Constraining the Opacity of the Universe with Fermi LAT

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The Extragalactic Background Light

- *What is it?*

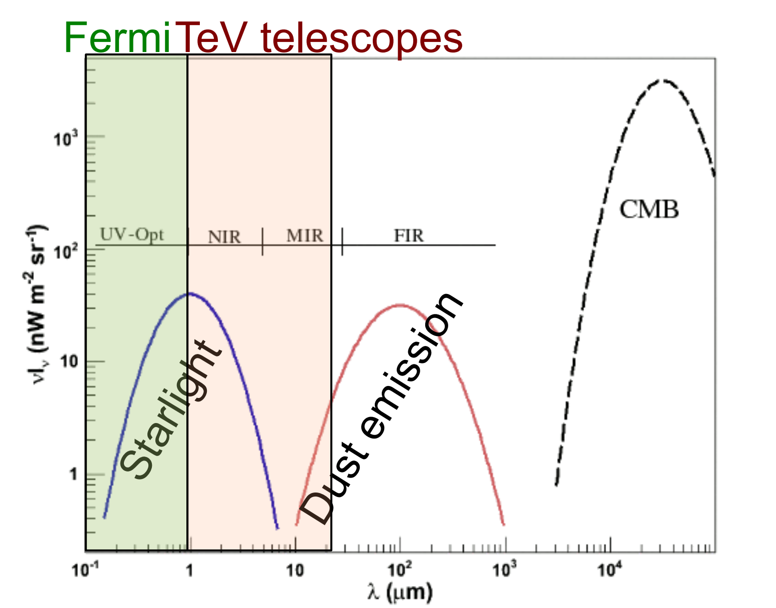
➢ Accumulation of all energy releases in the form of electromagnetic radiation. It includes everything but CMB and the foreground emission from anything local (Milky Way, Solar System, etc.). For gamma-ray astronomy, we are interested in the UV to IR wavelengths.

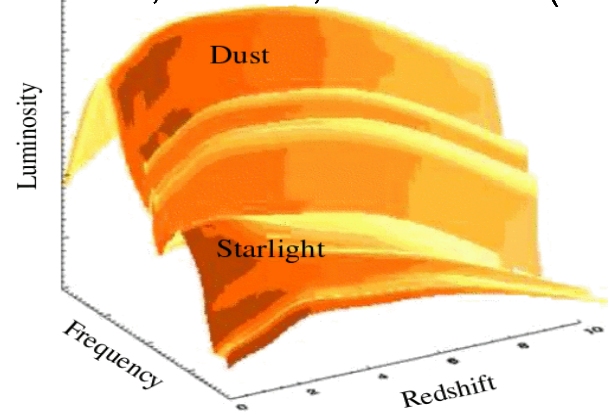
- *Why is it important?*

➢ Contains information about the evolution of matter in the universe: star formation history, dust extinction, light absorption and re-emission by dust, etc.

➢ Knowledge of the absorption effects due to EBL is necessary to infer the actual spectra of extragalactic gamma-ray sources.

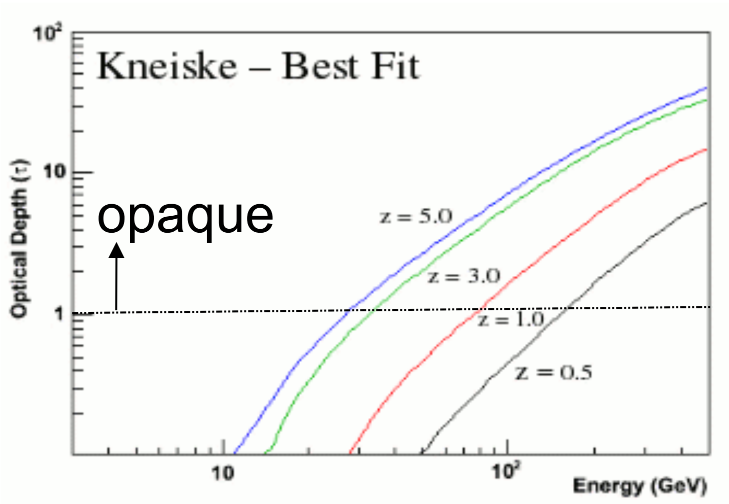
- Direct measurements of the EBL are very difficult because of foreground subtraction
- EBL **evolves** due to star formation, absorption and re-emission of light by dust

