

# MAGIC observations of the February 2014 flare of 1ES 1011+496 applied to the measurement of the Extragalactic Background Light density

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for the MAGIC collaboration

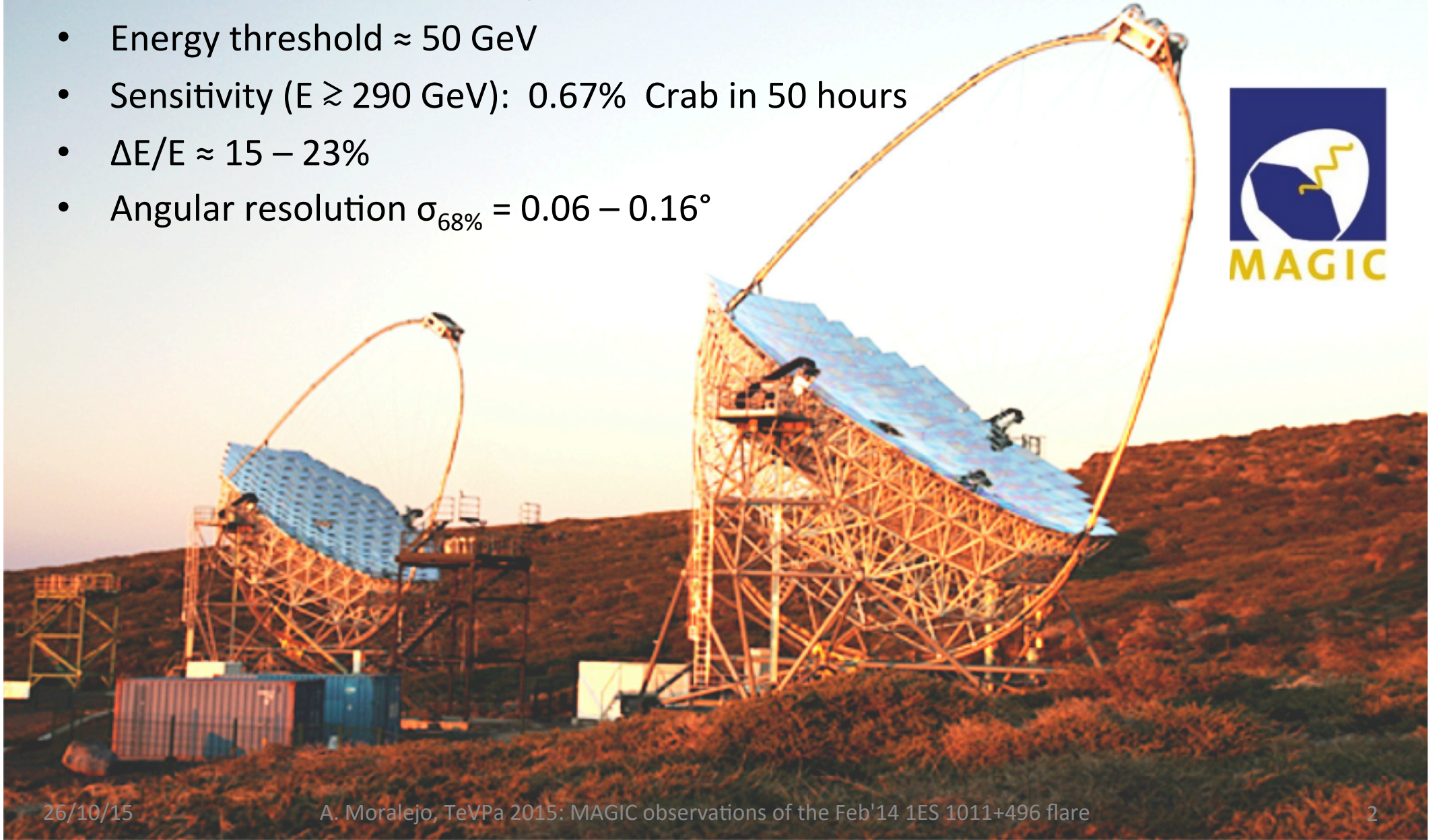


EXCELENCIA  
SEVERO  
OCHOA



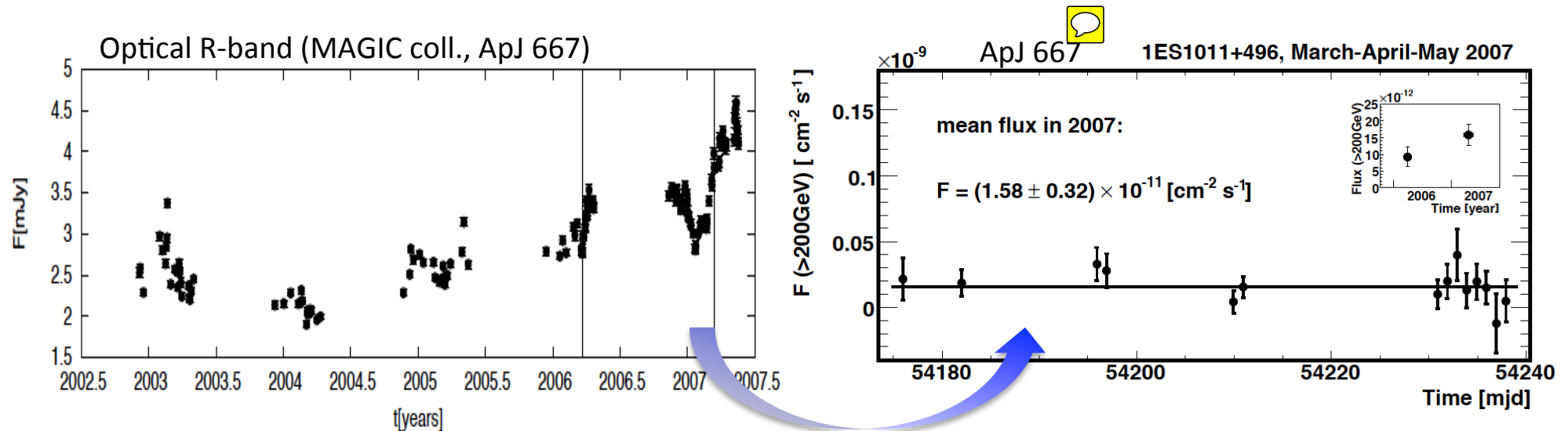
# The MAGIC telescopes

- System of two 17-m  $\varnothing$  imaging Cherenkov telescopes
