UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

INSPIRANDO TU MEJOR VERSIÓN

UDEM

LIV Class 2

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IFSC-USP - 21 Feb, 2024

Mrk401

Course Overview

Module ~~3~~ 2: Phenomenological Implications and Experimental Constraints

3.1 Observable Effects

- Discussion on observable effects of Lorentz symmetry violation in different physical phenomena (2-2)

3.2 Experimental Tests:

- Review of experimental methods for testing Lorentz symmetry violation and their implications

3.2 Current Constraints

- Overview of the current bounds on Lorentz symmetry violation from various experiments
- Comparison with theoretical predictions

3.3 Hands-on block

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$\gamma\gamma_b \to e^+e^-$

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

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

The threshold equation

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

Critical point

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

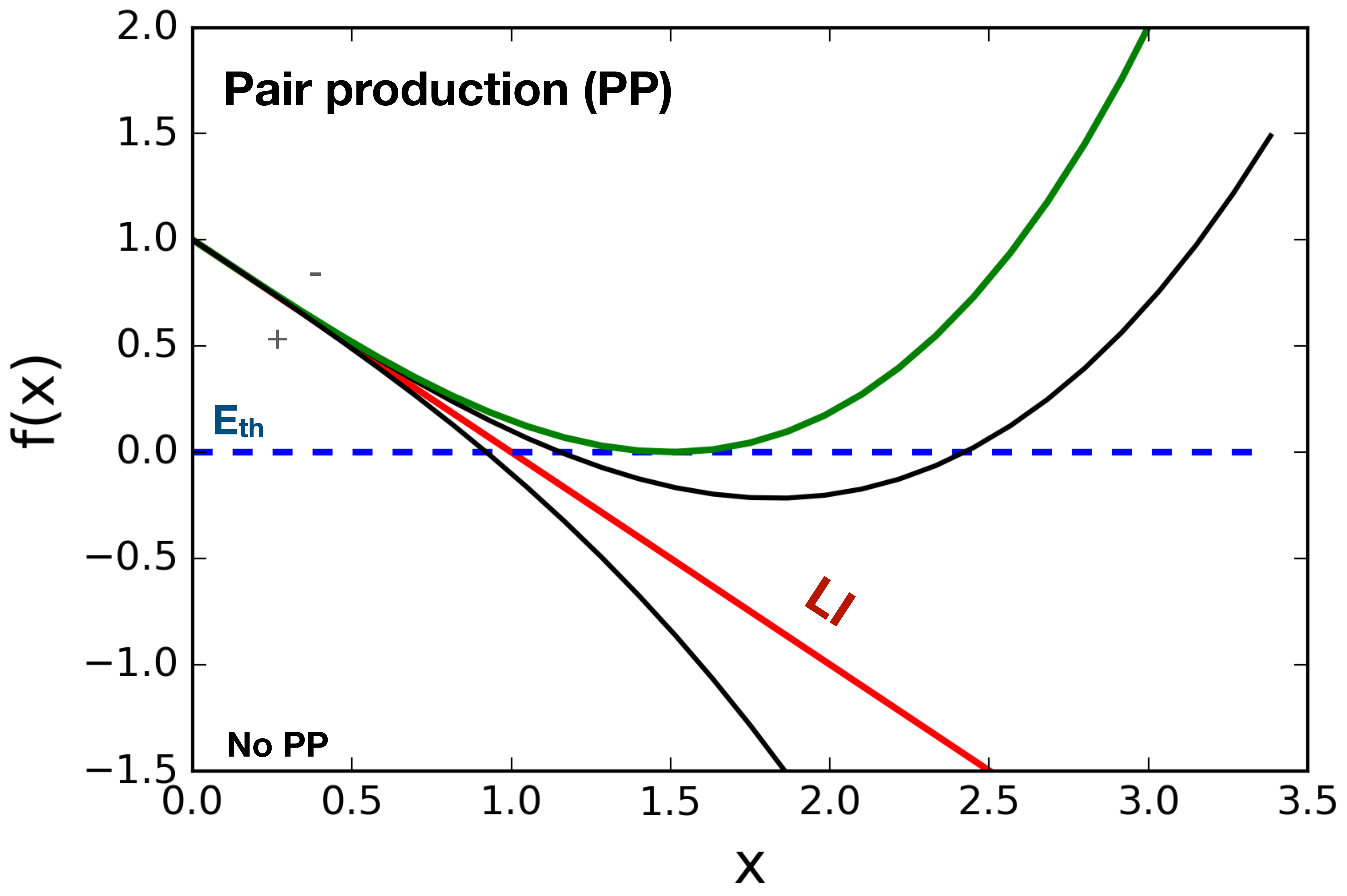
Background:

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

$\Lambda_n < 0$ Threshold-shifts

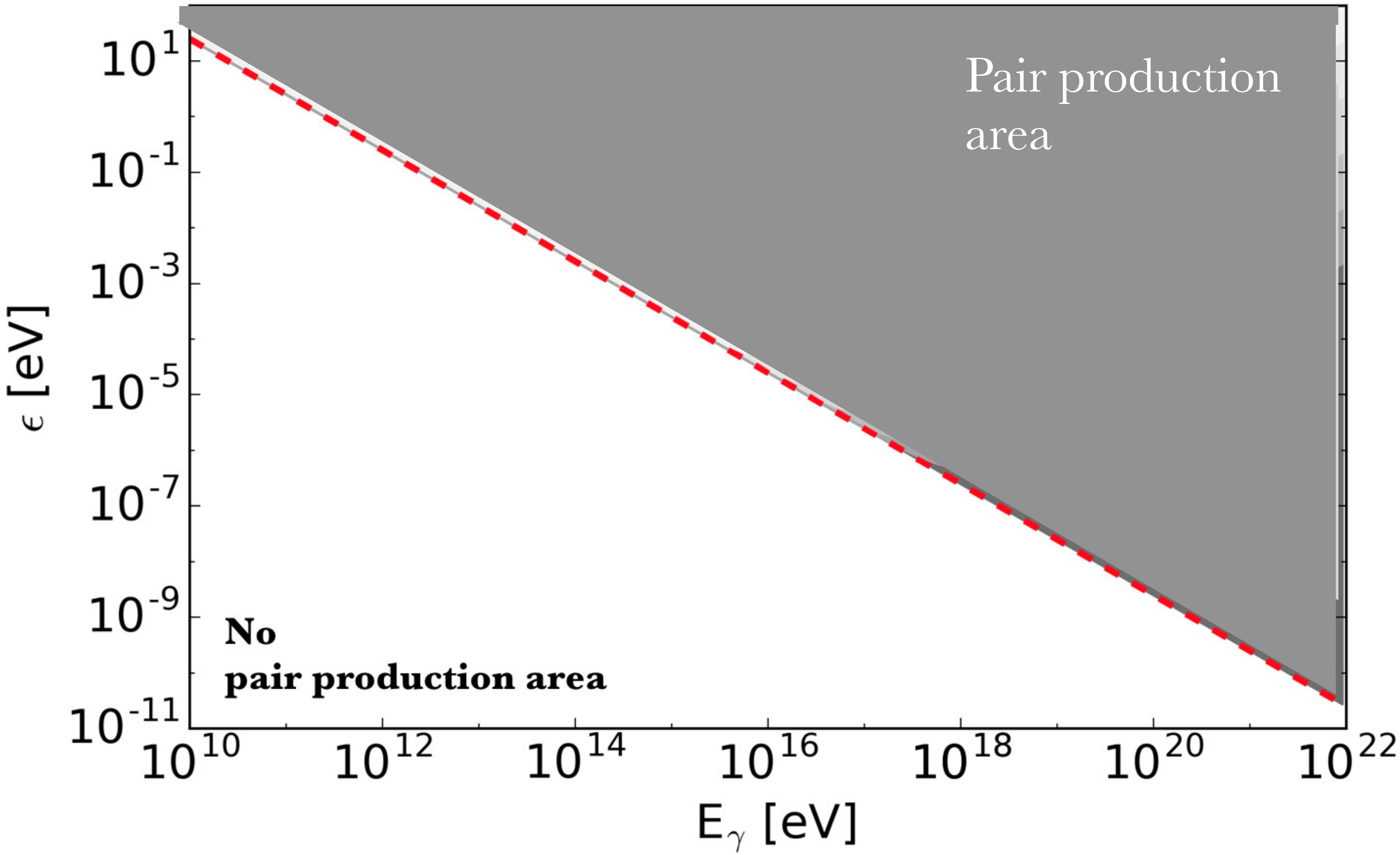
$\Lambda_n = 0$ LI scenario

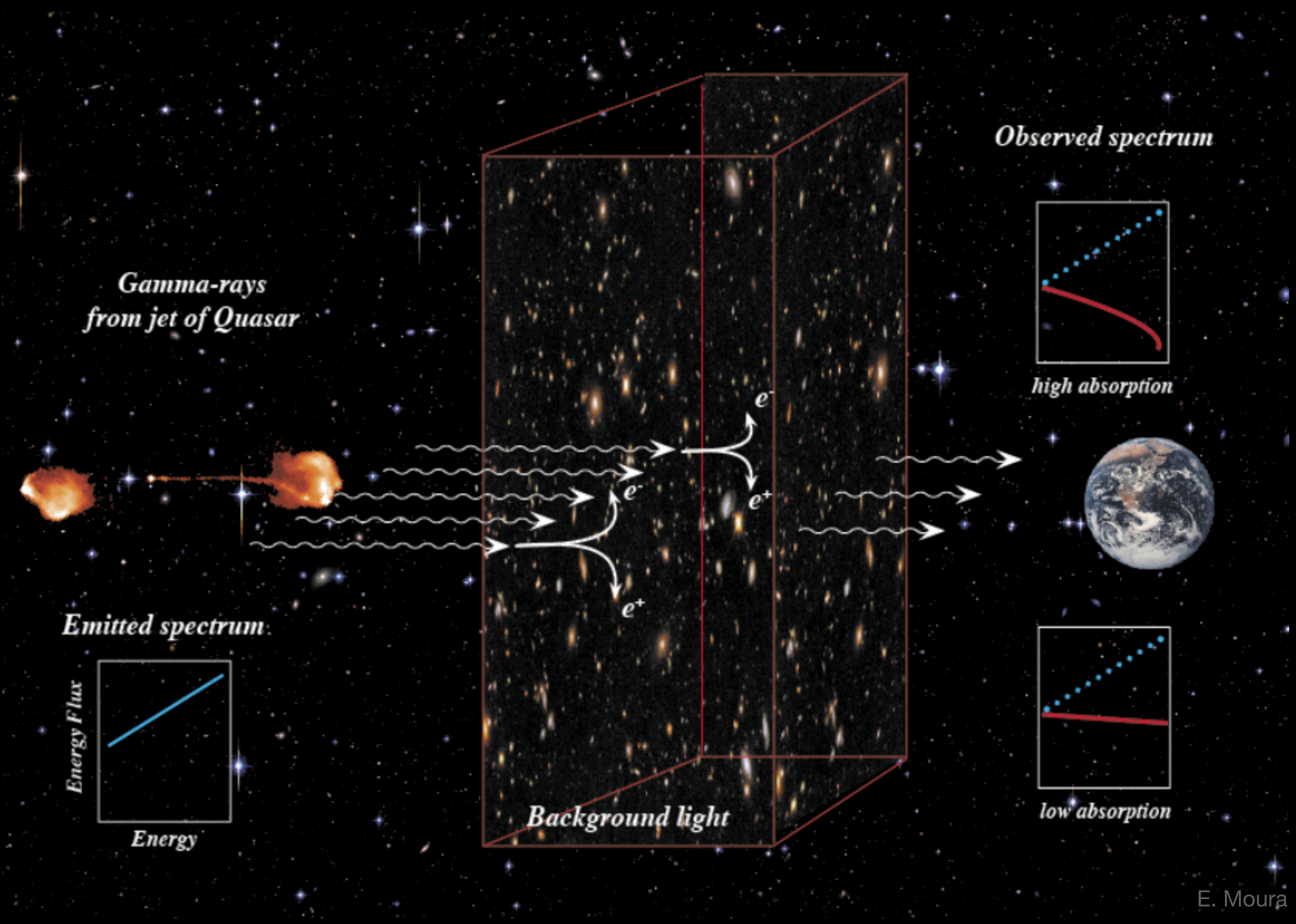
$\Lambda_n > 0$ +2nd Threshold



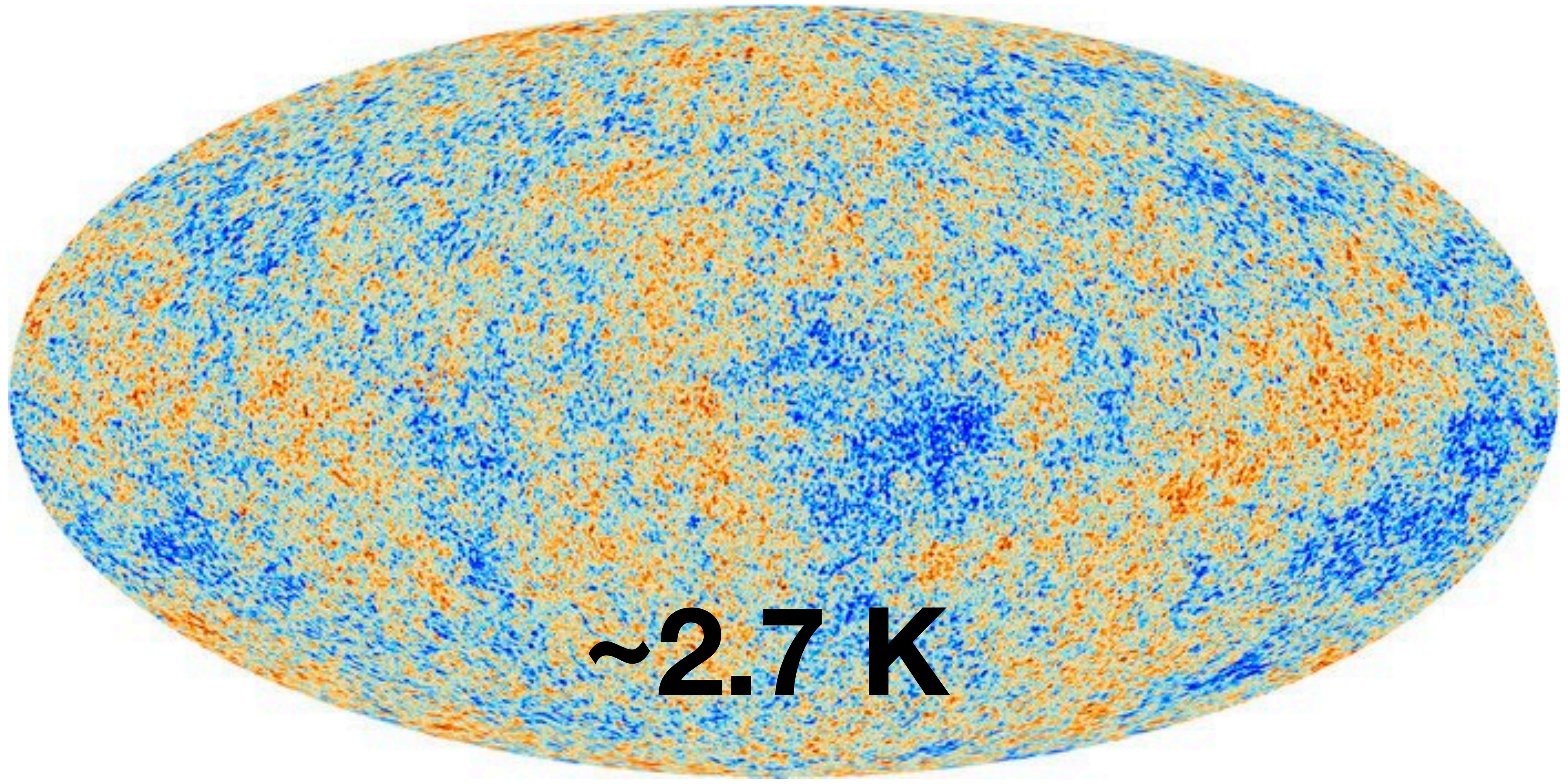
H. Martínez-Huerta, A. Pérez-Lorenzana.
Phys. Rev. D 95, 063001 (2017)

LI: Pair Production $\gamma\gamma_b \rightarrow e^+e^-$

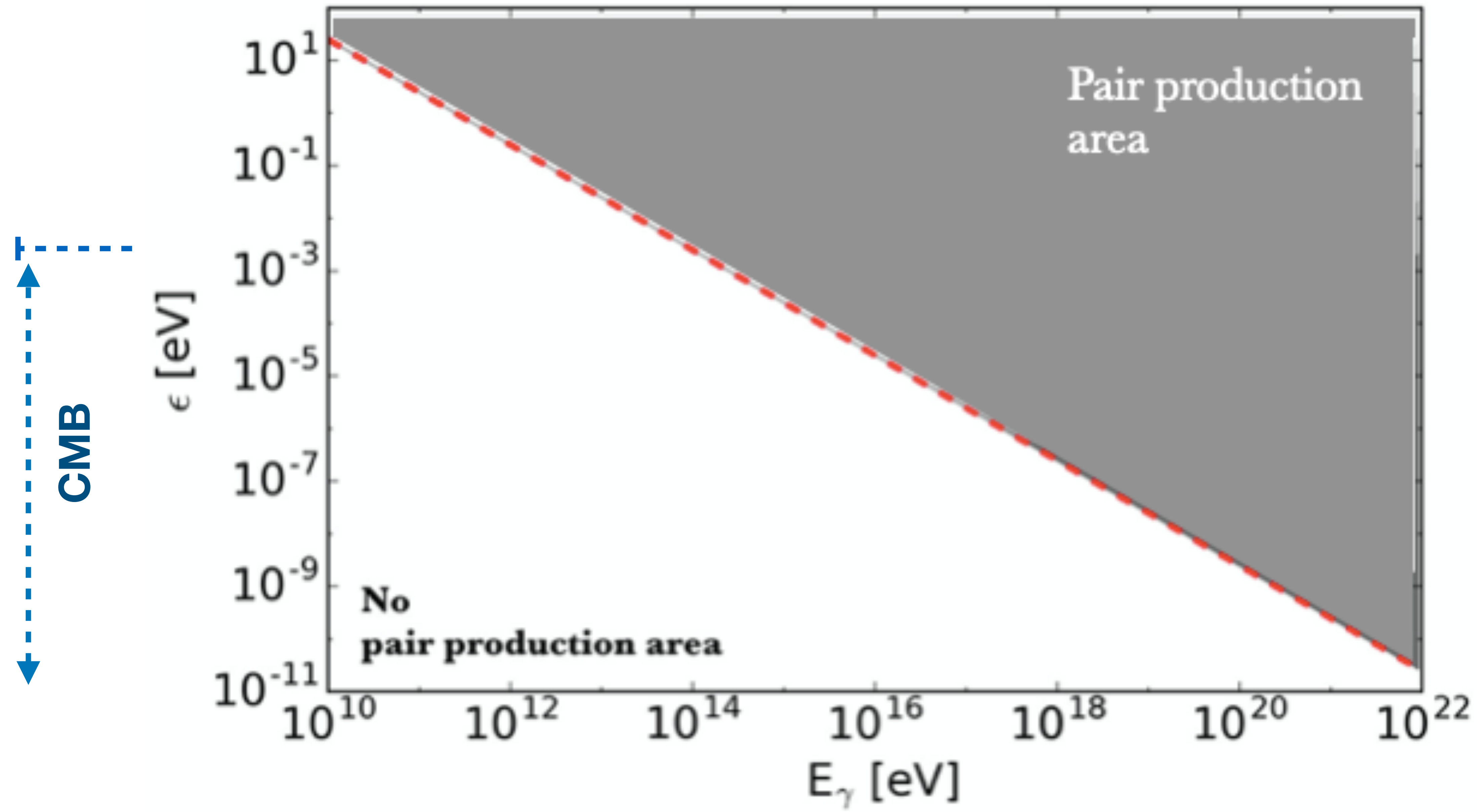



Observed spectrum
Gamma-rays
from jet of Quasar
high absorption
e-
e-
e+
e+
Emitted spectrum
Energy Flux
Energy
Background light
low absorption
E. Moura

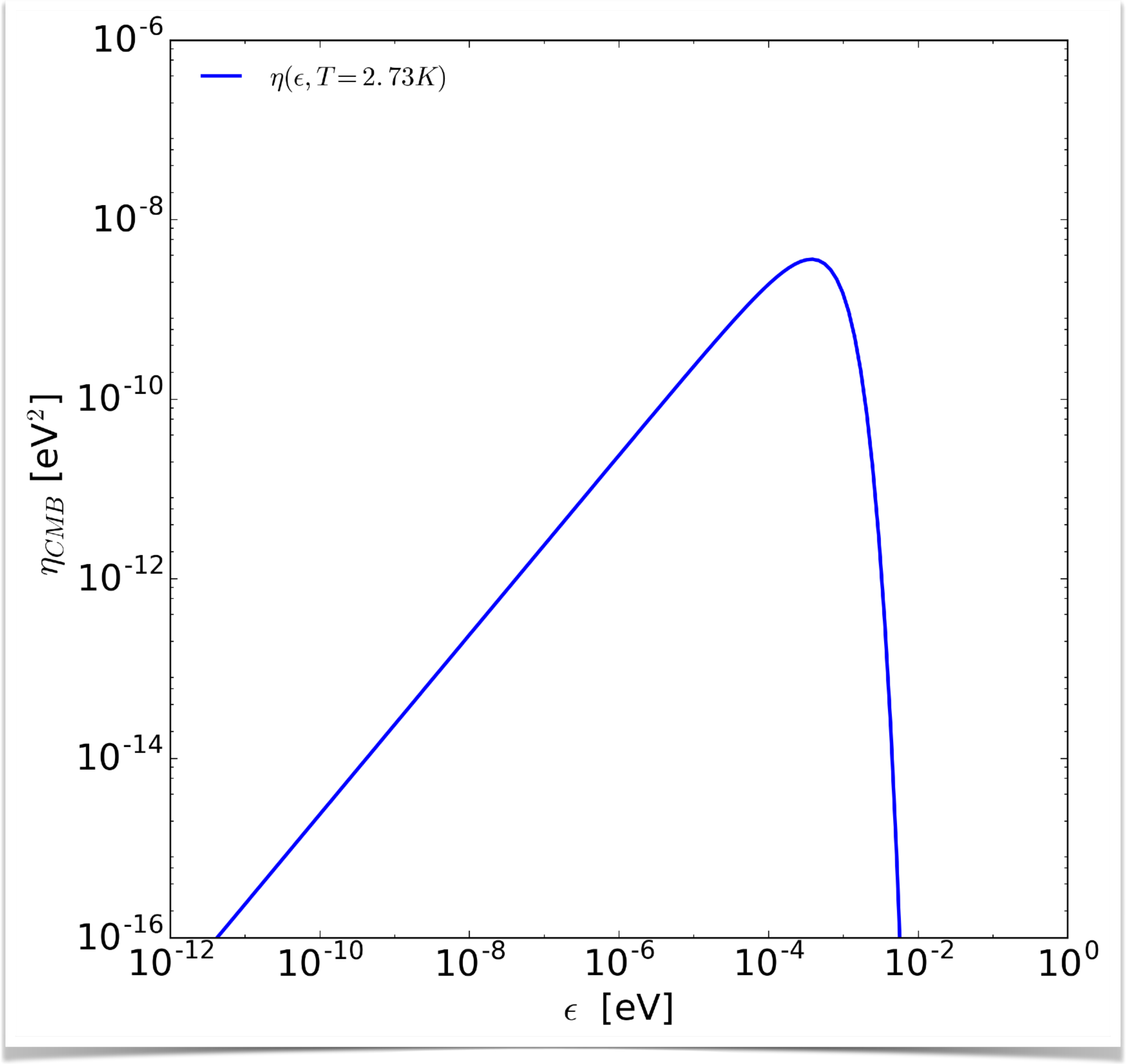
CMB



~2.7 K



CMB
Pair production area
No pair production area
ϵ [eV]
E$_\gamma$ [eV]



$\eta(\epsilon, T=2.73K)$
η_{CMB} [eV^2]
ϵ [eV]

Extragalactic Background Light (EBL)

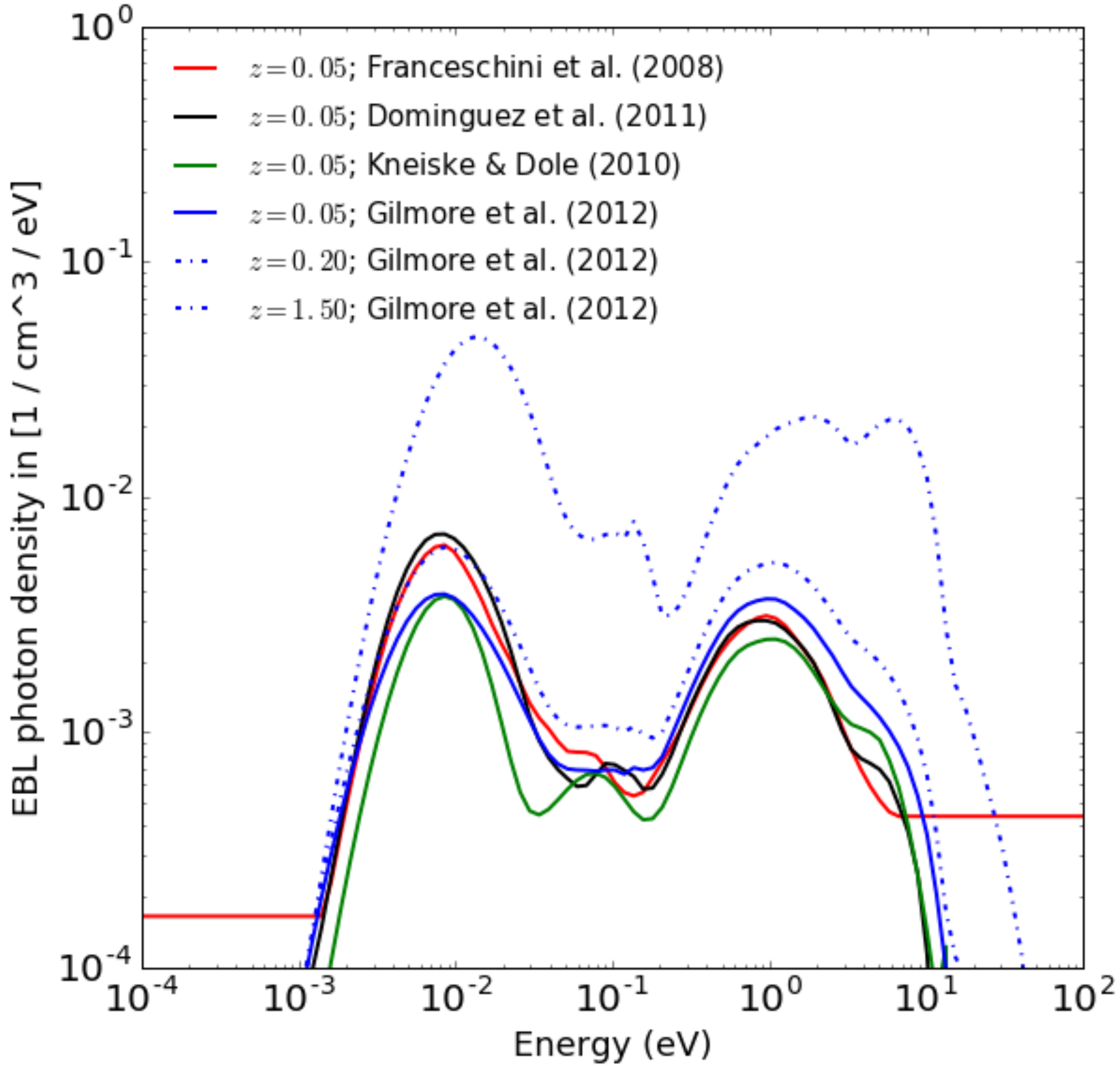
Light (0.1 -1000 μm) emitted throughout life in the Universe.

It hasn't been fully explained yet.

F*orward evolution models*: From initial conditions and extrapolated to the present.
Gilmore et al (2012)

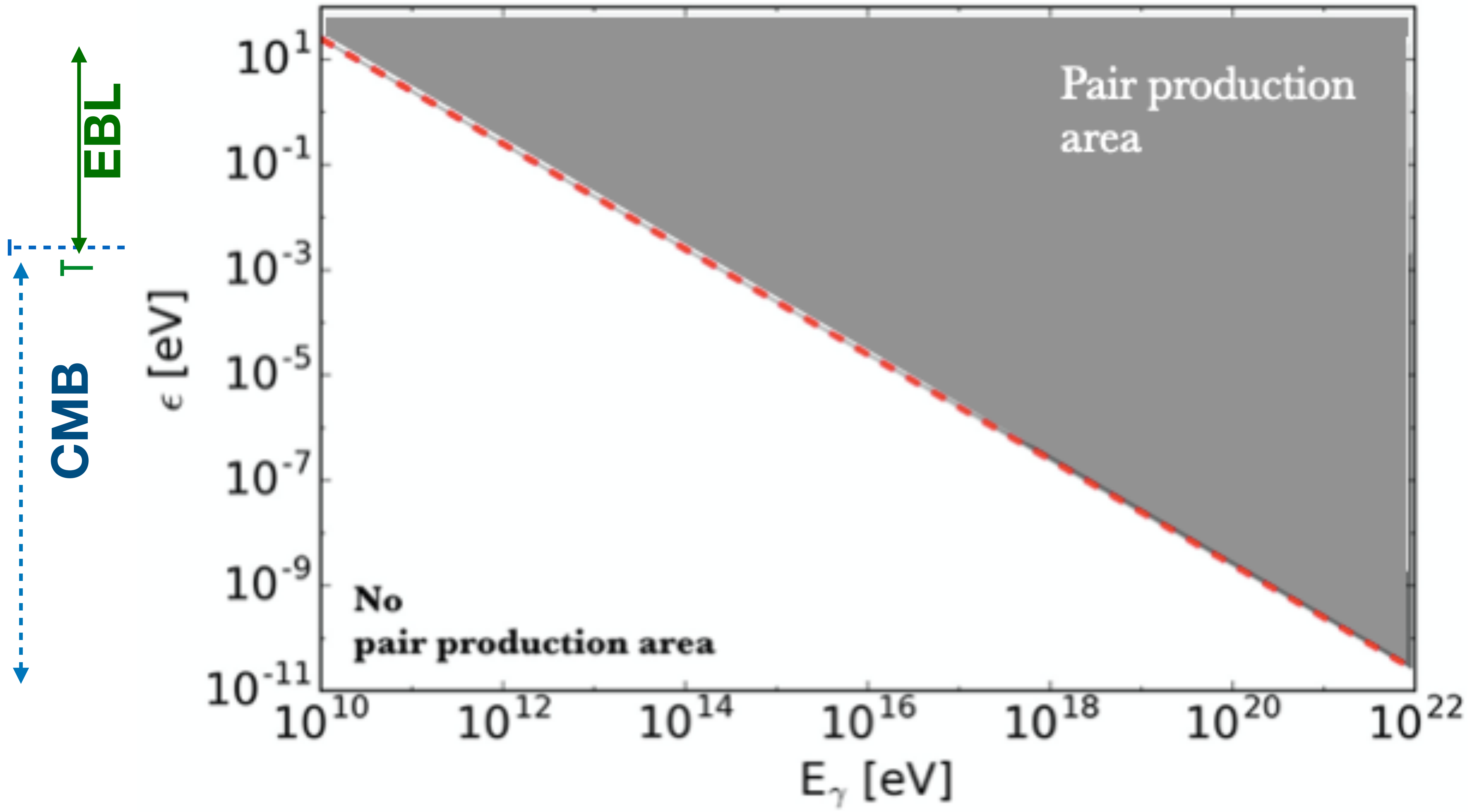
B*ackward evolution*: Extrapolates the current state of the data to the past. **Franceschini et al. (2008)**

E*mpirical models / observed evolution.* **Domínguez et al. (2011)**



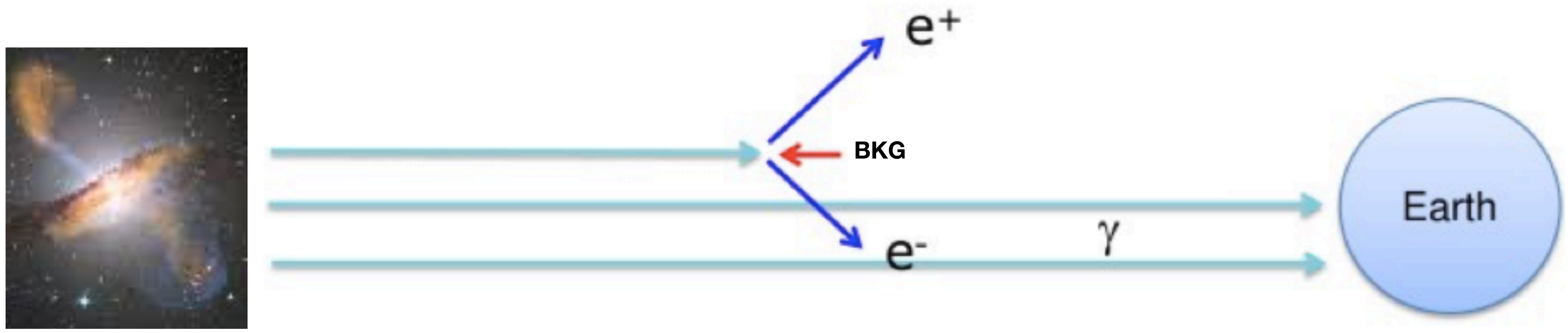
~5% of the energy density of the CMB

PP



EBL
CMB
Pair production area
No pair production area
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}

Optical Depth



$$\tau_\gamma(E_\gamma, z, n) = \int_0^{z_s} \mathrm{d}z \frac{\mathrm{d}l(z)}{\mathrm{d}z}$$

-COSMOLOGY -
The distance element

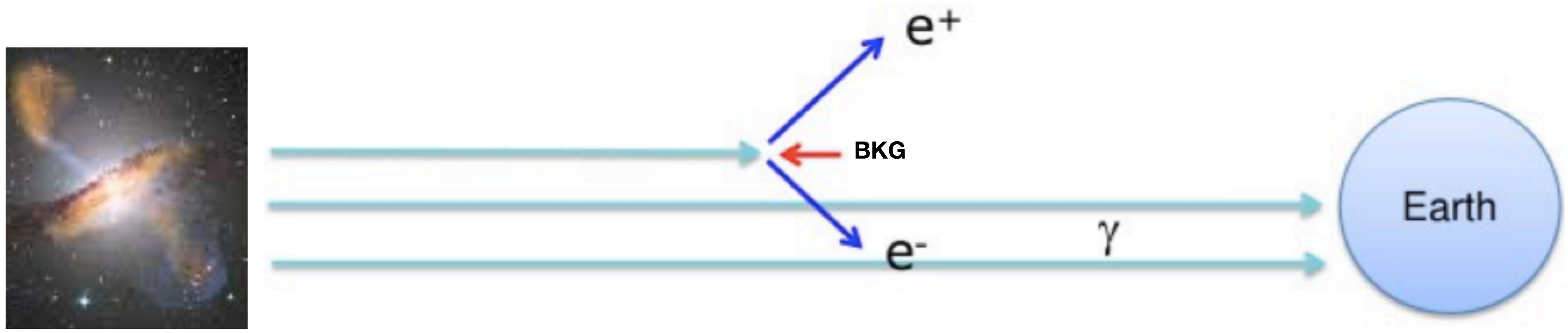
$$\times \int_{\epsilon_{th}}^{\infty} d\epsilon \; n_\gamma(\epsilon, z)$$

-ASTROPHYSICS-
Density of BKG photons

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

-PARTICLE PHYSICS-
Pair Production cross section
Breit & Wheeler 1934; Heitler 1960

Optical Depth



$$\tau_\gamma(E_\gamma, z, n) = \int_0^{z_s} \mathrm{d}z \frac{\mathrm{d}l(z)}{\mathrm{d}z}$$

$$\frac{\mathrm{d}l(z)}{\mathrm{d}z} = \frac{c}{H_0} \frac{1}{(1+z)\left[\Omega_\Lambda + \Omega_\mathrm{M}(1+z)^3\right]^{1/2}},$$

$$H_0 \simeq 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}},$$

$$\Omega_\Lambda \simeq 0.7$$

$$\Omega_\mathrm{M} \simeq 0.3$$

-COSMOLOGY -
The distance element

-ASTROPHYSICS-
Density of BKG photons

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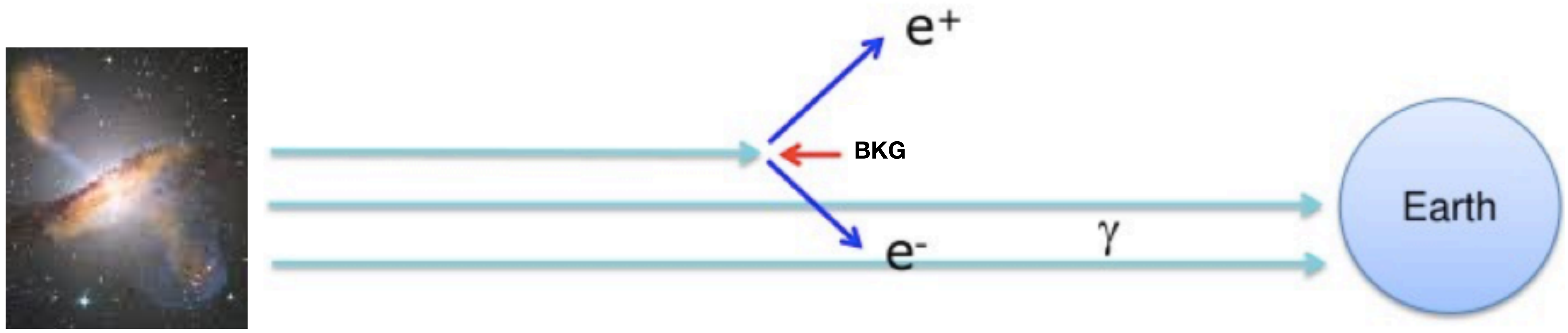
Optical Depth



Breit-Wheeler cross-section

$$\sigma_{\gamma\gamma}(E,\epsilon,\varphi)=\frac{2\pi\alpha^2}{3m_e^2}W(\beta)$$

$$\simeq 1.25\times 10^{-25}\,W(\beta)\,\mathrm{cm}^2,$$

Breit & Wheeler 1934; Heitler 1960

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

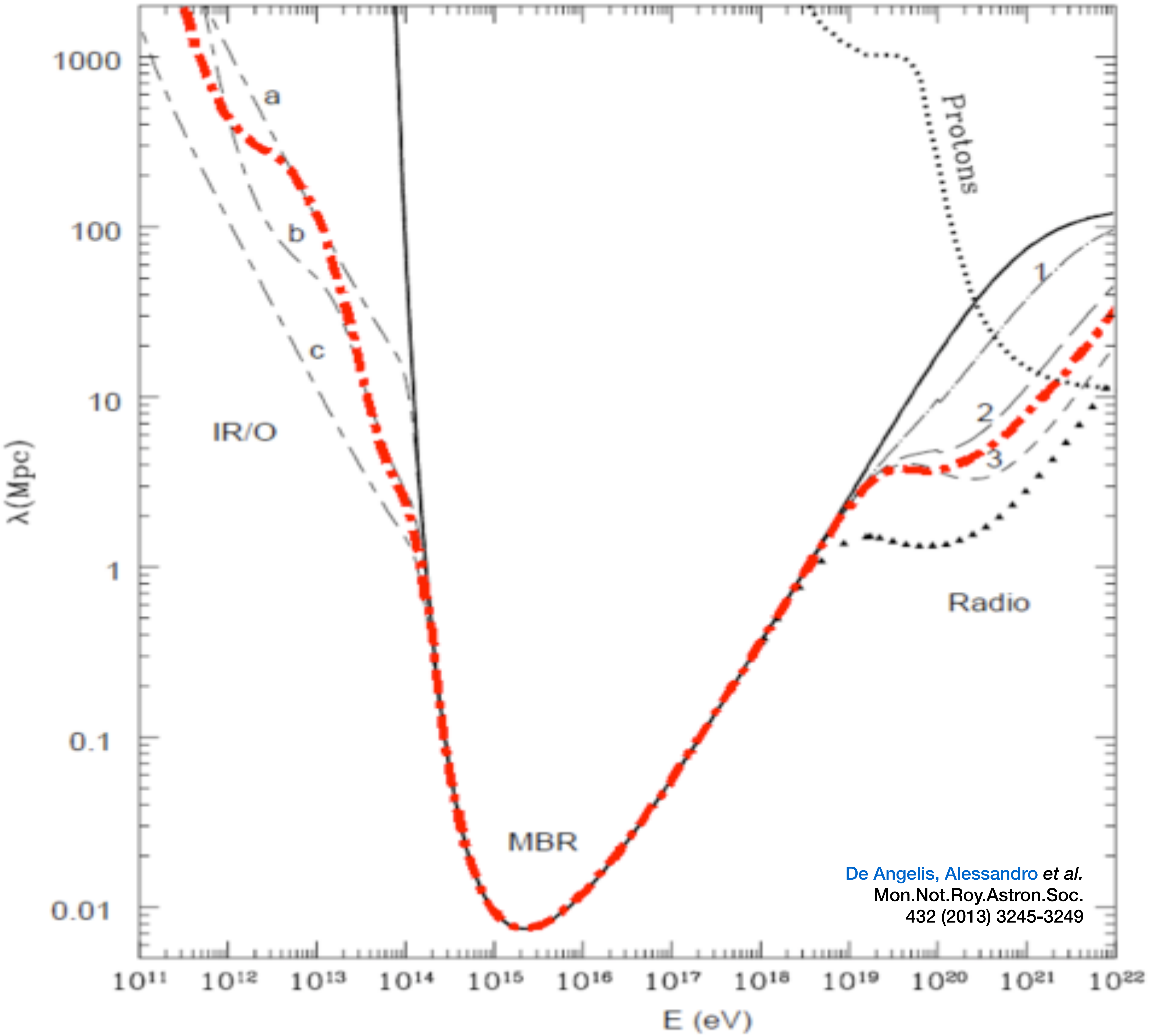
-COSMOLOGY -
The distance element

-ASTROPHYSICS-
Density of BKG photons

-PARTICLE PHYSICS-
Pair Production cross section
Breit & Wheeler 1934; Heitler 1960