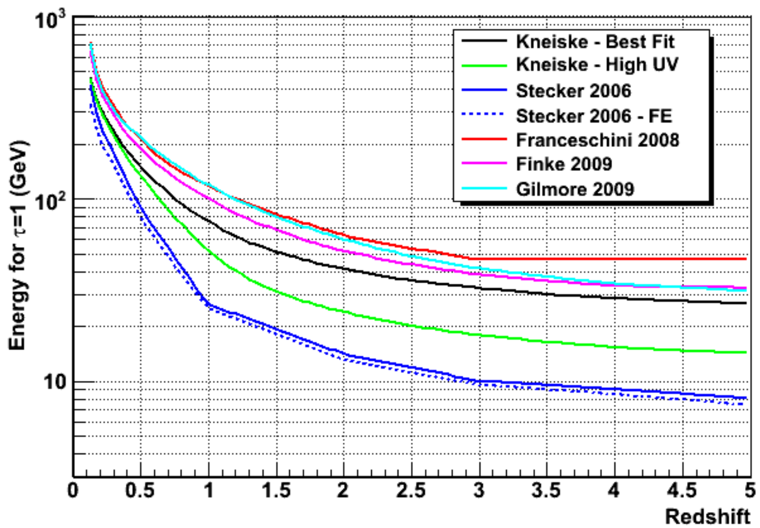




Primack, Bullock, Somerville (2005)

