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

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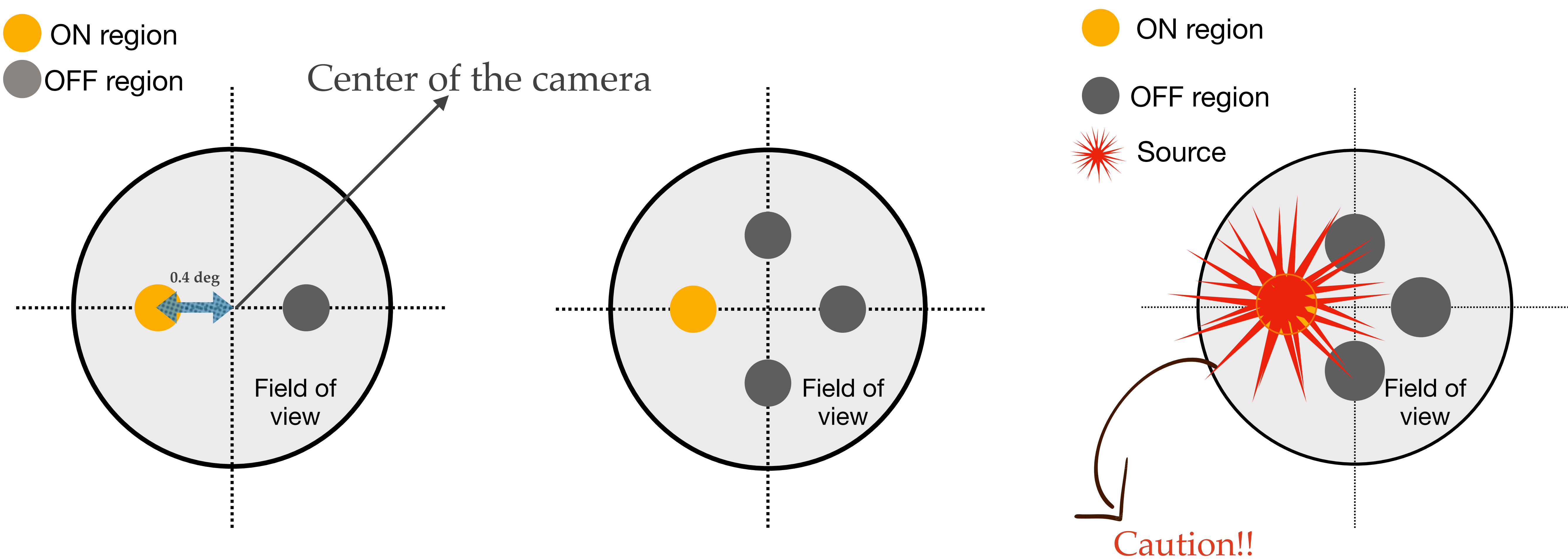
Outline

- Standard MAGIC/LST-1 observation
- Lorentz invariance violation
- Time of flight
- gLike
  - Unbinned maximum likelihood analysis
- Quantum gravity lower bounds and the redshift

ON/OFF regions



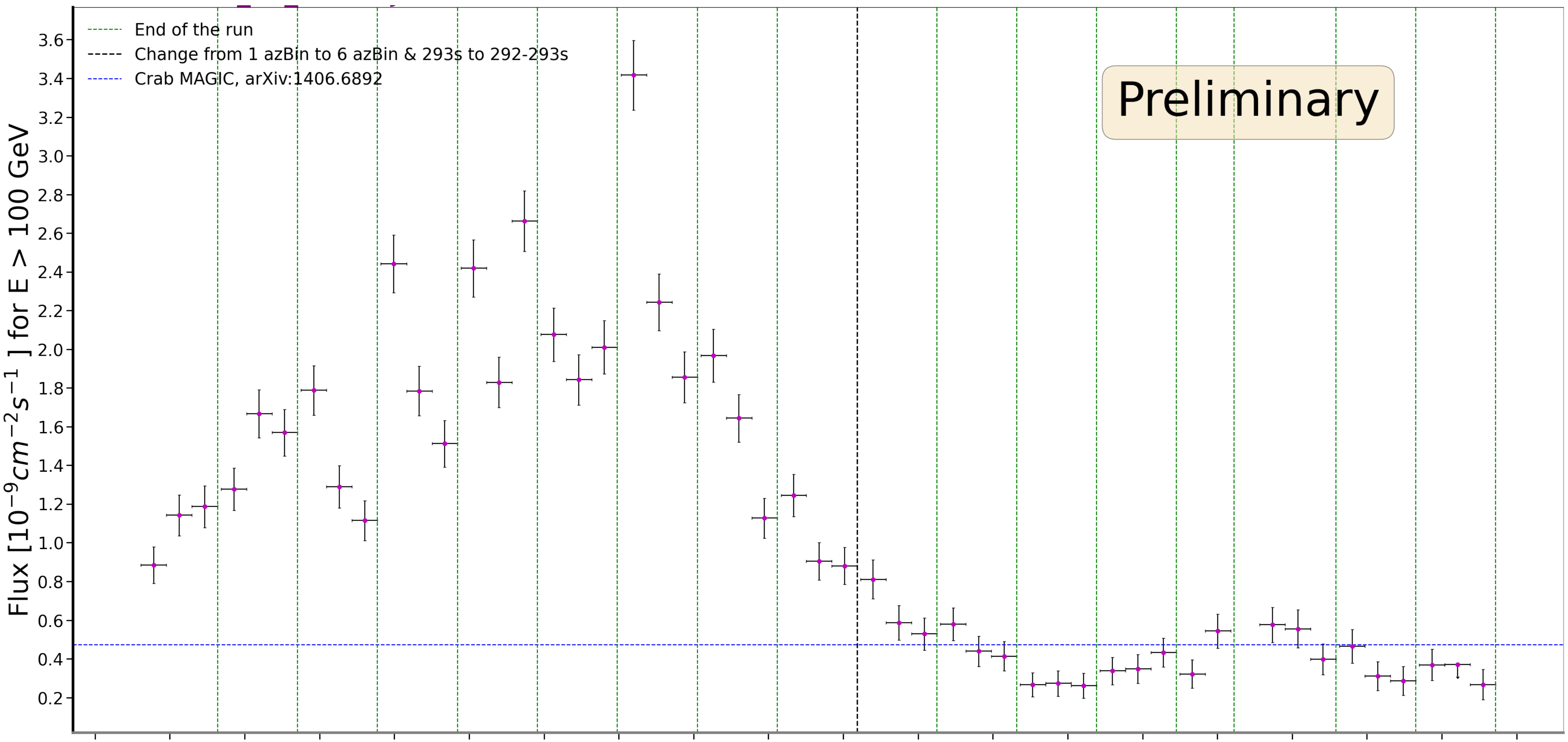
$$p_i^{(s)} = \frac{N_{ON} - \alpha N_{OFF}}{N_{ON}}$$

