# The Extragalactic Background Light in *Fermi*-LAT Era

(The *Fermi*-LAT collaboration, Science, 2018, 362, 1031)


Vaidehi S. Paliya

Deutsches Elektronen-Synchrotron DESY

Along with: M. Ajello, K. Helagason, J. Finke, A. Dominguez, A. Desai on behalf of the *Fermi*-LAT collaboration

(vaidehi.s.paliya@gmail.com)

# Extragalactic Background Light (EBL)


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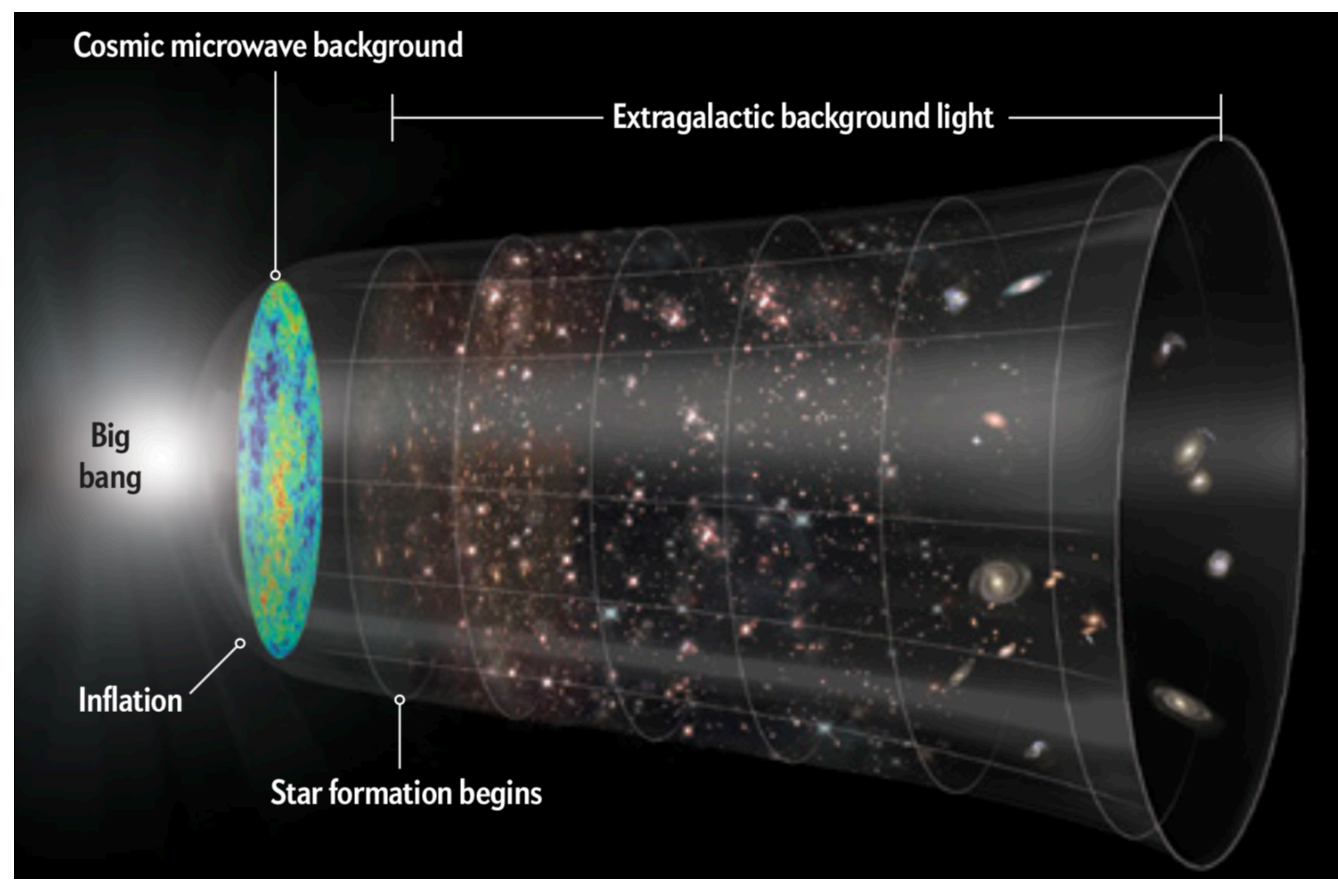

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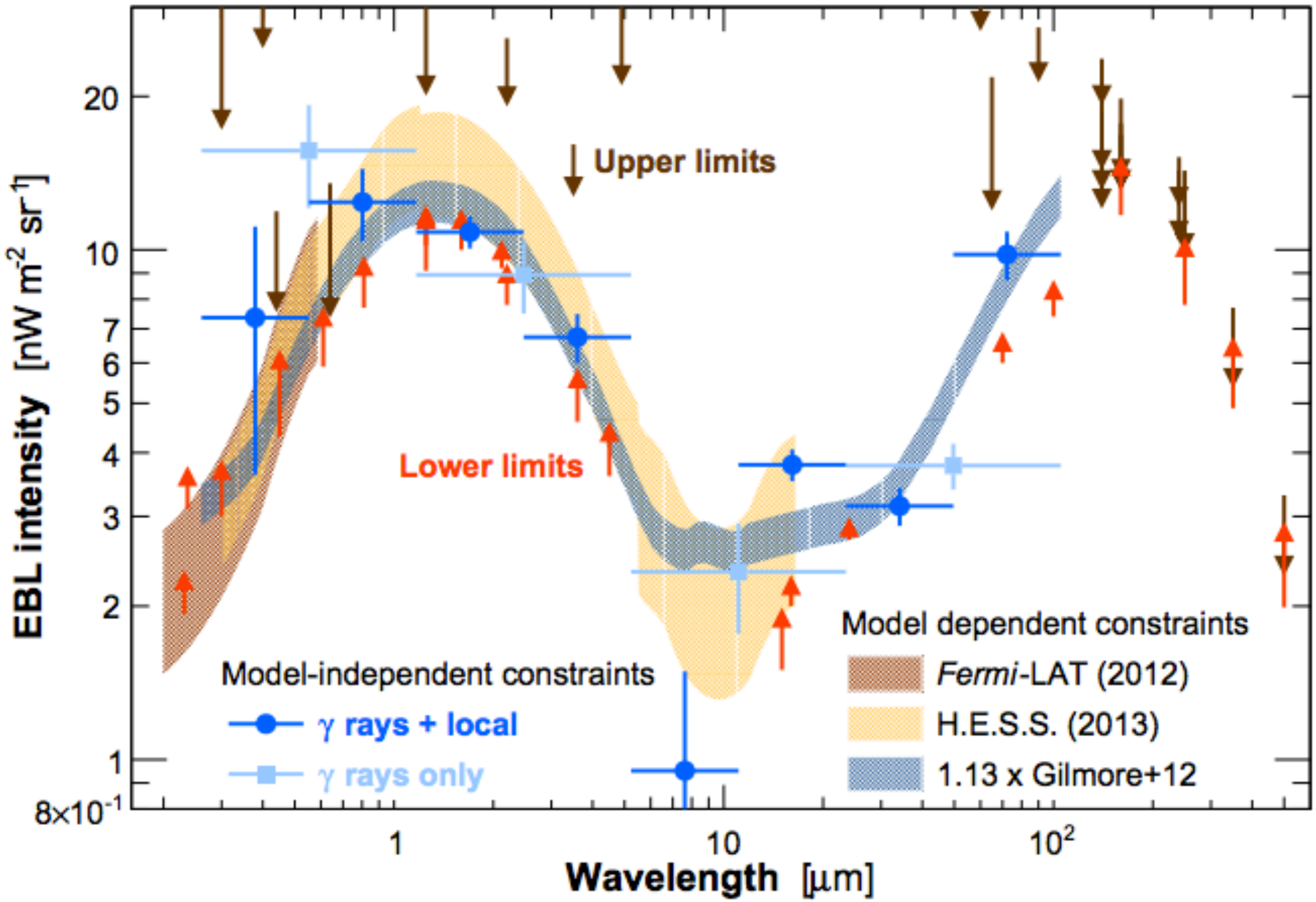
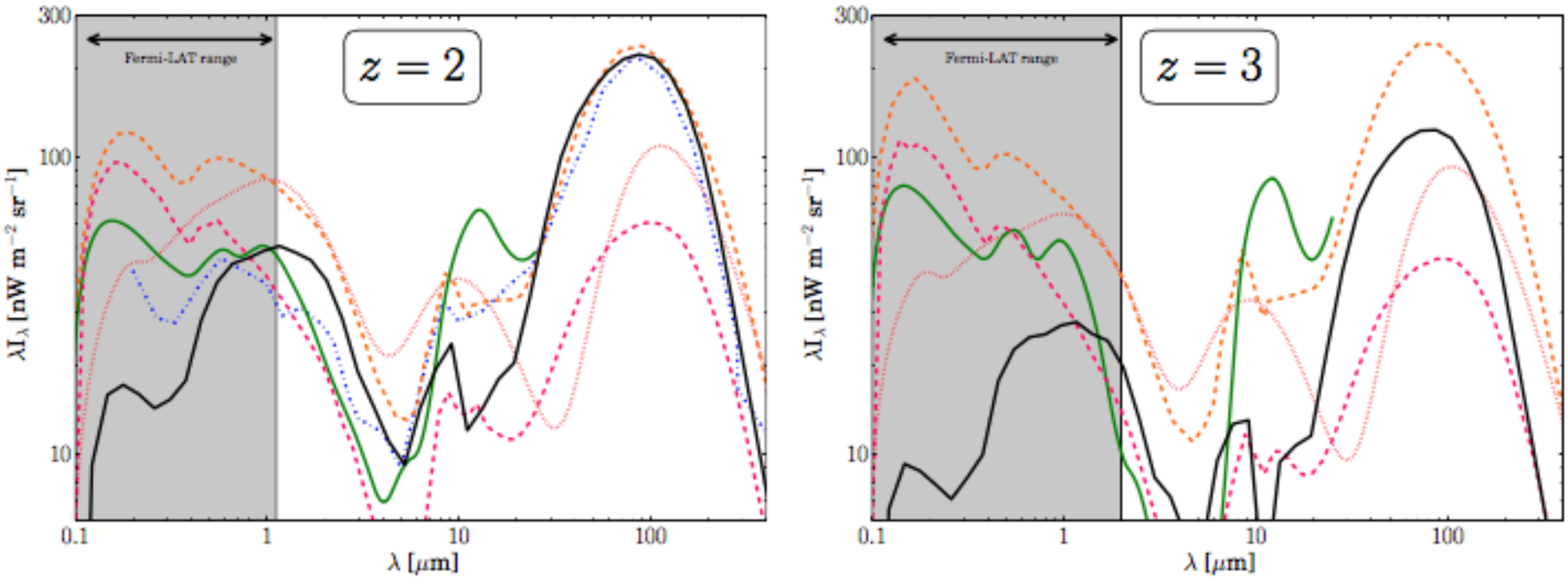



(Biteau & Williams, 2015)

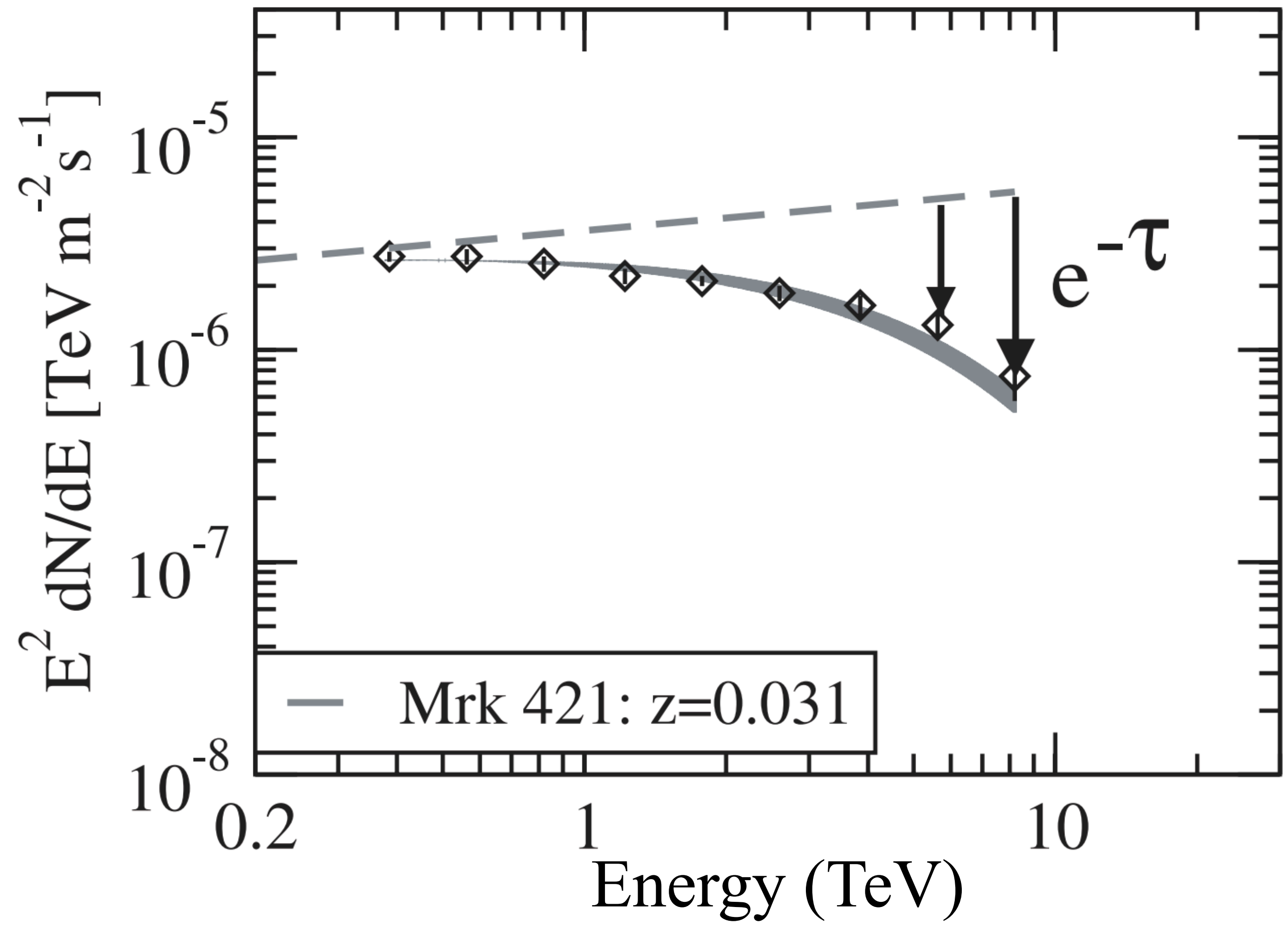
# Extragalactic Background Light (EBL)




