Quiz Time!

Name this instrument

Using VERITAS Observations of HBLs to Constrain the Extragalactic Background Light

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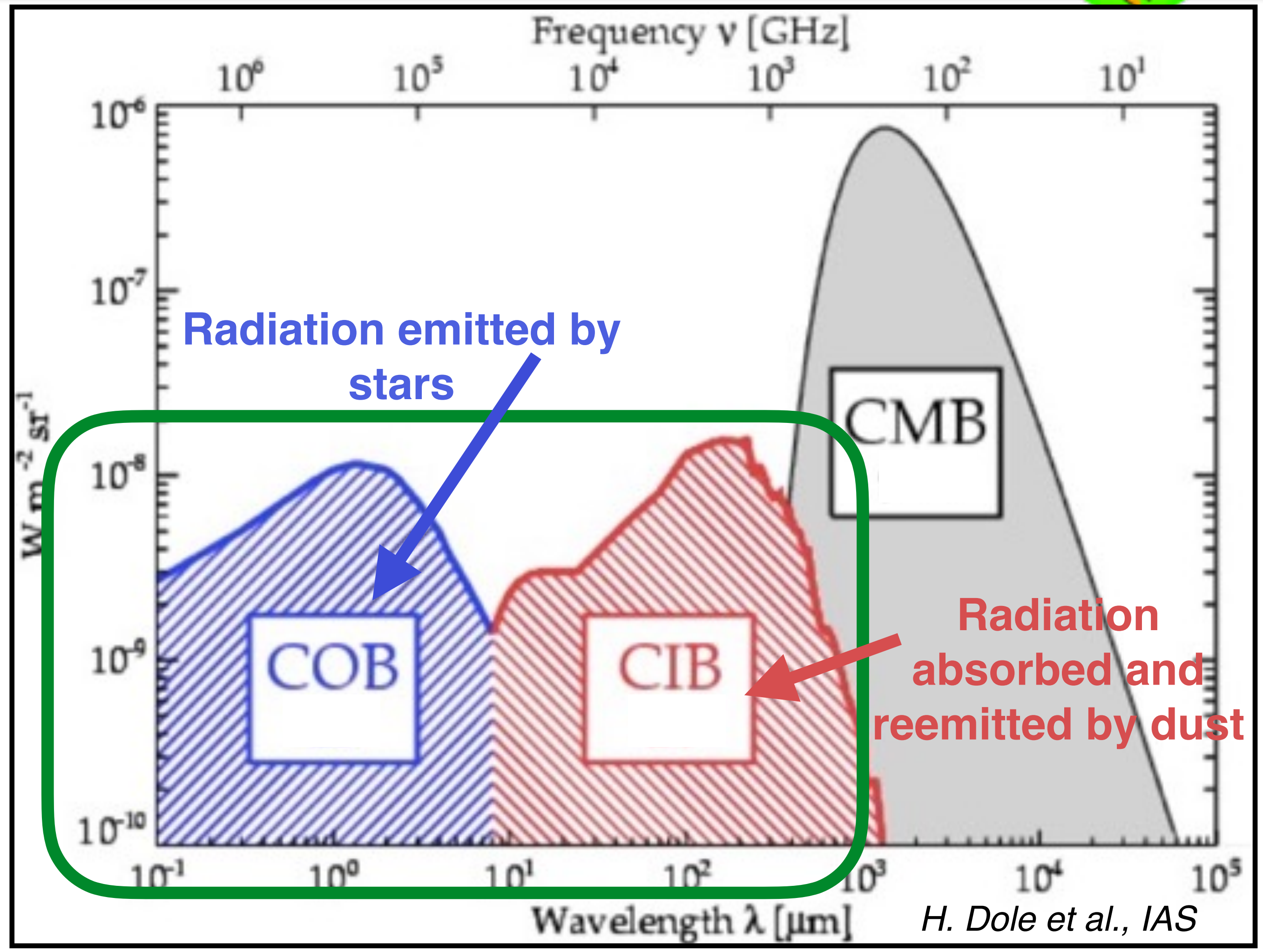
This Study

- Analyse HBLs observed by VERITAS and obtain the spectral and temporal properties
- Use a binned likelihood analysis to allow the highest energies and opacities to be probed
- Test multiple EBL models constructed using splines
- Rule out EBL models which result in an unphysical energy spectrum

