Limits on the LIV from UHECR astrophysics

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Paris – Thursday, November 30th, 2017

FAPESP

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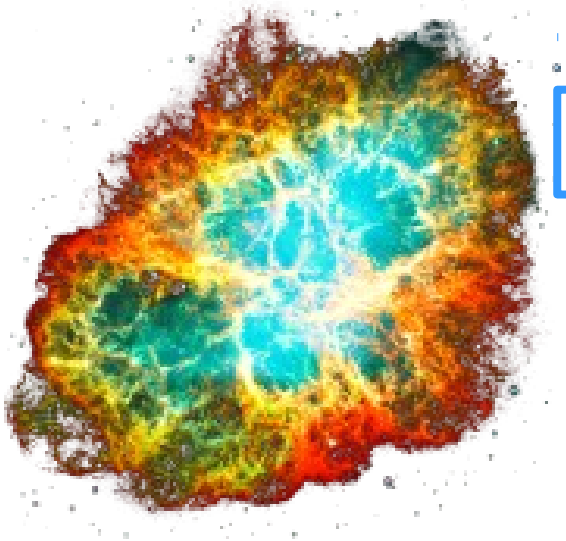
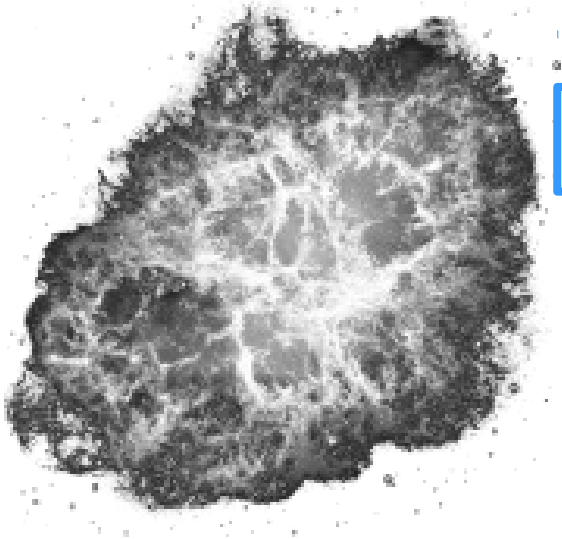
Objectives

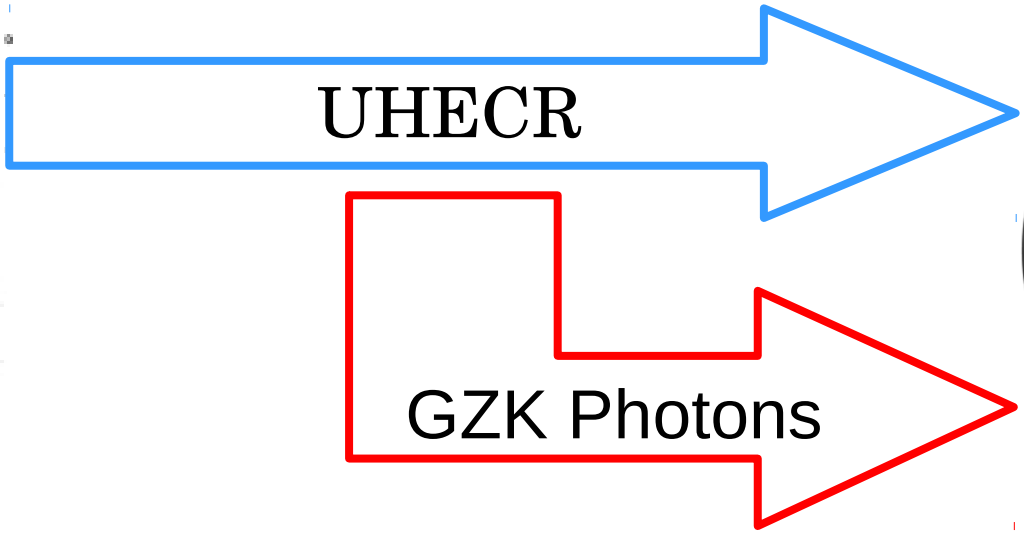
- Study the propagation of UHE photons ($E > 10^{18}$ eV) with LIV;
- Use the upper limits on the photon flux to impose upper limits on LIV;
- Study the influence of astrophysical models on such limits.

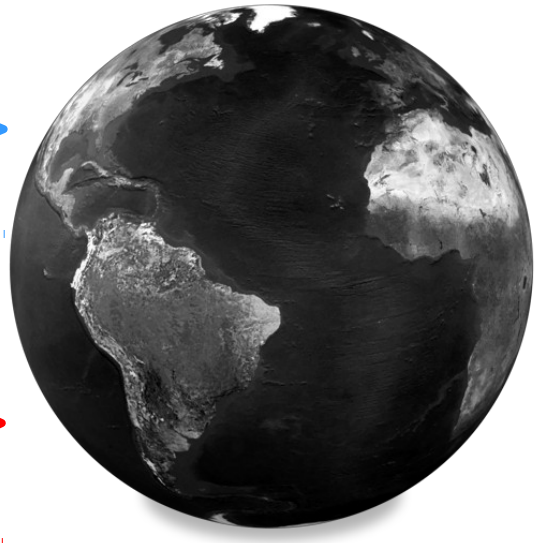


UHECR

GZK Photons







- Propagating UHECRs interact with the photon background producing pion, which later decay on EeV photons.
- In this work, LIV is considered only on the propagation of photons. The propagation of UHECRs is LI.

LIV framework

- LIV effects on the dispersion relation:

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

Modified energy threshold

- Propagating photons lose energy mainly via pair production:

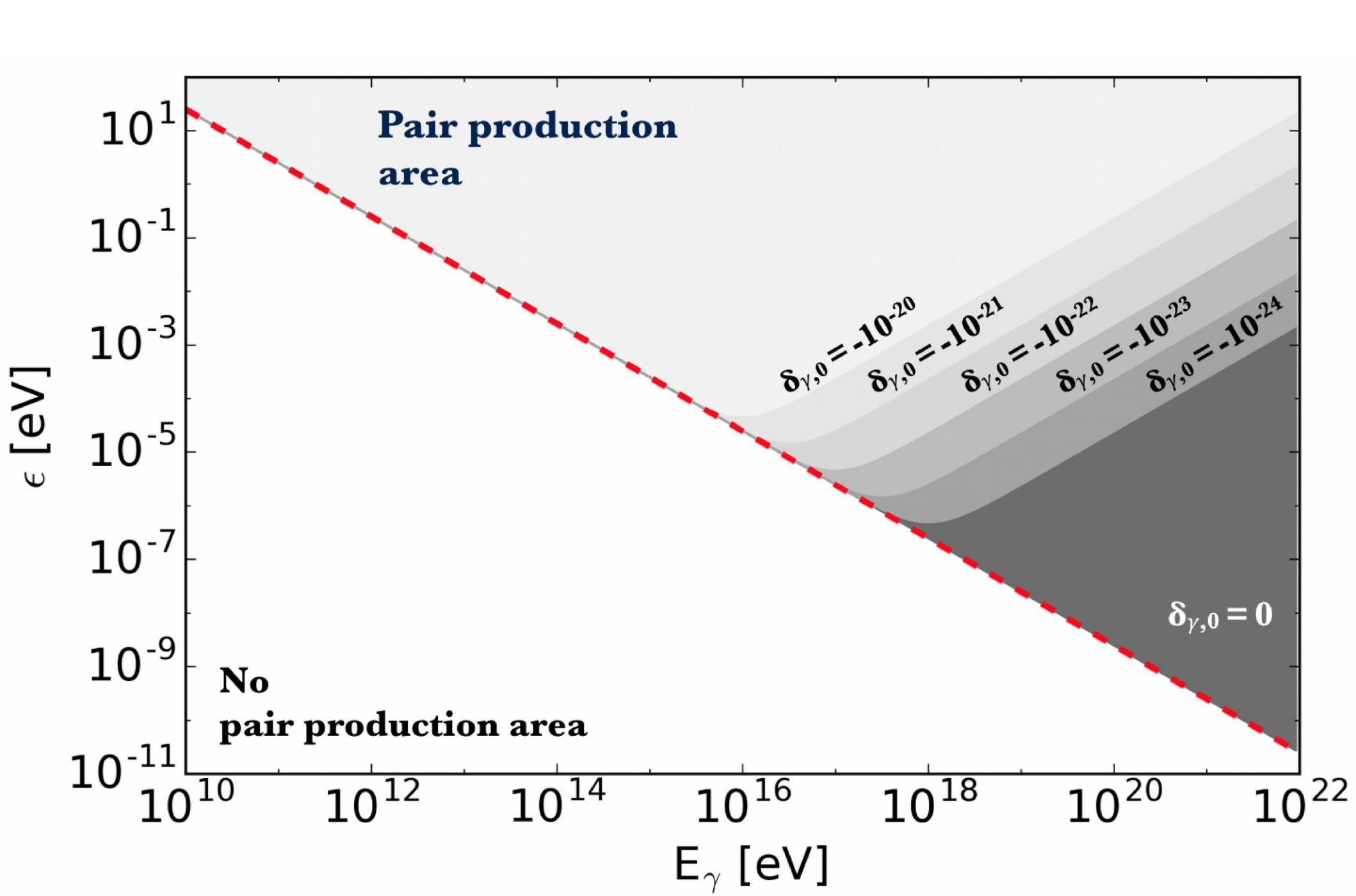
$$\gamma + \gamma_{CB} \rightarrow e^- + e^+$$

- We consider LIV on the photon sector and, therefore, only the dispersion relation for the photons is changed.

