An observational determination of the evolving extragalactic background light from the multiwavelength HST/CANDELS survey in the Fermi and CTA era

Alberto Saldana-Lopez,1,2 * Alberto Domínguez,2 † Pablo G. Pérez-González,3 ‡ Justin Finke,4 Marco Ajello,5 Joel R. Primack,6 Vaidehi S. Paliya,7 Abhishek Desai,8

1 Observatoire de Genève, Département d’Astronomie, Université de Genève, 51 Chemin Pegasi, 1290 Versoix, Switzerland
2 IPARCOS and Department of EMFTEL, Universidad Complutense de Madrid, E-28040 Madrid, Spain
3 Centro de Astrobiología (CAB, CSIC-INTA), Carretera de Ajalvir km4, E-28850 Torrejón de Ardoz, Madrid, Spain
4 U.S. Naval Research Laboratory, Code 7653, 4555 Overlook Avenue SW, Washington, DC 20375-5352, USA
5 Department of Physics and Astronomy, Clemson University, Kinard Lab of Physics, Clemson, SC 29634-0978, USA
6 Department of Physics, University of California, Santa Cruz, CA 95064, USA
7 Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263001, India
8 Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin-Madison, Madison, WI 53706, USA

Accepted 2021 August 6. Received 2021 July 23; in original form 2020 December 8

ABSTRACT
The diffuse extragalactic background light (EBL) is formed by ultraviolet (UV), optical, and infrared (IR) photons mainly produced by star formation processes over the history of the Universe, and contains essential information about galaxy evolution and cosmology. Here, we present a new determination of the evolving EBL spectral energy distribution using a novel approach purely based on galaxy data aiming to reduce current uncertainties on the higher redshifts and IR intensities. Our calculations use multiwavelength observations from the UV to the far-IR of a sample of approximately 150 000 galaxies detected up to \( z \approx 6 \) in the five fields of the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey from the Hubble Space Telescope. This is one of the most comprehensive and deepest multiwavelength galaxy datasets ever obtained. These unprecedented resources allow us to derive the overall EBL evolution up to \( z \approx 6 \) and its uncertainties. Our results agree with cosmic observables estimated from galaxy surveys and \( \gamma \)-ray attenuation such as monochromatic luminosity densities, including those in the far-IR, and star formation rate densities, also at the highest redshifts. Optical depths from our EBL approximation, which will be robust at high redshifts and for \( \gamma \)-rays up to tens of TeV, will be reported in a companion paper.

Keywords: galaxies: evolution – galaxies: formation – cosmology: diffuse radiation – infrared: diffuse background – gamma-rays: diffuse background

1 INTRODUCTION
Galaxy evolution processes involve the release of radiation to the intergalactic space mainly through two ways: (1) stellar emission and (2) thermal radiation from warmed dust. The former mechanism liberates photons from ultraviolet (UV) to optical and near-infrared (NIR) wavelengths, whereas the latter does both in the mid- and far-infrared range (MIR and FIR, respectively). The major contributors to the UV (sometimes optical) emission are populations of massive and/or young stars; as less massive, older and cooler ones preferentially emit in the NIR (e.g., Kippenhahn & Weigert 1990).

An important fraction of these UV/optical photons produce the excitation of vibrational and rotational levels of ions and molecules in the interstellar and intergalactic medium. Dust grains then heat up, increase their temperature, and emit radiation at lower energies, roughly as a modified black body whose spectrum peaks at wavelengths between 20 and 200 \( \mu m \), also in emission bands produced by the relaxation of the excited levels of polycyclic aromatic hydrocarbons (PAHs, e.g., Draine 2011). There is also some contribution from active galactic nuclei activity (e.g., Hauser & Dwek 2001).

All these photons, which are redshifted to longer wavelengths due to the cosmological expansion, travel through the intergalactic medium (IGM), accumulate in interstellar/intergalactic space, and produce the diffuse background radiation known as the extragalactic background light (EBL, e.g., Peebles 1993; Partridge & Peebles 1967; Hauser et al. 1998; Primack et al. 2011; Dwek...
Semianalytical models of galaxy formation (e.g., Somerville et al. 2010; Abdo et al. 2010; Meyer et al. 2012; Ackermann et al. 2011; Dermer et al. 2011b; Abe et al. 2010; Stecker et al. 2017; Driver et al. 2017; Bellstedt et al. 2020; Malkan et al. 2020). In particular, our previous model (Domínguez et al. 2011a) constructs the EBL SED using a galaxy sample of approximately 6,000 galaxies observed up to $z \sim 1$ selected from the All-wavelength Extended Groth Strip International Survey (AEGIS, Davis et al. 2007) on the Extended Groth Strip field. The multiband SED of these galaxies, which have their redshift detected at 24 µm, were convolved with a $K$-band galaxy luminosity function measured up to $z \sim 4$.

Here, we present a new determination of the evolving EBL-SED purely based on galaxy data. This original approach uses multiband observations of more than 150,000 galaxies in the five different fields of CANDELS, thus reducing uncertainties related to cosmic variance. This sample is a combination of the deepest galaxy surveys in UV (e.g., with GALEX), optical and NIR (with the Hubble Space Telescope and ground-based telescopes), MIR (with the Spitzer Infrared Space Telescope), FIR (with Spitzer and the Herschel Space Observatory) and contains a significant number of galaxies detected up to $z \sim 6$.

Our goal is reducing the uncertainties of current EBL models, which are mainly from (1) the EBL-SED evolution, and (2) the far-IR region. We approach (1) recovering a complete EBL evolution up to $z \sim 6$, and a better estimation of the FIR coverage (2) is given by accounting for the emissivity of non-detected sources in the IR. There is an accompanying paper focused on the derived optical depth and the implications for the propagation of $γ$ rays in space (Domínguez et al., in preparation).

This paper is organized as follows. In Sect. 2 we describe our galaxy sample based on the CANDELS surveys and ancillary data, whereas Sect. 3 explains the methodology and our EBL model formalism. In Sect. 4 we show the results and discuss them. Finally, a summary is presented in Sect. 5.

Throughout this analysis, a Chabrier (2003) initial mass function (IMF) and a standard $Λ$CDM cosmology is used, with a matter density parameter $Ω_M = 0.3$, a vacuum energy density parameter $Ω_\Lambda = 0.7$, and Hubble constant $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. 
Observational EBL from HST–CANDELS

2 DATA

2.1 The CANDELS multi-wavelength survey

CANDELS is one of the most ambitious Hubble Space Telescope (HST) observational programs (Grogin et al. 2011; Koekemoer et al. 2011). It involves more than 4 months of cumulative observing time between 2010 and 2013. The CANDELS HST surveys have selected a set of around 200 000 galaxies up to $z = 8$ using two of its instruments: the Advance Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3). Both provide NUV to NIR data collection (0.435-1.6 μm) thanks to broadband filter imaging. The CANDELS selection criteria enforced observation in WFC3/F160W filter (1.6 μm central wavelength, $H$-band) focusing on five fields: (1) Great Observatories Origins Deep Survey South (GOODS–S), (2) Ultra Deep Survey (UDS), (3) Cosmic Evolution Survey (COSMOS), (4) Extended Groth Strip (EGS), and (5) Great Observatories Origins Deep Survey North (GOODS–N), sorted by date of publication.

The CANDELS observing program is composed by two observational modes with different $H$-band limiting apparent magnitude ($m_{lim}^{H}$): CANDELS/Wide ($m_{lim}^{H} \sim 27$ AB) and CANDELS/Deep ($m_{lim}^{H} \sim 27.7$ AB). All these fields have a sky-projected area of around 200 arcmin$^2$ and host ~35 000 detected sources each. Table 1 shows a detailed description of the central RA/DEC coordinates, covered area, and number of sources. For this work, we use the catalogs published by the CANDELS team and released through the Rainbow database.

The CANDELS/GOODS–S sample is composed by 34 930 sources selected via HST/WFC3/F160W detection over HST/WFC3 F105W, F125W, and F160W original exposures on a 173 arcmin$^2$...
sky-area (Guo et al. 2013). The mosaic reaches a 5σ limiting depth (within an aperture radius of 0.17 arcsec) of 27.4 AB and 28.2 AB for CANDELS Wide and Deep modes. In addition to WFC3 bands, the catalog also includes data from UV (U-band from both CTIO/MOJAVE and VLT/VIMOS), optical (HST/ACS F435W, F606W, F775W, F814W, and F850LP), and NIR (HST/WFC3 F105W, F125W, F140W, and F160W; Subaru/MOIRCS Ks and CFHT/Megacam K) observations. The Hubble Deep field UV Legacy Survey (H20U) provides complementary observations to the CANDELS/GOODS–S Deep mode over a total area of ~100 arcmin² in the two filters F275W and F336W (Oesch et al. 2018).

