

Far-infrared *Herschel* SPIRE spectroscopy of lensed starbursts reveals physical conditions of ionised gas

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Submitted to MNRAS Main Journal, 2017 July ; Manuscript ID: MN-17-2572-MJ

ABSTRACT

The most intensively star-forming galaxies are extremely luminous at far-infrared (FIR) wavelengths, highly obscured at optical and ultraviolet wavelengths, and lie at $z \geq 1-3$. We present a programme of *Herschel* FIR spectroscopic observations with the SPIRE FTS and photometric observations with PACS, both on board *Herschel*, towards a sample of 45 gravitationally lensed, dusty starbursts across $z \sim 1-3.6$. In total, we detected 27 individual lines down to $3-\sigma$, including nine [C II] 158- μm lines with confirmed spectroscopic redshifts, five possible [C II] lines consistent with their far-infrared photometric redshifts, and in some individual sources a few [O III] 88- μm , [O III] 52- μm , [O I] 145- μm , [O I] 63- μm , [N II] 122- μm , and OH 119- μm (in absorption) lines. To derive the typical physical properties of the gas in the sample, we stack all spectra weighted by their intrinsic luminosity and by their 500- μm flux densities, with the spectra scaled to a common redshift. In the stacked spectra, we detect emission lines of [C II] 158- μm , [N II] 122- μm , [O III] 88- μm , [O III] 52- μm , [O I] 63- μm , and the absorption doublet of OH at 119- μm , at high fidelity. We find that the average electron densities traced by the [N II] and [O III] lines are higher than the average values in local star-forming galaxies and ULIRGs, using the same tracers. From the [N II]/[C II] and [O I]/[C II] ratios, we find that the [C II] emission is likely dominated by the photo-dominated regions (PDR), instead of by ionised gas or large-scale shocks.

Key words: galaxies: high-redshift — galaxies: active — galaxies: starburst — submillimetre: galaxies — infrared: galaxies —

1 INTRODUCTION

The mean star-formation rate (SFR) density in the Universe was much higher in the past, peaking around 10 billion years ago, at $z \approx 2$ (e.g. Hopkins & Beacom 2006; Madau & Dickinson 2014), at which time the SFR per unit co-moving volume peaked at levels

10–30 \times higher than the current rate. Most of the stars created at this time were located within low-mass ($M_* < 10^{10.5} M_\odot$) galaxies with moderate star-formation rates ($\text{SFR} \leq 100 M_\odot \text{ yr}^{-1}$) (e.g. Daddi et al. 2007; Hopkins et al. 2010; Sparre et al. 2015).

Surveys at far-infrared (FIR) and sub-millimetre (submm) wavelengths revealed a population of so-called submm galaxies

or dusty star-forming galaxies (SMGs or DSFGs, e.g. [Smail et al. 1997](#); [Eales et al. 2010](#)), mostly at $z = 1-3$ (e.g. [Chapman et al. 2005](#); [Simpson et al. 2014](#); [Danielson et al. 2017](#)), but with a smattering at $z > 4$ (e.g. [Ivison et al. 2016](#); [Asboth et al. 2016](#)), which can account for much of the submm background. These galaxies were forming stars at tremendous rates, $\geq 300 M_{\odot} \text{ yr}^{-1}$ (e.g. [Blain et al. 2002](#)) – intense star-formation events that are thought to have been powered primarily by major mergers (e.g. [Ivison et al. 2007](#); [Engel et al. 2010](#); [Ivison et al. 2011](#); [Oteo et al. 2016](#)), although some fraction are likely isolated, fragmenting gas disks (e.g. [Hodge et al. 2012](#)). The subsequent rapid period of physical evolution likely passes through a quasar stage into a compact passive galaxy, which grows via dry minor mergers into a massive elliptical galaxies at the present day (e.g. [Côté et al. 2007](#); [Naab et al. 2009](#)).

Determining the physical conditions of the ionised gas, powered directly by star formation, is one of the most important objectives that remain in our study of DSFGs. The interstellar medium (ISM) is central to many galaxy-wide physical processes, and is therefore critical to our understanding of the gas-star-black hole interplay and evolution of galaxies (e.g. [Kormendy & Ho 2013](#)). However, the large quantities of dust within these starbursts obscure the most common ISM tracers: rest-frame optical spectral lines from the recombination of hydrogen, and those from the most abundant metal species, C, N, O.

Atomic fine-structure forbidden transitions in the FIR, such as [C II] 158- μm , [N II] 122- μm , [O I] 63- μm and [O III] 88- μm are important coolants of the ISM, providing critical diagnostics of physical conditions across all redshifts (e.g. [Stacey et al. 1991](#); [Lord et al. 1996](#); [Herrera-Camus et al. 2016](#); [Zhao et al. 2016a](#); [Wardlow et al. 2017](#); [Herrera-Camus et al. 2018a,b](#)). Among these lines, [C II] 158- μm is probably the most important, and the best studied, since it is the brightest FIR line in most galaxies and often accounts for 0.1–1 per cent of the total FIR luminosity (e.g. [Stacey et al. 1991](#); [Díaz-Santos et al. 2013a](#)). However, neutral carbon (C) has an ionisation energy of 11.3 eV, meaning that it co-exists in both photo-dissociation regions (PDRs) and H II regions (e.g. [Stacey et al. 2010](#)). [C II] can be excited by three independent collisions excitation mechanisms, electrons, neutral hydrogen (H I), and molecular hydrogen (H₂). These mechanisms make the [C II] emission arising from nearly all ISM phases difficult to discriminate from each other.

The [N II] 205- μm transition provides complementary information on the origin of the [C II] 158- μm emission (e.g. [Oberst et al. 2006](#); [Walter et al. 2009b](#); [Stacey et al. 2010](#); [Decarli et al. 2014](#); [Pavesi et al. 2016](#)). The line ratio of [C II] 158- μm /[N II] 205- μm only depends on the abundances of N⁺ and C⁺ in the H II region, and the relative contributions of the neutral and ionised ISM phases, making the observed [C II]/[N II] line ratio an excellent probe of the fraction of [C II] from the ionised gas phase (e.g. [Oberst et al. 2011, 2006](#)).

