New measurements of the TeV optical depth for cosmological gamma-ray propagation

September 14th, 2024, Institut Pascal, Astroparticle Symposium 2024

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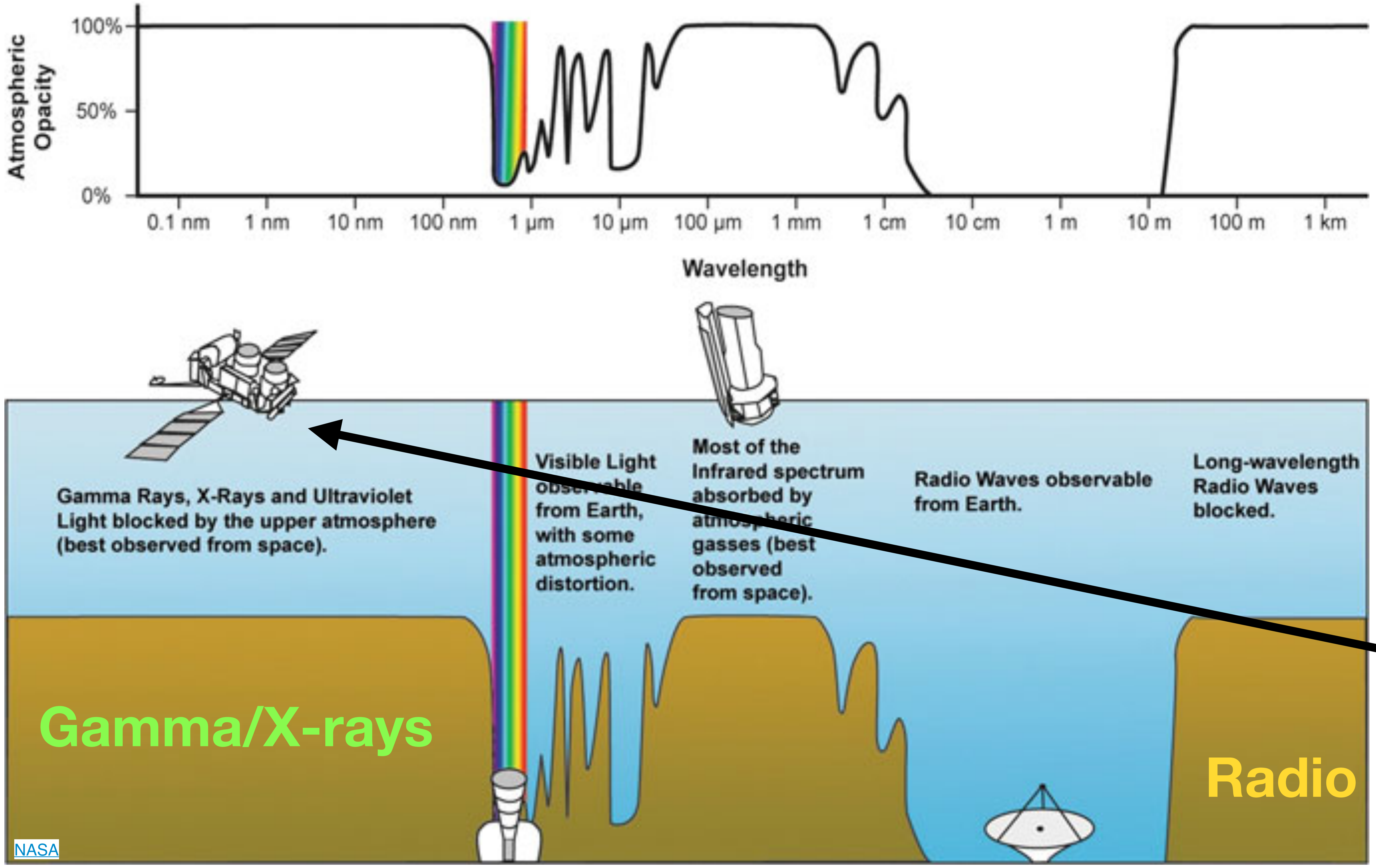
Introduction to Gamma-ray Telescopes

Opacity of the Universe



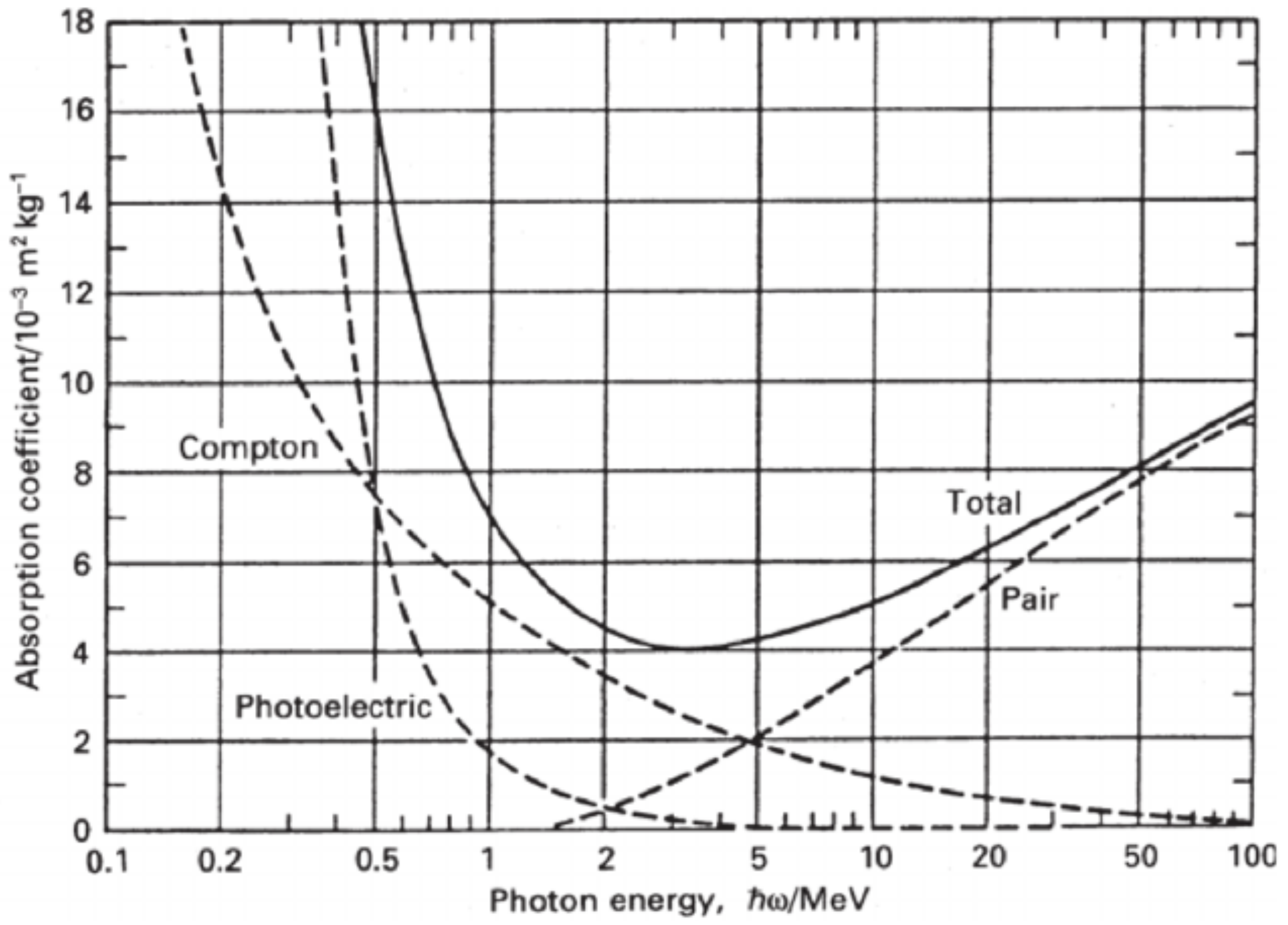
- Unlike radio waves or visible light, gamma rays are almost entirely "absorbed" through interactions with the atmosphere and do not reach the Earth's surface
- While the atmosphere can be a nuisance in this regard, without it, life as we know it wouldn't have been able to develop on the planet's surface—so we should be grateful for its protection (!)
- If we want to observe gamma rays, we'll have to send a satellite into space

Gamma-ray Observation from Space: Fermi satellite

- Gamma-ray observation satellite, Fermi satelite
- equipped with two gamma-ray detectors: a large-area telescope (LAT) and a gamma-ray burst monitor (GBM)
- detects gamma rays by pair-conversion in the calorimeter
- Energy range: 20 MeV- 300 GeV

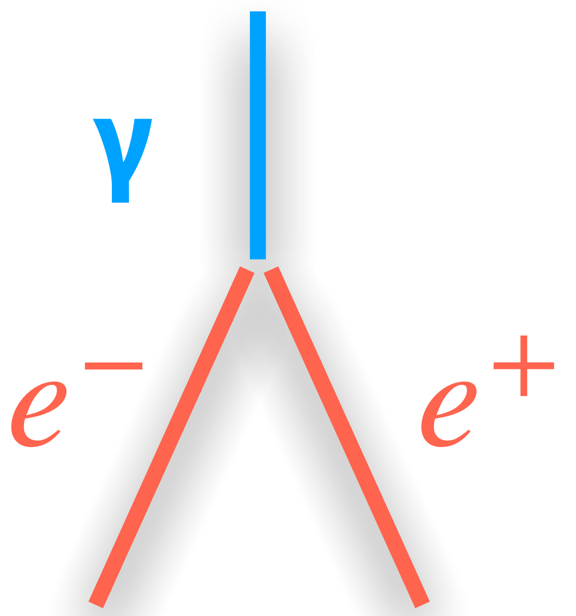
Ground-based gamma-ray observation

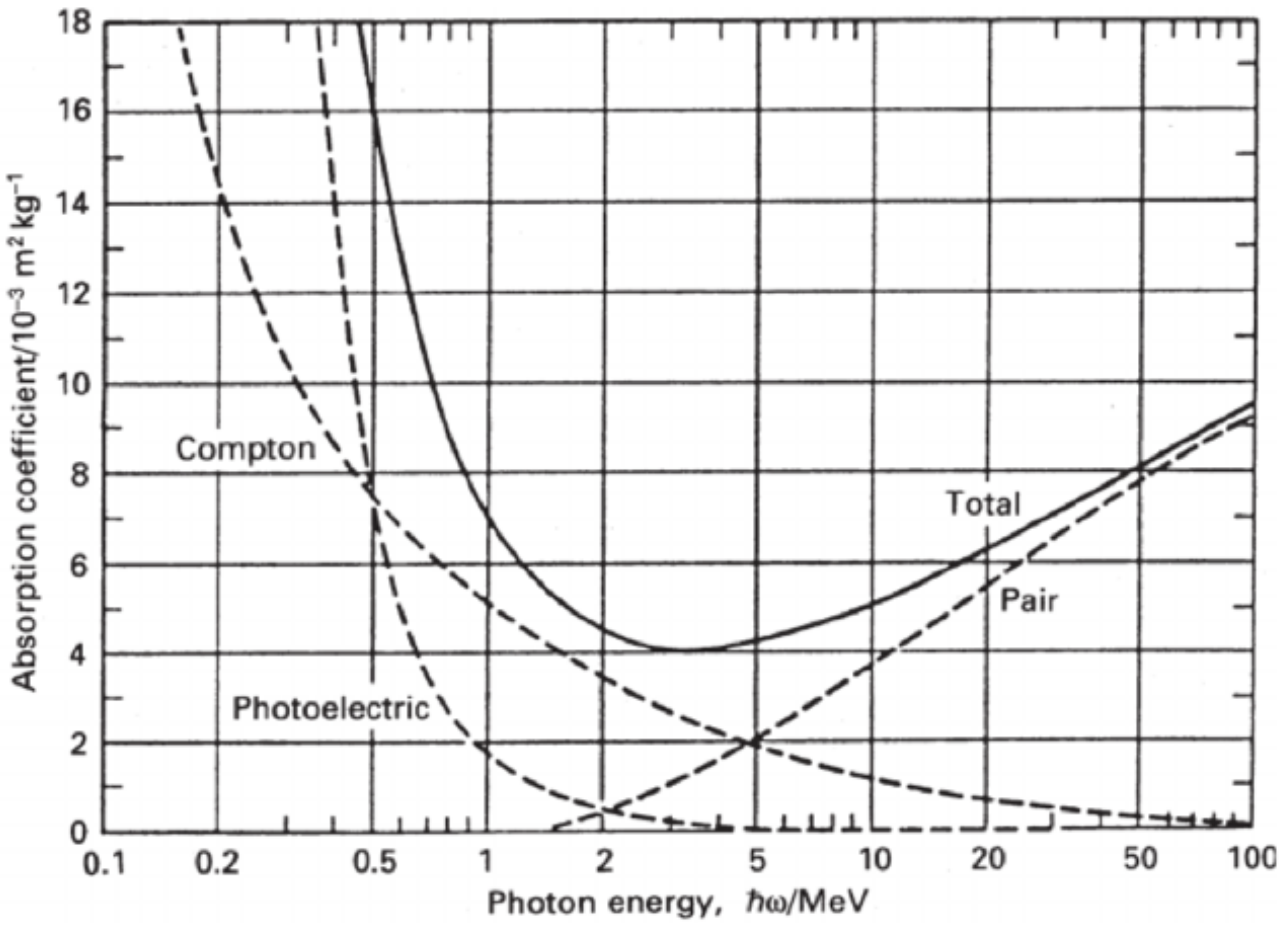
Don't give up on observing gamma rays from the ground just yet!
Let's take a look at what happens when very high-energy (VHE) gamma rays enter the atmosphere



Ground-based gamma-ray observation

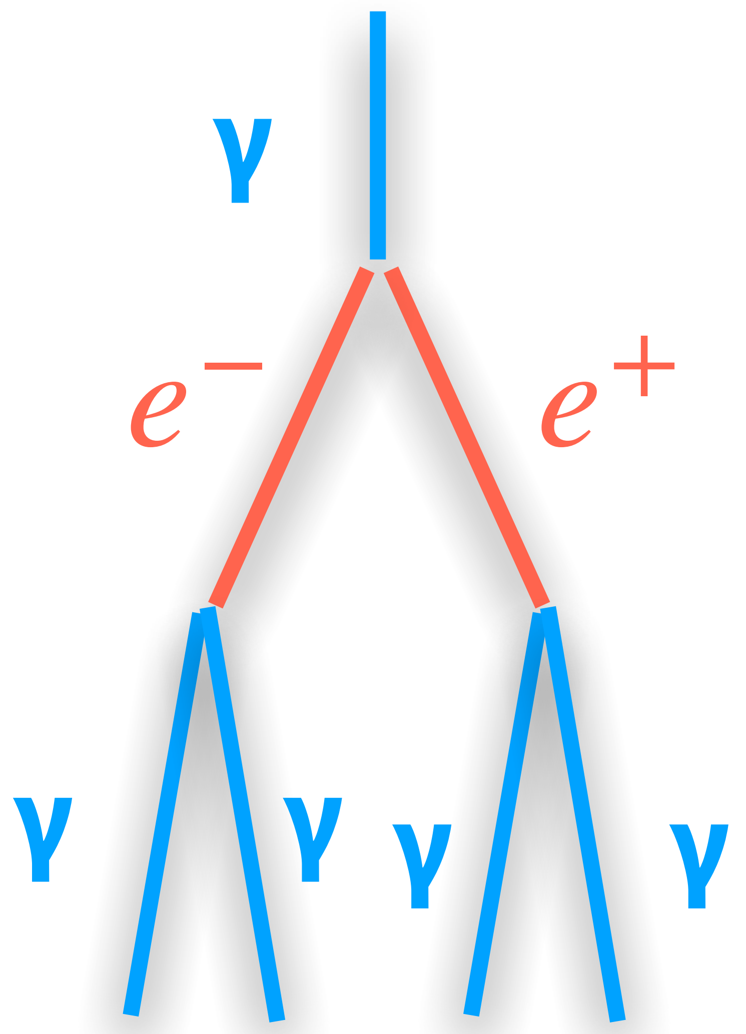
VHE gamma rays interact with the atmosphere and produce an electron-positron pair

