

# ***Euclid* preparation: XVIII. Cosmic Dawn Survey. Spitzer observations of the *Euclid* deep fields and calibration fields**

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## ABSTRACT

We present a new infrared survey covering the three *Euclid* deep fields and four other *Euclid* calibration fields using *Spitzer*'s Infrared Array Camera (IRAC). We have combined these new observations with all relevant IRAC archival data of these fields in order to produce the deepest possible mosaics of these regions. In total, these observations represent nearly 11 % of the total *Spitzer* mission time. The resulting mosaics cover a total of approximately 71.5 deg<sup>2</sup> in the 3.6 and 4.5 μm bands, and approximately 21.8 deg<sup>2</sup> in the 5.8 and 8 μm bands. They reach at least 24 AB magnitude (measured to 1σ, in a 2''5 aperture) in the 3.6 μm band and up to ~ 5 mag deeper in the deepest regions. The astrometry is tied to the Gaia astrometric reference system, and the typical astrometric uncertainty for sources with 16 < [3.6] < 19 is ≤ 0''.15. The photometric calibration is in excellent agreement with previous WISE measurements. We have extracted source number counts from the 3.6 μm band mosaics and they are in excellent agreement with previous measurements. Given that the *Spitzer* Space Telescope has now been decommissioned these mosaics are likely to be the definitive reduction of these IRAC data. This survey therefore represents an essential first step in assembling multi-wavelength data on the *Euclid* deep fields which are set to become some of the premier fields for extragalactic astronomy in the 2020s.

**Key words.** cosmology: observations — cosmology: large scale structure of universe — cosmology: dark matter — galaxies: formation — galaxies: evolution — surveys

## 1. Introduction

The *Euclid* mission will survey 15 000 deg<sup>2</sup> of the extragalactic sky to investigate the nature of dark energy and dark matter, and

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to study the formation and evolution of galaxies (Laureijs et al. 2011). To this end *Euclid* will obtain high resolution and high signal-to-noise imaging of a billion galaxies in a broad optical filter to measure their shapes and in three near-infrared (NIR) filters to measure their colours. It will also obtain high signal-to-noise NIR spectroscopy of about thirty million of these galaxies to measure abundances and redshifts. Additionally, photometric redshifts will be determined by combining the *Euclid* data with optical photometry from external surveys.

To reach the required precision on cosmological parameters and satisfy the stringent mission requirements on completeness, spectroscopic purity and shape noise bias, *Euclid* must also obtain observations with 40 times longer exposure per pixel than the main survey over regions covering at least  $40 \text{ deg}^2$ . To this end, three ‘deep’ fields have been selected by the Euclid Consortium. They are described in detail in Scaramella et al. (2021) and we give just a very brief description here. They are: (1) the Euclid Deep Field North (EDF-N), a roughly circular,  $10 \text{ deg}^2$  region centred on the well-studied north Ecliptic pole, (2) the Euclid Deep Field Fornax (EDF-F), also roughly circular and of  $10 \text{ deg}^2$ , centred on the Chandra Deep Field South and including the GOODS-S (Giavalisco et al. 2004) and the Hubble Ultra Deep Field (Beckwith et al. 2006), and (3) the Euclid Deep Field South (EDF-S), a pill-shaped area of  $20 \text{ deg}^2$  with no previous dedicated observations. In addition to these three deep fields *Euclid* will observe several fields for the calibration of photometric redshifts (photo- $z$ ). These fields need to be observed to a level 5 times deeper than the main survey and they are centred on some of the best studied extragalactic survey fields that already have extensive spectroscopic data: (1) the COSMOS field (2) the Extended Groth Strip (EGS), (3) the Hubble Deep Field North (HDF, also GOODS-N), and (4) the XMM-Large Scale Structure Survey field, which includes the Subaru XMM Deep Survey field (SXDS), and VIMOS VLT Deep Survey (VVDS)<sup>1</sup>.

While *Euclid* will observe these fields primarily for calibration purposes, those observations will provide an unprecedented data set to study galaxies to faint magnitudes and high redshifts. The survey efficiency of *Euclid* in the NIR bands is orders of magnitudes greater than that of ground-based telescopes (e.g., VISTA). The *Euclid* deep fields alone will be 30 times larger and one magnitude deeper than the latest UltraVISTA data release covering the COSMOS field, and will reach a depth of 26 mag in the  $Y, J, H$  filters ( $5\sigma$ ). In addition, *Euclid* carries a wide-field near-infrared grism spectrograph, the Near Infrared Spectrometer and Photometer (NISP), covering the  $0.92 < \lambda < 1.85 \mu\text{m}$  region, which will provide multiple spectra at numerous grism orientations for more than one million sources to a line flux limit similar to 3D-HST (Brammer et al. 2012) and over an area 200 times larger than the COSMOS field (depending on the scheduling of the blue grism observations). The observations of the deep fields will result in the most complete and deepest spectroscopic coverage produced by *Euclid*. Such a spectroscopic data set will be unique for the reconstruction of the galaxy environment at cosmic noon and for measuring the star formation rate from the  $H\alpha$  emission line intensity.

The deep and wide NIR data from *Euclid* are also ideal for detecting significant numbers of high-redshift ( $7 < z < 10$ ) galaxies, as the Lyman  $\alpha$  line is redshifted out of the optical into the NIR. However, in order to distinguish galaxy candidates from stars (primarily brown dwarfs), faint Balmer-break galaxies, and dusty star-forming galaxies at lower redshifts which all

can have similar NIR magnitudes and colours, deep optical and mid-infrared (MIR) data are also needed (Bouwens et al. 2019; Bridge et al. 2019; Bowler et al. 2020).

The Cosmic Dawn Survey (Toft et al., in prep) aims to obtain uniform, multi-wavelength imaging of the *Euclid* deep and calibration fields to limits matching the Euclid data for characterisation of high-redshift galaxies. The optical data will be provided by the Hawaii-Two-0 Subaru telescope/Hyper-SuprimeCam (HSC) survey (McPartland et al., in prep.) for the EDF-N and EDF-F and likely by the Vera C. Rubin Observatory for EDF-S and EDF-F. For the COSMOS and SXDS fields optical data are provided by the Subaru HSC Strategic program (HSC-SSP Aihara et al. 2011).

In this paper, we present the *Spitzer* Space Telescope (Werner et al. 2004) component of the Cosmic Dawn Survey, consisting primarily of  $3.6$  and  $4.5 \mu\text{m}$  observations of the three deep fields and parts of the calibration fields acquired with *Spitzer*’s IRAC camera (Fazio et al. 2004). Two dedicated programs were submitted for this purpose: the *Euclid*/WFIRST *Spitzer* Legacy Survey (SLS, requesting  $5\,286$  h, PI: Capak) covering the EDF-N and EDF-F fields, and the EDF-S survey (requesting  $687$  h, PI: Scarlata). These programmes were established based on the *Euclid* plans for the deep fields that were available at the time. All the fields had been observed, at least in part, before our new observations, and we processed our new data together with all relevant archival IRAC data, thus including data obtained during the cryogenic mission, i.e., data at  $5.8$  and  $8.0 \mu\text{m}$ . In this way we strive to produce the deepest possible MIR images (mosaics) of these fields to date. A significant improvement in our processing is that our pipeline ties the astrometry to the Gaia reference system which, given its higher precision, will greatly facilitate cross-identification with other data, which will of course also have to be tied to Gaia.