Unfortunately these lines are typically unobservable from the ground at low redshifts due to poor atmospheric transmission. The Spectral and Photometric Imaging REceiver (SPIRE) ([Griffin et al. 2010](#)) instrument aboard the *Herschel Space Observatory* ([Pilbratt et al. 2010](#)) incorporated a Fourier Transform Spectrometer (FTS), covering many of the brightest FIR lines. However, with its 3.5-m aperture, the few $\times 10$ -mJy flux densities exhibited by [C II] 158- μm in typical high-redshift DSFGs were well below the capabilities of *Herschel*'s SPIRE FTS, requiring prohibitively long integration times.

An alternative solution, exploited since the earliest SCUBA observations ([Smail et al. 1997](#)), is to use the flux boost provided

by gravitational lensing due to foreground galaxies, or clusters of galaxies. Most occurrences grant a factor of a few increase in brightness, but the most strongly lensed systems enable very detailed study of the background object (e.g. [Fu et al. 2012](#); [Bussmann et al. 2012, 2013](#); [Messias et al. 2014](#); [Dye et al. 2015](#); [Spilker et al. 2016](#)), as epitomised by SMM J2135–0102 – the Cosmic Eyelash – serendipitously discovered in the neighbourhood of a massive cluster, and possessing a high average amplification (37.5 ± 4.5 , [Swinbank et al. 2010, 2011](#)). Such strongly lensed DSFGs are rare ($\sim 0.26 \text{ deg}^{-2}$ – [Bussmann et al. 2013](#)), necessitating surveys covering large areas in order to assemble a statistically significant sample. This population can be selected efficiently at FIR/submm wavelengths, where the number density of unlensed sources at high flux densities drops quickly (after removal of local spiral galaxies and blazars), with $S_{500\mu\text{m}} > 100$ -mJy sources being strongly lensed DSFGs ([Negrello et al. 2010](#); [Wardlow et al. 2013](#)), with just a smattering of hyperluminous IR galaxies ([Ivison et al. 2013](#); [Fu et al. 2013](#)). Such FIR surveys have recently been undertaken (e.g. [Eales et al. 2010](#); [Vieira et al. 2010](#); [Oliver et al. 2012](#)), using the *Herschel Space Observatory* and the South Pole Telescope ([Carlstrom et al. 2011](#)), which has resulted in hundreds to thousands of strongly lensed DSFGs candidates (e.g. [Negrello et al. 2017](#); [Mocanu et al. 2013](#); [González-Nuevo et al. 2012](#)). Many of them have been confirmed as such by follow-up observations (e.g. [Spilker et al. 2016](#); [Negrello et al. 2014](#)).

In this paper we present the results of a *Herschel* Open Time programme comprising FIR spectroscopic observations of 45 gravitationally-lensed DSFGs using the SPIRE FTS aboard *Herschel*. This paper is organised as follows. Section 2 provides an overview of the sample selection and the overall properties of the data. Section 3 details the observations and data reduction for *Herschel* SPIRE FTS spectroscopy and PACS photometry. Section 4 presents the observed spectra and fitted dust spectral energy distributions (SEDs). Section 6 presents the stacked spectra and associated analysis. We discuss caveats in statistical biases, stacking methods, absorption contaminations and abundances in Section 8. We summarise our results and draw conclusions in Section 9. Throughout, we adopt a standard Λ -CDM cosmology with $\Omega_{\text{m}} = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 SAMPLE

In Table 1 we present basic information for our sample of 45 DSFGs, observed in OT1_RIVISON_1 and OT2_RIVISON_2. The majority of the targets were selected from the *Herschel* Astrophysical Terahertz Large Area Survey (*H-ATLAS*; [Eales et al. 2010](#)) and *Herschel* Multi-Tiered Extragalactic Survey (*HerMES*; [Oliver et al. 2012](#)) Large Mode Survey (*HeLMS*). *Herschel* SPIRE 250-, 350- and 500- μm images were used to identify strongly lensed DSFG candidates, from which we selected those satisfying $S_{350} \gtrsim 200$ mJy, with no indication that they could be a blazar or a $z \lesssim 0.1$ spiral, and with a color cut attempting to remove the highest redshift objects such that the [C II] 158- μm line would remain within the FTS spectral range. The SPIRE images show point sources, or only show marginally resolved features. The sample was supplemented with several objects for which substantial ancillary data existed, including SMM J2135–0102. About half of the sources have been confirmed to be lensed targets from submm continuum observations (e.g. [Bussmann et al. 2013](#)).

