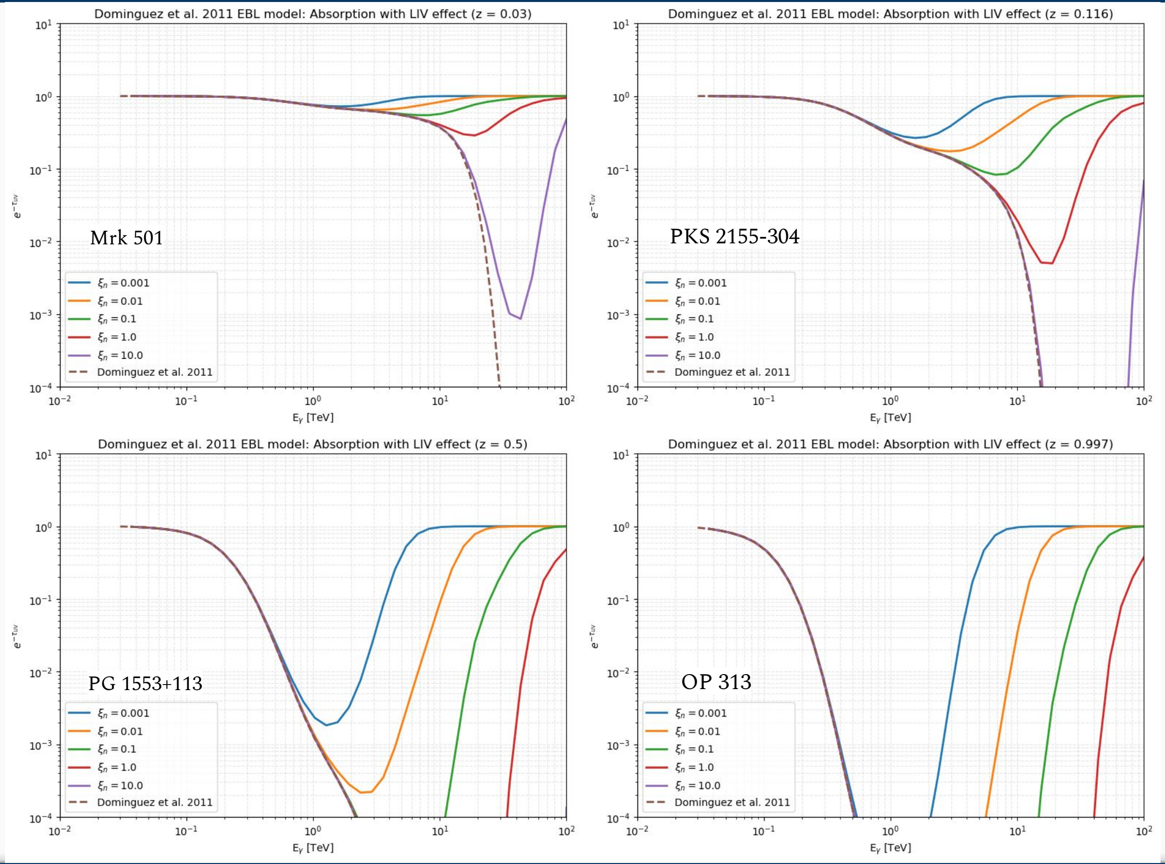
- ❑ Anomalous transparency at VHE: an excess in the gamma-ray flux at TeV energies is expected due to LIV.
- ❑ Detecting such features requires precise measurements of the VHE spectra of extragalactic sources.





Example: Linear LIV effects applied to the SED fit of BL Lac (z=0.069) on a historical dataset (SSDC). The spectral features appear at VHE.

LIV effects [n=1]: Absorption features in gamma-ray spectra



Project in Łódź: AGN modelling + LIV effects

AGNpy - Nigro et al. (2022) A&A 660, A18.
A python package focusing on the modelling and computation of the radiative processes of jetted AGN.

