IFSC UNIVERSIDADE DE SÃO PAULO
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FAPESP

Limits on Lorentz Invariance Violation from ultra high energy astrophysics

The Astrophysical Journal. 853, no.1, 23 (2018)

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IFSC-USP, Brazil

27-31 Aug 2018
Berlin
Germany

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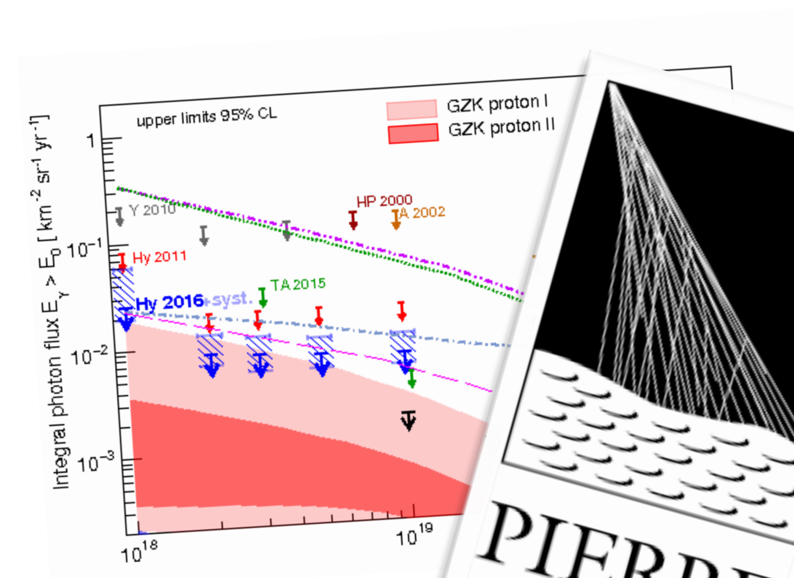
I. Lorentz invariance violation (LIV)

II. LIV + gamma-rays

III. Optical Depth + LIV

IV. GZK photon flux + LIV

V. LIV limits



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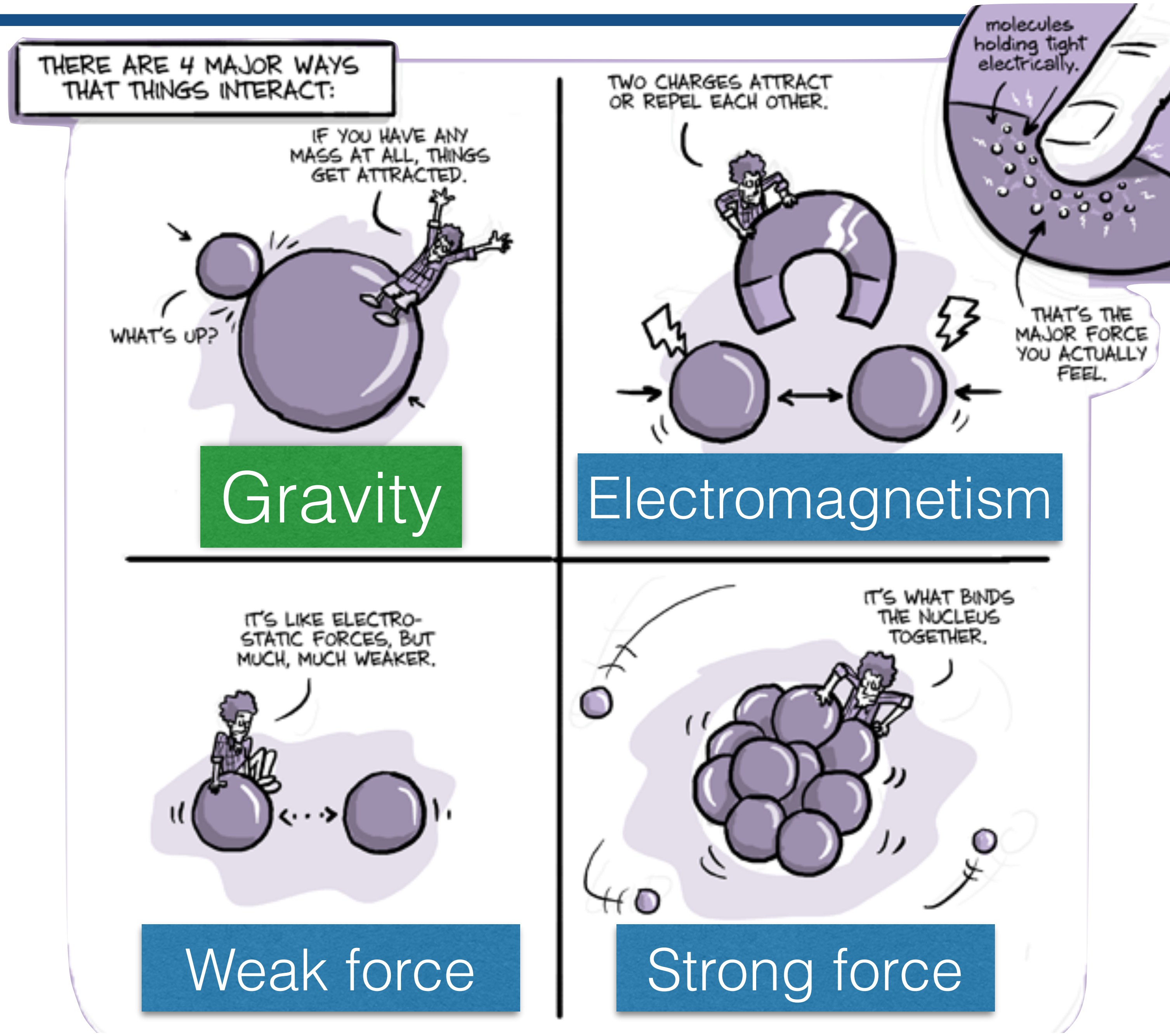
Fundamental Forces of Nature

General Relativity

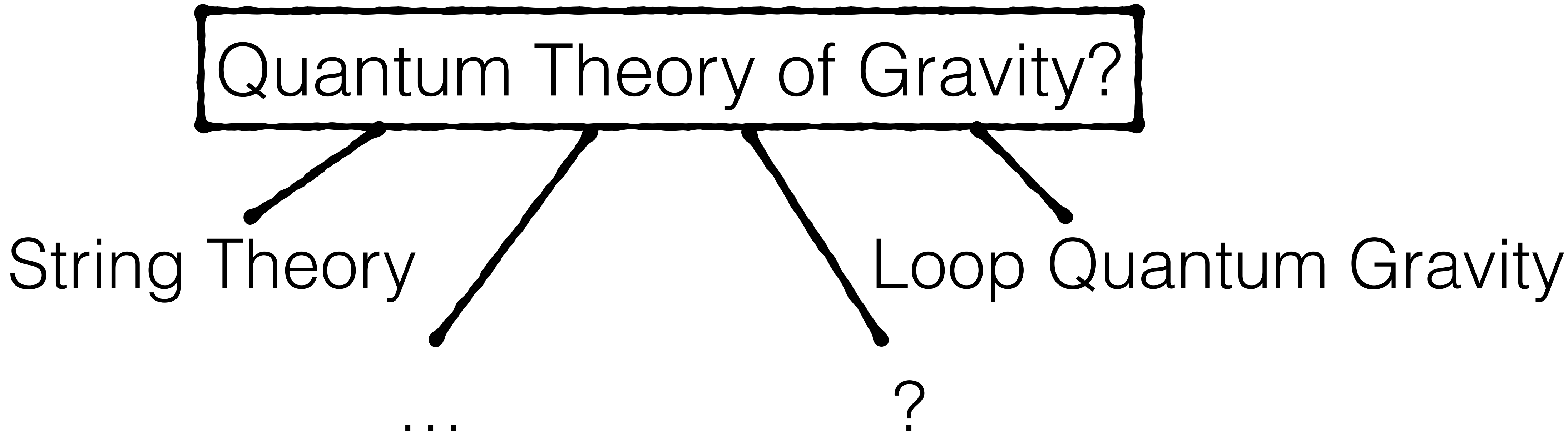
Geometrical Theory



Standard Model

Quantum Theory

- SM & GR: the best theories describing the 4-fundamental Forces.
- No conflict with predictions from either of them.
- **They are fundamentally different.**



New Physics involves new features, such as:

- [ ] Higher Dimensions of s-t
- [ ] Brane World scenarios
- [ ] Noncomutative geometries
- [ ] …
- [x] The law of relativity might not hold exactly at all energy scales ⟶ Lorentz Invariance Violation (LIV)

… LI may not be an exact symmetry of Nature

Generic LIV dispersion relation

$$E^2 - p^2 \pm \epsilon A^2 = m^2,$$

$E \gg m,$

$A = \{E, p\}$

$$\epsilon \to \epsilon(A)$$

A general modification to the dispersion relation would rather involve a general function of energy and momentum

$$\epsilon(A)A^2 = \epsilon(0)A^2 + \epsilon'(0)A^{(2+1)} + \frac{\epsilon''(0)}{2!}A^{(2+2)} + \frac{\epsilon'''(0)}{3!}A^{(2+3)} + \ldots$$

The dispersion relation:

$$E^2 - p^2 \pm \delta_n A^{n+2} = m^2,$$

$$\delta_n \overset{n \geq 1}{=} \epsilon^{(n)}/M^n = 1/(E_{LIV}^{(n)})^n$$

it is not necessarily bound to a particular LIV-model, which allows to generalize to some point the search of LIV-signatures.

LIV negligible at the lower standard energies

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Pair Production $\gamma_{VHE}\,\gamma_{BKG} \rightarrow e^+e^-$

$$\Lambda_{\gamma,n} x_\gamma^{n+2} + x_\gamma - 1 = 0$$

$$x_\gamma = \frac{E_\gamma}{E_\gamma^{\rm LI}}, \qquad \Lambda_{\gamma,n} = \frac{E_\gamma^{{\rm LI}\,(n+1)}}{4\epsilon}\delta_{\gamma,n}.$$

$\Lambda_n < 0$ Threshold-shifts

$\Lambda_n = 0$ LI scenario

$\Lambda_n > 0$ +2nd Threshold

The threshold equation

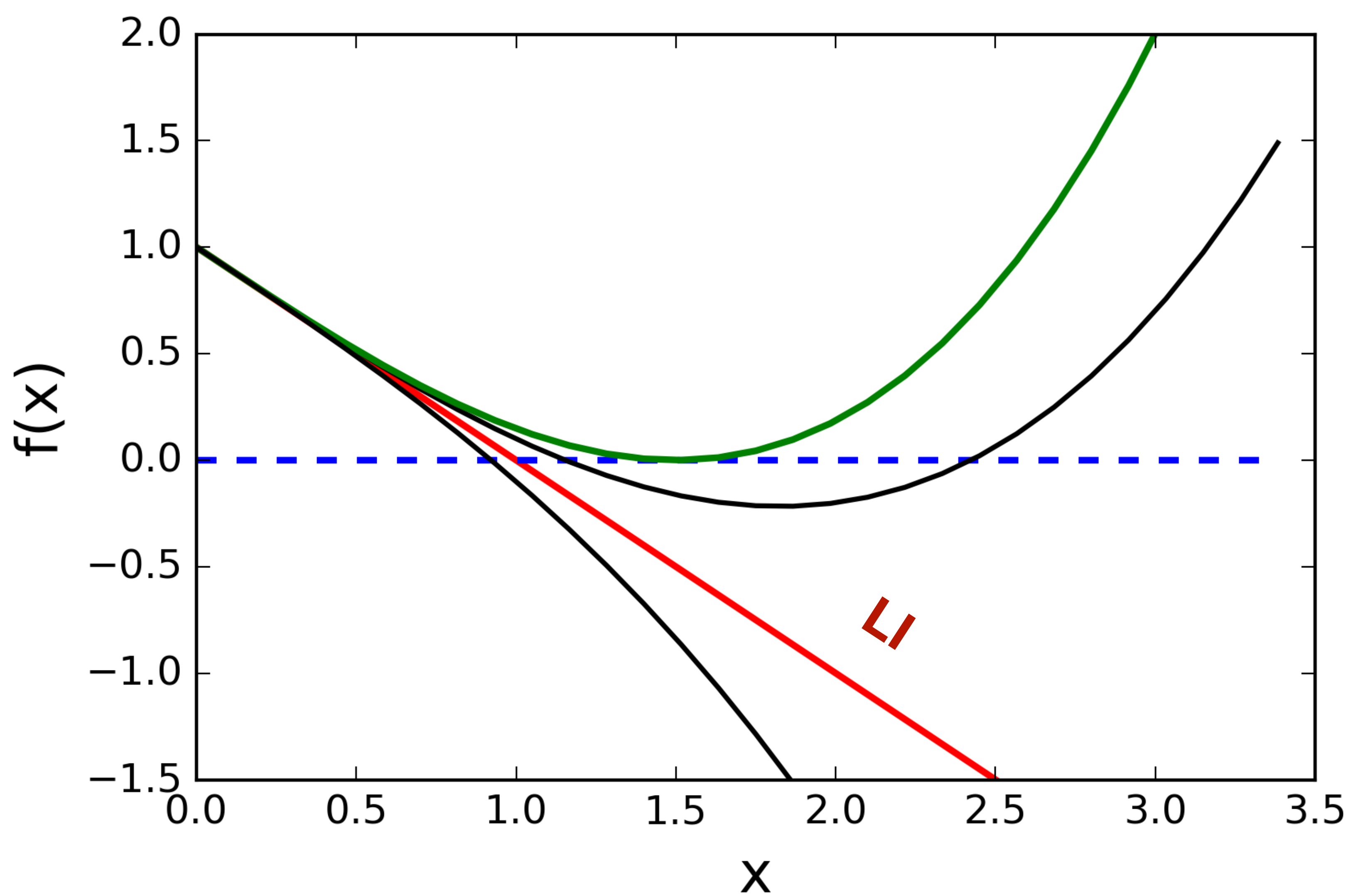
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma\epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

