ROYAL SOCIETY OPEN SCIENCE

rsos.royalsocietypublishing.org

Research

Article submitted to journal

Subject Areas:
Astronomy

Keywords:
Cosmology, galaxies: galaxy evolution

Author for correspondence:
Insert corresponding author name
e-mail: acooray@uci.edu

Extragalactic Background Light Measurements and Applications

Asantha Cooray

Department of Physics & Astronomy, University of California, Irvine, CA 92697

This review covers the measurements related to the extragalactic background light (EBL) intensity from gamma-rays to radio in the electromagnetic spectrum over 20 decades in the wavelength. The cosmic microwave background (CMB) remains the best measured spectrum with an accuracy better than 1%. The measurements related to the cosmic optical background (COB), centered at 1 μm, are impacted by the large zodiacal light associated with interplanetary dust in the inner Solar system. The best measurements of COB come from an indirect technique involving Gamma-ray spectra of bright blazars with an absorption feature resulting from pair-production off of COB photons. The cosmic infrared background (CIB) peaking at around 100 μm established an energetically important background with an intensity comparable to the optical background. This discovery paved the path for large aperture far-infrared and sub-millimeter observations resulting in the discovery of dusty, starbursting galaxies. Their role in galaxy formation and evolution remains an active area of research in modern-day astrophysics. The extreme UV background remains mostly unexplored and will be a challenge to measure due to the high Galactic background and absorption of extragalactic photons by the intergalactic medium at these EUV/soft X-ray energies. We also summarize our understanding of the spatial anisotropies and angular power spectra of intensity fluctuations. We motivate a precise direct measurement of the COB between 0.1 to 5 μm using a small aperture telescope observing either from the outer Solar system, at distances of 5 AU or more, or out of the ecliptic plane. Other future applications include improving our understanding of the background at TeV energies and spectral distortions of CMB and CIB.

THE ROYAL SOCIETY PUBLISHING

1. Introduction

The extragalactic background light (EBL) is the integrated intensity of all of the light emitted throughout the history of the universe across the whole of the electromagnetic spectrum. While EBL is sometimes defined as the extragalactic intensity spectrum from UV to infrared (e.g., see review in Dwek & Krennrich 2012), the total energy content of the universe in the electromagnetic spectrum spans close to 20 decades in the wavelength from gamma-rays to radio. Across this whole range, the EBL spectrum captures cosmological backgrounds associated with either primordial phenomena, such as the cosmic microwave background (CMB), or photons emitted by stars, galaxies, and active galactic nuclei (AGN) due to nucleosynthesis or other radiative processes, including dust scattering, absorption and reradiation. The EBL may also contain signals that are diffuse and extended, including high energy photons associated with dark matter particle decays or annihilation.

In the UV to infrared portion of the electromagnetic spectrum, the EBL spectrum captures the redshifted energy released from all stars and galaxies throughout the cosmic history, including first stellar objects, primordial black holes, and proto-galaxies. If precisely measured, the EBL spectrum can be used as a constraint on models of galaxy formation and evolution, while providing an anchor that connects global radiation energy density to star formation, metal production, and gas consumption. The microwave background spectrum at microns to mm-wave radio wavelengths, associated with CMB photons, has been measured to a precision better than a percent and is described by a black-body spectrum with a temperature of 2.7260 ± 0.0013 (Fixsen 2009). Such a measurement is facilitated by the fact that the CMB is the brightest of the EBL components with a factor of 30 to 40 higher energy density than the next brightest background at optical to infrared wavelengths. The CMB is also a well-known probe of cosmology. The anisotropies come from both primordial physics, at the epoch of last scattering when electrons and protons first combined to form hydrogen, or secondary effects during the propagation of photons. The latter includes effects associated with both gravitational and scattering effects. The angular power spectrum of CMB spatial anisotropies has now been measured down to a few arcminute scales with Planck and has been used to determine cosmological parameters such as the energy density contents, the spatial curvature, spectral index of primordial density perturbations laid out after an inflation epoch, among others.

Despite the limitations on the accuracy of existing EBL intensity measurements there have been some key breakthroughs due to intensity measurements of the sky. A classic example is the cosmic IR background (CIB) peaking at 100 μm. Its intensity was measured with instruments such as DIRBE (Hauser et al. 1998) and at wavelengths beginning 250 μm with FIRAS (Fixsen et al. 1998), both on COBE. The EBL intensity peaking at 100 microns was found to be roughly comparable to that of the optical background, suggesting that CIB at long wavelengths is energetically important as the optical/near-IR background dominated by galaxies. This then motivated high resolution far-infrared and sub-millimeter imaging from both space and ground and with increasing aperture sizes and sensitivity more of the CIB background has been resolved to point sources. These point sources are mainly dusty, star forming and starbursting galaxies at high redshifts (see review in Casey et al. 2014). Their role in galaxy formation and galaxy evolution remains one of the key topics in sub-mm astronomical observations today.

With a precise measurement of the EBL intensity spectrum, a cosmic consistency test can be performed as a function of the wavelength by comparing the integrated light from all galaxies, stars, AGN and other point sources, to the EBL intensity. Any discrepancies suggest the presence of new, diffuse emission that is unresolved by telescopes. The possibilities for new discoveries with profound implications for astronomy range from recombination signatures during reionization and diffuse photons associated with dark matter annihilation and their products. Related to the last scientific possibility important studies have been carried out, with more expected over the coming years, whether there is a diffuse signature at GeV energy scales

in the cosmic gamma-ray background (CGB) as measured by the Fermi-LAT that can be ascribed to dark matter (e.g., Ando & Ishiwata 2015).

In addition to the total EBL intensity significant information on the sources of emission and their nature comes from measurements that focus on the anisotropies of the intensity across the sky. These are in general quantified and measured in terms of the angular power spectrum or the correlation function. The well-studied example in the literature is the anisotropy power spectrum of the CMB, resulting in high-precision cosmological parameter measurements (e.g., Ade et al. 2015a). Anisotropy power spectra have also been measured for CIB, COB, and CGB leading to inferences on the properties of the source populations present at these wavelengths, especially on certain physical details related to the faint sources that are below the individual point source detection level.

The existing EBL intensity measurements are due to a combination of ground and space-based observations of the sky. Direct absolute intensity measurements must account for a variety of foregrounds both within the Solar system, such as Zodiacal light at optical and infrared wavelengths, to Milky Way, such as the Galactic emission at radio, infrared, X-ray or gamma rays. A good example of an indirect technique to measure EBL is the use of absorbed TeV spectra of individual blazars and other AGNs at cosmological distances to infer the number density of intervening infrared photons that are responsible of electron-positron pair-production by interactions with TeV photons. This has led to the best determined COB measurements in the literature, especially given the fact that modeling and removing Zodiacal light remains a challenge for direct EBL intensity measurements around 1 μm.

We summarize existing EBL intensity measurements in Figure 1 where we plot the spectral intensity λI_λ as a function of the wavelength λ. In this figure the area under each of the spectral components represents the total energy density associated with each of those backgrounds. Those values are listed in the caption of Figure 1 where the estimates were made using a statistical average of existing results from the literature. In most of these measurements large systematics, associated with foreground models, are likely to be still present. Here we briefly outline the techniques, foregrounds, and systematics associated with EBL measurements. We also discuss their applications for astrophysical and cosmological studies and briefly summarize studies related to spatial anisotropies. We cover from short to long wavelengths starting from the gamma-ray background.

(a) Gamma-Ray

The early measurements of the Cosmic Gamma-Ray Background (CGB) intensity came from SAS-2 between 40 and 300 MeV in 1978 (Fichtel et al. 1978), followed by EGRET between 40 Mev and 10 Gev in 1998 (Sreekumar et al. 1998; Strong et al. 2004). These measurements have been superseded in this decade by Fermi-LAT covering 100 MeV to 800 GeV with roughly 25-30 times better sensitivity than EGRET, as well as overall an improvement in the flux calibration. The CGB spectrum measured by Fermi-LAT shows a cutoff at energy scales around 280 GeV (Ackermann et al. 2015). Below this cut-off the spectrum can be described by a single power-law with a spectral index about 2.3 (± 0.05). The cutoff is explained as the disappearance of the high energy photons that are pair-producing via interactions with the infrared background photons that we discuss later (Aharonian et al. 2006; Ackermann et al. 2012a; Dominguez et al. 2011; Gilmore et al. 2012).

The CGB spectrum below the cutoff is mostly explained in terms of a combination of AGNs in the form of blazars and gamma-ray emission from star-forming galaxies (SFGs). Small, but non-negligible depending on the exact energy, comes from millisecond pulsars (MSPs), Type Ia supernovae, and gamma-rays from galaxy clusters. At energies above ~ 50 Gev blazars are able to fully account for the background, with an estimate of $86^{+16}_{-14}\%$ in explained by extrapolated blazar counts in Fermi-LAT Collaboration (2015). Between 0.1 and 50 Gev, blazars account for about 20% of the CGB. The rest are due to other populations of AGNs and SFGs. We refer the reader to a comprehensive review by Fornasa and Sánchez-Conde (2015) on the source populations contributing to CGB and existing population models in the literature.

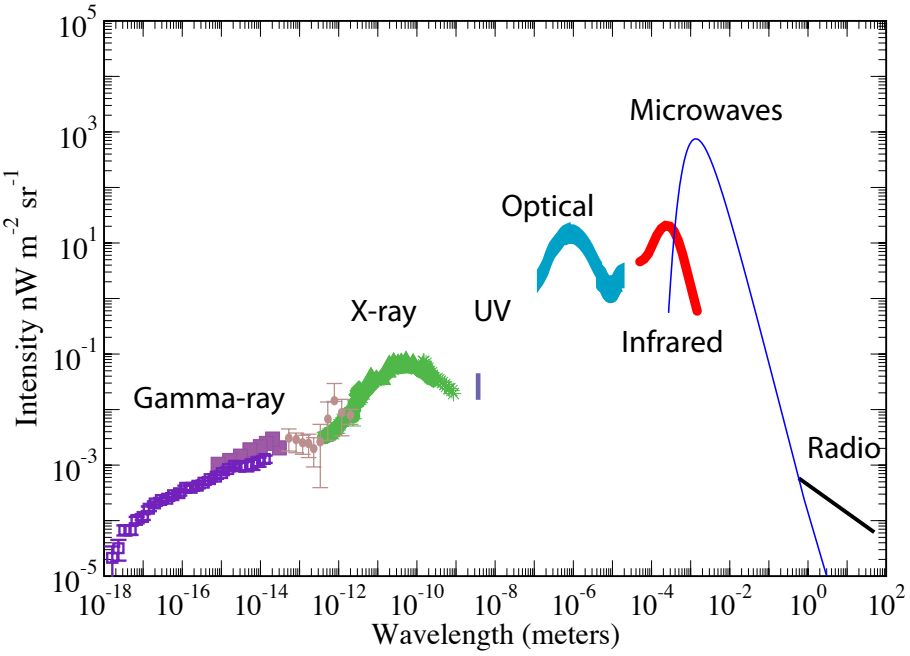

Figure 1. Intensity of the extragalactic background (νI_ν in units of nW m^{-2} sr^{-1}) as a function of the wavelength in meters. We combine the existing measurements from the literature to highlight the best determined estimates for the background from gamma-ray to radio. The cosmic microwave background (CMB) has the least uncertainty as the spectrum is determined to better than 1%. Cosmic optical background (COB) has large uncertainties involving direct measurements due to uncertain removal of the Zodiacal light foreground. Here we show the indirect estimate of EBL at optical wavelengths based on the TeV/gamma-ray absorption spectra of distant blazars. The UV/soft X-ray background at a wavelength of 10 to 100 nm remains unexplored. From left to right in increasing wavelength, the plotted datasets are: Fermi-LAT (the total extragalactic background composed of diffuse and resolved point sources; Ackermann et al. 2015) and EGRET (Sreekumar et al. 1998; we have removed three data points from Strong et al. 2004 at highest energies) in the Gamma-ray spectrum, COMPTEL (filled circles between Gamma-ray and X-rays; Weidenspointner et al. 2000) between Gamma-ray and X-rays, HEAO1 A2 and A4 (Marshall et al. 1980; Rothschild et al. 1983), INTEGRAL (Churazov et al. 2007), SWIFT/BAT (Ajello et al. 2008), Nagoya balloon experiment (Fukada et al. 1975), SMM (Watanabe et al. 2000), ASCA (Gendreau et al. 1995) and RXTE (Revnivtsev et al. 2003) in the hard to soft X-ray regime in green symbols, DXS and CHIPS in soft X-rays/Extreme UV (as discussed in Smith et al. 2014 as a line at 0.25 KeV), HESS in optical (Abramowski et al. 2012; see Figure 2 for other measurements), DIRBE (Hauser et al. 1998) and FIRAS (Lagache et al. 2000) in the far-infrared, FIRAS at microwaves (Mather et al. 1994; Fixsen et al. 1996) and ARCADE (Kogut et al. 2011) in the radio. The area under each of these backgrounds capture the total energy density of the photons in each of those wavelength regimes. From gamma-rays to radio the integrated intensity values in units of nW m^{-2} sr^{-1} for key EBL components are ~ 0.015 (gamma-ray), ~ 0.3 (X-ray), $0.01 - 0.02$ (lower and upper limits at 4.9 nm for Extreme UV), 24 ± 4 (with an additional ± 5 systematic; optical), $\sim 30 \pm 10$ (CIB), 960 (CMB), and < 0.001 (radio), respectively.

