New stringent limits on subluminal Lorentz invariance violation

Rodrigo Guedes Lang, Humberto Martínez-Huerta and Vitor de Souza

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FAPESP
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Lorentz invariance violation

- Key science projects in most experiments
- No signal detected
- How can we improve?
  - Data:
    - higher energies
    - better statistics - more events - more sources
  - Analysis techniques:
    - multiple sources - multi-wavelenght - multi-messenger
    - better understanding of the systematics

Phenomenological approach

Perturbative expansion

LIV coefficient

$$E_a^2 = p_a^2 + m_a^2 + \sum_{n=0}^{\infty} \delta_{a,n} E_a^{(n+2)}$$

Particle species

Suppressed by the energy

— LIV

LIV on astrophysics

$\delta_{had} > 0$

UHECR propagation

- Rodrigo Guedes Lang for the Pierre Auger Collaboration, **PoS(2019)327**;

$\delta_{\pi} < 0$

Pion decay

- Rubtsov, G. *et al.*, JCAP **1705**, 049 (2017);
- Rodrigo Guedes Lang for the Pierre Auger Collaboration, **PoS(2019)327**;

$\delta_{\gamma} > 0$

Photon decay

- Martínez-Huerta, H. *et al.*, Phys. Rev. D **95**, no. 6, 063001 (2017);
- Martínez-Huerta, H. *et al.* for the HAWC Collaboration, **PoS(2019)738**;

Time of flight

- Vasileiou, V. *et al.*, Phys. Rev. D **87**, no. 12, 122001 (2013);

Photon propagation

- Galaverni, M. *et al.*, Phys. Rev. Lett. **100**, 021102 (2008);
- Biteau, J. *et al.*, Astrophys. J. **812**, no. 1, 60 (2015);
- Lang, R. G. *et al.*, Astrophys. J. **853**, no. 1, 23 (2018);
- Lang, R. G. *et al.*, Phys. Rev. D **99**, no. 4, 043015 (2019);
- Martínez-Huerta, H. *et al.* for the CTA consortium, **PoS(2019)739**;
- Lang, R. G. for the Pierre Auger Collaboration, **PoS(2019)328**;

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$\delta_{\gamma} > 0$

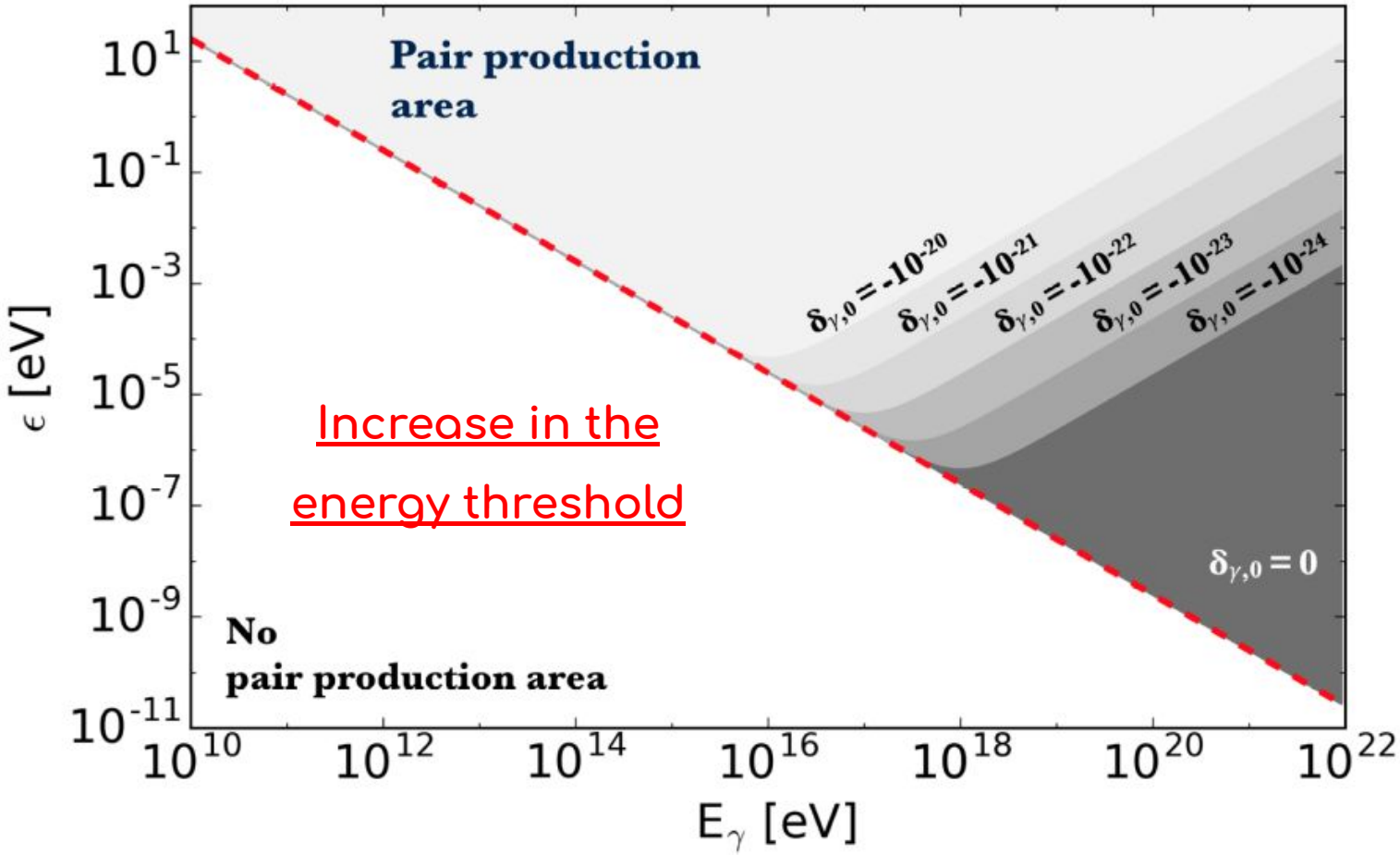
Pair production with LIV

$$\gamma + \gamma_{CB} \rightarrow e^- + e^+ \quad + \quad E_\gamma^2 = p_\gamma^2 + \delta_{\gamma,n} E^{n+2}$$

$$\epsilon_{th} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E^{n+1}}{4}$$

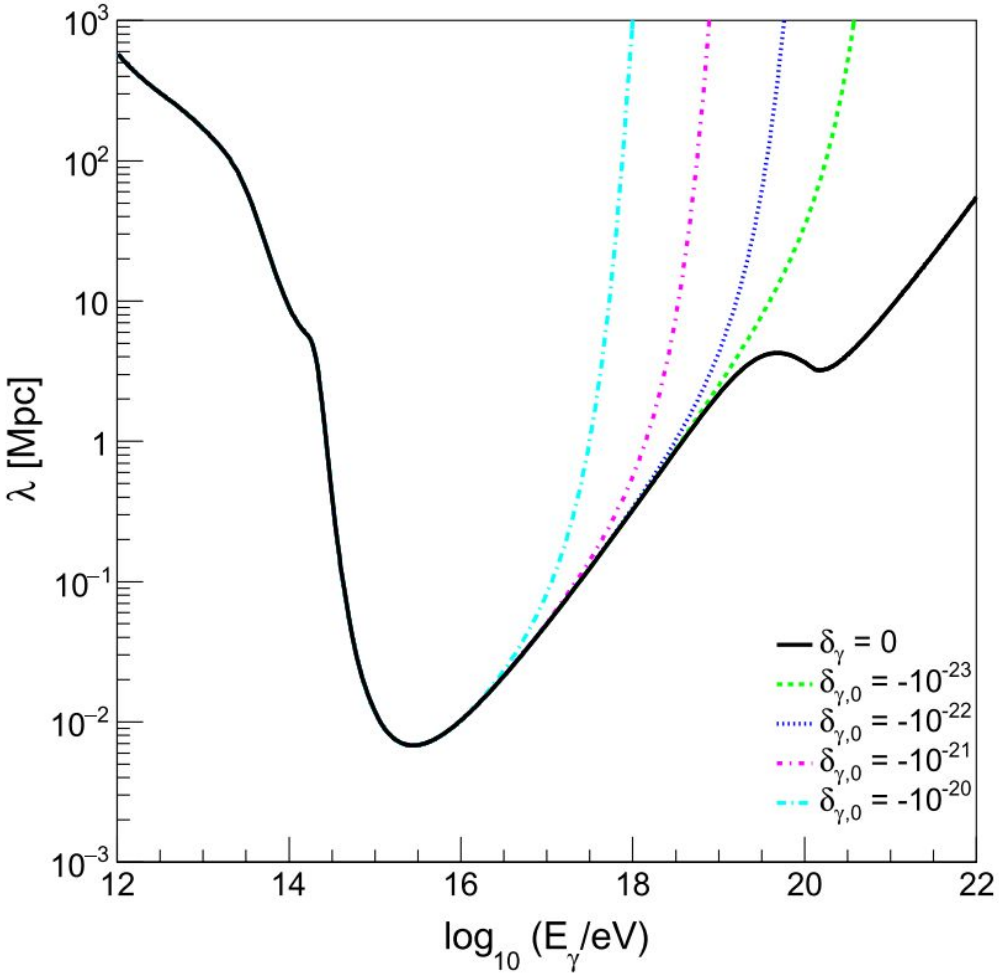
Energy threshold

LIV energy threshold



Increase in the energy threshold

LIV mean free path



Increase in the mean free path

LIV scenarios tested

UHE photons

The Astrophysical Journal, 853:23 (10pp), 2018 January 20 https://doi.org/10.3847/1538-4357/aa9f2c

Limits on the Lorentz Invariance Violation from UHECR Astrophysics

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Abstract

In this paper, the Lorentz invariance violation (LIV) is introduced in the calculations of photon propagation in the universe. LIV is considered in the photon sector, and the mean-free path of the $\gamma\gamma \to e^+e^-$ interaction is calculated. The corresponding photon horizon, including LIV effects, is used to predict major changes in the propagation of photons with energy above 10^{18} eV. The flux of GZK photons on Earth, considering LIV, is calculated for several source models of ultra-high-energy cosmic rays (UHECRs). The predicted flux of GZK gamma-rays is compared to the new upper limits on the photon flux obtained by the Pierre Auger Observatory in order to impose upper limits on the LIV coefficients of order $n = 0$, 1, and 2. The limits on the LIV coefficients derived here are more realistic than previous works and in some cases more restrictive. The analysis resulted in LIV upper limits in the photon sector of $\delta_{\gamma,0}^{\rm limit} \sim -10^{-20}$, $\delta_{\gamma,1}^{\rm limit} \sim -10^{-38}\,{\rm eV}^{-1}$, and $\delta_{\gamma,2}^{\rm limit} \sim -10^{-56}\,{\rm eV}^{-2}$ in the astrophysical scenario, which best describes UHECR data.

Key words: astroparticle physics – cosmic rays – relativistic processes

Lang, R. G., Martínez-Huerta, H. & de Souza, V, Astrophys. J., 2018 [arXiv:1701.04865]

TeV gamma-rays

PHYSICAL REVIEW D **99,** 043015 (2019)

Improved limits on Lorentz invariance violation from astrophysical gamma-ray sources

