

Constraints on Lorentz invariance violation using HAWC observations above 100 TeV

Humberto Martínez-Huerta,
(IFSC-USP, Brazil)
S. Marinelli,
J. T. Linnemann,
and J. Lundeen,
for the HAWC Collaboration

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THE ASTROPARTICLE PHYSICS CONFERENCE

Outline



I. Lorentz invariance violation (LIV)

II. Photon decay

III. HAWC

IV. HAWC LIV limits



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II. Photon decay

III. HAWC

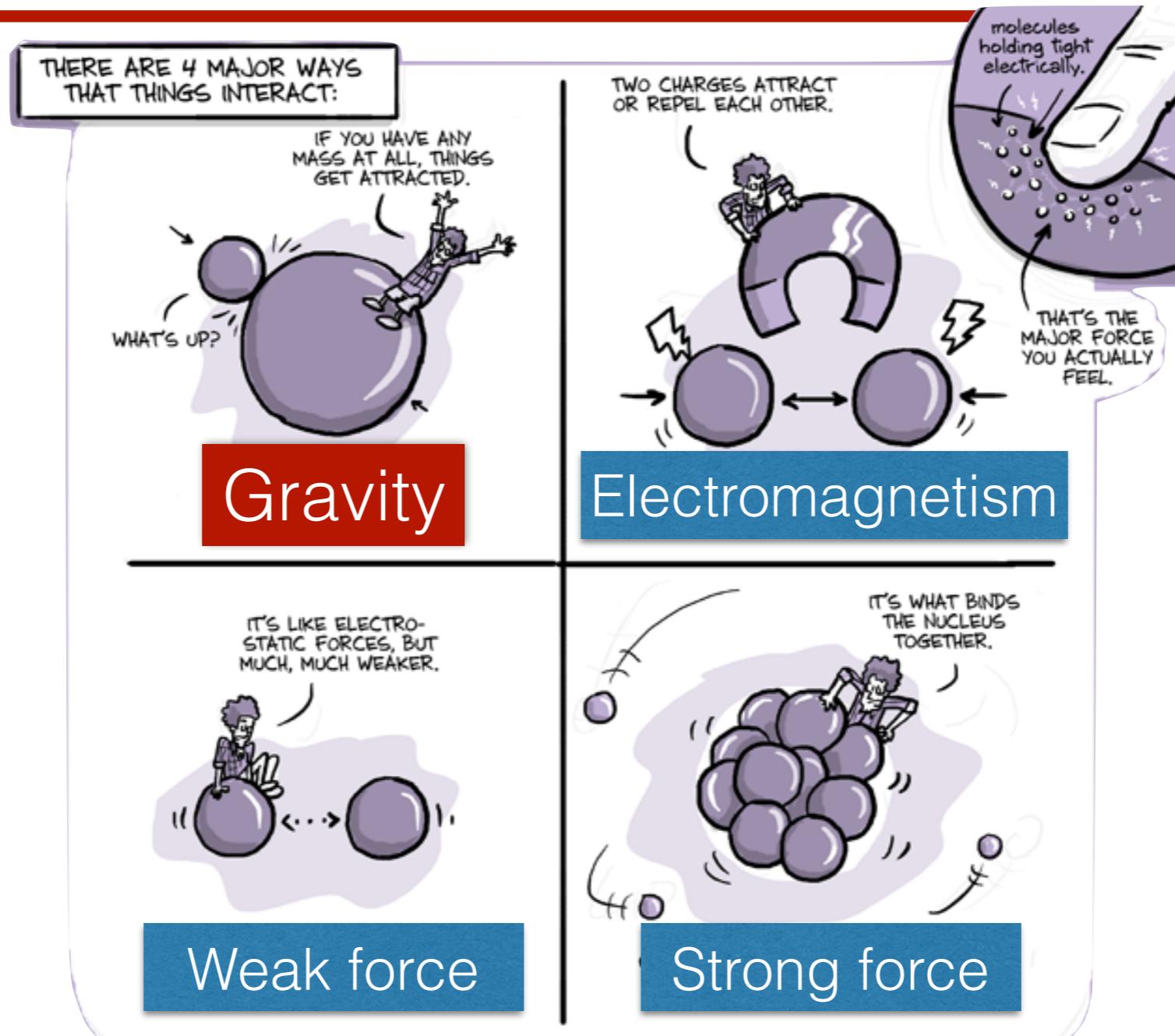
IV. HAWC LIV limits

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
- ...
- The law of relativity might not hold exactly at all energy scales



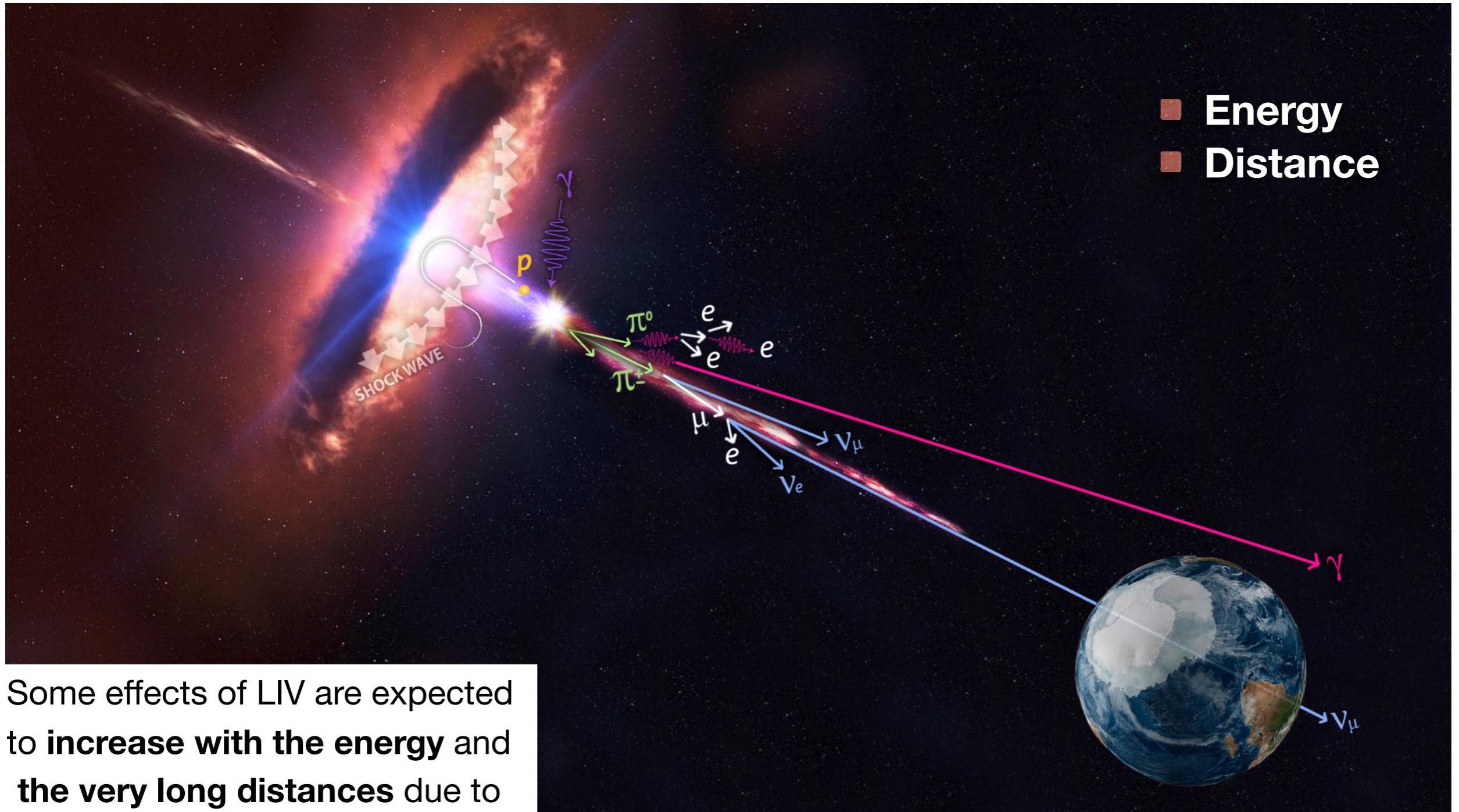
... LI may not be an **exact symmetry of Nature**