The literature also considers the possibility of a dark matter-induced signal in the gamma-ray background (see Bertone et al. 2005 for a review). This could be from dark matter that decays into standard particles (e.g., Bertone et al. 2007; Ibarra et al. 2008) or due to annihilation products (Abdo et al. 2010; see also Palomares-Ruiz & Siegal-Gaskins 2010). These gamma-rays will form an anisotropic signal associated with dark matter in our Galaxy. However, the signal is also expected to be present in all galaxies. The integrated signal from dark matter halos of all other galaxies will lead to a clustering signal in the gamma-ray background and must be separated from the clustering of all gamma-ray emitting faint extraglactic sources that also contribute to the

background. A direct detection of a signal associated with dark matter decay has been attempted towards Galactic center (e.g., Abazajian & Kaplinghat 2012) and nearby dwarf galaxies that are considered to be dark matter rich (e.g., Drlica-Wagner et al. 2015, Geringer-Sameth et al. 2015). The claims of gamma-ray excesses toward the Galactic center have been questioned as whether due to pulsars or other astrophysical foregrounds (e.g., Bartels et al. 2015; O'Leary et al. 2015), while the signal towards dwarf galaxies remain at the level of a 3σ detection (e.g., Hooper & Linden 2015).

Due to spatial resolution and the all-sky nature of the CBG measurements, Fermi-LAT also provides a treasure trove of data beyond the energy spectrum. In particular anisotropies or spatial fluctuations of the CGB have been pursued to study the nature of faint sources that can account for the small diffuse signals in the CBG below the point source detection of current high energy instruments. The angular power spectrum of the CGB is mostly Poisson or shot-noise like between multipole ell ranges of 150 to 500, corresponding to 30 arcminutes to 3 degree angular scales on the sky (e.g., Ackermann et al. 2012b). Moving beyond auto spectra, cross-correlations of the anisotropies can also be pursued (e.g., Xia et al. 2011). For an example the diffuse CGB signal from all of decaying dark matter in the universe can be studied via cross-correlations with large-scale structure tracers of the same dark matter, such as weak lensing maps (e.g., Camera et al. 2013). Existing cross-correlation attempts using Fermi-LAT data include both the CMB lensing map from Planck (Fornengo et al. 2015) and galaxy weak lensing in the CFHT Lensing Survey (Shirasaki et al. 2014). These studies are likely to be improved in the near future with wider area galaxy lensing surveys such as those expected from the Dark Energy Survey (DES) and Large Synoptic Survey Telescope (LSST).

Over the next decade, CGB studies will be extended to higher energies with the Cherenkov Telescope Array (CTA) with detections likely in 10 Gev to 10 TeV energy range (Acharya et al. 2013). CTA will allow studies related to CBG fluctuations at higher energies, especially TeV scales where there are still no reliable measurements on the spectrum or intensity fluctuations. We also lack a a complete understanding of the sources that contribute to CGB at 1 to 10 MeV scales, below the 100 MeV sensitivity of Fermi-LAT. This background spectrum based on EGRET and COMPTEL (Figure 1) suggests the possibility of a smooth connection to the cosmic X-ray background (CXB) at 10 to 100 KeV energy scales, though subject to large uncertainties in COMPTEL background light measurements. If continue to be confirmed such a smooth transition to X-rays suggest a different source population for the MeV background than the background at GeV energies. The leading possibility is a combination of Seyfert galaxies and flat-spectrum radio quasars that appear as bright MeV sources. Due to large uncertainties with EGRET and COMPTEL background measurements at these energy scales, however, we recommend a future experiment to improve background intensity measurements at MeV energy scales.

(b) X-Ray

Cosmic X-ray background (CXB) is generally divided into high and soft energies, with transition around an energy scale of 2 keV. Early measurements of the hard CXB intensity came from HEAO1 between 2-30 keV and 10-400 keV with A2 and A4 instruments. These measurements showed that the spectrum follows: $I(E) = 7.9 \times 10^{-0.29} \exp[-E/41.1\mathrm{keV}\,\mathrm{keVcm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{keV}^{-1}$, consistent with thermal bremsstrahlung radiation with a temperature $\sim$ 40 keV (e.g., Marshall et al. 1980; Rothschild et al. 1983; Garmire et al. 1992). Bulk of the energy density of CXB is thus at 30 keV, but understanding the sources at such a high X-ray energy has been slow. Previous surveys with SWIFT/BAT and Integral (Ajello et al. 2008; Churazov et al. 2007) only resolved 1% of the background to point sources at 30 keV. Current measurements in this energy scale are mainly from NuSTAR (Harrison et al. 2013).

Recent models show that in order to match both the redshift distribution of the faint X-ray sources in deep images with the *Chandra* X-ray Observatory and the overall CXB spectrum requires an evolving ratio of Type 1 (AGNs with visible nuclei) to Type 2 (with obscured broad-line regions) sources, such that there are more Type 2 Seyferts at higher redshifts (e.g., Menci

et al. 2004; Ueda et al. 2003; Gilli et al. 2007). Deep surveys with NuSTAR resolve 35% of the 8-24 KeV background to AGNs with obscuring columns up to 10^{25} cm^{-2} (Harrison et al. 2015), consistent with expectations from AGN population synthesis models (Worsley et al. 2005). Additional evidence for the presence of such highly absorbed AGNs exist as IR-bright sources in AKARI with 50% of the mid-IR AGN samples currently undetected in deep Chandra surveys (e.g., Krumpe et al. 2014).

The soft CXB has been measured with ROSAT down to 0.1 keV energies. At such low energies intensity measurements start to become challenging due to the Galactic signal and there is a clear indication for thermal emission from hot gas with a temperature of 10^6K associated with a hot component of the interstellar medium (ISM) or the Galactic halo. Deep ROSAT imaging data resolved 80% of the CXB at soft X-ray energies of 1 keV to to discrete sources, mainly bright AGNs. Chandra X-ray Observatory, with spatial resolution at the level of 0.5 arcsec, and XMM-Newton has resolved $> 90\%$ of the X-ray background at energies between 0.5 to 2 keV and $> 80\%$ at hard 2 to 9 keV energies (Worsley et al. 2005; Xue et al. 2012). The dominant source is AGNs with a non-negligible contribution from galaxy clusters (e.g., Wu & Xue 2001) and starbursting galaxies (e.g., Persic & Rephaeli 2003). The uncertainty in the unresolved intensity is not in the source population but in the overall normalization of the total XRB intensity.

With the background resolved to individual sources, anisotropy measurements of the CXB intensity and their applications have been limited when compared to similar studies at other wavelengths. In principle anisotropy studies can uncover diffuse X-ray sources or faint sources below the detection level. A recent example is the use of Chandra deep images to study the X-ray background fluctuations in combination with fluctuations measured with Spitzer at 3.6 μm (Cappelluti et al. 2013). This signal has been explained as due to the infrared and X-ray emission from direct collapse black holes (DCBHs) during reionization (Yue et al. 2013). An X-ray surveyor, such as the planned *Athena* mission, should facilitate more detailed studies on the diffuse background, faint unresolved sources in current deep surveys such as DCBHs, and multi-wavelength cross-correlation studies.

(c) UV

EBL measurements at UV wavelengths exist with GALEX at 150 nm (Murthy et al. 2010), with Voyager 1 and 2 at 110 nm (Murthy et al. 1999), and with Voyager UVS at 100 nm (Edelstein et al. 2000), though subject to both large statistical and systematic uncertainties. In the extreme UV (EUV) wavelengths below 100 nm, and down to 10 nm at energy scales of 0.1 KeV in soft X-rays, there are no useful measurements of the Cosmic UV background (CUVB) in the literature (Fig. 1). While technological developments can be expected, a measurement of the extragalactic EUV background will likely remain challenging due to absorption of the extragalactic photons by neutral hydrogen in our Galaxy and the intergalactic medium at wavelengths below 91.2 nm. Furthermore the Galactic soft X-ray/EUV background presents a considerable foreground that limits a reliable measurement of the UV background. And the next best measurements are in X-rays from a wavelength of 5 nm corresponding to energies of 0.25 KeV.

While a reliable background intensity might be challenging, further EUV observations are warranted since it is understood that bulk of the baryons exists in the warm intergalactic medium (Cen & Ostriker 1999) with signatures that involve emission and absorption lines around 50 nm (Tepper-Garcia et al. 2013). Based on Extreme UltraViolet Explorer (EUVE) data, there are some indications that certain galaxy clusters like Coma show excess EUV emission, especially at energies between 65 and 200 eV (Lieu et al. 1996). While the wavelength regime between 10 to 100 nm remains a crucial wavelength regime for further exploration, we recommend further attempts between 100 and 1000 nm in the UV as there are possibilities for some significant discoveries on the nature of warm intergalactic medium. Instruments on the planetary spacecraft to outer Solar system may continue to provide opportunities for UV background measurements, similar to past attempts with Voyager (Murthy et al. 1999; Edelstein et al. 2000). In this respect one near-term

