Galaxy properties derived with spectral energy distribution fitting in the Hawaii-Hubble Deep Field-North

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Received 2018 July 8; accepted 2018 September 28

Abstract We compile multi-wavelength data from ultraviolet to infrared (IR) bands as well as redshift and source-type information, for a large sample of 178 341 sources in the Hawaii-Hubble Deep Field-North field. A total of 145 635 sources among the full sample are classified/treated as galaxies and have redshift information available. We derive physical properties for these sources utilizing the spectral energy distribution fitting code CIGALE that is based on Bayesian analysis. Through various consistency and robustness checks, we find that our stellar-mass and star-formation rate (SFR) estimates are reliable, which is mainly due to two facts. Firstly, we adopt the most up-to-date and accurate redshifts and point spread functionmatched photometry; and secondly, we make sensible parameter choices with the CIGALE code and take into account the influences of mid-IR/far-IR data, star-formation history models, and AGN contribution. We release our catalog of galaxy properties publicly (including, e.g., redshift, stellar mass, SFR, age, metallicity, dust attenuation). It is the largest of its kind in this field and should facilitate future relevant studies on the formation and evolution of galaxies.

Key words: catalogs — galaxies: fundamental parameters — galaxies: star formation

1 INTRODUCTION

Galaxies, where stars are born and die, are gravitationally bounded components constituting our universe. Tracing galaxy formation and evolution has been a major focus in many large sky surveys, such as the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) and the Galaxy and Mass Assembly survey (GAMA; Driver et al. 2011; Liske et al. 2015). Understanding when and how galaxies form is key to deciphering the history and future of our universe. Galaxy properties, such as the stellar mass (M_*) , starformation rate (SFR), intrinsic luminosity, and dust attenuation, are crucial in investigating many aspects of galaxies, e.g., the differences between active galactic nuclei (AGNs) and normal galaxies (see, e.g., Netzer 2015 for a review), evolution of cosmic SFR (e.g., Madau & Dickinson 2014), galaxy stellar-mass function (e.g., Baldry et al. 2012), luminosity function (e.g., Aird et al. 2015; Finkelstein et al. 2015), and hot dust-obscured galaxies (e.g., Assef et al. 2015).

However, the big challenge for a survey is to identify sources as galaxies and carry out detailed follow-up spectroscopic and photometric research on them, especially for those with faint fluxes (e.g., Barger et al. 2008). Due to the flux-limit constraints of a survey, it is incredibly difficult to investigate galaxies that are in or close to the era of cosmic reionization from where it took over ten billion years for photons to reach us. That is why many epochs of the universe still remain largely unknown. Despite the difficulties mentioned above, much effort has been dedicated to deriving the physical properties of these very faint sources.

Thankfully, we now have an access to enormous amount of galaxy data owing to the advancement of large astronomical facilities and the devotion of astronomers around the world. Together, ground-based observatories and telescope arrays such as VLT, Keck, VLA, and ALMA, space observatories such as HST, Herschel, Chandra, NuSTAR, XMM-Newton, and Fermi, and large observational projects lasting for decades such as the Sloan Digital Sky Survey (SDSS; Pâris et al. 2017) and the 7 Ms Chandra Deep Field-South survey (CDF-S; Xue et al. 2011; Luo et al. 2017; Xue 2017), cover a broad range of the electromagnetic spectrum and have built up a mass of multi-wavelength data. Moreover, many researchers have contributed dramatically in creating basic templates, e.g., the stellar population models (e.g., Bruzual & Charlot 2003; Maraston 2005), dust attenuation curves (e.g., Calzetti et al. 1994, 2000), and dust emission templates in infrared (IR) bands (e.g., Chary & Elbaz 2001; Dale & Helou 2002). Given the rich spectroscopic and photometric information that has become available recently, it is convenient to derive galaxy properties by fitting their observed spectral energy distributions (SEDs) with model templates. Compared with other methods that constrain one single parameter based on one single feature (e.g., deriving SFRs via H α line strengths), SED fitting approach can provide estimates of a number of parameters simultaneously (e.g., Walcher et al. 2011).

Galaxy SED fitting is now a widely-used technique that has gained in popularity in recent decades. It has been proven that this method performs well in deriving a range of galaxy properties (e.g., redshift, M_* , SFR, dust mass, and metallicity) with high accuracy, as it calculates and optimizes these parameters self-consistently and simultaneously by taking into account how they influence each other and co-evolve (e.g., Walcher et al. 2011; Conroy 2013; Wright et al. 2016). However, there are some issues with SED fitting, such as the finer details of dust properties and dust-star geometries remaining to be investigated, and problems in estimating the age of the oldest stars, as well as likely degeneracies between parameters (e.g., Walcher et al. 2011). Further improvements in SED fitting would be expected once a better understanding of these existing issues is obtained.

Despite the wide use of SED fitting in deriving galaxy properties in many works, only a limited number of source catalogs in some sky areas that contain abundant information about galaxy properties (e.g., redshift, multiwavelength photometry, M_* , and SFR) have been published. For instance, Galametz et al. (2013) presented an ultraviolet (UV) to mid-IR (MIR) catalog in the UKIRT Infrared Deep Sky Survey (UKIDSS) Ultra-Deep Survey field, which contains 35 932 *HST*/F160W-selected sources in a sky area of 201.7 arcmin² and provides their SEDs. Mendel et al. (2014) provided a catalog of bulge, disk, and total stellar-mass estimates for SDSS DR7 that consists of almost 660000 galaxies. They argued that, various SED modeling assumptions may result in an additional 60% systematic uncertainty in mass estimation. Skelton et al. (2014) released a photometric catalog consisting of more than 200000 sources in five fields, which also includes stellar masses derived from the FAST code (Kriek et al. 2009). More recently, Santini et al. (2015) combined the efforts of ten different teams, who derived galaxy properties using the same photometry and redshifts with several different codes for the GOODS-S and UDS fields. They found that the stellar-mass estimates were greatly affected by the choice of the stellar isochrone library. Chang et al. (2015) combined the SDSS and WISE photometry for the full SDSS spectroscopic galaxy sample to create SEDs for a large and comprehensive catalog of 858 365 sources. They obtained the best-fit results using the MAGPHYS code (da Cunha et al. 2008).

In this paper, we compile multi-wavelength data from UV to IR in the Hawaii-Hubble Deep Field-North (H-HDF-N; Capak et al. 2004; Yang et al. 2014), which is a 0.4 deg² area centering around the GOODS-N (Giavalisco et al. 2004) and *Chandra* Deep Field-North (CDF-N; Alexander et al. 2003; Xue et al. 2016; Xue 2017) fields. After careful cross-matching between several catalogs that contain high-quality photometry and taking advantage of the SED-fitting technique, we produce a source property catalog that includes 145 635 galaxies, which is the largest of its kind in this field. After performing various robustness checks, we find that our stellar-mass and SFR estimates are reliable. We release our catalog publicly in order to facilitate future relevant studies.