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

ON/OFF normalisation

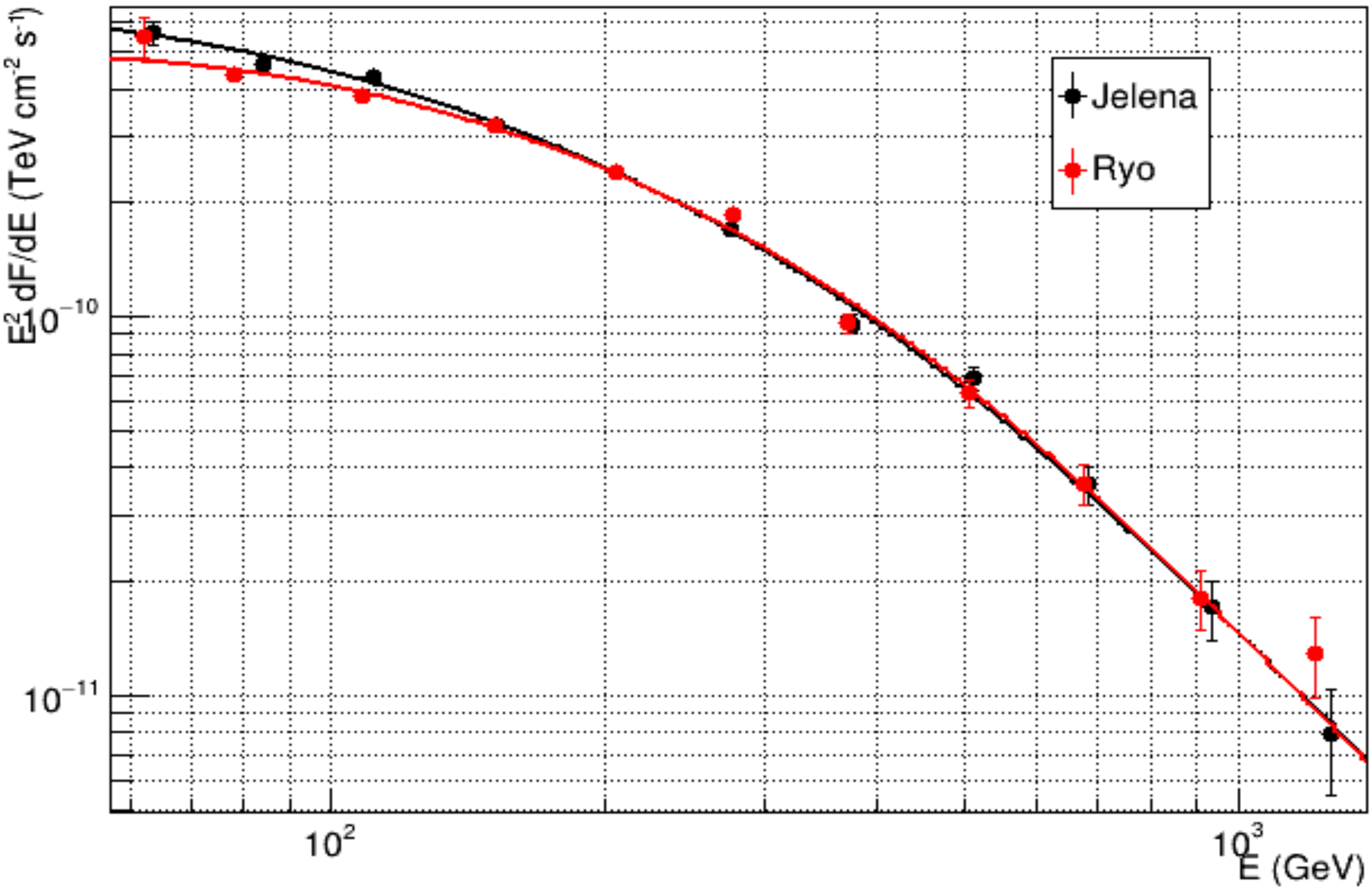
Light curve example

Time bin ~5 min



Time

Spectral energy distribution example



Lorentz invariance violation

- Modified photon dispersion relation (MPDR):

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

n = 1 linear contribution
n = 2 quadratic contribution

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

- Energy-dependent photon group velocity:

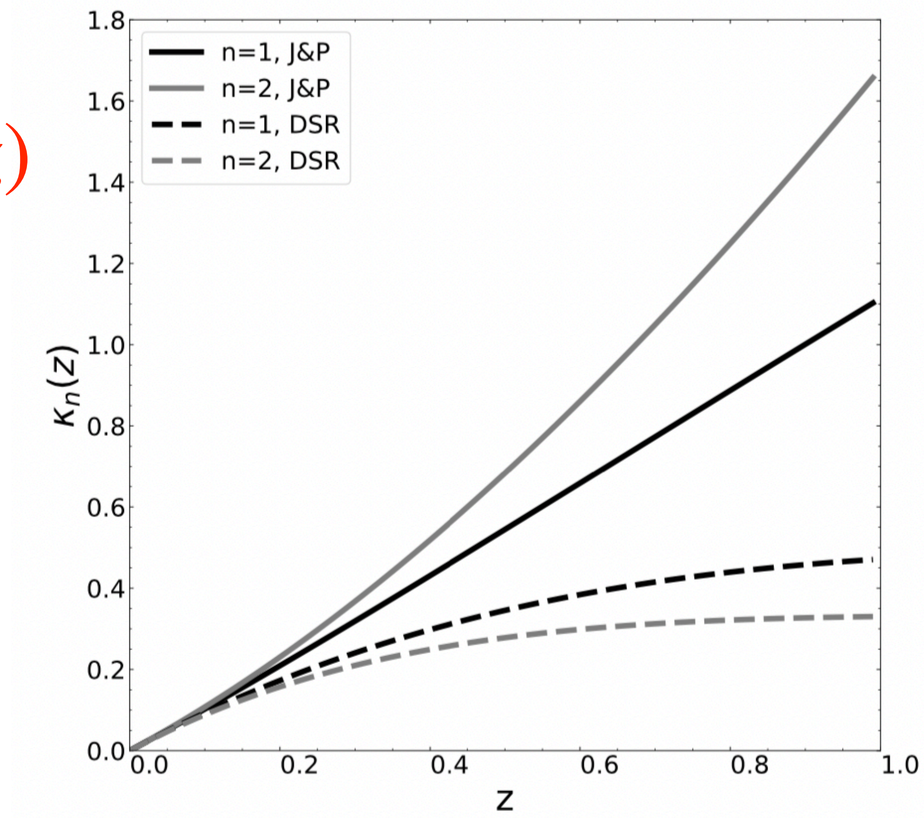
$$v_\gamma = \frac{\partial E}{\partial p} \simeq c\left[1 + \sum_{n=1}^{\infty} S_n \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG},n}}\right)^n\right]$$

minuscule effects

Consequences of MPDR: Time of flight

- Energy-dependent time delay:

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



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

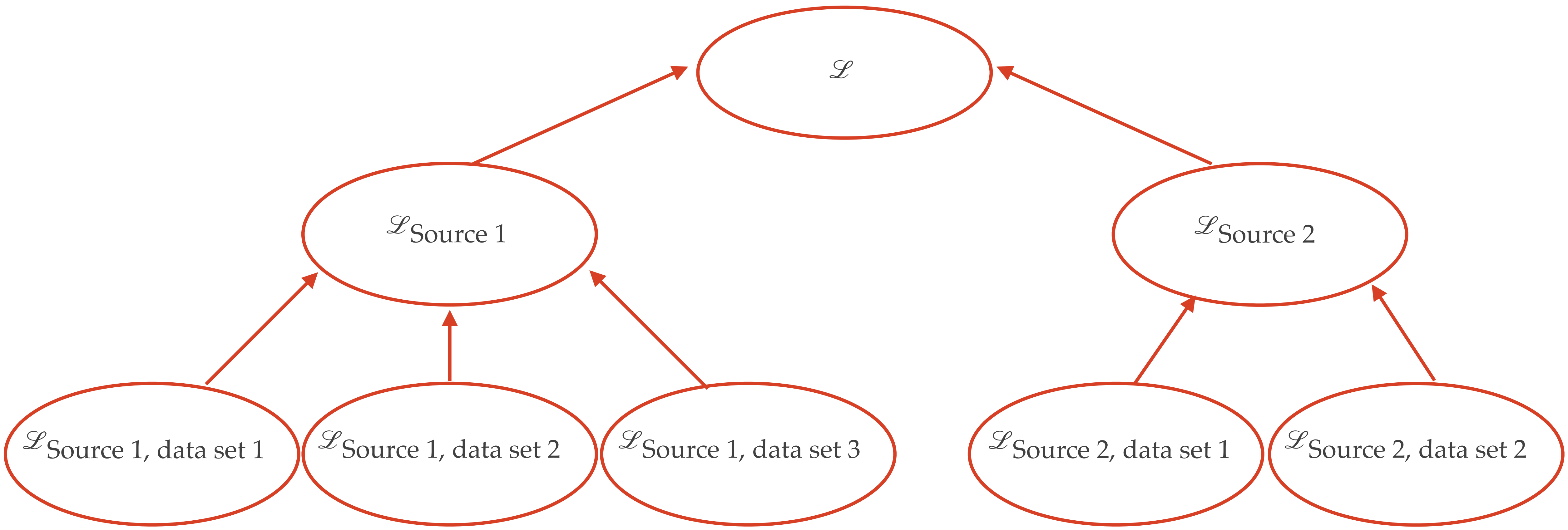
- Distance contribution:

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

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

gLike

- ROOT-based code framework for the numerical maximisation of joint likelihood functions
- Open source
- The joint likelihood ($\mathscr{L}$) 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:

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

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

- Probability distribution function:

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

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

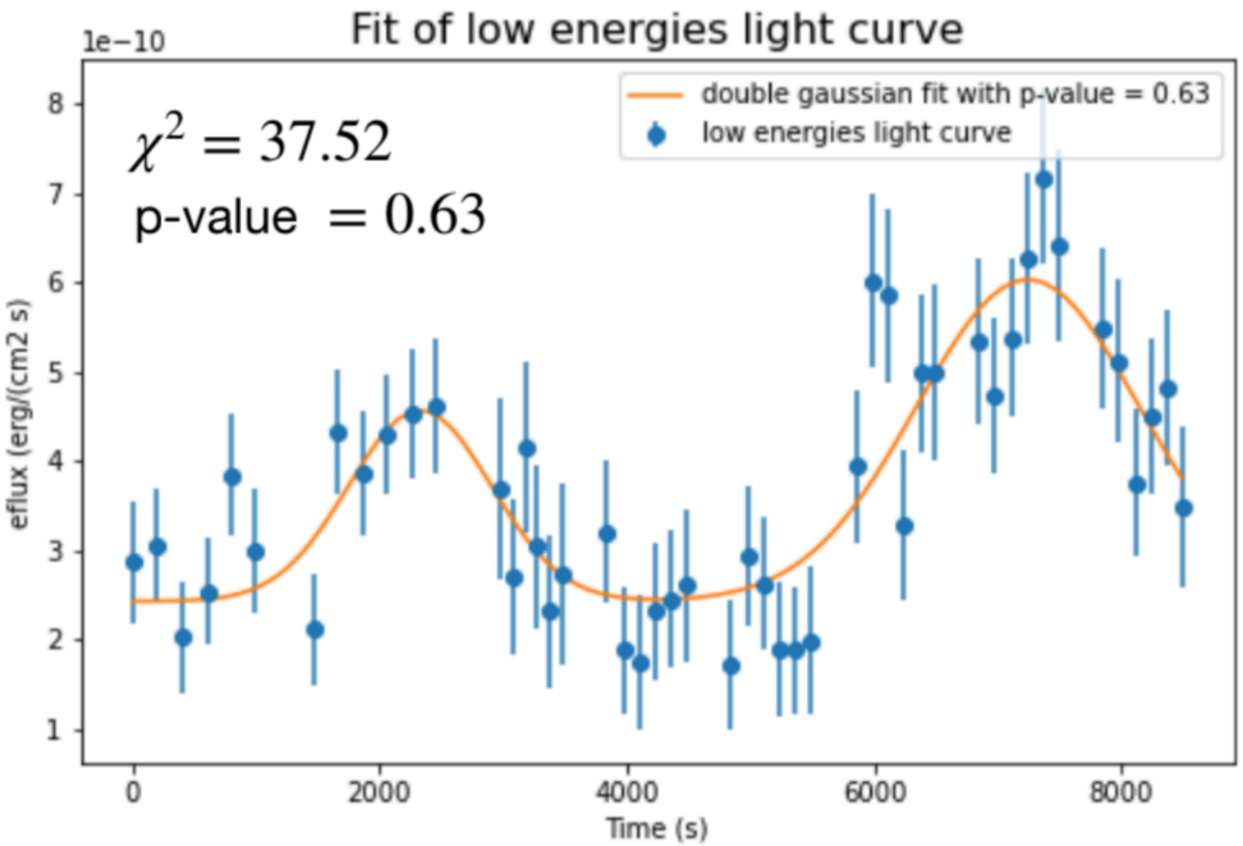
energy resolution and bias

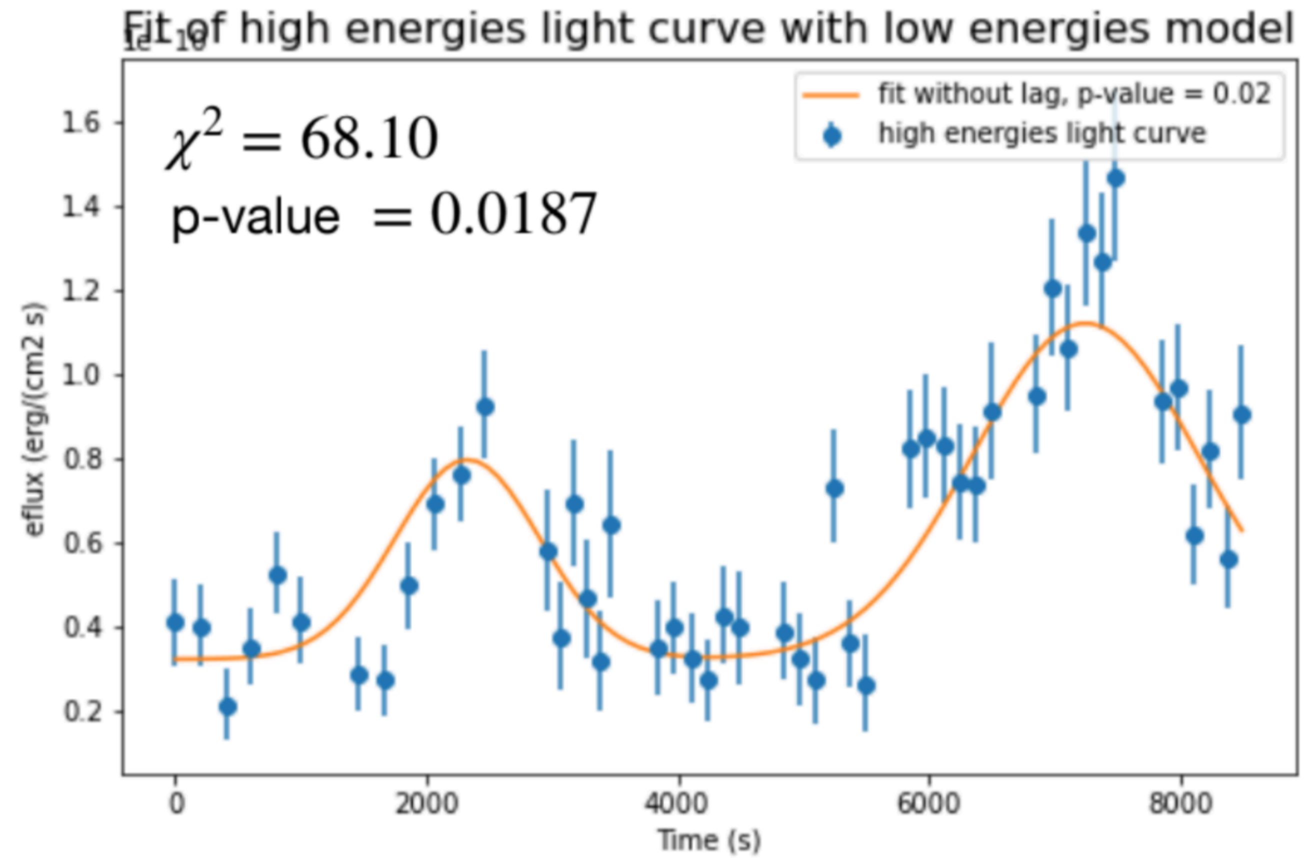
collection area

observed spectral distribution of gamma rays

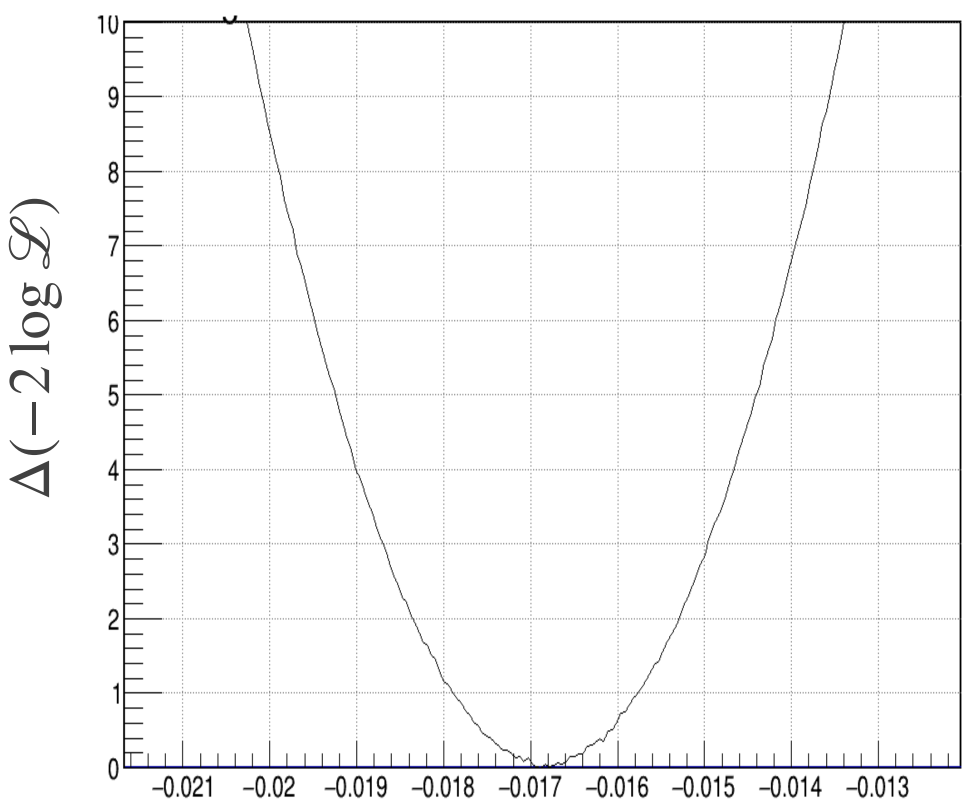
$$\eta_n = -S_n \frac{n+1}{2} \frac{1}{E_{\mathrm{QG},n}^n} \kappa_n(z_{\mathrm{s}})$$

How does it work?





Credit: Cyann Buisson



$$t_i' = t_i + \eta_n E_i^n$$

The likelihood is maximised for the eta that best recovers the low energy distribution

Quantum gravity lower bounds and the redshift

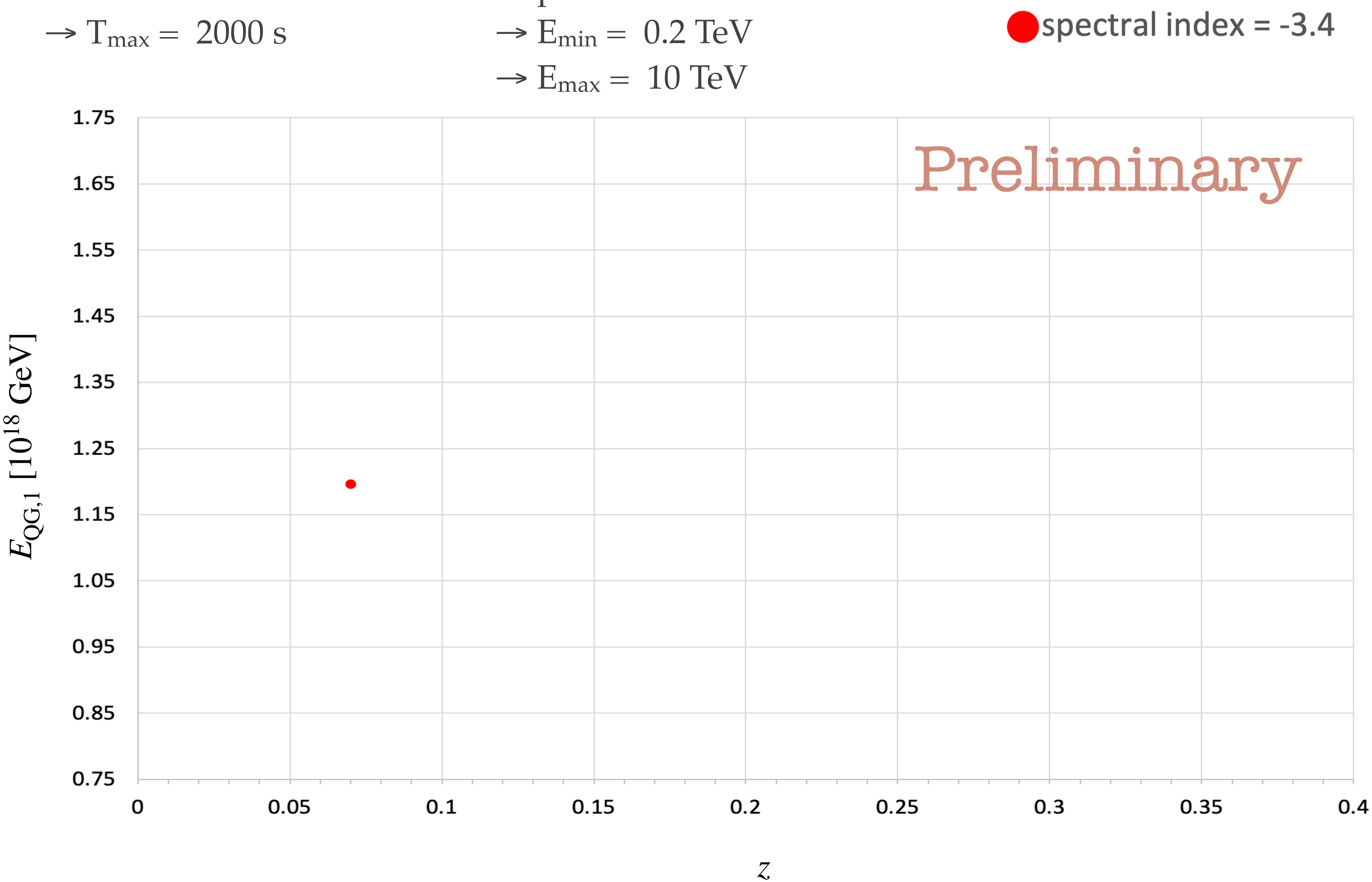
$E_{\mathrm{QG},1}$	$\propto$	E_{max}	t_{var}^{-1}	$z_{\mathrm{s}}^{\sim 1}$
$E_{\mathrm{QG},2}$	$\propto$	E_{max}	$t_{\mathrm{var}}^{-1/2}$	$z_{\mathrm{s}}^{\sim 2/3}$

