LIV and source intrinsic effects

BridgeQG Workshop

Bridging High-Energy Astrophysical Modelling and Lorentz Invariance Violation Studies

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Tomislav Terzić

Faculty of Physics
University of Rijeka

tomislav.terzic@gmail.com

LIV effects

- Testing for consequences of Lorentz symmetry breaking or deformation
  - Propagation time delays
  - Modified reaction thresholds
  - Modified reaction dynamics
  - Vacuum birefringence
  - Impact on neutrino oscillations

$$E_{\mathrm{i}}^2 = m_{\mathrm{i}}^2 c^4 + p_{\mathrm{i}}^2 c^2 \left[1 + \sum_{n=1}^{\infty} \eta_n^{(\mathrm{i})} \left(\frac{p_{\mathrm{i}} c}{E_{\mathrm{QG},n}^{(\mathrm{i})}} \right)^n \right]$$

Modified dispersion relation - the usual starting point for LIV tests

Check: Addazi et al. 2022 (arXiv: 2111.05659) for a comprehensive review of QG models and tests with cosmic messengers

See: QG-MM Catalogue for a census of measurement results

Testing & measuring LIV

- Typical accelerator experiment

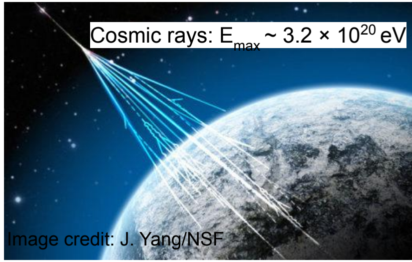
$$E_{\mathrm{i}}^2 = m_{\mathrm{i}}^2 c^4 + p_{\mathrm{i}}^2 c^2 \left[1 + \sum_{n=1}^{\infty} \eta_n^{(\mathrm{i})} \left(\frac{p_{\mathrm{i}} c}{E_{\mathrm{QG},n}^{(\mathrm{i})}} \right)^n \right]$$

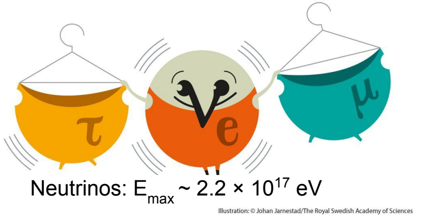
However

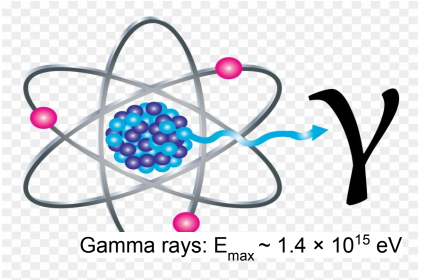
- Expected energy scale of QG: $E_{\mathrm{Pl}} \sim 10^{28}$ eV
- LHC $E = 10^{13}$ eV (10^{17} eV in proton rest frame)
- LHC $t \lesssim$ day

Astroparticles

- UHECR: $E \sim 10^{20}$ eV
- ν: $E \sim 10^{17}$ eV
- γ: $E \sim 10^{15}$ eV
- $t \sim 10^3 - 10^{10}$ years