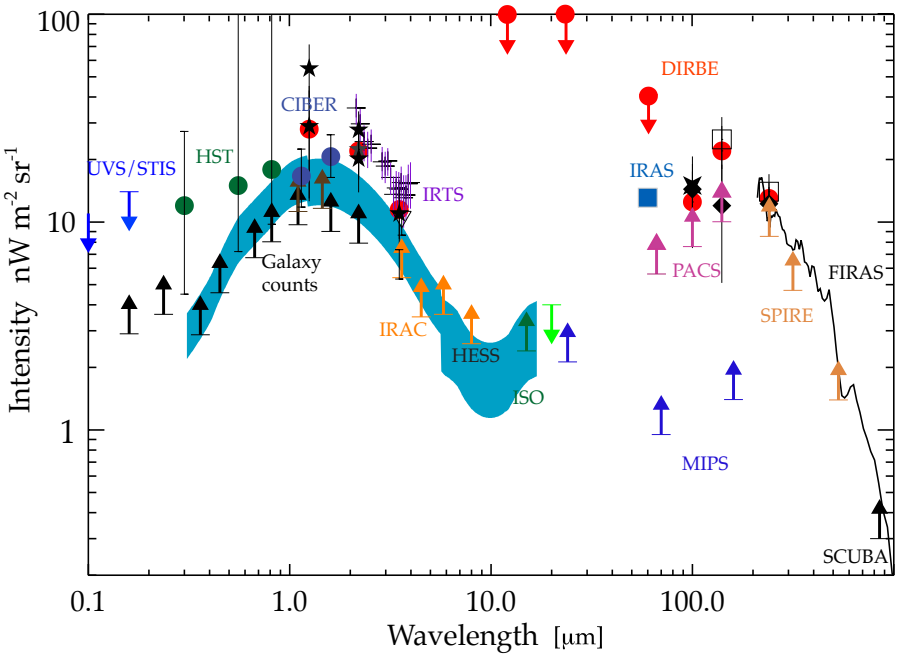

Figure 2. The cosmic optical and infrared background light from 0.1 to 100 μm. The data points with error bars are direct estimates using DIRBE (red circles: Wright 2004, Wright 2001; stars: Cambresy et al. 2001 at 1.25 and 2.2 μm; Gorjian et al. 2000 at 2.2 and 3.5 μm; Levenson et al. 2007 at 2.2 and 3.5 μm; open squares at 140 and 240 μm; Hauser et al. 1998), IRTS (purple crosses; Matsumoto et al. 2005), *Spitzer* at 3.6 μm (open triangle; Levenson & Wright 2008), *Hubble* (green circles; Bernstein 2007), UVS/STIS (blue upper limits; Edelstein et al. 2000; Brown et al. 2000), CIBER (blue circles; model-dependent based on fluctuation measurements; Zemcov et al. 2014), FIRAS (black line; with an overall uncertainty of 30% between 200 μm and 1.2mm; Lagache et al. 2000 also Fixsen et al. 1998), and IRAS (blue square; 60 μm fluctuation-based estimate of EBL with IRAS; Miville-Deschĥes et al. 2002). The lower limits to the EBL are from integrated or source counts using Hubble (Gardner et aL. 2000; Madau & Pozzetti 2000), Spitzer/IRAC (Fazio et al. 2004), ISO (Elbaz et al. 1999), Spitzer/MIPS (Papovich et al. 2004; Dole et al. 2004), Herschel/PACS (Berta et al. 2010), Herschel/SPIRE (Béthermin et al. 2012), and SCUBA (Smail et al. 2002). The blue shaded region is the estimate of EBL using the HESS TeV blazar absorption spectra (Abramowski et al. 2012). Apart from recent Herschel measurements, CIBER, and the estimate of EBL from HESS, all other measurements plotted here are tabulated in Hauser & Dwek (2011). This figure is based on a previous figure by Dole et al. (2006) that summarized these EBL and integrated galaxy count measurements.

possibility would be the use of New Horizons' Alice UV spectrometer (Stern et al. 2007) for a new background measurement at wavelengths around 140-180 nm.

(d) Optical/Near-Infrared

At optical and near-infrared (IR) wavelengths between 0.1 to 5 μm the EBL intensity is predominantly due to stellar emission from nucleosynthesis throughout the cosmic history (see Hauser & Dwek 2001 for a review). The cosmic optical background (COB) spectrum also includes radiative information from the reionization epoch. Due to redshifting of the UV photons to near-infrared emission from primordial sources is primarily at wavelengths longward of 1 μm (Santos et al. 2002; Salvaterra et al. 2003). This includes diffuse Ly-α and free-free radiation in addition to direct emission by stars and mini-quasars (e.g., Cooray & Yoshida 2004; Fernandez & Komatsu 2006).

At optical and near-IR the few attempts at absolute measurements involve DIRBE on COBE in several band-passes between 1.25 μm and 240 μm (Hauser et al. 1998; Cambresy et al. 2001; Gorjian et al. 2000; Levenson et al. 2007; Wright 2001; Wright 2004), IRTS, a small JAXA mission, between 1 and 4 μm (Matsumoto et al. 2005), Voyager (Edelstein et al. 2000) and Hubble (Brown et al. 2000; Bernstein et al. 2002; Bernstein 2007). Because DIRBEs confusion limit was 5th magnitude at 2.2 μm, all recent EBL measurements using DIRBE require subtraction of stellar light using ancillary measurements, such as 2MASS (Wright 2001; Levenson et al. 2007). While Hubble has been used for optical (Bernstein et al. 2002; Bernstein 2007) and far-UV (Brown et al. 2000) EBL measurements, the instrument was not designed for absolute photometry and required a careful subtraction of instrumental emission and baselines (e.g. dark current). Those measurements are subject to large uncertainties (e.g., Mattila 2003).

The dominant limitation for direct EBL intensity spectrum at these wavelengths is the Zodiacal light associated with scattered Solar light from micron-size dust interplanetary dust (IPD) particles near the Earth's orbit. Existing measurements with DIRBE on COBE make use of model to remove Zodiacal light (Kelsall et al. 1998) or slight variations (Wright 2001). The Zodiacal light foreground limits the accuracy of EBL intensity to roughly an order of magnitude at wavelengths about 1 micron (Hauser et al. 1998; Gorjian et al. 2000; Wright 2001; Cambresy et al. 2001; Matsumoto et al. 2005; Levenson & Wright 2007). Techniques to remove Zodiacal light includes monitoring of Fraunhofer lines in the dust scattered spectrum relative to the Solar spectrum and use of the equivalent width of the lines to estimate the column density of dust. In the case of HST results on the optical background the zodiacal emission based on the observed strength of the reflected Fraunhofer lines from a ground-based measurement (Bernstein et al. 2002). The sounding rocket experiment CIBER (Zemcov et al. 2013) is capable of absolute photometry (Tsumura et al. 2013) and results related to the optical/near-IR EBL are soon expected (Matsuura et al. in preparation). If Spitzer/IRAC shutter operations are allowed and successful, a carefully planned program should also be able to improve the absolute EBL measurements at 3.6 and 4.5 μm over the coming years.

In Figure 2 we summarize EBL intensity measurements between optical and IR wavelengths using absolute photometry, model-dependent estimates based on the EBL fluctuations, and the integrated galaxy light (IGL) from galaxy counts (lower limits). In general, the summed contribution of galaxies to the EBL does not reproduce the EBL measured by absolute photometric instruments. For example, at $\lambda = 3.5\,\mu$m the EBL measured by DIRBE from absolute photometry is 13.0 ± 4.8 nW m^{-2} sr^{-1} (Levenson et al. 2007), while the deepest pencil beam surveys with Spitzer at 3.6 μm give $6-9$ nW m^{-2} sr^{-1} (Fazio et al. 2004; Sullivan et al. 2007), with the best determination of $9.0^{+1.7}_{-0.9}$ nW m^{-2} sr^{-1} (Levenson & Wright 2008). At shorter wavelengths centered around 1 μm, and especially considering EBL measurements from IRTS (Matsumoto et al. 2005) this divergence is even more pronounced.

Note that model-dependent fluctuations-based estimates of EBL are in between IGL and absolute photometry measurements (at 1 μm, such estimates of EBL are from CIBER; Zemcov et al. 2014; Figure 2). Fluctuation measurements and angular power spectra of source-subtracted optical and near-IR background intensity have been presented with Spitzer at 3.6 μm and above (Kashlinsky et al. 2005; Kashlinsky et al. 2012; Cooray et al. 2012), AKARI at 2.4, 3.2 and 4.1 μm (Matsumoto et al. 2011), Hubble/NICMOS at 1.1 and 1.6 μm (Thompson et al. 2007), CIBER at 1.1 and 1.6 μm (Zemcov et al. 2014), and Hubble/ACS and WFC3 in 5 bands from 0.6 and 1.6 μm (Mitchell-Wynne et al. 2015). These measurements generally reveal a picture in which source counts, mainly galaxies, dominate the fluctuations with some evidence for additional components such as intra-halo light (IHL; Cooray et al. 2012; Zemcov et al. 2014), associated with diffuse stars in extended dark matter halos due to galaxy mergers and tidal stripping, and a signal from galaxies present during reionization at $z > 8$ (Mitchell-Wynne et al. 2015). Spitzer fluctuations have been also cross-correlated with far-infrared maps from Herschel/SPIRE (Thacker et al. 2015) and X-ray from Chandra (Cappelluti et al. 2013). The former provides allows a quantification of the total dust content as a function of redshift while the latter has been used to argue for the

presence of primordial direct collapse black holes (DCHBs; Yue et al. 2013). Over the coming decade significant improvements in the study of near-IR and optical fluctuations will come from planned cosmological missions such as Euclid and WFIRST. The small explorer SPHEREx (Doré et al. 2014), recently selected by NASA for a Phase A study, has the ability to conduct 3D intensity mapping of spectral lines such as Hα at $z \sim 2$ and Ly-α at $z > 6$ during reionization over large areas on the sky.

A leading possibility for the large difference between absolute photometry EBL and IGL is likely an unsubtracted foreground component, such as an underestimate of the Zodiacal light signal (Mattila 2006). If this difference, however, is real it would have significant implications given that the nature of the emission source must be diffuse and not point-like similar to galaxies. Fortunately, there is also a third technique to measure the EBL. Given the limitation of direct measurements possibly due to foregrounds, currently the best estimates of optical/near-IR EBL come from this indirect technique that makes use of the absorbed TeV/GeV spectra to constrain the optical and infrared background due to pair production (shaded region in Figure 2 from Abramowski et al. 2013). The modeling requires intrinsic spectrum for each blazar, but since this is not observed or available, EBL is inferred through statistical techniques that make use of a large sample of blazars over a wide range of cosmological distances. The existing measurements come from High Energy Stereoscopic System (HESS) array in Namibia (Aharonian et al. 2006; Abramowski et al. 2013) and Fermi/LAT (Ackermann 2012a; Gong & Cooray 2013). The discrepancy between absolute photometry and IGL-implied intensity is less severe when comparing galaxy counts to the EBL inferred from absorbed TeV spectra. The measurements are such that deep galaxy counts have effectively resolved all of the optical and near-IR photons to individual galaxies. The overall uncertainties, however, are still that the measurements leave the possibility for small signals such as IHL an reionization consistent with fluctuation measurements.

Given the large uncertainties, including systematics, with TeV measurements, and especially absolute photometry measurements, it is crucial that we improve on the optical and near-IR EBL intensity level. It is also clear that simply repeating an absolute photometry experiment like DIRBE or IRTS at 1 AU will not improve the current EBL spectrum at wavelengths less than 5 μm due to limitations coming from the foreground model. Improvements in EBL measurements will only come with a parallel improvement in our understanding of the IPD distribution in the Solar system, if measurements are limited to 1 AU, or from observations that are conducted outside of the zodiacal light dust cloud. In Figure 3 we show the expected zodiacal light intensity as a function of the radial distance from the Sun, based on the *in-situ* dust measurements from Pioneer 10; the dust density is dropping more rapidly than the r^{-1} profile expected from the Poynting-Robertson effect (Hanner et al. 1974). At distances of Jupiter these dust density measurements suggest a decrease in the zodiacal light intensity of roughly two orders of magnitude from the intensity level near Earth orbit. One possibility is the out-of-Zodi EBL measurements, such as the proposed piggy-back ZEBRA instrument on a planetary spacecraft to Jupiter or Saturn distances, or to travel outside of the ecliptic plane. Given the relatively small cost of the instrument necessary for the required observations we encourage attempts to measure EBL as a by-product of planetary spacecraft that explore the outer Solar system (Cooray et al. 2010).

(e) Far-Infrared

Absolute photometry measurements between 10 μm and 1000 μm, corresponding to the far-infrared EBL peak at around 100 μm (Figure 2), are mainly from DIRBE (Hauser et al. 1998) and FIRAS (Fixsen et al. 1998; Lagache et al. 2000). In general these measurements have an overall uncertainty at the level of 30%, all due to uncertain corrections associated with the foreground sky model. This background is generally referred to as the cosmic infrared background (CIB) in some literature, especially in the context of CMB experiments that also overlap in frequency ranges as the sub-millimeter wavelengths.

