Fermi Large Area Telescope Constraints on the Gamma-ray Opacity of the Universe

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On behalf of the Fermi collaboration

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'IR-UV' Extragalactic Background Light

Why is it important?

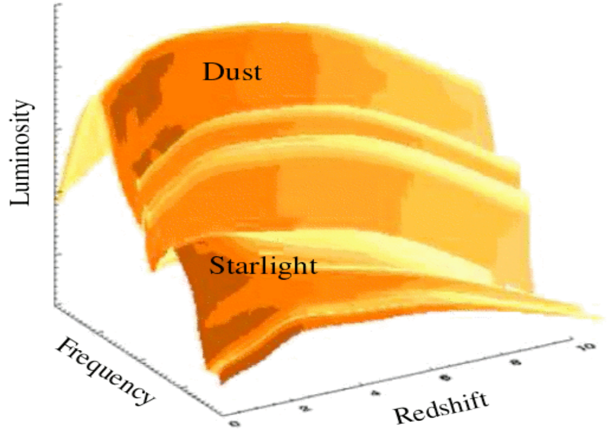
- Contains information about the evolution of matter in the universe: star formation history, dust extinction, light absorption and re-emission by dust, etc…
- Knowledge of the absorption effects due to EBL is necessary to infer the intrinsic spectra of extragalactic gamma-ray sources.

Measurement:

- Direct measurements of the IR-UV EBL are very difficult because of foreground subtraction
- Indirect measurement via observation of γ-ray attenuation due to pair production:

$$\gamma_{ebl} + \gamma_{\gamma\text{-ray}} \rightarrow e^- + e^+$$

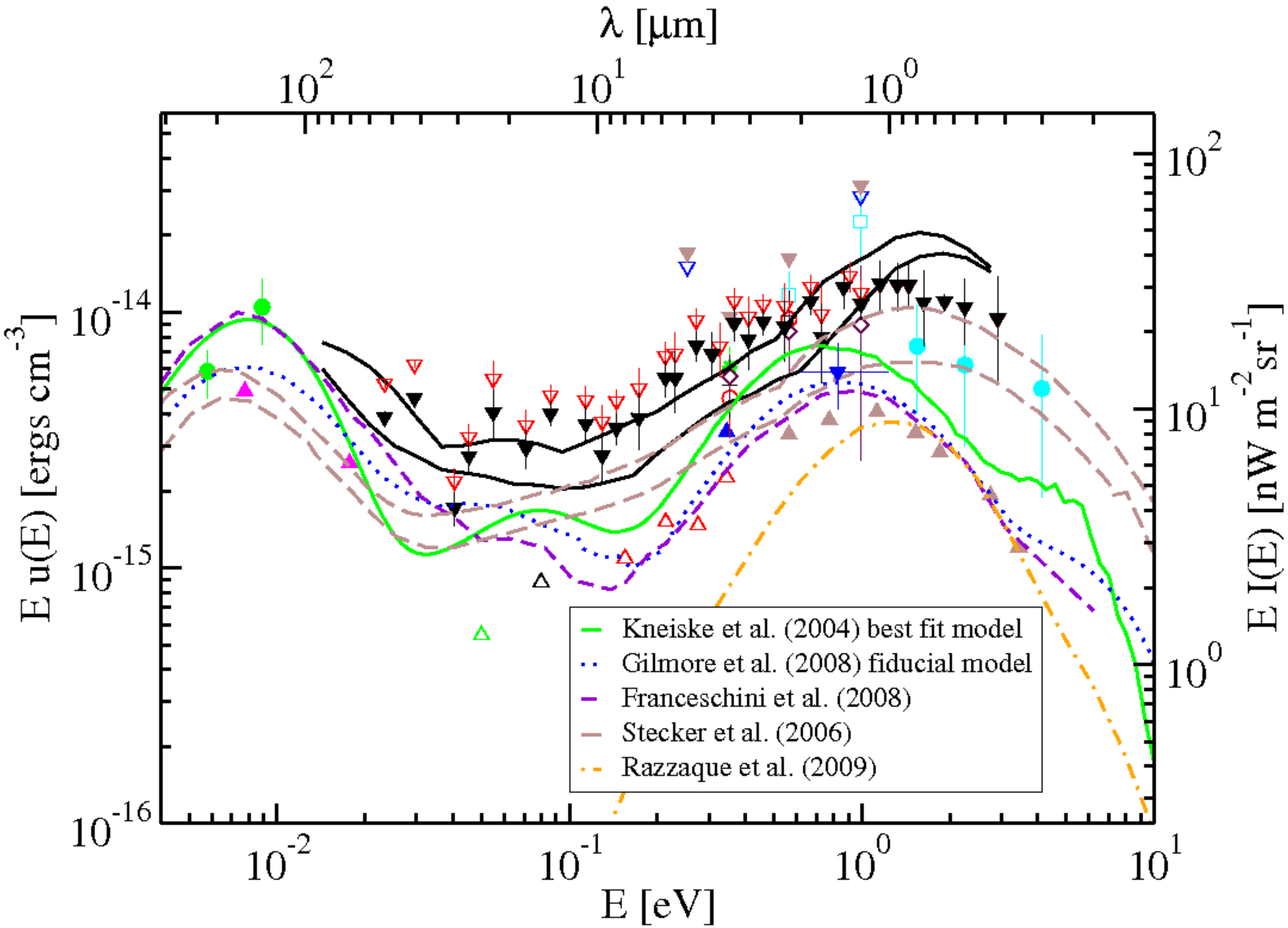
- The universe is optically thin below ~10 GeV
- gamma-ray astronomy sensitive to the IR-UV wavelengths of the EBL



Primack, Bullock, Somerville (2005)

