Testing fundamental physics with Astrophysical Sources: LIV

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Meeting of the Cosmic Rays Section of the Mexican Physical Society
3-5 Oct 2018

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II. Limits: TeV γ-rays

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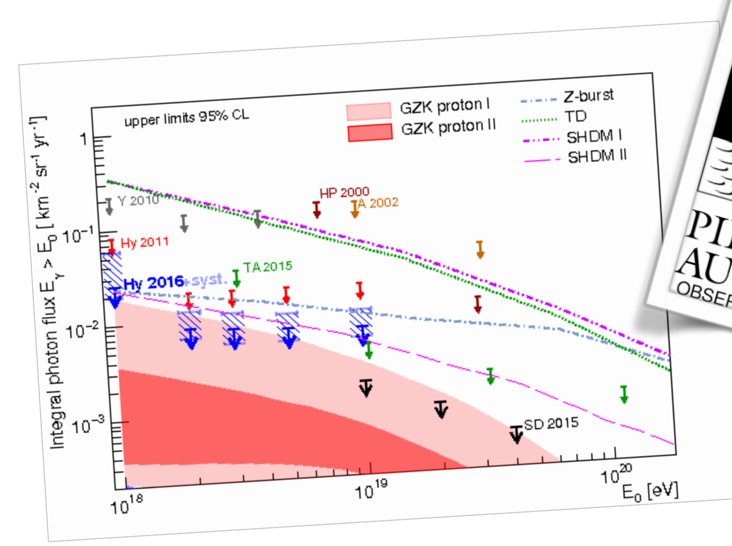
   ii. Photon Decay

   iii. Pair production threshold shifts

III. UHECR

   i. GZK-photons + LIV

   ii. Limits: UHECR



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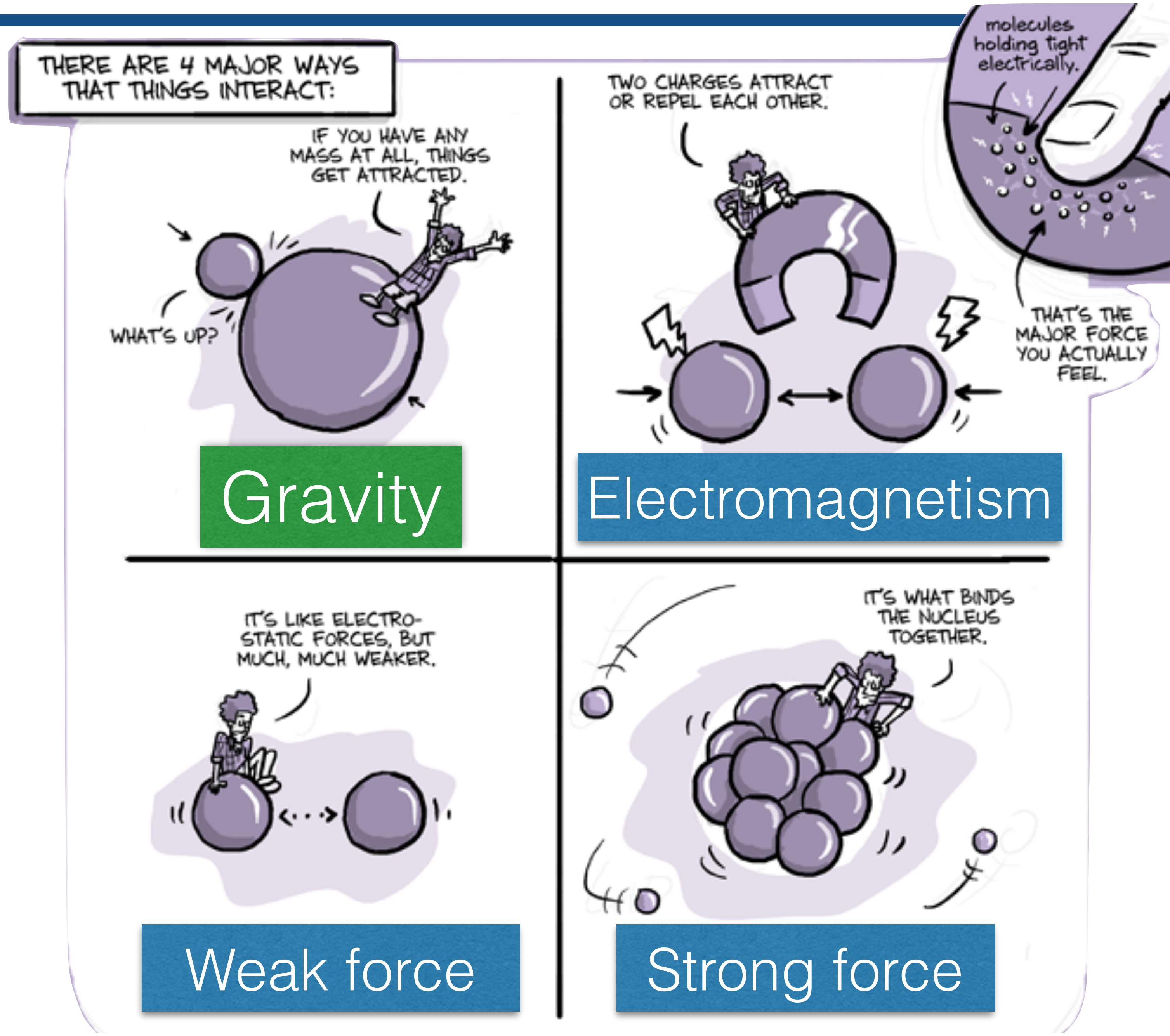
Fundamental Forces of Nature

General Relativity

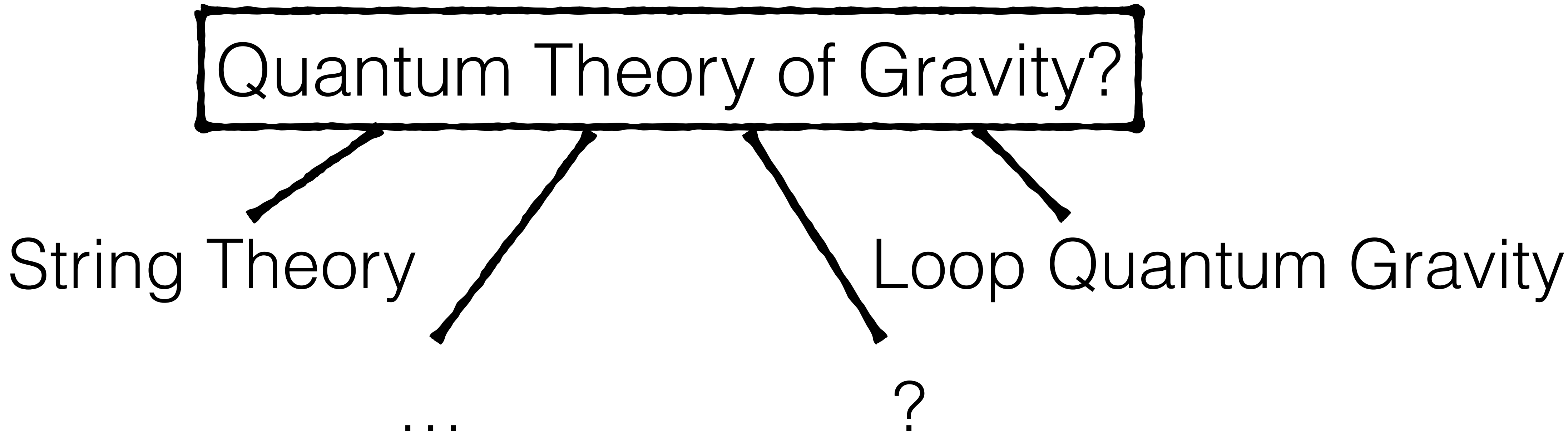
Geometrical Theory



Standard Model

Quantum Field 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
- ☐ …
- ☑ 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

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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

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

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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n=1

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n=2

The dispersion relation:

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

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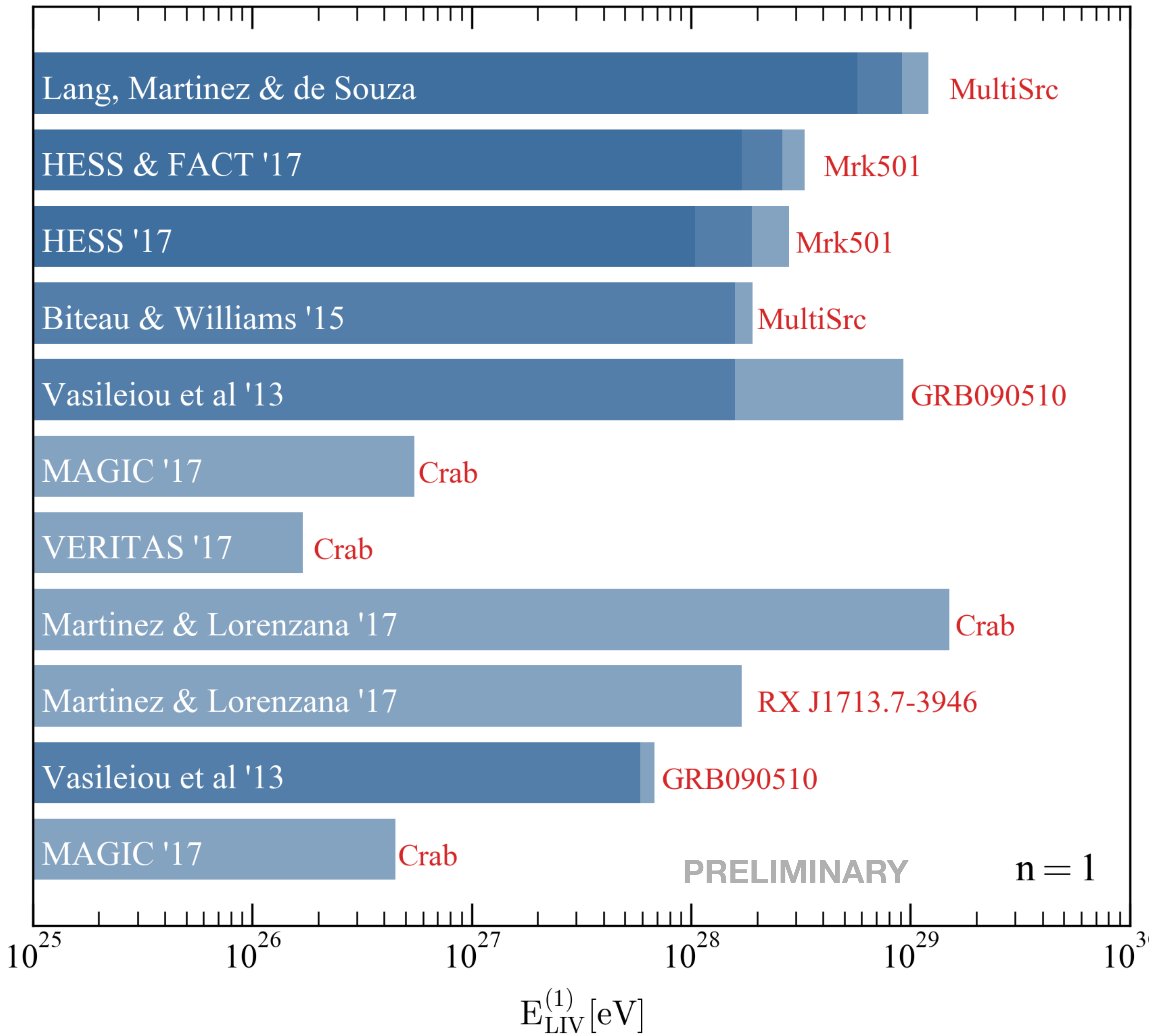
LIV limits by γ-rays



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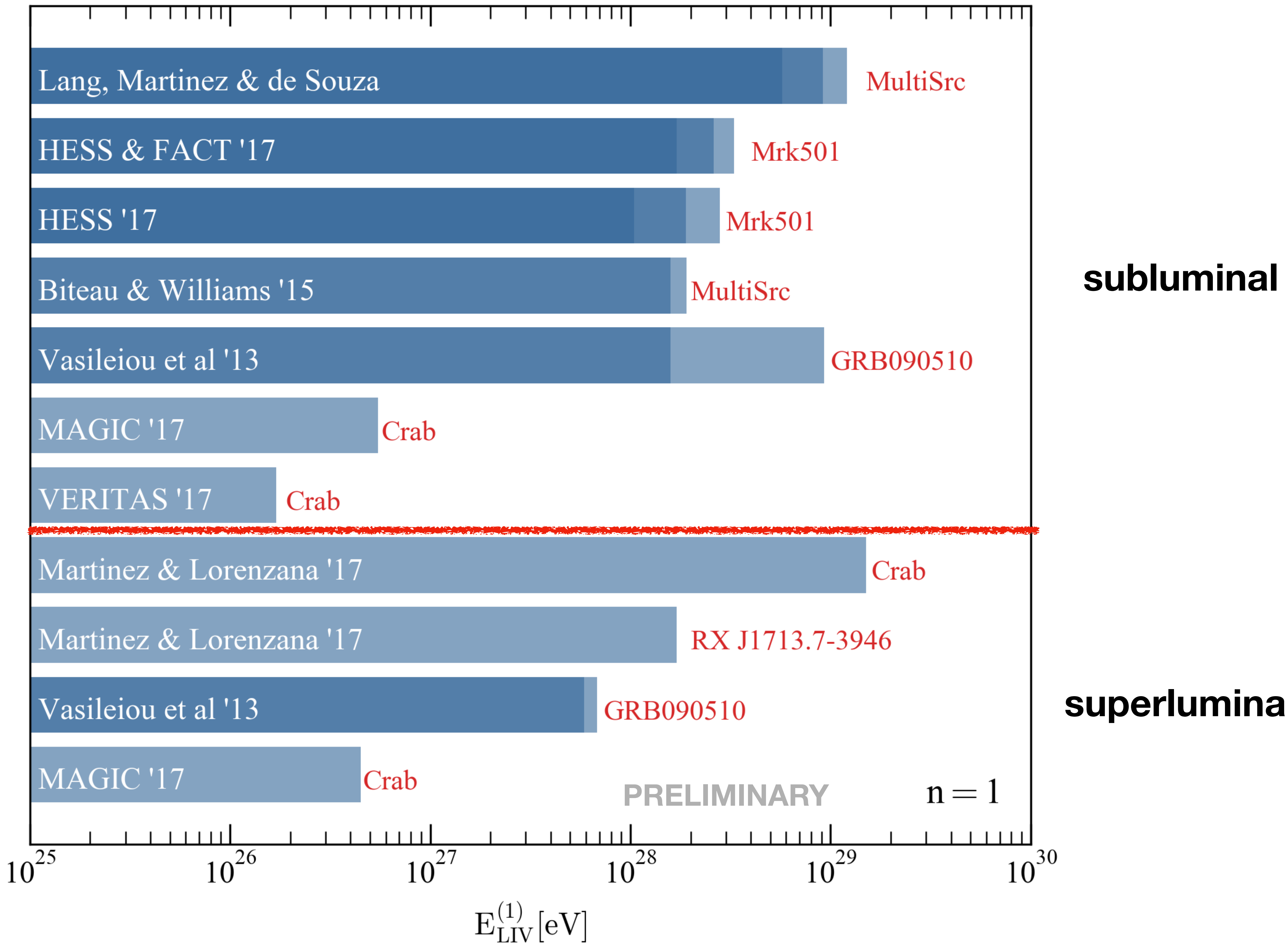
LIV limits by γ-rays



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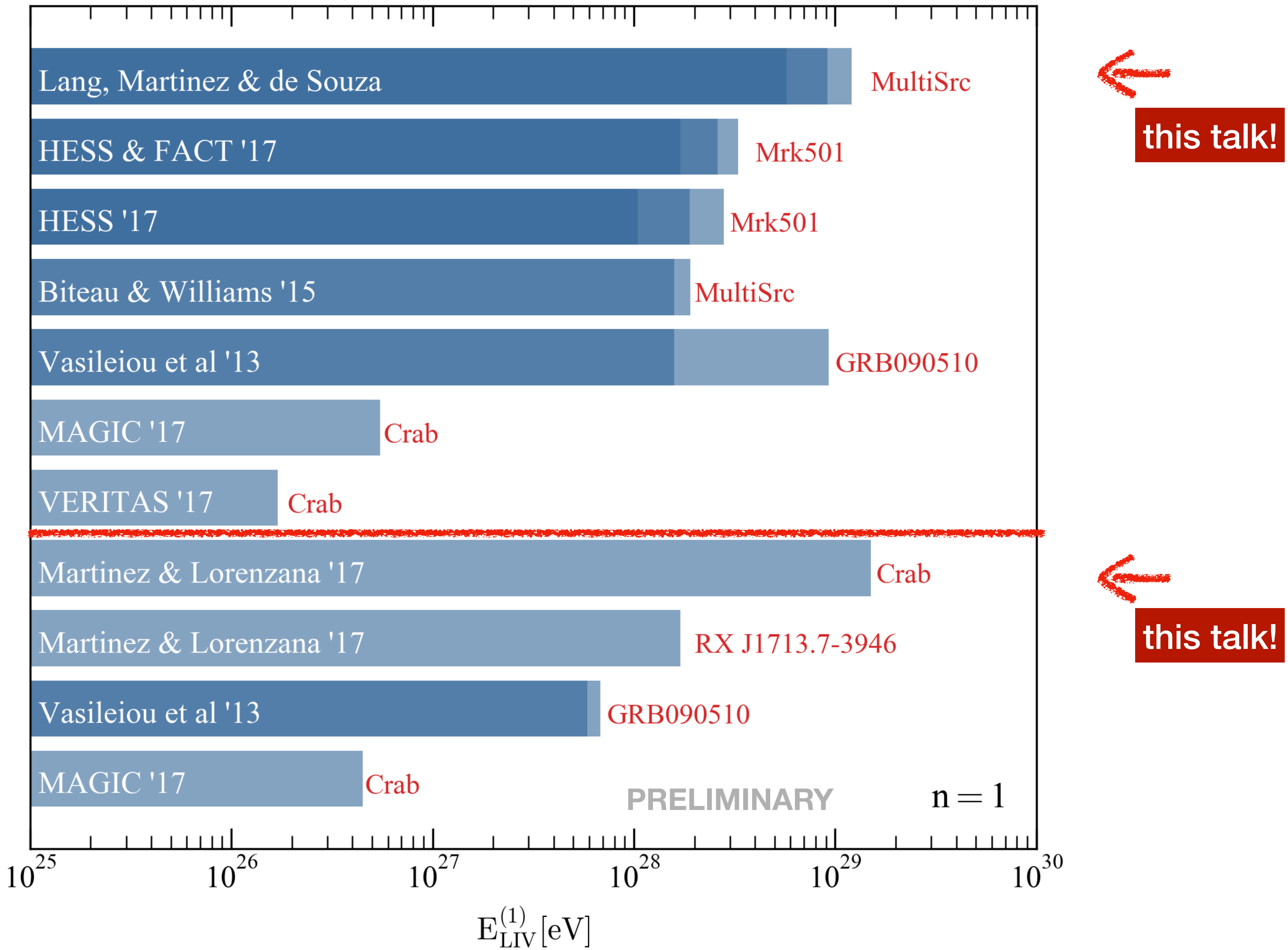

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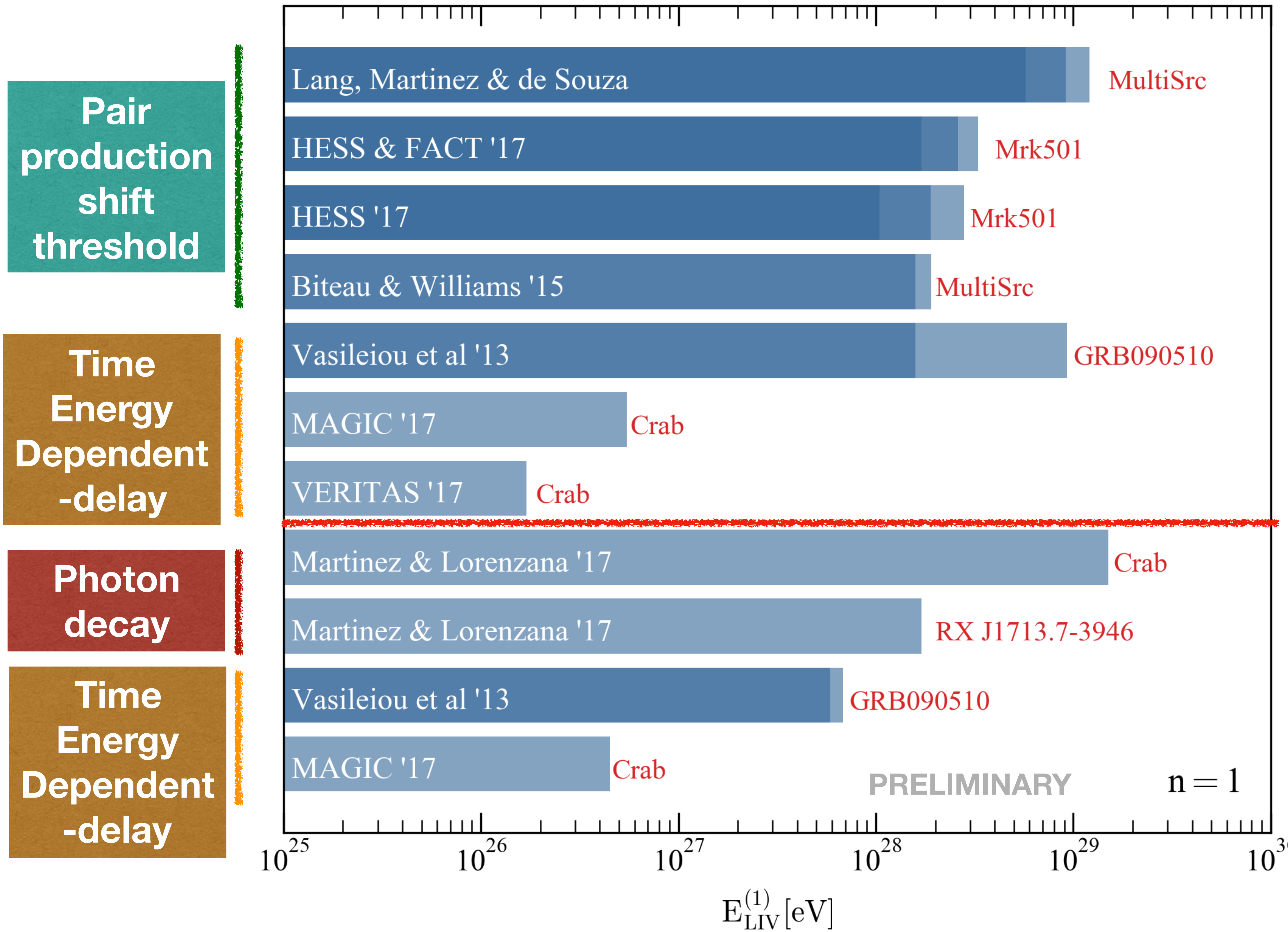

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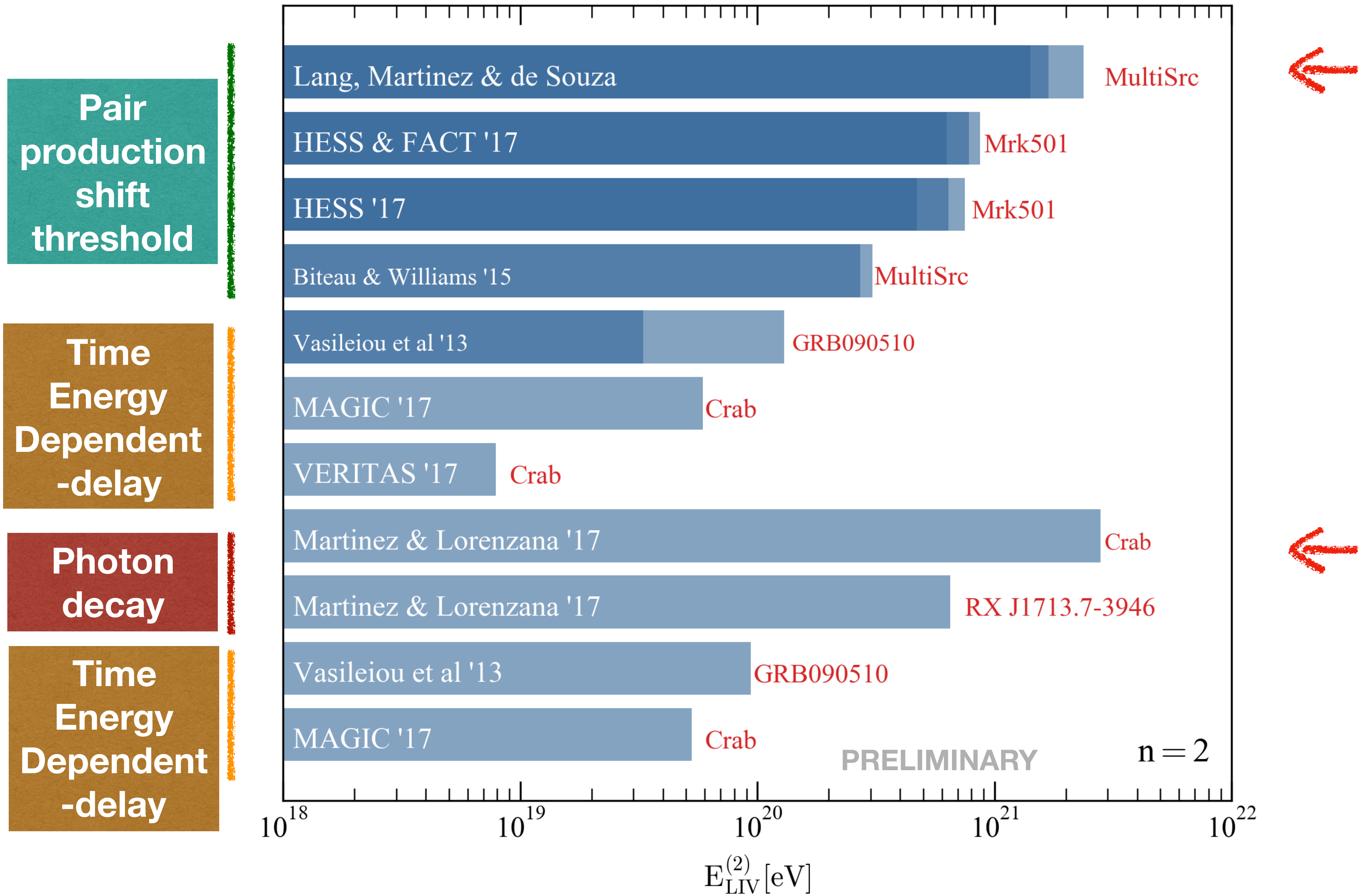

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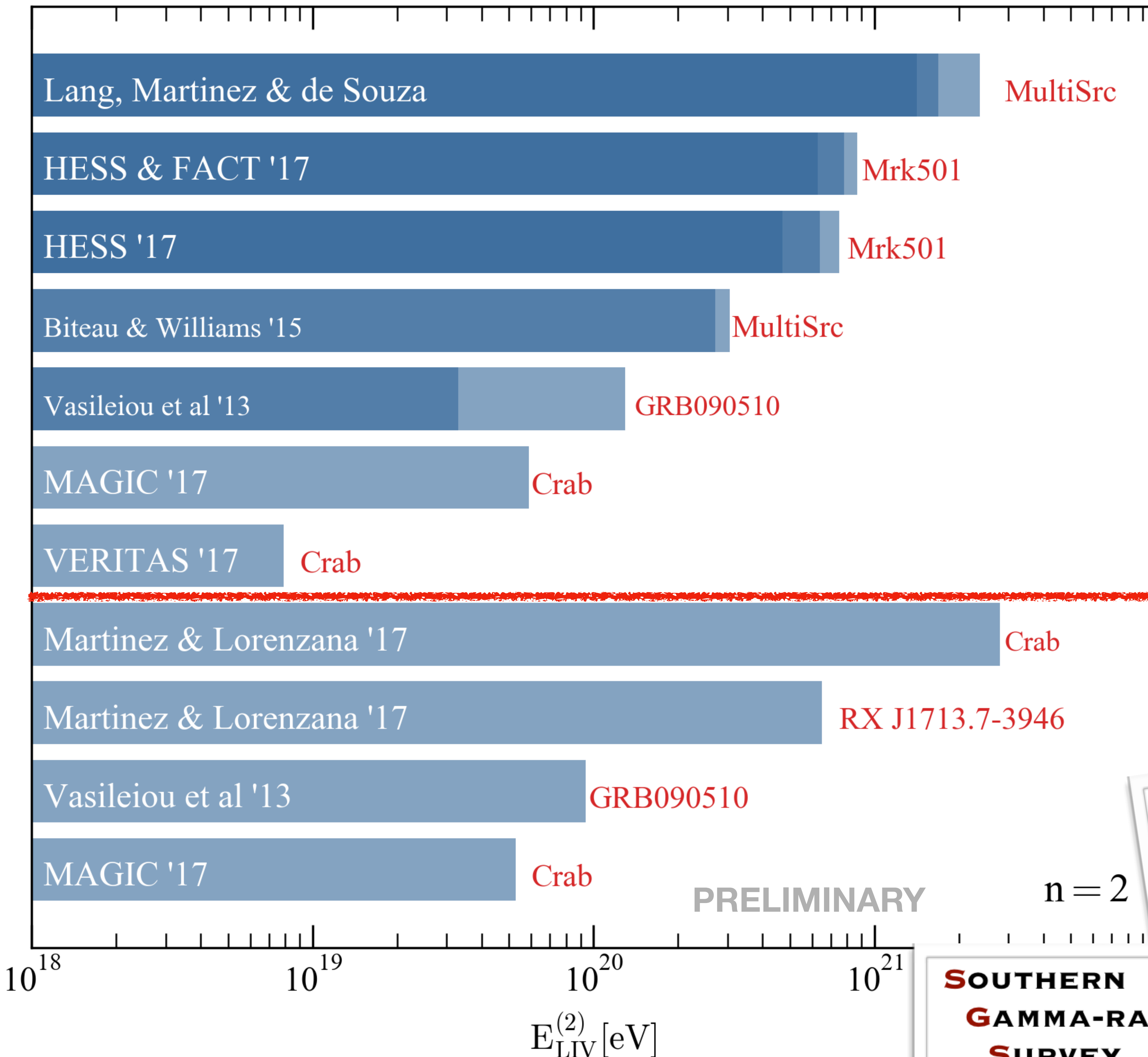
LIV limits by γ-rays

Pair production shift threshold

Time Energy Dependent -delay

Photon decay

Time Energy Dependent -delay



?

