Robust constraints on Lorentz Invariance Violation from H.E.S.S., MAGIC and VERITAS data combination

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Lorentz Invariance Violation (LIV)

Some quantum gravity (QG) models predict a modified dispersion relation of photons in vacuum such that their **speed would be energy-dependent.**

$$E^2 = p^2c^2\left[1 \pm \sum_{n=1}^{\infty}\left(\frac{E}{E_{QG}}\right)^n\right] \rightarrow v_n(E) = c\left[1 - (\pm)\frac{n+1}{2}\left(\frac{E}{E_{QG}}\right)^n\right]$$

$\rightarrow$ **Constrain the QG energy scale** $E_{QG} \sim E_P \sim 10^{19} GeV$

The LIV effect would translate, amongst others, into a **time-delay between the arrival time of photons with different energies.**

$$\Delta t \simeq \frac{n+1}{2}\frac{E_1^n - E_2^n}{E_P^n} f(z) \rightarrow \tau_n = \frac{\Delta t_n}{\Delta E_n} = \pm\frac{n+1}{2H_0 E_{QG}^n} f(z)$$

$f(z)$ is a **model-based distance** function accounting for cosmological effects.

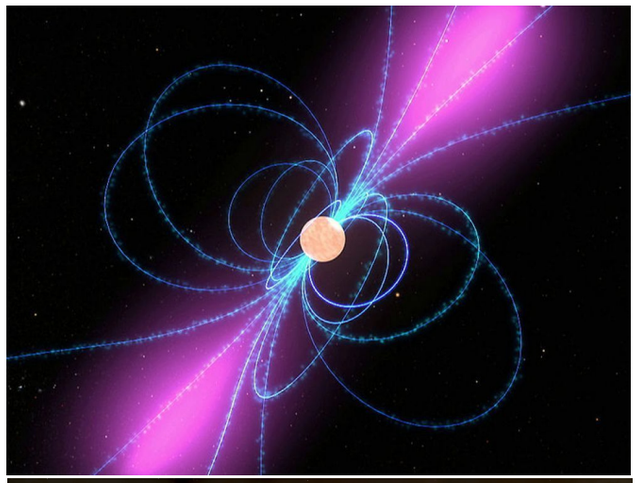
Astrophysical sources

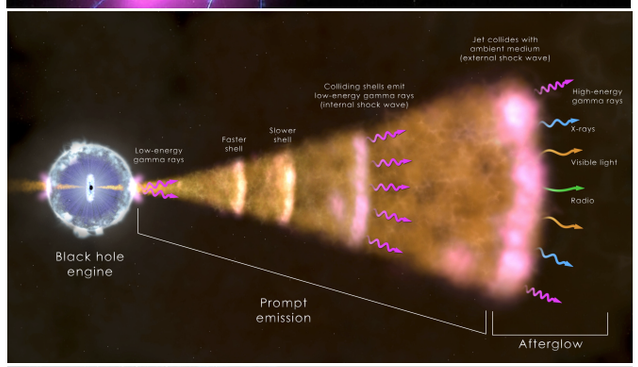
Measured delays maximized for sources:

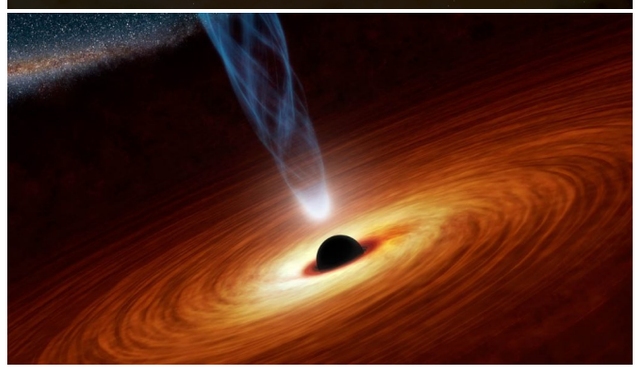
- At large distances
- With large energy range

+ High variability for precision

→ Cosmological sources + TeV gamma-rays







- **Pulsars**
  - **+** high variability, stable, large E spectrum
  - **-** very local
- **Gamma Ray Bursts (GRBs)**
  - **+** high variability, large z, large E spectrum
  - **-** random and difficult to catch
- **Flaring Active Galactic Nuclei (AGNs)**
  - **+** large z, large E spectrum, easier to catch
  - **-** random, smaller variability