- Buildup of the EBL largely undetermined
- Buildup fundamental to determine galaxy/stellar evolution processes

# Concept of the Measurement


Schroedter, 2005, ApJ, 628, 617

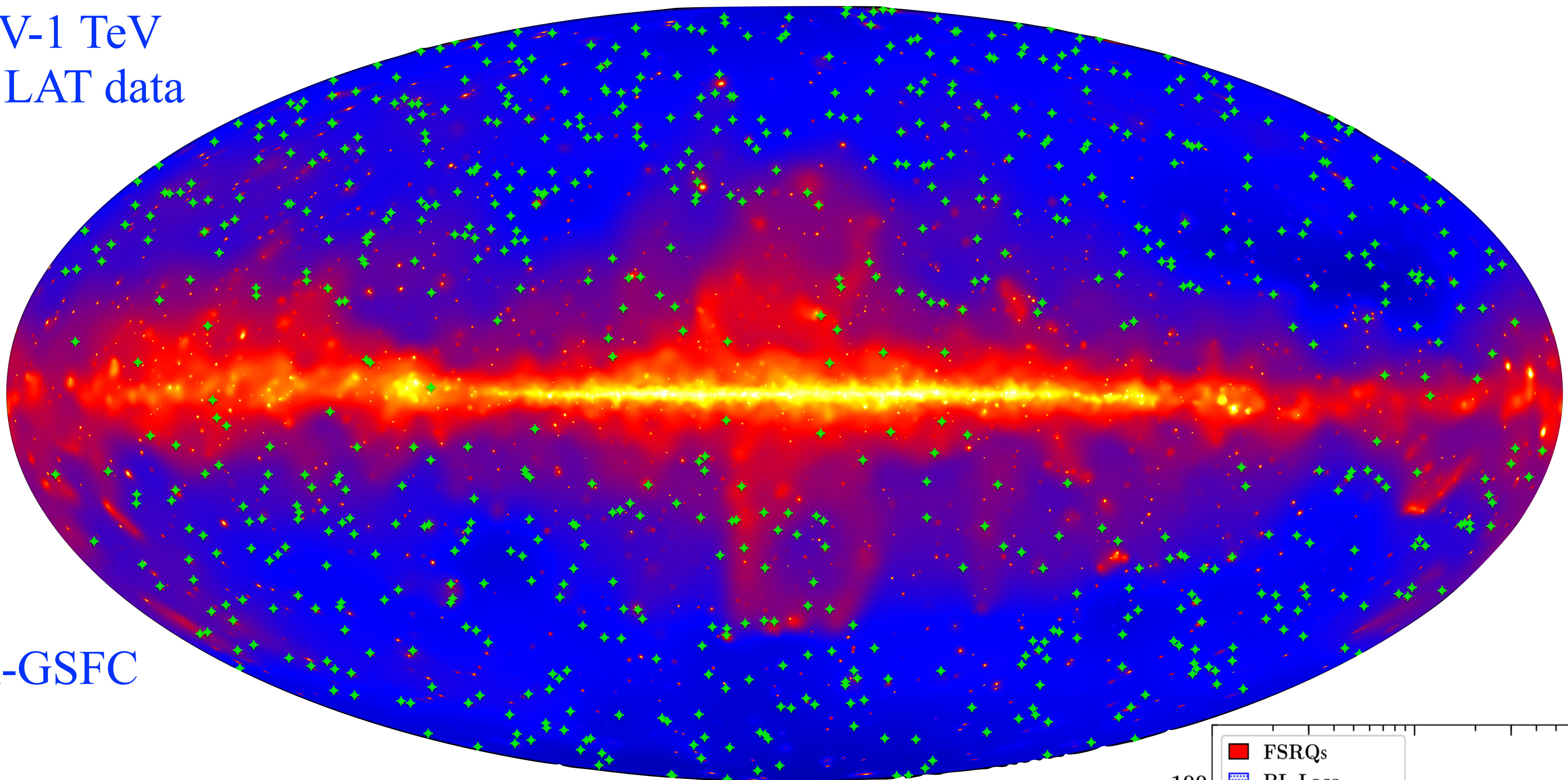



- Blazars = Lighthouse in the Universe
- EBL = cosmic fog that absorbs a fraction of the light originated from blazars

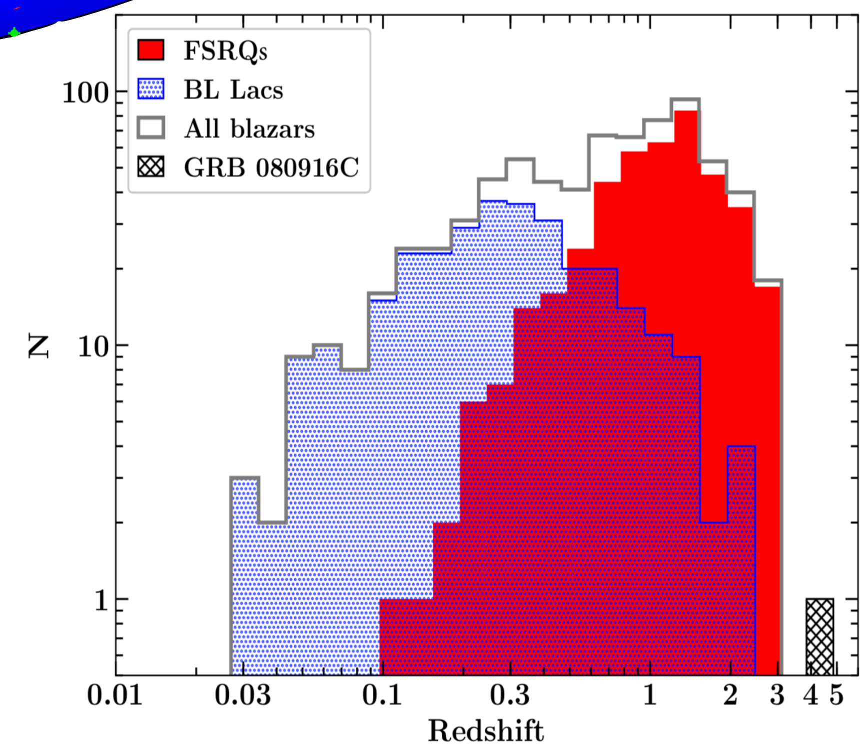
# This Project

- *Fermi* has completed a decade of sky-surveying operation
- More data → more photons → tighter constraints on EBL
- *Fermi*-LAT energy range provides a unique handling on the ‘intrinsic’ as well as absorbed γ-ray spectra
- *Fermi*-LAT has detected hundreds of blazars, including a few with z>3, which are crucial to study the EBL evolution
- In parallel, there were optical spectroscopic campaigns to determine the redshifts of BL Lac objects (http://archive.oapd.inaf.it/zbllac/ or so-called ZBLLAC program)
- This motivated us to study the EBL using *Fermi*-LAT

# The Sample

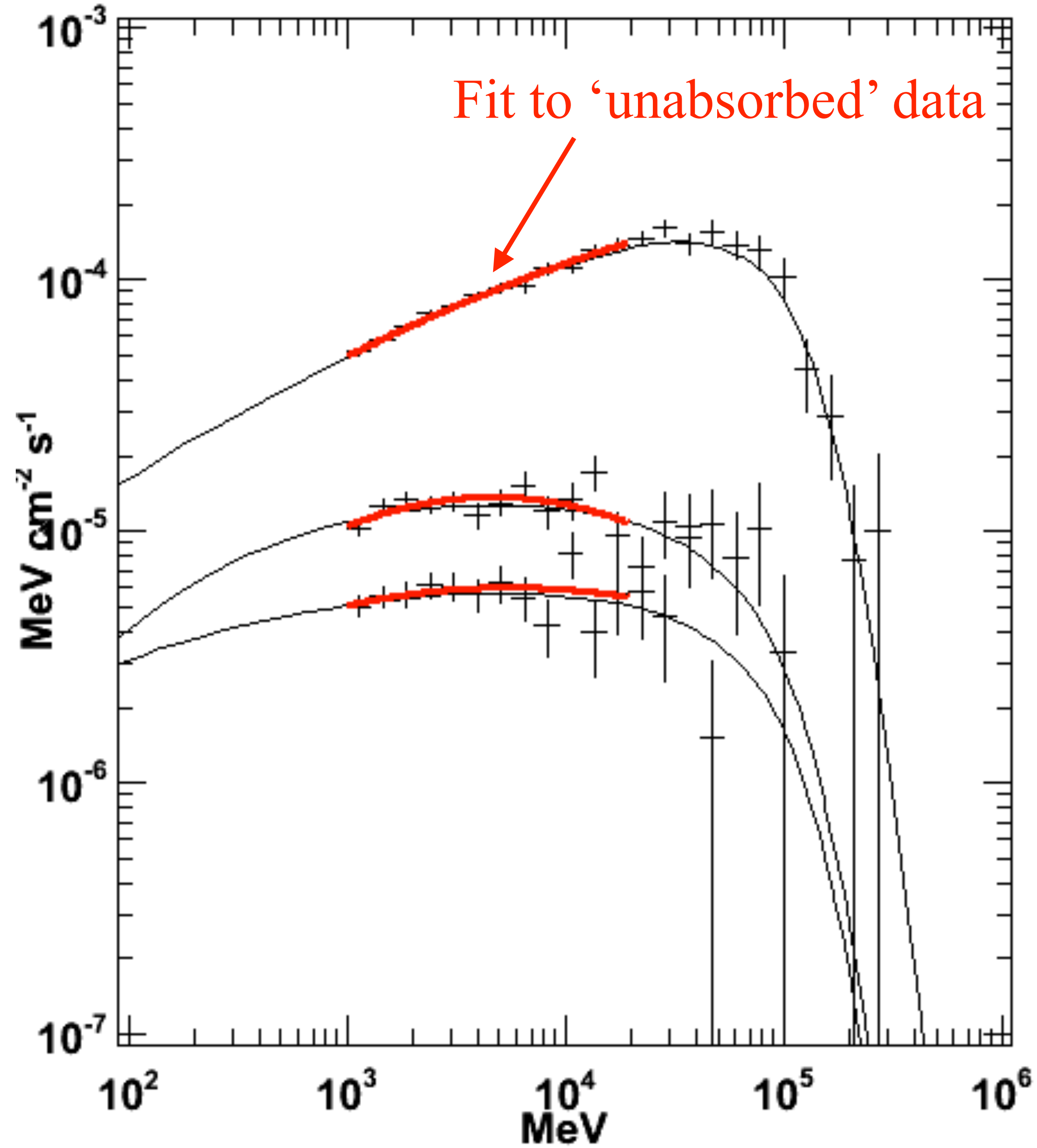



- 739 blazars (320 BL LACs + **419 FSRQs**) with confirmed redshifts (z=0.03-3.1)
- GRB 080916C (z=4.35); $E_{max}$ = 27.4 GeV
- Energy range: 1 GeV—1 TeV



# Analysis Steps

- Measure the ‘unabsorbed’ γ-ray spectra up to energy at which $\tau_{\gamma\gamma} \leq 0.1$ (i.e., negligible EBL absorption): ‘intrinsic’ spectrum



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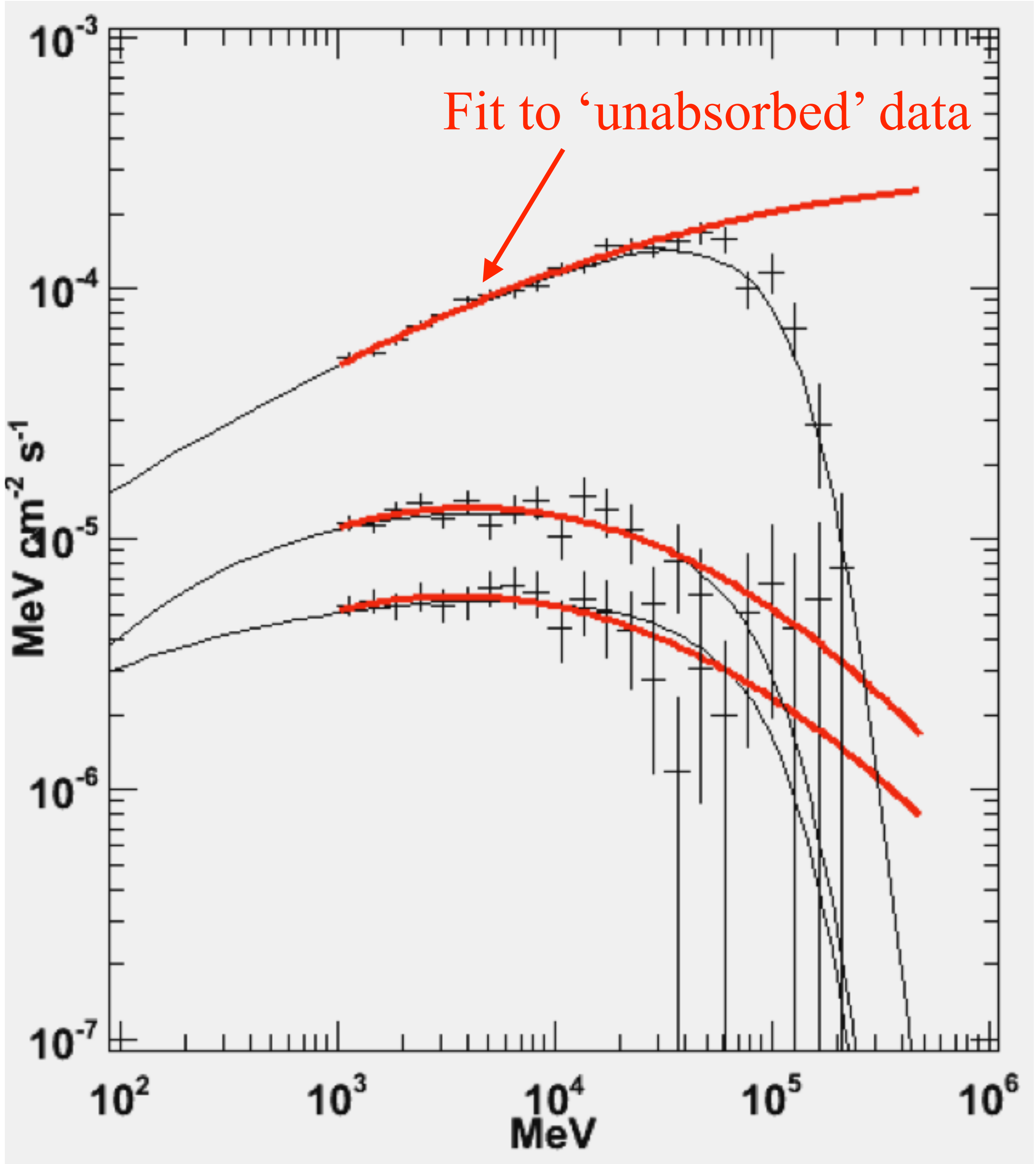
- Extrapolate the model to higher energies

