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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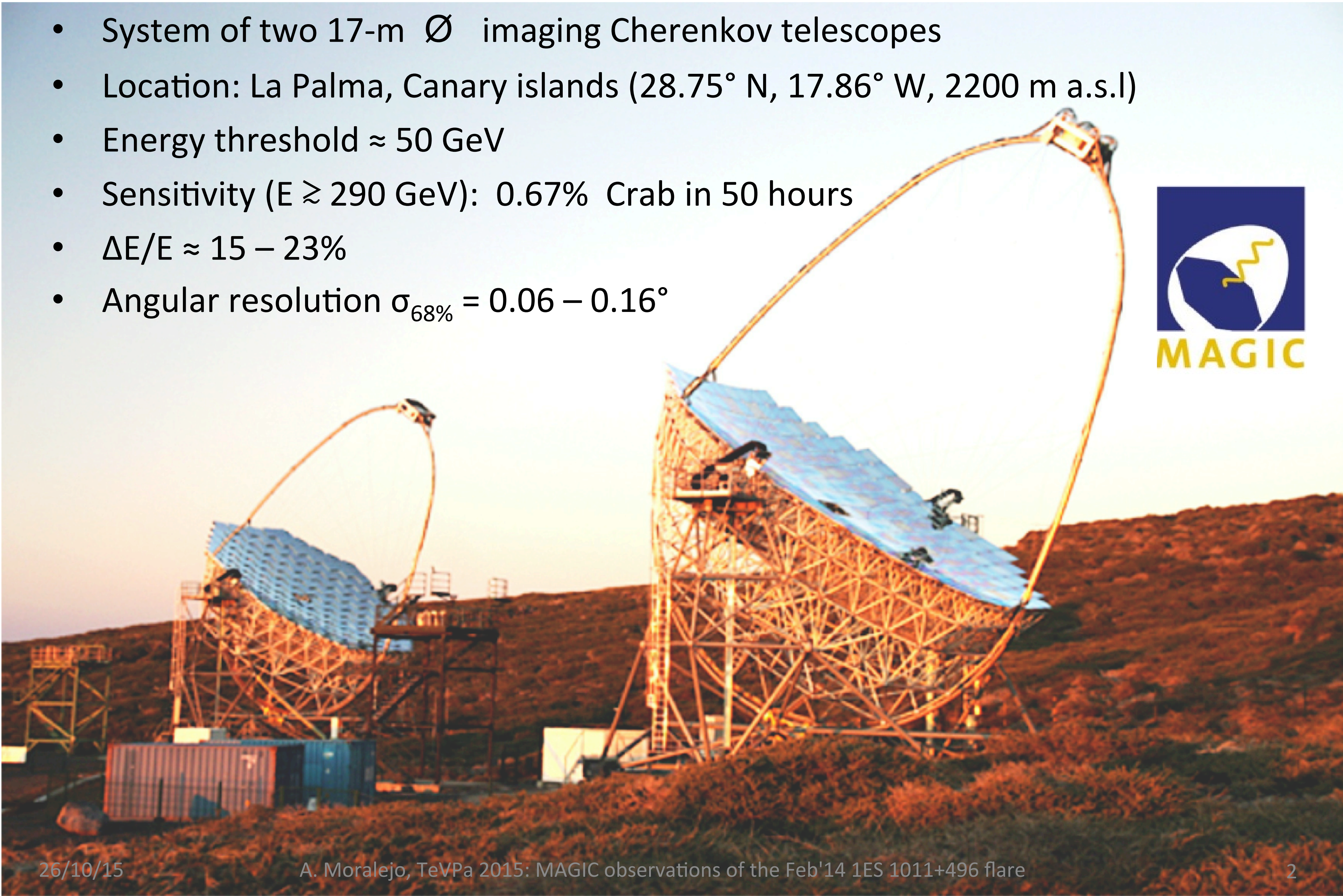
for the MAGIC collaboration

The MAGIC telescopes

- System of two 17-m Ø 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 ≳ 290 GeV): 0.67% Crab in 50 hours
- ΔE/E ≈ 15 – 23%
- Angular resolution $\sigma_{68\%}$ = 0.06 – 0.16°