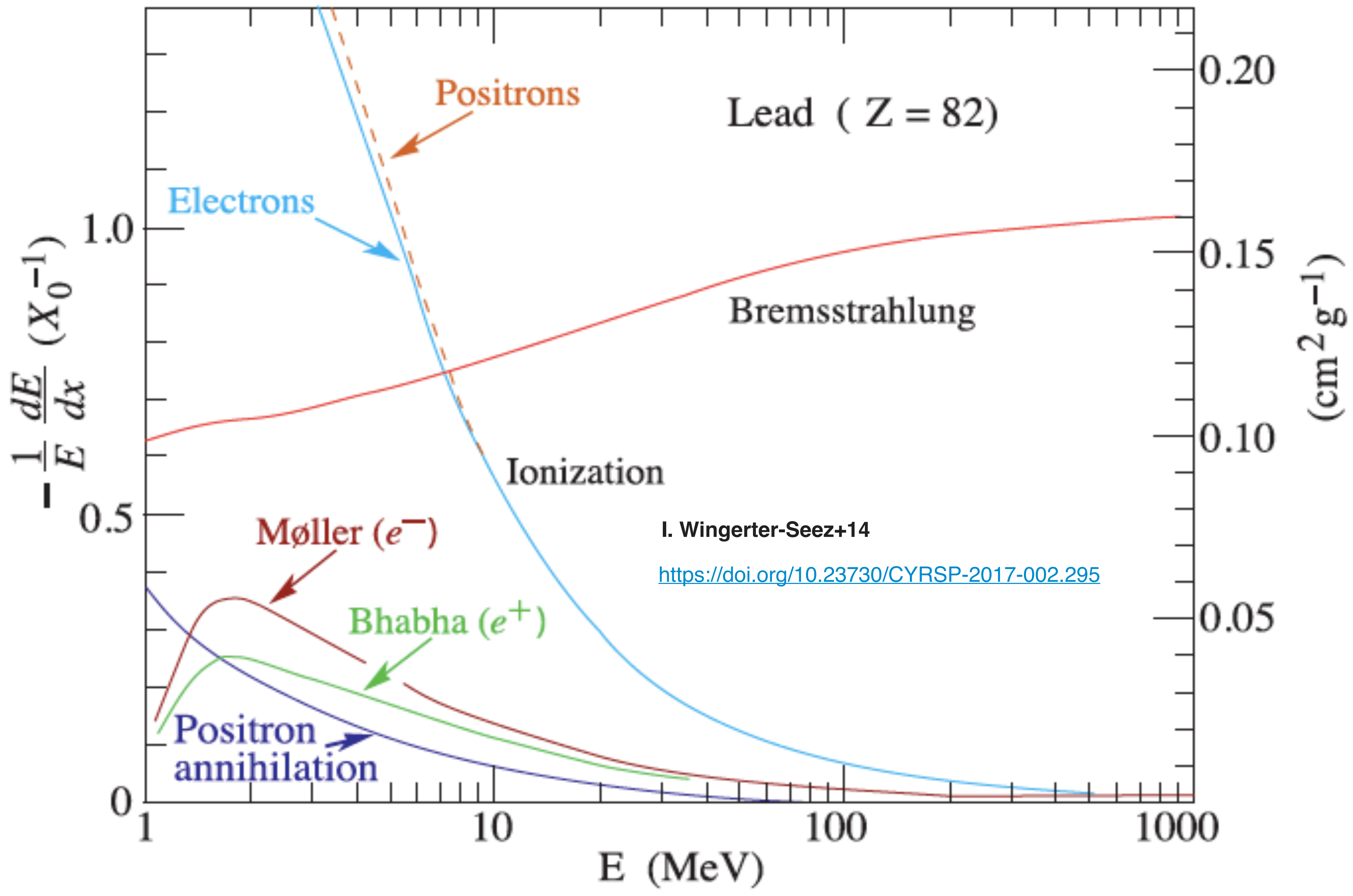




Ground-based gamma-ray observation

The electron and positron emit gamma rays through bremsstrahlung radiation





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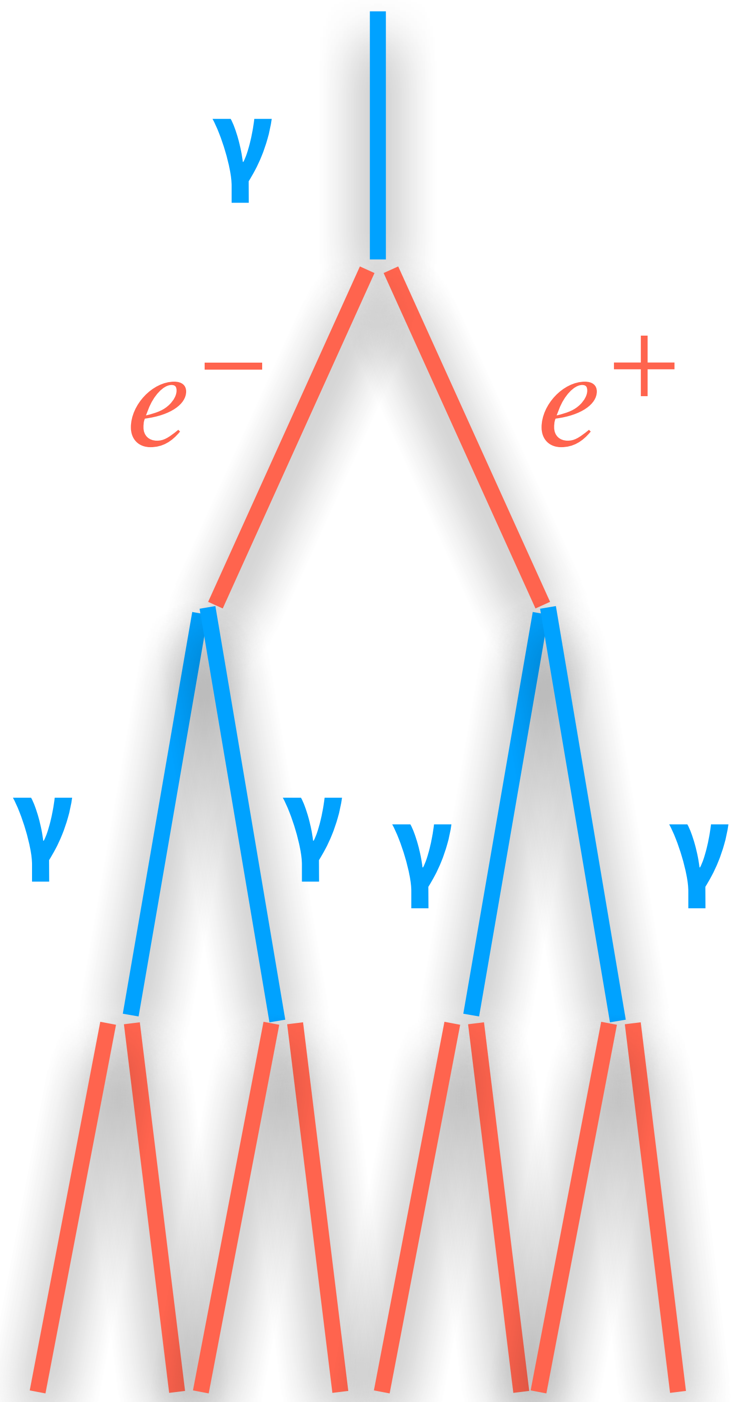
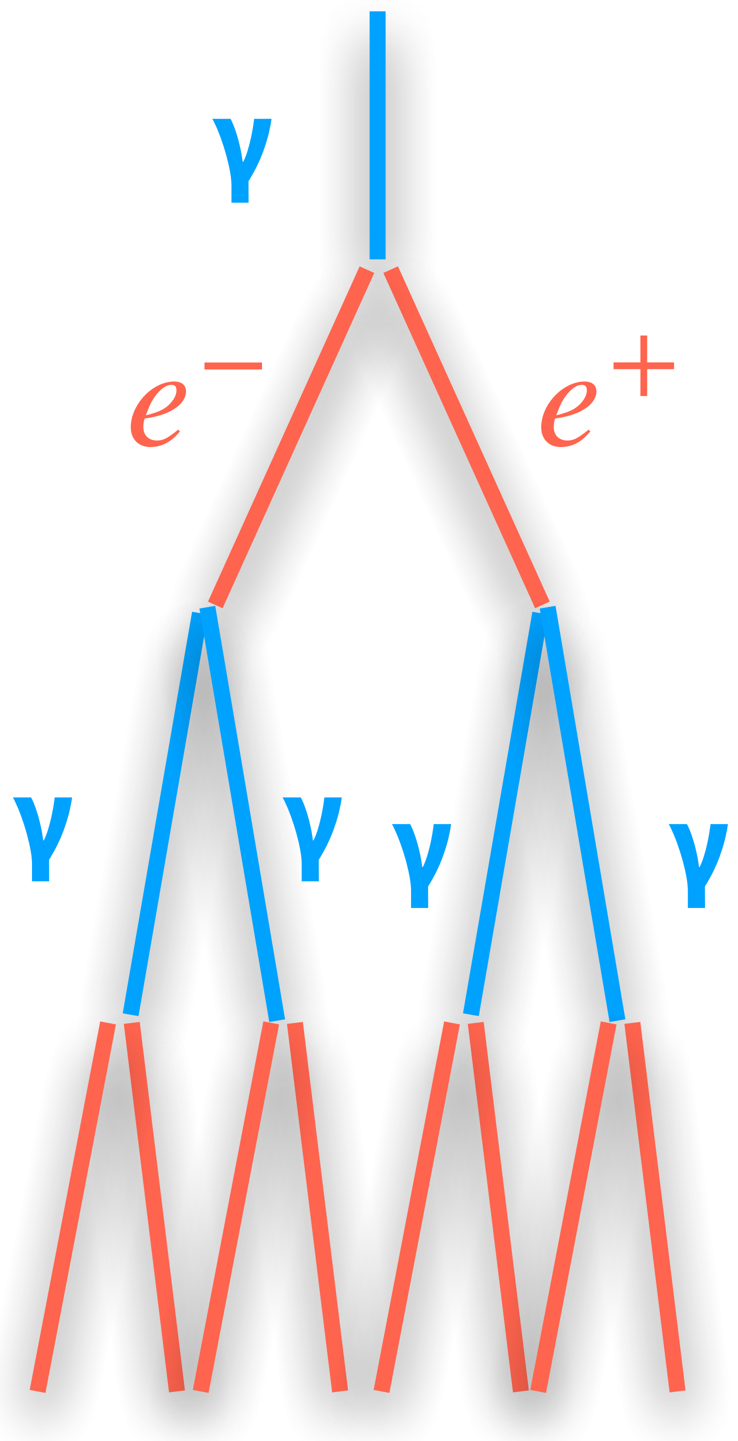


- Ionization takes over at the **Critical energy**= 560 MeV/Z
- Z of air ~ 7 (Mainly Nitrogen)
- So, Critical energy in air is about 560/7=80 MeV
- 1 TeV / 80MeV = 12500 products
- The charged particles produce **Cherenkov radiation**

Ground-based gamma-ray observation

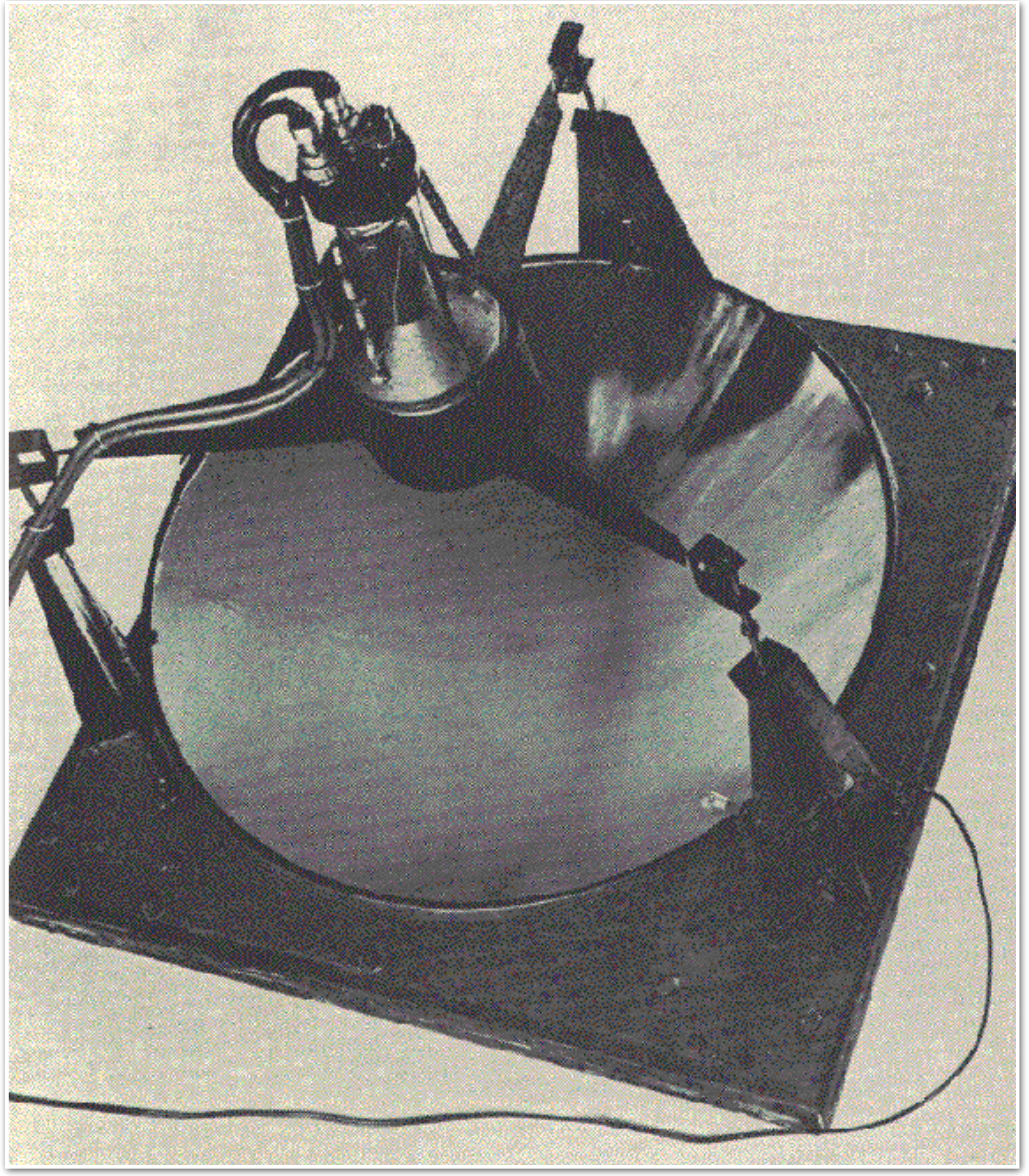
When VHE gamma rays enter the atmosphere, they trigger an air shower phenomenon



- The charged particles in the shower are moving faster than the speed of light in air or water (=c/n)
- A moving charge causes atoms to become polarised
- When the particle is moving quickly, the polarization is not symmetrical along the axis of motion, **resulting in a pulse of radiation**

Imaging Atmospheric Cherenkov Telescope

- A practical rule of thumb: a 1 TeV air shower typically generates around 100 photons per square meter.
- Suppose we detect pulses in the range of a few hundred millivolts
- Each photo-electron contributes about 5 mV, so around 100 photo-electrons are involved
- Given that the photomultiplier tube (PMT) has a photon-to-photo-electron conversion efficiency of approximately 20%, this would imply the detection of 100/0.2 = 500 photons
- If we assume the mirrors have an effective area of about $0.25 \times 0.25 \times \pi = 0.2\ m^2$, this suggests the shower contains 500/0.2 = 2500 photons per square meter
- From this, we can estimate the energy of the shower to be around 2500/100 = 25 TeV

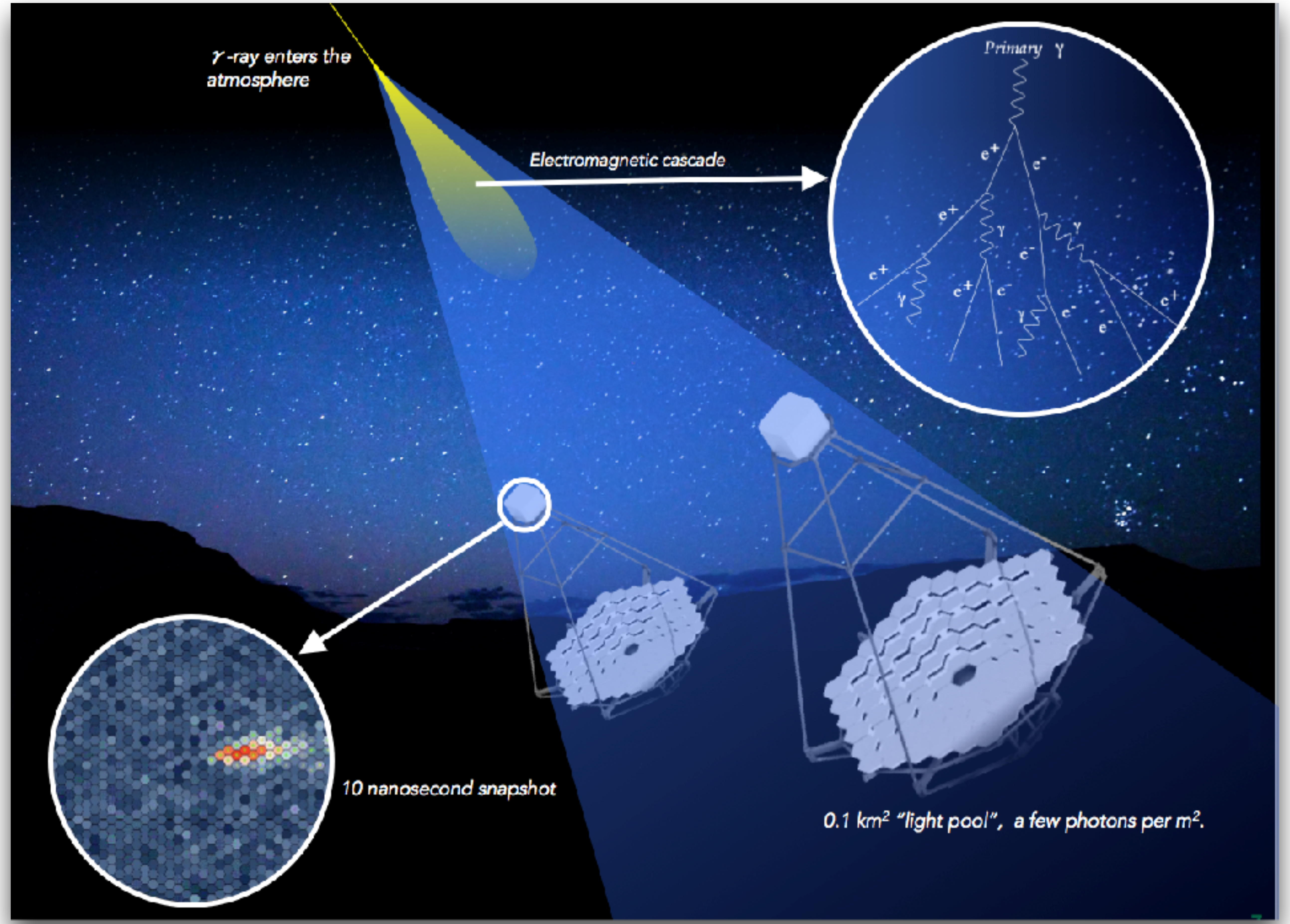


The first detection of Cherenkov light from extended air showers was performed by Galbraith and Jelley in 1952

Imaging Atmospheric Cherenkov Telescope

By observing Cherenkov light, we can indirectly detect cosmic gamma rays

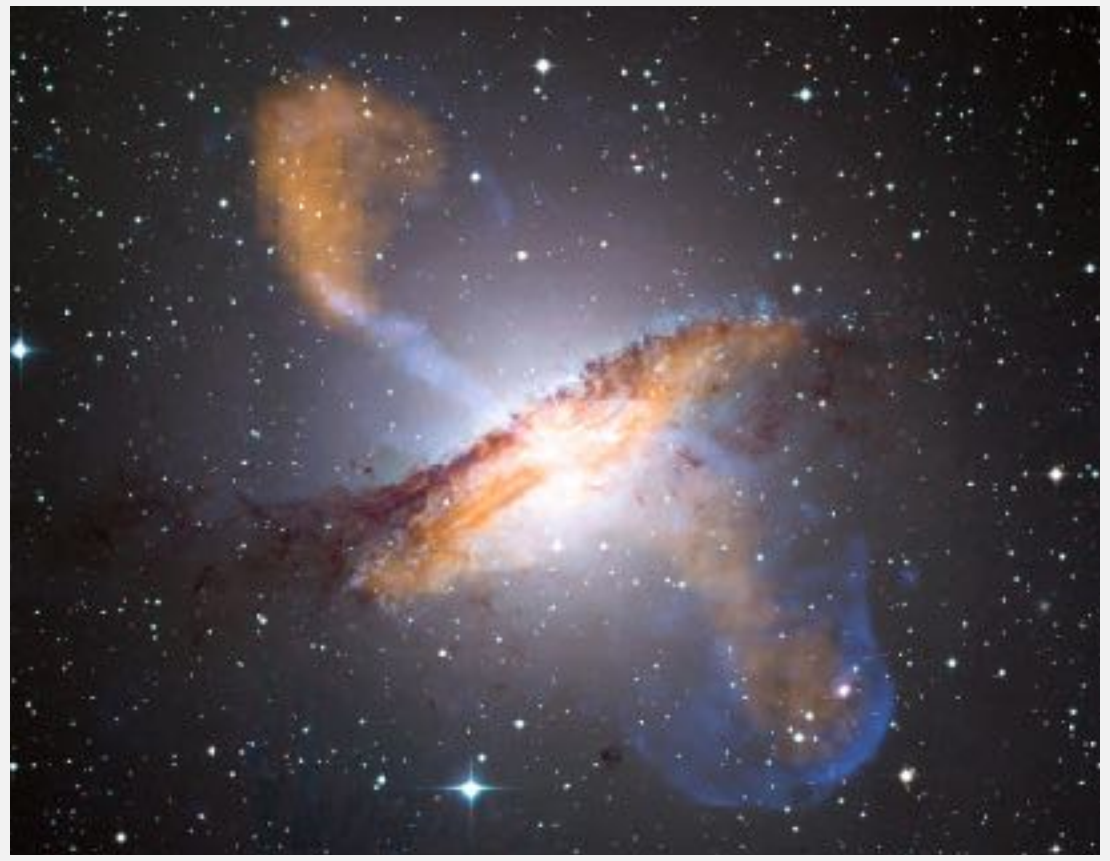
- Gamma rays interact with the atmosphere
  → Cherenkov radiation
- IACT reflects Cherenkov light through a mirror and captures the image with a focal plane camera
- The energy and direction of arrival of the gamma rays are reconstructed from the image information.
- We call our telescope: IACT

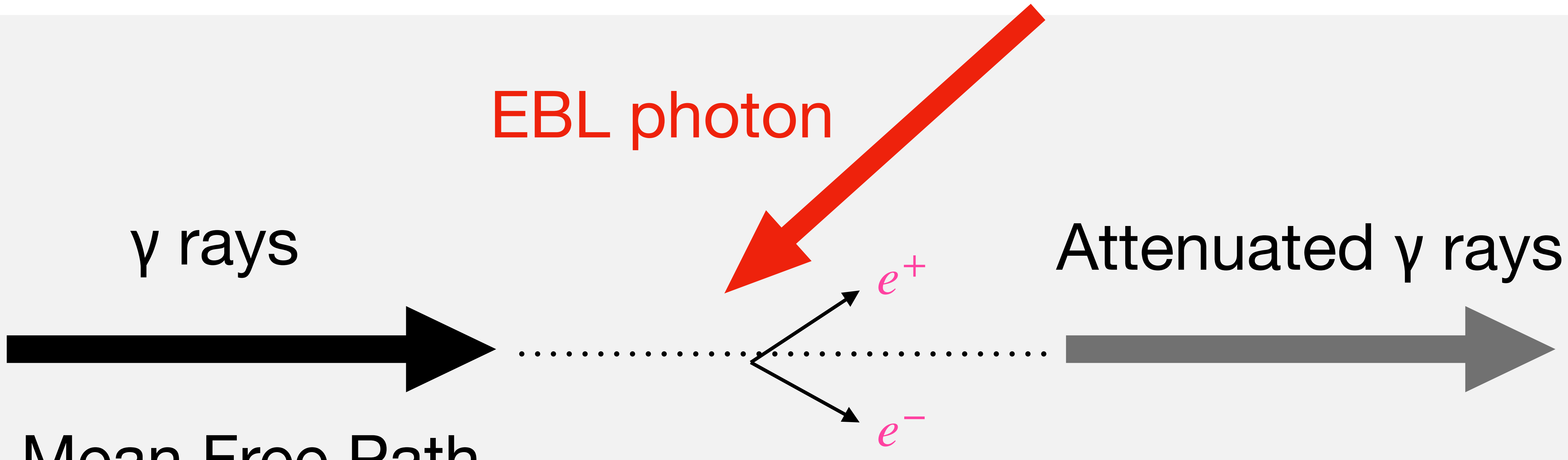


Gamma rays and EBL

Gamma rays and Extragalactic Background Light

- We are able to measure the EBL by observing gammarays. How does it work??





