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# Gamma-ray Spectra and the Extragalactic Background Light

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**Abstract.** Attenuation of very high-energy gamma rays by pair-production with UV, optical and IR extragalactic background light (EBL) photons provides a link between the history of galaxy formation and gamma-ray astronomy. We present results from our latest semi-analytic models (SAMs), which employ the main ingredients thought to be important to galaxy formation and evolution, as well as an improved method for reprocessing of starlight by dust to mid- and far-IR wavelengths. These SAMs are based upon a hierarchical structural formation scenario, and are successful in reproducing a large variety of observational constraints such as number counts, redshift-dependent luminosity and mass functions, and color bimodality. Our fiducial model is based upon a WMAP5 cosmology and estimates the dust emission spectral energy distribution using templates based on Spitzer data. This model predicts a background flux considerably lower than found in optical and near-IR measurements that rely on subtraction of zodiacal and galactic foregrounds, and near the lower bounds set by number counts of resolvable sources at many wavelengths. We show predictions for the effect on extragalactic gamma-ray observations, and conclude with a discussion of the implications of our work and how the science of gamma-ray astronomy will continue to help constrain cosmology.

## 1. Introduction

The extragalactic background light (EBL) consists of photons emitted by galaxies over the history of the universe. Interactions between EBL photons and gamma rays can obscure gamma-rays sources, and produce a link between the history of galaxy formation and VHE (very high-energy) astrophysics. Direct measurement of the EBL (e.g. [1]) is difficult, and because the EBL is produced across cosmological time from all types of galaxies, sophisticated modeling is required to understand the buildup of this photon population. Modeling the sources of the EBL has been done historically using a variety of techniques, including evolution of galaxy properties that are either inferred over some range in wavelength [2, 3, 4] or directly observed in galaxy surveys [5, hereafter D11], backwards evolution models which assume that the redshift dependent evolution

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of galaxies can be found by applying a prescription to the local population [6, 7], or forward-evolution techniques, which model the growth of galaxies forward in time [8, 9, 10]. We present here an overview of results from our latest semi-analytic models [10, 11, 12] (SAMs), which employ the main ingredients thought to be important to galaxy formation and evolution, as well as an improved model for reprocessing of starlight by dust to mid- and far-IR wavelengths. Our semi-analytic method has the advantage of producing the evolution seen in galaxy properties in a natural way by modeling the population forward in time from the high-redshift early universe.

## 2. Methods

The SAMs used here are based on a ΛCDM cosmology [13, 14], in which galaxies form and develop in an underlying system of merging and growing dark matter halos [15]. Our assumed cosmology is based upon WMAP5 parameters [16]. A full description of the model is available in refs. [10] and [12]; the former includes a comprehensive comparison with available astrophysical data. Star formation in our model occurs in two modes, quiescent star formation in isolated galaxies and merger-driven starbursts. The chemical enrichment and star formation history of each galaxy are used to predict the stellar emission spectrum. We have adopted the stellar population models of [17] in this work, and a Chabrier [18] initial mass function.

The amount, composition, and evolution of dust in galaxies plays a crucial role in determining the overall spectrum of the EBL. Our model uses a self-consistent approach to the absorption and reemission of starlight by dust, with all absorbed radiative energy reemitted in the IR using spectral templates that are determined by the total galaxy IR luminosity. The absorption model is based on the 2-component prescription of [19]. We introduce an additional redshift-dependent parameter in our fiducial model to avoid overproducing dust in high-redshift galaxies and improve agreement with observed UV luminosity functions. IR spectra of reemitted light are modeled using the IR templates of [20], which are based on observations of local IR-luminous galaxies and utilize data from all three instruments on the Spitzer Space Telescope. Being observationally-based, these templates suffer from AGN contamination, and being based on low-redshift observations they may not correctly represent the properties of high-redshift star-forming galaxies, which produce a substantial fraction of the IR background. For comparison, we also show a model that is lacking the evolutionary term in the dust prescription, and uses dust reemission templates from the older work of [21]. This is to facilitate comparison with a scheme that more closely resembles the SAM results of [8, 9]. This model is designated DGS99 in the following figures.

## 3. Results

### *3.1. Astrophysical Results*

In the left-hand panel of Figure 1, we show the local background flux, as a function of wavelength, as well as two older SAM predictions and the observational model of D11. All these models predict a background flux at UV to near-IR wavelengths that is near the level set by galaxy number counts ([22, 23, 24]). In the IR, and particularly around the far-IR peak at $\sim 100$ $\mu$m, there is a considerable amount of divergence between the models. There is an especially striking discrepancy between the predictions of our fiducial model and the observational model of D11, which predicts a factor $\sim 2$ higher contribution to the far-IR from rapidly star-forming galaxies. The DGS99 model shows a somewhat different shape in the mid- and far-IR, where the templates of [21], used in our previous work, have a substantially different spectral shape than the newer Spitzer-based templates of [20]; more discussion of this comparison can be found in [10]. The SAM prediction of [8] utilized a less-sophisticated dust absorption model in its galaxy treatment, and consequently underpredicts the background at wavelengths longer than 8 $\mu$m.

