Searching for LIV effects with SSTs and ASTRI

Tomislav Terzić

FIZRI Faculty of Physics
University of Rijeka

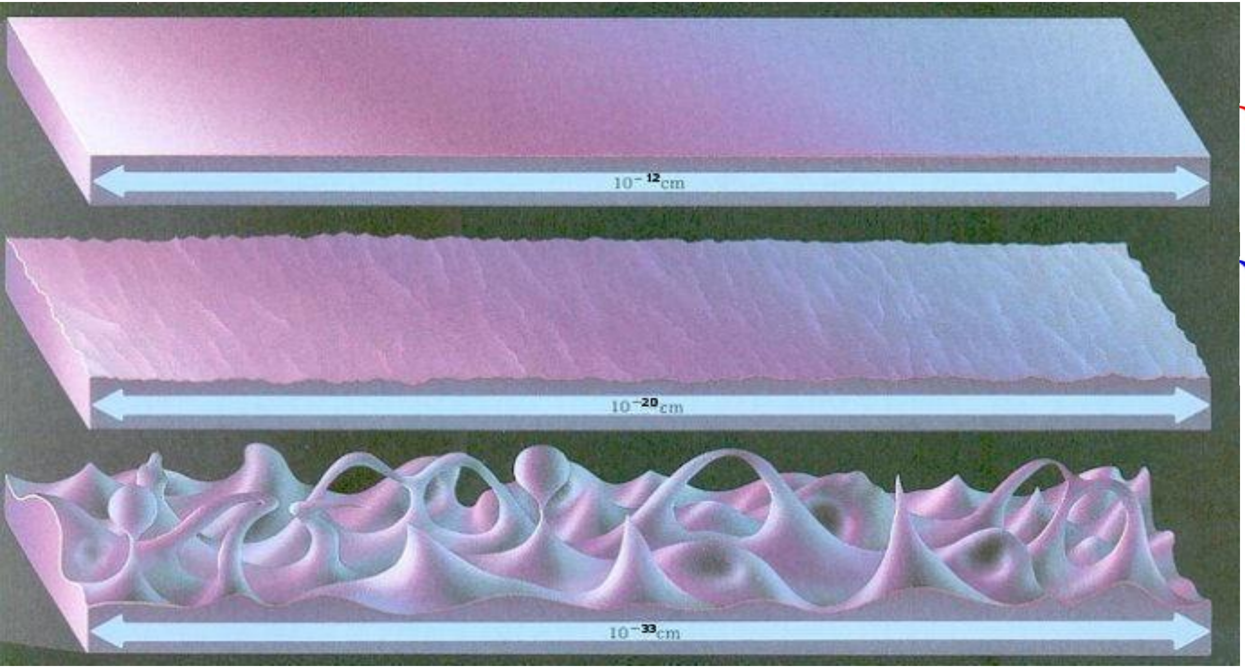
uniri-iz-25-119

SEXTEN CENTER FOR ASTROPHYSICS RICCARDO GIACCONI

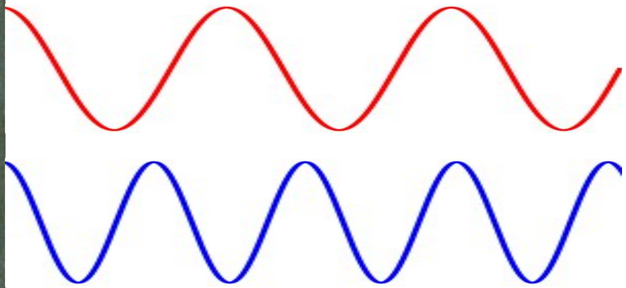
From 9 to 40: the SST Telescopes and Gamma-Ray Science with ASTRI and CTAO
Haus Sexten, 24 July 2026

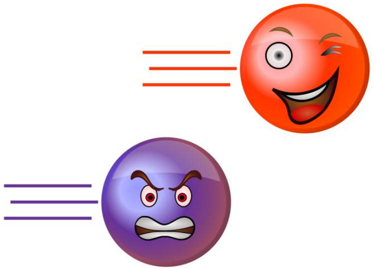
Hrvatska zaklada za znanost
IP-2022-10-4595

Lorentz invariance violation (LIV)



http://universe-review.ca/R01-07-quantumfoam.htm





Lorentz invariance violation (LIV)

- Modified photon dispersion relation
- Usual starting point in searches for effects of QG with gamma rays

S = ±1

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

photon energy

QG energy scale

Expectation:

$\mathrm{E_{QG,n}} = \mathcal{O}(E_{\mathrm{Pl}}) \simeq 1.22 \times 10^{19}\ \mathrm{GeV}$

- Not a direct consequence of any particular QG model
- Simple way of parametrizing “out of the ordinary” behaviour

Consequences of MDR

LIV reviews:

- Addazi et al. 2022 (arXiv:2111.05659) for a comprehensive review of QG models and tests with cosmic messengers
- Terzić et al. 2021 (arXiv:2109.09072) for a review focused on tests with gamma rays

- Energy dependent photon group velocity
- Modified reaction thresholds & cross sections
  - Breit-Wheeler $\gamma + \gamma_{EBL} \longrightarrow e^+ + e^-$
  - Bethe-Heitler $\gamma + N \longrightarrow e^+ + e^-$
  - Compton scattering → see Abdalla & Böttcher (2018); σ_{KN} needs to be derived in LIV framework
  - Synchrotron emission → energy range below ASTRI domain
  - Photon decay
  - Spontaneous gamma-ray emission

  } currently being revisited at theoretical level
  - …
- Vacuum birefringence → requires polarisation measurements
- …

Tiny but **cumulative** effects!

