First LIV constraint from a cooperation of Imaging Atmospheric Cherenkov Telescopes

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HRZZ
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For the ɣLIV WG

H.E.S.S.

CTAO
Large Sized Telescope

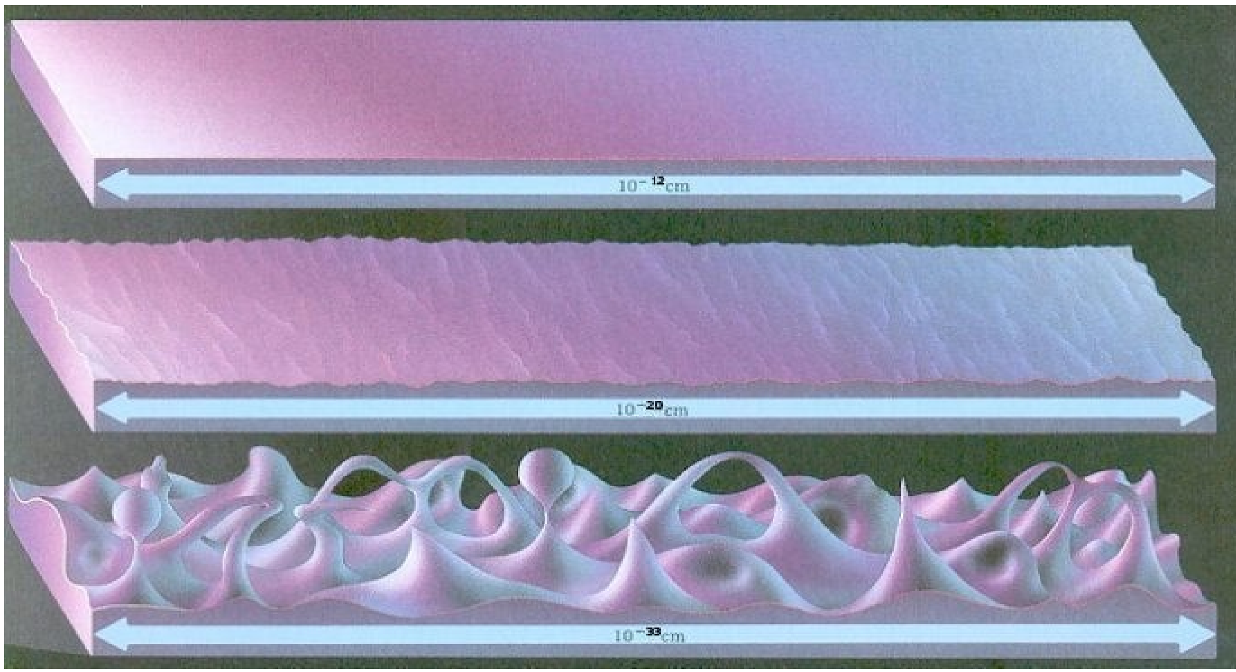
MAGIC

VERITAS

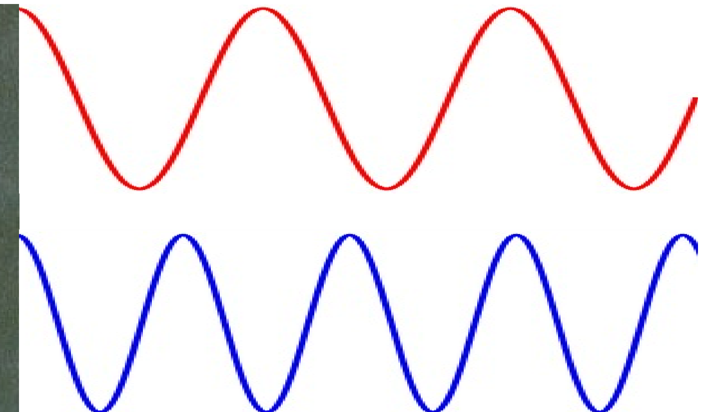
6 November 2025

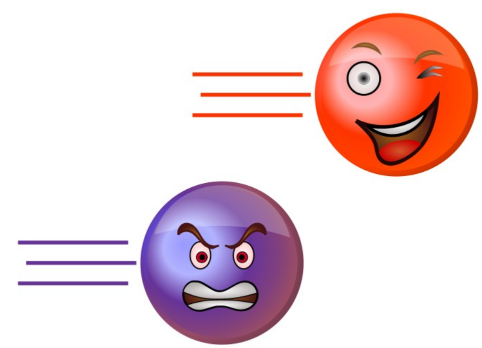
TeV Particle Astrophysics
TeVPA
Valencia 2025

Lorentz invariance violation (LIV)



http://universe-review.ca/R01-07-quantumfoam.htm





Lorentz invariance violation (LIV)

- Modified photon dispersion relation
- Usual starting point in searches for effects of QG with gamma rays

photon energy

$$E^2 = p^2c^2 \times \left[1 + \sum_{n=1}^{\infty} S_n \left(\frac{E}{E_{\mathrm{QG},n}}\right)^n\right]$$

QG energy scale

S = ±1

Expectation:

$$\mathrm{E}_{\mathrm{QG,n}} = \mathcal{O}(E_{\mathrm{Pl}}) \simeq 1.22 \times 10^{19}\,\mathrm{GeV}$$

- Not a direct consequence of any particular QG model
- Simple way of parametrizing “out of the ordinary” behaviour

Consequences of MDR

- Energy dependent photon group velocity
- Modified reaction thresholds
- Modified reaction cross sections
- Vacuum birefringence
- Modified Compton scattering
- Modified synchrotron radiation
- ...
-
- Tiny but **cumulative** effects

Consequences of MDR

Focus of today's talk

- Energy dependent photon group velocity
- Modified reaction thresholds
- Modified reaction cross sections
- Vacuum birefringence
- Modified Compton scattering
- Modified synchrotron radiation
- ...
-
- Tiny but **cumulative** effects

Check:

- Addazi et al. 2022 (arXiv:2111.05659) for a comprehensive review of QG models and tests with cosmic messengers
- Terzić et al. 2021 (arXiv:2109.09072) for a review focused on tests with gamma rays

Energy dependent photon group velocity

$$S_n = \begin{cases} +1, \text{ superluminal} \\ -1, \text{ subluminal} \end{cases} \qquad n = \begin{cases} 1, \text{ linear} \\ 2, \text{ quadratic} \end{cases}$$

$$v_\gamma = \frac{\partial E}{\partial p} \simeq c\left[1 + \sum_{n=1}^{\infty} S_n \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG},n}}\right)^n\right]$$

- Difference in the time of flight of two photons $E_h > E_l$

$$\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{\mathrm{H}_0 E_{QG}^n} \kappa_n(z)$$

