Lorentz invariance violation in astroparticle physics: subluminal and superluminal tests

Humberto Martínez-Huerta,
IFSC-USP, Brazil

November 28, 2019

Outline

I. **Introduction**

II. LIV-signatures for Astroparticle tests

   i. Threshold shifts

   ii. Photon Decay

   iii. Photon Spliting

   iv. Energy-dependent time delay

- **Phenomenology**
- **Experiment**
- **Future**

III. Limits: astrophysical photons

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- Experiment
- Future

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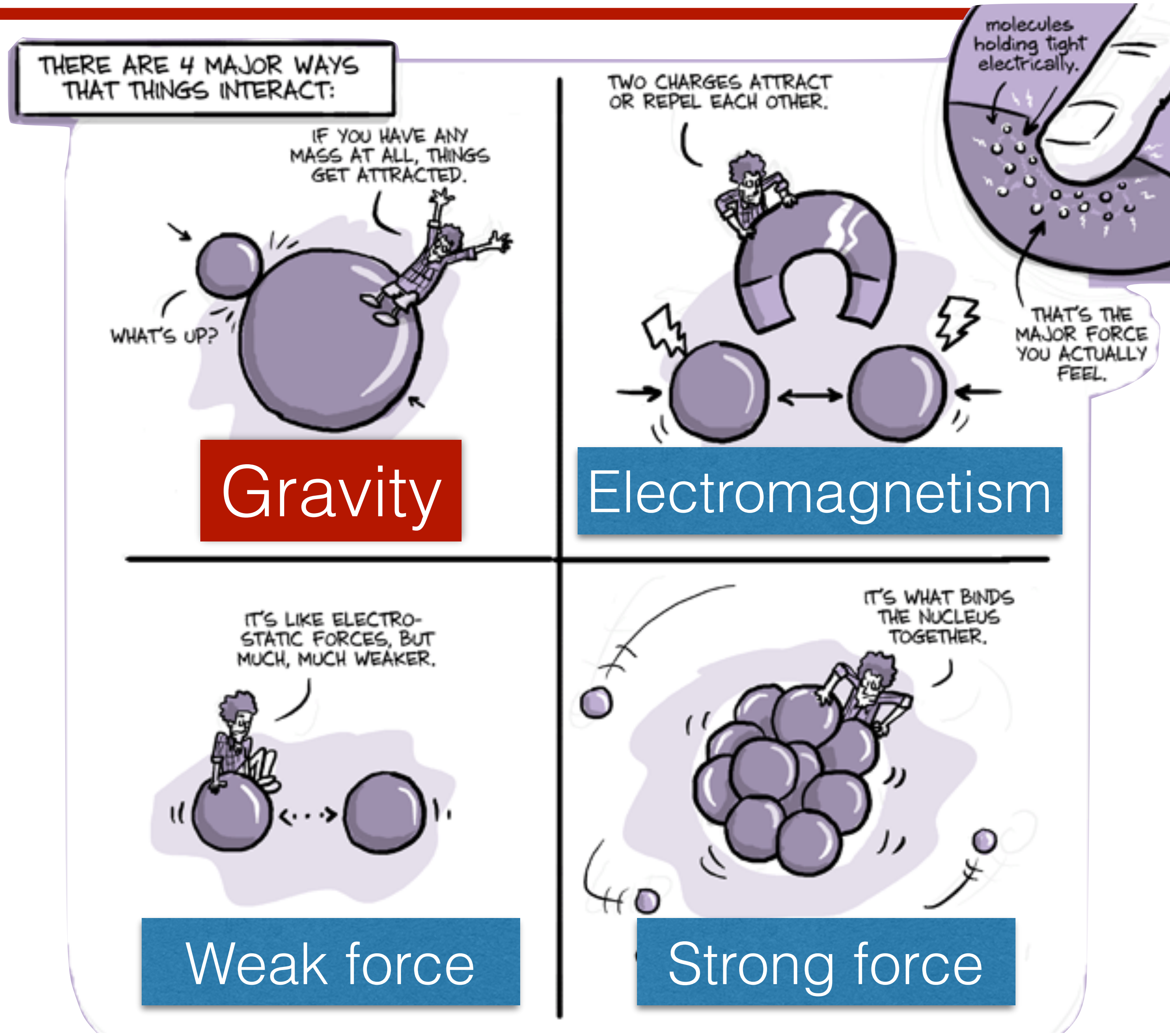
Fundamental Forces of Nature

General Relativity

Geometrical Theory



Standard Model

Quantum Theory

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

Quantum Theory of Gravity?

String Theory

Loop Quantum Gravity

…

?

New Physics involves new features, such as:

- [ ] Higher dimensions of space and time
- [ ] Brane world scenarios
- [ ] Non-commutative geometries
- [ ] …
- [x] The law of relativity might not hold exactly at all energy scales

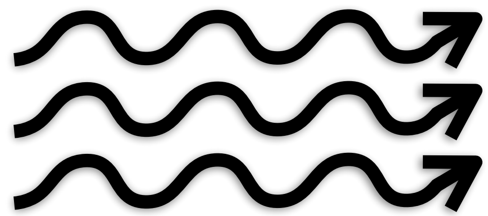
→ … **LI** may not be an **exact symmetry of Nature**

Lorentz Invariance Violation (LIV)

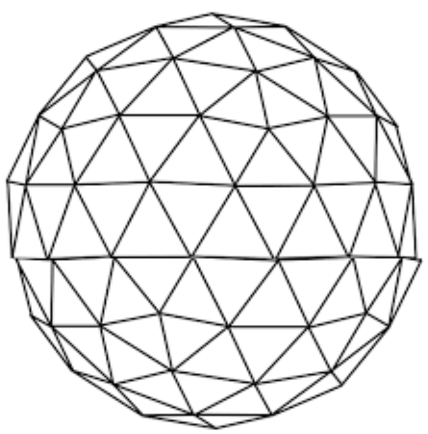
← Like any other **fundamental principle** exploring the limits of validity of **LI** has been an essential motivation for theoretical and experimental research

Symmetries: LIV

γ



$$c = 3 \times 10^8 \text{ m/s}$$

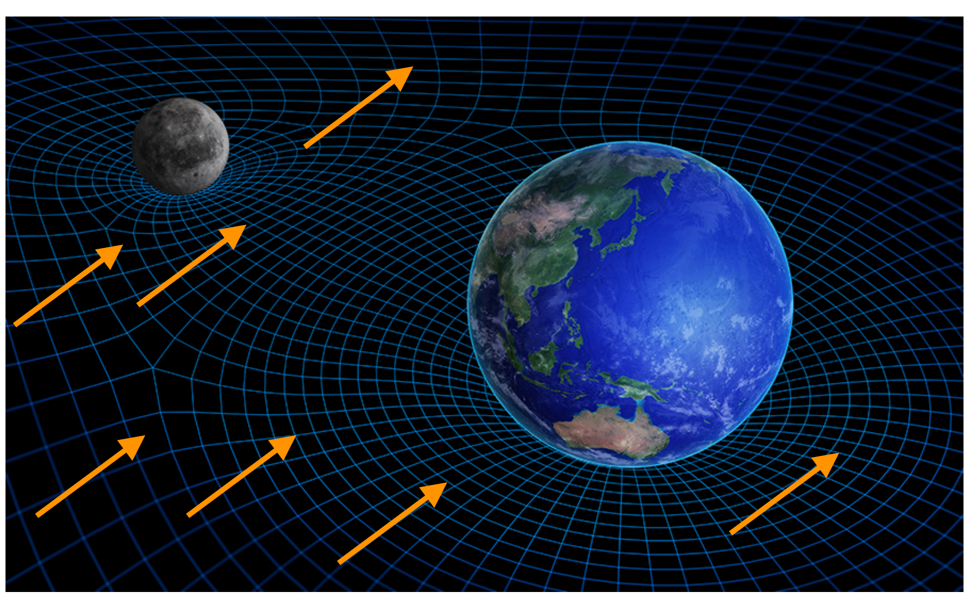


$$c \neq 3 \times 10^8 \text{ m/s}$$

$$c' = (1 \pm \delta)c$$

Fundamental Energy Scale

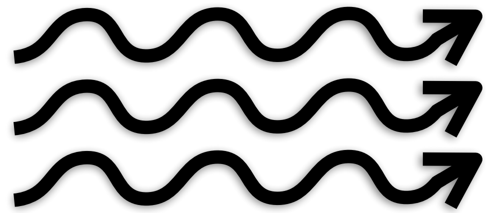
$$E_{QG} : E_{Pl} : E_{LIV}$$



$$c' = \left[1 \pm f\left(\frac{E_\gamma}{E_{\rm LIV}}\right) \pm \ldots\right] c$$

Symmetries: LIV

γ



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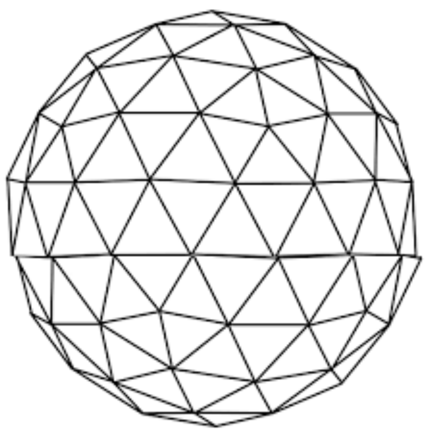

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Fundamental Energy Scale

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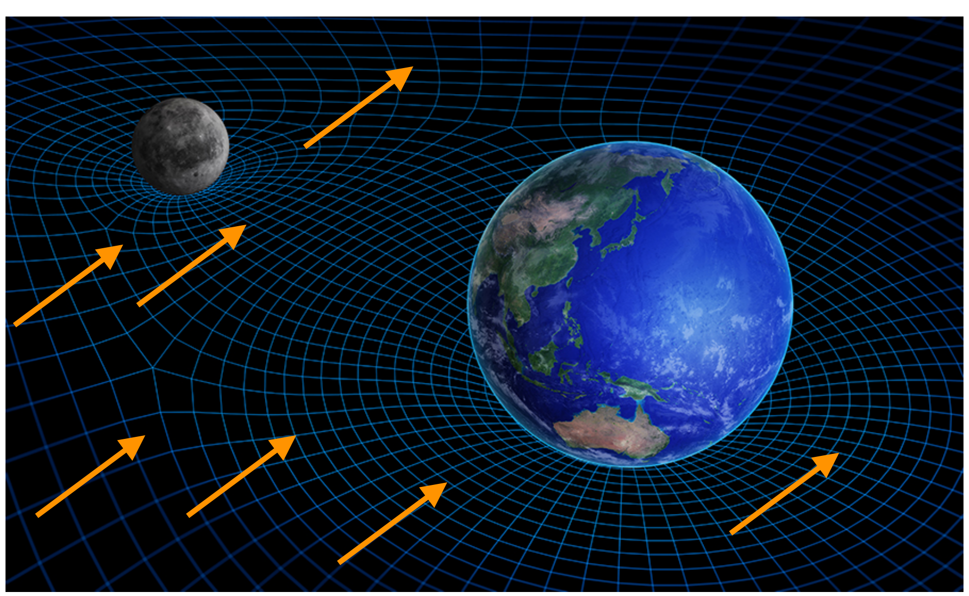
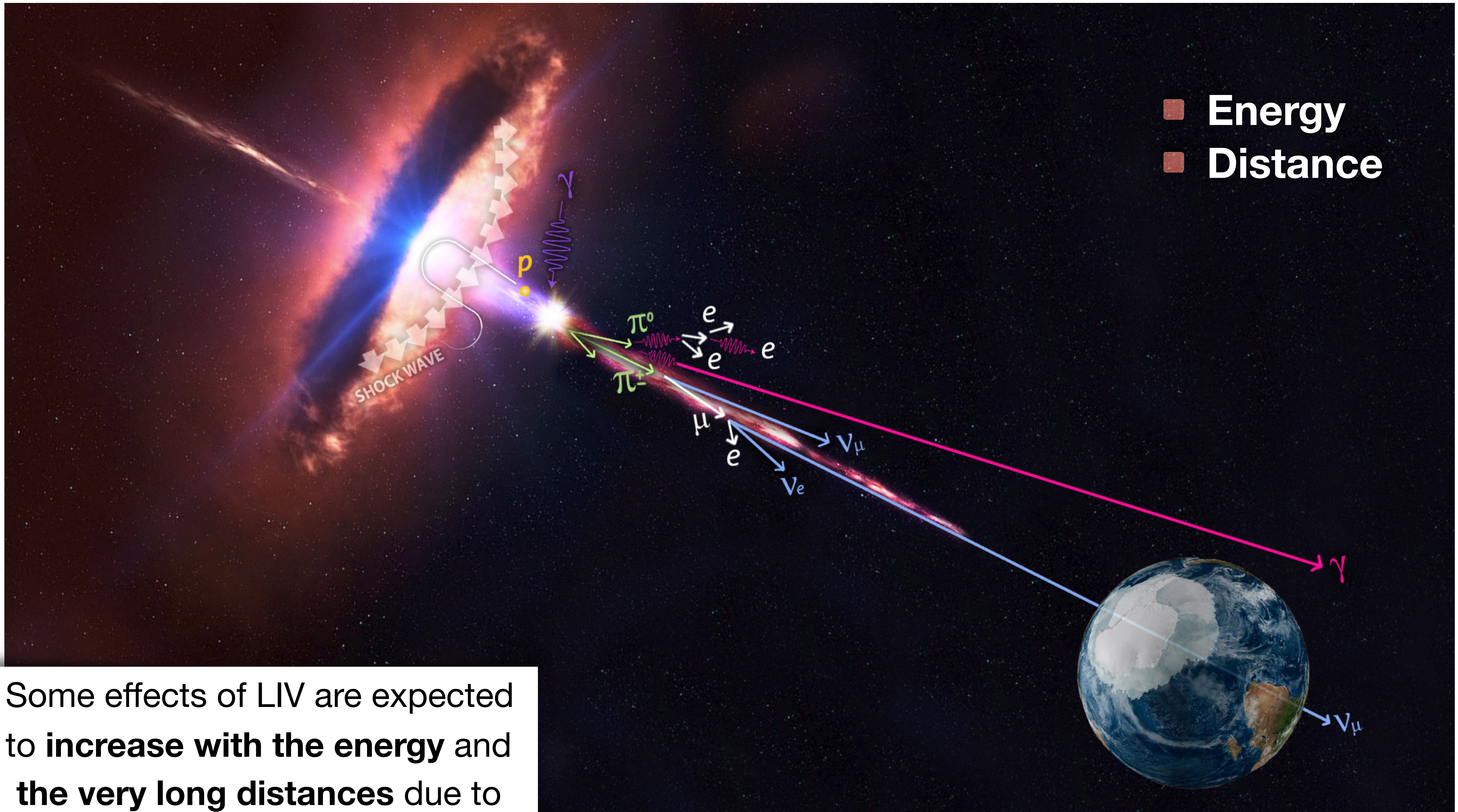


$$E_\gamma^2 - p_\gamma^2 = \delta_{\gamma,n}\; p_\gamma^2 \underset{n \geq 1}{\approx} \frac{E_\gamma^{n+2}}{\left(E_{\text{LIV}}^{(n)}\right)^n}$$

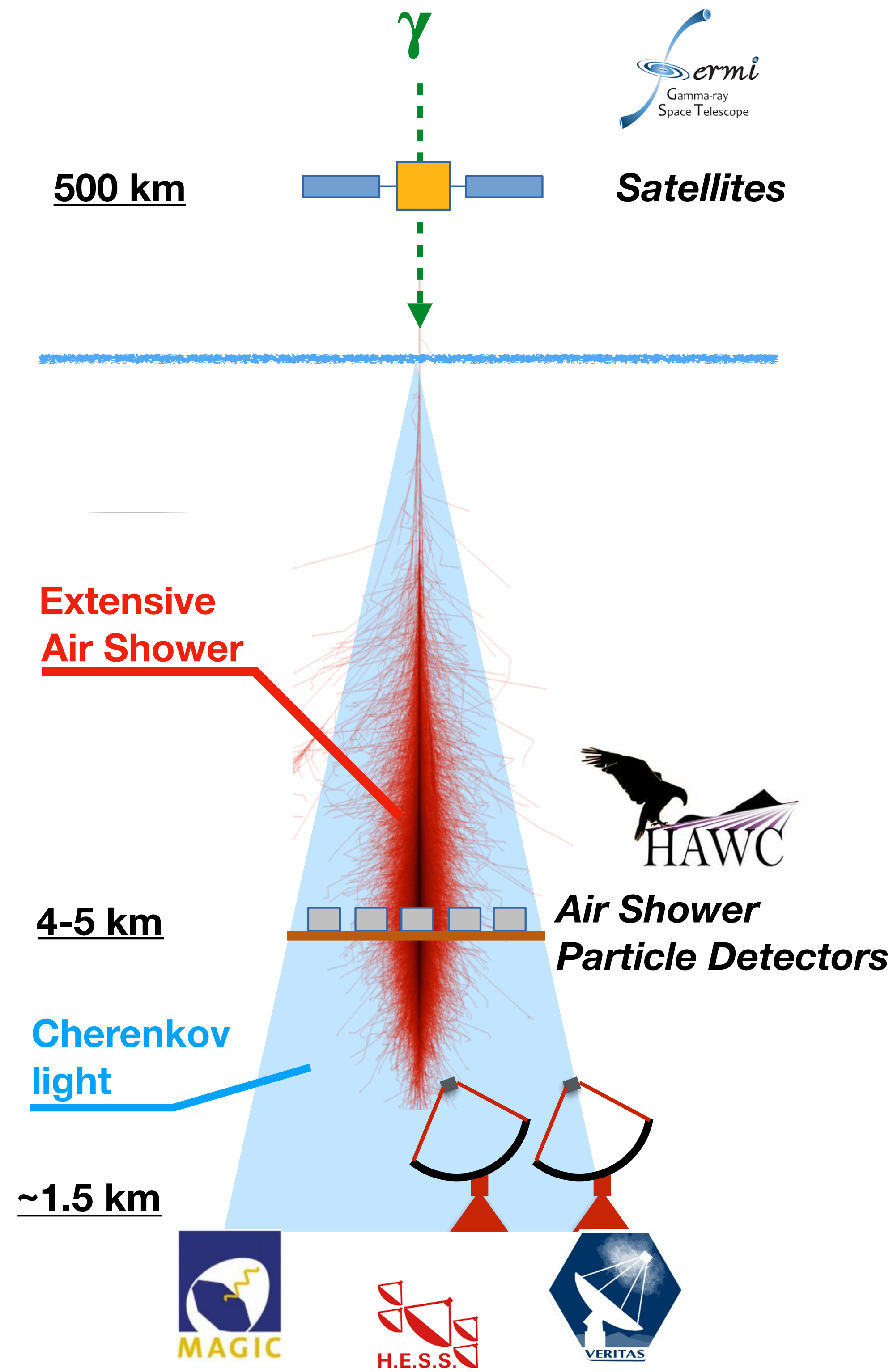
n = 0, 1, 2, …

Astroparticle Physics: Lab to test Fundamental Physics



Some effects of LIV are expected to **increase with the energy** and **the very long distances** due to cumulative processes

Astroparticle-Lab : Fundamental Physics



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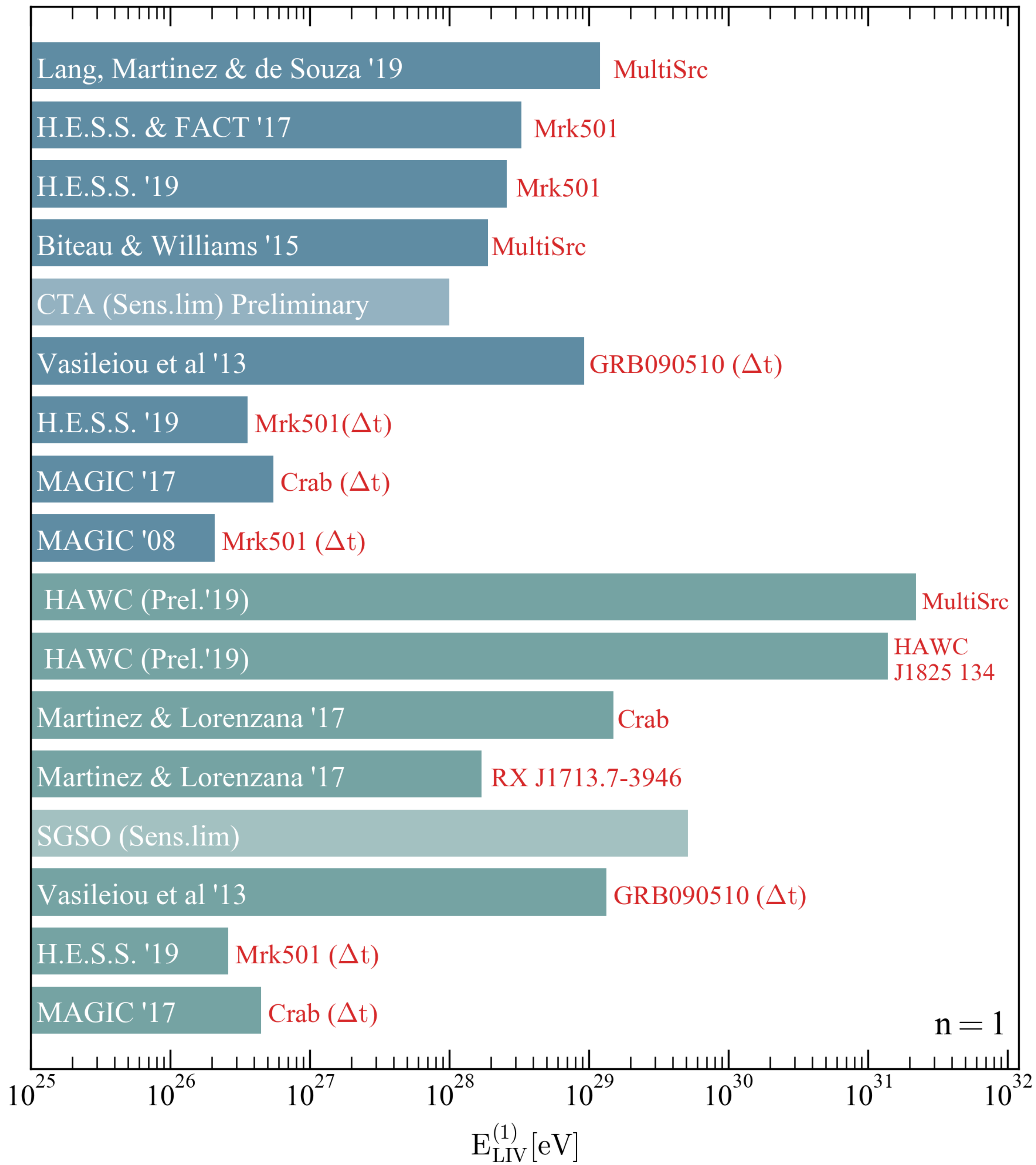
LIV limits



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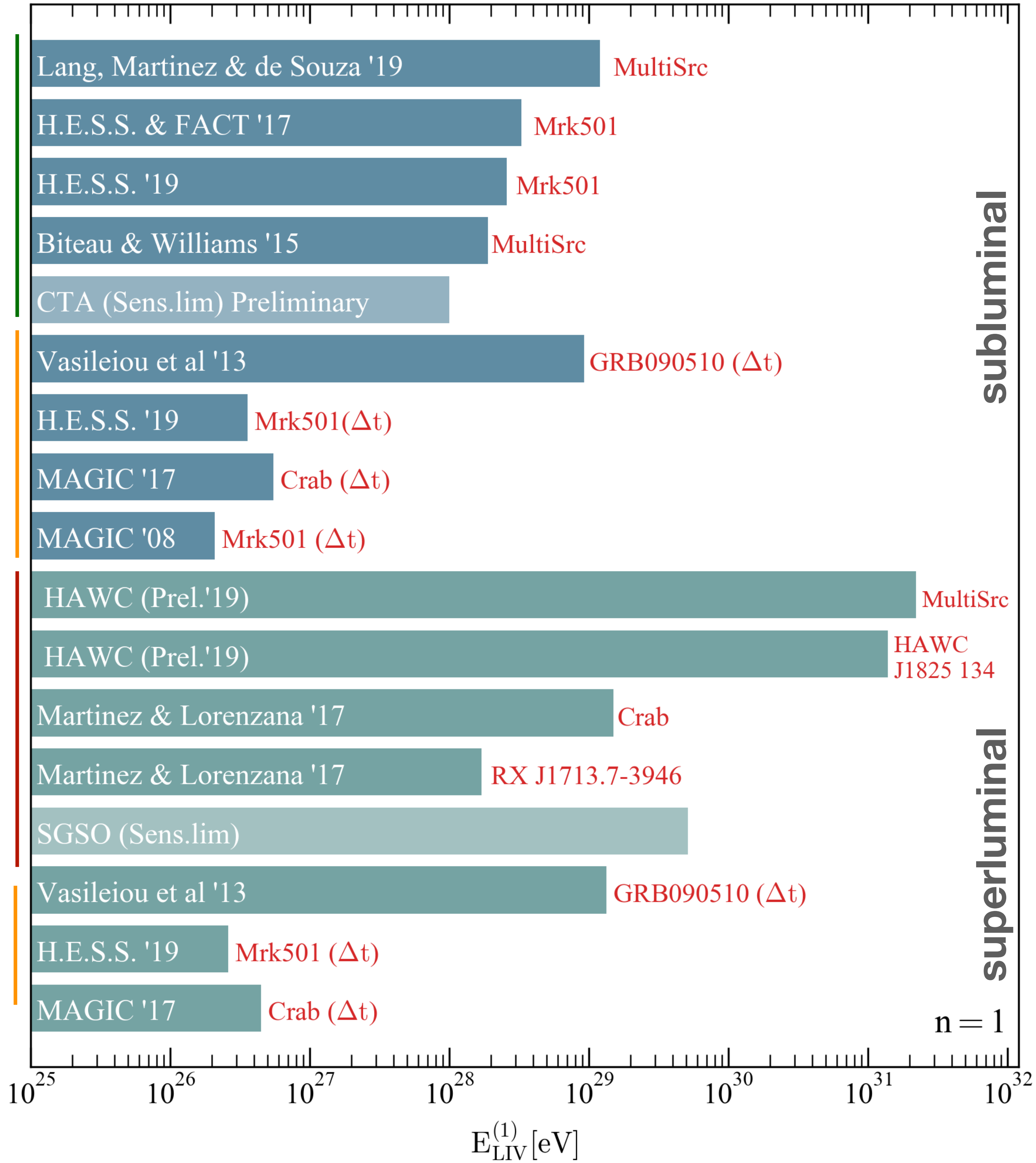
LIV limits

