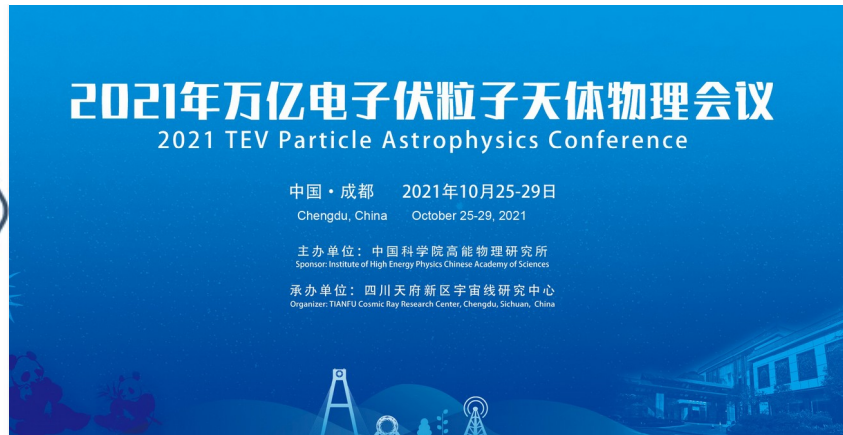
Advanced searches for Lorentz invariance violation with Cherenkov telescopes

Tomislav Terzić
University of Rijeka
Department of Physics
tomislav.terzic@gmail.com

In collaboration with
J. Bolmont*, S. Caroff*, G. D'Amico#, M. Gaug*, A. Gent*, A. Jacholkowska*, D. Kerszberg*#, C. Levy*, T.T.Y. Lin*, M. Martinez*#, L. Nogués*, A.N. Otte*, C. Perennes*#, J. Rico#, M. Ronco*

* LIV results combination working group
# LIV on GRB190114C on behalf of the MAGIC collaboration



Outline

- Lorentz invariance violation
- H.E.S.S. – MAGIC – VERITAS data combination
- Likelihood analysis
- Results
- Focus on GRB 190114C
- Takeaways

Lorentz invariance violation (LIV)

- Modified photon dispersion relation
  - The usual starting point in searches for effects of quantum gravity

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

photon energy

S = ±1

QG energy scale

- Simple way of parametrizing “out of the ordinary” behaviour

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 $E_h > E_l$

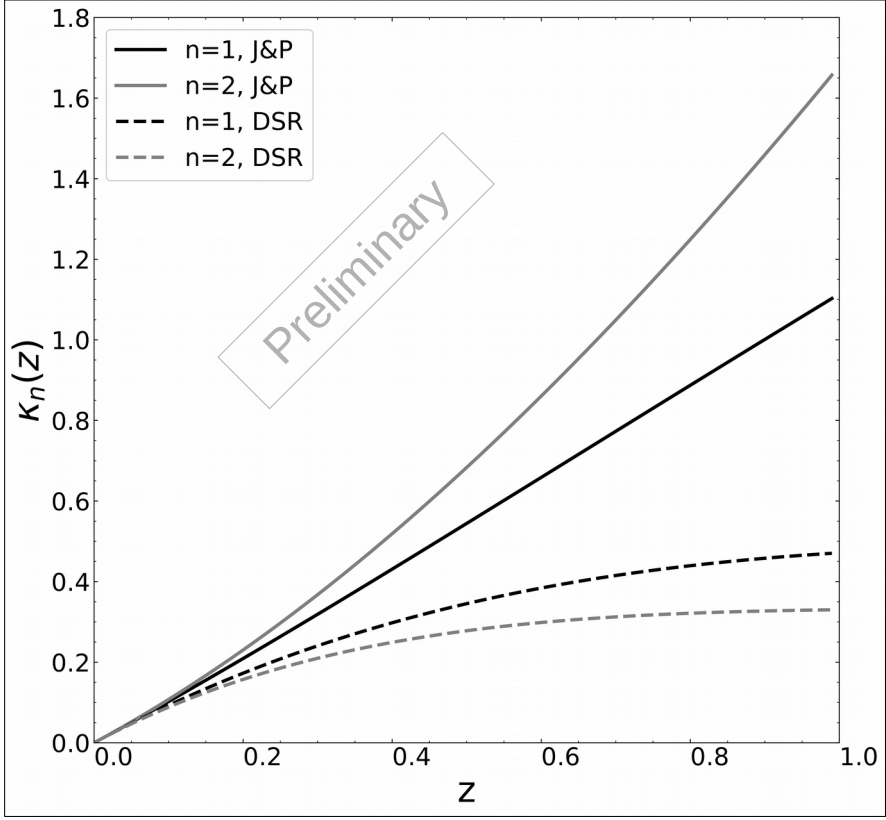
$$\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{\mathrm{H}_0 E_{QG}^n} \kappa_n(z)$$

- Effect accumulates over astronomical distances

Distance contributions

- Standard in literature (Jacob & Piran, 2008)

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



- Alternative expression (Rosati+ 2015)
  - One possible outcome of Doubly Special Relativity (DSR)
  - **First study** comparing two lag-redshift models

$$\kappa_n^{\mathrm{DSR}}(z) \equiv \int_0^z \frac{h^{2n}(z')dz'}{(1+z')^n \sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$h(z') \equiv 1 + z' - \sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda} \int_0^{z'} \frac{dz''}{\sqrt{\Omega_m (1+z'')^3 + \Omega_\Lambda}}$$

- Additional alternative expressions may be considered in future work

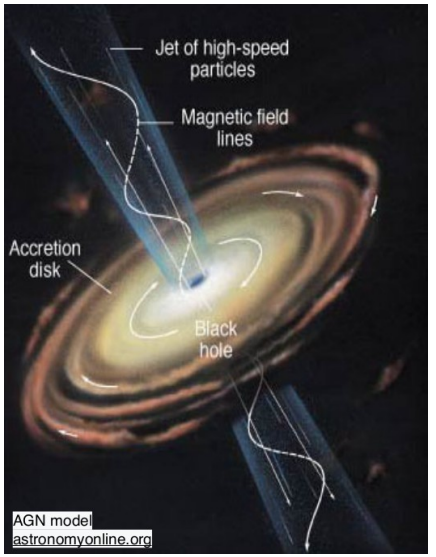
H.E.S.S. – MAGIC – VERITAS

In collaboration with: J. Bolmont, S. Caroff, M. Gaug, A. Gent, A. Jacholkowska, D. Kerszberg, C. Levy, T.T.Y. Lin, M. Martinez, L. Nogués, A.N. Otte, C. Perennes, M. Ronco

