Updated Fermi-LAT Constraints on the EBL

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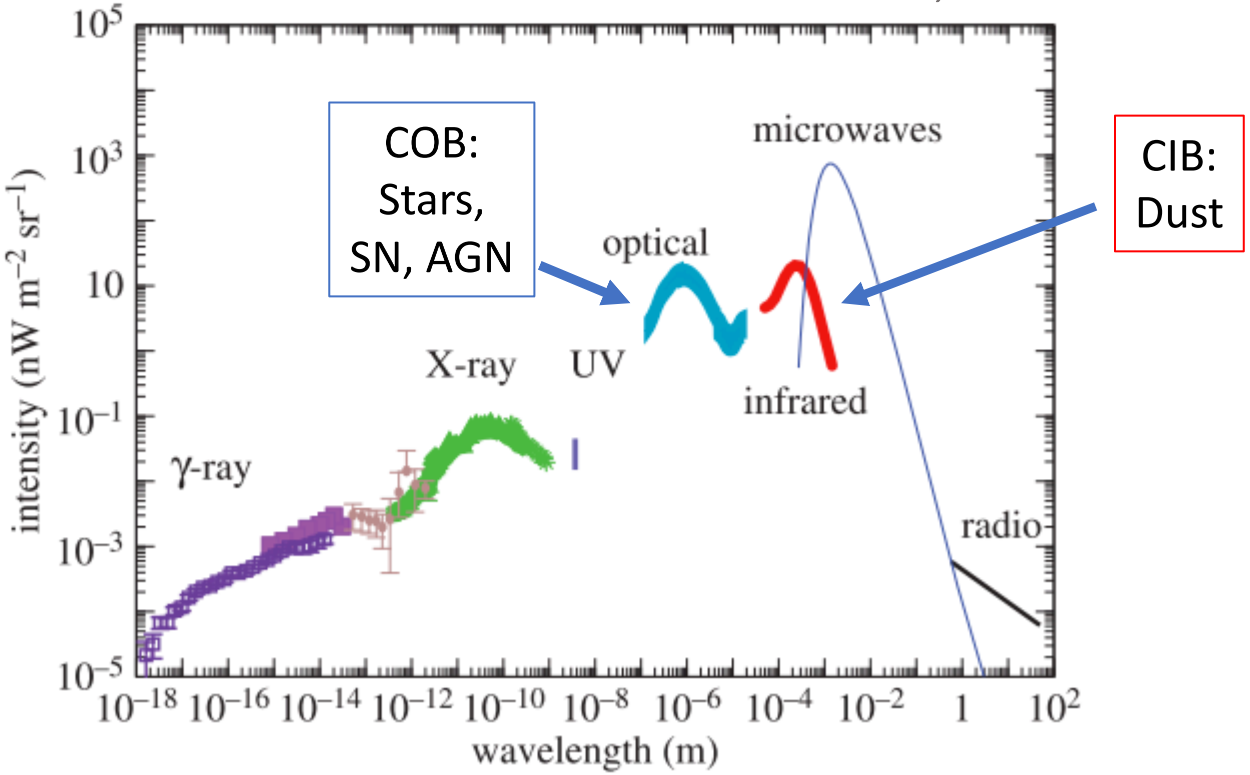
Abstract: The extragalactic background light (EBL) is a fundamental cosmological observable of our universe, allowing insight into the history of star formation within our universe. Extending between 0.1 - 1000 μm it is the UV to near-IR that is of interest in high and very high energy astronomy, where EBL photons interact via pair production to leave a visible imprint in the spectra of distant AGN. Multiple studies have been carried out using ground-based Cherenkov telescopes, which can observe the spectra of relatively nearby AGN to provide limits on the density of the EBL. These however do not reveal a great amount of detail concerning the evolution of the EBL with time, and therefore the star formation rate. The Fermi-LAT instrument, with its long exposure of the extragalactic sky, holds an extensive sample of AGN extending out to large redshifts ($z < 2.56$) and has been used by the Fermi-LAT collaboration to study the EBL. Here we further that study by combining a sample of 259 AGN, carefully modelling their spectral energy distributions and determine a redshift-dependent EBL correction factors to a range of models, taking into account the temporal and spectral variability of sources.

Overview

- Brief EBL intro
- EBL models
- Fermi-LAT as a probe for cosmology
- Simple idea of Method – basically what was done in previous paper
- Updates to method
    - Larger source selection
    - Full Fit
    - Temporal filtering
    - Spectral filtering
- Preliminary Results
- Future work/improvements.