Optical Depth

$\lambda = (cz)/(H_0\tau_\gamma)$

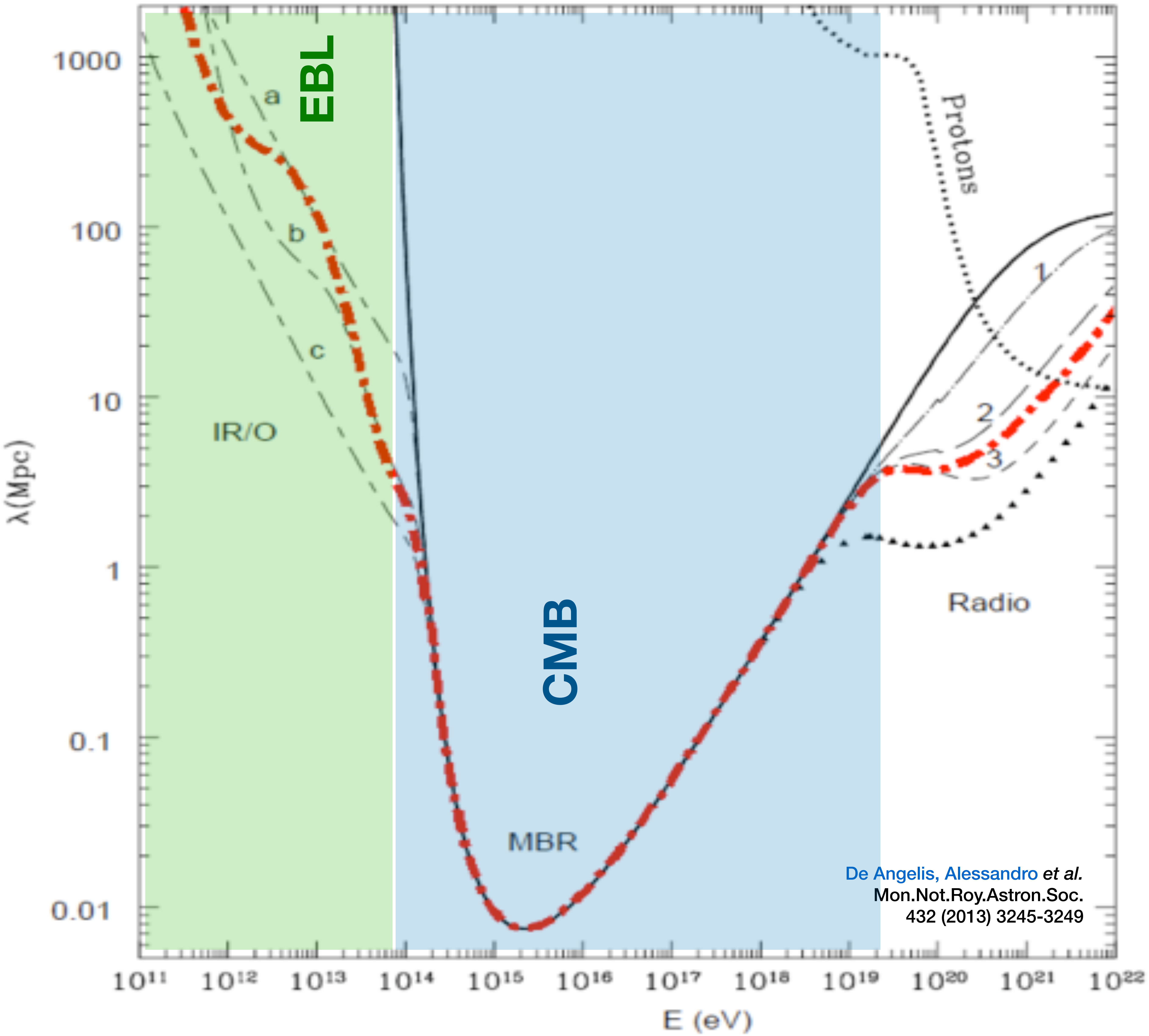


De Angelis, Alessandro *et al.*
Mon.Not.Roy.Astron.Soc.
432 (2013) 3245-3249

To the center of the Galaxy: 8.5e-6 Mph

Optical Depth

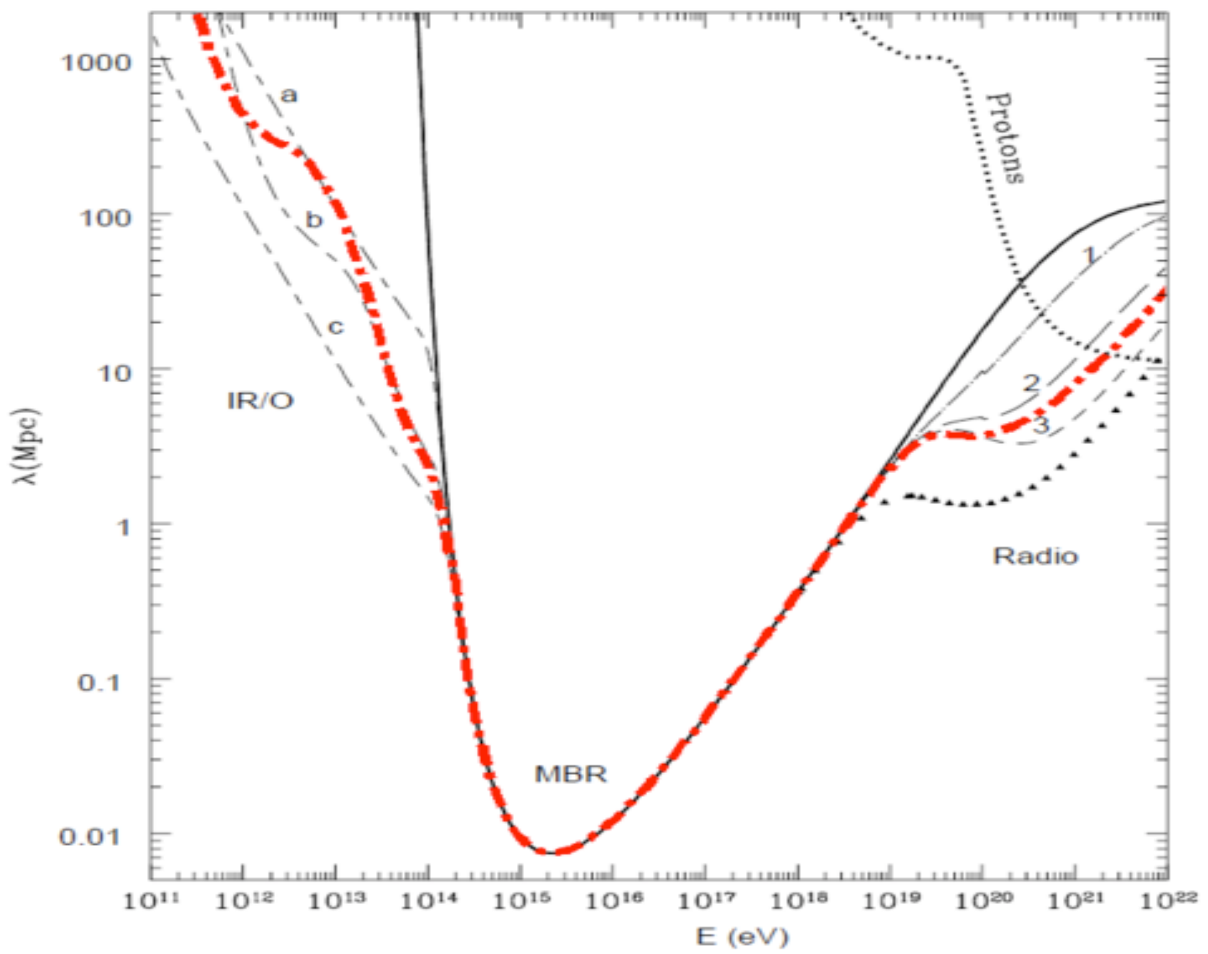
$$\lambda = (cz)/(\mathrm{H}_0\tau_\gamma)$$

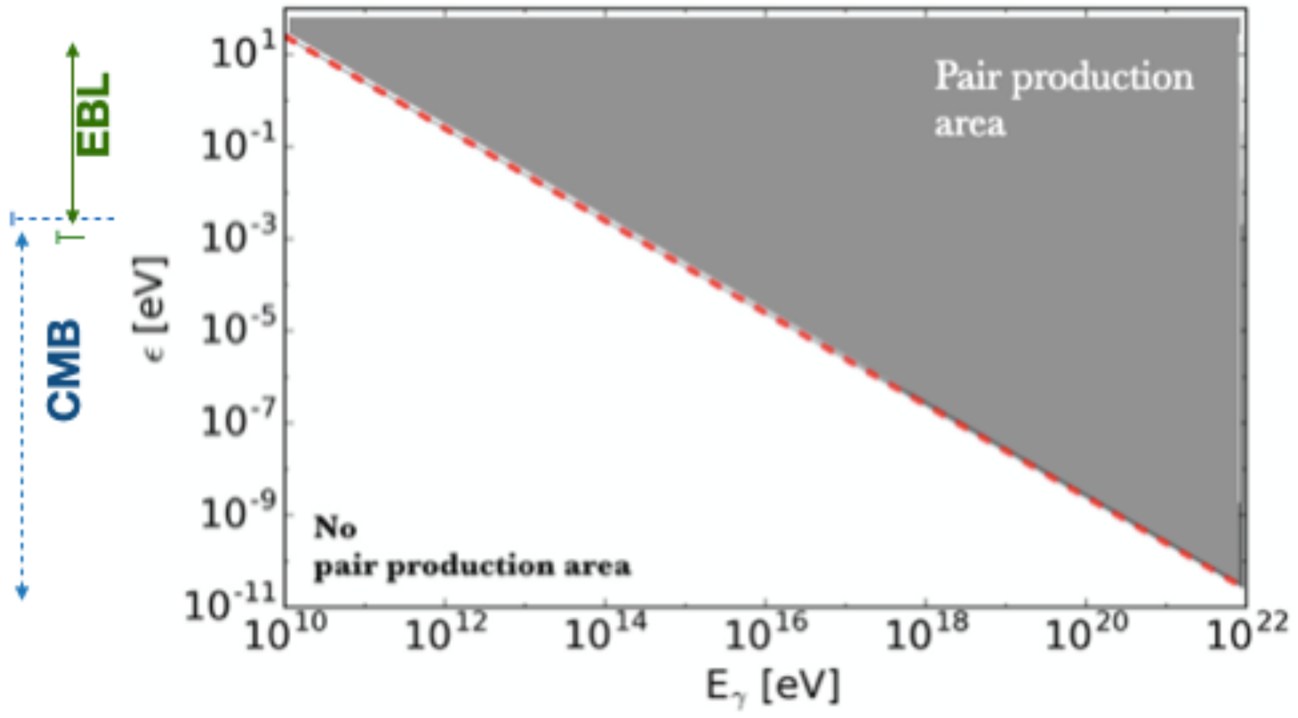


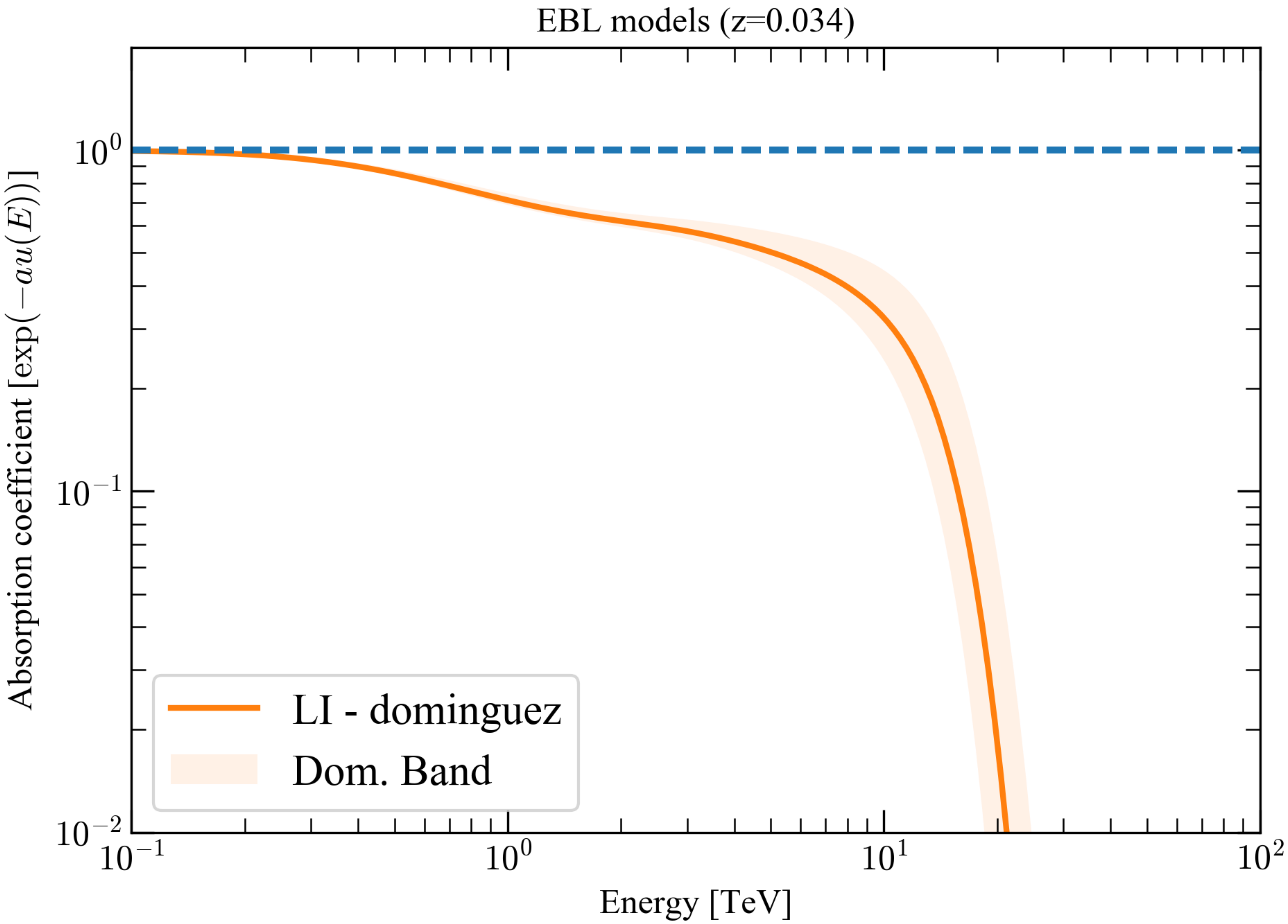
To the center of the Galaxy: 8.5e-6 Mph

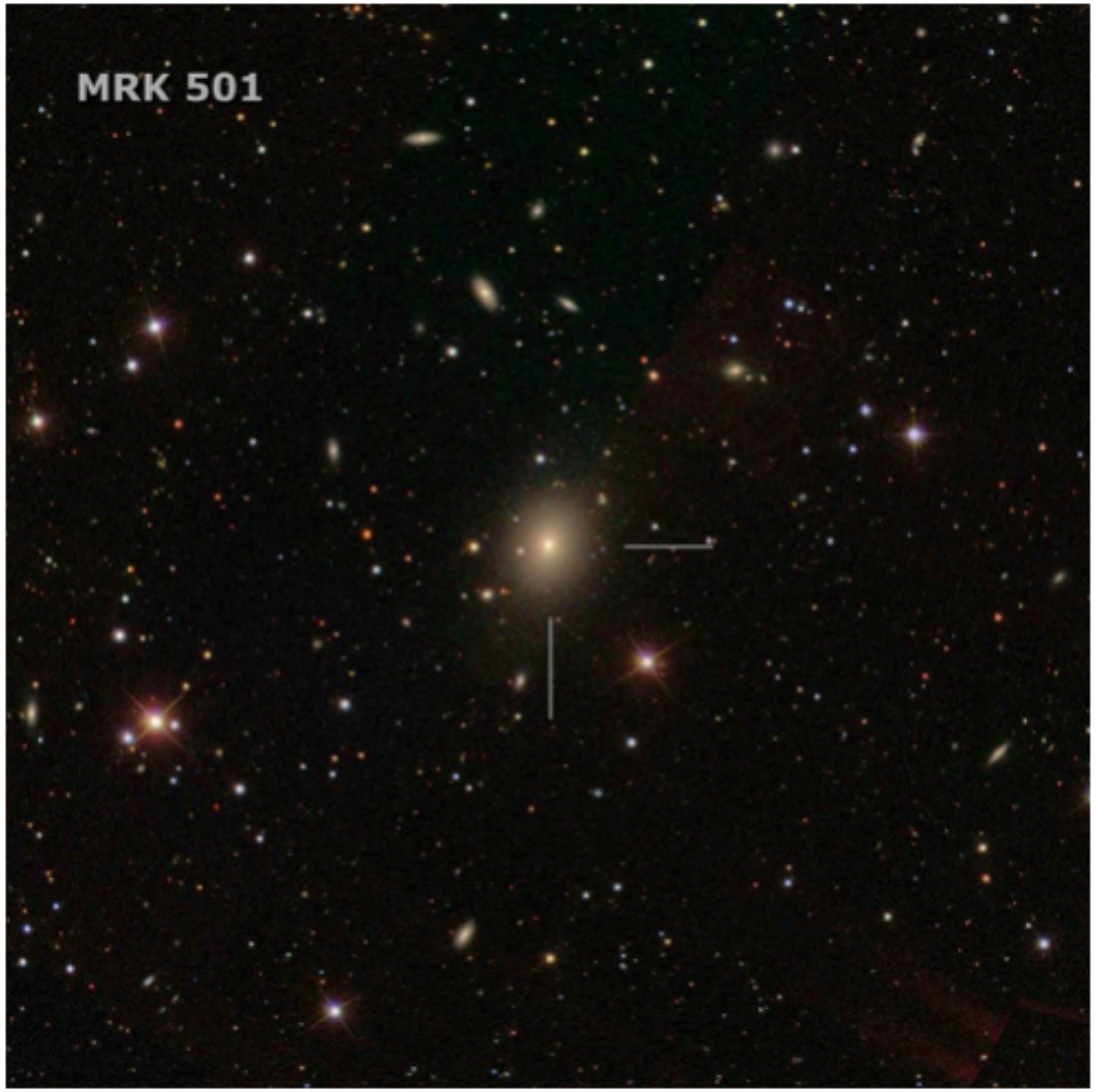
Attenuation

$$a(E, z) = e^{-\tau}(E, z)$$









RA: 253.4667
DEC: 39.7603

For a given EBL model at z=0.034

Find:

-The Optical Depth
-Attenuation

ebltable

Prerequisites

Python 3.5 or higher and the following packages:

- numpy
- scipy
- astropy

Installation

You can use pip to install the package:

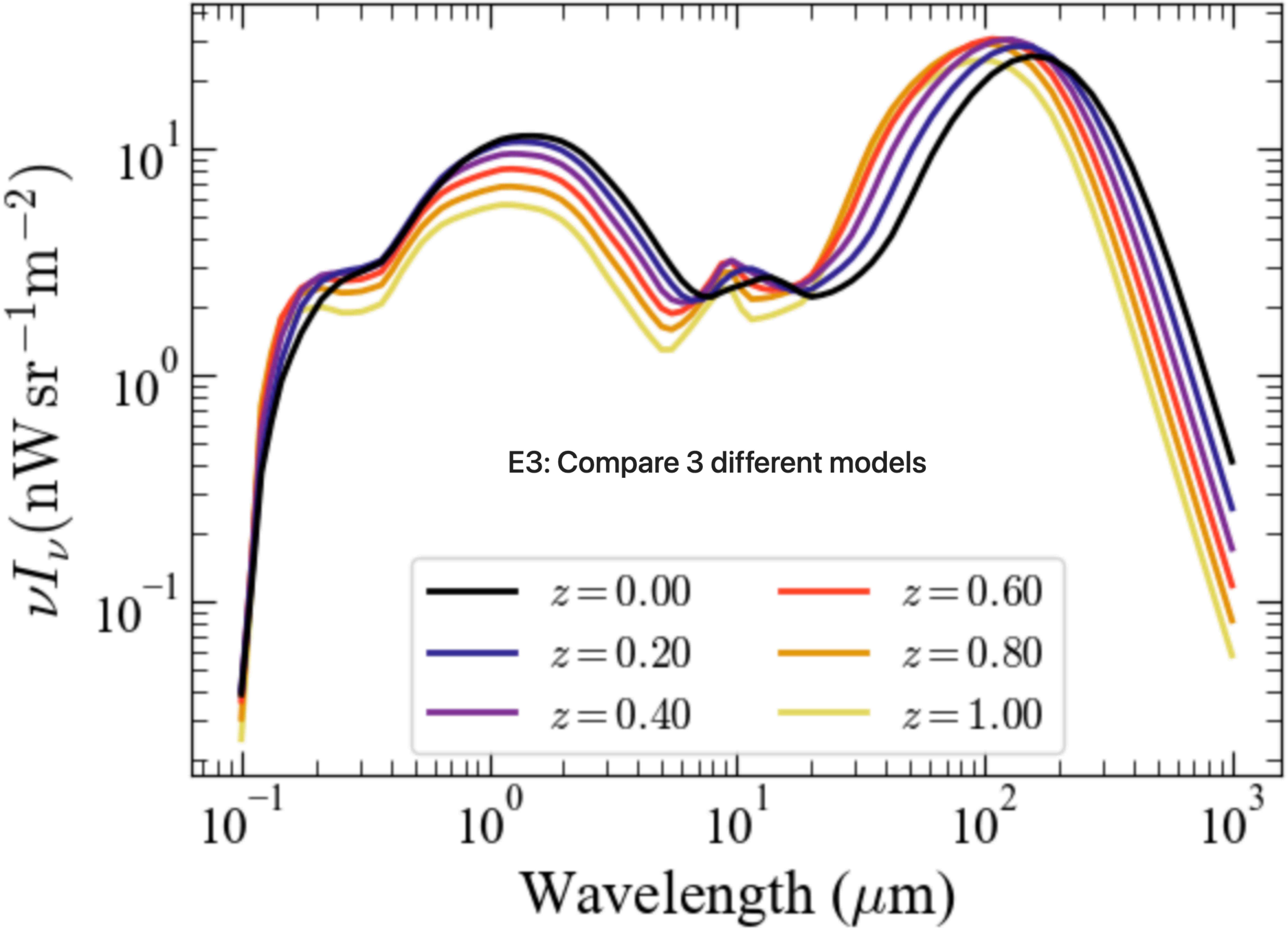
```
pip install ebltable
```

Example scripts and notebooks are provided on the github page in the example/ and notebooks/ folder, https://github.com/me-manu/ebltable

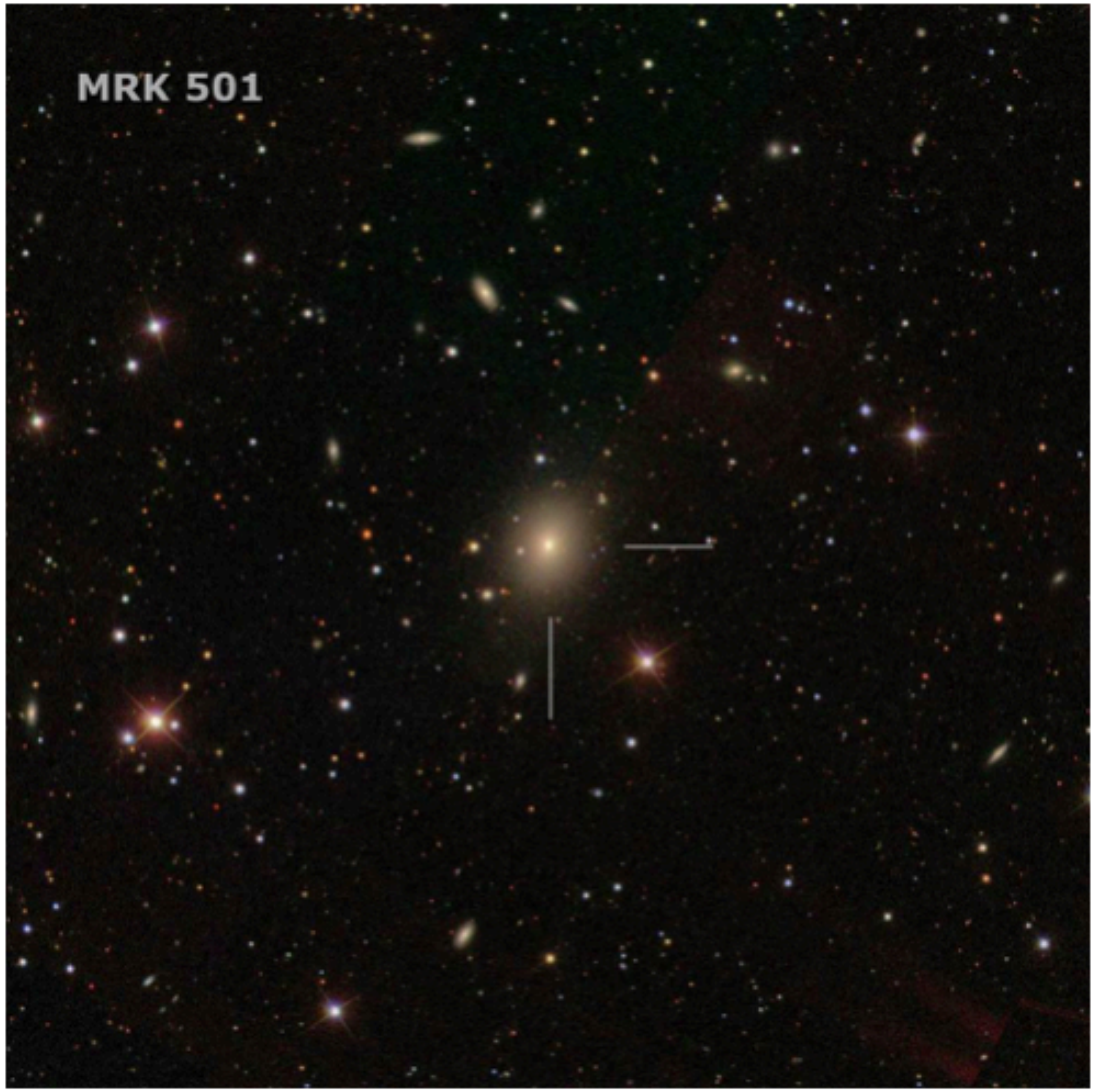
License

Available models

EBL model id	Model ref.	Web link
dominguez	Dominguez et al. (2012)	
dominguez-upper	Dominguez et al. (2012)	upper uncertainty bound
dominguez-lower	Dominguez et al. (2012)	lower uncertainty bound
franceschini	Franceschini et al. (2008)	http://www.astro.unipd.it/background/
finke	Finke et al. (2012)	http://www.phy.ohiou.edu/~finke/EBL/
finke2022	Finke et al. (2022)	https://zenodo.org/record/702307
saldana-lopez	Saldana-Lopez et al. (2021)	https://www.ucm.es/blazars/ebl
saldana-lopez-err	Saldana-Lopez et al. (2021) uncertainties	https://www.ucm.es/blazars/ebl
kneiske	Kneiske & Dole (2010)	
gilmore	Gilmore et al. (2012)	fiducial model
gilmore-fixed	Gilmore et al. (2012)	fixed model
inoue	Inuoe et al. (2013)	http://www.slac.stanford.edu/~yinoue/Download.html
inoue-low-pop3	Inuoe et al. (2013)	Low pop 3 contribution http://www.slac.stanford.edu/~yinoue/Download.html
inoue-up-pop3	Inuoe et al. (2013)	High pop 3 contribution http://www.slac.stanford.edu/~yinoue/Download.html
cuba	Haardt & Madau (2012)	http://www.ucolick.org/~pmadau/CUBA/HOME.html



E3: Compare 3 different models



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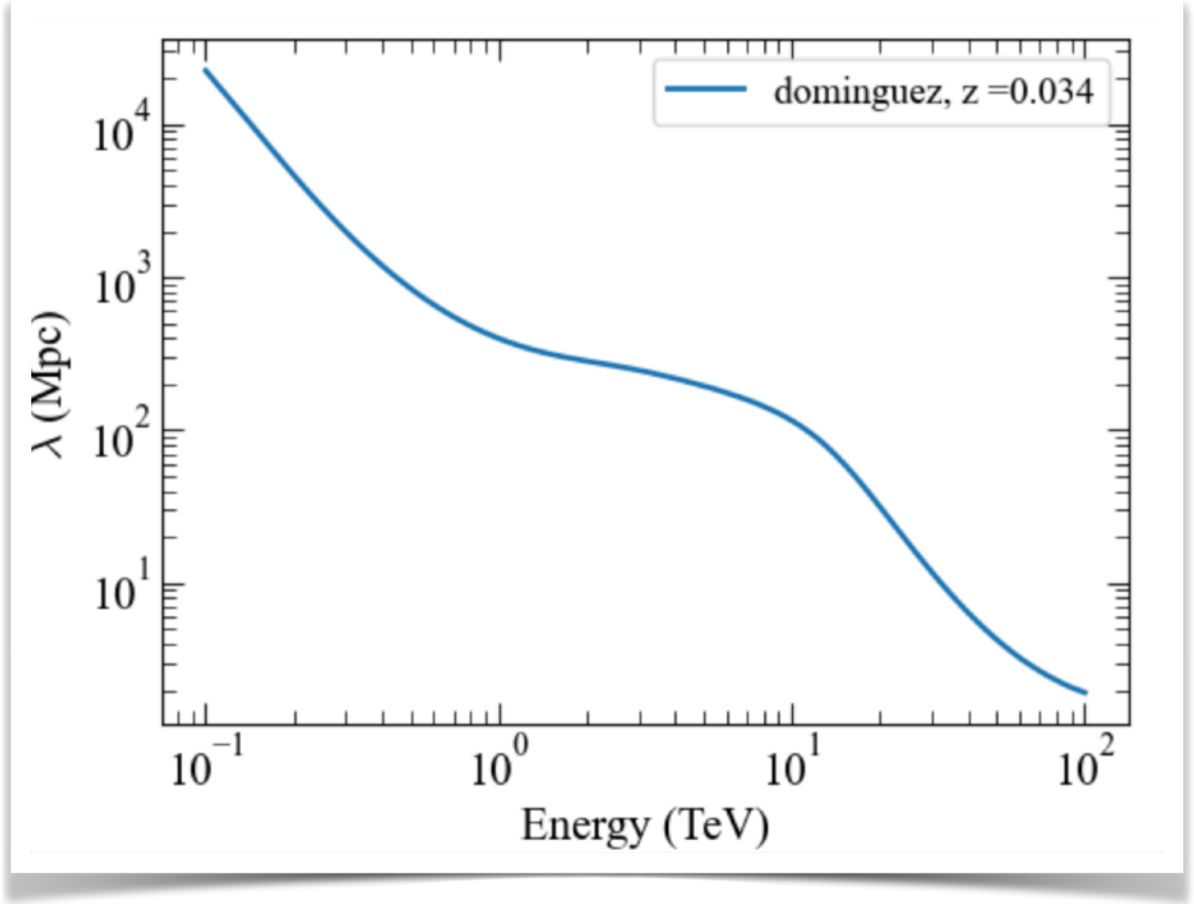
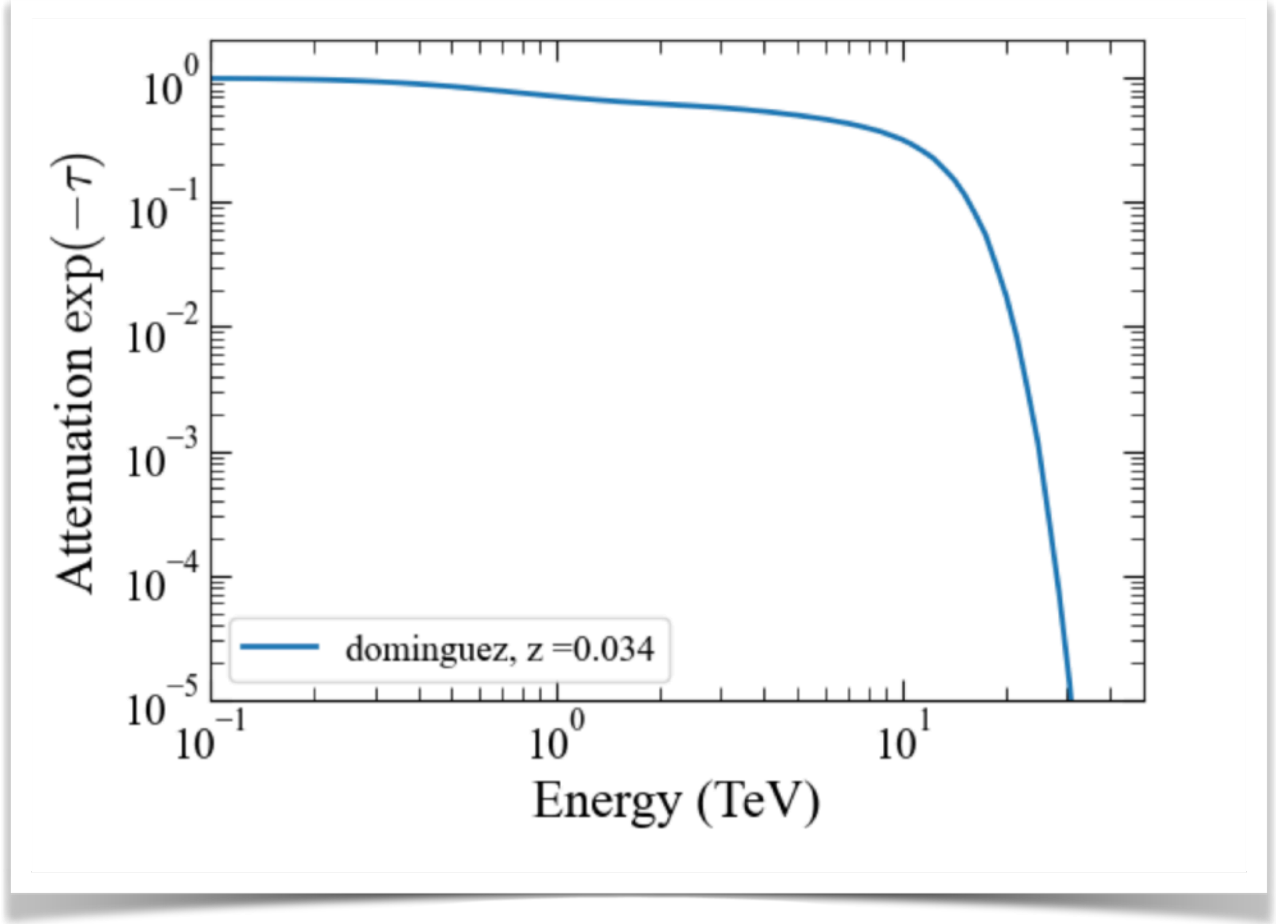
For a given EBL model at z=0.034

Find:

-The Optical Depth
-Attenuation





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inoue	Inuoe et al. (2013)	http://www.slac.stanford.edu/~yinoue/Download.html
inoue-low-pop3	Inuoe et al. (2013)	Low pop 3 contribution http://www.slac.stanford.edu/~yinoue/Download.html
inoue-up-pop3	Inuoe et al. (2013)	High pop 3 contribution http://www.slac.stanford.edu/~yinoue/Download.html
cuba	Haardt & Madau (2012)	http://www.ucolick.org/~pmadau/CUBA/HOME.html

Attenuation

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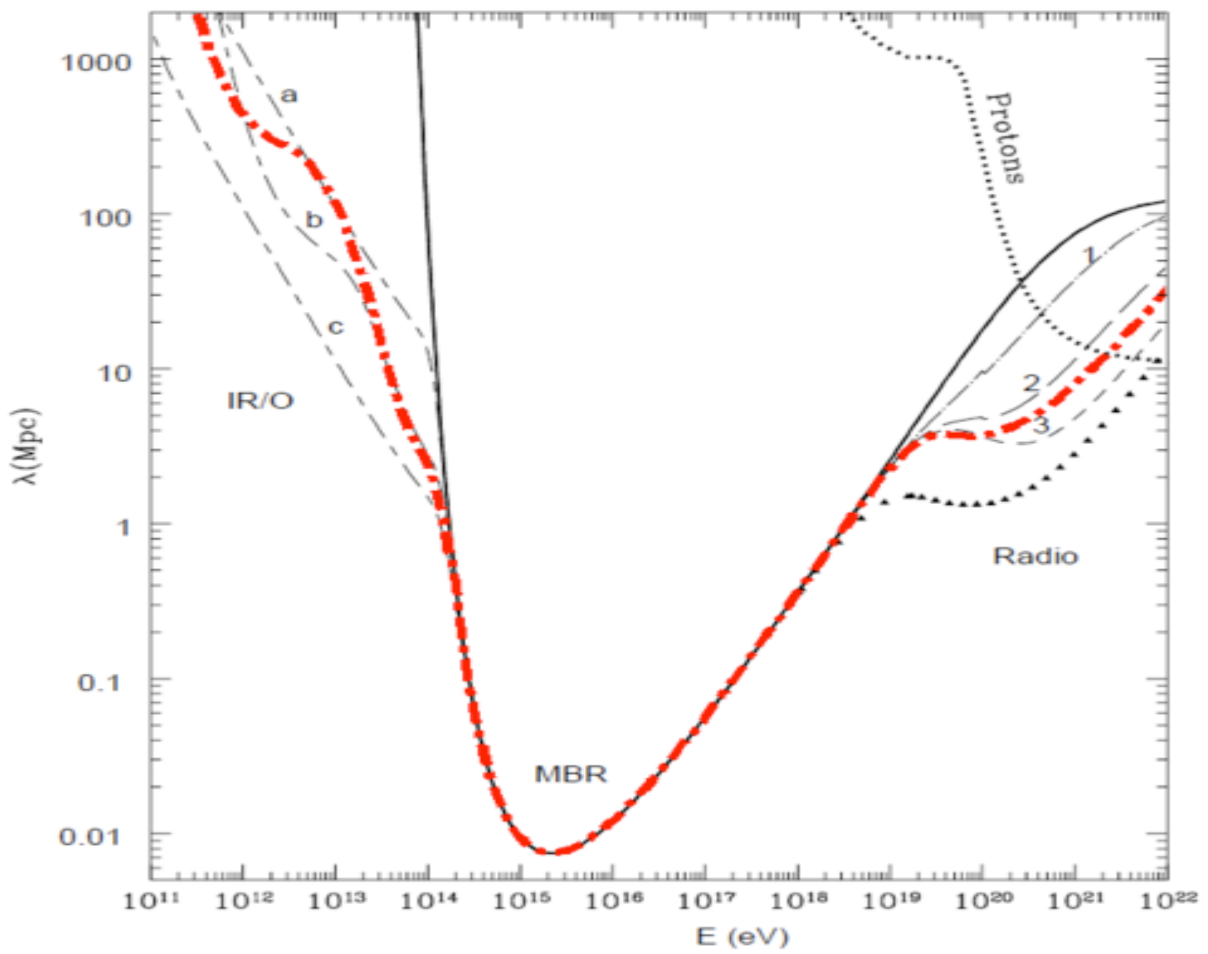

