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The Cosmological Optical Convergence: Extragalactic Background Light from TeV γ-Rays

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Submitted to ApJL

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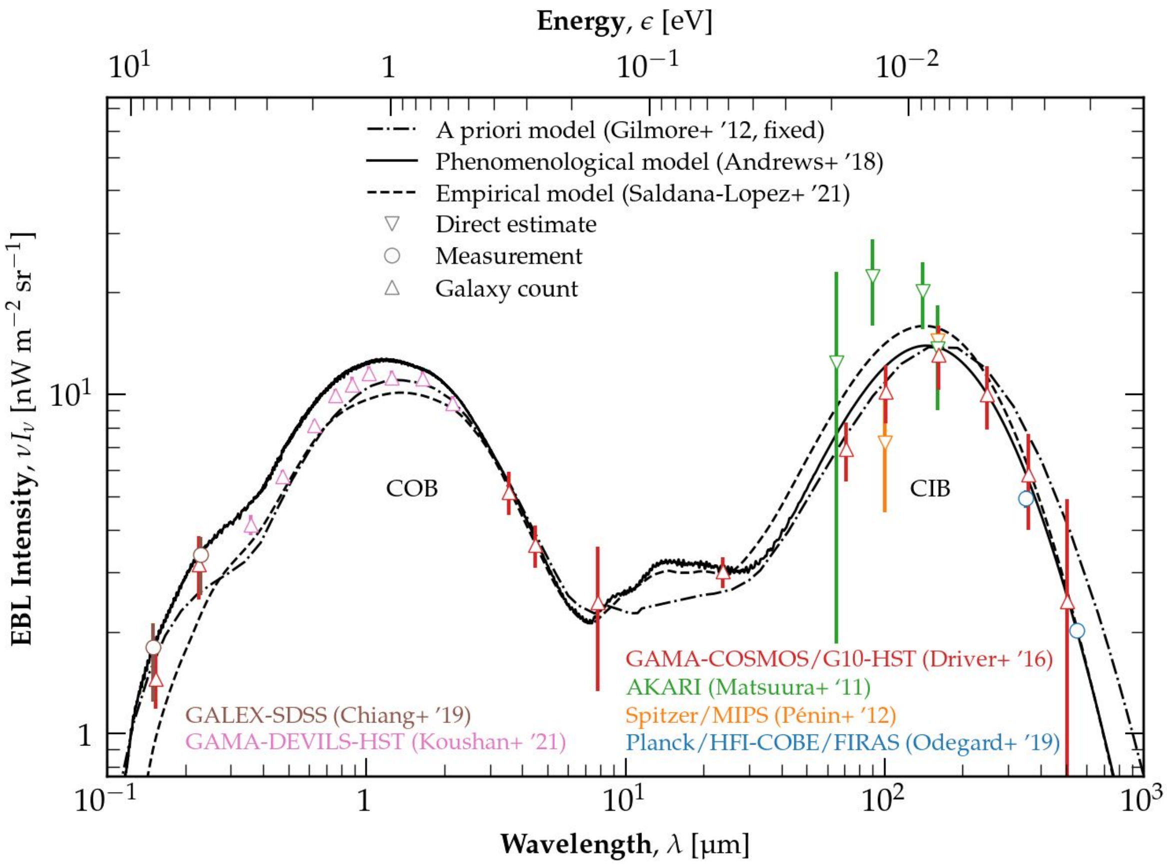
The Extragalactic Background Light



EBL: sum of all **optical** and **infrared** light from **thermal processes** in the universe

IGL: integrated galactic light, **resolved galaxies**, expected to make up most of the EBL

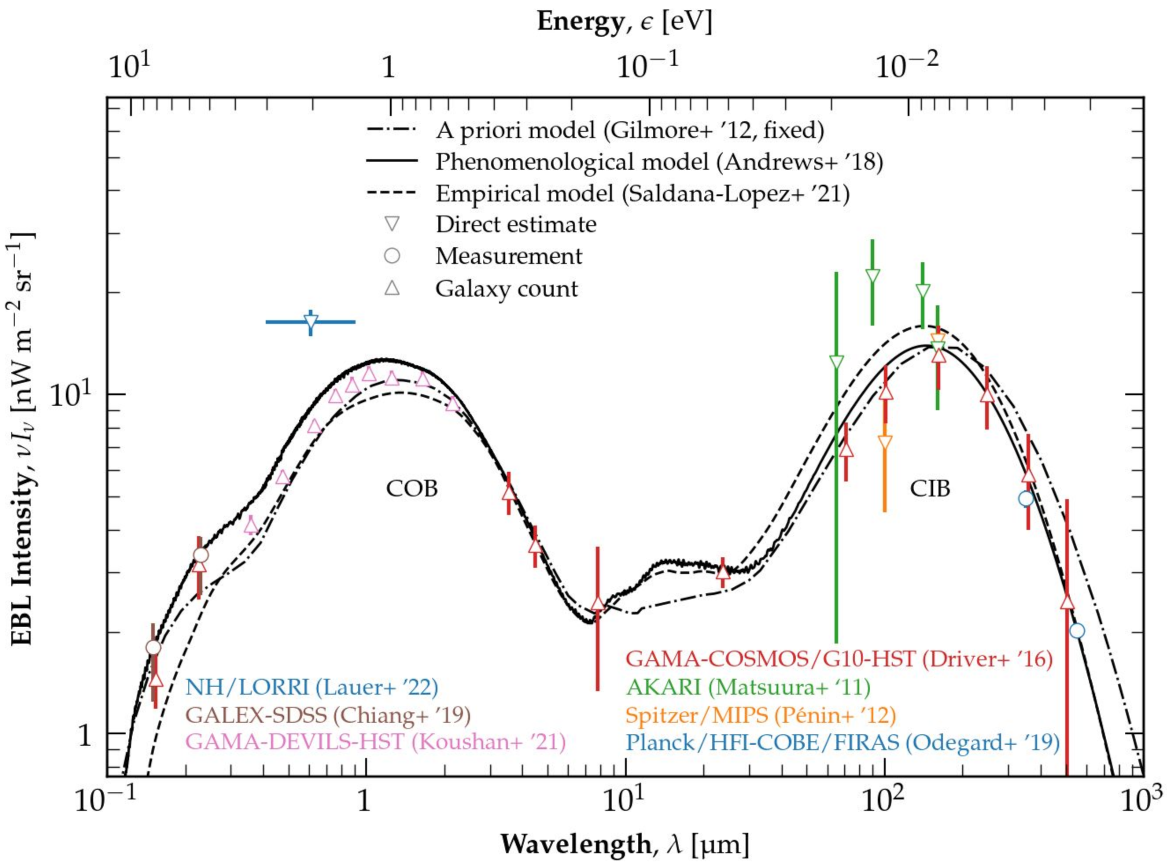
IGL ≤ EBL

➢ **Diffuse components?**

$$\nu I_\nu^{\rm EBL} = \nu I_\nu^{\rm IGL} \times (1 + f_{\rm diff})$$

J. Biteau, 10.5281/zenodo.7842239

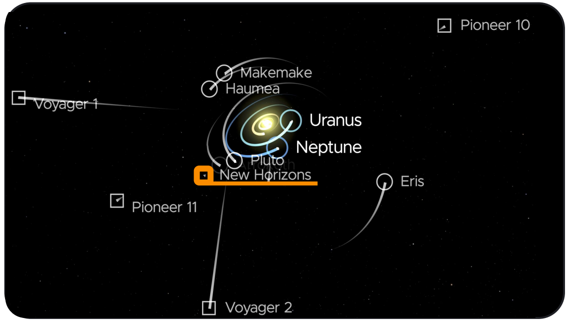
The cosmological optical controversy



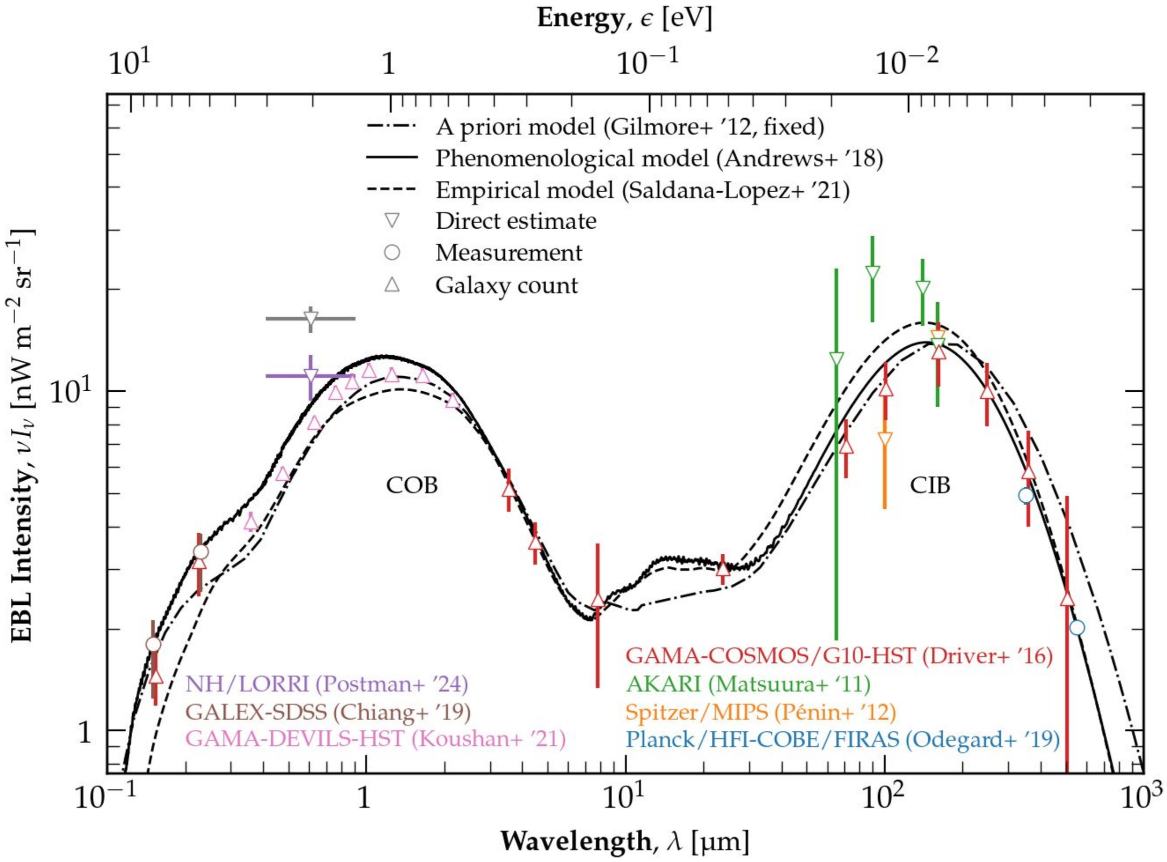
Direct meas.: light after **subtraction of foreground**

