

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

Abelardo Moralejo

Institut de Física d'Altes Energies
Barcelona Institute of Science and Technology

for the MAGIC collaboration

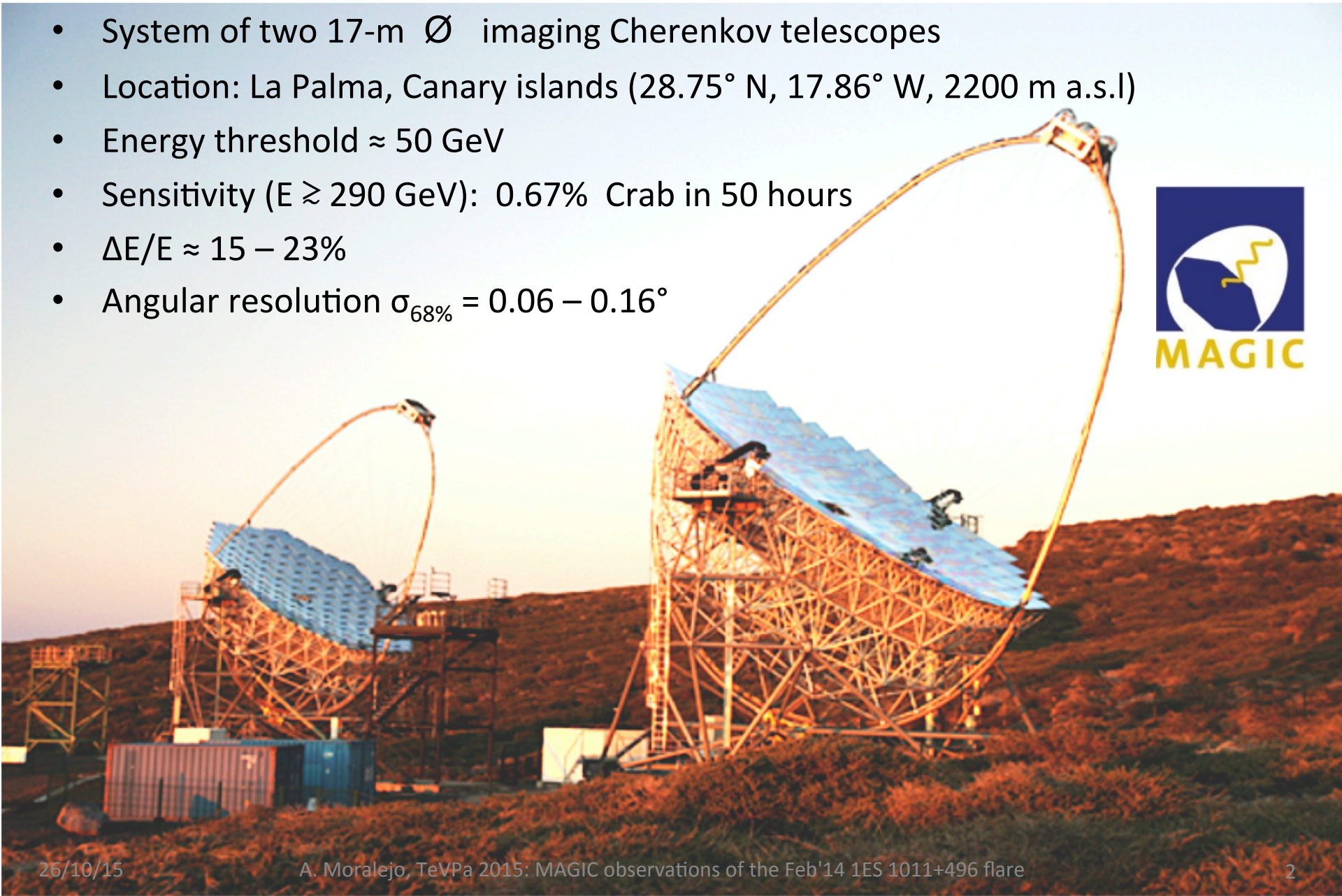


EXCELENCIA
SEVERO
OCHOA



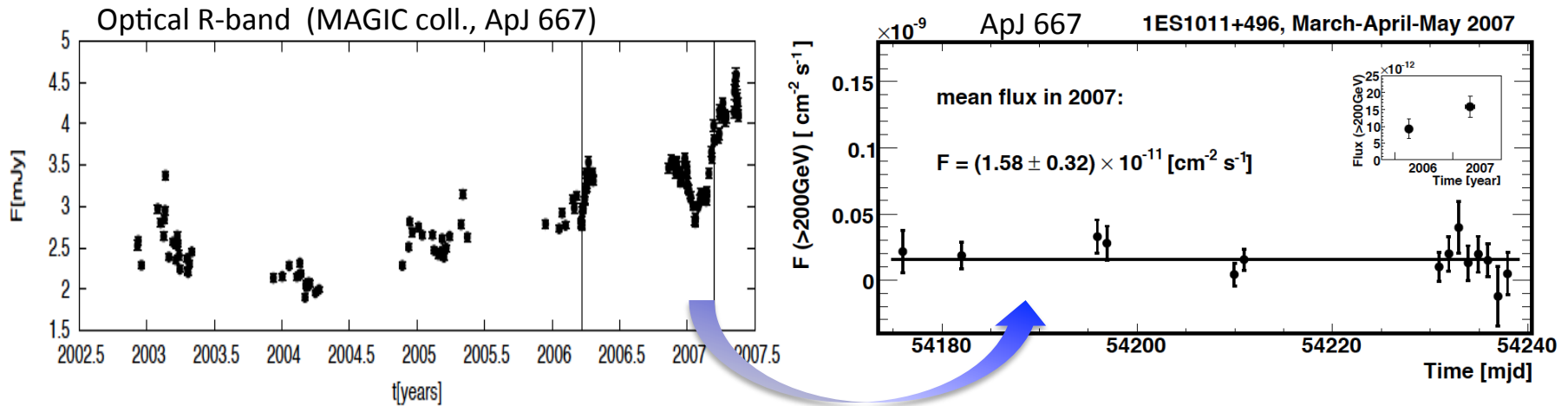
The MAGIC telescopes

- 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 ≈ 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

