The Measurement of the Expansion Rate of the Universe from γ-ray Attenuation*

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Collaborators:

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* **partly on behalf of the Fermi collaboration (Domínguez et al. 2013, ApJ, 770, 77)**

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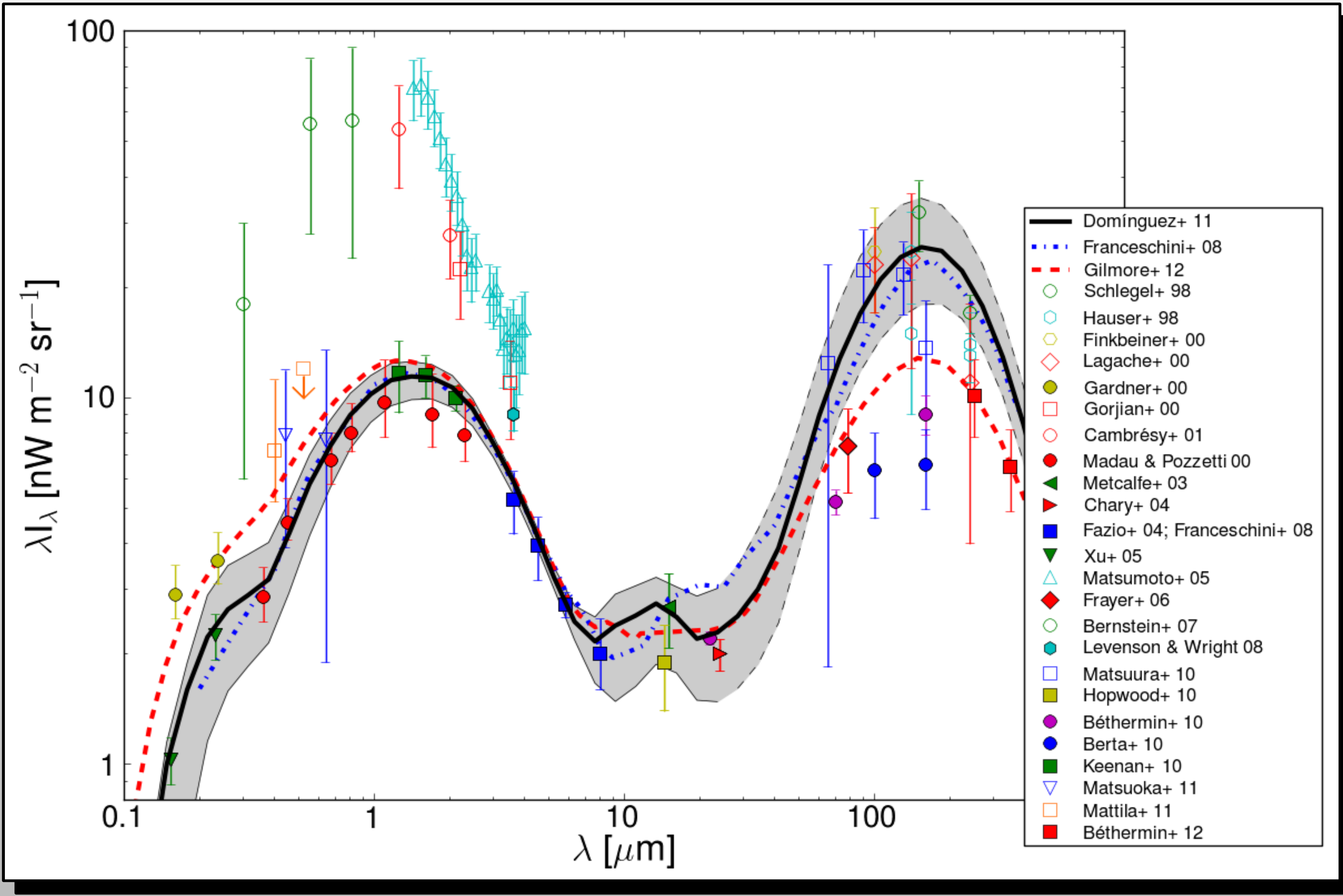
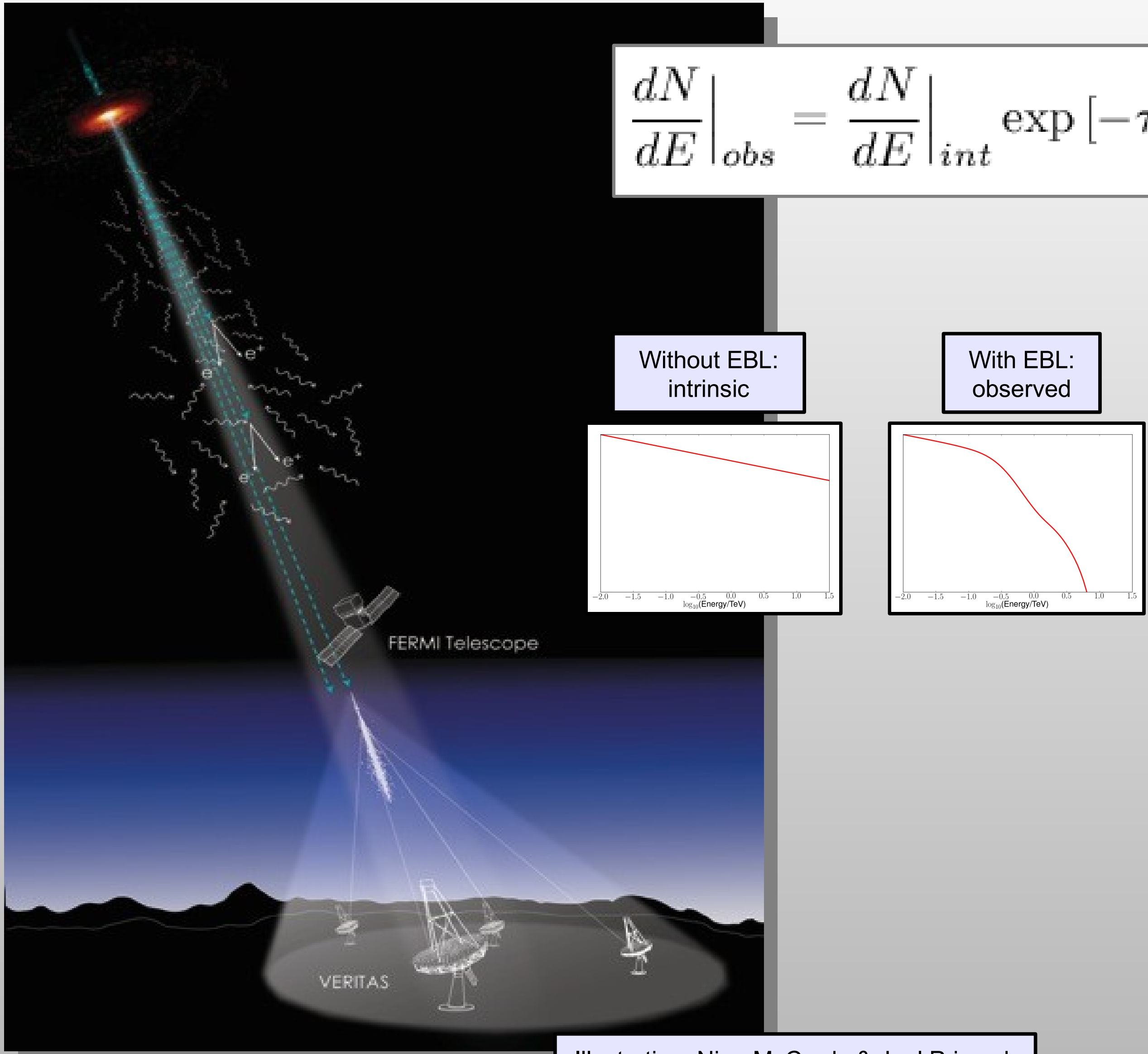
Local EBL: Data, γ-ray Limits, and Models



EBL models

Type of modeling and refs.	Galaxy number evolution	Galaxy emission
Type i, Forward evolution (Somerville+ 12; Gilmore+ 12; Inoue+ 13)	**Semi-analytical models**.	**Modeled**. Stars: Bruzual & Charlot 03 (BC03); Dust Absorption: Charlot & Fall, 00; Dust Re-emission: Rieke+ 09.
Type ii, Backward evolution (Franceschini+ 08)	**Observed** local-optical galaxy luminosity functions (starburst population) and near-IR galaxy luminosity functions up to z=1.4 (elliptical and spiral populations)	**Modeled**. Consider only a few galaxy types based on optical images.
Type iii, Inferred evolution (Finke+ 10; Kneiske & Dole 10)	**Parameterization** of the history of the star formation density of the universe. By construction, they do not include quiescent and AGN galaxies.	**Modeled**. Stars: Single bursts of solar metallicity from BC99 (Kneiske+)/BC03 (Finke+); Dust Absorption: General extinction law; Dust Re-emission: Modified black bodies.
Type iv, Observed evolution (Domínguez+ 11; Stecker+ 12; Helgason+ 12)	**Observed** near-IR galaxy luminosity functions up to z=4.	**Observed**. Multiwavelength photometry from the UV up to MIPS 24 for ~6000 galaxies up to z=1. Consider 25 different galaxy types.

