The Discovery of the EBL Attenuation in the Spectra of *Fermi* Blazars

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Ackermann+12, submitted

EBL and Gamma Rays

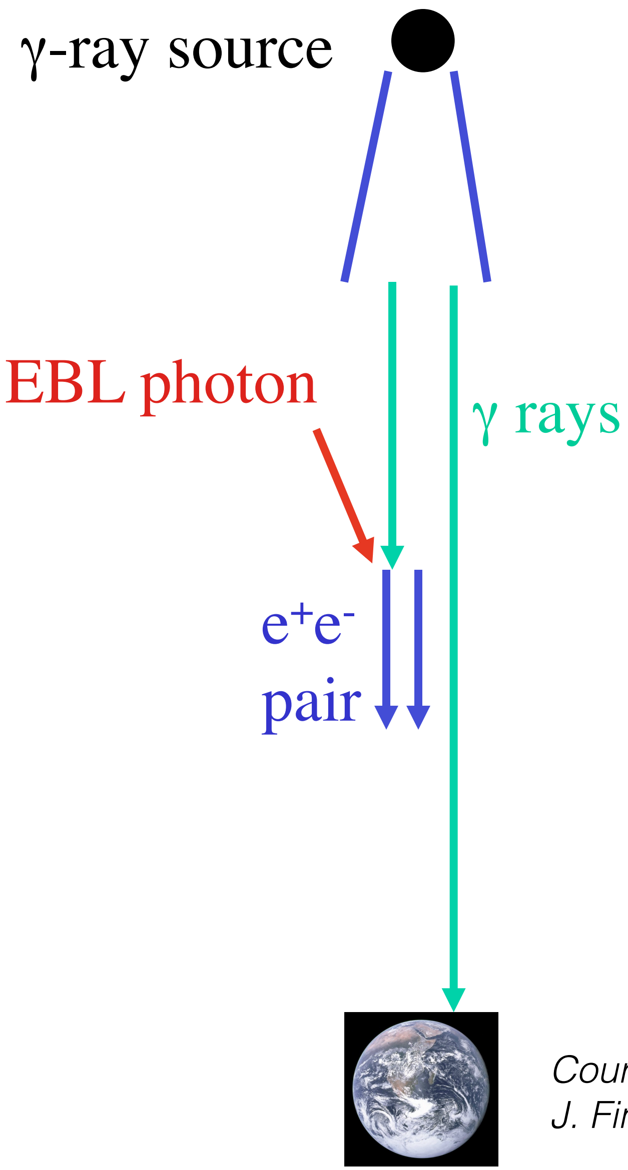
EBL photons extinguish extragalactic gamma rays.

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

Gamma rays we see are attenuated by:

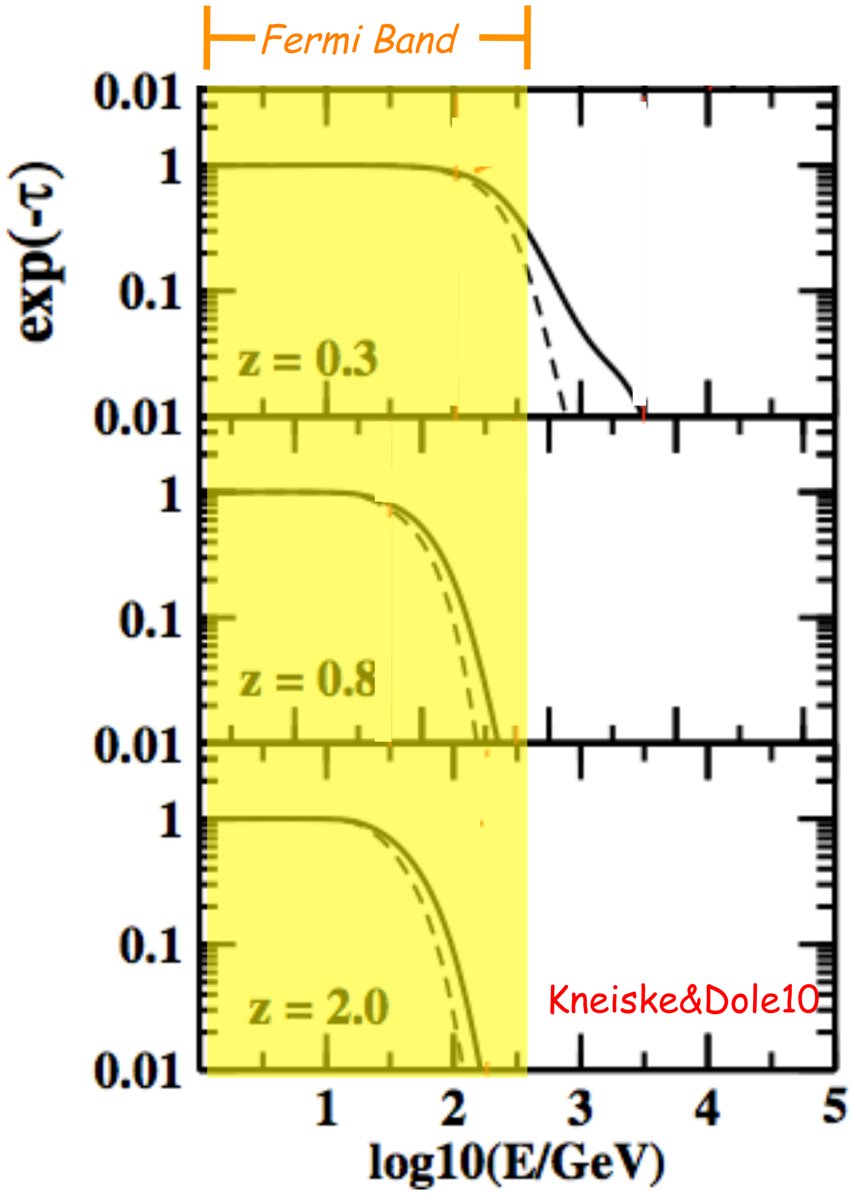
$F_{obs} = F_{int} \exp[-\tau_{\gamma\gamma}(E, z)]$.