Pair production threshold shifts

Energy-dependent time delay

Photon decay

Energy-dependent time delay



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LIV limits (Meeting DRC-2018)

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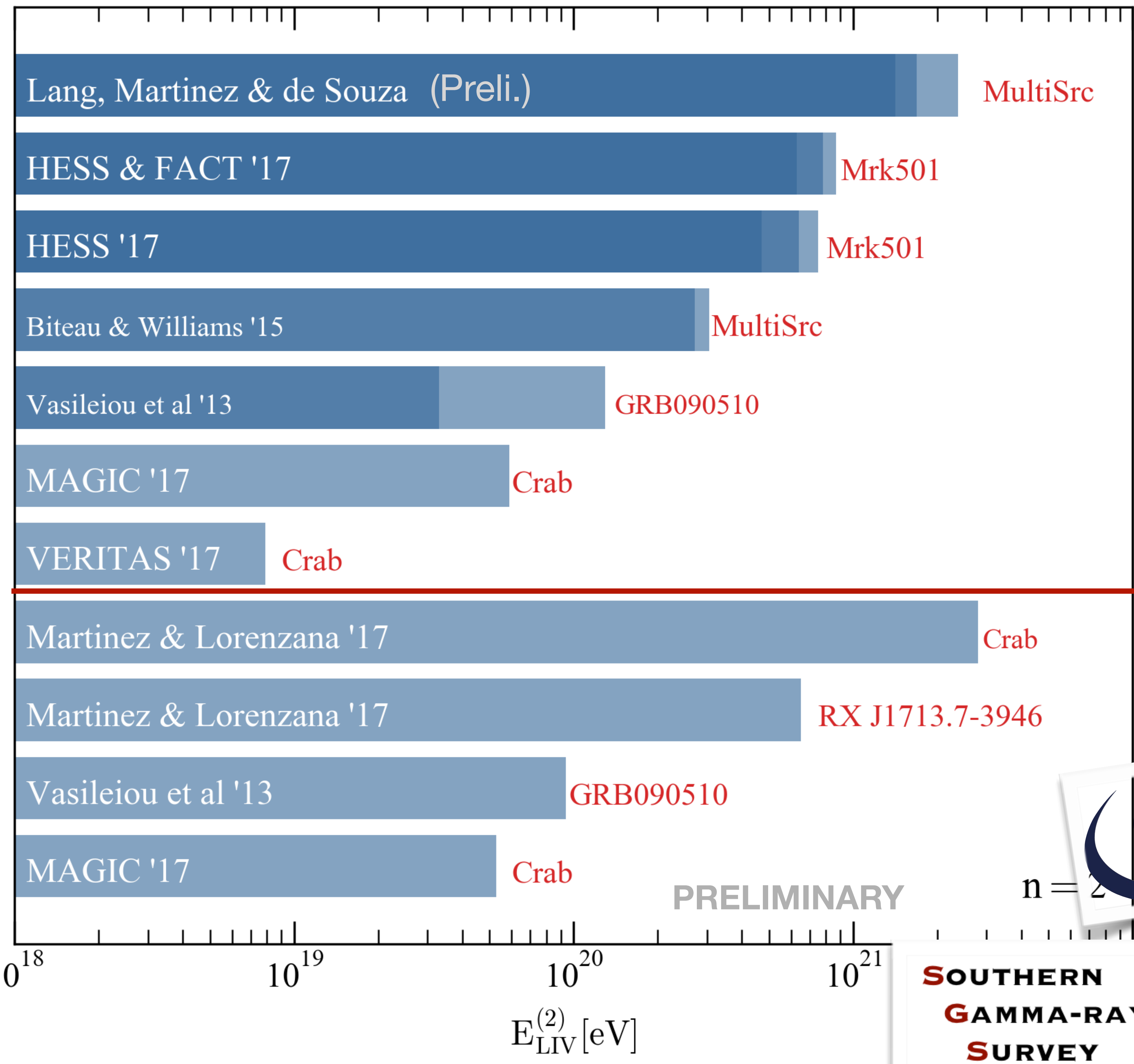
Energy-dependent time delay



Southern Gamma-Ray Survey Observatory

?

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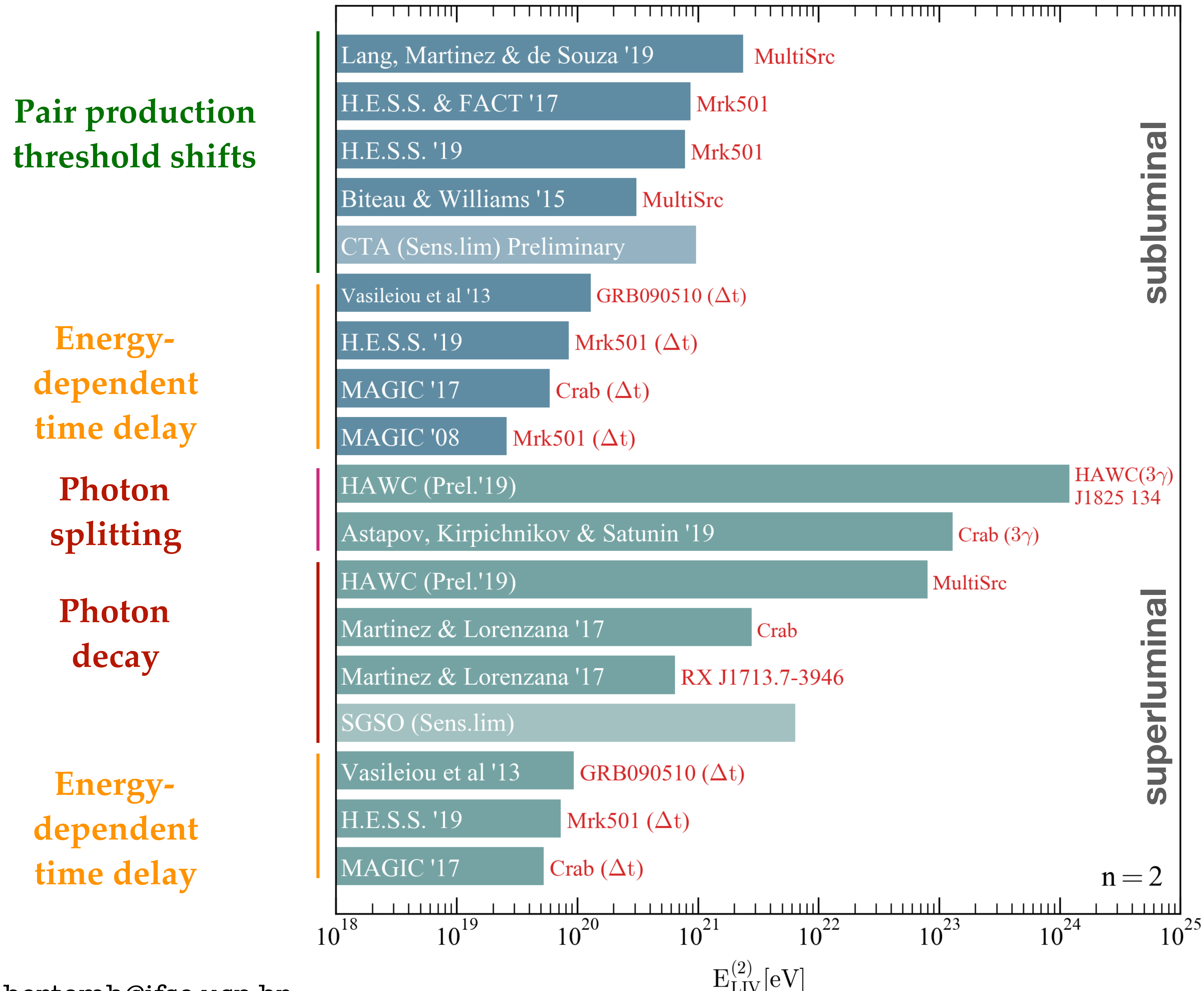
LIV limits



Pair production threshold shifts
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Lang, Martinez & de Souza '19
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HAWC(3γ) J1825 134
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subluminal
superluminal
n = 2
10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24} 10^{25}
$E^{(2)}_{LIV}$ [eV]

LIV limits

Pair production threshold shifts

Energy-dependent time delay

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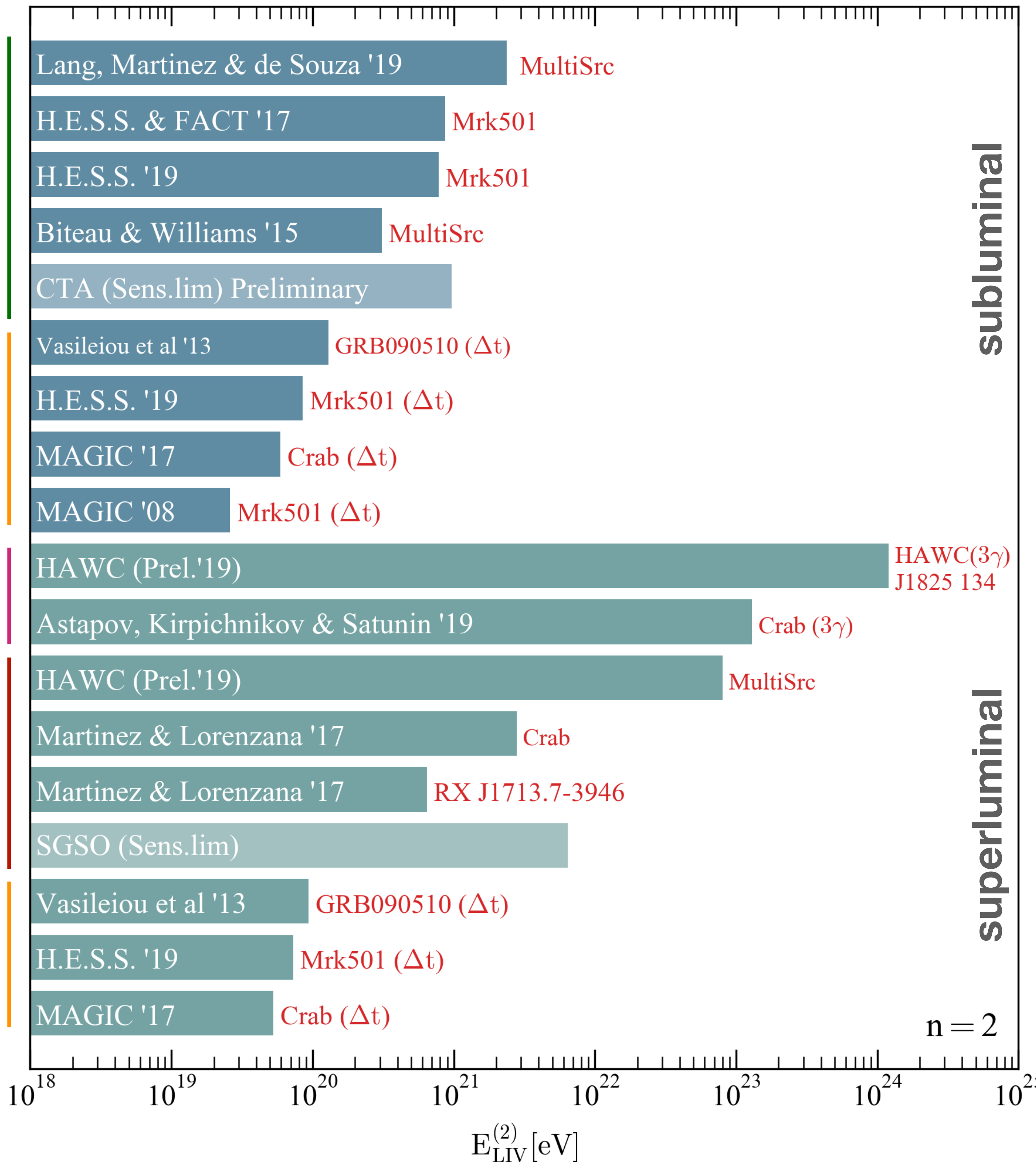
Energy-dependent time delay



Published

Updated

This Talk

New channel!

Released!

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LIV limits

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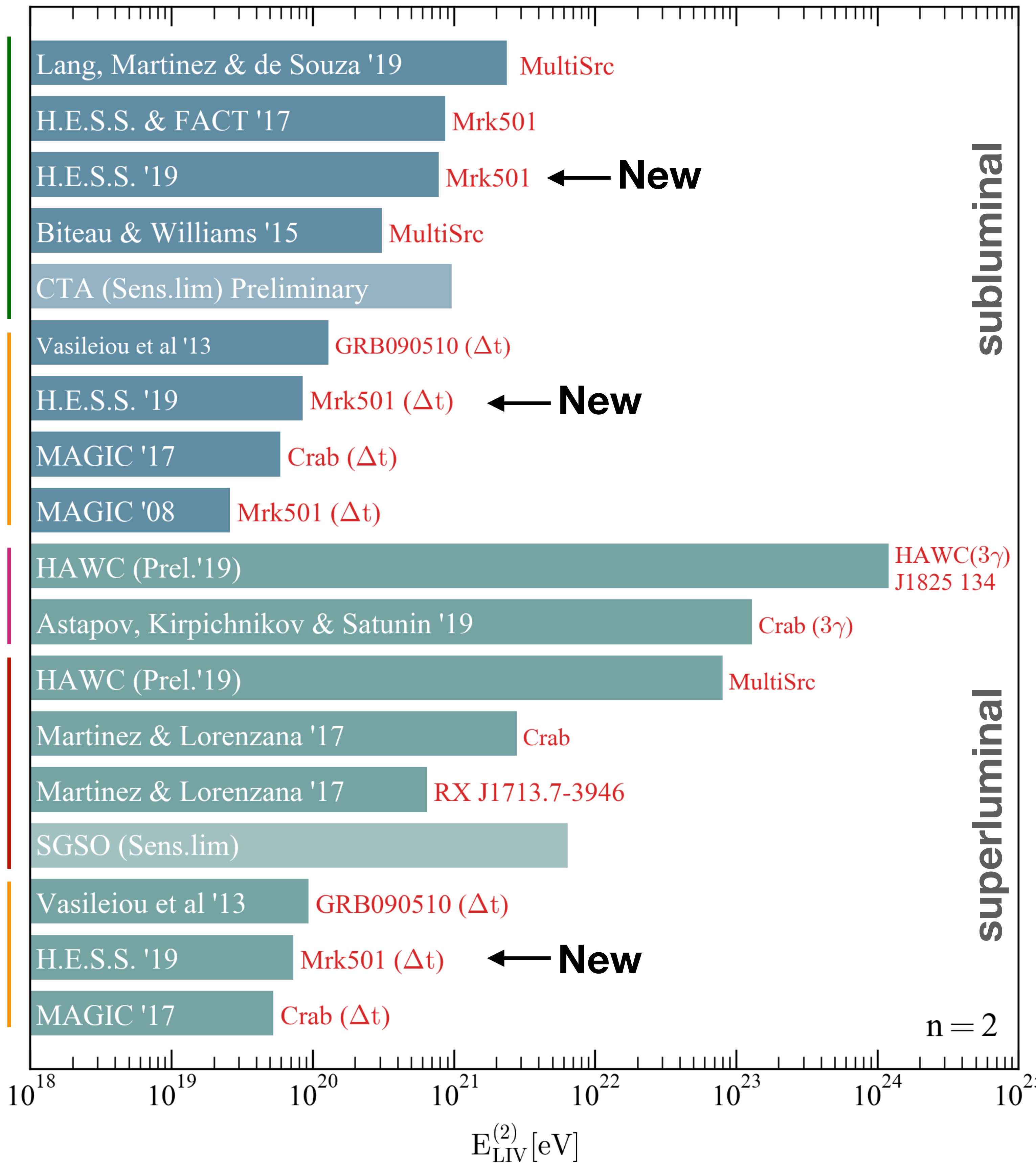

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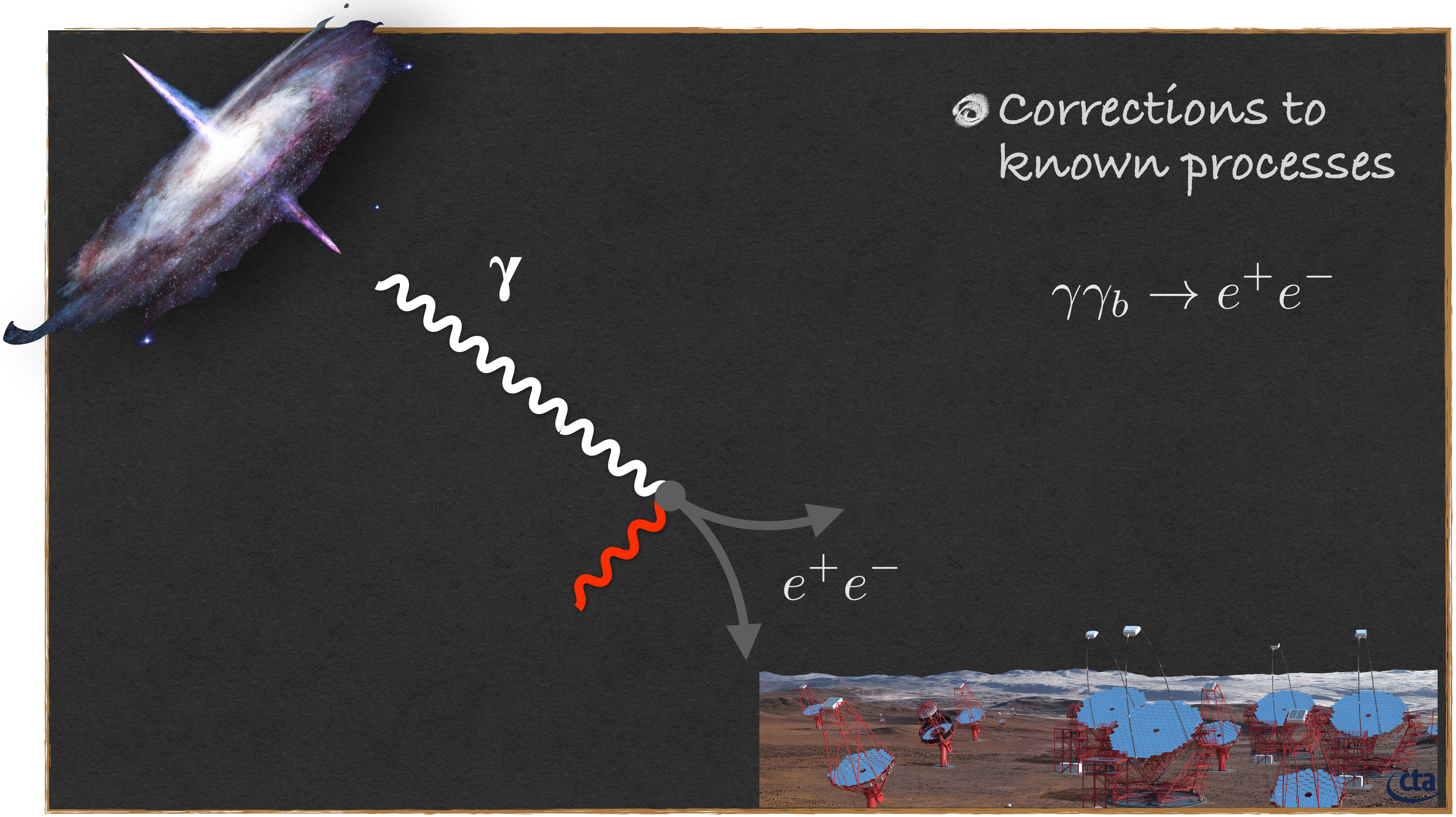
Test of Lorentz invariance violation



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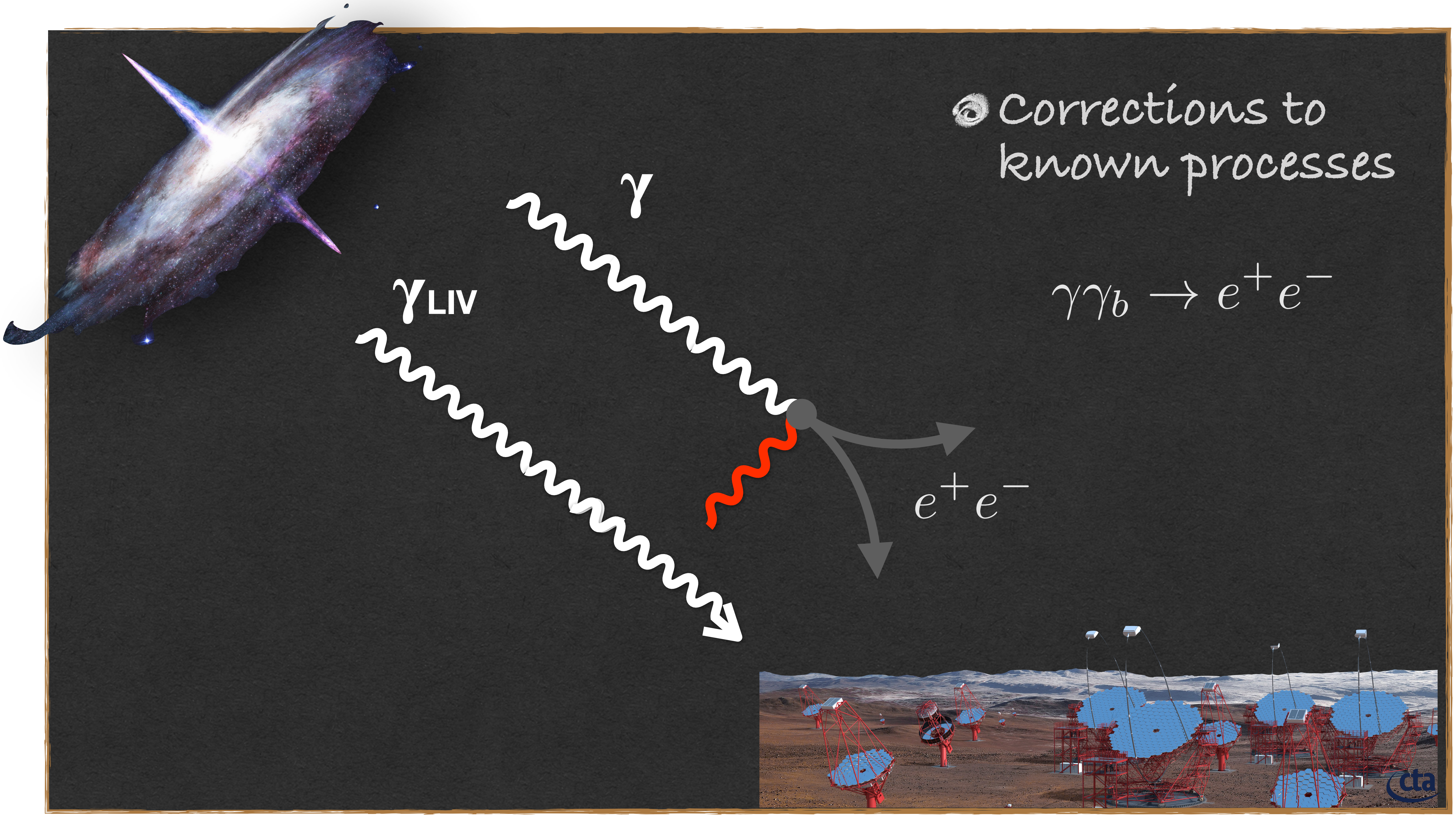
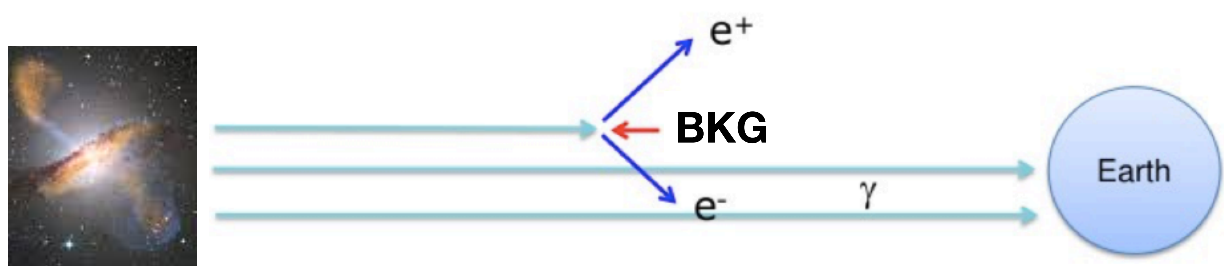


Pair Production (PP)

