The New Era of Multi-Messenger Astroparticle Physics, IFPU, February 2024

What is the present understanding of LIV with transients?

Samanta Macera, PhD Student at GSSI

Outline

- Basic theoretical framework
- Gamma-ray bursts as LIV laboratories
- Most recent results from GRBs
- Caveats: EBL absorption and intrinsic spectral lags
- Future prospects

LIV: (Very) Basic theoretical framework

Quantum Gravity ⟺ Energy-dependent dispersion relation $E_{\mathrm{Pl}} = \sqrt{\hbar c^5/G} \simeq 1.22 \times 10^{19}\ \mathrm{GeV}$

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

Vardanyan et al 2023
Amelino-Camelia et al 2002

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$$\Delta t_{LIV}(n, E_2, E_1) \simeq \mathcal{S}\frac{n+1}{2}\frac{E_2^n - E_1^n}{E_{\mathrm{QG},n}^n}\int_0^{z_s} dz\frac{(1+z)^n}{H(z)} \equiv \tau_n(E_2^n - E_1^n)$$

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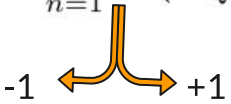

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LIV: Key Ingredients

$$\underbrace{\Delta t_{LIV}(n, E_2, E_1)}_{\substack{\text{Fast variability} \\ \text{(The sensitivity to detect TOF} \\ \text{effects depends inversely on the} \\ \text{signal variability)}}} \simeq \mathcal{S}\,\frac{n+1}{2}\,\frac{\overbrace{E_2^n - E_1^n}^{\text{Photons with different energies}}}{E_{\mathrm{QG},n}^n}\,\underbrace{\int_0^{z_s} dz\,\frac{(1+z)^n}{H(z)}}_{\text{Large Distances}} \equiv \tau_n(E_2^n - E_1^n)$$

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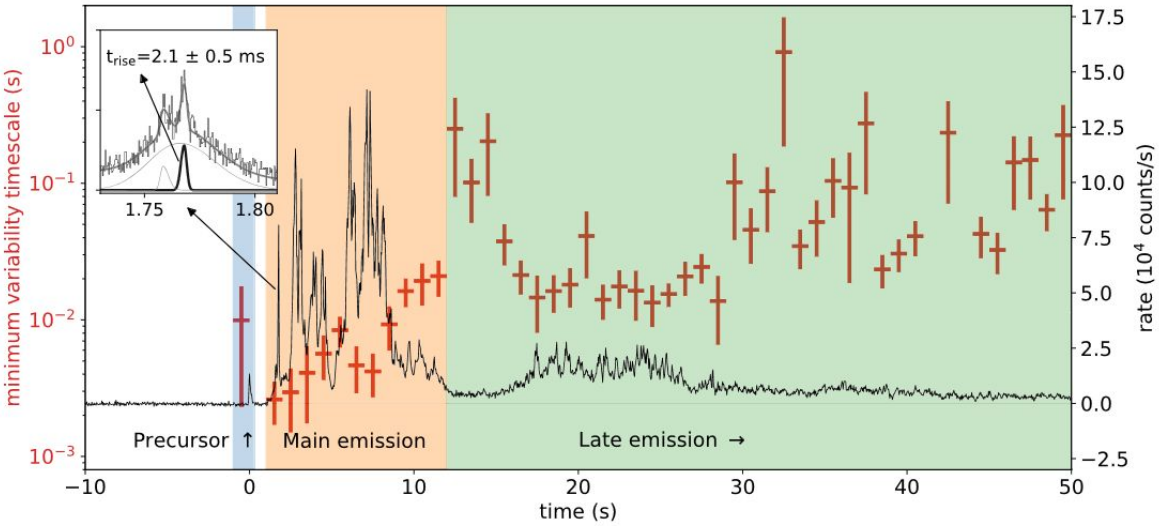
→ Gamma-ray Bursts