- Redshift variability of the limit is ruled by three processes:
  - Distance
  - EBL absorption
  - Delay accumulates with redshift

Quantum gravity lower bounds and the redshift

Temporal distribution
- → 1 Gaussian
- → $T_{max} = 2000$ s

Spectral distribution
- → power law
- → $E_{min} = 0.2$ TeV
- → $E_{max} = 10$ TeV



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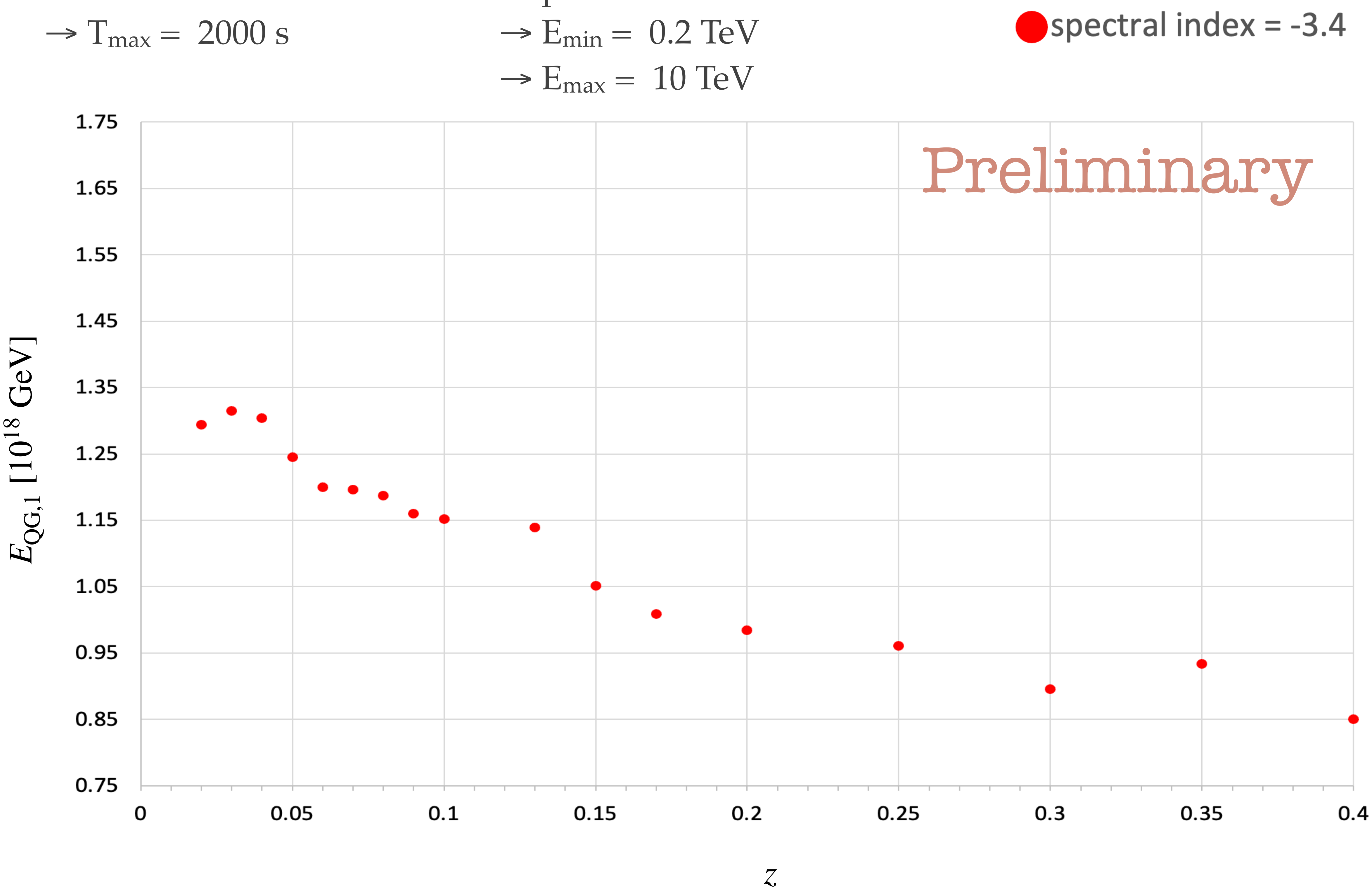

