

New searches for Lorentz invariance violations with MAGIC and LST-1 telescopes

Jelena Strišković¹, Daniel Kerszberg, Tomislav Terzić, Sami Caroff, Amélie Nigou, Javier Rico

¹Josip Juraj Strossmayer University of Osijek
Department of Physics

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Outline

- ❖ Lorentz invariance violation
- ❖ Time of flight
- ❖ gLike
 - ❖ Unbinned maximum likelihood analysis
 - ❖ Binned maximum likelihood analysis
- ❖ Very high energy gamma-ray sources
- ❖ Universe transparency
- ❖ Combination of different LIV effects

Lorentz invariance violation

- ❖ Modified photon dispersion relation (MPDR):

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

n = 1 linear contribution
n = 2 quadratic contribution

↓

$S_n = +1$ superluminal behaviour
 $S_n = -1$ subluminal behaviour

- ❖ Energy-dependent photon group velocity:

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

↓

minuscule effects

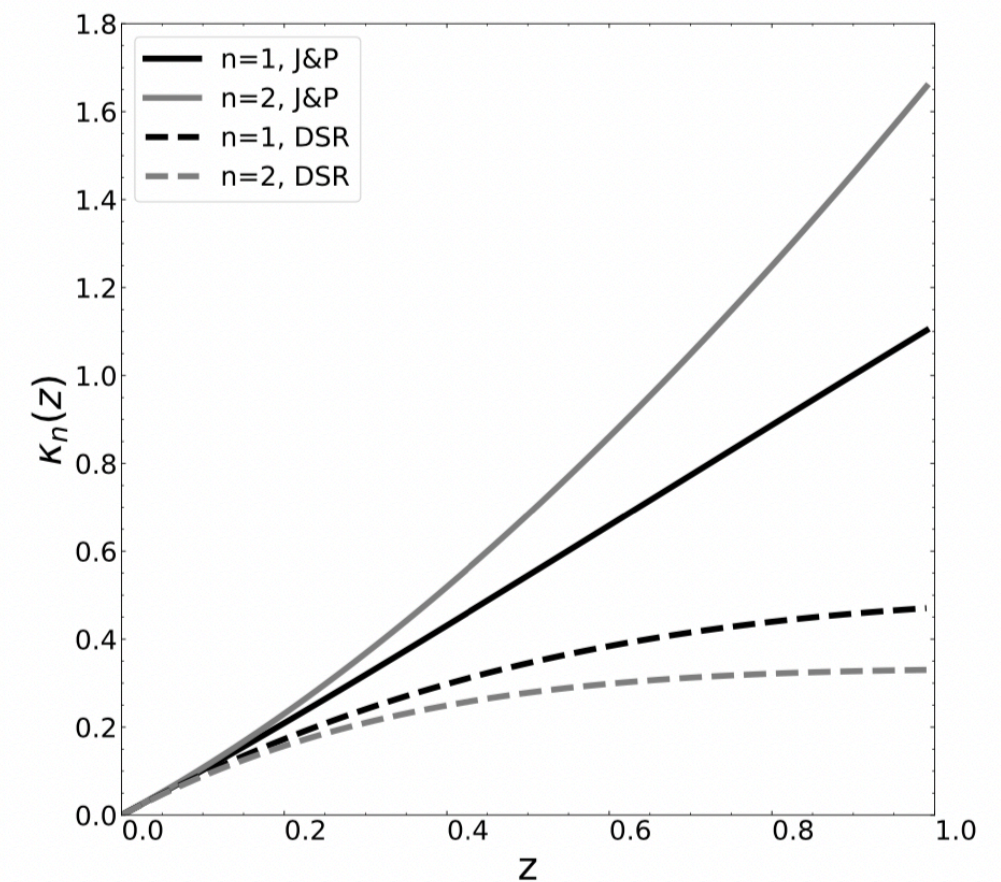
Consequences of MPDR: Time of flight

- ❖ Energy-dependent time delay:

$$\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{H_0 E_{QG}^n} \kappa_n(z)$$

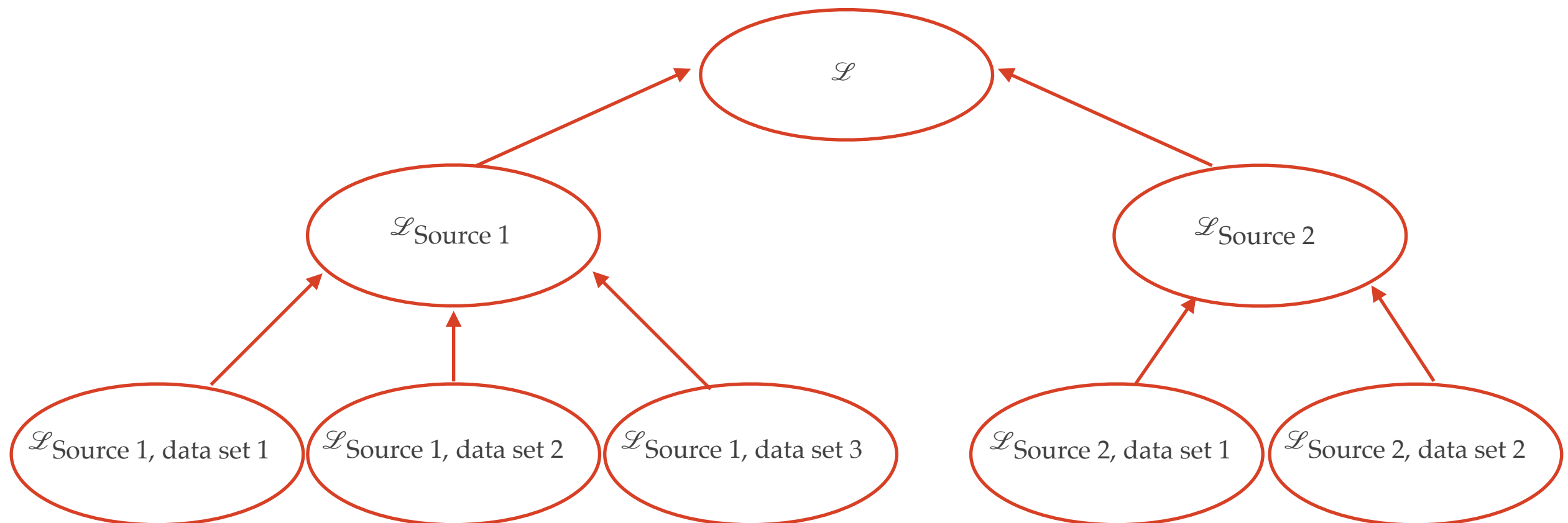
- ❖ Distance contribution:

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



J. Bolmont et al. (2022)
arXiv:2201.02087

- ❖ ROOT-based code framework for the numerical maximisation of joint likelihood functions
- ❖ Open source
- ❖ The joint likelihood ($\mathcal{L}$) function has one free parameter (g) and as many nuisance parameters as wanted



Unbinned maximum likelihood analysis

- ❖ Likelihood function for observed number of ON events:

$$\mathcal{L}(\eta_n) = \prod_{i=1}^{N_{\text{ON}}} \left(p_i^{(s)} \frac{f^{(s)}(E_i, t_i)}{\int_{E_{\min}}^{E_{\max}} dE \int_{t_{\min}}^{t_{\max}} f^{(s)}(E, t) dt} + p_i^{(b)} \frac{f^{(b)}(E_i, t_i)}{\int_{E_{\min}}^{E_{\max}} dE \int_{t_{\min}}^{t_{\max}} f^{(b)}(E, t) dt} \right)$$

ON/OFF normalisation

$$p_i^{(s)} = \frac{N_{\text{ON}} - \alpha N_{\text{OFF}}}{N_{\text{ON}}}$$

$$p_i^{(b)} = \frac{\alpha N_{\text{OFF}}}{N_{\text{ON}}}$$

- ❖ Probability distribution function:

$$f^{(s)}(E, t) = \int_0^\infty F(t + \eta_n E_{\text{true}}^n) \Phi_{\text{obs}}(E_{\text{true}}) G(E, E_{\text{true}}) A_{\text{eff}}(E_{\text{true}}, t) dE_{\text{true}}$$