Supports/Includes: Synch+SSC, EC scattering (BLR, Dusty Torus), Disk luminosity, wrappers to fit with gammapy, tools for load experimental data and adding systematic errors.

v0.4.0

>> Only supports computations of steady-state solutions.
  > Intrinsic delays are not considered in the modelling.
  > Not implemented: particle injection, energy gains/losses etc.

>> No LIV effects included in the EBL absorption.

>> No support for modelling an inhomogeneous blob.

>> No interacting multi-zone modelling.

PROJECT IMPLEMENTATION

AGN MODELLING for ToF studies:

- ✓ Add time-dependent modelling method into AGNpy.
- ✓ Add effects of particle injection/escape
- ✓ Compare computed results with other codes.
- ☐ (IN PROGRESS) Apply the ToF method to MWL data from AGN flares

LIV STUDIES (Spectral Method):

- ✓ Add the LIV effects on the EBL absorption.
  - ✓ >> 1st and 2nd order corrections
  - ✓ >> Incorporated as spectral model in Gammapy
- ✓ Obtain MWL data for AGN flares (BL Lac)
- ☐ (IN PROGRESS) Fitting using AGNpy + LIV effects in the EBL absorption

Time dependent AGN modelling with AGNpy

Input:
>> Blob parameters (R, z, D, B, n_e)

>> Initial electron density distribution (e.g. PL, BPL, LogParabola, etc..)

>> A list of energy change rate functions (e.g. synchrotron + SSC)

Algorithm:

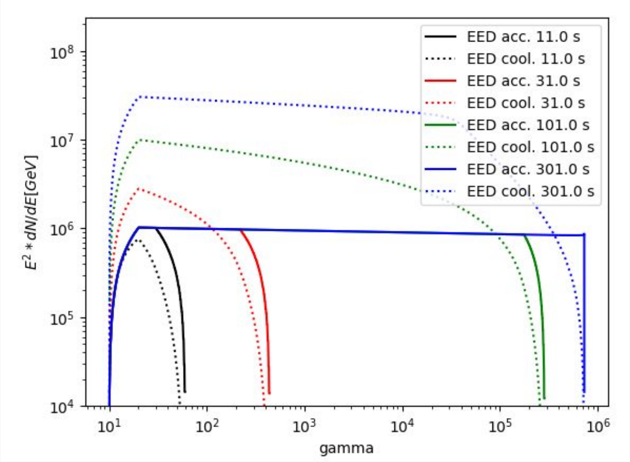
>> Computes the electron distribution changes with time, from the combined functions, using numerical methods.

>> Intelligent time splitting algorithm.

>> Acceleration, cooling and energy gains/losses are computed.

Output:

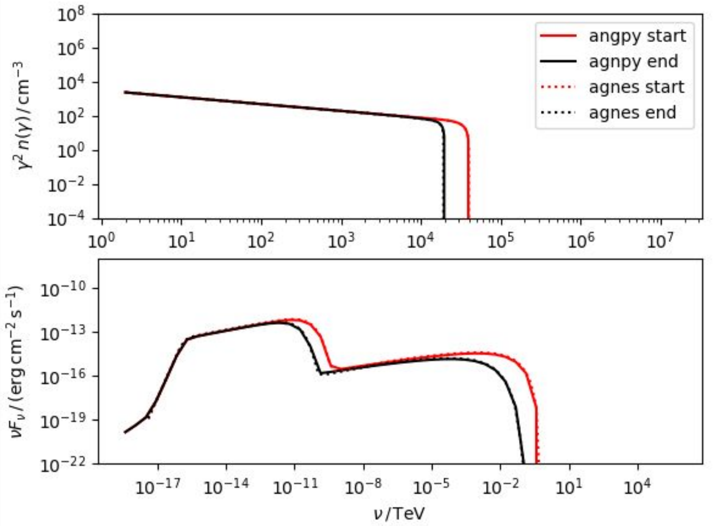
>> A new electron density distribution.