1 - Fast Variability and Spectral lag

Example of extreme variability: GRB 211211A



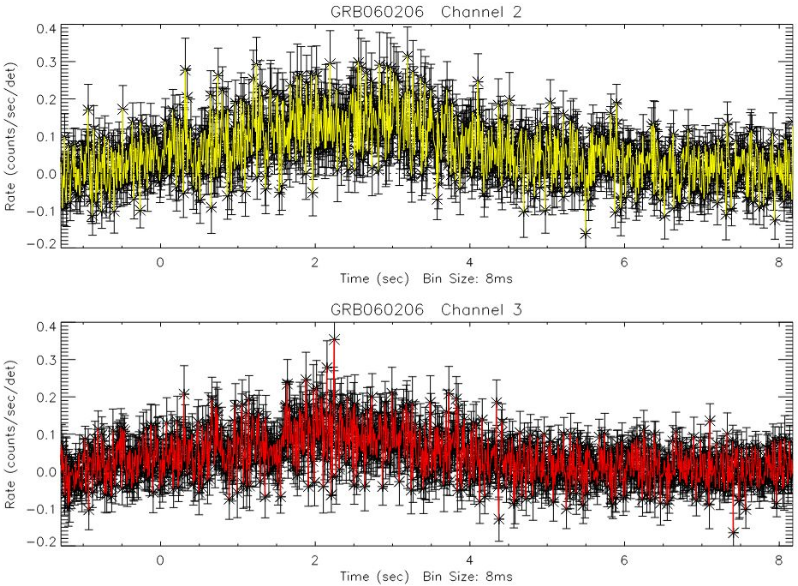
Veres et al 2023

1 - Fast Variability and Spectral lag

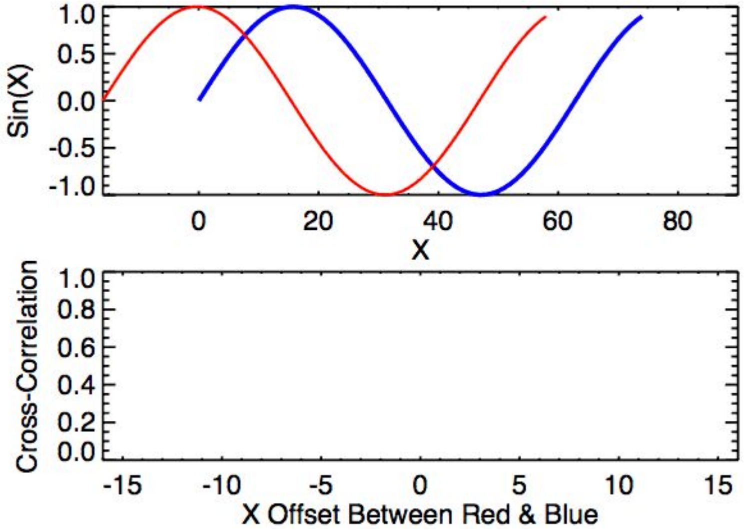
Spectral lag between different energy bands observed in many GRBs

$$\mathrm{CCF}_{\mathrm{Band}}(d, x, y) = \frac{\sum_{i=\max(1,1-d)}^{\min(N,N-d)} x_i \, y_{i+d}}{\sqrt{\sum_i x_i^2 \sum_i y_i^2}}$$

Ukwatta et al 2010



Light Curves from two different channels of *Swift*/BAT



CCF vs time delay

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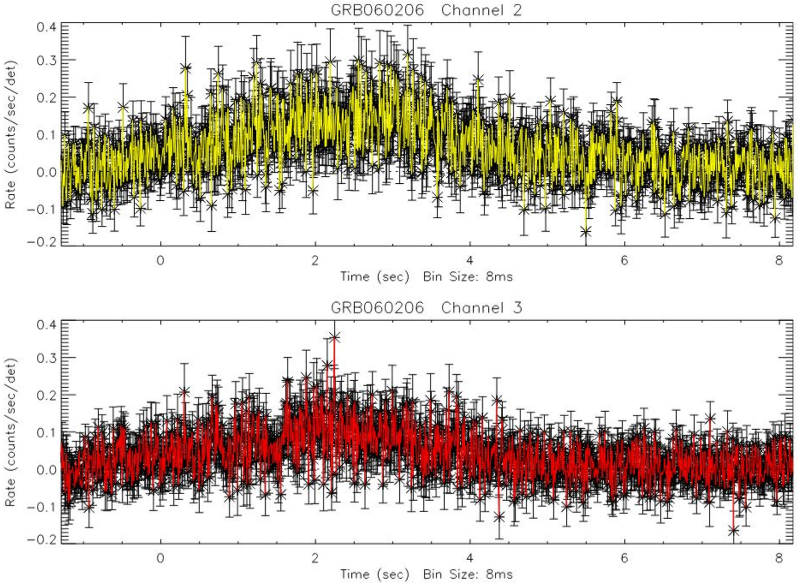
Ukwatta et al 2010