H.E.S.S. + MAGIC + VERITAS - Goals

- **Combine all available data from H.E.S.S., MAGIC and VERITAS in a joint analysis**

  → **Better limits on QG energy scale** with increased statistics

- Use different types of sources with different intrinsic characteristics

  → Several redshifts and source types help to disentangle between LIV and intrinsic variability of sources

  → Prepare the CTA era with the combination of data sets from 2 observation sites

Working group tasks

- **Development of a common software** in order to simulate, analyse and combine data-sets from different experiments: « *LIVelihood* ».
  For now we work on **simulations in order to calibrate and validate the method** including:
  - Instrument response functions for each instrument and each source
  - Computation and combination of systematics from different instruments
  - Different models on redshift dependency (LIV from Jacob & Piran, Deformed Special Relativity)

- List of sources (only published sources are studied) such that **all classes are represented** with different characteristics:
  - AGN
    - Markarian 501 (MAGIC) flare of 2005
    - PG 1553+113 (H.E.S.S.) flare of 2012
    - PKS 2155-304 (H.E.S.S.) flare of 2006
  - Pulsar
    - Crab (MAGIC, VERITAS)
    - Vela (H.E.S.S.)
  - GRB
    - 190114C (MAGIC) afterglow

Combination method

- Separate photon list in 2 sub-sets ⟶ low energy vs. high energy light curves (time distributions)
  - ✳ **Low energy light curve taken as LIV-free:** $\tau_n = 0$
- Use **maximum likelihood method** to estimate the mean delay separating the 2 sets
- Similar treatment for pulsars but time is replaced by phase

Telescopes IRFs — Spectrum — Light curve

$$R_{\rm Sig}(E,t|\tau_n) = \int_{E_{true}=0}^{\infty} D(E,E_{true})\,A_{\rm eff}(E_{true},t)\,\Lambda_{\rm Sig}(E_{true})\,F_{\rm Sig}(t-\tau_n\cdot E_{true}^{n})\,dE_{true}$$

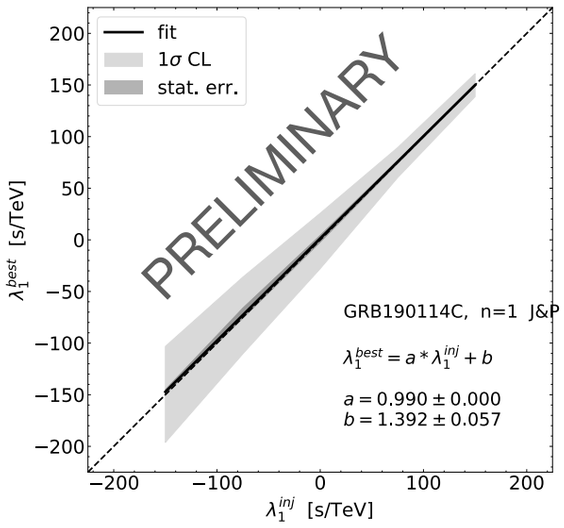
$$\mathcal{L}(\tau_n) = \prod^{N} \frac{R_{\rm Sig}(E,t|\tau_n)}{N_{\rm Sig}(\tau_n)}$$

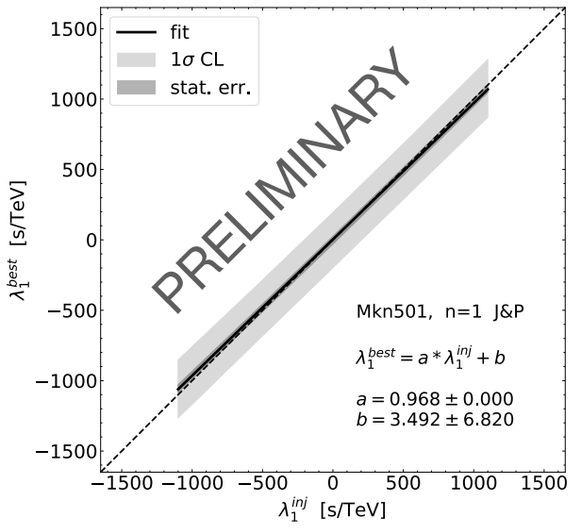
$$N_{\rm Sig}(\tau_n) = \int_{t=t_{min}}^{t_{max}} \int_{E=E_{cut}}^{E_{max}} R_{\rm Sig}(E,t|\tau_n)\,dE\,dt$$