We want to constrain the EBL models [$\tau_{\gamma\gamma}(E,z)$] based on γ-ray observations of blazars.



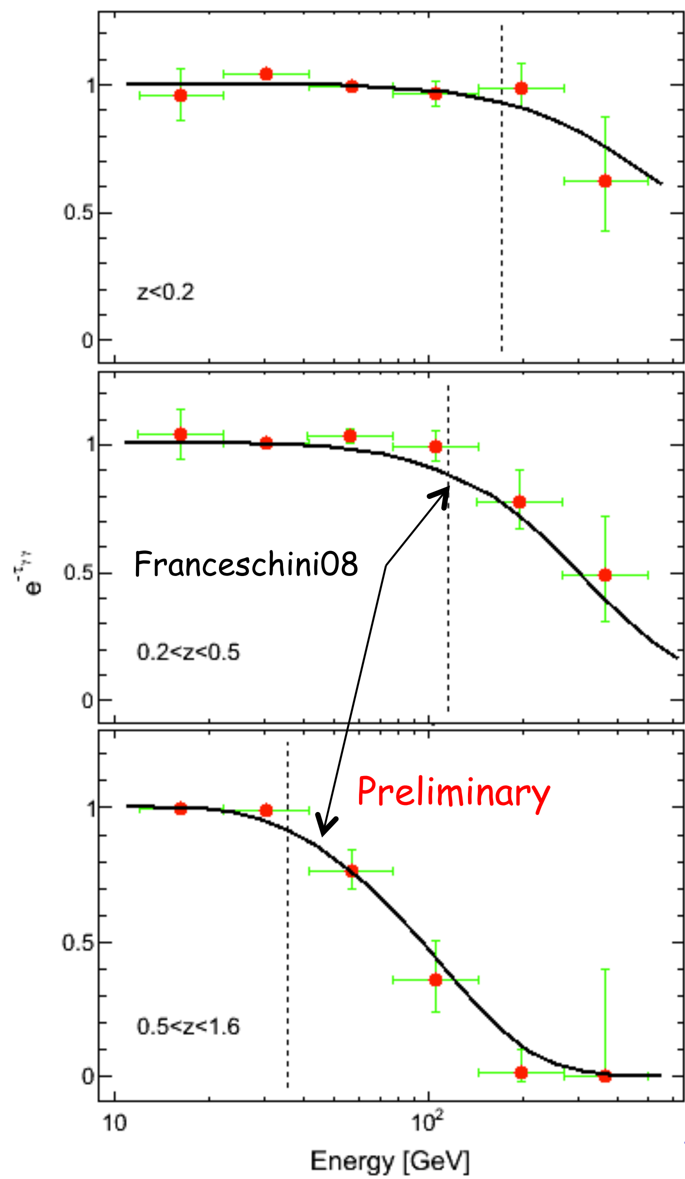
Courtesy J. Finke

This is what we should see



Most models predict an attenuation of >99% at z~1

This is WHAT we have seen

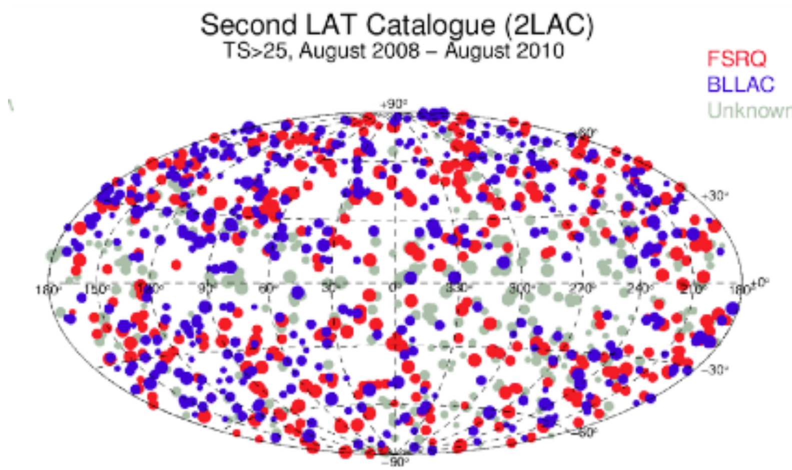


A Step back: where it all began

Large Area Telescope (LAT):

- >20 MeV - > 500 GeV
- 2.4 sr FoV (scans entire sky every ~3hrs)

- *Fermi* detected >1000 AGN with redshift upt to 3.1
- Perfect set to probe the EBL



2LAC-clean sample:
310 FSRQs
395 BL Lacs
156 Blazars with unknown type
24 AGNs

Ackermann+11, ApJ 743, 171

EBL study: Advantages of *Fermi*

1. *Fermi* detects blazars from z~0 to z~3 thus allowing us to measure/constrain the EBL at different epochs !

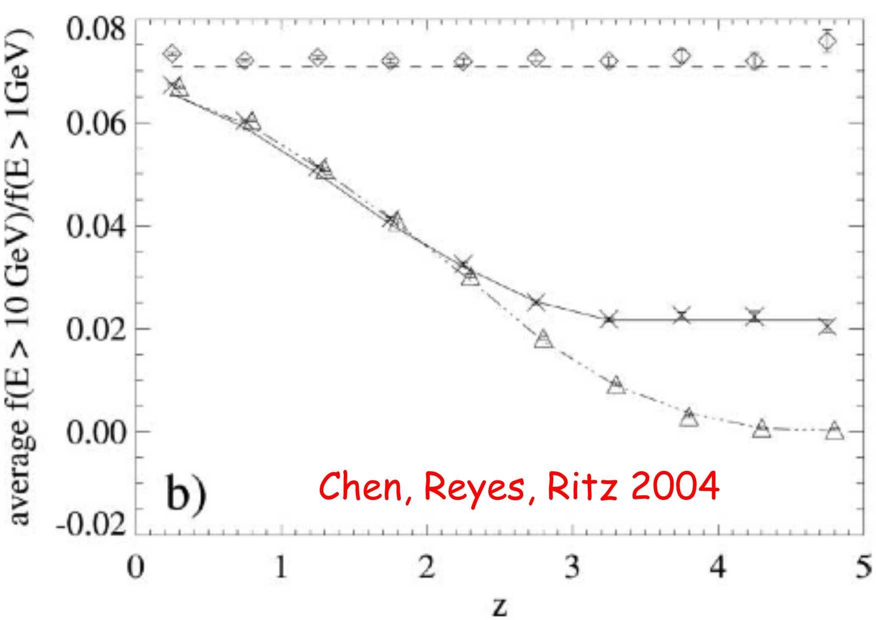
2. *Fermi*'s bandpass gives a unique handle on the *'intrinsic'* spectrum
   - *EBL absorption is negligible up to E<15 GeV for any redshift*