IAU Name	Short Name	R.A.	Dec.	Redshift	Notes
HATLAS J090740.0–004200	SDP.9	09h07m40.032s	–00d41m59.64s	1.577	
HATLAS J091043.0–000322	SDP.11	09h10m43.056s	–00d03m22.68s	1.784	
HATLAS J090302.9–014127	SDP.17	09h03m03.024s	–01d41m27.24s	2.3050	
HATLAS J090311.6+003906	SDP.81	09h03m09.408s	+00d39m06.48s	3.0425	
HATLAS J091305.0–005343	SDP.130	09h13m05.112s	–00d53m43.44s	2.6256	
HATLAS J085358.9+015537	G09-v1.40	08h53m58.872s	+01d55m37.56s	2.0923	
HATLAS J083051.0+013224	G09-v1.97	08h30m51.168s	+01d32m24.36s	3.634	
HATLAS J084933.4+021443	G09-v1.124	08h49m33.336s	+02d14m44.52s	2.4101	
HATLAS J091840.8+023047	G09-v1.326	09h18m40.92s	+02d30m46.08s	2.5812	
HATLAS J114638.0–001132	G12-v2.30	11h46m37.992s	–00d11m31.92s	3.2588	
HATLAS J113526.3–014606	G12-v2.43	11h35m26.28s	–01d46m06.6s	3.1275	
HATLAS J115820.1–013753	G12-v2.257	11h58m20.04s	–01d37m51.6s	2.1909	
HATLAS J142935.3–002836	G15-v2.19	14h29m35.232s	–00d28m36.12s	1.026	
HATLAS J141351.9–000026	G15-v2.235	14h13m52.08s	–00d00m24.48s	2.4778	
HATLAS J134429.4+303036	NA.v1.56	13h44m29.52s	+30d30m34.2s	2.3010	
HATLAS J133649.9+291801	NA.v1.144	13h36m49.992s	+29d17m59.64s	2.2024	
HATLAS J132859.3+292317	NA.v1.177	13h28m59.256s	+29d23m26.16s	2.778	
HATLAS J132504.4+311537	NA.v1.186	13h25m04.512s	+31d15m36s	1.8358	
HATLAS J132427.0+284452	NB.v1.43	13h24m27.216s	+28d44m49.2s	1.676	
HATLAS J133008.4+245900	NB.v1.78	13h30m08.52s	+24d58m59.16s	3.1112	
HATLAS J125632.7+233625	NC.v1.143	12h56m32.544s	+23d36m27.72s	3.565	
<i>HATLAS J223829.0–304148</i>	<i>SA.v1.44</i>	<i>22h38m29.472s</i>	<i>–30d41m49.2s</i>	<i>1.33± 0.11*</i>	
<i>HATLAS J222536.3–295646</i>	<i>SA.v1.53</i>	<i>22h25m36.48s</i>	<i>–29d56m49.56s</i>	<i>1.64± 0.16*</i>	
<i>HATLAS J232531.4–302234</i>	<i>SB.v1.143</i>	<i>23h25m31.608s</i>	<i>–30d22m35.76s</i>	<i>2.67± 0.13*</i>	
<i>HATLAS J232623.0–342640</i>	<i>SB.v1.202</i>	<i>23h26m23.064s</i>	<i>–34d26m43.8s</i>	<i>2.17± 0.11*</i>	
<i>HATLAS J232419.8–323924</i>	<i>SC.v1.128</i>	<i>23h24m19.944s</i>	<i>–32d39m28.08s</i>	<i>2.51± 0.15*</i>	
<i>HATLAS J000912.6–300809</i>	<i>SD.v1.70</i>	<i>00h09m12.864s</i>	<i>–30d08m09.24s</i>	<i>1.19± 0.10*</i>	
<i>HATLAS J000722.3–352014</i>	<i>SD.v1.133</i>	<i>00h07m22.272s</i>	<i>–35d20m15s</i>	<i>1.38± 0.11*</i>	
<i>HATLAS J002625.1–341737</i>	<i>SD.v1.328</i>	<i>00h26m25.176s</i>	<i>–34d17m38.4s</i>	<i>2.70± 0.16*</i>	
<i>HATLAS J004736.0–272953</i>	<i>SE.v1.165</i>	<i>00h47m36.072s</i>	<i>–27d29m53.16s</i>	<i>2.03± 0.15*</i>	
<i>HATLAS J010250.7–311721</i>	<i>SF.v1.88</i>	<i>01h02m50.88s</i>	<i>–31d17m23.64s</i>	<i>1.57± 0.13*</i>	
<i>HATLAS J012407.3–281435</i>	<i>SF.v1.100</i>	<i>01h24m07.536s</i>	<i>–28d14m35.16s</i>	<i>2.00± 0.13*</i>	
<i>HATLAS J014834.7–303532</i>	<i>SG.v1.77</i>	<i>01h48m34.704s</i>	<i>–30d35m32.64s</i>	<i>1.53± 0.13*</i>	
HERMES J004714.1+032453	HeLMS08	00h47m14.136s	+03d24m55.44s	1.19 [†]	no FTS spectra
HERMES J001626.0+042613	HeLMS22	00h16m26.064s	+04d26m12.48s	2.5093 [†]	no FTS spectra
HERMES J005159.4+062240	HeLMS18	00h51m59.448s	+06d22m41.52s	2.392 [†]	no FTS spectra
HERMES J233255.5–031134	HeLMS2	23h32m55.584s	–03d11m36.24s	2.6899 [†]	
HERMES J234051.3–041937	HeLMS7	23h24m39.576s	–04d39m34.2s	2.473 [†]	
HERMES J004723.3+015749	HeLMS9	00h47m23.352s	+01d57m50.76s	1.441 [†]	no FTS spectra
HERMES J001615.8+032433	HeLMS13	00h16m15.864s	+03d24m36.72s	2.765 [†]	no FTS spectra
HERMES J233255.7–053424	HeLMS15	23h32m55.824s	–05d34m26.76s	2.4024 [†]	no FTS spectra
HERMES J234051.3–041937	HeLMS5	23h40m51.528s	–04d19m40.8s	3.50 [†]	no FTS spectra
1HerMES S250 J142823.9+352619	HBoötes03	14h28m24.072s	+35d26m19.32s	1.325	
1HerMES S250 J021830.5–053124	HXMM02	02h18m30.672s	–05d31m31.44s	3.39	
SMM J213511.6–010252	Eyelash	21h35m11.64s	–01d02m52.44s	2.32591	

Table 1. Summary of the Galaxy sample.

[†]: Spectroscopic redshifts adopted from [Nayyeri et al. \(2016\)](#). *: Redshift estimated from photometric data, using the SED of average ALESS galaxies as the template ([Ivison et al. 2016](#)). For galaxy without spec-z information we label their names with italic fonts. The order of the table is organised by different survey fields and then by the right ascensions of the galaxies.

3 OBSERVATIONS AND DATA REDUCTION

3.1 PACS observations and flux density measurements

The original *H*-ATLAS parallel PACS imaging data at 100 and 160 μm have noise levels of $\sim 25 - 50$ mJy (almost ten times higher than our new targeted observations; see [Ibar et al. 2010a](#); [Eales et al. 2010](#)). They were insufficiently deep to detect many of our sample, and the targets outside *H*-ATLAS had no coverage at these wavelengths. To complement the SPIRE photometric measurements across the flux-density peak of their SEDs and to provide stronger constraints on their rest-frame mid-infrared (MIR) emission, we obtained deep imaging observations at 100 and 160 μm with *Herschel* PACS.

For each galaxy we obtained two cross-linked mini-scans with PACS, recording data at 100 and 160 μm simultaneously. Each mini-scan covers an area of $\sim 10' \times 3'$, with two orientations of 70 and 110°, resulted to three minutes on-source and a total of 791 seconds observing time including overhead. On average, we reach 1- σ depths of ~ 3 and 7 mJy at 100 and 160 μm , respectively. Archival mini-scan imaging data covering SMM J2135–0102 was combined with our two scans to produce a deeper image, which is particularly useful as this field has a large number of FIR sources visible in the region around the target lensed galaxy. Information about the *Herschel* PACS observations is listed in Appendix A.

