27/08/2018

TeV Particle Astrophysics Conference 2018

Extragalactic Background Light studies with the MAGIC telescopes

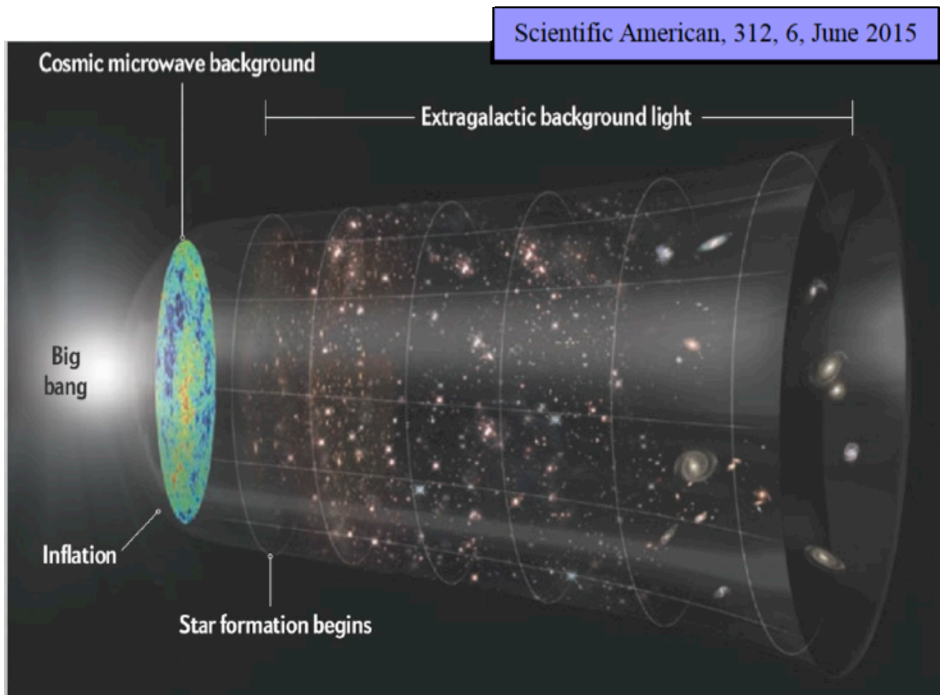
Mónica Vázquez Acosta - IAC

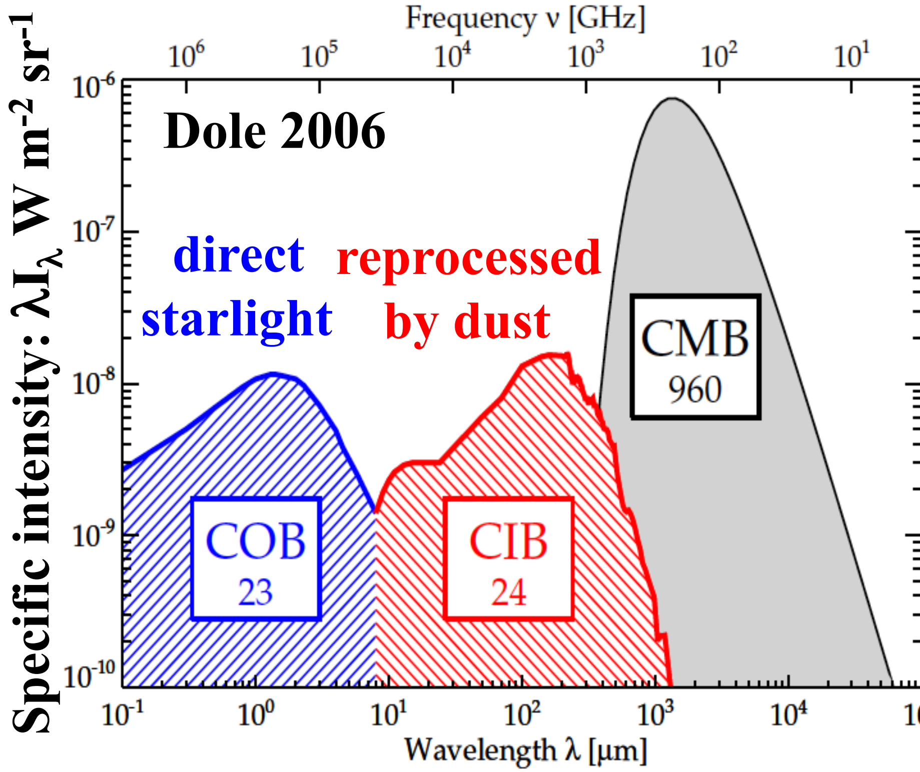
(on behalf of the MAGIC Collaboration)

Co-authors: A. Domínguez, V. Fallah Ramazani, T. Hassan, D. Mazin, A. Moralejo, M. Nievas Rosillo, E. Prandini, J. Sitarek, G. Vanzo

Extragalactic Background Light (EBL)

- **Optical-infrared diffuse background light accumulated during the history of the Universe, directly emitted by stars or reprocessed by dust**
- **Second largest diffuse background after Cosmic Microwave Background**
- **Contains crucial information on:**
  - **Star formation rate and galaxy evolution**
  - **Essential for energy balance of the Universe**



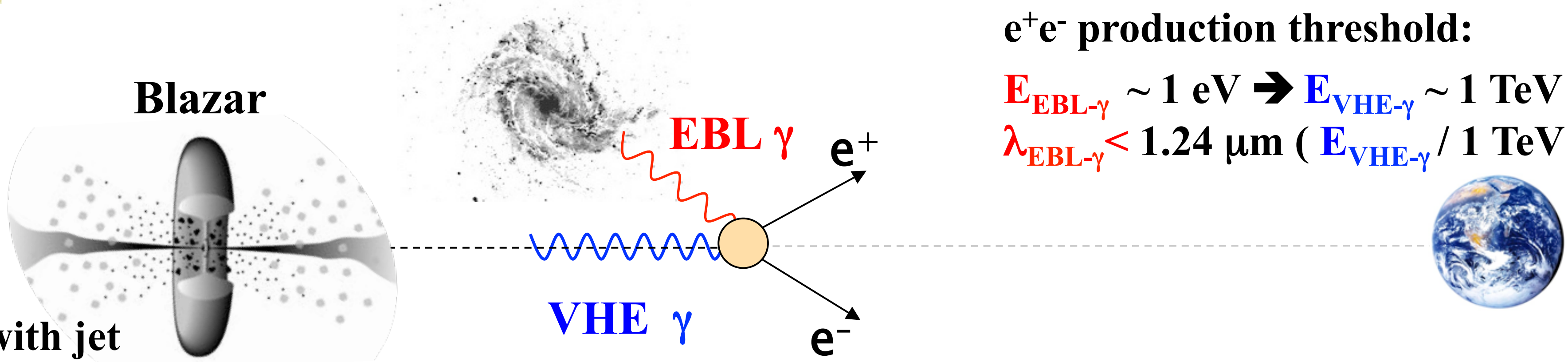


Gamma-rays as probe of EBL

e^+e^- production threshold:

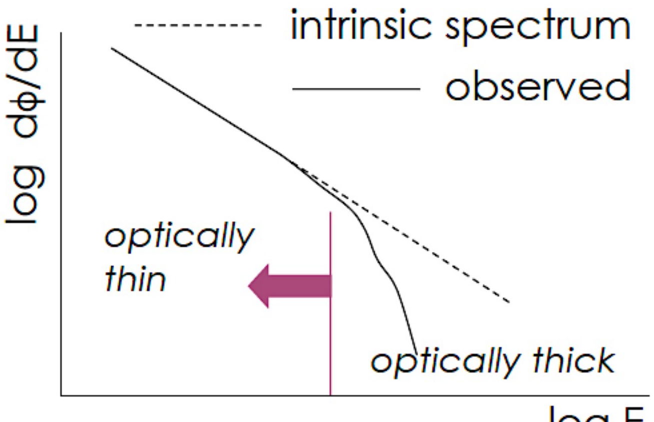
$E_{EBL-\gamma}$ ~ 1 eV ➔ $E_{VHE-\gamma}$ ~ 1 TeV

$\lambda_{EBL-\gamma} < 1.24\ \mu m\ (E_{VHE-\gamma} / 1\ TeV)$



AGN with jet
pointing to observer

- Very-high energy photons (gamma-rays) interact with EBL photons producing e^+e^- pairs
- The measured flux of gamma-rays from Blazars is attenuated due to EBL photons
- METHOD: use measured spectra of different blazars to probe EBL effects