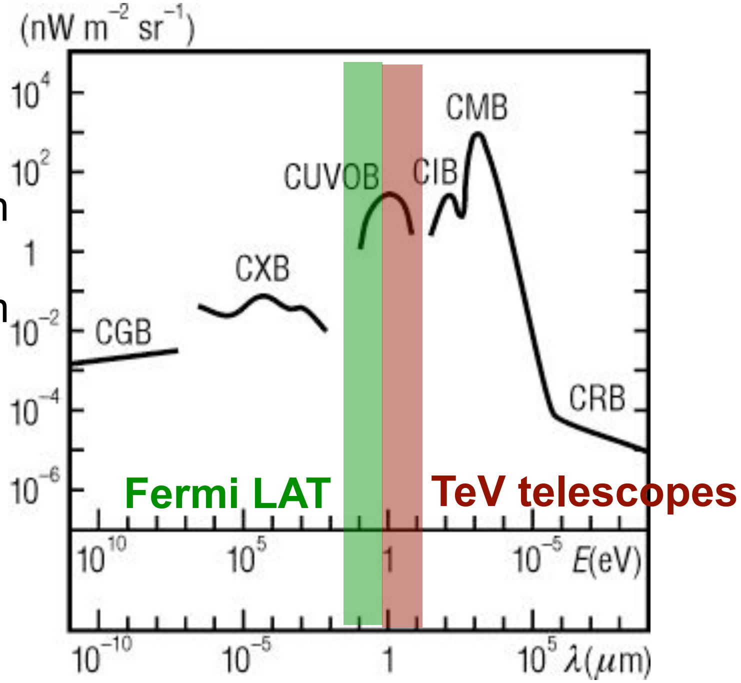
- EBL evolves due to star formation, absorption and re-emission of light by dust

Direct Observational Constraints on EBL



Finke & Razzaque (2009)

Constraining IR-UV EBL with γ-ray astronomy

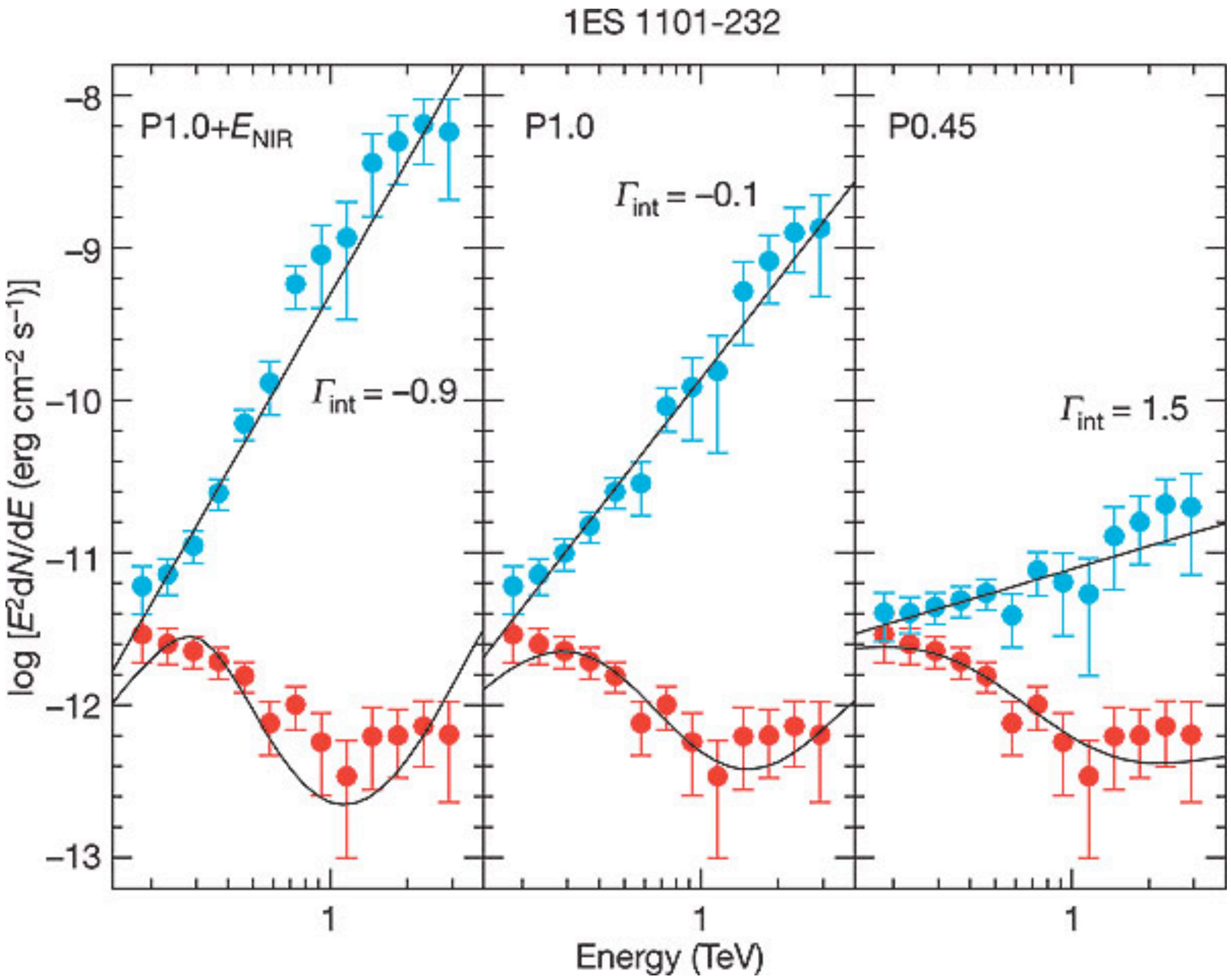


- *Fermi LAT: 20 MeV - 300 GeV*
  - ➢ sensitive to optical-UV: 10-300 x (1+z_{int}) nm (with z_{int} redshift where the pair production occurs)
  - ➢ Access to the unabsorbed part of the spectrum (<10 GeV):
    1) information on intrinsic spectrum of the source
    2) Possibility to detect high redshift sources
  - ➢ Capacity to probe EBL as a function of redshift

- *Air Cherenkov Telescopes (ACT): >100 GeV*
  - ➢ sensitive to optical-IR: >500 x (1+z_{int}) nm constraint (Constraints on IR)
  - ➢ EBL attenuation limits the capacity of these instruments to observe high redshift sources