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

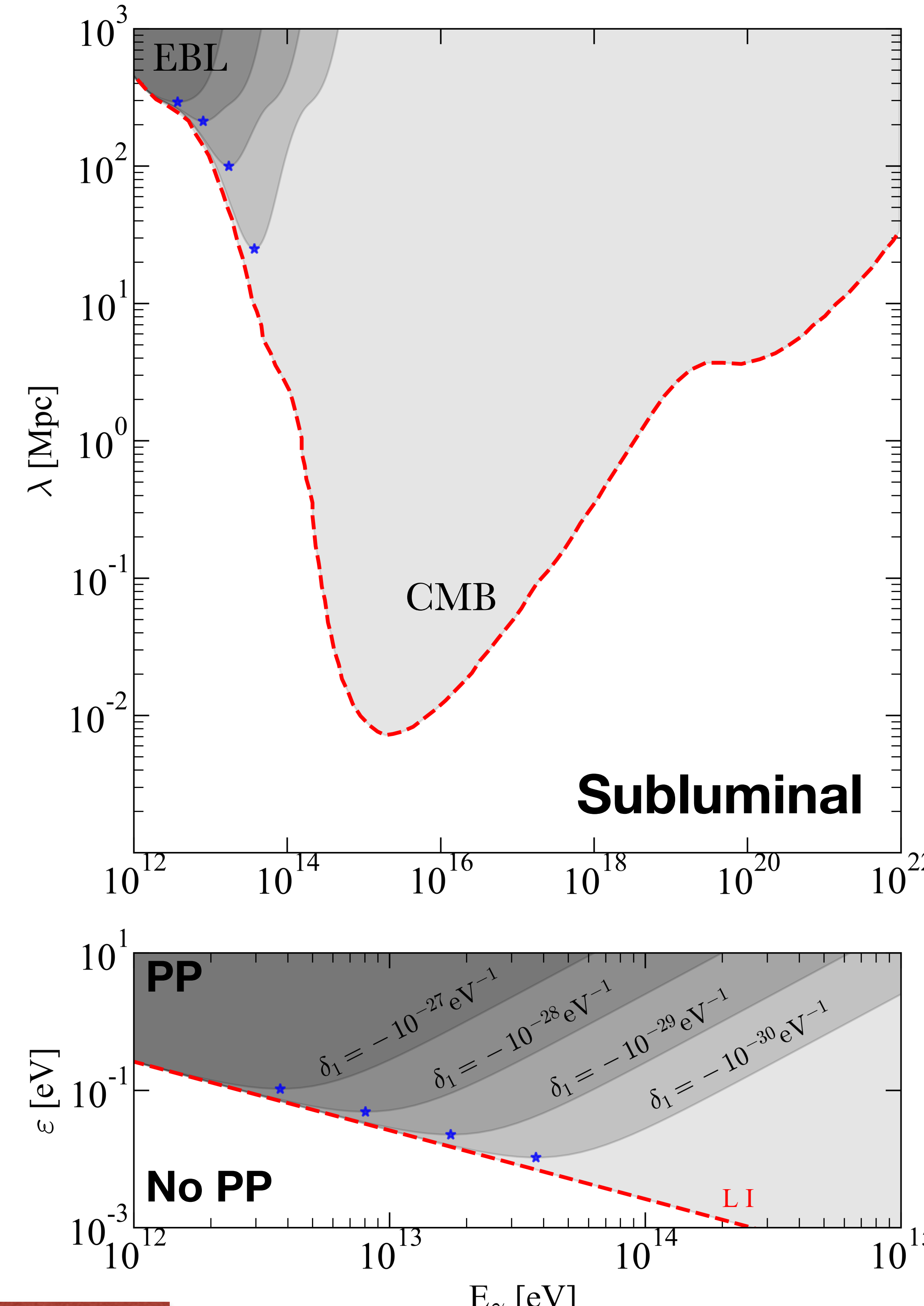


Optical depth:

$$\tau_\gamma(E_\gamma, z, \eta) \rightarrow \tau_\gamma(E_\gamma, z, \eta, n, E_{LIV}^{(n)})$$

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

Allowed PP region changes with the LIV parameter and the Energy



More photons!!

Martínez, Lang, and Souza
arXiv:1901.03205
Lang, Martinez & De Souza
ApJ 853, no.1, 23 (2018)

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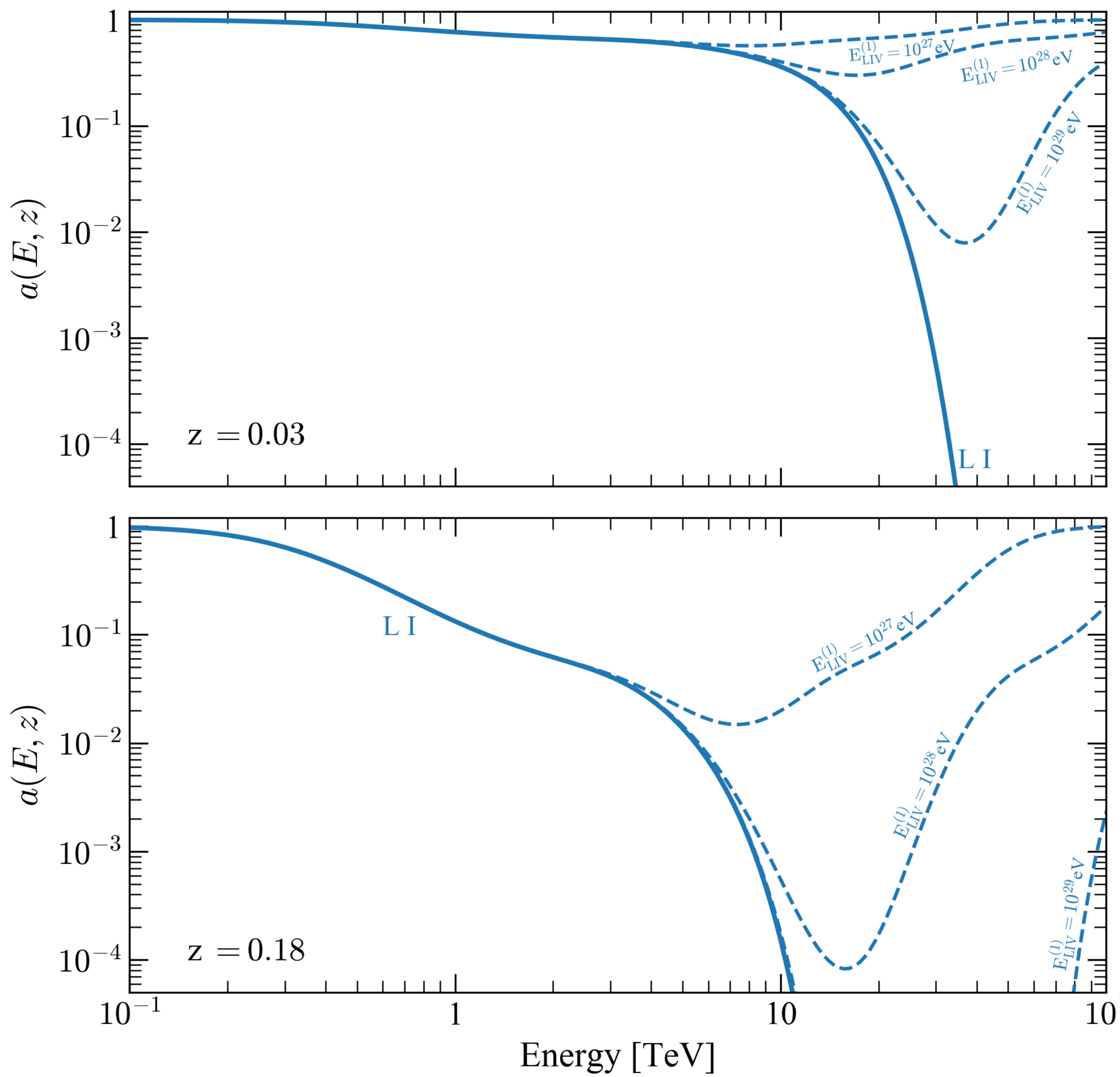
EBL-Attenuation + LIV

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

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.



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- **Experiment**
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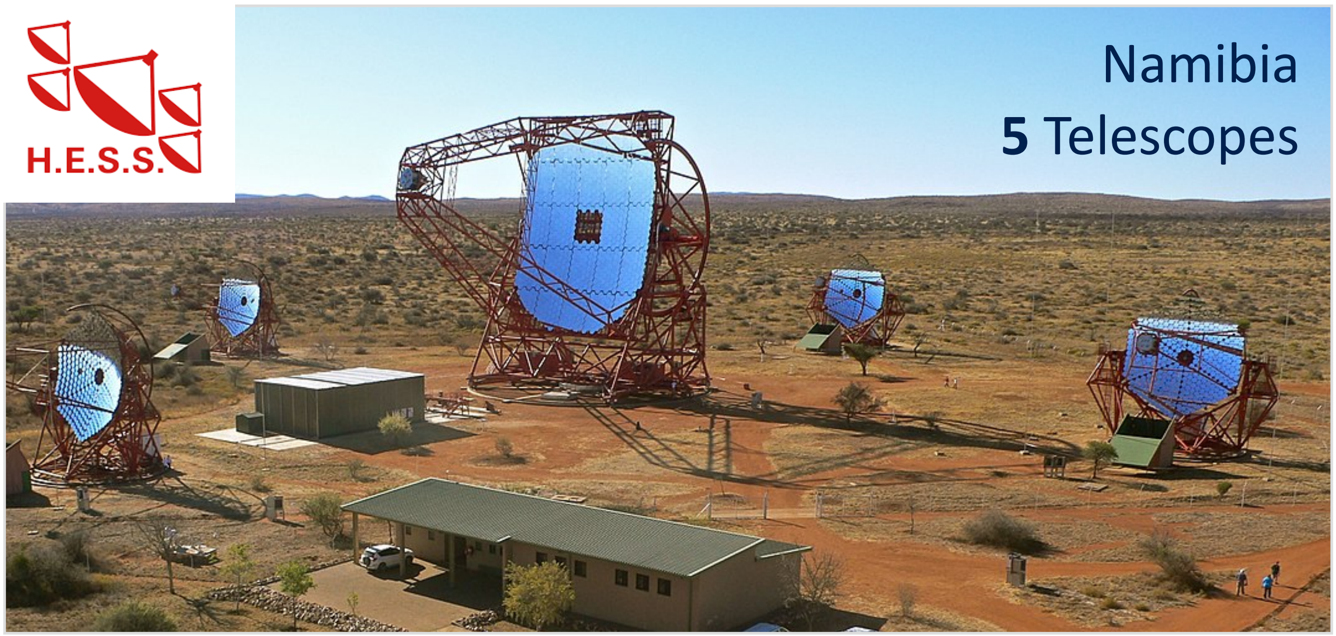
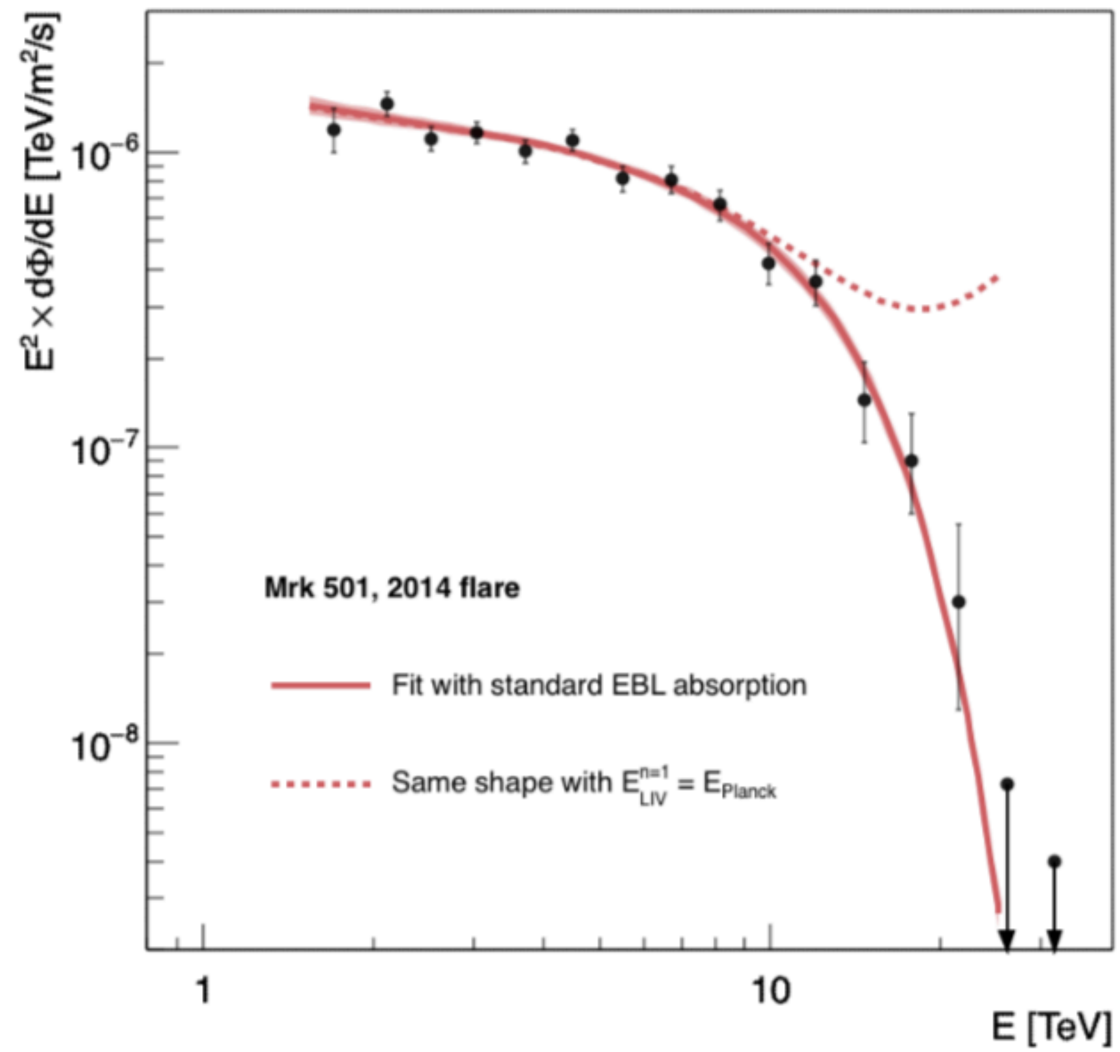




	$2\,\sigma$	$3\,\sigma$	$5\,\sigma$
n=1	2.8×10^{28} eV ($2.29 \times E_{Planck}$)	1.9×10^{28} eV ($1.6 \times E_{Planck}$)	1.04×10^{28} eV ($0.86 \times E_{Planck}$)
n=2	7.5×10^{20} eV	6.4×10^{20} eV	4.7×10^{20} eV

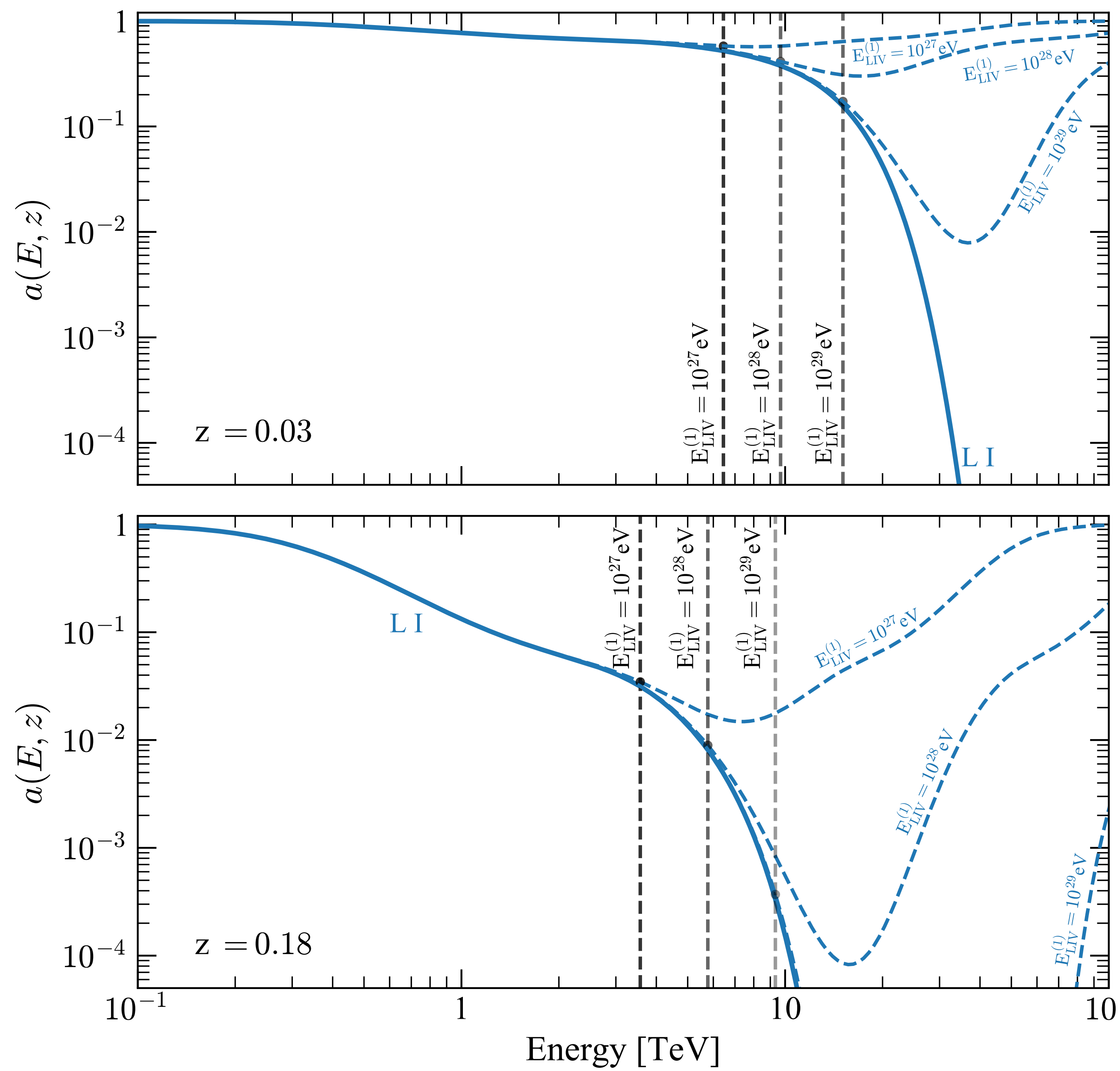
Lorentz and Brun for the HESS collaboration, RICAP16, 2016.

ApJ Vol 870, 2
arXiv:1901.05209

LIV Horizon

... one source?

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



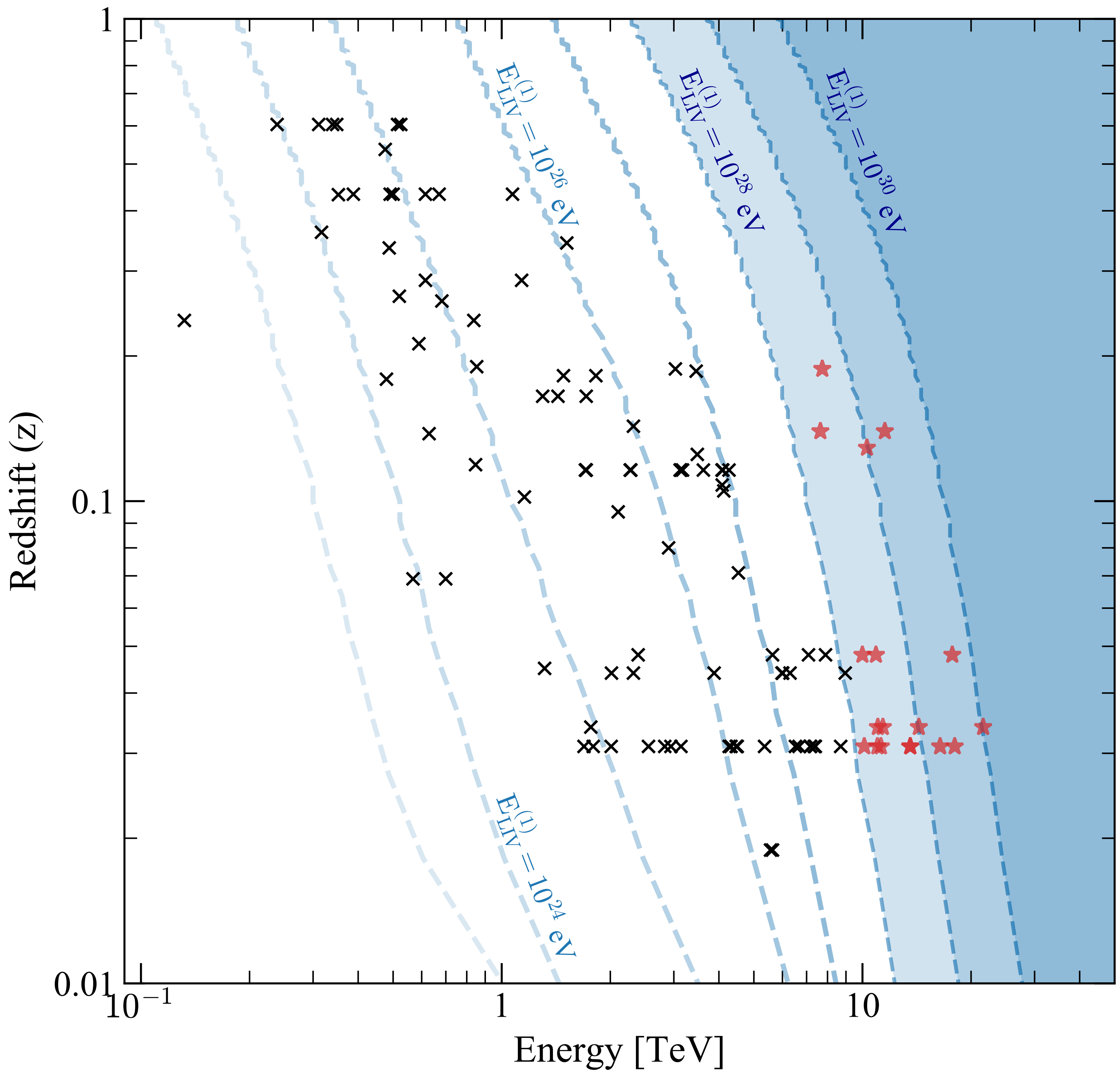
Lang, Martínez and Souza
Phys.Rev. D99 (2019) no.4, 043015

LIV Horizon

...Why use only one source?