Gamma-Ray Attenuation



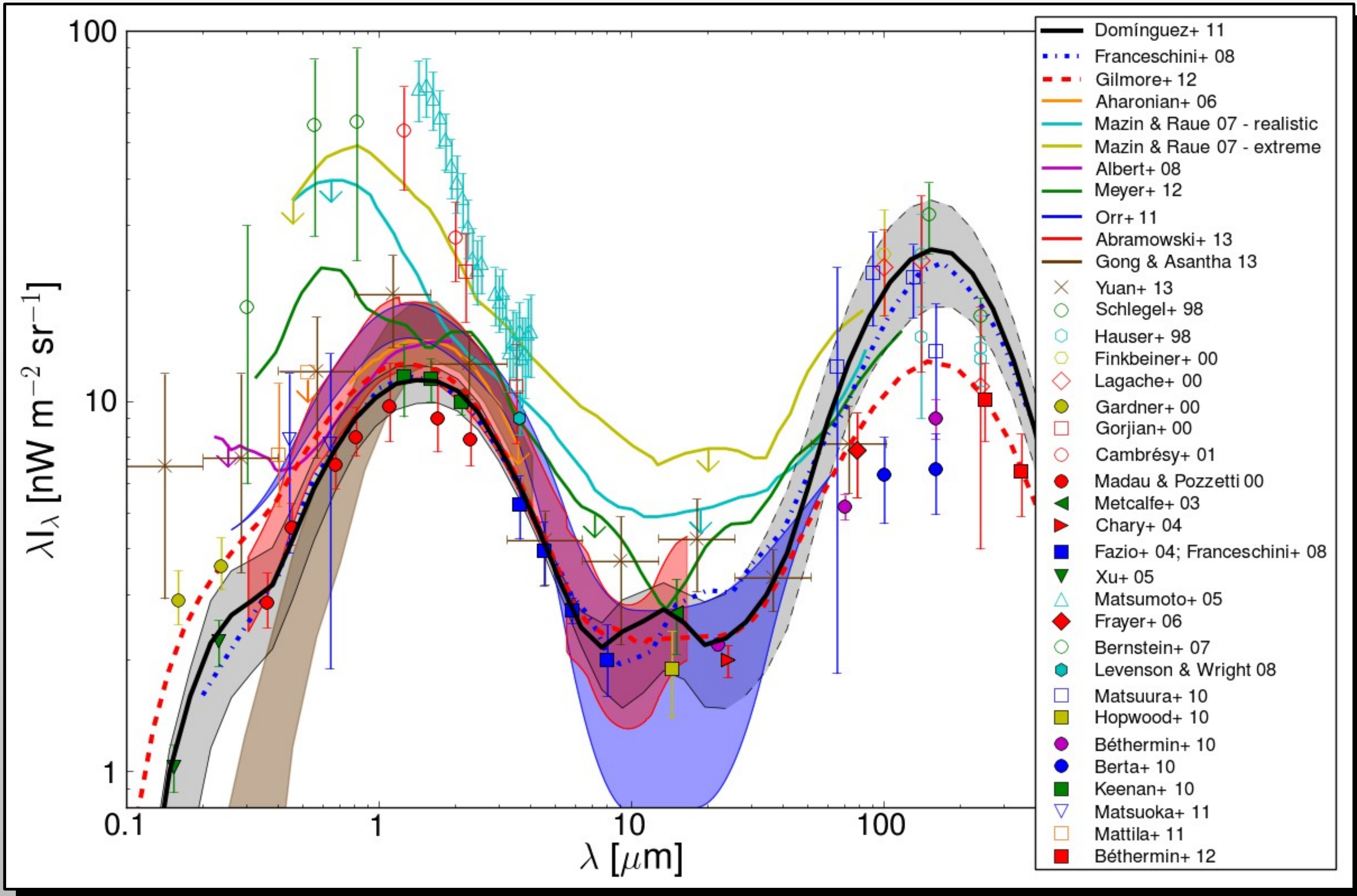
$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

Without EBL:
intrinsic

With EBL:
observed

Illustration: Nina McCurdy & Joel Primack

Local EBL: Data, γ-ray Limits, and Models



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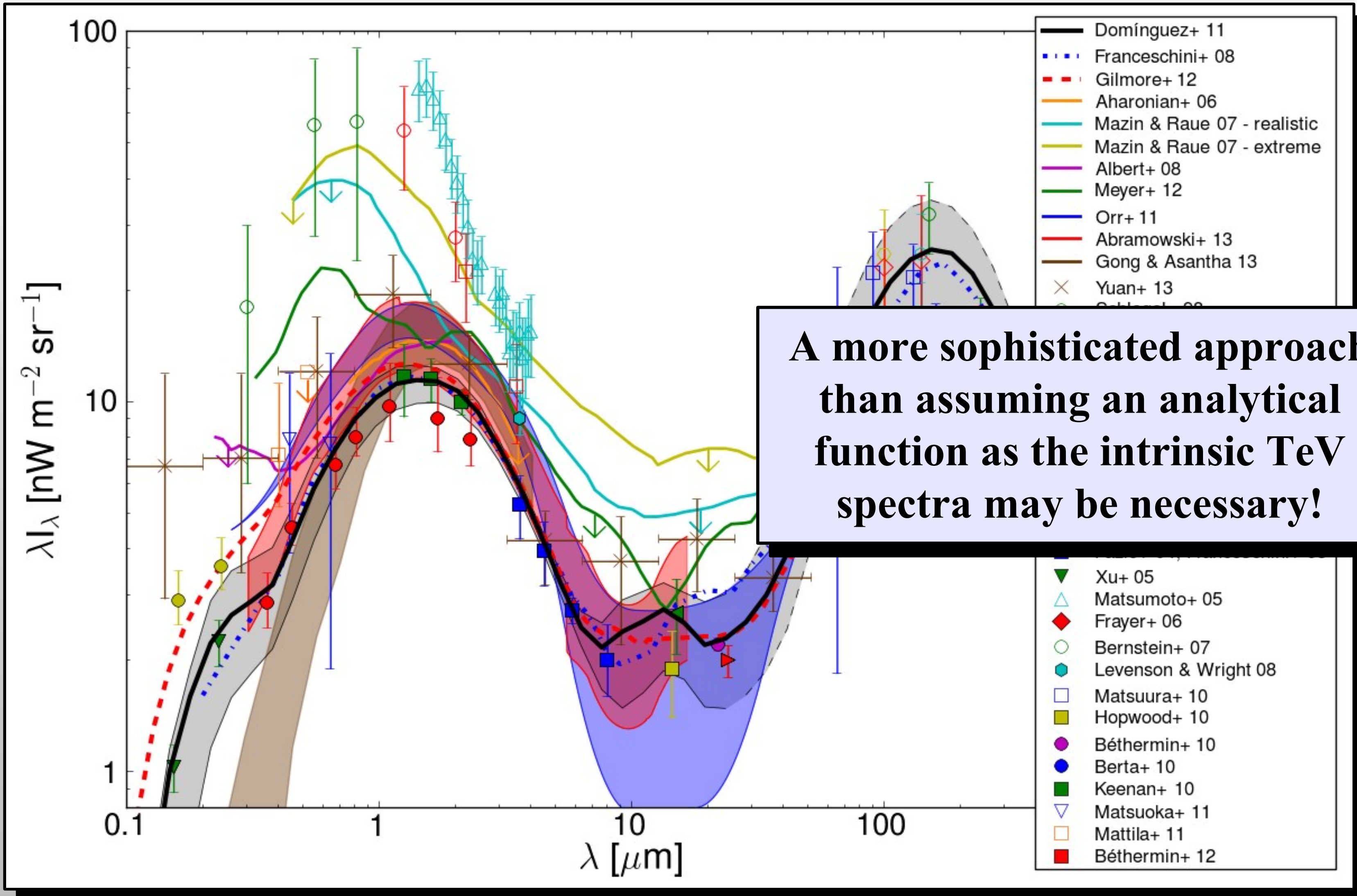
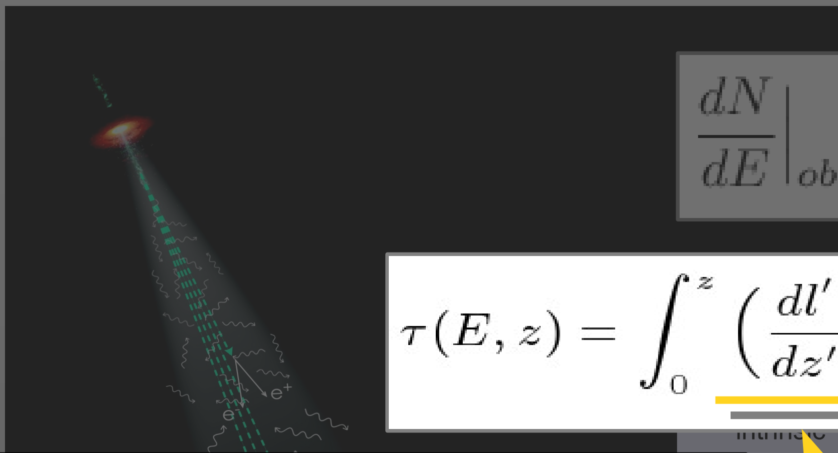


A more sophisticated approach than assuming an analytical function as the intrinsic TeV spectra may be necessary!