We adopted the *Herschel* Interactive Processing Environment (HIPE v12; [Ott 2010](#)) to process and combine the mini-scan data using the standard pipeline scripts. To remove the $1/f$ noise, a high-

Source	z	Amplification	$S_{70\mu\text{m}}$ mJy	$S_{100\mu\text{m}}$ mJy	$S_{160\mu\text{m}}$ mJy	$S_{250\mu\text{m}}$ mJy	$S_{350\mu\text{m}}$ mJy	$S_{500\mu\text{m}}$ / mJy	$S_{850\mu\text{m}}$ mJy	$S_{880\mu\text{m}}$ mJy
SDP.9	1.574	8.8 ± 2.2	–	307 ± 15	546 ± 20	478 ± 34	328 ± 24	171 ± 14	–	24.8 ± 3.3
SDP.11	1.786	10.9 ± 1.3	–	161 ± 10	363 ± 20	421 ± 30	371 ± 26	221 ± 17	52 ± 1	30.6 ± 2.4
SDP.17	2.305	4.9 ± 0.7	–	66 ± 7	244 ± 19	354 ± 25	339 ± 24	220 ± 17	–	54.7 ± 3.1
SDP.81	3.040	15.9 ± 0.7^a	< 9	–	58 ± 10	133 ± 11	186 ± 14	165 ± 14	108 ± 10	78.4 ± 8.2
SDP.130	2.6256	2.1 ± 0.3	< 9	–	66 ± 10	118 ± 9	137 ± 11	104 ± 9	67 ± 9	36.7 ± 3.9
G09-v1.40	2.093	15.3 ± 3.5	–	70 ± 4	280 ± 13	396 ± 28	368 ± 26	228 ± 17	–	61.4 ± 2.9
G09-v1.97	3.634	6.9 ± 0.6	–	53 ± 3	198 ± 10	249 ± 18	305 ± 22	269 ± 20	121 ± 8	85.5 ± 4.0
G09-v1.124	2.410	1.1 ± 0.1	16 ± 4	57 ± 4	169 ± 15	217 ± 16	249 ± 18	209 ± 16	62 ± 10	50.0 ± 3.5
G09-v1.326	2.5812	5.0 ± 1.0^b	–	41 ± 4	106 ± 10	126 ± 10	151 ± 12	128 ± 11	61 ± 9	18.8 ± 1.6
G12-v2.30	3.259	9.5 ± 0.6	30 ± 4	62 ± 4	235 ± 15	317 ± 23	358 ± 25	291 ± 21	142 ± 8	86.0 ± 4.9
G12-v2.43	3.127	17.0 ± 11.0^b	16 ± 3	81 ± 5	196 ± 11	279 ± 20	284 ± 21	205 ± 16	116 ± 9	48.6 ± 2.3
G12-v2.257	2.191	13.0 ± 7.0^b	15 ± 4	43 ± 5	143 ± 11	119 ± 9	124 ± 10	101 ± 9	40 ± 9	–
G15-v2.19	1.027	9.7 ± 0.7^c	316 ± 16	850 ± 10	1190 ± 53	802 ± 56	438 ± 31	200 ± 15	–	–
G15-v2.235	2.479	1.8 ± 0.3	–	48 ± 5	87 ± 6	189 ± 14	217 ± 16	176 ± 14	104 ± 11	33.3 ± 2.6
NA.v1.56	2.301	11.7 ± 0.9	14 ± 3	86 ± 4	308 ± 19	462 ± 33	466 ± 33	343 ± 25	142 ± 8	73.1 ± 2.4
NA.v1.144	2.202	4.4 ± 0.8	11 ± 3	47 ± 4	193 ± 10	294 ± 21	286 ± 21	194 ± 15	–	36.8 ± 2.9
NA.v1.177	2.778	–	–	40 ± 3	155 ± 14	268 ± 19	296 ± 21	249 ± 18	149 ± 11	50.1 ± 2.1
NA.v1.186	1.839	–	–	60 ± 6	163 ± 9	241 ± 18	227 ± 17	165 ± 13	39 ± 8	–
NB.v1.43	1.680	2.8 ± 0.4	–	52 ± 4	170 ± 24	342 ± 25	371 ± 27	251 ± 19	71 ± 10	30.2 ± 2.2
NB.v1.78	3.111	13.0 ± 1.5	40 ± 3	87 ± 4	212 ± 16	271 ± 20	278 ± 20	203 ± 16	108 ± 11	59.2 ± 4.3
NC.v1.143	3.565	11.3 ± 1.7	–	25 ± 3	97 ± 8	209 ± 16	289 ± 21	264 ± 20	160 ± 10	97.2 ± 6.5
SA.v1.44	$1.33 \pm 0.11^*$	–	–	93 ± 5	225 ± 14	252 ± 18	207 ± 15	100 ± 9	–	–
SA.v1.53	1.654^\ddagger	–	–	57 ± 3	163 ± 23	194 ± 16	200 ± 17	119 ± 14	–	–
SB.v1.143	2.42^\ddagger	–	–	35 ± 5	102 ± 15	176 ± 13	227 ± 17	176 ± 14	100 ± 9	–
SB.v1.202	2.055^\ddagger	–	–	42 ± 4	130 ± 17	154 ± 12	178 ± 13	123 ± 11	57 ± 11	–
SC.v1.128	2.574^\ddagger	–	–	35 ± 5	123 ± 13	213 ± 16	244 ± 18	169 ± 13	73 ± 10	–
SD.v1.70	$1.19 \pm 0.10^*$	–	–	156 ± 5	365 ± 23	353 ± 25	273 ± 20	156 ± 13	–	–
SD.v1.133	1.60^\ddagger	–	–	142 ± 5	267 ± 20	237 ± 17	193 ± 15	108 ± 10	–	–
SD.v1.328	$2.70 \pm 0.16^*$	–	–	< 10	70 ± 9	138 ± 11	186 ± 14	149 ± 12	92 ± 13	–
SE.v1.165	$2.03 \pm 0.15^*$	–	–	27 ± 3	108 ± 9	171 ± 13	197 ± 15	146 ± 12	–	–
SF.v1.88	$1.57 \pm 0.13^*$	–	–	73 ± 4	168 ± 9	268 ± 19	253 ± 19	168 ± 14	–	–
SF.v1.100	$2.00 \pm 0.13^*$	–	–	50 ± 4	135 ± 9	258 ± 19	271 ± 20	204 ± 16	94 ± 10	–
SG.v1.77	$1.53 \pm 0.13^*$	–	–	148 ± 9	344 ± 15	238 ± 18	220 ± 17	127 ± 13	–	–
HeLMS08	$1.52 \pm 0.11^*$	–	–	87 ± 10	227 ± 15	300 ± 22	246 ± 18	170 ± 15	–	–
HeLMS22	$2.46 \pm 0.18^*$	–	–	13 ± 3	65 ± 10	130 ± 15	180 ± 18	130 ± 15	–	–
HeLMS18	$2.07 \pm 0.13^*$	–	–	31 ± 3	91 ± 15	163 ± 13	202 ± 15	142 ± 12	–	–
HeLMS2	$2.41 \pm 0.19^*$	–	–	25 ± 4	146 ± 14	250 ± 18	324 ± 23	247 ± 19	–	–
HeLMS7	$1.97 \pm 0.14^*$	–	–	33 ± 4	129 ± 7	219 ± 16	227 ± 17	166 ± 13	–	–
HeLMS9	$1.18 \pm 0.11^*$	–	–	132 ± 4	340 ± 20	367 ± 25	293 ± 21	170 ± 14	–	–
HeLMS13	$2.05 \pm 0.16^*$	–	–	39 ± 3	168 ± 15	176 ± 13	210 ± 15	134 ± 11	–	–
HeLMS15	$2.66 \pm 0.17^*$	–	–	14 ± 3	44 ± 8	153 ± 12	186 ± 14	152 ± 13	–	–
HeLMS5	$2.73 \pm 0.21^*$	–	–	7 ± 3	68 ± 7	149 ± 12	197 ± 15	188 ± 15	–	–
HBoötes03	1.325	3.0 ± 1.5	–	104 ± 5	279 ± 16	323 ± 23	244 ± 18	140 ± 34	–	18.4 ± 2.5
HXMM02	3.395	4.4 ± 1.0	–	29 ± 3	93 ± 15	92 ± 10	122 ± 12	113 ± 11	–	66.0 ± 5.4
Eyelash	2.32591	37.5 ± 4.5^d	–	25 ± 3	147 ± 7	366 ± 55	429 ± 64	325 ± 49	115 ± 13	106.0 ± 12.0

