EBL constraints using a sample of TeV gamma-ray emitters measured with the MAGIC telescopes

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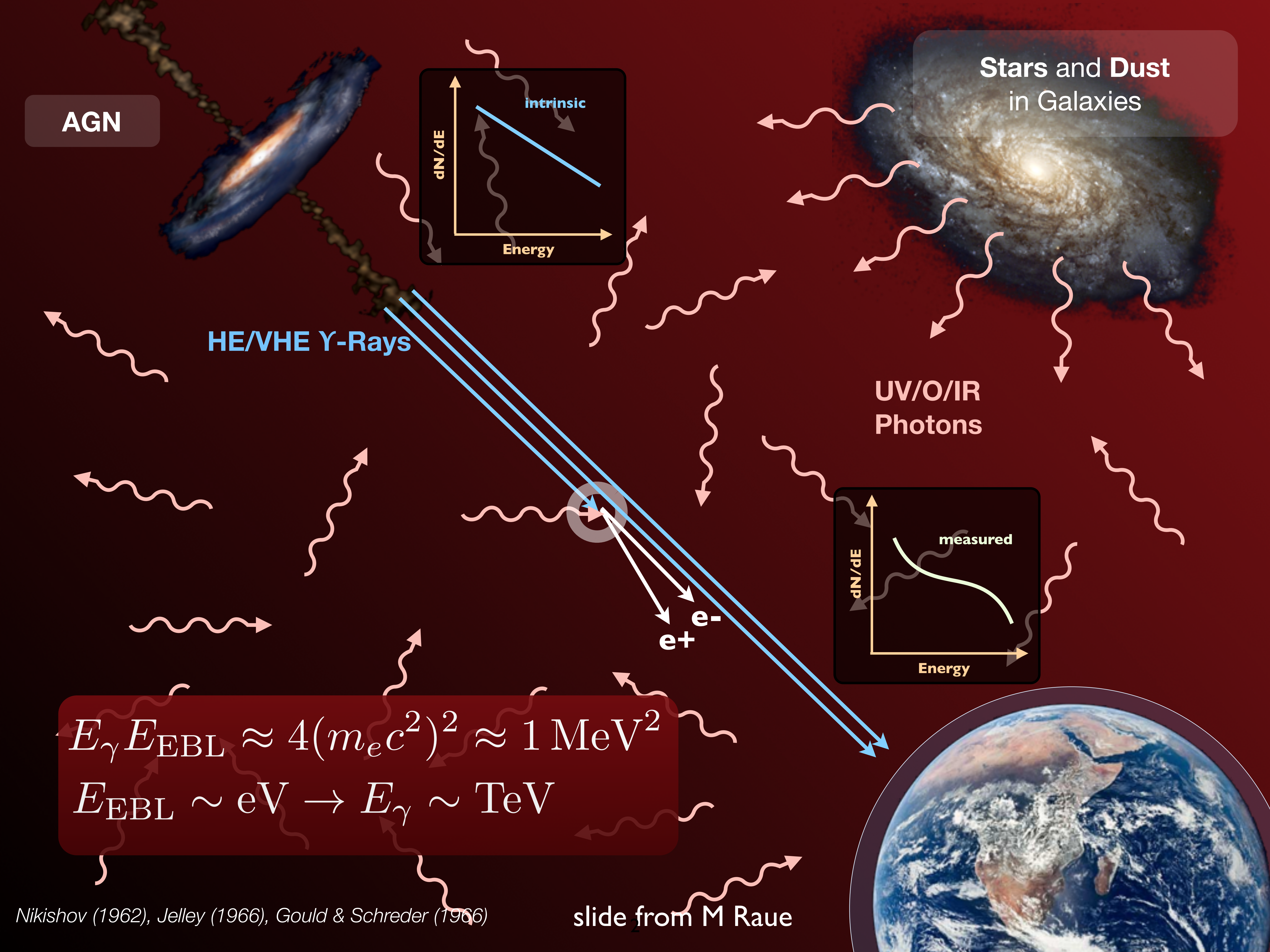
for the MAGIC Collaboration



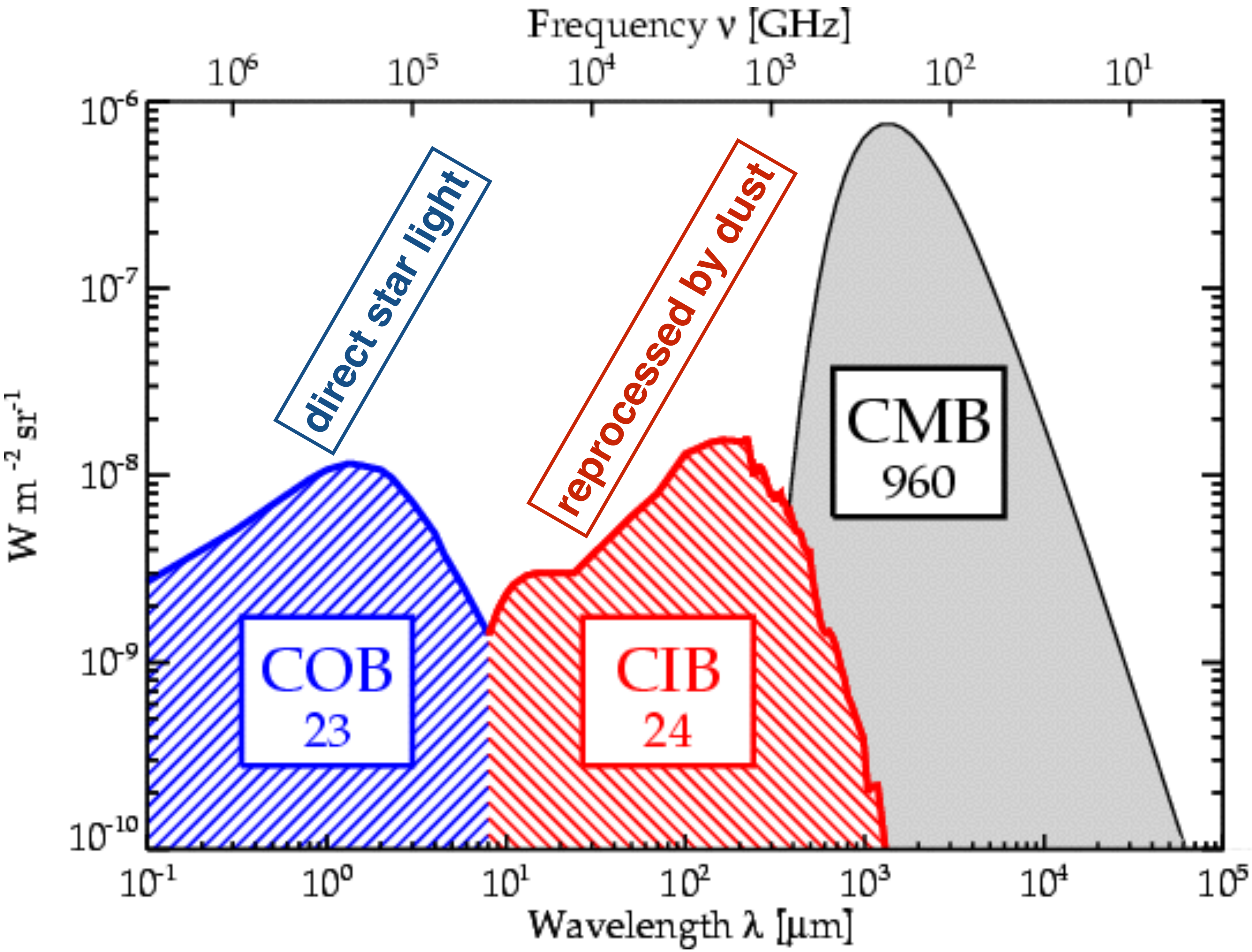
$$E_\gamma E_{\rm EBL} \approx 4(m_e c^2)^2 \approx 1\,{\rm MeV}^2$$

$$E_{\rm EBL} \sim {\rm eV} \rightarrow E_\gamma \sim {\rm TeV}$$

Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

slide from M Raue

EBL



Frequency ν [GHz]
10^6
10^5
10^4
10^3
10^2
10^1
10^-6
10^-7
10^-8
10^-9
10^-10
W m^-2 sr^-1
direct star light
reprocessed by dust
CMB
960
COB
23
CIB
24
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
Wavelength λ [μm]

Imprint of the EBL on spectra of HE/VHE gamma ray spectra of distant sources

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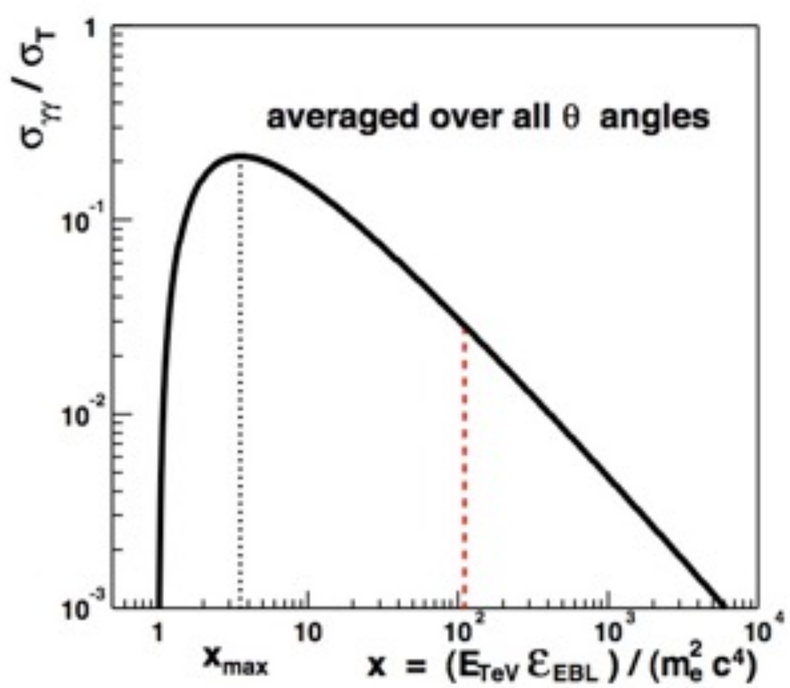
- Cross section of pair production:
  - peaks at ~4*Ethreshold
  - Delta function approximation is not precise

$$\sigma_{\gamma\gamma}(E,\epsilon,\theta) = \frac{3\sigma_T}{16}(1-\beta^2)\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right]$$

$$\text{with } \beta := \left(1-\frac{2m_e^2c^4}{E\,\epsilon\,(1-\cos\theta)}\right)^{1/2}$$



Attenuation of gamma-ray flux is calculated by integrating over number density of EBL, angles between photons, and distance to the source. The attenuation is sensitive to the EBL density.

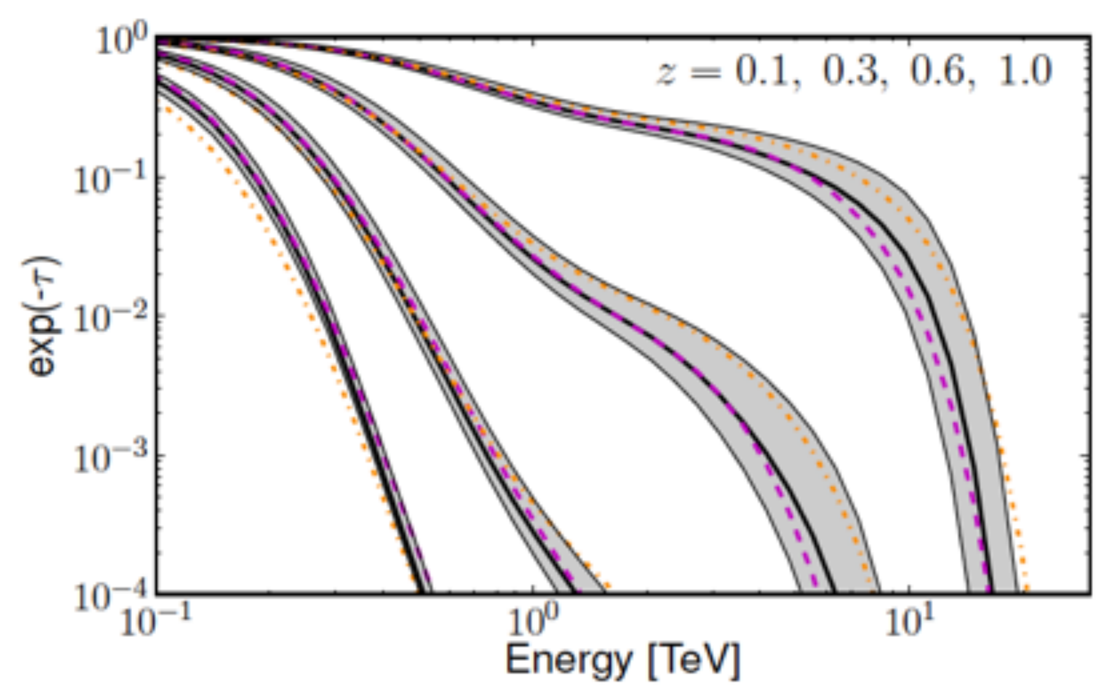
$$\tau(E_\gamma, z) = \int_0^z d\ell(z') \int_{-1}^{1} d\mu \frac{1-\mu}{2} \int_{\epsilon'_{th}}^{\infty} d\epsilon'\, n(\epsilon', z')\, \sigma_{\gamma\gamma}(\epsilon', E', \mu)$$

$$\mu := \cos\theta$$

$$n(\epsilon) := \text{EBL energy density}$$

$$d\ell(z) := \text{distance element}$$

Observed flux = Emitted flux x exp(-τ)