- *AGNs and GRBs are prime sources for such study*

Constraints on Local EBL from TeV Observations

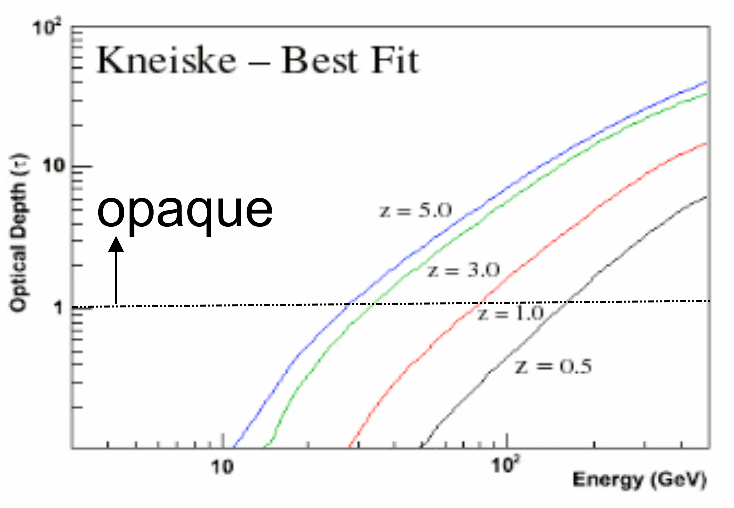


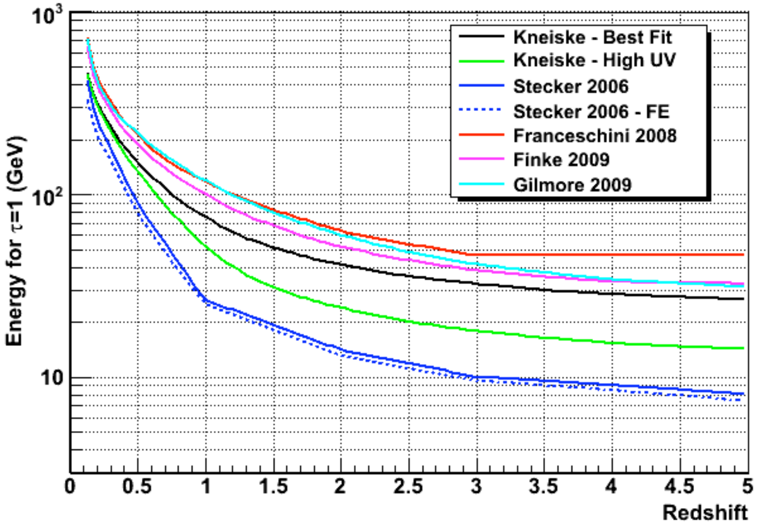
Aharonian et al. (2006)

EBL Models

- Three types of models:
- Backward Evolution
  - start with existing galaxy population and evolve backward in time
  - e.g. Stecker et al. (2006)
  - Problem: high-z galaxies very different from low-z galaxies
- Evolution inferred from Observations
  - e.g. Finke et al. (2009), Kneiske et al. (2004), Franceschini et al. (2008)
- Forward Evolution
  - start with cosmological initial conditions and model gas cooling, formation of galaxies including stars and AGN, feedback, dust absorption and re-emission
  - require semi-analytic models based on cosmological simulations
  - e.g. Somerville et al. (2008), Gilmore et al. (2009)
- All methods require modeling galactic SEDs.

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

- Fermi's improved performance with respect to EGRET allows us to:
    - **Study unexplored region 10 GeV < E < 100 GeV**, where EBL attenuation is relevant for high-redshift sources
    - **Larger sample** of blazars / GRBs (with z>0.5)
    - **Better understanding of intrinsic spectrum** in order to avoid biases (intrinsic rolloffs due to intrinsic absorption, particle distributions…)

- Relevant to EBL studies:
    - No attenuation below 10 GeV, therefore EBL attenuation doesn't limit Fermi's ability to **detect blazars/GRBs at high redshifts.**
    - Fermi-detected blazars are distributed over a wide range of redshifts (z~0-3), and GRBs are seen up to z~4.3. Therefore Fermi is **sensitive to the evolution of the EBL with redshift.**

- **What we have learned after 1 year with Fermi**:
    - FSRQs (which are the high-redshift sources) have steep spectral indices (Γ~2.4) and they present intrinsic breaks at 1-10 GeV (therefore not EBL associated).
    - Likewise for LSP-BLs (with slightly harder spectra)
    - HSP-BLs have hard spectra and no apparent breaks, however they are low-redshift sources
    - GRBs present strong evidence of additional component (GRB 090510, GRB 090902B).

Fermi LAT analysis

For the analysis presented next we use:

- **Energy>100 MeV** (effective area uncertain at lower energy)

- AGNs:
  - Data collected during the first 11 months of the mission
  - The sources from the 1st year Fermi-LAT AGN Catalog
  - - P6_V3_DIFFUSE instrument response function

- GRBs:
  - GRBs detected up to September 31st, 2010
  - P6_V3_TRANSIENT IRF (looser cut allowed by short time scales)

We use 4 different methods:

1. **Flux ratio** (search for redshift dependent EBL signature)
2. **Opacity UL** (UL in the opacity-redshift-energy phase space)
3. **Highest energy photons** (significance of rejection of EBL models)
4. **Likelihood method** (significance of rejection of EBL models)