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

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



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LIV Horizon

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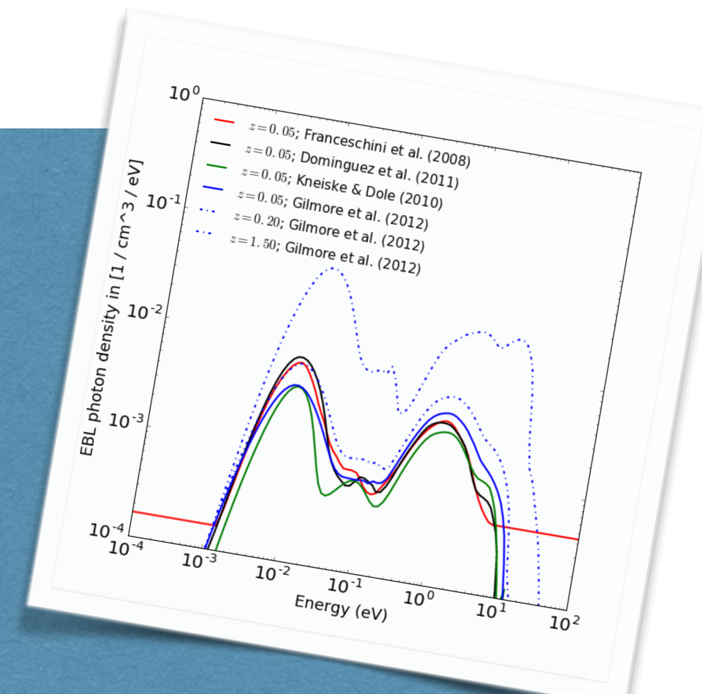
Source	Redshift	Experiment	Spectrum	Reference
Markarian 421	0.031	HEGRA	1999–2000	[48]
			2000–2001	[48]
		HESS	2000	[49]
		VERITAS	2006–2008 (low)	[50]
			2006–2008 (mid)	[50]
		TACTIC	2005–2006	[51]
			2009–2010	[52]
Markarian 501	0.034	TACTIC	2005–2006	[53]
		ARGO-YBJ	2008–2011	[54]
			2011 (flare)	[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 and Souza
Phys.Rev. D99 (2019) no.4, 043015

LIV Limits

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



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

Lang, Martínez and Souza
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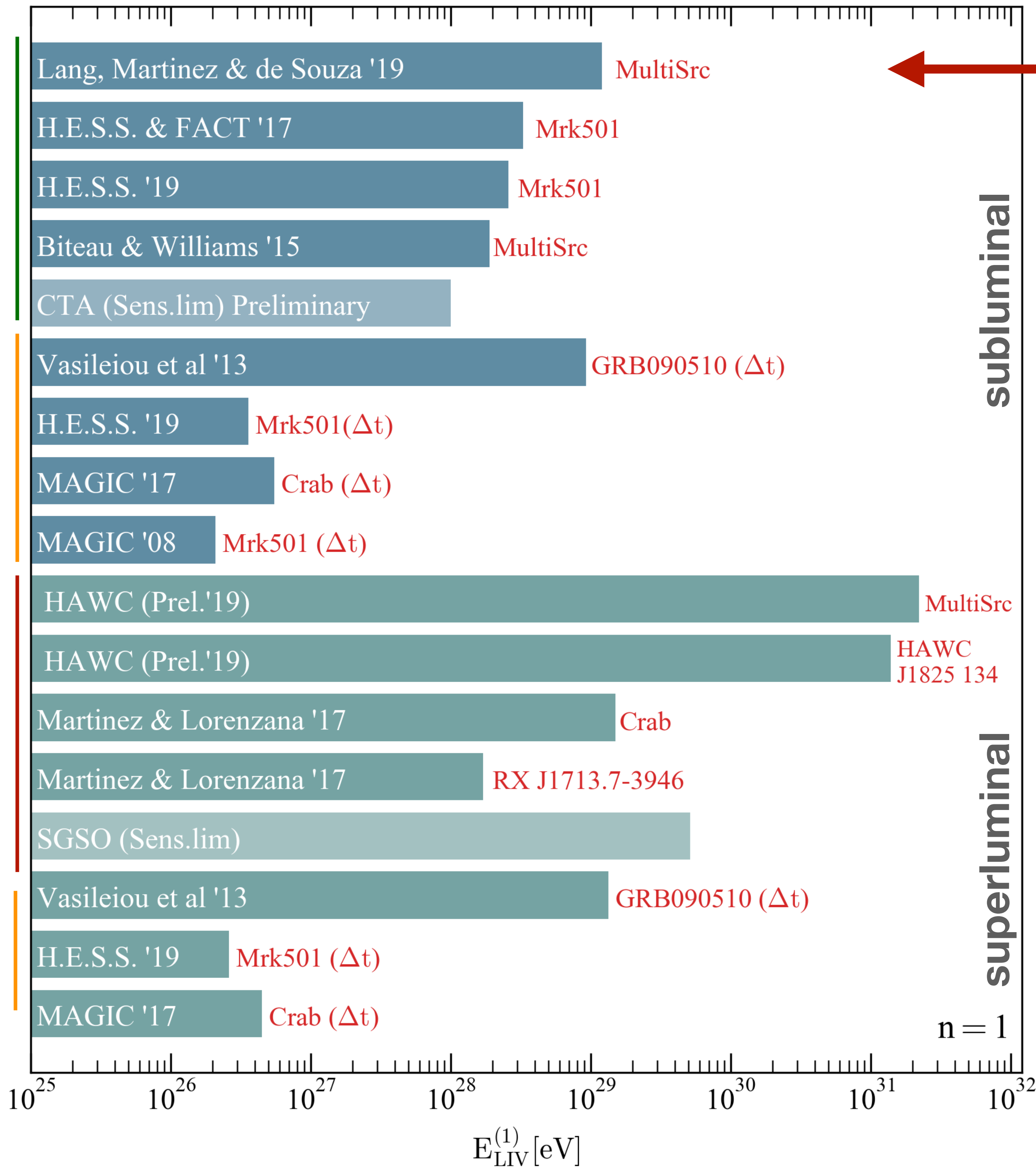
LIV limits

Pair production threshold shifts

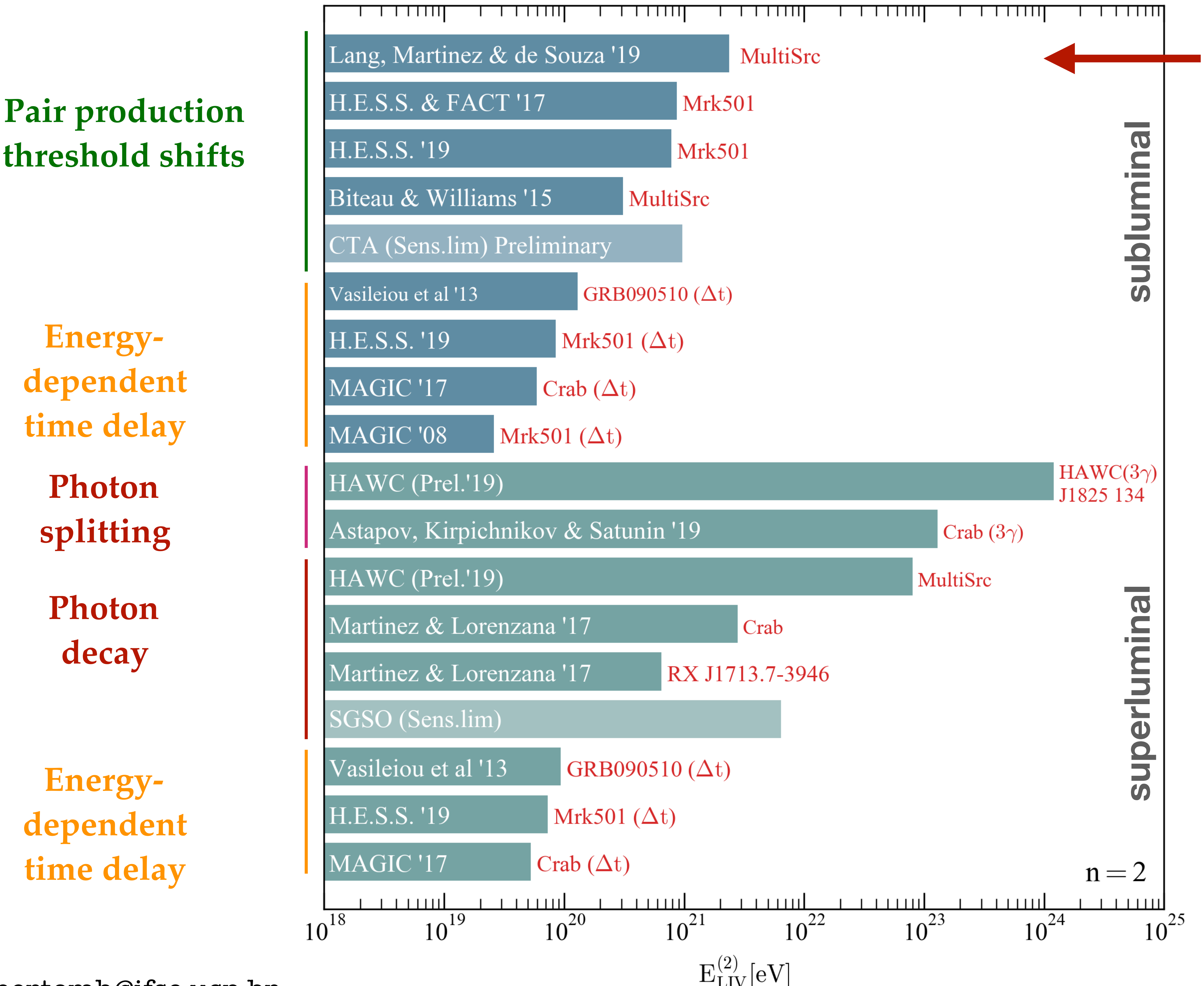
Energy-dependent time delay

Photon decay

Energy-dependent time delay



LIV limits



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$E^{(2)}_{LIV}$ [eV]

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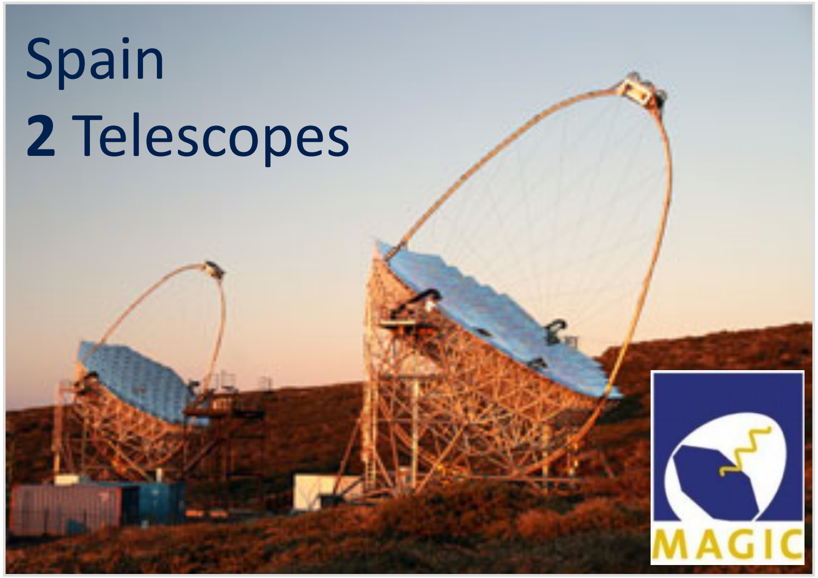
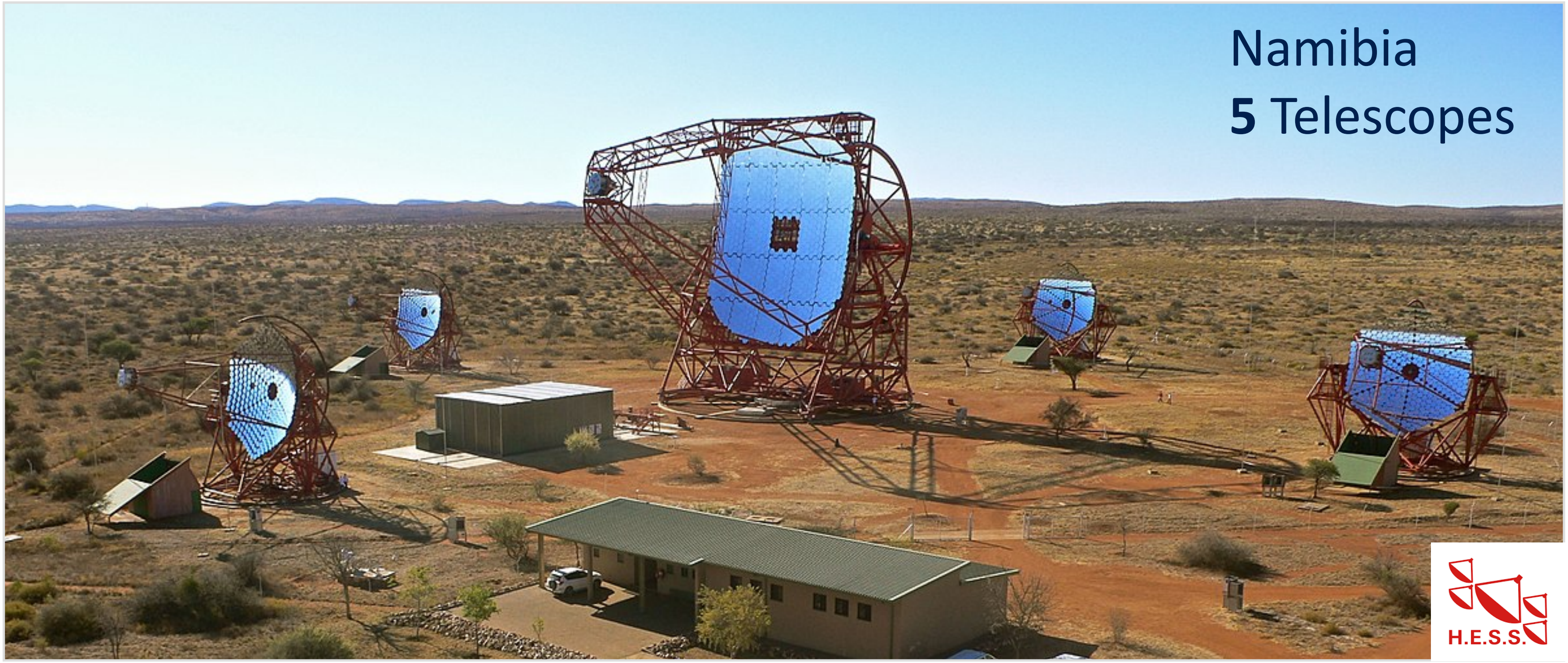
- Phenomenology
- Experiment
- **Future**

Current IACT



Imaging
Atmospheric
Cherenkov
Telescopes



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CTA Key Science Projects (KSPs)

CTA science program:

https://arxiv.org/abs/1709.07997

99 Telescopes
- 4 LST
- 25 MST
- 70 SSTs

The Array Locations

Array Coordinates
Latitude: 24° 41' 0.34" South
Longitude: 70° 18' 58.84" West

~5 km²

area covered by the array of telescopes

~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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CTA Consortium

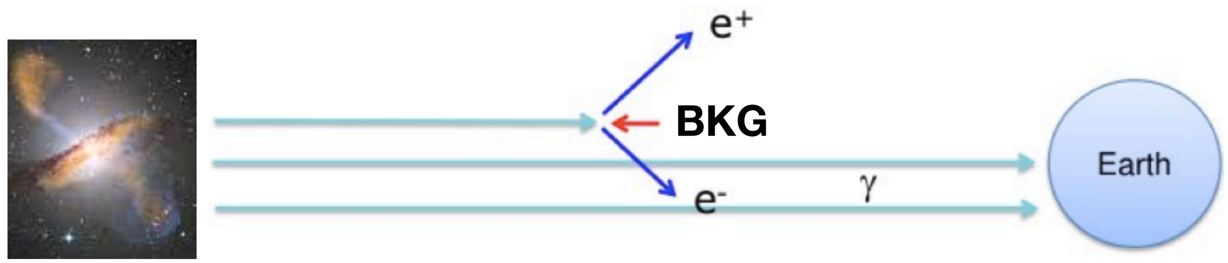
August 2019

31 Countries
~200 Institutes
~1500 members

humbertomh@ifsc.usp.br

Pair Production (PP)

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



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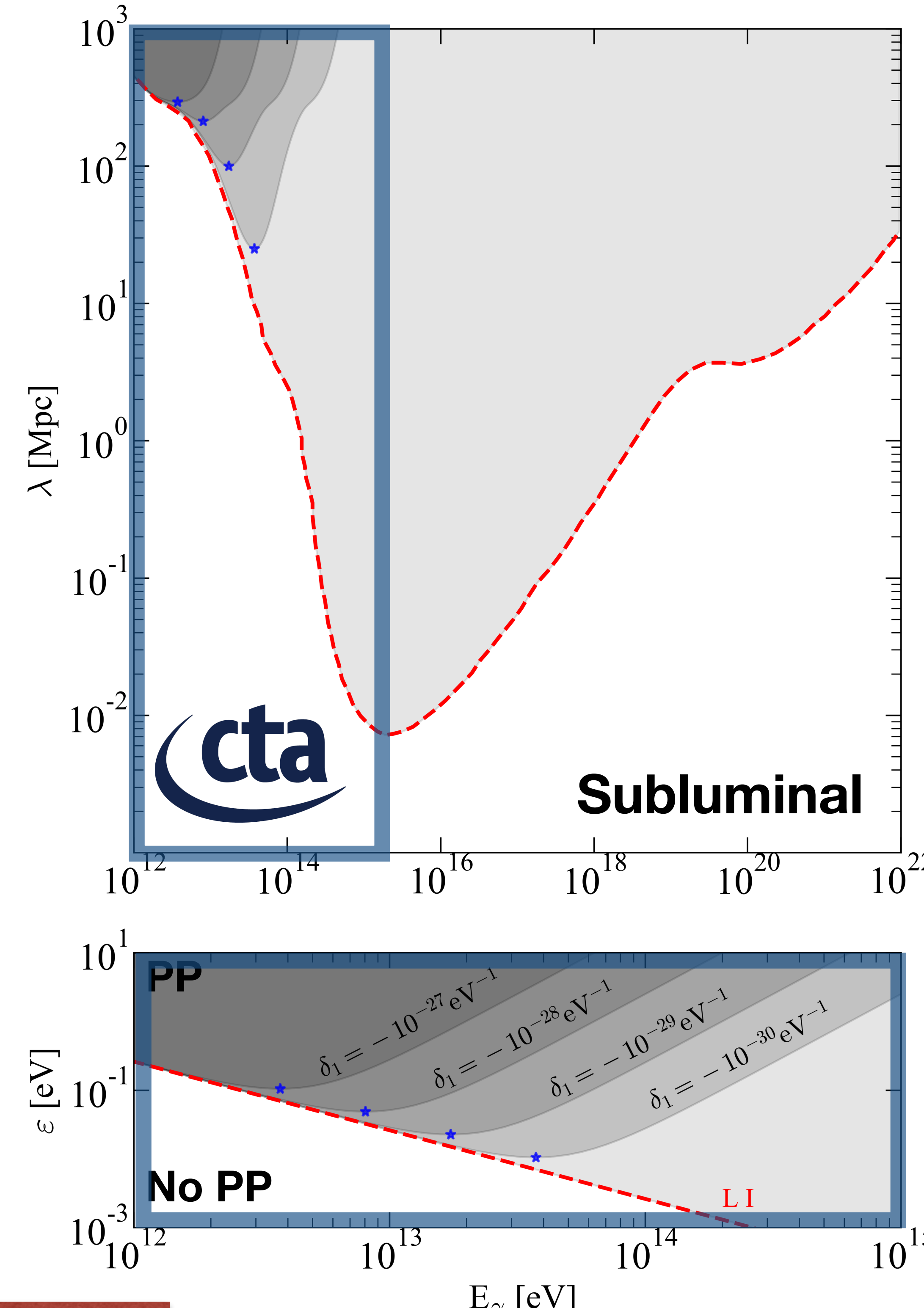

Martínez, Lang, and Souza
arXiv:1901.03205

More photons!!

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

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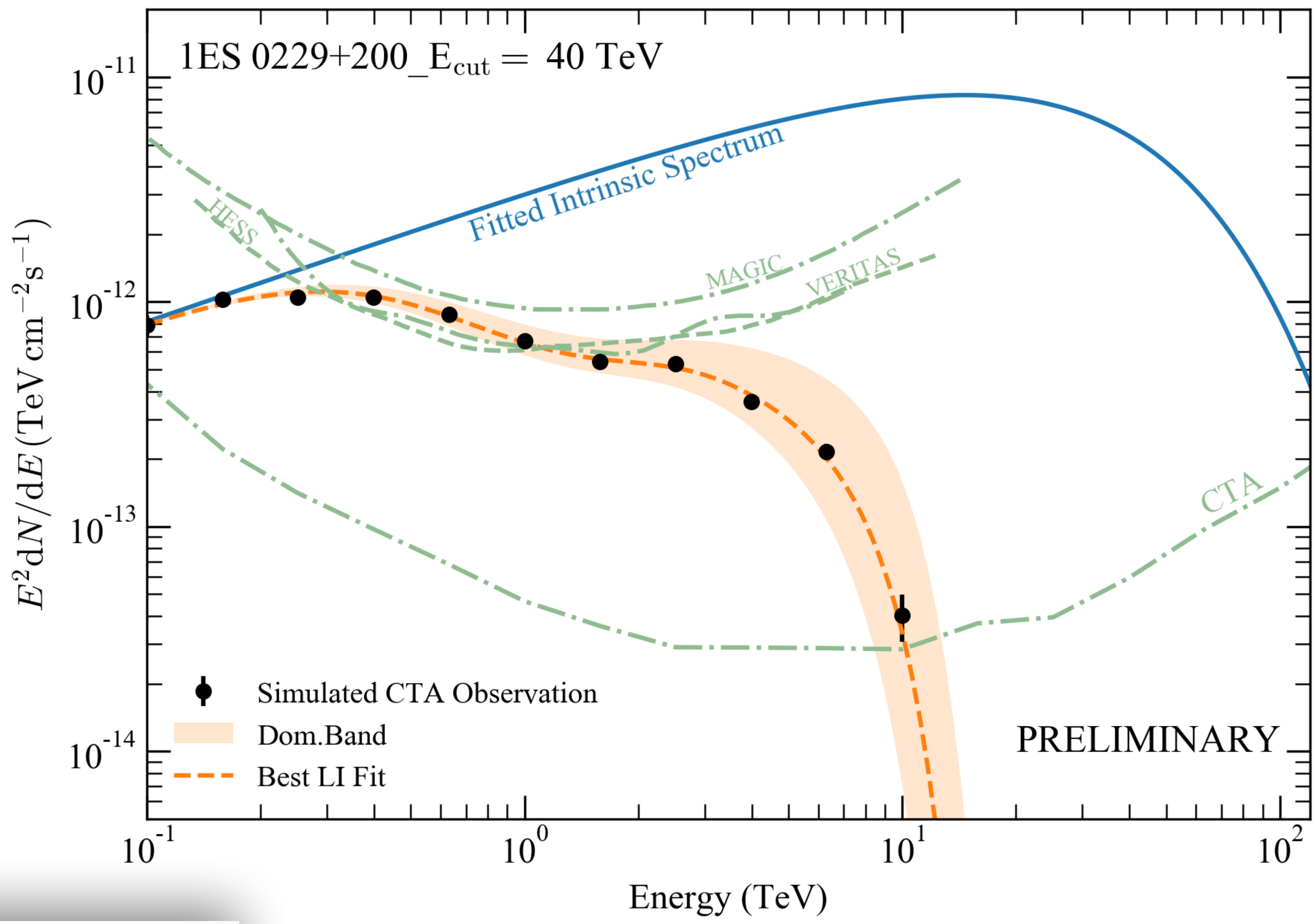
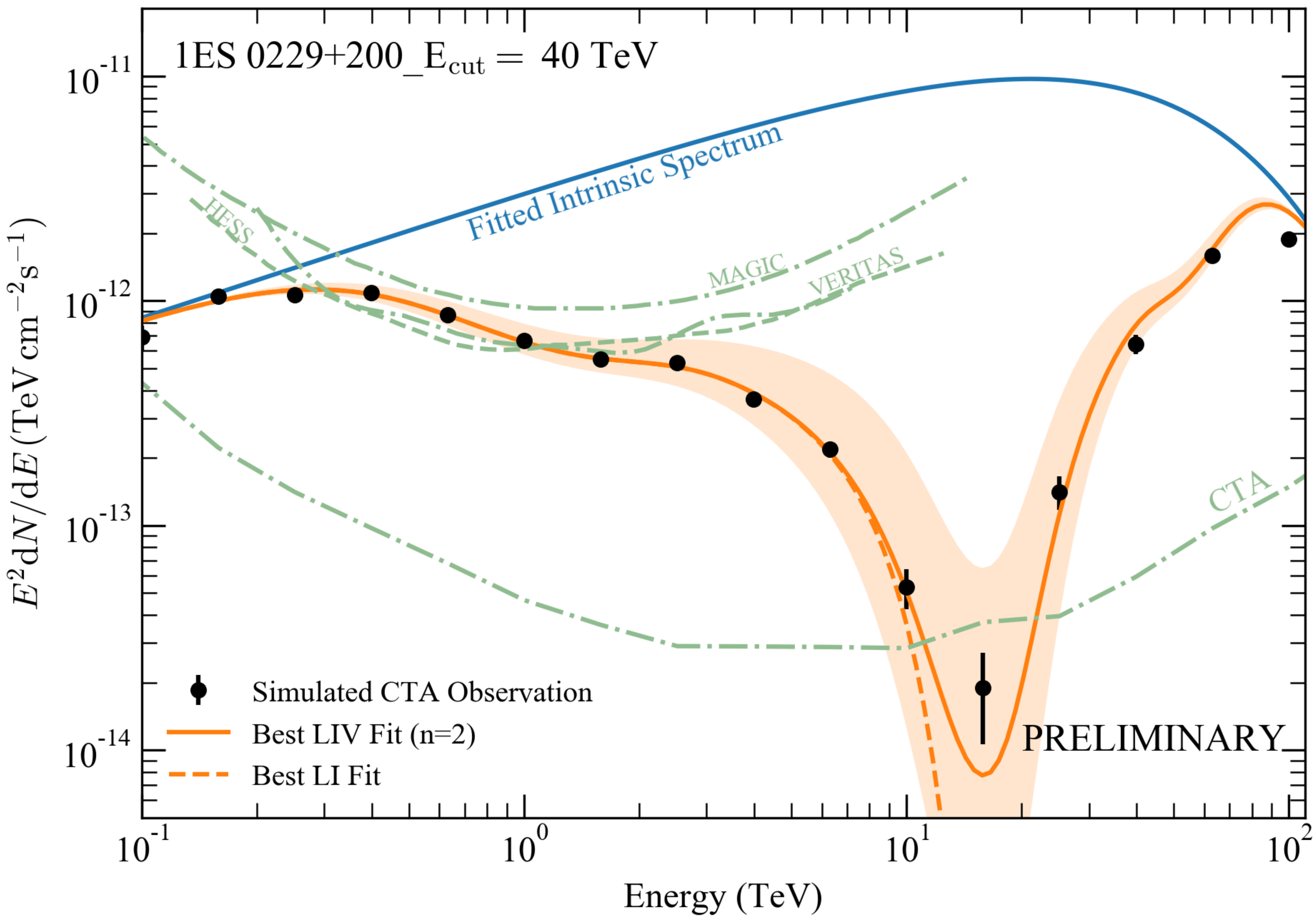
Simulating a LI signature with CTA