Table 2. FIR continuum flux densities of the sample. 250, 350 and 500 μm data from *H-ATLAS* and *HerMES*, uncertainties include a 7% calibration uncertainty (Swinyard et al. 2010; Bendo et al. 2013). Most of the 70 μm fluxes are from Wardlow et al. (2017), except for SDP.81 and SDP.130, which are measured with our PACS observations. 100 and 160 μm uncertainties include 2.75% and 4.15% calibration uncertainties respectively, following the PACS Photometer - Point-Source Flux Calibration document. The 850 μm data are from the SCUBA2 observations (Bakx et al. 2018). The 880 μm data is from Busmann et al. (2013) and Swinyard et al. (2010). We notice that the SCUBA2 850 μm fluxes are higher than the SMA 880 μm fluxes, likely due to the interferometric filtering issue. Where not otherwise noted, amplification values are taken from (Busmann et al. 2013). We also notice that for HXMM02, the new ALMA flux density is 63.33 ± 0.58 (i.e., Busmann et al. 2015), consistent with the SMA value. *: Redshift estimate from photometric data, using the SED of Eyelash as the template. †: Redshift is estimated from both photometric data and a possible (low significance) spectral feature. ^a Dye et al. (2015) ^b Estimate from CO line luminosity and FWHM from Harris et al. (2012) ^c Messias et al. (2014) ^d Swinbank et al. (2011)

pass filter was applied, after masking visible sources (e.g. Popesso et al. 2012). Corrections were adopted to the measured flux densities to compensate for the losses due to this filter. We also applied a color correction to take into account the spectral index within the bandpass of the PACS spectrometer¹.

¹ <http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb>

To measure the flux density, we first removed all visible background sources, masking with 8-10'' diameter circles, then fitted the global background and subtracted it from the masked image. The global background level was on the order of 10^{-6} Jy pixel⁻¹, making a negligible contribution to the final flux density measurements. We performed aperture photometry to remove the local background. Most targets displayed compact 100- μm emission within an aperture 5-7'' in radius. Therefore, we adopted aperture

corrections according to the encircled energy fraction (EEF) curves in the *Herschel* PACS manual², assuming point-like sources. A few targets displayed extended 100- μm emission that was clearly resolved by the PACS beam. For these sources, we used an aperture of $\sim 25\text{--}30''$ (FWHM) to ensure all the emission was included. Around a third of the targets were resolved by PACS into two components in our 100- and 160- μm maps, with separations ranging from $5''$ to $15''$, too close to be resolved by SPIRE. For these, we first identify the peak of individual emitting structure by fitting 2-D Gaussian distribution and performed aperture photometry on the two components separately and summed their flux densities within the SPIRE beam size. Among the sample, around half have been confirmed as lensed galaxies in previous studies (e.g. [Bussmann et al. 2013, 2015](#)). A few targets had components which displayed different S_{100}/S_{160} or S_{70}/S_{100} colors, perhaps indicative that they are not two segments from the same background lensed galaxy, but rather different galaxies along the line of sight. In Appendix B, we show postage-stamp images of the PACS observations of all of our targets.

The calibration uncertainties for the 100- and 160- μm images were $\sim 3\%$ and $\sim 4\%$ ³, respectively. We tested different high-pass filters, photometric aperture radii and mask radii, finding that these choices in total contribute uncertainties of $\lesssim 10\%$. In the end, we combine all these into our final estimate of the flux uncertainty. Typical noise levels are $\sim 0.1 \text{ mJy pix}^{-1}$ and $\sim 0.15 \text{ mJy pix}^{-1}$ for the 100- and 160- μm images, which are around 20 – 30 times deeper than the PACS maps of the *H-ATLAS* survey ([Ibar et al. 2010b; Smith et al. 2017a](#)). For the common sources in [Wardlow et al. \(2017\)](#), we have re-measured fluxes at 100- and 160- μm , and found consistent results differing by $< 5\%$. Measured flux densities are shown in Table 2, along with their SPIRE 250-, 350- and 500- μm and Submillimeter Array (SMA) 880- μm flux density measurements, taken from [Bussmann et al. \(2013\)](#).