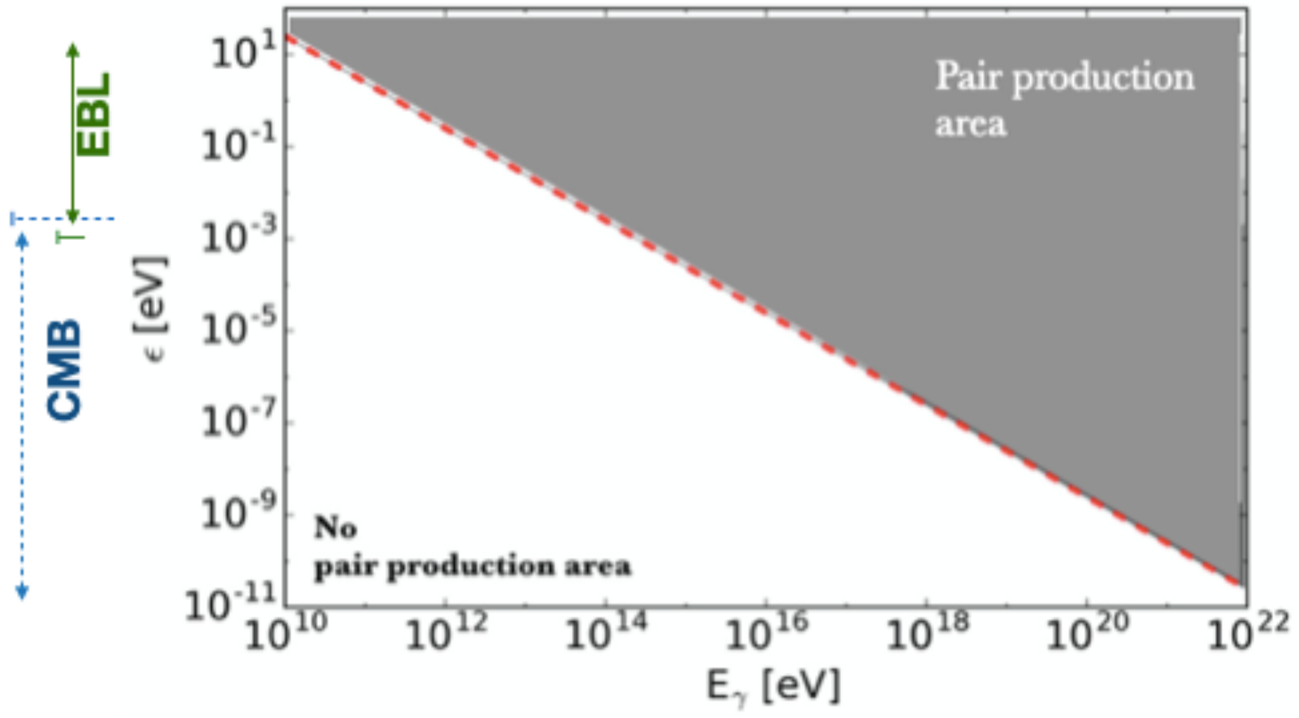

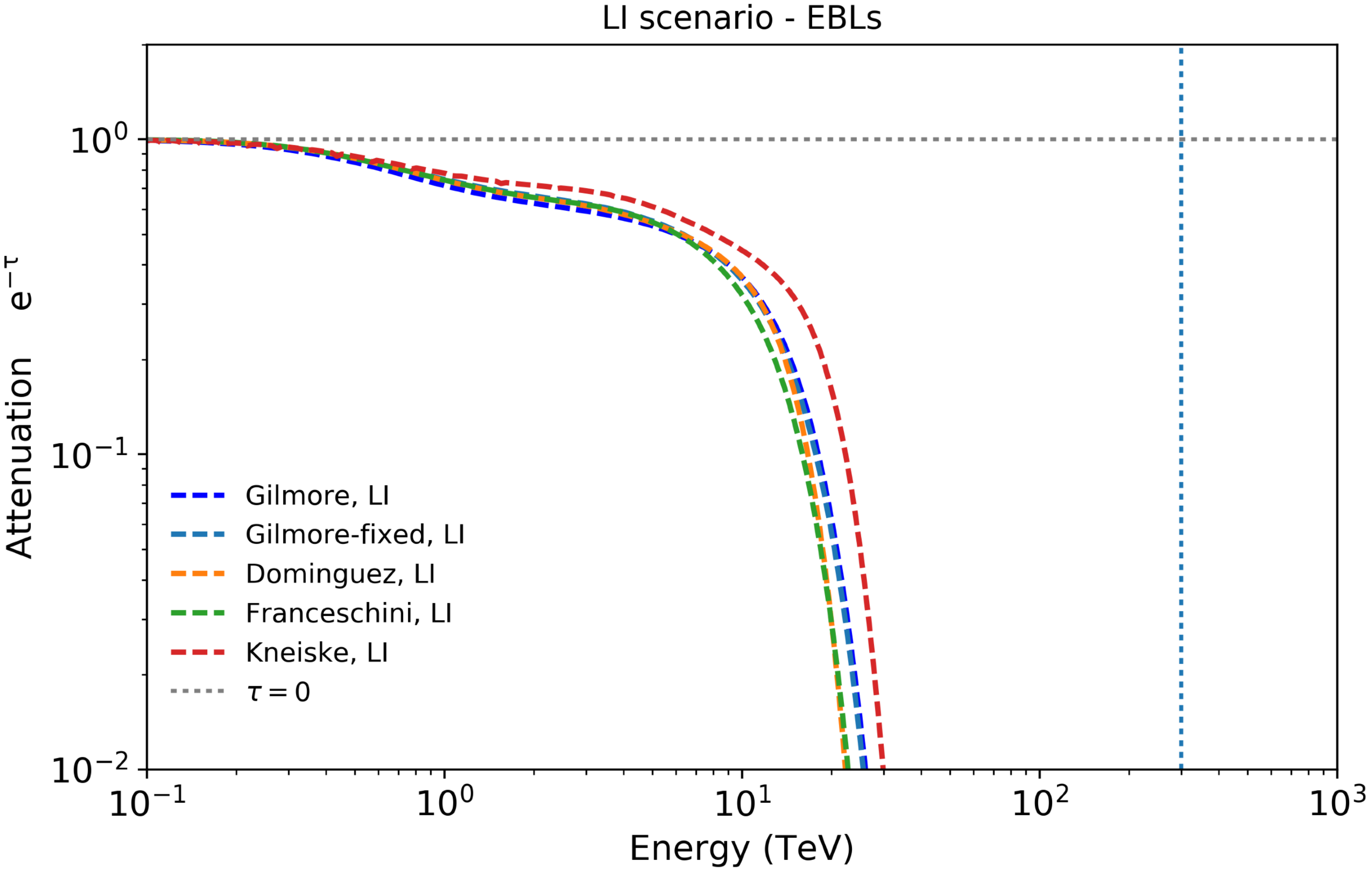

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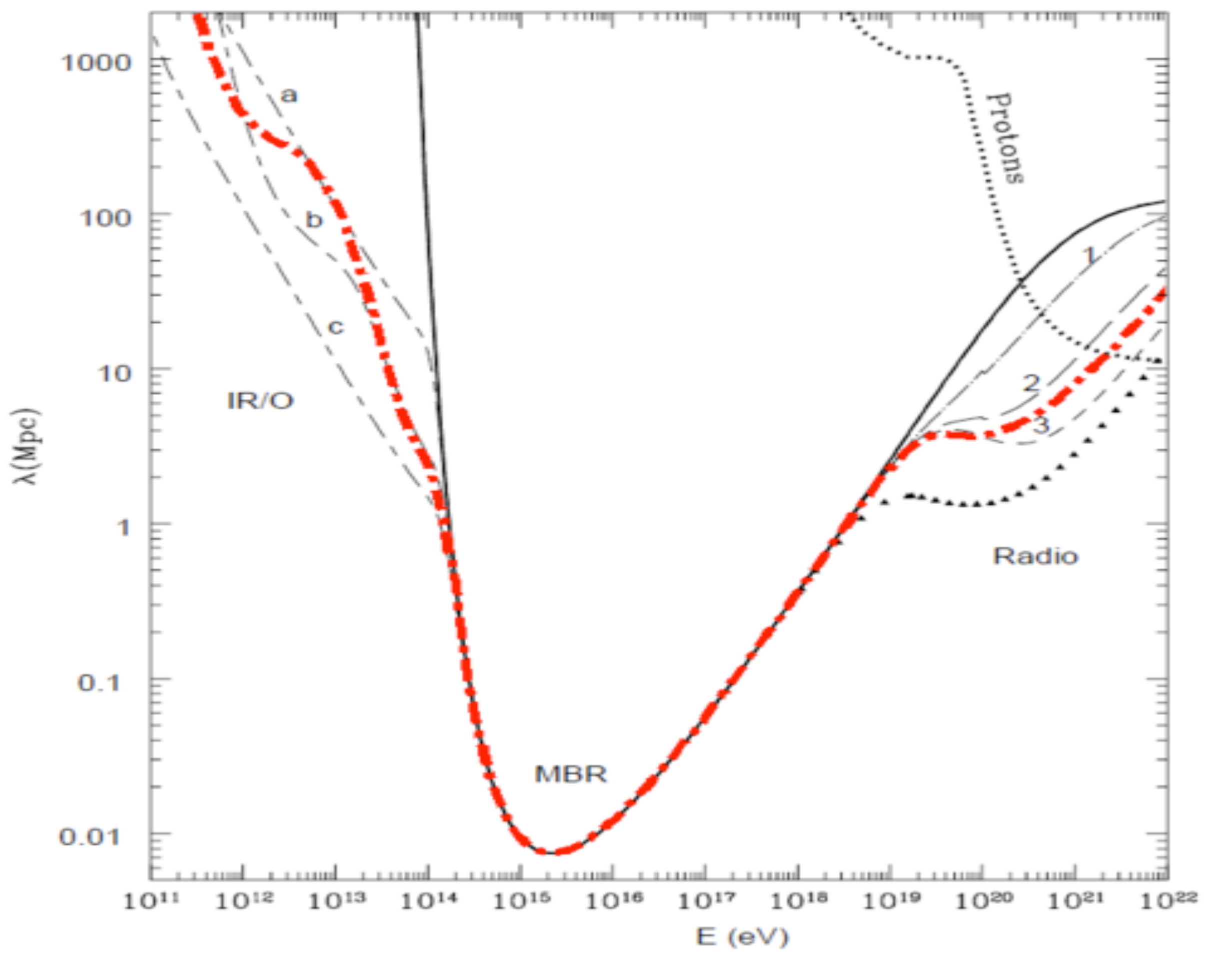
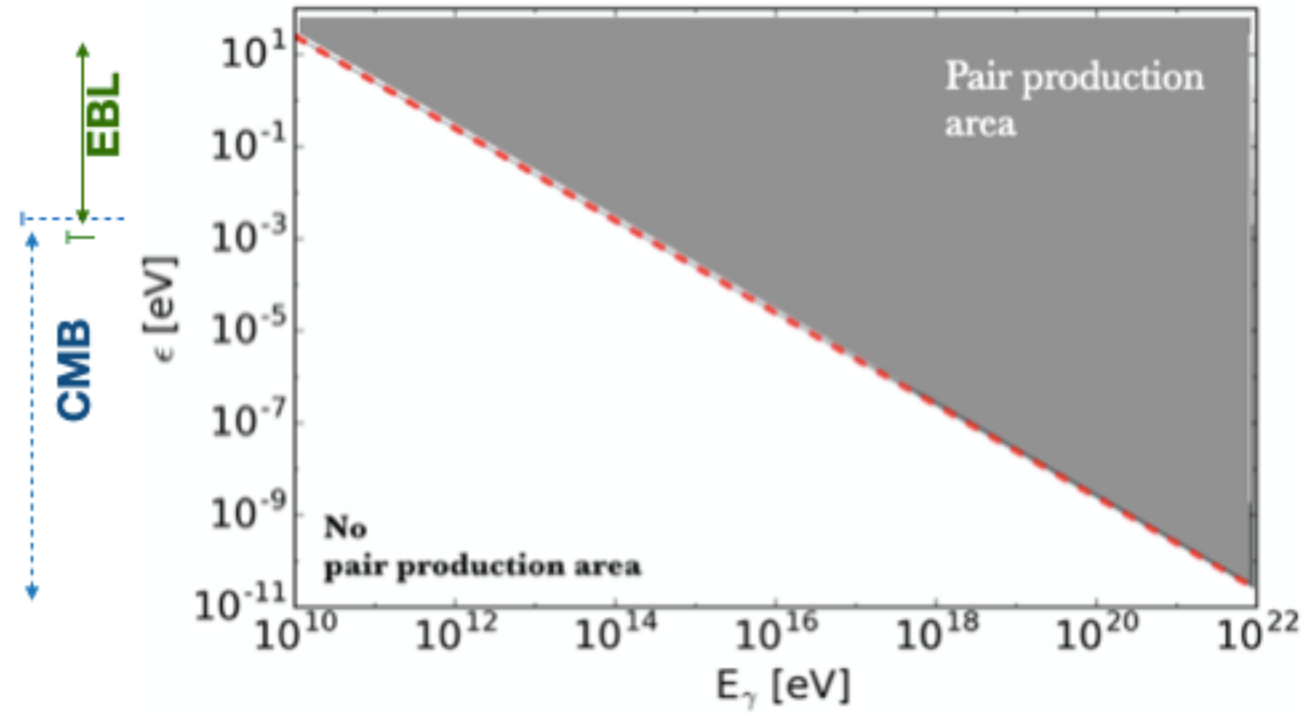
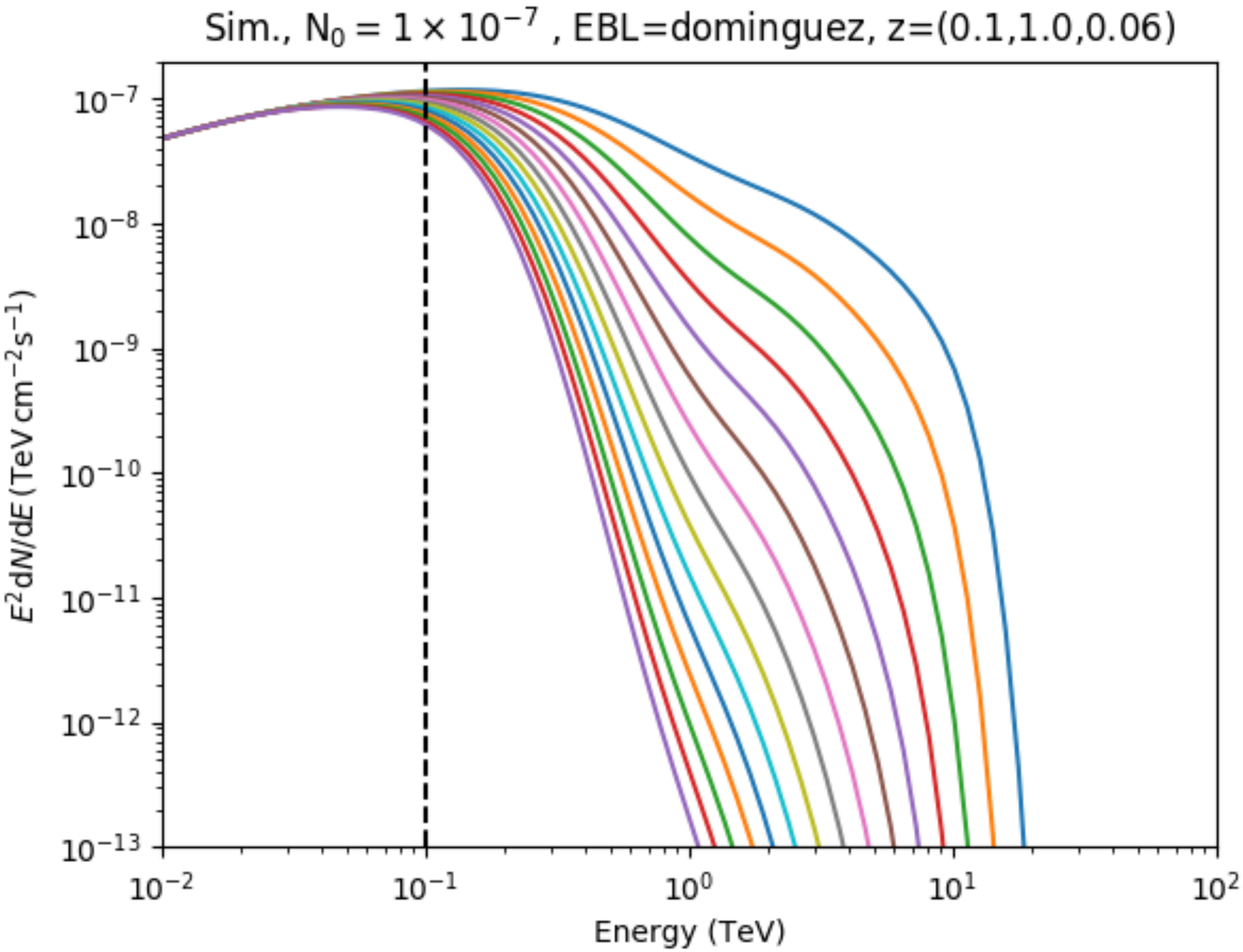
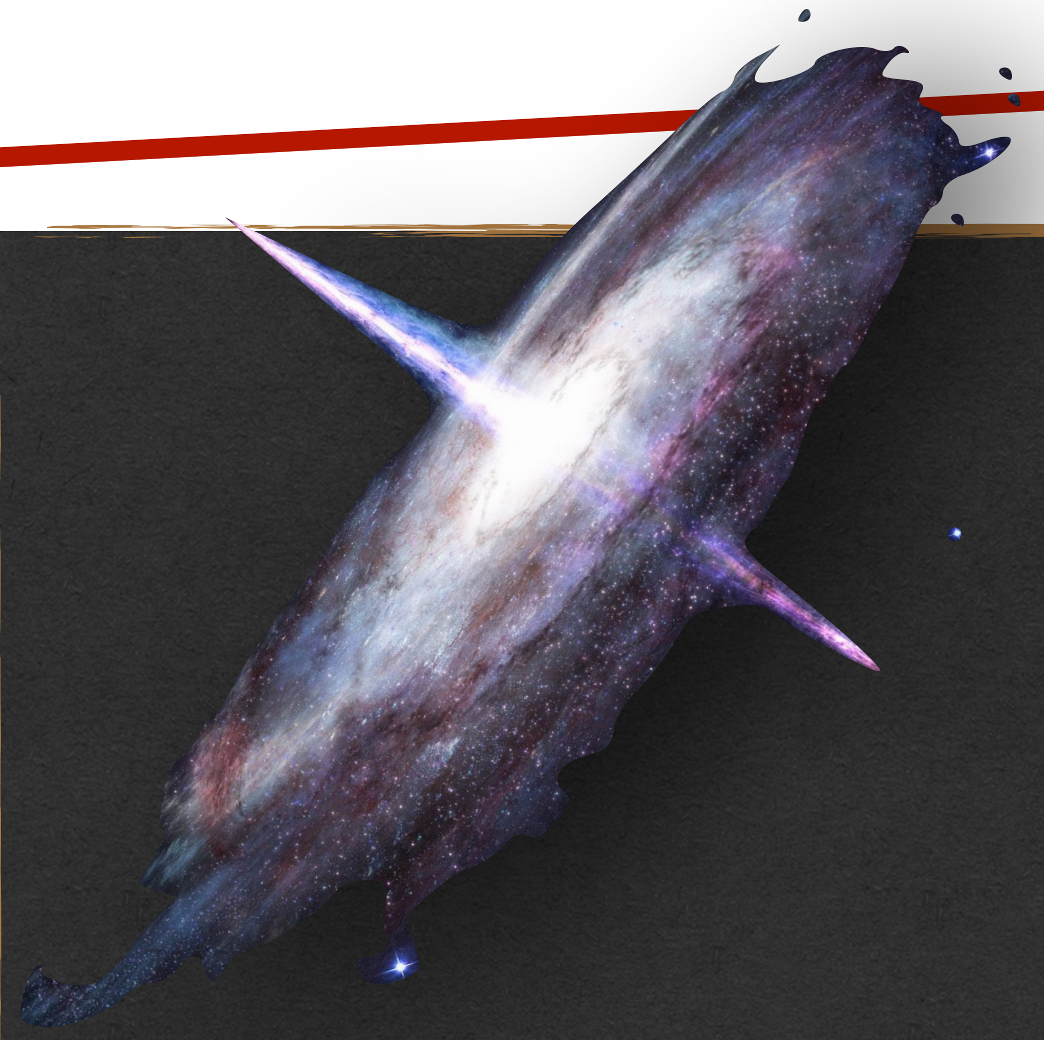
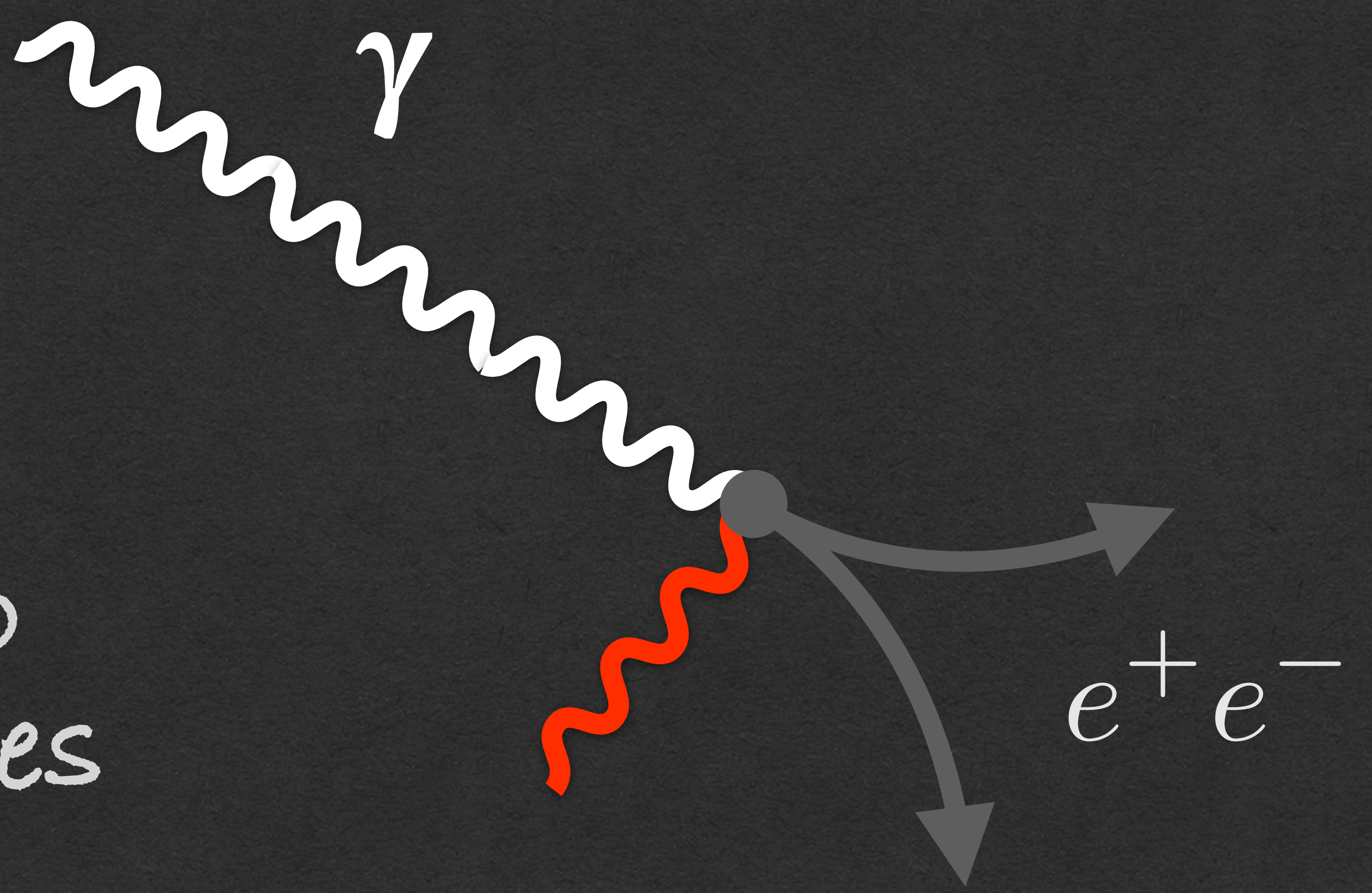






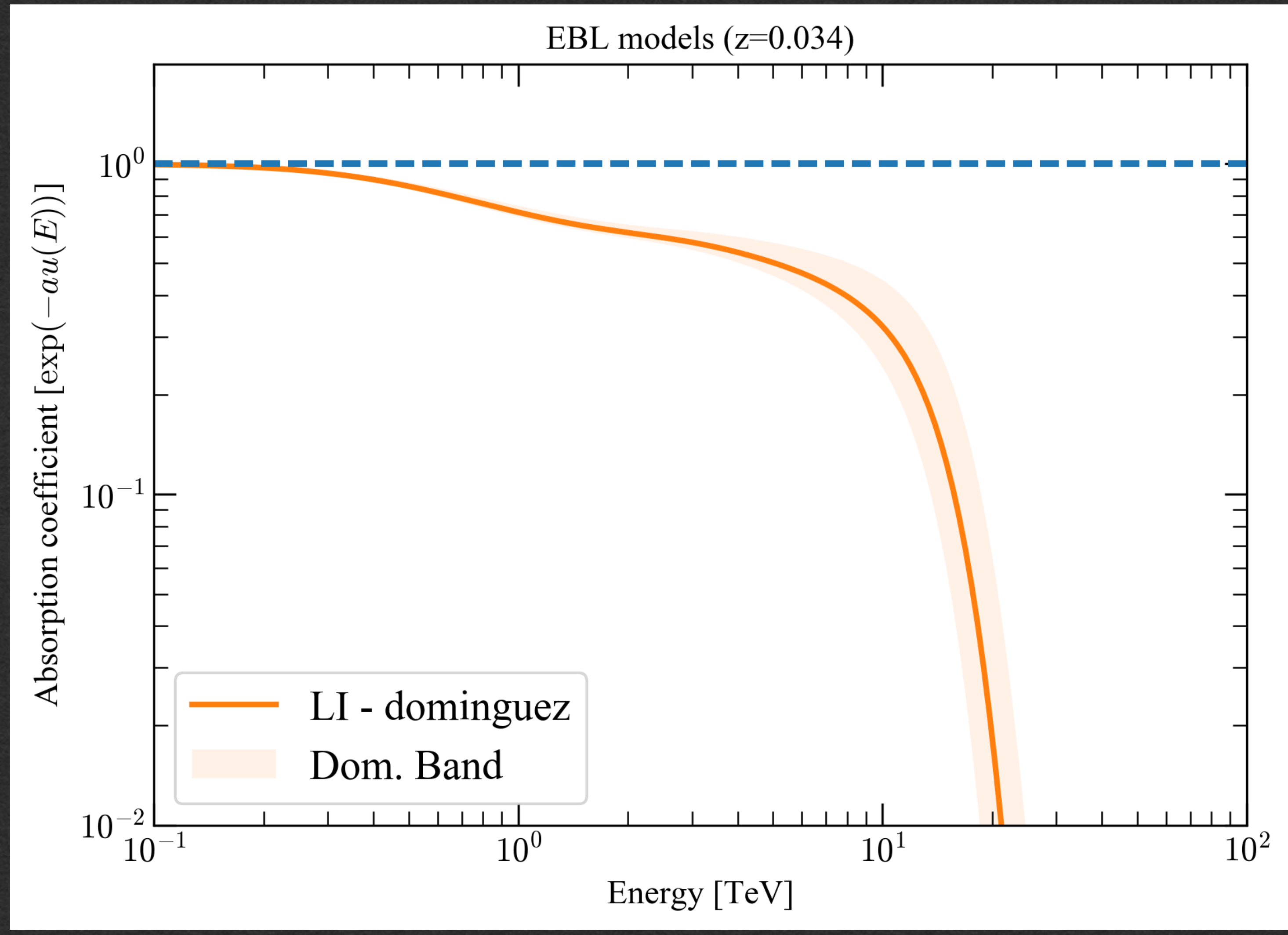
~~Test of Lorentz invariance violation~~

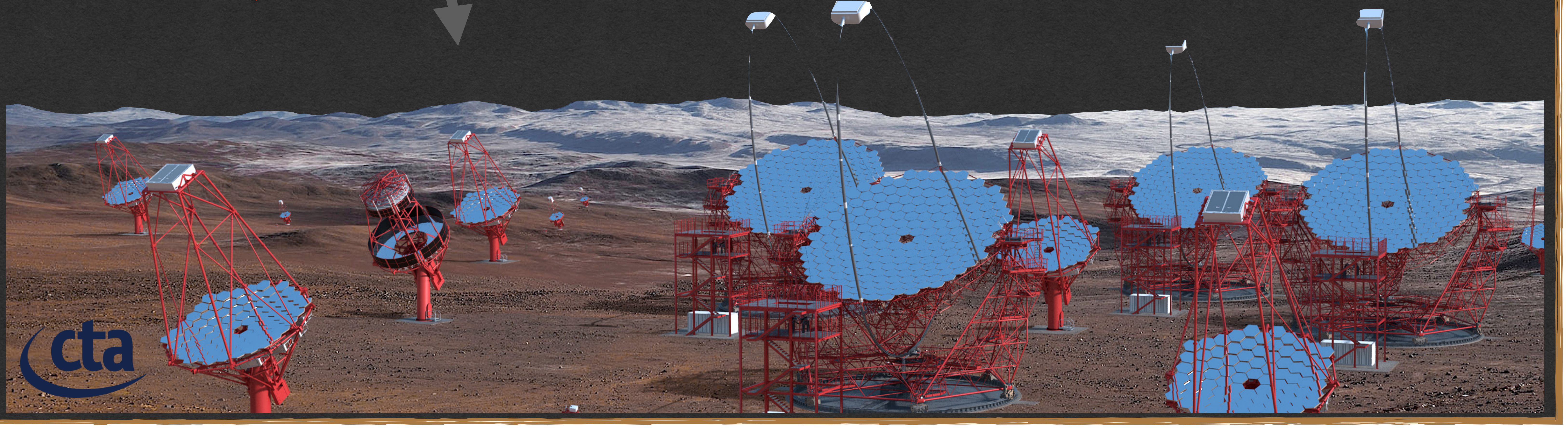




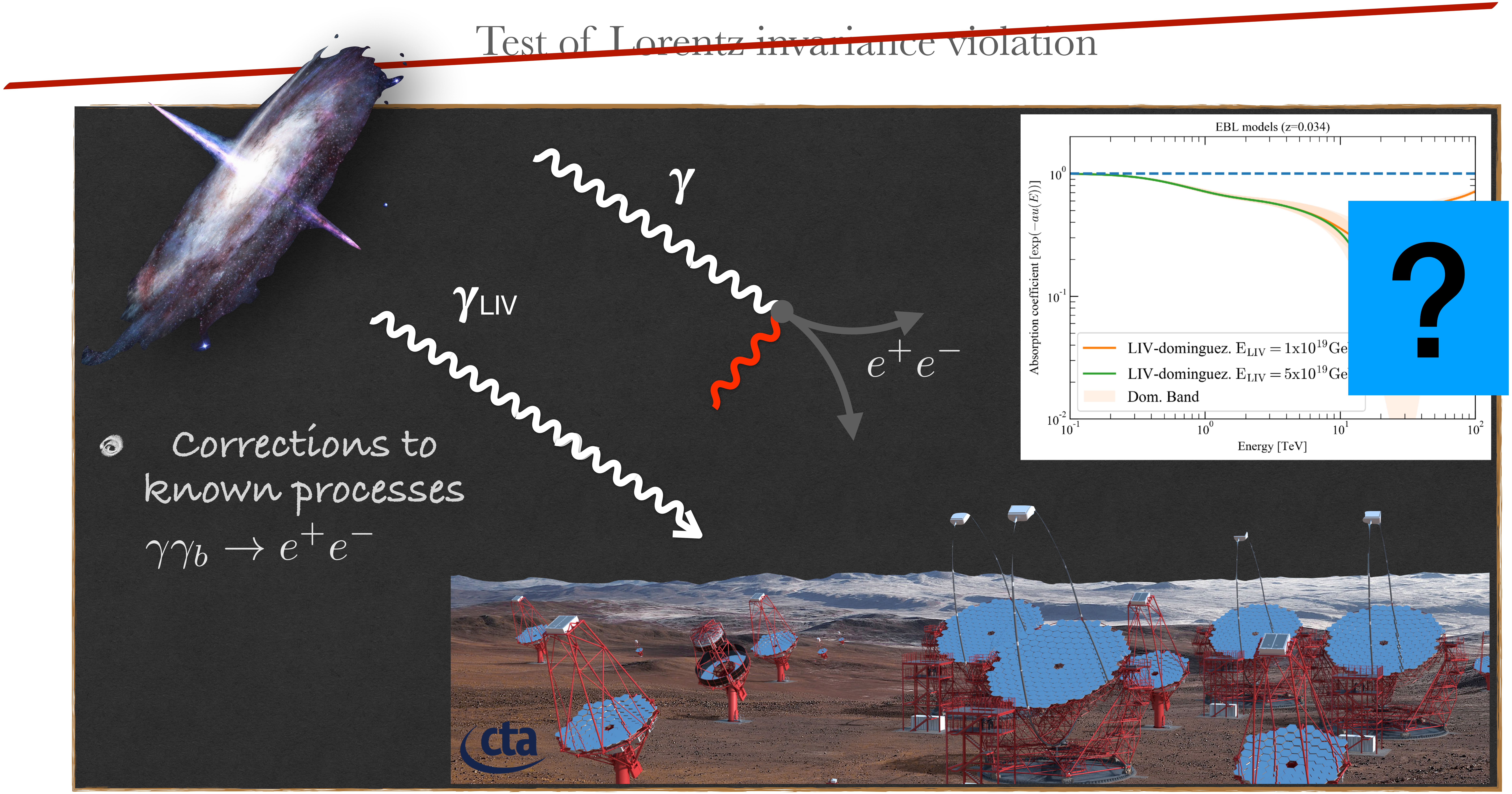
- Corrections to known processes

$\gamma\gamma_b \to e^+e^-$

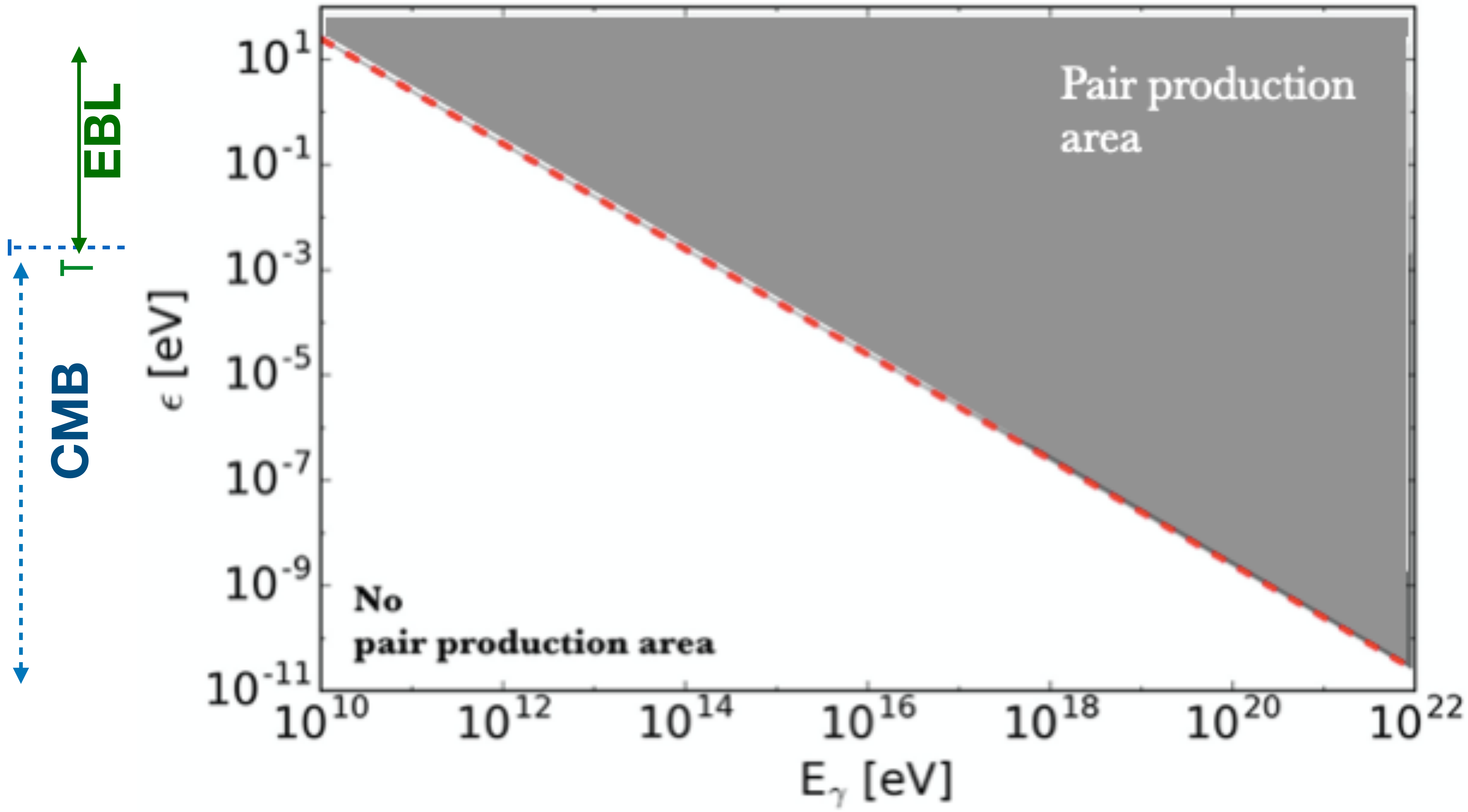




Test of Lorentz invariance violation

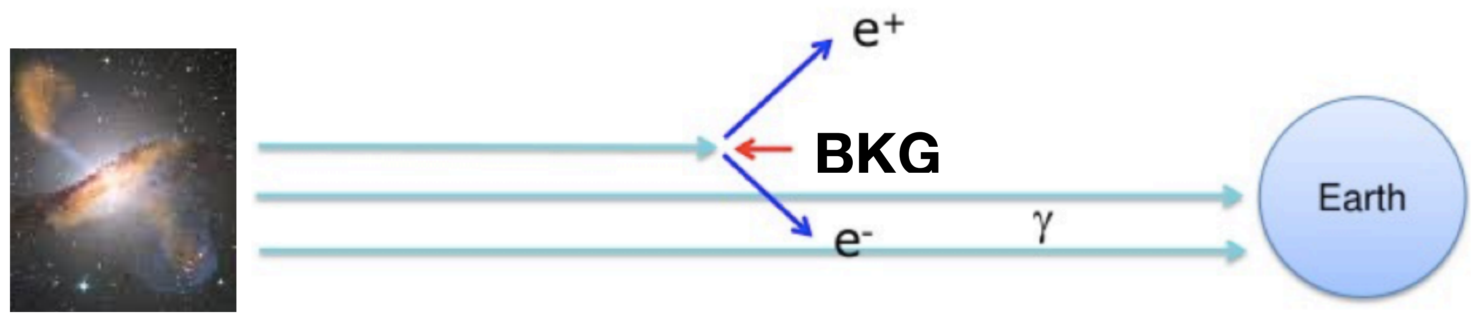


PP

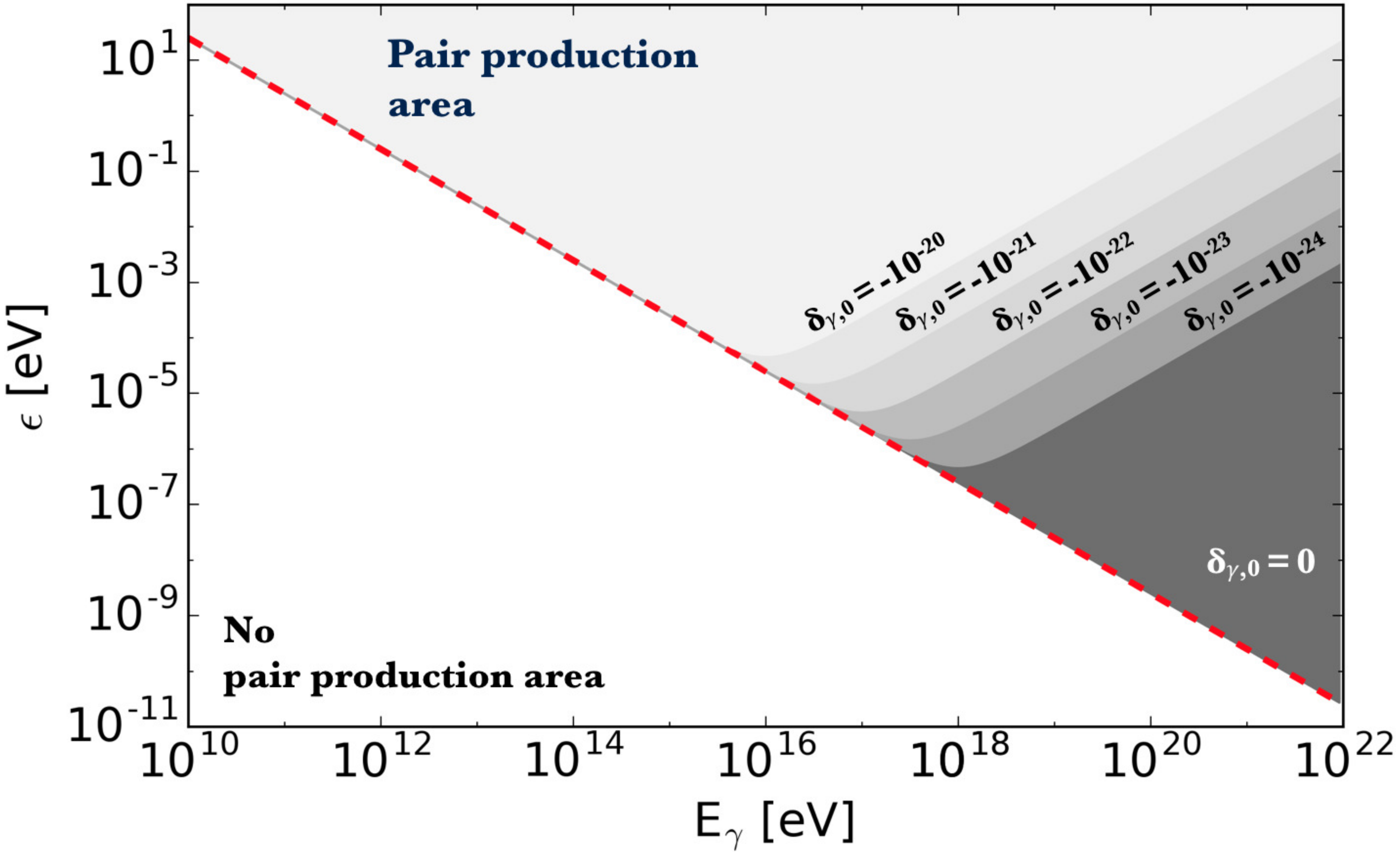


EBL
CMB
Pair production area
No pair production area
ϵ [eV]
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
E_γ [eV]

