Programme national hautes énergies

A γ-ray perspective on the cosmological optical controversy

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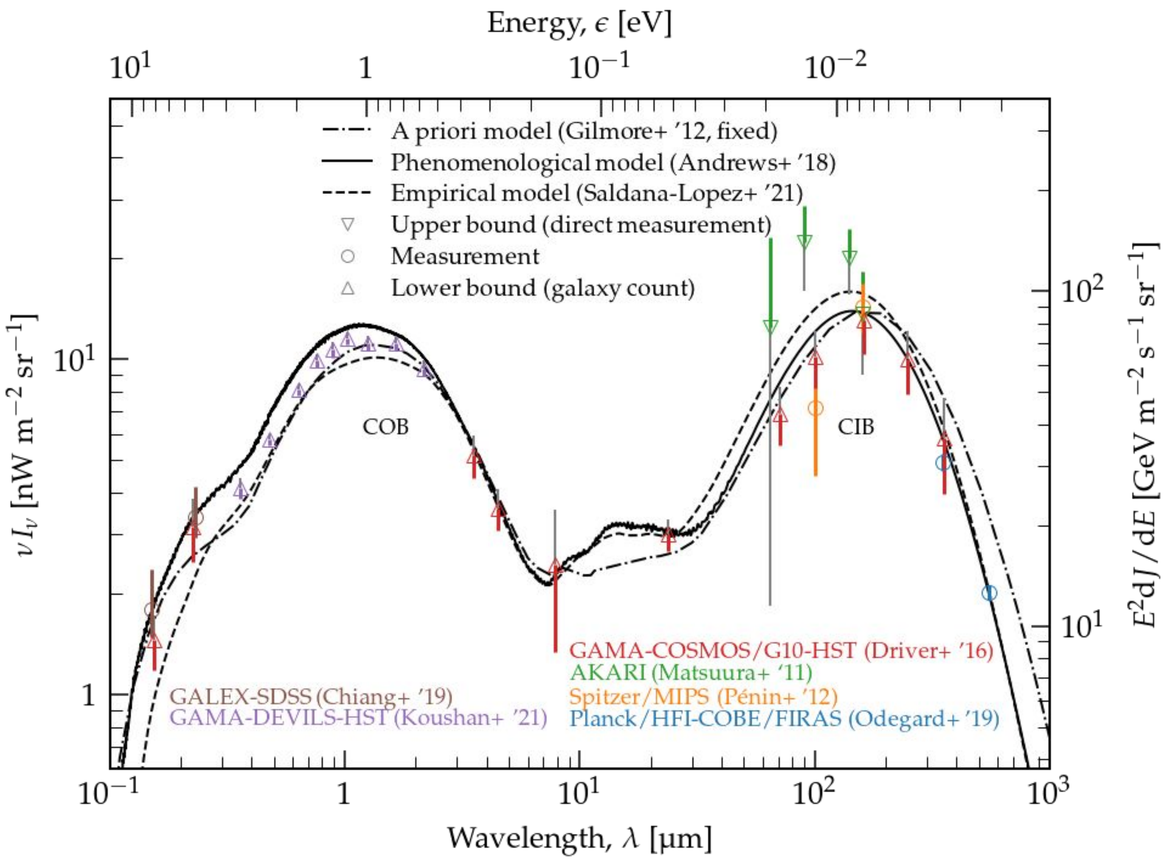
The Extragalactic Background Light



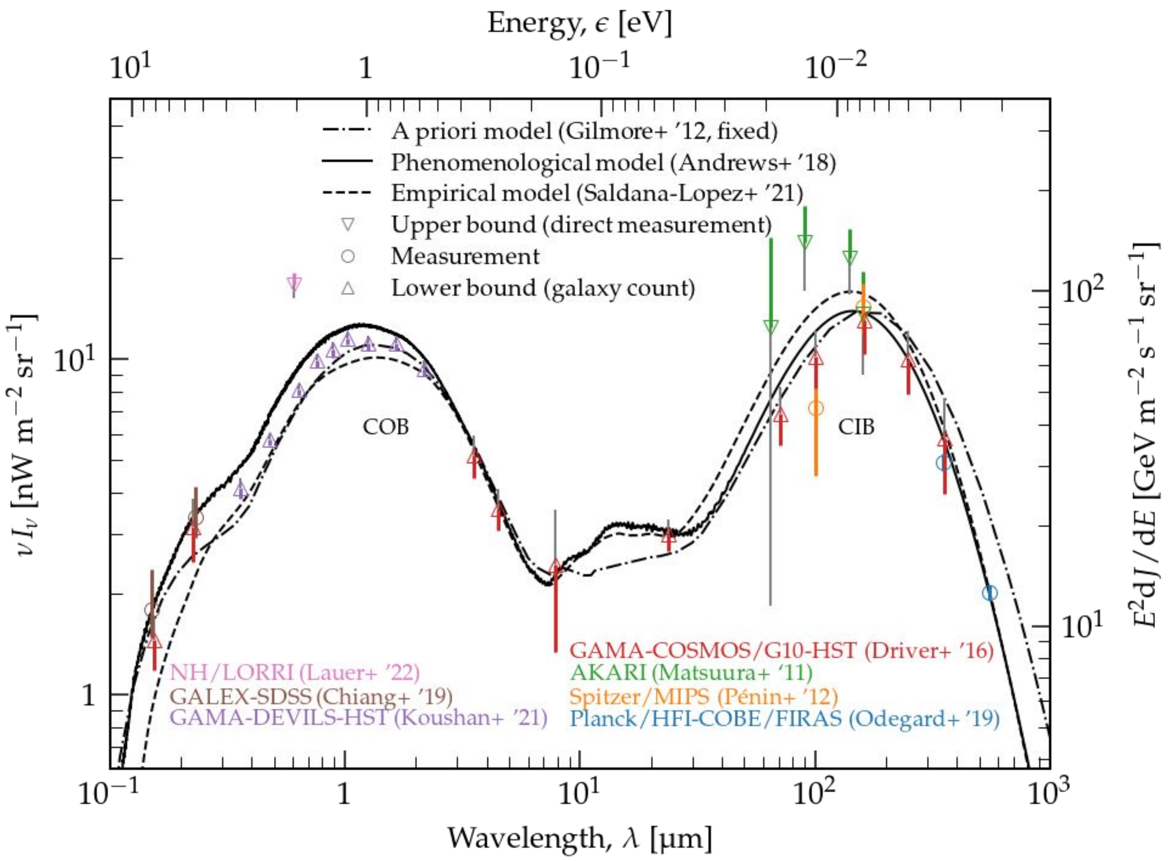
EBL: sum of all **optical** and **infrared** light from **thermal processes** in the universe