- Location: La Palma, Canary islands (28.75° N, 17.86° W, 2200 m a.s.l.)
- Energy threshold  $\approx 50$  GeV
- Sensitivity ( $E \gtrsim 290$  GeV): 0.67% Crab in 50 hours
- $\Delta E/E \approx 15 - 23\%$
- Angular resolution  $\sigma_{68\%} = 0.06 - 0.16^\circ$



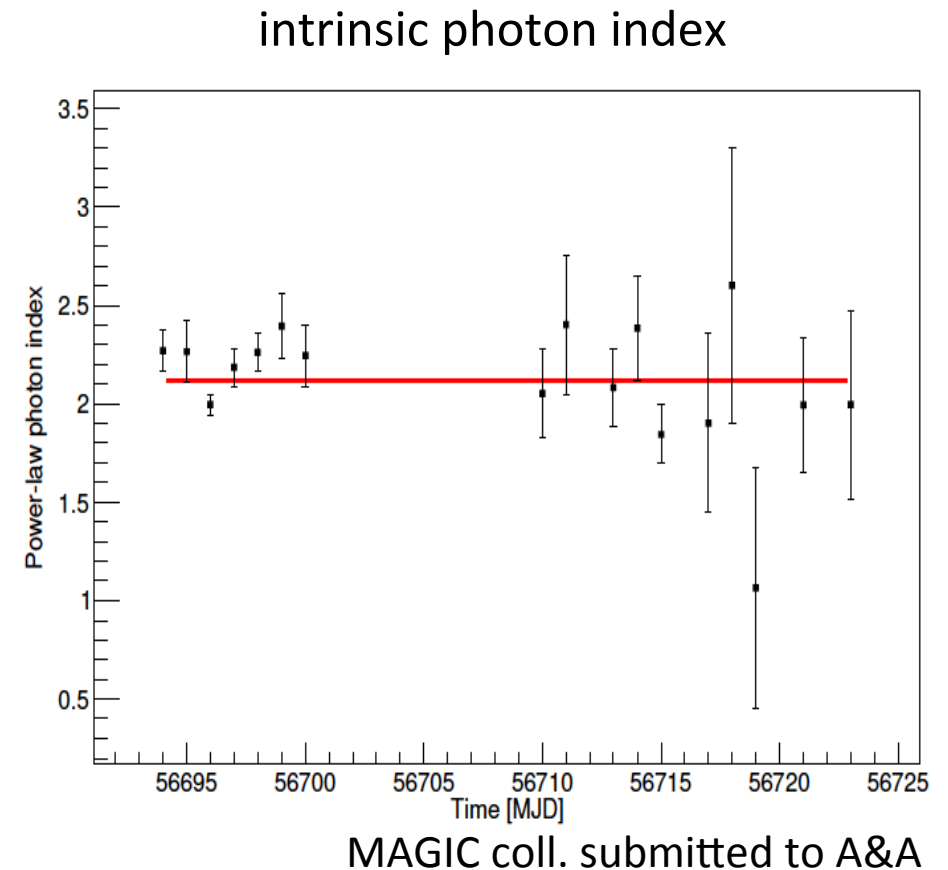
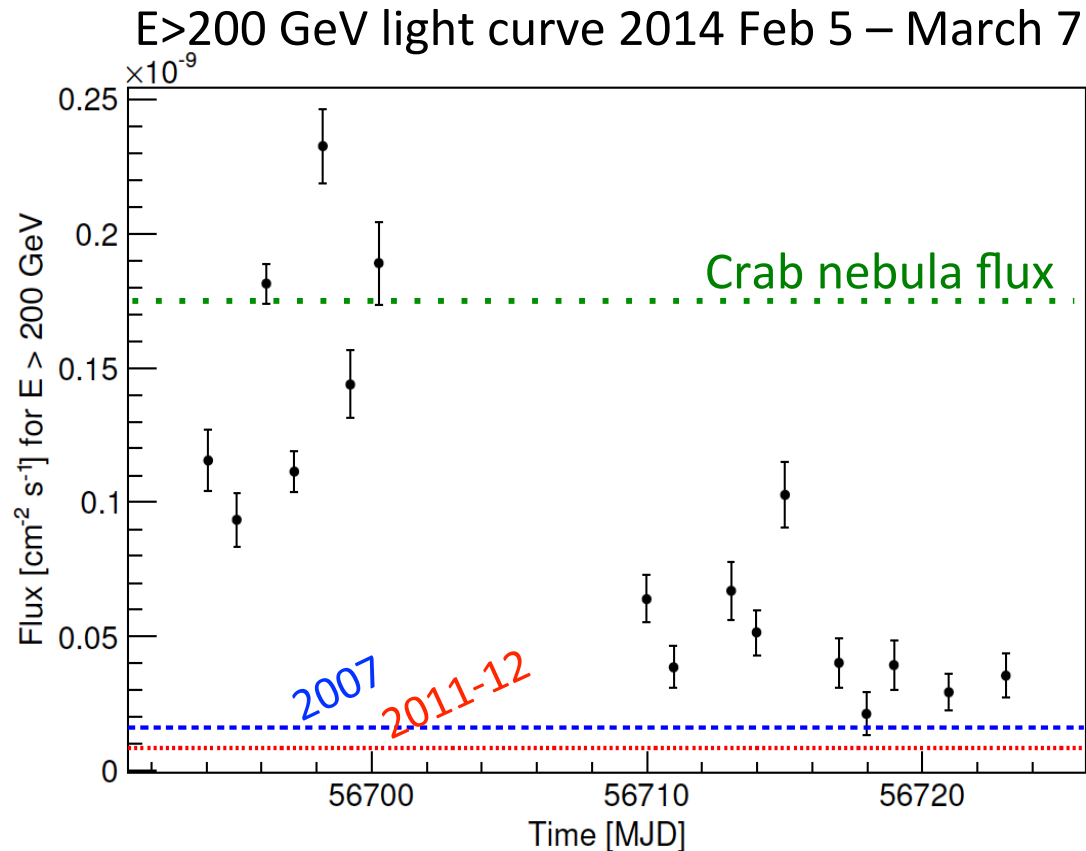
# 1ES 1011+496