Energy dependent photon group velocity

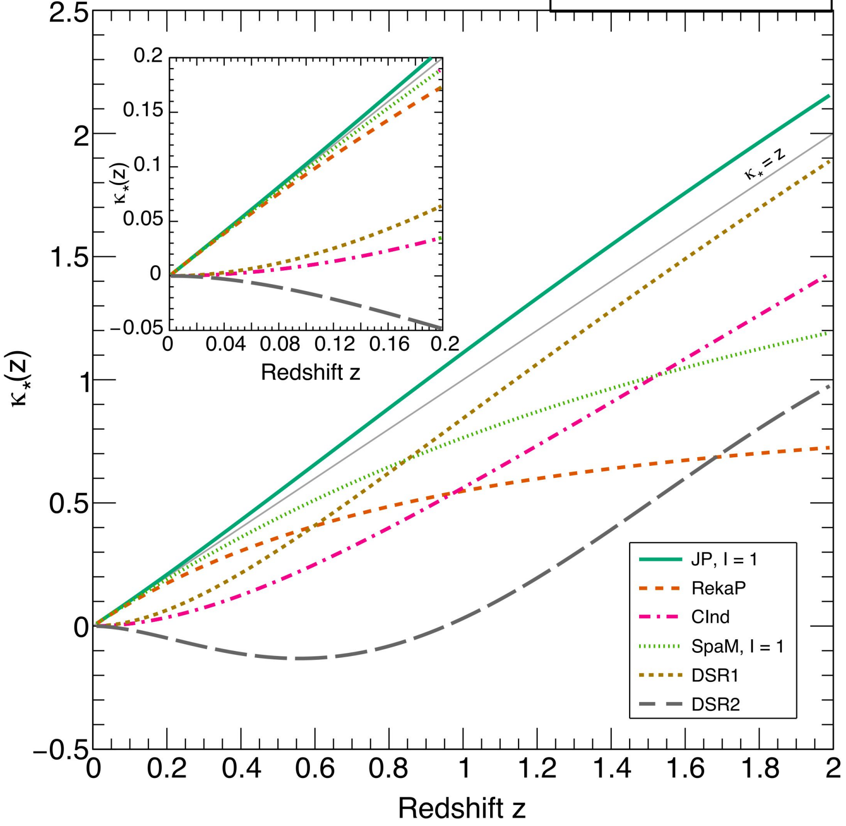
Caroff+ 2025

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

$$\Delta t_n \simeq \pm \frac{n+1}{2}\,\frac{E_h^n - E_l^n}{\mathrm{H}_0 E_{QG}^n}\,\kappa_n(z)$$

for JP model

$E_{\mathrm{QG},1}$	$\propto$	E_{max}	t_{var}^{-1}	$z_{\mathrm{s}}^{\sim 1}$
$E_{\mathrm{QG},2}$	$\propto$	E_{max}	$t_{\mathrm{var}}^{-1/2}$	$z_{\mathrm{s}}^{\sim 2/3}$



SST / ASTRI role

BL Lac flare sources for ASTRI and SSTs ?

Andreas Zech on Wednesday:

Some BL Lac / FR I sources to watch out for **VHE flares at the highest energies** :

Mrk 421 : spectrum during 2010 flare extends beyond 10 TeV, detected by ASTRI-1 and SST-1M

Mrk 501 : spectrum observed up to 20 TeV

M87 : spectrum observed up to 20 TeV

PKS 2155-304 : frequent and spectacular flares, spectrum observed up to ~5 TeV

1ES 1727+502 : VHE flaring detected with LHAASO > 1 TeV in 2024

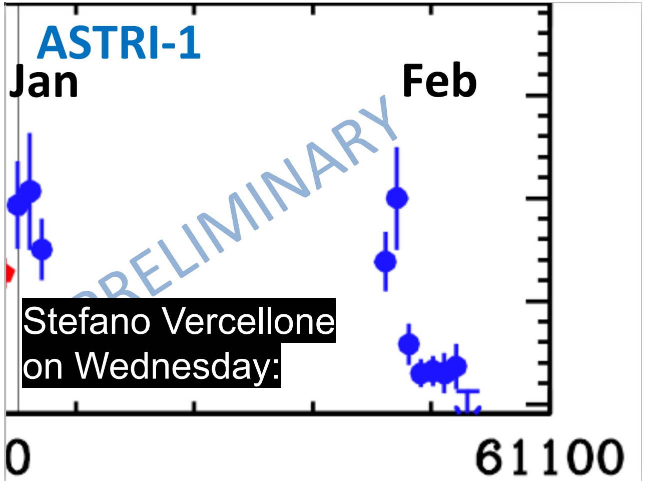
1ES 1426+428 : elevated state detected by VERITAS in 2021, spectrum extends >1 Tev

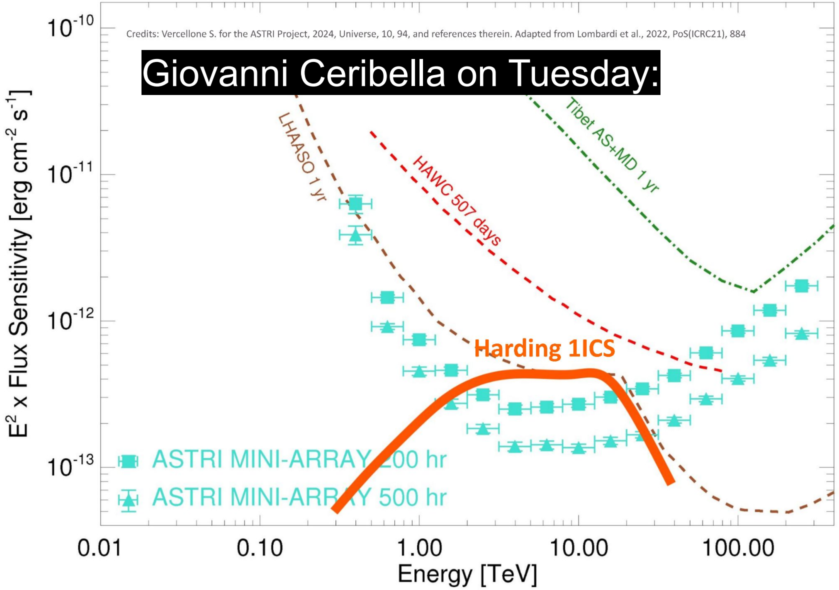
VER J0521+211 : large flare detected by VERITAS in 2020, spectrum extends >1 Tev

BL Lacertae : bright flare detected by LST-1 in 2022, spectrum extends >1 Tev

$$E_{\mathrm{QG},1} \quad \propto \quad E_{\max} \quad t_{\mathrm{var}}^{-1} \quad z_{\mathrm{s}}^{\sim 1}$$

$$E_{\mathrm{QG},2} \quad \propto \quad E_{\max} \quad t_{\mathrm{var}}^{-1/2} \quad z_{\mathrm{s}}^{\sim 2/3}$$