Extragalactic Background Light

- Second most intense source of cosmological background radiation.
- Consists of the redshifted radiation emitted across all epochs.
- The SED is expected to have a two peak structure.
- Of great cosmological significance, contains the history of star formation and the imprint of the first stars (Pop III)



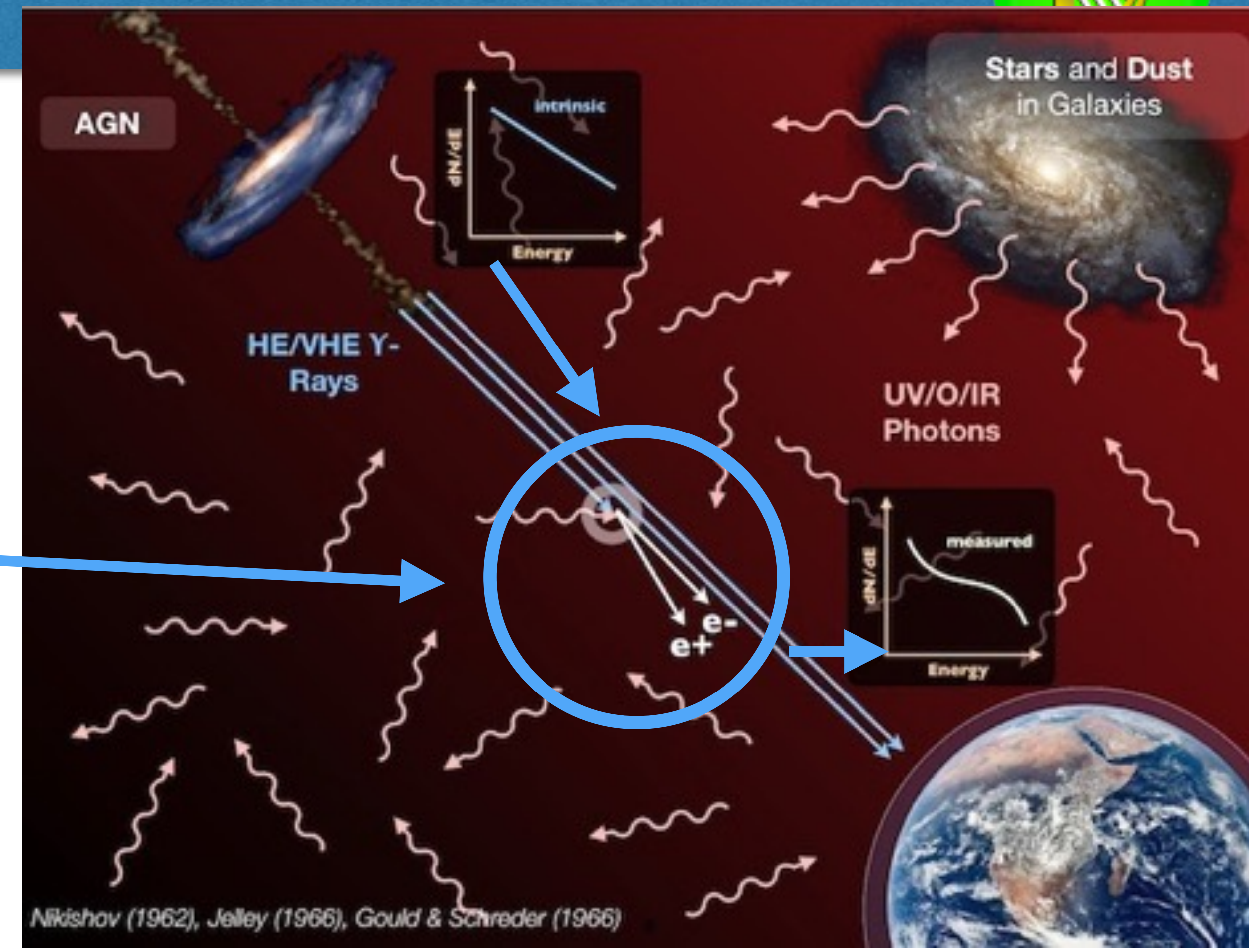
EBL Model	Overview
Gilmore et al 2012	Forward Evolution based on cosmological initial conditions and galaxy formation models
Franceschini et al 2008	Backwards Evolution based on source counts extrapolated backwards
Finke et all 2010	Inferred galaxy evolution based on measured qualities (e.g. star formation rates)