Optical Depth Predictions in the Fermi LAT energy Range



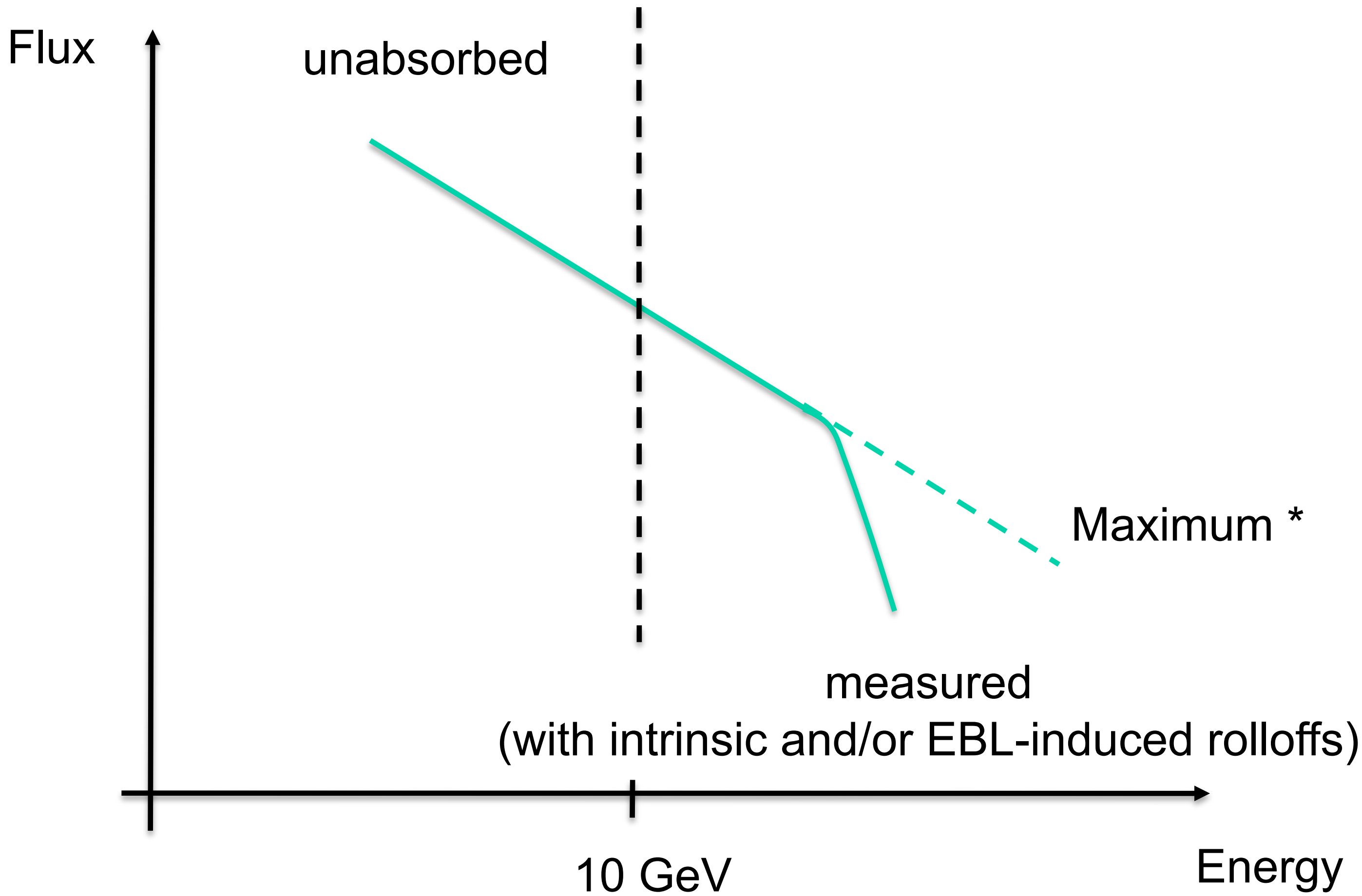


- At moderate to high redshifts (z~1-5) the optical depth is dominated by the UV part of the EBL for gamma-rays in the LAT energy range (i.e. it depends on the star formation rate and the effects of dust extinction), which is not well constrained. Measurement of the EBL at these redshifts is needed.
- The universe is "optically thin" to γ-rays with energy below ~ 10 GeV out to redshift z ~ 3 (z >~ 5 for some models)
- Gamma-ray instruments with a threshold much lower than ~100 GeV are required to probe the EBL at cosmological distances (z >~ 1).
- **Models make distinguishable predictions**

The Impact of Fermi on EBL Studies

- In general, Fermi's improved performance with respect to EGRET is allowing us to:
  - Study of the previously unexplored region 10 GeV < E < 100 GeV, where EBL attenuation is relevant for high-redshift sources
  - Work with a larger sample of blazars and – for the first time - a few GRBs
- Relevant to EBL studies:
  - For the relevant redshifts no attenuation is expected for γ-rays with energy below 10 GeV, thus EBL attenuation doesn't limit Fermi's ability to detect distant sources.
  - Fermi-detected sources are distributed over a wide range of redshifts (z~0-4), thus Fermi is sensitive in the energy range where EBL evolution is relevant.

EBL effects on Fermi spectra



* Assuming that there are no extra spectral components

Requirements for EBL Studies with Fermi

- Large sample of sources with:
  - Redshift z > 0.5, with reliable determination
  - High fluxes
    - With sufficient high-energy photons (E > 10 GeV) that can be reliably associated with the source
  - Solid understanding/expectations of their intrinsic spectrum in order to avoid biases (intrinsic rolloffs due to intrinsic absorption, or particle distributions, etc.)

- However, in the first two years of Fermi operations we have learned that:
  - FSRQs (which are the high-redshift sources) have steep spectral indices (Γ~2.5) and they present intrinsic breaks at 1-10 GeV.
  - Likewise for LBLs (with slightly harder spectra)
  - HBLs have hard spectra and no apparent breaks, however they are low-redshift sources

EBL Studies with Fermi after year One
ApJ accepted, arxiv: 1005.0996

For the results presented next we use:

- Data collected during the first year of the mission and sources in the first Fermi catalog 1LAC
- Photons with E > 100 MeV
- P6_V3_DIFFUSE instrument response functions

We use several methods:

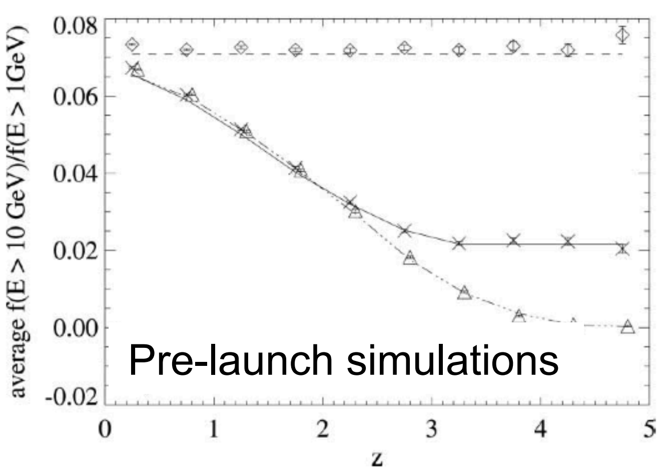
- Flux – Ratio F(E> 10 GeV) / F (E > 1 GeV)
- Highest energy photons
- Likelihood ratio test
- Opacity upper limits

Flux-Ratio Method

To quantify the attenuation of γ-ray emission by EBL absorption the following ratio is calculated:

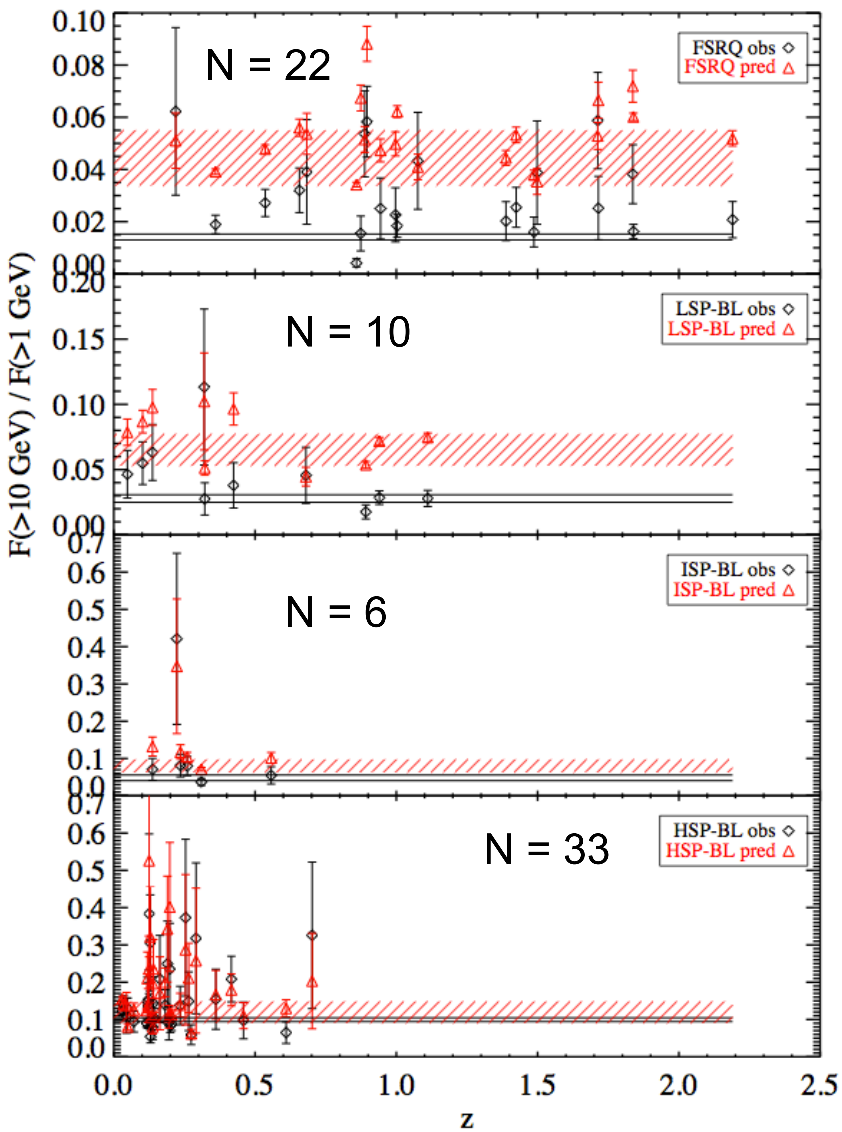
$$\boxed{\frac{F\,(E > 10\,GeV)}{F\,(E > 1\,GeV)}}$$

Chen, Reyes & Ritz (2004)



- F(E>10 GeV) is sensitive to EBL attenuation for 1<z<5 given the expected EBL density.
- Simple to calculate. The ratio is independent of blazar brightness
- Original paper assumed single luminosity function and spectral index distribution for all blazar subtypes, **which Fermi has clearly shown is inadequate**. Now the different blazar classes are analyzed separately.

Flux Ratio - Results



- No significant trend with redshift is observed (all distributions are consistent with a constant.