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

Astroparticle Physics: Lab to test Fundamental Physics



Modified dispersion relation

LI: $E_a^2 - p_a^2 = m_a^2$

LIV: $E^2 - p^2 \pm |f(A, \delta, M)| = m^2$

$$A = \{E, p\}$$

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

$$E \gg m,$$

$$E_a^2 - p_a^2 = m_a^2 \pm |\alpha_{a,n}| A_a^{n+2}; \quad |\alpha_n| = |\epsilon_0^{(n)}| / M^n = 1 / (E_{\text{LIV}}^{(n)})^n$$

$$n = 0, 1, 2, \dots$$

$$(d = 4, 5, 6, \dots)$$

$$\downarrow$$
$$E_{Pl}, E_{QG}$$

Family of MDRs that may lead to similar phenomenology in astroparticle physics!

Outline

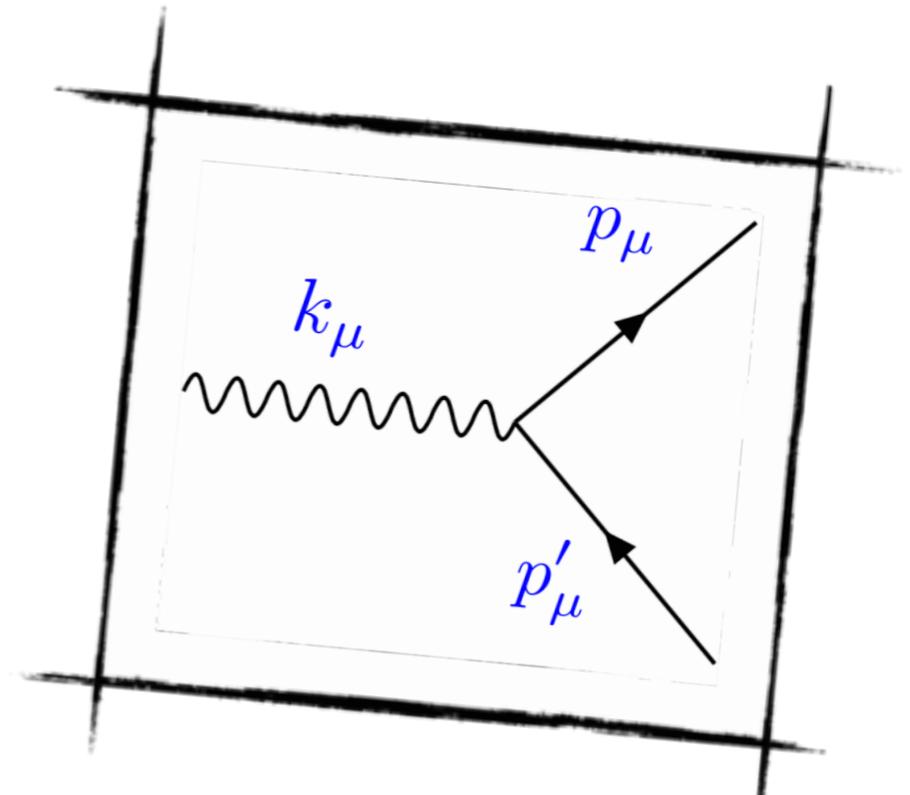


I. Lorentz invariance violation (LIV)

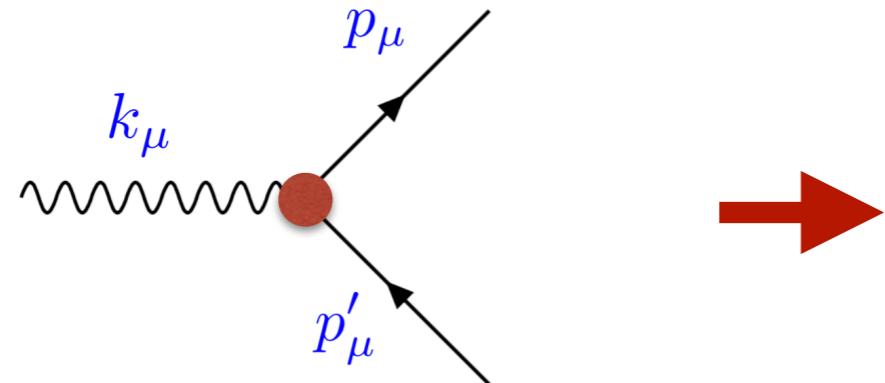
II. Photon decay

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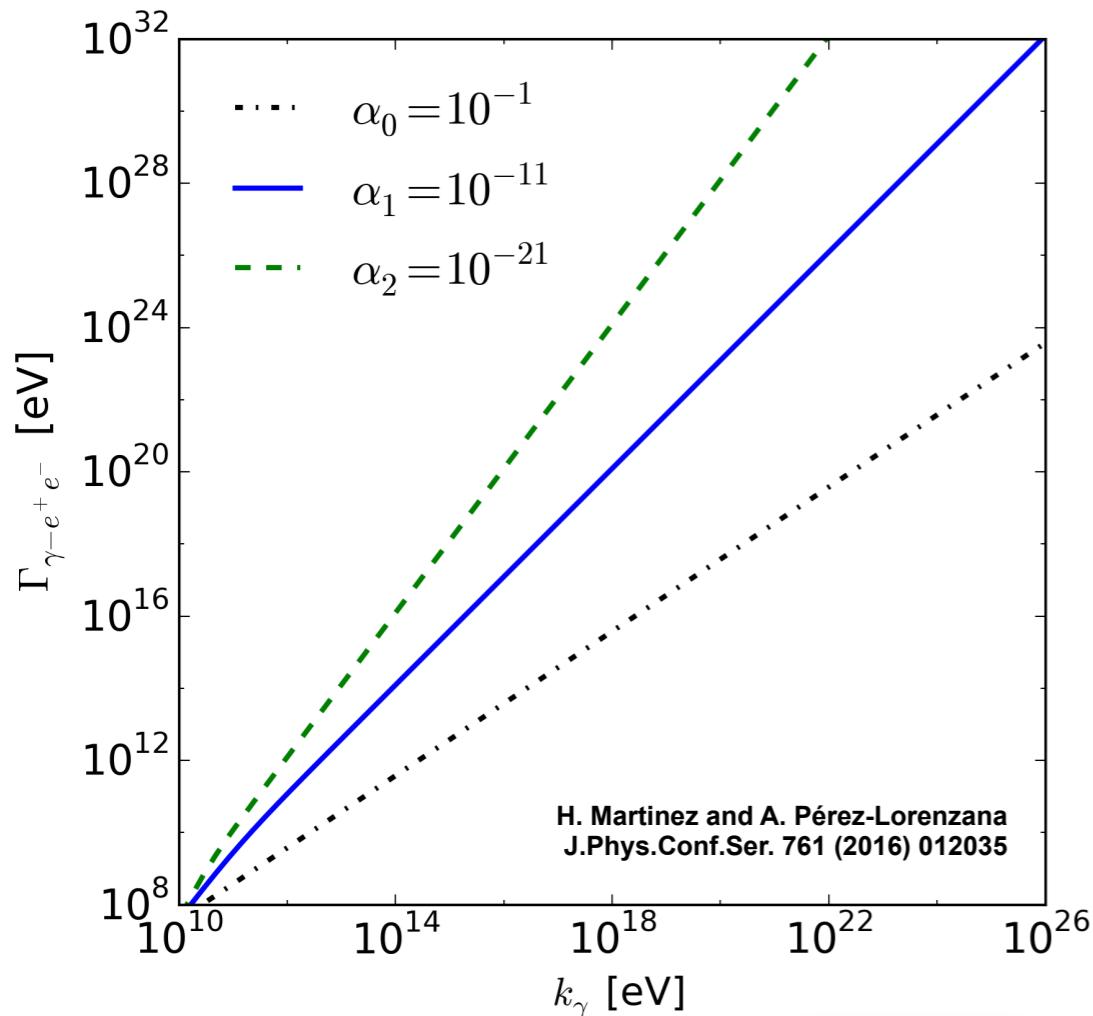
IV. HAWC LIV limits