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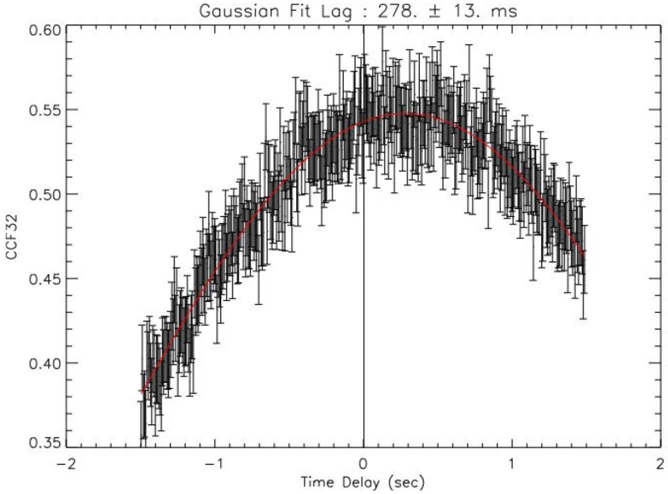


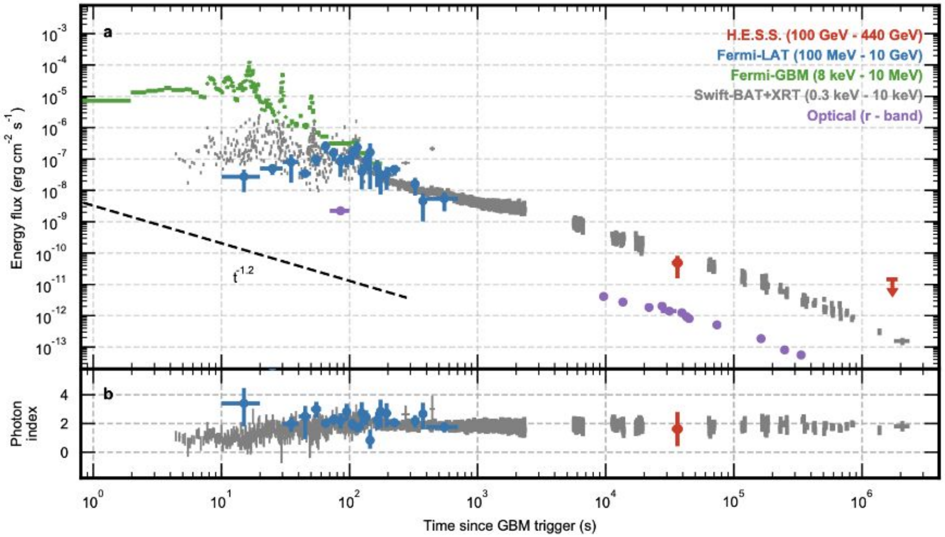
CCF vs time delay

2 - Highest energy photons

Some examples:

- GRB 090510 → 31 GeV (Fermi-LAT)
- GRB 080916C → 13 GeV (Fermi-LAT)
- GRB 090902B → 33.4 GeV (Fermi-LAT)
- GRB 180720B → 300 GeV (H.E.S.S.)
- GRB 190114C: → 1 TeV (Magic)
- GRB 221009A → > 10 TeV (LHAASO)

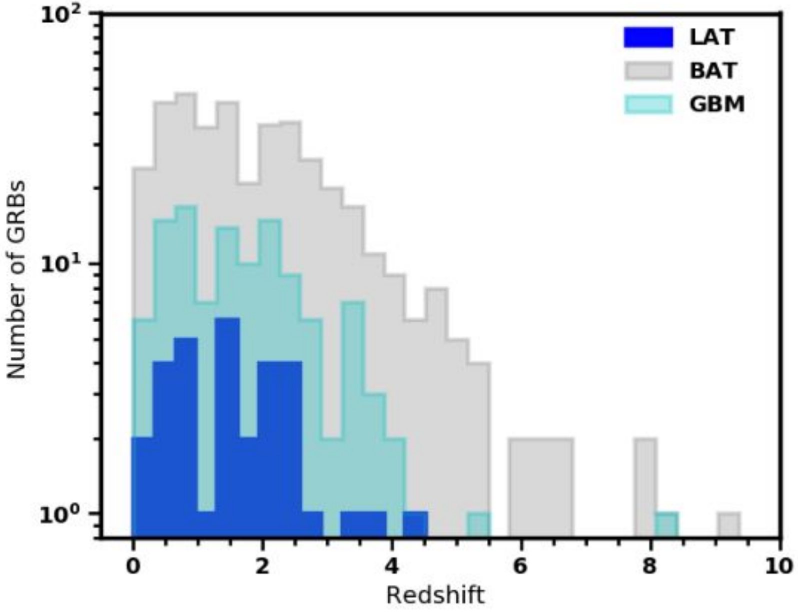
GRB 180720B



Abdalla et al 2019

3 - Large distances

Redshift distribution



Ajello et al 2019

Some estimates from GRBs:

Photon energy: ~ 30 GeV,
Average redshift: ~ 1,
Average delay : ~ 1s

$$\Delta t_{LIV}(n, E_2, E_1) \simeq \mathcal{S}\frac{n+1}{2}\frac{E_2^n - E_1^n}{E_{\mathrm{QG},n}^n}\int_0^{z_s} dz \frac{(1+z)^n}{H(z)}$$