Mean Free Path

$$\Gamma_{\gamma\gamma}^{-1}(E', z) = \int_0^\infty d\epsilon' \frac{dn(\epsilon', z)}{d\epsilon'} \int_{-1}^{1} d\cos\theta' \frac{1-\cos\theta'}{2} \sigma_{\gamma\gamma}(\beta') \Theta(\epsilon' - \epsilon'_{\text{th}})$$

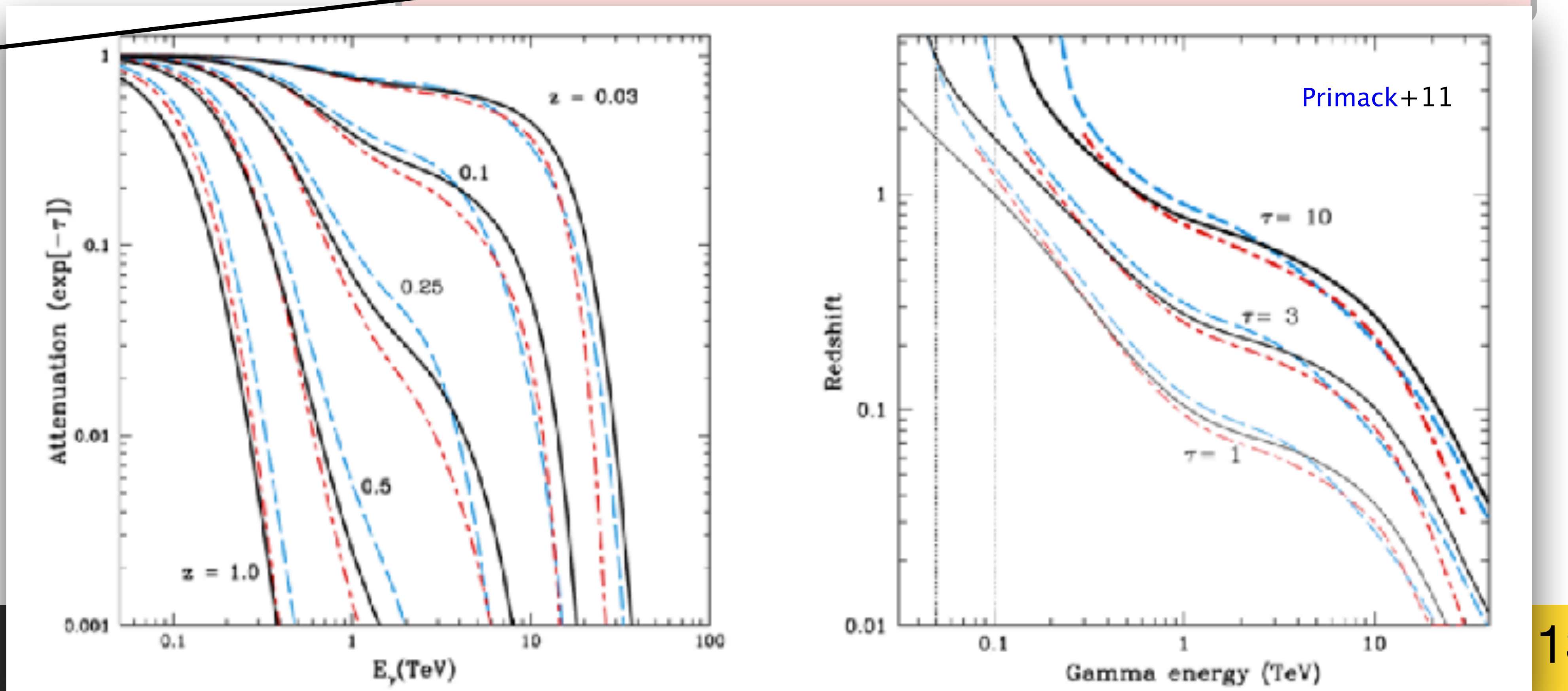
$$\beta'^2 = 1 - 2\left(m_e c^2\right)^2 / \left[E'\epsilon'(1-\cos\theta')\right]$$

$$\Phi_{\text{obs}}(E_\gamma, z) = e^{-\tau(E_\gamma, z)} \times \Phi_{\text{int}}(E_\gamma)$$

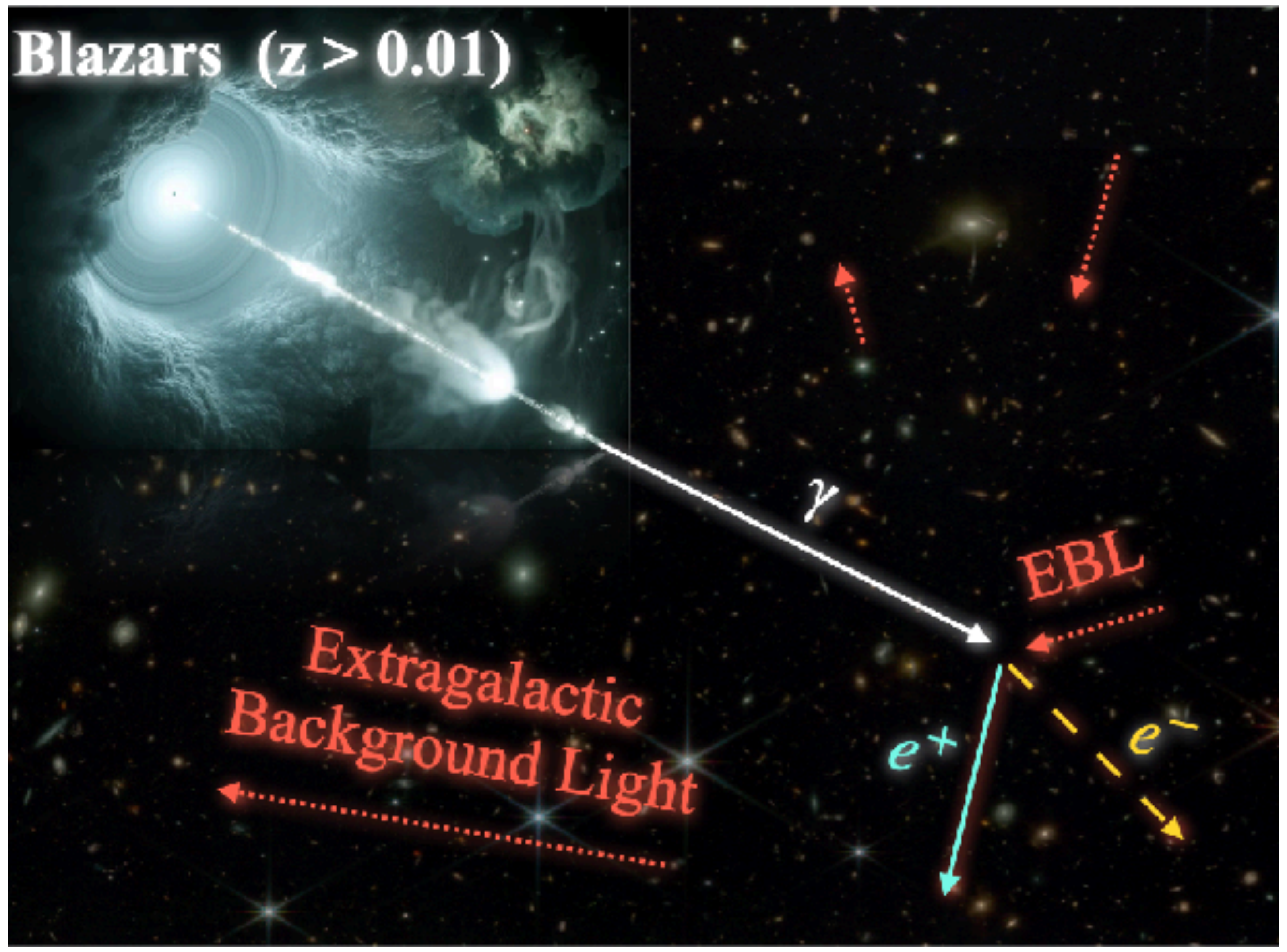
The gamma-ray absorption, quantified by the optical depth:

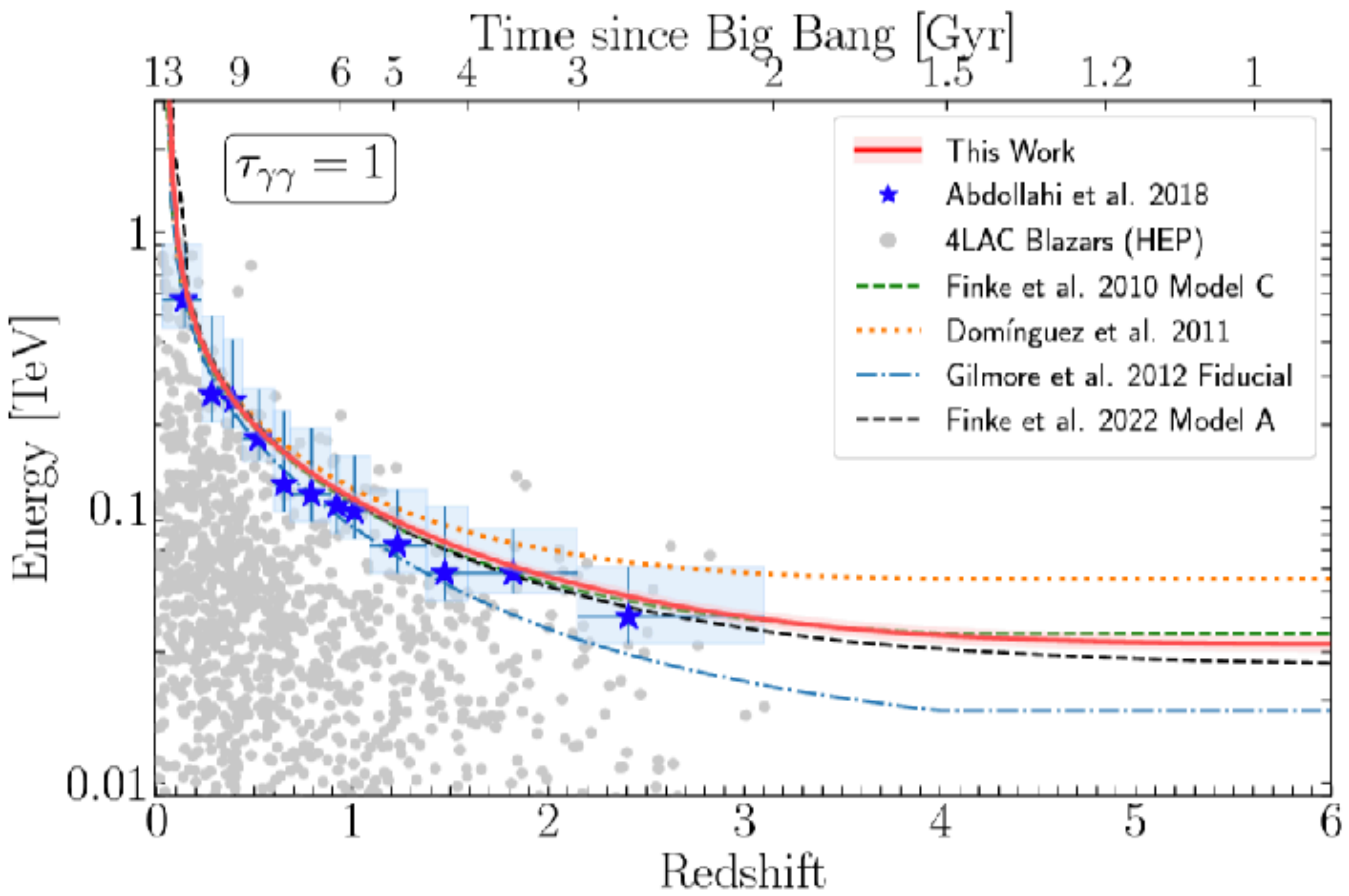
$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} \Gamma_{\gamma\gamma}^{-1}(E(1+z), z) \frac{d\ell(z)}{dz} dz$$

line-of-sight integral up to the redshift of the source over the mean-free path



Gamma-rays and Extragalactic Background Light





- Gamma rays interact with the EBL, resulting in an "attenuation effect" on gamma-ray propagation.
  - Observed attenuated gamma-ray spectrum of blazars retains signatures (or information) of the EBL
  - The information about its propagation is encapsulated in the optical depth. The redshift dependence at which the optical depth $\tau = 1$ is traditionally referred to as the "**gamma-ray horizon**"
- A minor note: For Fermi, the energy range sensitive to EBL absorption (around $O(10\ \mathrm{GeV})$) falls within a regime where statistical significance is hard to achieve due to limited effective area, placing these measurements at the fringes of Fermi's overall sensitivity. As a result, sources detectable beyond the gamma-ray horizon are exceedingly rare. In contrast, for Imaging Atmospheric Cherenkov Telescopes (IACTs), many more sources are detectable at energies exceeding the gamma-ray horizon, meaning that the term "horizon" does not carry the same observational significance. I once showed a plot at a conference comparing detection energies of an IACT-observed source with the gamma-ray horizon, and a theorist commented, "You're going beyond the horizon!"—something that indeed occurs regularly with IACTs, even if it might seem unusual to those more accustomed to Fermi plots.

EBL measurements with gamma-ray Observation

- When it comes to measuring the EBL through gamma-ray observations, here are the key advantages and disadvantages of this method:

Pros

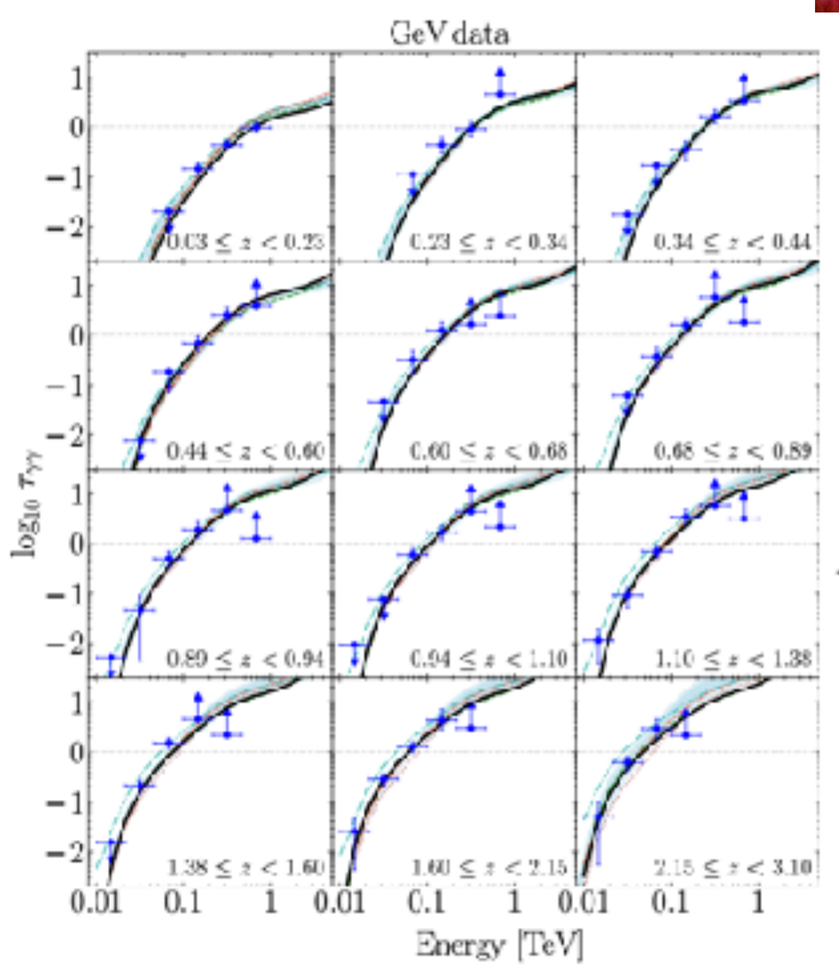
- ✓ **No Need to Subtract Intense Backgrounds**:
  Unlike direct observations, gamma-ray measurements do not require subtraction of intense background signals such as Zodiacal Light or Galactic Diffuse emission
- ✓ **Inherent Information on Redshift Evolution**:
  Since blazars are distributed across a wide range of redshifts, the gamma-ray data intrinsically contains information on the evolution of the EBL along the z-direction. However, it's important to note that this information is integrated along the line of sight.
- ✓ **Independence from Direct Observations**: This method provides a measurement that is largely independent of direct EBL observations, offering a complementary approach to understanding EBL properties and evolution.
- ✓ **True "Measurement" Rather Than Bounds**: With modern instruments, gamma-ray observations now allow actual measurements of the EBL, rather than setting upper or lower limits
- ✓ **Broad Wavelength Coverage with Fermi + IACT**: The combination of Fermi and IACTs enables EBL measurements across a broad wavelength range, from the near-infrared to (roughly spanning from nm to nm).

Cons / Difficulties

- ✓ **Modeling the Intrinsic Spectrum**:
  Since there is no direct way to determine the intrinsic spectrum of blazars, various assumptions often need to be introduced in this part of the analysis: Typically, several empirically validated analytical functions are prepared and tested to establish an intrinsic model
  - ✓ By assuming a healthy electron distribution and Synchrotron Self-Compton (SSC) processes, for instance, it is possible to produce a log-parabola shape at high-energy ranges.
- ✓ **Potential Modifications from External Factors**:
  The propagation assumptions can be modified by the presence of Axion-like Particles, the Intergalactic Magnetic Field, or Cosmic Voids, all of which could influence the measured results.
- ✓ **Dependence on EBL Models**: Most methods used in this context are dependent on specific EBL models. However, *Lucas+24* have achieved a breakthrough by applying Bayesian techniques to mitigate this dependence, allowing for more robust EBL measurement free from strict reliance on any particular model—an impressive accomplishment
- ✓ **Challenges from Blazar Variability**: Accounting for the variability of blazars is challenging. While a Bayesian algorithm can theoretically segment data based on light curve (LC) characteristics, in practice, this remains a complex issue.

Overview: EBL measurements with gammarays

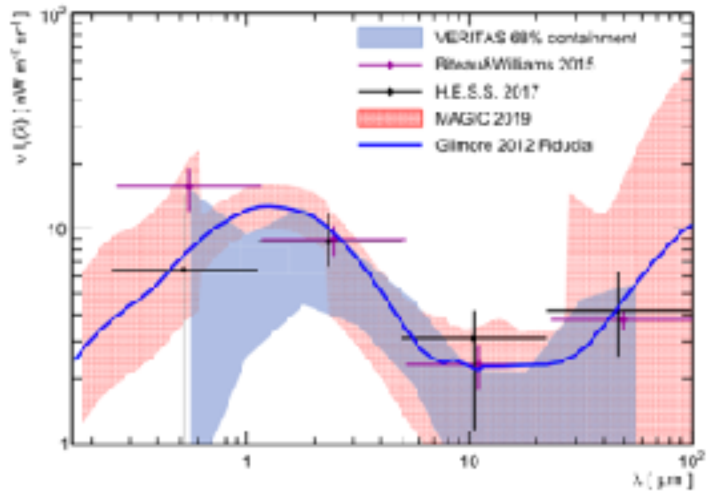
Fermi-LAT

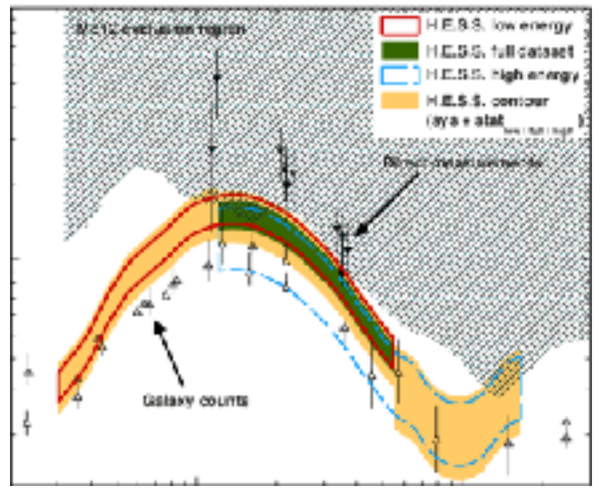


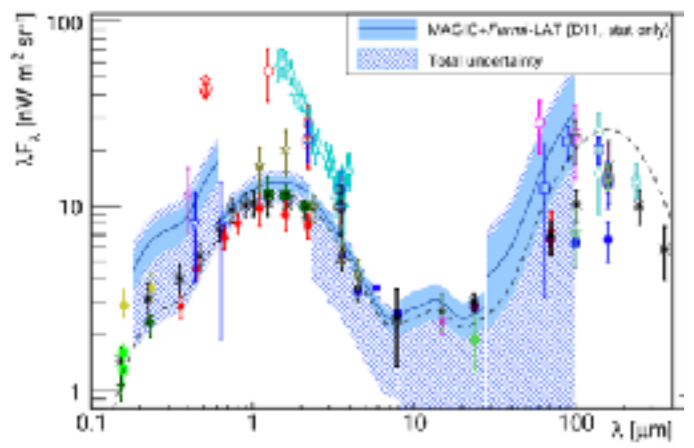
✓ Ackermann+12

✓ Abdollahi +18

IACTs





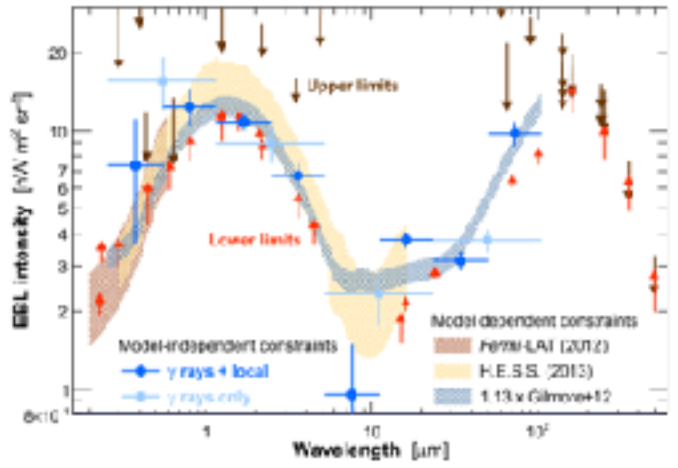


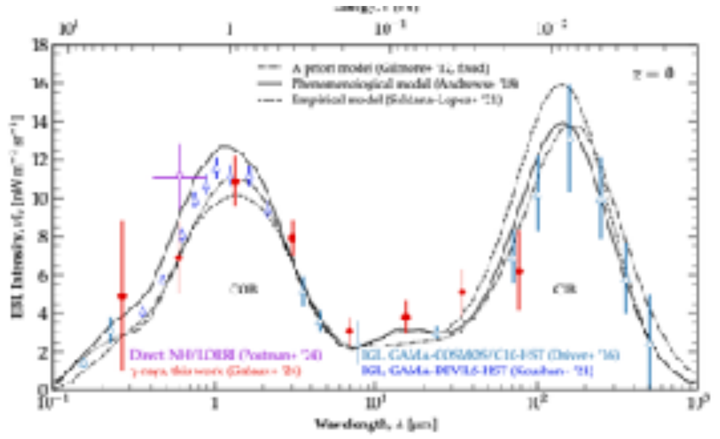
✓ VERITAS+19

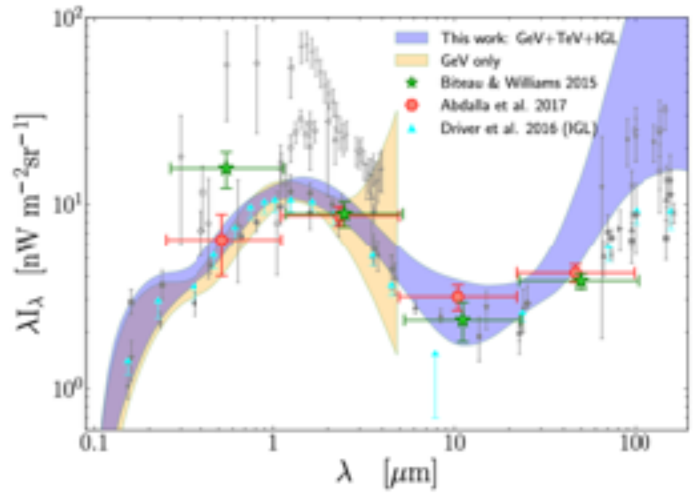
✓ MAGIC+19

✓ H.E.S.S.+17

Compilation-based Analysis







✓ Desai+19

✓ Biteau&Williams+15

✓ Lucas+24

GeV

✓ Using around $O(100)$ blazars (FSRQs and BL Lacs) detected by Fermi, measurements have been made for optical depth, EBL, and star formation rates