Modified energy threshold

- The effects on the kinematics on the interaction can be reduced to a correction in the energy threshold:

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


Pair production area
No pair production area
$\delta_{\gamma,0} = -10^{-20}$
$\delta_{\gamma,0} = -10^{-21}$
$\delta_{\gamma,0} = -10^{-22}$
$\delta_{\gamma,0} = -10^{-23}$
$\delta_{\gamma,0} = -10^{-24}$
$\delta_{\gamma,0} = 0$
ϵ [eV]
E_γ [eV]
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}

Modified mean free path

- Using the modified energy threshold it is possible to obtain the modified mean free path:

$$\lambda^{LIV} = \left[\int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \int_{\epsilon_{th}^{LIV}}^{\infty} d\epsilon n_{CB}(\epsilon, z) \sigma(E_\gamma, \epsilon, z) \right]^{-1}$$

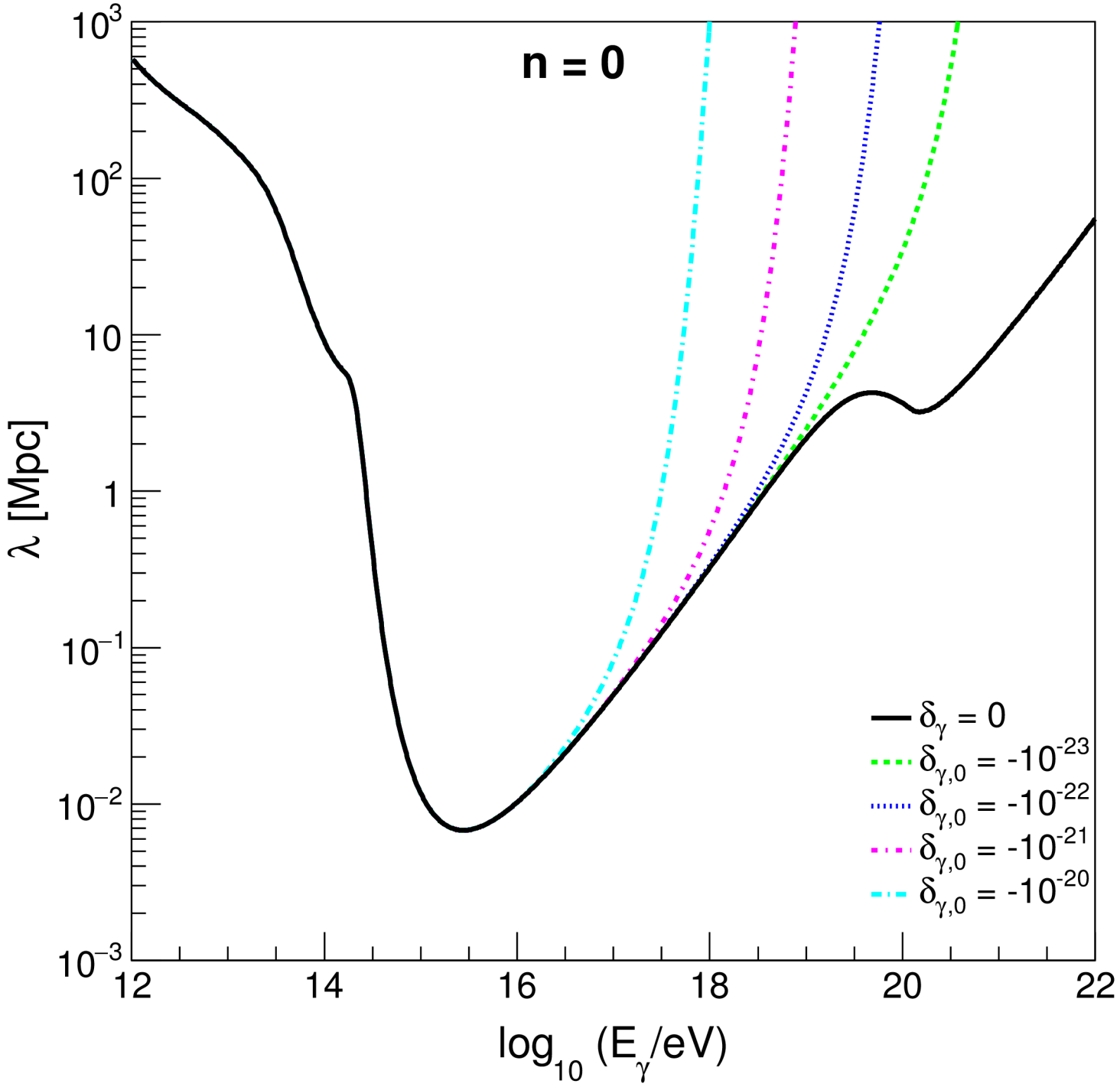
LIV energy threshold

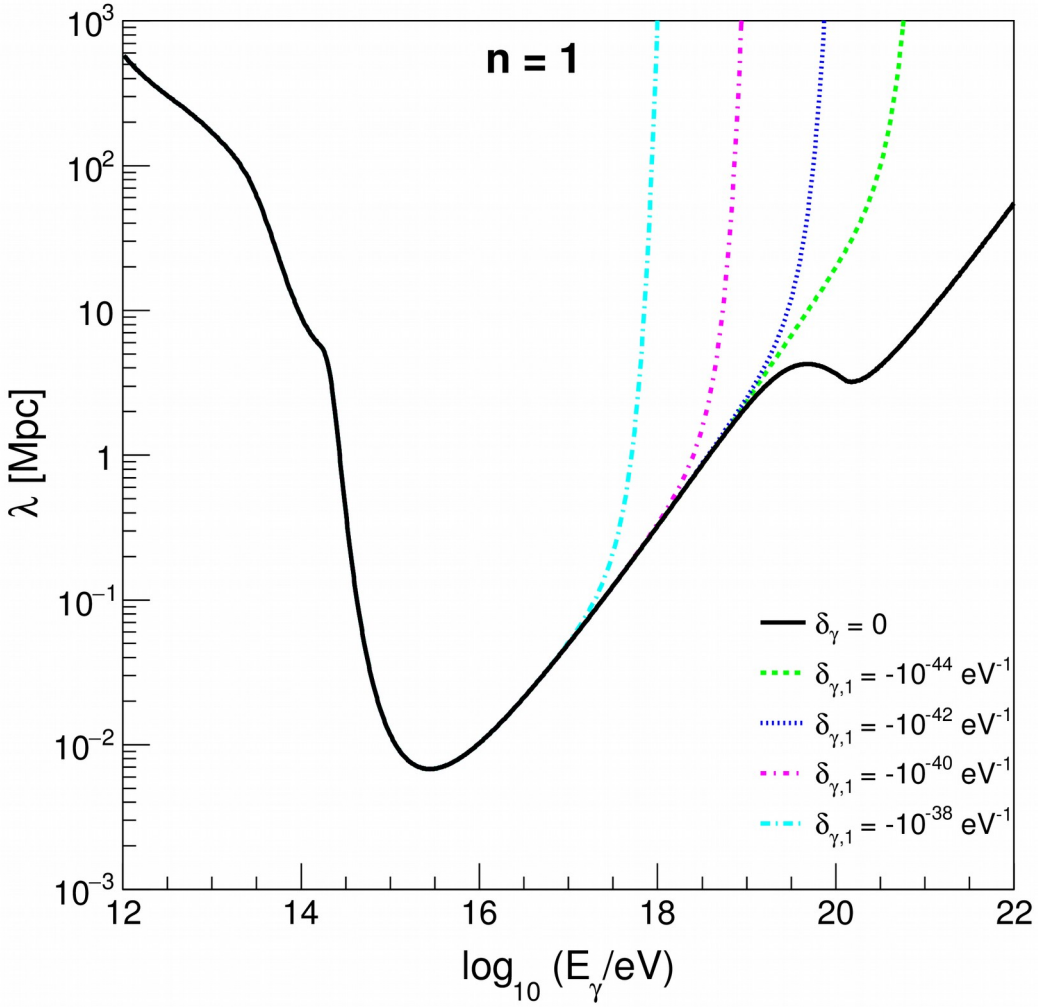
Photon background density:

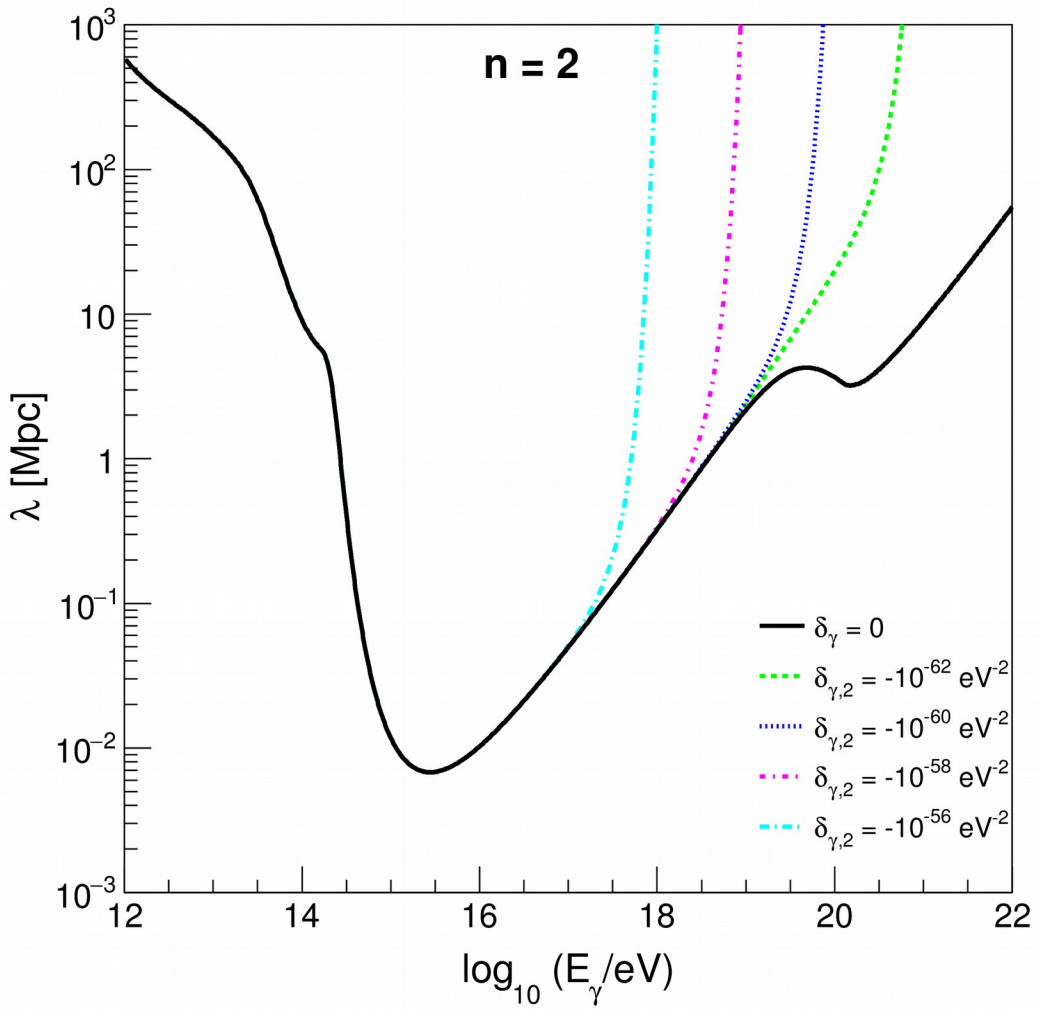
-EBL
-CMB
-RB

Cross-section:

Breit & Wheeler


n = 0
λ [Mpc]
log10 (Eγ/eV)
δγ = 0
δγ,0 = -10-23
δγ,0 = -10-22
δγ,0 = -10-21
δγ,0 = -10-20


n = 1
λ [Mpc]
log10 (Eγ/eV)
δγ = 0
δγ,1 = -10-44 eV-1
δγ,1 = -10-42 eV-1
δγ,1 = -10-40 eV-1
δγ,1 = -10-38 eV-1

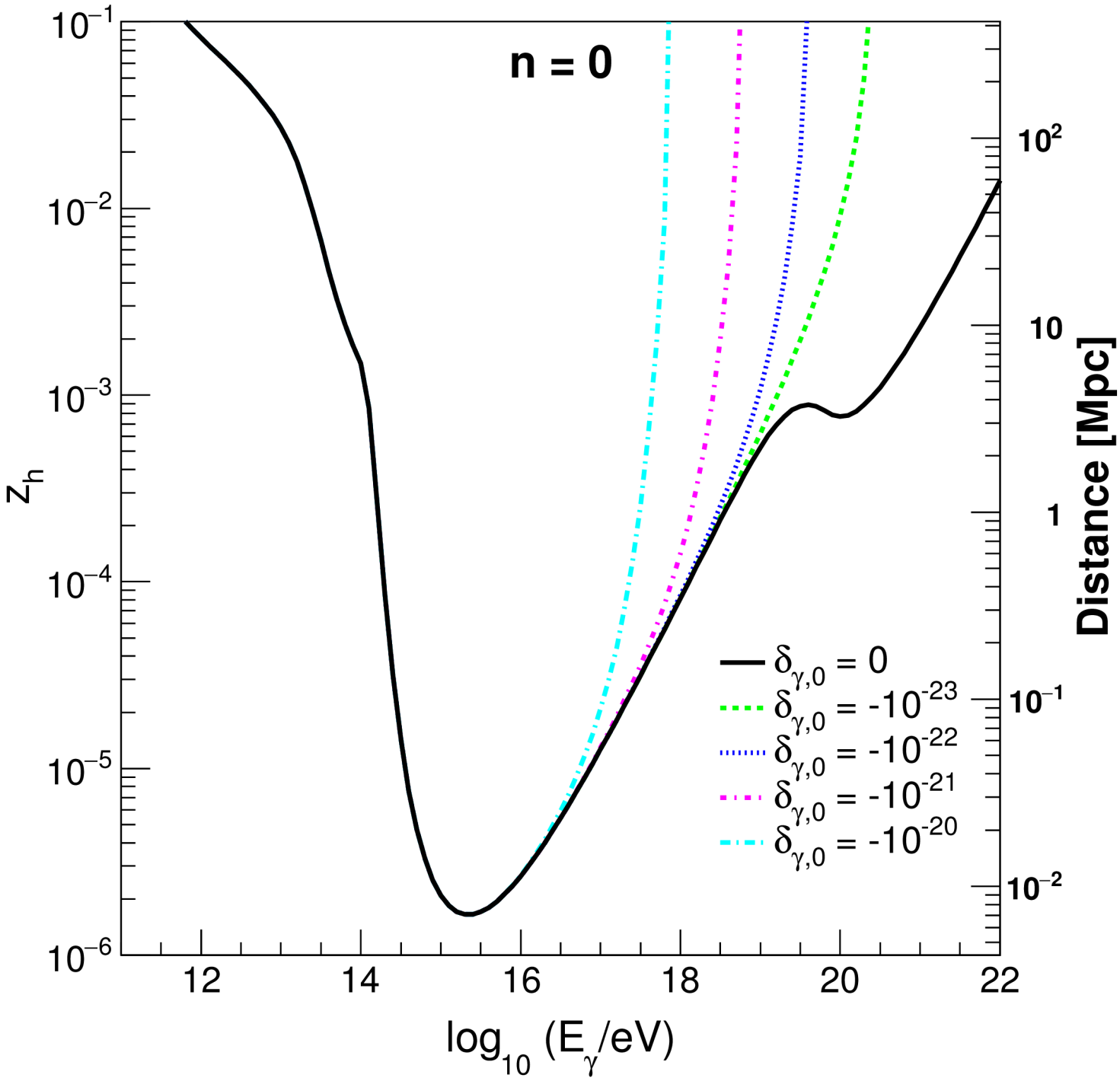

n = 2
λ [Mpc]
log10 (Eγ/eV)
δγ = 0
δγ,2 = -10-62 eV-2
δγ,2 = -10-60 eV-2
δγ,2 = -10-58 eV-2
δγ,2 = -10-56 eV-2