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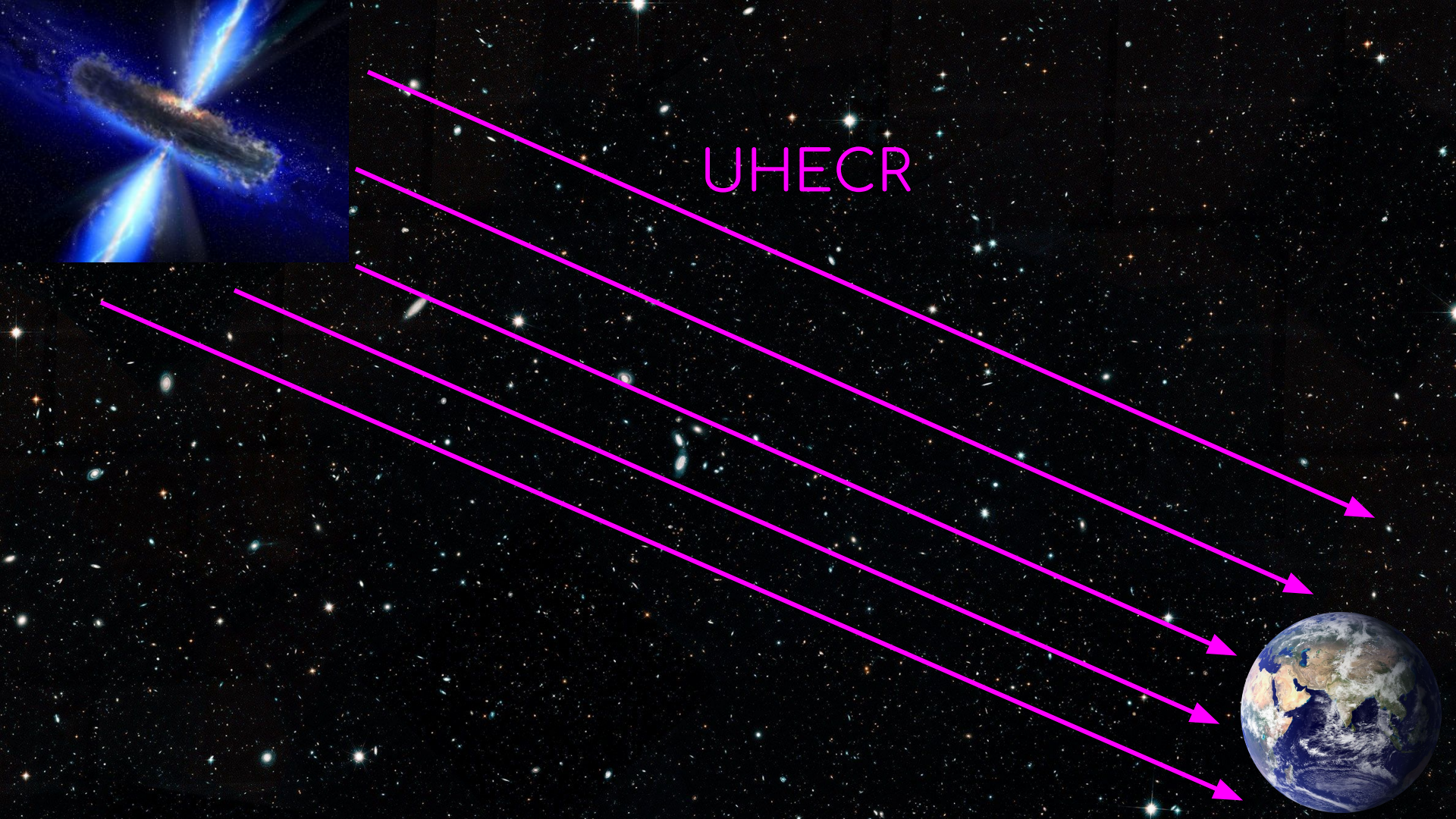
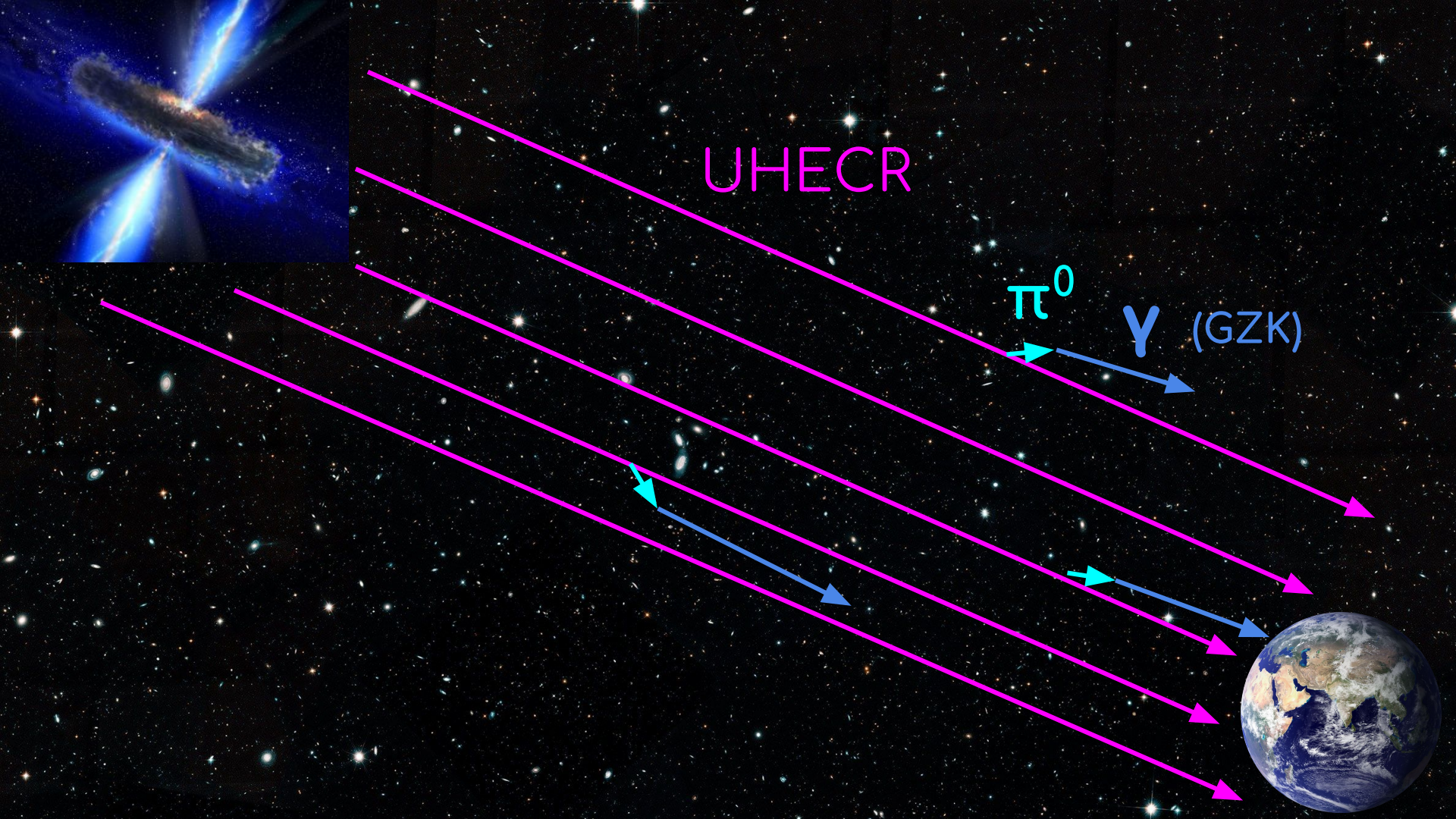
(Received 16 August 2018; published 28 February 2019)

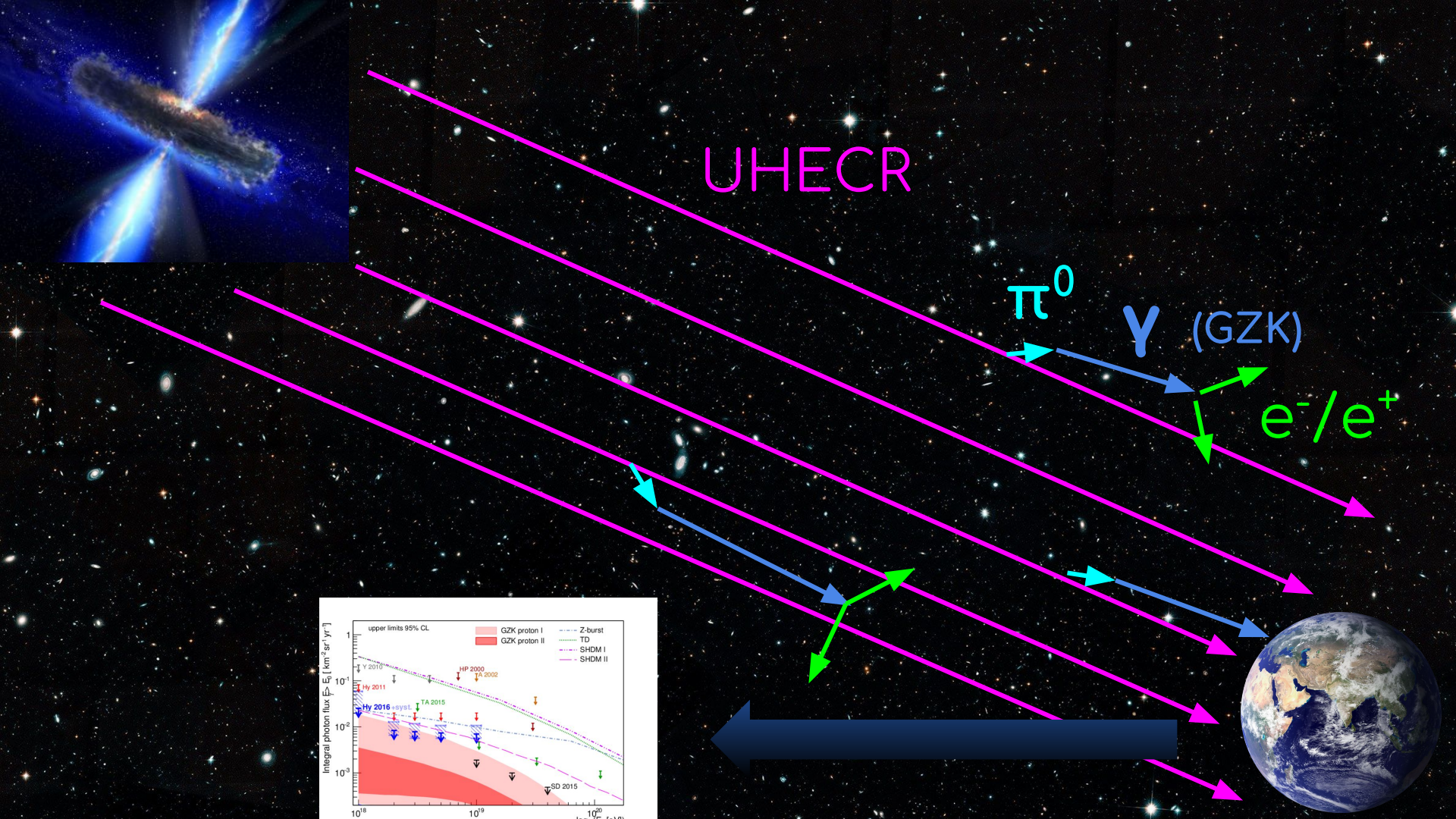
Lorentz invariance (LI) has a central role in science and its violation (LIV) at some high-energy scale has been related to possible solutions for several of the most intriguing puzzles in nature such as dark matter, dark energy, cosmic rays generation in extreme astrophysical objects and quantum gravity. We report on a search for LIV signal based on the propagation of gamma rays from astrophysical sources to Earth. An innovative data analysis is presented which allowed us to extract unprecedented information from the most updated data set composed of 111 energy spectra of 38 different sources measured by current gamma-ray observatories. No LIV signal was found, and we show that the data are best described by LI assumption. We derived limits for the LIV energy scale at least 3 times better than the ones currently available in the literature for subluminal signatures of LIV in high-energy gamma rays.