Checks for time evolution with AGNpy:

>> Inhomogeneous scenario:
1st zone: acc+cooling (solid line)
2nd zone: cooling only (dotted line)

>> A monoenergetic distribution at gamma=10 is continuously injected into the 1st zone.



Comparison with AGNES code:

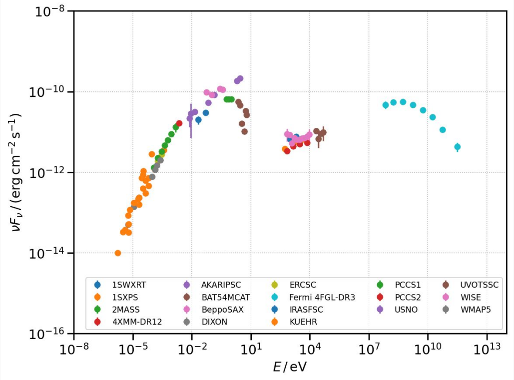
(https://gitlab.in2p3.fr/julien.bolmont/AGNES)

>> Synch dominated scenario

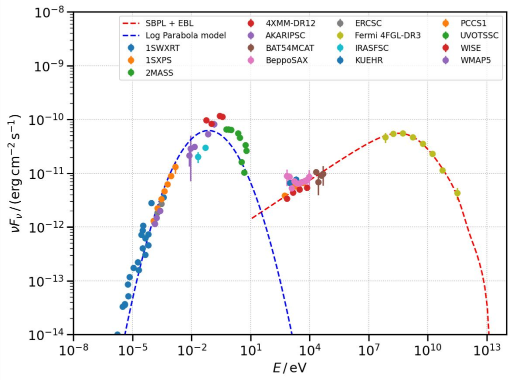
>> Same initial distribution: PL + CutOff

EBL Method Application: BL Lac (z=0.069)

Historical dataset (SSDC)



Fit: LogParabola + Smooth Broken Power-Law (SBPL)



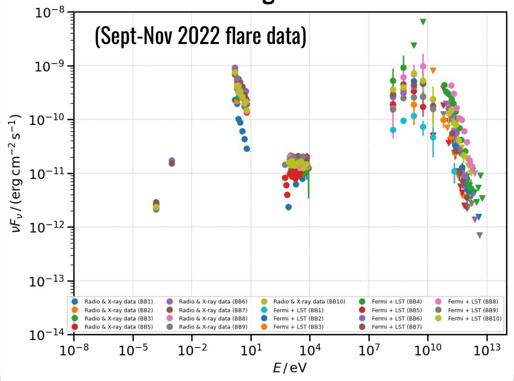
LogParabola:

$$\phi(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log\left(\frac{E}{E_0}\right)}$$

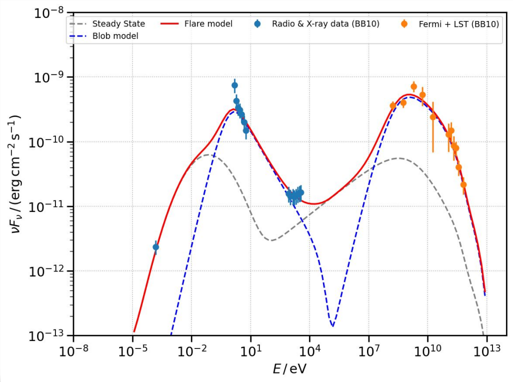
Smooth Broken Power-Law (SBPL):

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma 1}\left(1+\frac{E}{E_{break}}^{\frac{\Gamma 2-\Gamma 1}{\beta}}\right)^{-\beta}$$