Plot from Dominguez et al., MNRAS 410, 2556 (2011)

The MAGIC Telescopes

- Two 17m diameter Imaging Atmospheric Cherenkov Telescopes
- MAGIC-I: since 2004
- MAGIC-II: since 2009, start stereoscopic observations
- 2011-2012: major upgrade of the readout of both and camera of MAGIC-I
- Energy range 50GeV - over 50TeV, 0.6% Crab Nebula in 50h observations at E>250GeV
- See performance details in Aleksić et al., AP (2016) 72, 76-94

Method: Poissonian likelihood maximization

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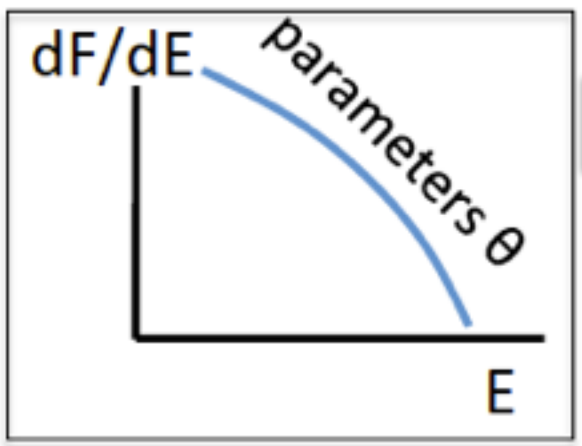
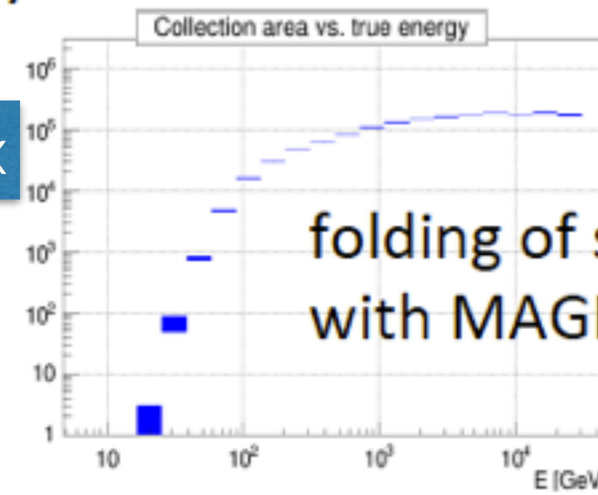
Spectrum 

X

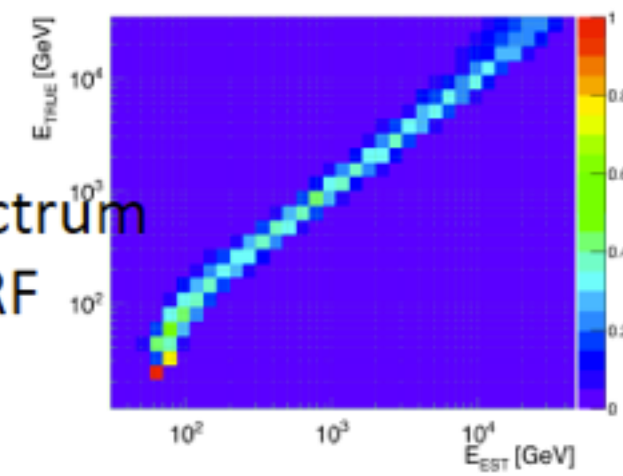
EBL(optional) 

X

Effective Area 

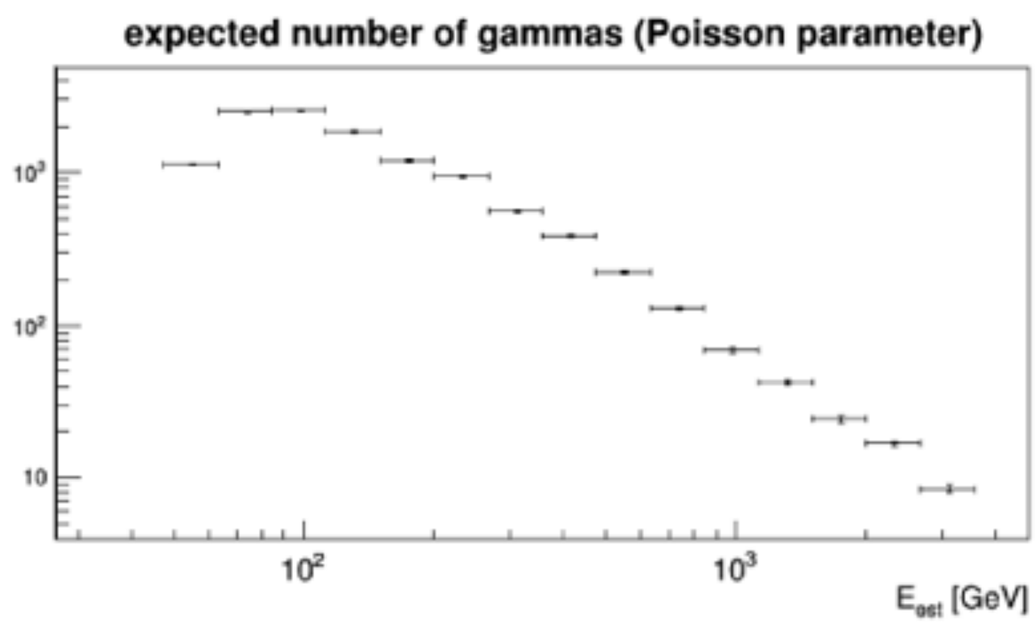
folding of spectrum with MAGIC IRF

X

Migration matrix 

X

Eff. time 



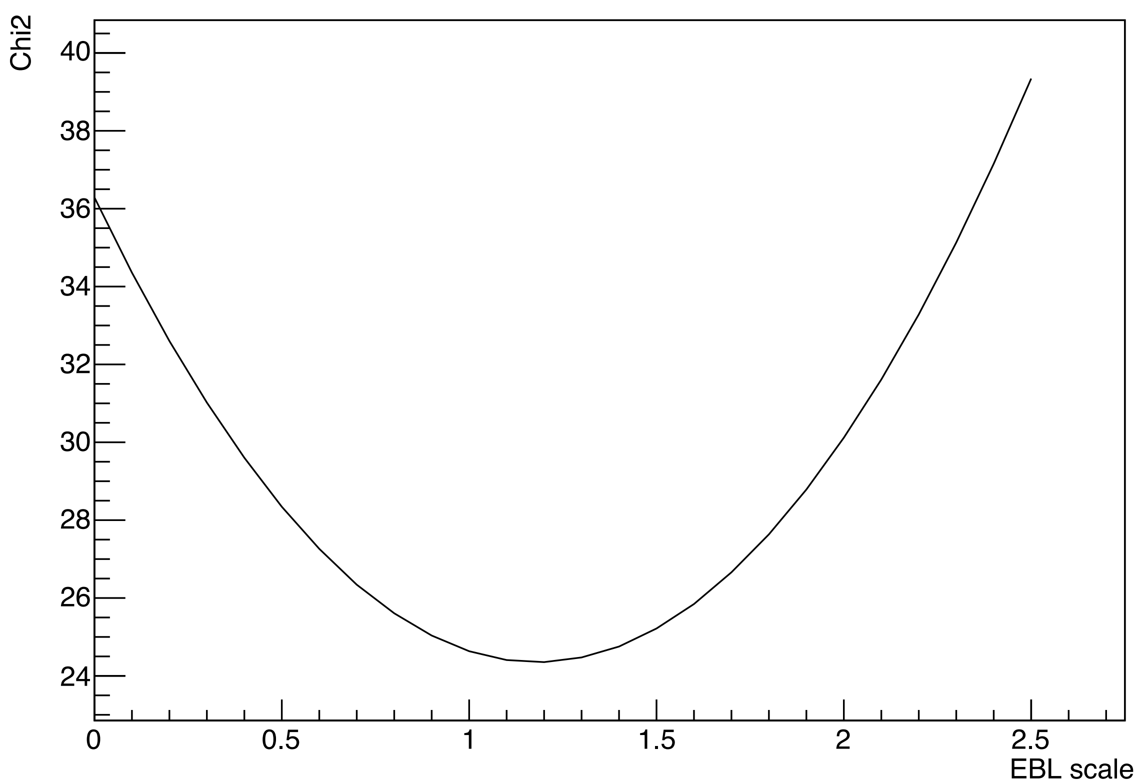
Convolution of assumed intrinsic spectrum, assumed EBL and telescope response function gives us an expected distribution of gammas.
This is compared with the measured distribution.

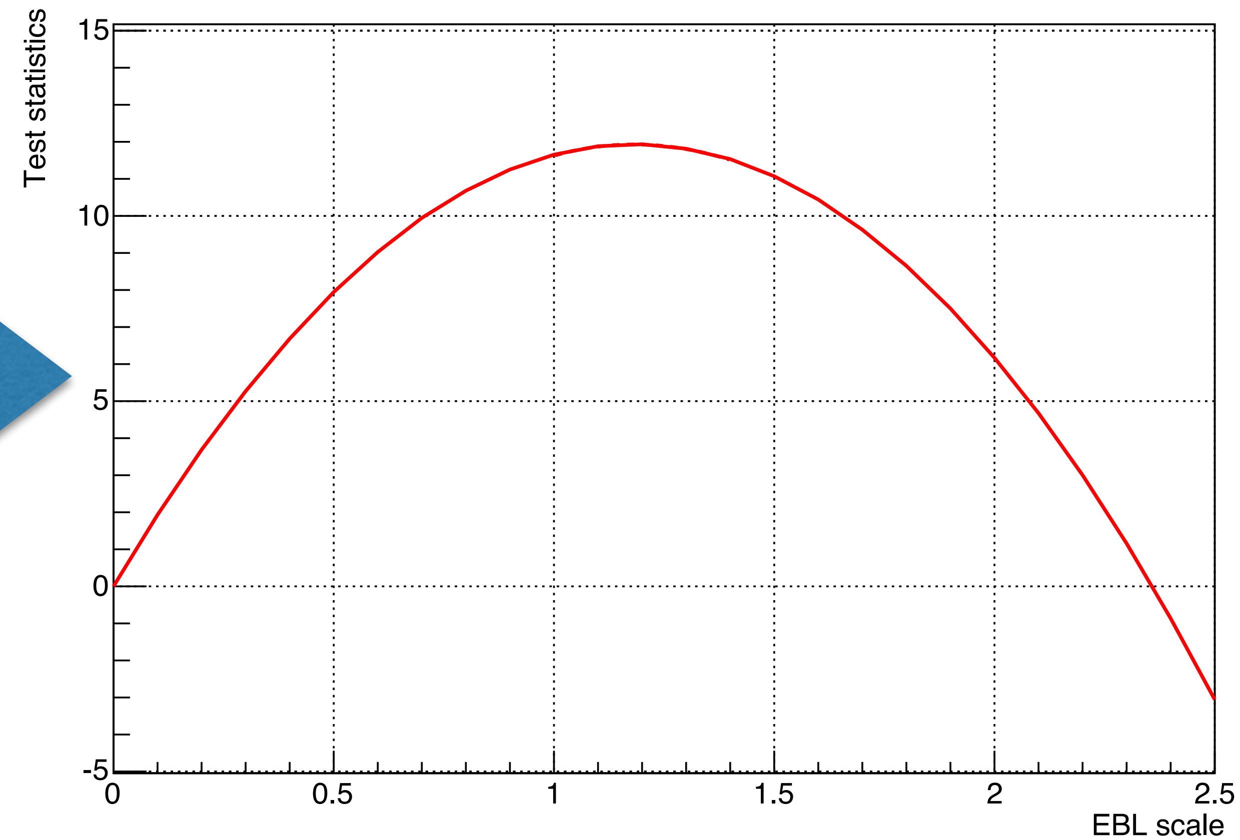
- Result of maximization: spectral parameters
- EBL treated as scalable density with a single parameter
  (same as done in previous studies, e.g. Ackermann et al (Fermi-LAT), Science 338, 1190 (2012), Abramowski et al. (HESS), A&A 550, A4 (2013))

Method: Poissonian likelihood maximization

Fit χ^2 vs. EBL density scale

$TS \equiv \chi^2 (EBL=0) - \chi^2 (EBL\ scale)$





- Scan of EBL scaling parameters and compare with EBL=0 case.
- Assume different intrinsic smooth parametrizations (PWL, LP, EPWL, ELP and SEPWL). Realized that PWL is a too strong assumptions. Use LP instead.