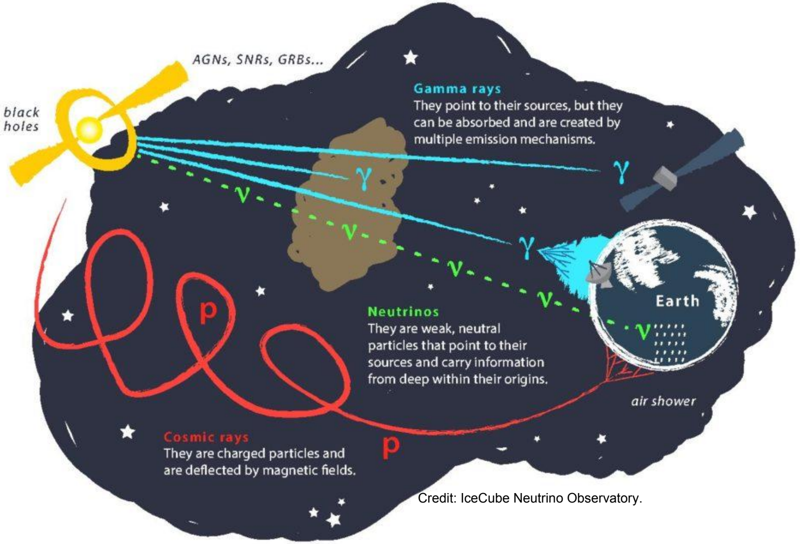




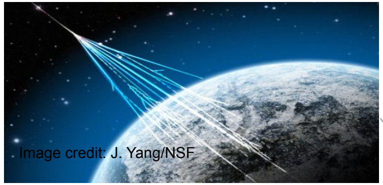


Messenger pros & cons

- Cosmic rays
  - Highest energies
  - Highest fluxes
  - Charged →trajectories deflected by magnetic fields
- Gamma rays
  - Straight propagation from the source
  - Easily detectable
  - Lowest energies
- Neutrinos
  - Straight propagation from the source
  - Probe interiors of sources
  - Notoriously difficult to detect
  - Poor angular resolution

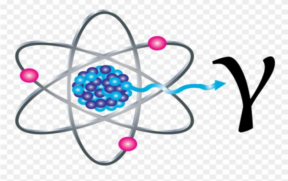


Credit: IceCube Neutrino Observatory.



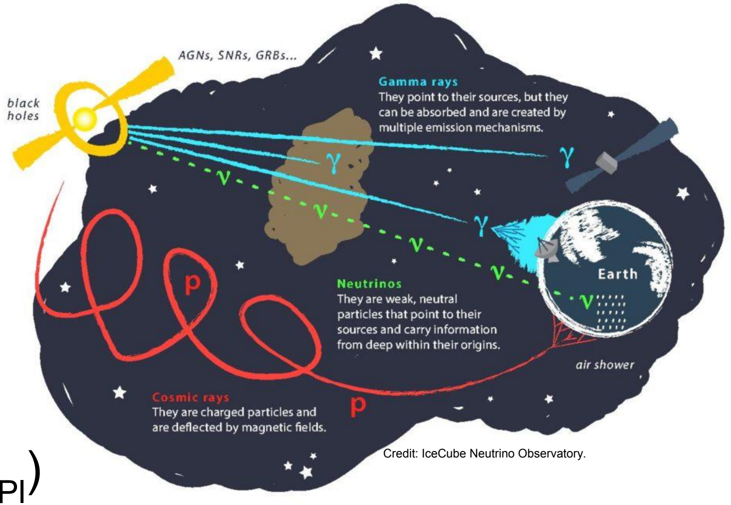
Cosmic rays: $E_{max} \sim 3.2 \times 10^{20}$ eV

Neutrinos: $E_{max} \sim 2.2 \times 10^{17}$ eV



Gamma rays: $E_{max} \sim 1.4 \times 10^{15}$ eV

Astroparticle tests of QG



Credit: IceCube Neutrino Observatory.

Fundamental physics accelerator experiment

- **Pros**
  - **Ultra-high energies**
    (although still orders of magnitude below E_{Pl})
  - Accumulation of effects on **Gyear** time scale

- **Cons: No control over & limited knowledge of**
  - Source: astrophysical accelerators
  - Propagation: CMB, EBL, IGMF, cosmology, spacetime curvature
  - Detector: atmosphere, ice, water

Gamma-ray time of flight

$$L_S(\lambda_n) = -\sum_{\text{i}} \log\left(\frac{dP}{dE_m dt}(E_{m,i}, t_i); \lambda_n\right) \qquad \lambda_n \equiv \frac{\Delta t_n}{\Delta E_n \ \kappa_n(z)} = \pm \frac{n+1}{2\text{H}_0 \ E_{QG}^n}$$