Southern Gamma-Ray Survey Observatory

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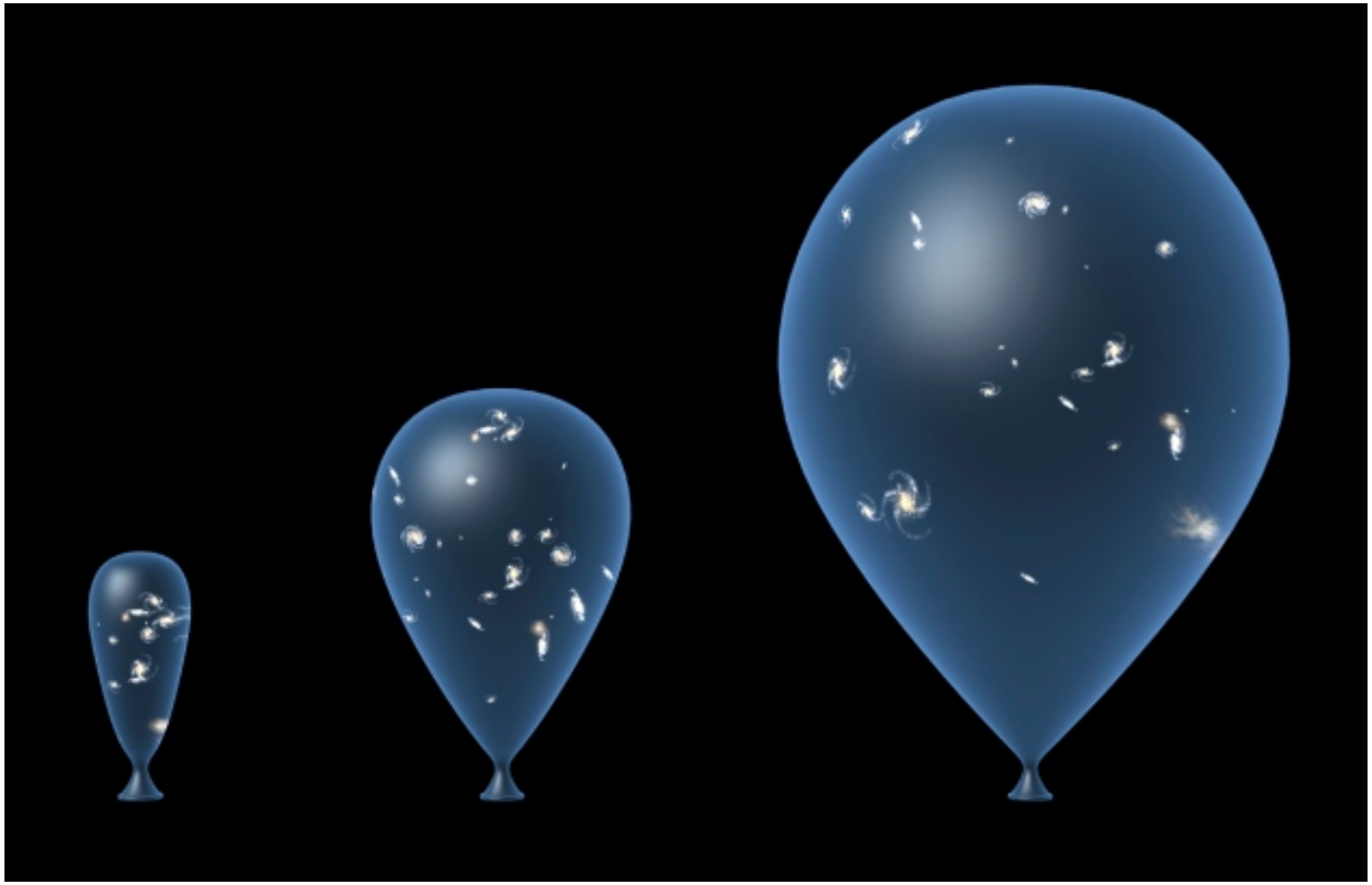
Time energy dependent delay

The corresponding differential relation between time and redshift is

$$dt = -H_0^{-1} \frac{dz}{(1+z)h(z)} \quad ; \quad h(z) = \sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}$$



Time energy dependent delay

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$$dt = -H_0^{-1} \frac{dz}{(1+z)h(z)} \quad ; \quad h(z) = \sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}$$

A particle with velocity u travels an elementary distance:

$$u\ dt = -H_0^{-1} \frac{u\ dz}{(1+z)h(z)}$$

Two particles with velocities differing by Δu

$$\longrightarrow \quad \Delta L = H_0^{-1} \int_0^z \frac{\Delta u\ dz}{(1+z)h(z)}$$

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LIV - energy dependence group velocity

$$E_\gamma^2 = p^2 \pm \left(\frac{E_\gamma^2}{E_{LIV}^{(n)}} \right)^n \longrightarrow u = \frac{\mathrm{dE}}{\mathrm{dp}} \approx 1 + \frac{n+1}{2} \left(\frac{E_\gamma}{E_{LIV}^{(n)}} \right)^n$$

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Time energy dependent delay

Constraints on Lorentz Invariance Violation from *Fermi*-Large Area Telescope Observations of Gamma-Ray Bursts

V. Vasileiou,[1,*] A. Jacholkowska,[2,†] F. Piron,[1] J. Bolmont,[2] C. Couturier,[2]
J. Granot,[3] F. W. Stecker,[4,5] J. Cohen-Tanugi,[1] and F. Longo[6,7]

GRB Name	PairView		SMM		Likelihood[a]	
	n=1, $s_{\pm}$=+1 (E_{PI} units)					
	95%	99.5%	95%	99.5%	95%	99.5%
080916C	0.11	0.081	0.09	0.067	0.22	0.2
090510	7.6	1.3	5.9	1.2	5.2	4.2
090902B	0.17	0.13	0.15	0.11	0.12	0.074
090926A	–	0.55	8	0.35	1.2	0.45
	n=1, $s_{\pm}$=-1 (E_{PI} units)					
	95%	99.5%	95%	99.5%	95%	99.5%
080916C	18	0.33	5.4	0.31	0.2	0.18
090510	0.56	0.48	0.57	0.48	11	3.6
090902B	0.38	0.2	0.86	0.28	0.37	0.11
090926A	0.24	0.18	0.2	0.12	0.17	0.15
	n=2, $s_{\pm}$=+1 (10^{10} GeV units)					
	95%	99.5%	95%	99.5%	95%	99.5%
080916C	0.31	0.28	0.24	0.21	0.35	0.33
090510	6.7	3.3	13	3.3	8.6	6.4
090902B	0.8	0.72	0.73	0.64	0.64	0.49
090926A	0.67	0.48	9.1	1.6	0.48	0.47
	n=2, $s_{\pm}$=-1 (10^{10} GeV units)					
	95%	99.5%	95%	99.5%	95%	99.5%
080916C	–	0.69	–	5.2	0.34	0.32
090510	1.9	1.5	1.9	1.5	9.4	5.4
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Time energy dependent delay

$$\Delta t = H_0^{-1}\left(\frac{\Delta E}{E_{LIV}^{(n)}}\right)^2 \int_0^z \frac{(1+z)dz}{h(z)}$$

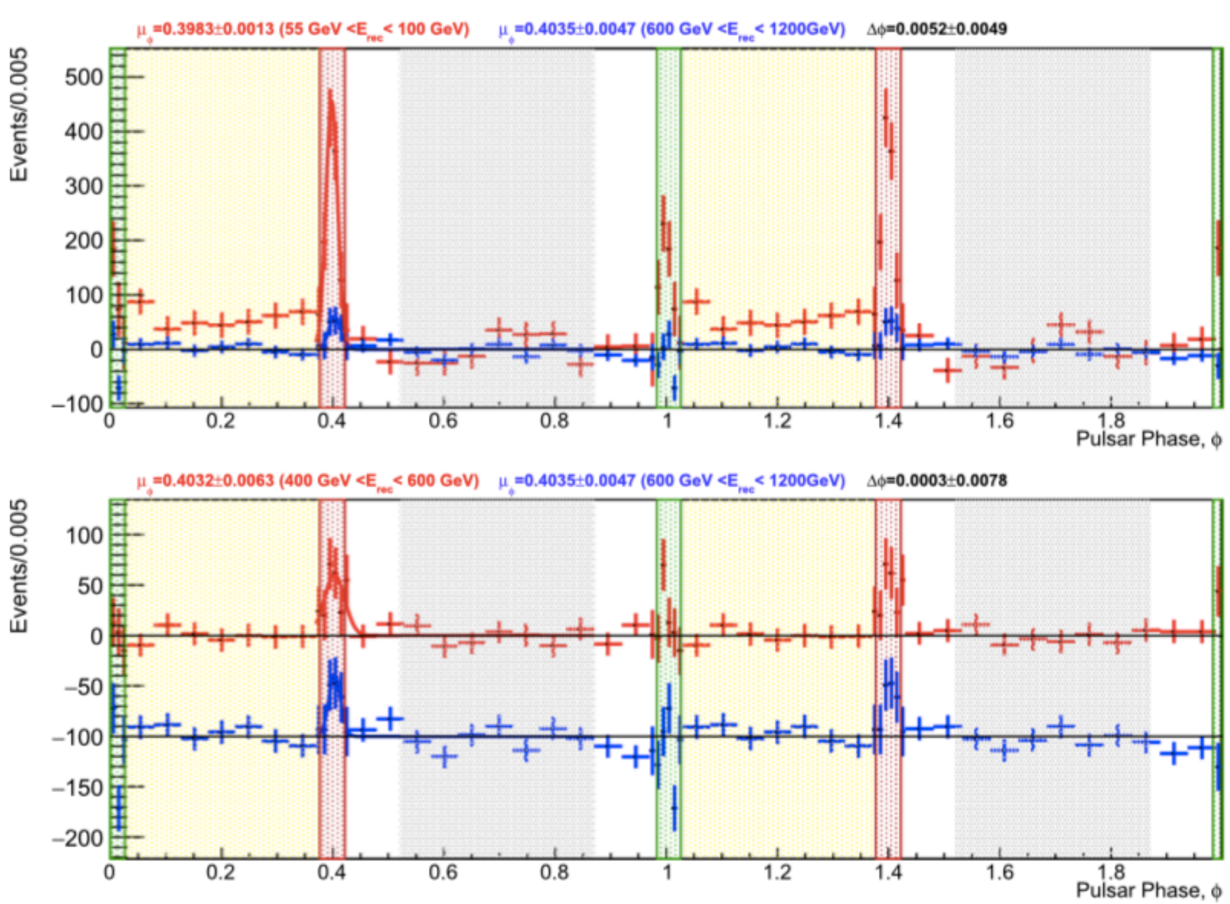


Table 2
Obtained 95%CL Limits from the Peak Comparison Method

Case	55–100 GeV versus 600–1200 GeV	400–600 GeV versus 600–1200 GeV
	E_{QG_1} (GeV)	
$\xi_1 = +1$	2.5×10^{17}	1.1×10^{17}
$\xi_1 = -1$	6.7×10^{17}	1.1×10^{17}
	E_{QG_2} (GeV)	
$\xi_2 = +1$	1.8×10^{10}	1.4×10^{10}
$\xi_2 = -1$	2.9×10^{10}	1.5×10^{10}

Time energy dependent delay

Source	Experiment	Limit on $E_{QG}^{(1)}$	Limit on $E_{QG}^{(2)}$	Distance	Δt	E_{max}	Ref.
HAWC Pulsar ref.	HAWC	10^{17} GeV	$9 \cdot 10^{9}$ GeV	2kpc	1 ms	500GeV	
HAWC GRB ref.	HAWC	$4.9 \cdot 10^{19}$ GeV	$1.1 \cdot 10^{11}$ GeV	$z = 1$	1 s	100GeV	

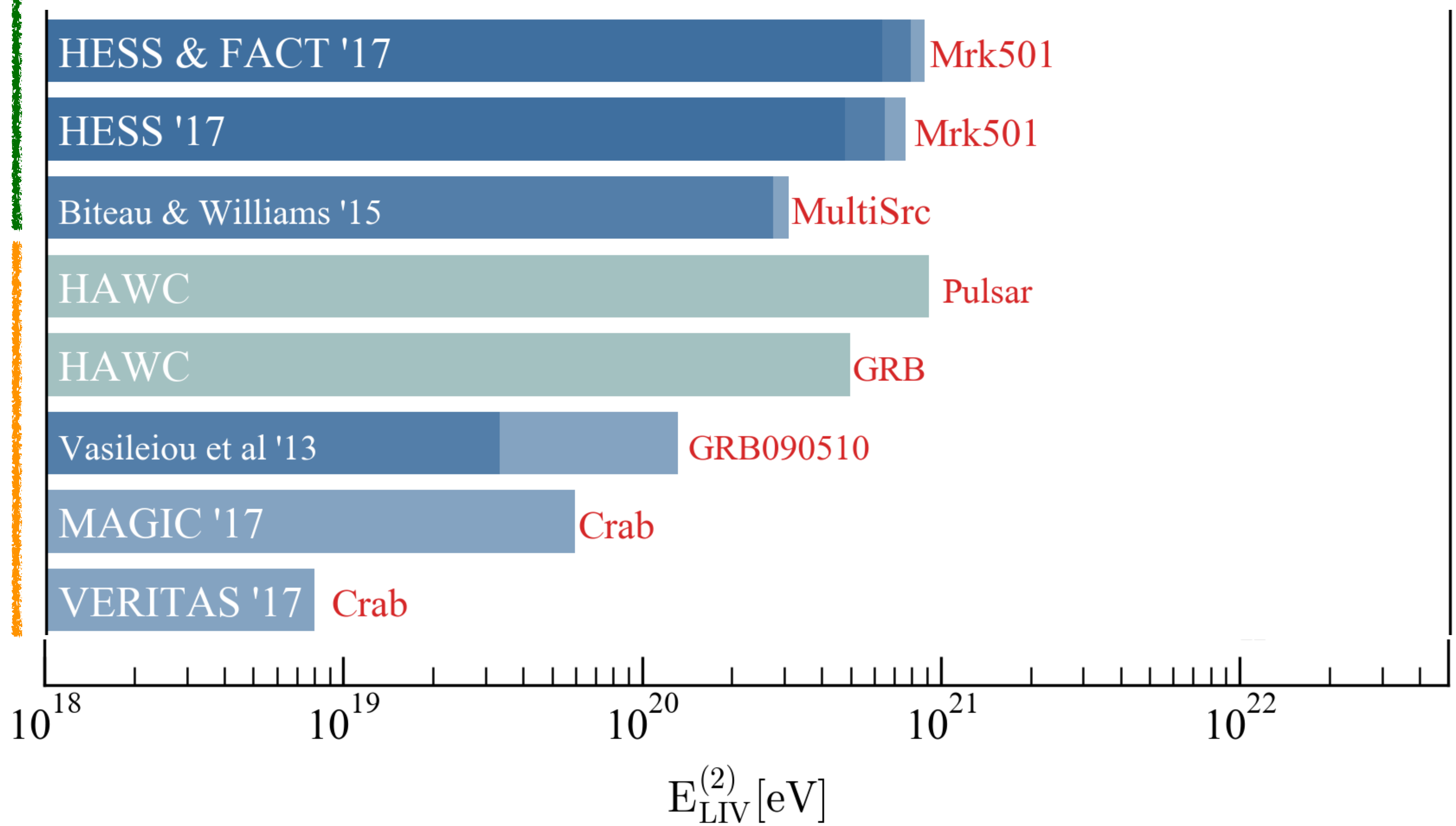
The potential of the HAWC observatory, based on the reference scenarios

Lukas Nellen et al.
HAWC- ICRC'15

Time energy dependent delay

Pair production shift threshold

Time Energy Dependent



Lukas Nellen et all
HAWC- ICRC'15

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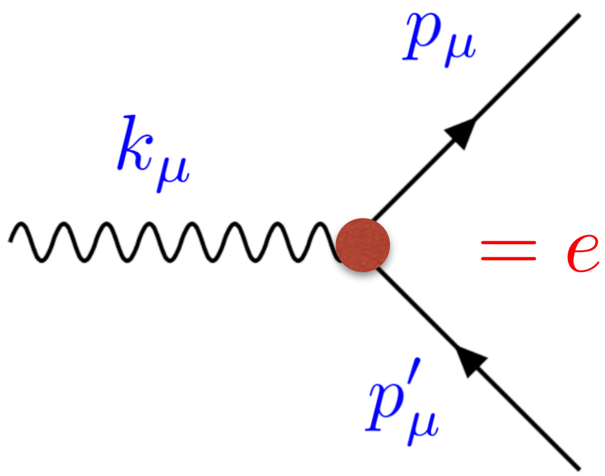
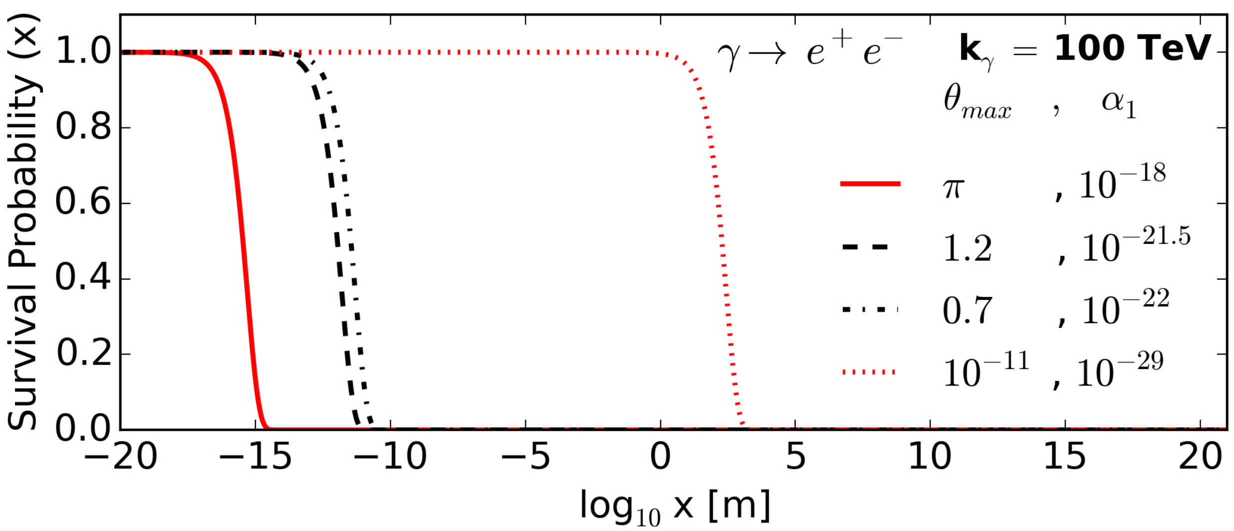
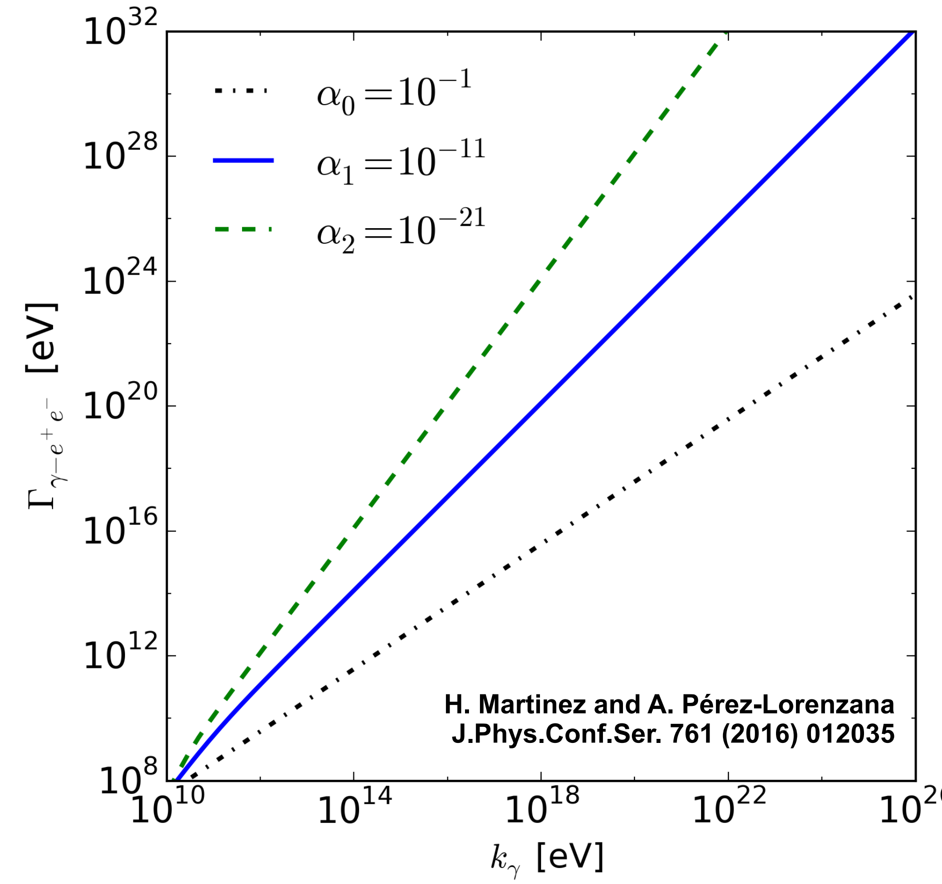
Photon decay



$$= e^2(4m^2 + \alpha_n k^{n+2})$$





$$E_{LIV}^{(n)} > E_\gamma \left[\frac{E_\gamma^2 - 4m_{e^-}^2}{4m_{e^-}^2} \right]^{1/n}$$

Above this energy threshold, the decay rate is quite efficient that photons should not arrive at Earth from astrophysical distances

If you observe VHE gamma-rays, the LIV process is restricted!!