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

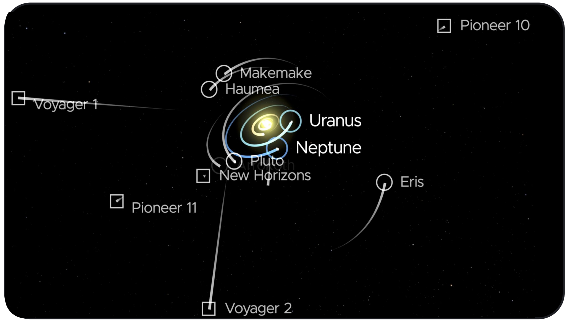
IGL ≤ EBL

J. Biteau, 10.5281/zenodo.7842239

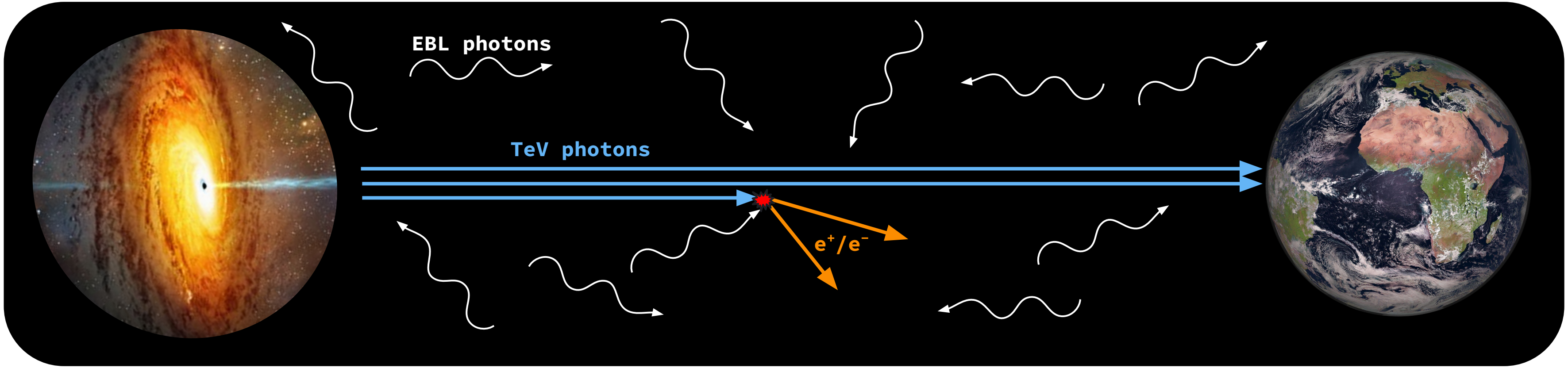
The cosmological optical controversy

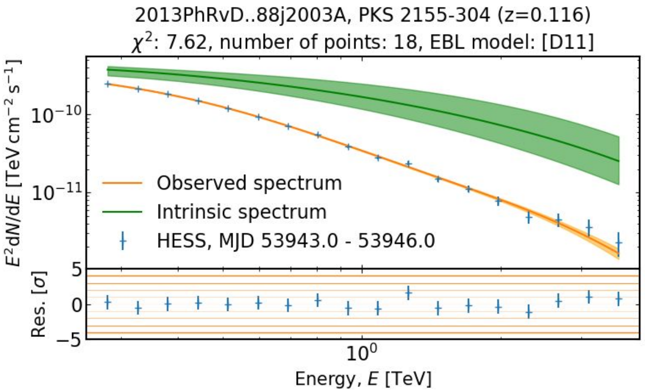


New Horizons probe showed a **4σ excess wrt IGL** measurements, from **beyond Pluto's orbit**



Propagation of TeV photons through the Universe



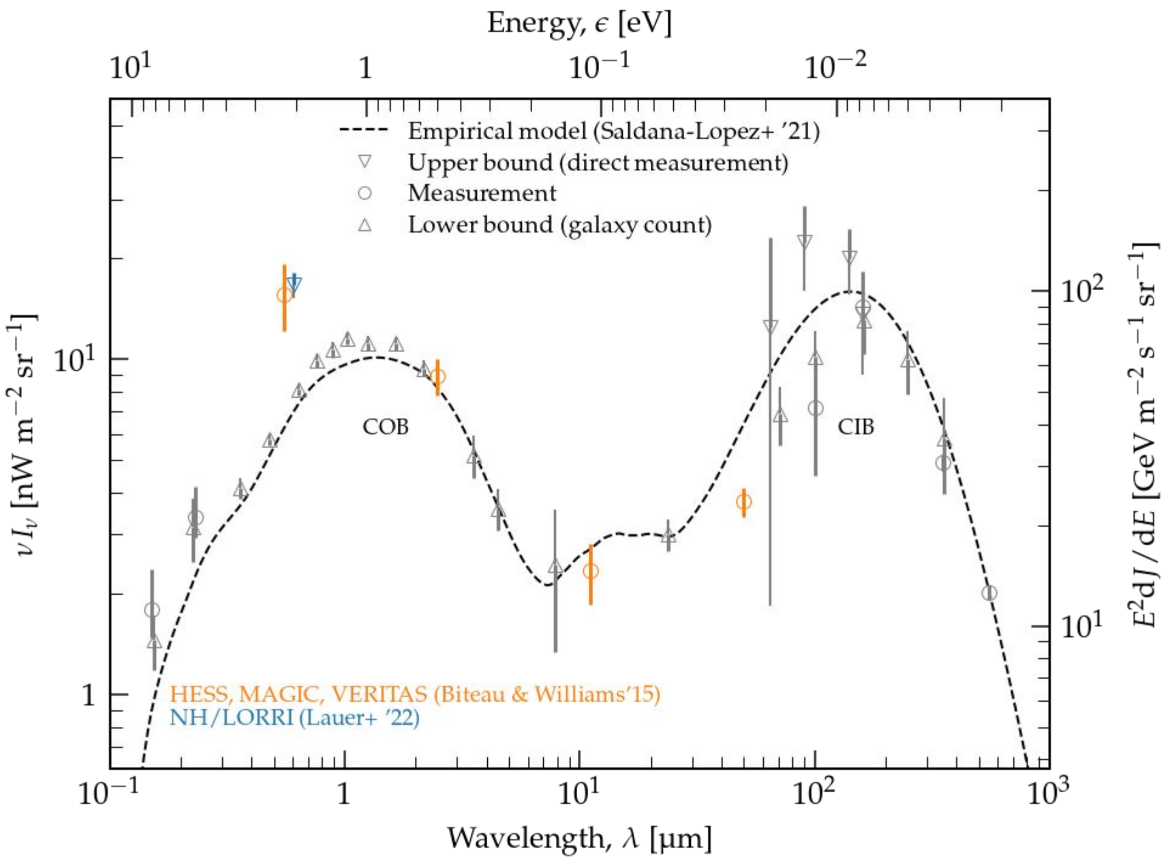


LG 2022
arXiv:2304.00808

Attenuation characterized by optical depth τ:

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

A gamma-ray cosmology answer?

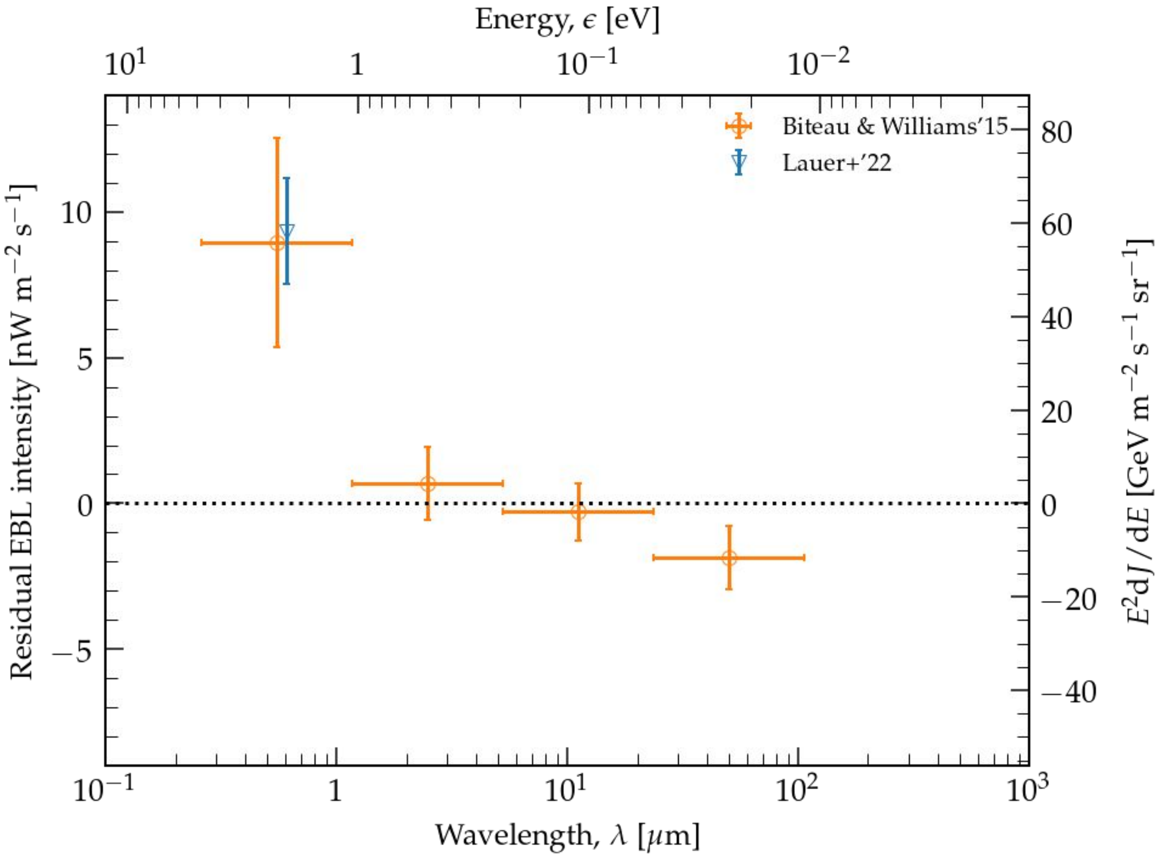


γ-ray cosmology

Reconstruct EBL using the **absorption imprint** on TeV spectra

Current γ-ray measurements cannot confirm nor infirm an excess wrt IGL

A gamma-ray cosmology answer?