$\gamma\gamma_b \rightarrow e^+e^-$

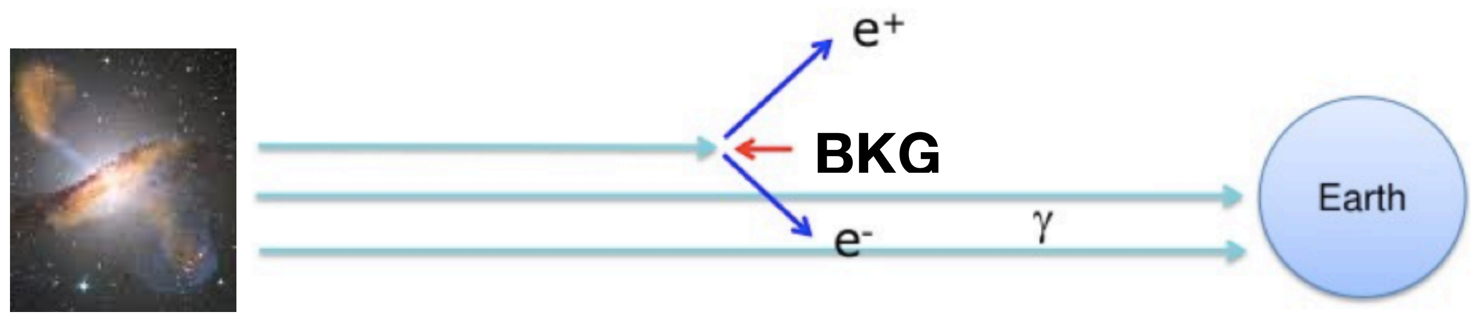


$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$

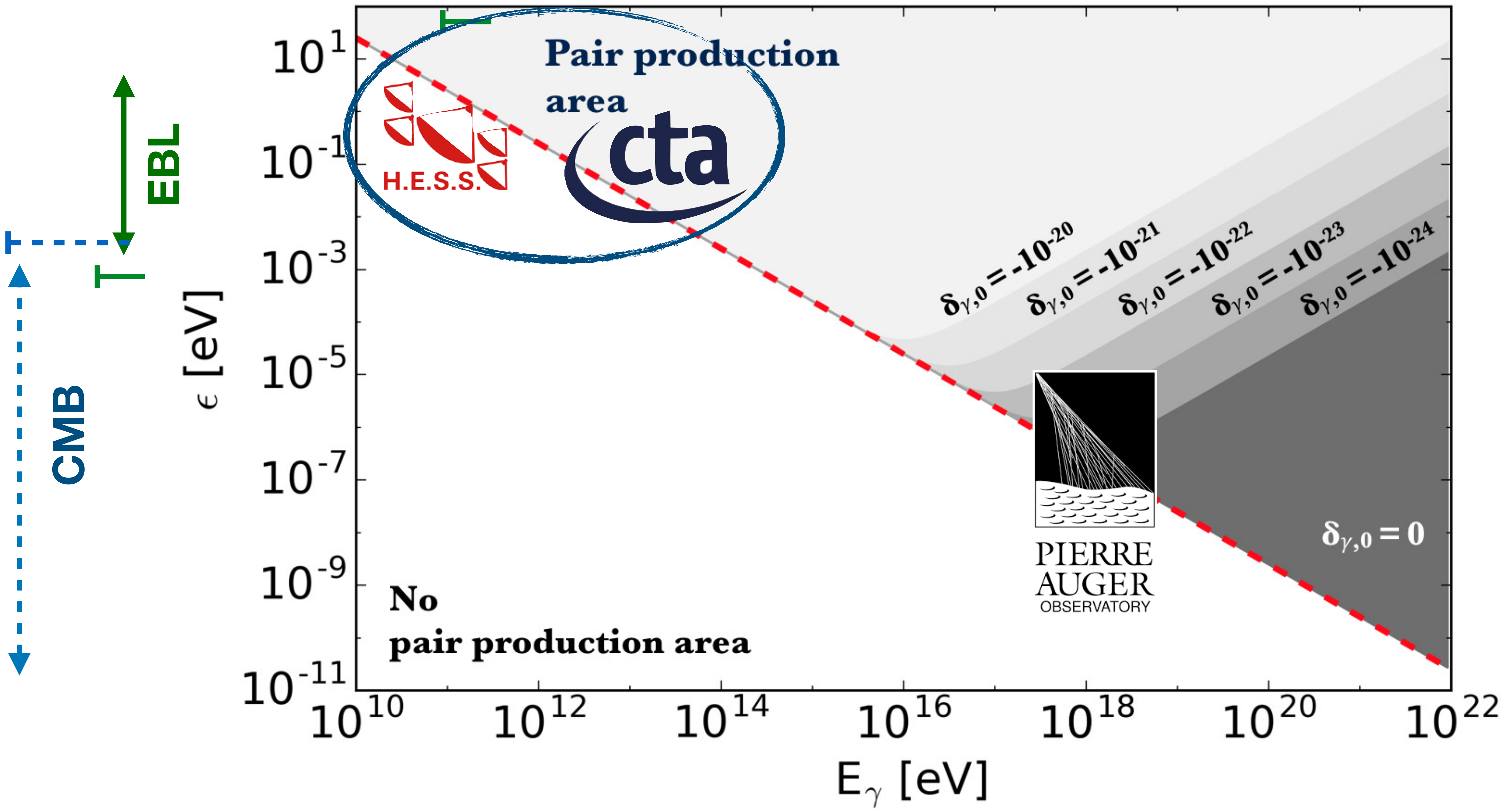


Allowed region change with the LIV parameter and the Energy

$$\gamma\gamma_b \rightarrow e^+e^-$$

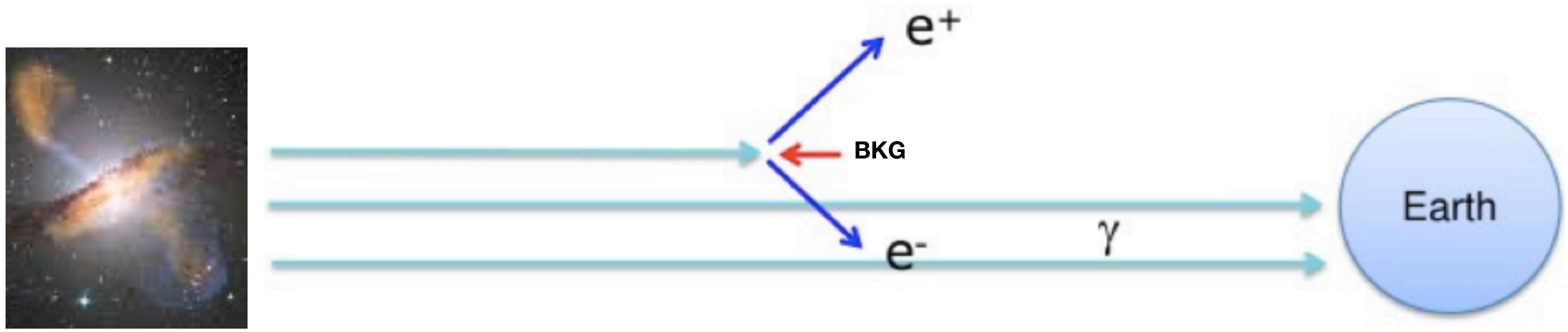


$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$



… deeper LIV effects

Optical Depth + LIV



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

-COSMOLOGÍA -
The distance element

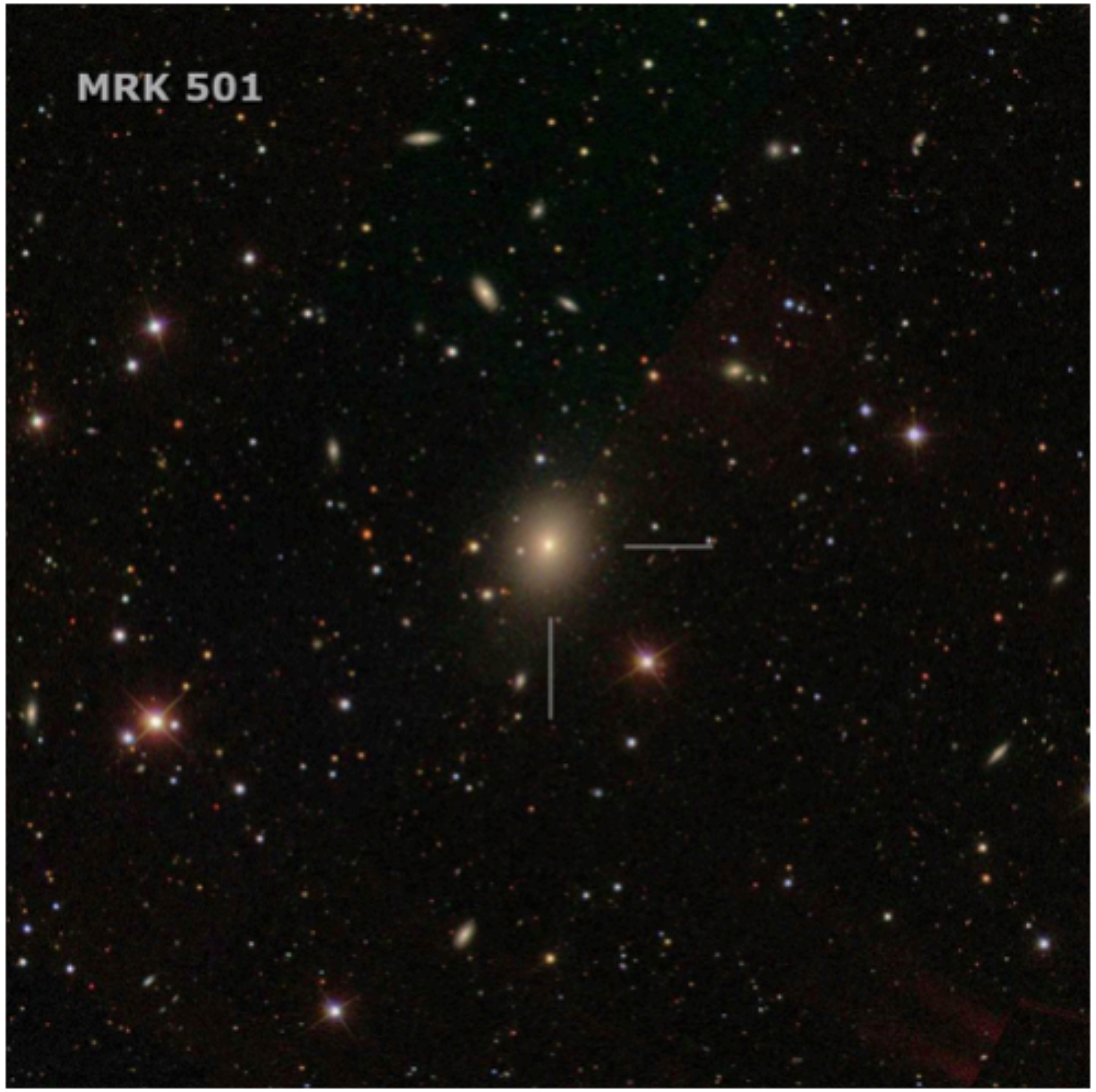
LIV →

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

-ASTRONOMÍA-
Density of BKG photons

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

-FÍSICA DE PARTÍCUAS-
Pair Production cross section
Breit & Wheeler 1934; Heitler 1960



RA: 253.4667
DEC: 39.7603

For a given EBL model at z=0.034

Find:

- [x] -The Optical Depth
- [x] -Attenuation

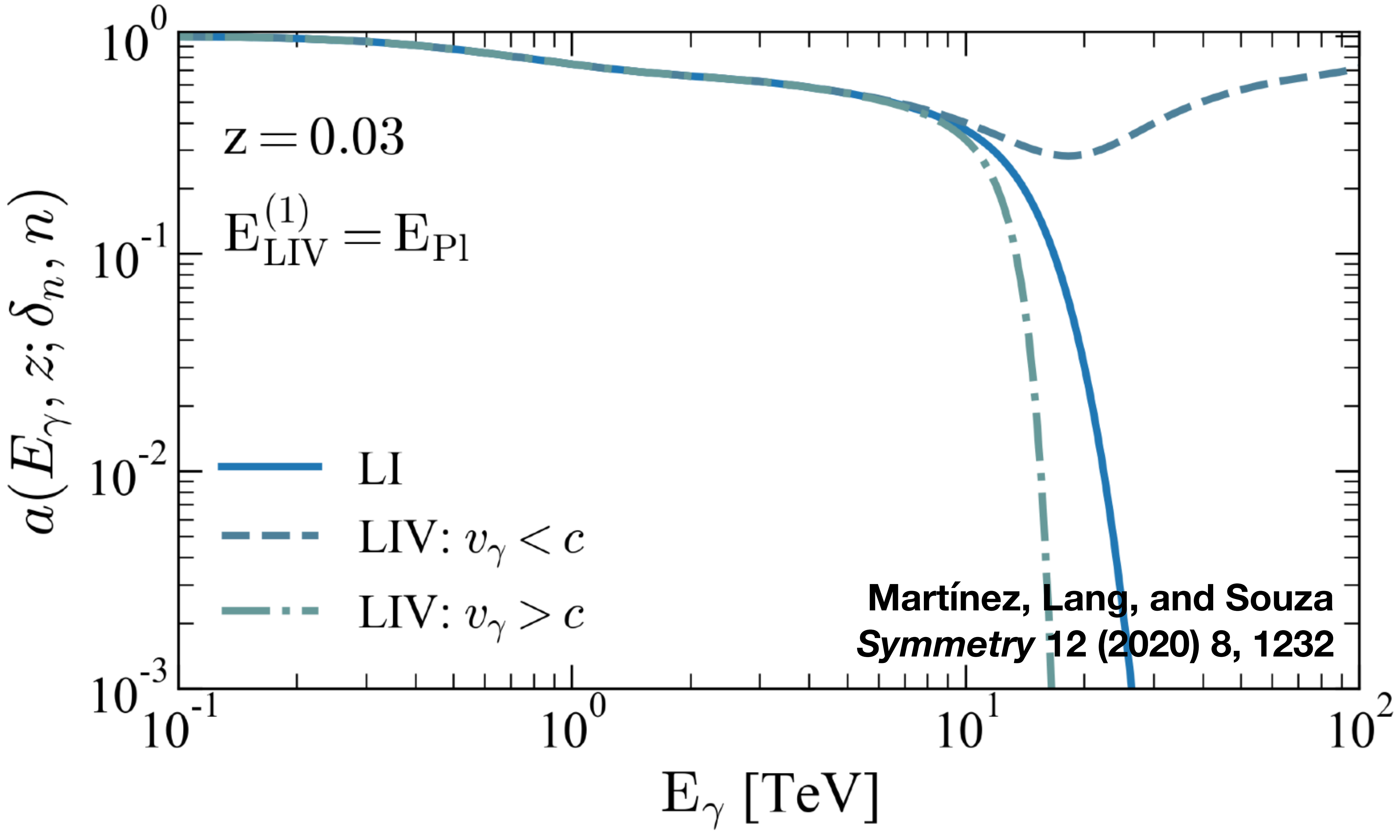
Include LIV_th

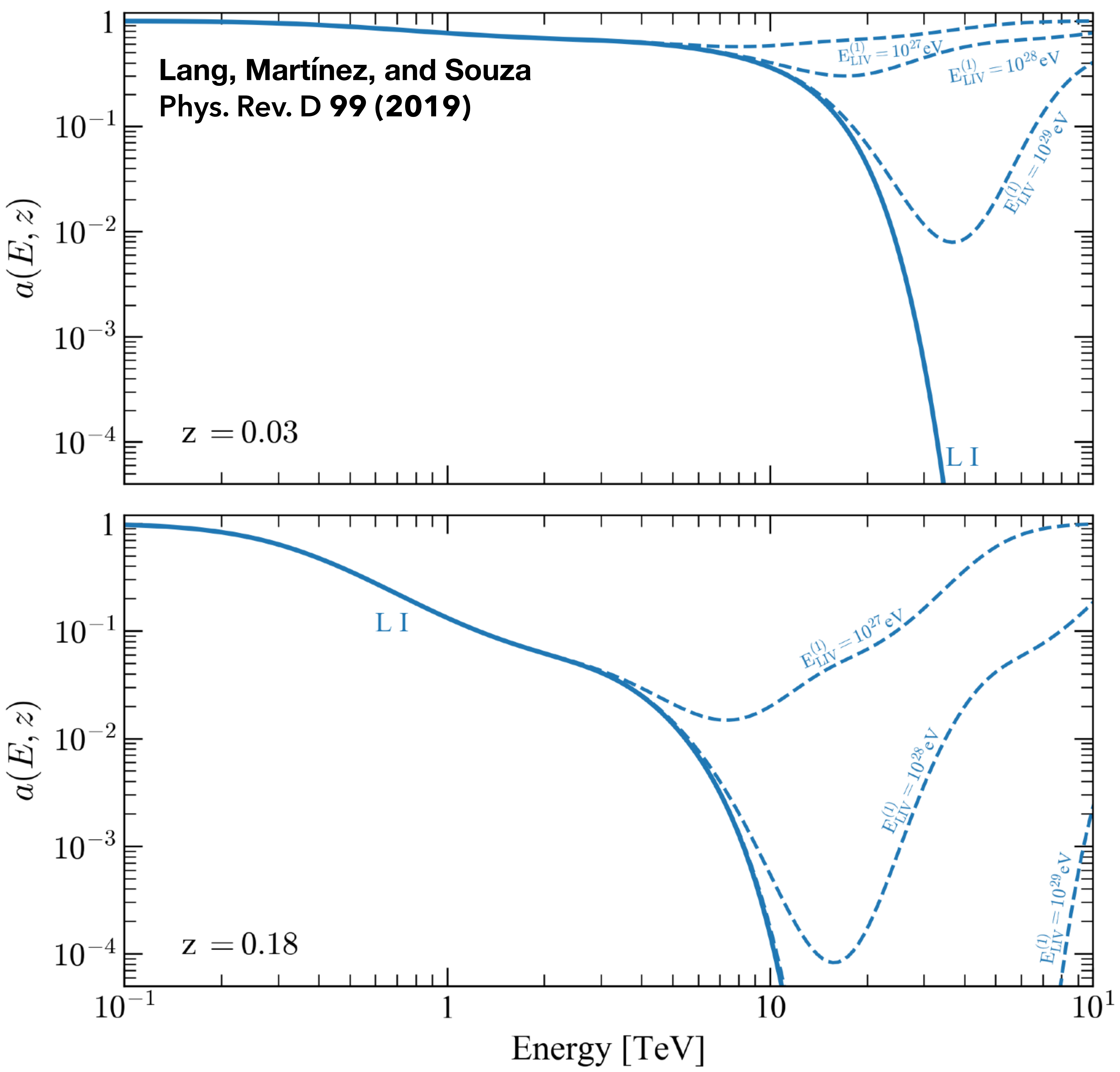
Try different

- [ ] z,
- [ ] ELIV,
- [ ] n….

What can you say about the differences?

EBL-Attenuation + LIV





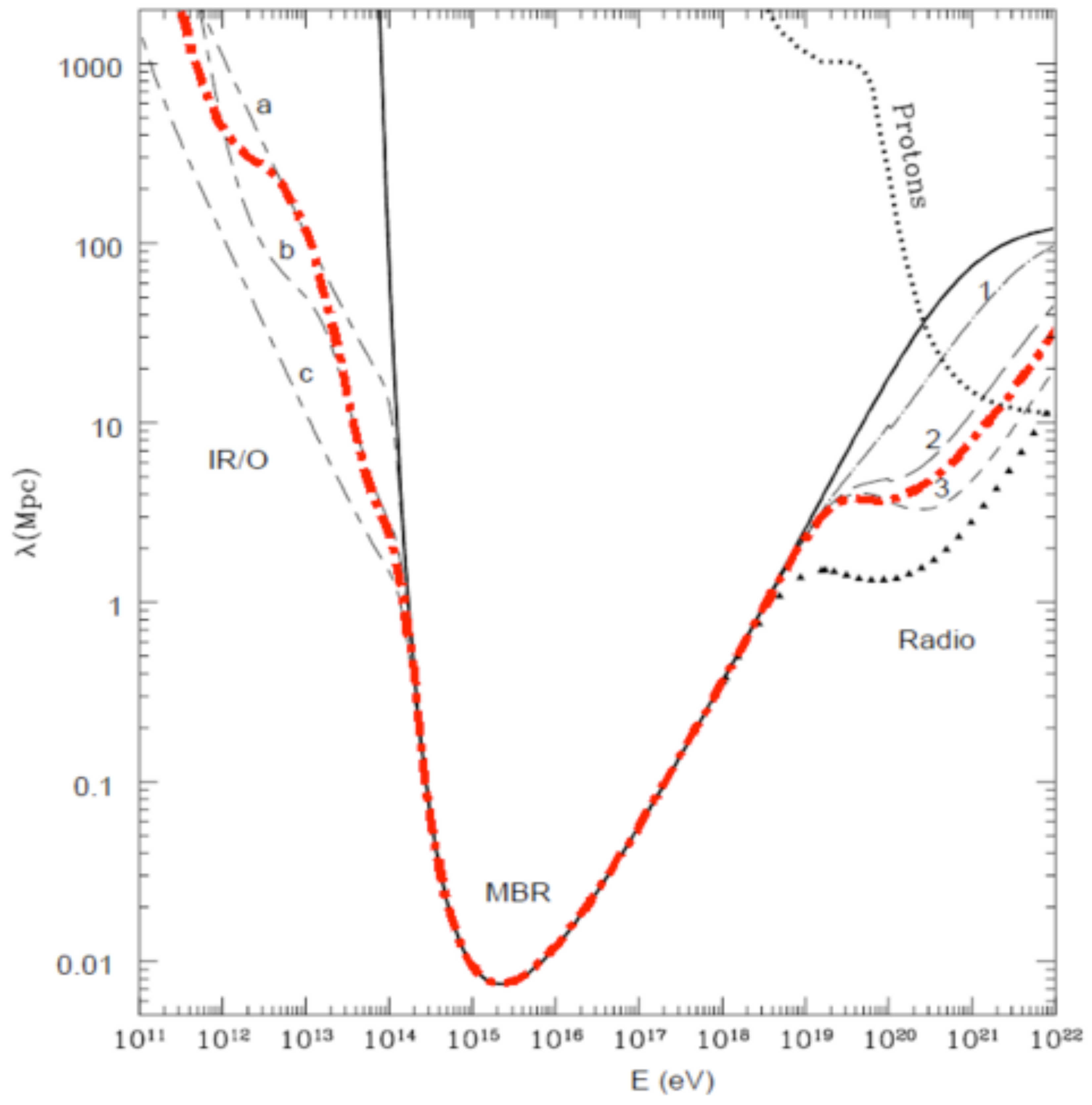
The intensity of the LIV effect depends on

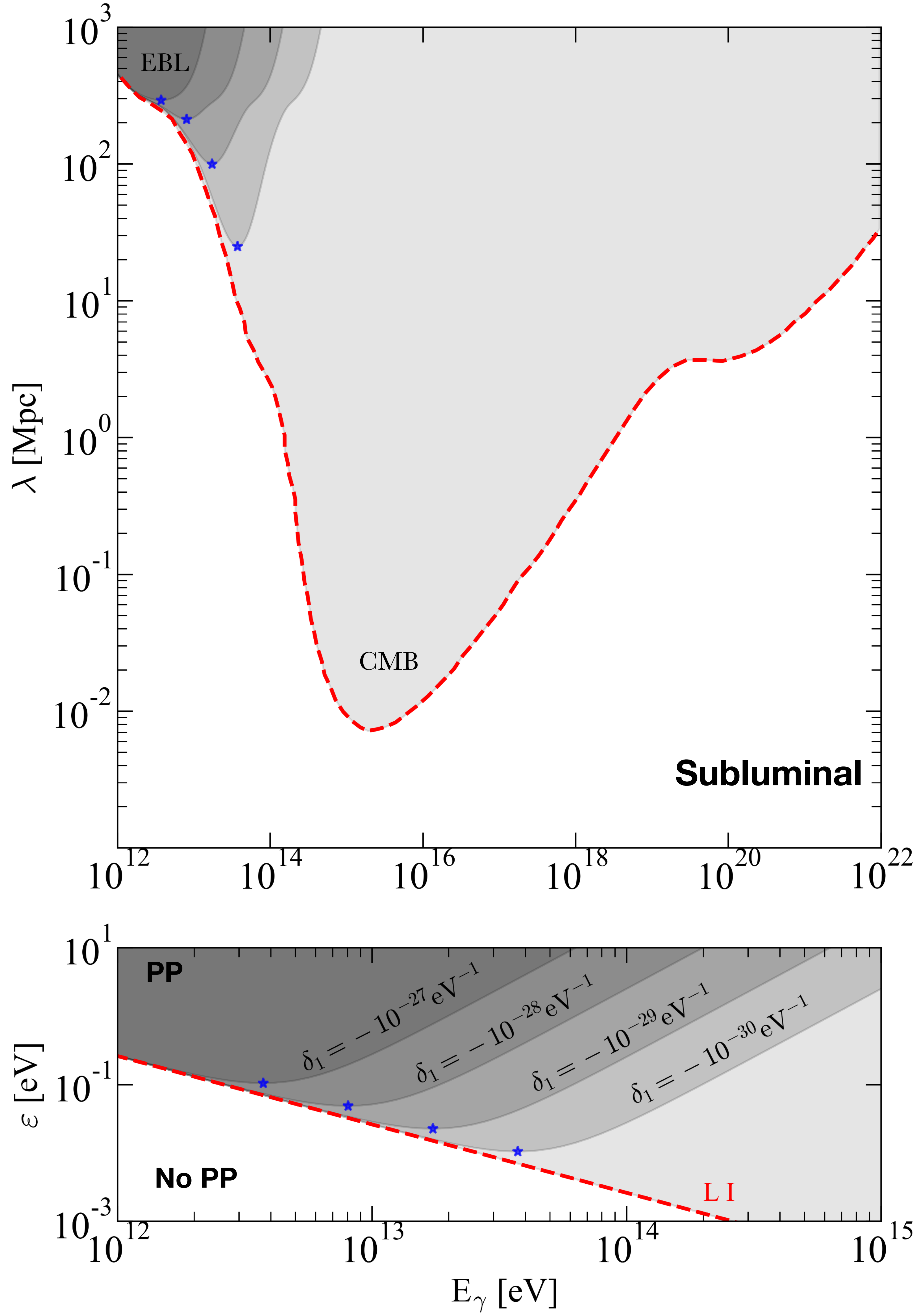
- E_γ : The energy of the γ-ray
- E_{LIV}: The LIV energy scale
- z: The distance of the source.

More photons!!

What would be the difference in the Optical Depth?

$$\gamma\gamma_b \to e^+e^-$$





What are the blue dots?

$\gamma\gamma_b \rightarrow e^+e^-$

$$\frac{m_e}{\omega} \ll 1, \quad \frac{\omega_b}{\omega} \ll 1,$$

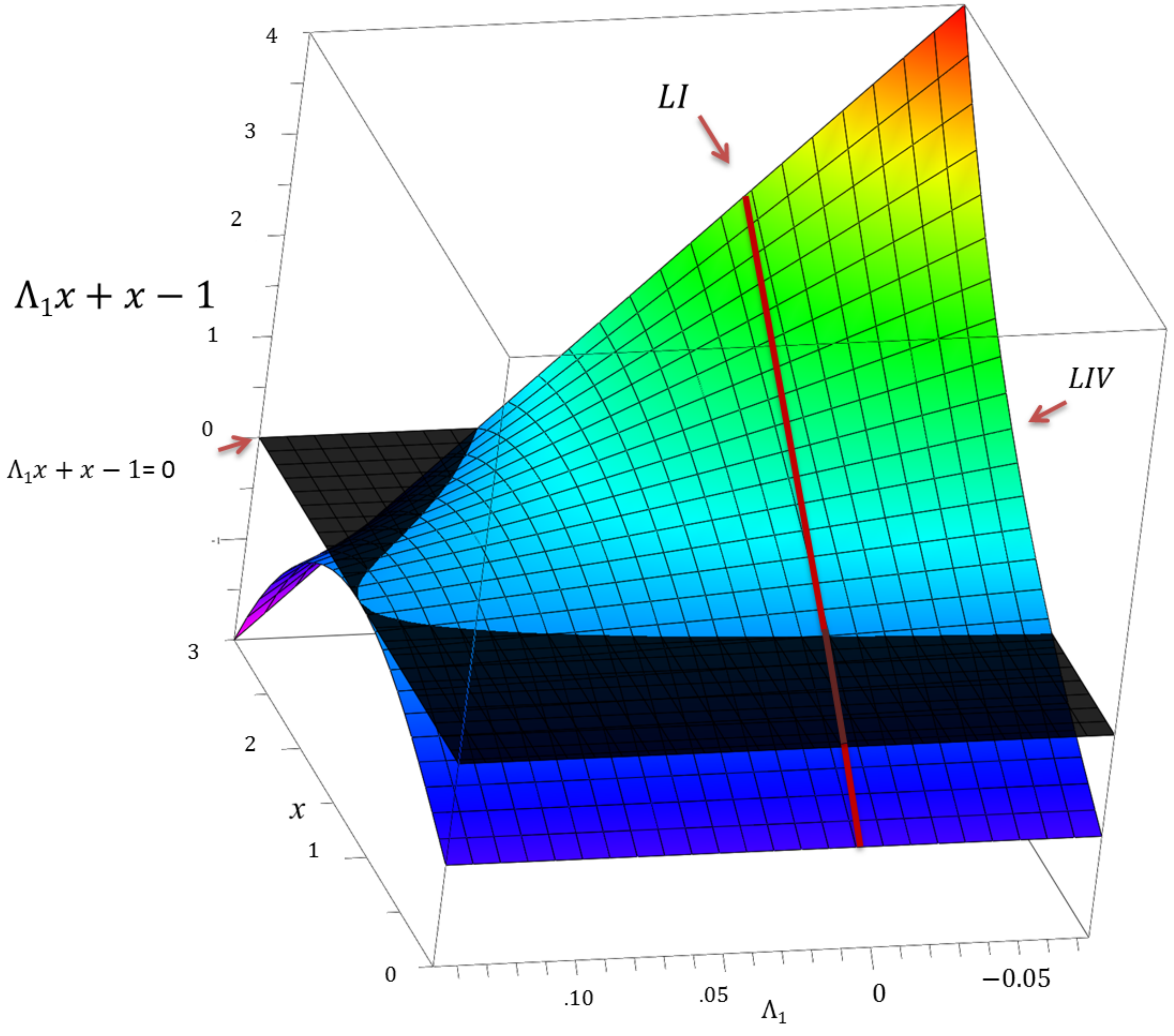
$$\boxed{4\omega\omega_b - \frac{m_e^2}{K(1-K)} = \left[\alpha_n - \alpha_{n+}K^{n+1} - \alpha_{n-}(1-K)^{n+1}\right]\omega^{n+2}.}$$

Let be:

$$x = \frac{4\omega_b K(1-K)}{m_e^2}\omega := \frac{1}{\omega_0}\omega,$$

$$\Lambda_n := \frac{\omega_0^{n+1}}{4\omega_b}\left[\alpha_n - \alpha_{n+}K^{n+1} - \alpha_{n-}(1-K)^{n+1}\right],$$

$$\boxed{\Lambda_n x^{n+2} - x + 1 = 0,}$$



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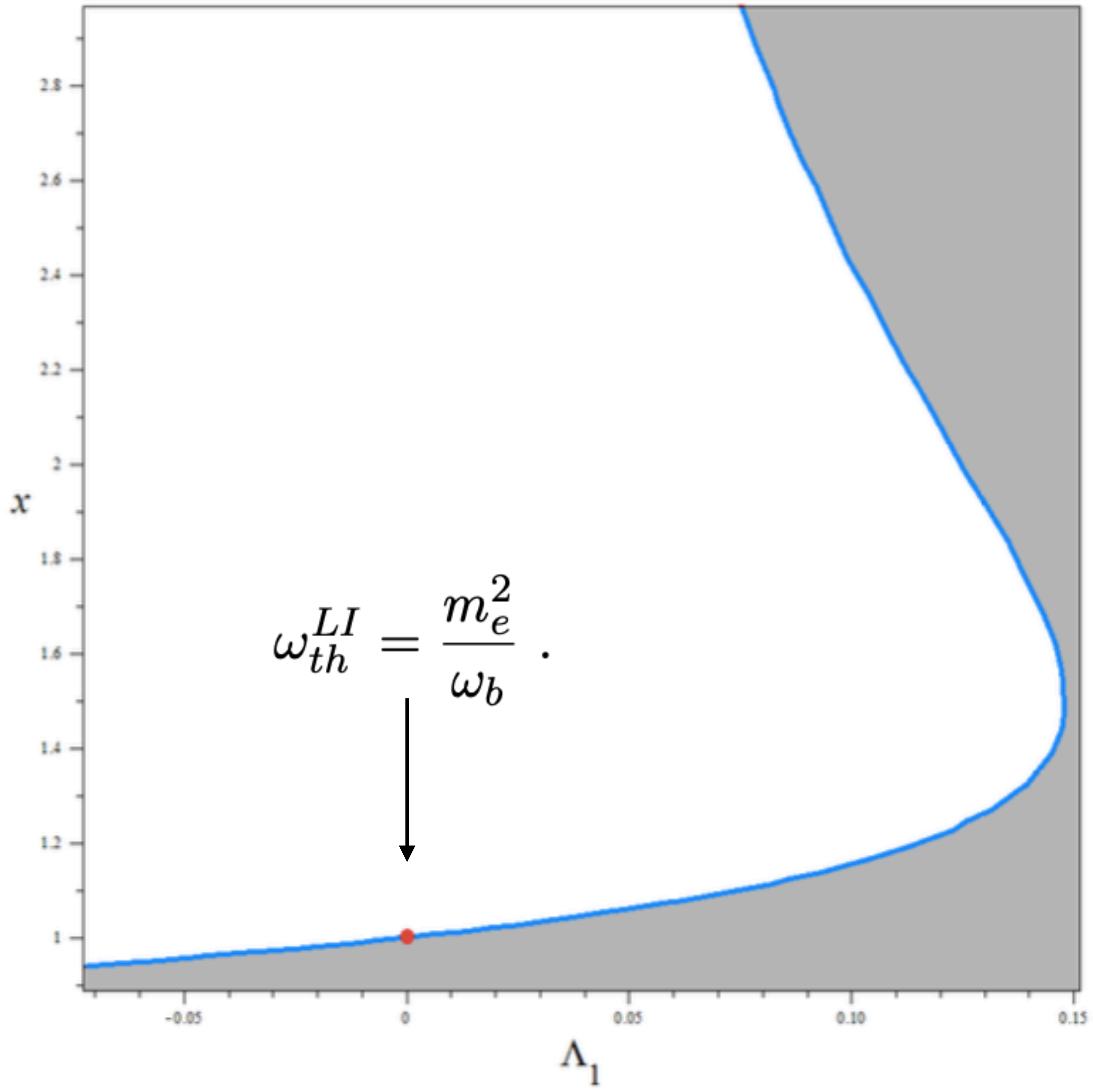


$\gamma\gamma_b \to e^+e^-$

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

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

The threshold equation

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

Critical point

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

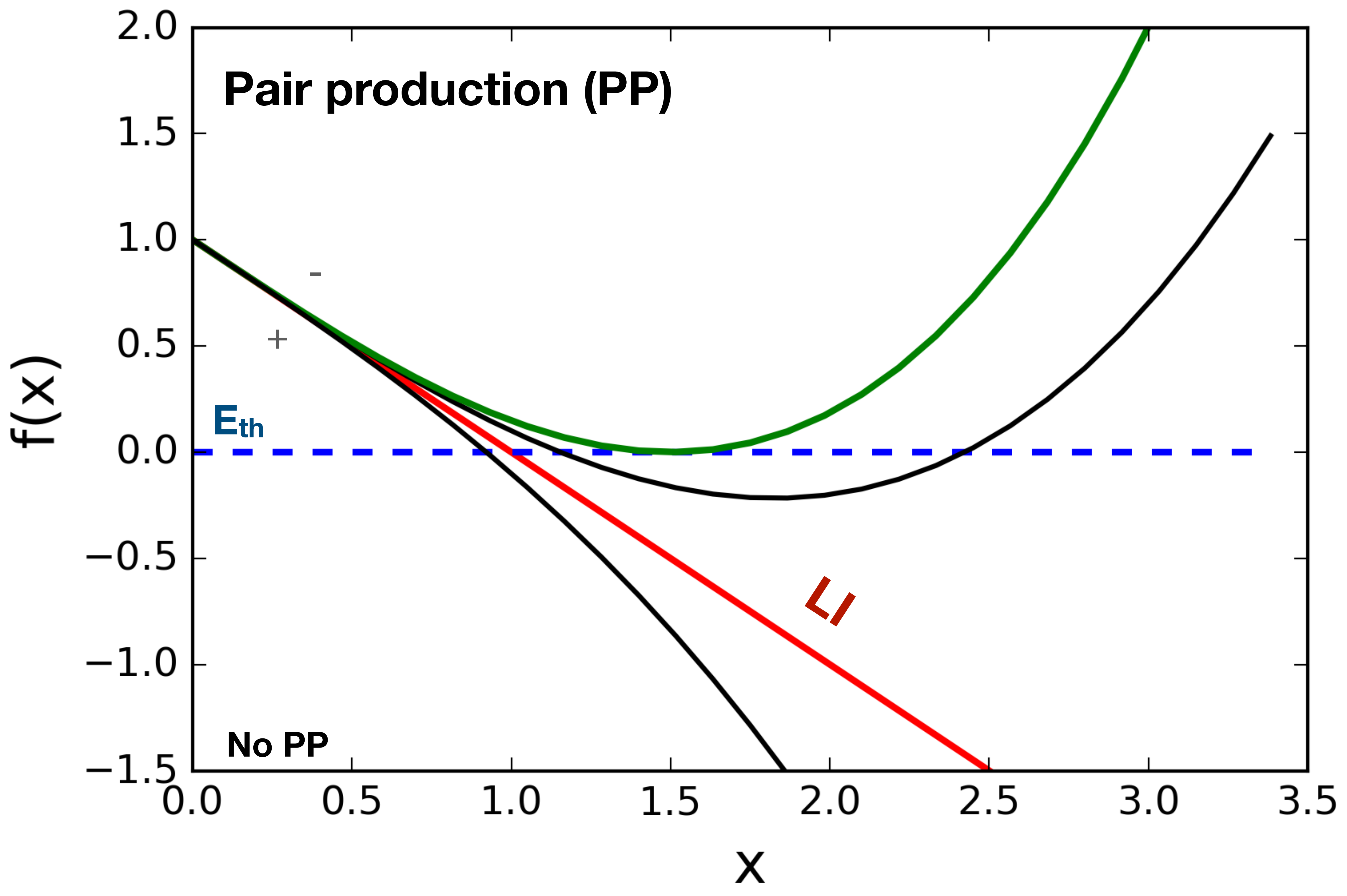
Background:

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

$\Lambda_n < 0$ Threshold-shifts

$\Lambda_n = 0$ LI scenario

$\Lambda_n > 0$ +2nd Threshold



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

$\gamma\gamma_b \to e^+e^-$

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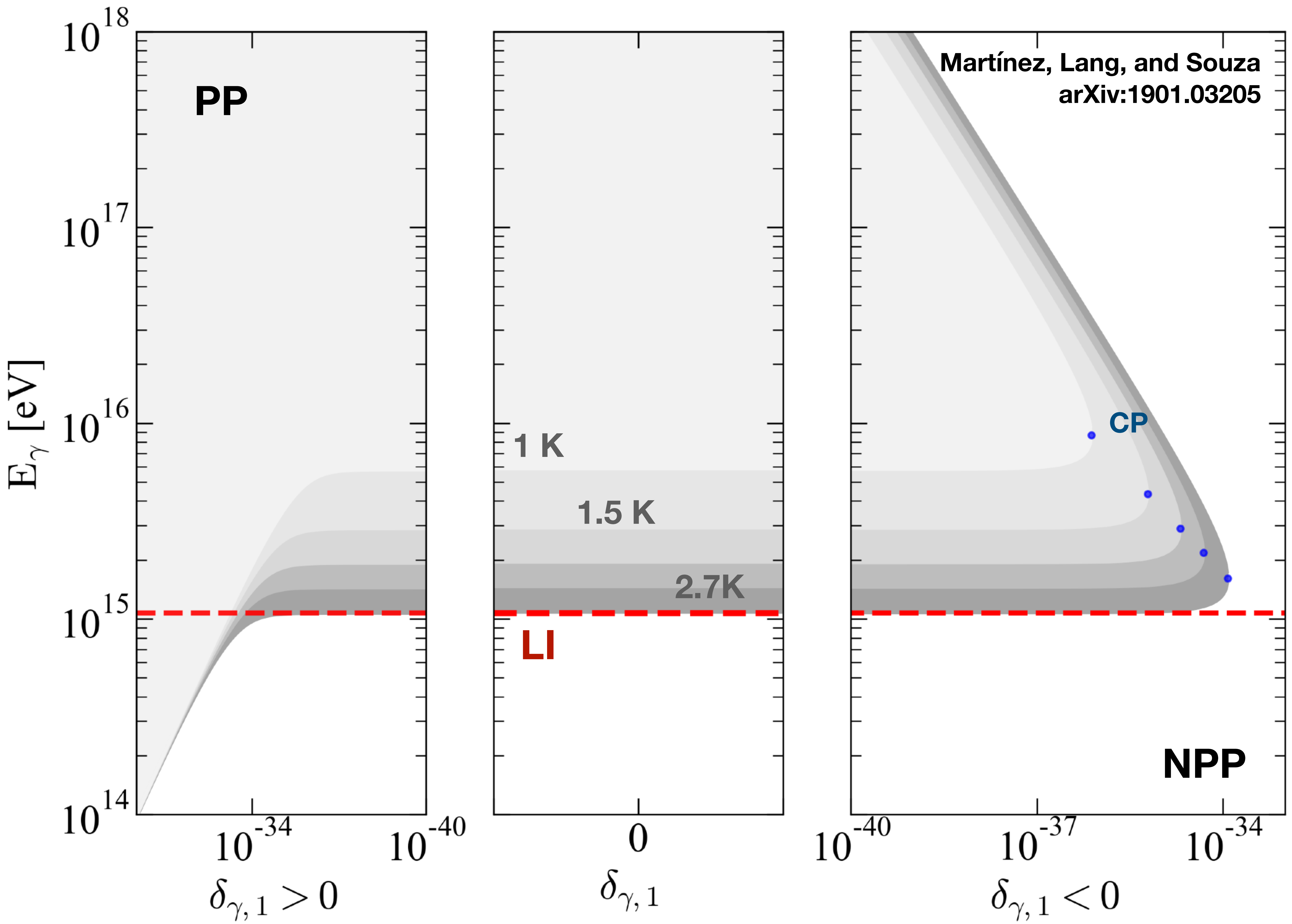