The CANDELS/UKIDSS-UDS sample comprises a 173 arcmin² area with 35 932 HST WFC3/F125W and F160W selected sources (5σ limiting depth of 27.5 AB, Galametz et al. 2013). This includes observations in the visible through HST/ACS (F606W and F814W), u-band data from CFHT/Megacam, B, V, Rc, i', and z' band data from Subaru/Suprime-Cam, Y and Ks band data from VLT/HAWK-I, and also J, H, and K band data from UKIDSS (Data Release 8, UKIRT/WFCAM).

The CANDELS/COSMOS catalog is based on HST/WFC3/F160W detection selection criteria with a 27.6 AB limiting magnitude (5σ depth) over a 216 arcmin² field, resulting in 38 671 sources with photometric data in several bands from UV to the IR (Nayyeri et al. 2017). This includes broadband photometry from HST/ACS (F606W, F814W), HST/WFC3 (F125W, F160W), CFHT (MegaPrime/u格z), Subaru (Suprime-Cam/ B, griz, Y) and VISTA (VIRCAM/ Y, J, H, Ks) in the visible and NIR bands, along with intermediate and narrow band photometry from Subaru and mediumband data from Mayall/NEWFIRM (J1, J2, J3, Y1, Y2, K), respectively.

The photometric catalog in the CANDELS/EGS is built on the HST/ACS and WFC observations and selected 41 457 sources reaching a F160W 5σ depth of 26.6 AB, over an area of 206 arcmin² (Stefanon et al. 2017). This sample includes the following bands: HST/ACS F606W and F814W; HST/WFC3 F125W, F140W, and F160W; CFHT/Megacam u*,g*,r*,i* and z*; CFHT/WIRCAM J, H and Ks and Mayall/NEWFIRM J1, J2, J3, H1, H2 and K.

Finally, the F160W selected CANDELS/GOODS-N sources comprise a 173 arcmin² sky-area and 35 445 sources (Barro et al. 2019, hereafter B19). The 5σ detection limits (0.17 arcsec aperture radius) of the mosaic ranges between mlim = 27.8 and 28.7 AB in the Wide and Deep regions. The multi-wavelength photometry has broadband data from the UV (U-band from KPNO and LBT), optical (HST/ACS F435W, F606W, F775W, F814W, and F850LP) and near-to-mid IR (HST/WFC3 F105W, F125W, F140W, and F160W; Subaru/MOIRCS Ks and CFHT/Megacam K) observations. In addition to the WFC3, this release also includes data from the 25 medium-band filter observations from the with the Survey for High-z Absorption Red and Dead Sources (SHARDS) program using the Gran Telescopio Canarias (Pérez-González et al. 2013).

Additionally in all fields, the Spitzer Infrared Space Telescope provides IRAC/ 3.6, 4.5, 5.8, 8.0 μm and MIPS/24 and 70 μm photometry; while Herschel does through PACS/ 100 and 160 μm, SPIRE/ 250, 350 and 500 μm. A description of the Spitzer and Herschel catalogs and procedures to identify the counterparts within the CANDELS catalogs is presented in B19 –see also Rawle et al. (2016)–, and the 5σ limiting fluxes for Spitzer/MIPS and Herschel/PACS and SPIRE are summarized in Table 2. Also included in the GOODS–S/N fields are the GALEX FUV and NUV photometry bands (0.1530 and 0.2310 μm, Morrissey et al. 2007).

A summary of the CANDELS Photometry Data Set listing most of the photometric bands publicly available for the CANDELS mission is presented in Table 3.

### 2.2 Sample selection and data filtering

In order to work with a well-characterized photometric sample, that is, in which every galaxy-SED can be recovered with acceptable uncertainties, we revise the parent CANDELS catalogs and purge problematic sources.

Our sample selection process is the following:

(i) F160W detection is required.

(ii) F160W signal-to-noise ratio (S/N) should be larger than 5, i.e., $S/N_{F160W} >= 5$.

(iii) We remove identified stars. Additional sources whose SEDs might be contaminated by the emission from nearby bright stars are purged by an additional cut in the F160W apparent magnitude ($m_{F160W} <= 19$) for the lowest redshift sources ($z_\text{cut} <= 0.15$). This step was optimized based on the BzK diagrams stellar locus and other point-like sources' parameters provided in the CANDELS catalogs, such as for instance CLASS_STAR (see e.g., Barro et al. 2011a,b; Guo et al. 2013).

---

Table 2. Flux upper-limits for CANDELS IR bands.

| GOODS-S | UDS | COSMOS | EGS | GOODS-N |
|---------|-----|--------|-----|---------|
| MIPS24 (μJy) | 30  | 70     | 70  | 45      | 30    |
| PACS100 (mjy) | 1.1 | 14.4   | 2.9 | 8.7     | 1.6   |
| PACS160 (mjy) | 3.4 | 26.7   | 6.6 | 13.1    | 3.6   |
| SPIRE250 (mjy) | 8.3 | 19.4   | 11.0| 14.7    | 9.0   |
| SPIRE350 (mjy) | 11.5| 19.2   | 9.6 | 17.3    | 12.9  |
| SPIRE500 (mjy) | 11.3| 20.0   | 11.2| 17.9    | 12.6  |

---

Figure 2. Galaxy number counts on every CANDELS field for our final F160W selected sample. Vertical dashed lines limit the F160W(AB) 50% level of completeness calculated by Guo et al. (2013) for GOODS–S and by B19 for GOODS–N, for comparison. Red shadowed region represents the number counts calculations by Nayyeri et al. (2017) for the COSMOS field.

---

3 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
Table 3. Summary of photometric broad- and intermediate-band data set available in *Rainbow Navigator* for the 5 CANDELS fields.