In addition to being essential for the identification of high-redshift galaxies, MIR data are crucial to reveal the stellar mass content of the high-redshift Universe (which is outside the scope of the *Euclid* core science). The *Euclid* data alone are not sufficient to characterise the stellar masses at  $z > 3.5$ , as the Balmer break is redshifted out of the reddest band of the NISP. Without MIR data, the interpretation of spectral energy distributions (SEDs) would rely on rest-frame ultraviolet emission which is strongly affected by dust attenuation and dominated by stellar light of new-born stars. Therefore, integrated quantities like the stellar mass would be highly unreliable (Bell & de Jong 2001). Moreover, photometric redshifts would be prone to catastrophic failures resulting from the mis-identification of the Lyman and Balmer breaks (e.g. Le Fèvre et al. 2015; Kauffmann et al. 2020). In summary, *Spitzer*/IRAC data are crucial for identifying the most distant objects (e.g. Bridge et al. 2019), for improving the accuracy of their photometric redshifts and for deriving their physical properties such as stellar masses, dust content, age, and star-formation rate from population synthesis models (e.g. Pérez-González et al. 2008; Caputi et al. 2015; Davidzon et al. 2017). The build-up of stellar mass, especially when confronted with the amount of matter residing in dark matter halos at high redshifts can be a highly discriminating test for galaxy formation models (Legrand et al. 2019). Extrapolation of recent work in the COSMOS field (Bowler et al. 2020) suggests that hundreds of the rarest, brightest  $z > 7$  galaxies are expected to be discovered in the *Euclid* deep fields. These provide unique constraints on cosmic reionisation, as the brightest galaxies form in the highest density regions of the Universe which are expected to be the sites of the first generation of stars and galaxies, and thus of reionisation bubbles (Trac et al. 2008).

<sup>1</sup> These are now known as the ‘Euclid Auxiliary Fields’ in *Euclid* terminology

The layout of this paper is as follows: Sect. 2 describes the observations, Sect. 3 presents our data processing techniques, and Sect. 4 compares our results to previous ones.

## 2. Observations

All observations described here were made with IRAC. In brief, IRAC is a four-channel array camera on the *Spitzer* Space Telescope, observing simultaneously four fields slightly separated on the sky at 3.6, 4.5, 5.8, and 8.0  $\mu\text{m}$ , known as channels 1–4, respectively. *Spitzer* science observations began in August 2003 but observations in channels 3 and 4 ceased once the on-board cryogen was exhausted (May 15, 2009). During the following ‘warm mission’ phase, channels 1 and 2 continued to operate until the end of operations in late January 2020, albeit with somewhat lower but still comparable performance. The earliest observations presented here are archival observations that were obtained in September 2003; the observations of the dedicated Capak program began in 2017 and the ones of the dedicated Scarlata program began in 2019. The dedicated observations continued until January 2020, shortly before the shutdown of the satellite. Figure 1 shows a histogram of the integration time accumulated in bins of 30 days over the observing period. These observations account for almost 1.5 million frames, a total integration time of 34 000 hr, all channels combined, and a total on-target time, omitting overheads, of just over 15 600 hr, or nearly 1.8 yr, which is approximately 11 % of the *Spitzer* Space Telescope mission time.

For our dedicated observations of EDF-N, EDF-S and EDF-F we adopted a consistent observing strategy that comprises blocks of  $3 \times 3$  maps with a step size of  $310''$ , a large three-point dither pattern and four repeats per position. Each block covers a  $15'1 \times 15'1$  region with a coverage of  $3 \times 4 \times 100\text{s}$  exposures per pixel. The block centres are offset between passes in order to ensure uniform coverage and enable self-calibration. Each block forms an AOR, or Astronomical Observation Request, in IRAC jargon. All other data included in our processing is archival data. It was obtained with a variety of observing strategies which we did not investigate in detail and which we do not attempt to summarise here. In Appendix C we list the Program IDs of all the observations processed; in bold the ones of our dedicated observations. The combination of the archival data with our own dedicated data produces a spatially variable depth in most fields; this is discussed further in Sect. 4.

A total of 292 IRAC observing programs are used in this work. Table 1 lists the ten largest programs in terms of observing time together with the PI of the program, the field concerned and program’s total integration time.

All observations are summarised in Table 2 which gives, for each field and channel, the number of frames (Data Collection Events or DCEs in IRAC terminology) used to produce the mosaics (note that this can be lower than the number of frames downloaded as some were discarded, see Sect. 3) together with the total observing time. For channels 1 and 2, on the left side of the table, the information is subdivided into the cryogenic part and the warm part of the mission.

## 3. Processing

### 3.1. Pre-processing and calibration

Processing begins with the *Level 1* data products generated by the Spitzer Science Center via their ‘Basic Calibrated Data’ pipeline (Lowrance et al. 2016), which were downloaded from

the NASA/IPAC Infrared Science Archive (IRSA<sup>2</sup>). They have had all well-understood instrumental signatures removed, have been flux-calibrated in units of  $\text{MJy sr}^{-1}$ , and are delivered with an uncertainty image and a mask image; they are described in detail in the IRAC Instrument Handbook<sup>3</sup>. More precisely, we begin from the ‘corrected basic calibration data’ products, which have file extensions `.cbcd` for the image, `.cbunc` for the uncertainty, and `.bimsk` for the mask. The files are grouped by AORs, namely sets of a few to several hundred DCEs obtained sequentially. All frames are  $256 \times 256$  pixels, the pixels are  $1'2$  wide, and the image file header contains the photometric solution and an initial astrometric solution.

The processing is done region by region. A first pass over the files is used to check the headers for completeness and to discard a few incomplete AORs, which accounts for most of the differences in the number of frames listed in Table 2 between channels 1 and 2, or 3 and 4. This is followed by the correction of the ‘first frame’ bias effect<sup>4</sup>. Next, the positions and magnitudes of WISE ((Wright et al. 2010), (Mainzer et al. 2011)) and Gaia DR2 (Gaia Collaboration et al. 2018) sources falling within the field are downloaded. The Gaia sources are first ‘projected’ to their location at the time of the observations using the Gaia proper motions. Next they are identified on each IRAC frame, their observed fluxes and positions determined in each frame using the APEX software (the point-source extractor in MOPEX<sup>5</sup>) in forced-photometry mode, and the positions are used to update the astrometric solution of each frame. There are typically 30–40 Gaia DR2 sources available for each frame. In channels 1 and 2 most of them are detected and used for the astrometric correction. In the longer-wavelength channels 3 and 4 only a few sources in total are detected and usable but that is still sufficient to determine an astrometric solution with negligible distortion as shown in Sect. 4.2.

An attempt was made to subtract bright stars in order to recover faint sources in their wings. For each AOR a model star built from the template PSFs described in the IRAC Instrument Handbook<sup>6</sup> (see Fig. 4.9 there) is scaled to the median of the fluxes of the star measured in that AOR, and is subtracted from each frame (of the AOR). Different templates are available for each filter and separately for the cryogenic and the warm missions. While this procedure worked quite well for moderately bright stars (which are of course the vast majority and which represent only a small loss in area), it introduced significant artefacts around the (few) very bright stars in the final mosaics. These artefacts included diffraction spikes corrected only out to a certain distance (out to where the template extends beyond the frame), other edge effects, and the subtraction of the core of bright galaxies. For these reasons the bright-star subtraction was not performed and the bright stars are left as they are.

