

Theoretical and experimental challenges in quantum gravity phenomenology



COST Action CA18108

Quantum gravity phenomenology in the multi-messenger approach

<https://qg-mm.unizar.es/>
<http://findico.capa.unizar.es/verH23>
<http://findico.capa.unizar.es/verH24>



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Theoretical and experimental challenges in quantum gravity phenomenology

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1. The development of quantum gravity phenomenology
2. The LIV and DSR paradigms
3. Some challenges in quantum gravity phenomenology
4. Conclusions



1. THE DEVELOPMENT OF QUANTUM GRAVITY PHENOMENOLOGY

INITIAL IDEAS IN QuGraPheno

Initial ideas and suggestions to test quantum gravity by amplification mechanisms:

- ▶ Testing CPT invariance in neutral mesons

(Ellis, Lopez, Mavromatos, Nanopoulos, PRD 1996)

$$\frac{|M_L - M_S|}{M_{L,S}} \sim 7 \cdot 10^{-15}$$

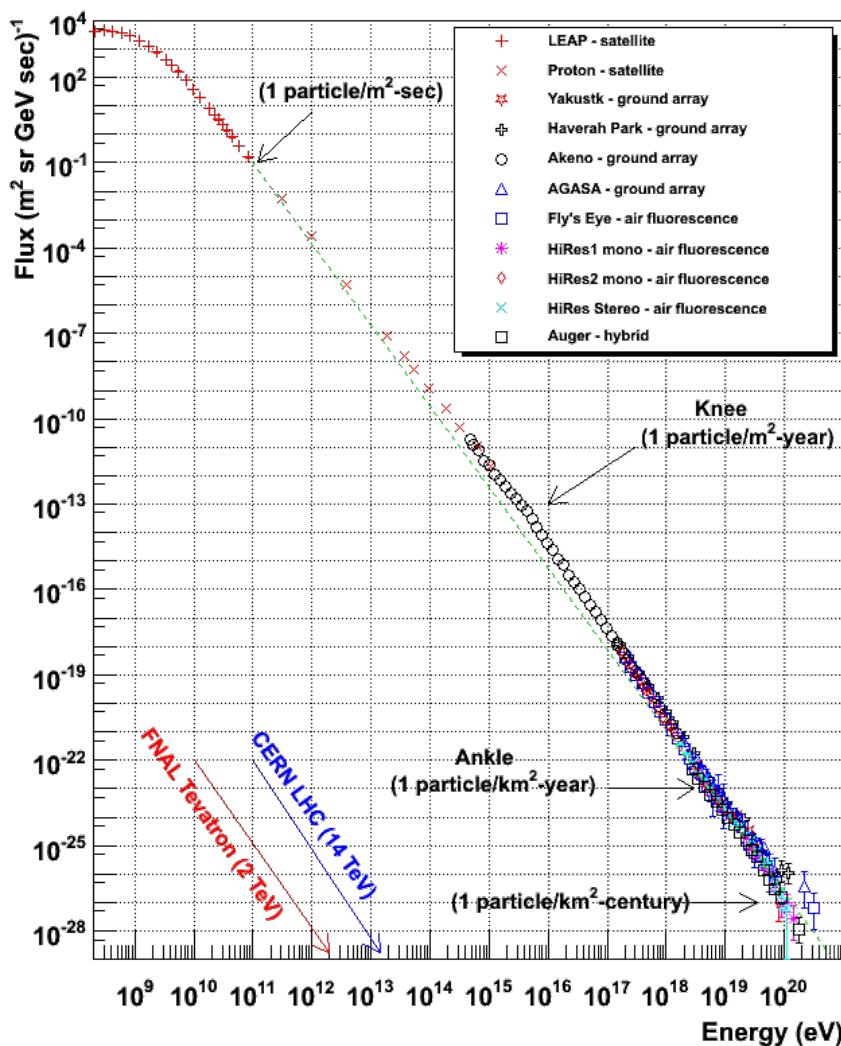
- ▶ Time of flight studies in GRBs (HEGRA, Whipple telescopes; EGRET satellite)

(Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar, Nature 1998)

$$\Delta t \approx \xi \frac{E}{E_{\text{QG}}} \frac{L}{c}$$

THE AGASA RESULTS AND THE GZK CUTOFF

Cosmic Ray Spectra of Various Experiments

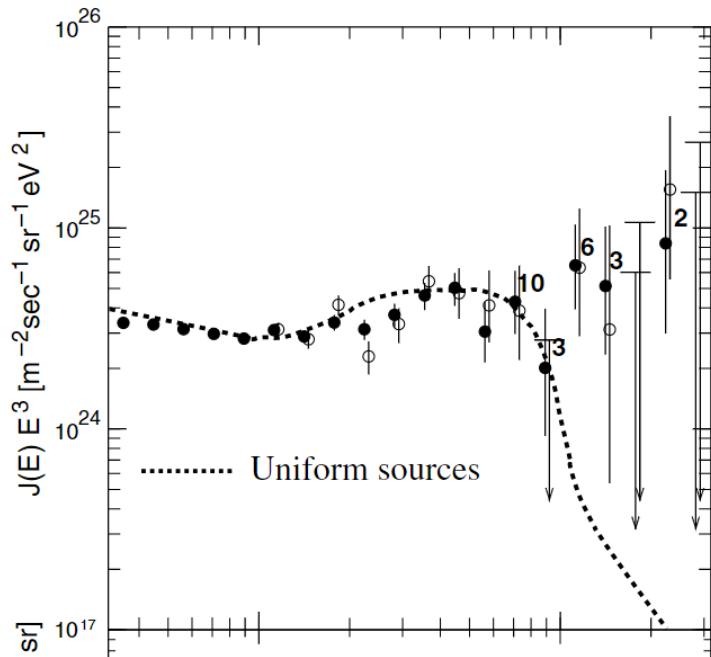


Cutoff GZK: $p + \gamma_{\text{CMB}} \rightarrow p + \pi$

$$E_{\text{GZK}} \simeq \frac{m_p m_\pi}{2E_\gamma} \simeq 3 \times 10^{20} \text{ eV} \times \left(\frac{2.7 \text{ K}}{E_\gamma} \right)$$

(Greisen, 1966; Zatsepin and Kuzmin, 1966)

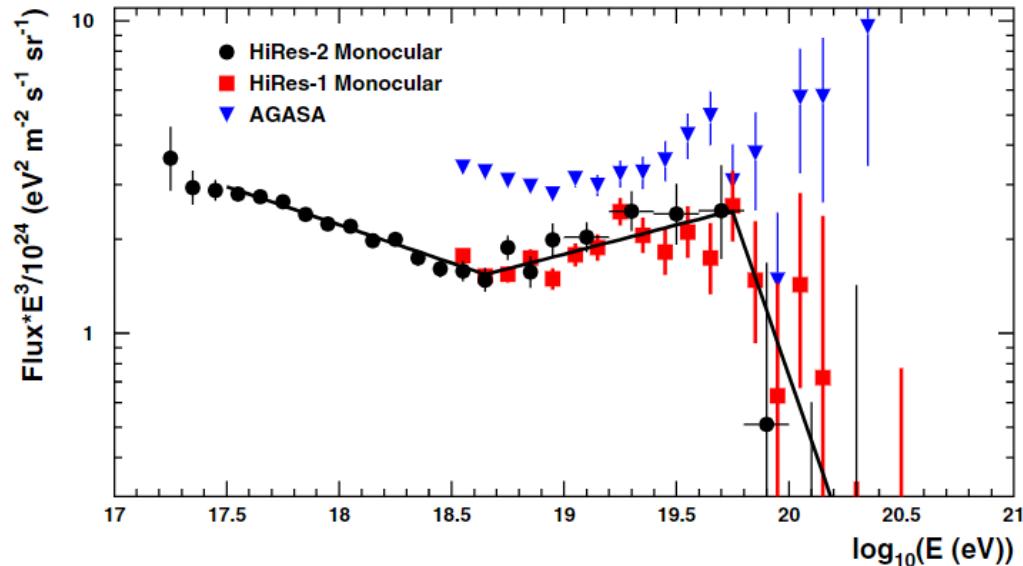
THE AGASA RESULTS AND THE GZK CUTOFF



(Takeda et al., Astrop. Phys. 2003,
Akeno Giant Air Shower Array
(AGASA) experiment)

$$E^2 - p^2 - m^2 \simeq \xi_n E^2 \left(\frac{E}{E_P} \right)^n$$

(Aloisio, Blasi, Ghia, Grillo, PRD 2000)



(Abbasi et al., PRL 2008,
High Resolution Fly's Eye (HiRES) experiment)

$\xi_n < 0$ No GZK cutoff

$\xi_n > 0$ $\xi_1 \lesssim 10^{-14}$
 $\xi_2 \lesssim 10^{-6}$

THE UHECR SPECTRUM

Telescope Array (TA)

