XXXII Annual Meeting
Division of Particles and Fields
Mexican Physical Society

UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

FAPESP

Limits on Lorentz Invariance Violation from ultra high energy astrophysics

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

Humberto Martínez,
Rodrigo Guedes Lang
Vitor De Souza
IFSC-USP, Brazil

28-30 mayo 2018
ICN-UNAM
México

Index

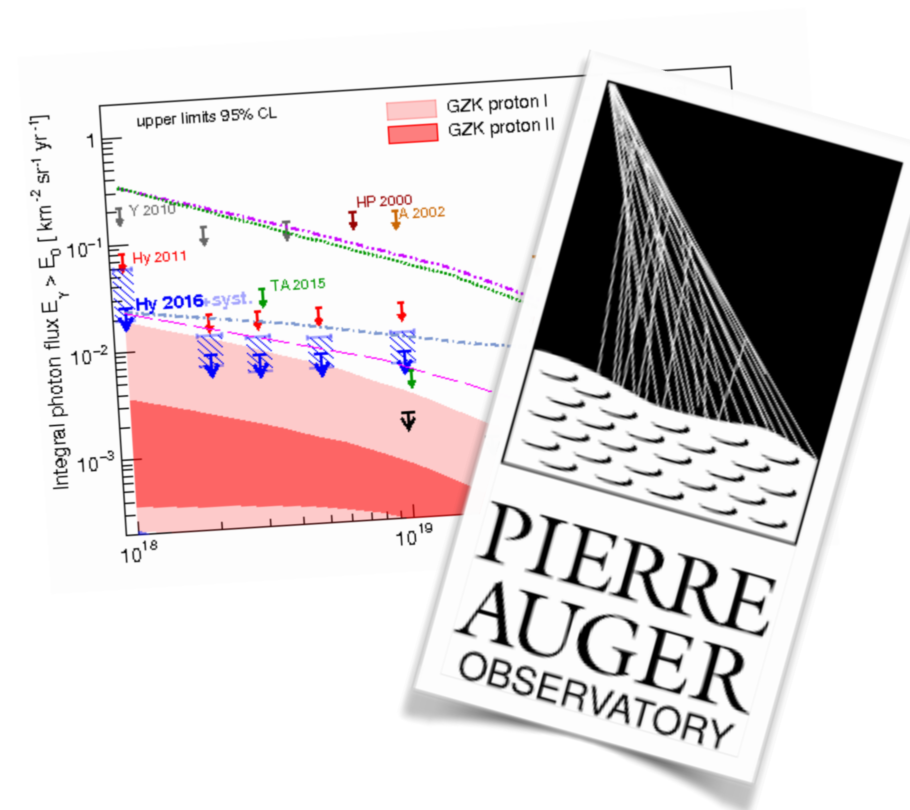
I. Lorentz invariance violation (LIV)

II. LIV + gamma-rays

III. Optical Depth + LIV

IV. GZK photon flux + LIV

V. LIV limits



Index

Fundamental Forces of Nature

Strong

Electromagnetism

Weak

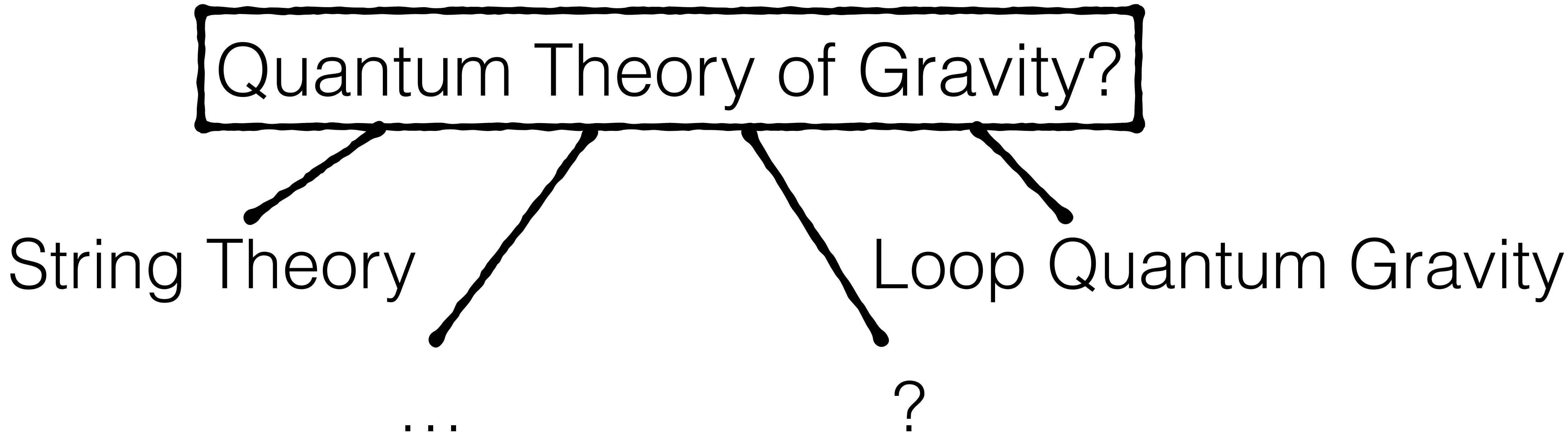
Gravity

Standard Model (SM) → Quantum Theory

General Relativity (GR) → Geometrical Theory

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

humbertomh@ifsc.usp.br



New Physics involves new features, such as:

- ☐ Higher Dimensions of s-t
- ☐ Brane World scenarios
- ☐ Noncomutative geometries
- ☐ …
- ☑ 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

↓

…VHE-UHE

humbertomh@ifsc.usp.br

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:

$$E^2 - p^2 \pm \delta_n A^{n+2} = m^2, \quad \delta_n \overset{n\geq 1}{=} \epsilon^{(n)}/M^n = 1/(E_{LIV}^{(n)})^n$$

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

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

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

n=1

The dispersion relation:

$$E^2 - p^2 \pm \delta_n A^{n+2} = m^2, \quad \delta_n \overset{n \geq 1}{=} \epsilon^{(n)}/M^n = 1/(E_{LIV}^{(n)})^n$$

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

humbertomh@ifsc.usp.br

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

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

n=2

The dispersion relation:

$$E^2 - p^2 \pm \delta_n A^{n+2} = m^2, \quad \delta_n \overset{n \geq 1}{=} \epsilon^{(n)}/M^n = 1/(E_{LIV}^{(n)})^n$$

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

Index

I. Lorentz invariance violation (LIV)

II. LIV + gamma-rays

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

III. Optical Depth + LIV

IV. GZK photon flux + LIV

V. LIV limits

Pair Production

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

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

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

$\Lambda_n < 0$ Threshold-shifts

$\Lambda_n = 0$ LI scenario

$\Lambda_n > 0$ +2nd Threshold

The threshold equation

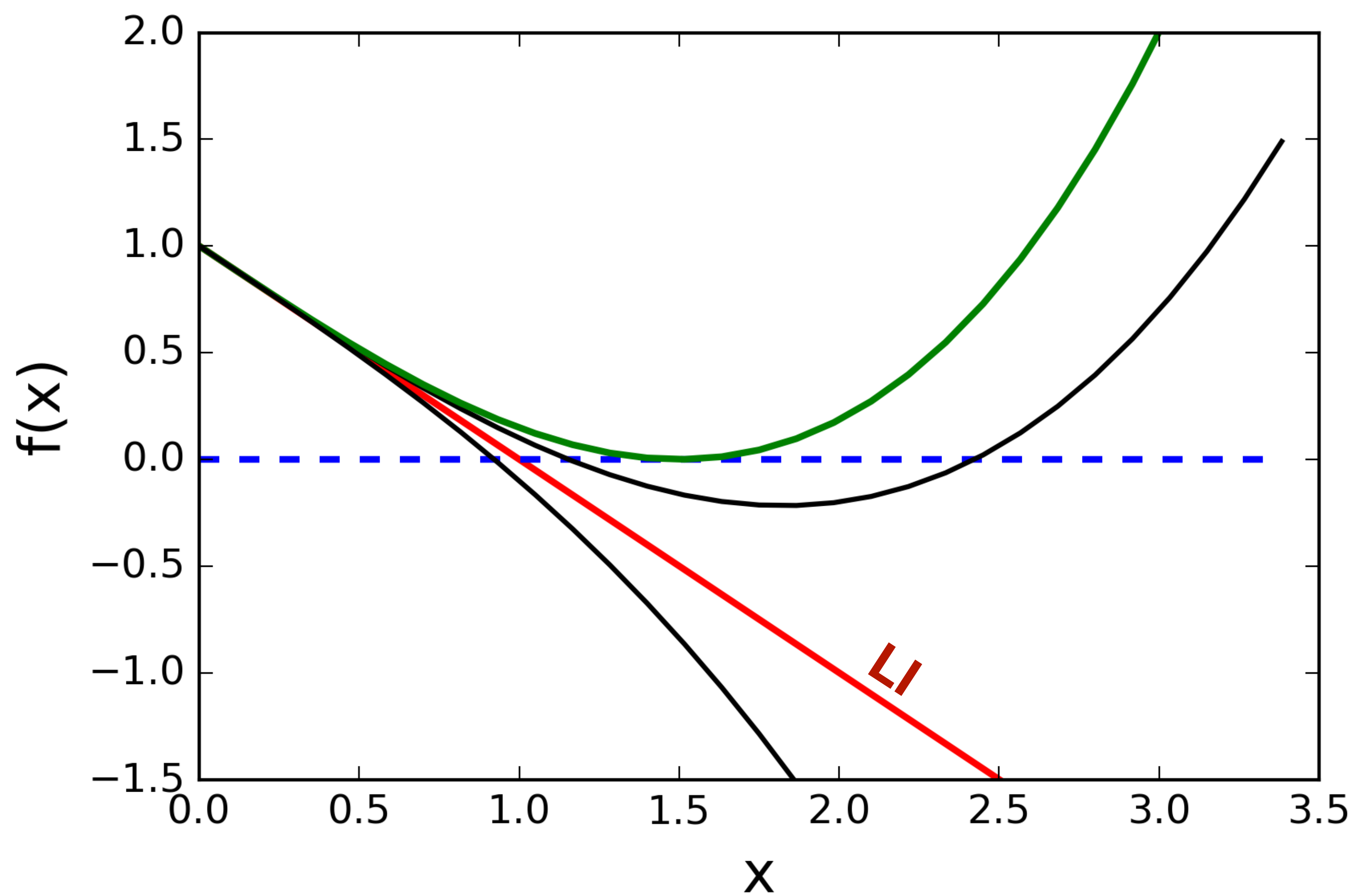
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma \epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

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

Background:

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



humbertomh@ifsc.usp.br

H. Martínez-Huerta, A. Pérez-Lorenzana.
Phys. Rev. D 95, 063001 (2017)

Pair Production

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

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

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

The threshold equation

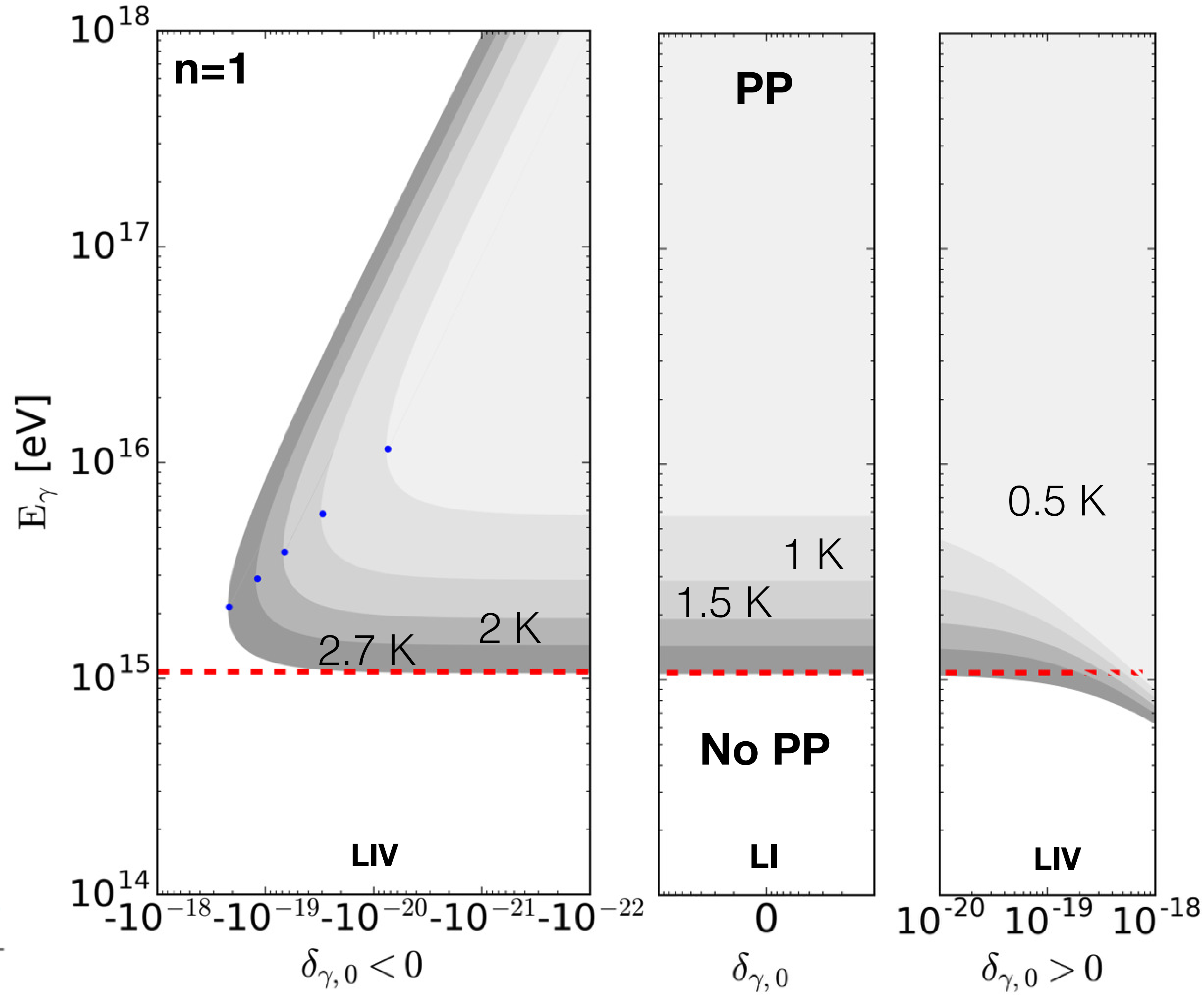
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma\epsilon - m_e^2\frac{1}{K(1-K)} = 0$$