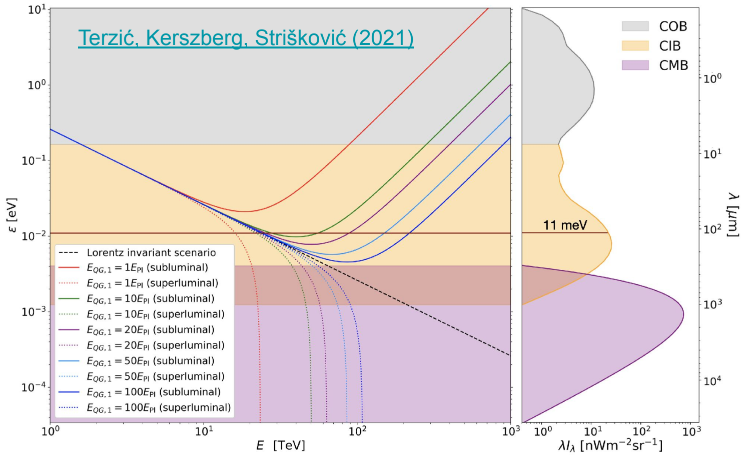


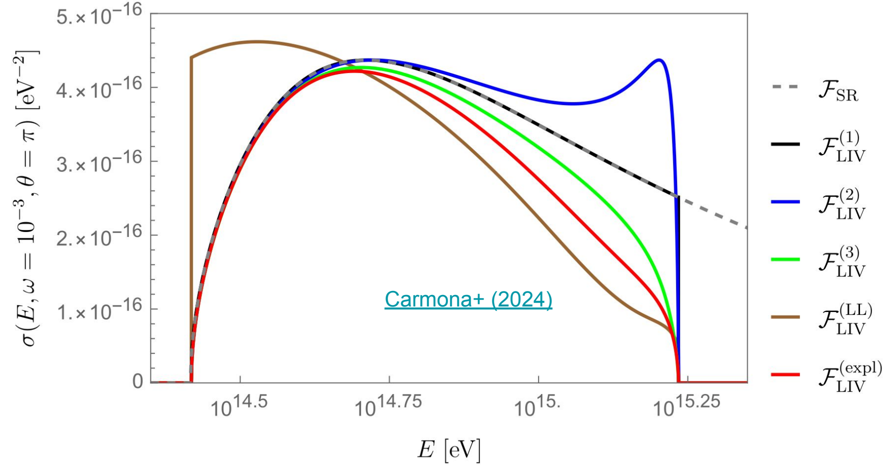
yLIV Working Group

- Present collaboration:
  H.E.S.S. – LST – MAGIC – VERITAS
- Energy range: ~20 GeV – 100 TeV
- Combining all available data
  - Increases statistics
  - Sources at different distances
  - Redshift dependency on the LIV effect
  - Different (types of) sources
    - Reduces the influence of source intrinsic effects
- Analysis code written and tested
- Currently analysing real data for the paper

[Bolmont+ 2022]

LIV-modified gamma-ray absorption



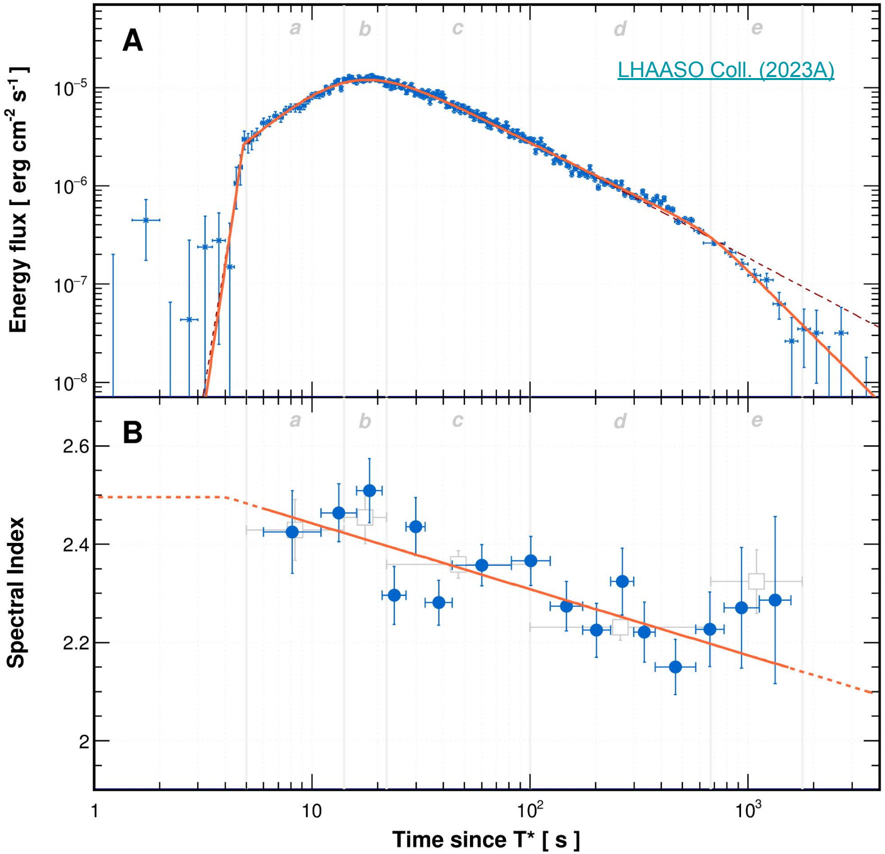


Favourable source characteristics

- Bright source → high y-ray flux → rich statistics
- Hard spectrum → ample events at the highest energies
- Steady spectrum → lower systematic uncertainties
- Faraway source → accumulated LIV effect
- But not too far → complete y-ray absorption regardless of LIV

GRB 221009A

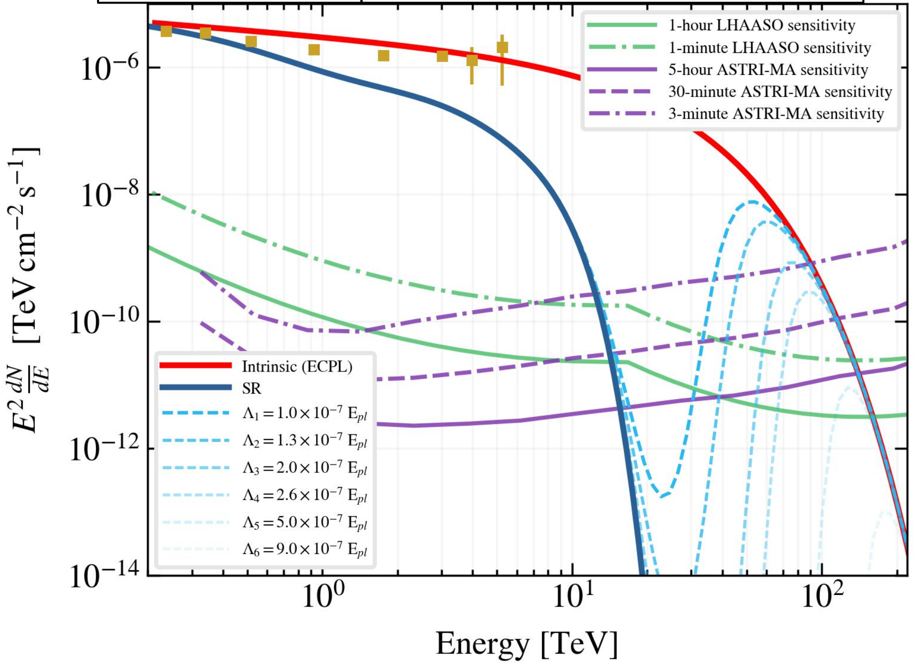
- Long GRB observed by LHAASO (2023A, 2023B): T_0 — T_0 + ~ 6000 sec
- BOAT (Brightest of all time) ✅
- The LHAASO-WCDA: > 6.4 x 10^4 γ-rays in [200 GeV, 7 TeV] range ✅
- LHAASO-KM2A: γ-rays up to ~ 13 TeV ✅
- $\boldsymbol{\alpha}$ ~ log(t) ❌ (but we've got it covered)
- redshift z = 0.151 ✅
- T_0 + 4536 s Carpet-2 detected a single photon-like event of E = 300 TeV from BOAT direction (Carpet-3 Coll. 2025)



Looking for LIV in BOAT

Adapted from Reščić+ (2026)

quadratic LIV (n = 2)