Modified photon horizon

- The effects become more tangible when we look at the photon horizon:

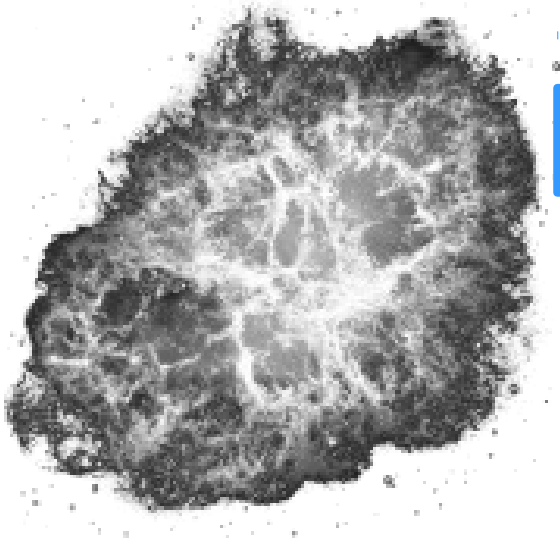
$$\tau^{LIV}(E_\gamma, z) = \int_0^z dz \frac{c}{H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}} \times \int_{-1}^{1} d(\cos\theta)\frac{1-\cos\theta}{2}\int_{\epsilon_{th}^{LIV}}^{\infty} d\epsilon n_{CB}(\epsilon, z)\sigma(E_\gamma, \epsilon, z)$$

$$\tau(E_\gamma, z) = 1 \leftrightarrow z_H$$


n = 0
z_h
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
12
14
16
18
20
22
$\log_{10}(E_\gamma/eV)$
Distance [Mpc]
10^2
10
1
10^{-1}
10^{-2}
$\delta_{\gamma,0} = 0$
$\delta_{\gamma,0} = -10^{-23}$
$\delta_{\gamma,0} = -10^{-22}$
$\delta_{\gamma,0} = -10^{-21}$
$\delta_{\gamma,0} = -10^{-20}$

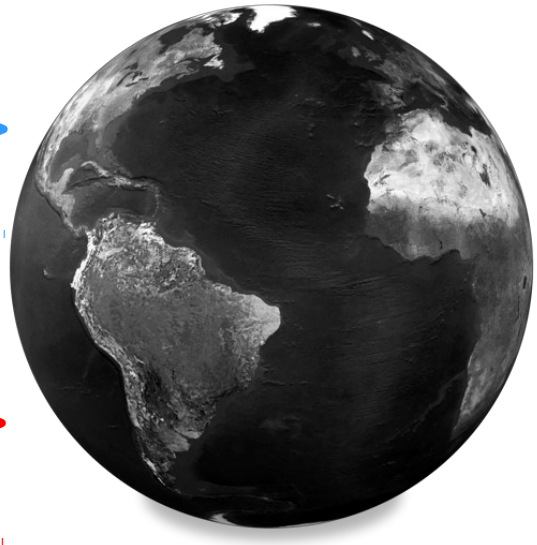
Propagation codes

- The modified mean free paths have been implemented in the CRPropa3/EleCa propagation codes;



UHECR

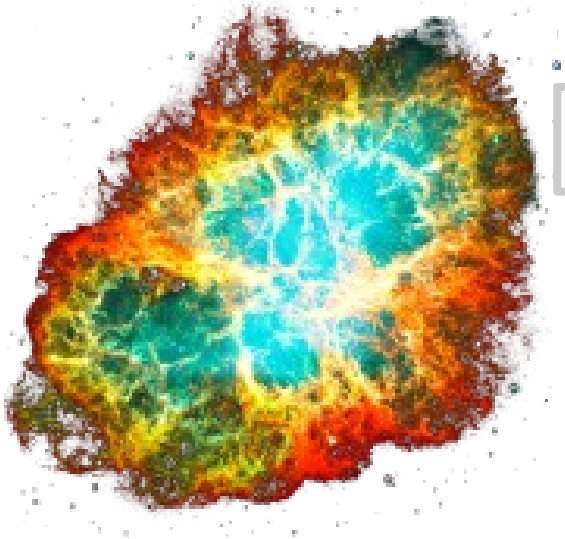
GZK Photons



Propagation:

- LIV on the photon propagation;

- Modified mean free paths implemented on MC codes.



UHECR

GZK Photons

- No source of UHECR has yet been identified;
- Several models proposing the distribution of sources on the universe and the composition and energy distribution of emitted UHECR have been discussed;
- The dependency on these models have been neglected in previous studies considering GZK photons.