| Instrument                  | Filter | λ (Å) | GOODS–S | UDS | COSMOS | EGS | GOODS–N |
|----------------------------|--------|-------|---------|-----|--------|-----|---------|
| GALEX                      | FUV    | 1 538 | ✓       | –   | –      | –   | ✓       |
| GALEX                      | NUV    | 2 315 | ✓       | –   | –      | –   | ✓       |
| Blanco/MOSAIC–II           | U, CTIO| 3 734 | ✓       | –   | –      | –   | –       |
| VLT/VIMOS                  | U, VIMOS| 3 722 | ✓       | –   | –      | –   | –       |
| KPN4m/Mosaic               | U      | 3 592 | –       | –   | –      | –   | ✓       |
| LBT/LBC                    | U      | 3 633 | –       | –   | –      | –   | ✓       |
| CFHT/MegaPrime             | u      | 3 817 | –       | –   | ✓      | –   | –       |
| CFHT/MegaPrime             | g      | 4 317 | –       | –   | ✓      | –   | –       |
| CFHT/MegaPrime             | r      | 6 220 | –       | –   | ✓      | –   | –       |
| CFHT/MegaPrime             | i      | 7 606 | –       | –   | ✓      | –   | –       |
| CFHT/MegaPrime             | z      | 8 816 | –       | –   | ✓      | –   | –       |
| CFHT/MegaCam               | u’     | 3 860 | –       | ✓   | –      | –   | ✓       |
| CFHT/MegaCam               | g’     | 4 890 | –       | –   | –      | –   | ✓       |
| CFHT/MegaCam               | r’     | 6 250 | –       | –   | –      | –   | ✓       |
| CFHT/MegaCam               | i’     | 7 690 | –       | –   | –      | –   | ✓       |
| CFHT/MegaCam               | z’     | 8 880 | –       | –   | ✓      | –   | –       |
| CFHT/MegaCam               | K      | 21 347| –       | –   | –      | –   | ✓       |
| Subaru/Suprime–Cam         | B      | 4 448 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | g      | 4 761 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | V      | 5 470 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | r*     | 6 276 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | R*     | 6 500 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | i*     | 7 671 | –       | ✓   | –      | –   | –       |
| Subaru/Suprime–Cam         | z*     | 9 096 | –       | ✓   | –      | –   | –       |
| Subaru/MOIRCS              | Ks     | 21 577| –       | –   | –      | –   | ✓       |
| HST/ACS                    | F435W  | 4 317 | ✓       | –   | –      | –   | ✓       |
| HST/ACS                    | F606W  | 5 918 | ✓       | ✓   | ✓      | ✓   | ✓       |
| HST/ACS                    | F775W  | 7 693 | ✓       | –   | –      | –   | ✓       |
| HST/ACS                    | F814W  | 8 047 | ✓       | ✓   | ✓      | ✓   | ✓       |
| HST/ACS                    | F850LP | 9 055 | ✓       | –   | –      | –   | ✓       |
| HST/WFC3                   | F098M  | 9 851 | ✓       | –   | –      | –   | –       |
| HST/WFC3                   | F105W  | 10 550| ✓       | –   | –      | –   | –       |
| HST/WFC3                   | F125W  | 12 486| ✓       | ✓   | ✓      | ✓   | ✓       |
| HST/WFC3                   | F140W  | 13 970| ✓       | –   | –      | –   | ✓       |
| HST/WFC3                   | F160W  | 15 370| ✓       | ✓   | ✓      | ✓   | ✓       |
| VISTA/VIRCAM               | Y      | 10 210| –       | –   | –      | –   | ✓       |
| VISTA/VIRCAM               | J      | 12 524| –       | ✓   | –      | –   | –       |
| VISTA/VIRCAM               | H      | 16 431| –       | –   | –      | –   | ✓       |
| VISTA/VIRCAM               | Ks     | 21 521| –       | –   | –      | –   | ✓       |
| VLT/ISAAC                  | Ks     | 21 605| ✓       | –   | –      | –   | –       |
| UKIRT/WFCAM                | J      | 12 510| –       | –   | ✓      | –   | –       |
| UKIRT/WFCAM                | H      | 16 360| –       | –   | ✓      | –   | –       |
| UKIRT/WFCAM                | K      | 22 060| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | J1     | 10 470| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | J2     | 11 950| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | J3     | 12 790| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | H1     | 15 610| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | H2     | 17 070| –       | –   | ✓      | –   | –       |
| Mayall/NEWFIRM             | K      | 21 700| –       | –   | ✓      | –   | –       |
| CFHT/WIRCAM                | J      | 12 540| –       | –   | –      | –   | ✓       |
| CFHT/WIRCAM                | H      | 16 360| –       | –   | –      | –   | ✓       |
| CFHT/WIRCAM                | Ks     | 21 590| –       | –   | –      | –   | ✓       |
| VLT/HAWK–1                 | Y      | 10 190| –       | –   | ✓      | –   | –       |
| VLT/HAWK–1                 | Ks     | 21 463| ✓       | –   | –      | –   | –       |
| Spitzer/IRAC               | 3.6 μm | 35 508| ✓       | ✓   | ✓      | ✓   | ✓       |
| Spitzer/IRAC               | 4.5 μm | 44 960| ✓       | ✓   | ✓      | ✓   | ✓       |
| Spitzer/IRAC               | 5.8 μm | 57 245| ✓       | ✓   | ✓      | ✓   | ✓       |
| Spitzer/IRAC               | 8.0 μm | 78 840| ✓       | ✓   | ✓      | ✓   | ✓       |
| Spitzer/MIPS               | MIPS/24| 238 440| ✓       | ✓   | ✓      | ✓   | ✓       |
| Spitzer/MIPS               | MIPS/70| 724 936| ✓       | ✓   | ✓      | ✓   | ✓       |
| Herschel/PACS              | PACS/100| 1 022 522| ✓       | ✓   | ✓      | ✓   | ✓       |
| Herschel/PACS              | PACS/160| 1 656 067| ✓       | ✓   | ✓      | ✓   | ✓       |
| Herschel/SPIRE             | SPIRE/250| 2 531 298| ✓       | ✓   | ✓      | ✓   | ✓       |
| Herschel/SPIRE             | SPIRE/350| 3 558 741| ✓       | ✓   | ✓      | ✓   | ✓       |
| Herschel/SPIRE             | SPIRE/500| 5 111 803| ✓       | ✓   | ✓      | ✓   | ✓       |
Examples of three reconstructed galaxy–SEDs for the 3 different types of source presented in Sect. 3 and sorted by redshift (see text). Left: galaxy with combined MIPS+Herschel FIR detections; the red, orange and green solid lines are the associated CE01, DH02 and R09 dust emission models (the dotted line fits only CE01 templates to MIPS/24 µm point). Middle: galaxy with no-IR counterpart by MIPS or Herschel; the solid red line comes from our L(TIR) using the SFR(UV)-excess, while the dashed line is the best fit with upper-limits. Right: galaxy with only MIPS/24 µm detection in the FIR; again, the solid red line correspond to our associated CE01 template following the 24 µm-to-L(TIR) W11 relation, while the dotted line is the best fit considering also Herschel upper-limits. The blue curve corresponds to the associated B19 stellar emission UV-to-NIR template for all the cases. CANDELS identifier, equatorial coordinates (RA, DEC), redshift, stellar mass, and measure/inferred L(TIR) are shown for every object.

Table 4. Data filtering procedure for the CANDELS EBL sample and resulting median (H), 0.05 (05%) and 0.95 (95%) quantiles values for every F160W (AB) magnitude distribution. The filtered sample is composed by 154,447/186,435 sources (82.8% of the total).

| Cut                  | GOODS-S | UDS | COSMOS | EGS | GOODS-N | Total |
|----------------------|---------|-----|--------|-----|---------|-------|
| CANDELS              | 34 930  | 35 932 | 38 671 | 41 457 | 35 445 | 186 435 |
| F160W detection      | 34 848  | 35 752 | 38 216 | 41 353 | 35 440 | 185 609 |
| S/N ≥ 5              | 32 224  | 28 222 | 33 327 | 32 577 | 29 269 | 155 619 |
| After removing stars | 32 170  | 28 742 | 33 297 | 32 518 | 29 242 | 155 969 |
| 0 ≤ z < 6            | 31 736  | 28 496 | 32 906 | 32 362 | 28 947 | 154 447 |
| F160W: H < 0.05       |          |      |        |      |         | 25.6427.48 |
| 0.05                 | 22.10    | 25.1326.56 | 25.1326.84 | 25.1426.69 | 25.2927.05 | 25.2527.00 |
| 0.95                 |          |      |        |      |         | 21.72    |
| 0.90                 |          |      |        |      |         | 21.70    |

In Table 4, we show the resulting number of sources after every filtering step independently for the five CANDELS fields and the final sample. The median for the F160W magnitude distributions with its 0.05 and 0.95 quantiles are given. Our final sample, that we call EBL sample, is composed by 154 447 out of a total of 186 435 sources (this is, 82.8% of the total). Figure 1 shows the filtering procedure on a magnitude versus redshift diagram for the GOODS-N field as example.

In Figure 2, we plot the differential galaxy number counts (number density) for the final EBL sample, and independently for each CANDELS field. We check the representativeness of our EBL sample compared to the parent sample in terms of this number density of sources (e.g., King & Ellis 1985). The procedure is the following: we fit a power law to the differential number density of objects, then typically the sample becomes incomplete when the observed differential number density significantly deviates from the best-fit power law at the faint end. For GOODS-S (Guo et al. 2013) and GOODS-N (B19), their actual differential number densities becomes lower than the best-fit power law by a factor of two at 26.6 and 25.9 AB, which is in agreement with the counts from our EBL sample. The COSMOS galaxy number counts from Nayyeri et al. (2017) are also plotted for comparison through the red shadowed band. In the forthcoming Sect. 4.2.1, we will approach how our sample selection criteria (mainly, F160W S/N cut) can affect the EBL intensity level.
Figure 5. $L_{\text{TIR}}$ versus redshift distribution. Orange points represent those sources with MIPS+Herschel combined detections (4071) and whose $L_{\text{TIR}}$ have been directly measured. Blue points are galaxies with only MIPS/24 $\mu$m detection (5391), and their corresponding $L_{\text{TIR}}$ comes from applying the W11 relation. Finally, grey points are sources no detected in the IR (144985), and our SFR(UV)-excess recipe was applied to obtain the $L_{\text{TIR}}$. For comparison, the GOODS–S/N 30 $\mu$Jy limiting fluxes curves are plotted using the W11 and Rujopakarn et al. (2013) expressions (W11 extrapolated out to $z = 6$).

Figure 6. Our completeness correction sketch. Left: the observed mass-density of objects for our EBL sample at $0.35 < z \leq 0.55$, in white open stars; the corresponding mass completeness limit is pointed by the dashed vertical line: $M^\text{lim} = 10^{7.5-8.0} M_\odot$. On the other hand, the prediction from the Ilbert et al. (2013) SMF for galaxies above this mass limit is highlighted by yellow stars. The grey shaded area represent the adopted SMF and our own Schechter fit to the data ($1\sigma$ band uncertainty). Right: UVJ color-color selection diagram (Williams et al. 2009) at $0.35 \leq z < 0.55$. The orange and blue circles indicate the quiescent and SF galaxies selected by this method on the corresponding mass completeness limit bin.
2.3 The Rainbow database

To access and retrieve CANDELS data, we use the Rainbow Cosmological Surveys Database (Barro et al. 2011a,b) through the publically accessible Rainbow Navigator\textsuperscript{4} web interface. This database collects a vast compilation of photometric and spectroscopic data for the CANDELS fields. Although independent SED fitting results are included in the CANDELS catalog papers, we prefer to use a homogenized SED method based on the Rainbow pipeline (see below). In addition, we use the UV- and IR-derived SFRs and the IR dust emission fits provided by the same Rainbow database pipeline, described for the 5 CANDELS fields in B19.