Results with 1ES1011+496

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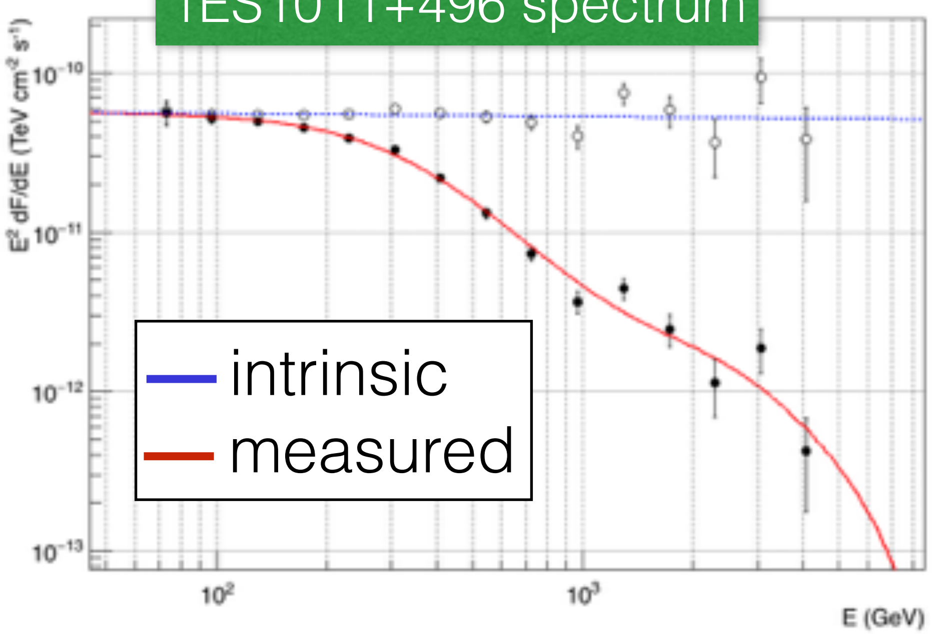
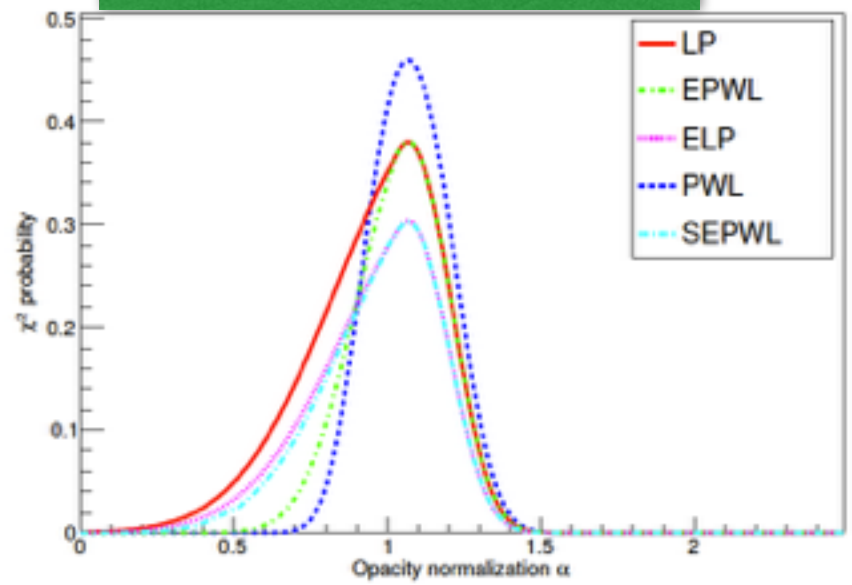
Ahnen et al. (MAGIC), A&A, 590, 24 (2016)

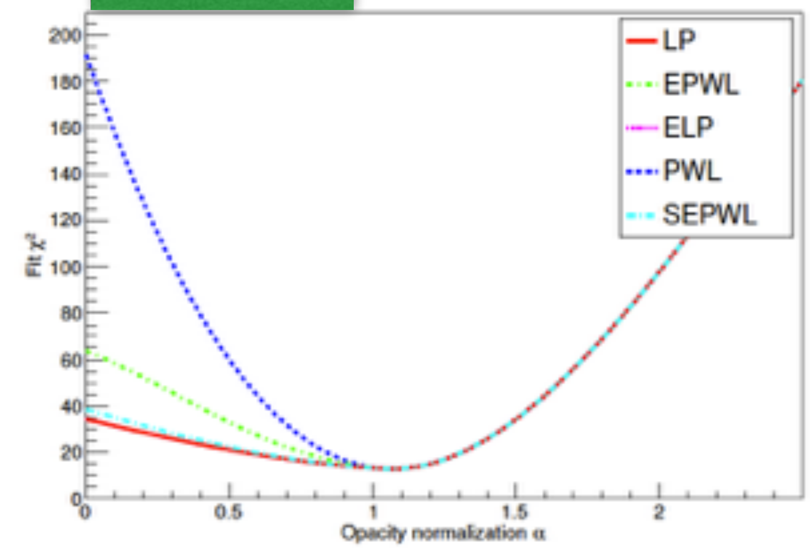
1ES1011+496 spectrum



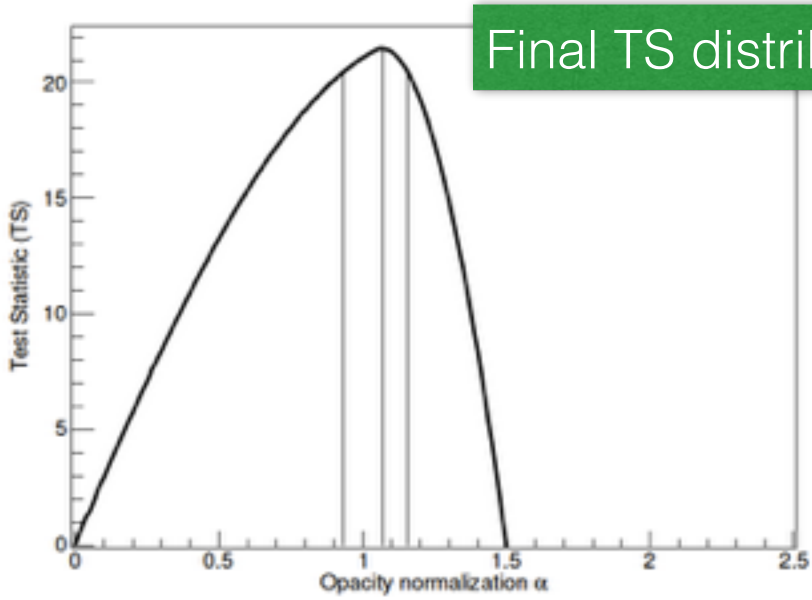
likel.ratio test probability



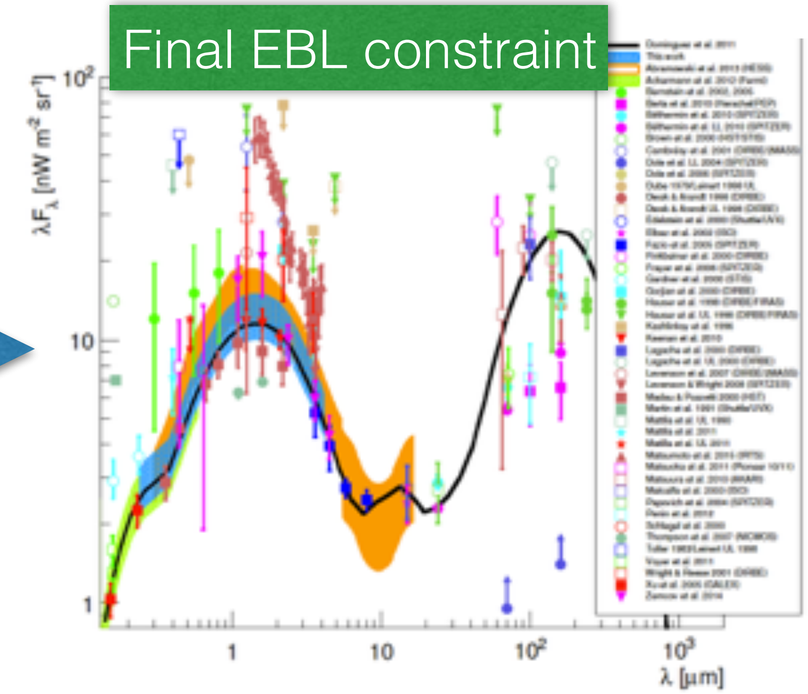
χ2 values



Final TS distribution



Final EBL constraint



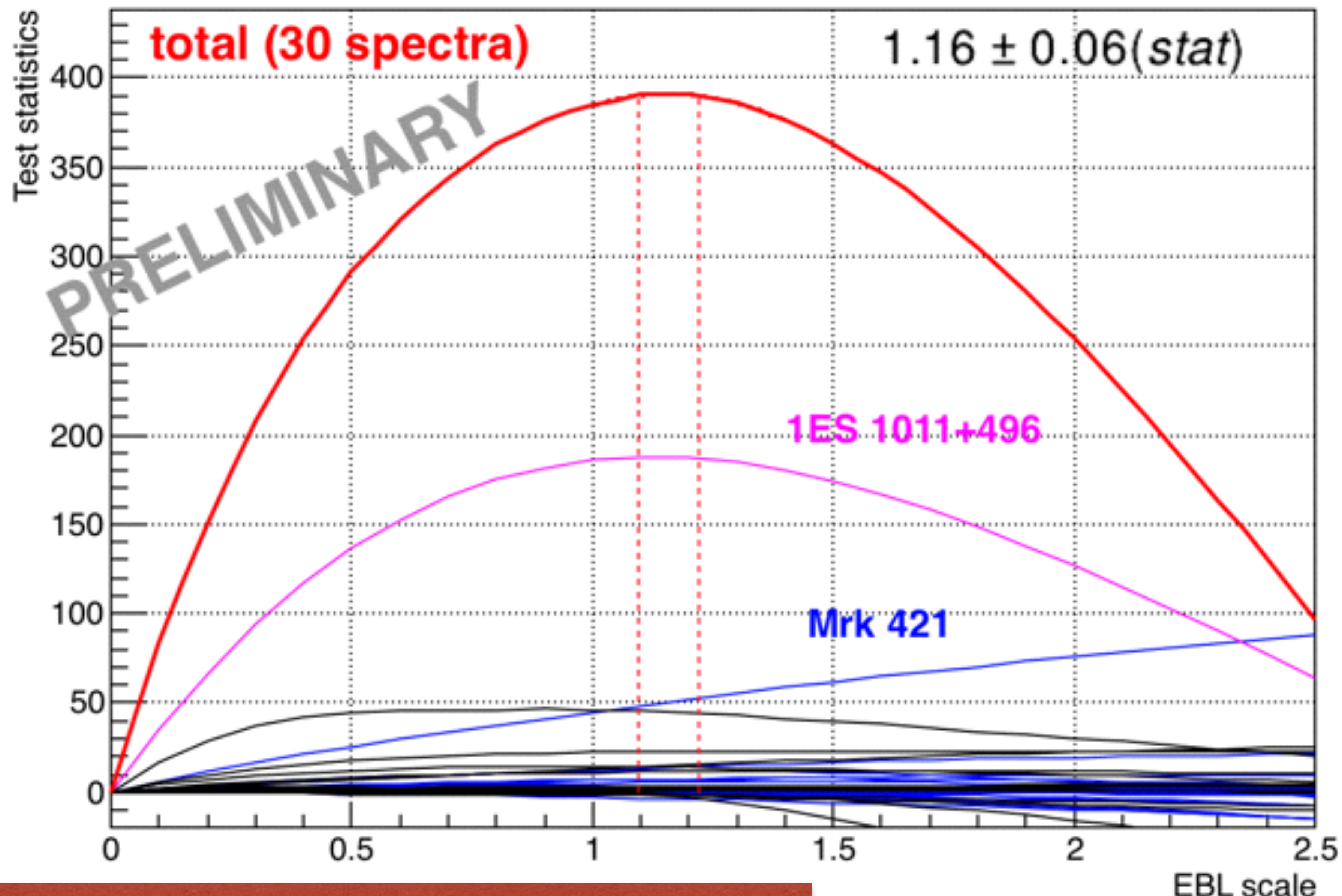
EBL normalization: $\alpha_0 = 1.07\ ^{+0.24}_{-0.20}$