The right-hand side of Figure 1 shows how the emissivity of galaxies evolves as a function of redshift. In the high-redshift UV, our fiducial model is found to match the data of [25] and

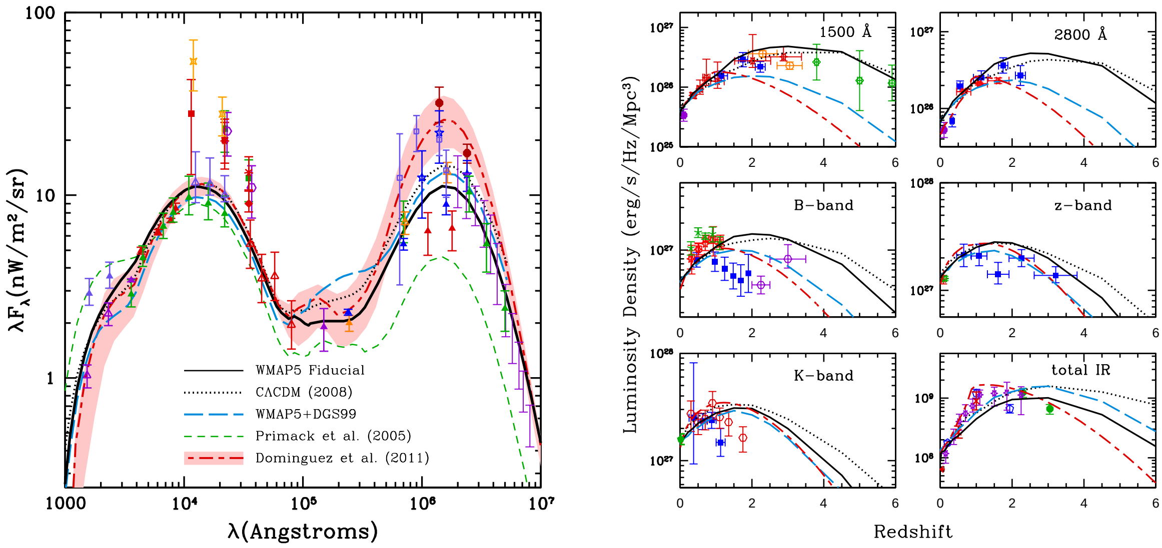


**Figure 1. Left:** The EBL predicted in our fiducial SAM and the 'DGS99' model. Shown for comparison are the models of [9] (CLCDM), the observational model of D11 with its associated error band, and [8]. Upward-pointing arrows are lower limits on the EBL from number counts seen in galaxy surveys, while other symbols are direct flux measurements. A complete list of the references for these data points can be found in [11].
**Right:** The evolving luminosity density in the universe at 5 wavelengths, and for all reemitted light in the IR. Note that for the latter, the y-axis has units of solar luminosities per Mpc$^3$. Line types here are as in the opposite panel. As before, observational references for this plot can be found in in [11].

others better than the DGS99 or D11 models, though this contribution has a minimal impact on the local background flux. The difference between the DGS99 and fiducial models is due entirely to the differing treatments of dust described in the last section. In the IR, the D11 model predicts a total flux that rises considerably faster with redshift than in any of our semi-analytic calculations. Several authors (e.g. [26, 27]) seem to support this rapid rise in IR output, and matching this fast evolution is an ongoing challenge for our semi-analytic models.

### *3.2. Gamma-ray Attenuation*

Photon-photon interactions with sufficient center-of-mass energy can create electron-positron pairs. For multi-GeV and TeV gamma rays, interactions with UV and IR background photons can create an optically-thick barrier to passage over cosmological distances [28, 29]. This effect has been used by a variety of authors in recent years to constrain the EBL and disfavor or exclude specific models [30, 31, 32, 33, 34]. In the left-hand panel of Figure 2, we show the impact of gamma-ray attenuation as a function of observed energy for the models of the previous section. Increasing distance causes absorption features to increase in magnitude and appear at lower energies. The plateau seen between 1 and 10 TeV at low redshift is a product of the mid-IR valley in the EBL spectrum, and the large photon density in the far-IR peak produces a cutoff at higher energy. The fiducial SAM model predicts less attenuation at multi-TeV energies than the best-fit prediction of the D11 observational model, as opacity at these energies is mainly due to mid- to far-IR photons. At lower sub-TeV energies, where gamma rays have only enough energy to scatter off of UV and optical background photons, the situation is reversed and our fiducial model produces more attenuation than either D11 or our DGS99 model. UV emission is