- High-frequency peaked BL Lac (HBL) @  $z = 0.212$
- First detected at VHE in 2007 with MAGIC-1 ( $F_{>200\text{GeV}} \approx 9\%$  Crab) during a high optical state; similar flux in 2008



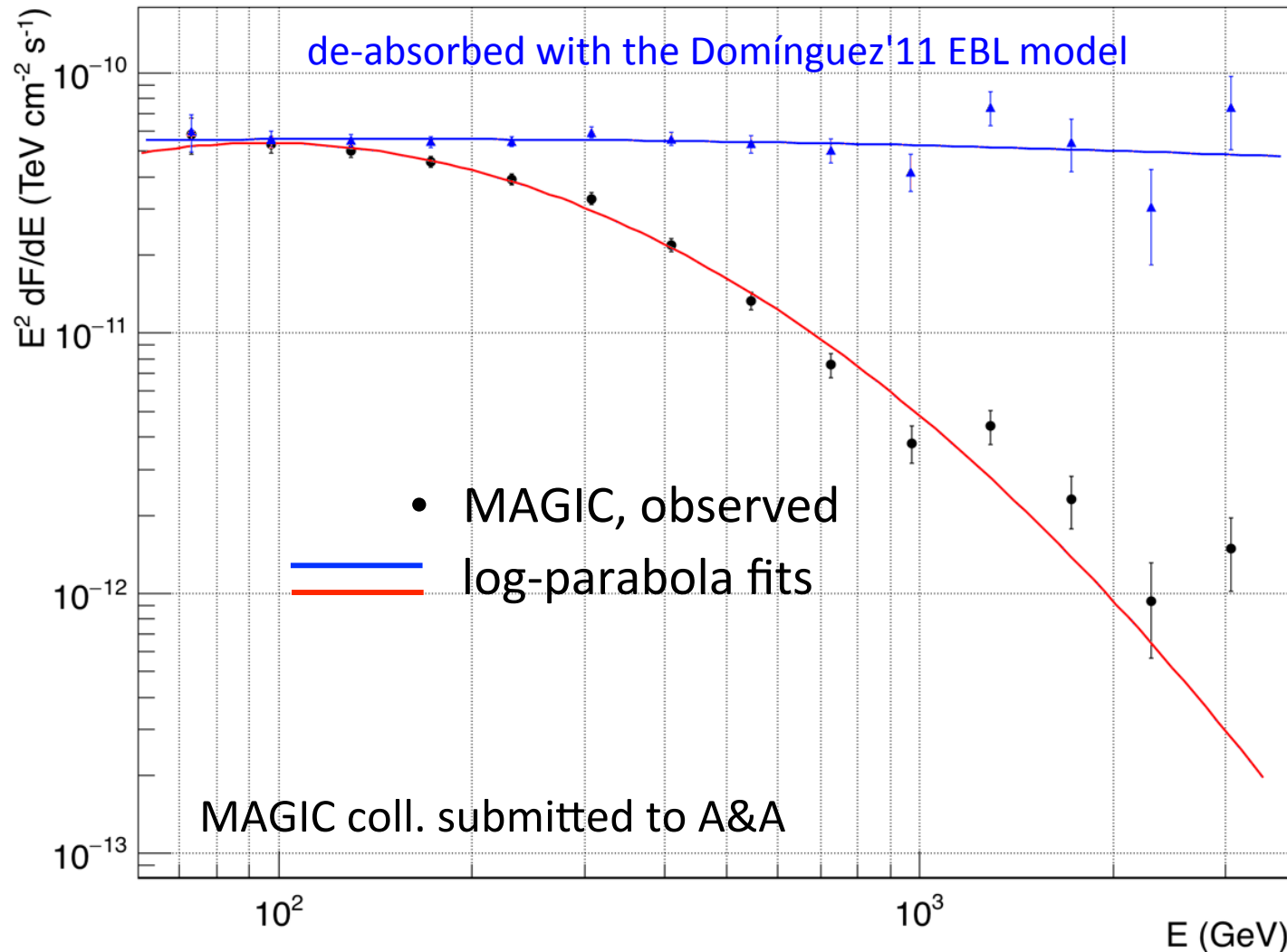
- Lower state in 2011-2012,  $F_{>200\text{GeV}} \approx 4\%$  Crab
- Observed again in 2014 for 17 good-quality nights, following an alert from VERITAS  $\Rightarrow$  reached flux above 1 Crab

# The 1ES 1011+496 flare on Feb 14



- Highest ever flux from this source in X- and  $\gamma$  rays
- Large VHE flux variability in day-timescales
- No evidence for intra-night variability ( $\sim 40'$ /night snapshots)
- Relatively stable spectral shape through the flare

# Average 1ES 1011+496 VHE SED during the Feb'14 flare



- Estimated **intrinsic spectrum** close to power-law
- Spectral points with up to factor  $\approx 50$  EBL-induced flux suppression