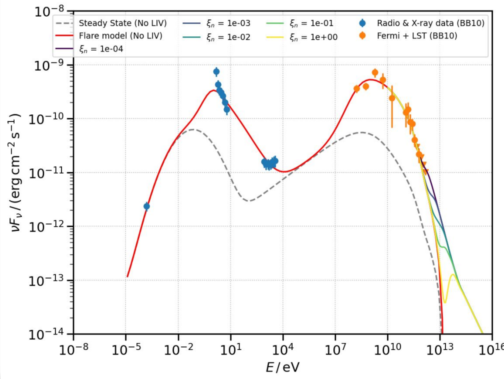
MWL datasets including VHE data from LST-1



Fit: Hist SED + one zone SSC model

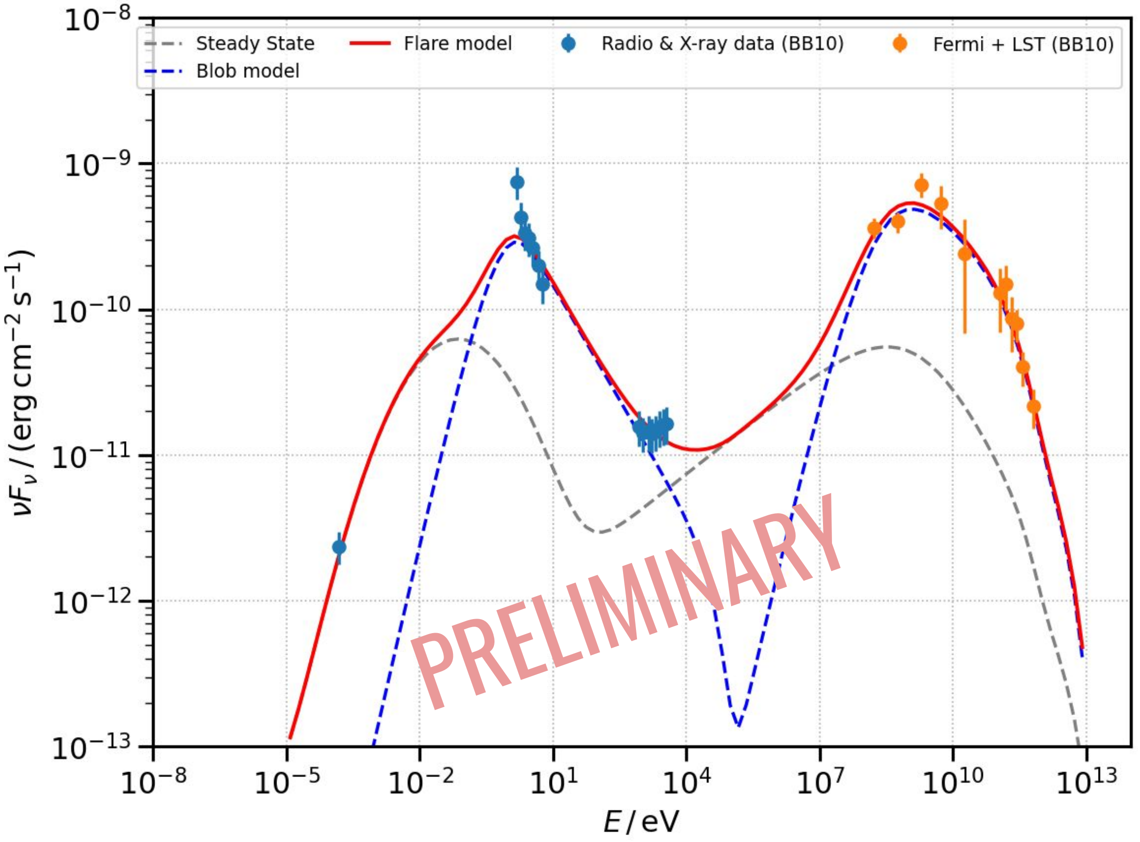


Estimation and constraints on the LIV parameter



Spectral points from J. Otero at SEA2024, subm. to A&A

AGN modelling and SED fit



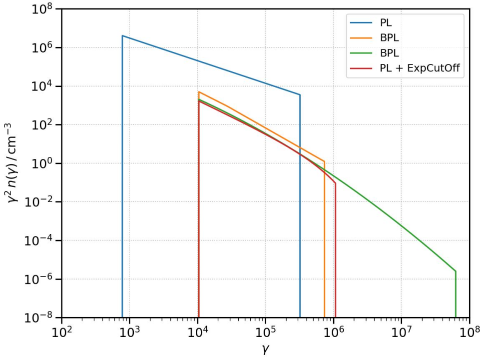
Steady State: LogParabola + SBPL

Blob Model: Synch + SSC (one zone)