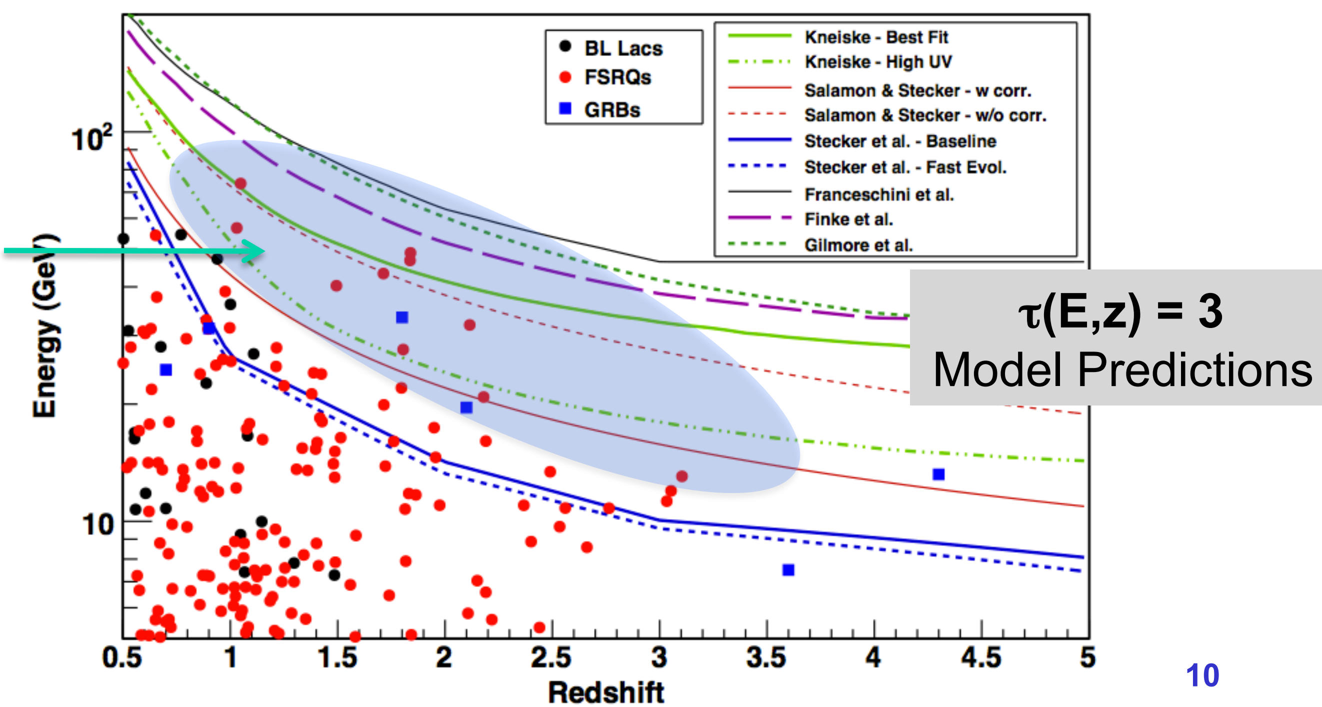
- HBLs detected so far by Fermi are low-redshift sources (z < ~ 0.5) where no EBL attenuation is expected below ~ 200 GeV

High Energy Photons

- Using LAT AGN catalog, we find the highest energy photon that can be associated with the source given the point-spread-function (68% containment).

- We check that the result doesn't change when using the most stringent "extra-diffuse" selection cuts (Abdo et al. 2010, Phys. Rev. Lett., 104, 101101), or a modified high-energy point-spread-function (arxiv:0912.3855) that provides a better match to the data

These high-energy photons populate a region heavily suppressed according to some EBL models.