- Plug an attenuation model and iteratively fit for the normalization parameter 'b'

  - b = 0: there is no EBL

  - b = 1: EBL absorption as predicted




$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b\cdot\tau_{model}}$$

# Analysis Steps

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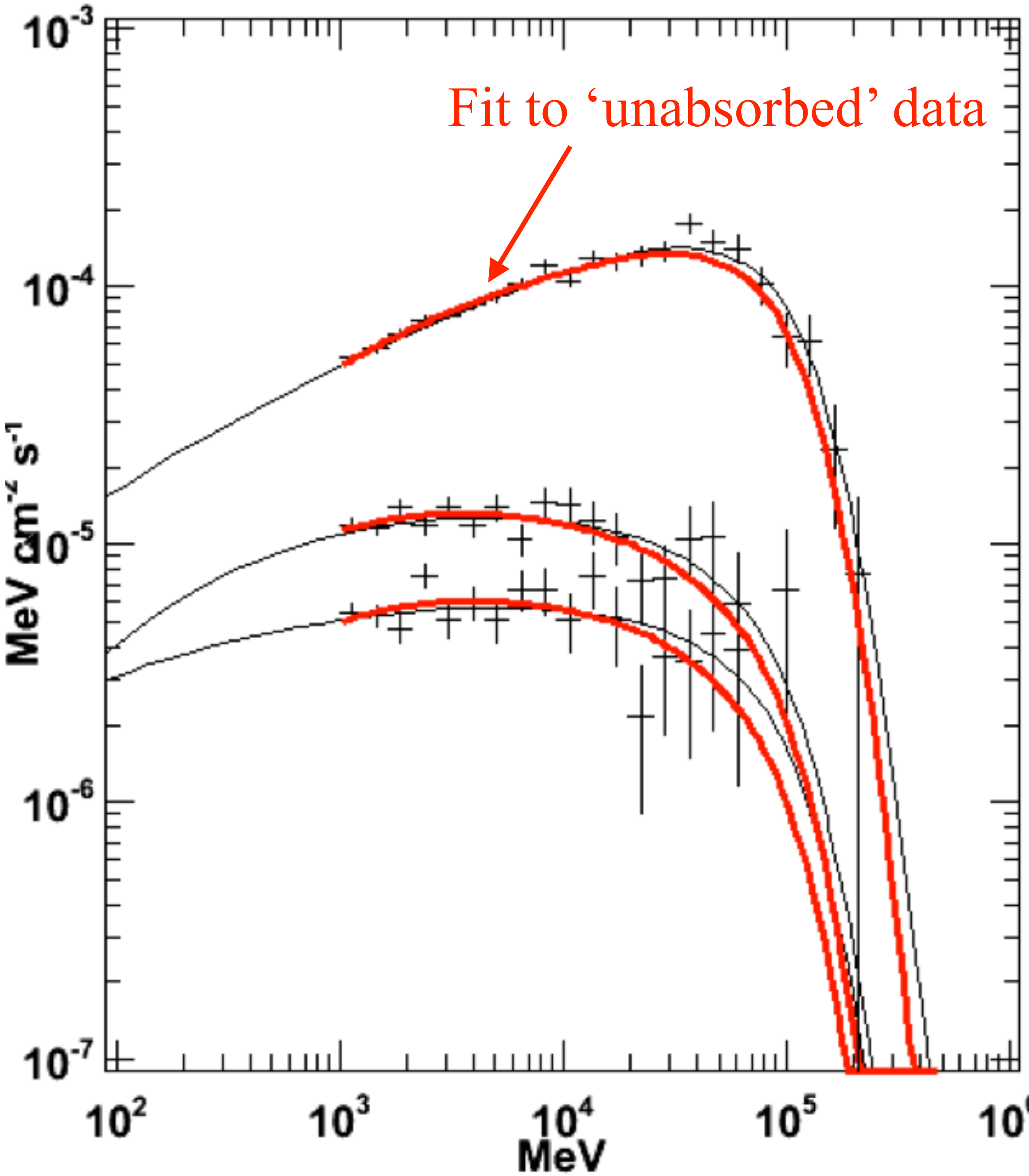
- Extrapolate the model to higher energies
- Plug an attenuation model and iteratively fit for the normalization parameter 'b'
  - b = 0: there is no EBL
  - b = 1: EBL absorption as predicted
  - b ≠ 1: EBL absorption is there but not as predicted




$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b\tau_{model}}$$

# Significance of the EBL Attenuation

- We compute the log-likelihood at every iteration of ‘b’ and determine the best-fitted ‘$b_0$’ and corresponding $TS_{EBL}$, for each blazar

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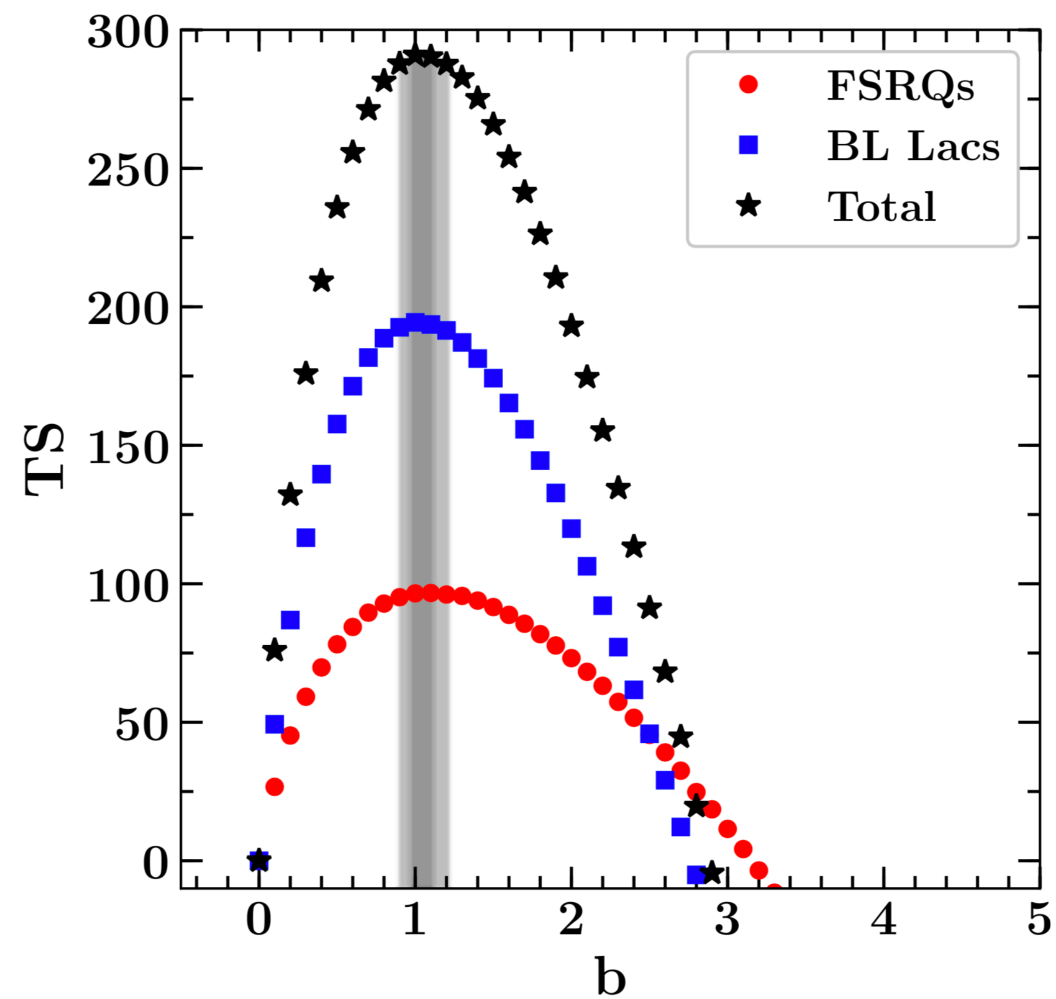
- Since log-likelihoods are additive, we **stack** them for all sources and derive the b value that maximized the global likelihood and gives the largest $TS_{EBL}$

- We get, $TS_{EBL}$ ~300 (~17σ). The previous best measurement had $TS_{EBL}$ = 36 (~6σ)

- BL Lacs, though lesser in number, contribute more due to their harder γ-ray spectra

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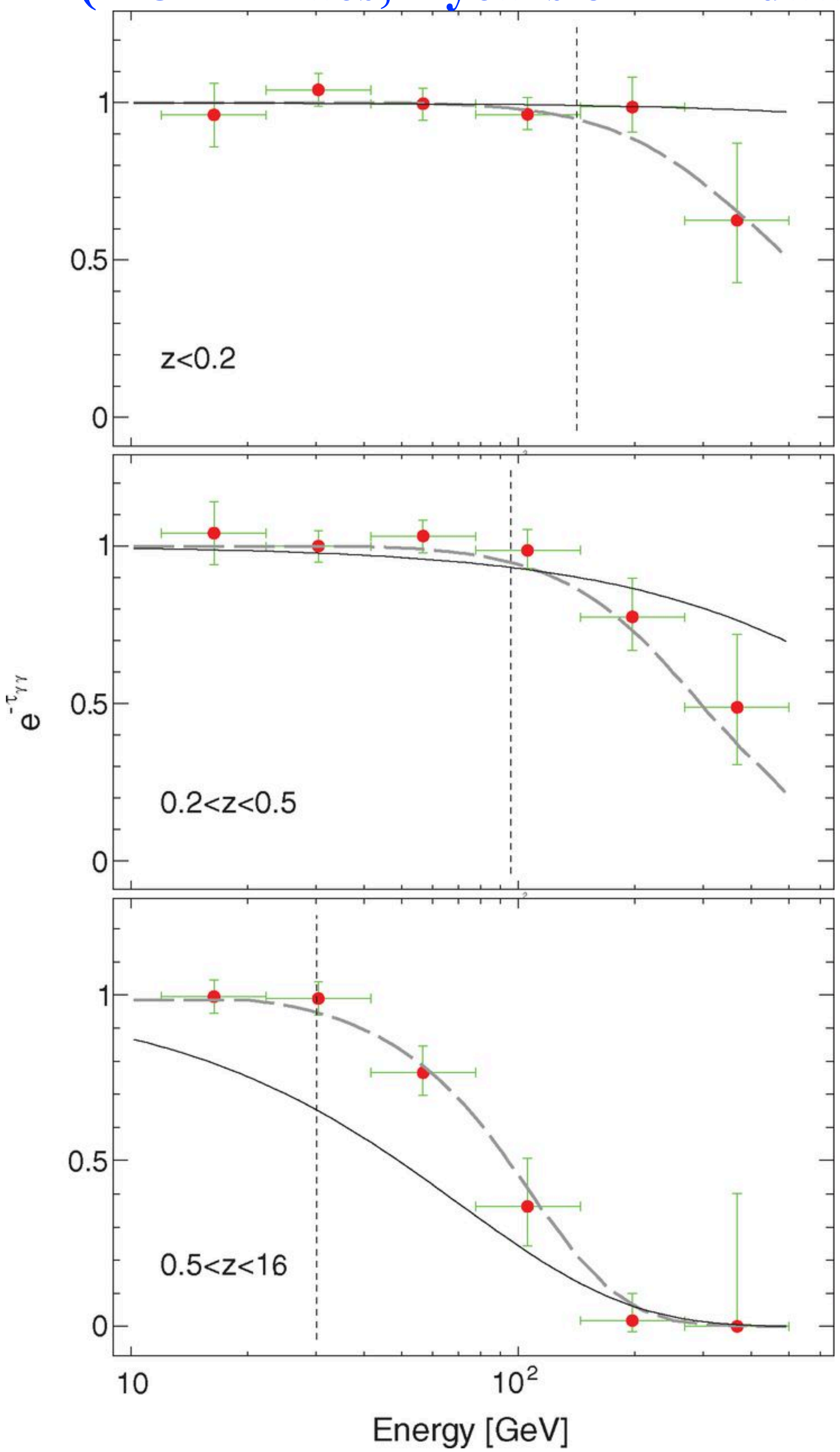
- **Uncertainty on the level of EBL ~7%**

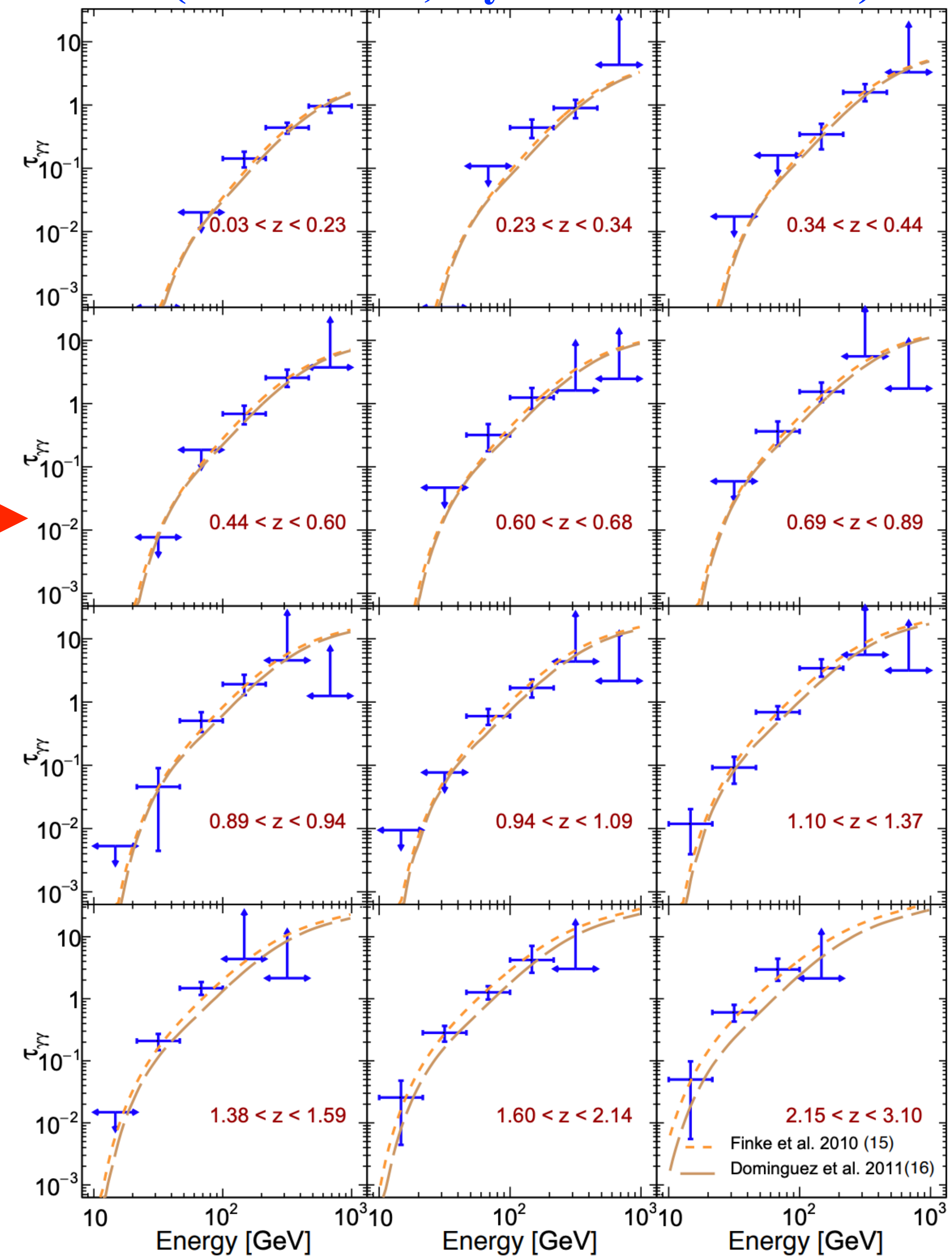
- **In 2012:**
  **the uncertainty was 25%**