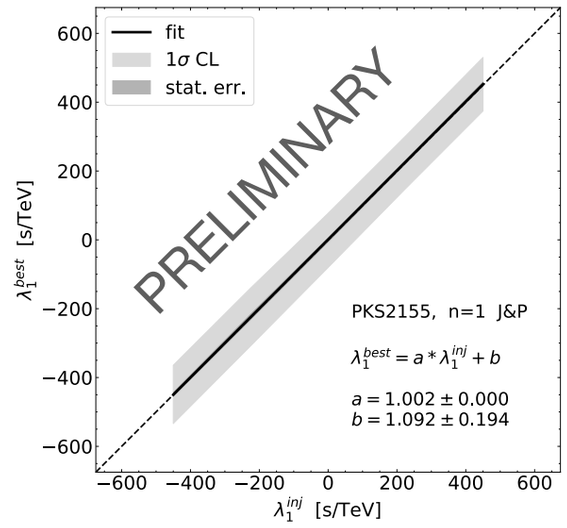
- Combination ⟶ **Instrument Response Functions** vary for each source and instrument
  - A tabulation method is used to fully take into account IRFs without any simplification
    - ✳ Pdf and normalisation are precomputed and stored in tables for each source
    - ✳ Then retrieved by interpolation over the tables during the likelihood maximisation

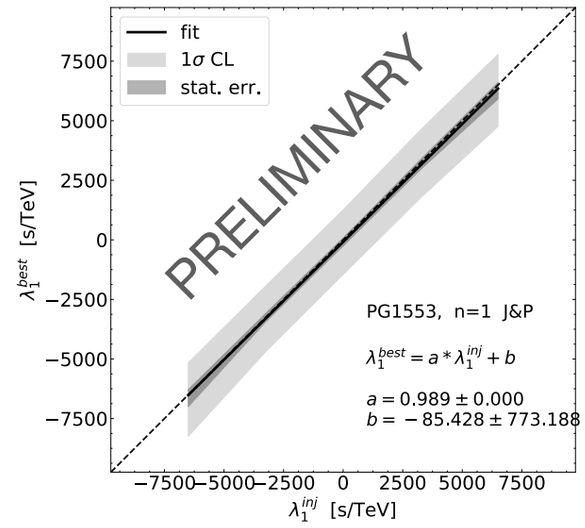
Calibration - individual sources

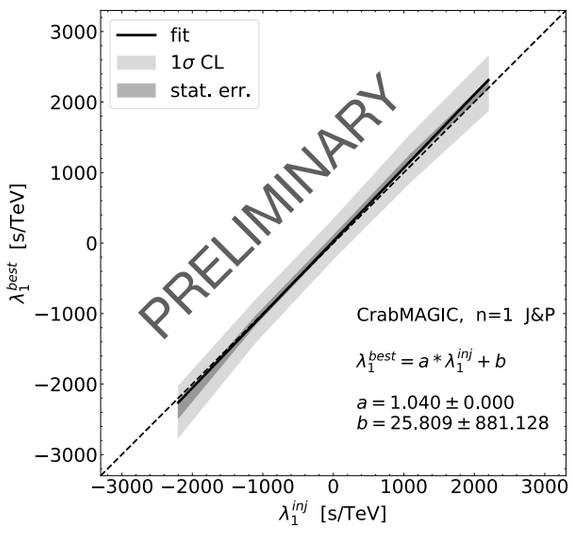
- Plots of **injected lag in the simulations vs. reconstructed lag** from the likelihood method (J&P model, linear)
- Worst case reaches at **maximum 8% error on the reconstruction**
- GRB highly asymmetric ⟶ expected from the highly asymmetric light curve (power law)