The Rainbow SED pipeline (see Barro et al. 2011a, b, and B19) use the Rainbow template fitting code developed by Pérez-González et al. (2005). Briefly, this program applies a \( \chi^2 \) minimization algorithm as:

\[
\chi^2 = \sum_{i=1}^{N} \frac{(F_{\text{obs},i} - A \times F_{\text{temp},i})^2}{\sigma_i^2},
\]

where \( F_{\text{obs},i} \) (\( F_{\text{temp},i} \)) is the observed (template) flux in the \( i \)th band, with an observational uncertainty \( \sigma_i \). The SED templates are first converted from rest- to observed-frame using a cosmological factor \( \times (1+z) \). The redshift is given by the CANDELS photometric or spectroscopic redshift when available. Uncertainties on the redshifts are not included in the analysis but Domínguez et al. (2011a) already showed that this does not produce a significant effect on the EBL intensities. A template renormalization factor, \( \mu \), is used to scale the observed SED to the associated template profile, and it accounts for the stellar mass and the luminosity distance for every galaxy. The UV-to-NIR region (defined in the 0.1 to 5.7 \( \mu \)m rest-frame wavelength interval) is modelled by stellar population templates, whereas the IR (from 5.7 to 1000 \( \mu \)m) is fitted independently by different dust emission models.

The stellar population templates are extracted from a semi-empirical library of 1,876 synthetic SEDs, built from GOODS-S/N IRAC selected sources (Pérez-González et al. 2008), and some AGN empirical templates from Polletta et al. (2007). Assuming a Chabrier IMF and a Calzetti extinction law (Calzetti 2001), the stellar emission of the reference templates is characterized using thePEGASE2.9 models (Fioc & Rocca-Volmerange 1997). The contribution from emission lines and the nebular continuum emitted by ionized gas are also considered. The models are obtained assuming a single stellar population, driven by an exponential star formation law. As a result, each final template is characterised by four physical parameters: the burst time scale, age, metallicity and dust extinction.

For the IR spectral region, B19 fit the observed IR fluxes to three different sets of dust emission templates: Chary & Elbaz (2001, hereafter CE01), Dale & Helou (2002, DH02), and Rieke et al. (2009, R09), assuming 5\( \sigma \) upper limits to the corresponding IR band in cases where there is no detection (Table 2).

In this work, we use the CANDELS photometric catalogs and redshifts, which together with the associated SED templates by Rainbow, allow us to reproduce the 0.1-1000 \( \mu \)m SED of every galaxy in our EBL sample. Failed fits and outliers are removed from the working sample by 3\( \sigma \) clipping applied to different bands along the galaxy-SEDs distribution. Figure 3 shows an example of a galaxy SED from GOODS-S with detection in all bands. This figure also includes the corresponding UV-to-optical SED template as well as the three dust emission models.

3 METHODOLOGY

3.1 Galaxy emissions in the mid- and far-infrared

In this paper, we aim at estimating the EBL at all wavelengths from the UV to the FIR as a function of redshift up to \( z \sim 6 \). Concerning the IR calculations, we have to take into account that a fraction of galaxies in a stellar mass limited sample such as ours are not actually detected by the deepest surveys carried out with Spitzer and Herschel telescopes. In order to cope with this obstacle, we have used an elaborate method to assign a dust emission SED in the mid- and far-infrared to every single galaxy. This method is based on actual flux measurements when available and on attenuation estimations and an energy-balance argument for sources below the detection limit of the IR surveys. We describe the method in detail in the following paragraphs.

In our EBL sample, 4,071 galaxies have simultaneous detections in Spitzer/MIPS+Herschel bands, i.e., \( \sim 2.6\% \) out of the total number of 154,447 galaxies, according to the prior-based catalogs in B19. For these sources, the IR SED can be recovered with high confidence. For another 5,391 galaxies (3.4\% of the entire sample), the reddest detected photometric point is MIPS/24 \( \mu \)m. There is no FIR detection for the rest of 144,985 \( (\sim 93.8\%) \). Given their large numbers and an imhomogeneous redshift distribution of the IR detections, their contribution to the IR background might be significant. In order to account for the whole EBL sample in our analysis, we consider 3 types of sources: (1) MIPS+Herschel detections, (2) MIPS/24 \( \mu \)m-only detections, and (3) no-FIR detections.

For type 1 where there is detection by both MIPS and at least one Herschel band, we take the best-fit CE01 template given by Rainbow to reproduce the IR-SED. Having a mid-to-far IR color allows us to obtain robust flux interpolations in the spectral region where the dust emission peaks and highly accurate estimations of the total infrared luminosity (\( L(\text{TIR}) \) hereafter, see Figure 3). \( L(\text{TIR}) \) is defined as the integrated luminosity between 8 and 1000 \( \mu \)m.

In case (2), sources where the reddest detection is MIPS/24 \( \mu \)m, the global dust emission has to be extrapolated from a single point. This extrapolation must be carried out with care since galaxies at different redshifts might present different warm-to-cold dust characteristics. Indeed, it is well known that Ultra-Luminous Infrared Galaxies (ULIRGs) at \( z \sim 2 \) present more prominent PAH features (probed by the MIPS datapoint) than galaxies of the same luminosity in the local Universe. High-\( z \) ULIRGs present SEDs which are more similar to local LIRGs, with strong PAH emission (see Papovich et al. 2011). We note, however, that we have far-IR detections for ULIRGs at high-redshift, so this effect is included in our data. For less luminous objects, systematic uncertainties are lower (see Sajina et al. 2012, R09). In any case, we obtain a dust emission model for every MIPS-only detection by first estimating a \( L(\text{TIR}) \) with methods that account for the redshift evolution of (U)LIRGs, and then assigning a model that matches that luminosity. For the first part of our method, we use the expression from Wuyts et al. (2011, hereafter W11) that derives the \( L(\text{TIR}) \) given the observed MIPS/24 \( \mu \)m flux density in mJy (\( F_\nu \)), using a coefficient \( C(z) \) that depends on the redshift of the galaxy,

\[
L(\text{TIR}) = [L_\odot] = C(z) \times F_\nu [\text{mJy}],
\]

where \( L_\odot \) corresponds to solar bolometric luminosity, for which we adopt \( L_\odot = 3.826 \times 10^{33} \text{ erg s}^{-1} \). Then, we associate a scaled CE01
Figure 7. Derived FUV (1500 Å), NUV (2800 Å), optical (B-band, 4400 Å) and NIR (K-band, 2.2 μm) luminosity densities between z = 0 and z = 6 (from top left to bottom right, respectively). The comparison data set includes the works of Andrews et al. (2017) at all bands, Dahlen et al. (2007) and Tresse et al. (2007) at the FUV, NUV and B-bands, and finally Budavári et al. (2005) for the FUV and NUV. Additional data sets in the FUV are Bouwens et al. (2016), Cucciati et al. (2012), Reddy & Steidel (2009) and Schiminovich et al. (2005). For the B-band we add the Marchesini et al. (2007) and Gabasch et al. (2004) data. And finally, we integrate the K-band LFs of Cirasuolo et al. (2010) and Mortlock et al. (2016), and include the Pozzetti et al. (2003) measurements.

Figure 8. Cosmic star-formation history (CSFH) derivation. Left: our total-IR (TIR) luminosity density at 8-1000 μm. The values from Burgarella et al. (PEP/HerMES 2013 2013), Rodighiero et al. (2010) and Pérez-González et al. (2005) are also plotted for comparison. Right: CSFH derived using our UV and TIR luminosity density estimations. The UV+IR data compilation of Madau & Dickinson (2014) are given together with the CSFH parametrization of the same paper (red line). Finally, the gamma-ray attenuation determination of the CSFH derived in Abdollahi et al. (2018) is shown as our fiducial comparison study (green shaded area). All values have been converted to a Chabrier IMF.
dust emission template to every inferred L(TIR). We choose the CE01 templates because they are normalized by L(TIR) luminosity, so that there is a direct association between L(TIR) and a CE01 template. We will discuss the implications of this choice in Sect. 4. Figure 3 shows an example of a galaxy of type (2), depicting in red the final dust-emission model. We note that our method also includes checking that the model is consistent with the upper limits imposed by the Herschel data, typically sampling the peak of the IR SED.