GeV ~ TeV

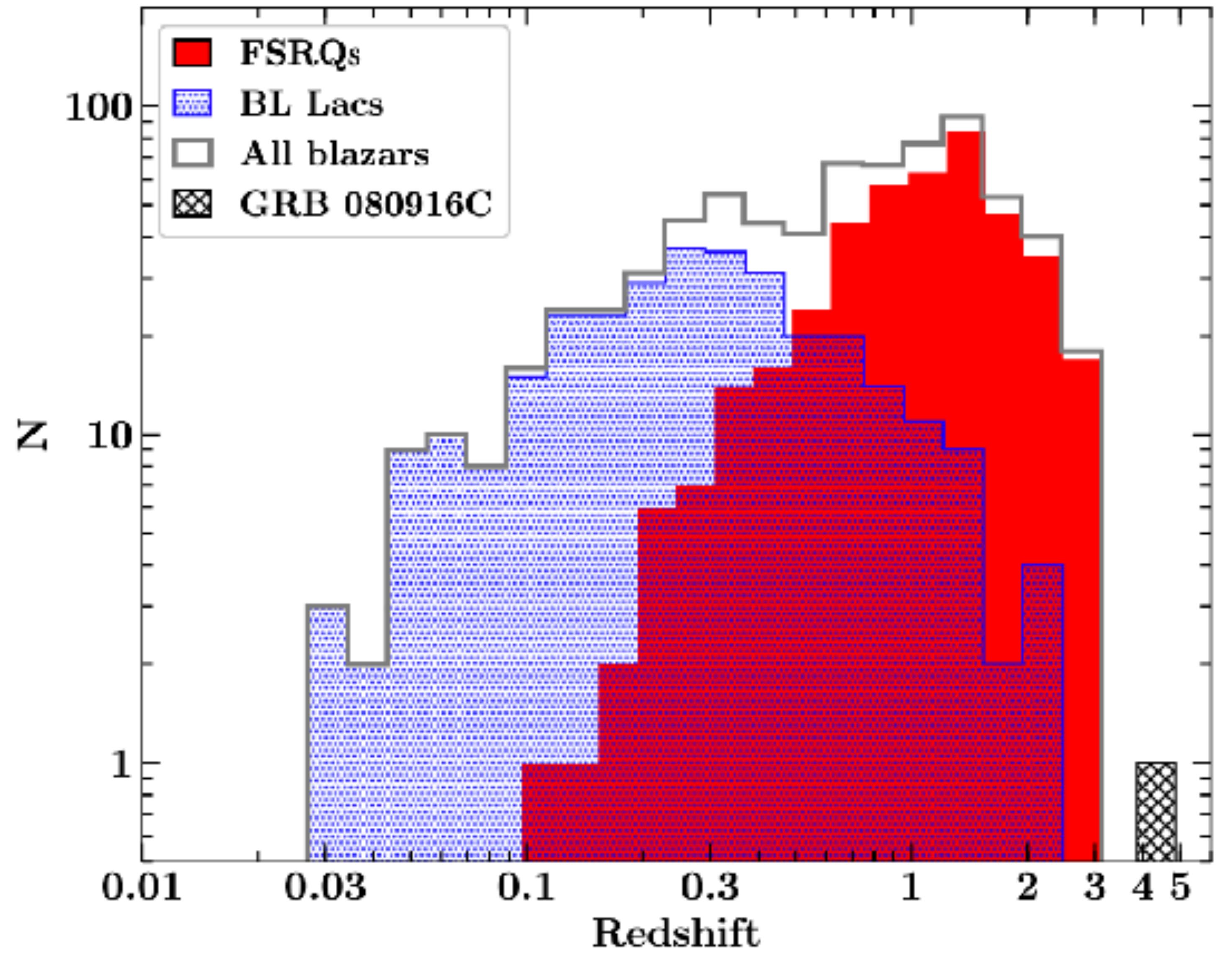
✓ Each of the current leading IACTs—MAGIC, HESS, and VERITAS—has placed constraints on the EBL using spectra from around $O(10)$ TeV blazars

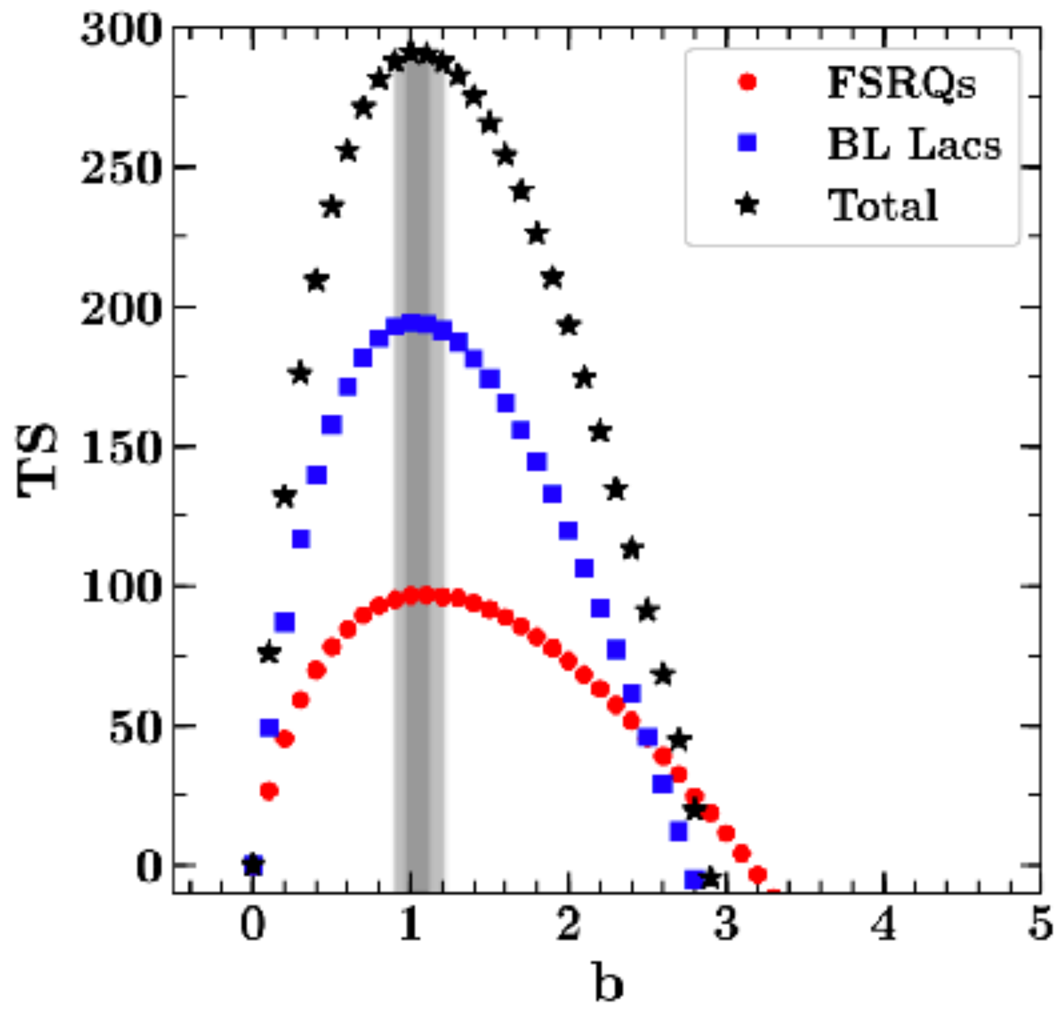
GeV + TeV (+ IGL)

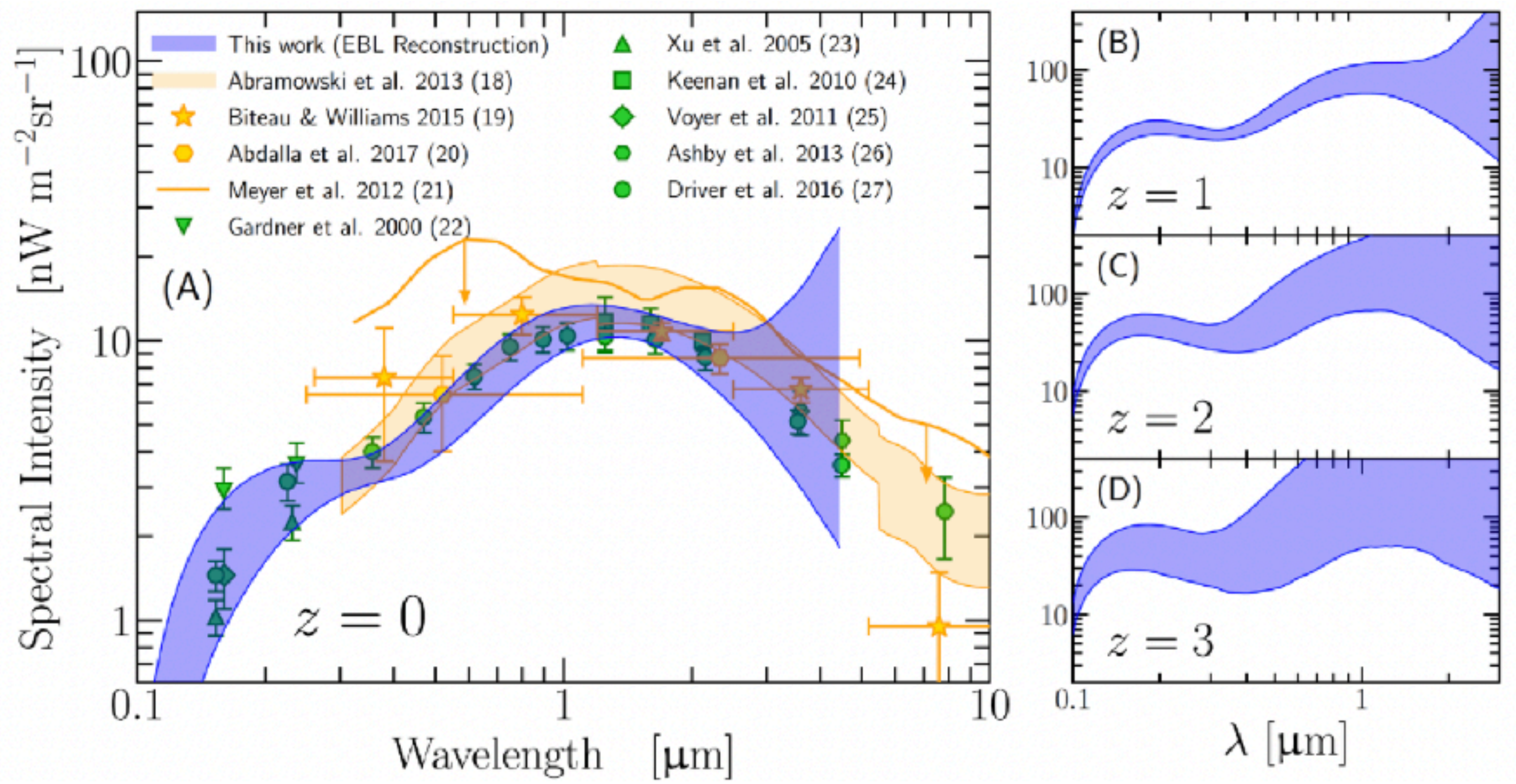
✓ A type of work that involves constructing catalogs from published DL4-level IACT data and using these to measure the EBL. This approach benefits from the strength of large blazar sample statistics

EBL measurements by Fermi-LAT in 2018

Abdollahi +18







- 739 blazars and one gamma-ray burst: spanning from z =0.03 to z = 3.1
- Reconstructed the evolution of the EBL and determine the star-formation history of the Universe over 90% of cosmic time
    - Star-formation history consistent with independent measurements from galaxy surveys, peaking at redshift z ~ 2

EBL measurements by MAGIC collaboration in 2019

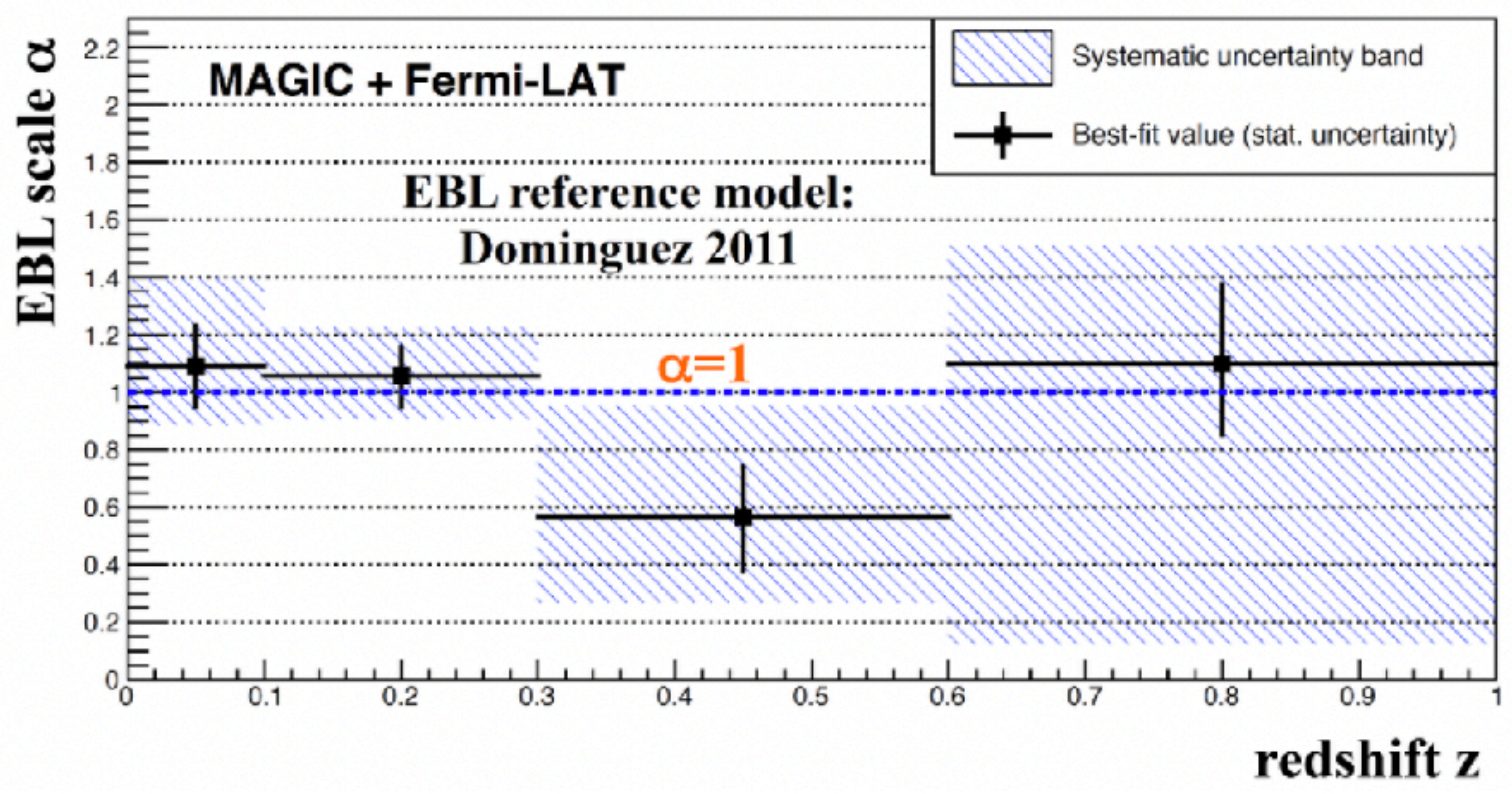
- Combined with Fermi-LAT spectra

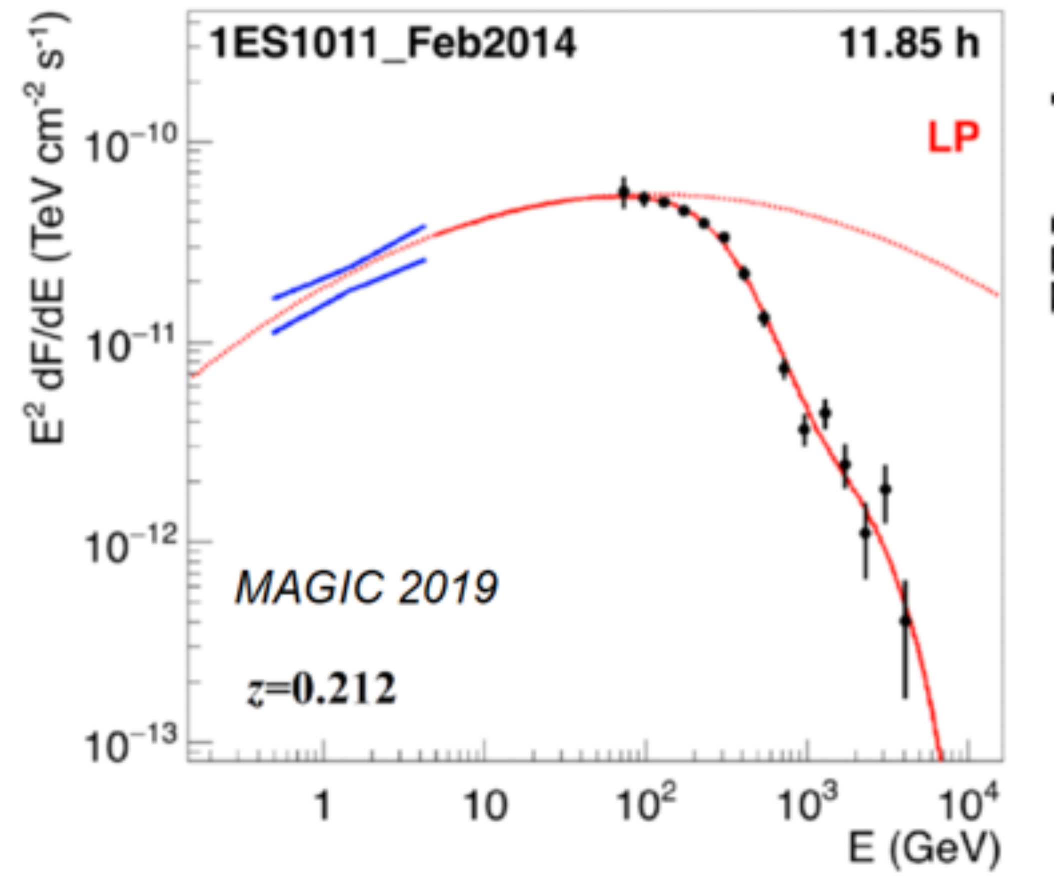
  - model-dependant and wavelength-resolved analysis (not purely model-independent)

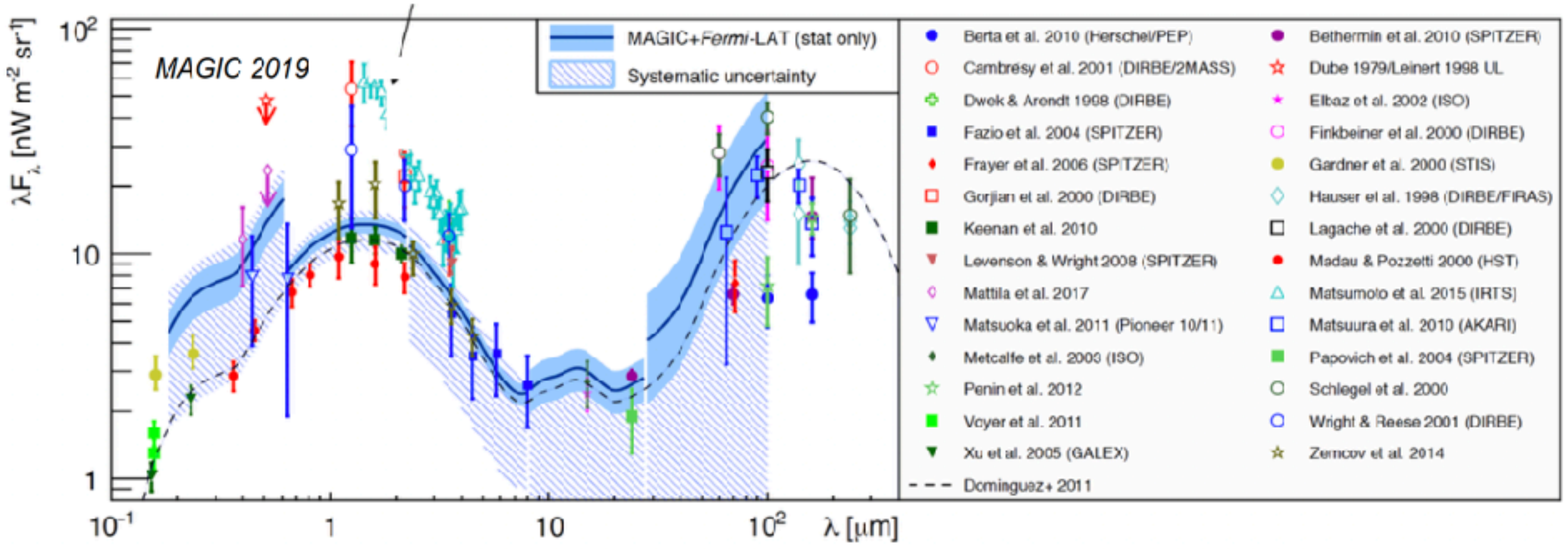
- 16 blazars (44 spectra in total 0.03 < z < 0.94)