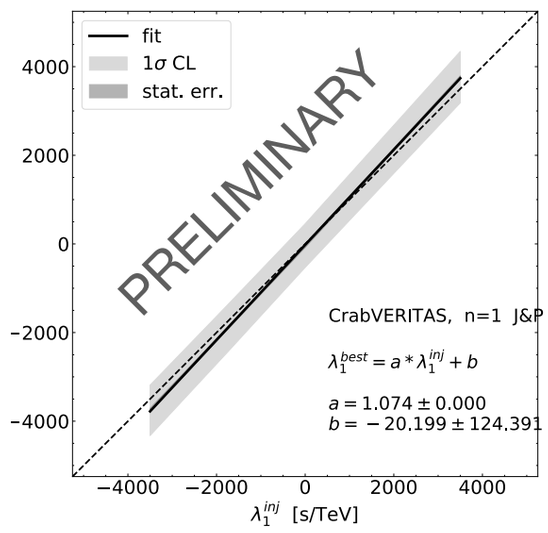


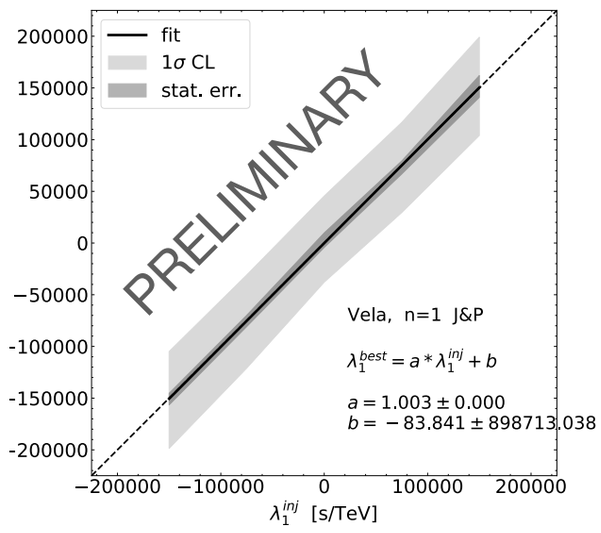






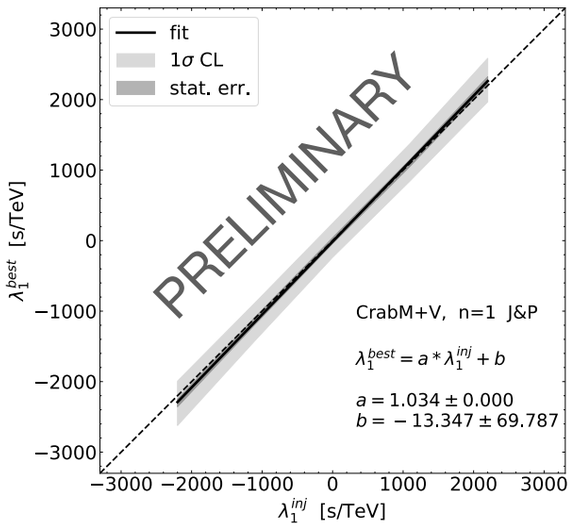


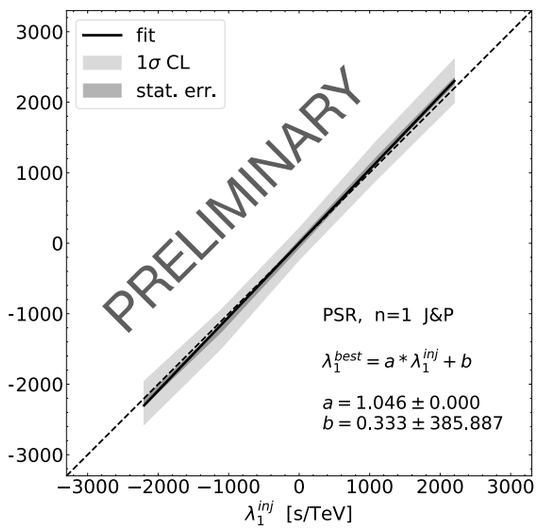


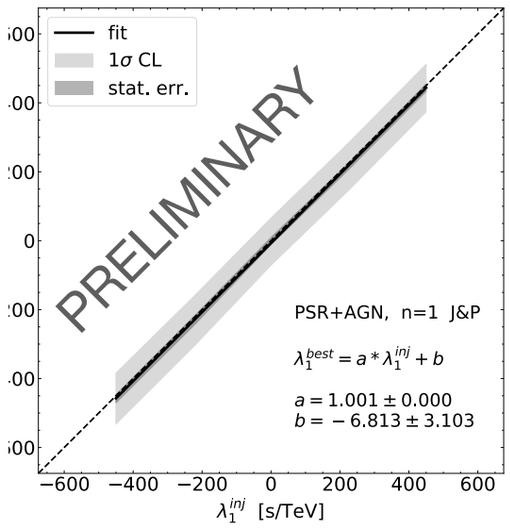


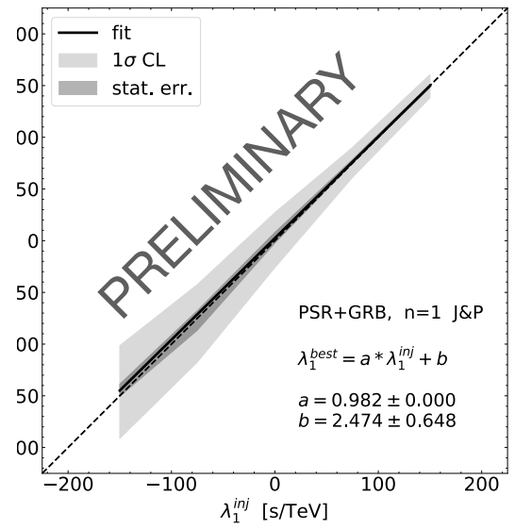
Calibration - combined sources

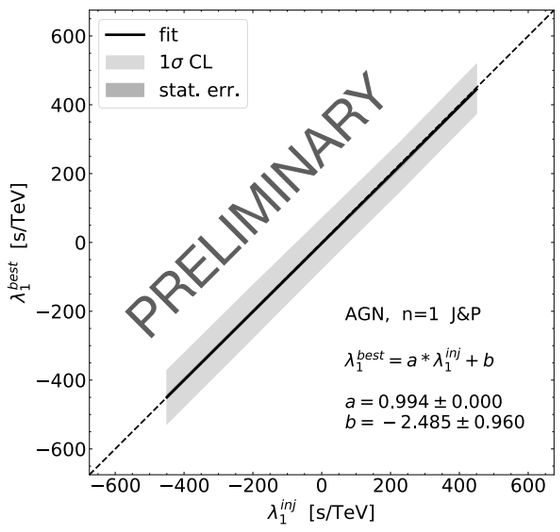
- Plots of **injected lag in the simulations vs. reconstructed lag** from the likelihood method (J&P model, linear)
- Worst case reaches at **maximum 3% error on the reconstruction**