instrumental effects

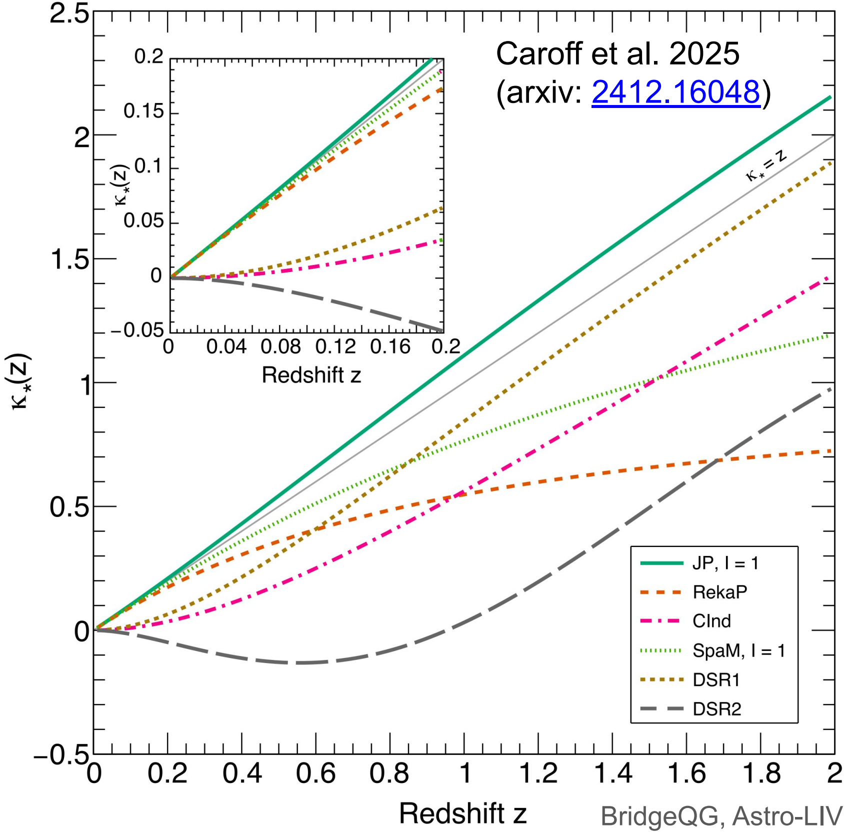
signal

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

background contributions

Bolmont et al. 2022 (arXiv:2201.02087)

LIV time-delay models



spectrum

light curve

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

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

LIV induced time delay

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

Source input

spectrum

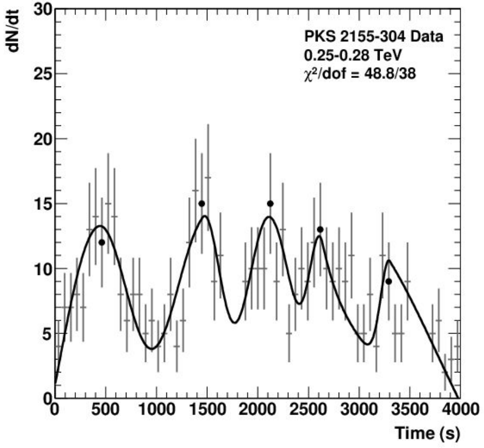
light curve

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

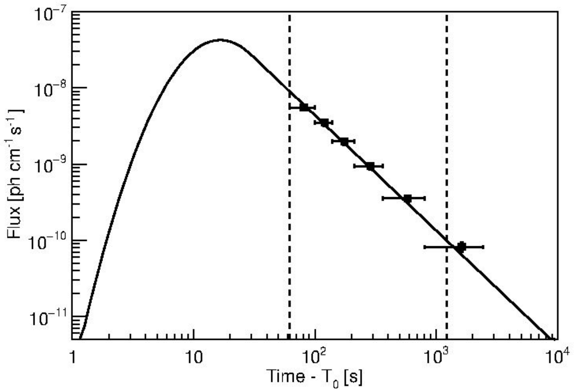
Assumptions

- Independent distributions in energy and time
- Spectrum usually obtained from the whole data set
- Light curve modelled in different ways
  - Identical temporal distributions in different energy bands
  - LIV effects on low-energy events negligible