γ-ray cosmology

Reconstruct EBL using the **absorption imprint** on TeV spectra

Current γ-ray measurements cannot confirm nor infirm an excess wrt IGL

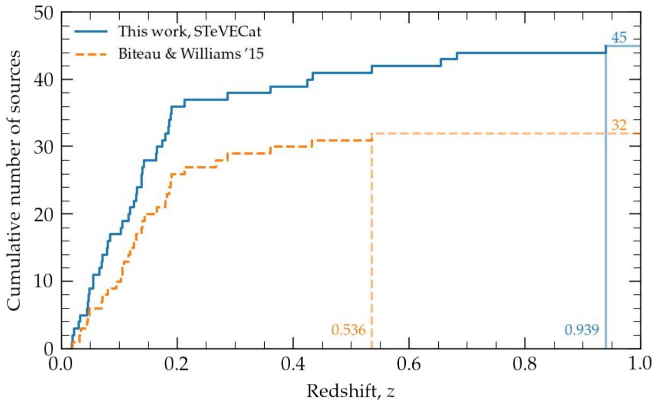
Data sample

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**

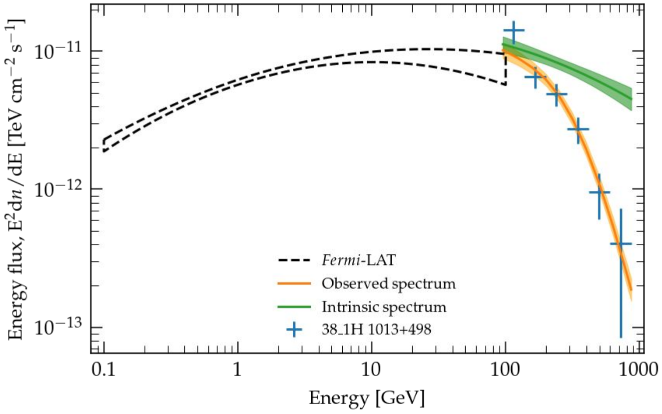
➢ **268 spectra** (**86 for B&W'15**)



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

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

➢ **95** contemporaneous spectra



Shortcomings of the Frequentist analysis

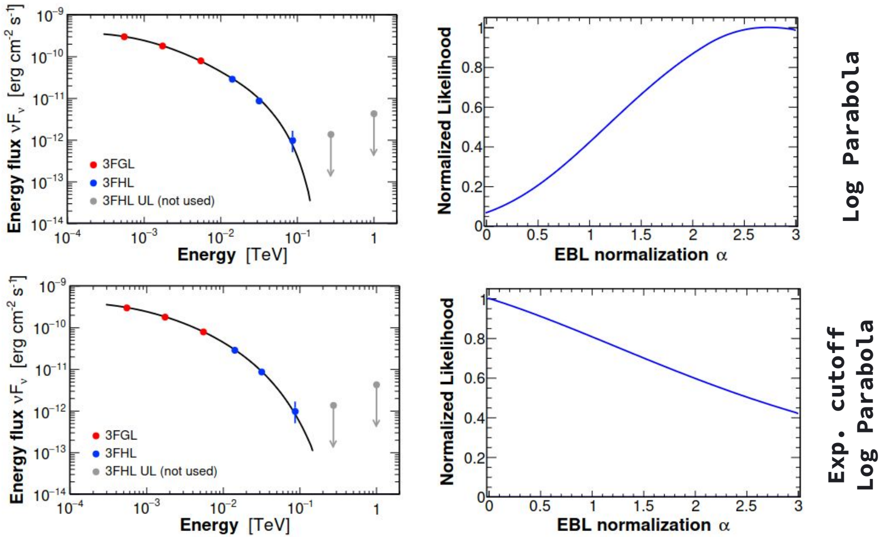
a EBL parameters
Θ spectral parameters

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

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

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

$$\mathbf{Pr}(\mathcal{D} \,|\, a) = \max_{\Theta}\left\{\mathbf{Pr}(\mathcal{D} \,|\, a, \Theta)\right\} = \max_{\Theta}\left\{\prod_k \mathbf{Pr}(D_k \,|\, a, \theta_k)\right\}$$



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**

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

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

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

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

Bayesian framework

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

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

$$\phi_{\varepsilon-\text{model}}(E, z, a, \Theta, \varepsilon) = \phi_{\text{model}}\left(\frac{E}{1+\varepsilon}, z, a, \Theta\right) \times \frac{1}{1+\varepsilon}$$

From samples to probability distributions

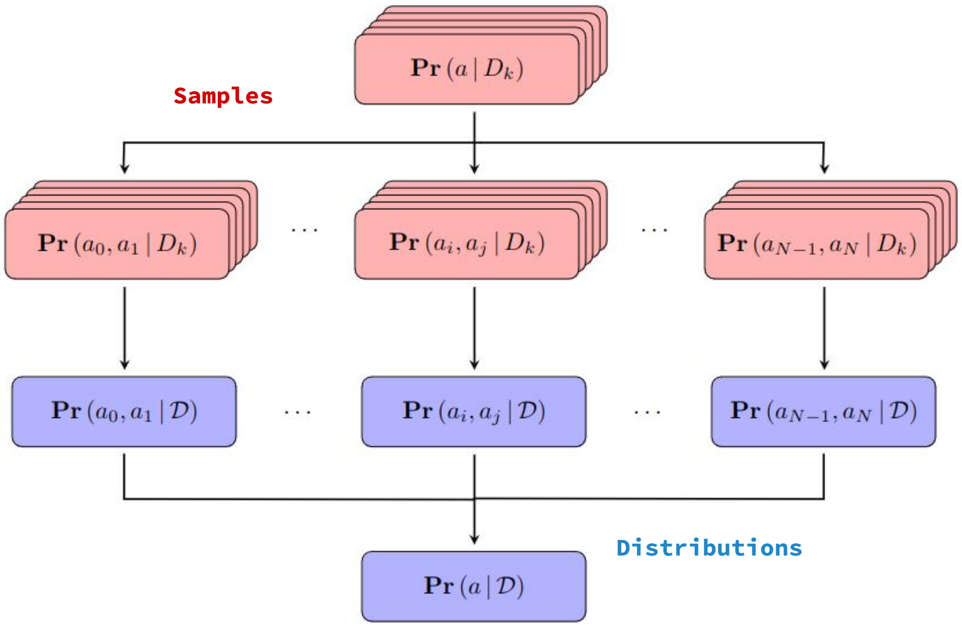
With n free parameters and **N spectra:**