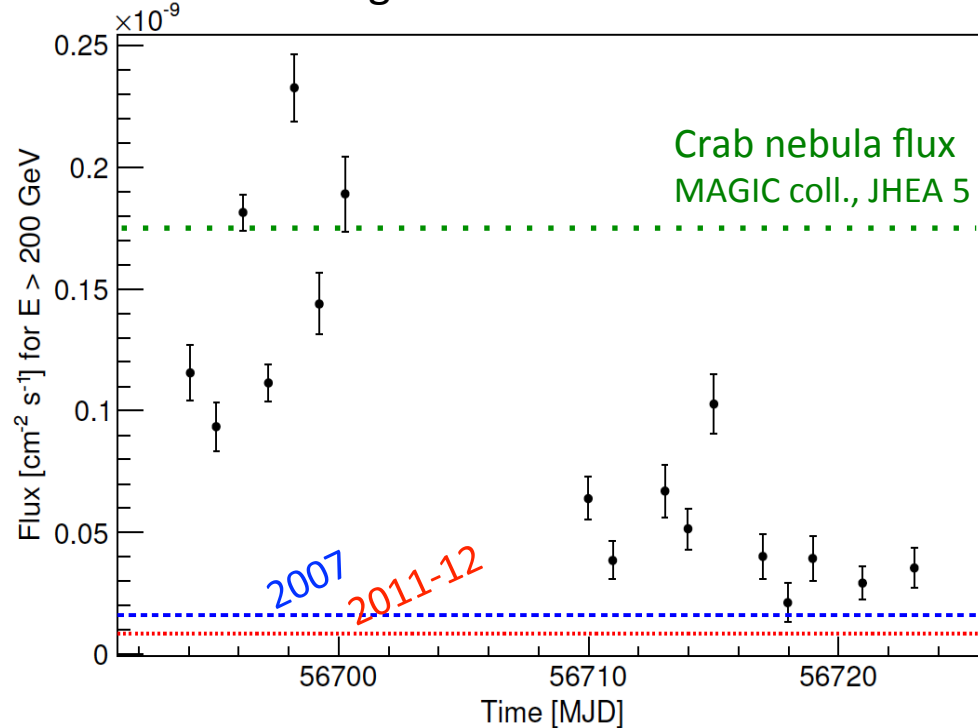
- High-frequency peaked BL Lac (HBL) @ $z = 0.212$
- First detected at VHE in 2007 with MAGIC-1 ($F_{>200\text{GeV}} \approx 9\%$ Crab) during a high optical state; similar flux in 2008



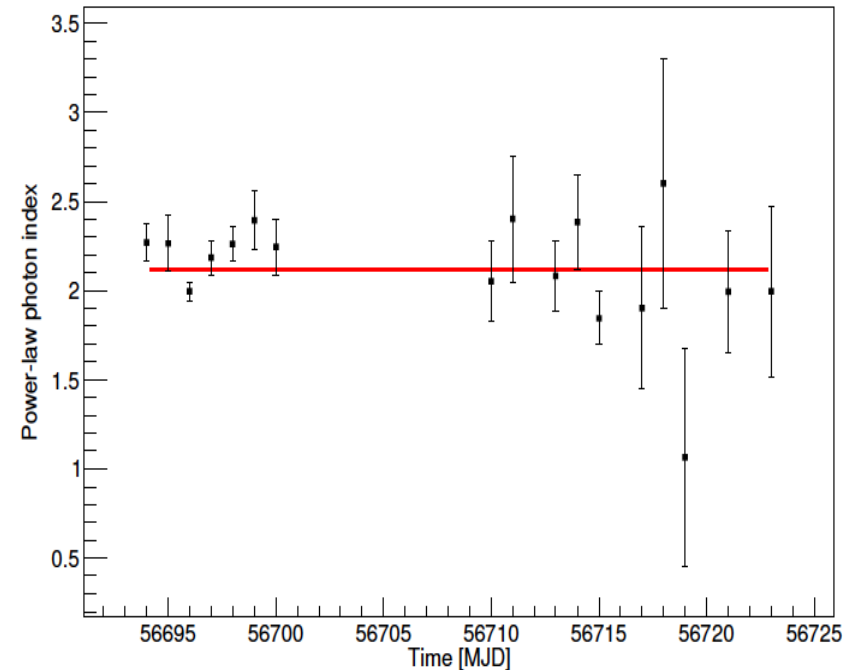
- Lower state in 2011-2012, $F_{>200\text{GeV}} \approx 4\%$ Crab
- Observed again in 2014 for 17 good-quality nights, following an alert from VERITAS \Rightarrow reached flux above 1 Crab