New Horizons probe: Suggested a **5σ excess wrt IGL**, from **beyond Pluto's orbit** (Lauer+ '21, '22)

⇨ **Optical controversy**



The cosmological optical convergence?



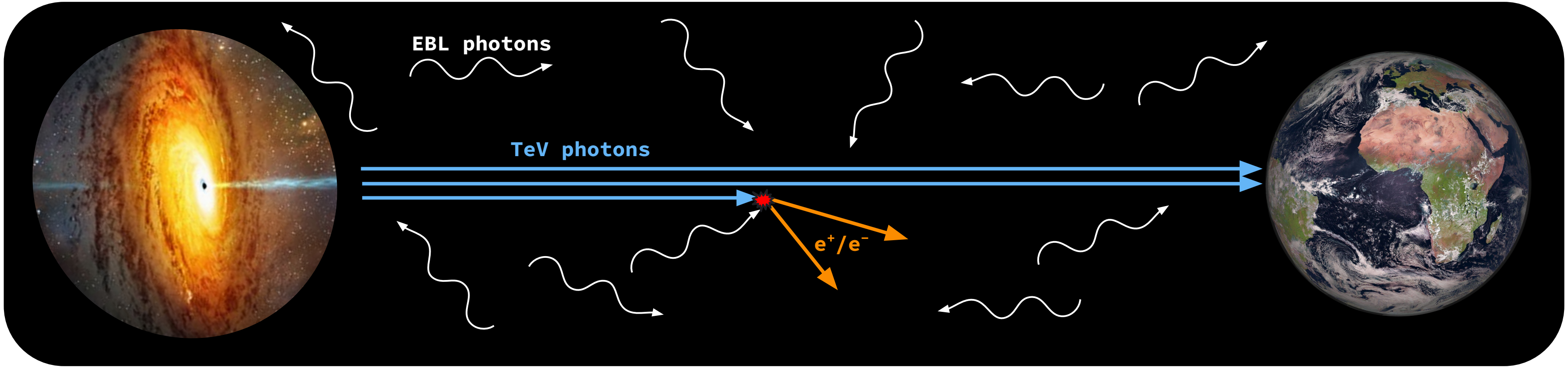
Latest **New Horizons data** shows **agreement with IGL** (Postman+ '24)

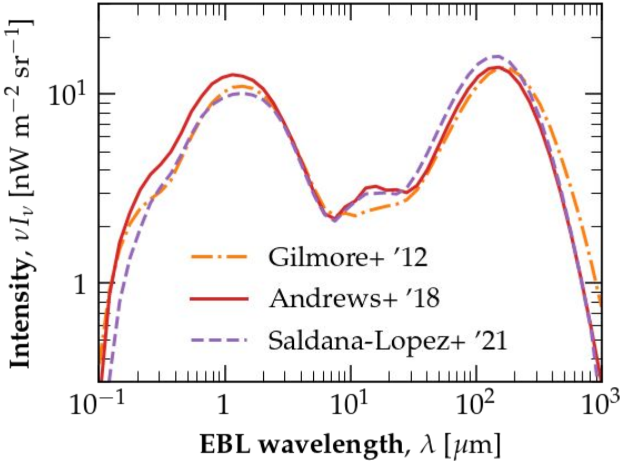
~~⇨ Optical controversy~~
★ **Optical convergence?**

Measurement only at **600nm**

J. Biteau, 10.5281/zenodo.7842239

Propagation of TeV photons through the Universe





Optical depth τ:

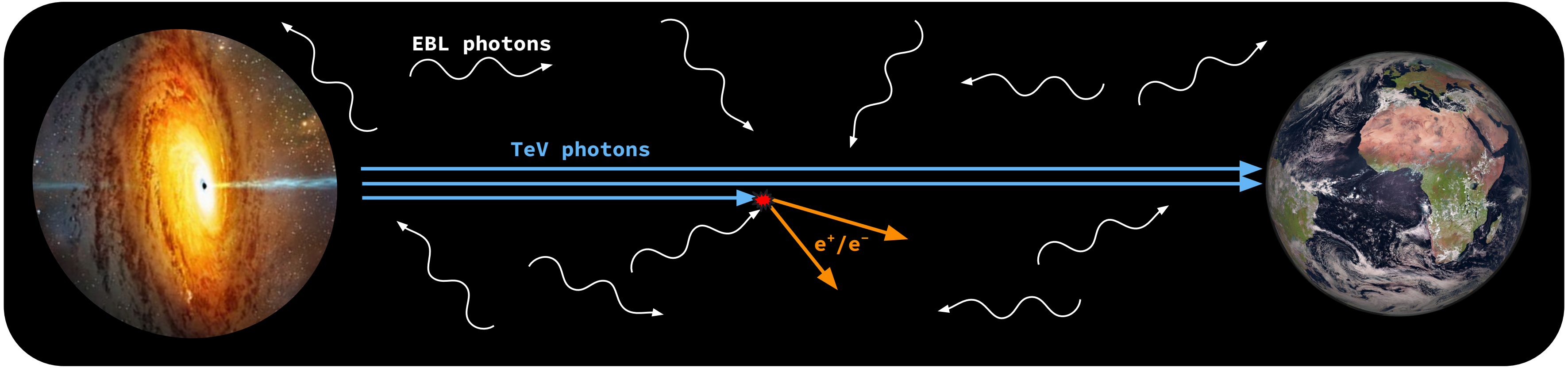
$$\Phi_{obs} = \Phi_{int} \times e^{-\tau}$$