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

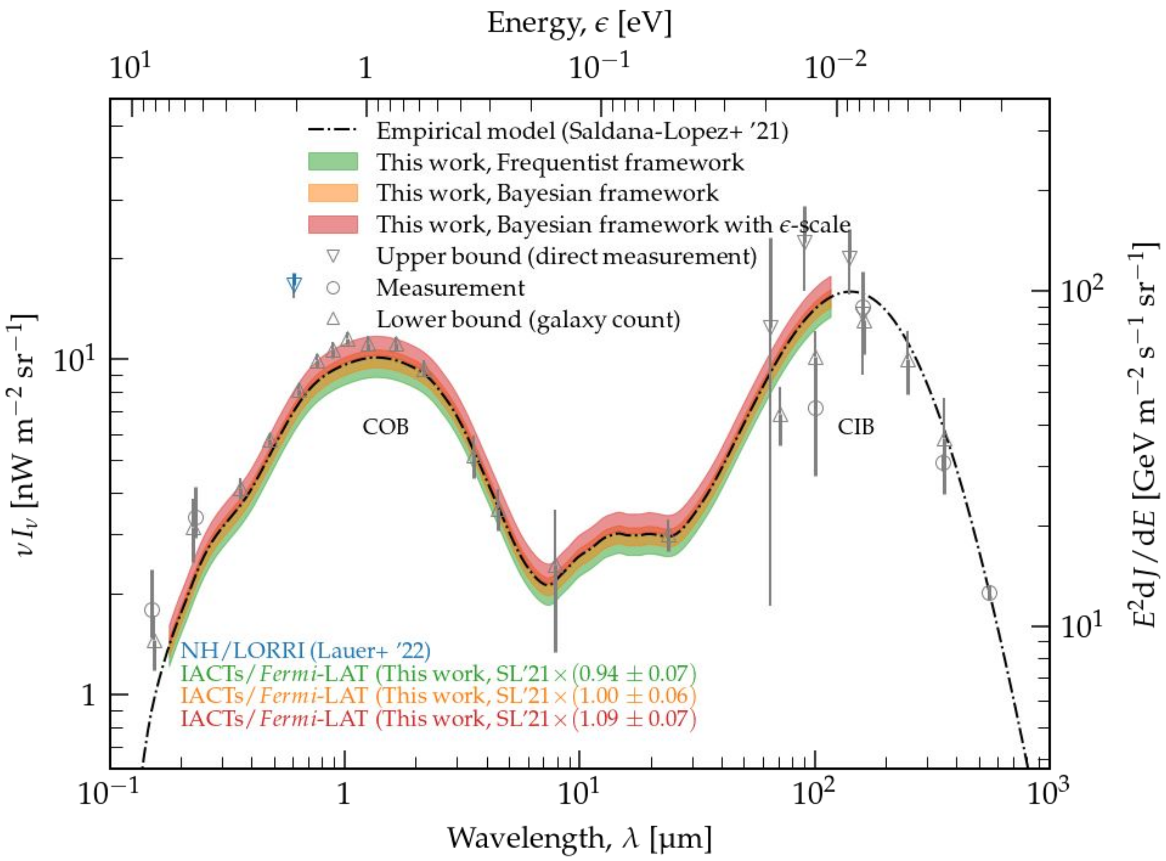
Complexity: $O(N^3 n^3)$

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

Complexity: $O(N n^3)$



Benchmarking the frameworks



Scale reference EBL model (Saldana-Lopez+'21) with normalization factor **a**:

$$\tau(E, z, a) = a \times \tau_{SL}(E, z)$$

Frequentist framework:
0.94 ±0.07

Bayesian framework:
1.00 ±0.06

Bayes.+ε-scale framework:
1.09 ±0.07

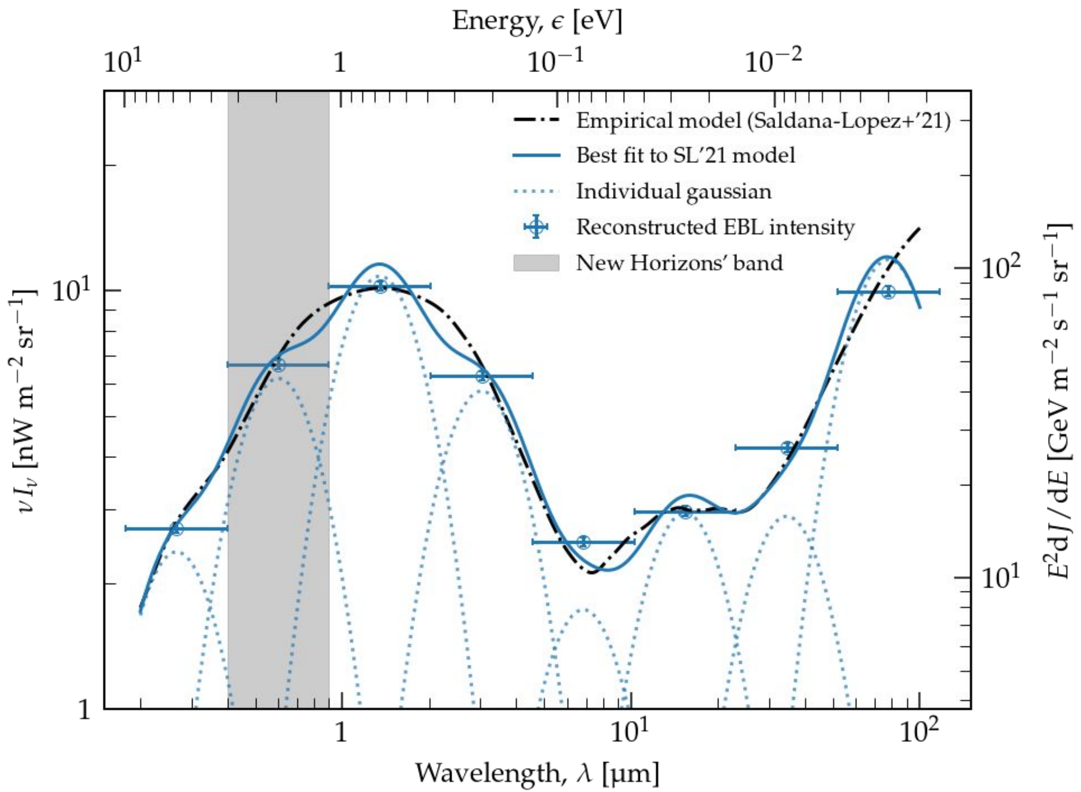
EBL parametrization

EBL model: Sum of 8 gaussians

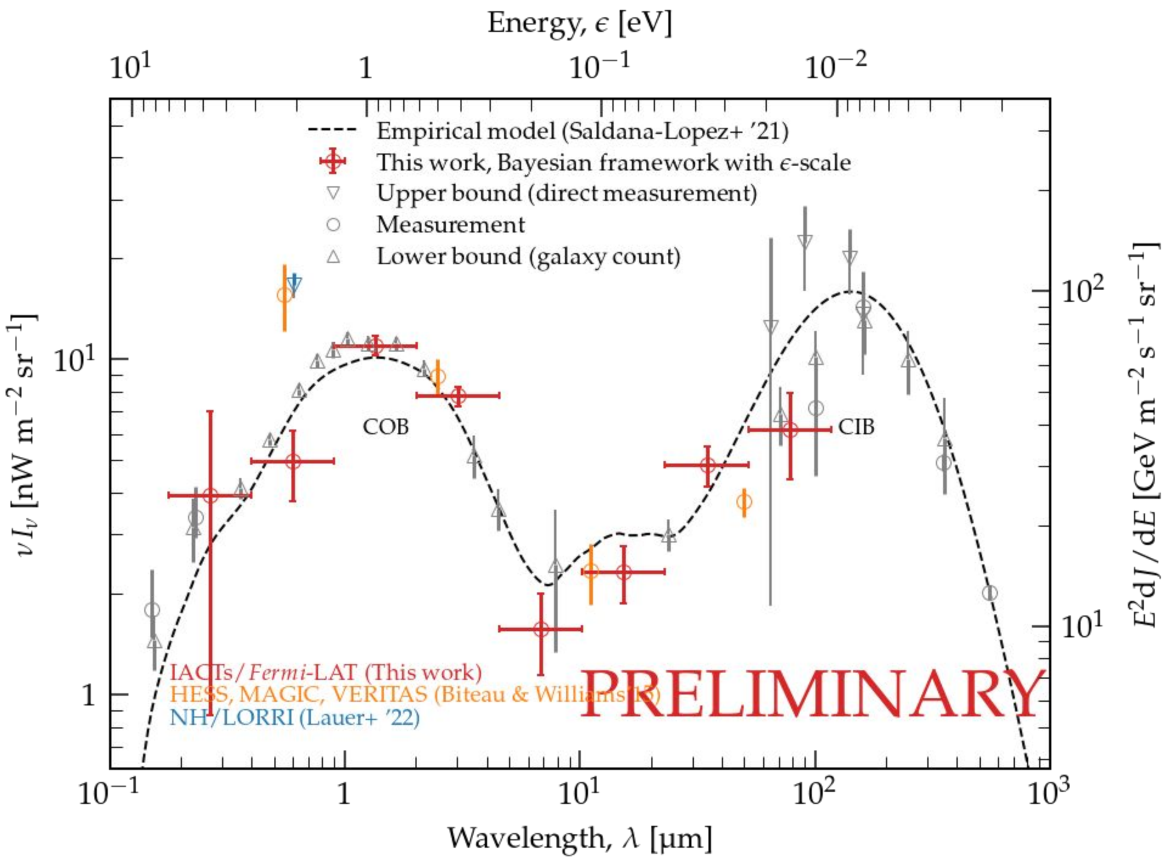
- ⇨ **Free amplitudes a_i**
- ⇨ Fixed widths & positions
  - ➢ **Match New Horizons'** band in 400-900nm