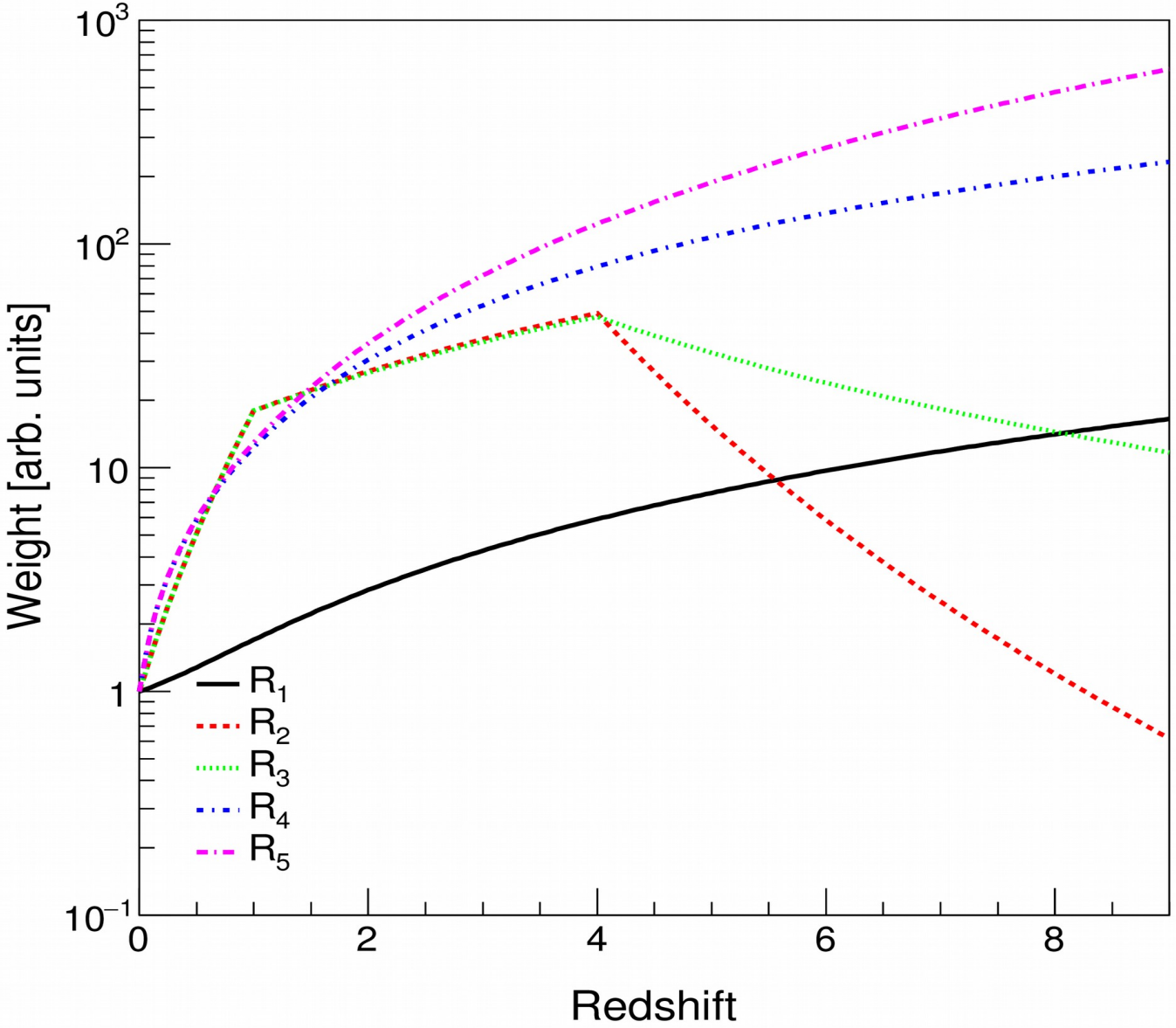
Models of UHECR sources

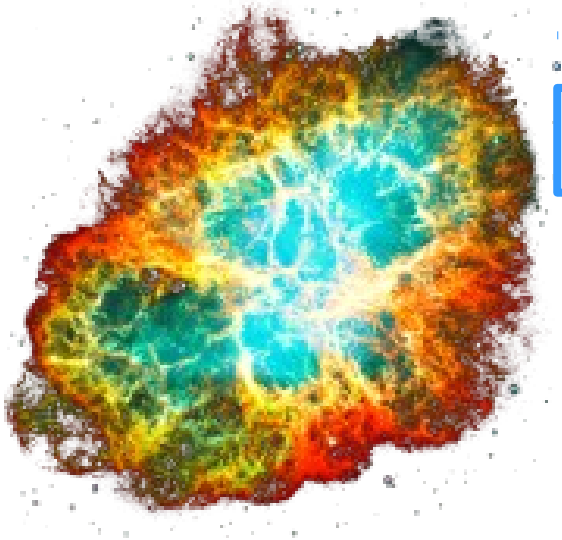
- 4 models (C_1 – C_4) have been used in this work. They all reduce to a power law with a rigidity cutoff:

$$\frac{dN}{dE_s} = \begin{cases} E_s^{-\Gamma} & , \text{for } R_s > R_{cut} \\ E_s^{-\Gamma} e^{(1-R_s/R_{cut})} & , \text{for } R_s \geq R_{cut} \end{cases}$$

- There are 5 free parameters, which are different per model.

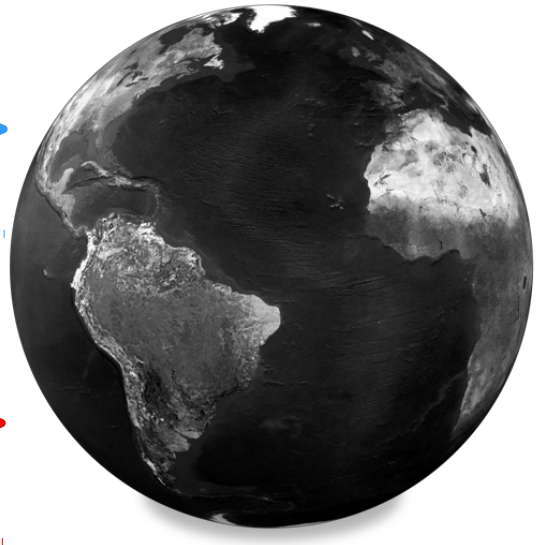
Models of sources distribution





UHECR

GZK Photons



Sources:

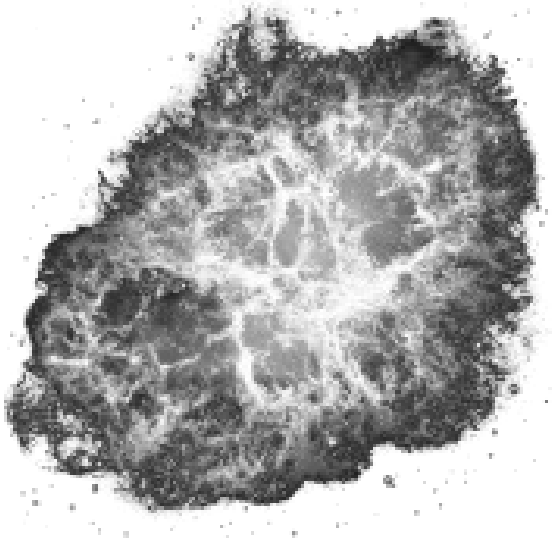
- 4 models for the UHECR sources;

- 5 models for the sources distribution.

Propagation:

- LIV on the photon propagation;

- Modified mean free paths implemented on MC codes.



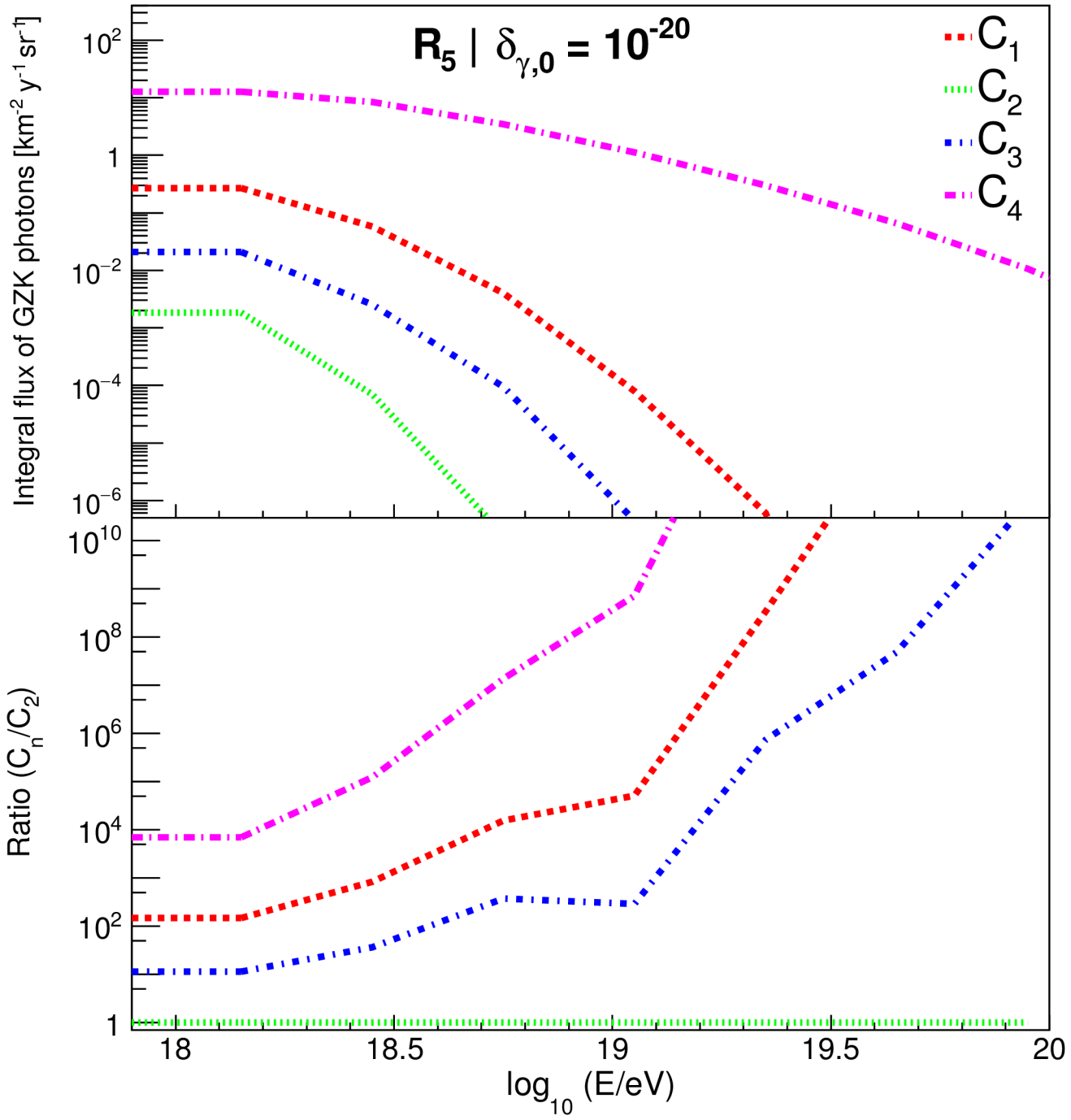
UHECR

GZK Photons

- The spectrum of UHECR was normalized to Pierre Auger's spectrum at $E = 10^{18.75}$ eV; (Inés Valiño for the Pierre Auger Collaboration, ICRC 2015)
- The fluxes of GZK photons were compared to the upper limits on the flux from Pierre Auger; (The Pierre Auger Collaboration, JCAP, 2017)
- For some models, upper limits on the LIV coefficients could be imposed.