### 3.2. Stacking and image combination

In the next step we compute a median image for all frames within an AOR which corrects for persistence in the detectors and also for any residual first-frame pattern that introduces structure in

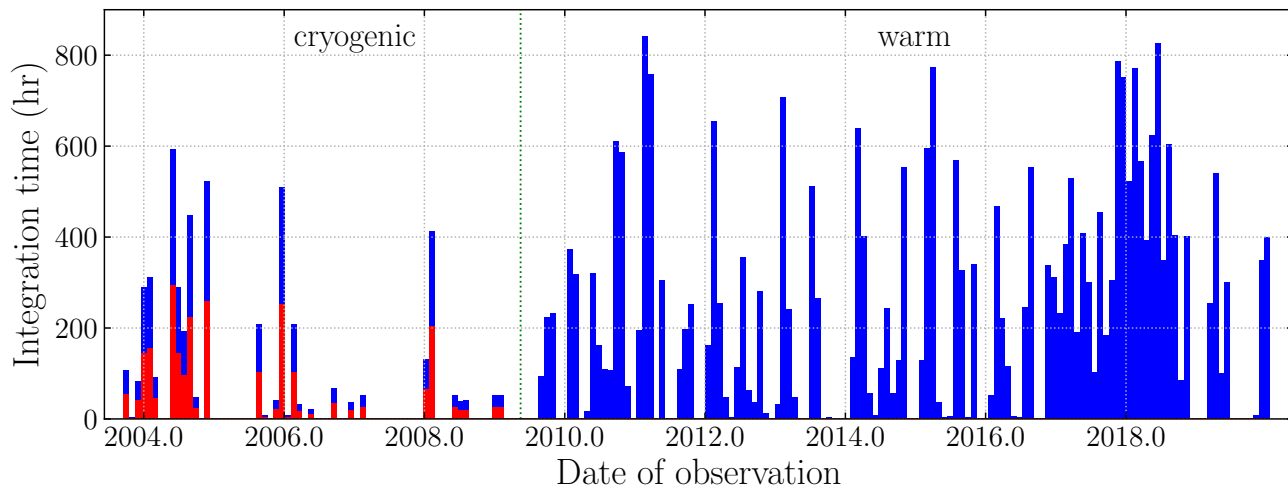
<sup>2</sup> <https://irsa.ipac.caltech.edu>

<sup>3</sup> <https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/home>

<sup>4</sup> <https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/26/>

<sup>5</sup> <https://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysistools/tools/mopex/>

<sup>6</sup> <https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/19/>



**Fig. 1.** Histogram of the exposure time of the data analysed here (including the few discarded observations) using bins of 30 days. Our dedicated observations began in November 2016 and comprise most of the data after that date. The red part of each bar accounts for observations in channels 3 and 4, the blue part for those in channels 1 and 2; the vertical dotted line at 2009.37 indicates the end of the cryogenic mission. No observations were made in channel 3 and 4 after the end of the cryogenic mission.

**Table 1.** The ten largest programmes, by Program ID

PID	Principal Investigator	Field	Time (hr)	Reference
61041	Giovanni Fazio	XMM	847	SEDS; Ashby et al. (2013)
61040	Giovanni Fazio	HDFN	914	SEDS; Ashby et al. (2013)
14235	Claudia Scarlata	EDF-S	1086	this paper
169	Mark Dickinson	HDFN	1104	GOODS; Labbé et al. (2015)
10042	Peter Capak	XMM	2033	this paper
90042	Peter Capak	COSM	2167	this paper
13094	Ivo Labbe	COSM	2483	GOODS; Labbé et al. (2015)
11016	Karina Caputi	COSM	3021	SMUVS; Ashby et al. (2013)
13058	Peter Capak	EDF-F	3162	this paper
13153	Peter Capak	EDF-N	4625	this paper

the background. In parallel, a background map is also created by iteratively clipping objects and masking them, and finally that background is subtracted from each frame of the AOR.

The final processing steps consist of resampling the background-subtracted frames onto a common grid with a scale of  $0''.6 \text{ pix}^{-1}$ , i.e., half the instrument pixel size, that covers all data in all channels and which is the same in all channels. We experimented with two MOPEX interpolation schemes to produce our final mosaics. We first tried the ‘drizzling’ (Fruchter & Hook 2002) scheme in which the final value of the output pixels is computed by considering the contribution of each input pixel in a smaller pixel grid in the output image. This procedure has excellent noise properties (it does not suffer from correlated pixels) when many input frames are available, but with few input frames it can produce artefacts in the output images. The second, simpler approach is to compute the value of each output pixel as a linear combination of the input pixel values. Although this procedure produces correlated noise, it works reliably for all the fields considered in this work which can have widely varying numbers of input images. Noise correlations can be estimated through simulations or by comparing sources in our drizzled and non-drizzled images. These comparisons show that the linear interpolation procedure leads to an underestimation of

aperture magnitude errors by 30 – 40% while the magnitudes themselves are unaffected.

Next, we use MOPEX to produce an average-combined image while rejecting outliers and excluding masked regions. The stacking pipeline also produces the following ancillary characterisation maps: (1) an uncertainty map produced by stacking the input uncertainty maps using the same shifts as for the signal stack, (2) a coverage map giving the number of frames contributing to each pixel, and (3) an exposure time map giving the total exposure time per pixel. As the exposure times are not the same for all the observing programmes, these last two maps are not simply scaled versions of each other.

### 3.3. On the spatial variation of the PSF in the stacks

The observations described here were made at many different satellite position angles (PAs), and thus when the images are stacked they must be rotated back to North upwards. This has the effect of rotating the PSF, which is fixed in the satellite’s reference frame. Since the PSF is not rotationally symmetric, due in particular to the diffraction spikes, the stacked image of a star will depend on when it was observed. As all parts of the stack

**Table 2.** Valid observations

Field	Ch.	cryo		warm		total		Ch.	total	
		Num	Time	Num	Time	Num	Time		Num	Time
EDF-N	1	5 859	52	113 521	2 380	119 380	2 432	3	5 856	52
EDF-N	2	5 857	52	113 204	2 467	119 061	2 519	4	7 667	50
EDF-F	1	14 299	363	105 781	2 672	120 080	3 035	3	14 301	363
EDF-F	2	14 299	363	105 779	2 764	120 078	3 127	4	29 686	352
EDF-S	1	n/a	n/a	21 982	534	21 982	534	3	n/a	n/a
EDF-S	2	n/a	n/a	21 982	552	21 982	552	4	n/a	n/a
COSMOS	1	7 014	185	191 072	4 886	198 086	5 071	3	7 011	185
COSMOS	2	7 013	185	191 031	5 052	198 044	5 237	4	13 894	179
EGS	1	4 673	192	44 101	551	48 774	743	3	4 672	192
EGS	2	4 673	192	44 101	569	48 774	761	4	14 535	186
HDFN	1	6 253	298	36 485	930	42 738	1 228	3	6 252	298
HDFN	2	6 253	298	36 485	962	42 738	1 260	4	22 496	288
XMM	1	10 264	154	98 027	2 410	108 291	2 564	3	10 265	154
XMM	2	10 265	154	98 030	2 495	108 295	2 649	4	14 321	151

**Notes.** Here ‘Num’ is the number of frames used, and ‘Time’ is the integration time, in hours, they contribute. The left part of the table is for channels 1 and 2, split between cryogenic and warm mission, the right part is for channels 3 & 4 which were used during the cryogenic mission only. Note that the EDF-S field was observed only during the warm mission.

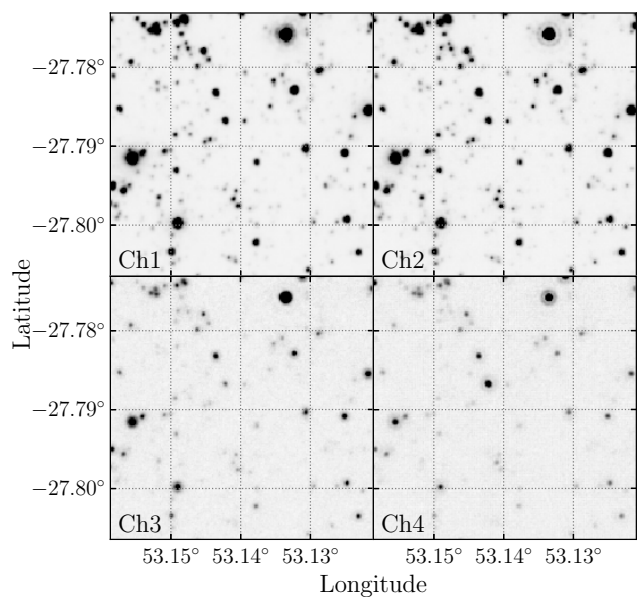
were not observed at the same time (or at the same PA), the PSF varies spatially in the stack.