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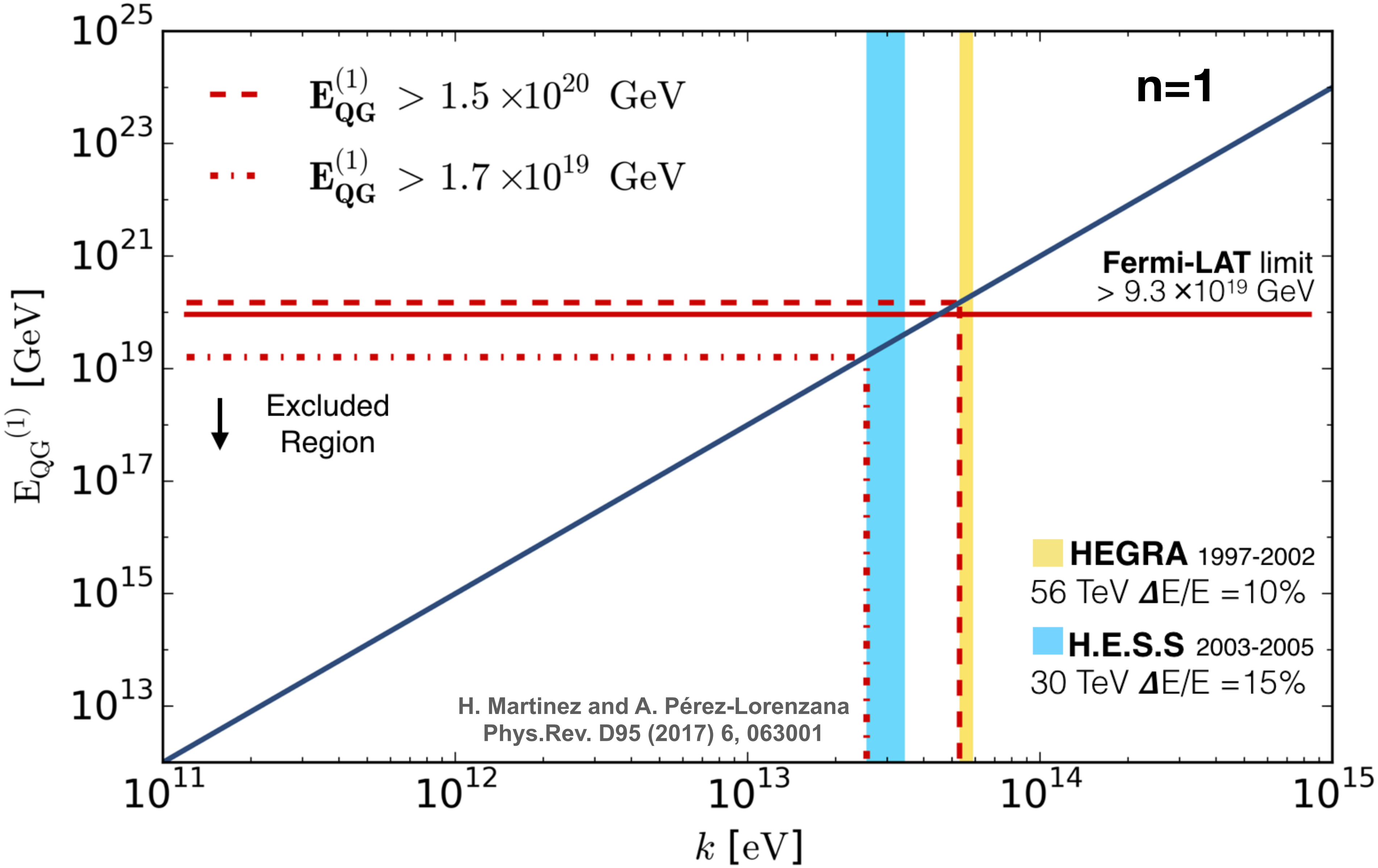
H. Martinez and A. Lorenzana
Phys.Rev. D95 (2017) 6, 063001

E_{LIV} excluded region due to $\gamma \rightarrow e+e-$



CRAB
HEGRA Collaboration.
The Astrophysical Journal,
614:897–913, 2004

SNR RX J1713.7.3946
HESS Collaboration,
Astron. Astrophys, **449**, 223
(2007)

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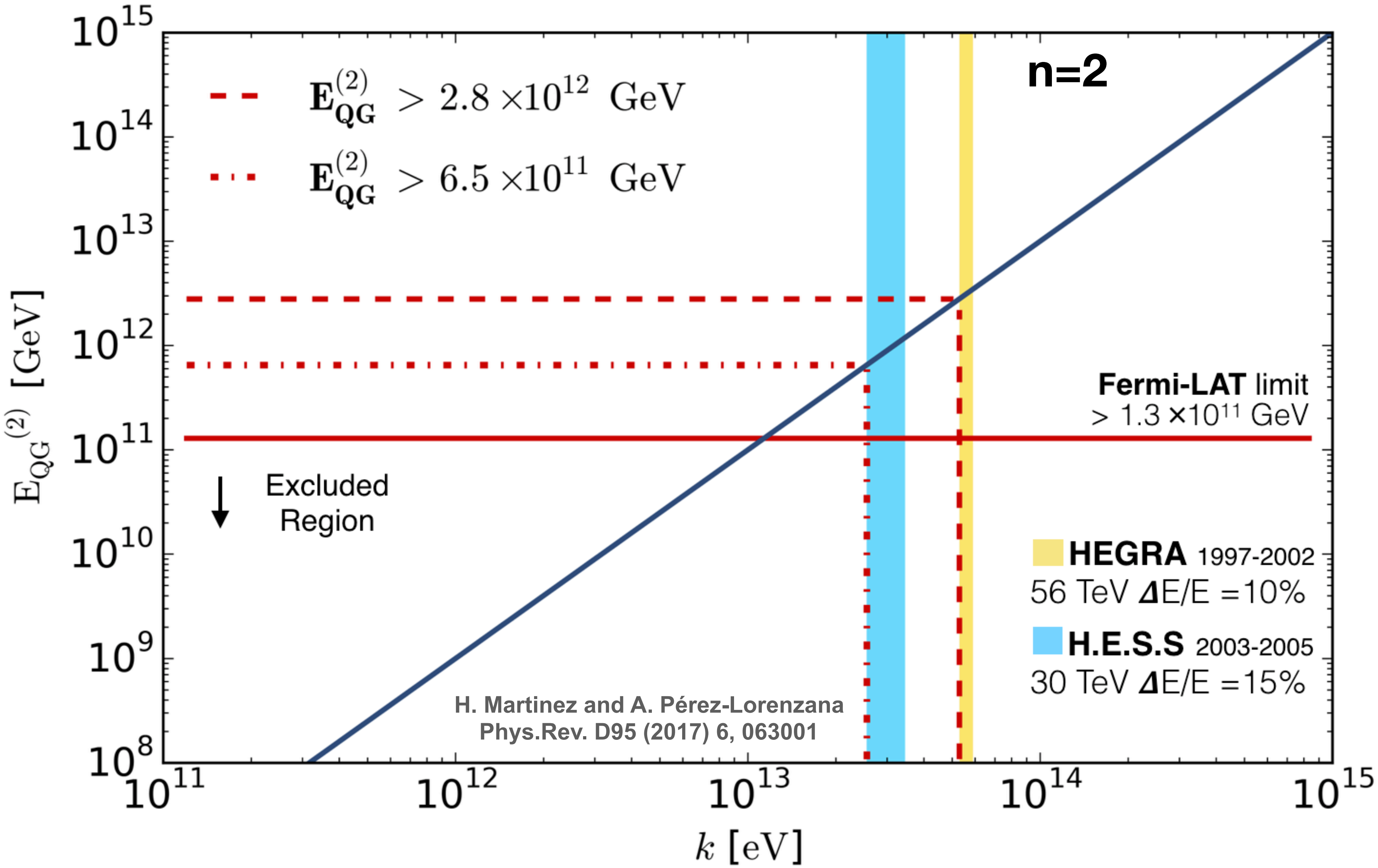

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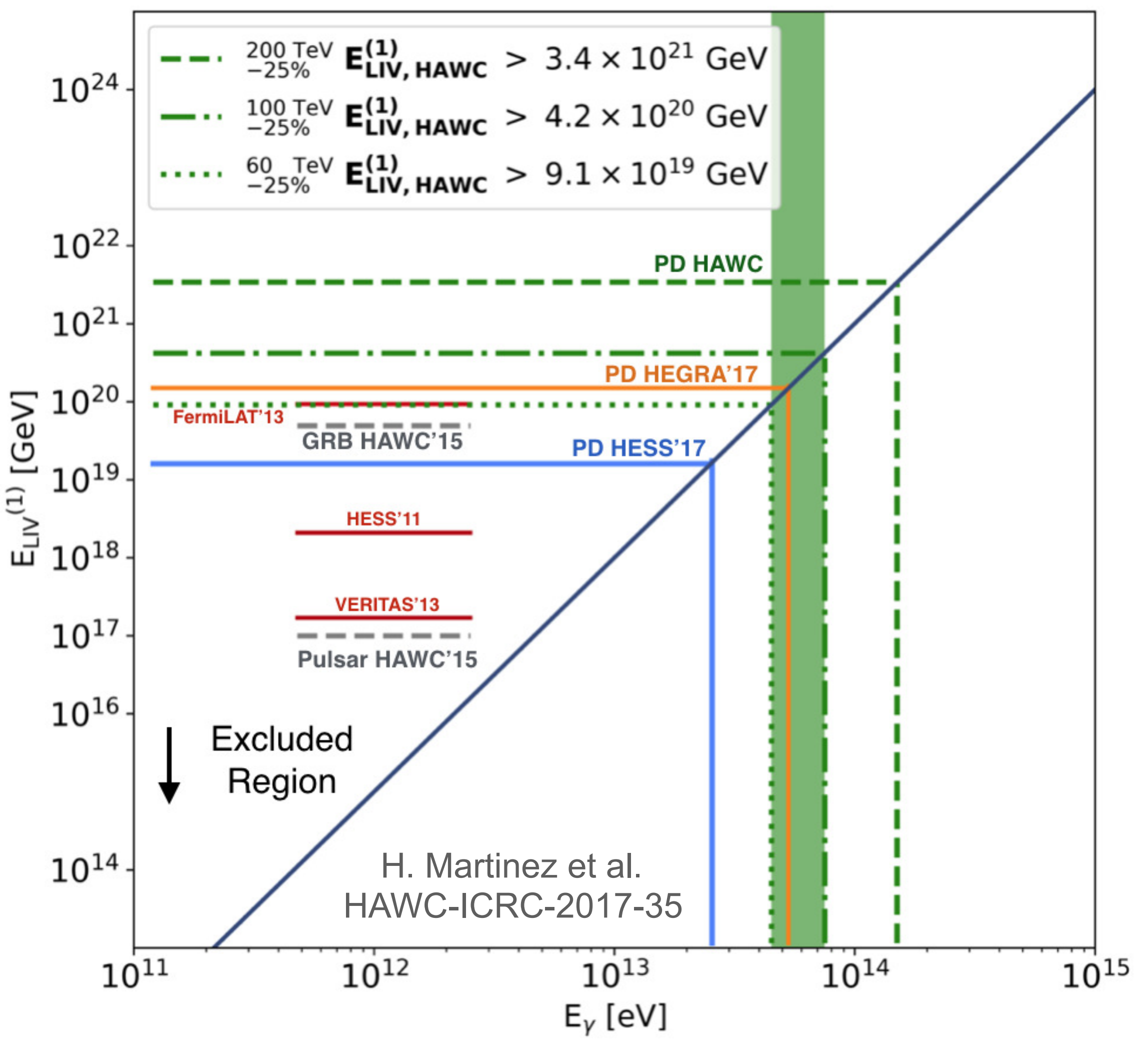

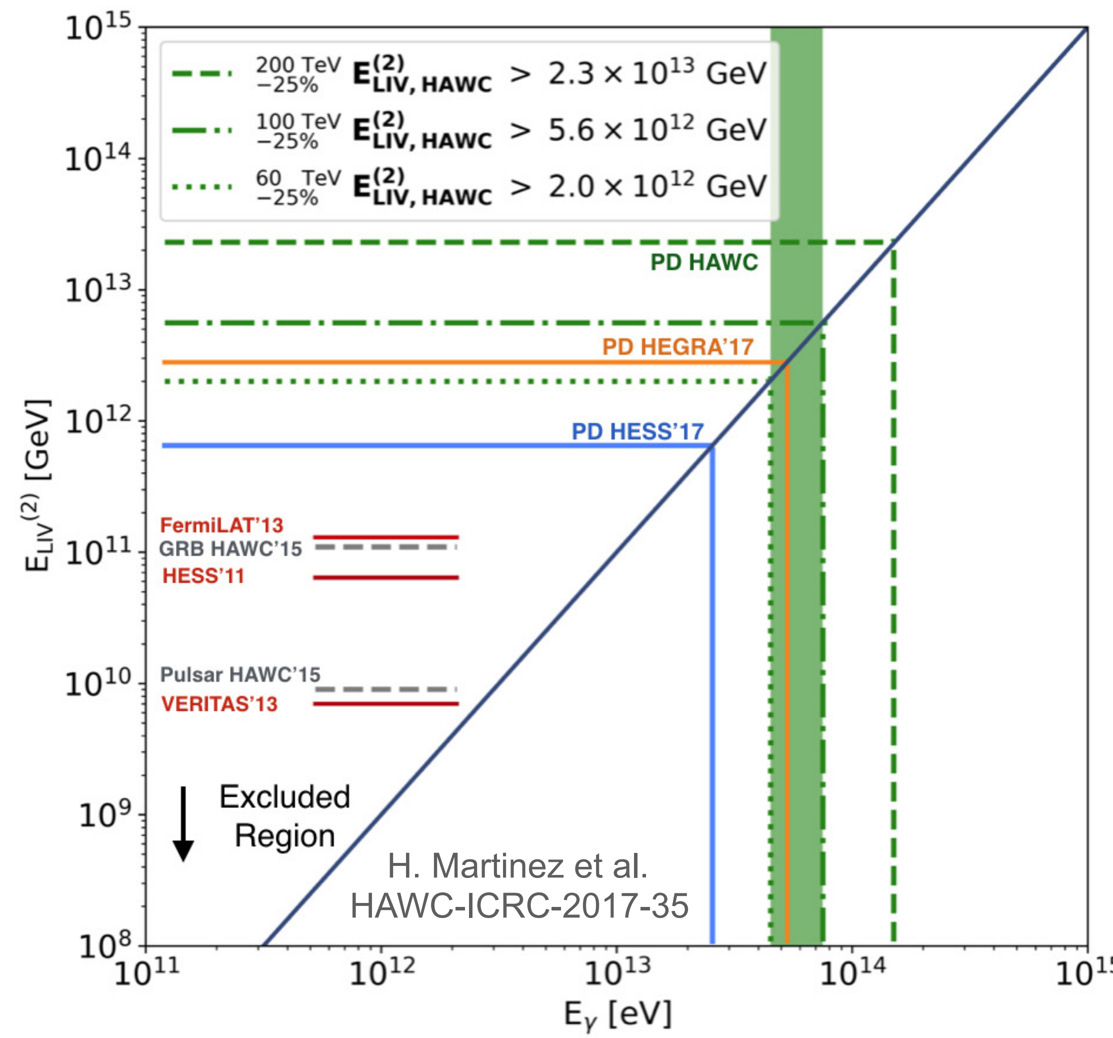

ELIV potential limits from HAWC

for n=1 (left), n=2 (right) and energy unc. of 25%.

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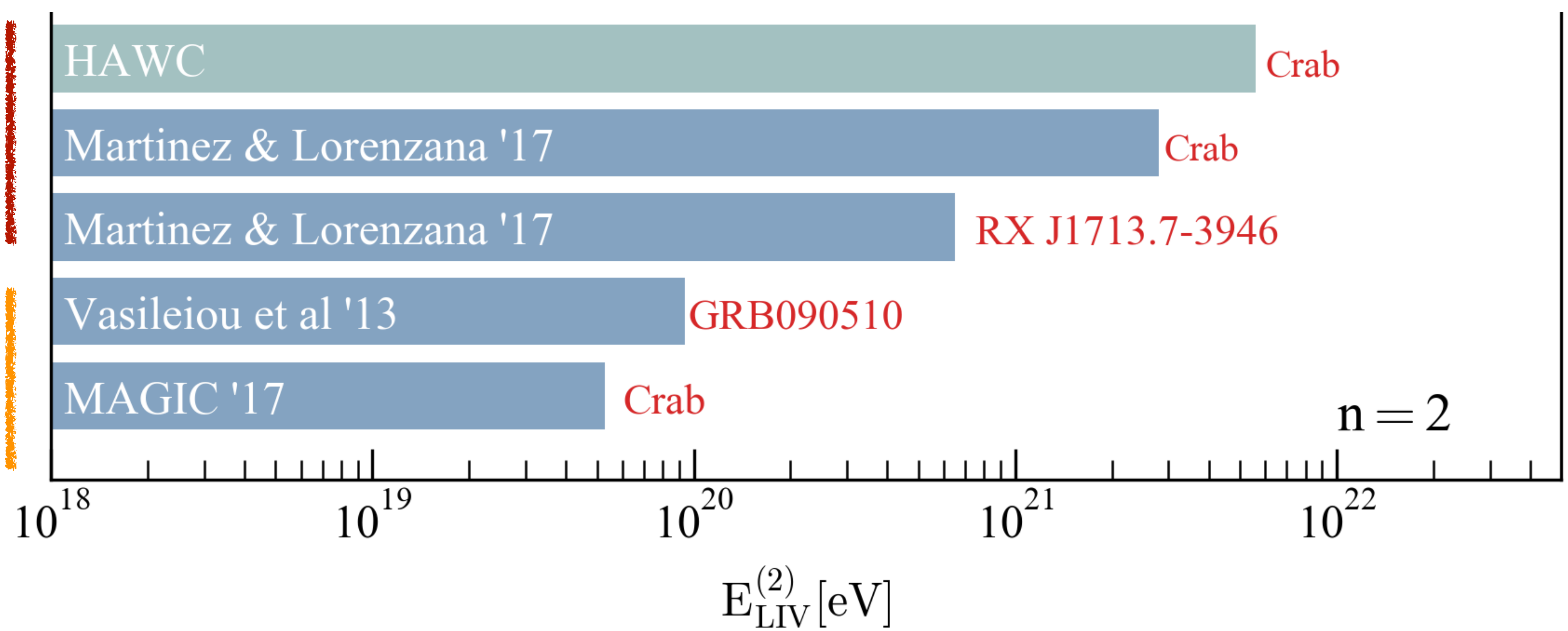
Photon decay

Time Energy Dependent



ELIV potential limits from HAWC

n=2 and energy unc. of 25%.

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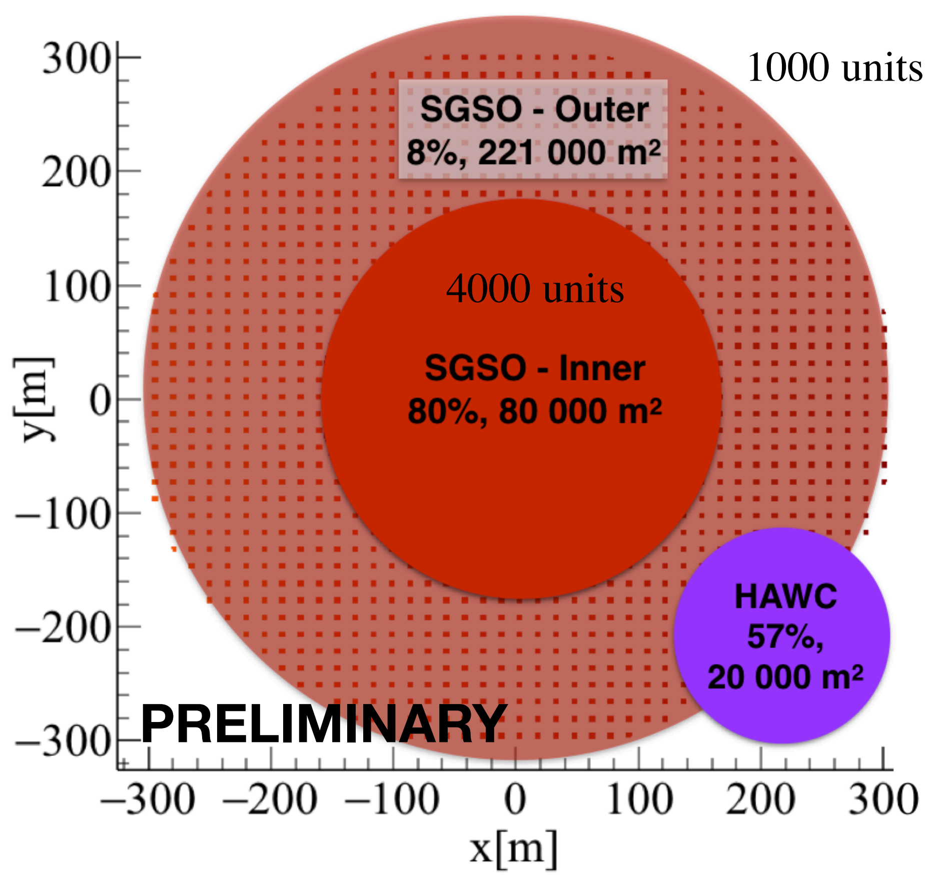
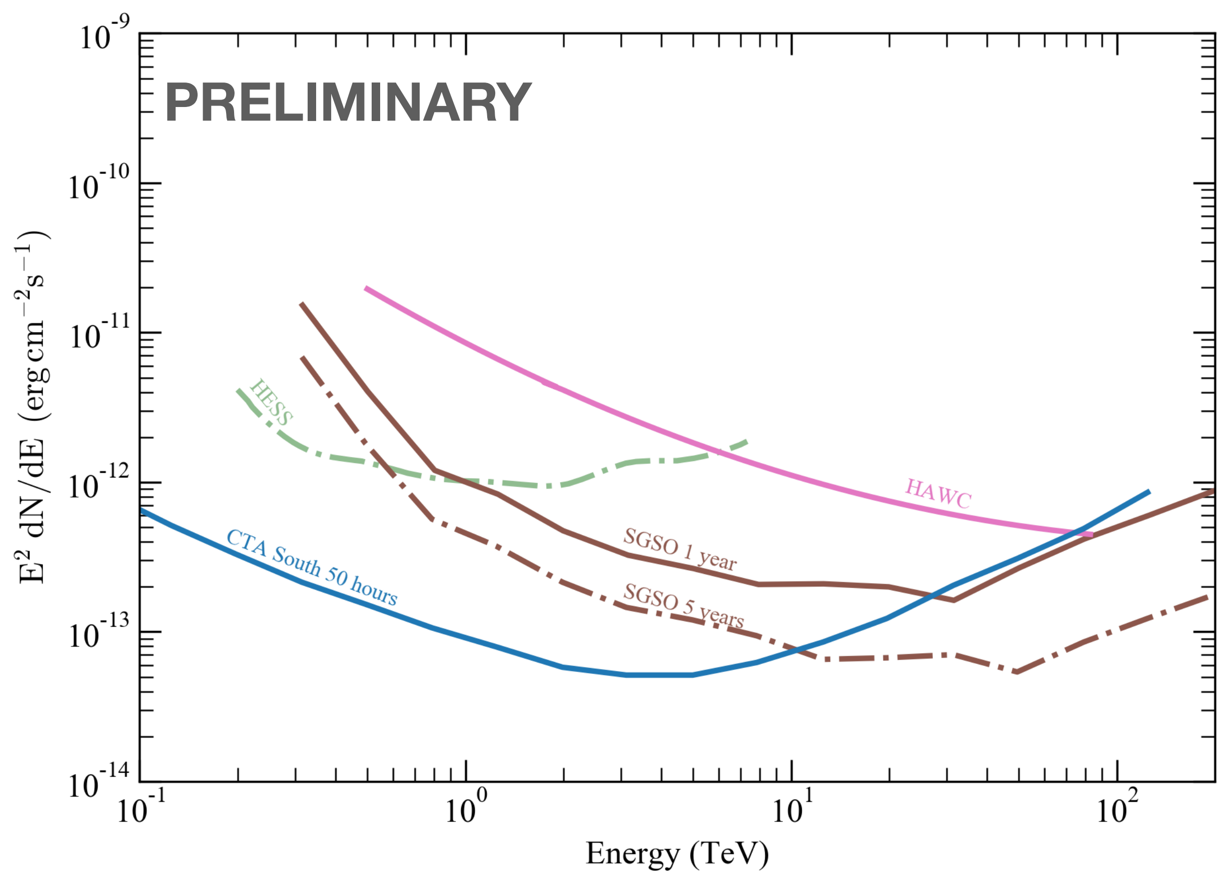
Searching LIV signatures with SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY





White paper in preparation

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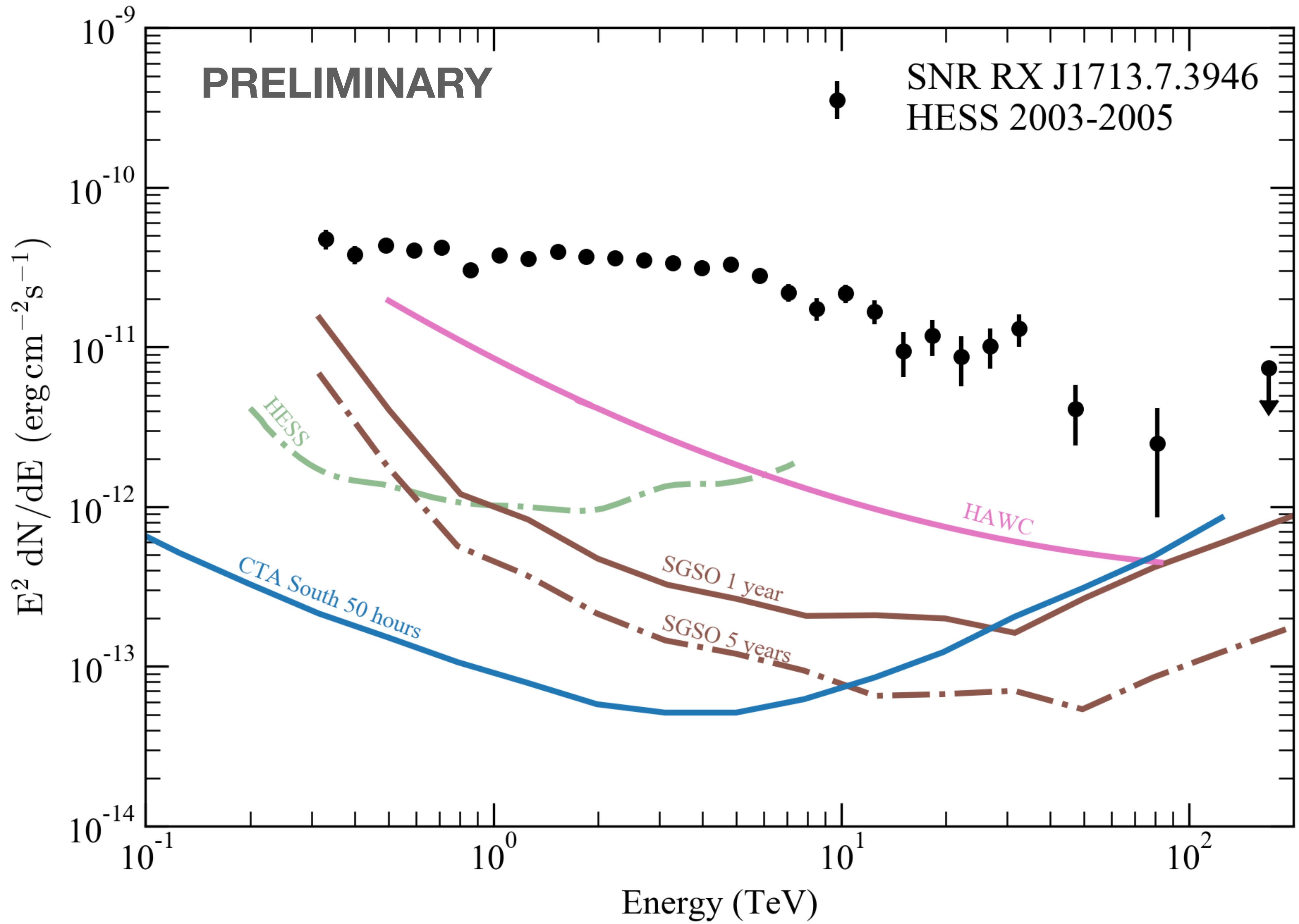
Searching LIV signatures with SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY



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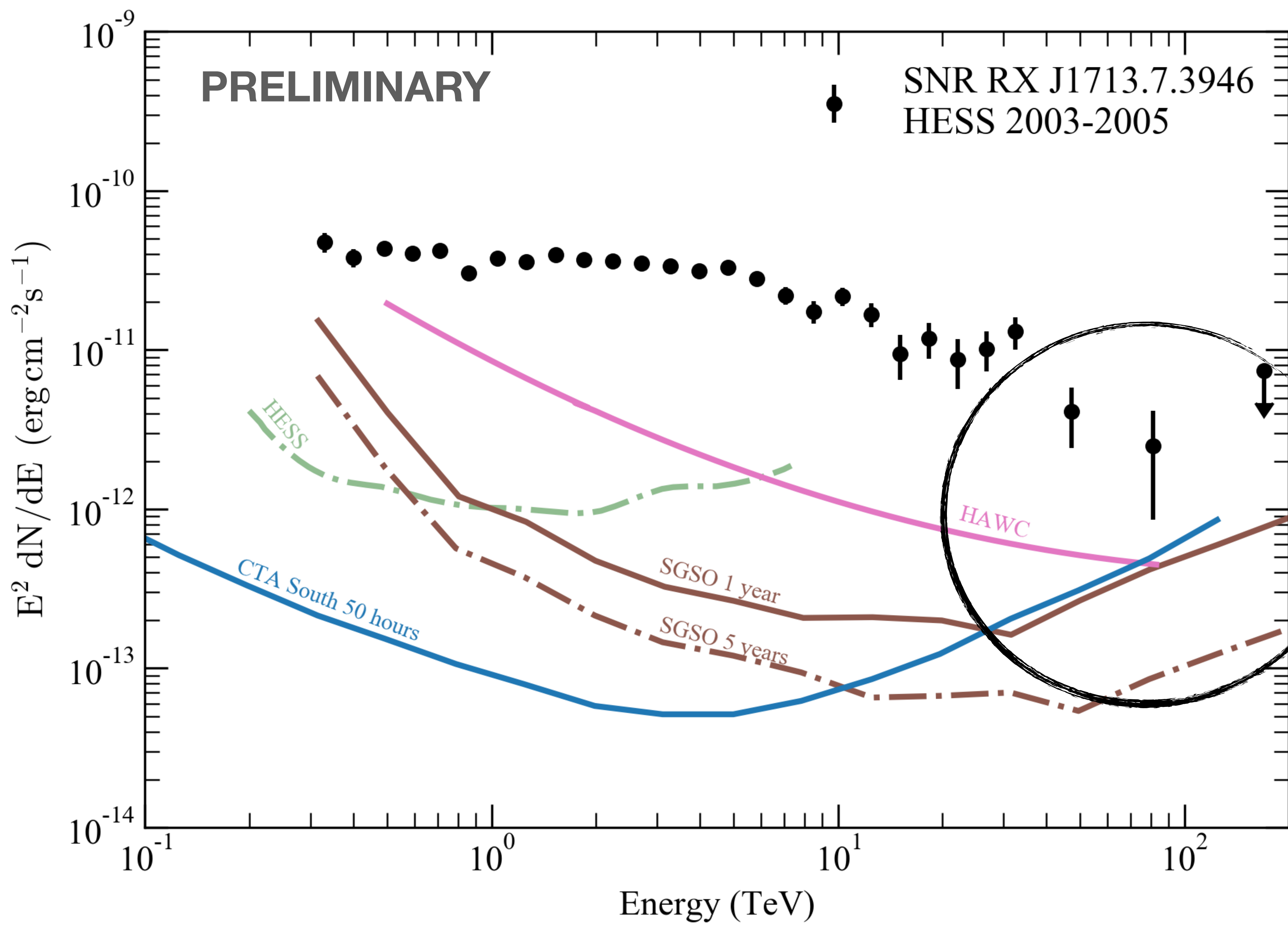
White paper in preparation

Searching LIV signatures with SGSO

Southern
Gamma-ray
Survey
Observatory



The higher the observed gamma-ray energy is, the stringent the limit!