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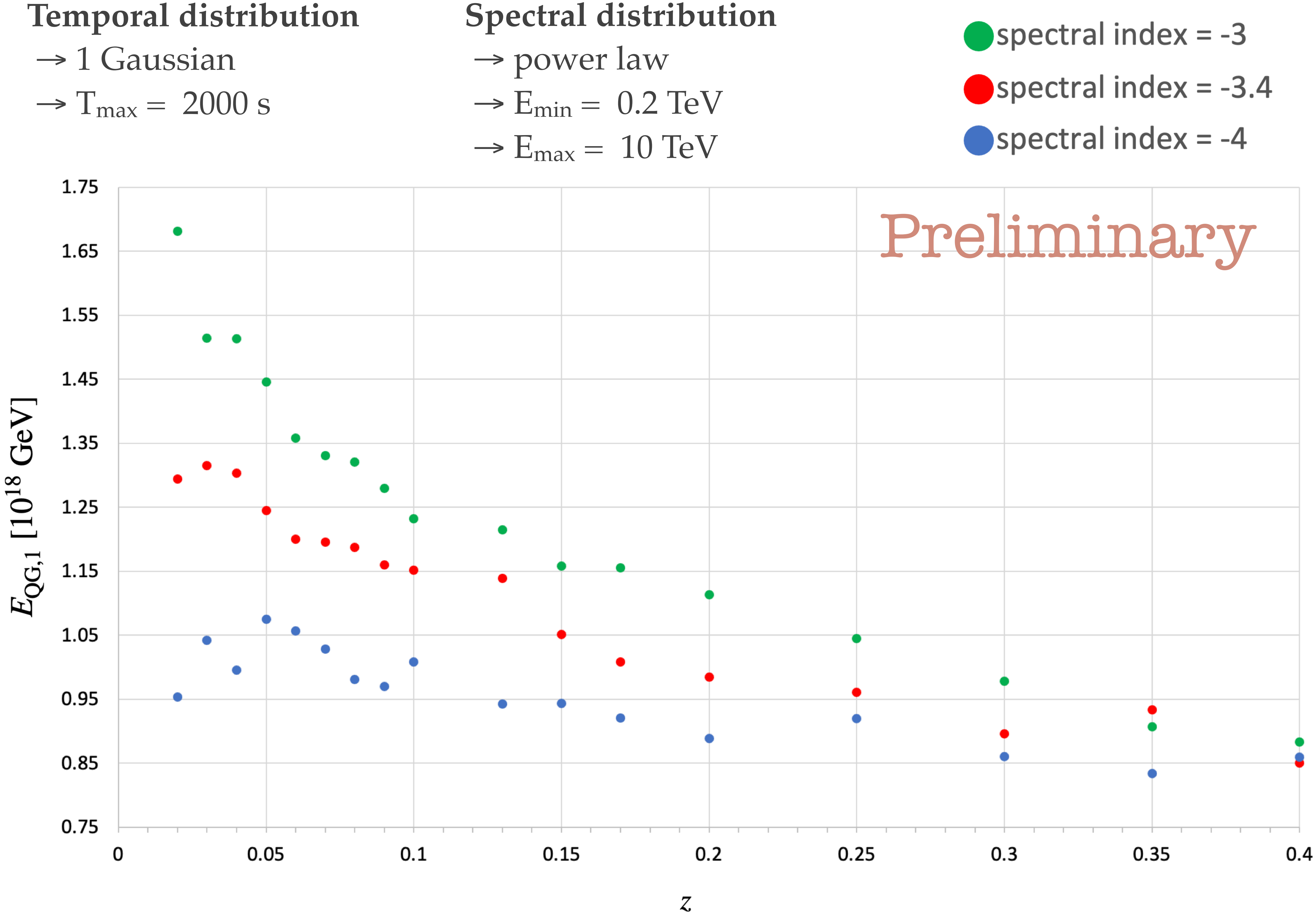
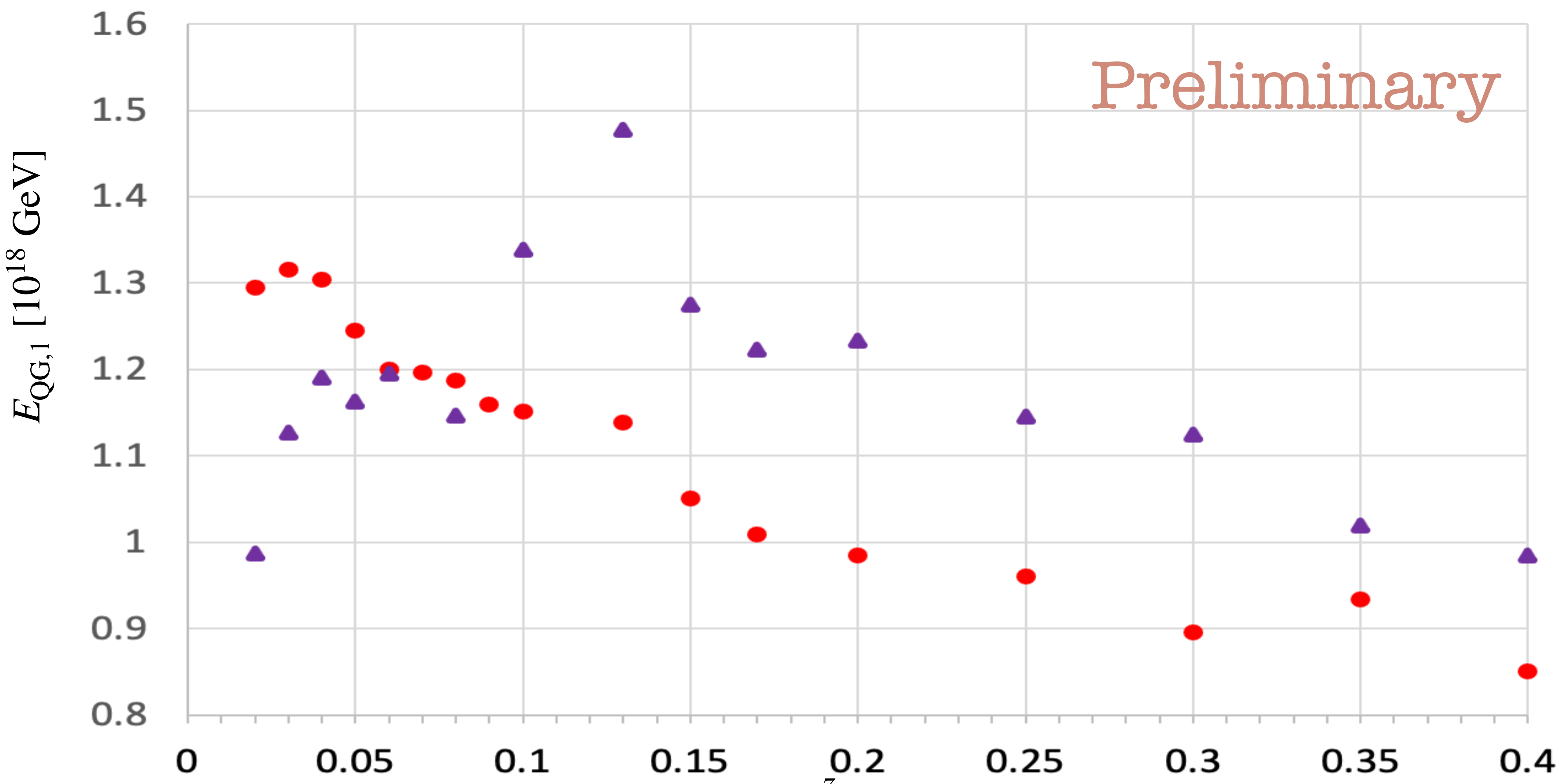