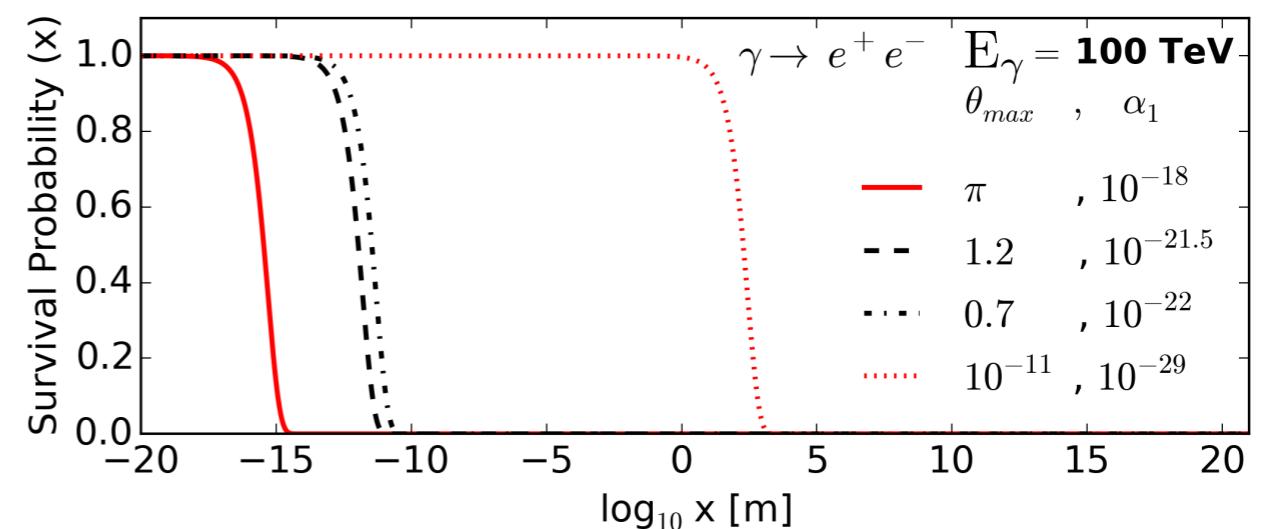
Photon decay



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



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

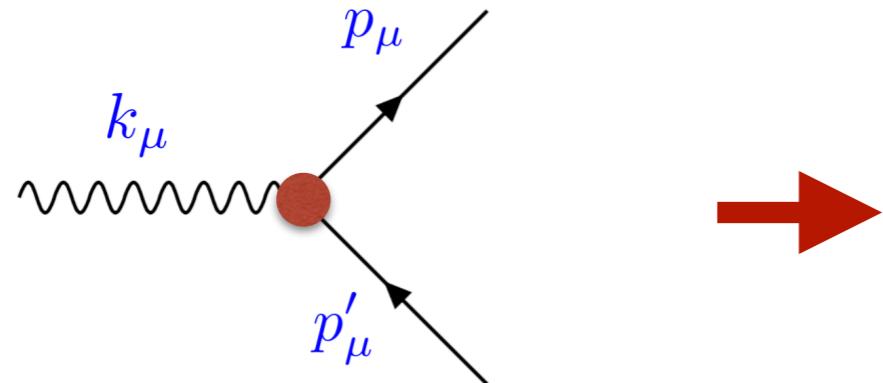


If you observe VHE gamma-rays,
the LIV process is restricted!!

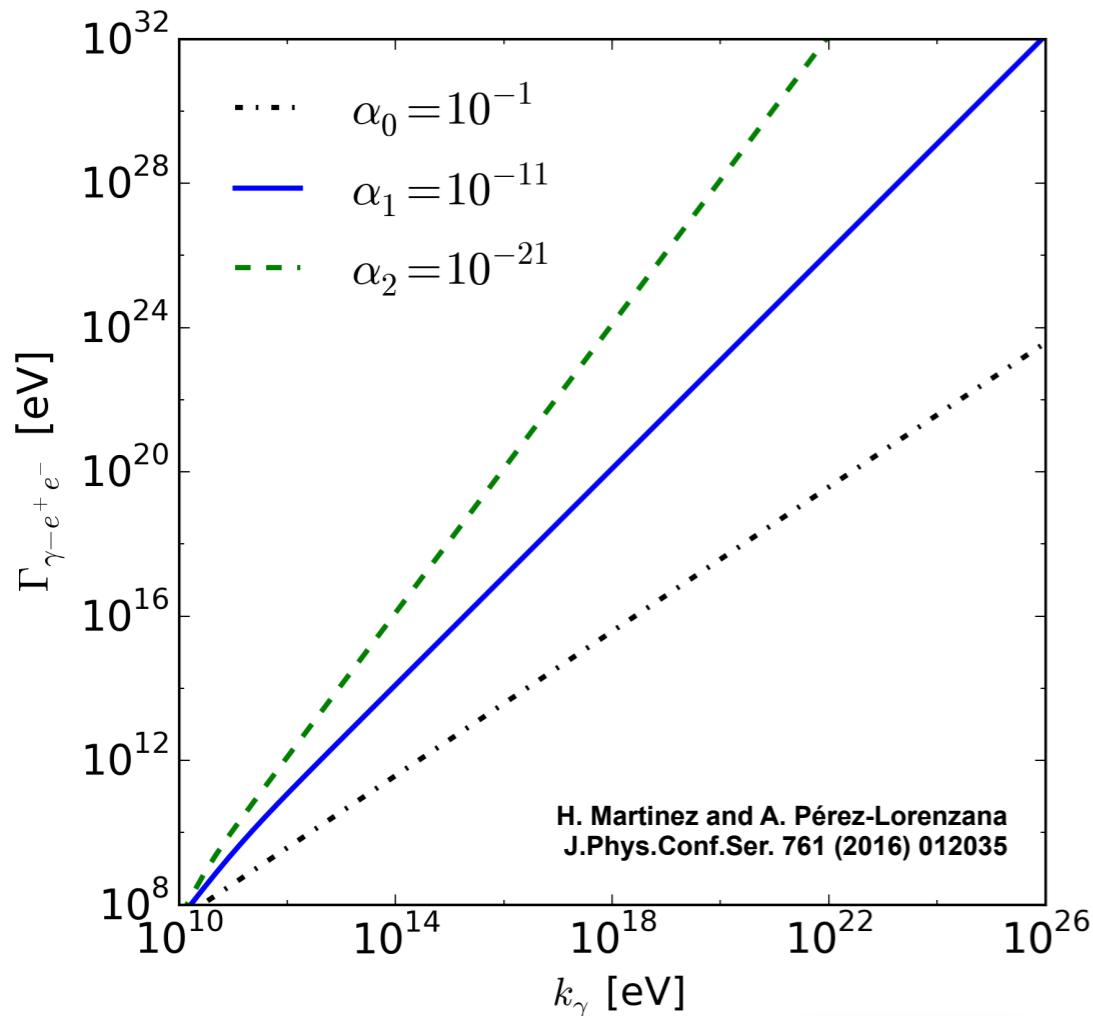
H. Martinez and A. Lorenzana
Phys.Rev. D95 (2017) 6, 063001