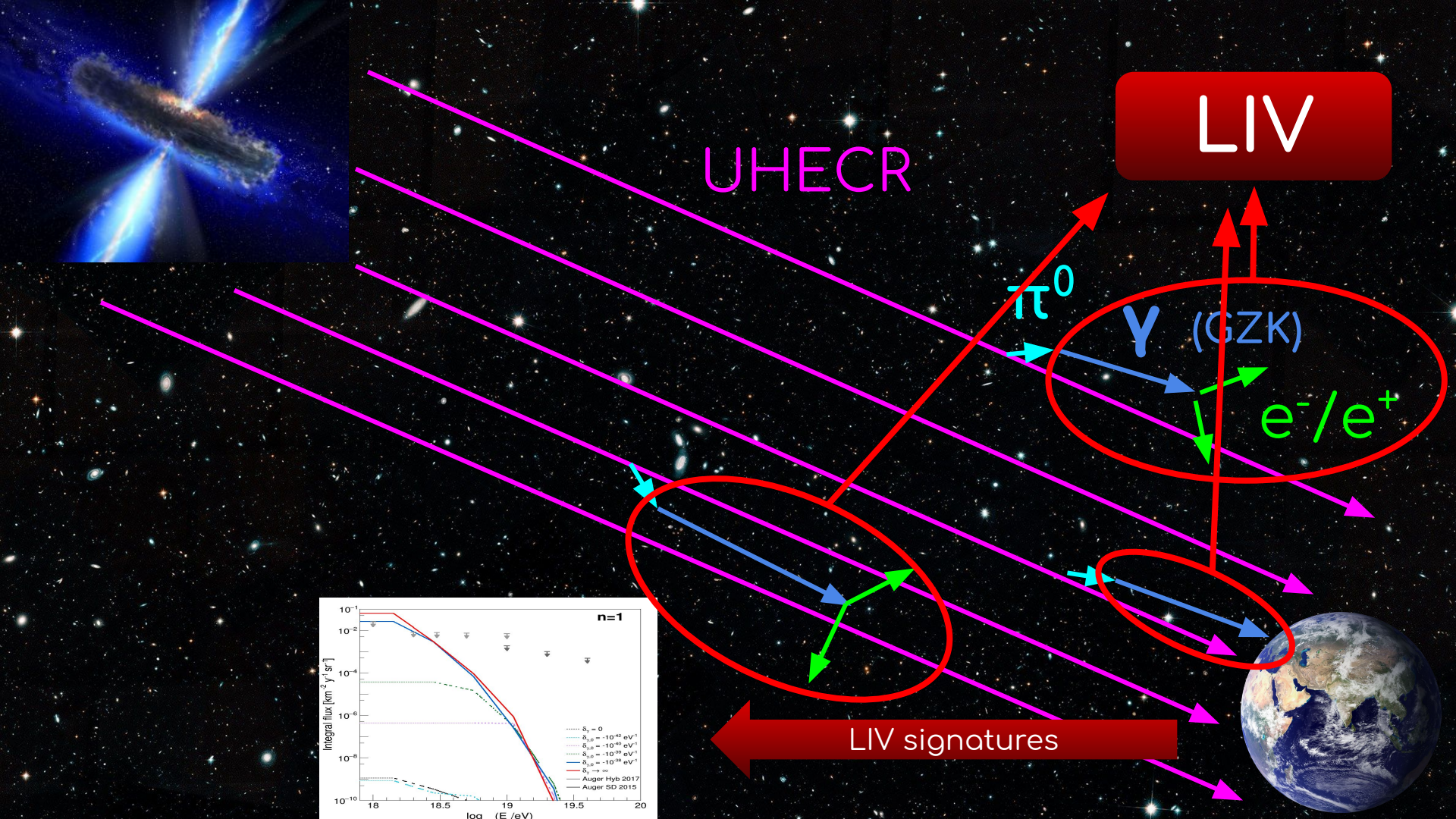
DOI: 10.1103/PhysRevD.99.043015

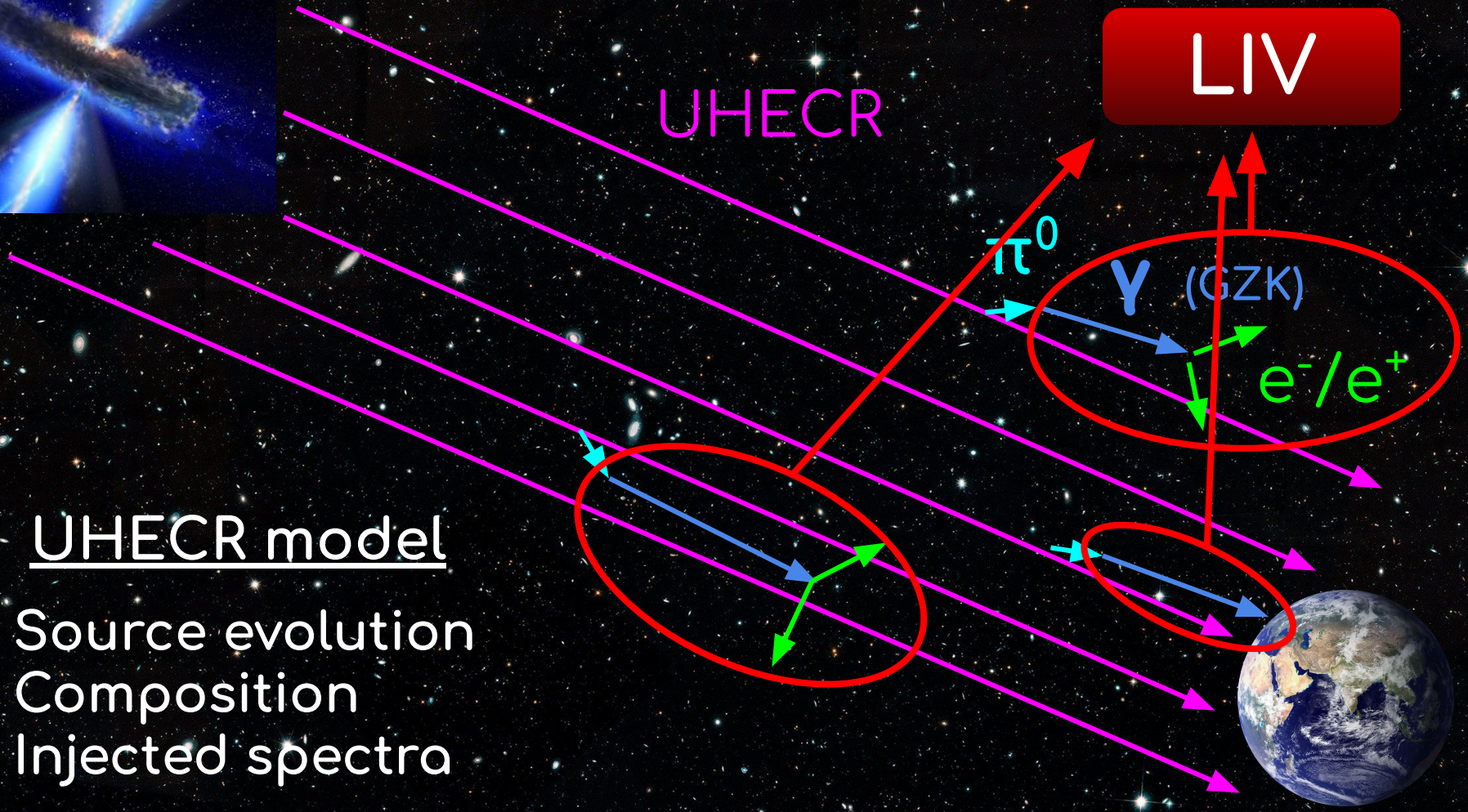
Lang, R. G., Martínez-Huerta, H. & de Souza, V, Phys. Rev. D, 2019 [arXiv:1810.13215]


UHECR


UHECR
π^0
γ (GZK)


UHECR
π0
γ (GZK)
e-/e+
upper limits 95% CL
GZK proton I
GZK proton II
Z-burst
TD
SHDM I
SHDM II
Y 2010
HP 2000
TA 2002
Hy 2011
Hy 2016 +syst.
TA 2015
SD 2015
Integral photon flux E> E0 [km-2 sr-1 yr-1]
1
10-1
10-2
10-3
1018
1019
1020


UHECR
LIV
π^0
γ (GZK)
e^-/e^+
LIV signatures
n=1
Integral flux [km^{-2} y^{-1} sr^{-1}]
log (E /eV)
Auger Hyb 2017
Auger SD 2015

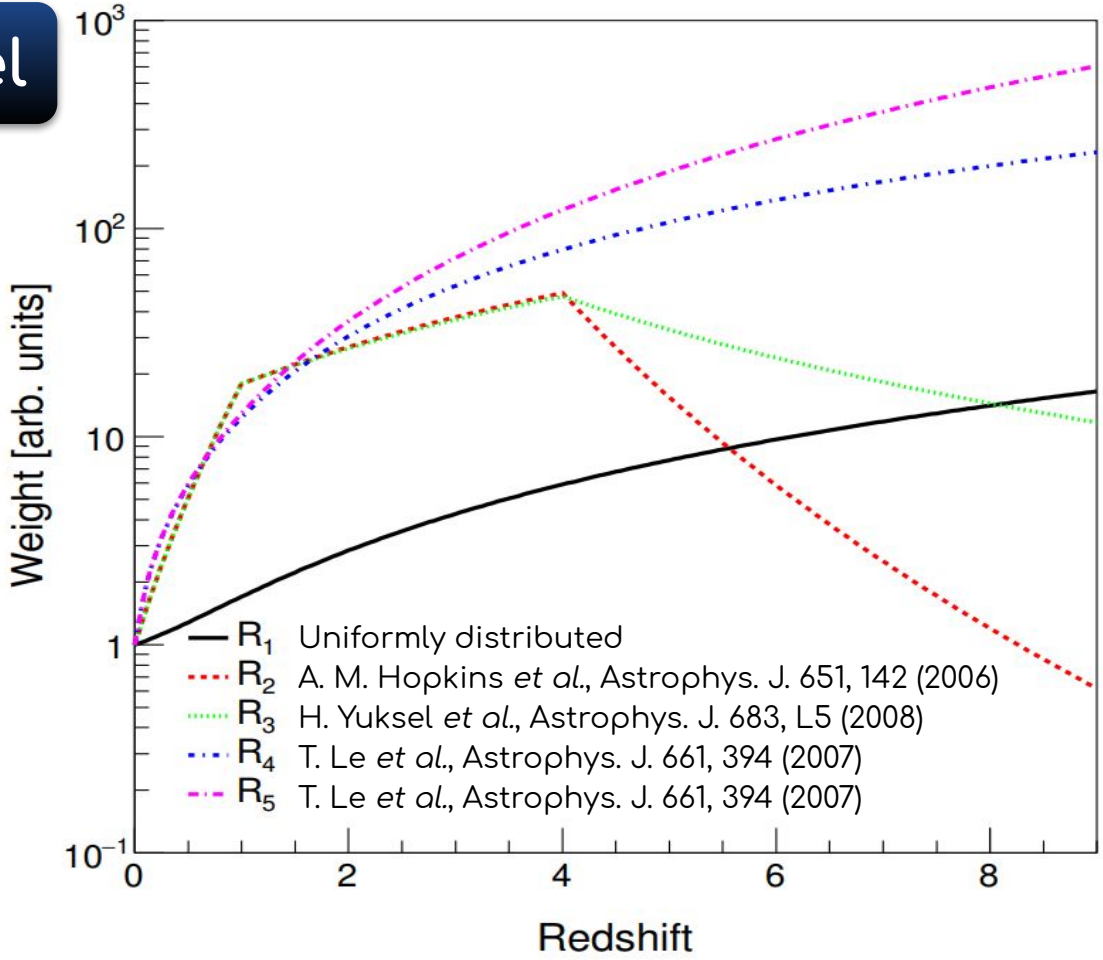


UHECR model

- Source evolution
- Composition
- Injected spectra

UHECR sources model

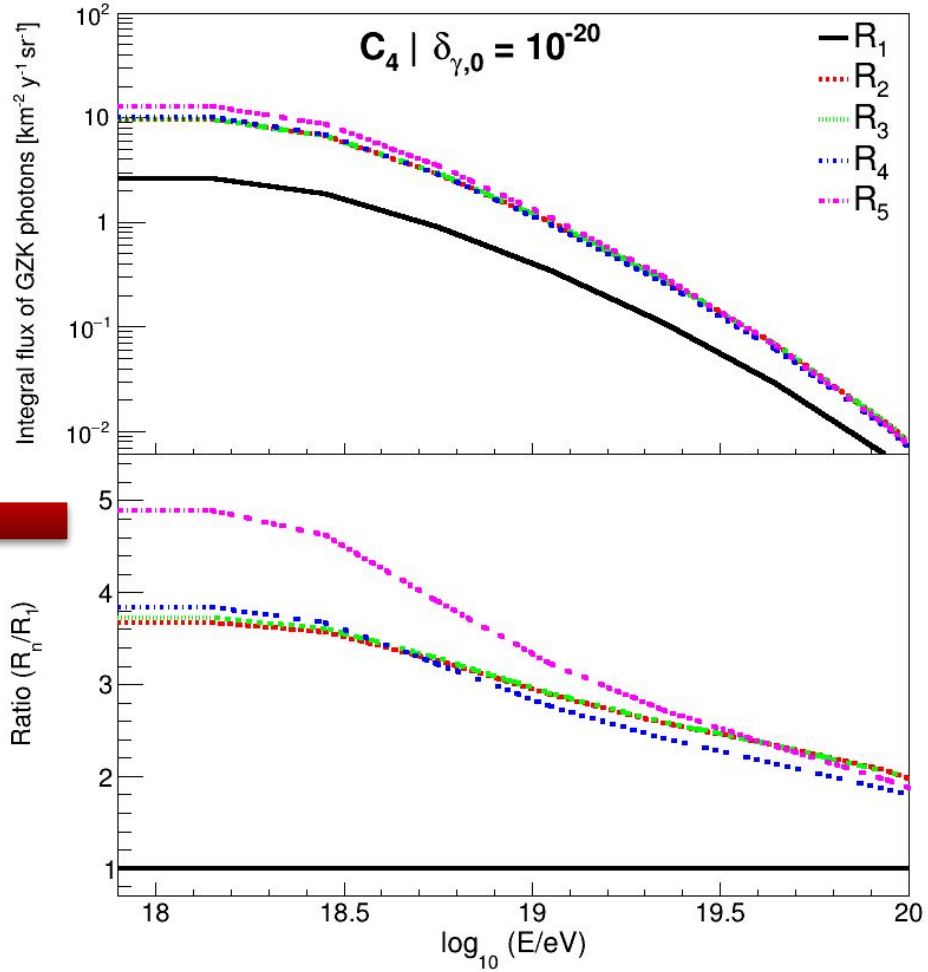
Source evolution



UHECR sources model

Source evolution

Up to ~500%



UHECR sources model

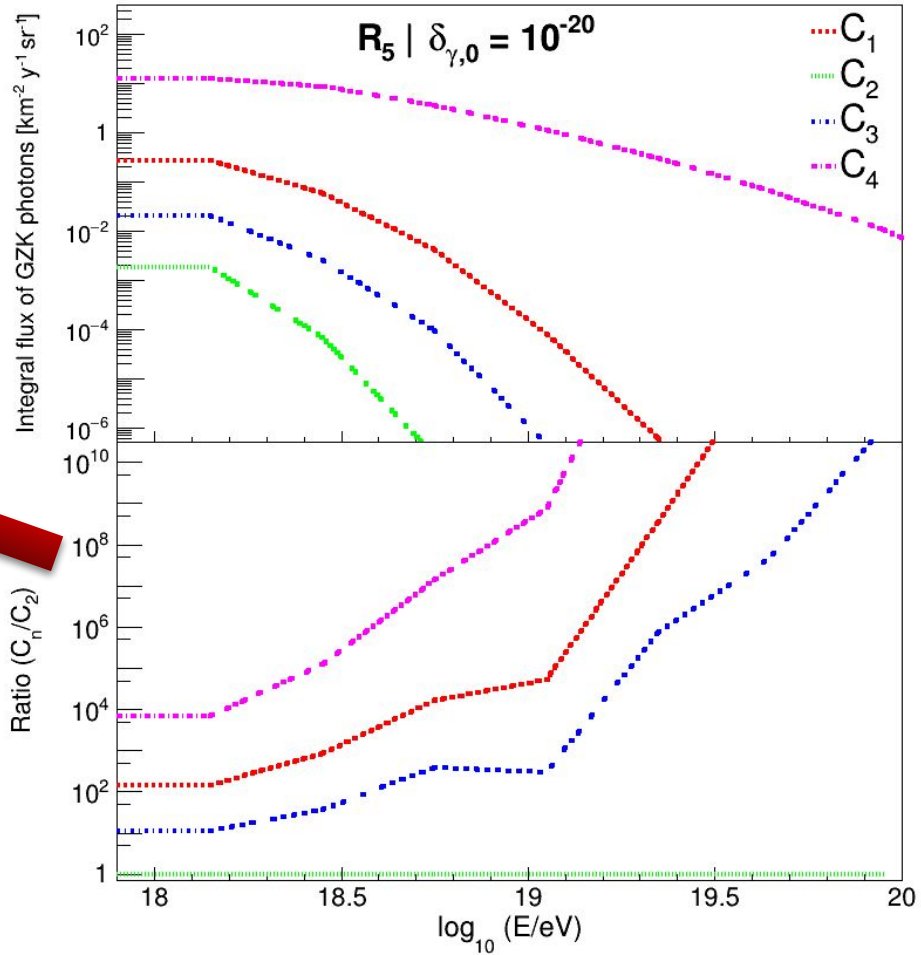
Composition/spectra

Model	Γ	$\log_{10}(R_{cut}/\mathrm{V})$	fH	fHe	fN	fSi	fFe	Reference
C_1	1	18.699	0.7692	0.1538	0.0461	0.0231	0.00759	Aloisio *et al.*, **JCAP**, 2014
C_2	1	18.5	0	0	0	1	0	Unger *et al.*, **PRD**, 2015
C_3	1.25	18.5	0.365	0.309	0.121	0.1066	0.098	Unger *et al.*, **PRD**, 2015
C_4	2.7	∞	1	0	0	0	0	Berezinsky *et al.*, **PRD**, 2006

UHECR sources model

Composition/spectra

Several orders of magnitude!