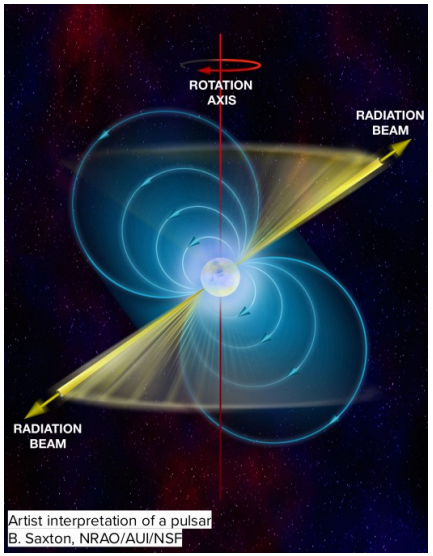
- Energy range: ~20 GeV – 100 TeV
- Combining all available data
  - Increases statistics
  - Sources at different distances
  - Different (types of) sources
- Disentangling LIV from source intrinsic effects
  - Emission modelling – ongoing effort (see e.g. Perennes+ 2020; Levy+ 2021)

Astrophysical sources

- All previously used in independent (single-source) LIV studies
- Active Galactic Nuclei
  - Markarian 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)
- Pulsars
  - Crab: MAGIC & VERITAS (Otte 2011; Zitzer 2013; 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 pulsar
B. Saxton, NRAO/AUI/NSF


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

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

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

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

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

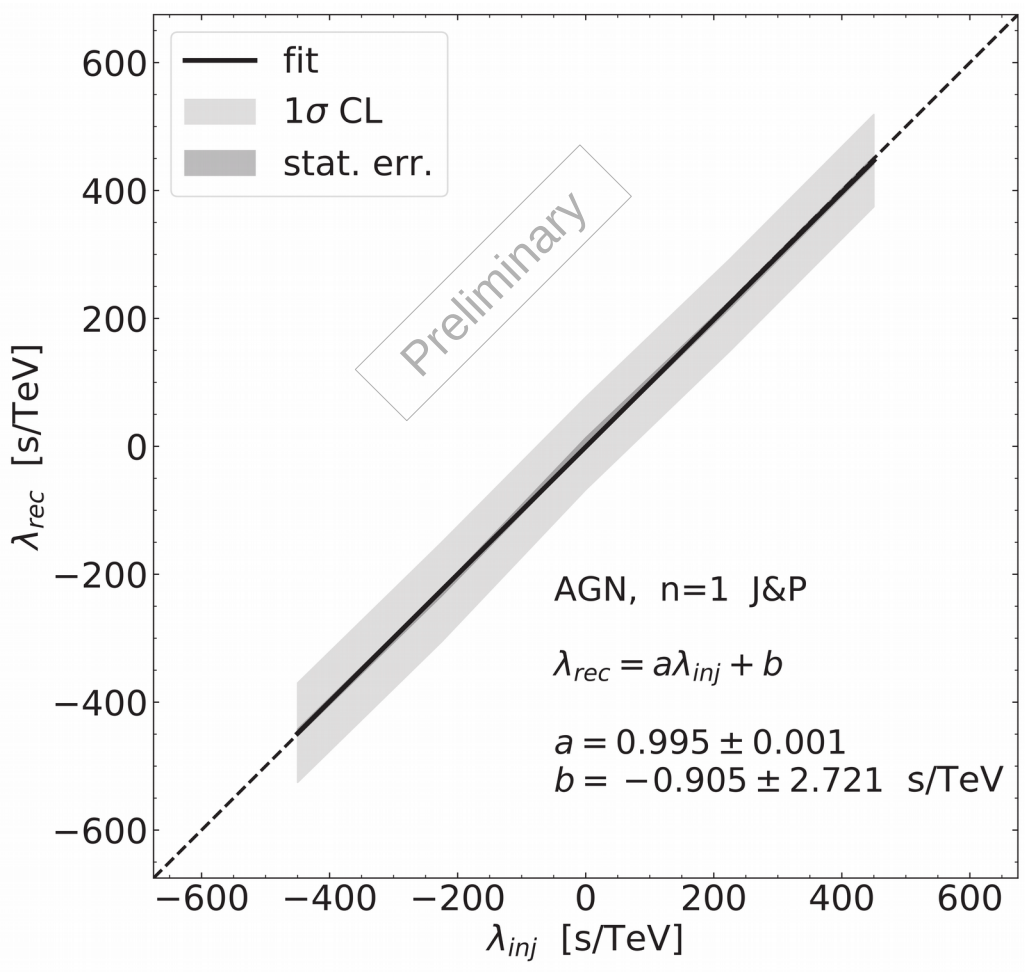
Likelihood analysis – on simulated datasets

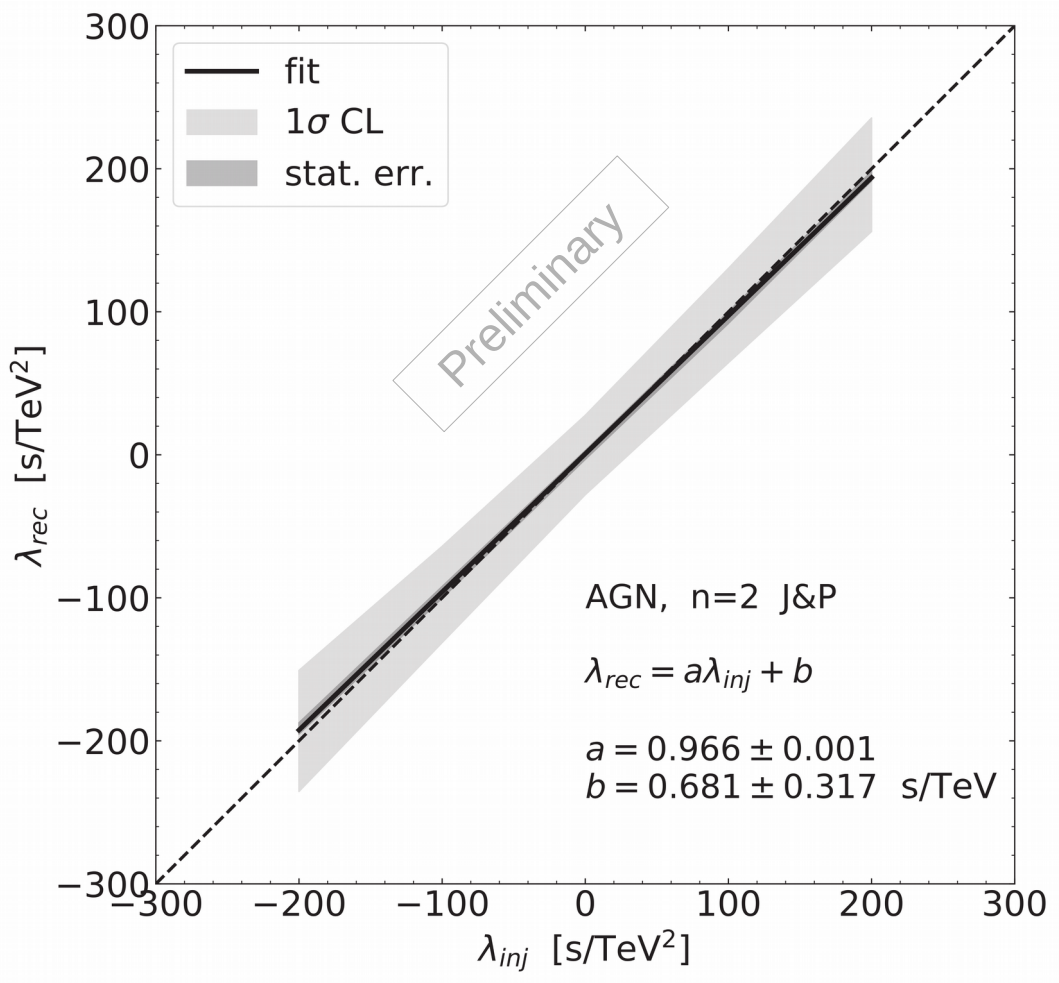
- Instrument Response Functions (IRFs) (effective area, migration matrix)
  - Provided for **each experiment** and for **each observation**
- **Low energy photons** used for building **light curve templates**
  - Assuming they are not affected by LIV
- **High energy photons** used to perform the **likelihood analysis**