$$\delta_{\gamma,n}^{lim} = -4\frac{\epsilon}{E_\gamma^{LI\ (n+1)}}\frac{(n+1)^{n+1}}{(n+2)^{n+2}}$$

Background:

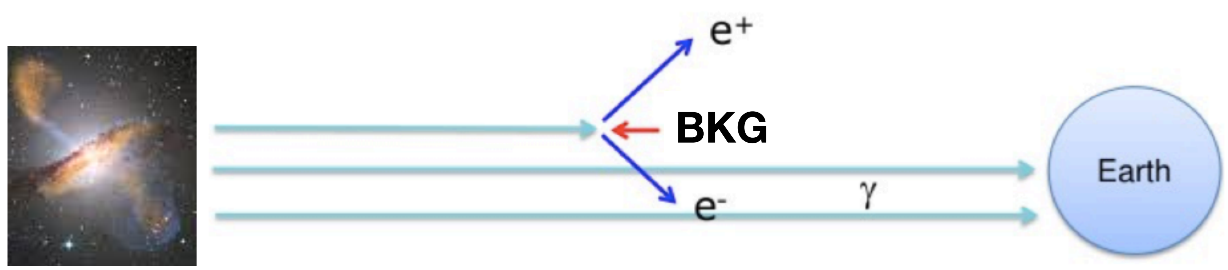
$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$



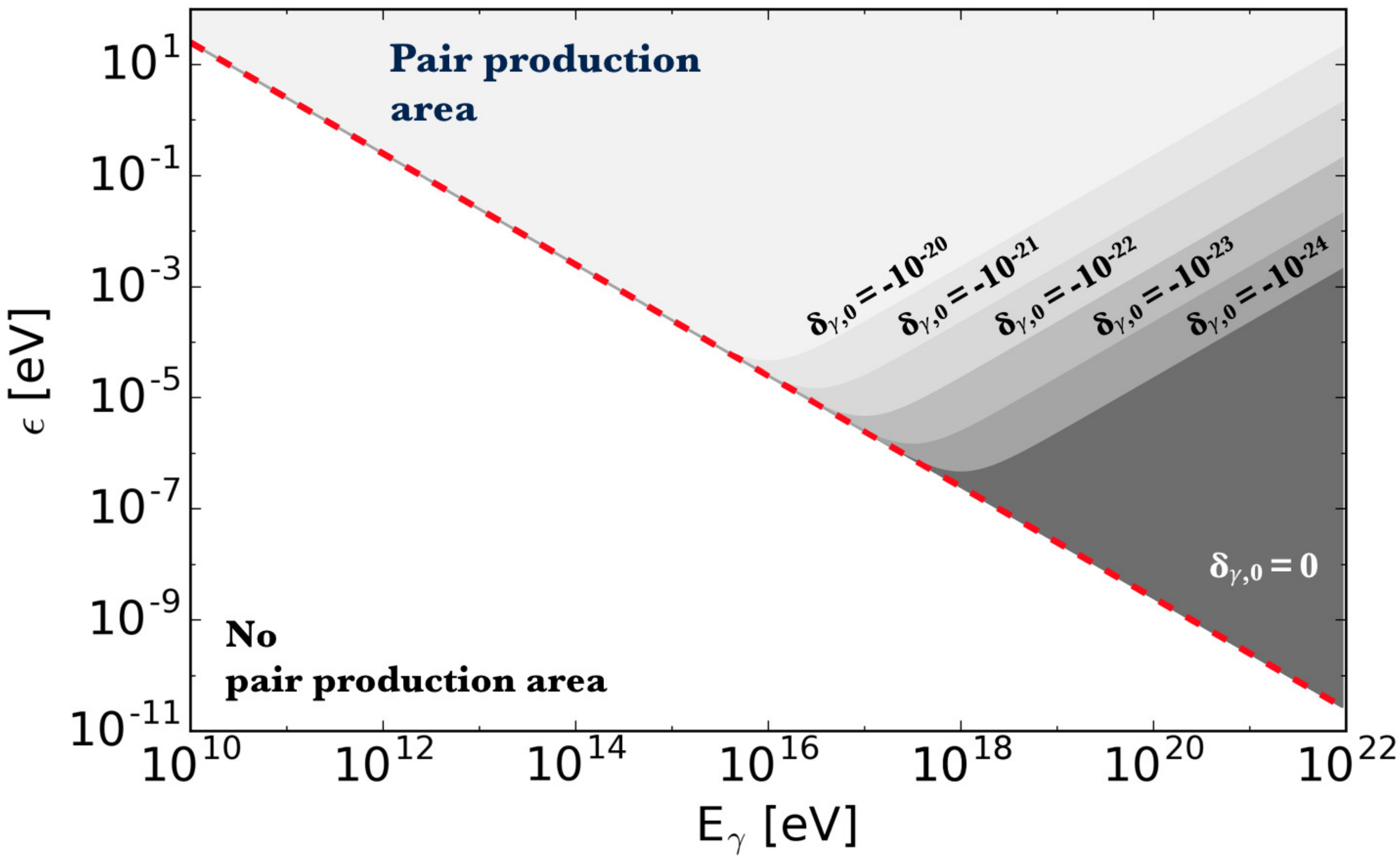
Phys. Rev. D 95, 063001 (2017)

Pair Production

$$\gamma_{VHE}\,\gamma_{BKG} \rightarrow e^+e^-$$



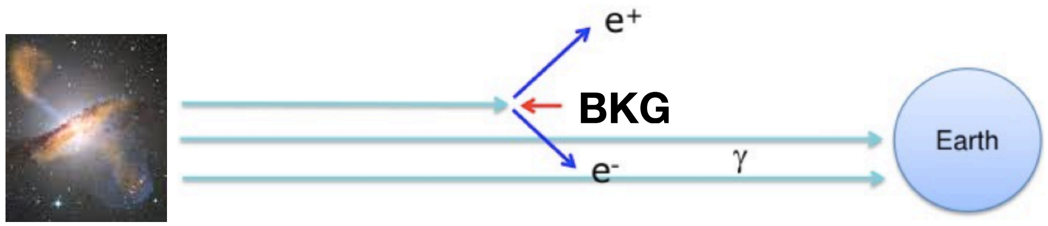
$$\epsilon_{th}^{LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$



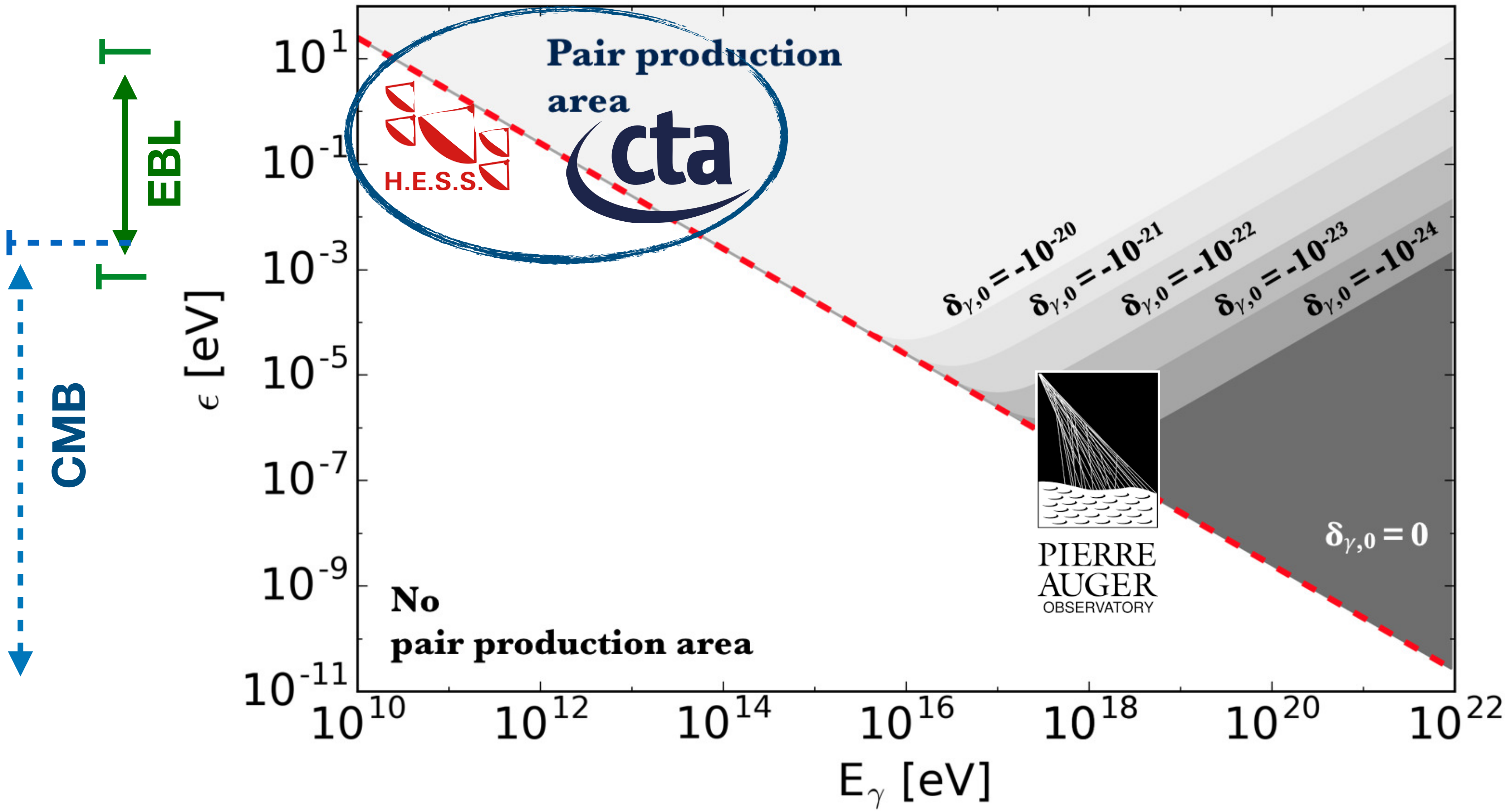
Allowed region change with the LIV parameter and the Energy