The 1ES 1011+496 flare on Feb'14

E>200 GeV light curve 2014 Feb 5 – March 7



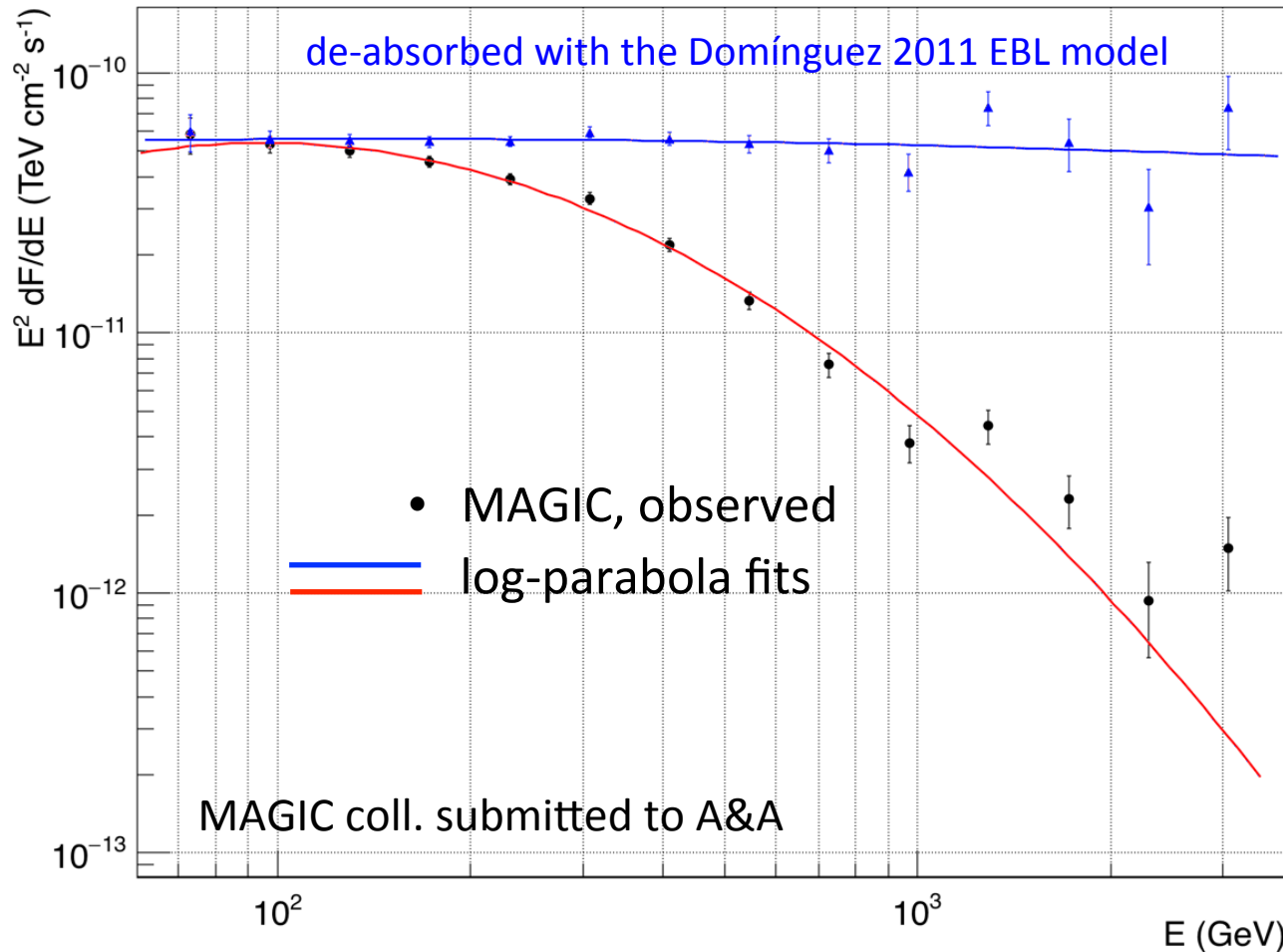
intrinsic photon index



MAGIC coll. submitted to A&A

- Highest ever flux from this source in X- and γ 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 ≈ 50 EBL-induced flux suppression