gammapy
Gamma-ray astronomy Python tools

H. Martínez-Huerta et al. (CTA Consortium) ICRC'19
arXiv:1908.09614

Simulating a LIV signature with CTA



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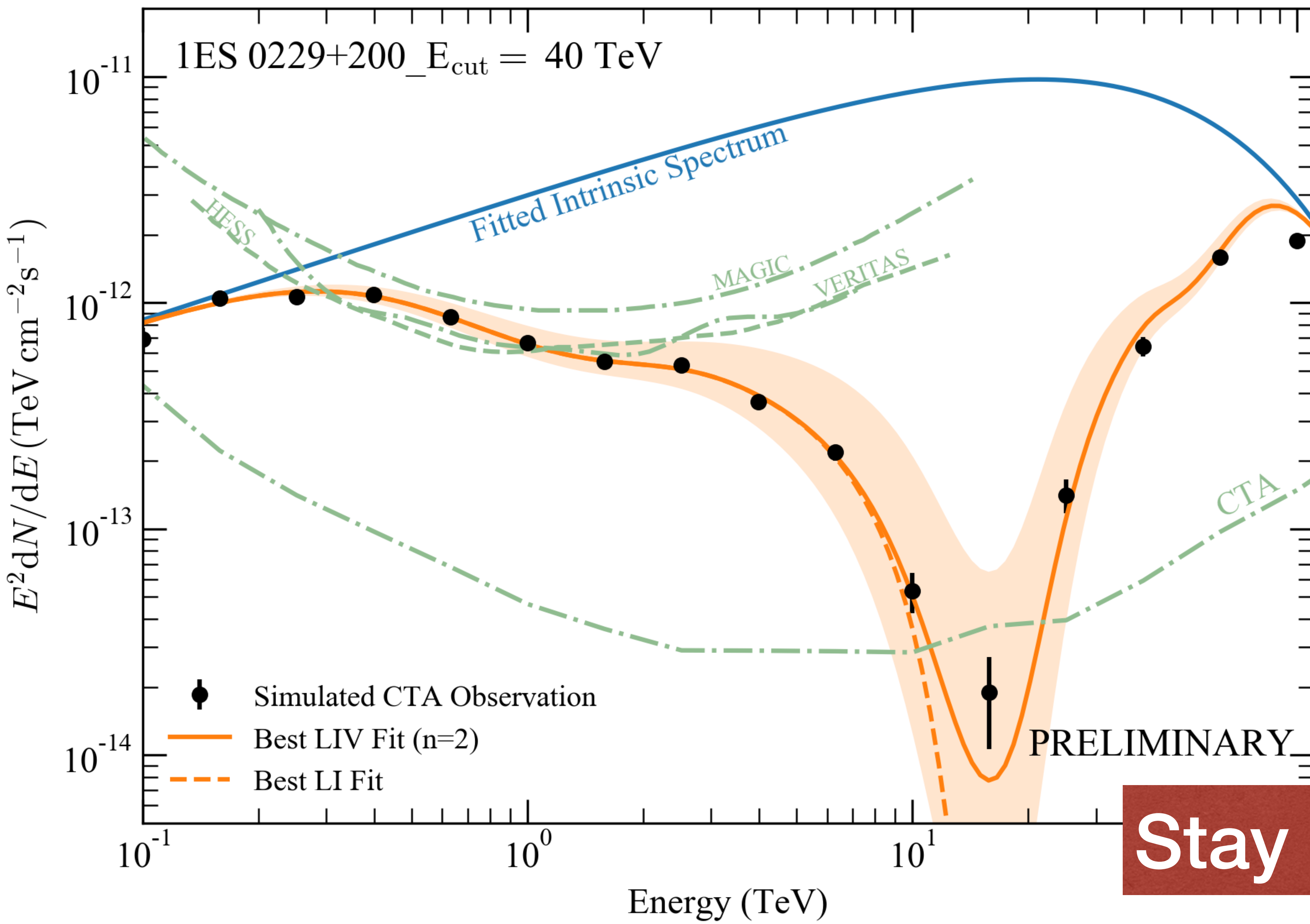
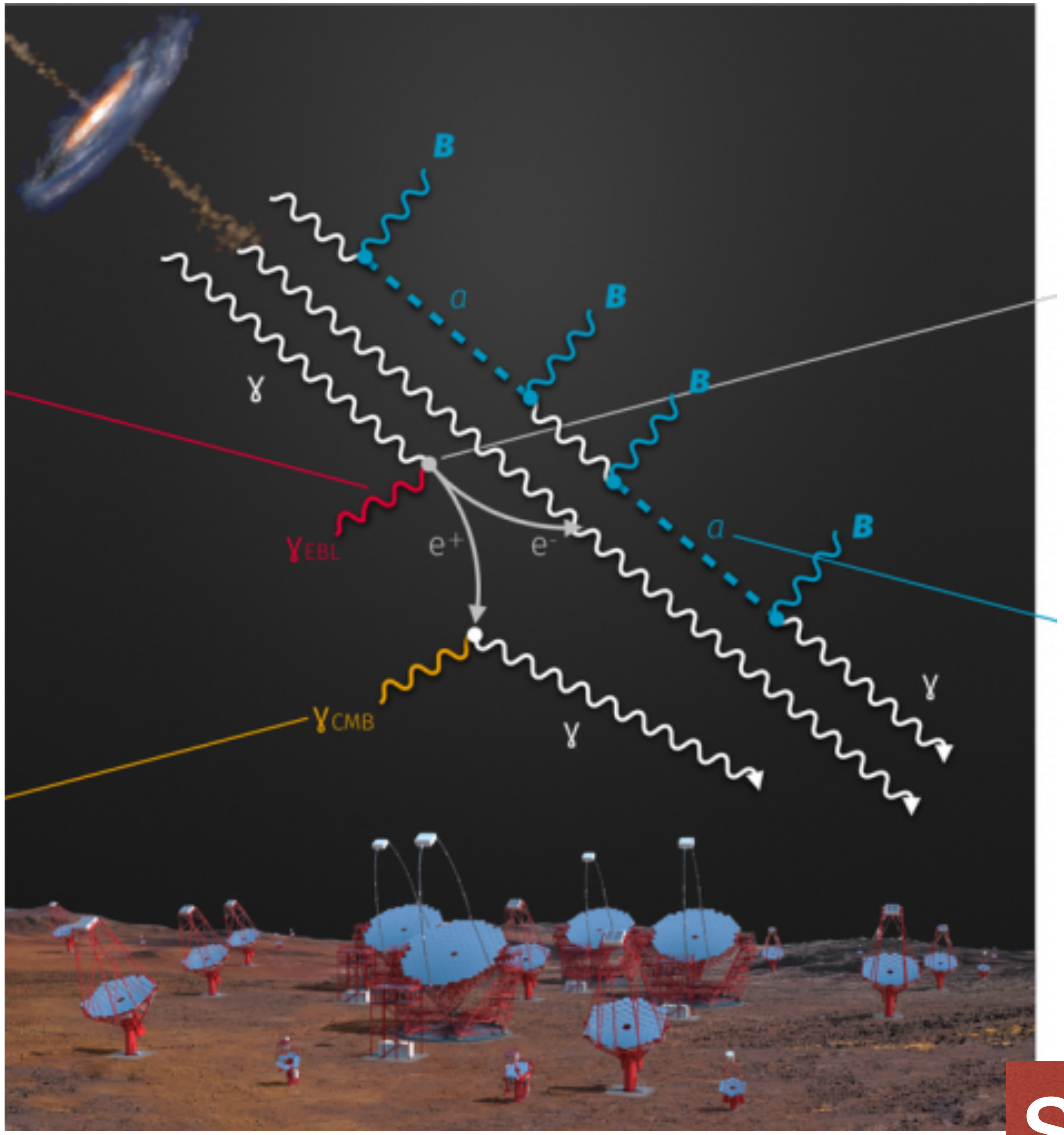


Stay tuned…

H. Martínez-Huerta et al. (CTA Consortium) ICRC'19
arXiv:1908.09614

Testing the frontiers of physics

Gamma rays produce electron-positron pairs when interacting with EBL photons



Exotic processes such as LIV or coupling to axion-like particles could modify the absorption, resulting in characteristic spectral features.

Stay tuned...

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

LIV limits

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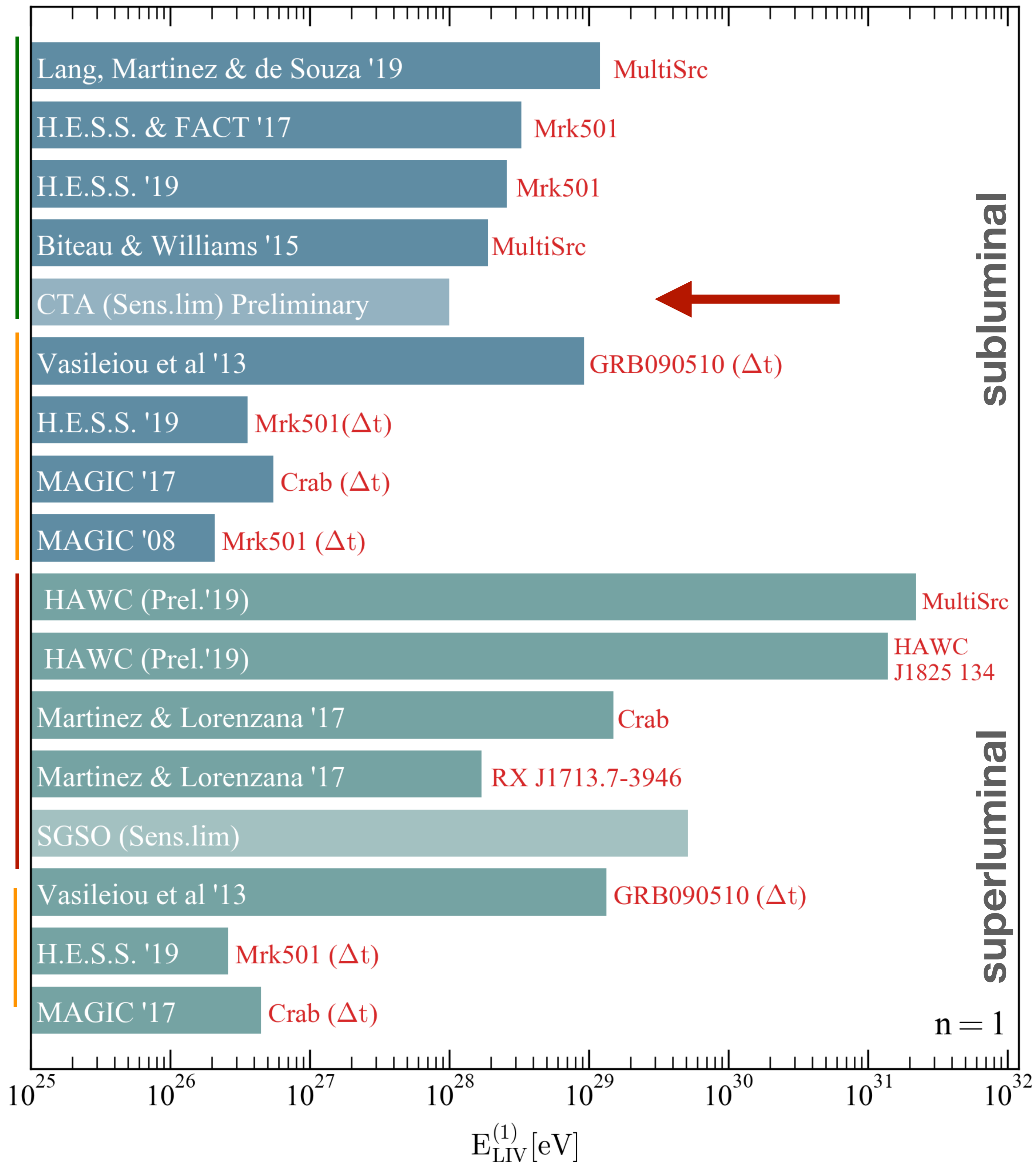
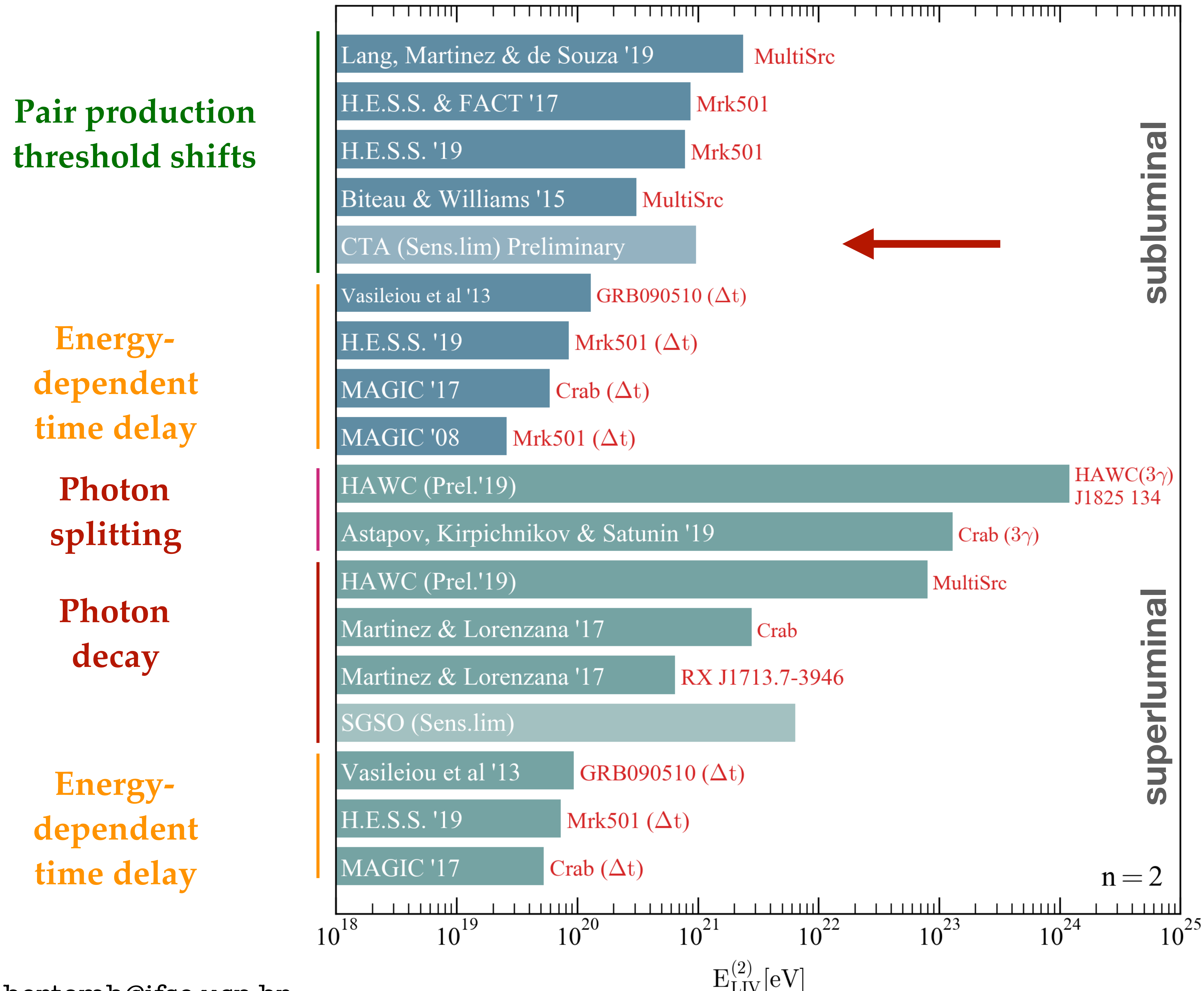


LIV limits



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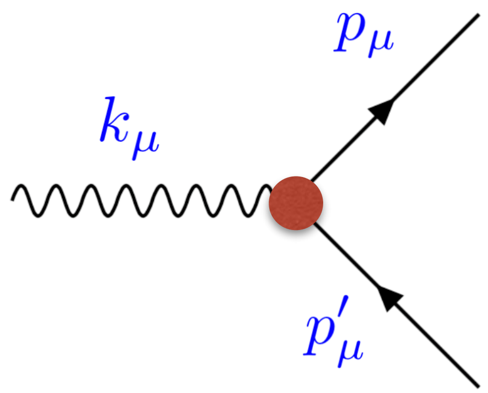
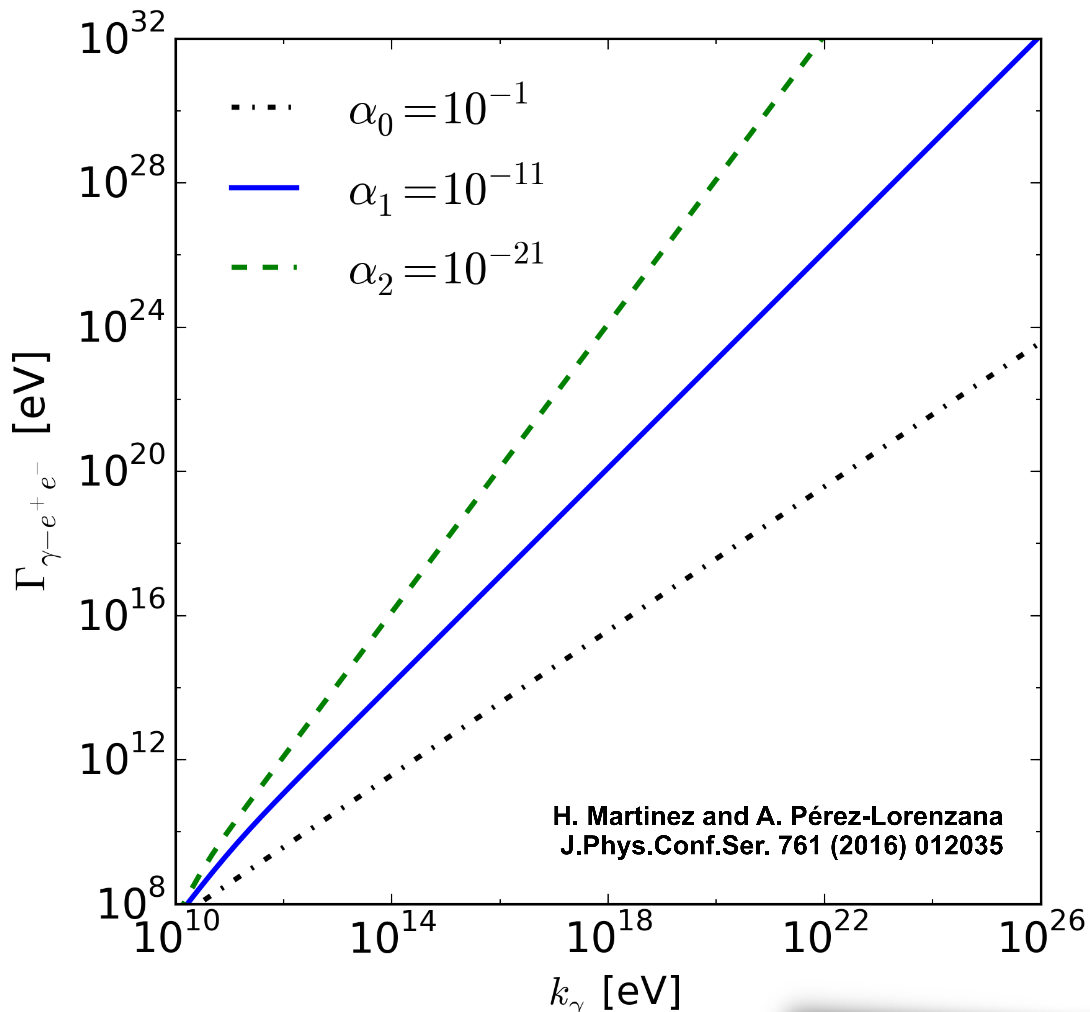
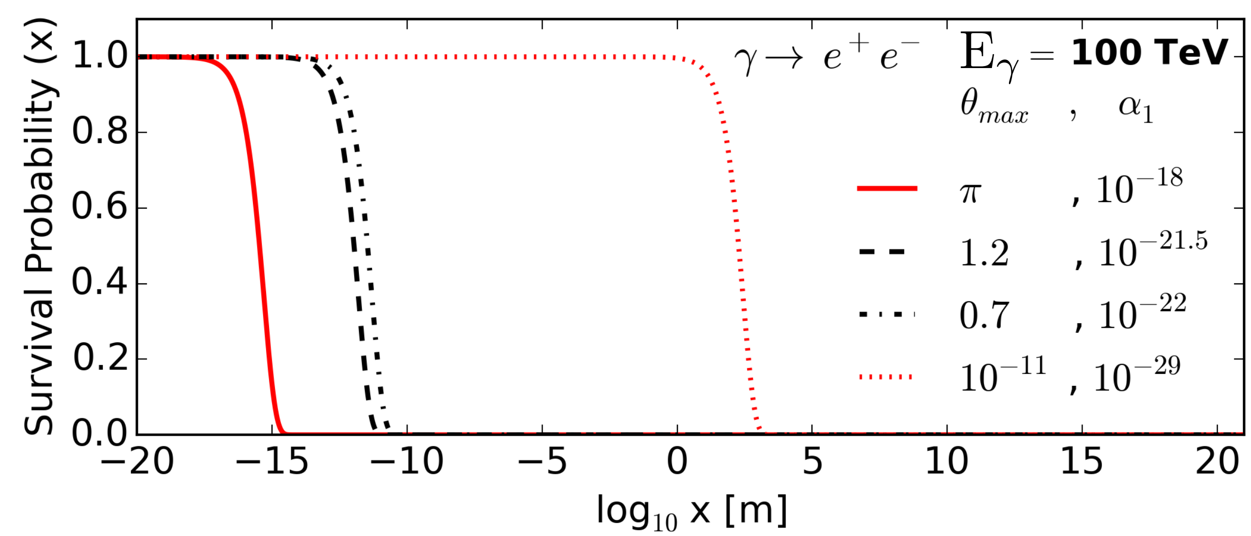
Photon decay



$$\boxed{\alpha_{\gamma,n} < E_\gamma^{-n}\left[\frac{4m_e^2}{E_\gamma^2 - 4m_e^2}\right]}$$



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



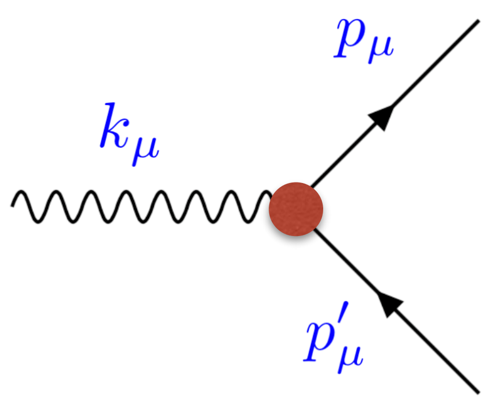
If you observe VHE gamma-rays, the LIV process is restricted!!