New sample

source	type	redshift z	period	eff. time (h)
Mrk 421 (15 spectra)	HBL	0,031	20130410-19, 20140426	40,4
1ES1959+650	HBL	0,048	20151106 - 18	4,8
OT546 (1ES1727+502)	HBL	0,055	20151012-1102	6,4
BL Lacertae	HBL	0,069	20150615	1,0
1ES 0229+200	HBL	0,14	2012-2015	105,2
1ES 1ES1011+496	HBL	0,212	20140206-0307	11,8
PKS1510-089	FSRQ	0,361	20150518-19	2,4
PKS1222+216	FSRQ	0,432	20100618	0,5
PG1553+113 (5 spectra)	HBL	0.43-0.58	2012-2-16	66,3
PKS1424+240	HBL	0,601	2014-324-0618	28,2
PKS1441+25	FSRQ	0,939	20150418-23	20,1
B 0218+35	FSRQ	0,944	20140725-26	2,1
Total				**289,2**

Results

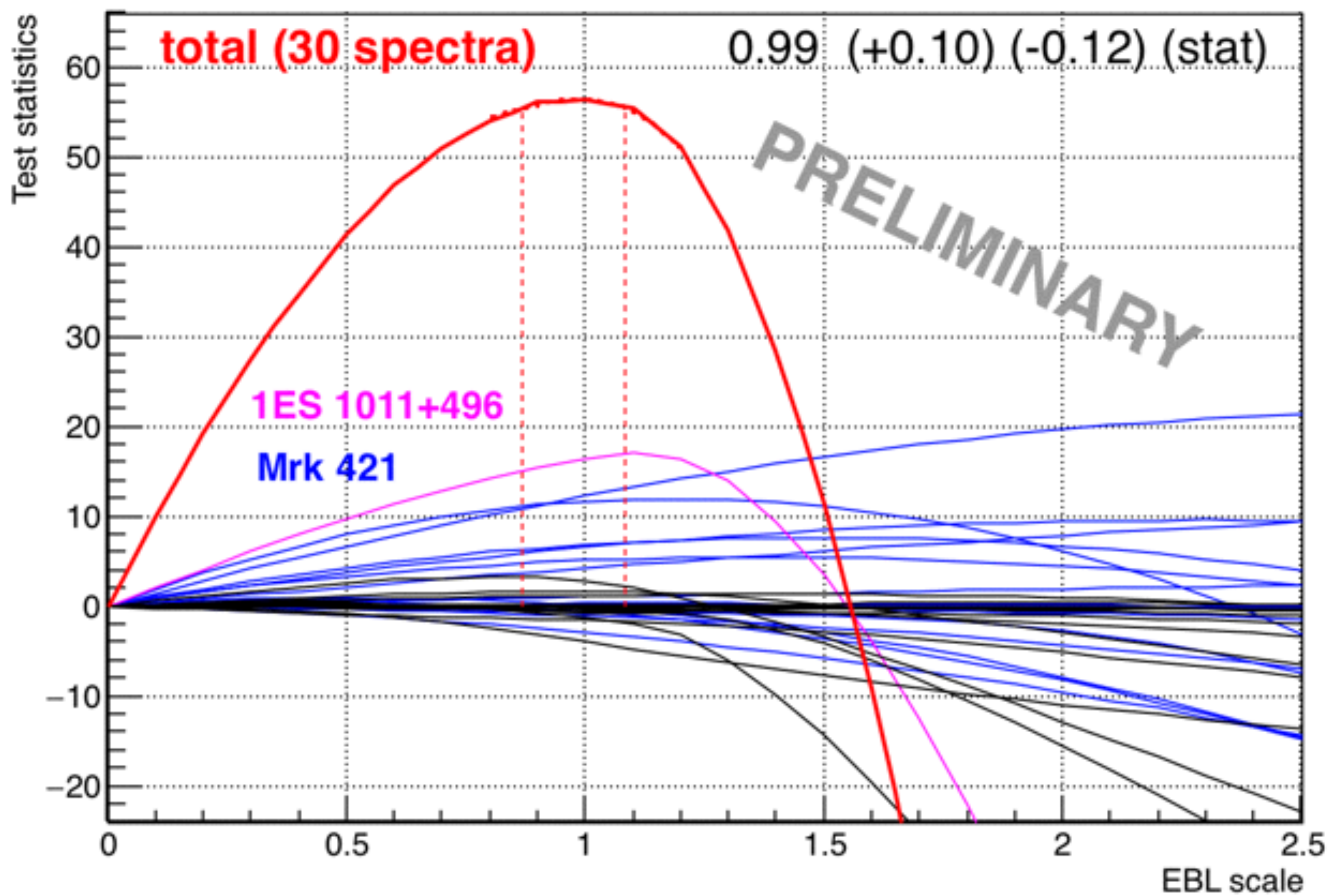
- Assuming power law as one of the possible models for the intrinsic spectrum



introduces risk of bias towards higher EBL

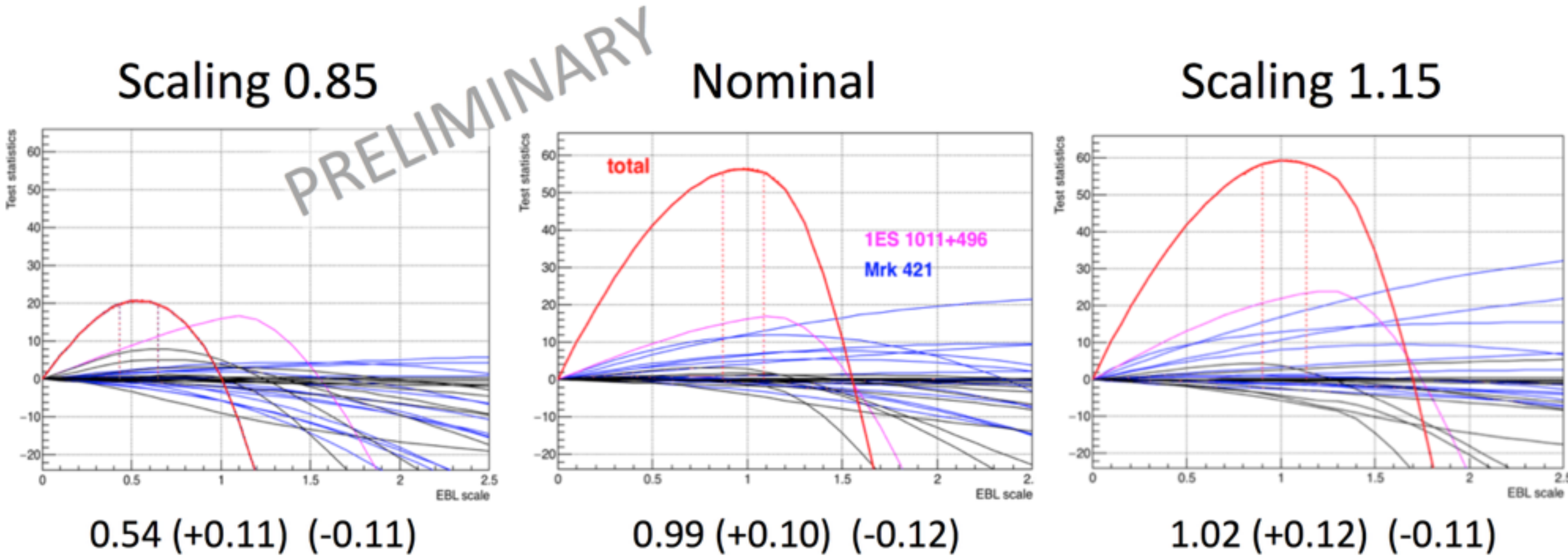
Results

- **Excluding** power law as one of the possible models for the intrinsic spectrum



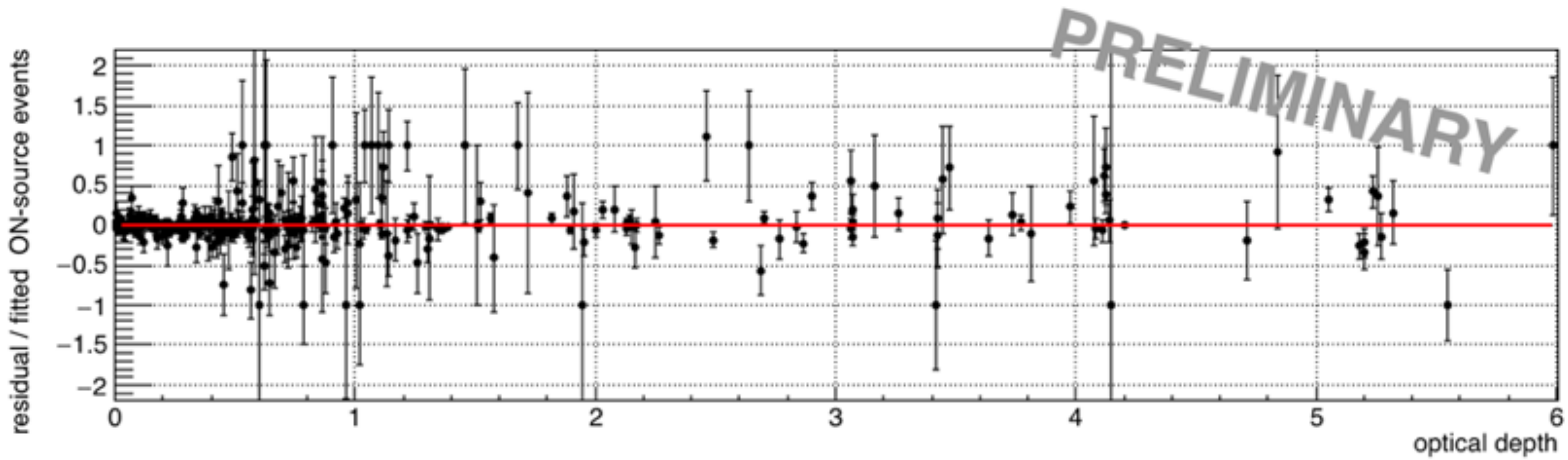
Results (systematics)

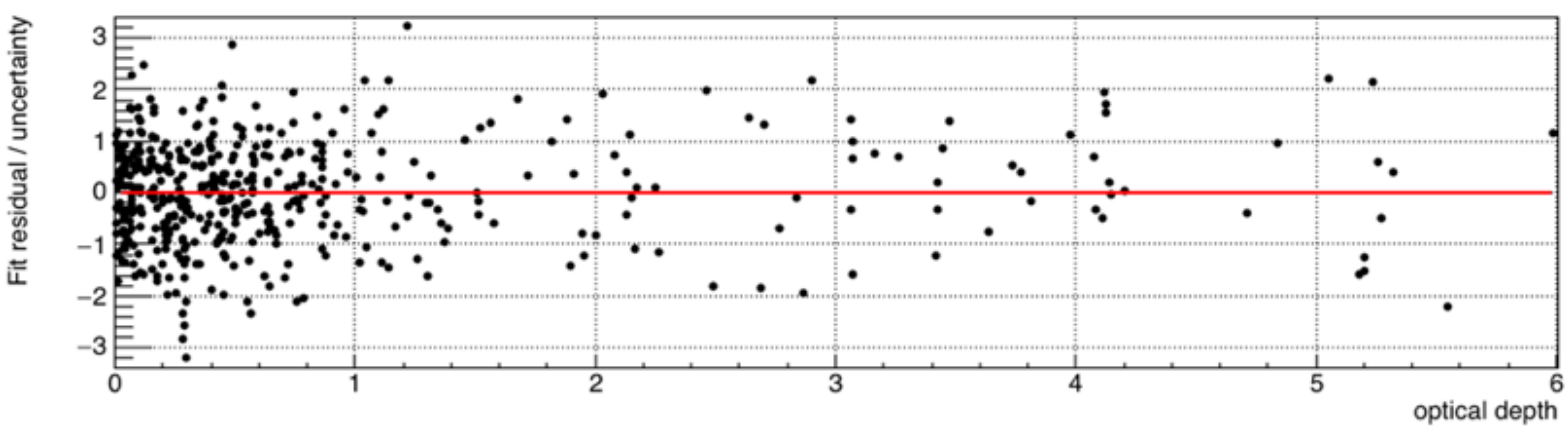
- Assuming the light yield is uncertain by +/-15% and repeating the entire analysis chain
- While +15% can be possible (bad weather), **-15% is highly unlikely** in average, over a large sample, as it would mean the atmosphere+telescope is 15% more transparent than we assume in Monte Carlo