Pair Production

$$\gamma_{VHE}\ \gamma_{BKG} \rightarrow e^+ e^-$$



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



… deeper LIV effects

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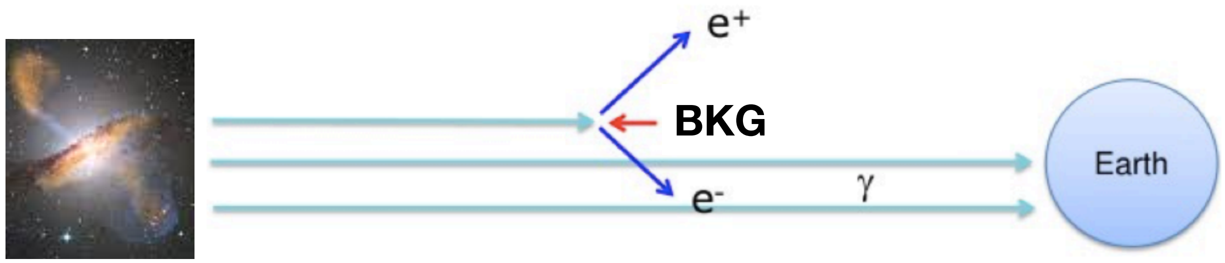
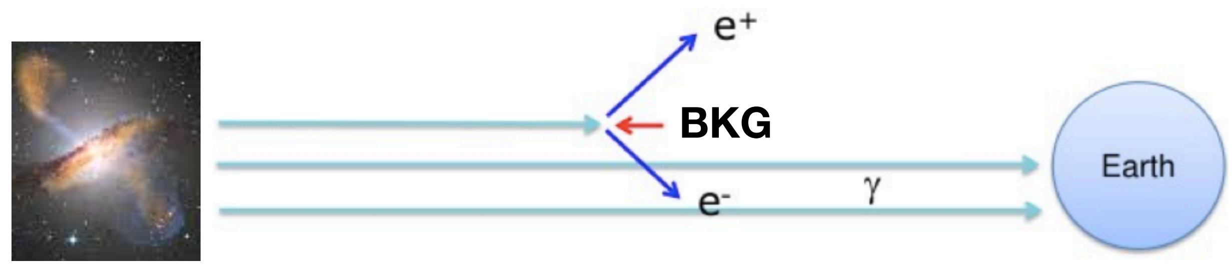


Optical depth



$$\tau_\gamma(E_\gamma, z, n) = \int_0^z dz \frac{c}{H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}}$$

The distance element

$$\times \int_{\epsilon_{th}}^{\infty} d\epsilon \; n_\gamma(\epsilon, z)$$

Density of BKG photons

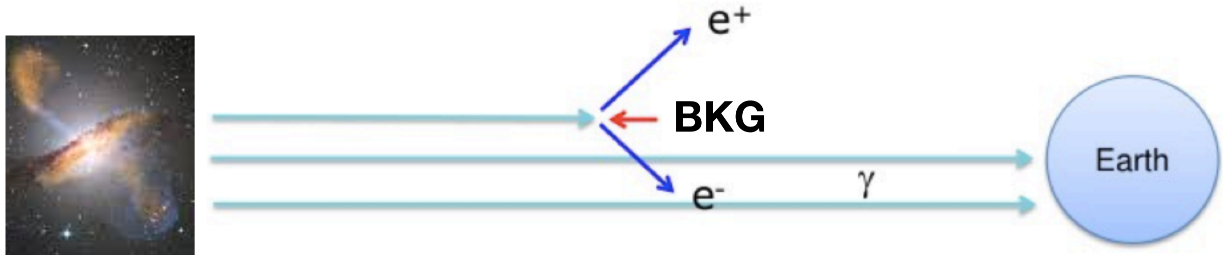
$$\times \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma(E_\gamma, \epsilon, z, \cos\theta)$$

Pair Production cross section

Breit & Wheeler 1934; Heitler 1960

De Angelis, Alessandro et al. Mon.Not.Roy.Astron.Soc. 432 (2013) 3245-3249

Optical depth + LIV



$$\tau_\gamma(E_\gamma, z, n, E_{LIV}^{(n)}) = \int_0^z dz \frac{c}{H_0(1+z)\sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}}$$

$$\times \int_{\epsilon_{th}^{LIV}}^{\infty} d\epsilon \; n_\gamma(\epsilon, z) \quad \times \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma(E_\gamma, \epsilon, z, \cos\theta)$$

LIV

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

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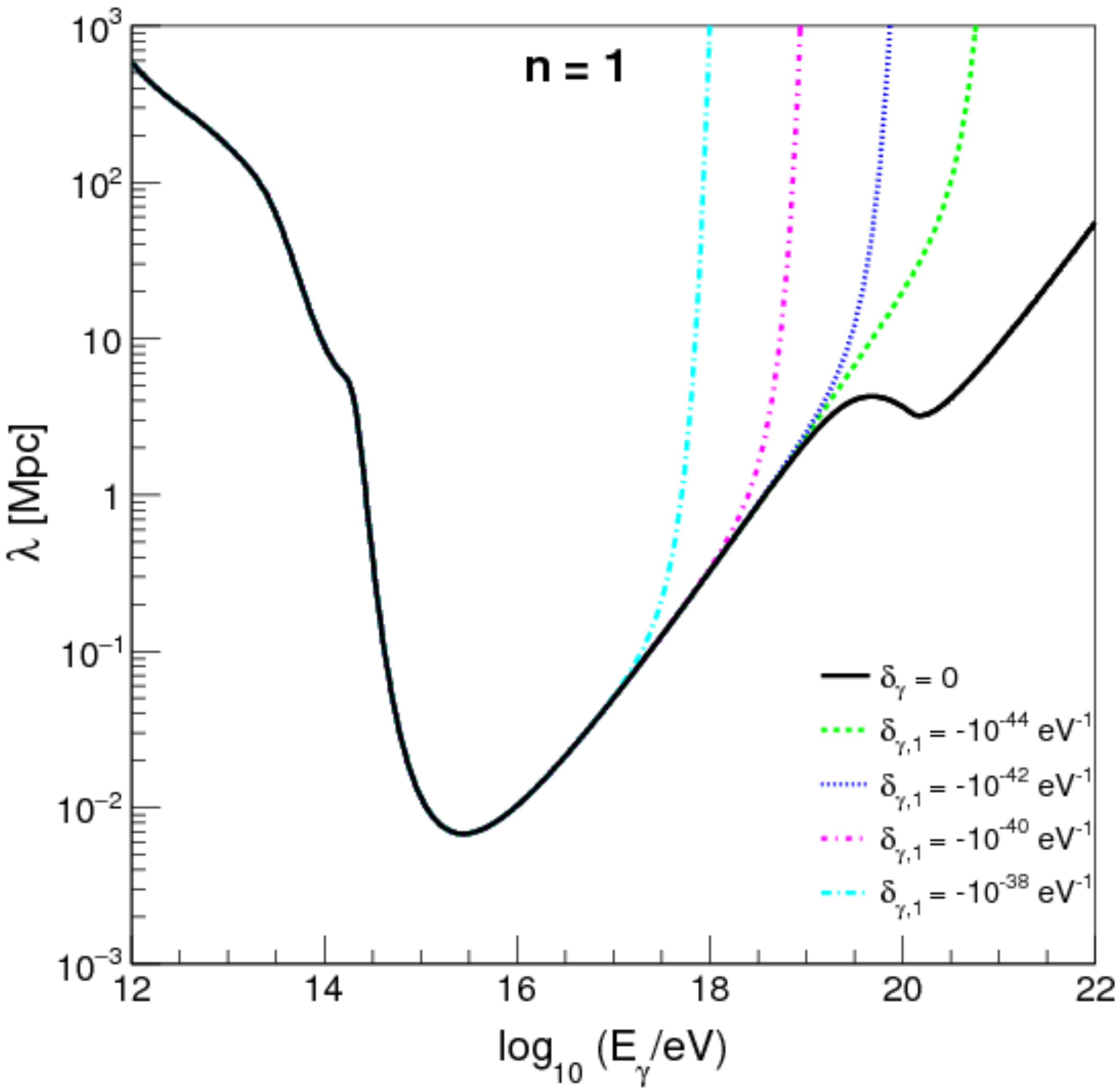
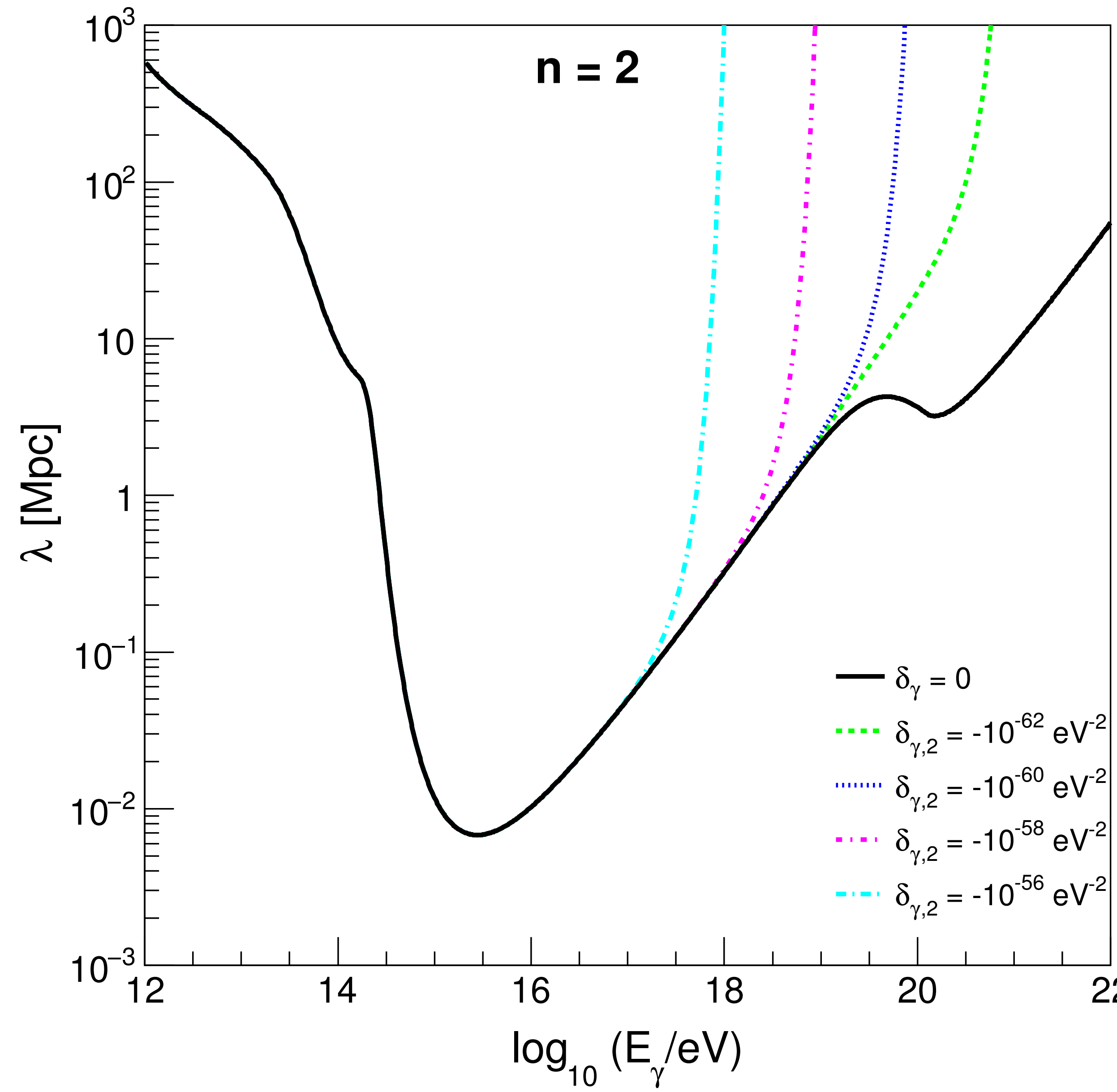
Optical depth

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





More photons!!