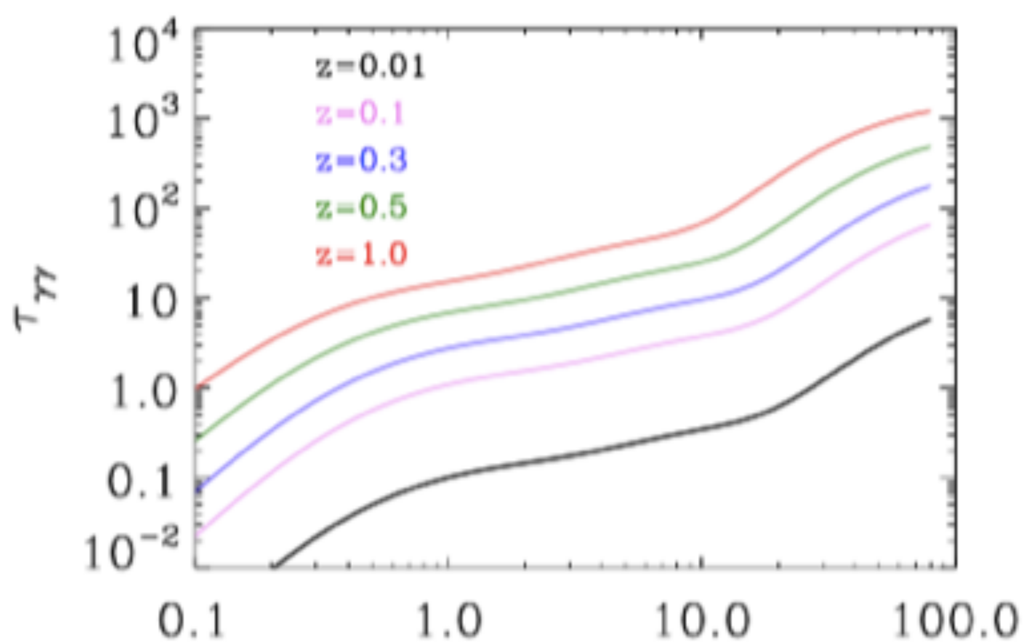
Extragalactic Background Light

- VHE (E > 100 GeV) photons can interact with EBL photons via photon-photon interactions.
- This attenuates the VHE flux from distant objects.
- Peak cross section occurs at (Mazin et al (2007)):

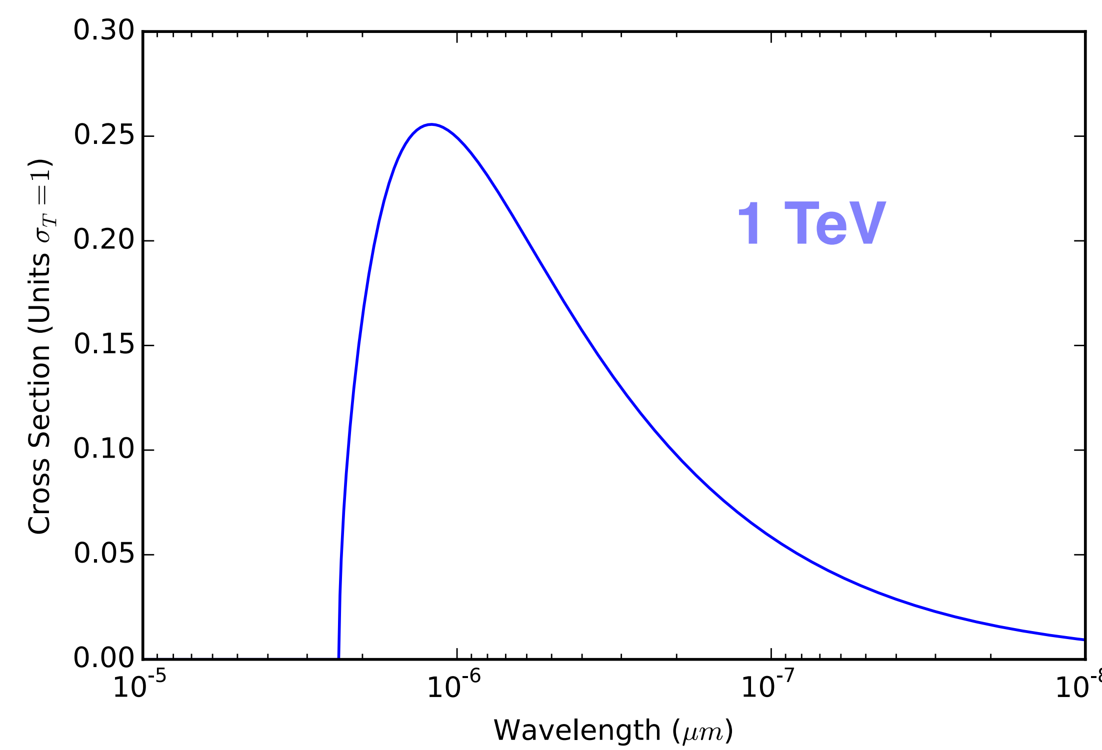
$$\lambda_{Max}(\mu m) \approx 1.24\ E_{\gamma}(TeV)$$