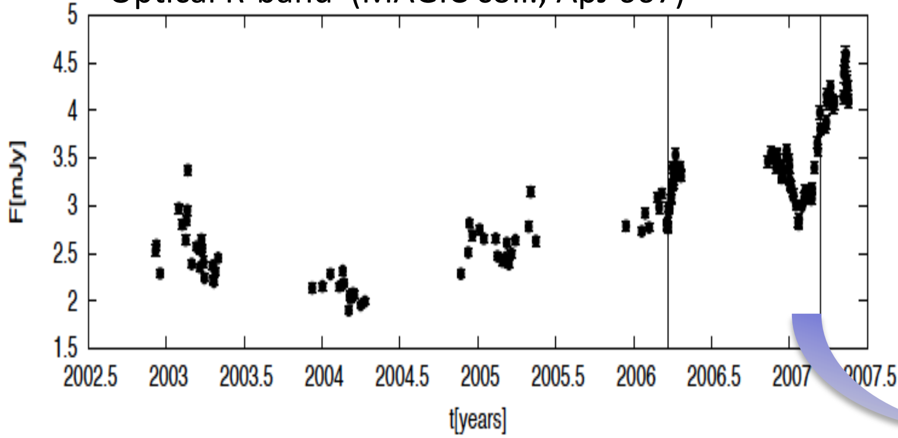


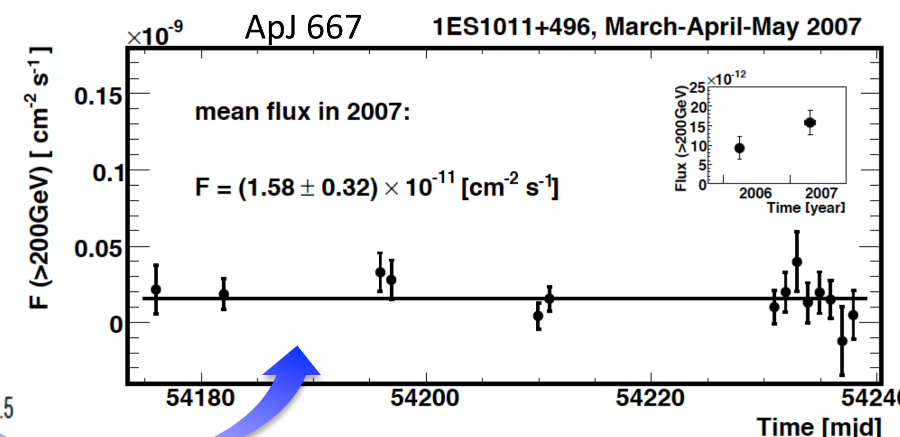
MAGIC

1ES 1011+496

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

Optical R-band (MAGIC coll., ApJ 667)

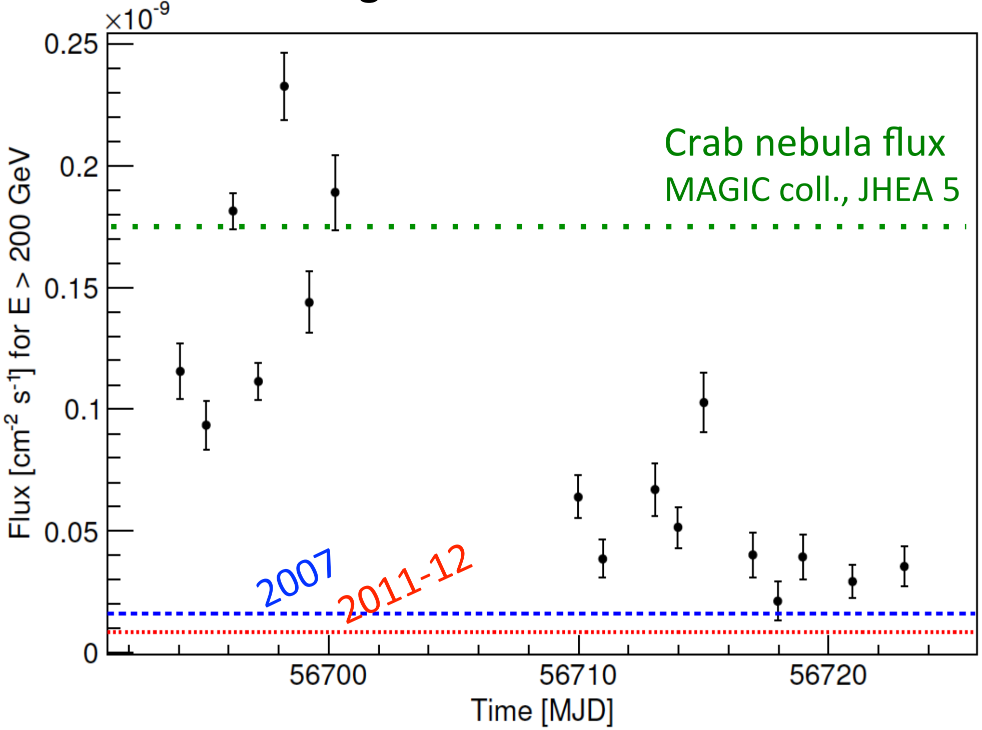




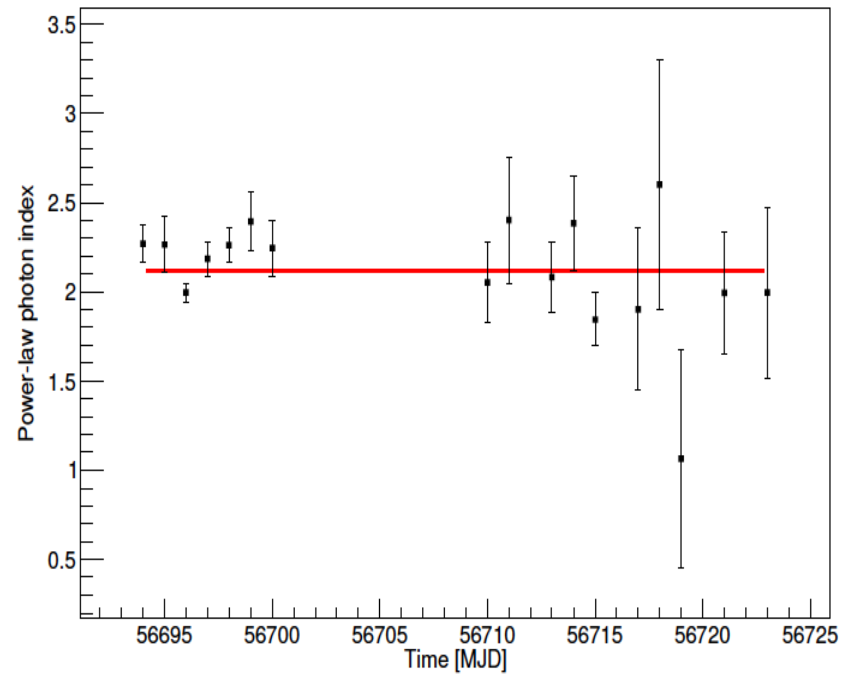
- Lower state in 2011-2012, $F_{>200GeV} \approx 4\%$ Crab
- Observed again in 2014 for 17 good-quality nights, following an alert from VERITAS ⟹ reached flux above 1 Crab