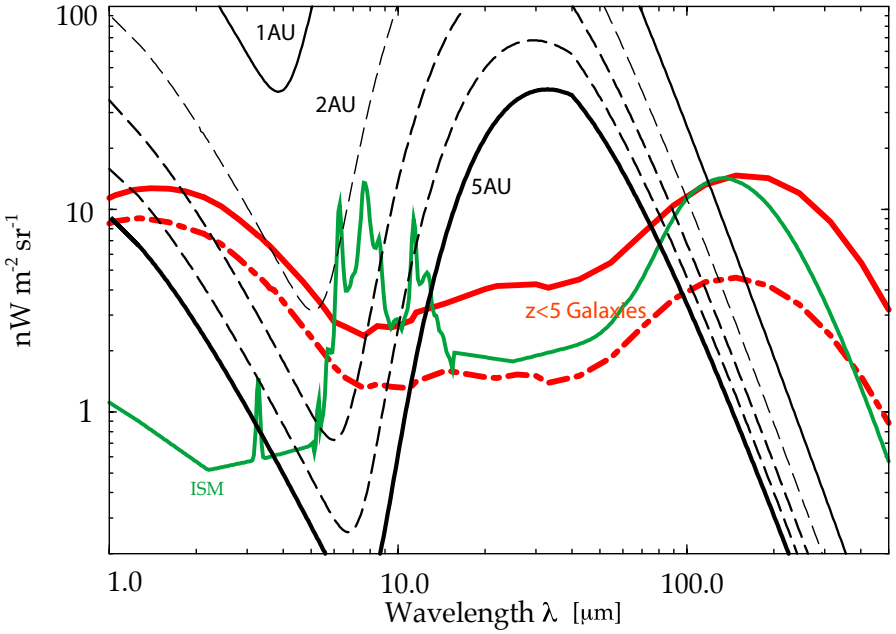

Figure 3. Zodiacal light intensity as a function of the radial distance from the Sun, based on the Pioneer 10 dust density estimates (Hanner et al. 2010) normalized to a radial profile from the Sun of $r^{-1.5}$. For reference we also show the optical to near-IR spectrum of the Galactic interstellar medium and two predictions from semi-analytical models on the total IGL from $z < 5$ galaxy populations (from Primack et al. 2008). The Zodical light intensity estimates as a function of the radial distance is based out of the calculations for ZEBRA concept instrument for the outer Solar system in Cooray et al. (2009).

With the absolute photometry measurements establishing a cosmologically important energy density in the universe at long infrared wavelengths, subsequent observations have focused on resolving this background to point sources with large aperture telescopes. While the fraction resolved was low with Spitzer/MIPS at 70 and 160 μm, significant improvements in our ability to detect and study distant galaxies came over the last five years with Herschel/PACS and SPIRE between 70 to 500 μm. In particular, Herschel/SPIRE resolved 15% (250 μm) to 5% (500 μm) of the background directly to sources (Oliver et al. 2010). Using statistics such as $P(D)$, probability of deflections, in deep SPIRE images, Glenn et al. (2010) resolved 60% (250 μm) to 43% (500 μm) of the background to source counts, especially sources below the individual point source detection level in maps. Methods involving stacking analysis resolve more of the background with recent analysis suggesting a resolved fraction greater than 90% (Viero et al. 2015). The sources that make up the far-infrared/submillimeter background are dusty, star-forming galaxies predominantly at high redshifts ($z > 1$). They are likely the dominant contribution to the cosmic star-formation rate density during the peak epoch of galaxy formation at $z \sim$ 2-3. We refer the reader to the comprehensive review by Casey et al. (2014) for properties of these galaxies.

Since COBE/DIRBE and FIRAS CIB intensity measurements the experimental focus has been on measurements related to the spatial anisotropies and the angular power spectrum of CIB intensity (Haiman & Knox 2000; Knox et al. 2001; Amblard & Cooray 2007). The power spectrum at 60 and 100 μm with IRAS allowed studies related to the spatial distribution properties of Galactic dust and an estimate of the total intensity of extragalactic sources through clustering and Poisson noise at small angular scales (e.g., Miville-Deschĥes et al. 2002). At 90 and 170 μm fluctuation measurements have also been attempted with ISO (Lagache & Puget 2000; Matsuhara

et al. 2000). Significant improvements in our ability to remove Galactic emission and detect extragalactic fluctuations have come from more recent experiments including Spitzer/MIPS at 160 μm (Lagache et al. 2007), AKARI at 90 μ (Matsuura et al. 2011), and BLAST at 250, 350 and 500 μm (Viero et al. 2009). Currently the best measurements of CIB power spectrum at a few degree to ten arcsecond angular scales are from Herschel/SPIRE (Amblard et al. 2010; Viero et al. 2013; Thacker et al. 2013), while best measurements at larger angular scales and spanning the whole sky are from Planck (Ade et al. 2011; Ade et al. 2013a). While there was a mismatch between Herschel/SPIRE and Planck CIB power spectra at overlapping angular scales with first measurements this difference has mostly gone away with the latest flux calibration of Planck/HFI data. In combination, Planck and Herschel allow studies of the CIB angular power spectrum from large linear scales with Planck to non-linear 1-halo term (Cooray & Sheth 2002) with Herschel maps. The measurements are useful to describe the spatial distribution of faint galaxies that make up the CIB and the relation between far-IR luminosity to dark matter halo mass (Shang et al. 2011; De Bernardis & Cooray 2012; Xia et al. 2012; Viero et al. 2013; Ade et al. 2013a).

Moving beyond the anisotropy power spectra, CIB fluctuations have also been used for cross-correlation studies. For example, far-IR galaxies are correlated with unresolved near-IR background detected with Spitzer and the cross-correlation of near and far-IR backgrounds improve models related to the dust distribution within dark matter halos (Thacker et al. 2015). Sources that make up CIB are mostly at $z > 1$. The foreground dark matter potentials that are responsible for lensing of the CMB is mostly at $z \sim$ 1-2 and CIB provides one of the best tracers of the projected dark matter related to CMB lensing (Song et al. 2002). This cross-correlation of CMB lensing with CIB maps has been studied with Planck (Ade et al. 2013b) and for detections of CMB lensing signal in the B-modes of CMB polarization (Hanson et al. 2013; Ade et al. 2014).

Additional future applications involving the far-IR/submm background include lensing of CIB fluctuations, that is CIB at $z \sim 3$ is expected to be gravitationally lensed by structures at $z < 1$, the search for a diffuse CIB components including intra-halo dust in dark matter halos that extend beyond the dusty disks of star-forming galaxies, and a detailed statistical comparison of dust in emission seen with CIB vs. dust seen in absorption through extinction studies (Ménard et al. 2007). While the recent focus has been on CIB fluctuations and its applications, the absolute CIB intensity still remains uncertain at the level of 30% and must be improved down to sub-percent level if detailed comparisons are to be made on the sources responsible for CIB vs. diffuse emission sources at far-IR wavelengths. The proposed Primordial Inflation Explorer (PIXIE; Kogut et al. 2014) has the capability to achieve such a measurement. Its' sensitivity should also be adequate for a detection of the CIB dipole allowing a comparison of the CIB and CMB dipoles.

(f) Microwaves

As shown in Figure 1, the cosmic microwave background (CMB), peaking at mm wavelengths between sub-mm and radio, is the dominant background intensity across all wavelengths in the electromagnetic spectrum. Its total integrated intensity of 960 nW m^{-2} sr^{-1} is roughly a factor of 30 higher than the integrated intensity of the infrared background, which remains the next highest energetic component of the universe. Since its' accidental discovery roughly 50 years ago, the high background intensity or photon energy density has facilitated its wide applications in cosmology, especially with spatial anisotropies and polarization using a large number of ground and space-based experiments, including COBE, WMAP and Planck. For recent reviews on CMB theory and experimental data summaries we refer the reader to Durrer (2015) and Komatsu et al. (2014).

While most of the experimental work in CMB concentrate on anisotropies and polarization, the best measurement of CMB spectrum, and correspondingly the best measurement of any EBL component from gamma-ray to radio, comes from COBE/FIRAS. It is described by a Planck function with a blackbody temperature of 2.7260 ± 0.0013 (Fixsen 2009), with spectral departure from blackbody currently limited by the data to be at the level in $\delta I_\nu / I_\nu < 10^{-5}$ (Mather et al. 1994; Fixsen et al. 1996). Distortions to the spectrum are expected at the micro and nano-Kelvin

level (for a general review see Chluba 2014). Detection and detailed study of these distortions, generated both during the early universe and at late times, remain a primary scientific goal for a next generation CMB experiment, such as PIXIE (Kogut et al. 2014), with sensitivity at least a factor of 30-100 better than FIRAS.

A well-known cosmological test related to the CMB temperature anisotropy power spectrum involves the location of the first acoustic peak in the multi-polar space (Kamionkowski et al. 1994). The CMB power spectrum from experiments like Planck now reveal the multiple acoustic peak structure in the anisotropy power spectrum from multipole moments 2 to ~ 2500 and across at least eight peaks. Along with constraints on cosmological parameters (Ade et al. 2015a), these observations now provide evidence for an initial spectrum of scale-invariant adiabatic density perturbations as expected under models involving inflation. It has been argued for a while that the smoking-gun signature of inflation would be the detection of stochastic background of gravitational waves associated with it. These gravitational-waves produce a distinct signature in the polarization of CMB in the form of a contribution to the curl, or magnetic-like, component of the polarization (Kamionkowski et al. 1997). While polarization from density, or scalar, perturbations dominate, due to the fact they have no handedness, there is no contribution to curl mode polarization from density perturbations. Thus the current generation, and one focus of next generation measurements, involves CMB polarization and especially detailed characterization of the B-modes of polarization.

In transit to us, CMB photons also encounter the large scale structure that defines the local universe; thus, several aspects of photon properties, such as the frequency or the direction of propagation, are affected. In the reionization epoch, variations are also imprinted when photons are scattered via electrons, moving with respect to the CMB. Though these secondary effects are in some cases insignificant compared to primary fluctuations, they leave certain imprints in the anisotropy structure and induce higher order correlations. A well-studied example of such a secondary effect with current generation CMB experiments is lensing of the CMB (Lewis & Challinor 2006), with a significant detection of the lensing effect in Planck (Ade et al. 2015b). The lensing of CMB is useful for cosmological applications involving structure formation and signatures leftover by a massive neutrinos. A Stage IV CMB experiment will be able to reach the neutrino mass threshold expected given the neutrino oscillation experiments (Abazajian et al. 2015). AS discussed with respect to Gamma-ray background, CMB lensing traces the large-scale structure that is also visible at other wavelengths. Therefore, improvements in our understanding of the nature of dark matter and faint sources at each of the backgrounds will likely come from cross-correlation studies. These are new topics in cosmology that will likely be improved over the coming years.

(g) Radio

The cosmic radio background (CRB) has been measured at multiple frequencies and in recent years with the balloon-borne ARCADE-2 experiment from 3 to 90 GHz (Kogut et al. 2011). When compared to CMB, Galactic synchrotron background, and extragalactic point sources, ARCADE 2 measured an excess radio background. For example, at 3 GHz ARCADE measured the equivalent antenna temperature to be 65 mK, once corrected for CMB and Galactic emission. At the same frequency the known radio galaxy counts contribute about 30 mK. If undetected radio sources account for the excess seen in ARCADE 2 they will need to form an extra peak in the Euclidean-normalized number counts of radio sources at flux densities around 1-100 nJy, but an explanation involving point sources is ruled by various deep radio observations and other arguments (e.g., Condon et al. 2012; Holder 2014; Vernstrom et al. 2014). The excess has also motivated alternative suggestions, such as decaying WIMP dark matter (e.g., Fornengo et al. 2011). A reanalysis of the Galactic synchrotron emission using multiple components instead of the single slab model for the Galactic plane synchrotron emission used by the ARCADE team, however, suggests that there is likely no excess over the background produced by known sources (Subrahmanyan &

Cowsik 2013). Future attempts to improve the radio background will thus likely also involve improvements to understanding and modeling of the Galactic radio foreground.

Current and next-generation experiments will likely focus more on the long wavelength radio background at frequencies around 100 MHz. These experiments are driven by the need to characterize the background intensity spectrum to study the global signature associated with 21-cm spin-flip transition of HI from the epoch of reionization. The global signal involves a strong absorption feature around 60-100 mK, associated with adiabatic cooling of gas, followed by a weak emission during the epoch of reionization (Furlanetto 2006). Detection of the expected absorption feature in the background intensity spectrum at frequencies around 60 MHz is challenging due to the large Galactic foreground at these low radio frequencies. Technology development studies are underway to pursue such a measurement from the Moon, including the lunar orbiter DARE (Dark Ages Radio Explorer; Jones et al. 2014). There are also a host of experiments underway at frequencies above 100 MHz focused on the intensity fluctuations, especially the power spectrum of 21-cm background during reionization and for absolute measurements of the sky intensity (see review by Pritchard & Loeb 2012).