EBL

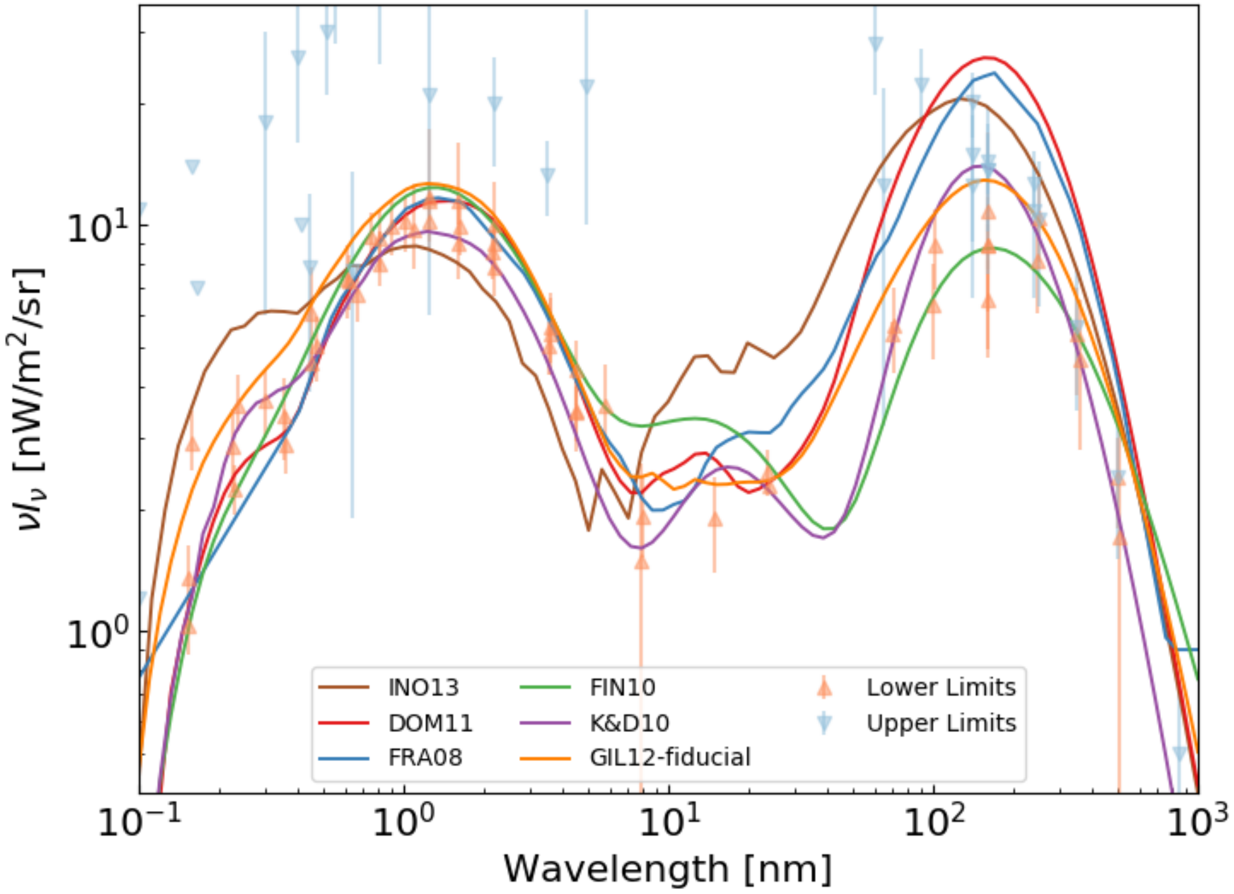
A. Cooray 2016



- EBL - Background light between 0.1-1000 μm
- Important cosmological observable, contains information on the galaxy and star formation history of the universe.
- Measurements: Direct difficult due to foreground emission, galaxy counts give lower limit

EBL Models

- EBL intensity estimated by integrating the total emission over redshift.
- **Forward Evolution (FE)** – Spectral properties of galaxies and stars obtained by evolving them from cosmological initial conditions
    - Fink et. al. 2010, Kneiske & Dole 2010
- **Backwards Evolution (BE)** - Spectral properties of galaxies and stars obtained by backward extrapolation of the local galaxy population.
    - Dominguez et. al. 2011, Franceschini et. al. 2008 (2017)
- **Semi-Analytical Models (SAM)** – use of SAM to include formation of galaxies and their interactions (~FE)
    - Gilmore et. al. 2012, Inoue 2013