VHE gamma rays as probes of EBL

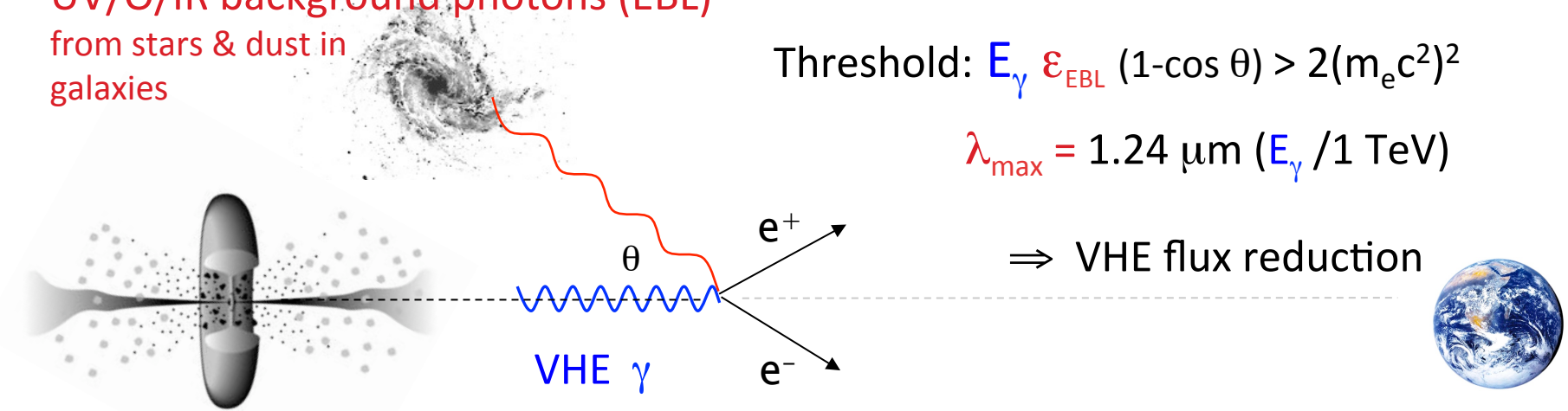
UV/O/IR background photons (EBL)

from stars & dust in galaxies

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

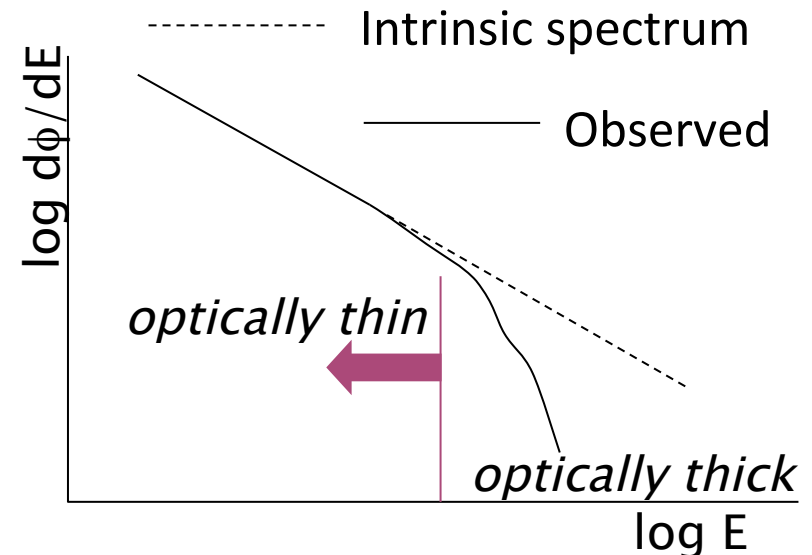
$$\lambda_{\text{max}} = 1.24 \mu\text{m} (E_{\gamma} / 1 \text{ TeV})$$