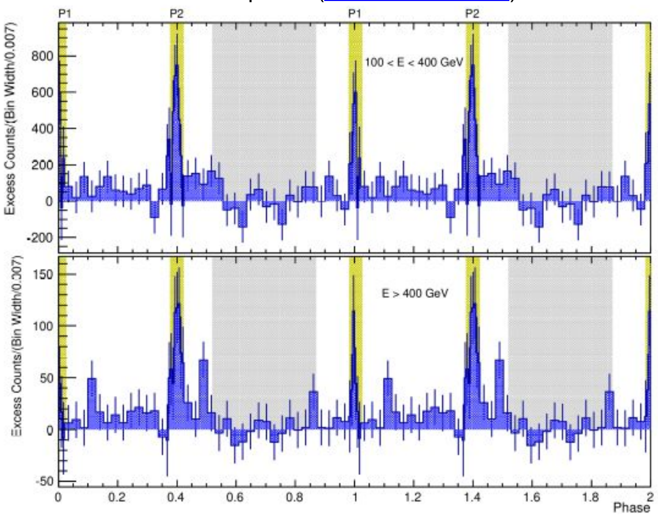
PKS 2155 (H.E.S.S. Coll. 2011)



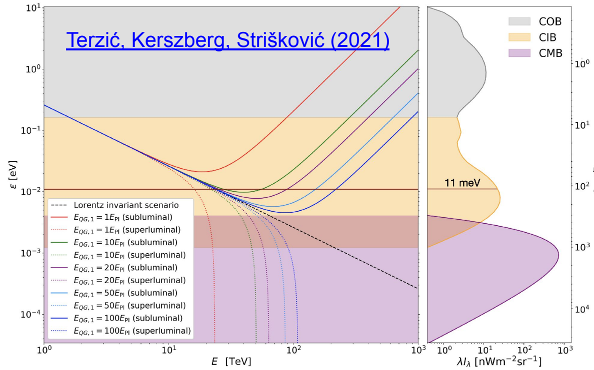
GRB 190114C (MAGIC Coll. 2020)

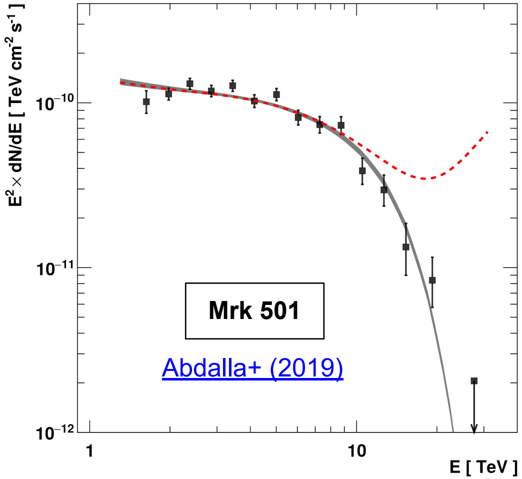


Crab pulsar (MAGIC Coll. 2016)



Modified gamma-ray reactions





- Modified kinematics and dynamics

$$\epsilon_{th} = \frac{m_e^2}{(1+z)E_\gamma} \longrightarrow \frac{m_e^2}{(1+z)E_\gamma} + S\frac{((1+z)E_\gamma)^{n+1}}{4E^n_{\mathrm{QG,n}}}$$

- LIV ambiguities: which particles are affected

$$\gamma + \gamma_{EBL} \longrightarrow e^+ + e^-$$

- Cosmological ambiguities

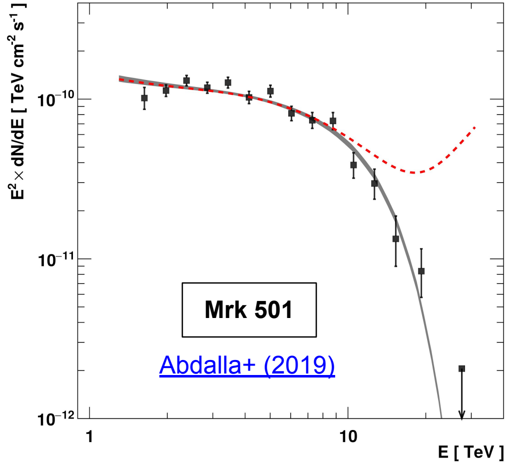
$$\tau(E_\gamma, z_s) = \int_0^{z_s} \mathrm{d}z \frac{\mathrm{d}l(z)}{\mathrm{d}z} \int_{\epsilon_{th}}^{\infty} d\epsilon \frac{dn_{EBL}(\epsilon, z)}{d\epsilon} \int_0^2 d\mu \frac{\mu}{2} \sigma_{\gamma\gamma}(s)$$