- Multiple simulated datasets created with different values of LIV parameter
- Unbinned maximum likelihood analysis performed on simulated datasets
  - Test whether our analysis properly reconstructs the injected LIV delay

Analysis calibration: AGN combined

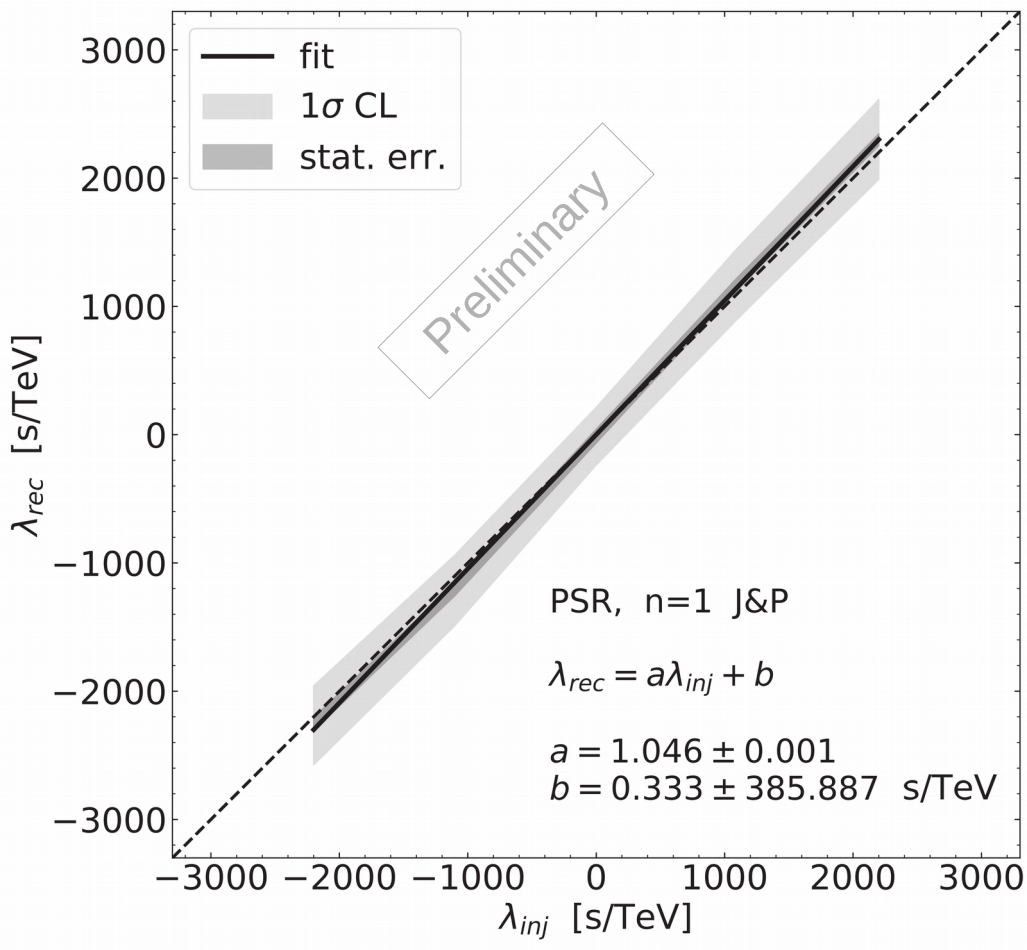
- Comparing the simulated time delay vs the reconstructed one
- Using J&P model