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

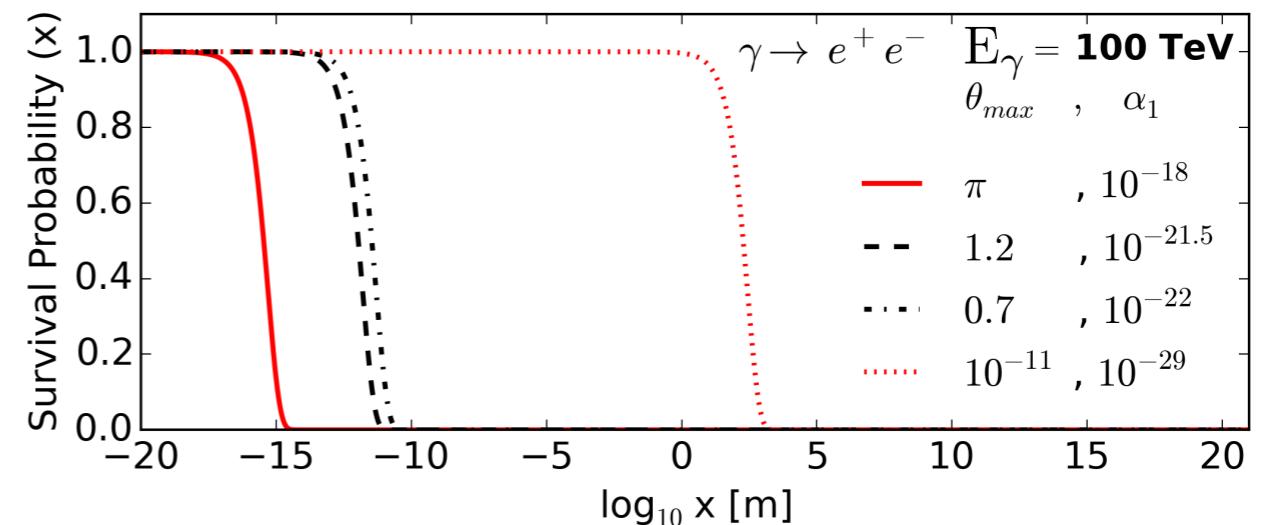
Photon decay



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



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



Search for the most energetic photons...