White paper in preparation

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Searching LIV signatures with SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY

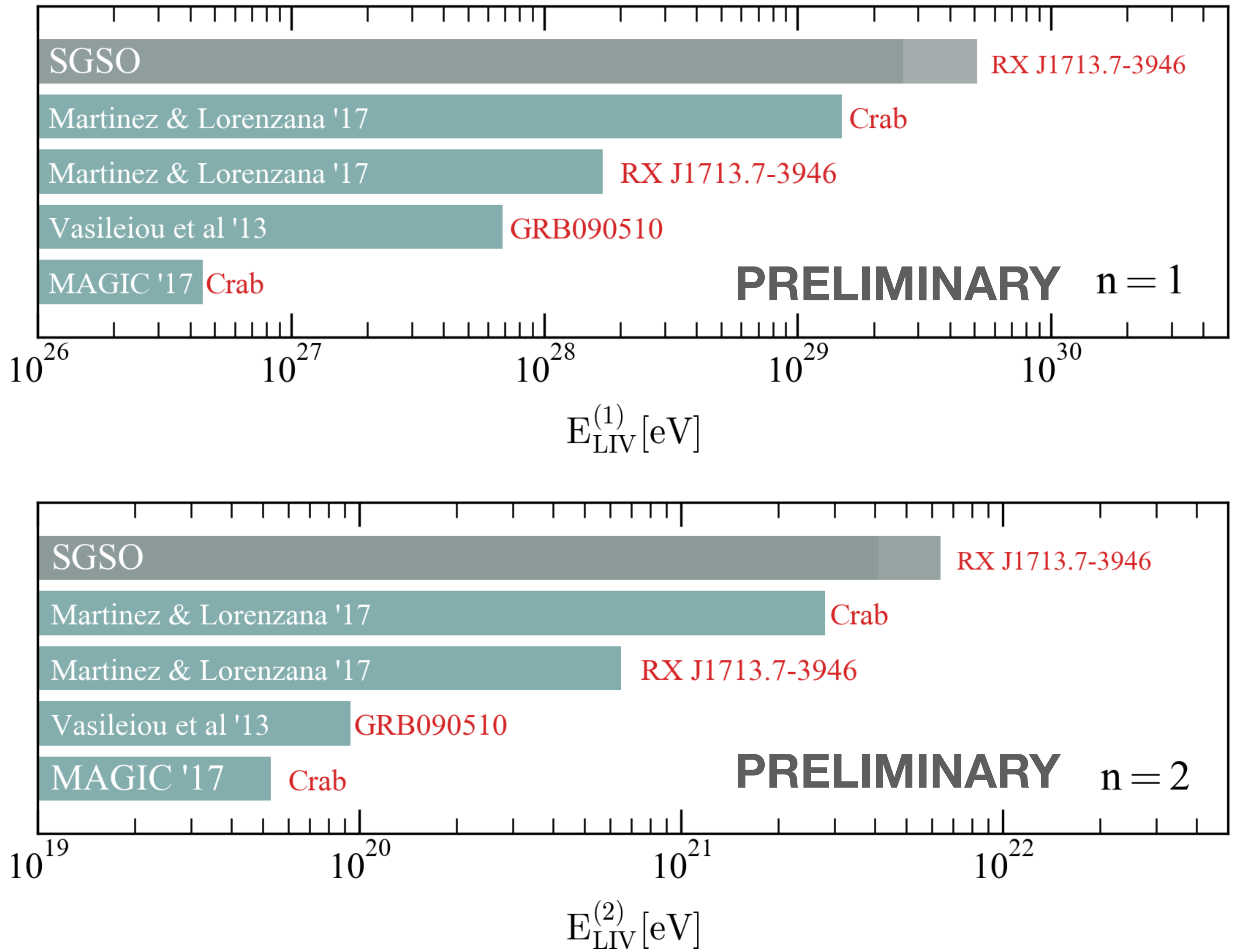

Fig. 1
LIV energy scale limits from superluminal searches including a potential reference of SGSO by measuring RXJ1713.7-3946 photons at **80 TeV** and **100 TeV** and the absence of photon decay into electron-positron pairs.

White paper in preparation

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Pair Production

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

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

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

$\Lambda_n < 0$ Threshold-shifts

$\Lambda_n = 0$ LI scenario

$\Lambda_n > 0$ +2nd Threshold

The threshold equation

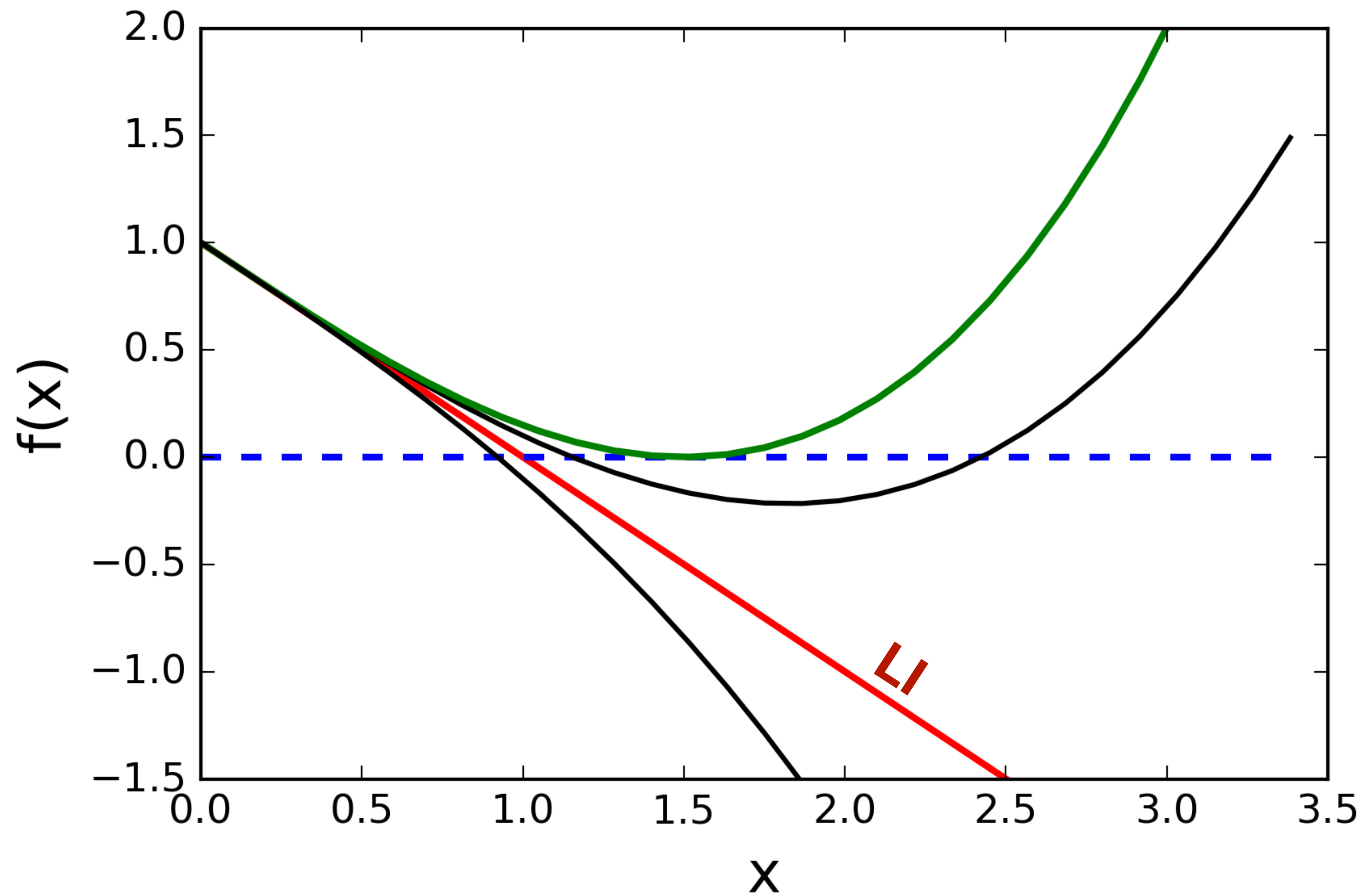
$$\delta_{\gamma,n} E_\gamma^{n+2} + 4E_\gamma \epsilon - m_e^2 \frac{1}{K(1-K)} = 0$$

Critical point

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

Background:

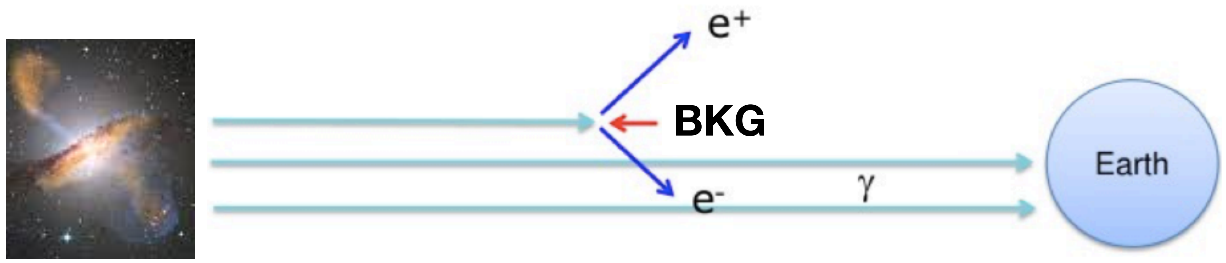
$$\epsilon_{th}^{\mathrm{LIV}} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E_\gamma^{n+1}}{4}$$



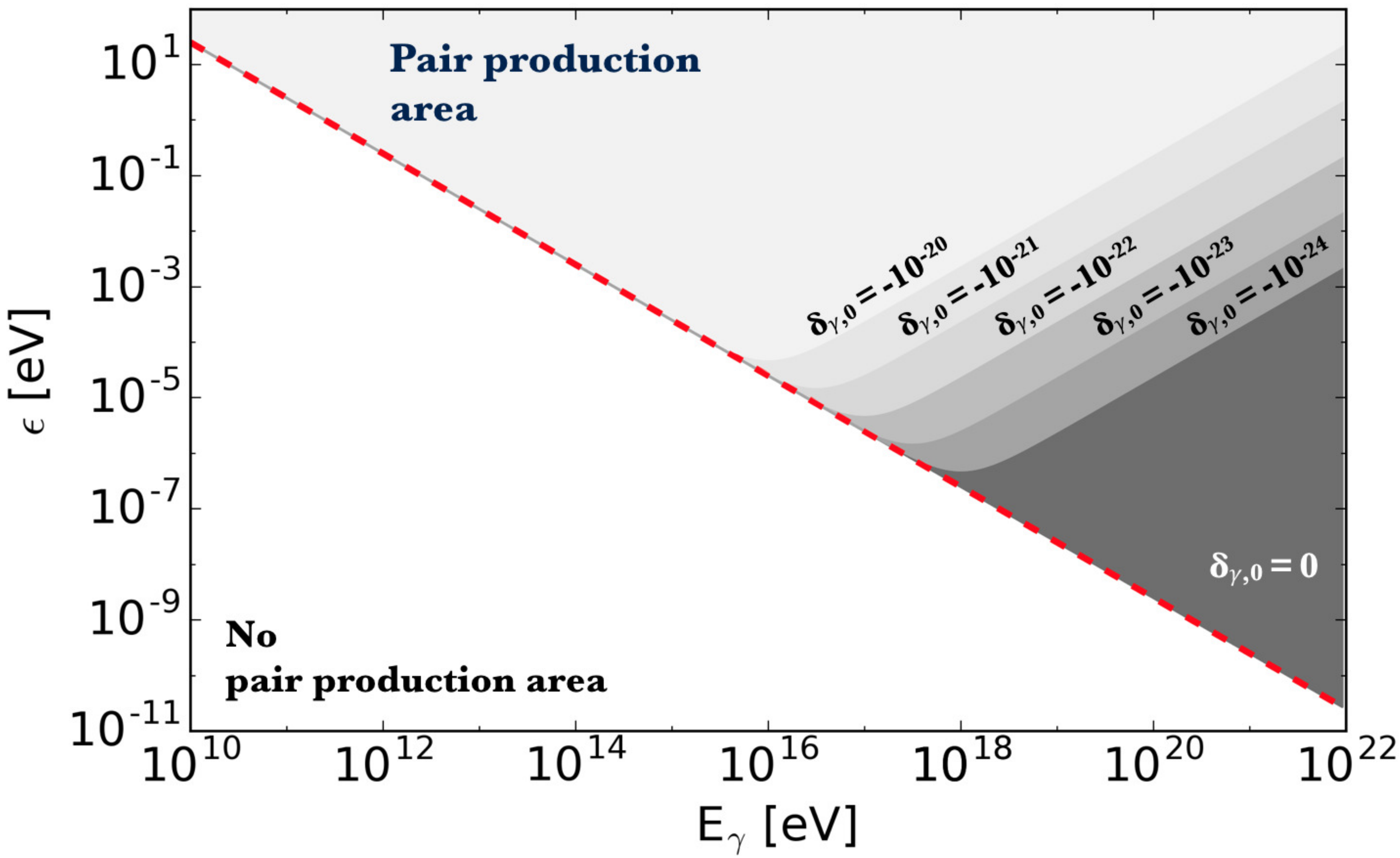
H. Martínez-Huerta, A. Pérez-Lorenzana. Phys. Rev. D 95, 063001 (2017)

Pair Production

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



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



Allowed region change with the LIV parameter and the Energy

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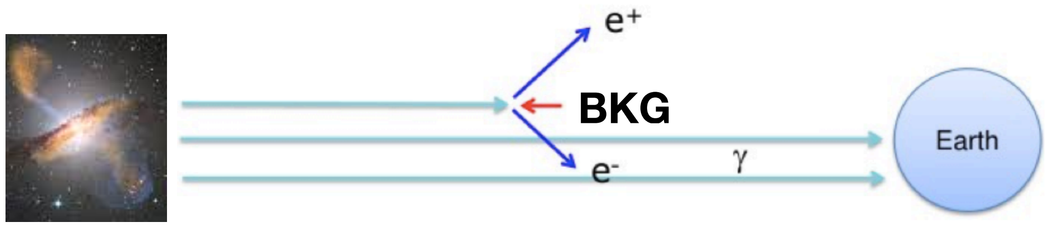
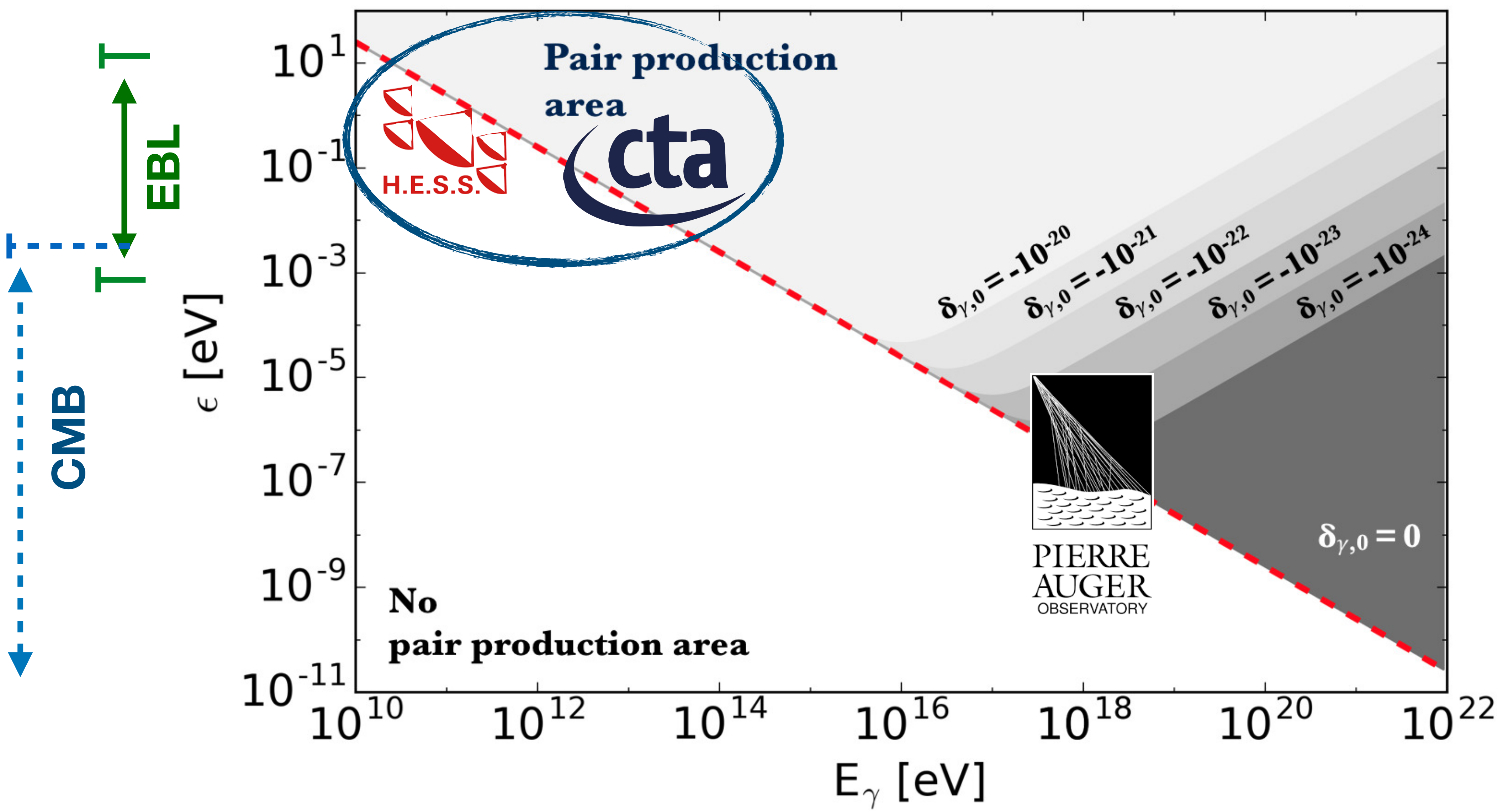
Pair Production

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

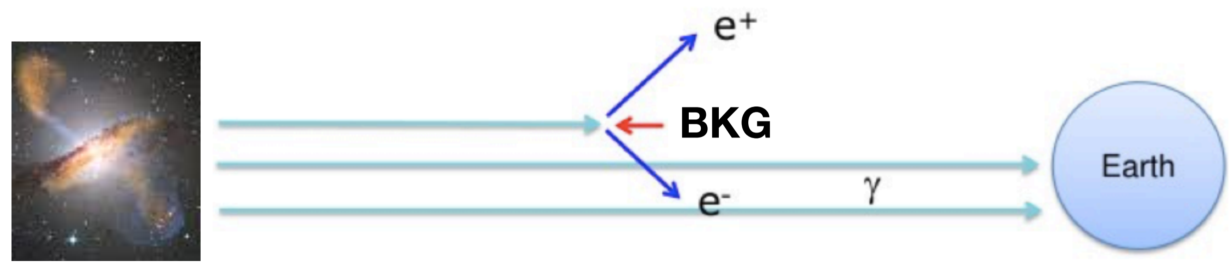


$$\epsilon_{th}^{\mathrm{LIV}} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E_\gamma^{n+1}}{4}$$



… deeper LIV effects

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

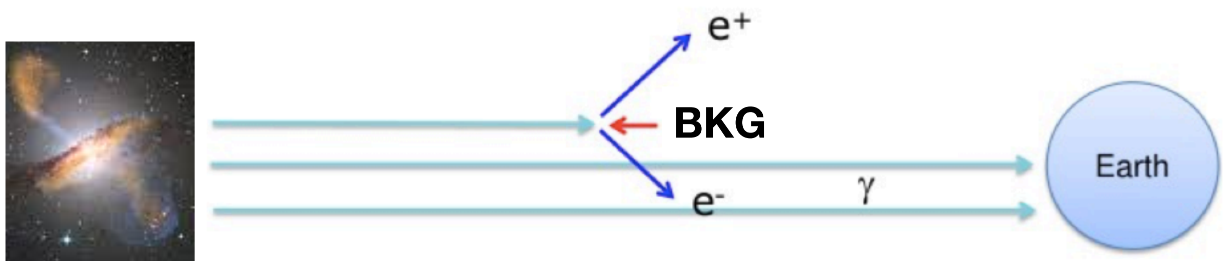
$$\times \int_{-1}^{1} d(\cos\theta) \frac{1-\cos\theta}{2} \sigma(E_\gamma, \epsilon, z, \cos\theta)$$

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



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

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

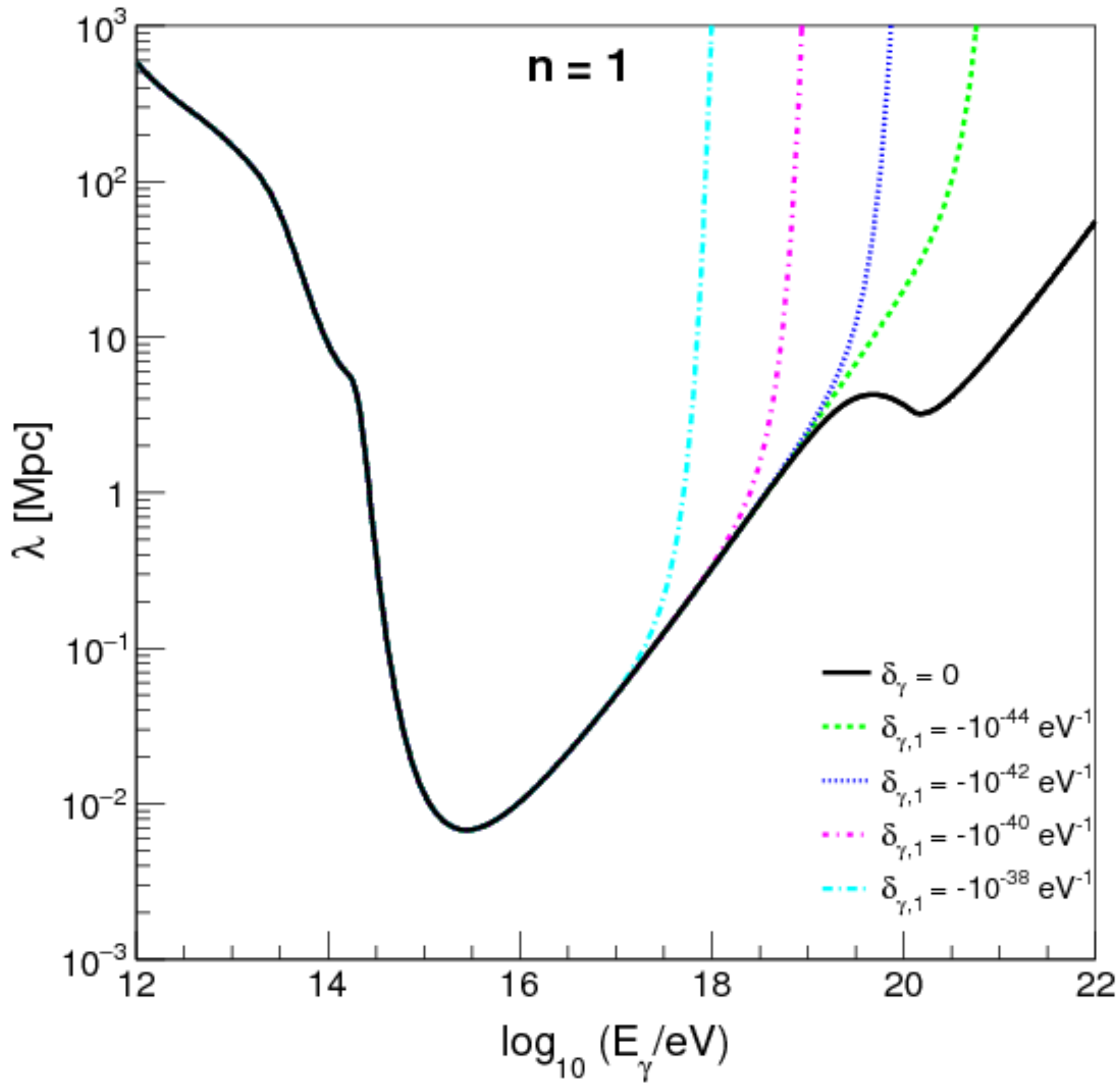
LIV

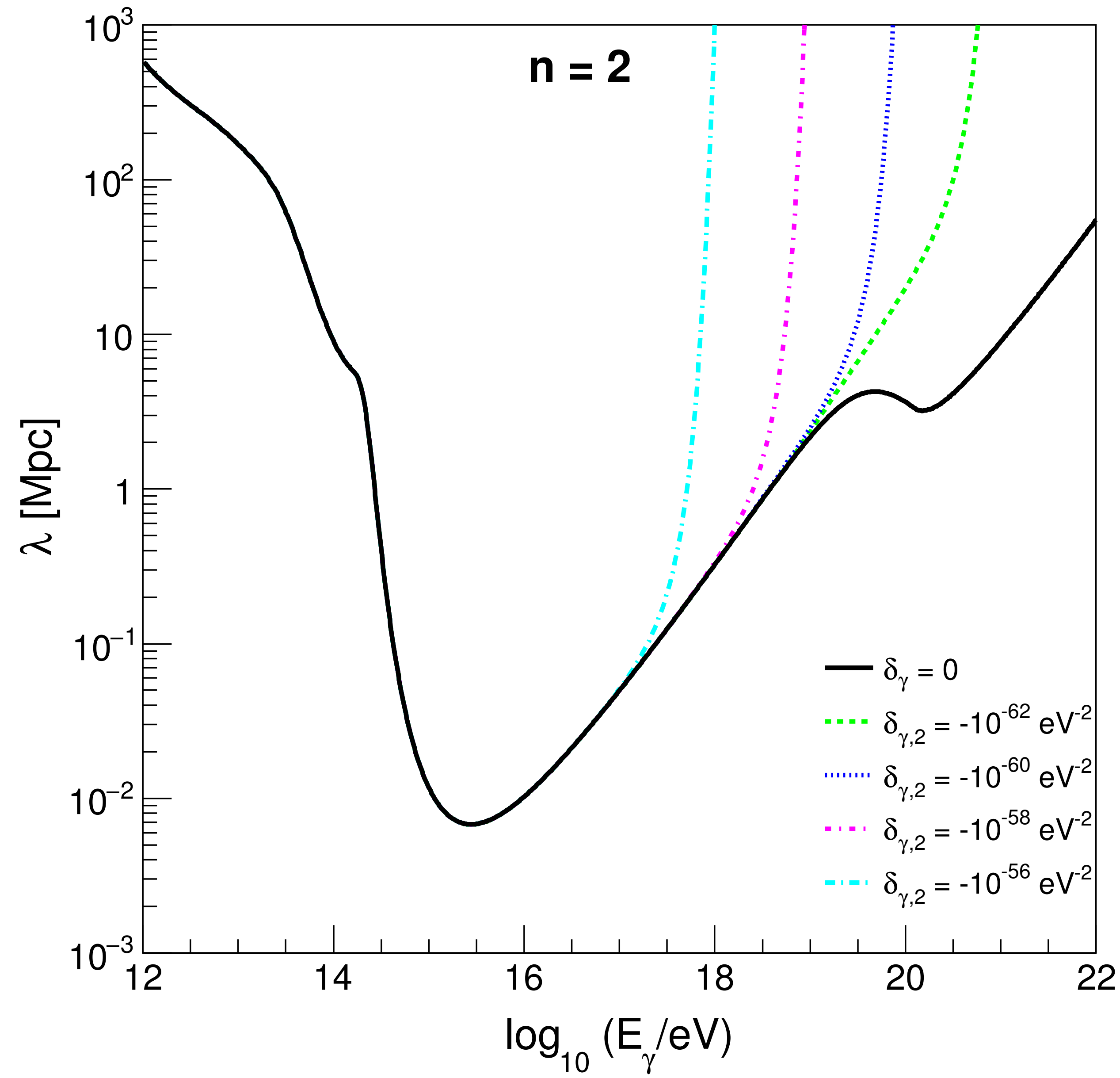
$$\epsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_{\gamma,n} E_\gamma^{n+1}}{4}$$

Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

Optical depth + LIV

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





Lang, Martinez & De Souza
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More photons!!