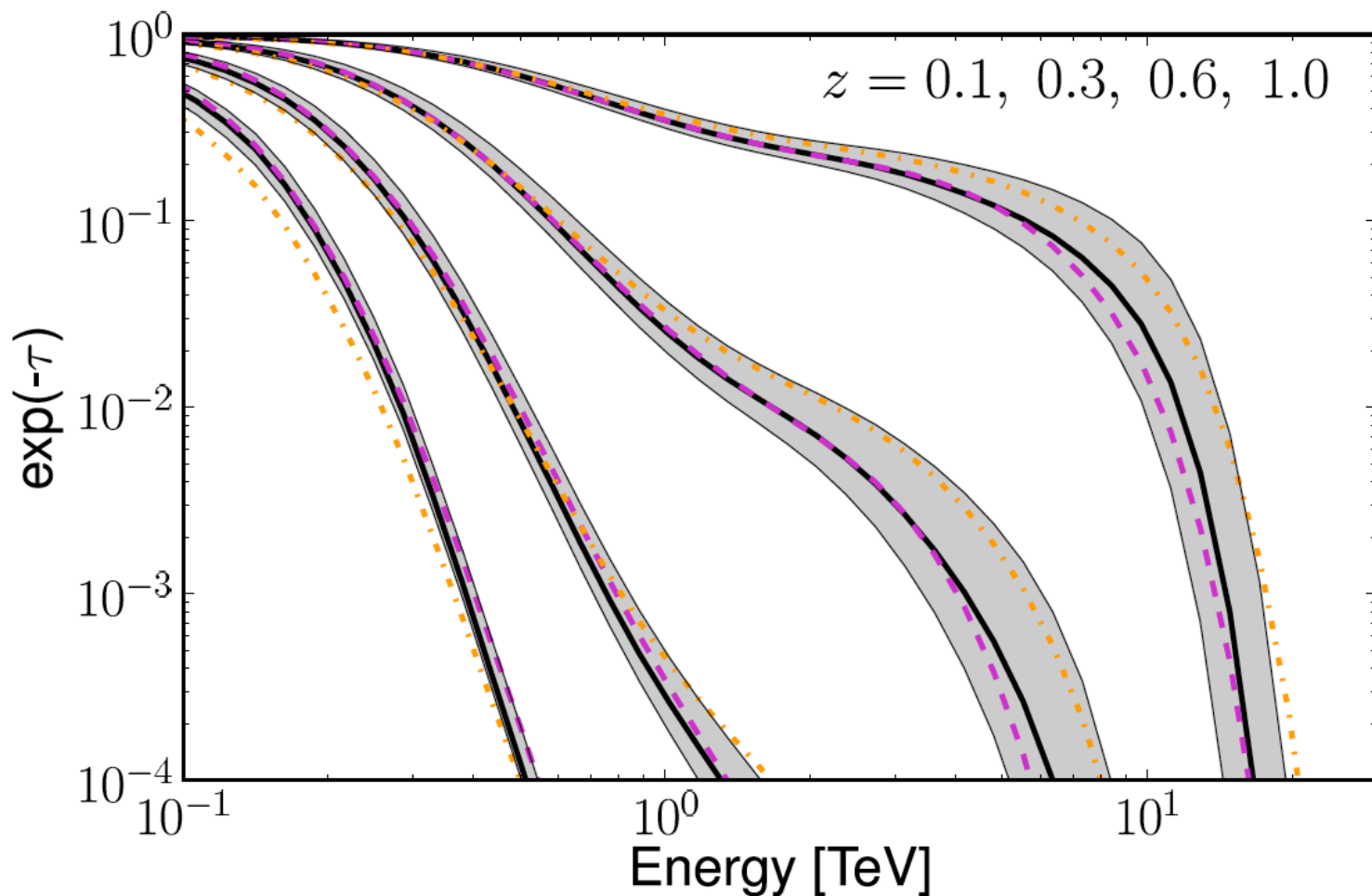
⇒ VHE flux reduction



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

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



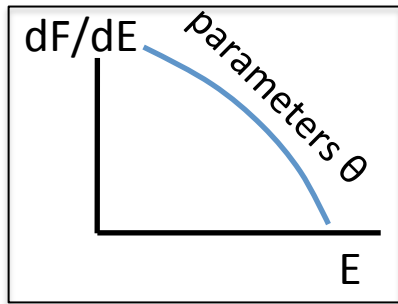


Domínguez
 Gilmore
 Franceschini '08

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

Poissonian likelihood maximization

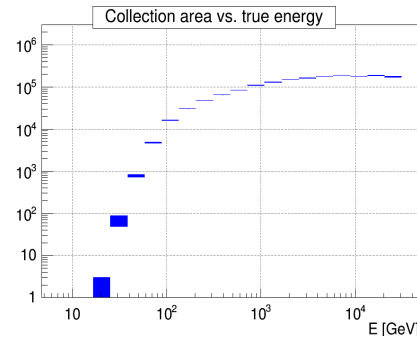
Spectrum



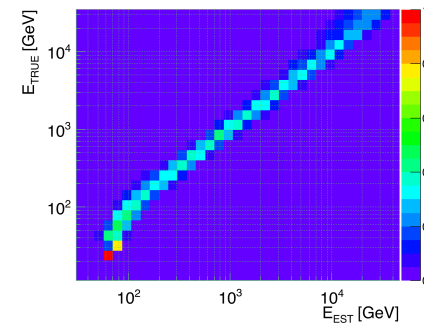
EBL



Effective Area



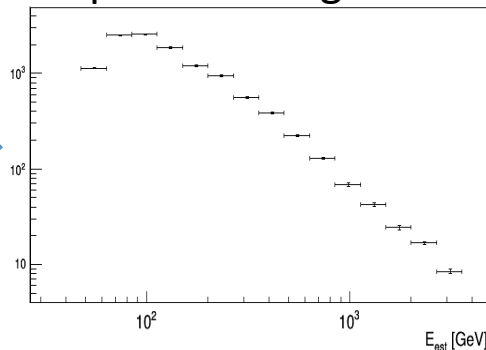
Energy migration matrix



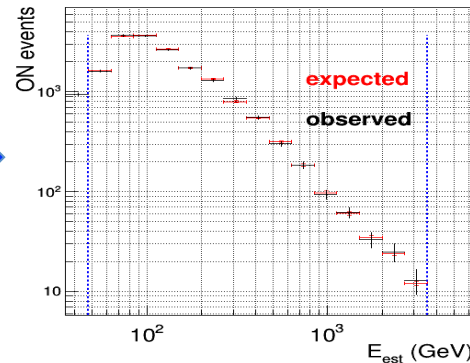
Eff. time



Expected # of gammas



ON-source events



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

- Used the Domínguez 2011 model as **EBL template, scaled by a factor α** 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 θ which maximize the **joint likelihood of the ON and OFF observations** vs. E_{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 cut-off power law	EPWL	$\phi_0(E/E_0)^{-\Gamma} \exp(-E/E_{cut})$
Exponential cut-off log-parabola	ELP	$\phi_0(E/E_0)^{-\Gamma-\beta \log(E/E_0)} \exp(-E/E_{cut})$
Super exponential cut-off power law	SEPWL	$\phi_0(E/E_0)^{-\Gamma} \exp(-(E/E_{cut})^\gamma)$