For type (3) sources, those with no detection in the IR, we perform an analysis of the attenuation by using the total SFRs presented in B19. In this paper, a calibration of the attenuation versus the UV-slope is carried out using the IRX-β relationship (Meurer et al. 1999) as a function of redshift and taking into account upper limits imposed by Spitzer and Herschel. The IRX-β relationship is found to be dependent of the total SFR, which is correlated with stellar mass via the main-sequence plot. In summary, different curves are used for different galaxies in order to obtain robust estimations of the attenuation even for galaxies below the MIPS and Herschel detection limits. Using these curves, an attenuation is assigned to every galaxy in the CANDELS surveys (and in our EBL sample, selected from them) and total SFRs are estimated starting from UV-based fluxes and slopes. For further discussion, we refer the reader to Domínguez Sánchez et al. (2016) and Rodríguez-Muñoz et al. (2019).

Total SFRs for every CANDELS galaxy are calculated in B19 by adding the contribution from TIR and the observed UV emission (see Eq. 3). This approach uses the Kennicutt relations (Kennicutt 1998) and assumes a Chabrier IMF (Chabrier 2003):

\[
\text{SFR} = \text{SFR}(UV) + \text{SFR}(TIR),
\]

\[
\text{SFR}[\text{M}_\odot\text{yr}^{-1}] = 1.07 \times 10^{-10} \left(3.3 \times L(2800) + L(TIR)\right)/L_\odot,
\]

where the observed rest-frame monochromatic luminosity at 2800 Å, L(2800), is chosen as representative of the unobscured UV SFR (uncorrected for dust extinction). L(TIR) is calculated integrating the galaxy–SED over the 8 to 1000 μm wavelength range.

For galaxies not detected in the IR, B19 provides a total SFR estimated from UV fluxes with the method described above, and an ‘observed’ SFR, obtained directly from the UV emission. Using these 2 quantities we can obtain the amount of star formation hidden by dust, which can then be translated to a TIR luminosity, and that can be used to assign a template to each galaxy. In this procedure, we again take into account the 5% intrinsic scatter in the L(TIR) relationship (see Eq. 3). This approach uses the Kennicutt relations (Kennicutt 1998) and assumes a Chabrier IMF (Chabrier 2003):

\[
\text{SFR}(UV) = \frac{\text{SFR}(TIR)}{L(TIR)} / \text{SFR}(UV),
\]

Finally, we can associate a scaled CE01 dust emission template to every L(TIR), similar to the procedure for galaxies in case (2). In Figure 3, we also show an example of this method. Note that the IR SED is roughly compatible with the 30 μJy MIPS/24 μm upper-limit flux density.

Figure 4 shows the L(TIR) distribution for the entire EBL sample before (i.e., assuming 5σ IR upper limits when appropriate) and after our own L(TIR) estimation for the three galaxy types. In addition, the same distribution is shown for the (1) and (2) cases, separately in the inset. Finally, the L(TIR) evolution with redshift is plotted in Figure 5, where (1), (2), and (3) are again highlighted. There is a cluster of galaxies placed in between z = 0 and z = 4 (~ 5% out of the total number of sources over the same redshift range) whose L(TIR) values are in between 10⁵−6 L_\odot. We studied and quantify the emission of these outliers and found that their contribution to the global IR background is within the uncertainties of our EBL model.

3.2 Extragalactic background light model formalism

The evolving EBL–SED can be obtained from stacking individual galaxy-SEDs and calculating the total luminosity density at different redshift bins.

The comoving luminosity density j(λ, z) can be interpreted as the energetic output of the Universe in a given comoving volume. It results from the emission of all the galaxies enclosed within the same volume, and it is measured in terms of total luminous power per unit comoving volume and frequency interval (erg s⁻¹ Mpc⁻³ Hz⁻¹). The monochromatic (i.e., at a given photometric band / central wavelength) luminosity densities at a given redshift range can be calculated by integrating the corresponding luminosity function (LF) at the same band and redshift range. Equivalently, we can estimate the luminosity density SED as a function of wavelength by adding all the galaxy-SEDs in the same redshift interval. The last approach is what we use in this work.

We divide our EBL galaxy sample into the following 15 redshift bins: Δz_j = z_j+1 - z_j, where z_j = (0, 0.2, 0.35, 0.55, 0.85, 1.25, 1.65, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6). The bins were chosen to have approximately the same cosmological time interval on each bin. We then stack together all the rest-frame galaxy-SEDs (L_\nu(λ, z_j)) contained in the same redshift bin (Δz_j). Finally we divide by the comoving cosmological volume (V_c(Δz_j)), and scale by the total solid angle (Ω_A) covered by the CANDELS survey over the whole sky:

\[
j(λ, Δz) = \frac{\sum_{j=1}^{n} L_\nu(λ, z_j)}{V_c(Δz) \cdot Ω_A}
\]

where n represents the number of galaxies at the Δz_j redshift interval. The comoving volume is defined, assuming a ΛCDM cosmology, as:

\[
V_c(z_j) = \frac{4πc^3}{3H_0^2} \int_{z_i}^{z_j} \frac{dz'}{Ω_Λ + Ω_M(1 + z')^3}
\]

with c = 2.99×10⁸ m/s, the speed of light in vacuum, and V_c(z) = V_c(z+1) - V_c(z). Finally, the EBL intensity at a certain wavelength λ and redshift z_j is produced by the contribution of light at shorter rest-frame wavelengths emitted in the light path since z_{max} = 6 to the current z_j. That is, the farther away we look, the shorter the rest-frame wavelength that contributes to our comoving EBL-SED, specifically by a (1 + z_j)/(1 + z') contracting factor; z < z' < z_{max}. Formally, this EBL-SED can be recovered from the evolving
comoving luminosity density integration as follows (Mo et al. 2010),
\[ M_\lambda (\lambda, z_i) = \frac{c^2}{4\pi H_0^2} \int_{z_i}^{z_{\text{max}}} f \left( \frac{L(1+z_i)}{(1+z')^3} \right) \frac{dt}{dz'} \, dz'. \] (8)

where \( M_\lambda (\lambda, z_i) \) is given in nW m\(^{-2}\) sr\(^{-1}\) units and the corresponding \( f(\lambda, z) \) function can be interpolated over an appropriate \( \delta z \) step size vector, if needed. The \( \frac{dt}{dz'} \) factor comes from the adopted ΛCDM cosmology:
\[ \frac{dt}{dz'} = \frac{1}{H_0 (1+z') \sqrt{\Omega_m + \Omega_{\Lambda} (1+z')^3}}. \] (9)

Uncertainties in the EBL-SED determination are calculated from every single galaxy SED, by varying the flux density of every photometric point over its 1σ error, and allowing the associated templates to scale with the errors in a Monte-Carlo approach (using 100 iterations for computational reasons). At the end, we have a 1σ band uncertainty for every galaxy-SED between 0.1 and 1000 μm. For sources with only MIPS/24 μm detection at the IR, we re-scale the IR templates only within the 24 μm flux density error bars, whereas we do not assume any error at the IR bands for the cases of non-detected IR sources (i.e., sources whose IR-SED has been obtained from the SFR(UV)-excess).

These SED uncertainties are properly propagated to the luminosity density through Eq. 6, and then to the EBL-SED using Eq. 8.

### 3.3 Completeness corrections

As we move to higher redshifts we probe less and less of the low-mass end of the stellar mass function (SMF), and the contribution from galaxies below the detection limit can be significant at the highest redshifts considered here (\( z > 3 \)).

In order to assess a completeness correction, we use two SMFs from the literature (Ilbert et al. 2013; Grazian et al. 2015), and assumed SEDs for the galaxies below the detection limit similar to the sources detected just above it. We explain the method in detail in the following paragraphs.

First, and for every redshift bin \( \Delta z_i \), we compute the expected number of sources below the mass completeness limit \( \phi_M (M_\star \leq M_{\text{lim}}^i, z_i) \), using the Ilbert et al. (2013) (0 ≤ \( z < 4 \)) and Grazian et al. (2015) (4 ≤ \( z < 6 \)) SMFs, as appropriate depending on the considered redshift range, and down to a given mass threshold of \( M_\star = 10^5 M_\odot \). An example of the mass-density of object estimated by the Ilbert et al. (2013) SMF is shown in Figure 6 for the 0.35 ≤ \( z < 0.55 \) redshift bin. We also perform and use our own single-Schechter fits to the SMF at those redshifts where the above-mentioned SMF don’t match the data really well (more importantly at the lowest redshifts).