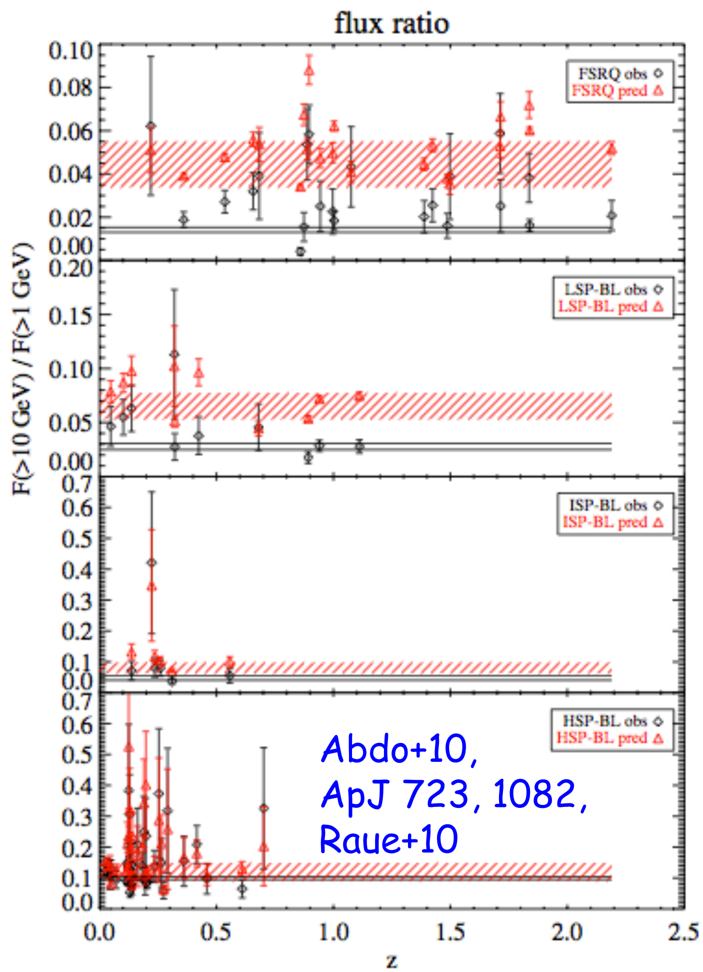
3. *Fermi's* continue all-sky observations allow us to address the impact of variable sources on EBL studies

Predictions and Reality

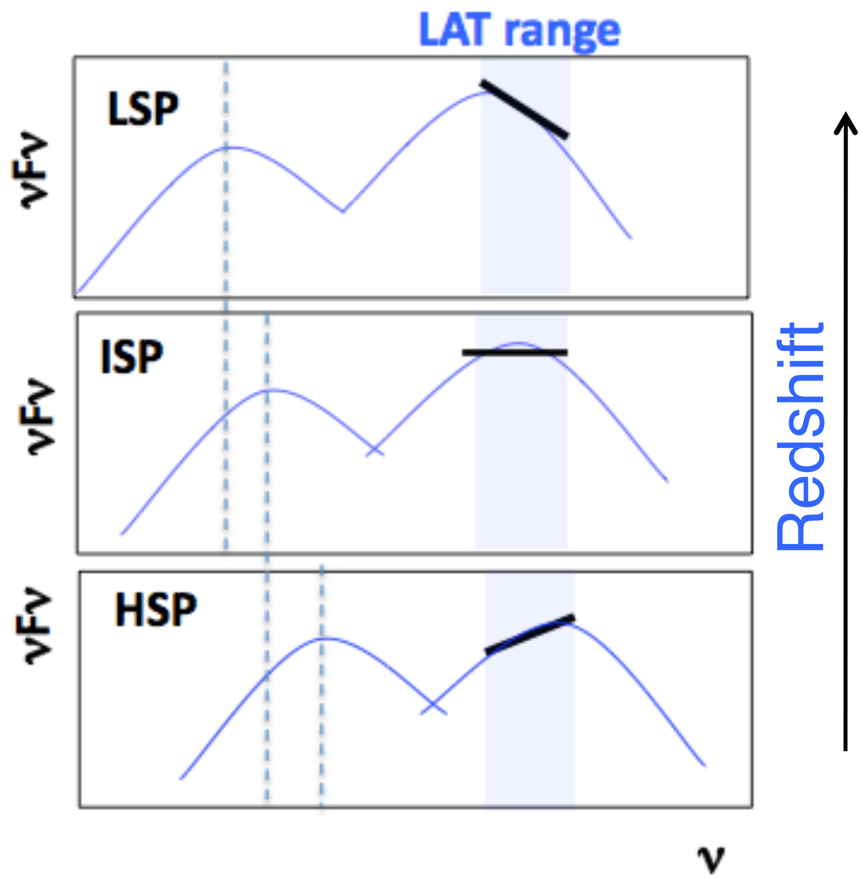
- EBL should cause an energy-dependent suppression of the HE flux which increases for larger redshifts

Reality is far more complex due to the non-standard nature of blazars





Predictions and Reality



Blazars spectra are type-dependent and the composition of the blazar sample evolves with redshift