  - 450 hours of observation in total

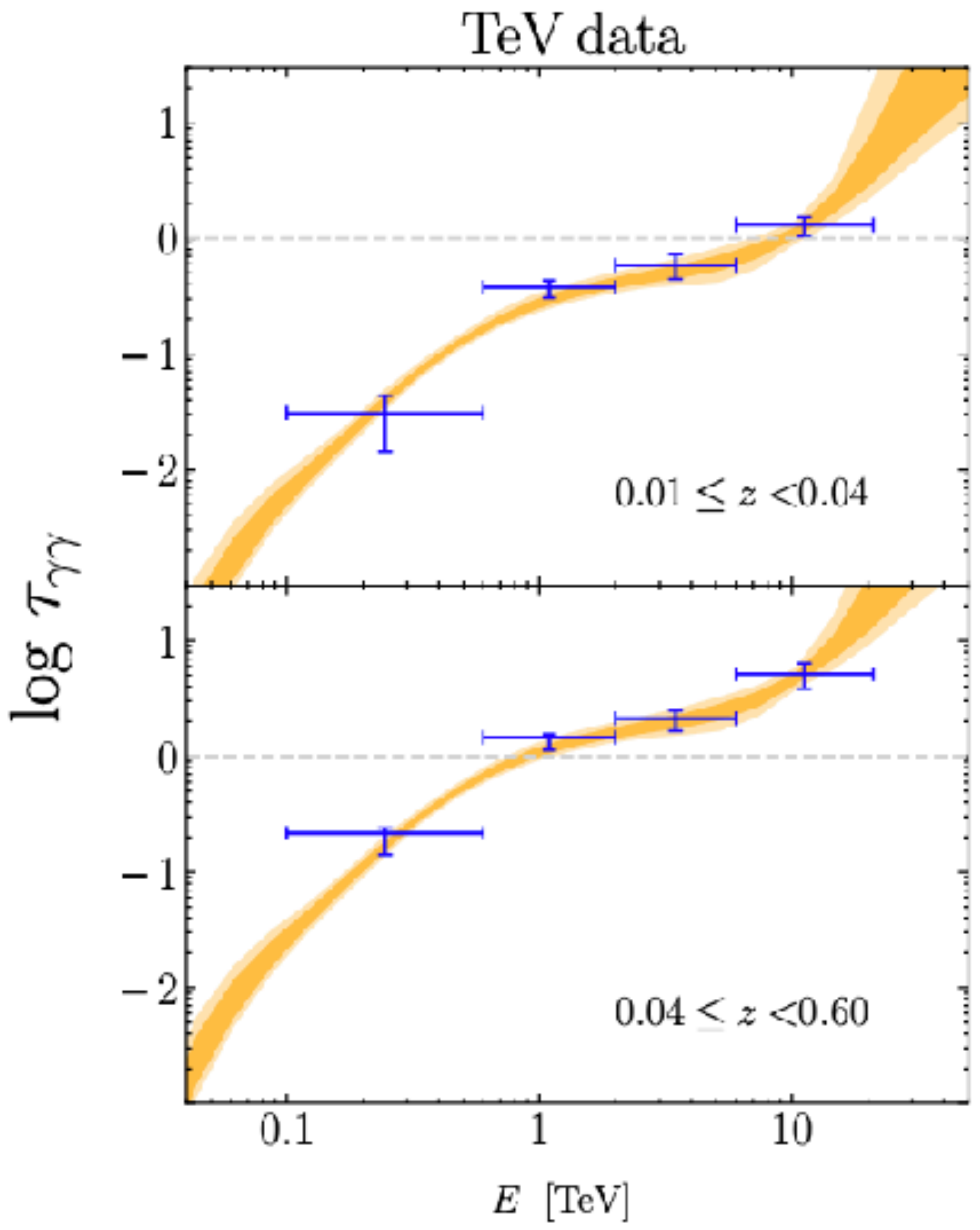
- Going to be updated by Roger Grau

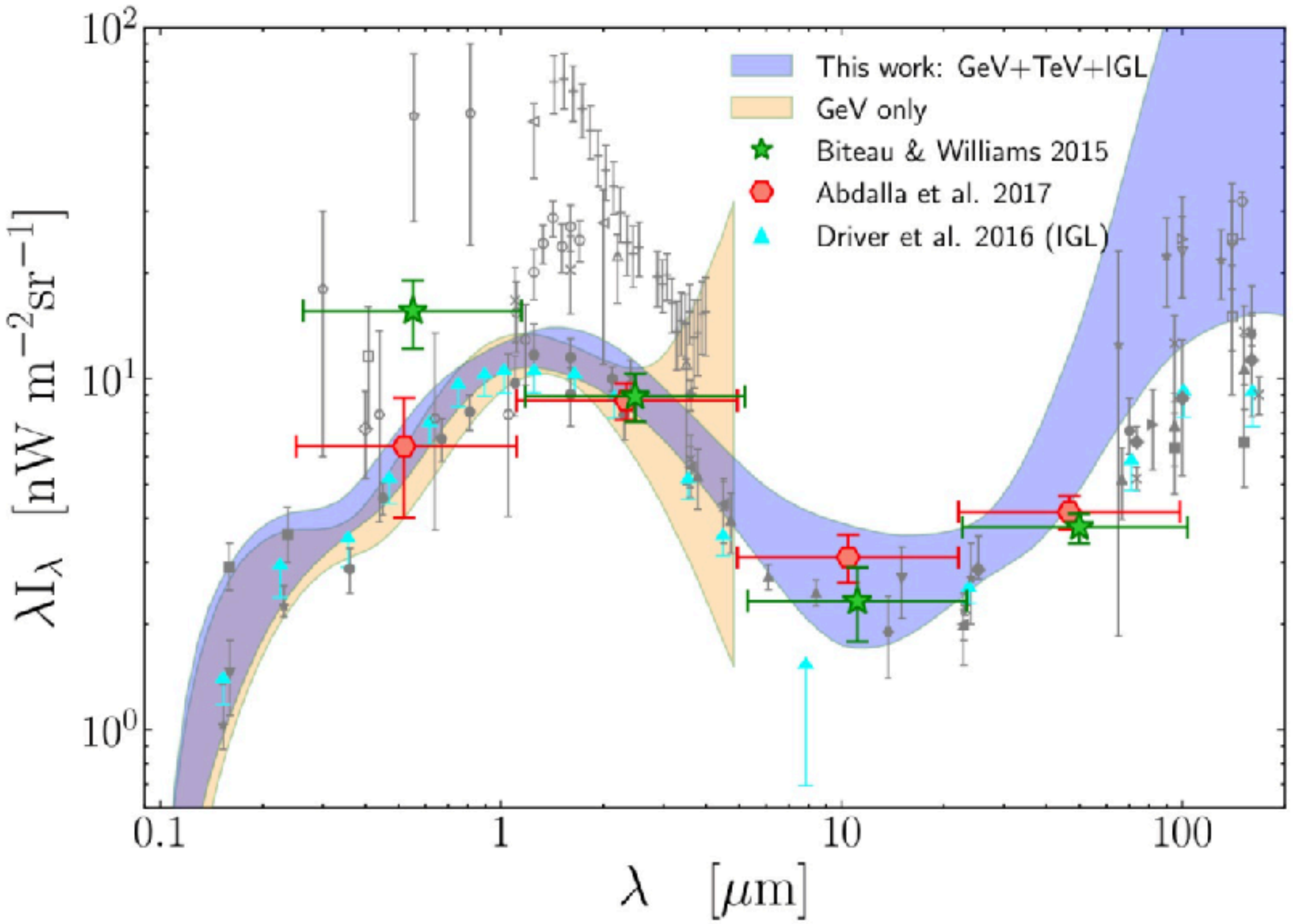


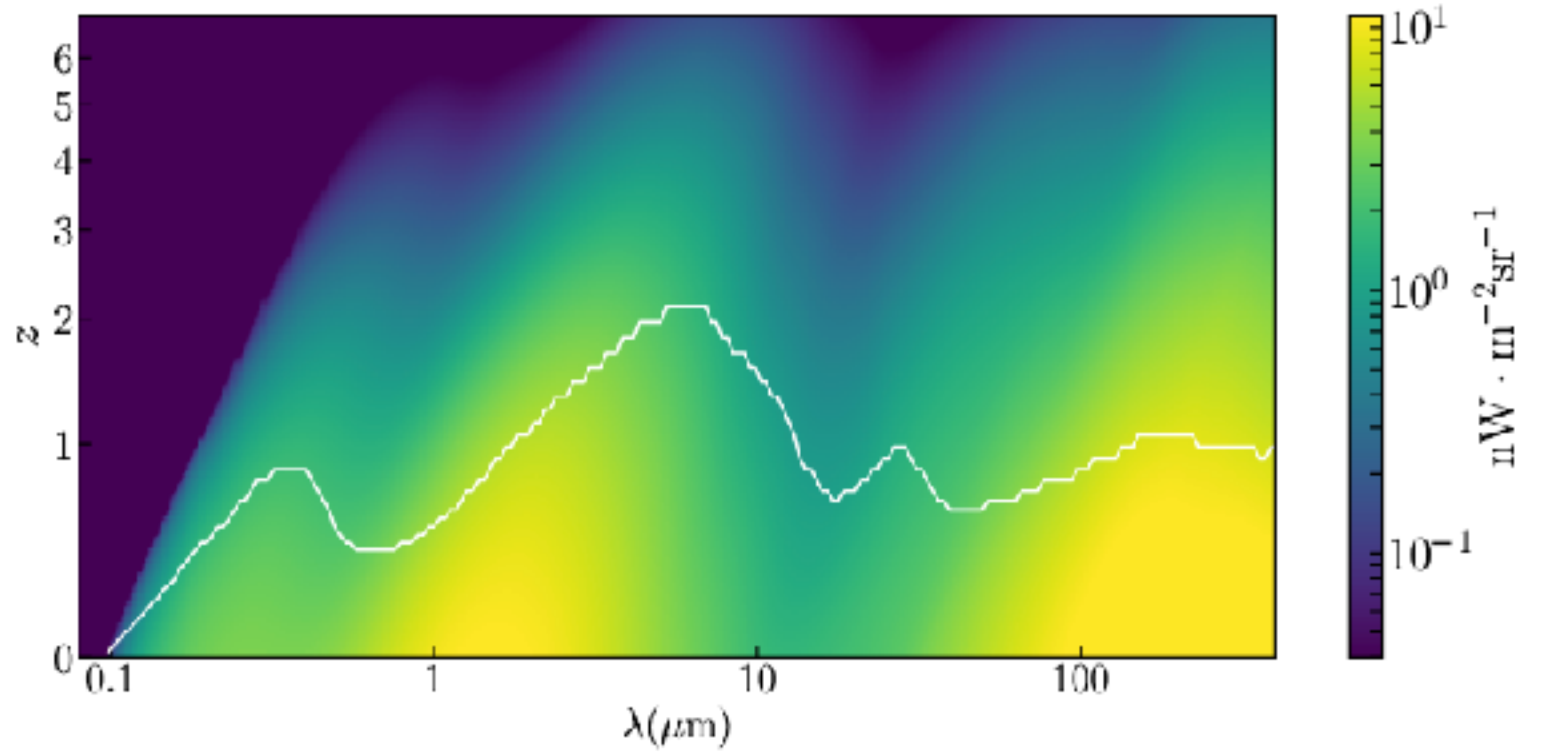




EBL measurements by Desai et al. in 2019





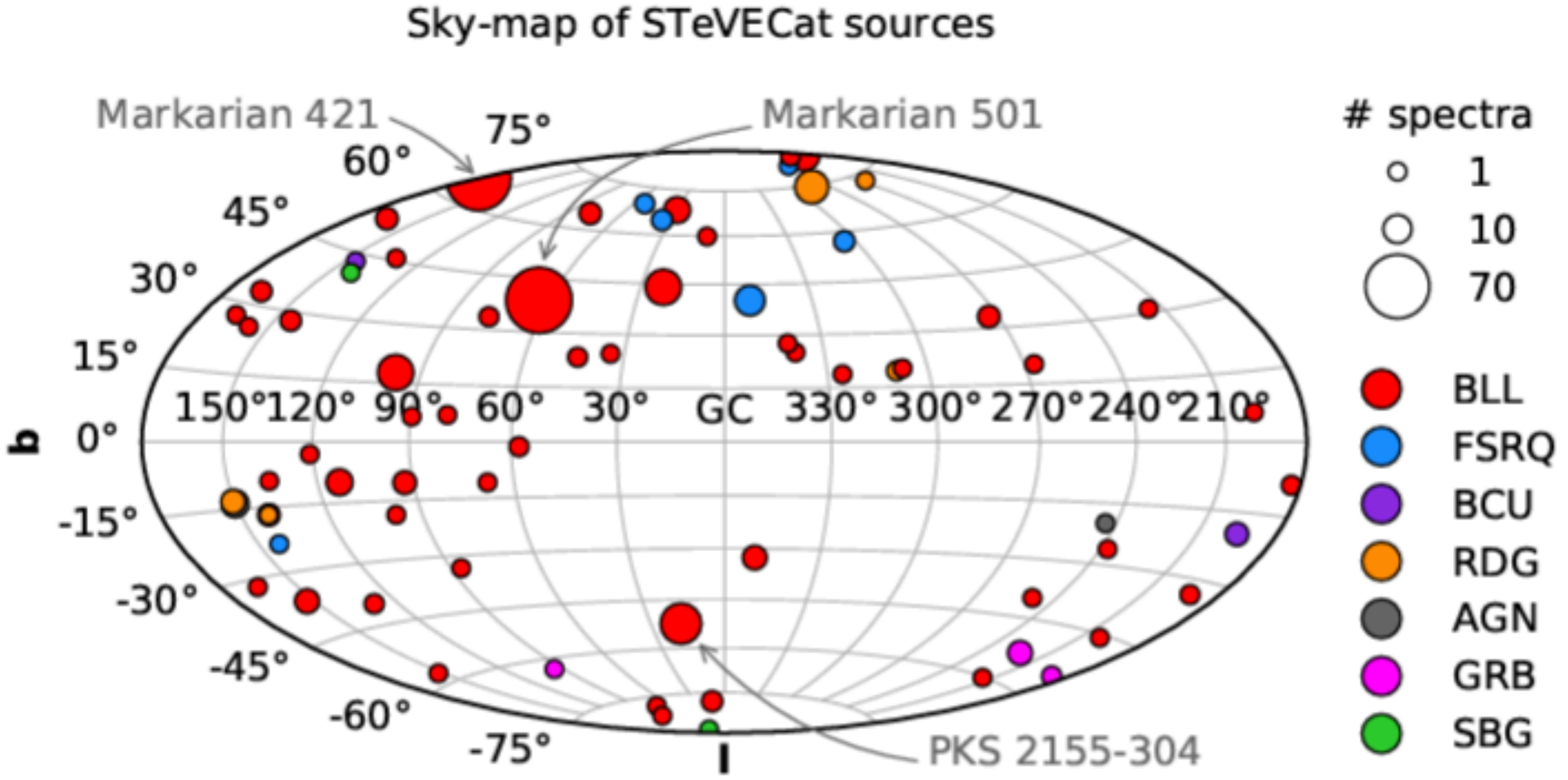


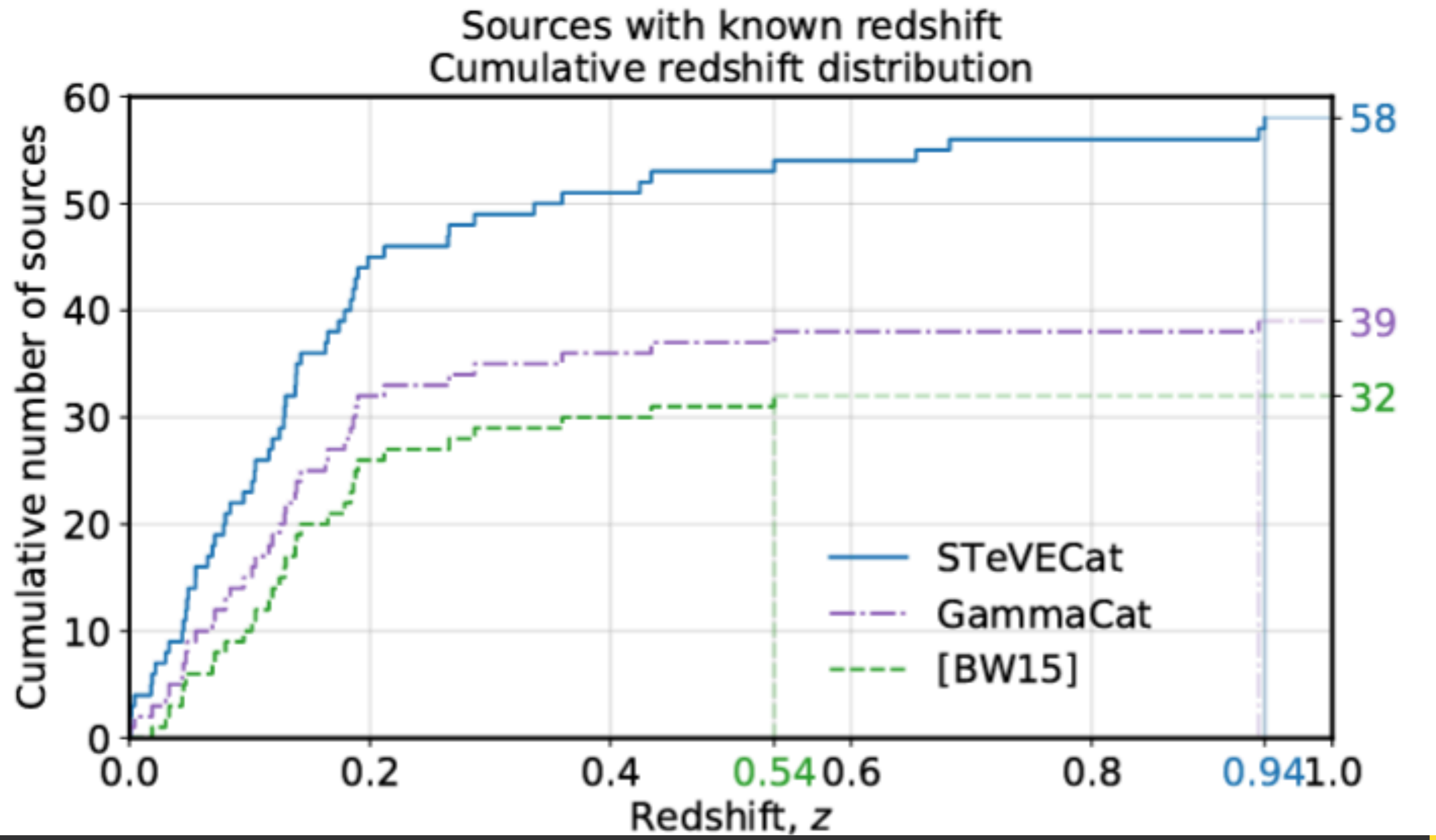
- 38 blazars taken for the dataset
- the first homogeneous measurement of the EBL spectral intensity covering the ultraviolet to infrared wavelengths (~ 0.1- 100μm)
- 2 redshift bins for the TeV Optical depth, with GeV optical depth data also incorporated to obtain the final EBL measurement.

New measurements of the TeV optical depth

Dataset: STeVECat

- the Spectral TeV Extragalactic Catalog, which gathers products of IACT observations from 1992 to 2021
- combines observations from 173 journal publications, compared to 72 in the previous reference compilation of extragalactic gamma-ray spectra
- The previous study that used the largest VHE sample was BW15, with 90 spectra from sources with known redshift.
- STeVECat collects **403** spectra from sources with known redshift in total





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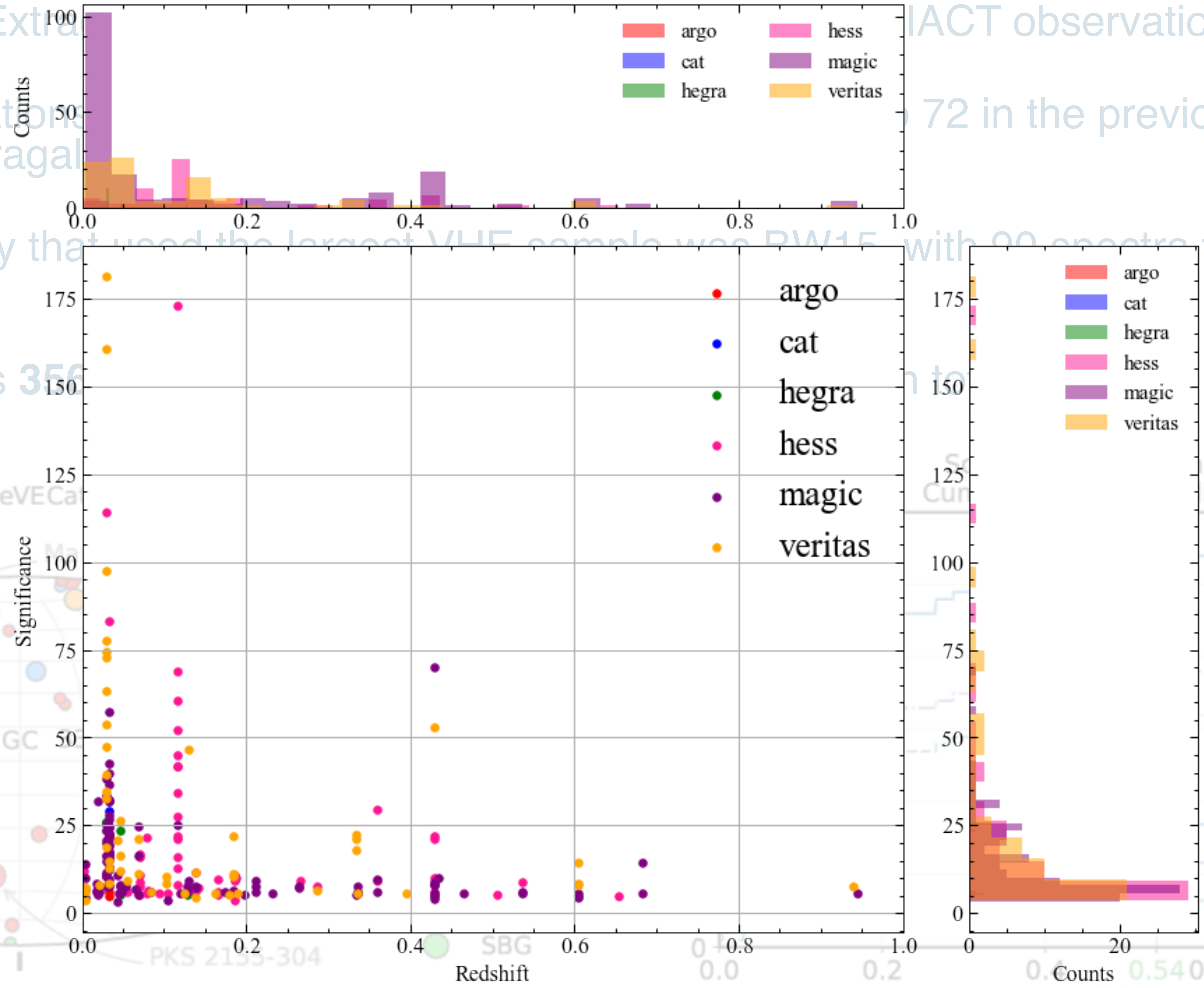