Gamma-Ray Attenuation



$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

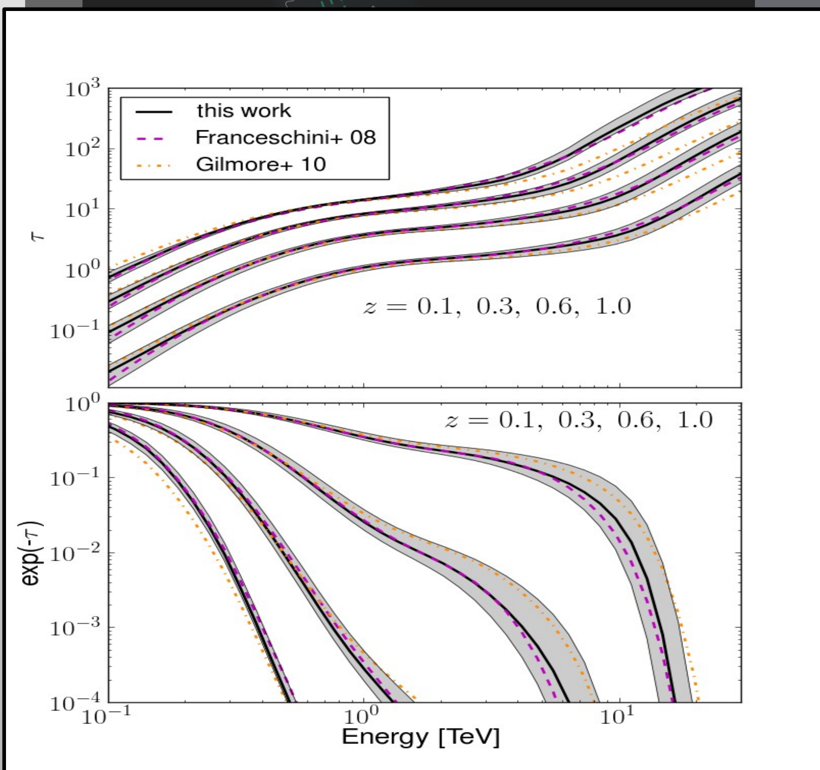
$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \; \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$

distance

Interaction angle

cross section

EBL photon density evolution



: Nina McCurdy & Joel Primack

Gamma-Ray Attenuation

$$\left.\frac{dN}{dE}\right|_{obs} = \left.\frac{dN}{dE}\right|_{int} \exp\left[-\tau(E,z)\right]$$

The cosmic gamma-ray horizon (CGRH) is by definition the energy E0 as a function of redshift at which the optical depth due to EBL is unity.

The measurement of the CGRH is a primary scientific goal of the Fermi Gamma-Ray Telescope (Hartmann 07; Stecker 07; Kashlinsky & Band 07)

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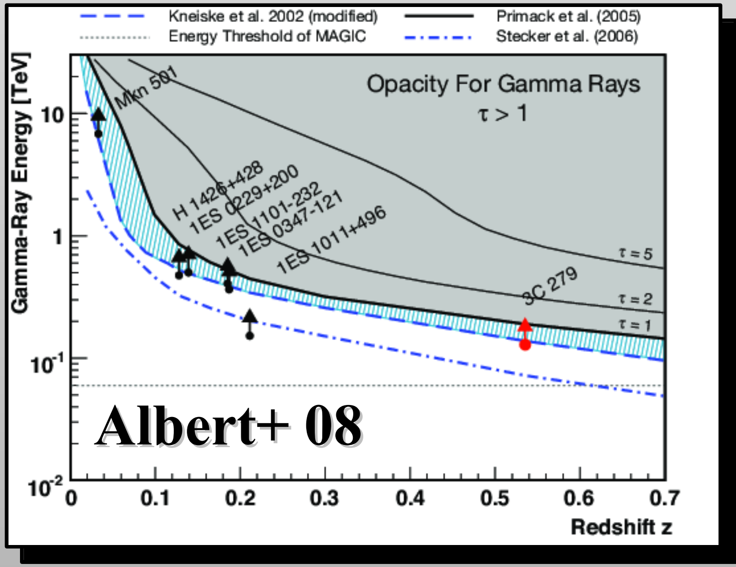

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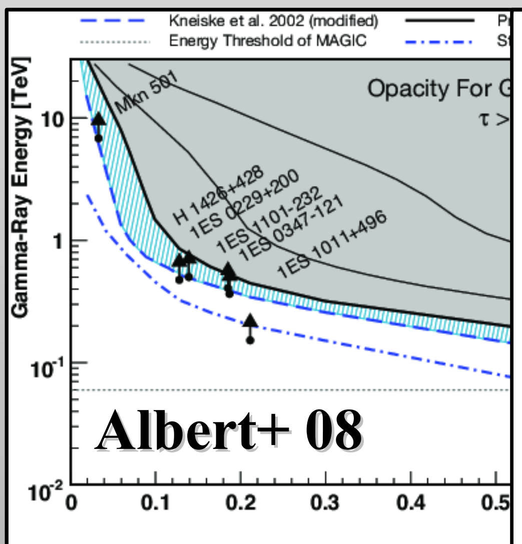

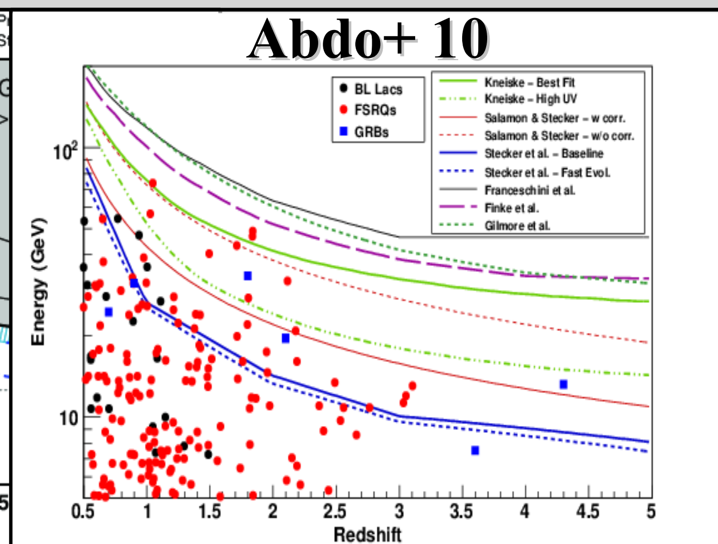

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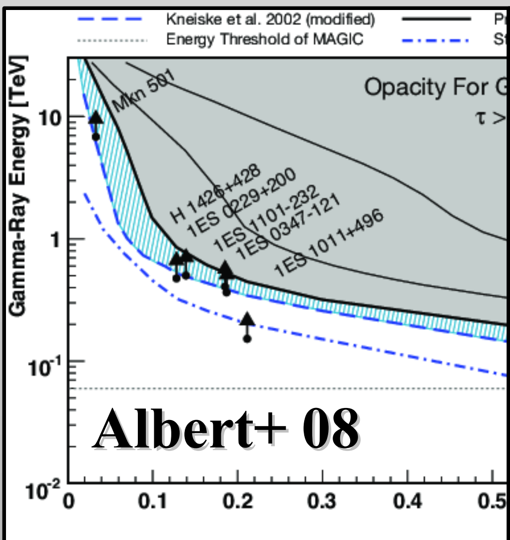
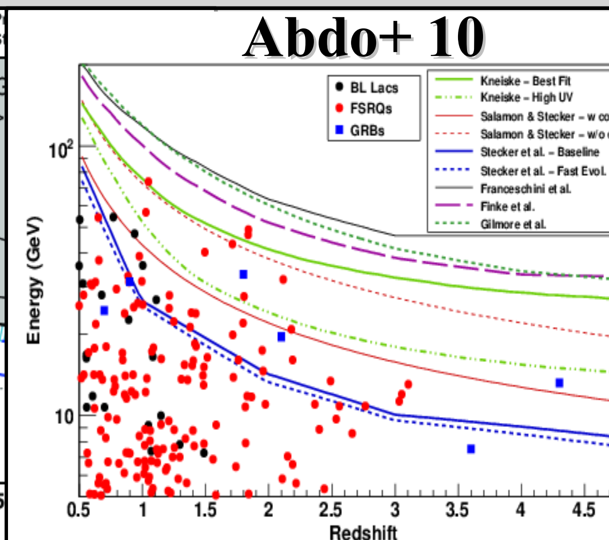
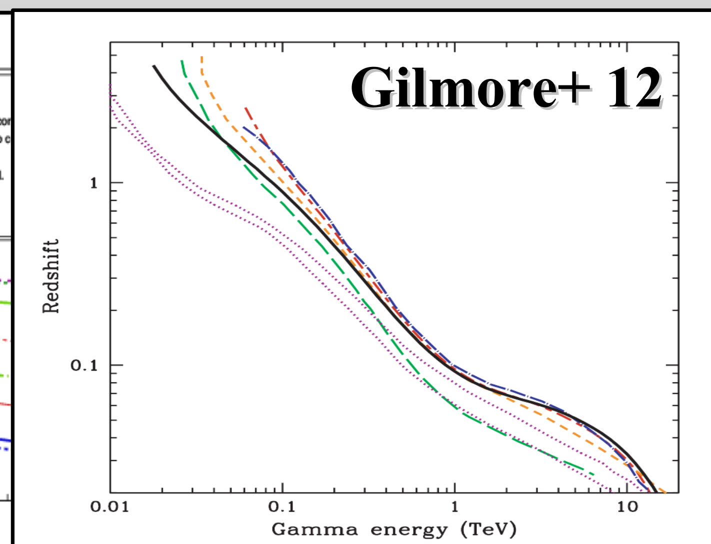