# VHE gamma rays as probes of EBL

UV/O/IR background photons (EBL)

from stars & dust in galaxies

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

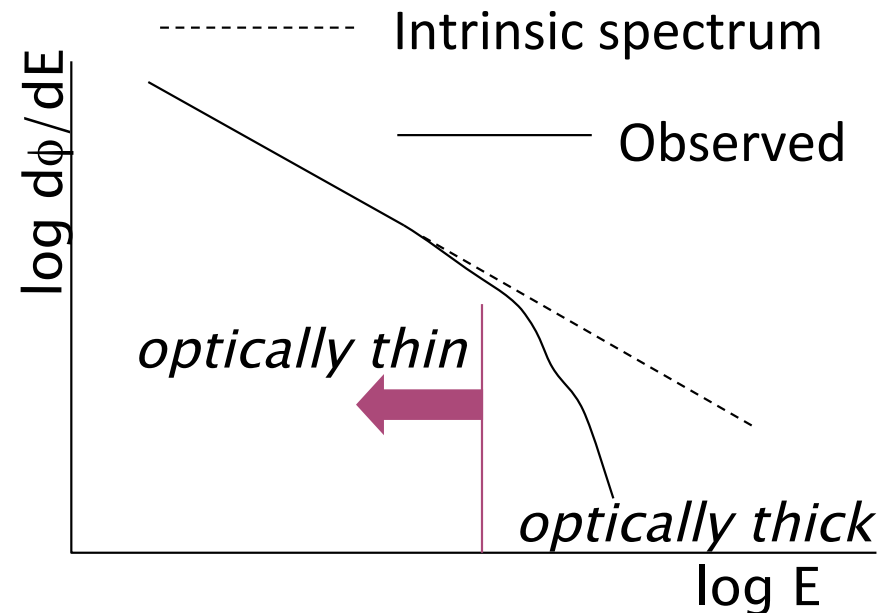
$$\lambda_{\text{max}} = 1.24 \mu\text{m} (E_\gamma / 1 \text{ TeV})$$

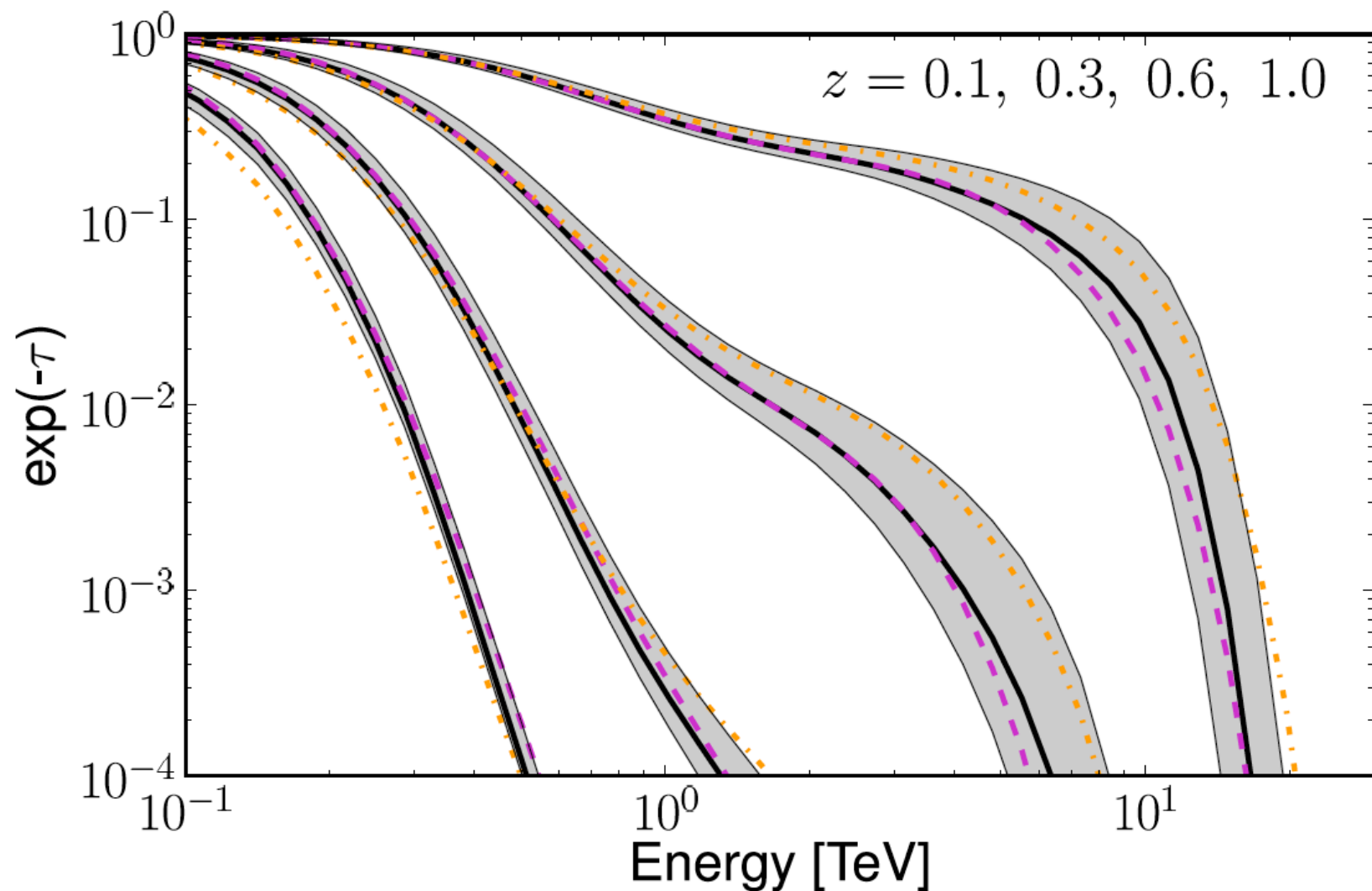
⇒ VHE flux reduction



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

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



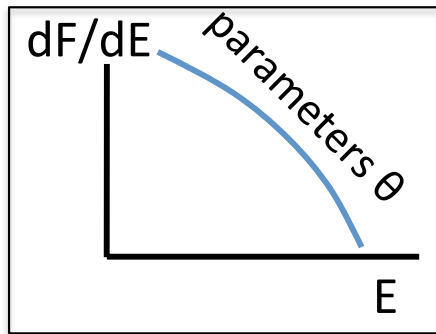


Domínguez
  Gilmore
  Franceschini '08

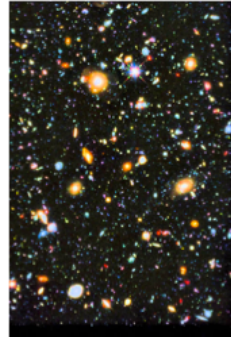
- EBL models predict an inflection point in transmission factor vs.  $E$  @  $\approx 1$  TeV
- Observable only at moderate redshifts
- This feature helps disentangle the effect of the EBL from the intrinsic spectral curvature