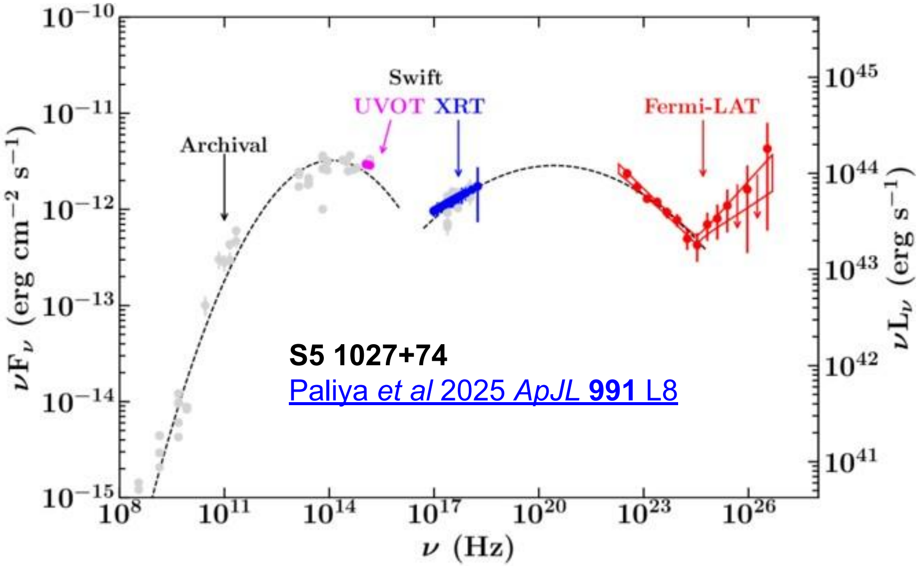
Source input

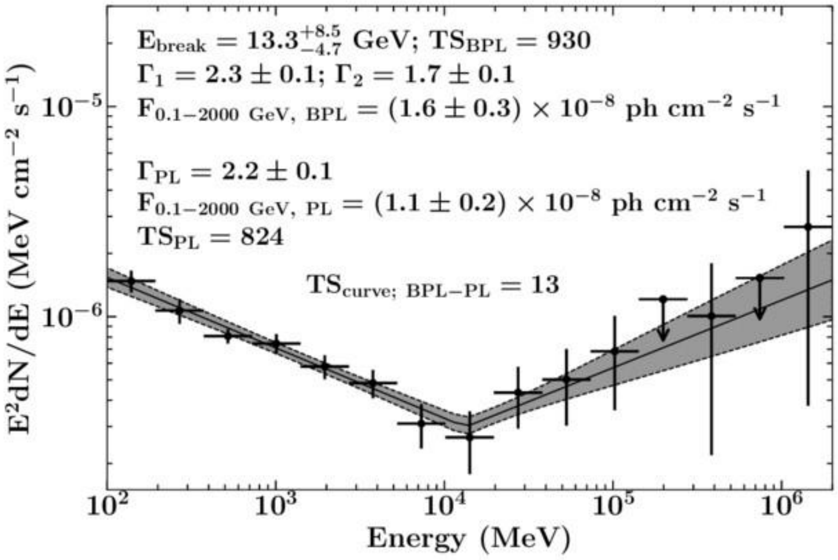
QUANTUM GRAVITY · BRIDGING HIGH & LOW ENERGIES

Assumptions

- Spectrum is expected to be continuous
- Spectral upturn is physically unexpected







LIV effects on particle acceleration and emission

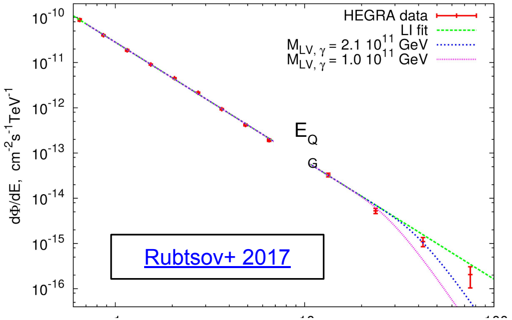
$$E_i^2 = m_i^2 c^4 + p_i^2 c^2 \left[1 + \sum_{n=1}^{\infty} \eta_n^{(i)} \left(\frac{p_i c}{E_{QG,n}^{(i)}} \right)^n \right]$$