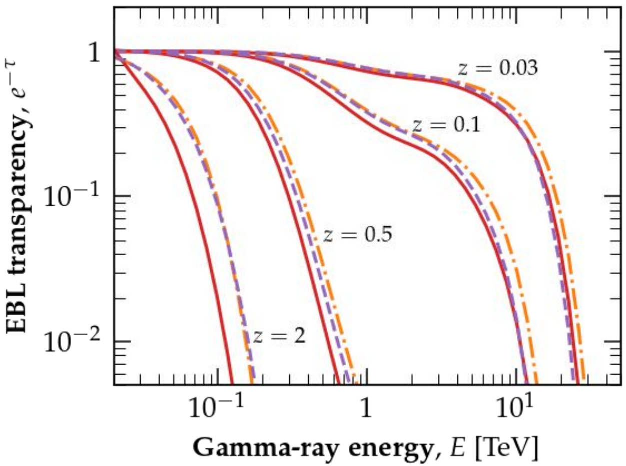
γ-ray data — ∝ 1/H₀ — EBL intensity

$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$

γγ cross-section

Propagation of TeV photons through the Universe





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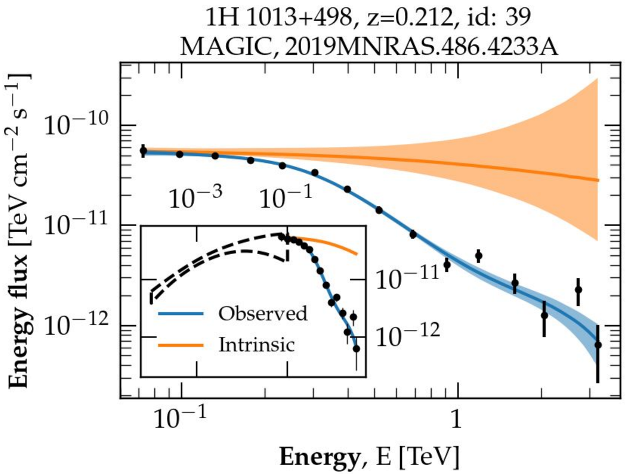
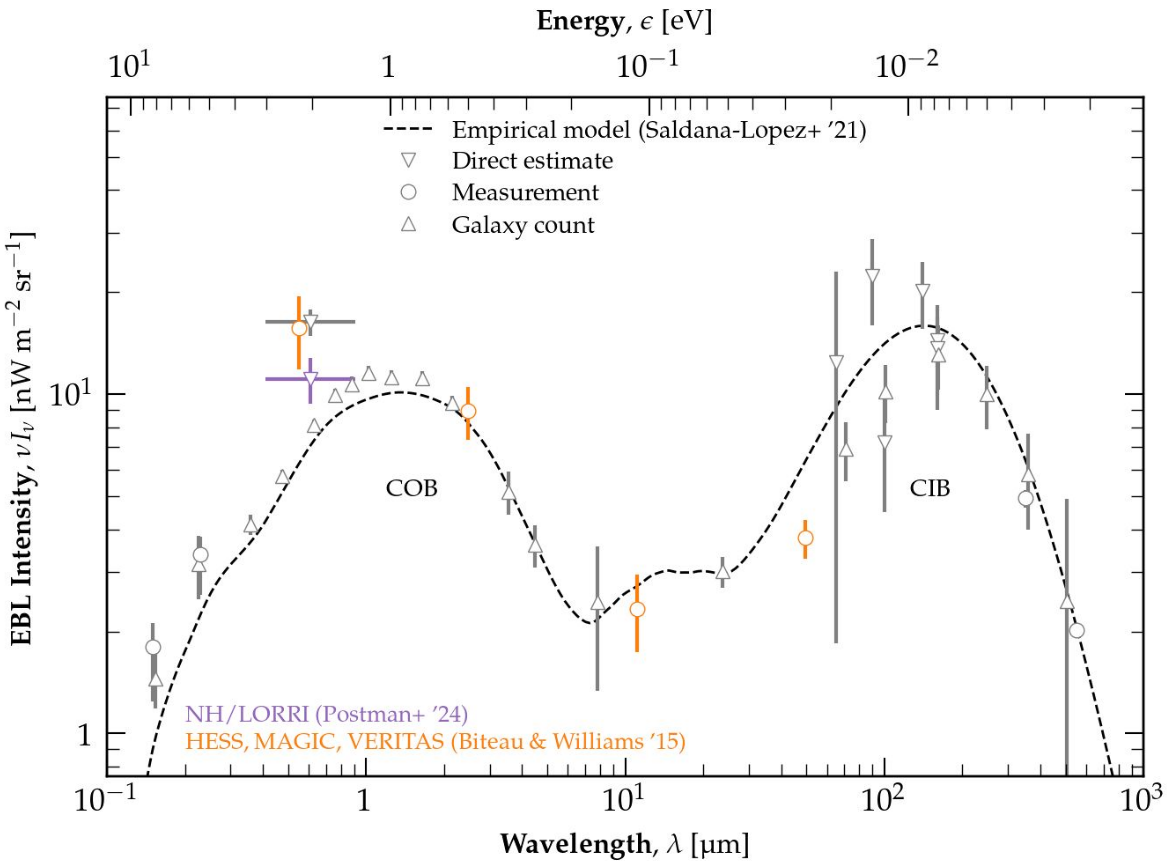


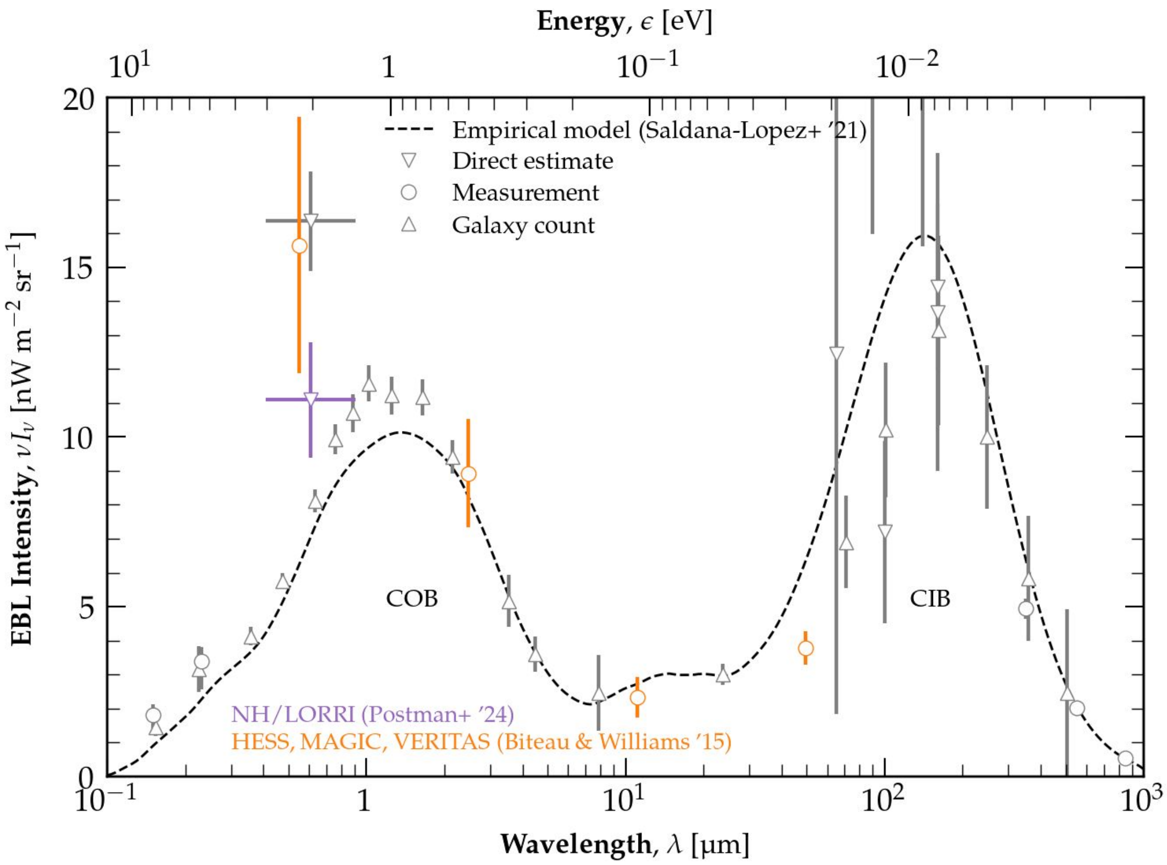
EBL measurements from gamma-ray cosmology



γ-ray cosmology:
Reconstruct EBL using the **absorption imprint** on TeV spectra

✓ **Compatible with IGL**

EBL measurements from gamma-ray cosmology



γ-ray cosmology:
Reconstruct EBL using the **absorption imprint** on TeV spectra

- ✓ **Compatible with IGL**
- ✗ **Lack precision**

γ-ray measurements could not confirm nor infirm an excess such as initially shown in Lauer+ '21/'22

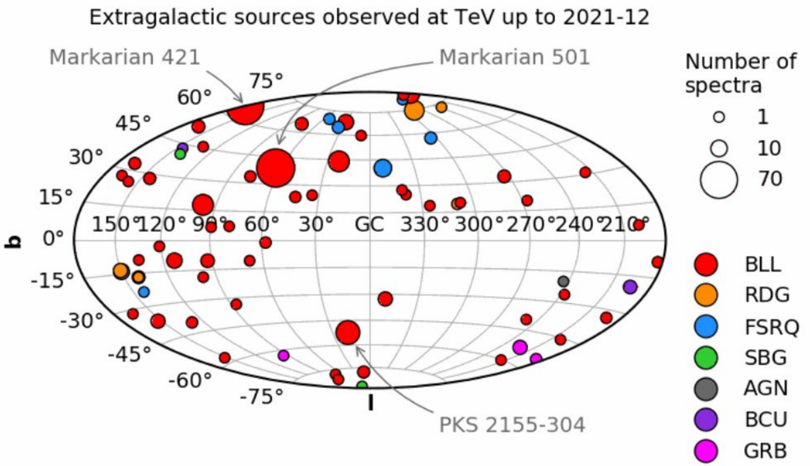
Data sample

TeV data: STeVECat, [10.5281/zenodo.8152245](https://doi.org/10.5281/zenodo.8152245)
Spectral TeV Extragalactic Catalog

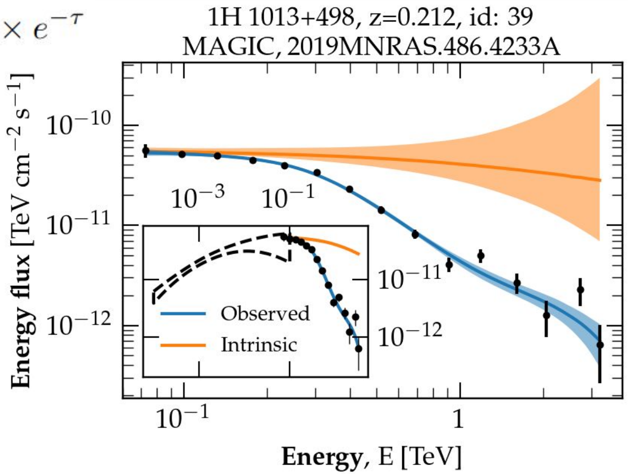
Archival spectra published by IACTs (H.E.S.S, MAGIC, VERITAS and other)

Selected spectra: at least 4 points, sources with solid **redshift > 0.01**

➢ **268 spectra** (**86 for B&W'15**)



$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$



GeV data: ***Fermi*-LAT**

Contemporaneous *Fermi*-LAT observations used as **priors** for spectral index and curvature