The 1ES 1011+496 flare on Feb'14

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



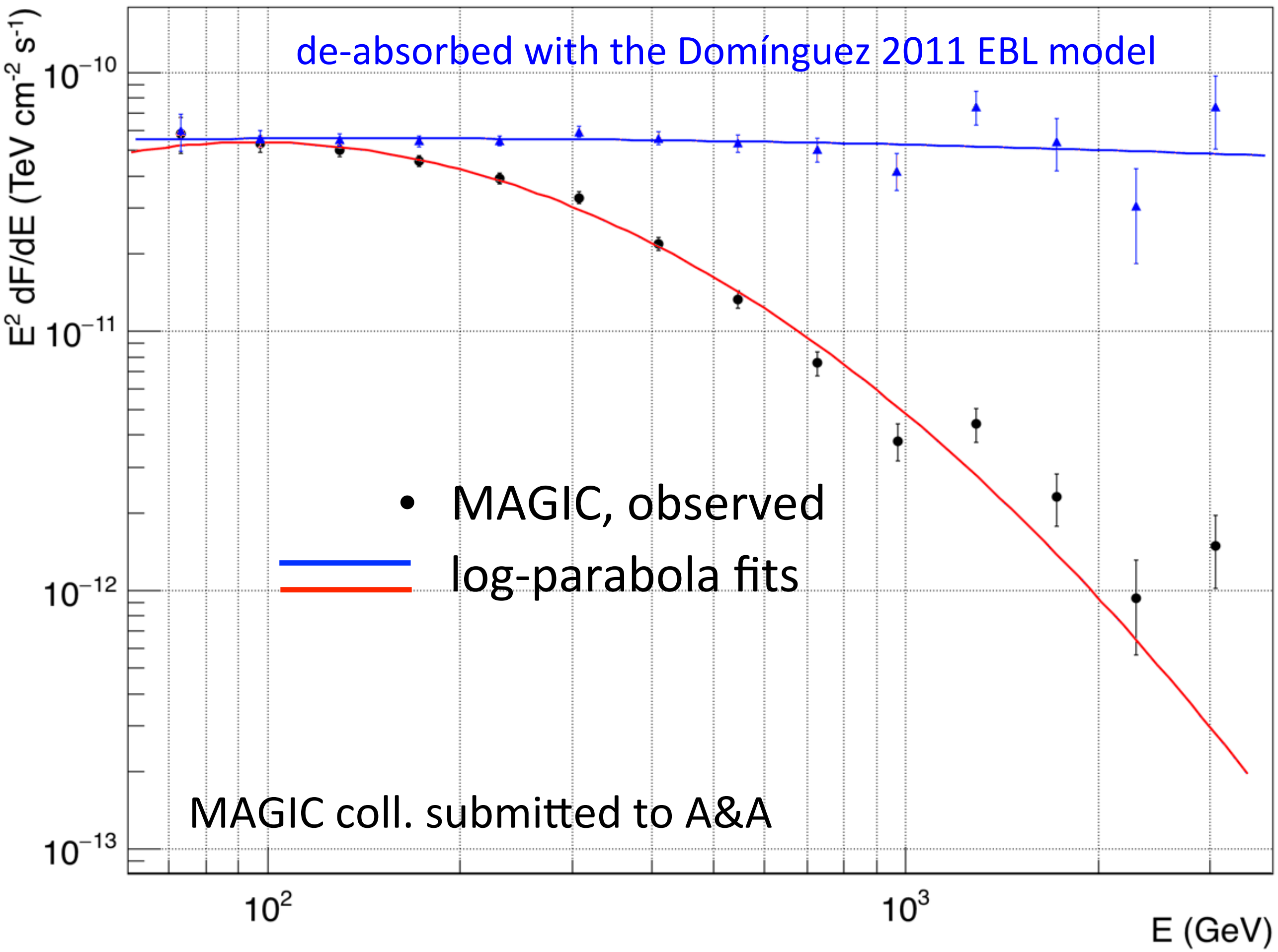
estimated intrinsic photon index



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 (~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