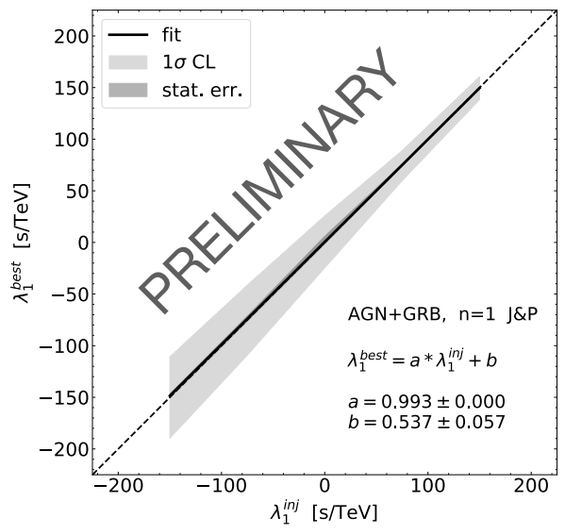


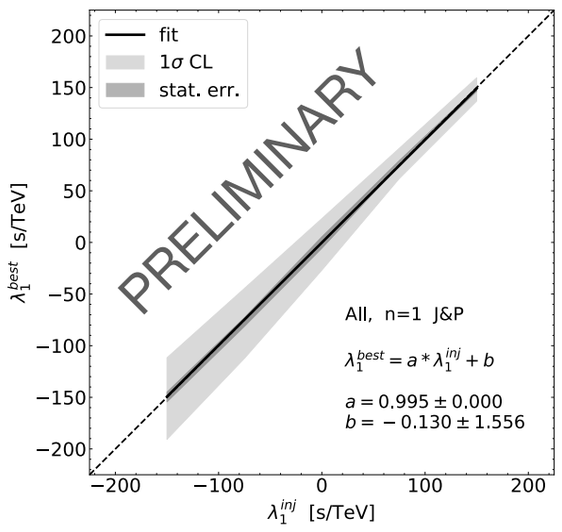












Systematics

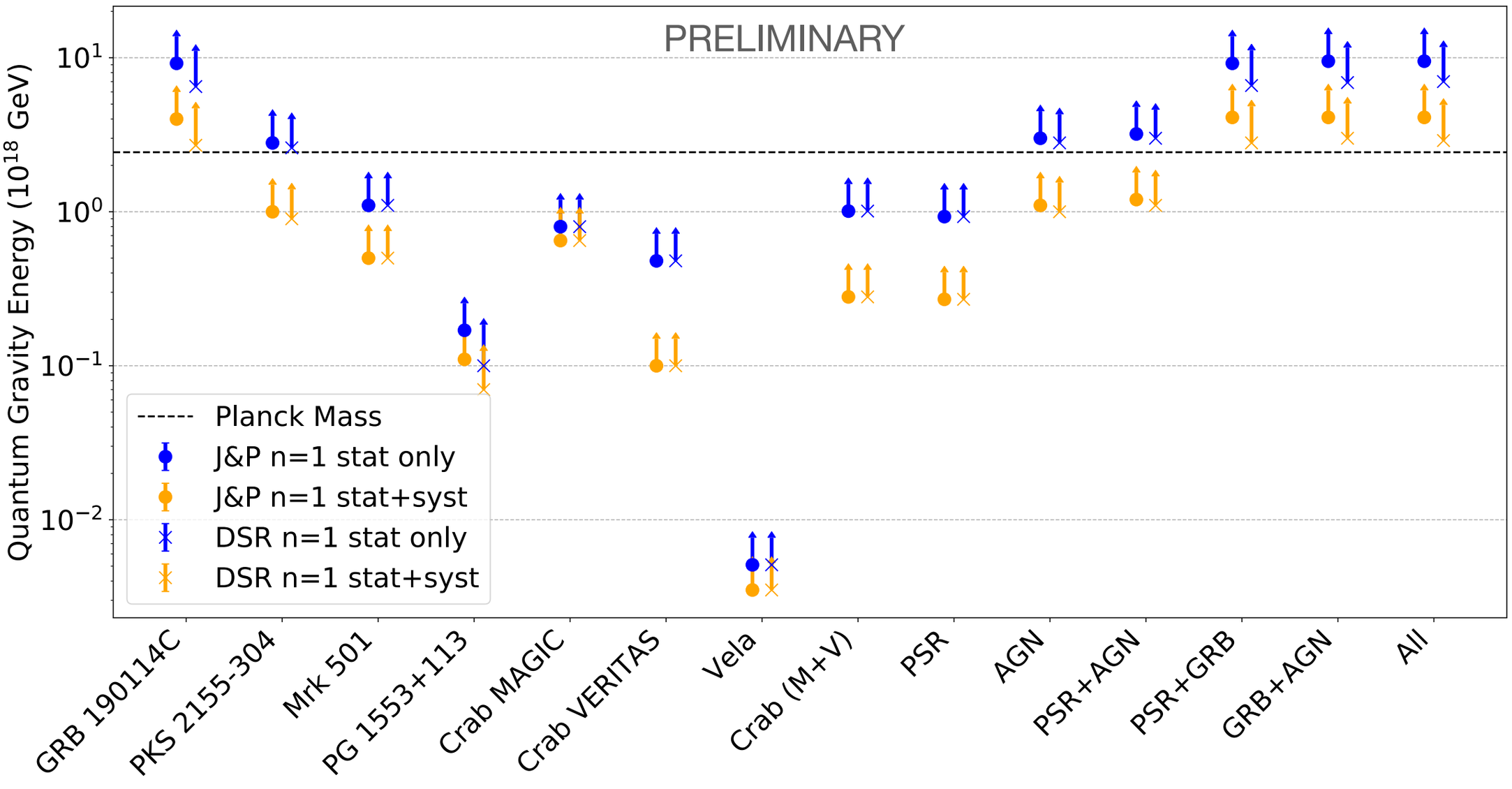
- Systematics effects are propagated to the lag using a **profile likelihood method**
- Each source of systematics is added as a **nuisance parameter** to the likelihood

$$L(\lambda_n, \vec{\theta}) = L_{data}(\lambda_n, \vec{\theta}) + L_{template}(\vec{\theta_C}) + L_\gamma(\theta_\gamma) + L_{BP}(\vec{\theta_{BP}}) + L_{ES}(\theta_{ES}) + L_z(\theta_z)$$

- Systematic types:
  - Low energy template statistics *(dominant in linear regime)*
  - Power law index uncertainty *(dominant in quadratic regime)*
  - Background proportion uncertainty
  - Energy scale uncertainty *(dominant in quadratic regime)*
  - Redshift uncertainty