➢ **64** contemporaneous spectra

Fermi-LAT study by M. Nievas-Rosillo

Shortcomings of the Frequentist analysis

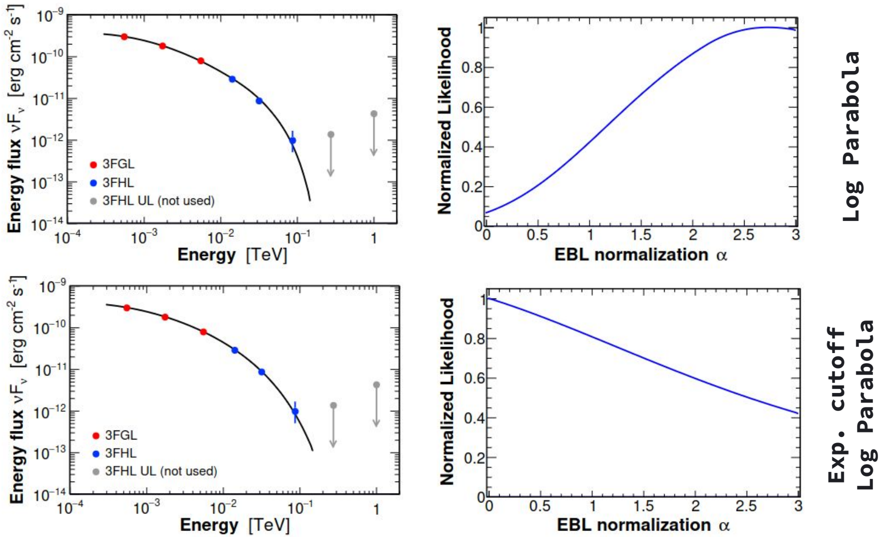
a EBL parameters
Θ spectral parameters

$$\phi_{\mathrm{model}}(E, z, a, \Theta) = \phi_{\mathrm{ELP}}(E, \Theta) \times e^{-\tau(E,z,a)}$$

$$\phi_{\mathrm{ELP}}(E, \Theta) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta \log\left(\frac{E}{E_0}\right)} \exp\left(-\lambda E\right)$$

With $\mathcal{D}$ observed **data**, **Likelihood**:

$$\begin{aligned}\mathbf{Pr}\left(\mathcal{D} \mid a\right) &= \max_{\Theta}\left\{\mathbf{Pr}\left(\mathcal{D} \mid a, \Theta\right)\right\} \\ &= \max_{\Theta}\left\{\prod_k \mathbf{Pr}\left(D_k \mid a, \theta_k\right)\right\}\end{aligned}$$



Frequentist framework

- Find best parameters a for a set of spectral models (**minimization**)
- **Update** the set of spectral models
- **Repeat** until convergence

The Bayesian Framework as an answer

a EBL parameters
Θ spectral parameters

$$\phi_{\text{model}}(E, z, a, \Theta) = \phi_{\text{ELP}}(E, \Theta) \times e^{-\tau(E,z,a)}$$

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With $\mathcal{D}$ observed **data**, **Likelihood**:

$$\begin{aligned} \mathbf{Pr}\left(\mathcal{D} \mid a\right) &= \int \mathrm{d}\Theta \, \mathbf{Pr}\left(\mathcal{D} \mid a, \Theta\right) \\ &= \int \mathrm{d}\Theta \prod_k \mathbf{Pr}\left(D_k \mid a, \theta_k\right) \end{aligned}$$

Bayesian framework

$$\mathbf{Pr}\left(a \mid \mathcal{D}\right) = \frac{\mathbf{Pr}\left(\mathcal{D} \mid a\right) \mathbf{Pr}\left(a\right)}{\mathbf{Pr}\left(\mathcal{D}\right)}$$

Compute the **full probability distribution** and **marginalize** over non-EBL parameters

- ⇨ **Sampling** with MCMC
- ⇨ **Uninformative priors**
- ⇨ All spectra as **log-parabola with exponential cutoff**
- ⇨ **Nuisance parameters**
  - ➢ Bias on the **energy scale**, ε

$$\phi_{\varepsilon\text{-model}}(E, z, a, \Theta, \varepsilon) = \phi_{\text{model}}\left(E \times e^{\varepsilon}, z, a, \Theta\right)$$

Model independent EBL parametrization

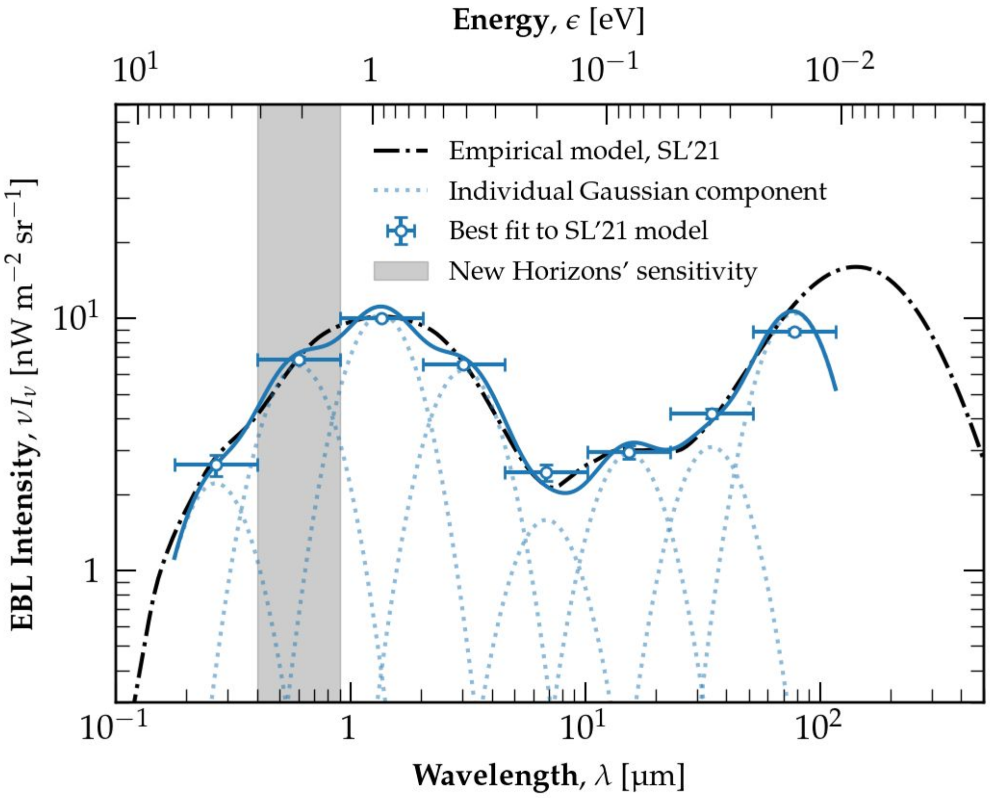
EBL model: **Sum of 8 Gaussians**

- ⇨ **Free amplitudes a_i**
- ⇨ Fixed widths & positions
  - ➢ **Match New Horizons'** band in 400 - 900 nm
- ⇨ **Redshift evolution** with nuisance parameter f_{evol}

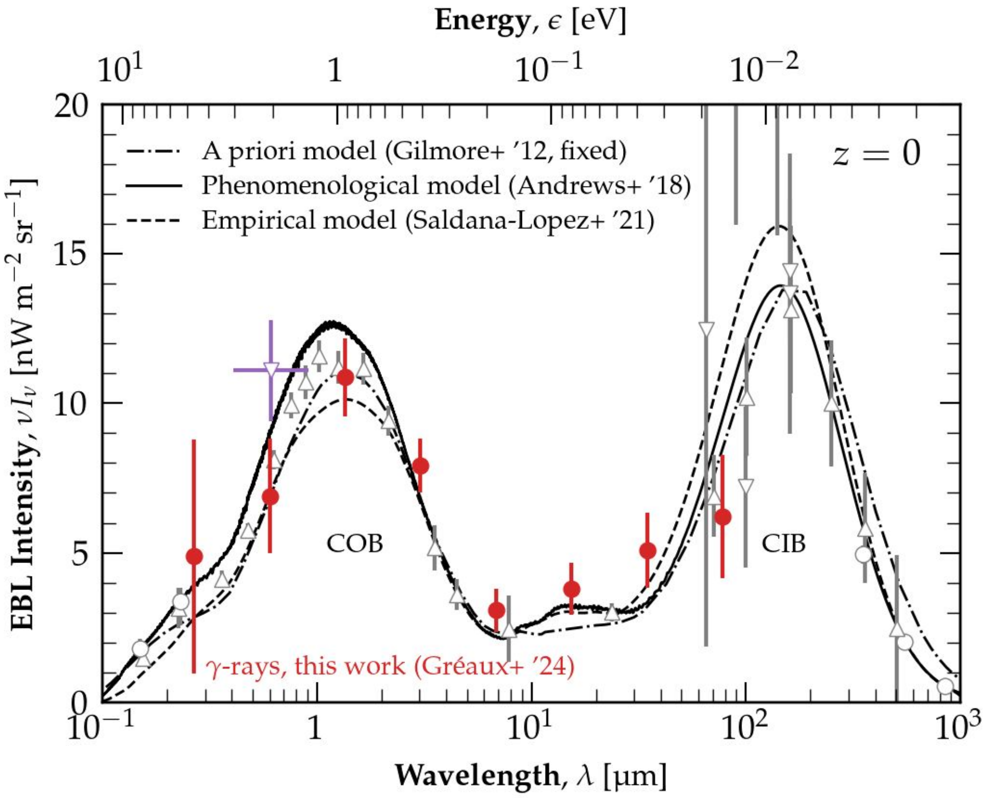
$$\nu I_\nu(l, a, z) = \sum_{i=1}^{8} a_i \times \exp\left(-\frac{(l - l_i)^2}{2\sigma^2}\right) \times (1+z)^{3-f_{\mathrm{evol}}}$$