# From ‘Detection’ to ‘Characterization’

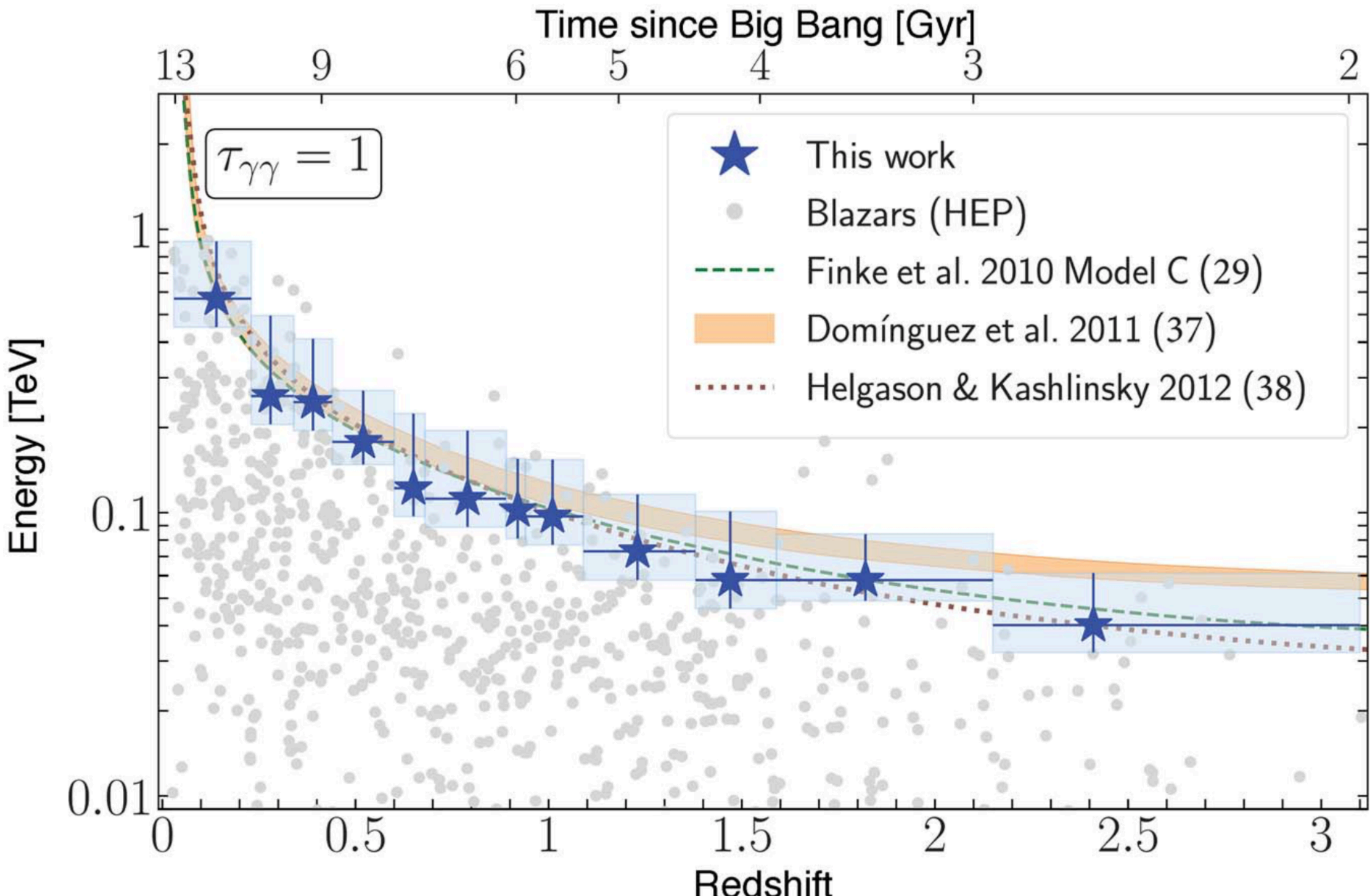
***Fermi*-LAT coll., 2012**
**(125 BL Lacs, 4 years of LAT data)**




***Fermi*-LAT coll., 2018**
**(739 blazars, 9 years of LAT data)**



# The Cosmic Gamma-Ray Horizon

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# EBL evolution

$$\tau_{\gamma\gamma}(E_\gamma, z_s) = c \int_0^{z_s} \left|\frac{dt}{dz}\right| dz \int_{-1}^{1} (1-\mu)\frac{d\mu}{2} \int_{2m_e^2c^4/\epsilon_\gamma(1-\mu)}^{\infty} \sigma(\epsilon_{\mathrm{EBL}}, \epsilon_\gamma, \mu) n_{\mathrm{EBL}}(\epsilon, z) d\epsilon_{\mathrm{EBL}}$$

**distance**

$$n_{\mathrm{EBL}}(\epsilon, z) = (1+z)^3 \int_z^{\infty} \frac{j(\epsilon, z)}{\epsilon} \left|\frac{dt}{dz'}\right| dz'$$

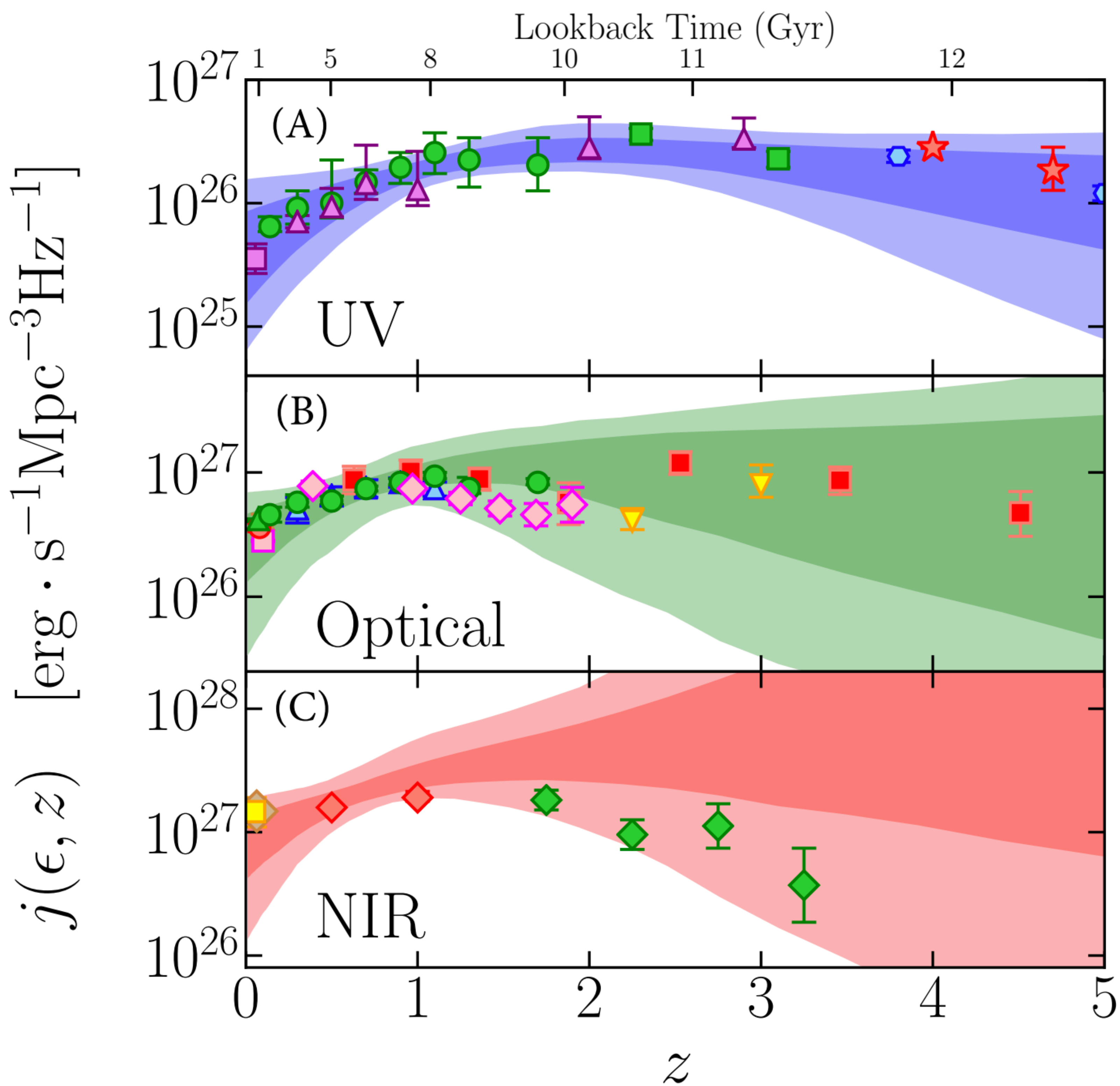
**cross-section**

**EBL photon Density Evolution**

- We can't invert 3-4 integrals, so we need to find another way
- Two methods, both fitted via MCMC to LAT τ data
- Method 1: model j(e,z) has sum of log-normal distributions that can evolve independently
- Method 2: use stellar population models (Finke et al. 2010) and optimize the parameters of the Cosmic Star Formation History

$$j(\lambda_i, z) = \sum_i a_i \cdot \exp\left[-\frac{(\log\lambda - \log\lambda_i)^2}{2\sigma^2}\right] \times \frac{(1+z)^{b_i}}{1+\left(\frac{1+z}{c_i}\right)^{d_i}}$$

# Cosmic Luminosity Density

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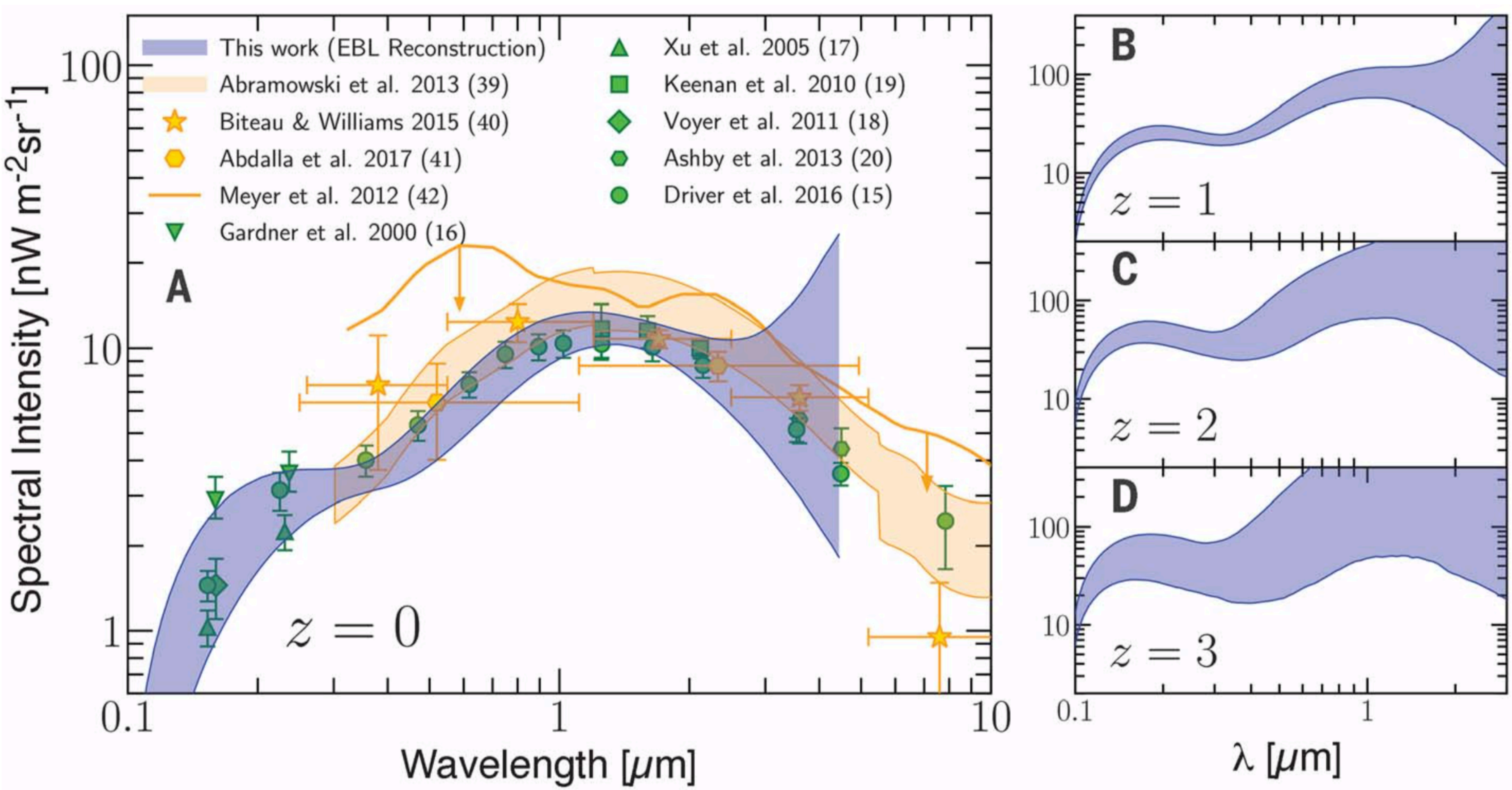
# EBL evolution