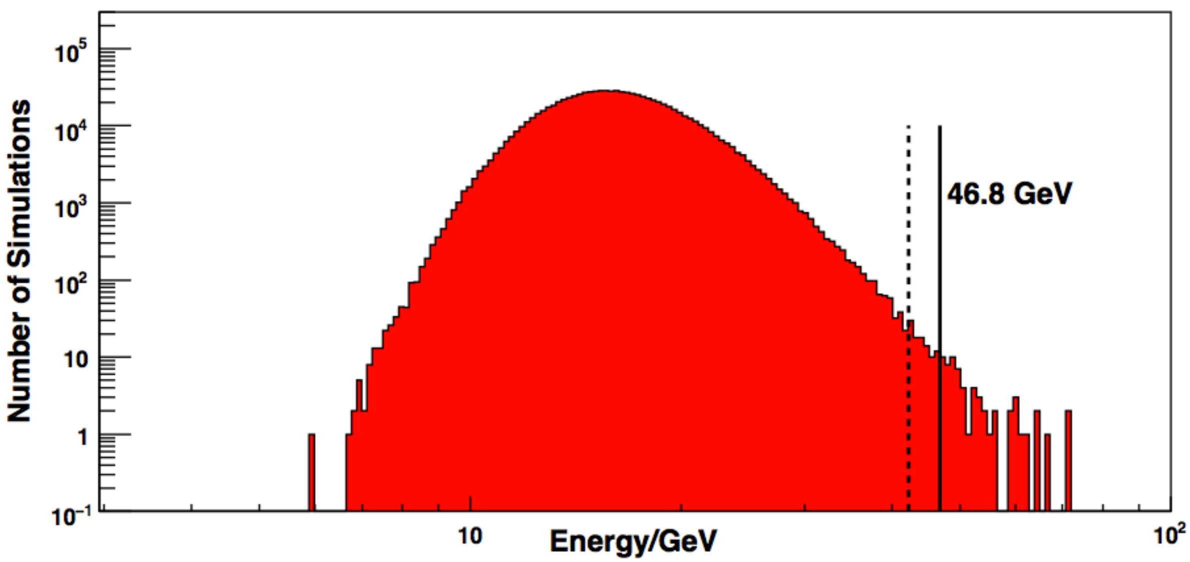
High Energy Photons

Source	z	E_{max} (GeV)	Conv. Type	$\Delta E/E$	68% radius	Separation	Chance Probability
J1147-3812 (PKS 1144-379)	1.05	73.7	*front*	10.7 %	0.054°	0.020°	7.0×10^{-4}
J1504+1029 (PKS 1502+106)	1.84	48.9	*back*	5.4%	0.114°	0.087°	5.6×10^{-3}
		35.1	*back*	12.4%	0.117°	0.086°	9.8×10^{-3}
		23.2	*front*	7.2%	0.072°	0.052°	5.6×10^{-3}
J0808-0751 (PKS 0805-07)	1.84	46.8	*front*	9.7%	0.057°	0.020°	1.5×10^{-3}
		33.1	*front*	5.9%	0.063°	0.038°	2.7×10^{-3}
		20.6	*front*	8.9%	0.075°	0.029°	6.9×10^{-3}
J1016+0513 (CRATES J1016+0513)	1.71	43.3	*front*	11.4%	0.054°	0.017°	1.2×10^{-3}
		16.8	*front*	6.3%	0.087°	0.035°	8.2×10^{-3}
		16.1	*front*	7.6%	0.084°	0.018°	8.2×10^{-3}
J0229-3643 (PKS 0227-369)	2.11	31.9	*front*	10.7%	0.060°	0.035°	1.7×10^{-3}
GRB 090902B	1.82	33.4	*back*	10.5%	0.117°	0.077°	6.0×10^{-8}
GRB 080916C	4.24	13.2	*back*	11.6%	0.175°	0.087°	2.0×10^{-6}

- Some sources have several constraining high energy photons
- Uncertainty in energy scale is ~10% on average
- Probability that a photon from the diffuse background is mistakenly associated with the source is small for blazars, negligible for GRBs.

MC Simulations

- What is the probability P_{HEP} that the highest energy photon detected by Fermi has energy Eo given an EBL model? (and extrapolating to high energies the unabsorbed part of the spectrum)



Distribution of high-energy photons from ~800000 simulations of PKS 0805-07 using Stecker's baseline EBL model.

$$P_{HEP} = \frac{\#\ \text{events}\ E > Eo}{\#\ \text{total}}$$

Since the probability that the high-energy photon is a background event is not negligible, the actual probability that the EBL model is consistent with the observation is:

$$P = P_{bkg} + P_{HEP}\,(1 - P_{bkg})$$

Constraints from High Energy Photons

Although we consider all models in the literature, we find that our observations only constrain Stecker 06's EBL model, since it predicts the strongest EBL attenuation.

Source	z	Energy (GeV)	P_{bkg}	HEP method applied to Stecker 06 P_{HEP}	$P_{rejection}$	HEP Rejection Significance
J1147-3812	1.05	73.7	7.0×10^{-4}	1.2×10^{-4}	8.1×10^{-4}	$3.2\ \sigma$
J1504+1029	1.84	48.9	5.6×10^{-3}	6.7×10^{-5}	5.7×10^{-3}	
		35.1	9.8×10^{-3}	6.8×10^{-3}	1.7×10^{-2}	
		23.2	5.6×10^{-3}	1.8×10^{-1}	1.9×10^{-1}	
				Combined $P_{rej} = 1.7 \times 10^{-5}$		$4.1\ \sigma$
J0808-0751	1.84	46.8	1.5×10^{-3}	1.9×10^{-4}	1.7×10^{-3}	
		33.1	2.7×10^{-3}	3.7×10^{-3}	6.4×10^{-3}	
		20.6	6.9×10^{-3}	2.5×10^{-1}	2.6×10^{-1}	
				Combined $P_{rej} = 2.8 \times 10^{-6}$		$4.5\ \sigma$
J1016+0513	1.71	43.3	1.1×10^{-3}	5.4×10^{-4}	1.6×10^{-3}	
		16.8	8.2×10^{-3}	4.9×10^{-1}	4.9×10^{-1}	
		16.1	8.2×10^{-3}	6.5×10^{-1}	6.5×10^{-1}	
				Combined $P_{rej} = 5.3 \times 10^{-4}$		$3.3\ \sigma$
J0229-3643	2.11	31.9	1.7×10^{-3}	8.9×10^{-5}	1.8×10^{-3}	$2.9\ \sigma$
GRB 090902B	1.82	33.4	2×10^{-6}	2.0×10^{-4}	2.0×10^{-4}	$3.7\ \sigma$
GRB 080916C	4.24	13.2	8×10^{-8}	6.5×10^{-4}	6.5×10^{-4}	$3.4\ \sigma$