- Maximum measured energy: E_{max} = 13 TeV
- Intrinsic spectrum:
  - reconstructed intrinsic spectrum in the T_0 + 231 — T_0 + 2000 s (first 5 reported time bins) and weight-averaged over time (procedure from Miceli+ 2024)
  - scale flux to fit the flux points from the T_0 + 231 — T_0 + 240 s (yellow points in the plot)
  - power-law with exponential cutoff to motivate E_{max}

$$\frac{dN_{\rm int}}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-E/E_{\rm cut}\right)$$

α = 2.3, E_0 = 1 TeV, E_{cut} = 13 TeV

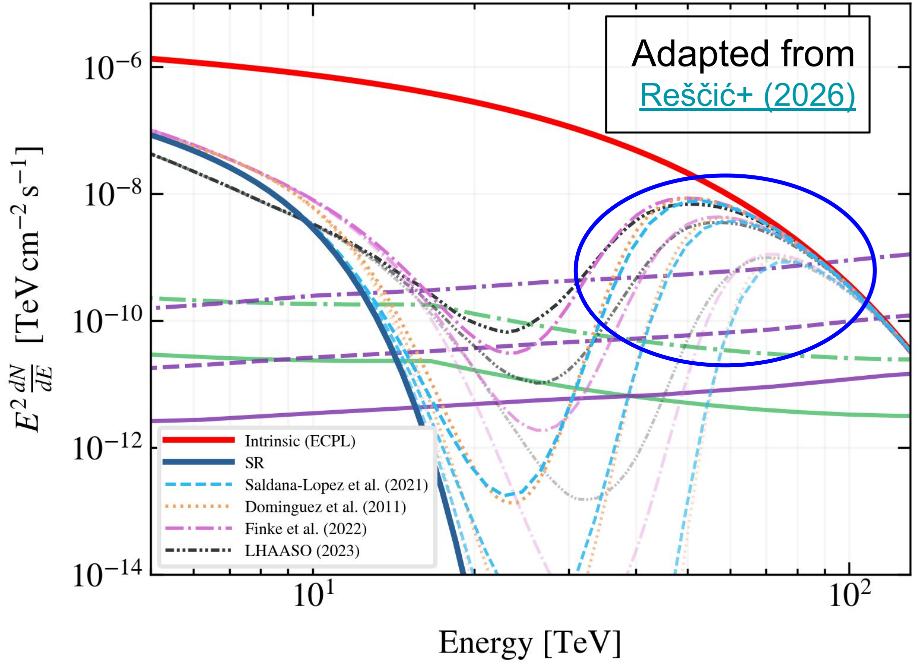
- EBL model: Saldana-Lopez (2021)
- LHAASO sensitivity curves

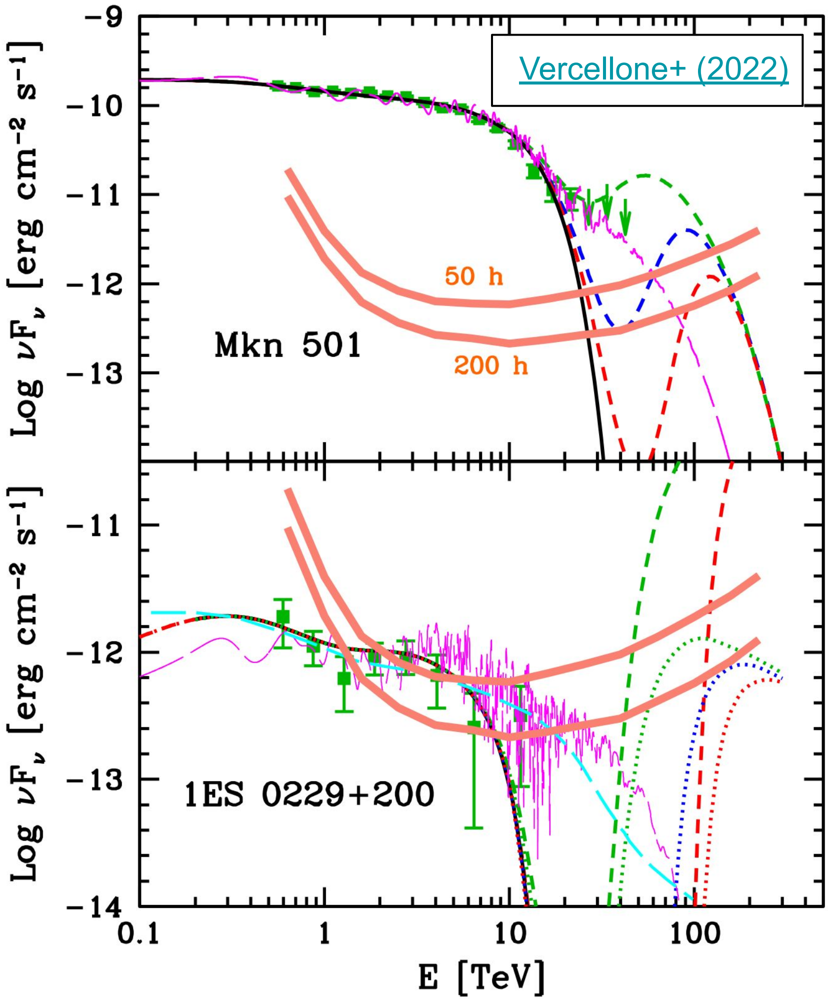
$$Sens(T_{\rm obs}) = Sens(1{\rm y})\sqrt{1\,{\rm year}/T_{\rm obs}}$$

- ASTRI sens. curves provided by S. Vercellone (Grazie mille!!), update of S. Lombardi+ (2022)
- Caveat: ASTRI sens. curves for Zd = 20 deg, GRB 221009A location from Canarias Zd = 30 – 55 deg

EBL model dependence

- EBL models: Saldana-Lopez (2021), Finke (2022), Dominguez (2011)





Maximum flux vs LIV energy scale

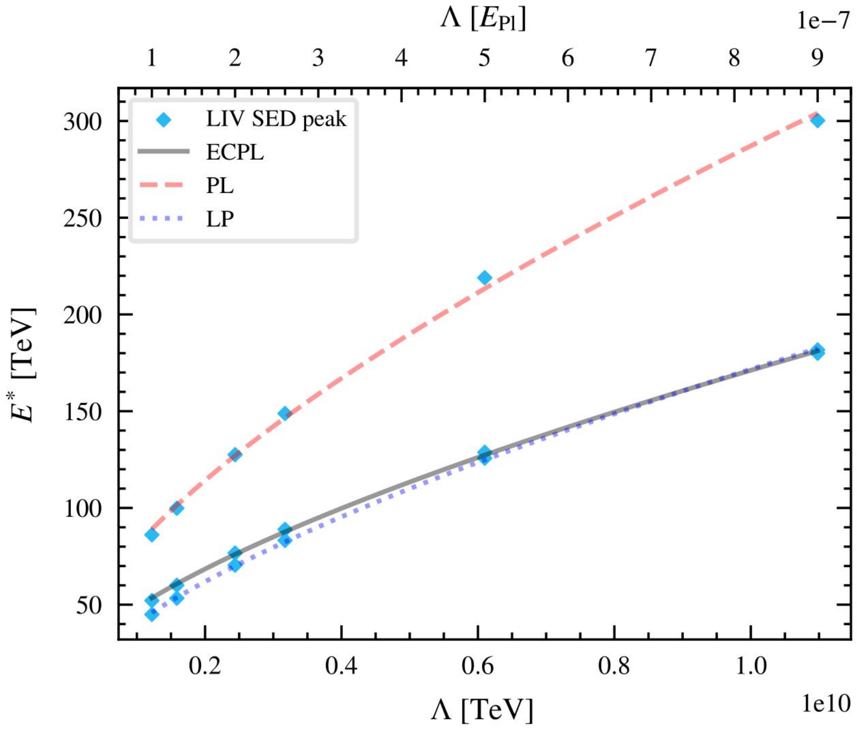
Reščić+ (2026)