- This results in a γ-ray horizon.





Dwek and Krennrich, 2012



Constraining the EBL

VHE observations of HBLs can be used to constrain the EBL by rejecting EBL models which result in unphysical intrinsic spectra

$$\left(\frac{dN}{dE}\right)^{obs} = \left(\frac{dN}{dE}\right)^{int} e^{-\tau(E,z)}$$

Where the optical depth τ,can be determined for a given EBL model (Dwek and Krennrich, 2012):

EBL photon density

Interaction angle

$\mu = \cos\theta$

Interaction cross section

Constraining the EBL

- Adopt a Mazin et al (2007) approach
- EBL models constructed using a grid as supporting points for splines
- Multiple models and shapes testable
- Spectra can be deabsorbed for each model
- Using a binned likelihood fit test the feasibility of the spectra by extrapolating the Fermi spectrum
- Use a large multi-source dataset (> 1000 hours) to reduced individual source effects

Mazin et al (2007)

HBLs with VERITAS

- VERITAS plans obtain deep exposures (200 hours each) on a number of Blazars, as part of it's long term plan
- Select a number of these blazars across a range of redshift
- Analyse the spectral and temporal properties of these sources

Source	Redshift	Exposure Hours* (A/B Weather)
1ES 1215+30	0.13	125.9
1ES 1218+304	0.182	138.6
PKS 1424+240	>0.6	180.1
H 1426+428	0.129	80
PG 1553+113	0.5	123.8
1ES 1959+650	0.048	24.1
1ES 2344+514	0.044	43.5
RGB J0710+919	0.125	125.1

*as of March 2016

Binned Likelihood Analysis

- We need to specify the model, $\left(\frac{dN}{dE}\right)^{pred}$ and how many excess counts it predicts, S^{pred}
- For a single energy bin at a particular zenith angle, noise level and wobble offset the model-predicted excess if given by Piron et al (2001):

Observation Duration **Total Model-Predicted Counts** **Response Matrix**

$$S^{pred} = Ton \int_{\tilde{E}_{min}}^{\tilde{E}_{max}} d\tilde{E} \int_0^{\infty} \left(\frac{dN}{dE}\right)^{pred} A_{Eff}(E)\Gamma(E \to \tilde{E})dE$$

Reconstructed Energy Bin **Effective Area**

$\Gamma\left(E \to \tilde{E}\right)$ Probability of measuring a photon with true energy E to have a reconstructed energy $\tilde{E}$

$\tilde{E}$ = Reconstructed Energy

E = True (Monte Carlo) Energy

Taking into account EBL attenuation we have:

$$\left(\frac{dN}{dE}\right)^{pred} = \left(\frac{dN}{dE}\right)^{intrinsic} e^{-\tau(E,z)}$$

Hence:

$$s^{pred} = T_{on} \int_{\tilde{E}_{min}}^{\tilde{E}_{max}} d\tilde{E} \int_0^{\infty} \left(\frac{dN}{dE}\right)^{intrinsic} e^{-\tau(E,z)} A_{Eff}(E)\Gamma\left(E \to \tilde{E}\right) dE$$