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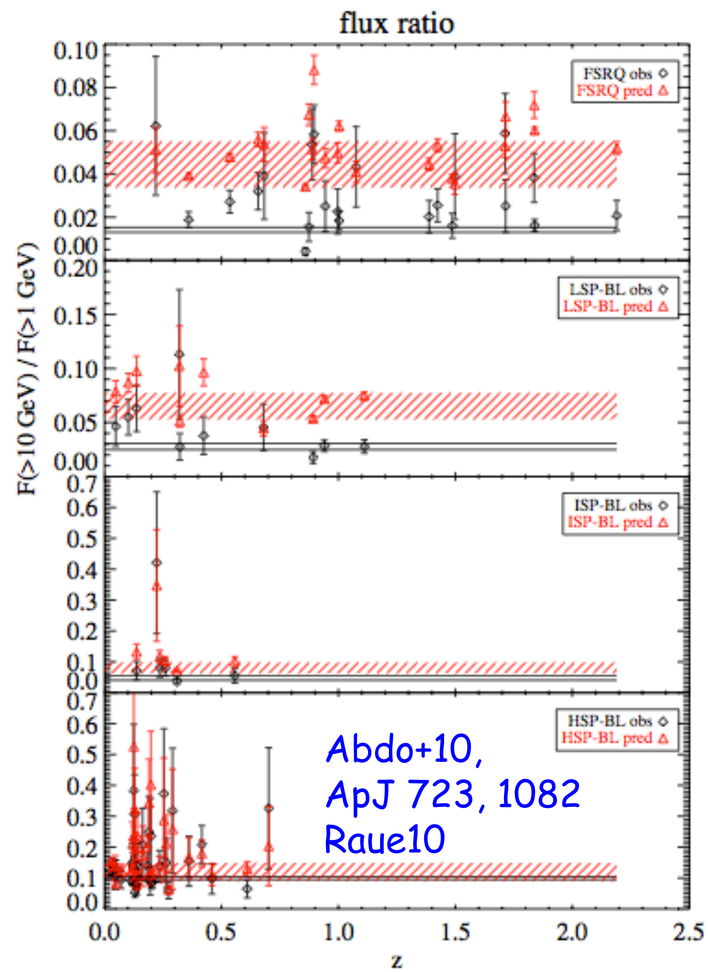


Abdo+10, ApJ 723, 1082
Raue10

Our Approach -- Analysis

- We look for the collective deviation of the spectra of blazars from their *intrinsic* spectra

Source selection

- We select 'non-variable' BL Lacs from 2LAC solely on the 3-10 GeV detection significance
- Advantages:
  - Hard spectrum sources
  - Weak, if any, external photon fields
- Disadvantages:
  - Only ~50% of *Fermi* BL Lacs have redshift

Analysis details

- 46months of data
- P7SOURCE_V6 or P7CLEAN_V6
- zenith angle < 100deg
- ROI radius = 15deg
- Standard P7 diffuse models
- <u>Energy range 1 – 500 GeV</u>

Analysis Procedure

- We define 3 redshift bins with 50 members each: z= 0-0.2, 0.2-0.5, 0.5 -1.6

- All BL Lacs are modeled with a *LogParabola* spectrum

- 3 Steps Procedure:
  1. fit each ROI (1-500 GeV) to optimize all components
  2. re-fit only up to the energy for which EBL absorption is negligible (we call this E_{crit})
     1. This step is needed to determine the properties of the intrinsic spectrum
  3. Combine the likelihoods of each ROI (for a z-bin) and fit "b"

- We evaluate 2 cases:

$$F(E)_{absorbed} = F(E)_{intrinsic} \cdot e^{-b \cdot \tau_{model}}$$

  1. Null hypothesis b=0 : there is no EBL
  2. Null hypothesis b=1 : the model prediction are correct

Composite Likelihood Results: 1

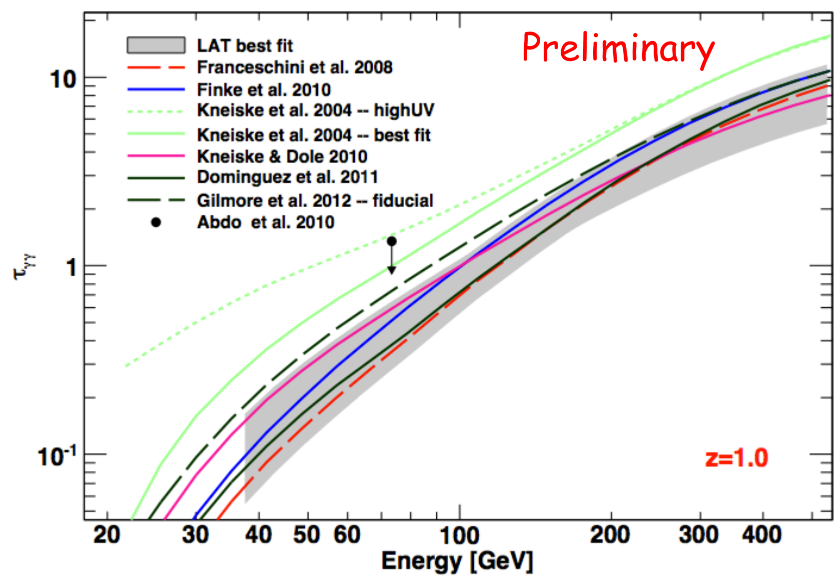
$$F(E)_{absorbed} = F(E)_{\text{int}\,rinsic} \cdot e^{-b \cdot \tau_{\text{mod}\,el}}$$

- Significance of the Detection:
  - Best-fit versus null hypothesis b=0: i.e. there is no EBL
- Significance of Rejection of a given EBL model:
  - Best-fit versus null hypothesis b=1: i.e. the EBL model predictions are correct
- We tested most of the EBL models: Franceschini08, Kneiske04, Kneiske&Dole10, Gilmore09-12, Dominguez11, Stecker+ etc
- Results (wrt to Franceschini+08 model):
  - z<0.2 : TS_{det}~4 and b=1.18(+/0.94)
  - 0.2<z<0.5: TS_{det}~7 and b=0.82(+/-0.41)
  - 0.5<z<1.6: TS_{det}~25 and b=1.29(+/-0.42)
  - Weighted average: b=1.02(+/-0.23)