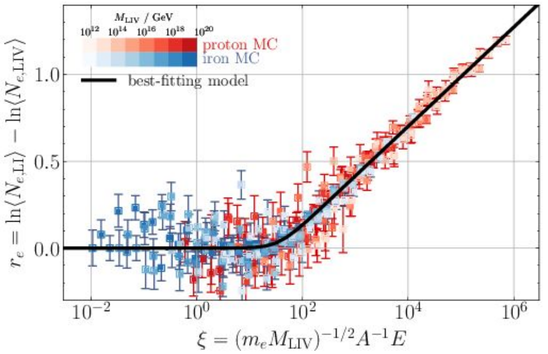
- η = +/- 1 → increased / decreased interaction rate
- Fermi acceleration mechanism more/less effective
- +1 → HE particles become unstable → limits on E_{max}
- -1 → extended lifetime of unstable particles
  - e.g. π^0 interacts before decaying
- -1 → upper limit on synchrotron radiation energy (Jacobson+ 2003)
- Limitation on Compton scattering – Abdalla & Böttcher (2018): LIV signatures expected to be important only for $E_\gamma \gtrsim 1$ PeV (see also Li & Ma, 2022)
- …

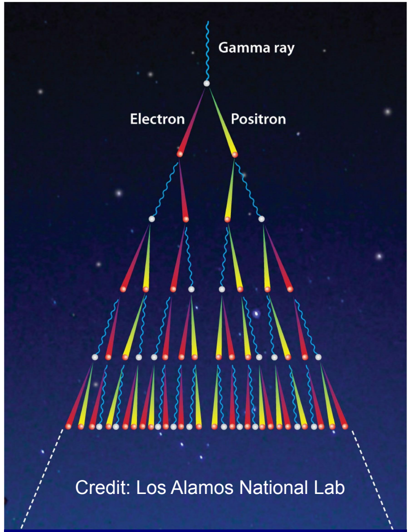
- This is all in addition to uncertainties in standard acceleration and emission modelling

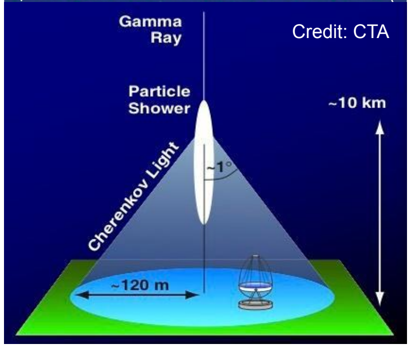
LIV effects on detection

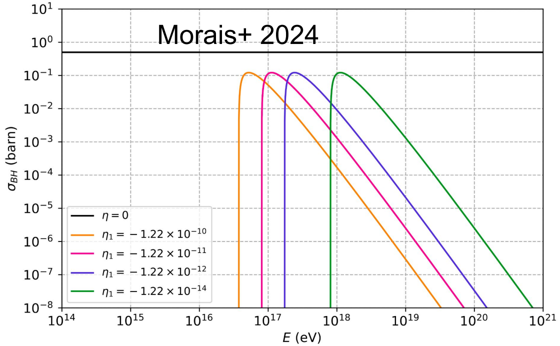
- η = +/- 1 → increased / decreased interaction rate
  - Overall effect opposite to the effect on propagation