5 source evolution

✖

4 composition/spectra

✖

5 LIV cases:

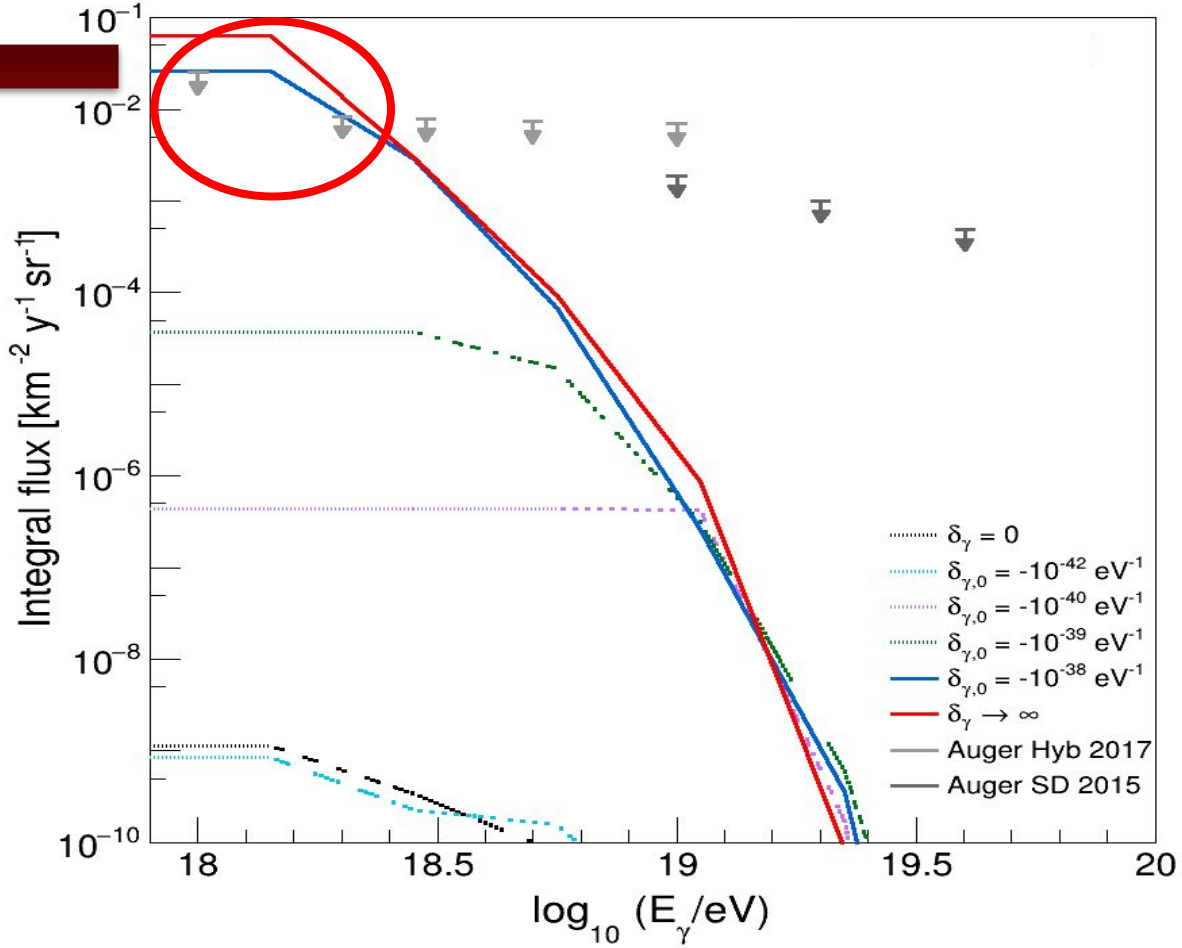
- LI ($\delta_\gamma = 0$);
- n = 0
- n = 1
- n = 2
- max LIV ($\delta_\gamma \to -\infty$)

→ CRPropa 3/EleCa

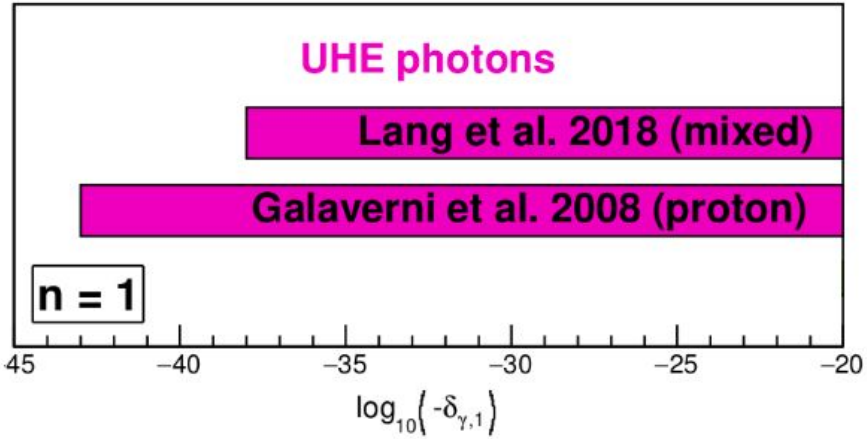
↓

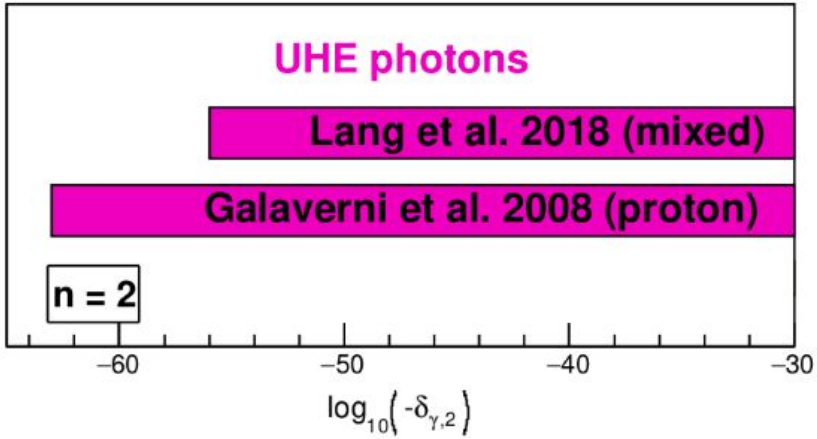
LIV photon flux

LIV limits


Integral flux [km^{-2} y^{-1} sr^{-1}]
10^{-1}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
18
18.5
19
19.5
20
$\log_{10}(E_\gamma/\mathrm{eV})$
$\delta_\gamma = 0$
$\delta_{\gamma,0} = -10^{-42}$ eV^{-1}
$\delta_{\gamma,0} = -10^{-40}$ eV^{-1}
$\delta_{\gamma,0} = -10^{-39}$ eV^{-1}
$\delta_{\gamma,0} = -10^{-38}$ eV^{-1}
$\delta_\gamma \to \infty$
Auger Hyb 2017
Auger SD 2015