Flux-Ratio Method

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

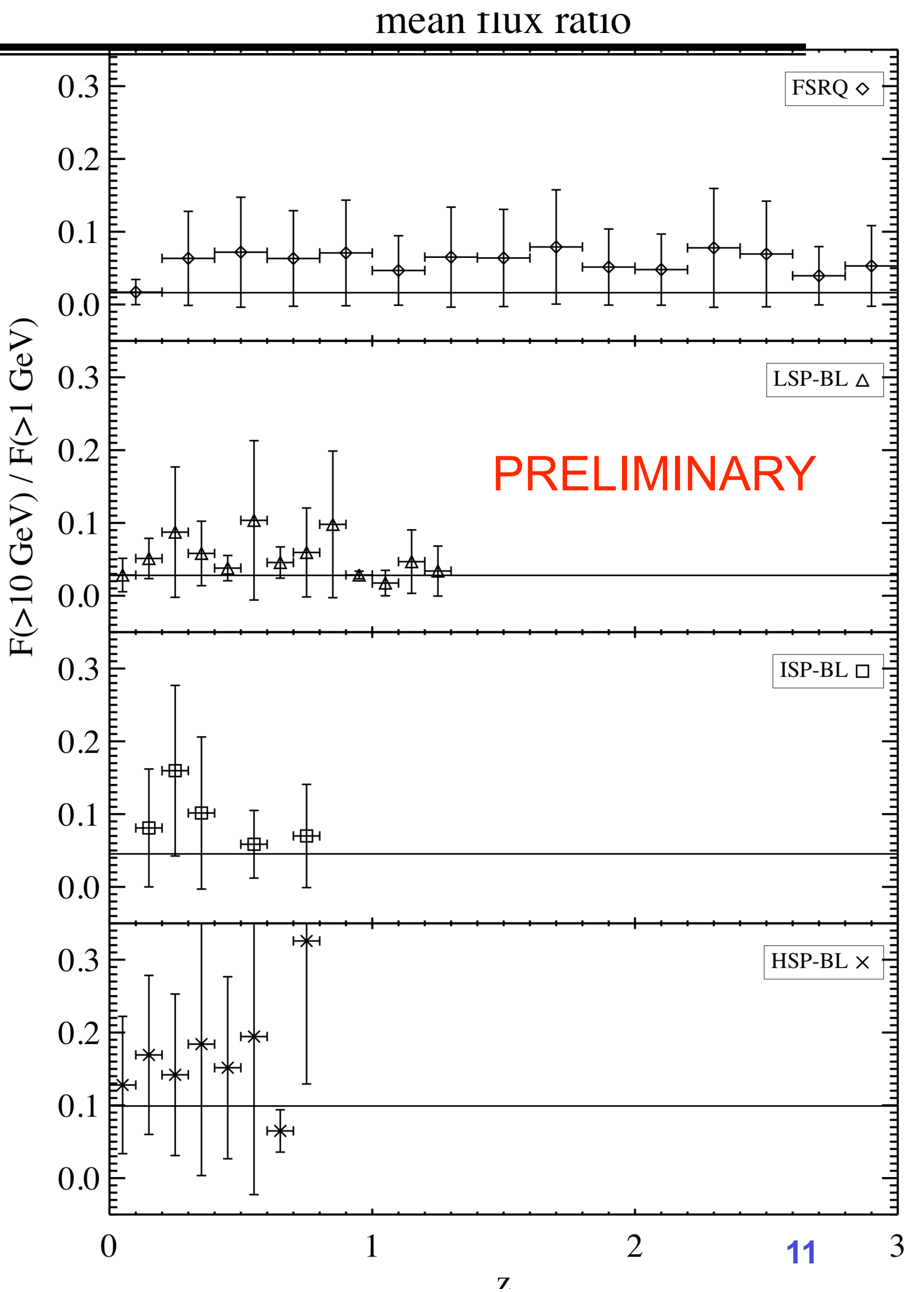
$$\boxed{\frac{F\,(E > 10\,GeV)}{F\,(E > 1\,GeV)}}$$

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

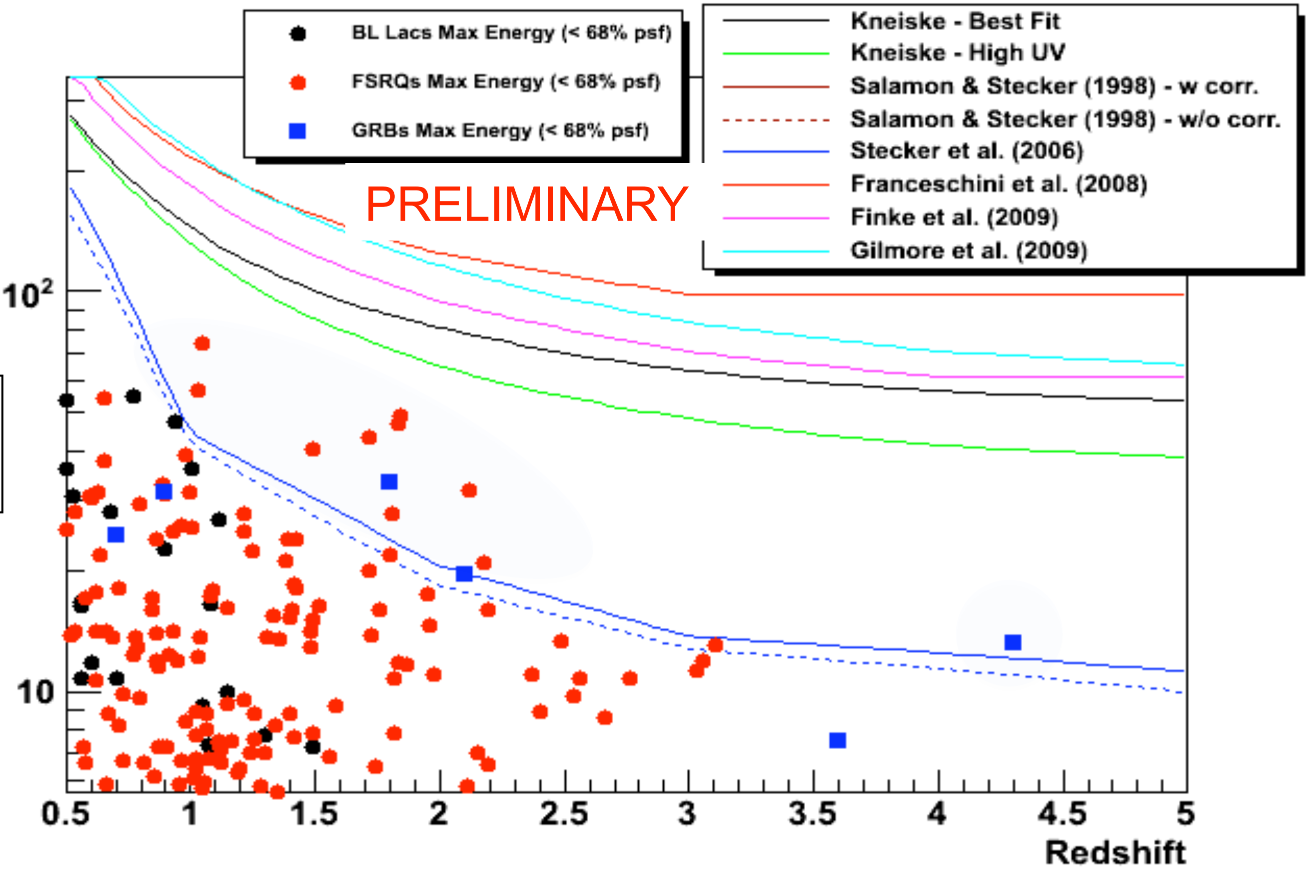
- Increasing flux ratio as a function of blazar class, from FSRQs through HSP-BLs.
- No significant trend with redshift is observed (all distributions are consistent with a constant).
- HSP-BLs detected so far by Fermi are low-redshift sources (z < ~ 0.5) where no EBL attenuation is expected below ~ 200 GeV.