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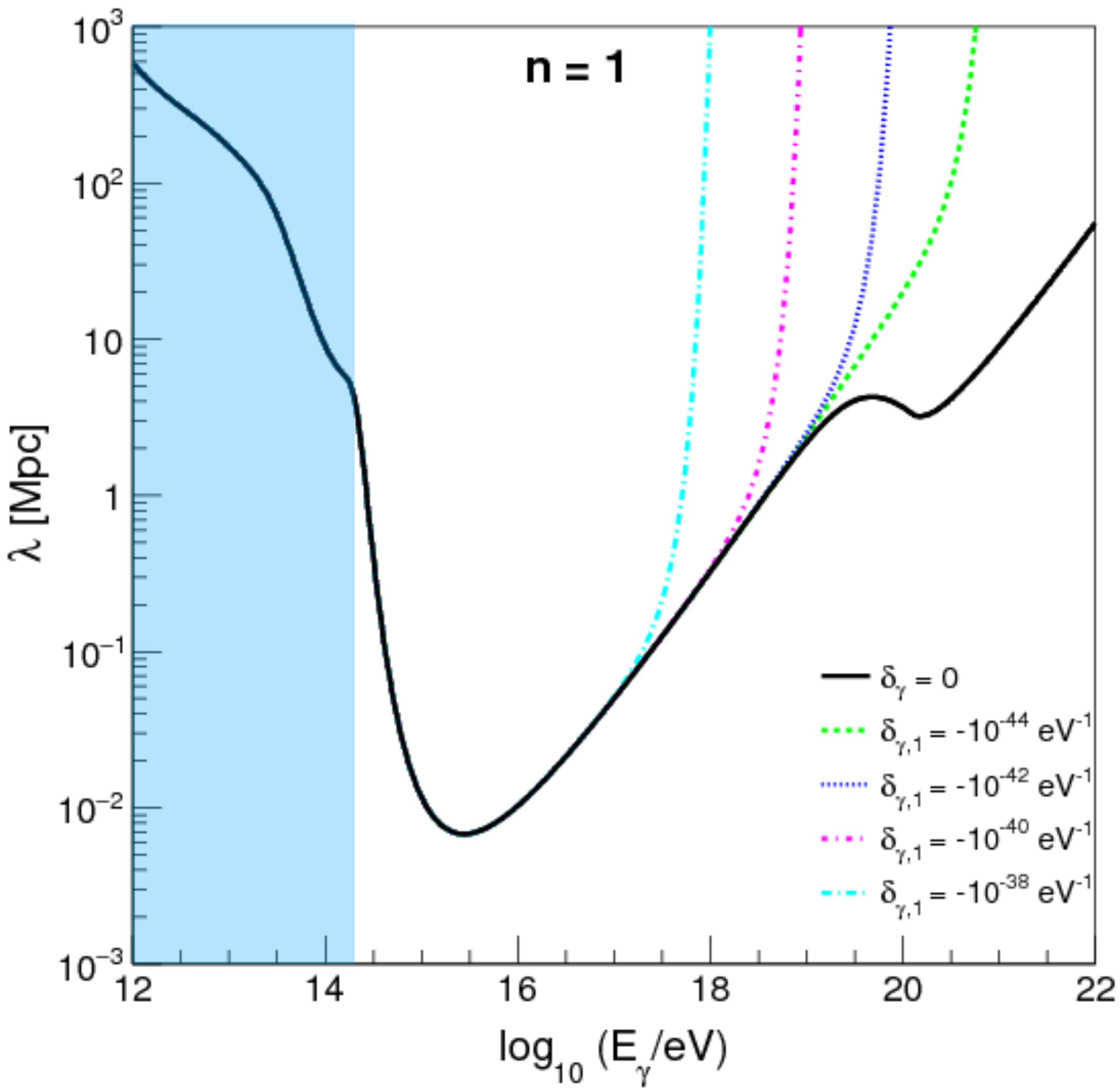
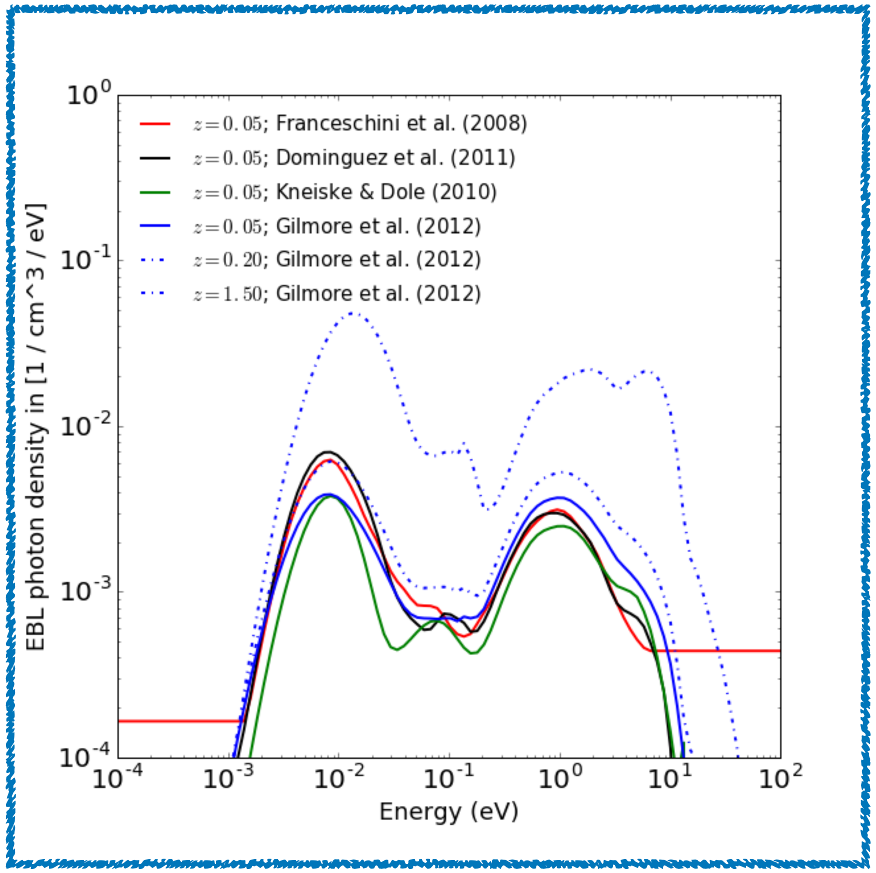
Optical depth

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

BKG density
EBL-photons





EBL: Gilmore & Ramirez-Ruiz (2010)

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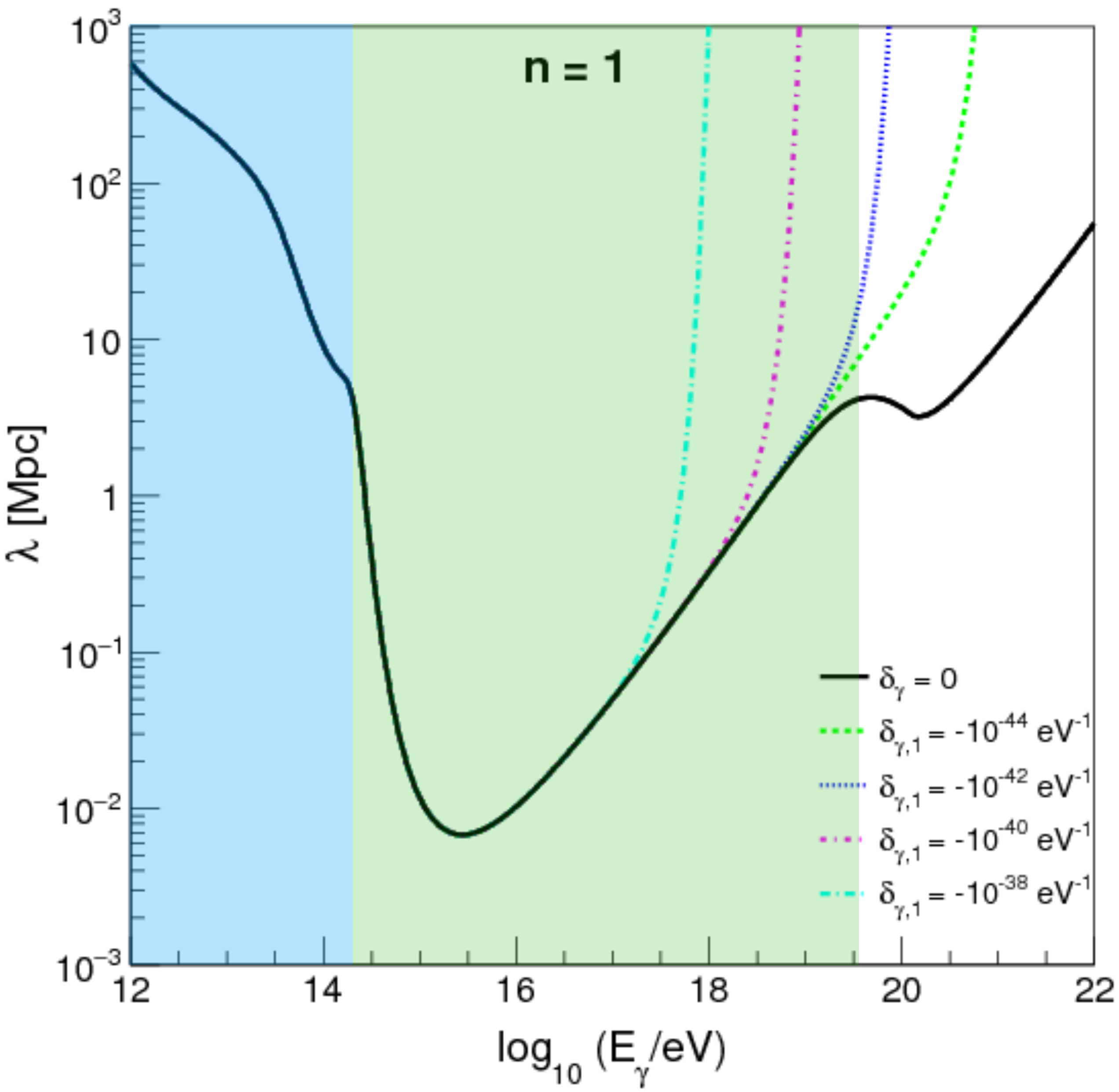
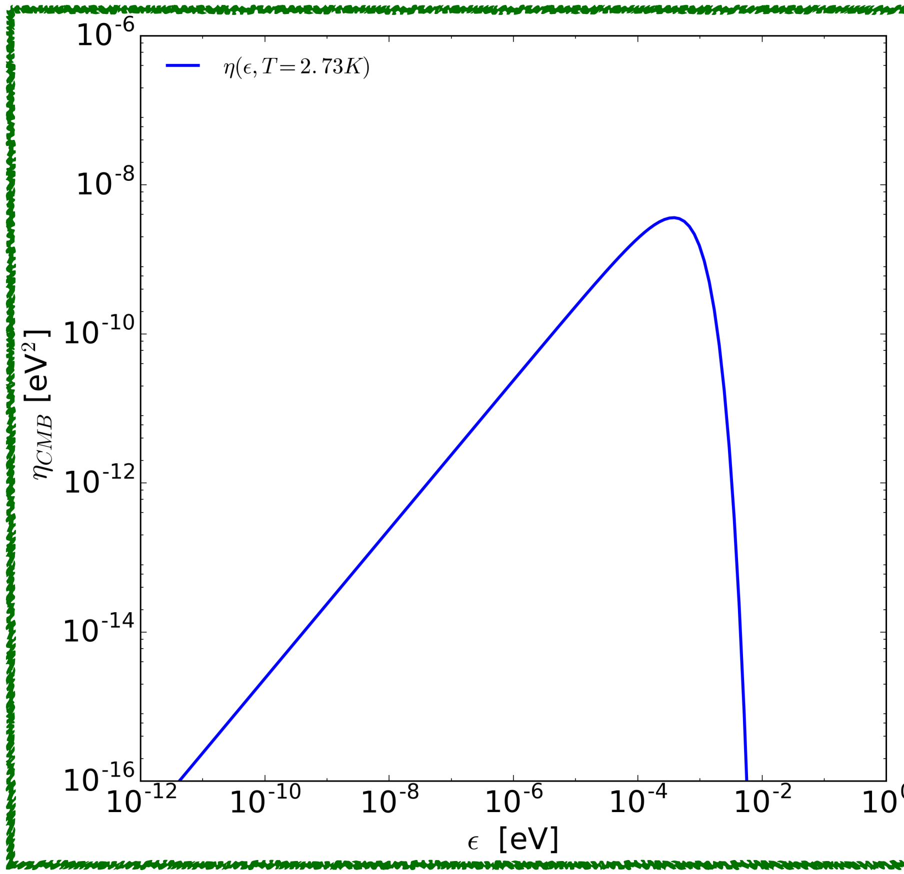
Optical depth