Effect accumulates over astronomical distances

- Optimising for parameter

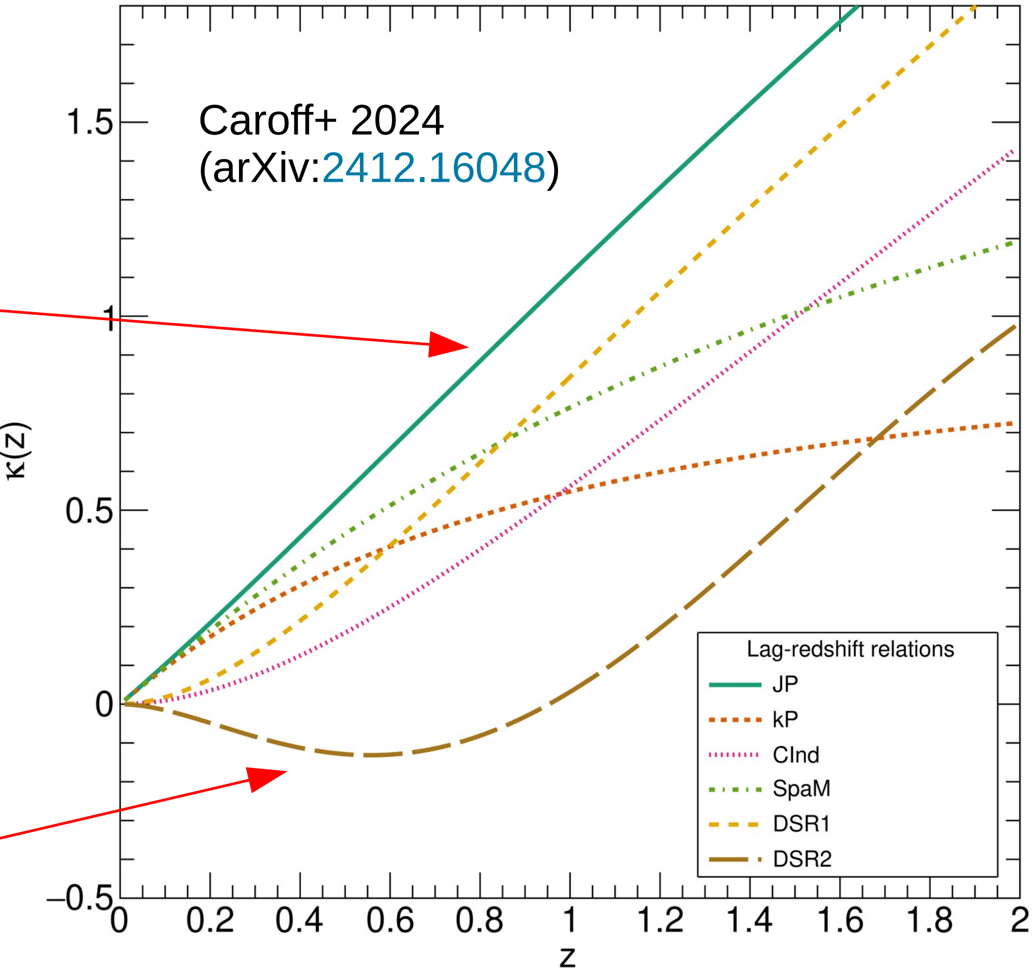
$$\lambda_n \equiv \frac{\Delta t_n}{\Delta E_n \; \kappa_n(z)} = \pm \frac{n+1}{2\mathrm{H}_0 \; E_{QG}^n}$$

Distance contributions comparison

Standard:
Jacob & Piran (2008, arXiv: 0712.2170)

$$\kappa_n^{\mathrm{J\&P}}(z) \equiv \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}\, dz'$$

Interesting to play with (DSR2)



- **First study** comparing two lag-redshift models
- Additional alternative expressions may be considered in future work

Time of Flight

for JP

- Sensitivity to QG energy scale

$E_{\rm QG,1}$	$\propto$	$E_{\rm max}$	$t_{\rm var}^{-1}$	$z_{\rm s}^{\sim 1}$
$E_{\rm QG,2}$	$\propto$	$E_{\rm max}$	$t_{\rm var}^{-1/2}$	$z_{\rm s}^{\sim 2/3}$

Terzić et al. 2021 (arXiv:2109.09072)