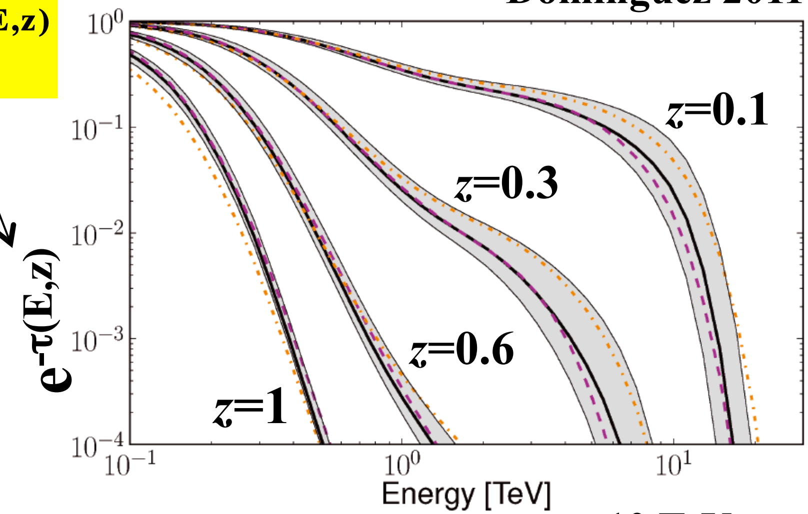


~ 100 GeV

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

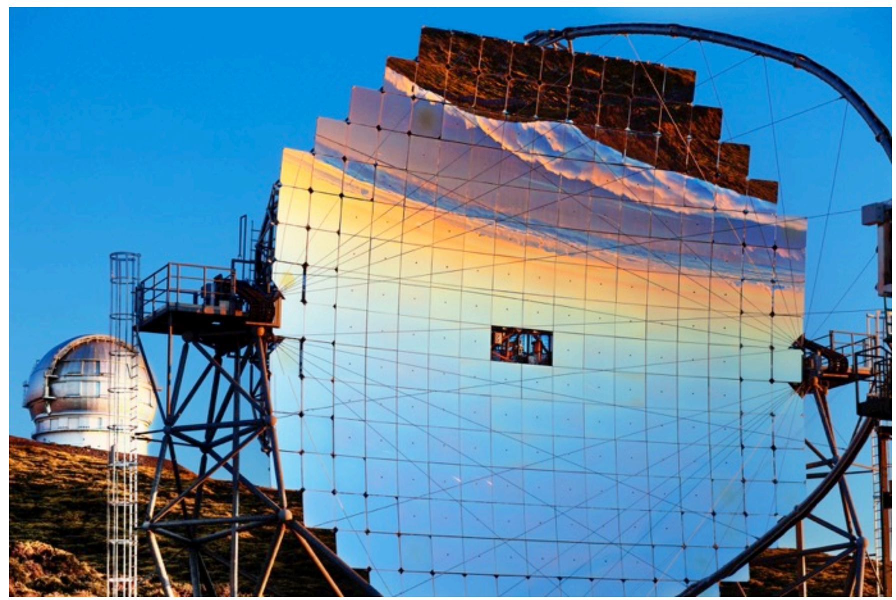
τ (E,z) : optical depth

Dominguez 2011



100 GeV 1 TeV 10 TeV

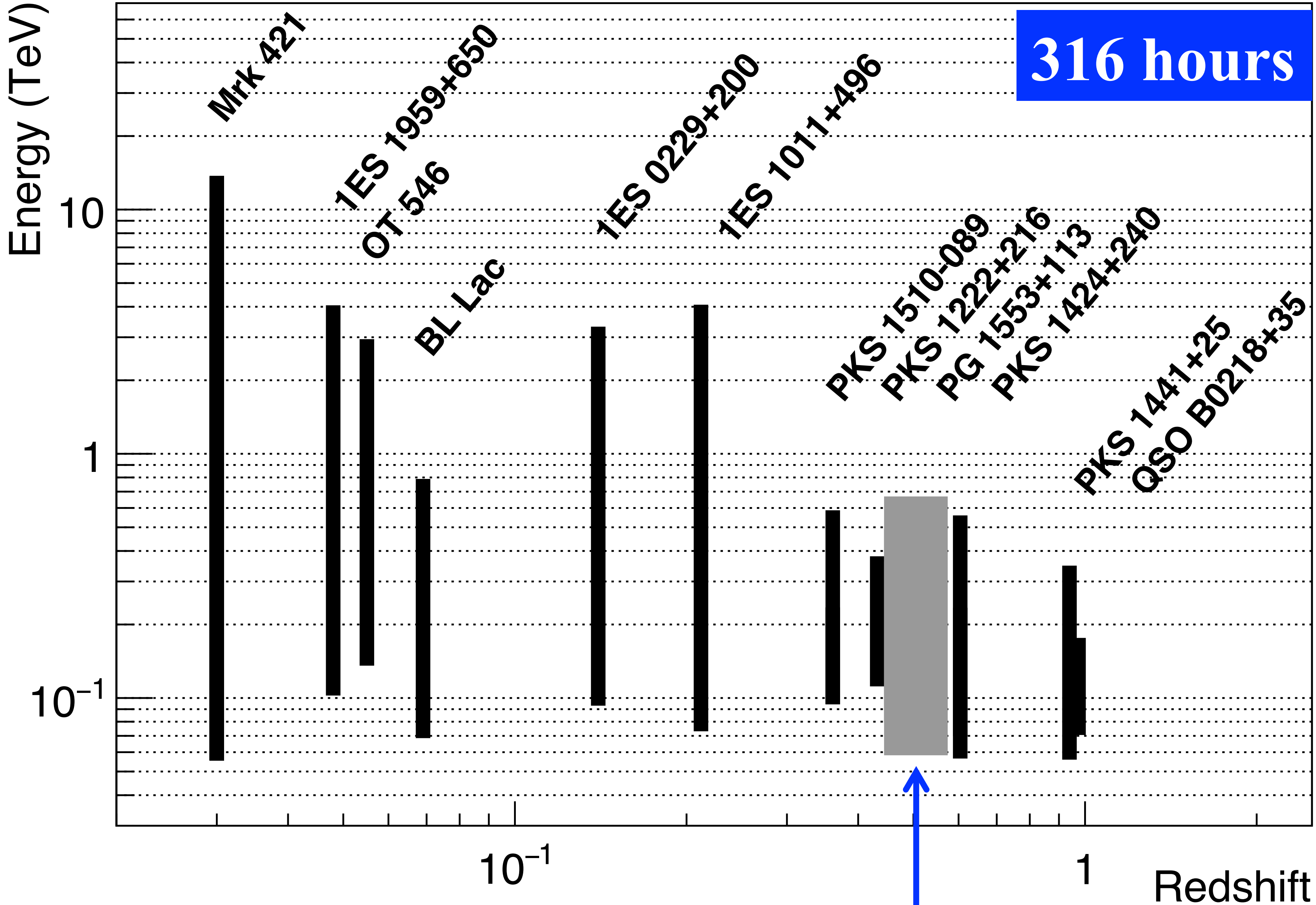
The MAGIC Telescopes @ORM



Two Cherenkov Telescopes of 17 meters in diameter

VHE-γ energy threshold: 50 GeV
Energy resolution: 15 – 25%
Field of view: 3.5°
Angular resolution: ~ 0.1°

MAGIC: Blazar sample for EBL studies



Energy: ~50 GeV-10 TeV, z: 0.030-0.944

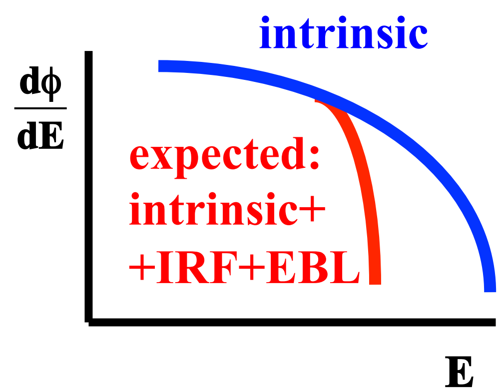
PG1553+113 (z: 0.43-0.58)

EBL measurement: Maximum Likelihood Fit

For each blazar **spectrum different functional forms of intrinsic spectra are assumed**

Function		# Parameters
EPWL	power-law with exponential cut-off	3
SEPWL	power-law with sub/super-exponential cut-off	4
LP	log-parabola	3
ELP	log-parabola with exponential cut-off	4

Power-law not considered to avoid all curvature of spectra attributed to EBL



The intrinsic spectra is folded with:

- **Instrument Response Function (IRF) of telescopes**
- **EBL model for the optical depth τ**

to obtain an expected spectra used to fit the data

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

Parameters in the likelihood fit:

- **parameters of intrinsic spectra function**
- **EBL scale: optical depth scaling parameter α**

The redshift of PG1553+113 is treated as a nuisance parameter in the fit (*z*: 0.43-0.58)

The intrinsic function with best fit p-value chosen

EBL models: extraction methods

1) **Forward evolution**: begins with **cosmological initial conditions** and follows a **forward evolution with time** with **semi-analytical models of galaxy formation** (eg. Gilmore 2012, Inoue 2013)

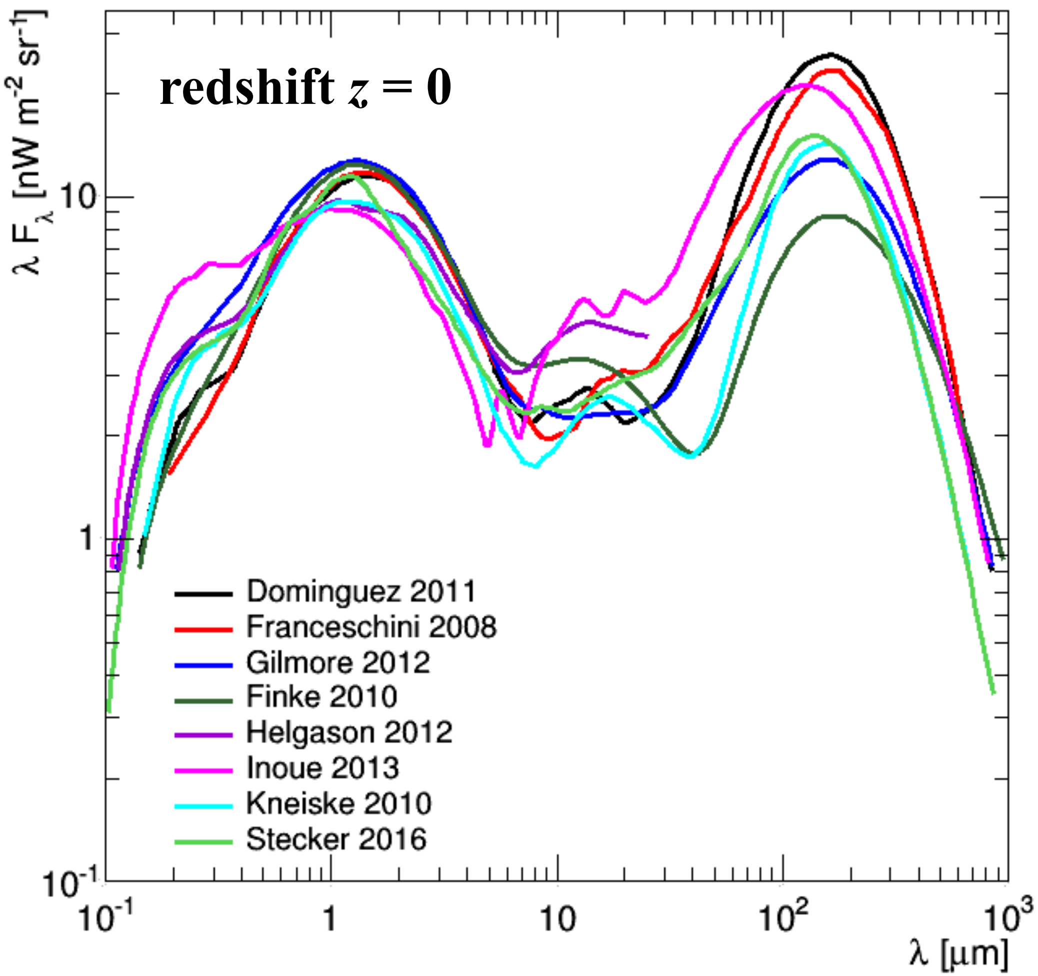
2) **Backward evolution**: begins with **existing galaxy populations** and **extrapolates them backwards in time** (eg. Franceschini 2008)

3) **Evolution of galaxy populations** inferred over a range of redshifts. The galaxy evolution is inferred **using some quantity derived from observations** such as the **star formation rate density of the Universe** (eg. Finke 2010, Kneiske 2010)

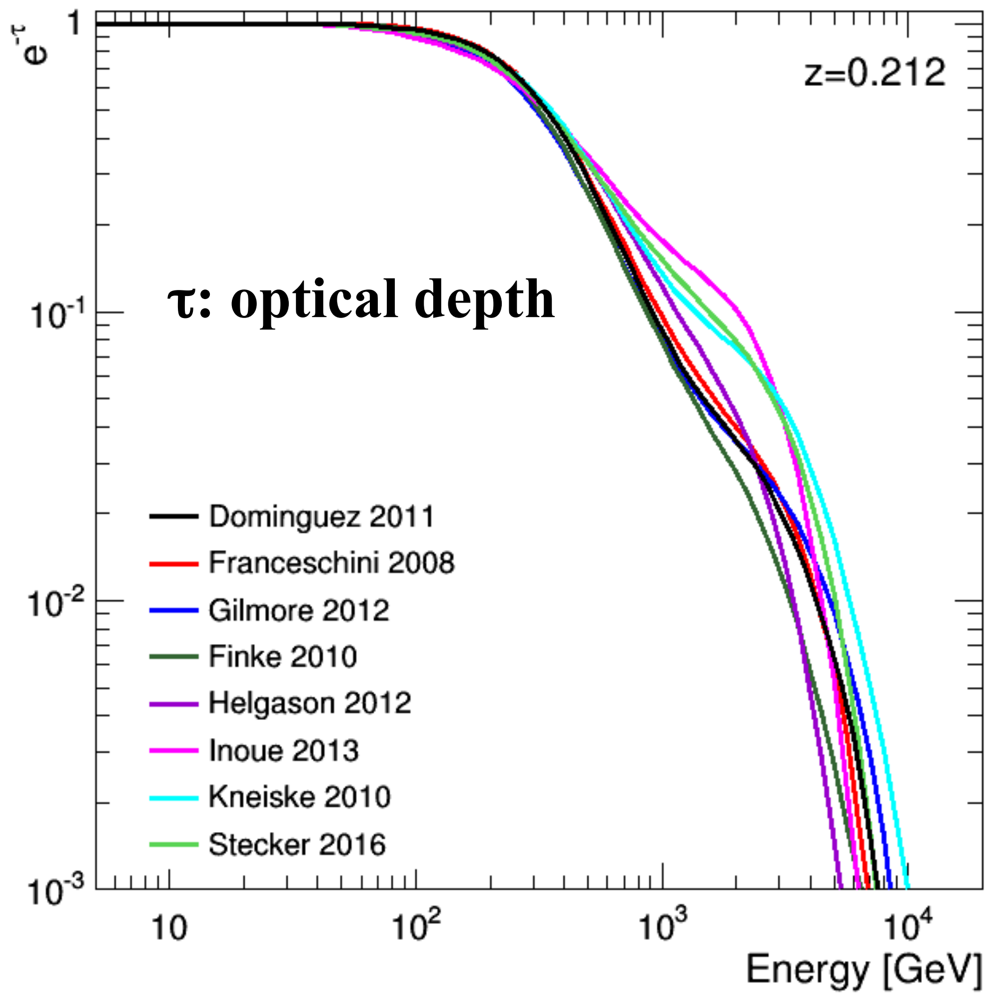
4) **Evolution of galaxy populations** that is **directly observed** over the range of redshifts that contribute significantly to EBL (eg. Dominguez 2011, Helgason 2012, Stecker 2016)