$F(t)$ - observed light curve (LC);
LC template

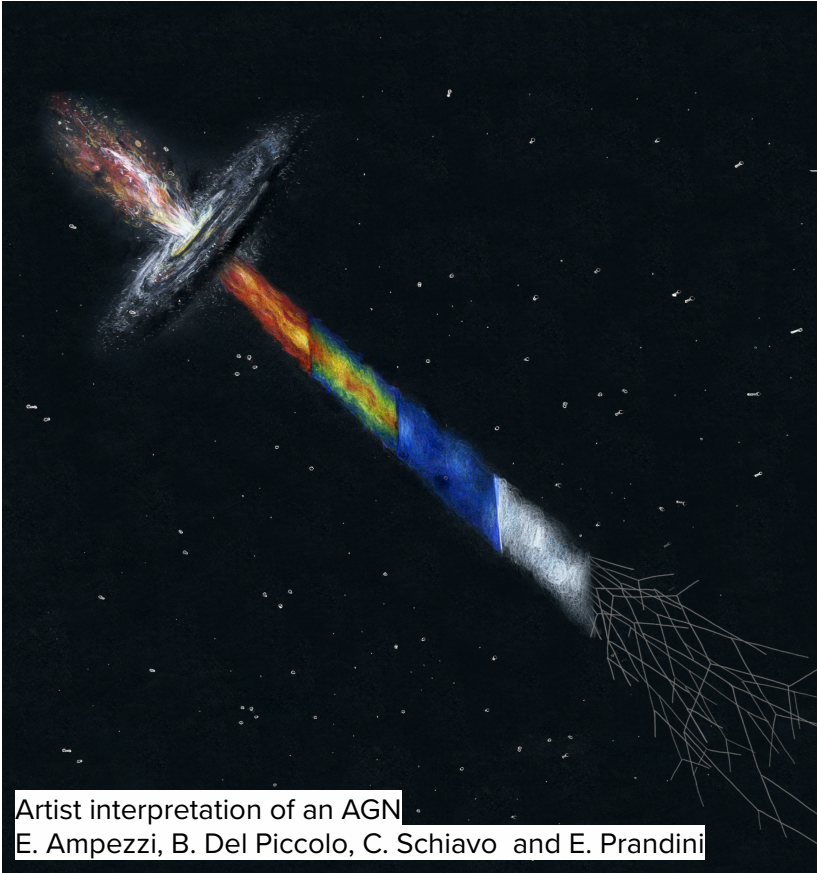
energy resolution and bias

collection area

observed spectral distribution of gamma rays

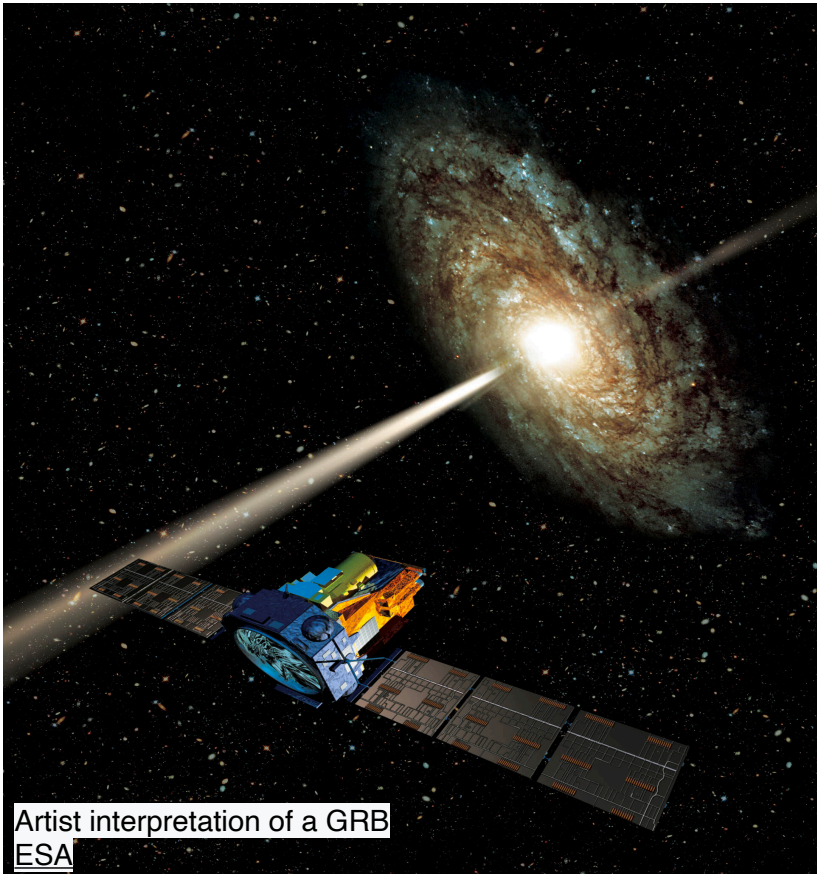
VHE gamma-ray sources suitable for LIV studies

Active Galactic Nuclei



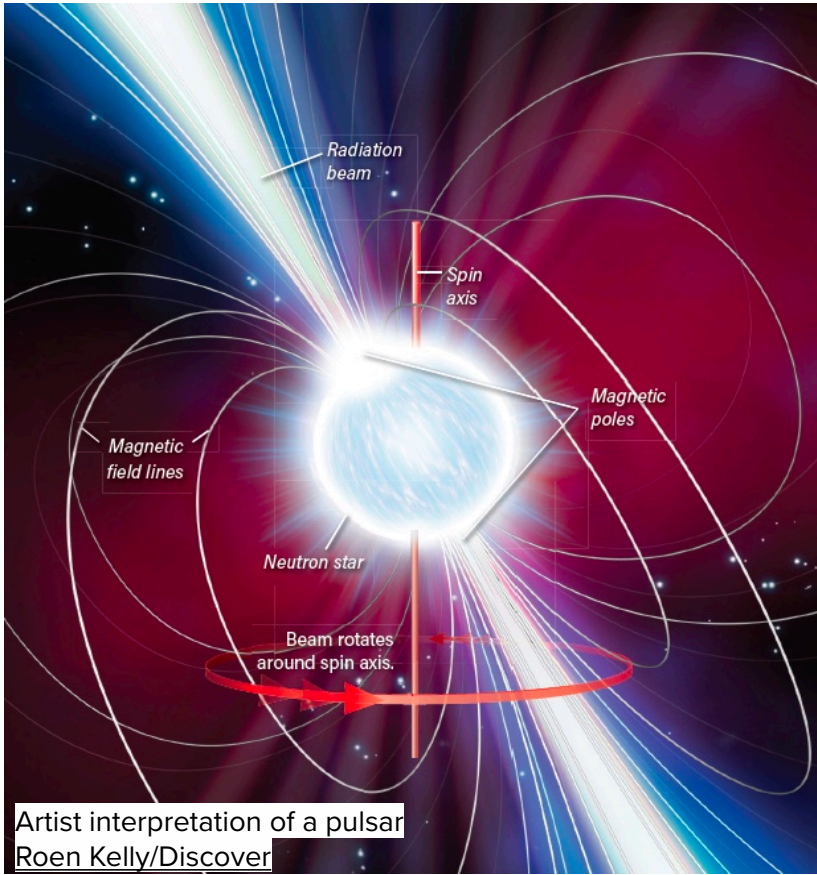
Mrk 501, Mrk 421
PKS 2155-304
PG 1553+113

Gamma-ray bursts



GRB 190114C

Pulsars



Crab
Vela

$E_{\text{QG},1}$	$\propto$	E_{max}	t_{var}^{-1}	$z_s^{\sim 1}$
$E_{\text{QG},2}$	$\propto$	E_{max}	$t_{\text{var}}^{-1/2}$	$z_s^{\sim 2/3}$