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



BKG density
CMB-photons



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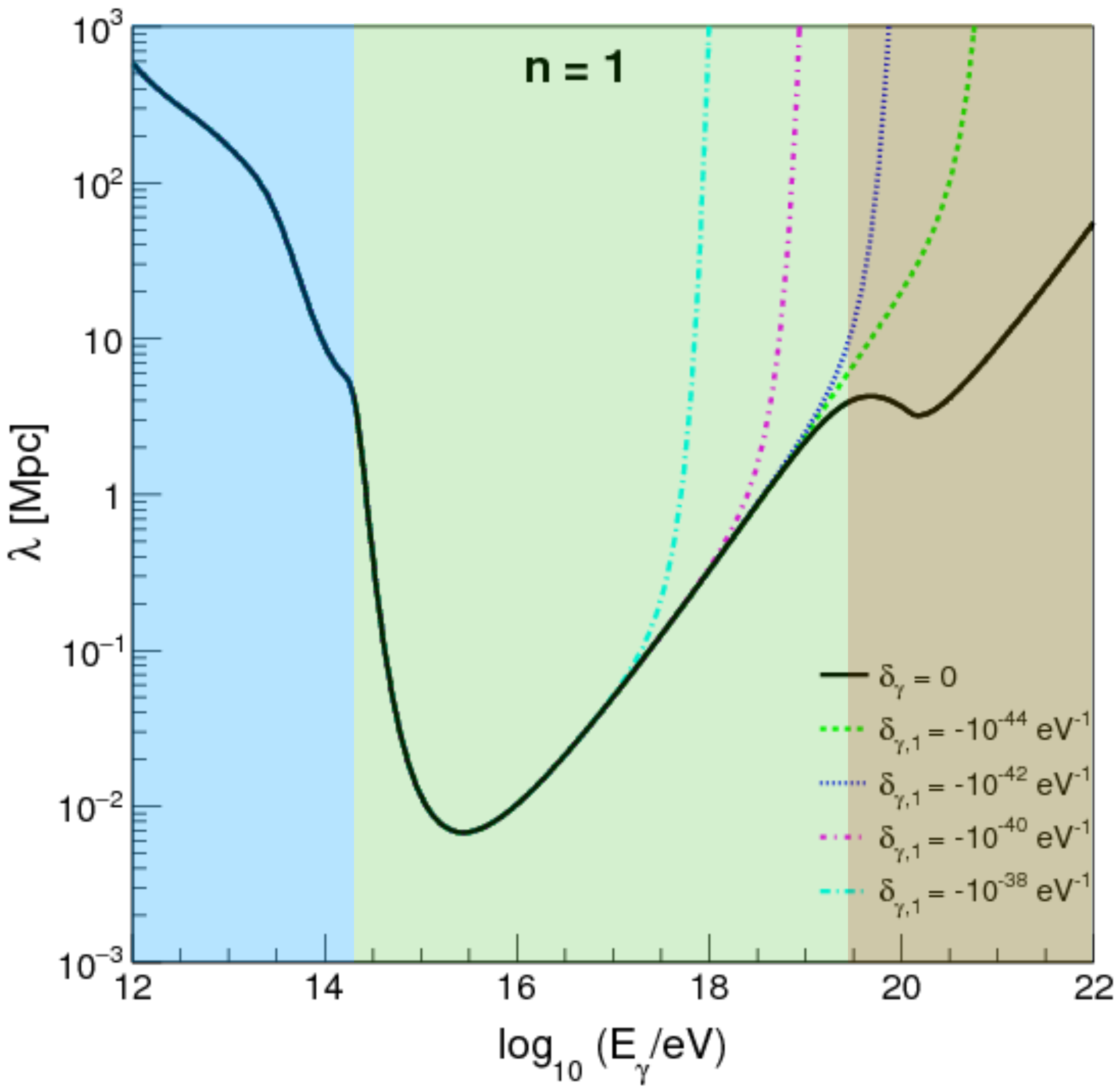
Optical depth

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



BKG density
Radio-photons

Data from Gervasi el al. (2008)

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Model of UHECR Sources

$$\frac{dN}{dE_s} = \begin{cases} E_s^{-\Gamma}, & \text{for } R_s < R_{\rm cut} \\ E_s^{-\Gamma} e^{1-R_s/R_{\rm cut}}, & \text{for } R_s \geqslant R_{\rm cut} \end{cases},$$

1. $\boldsymbol{C_1}$: Aloisio et al. (2014);
2. $\boldsymbol{C_2}$: Unger, Farrar, & Anchordoqui (2015)—Fiducial model (Unger et al. 2015);
3. $\boldsymbol{C_3}$: Unger et al. (2015) with the abundance of galactic nuclei from (Olive & Group 2014);
4. $\boldsymbol{C_4}$: Berezinsky, Gazizov, & Grigorieva (2007)—Dip model (Berezinsky et al. 2006).

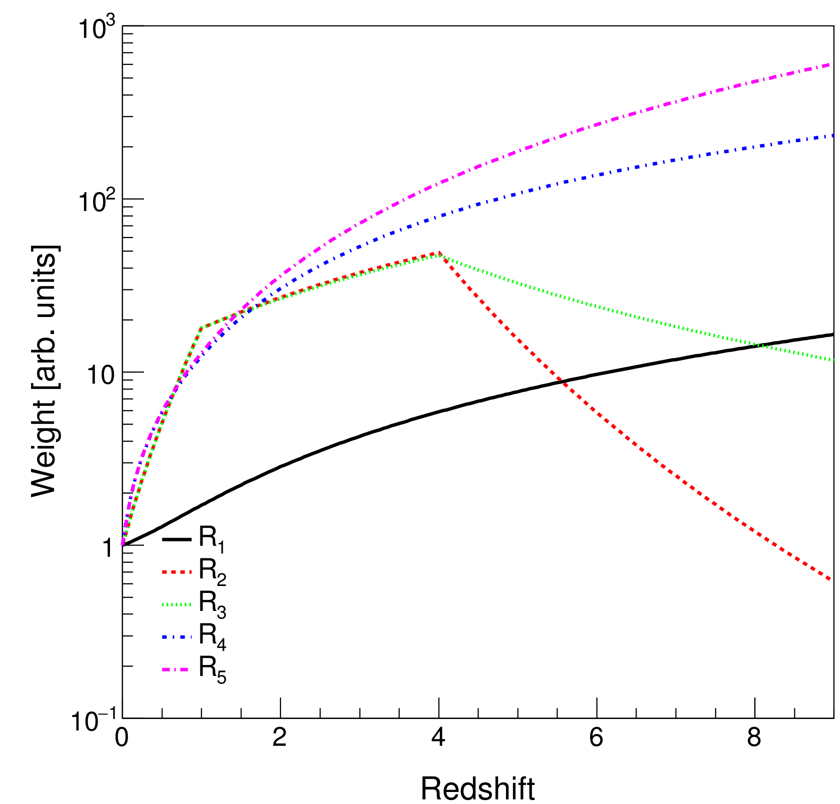
Parameters of the Four Source Models Used in This Paper

Model	Γ	$\log_{10}(R_{\rm cut}/V)$	*f*H	*f*He	*f*N	*f*Si	*f*Fe
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

Note. Γ is the spectral index, $R_{\rm cut}$ is the rigidity cutoff and *f*H, *f*He, *f*N, *f*Si, and *f*Fe are the fractions of each nuclei.

Models of Source Distribution

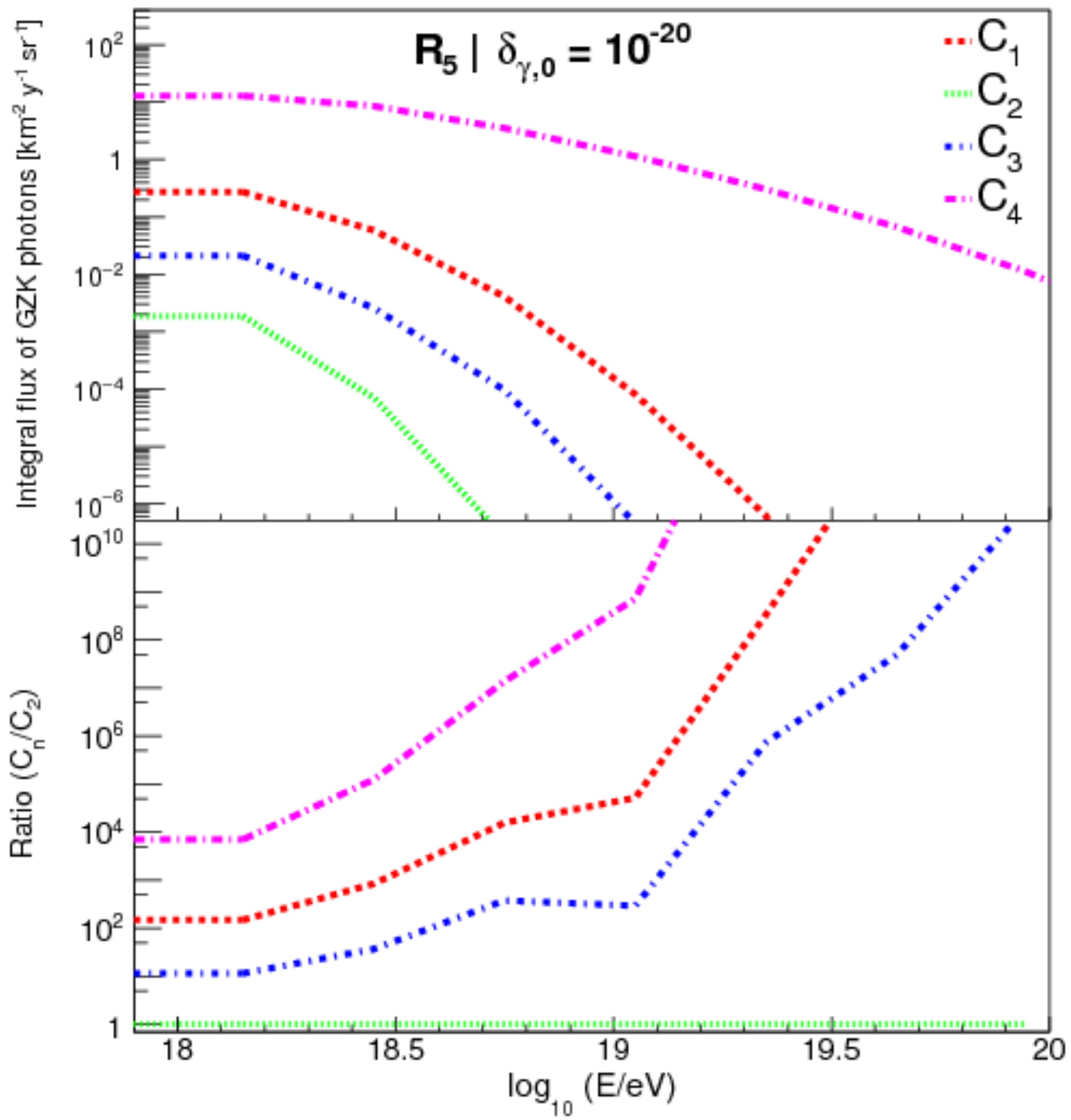
1. $\boldsymbol{R_1}$: sources are uniformly distributed in a comoving volume;
2. $\boldsymbol{R_2}$: sources follow the star formation distribution given in Hopkins & Beacom (2006). The evolution is proportional to $(1+z)^{3.4}$ for $z < 1$, to $(1+z)^{-0.26}$ for $1 \leqslant z < 4$ and to $(1+z)^{-7.8}$ for $z \geqslant 4$;
3. $\boldsymbol{R_3}$: sources follow the star formation distribution given in Yüksel et al. (2008). The evolution is proportional to $(1+z)^{3.4}$ for $z < 1$, to $(1+z)^{-0.3}$ for $1 \leqslant z < 4$ and to $(1+z)^{-3.5}$ for $z \geqslant 4$;
4. $\boldsymbol{R_4}$: sources follow the GRB rate evolution from Le & Dermer (2007). The evolution is proportional to $(1 + 8z)/[1 + (z/3)^{1.3}]$;
5. $\boldsymbol{R_5}$: sources follow the GRB rate evolution from Le & Dermer (2007). The evolution is proportional to $(1 + 11z)/[1 + (z/3)^{0.5}]$.