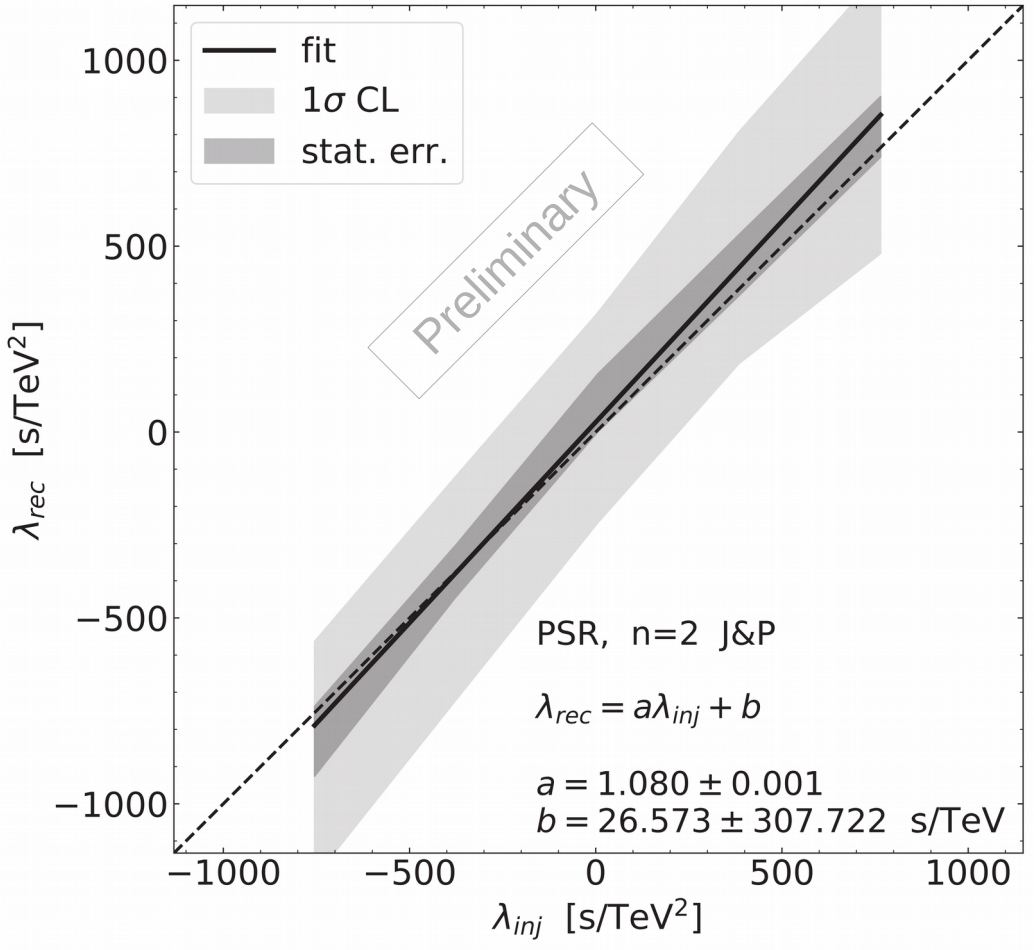




Analysis calibration: pulsars combined

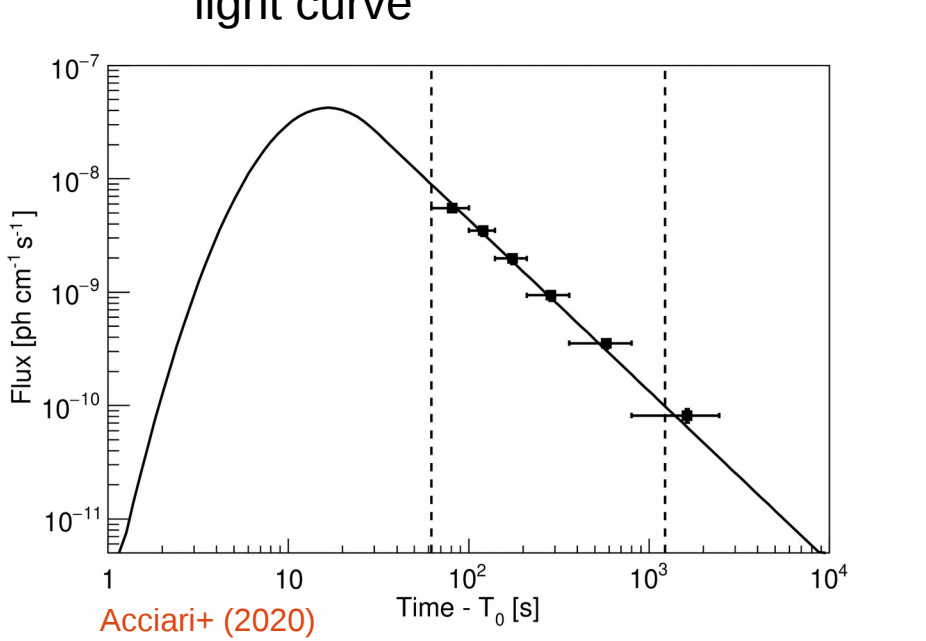
- Comparing the simulated time delay vs the reconstructed one
- Using J&P model



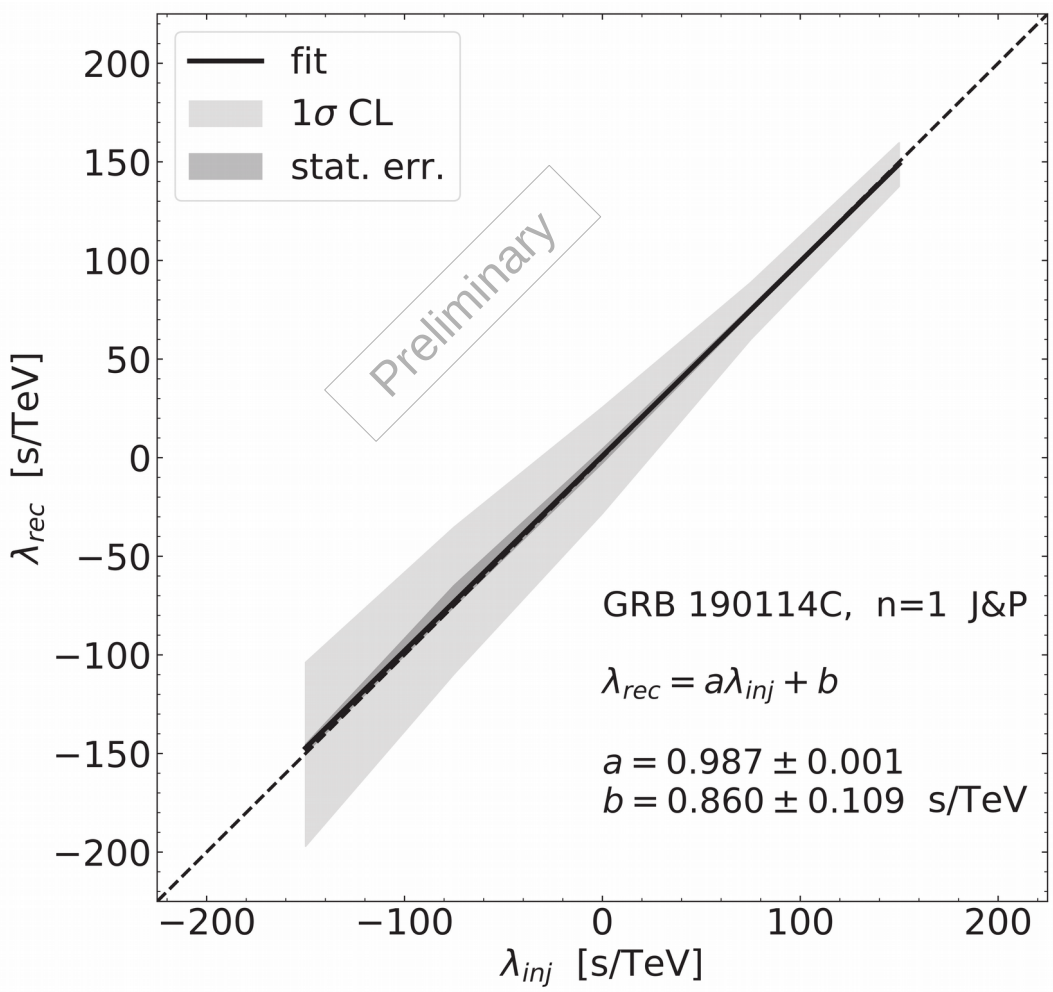


Analysis calibration: GRB

- Comparing the simulated time delay vs the reconstructed one
- Using J&P model & n = 1
- Notice asymmetric uncertainties
  - Consequence of the asymmetric light curve