Critical point

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

Background:

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



H. Martínez-Huerta, A. Pérez-Lorenzana.
Phys. Rev. D 95, 063001 (2017)

Pair Production

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

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

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

The threshold equation

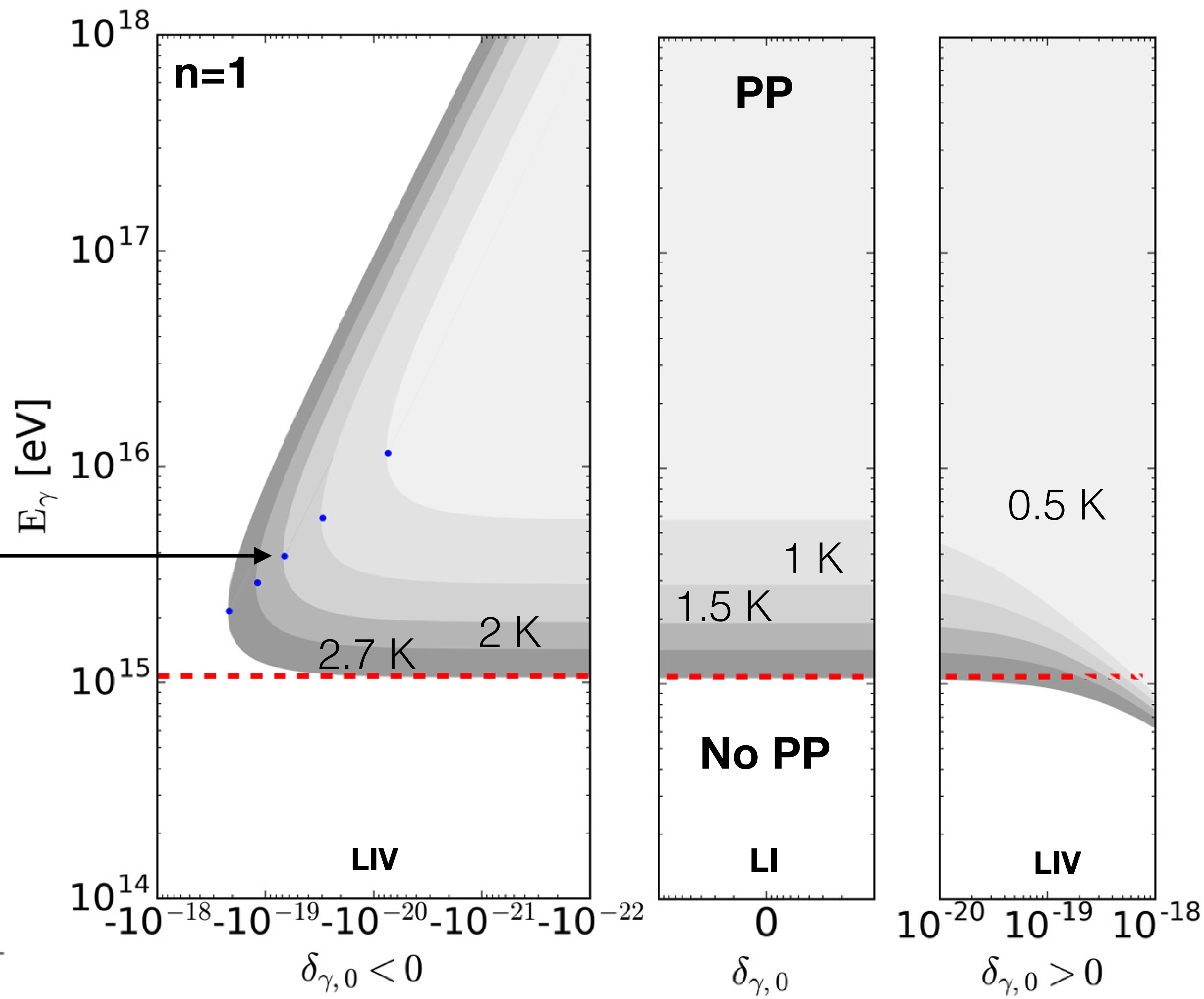
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma\epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

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

Background:

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

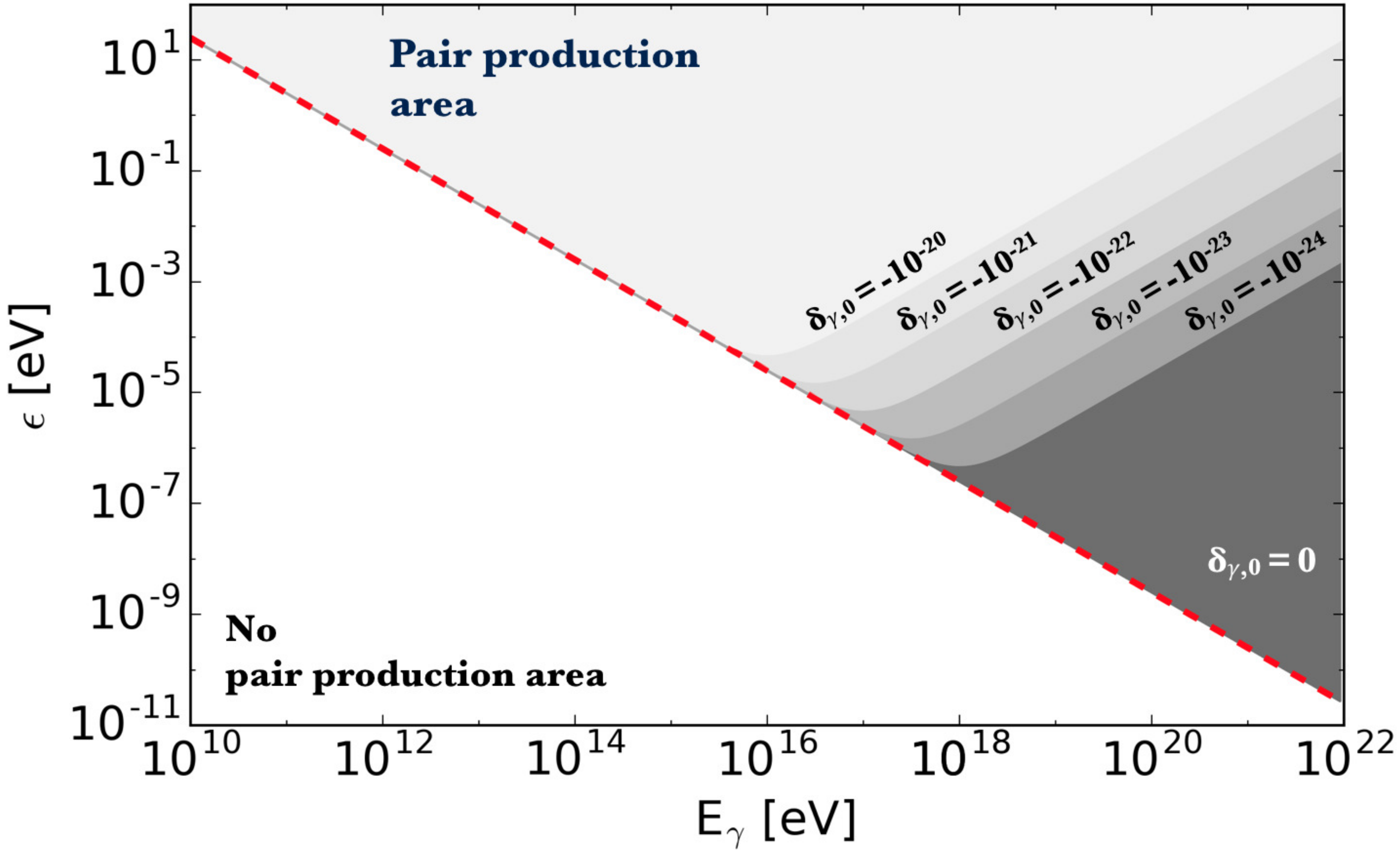


H. Martínez-Huerta, A. Pérez-Lorenzana.
Phys. Rev. D 95, 063001 (2017)

Pair Production

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

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

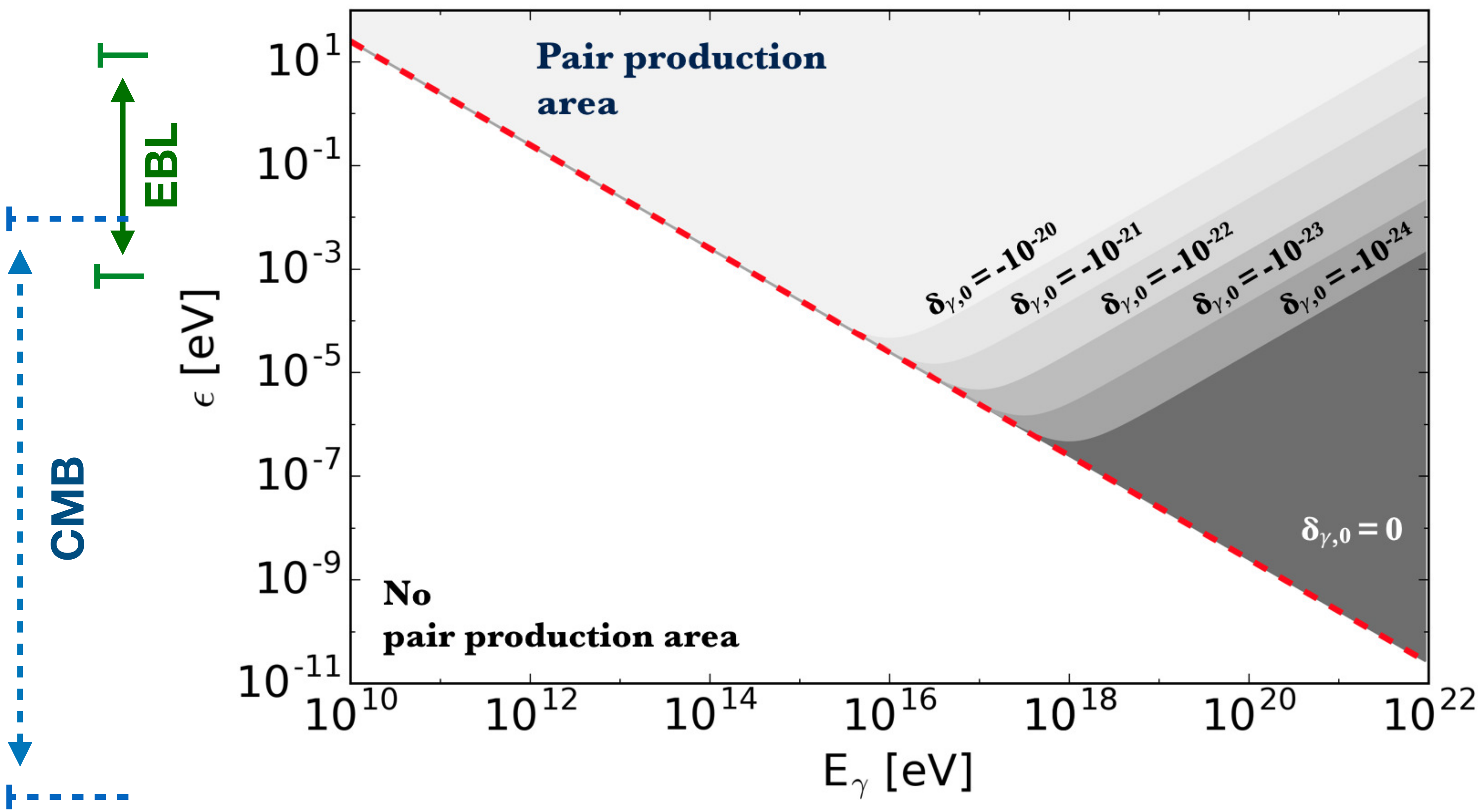


humbertomh@ifsc.usp.br

Pair Production

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

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

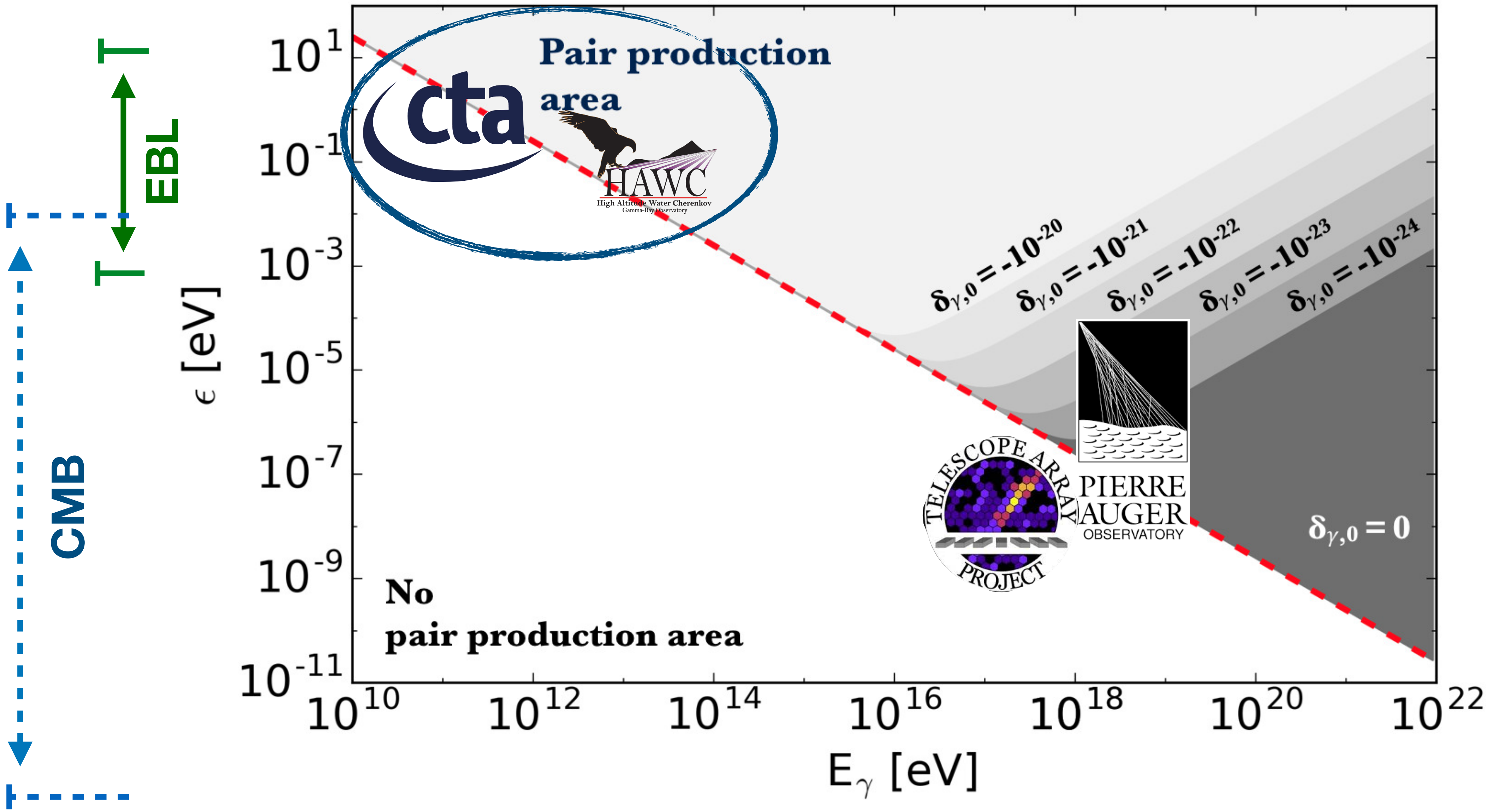


humbertomh@ifsc.usp.br

Pair Production

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

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



Index

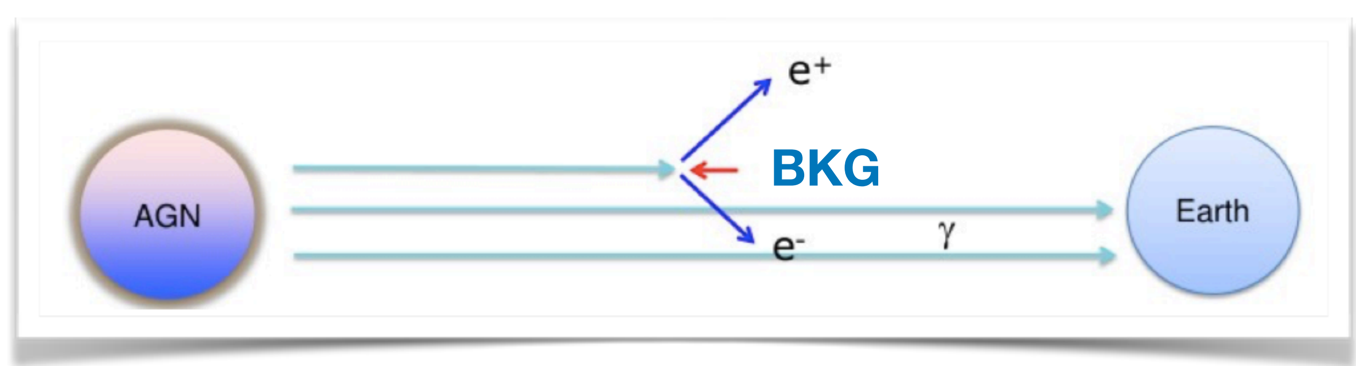
I. Lorentz invariance violation (LIV)

II. LIV + gamma-rays

III. Optical Depth + LIV

IV. GZK photon flux + LIV

V. LIV limits



Optical depth

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

$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$

The distance element

Density of BKG photons

Pair Production cross section

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

Optical depth + LIV

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

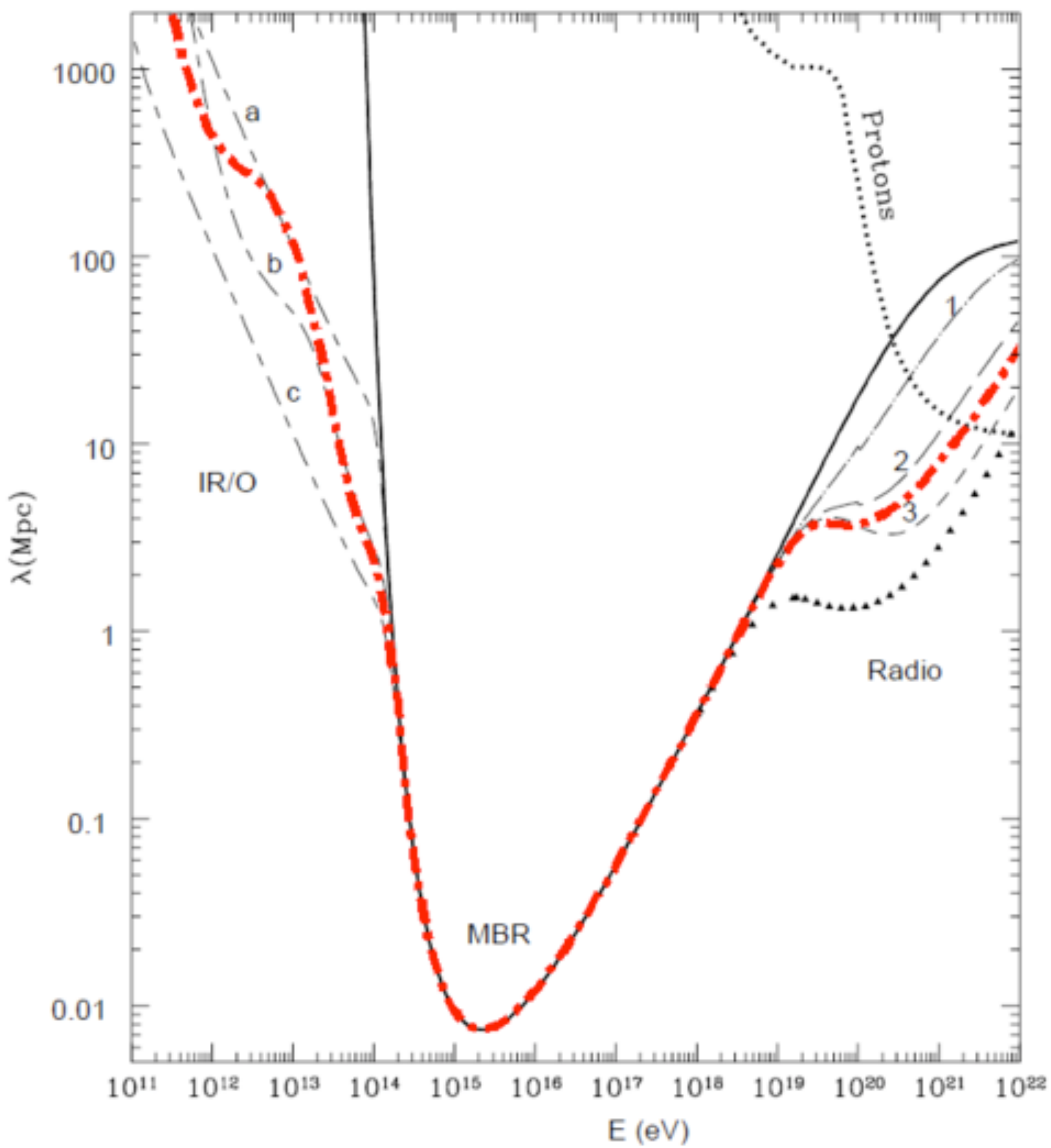
$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$