EBL models in the market

EBL Intensity vs wave-length



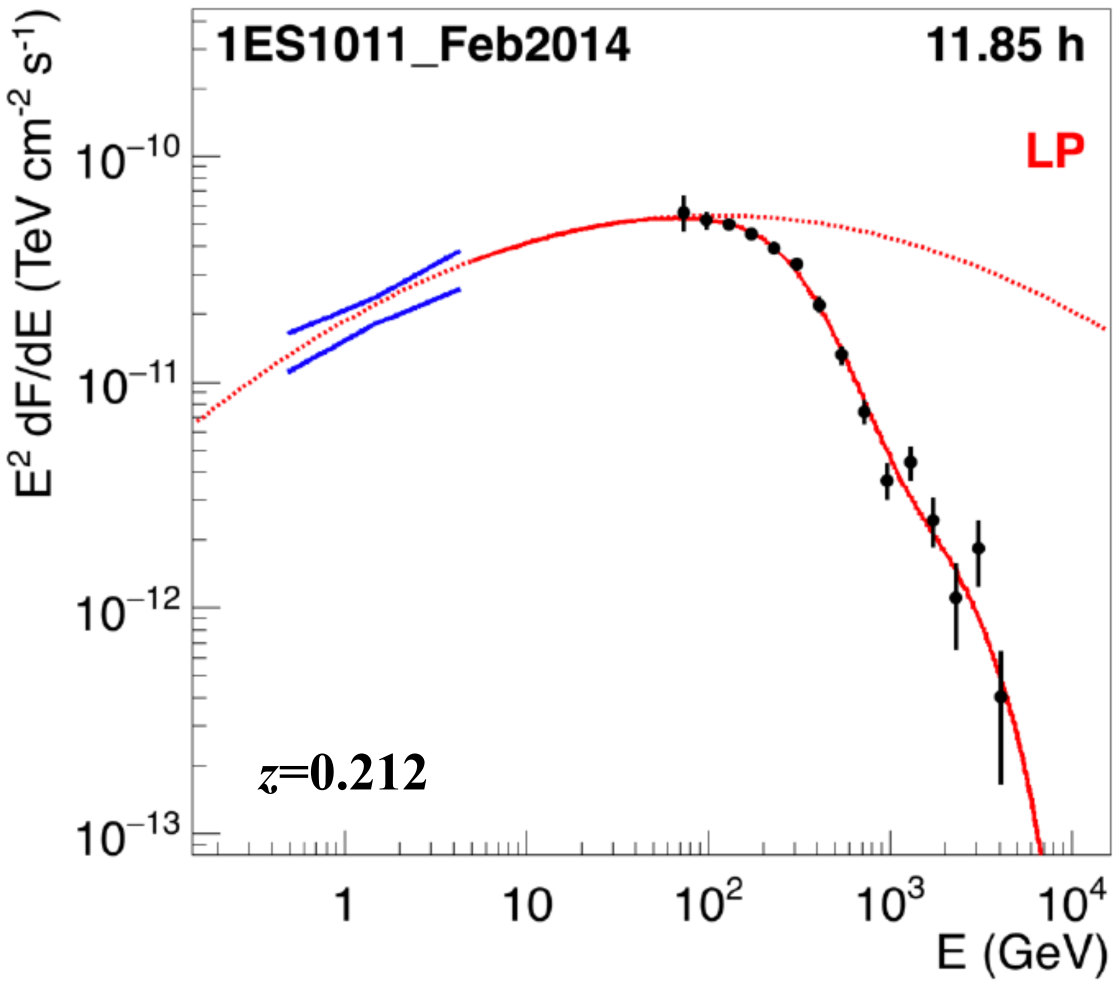
$e^{-\tau(E)}$ for fixed z=0.212



z (1ES1011+496) = 0.212

1ES1011+496: EBL imprint

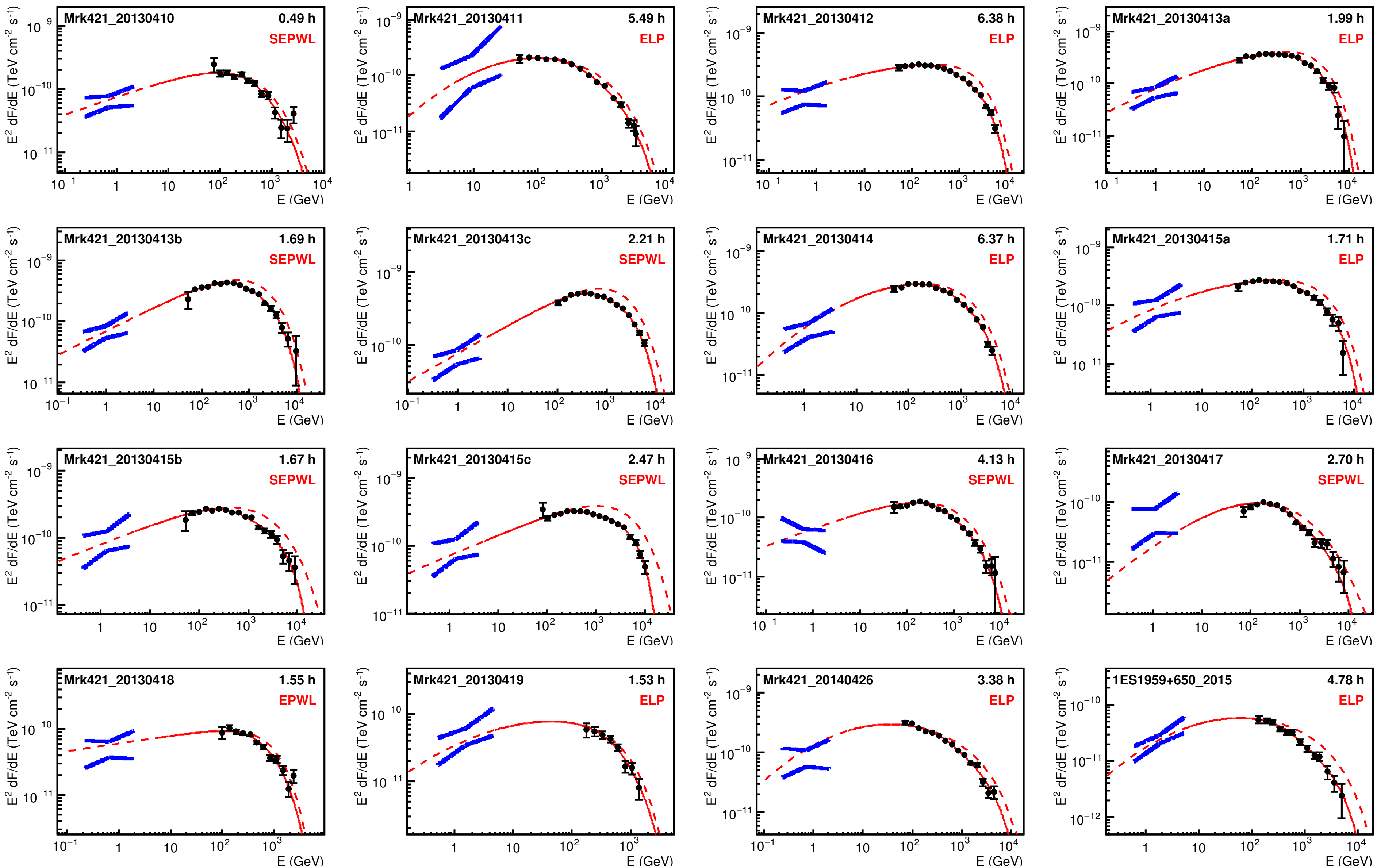
One of the most constraining blazars in the sample



Fermi-LAT bow-tie (flux &photon index) at lower energies is not affected by EBL much, but helps to constrain intrinsic spectrum

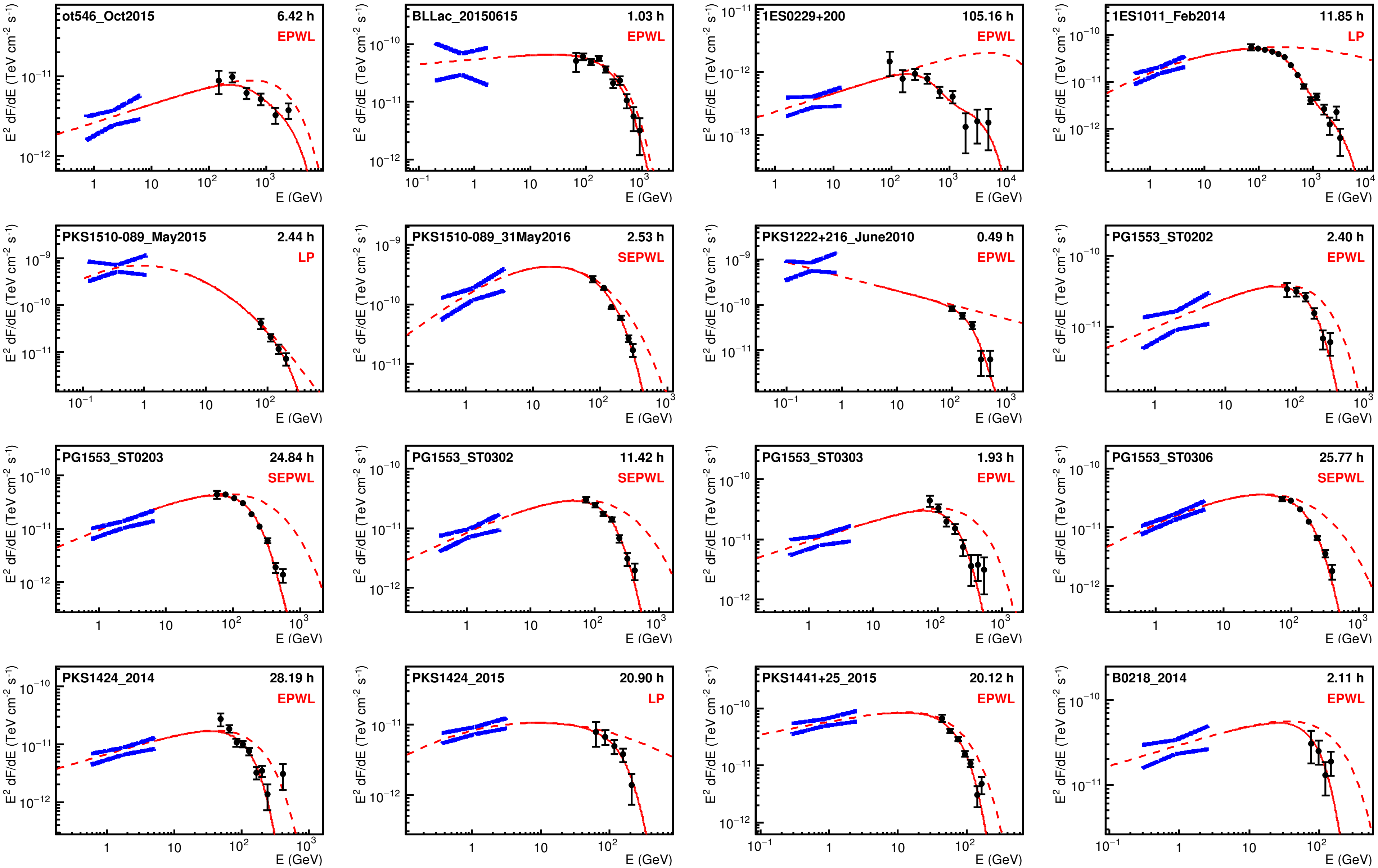
Spectral Energy Distribution of EBL data sample