H. Martinez and A. Lorenzana
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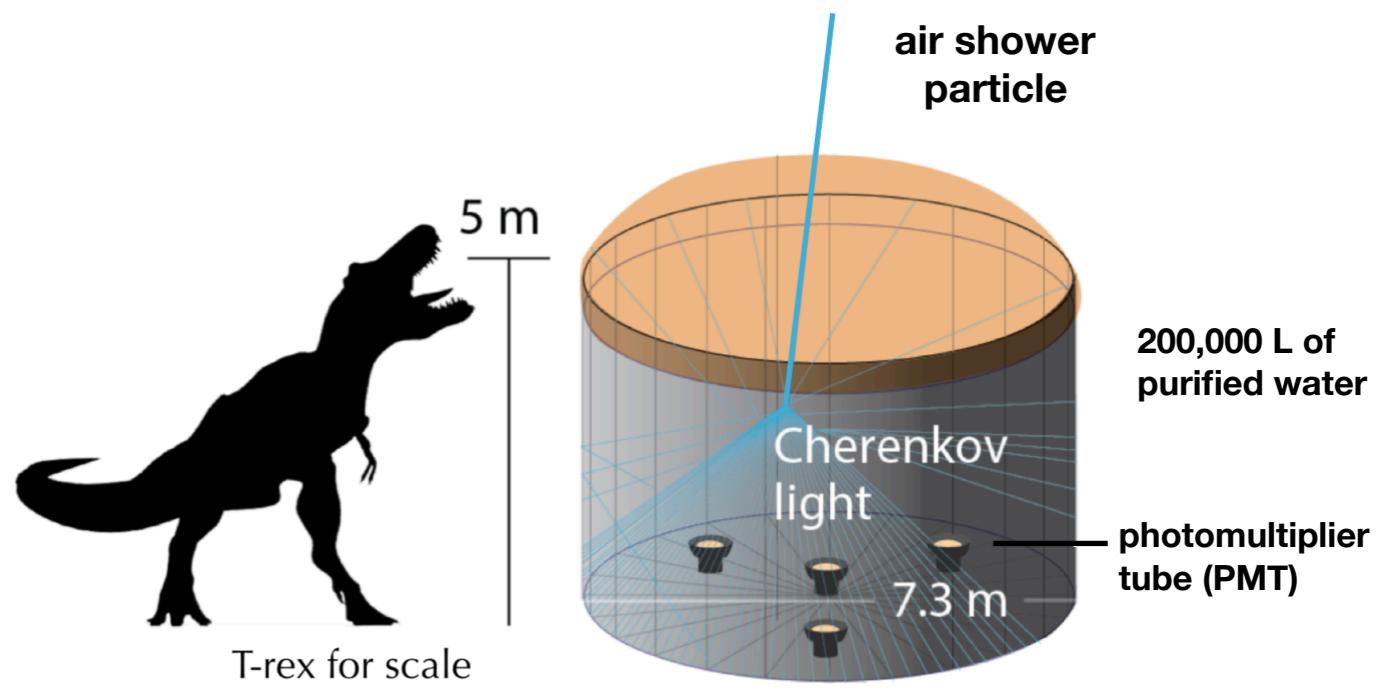
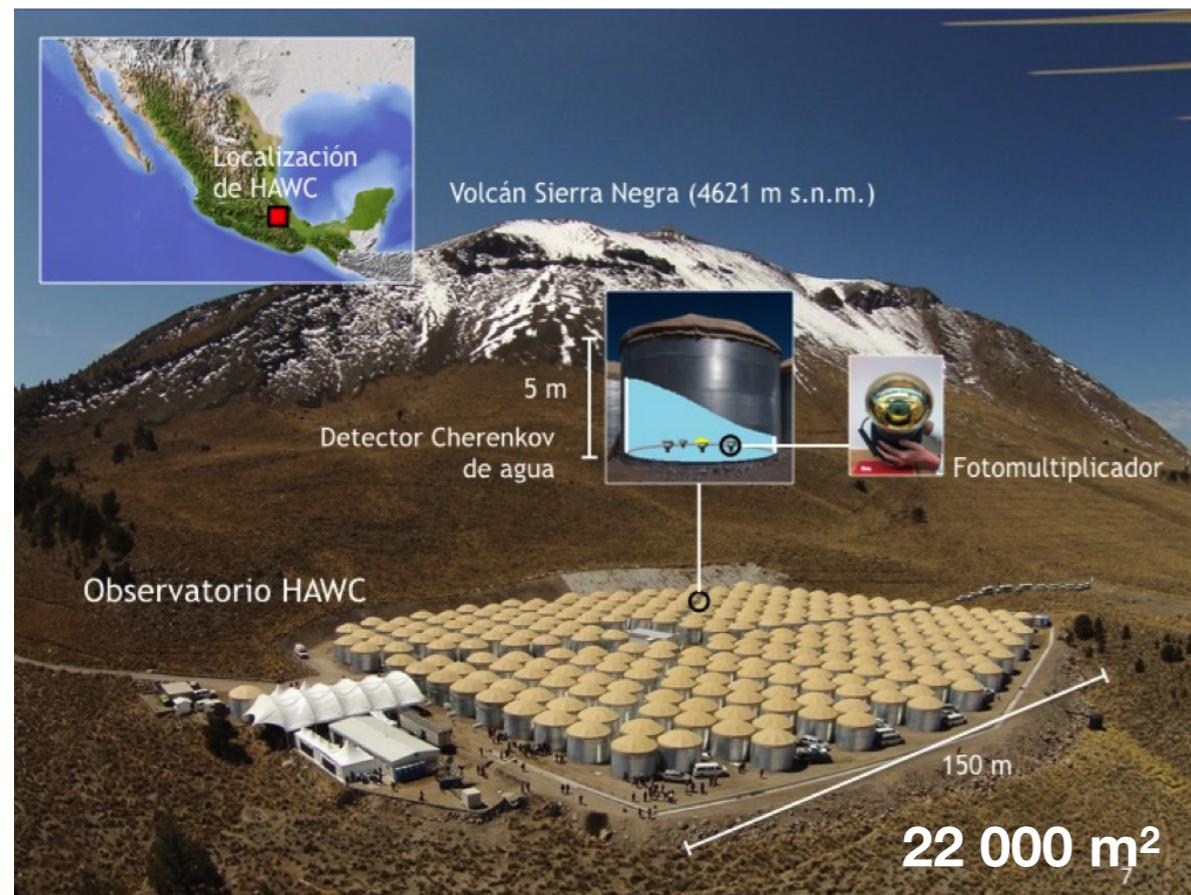
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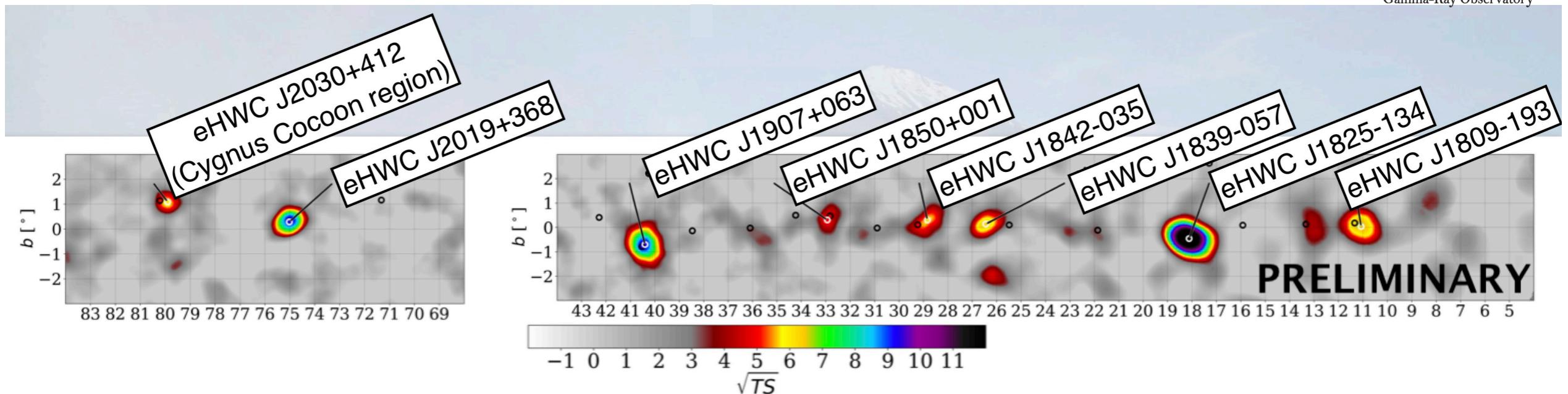
IV. HAWC LIV limits



The High Altitude Water Cherenkov



Highest energy sources



- Reported detailed measurements of γ -ray **>100 TeV**,
- Recent development of advanced energy-reconstruction algorithms, **artificial neural network**

Kelly Malone GAL2b

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> 56 TeV:

- | | | |
|---|---|--|
| <input checked="" type="checkbox"/> Crab , | <input checked="" type="checkbox"/> 2HWC J1825-134, | <input checked="" type="checkbox"/> 2HWC J2019+367 |
| <input checked="" type="checkbox"/> 2HWC J1839-057, | <input checked="" type="checkbox"/> 2HWC J2031+415 | |
| <input checked="" type="checkbox"/> 2HWC J1844-032, | <input type="checkbox"/> 2HWC J1809-190 | |
| <input checked="" type="checkbox"/> 2HWC J1908+063, | <input type="checkbox"/> 2HWC J1849+001 | |