This paper is structured as follows. Section 2 lists the data cube and the pre-process before the SED fitting procedure. Section 3 describes the fitting parameters and their space. Comparisons between our results and others as well as robustness checks are shown in Section 4. In Section 5 we discuss the factors that can affect our results. The final catalog is presented in Section 6. Finally, a brief summary of this work is included in Section 7. Throughout this paper, all magnitudes are quoted in the AB system, and we assume a cosmology with $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.27$, and $\Omega_{\Lambda} = 0.73$.

2 DATA COLLECTION AND COMPILATION

2.1 Base Source Catalogs and Cross-matching Results

We choose three catalogs as our base source catalogs: the photometric-redshift catalog in the H-HDF-N (Yang et al. 2014; hereafter Y14) that extracted point-spread function (PSF)-matched photometry in 15 bands and derived photometric redshifts using the EAzY code (Brammer et al. 2008); the CANDELS/3D-HST catalog in the GOODS-N field (Skelton et al. 2014; hereafter S14) that presented photometric redshifts determined using the EAzY code and also galaxy properties derived from the FAST code; and the ultra-deep Ks-band catalog in the GOODS-N field (Wang et al. 2010). The details of each base catalog are summarized in Table 1.

Aiming to create the most complete combined source catalog, we cross-match three base catalogs one by one in the order mentioned above to reach a maximum source number. We adopt 0.5'' as the matching radius. To account for the small non-uniformity in the astrometry between different catalogs, we match each catalog twice so as to increase the matching accuracy. For the first matching, we calculate the mean positional deviation between two individual catalogs, and correct the derived mean deviation (i.e., mean differences in RA and Dec between the matched sources) to each source of one catalog. We then perform the second matching using the updated astrometry. During each concatenation of the three base catalogs, only the coordinates of the unmatched sources of the second catalog will be appended to the coordinate list of the first catalog. By this means we obtain a combined source catalog that is composed of 178 341 sources, i.e., 131 678+ $(38\,279 - 17\,014) + (94\,951 - 69\,553) = 178\,341$ (see Table 1). While matching the remaining multi-wavelength catalogs and redshift catalogs to this combined source catalog, again, using a matching radius of 0.5'' (see Sect. 2.2), the unmatched parts are discarded, i.e., the source number of 178 341 remains unchanged for this operation.

In each matching step, we shift one catalog in eight directions (i.e., four axial directions in terms of right ascension and declination and four diagonal directions) with a 30" displacement and then re-correlate the sources in order to estimate the false-match rate (i.e., the mean matched source number divided by the original non-shifted matched source number). After the first-step astrometry correction, the false-match rate drops and the matched fraction rises in the second step. The final average false-match rates are in the range of 3.1% to 5.6%, with a typical value around 5% (see Table 1 for example). The lowest rate occurs when matching the spectroscopic-redshift catalog of Wirth et al. (2004) to the combined source catalog, due to the limited number of sources in Wirth et al. (2004); while the largest rate results from matching the S14 base catalog to the Y14 base catalog, due to the great depth (hence large source surface density) of the S14 catalog. Overall, these falsematch rates are small and will not significantly influence our results.

2.2 Redshift Information and Broadband SED Construction

The next step is to collect source-type and redshift information for the 178341 sources in the combined sample. We compile spectroscopic and photometric type classifications from a number of references and their relevant information is listed in Table 2. We determine the type of one source according to the following selection order of preference: spectroscopic type >S14 photometric type >Y14 photometric type. For X-ray-detected sources, we adopt the final classifications presented in Xue et al. (2016) CDF-N main and supplementary catalogs. A total of 152961 sources out of the 178341 sources have type information; the remaining sources have no such information in their respective original catalogs.

We follow a preference order of spectroscopic redshift >S14 photometric redshift >Y14 photometric redshift when choosing the redshift for each source. We use the 10552 sources that are classified as galaxies and have photometric redshifts from both S14 and Y14 to evaluate the consistency between redshift estimates. Overall, the two sets of photometric redshifts are in reasonable agreement, with the normalized median absolute deviation $\sigma_{\rm NMAD} = 0.058$ and an outlier (defined as $|\Delta z|/(1 + z_{\rm Y14}) > 0.15$ where $\Delta z = z_{\rm Y14} - z_{\rm S14}$) fraction of 13.3%. The difference between the photometric-redshift estimates may be due to the differences in the adopted galaxy templates, photometry, and other fitting details.

Since we focus on deriving galaxy properties, for sources that have been classified as stars, their redshifts are fixed to 0 and not included for further SED fitting. In some references, a fraction of sources are not explicitly classified as stars or galaxies. For example, a total of 24961 sources adopted from S14 are too faint to be classified with confidence. They are labeled as type undistinguished (see Table 2), and are retained in our SED fitting routine as long as they have non-zero redshifts, i.e., we treat them as galaxies.

After these procedures, we obtain the final galaxy sample of 145 635 galaxies (or treated as galaxies) that have redshift information available (98% being photometric redshifts) out of the 178 341 sources from the original sample. The redshift information is listed in Table 3. The redshift distribution of the final galaxy sample is shown in the left panel of Figure 1. Our sample covers a broad redshift span ranging from $z \sim 0$ to $z \sim 5$. It also contains a significant population at $z \sim 2$, which is well known as the peak epoch of star-formation activity. Therefore, our sample is

Base catalog	Area (deg^2)	Source number	Matching radius	False-match rate	Matched sources
Y14	0.40	131 678			
S14	0.05	38 279	0.5''	5.6%	17014
Wang et al. (2010)	0.25	94 951	0.5''	3.4%	69 553
Combined catalog	_	178 341	_		

 Table 1
 Base Catalogs and Cross-matching Results

Table 2 Source-type Information

Index	Reference	Matched Number	Star	Galaxy	Undistinguished	White Dwarf	No Info	X-ray AGN
		Spectroscopic			Catalog			
1	Barger et al. (2008)	2606	192	2414	0	0	0	0
2	Wirth et al. (2004)	2606	10	2596	0	0	0	0
3	Cowie et al. (2004)	66	10	56	0	0	0	0
4	Cooper et al. (2011)	81	2	79	0	0	0	0
5	S14	82	0	0	0	0	82	0
6	Y14	126	0	0	0	0	126	0
	Subtotal:	5567	214	5145	0	0	208	0
		Photometric			Catalog			
7	S14	32754	138	7655	24 961 ^a	0	0	0
8	Y14	113 944	4310	109 602	0	24	0	8
	Subtotal:	146 698	4448	117 257	24961	24	0	8
		X-ray			Catalog			
9	Xue et al. $(2016)^{b}$	627	16	75	0	0	0	536
10	Xue et al. $(2016)^{b}$	69	0	37	0	0	0	32
	Subtotal:	696	16	112	0	0	0	568
	Total:	152 961 ^c	4678	122 514	24961	24	208	576

Notes: ^a These sources in S14 are too faint to be classified with confidence and thus are assigned a specific type of "Undistinguished" (labeled as type=2 in our final catalog; see Sect. 6), which we retain for SED fitting once they have non-zero redshifts; ^b Type classifications are provided by the Xue et al. (2016) CDF-N main and supplementary catalogs, respectively; ^c This number is smaller than 178 341, due to the fact that some catalogs do not provide type classifications.

ideal for investigating stellar-mass assembly and the evolution of galaxies.