- LIV energy scale vs. Maximal measured energy

$$E^*(\Lambda) = a\Lambda^{2/3} + b$$

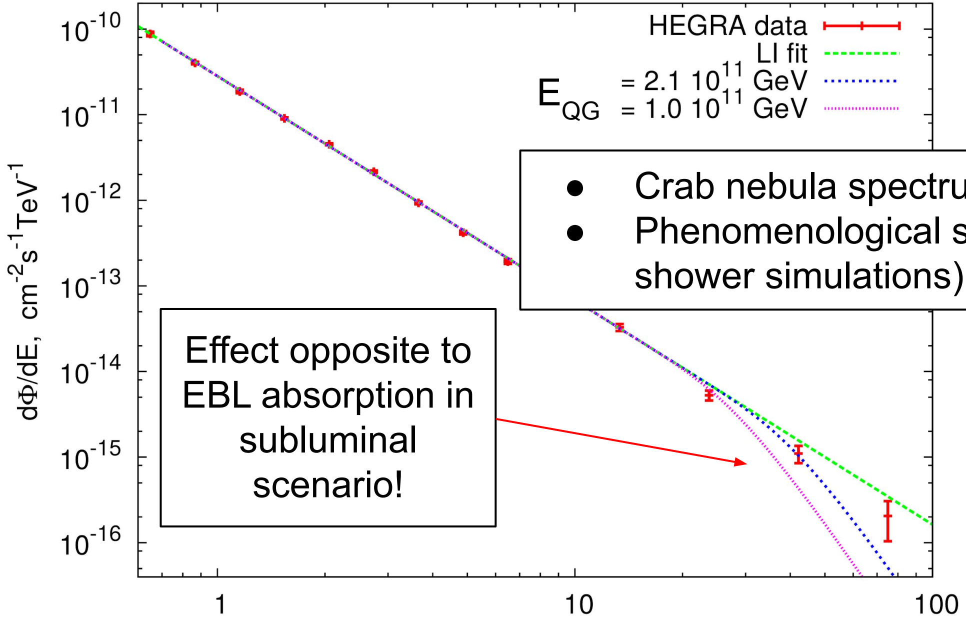
- Relation invariant of the intrinsic spectrum

Spectral model	a	b
ECPL	3.4×10^{-5}	1.5×10^{1}
PL	5.7×10^{-5}	2.4×10^{1}
LP	3.6×10^{-5}	4.8

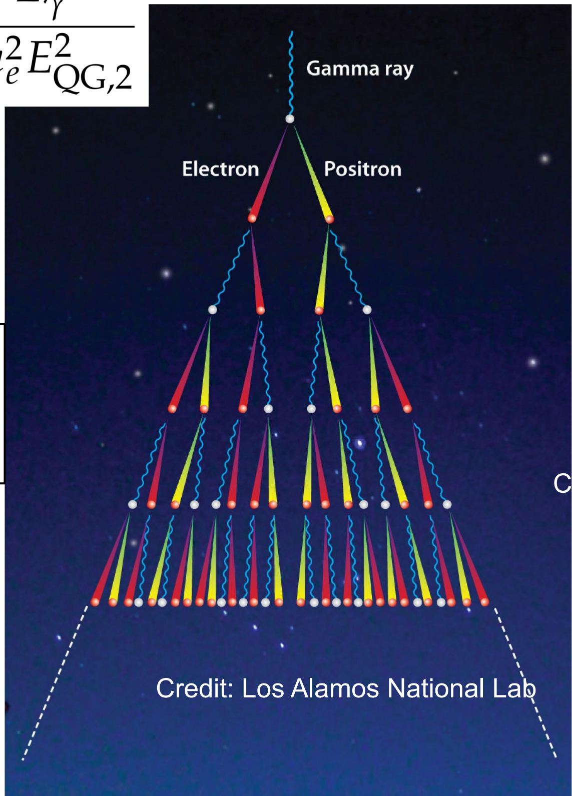


LIV impact on gamma-ray detection

$$\sigma_{\rm BH} = \frac{28 Z^2 \alpha^3}{9 m_e^2}\left(\log \frac{183}{Z^{1/3}} - \frac{1}{42}\right) \longrightarrow \frac{\sigma_{\rm BH}^{\rm LIV}}{\sigma_{\rm BH}} \simeq \frac{12 m_e^2 E_{\rm QG,2}^2}{7 E_\gamma^4} \cdot \log \frac{E_\gamma^4}{2 m_e^2 E_{\rm QG,2}^2}$$



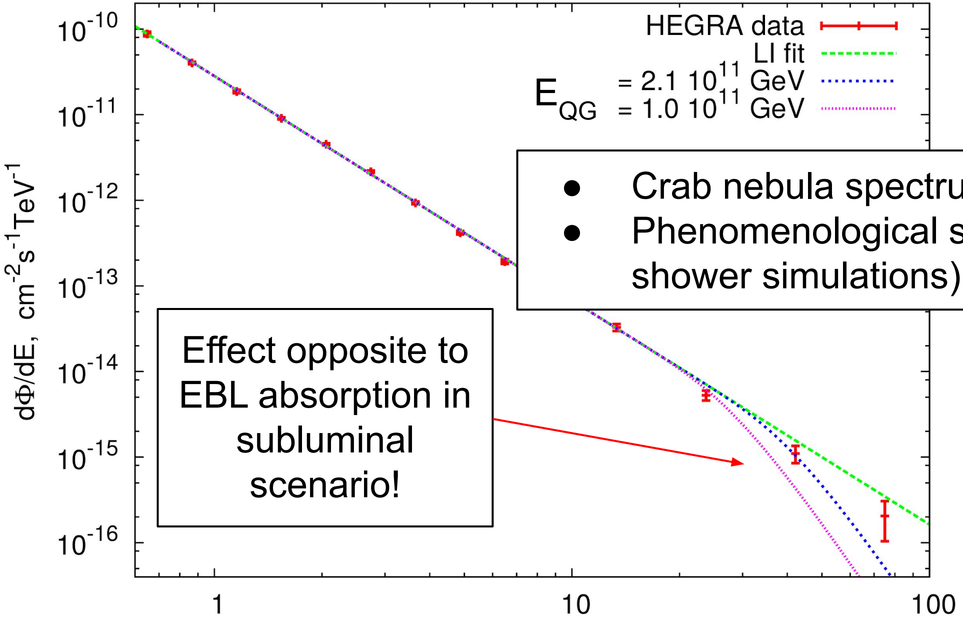
- Crab nebula spectrum (Rubtsov+ 2017)
- Phenomenological study (no LIV-modified shower simulations)



C

LIV impact on gamma-ray detection

$$\sigma_{\rm BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{1/3}} - \frac{1}{42}\right) \longrightarrow \frac{\sigma_{\rm BH}^{\rm LIV}}{\sigma_{\rm BH}} \simeq \frac{12m_e^2E_{\rm QG,2}^2}{7E_\gamma^4}\cdot\log\frac{E_\gamma^4}{2m_e^2E_{\rm QG,2}^2}$$



Effect opposite to EBL absorption in subluminal scenario!