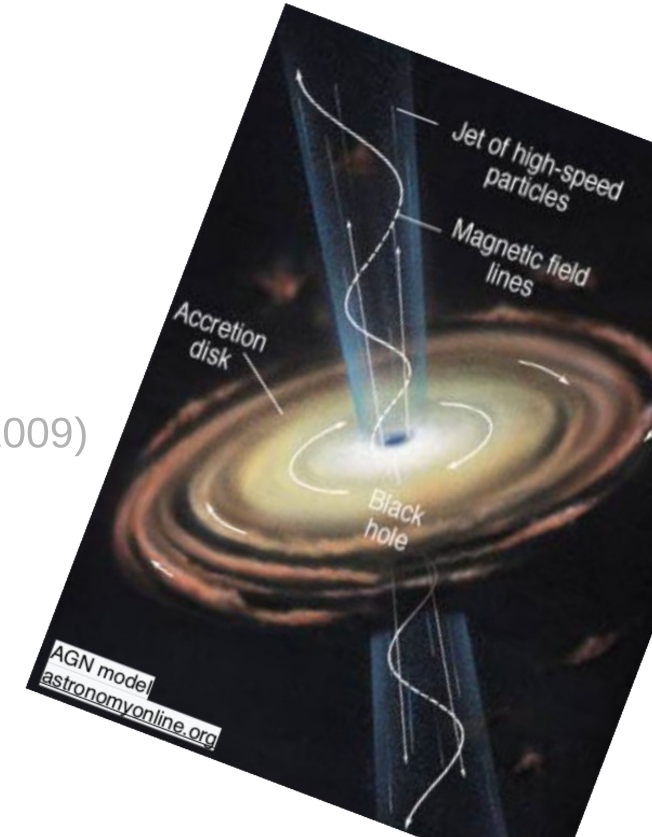
- Challenges:
  - Constraining emission time → Use fast variability sources
  - Resolving intrinsic energy-dependent time delays from LIV-induced ones → Use several different (types of) sources

γ-ray LIV WG

- Present collaboration:
  H.E.S.S. – LST – MAGIC – VERITAS
- Energy range: ~20 GeV – 100 TeV
- Combining available data
  - Increases statistics
  - Sources at different distances/redshifts
    discriminates between different LIV models
  - Different (types of) sources
    reduces the impact of intrinsic effects
- Analysis method: Bolmont+ 2022 (arXiv: 2201.02087)

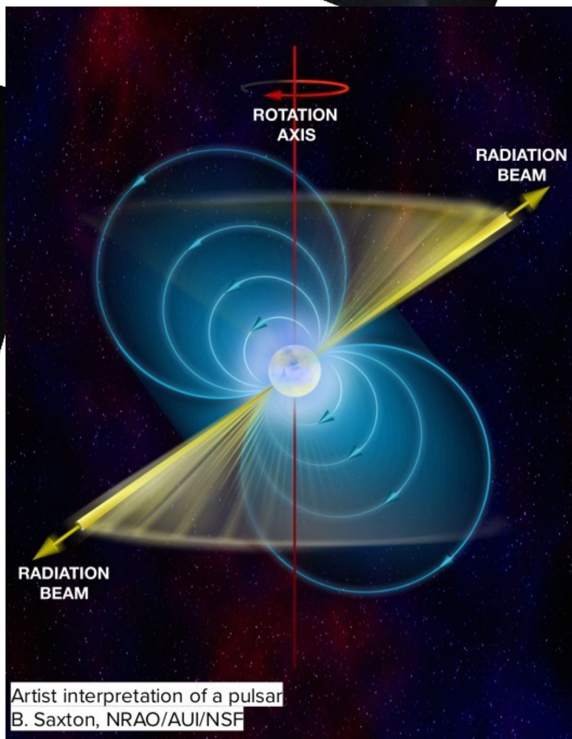
Astrophysical sources

- Active Galactic Nuclei
  - Mrk 501 2005 flare: MAGIC (Albert+ 2008; Martinez & Errando, 2009)
  - PKS 2155-304 2006 flare: H.E.S.S. (Aharonian+ 2008; Abramowski+ 2011)
  - PG 1553+113 2012 flare: H.E.S.S. (Abramowski+ 2015)
  - Mrk 421 2014 flare: MAGIC (Abe+ 2024)
  - 1ES 1959+650 2012 flare: VERITAS
  - BL Lac 2020 – 2021 flares: CTAO-LST
- Pulsars
  - Crab: MAGIC (Ahnen+ 2017)
  - Vela: H.E.S.S. (Chrétien+ 2015)
- Gamma-ray Bursts
  - GRB 190114C: MAGIC (Acciari+ 2020)