Quantum gravity lower bounds and the redshift

Circles

Temporal distribution

→ 1 Gaussian

→ $T_{\max} = 2000$ s

Spectral distribution

→ power law

→ $E_{\min} = 0.2$ TeV

→ $E_{\max} = 10$ TeV

Triangle

Temporal distribution

→ 5 Gaussians

→ $T_{\max} = 4000$ s

Spectral distribution

→ power law

→ $E_{\min} = 0.2$ TeV

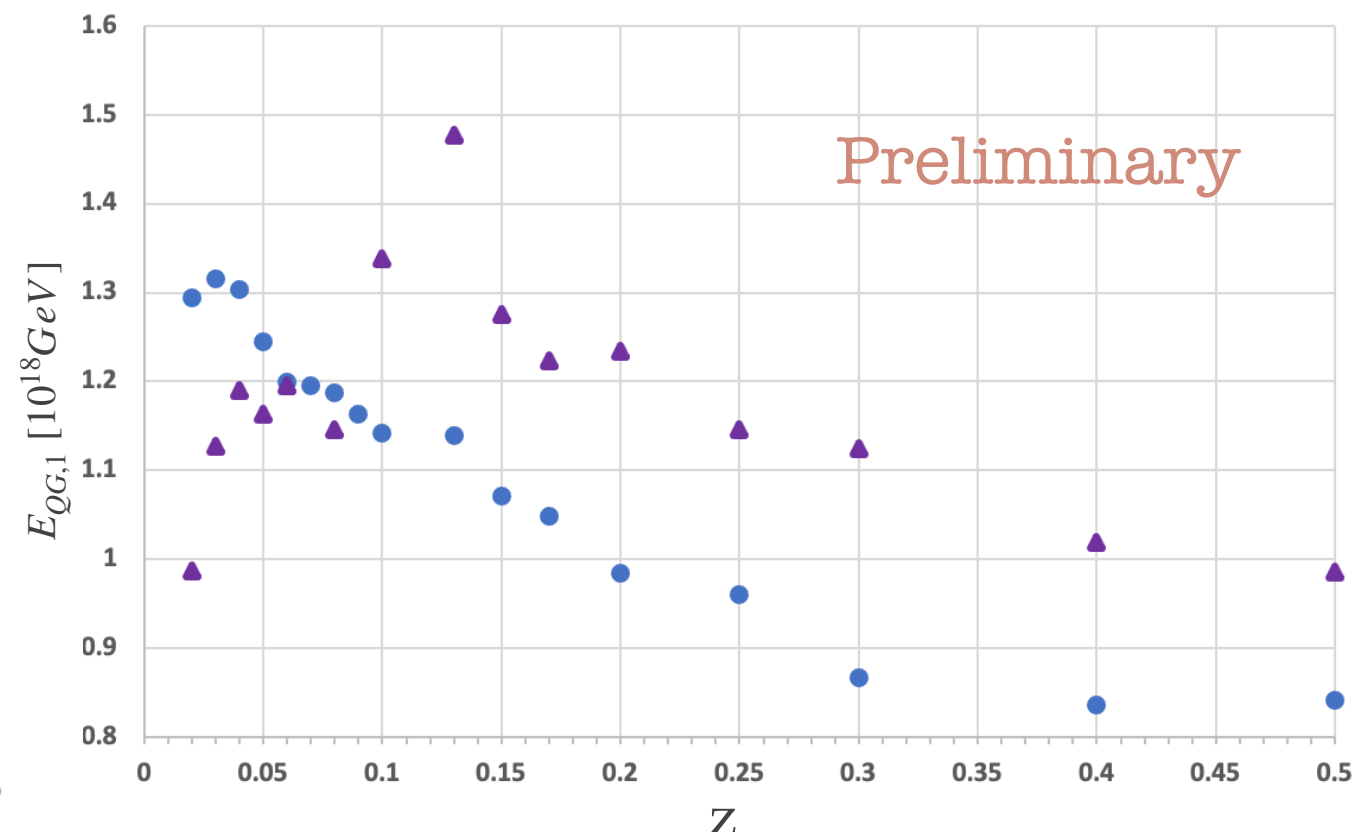
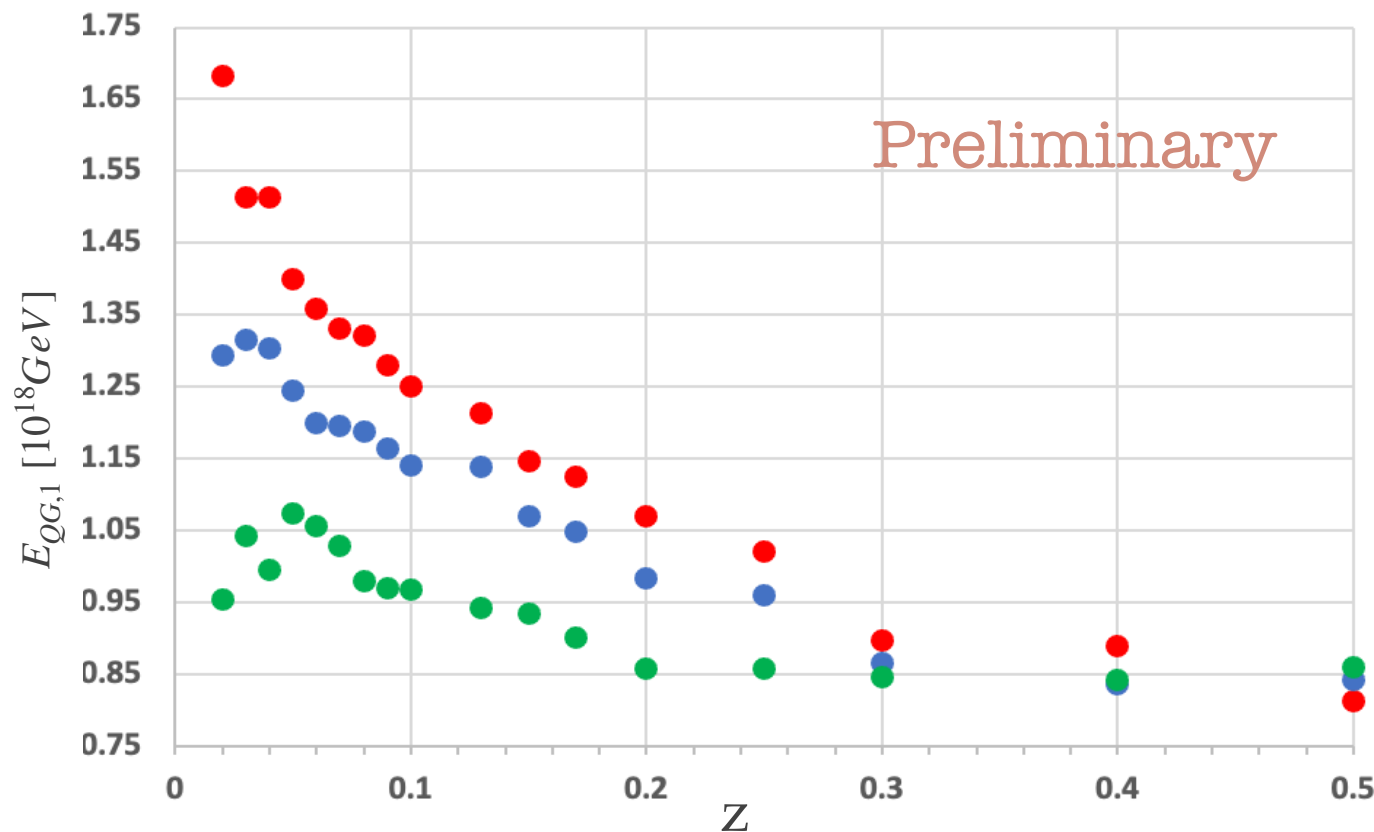
→ $E_{\max} = 10$ TeV

● spectral index = -3

● spectral index = -3.4

● spectral index = -4

▲ spectral index = -3.4



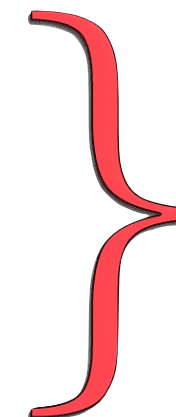
New interesting source: BL Lac

❖ Characteristics:

- ❖ $z = 0.069$
- ❖ Prototype for BL Lacertae objects
- ❖ Several exceptional, high flaring states detected by MAGIC and / or LST-1
- ❖ Significant intranight variability for several nights