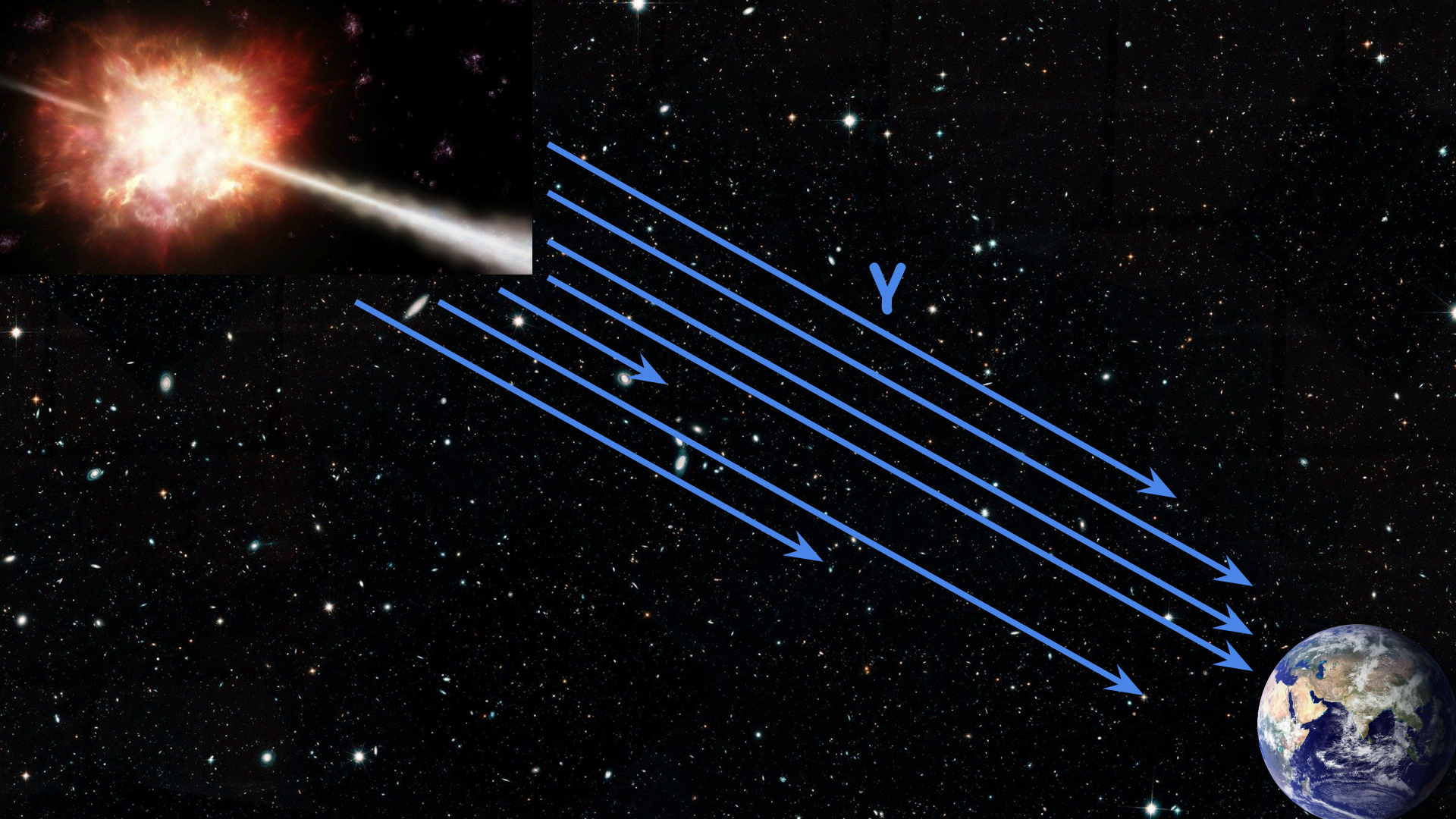
LIV limits

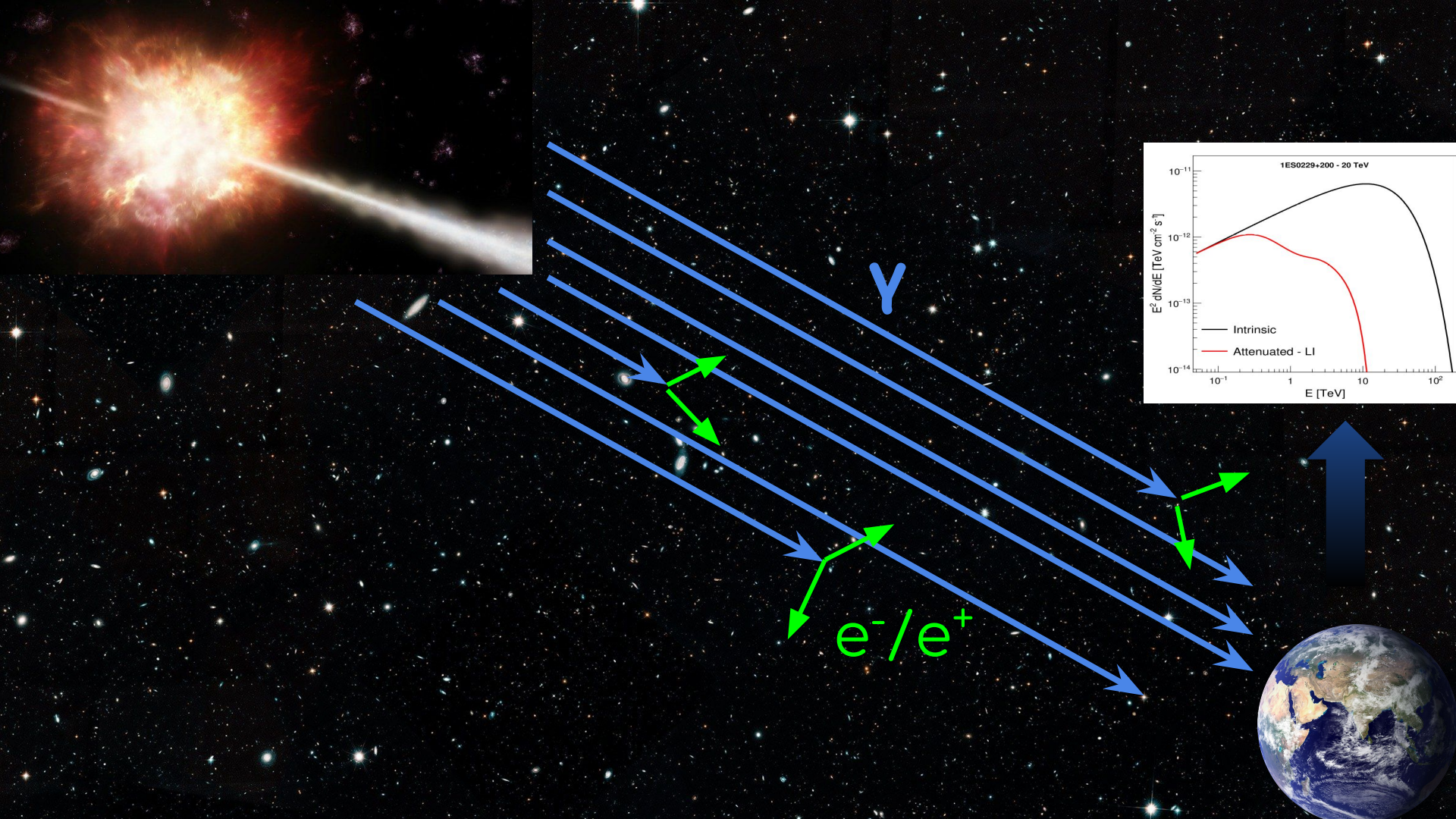


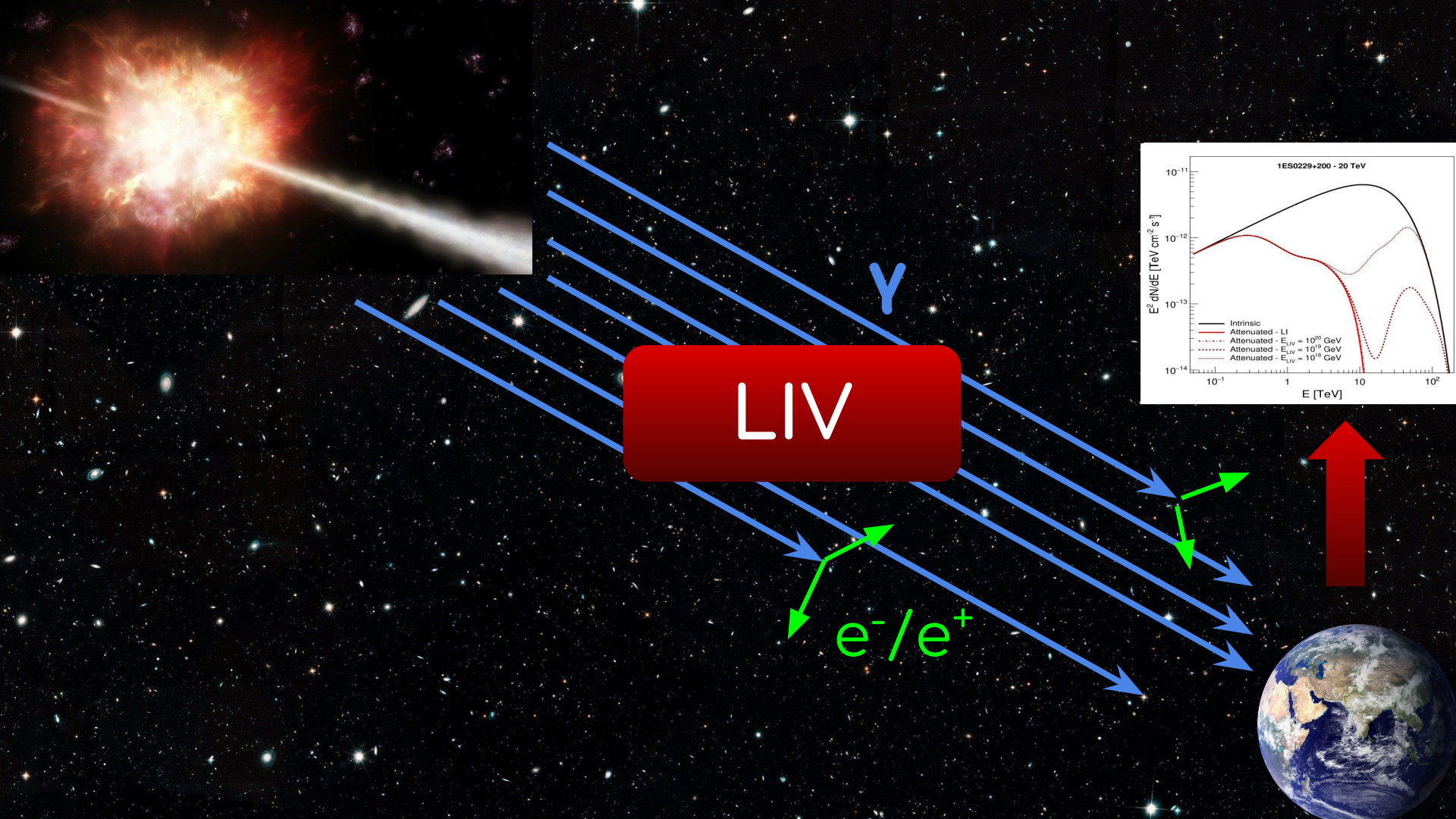


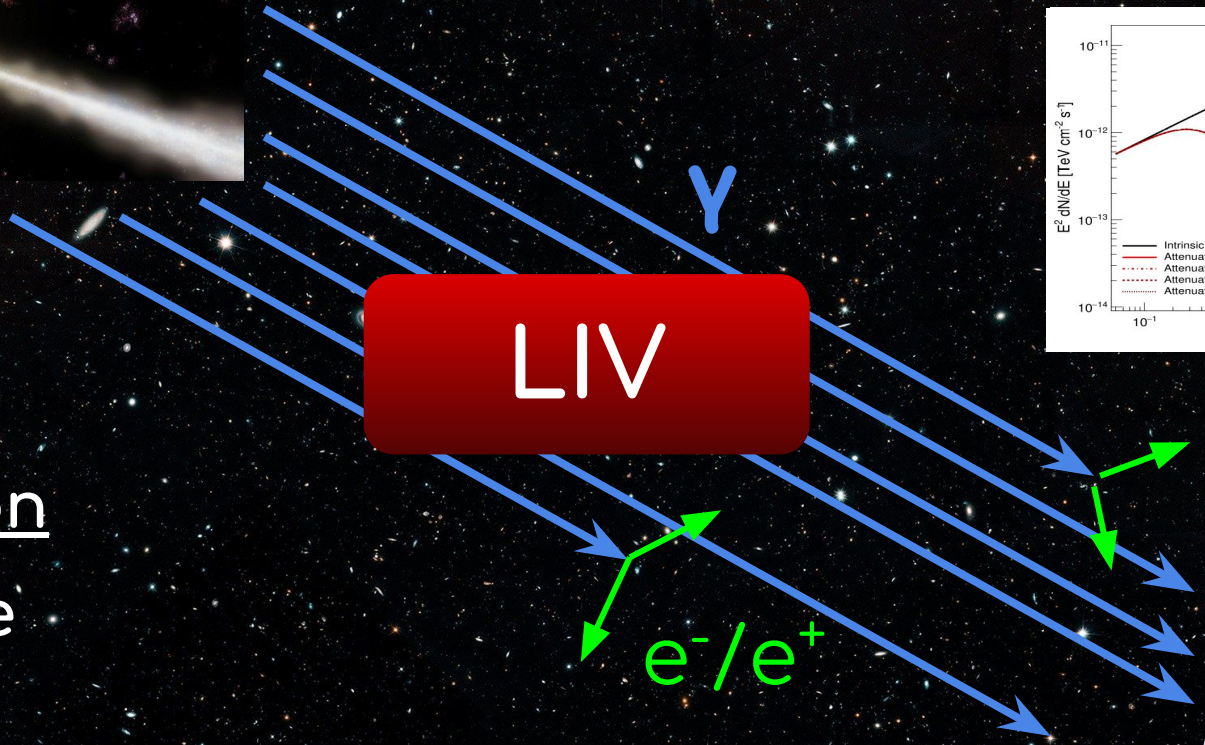
	Composition	Photon flux limits	UHECR spectrum
Galaverni *et al.* 2008	Proton	Auger 2007	AGASA 2008
Lang *et al.* 2018	Mixed	Auger 2017	Auger 2017

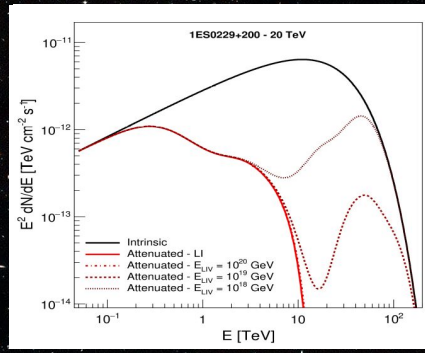
Updated and more realistic limits


γ


γ
e⁻/e⁺
1ES0229+200 - 20 TeV
E² dN/dE [TeV cm⁻² s⁻¹]
E [TeV]
Intrinsic
Attenuated - LI


γ
LIV
e⁻/e⁺
1ES0229+200 - 20 TeV
E² dN/dE [TeV cm⁻² s⁻¹]
E [TeV]
Intrinsic
Attenuated - LI
Attenuated - E_LIV = 10^20 GeV
Attenuated - E_LIV = 10^19 GeV
Attenuated - E_LIV = 10^18 GeV





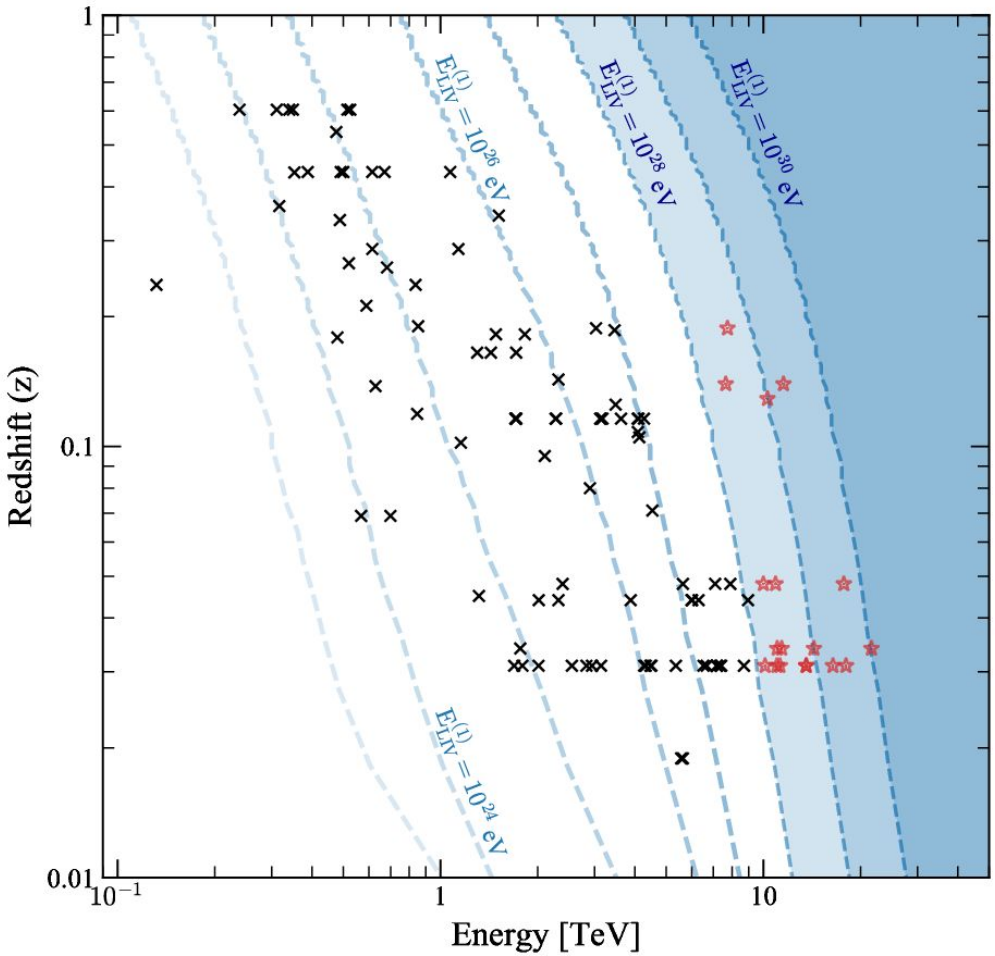
Propagation

- distance
- energy

Data selection

TeVCAT

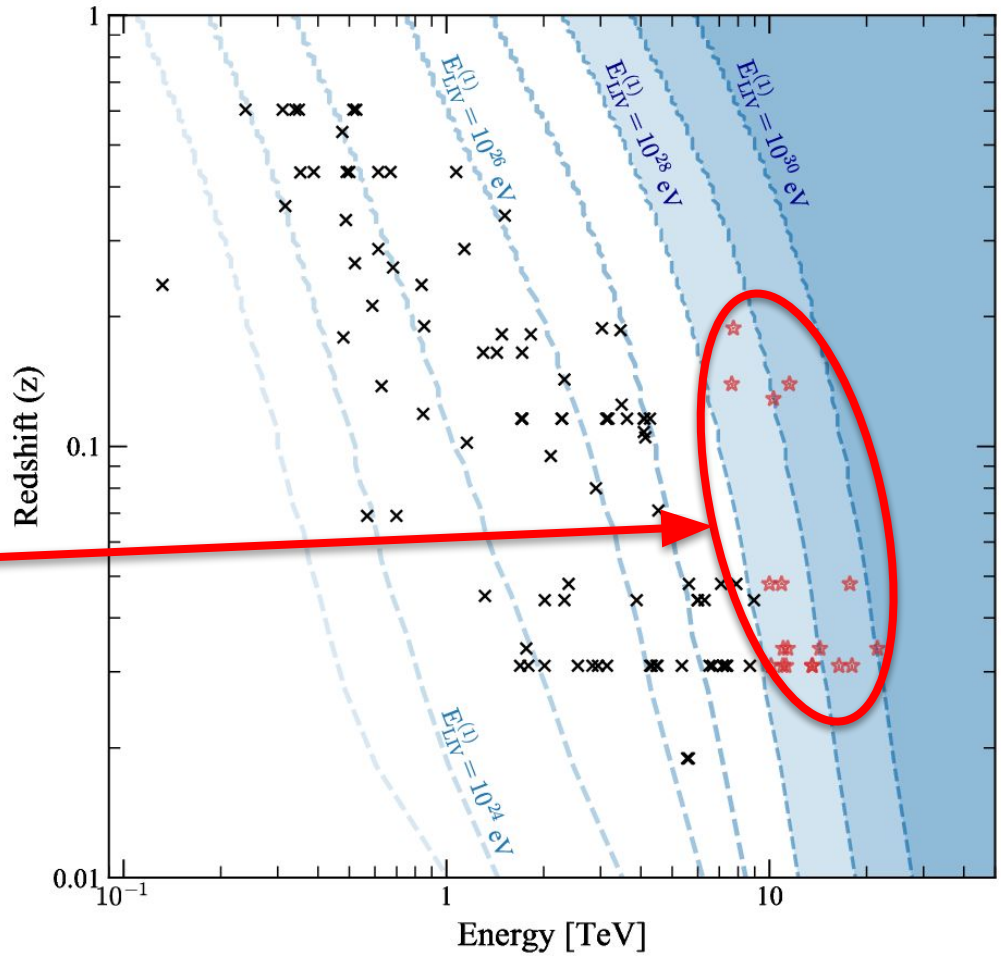
- Available
  - 111 measured spectra
  - 38 sources