AGN model
astronomyonline.org


Artist interpretation of a GRB
Superbossa.com and C. Righi



Artist interpretation of a pulsar
B. Saxton, NRAO/AUI/NSF

Results

- Using unbinned maximum likelihood approach
- First results based on:
  BL Lac (CTAO-LST), PKS 2155-304 (H.E.S.S.),
  1ES 1959+650 (VERITAS), GRB 190114C (MAGIC)

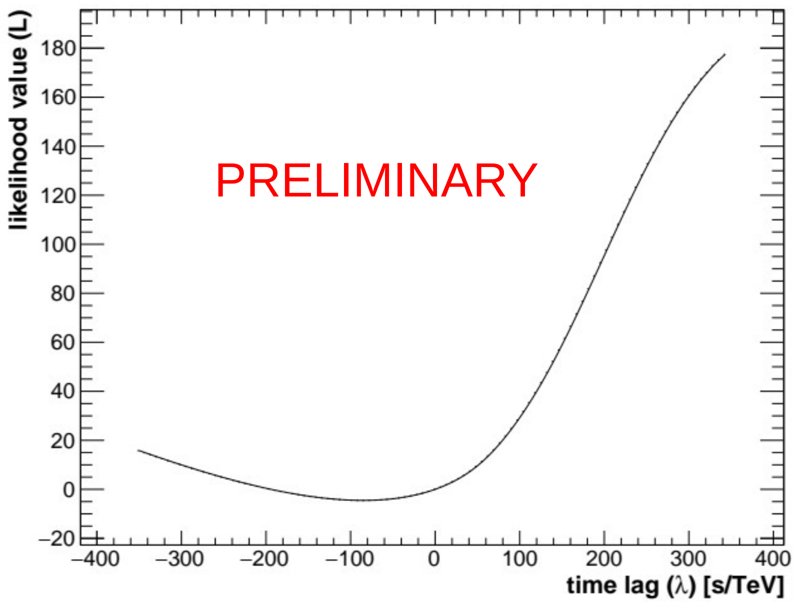
$$L_{comb}(\lambda_n) = \sum_{\text{all sources}} L_S(\lambda_n)$$

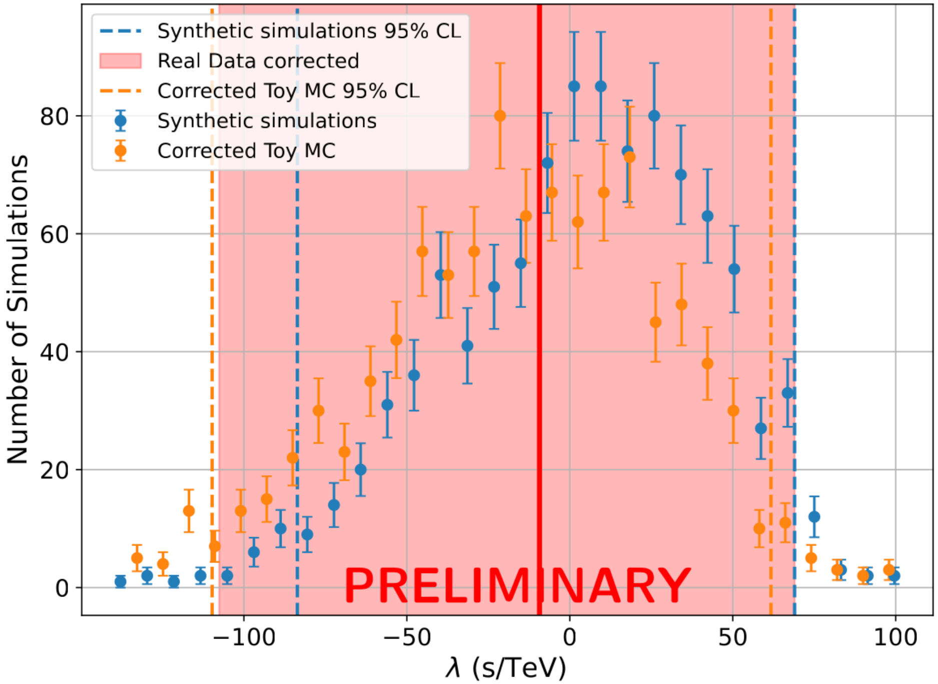
- Maximum likelihood for:

$$\lambda_{\text{rec}} = -80^{+78}_{-98}\,\text{s}/\text{TeV}$$

- Bias estimated using bootstrap
  Results corrected for bias:

$$\lambda_{\text{rec}} = -9.3^{+78}_{-98}\,\text{s}/\text{TeV}$$

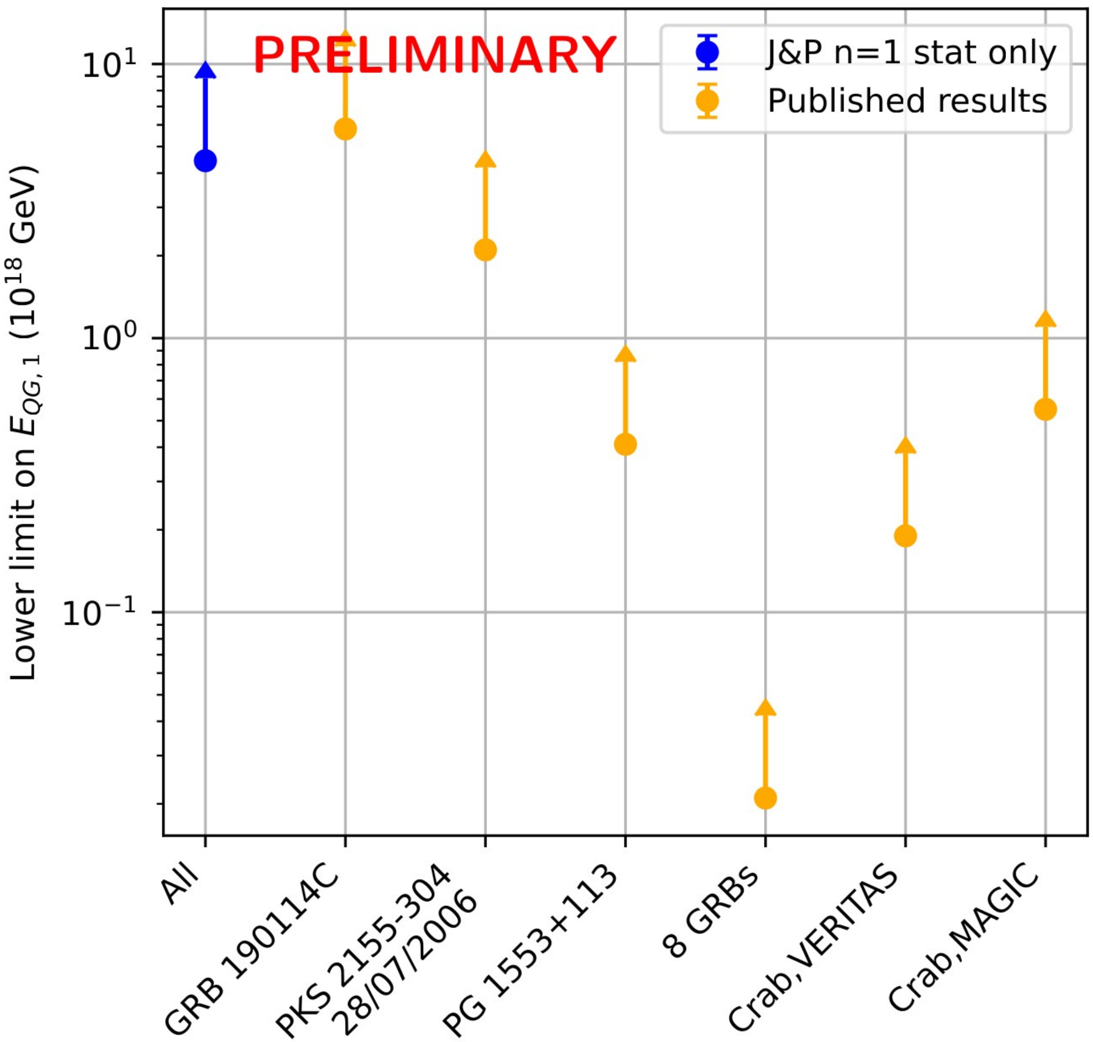




Results

- 2 time-delay models considered:
  - J&P (standard LIV, arXiv:0712.2170)
  - DSR2 designed to cancel the contribution from GRB 190114C (arXiv:2412.16048)

$E_{\mathrm{QG},1}$ [10^{18} GeV]	J&P	DSR2
superluminal	4.44	0.45
subluminal	5.58	0.62



- Systematics not fully taken into account → Final result will be less constraining
- Some sources still to be included in the analysis

Takeaways

- **First joint analysis** from a cooperation of IACTs data for LIV
  - H.E.S.S., CTAO-LST, MAGIC and VERITAS
  - Higher statistics of sources and photons
- **First combination of different types of sources**
  - Different intrinsic characteristics reduce influence of source intrinsic effects
  - Redshift dependency on the LIV effect
- **First comparison of different distance models**
- Instrument Response Functions
  - Vary for each source and for each instrument
  - Fully taken into account

- COST Action CA23130: https://www.cost.eu/actions/CA23130/
Bridging high and low energies in search of quantum gravity (BridgeQG)

Working Groups' Structure

WG	Working Group	Leader	Vice Leader