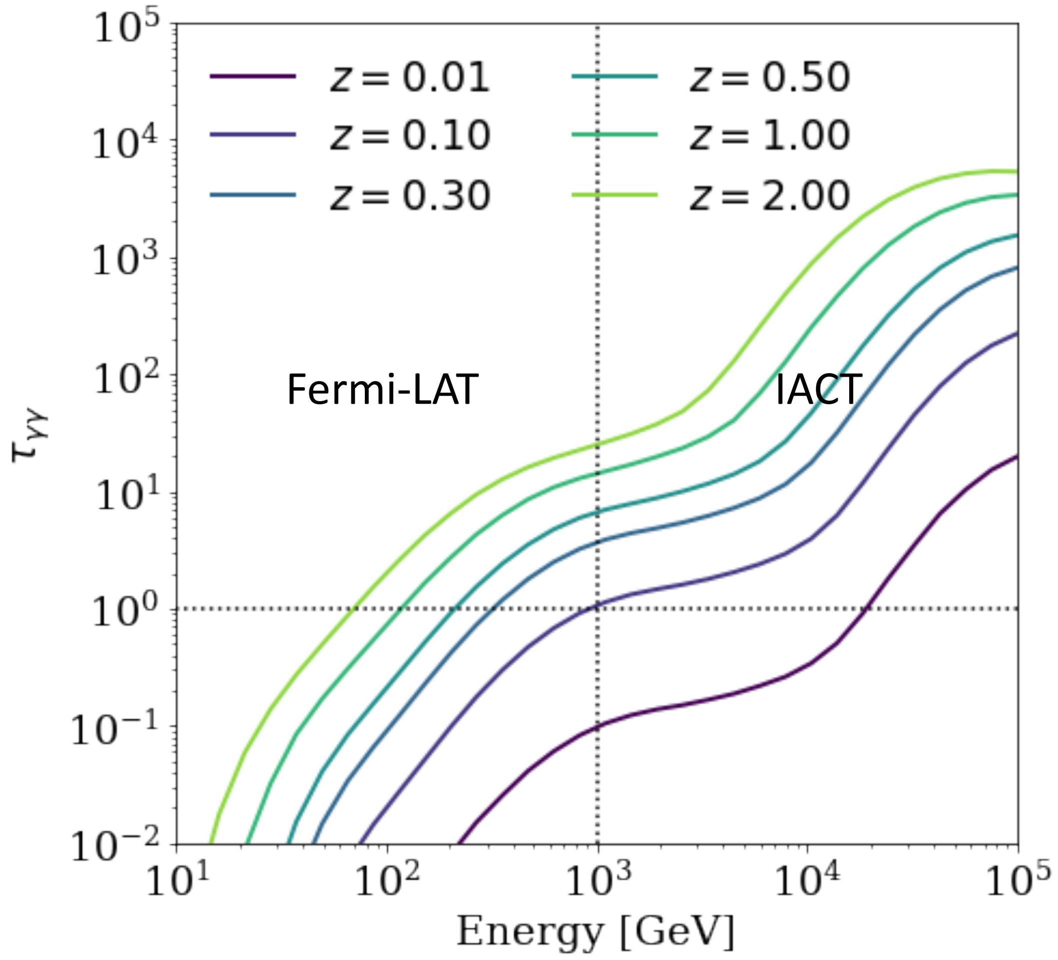


EBL + Gamma-rays

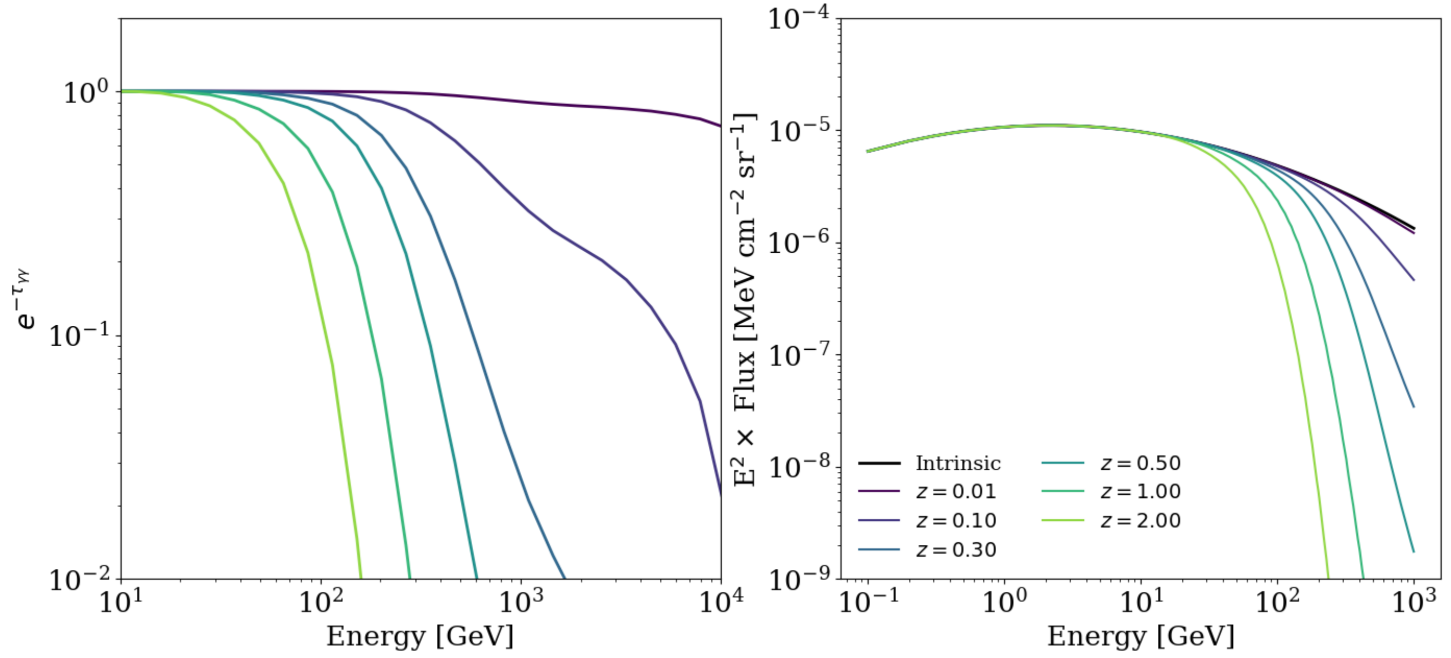
- Level of EBL intensity important for gamma-ray observations.
- Beam of high energy photons can be strongly attenuated by e^+e^- pair production through collision with low-energy photons.
- Therefore, for distant sources, the universe starts to become opaque to gamma-rays. This opacity is given by the optical depth

$$\tau(E_\gamma, z) = \frac{1}{2}\int_0^z dz\,\frac{dl}{dz}\int_{-1}^{1} du\,(1-u)\int_{E_{min}}^{\infty} dE_{bg}\, n(E_{bg}, z)\,\sigma(E_\gamma, E_{bg}, \theta)$$

- => Cosmological Line element, angular distribution and cross section for pair production, and the number density of EBL photons



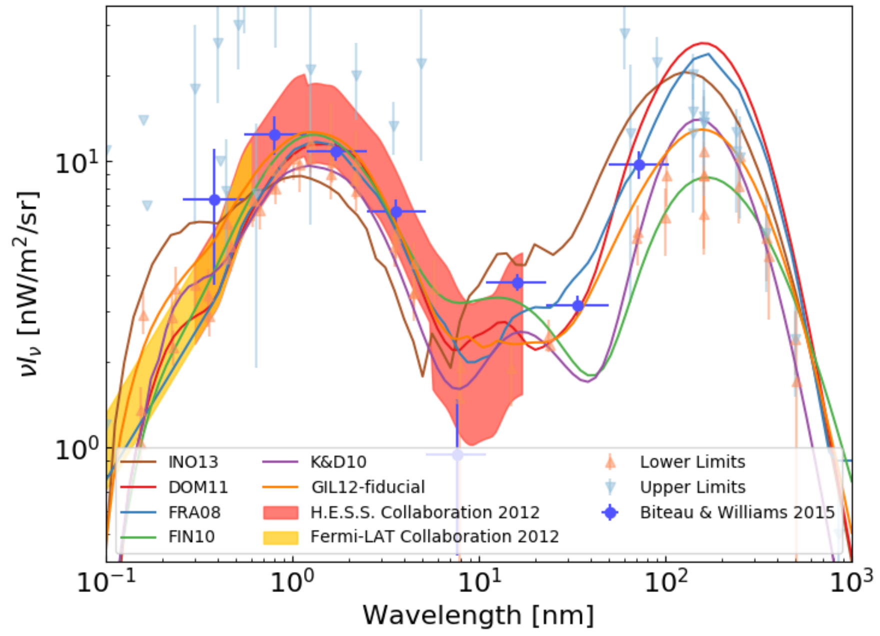
EBL + AGN Spectra

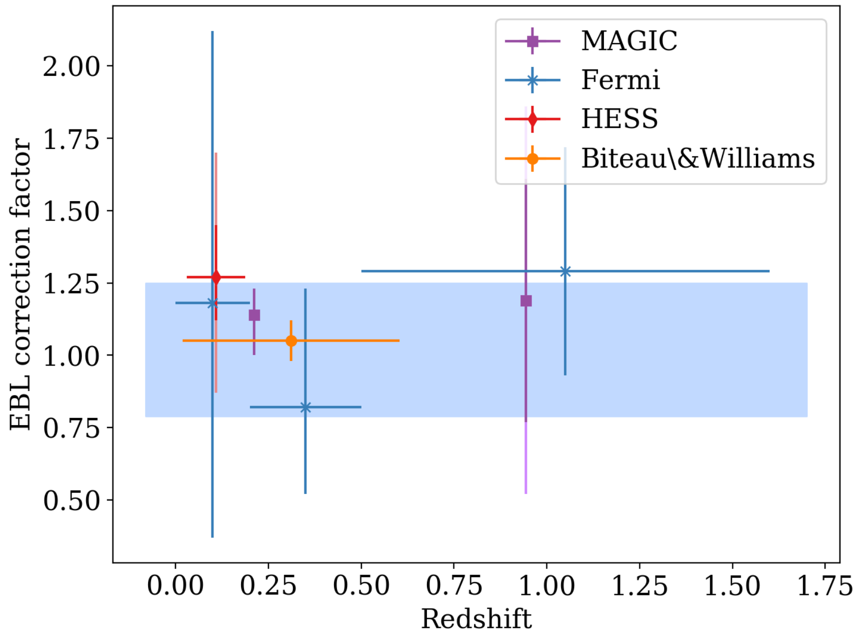


$$F_{obs}(E) = F_{int}(E) \cdot e^{-\tau_{\gamma\gamma}(E,z)}$$

- The cut-off for gamma-rays exits for all redshifts $\gtrsim$ 10 GeV
- The Fermi-LAT telescope is therefore well positioned to measure this feature with its energy range MeV -> ~TeV, which contains within itself both the intrinsic and absorbed spectrum
- While we cannot know the "intrinsic spectrum" in the absorbed energy range, the extrapolation from the unabsorbed is a good approximation.