Delta, UT, USA

507 detector stations, 680 km²

36 fluorescence telescopes

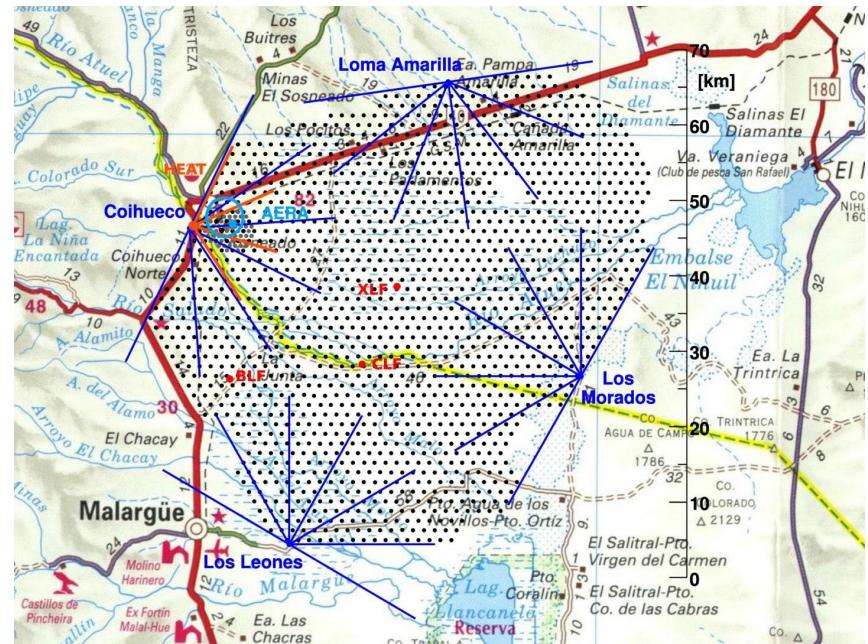


Pierre Auger Observatory

Province Mendoza, Argentina

1660 detector stations, 3000 km²

27 fluorescence telescopes



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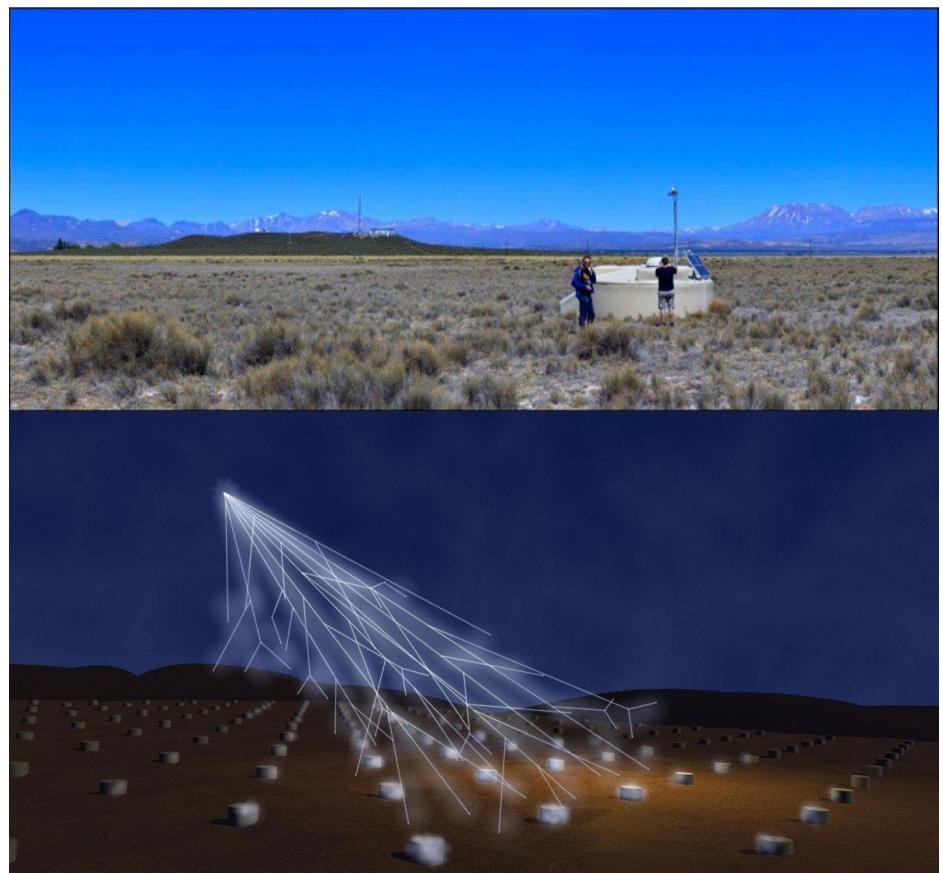


Pierre Auger Observatory

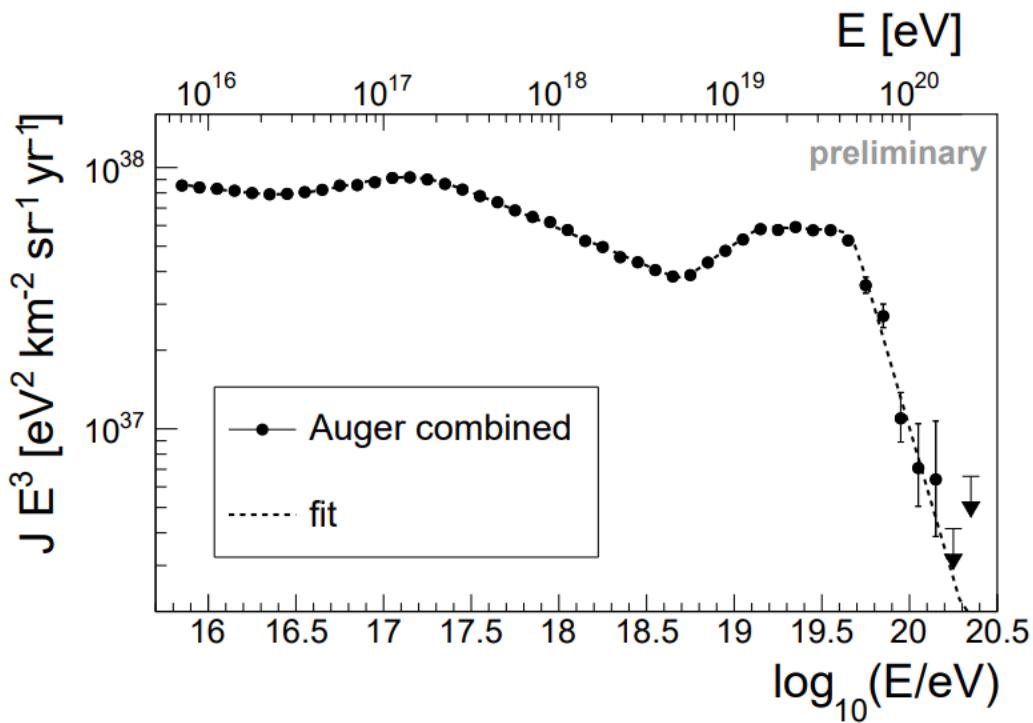
Province Mendoza, Argentina

1660 detector stations, 3000 km²

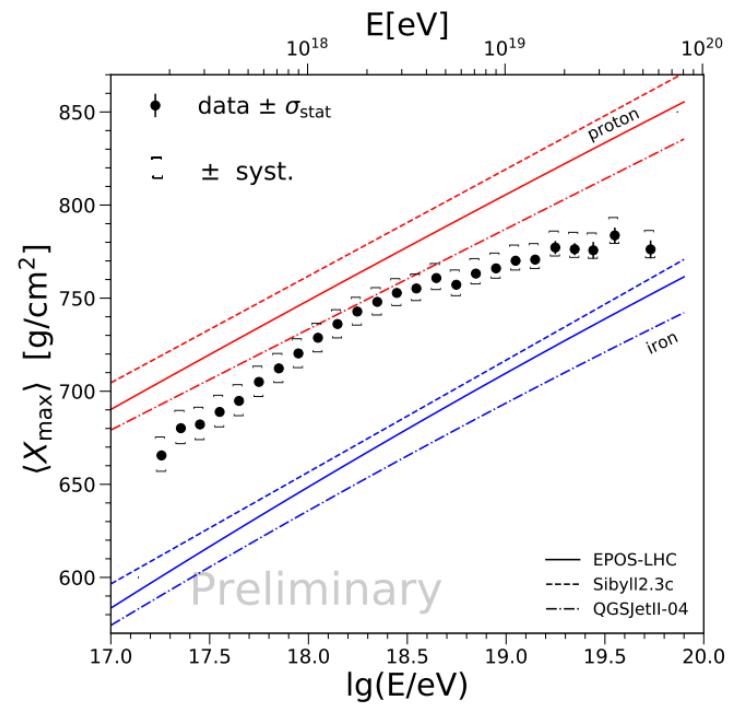
27 fluorescence telescopes



THE UHECR SPECTRUM

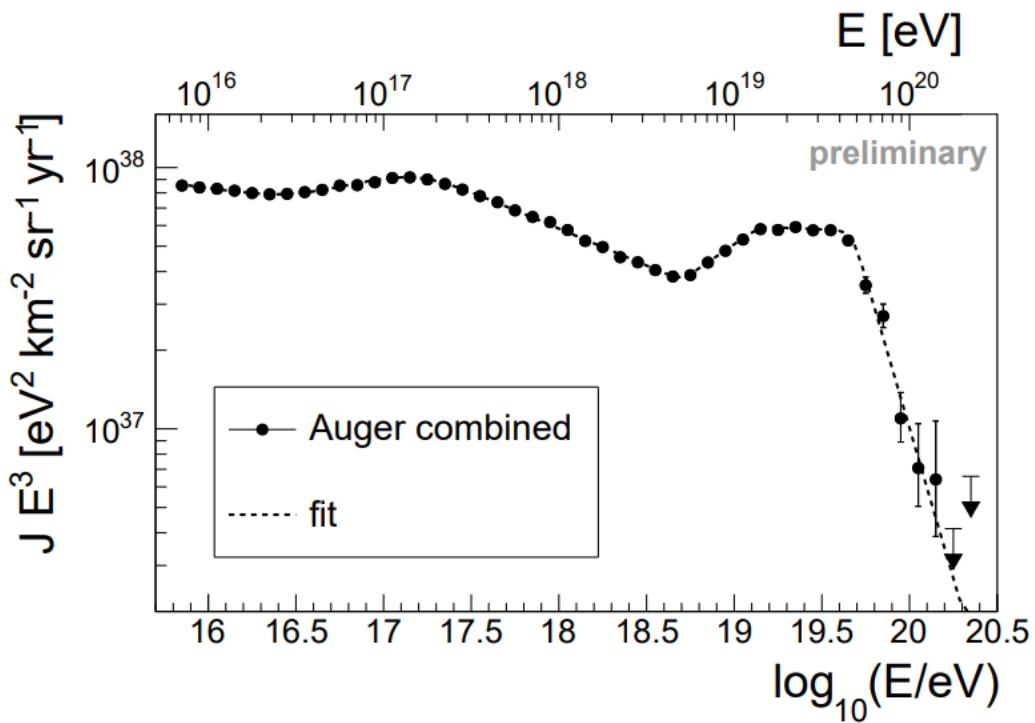


(Pierre Auger Collaboration, PoS (ICRC 2021)