New EBL measurements using STeVECat

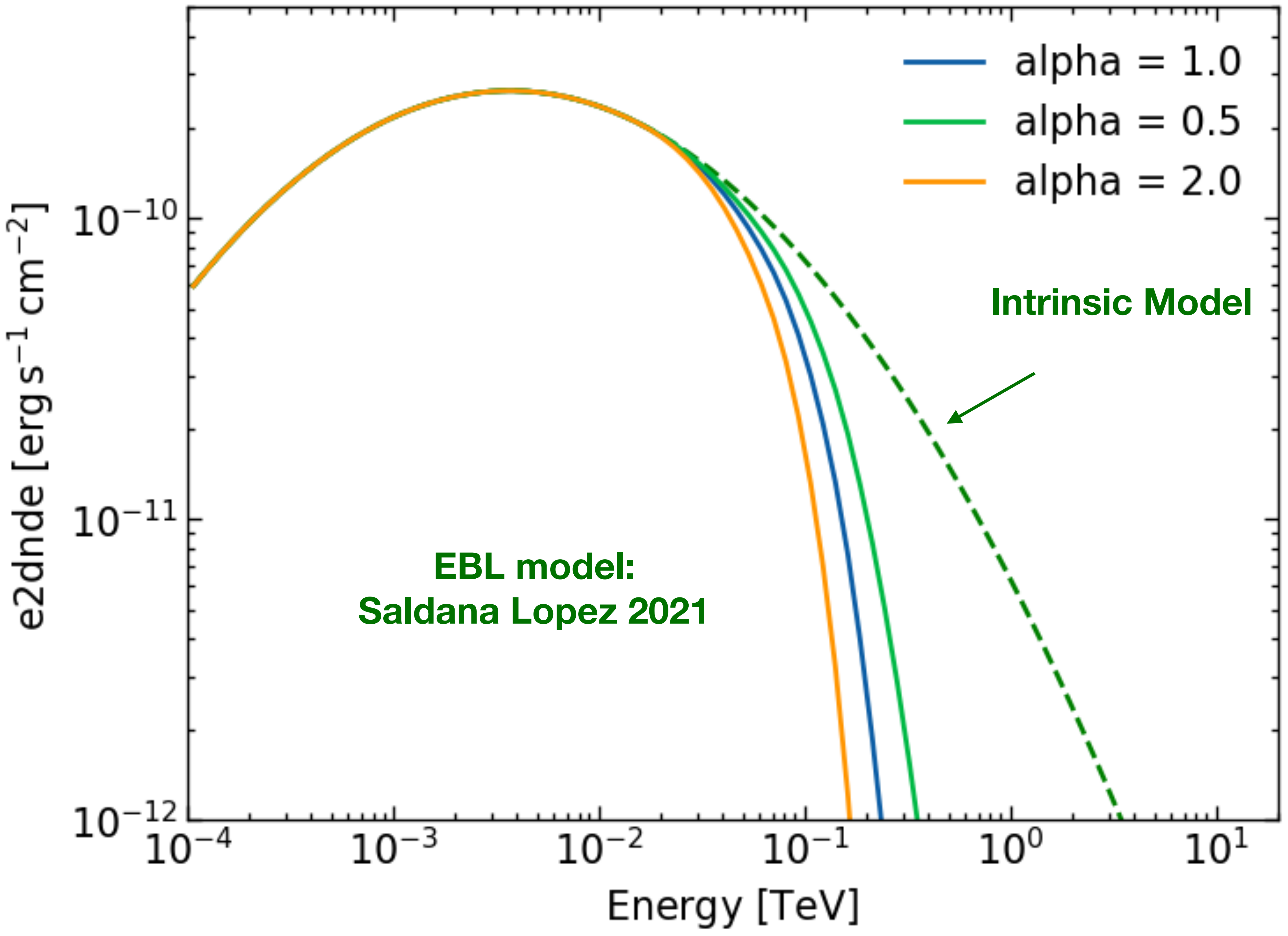
✦ How to measure the EBL

- Simple approach of doing this is to introduce one single scaling factor α against optical depth $\tau(E, z)$

$$\left(\frac{d\phi}{dE}\right)_{\text{observed}} = e^{-\alpha\tau(E,z)} \times \left(\frac{d\phi}{dE}\right)_{\text{intrinsic}}$$

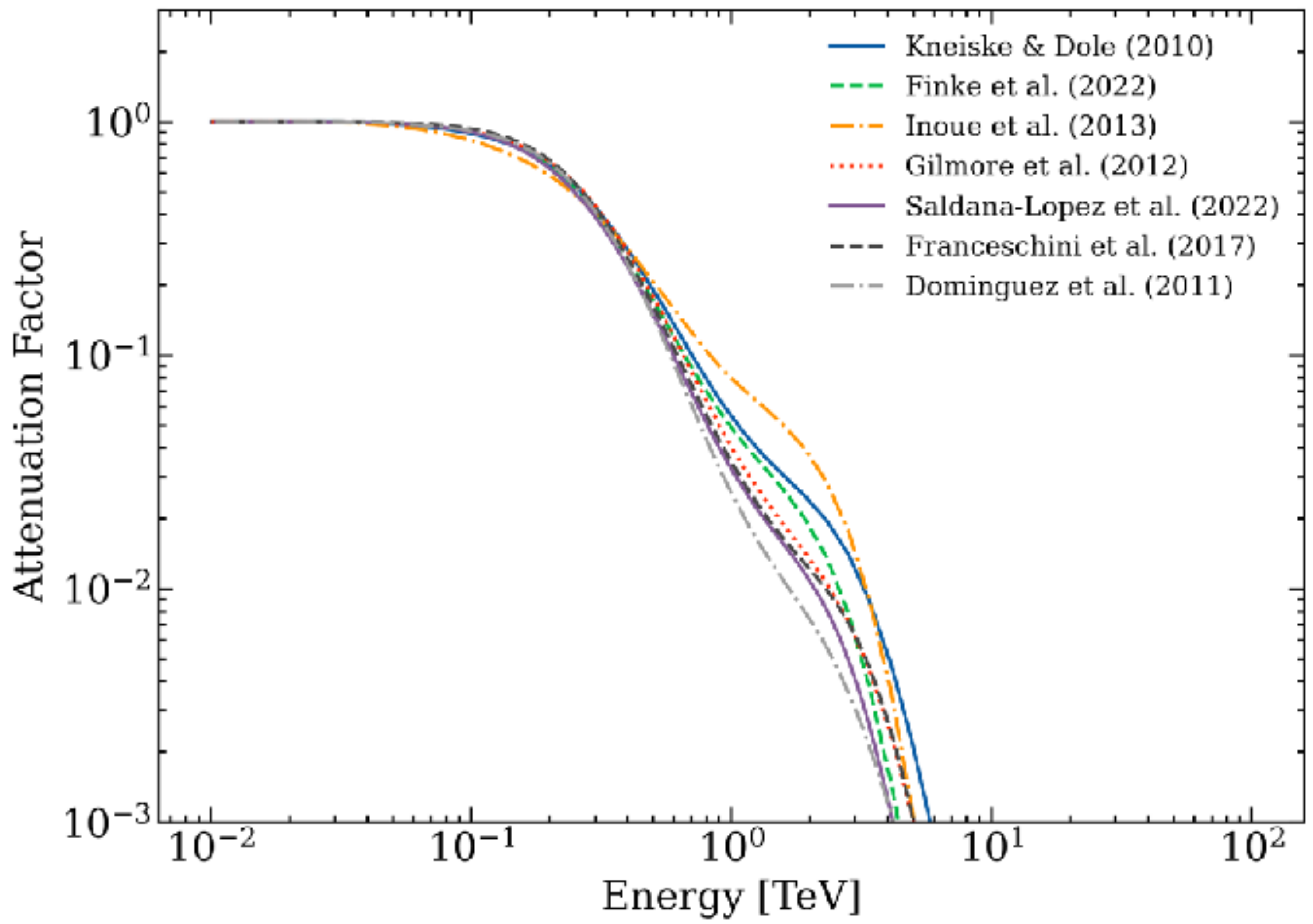
Perform the standard fitting through a Maximum Likelihood Method and perform a likelihood ratio test between the hypothesis for which α = 1 and the other hypothesis, for which α is free (0.2 ~ 2.5),

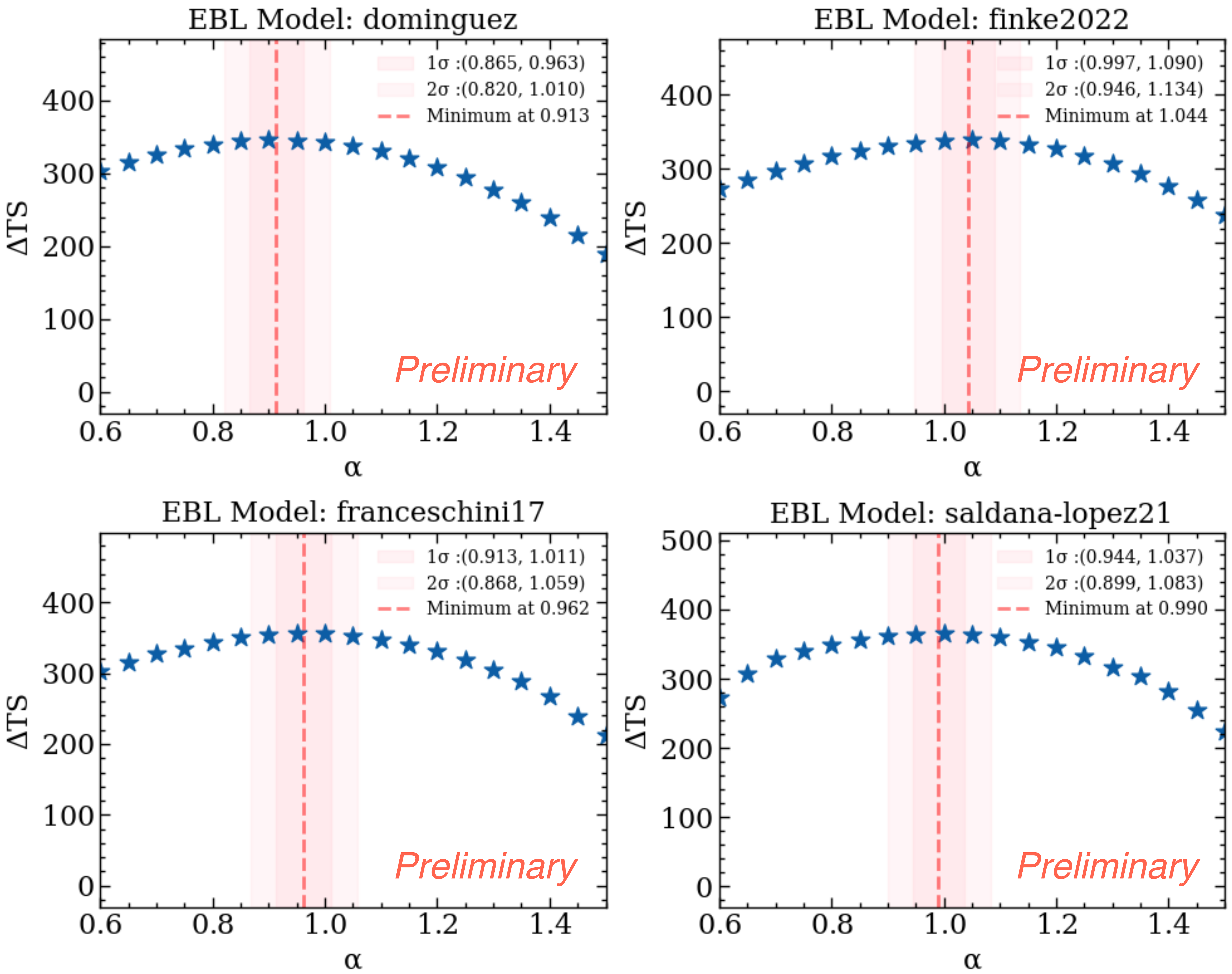
5. Plot the χ^2_{red} distribution and α_{best} is obtained with $(+\Delta\alpha_{+}, -\Delta\alpha_{-})$ uncertainty



New EBL measurements using STeVECat

- EBL measurement using profile maximum likelihood method has been performed using STeVECat
- All results are compatible with state-of-the-art EBL models!





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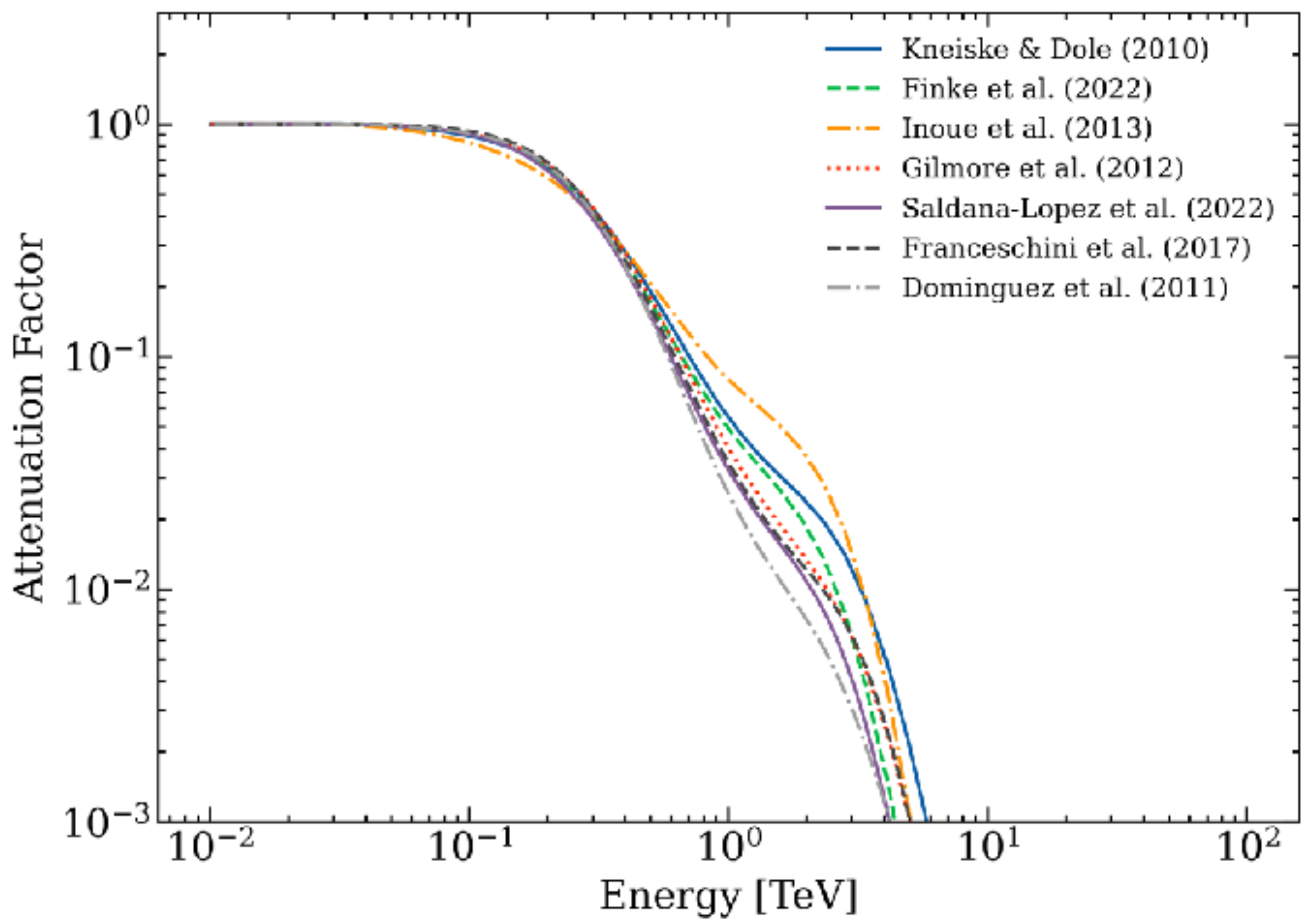

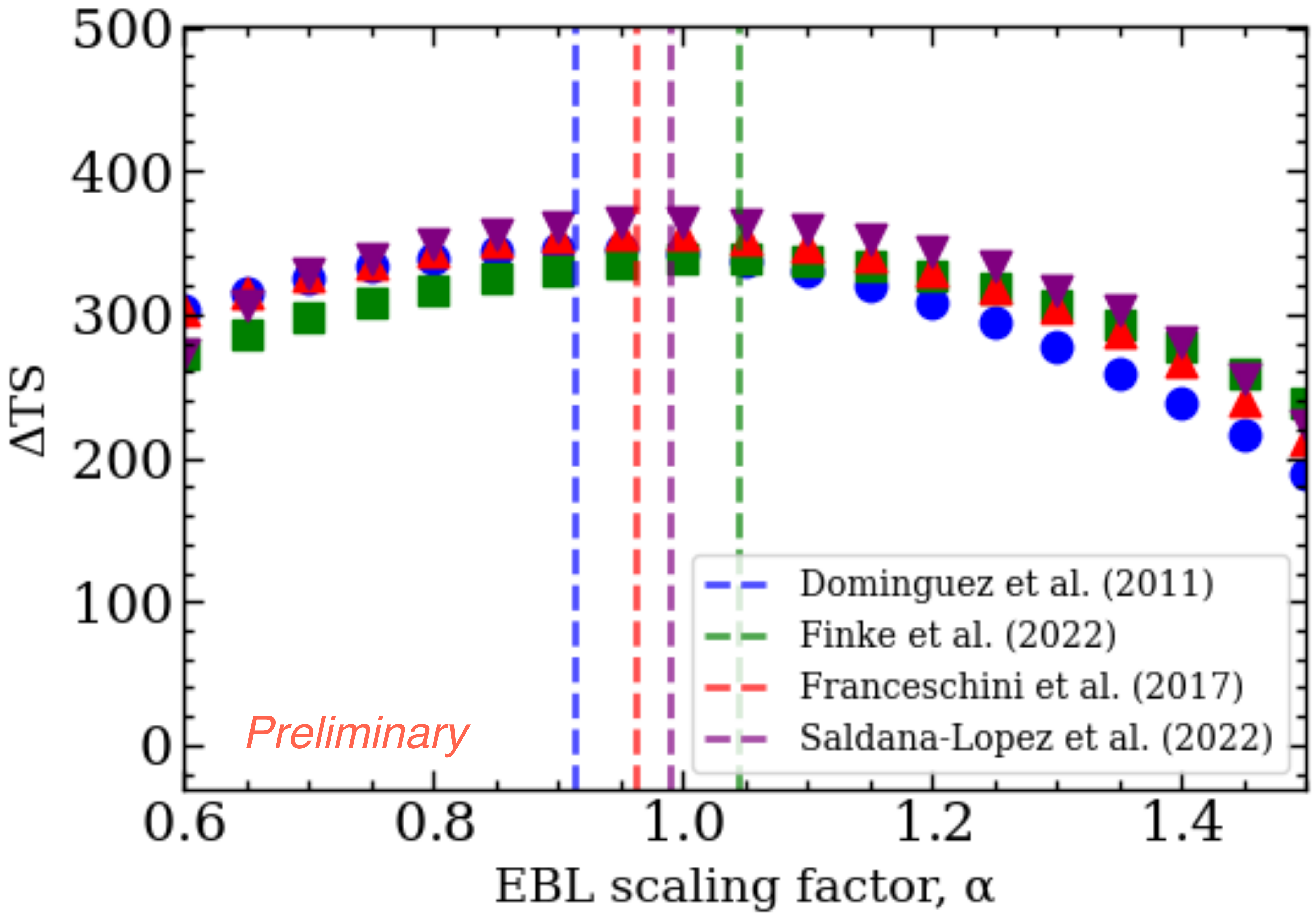

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Table 2.3: EBL density constraints (best-fit EBL scale factor α) using STeVECat