Upper limits on E_{QG} (linear)
Impact of systematics

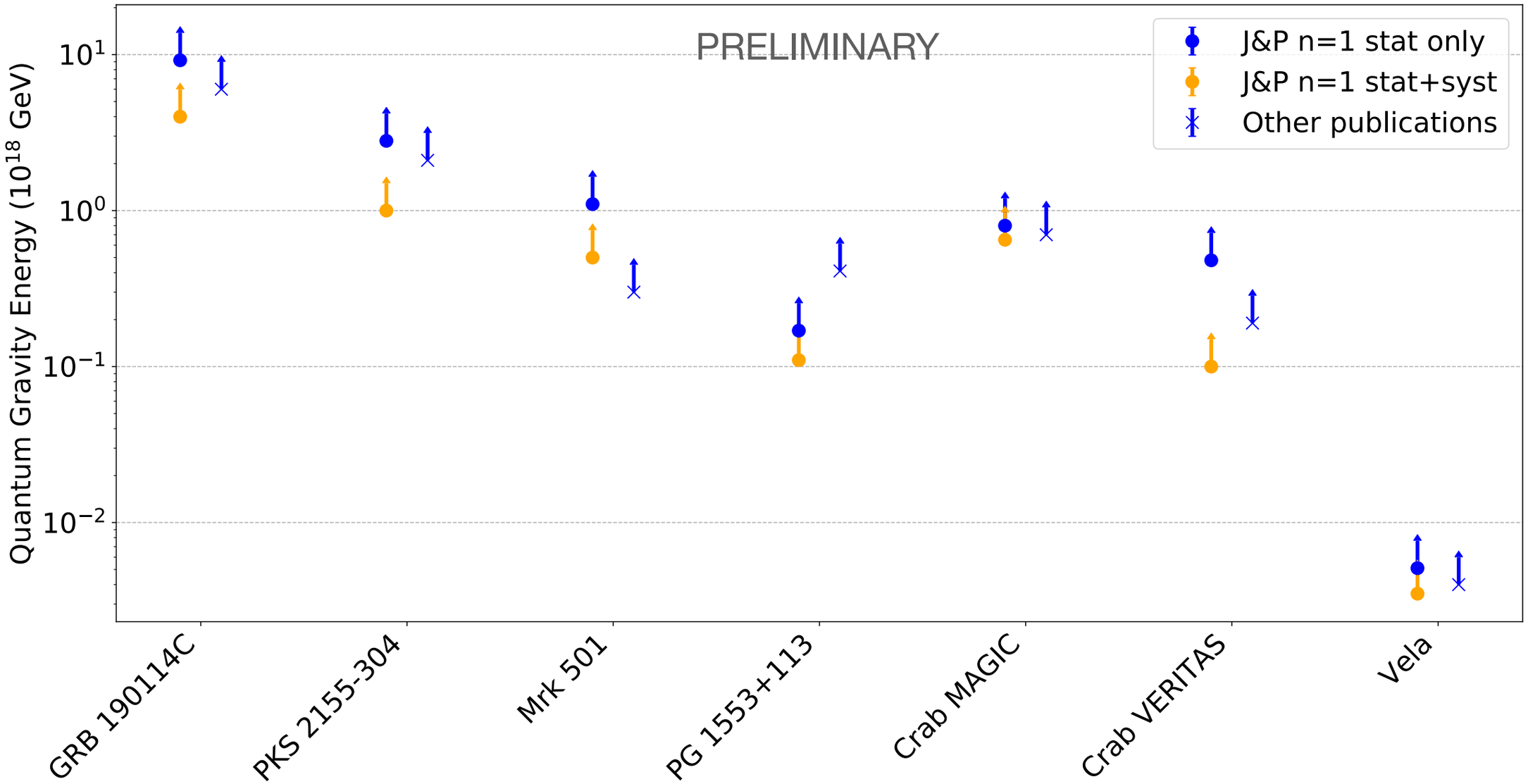
- Combinations are dominated by the most stringent source: GRB >> AGN >> PSR
- **Systematics bring down the limits by a factor ~ 2**