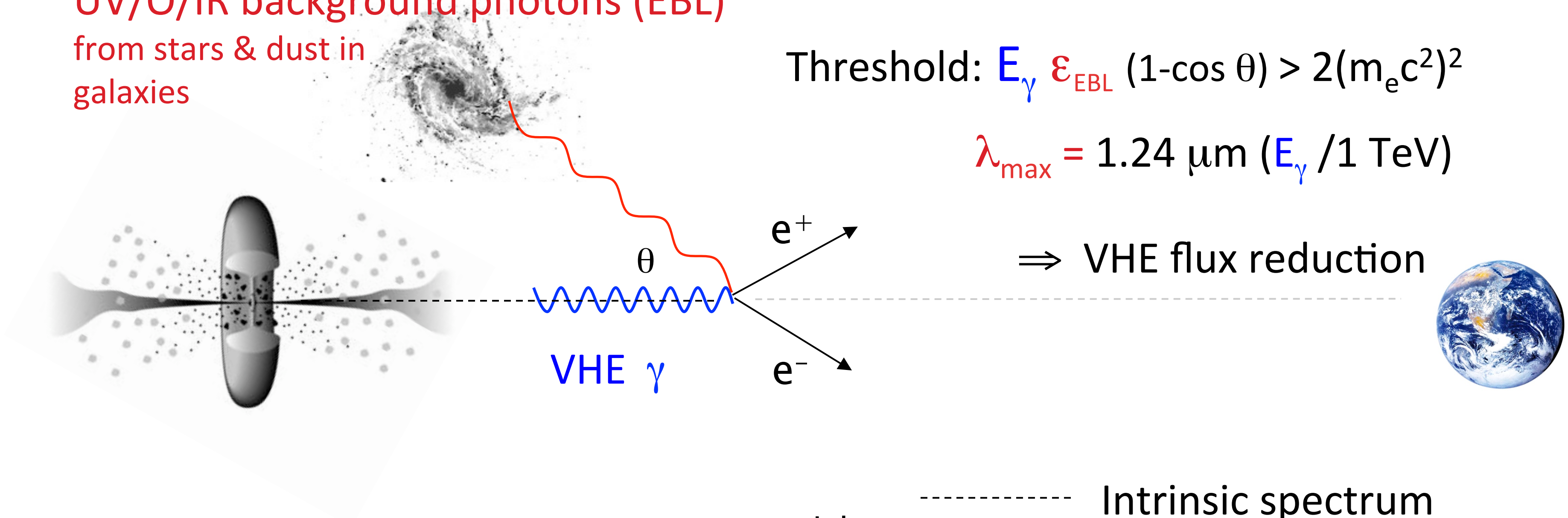
UV/O/IR background photons (EBL)

from stars & dust in galaxies

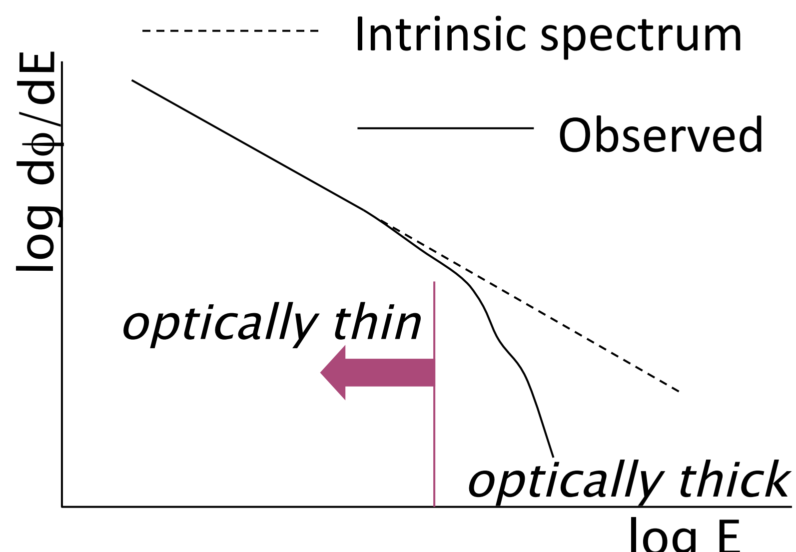
Threshold: $E_\gamma\ \varepsilon_{EBL}\ (1\text{-}\cos\theta) > 2(m_e c^2)^2$