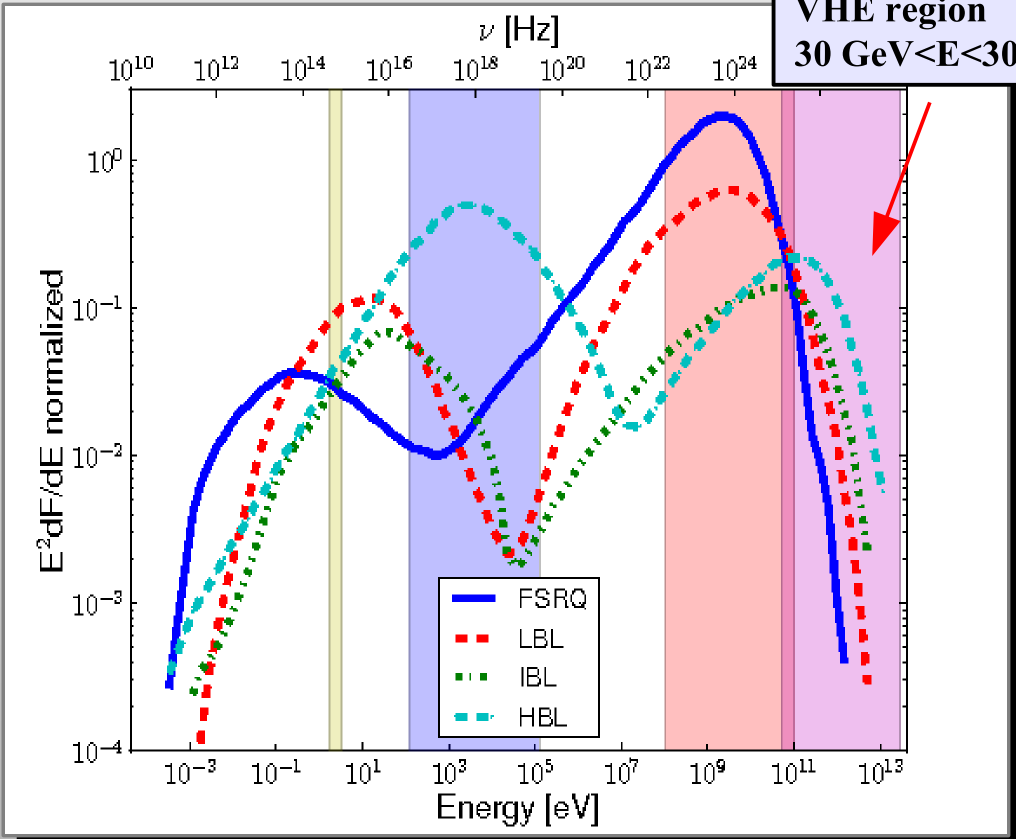


Sample and Synchrotron Self-Compton Models

Blazars: AGNs emitting at all wavelength with energetic jets pointing towards us.

Emission described by homogeneous synchrotron/synchrotron-self Compton model.

Quasi-simultaneous multiwavelength catalog of 15 BL Lacs (based on the compilation by Zhang et al. 2012).



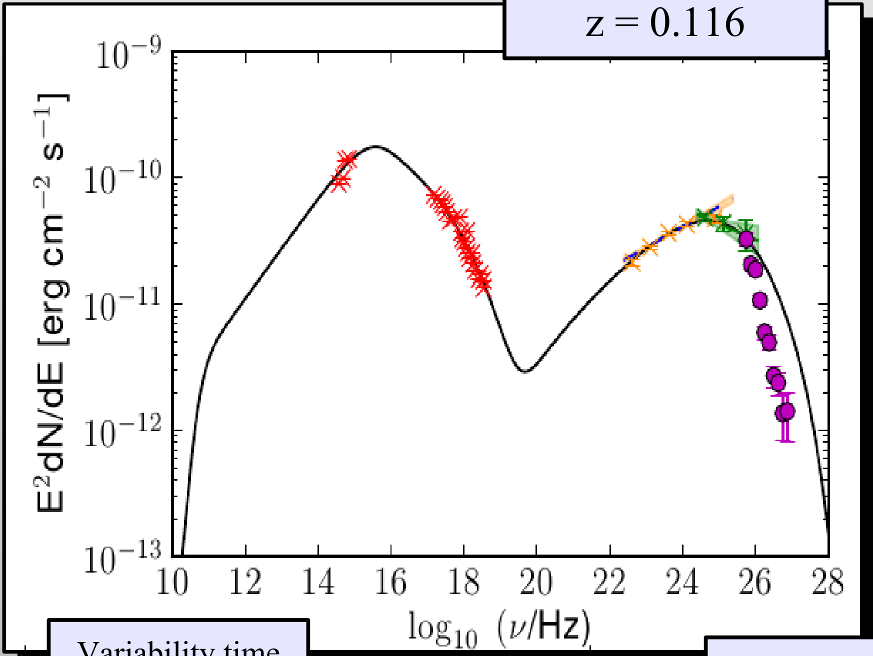
VHE region
30 GeV<E<30 TeV

Source	Redshift
Mkn 421	0.031
Mkn 501	0.034
1ES 2344+514	0.044
1ES 1959+650	0.048
PKS 2005-489	0.071
W Comae	0.102
PKS 2155-304	0.116
H 1426+428	0.129
1ES 0806+524	0.138
H 2356-309	0.165
1ES 1218+304	0.182
1ES 1101-232	0.186
1ES 1011+496	0.212
3C 66A	0.444
PG 1553+113	$0.500^{+0.080}_{-0.105}$

SED Multiwavelength Fits

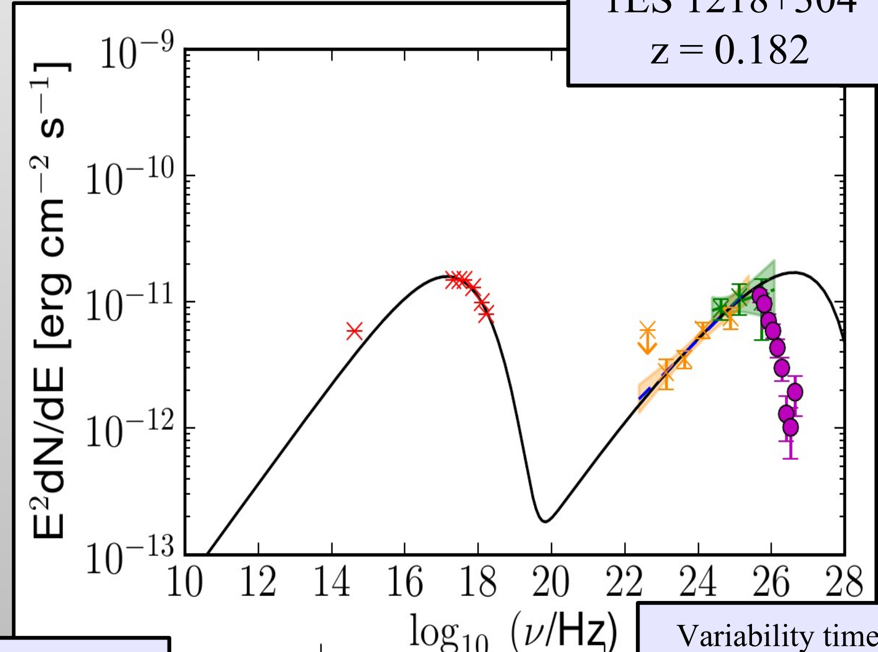
A one-zone synchrotron/SSC model is fit to the multiwavelength data excluding the Cherenkov data, which are EBL attenuated. Then, this fit is extrapolated to the VHE regime representing the intrinsic VHE spectrum. Technique similar to Mankuzhiyil et al. 2010.

PKS 2155-304
z = 0.116



Variability time scale 10^4 s (fast)

1ES 1218+304
z = 0.182



Variability time scale 10^5 s (slow)

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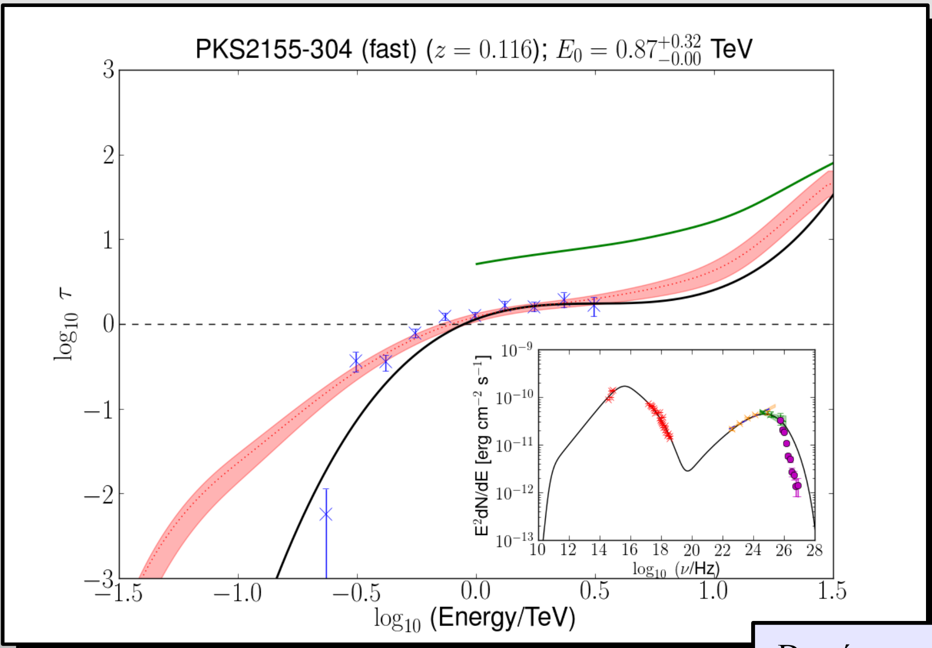
Optical Depth Estimation and Determination of the CGRH

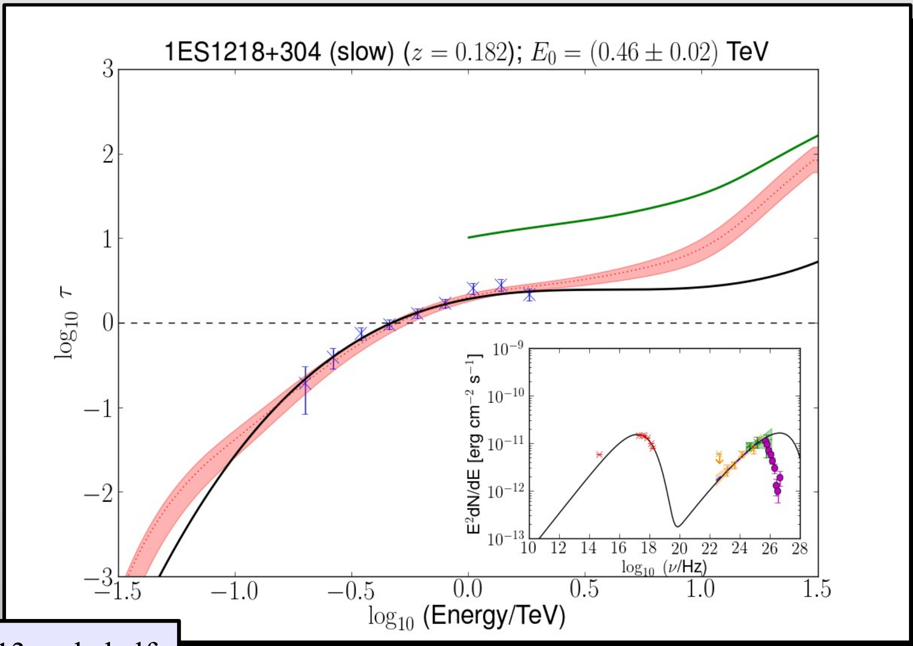
Maximum likelihood technique with three EBL-model independent conditions:

1.- The optical depth is lower than 1 at E = 0.03 TeV.