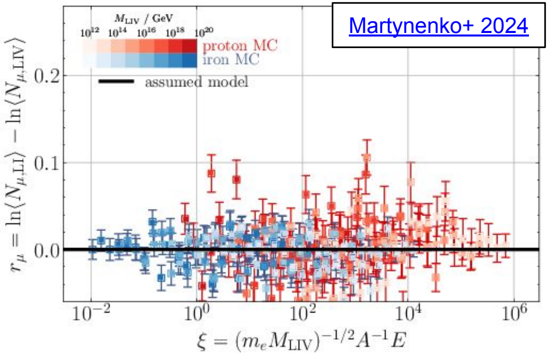












Takeaways

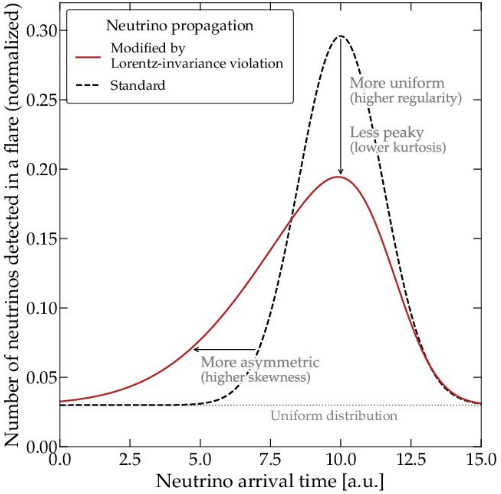
- Astroparticle experiments – significantly higher energies than ground based accelerator experiments
- Ambiguities and uncertainties related to emission, propagation, detection
- LIV studies plagued with some strong assumptions
- Studies based on UHECRs and neutrinos face field-specific but essentially similar issues
- Wish list:
  - Energy and temporal distribution of events at emission
  - UHECR → chemical composition + proton E_{max}

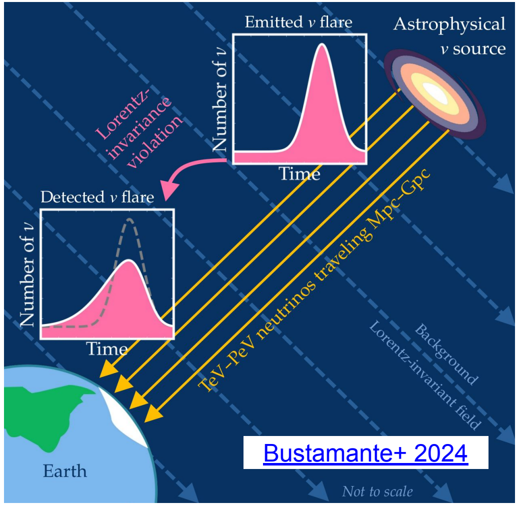
Backup

Neutrino time of flight

- Essentially same as gamma-ray time of flight

However
- Very low statistics
- Difficult association with sources → multi-messenger observations