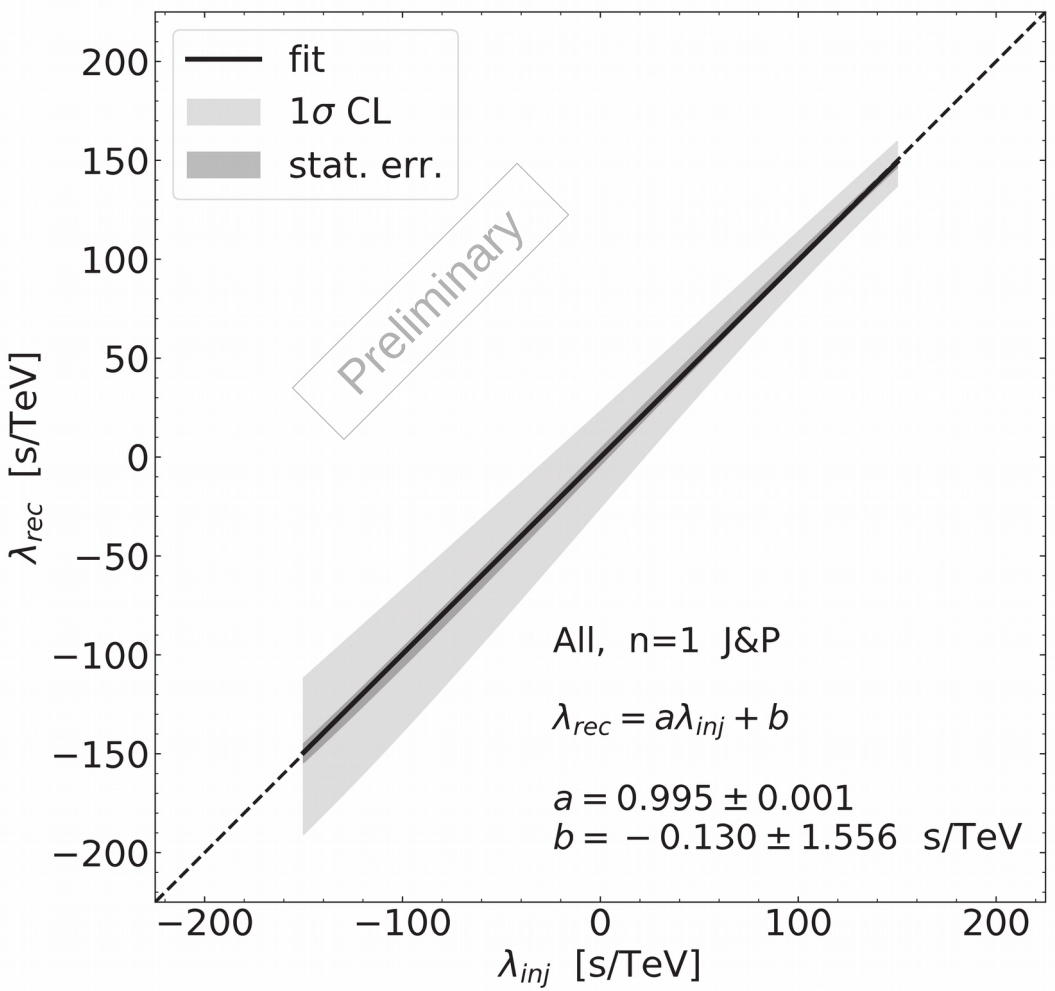


Acciari+ (2020)



Analysis calibration: all sources combined

- Comparing the simulated time delay vs the reconstructed one
- Using J&P model & $n = 1$
- Similar and consistent results:
  - for $n = 2$
  - in the DSR scenario (both for $n = 1$ & $n = 2$)
- Shape of the uncertainty band very similar to the one of GRB 190114C
  - Strong influence of GRB 190114C on the combined likelihood



Systematic uncertainties

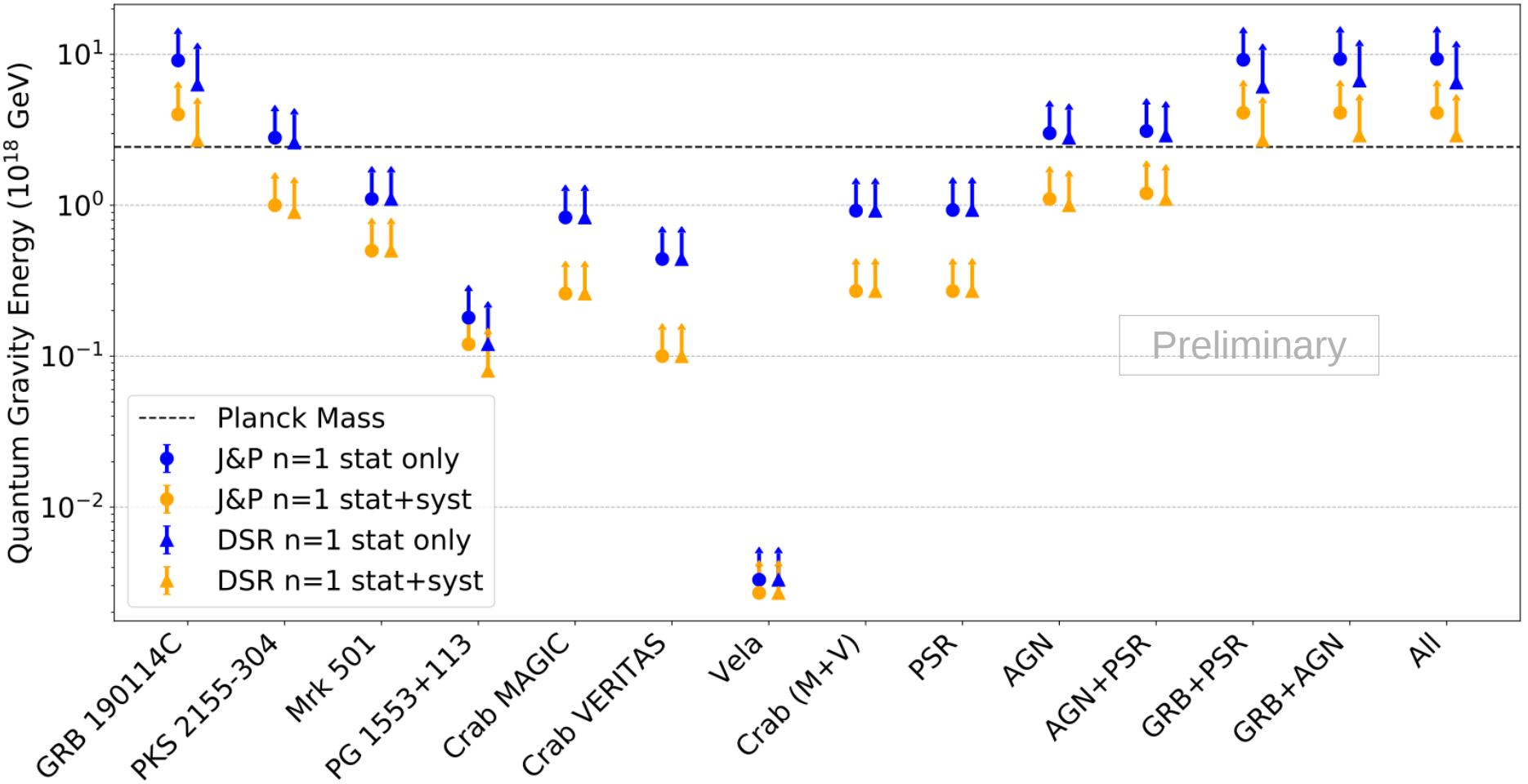
- Different systematic uncertainties considered:
  - Limited low energy statistics used to build the light curve template
  - Uncertainty on spectral power law index
  - Uncertainty on background/signal proportion
  - Uncertainty on the energy scale
  - Uncertainty on the redshift