E_{QG} ~ 10^{19} GeV
Planck Energy Scale

Caveat 1: EBL absorption

Photons can interact with the Extragalactic Background Light (EBL; $\sim 10^{-3}\ \mathrm{eV\ to\ 10\,eV}$) and produce pairs

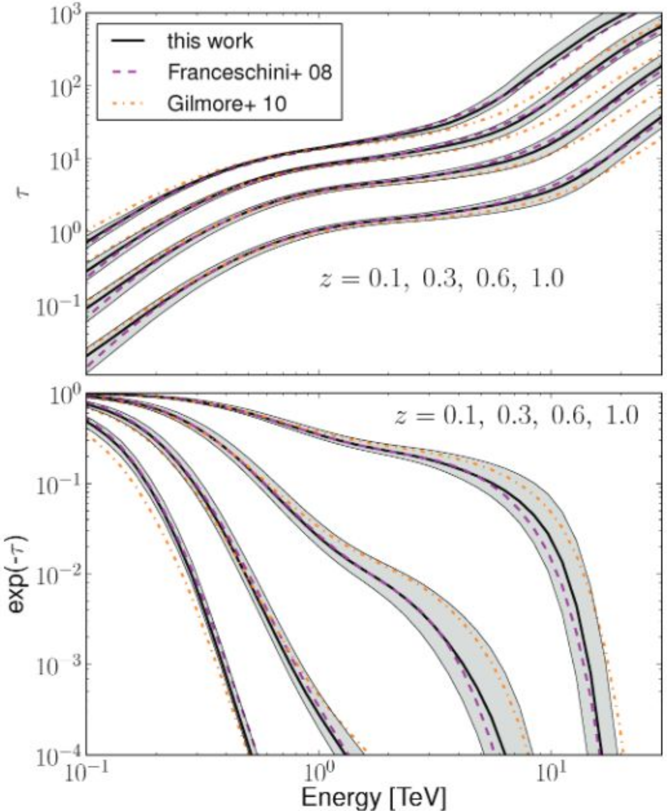
→ Attenuation of the flux

$$E_{\rm EBL} \approx \frac{2(m_e c^2)^2}{(1+z)^2 E} \approx 0.5(1+z)^{-2} E_{1\,\rm TeV}^{-1}\,\rm eV$$

$$\lambda_{\gamma\gamma}(E) = [\sigma_{\gamma\gamma} n_{\rm EBL}(E_{\rm EBL})]^{-1} \approx [0.26\sigma_T n_{\rm EBL}(E_{\rm EBL})]^{-1} \simeq 19 n_{\rm EBL,-1}^{-1}\,\rm Mpc$$