===== Electron Distribution: Model Comparison =====

PowerLaw	AIC = 144.21	reduced χ^2 = 6.32
BrokenPowerLaw	AIC = 45.52	reduced χ^2 = 1.58
LogParabola	AIC = 42.19	reduced χ^2 = 1.40
ExpCutoffPowerLaw	AIC = 43.58	reduced χ^2 = 1.50

>>> Best-fitting model: LogParabola <<<

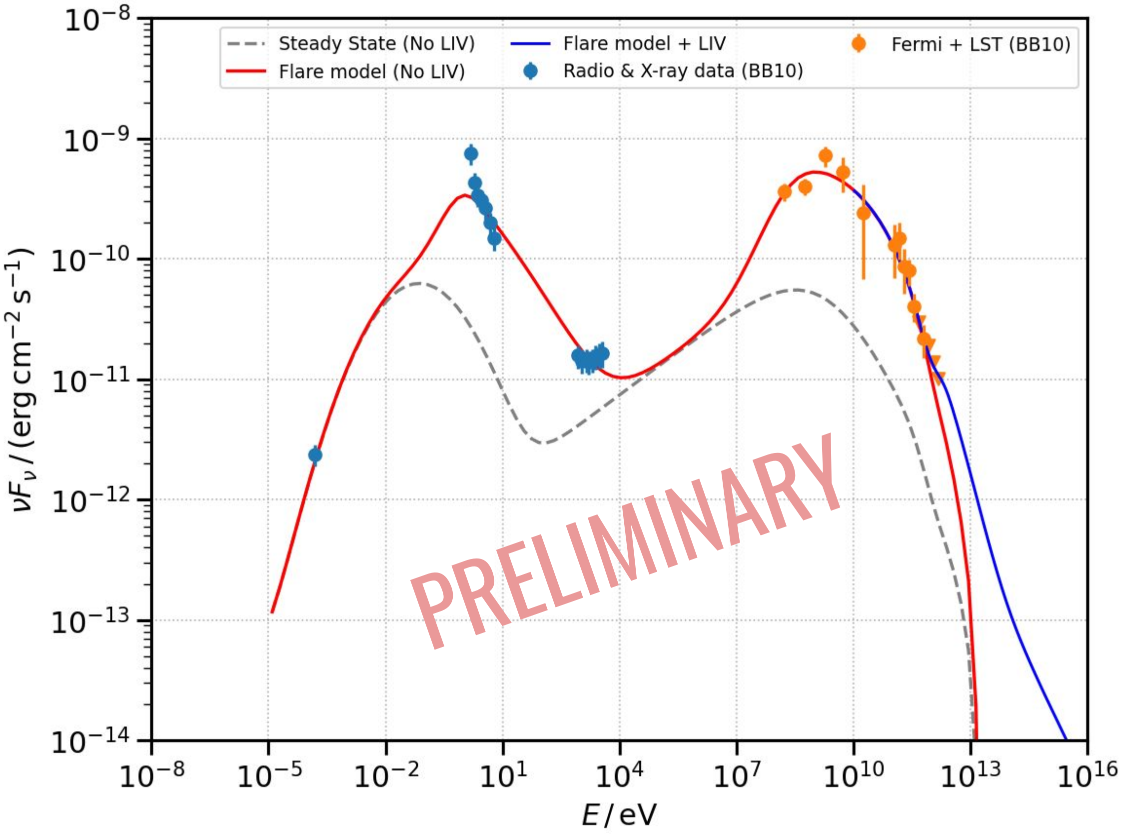


Blob Model Best-Fit Parameters:

delta_D = 30
B = 8.65e-2 G
R_blob = 1.3e+17 cm

Spectral points from J. Otero at SEA2024, subm. to A&A

Estimation and constraints on the LIV parameter



$$E_{QG,n} = \xi_n^{-1} \times E_{pl}$$

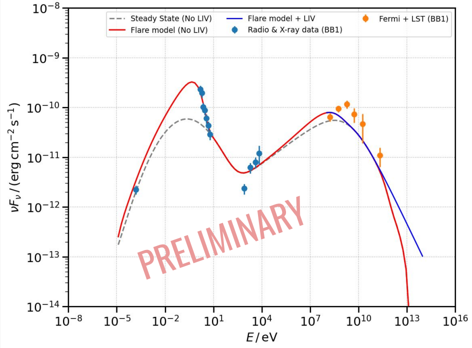
- ❑ The VHE data constrain the LIV effect on the EBL absorption.
- ❑ Best-fit value to the LIV parameter can be found for each dataset and the TS profiles can be combined (stacked) to predict a LIV limit.

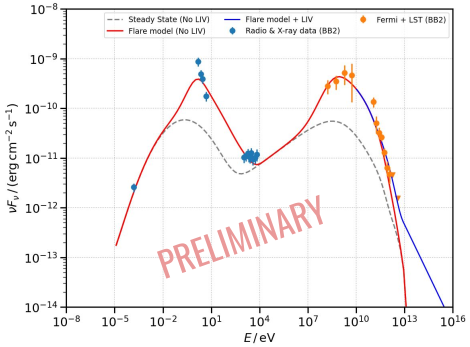
$$\Delta TS(\xi n) = TS(\xi n) - TSmin$$

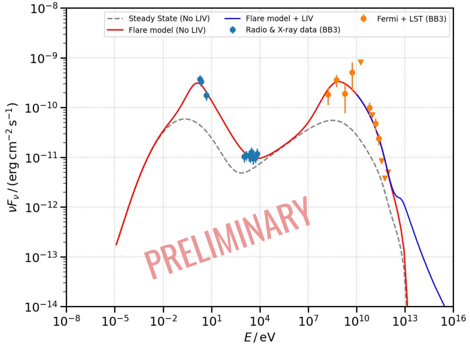
===== LIV Fittings =====
Optimization: Scipy Minuit Minimizer
Method: Migrad
free parameters: 7 (including xi_n)

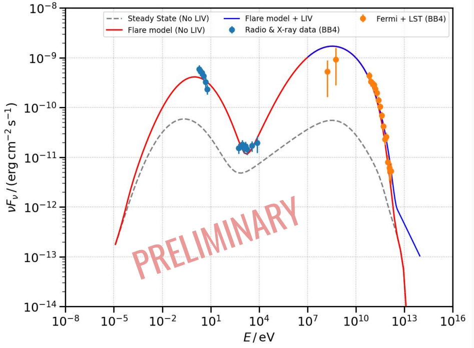
INTERPRETATION:
ξn=0 >> No LIV ;   larger values of ξn >> Stronger LIV effect

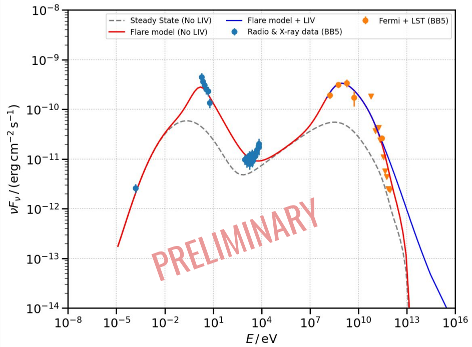
Flat TS profile >>>>> No LIV sensitivity

