Constraining the Opacity of the Universe with Fermi LAT Blazars

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The Extragalactic Background Light

- *What is it?*

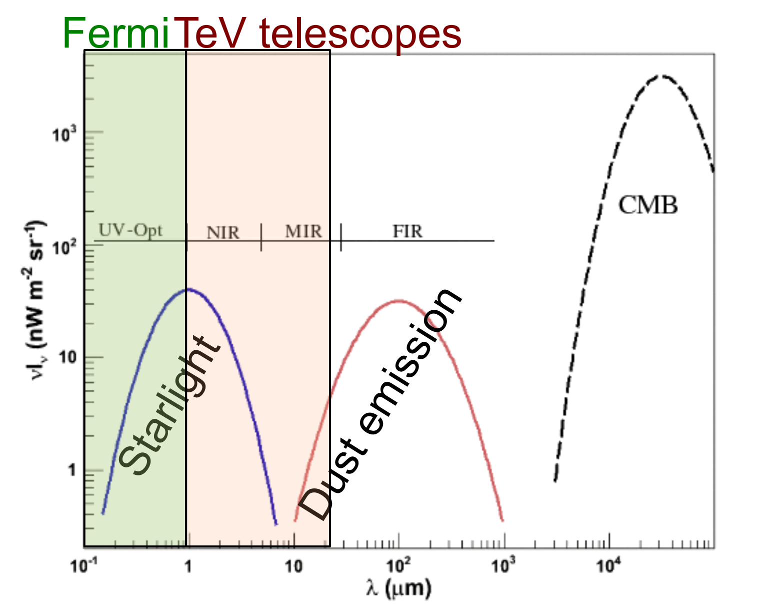
➢ Accumulation of all energy releases in the form of electromagnetic radiation. It includes everything but CMB and the foreground emission from anything local (Milky Way, Solar System, etc.). For gamma-ray astronomy, we are interested in the UV to IR wavelengths.

- *Why is it important?*

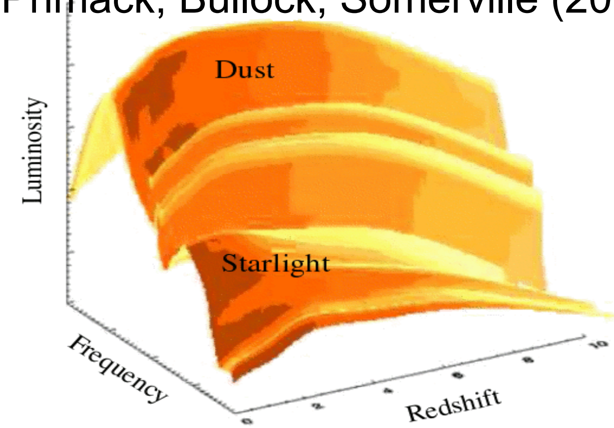
➢ Contains information about the evolution of matter in the universe: star formation history, dust extinction, light absorption and re-emission by dust, etc.

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

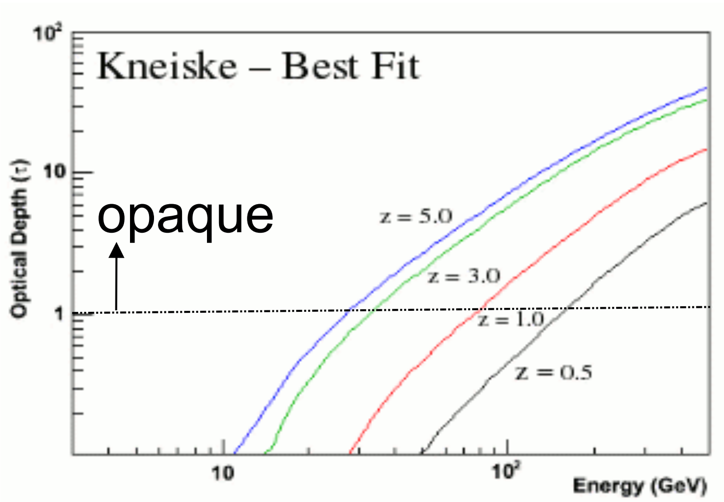
- Direct measurements of the EBL are very difficult because of foreground subtraction
- EBL **evolves** due to star formation, absorption and re-emission of light by dust