$$\tau_{\mathrm{model}}(E, z, a) = \sum_{i=1}^{8} a_i \times \tau_i(E, z)$$

First fully model-independent gamma-ray reconstruction of the EBL

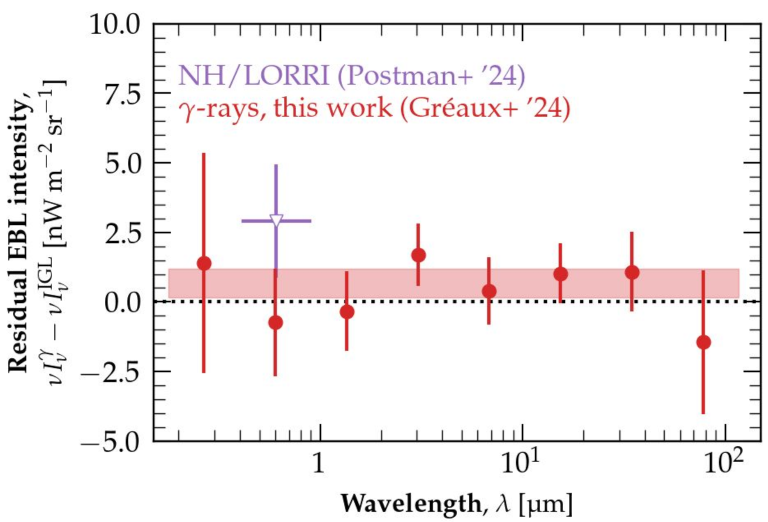


The cosmological optical convergence



Precision between 1 and 50µm:
Better than **±1.3 nW m-2 sr-1**

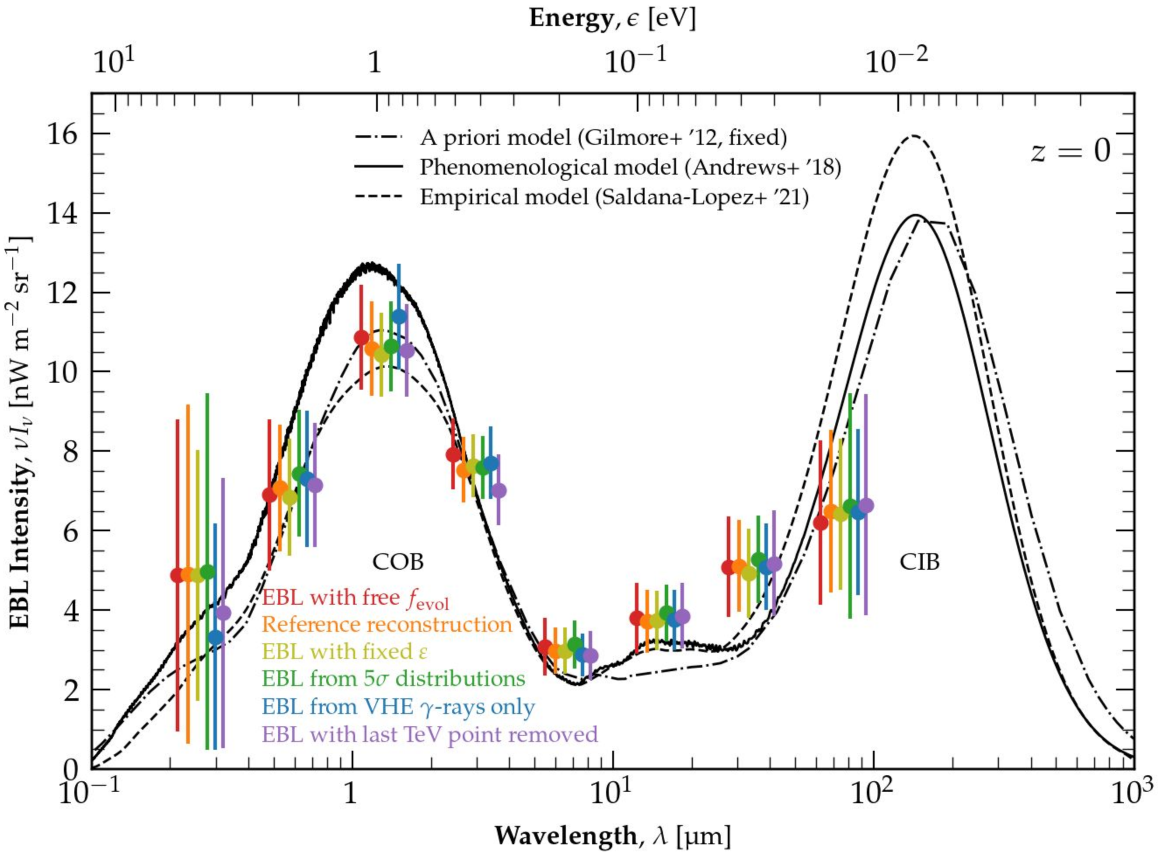
Exclude diffuse components with
$\mathbf{f_{diff}}$ **≤ 20%** at 95% C.L.



Reliability of the reconstruction

Negligible impact for:

- Parameterized EBL **redshift evolution**
- Nuisance parameter on **energy scale**
- **Variation** of the reconstruction **method**
- Assumption on **GeV-TeV spectral correlation**
- Bias from **highest energy flux point**
- **Dividing dataset** in two parts



Hubble constant measurement

γ-ray data — $\propto 1/H_0$ — IGL intensity

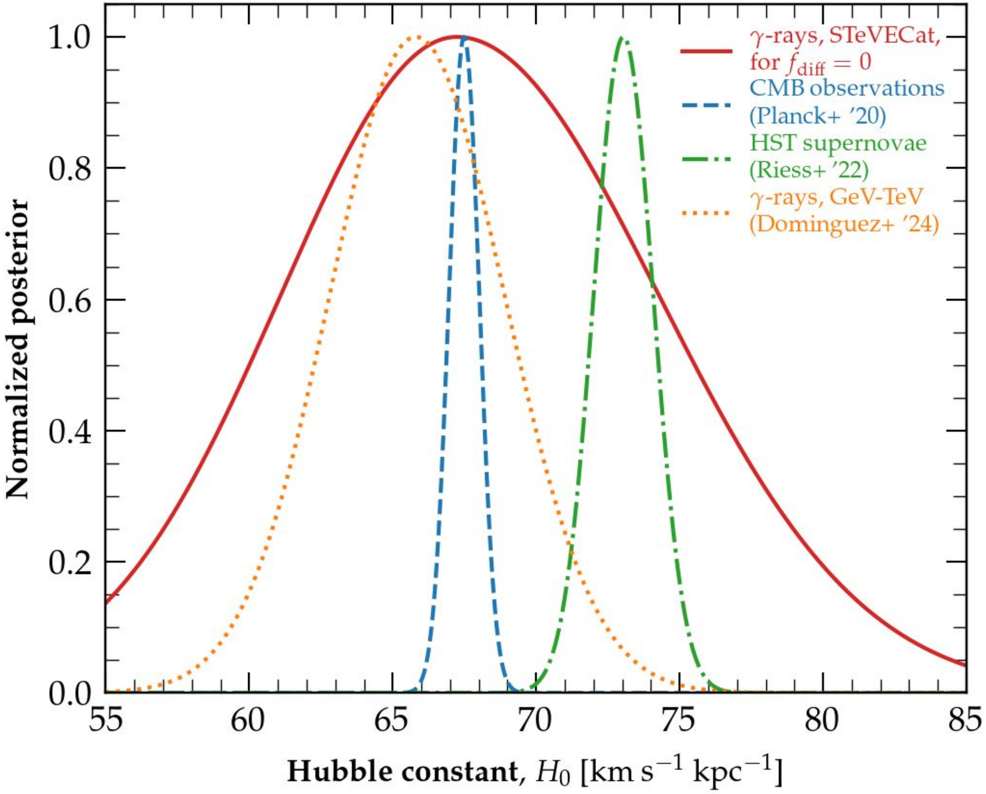
$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$

γγ cross-section

Use the γ-ray / IGL measurements to **measure H_0**:

H_0 = 67 ± 7 km s^{-1} Mpc^{-1} x (1 + f_{diff})

Independent from CMB / cepheids



Conclusion

New γ-ray EBL measurement

- ➢ **Submitted to ApJL**

- ⇨ **Bayesian** framework
  - ➢ Marginalize over spectral/nuisance parameters

- ⇨ New data corpus, **STeVECat**
  - ➢ Sample size ~tripled wrt previous

- ⇨ **Independent** from IGL, direct meas., and reference models
  - ➢ Only use γ-ray observations

- ⇨ **Reduced uncertainties** with respect to **previous γ-ray studies**

- ⇨ EBL from **γ-rays indistinguishable from IGL**

- ⇨ Constraint on **diffuse components**: $\mathbf{f_{diff}} \leq \mathbf{20\%}$ at 95% C.L.