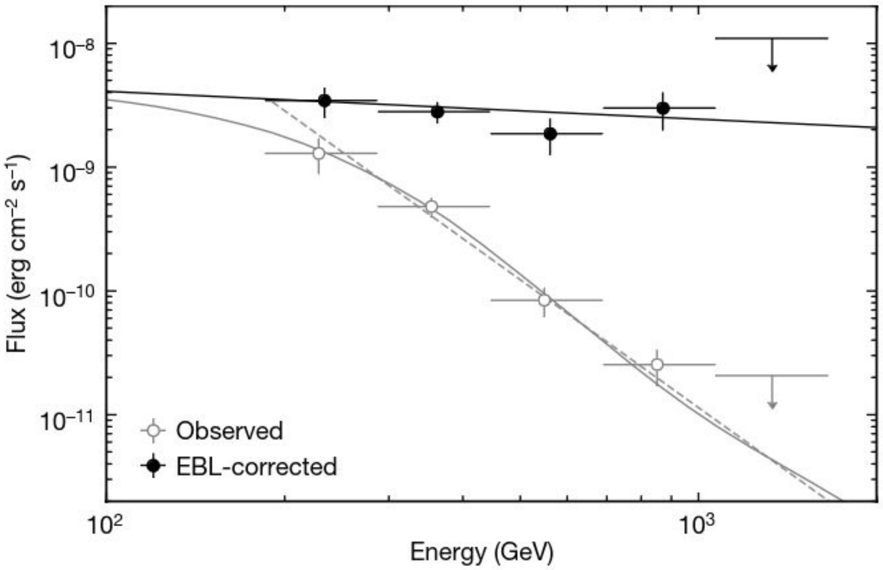
Gill et al 2022

Dominguez et al 2011

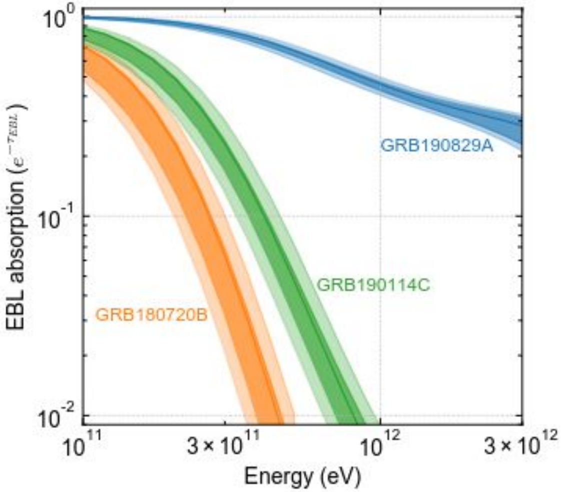


Caveat 1: EBL absorption

GRB 190114C



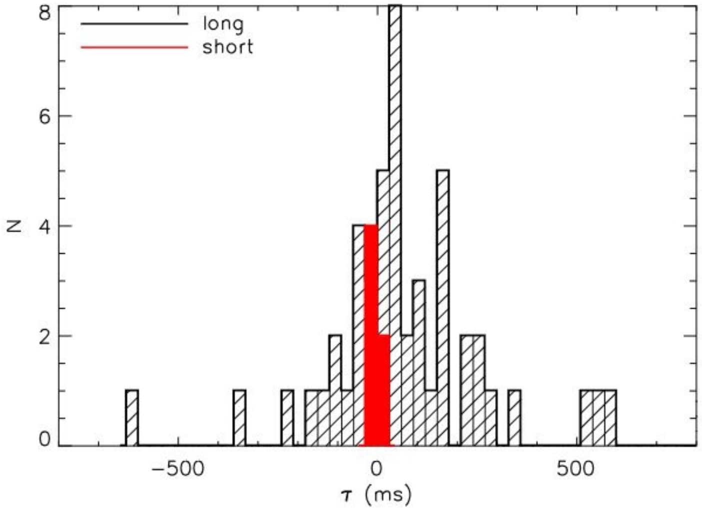
Magic Collaboration



H.E.S.S. Collaboration

Caveat 2: Spectral lag in GRBs

Spectral lags for long and short GRBs

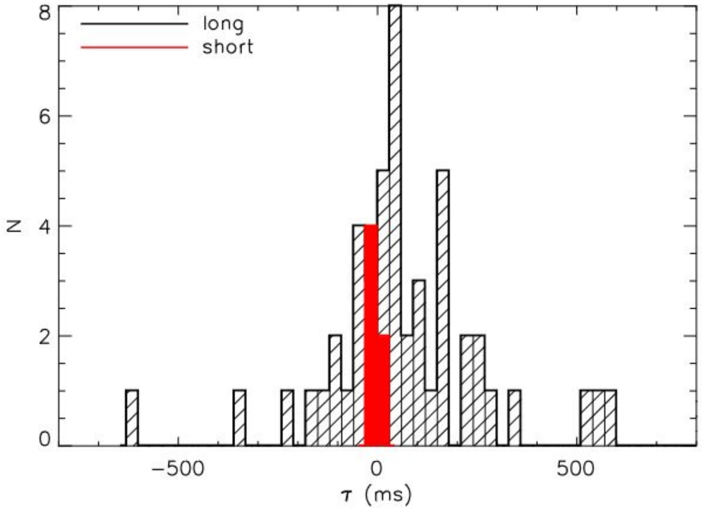


Bernardini et al 2015

- Both positive and negative lags for long GRBs;
- Short GRBs consistent with lag ~ 0 s;

Caveat 2: Spectral lag in GRBs → Intrinsic lag?

Spectral lags for long and short GRBs



Bernardini et al 2015

- Both positive and negative lags for long GRBs;
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Astrophysical origin of the delay

- ❖ Intrinsic cooling of radiating electrons;
- ❖ Accelerating outflows with decreasing B;
- ❖ Up-scattering of soft radiation via IC;
- ❖ Spectral evolution

$$\Delta\tau = \Delta\tau_{\rm int} + \Delta\tau_{\rm LIV} \qquad \Delta t_{\rm int} = b(1+z)$$

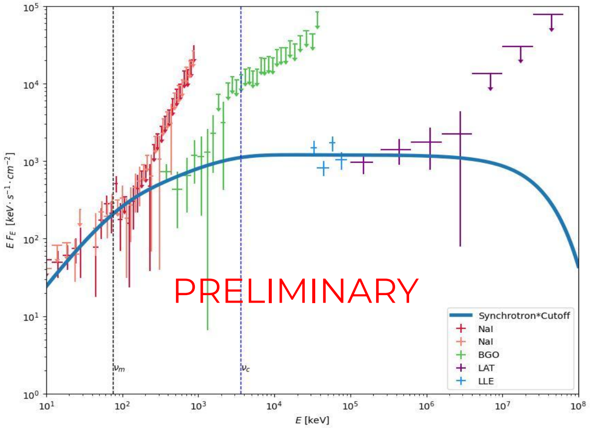
Vardanyan et al 2023

Caveat 3: High-energy photons from prompt or afterglow?