LIV hard cutoff

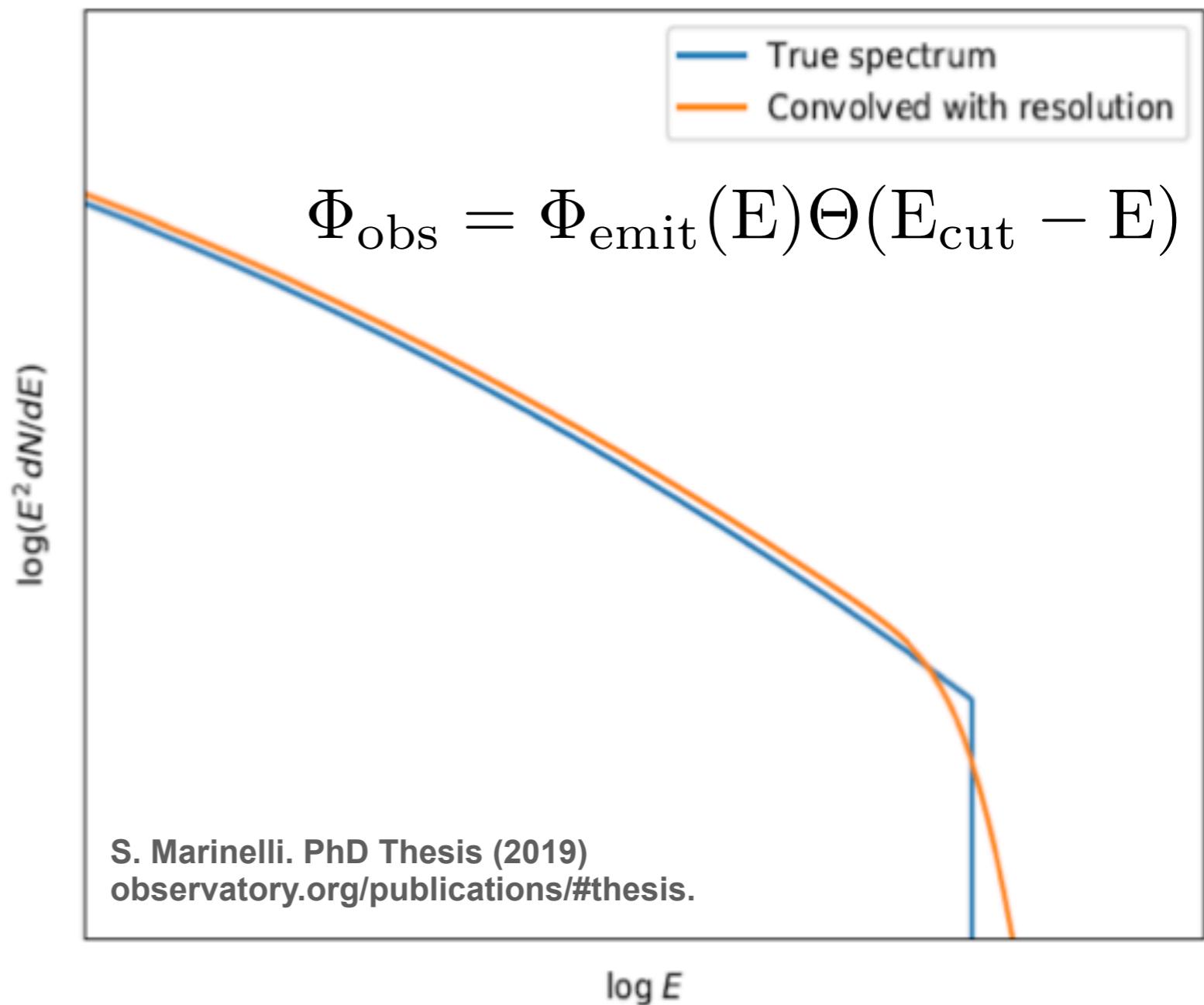


LIV hard cutoff at some energy E_c in the True spectrum

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{E}_c

$$D = 2 \ln \left(\frac{\mathcal{L}(\hat{E}_c)}{\mathcal{L}(\hat{E}_c \rightarrow \infty)} \right)$$



LIV hard cutoff



Source	p
2HWC J1825-134	1.000
2HWC J1908+063	0.990
Crab	1.000
2HWC J2031+415	0.714
2HWC J2019+367	0.828
J1839-057	0.357
2HWC J1844-032	0.294

Small p value
data favors a cutoff

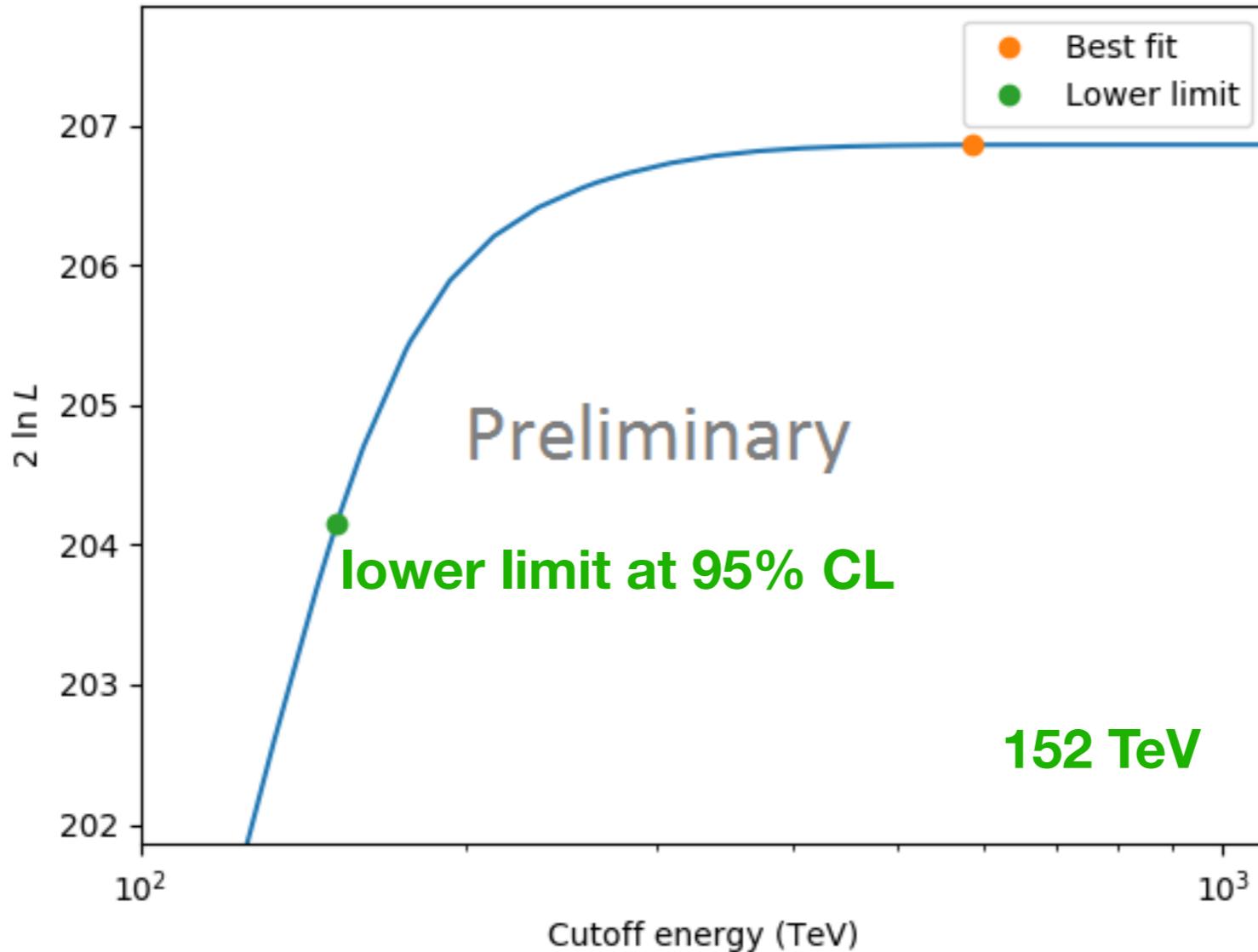
No statistically significant
evidence of **hard cutoffs**

J. Linnemann
GAI9

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LIV hard cutoff



Likelihood curve as a function of the LIV Energy cutoff in the
Crab analysis

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LIV limits (PRELIMINARY)



Source	E_c TeV	$ \alpha_0 $ 10^{-17}	$ \alpha_1 $ 10^{-31}eV^{-1}	$ \alpha_2 $ 10^{-45}eV^{-2}	$E_{\text{LIV}}^{(1)}$ 10^{30}eV	$E_{\text{LIV}}^{(2)}$ 10^{22}eV
2HWC J1825-134	253	1.63	0.64	0.26	15.5	6.26
2HWC J1908+063	213	2.30	1.08	0.51	9.25	4.44
Crab (HAWC)	152	4.52	2.97	1.96	3.4	2.26
2HWC J2031+415	144	5.04	3.5	2.43	2.9	2.02
2HWC J2019+367	121	7.13	5.6	4.87	1.7	1.43
J1839-057	79	16.74	21.1	26.8	0.47	0.61
2HWC J1844-032	77	17.62	22.9	29.7	0.44	0.58