High Energy Photons

- Constrain EBL models with sources with high energy emission
- Using LAT AGN catalog & LAT detected GRBs, we find the **highest energy photon** that can be associated with the source given the point-spread-function (68% containment radius).

$\tau(E,z) = 3$
Model Predictions



▨ **Region with HE photons starting to probe regions excluded by some EBL models -> need to investigate intrinsic spectrum of those particular sources**

High Energy Photons

➢ Individual probabilities of random association with a photon from the diffuse bkg are quite low.

PRELIMINARY

Source	z	Max observed energy	Conv. type	68% cont. radius (deg)	Separation (deg)	bkg probability
J0808-0751	**1.84**	**46.8 GeV (+5)**	**front**	**0.057**	**0.020**	**1.5e-3**
J1147-3812	**1.05**	**73.7 GeV**	**front**	**0.054**	**0.020**	**7.0e-4**
J1504+1029	**1.84**	**48.9 GeV (+6)**	**back**	**0.114**	**0.087**	**5.6e-3**
J1016+0513	**1.71**	**43.3 GeV (+2)**	**front**	**0.054**	**0.017**	**1.2e-3**
J0229-3643	**2.11**	**31.9 GeV**	**front**	**0.060**	**0.035**	**1.7e-3**
GRB 090902B	**1.82**	**33.4 GeV**	**back**	**0.117**	**0.077**	**6.0e-8**
GRB 080916C	**4.24**	**13.2 GeV**	**back**	**0.175**	**0.087**	**2.0e-6**

➢ GRB “bkg probability” much smaller (despite the larger ‘back’ PSF) as they are observed on much shorter time scales.

➢ The chance probability for all highest energy events associated with LAT sources leading to significant EBL constraints is extremely small.

UL in opacity-energy phase space

• Intrinsic spectrum is assumed to be the extrapolation of the low-energy part (<10 GeV) fitted with a PL or log-parabola where EBL attenuation is negligible.

• We assume that the intrinsic flux F_{int} (E) cannot be significantly higher than the value extrapolated from lower energies F_{max} (E) where EBL attenuation is null:

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

• The observed flux is evaluated from a likelihood method in the energy bin that contains the maximum energy photon (the entire energy range is divided in 4 bins/decade).

$$UL\tau_{(Emean,z)} \text{ (95\% c.l.)} = \text{Ln } (Fmax(E_{mean})/<Fobs>) + 2\sigma_{\tau}$$

where:

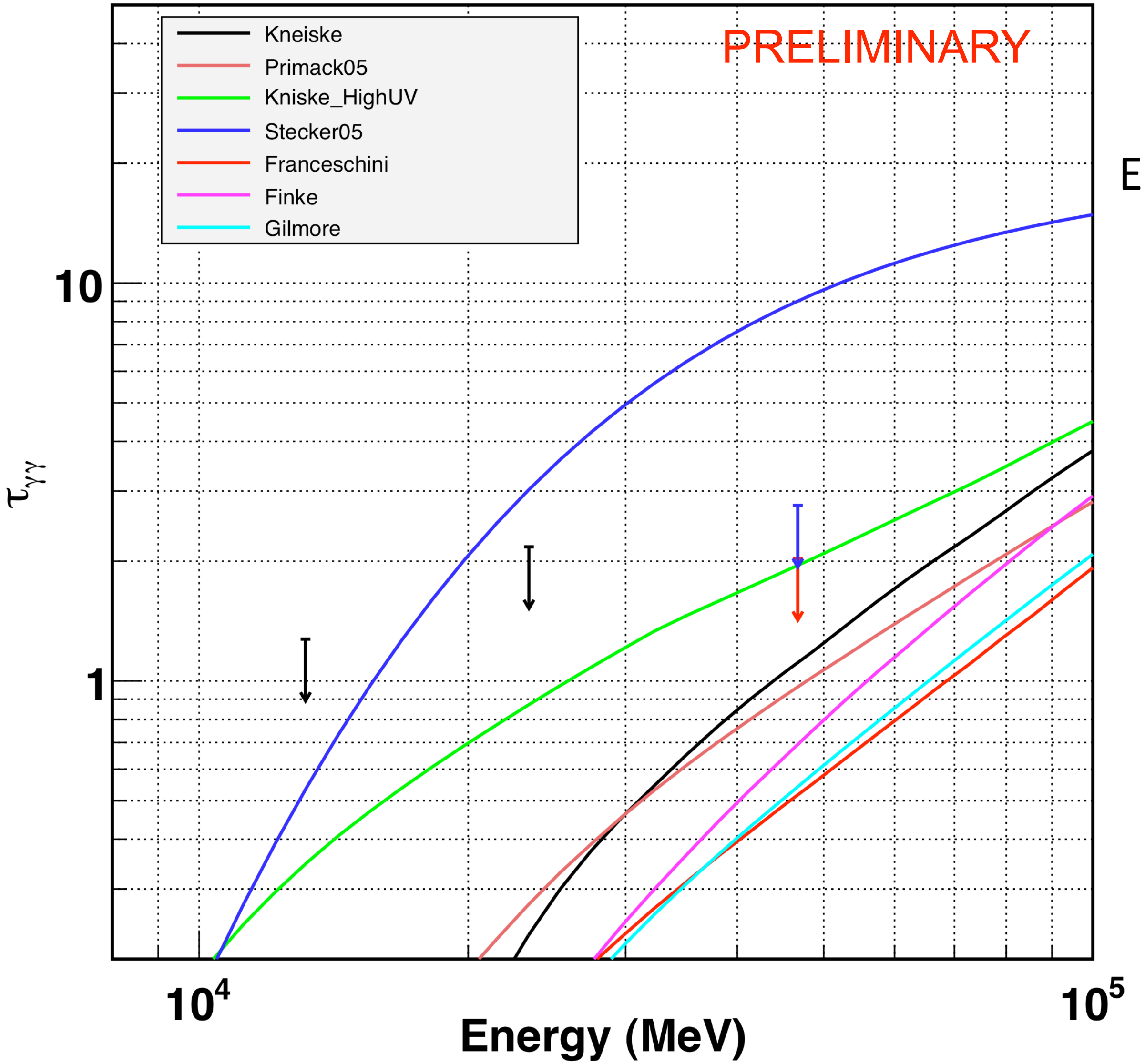
- <Fobs> is the mean observed flux in that energy bin