1	High-energy quantum gravity theory	Dr Christian Pfeifer	Prof Alessia Platania
2	High-energy quantum gravity experiment	Dr Tomislav Terzić	Dr Alba Domi
3	Low-energy gravitational effects in quantum systems	Dr Lin-Qing Chen	Dr Thomas Galley
4	Low-energy high-precision experiment	Dr Matteo Fadel	Dr Catalina Oana Curceanu
5	Connection between low-energy and high-energy QG	Dr Flavio Mercati	Dr Giacomo Rosati
6	Dissemination and Diversity	Dr Jelena Strišković	Dr Denitsa Staicova

Discover More

Back-up

Likelihood analysis – for single observation

observed spectrum

observed light curve

$$F_s(E_t, t; \lambda_n) = \frac{\Gamma_s(E_t)\, C_s\, (t - D(E_t, \lambda_n, z))}{N_s}$$

energy resolution

observation conditions

effective area

$$D(E_t, \lambda_n, z) = \lambda_n \times \kappa_n(z) \times E_t^n$$

LIV induced time delay

$$\frac{dP}{dE_m dt} = w_s \, \frac{\int A(E_t, \vec{\varepsilon}) M(E_t, E_m) \times F_s(E_t, t; \lambda_n) dE_t}{N'_s}$$

$$+ \sum_k w_{b,k} \, \frac{\int A(E_t, \vec{\varepsilon}) M(E_t, E_m) \times F_{b,k}(E_t, t) dE_t}{N'_{b,k}}$$

different background contributions

background no time delay

$$F_{b,k}(E_t, t) = \frac{\Gamma_{b,k}(E_t)\, C_{b,k}}{N_{b,k}}$$

See Bolmont+ 2022
arXiv: 2201.02087

Likelihood analysis – combining observations

- Single observation

$$L_S(\lambda_n) = -\sum_{\mathrm{i}} \log\left(\frac{dP}{dE_m dt}(E_{m,i}, t_i); \lambda_n\right)$$