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

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



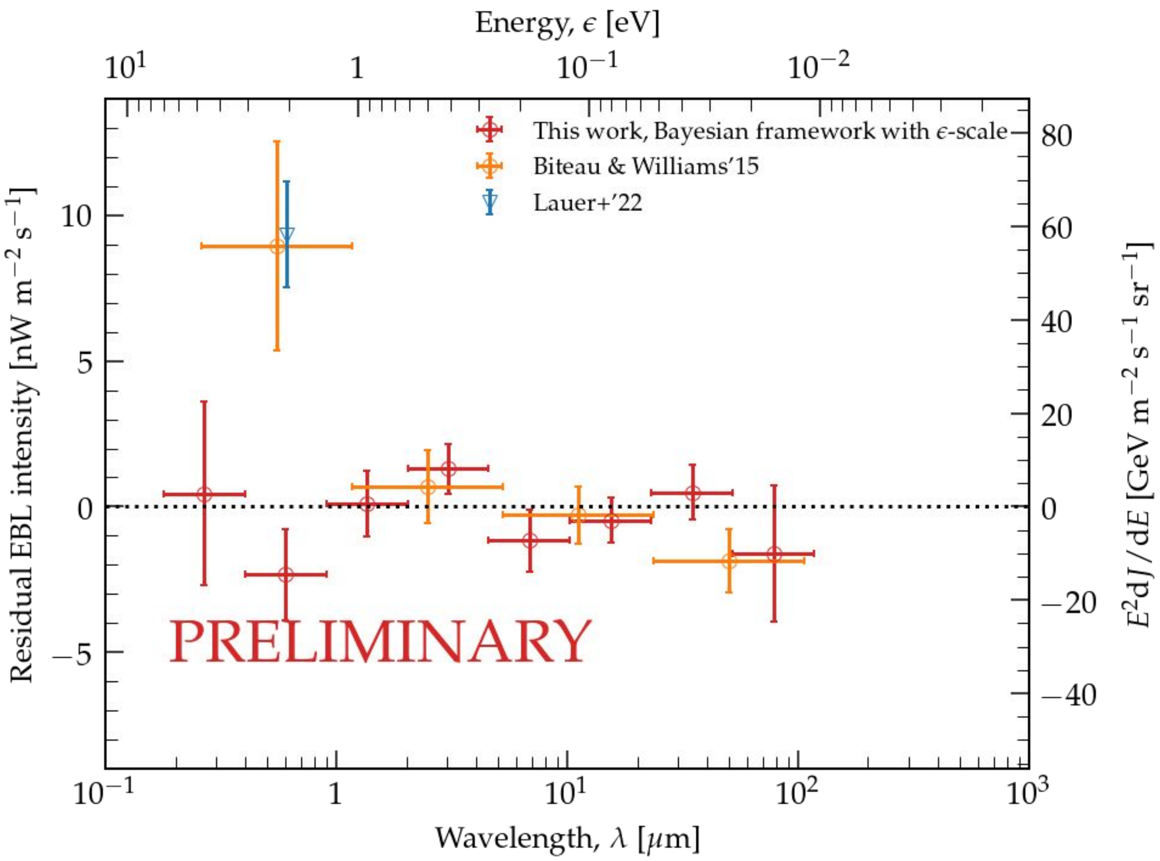
γ-ray constraints on the New-Horizons excess



Bayesian framework with energy-scale factor, **red**

Reduced uncertainties wrt **previous γ-ray studies**

γ-ray constraints on the New-Horizons excess



Bayesian framework with energy-scale factor, **red**

Reduced uncertainties wrt **previous γ-ray studies**

>5σ tension between **γ-rays** and **New Horizons**

With respect to **IGL:**

- No detected excess

Conclusion

We propose a **new γ-ray EBL measurement**:

- ⇨ **Bayesian** framework
  - ➢ Marginalize over spectral/nuisance parameters
- ⇨ New data corpus, **STeVECat**
  - ➢ Sample size ~tripled wrt previous
- ⇨ Independant from IGL / direct
  - ➢ Only use γ-ray observations
- ⇨ **Reduced uncertainties** with respect to **previous γ-ray studies**

At 600nm: currently **4σ tension** between **IGL** and **New Horizons**

- ⇨ **γ-rays compatible** with IGL
- ⇨ **>5σ tension** between γ-rays and New Horizons