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

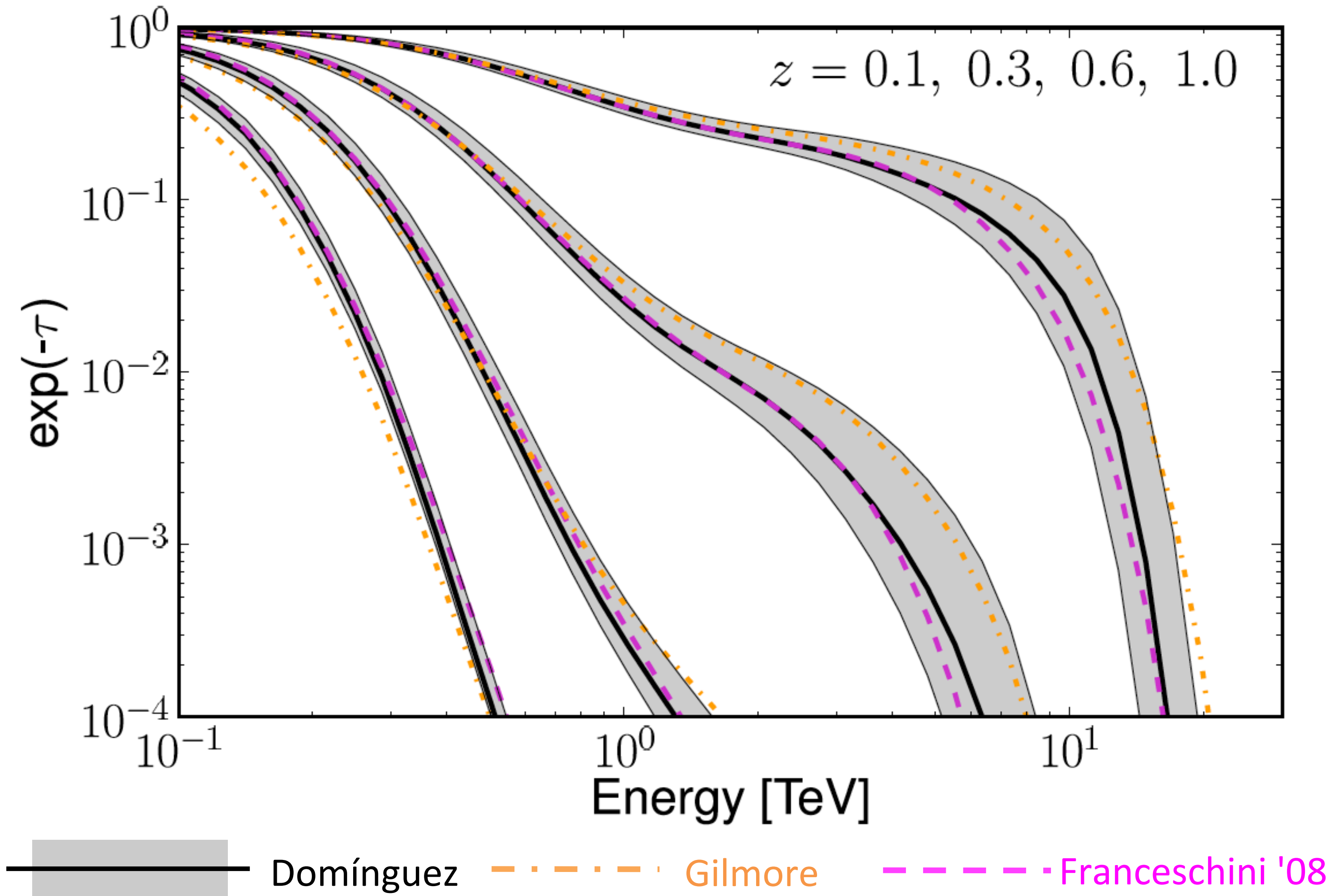
$\Rightarrow$ VHE flux reduction



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



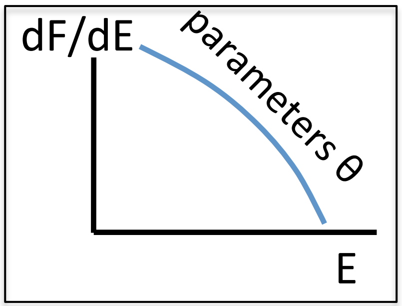
VHE photons can be used as a probe of Extragalactic Background Light



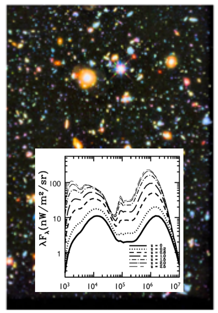
- EBL models predict an inflection point in transmission factor vs. E @ ≈1 TeV
- Observable only at moderate redshifts
- This feature helps disentangle the effect of the EBL from the intrinsic spectral curvature

Poissonian likelihood maximization

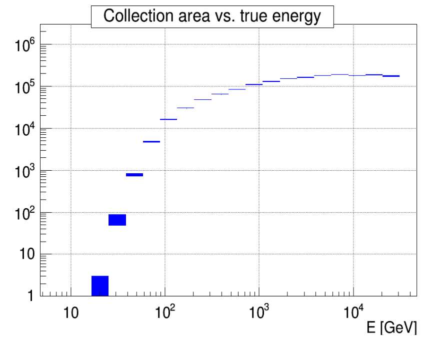
Spectrum



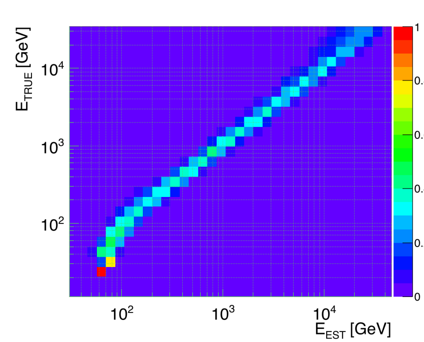
EBL



Effective Area

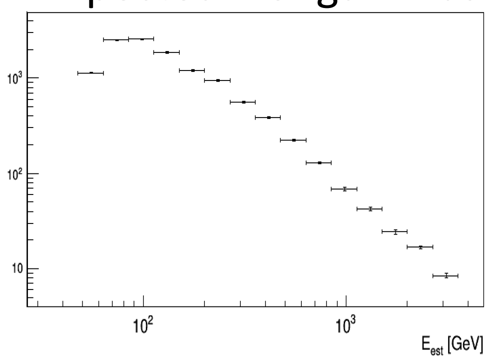


Energy migration matrix

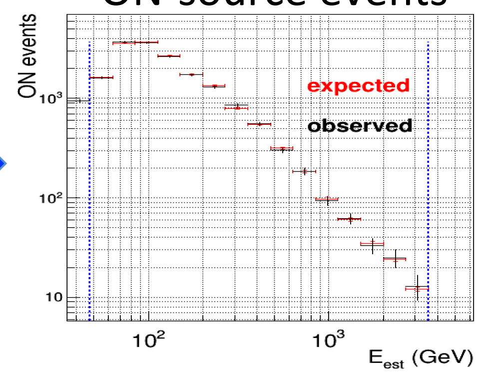


Eff. time

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

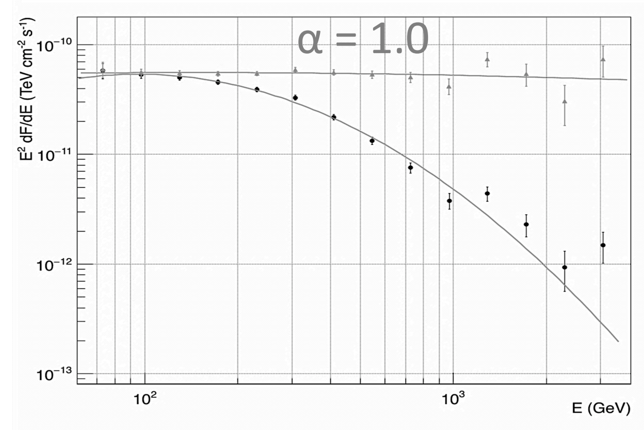
Name	Abbreviation	Formula
Power law	PWL	$\phi_0(E/E_0)^{-\Gamma}$
Log-parabola	LP	$\phi_0(E/E_0)^{-\Gamma-\beta\log(E/E_0)}$
Exponential cut-off power law	EPWL	$\phi_0(E/E_0)^{-\Gamma}\exp(-E/E_{cut})$
Exponential cut-off log-parabola	ELP	$\phi_0(E/E_0)^{-\Gamma-\beta\log(E/E_0)}\exp(-E/E_{cut})$
Super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