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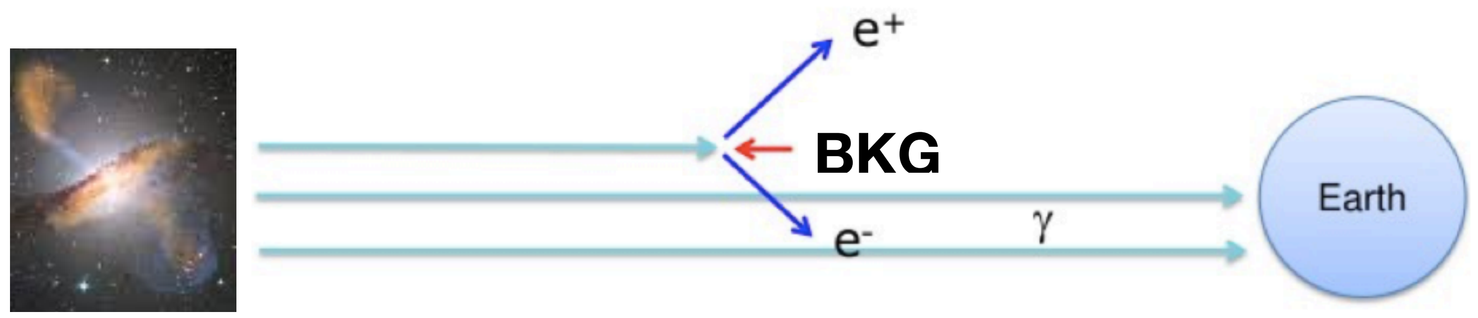
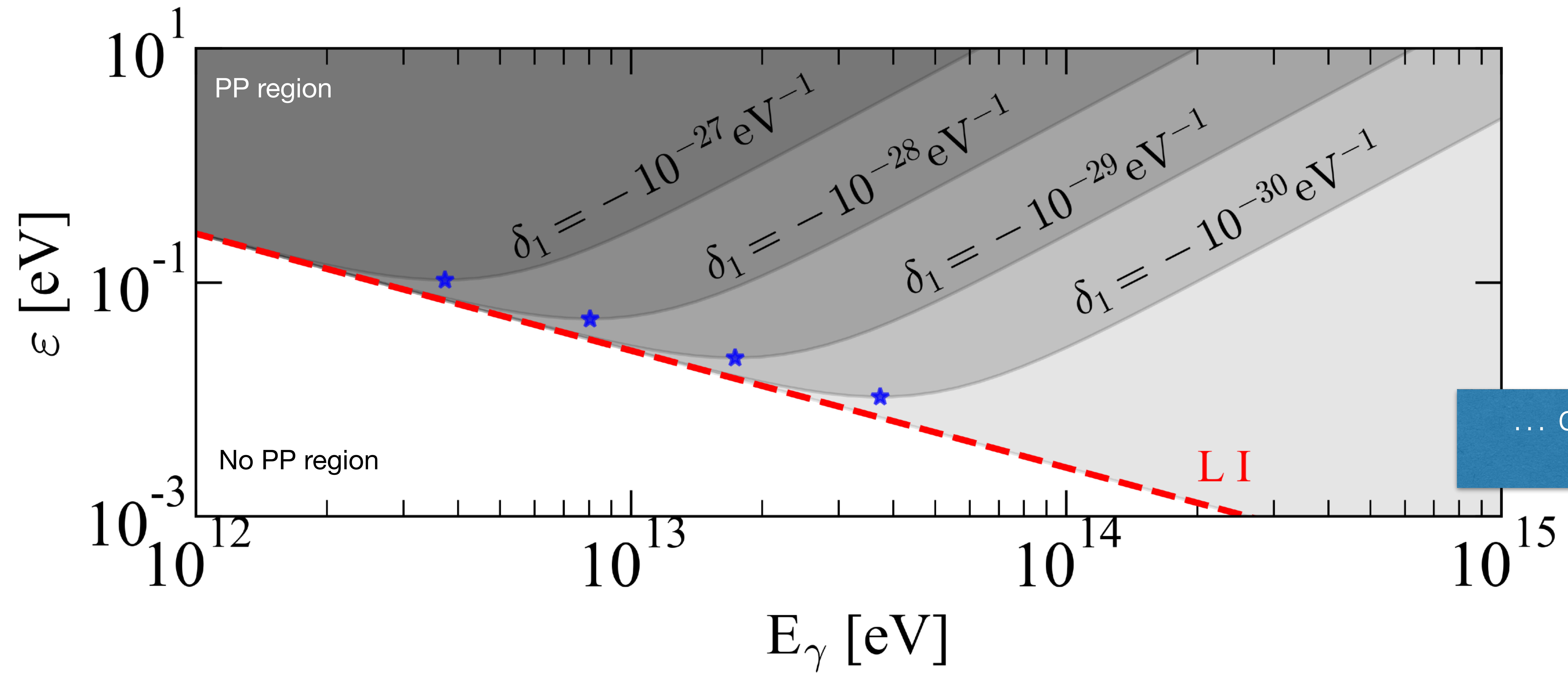
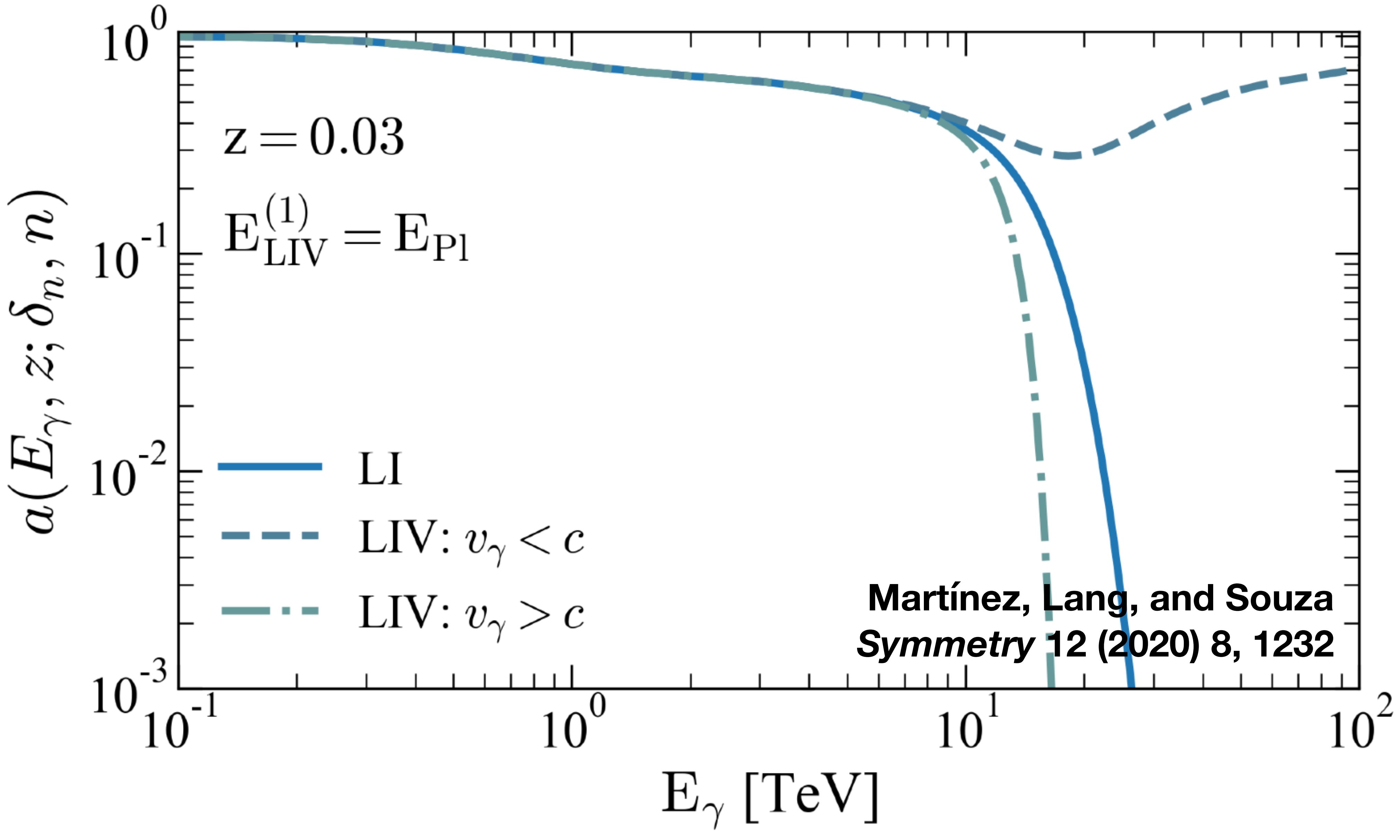


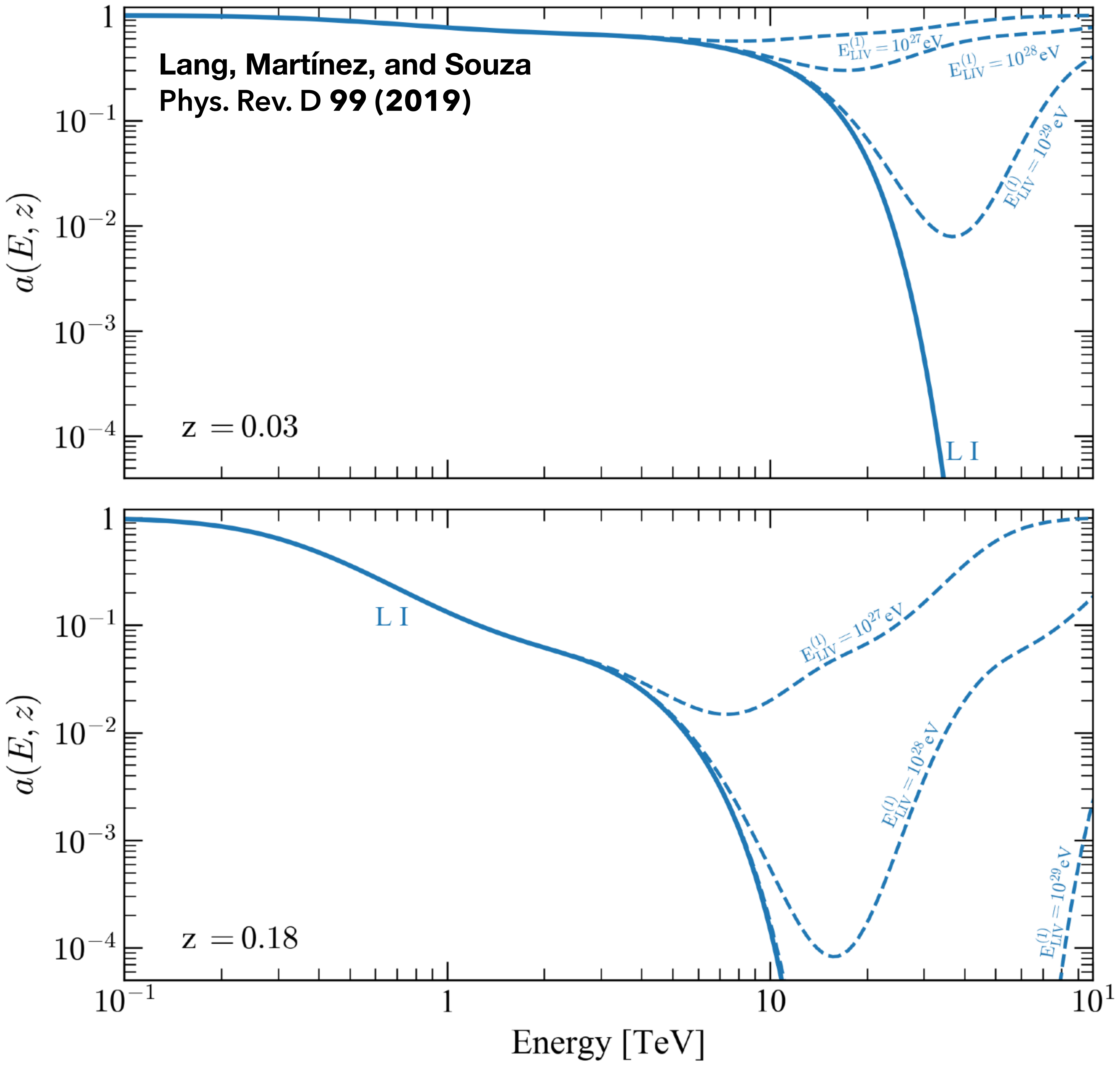
$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n}E_\gamma^{n+1}}{4}$$



… deeper LIV effects

EBL-Attenuation + LIV





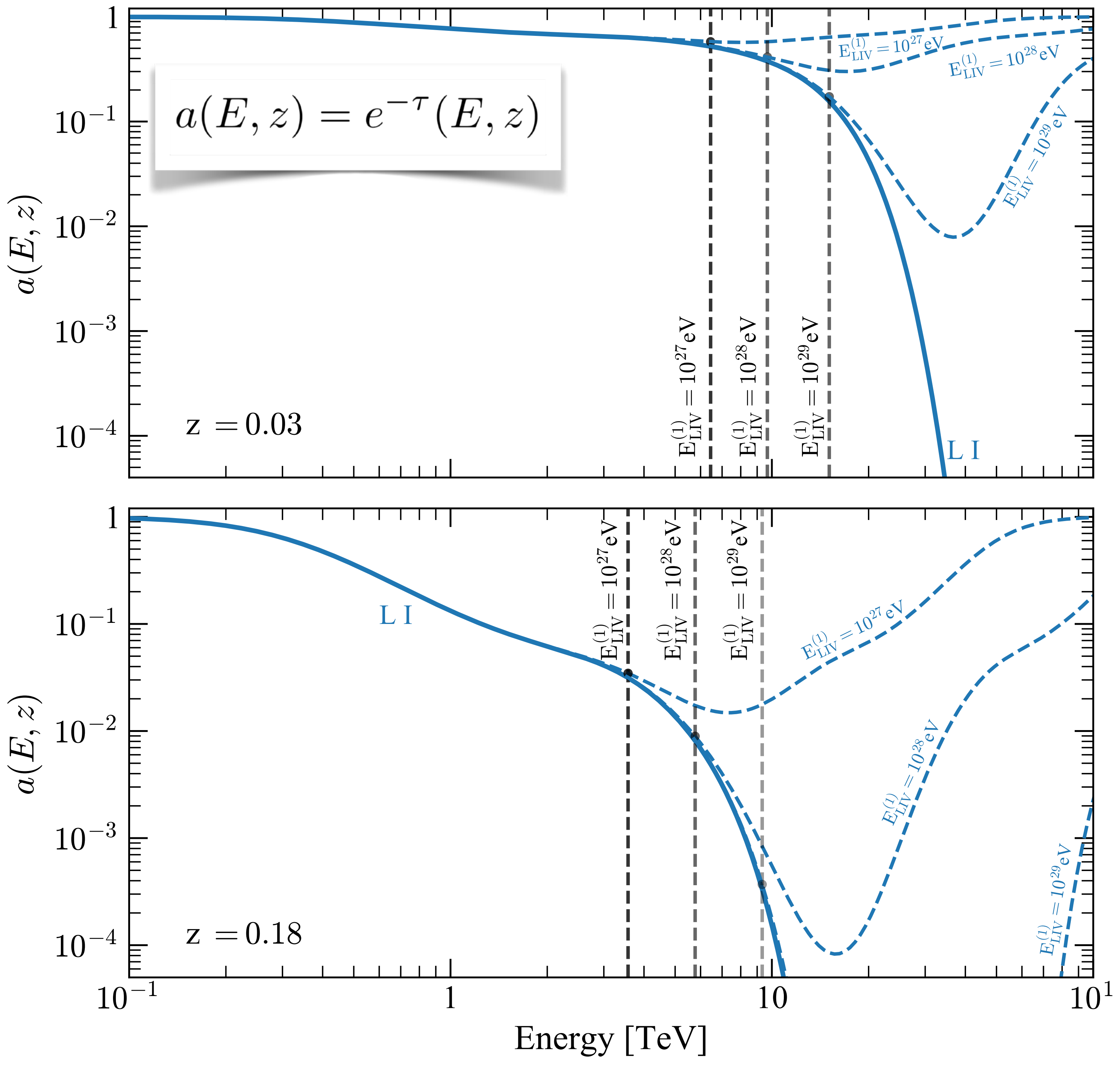
The intensity of the LIV effect depends on

- E_γ : The energy of the γ-ray
- E_{LIV}: The LIV energy scale
- z: The distance of the source.

More photons!!

LIV-Horizon

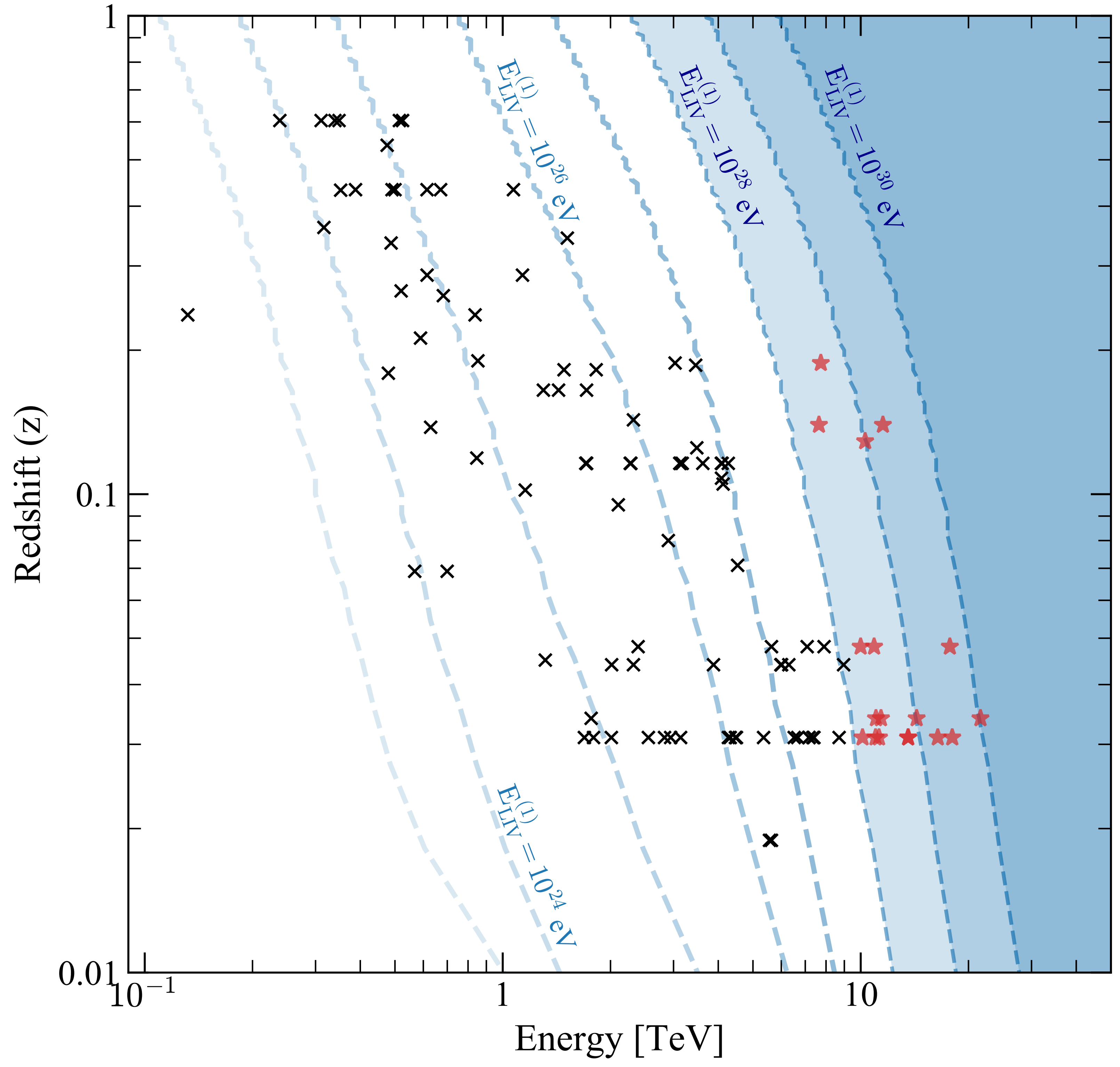
Phenomenology → Experiment



More photons!!

The most updated dataset composed of 111 energy spectra of 38 different sources in TeVCat

only 18 spectra from 6 sources have the potential to show LIV effects (constraint LIV)



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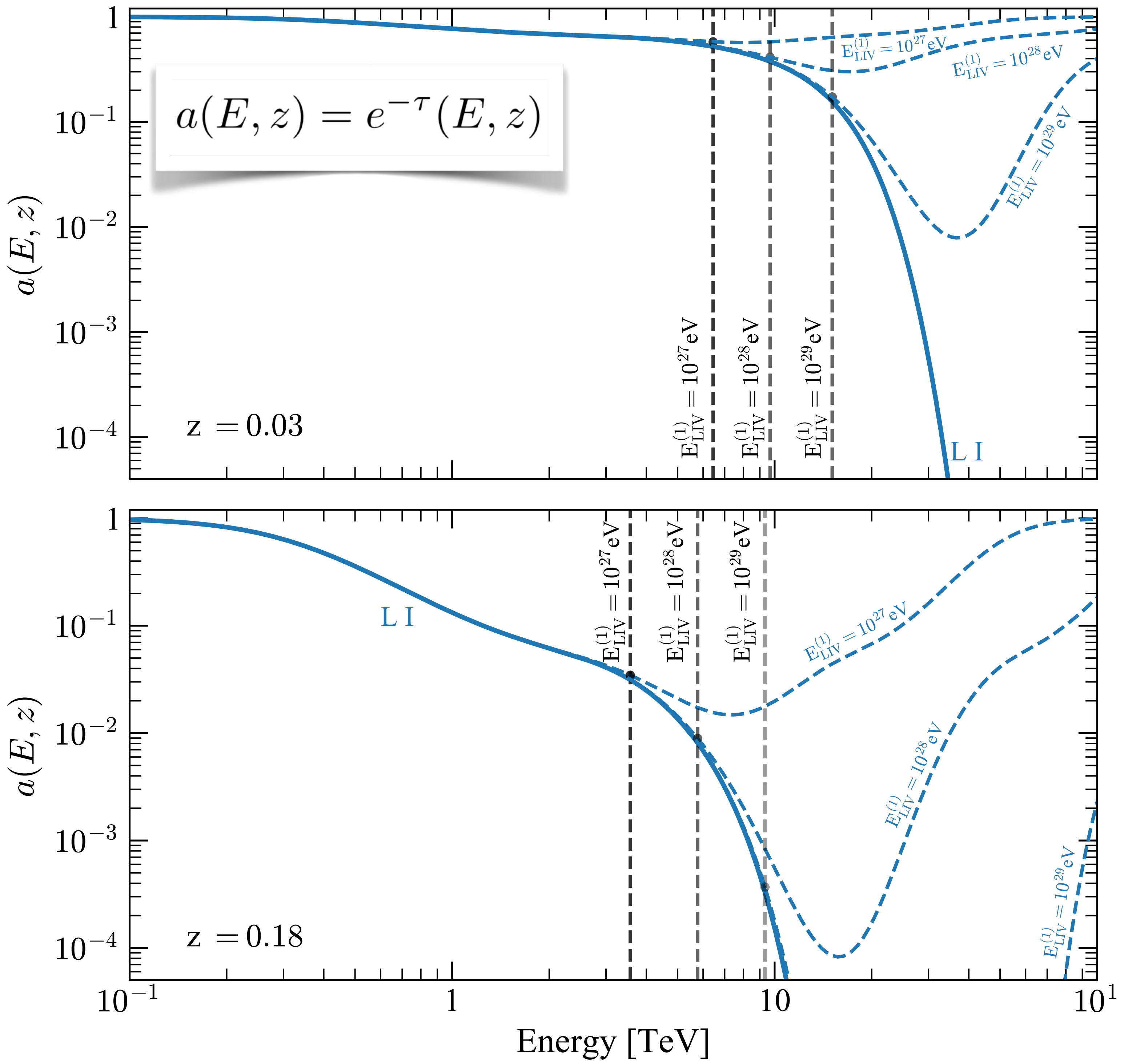
Lang, Martínez-Huerta and de Souza
Phys.Rev. D99 (2019) no.4.

LIV-Horizon

Phenomenology → Experiment



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More photons!!

The most updated dataset composed of 111 energy spectra of 38 different sources in TeVCat

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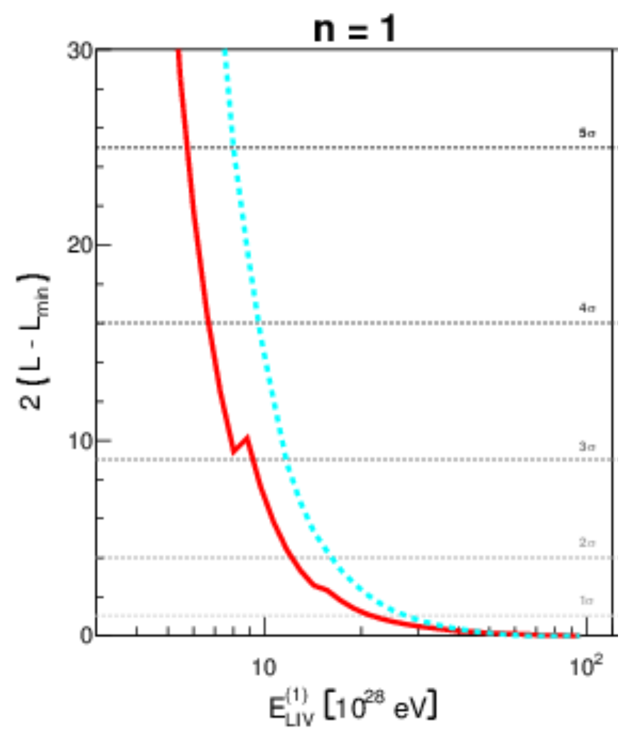
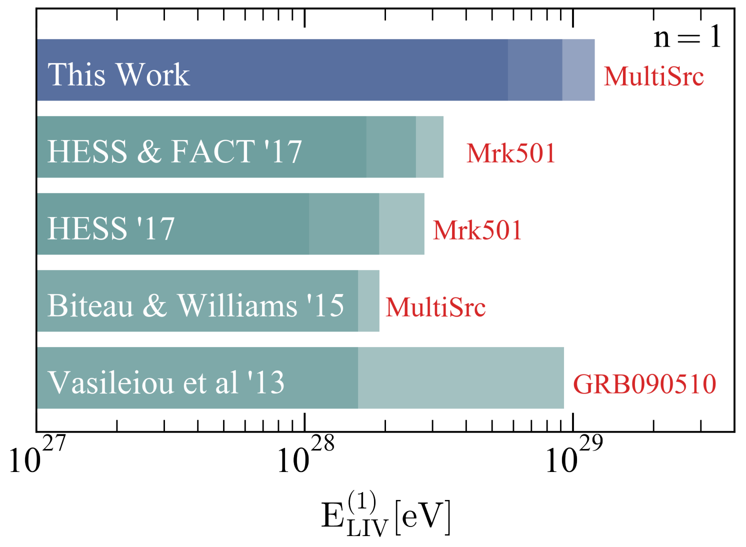
Irrespectively of many tested **uncertainties**
- Choices of the EBL models
- Model of the intrinsic spectrum
- Energy resolution
- Selection of spectra
- Selection of energy bins to be used in the calculation of the intrinsic energy spectra

Source	Redshift	Experiment	Spectrum	Reference
Markarian 421	0.031	HEGRA	1999–2000	[48]
			2000–2001	[48]
		HESS	2000	[49]
		VERITAS	2006–2008 (low)	[50]
			2006–2008 (mid)	[50]
		TACTIC	2005–2006	[51]
			2009–2010	[52]
Markarian 501	0.034	TACTIC	2005–2006	[53]
		ARGO-YBJ	2008–2011	[54]
			2011 (flare)	[54]
		HESS	2014 (flare)	[37]
1ES 1959 + 650	0.048	Whipple	2002 (flare)	[55]
		HEGRA	2002 (low)	[56]
			2002 (high)	[56]
H 1426 + 428	0.129	HEGRA	1999–2000	[57]
1ES 0229 + 200	0.1396	HESS	2005–2006	[58]
		VERITAS	2010–2011	[59]
1ES 0347-121	0.188	VERITAS	2006	[60]

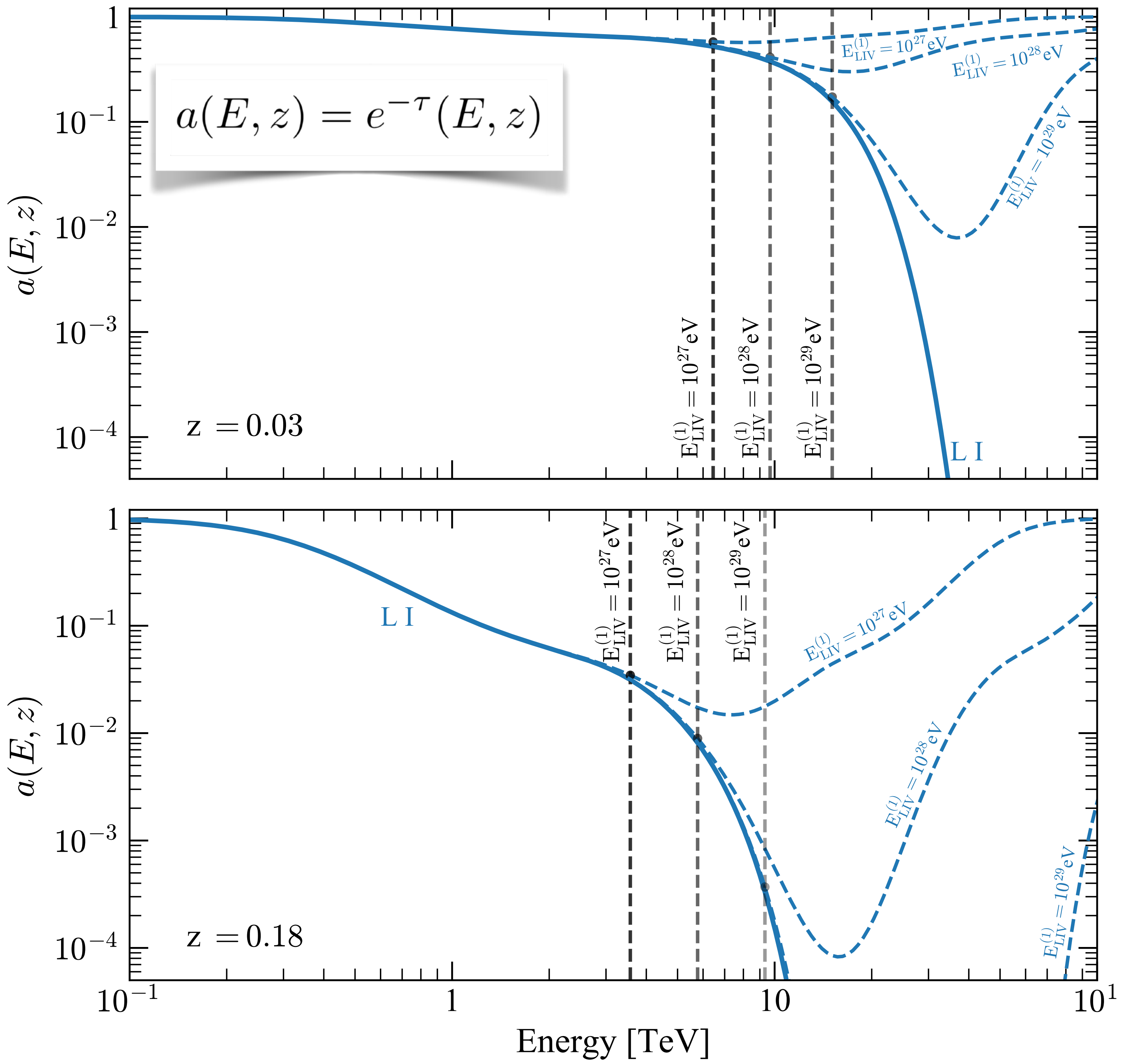




Lang, Martínez-Huerta and de Souza
Phys.Rev. D99 (2019) no.4.

LIV-Horizon

Phenomenology → Experiment



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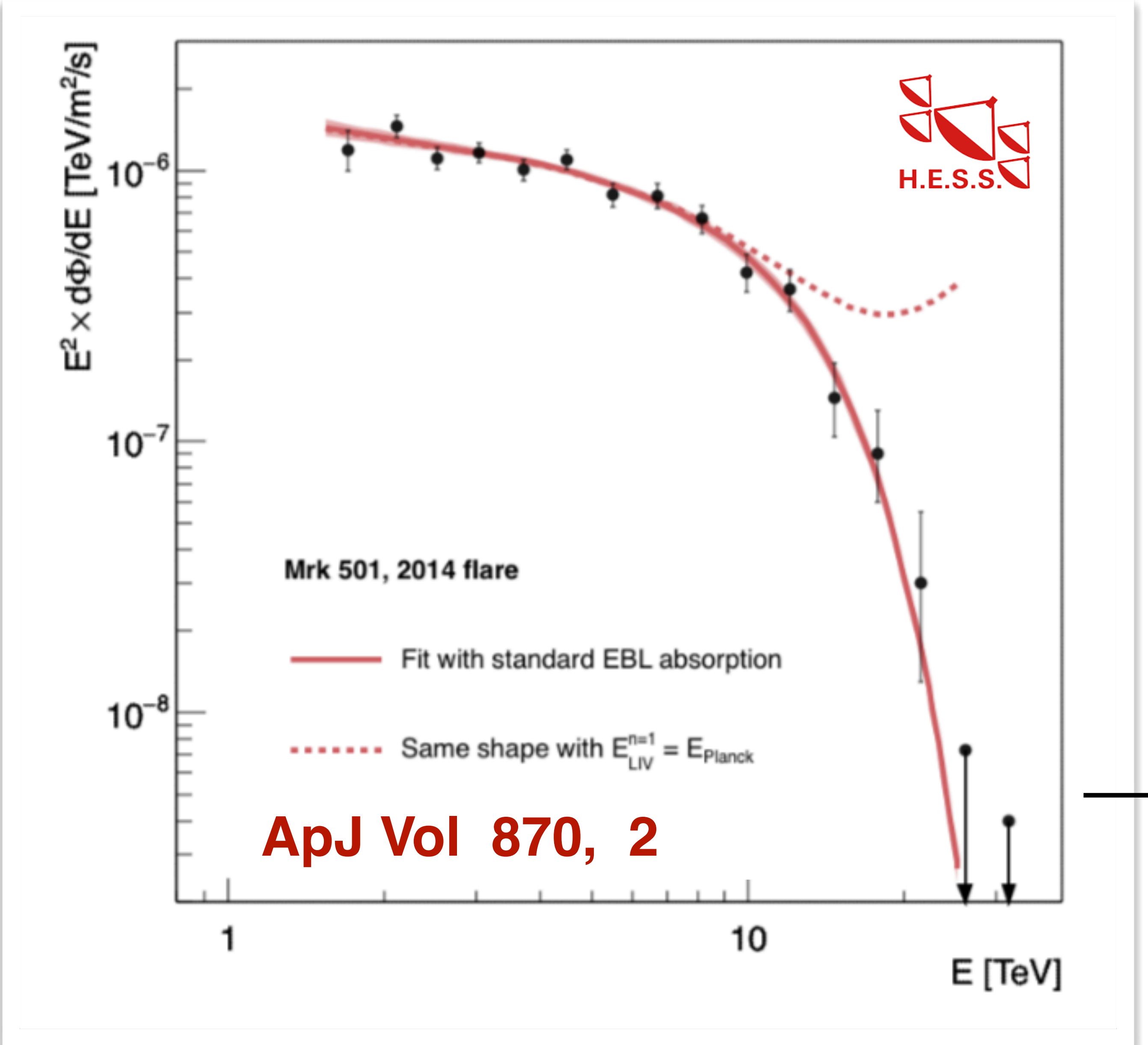
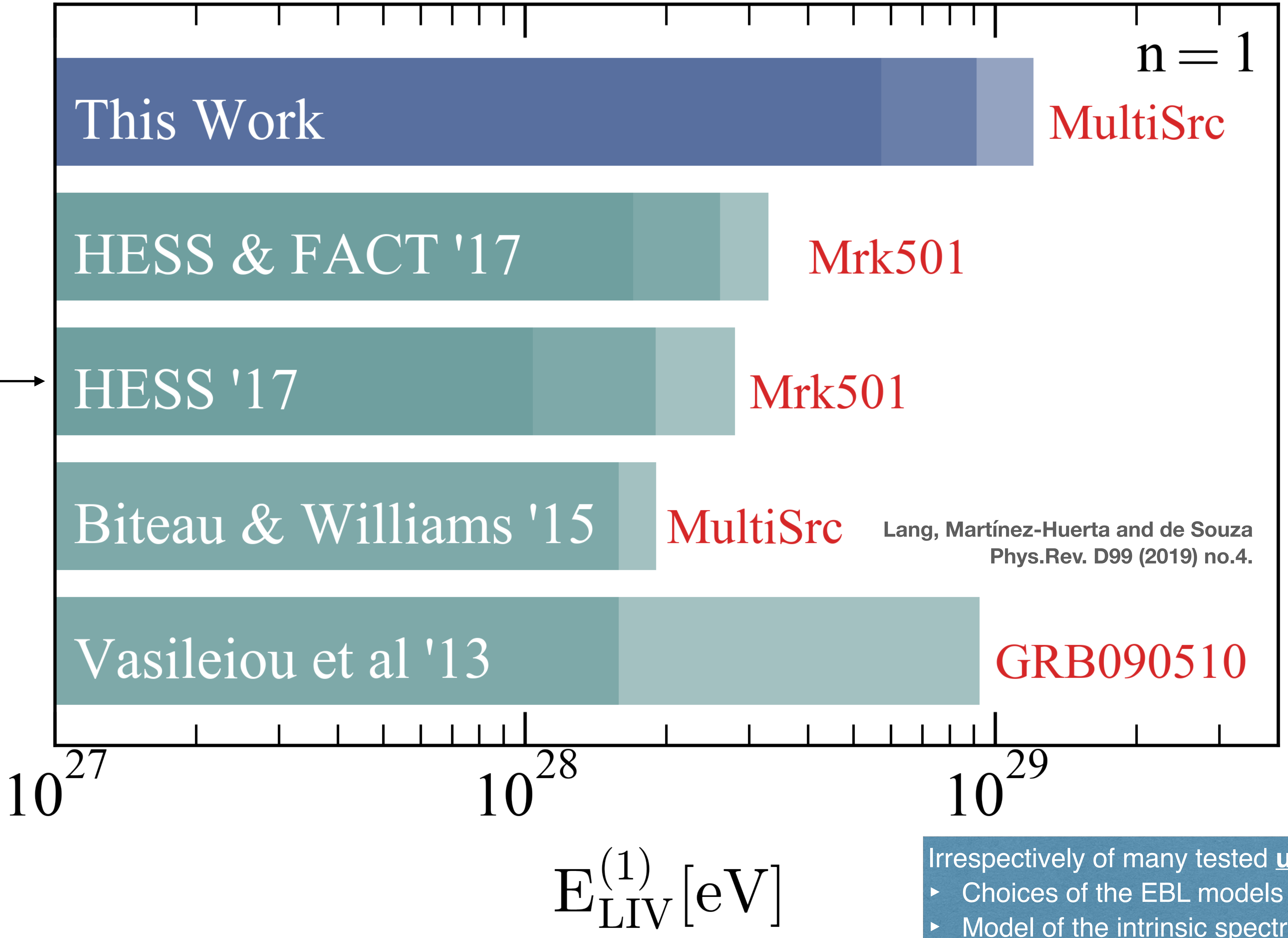
1ES 0347-121	0.188	VERITAS	2006	[60]

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

Lang, Martínez-Huerta and de Souza
Phys.Rev. D99 (2019) no.4.