EBL + Gamma-ray Observations

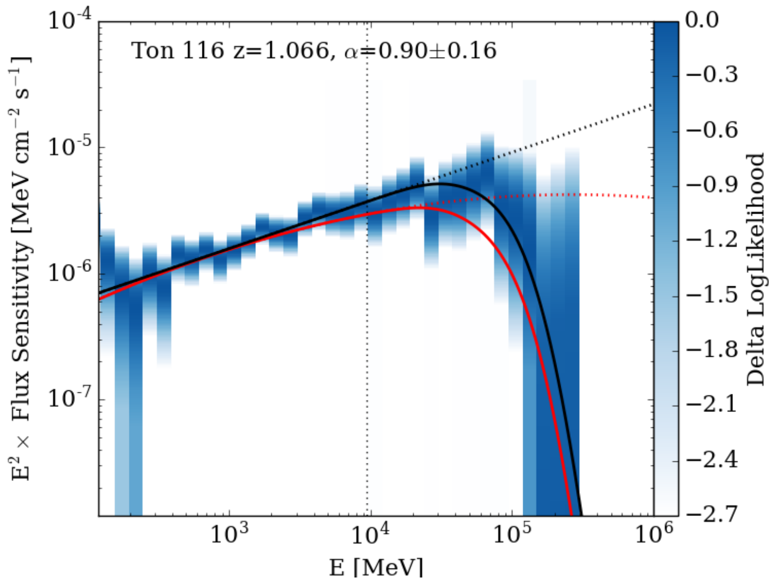


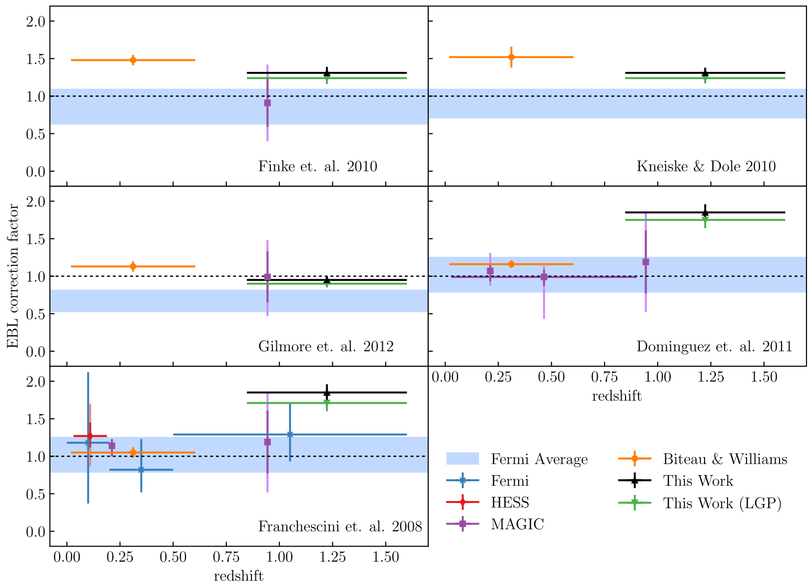


- A large source of limits on the EBL intensity from gamma-rays have been provided by ground based IACTs which probe the ~TeV energy range along with earlier work by Fermi LAT collaboration
- $F_{obs}(E) = F_{int}(E) \cdot e^{-a_{EBL} \cdot \tau_{\gamma\gamma}(E,z)}$
- By fitting AGN spectra and scanning over the a_{EBL} a likelihood profile can be obtained, and a correction factor derived.
- Correction factor used to look at the local EBL intensity along with evolution over redshift.

Initial Method

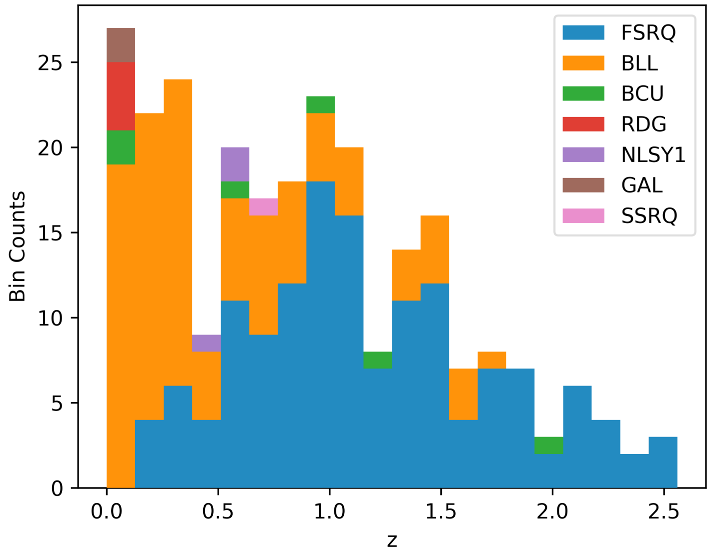
- Work performed in initial study (Armstrong17)
- Based on methods performed in HESS/Fermi.
- Fit the intrinsic spectrum unaffected by EBL absorption (<~10 GeV)
- Fit full data sets for each EBL model scanning over EBL correction factor, find maximum likelihood value.
- Drawbacks:
  - Did not take into account variability
  - Intrinsic spectrum fixed in EBL fitting step
  - Did not evaluate systematics