Fixed **Free** **Fixed** **Fixed**

Binned Likelihood Analysis

Looping Over each run and energy (azimuth, noise, zenith,….) bin
the log-likelihood is calculated by:

$$\log \mathcal{L}(\{\Lambda\}) = \sum_{i}^{NRuns} \sum_{j}^{Energy\ Bins} \Big[On_{i,j} \log(S_{i,j}^{Pred} + \alpha_{i,j} \hat{\hat{Off}}_{i,j}) + Off_{i,j} \log(\hat{\hat{Off}}_{i,j}) - (\alpha_{i,j} + 1)\hat{\hat{Off}}_{i,j} - S_{i,j}^{Pred} \Big]$$

$On_{i,j}$ = # On Counts $\hat{\hat{Off}}_{i,j}$ = Model predicted average off counts

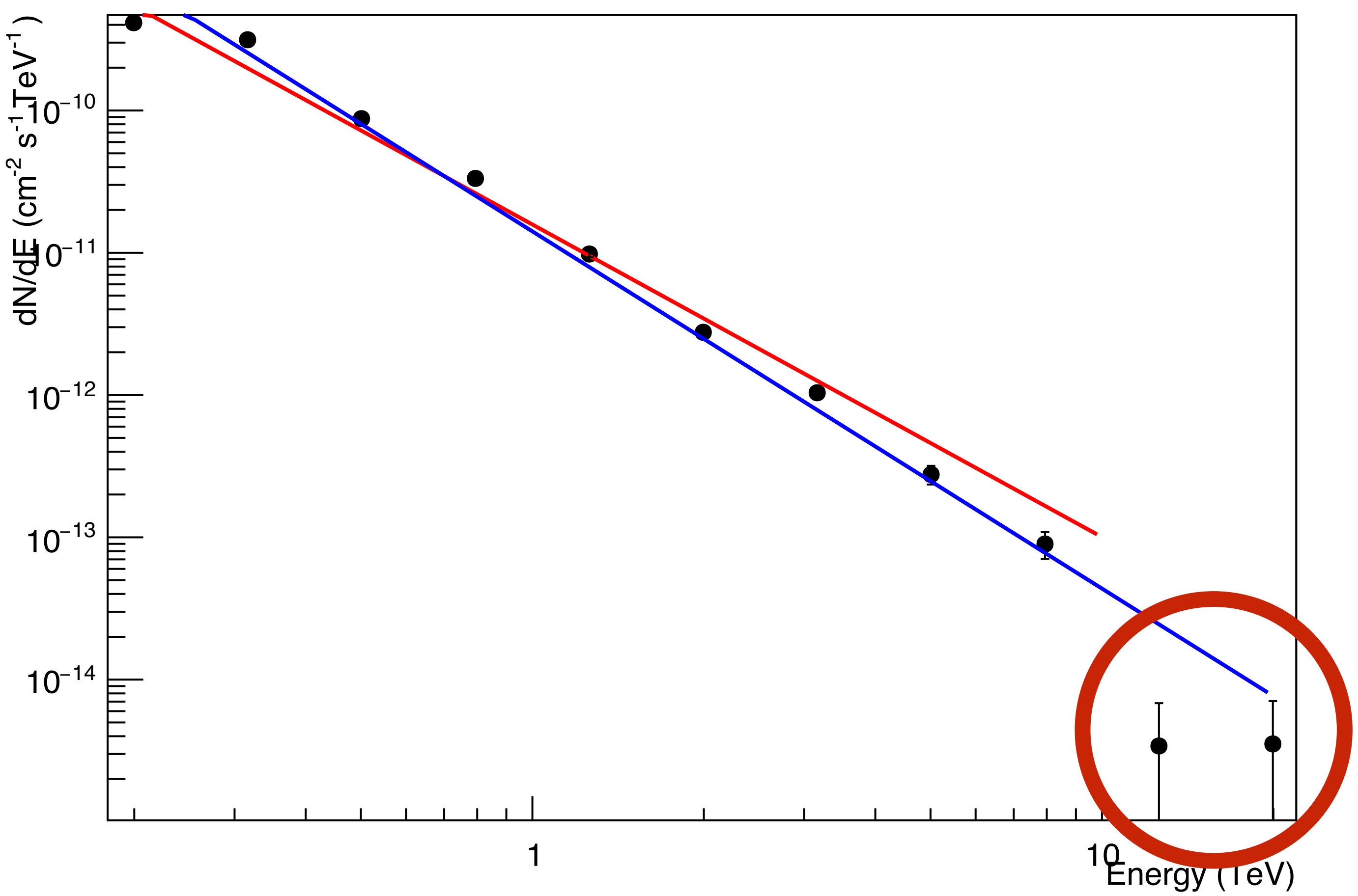
$Off_{i,j}$ = # Off Counts $\alpha_{i,j}$ = Ratio of On/Off exposure