Suggests a **local origin** (zodiacal, galactic) for the New Horizons excess

- ★ Estimate the impact of priors
- ★ Investigate other potential biases

Backup

Lucas Gréaux

Autocorrelation time

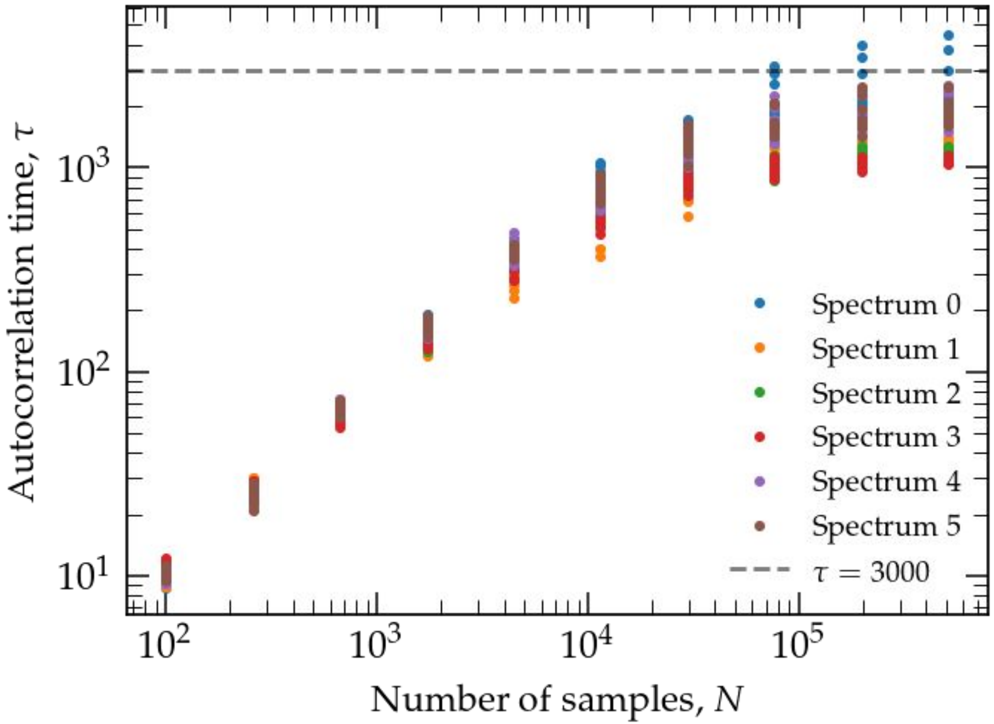
EBL model: Sum of 8 gaussians

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

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

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

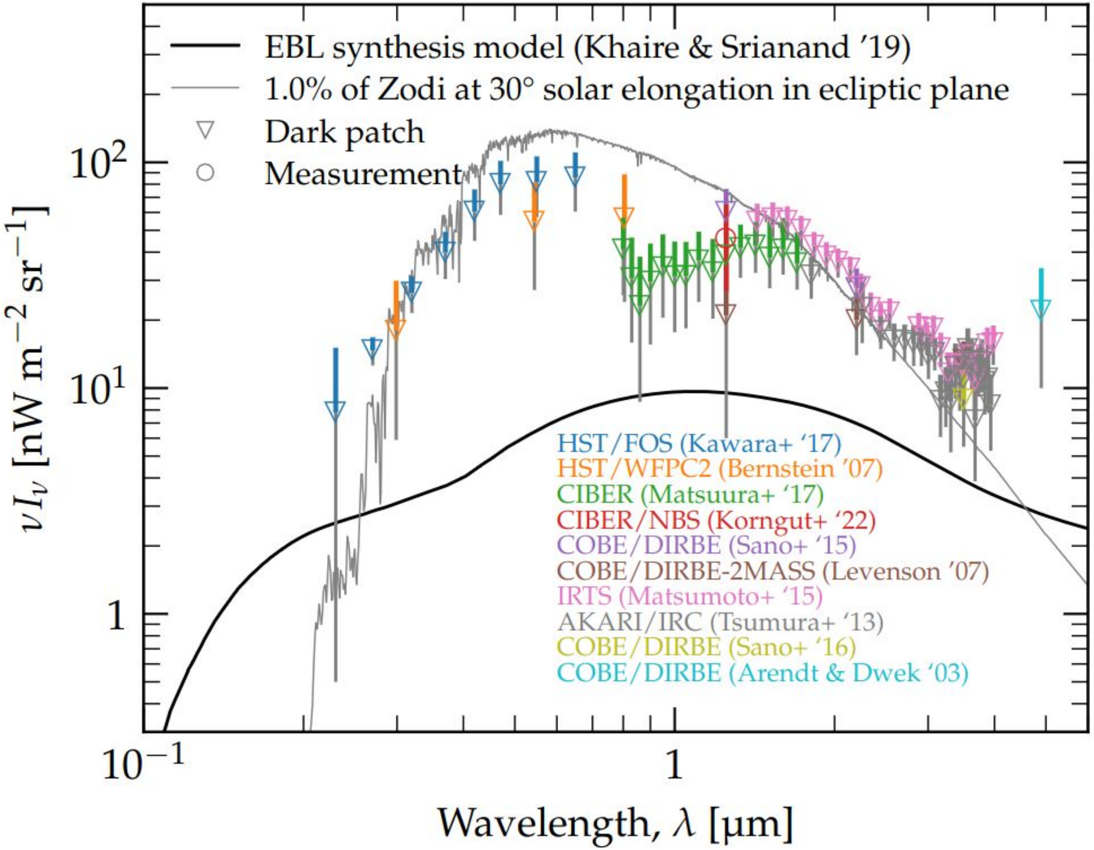
$$\sigma^2(\bar{f}) = \frac{\sigma^2(f)}{N}\underbrace{\left(1 + 2\sum_{t=1}^{N-1}\left(1 - \frac{t}{N}\right)\frac{\widehat{C}(t)}{\widehat{C}(0)}\right)}_{\xrightarrow[N\to\infty]{} \tau}$$



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

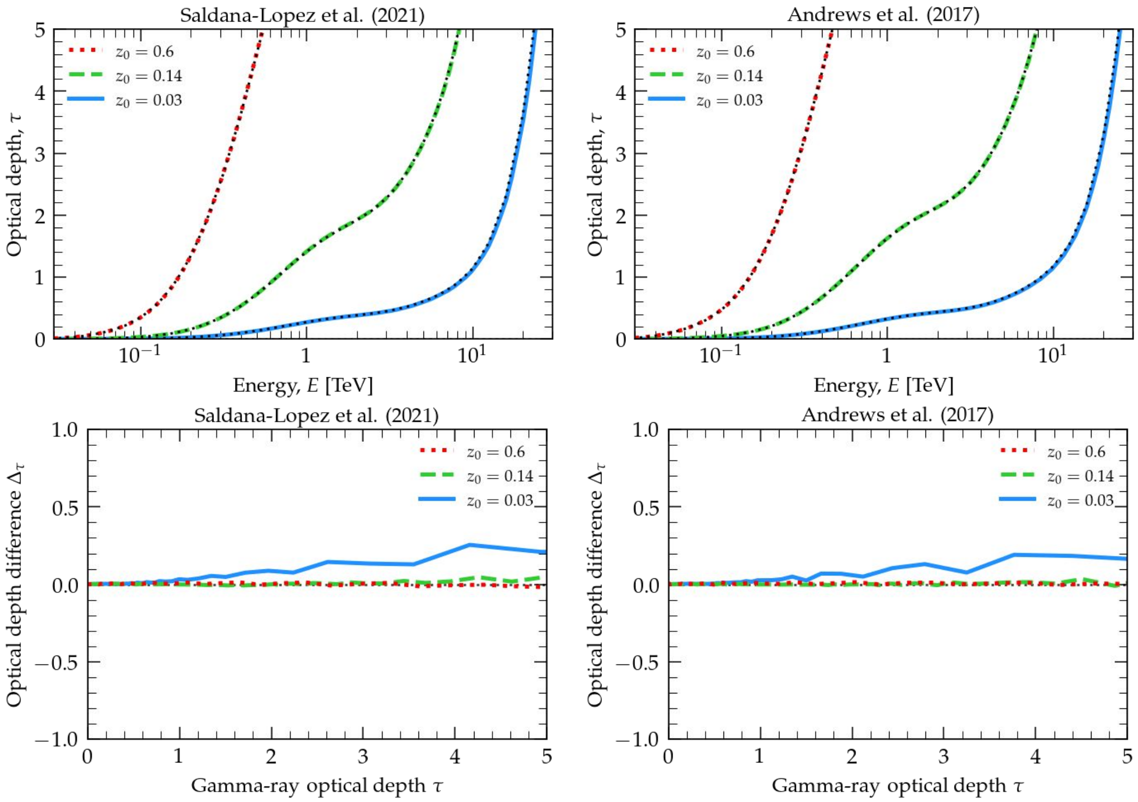
Computing EBL optical depth from reference EBL intensity

τ from EBL intensity (Biteau & Williams, 2015)

$$\tau(E_0, z_0) = \frac{3}{4}\frac{\sigma_T c}{H_0}\int_0^{z_0} \mathrm{d}z\, \frac{\partial l}{\partial z}(z) \int_0^{\infty} \mathrm{d}\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) \frac{1}{(1+z)^2}\left(\frac{m_e^2 c^4}{E_0 \epsilon}\right)^2 P(\beta_{\max})$$

$$\beta_{\max}^2 = 1 - \frac{m_e^2 c^4}{E_0 \epsilon}\frac{1}{1+z}$$

$$P(x) = \ln^2 2 - \frac{\pi^2}{6} + 2\,\mathrm{Li}_2\left(\frac{1-x}{2}\right) - \frac{x+x^3}{1-x^2} + (\ln(1+x) - 2\ln 2)\ln(1-x) + \frac{1}{2}\left(\ln^2(1-x) - \ln^2(1+x)\right) + \frac{1+x^4}{2(1-x^2)}\ln\frac{1+x}{1-x}$$



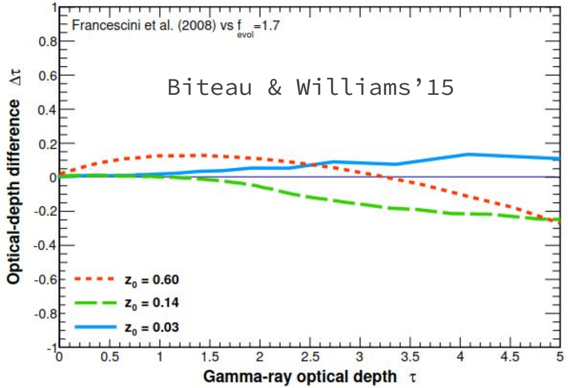
Evolving the reference EBL template with redshift