1. *~6σ detection of the EBL absorption feature*
2. *Data compatible with low-opacity models*

Composite Likelihood Results: 2

- A significant steepening in the blazars' spectra is detected
- This is consistent with that expected by a 'minimal' EBL:
  - i.e. EBL at the level of galaxy counts
  - 4 models rejected above 3sigma
- All the non-rejected models yield a significance of detection of 5.6-5.9 σ
- The level of EBL is 3-4 times lower than our previous UL (Abdo+10, ApJ 723, 1082)



EBL Detection Significance

Model Rejection Significance

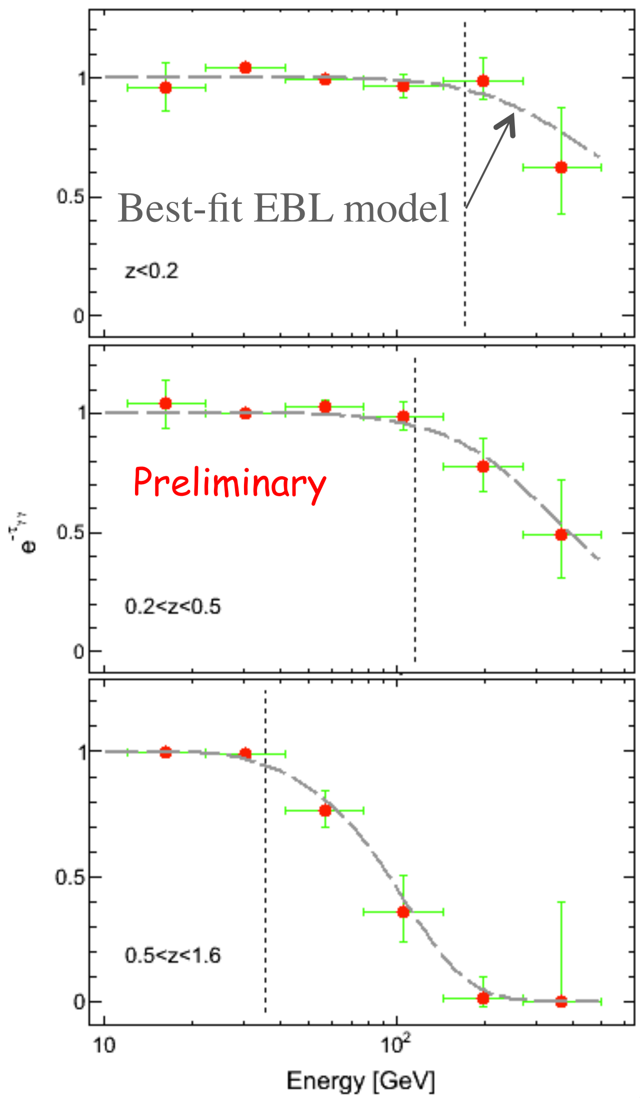
Model[a]	Significance of b=0 Rejection[b]	b[c]	Significance of b=1 Rejection[d]
Stecker et al. (2006) – fast evolution	4.6	0.10±0.02	17.1
Stecker et al. (2006) – baseline	4.6	0.12±0.03	15.1
Kneiske et al. (2004) – high UV	5.1	0.37±0.08	5.9
Kneiske et al. (2004) – best fit	5.8	0.53±0.12	3.2
Gilmore et al. (2012) – fiducial	5.6	0.67±0.14	1.9
Primack et al. (2005)	5.5	0.77±0.15	1.2
Dominguez et al. (2011)	5.9	1.02±0.23	1.1
Finke et al. (2010) – model C	5.8	0.86±0.23	1.0
Franceschini et al. (2008)	5.9	1.02±0.23	0.9
Gilmore et al. (2009)	5.8	0.97±0.22	0.9
Gilmore et al. (2012) – fixed	5.8	1.02±0.22	0.7
Kneiske & Dole (2010)	5.7	0.90±0.19	0.6
Gilmore et al. (2009)	5.8	0.99±0.22	0.6

Preliminary

Measurement of Tau with Energy and Redshift

- We use the composite likelihood in small energy bins to measure the collective deviation of the observed spectra from the intrinsic ones

- The cut-off moves in z and Energy exactly at expected for EBL absorption (for low opacity models)

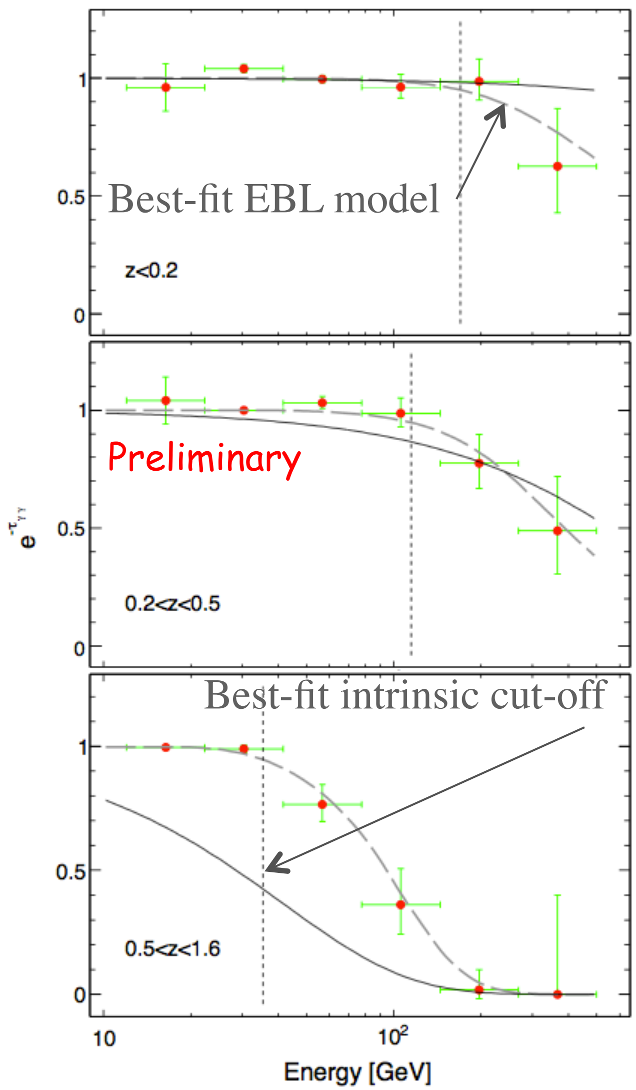


Measurement of Tau with Energy and Redshift

- We use the composite likelihood in small energy bins to measure the collective deviation of the observed spectra from the intrinsic ones