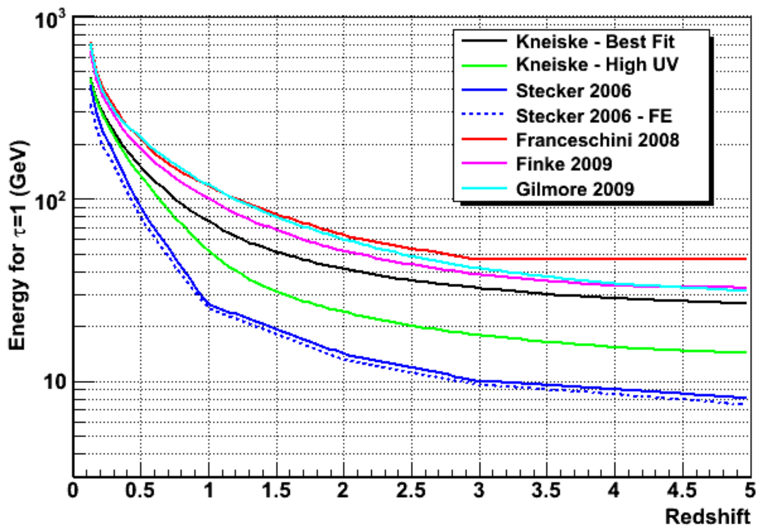


Primack, Bullock, Somerville (2005)



Optical Depth Predictions From EBL Models





- ➢ Models make distinguishable predictions
- ➢ The universe is "optically thin" to γ-rays with energy below ~ 10 GeV
- ➢ 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.
- ➢ Gamma-ray instruments with a threshold much lower than ~100 GeV are required to probe the EBL at cosmological distances (z >~ 1).

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
  - Have a better understanding of blazars over time
- Relevant to EBL studies:
  - No attenuation is expected for γ-rays with energy below 10 GeV, therefore EBL attenuation doesn’t limit Fermi's ability to detect blazars at high redshift.
  - Fermi-detected blazars are distributed over a wide range of redshifts (z~0-3), thus Fermi is sensitive to the evolution of the EBL.

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 year 1 of Fermi we have learned that:
  - FSRQs (which are the high-redshift sources) have steep spectral indices (Γ~2.4) 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

For the results presented next we use:

- Data collected during the first 11 months of the mission
- Photons with E> 100 MeV
- P6_V3_DIFFUSE instrument response functions
- The sources from the 1^{st} year Fermi-LAT AGN Catalog

We use two methods:
- Flux – Ratio F(E> 10 GeV) / F (E > 1 GeV)
- Highest energy photons

Flux-Ratio Method

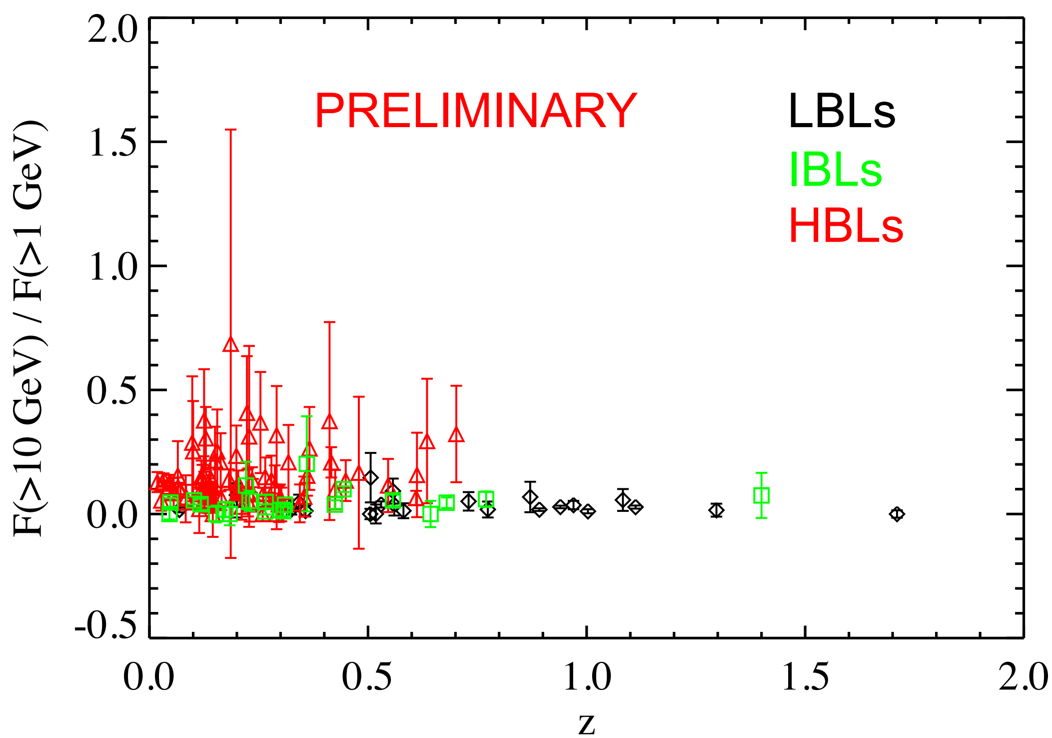
To quantify the attenuation of γ-ray emission by EBL absorption the following ratio is calculated:

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

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



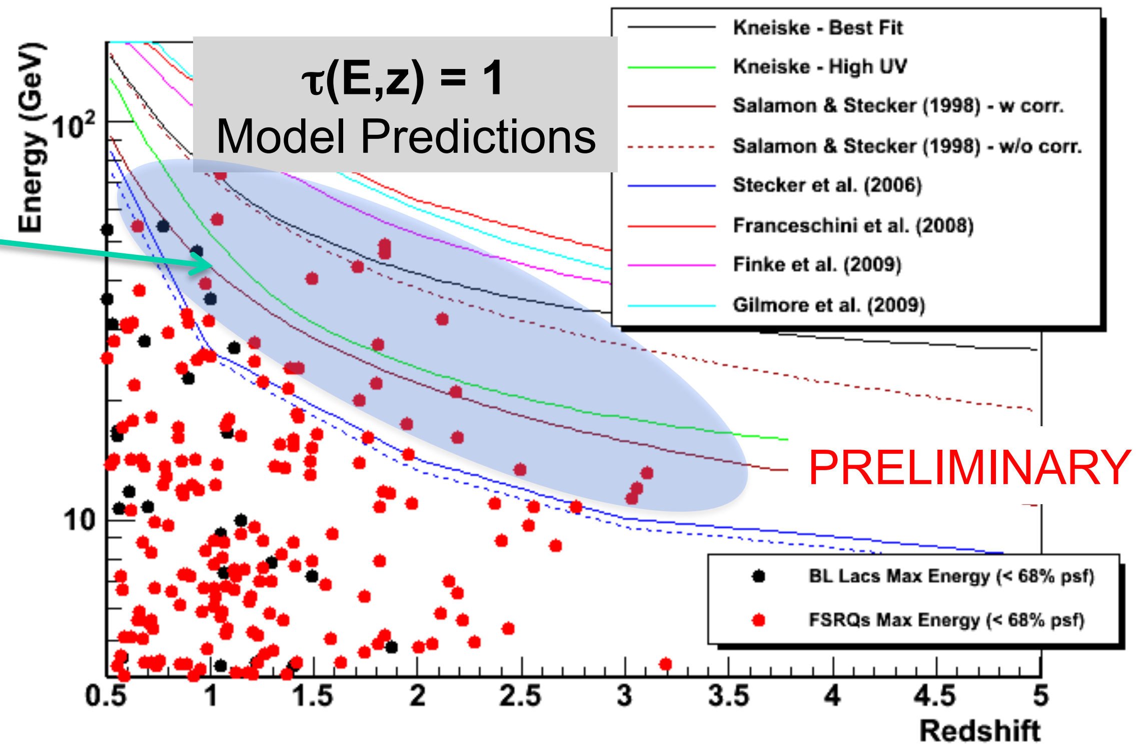
- HBLs are easily distinguishable from the other subclasses. They have the larger flux ratios.
- No significant trend with redshift is observed (all distributions are consistent with a constant.
- HBLs detected so far by Fermi are low-redshift sources (z < ~ 0.5) where no EBL attenuation is expected 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 (M. Ackerman's talk), or the modified high-energy point-spread-function (see T. Burnett's poster)

These high-energy photons are starting to probe regions excluded by some EBL models.