2. Summary

This review covers the measurements related to the extragalactic background light (EBL) intensity from gamma-rays to radio in the electromagnetic spectrum over 20 decades in the wavelength. The Cosmic Microwave Background (CMB) remains the best measured spectrum with an accuracy better than 1%. The measurements related to the Cosmic Optical Background (COB), centered at 1 μm, are impacted by the large Zodiacal light intensity associated with interplanetary dust-scattered sunlight in the inner Solar system. The best measurements of COB come from an indirect technique involving the absorption of Gamma-ray photons emitted by bright blazars and other active sources in the universe. The Cosmic Infrared Background (CIB) at wavelengths centered around 100 μm established an energetically important intensity level comparable to the optical background. This eventually resulted in the discovery of dusty, starbursting galaxies with large aperture telescopes and a deeper understanding of their importance in galaxy formation and evolution. The soft X-ray/extreme UV extragalactic background at wavelengths of 10 to 100 nm remains mostly unexplored, but is unlikely to be achieved easily due to the absorption of the extragalactic photons by the intervening neutral intergalactic medium and the interstellar medium of our Galaxy. We also summarize our understanding of spatial anisotropies of these backgrounds and the cosmological/astrophysical applications with angular power spectra of intensity fluctuations across the sky. We motivate a precise direct measurement of the COB between 0.1 to 5 μm using a small aperture telescope observing from either the outer Solar system or out of the ecliptic plane. Other future applications include improving our understanding of the background at TeV energies, improving the MeV background over the previous measurements with COMPTEL, radio background, and the spectral distortions to CMB and CIB.

Funding Statement

My research is funded by NSF (CAREER AST-0645427, AST-1310310) and NASA.

Competing Interests

I have no competing interests.

Acknowledgments

I thank my collaborators in CIBER, SPHEREx, CANDLES, HerMES, H-ATLAS, ZEBRA, especially Jamie Bock, Bill Reach, Michael Zemcov, Yan Gong, Ranga Chary, and many others for conversations related to topics covered in this review. Nick Timmons and Ketron Mitchell-Wynne

are acknowledged for help with figures and collection of data in figures 1 and 2 from the literature to electronic format. The radial intensity of Zodiacal light in figure 3 comes from calculations performed by Bill Reach for the ZEBRA concept instrument in Cooray et al. (2009). Figure 2 is an update to a similar figure from Dole et al. (2006) that discussed the measurements related to optical and infrared extragalactic background light and the integrated light from galaxy/source counts.

Data Accessibility

Electronic files listing the wavelength and intensity (in units of nW m^{-2} sr^{-1} as plotted in Figure 1) and the electronic versions of the figures are available from herschel.uci.edu.

References

1. Abazajian, K. N., & Kaplinghat, M. 2012, Detection of a gamma-ray source in the Galactic Center consistent with extended emission from dark matter annihilation and concentrated astrophysical emission, Physical Review D, 86, 083511, 10.1103/PhysRevD.86.083511.

2. Abazajian, K. N., Arnold, K., Austermann, J., Benson, C., Bischoff, J., Bock, J., Bond, J. R.,, Borrill, E., Calabrese, E., Carlstrom, J. E. et al. 2015, Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure, Astropart. Phys. 63, 66-80.

3. Abdo, A., Ackermann, M., Ajello, M., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B. et al. 2010, Constraints on Cosmological Dark Matter Annihilation from the Fermi-LAT Isotropic Diffuse Gamma-Ray Measurement, J. Cosmo. & Astroparticle Phys. 1004, 014, doi:10.1088/1475-7516/2010/04/014.

4. Abramowski, A., Acero, F., Aharonian, F., Akhperjanian, A. G., Anton, G., Balenderan, S., Balzer, A., Barnacka, A., Becherini, Y., Becker T. 2013, Measurement of the extragalactic background light imprint on the spectra of the brightest blazars observed with H.E.S.S, Astron. & Astrophys. 550, 4, doi:10.1051/0004-6361/201220355.

5. Acharya, B., Actis, M., Aghajani, T., Agnetta, G., Aguilar, J. et al. 2013, Introducing the CTA concept, Astropart.Phys. 43, 18. doi:10.1016/j.astropartphys.2013.01.007.

6. Ackermann, M., Ajello, M., Allafort, A., Schady, P., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bellazzini, R., Blandford, R. D. et al. 2012a, The Imprint of The Extragalactic Background Light in the Gamma-Ray Spectra of Blazars, Science 338, 1190-1192, doi:10.1126/science.1227160.

7. Ackermann, M., Ajello, M., Albert, A., Atwood, W. B., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R. et al. 2015, The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV, Astrophys. J. 799, 86, 10.1088/0004-637X/799/1/86.

8. Ackermann, M., Ajello, M., Albert, A., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Bloom, E. D. et al., 2012b, Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT, Phys. Rev. D85, 083007, doi:10.1103/PhysRevD.85.083007.

9. Ade, P. A. R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Balbi, A., Banday, A. J., Barreiro, R. B., Bartlett, J. G. et al. 2011, Planck early results. XVIII. The power spectrum of cosmic infrared background anisotropies, Astron. & Astrophys. 536, A18, doi:10.1051/0004-6361/201116461.

10. Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., Arnaud, M., Ashdown, M., Atrio-Barandela, F., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B. et al. 2013a, Planck 2013 results. XXX. Cosmic infrared background measurements and implications for star formation, Astron.

& Astrophys. 571, A30, doi:10.1051/0004-6361/201322093.

11. Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., Arnaud, M., Ashdown, M., Atrio-Barandela, F., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B. et al. 2013b, Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation, Astron. & Astrophys. 571, A18, doi:10.1051/0004-6361/201321540.

12. Ade, P. A. R., Akiba, Y., Anthony, A. E., Arnold, K., Atlas, M., Barron, D., Boettger, D., Borrill, J., Borys, C., Chapman, S. et al. 2014, Evidence for Gravitational Lensing of the Cosmic Microwave Background Polarization from Cross-Correlation with the Cosmic Infrared Background, Phys. Rev. Lett. 112, 131302, doi:10.1103/PhysRevLett.112.131302.

13. Ade, P. A. R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B., Bartlett, J. G., Bartolo, N. [Planck Collaboration] et al. 2015a, Planck 2015 results. XIII. Cosmological parameters, preprint arXiv:1502.01589.

14. Ade, P. A. R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B., Bartlett, J. G., Bartolo, N. [Planck Collaboration] et al. 2015b, Planck 2015 results. XV. Gravitational lensing, preprint, arXiv.org:1502.01591.

15. Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., Beilicke, M., Benbow, W., Berge, D., Bernlöhr, K., Boisson, C., Bolz, O., Borrel, V. et al. 2006, A low level of extragalactic background light as revealed by γ-rays from blazars, Nature, 440, 1018-1021, doi:10.1038/nature04680.

16. Ajello, M., Greiner, J., Sato, G., Willis, D. R., Kanbach, G., Strong, A. W., Diehl, R., Hasinger, G., Gehrels, N., Markwardt, C. B. et al. 2008, Cosmic X-ray background and Earth albedo Spectra with Swift/BAT, Astrophys. J. 689, 666 doi:10.1086/592595.

17. Amblard, A. & Cooray, A. 2007, Anisotropy Studies of the Unresolved Far-Infrared Background, Astrophys. J. 670, 903-911, doi:10.1086/522688.

18. Amblard, A., Cooray, A., Serra, P., Altieri, B., Arumugam, V., Aussel, H., Blain, A., Bock, J., Boselli, A., Buat, V. et al. 2011, Submillimetre galaxies reside in dark matter haloes with masses greater than 3×10^{11} solar masses, Nature, 470, 510-512, doi:10.1038/nature09771.

19. Ando, S. & Ishiwata, K. 2015, Constraints on decaying dark matter from the extragalactic gamma-ray background, J. Cosmo. & Astroparticle Phys., 05, 024, doi:10.1088/1475-7516/2015/05/024.

20. Bartels, R., Krishnamurthy, S. & Weniger, C. 2015, Strong support for the millisecond pulsar origin of the Galactic center GeV excess, preprint, arXiv.org:1506.05104.

21. Bernstein, R. A. 2007, The Optical Extragalactic Background Light: Revisions and Further Comments, Astrophys. J. 666, 663-673, doi:10.1086/519824.

22. Bernstein, R. A., Freedman, W. L., Madore, B. F. 2002, The First Detections of the Extragalactic Background Light at 3000, 5500, and 8000A. I. Results, Astrophys. J., 571, 56-84, doi:10.1086/339422.

23. Berta, S., Magnelli, B., Lutz, D., Altieri, B., Aussel, H., Andreani, P., Bauer, O., Bongiovanni, A., Cava, A., Cepa, J. et al. 2010, Dissecting the cosmic infra-red background with Herschel/PEP, Astron. & Astrophys. 518, L30, doi:10.1051/0004-6361/201014610.

24. Bertone, G., Hooper, D. & Silk, J. 2005, Particle dark matter: Evidence, candidates and constraints, Phys. Rept. 405, 279-390, doi:10.1016/j.physrep.2004.08.031.

25. Bertone, G., Buchmuller, W., Covi, L. & Ibarra, A. 2007, Gamma-Rays from Decaying Dark Matter, J. Cosmo. & Astroparticle Phys. 0711, 003, doi:10.1088/1475-7516/2007/11/003.

26. Béthermin, M., Le Floc'h, E., Ilbert, O., Conley, A., Lagache, G., Amblard, A., Arumugam, V., Aussel, H., Berta, S., Bock, J. et al. 2012, HerMES: deep number counts at 250 μm, 350 μm and 500 μm in the COSMOS and GOODS-N fields and the build-up of the cosmic infrared background, Astron. & Astrophys. 542, A58, doi:10.1051/0004-6361/201118698.

27. Brown, T., Kimble, R. A., Ferguson, H. C., Gardner, J. P., Collins, N. R. & Hill, R. S. 2000, Measurements of the Diffuse Ultraviolet Background and the Terrestrial Airglow with the Space Telescope Imaging Spectrograph. Astrophys. J., 120, 1153-1159, doi:10.1086/301468.

28. Burns, J. O., Lazio, J., Bale, S., Bowman, J., Bradley, R., Carilli, C., Furlanetto, S., Harker, G., Loeb, A. & Pritchard, J. 2012, Probing the first stars and black holes in the early Universe with the Dark Ages Radio Explorer (DARE), Adv. in Space Research, 49, 433-450, doi:10.1016/j.asr.2011.10.014.

29. Cambresy, L., Reach, W. T., Becihman, C. A. & Jarrett, T. H. 2001, The Cosmic Infrared Background at 1.25 and 2.2 Microns Using DIRBE and 2MASS: A Contribution Not Due to Galaxies?, Astroph. J., 555, 563-571, doi:10.1086/321470.

30. Camera, S., Fornasa, M., Fornengo, N., Regis, M. 2013, A Novel Approach in the Weakly Interacting Massive Particle Quest: Cross-correlation of Gamma-Ray Anisotropies and Cosmic Shear, Astrophys. J. 771, L5, doi:10.1088/2041-8205/771/1/L5.

31. Cappelluti, N., Kashlinsky, A., Arendt, R. G., Comastri, A., Fazio, G. G., Finoguenov, A., Hasinger, G., Mather, J. C., Miyaji, T., Moseley, S. H. 2013, Cross-correlating Cosmic Infrared and X-Ray Background Fluctuations: Evidence of Significant Black Hole Populations among the CIB Sources, Astrophys. J. 769, 68, doi:10.1088/0004-637X/769/1/68.

32. Casey, C. M., Narayanan, D. & Cooray, A. 2014, Dusty star-forming galaxies at high redshift, 2014, Phys. Reports, 541, 45, doi:10.1016/j.physrep.2014.02.009.