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# Cosmic Star-formation History

Stellar emissivity (luminosity density):

$$\epsilon\, j_\epsilon^{stars}(z) = m_e c^2 \epsilon^2 \frac{dN}{dt\, d\epsilon\, dV} = \epsilon^2 \underbrace{f_{esc}(\epsilon)}_{\text{Dust absorption}} \int_{m_{min}}^{m_{max}} dm\, \underbrace{\xi(m)}_{\text{IMF}}\, \underbrace{\dot{N}_*(\epsilon; m, t_*(z))}_{\text{Stellar photons}}$$

$$\times \int_z^{z_{max}} dz_1 \underbrace{\left|\frac{dt_*}{dz_1}\right|}_{\text{Expansion of universe}} \underbrace{\psi(z_1)}_{\text{SFR}} .$$

Stellar parameters from Eggleton et al. (1989), ApJ, 347, 998
Dust absorption: Driver et al. (2008), ApJ, 678, L101

Dust emission computed self-consistently:

$$f_n \int d\epsilon\, \frac{1}{f_{esc}(\epsilon)} [1 - f_{esc}(\epsilon)]\, j_\epsilon^{stars}(z) = \int d\epsilon\, j_{\epsilon,n}(\Theta_n)$$

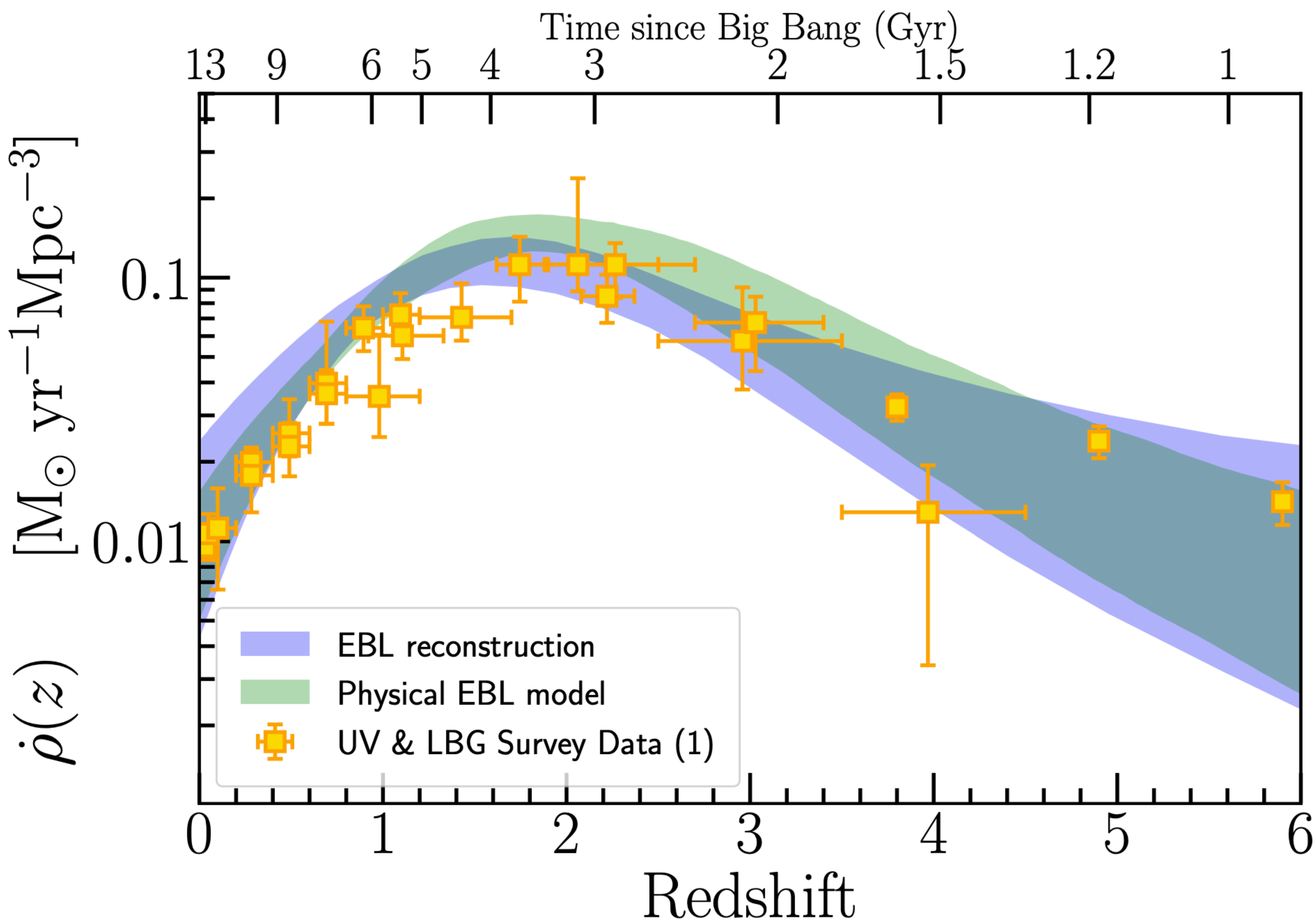
Three component dust model:

| Component | $n$ | $f_n$ | $T_n$ [K] | $\Theta_n$ [$10^{-9}$] |
|---|---|---|---|---|
| Warm Large Grains | 1 | 0.60 | 40 | 7 |
| Hot Small Grains | 2 | 0.05 | 70 | 12 |
| PAHs | 3 | 0.35 | 450 | 76 |

EBL energy density: $$\epsilon\, u_{EBL}(\epsilon; z) = \int_z^{z_{max}} dz_1\, \frac{\epsilon'' j_{\epsilon''}(z_1)}{(1+z_1)} \left|\frac{dt_*}{dz_1}\right|$$

JF, Razzaque, & Dermer, (2010), ApJ, 712, 238
Razzaque, Dermer, & JF, (2009), ApJ, 697, 483

# Cosmic Star-formation History

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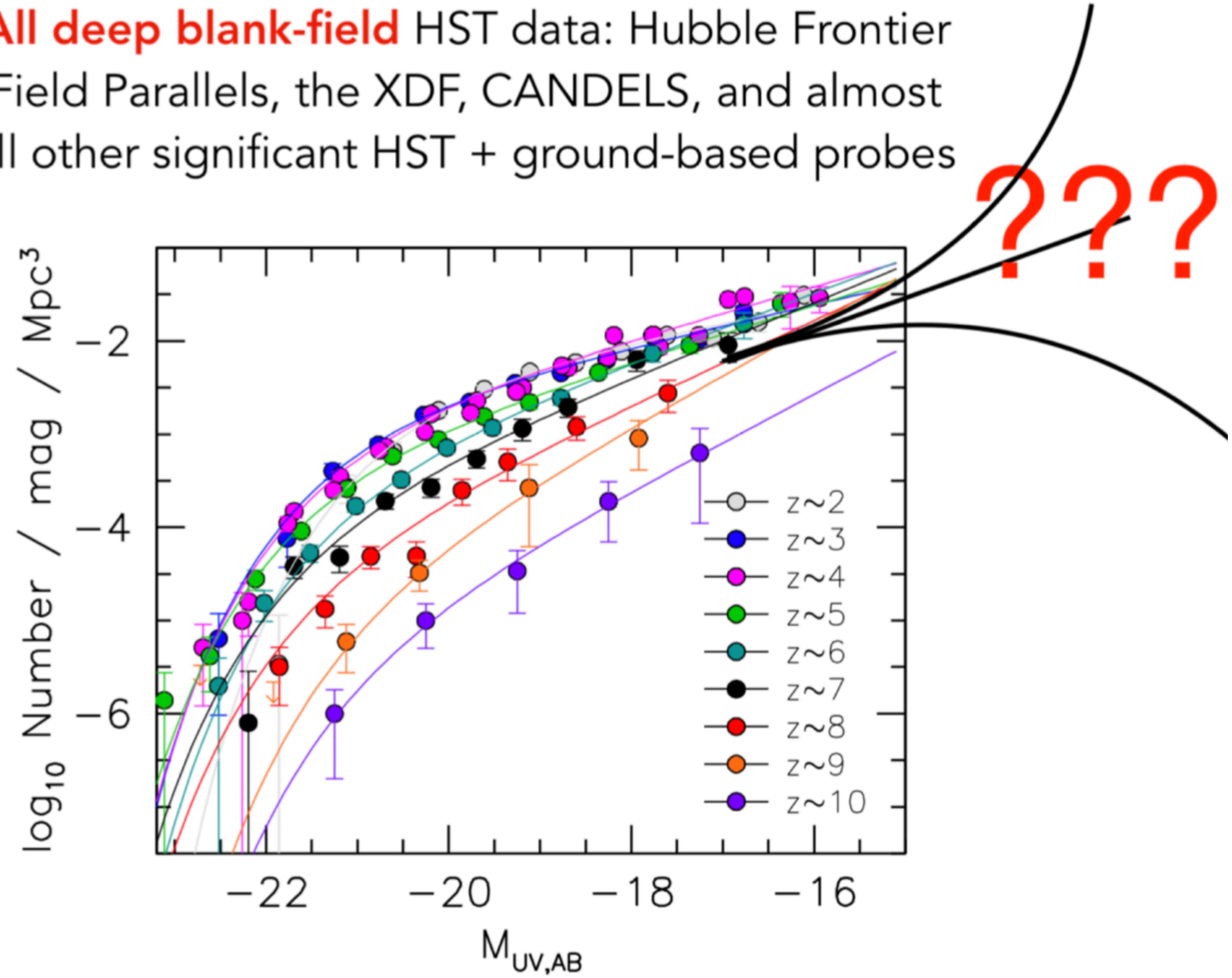
# Re-ionization

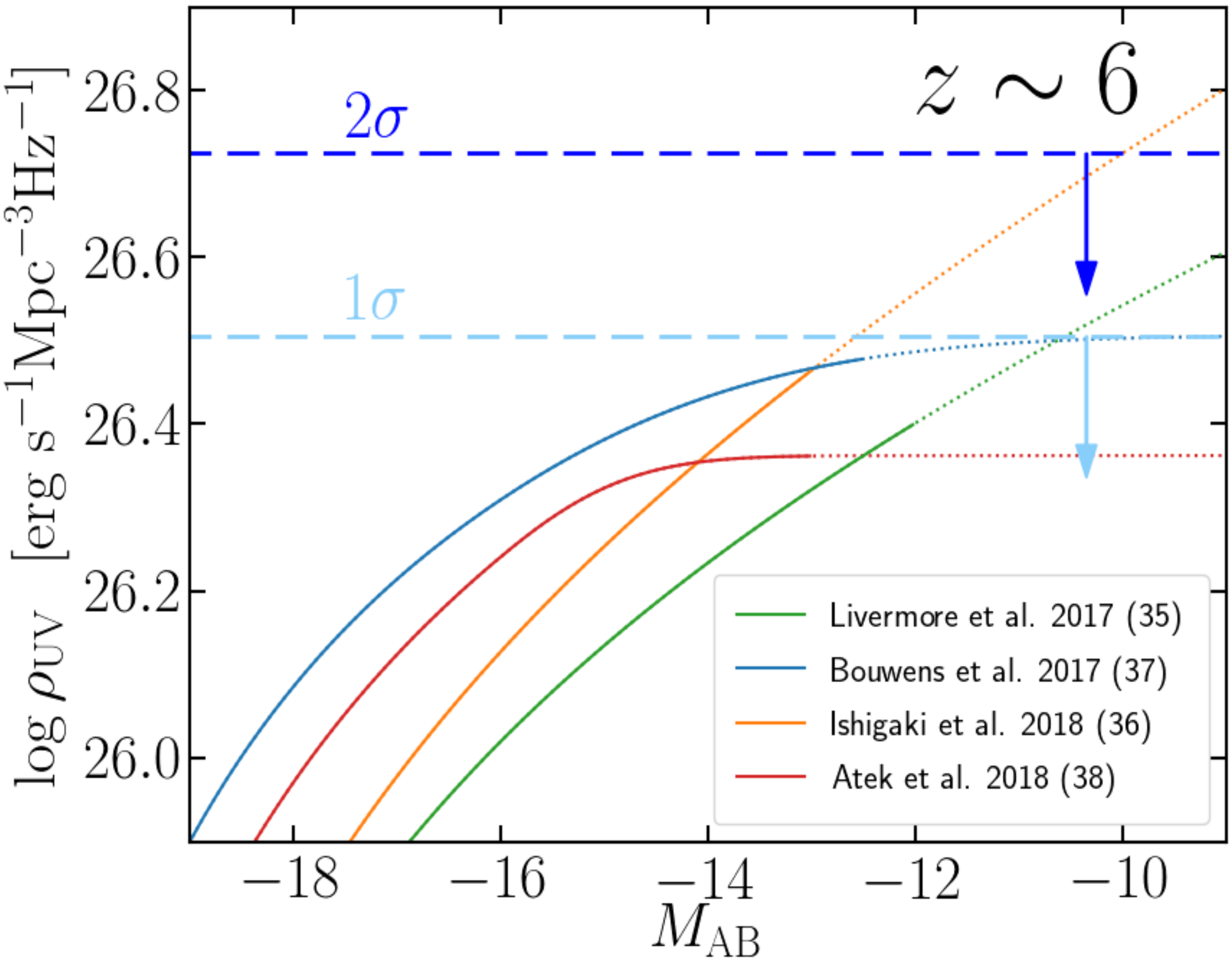
*Hubble* Frontier Fields

**All deep blank-field** HST data: Hubble Frontier Field Parallels, the XDF, CANDELS, and almost all other significant HST + ground-based probes