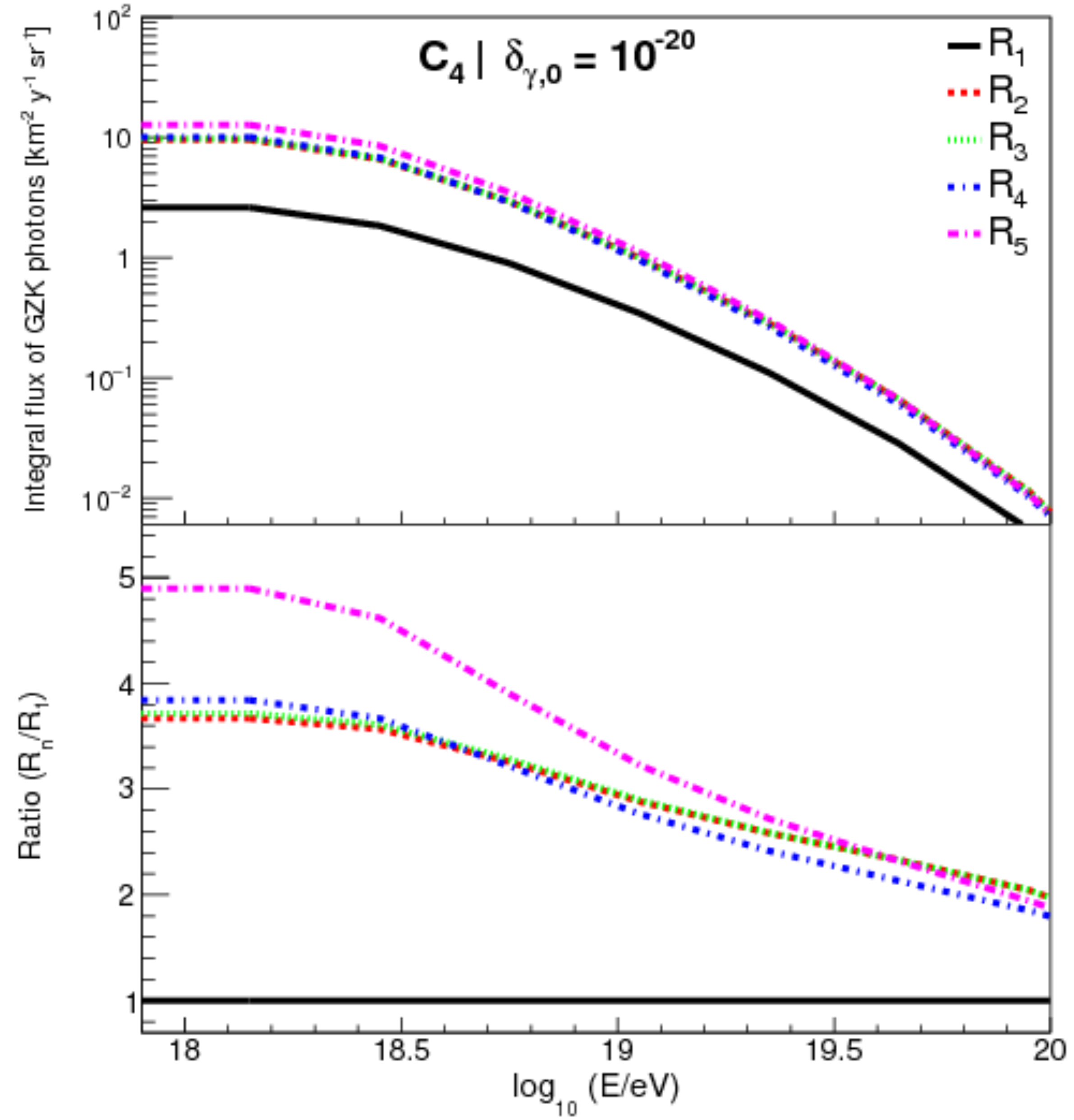
CRPropa3/EleCa (Settimo & Domenico 2015; Batista et al. 2016)

Integral flux of GZK photons

... for each source model



... for each source evolution model



Different LIV coefficients result in a shift up an down

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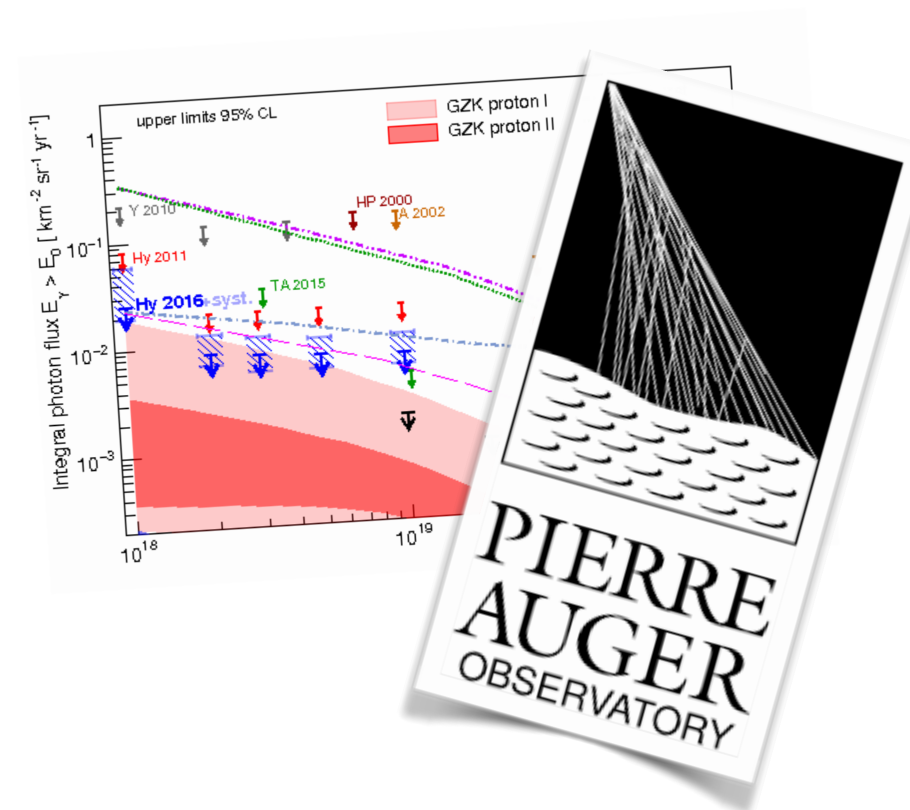
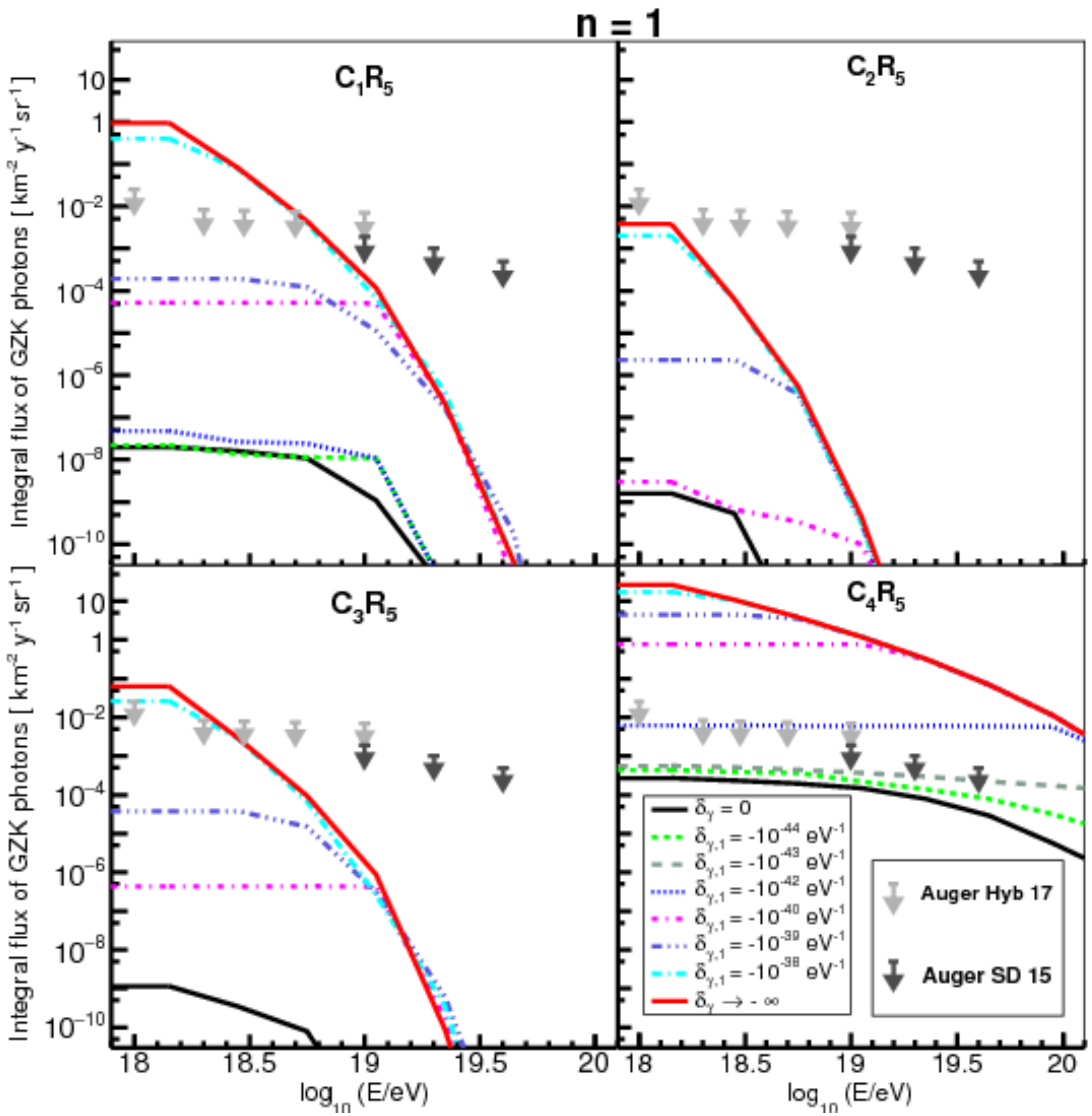
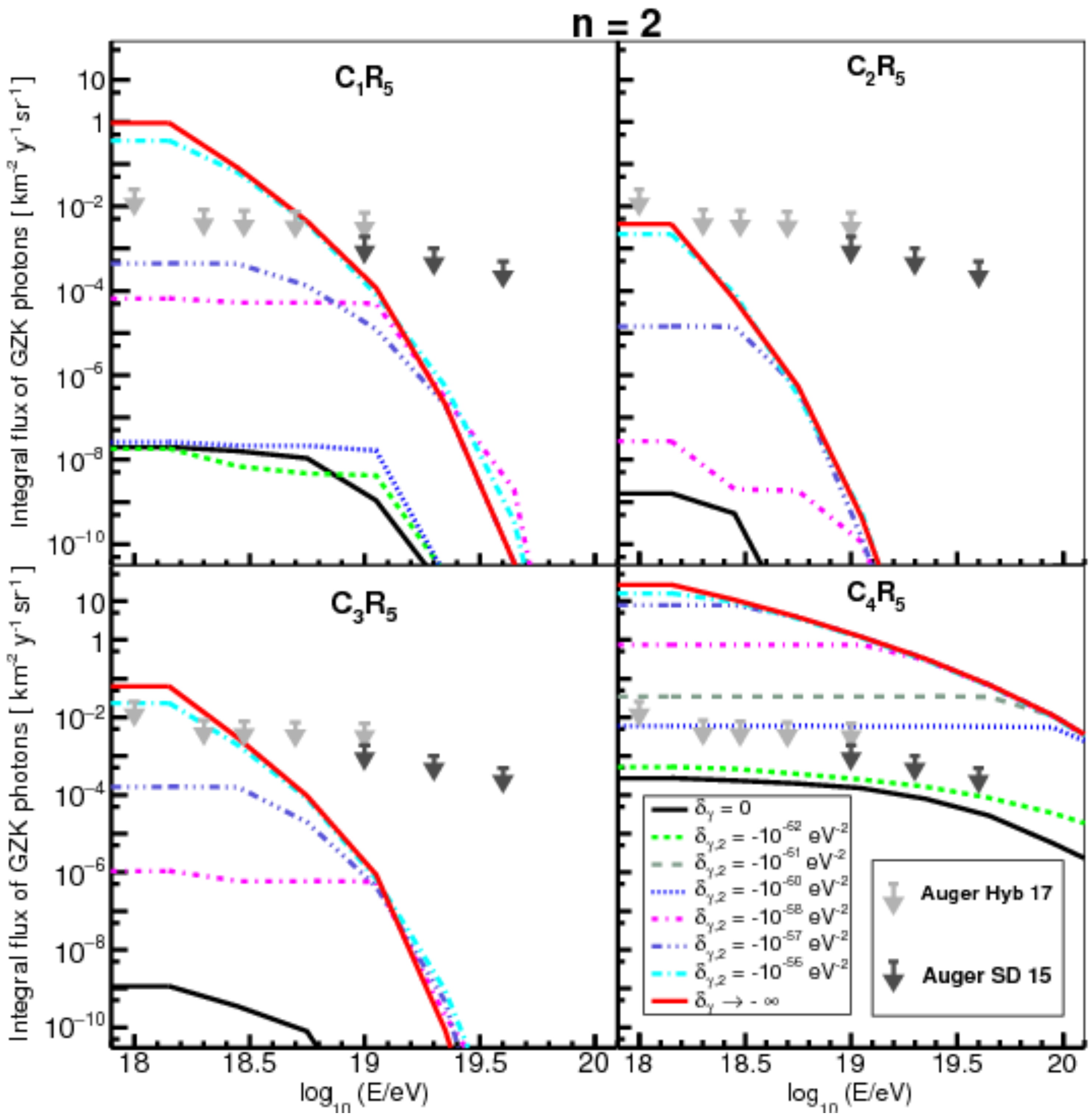