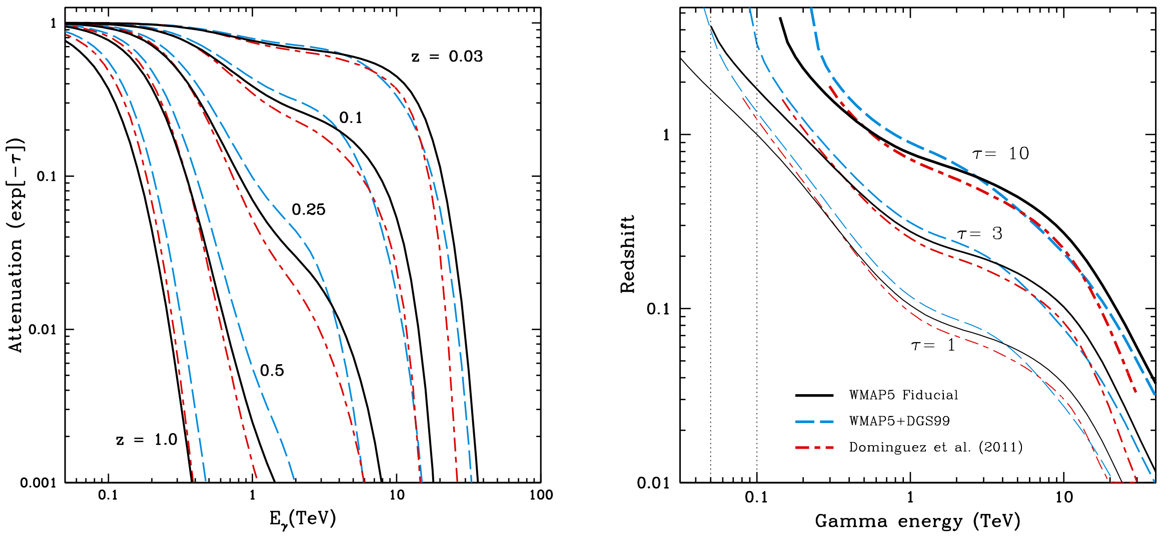


**Figure 2. Left:** The attenuation $e^{-\tau}$ of gamma rays vs. gamma-ray energy, for sources at $z = 0.03$, 0.1, 0.25, and 0.5, and 1. Results are compared for our fiducial (solid) and DGS99 (dashed blue) models, as well as the model of D11 (red dash-dotted).
**Right:** The gamma-ray attenuation edges for the fiducial (solid black) and DGS99 (dashed blue) models and model of D11 (red dash-dotted). The curves show the redshift at which the pair-production optical depth $\tau$ reaches the indicated value for a particular observed gamma-ray energy. The triplets of curves from lower left to upper right are the contours for $\tau = 1$, 3, and 10. We have included thin dotted lines to guide the eye at 50 and 100 GeV.

more suppressed by dust in these cases, and the UV EBL does not evolve as strongly in redshift. The right-hand panel of this plot is the 'attenuation edge', meaning the source redshift above which gamma rays suffer more attenuation than a given value. Contours here represent limits of $\tau = 1$, 3 and 10, corresponding respectively to modifications of the intrinsic flux by factors of 0.37, 0.05, and 0.000045. The thin dotted vertical lines on this plot at 50 and 100 GeV show the typical energy thresholds of current-generation ground-based atmospheric Cherenkov telescopes. The H.E.S.S. and VERITAS telescope arrays have typically claimed thresholds of $\sim$ 100 GeV, and the MAGIC telescope has viewed sources at energies as low as 50-60 GeV. The proposed CTA experiment will have a threshold below 50 GeV [35]. Our results suggest that the EBL will create a significant barrier to observations in the lower part of the CTA energy range only for source redshifts well above unity.

Figure 3, left panel, shows how the spectra of known gamma-ray blazars observed by ground-based Cherenkov telescopes are affected by the cumulative impact of our predicted EBL, including the evolution in redshift. As discussed in [31], a standard assumption in blazar emission scenarios is that the VHE spectra cannot be harder than $\Gamma = -1.5$, with $dN/dE \propto E^{-\Gamma}$. In the figure, the hardening of spectra resulting from de-convolving with our assumed EBL models is shown compared with the blazar redshift. More details on this and a data table with blazar information can be found in [11]. We find that our models are consistent with this standard assumption.