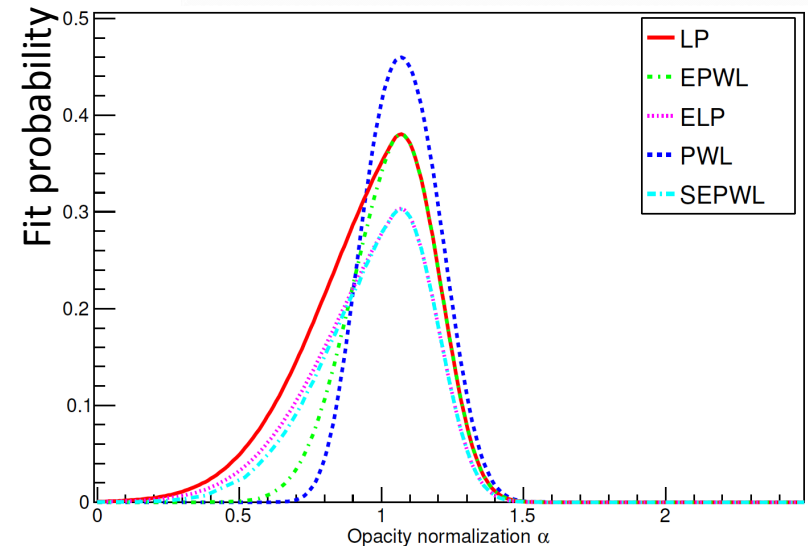
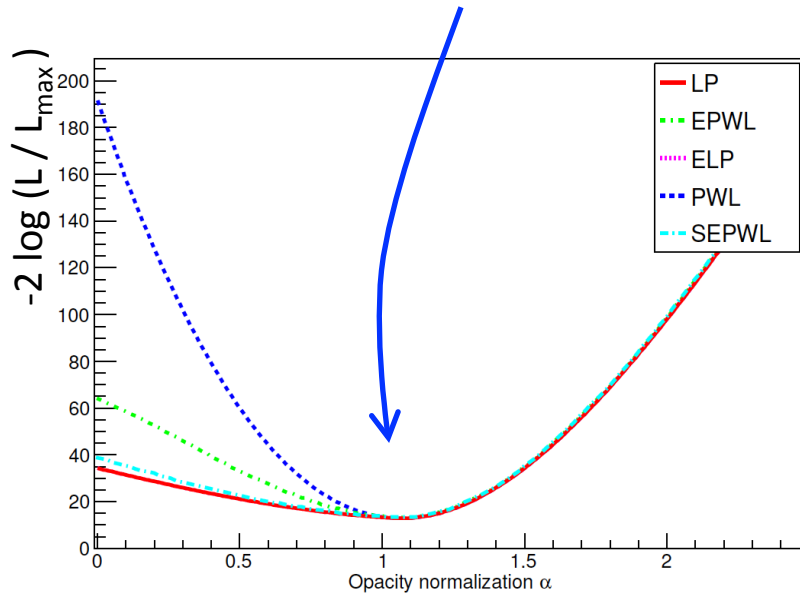
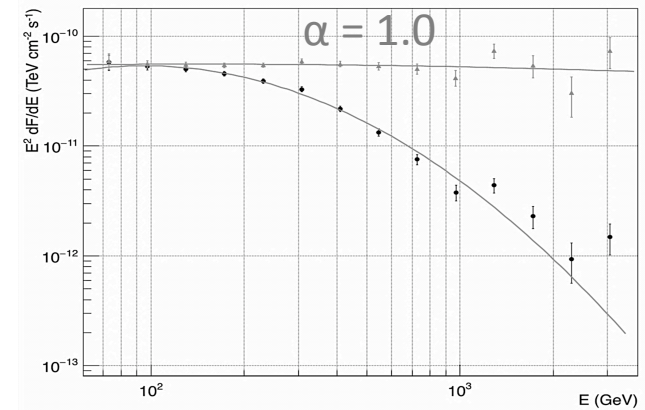
- Functions with up to 4 parameters
- Intrinsic spectrum forced to be concave (i.e. softer as E increases)
- These have shown to be good models for BL Lac spectra in the optically-thin regime (from past observations with Fermi-LAT & IACTs)

α : opacity normalization
(= EBL density scaling)