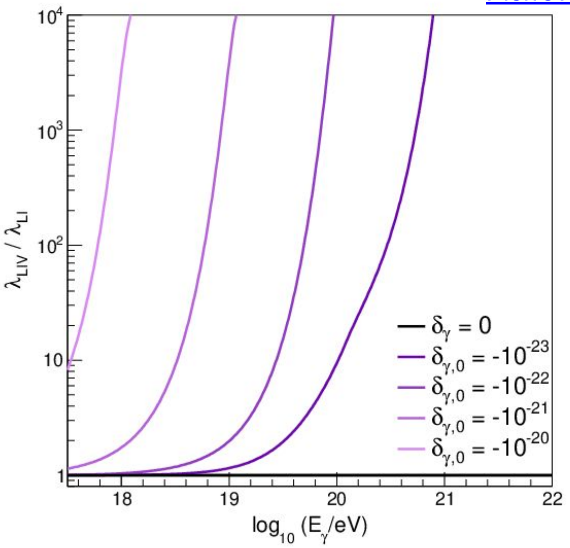


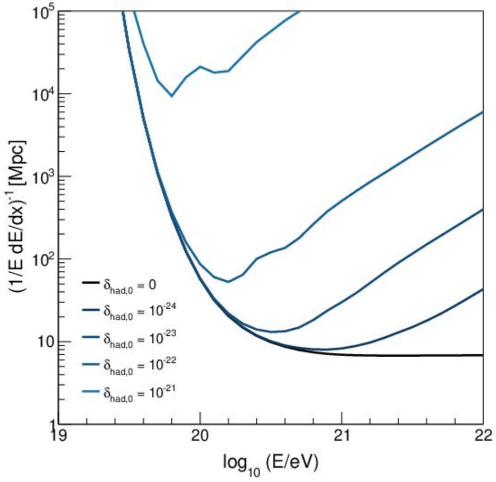


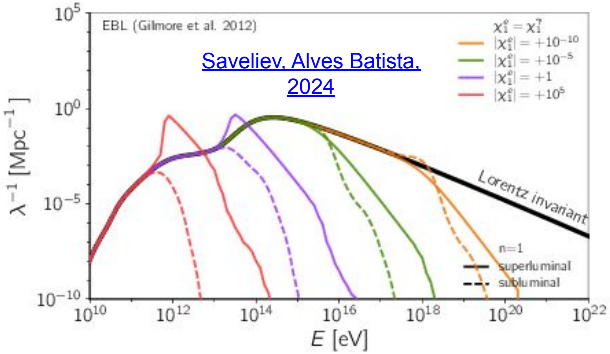
Modified gamma-ray reactions

- Based on cosmic ray, gamma ray, and neutrino interactions and stability
  - Increased/decreased universe transparency
  - Superluminal massless particle decay
  - Vacuum Čerenkov emission

Pierre Auger Collab. 2022







Saveliev, Alves Batista, 2024

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

Bolmont et al. 2022
(arXiv:2201.02087)

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

Likelihood analysis for time delays

From: LIV on Mrk 421 by MAGIC Abe et al. JCAP07(2024)044 and Strišković (2025)

$$\mathcal{L} = \prod_{i=1}^{N_t} \prod_{j=1}^{N_E} \mathcal{P}(s_{i,j}, b_{i,j} | N_{\mathrm{on},i,j}, N_{\mathrm{off},i,j})$$

- bins in time: N_t
- bins in energy: N_E
- expected signal count: $s_{i,j}$
- expected background count: $b_{i,j}$
- detected count in ON region: $N_{\mathrm{on},i,j}$
- detected count in OFF region: $N_{\mathrm{off},i,j}$

$$\mathcal{P}(s,b) = \frac{(s+\alpha b)^{N_{\mathrm{on}}}}{N_{\mathrm{on}}!} e^{-(s+\alpha b)} \frac{b^{N_{\mathrm{off}}}}{N_{\mathrm{off}}!} e^{-b}$$

$$s_{i,j} = \sum_{k=1}^{N_{\mathrm{bin}}} \int_{\Delta E'_j} dE' \int dE \, \frac{d\Phi_k(E)}{dE} \, B(E) \, A_i(E) \, G_i(E'|E) \, \Delta t_{i,k}(\eta_n, E)$$

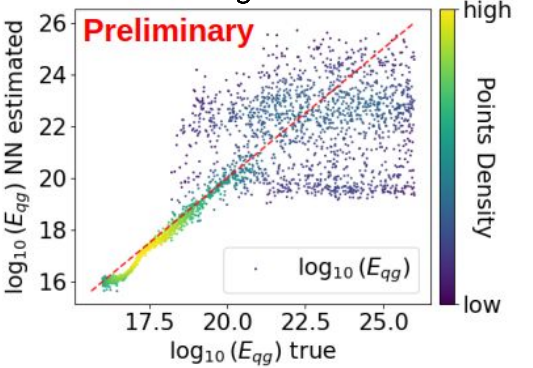
Combining LIV effects

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - m\bar{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\varkappa\bar{\psi}\gamma^{i}D_{i}\psi + \frac{ig}{M^2}D_j\bar{\psi}\gamma^{i}D_{i}D_{j}\psi + \frac{\xi}{4M^2}F_{kj}\partial_i^2F^{kj},$$

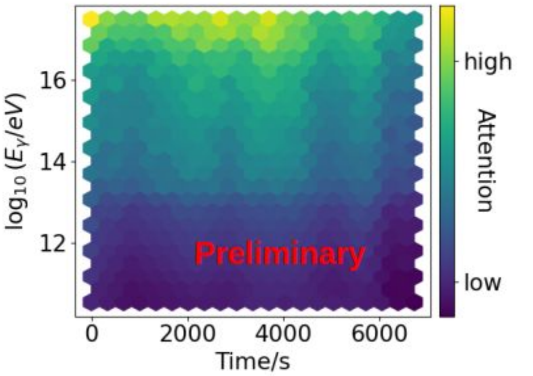
Rubtsov et al. (2012)

- n = 1: time delays + modified interactions + vacuum birefringence
- n = 2: time delays + modified interactions (Rubtsov+ case)
- affected particles?

ANN-VIL – attempt at combining LIV effects



Terzić & Mrakovčić (2025)



Mrk 421 MAGIC flare 2014

Strišković (2025)