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

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Crab (HEGRA) 2017	~ 56	-	66.7	128	0.15	0.28
Tevatron 2016	0.442	6×10^5	-	-	-	-
RX J1713.7-3946 (HESS) 2008	30	180	-	-	-	-
Coleman & Glashow (1997)	20	100	-	-	-	-
GRB09510 (<i>Fermi</i>) 2013 $v > c$	-	-	-	-	0.134	0.009
GRB09510 (<i>Fermi</i>) 2013 $v < c$	-	-	-	-	0.093	0.013
Crab (HEGRA) 2019	75	-	-	0.059	-	13



For Refs. see
PoS(ICRC2019)738

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~ x60

~ x100



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LIV limits (PRELIMINARY)

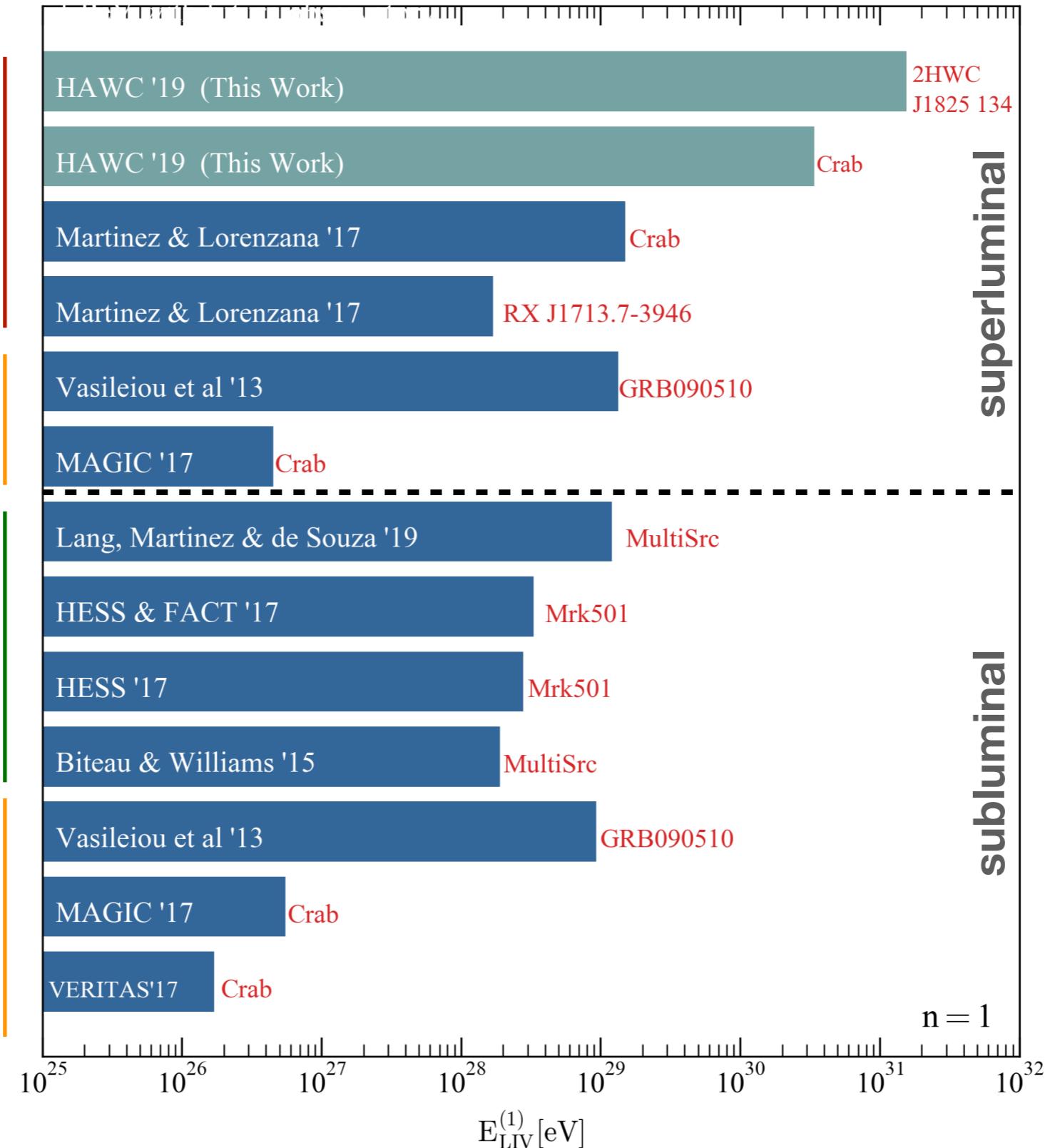


Photon decay

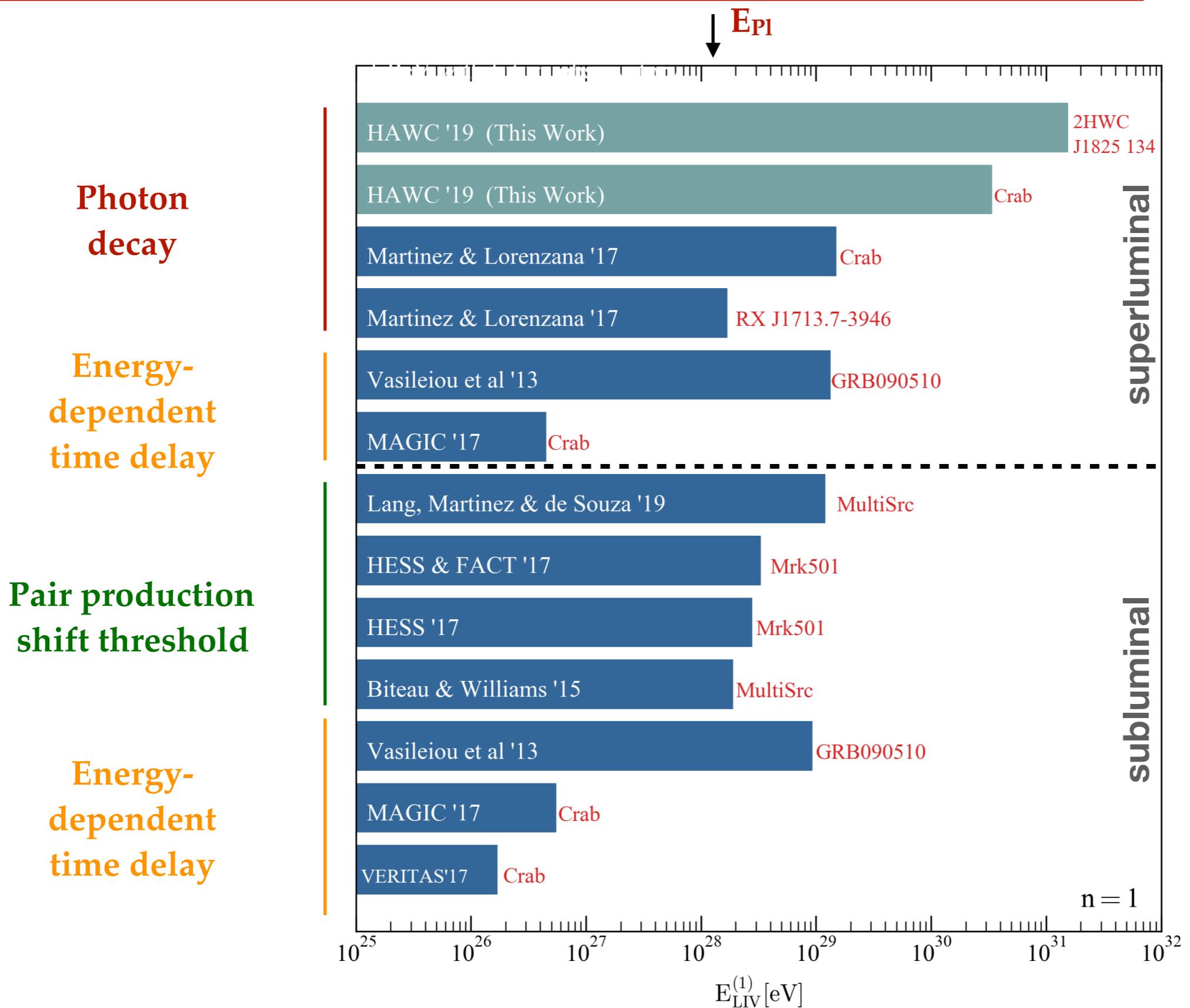
Energy-dependent time delay

Pair production shift threshold

Energy-dependent time delay



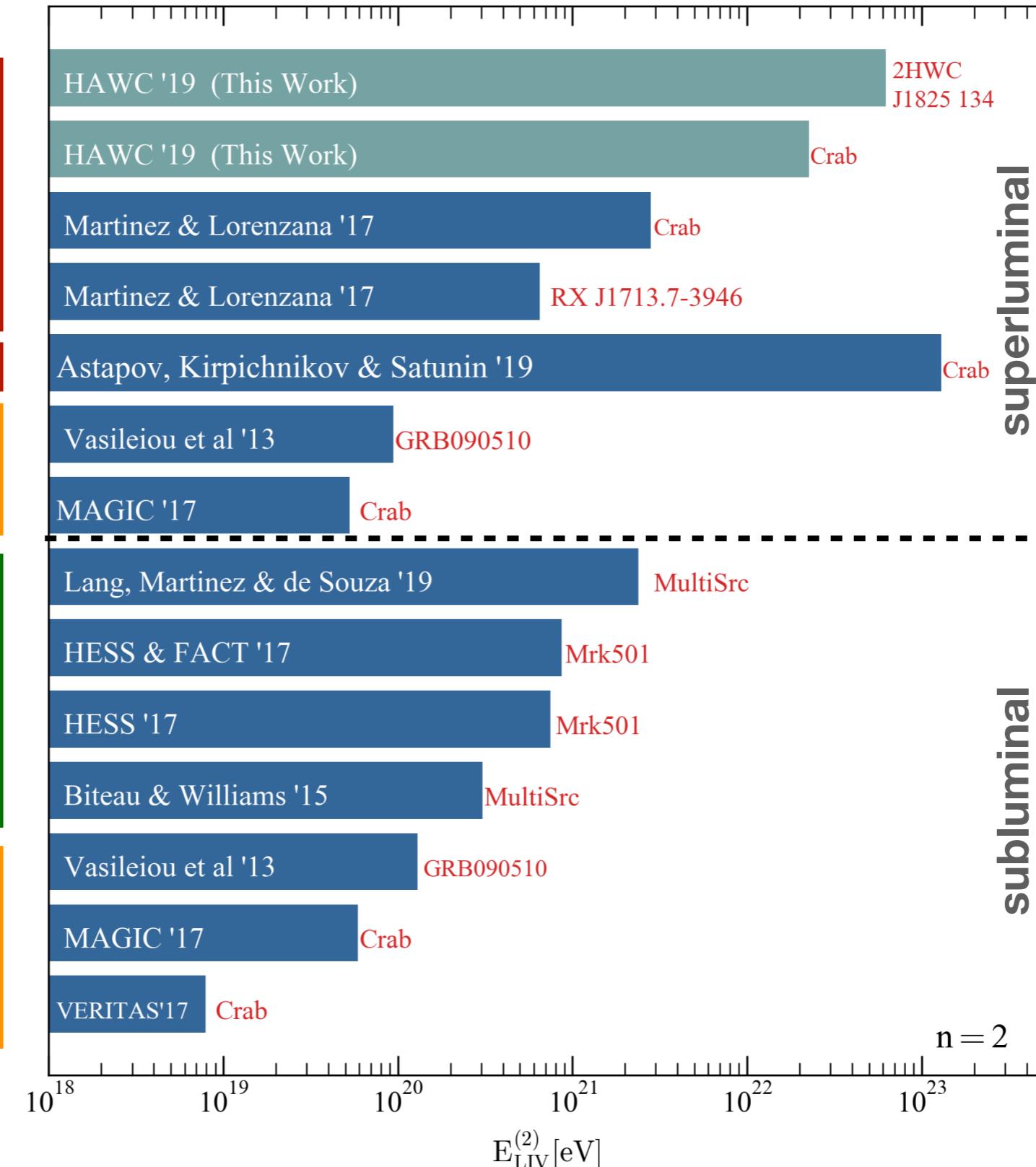
LIV limits (PRELIMINARY)



LIV limits (PRELIMINARY)



- Photon decay**
- Photon splitting**
- Energy-dependent time delay**
- Pair production shift threshold**
- Energy-dependent time delay**



Conclusions



- ◆ The HAWC observatory **measurements of the highest-energy photons** can be used as a **test to probe fundamental physics** such as Lorentz invariance.