Results

- Testing hypothesis of possible turn up at highest tau values

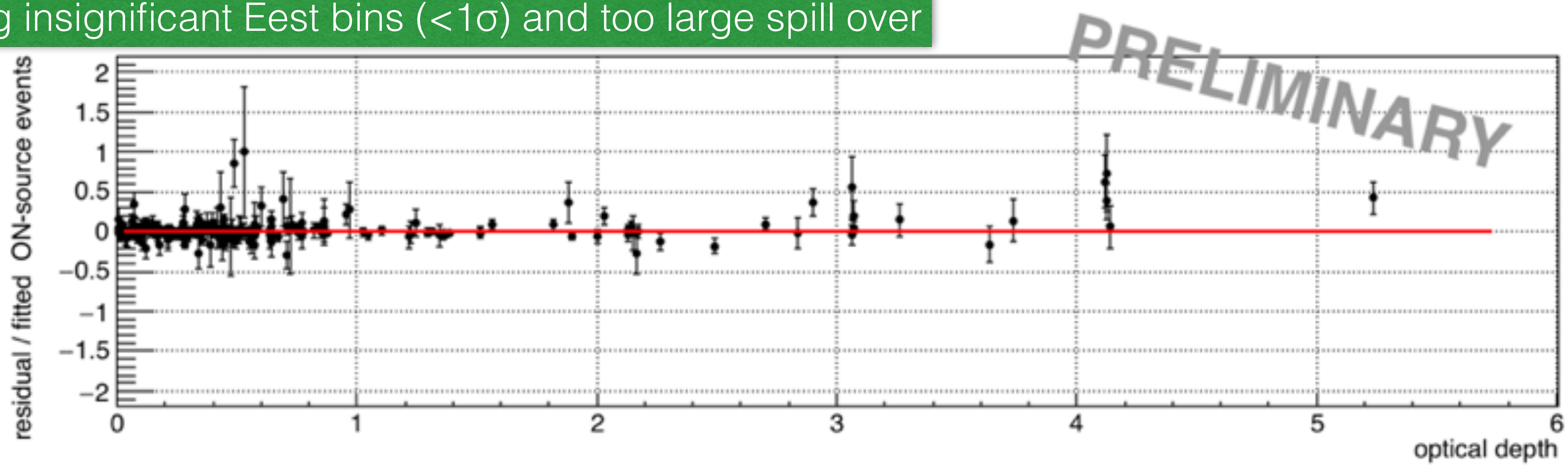


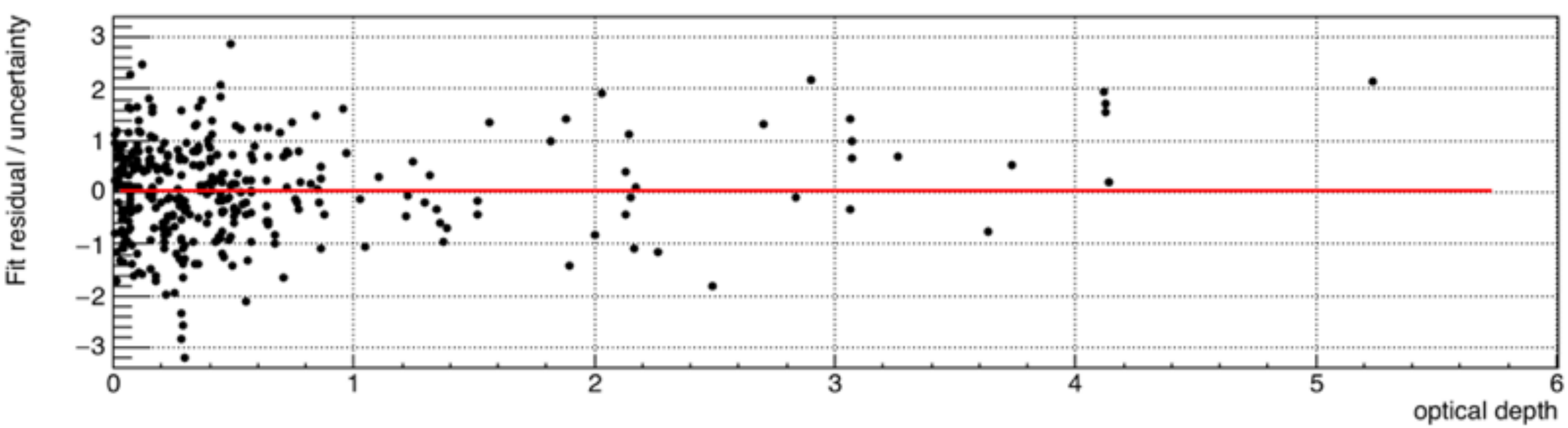


Results

- Testing hypothesis of possible turn up at highest tau values

+ removing insignificant Eest bins (<1σ) and too large spill over





Final result

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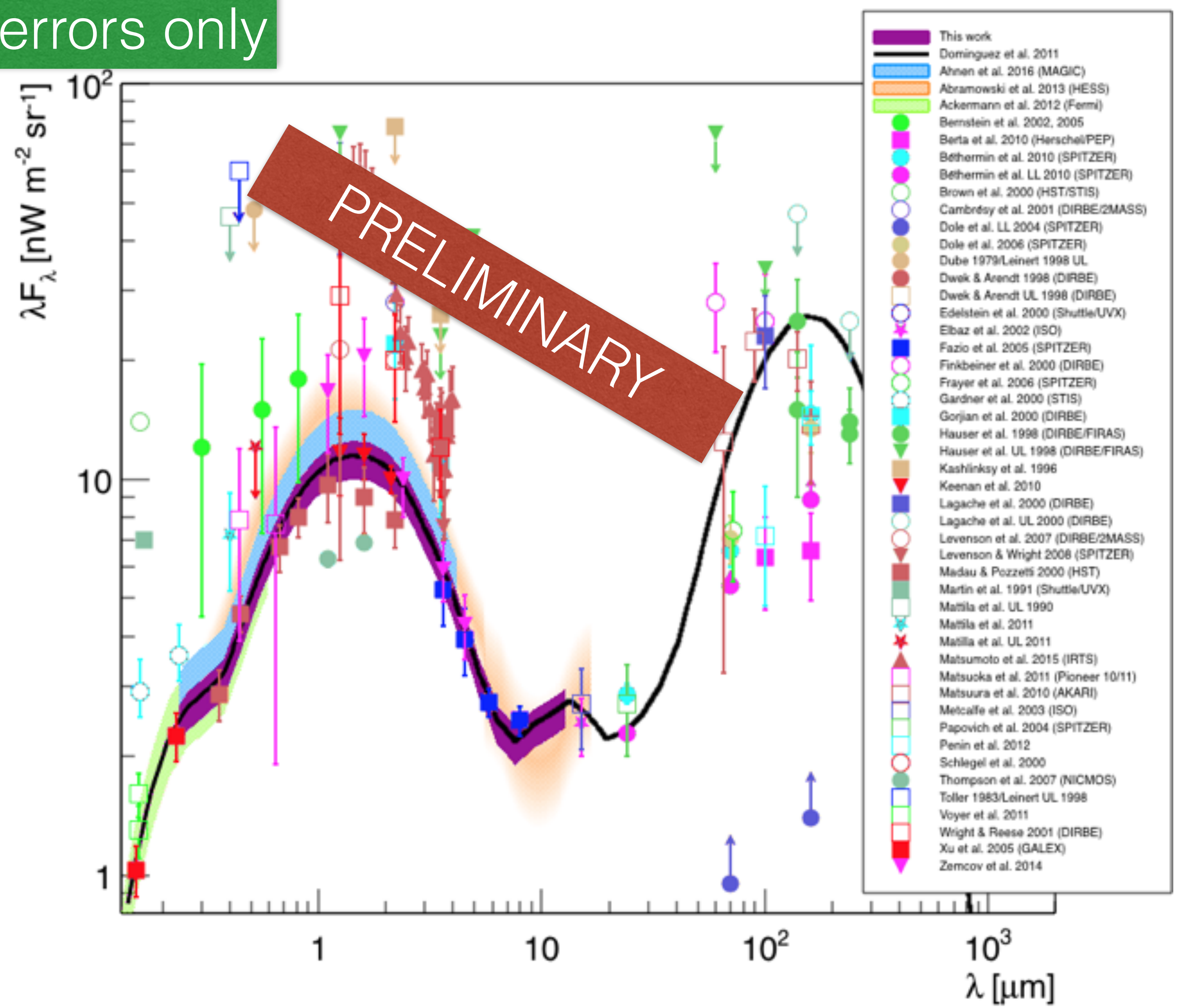
statistical errors only