Irrespectively of many tested **uncertainties**

- Choices of the EBL models
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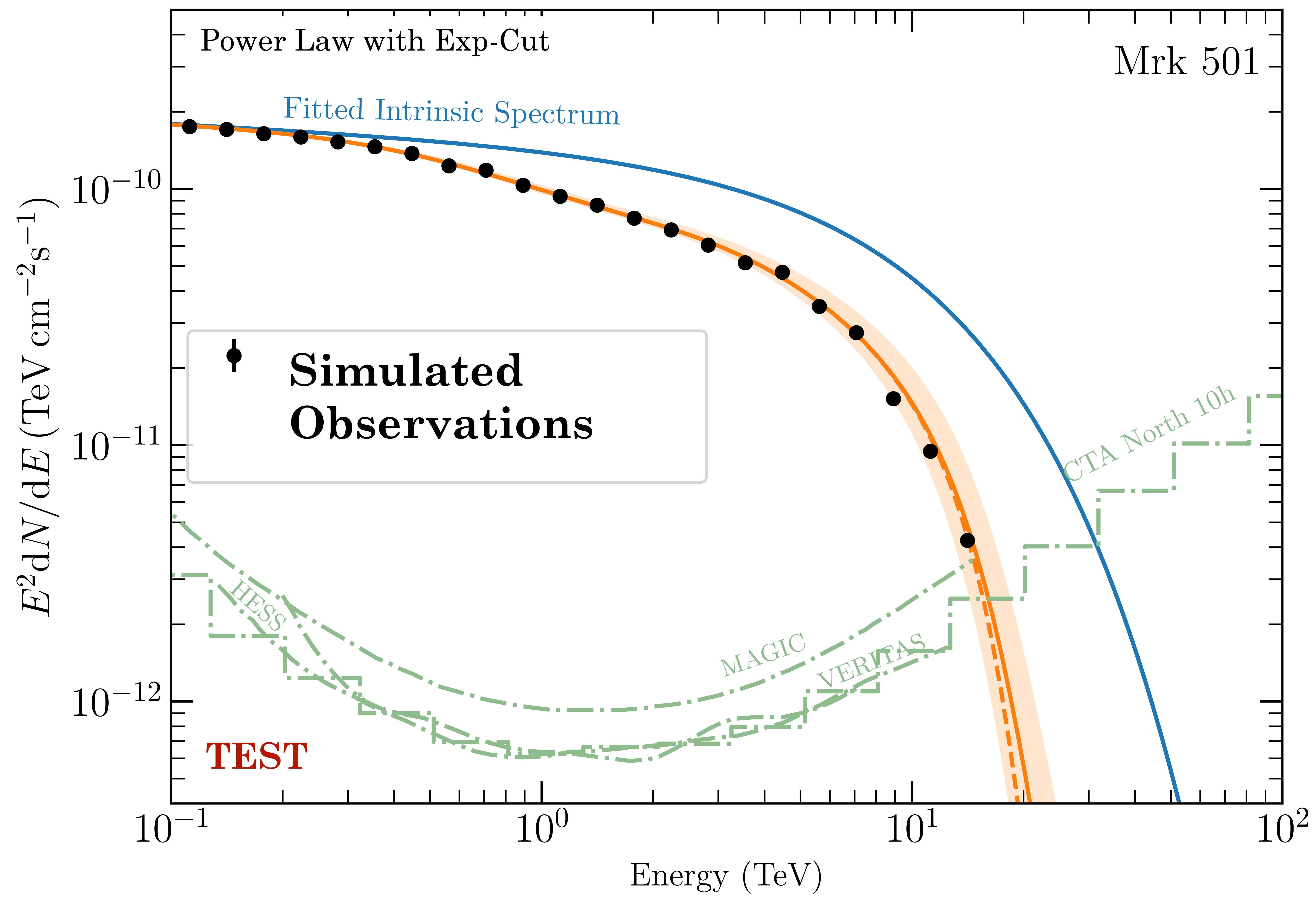
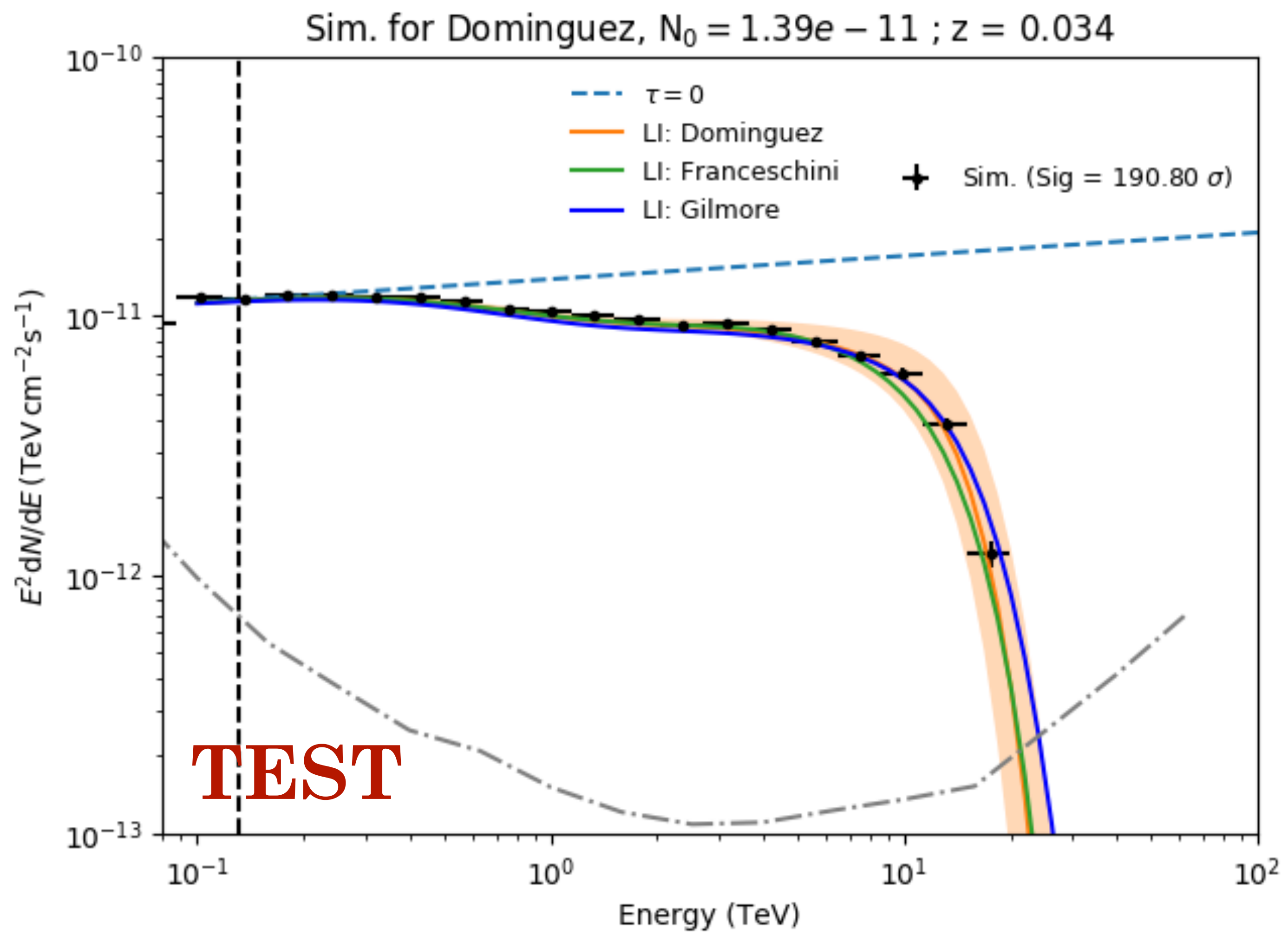
- Energy resolution
- Selection of spectra
- Selection of energy bins to be used in the calculation of the intrinsic energy spectra

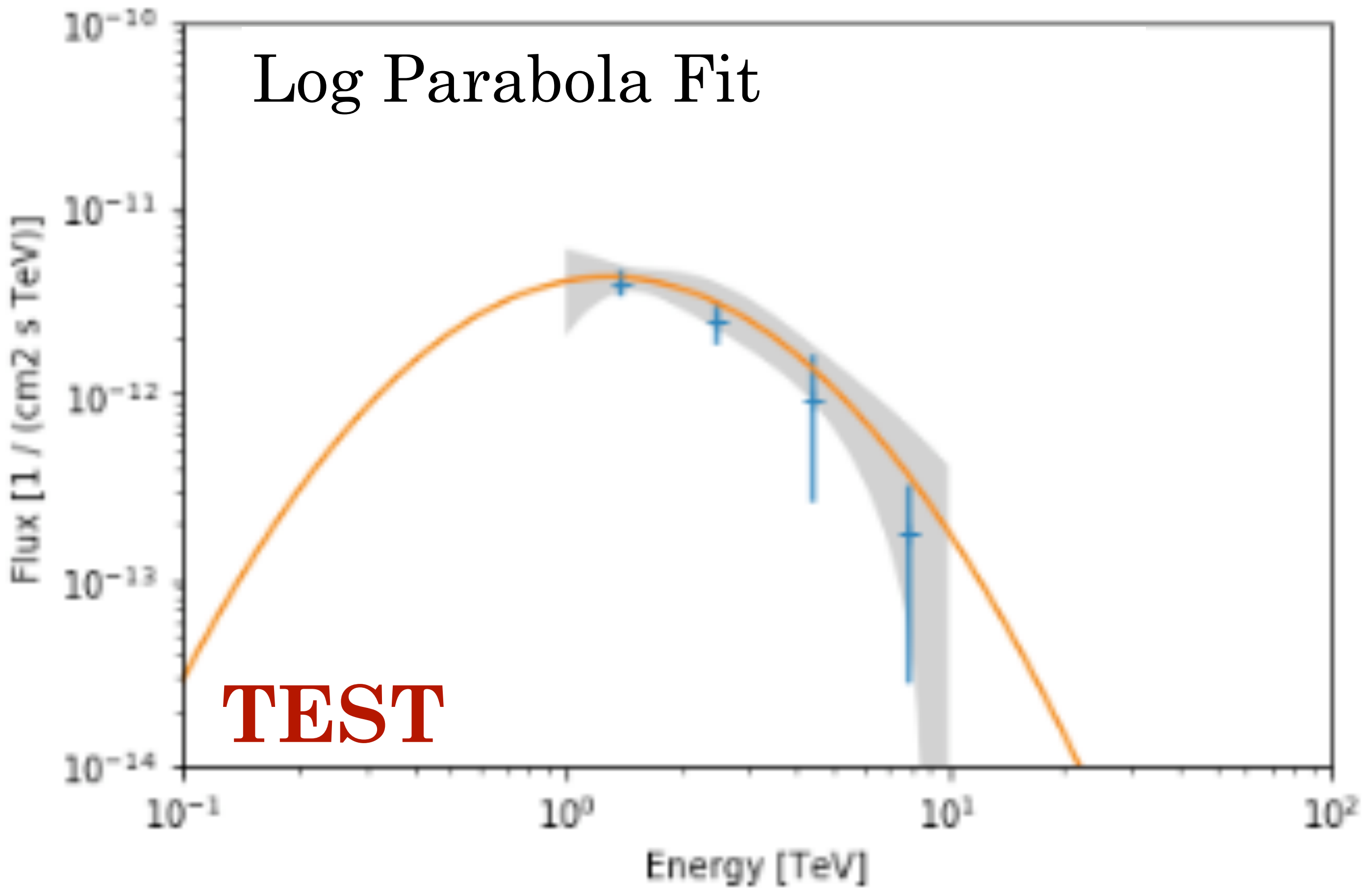
Analysis



Power Law with Exp-Cut
Mrk 501
Fitted Intrinsic Spectrum
Simulated Observations
CTA North 10h
HESS
MAGIC
VERITAS
TEST
$E^2 dN/dE$ (TeV cm^{-2}s^{-1})
Energy (TeV)



Sim. for Dominguez, $N_0 = 1.39e-11$; z = 0.034
$\tau = 0$
LI: Dominguez
LI: Franceschini
LI: Gilmore
Sim. (Sig = 190.80 σ)
TEST
Energy (TeV)



Log Parabola Fit
TEST
Flux [1 / (cm2 s TeV)]
Energy [TeV]

Work cases

Two possible scenarios

- **Finding LIV signal**

  Input LIV simulations and find CTA detection.

- **Excluding LIV signal**

  Input LI simulations and find CTA LIV rejection.

Work cases

Two possible scenarios

- **Finding LIV signal**

  Input LIV simulations and find CTA detection.

- **Excluding LIV signal**

  Input LI simulations and find CTA LIV rejection.

Finding LIV signal

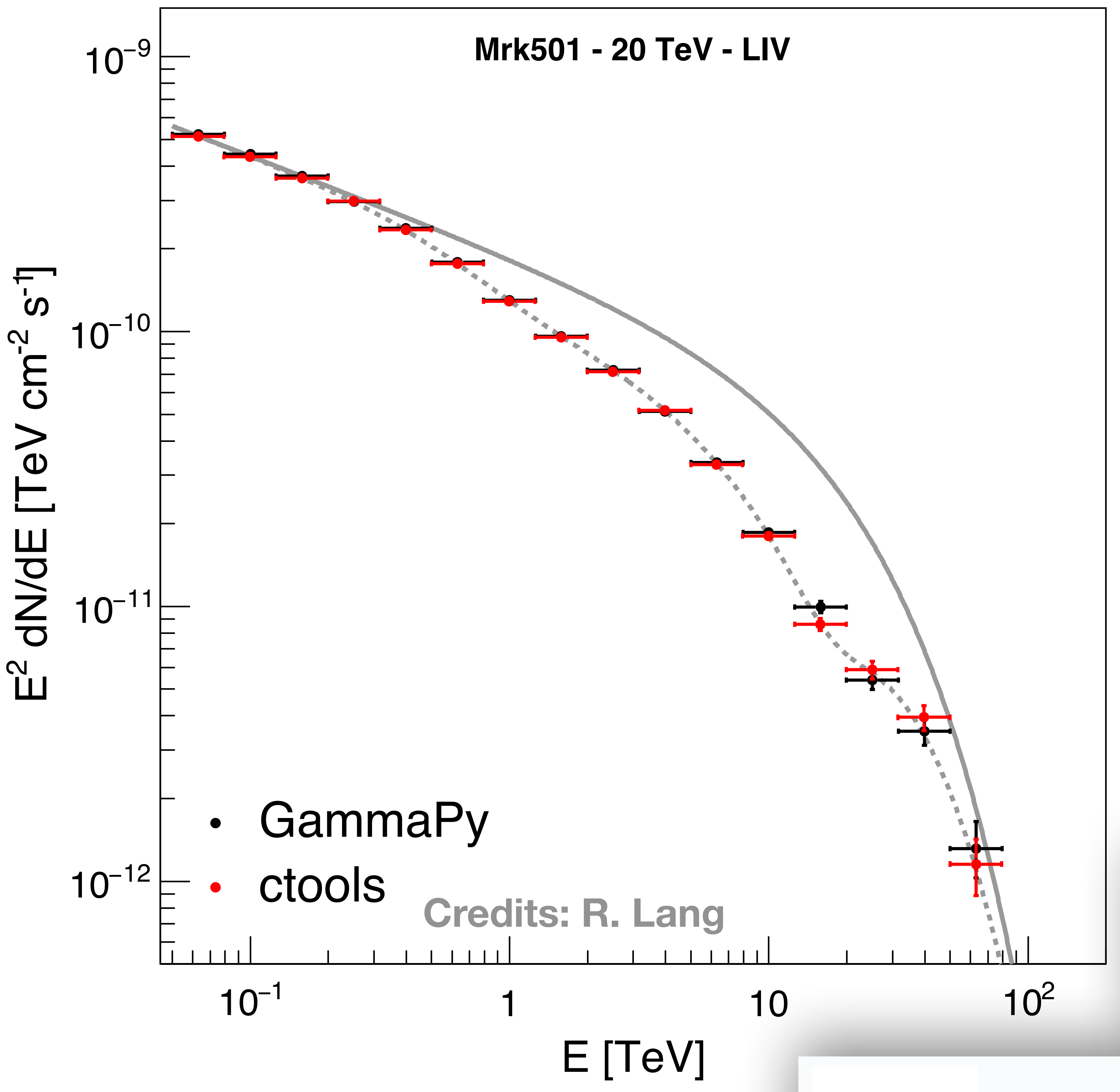
1. LIV- Simulation

2. Find the best Fit_{-LIV}

3. Find the best Fit_{-LI}

4. LIV signal significance

Simulation cross-check



Finding LIV signal

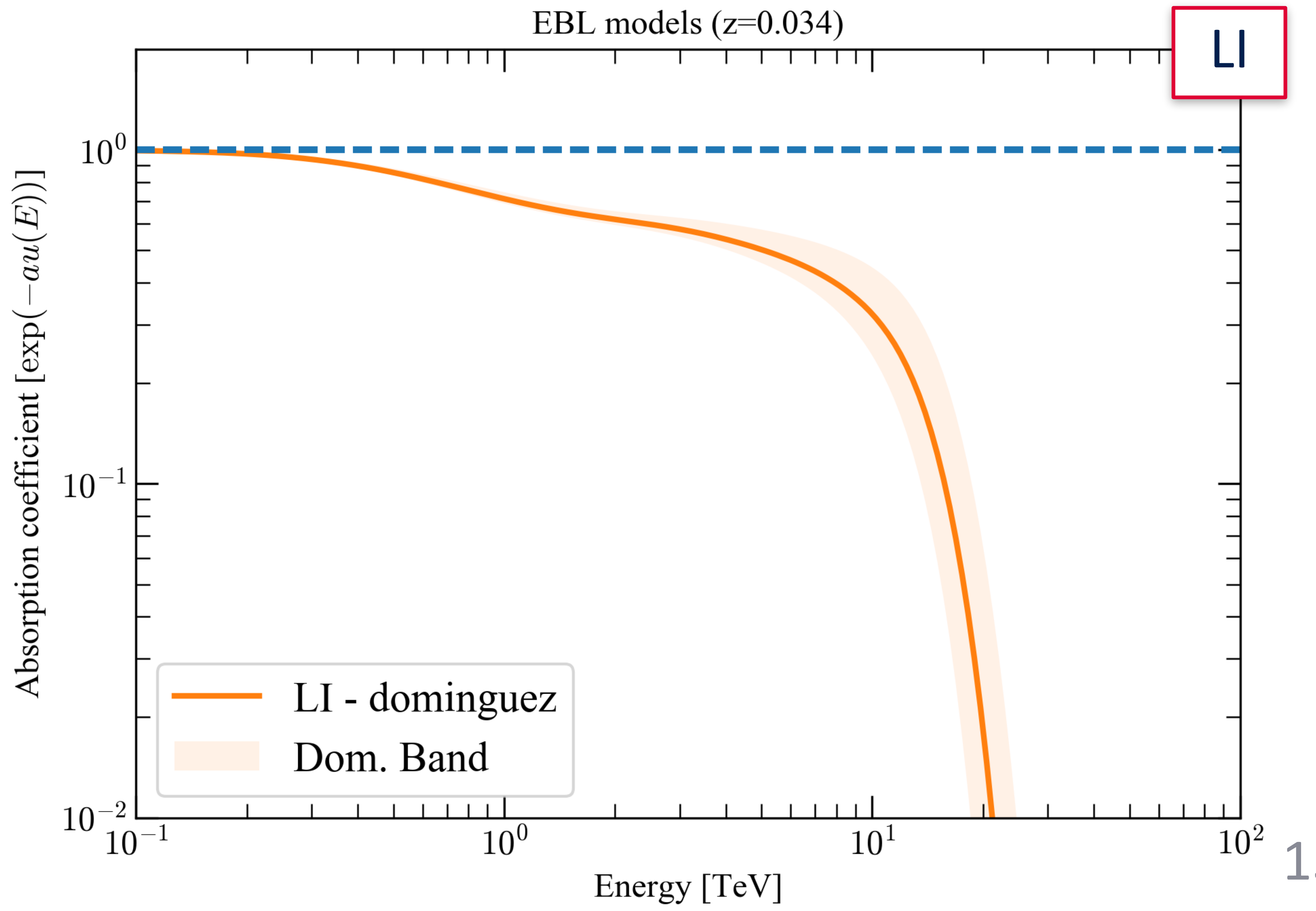
1. LIV- Simulation

2. Find the best **Fit$_{-LI}$**

3. Find the best **Fit$_{-LIV}$**

4. LIV signal significance

Free parameters
N_0 [TeV^{-1} cm^2 s^{-1}]
Index
Ec [TeV]



Finding LIV signal

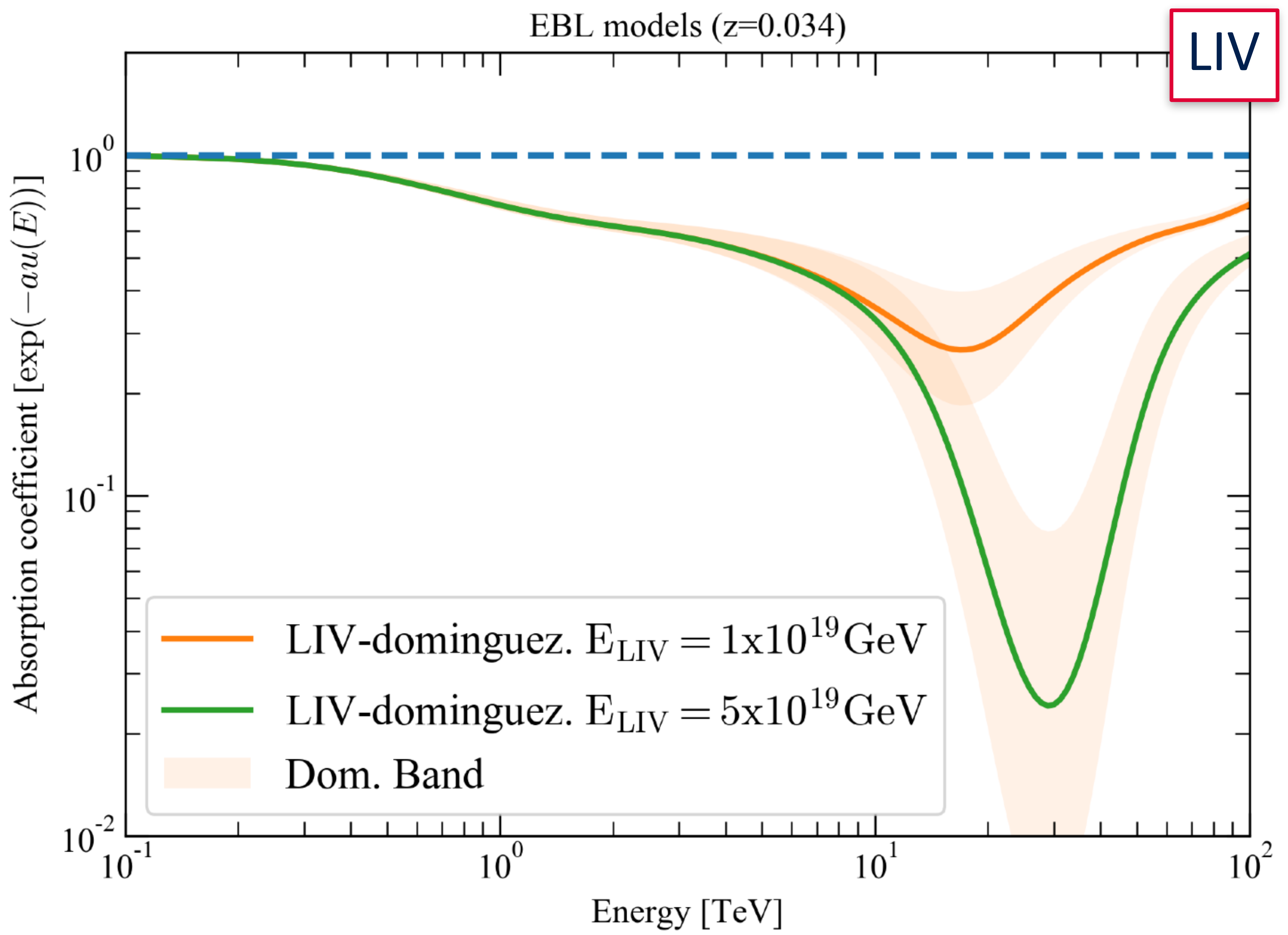
1. LIV- Simulation

2. Find the best **Fit$_{\text{-LI}}$**

3. Find the best **Fit$_{\text{-LIV}}$**

4. LIV signal significance

Free parameters
E_{LIV} [GeV]
N_0 [TeV^{-1} cm^2 s^{-1}]
Index
Ec [TeV]



Finding LIV signal

1. LIV- Simulation
2. Find the best **Fit$_{\text{-LI}}$**
3. Find the best **Fit$_{\text{-LIV}}$**
4. LIV signal significance

×

Src - cases

- **Mrk501**
  - Scenario A
  - Scenario B
- **1ES 0229+200**
  - …

×

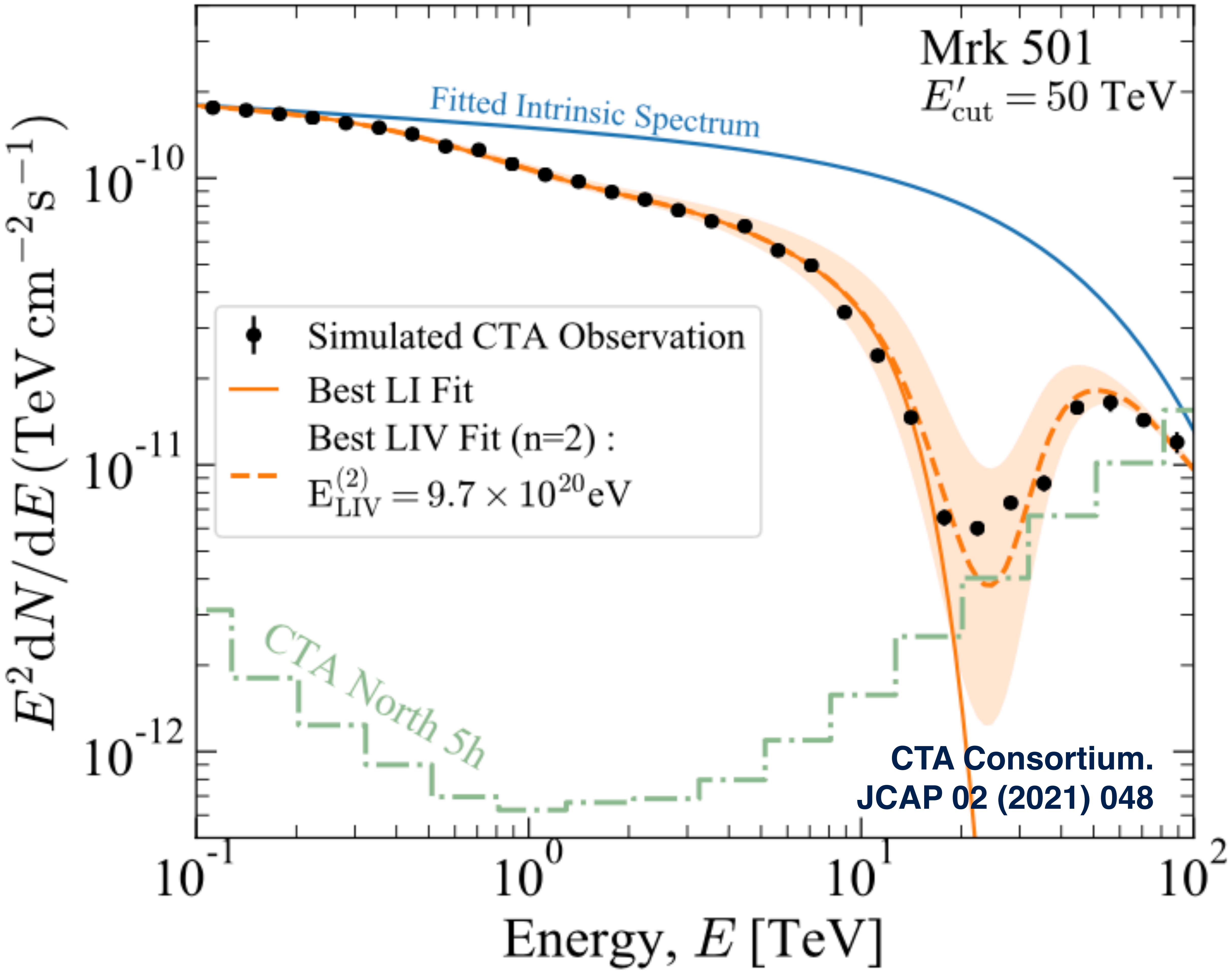
n=1

n=2

gammapy

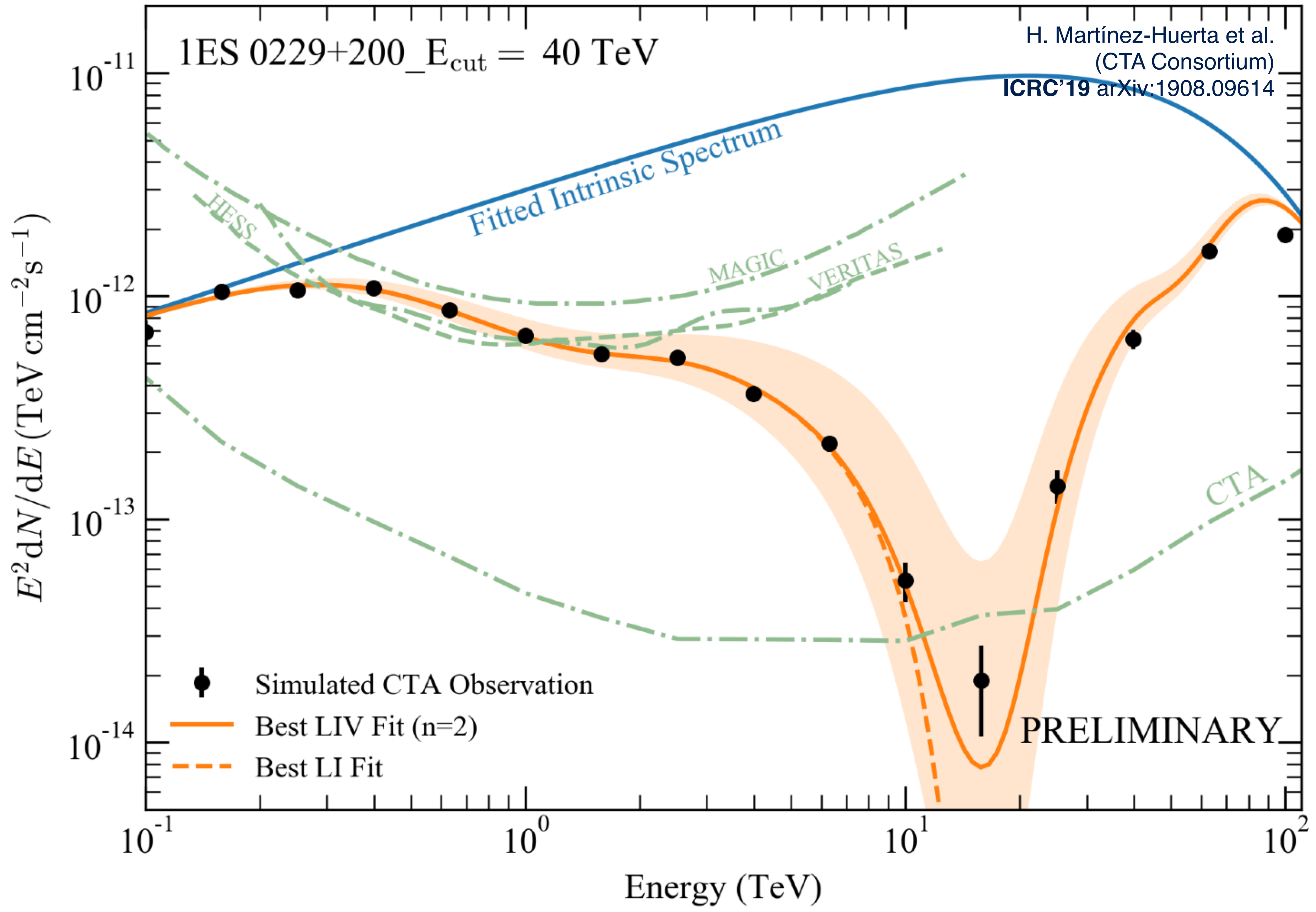
Gamma-ray astronomy Python tools

Finding LIV signal



Simulation of Mrk501 with E_{cut} = 50TeV assuming LIV with $E^{(2)}_{LIV} = 10^{21}$ eV

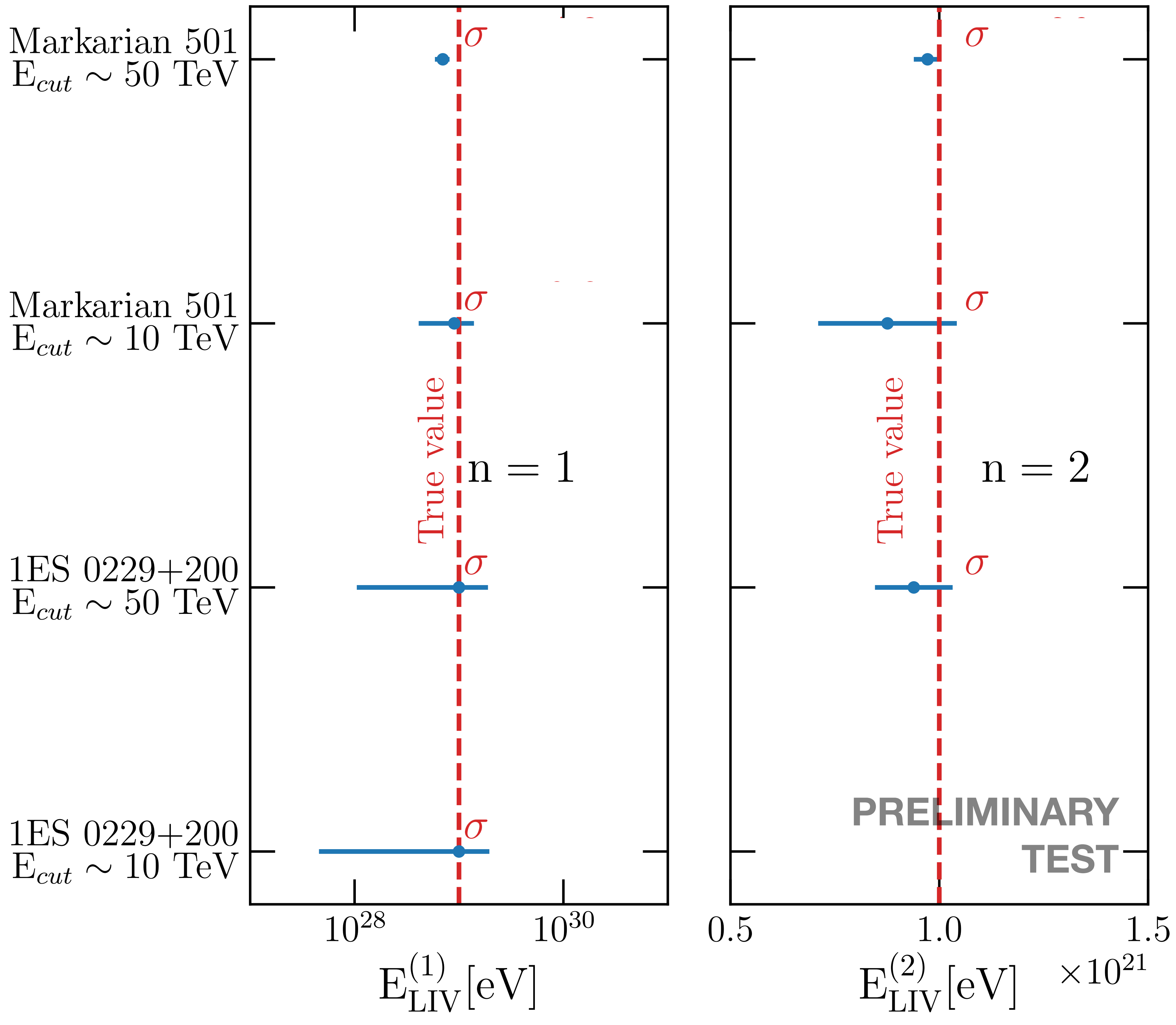
Simulation of 1ES 0229+200 with E_{cut} = 40 TeV assuming LIV with $E^{(2)}_{LIV} = 10^{21}$ eV



Finding LIV signal

1. LIV- Simulation
2. Find the best $\mathbf{Fit}_{\text{-LI}}$
3. Find the best $\mathbf{Fit}_{\text{-LIV}}$
4. LIV signal significance

Agreement between best-fit parameters and the simulated true values.

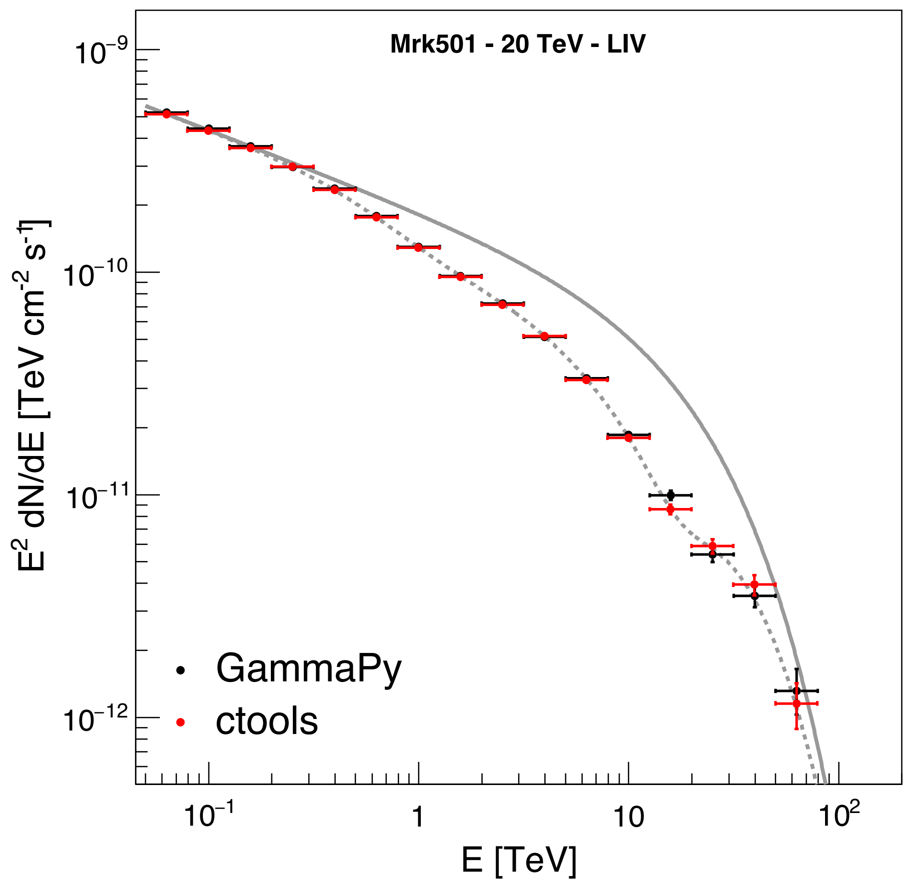


Probing physics up to the Planck scale and above

CTA potential to find a LIV signal

Input LIV simulations and find CTA detection.

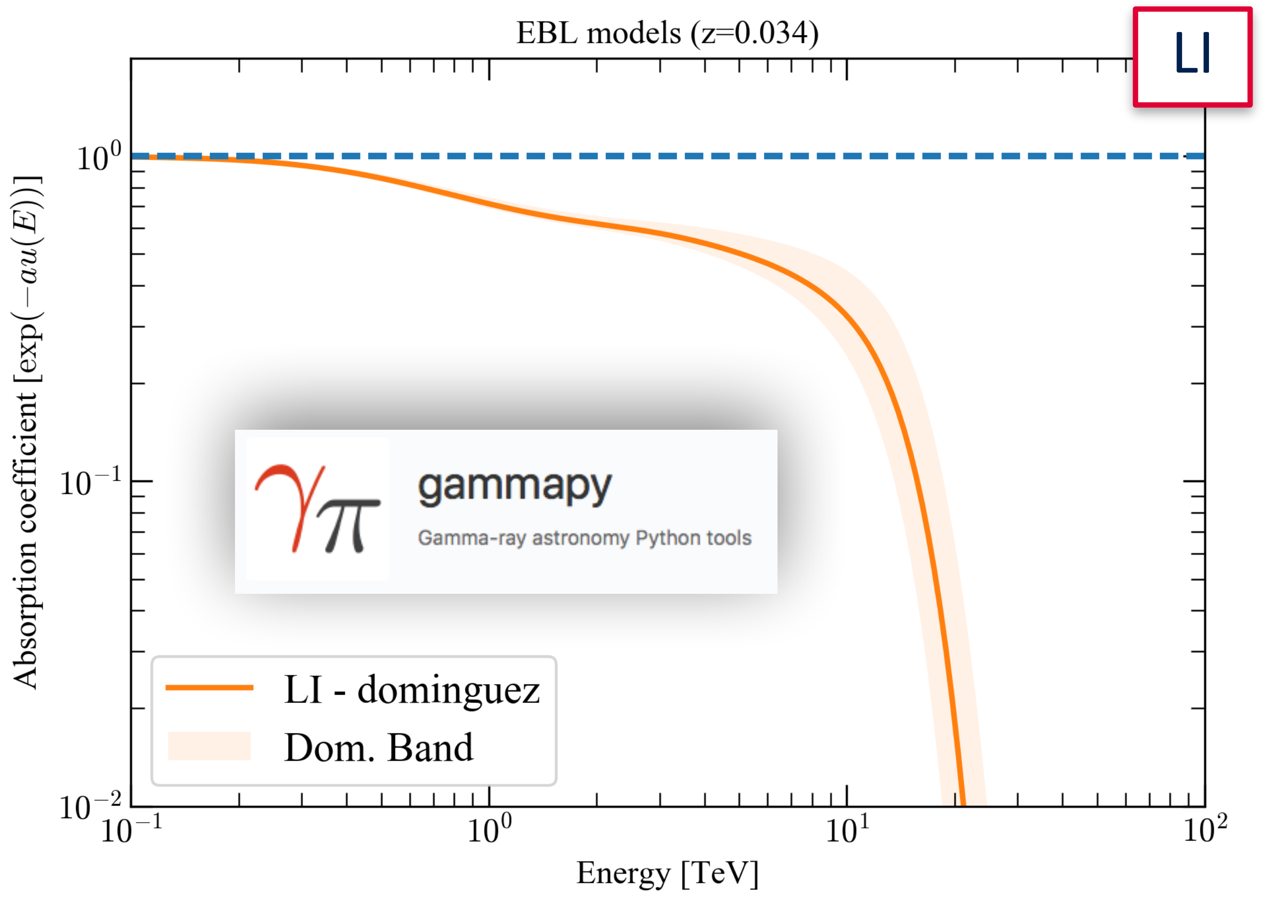
1. LIV- Simulation



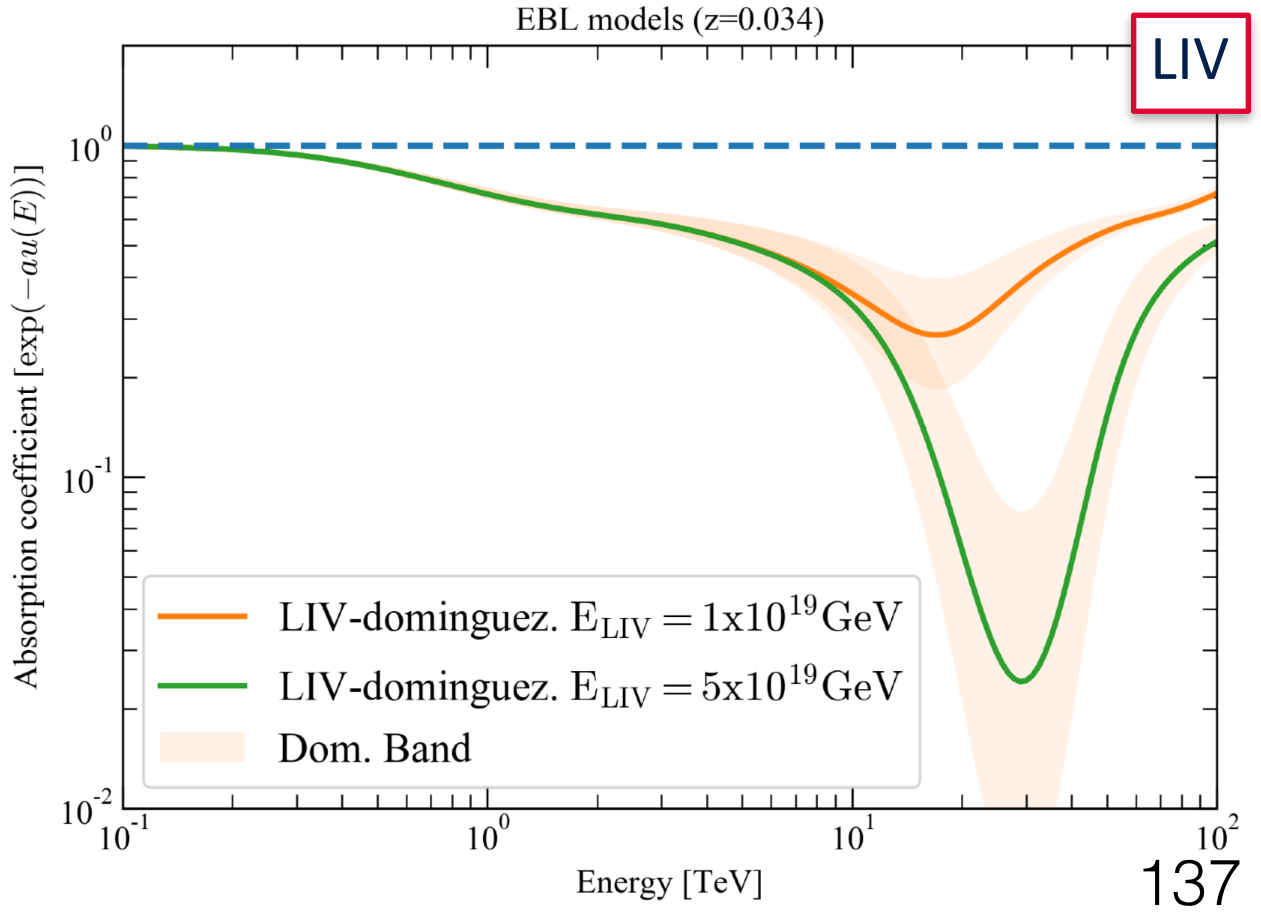
ctools
gammapy
Gamma-ray astronomy Python tools

- Source parameter x2-Src, x2-cases
- Analysis Parameters
- LIV Parameters x2 (n=1,2)
- ELB model x2 (LI/LIV)

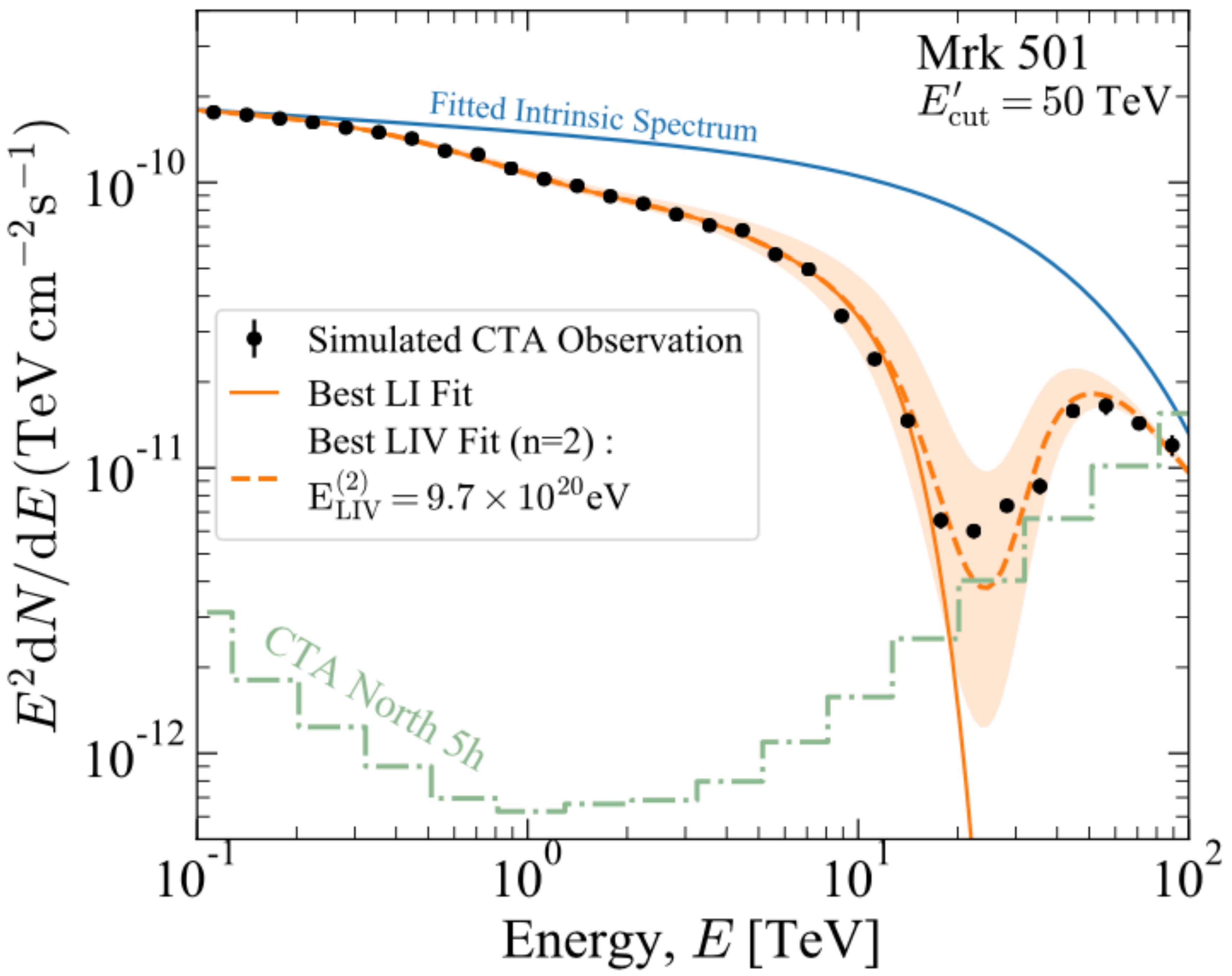
2. Find the best **Fit-LI**



3. Find the best **Fit-LIV**



4. LIV signal significance



Simulation of Mrk501 with E_{cut} = 50TeV assuming LIV with $E^{(2)}_{LIV} = 10^{21}$ eV

Agreement between best-fit parameters and the simulated true values.