By maximising the above equation we can obtain the MLE for the model parameters $\hat{\Lambda}$

Sanity Test

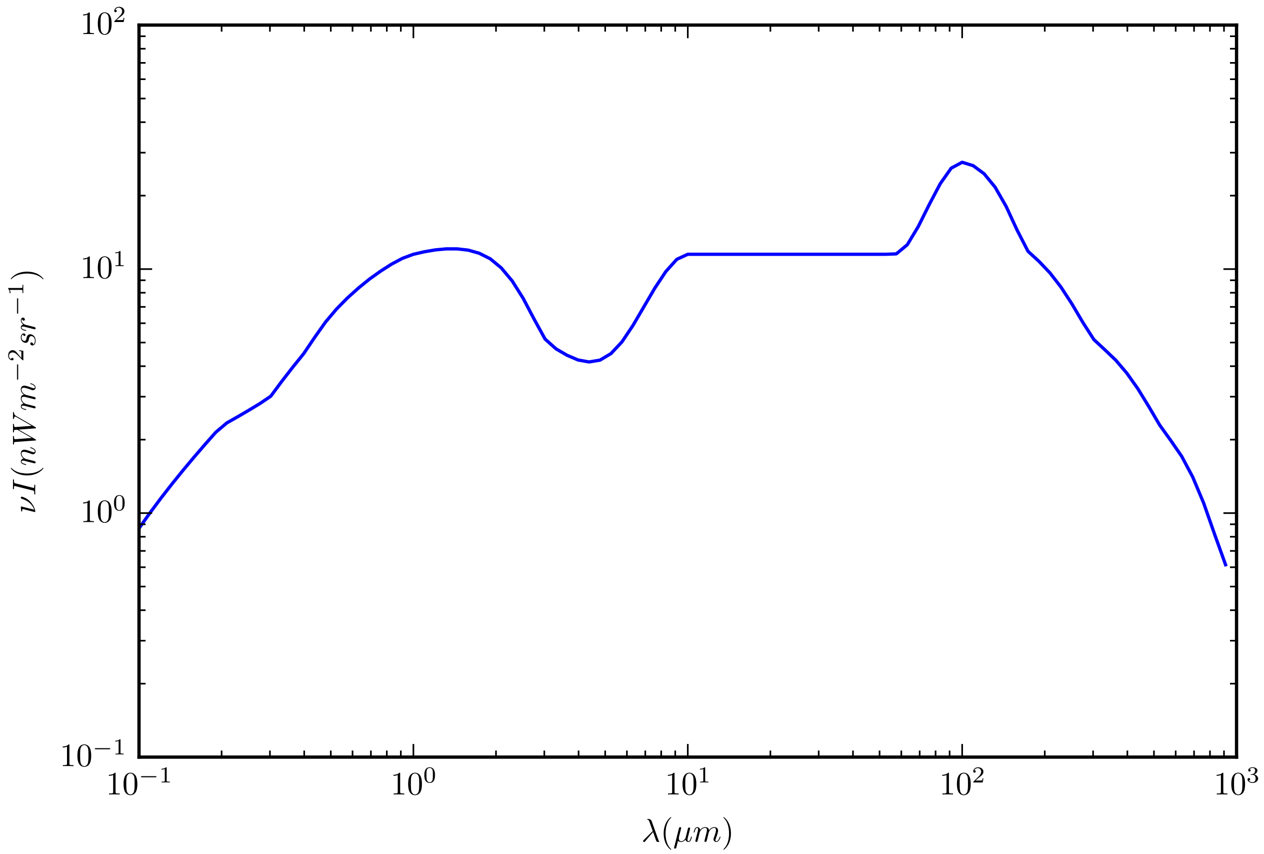
- 11.5 hours of Simulated Crab-like Observations
- Artificial curvature added
- Only statistical errors considered
- Fit both with a power law
- Excluding final energy points artificially hardens spectrum