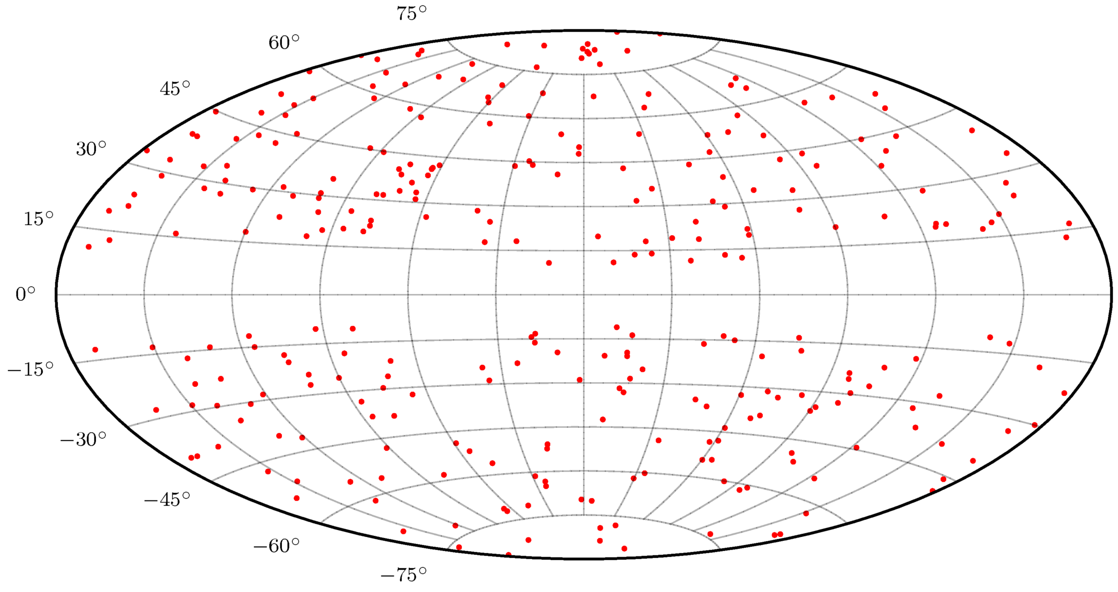




Source/Data Selection

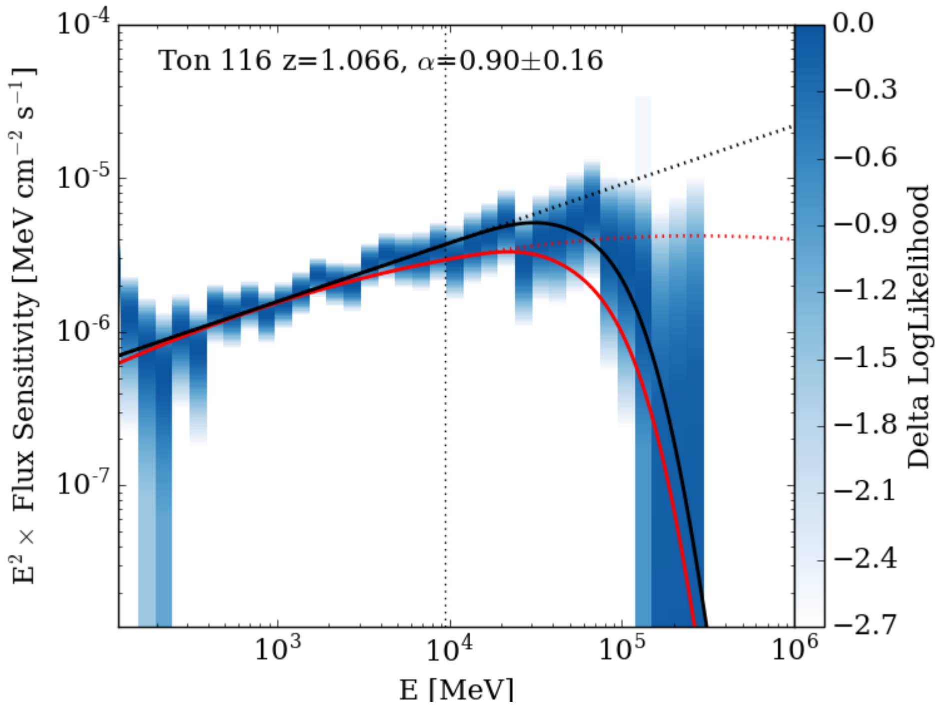
- Used 8 years of Fermi-LAT data between 100 MeV – 500 GeV
- Selected all sources from the 3FGL with |b|>10 degrees, significance >20 σ, and with corresponding redshift data (extracted from simbad) = 259 sources
- Binned likelihood analysis
  - (v10r0p5)
  - (Data_qual>0) && (Lat_config==1)
  - 90° zenith cut
  - SOURCE (Front and back)
  - P8R2_SOURCE_V6 IRFs
  - ROI 10° x 10°
  - 10 bins per decade
  - including 3FGL sources within 20°
- Obtained global fit





EBL Fitting

- EBL model is optimised using likelihood profiles extracted for each spectral energy bin from the Fermi tools
- Fit first the intrinsic spectrum (log par parameters) then fits again with all free including EBL correction factor
- Statistical significance is given by Wilks' Theorem.



Log Parabola Fit

$$\Phi = N\left(\frac{E}{E_b}\right)^{-\alpha-\beta\log\left(\frac{E}{E_b}\right)}$$

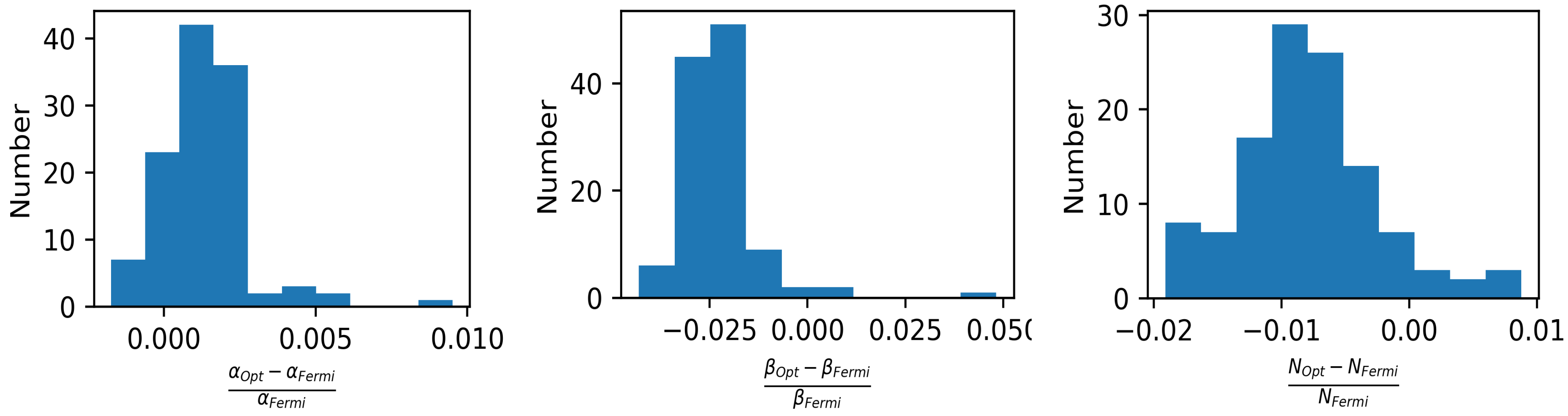
Initial values for EBL fit

EBL fit with attenuation

$$\Phi = N\left(\frac{E}{E_b}\right)^{-\alpha-\beta\log\left(\frac{E}{E_b}\right)} e^{-a_{EBL}\cdot\tau_{\gamma\gamma}(E,z)}$$