After the final galaxy sample is secured, we start to construct the broadband SED ranging from UV to IR (i.e., $\lambda \leq 8 \ \mu m$ in this work) for each source. We list the information of the photometric bands we adopt in Table 4. More details are available from table 1 of Y14, table 4 of Wang et al. (2010), tables 2–6 of Ashby et al. (2013), and table 6 of S14 (we exclude IRAC1, IRAC2, Subaru *B*, *V*, *z'*, *i'* and *r'* filters according to the known issues listed in the 3D-HST website). All the photometric data used in SED fitting, where necessary, are corrected to be the total fluxes for aperture effect. In addition, for sources with only flux errors provided in the original references (which means no detection), the flux errors are treated as 1σ upper limits on fluxes (i.e., error±error).

Most of our multi-wavelength data are from Y14, which provides PSF-matched photometry from a number of optical-to-IR images. For one band that has two photometric data points available given by different references, we make the following arrangements for photometry: (a) If one of the two origins is a PSF-matched catalog, we assign this photometry a higher priority with the other being supplementary. During supplementation, we select a neighboring band as the reference band. Only the supplementary photometry that lies within 1 dex (in terms of flux level) of the reference band is retained. (b) If the two sets of photometry are both from PSF-matched catalogs or aperturecorrected catalogs, we perform a consistency check: if the absolute flux difference is smaller than the sum of two flux errors, the mean value is adopted; otherwise, we keep the one whose flux is closer to the reference band. (c) When

Index	Reference	Matched Number	Galaxy	Undistinguished	No Info	X-ray AGN
		Spectroscopic	Catalog			
1	Barger et al. (2008)	2414	2414	0	0	0
2	Wirth et al. (2004)	141	141	0	0	0
3	Cowie et al. (2004)	56	56	0	0	0
4	Cooper et al. (2011)	79	79	0	0	0
5	S14	79	0	0	79	0
6	Y14	118	0	0	118	0
	Subtotal:	2887	2690	0	197	0
		Photometric	Catalog			
7	S14	32 458	7552	24 906	0	0
8	Y14	109 610	109 602	0	0	8
	Subtotal:	142 068	117 154	24 906	0	8
		X-ray	Catalog			
9	Xue et al. $(2016)^{b}$	611	75	0	0	536
10	Xue et al. $(2016)^{b}$	69	37	0	0	32
	Subtotal:	680	112	0	0	568
	Total:	145 635	119956	24 906	197	576

 Table 3 Redshift Information^a

Notes: ^{*a*} Stars and sources without redshift information are not included for SED fitting. ^{*b*} Redshifts are provided by the Xue et al. (2016) CDF-N main and supplementary catalogs, respectively.

one certain band has more than two origins, we select one or two as the highest priority according to the reliability of their photometry, and then follow the aforementioned procedures.

3 SED FITTING PARAMETERS

To obtain crucial galaxy properties of our sample, we carry out multi-wavelength SED fitting using the PCIGALE code to fit the broadband SED as constructed in Section 2.2. PCIGALE is a python version of CIGALE (Code Investigating GALaxy Evolution)¹ whose algorithm was first written by Burgarella et al. (2005) and further developed by Noll et al. (2009). Based on Bayesian analysis, CIGALE can reliably derive a variety of galaxy parameters, such as M_* , stellar age, SFR, and dust attenuation, which are vital to understanding the formation and evolution of galaxies.

In order to fit the observed SEDs, first we have to build a template library that contains various galaxy SEDs with different parameters. The galaxy SEDs are generated from the combination of several modules, such as the stellar population model (Bruzual & Charlot 2003, hereafter BC03), the dust attenuation curve (Calzetti et al. 2000), the IR emission by dust that originates from UV/optical photons being absorbed and re-radiated in longer wavelengths (Draine & Li 2007; Dale et al. 2014), as well as AGN radiation (Fritz et al. 2006). These modules are all incorporated into CIGALE and are convenient for us to invoke. Below we describe the modules used in the fitting routine and the adopted parameter space.

Star-formation history (SFH) is one of the most important components that determine galaxy growth history and has a significant impact on the derived galaxy properties. In a real galaxy the SFH can be very complicated and difficult to depict. In attempts to reproduce the real SFH using simple functions, several scenarios have been proposed. For example, the exponentially declining model assumes that the SFR decreases exponentially with a characteristic timescale τ (i.e., the 1τ -dec model); the 2τ -dec model adds a late starburst to the 1τ -dec model; and the so-called delayed- τ model represents an earlier rising and then declining SFR evolution (e.g., $SFR(t) \propto t/\tau^2 \cdot \exp(-t/\tau)$; see Santini et al. 2015). We choose the delayed- τ model as our SFH since Ciesla et al. (2017) demonstrated that this SFH provides better estimates of galaxy properties compared with both observations and hydrodynamical simulations (see Sect. 5.2 for relevant discussions). Moreover, this model has fewer parameters, which effectively reduces degeneracy. We allow both τ and the oldest stellar age t to vary between 1 and 10000 Myr.

The BC03 simple stellar population (SSP) synthesis model is used to generate the emission from the stellar pop-

¹ See https://cigale.lam.fr/.

Band	Depth (mag)	PSF Size	Zero Point	Reference	Depth (mag)	Aperture	Reference
IT	(iiiag) 26.3	1.26//	31 360	V14	(iiiag)	1.5//	\$14
B	26.3	1.20	31.136	114 V14	20.4	1.5	514
$\frac{D}{V}$	20.5	1.15	24 707	114 V14			—
V D	25.8	1.50	34.707	114 V14			
	20.0	1.00	34.070	114 V14			
1	25.1	1.08	33.481	¥ 14	_	_	—
z Th	24.9	1.08''	33.946	¥ 14			—
Jo	24.5	1.11''	23.900	¥14			
J^{o}		—	_	_	25.0	1.0"	S14
H ,	22.9	1.32"	23.900	Y14	24.3	1.0"	S14
HK'	22.3	1.20"	30.132	Y14	_		—
Ks^b	23.7	1.08''	23.900	Y14	$0.18 \ \mu Jy^d$	5''	Wang et al. (2010)
Ks^b		_	—	_	24.7	1.0"	S14
$3.6 \ \mu m^c$	25.1/24.5	2.53"/2.40"	21.581/21.581	Y14	$0.11 \ \mu Jy^d$	4''-6''	Wang et al. (2010)
$4.5 \ \mu m^c$	24.6/24.2	2.53"/2.43"	21.581/21.581	Y14	$0.12 \ \mu Jy^d$	4''-6''	Wang et al. (2010)
5.8 µm	22.6	2.96"	21.581	Y14	$0.42 \ \mu Jy^d$	4''-6''	Wang et al. (2010)
					22.8	3.0"	S14
8.0 µm	22.7	3.24″	21.581	Y14	$0.42 \ \mu Jy^d$	4''-6''	Wang et al. (2010)
					22.7	3.0"	S14
F606W		_	_	_	27.4	0.7"	S14
F125W	_	_	_	_	26.7	0.7"	S14
F140W	_	_	_	_	25.9	0.7"	S14
F160W	_	_	_	_	26.1	0.7"	S14
F435W	_	_	_	_	27.1	0.7"	S14
F775W	_	_	_	_	26.9	0.7″	S14
F860LP	_	_	_	_	26.7	0.7"	S14
G				_	26.3	1.2"	S14
Rs					25.6	1.2"	S14