Bouwens+2018 (in prep); Oesch+2017

# Re-ionization

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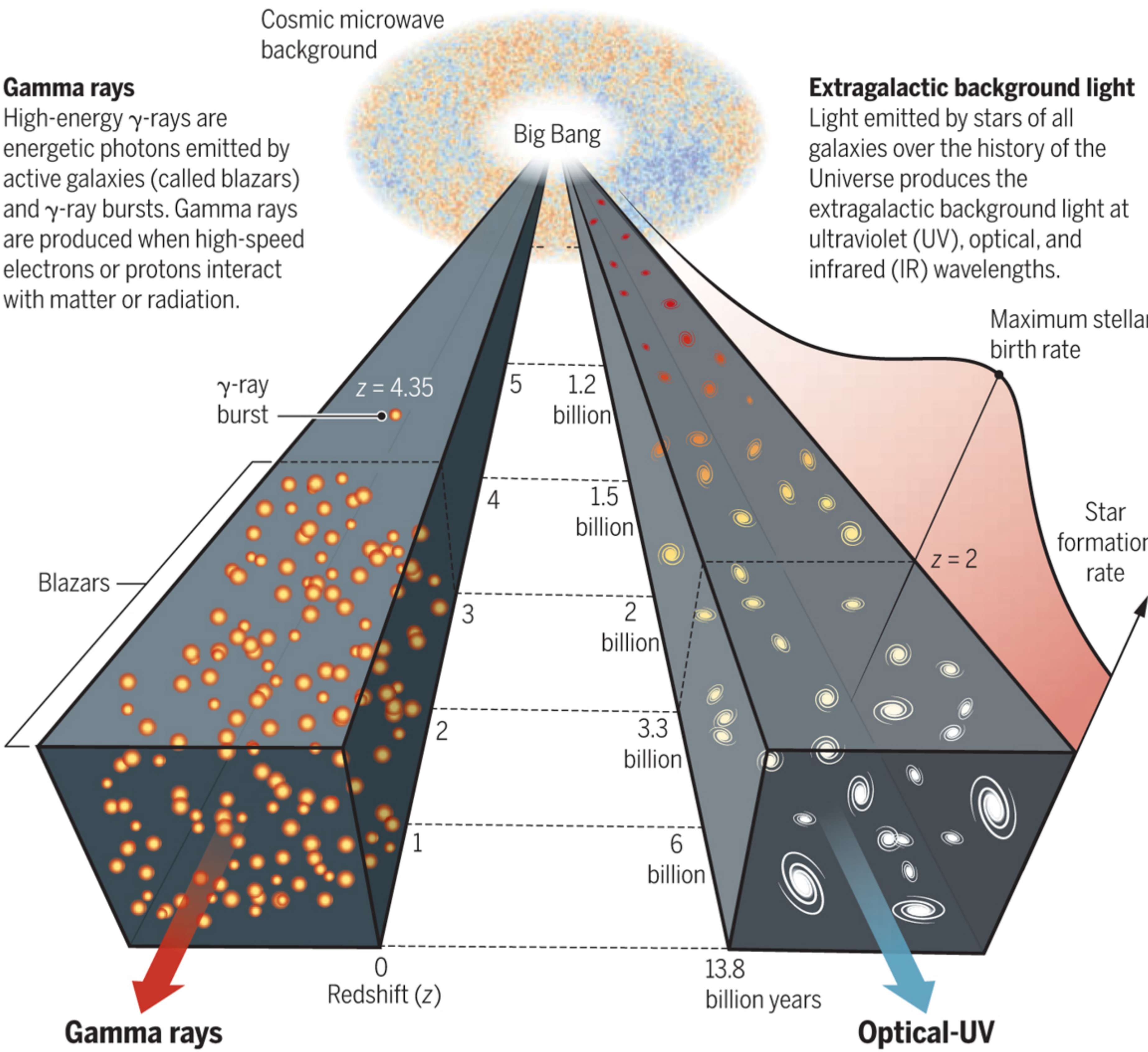
# Star formation history

The rate of star formation can be determined by measuring the light from galaxies. The rate can also be determined by measuring the distortion of the high-energy γ-ray flux when interacting with this light. Peak star formation is estimated to have occurred approximately 10 billion years ago.




©: Science

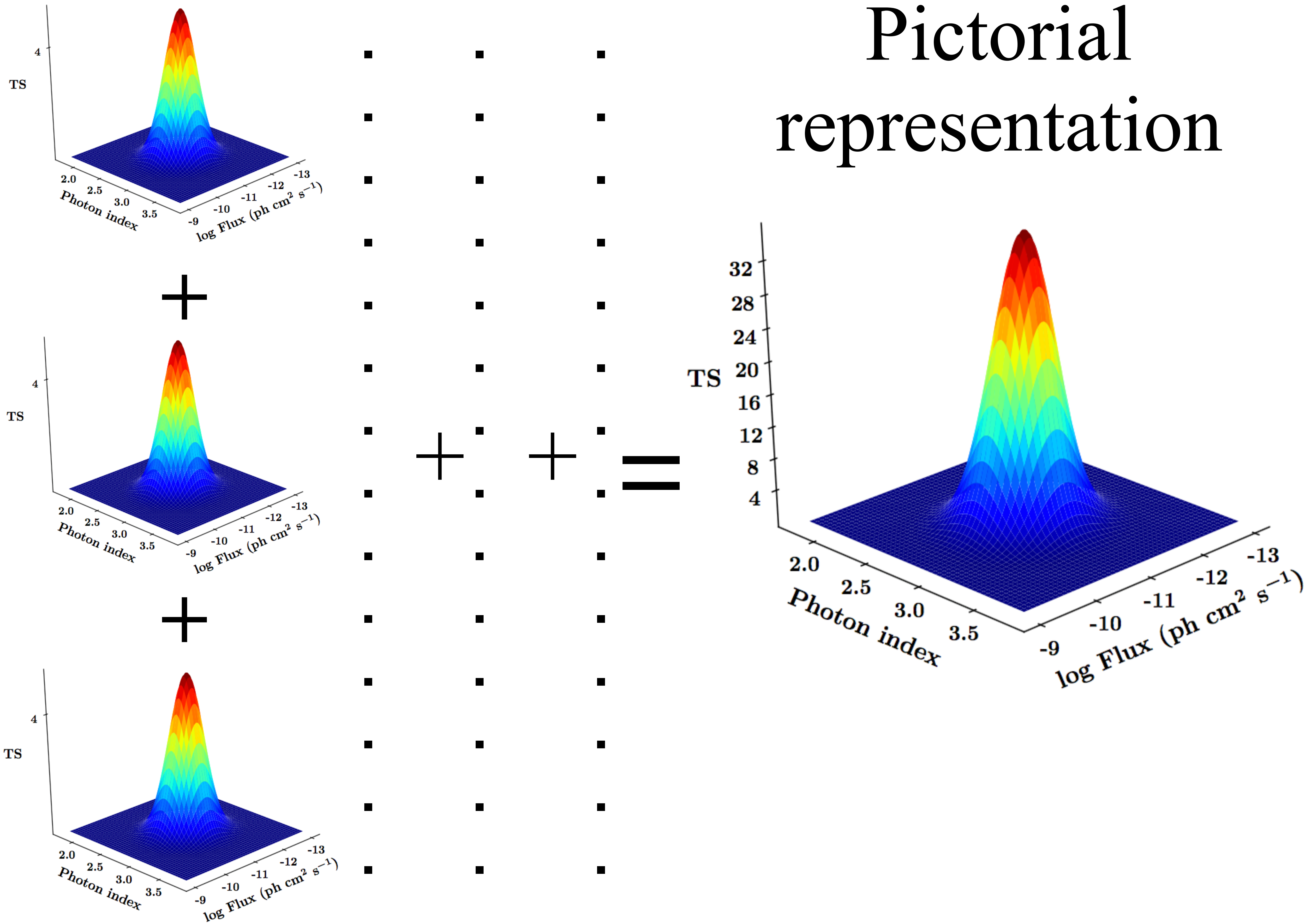
# Extending the Stacking Pipeline

- Extend $TS_{EBL}$ vs. b stacking to $TS_{detection}$ vs. Flux & Index stacking

- Perform an average analysis of the *Fermi*-LAT data
- Search for new γ-ray emitters and make the ROI perfect. Ensure the final sample to consist only γ-ray undetected objects

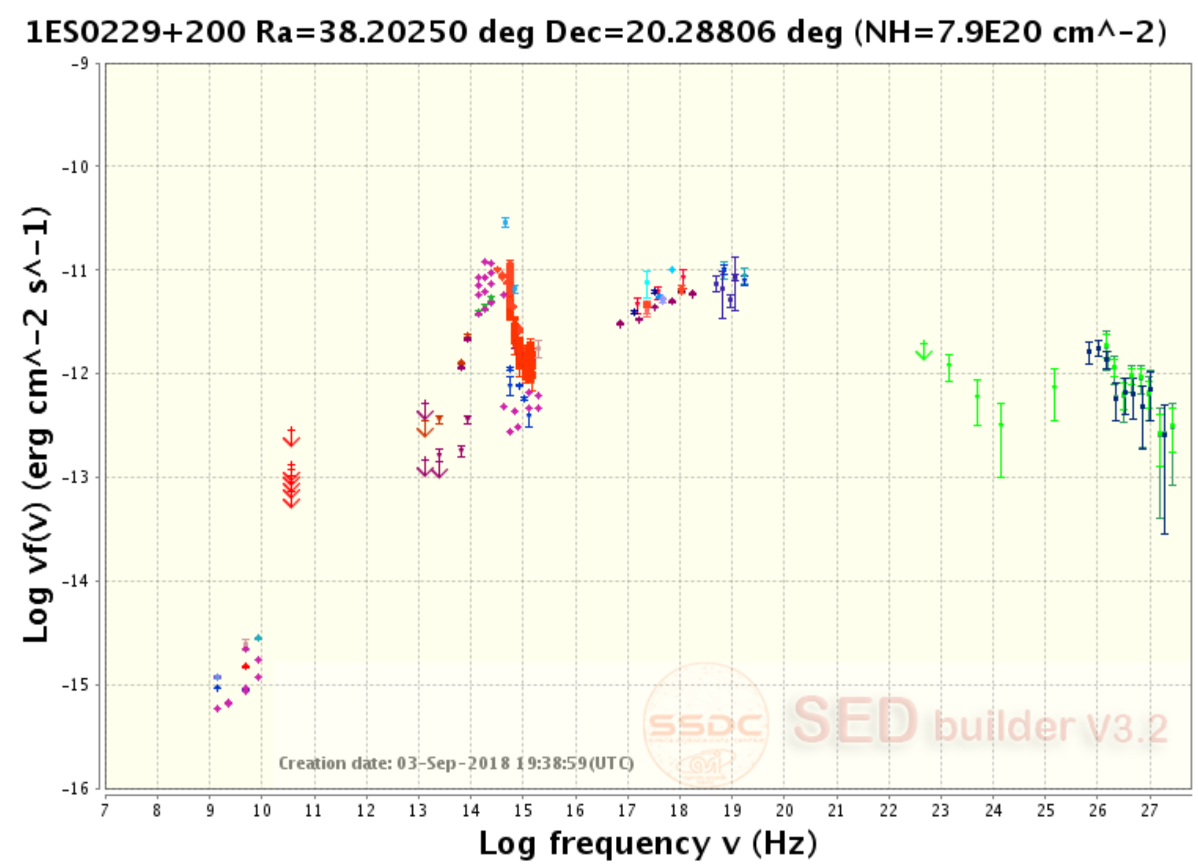
- Make a grid of photon flux (e.g. $10^{-15}$ to $10^{-8}$ ph/cm$^2$/s, in 50 logarithmic steps) and photon index (e.g. 1.5:3.5:0.1)
- The pipeline determines the likelihood value at every grid point. This is repeated for all sources in the sample
- Then, it combines the likelihood profiles of the whole sample and determines the overall peak position, i.e. peak flux, photon index and TS_peak

# Pictorial representation



# Extreme BL Lacs

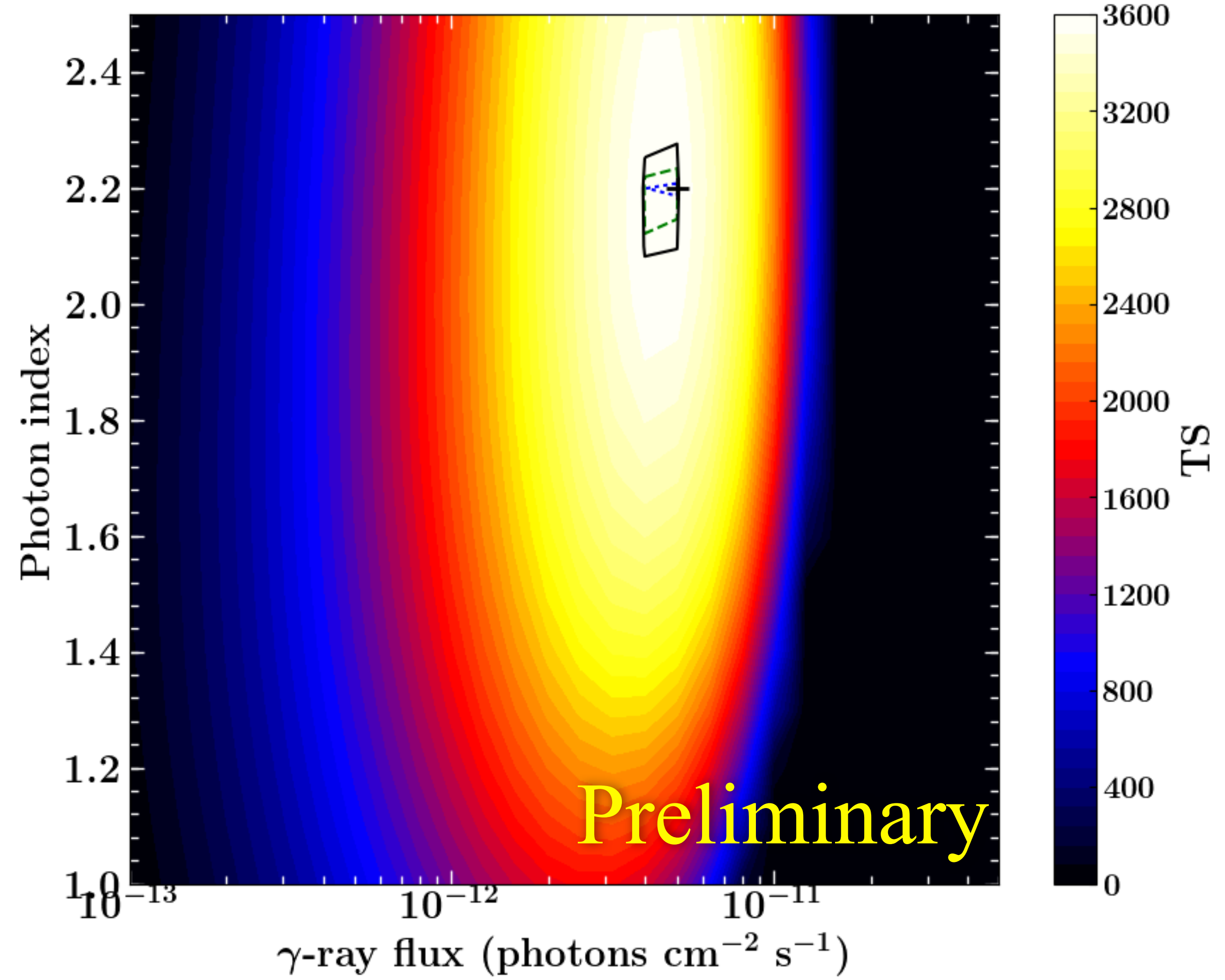
- High synchrotron peak ($\nu_{peak}$>$10^{15}$ Hz) BL Lacs that are yet to be detected with *Fermi*-LAT in large numbers
- Sample is made from 1WHSP + 2WHSP BL Lac catalogs (Arsioli+, 2015, A&A, 579, 34, Chang+ 2017, A&A, 598, 17)
- The energy range is **10-800** GeV
- After pre-processing, removed all γ-ray detected ones
- About ~1000 extreme BL Lacs are then stacked