# Poissonian likelihood maximization

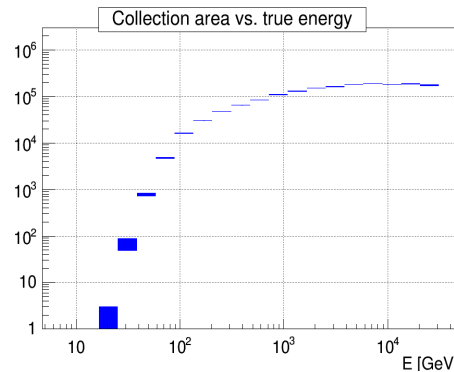
Spectrum



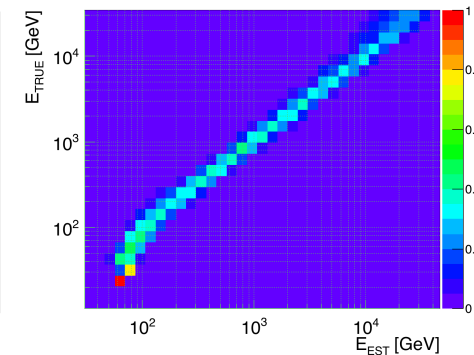
EBL



Effective Area



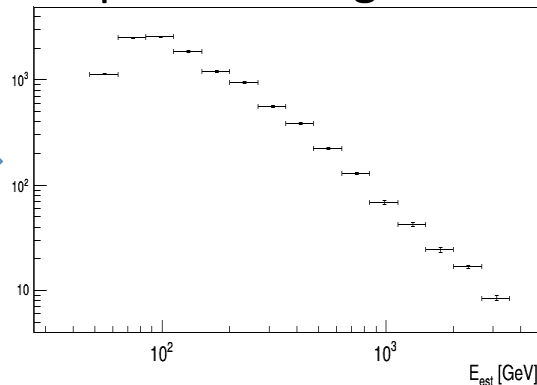
Energy migration matrix



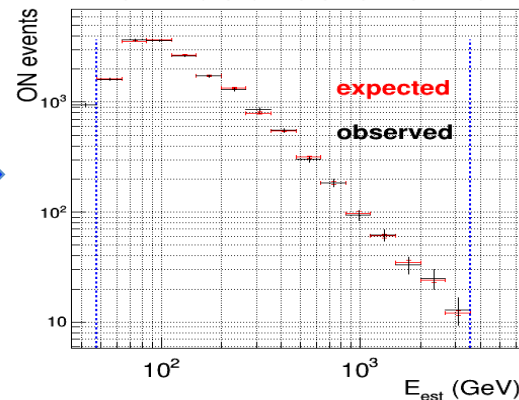
Eff. time



Expected # of gammas



ON-source events



Poisson parameters of the background in each  $E_{\text{est}}$  bin are treated as nuisance parameters

- Used the Domínguez 2011 model as **EBL template**, scaled by a factor  $\alpha$  in the range  $[0, 2.5]$  – same as the Fermi-LAT and H.E.S.S. approach
- For each EBL assumption, find the spectral parameters  $\theta$  which maximize the **joint likelihood of the ON and OFF observations** vs.  $E_{\text{est}}$



# Tested intrinsic spectral functions

| Name                                   | Abbreviation | Formula  |
|--|--------------|--|
| Power law                              | PWL          | $\phi_0(E/E_0)^{-\Gamma}$                                    |
| Log-parabola                           | LP           | $\phi_0(E/E_0)^{-\Gamma-\beta \log(E/E_0)}$                  |
| Exponential<br>cut-off power law       | EPWL         | $\phi_0(E/E_0)^{-\Gamma} \exp(-E/E_{cut})$                   |
| Exponential<br>cut-off log-parabola    | ELP          | $\phi_0(E/E_0)^{-\Gamma-\beta \log(E/E_0)} \exp(-E/E_{cut})$ |
| Super exponential<br>cut-off power law | SEPWL        | $\phi_0(E/E_0)^{-\Gamma} \exp(-(E/E_{cut})^\gamma)$          |

