Measurement of the Extragalactic Background Light with VERITAS

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Extragalactic Background Light

Light from reionization, star formation, galaxy evolution, emission by active galactic nuclei

- COB = Cosmic optical background
- Light from stars, galaxies, etc

- CIB = Cosmic infrared background
- Light reprocessed by dust

*Connection to other diffuse fields (X-ray, radio, neutrino)
Indirect Measurements of EBL with Gamma-ray Emitters

Photons from distant gamma-ray sources interact with EBL photons via pair production, VHE $\gamma$-ray flux attenuated.
TeV Transparency

- Optical depth $\tau$ increases with energy and redshift
  - Depends on $\gamma\gamma$ interaction cross-section and number density of EBL photons (product integrated over distance, energy and angle)

To probe full EBL spectrum, need gamma-ray sources emitting to high energies, located out to large distances
Probing the EBL Spectrum

\[ \lambda_{\text{EBL}} \simeq 0.5 - 5 \, \mu m \times \left( \frac{E_\gamma}{1 \, \text{TeV}} \right) \times (1 + z)^2 \]

\[ \text{W m}^{-2} \text{sr}^{-1} \]

\[ \text{W m}^{-2} \text{sr}^{-1} \]

Dominated by distant sources

Dominated by (relatively) nearby and "extreme" sources

Dole 2006

CMB

COB

CIB

Wavelength \( \lambda \) [\( \mu m \)]

Frequency \( \nu \) [GHz]

**References**


Probing the EBL Spectrum

\[ \lambda_{\text{EBL}} \simeq 0.5 - 5 \mu m \times \left( \frac{E_{\gamma}}{1 \text{ TeV}} \right) \times (1 + z)^2 \]

Best measurements from Fermi-LAT!

Dominated by distant sources

Dominated by (relatively) nearby and “extreme” sources

Wavelength [\mu m]

\[ 10^{-1} \quad 10^{0} \quad 10^{1} \quad 10^{2} \quad 10^{3} \quad 10^{4} \quad 10^{5} \]

\[ 10^{-10} \quad 10^{-9} \quad \text{W m}^{-2} \text{ sr}^{-1} \]

\[ 10^{0} \quad 10^{1} \quad 10^{2} \quad 10^{3} \quad 10^{4} \quad 10^{5} \]

\[ \lambda_{\text{EBL}} \]

\[ E_{\gamma} \]

\[ (1 + z)^2 \]

\[ \text{CMB} \]

\[ \text{COB} \]

\[ \text{CIB} \]
EBL Measurements with Blazars

- Gamma-ray emission to > 1 TeV
- Detected to high redshifts (e.g. PKS 1424+240 @ z=0.604)
- Confounding factors
  - Intrinsic spectral curvature/cut-offs
  - Extreme flux variability, spectral variability
  - Redshift measurements
Veritas Instrument

**VERITAS Instrument**

- **very-high-energy γ-ray**
- **air shower**
- **Cherenkov light pool**
- **Telescope field of view**
- **Multiple telescopes for stereoscopic imaging**
- **Photomultiplier tube cameras for faint & fast signal**

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**FLW Observatory in southern AZ**

- **Energy range:** ~85 GeV - 30 TeV
- **Angular resolution:** 0.1° @ 1 TeV
- **Field of view:** 3.5°

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Credit: J. Holder
VERITAS source sample

* High & low states treated separately

redshift

0
10^{-1}

[Graph showing detection significance vs. redshift for various sources, including PKS 1424+240, PG 1553+113, 3C 66A*, 1ES 0502+113, and other sources. The graph includes notes about high and low states treated separately.]
VERITAS EBL Measurement

- Generic EBL shapes @ z=0
- Redshift evolution tuned to track theoretical models
- Calculated opacities used to correct observed spectra
VERITAS EBL analysis

Input:
- Observed spectrum
- Opacity graphs
- Weight file

Fit observed spectrum w. power law flag if good

Interpolate to find \( \tau \) for source redshift, energy of spectral points

Fit deabsorbed spectrum
- Power law only if observed fit by PL
- Otherwise PL, PL+exp. cutoff, log parabola
- Require \( \Gamma_{\text{deabs}} > 1.0 \)

Output: \( \exp(-\chi^2/2) \)-weighted distribution of model intensities at different \( \lambda_{\text{EBL}} \)
Systematic uncertainties & stability

Systematic uncertainties

- Number of EBL shapes considered
- Energy scale uncertainty
- Uncertainty in redshift evolution
- Sources with uncertain redshift

Robustness check

- Remove sources one by one
VERITAS EBL Measurement in Context

ICRC 2019

VERITAS 68% containment
Biteau&Williams 2015
H.E.S.S. 2017
MAGIC 2019
Gilmore 2012 Fiducial
Is the EBL resolved?

Stellar SED at each redshift, and an LMC extinction law was applied to model the spectrum of the reradiated IR emission. The model reproduces various observational constraints, including the comoving radiation background at rest-frame 0.44, 1.0, and 2.2 μm. A power-law distribution in dust temperature was used to calculate the amount of starlight that is absorbed by dust, and the spectrum of the reradiated IR emission. The model reproduces various observational constraints, including the comoving radiation background at rest-frame 0.44, 1.0, and 2.2 μm.

5.4. Semi-analytical (SA) models

SA models are inherently complex, incorporating a large number of microscopic and large scale parameters needed to calculate the evolution of the stellar radiation field, the heating and cooling of the interstellar medium and its chemical enrichment, the expansion, absorption, and supernovae feedback processes that quench their formation, and the growth of the central black hole. A detailed description of recent developments and references to previous analysis can be found in Dwek & Krennrich (2013).

The attenuation of the ISM gas as determined by many different processes: their number counts and luminosity function in different wavebands and redshifts, their mass function, the cosmic star formation rate, the growth of the central black hole, and the fraction of the infalling gas that determines the intergalactic medium through infall and galactic winds, and the growth of the central black hole. A power-law distribution in dust temperature was used to calculate the amount of starlight that is absorbed by dust, and the spectrum of the reradiated IR emission. The model reproduces various observational constraints, including the comoving radiation background at rest-frame 0.44, 1.0, and 2.2 μm.

5.5. Comparison of model predictions with observations

A detailed comparison of all model types with EBL limits and EBL. In general, all models, except for the BE models of Stecker et al. 2010, failed to reproduce various observational constraints, including the comoving radiation background at rest-frame 0.44, 1.0, and 2.2 μm. A detailed comparison of all model types with EBL limits and EBL. In general, all models, except for the BE models of Stecker et al. 2010, failed to reproduce various observational constraints, including the comoving radiation background at rest-frame 0.44, 1.0, and 2.2 μm.

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Still have work to do at large λ_{EBL}
Conclusions

• New VERITAS EBL measurement based on ~10 years of blazar observations

• VERITAS measurement consistent with lower limits on EBL intensity from galaxy counts

• VERITAS measurement consistent with theoretical predictions and other gamma-ray measurements

• What now?
  
  • **Longest wavelengths** still loosely constrained
  
  • Bright, nearby sources (Markarians, M87 flares?)