- The cut-off moves in z and Energy as expected for EBL absorption (for low opacity models)

- It is difficult to explain this attenuation with an intrinsic property of BL Lacs
  1. BL Lacs required to evolve across the z=0.2 barrier
  2. Attenuation change with energy and redshift cannot be explained by an intrinsic cut-off that changes from source to source because of redshift and blazar sequence effects



Linear Increase of the TS

- The signal is distributed over all the sources, with each source contributing ~0.5 to the TS

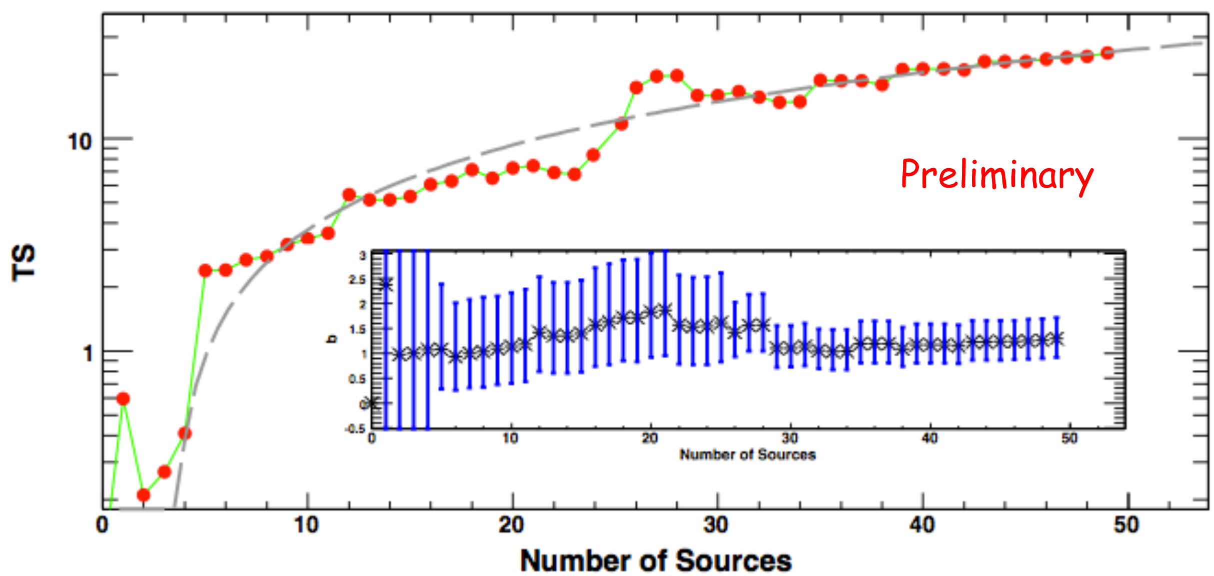


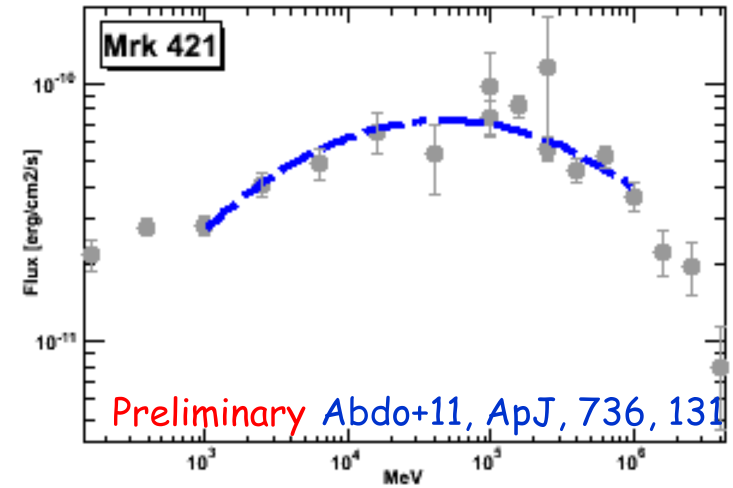
Figure 4 Increase in the TS value of the (renormalized) EBL model of (7) produced in the joint likelihood while adding one source at a time. The dashed line shows the best-fit linear increase of the TS with the number of sources. The inset shows the best fit value of the renormalization parameter b applied to the opacity predicted by (7) (see text for details).

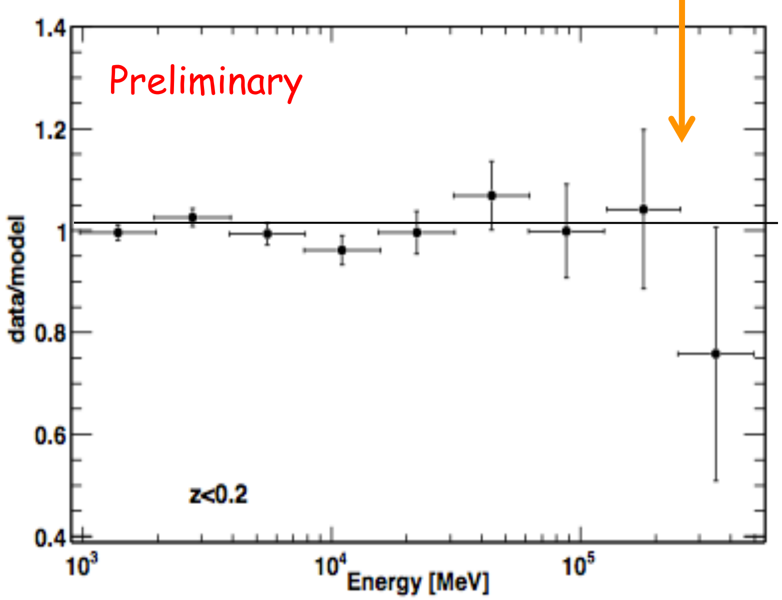
Is the LogParabola good for the intrinsic spec. ?