$$L(\lambda_n, \vec{\theta}) = L_{\mathrm{S}}(\lambda_n, \vec{\theta}) + L_{\mathrm{template}}(\vec{\theta}_{\mathrm{C}}) + L_{\gamma}(\theta_{\gamma}) + L_{\mathrm{B}}(\vec{\theta}_{\mathrm{B}}) + L_{\mathrm{ES}}(\theta_{\mathrm{ES}}) + L_{\mathrm{z}}(\theta_{\mathrm{z}})$$

- **All sources of uncertainties added to the likelihood as nuisance parameters**
- Constraints on QG energy scale:
  - Based on simulations only
  - Several hundred of realizations for each light curve
  - Closer to the real performance of the instrument
    → especially important when performing multi-instrument analysis

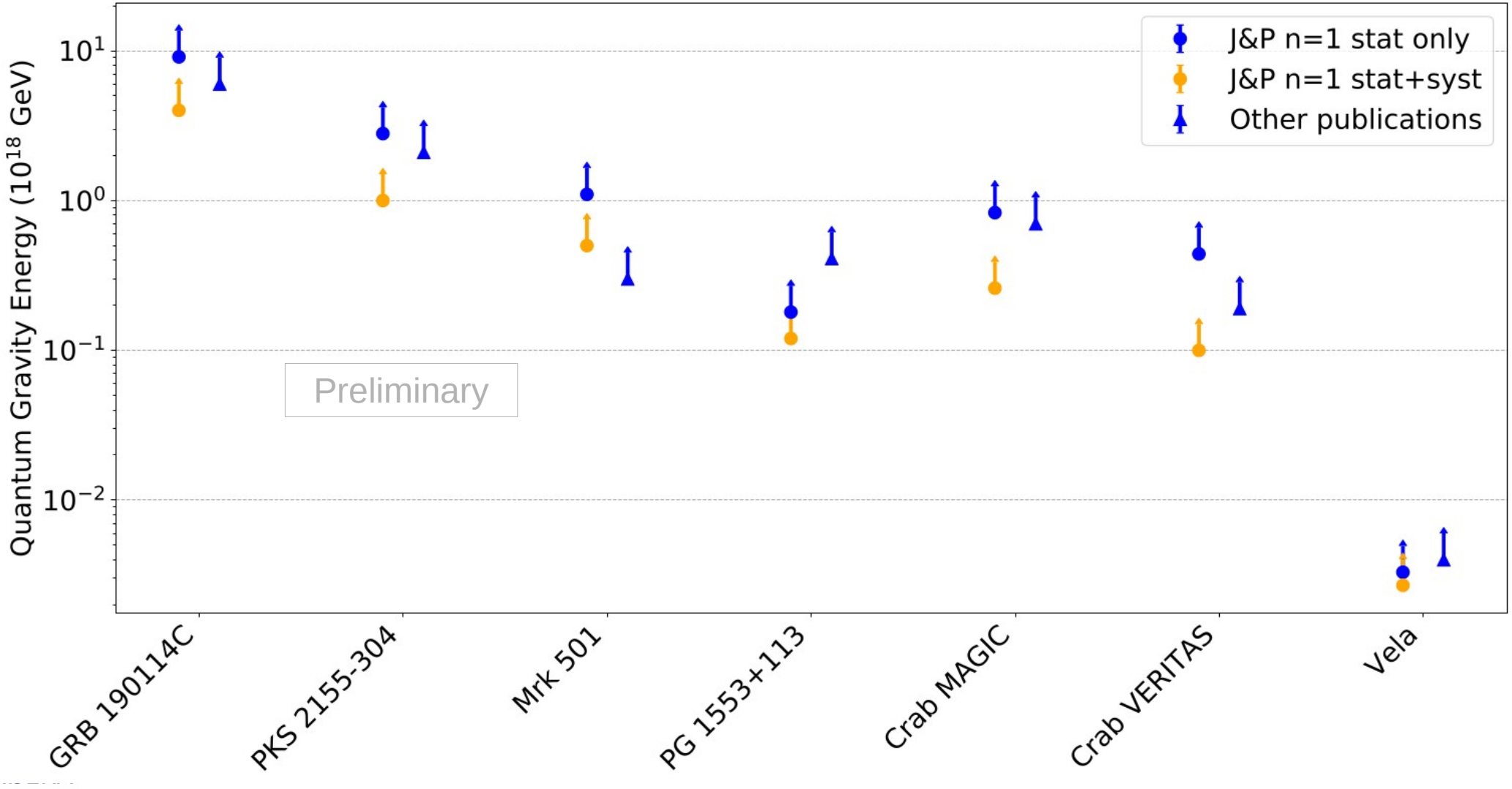
Results: bounds on QG energy scale

- 95% CL lower limits obtained for individual objects and combinations



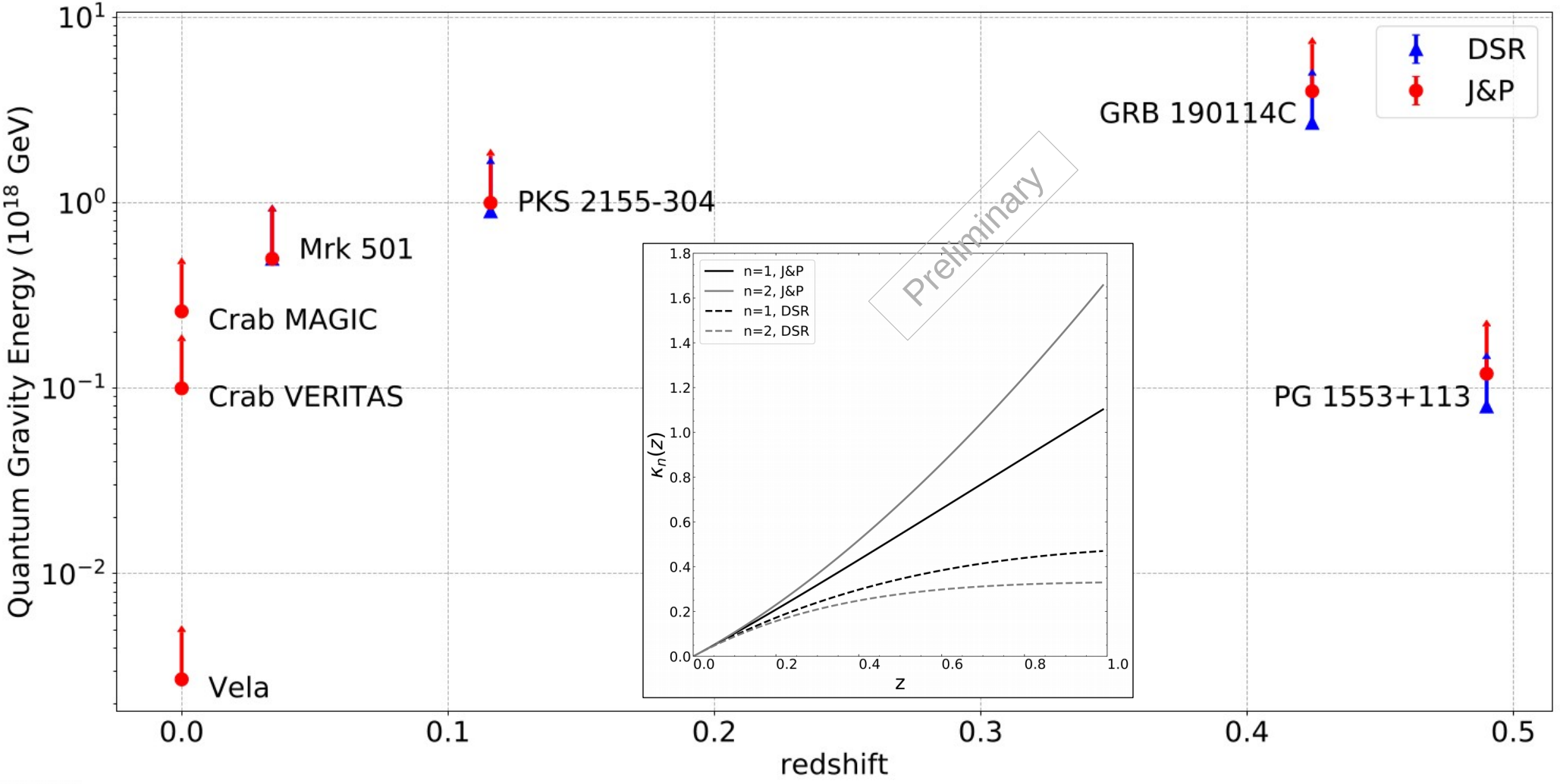
Results: comparison with published results

- 95% CL lower limits obtained for $n = 1$



Results: redshift dependence

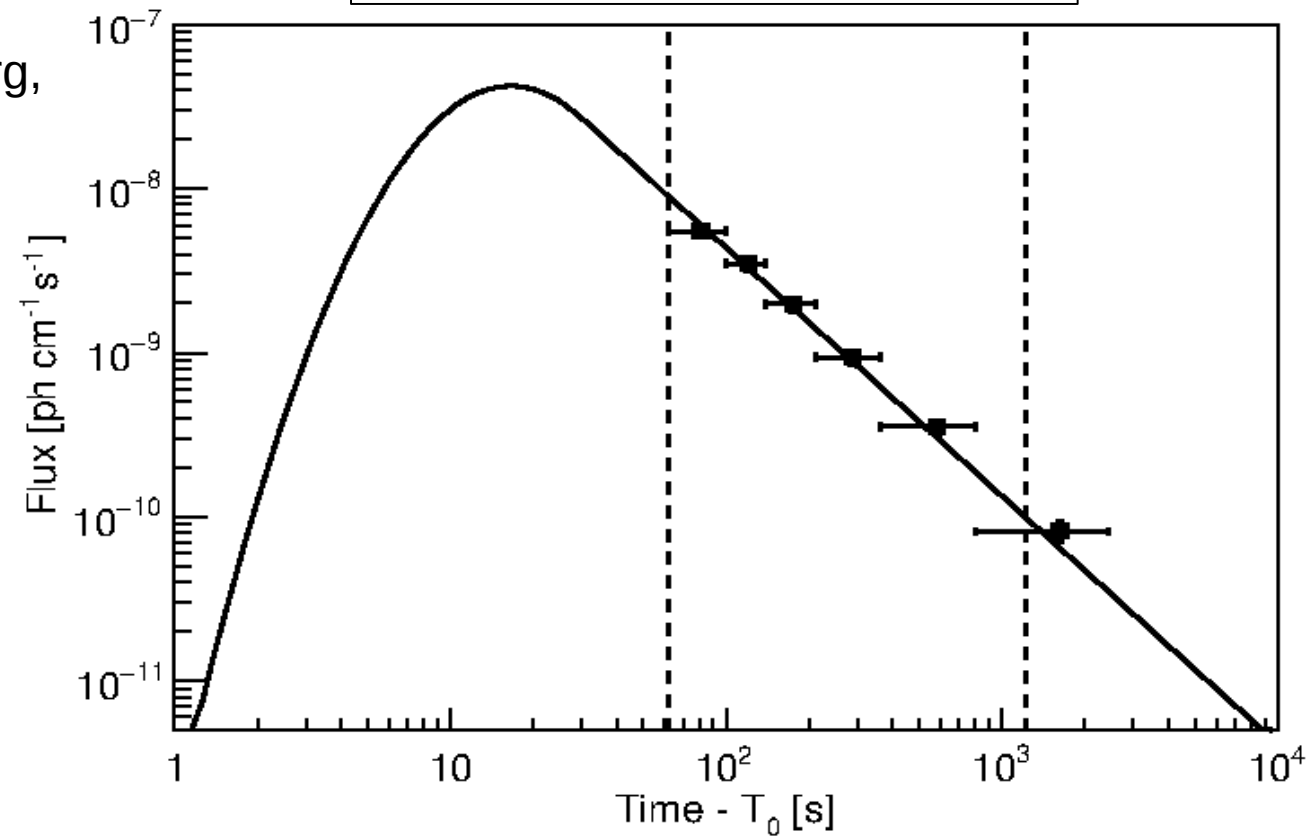
- Redshift dependence of J&P vs DSR distance models
- 95% CL lower limits obtained for n = 1, systematic included