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

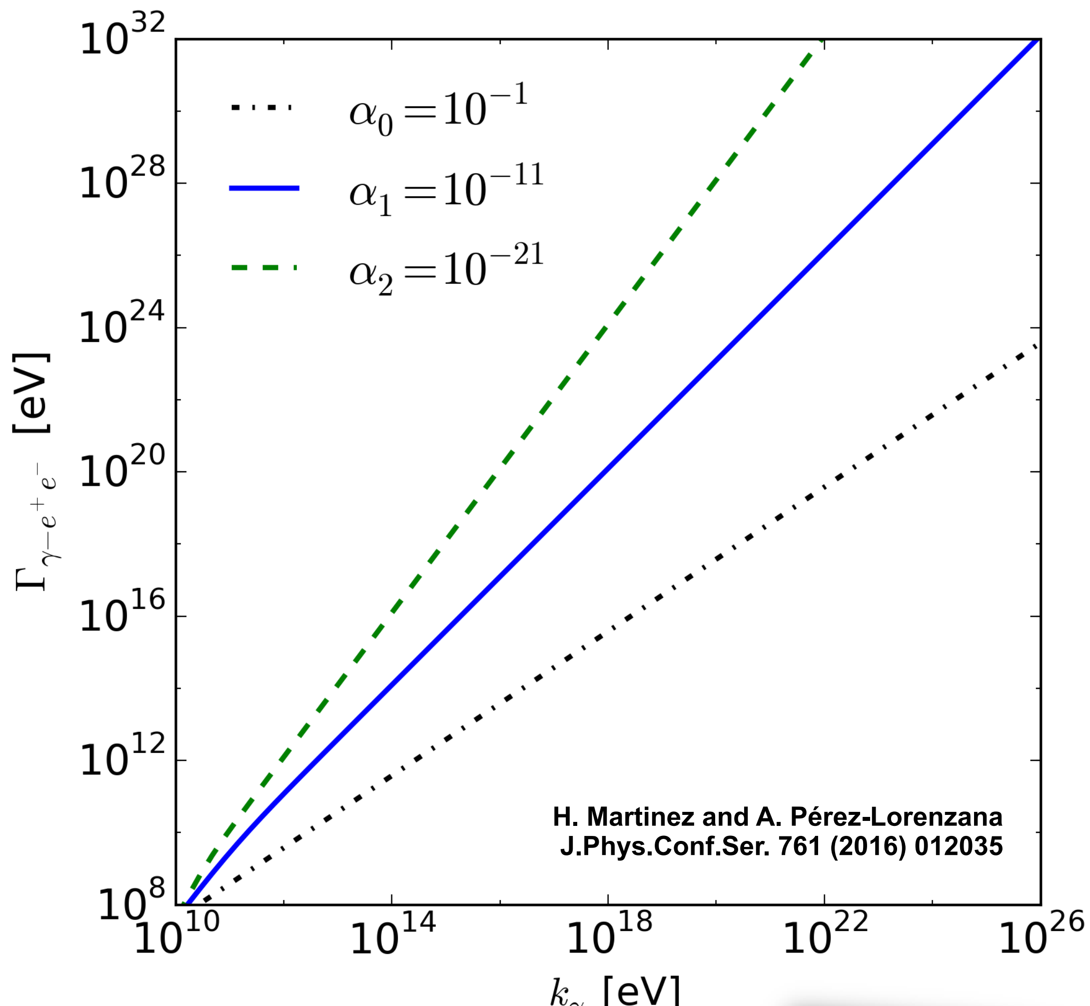
(n=0) SME: Phys. Rev. D 96, 116011 (2017)

humbertomh@ifsc.usp.br

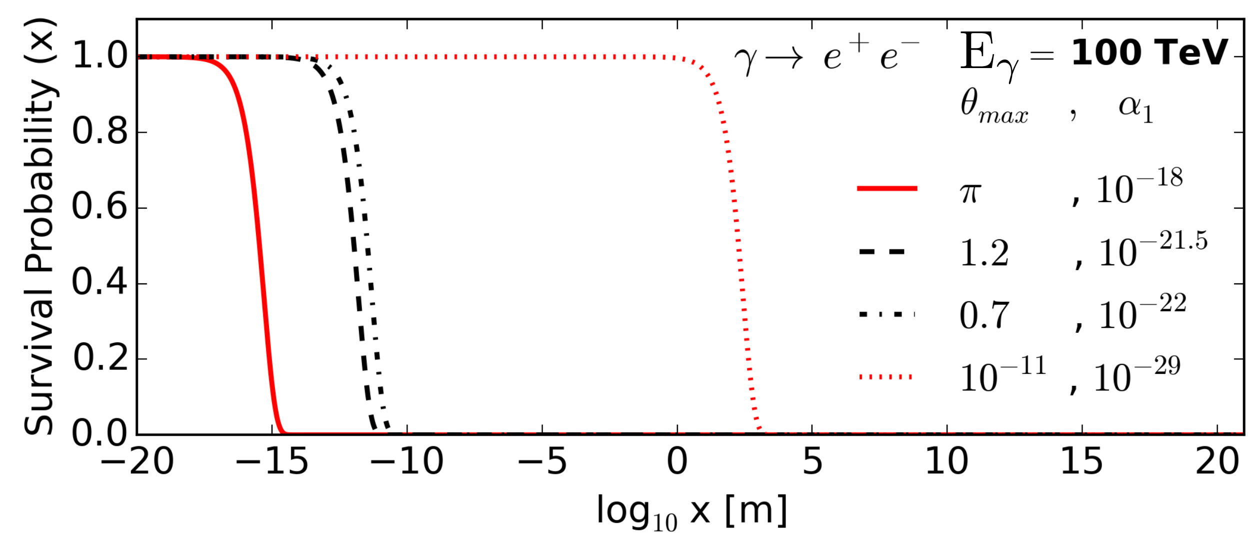
Photon decay



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



Above this energy threshold, the decay rate is <u>quite efficient</u> that photons should not arrive at Earth from <u>cosmological distances</u>



Search for the most energetic photons…

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

Outline

I. **Introduction**

II. LIV-signatures for Astroparticle tests

i. Threshold shifts

ii. Photon Decay

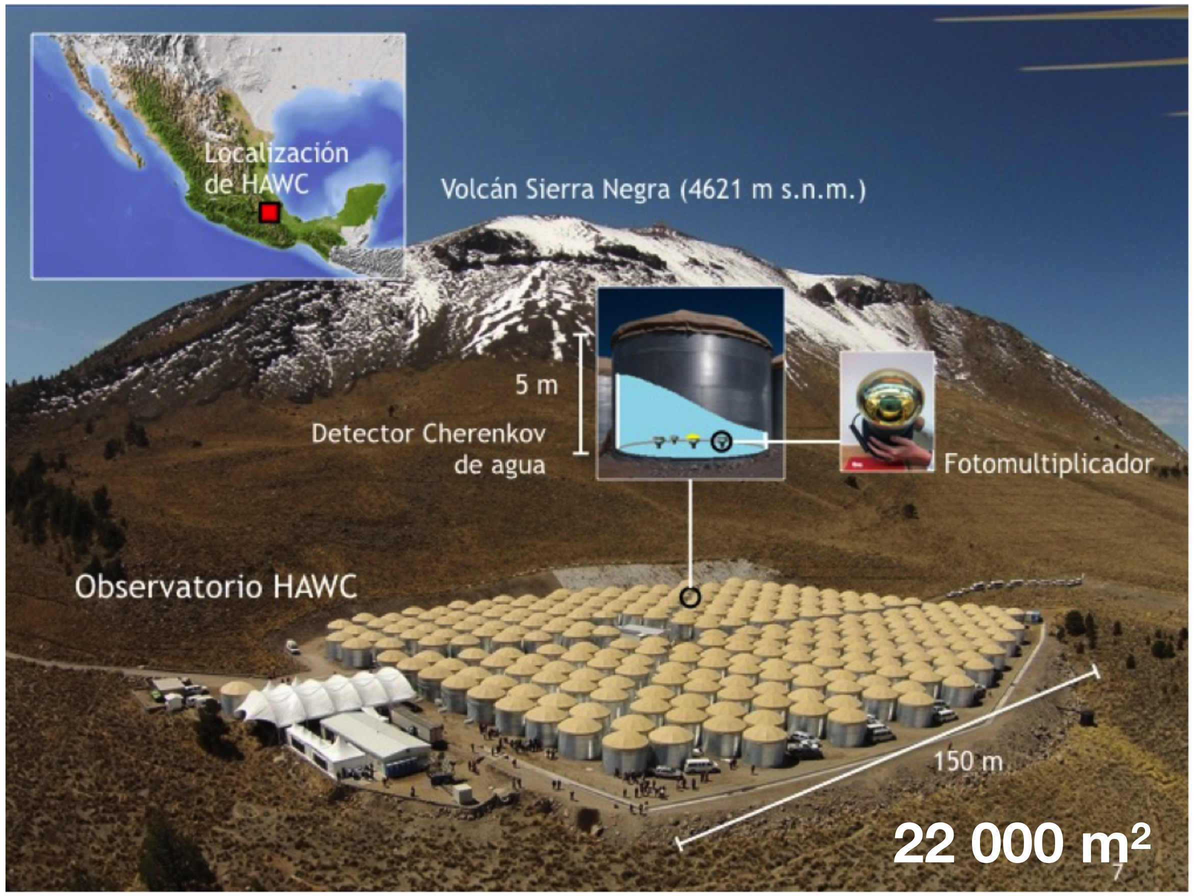
iii. Photon Spliting

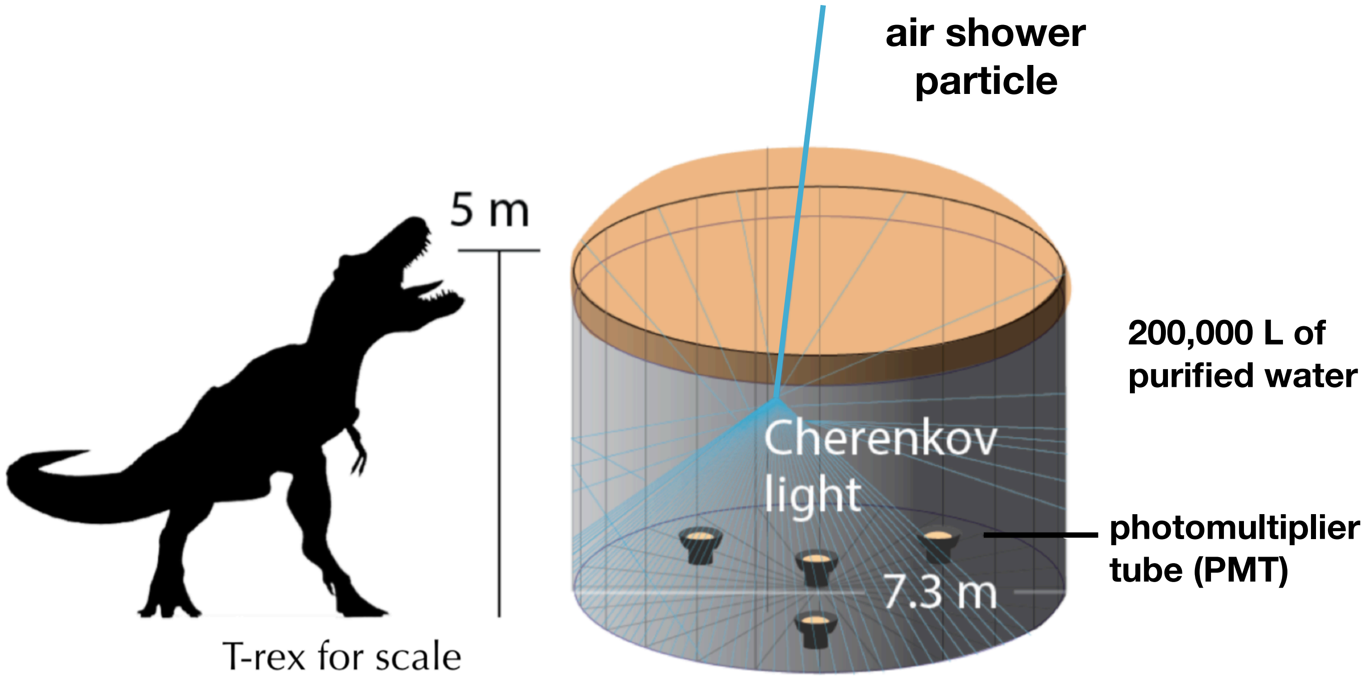
iv. Energy-dependent time delay

III. Limits: astrophysical photons

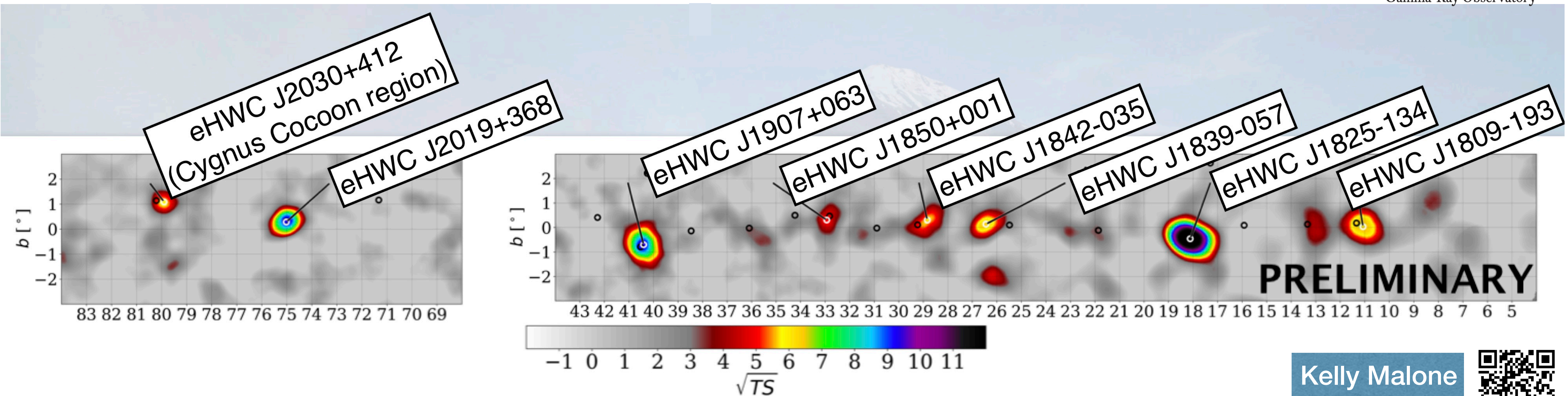
- Phenomenology
- **Experiment**
- Future

The High Altitude Water Cherenkov





Highest energy sources



Kelly Malone

PoS ICRC19 723

-Reported detailed measurements of γ-ray >**100 TeV**,

-Recent development of advanced energy-reconstruction algorithms, **artificial neural network**

HAWC Collaboration
arXiv:1909.08609

> 56 TeV:

- ☑ **Crab**,
- ☑ 2HWC J1825−134,
- ☑ 2HWC J1839−057,
- ☑ 2HWC J1844−032,
- ☑ 2HWC J1908+063,
- ☑ 2HWC J2019+367
- ☑ 2HWC J2031+415
- ☐ 2HWC J1809-190
- ☐ 2HWC J1849+001

PoS ICRC19 723
PoS(ICRC2019)738

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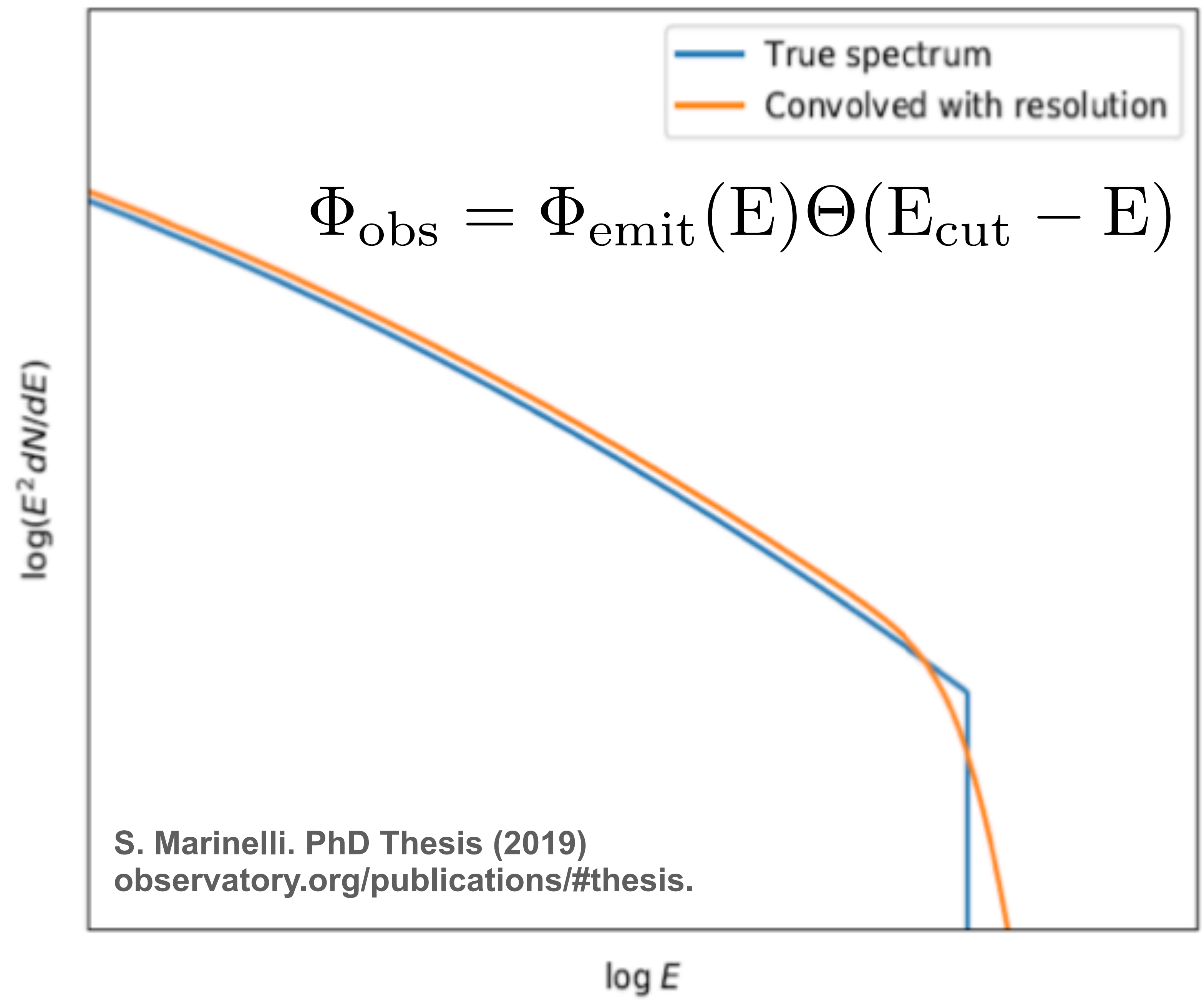
LIV hard cutoff

LIV hard cutoff at some energy Ec in the True spectrum

softened in the observed spectra due to the effects of the detector energy resolution

A profile **log-likelihood** is performed to find the best-fit spectrum model for each source, including a energy cutoff, $\hat{\mathrm{E}}_{\mathrm{c}}$

$$D = 2\ln\left(\frac{\mathscr{L}(\hat{\mathrm{E}}_{\mathrm{c}})}{\mathscr{L}(\hat{\mathrm{E}}_{\mathrm{c}} \to \infty)}\right)$$



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PoS ICRC19 738

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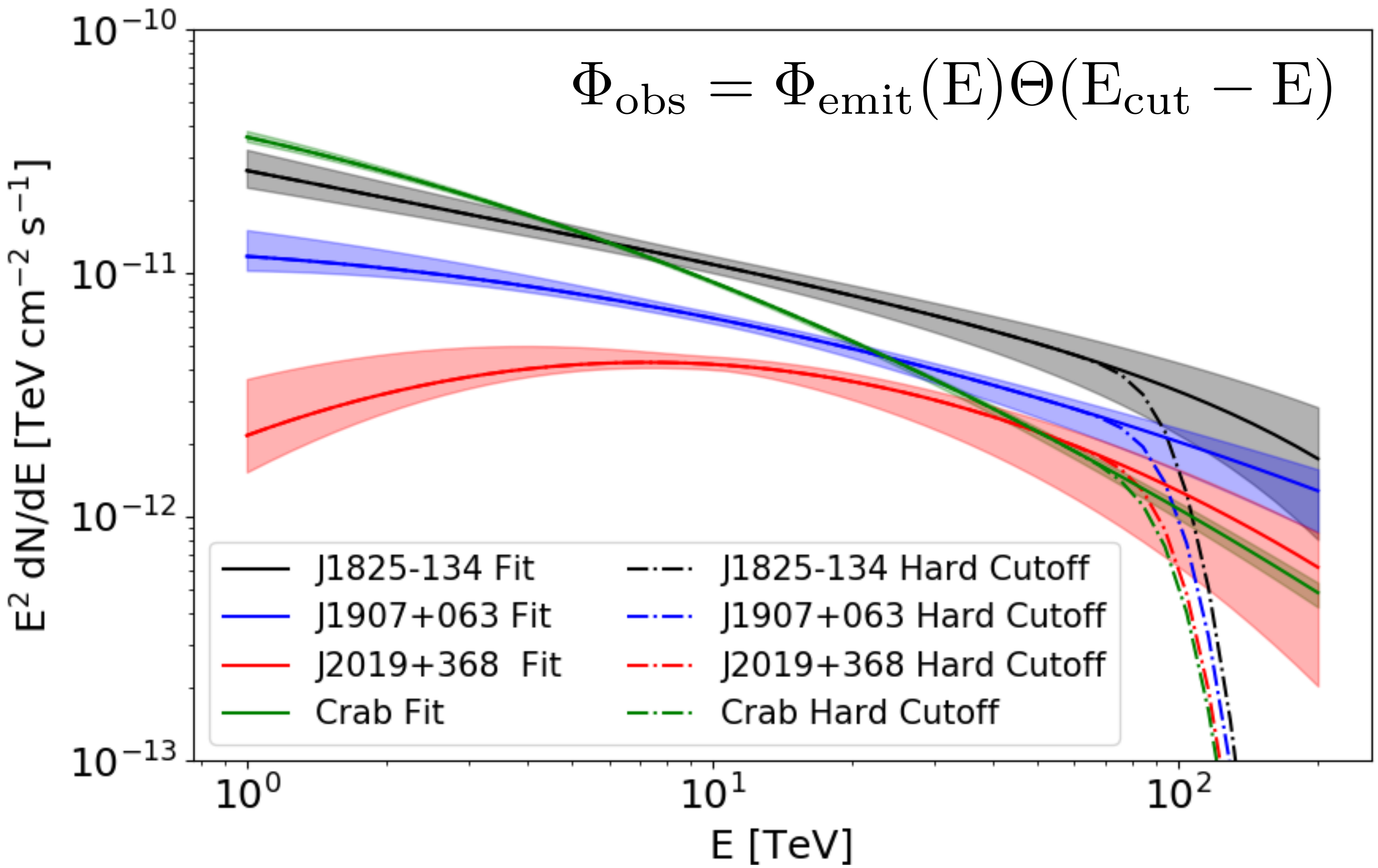
LIV hard cutoff



Source	p-value	$E_c(95\%)$	$E_c(3\sigma)$
eHWC J1825-134	1.000	244	158
eHWC J1907+063	0.990	218	162
eHWC J0534+220 (Crab)	1.000	152	104
eHWC J2019+368	0.828	120	88

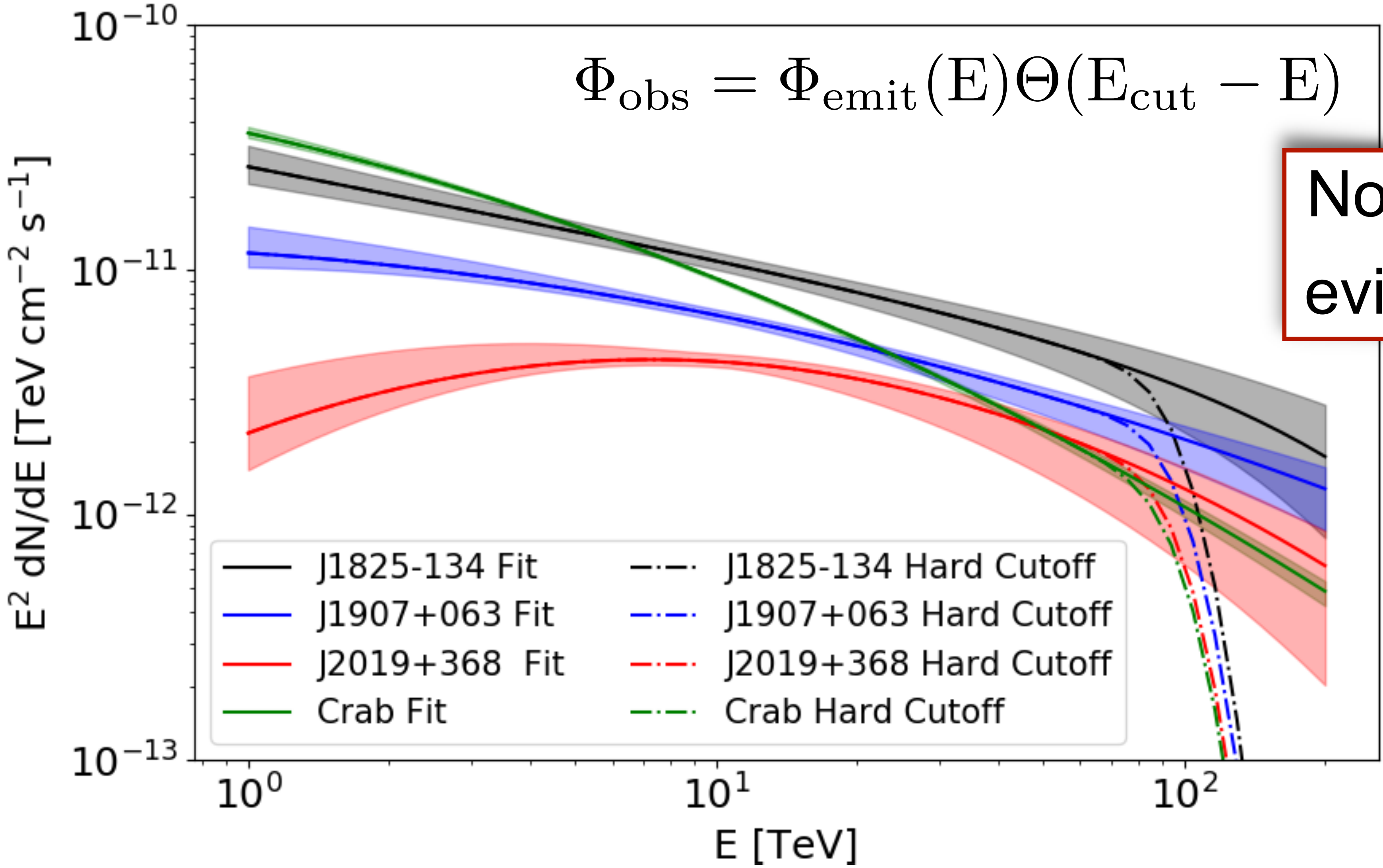
Table I. HAWC sources and Photon Energy Limits (TeV).