— Fermi-LAT ● MAGIC — Expected spectra (best fit) - - - Intrinsic spectra



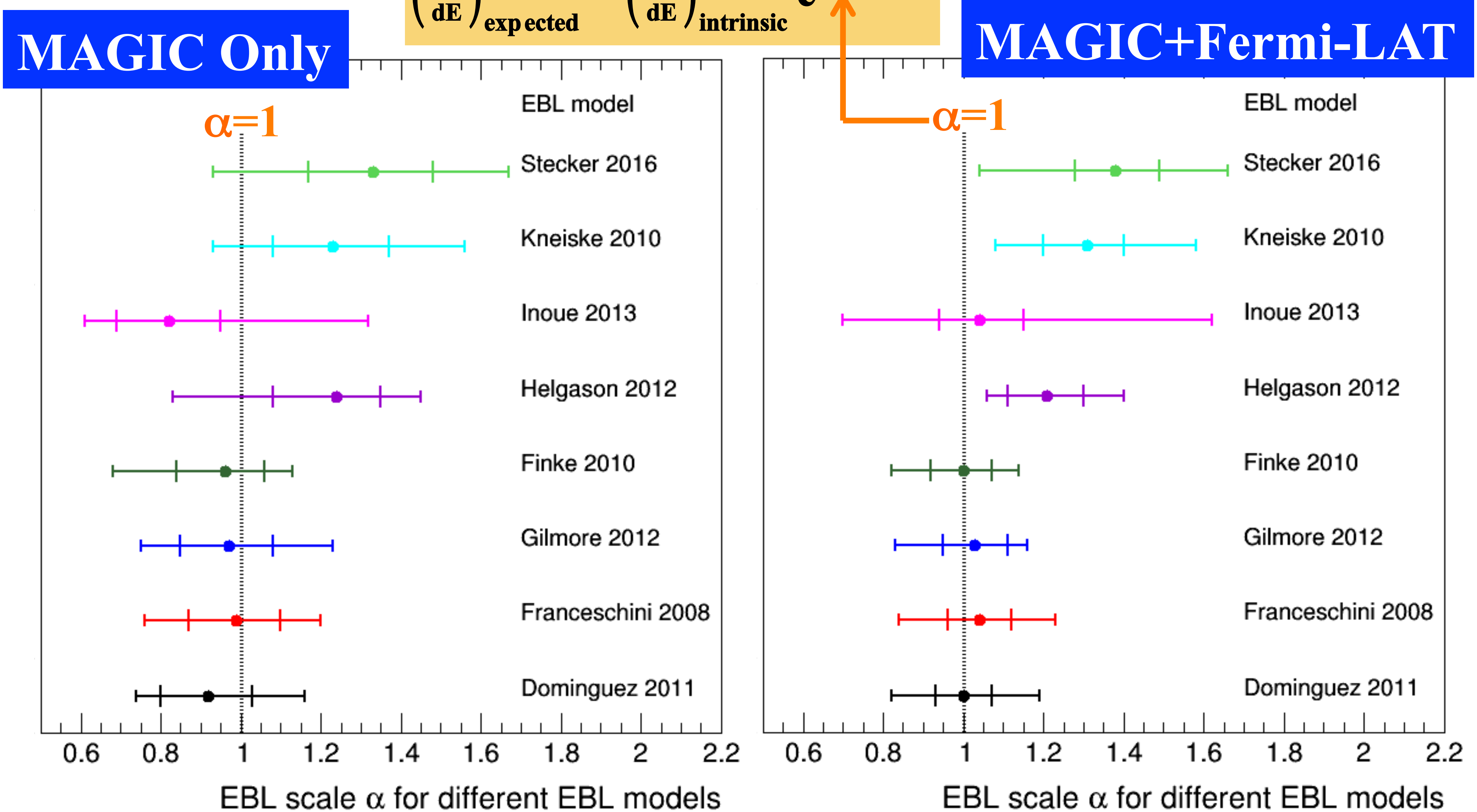
Spectral Energy Distribution of EBL data sample

Fermi-LAT ● MAGIC — Expected spectra (best fit) --- Intrinsic spectra



EBL scale measurements: statistical + systematic uncertainties

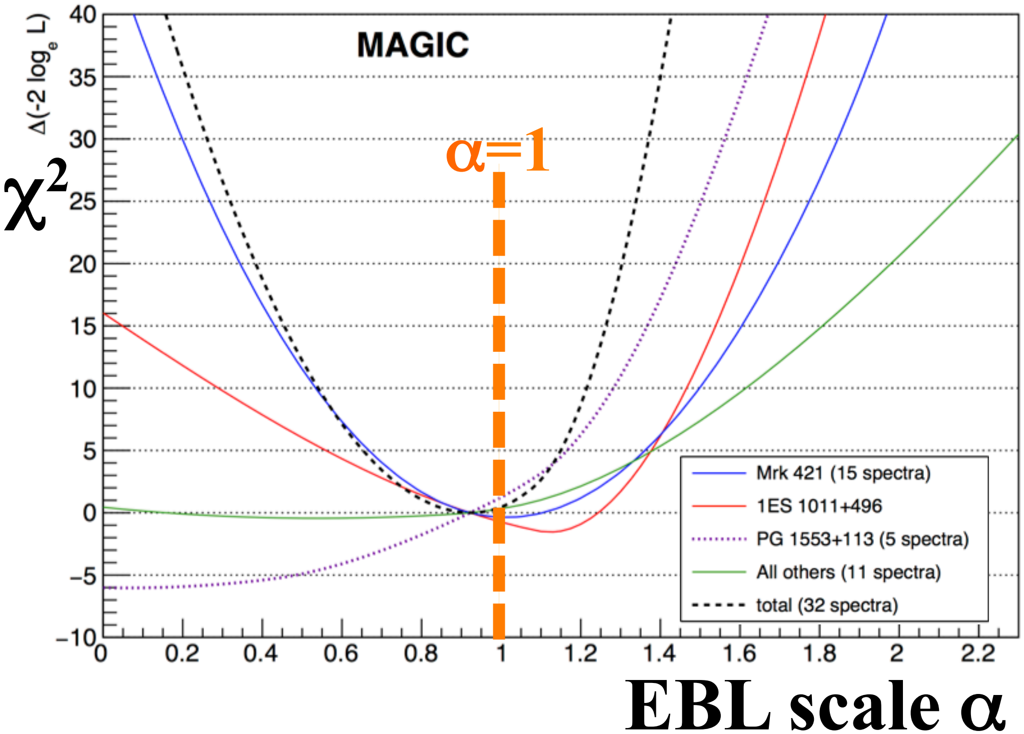
$$\left(\frac{d\phi}{dE}\right)_{expected} = \left(\frac{d\phi}{dE}\right)_{intrinsic} e^{-\alpha\,\tau(E,z)}$$



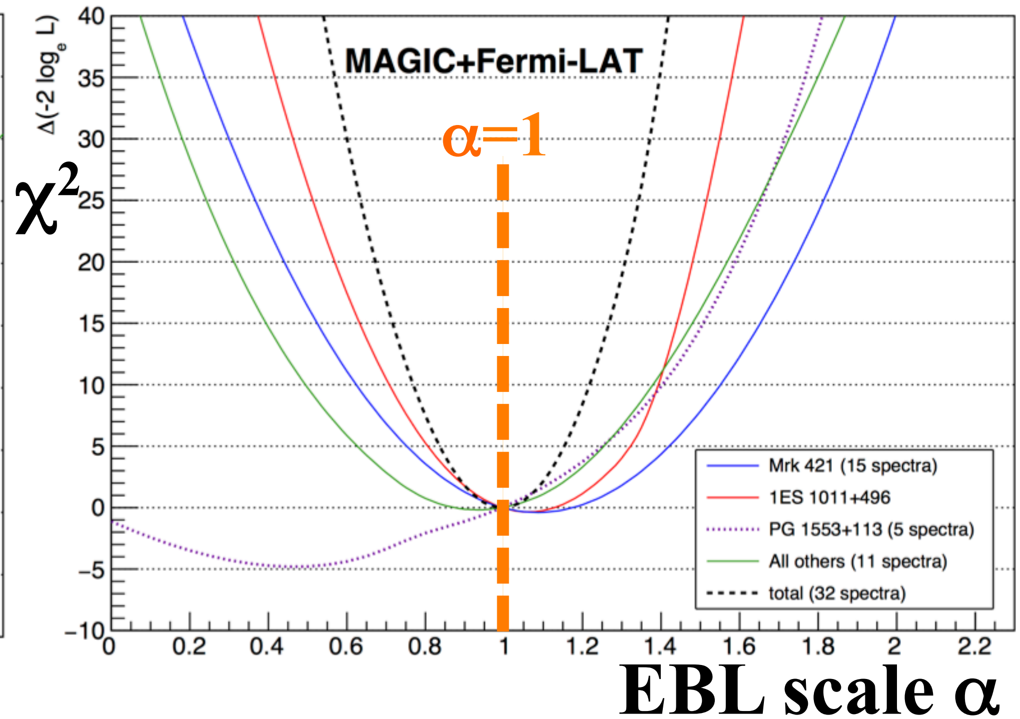
Data compatible with EBL scale α=1, for all EBL models tested

EBL Fit: Profile likelihood

MAGIC Only



MAGIC+Fermi-LAT



PG1553+113 helps in the upper constraint of the EBL scale

Mrk421, 1ES1011+496 & all other sources favour an EBL scale α≈1 compatible with the Dominguez 11 EBL model

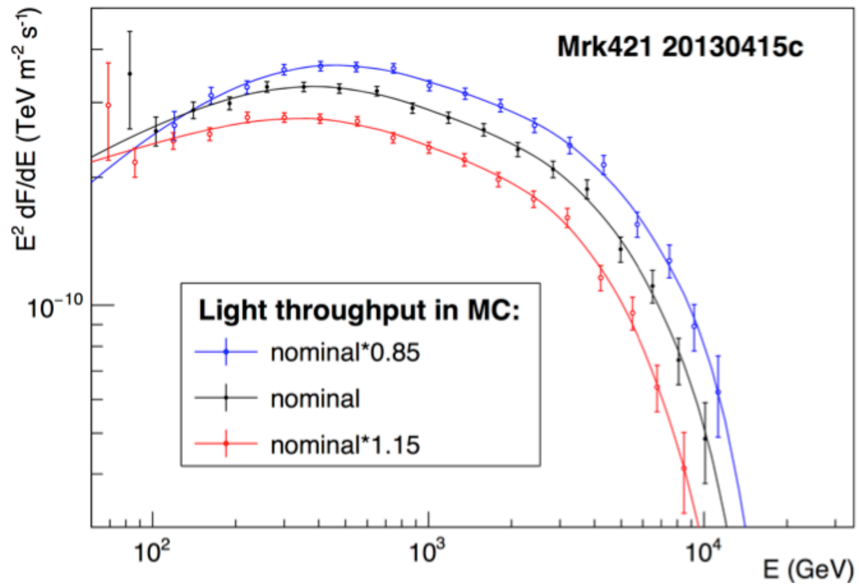
Summary of EBL scale measurements

EBL model	Data	Best-fit scale	Stat.	Stat+Syst.
Dominguez 2011	MAGIC-only	0.92	+0.11, -0.12	+0.24, -0.18
	MAGIC+Fermi-LAT	1.00	+0.07, -0.07	+0.19, -0.18
Finke 2010	MAGIC-only	0.96	+0.10, -0.12	+0.17, -0.28
	MAGIC+Fermi-LAT	1.00	+0.07, -0.08	+0.14, -0.18
Franceschini 2008	MAGIC-only	0.99	+0.11, -0.12	+0.21, -0.23
	MAGIC+Fermi-LAT	1.04	+0.08, -0.08	+0.19, -0.20
Gilmore 2012	MAGIC-only	0.97	+0.11, -0.12	+0.26, -0.22
	MAGIC+Fermi-LAT	1.03	+0.08, -0.08	+0.13, -0.20
Helgason 2012	MAGIC-only	1.24	+0.11, -0.16	+0.21, -0.41
	MAGIC+Fermi-LAT	1.21	+0.09, -0.10	+0.19, -0.15
Inoue 2013	MAGIC-only	0.82	+0.13, -0.13	+0.50, -0.21
	MAGIC+Fermi-LAT	1.04	+0.11, -0.10	+0.58, -0.34
Stecker 2016	MAGIC-only	1.33	+0.15, -0.16	+0.34, 0.40
	MAGIC+Fermi-LAT	1.38	+0.11, -0.10	+0.28, -0.34
Kneiske 2010	MAGIC-only	1.23	+0.14, -0.15	+0.33, -0.30
	MAGIC+Fermi-LAT	1.31	+0.09, -0.11	+0.27, -0.23