Data selection

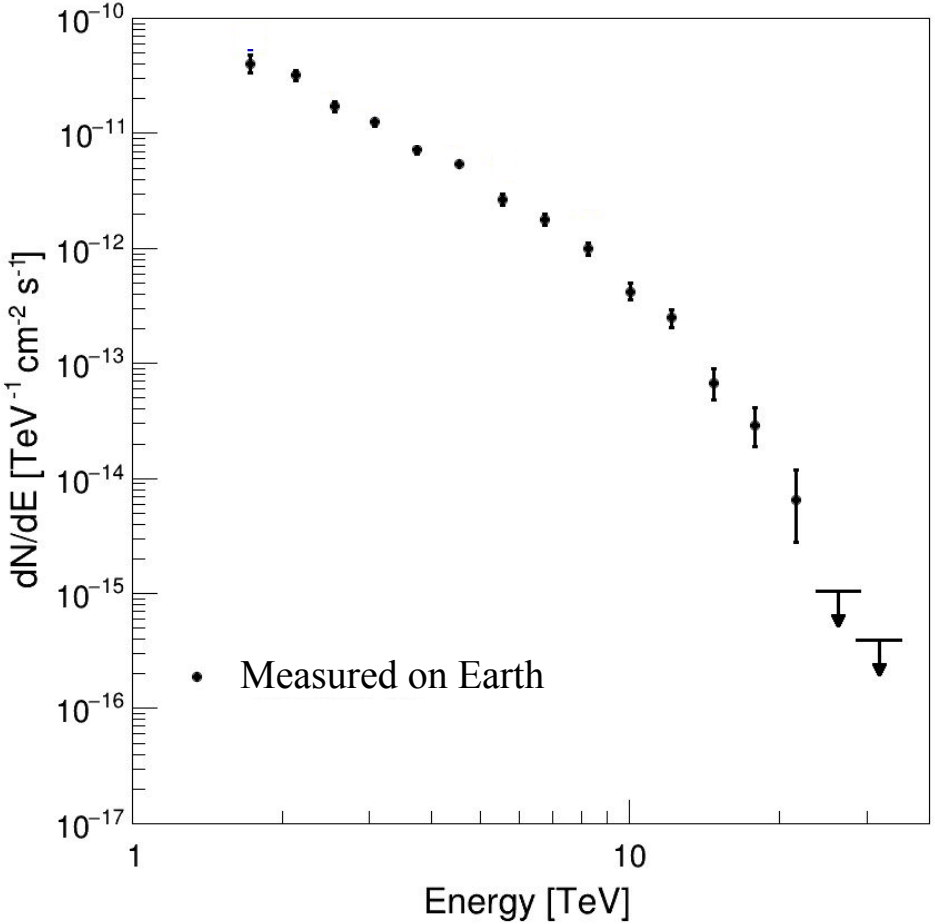
TeVCAT

- Available
  - 111 measured spectra
  - 38 sources
- Useful
  - 18 measured spectra
  - 6 sources



Analysis procedure

- For each E_{LIV}:
  - For each measurement:
    I. Intrinsic spectrum reconstruction:
       - LIV region
       - Exponential cutoff power-law fitting
    II. Expected LIV spectrum calculation:
       - Energy resolution
    III. Comparison with data:
       - Upper limits
       - Most and least conservative LIV-favored and LIV- disfavored



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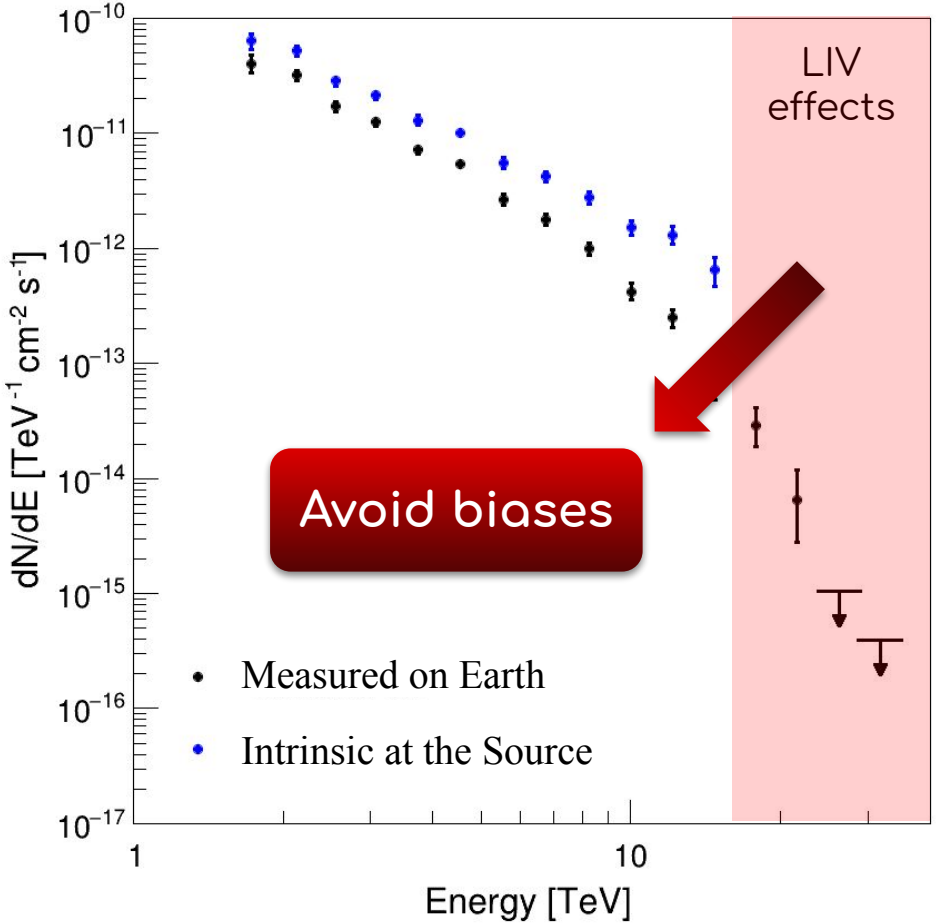

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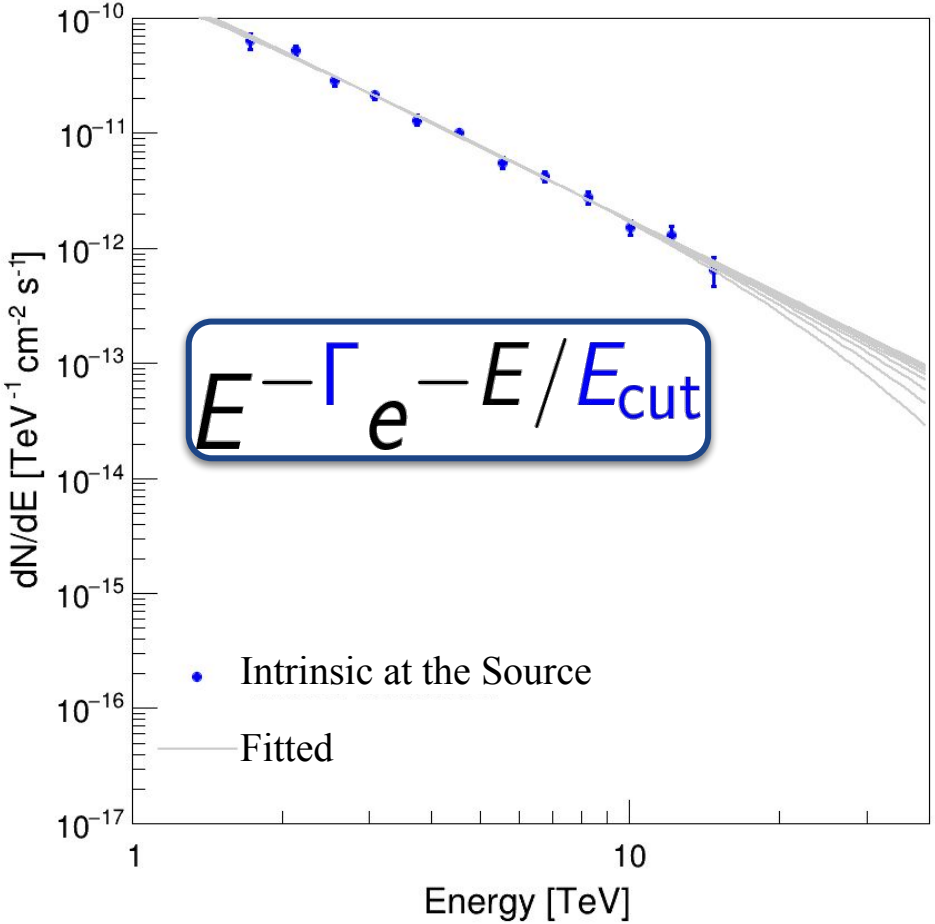

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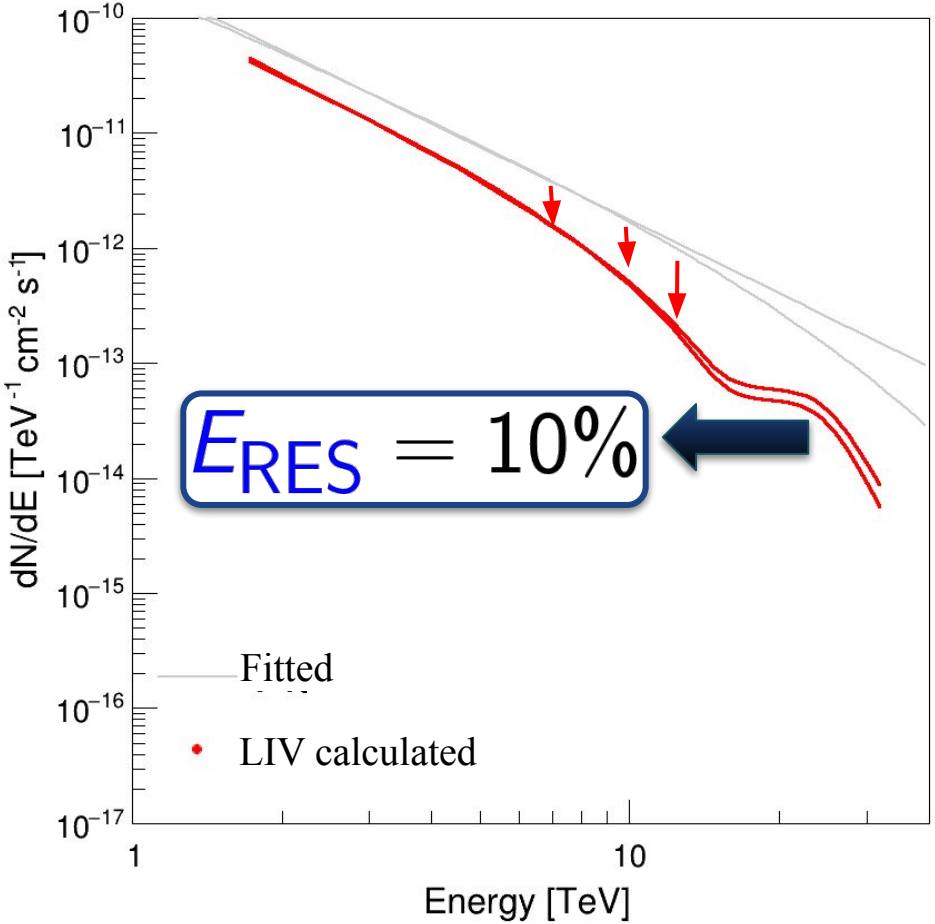