- ⇨ $H_0 = 67 \pm 7$ km s^{-1} Mpc^{-1} x $(1 + f_{diff})$

IGL precision of ~1% expected for **LSST, Euclid, JWST**

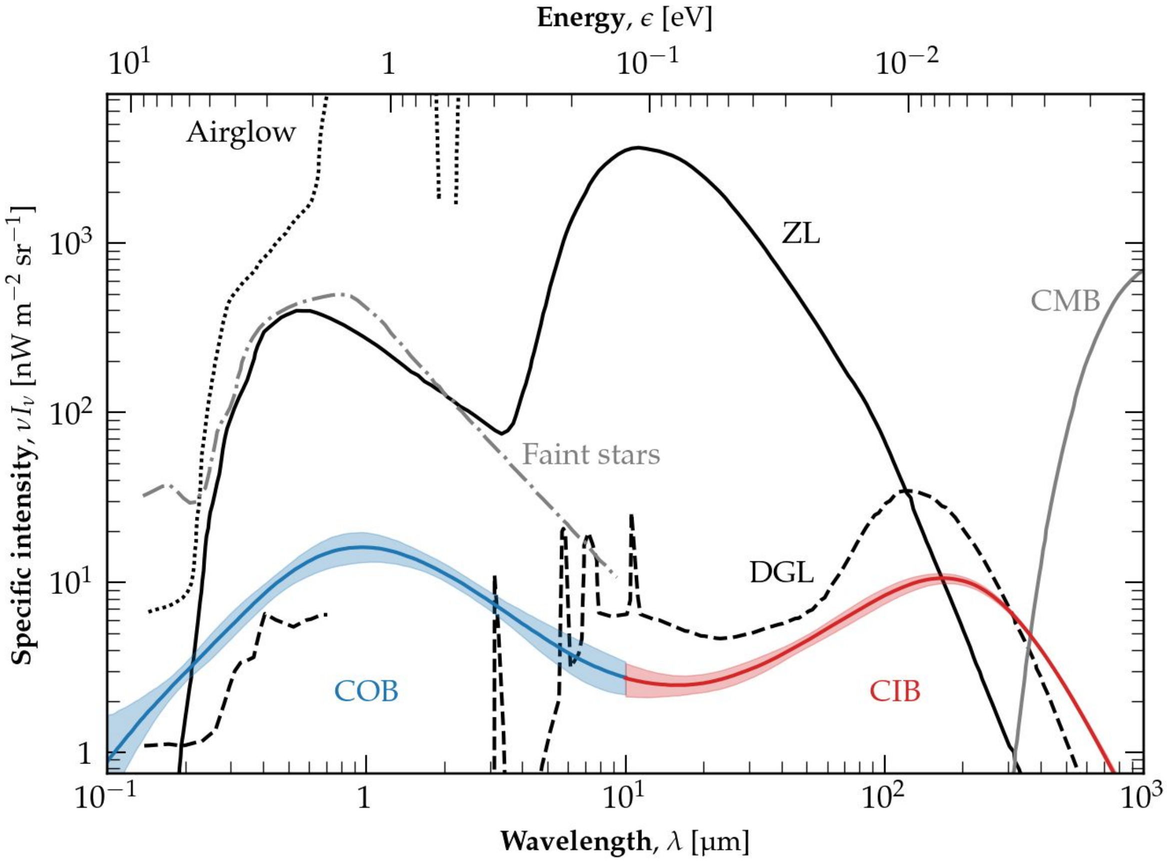
Reionization contribution expected at ~0.1-1 nW m^{-2} sr^{-1} (~0.1-1% of EBL)

- ★ **Current γ instruments'** precision: **±1.3 nW m-2 sr-1**

- ★ **CTAO should bring exciting results**

Appendix

The cosmological optical controversy



Adapted from C. Leinert, 10.1038/128704a0 and J. Biteau, 10.5281/zenodo.7842239

Direct measurements: light after **subtraction of foreground**

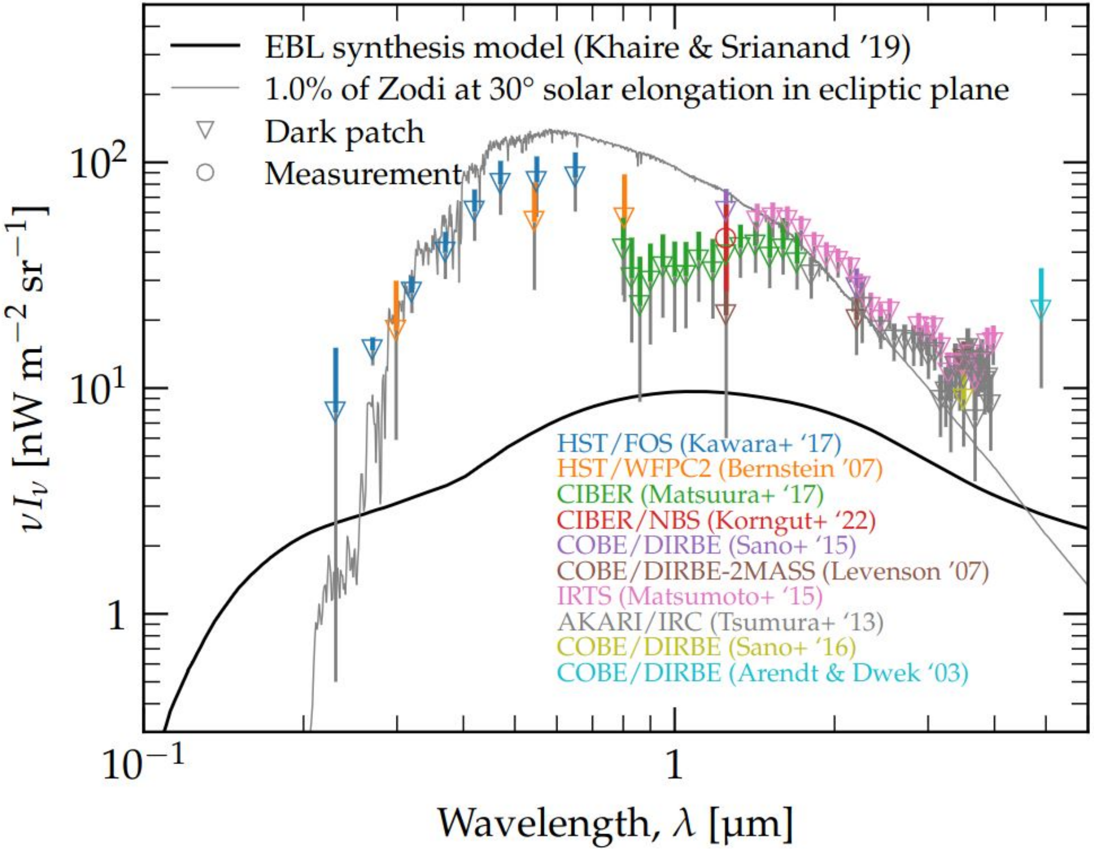
Zodiacal light (ZL): Sunlight scattered on Solar System dust

- ➢ **ZL outshines EBL** by more than an order of magnitude

Direct measurements at 1µm

Direct measurements from low orbit instruments and **Zodiacal lights** (Zodi)

The resemblance between the solar spectrum and the data suggests an unaccounted-for Zodi component

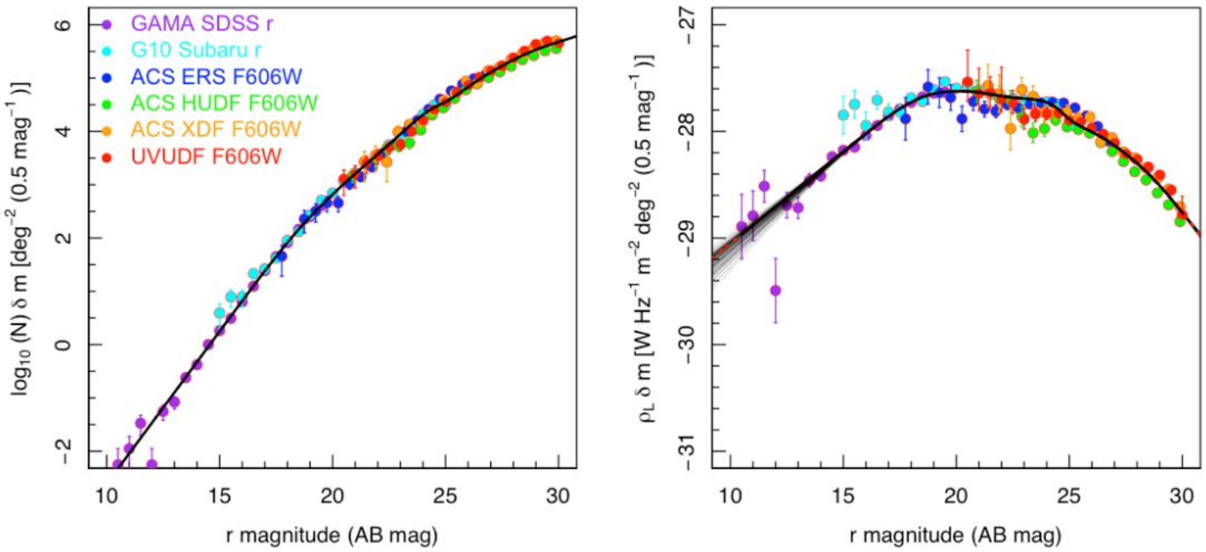


J. Biteau, 10.5281/zenodo.7842239

IGL measurements

IGL: integrated galactic light, **resolved galaxies**, expected to make up most of the EBL

Measured from galaxy surveys, contribution mainly derived from **intermediate-magnitude galaxies**