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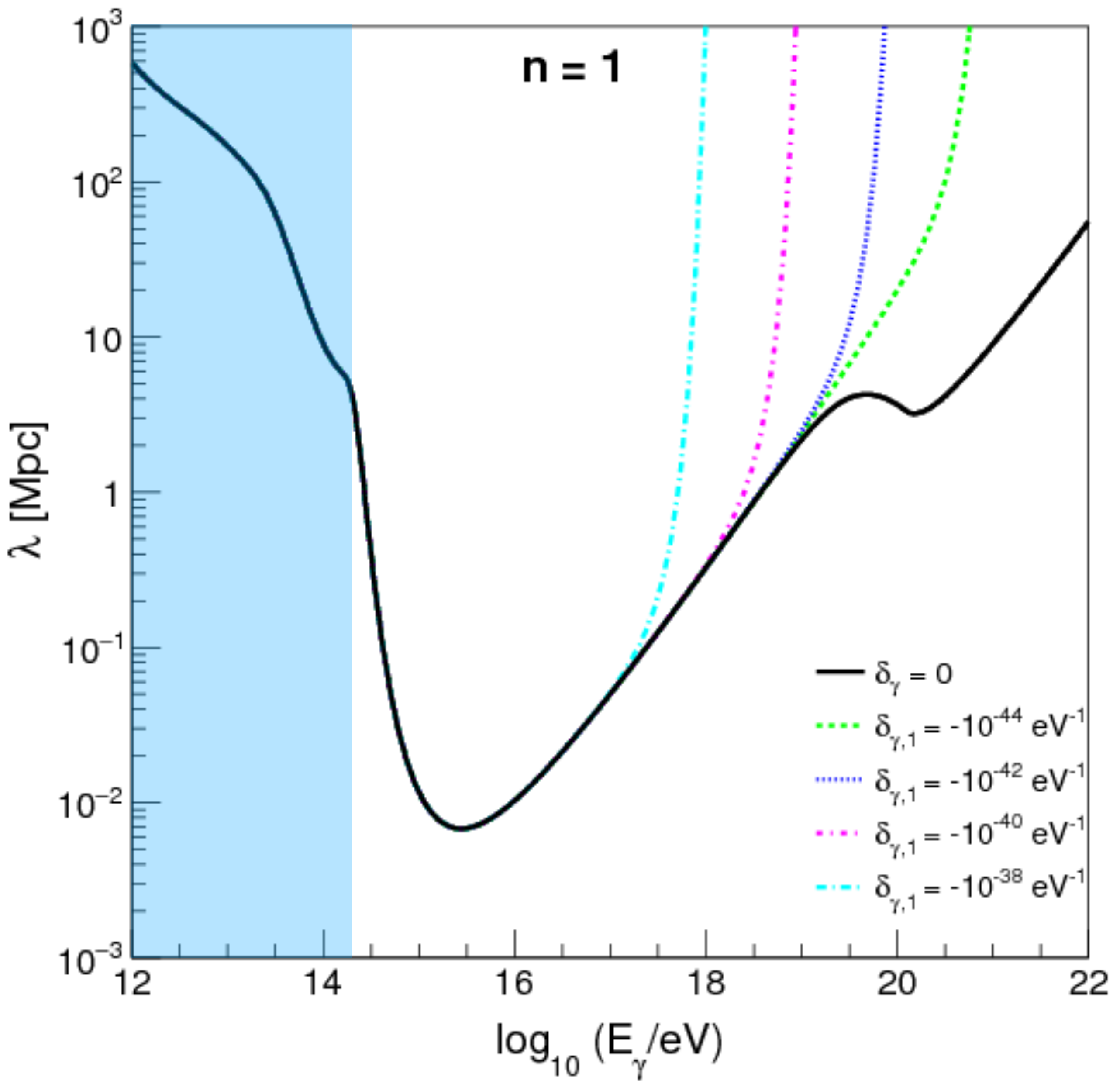
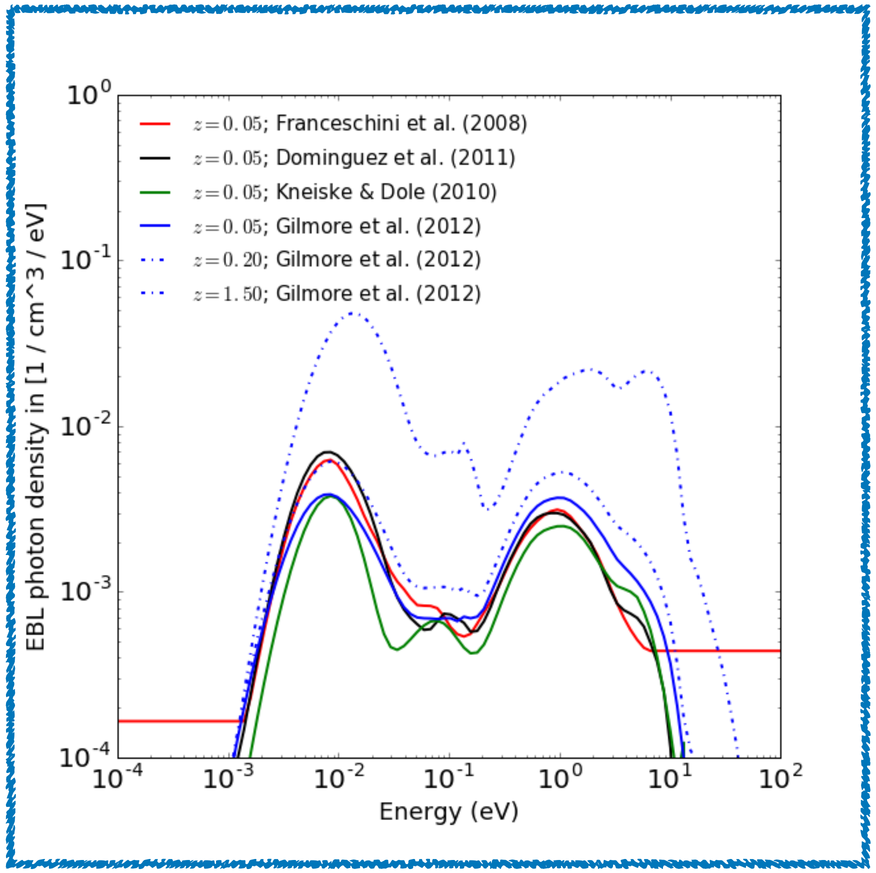
Optical depth + LIV

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



BKG density
EBL-photons

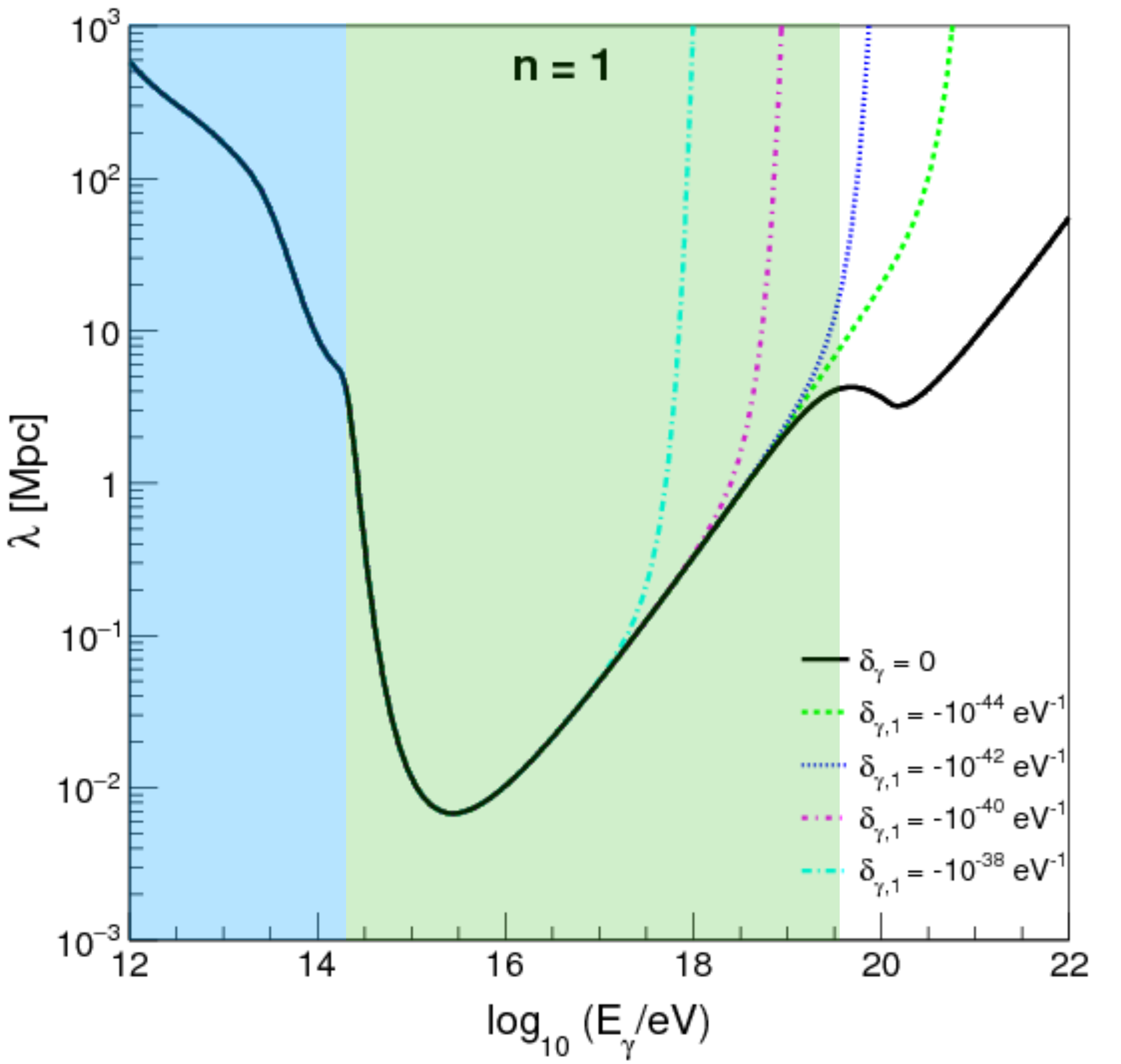


EBL: Gilmore & Ramirez-Ruiz (2010)

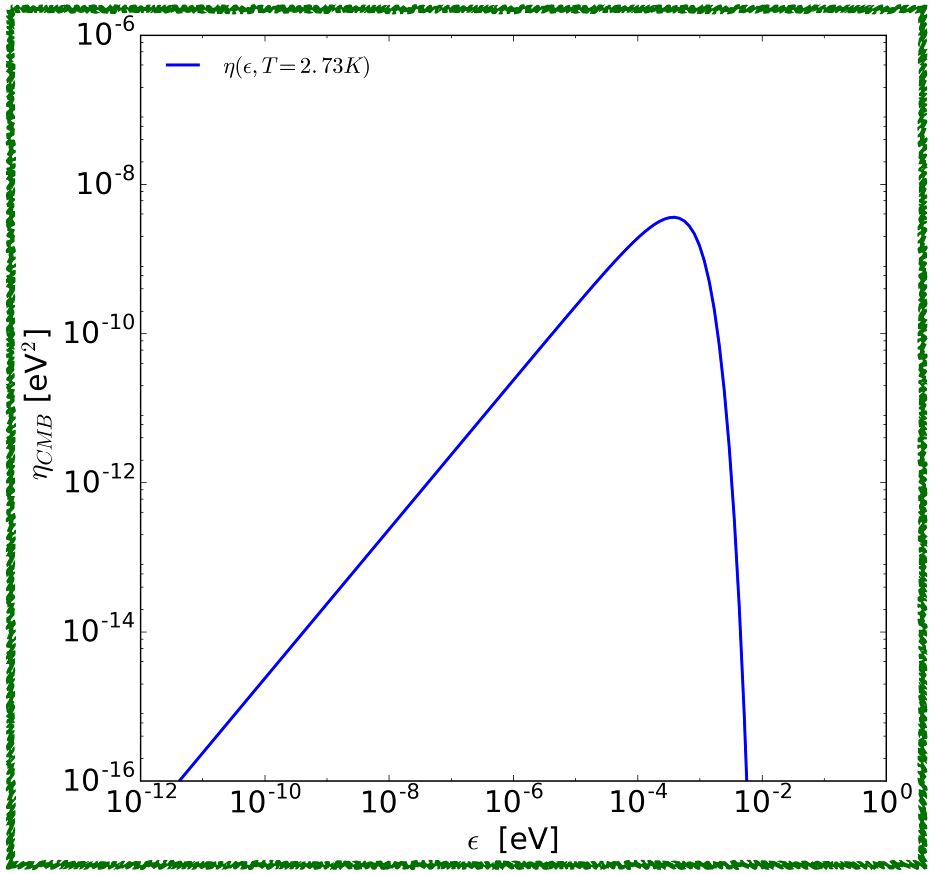
Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

Optical depth + LIV

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



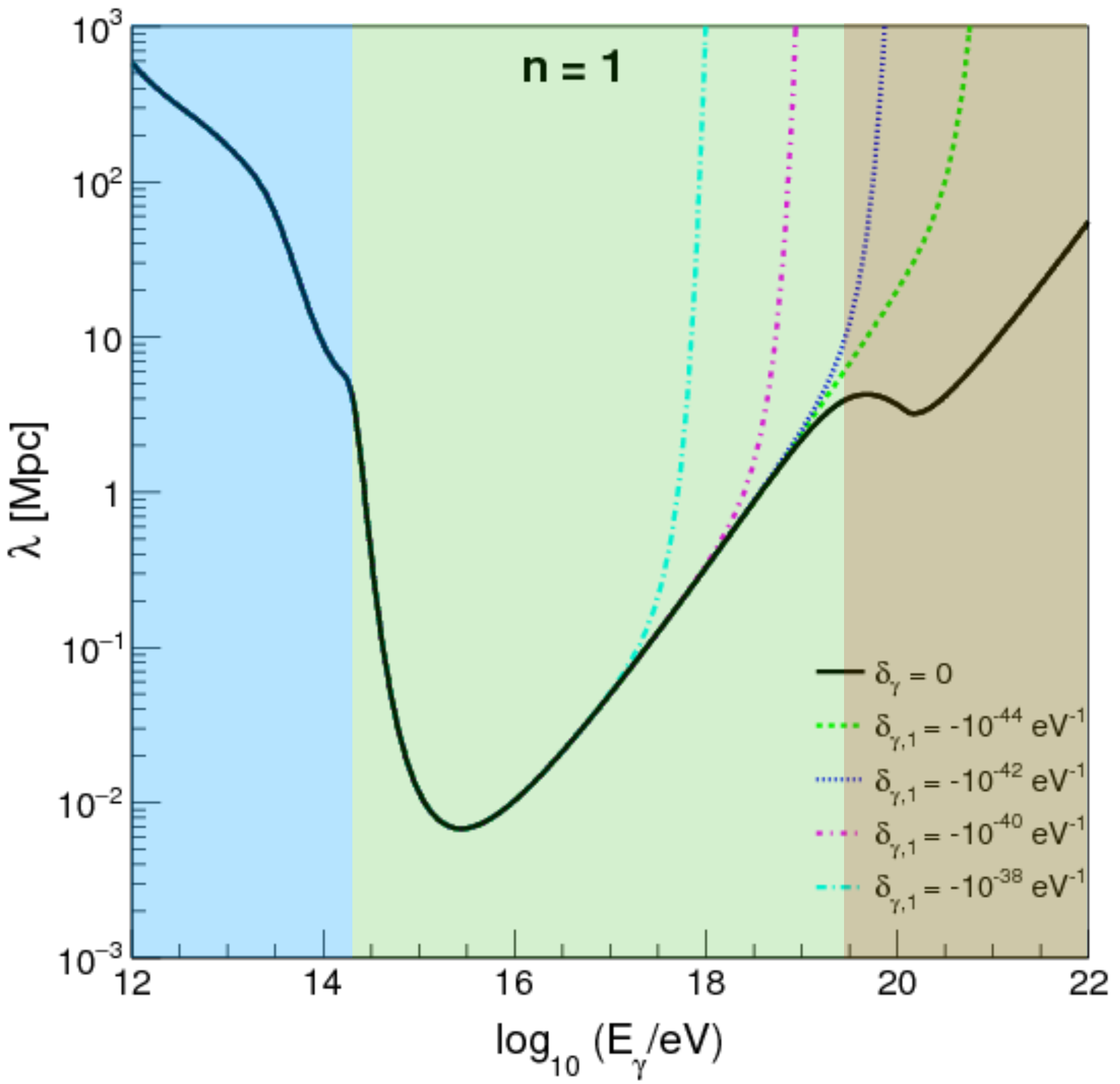
BKG density
CMB-photons



Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

Optical depth + LIV

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



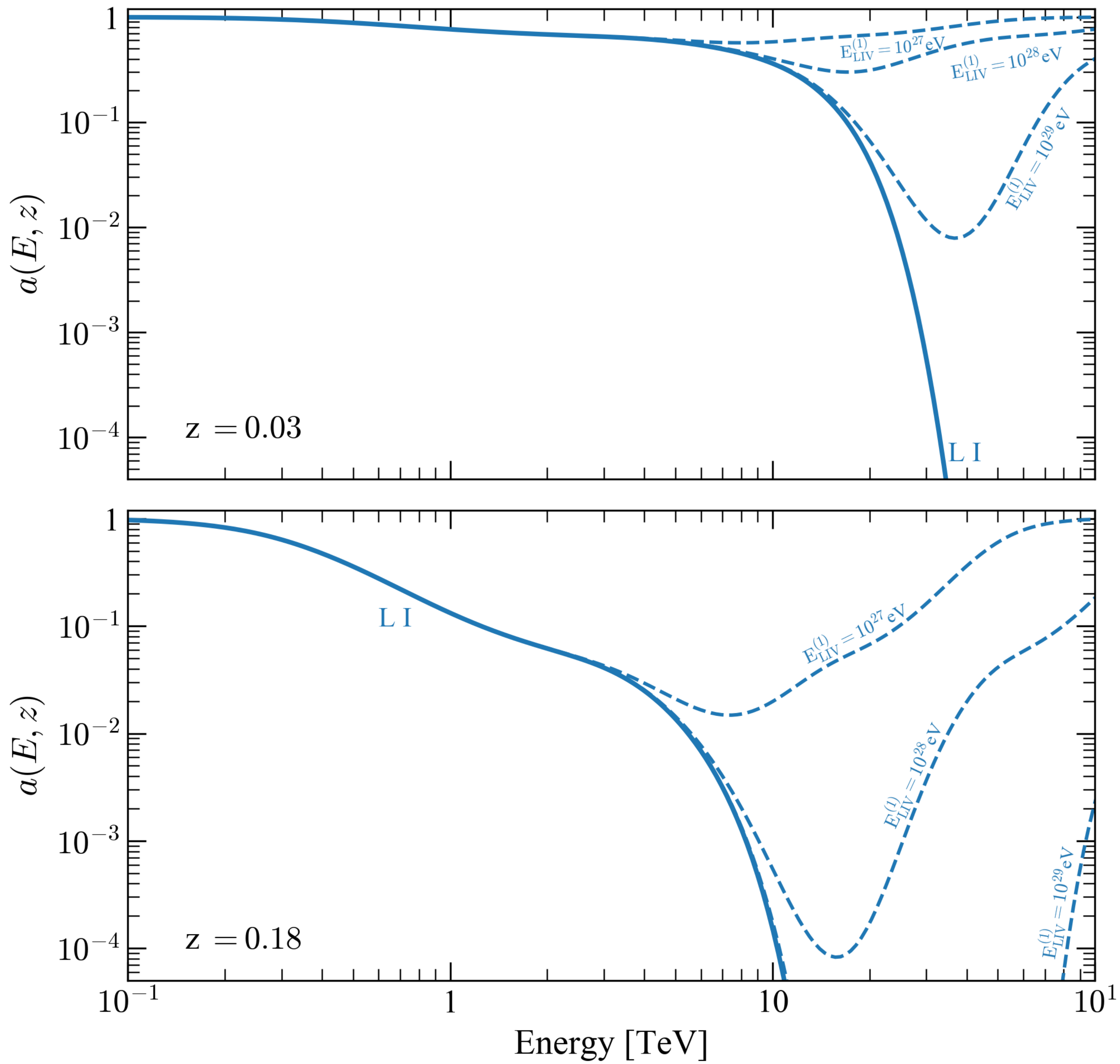
BKG density
Radio-photons

Data from Gervasi el al. (2008)

Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

EBL-Attenuation + LIV

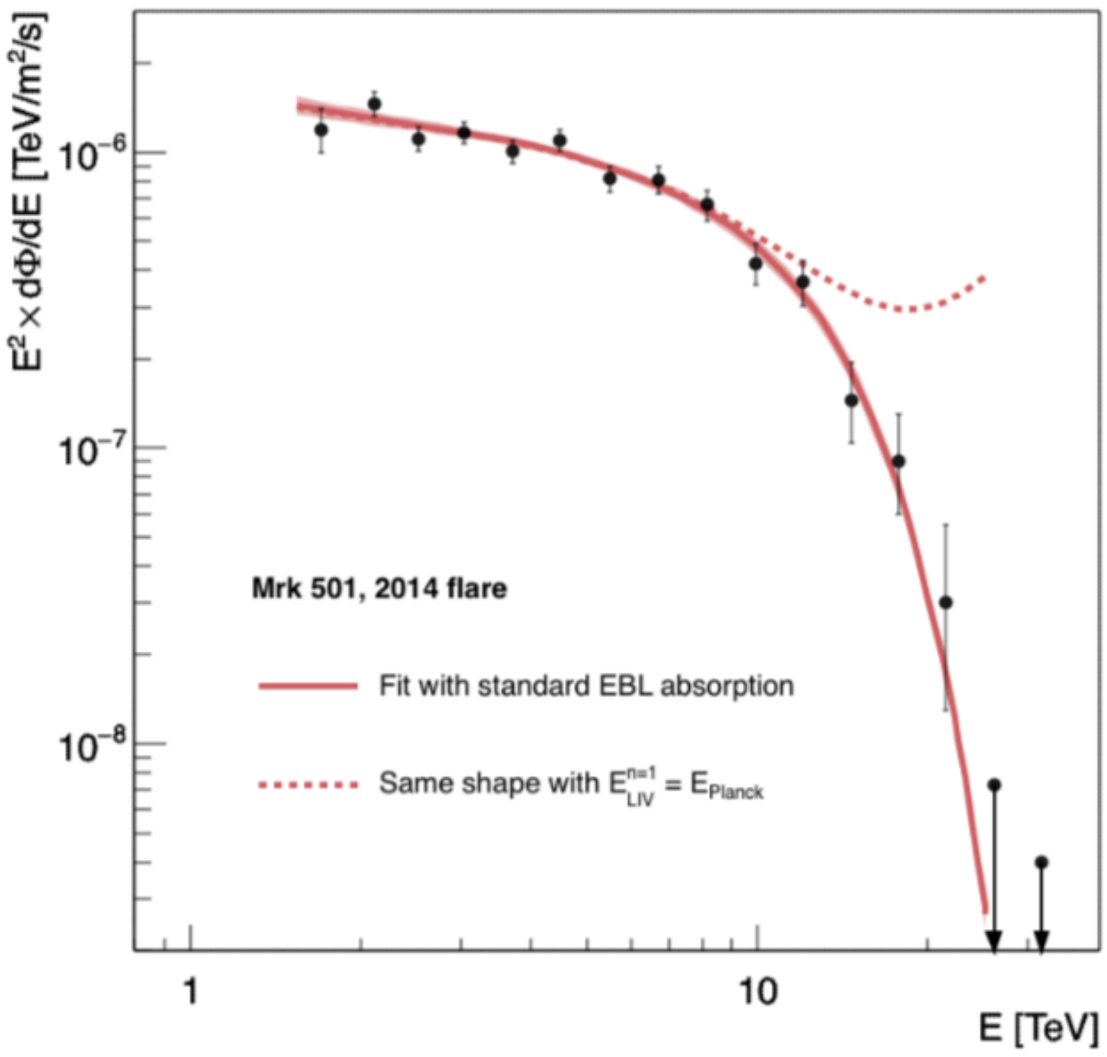
$$a(E, z) = e^{-\tau}(E, z)$$

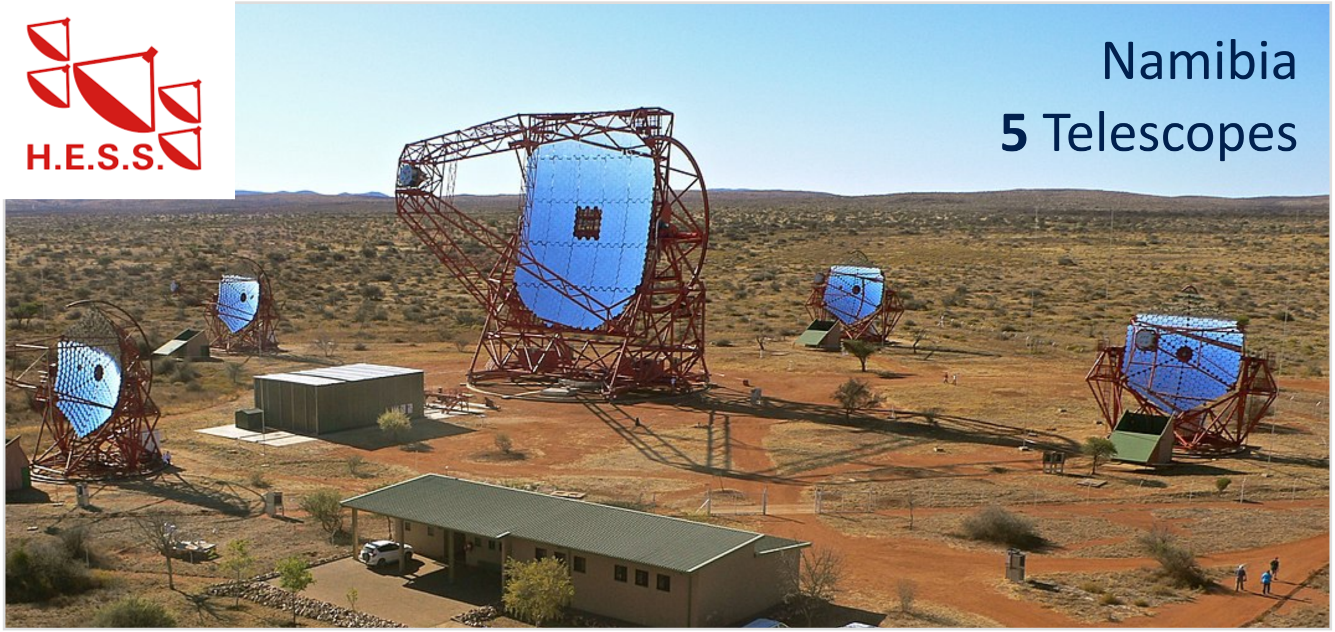


The intensity of the LIV effect depends on

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

EBL-Attenuation + LIV





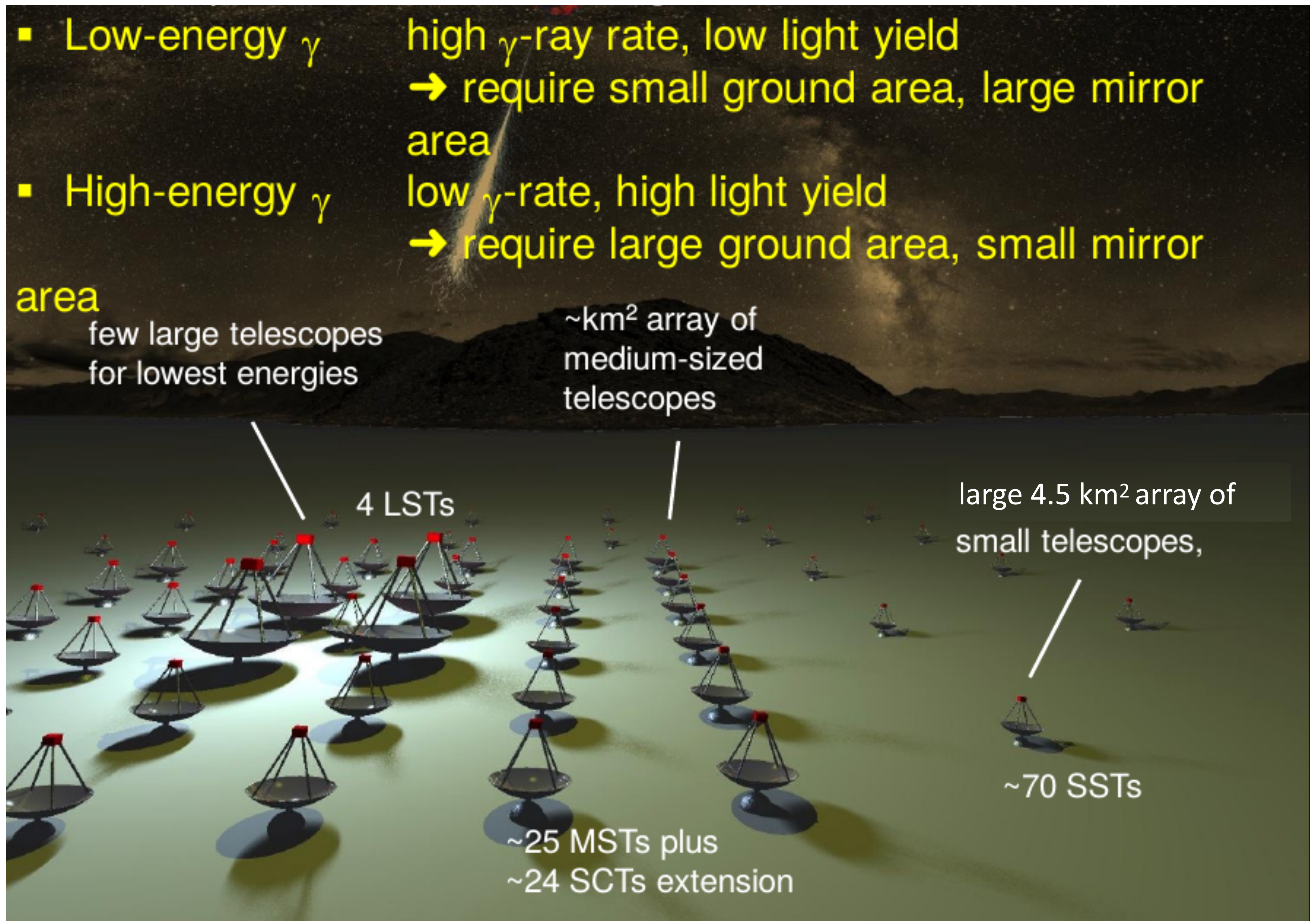
	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{Planck}$)	1.9×10^{28} eV ($1.6 \times E_{Planck}$)	1.04×10^{28} eV ($0.86 \times E_{Planck}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

Lorentz and Brun for the HESS collaboration, RICAP16, 2016.