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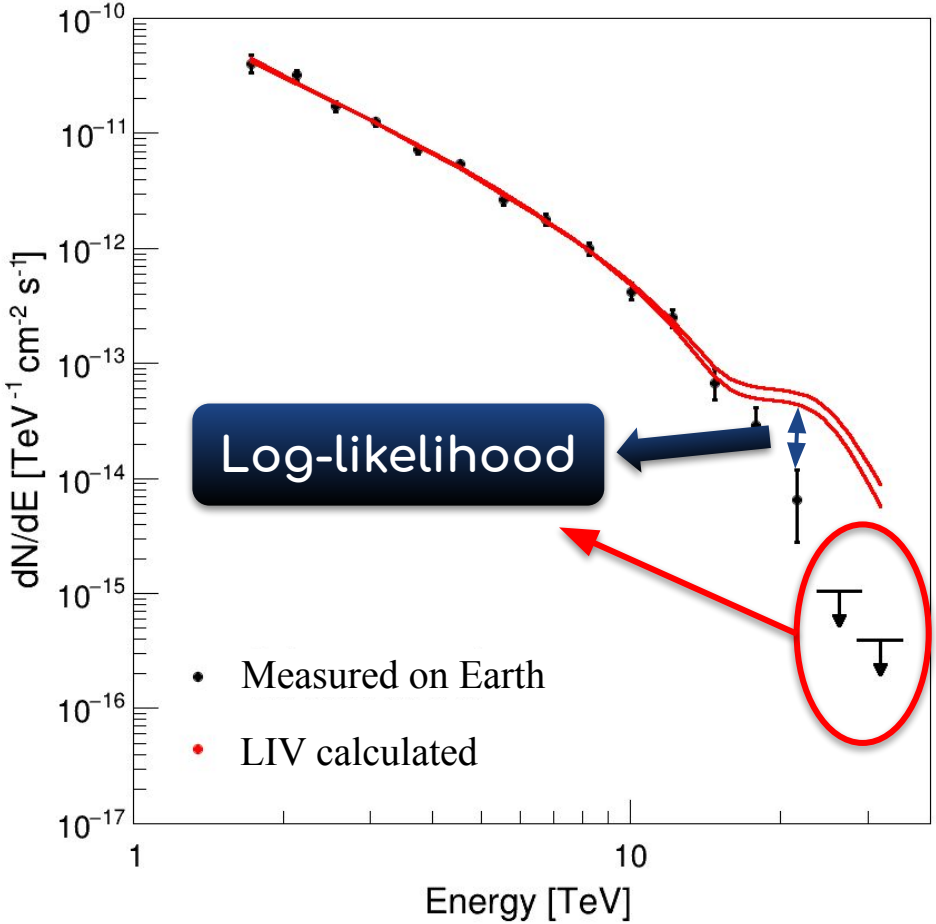
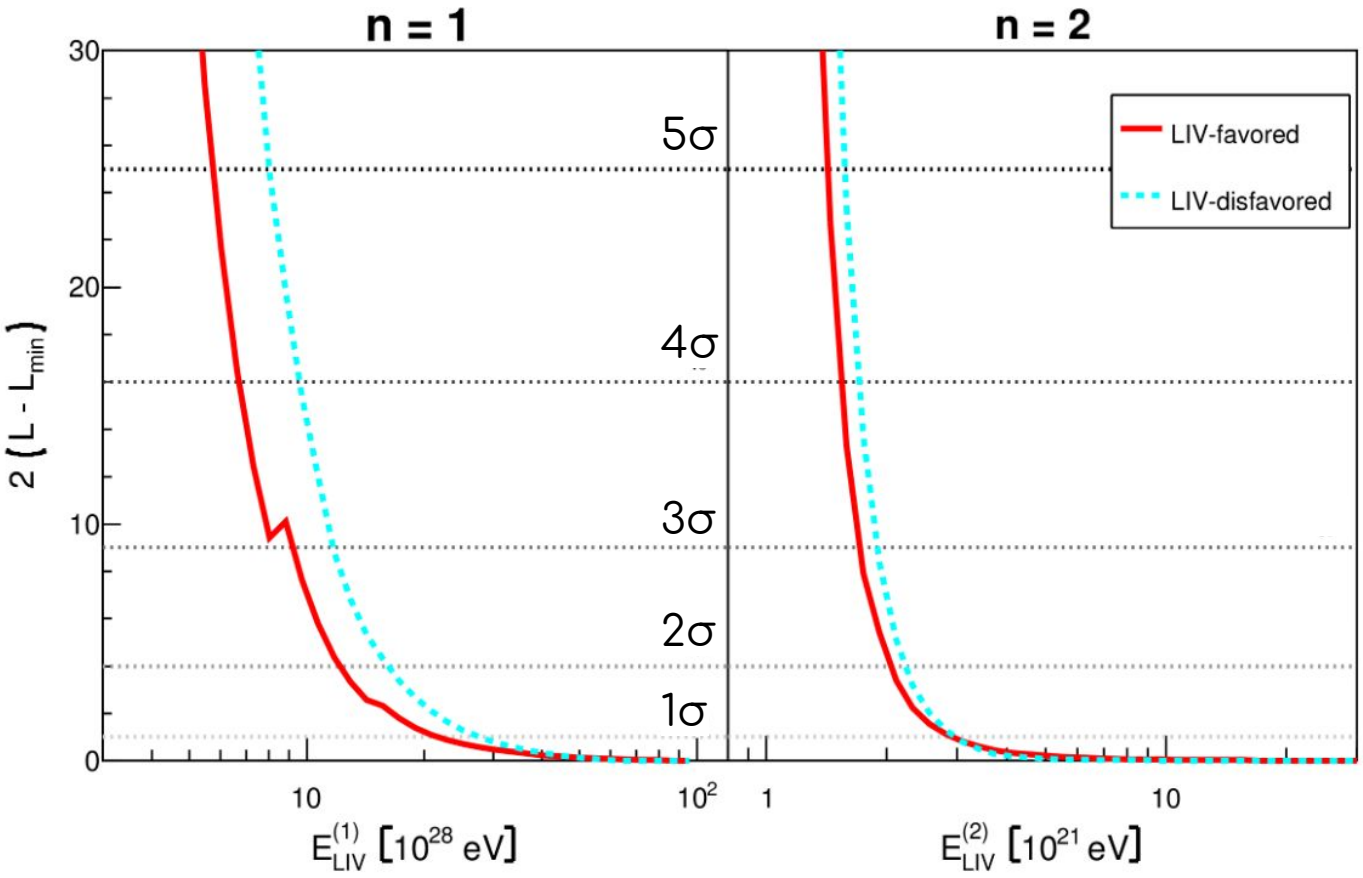
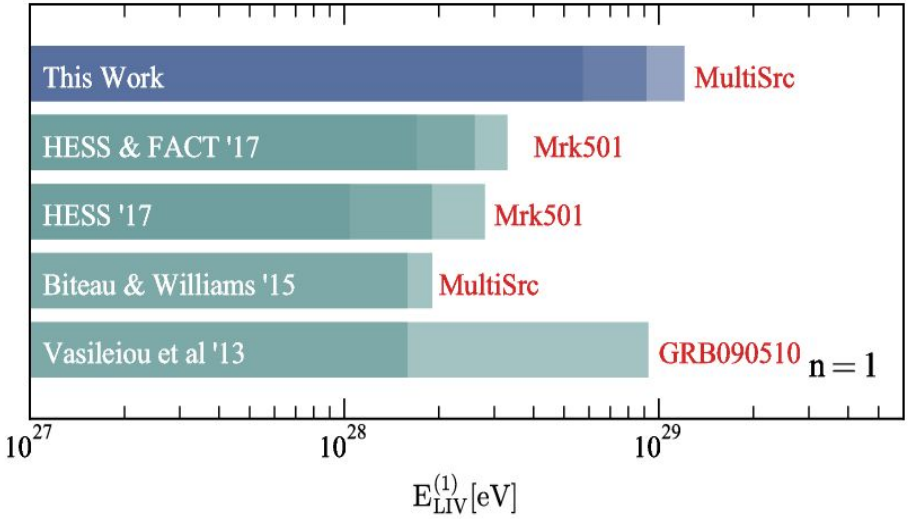


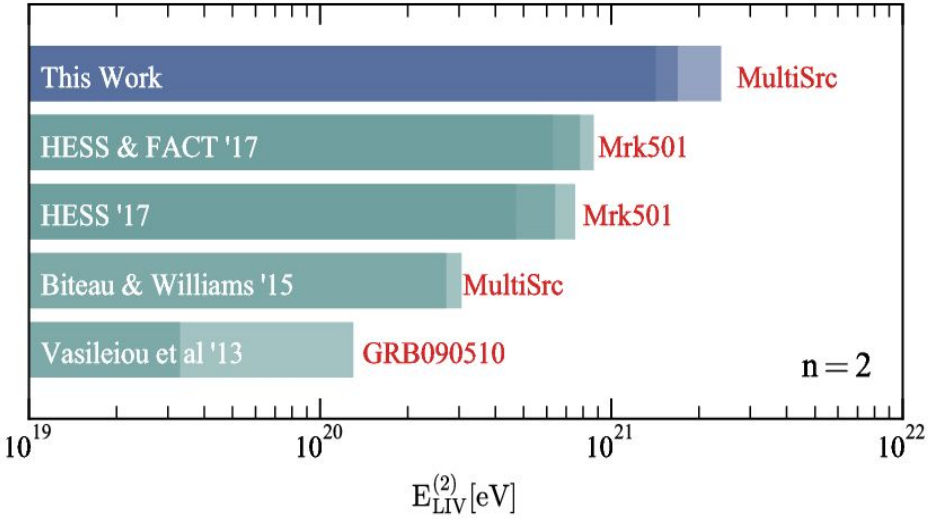
Results

- Data best described by LI assumption
- Limits on the LIV energy scale imposed



LIV limits





At least 3 times better

More conservative

Less biased

Conclusions: new LIV Limits

UHE photons

- UHECRs sources models
  - Huge impact!
- LIV Limits
  - Updated data
  - Realistic models

$$\begin{cases} \delta_{\gamma,0} \gtrsim -10^{-20} \\ \delta_{\gamma,1} \gtrsim -10^{-38}\ \mathrm{eV}^{-1} \\ \delta_{\gamma,2} \gtrsim -10^{-56}\ \mathrm{eV}^{-2} \end{cases}$$

TeV gamma-rays

- New technique:
  - Method to choose source
  - Better systematics control
- LIV limits
  - More robust
  - More stringent

$$\begin{cases} & \{2\sigma, 3\sigma, 5\sigma\} \\ E_{LIV}^{(1)} > & \{12.08, 9.14, 5.73\} \times 10^{28}\ \mathrm{eV} \\ E_{LIV}^{(2)} > & \{2.38, 1.69, 1.42\} \times 10^{21}\ \mathrm{eV} \end{cases}$$

BACKUP

Phenomenological approach

$$E_a^2 = p_a^2 + m_a^2 + \sum_{n=0}^{\infty} \delta_{a,n} \underline{E_a^{(n+2)}}$$

Suppressed by the energy

ASTROPHYSICS

— LIV

LIV coefficient

- Free parameter to be constrained;
- Can be either positive or negative;
- Each order treated separately;
- Also presented as LIV energy scale;

* (n) is just an index for the approximation order

$$\delta_{a,n} \longleftrightarrow E_{LIV}^{(n)} = \frac{1}{(|\delta_{a,n}|)^{1/n}}$$

Limits for other UHECR source models

Model	Γ	$\log_{10}(R_{cut}/\mathrm{V})$	fH	fHe	fN	fSi	fFe	Reference
C_1	1	18.699	0.7692	0.1538	0.0461	0.0231	0.00759	Aloisio *et al.*, **JCAP**, 2014
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C_3	1.25	18.5	0.365	0.309	0.121	0.1066	0.098	Unger *et al.*, **PRD**, 2015
C_4	2.7	∞	1	0	0	0	0	Berezinsky *et al.*, **PRD**, 2006

Model	$\delta_{\gamma,0}^{limit}$	$\delta_{\gamma,1}^{limit}[\mathrm{eV}^{-1}]$	$\delta_{\gamma,2}^{limit}[\mathrm{eV}^{-2}]$
C_1R_5	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
C_2R_5	-	-	-
C_3R_5	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
C_4R_5	$\sim -10^{-22}$	$\sim -10^{-42}$	$\sim -10^{-60}$

Lang, R., Martínez-Huerta, H & de Souza, V. **Astrophys. J.**, 2018

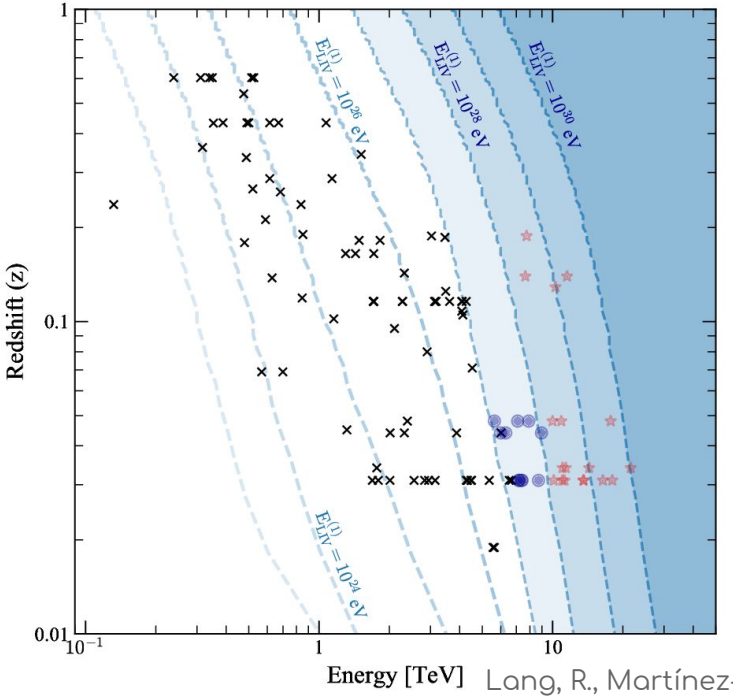
LIV limits for other EBL models

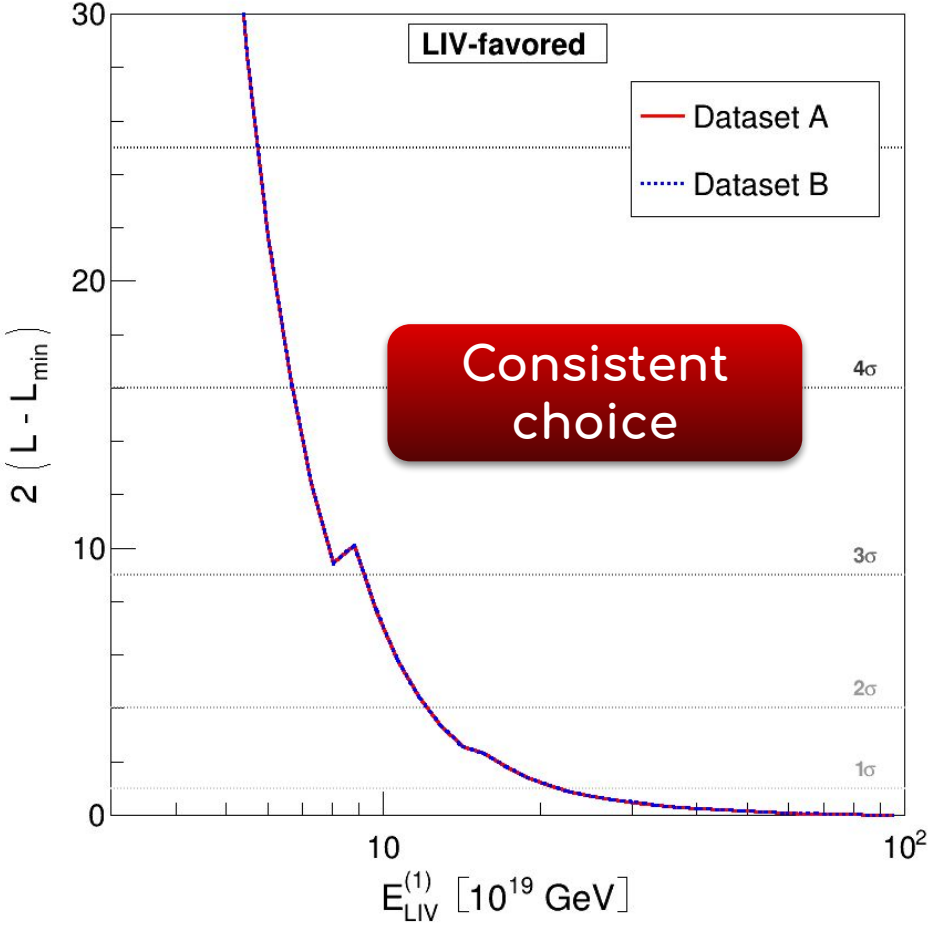
	Franceschini			Dominguez			Gilmore		
	2σ	3σ	5σ	2σ	3σ	5σ	2σ	3σ	5σ
$E_{\mathrm{LIV}}^{(1)}$ $[10^{28}$ eV$]$	12.08	9.14	5.73	6.85	5.62	4.17	14.89	9.80	4.74
$E_{\mathrm{LIV}}^{(2)}$ $[10^{21}$ eV$]$	2.38	1.69	1.42	1.56	1.40	1.14	2.17	1.78	1.31