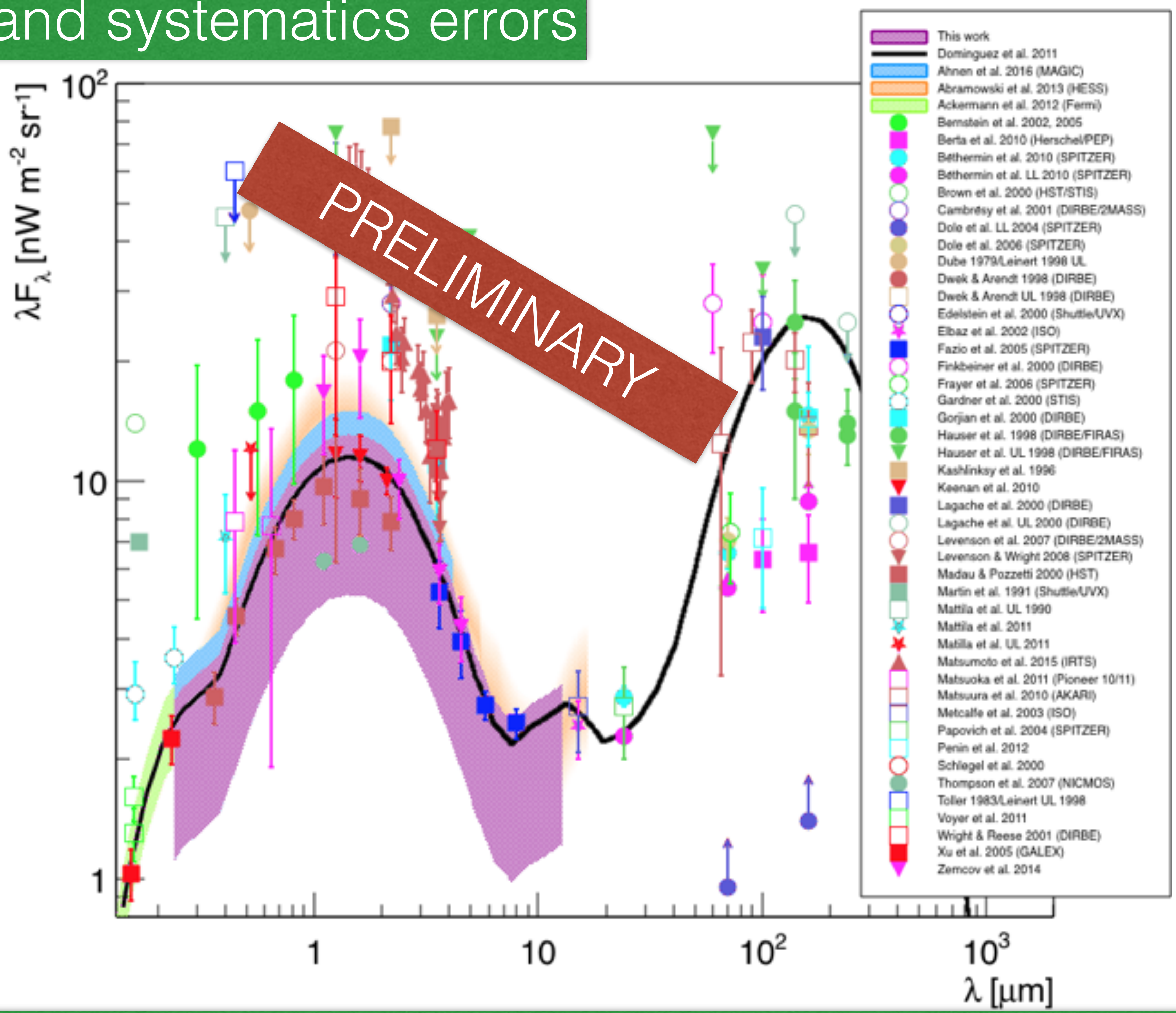


EBL normalization

$\alpha_0 = 0.99^{+0.10}_{-0.11}$

Final result

statistical and systematics errors



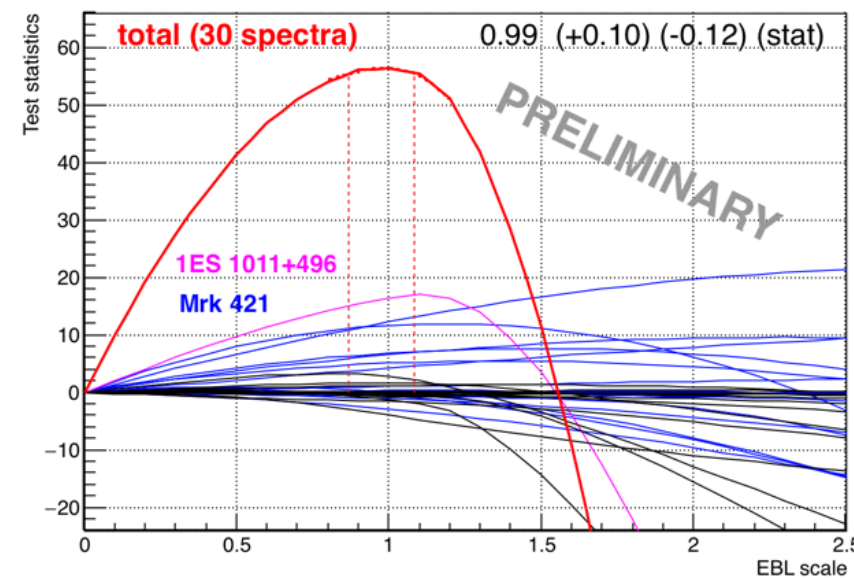
EBL normalization

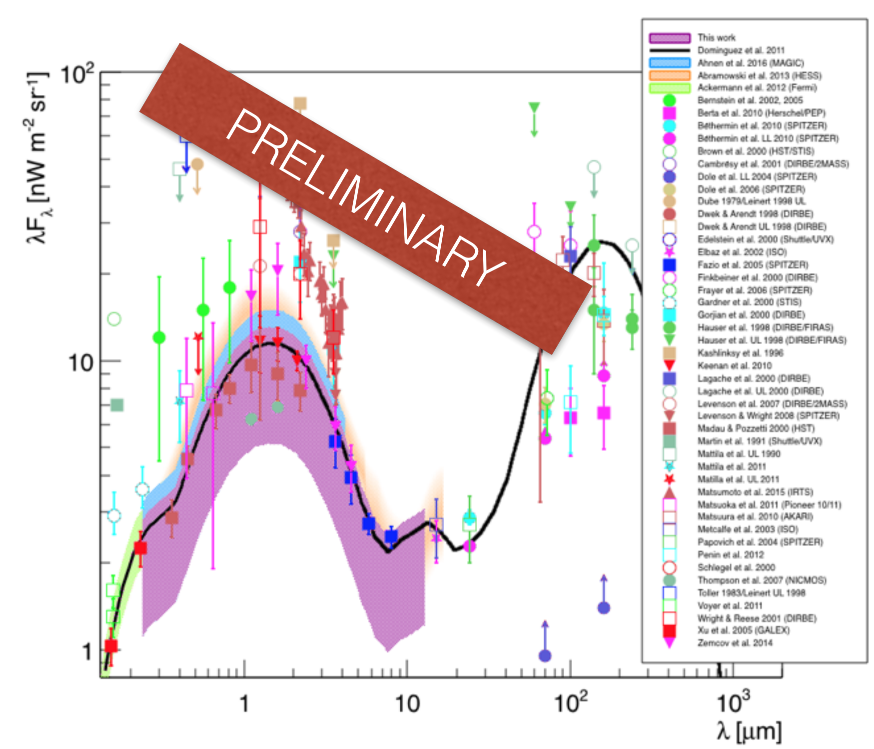
$\alpha_0 = 0.99\ ^{+0.15}_{-0.56}$

very conservative on the lower side as commented earlier

Summary

- MAGIC observed several extragalactic sources that are useful for EBL constraints
- Power-law assumption for intrinsic spectra is prone to bias towards higher EBL and not used here
- new results suggests <14% more EBL than in state-of-the-art EBL models
  - $\alpha_0 = 0.99^{+0.15}_{-0.56}$, including systematics
- These limits are
  - robust
  - lower limit too conservative
- Wavelength resolved limits are in progress, stay tuned





BACKUP

all SEDs residuals

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all SED residuals

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Idea behind the EBL limits

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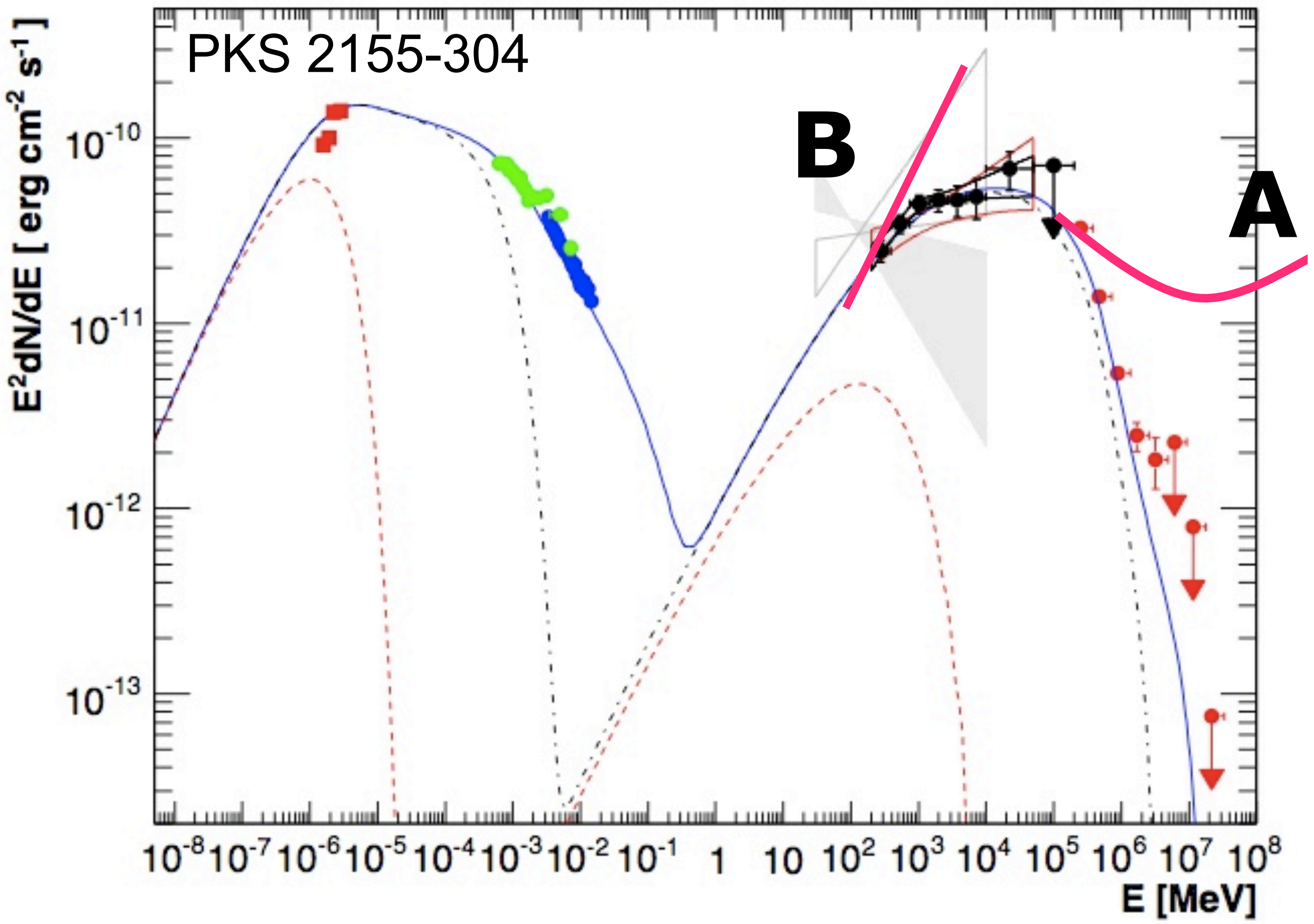
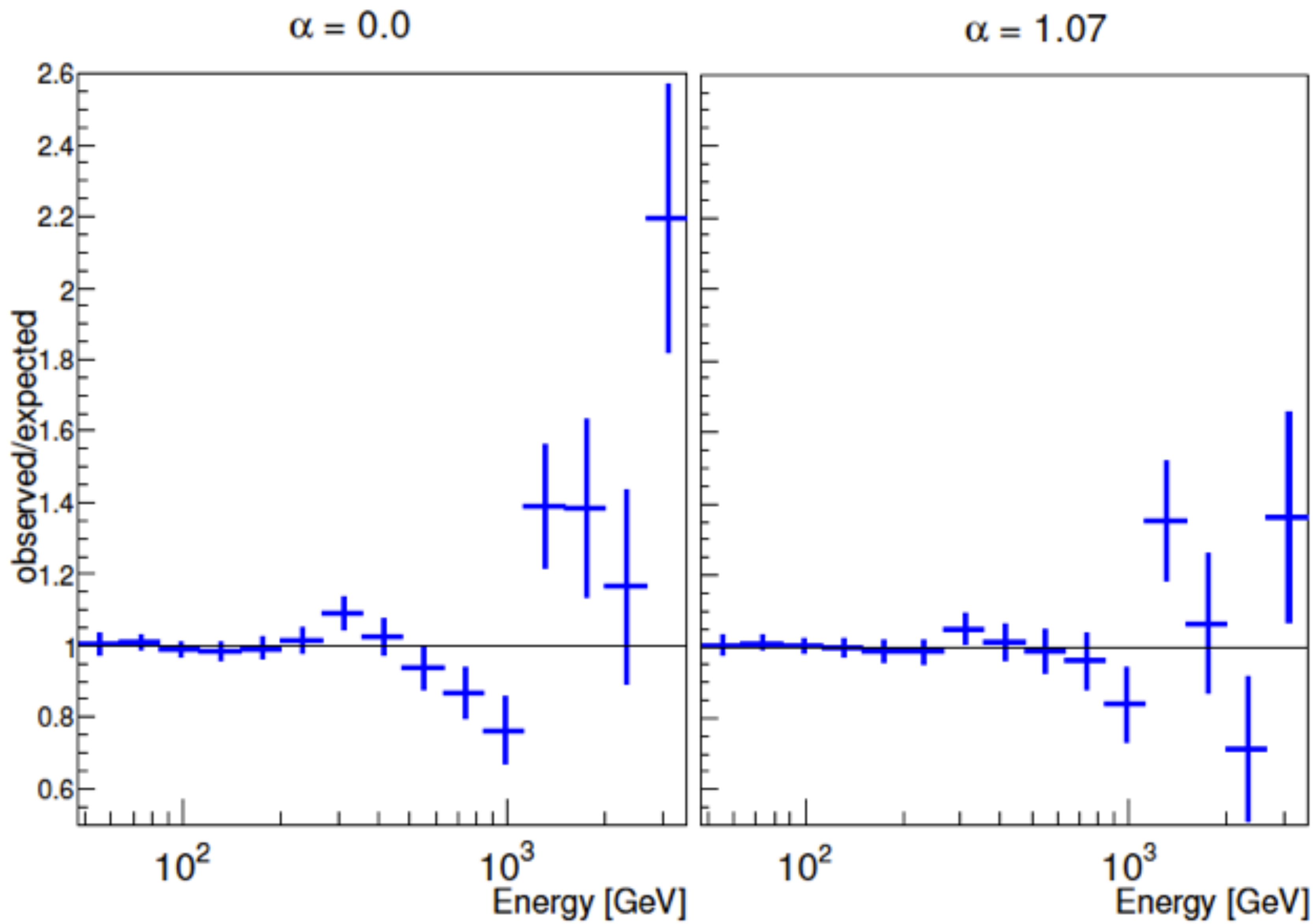
very simplified way of seeing it:

- The reconstructed AGN spectrum (after correcting for the EBL effect) must be reasonable
- Reasonable means:
  - no pile-up at high energies
  - smooth shape (as it is smooth at lower energies)
  - spectral slope to harder than 1.5 (corresponding to canonical electron spectrum with index 2)
- In case unreasonable intrinsic spectrum is obtained the assumed EBL can be ruled out