- ◆ We have tested **LIV photon decay** through the study of **seven sources** with significant high energy emission: none of them favor a spectrum with a hard cutoff.
- ◆ Preliminary **stringent limits to LIV**.
- ▶ A study including detailed systematic uncertainties in the source spectra and HAWC detector response will be addressed in a **future publication**.

Thanks!



Modified dispersion relation

LI: $E_a^2 - p_a^2 = m_a^2$

LIV: $E^2 - p^2 \pm |f(A, \delta, M)| = m^2$

$$A = \{E, p\}$$

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

$$E \gg m,$$

$$E_a^2 - p_a^2 = m_a^2 \pm |\alpha_{a,n}| A_a^{n+2} \quad ; \quad |\alpha_n| = |\epsilon_0^{(n)}| / M^n = 1 / (E_{\text{LIV}}^{(n)})^n$$

Photons:

$$E_\gamma^2 = p_\gamma^2 + \xi_n^\pm \frac{p_\gamma^{n+2}}{M^n} \quad \xi_n^+ = (-1)^n \xi_n^-$$

M. Galaverina and G. Sigl
Phys.Rev. D78 (2008) 063003

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Photons:

$$\omega_{modM}(\mathbf{k}) = \sqrt{\frac{1 - \tilde{\kappa}_{tr}}{1 + \tilde{\kappa}_{tr}}} k, \quad k = |\mathbf{k}|,$$

F. Klinkhamer and M. Schreck,
Phys. Rev. D 78, 085026 (2008)

$$E_\gamma^2 - (1 - \tilde{\kappa}_{tr}) \vec{p}^2 = 0$$

M. Hohensee, R Lehnert, D Phillips, and R. Walsworth
Phys.Rev.D80:036010, (2009)