S. Driver, 10.3847/0004-637X/827/2/108

Hubble constant from gamma rays

γ-ray data — $\propto 1/H_0$ — IGL intensity

$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$

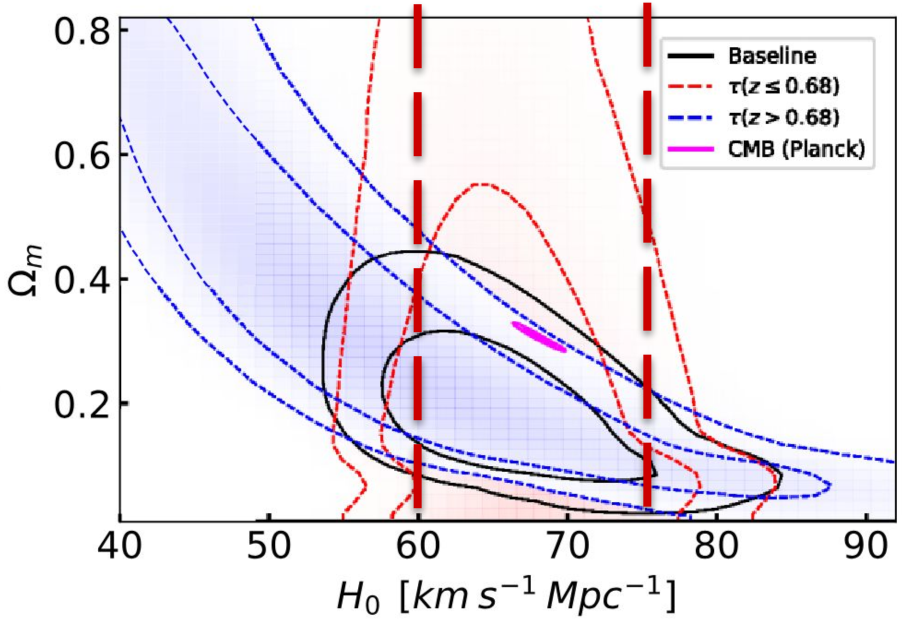
γγ cross-section

Domínguez+ ‘24

- ➢ **VHE+HE** γ-ray vs **evolving IGL**
- ➢ **Model dependent**

Gréaux+ ‘24

- ➢ **VHE** γ-ray vs **IGL at z = 0**
- ➢ **Model independent**

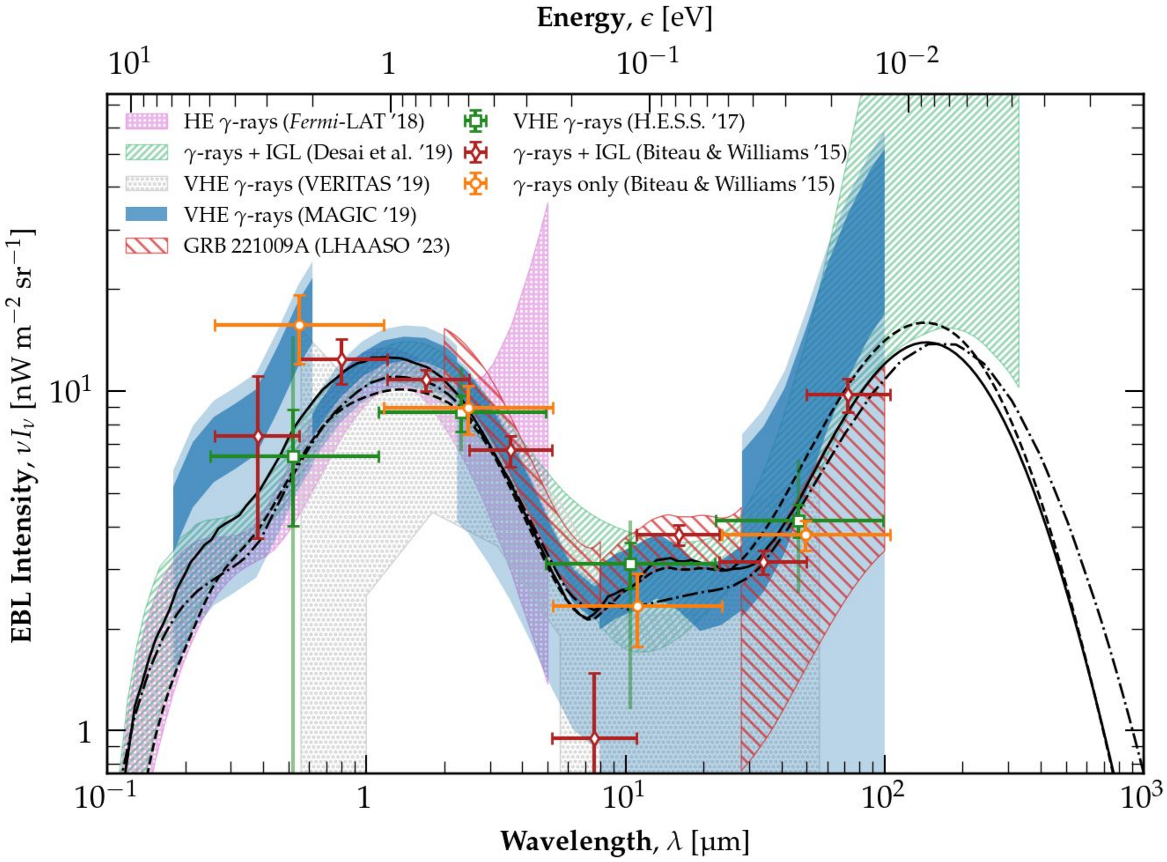


H_0 = 67 ± 7 km s^{-1} Mpc^{-1} x (1 + f_{diff})

- ➢ **Coherent with D24** for low z

A. Domínguez, 10.1093/mnras/stad3425

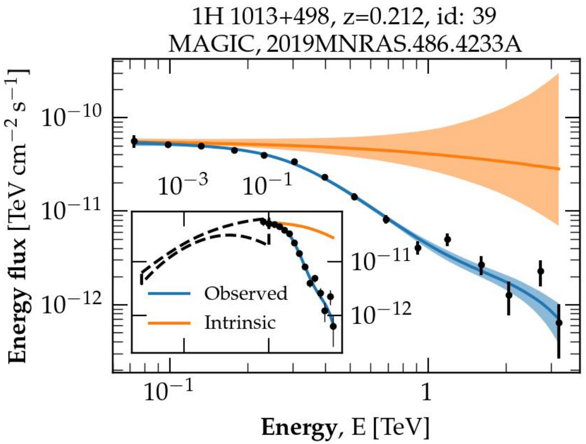
EBL measurements from gamma-ray cosmology



EBL from the **absorption imprint** on TeV spectra:

$$\Phi_{\rm obs} = \Phi_{\rm int} \times e^{-\tau}$$

$$\tau(E_\gamma, z_0) = \int_0^{z_0} dz \frac{\partial L}{\partial z}(z) \int_0^{\infty} d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \int_{-1}^{1} d\mu \frac{1-\mu}{2} \sigma_{\gamma\gamma}(E_\gamma(1+z), \epsilon, \mu)$$



From samples to probability distributions

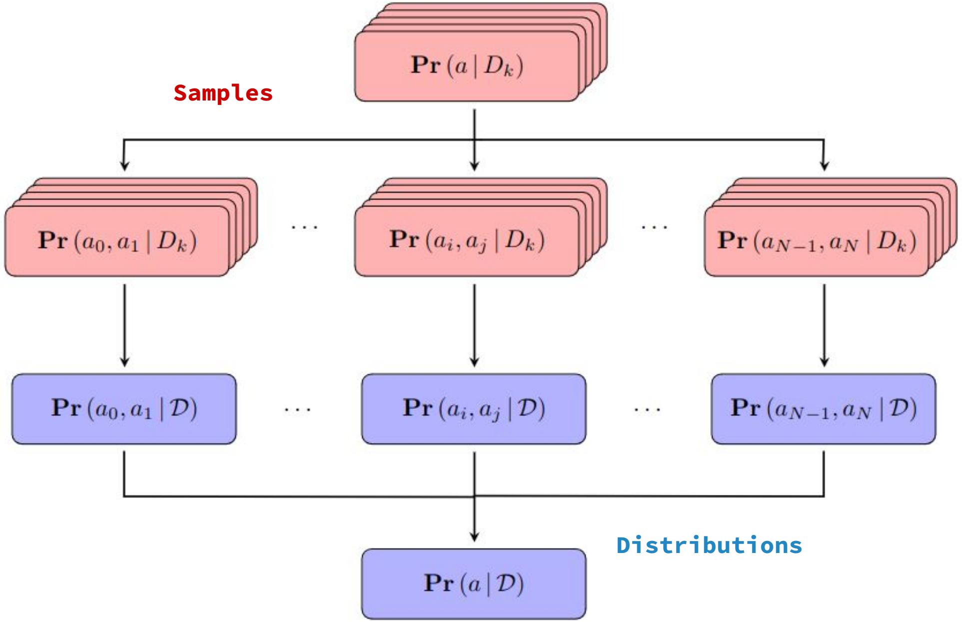
With n free parameters and **N spectra**:

$$\mathbf{Pr}(\mathcal{D} \mid a) = \int \mathrm{d}\Theta \prod_{k=1}^{N} \mathbf{Pr}(D_k \mid a, \theta_k)$$

Complexity: $O(N^3 n^3)$

$$\mathbf{Pr}(\mathcal{D} \mid a) = \prod_{k=1}^{N} \int \mathrm{d}\theta_k \, \mathbf{Pr}(D_k \mid a, \theta_k)$$