- Crab nebula spectrum (Rubtsov+ 2017)
- Phenomenological study (no LIV-modified shower simulations)

Shower simulations with LIV

BridgeQG

C8

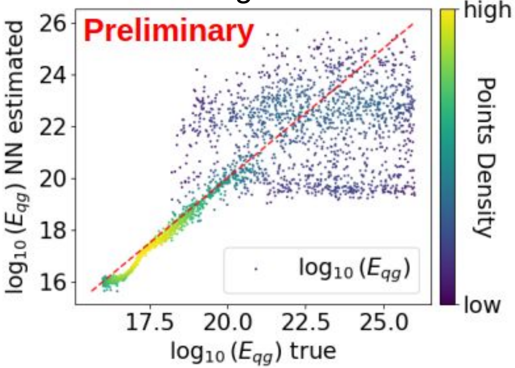
Combining LIV effects

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\varkappa\bar{\psi}\gamma^i D_i\psi + \frac{ig}{M^2}D_j\bar{\psi}\gamma^i D_i D_j\psi + \frac{\xi}{4M^2}F_{kj}\partial_i^2 F^{kj},$$

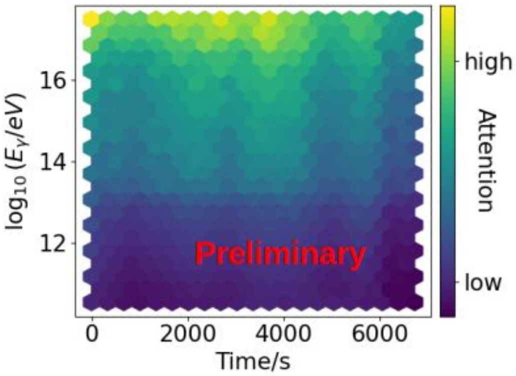
Rubtsov+ 2012

- n = 1: time delays + modified interactions + vacuum birefringence
- n = 2: time delays + modified interactions (Rubtsov+ case)

ANN-VIL – attempt at combining LIV effects

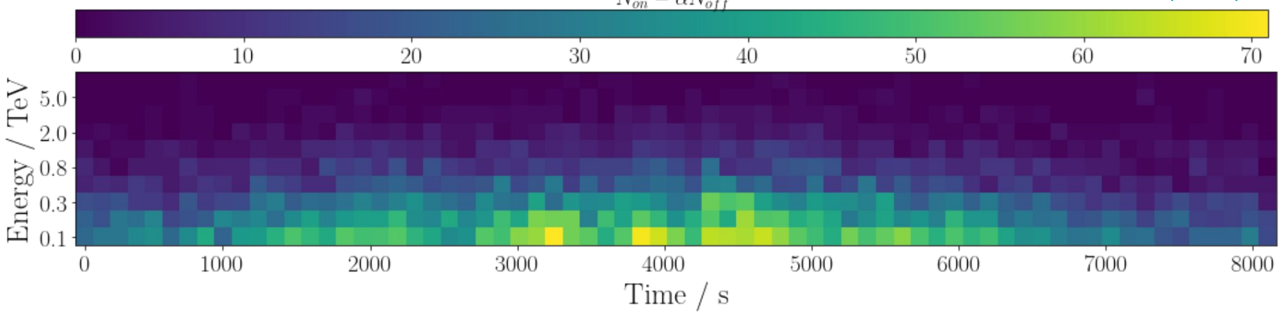


Terzić & Mrakovčić (2025)



Mrk 421 MAGIC flare 2014

Strišković (2025)



Takeaways

- SSTs and ASTRI window towards LIV wide open
- Main advantage: sensitivity to highest energies among Cherenkov telescopes
- Time delays
  - Focus on highly variable sources in the E > 1 TeV domain (blazars, pulsars, GRBs?)
- gamma-ray absorption
  - Focus on spectral recovery region (no absorption → no EBL-model dependence)
  - Use proper LIV-modified reaction thresholds and cross sections
- EM atmospheric showers development → the higher the energy, the better
- Testing coexisting LIV effects on individual samples

Backup

ToF systematics

Bolmont+ 2022

Table A1. Summary of systematic uncertainties for all sources and combinations simulated for the J&P case.