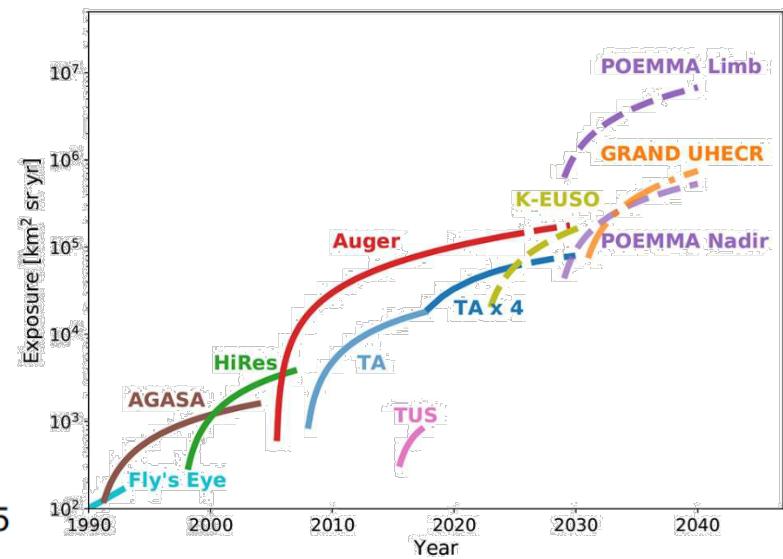


(Pierre Auger Collaboration, PoS (ICRC 2019)

THE UHECR SPECTRUM



(Pierre Auger Collaboration, PoS (ICRC 2021)



(Alves Batista et al.,
Front. Astron. Space Sci., 2019)

TIME DELAY STUDIES



$$E^2 \simeq p^2 c^2 \left[1 - \sum_{n=1}^{\infty} s_{\pm} \left(\frac{E}{E_{\text{QG},n}} \right)^n \right]$$

$$v(E) = \frac{\partial E}{\partial p} \approx c \left[1 - s_{\pm} \frac{n+1}{2} \left(\frac{E}{E_{\text{QG},n}} \right)^n \right]$$

$$\begin{aligned} \Delta t_{\text{LIV}} &= t_h - t_l \\ &= s_{\pm} \frac{1+n}{2H_0} \frac{E_h^n - E_l^n}{E_{\text{QG},n}^n} \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} \end{aligned}$$

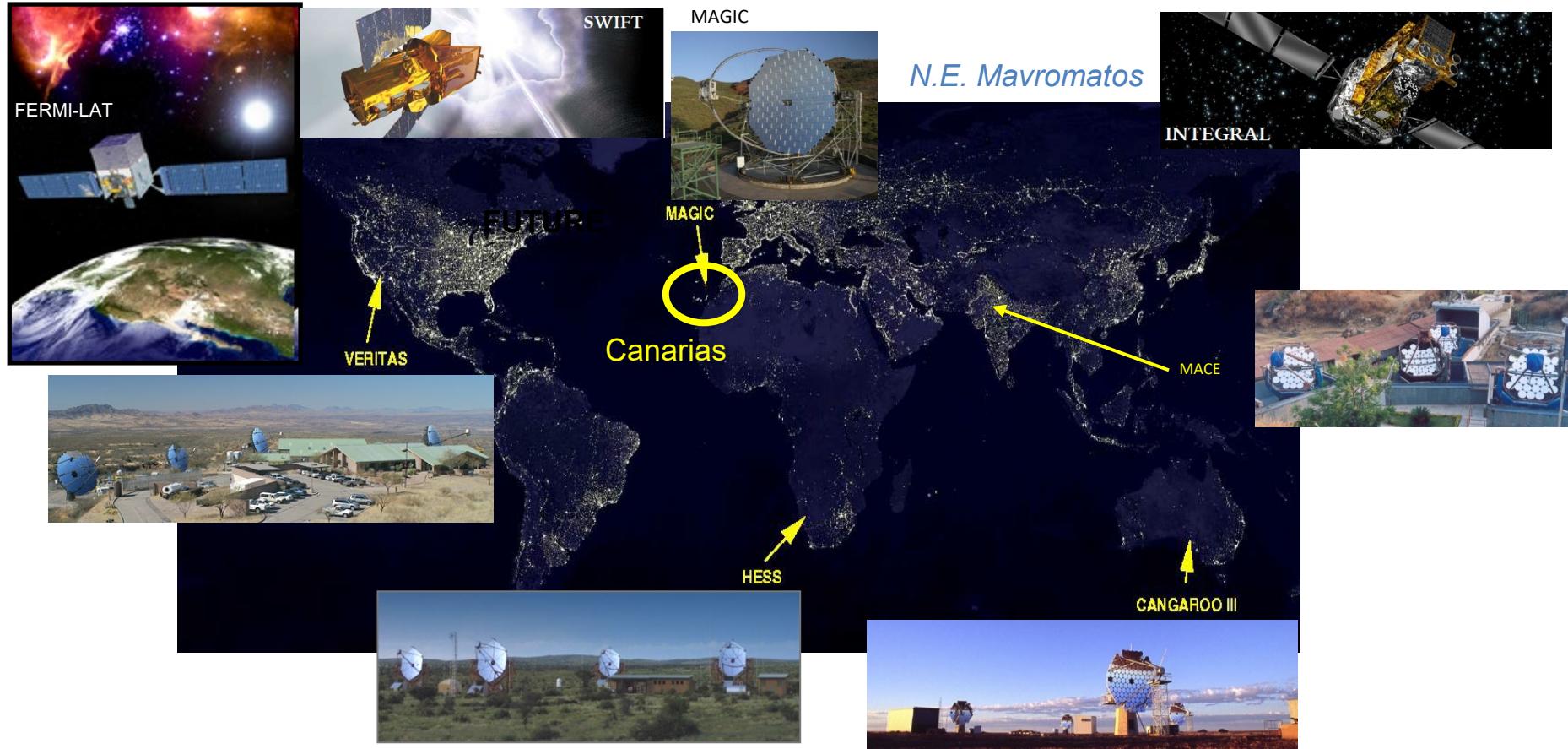
TIME DELAY STUDIES

(Wei, Wu, Front. Phys., 2021)

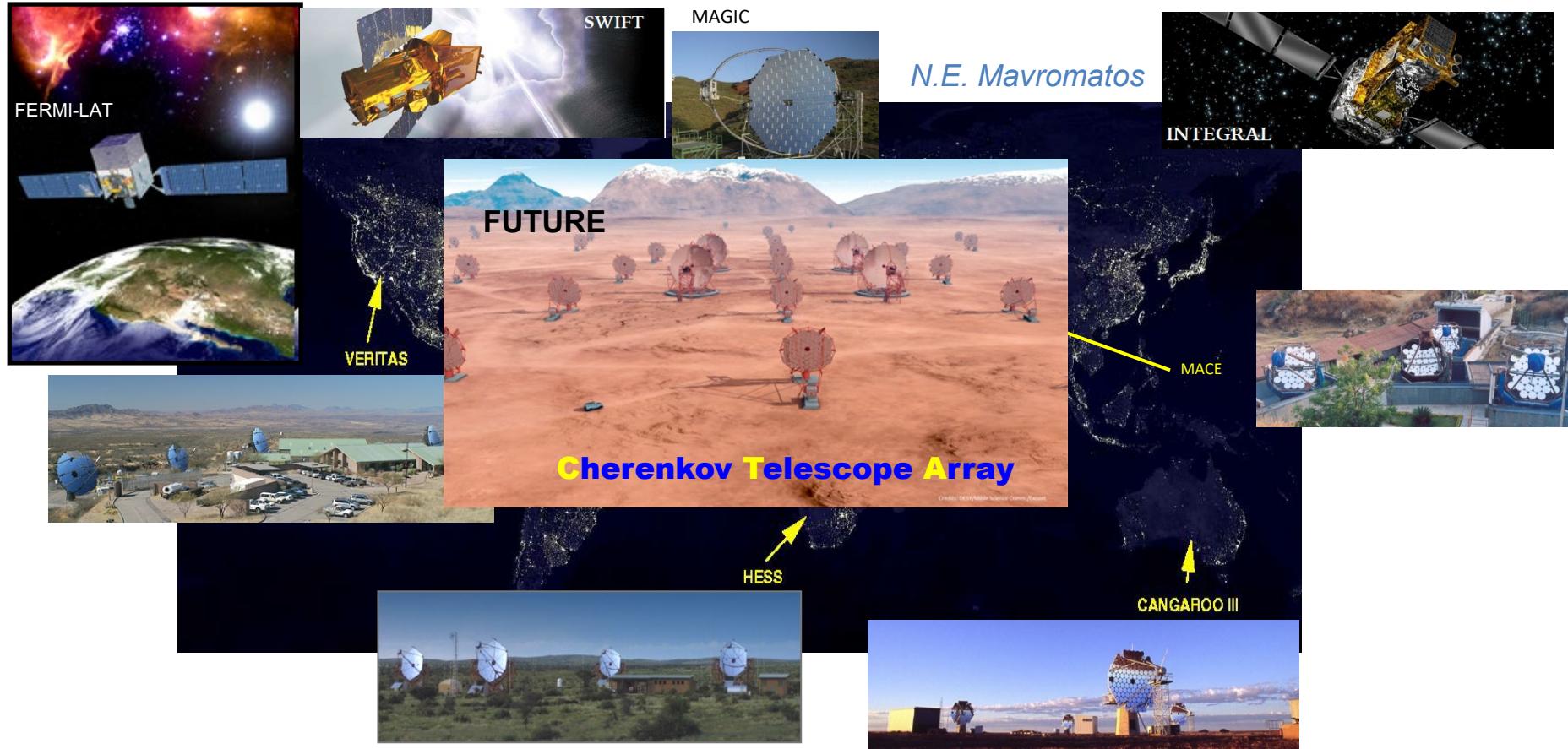
Table 1 A selection of lower limits on $E_{\text{QG},n}$ for linear ($n = 1$) and quadratic ($n = 2$) LIV for the subluminal ($s_{\pm} = +1$) and superluminal ($s_{\pm} = -1$) cases. These limits were obtained from vacuum dispersion time-of-flight measurements of various astrophysical sources.