Cherenkov Telescope Array

99 Telescopes
- 4 LST
- 25 MST
- 70 SSTs

Energy range
20 GeV - 300 TeV



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CTA Consortium

August 2018

31 Contries
92 Parties
202 Institutes
1466 members (513 FTE)

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  - Ruben Alfaro
  - Alejandro Lara
  - William Lee
  - Maria Magdalena
  - Lukas Nellen
  - Andrés Sandoval
  - Gagik Tovmassian
- 2 Engineers
  - Fernando Garfias
  - Arturo Iriarte

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  - Profa. Manuela Vecchi
  - Profa. Cibelle Celestino
  - Dr. Humberto Huerta
  - Dr. Aion Viana
  - Edyvania Martins
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  - Luan Arbeletche
  - Andres Delgado
  - Rodrigo Guedes Lang
  - Danielle Kaori
- IF-USP
  - Prof. Edivaldo Moura
  - Douglas Pimentel
- UFABC
  - Prof. Marcelo Leigui
  - Raquel de Almeida
- UFSCar
  - Dr. Gustavo Rojas
- UFPR
  - Prof. Rita de Cássia
- EEL / USP
  - Prof. Fernando Catalani
  - Prof. Carlos Todero
- SAIFR / IFT - UNESP
  - Dr. Fabio Iocco
  - Dr Ekaterina Karukes
  - Maria Benito

CTA Brazil

12 Instituions

25 Scientists

16 Students

5 Technicians

CTA - Rio

- CBPF
  - Prof. Ulisses de Almeida
  - Prof. Ronald Shellard
  - Bruno Arsioli
  - Bernardo Fraga
  - Rodrigo Cardoso
  - Amanda Carvalho

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- IAG – USP
  - Profa. Elisabete dal Pino
  - Prof. Rodrigo Nemmen
  - Dr. Rafael Batistai
  - Dr. Chandra Singh
  - Dr. Grzegorz Kowal
  - Dr. Reinaldo Lima
  - Dr. Paramita Barai
  - Dr. Luis Kadowki
  - Dr. Claudio Melioli
  - Dr. Juan Ramirez
  - Tania Torrejon
  - Renato Gimenes
  - Pankaj Kushwaha
  - Saib Hussain
  - Carlos Fermino
  - Raniere Menezes
  - William Bohórquez
  - Lucas Santos
- UNICSul
  - Prof. Anderson Caproni
- EACH / USP
  - Prof. Diego Falceta-Gonçalves
  - Mohammad Ali

The Array Locations

Array Coordinates
Latitude: 24° 41’ 0.34” South
Longitude: 70° 18’ 58.84” West

CTA South
Chile, Paranal

~5 km²

area covered by the array of telescopes

CTA North
Spain, La Palma

~0.5 km²

area covered by the array of telescopes

Array Coordinates
Longitude: 17° 53’ 31.218” West
Latitude: 28° 45‘ 43.7904” North

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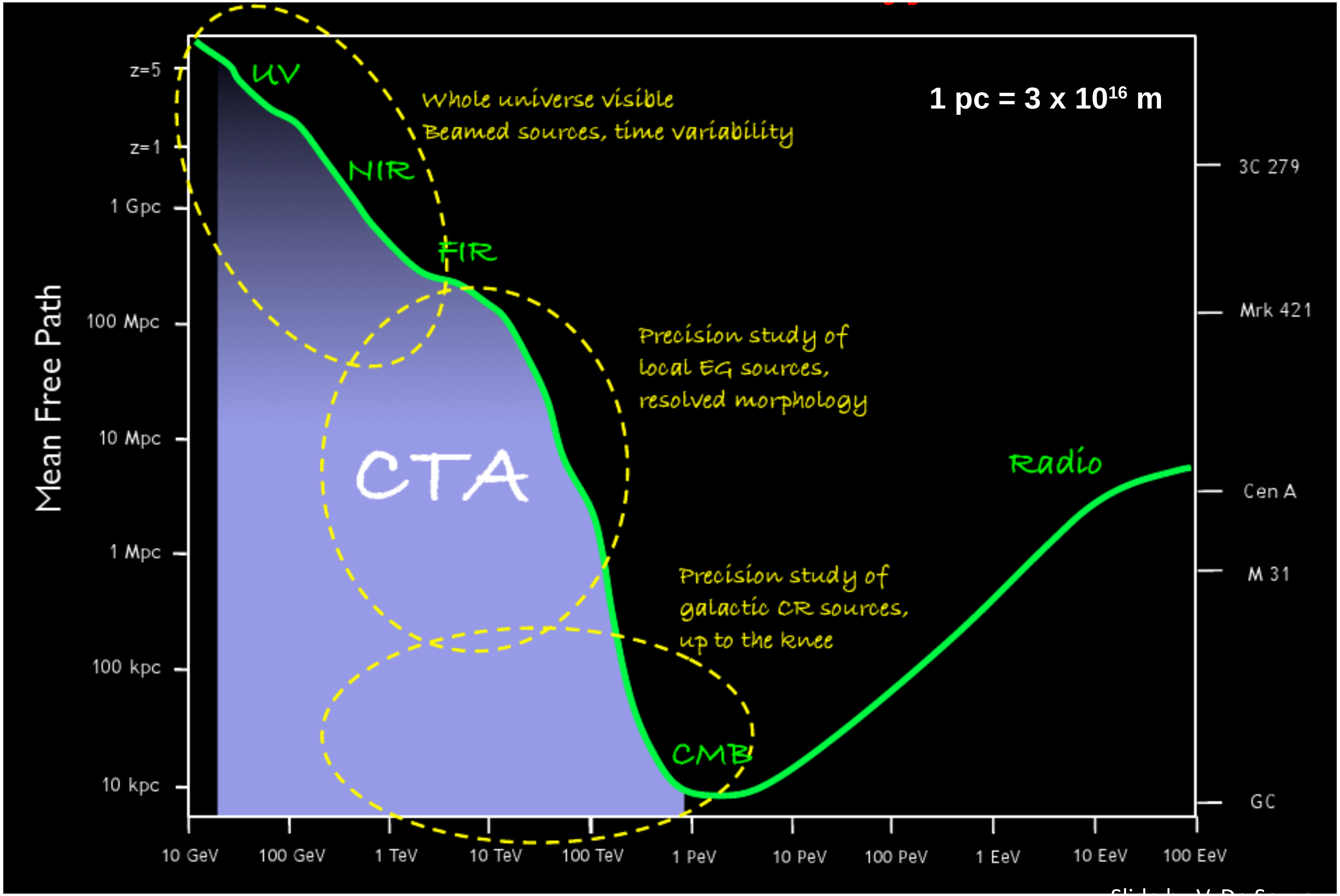
The γ-ray horizon



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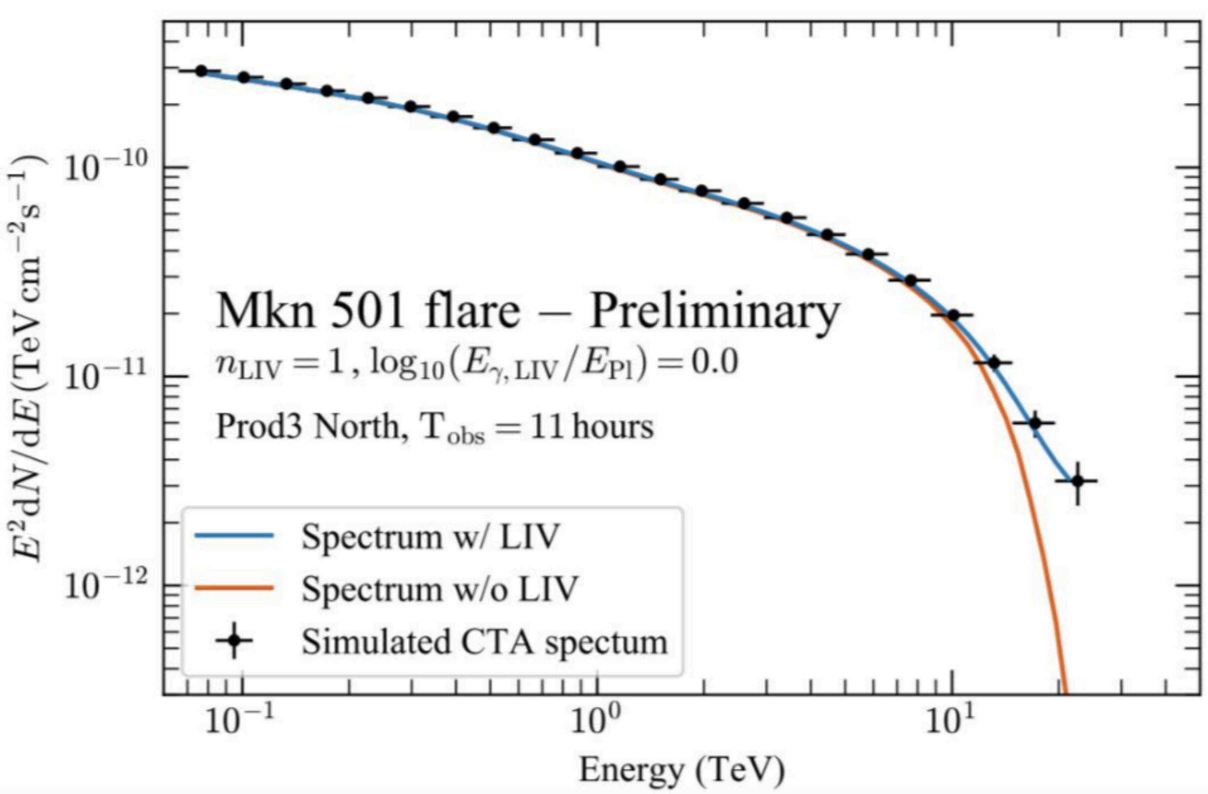
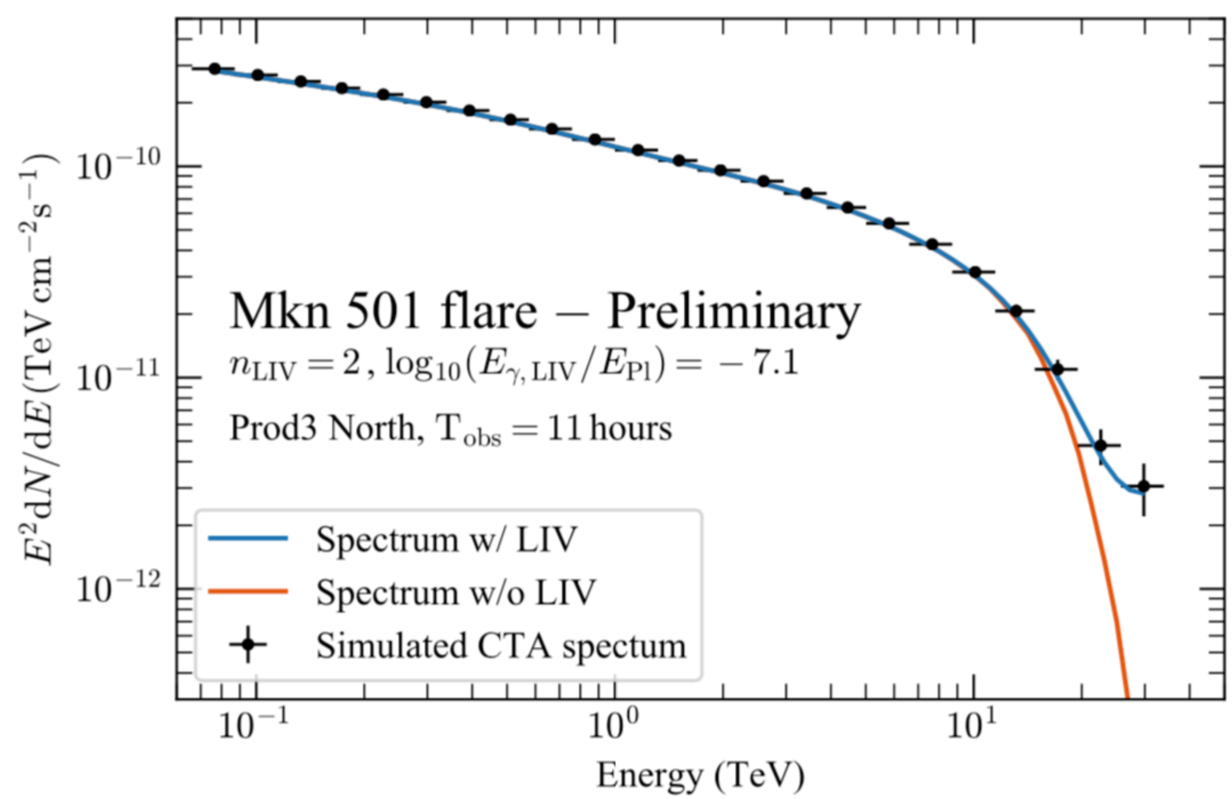
EBL-Attenuation + LIV





F. Gate et al (CTA Consortium) ICRC'17
arXiv:1709.04185

LIV TeV Horizon

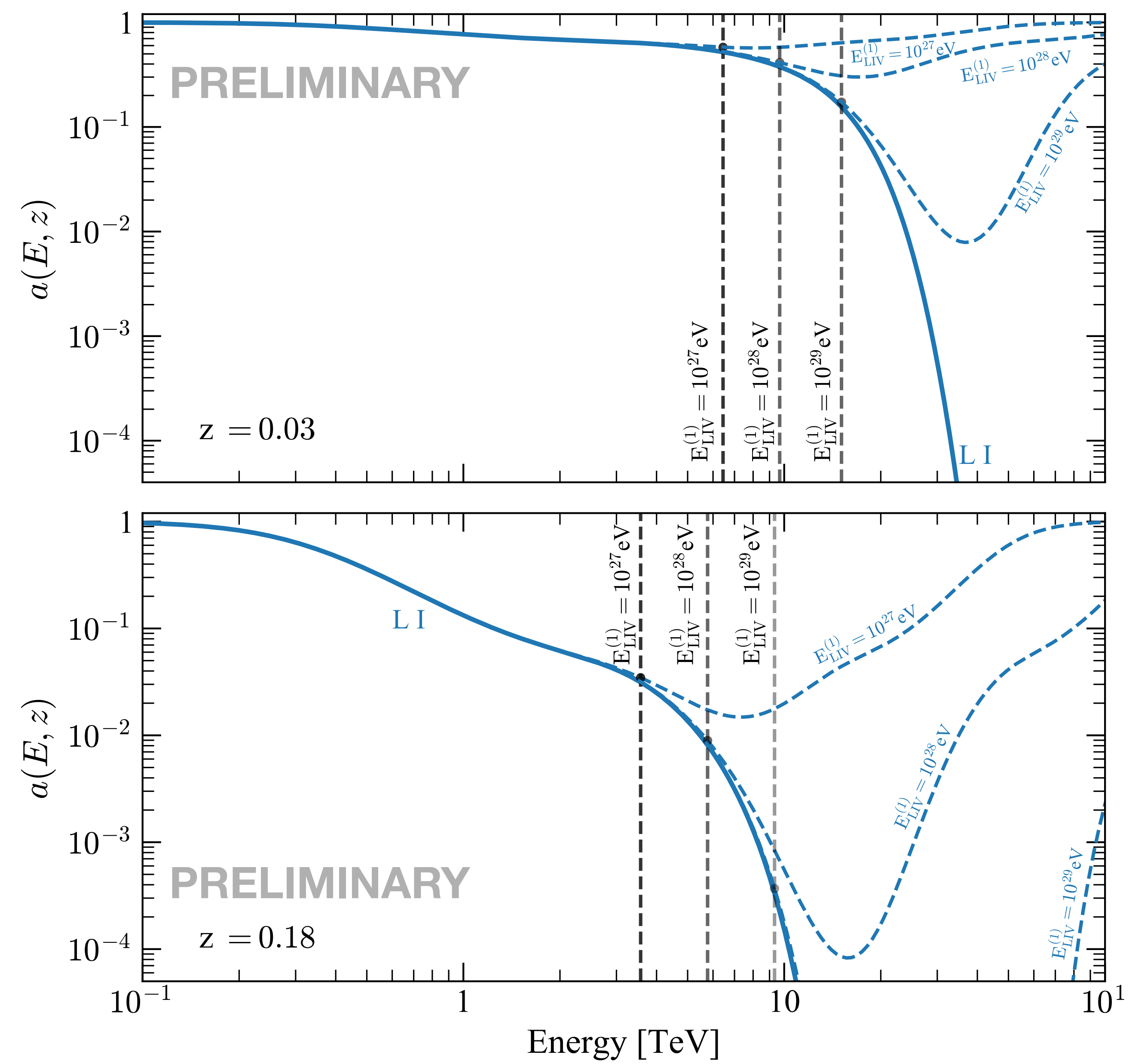
…Why use only one source?

There are ~111 measured energy spectra in the TeVCat !

LIV TeV Horizon

...Why use only one source?

There are ~111 measured energy spectra in the TeVCat !



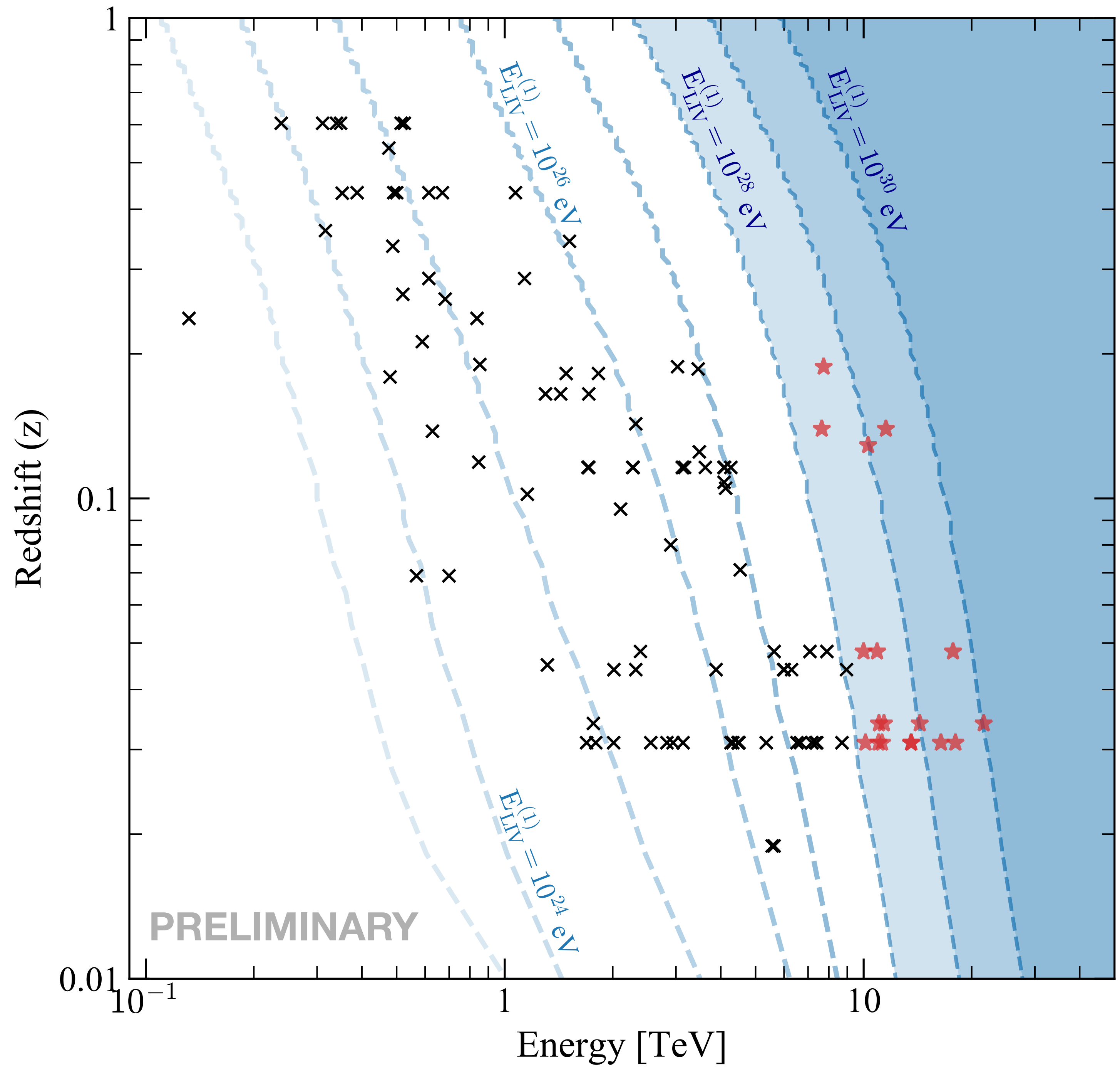
Lang, Martínez and De Souza
arXiv:1810.13215
Submitted

humbertomh@ifsc.usp.br

LIV TeV Horizon

...Why use only one source?

There are ~111 measured energy spectra in the TeVCat !



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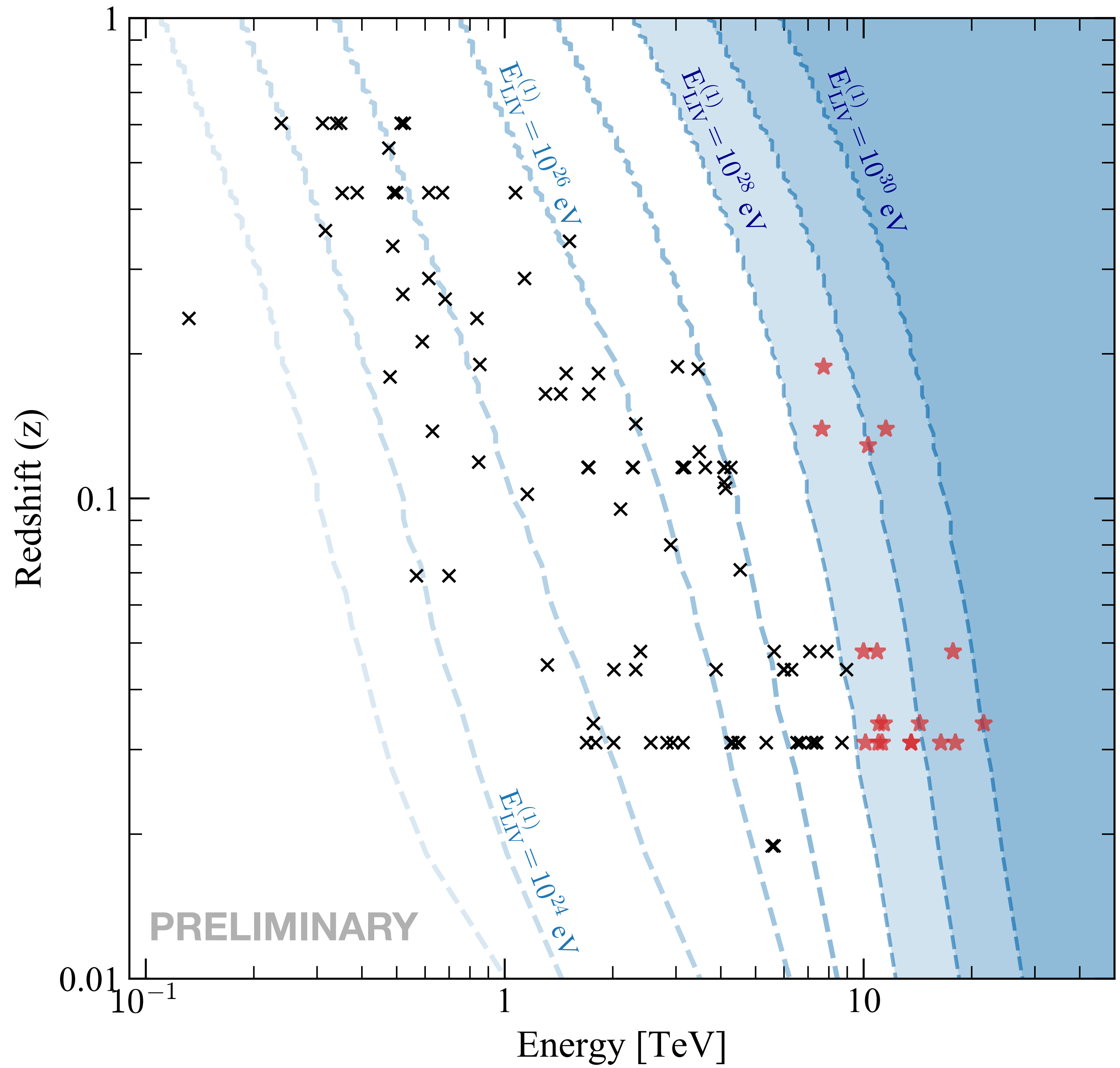
Submitted

LIV TeV Horizon

...Why use only one source?

There are ~111 measured energy spectra in the TeVCat !