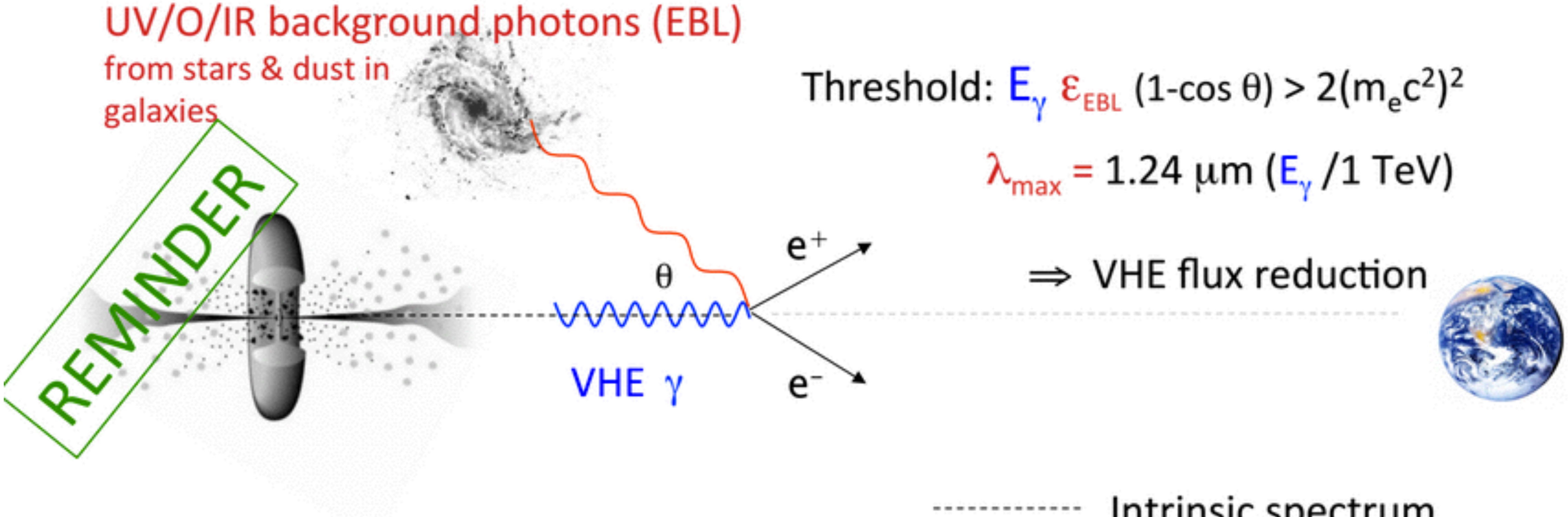
1ES1011 result for LogParabola

Residuals:



Constraining range is between 0.2 and 3.5 TeV

VHE gamma rays as probes of the EBL

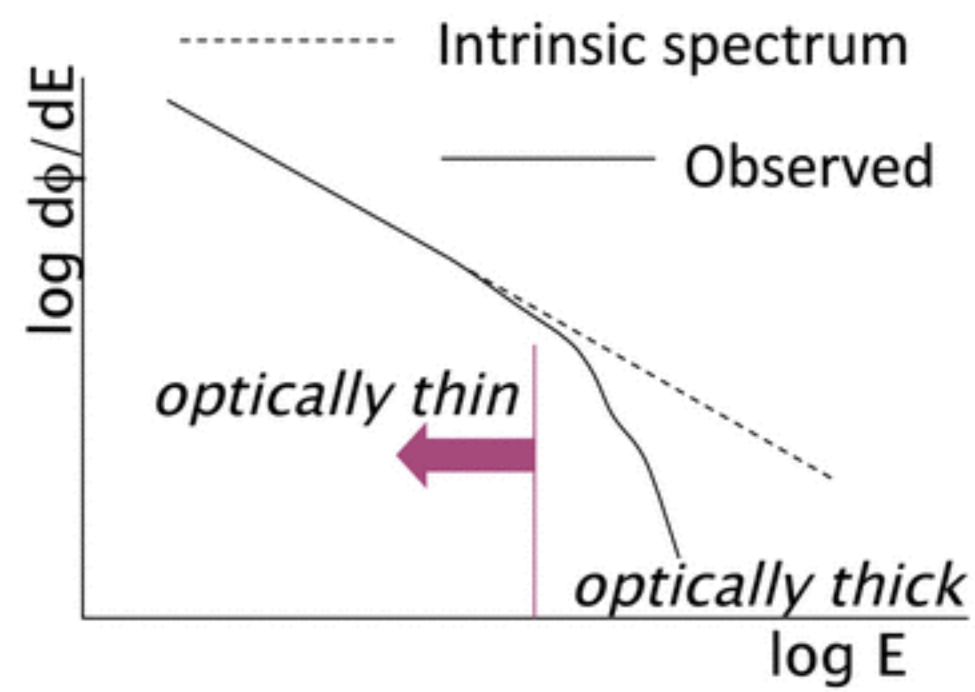


Threshold: $E_\gamma \, \varepsilon_{EBL} \, (1\text{-}\cos\theta) > 2(m_e c^2)^2$

λ_{max} = 1.24 μm (E_γ /1 TeV)

⇒ VHE flux reduction

- observed flux: $e^{-\tau}$ × emitted flux
- τ : optical depth
- $\tau = \tau(E, z)$



VHE photons can be used as a probe of Extragalactic Background Light

Likelihood maximization

- 5 functions are tested:
  - power law (PL), $\phi_0(E/E_0)^{-\Gamma}$
  - power law with exponential cut-off (EPWL), $\phi_0(E/E_0)^{-\Gamma}\exp(-E/E_{\mathrm{cut}})$
  - log-parabola (LP), $\phi_0(E/E_0)^{-a-b\log(E/E_0)}$
  - log-parabola with exponential cut-off (ELP) $\phi_0(E/E_0)^{-a-b\log(E/E_0)}\exp(-E/E_{\mathrm{cut}})$
  - and power law with super-exponential cut-off (SEPWL). $\phi_0(E/E_0)^{-\Gamma}\exp\left(-(E/E_{\mathrm{cut}})^{\gamma}\right)$
- In the case of LP and ELP, both have the "trick" of doing *b* -> b^2 to avoid a positive curvature.
- The most complex functions (e.g. LP) takes as starting parameters for the fit the parameters of the already fitted nested functions (e.g. PWL)

Of these, only the SBPWL,

$$\frac{dF}{dE} = f_0\left(\frac{E}{E_0}\right)^{-\Gamma_1}\left[1+\left(\frac{E}{E_b}\right)^{g}\right]^{\frac{\Gamma_1-\Gamma_2}{g}}$$

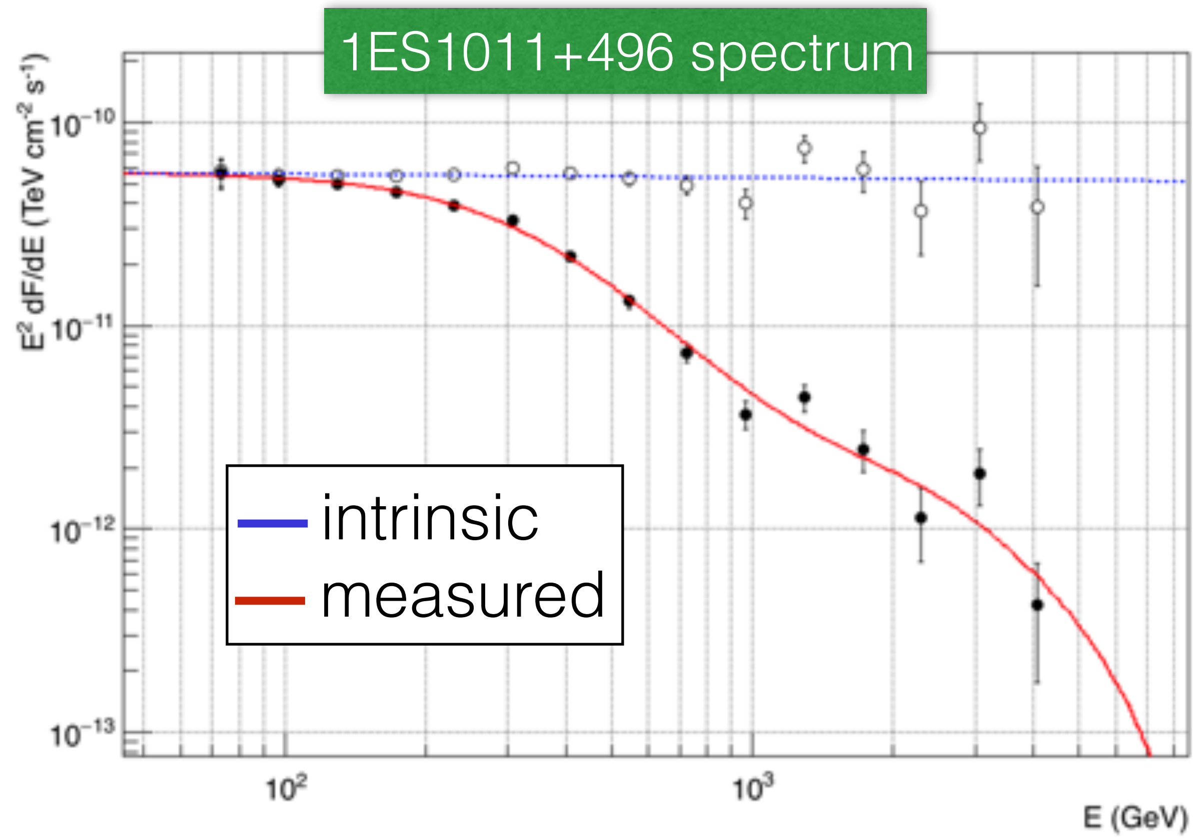
achieves an acceptable fit (P = 0.17, χ^2/d.o.f.= 12.8/9).

1ES1011+496

- Use likelihood maximization fit
- Null hypothesis:
  - there is no EBL
  - the spectrum is concave
  - the spectrum follows a smooth shape
- Tested hypothesis: there is EBL
- Tested shapes:
  - power law
  - power law with cutoff
  - log-parabola
  - log parabola with cutoff
  - power law with super(sub)exponential cutoff

$$dN/dE_{obs} = dN/dE_{int}\ \mathrm{pow}\ (-\alpha\ \tau_{model})$$

averaged differential energy spectrum



Basically you compare:
fit with EBL vs. **fit without EBL**

Results

- All tested functions prefer a presence of EBL, and EBL level < 1.3 * EBLmodel
- Best fit is at around α = 1.07, i.e. the state of the art EBL (Franceschini et al 2008, Dominguez et al. 2010, etc) is preferred.

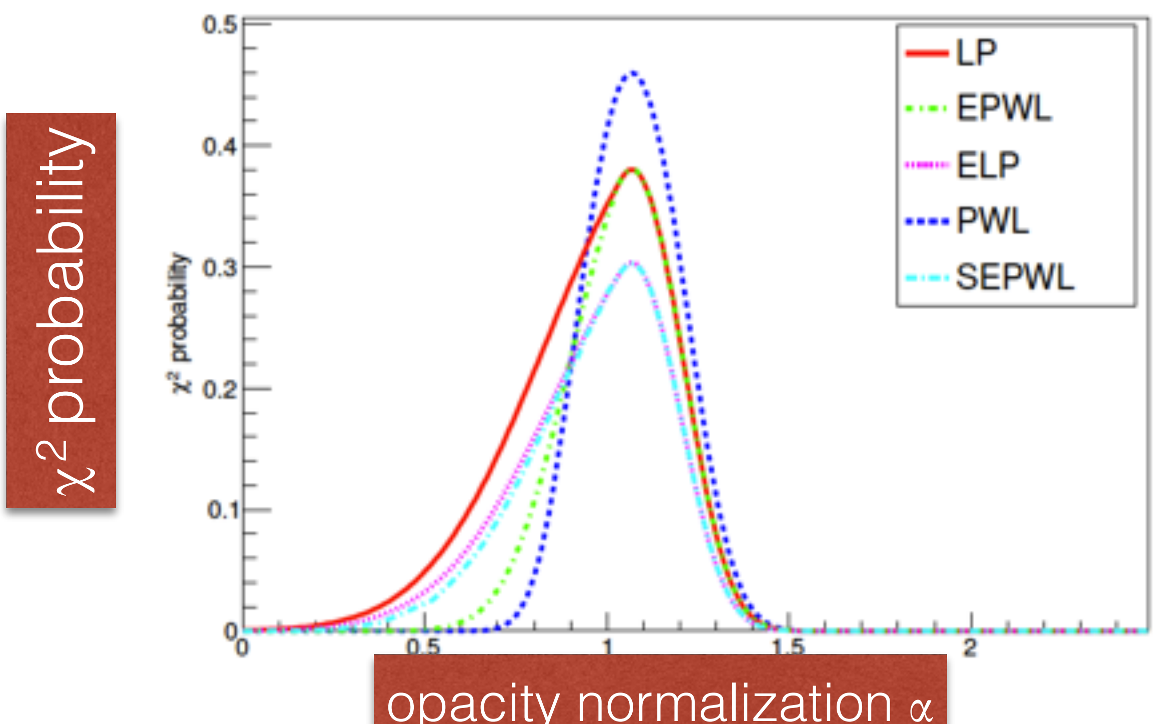


Fig. 4. χ^2 probability distributions for the average spectrum of the Feb-March flare of 1ES 1011+496 for the 5 models tested. PWL in blue (dashed line), LP in red (solid line), EPWL in green (dash-dot line), ELP in pink (dotted line) and SEPWL in light blue (long dash-dot line).