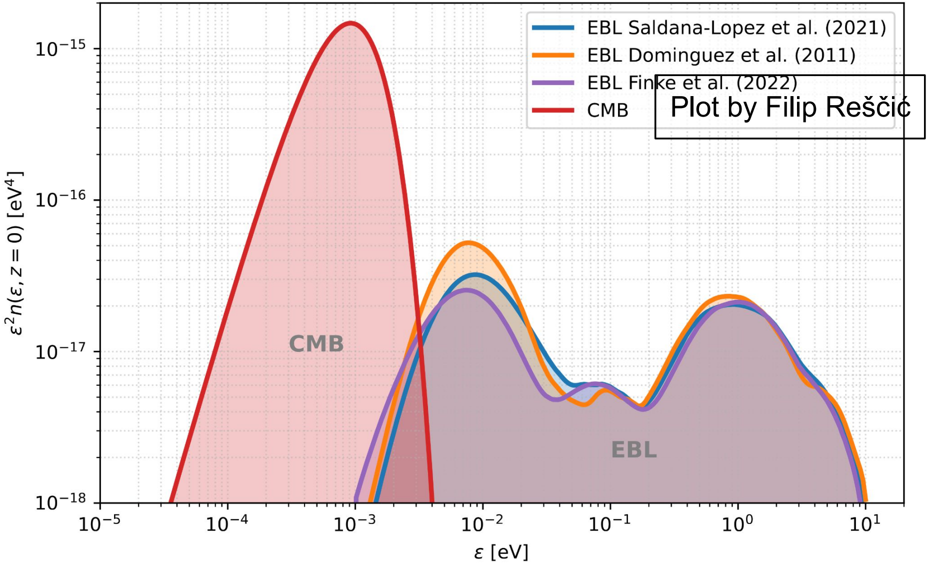
Source	Correction order	Template statistics (s.TeV^{-n})	Energy scale (s.TeV^{-n})	Background normalization (s.TeV^{-n})	Uncertainty on power law index (s.TeV^{-n})	Distance/redshift uncertainty (s.TeV^{-n})	Reconstruction uncertainty (s.TeV^{-n})	All syst. combined (s.TeV^{-n})
GRB 190114C	$n = 1$	17.8	6.9	8.0	9.4	< 7.7	3.0	25.6
	$n = 2$	9.4	12.4	1.7	15.4	< 9	4.2	24.1
PKS 2155-304	$n = 1$	101	11.7	< 20	< 22	17.8	< 3.3	107
	$n = 2$	21.8	19.3	0.7	8.1	12.0	< 2.2	37.4
Mrk 501	$n = 1$	155	56	< 51	49	1.	< 8.5	197
	$n = 2$	11.2	18.3	< 10.3	9.3	0.19	< 1.6	28.8
PG1553+113	$n = 1$	631	150	324	< 361	112	< 64	727
	$n = 2$	916	638	537	< 552	338	< 112	1282
Crab V	$n = 1$	897	137	< 73	142	145	< 25	1135
	$n = 2$	1141	410	< 264	694	265	< 174	1820
Crab M	$n = 1$	371	66	7	23	74	< 11	416
	$n = 2$	167	64.5	61	24	48	< 72	190
Vela	$n = 1$	1.36×10^4	1.03×10^4	0.46×10^4	$< 1.3 \times 10^4$	1.30×10^3	$< 5.87 \times 10^3$	2.28×10^4
	$n = 2$	1.0×10^5	2.05×10^5	0.48×10^5	$< 1.5 \times 10^5$	1.57×10^5	$< 0.95 \times 10^5$	3.05×10^5
Crab (M+V)	$n = 1$	357	49	< 56	32	61	< 32	398
	$n = 2$	161	59	45	59	38	< 83	197
PSR	$n = 1$	355	52	< 58	38	58	< 11	394
	$n = 2$	90	71	49	24	62	< 55	138
AGN	$n = 1$	89.5	12	< 15	3.7	15.8	< 2.9	94.9
	$n = 2$	10.1	11.1	< 6	6.2	3.4	< 1.3	19.7
AGN+PSR	$n = 1$	85	11	< 18	5	15	< 2.9	91
	$n = 2$	9.6	10.9	< 8	5.9	4.5	< 1.1	17.8
GRB+AGN	$n = 1$	17.8	5.8	6.8	8.3	1.4	3.3	24.5
	$n = 2$	6.8	7.8	< 6.6	9.0	1.7	1.4	16.2
GRB+PSR	$n = 1$	17.5	6.7	7.9	9.1	1.0	3.2	24.9
	$n = 2$	8.1	11.3	1.6	12.7	2.8	< 1.1	19.4
All	$n = 1$	18.0	5.8	6.7	8.2	1.5	4.1	24.8
	$n = 2$	7.5	7.7	< 6.2	8.2	2.4	4.8	16.4

VHE gamma-ray absorption

- Low-energy photon background (CMB, EBL, radio, ...)
- Breit & Wheeler (1934):

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

- gamma-ray energy determines the dominant target photon field [De Angelis, 2013]:
  - 0.1 TeV ≤ E ≤ 100 TeV → EBL
  - 100 TeV ≤ E ≤ 10^7 TeV → CMB
- Most recent state-of-the-art EBL models:
  - Saldana-Lopez et al. (2021)
  - Finke et al. (2022)



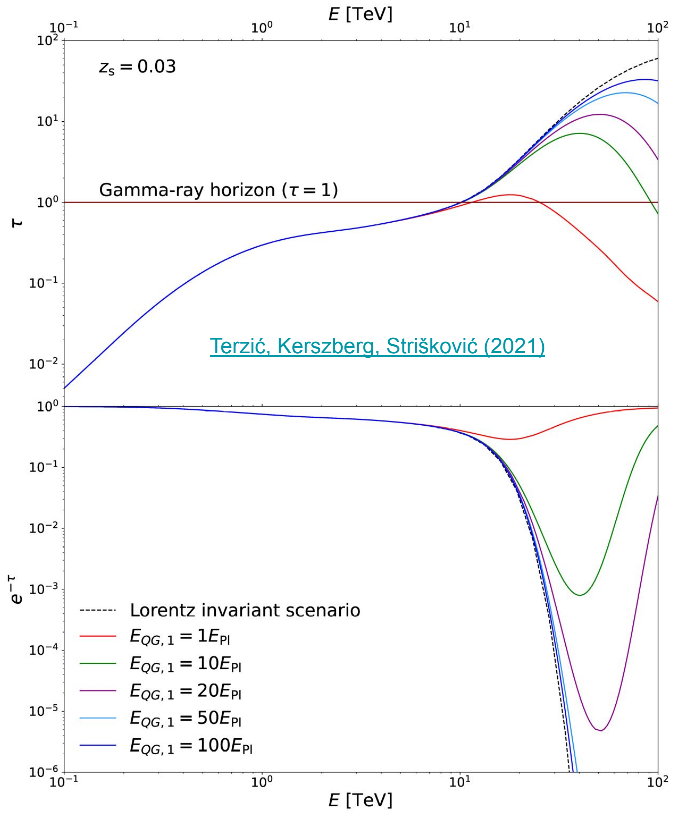
Methodology

1. Intrinsic spectrum: extrapolate reconstructed intrinsic state into the 100 TeV energy range
2. Investigate gamma-ray absorption assuming <u>subluminal quadratic LIV</u> at different LIV energy scales Λ

$$\frac{dN_{\rm obs}}{dE} = \frac{dN_{\rm int}}{dE} \times e^{-\tau(E, z_s; \Lambda)}$$

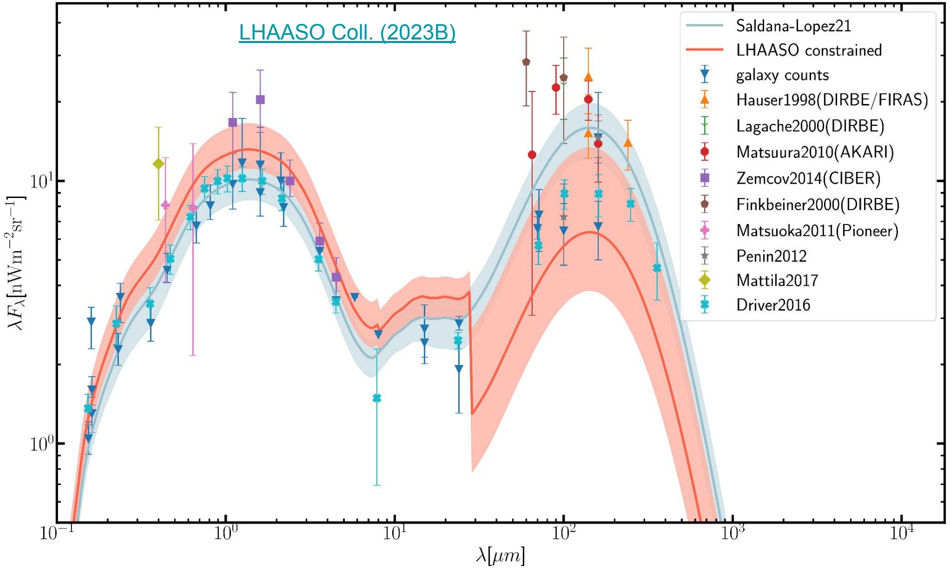
$$\tau(E, z_s; \Lambda) = \int_0^{z_s} dz \, \frac{dl}{dz} \int_{-1}^{1} d\cos\theta \left(\frac{1-\cos\theta}{2}\right) \times \int_{\varepsilon_{\rm thr}(E,\theta,z;\Lambda)}^{\infty} d\varepsilon \; n(\varepsilon, z)\, \sigma(E(1+z), \varepsilon, \theta; \Lambda)\,.$$