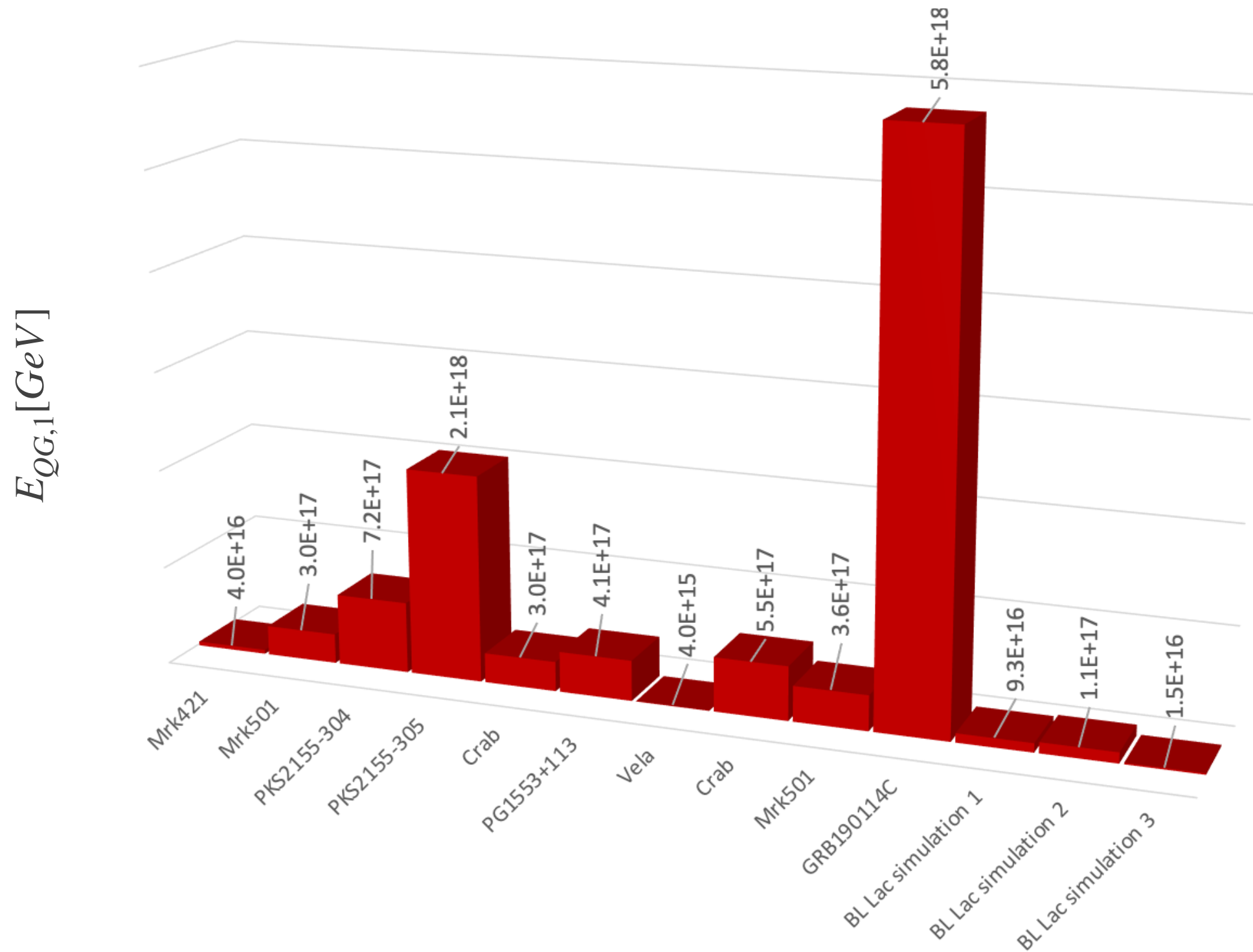
❖ Preliminary simulated QG lower limits:

- ❖ 2020_09_20: $E_{QG,1} = 0.09271 \times 10^{18} \text{GeV}$
- ❖ 2021_08_08: $E_{QG,1} = 0.10651 \times 10^{18} \text{GeV}$
- ❖ 2021_08_10: $E_{QG,1} = 0.01504 \times 10^{18} \text{GeV}$



Next: Combine
MAGIC + LST-1 data

Lower bounds on the LIV energy scale obtained with IACTs



- ❖ We need to improve light curve templates especially for 2020_09_20

Binned maximum likelihood analysis

- ❖ Likelihood function for observed number of ON events:

$$\mathcal{L}(\eta_n) = \prod_{i=1}^{N_E} \prod_{j=1}^{N_t} P\left(s_{i,j}(\eta; \mu) + b_{i,j} \mid N_{i,j}^{ON}\right) P\left(\alpha b_{i,j} \mid N_{i,j}^{OFF}\right)$$

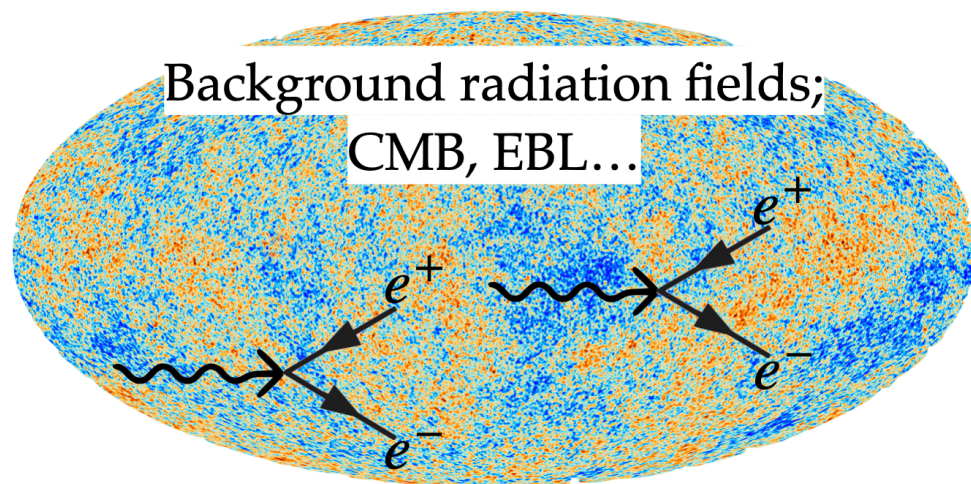
nuisance parameters

$$s_{i,j} = \int_{E_{i,\min}}^{E_{i,\max}} dE \int_{t_{j,\min}}^{t_{j,\max}} dt \int_0^\infty F(t + \eta_n E^n \mid \mu) \Phi_{\text{obs}}(E) G(E, E_{\text{true}}) A_{\text{eff}}(E_{\text{true}}, t) dE_{\text{true}}$$

- ❖ Template for the OFF not needed (just binned data from the OFF region)
- ❖ Better handling of systematics
- ❖ Currently implementing it in gLike

Combining different LIV effects

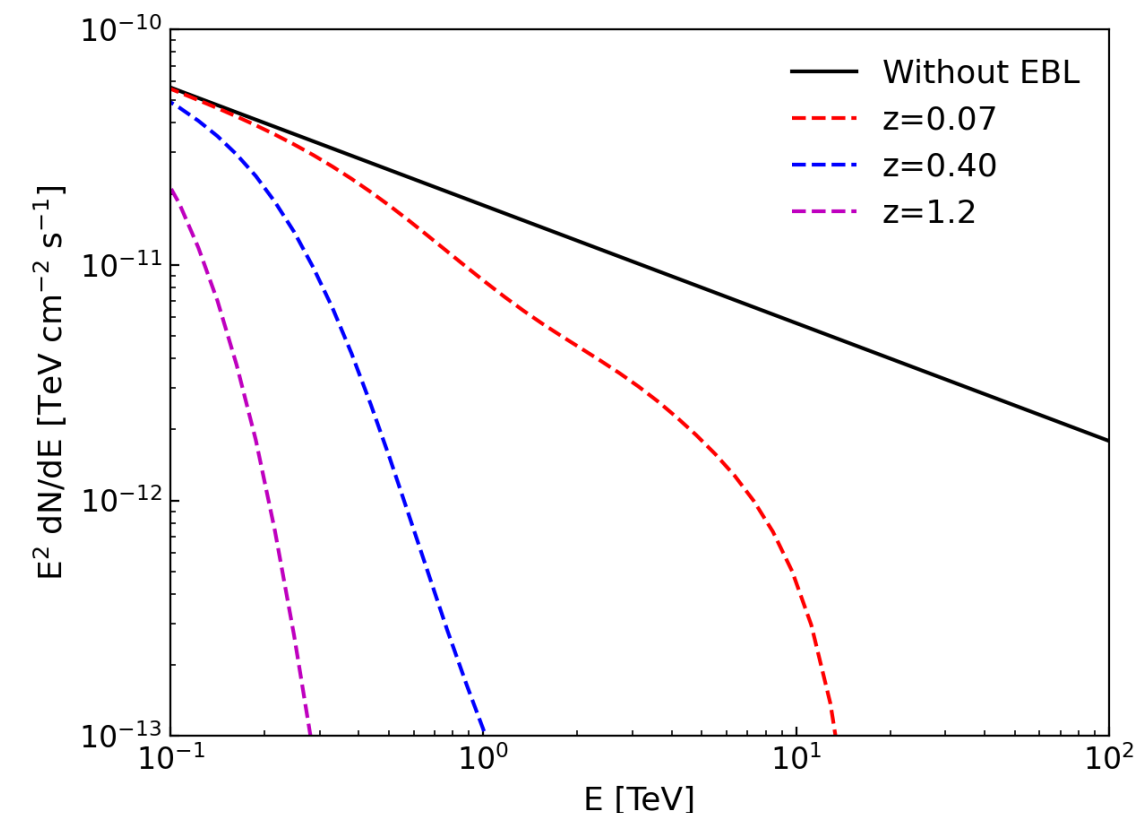
- ❖ During CA18108 STSM idea of combining time and spectral LIV methods using **LIVelihood** (IACT LIV task force)
- ❖ **Fist study combining two different LIV effects**
- ❖ Reminder:



$$\Phi_{\text{obs}}(E) = \Phi_{\text{int}} \left(E (1 + z_s) \right) \times e^{-\tau(E, z_s)}$$

$$\tau(E, z_s) = \int_0^{z_s} \frac{dl}{dz} dz \int_{-1}^1 \frac{1 - \cos \theta'}{2} d \cos \theta' \int_{\epsilon'_{th}}^{\infty} \sigma_{\gamma\gamma}(s) n(\epsilon', z) d\epsilon'$$

Observed spectrum



Changes in pair creation due to the MPDR

❖ Energy reaction threshold:

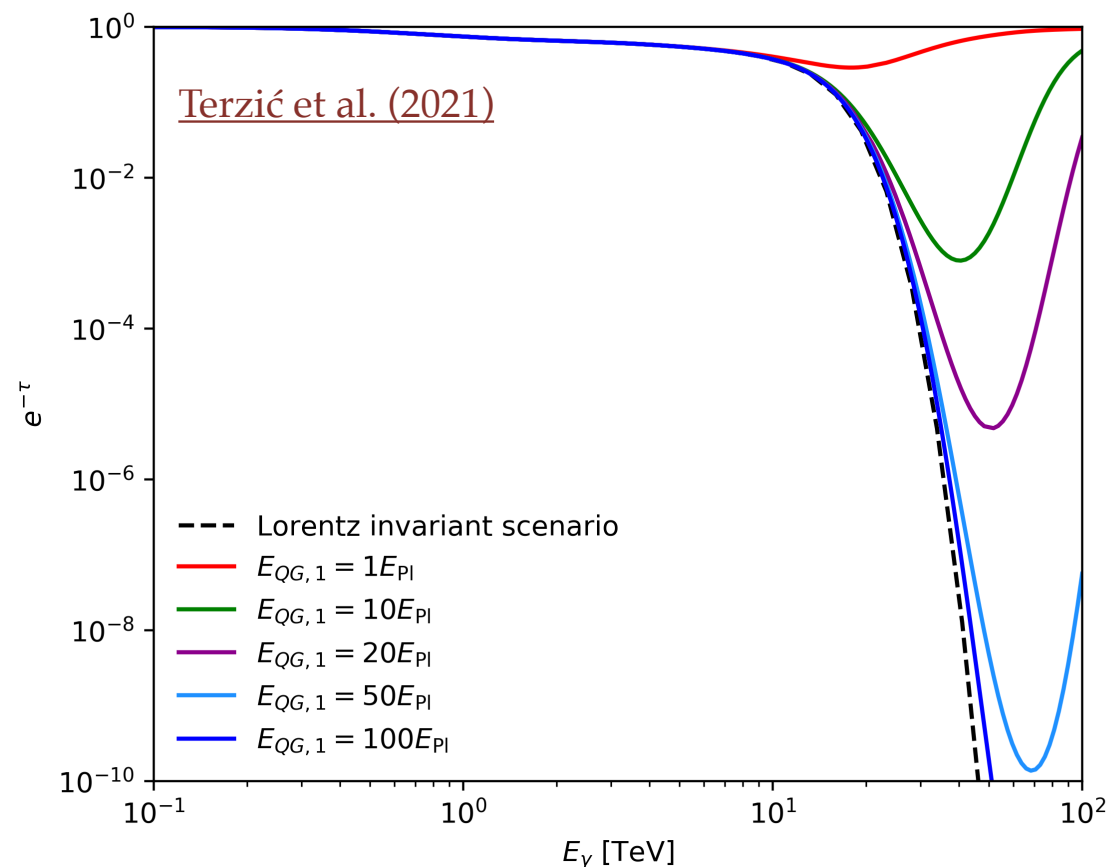
$$\epsilon'_{th} = \frac{2m_e^2 c^4}{E' (1 - \cos \theta')} \longrightarrow \epsilon'_{th} = \frac{2m_e^2 c^4}{E' (1 - \cos \theta')} - \frac{S}{2 (1 - \cos \theta')} \left(\frac{E'}{E_{QG,n}} \right)^n E'$$

❖ Gamma-gamma cross section:

❖ Functional form of $\sigma_{\gamma\gamma}(s)$ remains the same but s changes

$$s = 2E'\epsilon' (1 - \cos \theta') \longrightarrow s = 2E'\epsilon' (1 - \cos \theta') + S \left(\frac{E'}{E_{QG,n}} \right)^n E'^2$$

Combining two effects in LIVelihood



$$\Phi_{\text{obs}}(E) = \Phi_{\text{int}} \left(E (1 + z_s) \right) \times e^{-\tau(E, z_s)}$$

$$\tau(E, z_s) = \int_0^{z_s} \frac{dl}{dz} dz \int_{-1}^1 \frac{1 - \cos \theta'}{2} d \cos \theta' \int_{\epsilon'_{th}}^{\infty} \sigma_{\gamma\gamma}(s) n(\epsilon', z) d\epsilon'$$

$$f^{(s)}(E, t) = \int_0^{\infty} F(t + \eta_n E_{\text{true}}^n) \Phi_{\text{obs}}(E_{\text{true}}) G(E, E_{\text{true}}) A_{\text{eff}}(E_{\text{true}}, t) dE_{\text{true}}$$

3D LUT for tau: gamma ray energy vs redshift vs eta

$$\eta_n = -S_n \frac{n+1}{2} \frac{1}{E_{QG,n}^n} \kappa_n(z_s)$$

Conclusions

- ❖ **gLike:**
 - ❖ Numerical maximisation of joint likelihood functions
 - ❖ Combining data from different sources or instruments to produce one limit
- ❖ New interesting source for LIV: BL Lac → complex LC template
- ❖ Binned ML analysis:
 - ❖ Should decrease slightly the sensitivity but it would provide more robust results
 - ❖ **Can handle any complex LC**
- ❖ **LIVelihood:** Combining two effect of MPDR: Time of flight and changes in optical depth
- ❖ **Stay tuned for first exciting results!**