- The "baseline" Stecker 06 model is significantly constrained by different independent observations.
- The "fast evolution" model of Stecker 06 is even more constrained since it predicts higher opacities
- The rejection power of the technique is limited by P_{bkg} which depends on the size of the search region around each source (defined *a priori*).

Likelihood Ratio Test

In this method we compare the likelihood (L) of two hypothesis:

- The source spectrum is described by the unabsorbed flux (derived from the E < 10 GeV spectrum) that is convolved with the EBL attenuation predicted by the model under consideration

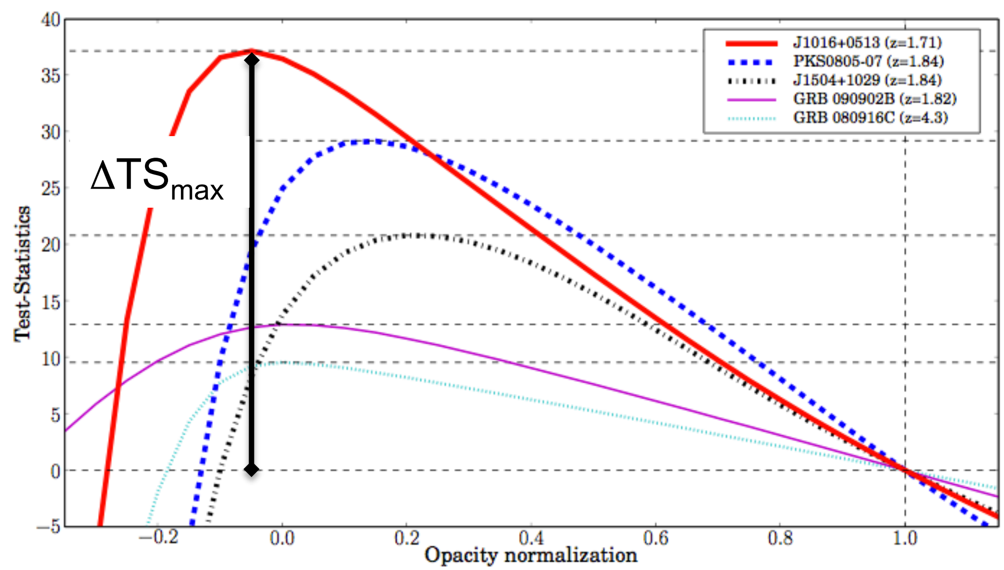
$$\mathrm{Exp}\,(-\tau_{model})\times F\,(E)$$

- Same as above but with a scale factor α for the the optical depth τ

$$\mathrm{Exp}\,(-\alpha\,.\,\tau_{model})\times F\,(E)$$

- Following Wilk's theorem, the test statistic TS = -2 x (log (L_0) – log(L_1)) is distributed as χ_1^2 and provides a measure of the rejection significance of the null hypothesis (α = 1).

Source	Rej. Significance
J1147-3812	3.7 σ
J1504+1029	4.6 σ
J0808-0751	5.4 σ
J1016+0513	6.0 σ
J0229-3643	3.2 σ
GRB 090902B	3.6 σ
GRB 080916C	3.1 σ



Multi-trial and Combined Probabilities

- A large number of LAT blazars and GRBs was considered while searching for high energy photons. The effect of multiple trials should be considered

$$P_{post} = 1 - (1 - P_{pre})^{1/N\_trials}$$

- Of the ~700 sources in the LAT AGN catalog, about ~200 (plus a handful of LAT-detected GRBs) have high enough redshift to be useful for EBL analysis.