 Table 4 List of Multi-wavelength Data^a

Notes: ^{*a*} The left and right portions of this table are for the PSF-matched and aperture photometry, respectively. ^{*b*} These are two slightly different filters from two telescopes with the same name. ^{*c*} These two photometric bands in Y14 have two origins. ^{*d*} These depths (in units of μ Jy) from Wang et al. (2010) are median 1σ errors among sources detected at $\geq 3\sigma$, unlike other depths (in units of magnitude) quoted at 5σ .

ulation by assuming a Chabrier initial mass function (IMF; Chabrier 2003). In terms of metallicity, CIGALE code provides several options to choose from, ranging from 0.02 to 2.5 times solar metallicity.

The attenuation of the stellar emission due to absorption and scattering by dust grains is described by extinction curves. We utilize the widely used Calzetti attenuation law (Calzetti et al. 2000) with the color excess E(B-V) of the young population ranging from 0 to 1, while freezing the reduction factor for the color excess of the older population to a constant default value of 0.44.

Dust re-radiates the absorbed UV and optical photons predominantly at longer wavelengths. CIGALE provides four sets of dust emission templates (Dale & Helou 2002; Draine & Li 2007; Casey 2012; Dale et al. 2014). Given the time-consuming nature of the fitting procedure, we select the Dale et al. (2014) template set since it has fewer free parameters and models the AGN emission simultaneously. Considering the limited number of X-ray detected sources in our sample that are usually moderately luminous (see Xue et al. 2010, 2016), we assume a low to moderate AGN contribution to the total galaxy SED, i.e., the AGN fraction varies between 0.0 and 0.6 (see Sect. 5.3 for relevant discussions). The heating intensity slope, α , which describes the peak wavelength of the dust emission (see fig. 5 in Noll et al. 2009), is allowed to vary among 1.5, 2.0 and 2.5. The full parameter space we adopt for each module is summarized in Table 5. During the fitting, the CIGALE code itself discards unphysical solutions where galaxies are older than the age of the Universe at their respective redshifts.

4 SED FITTING RESULT AND RELIABILITY CHECK

Figure 2 presents an example of the best-fit SED given by CIGALE. The distributions of the derived stellar masses and SFRs are demonstrated in the middle and right panel of Figure 1, respectively. For simplicity, we set the SFRs and/or their errors as less than $0.1 M_{\odot} \text{ yr}^{-1}$ to

Module Parameter Value star-formation history τ 1-10000 Myr (9 steps)^a delayed- τ model 1-10 000 Myr (19 steps)^b age Chabrier (2003) simple stellar population initial mass function BC03 metallicity (solar) 0.02, 0.2, 0.4, 1, 2.5 1, 5, 10, 50, 100, 500, 1000 Myr separation age E(B-V) of young population 0-1.0 (in steps of 0.1) dust attenuation dust emission & AGN contribution AGN fraction 0.0-0.6 (in steps of 0.1) heating intensity α 1.5, 2, 2.5

Table 5 Parameter Space of the Delayed- τ Model

Notes: ^{*a*} The 9 values are 1, 5, 10, 50, 100, 500, 1000, 5000, and 10 000 Myr. ^{*b*} The 19 values are 1, 5, 10, 50, 100, 200, 400, 600, 800, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000 and 10 000 Myr.

0.1 M_{\odot} yr⁻¹. The striking spike that denotes this considerably small SFR value in the right panel appears ubiquitous in galaxy property catalogs based on SED fitting (see, e.g., results from ten groups in Santini et al. 2015).

In the remainder of this section, we check the reliability of our result and the consistency with previous works through various methods. Since the most concerning galaxy properties are stellar mass and SFR, we only consider these two parameters here, but also include the other parameters (i.e., stellar age, metallicity, and dust attenuation) in the final catalog (see Sect. 6). In order to make a meaningful and fair comparison, we require our sources for comparison to have data (including upper limits) on > 10filters (unless specified otherwise) in order to ensure a reasonable quality of SED fitting results. Furthermore, we require a redshift match between the common sources in the reference works (denoted as z_1) and our work (denoted as z_2), i.e., $|z_1 - z_2|/(1 + z_1) \le 0.05$. Note that this is a relatively loose requirement, especially at high redshifts; different redshift values adopted in various works can lead to inconsistent SED fitting results.

4.1 Stellar Mass Comparison

We first compare our stellar mass estimation with S14 as shown in the left panel of Figure 3. S14 adopted the 1τ -dec SFH, the BC03 stellar population synthesis model with a Chabrier (2003) IMF, and solar metallicity when deriving stellar mass using the FAST code. We note that, as S14 is one of the three base catalogs, our final catalog retains many photometry and redshift data from it. As a result, it is not surprising that stellar masses derived from our work are consistent with theirs. Among the 28 894 redshift-matched pairs, the median value of the logarithmic stellar-mass ratio between S14 and our work is -0.086 dex, and the median absolute deviation (MAD) is 0.148 dex (in subsequent comparisons, all ratios are quoted in the logarithmic scale and we omit the logarithmic term hereafter for brevity).

We then conduct another comparison with Xue et al. (2010, hereafter Xue10) which calculated stellar mass based on the tight correlations between rest-frame optical colors and mass-to-light ratios. The result is shown in the right panel of Figure 3. Given that the formula used in Xue10 (i.e., their equation 1) was adapted with a Kroupa (2001) IMF, we divide the stellar mass in Xue10 by a factor of 1.06 according to Equation (2) in Speagle et al. (2014, and references therein), in order to make their estimates adapt our adopted Chabrier (2003) IMF. We find a median stellar-mass ratio of -0.056 dex and MAD = 0.161 dex for the 1603 redshift-matched pairs.

According to the above comparisons, it is clear that our stellar-mass estimation is in good agreement with that of previous works (i.e., median offsets <0.1 dex), albeit with reasonably small scatters (i.e., MAD~0.15 dex) that arise from differences in the adopted photometry, redshifts and derivation details. Therefore, our SED fitting procedure is able to provide robust stellar-mass estimates.