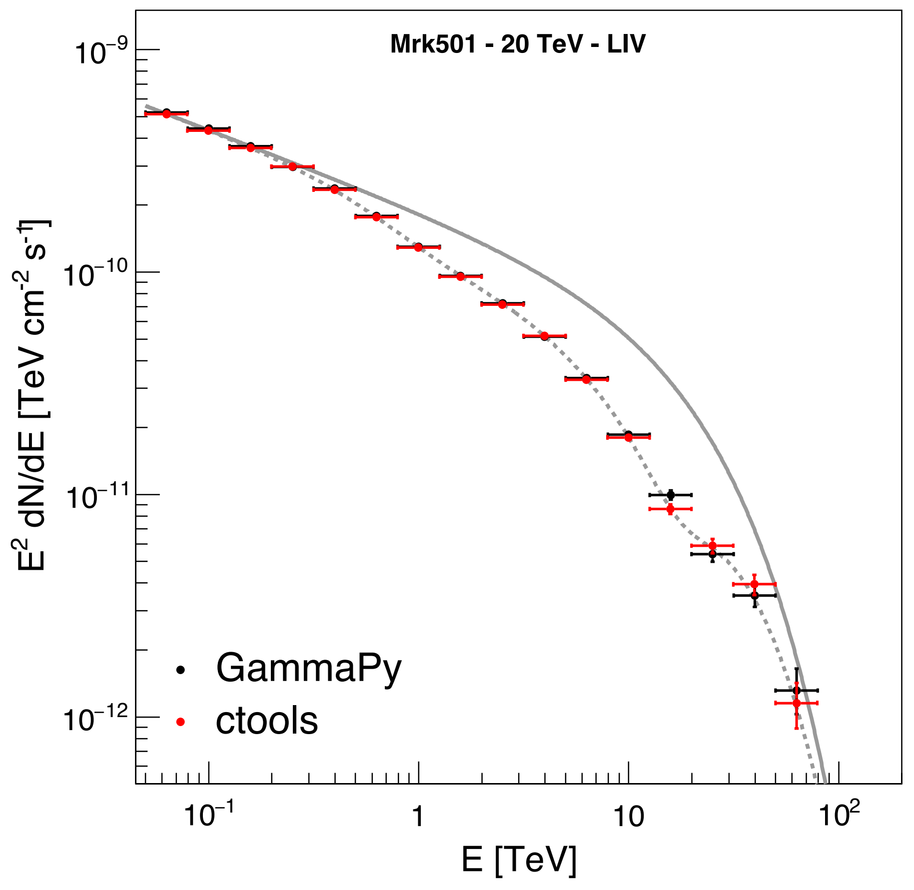
CTA Consortium.
JCAP 02 (2021) 048

Probing physics up to the Planck scale and above

❖ CTA potential to find a LIV signal

Input LIV simulations and find CTA detection.

1. LIV- Simulation



- Source parameter x2-Src, x2-cases
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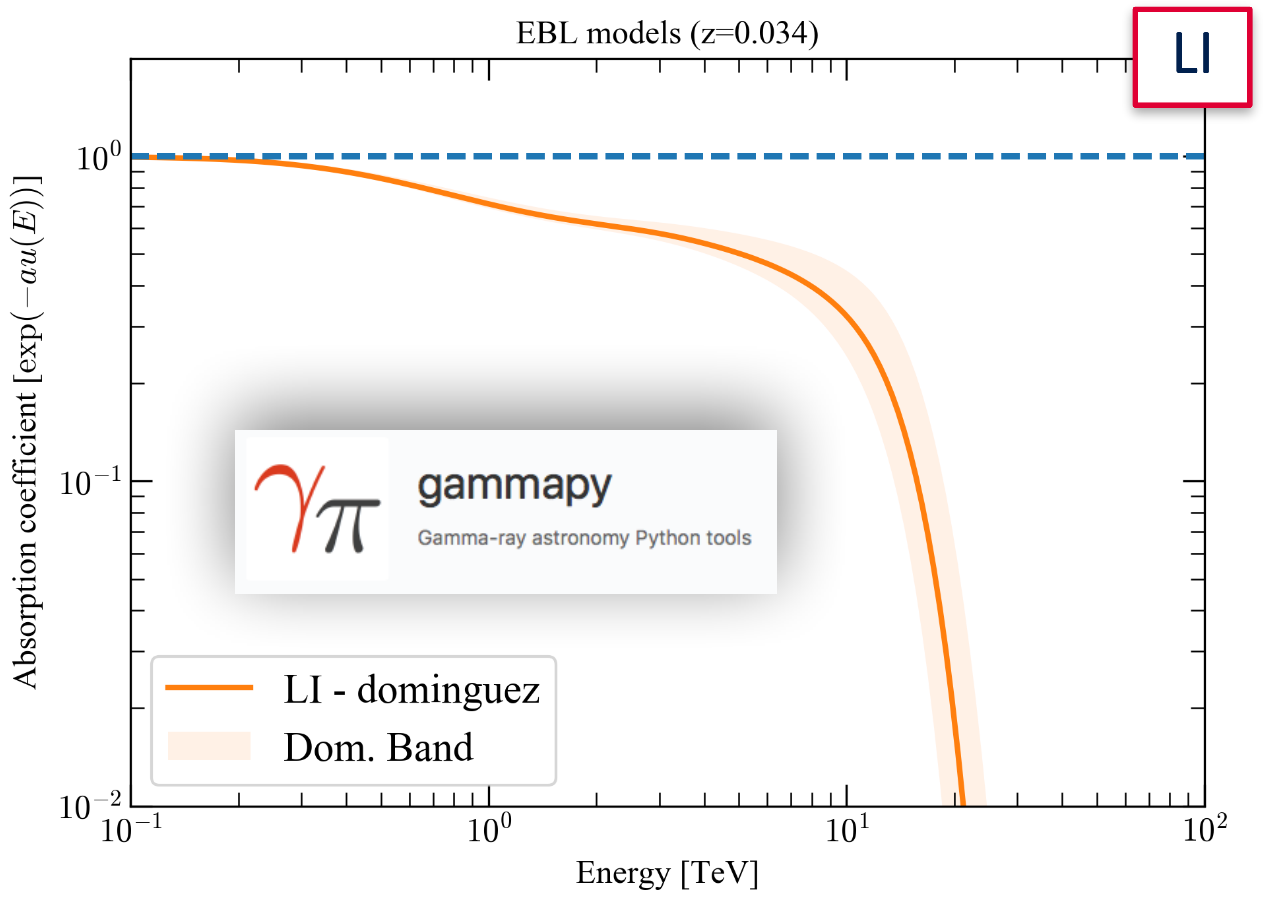
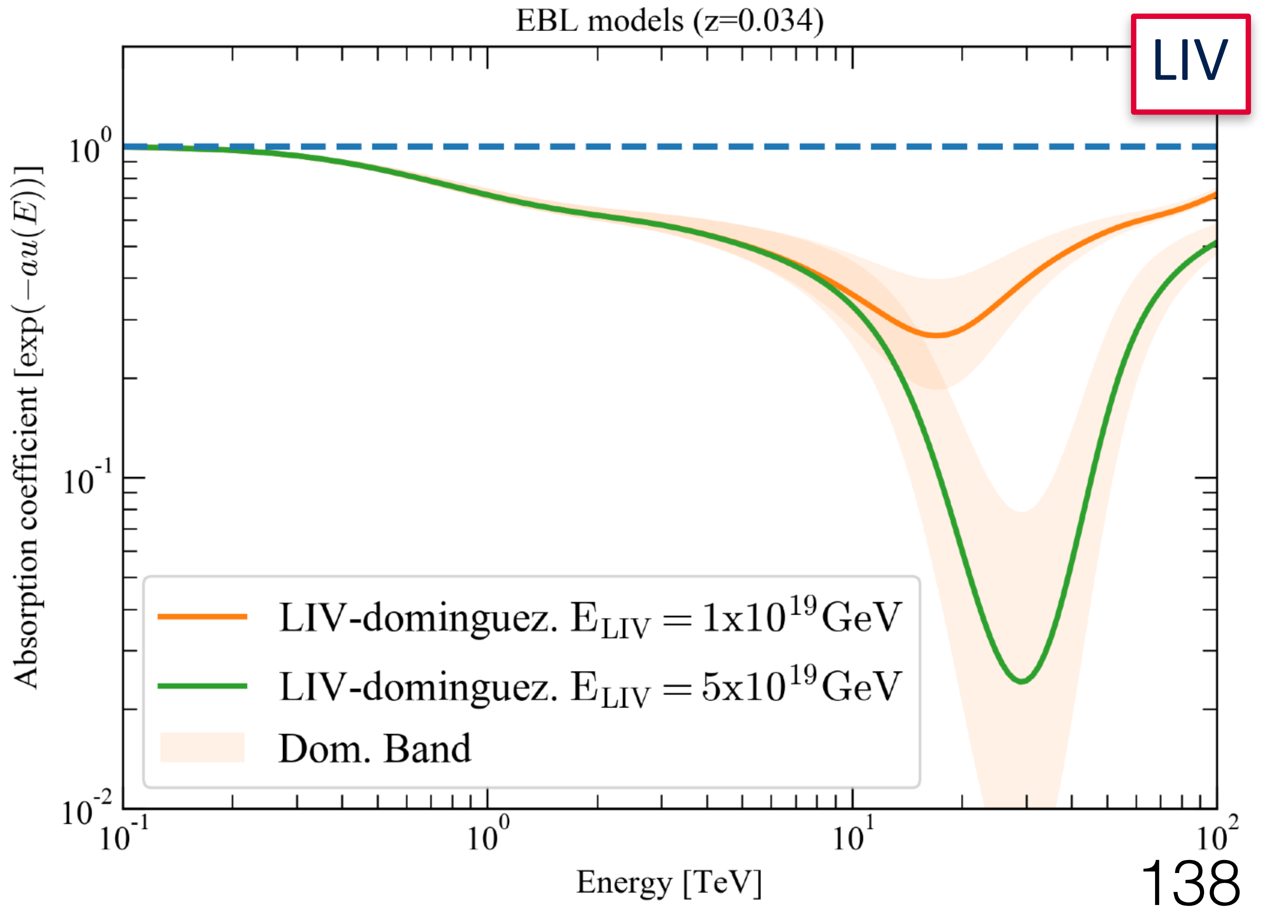
- LIV Parameters x2 (n=1,2)
- ELB model x2 (LI/LIV)

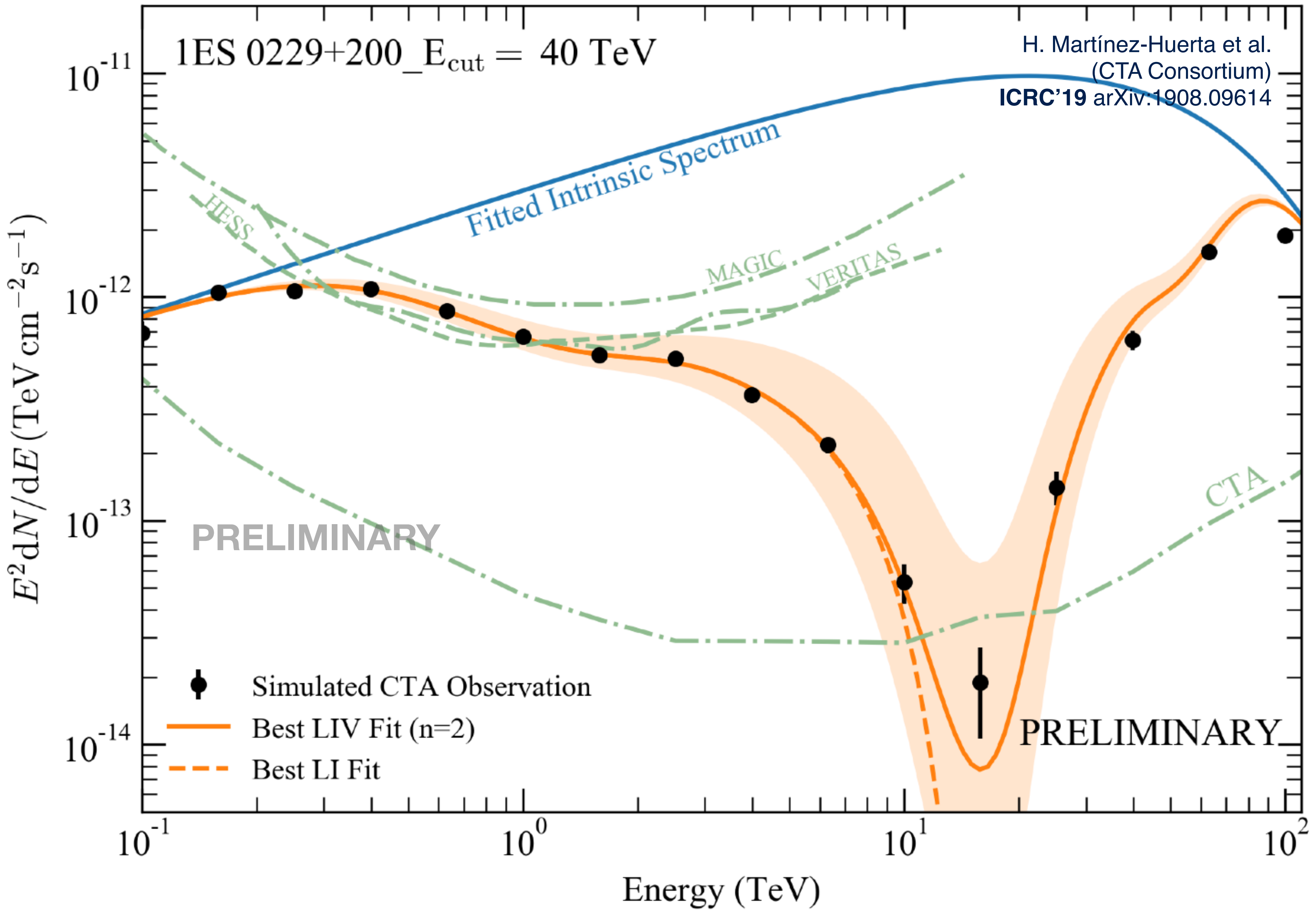
2. Find the best **Fit-LI**



3. Find the best **Fit-LIV**



4. LIV signal significance



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Agreement between best-fit parameters and the simulated true values.

CTA Consortium.
JCAP 02 (2021) 048

Work cases

Two possible scenarios

- **Finding LIV signal**

  Input LIV simulations and find CTA detection.

- **Excluding LIV signal**

  Input LI simulations and find CTA LIV rejection.

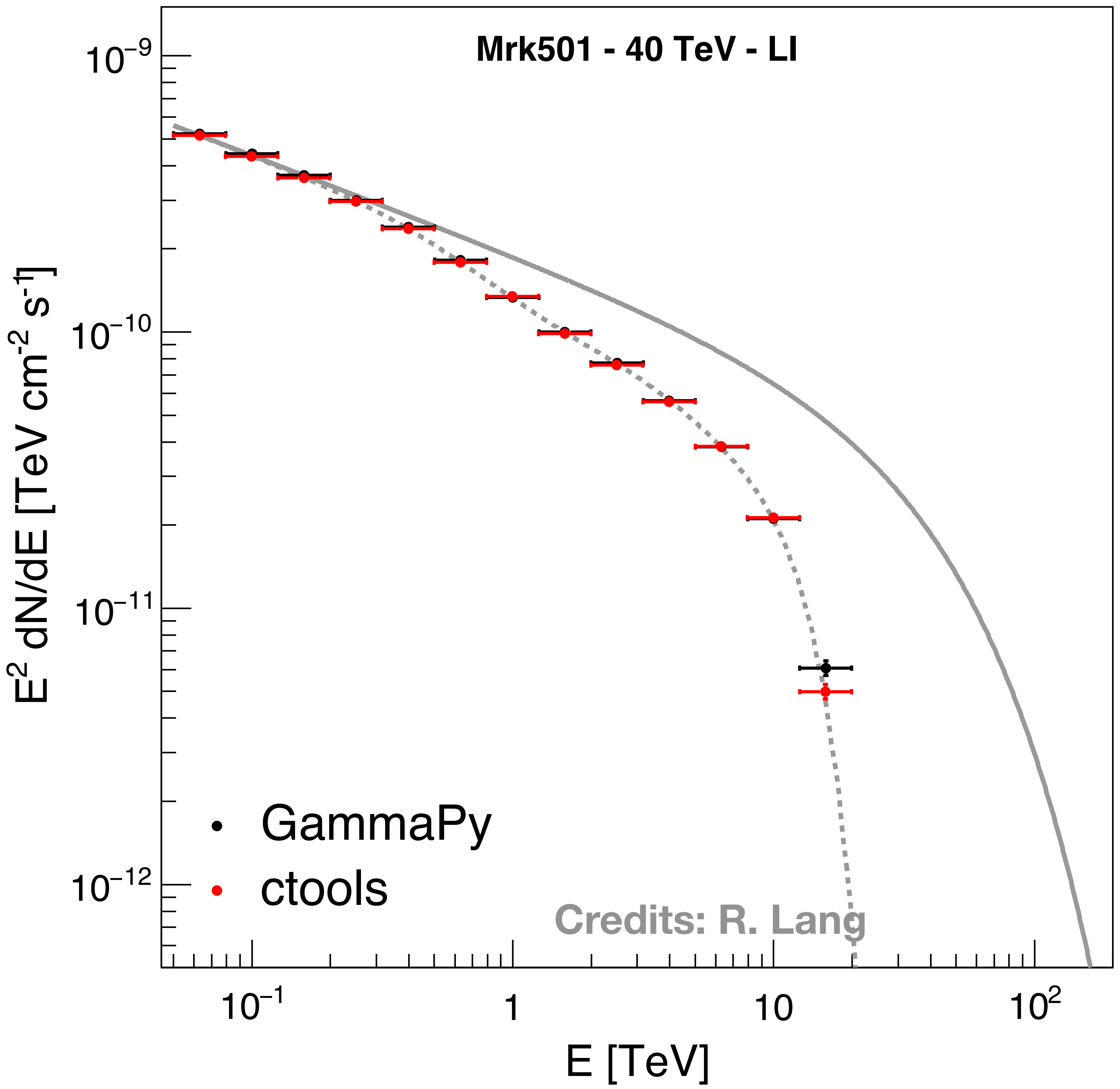
Excluding LIV signal

1. LI- Simulation ← Different step from the previous scenario
2. Find the best $\mathbf{Fit}_{\text{-LI}}$
3. Find the best $\mathbf{Fit}_{\text{-LIV}}$
4. Exclusion significance | **5 σ**, **3 σ**, **2 σ** ← Different step from the previous scenario

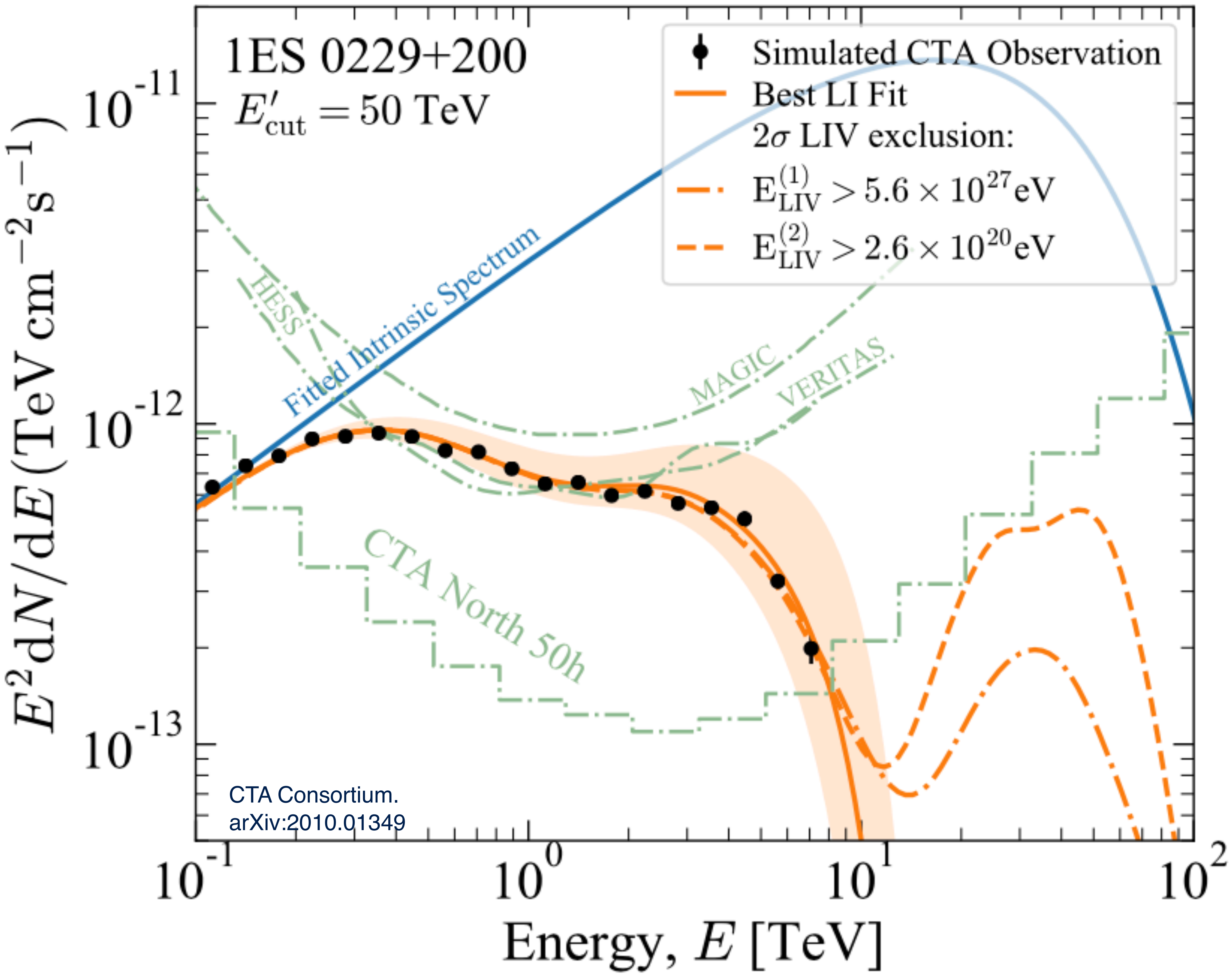
Excluding LIV signal

Simulation cross-check

1. LIV- Simulation
2. Find the best **Fit-LI**
3. Find the best **Fit-LIV**
4. Exclusion significance



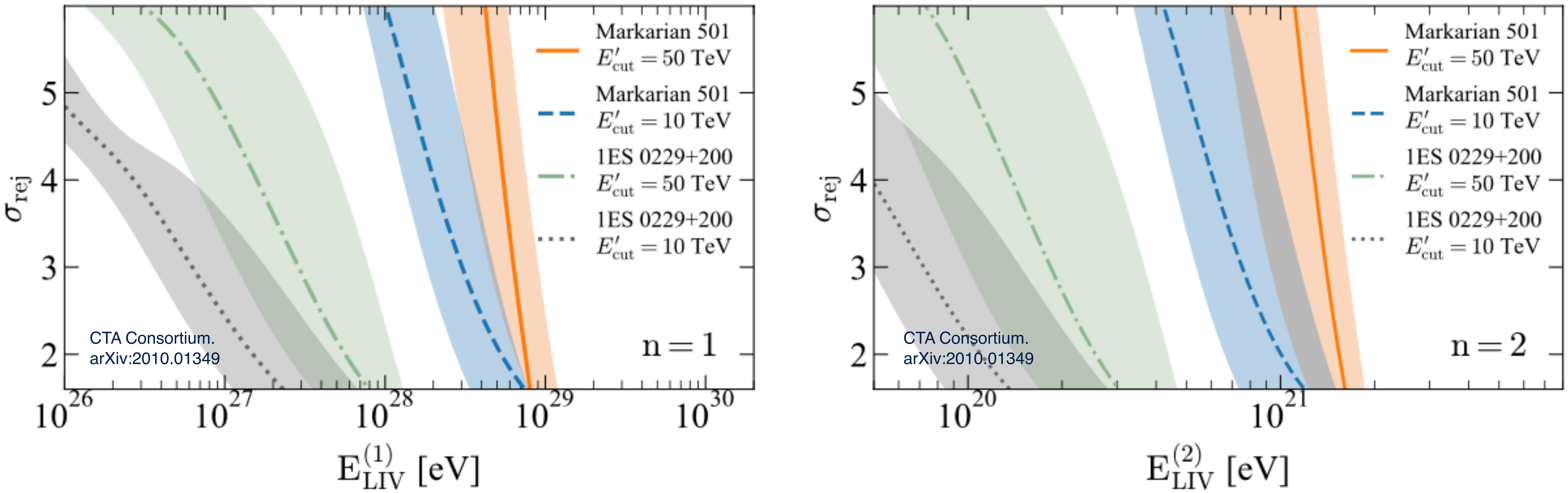
Excluding LIV signal



Simulation of 1ES0229+200 with E_{cut} = 50TeV and LI propagation.

The LIV models excluded at 2 σ for n = 1 and 2 are also shown for comparison

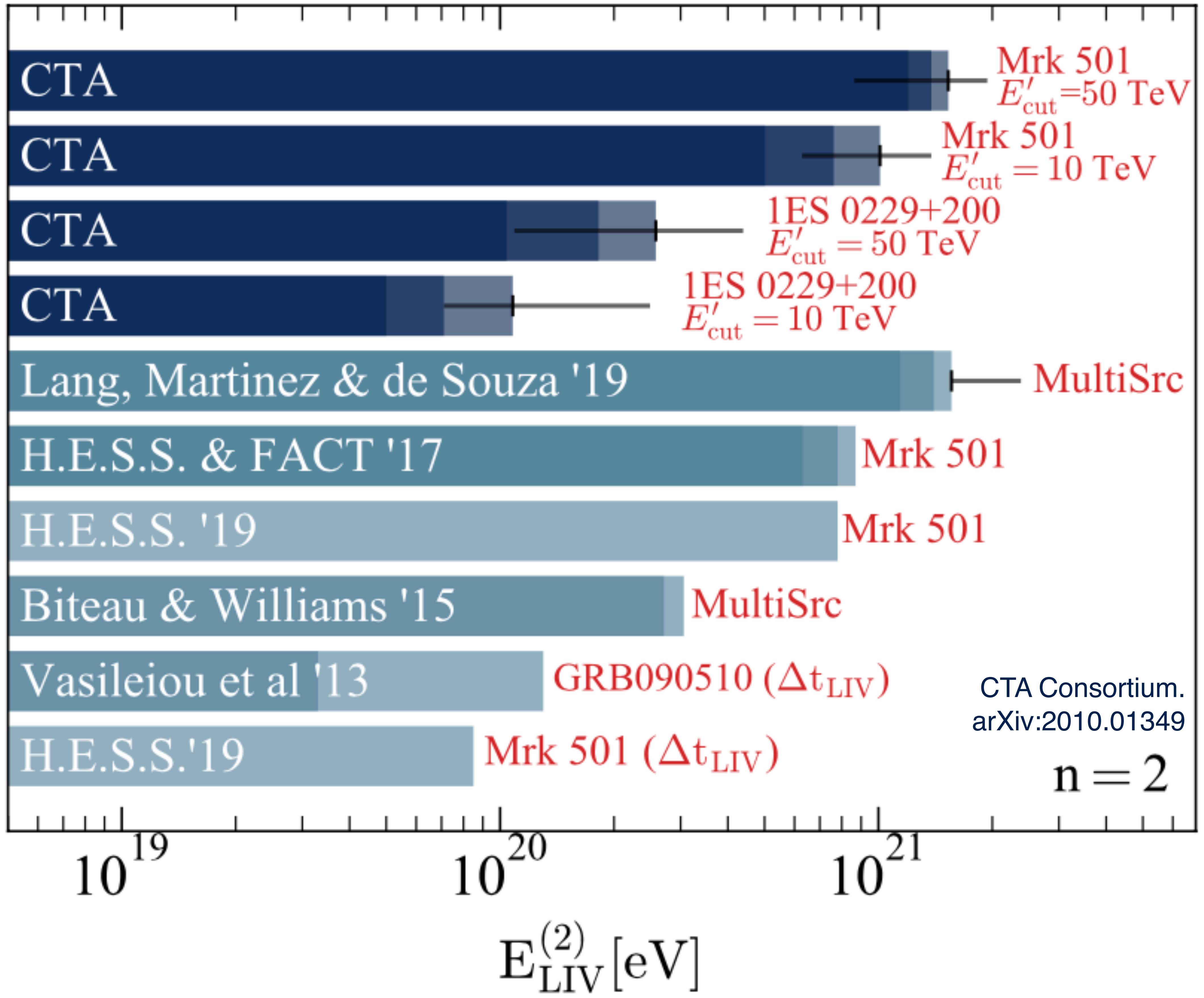
Excluding LIV signal



Confidence level for the rejection of LIV energy scales for n=1 and n=2,

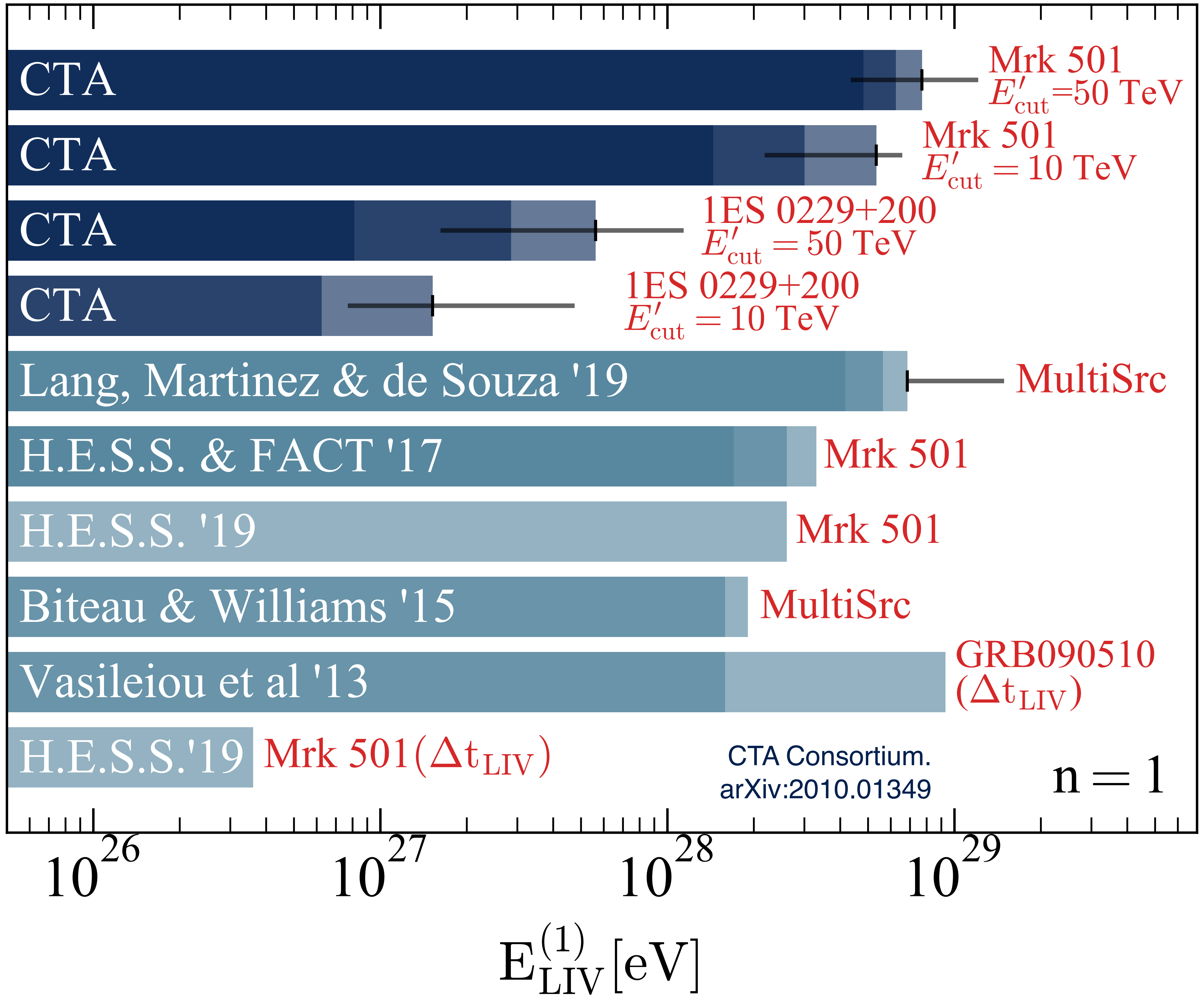
including the **EBL systematic error**

Excluding LIV signal



- CTA shows competitive sensitivity limits **using a single source analysis.**
- Better confidence levels are marked with darker colors.
- Systematic errors are shown in black for the 2σ limit.

Excluding LIV signal



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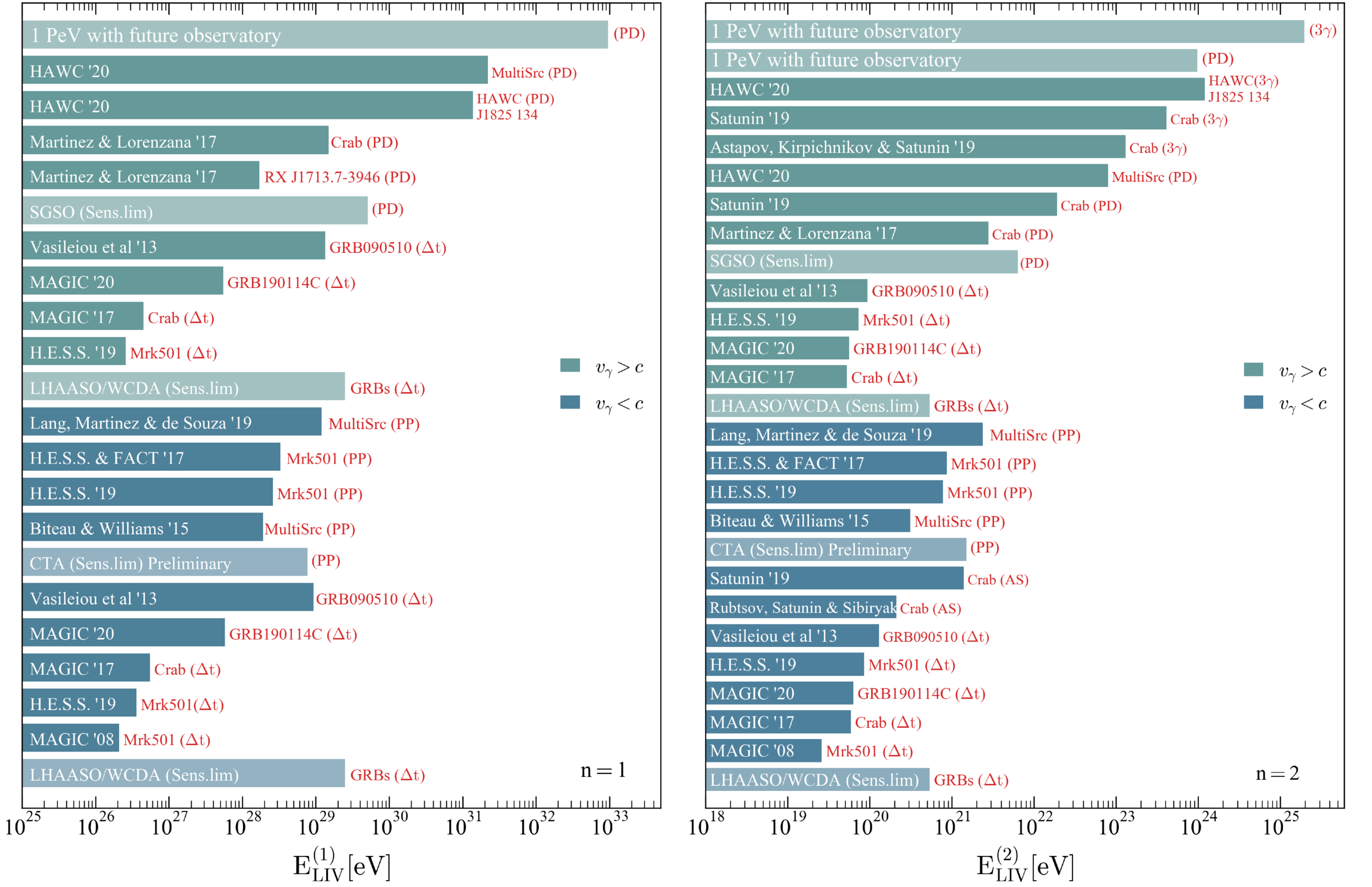
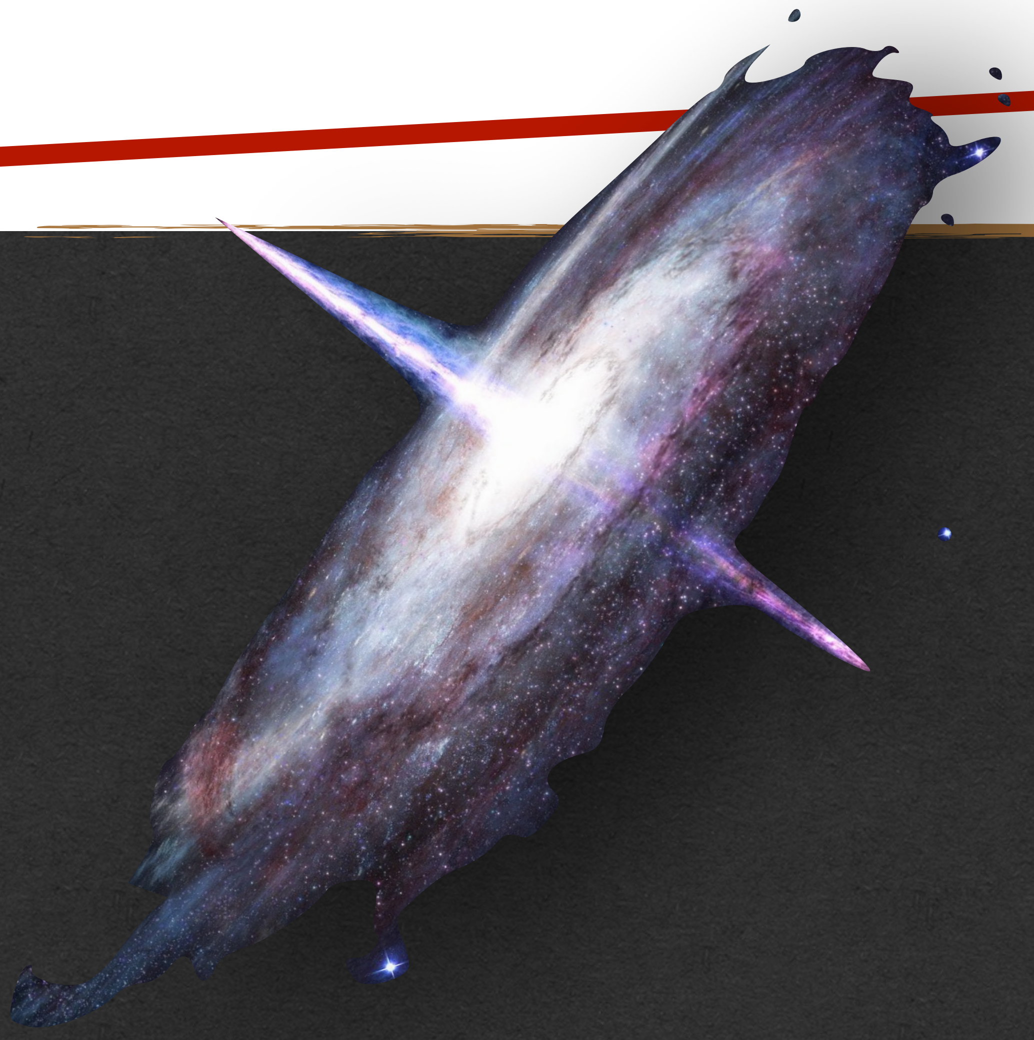
- Systematic errors are shown in black for the 2σ limit.