Secondly, we build UV1 color-color diagrams for every redshift bin (Williams et al. 2009; Whitaker et al. 2011), and compute the fraction of quiescent \( (f_Q) \) and star-forming galaxies \( (f_{SF}) \) within the 0.5 dex mass bin immediately above of the corresponding completeness limit. We also assume that the empirical UV relation that separates quiescent from SF galaxies at the low redshifts is still valid at \( z > 3 \).

Then, we compute the average SED \( (L_\nu (\lambda, z_i))_{M_{\text{lim}}} \) for these galaxies at the mass limit as the weighted median SED of quiescent and SF galaxies analyzed before; that is:
\[ (L_\nu (\lambda, z_i))_{M_{\text{lim}}} = f_{Q,i} \times (L_\nu (\lambda, z_i)_Q)^+ + f_{SF,i} \times (L_\nu (\lambda, z_i)_SF)^-. \] (10)

Following this approach, the additional contribution to the total luminosity density of galaxies below the mass completeness limit is:
\[ j(\lambda, z_i) \leq M_{\text{lim}}^i = \left( (L_\nu (\lambda, z_i))_{M_{\text{lim}}} - (L_\nu (\lambda, z_i)_Q)^+ \right) \times \int_{M_{\text{lim}}^i}^{M_{\text{max}}} \phi_M (M_\star) \leq M_{\text{lim}}^i, z_i \, dM_\star, \] (11)

where the integral comes from the SMF definition: \( d\phi_{M_\star} = dN / (dV, dM_\star) \), with \( N \) being the number of galaxies per mass bin and comoving volume element. Therefore, the total corrected luminosity density \( j(\lambda, z_i) \) is the sum of both the observed \( j(\lambda, z_i)_\text{obs} \), obtained by the stacking of galaxies up to every limiting mass) and this additional contribution of low-mass galaxies; i.e., :
\[ j(\lambda, z_i) = j(\lambda, z_i)_\text{obs} + j(\lambda, z_i) \leq M_{\text{lim}}^i. \] (12)

This is, indeed, the luminosity density that has to be introduced in Eq. 6 and 8. However, the effect of our completeness corrections on the EBL-SED is noticeable only at the higher redshifts. At \( z = 0.1 \) the contribution from the corrections to the total integrated EBL is only of 6%, at \( z = 1, z = 3, z = 5 \) is 10%, 15%, and 20%, respectively. The uncertainties on these completeness corrections are included in the luminosity densities by adding in quadrature the difference between the corrected and non-corrected (observed) luminosity densities at every wavelength.

### 4 RESULTS AND DISCUSSION

#### 4.1 Luminosity densities and cosmic star formation history

Following the formalism described in the previous section, we derive the monochromatic luminosity density in different bands, and compare our results with a set of measurements from the literature. In particular, we compare with FUV (1500 Å), NUV (2800 Å), optical (B-band, 4400 Å) and NIR (K-band, 2.2 μm) luminosity densities between \( z = 0 \) and \( z = 6 \) (see Figure 7).

The FUV (1500 Å) and NUV (2800 Å) luminosity density results are shown together with the values of Budavári et al. (2005) and Andrews et al. (2017) at low-z; and Reddy & Steidel (2009) and Bouwens et al. (2016) at high-z. Spanning the entire redshift range we compare with Cucciati et al. (2012), Dahlen et al. (2007), Tresse et al. (2007) and Schiminovich et al. (2005). Our calculations and the literature agree within 1σ at all redshifts, excepting the FUV estimations from Lyman-Break Galaxies surveys (Reddy & Steidel 2009) at \( z = 3 - 4 \), where our points fall systematically above the factor 8 above.

In Figure 7, the B-band luminosity density (4400 Å) is compared with Tresse et al. (2007) and Dahlen et al. (2007), and Andrews et al. (2017). Additional data compilations at high-z come from Marchesini et al. (2007) and Gabasch et al. (2004) works. Again, our concordance with the literature up to \( z = 1 \) is noticeable, whereas at \( 1 \leq z < 2 \), our data fall systematically above most of the optical-LF integrations by a factor of x1.5. Beyond \( z \geq 2 \), comparison fails because of the different values between the different measurements reported in the literature. Our estimates at \( z > 2 \) are within 1σ agreement with Gabasch et al. (2004) and a factor x3 above Marchesini et al. (2007) at \( z = 2 - 3 \).

The K-band luminosity density is presented in Figure 7 together with the Andrews et al. (2017) and Pozzetti et al. (2003)
Figure 9. The local ($z = 0$) spectral energy distribution of the EBL (black solid line, $1\sigma$ model uncertainties is enclosed within the blue shaded area). The green dotted and brown dashed-dotted lines are the semianalytical and phenomenological models of Gilmore et al. (2012) and Finke et al. (2010), while the dashed blue and pink lines corresponds to the Domínguez et al. (2011a) and Helgason & Kashlinsky (2012) empirical curves, respectively. The yellow band spans over the $1\sigma$ limits for the local EBL determination of Desai et al. (2019), from blazars’ gamma-ray attenuation spectra. Finally, the red filled points come from galaxy number counts in Driver et al. (2016b). Open symbols constitute a compilation of diverse direct measurements from the literature (see text).

Figure 10. Comparison between different EBL models and measurements of the Cosmic Optical (COB, 0.1–8 $\mu$m) and Infrared Backgrounds (CIB, 8–1000 $\mu$m) at $z = 0$ (similar to Driver et al. 2016b). The results from This Work are shown in black, while in brown, blue, green and yellow are the results from Finke et al. (2010), Domínguez et al. (2011a), Gilmore et al. (2012) and Domínguez et al. (2019) models, respectively. The results from Madau & Pozzetti (2000), Dole et al. (2006), Béthermin & Dole (2011) and Driver et al. (2016b) galaxy number counts are chronologically plotted in light-blue, purple, grey and red. We also show the measured CIB if only combined MIPS+Herschel detections are included in our work, as discussed in the text. Uncertainties have been included only when available in the literature.

Published values at low-$z$. We also include the results from the integration of the Mortlock et al. (2016) and Cirasuolo et al. (2010) $K$-band LFs. We are compatible within uncertainties with work of Mortlock et al. (2016) and Andrews et al. (2017). Our NIR intensities are systematically above the values given by Pozzetti et al. (2003) and Cirasuolo et al. (2010) at all redshifts. The reason is that these studies are shallower in fluxes than ours.

An observable directly related with the CSFR density is the TIR luminosity density. Our $j_{TIR}$ is shown in Figure 8 over $0 \leq z < 6$, as well as the estimations from Pérez-González et al. (2005), Rodighiero et al. (2010), and Burgarella et al. (2013, PEP/HerMES 2013). Note that the agreement between the different measurements is good at all redshifts.

Finally, the cosmic star-formation history (CSFH) can be computed following Eq. 3, using the NUV and TIR luminosities. Our CSFH between $0 \leq z < 6$ is shown in Figure 8 in comparison with
the Madau & Dickinson (2014), Rodríguez-Puebla et al. (2017), Abdollahi et al. (2018) and Behroozi et al. (2019) results (all results have been converted to a Chabrier IMF when needed). We stress that our result is in agreement within errors up to $z \sim 6$ with those from $\gamma$-ray attenuation. Since the $\gamma$-ray technique is sensitive to all light produced by galaxies, even those too faint that escape the detection in galaxy surveys, we conclude that our model, including completeness correction, is correctly reproducing most of the galaxy contribution.

4.2 Spectral energy distribution of the EBL

4.2.1 The local extragalactic background light

Applying Eq. 8 to our total luminosity density, we can estimate the evolving EBL. To do that we have interpolated the set of 15 luminosity density SED into a 2-dimensional $(z, \lambda)$ grid with $\delta z = 0.1$ steps in the $0 \leq z < 6$ interval, and a common spectral synthetic resolution of $\delta (\log \lambda[\mu m]) = 0.01$ in the $0.1$–$1000$ $\mu m$ range.

Figure 9 shows the local EBL SED. This SED is compared with the results from other methodologies such as direct detection (Schlegel et al. 1998; Hauser et al. 1998; Lagache et al. 2000; Gorch et al. 2000; Finkbeiner et al. 1999; Cambrésy et al. 2001; Matsumoto et al. 2005; Bernstein 2007; Matsuura et al. 2011; Matsumoto et al. 2011; Zemcov et al. 2014; Mattila et al. 2017; Matsuura et al. 2017; Lauer et al. 2020)\(^6\), galaxy counts Driver et al. (2016b), $\gamma$-ray attenuation (Desai et al. 2019) and other EBL models (Finke et al. 2010; Dominguez et al. 2011a; Helgason & Kashlinsky 2012; Gilmore et al. 2012).