LIV

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

Optical depth

$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$

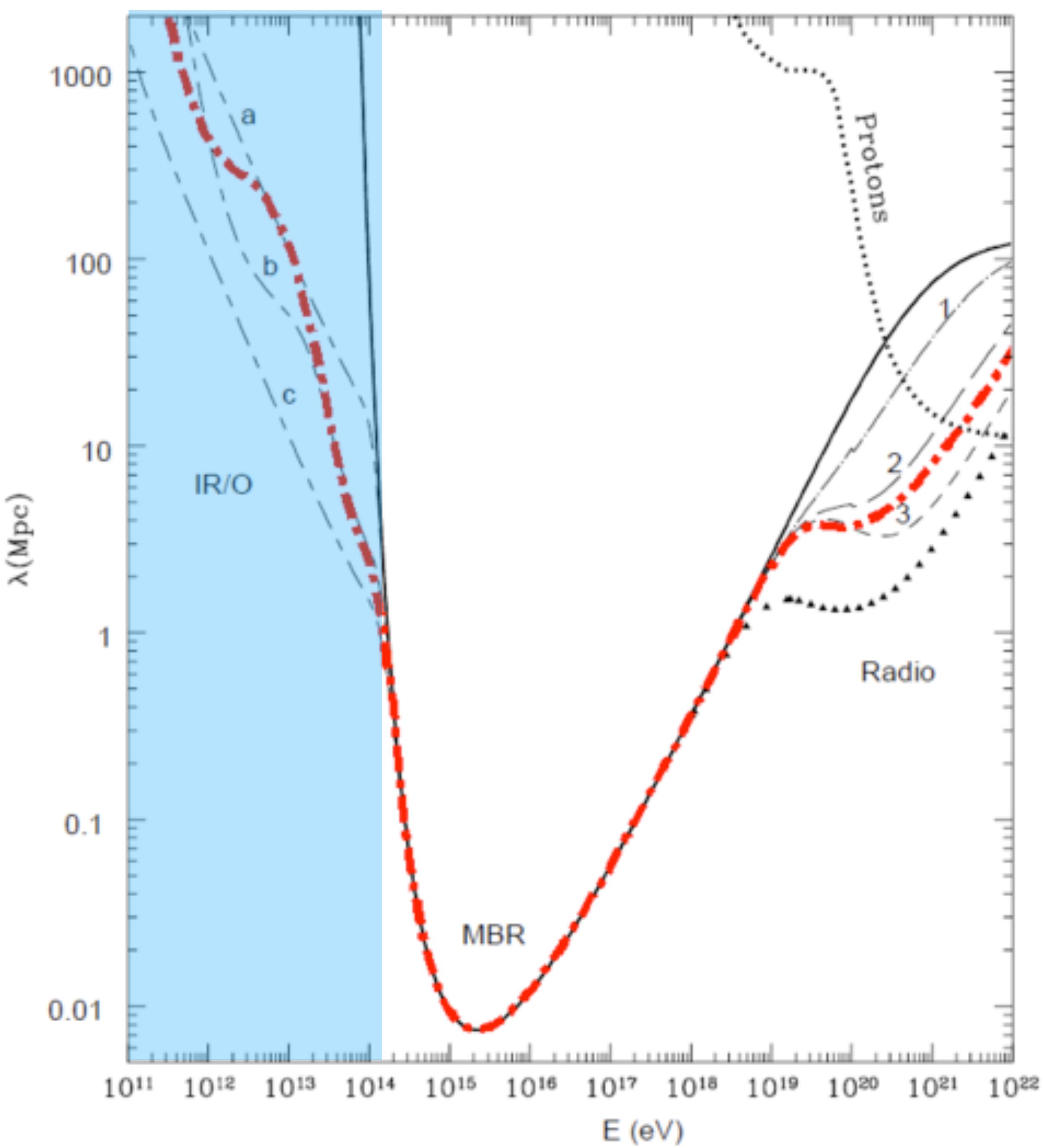


De Angelis, Alessandro et al.
Mon.Not.Roy.Astron.Soc.
432 (2013) 3245-3249

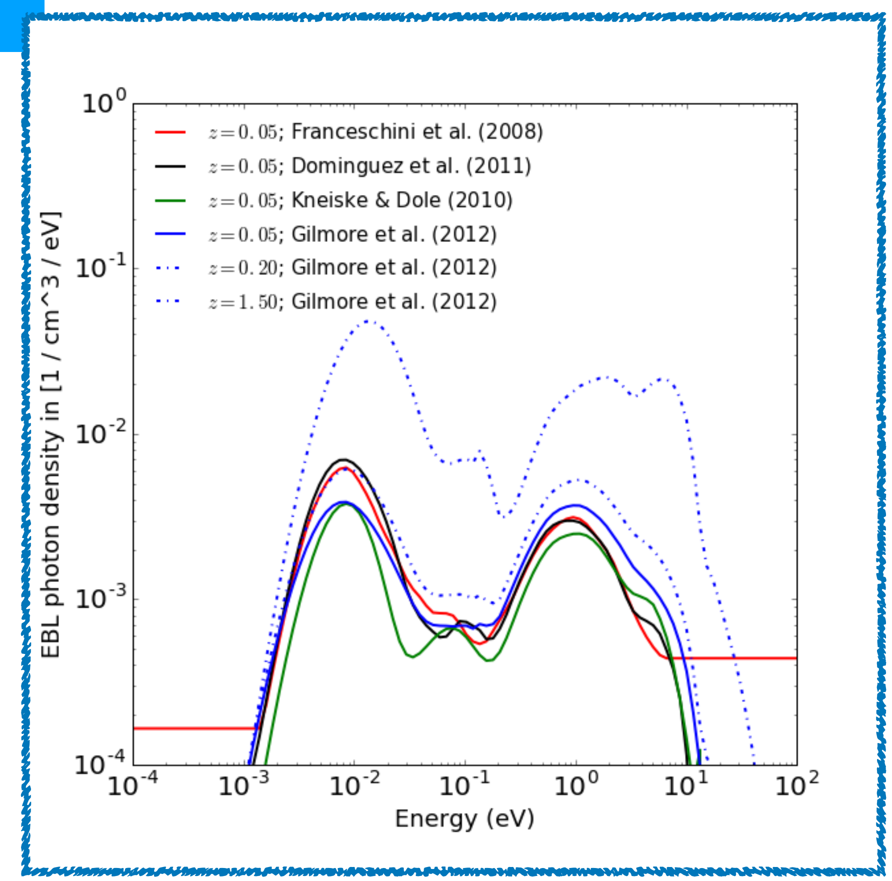
humbertomh@ifsc.usp.br

Optical depth

$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$



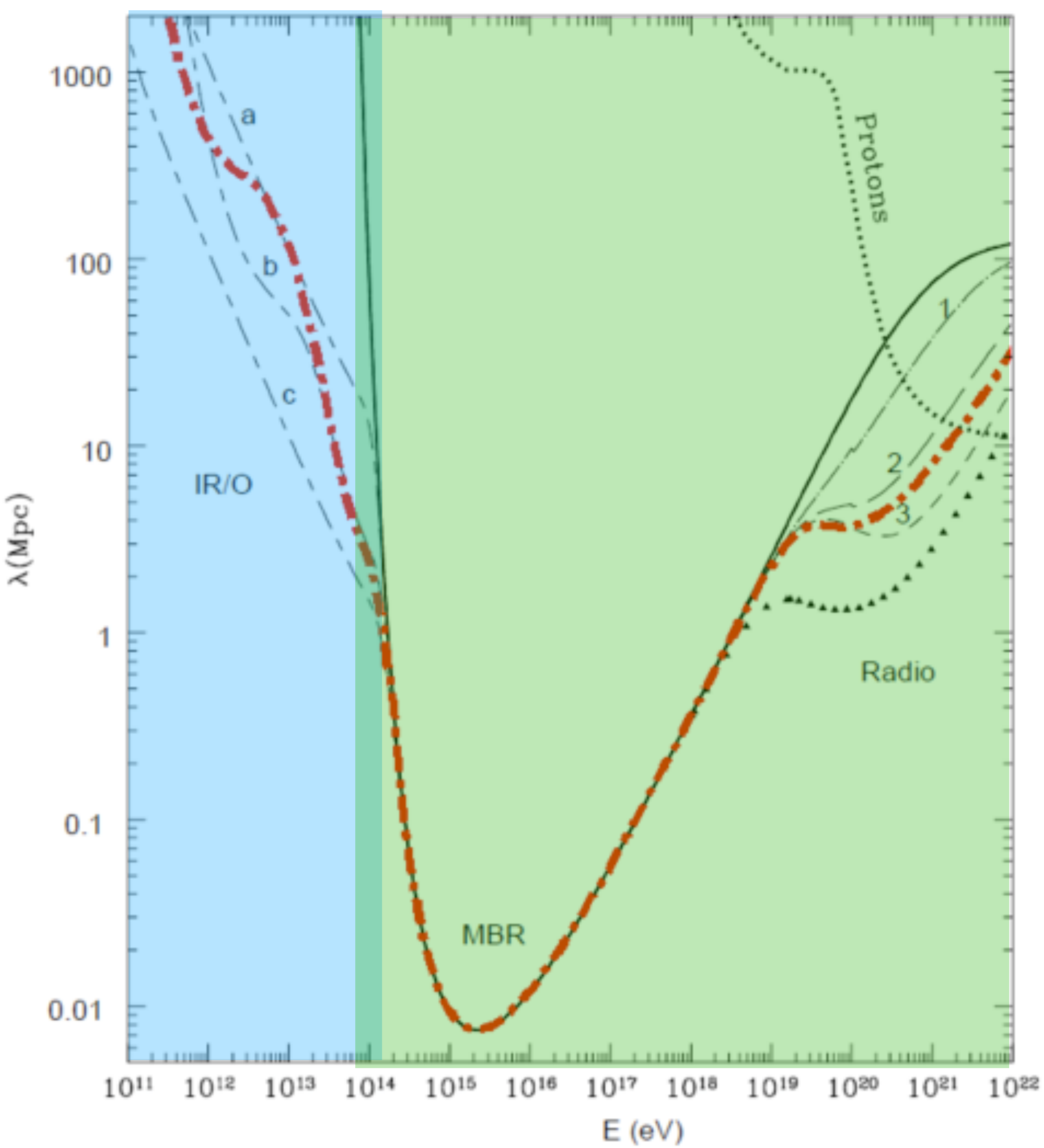
density of EBL photons



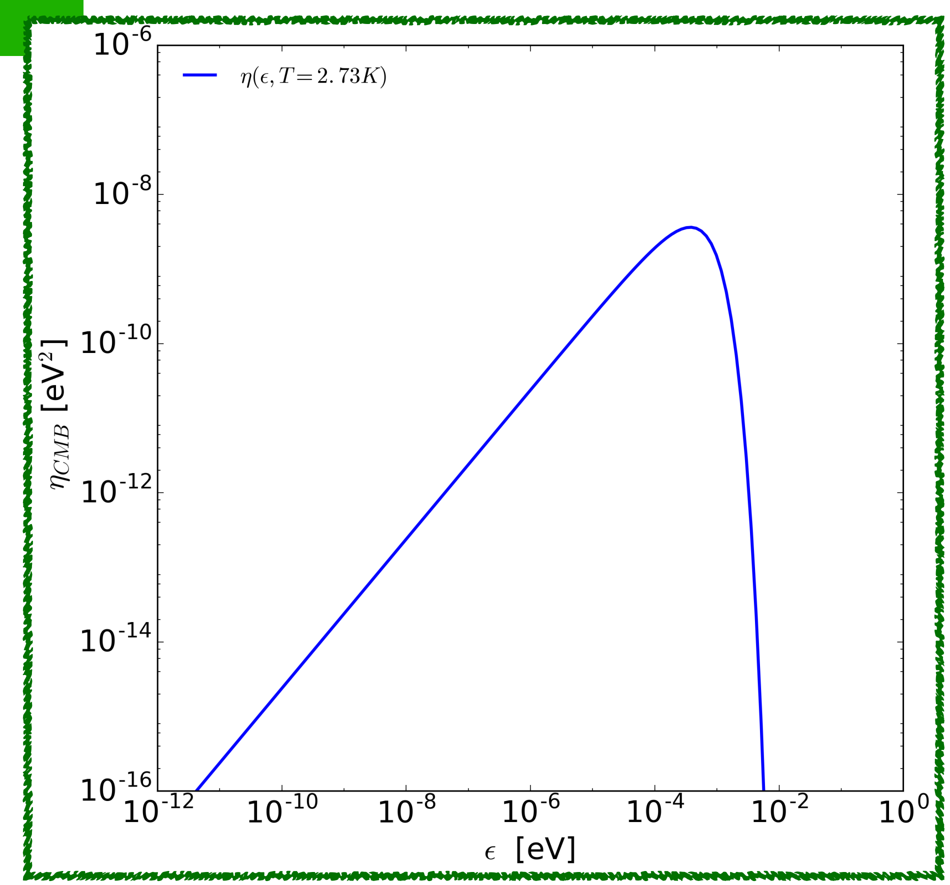
De Angelis, Alessandro et al.
Mon.Not.Roy.Astron.Soc.
432 (2013) 3245-3249

Optical depth

$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$



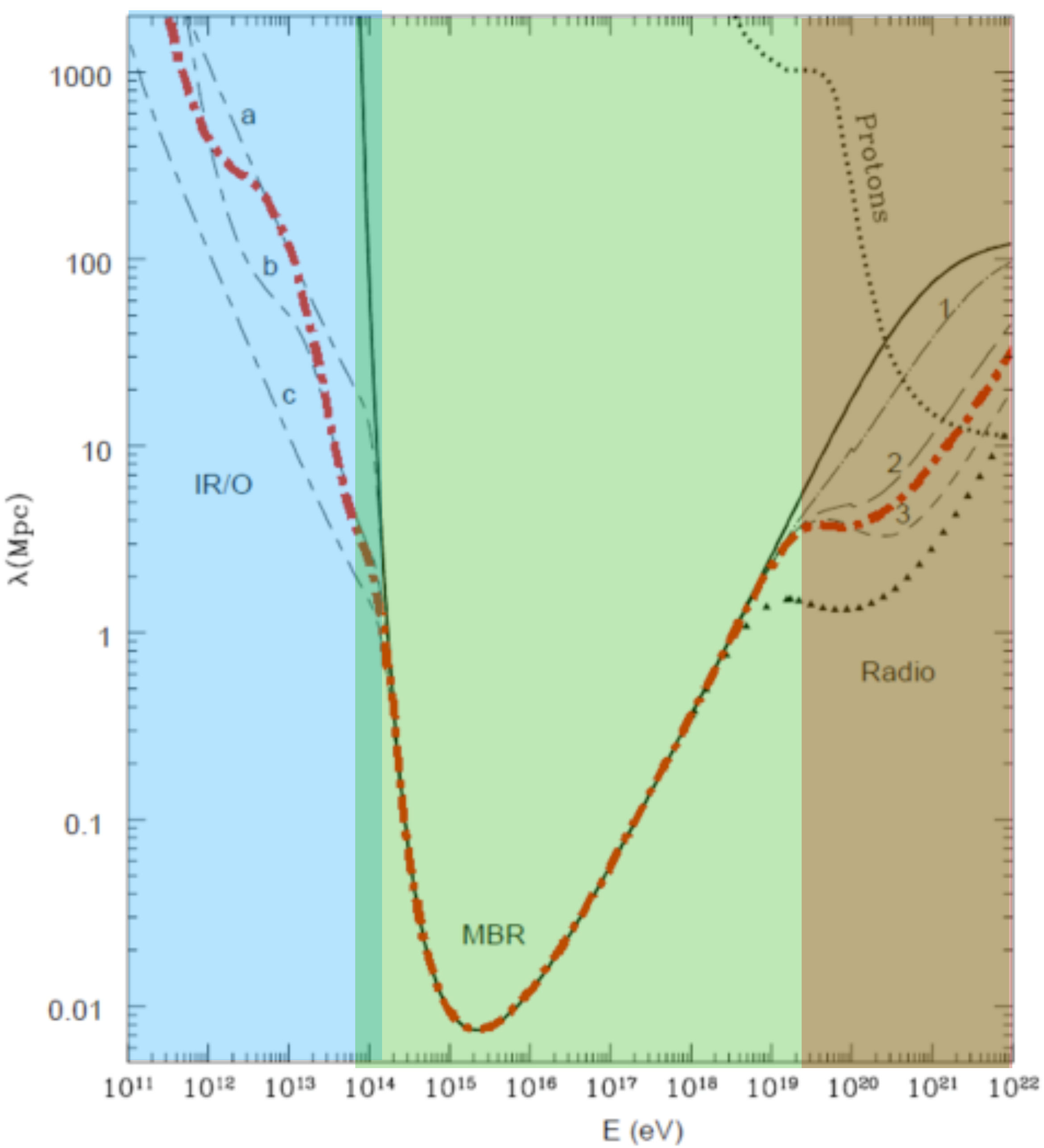
density of CMB photons



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

Optical depth

$$\tau(E_\gamma, z; E_{LIV}^{(n)}, n) = \int_0^{z_0} dz \frac{\partial L(z)}{\partial z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{\partial n(\epsilon, z)}{\partial \epsilon} \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma_{\gamma\gamma_{EBL}}(E_\gamma, z, \epsilon, \cos\theta)$$