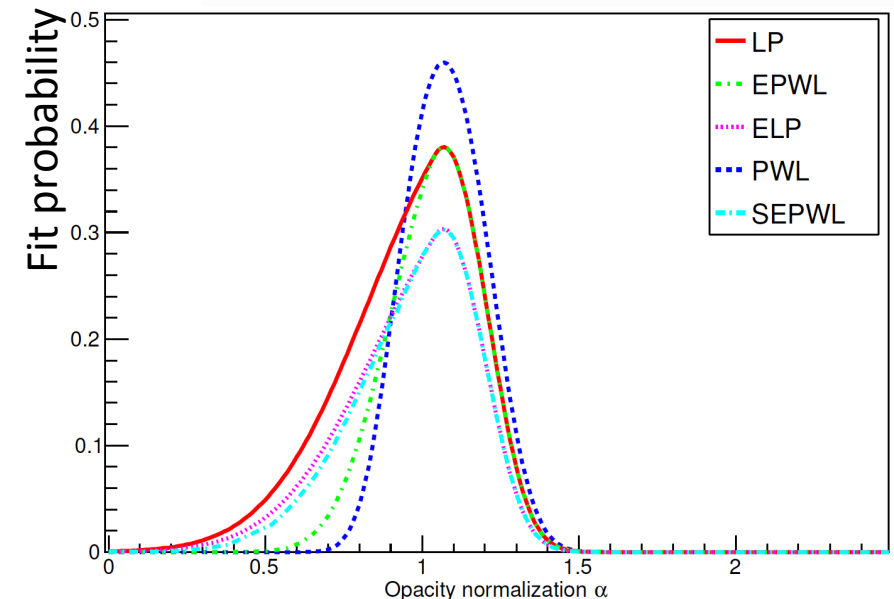
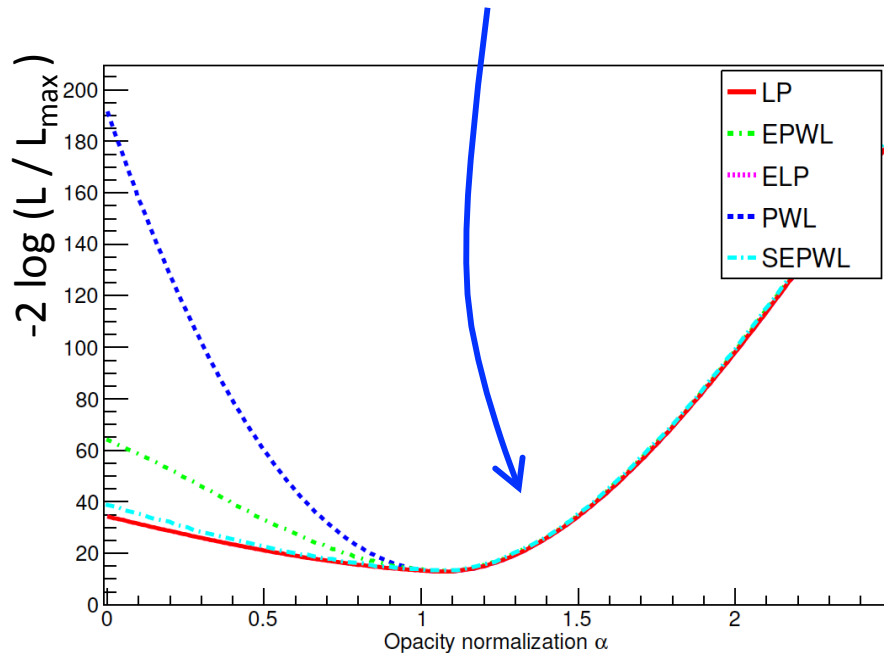
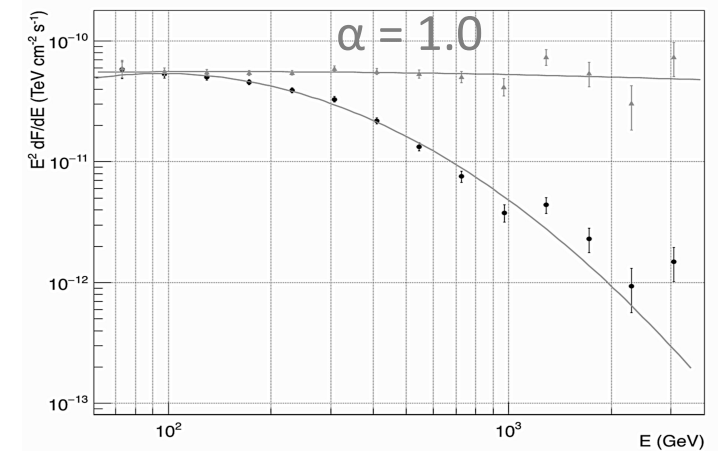
- Functions with up to 4 parameters
- Intrinsic spectrum forced to be concave (i.e. softer as E increases)
- These have shown to be good models for BL Lac spectra in the optically-thin regime (from past observations with Fermi-LAT & IACTs)

$\alpha$  : opacity normalization  
(= EBL density scaling)