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

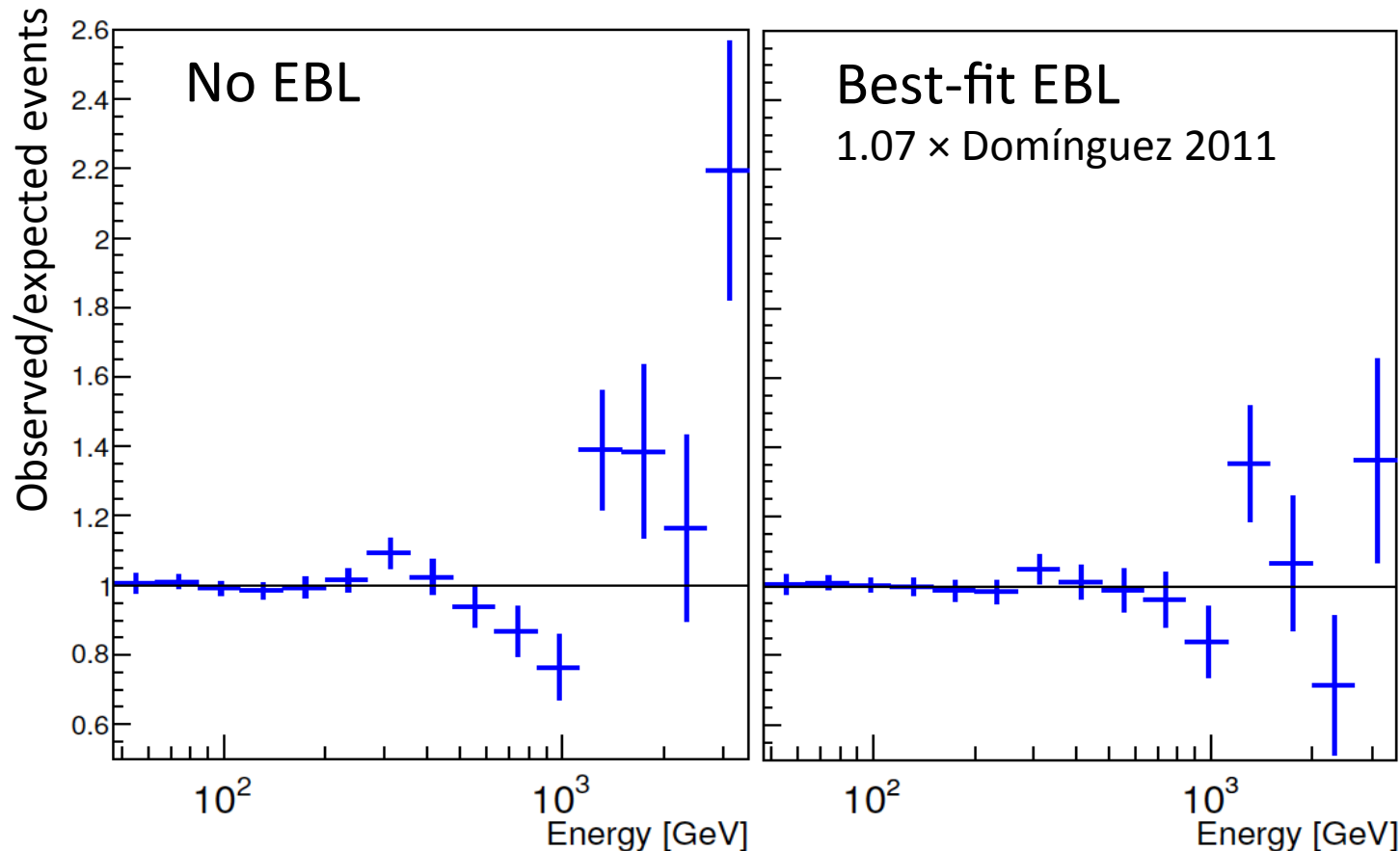
Likelihood vs. α

- 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



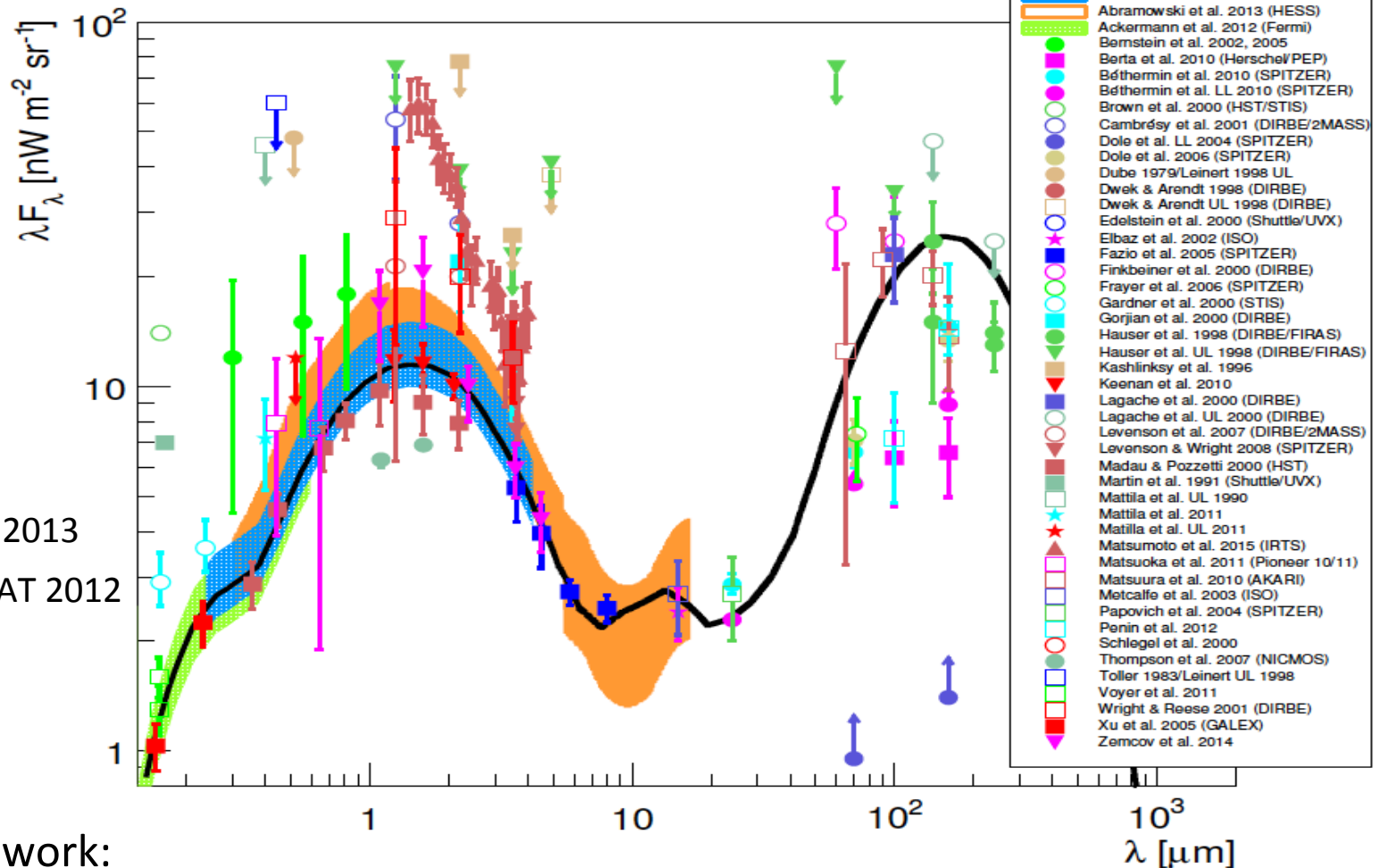
- Power-law provides best fit probability (fewest parameters), but choosing it as intrinsic model means *all* spectral curvature would be *attributed to* EBL (!)
- With the log-parabola, best fit achieved for $\alpha = 1.07 (+0.09, -0.13)_{\text{STAT}}$
- When the $\pm 15\%$ uncertainty in the overall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