GZK photon flux + LIV



GZK photon flux + LIV



Model C_3R_5 was shown to (best) describe the energy spectrum, composition, and arrival direction of UHECR*

*M. Unger et al 2015, Phys. Rev. D, 92, 123001

LIV limits

Limits on the LIV Coefficients Imposed by This Work for Each Source Model and LIV Order (n)

Model	$\delta_{\gamma,0}^{\rm limit}$	$\delta_{\gamma,1}^{\rm limit}\,({\rm eV}^{-1})$	$\delta_{\gamma,2}^{\rm limit}\,({\rm eV}^{-2})$
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	$\sim -10^{-22}$	$\sim -10^{-42}$	$\sim -10^{-60}$

Limits on the LIV Coefficients Imposed by Other Works Based on Gamma-Ray Propagation

Model	$\delta_{\gamma,0}^{\rm limit}$	$\delta_{\gamma,1}^{\rm limit}\,({\rm eV}^{-1})$	$\delta_{\gamma,2}^{\rm limit}\,({\rm eV}^{-2})$
Galaverni & Sigl (2008a)	...	-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}

Conclusions and remarks

- We studied the effect of possible LIV in the propagation of photons in the universe.
- The **mean-free path of the pair production** interaction was calculated **considering LIV effects**.
- We found that even moderate LIV coefficients introduce a significant change in the mean-free path of the interaction.
- **The GZK photon flux including LIV was obtained** for different source models and source distribution models.
- **Limits to the LIV** coefficient were established based on source models **compatible with the most updated data of UHECR**.

- The limits presented here are several orders of magnitude more restrictive than previous calculations based on the arrival time of TeV photons; however, the comparison is not straightforward due to different systematics of the measurements and energy of the photons.

Thanks!

Pair Production

$$\gamma_{VHE}\ \gamma_{BKG} \rightarrow e^+ e^-$$

$$\Lambda_{\gamma,n} x_\gamma^{n+2} + x_\gamma - 1 = 0$$

$$x_\gamma = \frac{E_\gamma}{E_\gamma^{\rm LI}}, \qquad \Lambda_{\gamma,n} = \frac{E_\gamma^{{\rm LI}\,(n+1)}}{4\epsilon}\delta_{\gamma,n}.$$

The threshold equation

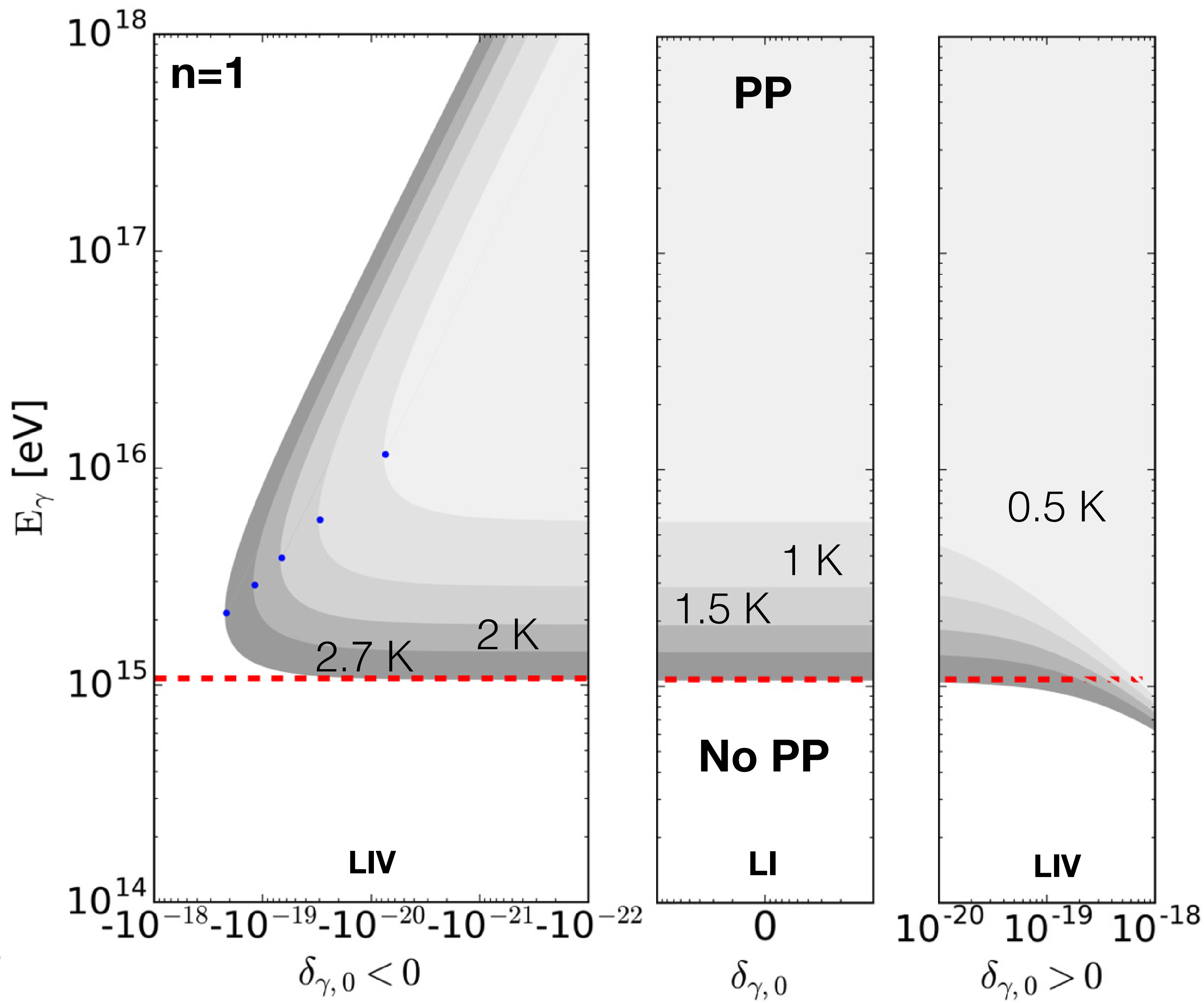
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma \epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

$$\delta_{\gamma,n}^{lim} = -4\frac{\epsilon}{E_\gamma^{LI\ (n+1)}}\frac{(n+1)^{n+1}}{(n+2)^{n+2}}$$

Background:

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



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Phys. Rev. D 95, 063001 (2017)

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$$x_\gamma = \frac{E_\gamma}{E_\gamma^{\rm LI}}, \qquad \Lambda_{\gamma,n} = \frac{E_\gamma^{{\rm LI}\,(n+1)}}{4\epsilon}\delta_{\gamma,n}.$$

The threshold equation

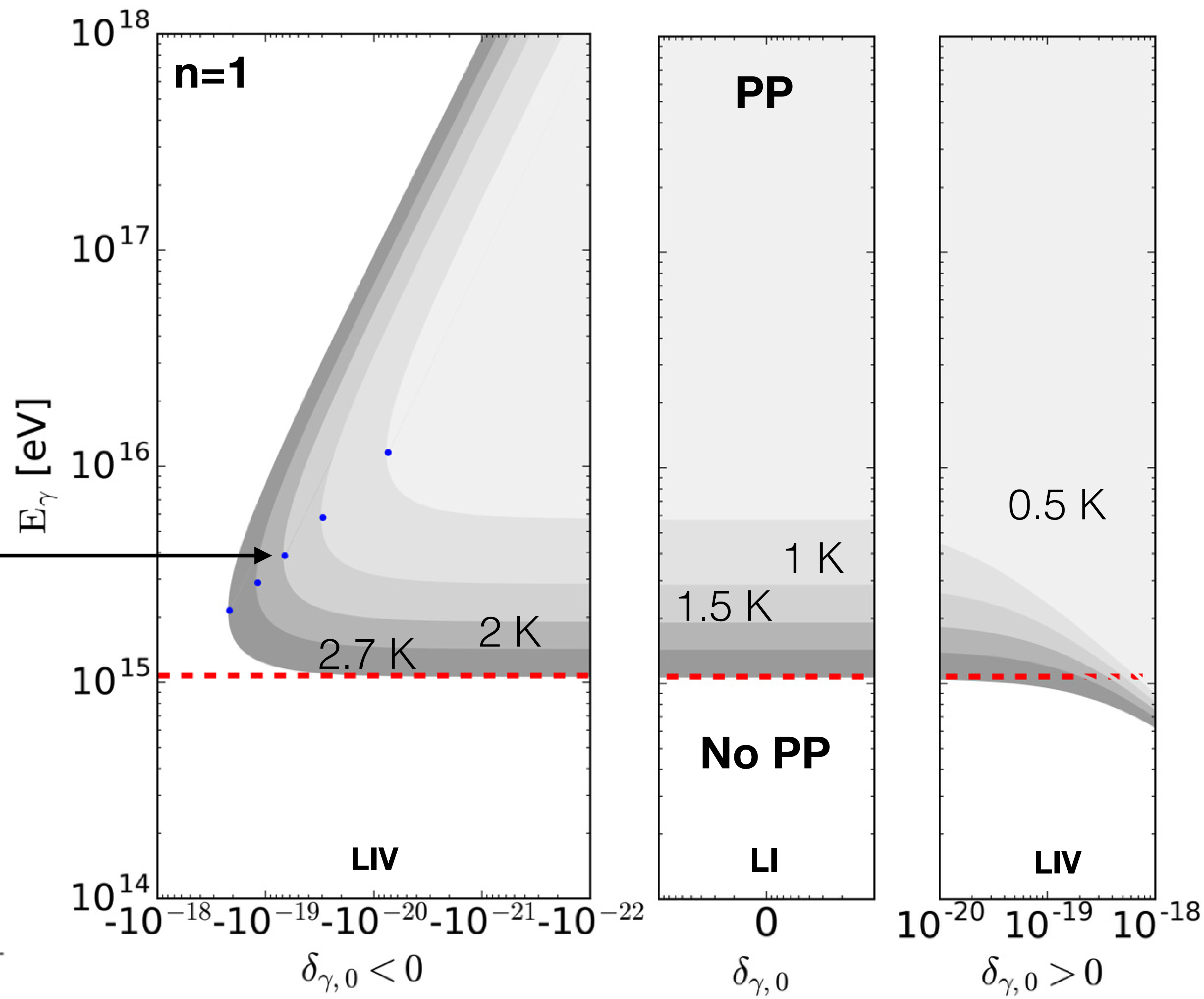
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma \epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

$$\delta_{\gamma,n}^{lim} = -4\frac{\epsilon}{E_\gamma^{LI\ (n+1)}} \frac{(n+1)^{n+1}}{(n+2)^{n+2}}$$

Background:

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



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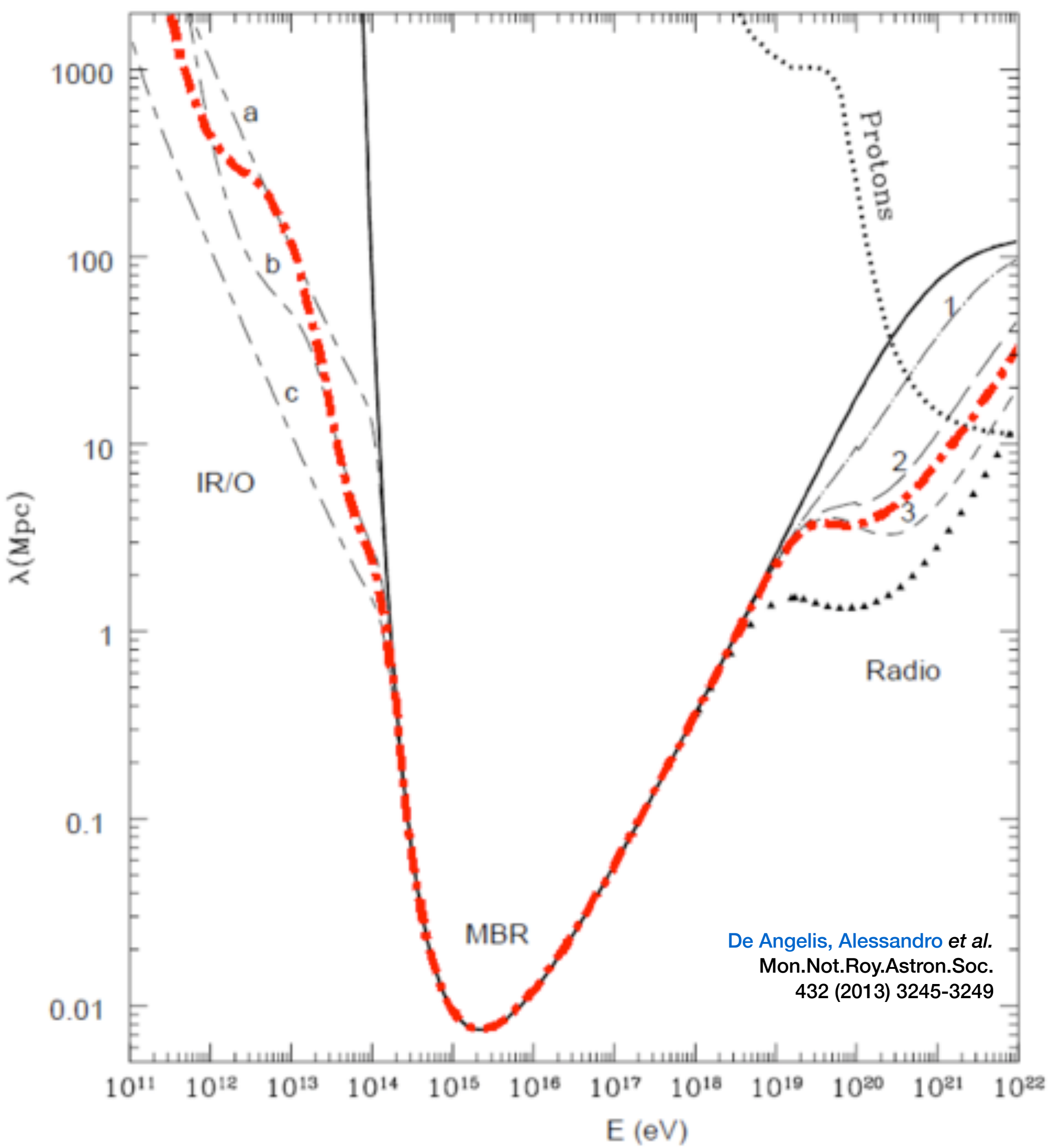
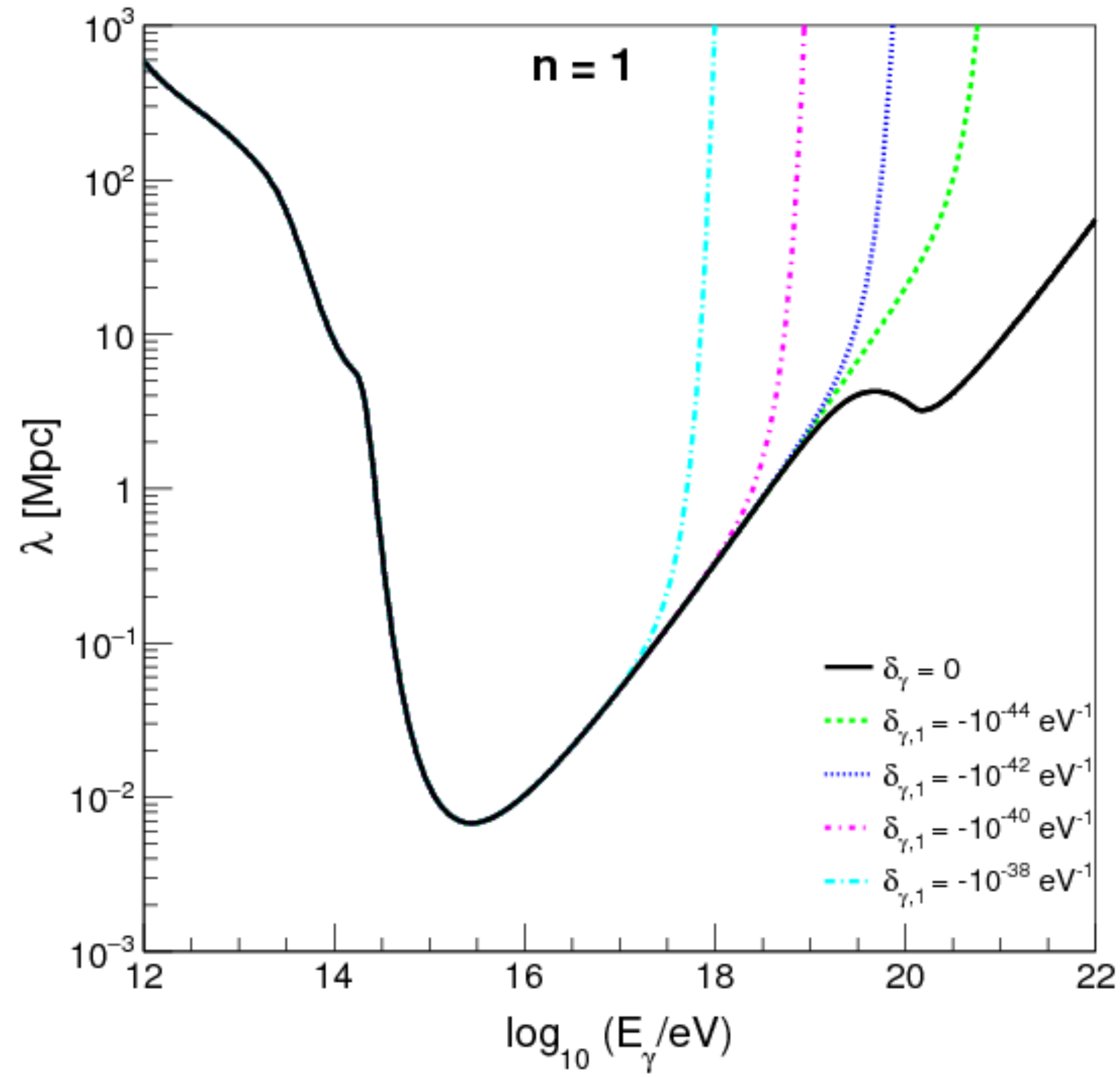
Optical Depth + LIV

LI



LIV



GZK photon flux

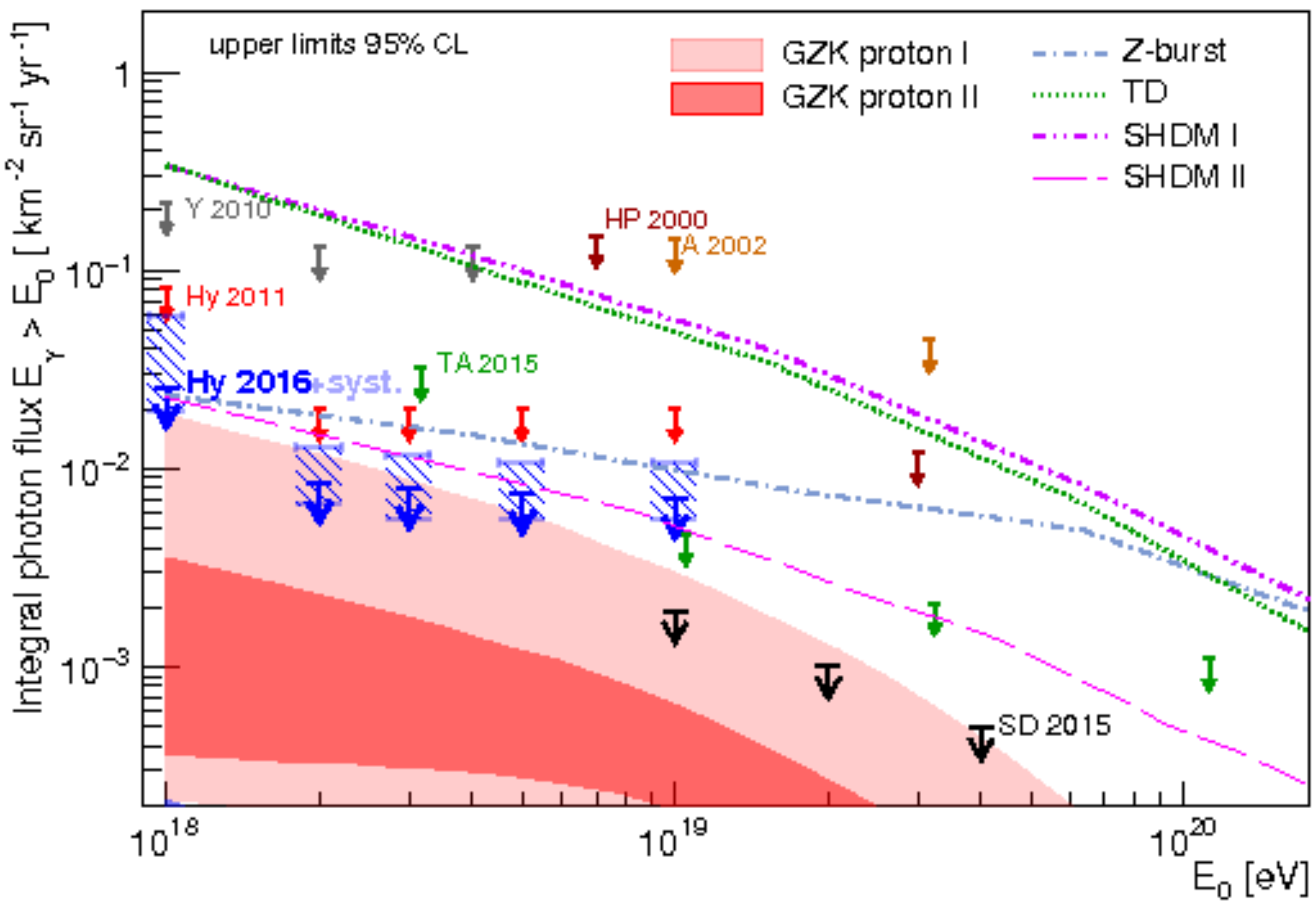


Figure 6. Upper limits on the integral photon flux derived from 9 years of hybrid data (blue arrows, Hy 2016) for a photon flux E^{-2} and no background subtraction. The limits obtained when the detector systematic uncertainties are taken into account are shown as horizontal segments (light blue) delimiting a dashed-filled box at each energy threshold. Previous limits from Auger: (SD [20] and Hybrid 2011 [19]), for Telescope Array (TA) [59], AGASA (A) [60], Yakutsk (Y) [61] and Haverah Park (HP) [62] are shown for comparison. None of them includes systematic uncertainties. The shaded regions and the lines give the predictions for the GZK photon flux [14, 16] and for top-down models (TD, Z-Burst, SHDM I [63] and SHDM II [21]).

The Pierre Auger Collaboration, JCAP04 (2017) 009