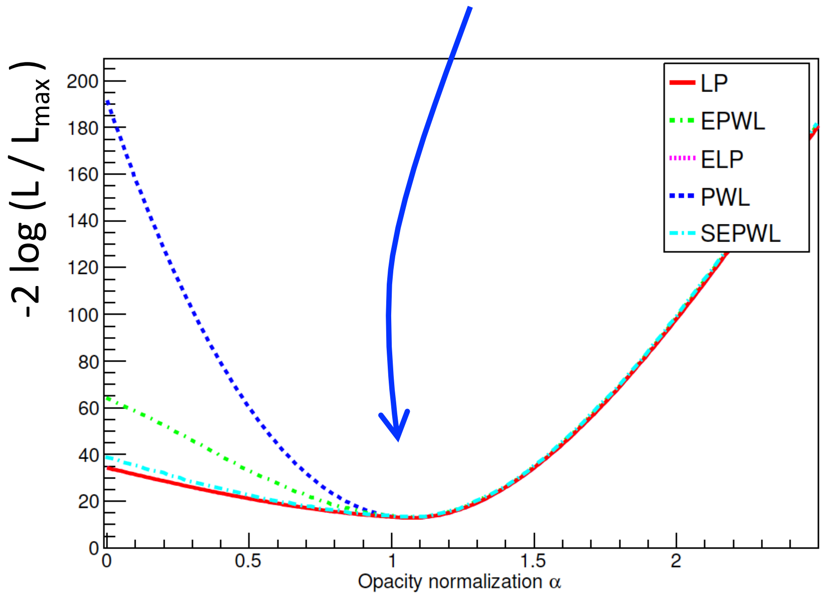
α : opacity normalization
(= EBL density scaling)

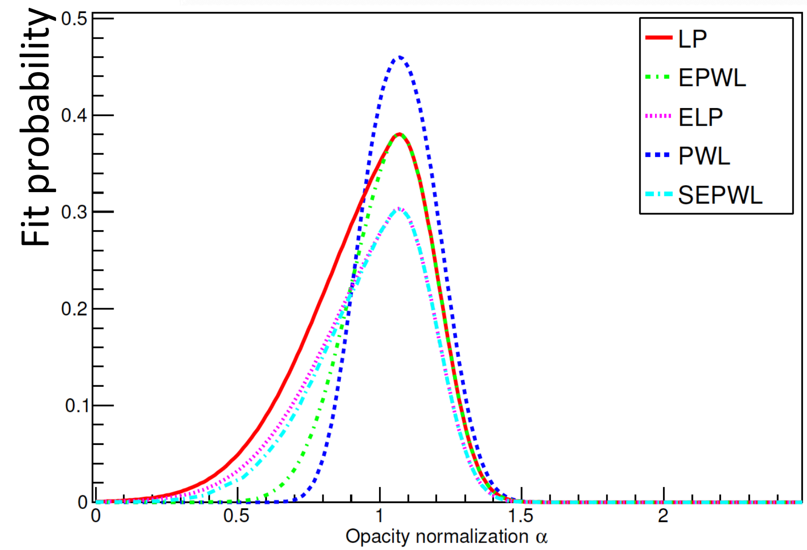
$$\left(\frac{d\phi}{dE}\right)_{\text{observed}} = \left(\frac{d\phi}{dE}\right)_{\text{intrinsic}} \times e^{-\alpha\tau(E,z)}$$