Source(s)	Instrument	Technique	$E_{\text{QG},1}$ (GeV)		$E_{\text{QG},2}$ (GeV)		Refs.
			$s_{\pm} = +1$	$s_{\pm} = -1$	$s_{\pm} = +1$	$s_{\pm} = -1$	
9 GRBs ^a	BATSE+OSSE	Wavelets	6.9×10^{15}	—	2.9×10^6	—	[107]
GRB 021206 ^b	RHESSI	Peak times at different energies	1.8×10^{17}	—	—	—	[108]
35 GRBs ^c +Swift	BATSE+HETE-2 +Swift	Wavelets	1.4×10^{16}	—	—	—	[18, 106]
GRB 051221A	Konus-Wind+Swift	Peak times of the light curves in different energy bands	6.6×10^{16}	—	6.2×10^6	—	[109]
15 GRBs	HETE-2	Wavelets	2.0×10^{15}	—	—	—	[110]
11 GRBs	INTEGRAL	Likelihood	3.2×10^{11}	—	—	—	[111]
GRB 080916C	Fermi GBM+LAT	Associating a 13.2 GeV photon with the trigger time	1.3×10^{18}	—	—	—	[21]
GRB 090510	Fermi GBM+LAT	Associating a 31 GeV photon with the start of the first GBM pulse	1.5×10^{19}	—	—	—	[22]
	Fermi/LAT	PairView+Likelihood +Sharpness-Maximization Method	9.3×10^{19}	1.3×10^{20}	1.3×10^{11}	9.4×10^{10}	[25]
GRB 160625B	Fermi/GBM	Spectral lag transition	0.5×10^{16}	—	1.4×10^7	—	[29]
56 GRBs	Swift	Rest-frame spectral lags	2.0×10^{14}	—	—	—	[31]
GRB 190114C	MAGIC	Likelihood	5.8×10^{18}	5.5×10^{18}	6.3×10^{10}	5.6×10^{10}	[33]
Mrk 421	Whipple	Binning	4.0×10^{16}	—	—	—	[34]
Mrk 501	MAGIC	Energy cost function	2.1×10^{17}	—	2.6×10^{10}	—	[128]
		Likelihood	3.0×10^{17}	—	5.7×10^{10}	—	[129]
	H.E.S.S.	Likelihood	3.6×10^{17}	2.6×10^{17}	8.5×10^{10}	7.3×10^{10}	[130]
PKS 2155-304	H.E.S.S.	Modified cross correlation function	7.2×10^{17}	—	1.4×10^9	—	[131]
		Likelihood	2.1×10^{18}	—	6.4×10^{10}	—	[132]
Crab pulsar	CGRO/EGRET	Pulse arrival times in different energy bands	1.8×10^{15}	—	—	—	[35]
	VERITAS	Likelihood	3.0×10^{17}	—	7.0×10^9	—	[133]
	MAGIC	Dispersion Cancellation	1.9×10^{17}	1.7×10^{17}	—	—	[134]
		Likelihood	5.5×10^{17}	4.5×10^{17}	5.9×10^{10}	5.3×10^{10}	[135]

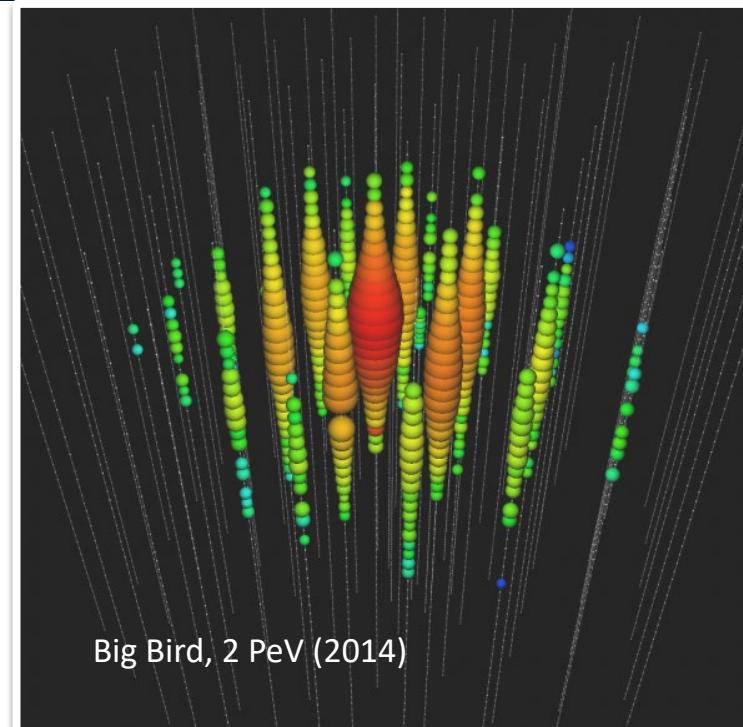
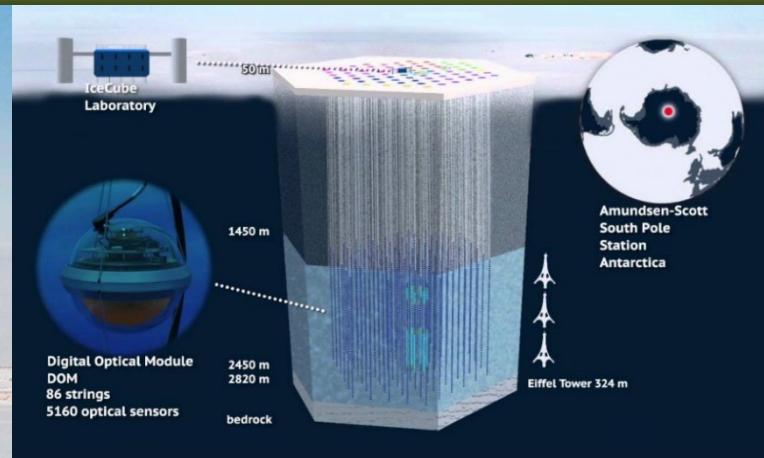
TIME DELAY STUDIES



TIME DELAY STUDIES



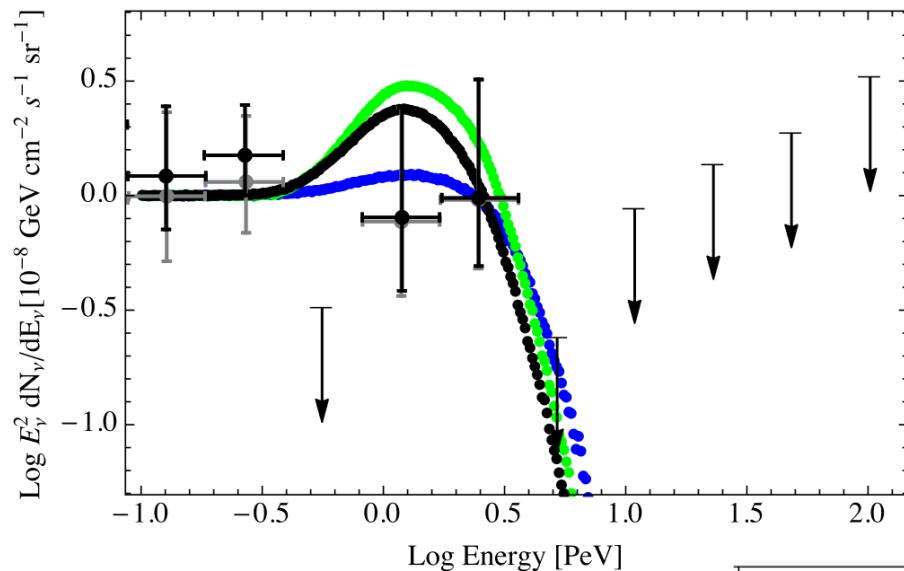
ASTROPHYSICAL NEUTRINOS ENTER THE GAME



1. The development of QuGraPheno

BPU11 Congress, Belgrade 2022

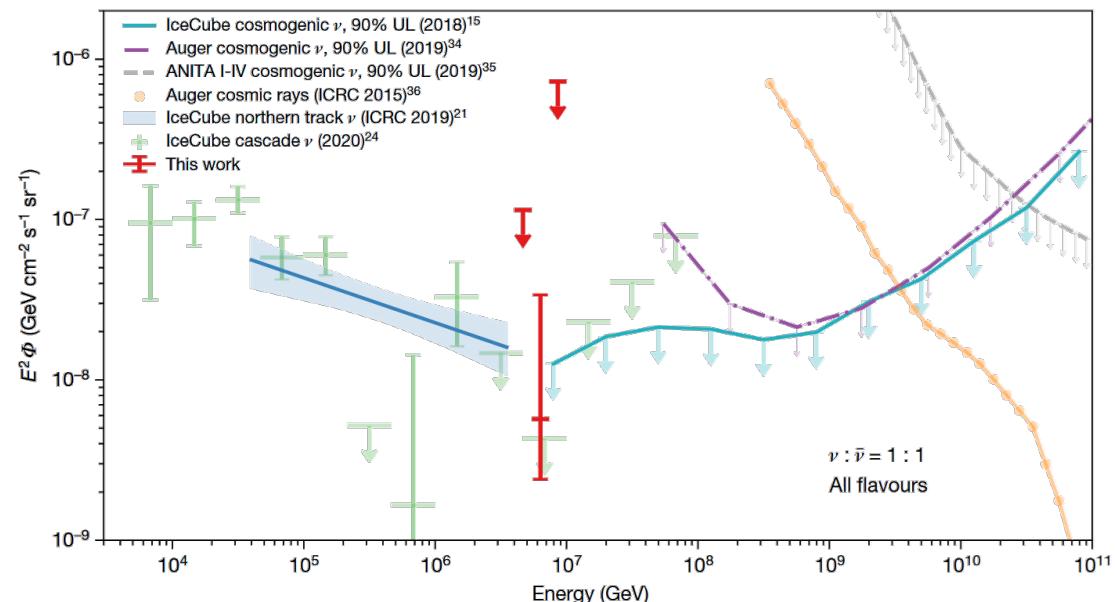
ASTROPHYSICAL NEUTRINOS ENTER THE GAME



Astrophysical neutrino flux
from IceCube data (points)
(IceCube Collab., PRL 2014)