(Credit: ASDC)

# Extreme BL Lacs: Stacking

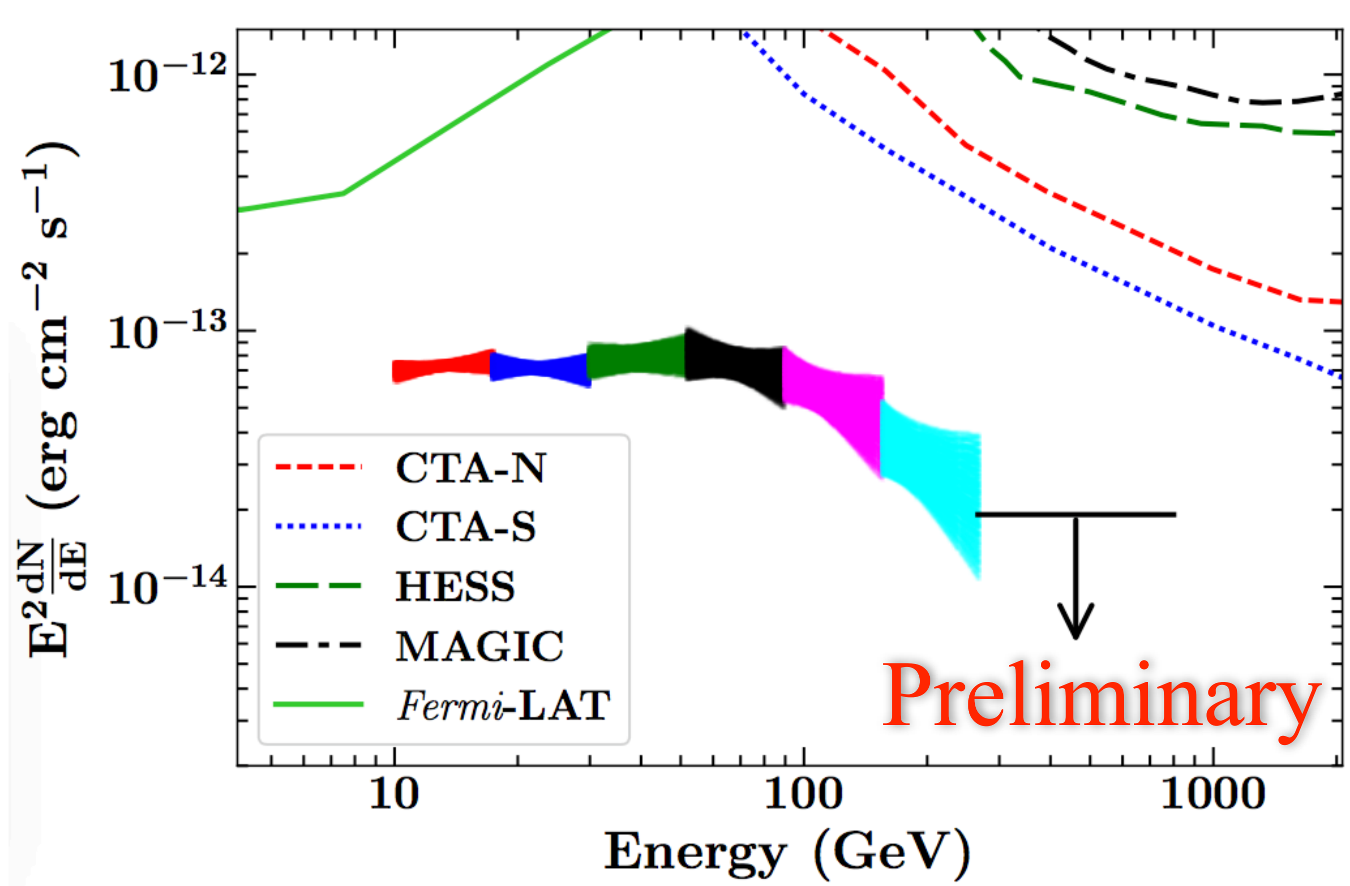
- These LAT undetected blazars are γ-ray emitters
- Note the low flux limit probed by the stacking
- Gamma-ray spectrum is not extremely hard (possible role of the EBL absorption)




- Repeated the analysis in different energy bins (i.e., a stacked spectrum)

# Extreme BL Lacs: Stacked Spectrum

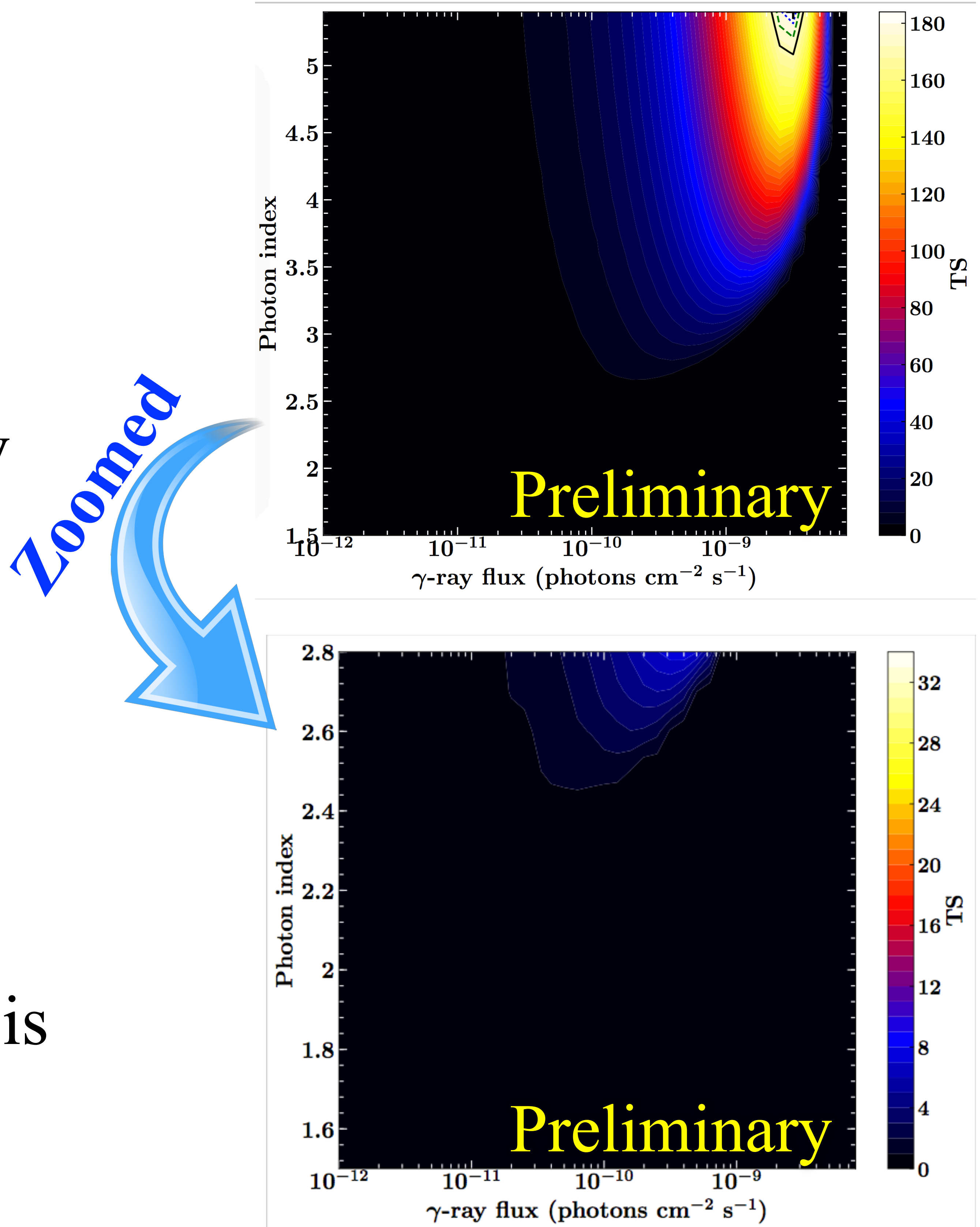
- The stacked γ-ray spectrum lies well below the sensitivity limits of the currently operating HE/ VHE facilities and also CTA
- A turnover around 100 GeV possibly due to EBL &/or peak of the inverse Compton mechanism
- Further investigation ongoing




stacking pipeline is powerful 😎

# Background Stacking

- The idea is to stack the pure background emission
- Randomly selected 1000 sky positions not associated with any known γ-ray source
- Repeated the entire analysis
- There is some excess emission, however, it is very soft (index > 5.4) and hence our source analysis remains unaffected

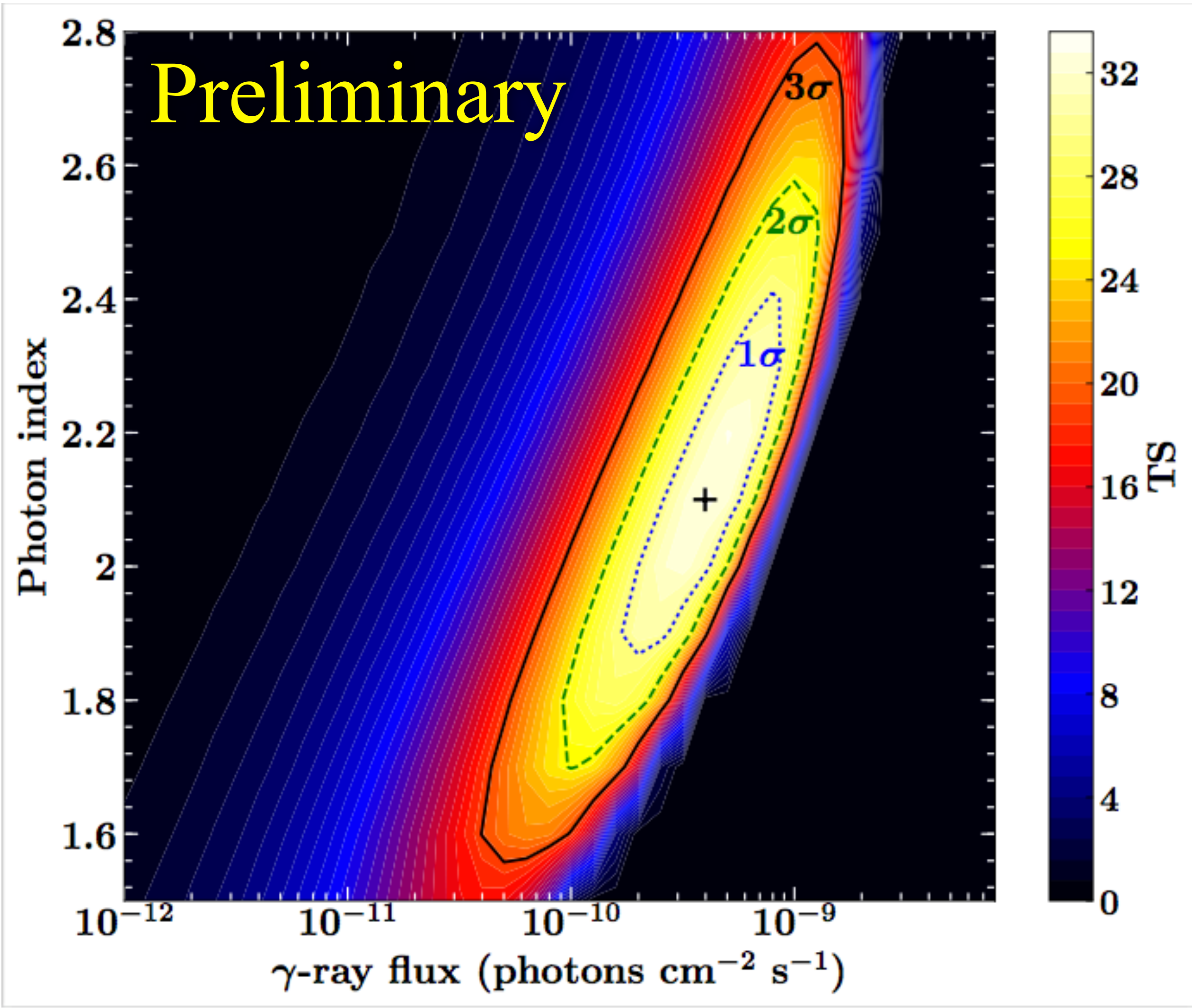


# Simulation

- Input average flux & index (6.4±0.6) e-10 ph/cm²/s & 2.21±0.23 for a sample of 50 sources

- Simulated stacked population gives
  - photon flux: (6.1±1.8) e-10 ph/ cm²/s
  - photon index: 2.08±0.12

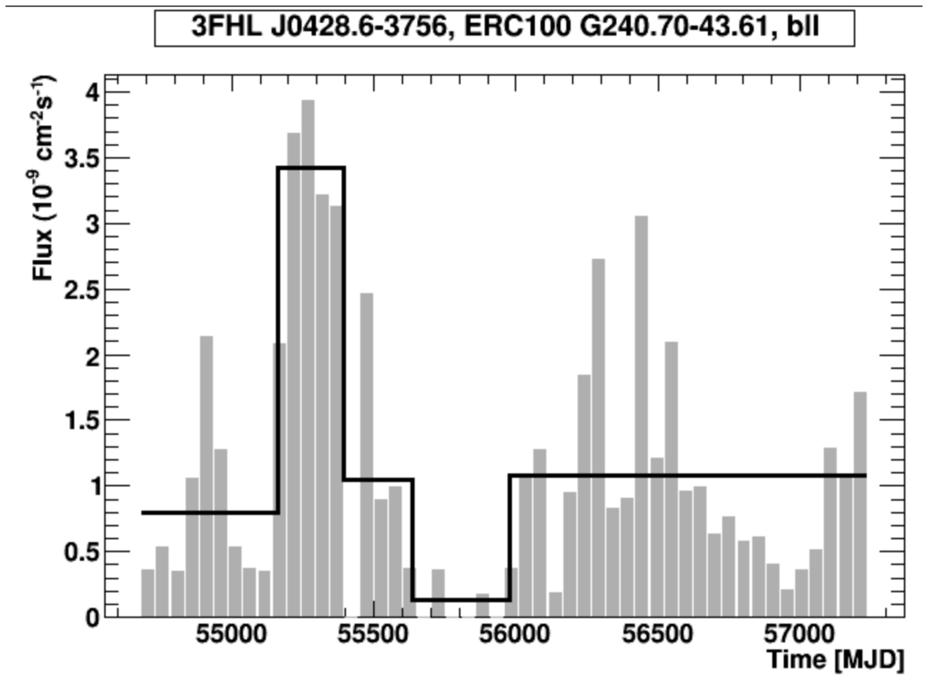
- Confirms the robustness of the developed procedure