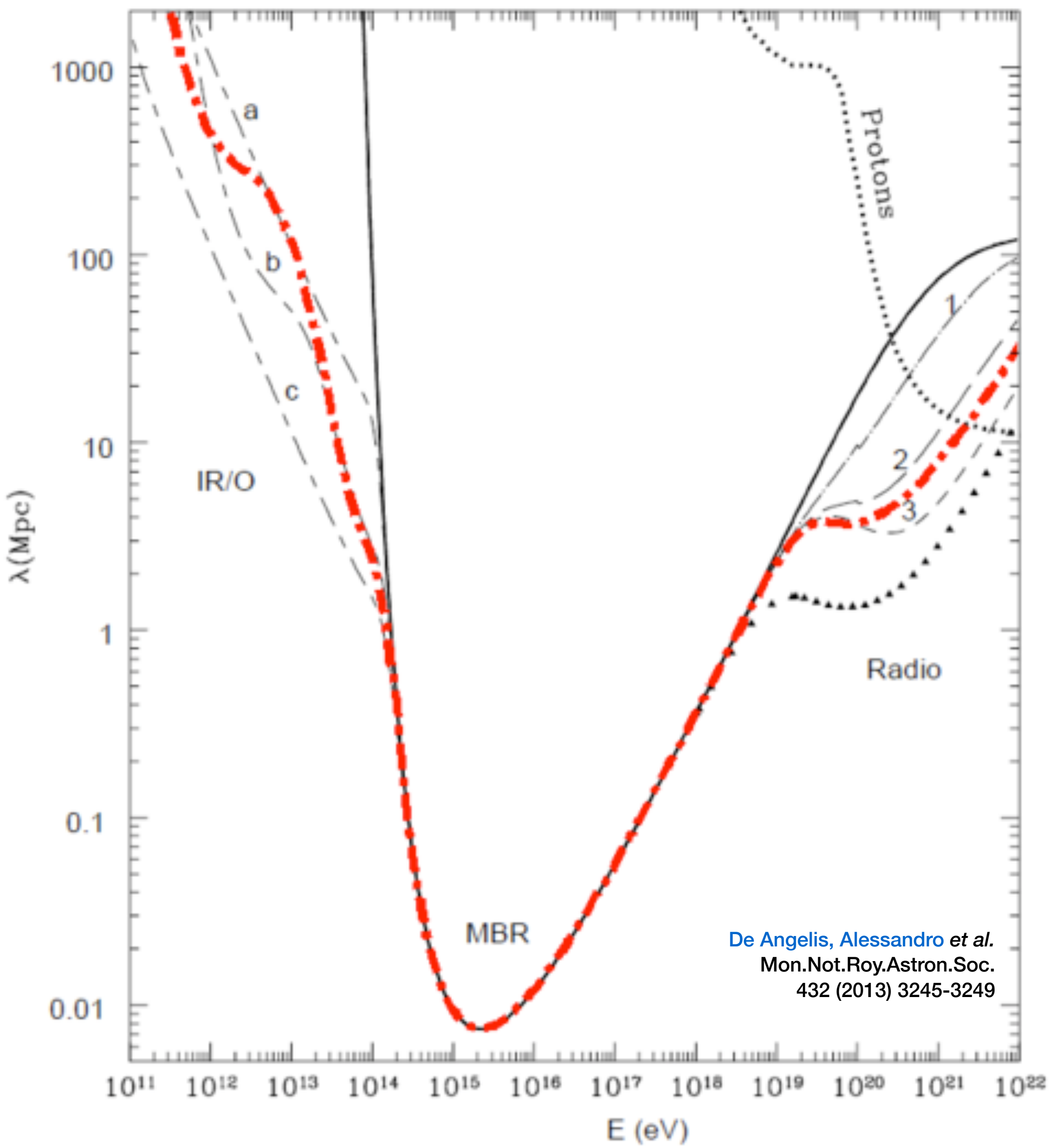


density of Radio photons

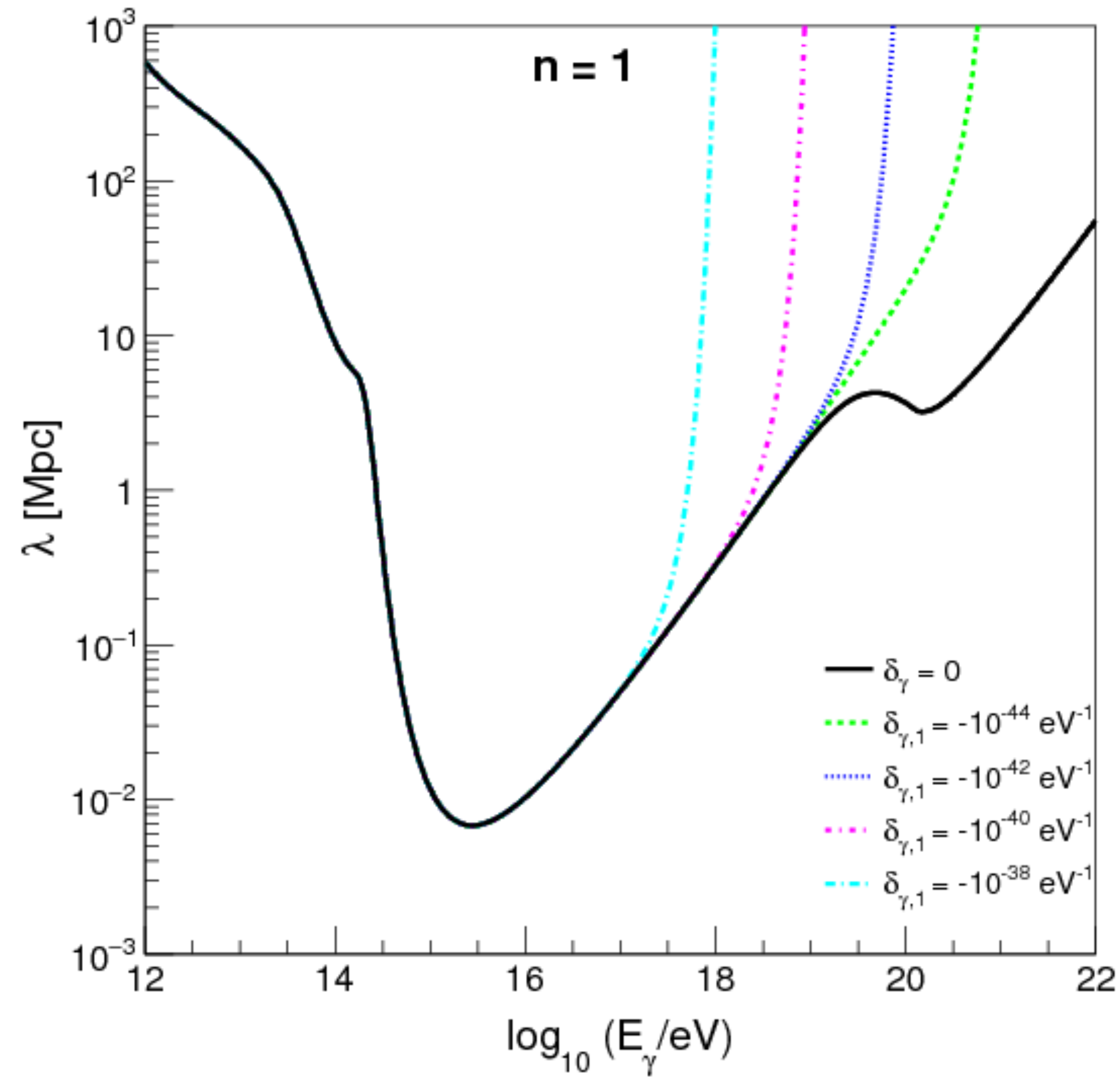
De Angelis, Alessandro et al.
Mon.Not.Roy.Astron.Soc.
432 (2013) 3245-3249