The COSMOS field, which is near the Equator, was observable only at specific times and therefore with a very restricted range of PAs; the PSF in the COSMOS stacks is thus quite homogeneous. But in the EDF-N, which was in a continuous viewing zone, observations were obtained at many different PAs, yielding more complicated and more spatially variable PSF. This effect is very important for PSF-based photometry: the PSF at each position of the stack has to be reconstructed by stacking the nominal PSF at the PAs of the observations at that position, as did e.g., Labbe et al. (2015) for the GOODS-South and HUDF fields, and also Weaver et al. (submitted) for the production of the COSMOS2020 catalogue. The latter used the PRFmap code by Andreas Faisst, available at <https://github.com/cosmic-dawn/prfmap> for that purpose. While doing such photometry is beyond the scope of this paper, we nevertheless provide, for each stack, a table of the PAs of each frame used in the stack. For completeness those tables also contain the frame coordinates, the MJD of the observation, and the exposure time; see Appendix A for more details.

### 3.4. Products

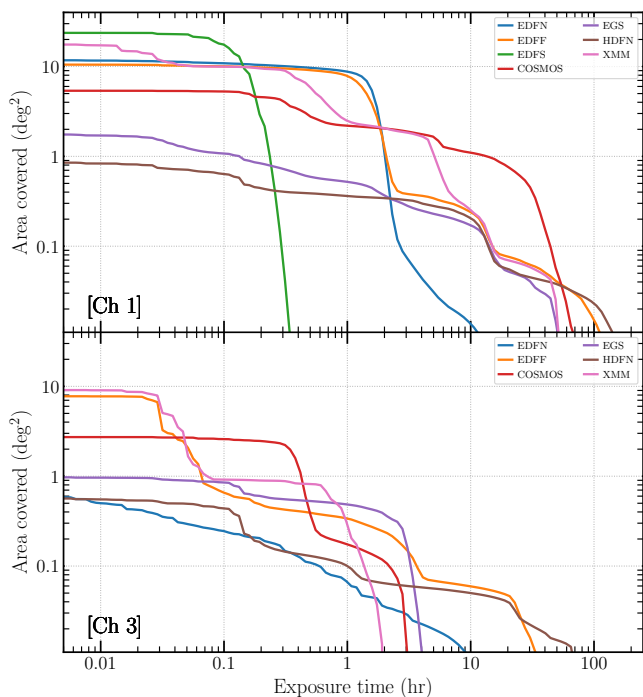
As an example of the data quality, Fig. 2 shows a zoomed section of the EDF-F mosaic in the four channels near the region of maximum coverage. We do not provide here figures of the full mosaics as they would be physically too small to show anything informative other than the overall coverage.

Maps of the integration time per pixel for channels 1 and 3 of all the fields are presented in Appendix B. Since channel 2 is observed together with channel 1, and similarly for channels 4 and 3, the paired channels have very similar coverage, albeit slightly shifted in position. The  $10 \text{ deg}^2$  circular area of EDF-N and EDF-F and the  $20 \text{ deg}^2$  pill-shaped area of EDF-S are easily seen on those figures. Also, and with the exception of EDF-S, for



**Fig. 2.** Detail of EDF-F mosaic in the region near that of maximum exposure time, which here is the same for all four channels. Images are  $200 \times 200$  pixels, or  $2' \times 2'$ . Display levels are  $-\sigma$  to  $+8\sigma$ , where  $\sigma$  is the standard deviation of the sky pixels, which is  $\sim 0.005 \text{ MJy sr}^{-1}$  for channels 1 & 2, and  $\sim 0.013 \text{ MJy sr}^{-1}$  for channels 3 & 4.

which there are only observations done specifically for this programme and no archival data, the integration time per pixel, and consequently the depth reached, is far from uniform, with only a small part of the total area of each field having been observed for more than a few hours. In fact, the median integration time per pixel is larger than 1 hr for only two fields. Table 3 gives the median and maximum pixel integration time for each field and each channel.



**Fig. 3.** Cumulative area coverage as a function of exposure time for channels 1 and 3, for all fields. The figures for channels 2 and 4 are similar to the ones above, as explained in the text.

**Table 3.** Median and maximum pixel integration time in hours

Field	ch1	ch2	ch3	ch4
COSMOS	0.51	93.7	0.50	97.1
EDF-F	1.33	199.7	1.33	149.5
EDF-N	1.47	23.4	1.56	21.3
EDF-S	0.13	0.5	0.16	0.5
EGS	0.16	71.1	0.16	71.6
HDFN	0.16	236.2	0.16	224.4
XMM	0.31	65.9	0.33	67.1

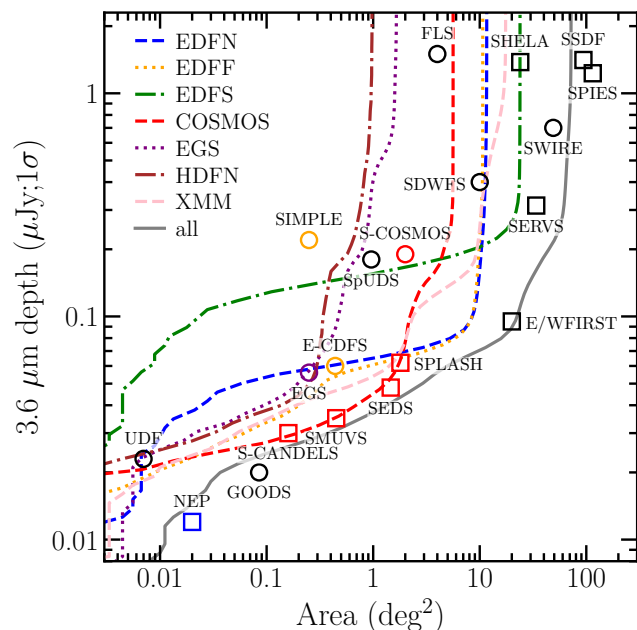
That variation of area covered as a function of exposure time for channels 1 and 3 and for all fields is shown graphically in Fig. 3 which presents a cumulative histogram of the area covered vs. exposure time. The intersection of the curve with the vertical axis thus gives the total area covered for that field and these areas are also listed in Table 4. EDF-S is the most uniformly observed field and it covers the largest area, but it is also the shallowest, with only 0.1 hr per pixel on average, and it is also the only field with no channel 3 and 4 data. EDF-F and EDF-N reach the target coverage of 10 deg<sup>2</sup> with about 1 hr of exposure time, with the latter showing deeper coverage over smaller zones. The other fields were covered by many observing programs with different objectives and which covered specific areas to different depths. The combination of these programs with our own yields a curve with many plateaus. Finally, there are a few small parts of the EDF-F and HDFN fields that have more than 100 hr of exposure time.

**Table 4.** Location and area, in deg<sup>2</sup>, covered in each field

Field	RA	Dec	ch1	ch2	ch3	ch4
EDF-N	17 <sup>h</sup> 58 <sup>m</sup>	66° 36′	11.74	11.54	0.61	0.62
EDF-F	3 <sup>h</sup> 32 <sup>m</sup>	−28° 12′	10.52	11.05	7.78	7.77
EDF-S	4 <sup>h</sup> 5 <sup>m</sup>	−48° 30′	23.60	23.14	–	–
COSMOS	10 <sup>h</sup> 0 <sup>m</sup>	2° 12′	5.37	5.46	2.72	2.72
EGS	14 <sup>h</sup> 19 <sup>m</sup>	52° 42′	1.76	1.80	0.97	0.98
HDFN	12 <sup>h</sup> 37 <sup>m</sup>	62° 24′	0.91	0.91	0.57	0.63
XMM	2 <sup>h</sup> 27 <sup>m</sup>	−4° 36′	17.54	17.48	9.09	9.10

### 3.5. Final sensitivities

We estimate the sensitivities of the stacked images by measuring the flux in circular 2′.5 diameter apertures randomly placed across each image after masking the regions with detected objects using the SExtractor (Bertin & Arnouts 1996) segmentation map. The sensitivity is then computed as the standard deviation of these fluxes (3 $\sigma$  clipped). This procedure is done in 200 × 200 pixel cells (4 arcmin<sup>2</sup>). Figure 4 shows the cumulative area covered as a function of sensitivity for the channel 1 mosaics. Note the similarity between this figure and the top panel of Fig. 3 once the latter is rotated by 90 degrees. The solid line shows our total depth, summed over all our survey fields. Also shown in the figure are the published sensitivities of the surveys that are included in our data and analyses. Generally, our measured sensitivities are consistent with literature measurements for surveys of equivalent exposure time.