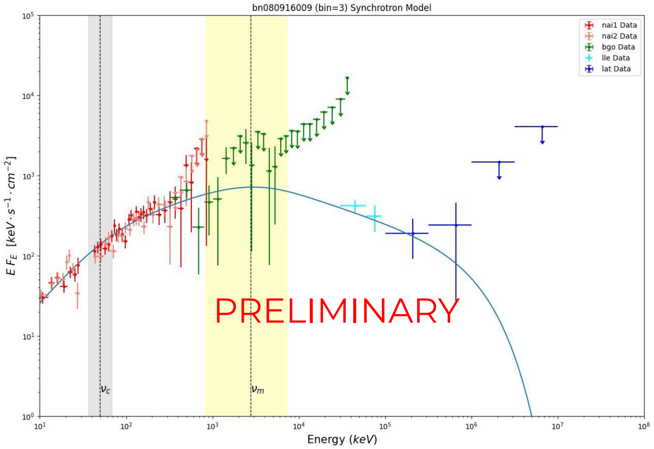
→ Important to have a proper physical model to estimate the true delay time

Synchrotron model? → Time-resolved analysis of a sample of 14 GRBs, spectra fitted with **physical models** (synchrotron and synchrotron + power-law) in the energy range **10 keV - 10 GeV**

GRB 090510



GRB 080916C



Lorentz Invariance Violation with Gamma-ray Bursts

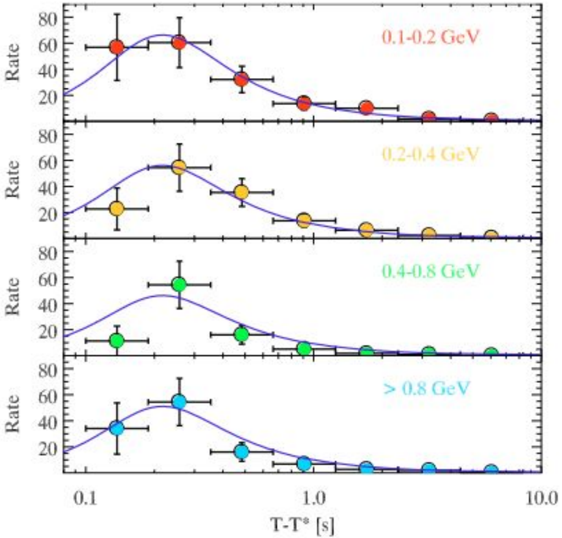
LIV with GRBs: current results

Ghirlanda et al 2010

→ Study of GRB 090510 at energies > 0.1 GeV,

→ highest photon energy 31 GeV, whose arrival time coincides with the peak of afterglow emission;

→ assume that it is produced at the beginning of the afterglow, and it arrives delayed by 0.22 *s*



Result: $M_{\rm QG} > 4.7 M_{\rm Planck}$

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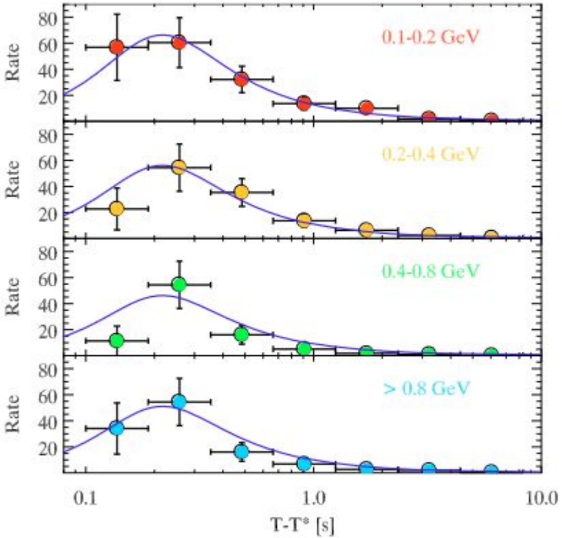

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Ackermann et al 2009

→ Study of GRB 090510;

→ highest photon energy 31 GeV, interpreted as prompt-related;