Optical Depth + LIV

LI

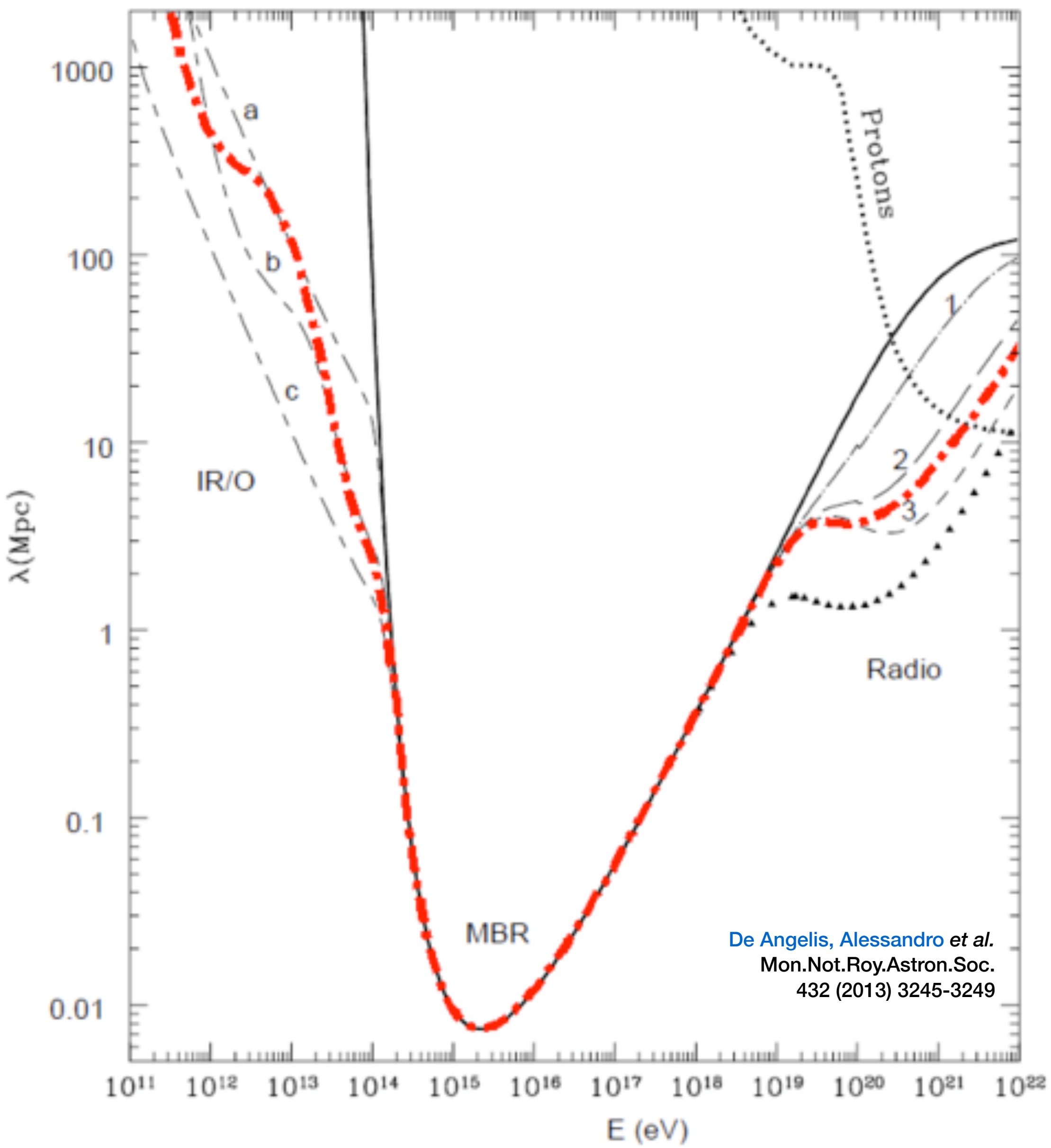


LIV

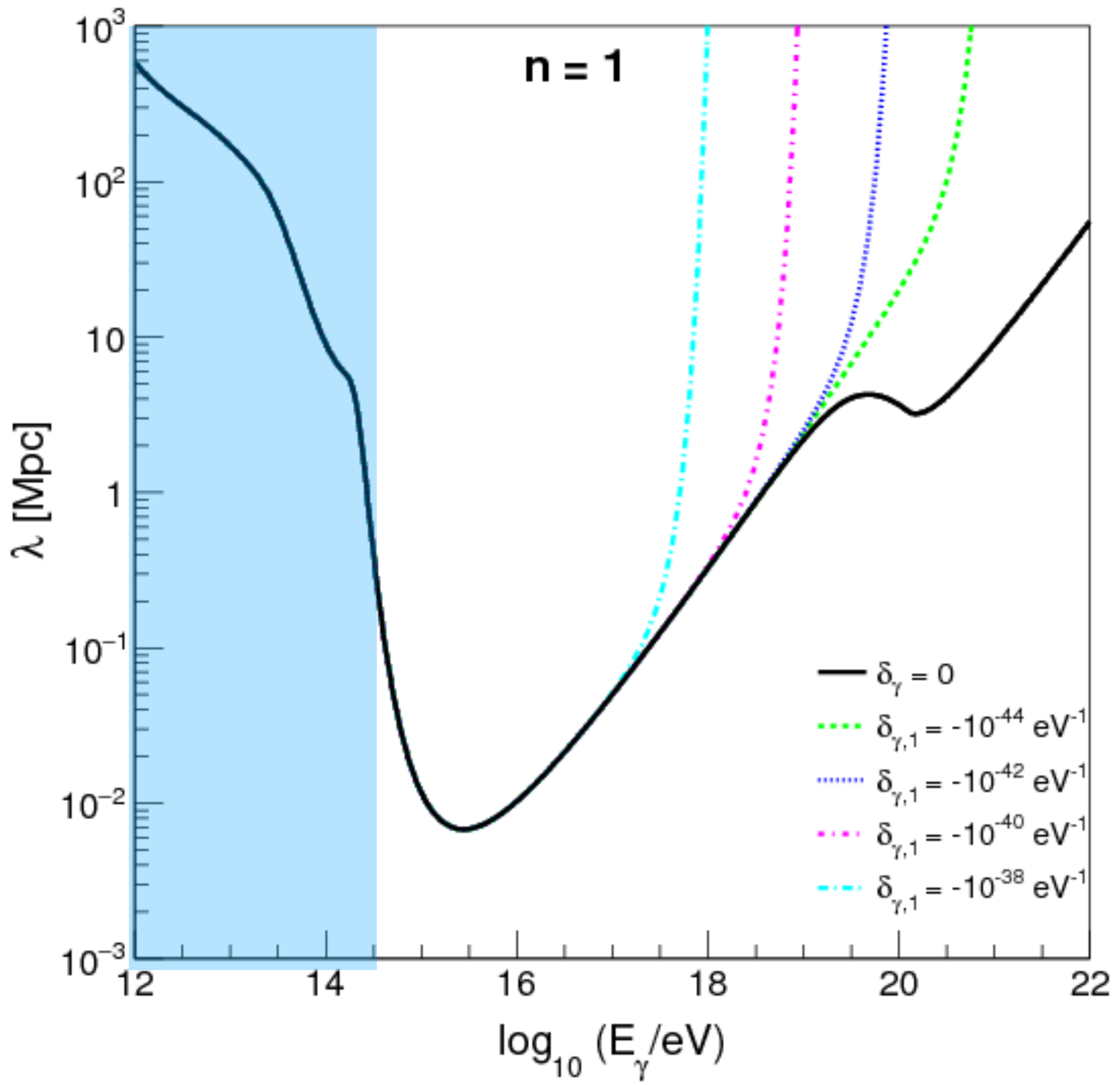


Optical Depth + LIV

LI

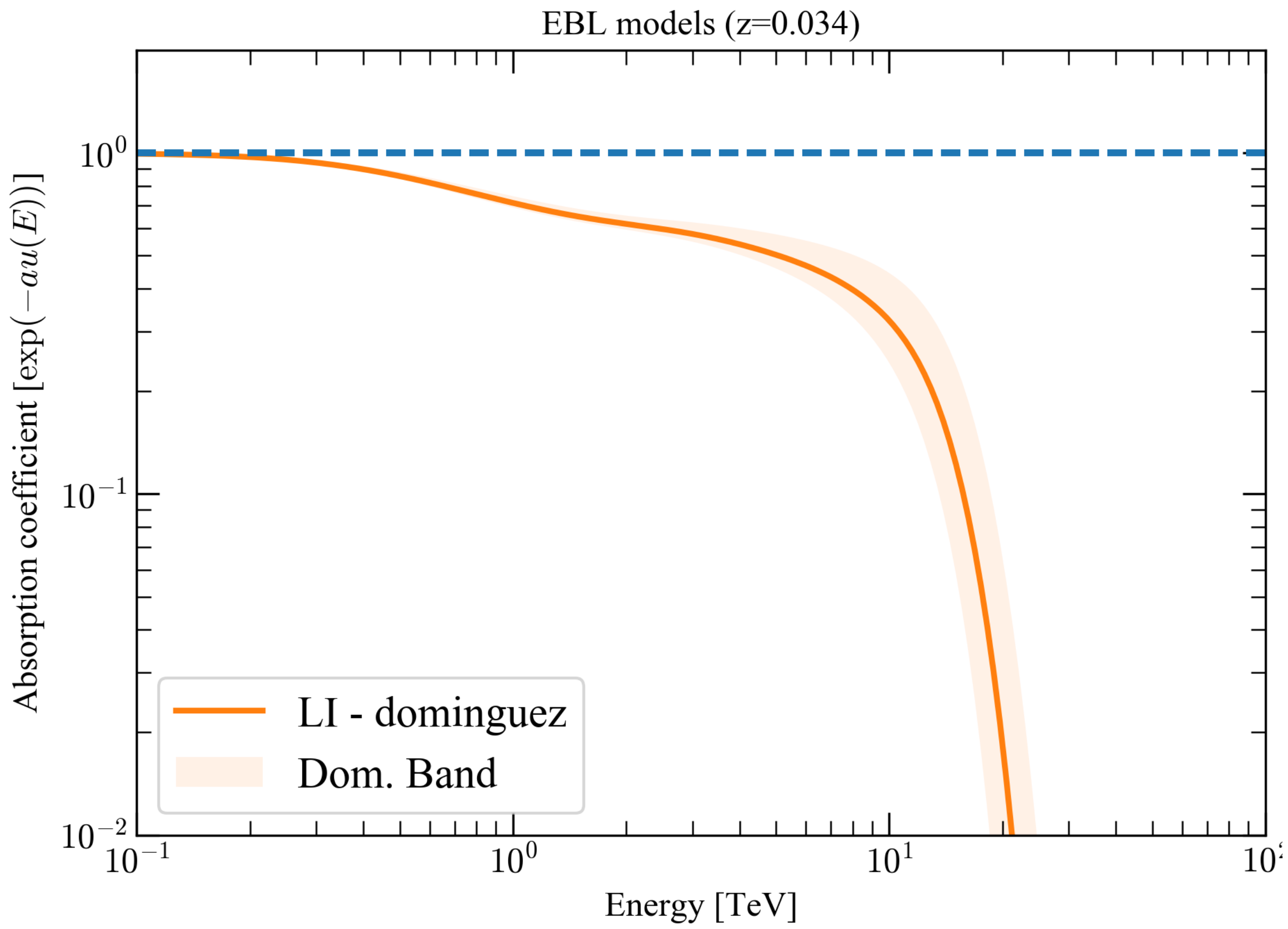


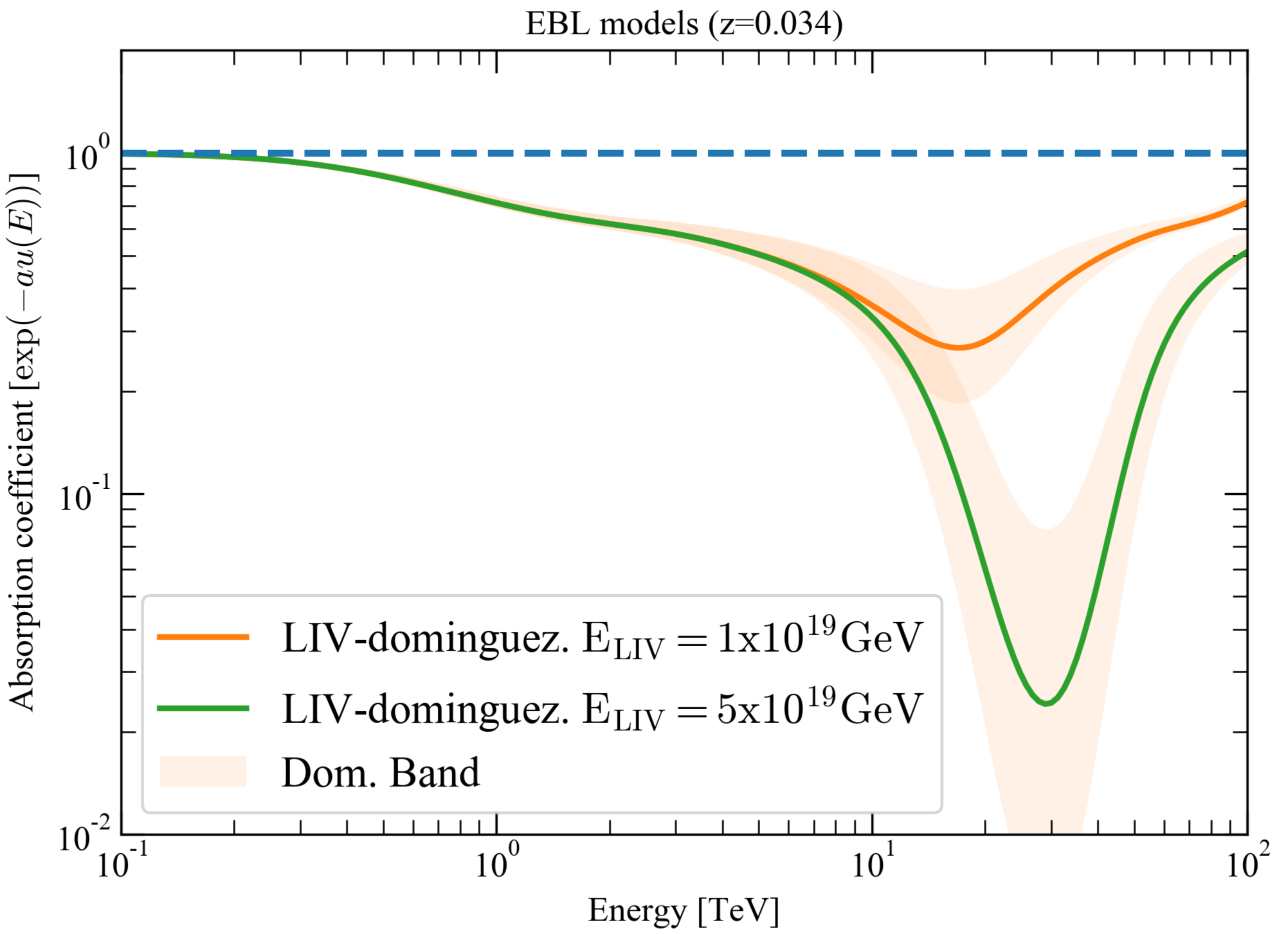
LIV



Optical Depth + LIV

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

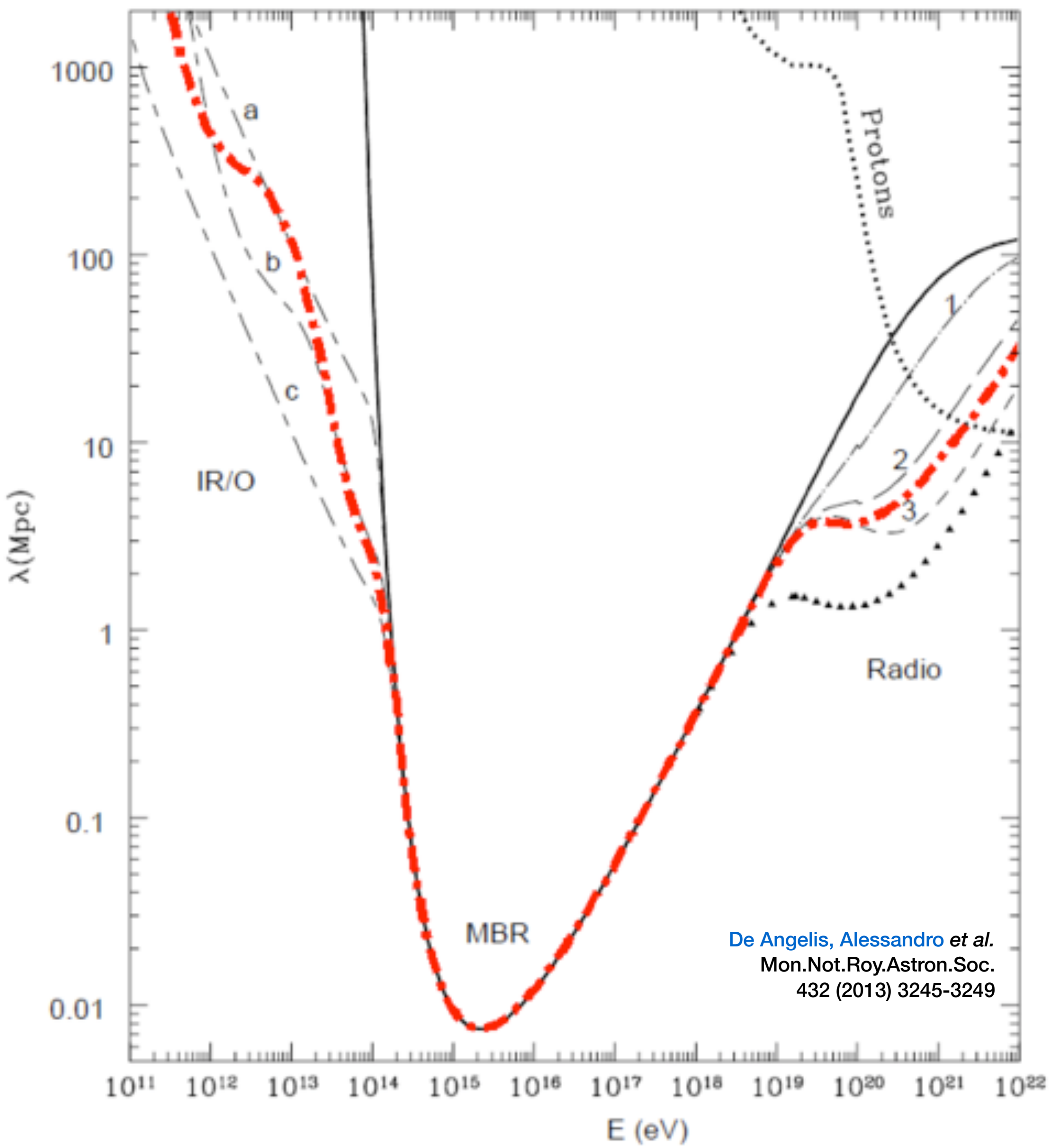




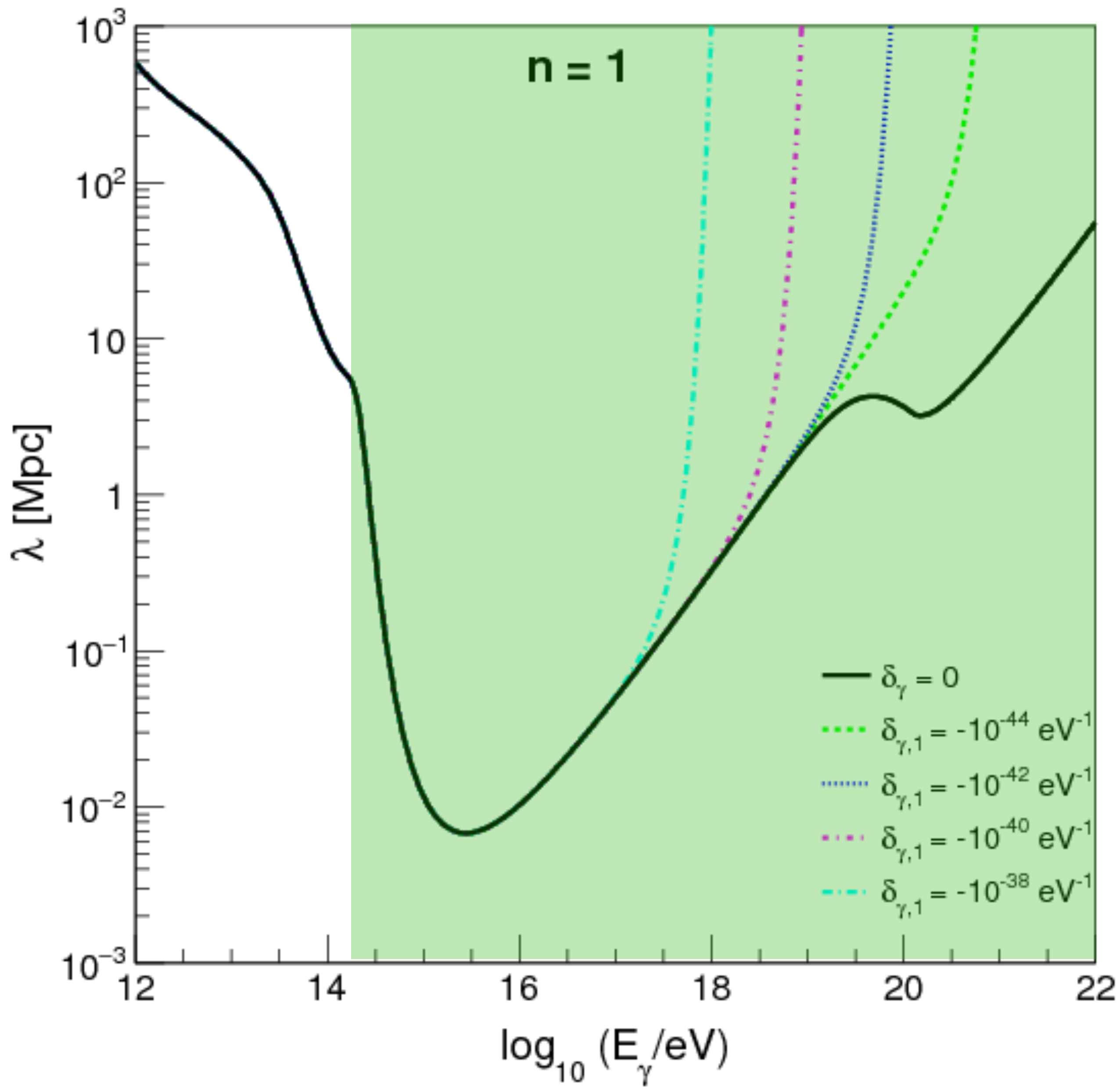
https://www.cta-observatory.org/what-propogation-of-energetic-light-can-tell-us/

Optical Depth + LIV

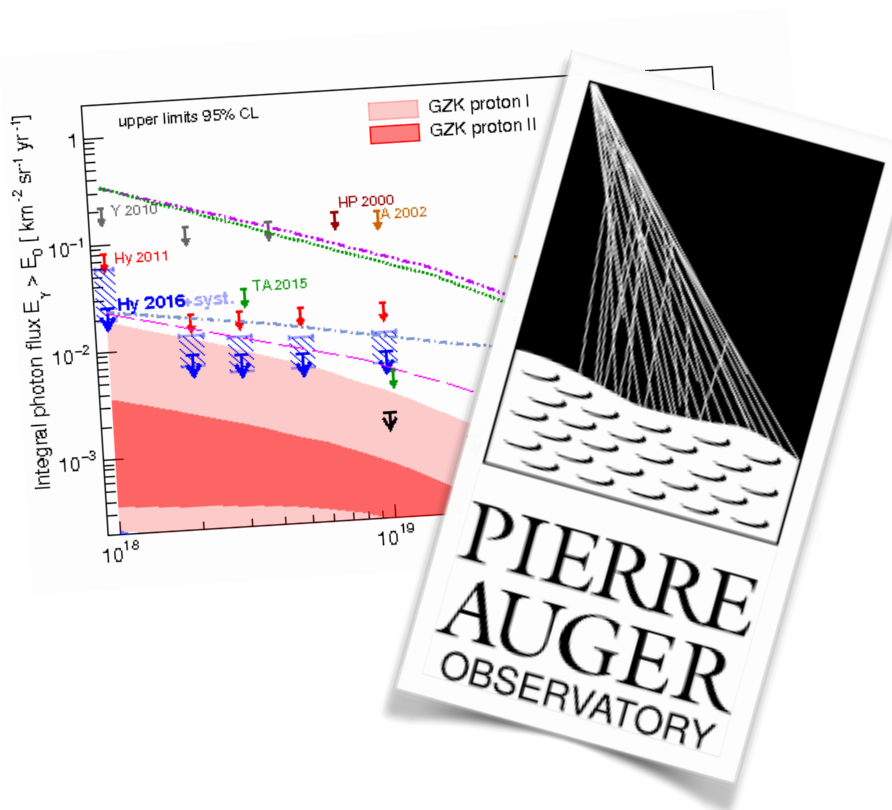
LI



LIV



Index


upper limits 95% CL
GZK proton I
GZK proton II
Integral photon flux $E_\gamma > E_0$ [km^{-2} sr^{-1} yr^{-1}]
1
10^{-1}
10^{-2}
10^{-3}
10^{18}
10^{19}
Y 2010
HP 2000
TA 2002
Hy 2011
TA 2015