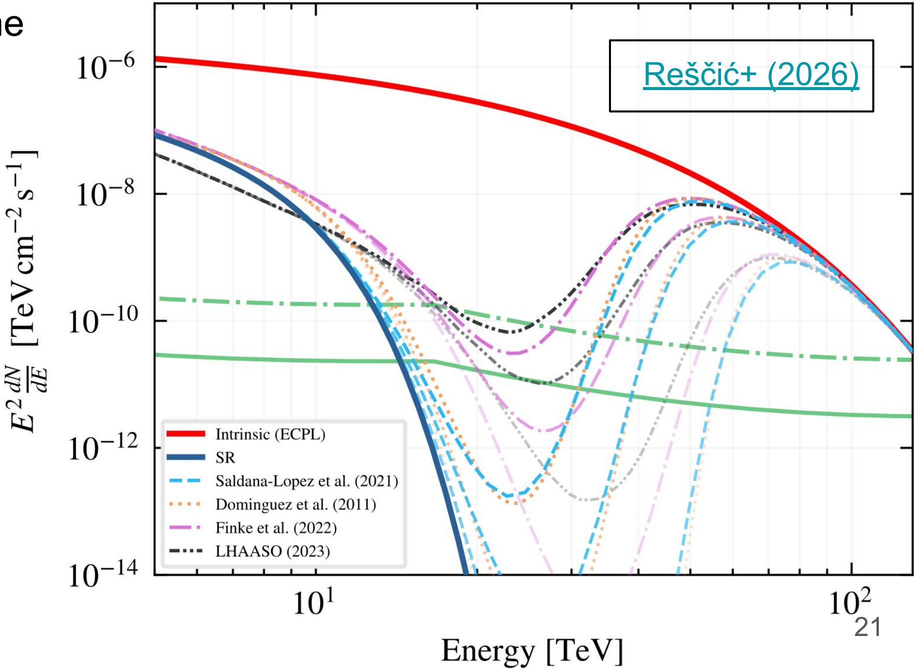
3. Identify energy intervals in which LIV-enabled flux recovery could be detected



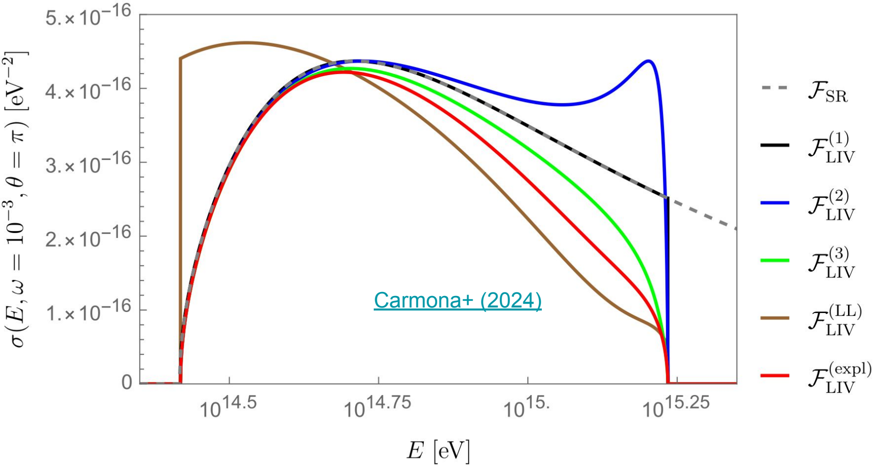
LHAASO scaled EBL

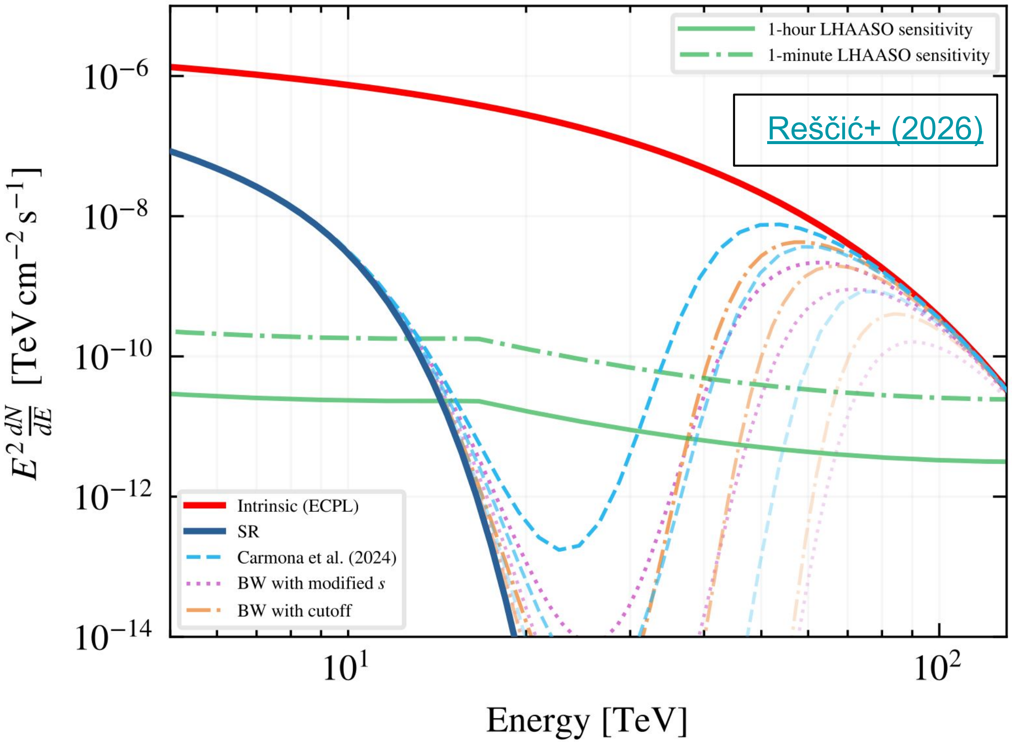
- LHAASO: EBL scaled based on GRB 221009A observations assuming standard physics
  - EBL intensity: 40% Saldana-Lopez (2021) → lower y-ray absorption – same effect as LIV
  - LIV-recovered spectral peaks remain ~ same





LIV-modified cross section influence





- □$_{\mathrm{LIV}}^{(\mathrm{expl})}$ → Carmona et al. (2024)
- □$_{\mathrm{LIV}}^{(2)}$ → BW with modified s
- □$_{\mathrm{LIV}}^{(1)}$ → BW with cutoff