Backup

Jelena Strišković

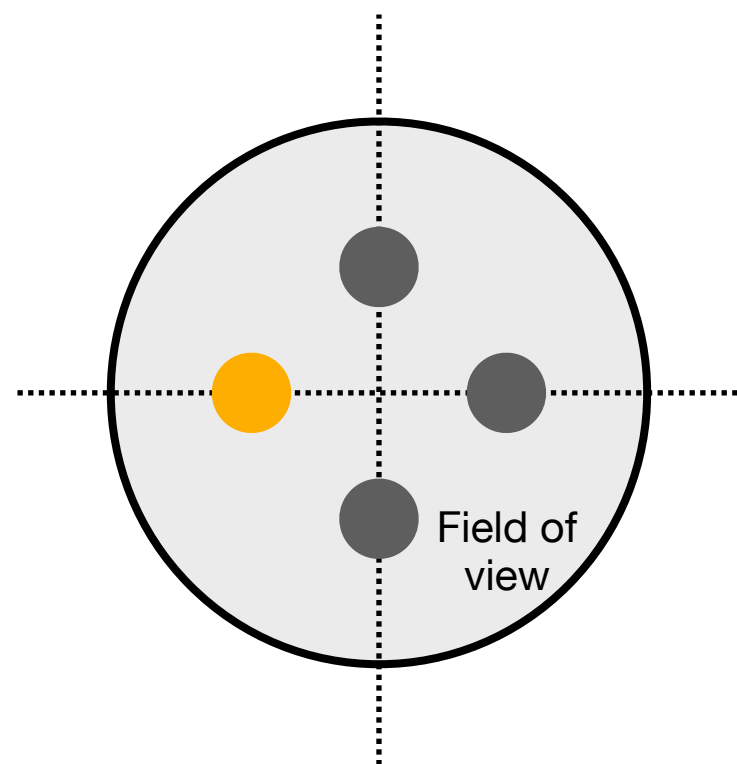
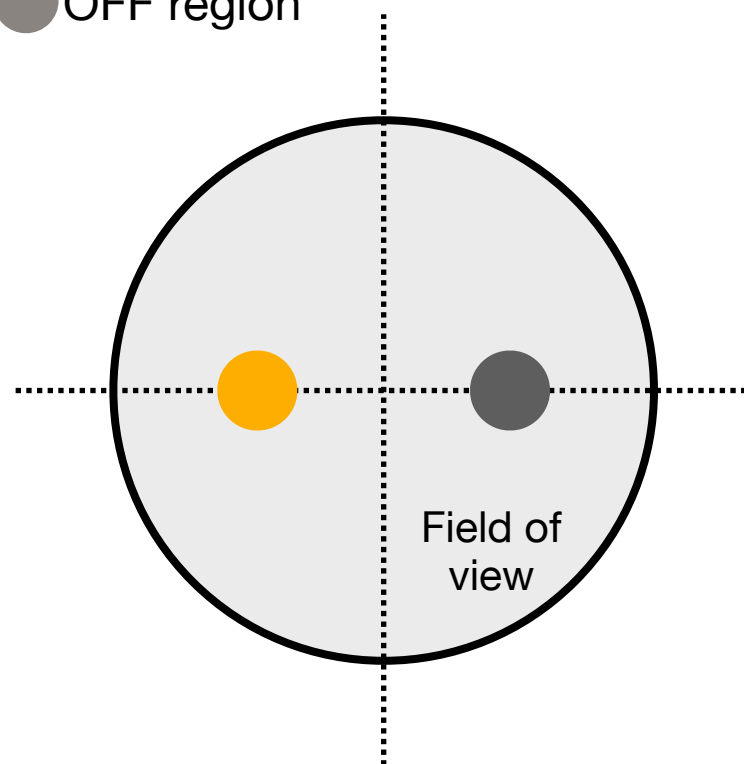
Likelihood elements: ON/OFF normalisation

ON/OFF
normalisation

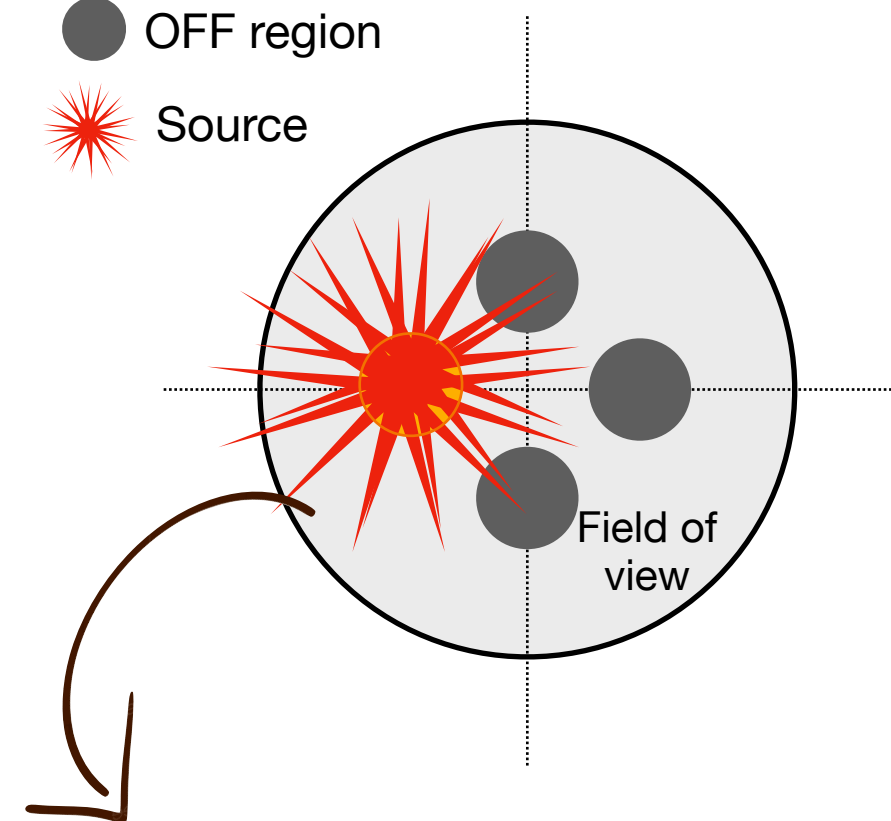
$$p_i^{(s)} = \frac{N_{\text{ON}} - \alpha N_{\text{OFF}}}{N_{\text{ON}}}$$