$M_{\rm QG,1}/M_{\rm Planck} > 102$

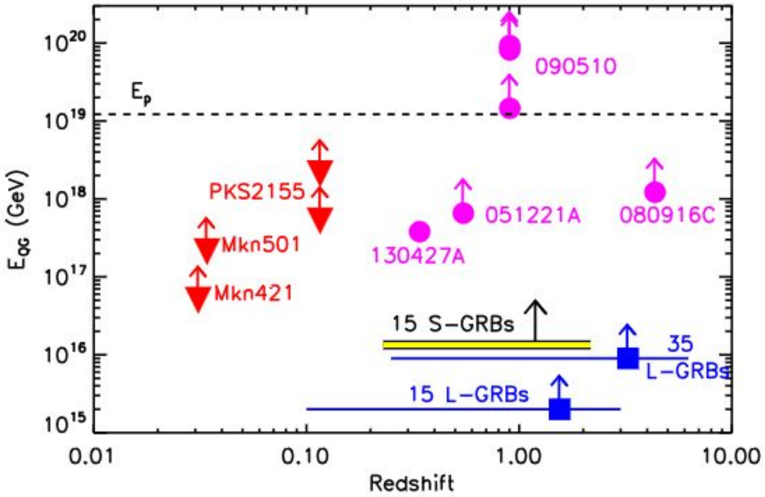
Important assumptions on the physical model of prompt emission

LIV with GRBs: current results

Bernardini et al 2017

→ Study of a sample of 21 short GRBs (classified by *Swift*-BAT) with measured z

→ Use the discrete CCF to measure the lag between two different channels (50-100 keV, 150-200 keV)



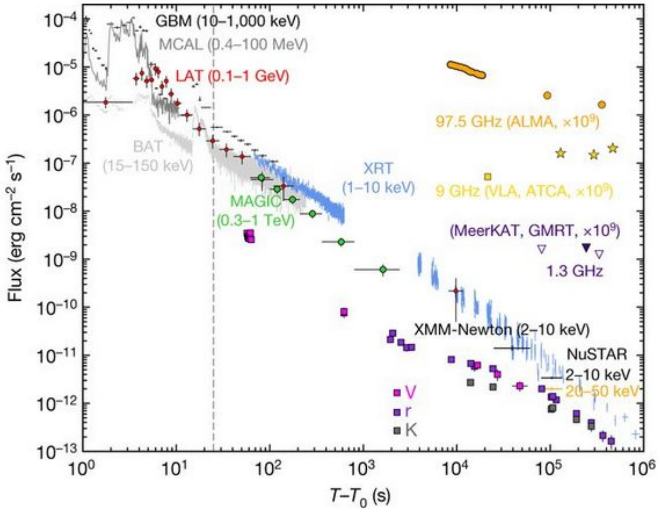
Result:

$$E_{QG} > 1.48 \times 10^{16} \text{ GeV (95\% c.l.)}.$$

LIV with GRBs: current results

GRB 190114C

- Detection of photons above 0.2 TeV;
- Conservative assumptions on the intrinsic spectral and temporal emission properties;
- Use models for the light curve;
- Maximum likelihood analysis



Veres et al 2019,
Magic Collaboration

Result: $E_{\mathrm{QG},1} > 0.58 \times 10^{19}\,\mathrm{GeV}$

→ below the limits put by GRB 090510

Acciari et al 2020, Magic Collaboration

LIV with GRBs: current results

LHAASO Collaboration, 2023

→ Study of GRB 221009A

Prompt emission still ongoing

→ Detection of gamma rays up to 13 TeV for the first time during 230-900s after the trigger;

Result: $M_{QG,1}/M_{Planck} > 1.5$ ⇒ In agreement with Ackermann et al 2009 for GRB 090510

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LHAASO Collaboration, 2023

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… How do we proceed?

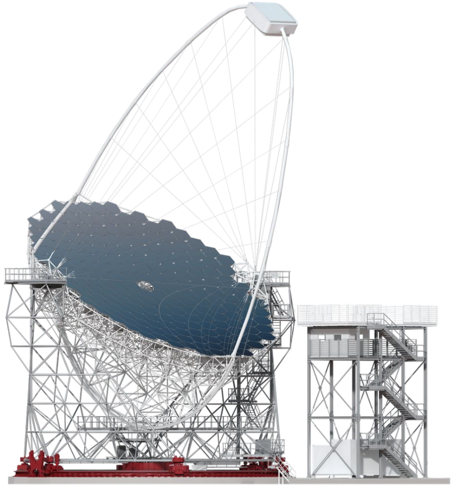
- ❏ Better sensitivity in the 0.1 - 100 GeV energy range
- ❏ High-energy and very high-energy observations during prompt (High energy photons + fast variability)