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



Lang, Martínez and De Souza
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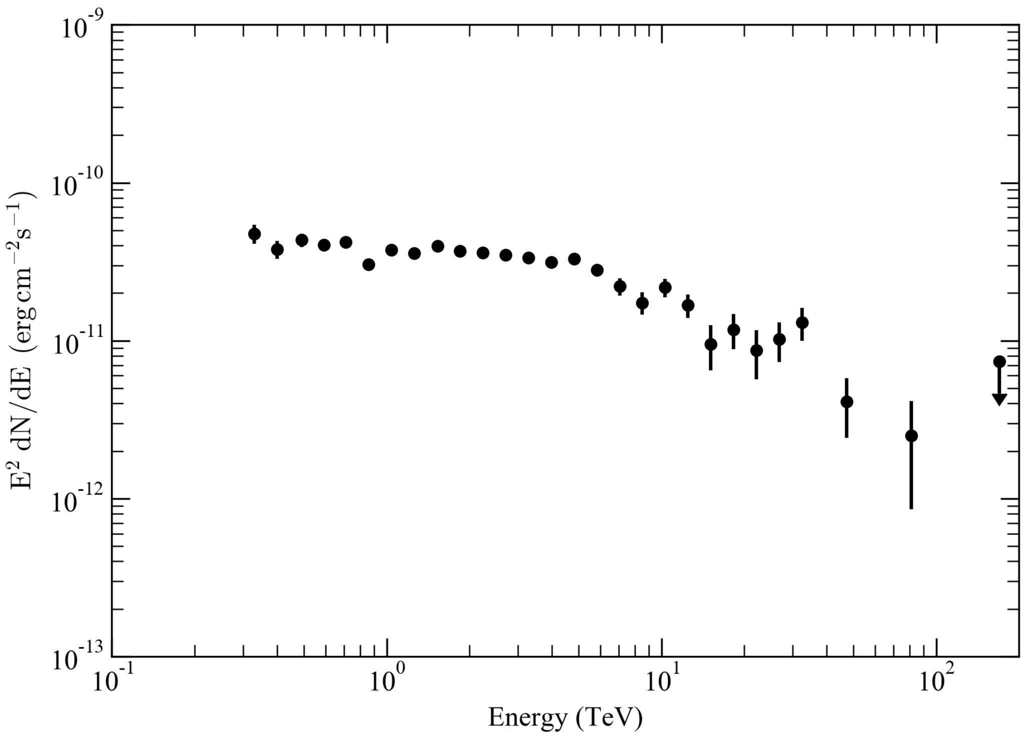
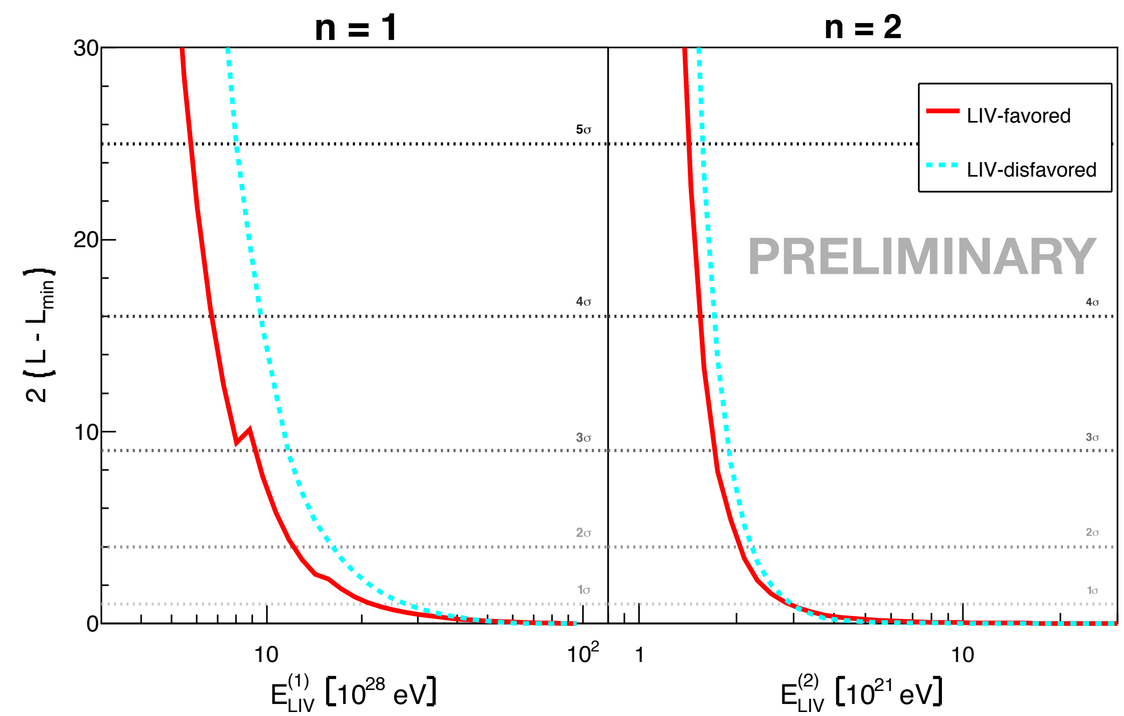
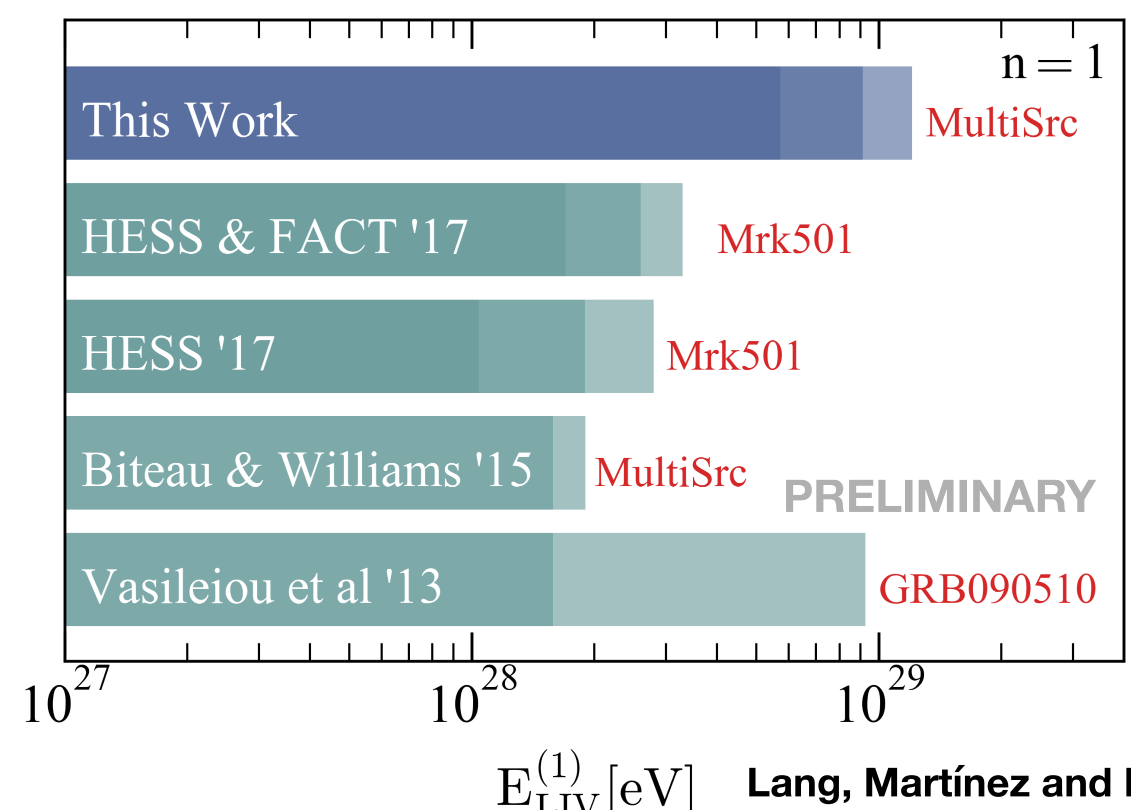
Submitted

New best LIV limits!





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



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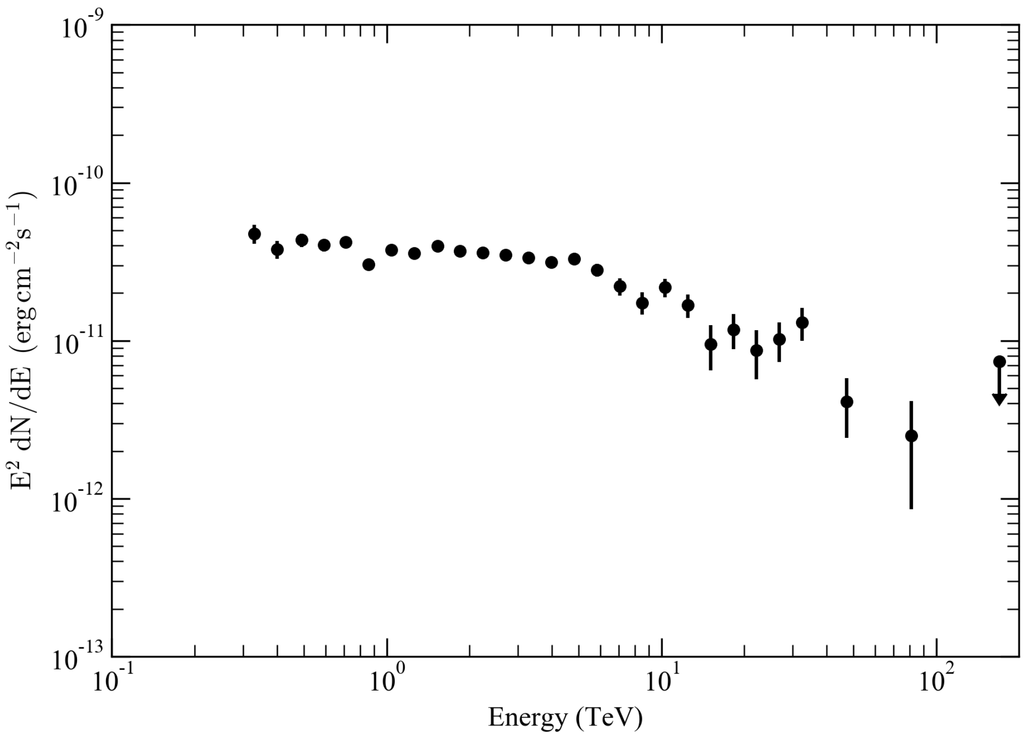

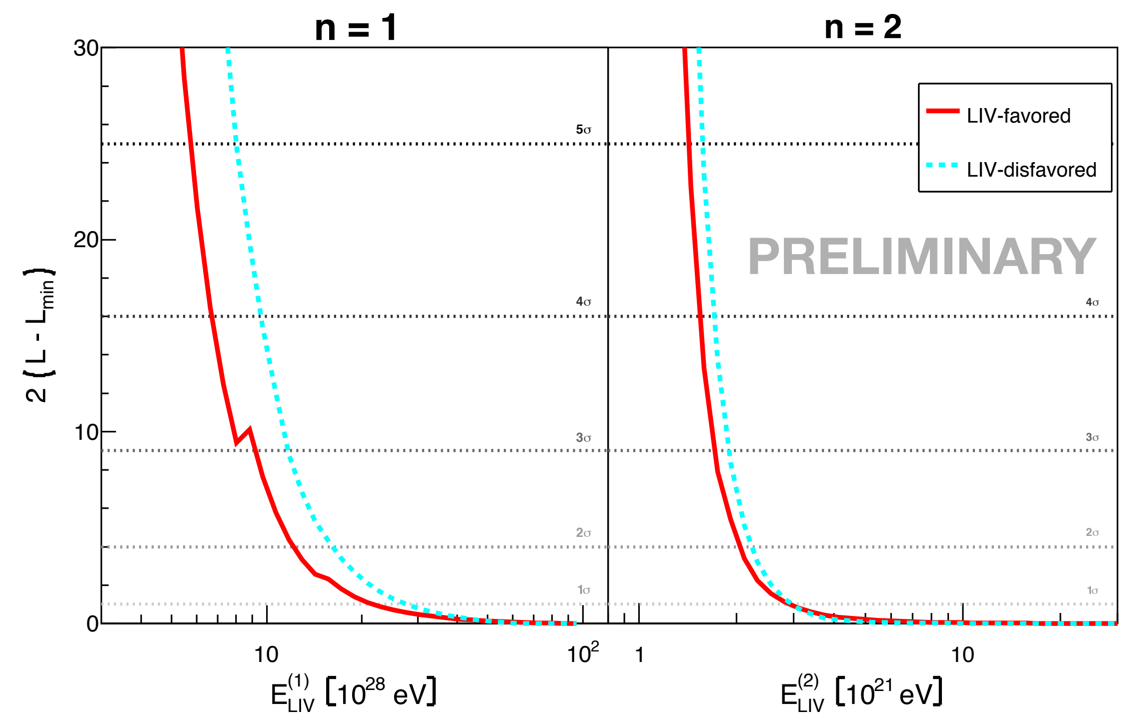

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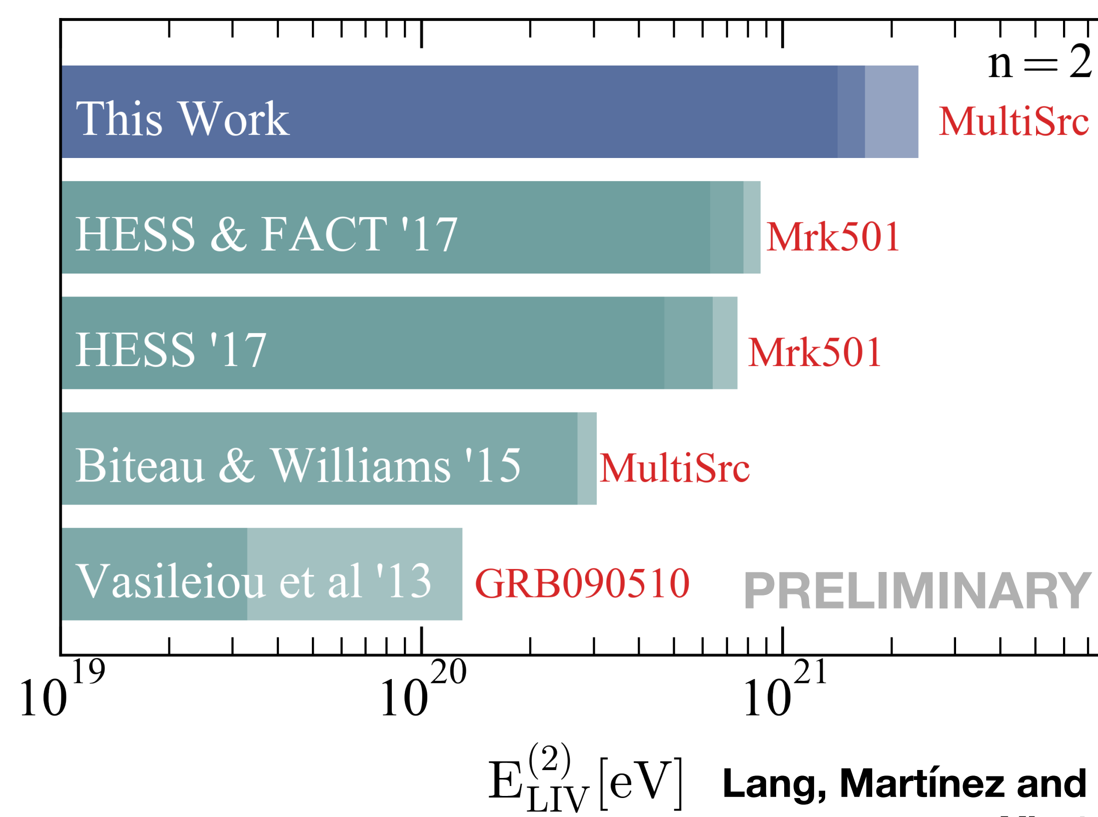
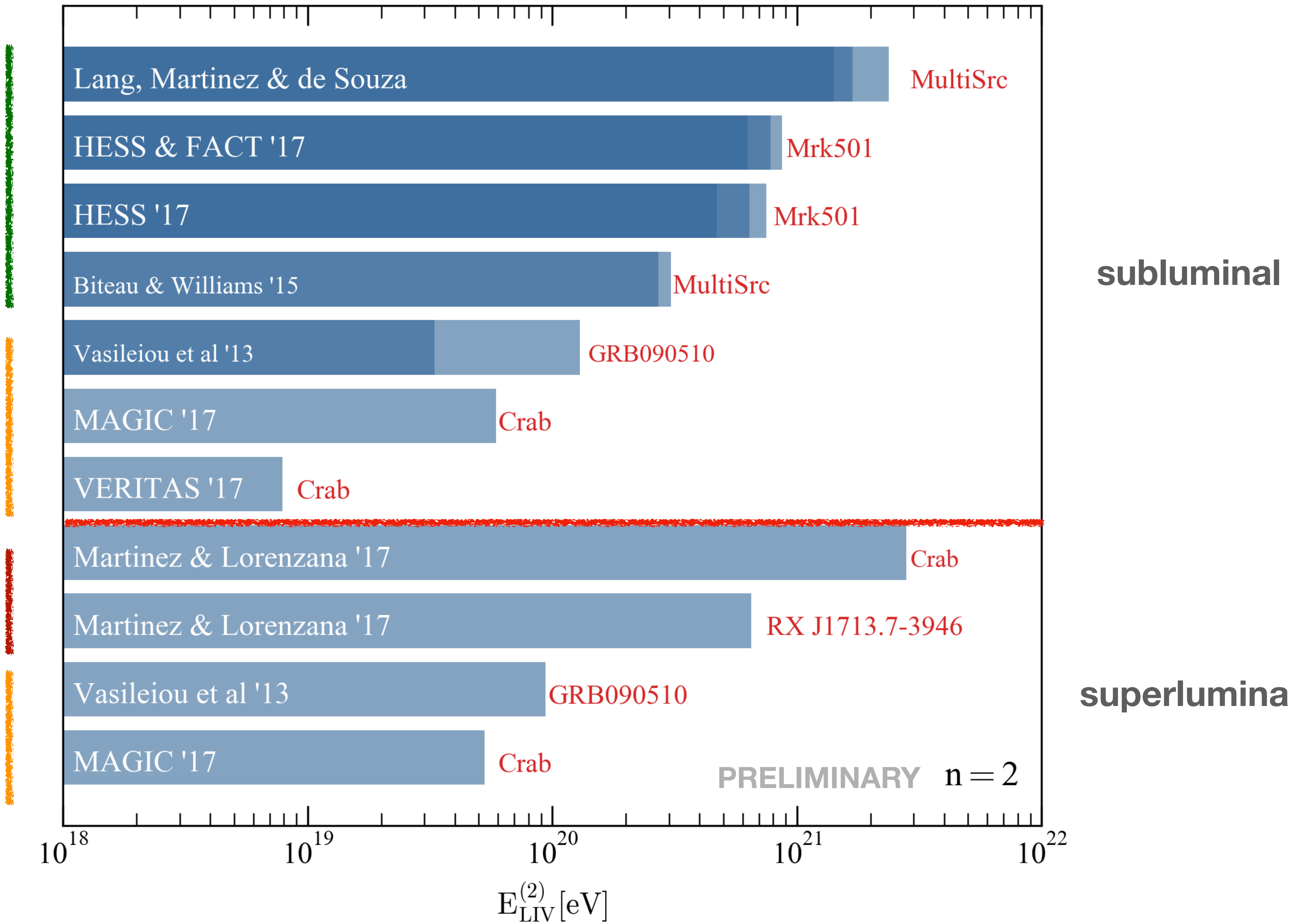


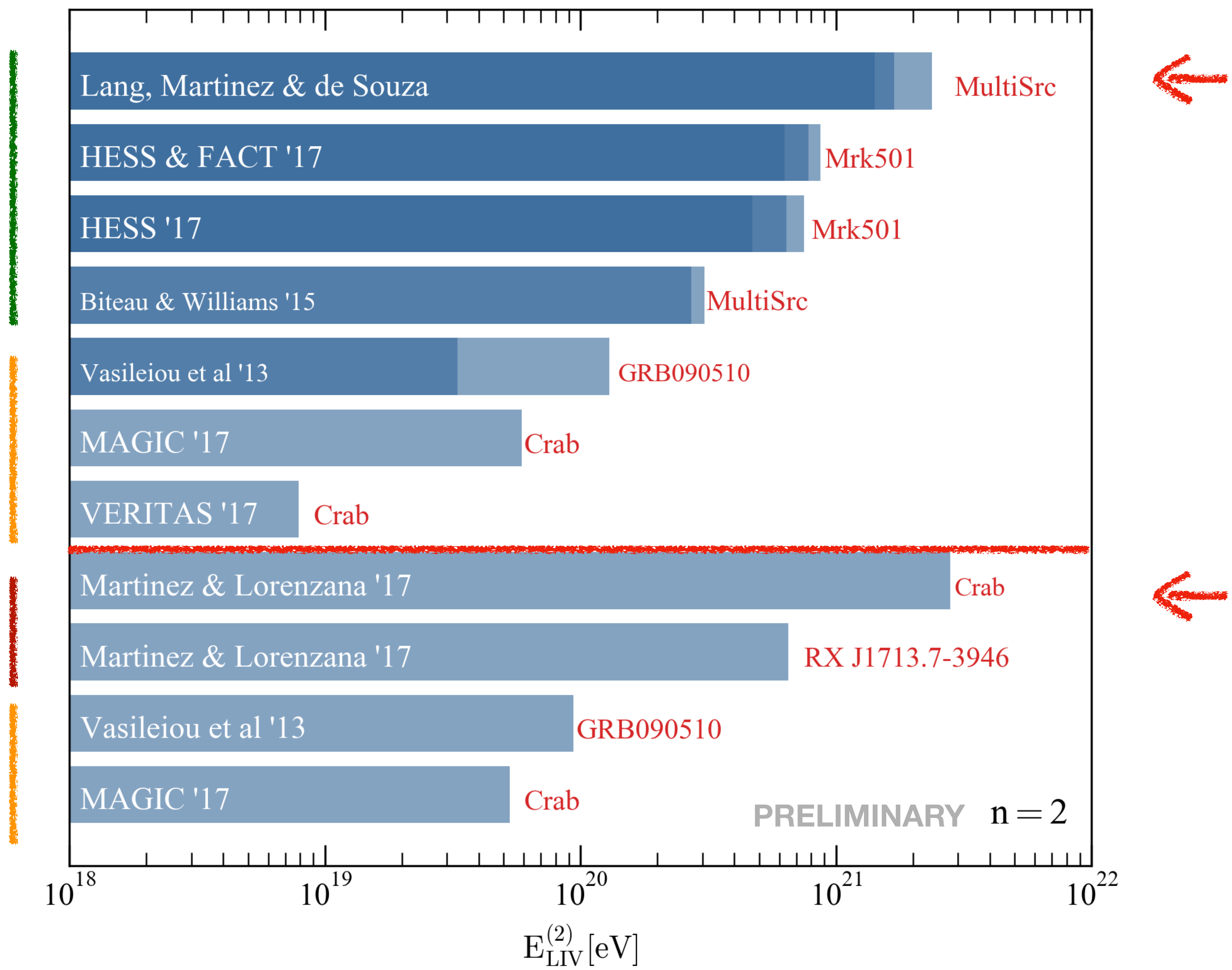
Lang, Martínez and De Souza
arXiv:1810.13215
Submitted

humbertomh@ifsc.usp.br

LIV limits : γ-rays



LIV limits : γ-rays



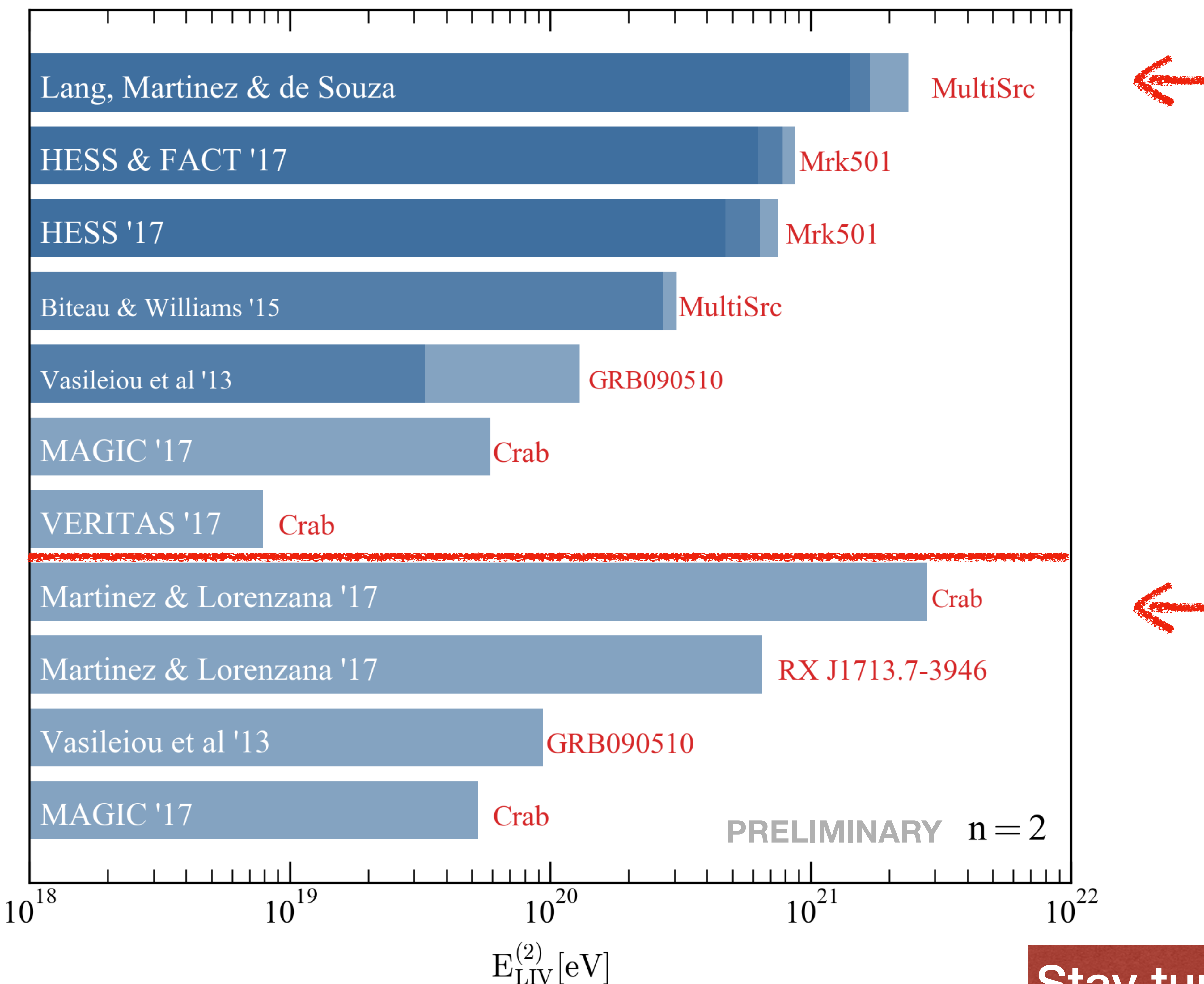
LIV limits : γ-rays

Pair production shift threshold

Time energy dependent delay

Photon decay

Time energy Dependent delay



Stay tuned...

Conclusions and remarks I

- **Astroparticle physics has recently reached the status of precision science** due to the construction of new observatories, operating innovative technologies and the detection of large numbers of events and sources.

  - ➡ The precise measurements of cosmic and gamma rays can be used as test for fundamental physics, such as the Lorentz invariance violation.

- We have established **the best limits** to the LIV energy scale to the superluminal and subliminal regime.

  - We developed **a new analysis procedures for searching LIV signatures** using multiple TeV measured energy spectra.