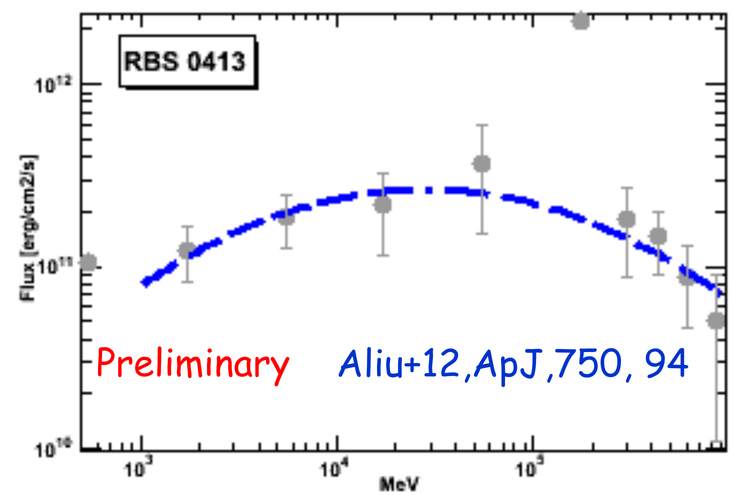
- Answer: *We believe it is good over the chosen energy range*
  1. For z<0.2, EBL absorption becomes important only for E>150GeV

Evidences

- Fit to GeV – TeV: OK
- Residuals to z<0.2 fit: flat







More Tests

- Results are robust against change of IRF/dataset
  - Systematic of ~10% on $tau_{\gamma\gamma}$ from IRF
- Results are confirmed when treating the classes independently:
  - HSPs dominate the signal (TS~25)
  - ISPs contribute a little (TS~10)
  - LSPs too soft
- Results do not depend on highest-z sources
- Results are robust against inclusion/exclusion of most variable sources
- Results are only weakly dependent on the accuracy of redshifts (i.e. if some redshifts are lower limits)
- The residual ~30 BL Lacs contribute a TS~3.5
- Results confirmed when decreasing dramatically E_{crit}

Conclusion

- *Fermi* performed a measurement of the γ-ray opacity:
  - It relies on the assumption that there is no 'conspiracy' in the nature of BL Lacs (or HSPs) that brings them to evolve in a way that mimics EBL absorption from z~0 to z~1.6
- The measurement is in good agreement with recent EBL models that predict a minimal EBL based on resolved galaxy counts
- The opacity is a factor >3 smaller than the previous LAT upper limit

A Lot More To Come

Michael Shaw

>200 BL Lacs will soon have a constrained redshift

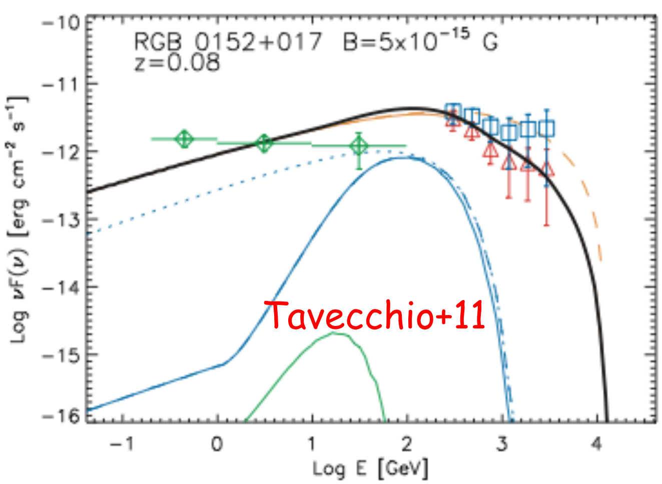
See Mike's Poster P2-35

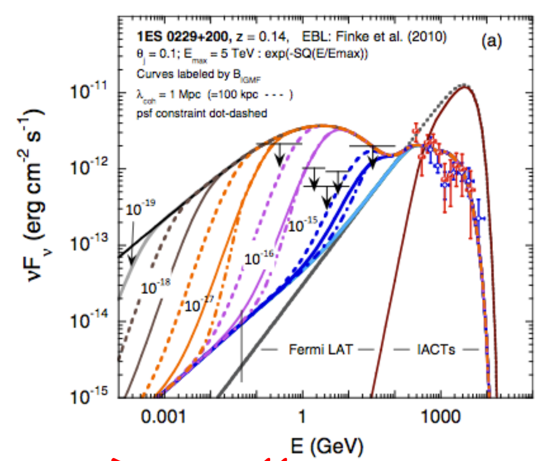
The End

Cascades and IGMF

- Cascade emission of TeV γ rays is reprocessed in the GeV energy range
- It may represent a substantial fraction of the GeV spectrum, depending on:
  - Intensity of the EBL
  - Intensity of the IGMF and its coherent length
  - Position of the high-energy SED peak

- For IGMF of $\geq 10^{-15}$ G (Neronov&Vovk10, Tavecchio11) the cascade component is greatly suppressed
- For IC peaks <10TeV (i.e. all but extreme HSPs) the cascade component is not expected to be large