3.2 SPIRE FTS observations and data reduction

The SPIRE FTS instrument (i.e., [Griffin et al. 2010](#)) is comprised of two bolometer arrays (SSW and SLW), covering the wavelength ranges $\lambda_{\text{obs}} = 191\text{--}318$ and $295\text{--}671 \mu\text{m}$, which corresponds to [C II] redshift ranges of 0.2 to 1.0 and 0.85 to 3.2, respectively. The observations were performed in the high-resolution mode, in which each mirror scan takes 66.6 s, producing a maximum optical path difference of 12.56 cm, resulting a uniform spectral resolution of $\sim 1.2 \text{ GHz}$.

The profile of the SPIRE FTS beam varies with observing frequency in a complex manner ([Makiwa et al. 2013](#)). The effective angular resolution varies from $\sim 17''$ at the highest SSW frequency to a maximum of $\sim 42''$ at the lowest SLW frequency ([Swinyard et al. 2010; Makiwa et al. 2013](#)). The pointing accuracy was within $2''$ ([Pilbratt et al. 2010](#)). Our target sizes are mostly less than $2\text{--}3''$, as revealed by high-resolution submm and radio imaging (e.g. [Bussmann et al. 2013](#)), except for G09.124 which consists of multiple galaxies at $z = 2.4$ with separations of up to $10.5''$ (e.g. [Iverson et al. 2013](#)).

² <http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb>

³ According to the PACS Photometer - Point-Source Flux Calibration document 2011. http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/pacs_bolo_fluxcal_report_v1.pdf

We obtained spectra of 38 sources, including five repeat observations of SMMJ2135–0102 (see [George et al. 2014](#)). Each observation consisted of 100 repetitions (100 forward and 100 reverse scans of the SMEC mirror), corresponding to 13320 s of on-source integration time. The SLW detectors are separated by $51''$, and the SSW detectors by $33''$, sufficiently far to avoid sidelobe contamination by emission from the targets. The central detectors of the arrays were centred on the target in each case.

We reprocessed the data from each observing epoch using the *Herschel* data processing pipeline ([Fulton et al. 2010](#)) within HIPE ([Ott 2010](#)) v14.2. The version of the calibration data is SPIRE_CAL_14_3. Due to the weakness of the emission from the sample, in most galaxies we could not obtain a good detection of the continuum level using the pipeline (e.g. [Hopwood et al. 2014, 2015; Fulton et al. 2016](#)), so their SLW and SSW spectra could not be matched to each other. This likely generates systematic continuum offsets as a function of frequency (e.g. [Hopwood et al. 2015](#)), which adds uncertainties to the spectra. The continuum levels detected with SPIRE/FTS have a good agreement with the SPIRE photometry, in general ([Makiwa et al. 2016; Valtchanov et al. 2018](#)). For rare cases ($\lesssim 30\%$) where the baselines between SLW and SSW match each other, the continuum levels estimated from the FTS spectra at $\sim 250 \mu\text{m}$ are consistent with those measured from SPIRE photometric fluxes within $\sim 30\%$.

For SLW and SSW, especially at the high-frequency end of the SLW spectra, about half of the spectra show a high level of fringing at the band edges (at the levels of $\geq 0.5 \text{ Jy}$), in particular at the high frequency end of SLW spectra. Lower amplitude fringing is observed in all spectra. The fringing can be traced to resonant cavities that exist within the spectrometer (for example the air-gaps between the different band defining filters and/or field lenses) and their effect on continuum calibration. The imperfect subtraction of the warm background generated by the *Herschel* telescope has its root in the derived relative spectral response function (RSRF, e.g. *Herschel* workshop⁴ 2014, [Swinyard et al. 2014; Fulton et al. 2014](#)). These fringes represent correlated pink ($1/f$) noise, which is the dominant noise contribution to our spectra and to the overall shape of the continuum. Moreover, the ripples not only vary with time, which can be seen in the six separate scans of SMMJ2135–0102, but they also vary between adjacent scans of different targets. It is not possible to fit polynomial baselines to subtract these ripples.

We tried baseline subtraction to remove the fringes, by subtracting spectra obtained on dark sky on the same observational days (OD) or subtracting an average spectra from off-centre pixels. However, due to small differences in the thermal environment of the telescope, spectrometer fringes remain the dominant source of spectral noise. This is not only because the weak level of the continuum response is not well calibrated, for the science target, for the dark sky, and for the spectra observed with the off-centre pixels, but also because subtracting another spectrum – with a different continuum and telescope model calibration error – adds noise.

Fortunately, these fringes appear as relatively low spatial frequencies which do not seriously impede extraction of parameters from narrow spectral lines. Real line emission displays a relatively narrow width (FWHM) of $\sim 2\text{--}3 \text{ GHz}$, which is the convolution of a typical linewidth of $\sim 500 \text{ km s}^{-1}$ and the 1.2-GHz Sinc width at the lowest observing frequency, $\sim 500 \text{ GHz}$.

We therefore performed baseline fitting designed to subtract the low-frequency features of the spectra. To this end, we masked 2-

⁴ <https://nhscsci.ipac.caltech.edu/sc/index.php/Workshops/Fall2014Talks>

GHz frequency ranges (corresponding to $\sim 500 \text{ km s}^{-1}$ at $z = 2$ for [C II] 158- μm) around the few strong lines ([C II] 158- μm , [O III] 88- μm , and OH 119- μm), then we convolved the masked spectra with a Gaussian profile with 15-GHz FWHM in order to derive an overall local baseline profile which fits the fringes very well and does not contaminate the narrow line features. We then subtracted the baseline profiles from the original spectra to obtain the final spectra for each target. We tested this method by inserting artificial spectral signals into the raw data, subtracting the baseline, then fitting the signal, in order to determine whether we can recover the line flux. The tests demonstrated that a robust flux measurement can be recovered after the baseline subtraction. We present the detailed tested results in Appendix C and show the final spectra of our targets in Appendix D.