-E_{mean} is the weighted mean energy value in the highest energy bin

-σ_{τ} is obtained from the propagation of uncertainties on Fobs and Fmax

UL in opacity-energy phase space

1FGLJ0808-0750 - PKS0805-07 -- Redshift: 1.84



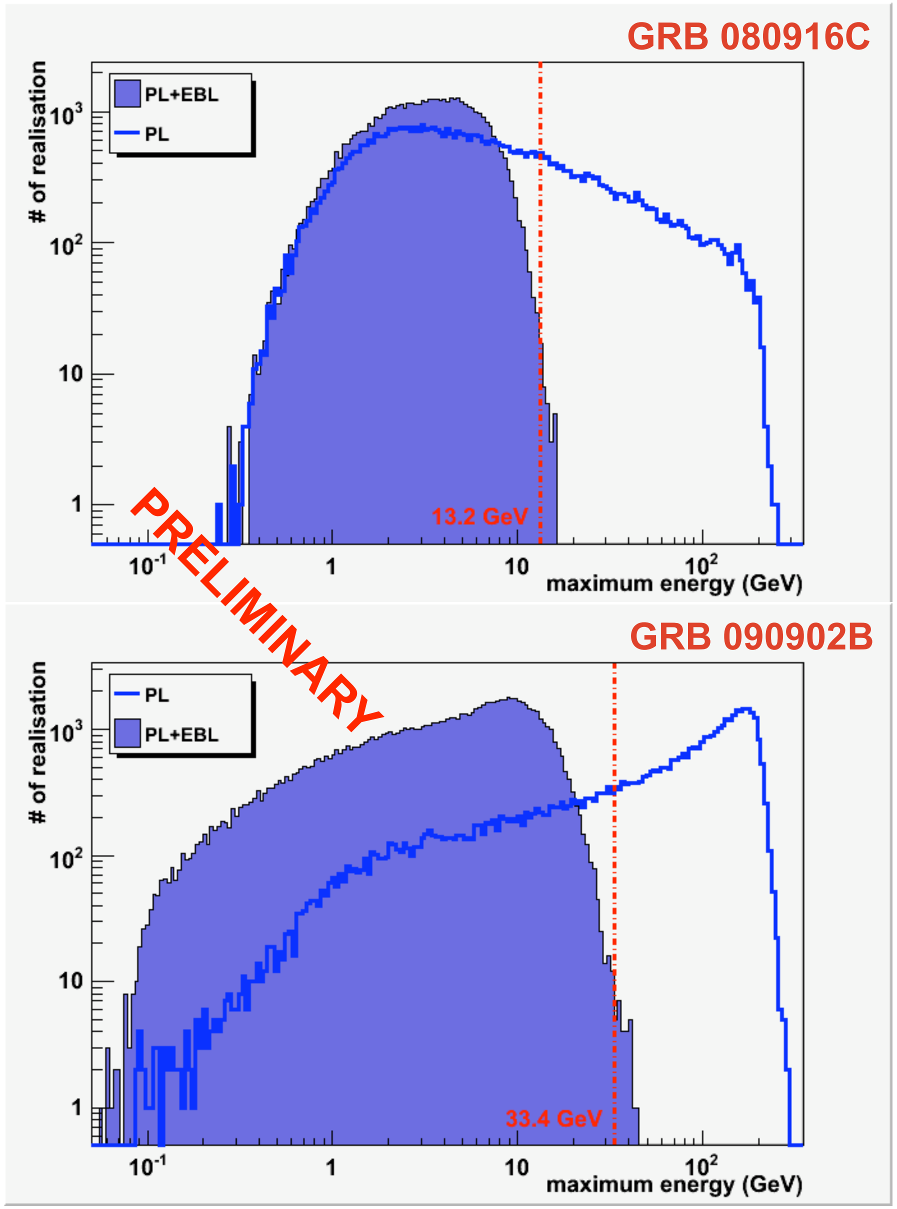
PKS 0805-07

z = 1.84

E_{mean} = 41.43 GeV

τ< 2.04 (95% c.l.)