4.2 SFR Comparison

We then check the consistency of SFR estimates with previous works. In the first place, we compare our work with Whitaker et al. (2014) (hereafter W14), which derived SFRs for S14 sources using empirical relations (see W14 for details), and with Xue10. The latter separated their sample into two groups: sources with *Spitzer* MIPS 24 µm detection and without (denoted as upper limits). For the MIPS detected sources, they calculated SFRs using the empirical relation between SFR and UV+IR luminosity (in units of solar luminosity) as described by the following



Fig. 1 Distributions of redshift, stellar mass (logarithmic scale), and SFR (logarithmic scale; values of <0.1 set to $0.1 M_{\odot} \text{ yr}^{-1}$) for the final galaxy sample of 145 635 sources. The first quartile, median and third quartile errors are 0.168, 0.235, 0.334 dex for stellar mass and 0.346, 0.420, 0.553 dex for SFR, respectively.



Best model for 78233 at z = 0.798. Reduced χ^2 =1.1

Fig. 2 Best-fit SED model for the source with id = 78233 as provided by CIGALE.

equation:

SFR
$$(M_{\odot} \,\mathrm{yr}^{-1}) = 9.8 \times 10^{-11} (L_{\rm UV}/L_{\odot} + L_{\rm IR}/L_{\odot}).$$
 (1)

The IR luminosity is extracted from the 24 μ m flux – L_{IR} correlation using the Chary & Elbaz (2001) templates, while the UV luminosity is calculated from the best-fit SED (see Sect. 3.3 of Xue10 for details). For the MIPS undetected sources, they presented upper limits on SFRs again using Equation (1) and also provided SED fitting derived SFRs in their full unpublished catalog.

The comparison result is shown in Figure 4. The cyan dots and yellow triangles represent sources with and without MIPS 24 μ m detection in Xue10, respectively. Clearly, for sources matched with W14 (top panels) and Xue10

with 24 μ m detection (bottom panels), there exists an over-density above/below the one-to-one line respectively, while for those without 24 μ m detection (i.e., upper limits), our SFR estimates are systematically larger than those in Xue10. The median ratio of the W14 SFR estimates to ours reaches ~ 0.3 dex (see explanations below). To increase the source number for comparison with Xue10, we then compare with the full unpublished catalog of Xue10 in the bottom-right panel of Figure 4. We also find deviations between Xue10 and our SFR estimates (e.g., a median offset of -0.201 dex and MAD = 0.332 dex for the 2895 matched pairs with MIPS detection). However, we note that the 24 μ m photometry used in Xue10 was extracted from an unpublished catalog, the majority of which has relatively



Fig. 3 (*Left*) Histogram of the logarithmic stellar-mass ratio between S14 and our work, with the median value (shown as the *dashed-dot line*), MAD, and number of matched pairs annotated. (*Right*) Same as for the left panel, but for the comparison between Xue10 and our work.



Fig. 4 (*Top*) SFR comparison with W14. We only show sources with better MIPS measurements and exclude SFRs of less than $0.1 M_{\odot} \text{ yr}^{-1}$ for the upper right panel. (*Bottom Left*) SFR comparison with the Xue10 published catalog. The *cyan dots* and *yellow triangles* denote sources with (1272 sources) and without (331 sources with upper limits on SFRs) MIPS 24 µm detection in Xue10, respectively. The *red dashed line* represents the 1-to-1 relation. (*Bottom Right*) Histograms of the logarithmic SFR ratio between the Xue10 full unpublished catalog and this work. We exclude sources with SFRs of less than 0.1 $M_{\odot} \text{ yr}^{-1}$. The *cyan* and *yellow* colors represent 2895 sources with, and 123 95 sources without, MIPS 24 µm detection in Xue10, respectively; and the latter (i.e., *yellow*) corresponds to SED fitting derived SFRs in Xue10. From this figure on, the *short* (*horizontal* and/or *vertical*) *segments* in the panel corners indicate the respective median errors (when available) on the measured parameters (SFR here) multiplied by 2.

low signal-to-noise ratios. Furthermore, the photometric data used in Xue10 and in our work are adopted from different catalogs and may have systematic differences. As mentioned in Y14, the more accurate PSF-matched photometry published in their work (and adopted by our work) has a 0.1 mag median offset and a 0.15 mag scatter compared with aperture-corrected photometry (as adopted in, e.g., Xue10). Therefore, the different photometric data and redshifts adopted in various works all have significant influences on SFR estimation. In addition, we notice that the derived SFRs can still be poorly constrained and highly uncertain even with the same photometry and redshifts. We compare the SFR estimates derived from ten groups in Santini et al. (2015), who utilized exactly the same data but different SED fitting parameters and codes, and find large scatters and deviations among the results of each group. Therefore, the SFR estimation is highly data and model dependent.

Aiming to investigate whether the disagreement in SFR estimation is partly due to the different calculation methods adopted in Xue10 and in our work, we also utilize Equation 1 (correcting for IMF difference) as in Xue10 to estimate SFRs and make another comparison. The $L_{\rm IR}$ is calculated by integrating the dust emission of the bestfit SED for each source in the rest-frame 8-1000 µm, while the $L_{\rm UV}$ is represented by 3.3 times the rest-frame 2800Å galaxy luminosity based on the best-fit SED (see sect. 3.3 of Xue10). The comparison is shown in Figure 5. The blue histograms are for the logarithmic ratios between Xue10 SFRs and our SFRs derived with CIGALE (denoted as SFR_{cigale}), while the green histograms are for those between Xue10 SFRs and our SFRs derived using Equation (1) (denoted as SFR_{lumin}). It is obvious that when we adopt the same formula as in Xue10 to calculate the SFR, the results vary significantly and appear more consistent with those from Xue10 in some aspects but not in others: for the 2873 sources with MIPS detection, the median offset changes from -0.203 to 0.199 dex, and MAD reduces from 0.329 to 0.279 dex; for the 12346 sources without MIPS detection, the median offset reduces from -0.794 to -0.319 dex, but MAD increases from 0.177 to 0.371 dex. This demonstrates that the SFR estimation is highly method-dependent.

As a sensible check, in Figure 6 we then directly compare our SFR_{cigale} and SFR_{lumin} estimates with those derived using the empirical star-forming main-sequence (MS) relation presented in Speagle et al. (2014). Speagle et al. (2014) compiled 25 studies on the MS from the literature to derive a robust functional form. We also plot a comparison in Figure 7 including 8918 sources both in our work and in W14, with SFR >0.1 M_{\odot} yr⁻¹, to consolidate our results.

The red filled contours of both panels in Figure 6 are obtained using our stellar-mass estimates in conjunction with the expected SFRs according to the Speagle et al. (2014) MS relation given our stellar-mass estimates, while the green open contours are for our stellar-mass and SFR_{cigale} (SFR_{lumin}) estimates in the left (right) panel. For Figure 7, the red filled contours are plotted using respective stellar mass estimates (ours in the left panel and those from S14 in the right panel) combined with their corresponding expected SFRs, while the blue open contours are made using mass and SFR estimates derived from SED fitting in our work (left) and from the S14 stellar mass plus

W14 SFR (right). Evidently, our SFR_{cigale}– $M_{\star,cigale}$ relation is in good agreement with the Speagle et al. (2014) MS relation (left panels of Figs. 6 and 7), and there is a systematic offset and an apparent misalignment between the SFR_{lumin}– M_{\star} , SFR_{W14}– M_{\star} relation and the Speagle et al. (2014) MS relation (right panels of Figs. 6 and 7). We argue that this misalignment results from the two different methods used in deriving the two parameters, i.e., calculation from empirical relation and SED fitting. While for the left panels, the two parameters are both derived from SED fitting and are thus self-consistent.