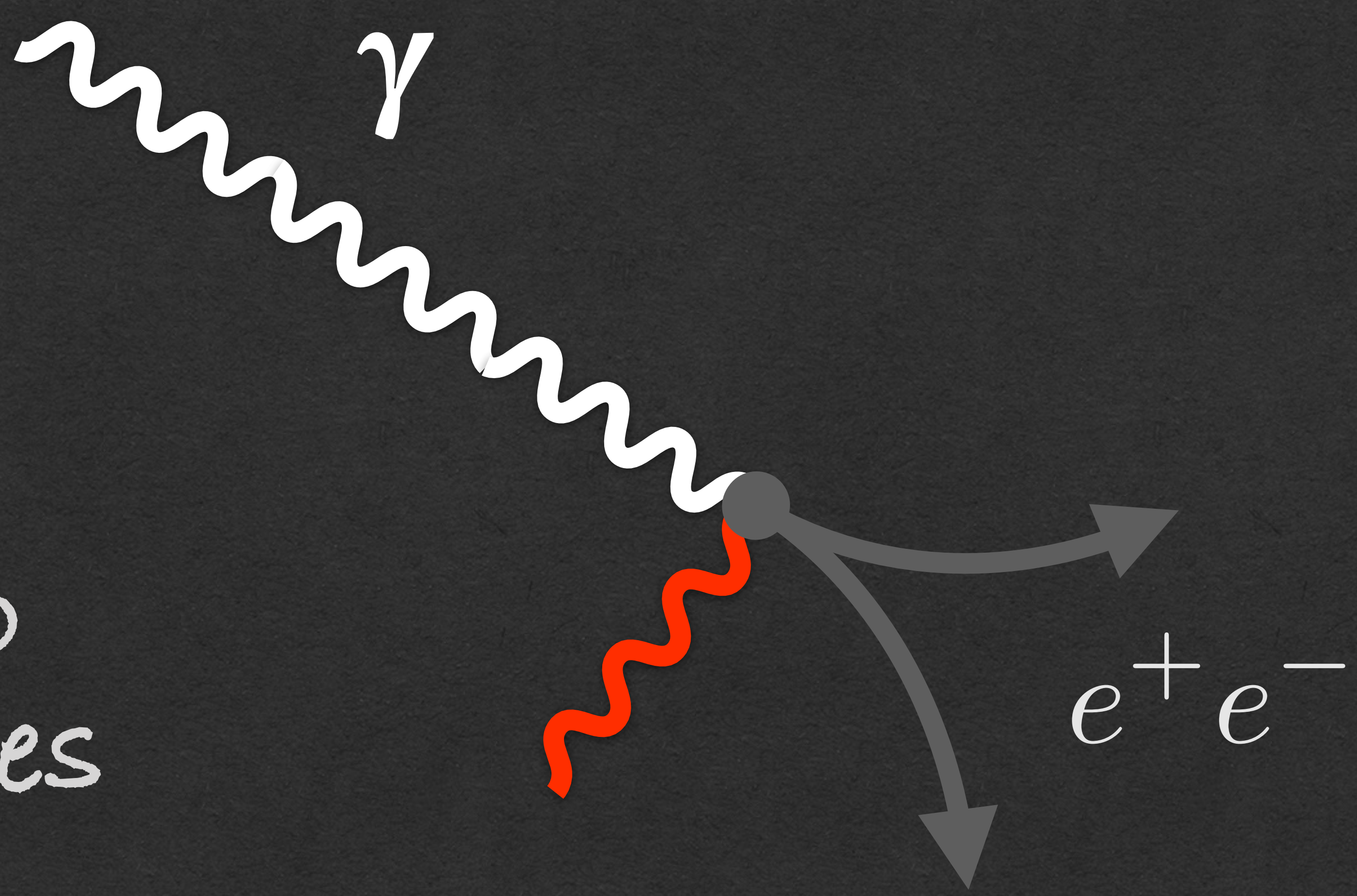
Strong LIV Exclusion limits in the photon sector by astroparticle tests

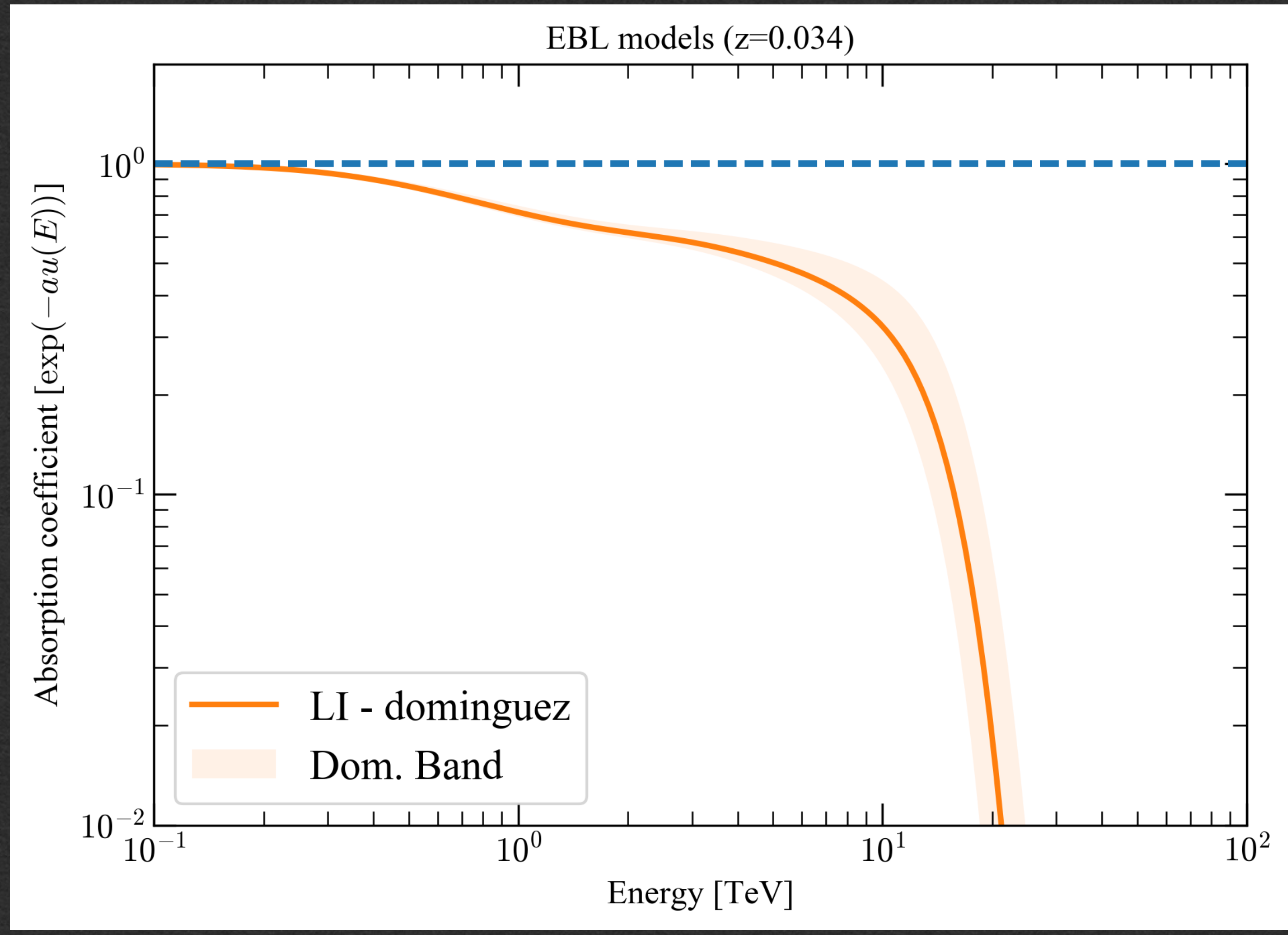


Based on:
Symmetry 2020, 12, 1232.

~~Test of Lorentz invariance violation~~

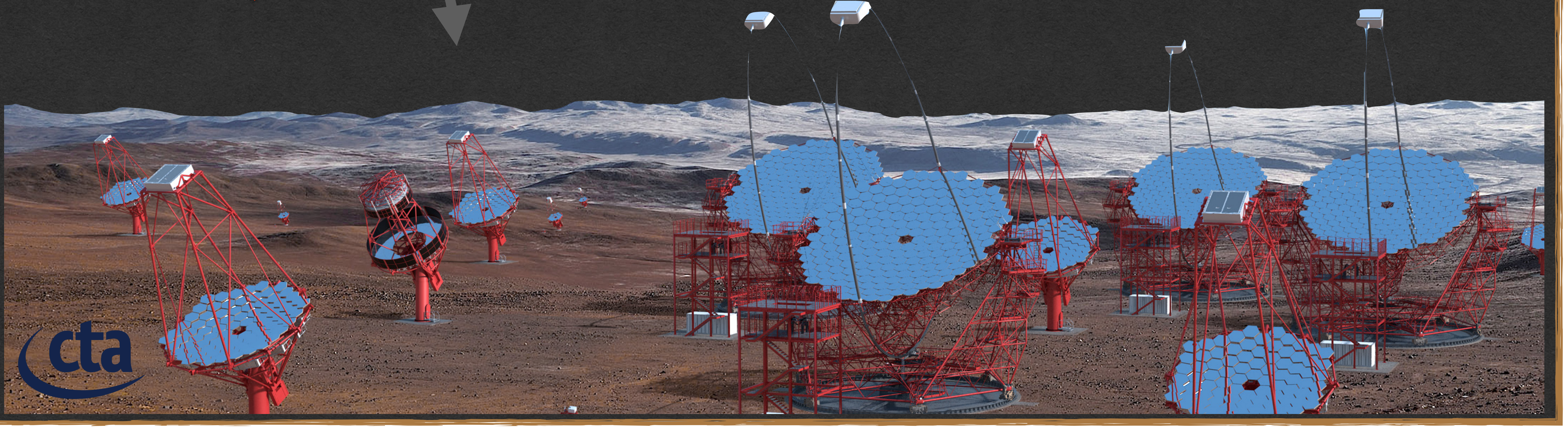




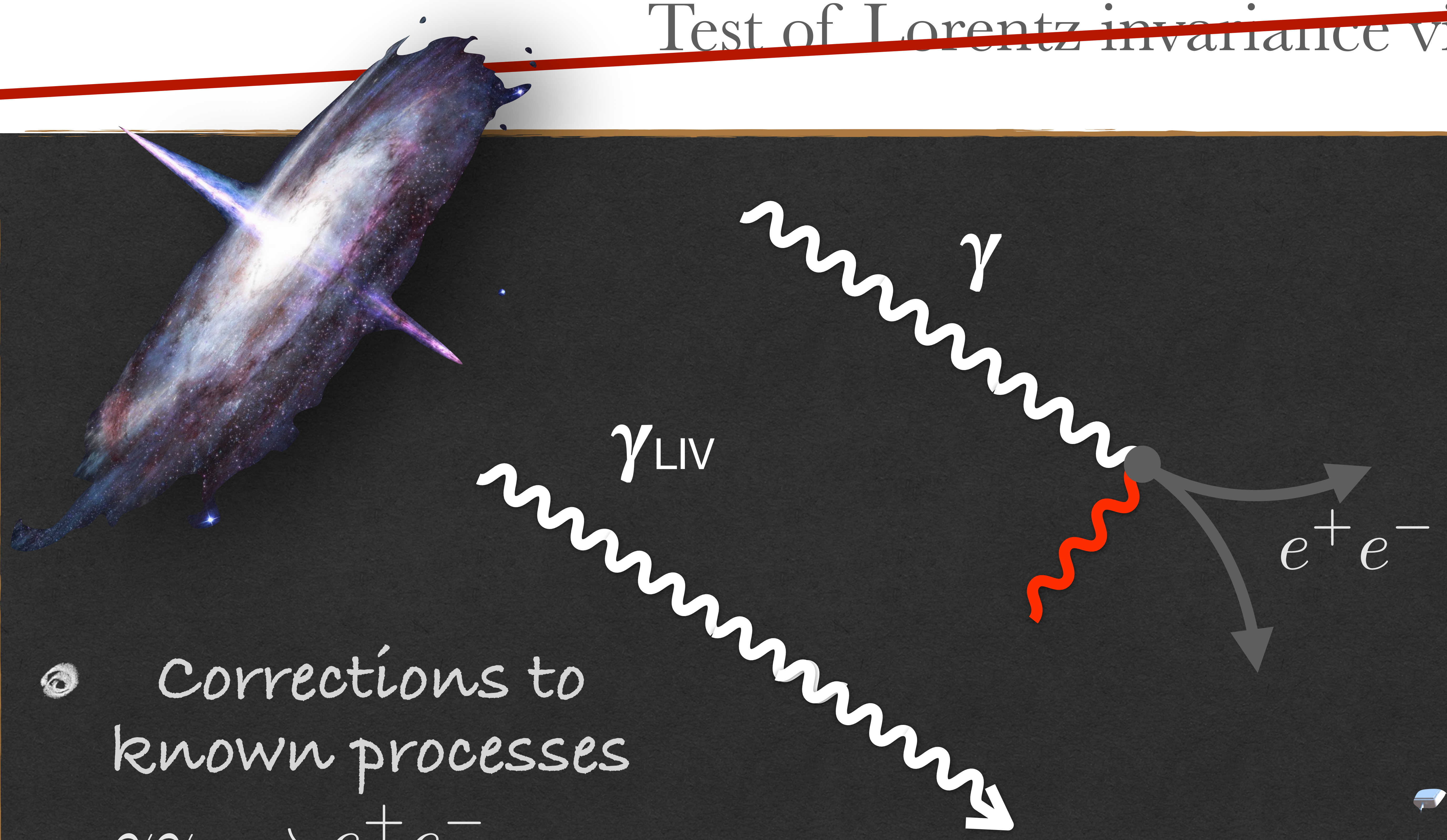


- Corrections to known processes

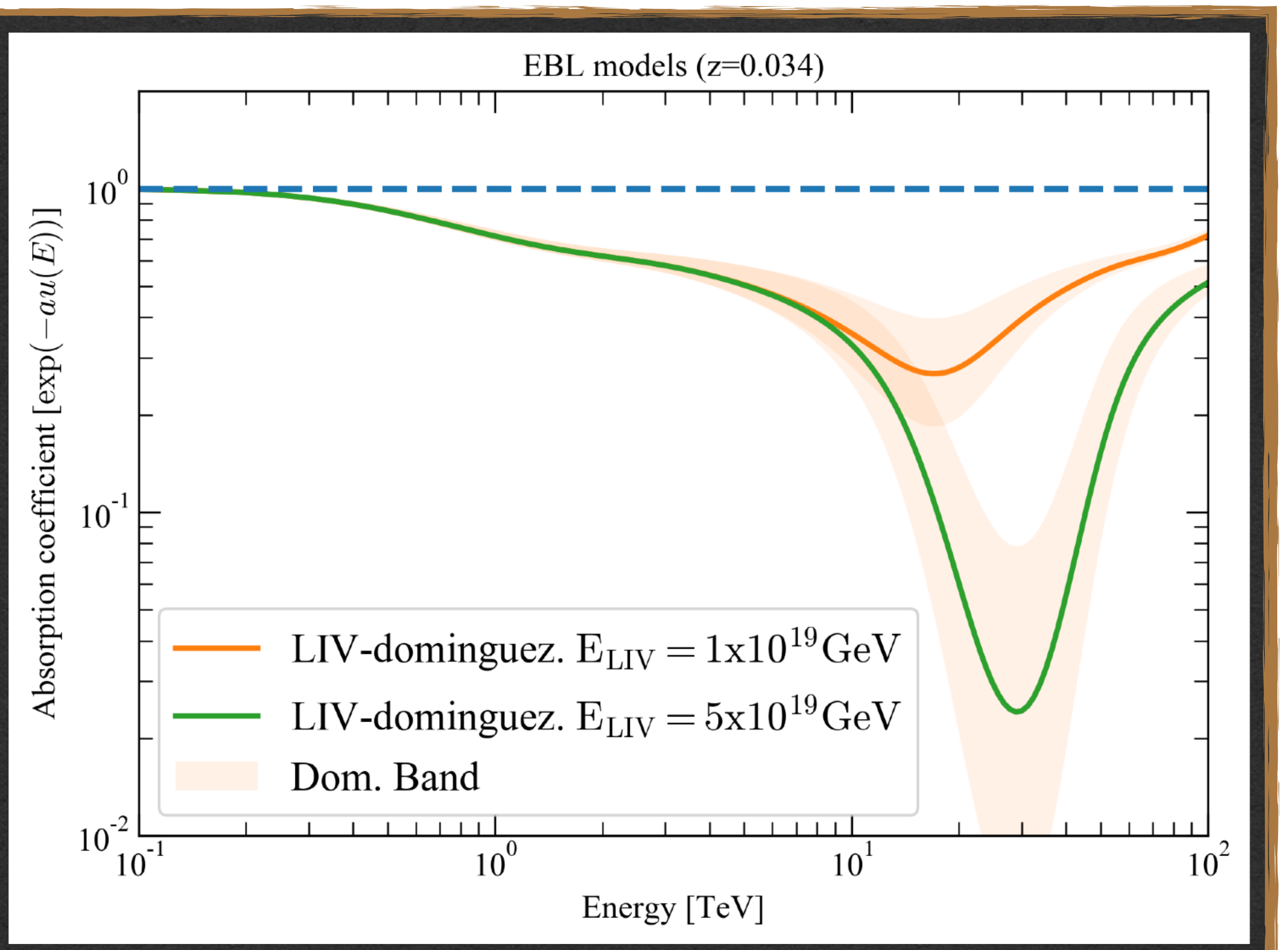
$\gamma\gamma_b \to e^+e^-$

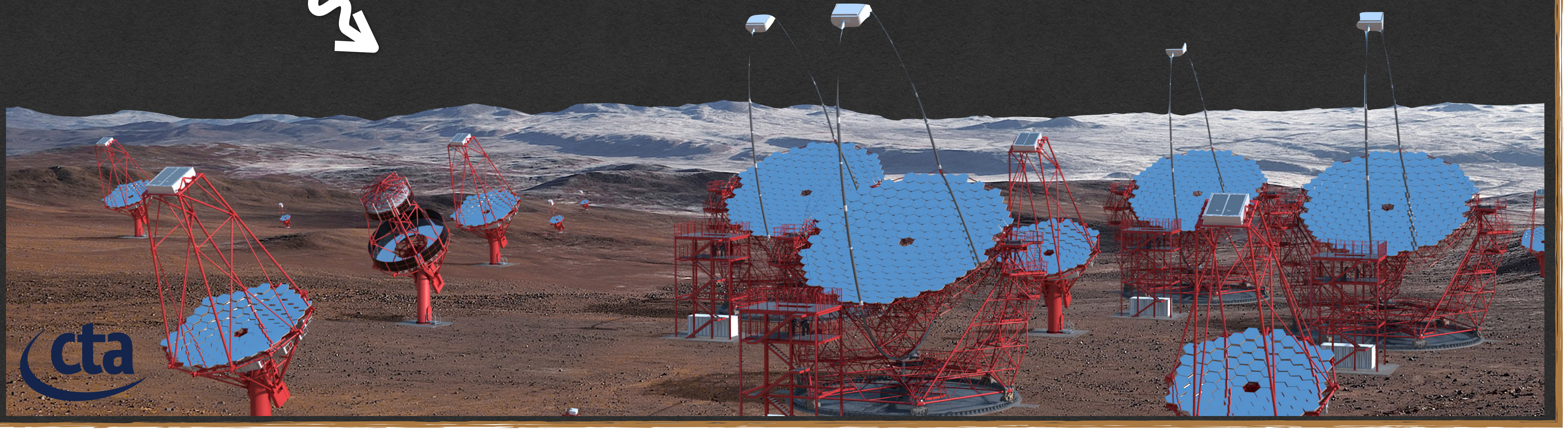


~~Test of Lorentz invariance violation~~

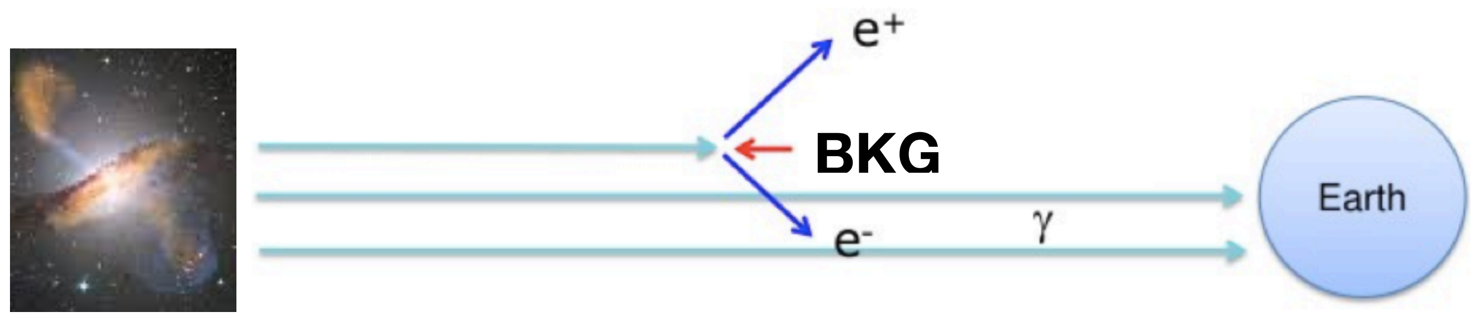


- Corrections to known processes $\gamma\gamma_b \rightarrow e^+e^-$

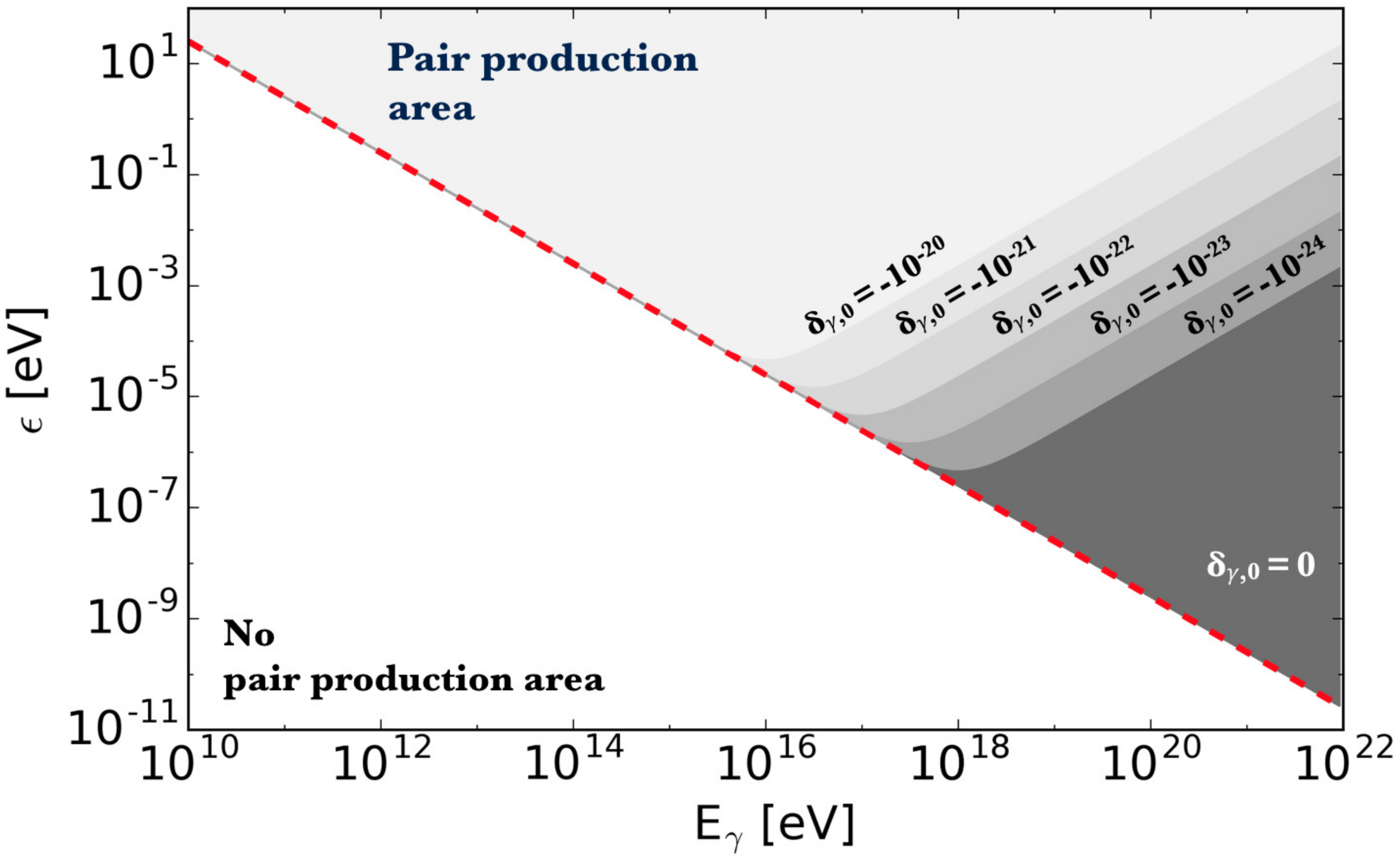




$\gamma\gamma_b \rightarrow e^+e^-$

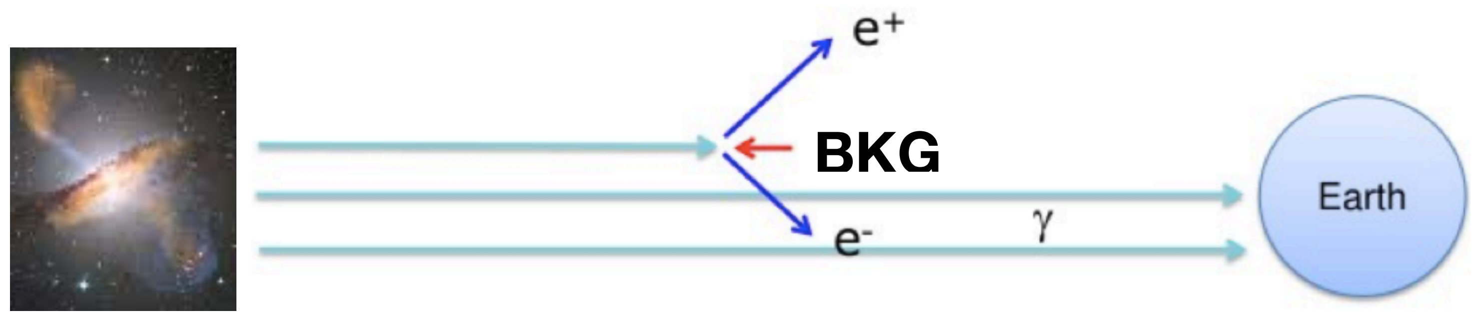


$$E^{th}_{\gamma_b} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{1}{4}\delta_n^{tot}\, E_\gamma^{n+1},$$



Allowed region change with the LIV parameter and the Energy

Critical points



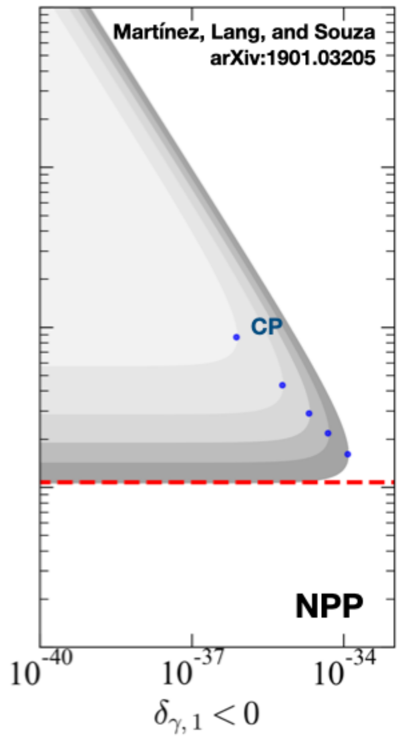
$$E_a^2 - p_a^2 = m_a^2 \pm |\delta_{n,a}| E_a^{(n+2)},$$

$$E_{\gamma_b}^{th} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{1}{4}\delta_n^{tot}\, E_\gamma^{n+1},$$

$$\delta_n^{\rm tot} = \delta_{\gamma,n} - \delta_{+,n}K^{n+1} - \delta_{-,n}(1-K)^{n+1}.$$

$$\delta_n^{cr}(\varepsilon;n) = \frac{(n+1)^{n+1}}{(n+2)^{n+2}}\left(\frac{4K(1-K)}{m_e^2}\right)^{n+1} 4\varepsilon^{n+2}.$$

$$E_\gamma^{cr}(\varepsilon;n) = \frac{n+2}{n+1}\frac{m_e^2}{4K(1-K)}\frac{1}{\varepsilon}$$

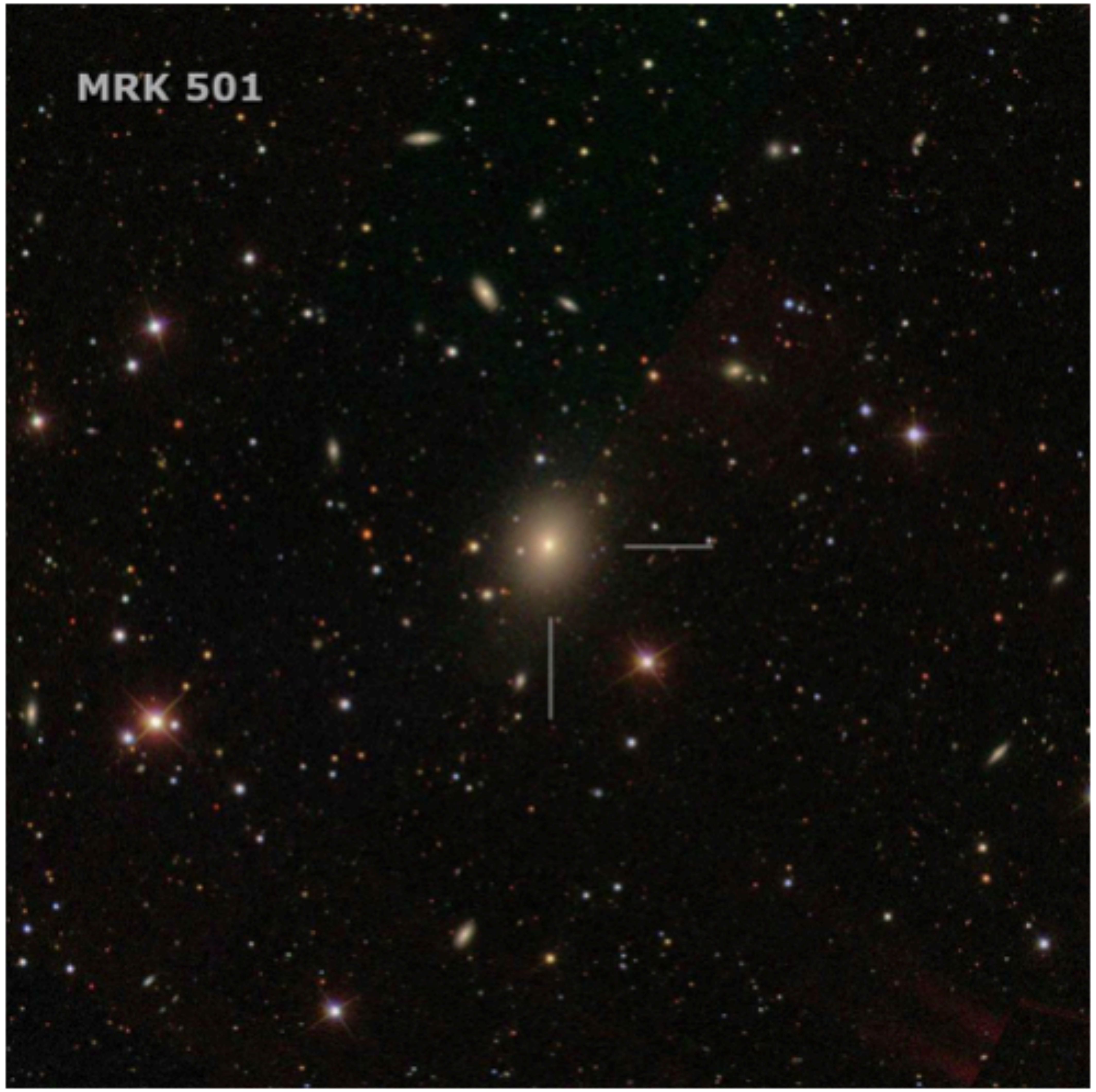


if LIV is such that, $\delta_n = \delta_{\gamma,n} = \delta_{\pm,n}$, for the scenario with $K = 1/2$, $\longrightarrow$ $\delta_n^{\rm tot} = (1 - \frac{1}{2^n})\delta_n.$

when LIV is considered only (or dominated by) the photon sector, i.e. $\delta_\pm = 0$ (or $\delta_\gamma \gg \delta_\pm$), $\longrightarrow$ $\delta_n^{\rm tot} = \delta_{\gamma,n}$ (or $\approx \delta_{\gamma,n}$).

factor of $(1 - \frac{1}{2^n})$ between this two set of scenarios.

Martínez, Lang, and Souza
arXiv:1901.03205 BHCB2018



RA: 253.4667
DEC: 39.7603

For a given EBL model at z=0.034

Find:

- [x] -The Optical Depth
- [x] -Attenuation

Include LIV_th

Try different

- [x] z,
- [x] ELIV,
- [x] n….

What can you say about the differences?

- [ ] What about the superluminal scenario?

E4: What would the attenuation look like with LIV and without for a source with the following characteristics

z=0.034

$$\phi_{\rm int}(E_\gamma) = \phi_0 (E_\gamma/E_0)^{-\Gamma} \exp\left(-E_\gamma/E_{\rm cut}\right),$$

M.-H. Ulrich, et al. ApJ 198, 261–266

E_0 [TeV]	Normalization [/cm^2 s TeV]	Γ
1.42	8.27×10^{-12}	2.19

$$E_{cut} = 40TeV$$

$$E_{cut} = 60TeV$$

E4*: Use the LIV attenuation from ebltable in a gammapy analysis

E 5: Modify the ebl_from_model to use (+) scenario

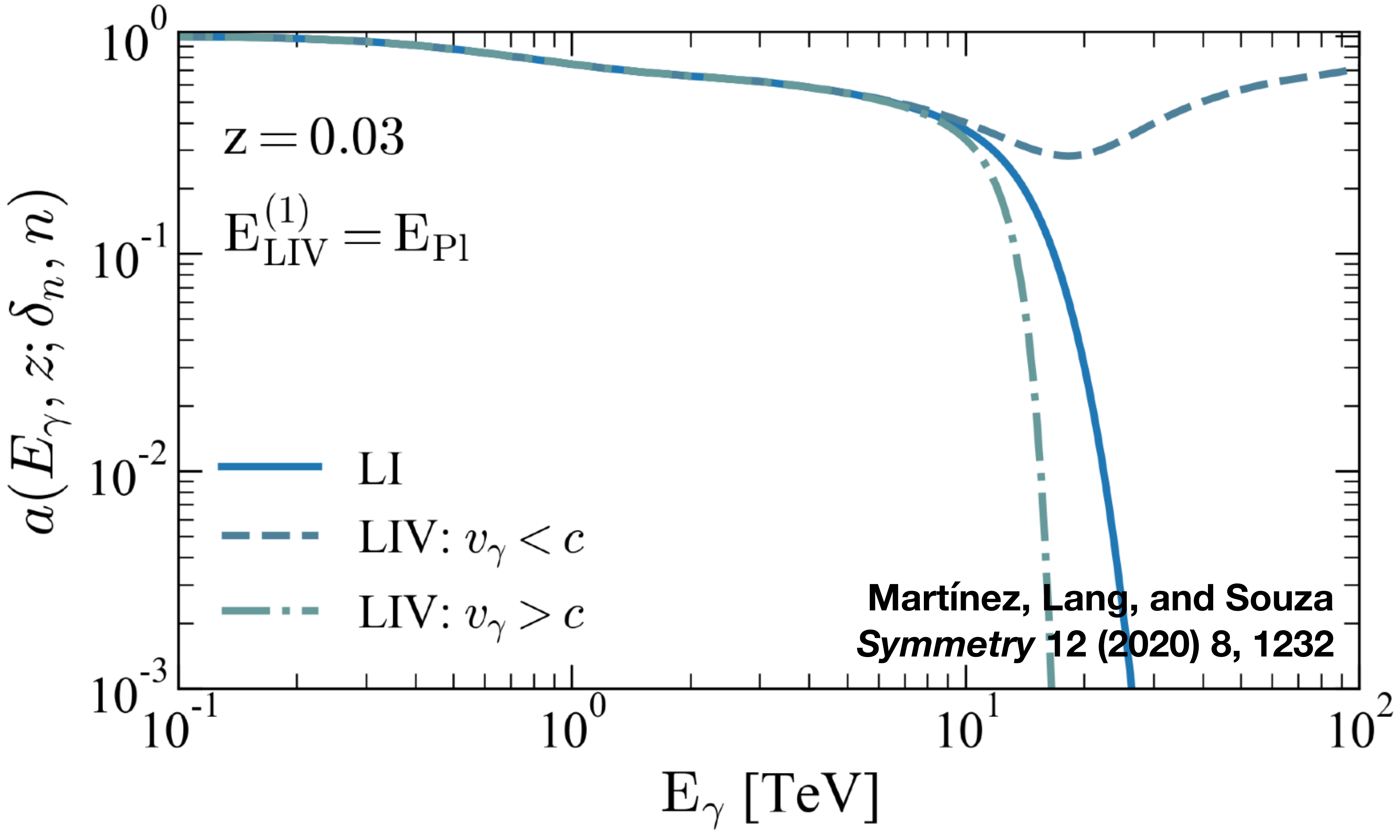
ebltable / ebltable / ebl_from_model.py

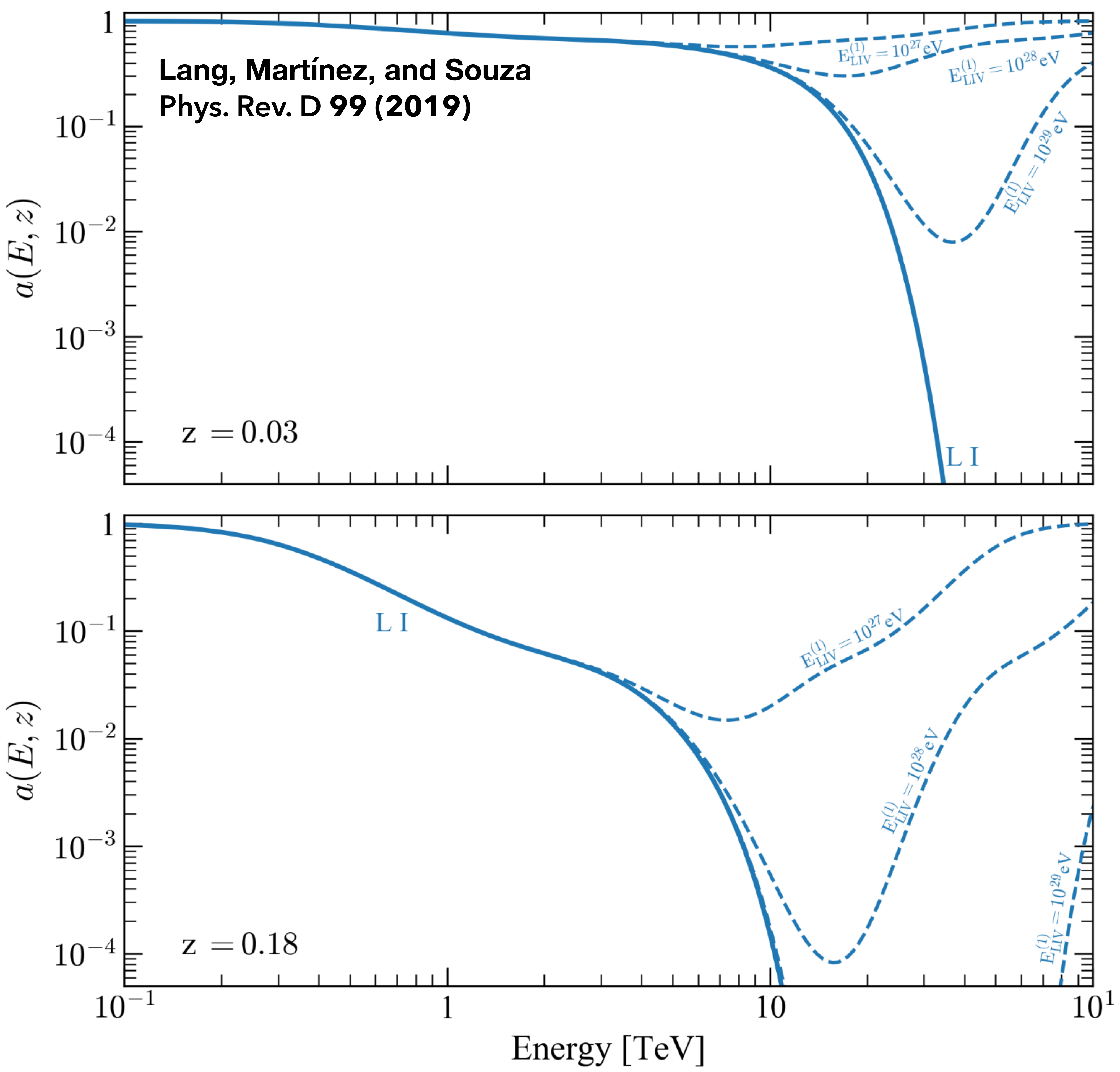
Code Blame 557 lines (452 loc) · 19.1 KB

```
import os
import astropy.units as u
import astropy.constants as c
from collections.abc import Iterable
from scipy.integrate import simps
from os.path import join
from astropy.cosmology import Planck15 as cosmo
from scipy.special import spence  # equals gsl_sf_dilog(1-z)
from .interpolate import GridInterpolator
# ------------------------------------------------------------#

# planck mass in eV
Mpl_eV = (np.sqrt(c.hbar * c.c / c.G) * c.c ** 2.).to('eV').value
# electron mass in eV
m_e_eV = (c.m_e * c.c ** 2.).to('eV').value
# Available models
models = ('franceschini',
          'kneiske',
          'dominguez',
          'dominguez-upper',
          'dominguez-lower',
          'saldana-lopez',
          'saldana-lopez-err',
          'gilmore',
```

EBL-Attenuation + LIV





The intensity of the LIV effect depends on

- E_γ : The energy of the γ-ray
- E_{LIV}: The LIV energy scale
- z: The distance of the source.

Less photons!!

$\gamma\gamma_b \rightarrow e^+e^-$