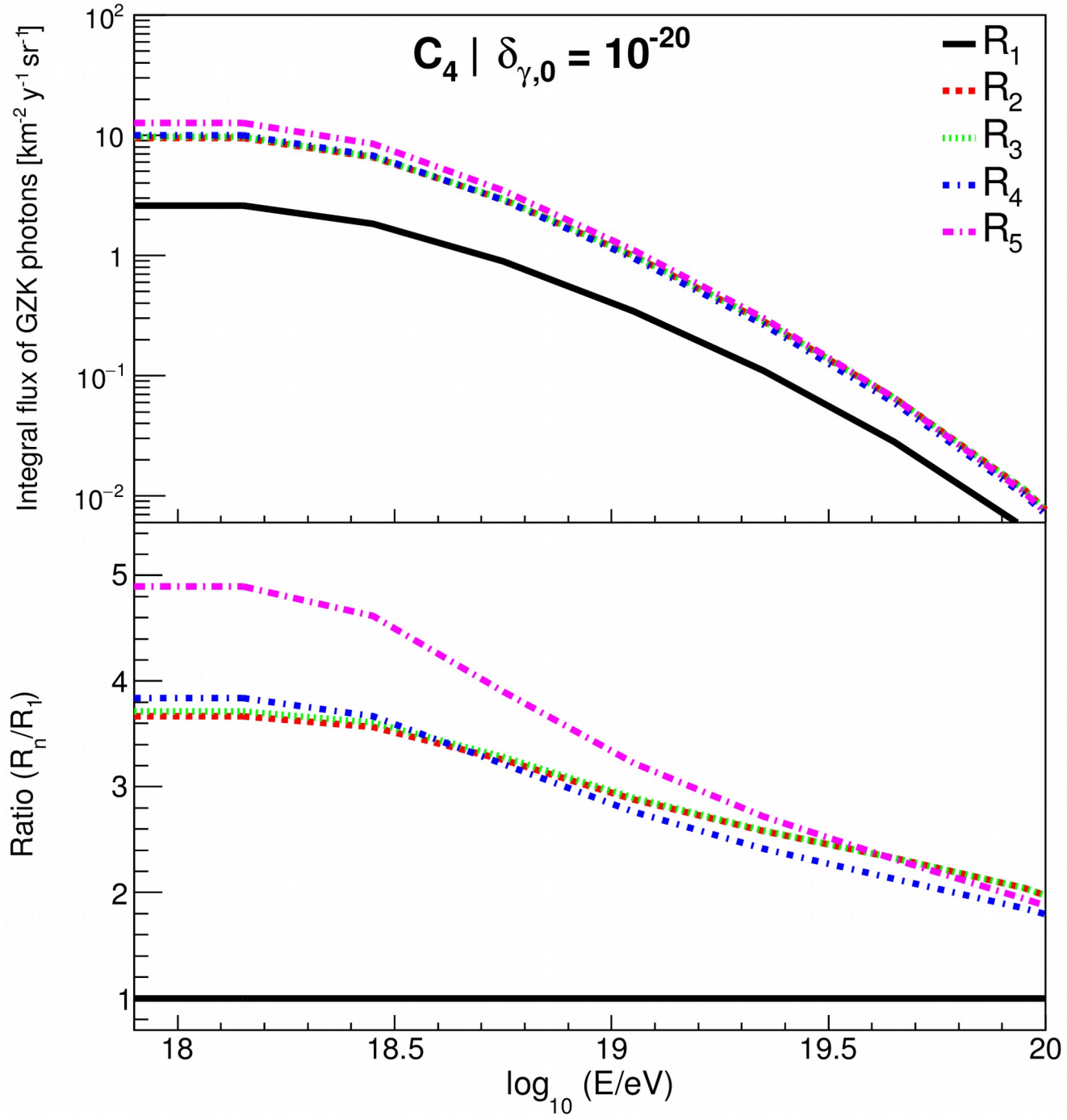
UHECR model dependency:

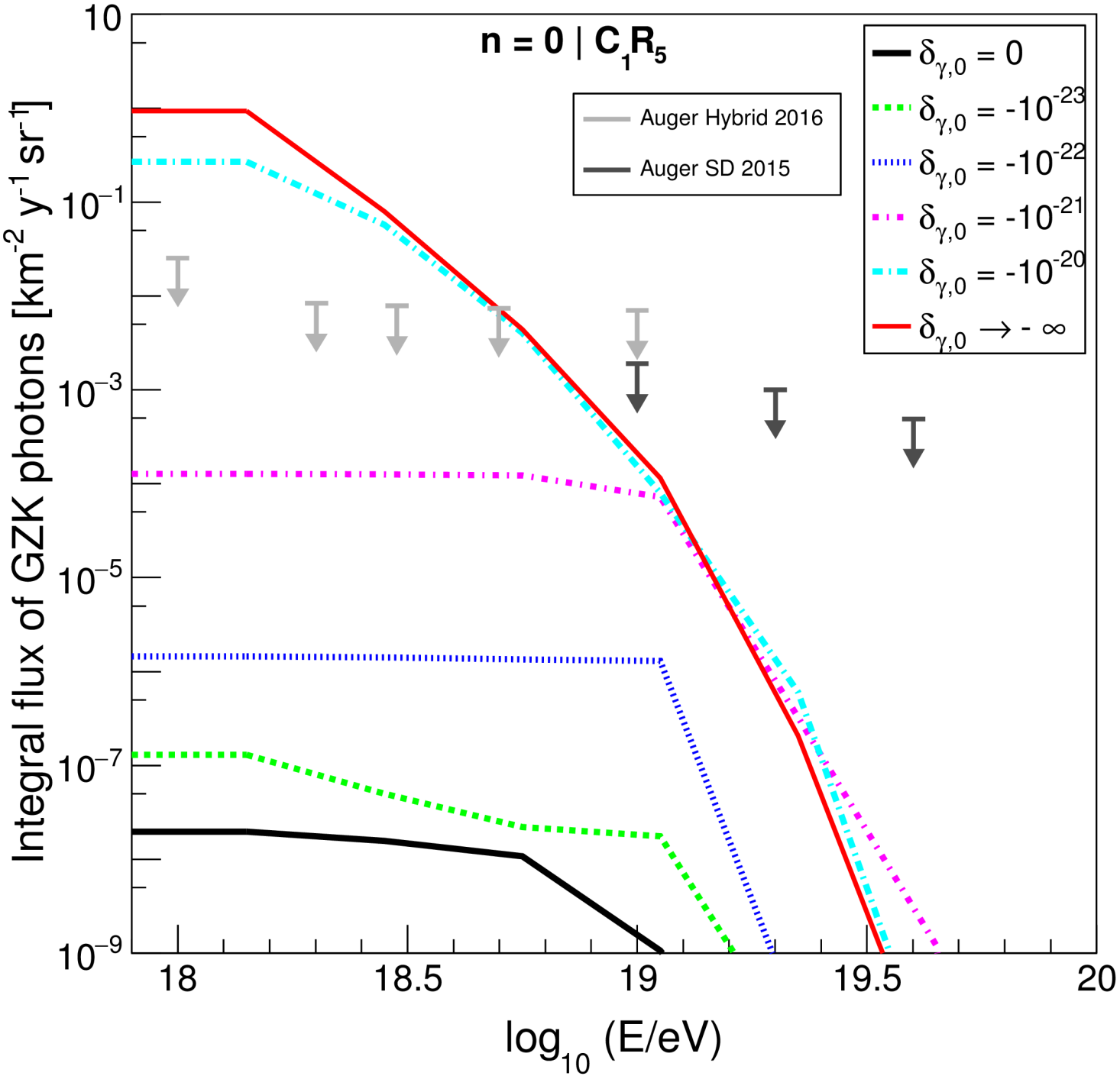
over 4 orders of magnitude

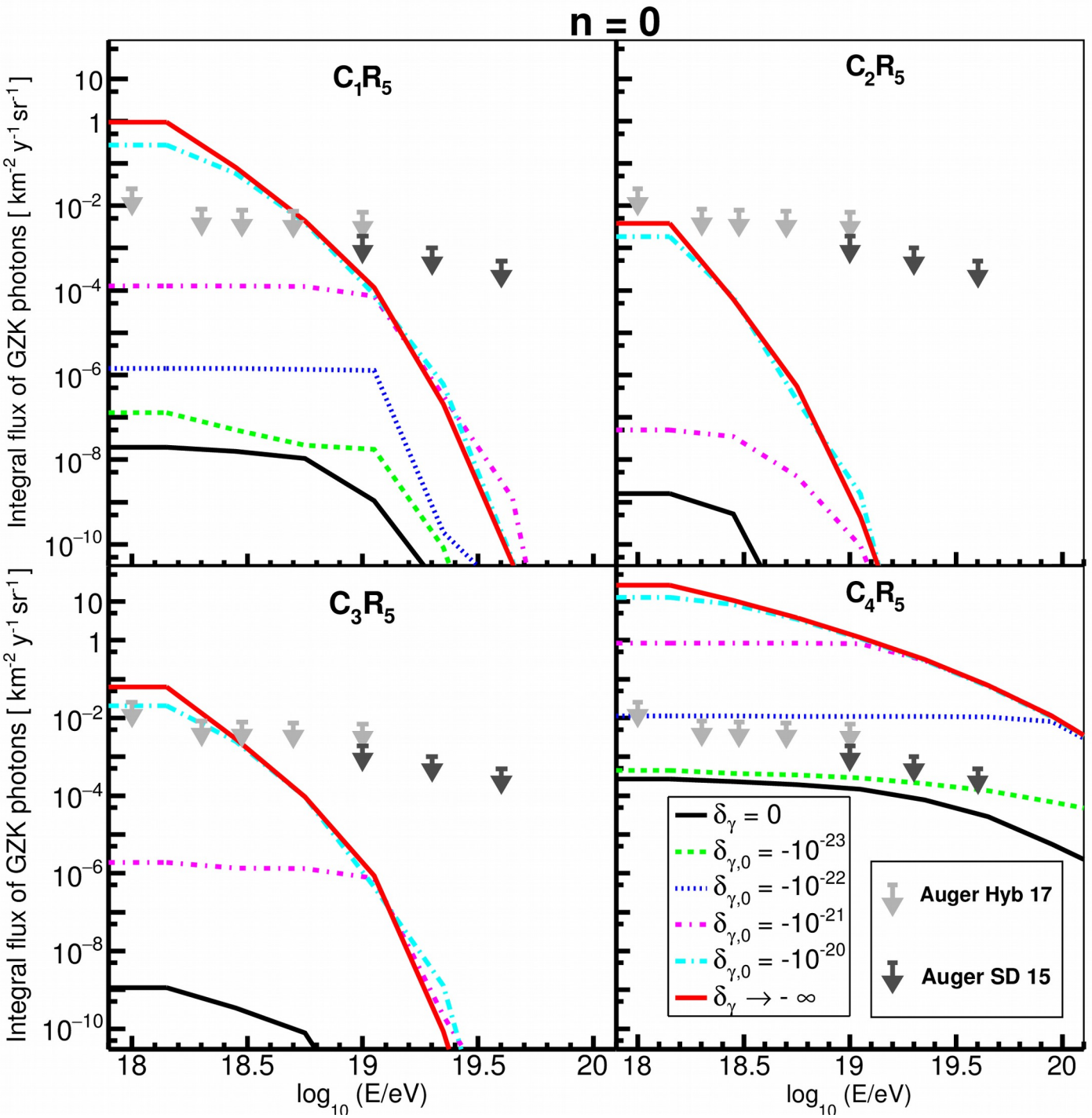


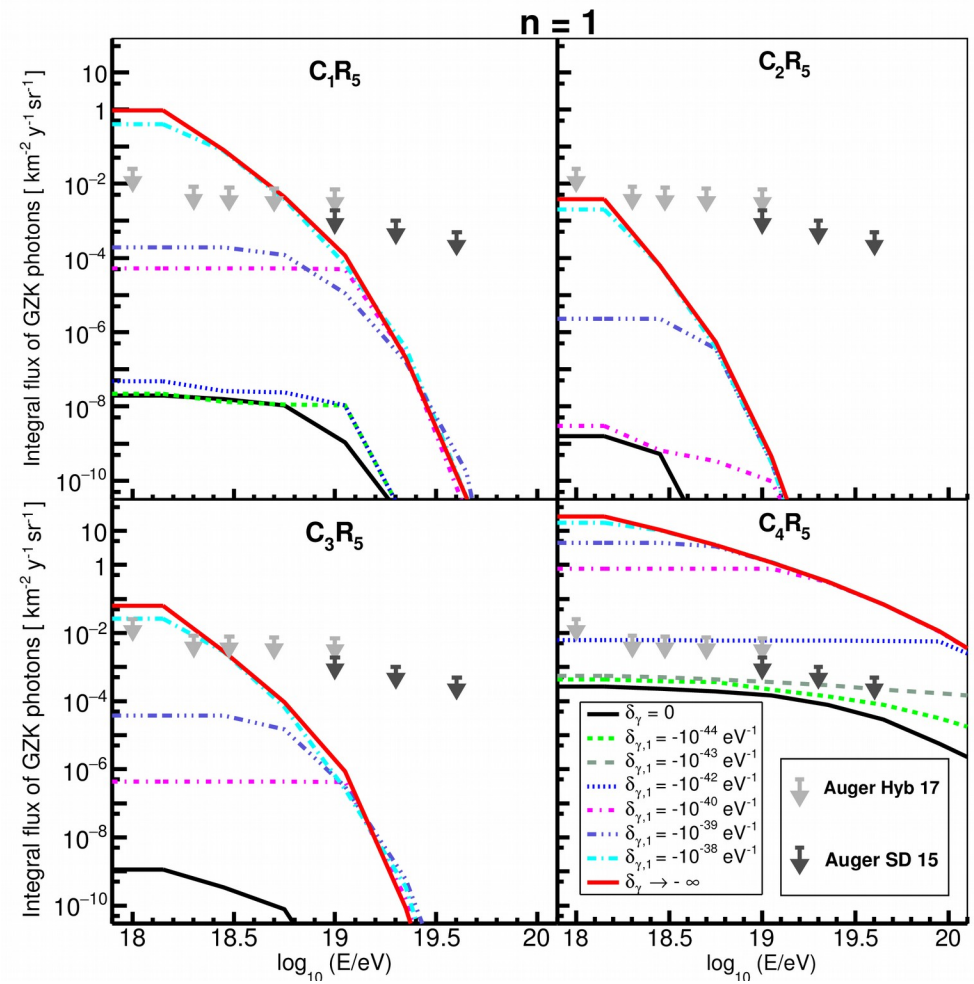
Sources distribution dependency:

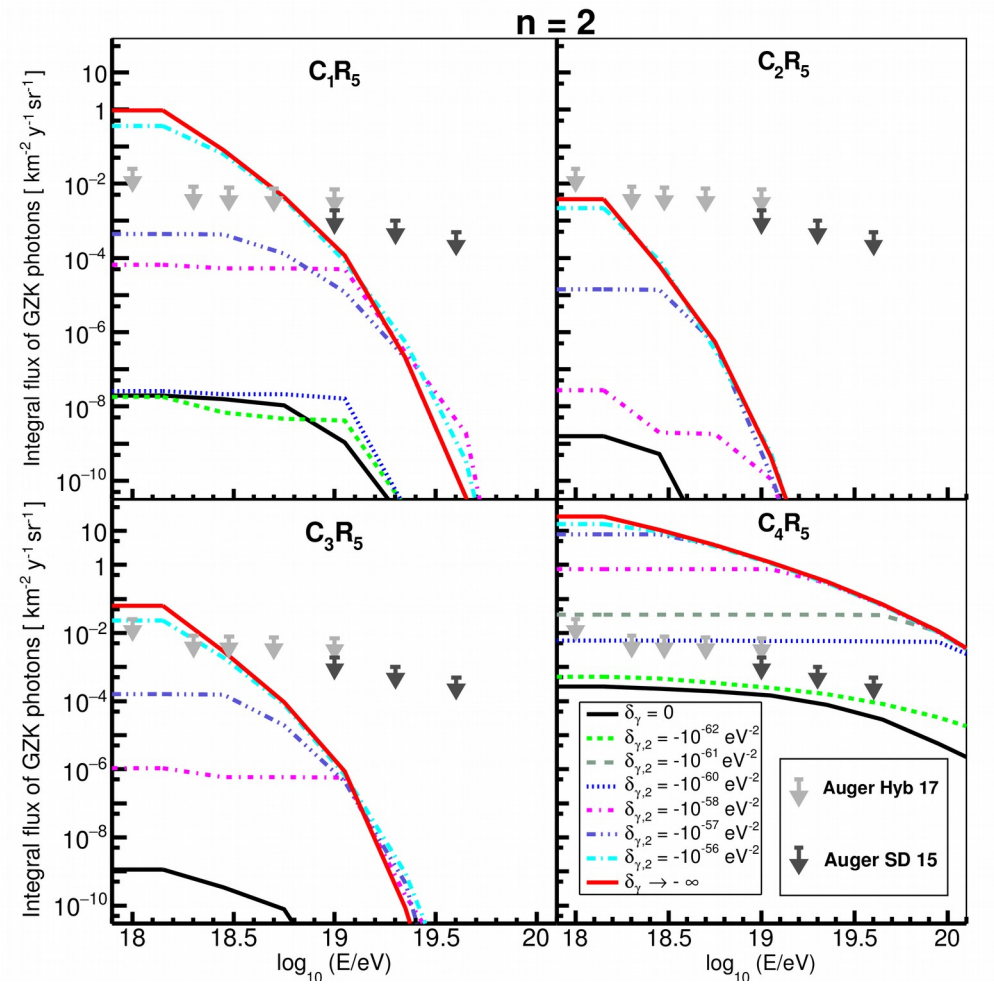
~500%

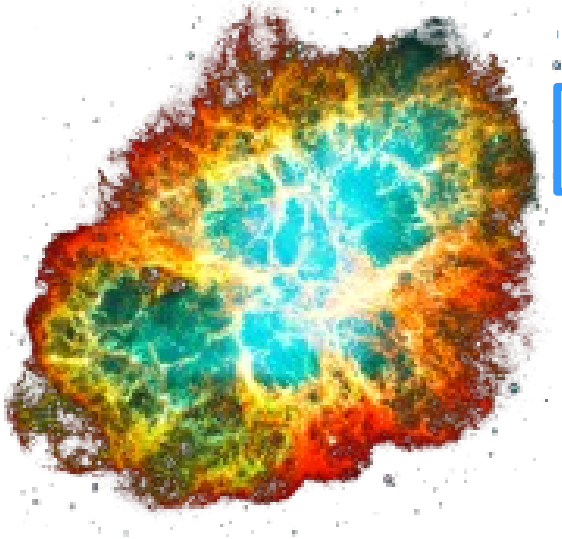



n = 0 | C1R5
Auger Hybrid 2016
Auger SD 2015
δγ,0 = 0
δγ,0 = -10-23
δγ,0 = -10-22
δγ,0 = -10-21
δγ,0 = -10-20
δγ,0 → - ∞
Integral flux of GZK photons [km-2 y-1 sr-1]
log10 (E/eV)
10
10−1
10−3
10−5
10−7
10−9
18
18.5
19
19.5
20


n = 0
C1R5
C2R5
C3R5
C4R5
Integral flux of GZK photons [km-2 y-1 sr-1]
log10 (E/eV)
δγ = 0
δγ,0 = -10-23
δγ,0 = -10-22
δγ,0 = -10-21
δγ,0 = -10-20
δγ → - ∞
Auger Hyb 17
Auger SD 15


n = 1
C1R5
C2R5
C3R5
C4R5
Integral flux of GZK photons [km-2 y-1 sr-1]
log10 (E/eV)
δγ = 0
δγ,1 = -10-44 eV-1
δγ,1 = -10-43 eV-1
δγ,1 = -10-42 eV-1
δγ,1 = -10-40 eV-1
δγ,1 = -10-39 eV-1
δγ,1 = -10-38 eV-1
δγ → - ∞
Auger Hyb 17
Auger SD 15


n = 2
C1R5
C2R5
C3R5
C4R5
Integral flux of GZK photons [km-2 y-1 sr-1]
log10 (E/eV)
δγ = 0
δγ,2 = -10-62 eV-2
δγ,2 = -10-61 eV-2
δγ,2 = -10-60 eV-2
δγ,2 = -10-58 eV-2
δγ,2 = -10-57 eV-2
δγ,2 = -10-56 eV-2
δγ → - ∞
Auger Hyb 17
Auger SD 15



UHECR

GZK Photons

Sources:

- 4 models for the UHECR sources;

- 5 models for the sources distribution.

Propagation:

- LIV on the photon propagation;

- Modified mean free paths implemented on MC codes.

Spectra:

- UHECR normalized to Auger's spectrum;

- GZK photon flux compared to Auger's upper limits.

LIV Limits

LIV limits

Model	$\delta_{\gamma,0}^{limit}$	$\delta_{\gamma,1}^{limit}[\mathrm{eV}^{-1}]$	$\delta_{\gamma,2}^{limit}[\mathrm{eV}^{-2}]$
$C_1 R_5$	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
$C_2 R_5$	-	-	-
$C_3 R_5$	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
$C_4 R_5$	$\sim -10^{-22}$	$\sim -10^{-42}$	$\sim -10^{-60}$

Model	$\delta_{\gamma,0}^{limit}$	$\delta_{\gamma,1}^{limit}[\mathrm{eV}^{-1}]$	$\delta_{\gamma,2}^{limit}[\mathrm{eV}^{-2}]$
Galaverni & Sigl (2008)	-	-1.97×10^{-43}	-1.61×10^{-63}
H.E.S.S. - PKS 2155-304 (2011)	-	-4.76×10^{-28}	-2.44×10^{-40}
Fermi - GRB 090510 (2013)	-	-1.08×10^{-29}	-5.92×10^{-41}
H.E.S.S. - Mrk 501 (2017)	-	-9.62×10^{-29}	-4.53×10^{-42}

LIV limits

Model	$\delta_{\gamma,0}^{limit}$	$\delta_{\gamma,1}^{limit}[\mathrm{eV}^{-1}]$	$\delta_{\gamma,2}^{limit}[\mathrm{eV}^{-2}]$
$C_1 R_5$	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
$C_2 R_5$	-	-	-
$C_3 R_5$	$\sim -10^{-20}$	$\sim -10^{-38}$	$\sim -10^{-56}$
$C_4 R_5$	$\sim -10^{-22}$	$\sim -10^{-42}$	$\sim -10^{-60}$

Model	$\delta_{\gamma,0}^{limit}$	δ^{lim}
Galaverni & Sigl (2008)	-	-1
H.E.S.S. - PKS 2155-304 (2011)	-	-4
Fermi - GRB 090510 (2013)	-	-1
H.E.S.S. - Mrk 501 (2017)	-	-9

TeV photons:

- Comparison is not straight-forward due to different systematics and energies!!

Comparison with previous limits

	Galaverni & Sigl (2008)	This work (2017)
Photon background	CMB peak	Full integration (EBL, CMB and RB)
Propagation	-	Monte Carlo (CRPropa 3/EleCa)
UHECR spectrum and photon flux	AGASA (2006)	Auger (2015)
Injection spectra	Pure proton (in contrast with Auger X_{max} data)	4 models
Sources evolution	Only homogeneous	5 models

Conclusions

- The effects of LIV on the propagation of photons have been studied;
- The energy threshold and mean free path including LIV for the pair production as well as the photon horizon have been obtained;
- For the first time, the dependency of the GZK photon flux including LIV on the models for UHECR sources have been discussed;
- Limits on the LIV coefficient have been imposed ;
- These limits are more conservative and up to date than the previous ones using the same technique.

Models of UHECR sources

- **C_1:** Aloisio, Berezinsky & Blasi (2014);
- **C_2:** Unger, Farrar & Anchordoqui (2015) – fiducial;
- **C_3:** Unger, Farrar & Anchordoqui (2015) – abundance of galactic nuclei;
- **C_4:** Berezinsky, Gazizov & Grigorieva (2007) – dip model;

Model	Γ	$log_{10}(R_{cut}/V)$	fH	fHe	fN	fSi	fFe
C_1	1	18.699	0.7692	0.1538	0.0461	0.0231	0.00759
C_2	1	18.5	0	0	0	1	0
C_3	1.25	18.5	0.365	0.309	0.121	0.1066	0.098
C_4	2.7	∞	1	0	0	0	0

Models of sources distribution

- **R_1:** Sources uniformly distributed in a comoving volume;
- **R_2:** Sources follow the star formation distribution from Hopkins & Beacom (2006);
- **R_3:** Sources follow the star formation distribution from Yksel et al. (2008);
- **R_4:** Sources follow one of the GRB rate evolution from Le & Dermer (2007);
- **R_5:** Sources follow one of the GRB rate evolution from Le & Dermer (2007).