Hy 2016
syst.
PIERRE
AUGER
OBSERVATORY

GZK photon flux

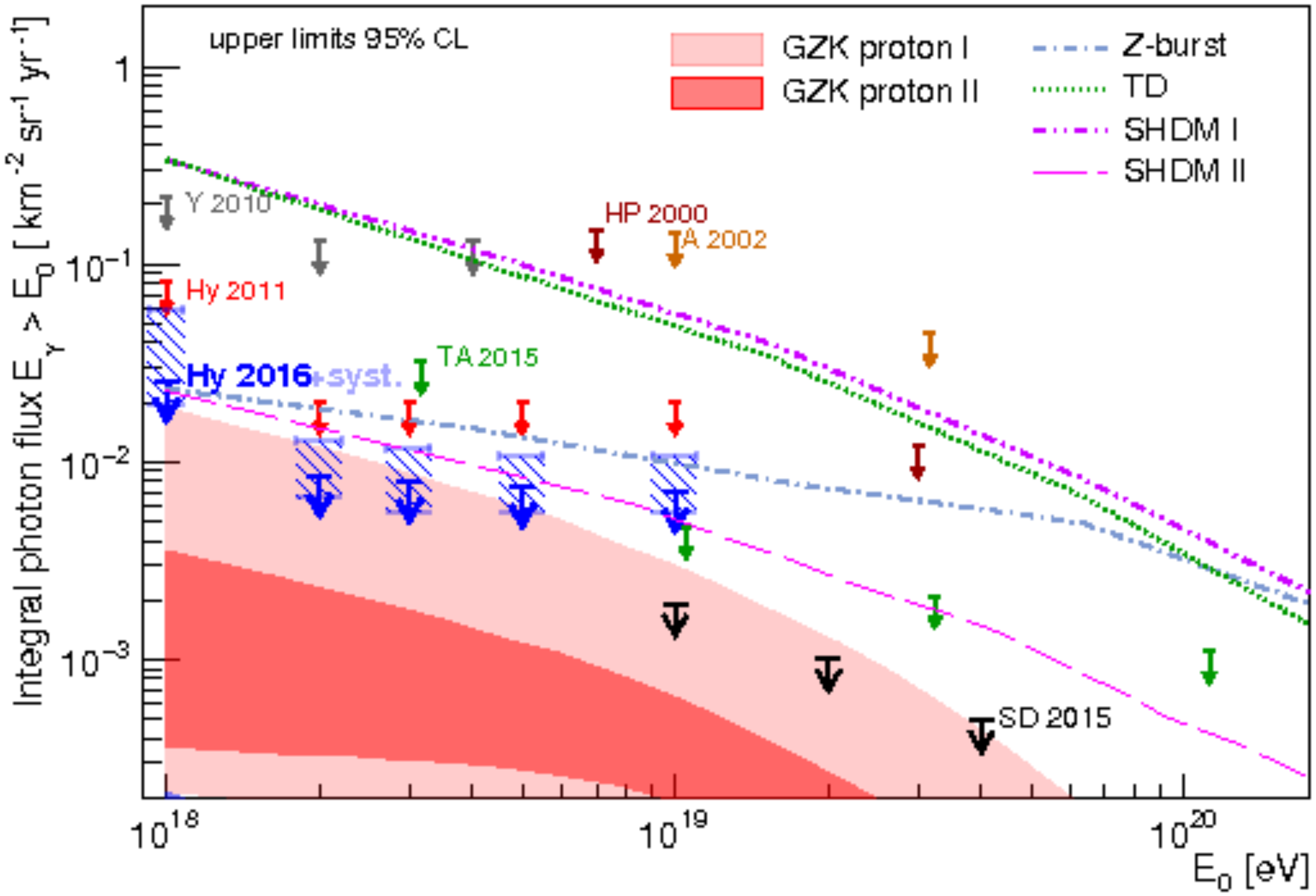


Figure 6. Upper limits on the integral photon flux derived from 9 years of hybrid data (blue arrows, Hy 2016) for a photon flux E^{-2} and no background subtraction. The limits obtained when the detector systematic uncertainties are taken into account are shown as horizontal segments (light blue) delimiting 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

UHECR

Parameters of the Four Source Models Used in This Paper

Model	Γ	$\log_{10}(R_{\rm cut}/V)$	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

Note. Γ is the spectral index, $R_{\rm cut}$ is the rigidity cutoff and fH, fHe, fN, fSi, and fFe are the fractions of each nuclei.