2.- The optical depth is lower than the optical depth calculated from the EBL upper limits from Mazin & Raue, 07; especially 1 < τ < UL(z) at E = 30 TeV.

3.- The polynomial is monotonically increasing with the energy.





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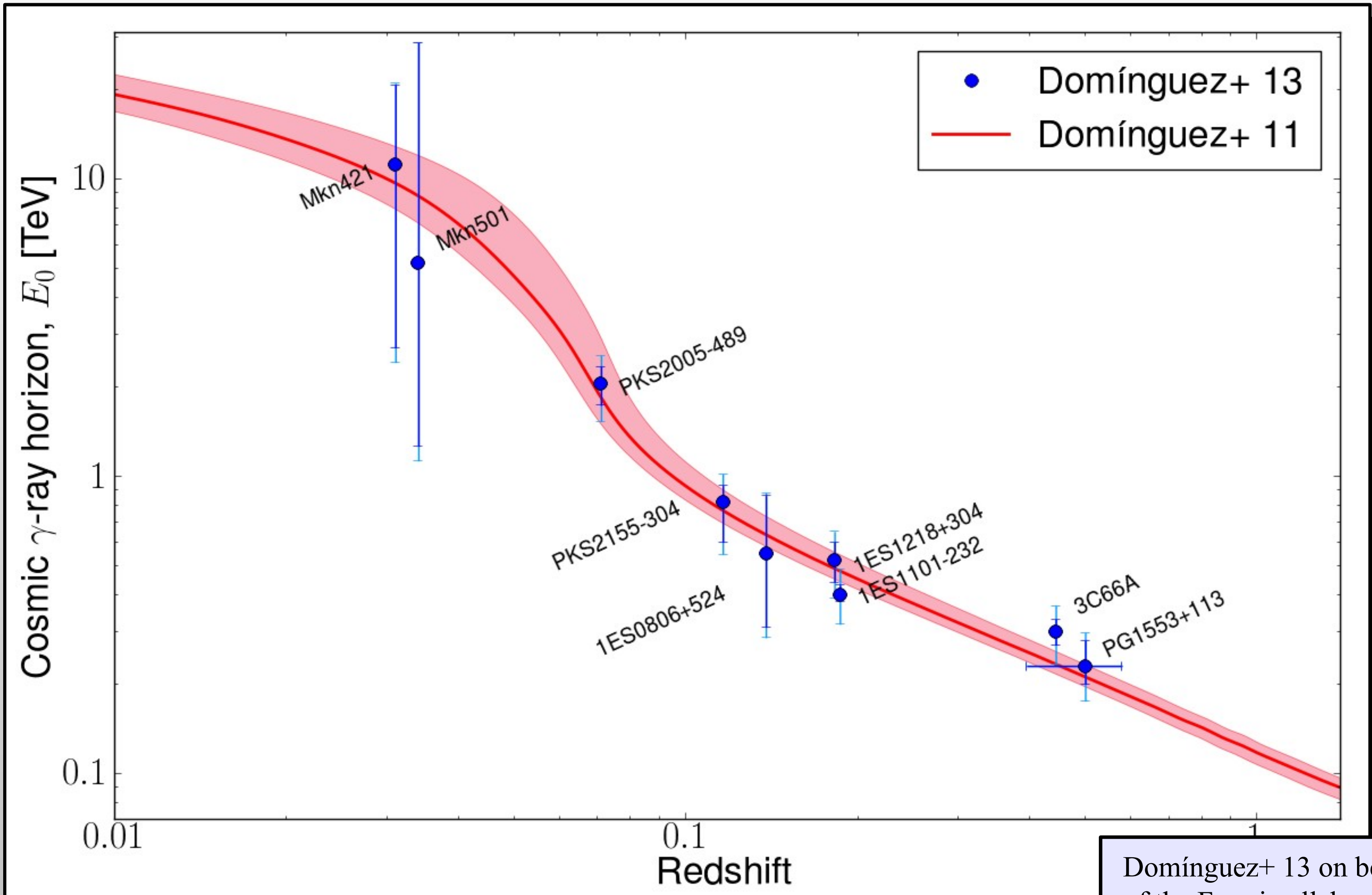
Cosmic γ-ray Horizon: Results



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There are 4 out of 15 cases where our maximum likelihood methodology could not be applied since the prediction from the synchrotron/SSC model was lower than the detected flux by the Cherenkov telescopes.

Two other cases where the statistical uncertainties were too large to set any constraint on E0.

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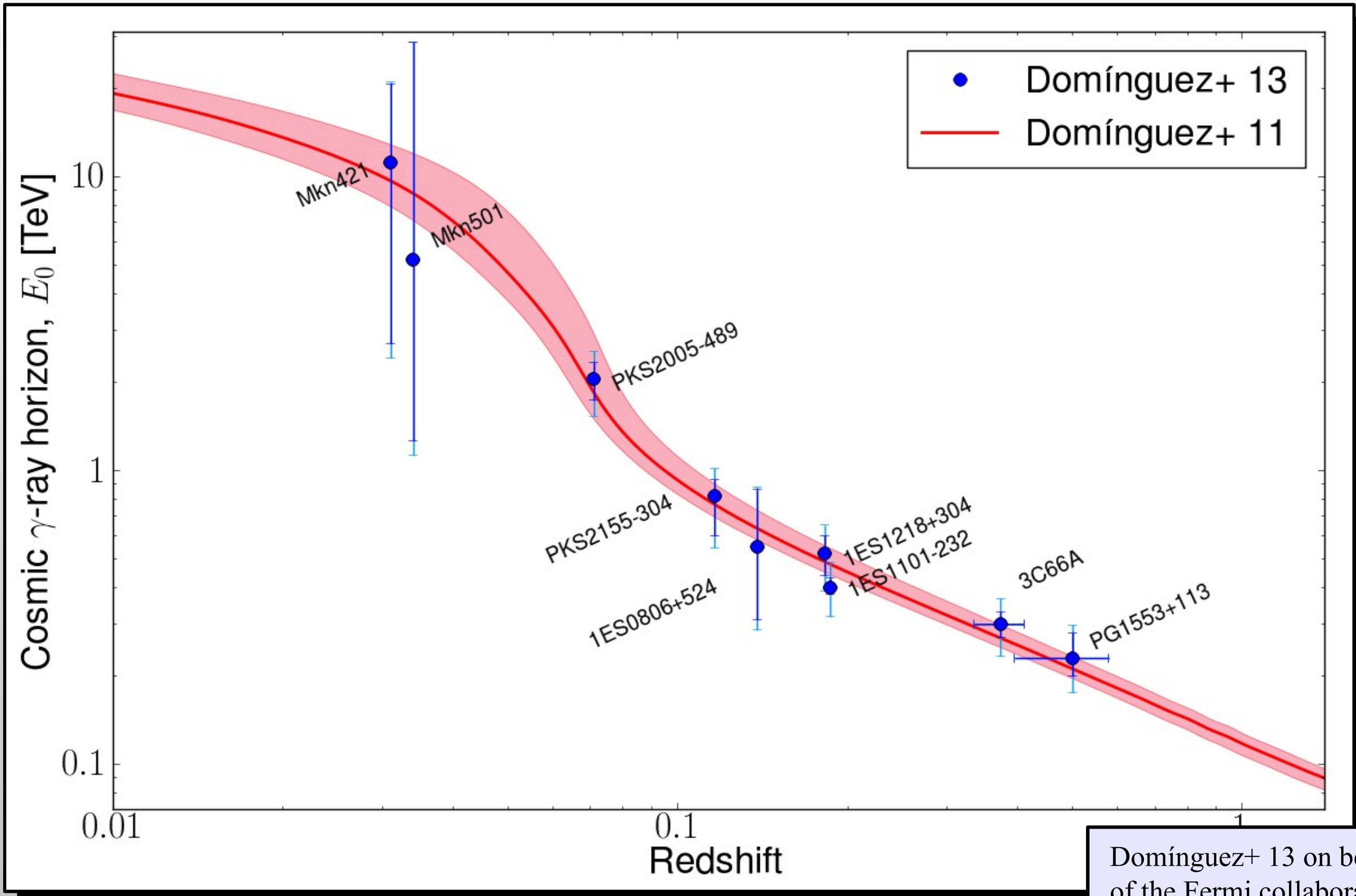