Therefore, our SFR estimates are reliable given that we rely on an optimal combination of the most up-to-date and accurate redshifts and PSF-matched photometry as well as appropriate parameter choices with the CIGALE code that is based on sophisticated Bayesian analysis, although it is challenging to obtain solid SFR estimates.

5 DISCUSSION

5.1 Influence of FIR Data

Since a portion of the stellar emission at UV/optical wavelengths is absorbed and re-radiated in the far-IR (FIR), the Herschel PACS and SPIRE instruments, which cover the observed-frame 100, 160, 250, 350 and 500 µm wavelengths, can provide vital constraints on the galaxy FIR SED. However, the vast majority of our sources do not have any Herschel detection/coverage, therefore the SFRs derived above do not utilize any Herschel data. To check the reliability of our SED fitting result without including Herschel data, we compare the predicted FIR fluxes from the best-fit SEDs with the observed Herschel fluxes. We cross-match with the GOODS-Herschel (Elbaz et al. 2011) and Herschel/PEP (Lutz et al. 2011) catalogs to generate a subsample that contains 2205 sources with at least one MIPS 24 µm or Herschel band detection, and compile their PACS and/or SPIRE fluxes. We then convolve the best-fit SEDs with the five PACS and SPIRE filter response curves to calculate the predicted fluxes and directly compare them with real detections. As shown in Figure 8, the logarithmic ratios between the predicted PACS 100 μm and 160 μm fluxes to the observed ones peak close to zero (with median offsets ≈ 0.1 dex), indicating that, statistically, our best-fit SEDs are able to reproduce the observed emission at wavelengths extending to 160 μ m, albeit with MAD \approx 0.3–0.4 dex. However, at 250, 350 and 500 µm, we systematically underestimate the fluxes by $\approx 0.2-0.5$ dex. We note that due to the low angular resolution in the SPIRE passbands (i.e., 18" at 250 µm, 25" at 350 µm, and 36" at 500 µm, respectively), the source confusion problem dramatically



Fig. 5 (*Left*) Histograms of the logarithmic SFR ratio between Xue10 and our work for the 2873 sources with MIPS detection in Xue10. The *blue (green)* color is for the comparison between Xue10 SFR and our SFR_{cigale} (SFR_{lumin}). (*Right*) Same as for the left panel, but for the 12 346 sources without MIPS detection in Xue10. In both panels, sources with Xue10 SFR/SFR_{cigale}/SFR_{lumin} <0.1 M_{\odot} yr⁻¹ are not included.



Fig. 6 (*Left*) Comparison for 92 161 sources between our SFR_{cigale}– $M_{\star,cigale}$ (green open contours) and the Speagle et al. (2014) MS relation (*red filled contours*). (*Right*) Same as for the left panel, but for our SFR_{lumin}– $M_{\star,cigale}$. In both panels, sources with SFR <0.1 M_{\odot} yr⁻¹ are not included.



Fig.7 (*Left*) Comparison for 8918 sources between our SFR_{cigale}– $M_{\star,cigale}$ (*blue open contours*) and the Speagle et al. (2014) MS relation (*red filled contours*). (*Right*) Same as for the left panel, but for the W14 SFR plus S14 mass. In both panels, sources with SFR < 0.1 M_{\odot} yr⁻¹ are not included.

limits the accuracy of the measured photometry (Shu et al. 2016). The SPIRE fluxes may be composed of contributions of several objects rather than an individual source, which can induce significant overestimation of the real fluxes. Therefore, the systematic difference between the predicted and observed fluxes at SPIRE wavelengths may be due to inaccurate photometry rather than any SED fitting issue, in contrast to the consistency of fluxes at PACS wavelengths.

So far, the longest wavelength we adopt in the SED fitting is the IRAC 8 µm, and only 58% of our sources possess real detections in this band. The SFRs may be poorly constrained due to the lack of MIR and FIR data. To further check the reliability of the derived galaxy parameters without longer wavelength data, we perform a simple test. Unlike before, this time we include the MIR and FIR data (i.e., $\gtrsim 24 \ \mu m$) in the fitting routine to obtain the bestfit SEDs. In the meantime, we carry out the SED fitting using the MIR and FIR data alone by minimizing the χ^2 values between other galaxy templates and the observed data. We then calculate the IR luminosities with these templates, and compare them to those calculated from SED fitting with and without MIR and FIR data respectively, in order to check whether the lack of longer wavelength data significantly biases our result.

We utilize two sets of other galaxy templates. Chary & Elbaz (2001, hereafter CE01) presented 105 MIR–FIR templates based on local galaxies. In addition, Kirkpatrick et al. (2012, hereafter K12) presented two sets of SED templates for z < 1 and z > 1 star-forming galaxies. They combined deep photometry and Spitzer spectroscopy for 151 IR luminous galaxies in the GOODS-N and E-CDF-S fields, in an attempt to decompose the star-forming activity and AGN contribution in the MIR band. These templates are ideal for our studies since a prominent fraction of our sources are high-redshift star-forming galaxies.

We then convolve the K12 and CE01 templates with the filter transmission curves and compare them with observed MIR and FIR data points to determine the best normalizations by minimizing the χ^2 . Then we make direct comparisons of the rest-frame 8-1000 µm IR luminosities with the values obtained through broadband SED fitting under the two circumstances (i.e., with and without MIR-FIR data). The results of fitting K12 and CE01 templates are shown in Figure 9 and Figure 10, respectively. The upper (lower) panels are the IR luminosity comparison between the cases of using the K12/CE01 templates with only the MIR and FIR data and performing broadband SED fitting without (with) MIR and FIR data. It seems that the two sets of IR luminosities are more tightly correlated (i.e., smaller MAD) when MIR-FIR data are involved, in contrast to the larger scatters when MIR-FIR data are not being used. We compare AGNs (see Sect. 5.3) with normal galaxies, and find that they share the same trend, i.e., with similar distributions, median and MAD values. This indicates that the inclusion of MIR and FIR data does affect the fitting accuracy (i.e., in terms of MAD values) but not the

median offsets, whichever the source is, a normal galaxy or an AGN.

Then we directly compare the results of the 2205 CIGALE derived stellar masses, SFRs, and IR luminosities (using K12 templates) with and without MIR–FIR data, as shown in Figure 11. The left panels show that the two sets of stellar-mass estimates are in excellent agreement with each other. This is expected because the absence of MIR and/or FIR data should not have a significant impact on the stellar-mass estimation since it is mainly constrained from the rest-frame optical colors that are well-covered by our broadband SEDs. In contrast, the SFR (i.e., the middle panels) and IR luminosity (i.e., the right panels) estimates under the two circumstances show larger scatters (yet no systematic offsets), which demonstrates again that MIR and FIR data do affect the accuracy of SFR estimation.