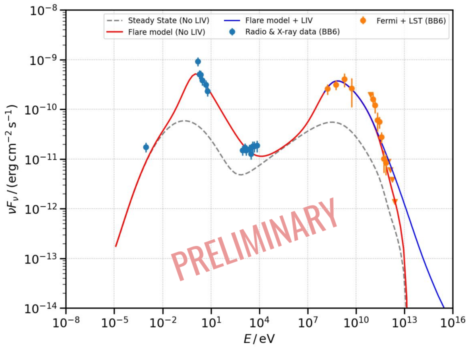


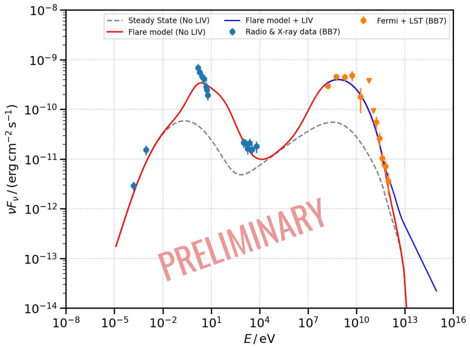


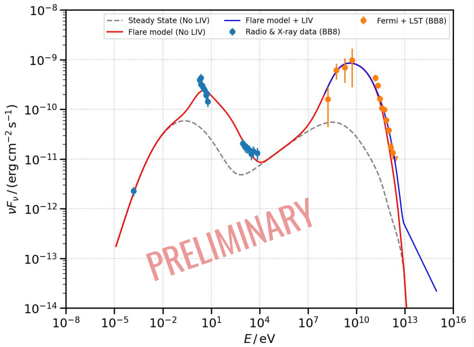


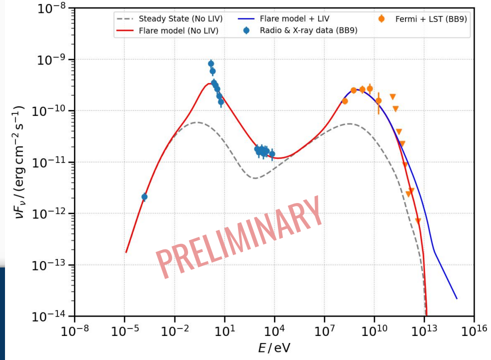


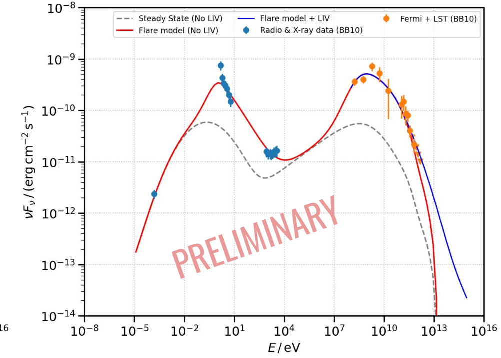












WORK IN PROGRESS:

- ✔ Best-fit model for 10 datasets provided for BL Lac.
- ❏ Estimation of LIV parameter for each dataset.
- ❏ Combine the results to get the first predicted LIV limit for a source using the EBL method and LST data.