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

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

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

UHECR

Parameters of the Four Source Models Used in This Paper

Model	Γ	$\log_{10}(R_{\rm cut}/V)$	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

Note. Γ is the spectral index, $R_{\rm cut}$ is the rigidity cutoff and fH, fHe, fN, fSi, and fFe are the fractions of each nuclei.

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

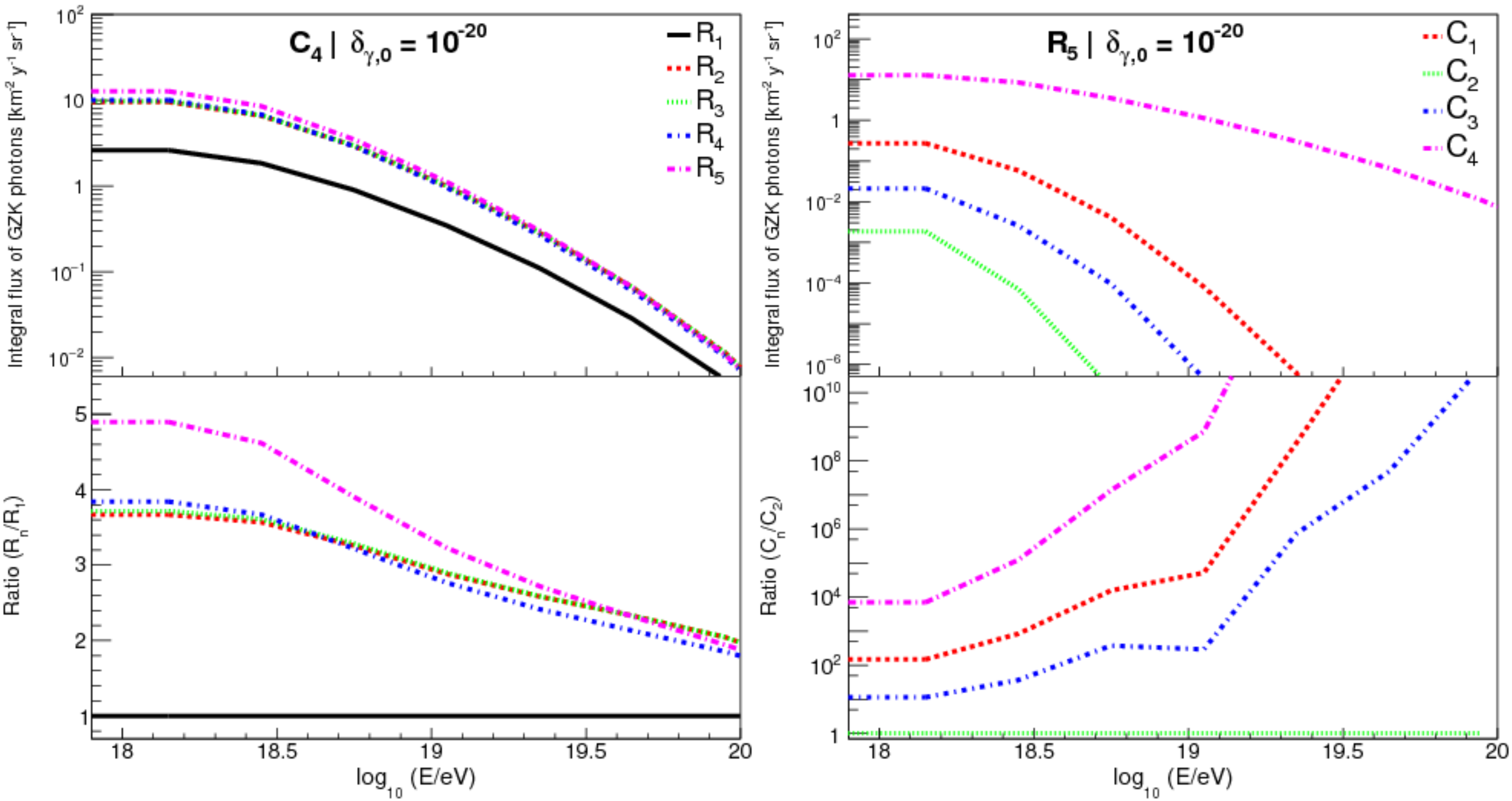
$$\frac{dN}{dE_s} = \begin{cases} E_s^{-\Gamma}, & \text{for } R_s < R_{\rm cut} \\ E_s^{-\Gamma} e^{1-R_s/R_{\rm cut}}, & \text{for } R_s \geqslant R_{\rm cut} \end{cases},$$

Models of Source Distribution

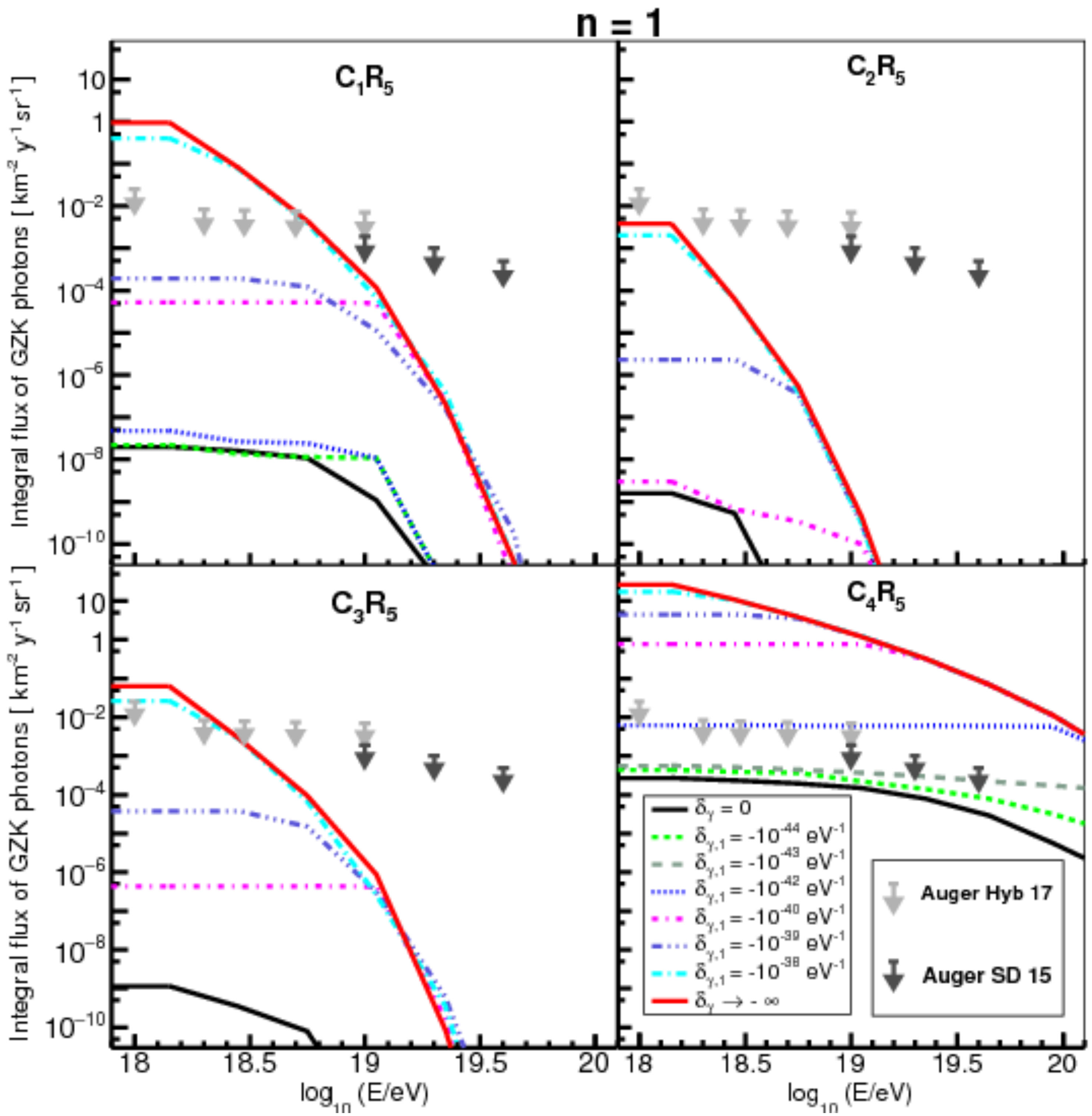
1. R_1: sources are uniformly distributed in a comoving volume;
2. R_2: sources follow the star formation distribution given in Hopkins & Beacom (2006). The evolution is proportional to $(1+z)^{3.4}$ for $z < 1$, to $(1+z)^{-0.26}$ for $1 \leqslant z < 4$ and to $(1+z)^{-7.8}$ for $z \geqslant 4$;
3. 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. 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. 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)

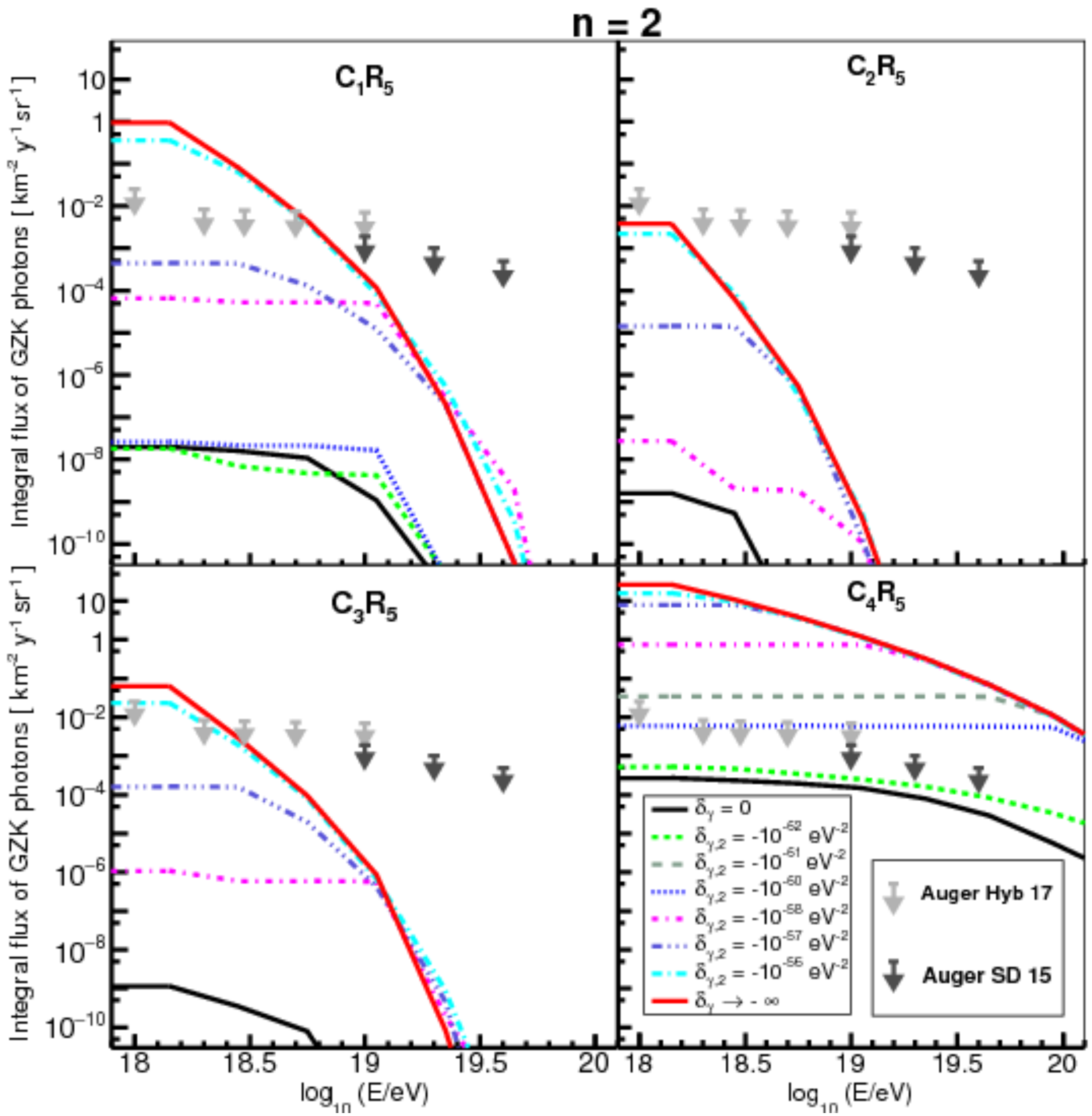
GZK photon flux + LIV



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, PhRvD, 92, 123001

Index

LIV limits

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

Model	$\delta_{\gamma,0}^{\text{limit}}$	$\delta_{\gamma,1}^{\text{limit}}(\text{eV}^{-1})$	$\delta_{\gamma,2}^{\text{limit}}(\text{eV}^{-2})$
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	$\delta_{\gamma,0}^{\text{limit}}$	$\delta_{\gamma,1}^{\text{limit}}(\text{eV}^{-1})$	$\delta_{\gamma,2}^{\text{limit}}(\text{eV}^{-2})$
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
- Stringent 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!