In conclusion, although our SED fitting can predict *Herschel* PACS fluxes even when no MIR/FIR data are included, it only works for monochromatic fluxes up to 160 μ m with large scatters. When it comes to IR luminosity and SFR estimates, the ratios between the results with and without MIR/FIR data show no apparent systematic offsets but large scatters, indicating that the accuracy of SFR estimation is highly (MIR/FIR) data-dependent.

5.2 Influence of SFH Models

Previous studies have shown that both the delayed- τ model adopted in this work and the widely-used 2τ -dec model can reproduce M_* and SFRs by fitting the mock galaxy SEDs (Ciesla et al. 2015, 2016). They also found that the 2τ -dec model may have better performance at recovering the input M_* and SFRs, although it has an issue in calculating the galaxy age since it significantly underestimates this parameter. As we discussed in Section 4.2, unlike stellarmass estimation, SFR estimates using the delayed- τ model are relatively less constrained and suffer large dispersion when compared with previous works. To test whether the 2τ -dec model can better constrain M_* and SFRs using real observed data, we change our SFH into the 2τ -dec model and re-fit the galaxy SEDs. The 2τ -dec model divides stars into old and young populations and is expressed by adding a late burst to the 1τ -dec SFH:

SFR(t) =
$$\begin{cases} e^{-t/\tau_1}, \ t < t_1 - t_2 \\ e^{-t/\tau_1} + k \times e^{-t/\tau_2}, \ t > t_1 - t_2 \end{cases}$$
 (2)

where τ_1 and τ_2 (t_1 and t_2) are the e-folding times (ages) of the old and young stellar populations, respectively, and k is the mass fraction of the late burst. The adopted parameter space for the 2τ -dec model is listed in Table 6. The results are directly compared with those obtained through the



Fig.8 Comparison between best-fit SED predicted fluxes with real detections at five *Herschel* passbands. The numbers of sources available for comparison are indicated in the legend.



Fig.9 (*Upper*) Comparison between IR luminosities integrated using our best-fit templates (without MIR/FIR data; denoted as "w/o IR" hereafter) and best-fit K12 templates for 2205 sources. The *red dashed line* represents the 1-to-1 relation. (*Lower*) Comparison between IR luminosities integrated using our best-fit templates (with MIR/FIR data; denoted as "w/ IR" hereafter) and best-fit K12 templates. The *orange* and *blue dots* represent AGNs and normal galaxies respectively in the left panels, while the *black histograms* in the right panels do not separate them.



Fig. 10 Same as for Fig. 9, but for comparison between using our best-fit templates (without and with MIR/FIR data) and best-fit CE01 templates.



Fig. 11 Comparisons of stellar mass (*Left*), SFR (*Middle*; sources with $< 0.1 M_{\odot} \text{ yr}^{-1}$ not included), and IR luminosity (*Right*) estimates between the cases of fitting with and without MIR–FIR data. The *orange* and *blue dots* represent AGNs and normal galaxies respectively in the top panels, while the *black histograms* in the bottom panels do not separate them.



Fig. 12 Comparisons between the S14 (*Top row*), Xue10 (*Middle row*), and our delayed- τ derived (*Bottom row*) stellar-mass estimates and those derived with the 2τ -dec SFH model, respectively.

delayed- τ model as well as the reference works. We note that here we do not take other SFH models such as constant SFH, linearly increasing SFH or truncated SFH into consideration, since the galaxy parameters derived using these models deviate severely from the 1τ -dec and delayed- τ models, as shown in Santini et al. (2015). The size of the template library under the 2τ -dec model is dramatically larger than that under the delayed- τ model due to its additional parameters. We only consider sources with better photometry (e.g., having data from = 25 filters for the comparison between the S14 and 2τ -dec results) and adopt simple parameter space (see Table 6)

in order to avoid memory crashes and to speed up the computation.

Figure 12 presents three sets of comparisons between the S14, Xue10, and our delayed- τ stellar-mass estimates and the 2τ -dec ones, respectively. It is clear that, for all these comparisons, the 2τ -dec stellar masses are systematically larger than the other estimates, with median offsets ranging from -0.146 to -0.345 dex and MAD $\approx 0.1-0.2$ dex. Figure 13 shows the comparison between our delayed- τ SFR estimates and the 2τ -dec ones, indicating that the 2τ -dec SFRs are systematically smaller than the delayed- τ SFRs, with a median offset of 0.167 dex and MAD = 0.210 dex. Given the above analysis, we favor the results derived from the delayed- τ SFH model.

5.3 Influence of AGN Contribution

During the fitting routine, we assign the AGN fraction in the Dale et al. (2014) model a series of values from 0.0 to 0.6 (see Table 5). In order to check whether the inclusion of AGN contribution makes a difference, we use the 576 X-ray AGNs (see Table 3) as a subsample and make comparisons of the fitting derived values with those derived without contribution (i.e., fixed at 0) from AGNs.

The result is shown in Figure 14. It is evident that stellar-mass estimates are roughly distributed along the 1to-1 line, in spite of an over-density occurring under the 1-to-1 line. This over-density is caused by the fact that taking AGN contribution into account results in a slightly redder stellar continuum emission for the galaxy component, which eventually leads to a best fit of an older stellar population and thus a higher stellar mass. In contrast, SFR estimates in the case of AGN contribution being considered are systematically smaller than those not considering AGN contribution, especially for those with large AGN contributions, due to a portion of the UV and IR emission being accounted for by AGNs. Therefore, we make sure that this parameter of AGN contribution does affect the final results. For the sources not detected in the 2 Ms CDF-N (Xue et al. 2016), we still invoke this varying parameter since some weak and/or highly obscured AGNs may be missed in the Chandra catalog. Even for these galaxies, it is still beneficial to decompose the contribution from AGN and star-forming activities in order to obtain more reliable estimates of galaxy properties.

6 FINAL CATALOG

We provide a final catalog of source properties and make it publicly available. For ease of use, in Table 7 we present our catalog that consists of a total of 36 columns for the 178 341 sources (for completeness, we also include stars and sources without redshift information), and describe their details below:

- Column (1) gives the source identity number (id) ranging from 1 to 178 341. Sources are sorted according to the order of their appearance in the three base catalogs (in the order of Y14, S14 and Wang et al. 2010).
- (2) Columns (2) and (3) give the right ascension (RA) and declination (Dec) in the J2000.0 frame (in units of degree), respectively. The positions adopted from S14 and Wang et al. (2010) are corrected by the mean deviations calculated in the first cross-match step as mentioned in Section 2 (i.e., RA_{S14} = RA_{S14,original} 0.147"; Dec_{S14} = Dec_{S14,original} 0.071"; RA_{Wang10} = RA_{Wang10,original} 0.207"; Dec_{Wang10} = Dec_{Wang10,original} 0.086").
- (3) Column (4) gives the preferred redshift value, Column (5) gives the type information, and Column (6) lists the corresponding reference index rz (see Table 2). The white dwarfs (24 sources; see Y14) and stars (4678 sources) are represented by -2 and -1, respectively. Galaxies (122514 sources) are labeled as 0 while X-ray AGNs (576 sources) are marked as 1. Sources that are too faint to be distinguished in S14 (24961 sources) are labeled as 2. The remaining sources do not have a type classification in the original catalogs. When no information is available, the type classification and reference are set to the default value -99.
- (4) Column (7) gives the number of filters (including upper limits) used in the SED fitting. The minimum, maximum, mean and median numbers of filters are 2, 25, 12.6 and 13, respectively. We caution that for sources with a small number of filters, care should be taken when using the fitting results.
- (5) Columns (8)–(11) give three flags extracted from Y14 and one flag extracted from S14, respectively. The Qz flag indicates photometric redshift quality where lower values represent higher quality. The S/N ratio flag gives the source-detection significance. Cr flag indicates whether the source is in the central H-HDF-N region. Column (11) is from S14 and indicates the quality of photometry (for more details, refer to sect. 3.8 in S14). These flags serve as selection criteria in addition to filter number (Col. (7)) and reduced χ² (Col. (12)) when using our fitting results.
- (6) Columns (12)–(36) give the SED fitting results for the 145 635 sources that are classified/treated as galaxies and have redshift information available (the remaining sources have all these columns set as "–"), includ-

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Module	Parameter	Value
Star-formation history $2 au$ -dec model	$ au_1$ of the old population $ au_2$ of the young population age (t_1) of the old population age (t_2) of the young population Burst fraction (k)	1, 10, 100, 1000, 10 000 Myr 1, 10, 100, 1000, 10 000 Myr 1000, 5000, 10 000 Myr 1, 10, 100, 1000 Myr 0.01, 0.05, 0.1
Dust attenuation	E(B-V) of young population	0–1 (in steps of 0.2)

Table 6 Parameter Space of the 2τ -dec Model

Table 7 Final Catalog

Index	Column	Unit	Meaning
1	id	_	sequence number
2	RAdeg	degree	right ascension in J2000 frame
3	DEdeg	degree	declination in J2000 frame
4	redshift	_	spectroscopic or photometric redshift
5	type	_	type information
6	ťΖ	—	reference of redshift
7	filter	—	number of filters (including upper limits)
8	Qz_Y14	_	redshift quality parameter extracted from Y14
9	S/N_Y14	_	S/N ratio extracted from Y14
10	cr_Y14	_	flag extracted from Y14
11	use_phot_S14	_	flag extracted from S14
12	red_chi2	—	reduced χ^2
13	mass	M_{\odot}	mass in logarithmic unit
14	mass_err	M_{\odot}	mass uncertainty in logarithmic unit
15	SFR	$M_{\odot}~{ m yr}^{-1}$	SFR in logarithmic unit
16	SFR_err	$M_{\odot}~{ m yr}^{-1}$	SFR uncertainty in logarithmic unit
17	au	Myr	characteristic timescale
18	τ_{err}	Myr	uncertainty of characteristic timescale
19	age	Myr	age of the oldest population
20	age_err	Myr	uncertainty of age of the oldest population
21	metallicity	—	metallicity
22	metallicity_err	_	uncertainty of metallicity
23	AV_old	mag	AV of old population
24	AV_old_err	mag	uncertainty of AV of old population
25	AV_young	mag	AV of young population
26	AV_young_err	mag	uncertainty of AV of young population
27	AGNfrac	—	AGN fraction defined in Dale et al. (2014)
28-36	U-Ks	mJy	flux density in best-fit SED

Notes: The full table contains 36 columns of information for 178 341 sources, which is available in the online journal (*http://www.raa-journal.org/docs/Supp/ms4250table7_finalcat.fits.zip*).

ing the reduced χ^2 , stellar mass and associated uncertainty (logarithmic scale; in units of M_{\odot}), SFR and associated uncertainty (logarithmic scale; in units of M_{\odot} yr⁻¹; any value of < 0.1 set to 0.1 M_{\odot} yr⁻¹), characteristic timescale τ (Myr) and associated uncertainty, age of the oldest population (Myr) and associated uncertainty, metallicity and associated uncertainty, attenuation $A_{\rm V}$ (mag) of old and young populations and their associated uncertainties, AGN fraction,

and 9-band flux densities derived from the best-fit SED (i.e., *U*, *B*, *V*, *R*, *I*, *z*, *J*, *H* and *Ks* band; mJy).

7 SUMMARY

In this work, we compile multi-wavelength photometry ranging from UV to IR and other valuable information such as redshift and type classification for a large sample of 17 341 sources in the H-HDF-N field (see Tables 1, 2 and 4). Taking into account the influences of MIR/FIR



Fig. 13 Comparison between our delayed- τ derived SFR estimates and those derived with the 2τ -dec SFH model. In the right panel, sources with either SFR $\leq 0.1 M_{\odot} \text{ yr}^{-1}$ are not included.



Fig. 14 Comparisons of stellar mass (*Left*) and SFR (*Right*) estimates between the cases of SED fitting with and without AGN contribution. The data points are color-coded according to their respective AGN fractions.

data, SFH models, and AGN contribution (see Sect. 5), we utilize the SED fitting code CIGALE that is based on Bayesian analysis to derive stellar masses, SFRs, and other properties for 145 635 sources among the full sample, which are classified/treated as galaxies and have red-shift information available (see Sect. 3 and Table 3).

Through various consistency and robustness checks (see Sect. 4.1), we find that our stellar-mass estimates are in excellent agreement (i.e., a median offset of <0.1 dex and MAD ≤ 0.17 dex) with those of previous works, which involved different photometry and were derived from SED fitting with the FAST code (S14) or based on the mass-to-light ratios (Xue10). Therefore we conclude that stellar mass is a parameter that can be robustly retrieved via broadband SED fitting.

In contrast, the estimation of SFR is more challenging. Unlike stellar-mass estimation, SFR estimation depends much more sensitively on the calculation method (see Sect. 4.2), the wavelength coverage of the photometric data (especially the *Herschel* FIR data; see Sect. 5.1), the assumed SFH (see Sect. 5.2), and the likely AGN contribution (see Sect. 5.3). Nevertheless, we manage to obtain reliable SFR estimates (see Sect. 4.2), as we adopt the most up-to-date and accurate redshifts and PSF-matched photometry (see Sect. 2) and make sensible parameter choices with the CIGALE code (see Sect. 3).

We make our catalog of galaxy properties (including, e.g., redshift, stellar mass, SFR, age, metallicity, dust attenuation; see Sect. 6 and Table 7) publicly available, which is the largest of its kind in the H-HDF-N. This catalog should be beneficial to many future studies that aim to improve our understanding of various questions regarding the formation and evolution of galaxies. Acknowledgements We thank the referee for useful comments that helped improve this paper. We acknowledge support from the 973 Program (2015CB857004), the National Natural Science Foundation of China (Grant Nos. 11890693, 11473026 and 11421303), and the CAS Frontier Science Key Research Program (QYZDJ-SSW-SLH006).

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