‘Highest energy event’ technique

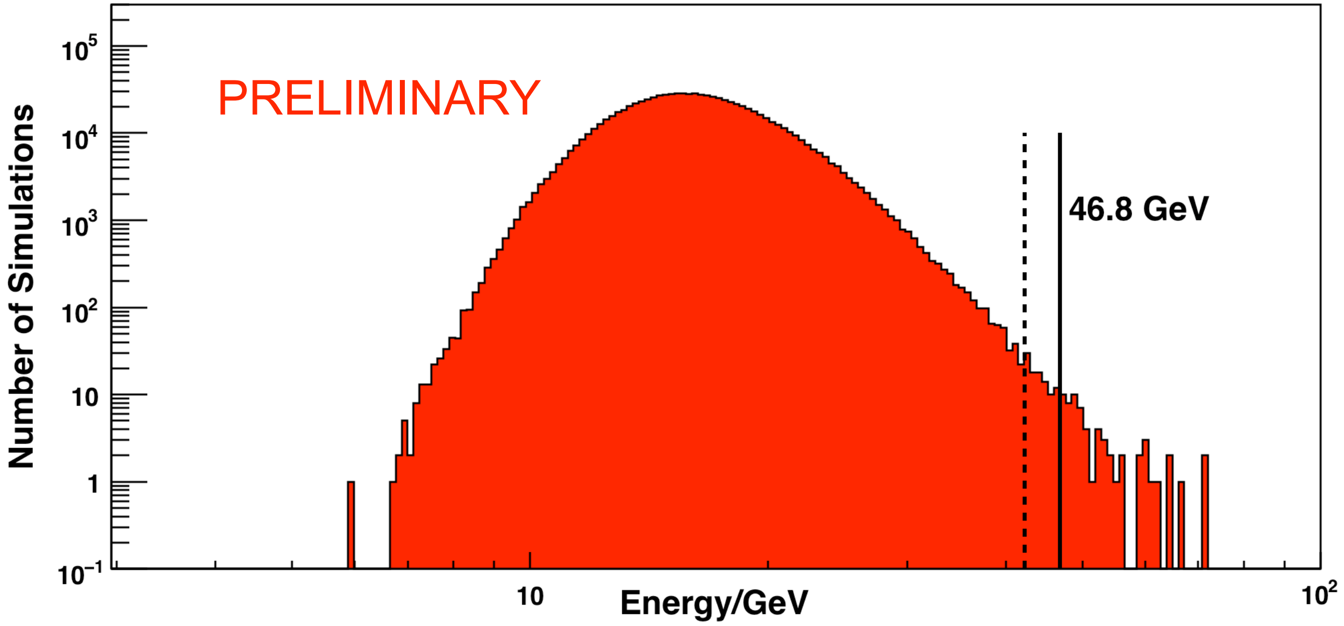


Recipe:

1. Constrain the “low” energy spectrum (in energy range where τ<<1)
2. MC simulations assuming intrinsic “high-energy” spectrum is the extrapolation of the low-energy behavior + EBL absorption (spectral uncertainty taken into account)
3. Evaluate the distribution of highest energy event.
4. Estimate the chance probability of detecting an event with energy $>E_{max}-\sigma_{Emax}$
5. Combine P_{bkg} and P_{HEP} for all photons above 15 GeV to obtain Combined $P_{rejection}$

‘Highest energy event’ technique

- We produced ~800000 simulations for each AGN and ~100000 for each GRB in order to model accurately the high energy tails of the photon distribution



- For J0808-0751 and the EBL model of Stecker et al. (2006) the probability of having a high energy photon with energy $E_{max} - \sigma_{Emax}$ is **6.8 x 10^{-5}**

Preliminary Results - ‘highest energy evt’ method

Source	redshift	Max energy	τ (St06 baseline)	Significance of rejection
J0808-0751	1.84	46.8 GeV	11.7	4.5 σ
J1504+1029*	1.84	48.9 GeV	12.2	4.1 σ
J1147-3812	1.05	73.7 GeV	7.1	3.2 σ
GRB 090902B	1.82	33.4 GeV	7.7	3.7 σ
GRB 080916C	4.24	13.2 GeV	5.0	3.4 σ

PRELIMINARY

- **Significances of rejection are for Stecker’s “baseline” model.**
- Stecker’s ‘’fast evolution” model rejected at even higher significance since it is more opaque.

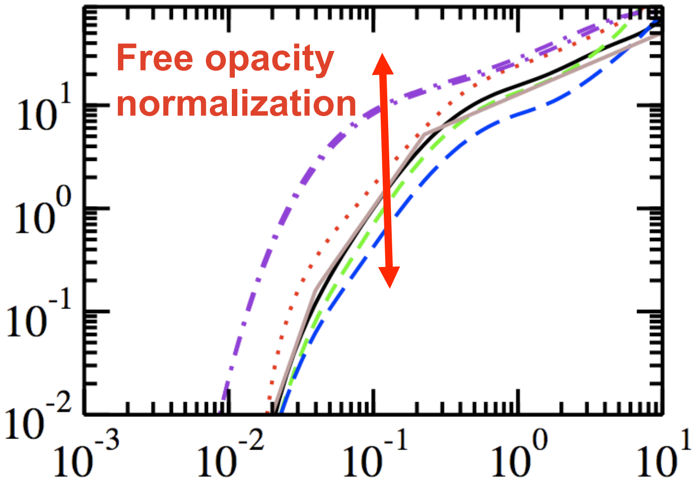
- All other models are optically thin at the maximum energy observed and cannot be constrained with current data.

Likelihood method

- ➢ Null-hypothesis tested: powerlaw + EBL absorption (fixed at its predicted value)

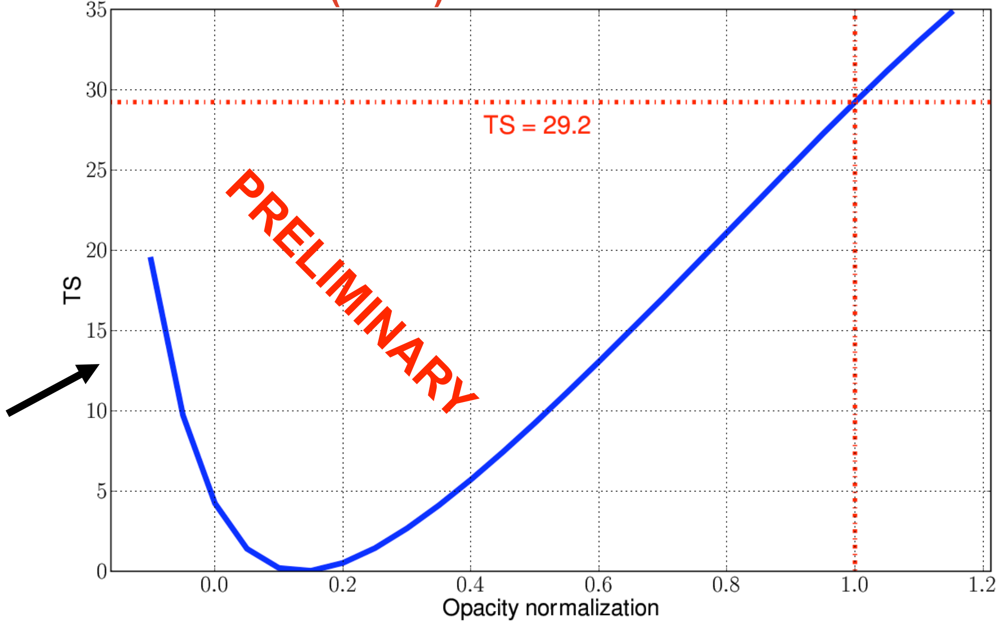
- ➢ **EBL opacity normalization left as a free parameter** in order to determine the most reasonable range for this parameter via a **profile likelihood**.