Neutrino spectrum with LIV
propagation, showing a cutoff
(Stecker, Scully, Liberati, Mattingly, PRD 2015)

Detection of an event at the
Glashow resonance
(IceCube Collab., Nature 2021)



GWs AND MULTI-MESSENGER ASTRONOMY

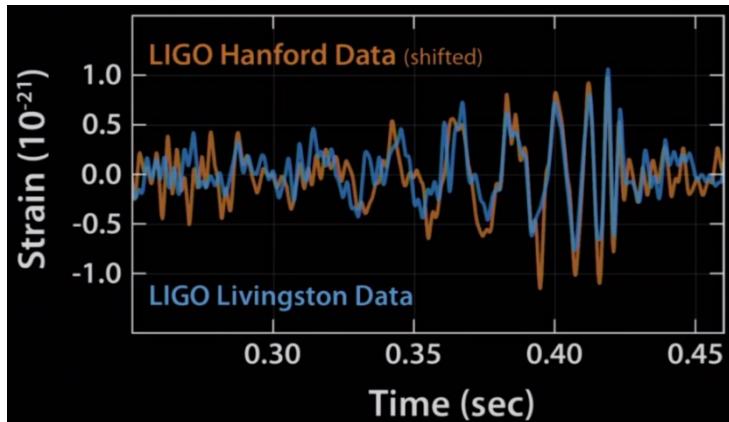
LIGO



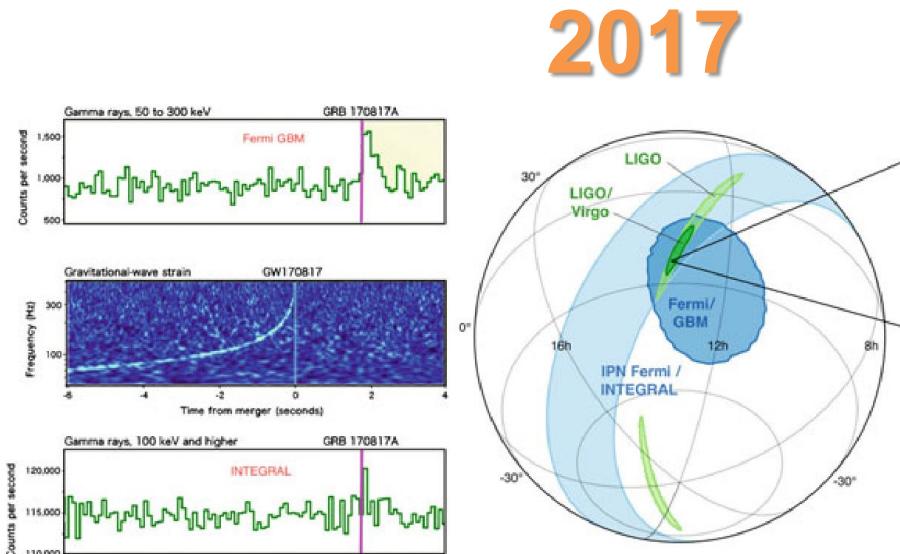
VIRGO



GWs AND MULTI-MESSENGER ASTRONOMY



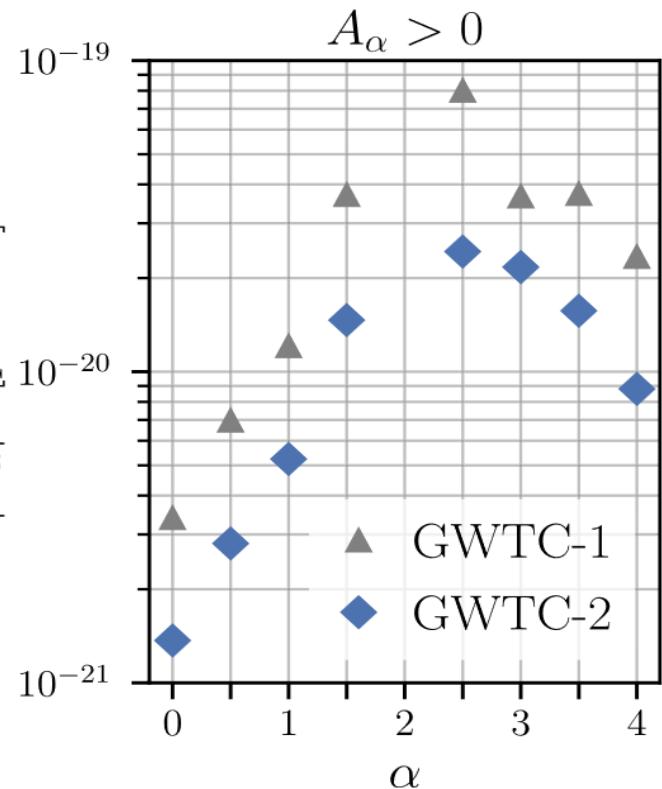
2015



2017

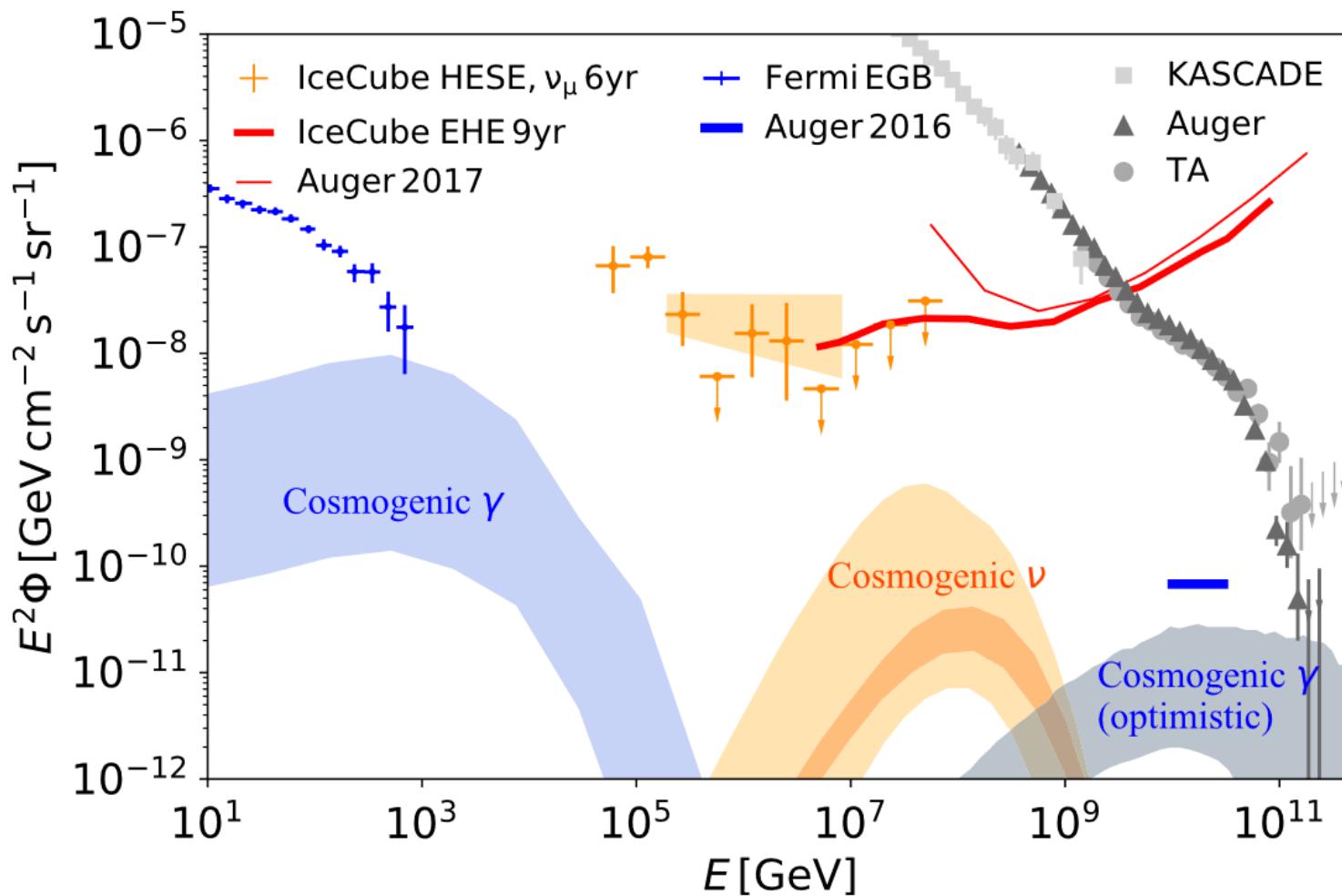
Constraints on the graviton dispersion relation:

$$E^2 = p^2 c^2 + A_\alpha p^\alpha c^\alpha$$



(LIGO-VIRGO Collab., PRD 2021)

GWs AND MULTI-MESSENGER ASTRONOMY



(Alves Batista et al., Front. Astron. Space Sci., 2019)

2. THE LIV AND DSR PARADIGMS

DEFORMED RELATIVISTIC KINEMATICS

$$A_1(p^{(1)}) + A_2(p^{(2)}) \rightarrow A_3(p^{(3)}) + A_4(p^{(4)})$$

- ▶ Special relativity:

$$p_\mu^{(1)} + p_\mu^{(2)} = p_\mu^{(3)} + p_\mu^{(4)}, \quad p^{(i)2} = m_i^2,$$