# Summary & Outlook

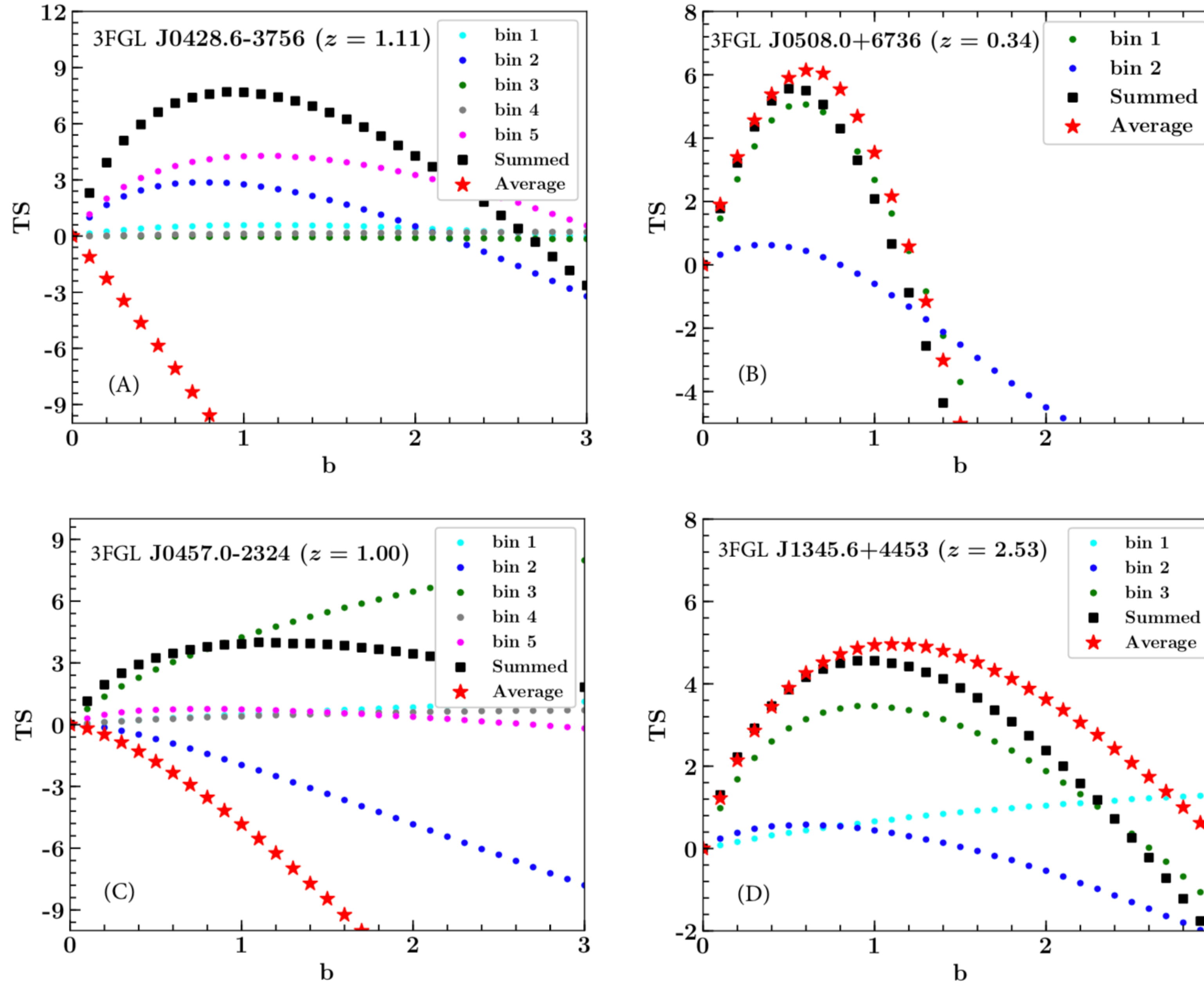
- LAT has produced an unprecedented measurement of the EBL optical depth at 12 different epochs
- It allowed us to
  - measure the EBL well up to z~3
  - measure the UV/optical/NIR luminosity densities
  - measure the Universe's star-formation history
  - Provide the only upper limit to the galaxy luminosity density at the end of the re-ionization era
- We have characterized the average γ-ray spectrum of extreme BL Lacs undetected above 10 GeV
- Final goal: determine contributions of these populations to the extragalactic and isotropic γ-ray backgrounds
- Future: test various other types of source populations: high-redshift blazars, narrow line Seyfert 1 galaxies, High mass X-ray binaries, clusters, etc.

# Variability




- We have considered variable sources using 3FHL catalog Bayesian blocks

- The entire procedure was repeated and suitably incorporated in the final results

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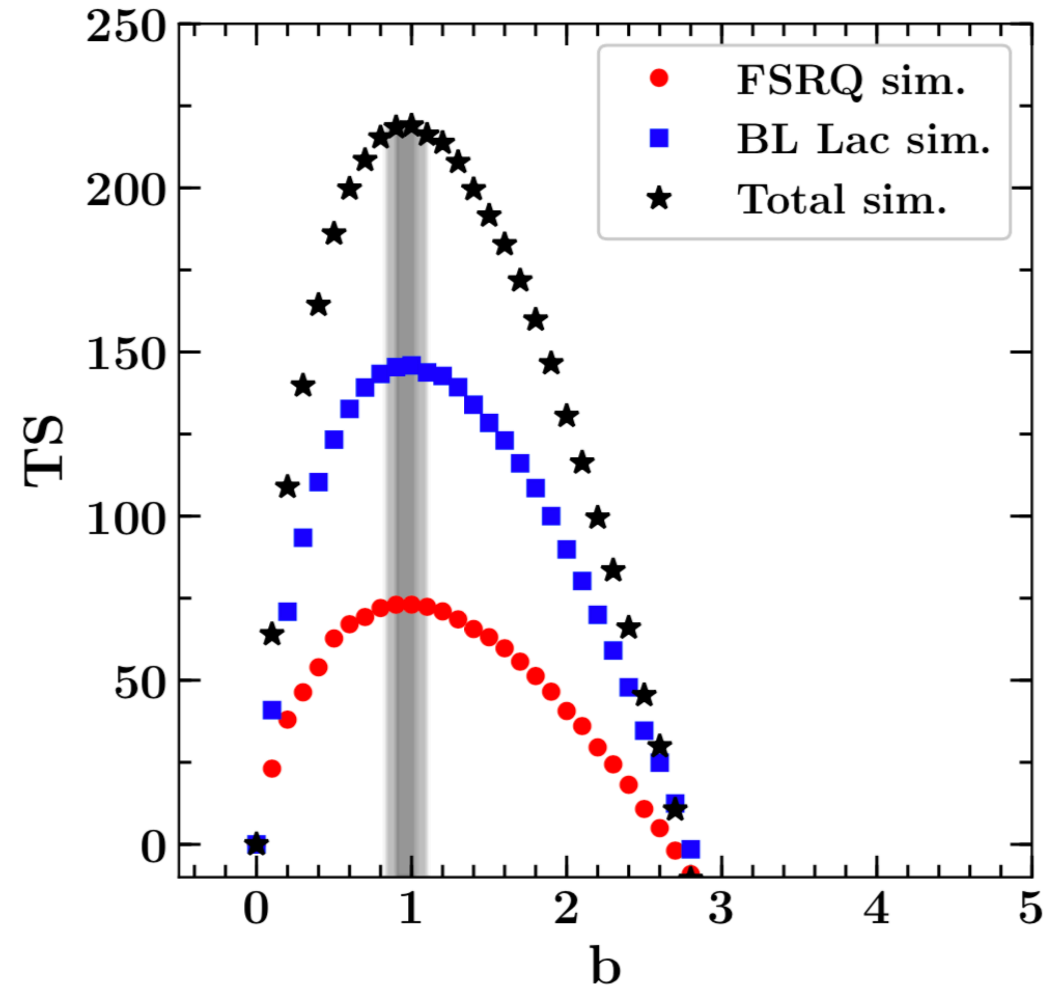
# Simulations

- The developed pipeline was tested and optimized using extensive Monte Carlo simulations of synthetic blazar SEDs

- We employ physically motivated SEDs of FSRQs and BL Lacs that reproduce the characteristics of γ-ray emitting blazars

    - Considered different peak positions, luminosity, Klein-Nishina effect, spectral curvature, location of the emission regions + EBL attenuation

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- *Fermi*-LAT data are simulated and analyzed with the previous prescription

- Various parameters (e.g., Emin = 1 GeV) were decided based on the simulation results

# Testing Models

| Model | Ref. | Significance of $b$=0 Rejection | $b$ | Significance of $b$=1 Rejection |
|---|---|---|---|---|
| *Scully et al. (2014) – high* | (49) | 16.0 | 0.42±0.03 | 17.4 |
| *Kneiske et al. (2004) – best -fit* | (50) | 16.9 | 0.68±0.05 | 6.0 |
| *Gilmore et al. (2012) – fixed* | (51) | 16.7 | 1.30±0.10 | 3.0 |
| *Gilmore et al. (2012) – fiducial* | (51) | 16.6 | 0.81±0.06 | 2.9 |
| *Dominguez et al. (2011)* | (37) | 16.6 | 1.31±0.10 | 2.9 |
| *Franceschini et al. (2017)* | (52) | 16.4 | 1.25±0.10 | 2.5 |
| *Gilmore et al. (2009)* | (53) | 16.7 | 1.03±0.08 | 2.4 |
| *Inoue et al. (2013)* | (54) | 16.2 | 0.87±0.06 | 2.1 |
| *Kneiske & Dole (2010)* | (55) | 16.8 | 0.94±0.08 | 1.7 |
| *Helgason et al. (2012)* | (38) | 16.5 | 1.10±0.08 | 1.3 |
| *Finke et al. (2010) – model C* | (29) | 17.1 | 1.03±0.08 | 0.4 |
| *Scully et al. (2014) – low* | (49) | 16.0 | 1.00±0.07 | 0.1 |

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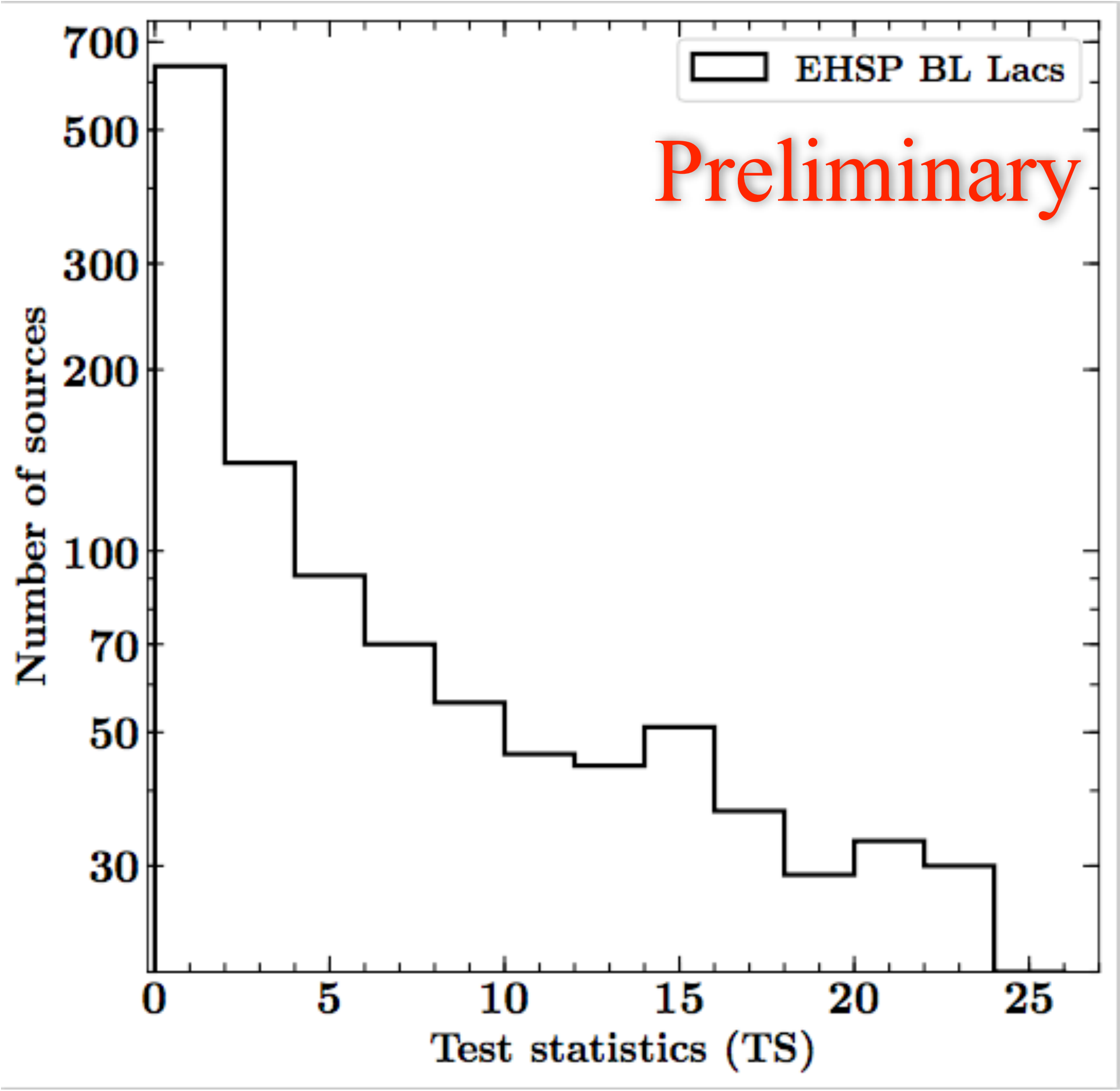
# TS Histogram




Extreme BL Lac objects