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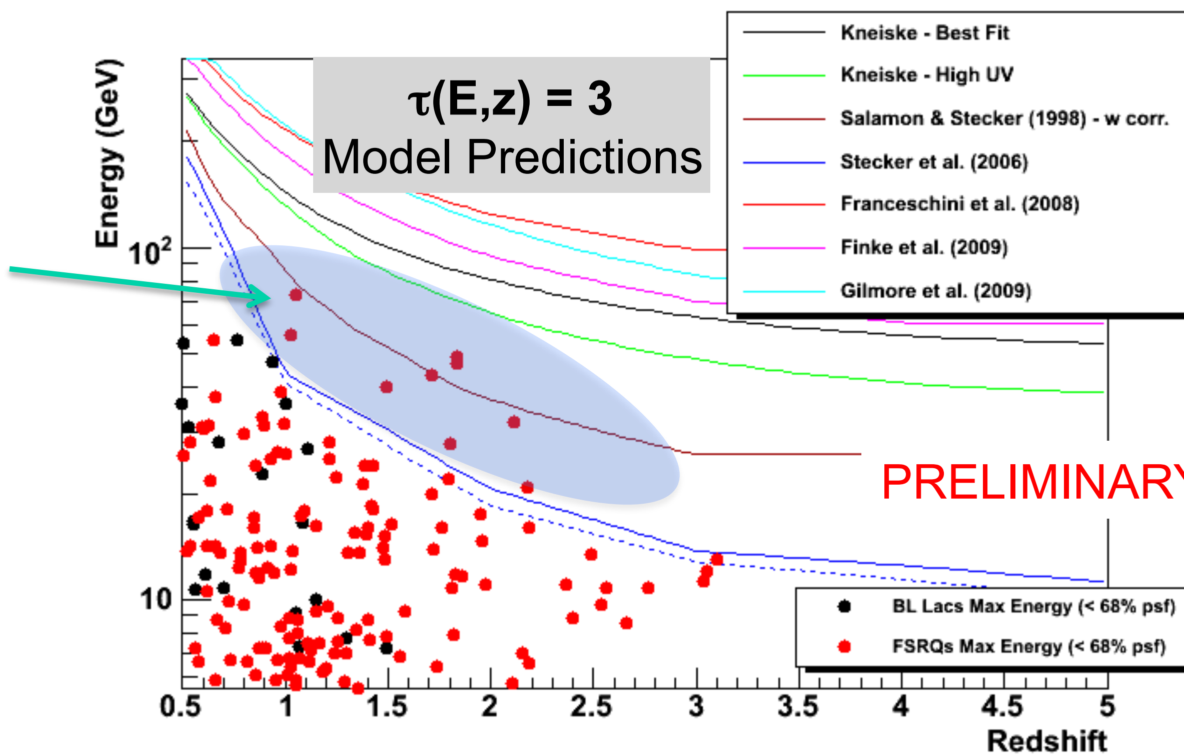

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Source	Redshift	Energy (GeV)	Conv Type	68% rad	Prob
J1147-3812	1.05	73.69	front	0.055	4.E-03
J0808-0751	1.84	46.77	front	0.058	4.E-03
J1016+0513	1.71	43.27	front	0.055	4.E-03
BZQ J1408-0752	1.49	40.27	front	0.056	4.E-03
J0229-3643	2.11	31.93	front	0.061	5.E-03
J1504+1029	1.84	48.9	back	0.116	0.018
J1012+2439	1.81	27.61	back	0.124	0.02
J0539-2839	3.1	13.04	back	0.178	0.04

Prob = Probability of random association with a photon from the diffuse background

Constraints from High Energy Photons

The flux observed at high energies is calculated based on the highest energy photon according to:

$$F_{obs}(E_{max}) = 1 / [\delta E \text{ Exposure}(E_{max}, \Delta t)]$$

We assume that the intrinsic flux Fint (Emax) cannot be significantly higher than the value extrapolated from lower energies Fmax (Emax) where EBL attenuation is null:

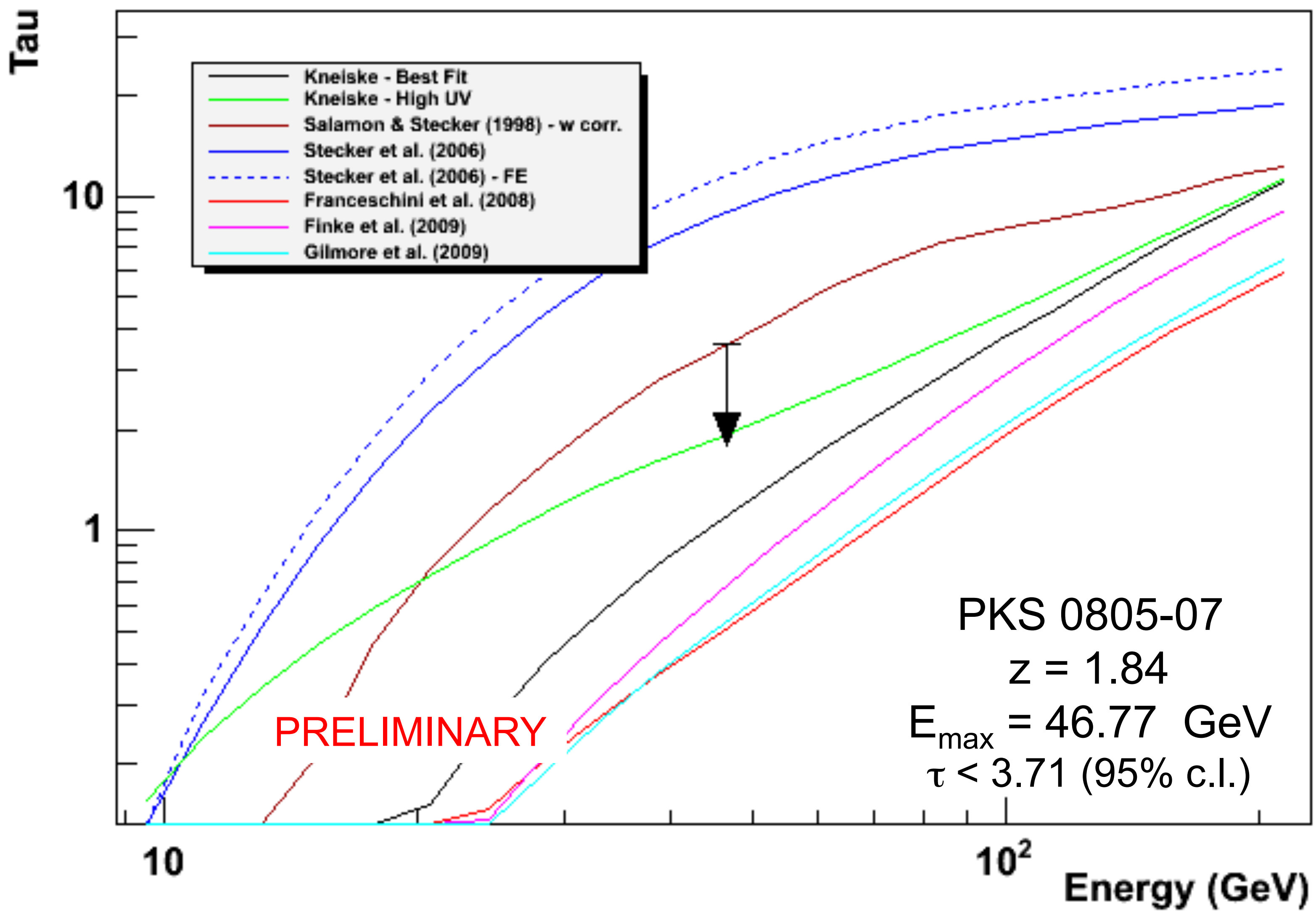
$$F_{int} = \exp [\tau(E,z)] \times F_{obs} < F_{max}$$