33. Cen, R. & Ostriker. J. P. 1999, Where are the baryons?, Astrophys. J. 514, 1-6.

34. Chluba, J. 2014, Science with CMB spectral distortions, Proceedings of the XLIXth RENCONTRES DE MORIOND, preprint arXiv.org:1405.6938.

35. Churazov, E., R. Sunyaev, R., Revnivtsev, M., Sazonov, S., Molkov, S., Grebenev, S., Winkler, C., Parmar, A., Bazzano, A., Falanga, M. et al. 2007, INTEGRAL observations of the cosmic X-ray background in the 5-100 keV range via occultation by the Earth, Astron. & Astrophys. 467, 529 doi:10.1051/0004-6361:20066230.

36. Condon, J. J., Cotton, W. D., Fomalont, E. B., Kellermann, K. I., Miller, N., Perley, R. A., Scott, D., Vernstrom, T. & Wall, J. V. 2012, Resolving the Radio Source Background: Deeper Understanding through Confusion, Astrophys. J. 758, 23, doi:10.1088/0004-637X/758/1/23.

37. Cooray, A. & Sheth, R. 2002, Halo models of large scale structure, Phys. Reports, 372, 1-129, doi:10.1016/S0370-1573(02)00276-4.

38. Cooray, A. & Yoshida, N. 2004, First sources in infrared light: stars, supernovae and miniquasars, Mon. Not. Royal Astron. Soc. 351, L71-L77, doi:10.1111/j.1365-2966.2004.08047.x.

39. Cooray, A., Amblard, A., Becihman, C., Benford, D., Bernstein, R., Bock, J. J., Brodwin, M., Bromm, V., Cen, R., Chary, R. R. et al. 2009, A New Era in Extragalactic Background Light Measurements: The Cosmic History of Accretion, Nucleosynthesis and Reionization, Astro2010: The Astronomy and Astrophysics Decadal Survey, Science White Papers, no. 54.

40. Cooray, A., Smidt, J., de Bernardis, F., Gong, Y., Stern, D., Ashby, M. L. N., Eisenhardt, P. R., Frazer, C. C., Gonzalez, A. H., Kochanek, C. S. et al. 2012, Near-infrared background anisotropies from diffuse intrahalo light of galaxies, Nature, 490, 514-516,

doi:10.1038/nature11474.

41. De Bernardis, F. & Cooray. A. 2012, A Conditional Luminosity Function Model of the Cosmic Far-infrared Background Anisotropy Power Spectrum, Astrophys. J. 760, 14, doi:10.1088/0004-637X/760/1/14.

42. Dominguez, A., Primack, J., Rosario, D., Prada, F., Gilmore, R. et al. 2011, Extragalactic Background Light Inferred from AEGIS Galaxy SED-type Fractions, Mon.Not.Ray.Astron.Soc. 410, 2556-2578.

43. Dole, H., Le Floc'h, E., Pérez-González, P. G., Papovich, C., Egami, E., Lagache, G., Alonso-Herrero, A., Engelbracht, C. W., Gordon, K. D., Hines, D. C. et al. 2004, Far-infrared Source Counts at 70 and 160 Microns in Spitzer Deep Surveys, Astroph. J. Supp. 154, 87-92, doi:10.1086/422472.

44. Dole, H., Lagache, G., Puget, J.-L., Caputi, K. I., Fernández-Conde, N., Le Floc'h, E., Papovich, C., Pérez-González, P. G., Rieke, G. H. & Baylock, M. 2006, The cosmic infrared background resolved by Spitzer: Contributions of mid-infrared galaxies to the far-infrared background, Astron. & Astroph. 451, 417-426, doi:10.1051/0004-6361:20054446.

45. Doré, O., Bock, J., Ashby, M., Capak, P., Cooray, A., de Putter, R., Eifler, T., Flagey, N., Gong, Y., Habib, S. et al. 2014, Cosmology with the SPHEREX All-Sky Spectral Survey, preprint, arXiv.org:1412.4872.

46. Drlica-Wagner, A., Albert, A., Bechtol, K., Wood, M., Strigari, L., Sanchez-Conde, M., Baldini, L., Essig, J., Cohen-Tanugi, B., Anderson, R. 2015, Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data, Astrophys. J., 809, L4, doi:10.1088/2041-8205/809/1/L4.

47. Durrer, R. 2015, The cosmic microwave background: the history of its experimental investigation and its significance for cosmology, Classical and Quantum Gravity, 12, 124007, doi:10.1088/0264-9381/32/12/124007.

48. Dwek, E., & Krennrich, F. 2013, The extragalactic background light and the gamma-ray opacity of the universe, Astroparticle Physics, 43, 112, doi:10.1016/j.astropartphys.2012.09.003.

49. Edelstein, J., Bowyer, S. & Lampton, M. 2000, Reanalysis of Voyager Ultraviolet Spectrometer Limits to the Extreme-Ultraviolet and Far-Ultraviolet Diffuse Astronomical Flux, Astrophys. J. 539, 187-190, doi:10.1086/309192.

50. Elbaz, D., Cesarsky, C. J., Fadda, D., Aussel, H., Désert, F. X., Franceschini, A., Flores, H., Harwit, M., Puget, J. L., Starck, J. L. et al. 1999, Source counts from the 15 μm ISOCAM Deep Surveys, Astron. & Astrophys. 351, L37-L40.

51. Fazio, G. G., Ashby, M. L. N., Barmby, P., Hora, J. L., Huang, J.-S., Pahre, M. A., Wang, Z., Willner, S. P., Arendt, R. G., Moseley, S. H. et al. 2004, Number Counts at 3 μm $< \lambda <$ 10 μm from the Spitzer Space Telescope, Astrophys. J. Supp. 154, 39-43, doi:10.1086/422585.

52. Fermi-LAT Collaboration 2015, Resolving the Extragalactic γ-ray Background above 50 GeV with Fermi-LAT, arXiv.org:1511.00693.

53. Fernandez, E. & Komatsu, E. 2006, The Cosmic Near-Infrared Background: Remnant Light from Early Stars, Astroph. J., 646, 703-718, doi:10.1086/505126.

54. Fichtel, C. E., Simpson, G. A., Thompson, D. J. 1978, Diffuse gamma radiation, Astrophys. J. 222, 883-849, doi:10.1086/156202.

55. Fixsen, D. J., Cheng, E. S., Gales, J. M., Mather, J. C., Shafer, R. A. & Wright, E. L. 1996, The Cosmic Microwave Background Spectrum from the Full COBE FIRAS Data Set, Astrophys. J.

473, 576, doi:10.1086/178173.

56. Fixsen, D. J., Dwek, E., Mather, J. C., Bennett, C. L. & Shafer, R. A. 1998, The Spectrum of the Extragalactic Far-Infrared Background from the COBE FIRAS Observations, Astrophys. J. 508, 123, doi:10.1086/306383

57. Fixsen, D. J. 2009, The Temperature of the Cosmic Microwave Background, Astrophys. J. 707, 916, doi: 10.1088/0004-637X/707/2/916.

58. Fornasa, M. & Sánchez-Conde, M. A. 2015, The nature of the Diffuse Gamma-Ray Background, preprint, arXiv:1502.02866.

59. Fornengo, N., Lineros, R., Regis, M. & Taoso, M. 2011, Possibility of a Dark Matter Interpretation for the Excess in Isotropic Radio Emission Reported by ARCADE, Phys. Rev. Lett. 107, 27, doi:10.1103/PhysRevLett.107.271302.

60. Fornengo, N., Perotto, L., Regis, M., Camera, S. 2015, Evidence of Cross-correlation between the CMB Lensing and the Gamma-Ray Sky, Astrophys. J. 802, L1, doi:10.1088/2041-8205/802/1/L1.

61. Fukada, Y., Hayakawa, S., Ikeda, M., Kasahara, I., Makino, F., Tanaka, Y. 1975, Rocket observation of energy spectrum of diffuse hard X-rays, Astrophysics and Space Science 32, L1-L5, doi:10.1007/BF00646232.

62. Furlanetto, S. R. 2006, The global 21-centimeter background from high redshifts, Mon. Not. Royal Astron. Soc. 371, 867-878.

63. Gardner, J. P., Brown, T. M. & Ferguson, H. C. 2000, Ultraviolet Galaxy Counts from Space Telescope Imaging Spectrograph Observations of the Hubble Deep Fields, Astrophys. J. 542, L79-L82, doi:10.1086/312930.

64. Garmire, G. P., Nousek, J. A., Apparao, K. M. W., Burrows, D. N., Fink, R. L., Kraft, R. P. 1992, The soft X-ray diffuse background observed with the HEAO 1 low-energy detectors, Astrophys. J. 399, 694-703, doi:10.1086/171962

65. Gendreau, K. C., Mushotzky, R., Fabian, A. C., Holt, S. S., Kii, T., Serlemitsos, P. J. et al. 1995, ASCA Observations of the Spectrum of the X-Ray Background, Publications of the Astronomical Society of Japan, 47, L5-L9.

66. Geringer-Sameth, A., Walker, M. G., Koushiappas, S. M., Kopsov, S. E., Belokurov, V., Torrealba, G., Evans, N. W. 2015, Indication of Gamma-Ray Emission from the Newly Discovered Dwarf Galaxy Reticulum II, Phys. Rev. Lett. 115, 081101, doi:10.1103/PhysRevLett.115.081101.

67. Gilli, R., Comastri, A., Hasinger, G. 2007, The synthesis of the cosmic X-ray background in the Chandra and XMM-Newton era, Astron. & Astrophys., 463, 79-96.

68. Gilmore, R., Somerville, R., Primack, J. & Dominguez, A. 2012, Semi-analytic modeling of the EBL and consequences for extragalactic gamma-ray spectra, Mon.Not.Roy.Astron.Soc. 422, 3189, doi:10.1111/j.1365-2966.2012.20841.x.

69. Glenn, J., Conley, A., Béthermin, M., Altieri, B., Amblard, A., Arumugam, V., Aussel, H., Babbedge, T., Blain, A., Bock, J. et al. 2010 HerMES: deep galaxy number counts from a P(D) fluctuation analysis of SPIRE Science Demonstration Phase observations, Mon. Not. Royal Astron. Soc. 409, 109-121, doi:10.1111/j.1365-2966.2010.17781.x.

70. Gong, Y. & Cooray, A. 2013, The Extragalactic Background Light from the Measurements of the Attenuation of High-energy Gamma-Ray Spectrum, Astrophys. J. 772, L12,

doi:10.1088/2041-8205/772/1/L12.

71. Gorjian, V., Wright, E. L. & Chary, R. R. 2000, Tentative Detection of the Cosmic Infrared Background at 2.2 and 3.5 Microns Using Ground-based and Space-based Observations, Astrophy. J., 536, 550-560, doi:10.1086/308974.

72. Haiman, Z. & Knox, L. 2000, Correlations in the Far-Infrared Background, Astrophys. J. 530, 124-132, doi:10.1086/308374.

73. Hanner, M. S., Weinberg, J. L., DeShields, L. M., II, Green, B. A. & Toller, G. N. 1974, Zodiacal light and the asteroid belt: The view from Pioneer 10, J. Geophys. Research 79, 3671, doi:10.1029/JA079i025p03671.

74. Hanson, D., Hoover, S., Crites, A., Ade, P. A. R., Aird, K. A., Austermann, J. E., Beall, J. A., Bender, A. N., Benson, B. A., Bleem, L. E. et al. 2013, Detection of B-Mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope, Phys. Rev. Lett. 111, 141301, doi:10.1103/PhysRevLett.111.141301.

75. Harrison, F. A., Craig, W. W., Christensen, F. E., Hailey, C. J., Zhang, W. W., Boggs, S. E., Stern, D., Cook, W. R., Forster, K., Giommi, P. et al. 2013, The Nuclear Spectroscopic Telescope Array (NuStar) High-energy X-ray Mission, Astrophys. J. 770, 103, doi:10.1088/0004-637X/770/2/103.