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

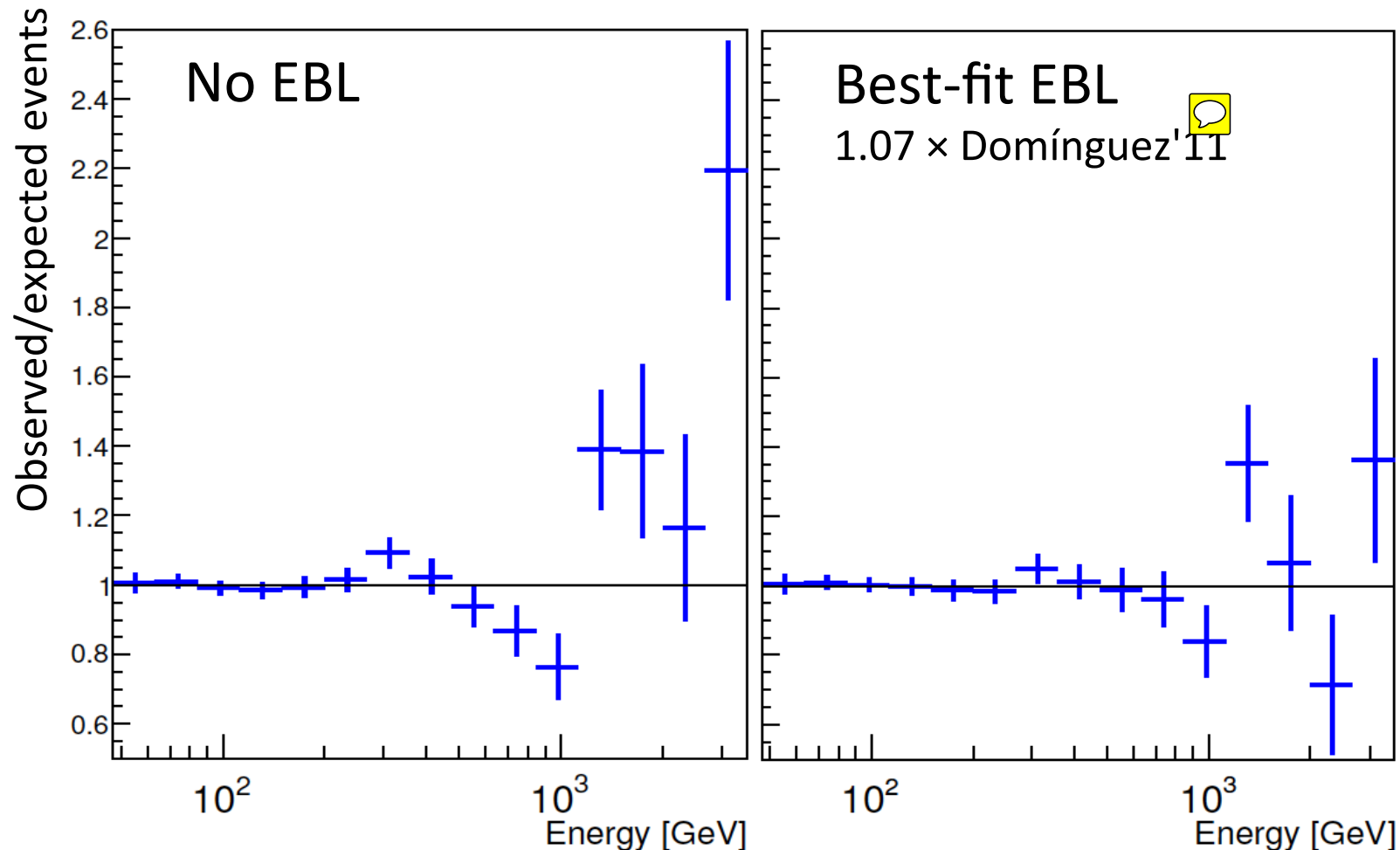
# Likelihood vs. $\alpha$

- For EBL scalings  $\gtrsim 1.1$ , intrinsic spectrum would have to be *convex* to reproduce MAGIC data
- $\Rightarrow$  all functions degenerate into a power-law



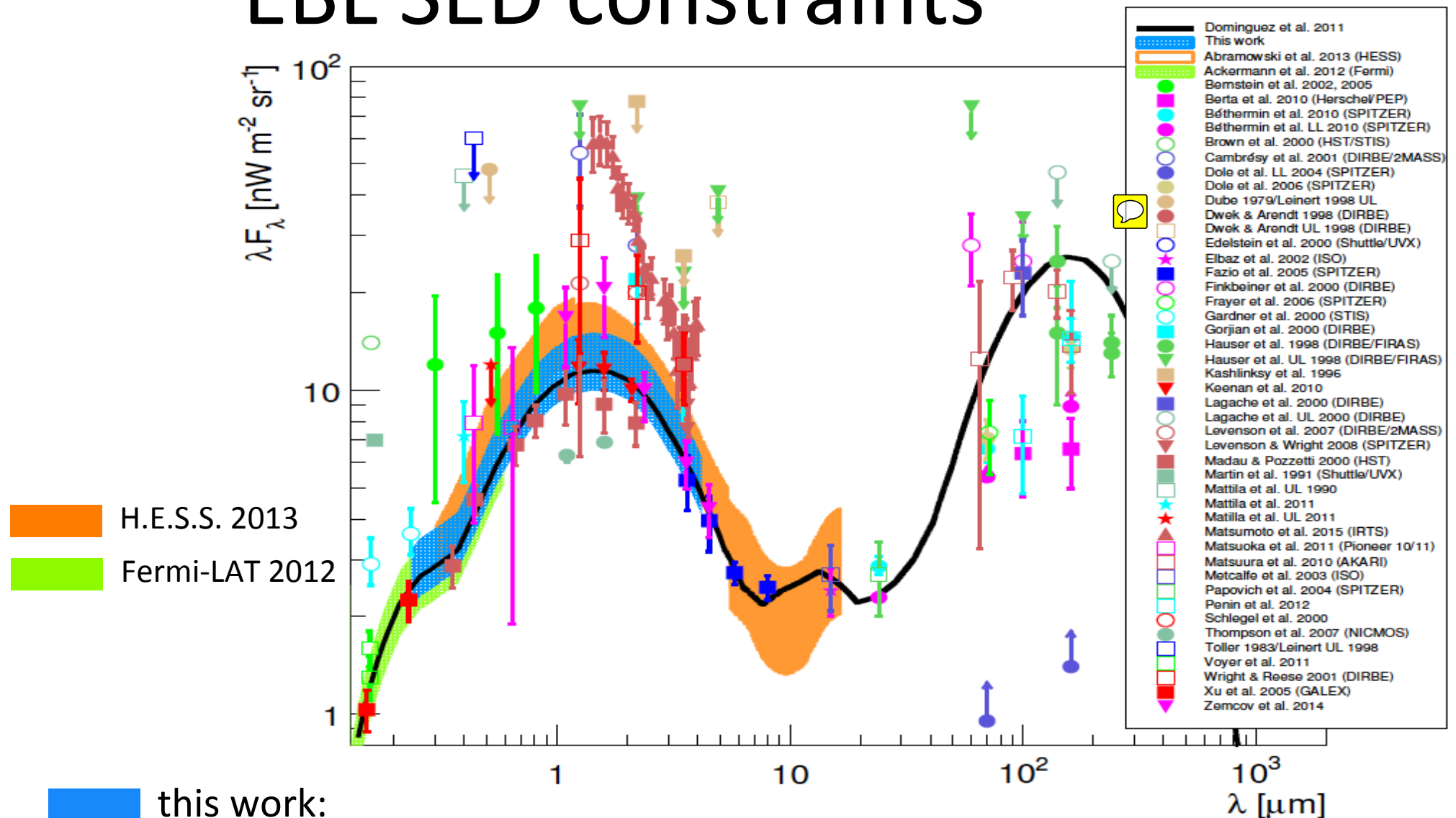
- Power-law provides best fit probability (fewest parameters), but choosing it as intrinsic model means *all* spectral curvature would be *attributed to* EBL (!)
- With the log-parabola, best fit achieved for  $\alpha = 1.07 (+0.09, -0.13)_{\text{STAT}}$
- When the  $\pm 15\%$  uncertainty in the overall (atmosphere+telescopes) light throughput is taken into account:  $\alpha = 1.07 (+0.24, -0.20)_{\text{STAT+SYS}}$