**Fig. 4.** Sensitivity of the *Spitzer*/IRAC channel 1 data as a function of cumulative area coverage. The coloured lines illustrate 1 $\sigma$  depths measured in empty 2′.5 diameter apertures in each field. The grey solid line is the total area observed to a given depth summed over different surveys. The data points indicate point-source sensitivities at 1 $\sigma$  compiled in Ashby et al. (2018) (note that some of these data are included in our stacks). The circles and squares represent surveys executed during cryogenic and warm missions, respectively.



## 4. Validation and quality control

As part of our validation process we compare photometry and astrometry of sources in our stacks with reference catalogues and also extract number counts that can be compared to previous works.

### 4.1. Catalogue extraction

We begin by extracting source catalogues from the channels 1 and 2 stacks of all fields using SExtractor. We adopt the usual approach of searching for objects that contain a minimum number of connected pixels above a specified noise threshold (in this case  $2\sigma$ ) and measuring their aperture magnitudes. In the case of our moderately deep IRAC data, where many sources are blended due to the large IRAC PSF, this approach is known to miss faint sources. However, these faint sources are not required for our quality assessment purposes and a shallower catalogue is entirely sufficient. SExtractor estimates a global background on a grid with mesh size of  $32 \times 32$  pixels (recall that pixels are  $0''.6$  wide). This background is smoothed with a  $5 \times 5$  pixel Gaussian kernel with FWHM =  $1''.5$ . For each source, the flux is measured within a circular aperture of  $7''$  diameter and a local background is estimated within an annulus of width 32 pixels around the isophotal limits. The measured fluxes were converted from MJy/sr to AB magnitude using a zero-point of 21.58 (which accounts for a zero-magnitude flux of 3631 Jy and a pixel size of  $0''.6^7$ ), and the latter were converted to total magnitude using the aperture corrections given in the IRAC Instrument Handbook for the warm mission ( $-0.1164$  and  $-0.1158$  for channel 1 and channel 2 respectively), which covers the vast majority of the data, while the correction for the cryogenic mission differs at only the 1–2% level<sup>8</sup>. A list of relevant SExtractor parameters used for the catalogue extraction can be found in Table 5.

**Table 5.** SExtractor parameters used for detection and photometry.

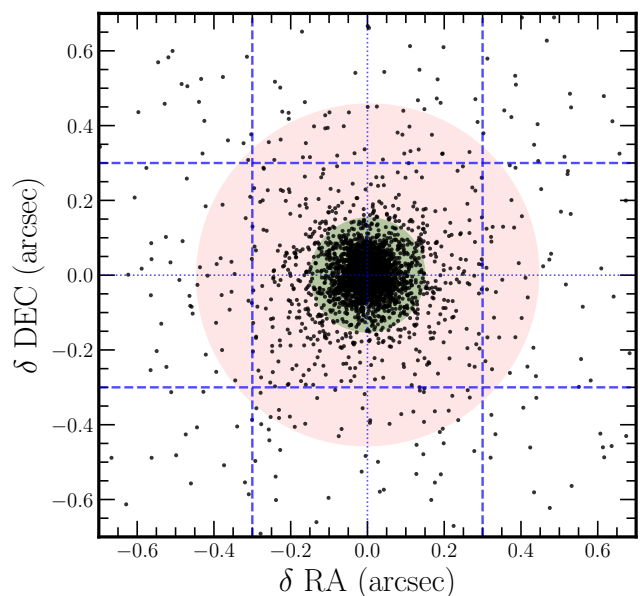
Parameter name	Value
DETECT_MINAREA	5
DETECT_MAXAREA	1000000
THRESH_TYPE	RELATIVE
DETECT_THRESH	2
ANALYSIS_THRESH	2
FILTER_NAME	gauss_2.5_5x5.conv
DEBLEND_NTHRESH	32
DEBLEND_MINCONT	0.00001
BACK_SIZE	32
BACKPHOTO_THICK	32
BACK_FILTERSIZE	3
BACKPHOTO_TYPE	LOCAL
MAG_ZEROPOINT	21.58
PHOT_AUTOPARAMS	2.5,5.0
PIXEL_SCALE	0.60

### 4.2. Astrometric and photometric validation

Using the catalogues extracted above, we evaluate the astrometric accuracy of our stacked images. For each field we cross-match sources with magnitude  $16 < [3.6] < 19$  within  $1''$  of their counterparts in the Gaia DR2 catalogue. This magnitude range was adopted to ensure only bright, non-blended sources were chosen. We now present a detailed analysis for EDF-N but other fields are similar.

Figure 5 shows the difference between reference and measured coordinates (for clarity, only one point in ten is shown). The heavy blue dashed line gives the size of one pixel in the stacked image (which is half the size of the instrument pixel). Similarly (again showing only one in ten points), Fig. 6 shows, for each coordinate, the difference between the reference and the measured value as a function of position along the other coordinate. The thick red dashed line shows a running median computed over a bin containing 20 points. The flatness of this line indicates that there is no significant spatial variation in astrometric precision. Considering all fields, we find that the  $1\sigma$  precision (measured as the RMS of the difference between positions in our catalogue and those in Gaia DR2) is  $0''.15$ . Furthermore, the median value is always  $\lesssim 0''.1$ , with the exception of the sparsely-covered HDF-N field where it is  $\lesssim 0''.2$ .

These measurements demonstrate that the astrometric solutions have been correctly applied to the individual images and that the combined images are free of residuals on a scale much smaller than an individual mosaic pixel, which is more than sufficient to measure precise infrared and optical-infrared colours.

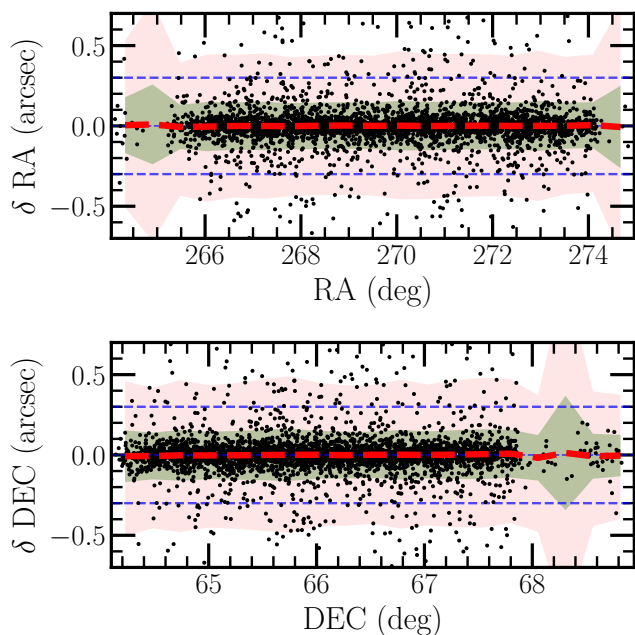


**Fig. 5.** The difference between the reference and the measured position, in arcseconds, of Gaia DR2 catalogue sources with  $16 < [3.6] < 19$  total magnitudes extracted from the EDF-N channel 1 mosaic. The blue dashed lines indicate the size of one mosaic pixel. The blue dotted lines go through the origin. The shaded regions are ellipses containing 68% and 99% of all sources respectively. For clarity, only one in ten sources is plotted.