76. Harrison, F. A., Aird, J., Civano, F. et al. 2015, The NuSTAR Extragalactic Surveys: The Number Counts of Active Galactic Nuclei and the Resolved Fraction of the Cosmic X-ray Background, preprint, arXiv.org:1511.04183.

77. Hauser, M. G. & Dwek, E. 2001, The Cosmic Infrared Background: Measurements and Implications, Ann. Rev. Astron. & Astroph. 39, 249-307, doi:10.1146/annurev.astro.39.1.249.

78. Hauser, M. G., Arendt, R. G., Kelsall, T., Dwek, N., Odegard, J. L., Weiland, H. T., Freudenreich, H. T., Reach, W. T., Silverberg, R. F., Moseley, S. H., et al. The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. I. Limits and Detections, Astrophys. J. 508, 25, doi:10.1086/306379.

79. Holder, G. 2014, The Unusual Smoothness of the Extragalactic Unresolved Radio Background, Astrophys. J. 780, 112, doi:10.1088/0004-637X/780/1/112.

80. Hooper, D. & Linden, T. 2015, On The Gamma-Ray Emission From Reticulum II and Other Dwarf Galaxies, J. Cosmo & Astroparticle Phys. 09, 016, doi:10.1088/1475-7516/2015/09/016.

81. Ibarra, A. & Tran, D. 2008, Gamma-ray Spectrum from Gravitino Dark Matter Decay, Phys. Rev. Lett. 100, 061301, doi:10.1103/PhysRevLett.100.061301.

82. Kamionkowski, M., Spergel, D. N. & Sugiyama, N. 2004, Small-scale cosmic microwave background anisotropies as probe of the geometry of the universe, Astrophys. J. 426, L57-L60, doi:10.1086/187339.

83. Kamionkowski, M., Kosowsky, A. & Stebbins, A. 1997, A Probe of Primordial Gravity Waves and Vorticity, Phys. Rev. Lett. 78, 2058-2061, doi:10.1103/PhysRevLett.78.2058.

84. Kashlinsky, A., Arendt, R. G., Mather, J. & Moseley, H. 2005, Tracing the first stars with fluctuations of the cosmic infrared background, Nature, 438, 45-50, doi:10.1038/nature04143.

85. Kashlinsky, A., Arendt, R. G., Ashby, M. L. N., Fazio, G. G., Mather, J. & Moseley, S. H. 2012, New Measurements of the Cosmic Infrared Background Fluctuations in Deep Spitzer/IRAC Survey Data and Their Cosmological Implications, Astrophy. J. 753, 63, doi:10.1088/0004-637X/753/1/63.

86. Kelsall, T., Weiland, J. L., Franz, B. A., Reach, W. T., Arendt, R. G., Dwek, E., Freudenreich, H. T., Hauser, M. G., Moseley, S. H., Odegard, N. P. et al. 1998, The COBE Diffuse Infrared Background Experiment Search for the Cosmic Infrared Background. II. Model of the Interplanetary Dust Cloud, Astrophys. J. 508, 44-73, doi:10.1086/306380.

87. Knox, L., Cooray, A., Eisenstein, D. & Haiman, Z. 2001, Probing Early Structure Formation with Far-Infrared Background Correlations, Astrophys. J. 550, 7-20, doi:10.1086/319732.

88. Kogut, A., Fixsen, D. J., Levin, S. M., Limon, M., Lubin, P. M., Mirel, P., Seiffert, M., Singal, J., Villela, T., Wollack, E. & Wuensche, C. A. et al. 2011, ARCADE 2 Observations of Galactic Radio Emission, Astrophys. J. 734, 4, doi:10.1088/0004-637X/734/1/4.

89. Kogut, A., Chuss, D. T., Dotson, J., Dwek, E., Fixsen, D. J., Halpern, M., Hinshaw, G. F., Meyer, S., Moseley, S. H., Seiffert, M. D. et al. 2014, The Primordial Inflation Explorer (PIXIE), Proceedings of the SPIE, 9143, 91431E, doi:10.1117/12.2056840.

90. Komatsu, E., Bennett, C., Barnes, C., Bean, R., Dore, O., Dunkley, J., Gold, B., Greason, M. R. et al. 2014, results from the Wilkinson Microwave Anisotropy Probe, Progress of Theoretical and Experimental Physics, 2014, 06B10224, doi:10.1093/ptep/ptu083.

91. Krumpe, M., Miyaji, T., Brunner, H., Hanami, H., Ishigaki, T., Takagi, T., Markowitz, A. G., Goto, T., Malkan, M. A., Matsuhara, H. et al. 2015, Mon. Not. Royal Astron. Soc. 446, 911-931, doi:10.1093/mnras/stu2010.

92. Lagache, G., Haffner, L.M., Reynolds, R. J. & Tufte, S. L. 2000, Evidence for dust emission in the Warm Ionised Medium sing WHAM data, Astro. & Astrophys. 354, 247-252.

93. Lagache, G. & Puget, J.-L. 2000, Detection of the extra-Galactic background fluctuations at 170 μm, Astron. & Astrophys. 355, 17-22.

94. Lagache, G., Bavouzet, N., Fernandez-Conde, N., Ponthieu, N., Rodet, T., Dole, H., Miville-Deschênes, M.-A. & Puget, J.-L. 2007, Correlated Anisotropies in the Cosmic Far-Infrared Background Detected by the Multiband Imaging Photometer for Spitzer: Constraint on the Bias, Astrophys. J. 665, L89-L92, doi:10.1086/521301.

95. Levenson, L., Wright, E. & Johnson, B. D. 2007, DIRBE Minus 2MASS: Confirming the CIRB in 40 New Regions at 2.2 and 3.5 μm, Astrophys. J., 666, 34-44, doi:10.1086/520112.

96. Levenson. L. & Wright, E. L. 2008, Probing the 3.6 μm CIRB with Spitzer in Three DIRBE Dark Spots, Astrophys. J. 683, 585-596, doi:10.1086/589808.

97. Lewis, A. & Challinor, A. 2006, Weak gravitational lensing of the CMB, Phys. Reports, 429, 1-65, doi:10.1016/j.physrep.2006.03.002.

98. Lieu, R., Mittaz, J.P.D., Bowyer, S., Breen, J.O., Lockman, F.J., Murphy, E.M. & Hwang, C. -Y. 1996b, Science, 274, 1335.

99. Madau, P. & Pozzetti, L. 2000, Deep galaxy counts, extragalactic background light and the stellar baryon budget, Mon. Not. Royal Astron. Soc. 312, L9-L15, doi:10.1046/j.1365-8711.2000.03268.x.

100. Marshall, F. E., Boldt, E. A., Holt, S. S., Miller, R. B., Mushotzky, R. F., Rose, L. A., Rothschild, R. E. & Serlemitsos, P. J. 1980, The diffuse X-ray background spectrum from 3 to 50 keV, Astrophys. J. 235, 4-10, doi:10.1086/157601.

101. Mather, J. C., Cheng, E. S., Cottingham, D. A., Eplee, R. E., Jr., Fixsen, D. J., Hewagama, T., Isaacman, R. B., Jensen, K. A., Meyer, S. S., Noerdlinger, P. D. et al. 1994, Measurement of the cosmic microwave background spectrum by the COBE FIRAS instrument, Astrophys. J. 420,

439-444, doi:10.1086/173574.

102. Matsuhara, H., Kawara, K., Sato, Y., Taniguchi, Y., Okuda, H., Matsumoto, T., Sofue, Y., Wakamatsu, K., Cowie, L. L., Joseph, R. D. & Sanders, D. B. 2000, ISO deep far-infrared survey in the "Lockman Hole". II. Power spectrum analysis: evidence of a strong evolution in number counts, Astron. & Astrophys. 361, 407-414.

103. Mattila, K. 2003, Has the Optical Extragalactic Background Light Been Detected?, Astrophys. J. 591, 119-124, doi:10.1086/375182.

104. Mattila, K. 2006, The 1-μm discontinuity in the extragalactic background light spectrum: an artefact of foreground subtraction, Mon. Not. Royal Astron. Soc., 372, 1253-1258, doi:10.1111/j.1365-2966.2006.10934.x.

105. Matsumoto, T., Matsuura, S., Murakami, H., Tanaka, M., Freund, M., Lim, M., Cohen, M., Kawada, M. & Noda, M. 2005, Infrared Telescope in Space Observations of the Near-Infrared Extragalactic Background Light, Astrophys. J. 626, 31-43, doi:10.1086/429383.

106. Matsumoto, T., Seo, H. J., Jeong, W.-S., Lee, H. M., Matsuura, S., Matsuhara, H., Oyabu, S., Pyo, J. & Wada, T. 2011, AKARI Observation of the Fluctuation of the Near-infrared Background, 742, 124, doi:10.1088/0004-637X/742/2/124.

107. Matsuura, S., Shirahata, M., Kawada, M., Takeuchi, T. T., Burgarella, D., Clements, D. L., Jeong, W.-S., Hanami, H., Khan, S. A., Matsuhara, H. et al. 2011, Detection of the Cosmic Far-infrared Background in AKARI Deep Field South, Astrophys. J. 737, 2, doi:10.1088/0004-637X/737/1/2.

108. Ménard, B., Nestor, D., Turnshek, D., Quider, A., Richards, G., Chelouche, D. & Rao, S. 2007, Lensing, reddening and extinction effects of MgII absorbers from $z = 0.4$ to 2, Mon. Not. Royal Astron. Soc. 385, 1053-1066, doi:10.1111/j.1365-2966.2008.12909.x.

109. Mitchell-Wynne, K., Cooray, A., Gong, Y., Ashby, M., Dolch, T., Ferguson, H. C., Finkelstein, S., Grogin, N., Kocevski, D., Koekemoer, A. et al. 2015, Ultraviolet Luminosity Density of the Universe During the Epoch of Reionization, Nature Comms. 6, 7945, doi:10.1038/NCOMMS8945.

110. Miville-Deschênes, M.-A., Lagache, G. & Puget, J.-L. 2002, Power spectrum of the cosmic infrared background at 60 and 100 μm with IRAS, Astron. & Astrophys. 393, 749-756, doi:10.1051/0004-6361:20020929.

111. Murthy, J., Doyle, J., Matthew, E., Henry, R. C. & Holberg, J. B. 1999, An Analysis of 17 Years of Voyager Observations of the Diffuse Far-Ultraviolet Radiation Field, Astrophys. J, 522, 904-914, doi:10.1086/307652.

112. Murthy, J., Henry, R. C., Sujatha, N. V. 2010, Mapping the Diffuse Ultraviolet Sky with the Galaxy Evolution Explorer, Astrophys. J. 724, 1389-1395, doi:10.1088/0004-637X/724/2/1389.

113. Menci, N., Fiore, F., Perola G. C. & Cavaliere, A. 2004, X-Ray Evolution of Active Galactic Nuclei and Hierarchical Galaxy Formation, Astrophys. J. 605, 58-66, 2004

114. Oliver, S., Wang, L., Smith, A. J., Altieri, B., Amblard, A., Arumugam, V., Auld, R., Aussel, H., Babbedge, T., Blain, A. et al. 2010, HerMES: SPIRE galaxy number counts at 250, 350, and 500 μm, Astron. & Astrophys. 518, L21, doi:10.1051/0004-6361/201014697.

115. O'Leary, R. M., Kistler, M. D., Kerr, M. & Dexter, J. 2015, Young Pulsars and the Galactic Center GeV Gamma-ray Excess, preprint, arXiv.org:1504.02477.

116. Palomares-Ruiz, S. & Siegal-Gaskins, J. M. 2010, Annihilation vs. Decay: Constraining dark matter properties from a gamma-ray detection, J. Cosmo. & Astroparticle Phys. 1007, 023,

doi:10.1088/1475-7516/2010/07/023.

117. Papovich, C., Dole, H., Egami, E., Le Floc'h, E., Pérez-González, P. G., Alonso-Herrero, A., Bai, L., Beichman, C. A., Blaylock, M., Engelbracht, C. W. et al. 2004, The 24 Micron Source Counts in Deep Spitzer Space Telescope Surveys, Astrophys. J. Supp. 154, 70-74, doi:10.1086/422880.