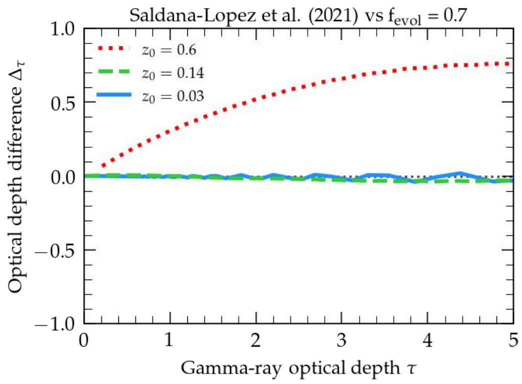
Decorelate energy and redshift evolution:

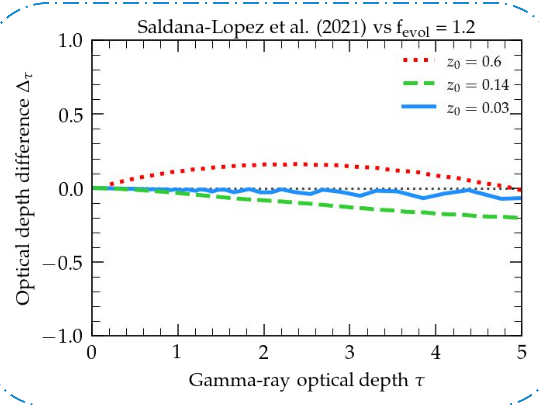
$$d\epsilon \frac{\partial n}{\partial \epsilon}(\epsilon, z) = d\epsilon_0 \frac{\partial n}{\partial \epsilon_0}(\epsilon_0, 0) \times evol(z)$$