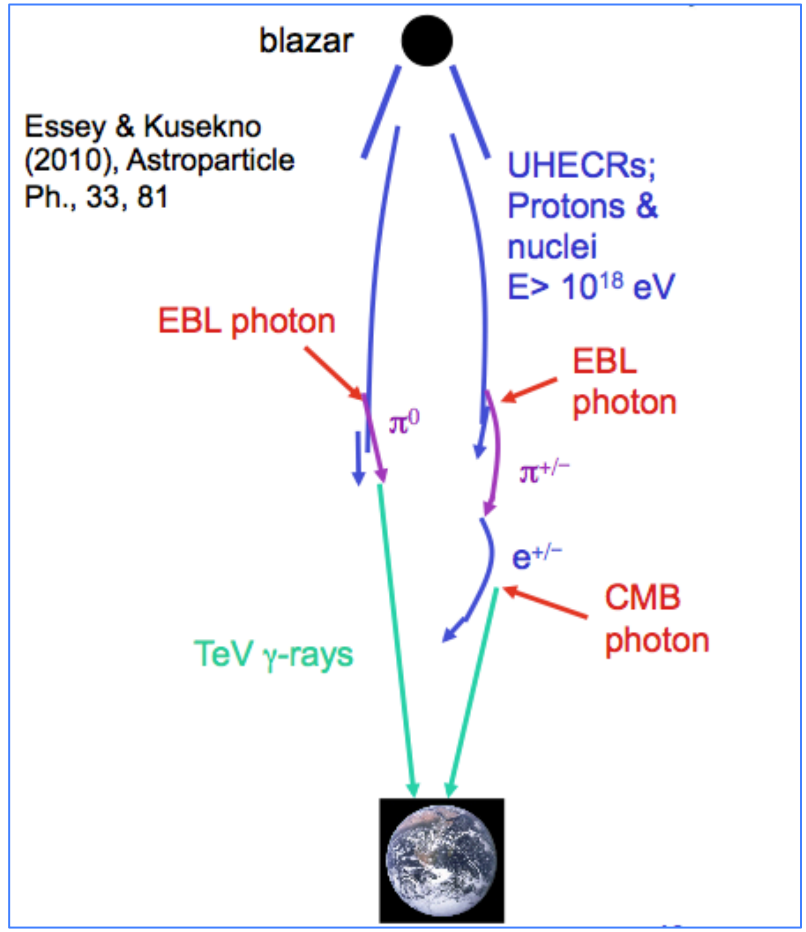




Dermer+11

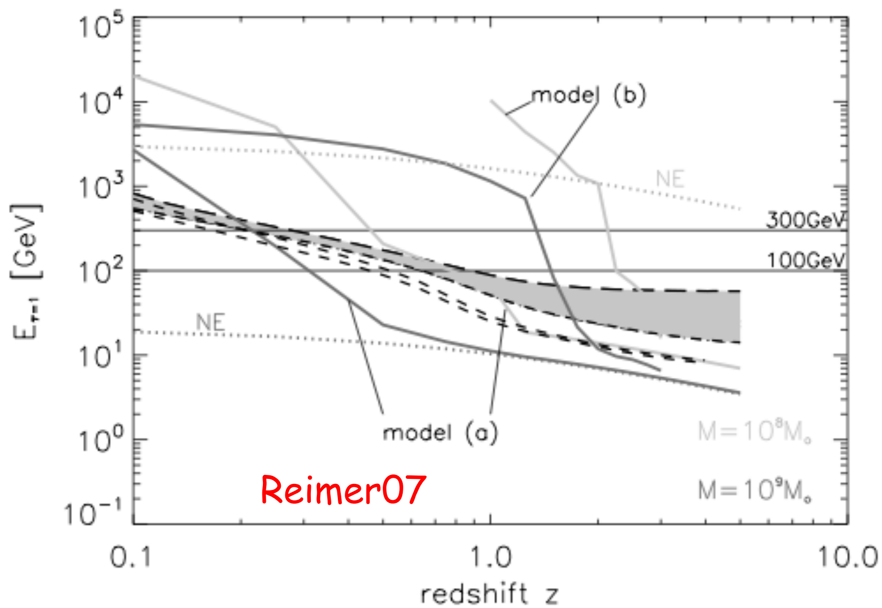
Ultra High Energy Cosmic Rays

- Blazars might be accelerating CRs as well
- CRs would travel further and interact with the EBL/CMB to generate γ rays
- γ-rays would then suffer EBL absorption
- Intense IGMF would deflect cascades out of line-of-sight



Intrinsic Absorption

- Absorption of gamma rays on the photons of the BLR/disk might show a redshift dependence due to the accretion history of the Universe (Reimer07)
- Most of the signal is in HSPs
- However:
  - Redshift dependence is not the same as that of EBL
  - If the emission region is far from the core, then no absorpti



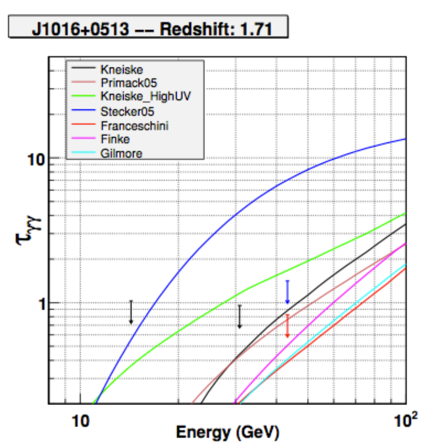
State of the Art

- In the first EBL paper (2010, ApJ 723, 1082) a variety of techniques were used to set constrain the opacity $\tau_{\gamma\gamma}$ using data from GRBs and Blazars

- Upper limits on the opacity can be derived from the ratio of the unabsorbed and the absorbed flux:

$$F_{absorbed} / F_{unabsorbed} = e^{-\tau}$$

- ULs are conservative as they include intrinsic spectral curvature



Source selection

- Delicate problem:
  - Ideally we would like to select a population:
    - Whose properties do not change with redshift
    - Is not affected by intrinsic absorption of photons on the BLR/disk
    - Have hard spectra to probe the EBL
- Such selection is impossible:
  - Blazar types change with redshift
    - HSP -> ISP -> LSP
- FSRQs are soft, have intense photon fields, are very variable:
  - No ideal candidates
- We select BL Lacs:
  - Advantages:
    - Have hard spectrum
    - We think they might not have strong photon fields
  - Disadvantages:
    - Type evolves with z
    - 50% in 2LAC do not have z