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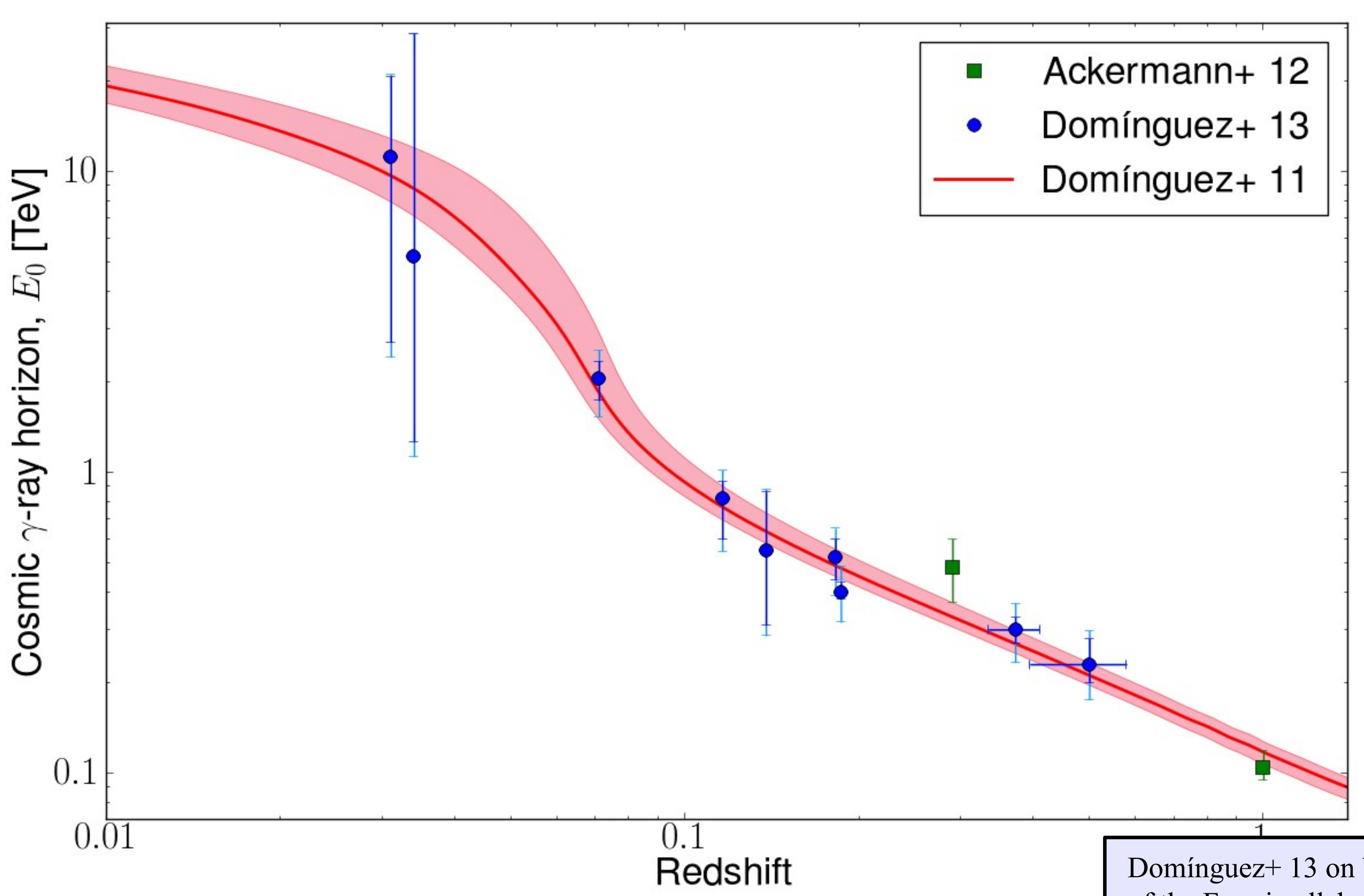

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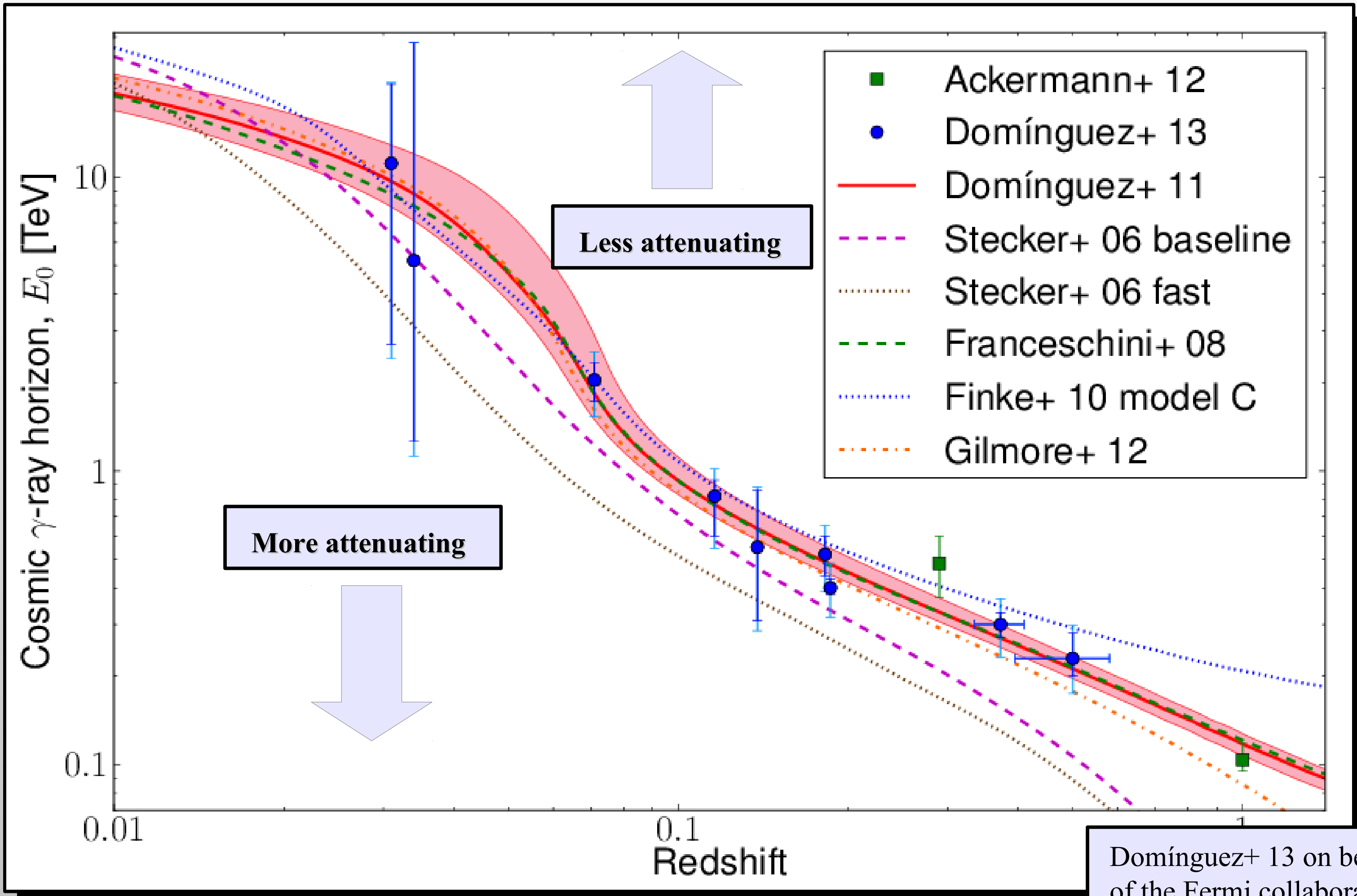