\(^6\) A re-analysis of the Zodiacal light beyond the Earth orbit detected by Pioneer 10 (Matsumoto et al. 2018), suggests that instrumental offsets affected the Matsuura et al. (2011) measurements.

Figure 9 shows that our model is 1$\sigma$ compatible with the galaxy count data from Driver et al. (2016b). The largest differences between the results from several models occur at the IR. Dominguez et al. (2011a) estimate a larger IR background by factor of $\times 2$ at the IR peak. This was a possibility discussed in the paper since they did not have FIR photometry and that spectral region came from extrapolations. On the other side, Finke et al. (2010) estimate a lower FIR contribution at $\sim 200$ $\mu m$ by a $\times 1.5$ factor.

In the MIR coverage, although our curve is compatible with Béthermin & Dole (2011) at $24$ $\mu m$, and marginally compatible with Dole et al. (2006) within 1$\sigma$, our results sits above most of the models in the 10–20 $\mu m$ range (excepting Helgason & Kashlinsky (2012)). This may be because of the chosen CE01 IR templates. Since they are calibrated with low-$z$ galaxy observations, they included a higher level of PAHs emission, which could raise up the EBL intensity at those wavelengths in our calculation.

Most of the direct detection data are not compatible with our estimates. It is possible that these data, at least, in the optical and IR, can be strongly affected by zodiacal light contamination. However, there are some exceptions.

The more sophisticated approach by Mattila et al. (2017), the “Dark Cloud shadow” method is higher but compatible within 2$\sigma$ with our calculations at 0.4 $\mu m$ (11.6 $\pm$ 4.4 nW m$^{-2}$ sr$^{-1}$, see previous reference for more details). Zemcov et al. (2014) used fluctuations in the pixel intensity power spectrum to measure the EBL at 1.1 and 1.6 $\mu m$. They report a slightly higher (but still compatible at 1.1 $\mu m$) EBL intensity with respect to us: 16.7$^{+5}_{-4}$, 20.4$^{+6}_{-5}$ nW m$^{-2}$ sr$^{-1}$, respectively (see also Matsumoto 2020). These techniques are less biased by zodiacal foreground contamination. Finally, the recent work by Lauer et al. (2020) using New Horizons measured the EBL at 0.6 $\mu m$ using direct detection at a distance of around 40 AU from the Earth. At that distance, zodiacal light
Figure 12. Evolving SED of the EBL between $z = 0$ and $z = 6$ in the different redshift snapshots of our model. Also plotted are the results of the Finke et al. (2010), Domínguez et al. (2011a), Helgason & Kashlinsky (2012) and Gilmore et al. (2012) models, with the same styles as in Figure 9. The yellow band correspond to the results of Abdollahi et al. (2018), interpolated between $z = 0$ and $z = 3$. Each model has been extended up to its particular maximum redshift, and interpolated to the intermediate redshift values.

Finally, we estimate the influence of our sample selection in the local EBL intensity. As discussed in Sect. 2.2, the strongest cut in our sample is $S/N = 5$ at the HST/WFC3/F160W band. We calculate F160W galaxy number counts imposing $S/N = 2$ (see Figure 2 and methods in Driver et al. (2016b)). This results in an intensity of $\sim 12.2 \text{ nW m}^{-2} \text{ sr}^{-1}$, which is 15% larger but still compatible with the 1-sigma level with the output from our model of $\sim 10.6 \pm 1.7 \text{ nW m}^{-2} \text{ sr}^{-1}$.

4.2.2 Cosmic Optical (COB) and Infrared (CIB) Backgrounds

The total EBL intensity ($I_{bol}$, bolometric) integrated over all wavelengths and at any redshift, can be computed by doing:

$$I_{bol} = \int_{\lambda_{min}}^{\lambda_{max}} \lambda A(\lambda, z) d\lambda / A$$

(13)

where, in our case, $\lambda_{min} = 0.1 \mu m$ and $\lambda_{max} = 1000 \mu m$. Our calculations give an integrated local EBL intensity (Eq. 13) of $55.1 \pm 8.6 \text{ nW m}^{-2} \text{ sr}^{-1}$. This is roughly a factor of $\times 15$ lower than...
the CMB intensity of ~960 nW m$^{-2}$ sr$^{-1}$ (Cooray 2016; Planck Collaboration et al. 2019). We can divide the EBL into the cosmic optical background (COB, 0.1–8 μm) and cosmic infrared background (CIB, 8–1000 μm). The integrated intensities of these two regions are shown in Figure 10 in comparison with the results from other works. Note that the COB is well constrained by all models within a factor of less than ×1.5; we get an integrated intensity of 23.1±4.0 nW m$^{-2}$ sr$^{-1}$. However, the data dispersion is larger in the CIB region, where we estimate the CIB intensity is 32.0±7.6 nW m$^{-2}$ sr$^{-1}$. We also reproduce this analysis by restricting our sample to only the MIPS+Herschel detected sources (i.e., those galaxies for which the L(TIR) was directly measured). At lower redshifts, MIPS+Herschel sources are biased towards galaxies with a median stellar mass of $M_\ast \sim 10^{10} M_\odot$, against $M_\ast \sim 10^8 M_\odot$ of the whole galaxy population at $z = 0$. As a result, we conclude that the MIPS+Herschel resolved galaxies in our EBL sample contribute with the ~40% and ~70% of the integrated COB and CIB, respectively. This is in agreement with previous searches as those by Dole et al. (2006), where they also estimated a ~70% of resolved CIB by Spitzer. These values are also shown in Figure 10 (COB value for MIPS+Herschel is below the intensity range of the plot).

Figure 11 reveals the local COB and CIB contributions from quiescent versus SF galaxies according to UVJ diagram. SF galaxies dominate both the COB and CIB, making up ~80% and ~90% of the integrated EBL intensity, respectively. This SF relative contribution increases rapidly with redshift, while the quiescent contribution is mainly driven by passive galaxies at $z < 1$, and becomes negligible at higher redshifts, where the quiescent population progressively disappears.

### 4.2.3 Extragalactic background light redshift evolution

The evolution of the EBL with redshift is plotted in Figure 12 and compared with results from different models from the literature (Finke et al. 2010; Domínguez et al. 2011a; Helgason & Kashlinsky 2012; Gilmore et al. 2012) as well as from methodologies based on γ-ray attenuation measurements (Abdollahi et al. 2018).

Figure 12 shows that most current EBL models are compatible in the UV/optical peak at $z < 1$, however at higher redshifts different models diverge by about an order of magnitude in the UV. In the IR, there is a large disagreement between models at all redshifts, up to a factor of ×5 at the highest redshifts. These discrepancies led to significantly different optical depths at high redshifts for the lower energies ($\sim 50 - 100$ GeV) and at any redshift for the highest energies ($E \leq 10$ TeV, see Domínguez et al., in preparation).

Furthermore, we can see in Figure 12 that our model generally agrees within 1σ with the latest results from γ-ray attenuation by Fermi-LAT (Abdollahi et al. 2018). These γ-ray results tend to be on the higher end of our spectral intensities for the higher redshifts, although compatible within 2σ. This situation was already noted by Abdollahi et al. (2018) in comparison with previous EBL models. Note that models tend to go on the lower bound of the γ-ray attenuation uncertainty band. Furthermore, interestingly, the γ-ray attenuation technique is sensitive to all light, even light that escapes galaxy surveys. Therefore, this discrepancy between galaxy surveys and γ-ray attenuation data, although not highly significant, could point to galaxy surveys’ incompleteness in the NIR.

We finally see in Figure 13 how photons populating the EBL at various wavelengths today were produced as a function of redshift. Photons in today’s far-IR peak were emitted considerably earlier than photons in the optical peak. Our estimates show that approximately 80% (±20%) of the local 500 μm light comes from $z > 1$.

This result, related with the existence of obscured starburst galaxies at high redshifts, is compatible with previous findings from the Balloon-borne Large-Aperture Submillimeter Telescope (Devlin et al. 2009; Marsden et al. 2009), Spitzer (Jauzac et al. 2011), and Herschel (Béthermin et al. 2012). However, only around 30% (±5%) of the local 2.2 μm light comes from $z > 1$, therefore the big majority of the local EBL at the optical peak was produced at $z < 1$.