Nevertheless, the constraints from the different sources can be combined. The rejection significance for Stecker 06's "baseline" model:

  - Using Fisher's method (Fisher 1925) on the high-energy photons set
    ➔ 8.9 σ (7.7 σ w/o GRBs)
  - Adding the likelihood profiles to calculate an overall ΔTS_{max}
    ➔ 11.4 σ

Stecker 06's "baseline" model:

Source	Pre	Post
J1147-3812	3.7 σ	2.0 σ
J1504+1029	4.6 σ	3.3 σ
J0808-0751	5.4 σ	4.4 σ
J1016+0513	6.0 σ	5.1 σ
J0229-3643	3.2 σ	1.2 σ
GRB 090902B	3.6 σ	1.9 σ
GRB 080916C	3.1 σ	1.0 σ

- "Baseline" and "fast evolution" EBL models by Stecker et al. 06 are rejected with high significance
- Other models are not significantly constrained even after combining different sources

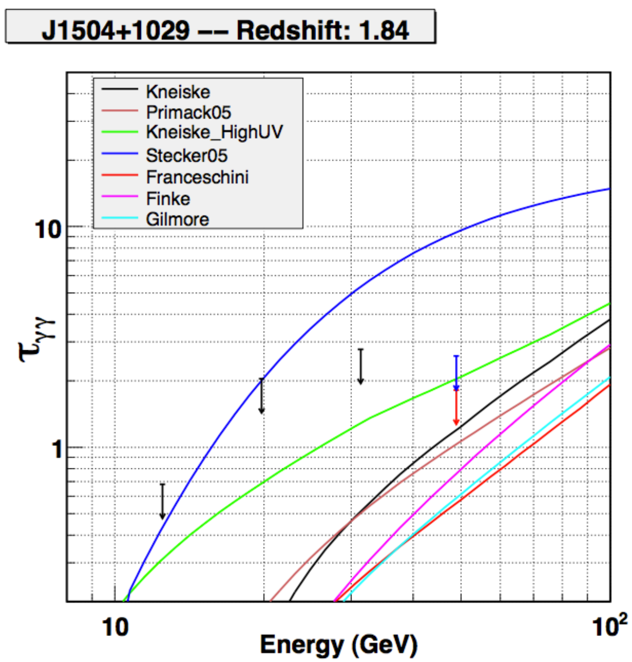
Opacity Upper Limits

In the absence of intrinsic hardening of the source spectrum at high energies, the intrinsic source flux F_{int} (E) is bounded by the flux extrapolated from low energies (E < 10 GeV) where EBL attenuation is negligible

$$F_{int} = \exp[\,\tau(E,z)\,] \times F_{obs} < F_{ext}$$

and thus,

$$\tau(E,z) < \mathrm{Ln}\,(F_{ext}/F_{obs})$$



See Silvia Raino's poster for a complete description of the method and its results.

Interpretation and Conclusions

- The highest energy photons from distant sources detected by Fermi probe the UV EBL, which is closely related to the star formation rate and its evolution over cosmic time.

- The current results disfavor a UV background intensity at the level predicted by Stecker et al. 2006. The high flux predicted by this model at UV wavelengths is due in part to the absence of absorption of light by dust in star-forming regions.

- All other EBL models are of such low UV flux that they are not constrained by the current data. Future work with improved methods and a larger data set may result in better constraints for those models, which are more directly tied to an assumed star formation rate.

- Together with the results from VHE instruments (Aharonian et al. 2006, Mazin & Raue 2007), gamma-ray observations have shown that the EBL intensity is lower than predicted by the extreme models.

BACKUP SLIDES

Flux Ratio

Among the AGN sample described in Section 2.1 we find that 237 FSRQs, 110 BL Lacs and 25 other AGNs are clean[6] 1LAC associations with known redshift and detectable fluxes at energies ≥ 1 GeV. There are 30 LSP-, 18 ISP- and 60 HSP- BL Lacs in this sub-sample.

Of these AGN, only 22 FSRQs, 49 BL Lacs, and 1 other AGN have flux detections rather than upper limits above 10 GeV, including 10 LSP-, 6 ISP-, and 33 HSP-BL Lacs. For each of these BL Lacs and FSRQs, we calculated the ratio between the fluxes above 10 GeV and 1 GeV and their corresponding statistical errors following Chen et al. (2004).

Blazar type	Num	Γ	ratio (pred)	mean ratio (obs)	red. χ^2	prob
FSRQ	22	2.3 ± 0.1	0.04 ± 0.01	0.014 ± 0.001	4.38	1.8×10^{-10}
LSP-BL	10	2.2 ± 0.1	0.07 ± 0.01	0.028 ± 0.003	1.65	0.11
ISP-BL	6	2.1 ± 0.1	0.08 ± 0.02	0.048 ± 0.008	1.86	0.11
HSP-BL	33	1.9 ± 0.1	0.12 ± 0.03	0.100 ± 0.005	1.29	0.13

Table 1: Spectral indices, mean predicted and observed flux ratios, and reduced χ^2 and probability for blazar sub-populations