- ➢ This method is found to be the most powerful when several high energy events can be used to constrain EBL

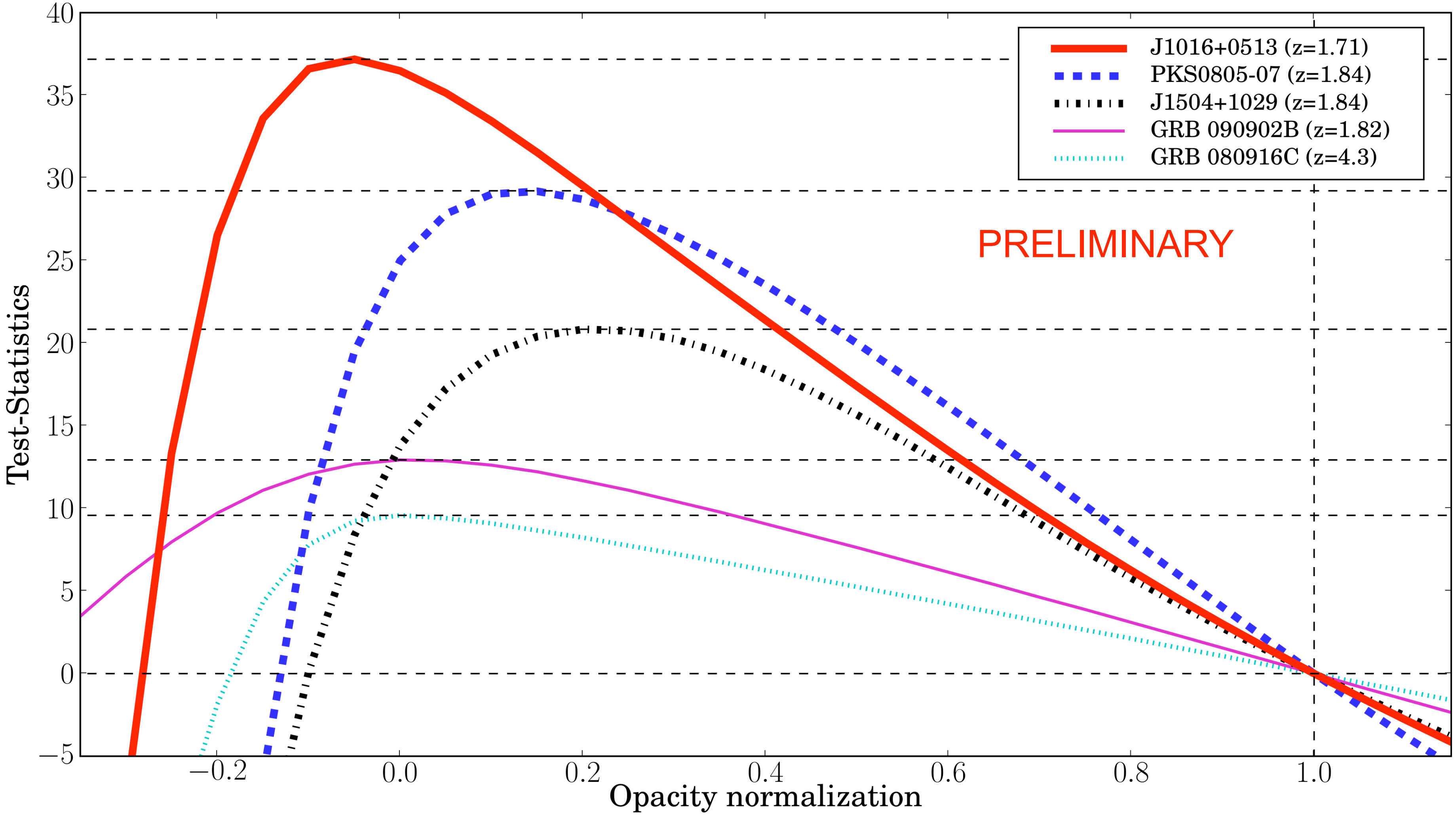


- ➢ Assuming Stecker's baseline model (fast evolution model can be rejected with stronger significance): **3 σ range: [-0.048,0.47]**. Value of '1' is excluded from this region and can be excluded with a **5.4 σ significance**.

J0808-0751 (z~1.8)



Likelihood method



Preliminary Results – likelihood method

Source	redshift	Significance of rejection	
		Pre-trial	Post-trial
J1016+0513	1.71	6.0 σ	5.1 σ
J0808-0751	1.84	5.4 σ	4.4 σ
J1504+1029*	1.84	4.6 σ	3.3 σ
J1147-3812	1.05	3.7 σ	2.0 σ
GRB 090902B	1.82	3.6 σ	1.9 σ
GRB 080916C	4.24	3.1 σ	1.0 σ

PRELIMINARY

- **Significances of rejection are for Stecker's "baseline" model.**
- Stecker's ''fast evolution" model rejected at even higher significance since it is more opaque.

Conclusions

- Results from first year of Fermi data reject with high significance EBL models that predict large opacities.
  - Combining all sources together results in a rejection significance of ~10.8 σ (~9.3 σ without GRBs) for HEP and 11.4 σ for LRT for the model of Stecker at al. (2006).
- 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.
- Submitted to ApJ, available on arXiv:1005.0996