EBL scale measurement: systematic uncertainties

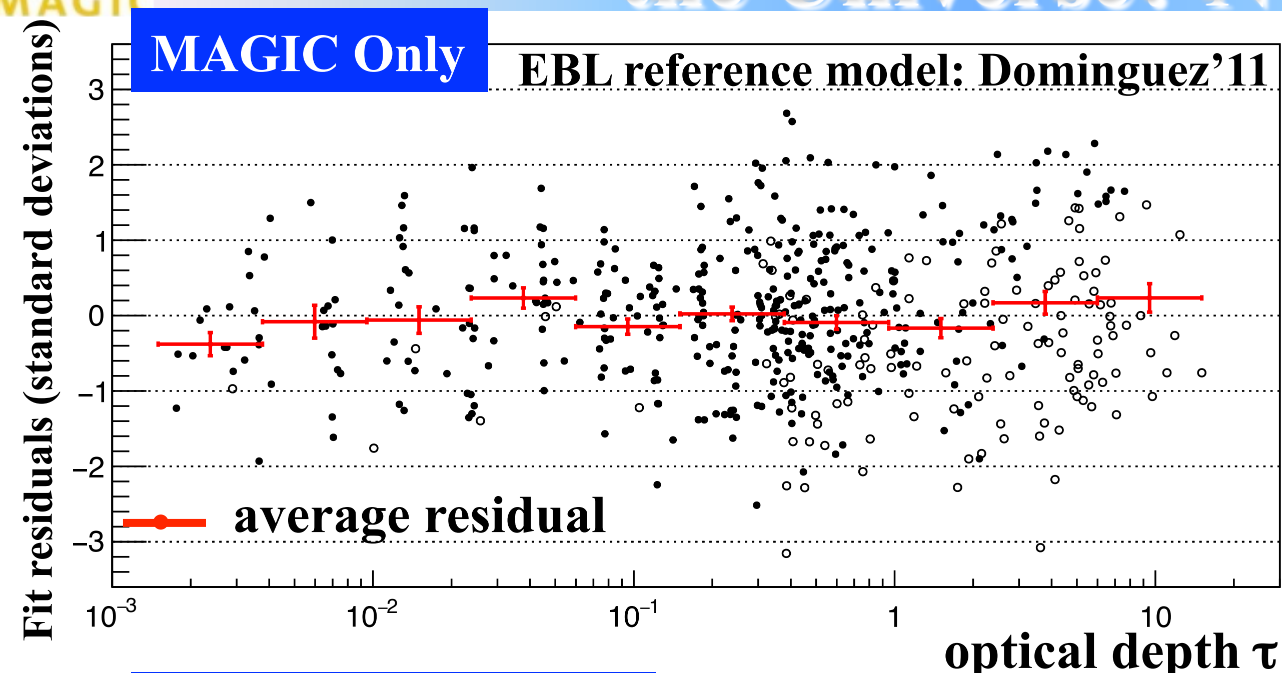
Two main sources of systematic uncertainties:

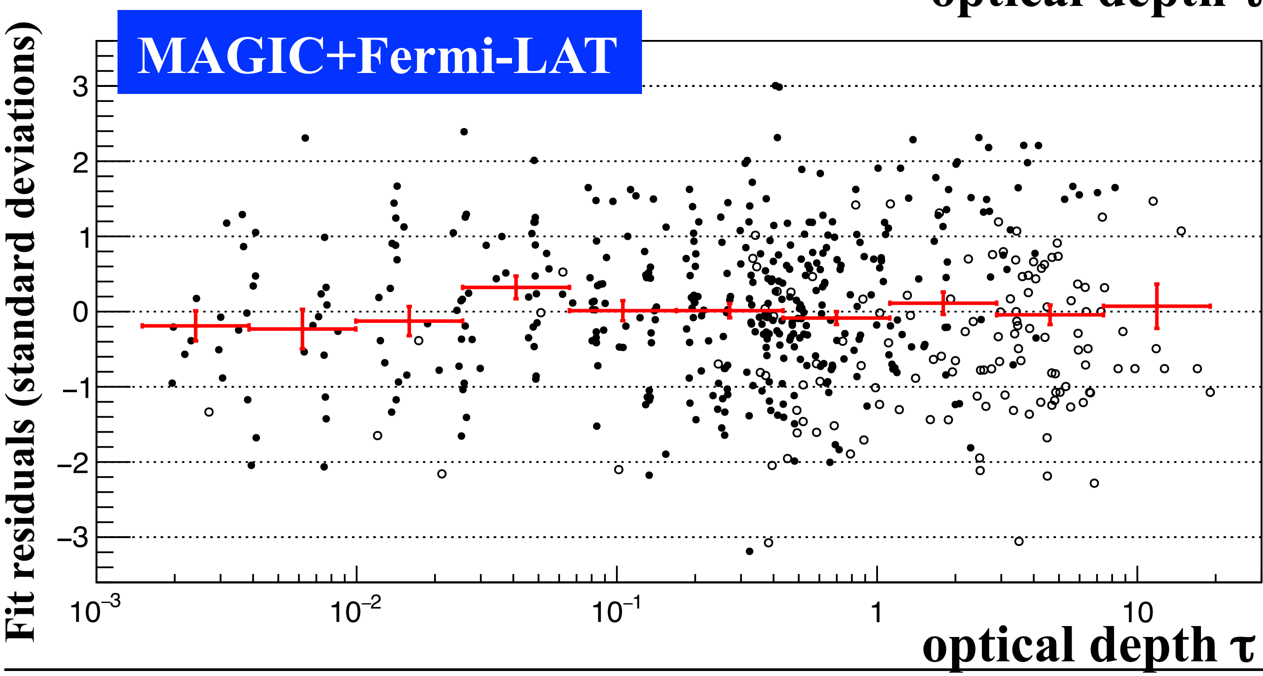
- **Absolute telescope calibration + effect of the atmosphere**
  - **vary light scale (throughput) by ±15% & redo likelihood fit**



- **Choice of intrinsic spectral model**
  - **allow limit-case of power-law: forces EBL to account for all the spectral curvature**
  - **choose best-fitting functions at the lower EBL limit from galaxy counts –1σ (Madau&Pozzetti)**

Anomalies in transparency of the Universe? NO!





Fit residuals versus optical depth:

No anomaly observed

Optical depth calculated for best-fit EBL scale

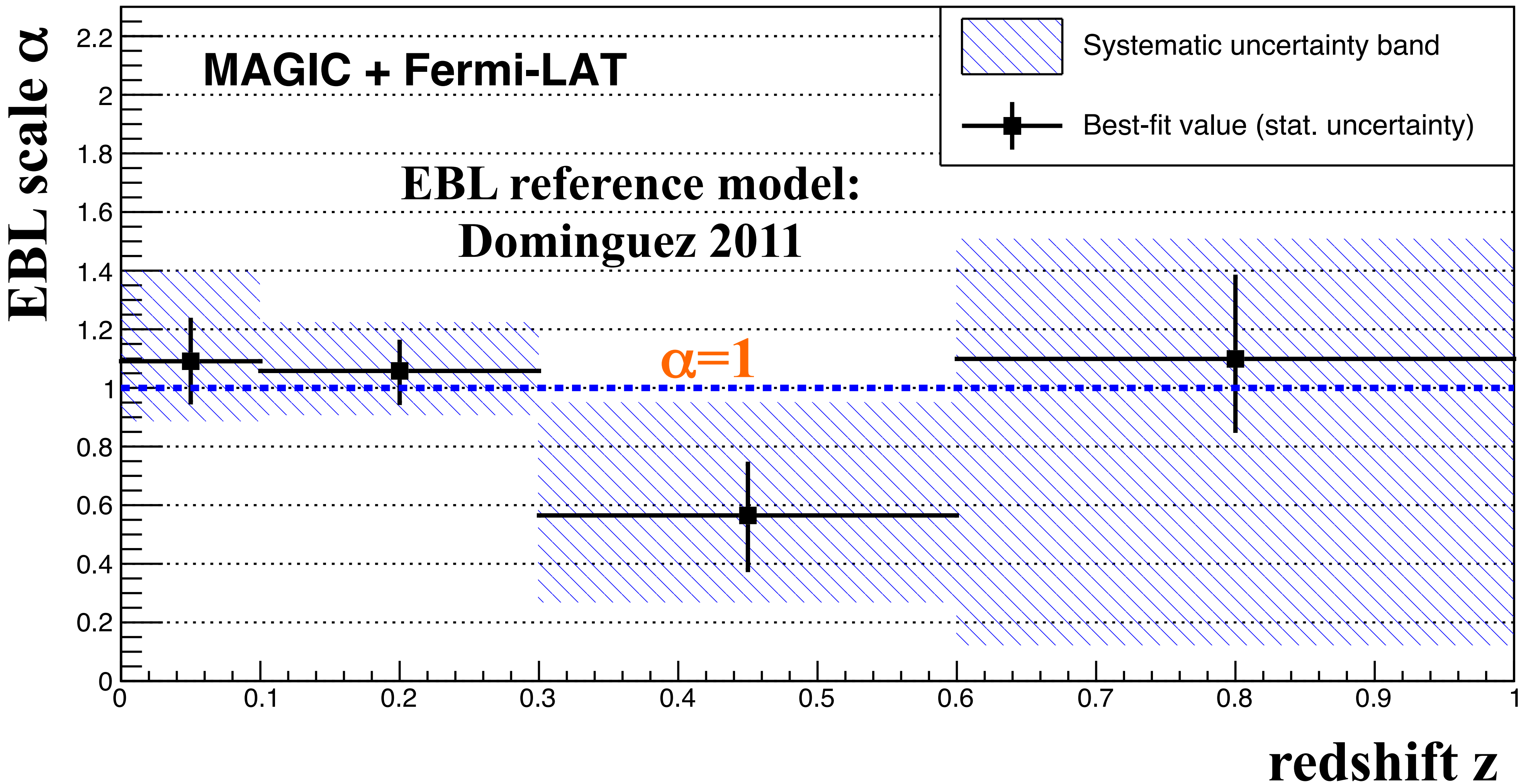
Each point corresponds to one bin in estimated energy of the 32 spectra used in the EBL likelihood fit

Bins with at least one signal or background event shown

Filled symbols are bins with 1.5σ gamma-ray excess. This biases towards positive values in low statistic bins!