Likelihood vs. α



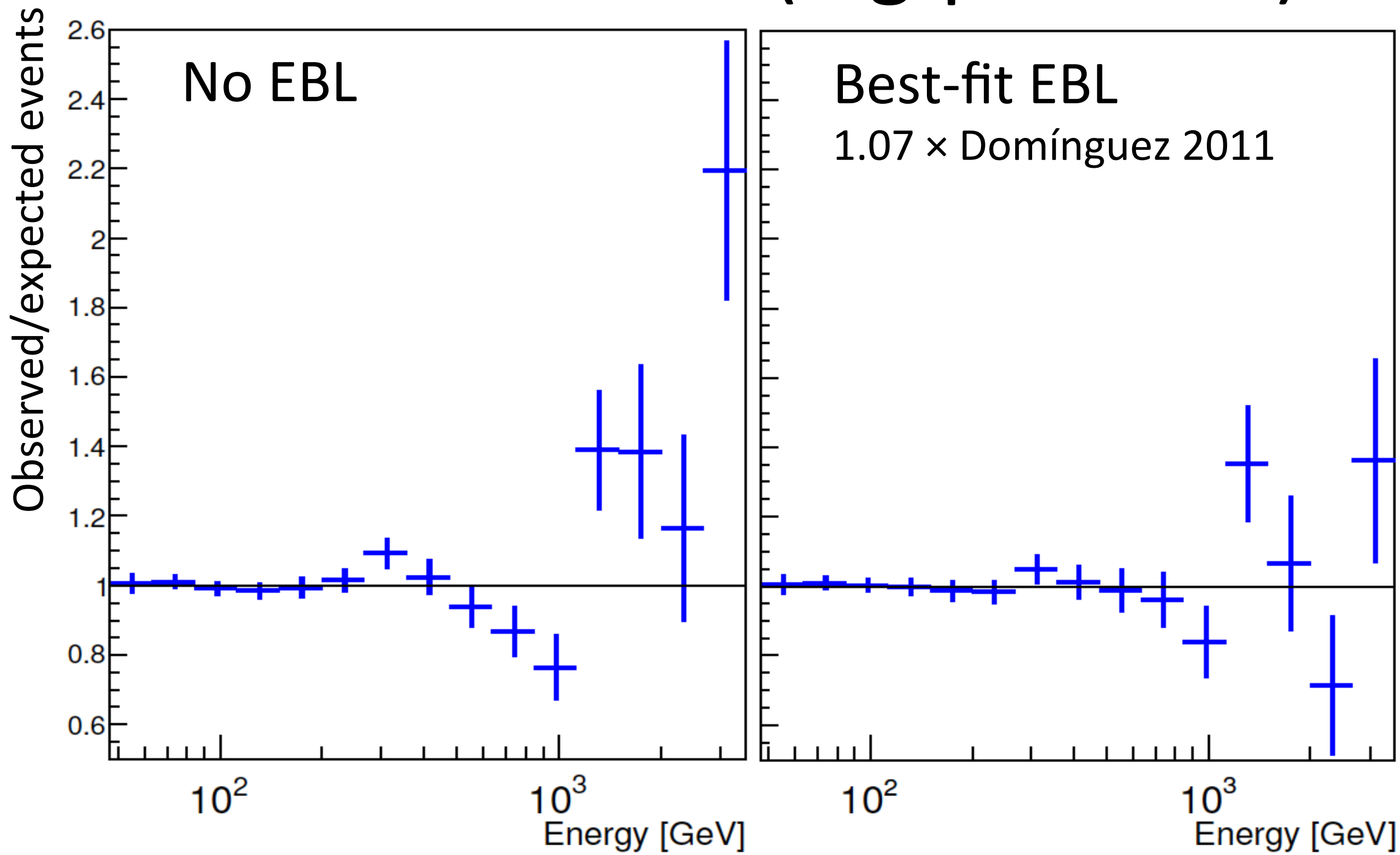
- For EBL scalings ≳ 1.1, intrinsic spectrum would have to be *convex* to reproduce MAGIC data
- ⟹ all functions degenerate into a power-law





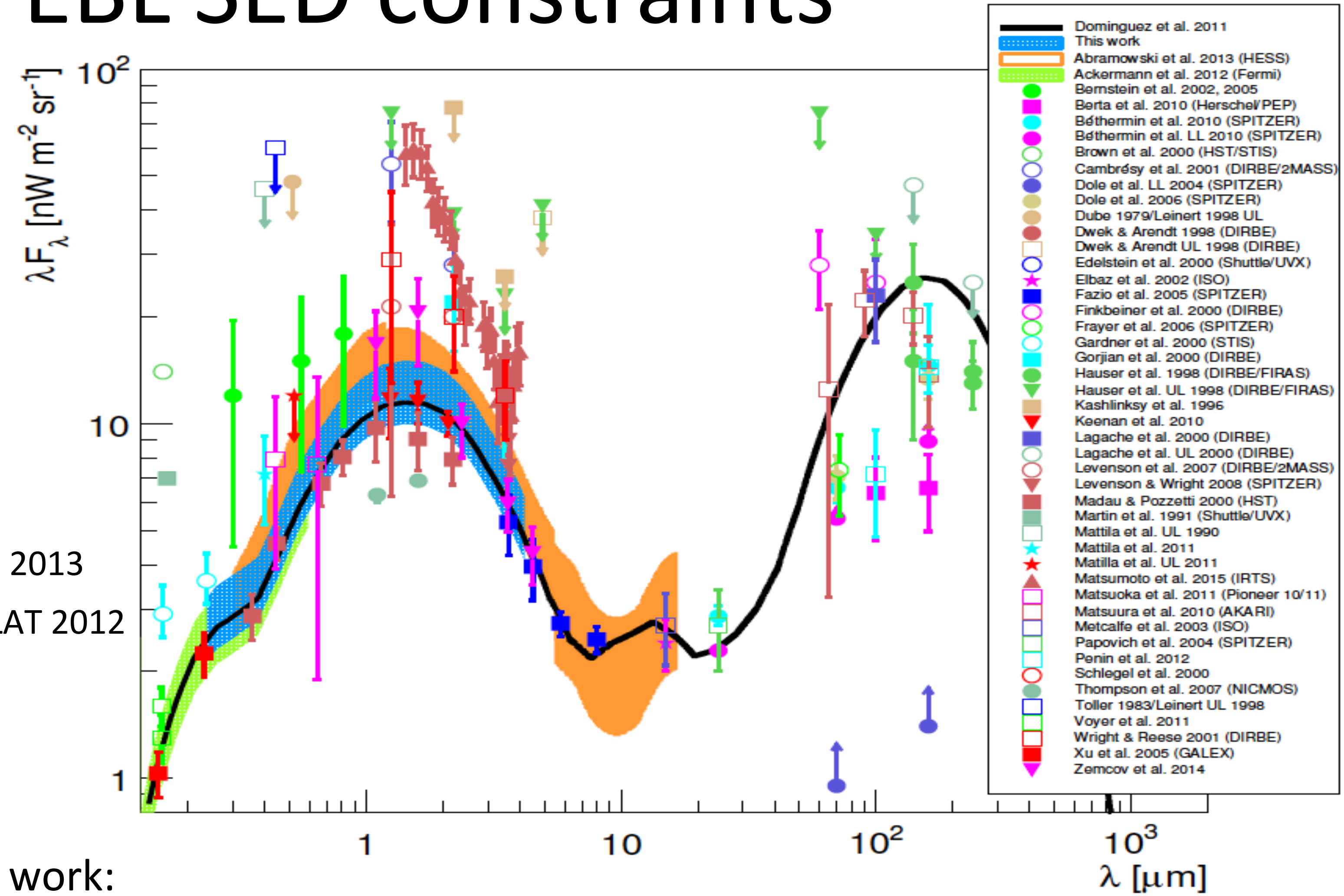
- Power-law provides best fit probability (fewest parameters), but choosing it as intrinsic model means *all* spectral curvature would be *attributed to* EBL (!)
- With the log-parabola, best fit achieved for $\alpha = 1.07\ (+0.09, -0.13)_{STAT}$
- When the ±15% uncertainty in the overall (atmosphere+telescopes)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