Lang, R., Martínez-Huerta, H & de Souza, V. **Phys. Rev. D**, 2019

Systematics

- Data selection;

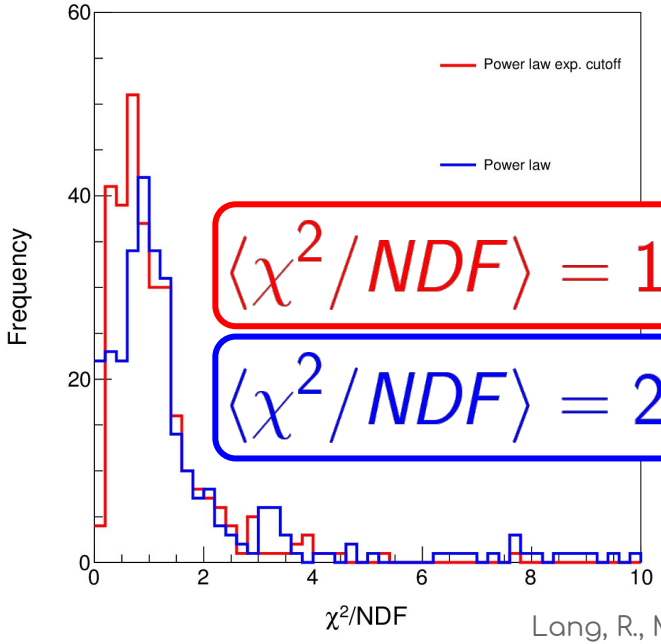




Lang, R., Martínez-Huerta, H & de Souza, V. Phys. Rev. D, 2019

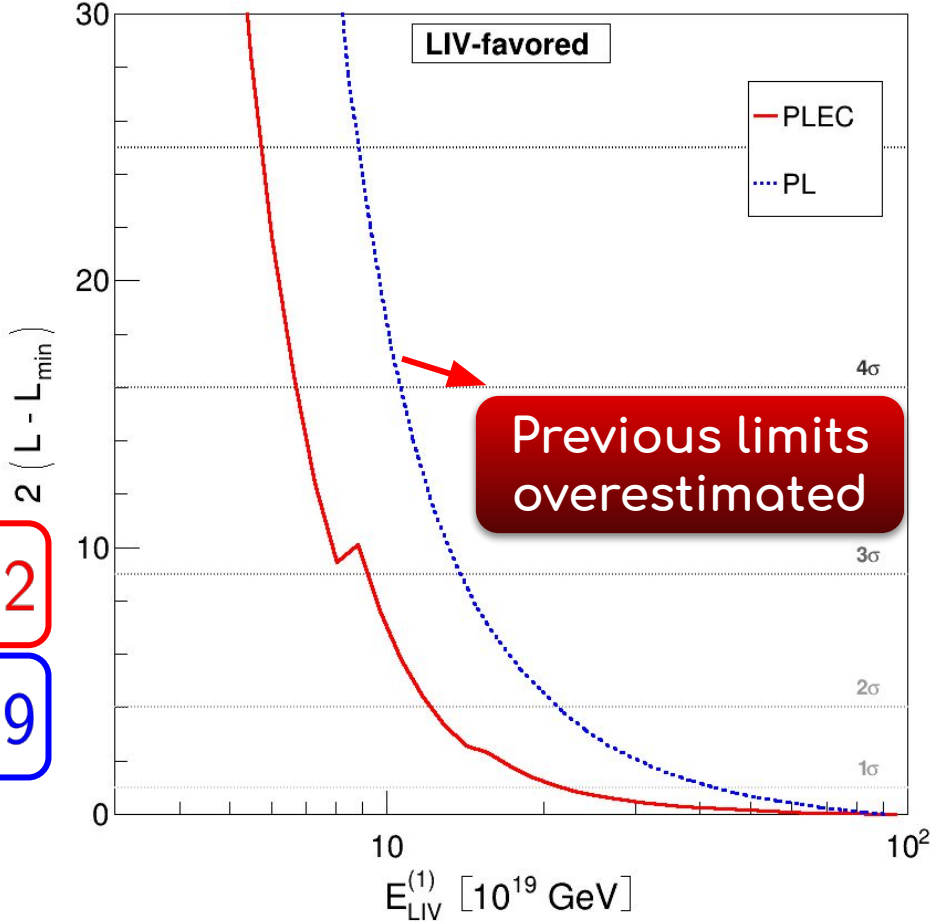
Systematics

- Data selection;
- Intrinsic spectra (PLEC);



$$\langle \chi^2/NDF \rangle = 1.12 \pm 0.92$$

$$\langle \chi^2/NDF \rangle = 2.04 \pm 3.09$$

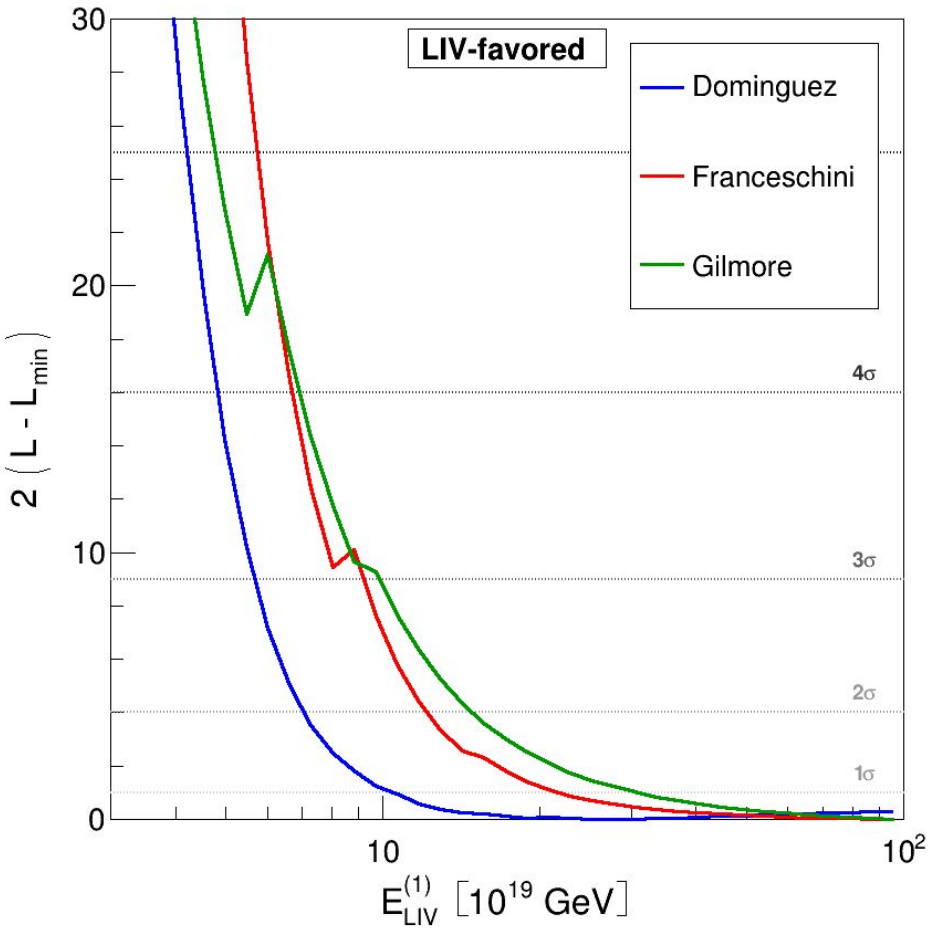


Previous limits overestimated

Lang, R., Martínez-Huerta, H & de Souza, V. Phys. Rev. D, 2019

Systematics

- Data selection;
- Intrinsic spectra (PLEC);
- EBL model (Franceschini);

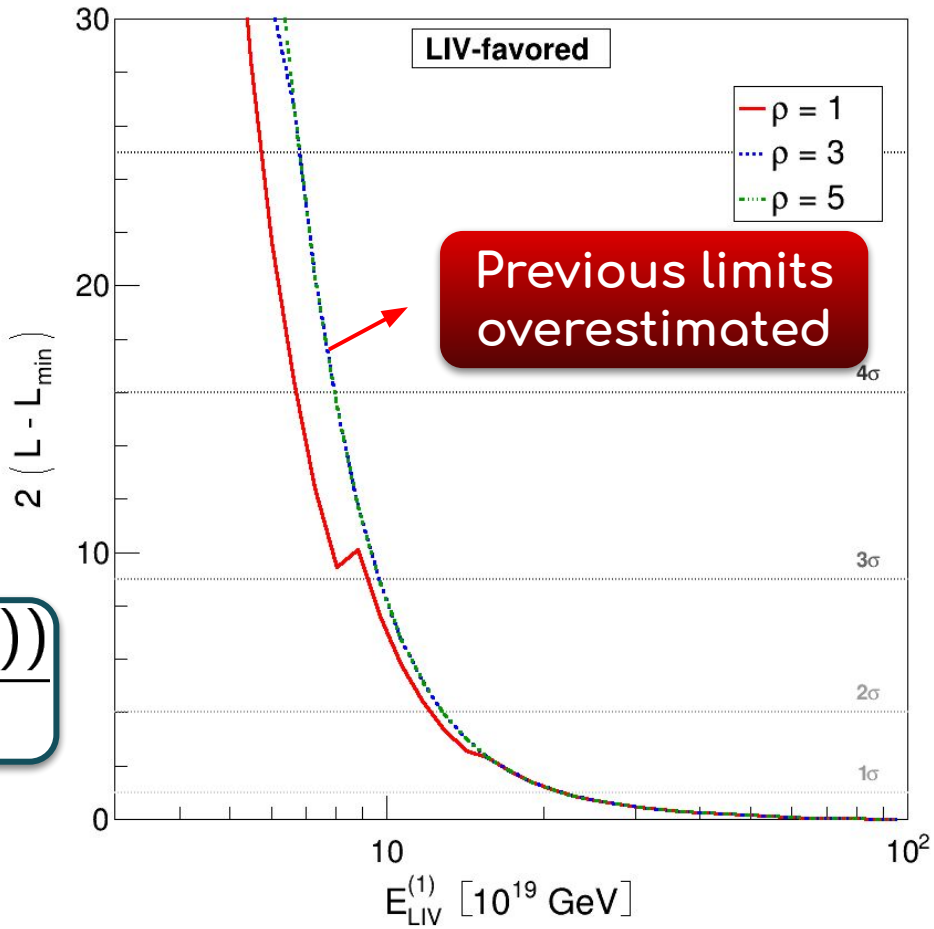


Lang, R., Martínez-Huerta, H & de Souza, V. **Phys. Rev. D**, 2019

Systematics

- Data selection;
- Intrinsic spectra (PLEC);
- EBL model (Franceschini);
- Bins selection (ρ=1);

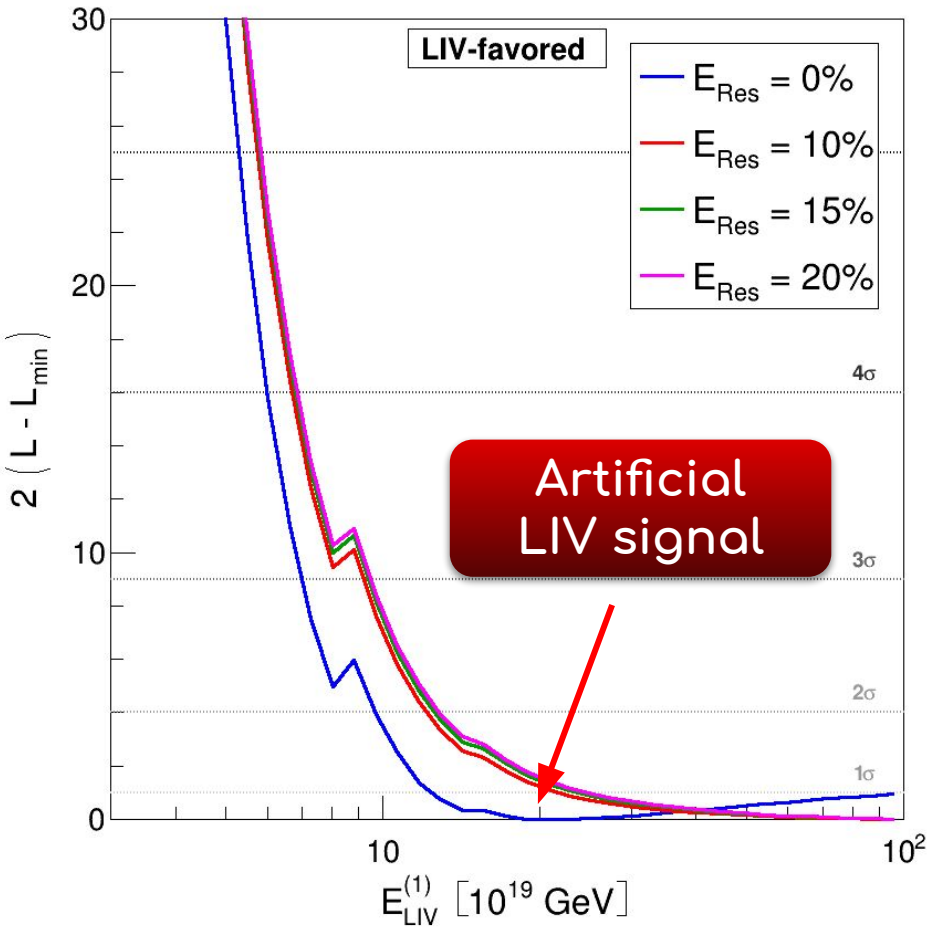
$$\frac{a_{\mathrm{LIV}}}{a_{\mathrm{LI}}} \leq \frac{J_{\mathrm{meas}}(E) + \rho\sigma\left(J_{\mathrm{meas}}(E)\right)}{J_{\mathrm{meas}}(E)}$$



Lang, R., Martínez-Huerta, H & de Souza, V. **Phys. Rev. D**, 2019

Systematics

- Data selection;
- Intrinsic spectra (PLEC);
- EBL model (Franceschini);
- Bins selection (ρ=1);
- Energy resolution (E_{RES} = 10%).



Lang, R., Martínez-Huerta, H & de Souza, V. Phys. Rev. D, 2019