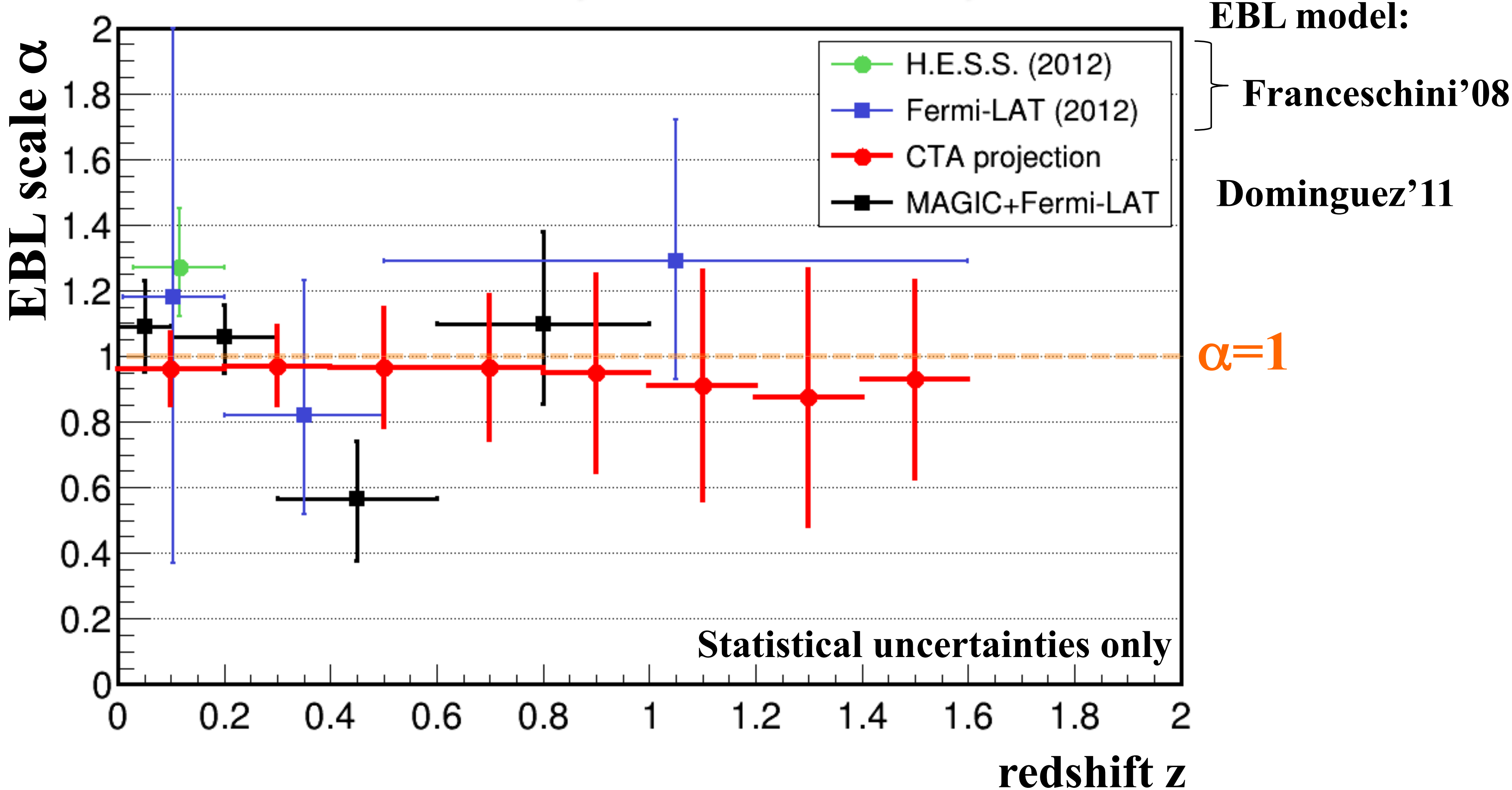
EBL scale: redshift evolution

Data compatible with an EBL scale α=1 for all *z* ranges studied



Blazar sample in *z* range: 0.030-0.944

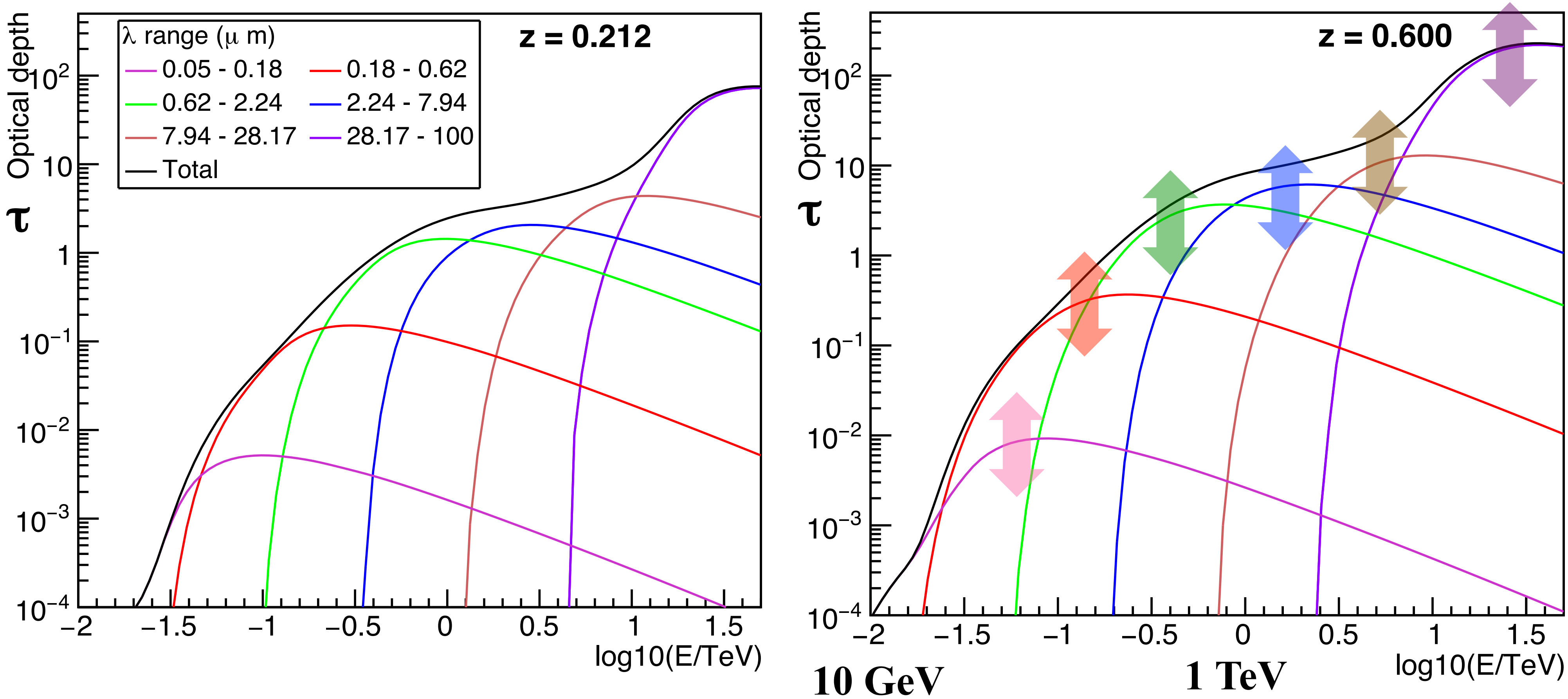
EBL scale redshift evolution comparison H.E.S.S., Fermi-LAT, CTA



Different criteria to choose intrinsic spectral function

CTA: assumed quiescent & flare states of 10 sources per redshift bin & average flux level of 25% of the Crab nebula at 100 GeV prior to absorption [Astrophys. J. 840 (2017) 2, 74]

EBL models: optical depth wave-length dependence



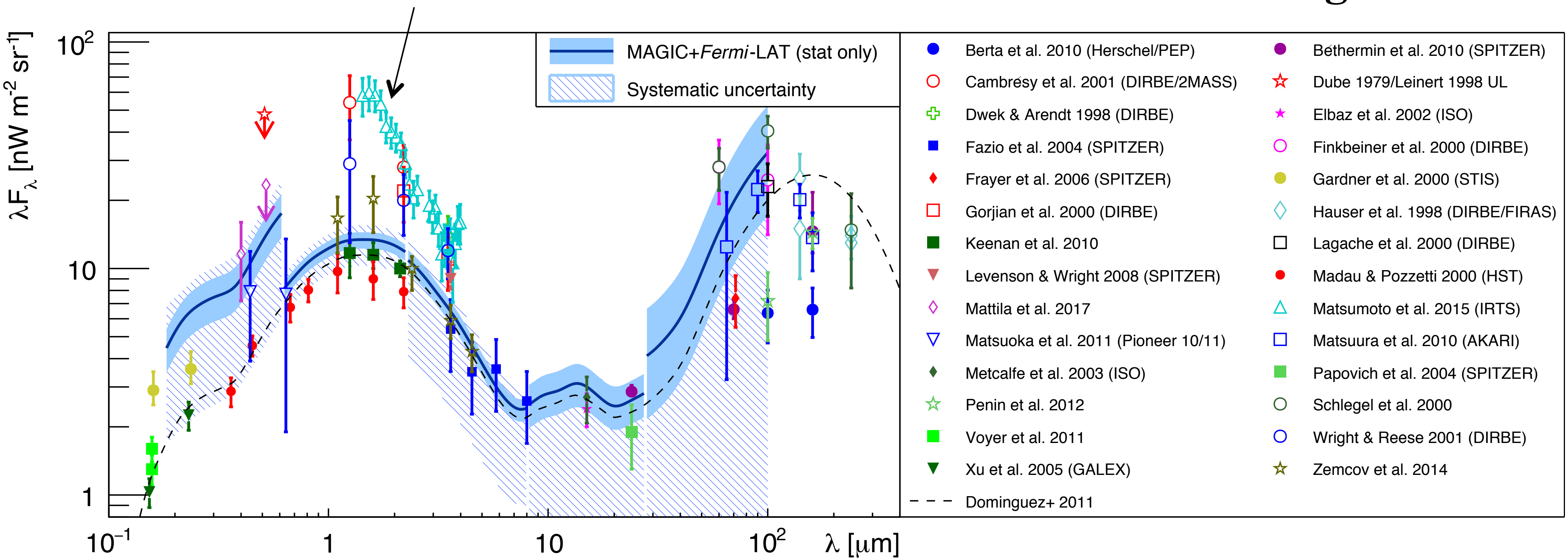
$$\left(\frac{d\phi}{dE}\right)_{expected} = \left(\frac{d\phi}{dE}\right)_{intrinsic} e^{-\alpha_1 \tau_1} e^{-\alpha_2 \tau_2} e^{-\alpha_3 \tau_3} e^{-\alpha_4 \tau_4} e^{-\alpha_5 \tau_5} e^{-\alpha_6 \tau_6}$$

τ_1: 0.05-0.18 μm, τ_2: 0.18-0.62 μm, τ_3: 0.62-2.24 μm, τ_4: 2.24-7.94 μm, τ_5: 7.94-28.17 μm, τ_6: 28.17-100 μm

Each optical depth factor is floated independently in the likelihood fit

EBL: wave-length resolved

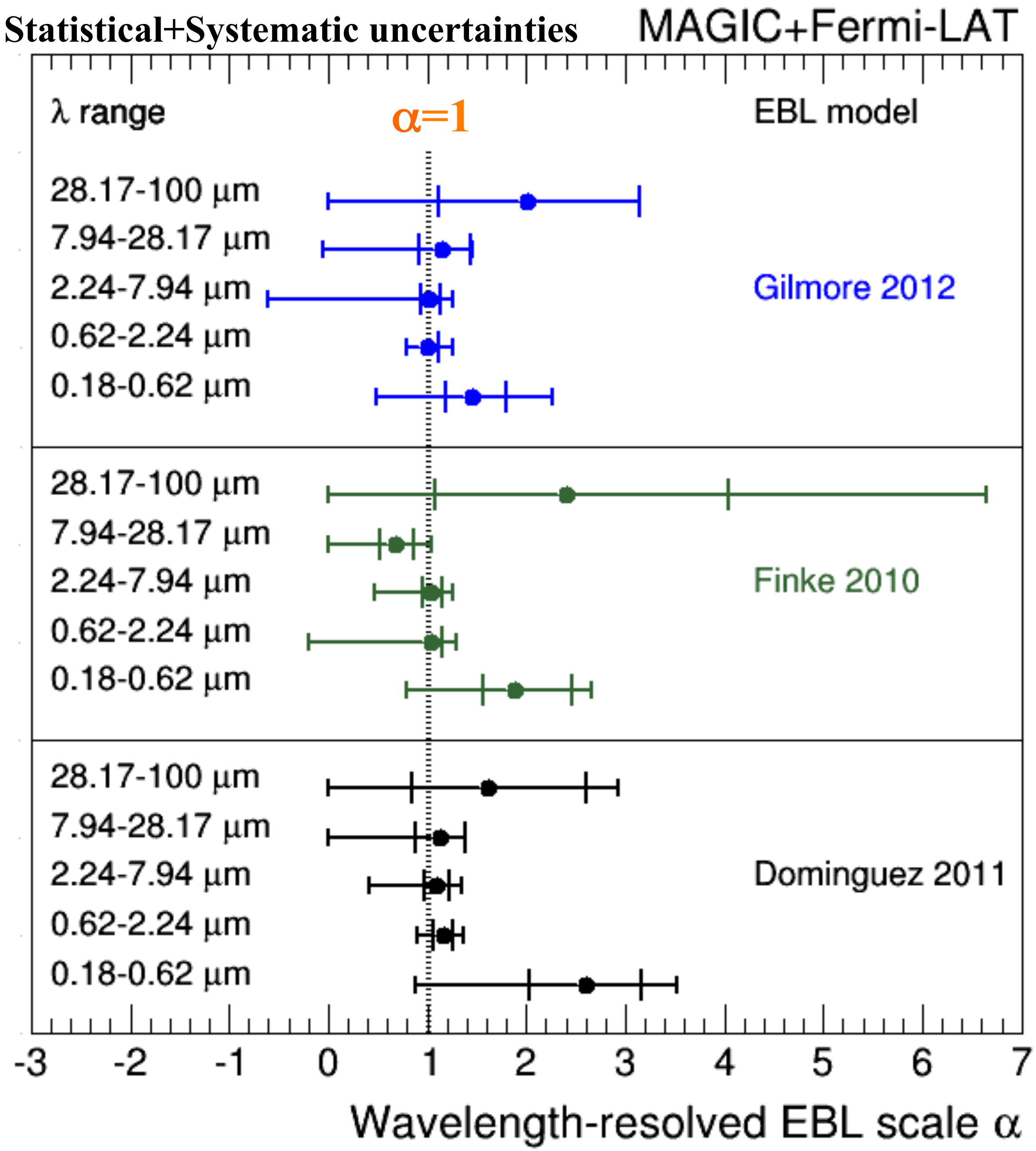
Direct measurement suffers from zodiacal light



MAGIC+FermiLAT wave-length resolved EBL measurement compatible with Dominguez 2011 EBL model (– – –)

Open symbols: direct EBL measurements
Filled symbols: lower EBL limits from galaxy counts