Finally, we perform a simple check on the photometric calibration of our mosaics. As described previously, individual images are photometrically calibrated by the Spitzer Science Center (SSC). Following the validation procedures outlined by the SSC, we compare magnitudes of objects in our catalogues with

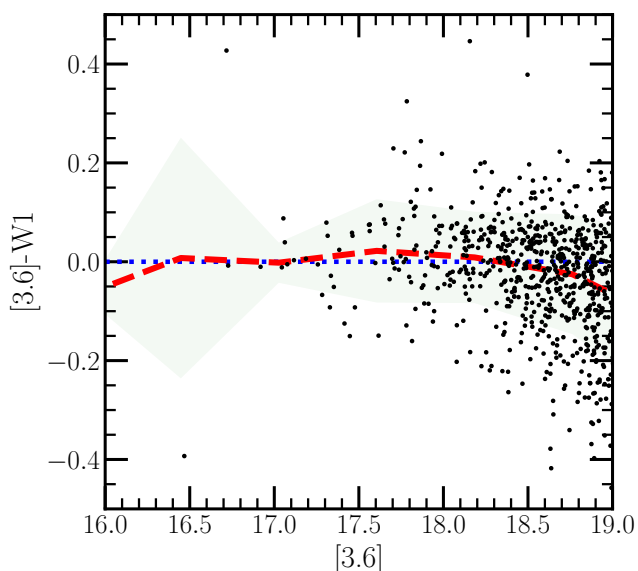
<sup>7</sup> <https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/19/>

<sup>8</sup> [https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/ap\\_corr\\_warm/](https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/ap_corr_warm/)



**Fig. 6.** The difference between the reference Gaia DR2 catalogue and the measured RA (top panel) and DEC (bottom panel) of sources in the EDF-N channel 1 mosaic with  $16 < [3.6] < 19$  total magnitudes as a function of the coordinate. The solid red line shows a running median computed in bins of 20 points, and the shaded areas indicate the regions containing 68% and 99% of all sources respectively.

those in the WISE survey. Because of the difference between the WISE W1 and IRAC channel 1 filter profiles, we select objects with  $[3.6] - [4.5] \sim 0$ . Figure 7 shows the magnitude difference for the EDF-N field, and the agreement is excellent. Further comparisons with photometric measurements in previous COSMOS IRAC surveys can be found in the Appendix of Weaver et al.



**Fig. 7.** Photometric comparison with the WISE survey. The magnitude measured in 7'' apertures for flat-spectrum objects ( $[3.6] - [4.5] \sim 0$ ) is compared with W1 magnitudes in the ALLWISE survey. The shaded area represents the 68% confidence interval.

### 4.3. Magnitude number counts

We compute the differential number counts in channel 1 in each field using the corrected 7'' aperture magnitudes. Since the IRAC PSF is too large to perform morphological source classification, we simply include all objects detected. These are shown in Fig. 8, where the red circles with uncertainties present our measurements and the lines show the number counts from the literature; the bottom-right panel shows the mean of all fields. We compare our number counts with those presented in Ashby et al. (2013) who also surveyed many of our fields and also with those computed using the new COSMOS2020 photometric catalogue (Weaver et al., submitted) which we use as a reference.

There is a general agreement in the number counts in all the fields with Ashby et al. (2013) and COSMOS2020 for  $16 < [3.6] < 22$ . At brighter magnitudes the COSMOS2020 counts drop off as bright sources were not included. At fainter magnitudes, our aperture-based catalogues are confusion-limited and thus incomplete. Conversely, the COSMOS2020 catalogue, which uses a high-resolution prior for the detection and a profile-fitting method for the measurement, is complete up to significantly fainter magnitudes.

EDF-N counts are slightly higher than the other fields at bright magnitudes. To investigate this difference we simulated a stellar catalogue of  $1 \text{ deg}^2$  centred on EDF-N using TRILEGAL (Girardi et al. 2005) and compared counts from this simulated catalogue with our observations, shown in Fig. 9. At bright magnitudes, where stars are expected to outnumber galaxies, our counts are in reasonable agreement with TRILEGAL predictions, and in excellent agreement with the number counts extracted from the AllWISE (Wright et al. 2010) catalogue for this field. These comparisons indicate that the difference between EDF-N and other fields is largely due to the higher density of stellar sources in there, consistent with its lower Galactic latitude.

## 5. Summary

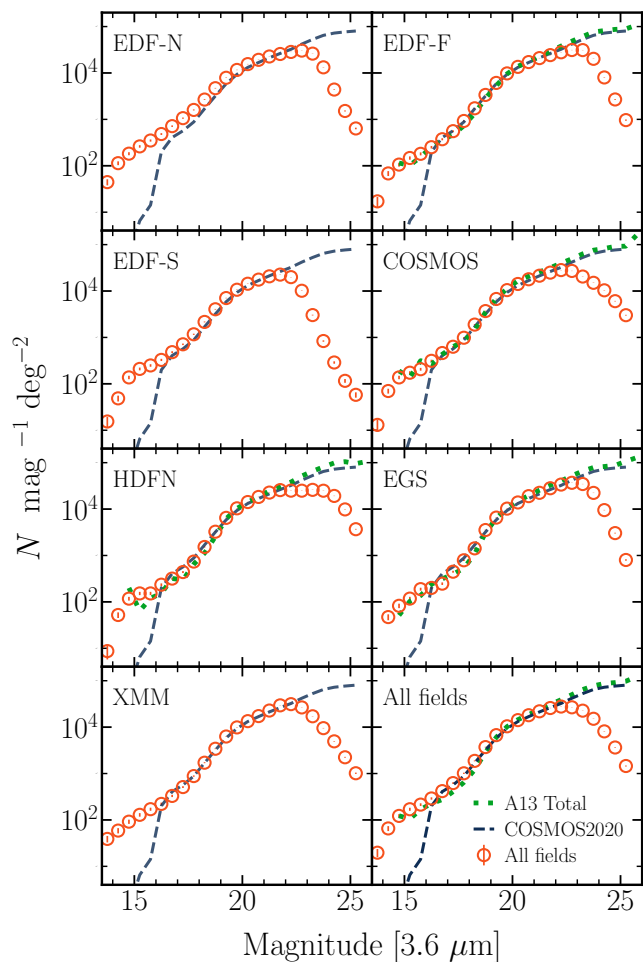
We have presented the *Spitzer*/IRAC mid-infrared component of the Cosmic Dawn Survey: an effort to complement the *Euclid* mission's observations of deep and calibration fields with deep longer-wavelength data to enable high redshift legacy science.

The survey consists of two major new programs covering the three *Euclid* deep fields (EDF-N, EDF-F and EDF-S) and a homogeneous reprocessing of all existing data in *Euclid*'s four calibration fields (COSMOS, XMM, EGS and HDFN). We have processed new data together with all relevant archival data to produce mosaics of these fields covering a total of  $\sim 71 \text{ deg}^2$  in IRAC channels 1 and 2. Furthermore, the new mosaics are tied to the Gaia astrometric reference system. The MIR data will be essential for a wide range of legacy science with *Euclid*, including improved star/galaxy separation, more accurate photometric redshifts, determination of stellar masses of galaxies, and the construction of complete galaxy samples at  $z > 2$  with well understood selection effects.