GRB 190114C: LIV analysis on real dataset

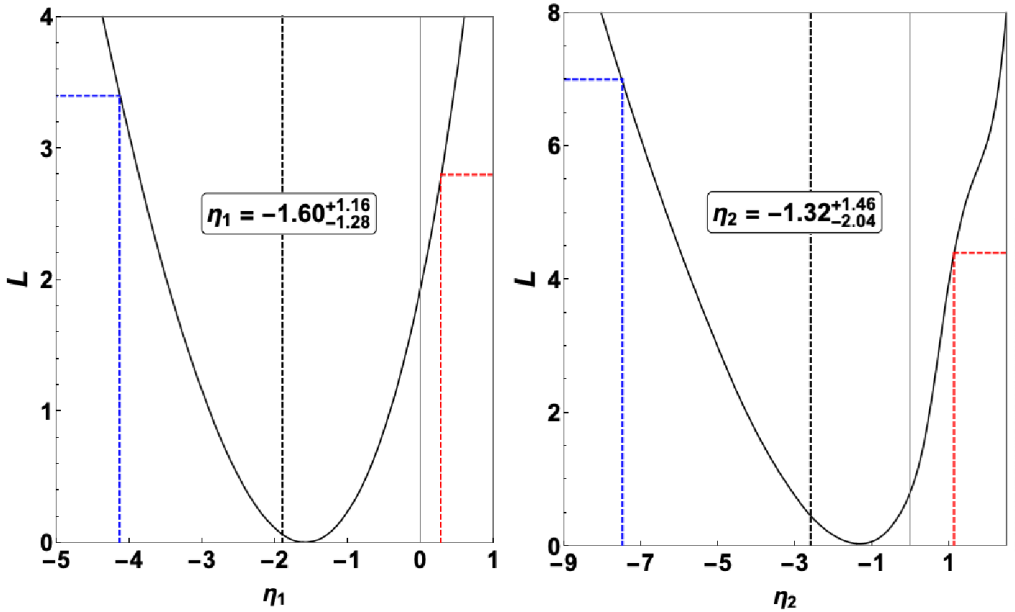
- Highest energies ever observed from a gamma-ray burst (MAGIC: Acciari+ 2019a)
- **Moderate redshift: 0.4245 ± 0.0005**
- **Fast variability light curve**
- Energy distribution: Power law with $E_{max} \approx 2$ TeV
- Dedicated LIV analysis (Terzić, D'Amico, Kerszberg, Martinez, Perennes, Rico, MAGIC Coll)

Temporal distribution (from: Acciari+ 2019b)



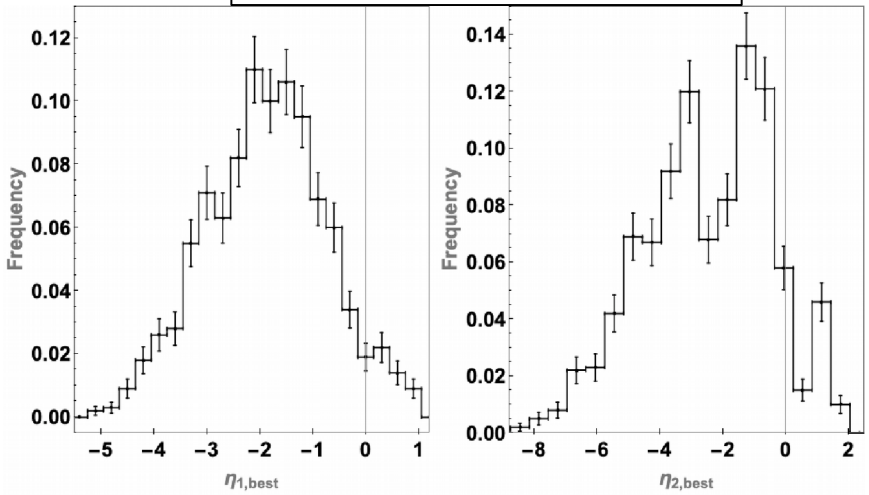
GRB 190114C: LIV analysis comparison

Likelihood maximisation results (Acciari+ 2020)

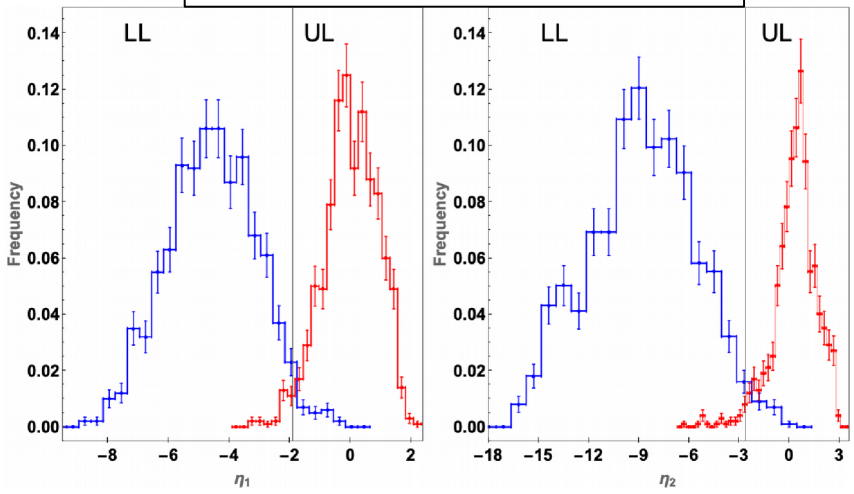


LC template	MAGIC real data	LIV combination simulations	
Distance	J&P	J&P	DSR
$E_{\mathrm{QG},1}$ $[10^{18}\,\mathrm{GeV}]$	5.8	4.0	2.7
$E_{\mathrm{QG},2}$ $[10^{10}\,\mathrm{GeV}]$	6.3	8.3	5.8

Bias estimation



Confidence interval



Takeaways

- **First joint analysis** of H.E.S.S., MAGIC and VERITAS data for LIV
  - 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
- 2nd paper (on real data) to follow