Technique Verification

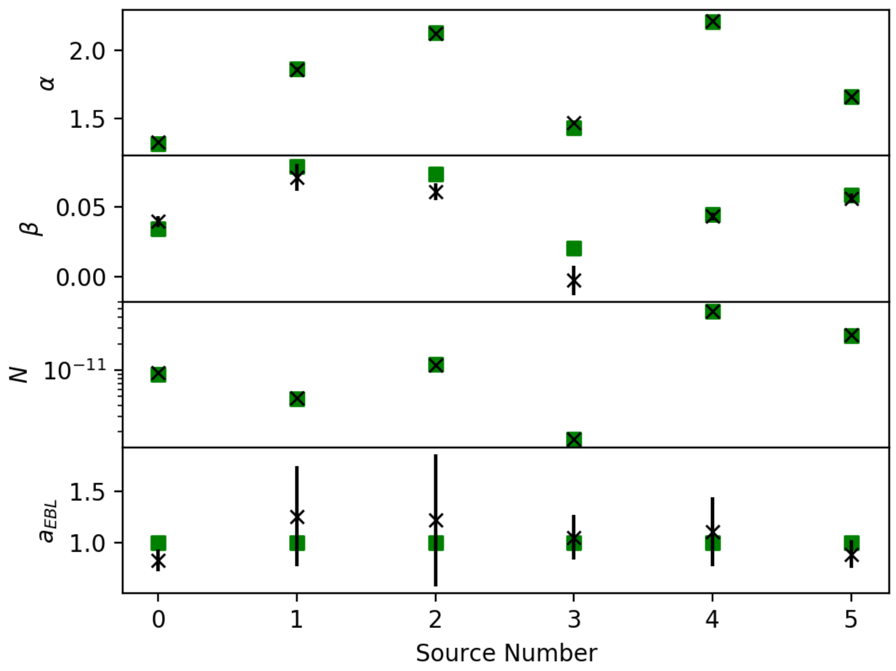
- Compare the values calculated by this method to that found using the Fermi tools (Using sources that are log parabola in the 3FGL)

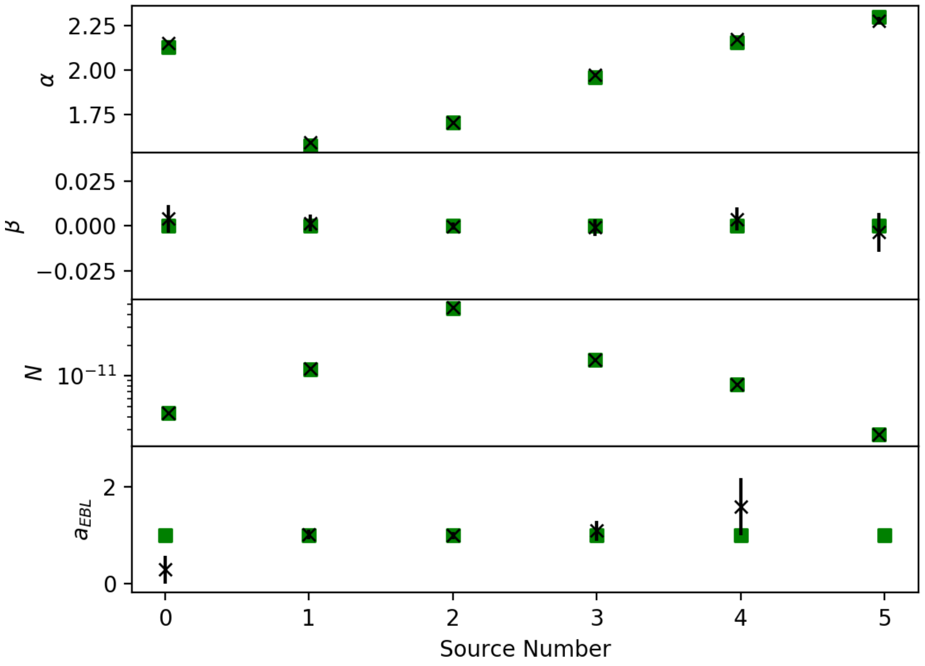


- Within 2% in raw parameter values, smaller in $\Delta \log L$. Some small bias.

Technique Verification

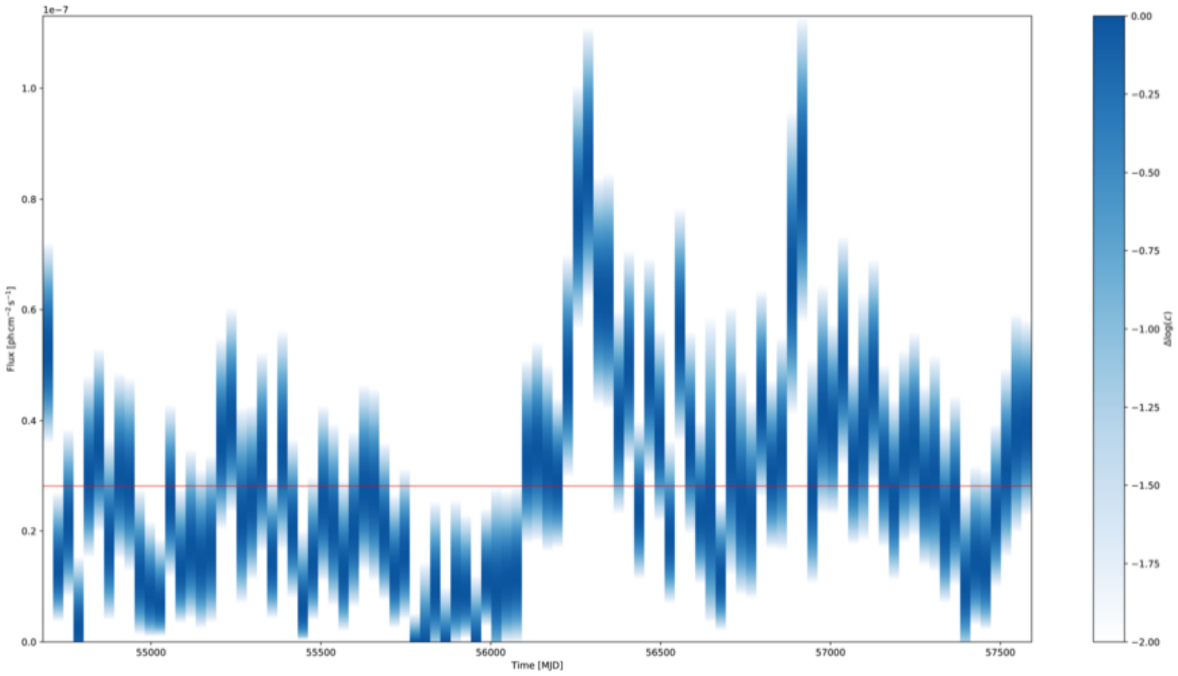
- Performed cross check, simulating sources using gtobssim. Used the same method to reconstruct the input parameters.