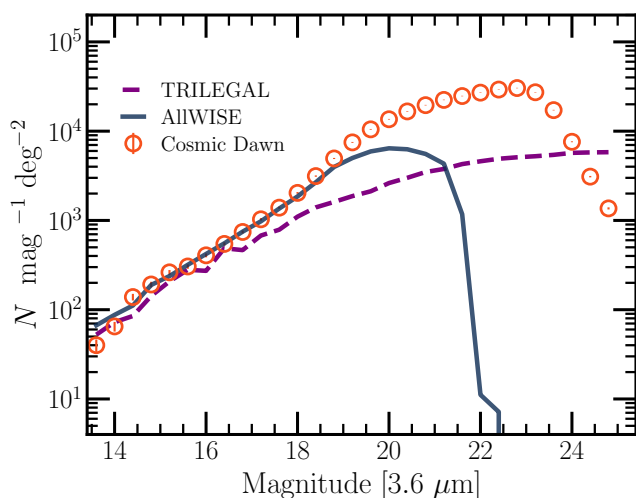
We validated our final products by comparing catalogues extracted from channels 1 and 2 to external catalogues. In all fields, comparing with Gaia DR2, the residual astrometric uncertainty for sources with total magnitudes  $16 < [3.6] < 19$  is around  $0''.15$  ( $1\sigma$ ). Our photometric measurements are in excellent agreement with WISE photometry and our number counts are consistent with previous determinations.

The Cosmic Dawn Survey *Spitzer* survey presented here represents the first essential step in assembling the required multi-wavelength coverage in the *Euclid* deep fields which are set to





**Fig. 8.** Magnitude number counts in channel 1 (red circles) together with COSMOS2020 (long dashed lines) and Ashby et al. (2013, hereafter A13; short dotted green lines). The bottom right panel shows the mean of all fields compared to , and the legend there applies to all panels.



**Fig. 9.** Magnitude number counts in the EDF-N field compared to AllWISE and the predicted stellar number counts from TRILEGAL.

become some of the most important fields in extragalactic astronomy for the coming decade. Since the *Spitzer* mission has finished, and all available data in these fields have been pro-

cessed with the latest reduction pipeline, the resulting mosaics will remain the deepest and widest MIR imaging survey for the foreseeable future. No existing or approved future observatories are capable of obtaining such data. While JWST is more sensitive and has higher spatial resolution at these wavelengths, its mapping speed is too slow to cover comparable degree-scale areas.

In the context of the Cosmic Dawn Survey, several programs are currently underway to add data at other wavelengths to the *Euclid* deep fields and calibration fields. In particular deep optical data in the EDF-N and EDF-F are currently being obtained with the Subaru’s Hyper-Suprime-Cam instrument as part of the Hawaii-Two-0 program (McPartland et al., in prep). These fields are also being targeted with high spatial resolution millimeter observations as part of the planned Large-scale Structure Survey with the Toltech Camera<sup>9</sup> on the Large Millimeter Telescope (LMT Pope et al. 2019). A deep *U*-band survey is also underway with the CFHT (Zalesky et al., in prep). EDF-S is being covered with K-band observations from the VISTA telescope (Nonino et al., private communication), and planning is ongoing to obtain optical data with the Vera C. Rubin Observatory.

The Cosmic Dawn Survey *Spitzer* mosaics and associated products described here can be downloaded from the IRSA web site, Appendix A gives the details of the download site and the naming convention used. The community is encouraged to make use of them for their science.

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<sup>9</sup> <http://toltec.astro.umass.edu/>

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## Appendix A: Delivered data products

The new mosaics and associated products can be obtained from the IRSA website at [https://irsa.ipac.caltech.edu/data/SPITZER/Cosmic\\_Dawn](https://irsa.ipac.caltech.edu/data/SPITZER/Cosmic_Dawn) (ATTN: the products will become available once the paper is accepted; the URL may be updated at publication time). The file naming convention for the stacks is as follows:

`CDS_{field}_ch{N}_{type}_v24.fits`

where `field` is the field name, `N` is the channel number, and `type` is one of

`ima`: for the flux image,  
`cov`: for the coverage in terms of number of frames used to build each pixel of the mosaic,  
`tim`: for the exposure time in sec of the pixel, and  
`unc`: for the uncertainty as determined from the standard deviation of the image pixels that contributed to the mosaic pixel.

Also, Table A.1 gives the precise J2000 coordinates of the field tangent point in decimal degrees, the reference pixel corresponding to that tangent point, and size, in pixels, of the mosaics. These values are the same for all channels of a field and for all the ancillary images. The pixel scale is 0".60 per pixel for all mosaics.

The tables with the observation date, coordinates, position angles, and exposure times of the input frames are provided in IPAC format and are gzipped to reduce their size. Their names are as follows:

`CDS_{field}_ch{N}_info_v24.tbl.gz`

The first few lines of the table for channel 1 of the EGS field are as follows:

MJD	RA	DEC	PA	ExpTime
double	double	double	double	double
day	deg	deg	deg	sec
null	null	null	null	null
53822.6296863	214.458364468008	51.9912156620541	-126.246899270774	0.4
53822.6297117	214.458364468008	51.9912156620541	-126.247055616923	10.4
53822.6298641	214.458364468008	51.9912156620541	-126.246928305428	96.8
53822.6312156	214.383044470269	52.0556500561605	-126.304483006668	96.8

The coordinates are in degrees of longitude and latitude (Equatorial, J2000) and the PAs are measured eastward of North.

## Appendix B: Coverage maps

Figures B.1 and B.2 show the full set of pixel exposure time maps for channels 1 and 3; channels, 2 and 4 are similar though slightly shifted in location. A square root scaling is applied in order to emphasise the differences at the low levels, and the same maximum is used for all fields in each channel. As EDF-S was not observed in channel 3, a blank field is placed there.

## Appendix C: PID numbers

Table C.1 lists the *Spitzer* Program-IDs (PIDs) of all the observations processed here. In bold the ones of the observing programmes that we planned for this work, the others are of the other archival observations that we reprocessed.