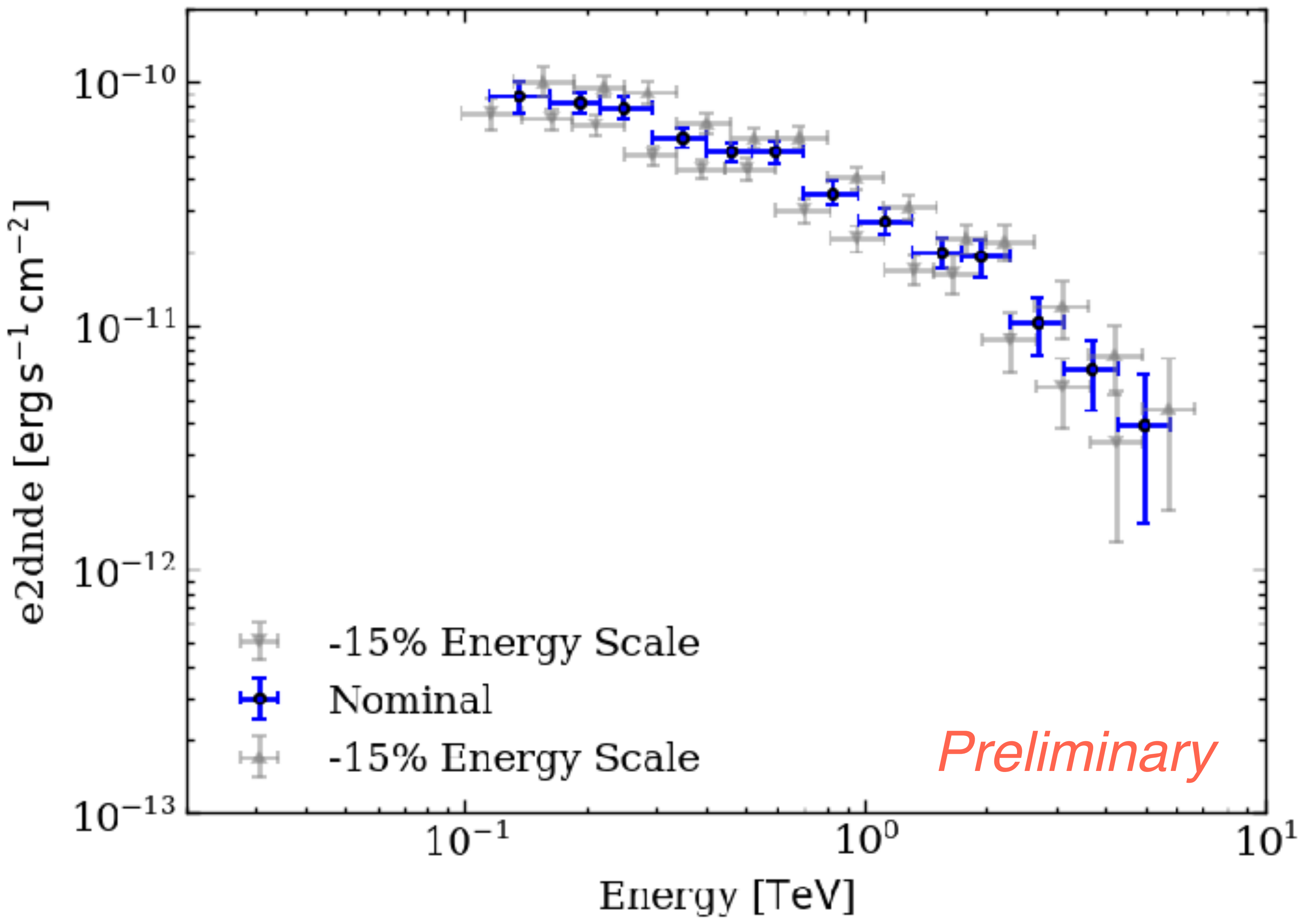
EBL Model	Best-fit α (68% C.I.)	Best-fit α (95% C.I.)	$R^{\sigma}(\alpha = 1)$	$R^{\sigma}(\alpha = 0)$	ΔTS
Dominguez et al. (2011)	$0.91^{+0.05}_{-0.05}$	$0.91^{+0.08}_{-0.08}$	$1.8\ \sigma$	$18.6\ \sigma$	345.6
Finke et al. (2022)	$1.04^{+0.05}_{-0.05}$	$1.04^{+0.10}_{-0.09}$	$0.93\ \sigma$	$18.4\ \sigma$	339.1
Franceschini et al. (2017)	$0.96^{+0.05}_{-0.05}$	$0.96^{+0.09}_{-0.09}$	$0.79\ \sigma$	$18.9\ \sigma$	356.0
Saldana-Lopez et al. (2022)	$0.99^{+0.05}_{-0.05}$	$0.99^{+0.08}_{-0.09}$	$0.21\ \sigma$	$19.1\ \sigma$	365.1
Gilmore-fixed et al. (2012)	$1.03^{+0.06}_{-0.08}$	$1.03^{+0.11}_{-0.12}$	$0.8\ \sigma$	$19\ \sigma$	368.5
Inoue et al. (2013)	$1.05^{+0.12}_{-0.04}$	$1.05^{+0.17}_{-0.07}$	$1.2\ \sigma$	$15.4\ \sigma$	324.2
Kneiske & Dole (2010)	$1.12^{+0.06}_{-0.05}$	$1.12^{+0.11}_{-0.10}$	$2.4\ \sigma$	$18.4\ \sigma$	339.6

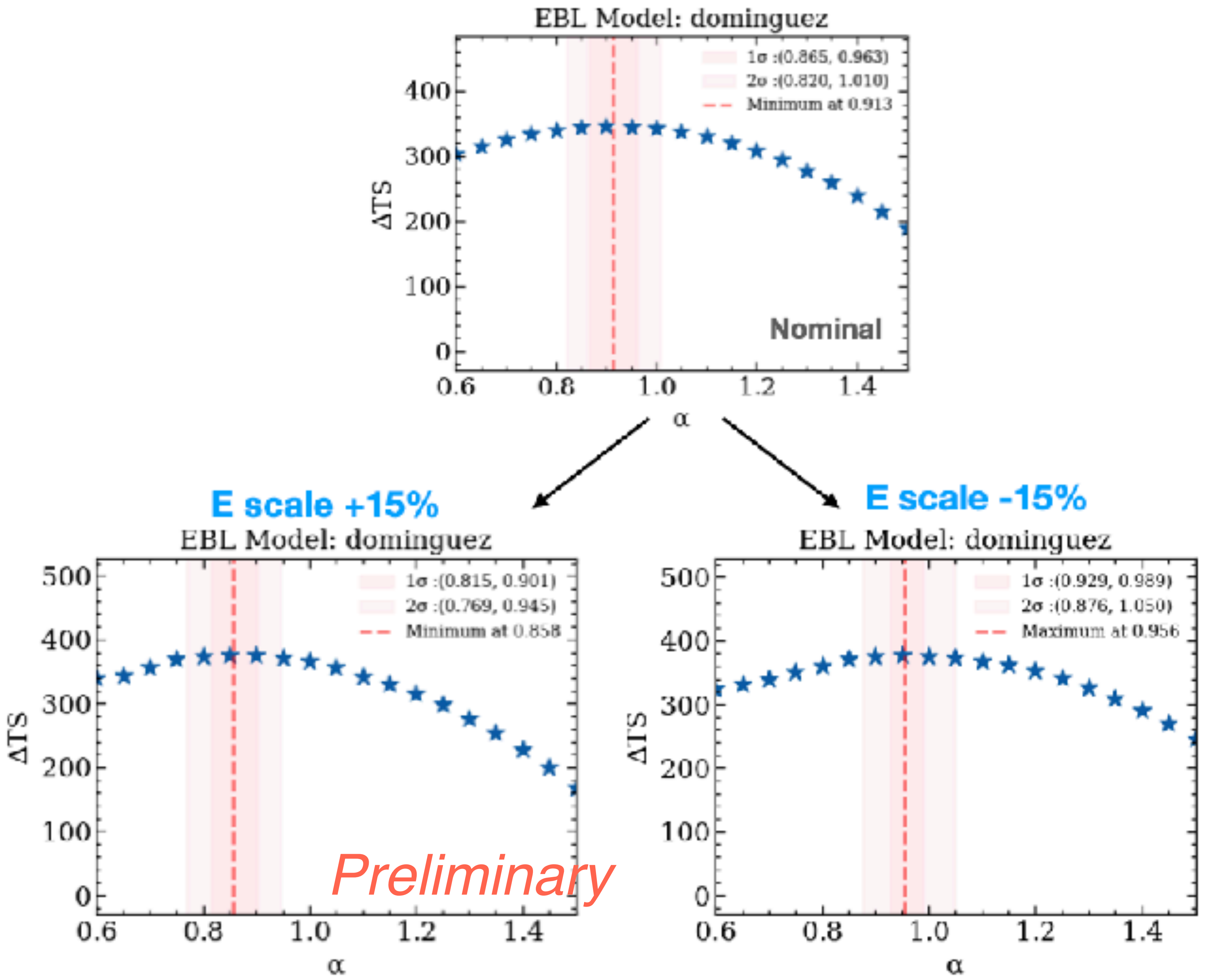
Including systematics

- The following two sources of systematic errors were considered:

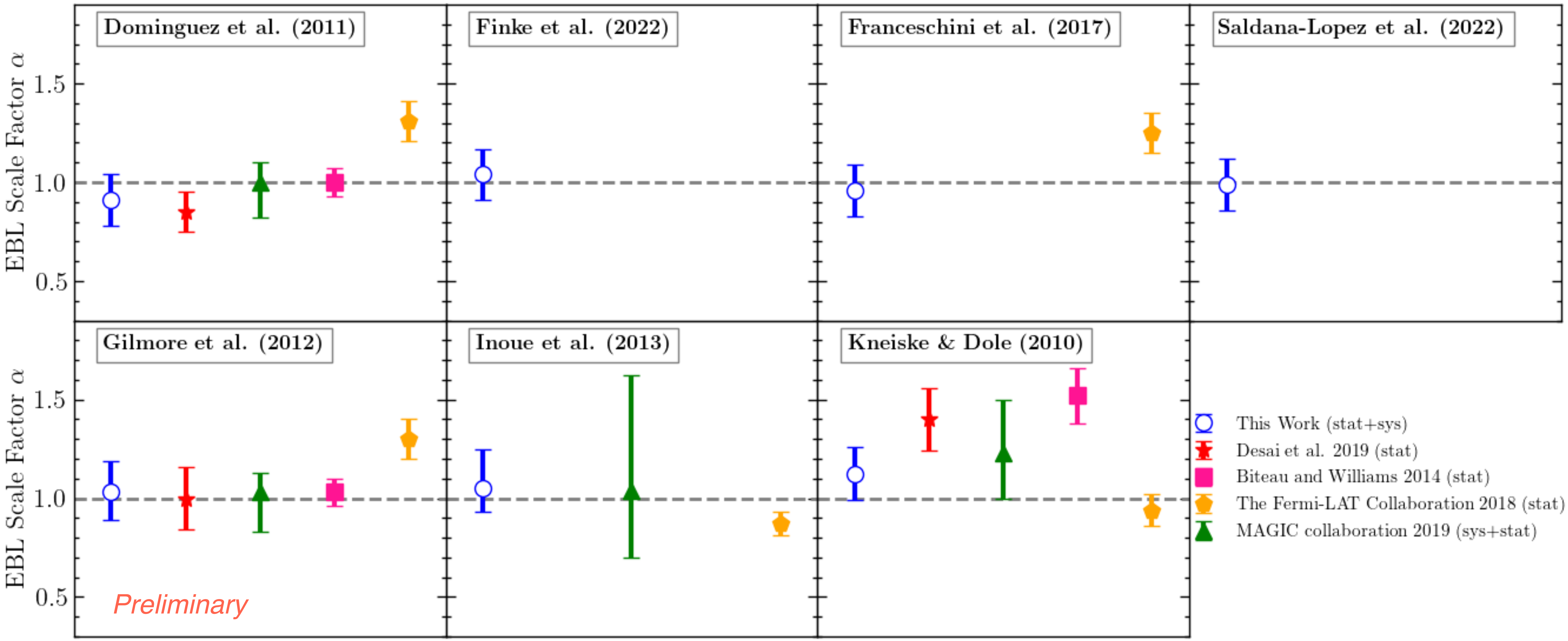
  ✓Introducing a ±15% variation in the energy scale and evaluating its impact on the EBL scale factor.

  ✓Excluding the power-law model from the model selection and assessing its impact on the EBL scale factor



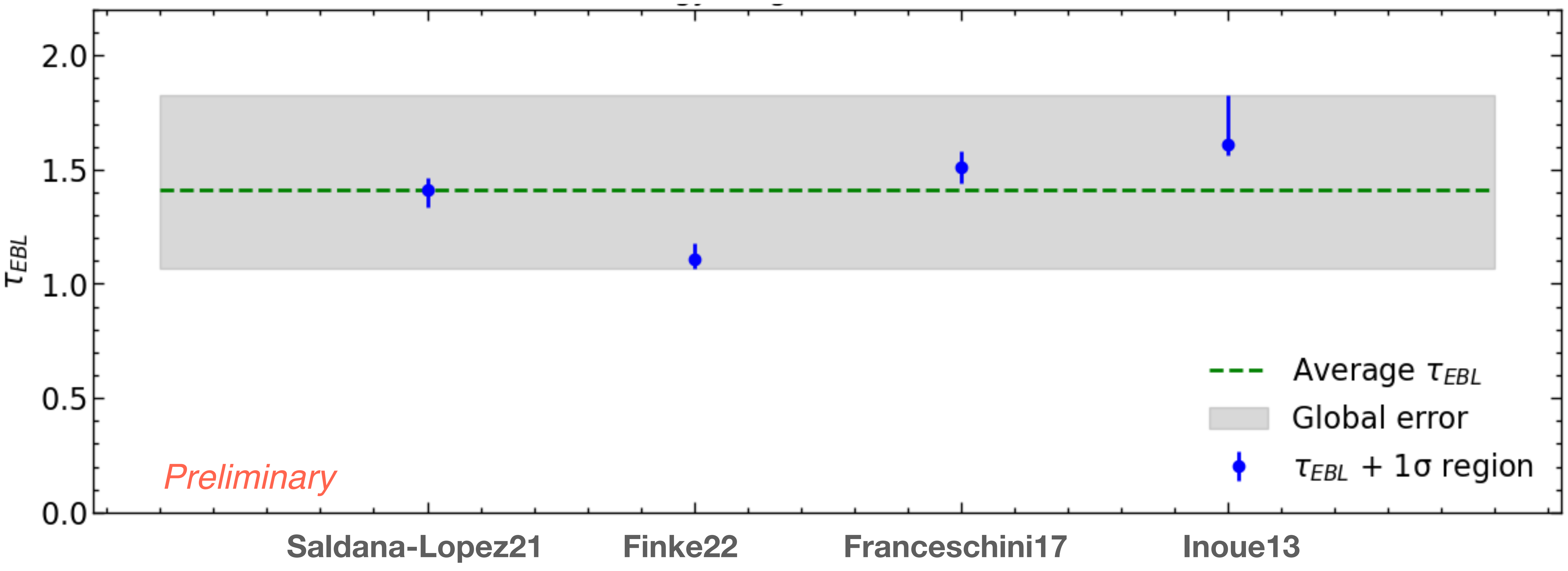


Results: New EBL measurements using STeVECat



TeV Optical Depth Measurements

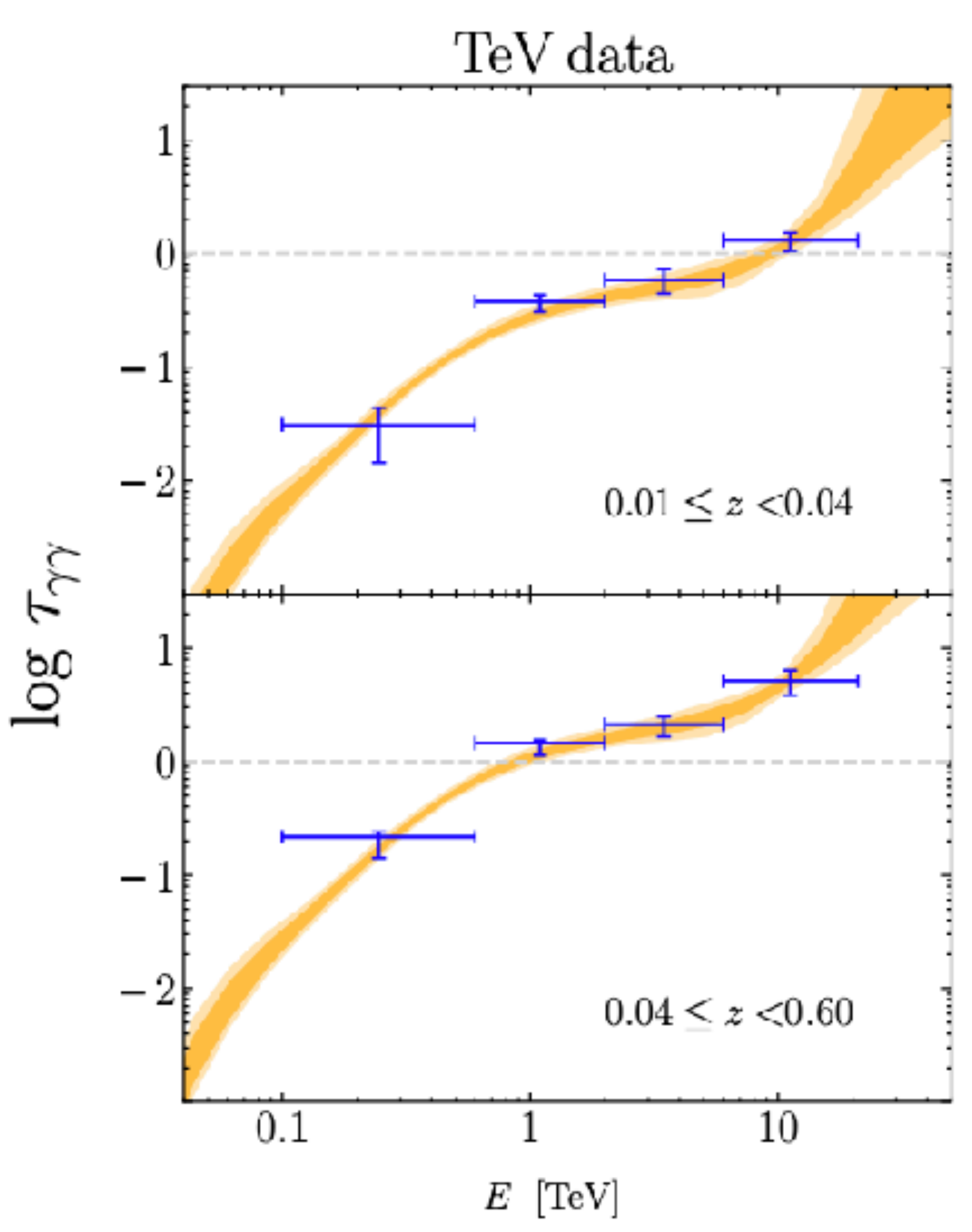
- For each energy and redshift bin, a stacked TS vs scaling factor profile is derived
- In a given energy and redshift bin, the optical depth is determined as the average of the four individual optical depth measurements, each derived using a different EBL model.
  - The uncertainty is set to cover the full range of uncertainties from all four optical depth measurements.
- Redshift bins are chosen such that they contain the same signal strength



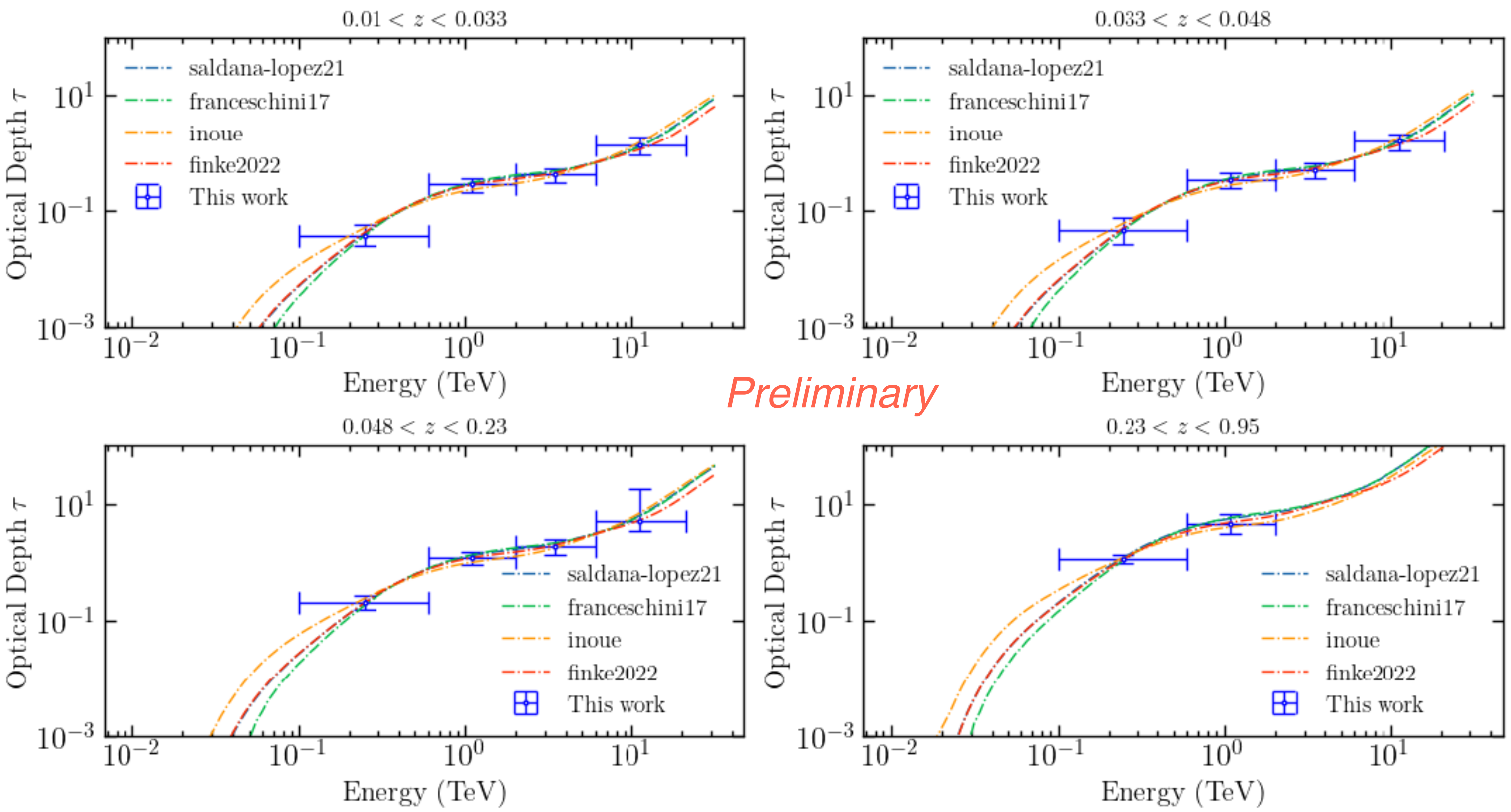
TeV Optical Depth Measurements

- We refined the redshift binning to achieve similar TS values across each bin against Desai et al. 2019, allowing us to double the resolution in optical depth measurements
- The representative redshift for each bin was determined by calculating the TS-weighted average of sources within that bin