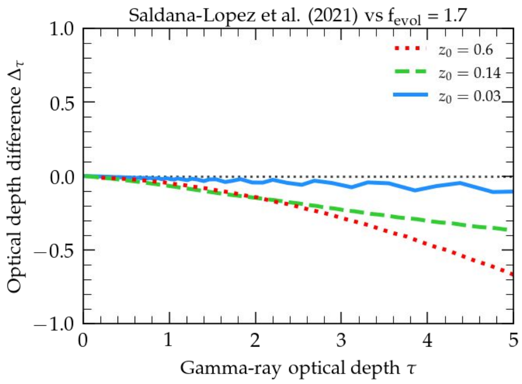
$$evol(z) = (1+z)^{3-f_{\rm evol}}$$

For Saldana-Lopez et al. (2021): f_{evol} **= 1.2**



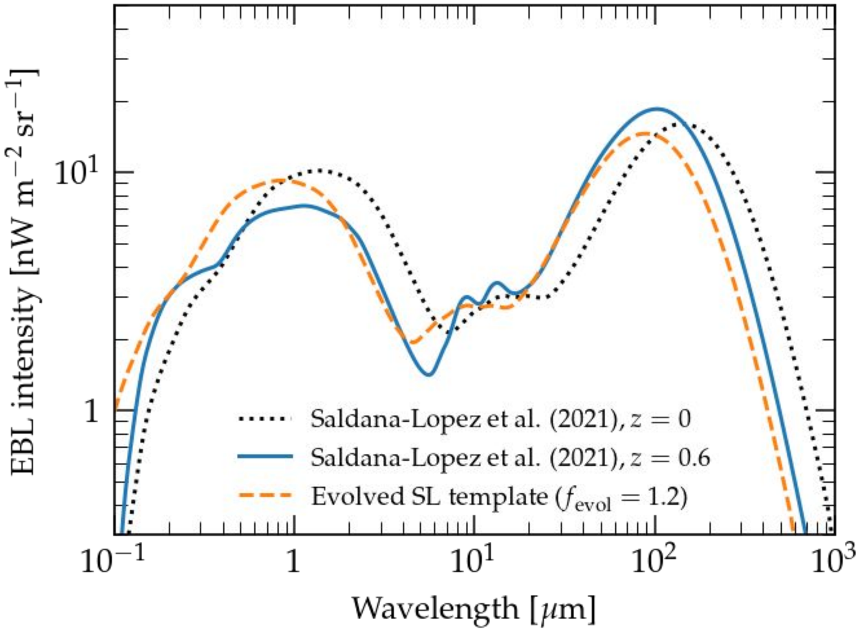




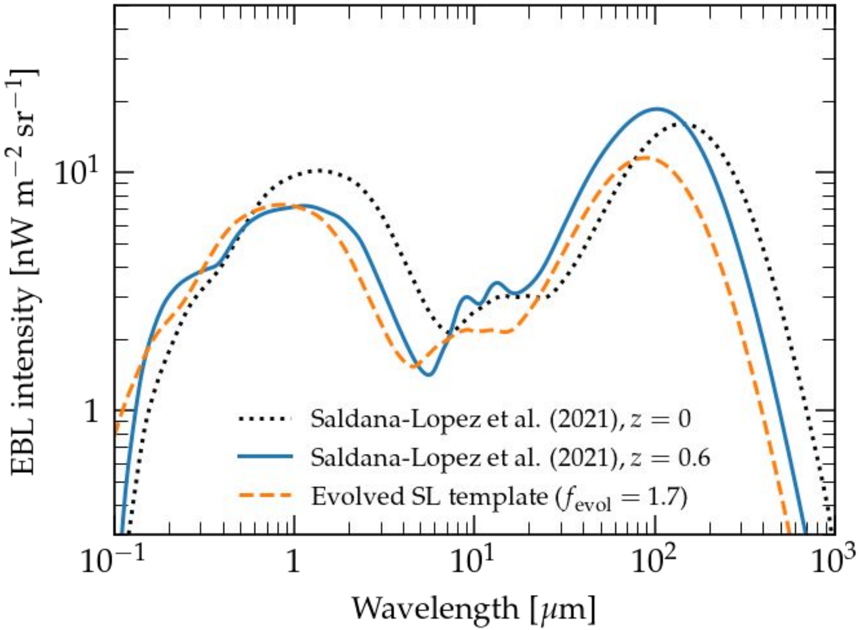


Evolving the reference EBL template with redshift

f_{evol} = **1.2**, z = 0.6

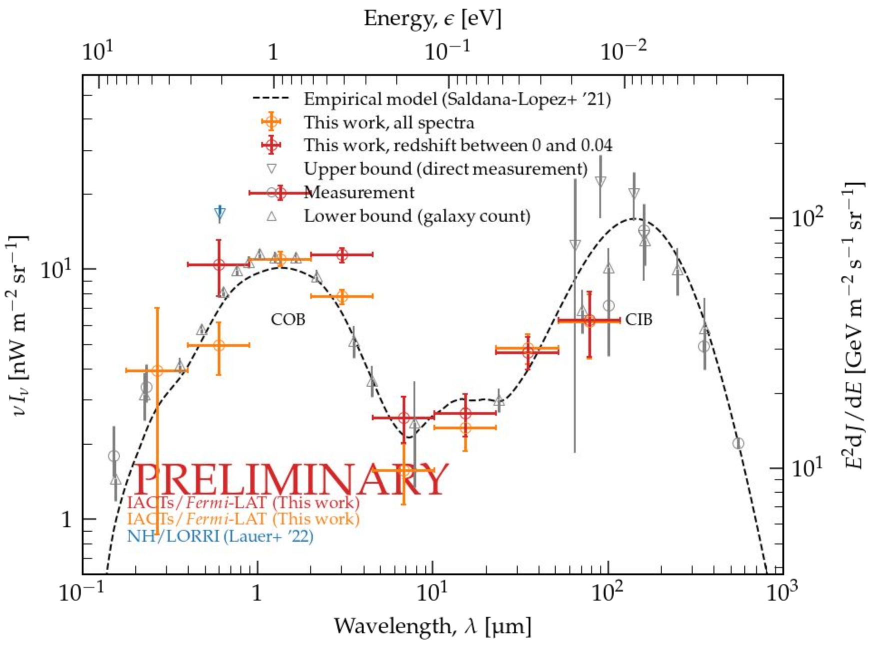


f_{evol} = **1.7**, z = 0.6

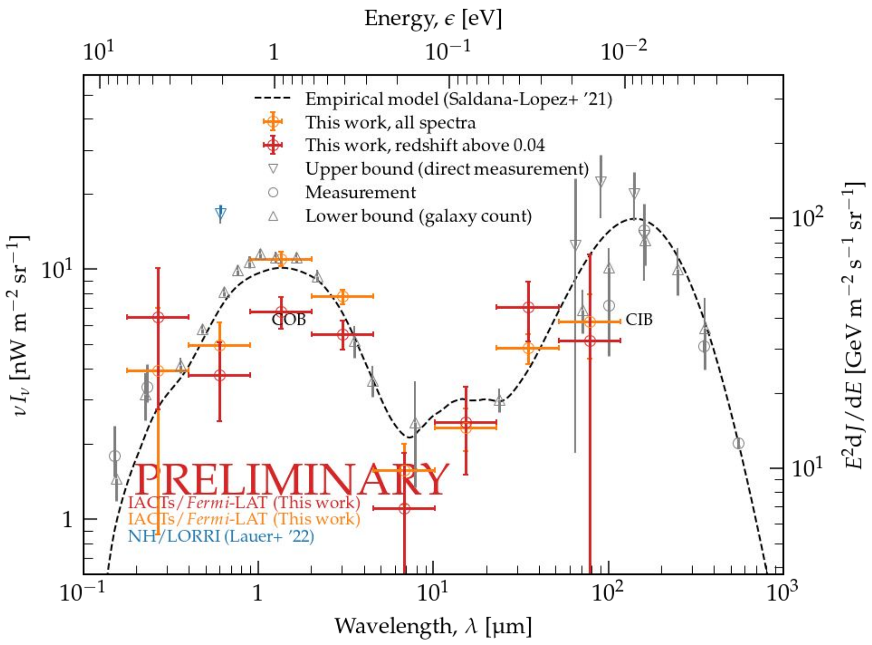


Reconstruction for low and high redshift spectra

Framework: Bayesian with ε, z < 0.04

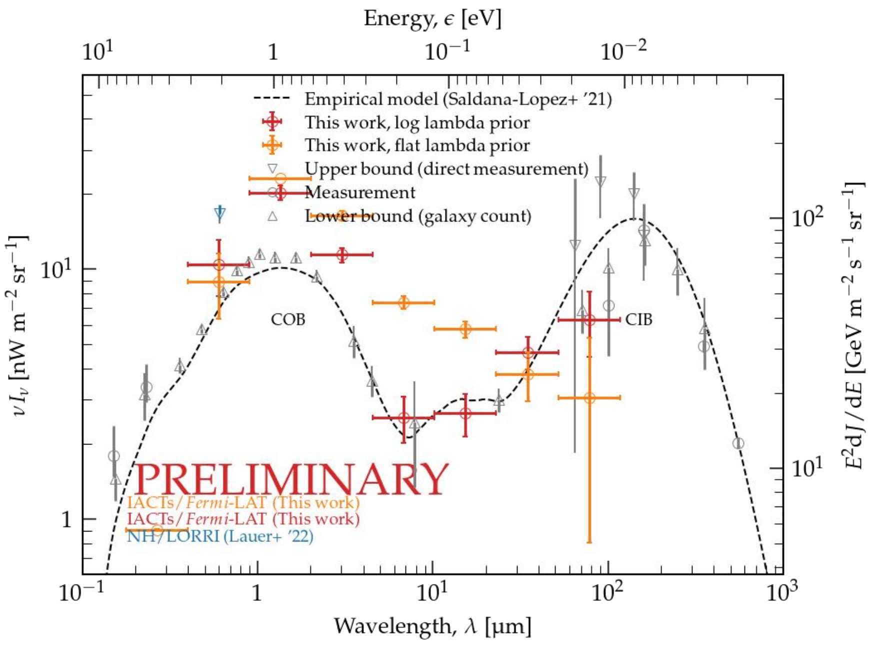


Framework: Bayesian with ε, z > 0.04

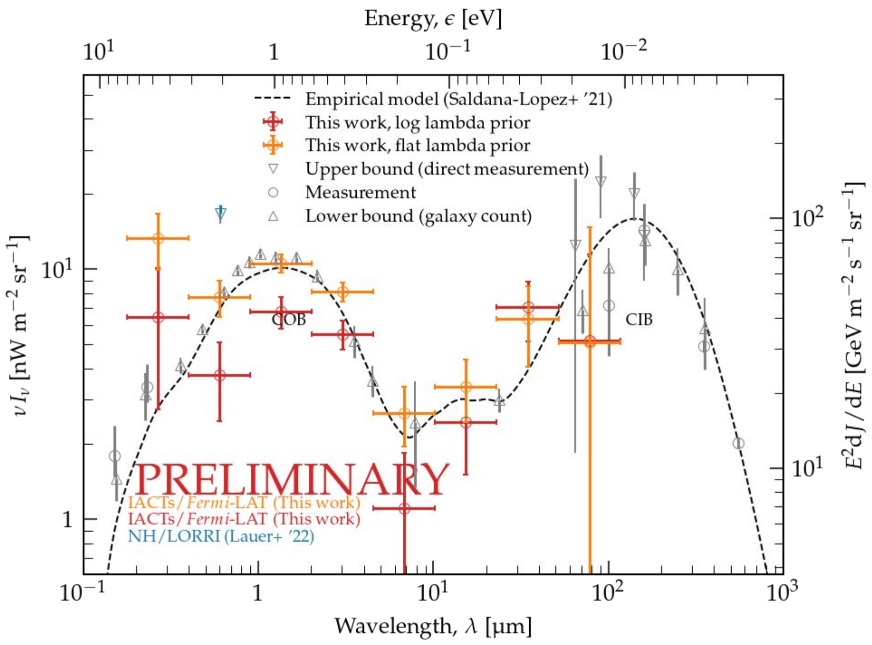


Reconstruction for low and high redshift, varying prior

Framework: Bayesian with ε, z < 0.04

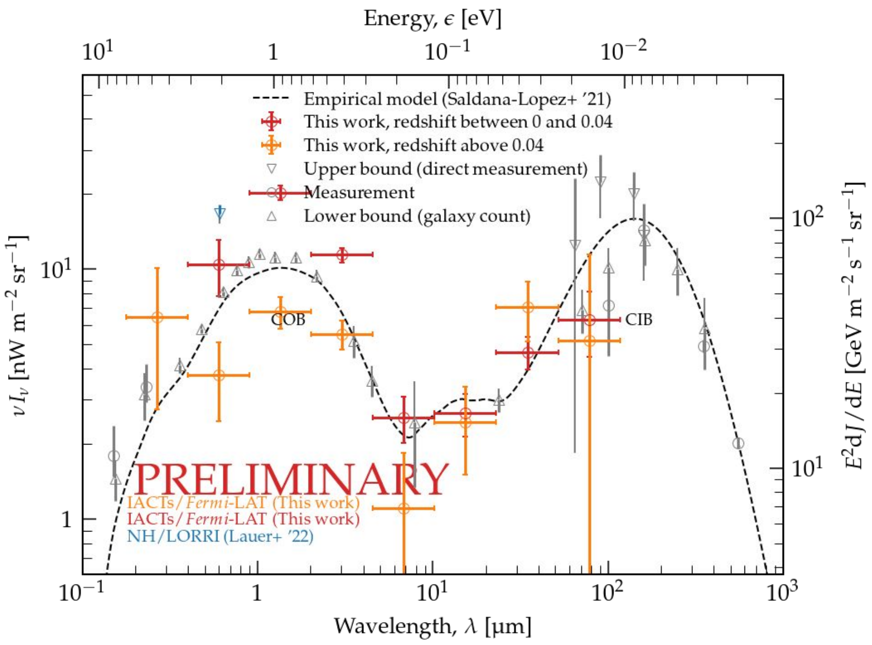


Framework: Bayesian with ε, z > 0.04



Reconstruction for low and high redshift, varying prior

Framework: Bayesian, log lambda prior



Framework: Bayesian, flat lambda prior