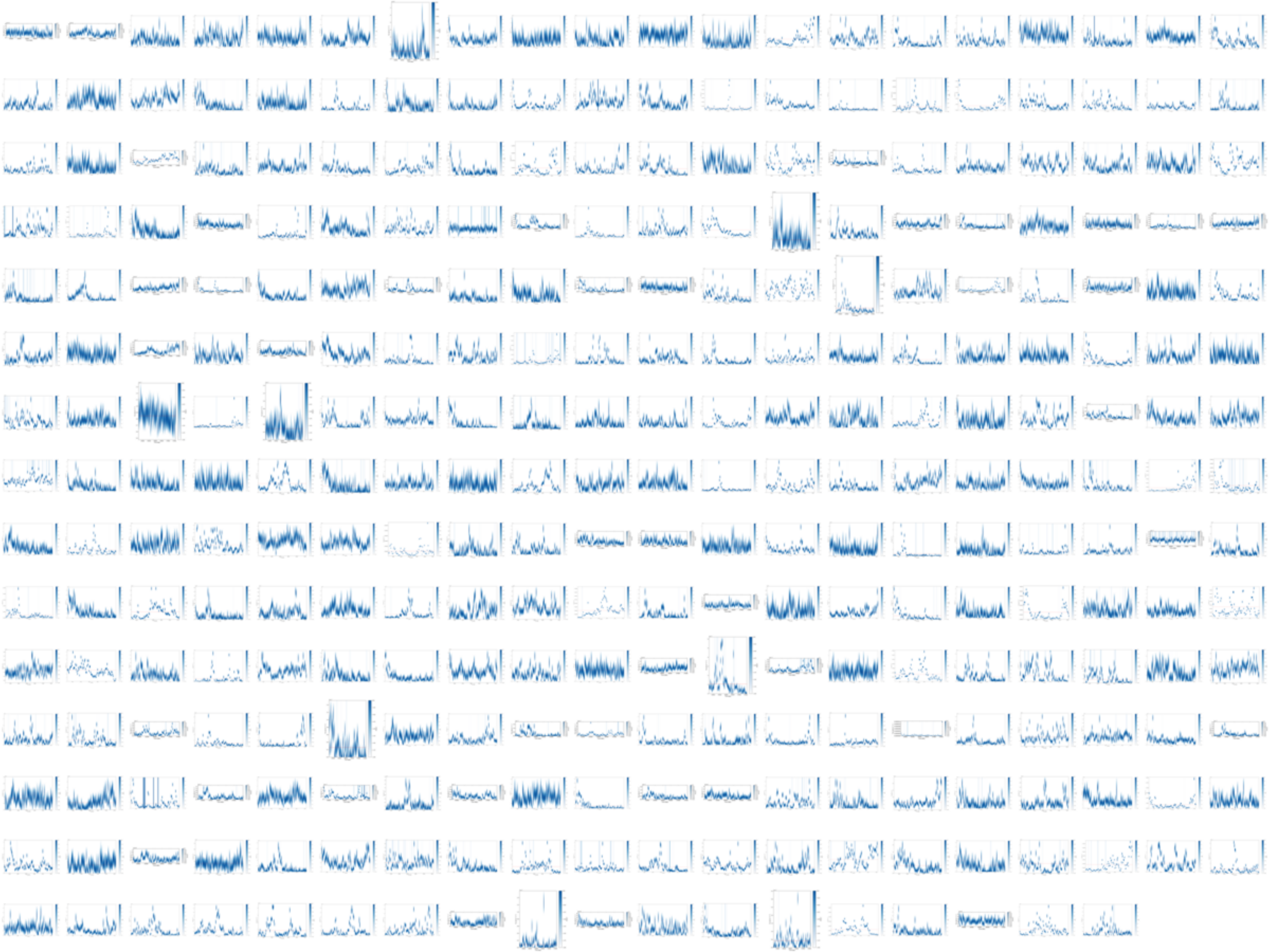


Temporal Variability

- In previous studies of the EBL by Fermi, a cut on the sources variability was included (TS_{var} < 72.44).
- We include the same cut, and additionally compute the lightcurves for each source. Re-evaluating TS_{var} for the larger data
- Distributed as χ^2 with 96 degrees of freedom



$$TS_{var} = 2\sum_i [\,\log L(\mathrm{F}_i) - \log L(\mathrm{F}_{const})\,]$$



Spectral Variability

- One reason for the cut on temporal variability is to attempt to remove sources that will have periods of differing flux, and therefore potentially spectral characteristics that are convolved in the full analyses.
- We aim to study this further by defining the parameter $TS_{spec\ var}$

$$TS_{spec\ var} = 2\sum_i [\ \log L(\Gamma_i) - \log L(\Gamma_{const})\ ]$$

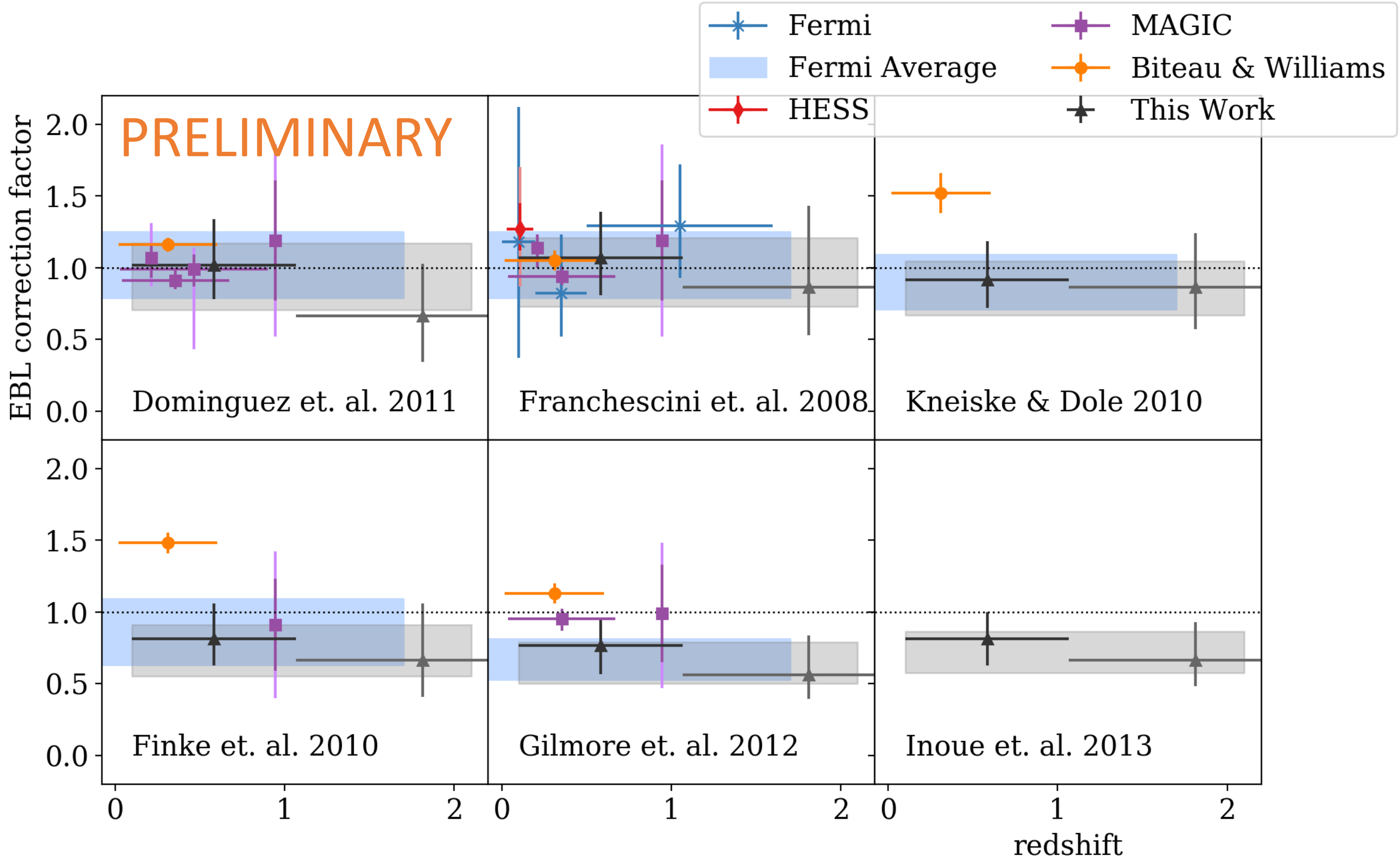
- Monte Carlo validation of statistic is ongoing