## 4. Discussion

The EBL presents one of the primary barriers to extragalactic gamma-ray astronomy with ground-based instruments. Our determination of a fairly low extragalactic background across

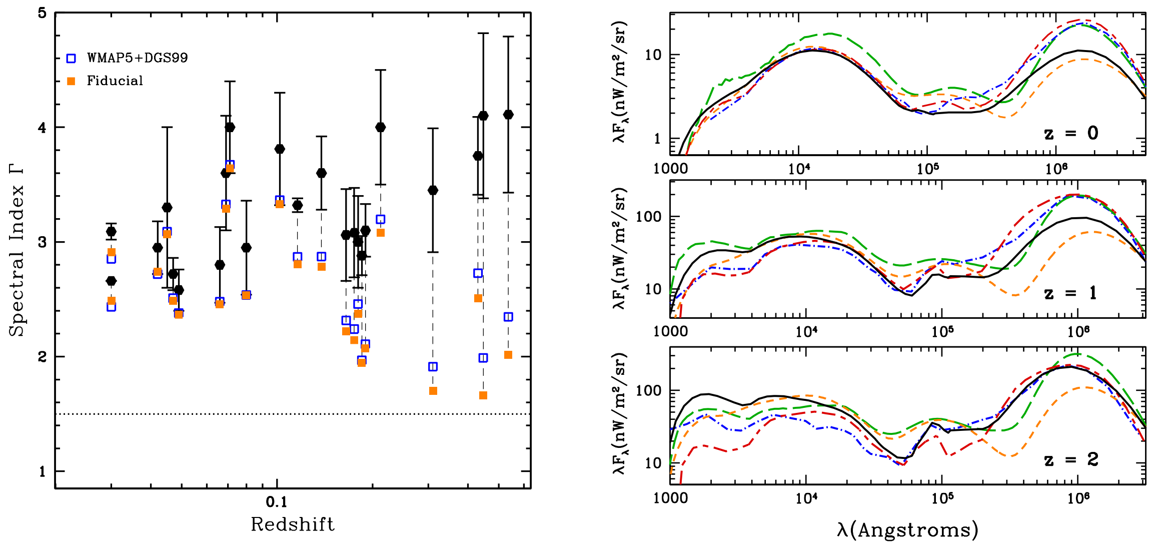


**Figure 3. Left:** Spectral corrections for our two semi-analytic EBL predictions to the measured spectral indices of gamma-ray blazars. The measured spectral index ($\Gamma$; $dN/dE \propto E^{-\Gamma}$) and redshift of each blazar is shown as a black hexagon with error bars, with the index corrected via the fiducial EBL shown as a solid orange point, and that corrected by the DGS99 model as an open blue point. The horizontal dotted line shows $\Gamma = 1.5$, which is typically taken as the hardest spectrum possible under usual assumptions. Some points have been shifted sideways slightly for readability.
**Right:** Our EBL predictions compared with several recent models from the literature. The solid black line shows the proper flux density from our WMAP5 model in the local universe and at $z = 1$ and $z = 2$. Other lines are from [7] (dashed-dotted blue), the best-fit model of [2] (long-dashed green), D11 (long-short dashed red), and model 'C' from [4] (dashed orange).

the optical and near- to mid-IR, supported by convergence with alternative methods such as [7] and D11, is an optimistic prediction for the future of the field. The weight of this evidence also increasingly points to an EBL that is well-known over this wavelength range, at a level near that of resolved number counts, though many questions remain about its redshift evolution due to uncertainty in high-redshift data.

In the right-hand side of Figure 3, we show a full comparison with several other recent EBL models in the local universe, and at redshifts 1 and 2. While these models tend to agree well in local flux predictions across the UV to near-IR peak, there is a considerable discrepancy in how flux at these wavelengths evolves to higher redshift. Models which make very similar predictions at $z = 0$ can have diverging predictions at $z > 0$, due to differing treatments of galaxy evolution. Studying the attenuation of extragalactic gamma rays is one way to constrain these differing predictions. TeV sources have now been detected above redshift 0.5 by ground-based telescopes [33], and at these distances the differences in evolution between EBL models become important. Fermi LAT has detected multi-GeV blazars and GRBs at much higher redshifts [36, 37]. While the limits from the first-year of LAT observations [34] only constrain extreme scenarios, more data from Fermi, combined with upgraded ground-based telescopes or future proposed experiments such as CTA may put interesting constraints on background evolution.

In the far-IR, a factor $\sim 3$ uncertainty exists in the absolute level of the EBL. As our treatment of these wavelengths is still rather primitive, we hope to upgrade our models in the future to better replicate the SEDs of high redshift star-forming galaxies which produce a significant fraction of the long-wavelength background, and test our predictions against new Herschel data. Gathering more multi-TeV data on nearby blazars such as Mkn 421 ($z = 0.031$) and Mkn 501 ($z = 0.034$) could also help constrain the normalization of the far-IR peak, by exploring the details of the cutoff that the EBL induces on the spectra at 10 to 30 TeV.

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