Small p value
data favors a cutoff

PoS ICRC19 723
PoS(ICRC2019)738
arXiv:1911.08070
(submitted)

humbertomh@ifsc.usp.br

LIV hard cutoff



No statistically significant evidence of **hard cutoffs**

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PoS ICRC19 723
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arXiv:1911.08070 (submitted)

LIV limits (PRELIMINARY)

Source	E_c TeV	L kpc	α_0 10^{-17}	α_1 $10^{-32}\mathrm{eV}^{-1}$	α_2 $10^{-48}\mathrm{eV}^{-2}$	$\alpha_{2(3\gamma)}$ $10^{-48}\mathrm{eV}^{-2}$	$E^{(1)}_{\mathrm{LIV}}$ $10^{31}\mathrm{eV}$	$E^{(2)}_{\mathrm{LIV}}$ $10^{23}\mathrm{eV}$
eHWC J1825-134	244	1.55	1.75	7.19	295	0.70	1.39	0.58
eHWC J1907+063	218	2.37	2.2	10.1	462	0.99	0.99	0.47
eHWC J0534+220 (Crab)	152	2	4.52	29.7	1960	4.01	0.34	0.23
eHWC J2019+368	120	1.8	7.25	60.4	5040	10.1	0.17	0.14
Combined	285	-	1.29	4.51	158	-	2.22	0.8
Crab (HEGRA) 2017 [12]	~ 56	-	-	667	127551	-	.015	.028
Tevatron 2016 [13]	0.442	-	6×10^5	-	-	-	-	-
Crab (HEGRA) 2013 [27]	56	-	40	-	-	-	-	-
RX J1713.7–3946 (HESS) 2008 [15]	30	-	180	-	-	-	-	-
Crab (Themistocle) 1997 [14]	20	-	300	-	-	-	-	-
GRB09510 (*Fermi*-LAT) 2013 $v > c$ [16]	-	-	-	746	123456790	-	0.0134	0.0009
GRB09510 (*Fermi*-LAT) 2013 $v < c$ [16]	-	-	-	1075	59171598	-	0.0093	0.0013
Crab (HEGRA) 2019 [17]	75	2	-	-	-	59	-	-

Derived **95%** CL lower limits on Ec and its different LIV coefficients

humbertomh@ifsc.usp.br

arXiv:1911.08070 (submitted)

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~ x30

~ x150

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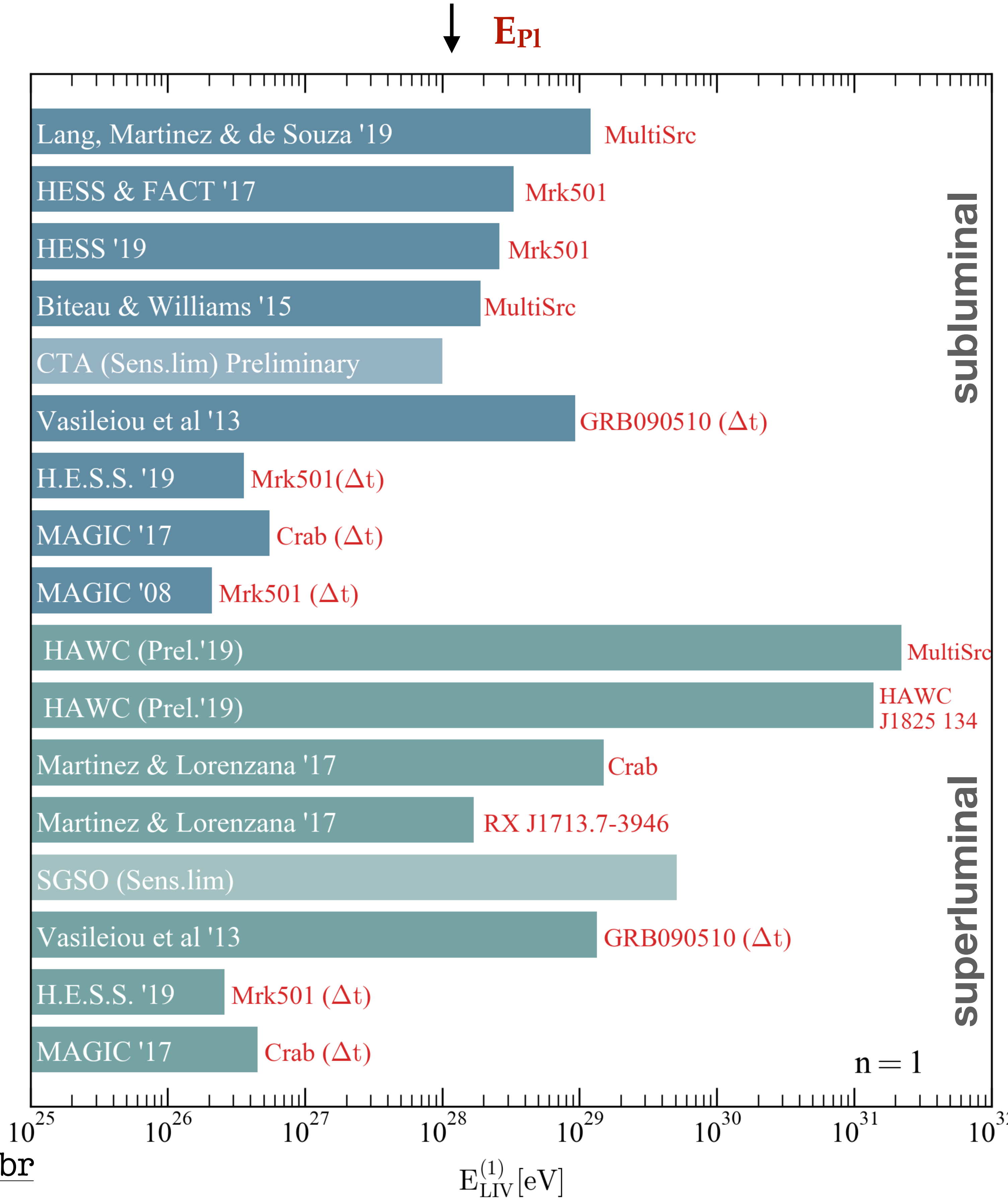
arXiv:1911.08070
(submitted)

LIV limits



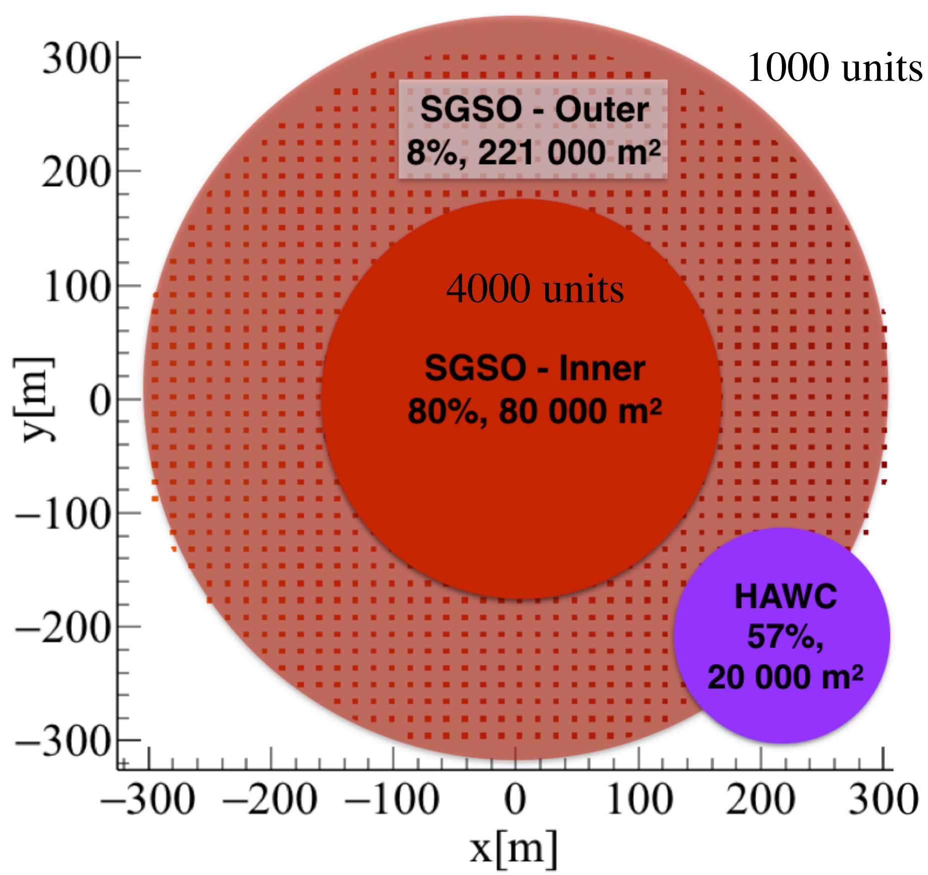
>1800 E_{Pl} !!

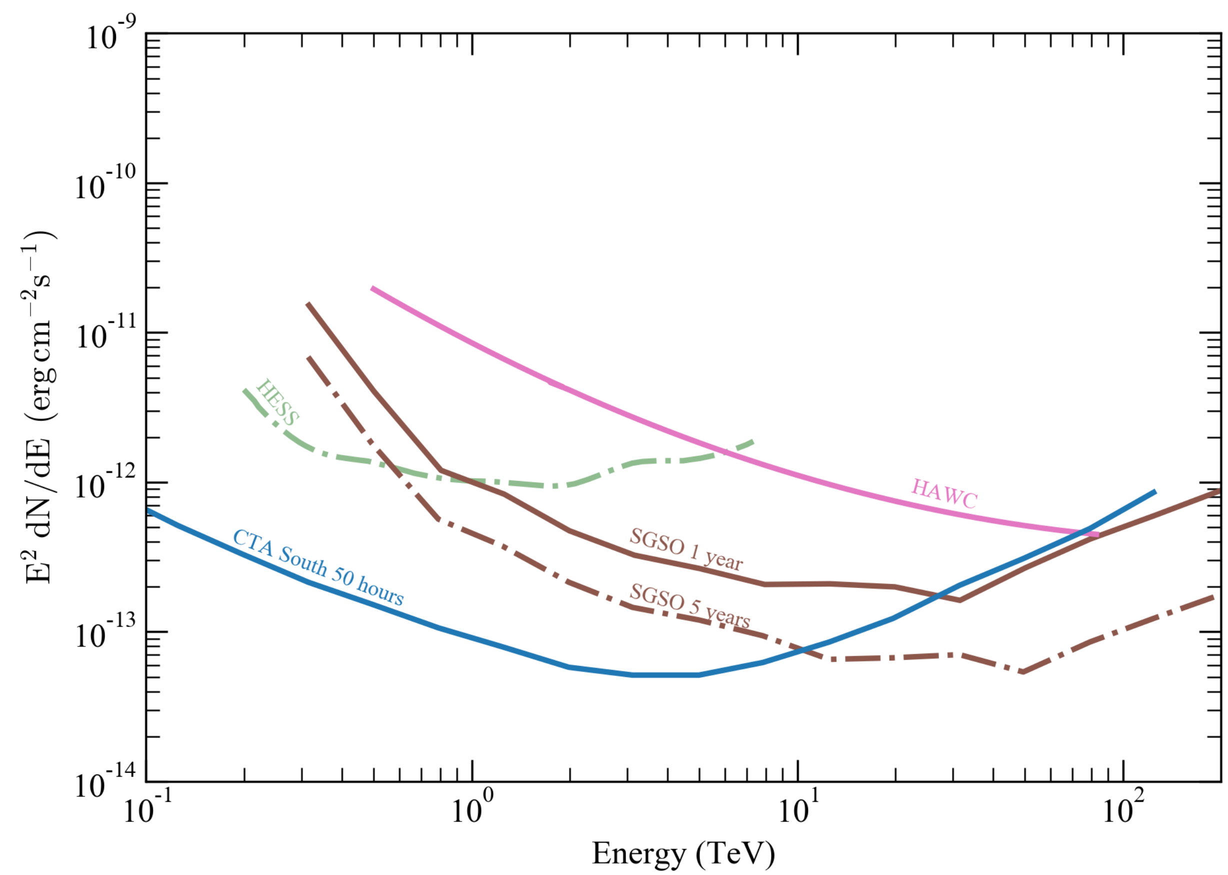
Outline

- Phenomenology
- Experiment
- **Future**

Searching LIV signatures with SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY





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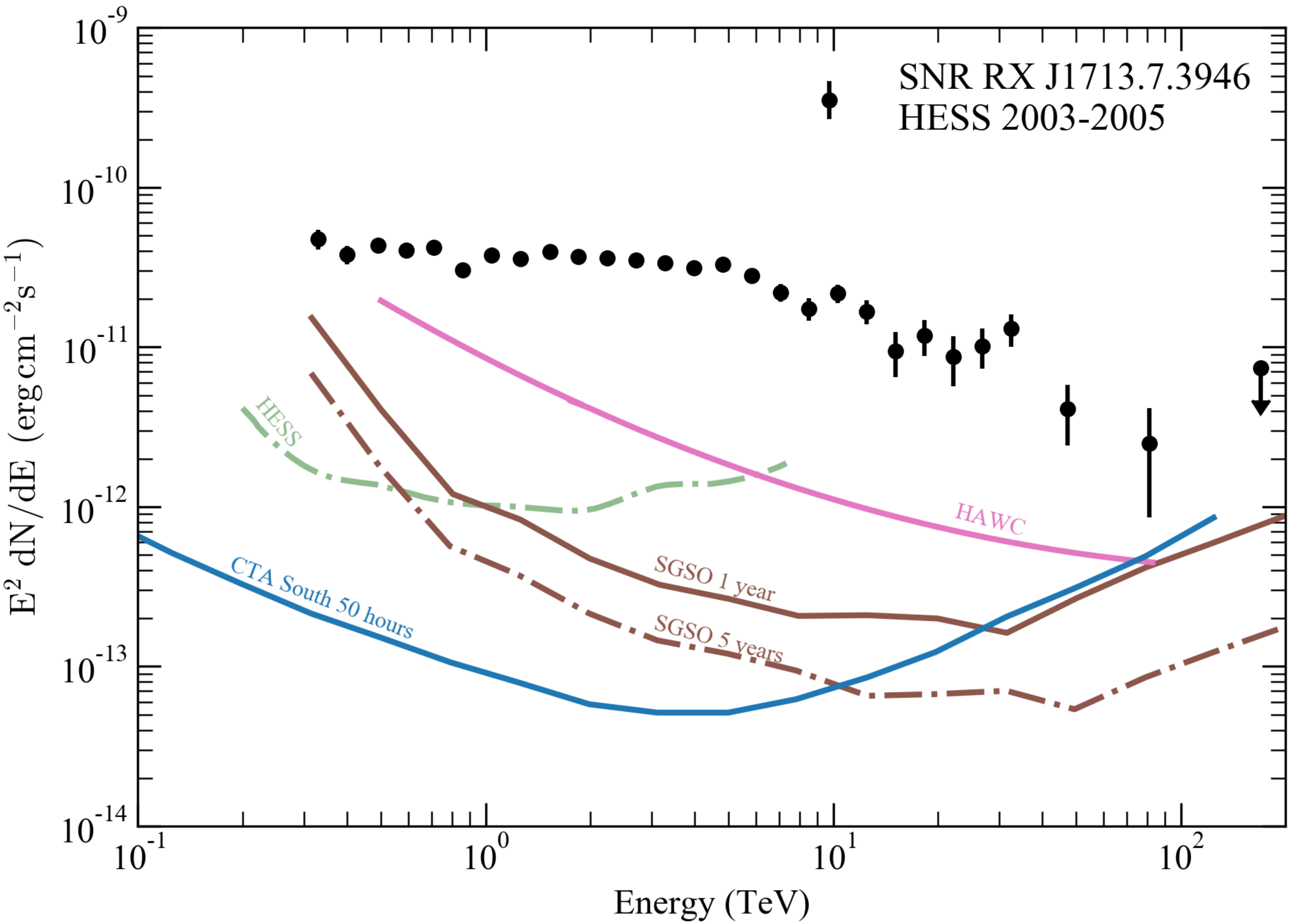
SGSO-White Paper
ArXiv: 1902.08429

Searching LIV signatures with SGSO



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SGSO-White Paper
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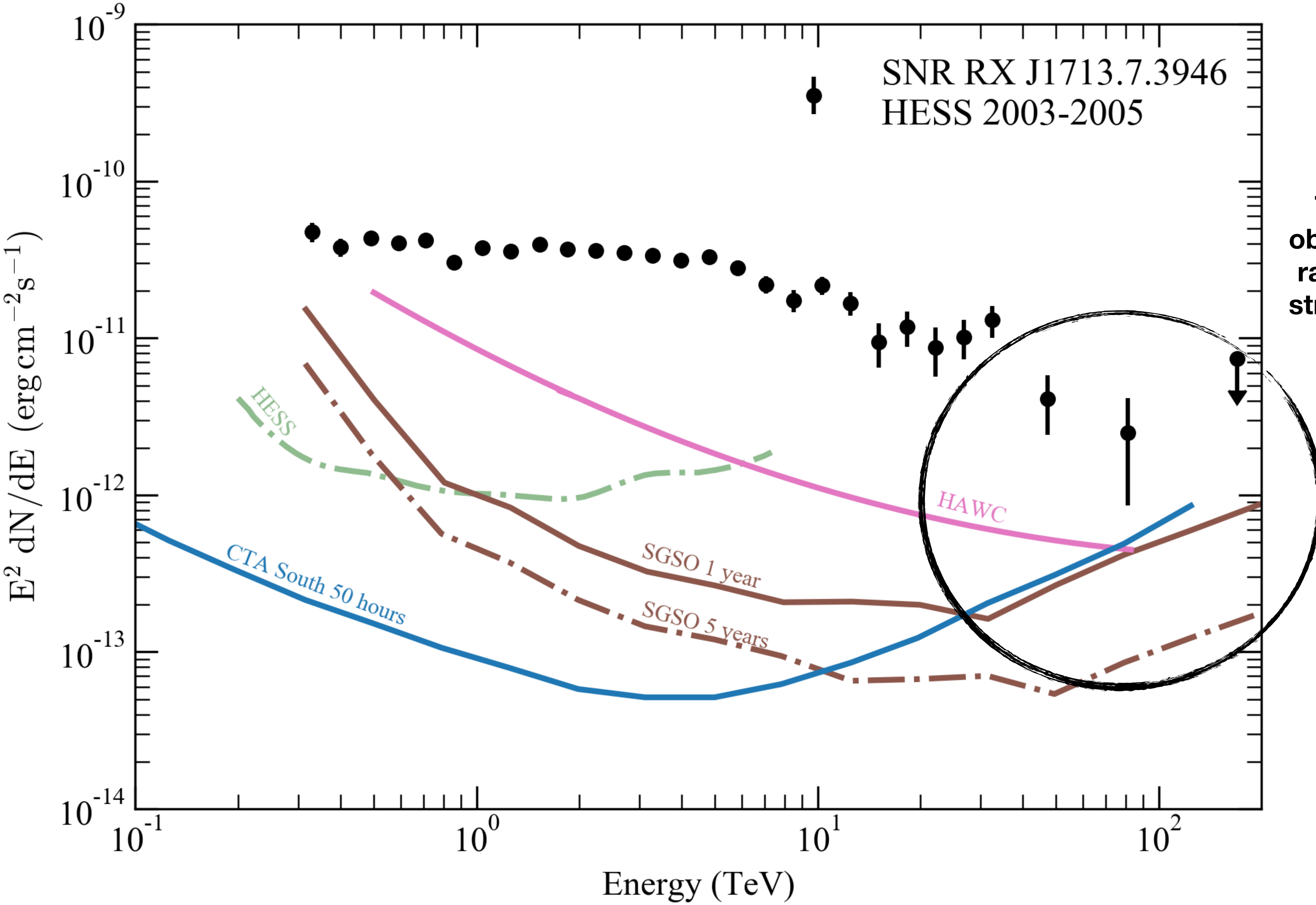
Searching LIV signatures with SGSO

SOUTHERN
GAMMA-RAY
SURVEY
OBSERVATORY



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

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SGSO-White Paper
ArXiv: 1902.08429

Searching LIV signatures with SGSO

SOUTHERN GAMMA-RAY SURVEY OBSERVATORY

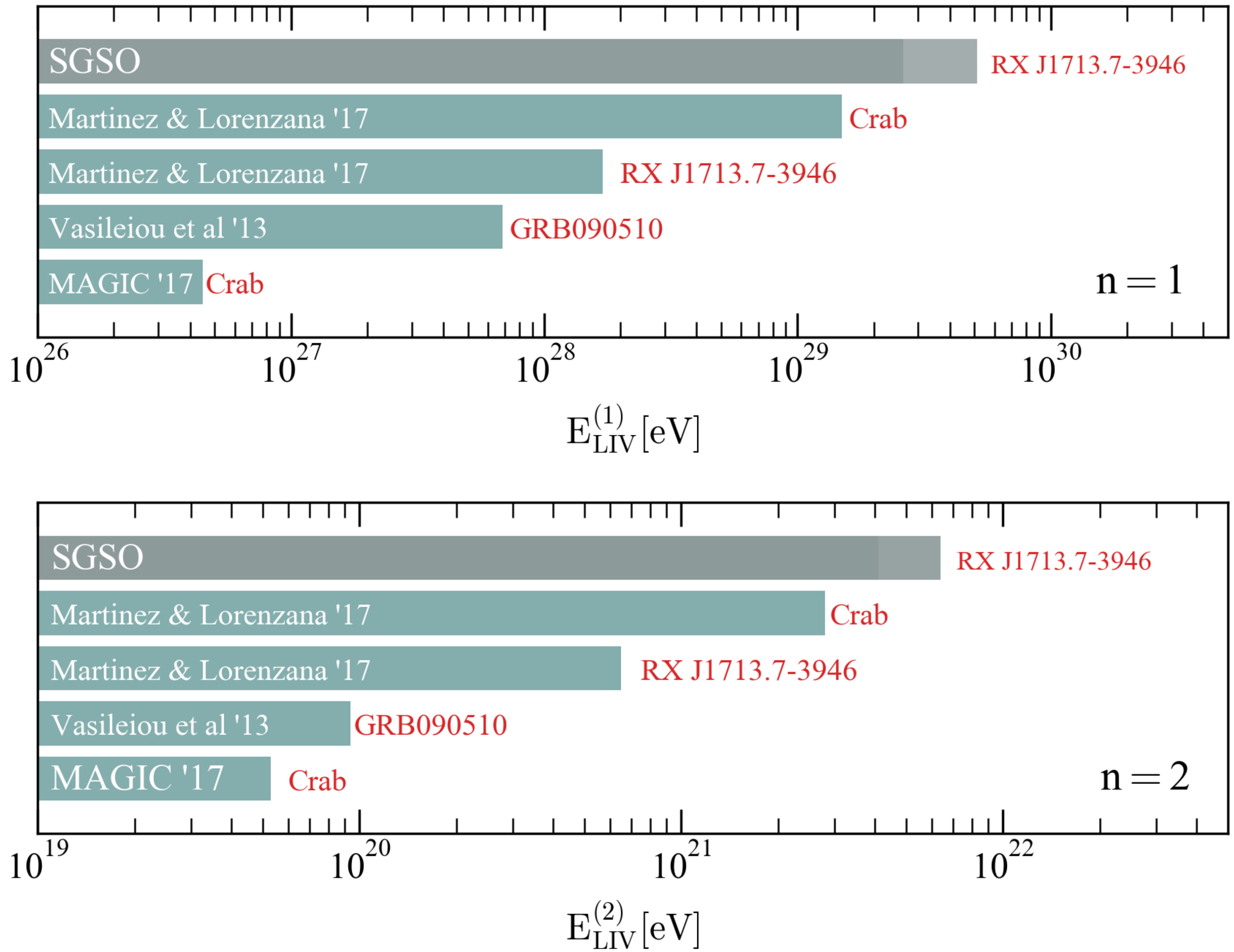

Fig. 1
LIV energy scale limits from superluminal searches including a potential reference of SGSO by measuring RXJ1713.7-3946 photons at **80 TeV** and **100 TeV** and the absence of photon decay into electron-positron pairs.

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SGSO-White Paper
ArXiv: 1902.08429

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- Phenomenology
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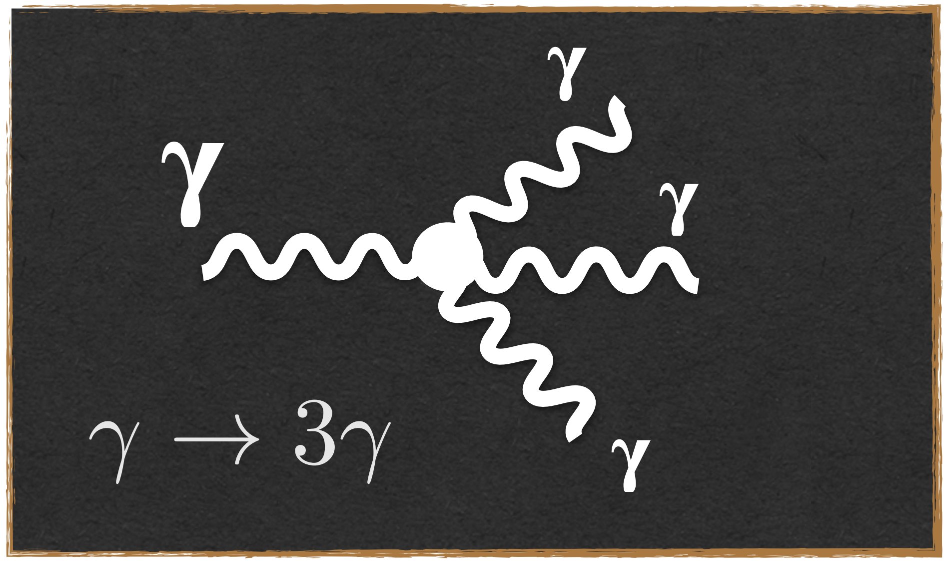
Photon splitting



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2M_{LV}^2}F_{ij}\Delta^2 F^{ij}$$

$$E_\gamma^2 = k_\gamma^2 + \frac{k_\gamma^4}{M_{LV}^2}$$

n=2

$$\Gamma_{\gamma\to3\gamma} = 5\times10^{-14}\frac{E_\gamma^{19}}{m_e{}^8 E_{LIV}^{(2)\ 10}},$$

it has no threshold!