Quantum gravity lower bounds and the redshift

Circle
Temporal distribution
→ 1 Gaussian
→ T_{max} = 2000 s

Triangle
Temporal distribution
→ 5 Gaussians
→ T_{max} = 4000 s

Spectral distribution
→ power law spectral index = -3.4



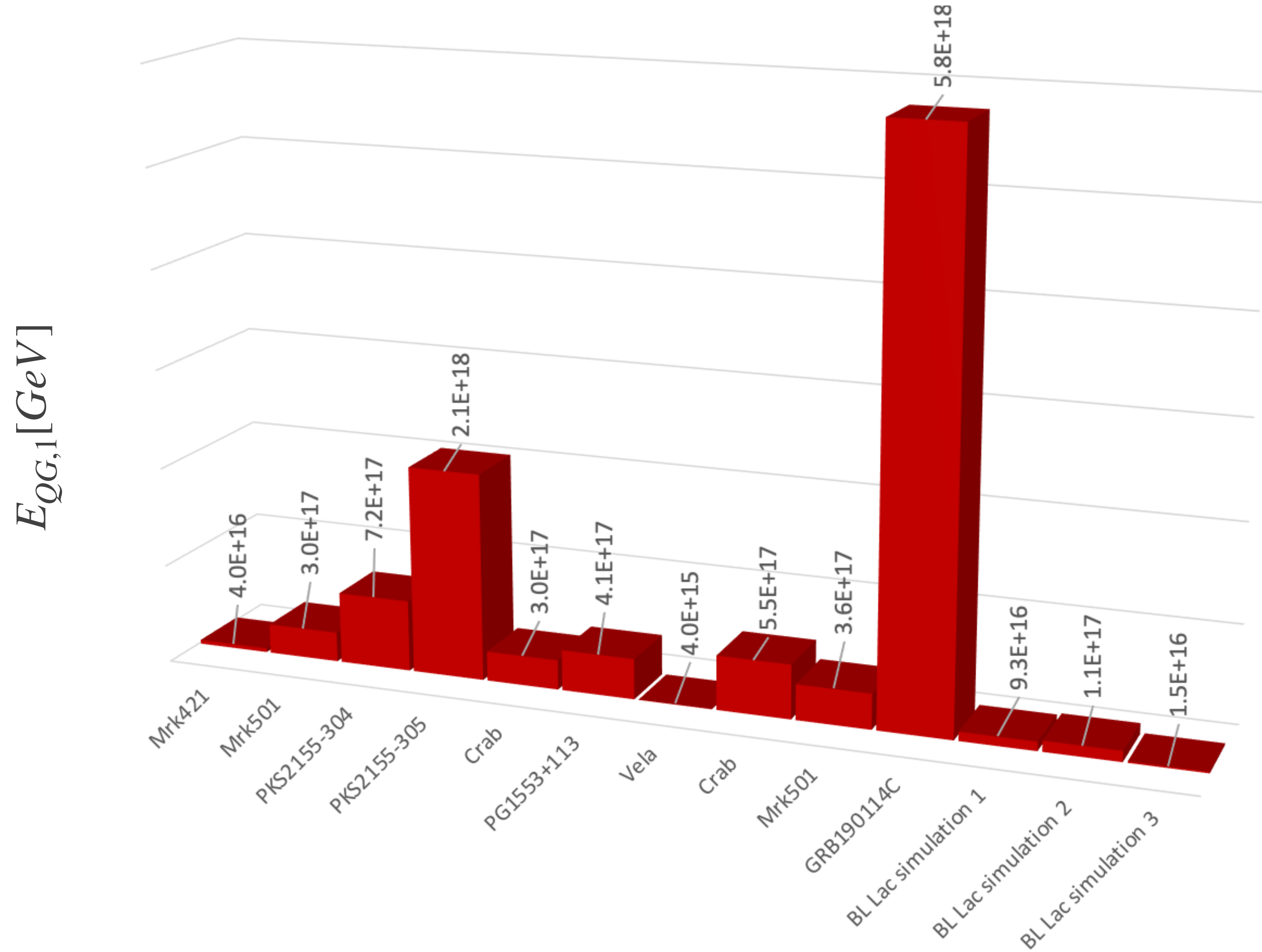
New interesting source: BL Lac

- 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

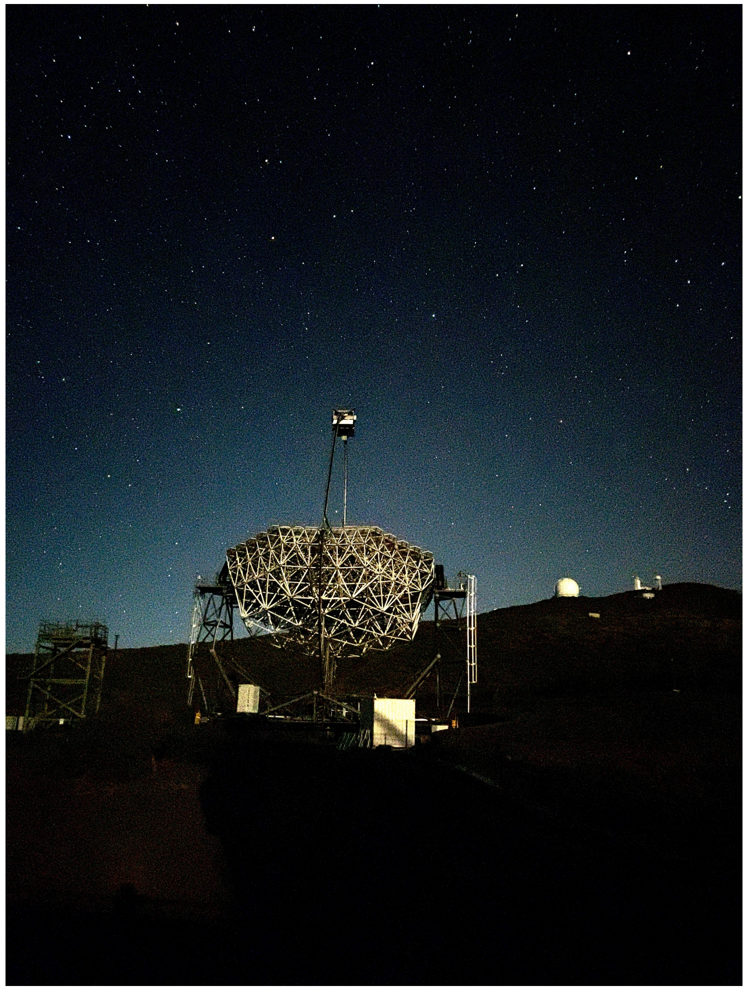
Lower bounds on the LIV energy scale obtained with IACTs