Invariance under linear Lorentz transformations: $p_\mu^{(i)'} = L_\mu^\nu p_\nu^{(i)}$

- ▶ Deformed relativistic kinematics MCL + MDR:

$$\left[p^{(1)} \oplus p^{(2)} \right]_\mu = \left[p^{(3)} \oplus p^{(4)} \right]_\mu, \quad C(p^{(i)}, \Lambda) = m_i^2,$$

Deformed kinematics: SR is obtained in the $\Lambda \rightarrow \infty$ limit

Relativistic invariance under Λ -deformed Lorentz transformations: $(k, l) \rightarrow (k', l')$

$$\left[p^{(1)'} \oplus p^{(2)'} \right]_\mu = \left[p^{(3)'} \oplus p^{(4)'} \right]_\mu, \quad C(p^{(i)'}, \Lambda) = m_i^2$$

EXAMPLE: A FIRST-ORDER DSR

► MDR: $C(p) = p_0^2 - \vec{p}^2 + \frac{\alpha_1}{\Lambda} p_0^3 + \frac{\alpha_2}{\Lambda} p_0 \vec{p}^2 = m^2$

► MCL: $[p \oplus q]_0 = p_0 + q_0 + \frac{\beta_1}{\Lambda} p_0 q_0 + \frac{\beta_2}{\Lambda} \vec{p} \cdot \vec{q}$

$$[p \oplus q]_i = p_i + q_i + \frac{\gamma_1}{\Lambda} p_0 q_i + \frac{\gamma_2}{\Lambda} p_i q_0$$

► Relativity principle: (Carmona, Cortés, Mercati, PRD 2012)

$$\alpha_1 = -\beta_1 \quad \alpha_2 = \gamma_1 + \gamma_2 - \beta_2$$

(generalization of the “golden rule” derived in (Amelino-Camelia, PRD 2012)

► Because of these “golden rules”, the kinematics of the relativistic invariance (DSR) and non-invariance (LIV) cases is very different

PAIR PRODUCTION IN A PHOTON BACKGROUND



- ▶ SR threshold: $E_{\text{th}}^{\text{SR}} = \frac{m_e^2}{\varepsilon}$
- ▶ Beyond SR threshold equation:

$$\frac{\gamma_1 + \gamma_2 - \beta_1 - \beta_2 - \alpha_1 - \alpha_2}{8\Lambda} E_{\text{th}}^3 + \mathcal{O}\left(\frac{E^2 \varepsilon}{\Lambda}, \frac{Em_e^2}{\Lambda}\right) + E_{\text{th}} \varepsilon - m_e^2 = 0$$

LIV case:

$$\gamma_i = \beta_i = 0$$

$$E_{\text{th}}^{\text{LIV}} \approx \frac{m_e^2}{\varepsilon} \left[1 + \frac{(m_e^2)^2}{\varepsilon^3} \frac{\alpha_1 + \alpha_2}{8\Lambda} \right] = \frac{m_e^2}{\varepsilon} \left[1 + \frac{\frac{m_e^2}{\varepsilon^2}}{\varepsilon \Lambda_{\text{eff}}} \frac{m_e^2}{\varepsilon \Lambda_{\text{eff}}} \right]$$

DSR case:

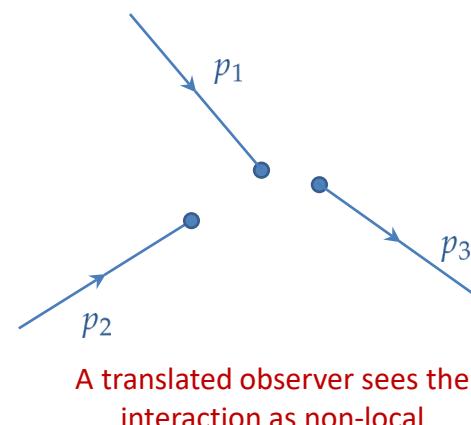
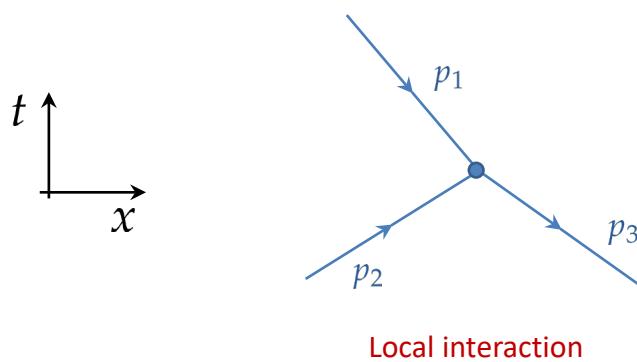
$$E_{\text{th}}^{\text{DSR}} \approx \frac{m_e^2}{\varepsilon} \left[1 + \frac{\beta_1 + \beta_2 + 3\gamma_2 - \gamma_1}{4\Lambda} \frac{m_e^2}{\varepsilon} \right] = \frac{m_e^2}{\varepsilon} \left[1 + \frac{m_e^2}{\varepsilon \Lambda_{\text{eff}}} \right]$$

$$\gamma_1 + \gamma_2 - \beta_1 - \beta_2 - \alpha_1 - \alpha_2 = 0$$

[for $\varepsilon \sim \text{CMB}$ and $\sim 10\%$ correction, bound on Λ is $\sim M_P$ (LIV), $\sim \text{PeV}$ (DSR)]

ABOUT LOCALITY

- ▶ Conservation of total momentum $\mathcal{P} \leftrightarrow$ translational invariance
- ▶ Special relativity: $\mathcal{P} = \sum p_i$, translations are **constant** displacements
$$x_i \rightarrow x_i + a \quad \forall i$$
- ▶ Deformed relativistic kinematics: $\mathcal{P} = \oplus p_i$, translations are **momentum-dependent** displacements
$$x_i \rightarrow x_i + f(\{p\})$$
- ▶ SR has the property of **absolute** locality; in a deformed relativistic kinematics, however, this property is **lost**



RELATIVE LOCALITY

- ▶ Classical model of worldlines through a variational principle: **relative locality**
(Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin, PRD 2011)

$$S_{\text{total}} = S_{\text{free}}^{\text{in}} + S_{\text{free}}^{\text{out}} + S_{\text{int}}$$

$$S_{\text{free}}^{\text{in}} = \sum_{J=1}^N \int_{-\infty}^0 d\tau \left(x_J^\mu \dot{p}_\mu^J + \mathcal{N}_J \left(C(p^J) - m_J^2 \right) \right)$$

$$S_{\text{free}}^{\text{out}} = \sum_{J=N+1}^{2N} \int_0^\infty d\tau \left(x_J^\mu \dot{p}_\mu^J + \mathcal{N}_J \left(C(p^J) - m_J^2 \right) \right)$$

$$S_{\text{int}} = \left(\bigoplus_{N+1 \leq J \leq 2N} p_\nu^J(0) - \bigoplus_{1 \leq J \leq N} p_\nu^J(0) \right) z^\nu$$

$$\delta S_{\text{total}} = 0 \text{ for any } \delta z^\mu, \delta x_J^\mu, \delta p_\mu^J:$$

$$x_J^\mu(0) = z^\nu \frac{\partial \mathcal{P}_\nu}{\partial p_\mu^J} \forall J$$

$$\mathcal{P} = \bigoplus_{1 \leq J \leq N} p^J(0) = \bigoplus_{N+1 \leq J \leq 2N} p^J(0)$$

The interaction is seen as local only for the observer which establishes the origin of space-time coordinates at the interaction vertex
(corresponding to $z^\mu = 0$)

3. SOME CHALLENGES IN QUANTUM GRAVITY PHENOMENOLOGY

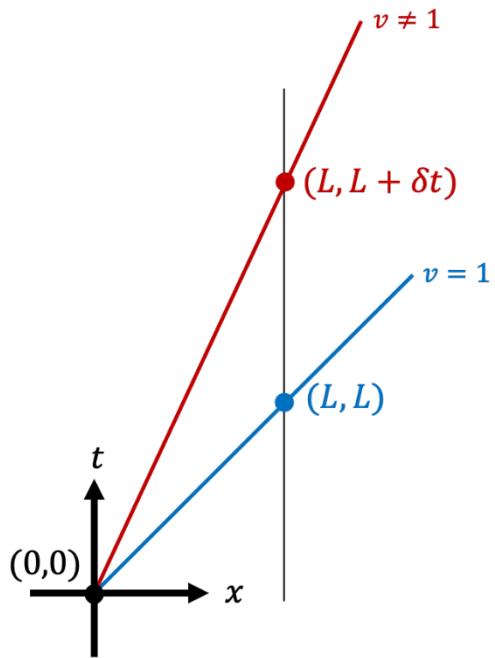
#1 – DETERMINATION OF TIME DELAYS

We need **new strategies** to give a definite answer wrt the presence or not of time delays:

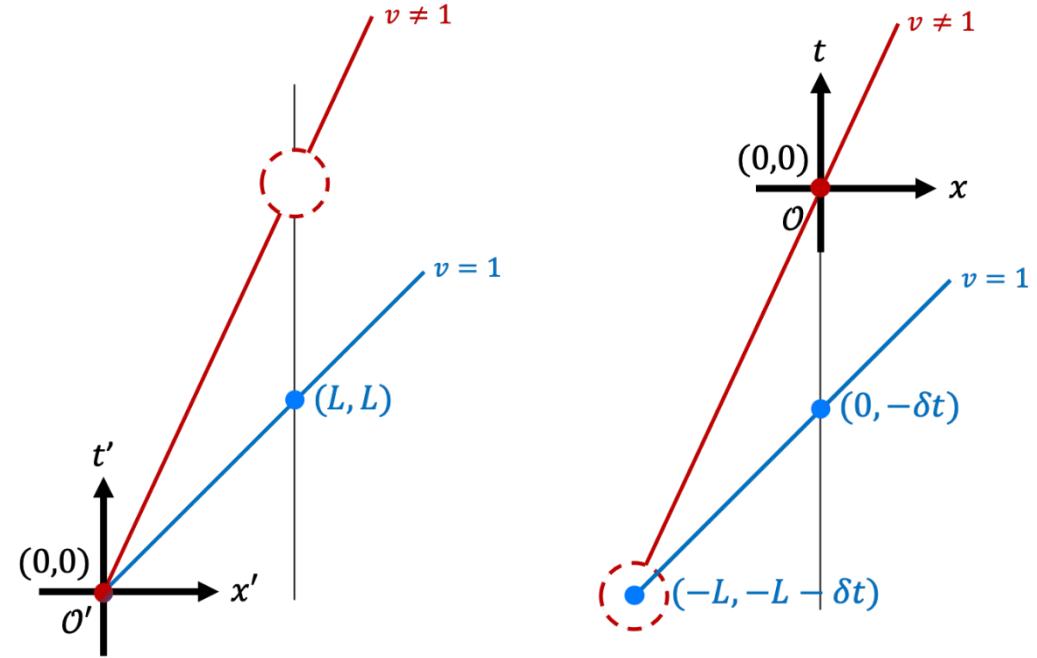
- ▶ Combination of experiments, as in the IACT's LIV consortium
(Bolmont et al., The Astrophysical Journal 2022)
- ▶ Inclusion of propagation effects in the analyses (such as non-standard interactions with the photon background)
- ▶ New approaches to minimize the intrinsic effects at the sources
(Levi, Sol, Bolmont et al., PoS ICRC21)
- ▶ A better understanding of the predictions of DSR with respect to time delays

TIME DELAYS: LIV vs DSR

LIV



DSR



TIME DELAYS IN DSR

The translation between observers \mathcal{O} and \mathcal{O}' can be described using the most general **first-order deformation of the Poincaré algebra** (in powers of a energy scale Λ) acting on the canonical one-particle phase space (x, t, Π, Ω) :

$$E = \Omega + \frac{a_1}{\Lambda} \Omega^2 + \frac{a_2}{\Lambda} \Pi^2, \quad P = \Pi + \frac{a_3}{\Lambda} \Omega \Pi,$$
$$N = x \Omega - t \Pi + \frac{a_4}{\Lambda} x \Omega^2 + \frac{a_5}{\Lambda} x \Pi^2 - \frac{a_6}{\Lambda} t \Omega \Pi,$$

The **MDR** for photons that is derived from the Casimir of the algebra is:

$$\Omega = \Pi - \frac{(a_4 + a_5 - a_6)}{3\Lambda} \Pi^2$$

The **time delay** δt is obtained as:

$$\delta t = L \left[\frac{2(a_4 + a_5 - a_6)}{3\Lambda} \Pi - \frac{2(a_1 + a_2 - a_3)}{\Lambda} \Pi \right]$$

- ▶ It is a sum of two contributions that can cancel, producing no observable time delays
- ▶ The time delay is invariant under the change of energy-momentum variables
- ▶ This model is compatible with relative locality

(Carmona, Cortés, Relancio, Reyes, arXiv: 2207-03799)

#2 – SPECTRUM MODIFICATIONS

- ▶ Most of the analyses looking for QuGra corrections have been done at the kinematic level, e.g., looking for the generation, suppression or modification of **thresholds of reactions**, such as those related to the GZK cutoff
- ▶ A more complete analysis of the expected **effects on the spectra** of the cosmic messengers will be necessary to reveal quantum gravity footprints:
 - ▶ Analysis of the end of the UHECR spectrum
 - ▶ Influence of the cosmic backgrounds
 - ▶ Simulations of atmospheric showers
- ▶ It will be necessary a better understanding of the **dynamics** of the LIV and DSR cases

Article | Published: 17 May 2021

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

Zhen Cao , F. A. Aharonian , [...] X. Zuo

Nature 594, 33–36 (2021) | Cite this article

13k Accesses | 1 Citations | 686 Altmetric | Metrics

Abstract

The extension of the cosmic-ray spectrum beyond 1 petaelectronvolt (PeV; 10^{15} electronvolts) indicates the existence of the so-called PeVatrons—cosmic-ray factories that accelerate particles to PeV energies. We need to locate and identify such objects to find the origin of Galactic cosmic rays¹. The principal signature of both electron and proton PeVatrons is ultrahigh-energy (exceeding 100 TeV) γ radiation. Evidence of the presence of a proton PeVatron has been found in the Galactic Centre, according to the detection of a hard-

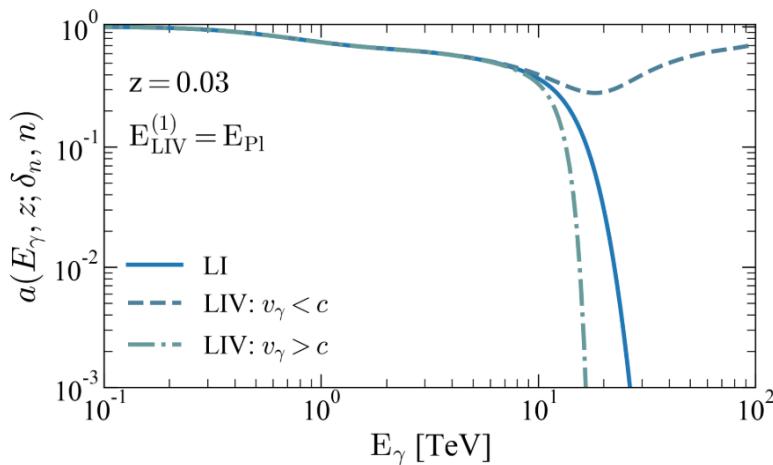
LIV and LHAASO

- ▶ Allowed process in special relativity (SR): $\gamma + \gamma_b \rightarrow e^+ + e^-$
- ▶ LIV: modification of the dispersion relation

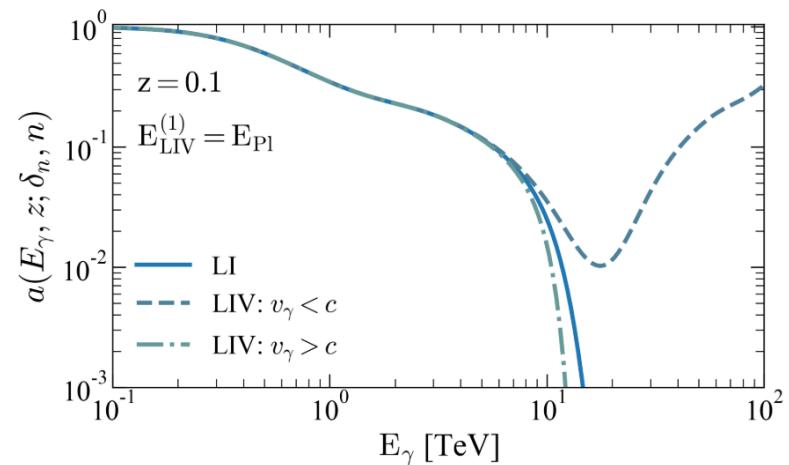
$$E_\gamma^2 - p_\gamma^2 = \pm |\delta_{\gamma,n}| E^{n+2} \quad \rightarrow \quad \varepsilon^{\text{thr}} = \frac{m_e^2}{E_\gamma} - \frac{1}{4} (\pm |\delta_{\gamma,n}|) E_\gamma^{n+1}$$

+ superluminal, $v_\gamma > c$
 - subluminal, $v_\gamma < c$

$$a(E_\gamma, z; \delta_n, n) = \exp(-\tau)$$



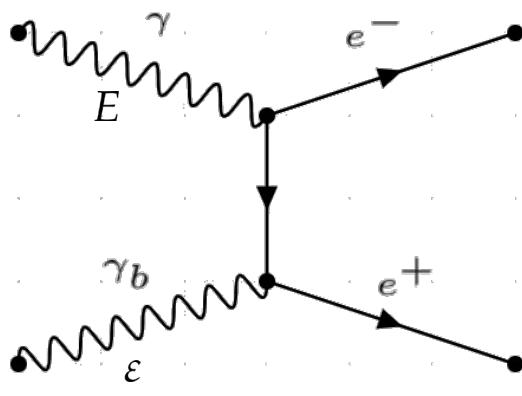
Absorption of TeV photons in the EBL



- ▶ Sensitivity of $E_{\text{LIV}}^{(1)} = (|\delta_{\gamma,1}|)^{-1}$ to the Planck scale
- ▶ LHAASO results **severely constrains** the superluminal scenario because of pair-emission ($\gamma \rightarrow e^+ e^-$) and photon splitting ($\gamma \rightarrow 3\gamma$) processes

(H. Martínez-Huerta et al., Symmetry 2020)

ABSORPTION OF VHE PHOTONS IN SR



► Probability of survival of a VHE photon:

$$P_{\gamma \rightarrow \gamma}(E, z_s) = \exp(-\tau_\gamma(E, z_s))$$

At low redshift:

$$P_{\gamma \rightarrow \gamma}(E, D) \approx \exp(-D/\lambda_\gamma(E))$$

$$\frac{1}{\lambda_\gamma(E)} = \int_{-1}^1 d(\cos \theta) \frac{1 - \cos \theta}{2} \int_{\varepsilon^{\text{thr}}}^{\infty} d\varepsilon n_\gamma(\varepsilon) \sigma_{\gamma\gamma}(E, \varepsilon, \theta)$$