### 5 SUMMARY

We present an empirical determination of the evolving EBL SED up to $z \sim 6$. In this study, the focus is on reducing current uncertainties on the EBL; that is, the FIR spectral region and the overall evolution with redshift. This is achieved by using unprecedented data from the CANDELS survey to consistently build the multiwavelength SED of approximately 150 000 galaxies from the UV to the FIR in five cosmological fields.

The UV-to-optical SED of every galaxy is reproduced following the work by Barro et al. (2019), whereas for the IR part we follow different approaches, according to whether the galaxy is detected in the FIR or not. We then compute the total galaxy luminosity density of the Universe over redshift by SED stacking and correcting for incompleteness, then we add up all this light to compute the evolving EBL. Our model generally reproduces (1) a diversity of FUV, NUV, optical, NIR and TIR luminosity density in the literature, (2) the CSFH, which is in agreement with the usual galaxy evolutionary hierarchical scenarios, (3) lower bound of the direct detection data, (4) galaxy counts and (5) latest results from γ-ray attenuation.

The improvements presented here will be beneficial for the derivation of robust optical depths for γ-ray photon fluxes and therefore, the interpretation of extragalactic VHE observations with Fermi LAT, current Cherenkov telescopes, and the upcoming Cherenkov Telescope Array (Domínguez et al., in preparation).
ACKNOWLEDGEMENTS

ASL acknowledges support from grants FNS-OB5347 and ESP2017-87291-P (AEI/FEDER-UE). AD acknowledges the support of the Ramón y Cajal program from the Spanish MINECO. PGP acknowledges support from Spanish Government grant PGC2018-093499-B-I00. This work has made use of the Rainbow database, which is operated by the Centro de Astrobiología (CAB/INTA), partnered with the University of California Observatories at Santa Cruz (UCO/Lick,UCSC). This work is based in part on observations made with the Spitzer Infrared Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

DATA AVAILABILITY

The data products underlying this article are available in the following website: https://www.ucm.es/blazars/ebl.

REFERENCES

Abdalla H., Böttcher M., 2018, ApJ, 865, 159
Abdalla H., et al., 2020, MNRAS, 494, 5590
Abdo A. A., et al., 2010, ApJ, 723, 1082
Abdollahi S., et al., 2018, Science, 362, 1031
Abeysekara A. U., et al., 2019, ApJ, 885, 150
Acciari V. A., et al., 2019, MNRAS, 486, 4233
Ackermann M., et al., 2012, Science, 338, 1190
Ackermann M., et al., 2018, ApJS, 237, 32
Aharonian F., et al., 2006, Nature, 440, 1018
Aharonian F. A., et al., 2007, A&A, 475, L9
Andrews S. K., et al., 2017, MNRAS, 470, 1342
Andrews S. K., Driver S. P., Davies L. J. M., Lagos C. d. P., Robotham A. S. G., 2018, MNRAS, 474, 898
Arlen T. C., Vassilev V. V., Weisgarber T., Wakely S. P., Yusef Shafi S., Andrews S. K., Driver S. P., Davies L. J. M., Lagos C. d. P., Robotham A. S. G., et al., 2017, MNRAS, 470, 1342
Arlen T. C., et al., 2010, MNRAS, 401, 1166
Béthermin M., Dole H., 2011, arXiv e-prints, p. arXiv:1102.1827
Bernstein R. A., 2007, ApJ, 666, 663
Bouwens R. J., et al., 2016, ApJ, 827, 108
Bouwens R. J., et al., 2017, ApJ, 833, 72
Buehler R., Gallardo G., Maier G., Domínguez A., et al., 2020, arXiv e-prints, p. arXiv:2004.09396
Béthermin M., et al., 2013, ApJS, 206, 10
Bernstein R. A., 2007, ApJ, 666, 663
Bouwens R. J., et al., 2016, ApJ, 827, 108
Observational EBL from HST–CANDELS

Malkan M. A., Stecker F. W., 2001, ApJ, 555, 641
Malkan M. A., Scully S. T., Stecker F. W., 2020, arXiv e-prints, p. arXiv:2004.10644
Marchesini D., et al., 2007, ApJ, 656, 42
Marsden G., et al., 2009, ApJ, 707, 1729
Matsumoto T., 2020, Proceedings of the Japan Academy, Series B, 96, 335
Matsumoto T., et al., 2005, ApJ, 626, 31
Matsumoto T., Tsumura K., Matsuoka Y., Pyo J., 2018, AJ, 156, 86
Matsuoka Y., Ienaka N., Kawara K., Oyabu S., 2011, ApJ, 736, 119
Matsuura S., et al., 2011, ApJ, 737, 2
Matsuura S., et al., 2017, ApJ, 839, 7
Mattila K., 2006, MNRAS, 372, 1253
Mattila K., Väisänen P., Lehtinen K., von Appen-Schnur G., Leinert C., 2017, MNRAS, 470, 2152
Mazin D., Raue M., 2007, A&A, 471, 439
Meurer G. R., Heckman T. M., Calzetti D., 1999, ApJ, 521, 64
Meyer M., Raue M., Mazin D., Horns D., 2012, A&A, 542, A59
Mo H., van den Bosch F. C., White S., 2010, Galaxy Formation and Evolution
Morrissette M., et al., 2007, ApJS, 173, 682
Morlock A., et al., 2016, MNRAS, 458, 3478
Nayyeri H., et al., 2017, ApJS, 228, 7
Neronov A., Vovk I., 2010, Science, 328, 73
Oesch P. A., et al., 2018, ApJS, 237, 12
Paliya V. S., Domínguez A., Ajello M., Franckowiak A., Hartmann D., 2019, ApJ, 882, L3
Papovich C., Finkelstein S. L., Ferguson H. C., Lotz J. M., Giavalisco M., 2011, MNRAS, 412, 1123
Partridge R. B., Peebles P. J. E., 1967, ApJ, 148, 377
Peebles P. J. E., 1993, Principles of Physical Cosmology
Pérez-González P. G., et al., 2005, ApJ, 630, 82
Pérez-González P. G., et al., 2008, ApJ, 675, 234
Pérez-González P. G., et al., 2013, ApJ, 762, 46
Planck Collaboration et al., 2019, arXiv e-prints, p. arXiv:1907.12875
Polletta M., et al., 2007, ApJ, 663, 81
Pozzetti L., et al., 2003, A&A, 402, 837
Prandini E., Bonnoli G., Maraschi L., Mariotti M., Tavecchio F., 2010, MNRAS, 405, L76
Primack J. R., Domínguez A., Gilmore R. C., Somerville R. S., 2011, in Aharonson F. A., Hofmann W., Rieber F. M., eds, American Institute of Physics Conference Series Vol. 1381, 25th Texas Symposium on Relativistic AstroPhysics (Texas 2010), pp 72–83 (arXiv:1107.2566), doi:10.1063/1.3635825
Rawle T. D., et al., 2016, MNRAS, 459, 1626
Reddy N. A., Steidel C. C., 2009, ApJ, 692, 778
Rieke G. H., Alonso-Herrero A., Weiner B. J., Pérez-González P. G., Blaylock M., Donley J. L., Marcillac D., 2009, ApJ, 692, 556
Rodighiero G., et al., 2010, A&A, 515, A8
Rodríguez-Muñoz L., et al., 2019, MNRAS, 485, 586
Rodríguez-Puebla A., Primack J. R., Avila-Reese V., Faber S. M., 2017, MNRAS, 470, 651
Rujopakarn W., Rieke G. H., Weiner B. J., Pérez-González P., Rex M., Walth G. L., Kartaltepe J. S., 2013, ApJ, 767, 73
Sajina A., Yan L., Fadda D., Dasyra K., Huynh M., 2012, ApJ, 757, 13
Sánchez-Conde M. A., Paneque D., Bloom E., Prada F., Domínguez A., 2009, Phys. Rev. D, 79, 123511
Schiminovich D., et al., 2005, ApJ, 619, L47
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Somerville R. S., Lee K., Ferguson H. C., Gardner J. P., Moustakas L. A., Giavalisco M., 2004, ApJ, 600, L171
Somerville R. S., Gilmore R. C., Primack J. R., Domínguez A., 2012, MNRAS, 423, 1992
Stecker F. W., de Jager O. C., Salamon M. H., 1992, ApJ, 390, L49
Stecker F. W., Scully S. T., Malkan M. A., 2016, ApJ, 827, 6
Sternan M., et al., 2017, ApJS, 229, 32
Tavecchio F., Ghisellini G., Foschini L., Bonnoli G., Ghirlanda G., Coppi P., 2010, MNRAS, 406, L70
Tresse L., et al., 2007, A&A, 472, 403
Whitaker K. E., et al., 2011, ApJ, 735, 86

This paper has been typeset from a TeX/LaTeX file prepared by the author.