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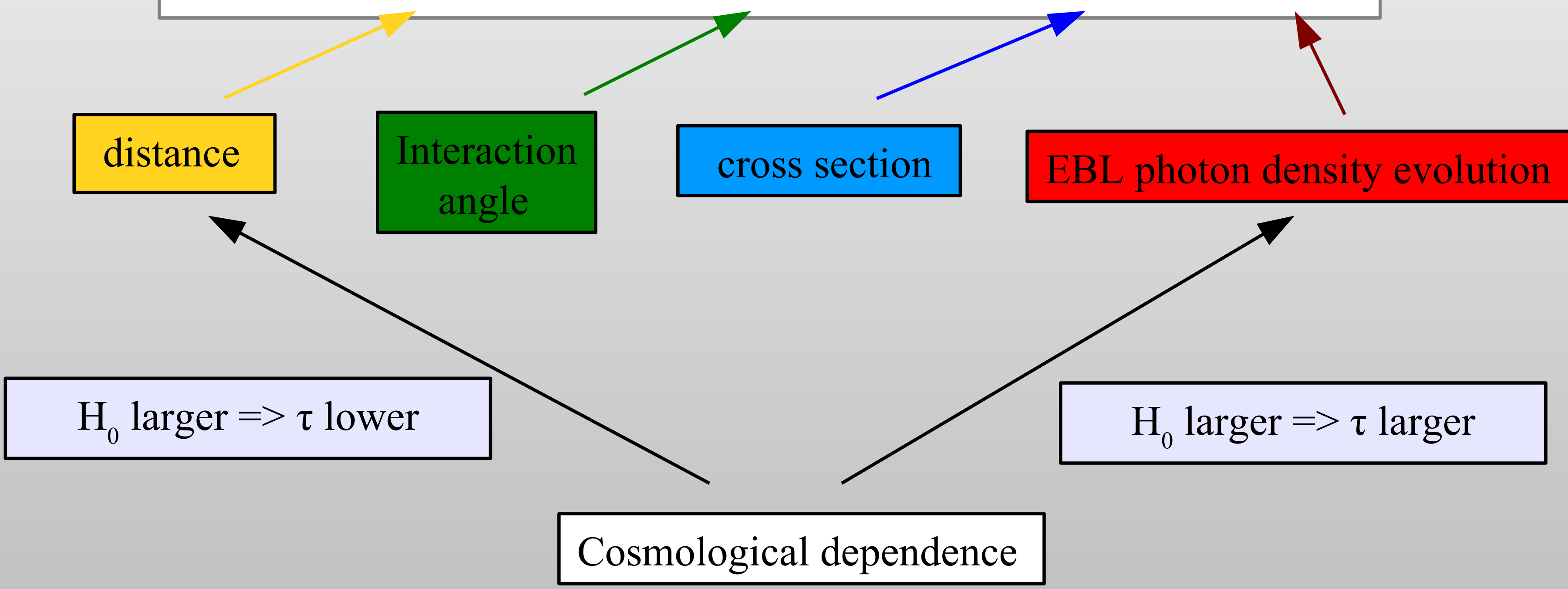
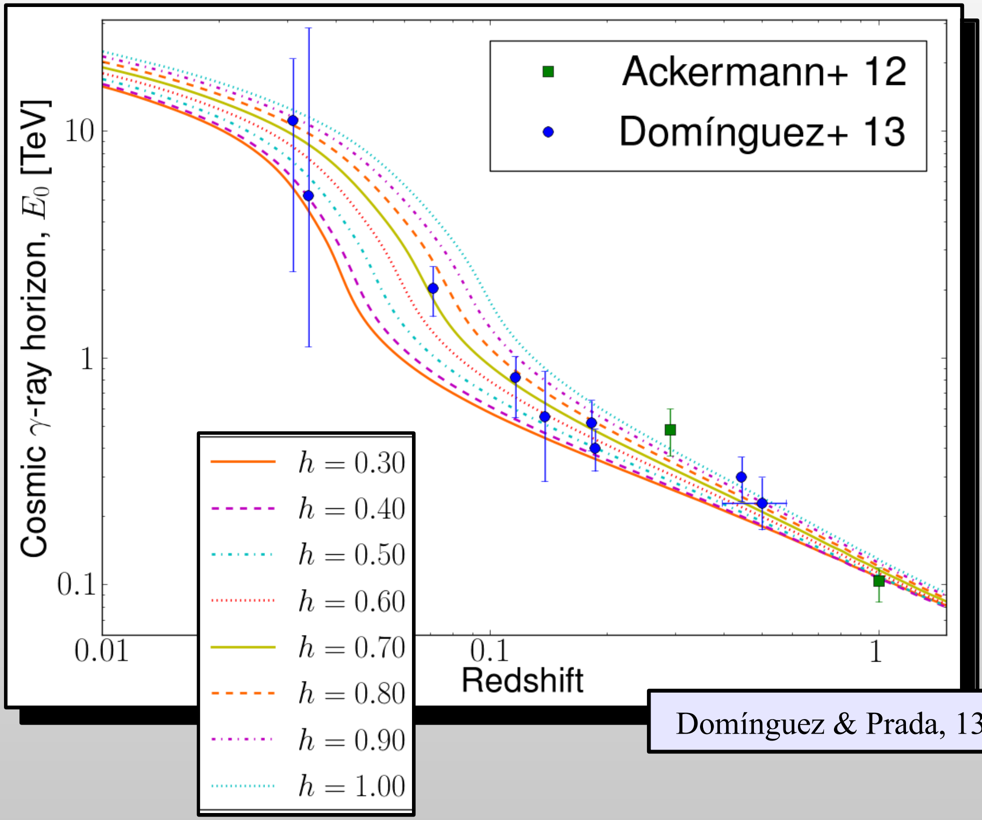
Cosmic γ-ray Horizon: Cosmological Dependence

$$\tau(E,z) = \int_0^z \left(\frac{dl'}{dz'}\right) dz' \int_0^2 d\mu \frac{\mu}{2} \int_{\varepsilon_{min}}^{\infty} d\varepsilon' \, \sigma_{\gamma\gamma}(\beta') n(\varepsilon', z')$$



Cosmological Dependence: Assumed flat ΛCDM



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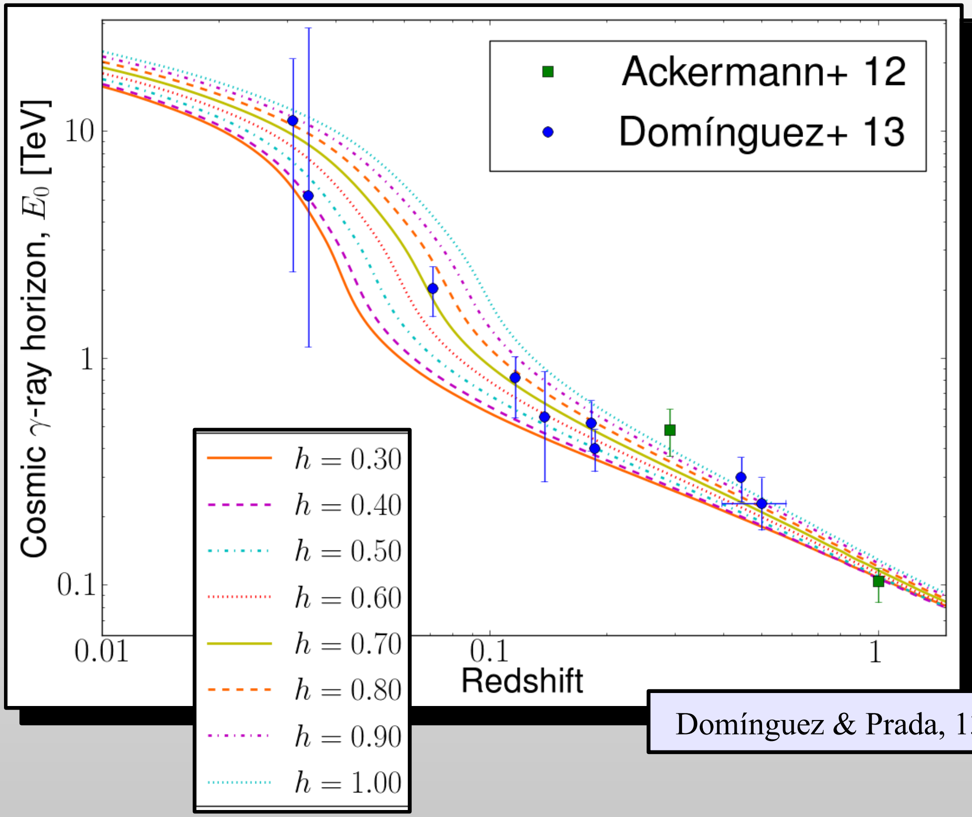

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$$H_0 = 71.8\,^{+4.6}_{-5.6}\,^{+7.2}_{-13.8}\ \text{km/s/Mpc}$$

Statistical uncertainties — **Systematic uncertainties**

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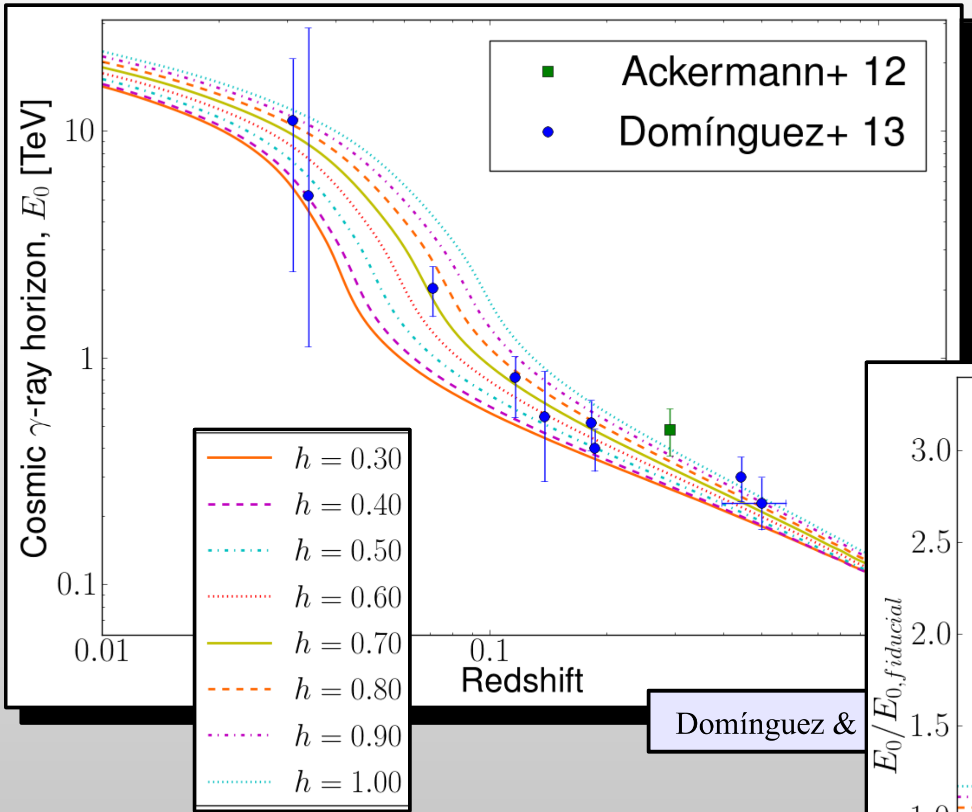