It becomes significant when photons propagate through cosmological distances **-> cutoff**

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

K. Astapov, D. Kirpichnikov, and P. Satunin, JCAP 1904, 054 (2019)

Outline

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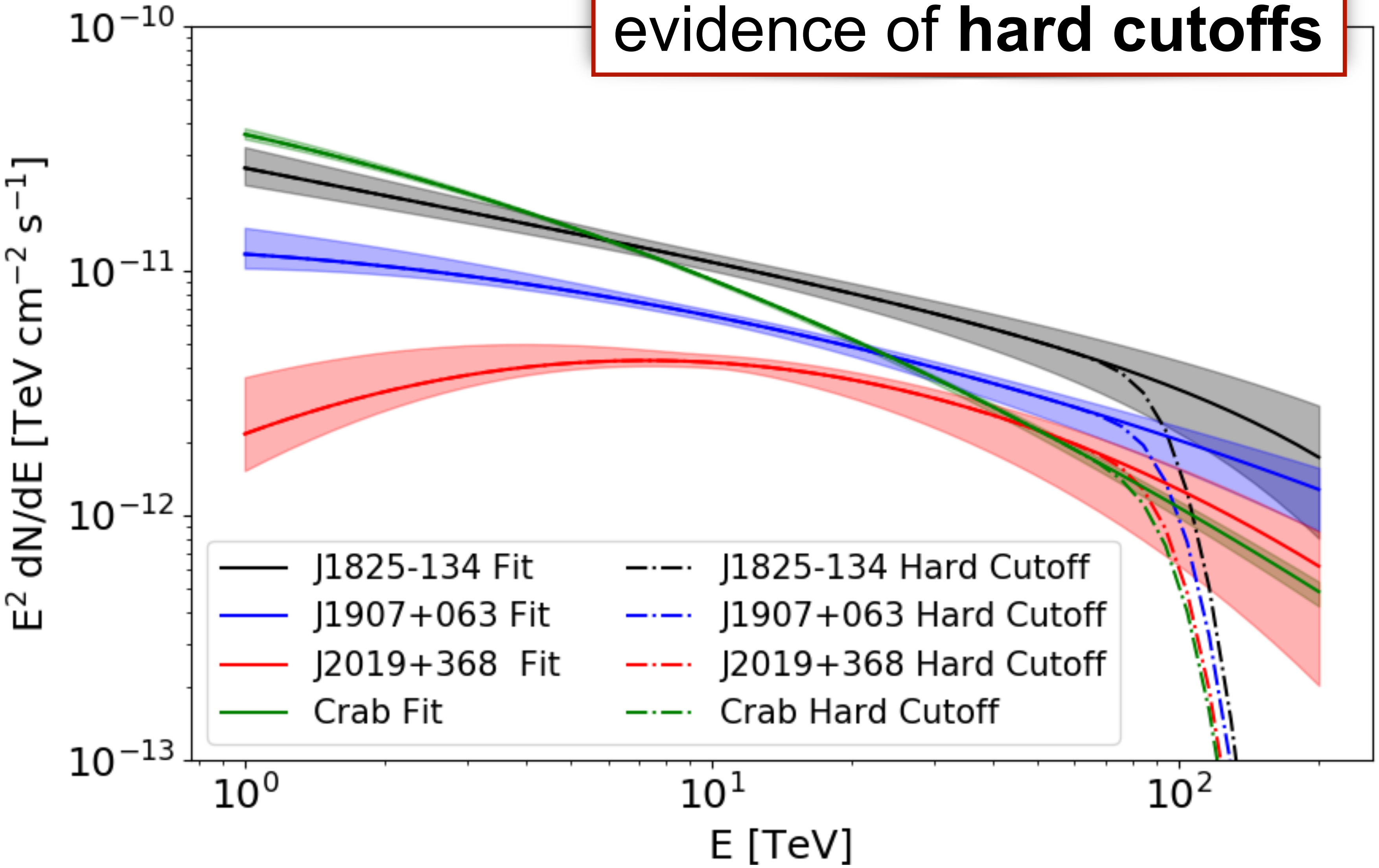
LIV hard cutoff

No statistically significant evidence of **hard cutoffs**



Source	E_c TeV	L kpc
J1825-134	244	1.55
J1907+063	218	2.37
J0534+220	152	2
J2019+368	120	1.8
Combined	285	-

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HAWC Collaboration
arXiv 1911.08070

LIV hard cutoff

$$L\,\Gamma = 1$$

$$E^{(2)}_{LIV} > 3.33 \times 10^{19}\mathrm{eV} \left(\frac{L}{\mathrm{kpc}}\right)^{0.1} \left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{1.9}$$

Source	$\mathrm{E_c}$ TeV	L kpc	$\mathrm{E^{(2)}_{LIV}}$ (3γ) 10^{23}eV
J1825-134	244	1.55	12
J1907+063	218	2.37	10.1
J0534+220	152	2	4.99
J2019+368	120	1.8	3.15
Combined	285	-	-

humbertomh@ifsc.usp.br

HAWC Collaboration
arXiv 1911.08070

LIV limits

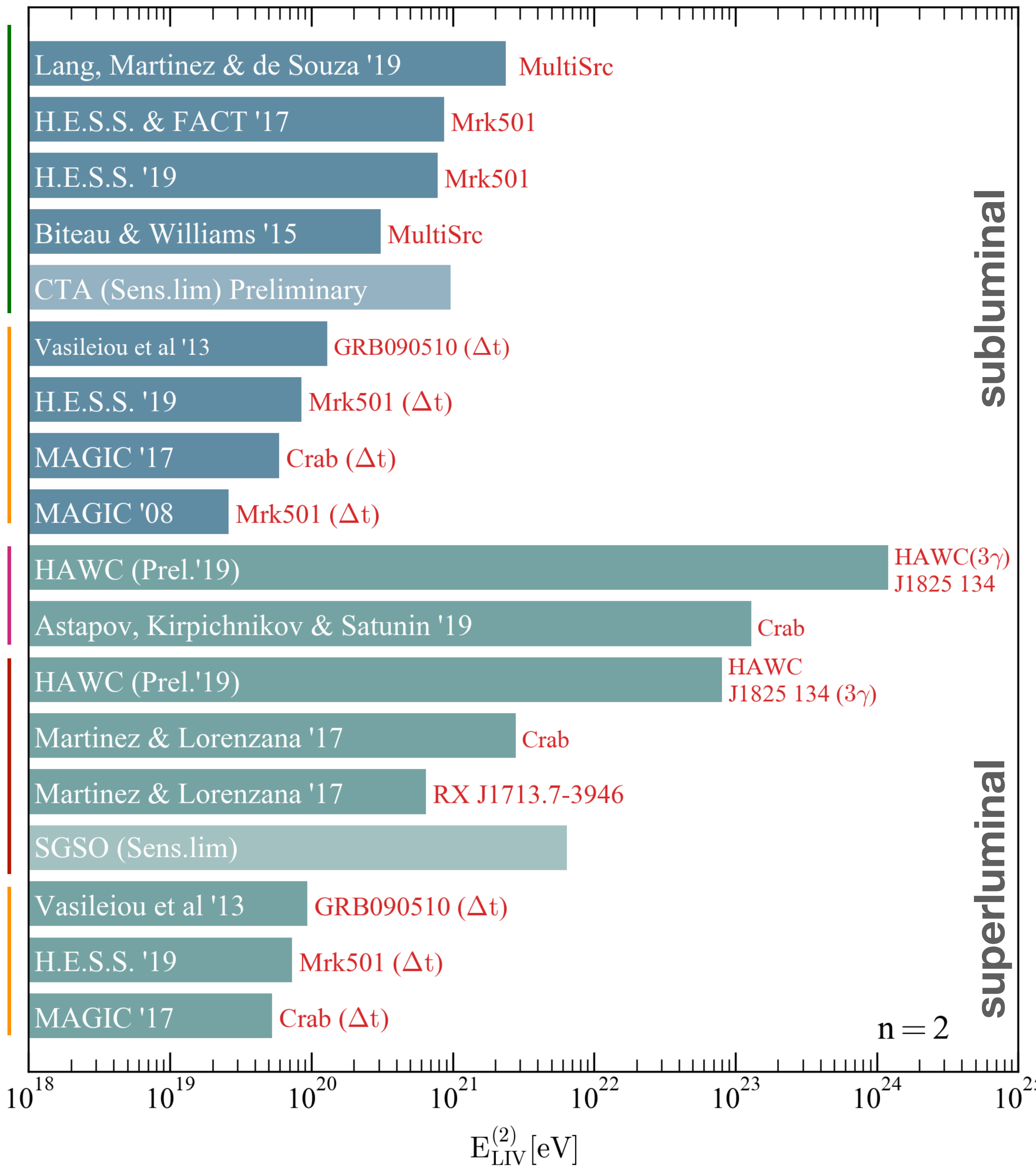
Pair production threshold shifts

Energy-dependent time delay

Photon splitting

Photon decay

Energy-dependent time delay



HAWC Collaboration
arXiv 1911.08070

humbertomh@ifsc.usp.br

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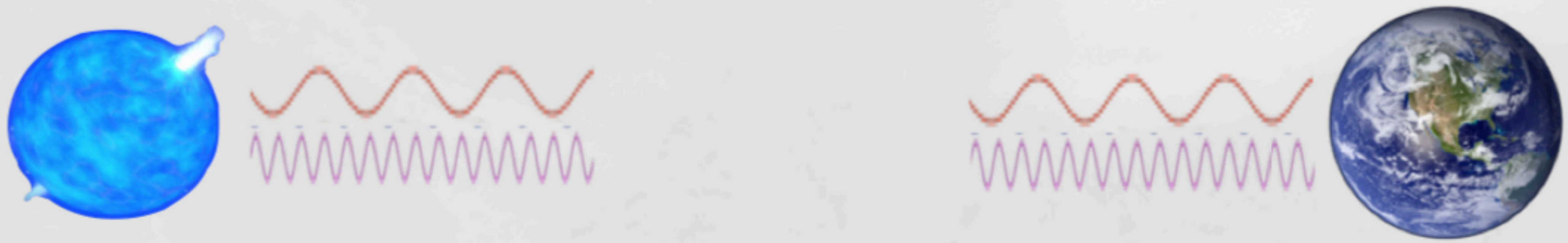
Energy-dependent time delay

Observation: Difference in arrival time

Constant speed of light

Photons **emitted simultaneously** will **arrive simultaneously**



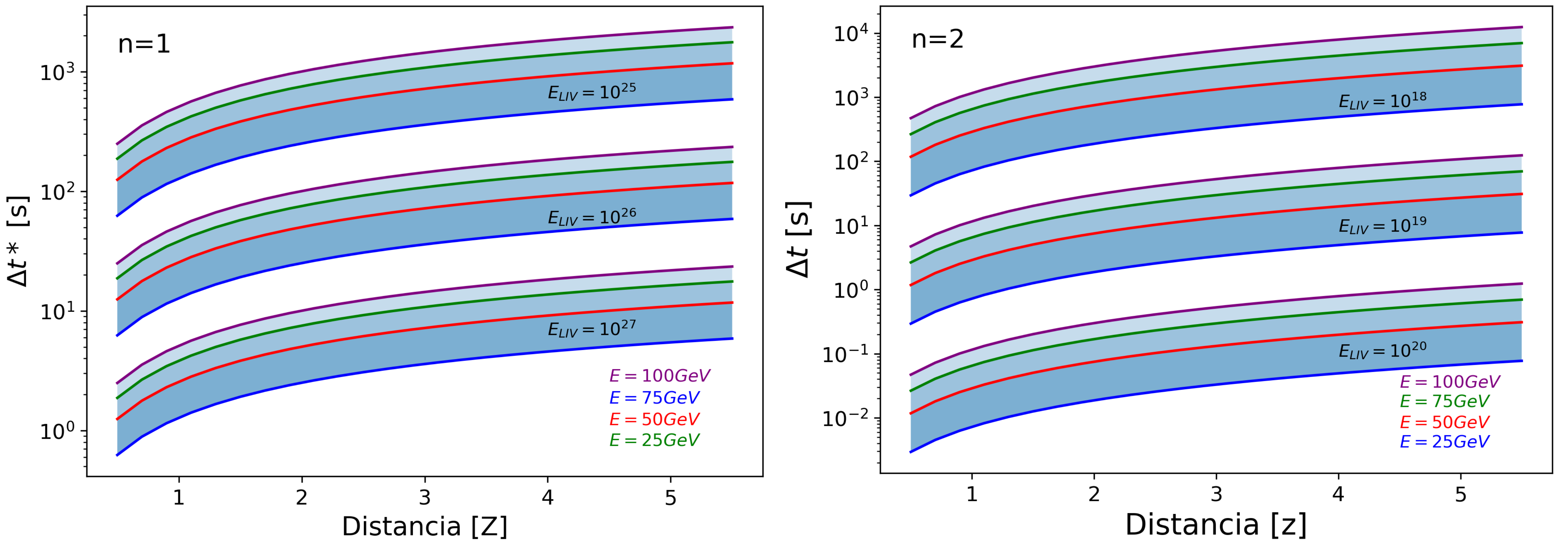
Energy dependent speed of light

The velocity of photons and therefore their travel time could depend on their energy: Photons **emitted simultaneously** will **arrive at different times**

Lukas Nellen et al.

Energy-dependent time delay

R. Rodrigues (2019)



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

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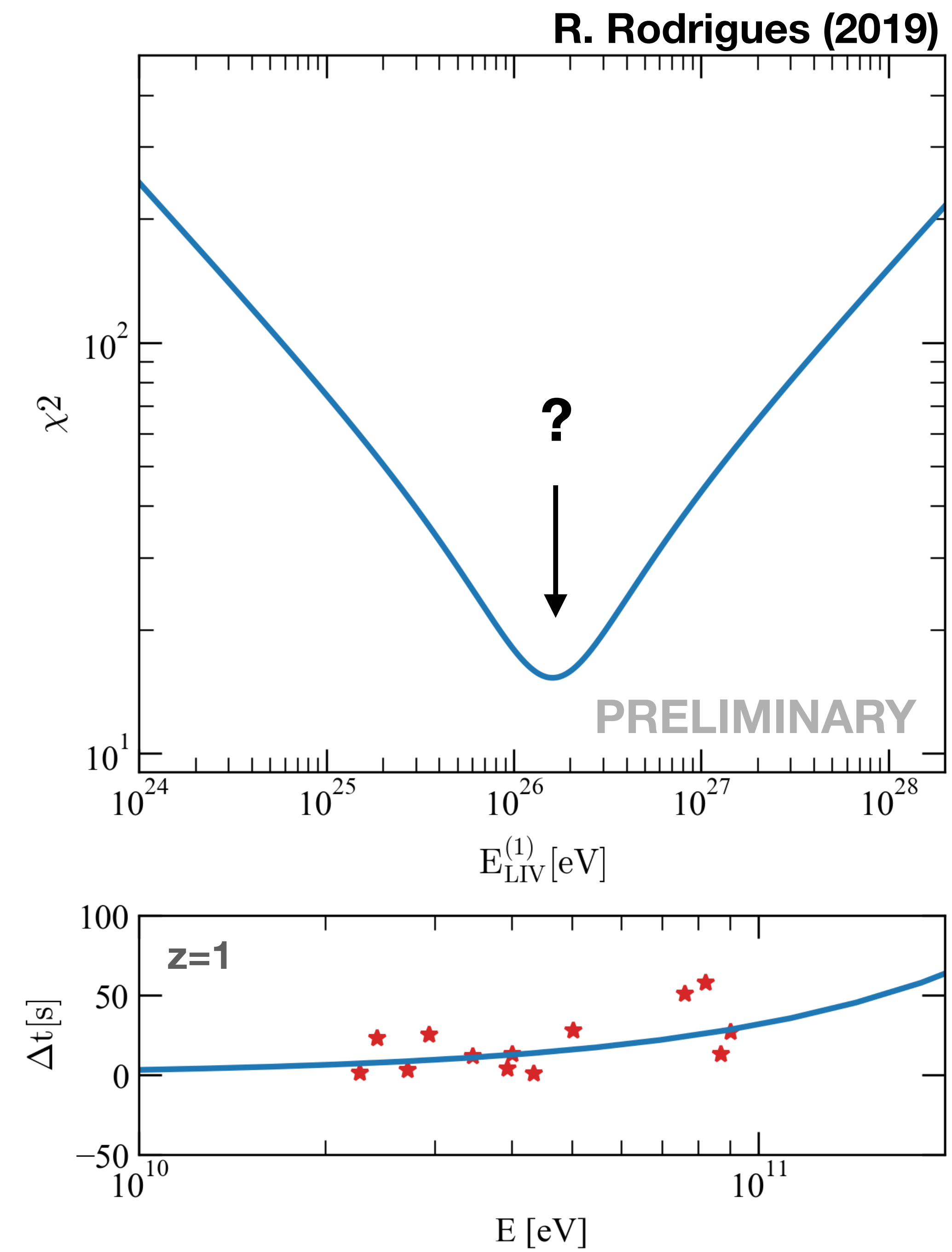
Energy-dependent time delay

	$E_{\rm em}$[GeV]	$E_{\rm obs}$[GeV]	E^*[GeV]	Δt [s]	z	GRB
1	40.1	14.2	25.4	4.40	1.82	090902B
2	43.5	15.4	27.6	35.84	1.82	090902B
3	51.1	18.1	32.4	16.40	1.82	090902B
4	56.9	29.9	26.9	0.86	0.90	090510
5	60.5	19.5	40.0	20.51	2.11	090926A
6	66.5	12.4	47.1	10.56	4.35	080916C
7	70.6	29.8	40.7	33.08	1.37	100414A
8	103.3	77.1	25.2	18.10	0.34	130427A
9	112.5	39.9	71.5	71.98	1.82	090902B
10	112.6	51.9	60.7	62.59	1.17	160509A
11	146.7	27.4	104.1	34.53	4.35	080916C
12*	33.6	11.9	21.3	1.90	1.82	090902B
13*	35.8	12.7	22.8	32.61	1.82	090902B

Nat. Astron. 1, 0139 (2017)
G. Amelino-Camelia et al.



Do they have a LIV behavior?

Stay tuned…

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I. **Introduction**

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   i. Threshold shifts

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   iii. Energy-dependent time delay

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Energy-dependent time delay

High Altitude Water Cherenkov
Gamma-Ray Observatory

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

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III. **Limits: astrophysical photons**

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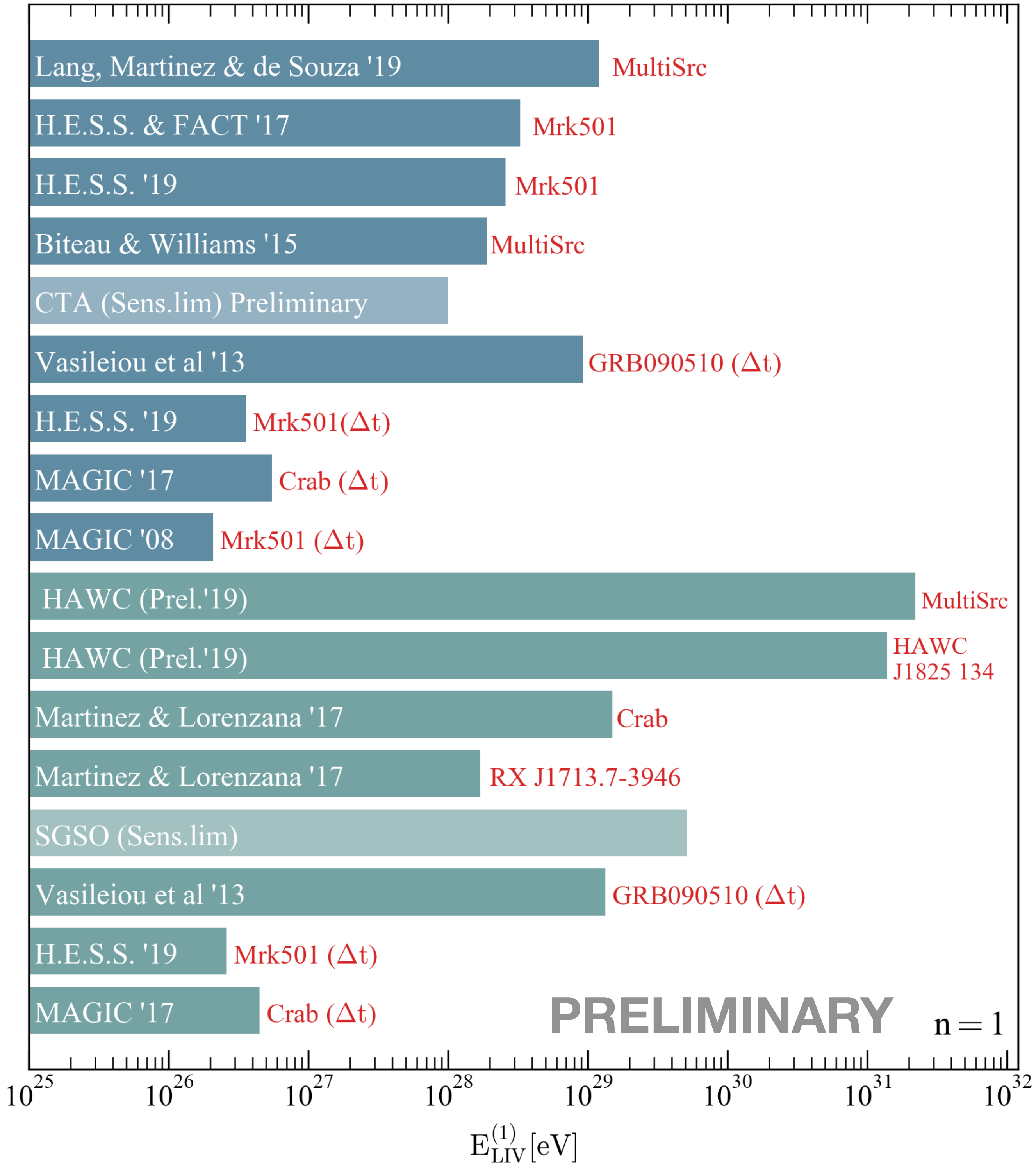
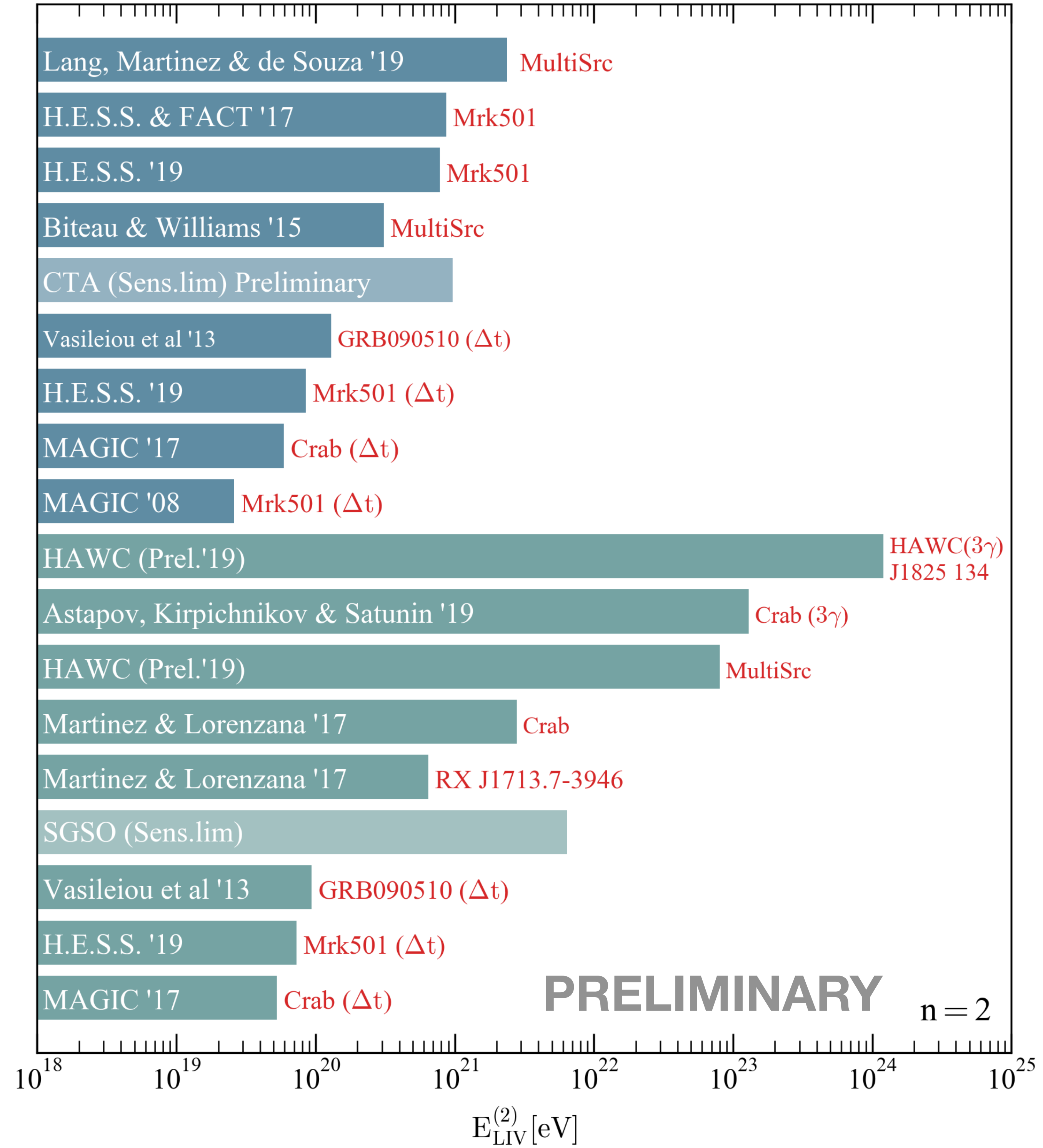
LIV limits: Meeting DRC 2019





Conclusions and remarks

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

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

- I have presented different types of astrophysical LIV signatures through the generic modification to particle dispersion relation in the photon sector, such as **pair production threshold shifts, energy-dependent time delay, photon splitting, and photon decay**.

  - ➡ There is an **active** and **dynamic** field in astroparticle physics looking for LIV signatures.

  - There are studies in progress to study the potential to test / constrain LIV signatures in astroparticle physics Experiments: **HAWC, Auger, Magic, Veritas, HESS, SGSO, CTA...**

Thanks!