Using $s = 2E\varepsilon(1 - \cos \theta)$,

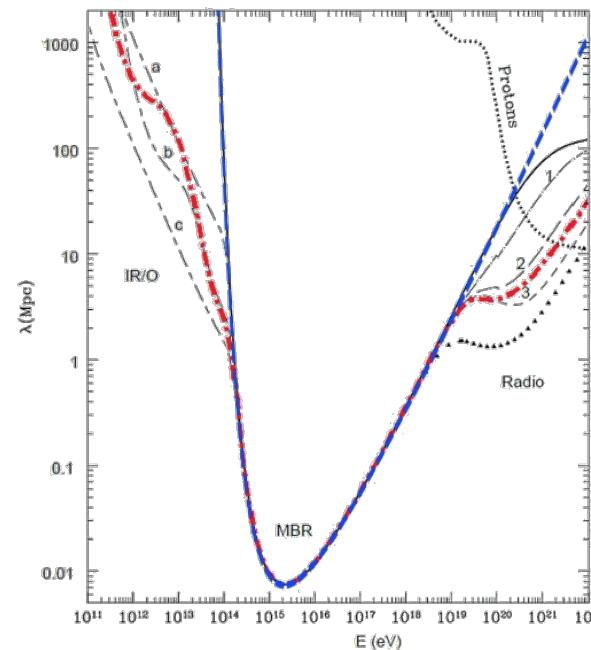
$$\frac{1}{\lambda_\gamma(E)} = \frac{1}{8E^2} \int_{4m_e^2}^{\infty} ds s \sigma_{\gamma\gamma}(s) \int_{s/(4E)}^{\infty} d\varepsilon \frac{1}{\varepsilon^2} n_\gamma(\varepsilon)$$

and taking

$$n_\gamma(\varepsilon) = (\varepsilon/\pi)^2 (e^{\varepsilon/kT_0} - 1)^{-1}$$

$$T_0 = 2.73 \text{ K}$$

$\sigma_{\gamma\gamma}(s) \equiv$ Breit-Wheeler cross section

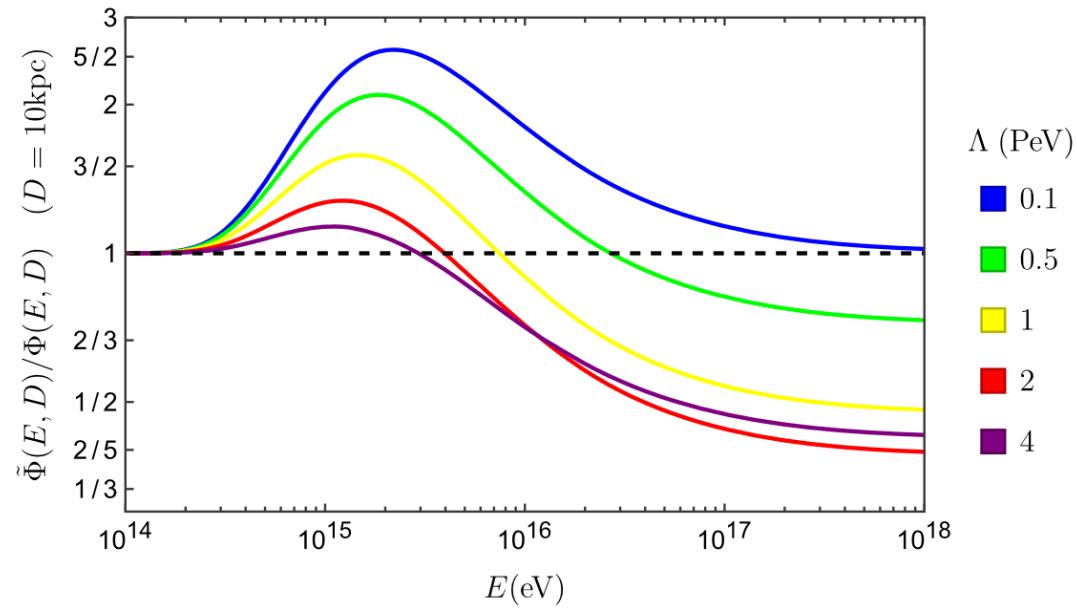
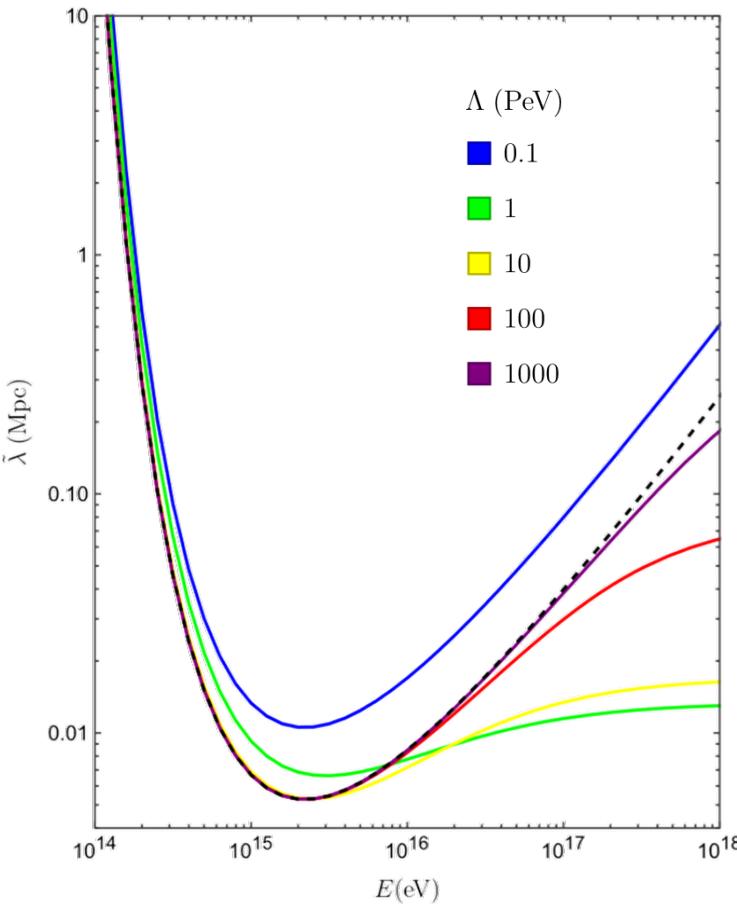


(De Angelis,
Galanti,
Roncadelli,
MNRAS 2013)

ABSORPTION OF VHE PHOTONS IN DSR

In DSR, a good approximation turns out to be:

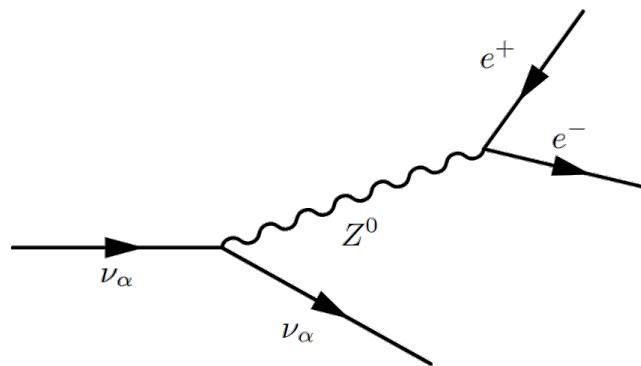
$$\tilde{\sigma}_{\gamma\gamma}(\tilde{s}, \tilde{s}/\Lambda^2) \approx \tilde{\sigma}_{\gamma\gamma}(\tilde{s}, 0) \doteq \tilde{\sigma}_{\gamma\gamma}(\tilde{s}) \approx \sigma_{\gamma\gamma}(\tilde{s})$$



(Carmona, Cortés, Relancio, Reyes, Vincueria, Eur. Phys. J. Plus 2022)

#3 – DYNAMICAL CALCULATIONS

- ▶ LIV decay widths (as in the case of superluminal neutrinos) have been studied in the framework of the SME, mostly for the case of $d = 4$ LIV operators



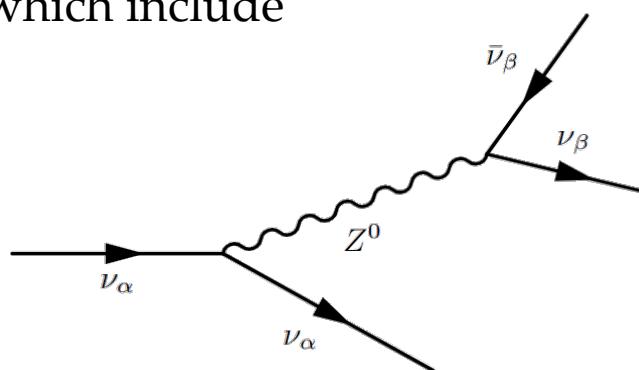
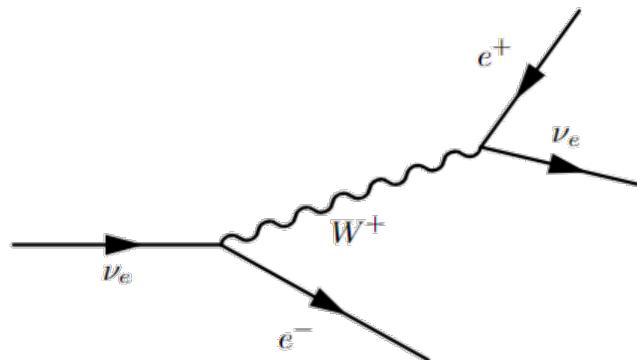
(Cohen, Glashow, PRL 2011)

(Bezrukov, Lee, PRD 2012)

(Huo, Li, Liao, Nanopoulos, Qi, PRD 2012)

(Carmona, Cortés, Mazón, PRD 2012)

- ▶ The detailed study of the spectrum of superluminal neutrinos will require specific calculations for $d > 4$ operators which include



(Carmona, Cortés, Relancio, Reyes, in preparation)

4. CONCLUSIONS

FINAL THOUGHTS

- ▶ Quantum gravity phenomenology has shown to be more **elusive and subtle** than initially thought
- ▶ The **first twenty years** of this field has allowed us to put into practice smart theoretical and experimental ideas, but the expected effects have turned out to be not as direct as they could have been foreseen and **further efforts** will be needed to discover quantum gravity footprints
- ▶ Fortunately, a **new generation of experiments** (IceCube Gen-2, the upgrades of the Pierre Auger observatory, CTA, LHAASO,...) is going to produce new results, at higher energies and sensitivities, in the coming years
- ▶ This represents an **outstanding opportunity** to develop new strategies and approaches for the transition from an exploratory stage to a **precision era**, favored by the experimental advances in the detection of the cosmic messengers in their high-energy regime

Thanks for your attention