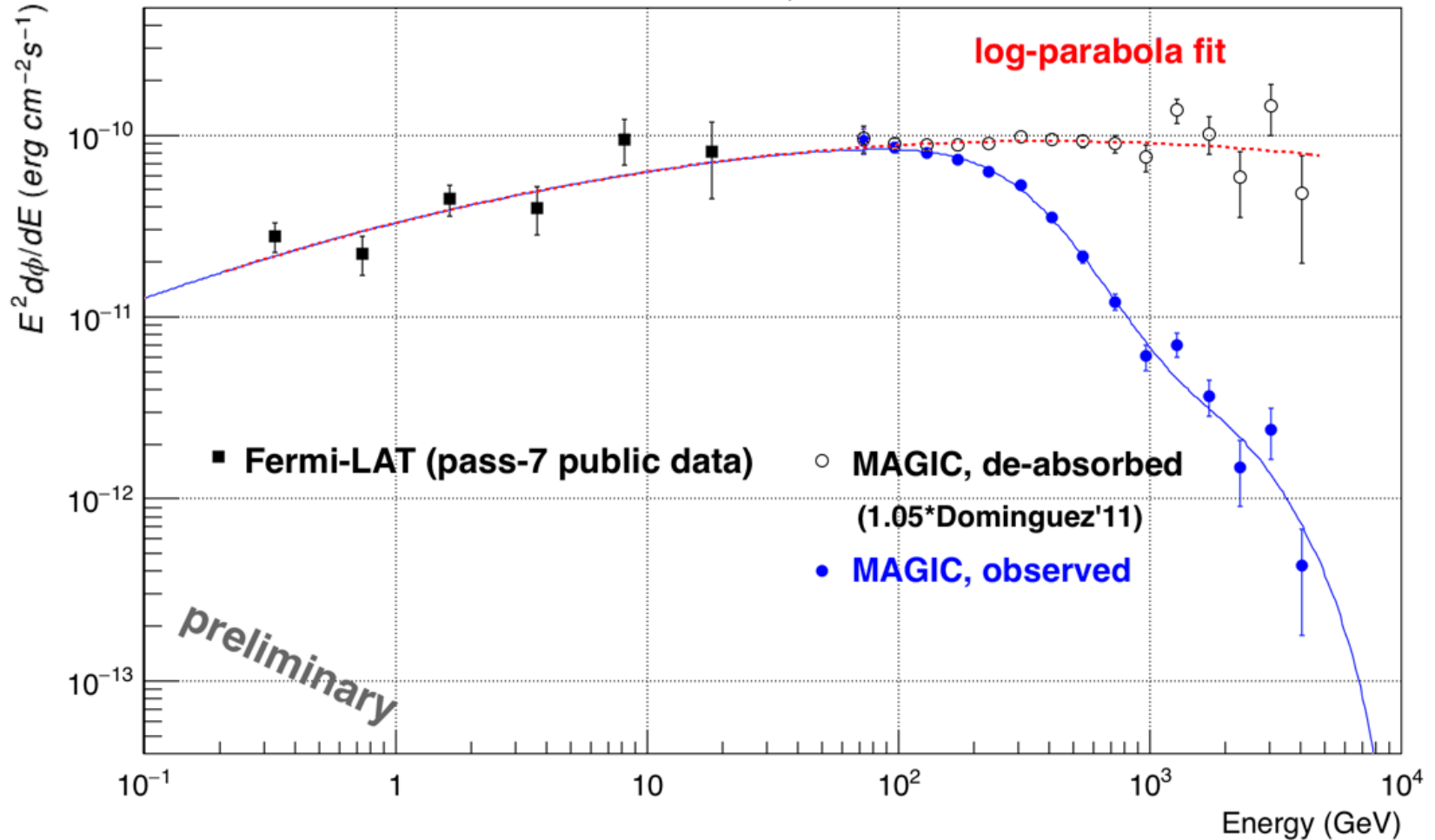


$$\lambda F_{\lambda} = 12.27 (+2.75, -2.29)_{\text{stat+sys}} \text{ nW m}^{-2} \text{ sr}^{-1} \text{ at } 1.4 \mu\text{m}$$

- 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 ($1.05 \times \text{Domínguez 2011}$) – 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