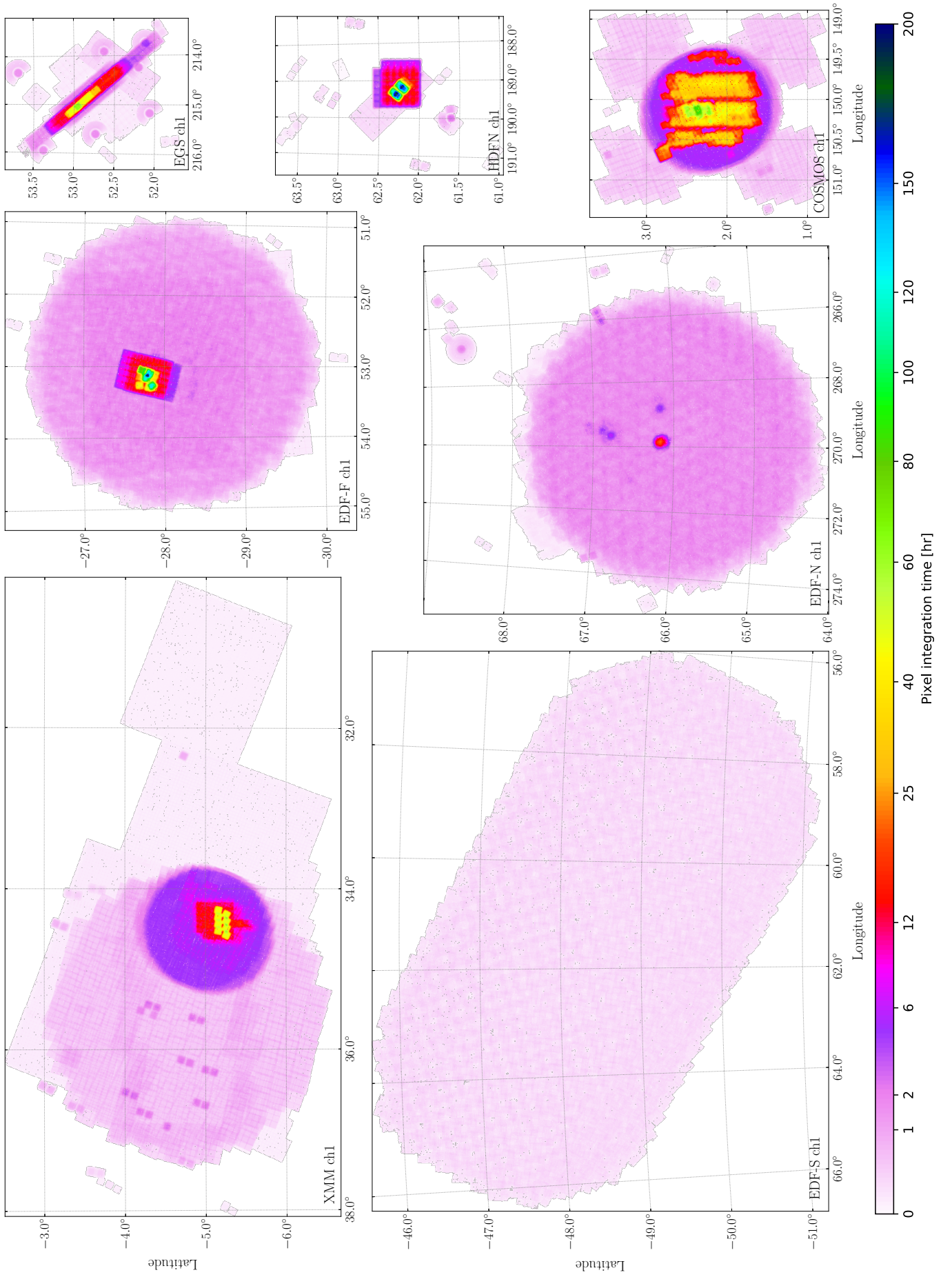
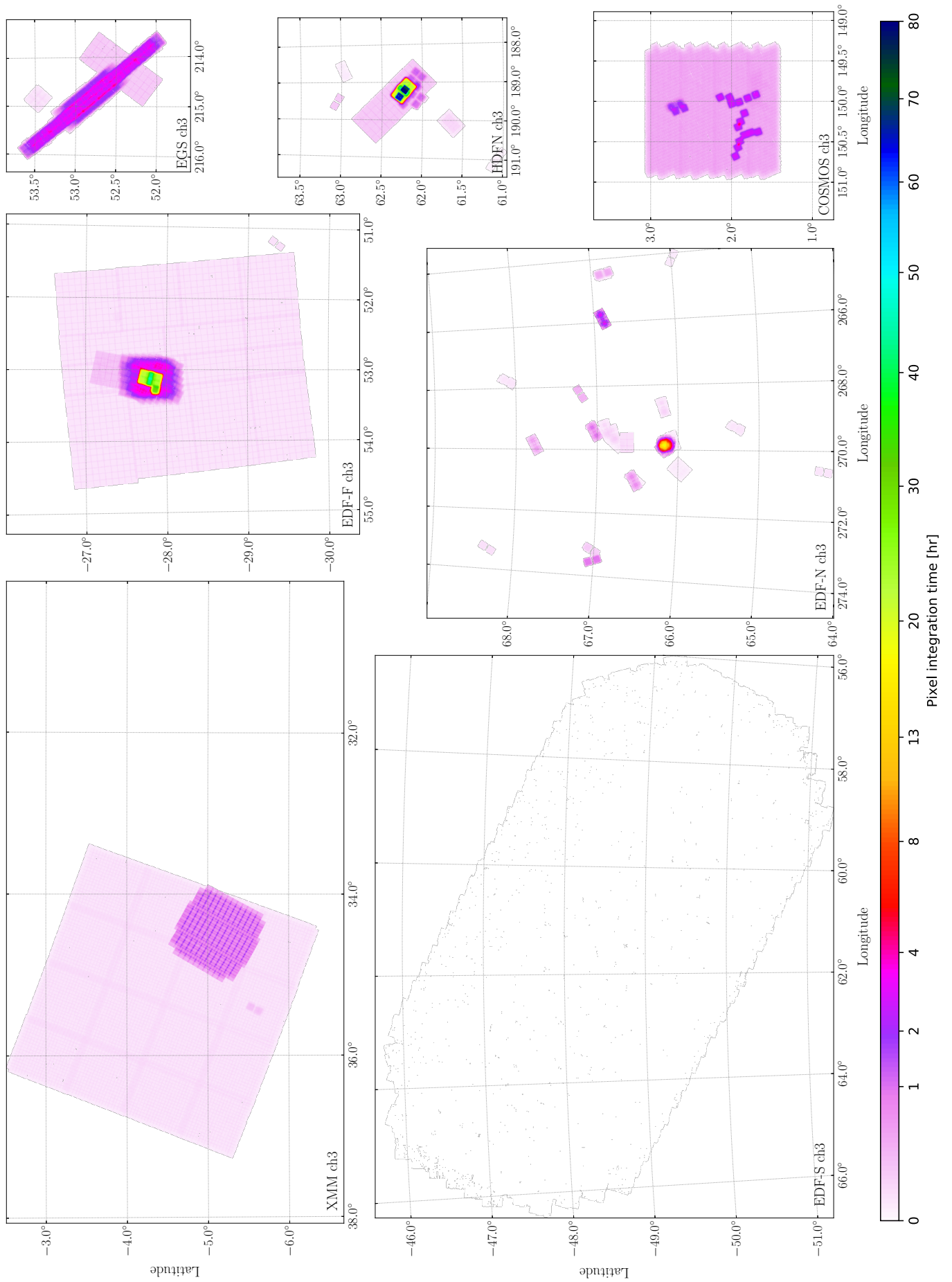


Fig. B.1. Integration time maps for channel 1





**Fig. B.2.** Integration time maps for channel 3. A blank field is included for EDF-S which was not observed in that channel and in order to have the same structure as B.1

**Table A.1.** Data products information

Field	Longitude	Latitude	<i>x</i> -size	<i>y</i> -size	<i>x</i> -ref.pix	<i>y</i> -ref.pix
EDF-N	269.485804	66.590708	27 410	30 148	13 705.55	15 074.53
EDF-F	53.062008	−28.205431	23 751	26 204	11 876.02	13 102.29
EDF-S	61.301724	−48.496065	41 676	33 976	20 838.59	16 988.50
COSMOS	150.178292	2.220994	15 440	17 804	7 720.46	8 902.40
EGS	214.781187	52.720882	11 278	13 649	5 639.32	6 824.97
HDFN	189.405434	62.373754	11 813	1 979	5 907.03	8 489.78
XMM	34.101249	−4.598575	47 583	25 022	23 791.97	12 511.69

**Notes.** Longitude and latitude are Equatorial and J2000, for the image tangent point. These values are valid for all four channels of each field and for their ancillary images.

**Table C.1.** *Spitzer* Program IDs

Field	PIDs
EDF-N	68 609 613 618–624 1101 1125 1188 1189 1191—1200 1317 1334 1600—1700 1910—1949 1951 1953–1961 1963–1983 2314 3286 3329 3672 10147 11161 <b>13153</b> 20466 30432 40385 60046 70062 70162 80109 80113 80243 80245 90209
EDF-F	81 82 184 194 2313 11080 <b>13058</b> 20708 30866 40058 60022 61009 61052 70039 70145 70204 80217
EDF-S	<b>14235</b>
COSMOS	10159 11016 12103 13094 13104 14045 14081 14203 20070 40801 50310 61043 61060 70023 80057 80062 80134 80159 90042
EGS	8 10084 11065 11080 13118 20754 41023 60145 61042 80069 80156 80216 90180
HDFN	81 169 1304 10136 11004 11063 11080 11134 12095 13053 20218 30411 30476 40204 60122 60145 61040 61062 61063 70162 80215
XMM	181 3248 10042 11086 40021 60024 61041 61060 61061 70039 70062 80149 80156 80159 80218 90038 90175 90177