$$p_i^{(b)} = \frac{\alpha N_{\text{OFF}}}{N_{\text{ON}}}$$

● ON region
● OFF region



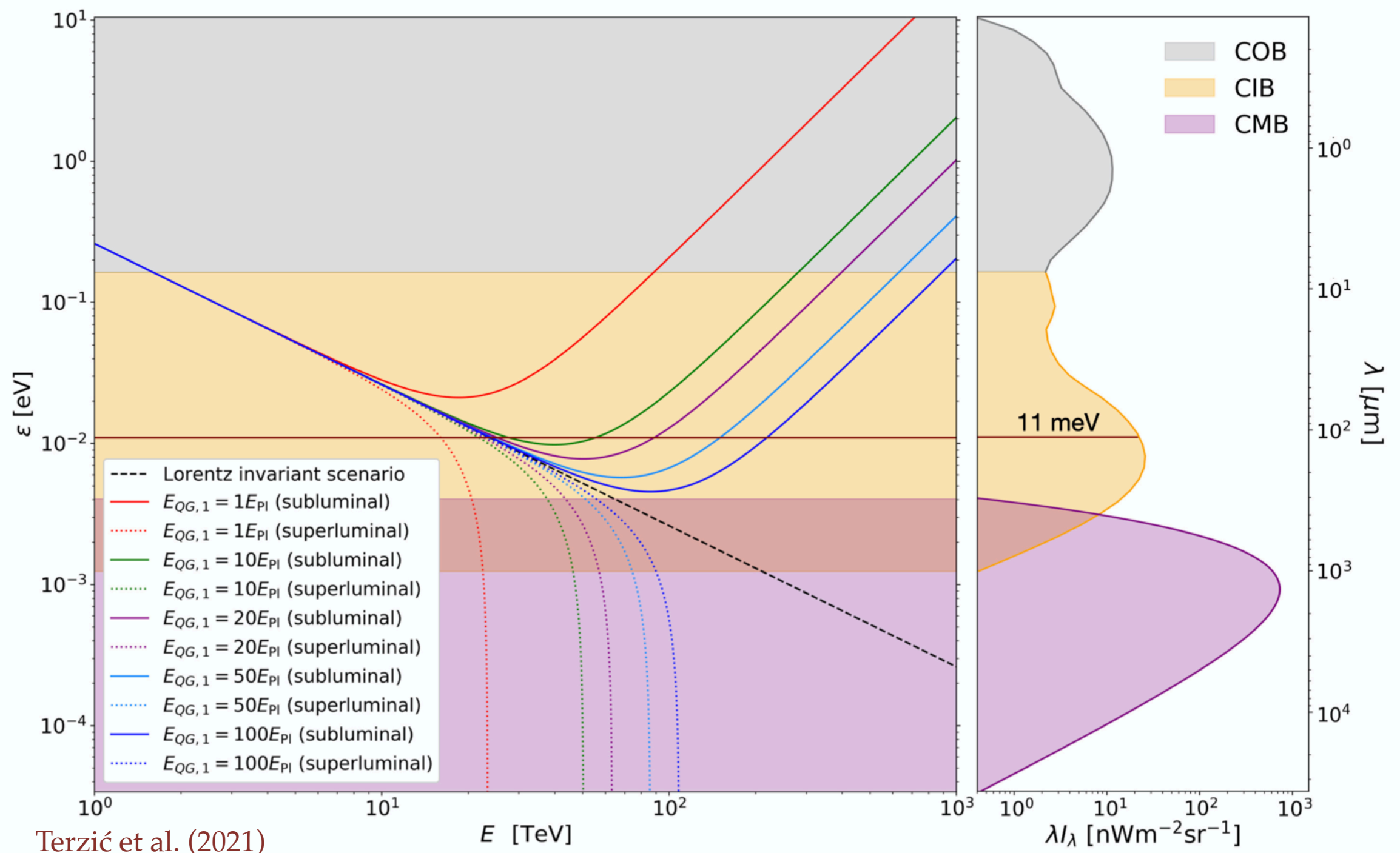
● ON region
● OFF region
★ Source



Caution!!

Consequences of MPDR: changes in energy reaction threshold

$$\epsilon'_{th} = \frac{2m_e^2 c^4}{E' (1 - \cos \theta')} \longrightarrow \epsilon'_{th} = \frac{2m_e^2 c^4}{E' (1 - \cos \theta')} - \frac{S}{2 (1 - \cos \theta')} \left(\frac{E'}{E_{QG,n}} \right)^n E'$$



Terzić et al. (2021)

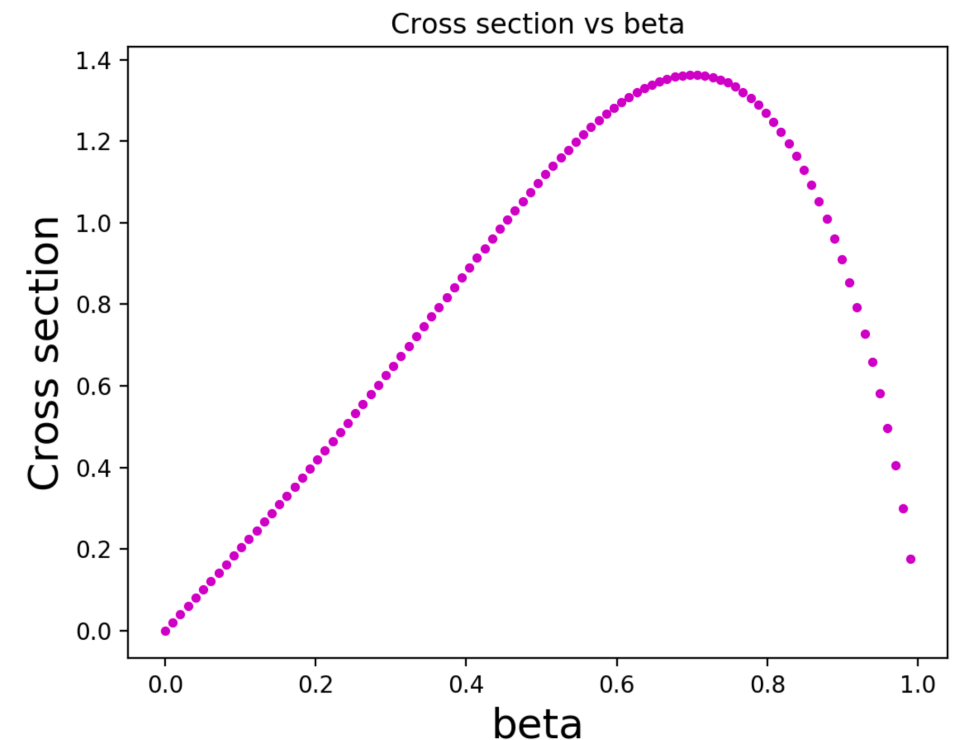
Gamma - gamma cross section

$$\sigma_{\gamma\gamma}(E_\gamma, \epsilon', \mu') = \frac{2\pi\alpha^2}{3m_e^2} W(\beta') = \simeq 1.25 \cdot 10^{-25} W(\beta') \text{cm}^2$$

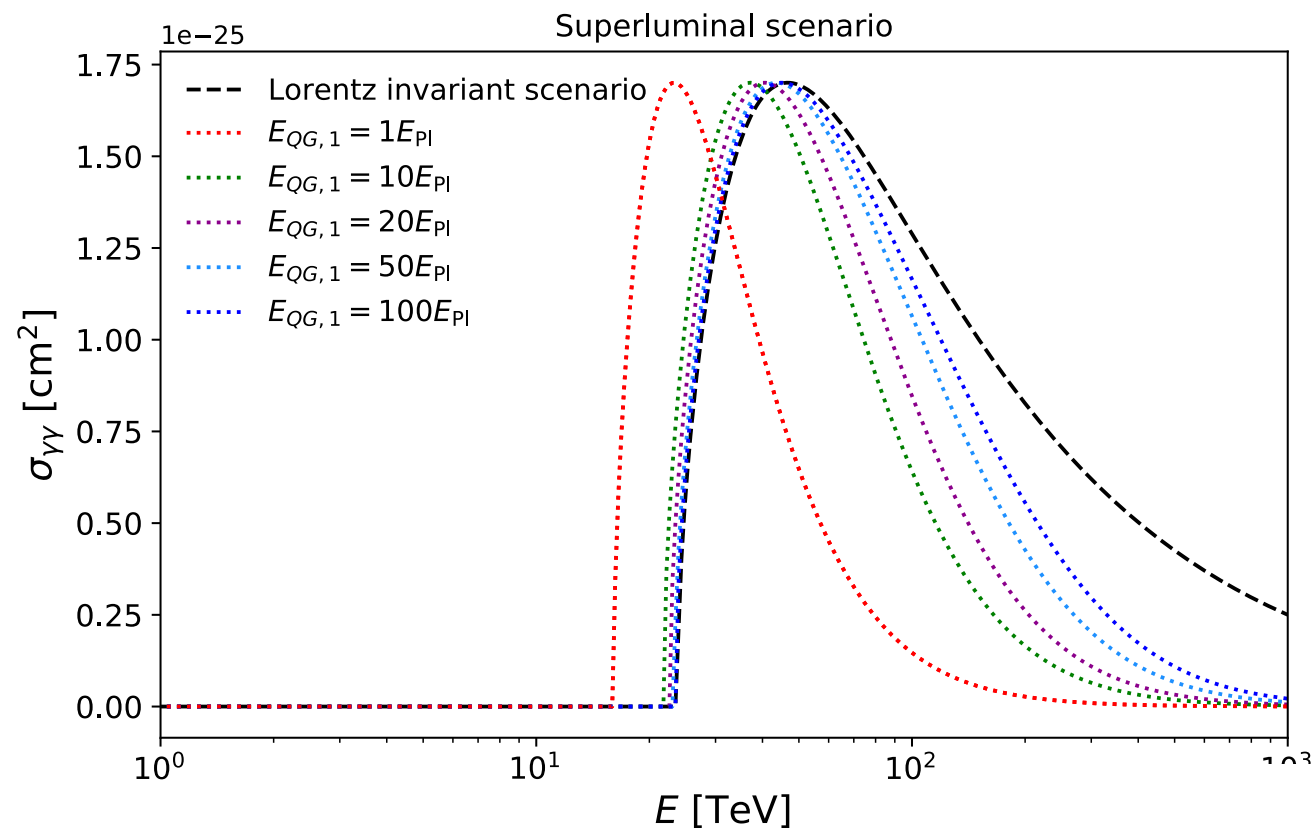
$$W(\beta') = (1 - \beta'^2) \left[2\beta'(\beta'^2 - 2) + (3 - \beta'^4) \ln \left(\frac{1 + \beta'}{1 - \beta'} \right) \right]$$

$$\beta'(E_\gamma, \epsilon', \mu') \equiv \left[1 - \frac{2m_e^2 c^4}{E_\gamma(1 + z)\epsilon'\mu'} \right]^{1/2} = \left[1 - \frac{4m_e^2 c^4}{s} \right]^{1/2}$$

$$\sigma_{\gamma\gamma}^{\text{max}} \simeq 1.70 \cdot 10^{-25} \text{cm}^2 \text{ for } \beta \simeq 0.70.$$