EBL: wave-length resolved

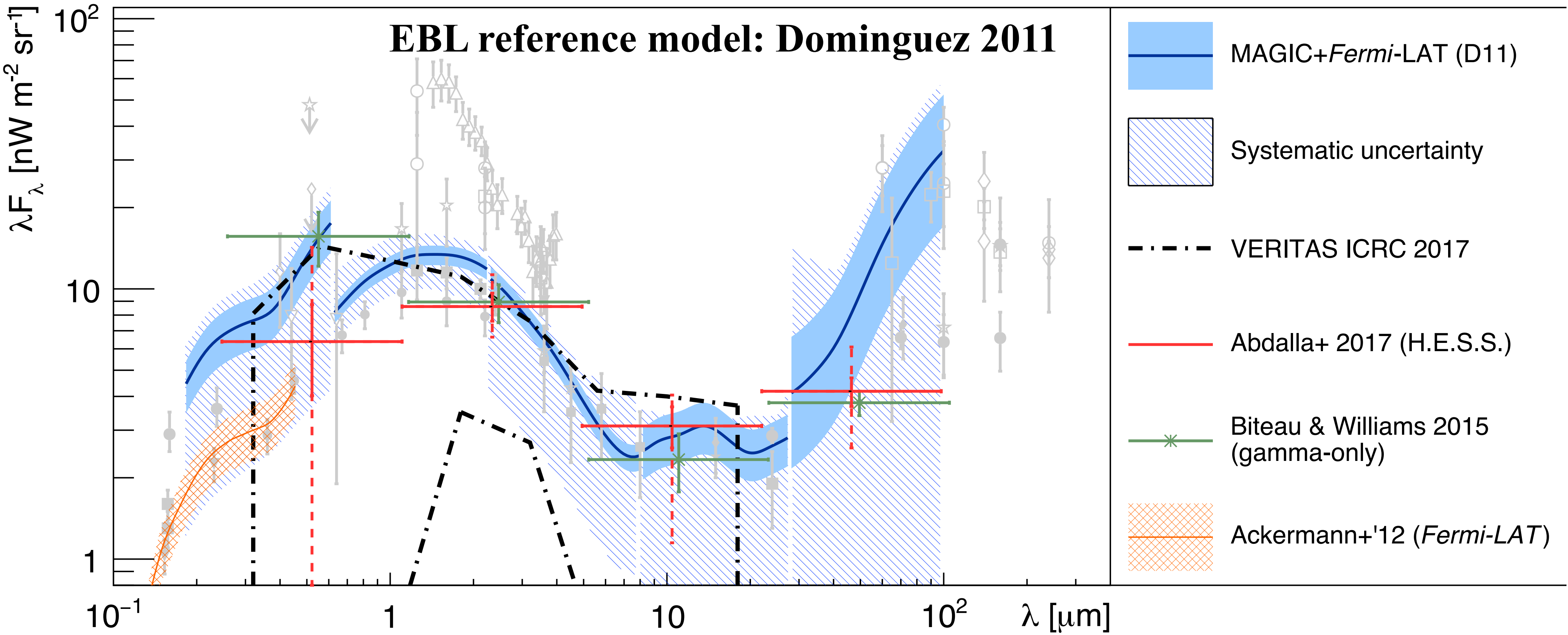


MAGIC+FermiLAT wave-length resolved EBL scale α compatible with EBL models:

- **Gilmore 2012**
- **Finke 2010**
- **Dominguez 2011**

EBL: wave-length resolved

MAGIC+Fermi-LAT wave-length resolved EBL extraction consistent with other gamma-ray measurements (H.E.S.S., VERITAS, Fermi-LAT)



The uncertainty associated to the EBL model (obtained with Gilmore 2012, Finke2010) has been included in the systematic uncertainty

Summary

- A measurement of the Extragalactic Background Light from a likelihood fit to 32 spectra of blazars from 316 hours of data of the MAGIC telescopes has been obtained

- The results are compatible with state-of-the art EBL models

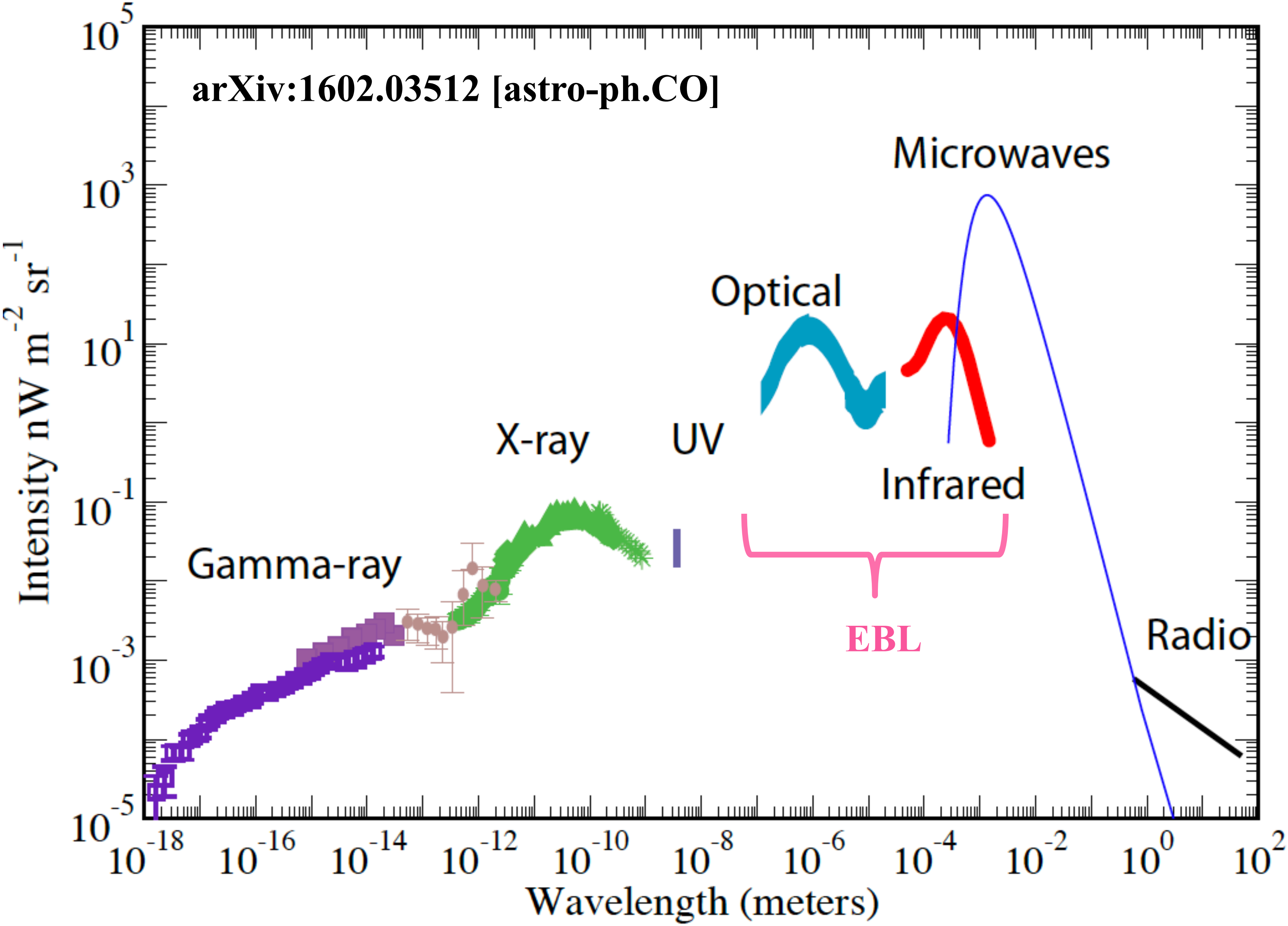
- No anomaly in the transparency of the Universe observed

- EBL scale measurements as a function of the redshift and wave-length resolved have been obtained for the first time using data from MAGIC + Fermi-LAT

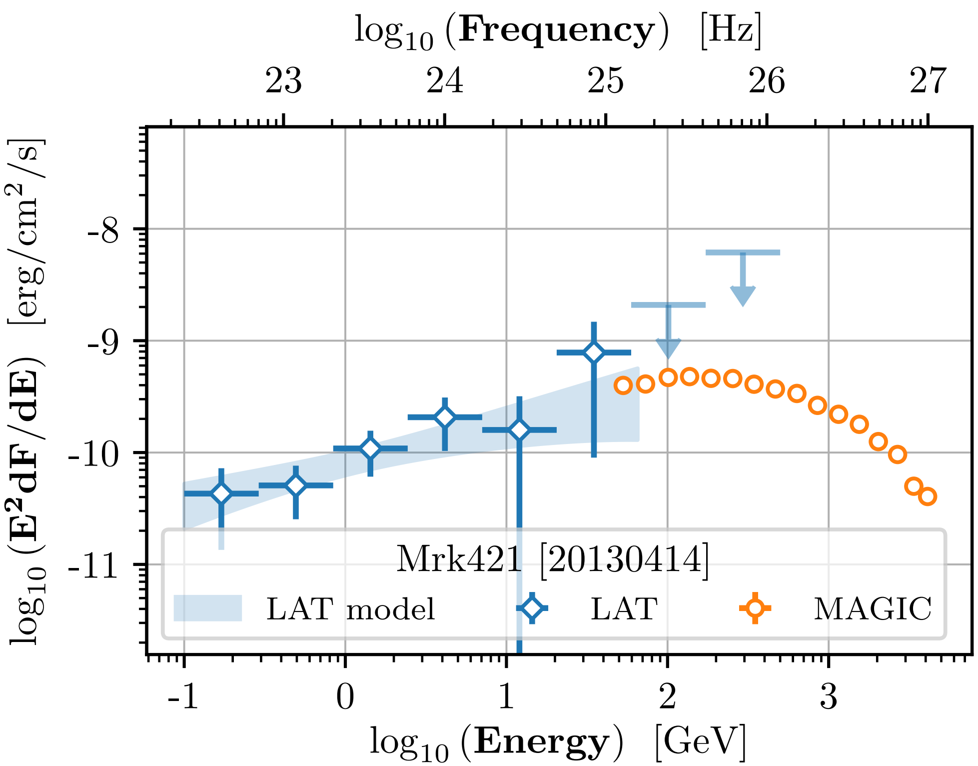
➔ the measurement has been possible due to the large sample of extragalactic sources observed by MAGIC, in a broad energy & redshift z range