- Combining observations

$$L_{comb}(\lambda_n) = \sum_{\text{all sources}} L_S(\lambda_n)$$

- Optimising for parameter

$$\lambda_n \equiv \frac{\Delta t_n}{\Delta E_n \ \kappa_n(z)} = \pm \frac{n+1}{2\mathrm{H}_0 \ E_{QG}^n}$$

See Bolmont+ 2022
arXiv: 2201.02087

Systematics

See Bolmont+ 2022
arXiv: 2201.02087

Table A1. Summary of systematic uncertainties for all sources and combinations simulated for the J&P case.

Source	Correction order	Template statistics (s.TeV^{-n})	Energy scale (s.TeV^{-n})	Background normalization (s.TeV^{-n})	Uncertainty on power law index (s.TeV^{-n})	Distance/redshift uncertainty (s.TeV^{-n})	Reconstruction uncertainty (s.TeV^{-n})	All syst. combined (s.TeV^{-n})
GRB 190114C	$n = 1$	17.8	6.9	8.0	9.4	< 7.7	3.0	25.6
	$n = 2$	9.4	12.4	1.7	15.4	< 9	4.2	24.1
PKS 2155-304	$n = 1$	101	11.7	< 20	< 22	17.8	< 3.3	107
	$n = 2$	21.8	19.3	0.7	8.1	12.0	< 2.2	37.4
Mrk 501	$n = 1$	155	56	< 51	49	1.	< 8.5	197
	$n = 2$	11.2	18.3	< 10.3	9.3	0.19	< 1.6	28.8
PG1553+113	$n = 1$	631	150	324	< 361	112	< 64	727
	$n = 2$	916	638	537	< 552	338	< 112	1282
Crab V	$n = 1$	897	137	< 73	142	145	< 25	1135
	$n = 2$	1141	410	< 264	694	265	< 174	1820
Crab M	$n = 1$	371	66	7	23	74	< 11	416
	$n = 2$	167	64.5	61	24	48	< 72	190
Vela	$n = 1$	1.36×10^4	1.03×10^4	0.46×10^4	$< 1.3 \times 10^4$	1.30×10^3	$< 5.87 \times 10^3$	2.28×10^4
	$n = 2$	1.0×10^5	2.05×10^5	0.48×10^5	$< 1.5 \times 10^5$	1.57×10^5	$< 0.95 \times 10^5$	3.05×10^5
Crab (M+V)	$n = 1$	357	49	< 56	32	61	< 32	398
	$n = 2$	161	59	45	59	38	< 83	197
PSR	$n = 1$	355	52	< 58	38	58	< 11	394
	$n = 2$	90	71	49	24	62	< 55	138
AGN	$n = 1$	89.5	12	< 15	3.7	15.8	< 2.9	94.9
	$n = 2$	10.1	11.1	< 6	6.2	3.4	< 1.3	19.7
AGN+PSR	$n = 1$	85	11	< 18	5	15	< 2.9	91
	$n = 2$	9.6	10.9	< 8	5.9	4.5	< 1.1	17.8
GRB+AGN	$n = 1$	17.8	5.8	6.8	8.3	1.4	3.3	24.5
	$n = 2$	6.8	7.8	< 6.6	9.0	1.7	1.4	16.2
GRB+PSR	$n = 1$	17.5	6.7	7.9	9.1	1.0	3.2	24.9
	$n = 2$	8.1	11.3	1.6	12.7	2.8	< 1.1	19.4
All	$n = 1$	18.0	5.8	6.7	8.2	1.5	4.1	24.8
	$n = 2$	7.5	7.7	< 6.2	8.2	2.4	4.8	16.4