The default spectral response of *Herschel* FTS is a Sinc function with a uniform width of ~ 1.2 GHz. We present the raw spectra at the original spectral resolution. Measurements of the [C II] spectral line flux densities were made by fitting a Sinc+Gaussian function – considering the large line width of a typical high-redshift DSFG – (e.g. Frayer et al. 1998; Bothwell et al. 2013; Yang et al. 2017) – to each spectra, and a Gaussian function to the stacked spectra. Several FTS spectra from this dataset have been published previously (e.g. Valtchanov et al. 2011; George et al. 2013, 2014). Here, we include re-reductions of those data with the latest pipeline (HIPE v14.2). The line fluxes and uncertainties are shown in Table 3 and cut-out spectral regions around the [C II] 158- μm line are shown in Fig. 3.

3.3 APEX observations and data reduction

To check the [C II] flux and to resolve the line profiles of galaxies detected in our *Herschel* observations, we obtained ground-based observations of SDP.11 and NA.v1.186 with the 12-m Atacama Pathfinder EXperiment (APEX) telescope on the Chajnantor Plateau in Chile, in good (pwv < 0.6 mm) weather conditions. We conducted the observations during the science verification phase of the band-9 Swedish ESO PI receiver for APEX (i.e., SEPIA B9, Belitsky et al. 2018) during 2016 August and September. The project number is E-097.F-9808A-2016.

All observations were performed in a wobbler-switching mode. Beam throws were $2'$, offset in azimuth. The focus was determined using Mars. Pointing was corrected every 30 min using nearby carbon stars, resulting in a typical uncertainty of $2''$ (r.m.s.). Typical system temperatures were 600–1000 K. The Fast Fourier Transform Spectrometer backend provided a bandwidth of 4 GHz. The beamsize was $\sim 8''$ at 670 GHz. All data were reduced with the CLASS package in GILDAS⁵.

We first combine the spectral data of each sub-scan obtained in two different spectrometers, which have 2.5 GHz bandwidth each, and an overlap of 1 GHz. The data from two spectrometers can not be simply added since sometimes they have different continuum levels (even after the wobbler-switch). The source spectra are centralised in the overlapped region, so the spectrum obtained in each spectrometer only covers one side of the line-free channels (baseline). If the baseline is fitted (and subtracted) to the spectrum from each spectrometer individually, the slope of the order-1 polynomial baseline is little constrained.

To combine the data from the two spectrometer for each individual sub-scan, we fit the spectra in the overlapped frequency

range and combine the two spectra with a uniform weighting. We also removed ~ 50 MHz at both spectral edges, to avoid poor responses there. Then, we checked the line profiles of the CO transitions in the literature (see Oteo et al. 2017, for SDP.11) and establish the velocity range over which a linear baseline fit will be applied. For NA.v1.186, we set the velocity range to $\pm 400 \text{ km s}^{-1}$ for its emission. Linear baselines were subtracted after inspecting each individual combined spectrum. An automatic quality control is made to get rid of the spectra whose noise is much higher than the theoretical one (Zhang & et al. 2018, Details are described in the James Clerk Maxwell Telescope MALATANG survey⁶). Only $< 5\%$ of the data are thrown away for poor baseline qualities. We converted the antenna temperatures (T_{A}^*) to flux density using the telescope efficiency of $150 \pm 30 \text{ Jy K}^{-1}$, which was determined using Callisto and Mars during the science verification tests. The flux uncertainty is estimated to be $\sim 25\%$.

4 RESULTS AND ANALYSIS

4.1 *Herschel* photometry

Fig. 1 presents a color-color plot of the *Herschel* SPIRE flux densities of the sample. Following Amblard et al. (2010), we generate $> 2 \times 10^6$ SEDs of single-temperature modified blackbodies (MBB) and fill their colors as the background. The MBBs are generated with a flux density F_{ν} :

$$F_{\nu} = \varepsilon_{\nu} B_{\nu} \propto \frac{\nu^{3+\beta}}{\exp(\frac{h\nu}{kT_{\text{d}}}) - 1} \quad (1)$$

where ε_{ν} is the frequency-dependent emissivity, $\varepsilon_{\nu} \propto \nu^{\beta}$, T_{d} is the dust temperature and β is the dust emissivity index.

To generate these models, we randomly sample a uniform range of T_{d} from 15 to 60 K, of redshift from 0.1 to 7.0, of β from 1.0 to 2.5. We limit the plots with extreme color limits of $S_{500}/S_{350} > 3$ and $S_{250}/S_{350} > 3.5$. For computing the colors, we also randomly add an extra noise to each modeled data point with a Gaussian standard deviation of 10% of its flux. Then we bin the modeled data points with a hexagonal binning method and plot the average colors in a hexagonal box. The SPIRE colors of the sample are well within the limits defined by the models we have considered. We adopt the SED template of SMM J2135–0102, shift it to different redshifts and measure the ‘observed’ S_{500}/S_{350} and S_{250}/S_{350} colors. Then we plot the simulated colors as a dashed line, with their redshifts marked, to compare with the observed values. As displayed, the sample appears relatively similar to the track of SMM J2135–0102 in the observed frame, although the average colors of S_{250}/S_{350} and S_{350}/S_{500} are a little higher than those of SMM J2135–0102. This is expected due to the very high magnification factor experienced by SMM J2135–0102, which allows a less-extreme galaxy with a relatively lower SFR surface density, and therefore a likely lower dust temperature, to reach flux densities comparable to the others in our sample. The distribution and the trend also seem to be consistent with those shown by Yuan et al. (2015), who use different templates to model the SPIRE color-color plots in high-redshift DSFGs and show that higher T_{d} and/or smaller β could produce the observed colors. We also present two