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
- Likelihood ratio test: (log-parabola*best-fit EBL) is preferred at the 4.6-σ level to the log-parabola as a model for the observed spectrum

EBL SED constraints



H.E.S.S. 2013

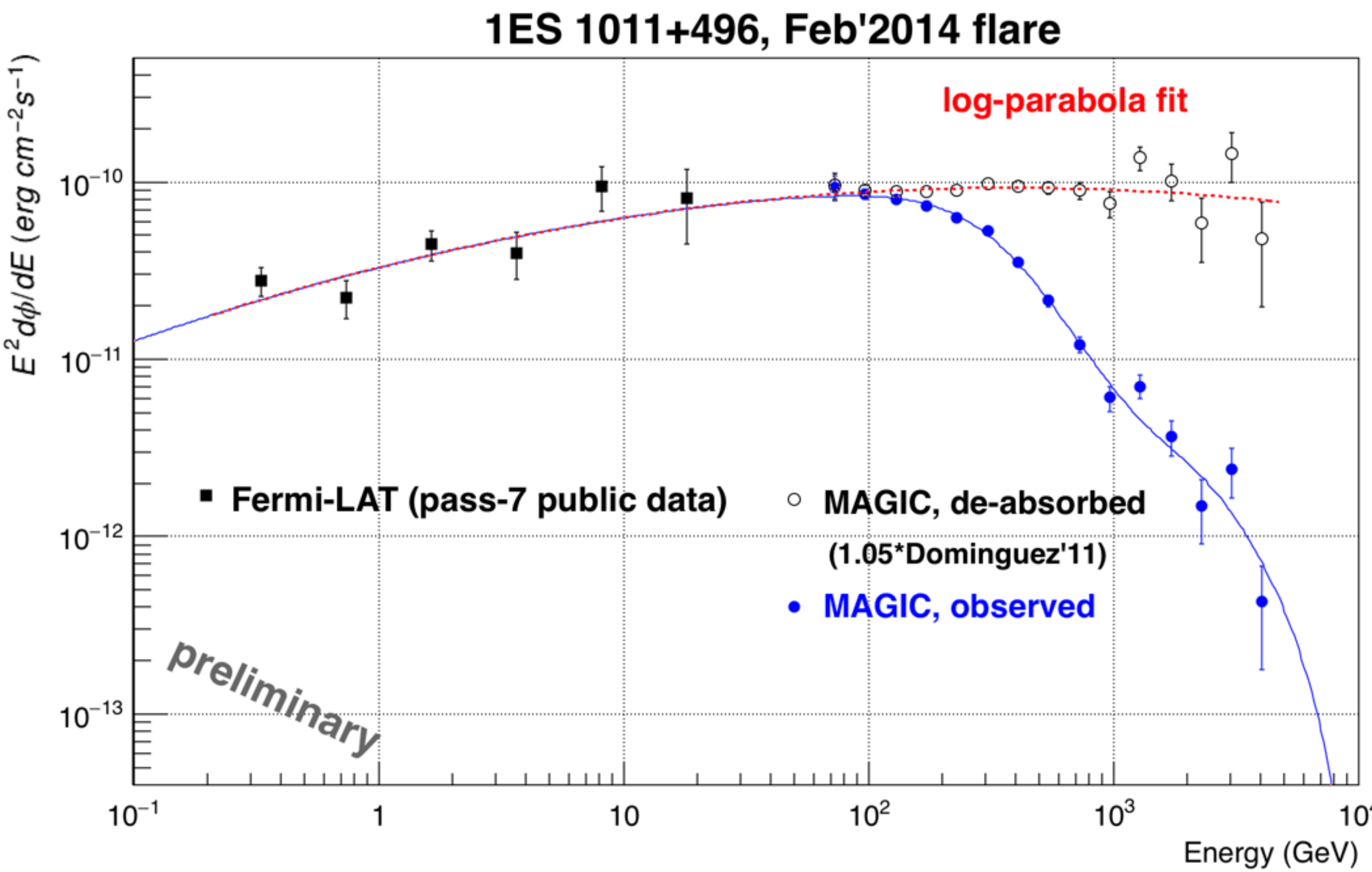
Fermi-LAT 2012

this work:

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

- 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



- Joint fit with contemporaneous Fermi-LAT data results in similar best-fit EBL scaling (1.05 × 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)$_{STAT+SYS}$, 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