Upper limits on E_{QG} (linear)
Comparison with papers

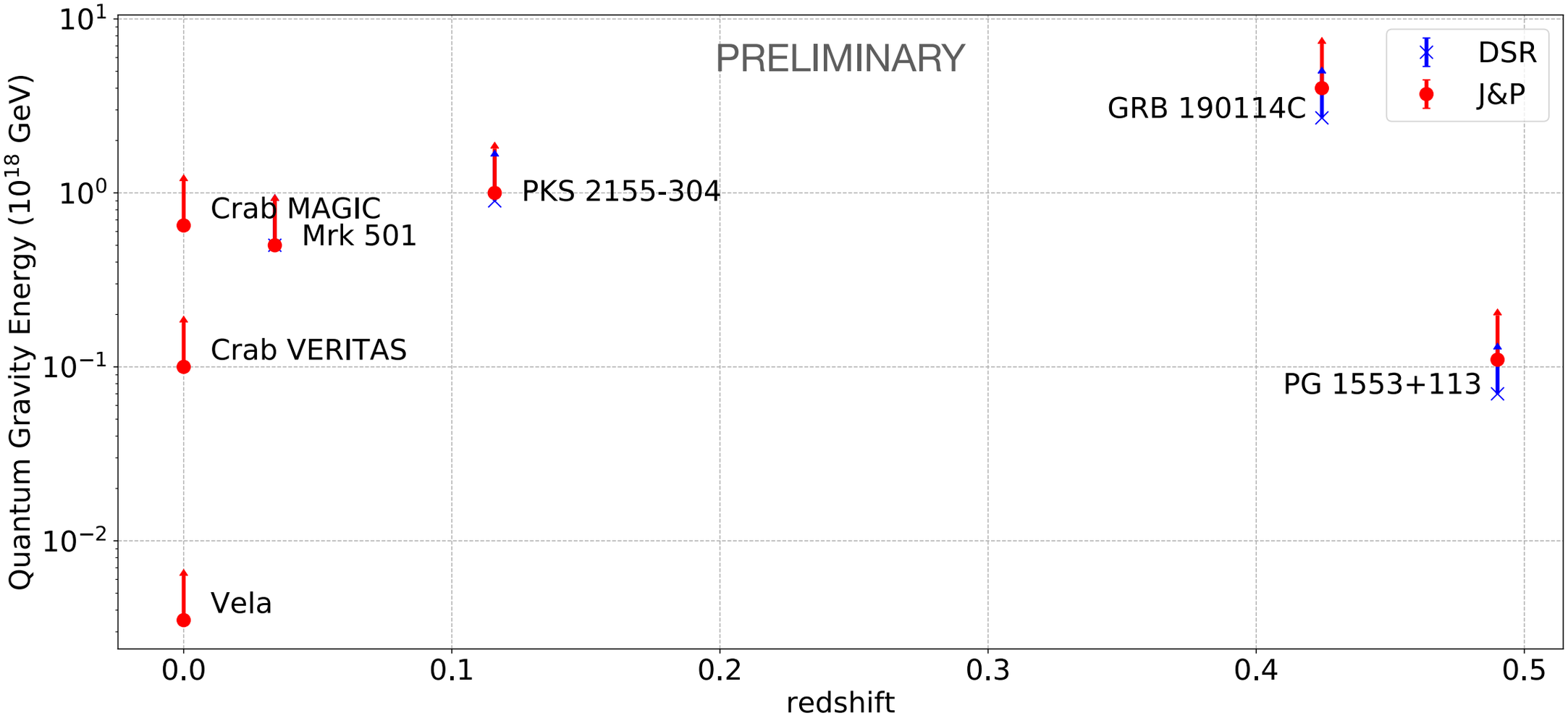
- Similar results than what has been found in previous LIV analysis
- Different evaluation method of IRF and systematics, simulation based study

  ⟶ the new limits are less constraining than the ones in older papers



Upper limits on E_{QG} (linear) Redshift dependency

- **Visible impact of the redshift model** on limits for sources at large z:
  - The J&P model tends to emphasize contribution from large redshift sources
  - The DSR model tends to balance source's contribution
  - Pulsars do not depend on lag-distance models ⟶ reference for comparison



Conclusion

- Combination code for the LIV is ready and operational
- Fully take into account IRFs thanks to a tabulation method
- Deep study of systematics dominated by template stat. (linear), energy scale & PL index (quad.)
- Limits are found to be less constraining than in previous studies due to a different evaluation method of systematics and the simulation based study
- Calibration shows good reconstruction with errors of a few percent
- Combinations are dominated by the most stringent source in the sample
- Lag-distance models have an important impact on combinations: J&P emphasizes large z sources while DSR balance contributions
- Next step: use the method to combine all the available data collected by H.E.S.S., MAGIC and VERITAS