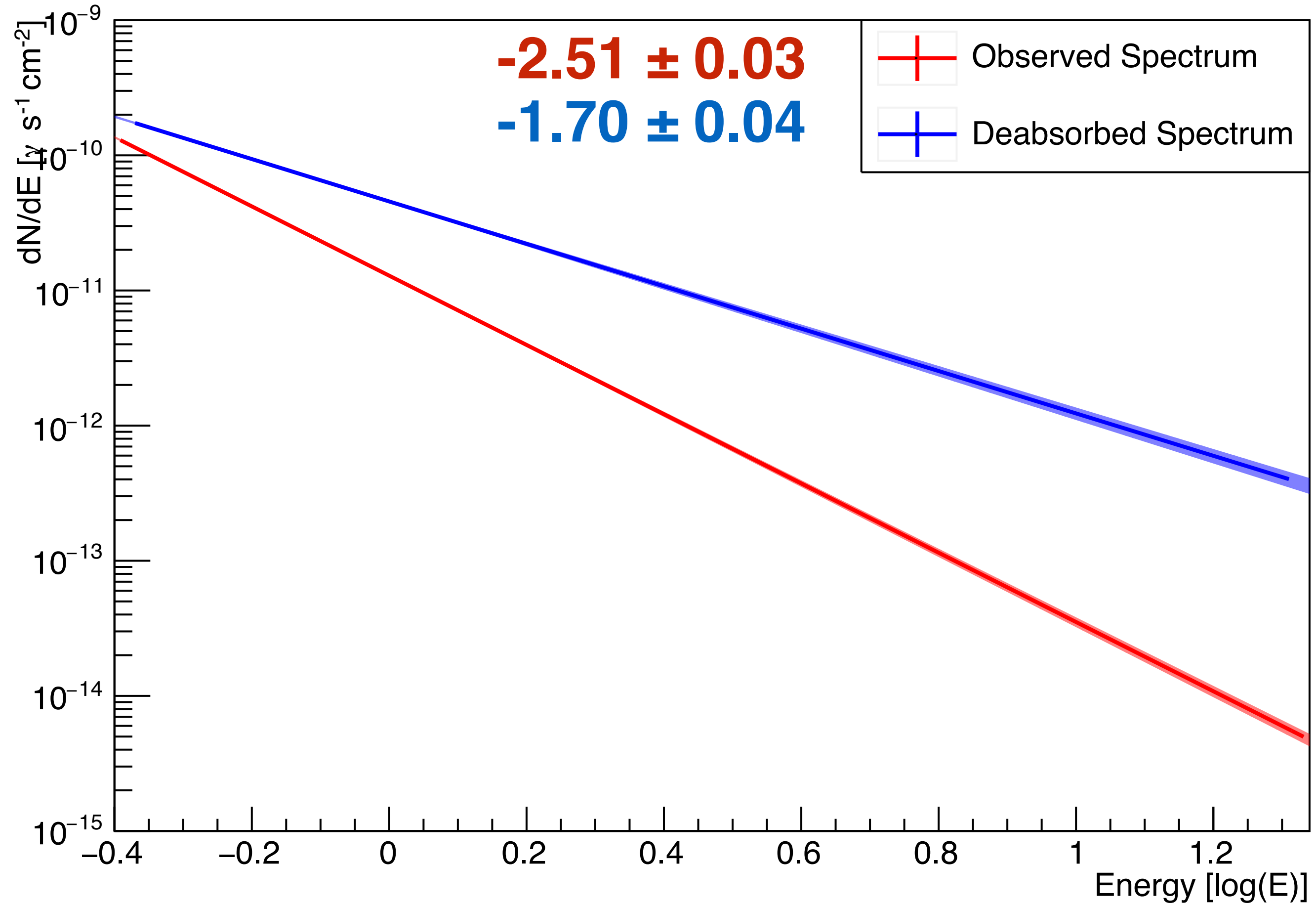
Fit Type	Normalisation (cm^{-2} s^{-1} TeV^{-1})	Spectral Index
Chi^2	(1.58 ± 0.03) x 10^{-11}	-2.2 ± 0.01
Likelihood	(1.41 ± 0.03) x 10^{-11}	-2.51 ± 0.03