  - We are studying the potential to test / constrain LIV signatures with **HAWC, SGSO** and **CTA**

Index

I. Lorentz invariance violation (LIV)

II. Limits: TeV γ-rays

   i. Time Energy Dependent delay

   ii. Photon Decay

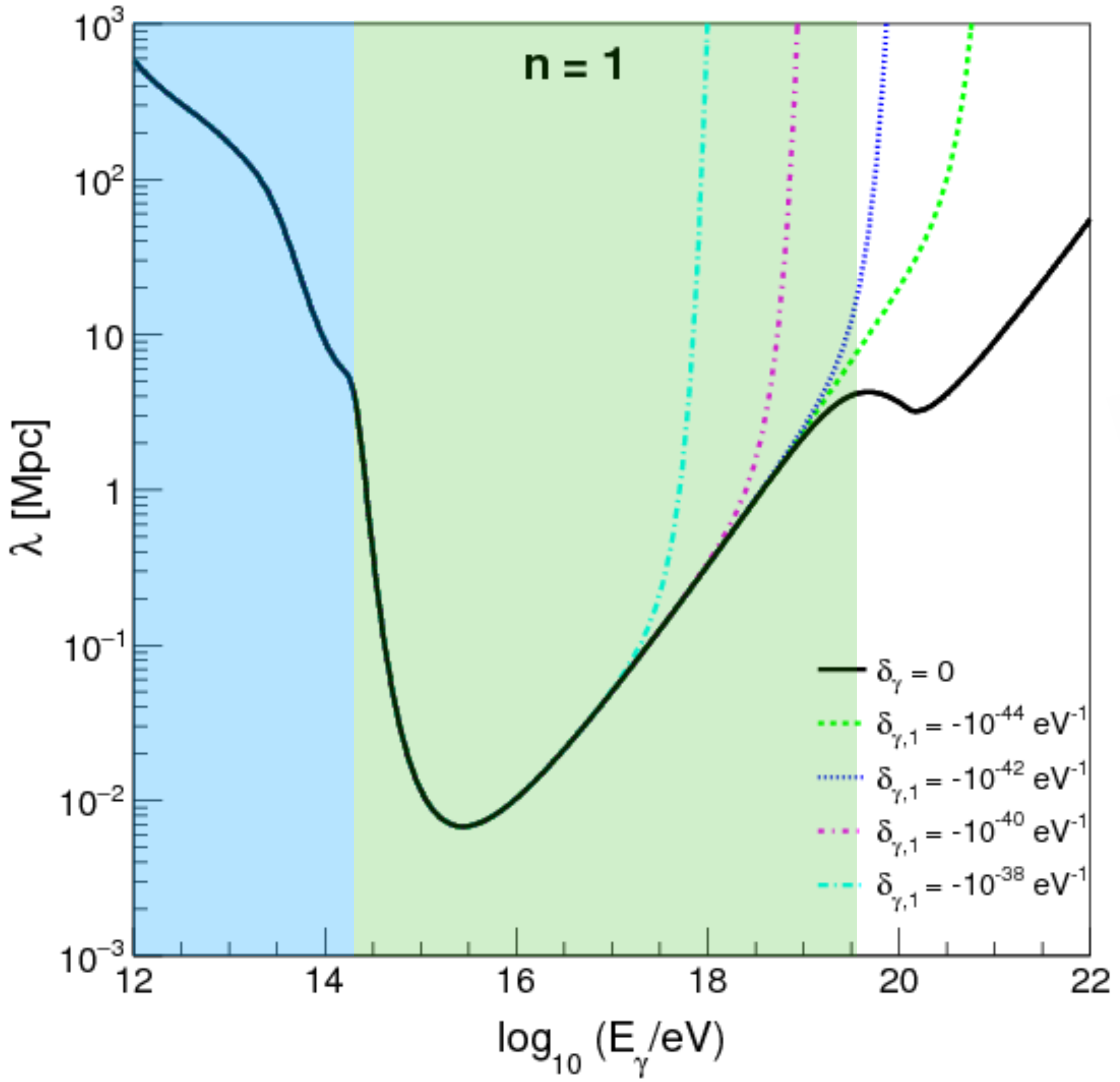
   iii. Pair production threshold shifts

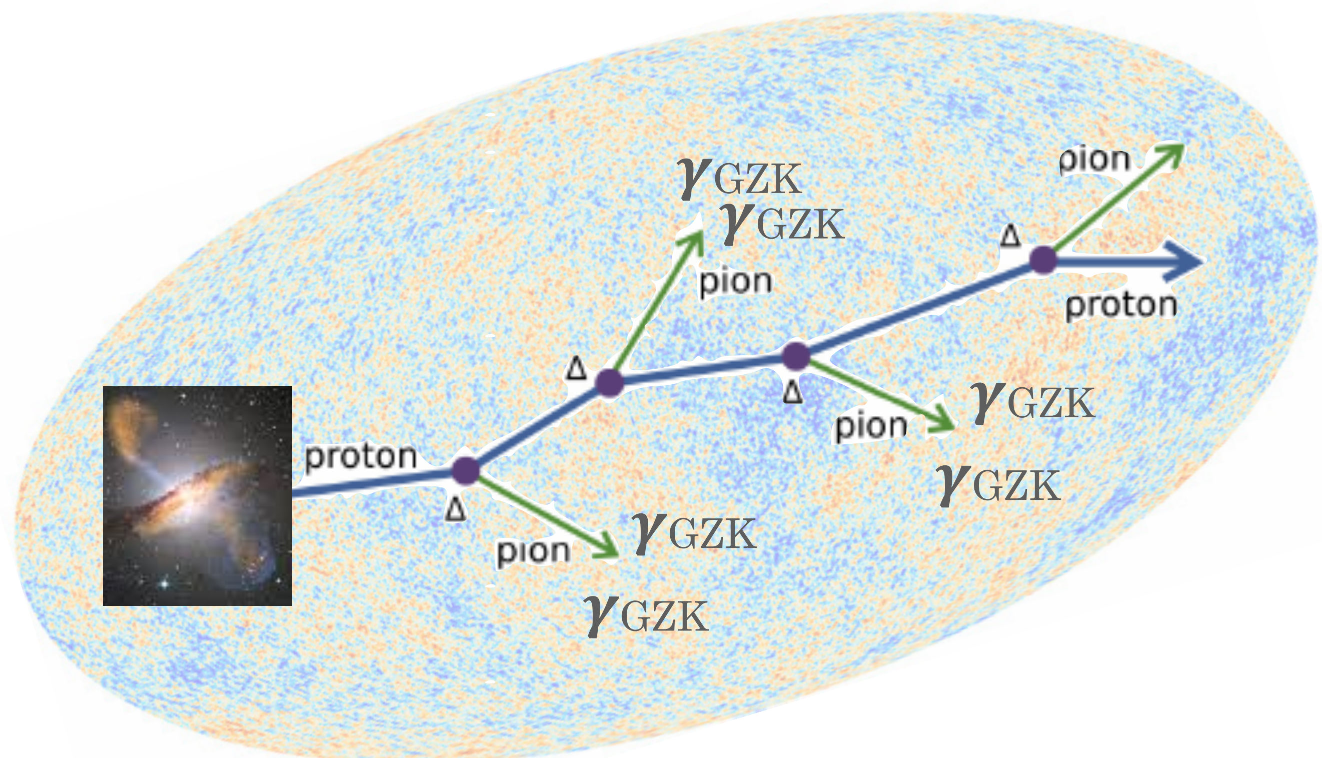
III. UHECR

   i. GZK-photons + LIV

   ii. Limits

GZK photons + LIV





Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

Model of UHECR Sources

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

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).

Parameters of the Four Source Models Used in This Paper

Model	Γ	$\log_{10}(R_{\text{cut}}/V)$	*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_{cut} is the rigidity cutoff and *f*H, *f*He, *f*N, *f*Si, and *f*Fe are the fractions of each nuclei.

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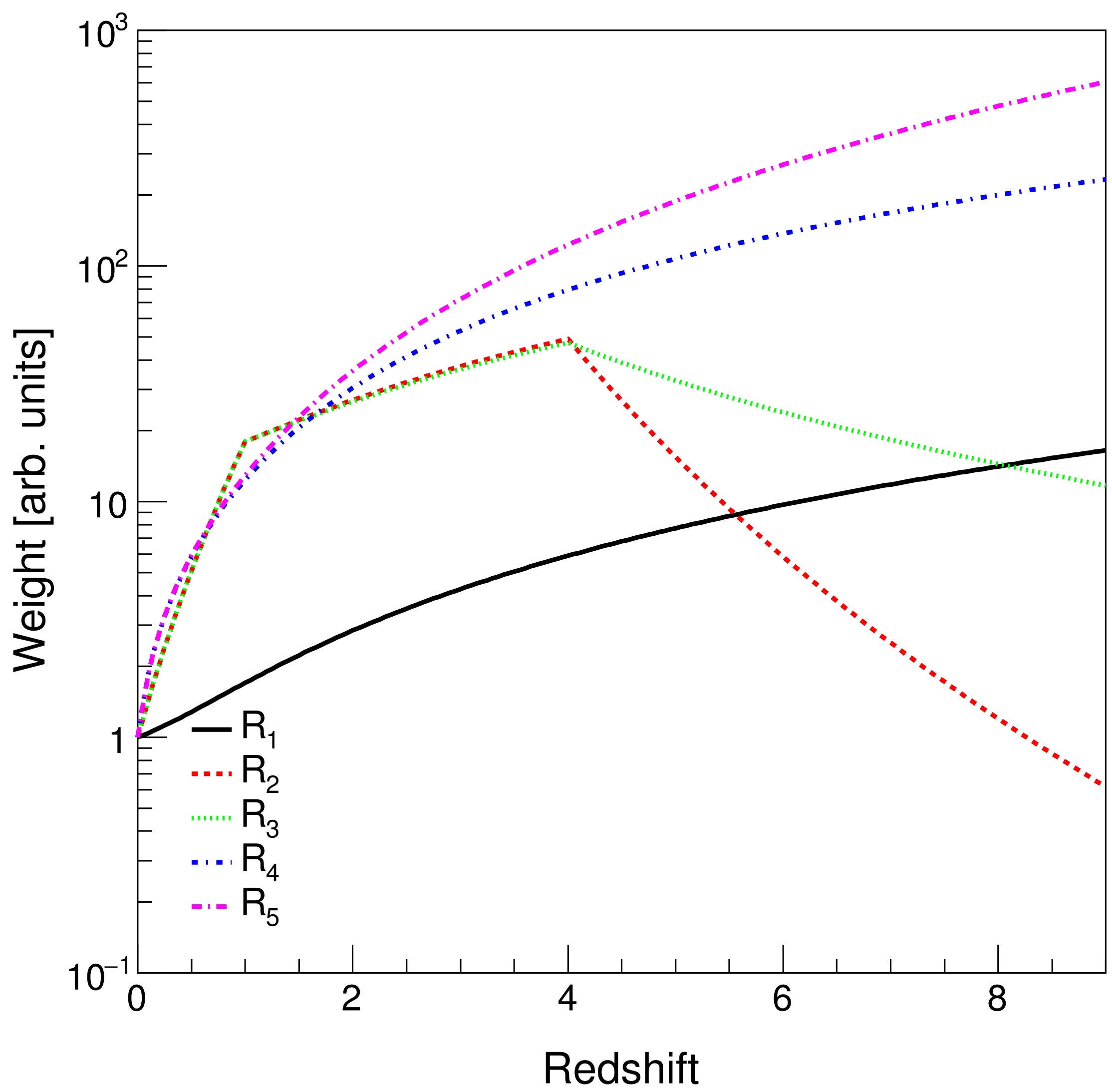
Model of UHECR Sources

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 $(1 + 11z)/[1 + (z/3)^{0.5}]$.



Lang, Martinez & De Souza
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Model of UHECR Sources

Models of Source Distribution

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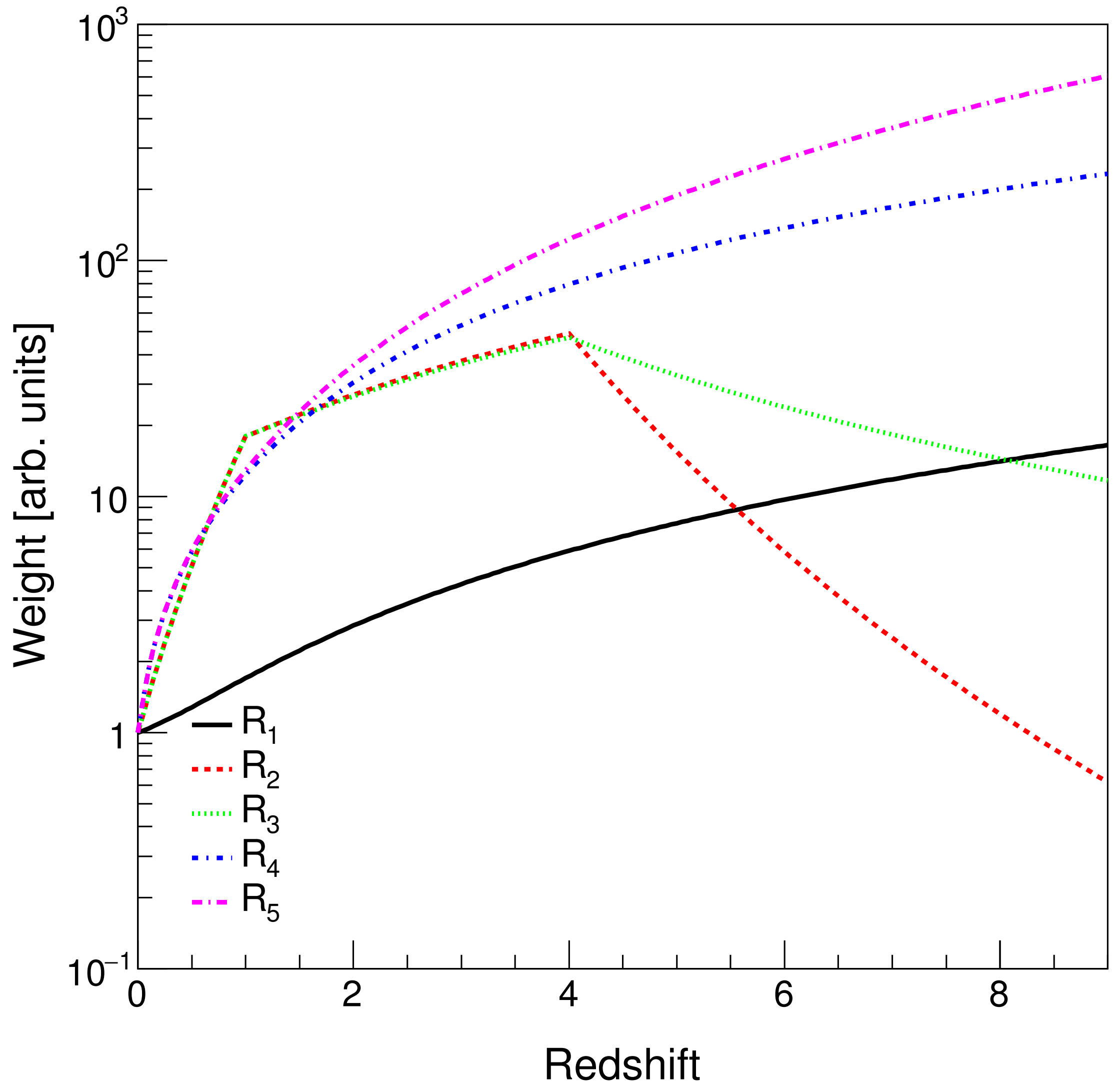
4. R_4: sources follow the GRB rate evolution from Le & Dermer (2007). The evolution is proportional to $(1 + 8z)/[1 + (z/3)^{1.3}]$;
5. R_5: sources follow the GRB rate evolution from Le & Dermer (2007). The evolution is proportional to $(1 + 11z)/[1 + (z/3)^{0.5}]$.



CRPropa3/EleCA

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

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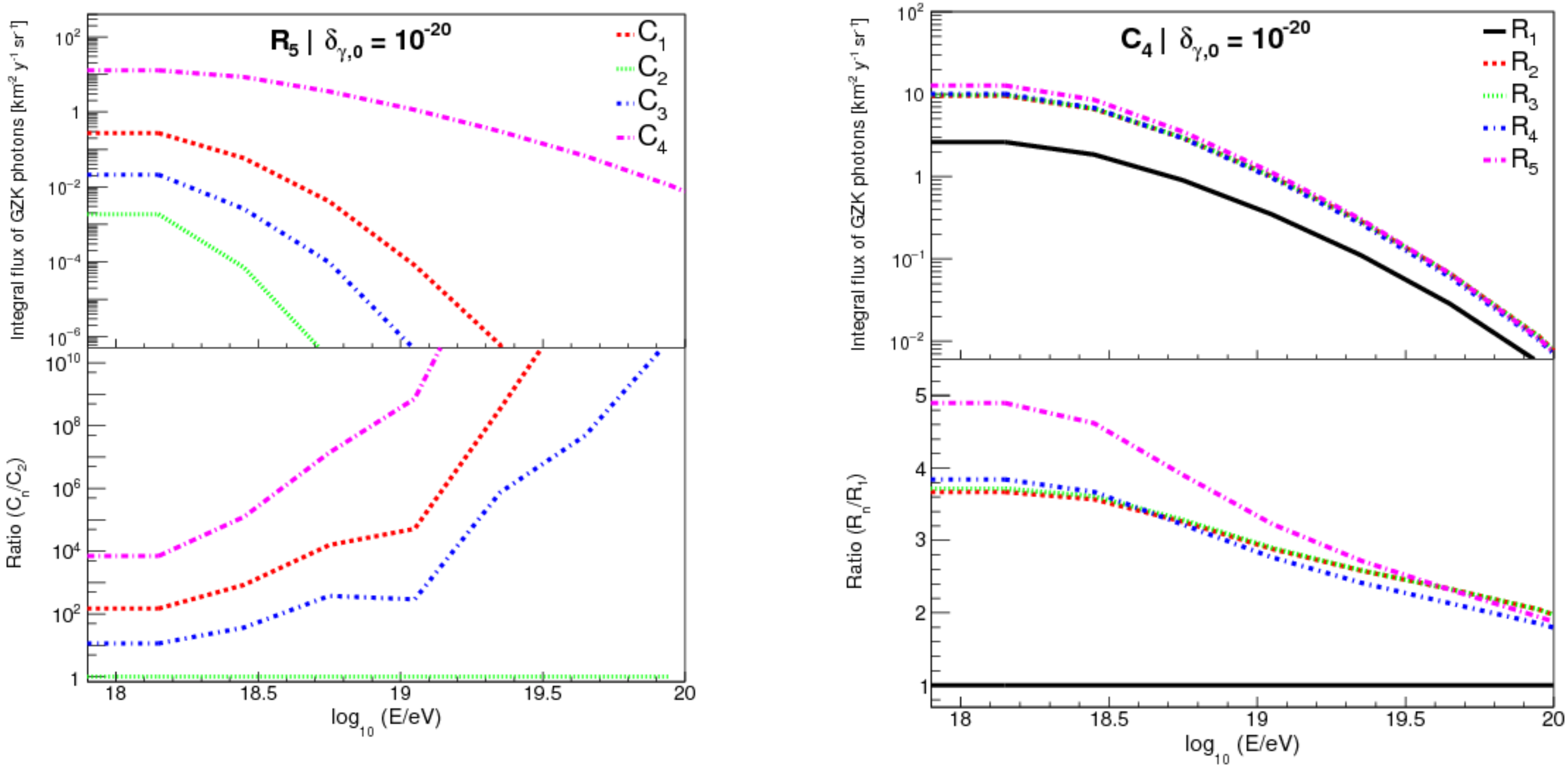
Integral flux of GZK photons + LIV

… for each source model **… for each source evolution model**



Different LIV coefficients result in a shift up an down

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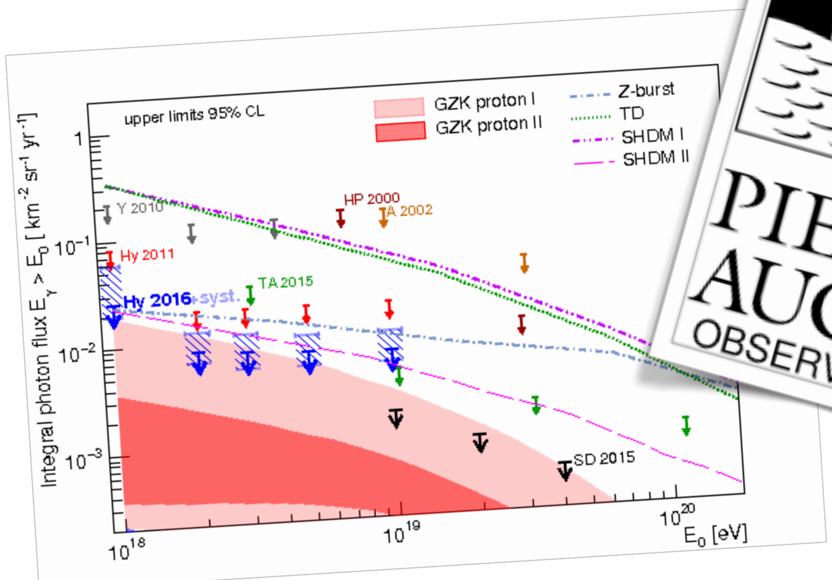
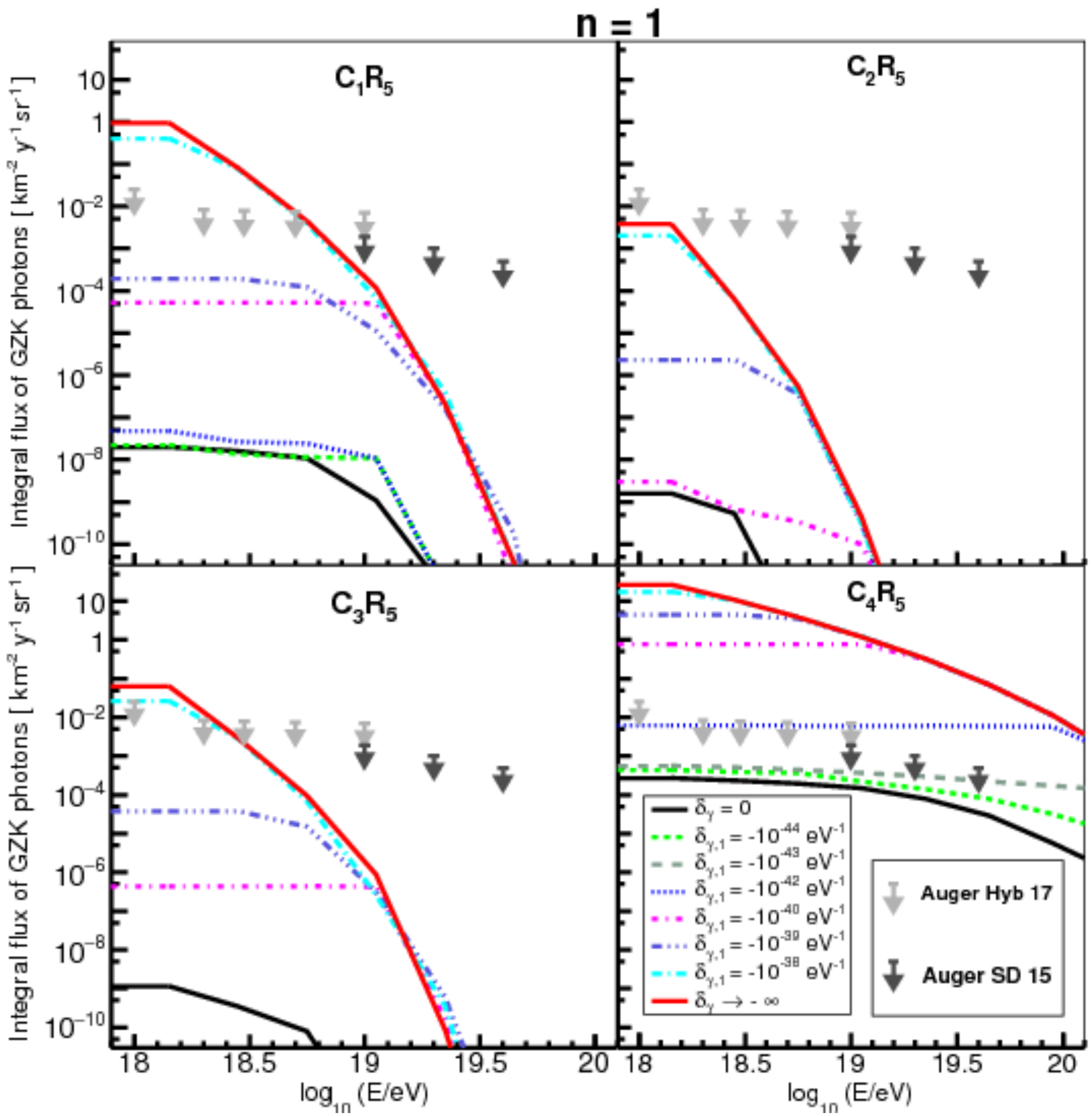
i. GZK-photons + LIV

ii. Limits



GZK photon flux + LIV



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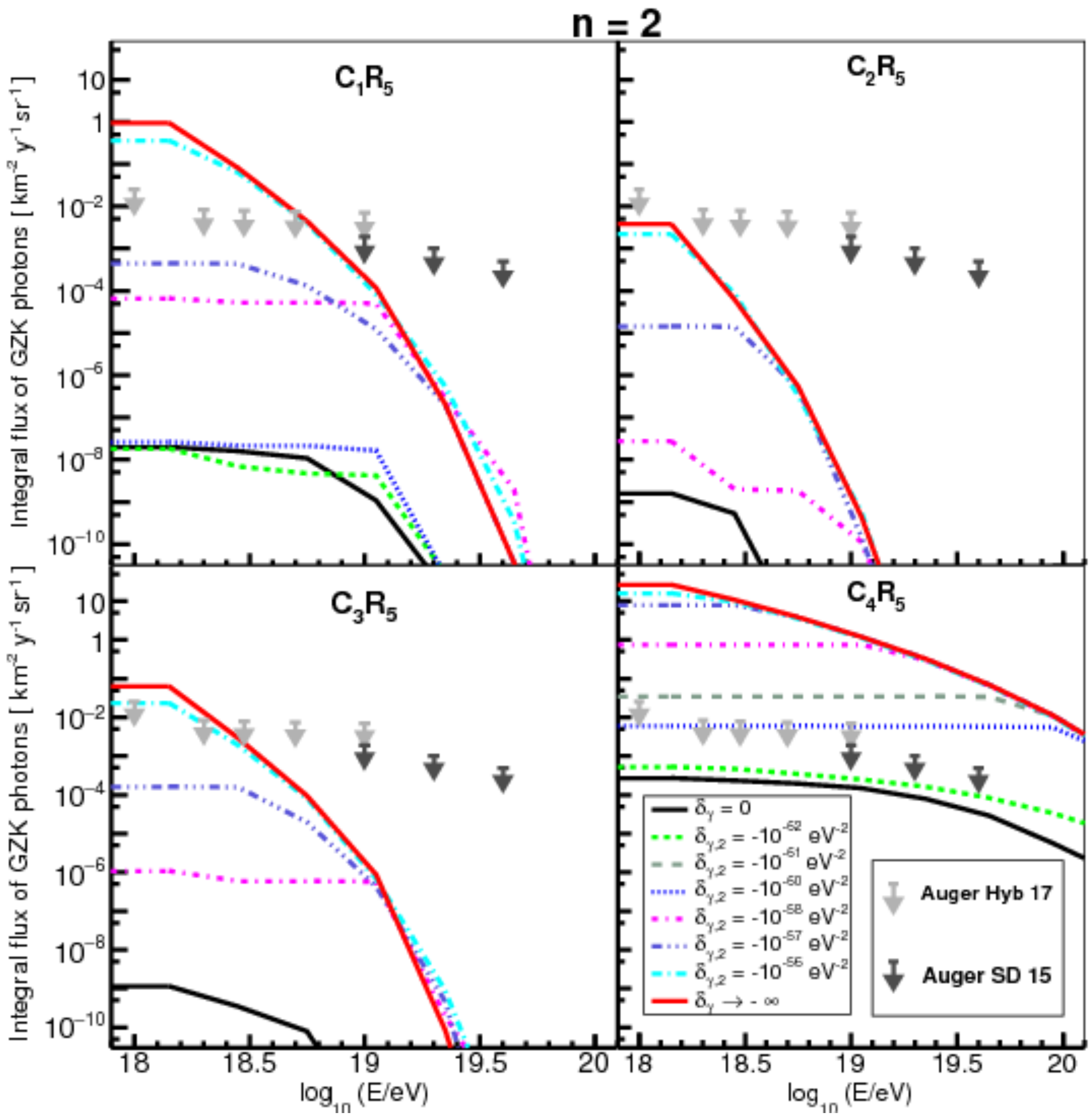
GZK photon flux + LIV



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

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Conclusions and remarks II

- **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!