Preliminary Results

- σ_{var} *and* $\sigma_{specvar} < 8$
  - Needs evaluating

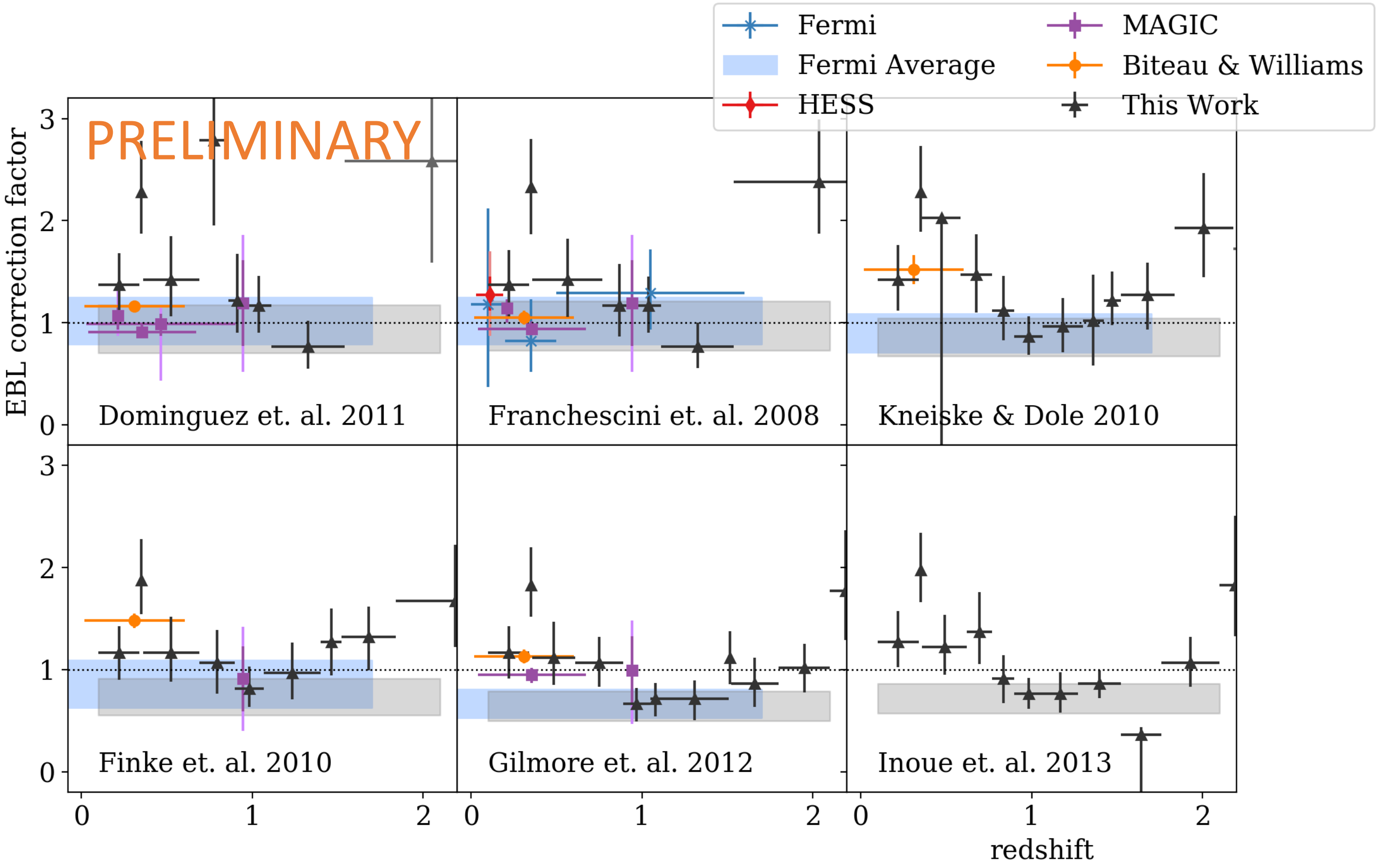
- $\alpha_{DOM} = 0.916 + 0.257 - 0.212$
- $\alpha_{FRA} = 0.966 + 0.242 - 0.239$
- $\alpha_{K\&D} = 0.865 + 0.180 - 0.195$
- $\alpha_{FIN} = 0.713 + 0.196 - 0.162$
- $\alpha_{GIL} = 0.612 + 0.178 - 0.114$
- $\alpha_{INO} = 0.713 + 0.151 - 0.141$

- Still need to look at systematics:
  Redshifts
  Analysis technique (validation)
  Variability



Preliminary Results

- No cut applied on TS_{var} or $\sigma_{specvar}$
- Seems to be strong dependence on Variability
- Next step is to look at non variable periods for each source (combined)



Summary + Next Steps

- Have derived EBL correction factors for range of models
- Calculated the temporal and spectral variability
- Results only slightly better than previous Fermi-LAT results

- Confirm reference distribution for $\Delta TS_{spec\ var}$ with MC
- Calculate redshifts from EBL (identify bad redshifts?)
- Bin the data in non-variable time periods as identified by TS_{var}

Still lots to do!

Backup

Non Variable Sources Over Time