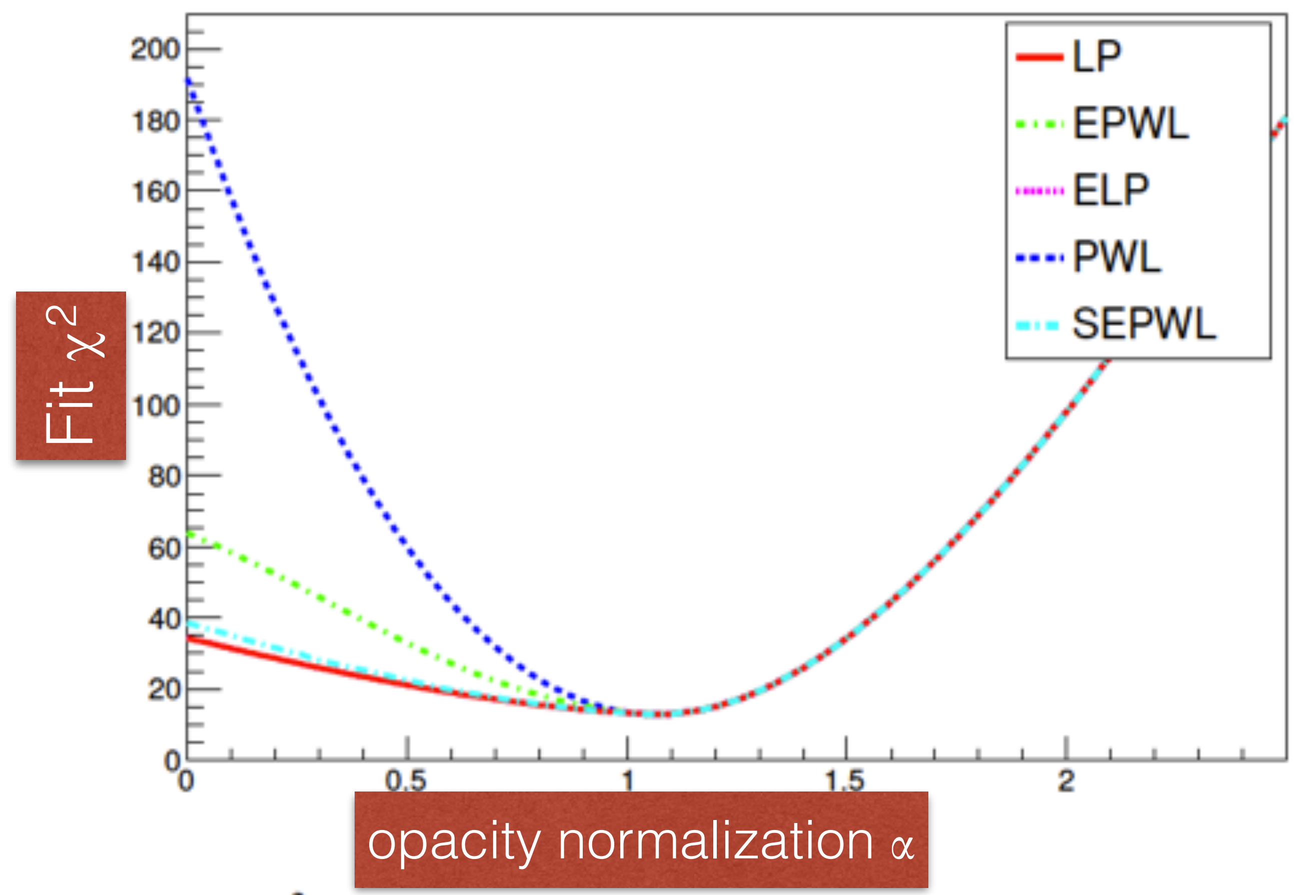


Fig. 5. Fit χ^2 distributions for the average spectrum of the Feb-March flare of 1ES 1011+496 for the 5 models tested. PWL in blue (dashed line), LP in red (solid line), EPWL in green (dot-dash line) and ELP in pink (dotted line) and SEPWL in light blue (long dash-dot line). The LP red line is overlapping ELP pink line. Notice how all curves converge after reaching the minimum.

Results

Table 1. χ^2 probabilities (P) for the cases of $\alpha = 0.0$ and $\alpha = 1.07$

Function	$P(\alpha = 0.0)$	$P(\alpha = 1.07)$
LP	6.0×10^{-4}	0.38
PWL	7.0×10^{-34}	0.46
EPWL	4.5×10^{-9}	0.38
ELP	3.2×10^{-4}	0.30
SEPWL	6.2×10^{-5}	0.30

- For the final result we select the Log parabola (LP) one because:
  - power law hypothesis is a too strong assumption
  - No preference between EPWL and LP
  - all functions behave identically for $\alpha > 1.07$

Test Statistics (TS) for Log Parabola assumption

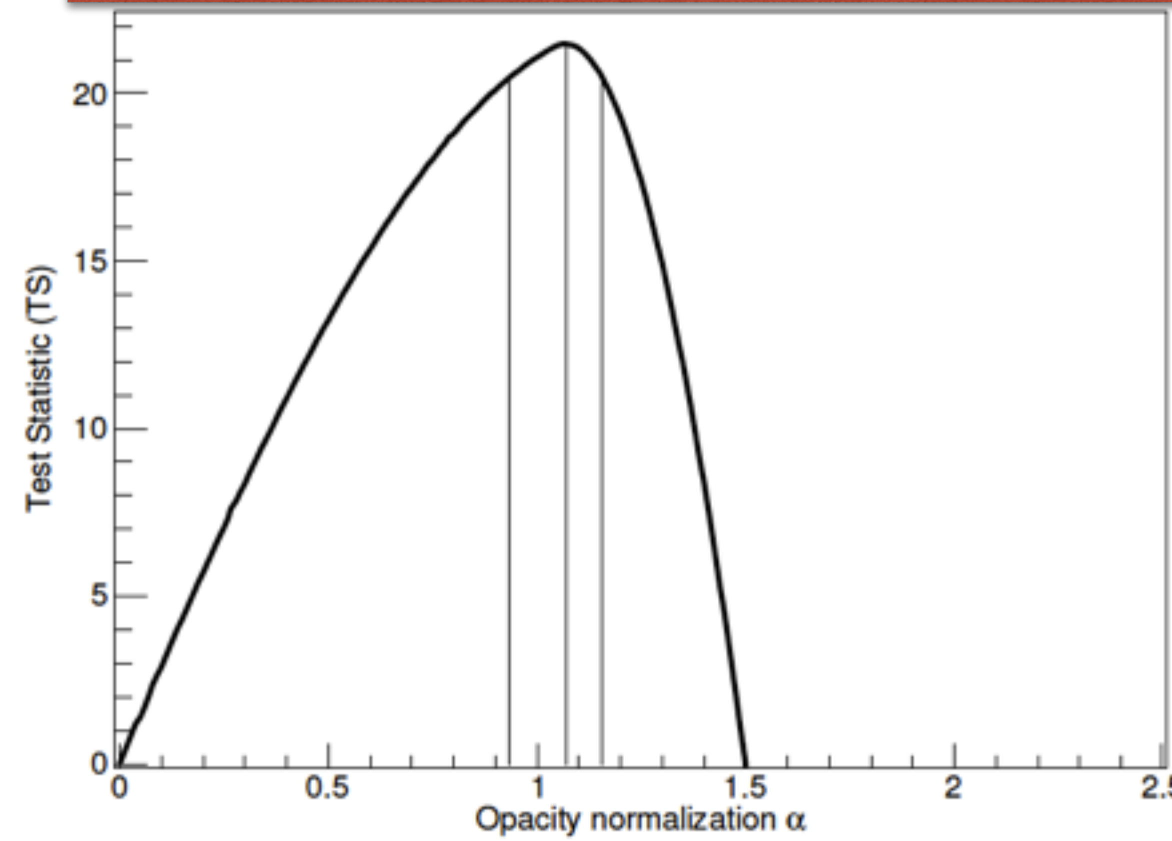
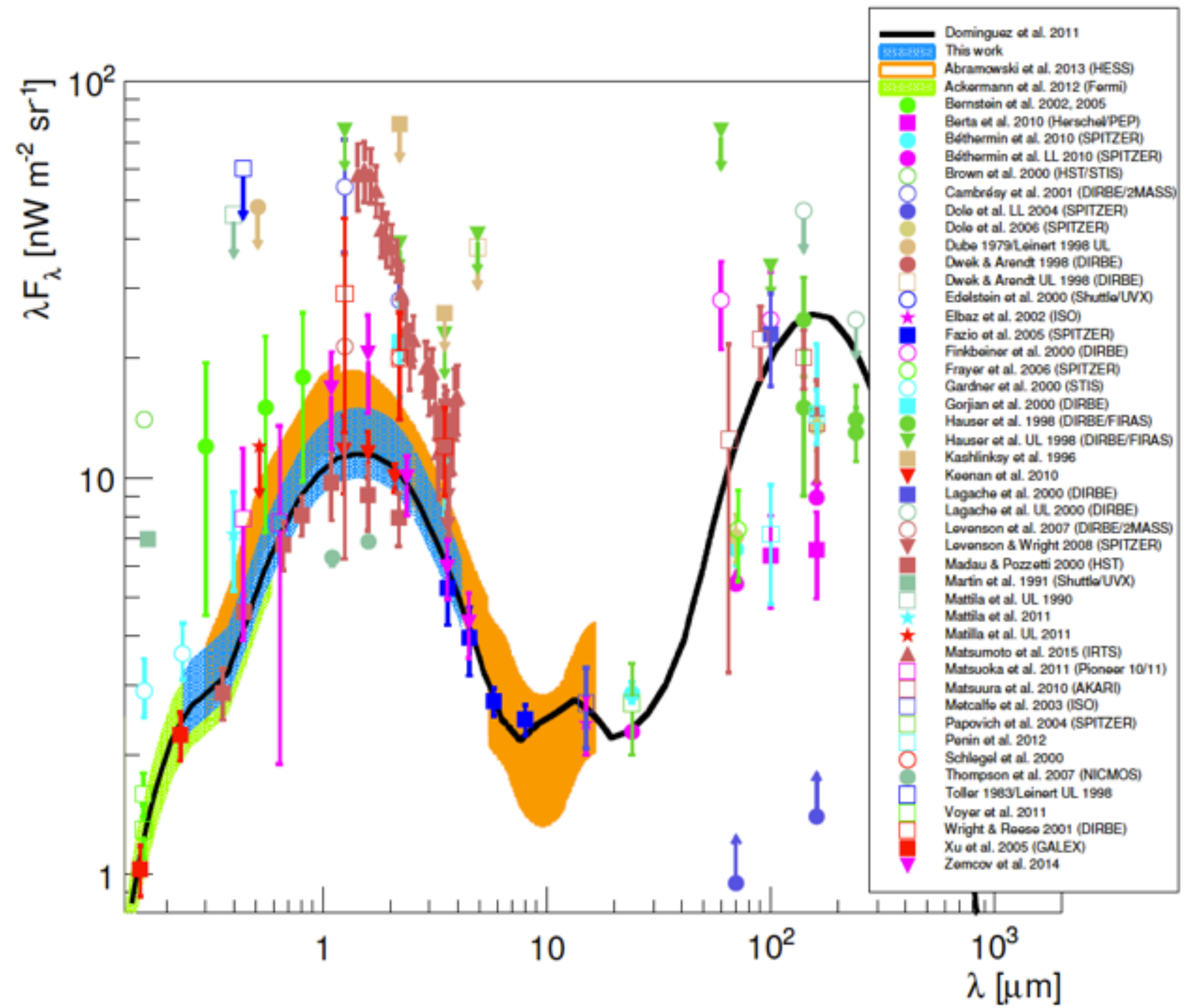


Fig. 6. Test statistics distribution for the data sample for the 2014 Feb-March flare of 1ES 1011+496. The vertical lines mark the maximum and the uncertainty corresponding to 1 σ.

$$TS = 21.5,\ \alpha_0 = 1.07^{+0.09}_{-0.13}\text{, statistically}$$

$$\alpha_0 = 1.07^{+0.20}_{-0.24}\text{, including systematics}$$

Results



EBL density at $\lambda=1.4\mu m$: $F_\lambda = 12.27^{+2.75}_{-2.29}$