Future Prospects

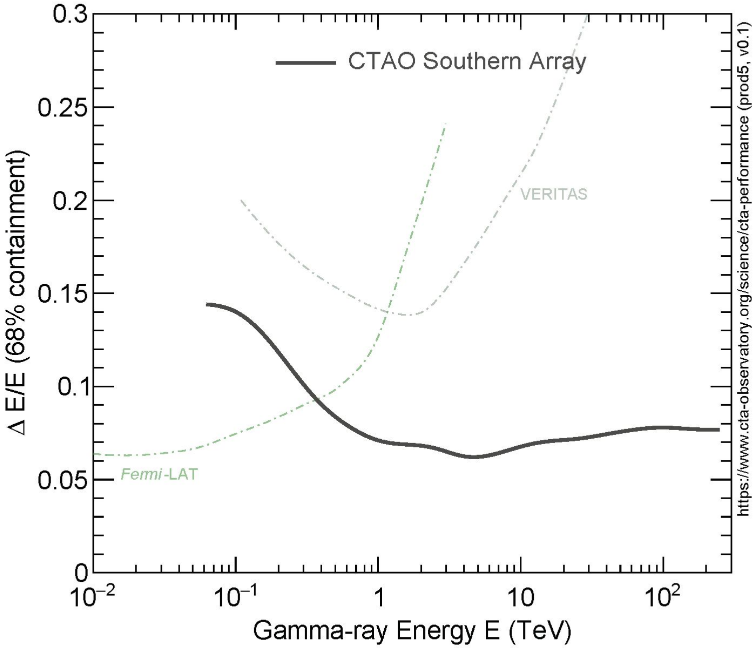
Image credit: Moritz Huetten

LIV with Large Sized Telescope

- Sensitivity between 20 and 150 GeV;
  - Threshold energy down to ~25 GeV
- Ability to re-position within 20 s → good for observing GRBs early emission; →see Biswajit Banerjee's talk
- Parabolic mirror: 23 m, ~400 m²
- Field of View ~ 4.3°



Credit: G. Pérez, IAC, SMM



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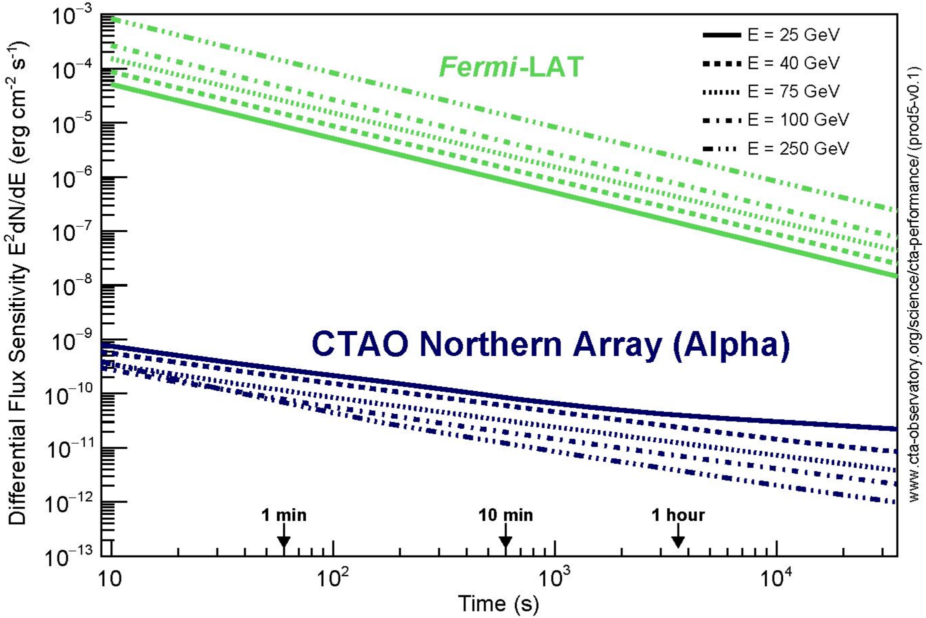

GRB 090510

HE photon ~ 30 GeV

Time-delay ~ 1 s

If flux observations improved by a factor ~ 10 (at least)

→ we can detect sources like GRB 090510 with much higher redshift → **better constraints on LIV**

Conclusions

- LIV theories can be tested with Gamma-ray Bursts;
- So far we have lower limits which seems to push the quantum gravity energy scale at energies higher than the Planck energy, excluding some theories;
- In order to improve our understanding of LIV theories, we need:
    - Instruments with better sensitivity in the high-energy range;
    - Observation of high energy photons during the prompt phase of GRBs;
    - Proper modelling of the prompt emission
    - inferred LIV limits could be significantly affected by poorly understood intrinsic source effects

Thank you for your attention

Image credit: Moritz Huetten