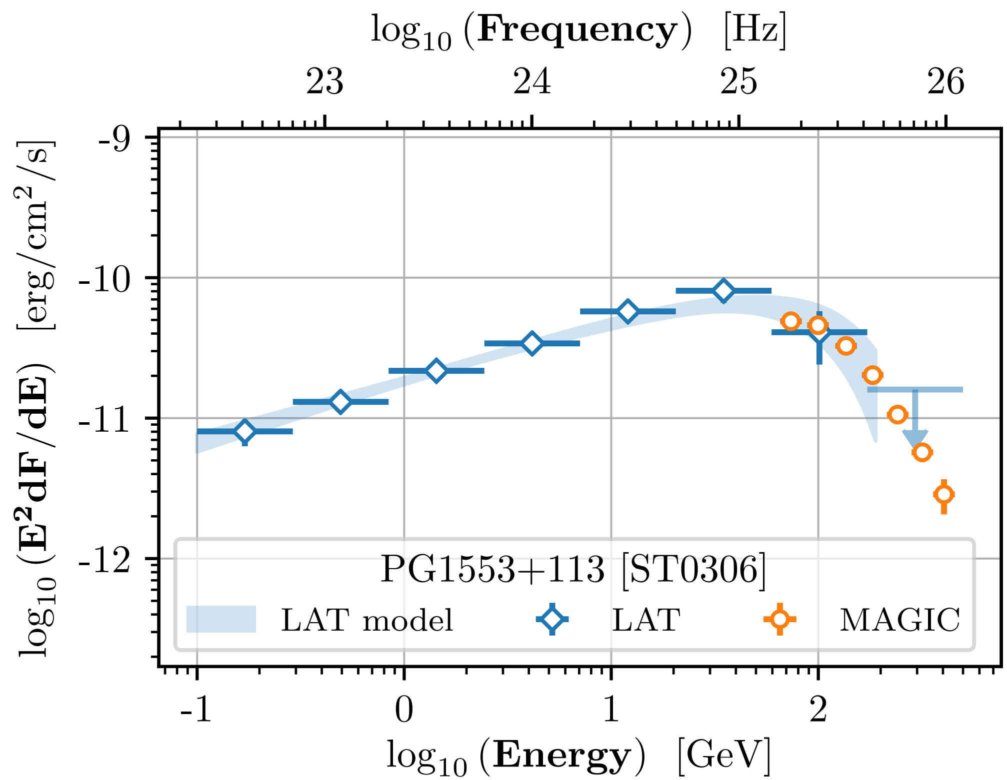
BACKUP

Diffuse Background Radiation



Example MAGIC+Fermi-LAT SEDs: Mrk421 and PG1553+113

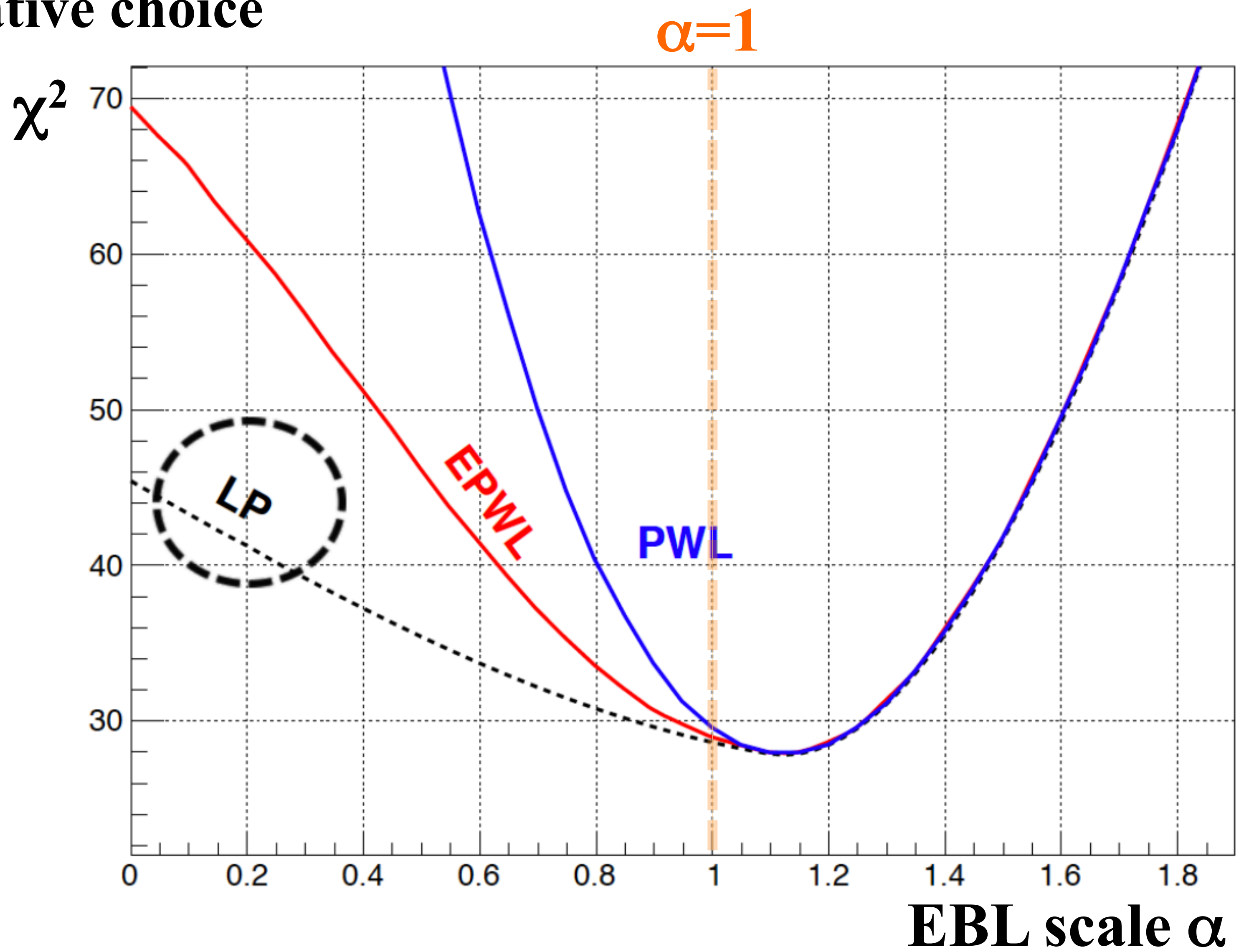




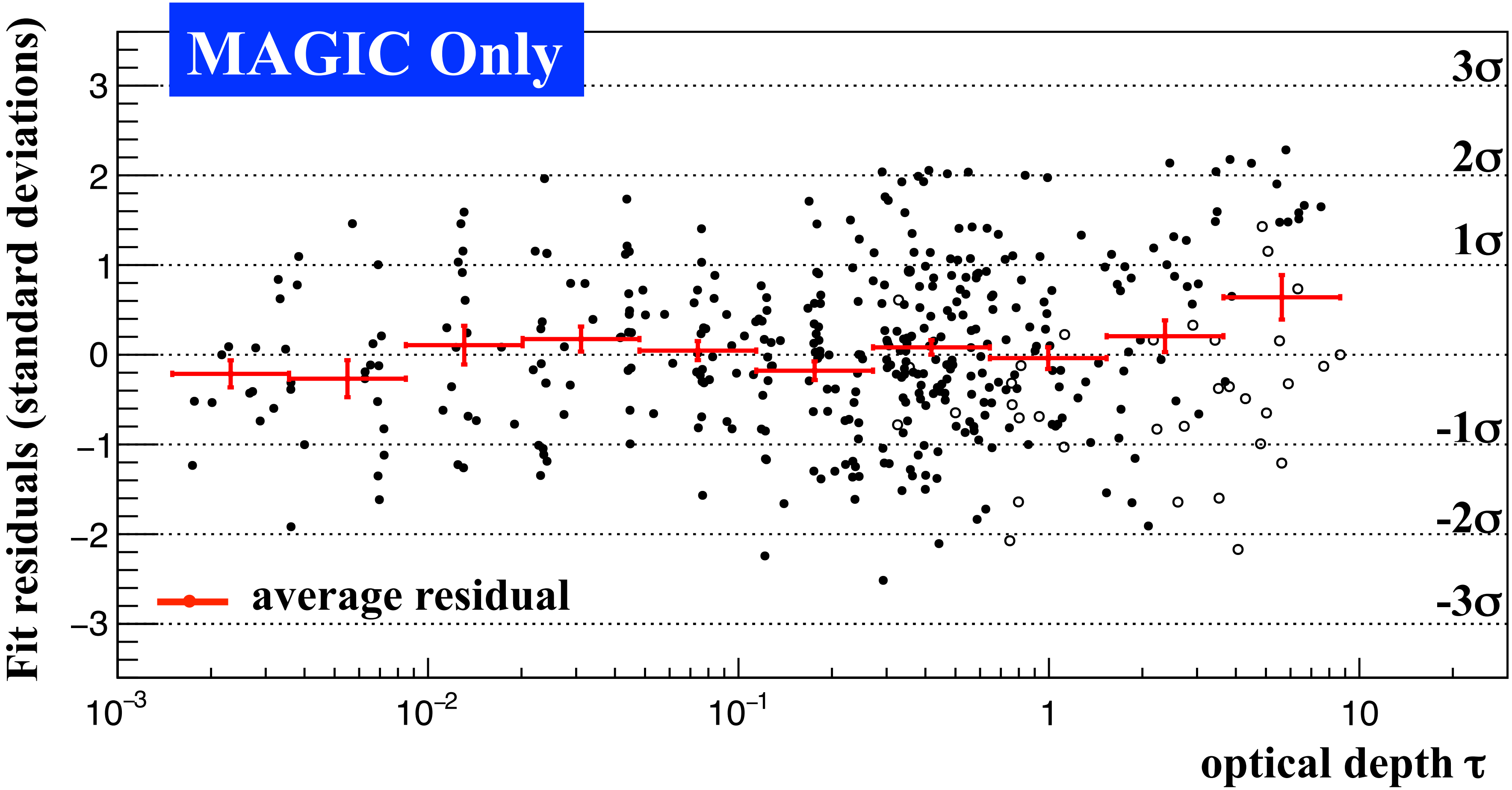
Good level of agreement of MAGIC spectral points and High Energy bow-ties & spectral points of Fermi-LAT data

Blazar intrinsic spectrum: function choice

If two functions have the same p-value, the one with flatter χ^2 taken: conservative choice

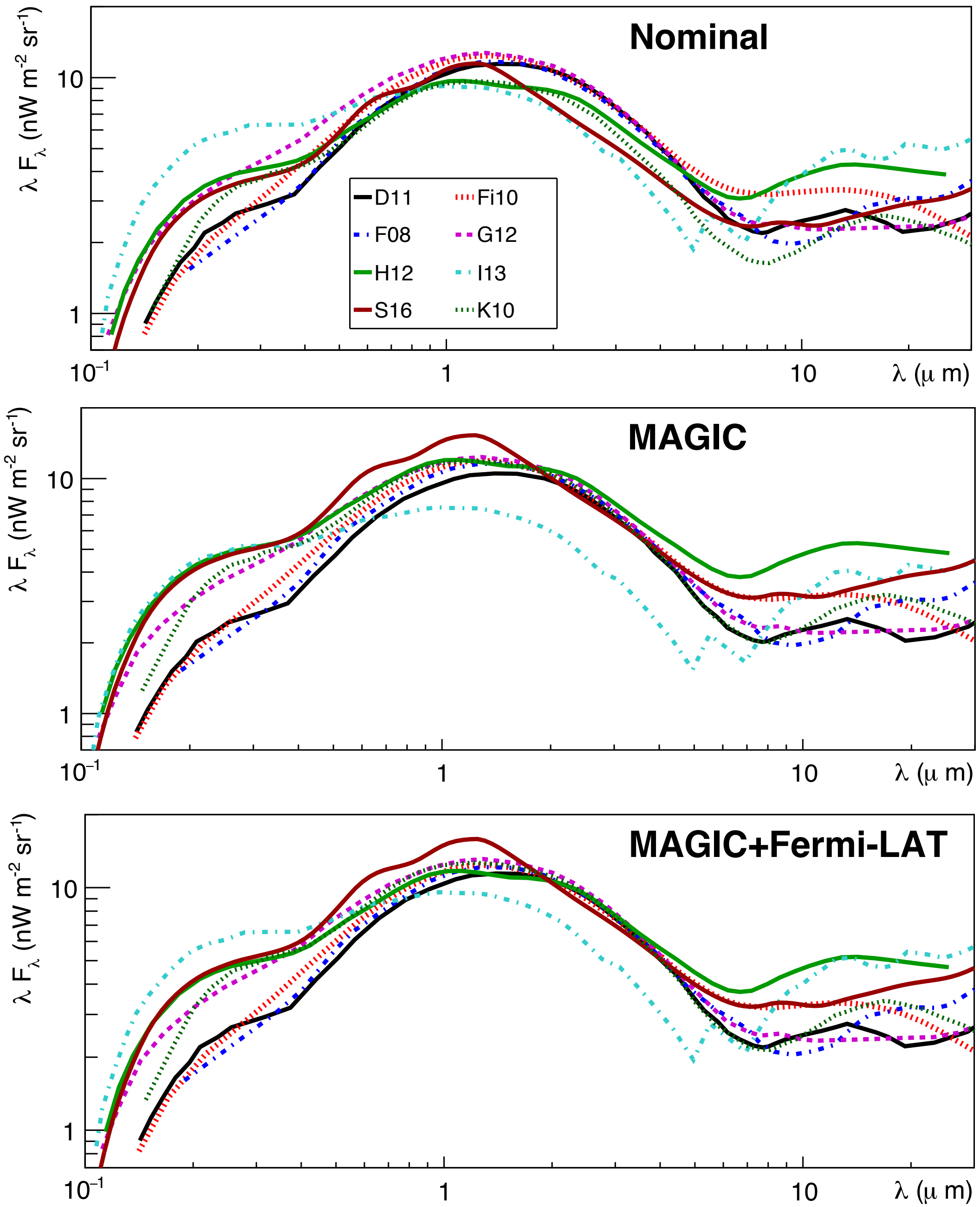


Anomalies in transparency of the Universe? NO!



Fit residuals versus optical depth with analysis after removing low significance points (< 1.5σ) at the high- & low-energy ends of spectra

EBL models scaled to best fit values



EBL: wave-length resolved compared to different EBL models