118. Persic, M. & Rephaeli, Y. 2003, Starburst galaxies and the X-ray background, Astron. & Astroph. 399, 9-17, doi:10.1051/0004-6361:20021738.

119. Primack, J., Gilmore, R. & Sommerville, R. S. 2008, Diffuse Extragalactic Background Radiation, HIGH ENERGY GAMMA-RAY ASTRONOMY: Proceedings of the 4th International Meeting on High Energy Gamma-Ray Astronomy. AIP Conference Proceedings, 1085, 71-82, doi:10.1063/1.3076779.

120. Pritchard, J. R. & Loeb, A. 2012, 21 cm cosmology in the 21st century, Reports on Prog. in Phys. 75, 086901, doi:10.1088/0034-4885/75/8/086901.

121. Revnivtsev, M., Gilfanov, M., Sunyaev, R., Jahoda, K., Markwardt, C. 2003, The spectrum of the cosmic X-ray background observed by RTXE/PCA, Astronomy and Astrophysics, 411, 329-334, doi:10.1051/0004-6361:20031386.

122. Rothschild, R. E., Baity, W. A., Gruber, D. E., Matteson, J. L., Peterson, L. E. & Mushotzky, R. F. 1983, 2-165 keV observations of active galaxies and the diffuse background, Astrophys. J. 269, 423-437, doi:10.1086/161053.

123. Salvaterra, R. & Ferrara, A. 2003, The imprint of the cosmic dark ages on the near-infrared background, Mon. Not. Royal Astron. Soc. 339, 973-982, doi:10.1046/j.1365-8711.2003.06244.x.

124. Santos, M. R., Bromm, V. & Kamionkowski, M. 2002, The contribution of the first stars to the cosmic infrared background, Mon. Not. Royal Astron. Soc, 336, 1082=1092, doi:10.1046/j.1365-8711.2002.05895.x.

125. Shang, C., Haiman, Z., Knox, L. & Oh, S.-P. Improved models for cosmic infrared background anisotropies: new constraints on the infrared galaxy population, Mon. Not. Royal Astron. Soc. 421, 2832-2845, doi:10.1111/j.1365-2966.2012.20510.x.

126. Shirasaki, M., Horiuchi, S. & Yoshida, N. 2014, Cross-Correlation of Cosmic Shear and Extragalactic Gamma-ray Background: Constraints on the Dark Matter Annihilation Cross-Section, Phys. Rev. D, 90, 063502, doi:10.1103/PhysRevD.90.063502.

127. Smail, I., Ivison, R. J. Blain, A. W. & Kneib, J.-P. 2002, The nature of faint submillimetre-selected galaxies, Mon. Not. Royal Astron. Soc. 331, 495-520, doi:10.1046/j.1365-8711.2002.05203.x.

128. Smith, R. K., Foster, A. R., Edgar, R. J., Brickhouse, N. S. 2014, Resolving the Origin of the Diffuse Soft X-Ray Background, The Astrophysical Journal, 787, 1, 77, doi:10.1088/0004-637X/787/1/77.

129. Song, Y.-S., Cooray, A., Knox, L. & Zaldarriaga, M. 2003, The Far-Infrared Background Correlation with Cosmic Microwave Background Lensing, Astrophys. J. 590, 664-672, doi:10.1086/375188.

130. Sreekumar, P., Bertsch, D. L., Dingus, B. L., Esposito, J. A., Fichtel, C. E., Hartman, R. C., Hunter, S. D., Kanbach, G., Kniffen, D. A. Lin, Y. C. et al., 1998, EGRET observations of the extragalactic gamma-ray emission, Astrophys.J. 494, 523-534, doi:10.1086/305222.

131. Stern, S. A., Slater, D. C., Scherrer, J., Stone, J., Dirks, G., Versteeg, M., Davis, M., Gladstone, G. R., Parker, J., Young, L. A., Siegmund, O. 2007, ALICE: The Ultraviolet Imaging Spectrograph

Aboard the New Horizons Pluto-Kuiper Belt Mission, Space Science Reviews, 140, 155-187, doi:10.1007/s11214-008-9407-3.

132. Strong, A. W., Moskalenko, I. V., Reimer, O. 2004, A New Determination of the Extragalactic Diffuse Gamma-Ray Background from EGRET Data, Astrophys.J. 613, 956-961, 10.1086/423196.

133. Subrahmanyan, R. & Cowsik, R. 2013, Is there an Unaccounted for Excess in the Extragalactic Cosmic Radio Background?, Astrophys. J. 776, 42, doi: 10.1088/0004-637X/776/1/42.

134. Sullivan, I., Cooray, A., Chary, R.-R., Bock, J. J., Brodwin, M., Brown, M. J. I., Dey, A., Dickinson, M., Eisenhardt, P., Ferguson, H. C. et al. 2007, Clustering of the IR Background Light with Spitzer: Contribution from Resolved Sources, Astrophys. J. 657, 37-50, doi:10.1086/511293.

135. Tepper-Garcia, T., Richter, P. & Schaye, J. 2013, Absorption signatures of warm-hot gas at low redshift: Ne VIII, Mon. Not. Royal Astron. Soc. 436, 2053, doi:10.1093/mnras/stt1712.

136. Thacker, C., Cooray, A., Smidt, J., De Bernardis, F., Mitchell-Wynne, K., Amblard, A., Auld, R., Baes, M., Clements, D. L., Dariush, A. et al. 2013, H-ATLAS: The Cosmic Abundance of Dust from the Far-infrared Background Power Spectrum, Astrophys. J. 768, 58, doi:10.1088/0004-637X/768/1/58.

137. Thacker, C., Gong, Y., Cooray, A., De Bernardis, F., Smidt, J. & Mitchell-Wynne, K. 2015, Cross-Correlation of Near and Far-Infrared Background Anisotropies as Traced by Spitzer and Herschel, preprint, arXiv.org:1412.4009.

138. Thompson, R. I., Eisenstein, D., Fan, X., Rieke, M. & Kennicutt, R. C. 2007, Evidence for a $z < 8$ Origin of the Source-subtracted Near-Infrared Background, Astrophys. J. 666, 658-662, doi:10.1086/520634.

139. Tsumura, K., Arai, T., Battle, J., Bock, J., Brown, S., Cooray, A., Hristov, V., Keating, B., Kim, M. G., Lee, D. H. et al. 2013, The Cosmic Infrared Background Experiment (CIBER): The Low Resolution Spectrometer, Astrophys. J., 207, 33, doi:10.1088/0067-0049/207/2/33.

140. Ueda, Y., Akiyama, M., Ohta, K and Miyaji, T. 2003, Cosmological Evolution of the Hard X-Ray Active Galactic Nucleus Luminosity Function and the Origin of the Hard X-Ray Background Astrophys. J., 598, 886-908

141. Vernstrom, T., Scott, D., Wall, J. V., Condon, J. J., Cotton, W., Fomalont, E. B., Kellermann, K. I., Miller, N., Perley, R. A. 2014, Deep 3 GHz number counts from a fluctuation analysis, Monthly Notices of the Royal Astronomical Society, 440, 2791-2809, doi:10.1093/mnras/stu470.

142. Viero, M. P., Ade, P. A. R., Bock, James J., Chapin, E. L., Devlin, M. J., Griffin, M., Gundersen, J. O., Halpern, M., Hargrave, P. C., Hughes, D. H. et al. 2009, BLAST: Correlations in the Cosmic Far-Infrared Background at 250, 350, and 500 μm Reveal Clustering of Star-forming Galaxies, Astrophys. J., 707, 1766-1778, doi:10.1088/0004-637X/707/2/1766.

143. Viero, M. P., Wang, L., Zemcov, M., Addison, G., Amblard, A., Arumugam, V., Aussel, H., Béthermin, M., Bock, J., Boselli, A. et al. 2013, HerMES: Cosmic Infrared Background Anisotropies and the Clustering of Dusty Star-forming Galaxies, Astrophys. J. 772, 77, doi:10.1088/0004-637X/772/1/77.

144. Viero, M., Moncelsi, L., Quadri, M., Béthermin, M., Bock, J. J., Burgarella, D., Chapman, S. C., Clements, D. L., Conley, A. Conversi, L. et al. 2015, HerMES: Current Cosmic Infrared Background Estimates Can be Explained by Known Galaxies and their Faint Companions at $z < 4$, Astrophys. J. 809, L22, doi:10.1088/2041-8205/809/2/L22.

145. Watanabe, K., Leising, M. D., Share, G. H., Kinzer, R. L. 2000, The MeV cosmic gamma-ray

background measured with SMM, THE FIFTH COMPTON SYMPOSIUM. AIP Conference Proceedings, 510, 471-475, doi:10.1063/1.1303252

146. Weidenspointner, G., Varendorff, M., Kappadath, S. C., Bennett, K., Bloemen, H., Diehl, R., Hermsen, W., Lichti, G. G., Ryan, J., SchÃűnfelder, V. 2000, The cosmic diffuse gamma-ray background measured with COMPTEL, THE FIFTH COMPTON SYMPOSIUM. AIP Conference Proceedings, Volume 510, 467-470, doi:10.1063/1.1307028

147. Wright, E. L. 2001, DIRBE minus 2MASS: Confirming the Cosmic Infrared Background at 2.2 Microns, Astroph. J., 553, 538-544,doi:10.1086/320942.

148. Wright, E. L. 2004, COBE observations of the cosmic infrared background, New Astro. Rev. 48, 465-468, doi:10.1016/j.newar.2003.12.054.

149. Worsley, M. A., Fabian, A. C., Bauer, F. E., Alexander, D. M., Hasinger, G., Mateos, S., Brunner, H., Brandt, W. N. & Schneider, D. P. 2005, The unresolved hard X-ray background: the missing source population implied by the Chandra and XMM-Newton deep fields, Mon. Not. Royal Astron. Soc. 357, 1281-1287, doi:10.1111/j.1365-2966.2005.08731.x.

150. Wu, X.-P. & Xue, Y.-J. 2001, The X-Ray Background from Groups and Clusters of Galaxies, Astrophs. J. 560, 544-548.

151. Xia, J.-Q., Cuoco, A., Branchini, E., Fornasa, M., Viel, M. 2011, A cross-correlation study of the Fermi-LAT -ray diffuse extragalactic signal, Mon.Not.Roy.Astron.Soc. 416, 2247-2264, doi:10.1111/j.1365-2966.2011.19200.x.

152. Xia, J.-Q., Negrello, M., Lapi, A., De Zotti, G., Danese, L. & Viel, M. 2012, Clustering of submillimetre galaxies in a self-regulated baryon collapse model, Mon. Not. Royal Astron. Soc. 422, 1324-1331, doi:10.1111/j.1365-2966.2012.20705.x.

153. Xue, Y. Q., Wang, S. X., Brandt, W. N., Luo, B., Alexander, D. M., Bauer, F. E., Comastri, A., Fabian, A. C., Gilli, R., Lehmer. B. D. et al. 2012, Tracking down the Source Population Responsible for the Unresolved Cosmic 6-8 keV Background, Astroph. J. 758, 129, doi:10.1088/0004-637X/758/2/129.

154. Yue, B., Ferrara, A., Salvaterra, R. & Chen, X. 2013, The contribution of high-redshift galaxies to the near-infrared background, Mon. Not. Royal Astron. Soc. 431, 383-393, doi:10.1093/mnras/stt174.

155. Zemcov, M., Smidt, J., Arai, T., Bock, J., Cooray, A., Gong, Y., Kim, M.G., Korngut, P., Lam, A., Lee, D.H. et al. 2014, On the origin of near-infrared extragalactic background light anisotropy, Science, 346, 732-735, doi:10.1126/science.1258168.

156. Zemcov, M., Arai, T., Battle, J., Bock, J., Cooray, A., Hristov, V., Keating, B., Kim, M. G., Lee, D. H., Levenson, L. R. et al. 2013, The Cosmic Infrared Background Experiment (CIBER): A Sounding Rocket Payload to Study the near Infrared Extragalactic Background Light, Astrophys. J. Supp. 207, 16, doi:10.1088/0067-0049/207/2/31.