Desai et al. 2019



This work



Prospects and Conclusion

Outlook

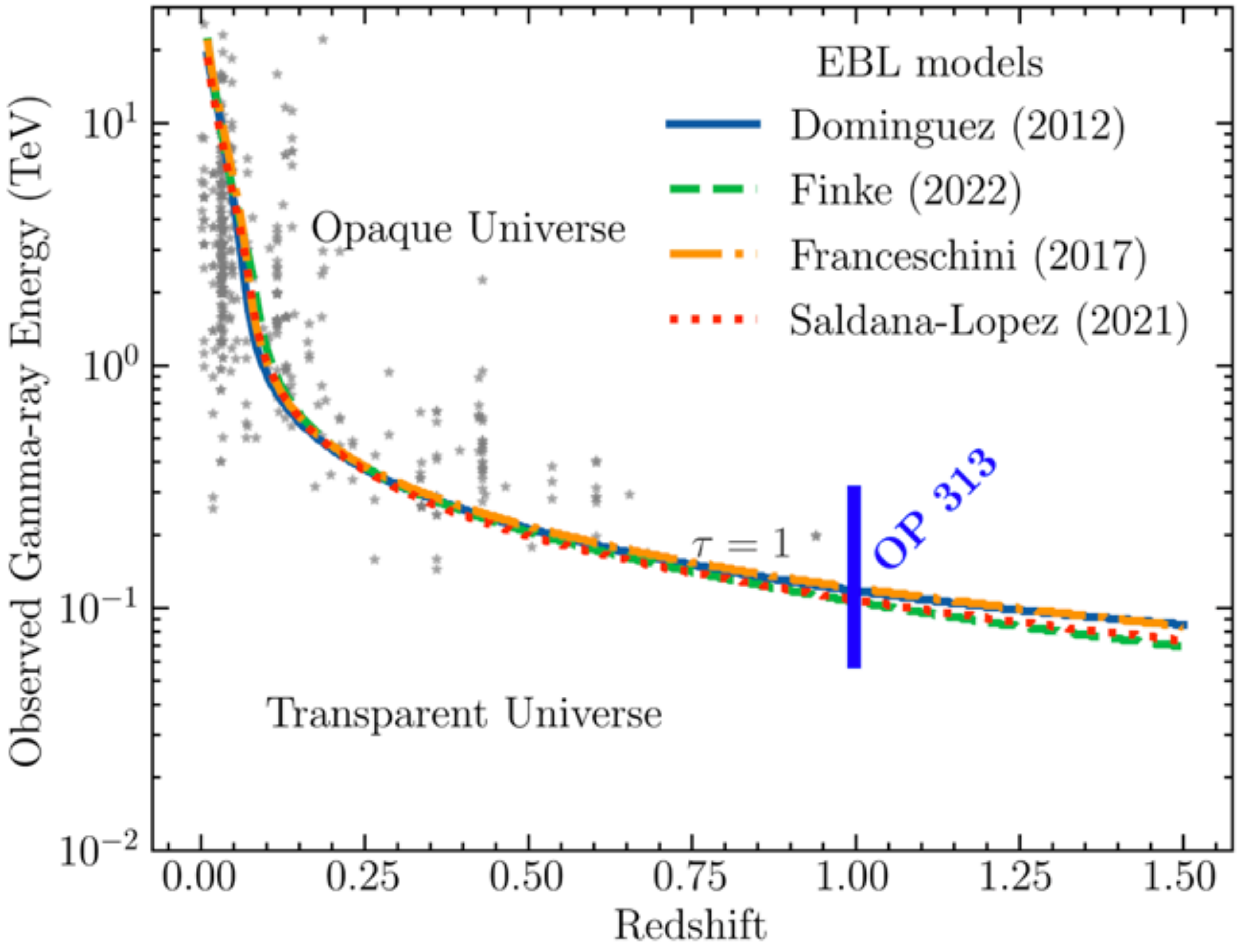
- On the Fermi-LAT side, work is currently underway in collaboration with Clemson University to update optical depth measurements using the 4FGL catalog and several of the latest EBL models
  - In Abdollahi et al. (2018), approximately **750 blazars** were analyzed, but we now plan to use around **1,500 blazars**
- Both sides—this work on the TeV range and Fermi's GeV optical depth—are working toward **reconstructing the EBL based on the updated optical depth measurements**, so stay tuned for the publication.
  - Naturally, this could also lead to **new constraints on the Hubble constant**, though EBL model dependence remains an issue
- While the STeVECat is a comprehensive and excellent catalog, to achieve a truly accurate estimate of systematic errors (which significantly impact EBL measurements), **it is essential to reconstruct the EBL starting from the data level (DL3), including the IRF**
  - Given the current dataset, the next logical step is a comprehensive EBL study, collecting data at the DL3 level from HESS, VERITAS, MAGIC
- Since around 2020, the CTAO's Prototype Large-Sized Telescope (LST-1) has started observations, and **it recently detected VHE gamma rays from the blazar OP 313, the most distant (z = 0.997) blazar observed so far in the VHE range**
  - This result suggests that the LST is already beginning to expand the observable universe in the VHE range
- Btw, as a realistic projection, with 4 LSTs, **up to what redshift** might we expect to observe?

OP 313: The New Kid on the VHE Cosmic Block!

Thanks to the low energy threshold of LST-1, we detected the first VHE emission from OP 313 during its flare state in December 2023

- First scientific discovery of the LST-1: ATel #16381
- Furthest FSRQ (z = 0.997) ever detected in VHE by IACTs (Schneider et al., 2010)
  - The **10th** VHE FSRQ

LST-1 is pushing the limit of the observable VHE universe!



The Astronomer's Telegram

First detection of VHE gamma-ray emission from FSRQ OP 313 with LST-1

ATel #16381; *Juan Cortina (CIEMAT) for the CTAO LST collaboration*

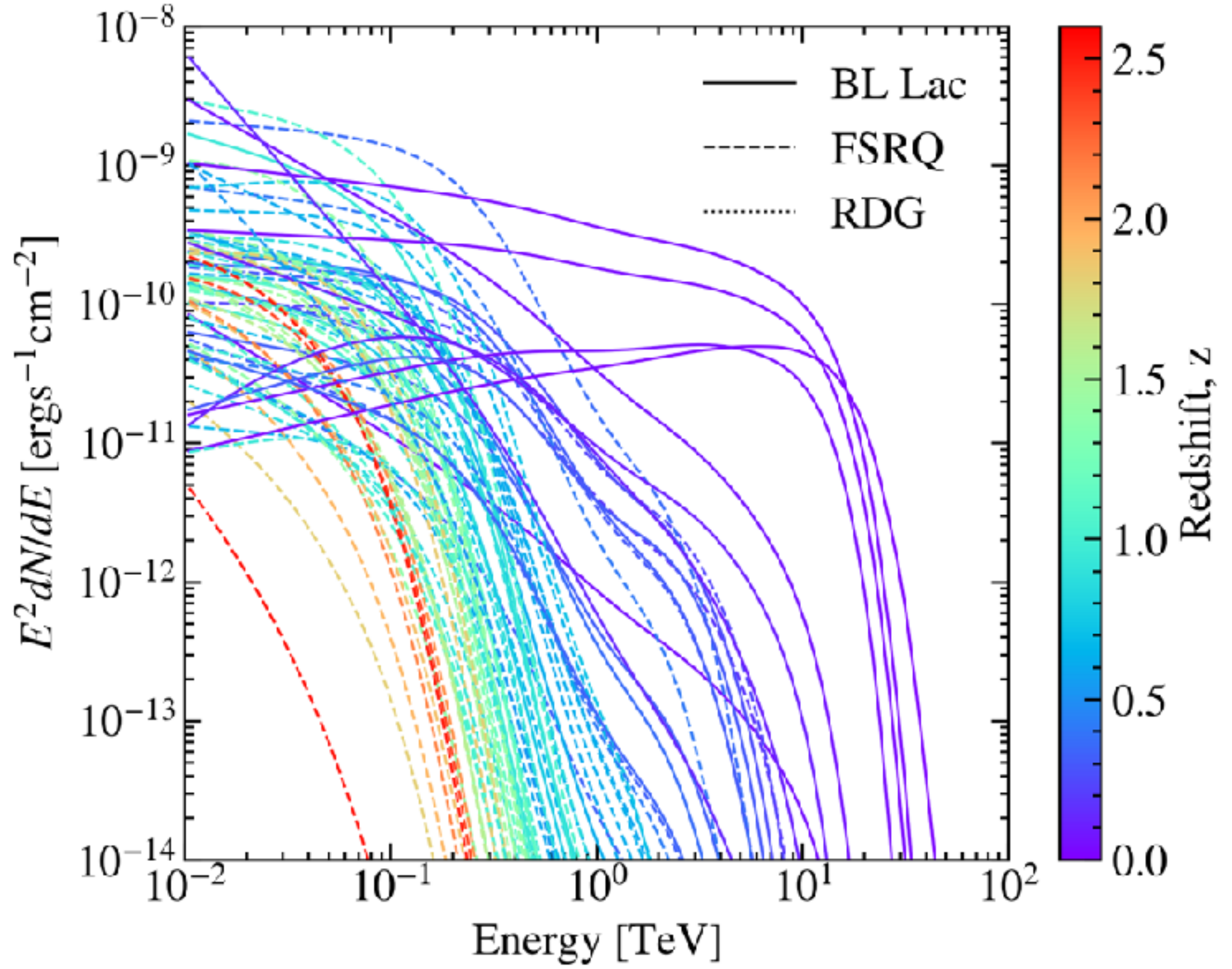
*on **15 Dec 2023; 14:31 UT***

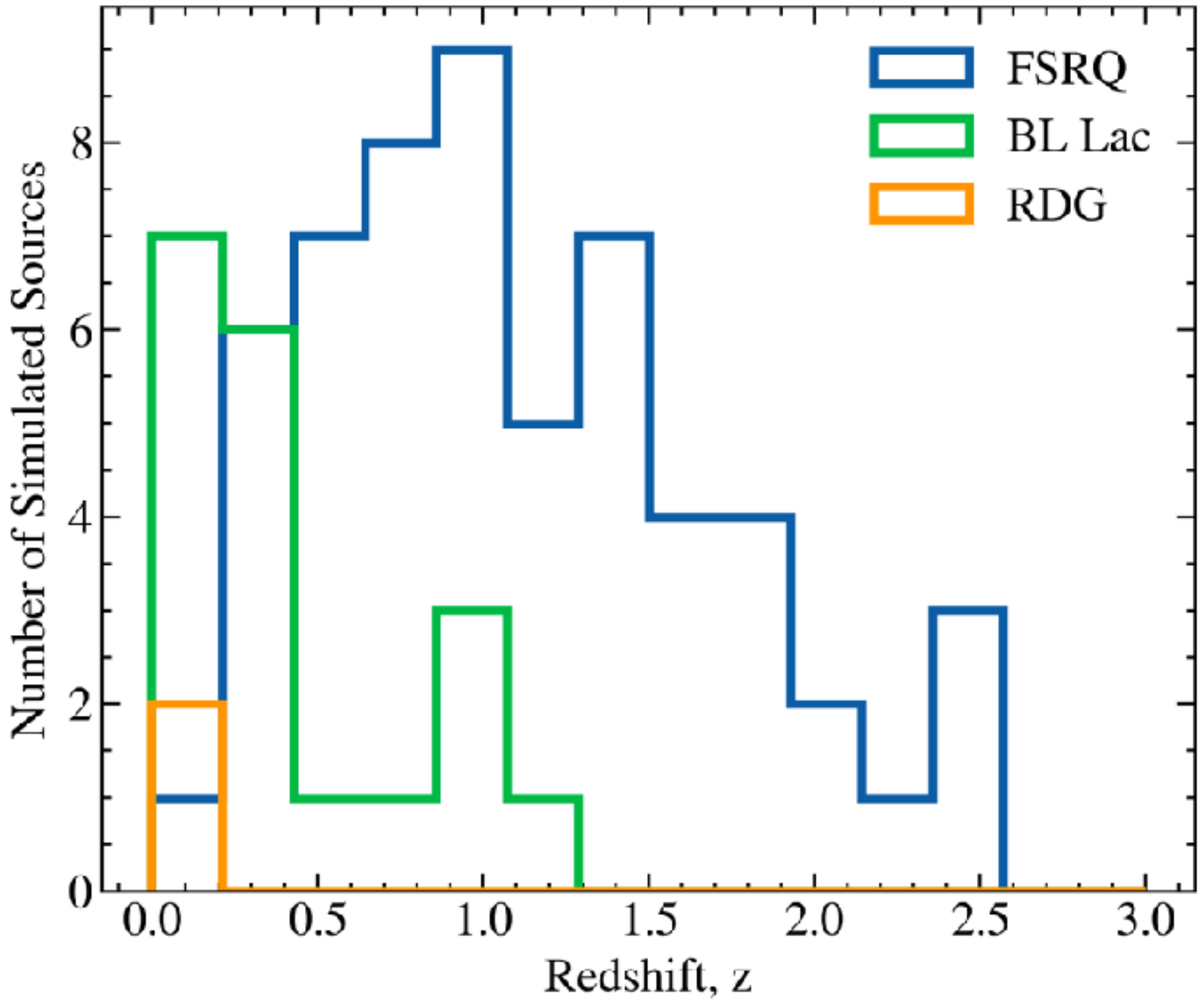
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, AGN, Blazar, Quasar

How far we can see with 4LSTs?

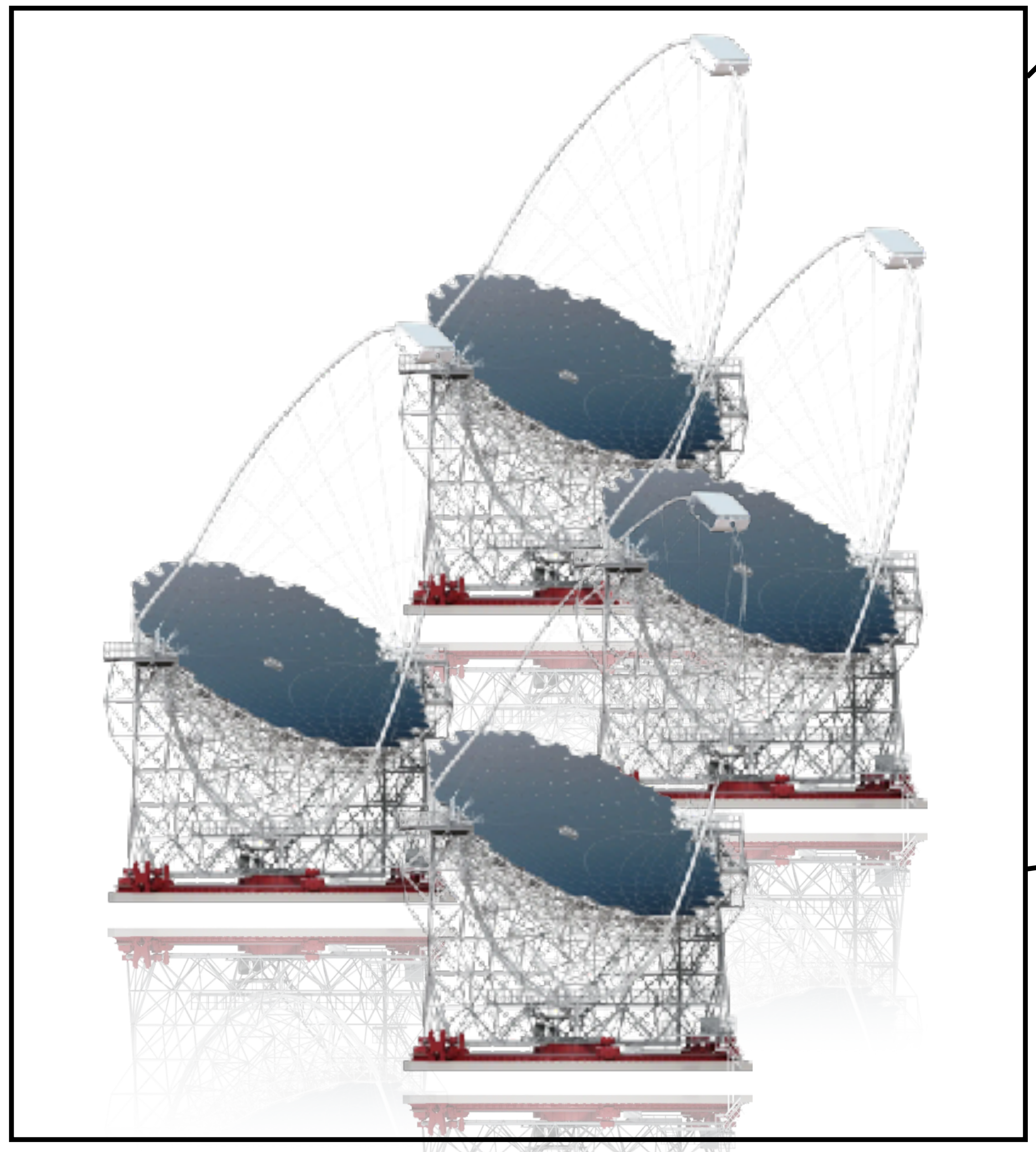
- Flare sample taken from the CTA Cosmology KSP paper: "Sensitivity of the Cherenkov Telescope Array" for Probing Cosmology and fundamental physics with gamma-ray propagation" (Table 4-5)
- EBL (Saldana-Lopez 2021) absorption based on its redshift
  - Altitude, Nighttime, Moon constraint considered
  - Exposure: 10 hours for each source

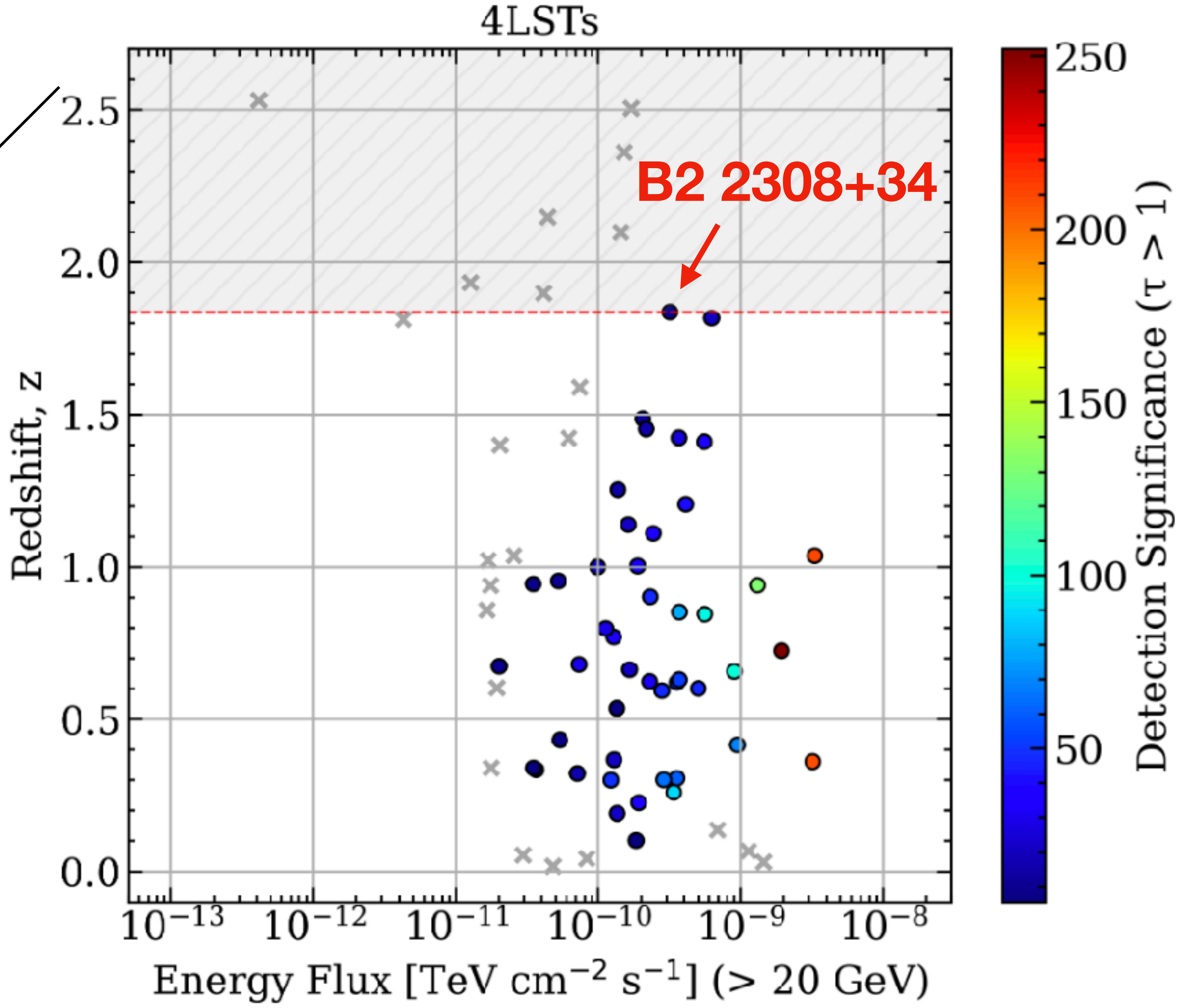




How far we can see with 4LSTs?

- With four LSTs, the detectable range in energy regions strongly affected by EBL absorption (where $\tau > 1$) is expected to reach up to approximately $z \sim 1.8$.
- For samples at $z > 2.0$, placing stringent constraints on the EBL remains challenging, meaning this range continues to be primarily within Fermi-LAT's domain





Conclusion

- By leveraging the STeVECat catalog, we achieved optical depth measurements with **twice the redshift resolution of previous studies**, providing finer insights into EBL absorption effects across redshift

- Efforts are underway on the Fermi side to update previous measurements, and we are now combining all available data to achieve the highest precision EBL measurements to date

- The **LST-1 on the CTA has already expanded VHE observations to unprecedented redshifts** ($z = 0.997$, OP 313).

    - With additional LSTs, we anticipate extending this range to around $z \sim 2$, while continued work at GeV and TeV scales will provide new insights into both EBL and cosmological parameters, including the Hubble constant measurements