Complexity: $O(N n^3)$



Autocorrelation time

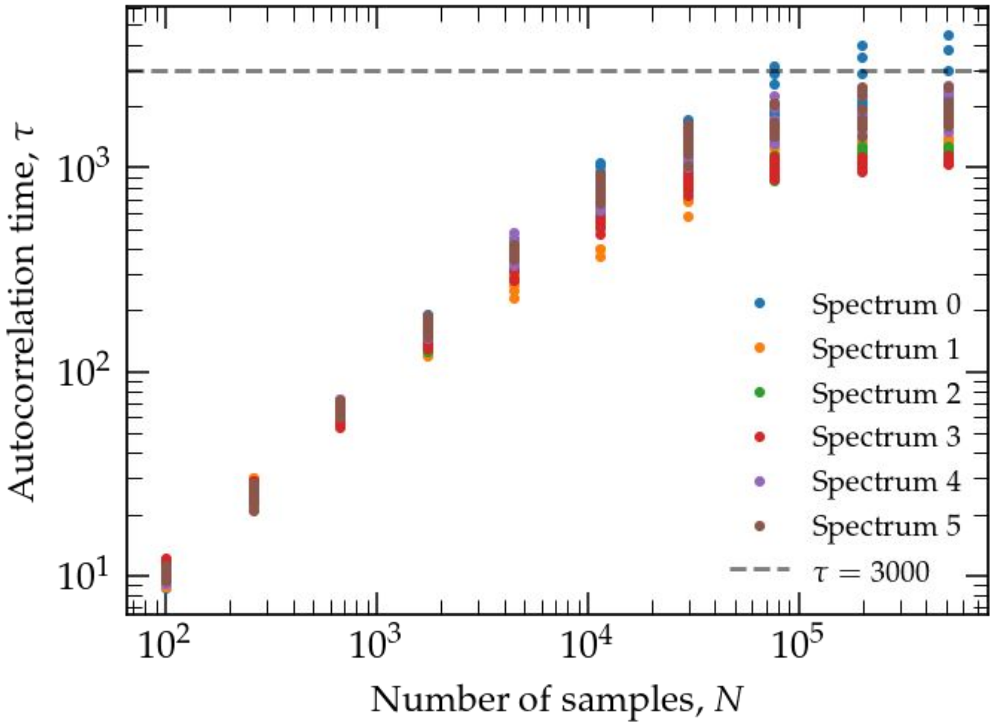
EBL model: Sum of 8 gaussians

Autocorrelation time: τ such that a chain of length N has **N/τ independent samples**

$$\sigma^2(\bar{f}) = \langle(\frac{1}{N}\sum_i f_i)^2\rangle - \langle\frac{1}{N}\sum_i f_i\rangle^2$$

$$= \frac{1}{N^2}\sum_{i,j}\langle f_i f_j\rangle - \langle f_i\rangle\langle f_j\rangle = \frac{1}{N^2}\sum_{i,j}\widehat{C}_{ij}$$

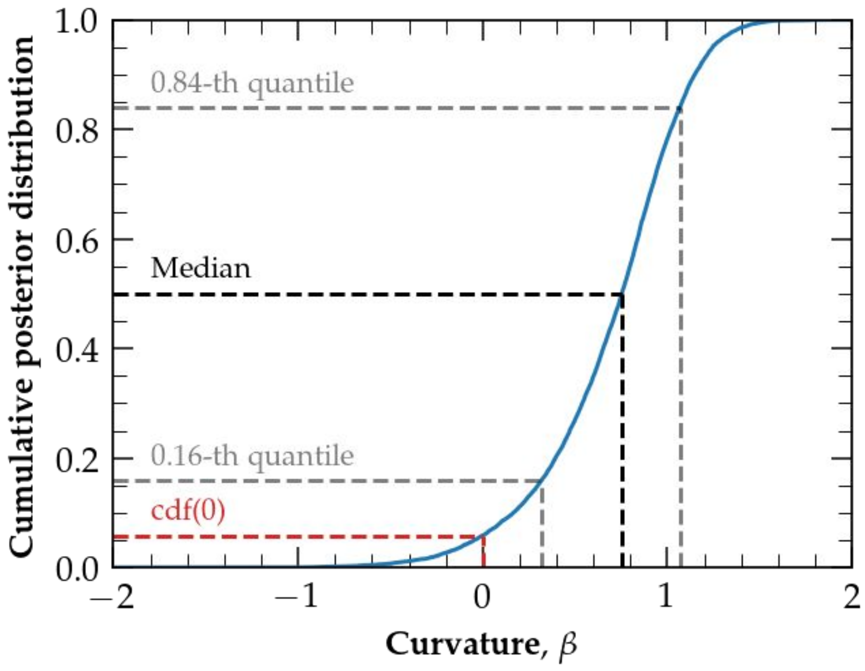
$$\sigma^2(\bar{f}) = \frac{\sigma^2(f)}{N}\underbrace{\left(1 + 2\sum_{t=1}^{N-1}\left(1 - \frac{t}{N}\right)\frac{\widehat{C}(t)}{\widehat{C}(0)}\right)}_{\xrightarrow[N\to\infty]{} \tau}$$

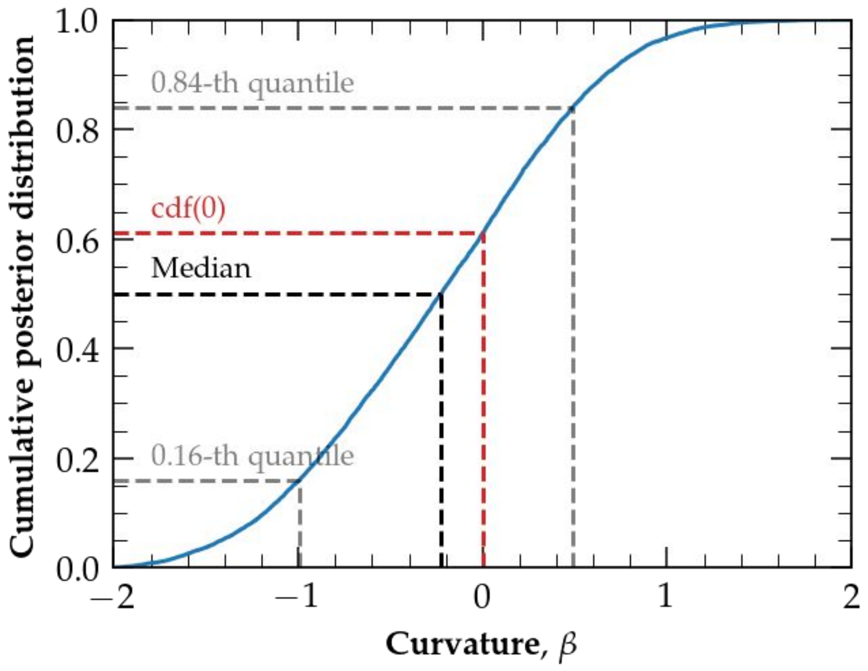


Reconstructed spectral parameters

Reconstruct two values of interest from posterior distribution of each spectrum

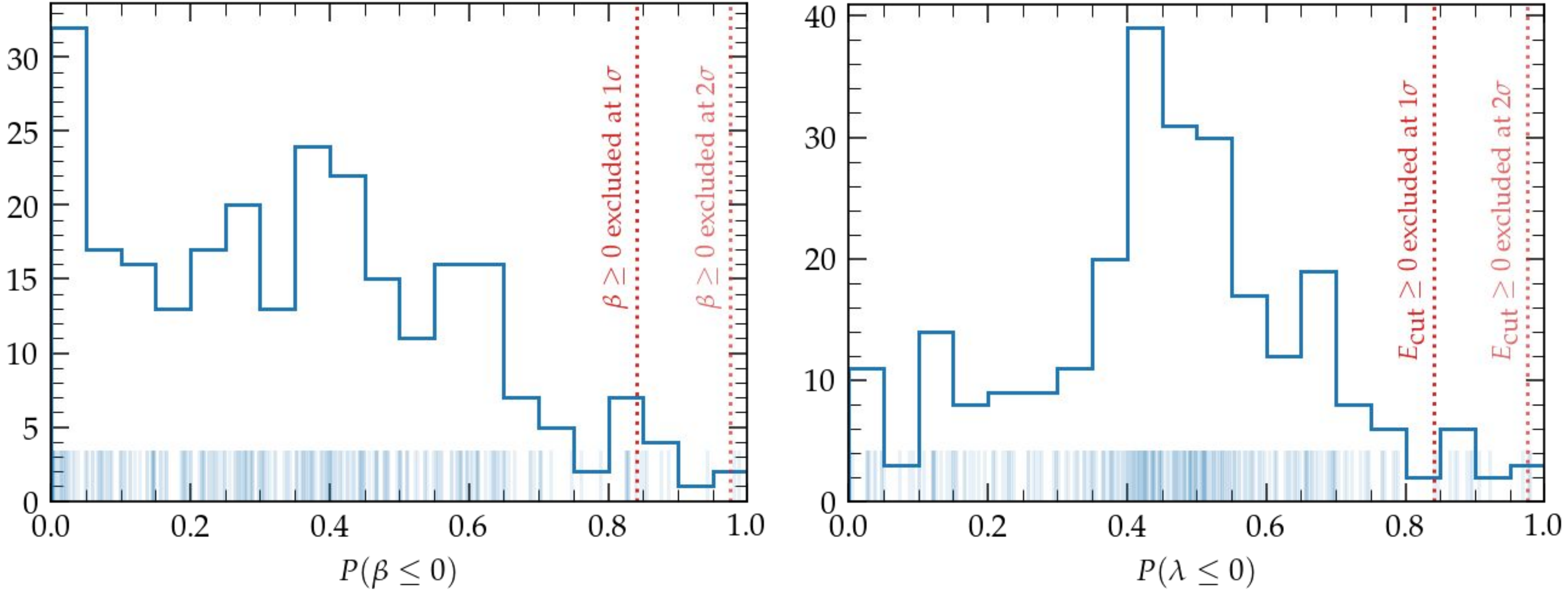
- **Median** (reconstructed parameter p)
- **cdf(0)** = P(p≤0)





Reconstructed spectral parameters: curvature & energy cutoff

On the scale of the dataset, reconstructed spectra are physical



Gamma-ray spectral residuals

Distribution of spectral residuals over the complete dataset

EBL model: Sum of 8 Gaussians

Reconstruction compatible with a Gaussian with **μ = 0.2, σ = 0.7**

Slight tendency to underestimate the data in the modelling