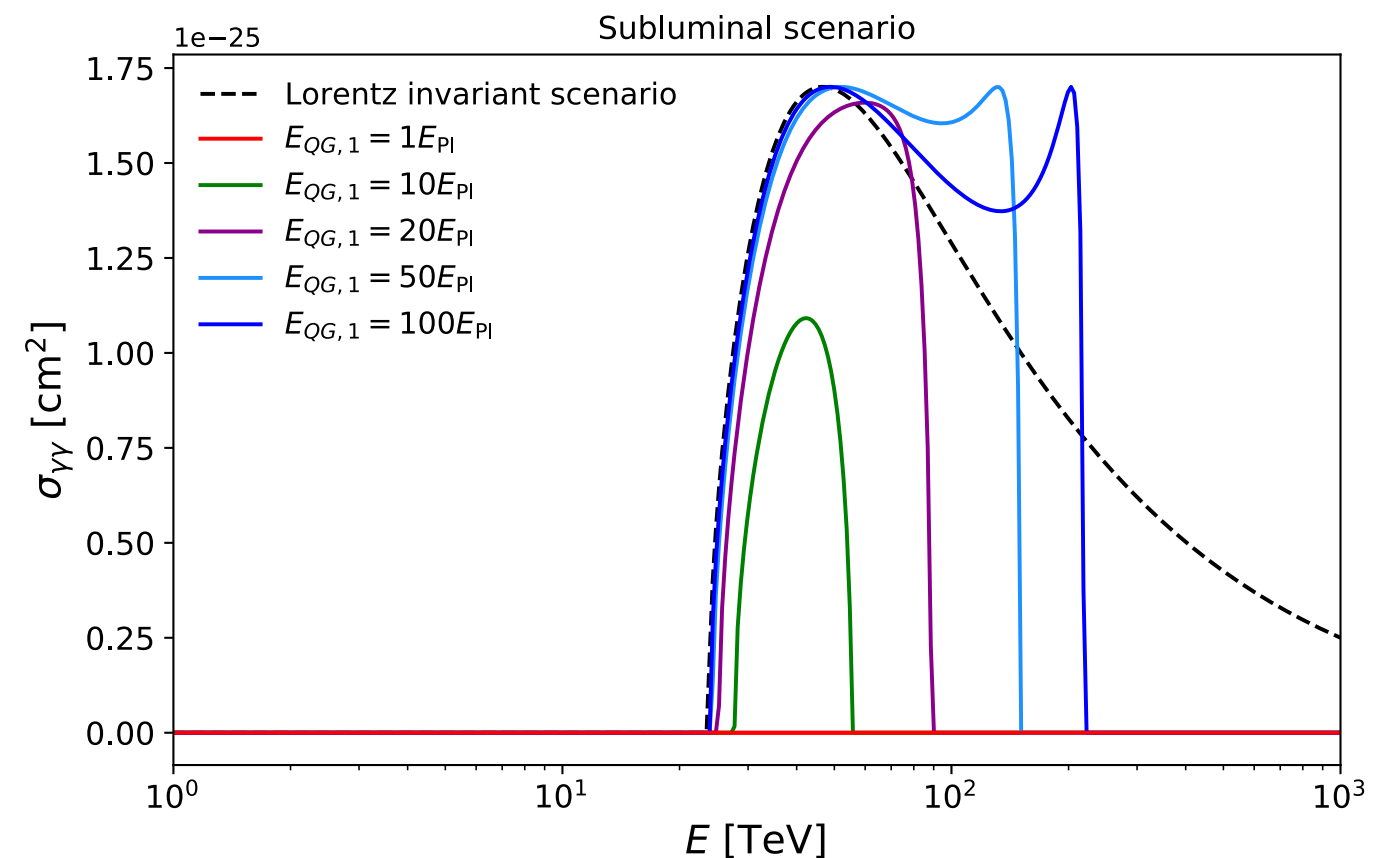
Consequences of MPDR: changes in $\sigma_{\gamma\gamma}$



Terzić et al. (2021)

Functional form of $\sigma_{\gamma\gamma}(s)$ remains the same
but s changes

$$s = 2E'\epsilon'(1 - \cos \theta') + S \left(\frac{E'}{E_{QG,n}} \right)^n E^2$$



Bounds on the LIV energy scale

Effect	Source	Type	Distance	Method	$E_{QG,1}$ [GeV]	$E_{QG,2}$ [GeV]	Instr.
Time delay	Mrk 421	AGN	$z = 0.031$	band comparison	(−) 0.4×10^{17}		Whipple
Time delay	Mrk 501	AGN	$z = 0.034$	ECF	(−) 2.1×10^{17}	(−) 2.6×10^{10}	MAGIC
Time delay	Mrk 501	AGN	$z = 0.034$	ML	(−) $3.0 \times 10^{17}{}^{\dagger}$	(−) $5.7 \times 10^{10}{}^{\dagger}$	MAGIC
Time delay	PKS 2155-304	AGN	$z = 0.116$	MCCF CWT	(−) 7.2×10^{17} (−) 5.2×10^{17}	(−) 1.4×10^9	H.E.S.S.
Time delay	PKS 2155-304	AGN	$z = 0.116$	ML	(−) 2.1×10^{18}	(−) 6.4×10^{10}	H.E.S.S.
Time delay	GRB 090510	GRB	$z = 0.9$	PV, SMM, and ML	(−) 2.2×10^{19} (+) 3.9×10^{19}	(−) 4.0×10^{10} (+) 3.0×10^{10}	LAT
Time delay	Crab	Pulsar	$d = 2$ kpc	PC DisCan	(−) 3.0×10^{17} (−) 1.9×10^{17} (+) 1.7×10^{17}	(−) 7.0×10^9	VERITAS
Time delay	PG 1553+113	AGN	$z = 0.49$	ML	(−) 4.1×10^{17} (+) 2.8×10^{17}	(−) 2.1×10^{10} (+) 1.7×10^{10}	H.E.S.S.
Time delay	Vela	Pulsar	$d = 0.3$ kpc	ML	(−) 4.0×10^{15} (+) 3.7×10^{15}		H.E.S.S.
Universe transparency	Multiple (30)	AGN	$z = 0.019 - 0.287$	TS	(−) 8.6×10^{18}		Multiple
Bethe–Heitler	Crab	Nebula	$d = 2$ kpc	ML		(−) 2.1×10^{11} (−) 1.3×10^{11}	HEGRA H.E.S.S.
Time delay	Crab	Pulsar	$d = 2$ kpc	PC ML	(−) 1.1×10^{17} (+) 1.1×10^{17} (−) 5.5×10^{17} (+) 4.5×10^{17}	(−) 1.4×10^{10} (+) 1.5×10^{10} (−) 5.9×10^{10} (+) 5.3×10^{10}	MAGIC
Time delay	Mrk 501	AGN	$z = 0.034$	ML	(−) 3.6×10^{17} (+) 2.6×10^{17}	(−) 8.5×10^{10} (+) 7.3×10^{10}	H.E.S.S.
Universe transparency	Multiple (6)	AGN	$z = 0.031 - 0.188$	TS	(−) 2.6×10^{19}	(−) 7.8×10^{11}	
Universe transparency	Multiple (6)	AGN	$z = 0.031 - 0.188$	TS	(−) 6.9×10^{19}	(−) 1.6×10^{12}	Multiple
Photon decay Photon splitting	Multiple (4)	Galactic	$d = 1.55 - 2.37$ kpc	TS	(+) 2.2×10^{22}	(+) 0.8×10^{14} (+) 1.0×10^{15}	HAWC
Time delay	GRB 190114C	GRB	$z = 0.4245$	ML	(−) 5.8×10^{18} (+) 5.5×10^{18}	(−) 6.3×10^{10} (+) 5.6×10^{10}	MAGIC
Photon decay Photon splitting	J2032+4102	Stellar cluster	$d = 1.4$ kpc	TS	(+) 1.2×10^{24}	(+) 1.1×10^{15} (+) 2.0×10^{16}	LHAASO