PERSPECTIVES FOR THE FUTURE

AGN MODELLING

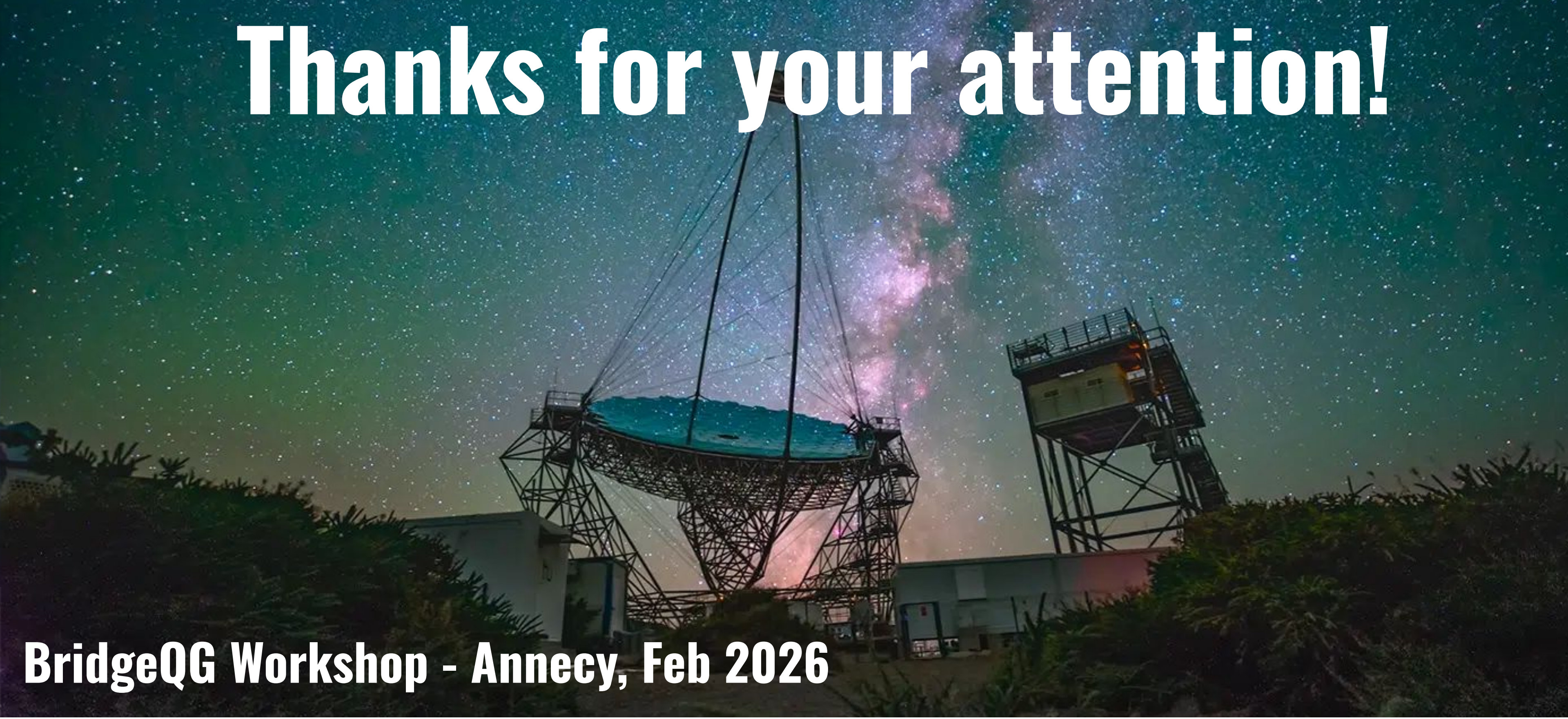
- ✓ Implementation for time-dependent modelling algorithm in AGNpy has been implemented and tested.

LIV STUDIES

- ❑ Spectral Method:
  - ❑ Finalize the estimation of the LIV parameter for the given datasets of BL Lac.
  - ❑ Check other VHE source candidates (MWL data + LST-1 observations: OP 313, …)
  - ❑ Preparing a publication to present the methodology and show initial results for BL Lac dataset.

- ❑ ToF Method:
  - ❑ Use the upgraded version of AGNpy to model and search for LIV induced time delays on selected blazar flares.
  - ❑ Check for the complementarity and compatibility of the results between the two methods.

Thanks for your attention!



BridgeQG Workshop - Annecy, Feb 2026

CTAO | LST COLLABORATION

UNIVERSITY OF LODZ

A. Rosales de León on behalf the Łódź working group:
J. Sitarek, W. Bednarek & G. Borkowski