# Fit residuals (log-parabola)



- "Wiggly structure" in the *observed* spectrum clearly reduced with EBL correction, as expected if it is an imprint of the EBL absorption
- (log-parabola\*best-fit EBL) is preferred at the  $4.6\text{-}\sigma$  level to the log-parabola as a model for the observed spectrum

# EBL SED constraints

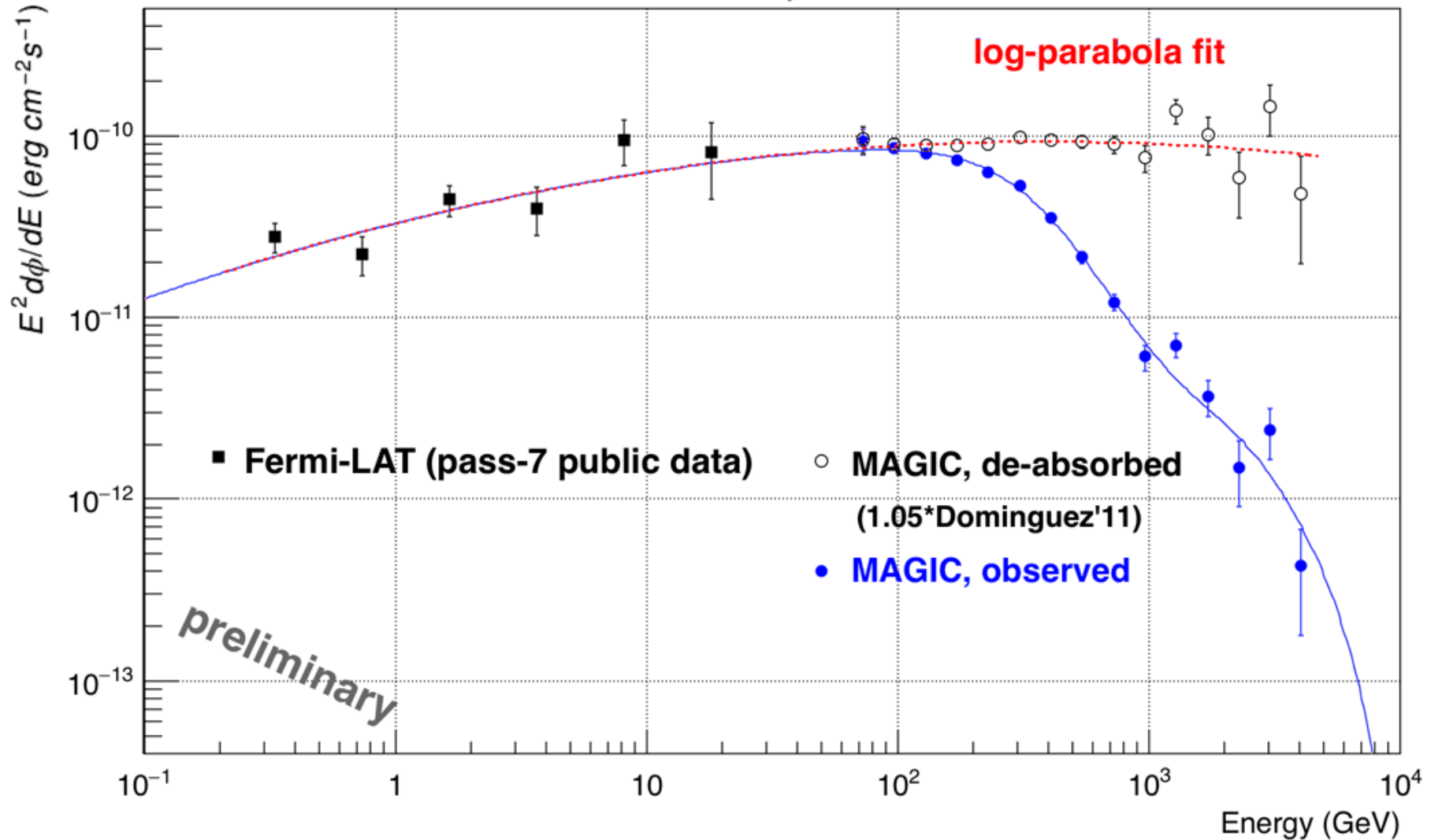


$\lambda F_{\lambda} = 12.27 (+2.75, -2.29)_{\text{stat+sys}} \text{ nW m}^{-2} \text{ sr}^{-1} \text{ at } 1.4 \mu\text{m}$

- Compatible with H.E.S.S. and Fermi-LAT results, and with lower limits
- No indication of sources of optical-near IR unaccounted for in the EBL modelling

# HE + VHE SED



1ES 1011+496, Feb'2014 flare



- Joint fit with contemporaneous Fermi-LAT data results in similar best-fit EBL scaling (1.05 × Domínguez'11) – work in progress



# Conclusions

- The February  2014 flare of 1ES1011+496, a high-frequency peaked BL Lac, is an ideal sample to probe the EBL
- The hard intrinsic spectrum and intermediate redshift allows to detect a clear imprint of the EBL on the MAGIC data
- Best-fit EBL density is  $1.07 (+0.24, -0.20)_{\text{STAT+SYS}}$ , relative to the Domínguez  2011 model used as template
- Result compatible with existing EBL constraints
- No hint of additional sources of EBL not considered in the model, neither of any propagation anomalies 