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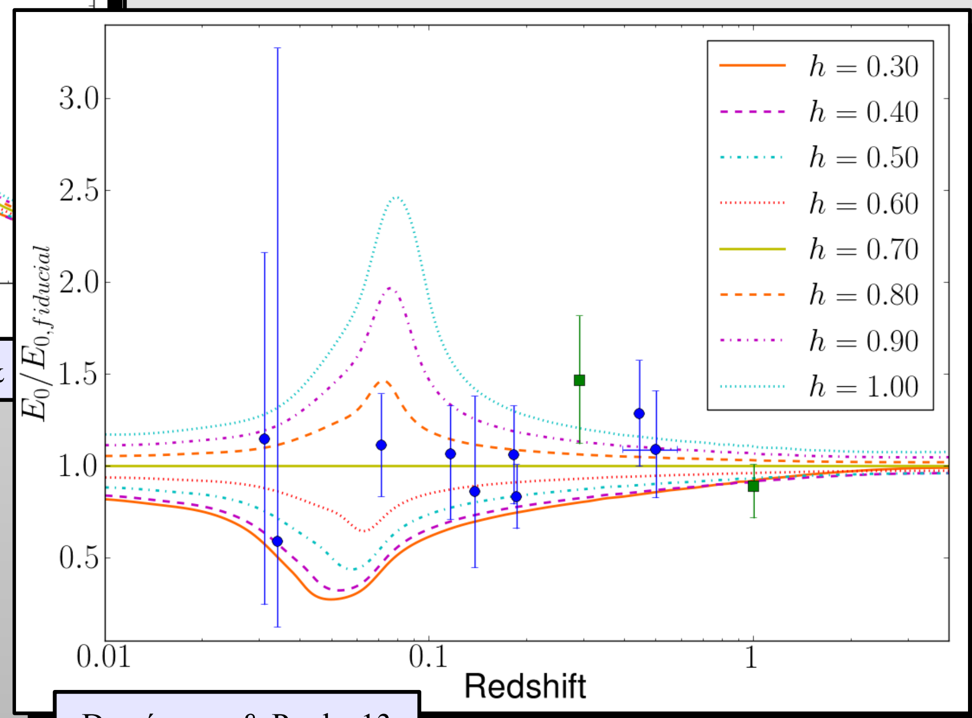

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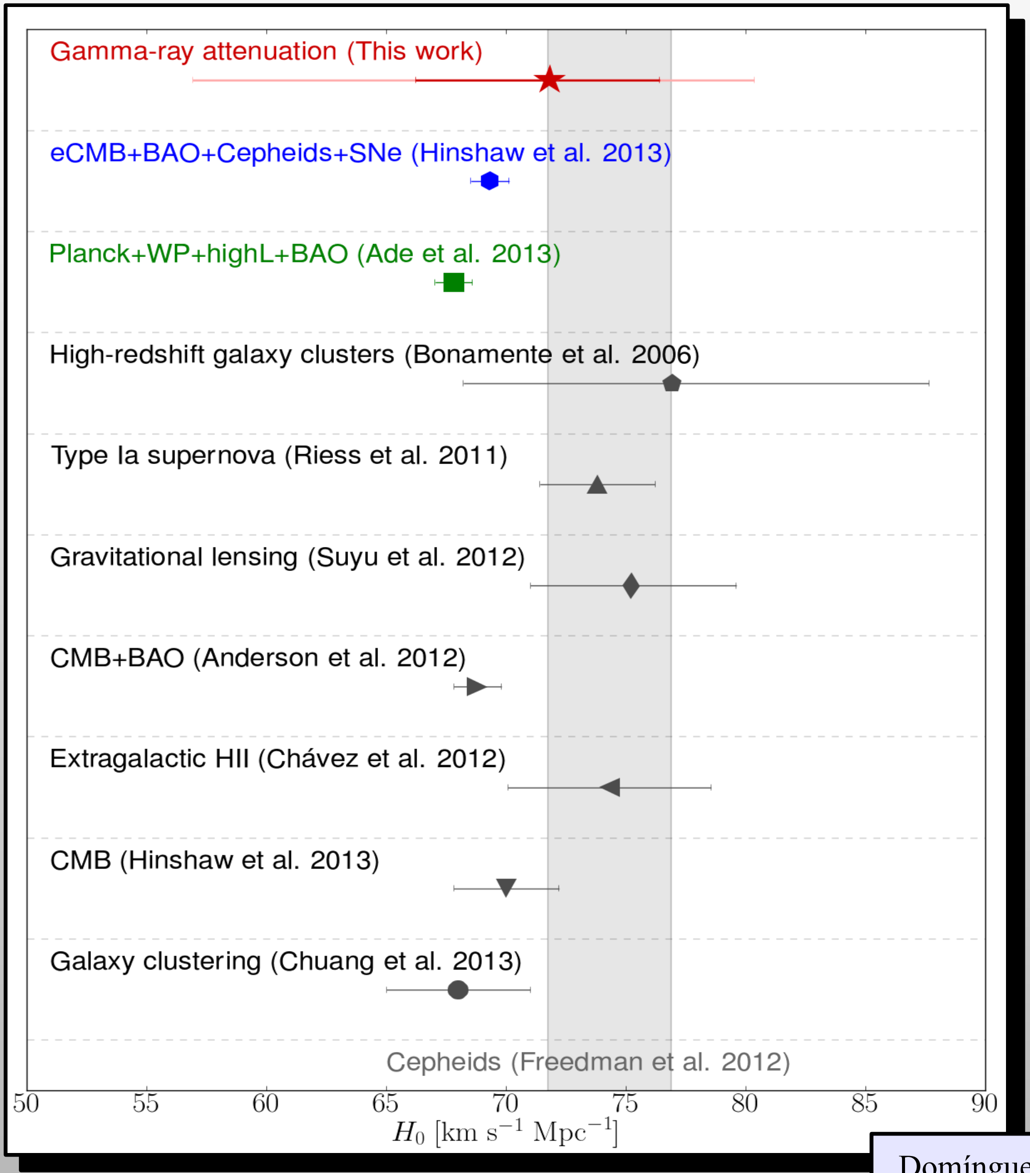
The Hubble Constant from Different Methodologies



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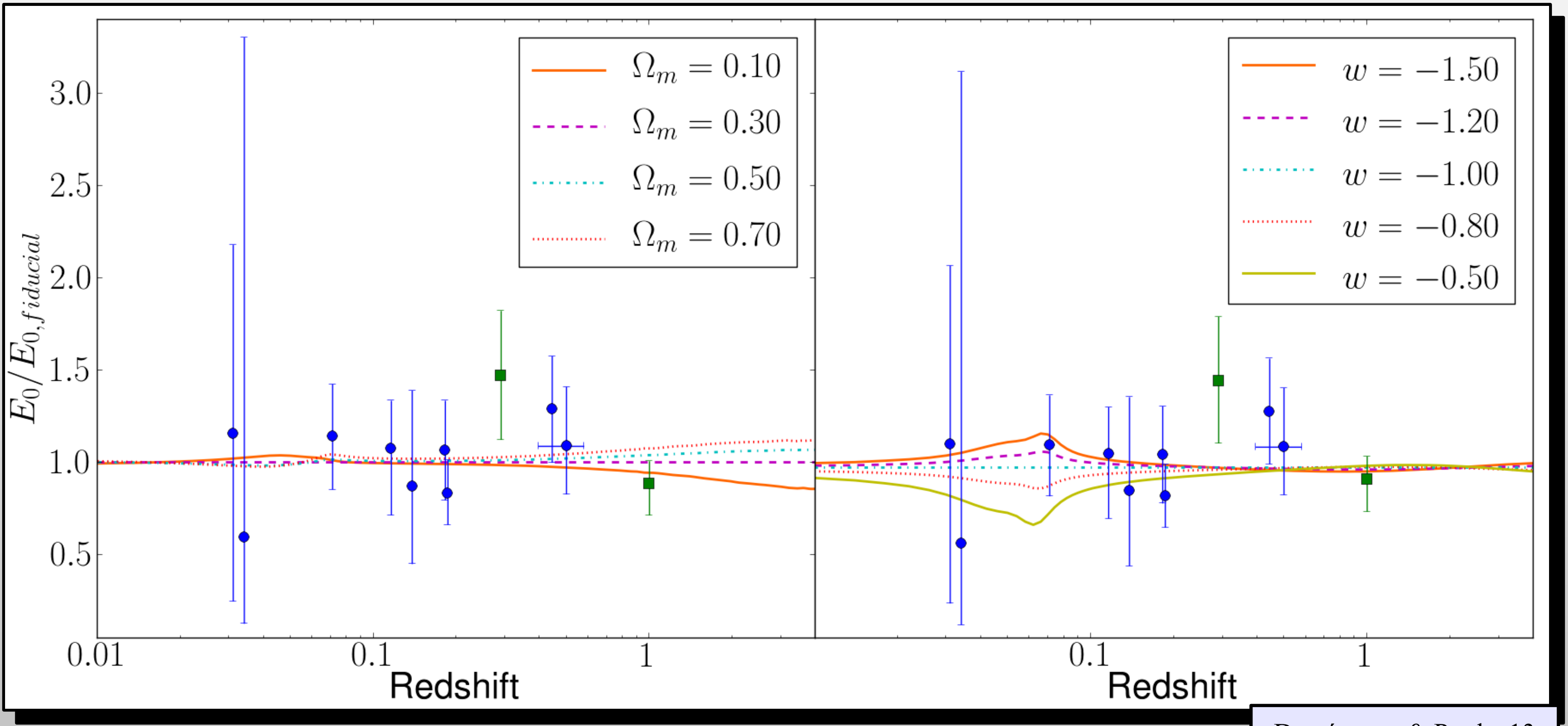
Cosmological Parameters: Ω_m and ω_0



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Summary

1.- The first statistically significant detection of the CGRH that is independent of any EBL model has been presented.

2. This detection is compatible with the recent EBL direct detection in the optical, galaxy counts, and upper limits from gamma-ray attenuation. This constrains the contribution to the low redshift EBL from faint or high redshift galaxies that escape to current galaxy surveys and any other potential contribution.

3.- The detection of the CGRH allow us to derive the expansion rate of the Universe (the Hubble constant) from a novel technique using γ-ray attenuation, whose value is compatible with other rather mature techniques.

$H_0 = 71.8\,^{+4.6}_{-5.6}\,^{+7.2}_{-13.8}$ km/s/Mpc

4.- The cosmological parameters Ω_m and w cannot be constrained with current data.