Non Gaussian Statistics
 # Counts < 5
Significance < 2

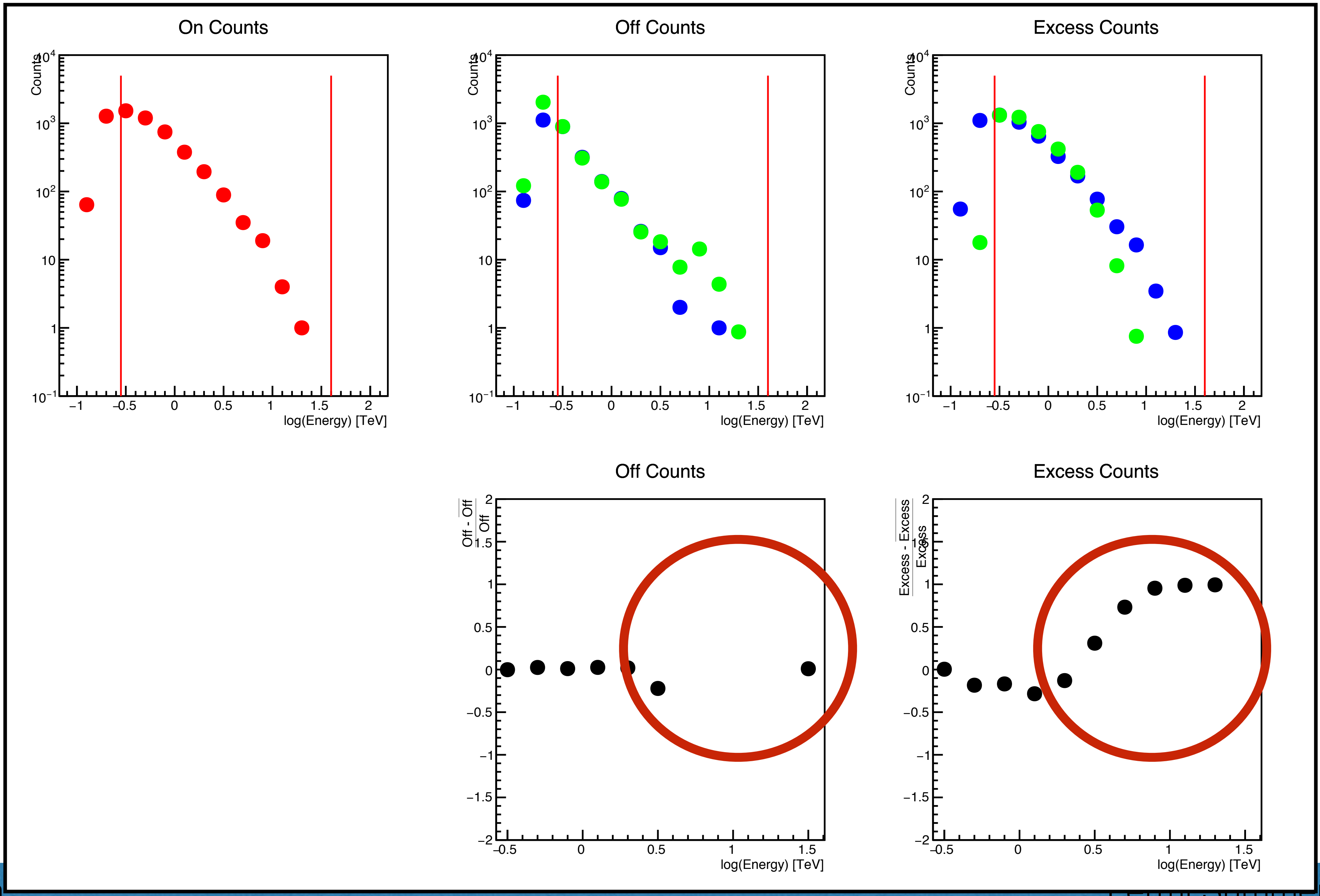
Assume our Crab-like source is at a redshift of z = 0.04





Sanity Test

But the Crab is not at z = 0.04!



Future Plans

- Complete study of binned likelihood method and systematics
- Reduce and analyse large (> 1000 hours) datasets
- Analyse Fermi data to obtain simultaneous spectra
- Test intrinsic spectra to remove EBL models
- Apply joint likelihood fit to obtain a best fit EBL model

Questions/Comments

The view from the top of Mt Hopkins