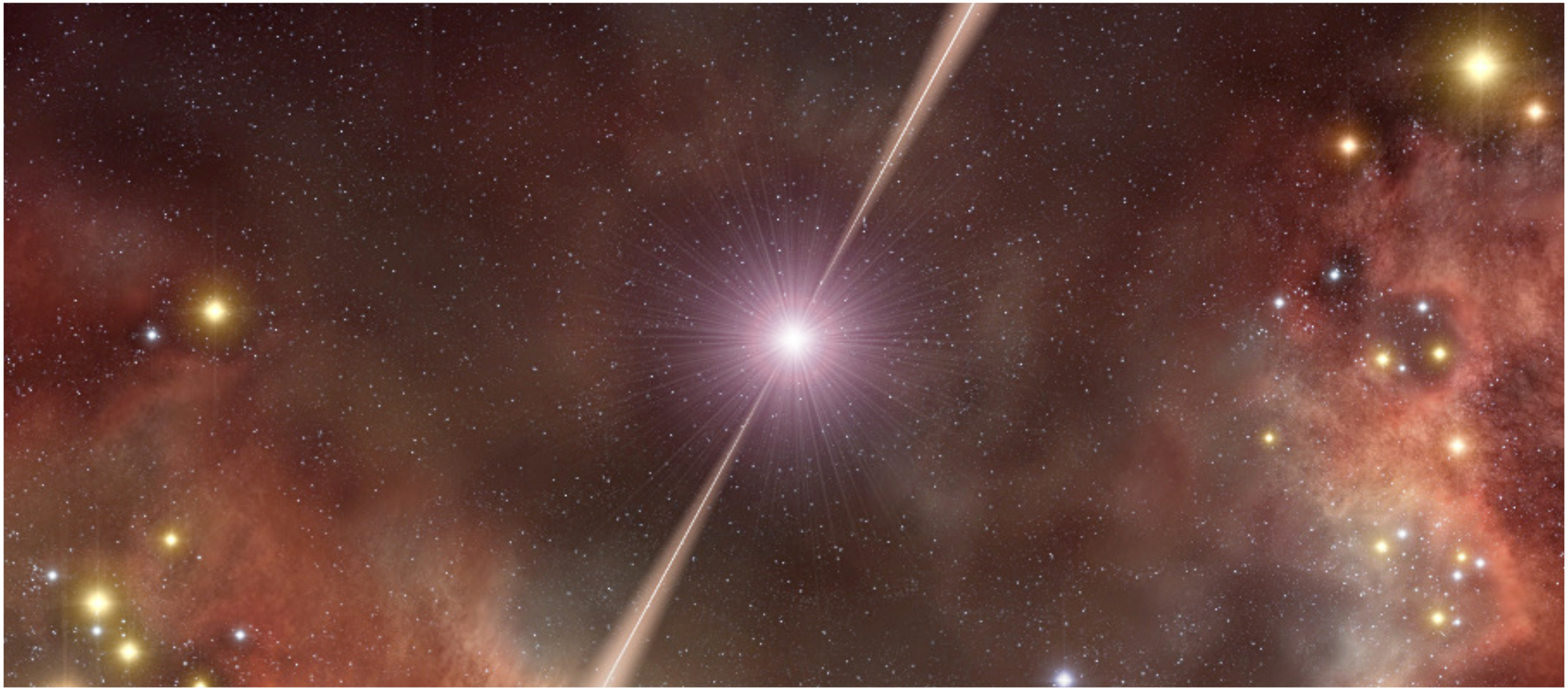
- We need to improve light curve templates especially for 2020_09_20 → binned maximum likelihood analysis

Conclusions

- gLike:
  - Numerical maximisation of joint likelihood functions
  - Combining data from different sources or instruments to produce one limit
- Sensitivity to QG changes with distance
- New interesting source for LIV: BL Lac
  - complex LC template
- Binned ML analysis:
  - Should decrease slightly the sensitivity
  - Can handle any complex LC



- Stay tuned for first exciting results!



Backup

Jelena Strišković

Binned maximum likelihood analysis

- Likelihood function for observed number of ON events:

nuisance parameters

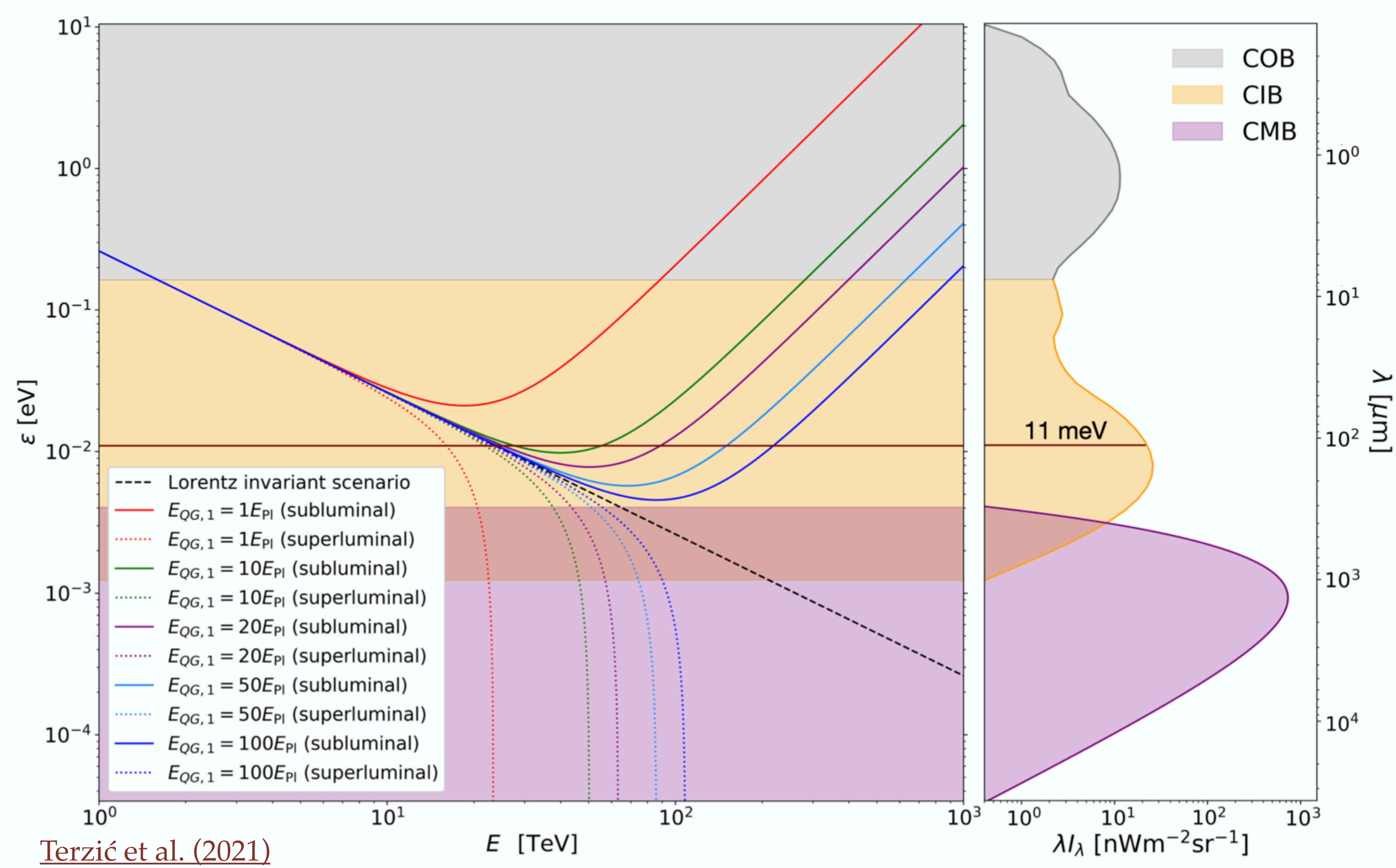
$$\mathscr{L}\left(\eta_n\right) = \prod_{i=1}^{N_\mathrm{E}} \prod_{j=1}^{N_\mathrm{t}} P\left(s_{i,j}(\eta;\mu) + b_{i,j} \,|\, N_{i,j}^{ON}\right) P\left(\alpha b_{i,j} \,|\, N_{i,j}^{OFF}\right)$$

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

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

Consequences of MPDR: changes in energy reaction threshold

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



Terzić et al. (2021)

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