and thus,

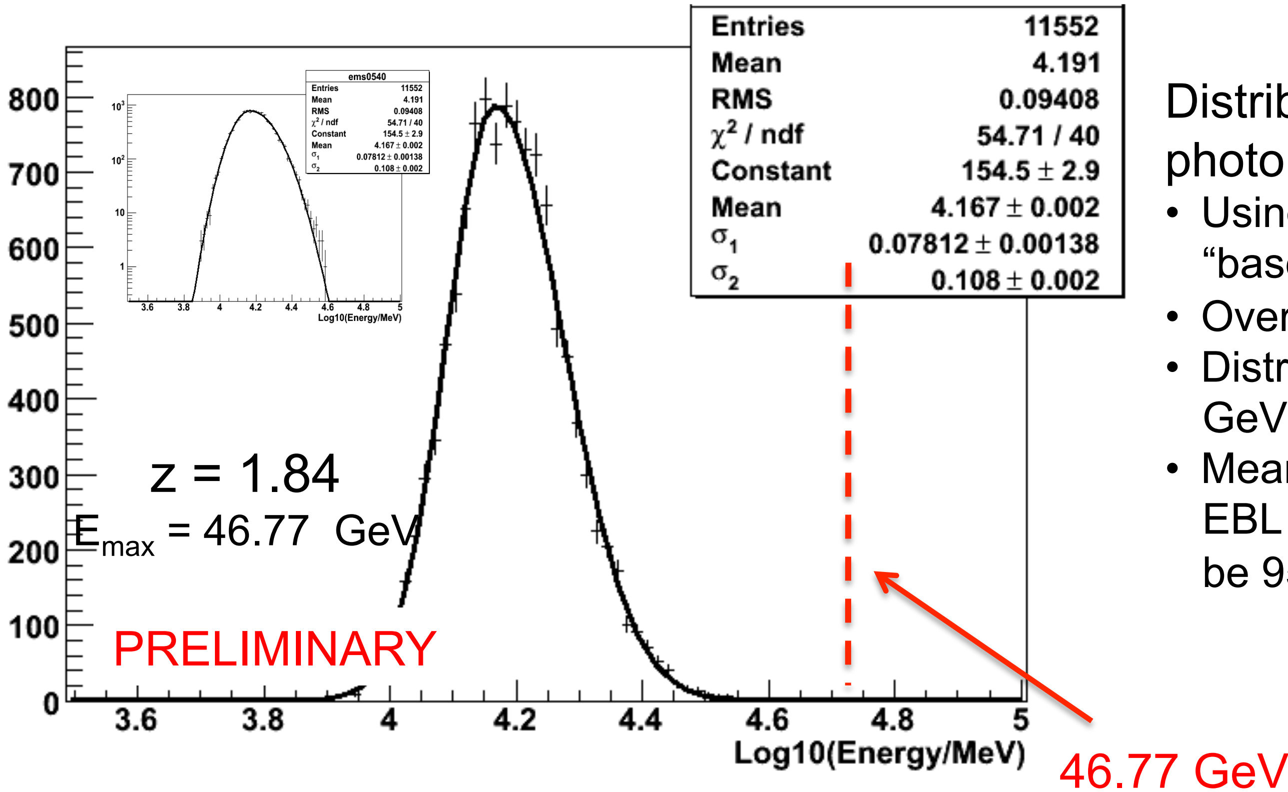
$$\tau(E,z) < \mathrm{Ln} (F_{max}/F_{obs})$$

This method was originally proposed by Soeb Razzaque and colleagues at NRL.

Constraints from High Energy Photons



MC Simulations



Distribution of highest energy photons from MC Simulation:

- Using Stecker et al. 2006 "baseline" EBL model
- Over 11000 simulations
- Distribution's mean = 15.52 GeV
- Mean of distribution with no EBL attenuation effects would be 95.5 GeV (from sims)

For this source and EBL model the probability of having a high energy photon with energy 46.77 GeV or greater is **1.9 x 10^{-6}** (a **4.6** σ result)

Preliminary Results

Source	Redshift	Energy (GeV)	Tau Limit	Tau (Stecker)	Tau (Finke)
J1147-3812	1.05	73.69	1.94	7.13	0.59
J0808-0751	1.84	46.77	3.71	11.68	0.70
J1016+0513	1.71	43.27	2.64	8.96	0.51
J1408-0752	1.49	40.27	1.95	5.91	0.32
J0229-3643	2.11	31.93	1.38	10.23	0.38
J1504+1029	1.84	48.90	4.55	12.20	0.72
J1012+2439	1.81	27.61	2.20	8.78	0.29
J0539-2839	3.10	13.04	2.07	3.32	0.06

Here we compare the limits obtained with Fermi with a couple of EBL models from the literature:
Stecker et al. 2006 "fast evolution model". ApJ, 648, 774 (2006)
Finke et al. 2009, submitted to ApJ, arXiv:0905.1115

Conclusions

- Results from first year of Fermi data reject with high significance EBL models that predict large opacities in the 20-50 GeV energy range for distant sources

- Over time the methodology presented here will result in more constraining limits as more high-energy photons / sources are detected and a more precise knowledge of the spectra of the sources is achieved.