⁵ <http://www.iram.fr/IRAMFR/GILDAS>

⁶ https://github.com/malatang-jcmt-survey/auto_qualification

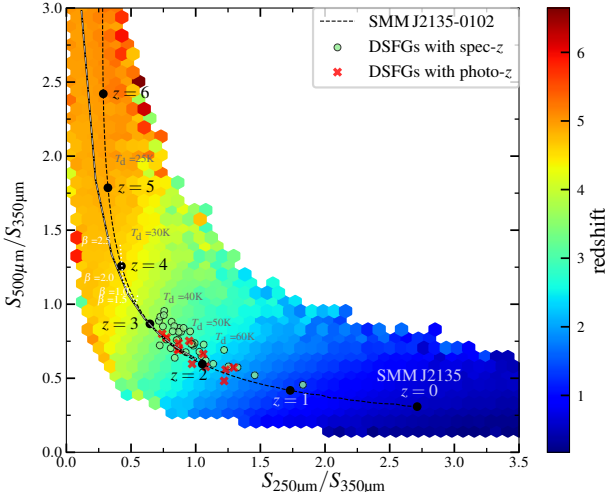


Figure 1. *Herschel* SPIRE flux density ratios for the sample. Sources with known redshifts are displayed as green circles, those without as red crosses. Underlaid are a dashed line displaying the expected flux density ratios of SMM J2135–0102 with changing redshift, determined from the SED presented in Ivison et al. (2010c), and shading displaying the predicted colors of 10^6 modified blackbody sources with a range of redshifts, dust temperatures, dust spectral emissivity indices and a flux density measurement uncertainty of 10%, based on Figure 1 of Amblard et al. (2010). White dotted line indicates the color track of various β at $T_d = 30$ K. Gray dash-dotted line indicates the color track of various T_d , with $\beta = 1.8$.

tracks to demonstrate the physical parameters that drive the spread of values in Fig. 1. The white dotted line presents the color track for $T_d = 30$ K, with β varying from 1.0 to 2.5. The gray dash-dotted line presents the track for $\beta = 1.8$, with T_d ranges from 20 K to 60 K. The degeneracy between T_d and β is clearly seen from the similarity of the two tracks, whilst the temperature seems to be more sensitive in shifts along the redshift axis.

Fig. 2 shows the spectroscopic redshift distribution of the sample. The redshift distribution of strongly-lensed DSFGs predicted by Negrello et al. (2007) has a higher mean value than observed in our sample. This is due partly to the different flux-density cuts employed, with our primarily $S_{350} > 200$ -mJy subsample of the lens candidates preferentially selecting lower redshift objects than the $S_{500} > 100$ mJy used by Negrello et al. (2007). This is compounded by the methods and instruments used to determine spectroscopic redshifts for our galaxy sample. Further details of specific galaxies are given in Appendix E.

Galaxies at $z > 3$ show higher flux densities than that scaled from Eyelash, indicating that the $z > 3$ galaxies in our sample are on average not only brighter after lensing but much more intrinsically luminous than SMM J2135–0102, which has the highest lensing amplification 37.5 ± 4.5 in the known sample.

4.2 Dust SED modeling

As a first step towards understanding the physical properties of these galaxies, we start by fitting their SEDs using broad-band continuum flux densities from our multi-wavelength imaging observations. The SEDs are constructed by combining our recently obtained PACS photometric data with the 250-, 350- and 500- μ m photometric measurements obtained with SPIRE, the 850- μ m flux densities measured with the Submillimetre Common-User Bolometer Array 2 onboard JCMT (Bakx et al. 2018; Holland et al. 2013),

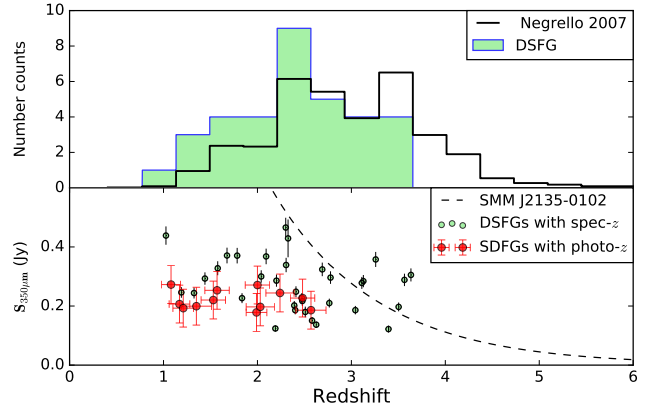


Figure 2. *Upper:* Redshift distribution of sources in the sample. The shaded histogram displays the number of sources within our sample in redshift bins of $\Delta z = 0.36$, and the area under the solid line displays the predicted redshift distribution of strongly lensed DSFGs with $\{S_{250}, S_{350}, S_{500}\} > 100$ mJy from Negrello et al. (2007), scaled to the same number of sources.

Lower: *Herschel* SPIRE 350- μ m flux densities as a function of the redshift distribution. Vertical lines show the uncertainties in flux density. Horizontal lines show uncertainties in photometric redshifts. The dashed line represents the 350- μ m flux density expected to be observed from a SMM J2135–0102-like galaxy at different redshifts.

the 880- μ m flux densities measured with SMA (Bussmann et al. 2013), the 1.2- and 2-mm data measured with the Institut de Radioastronomie Millimétrique’s NOrthern Extended Millimeter Array (NOEMA Yang et al. 2016) and the 1.4-GHz radio continuum data from the literature (Becker et al. 1995). We list the measured FIR flux densities at *Herschel* wavelengths in Table 2.

We first used a single-temperature MBB model to fit the observed dust SEDs. However, more than half of the sources could not be fitted adequately with a single MBB, indicating that either multiple excitation components are needed, or the assumption of a single-MBB dust emission does not hold. Also, the dust emission is assumed to be optically thin, which may not be valid for our extreme targets. The MBB fitting is also biased by the data in the Wien regime, meaning that the luminosities are systematically under-estimated. On the other hand, there are not enough data points at the longer wavelengths to fit two independent MBB models for most of the sources.

Instead, we estimate the dust properties with a power-law temperature distribution method introduced by Kovács et al. (2010). We model the FIR SEDs with dust emission following a thermally-motivated power-law distribution of dust masses, M_d , with temperature components T : $\frac{dM_d}{dT} \propto T^{-\gamma}$, and a low-temperature cutoff. This model does not assume optically thin dust emission everywhere and this simple prescription can reproduce both the Wien and Rayleigh-Jeans sides of the FIR peak. For consistency, all sources are modelled using this method, regardless of previous independent determinations of their SEDs.

For the SED modelling for the high-redshift DSFGs, we fit the black-body model and a power-law synchrotron emission component simultaneously. Thermal free-free emission is unlikely to contaminate strongly in our fitting wavelengths (e.g., Aravena et al. 2013), so we excluded it from the fitting. The power-law index, γ , of the dust is fixed to be 7.2, the best-fitting value found in lo-

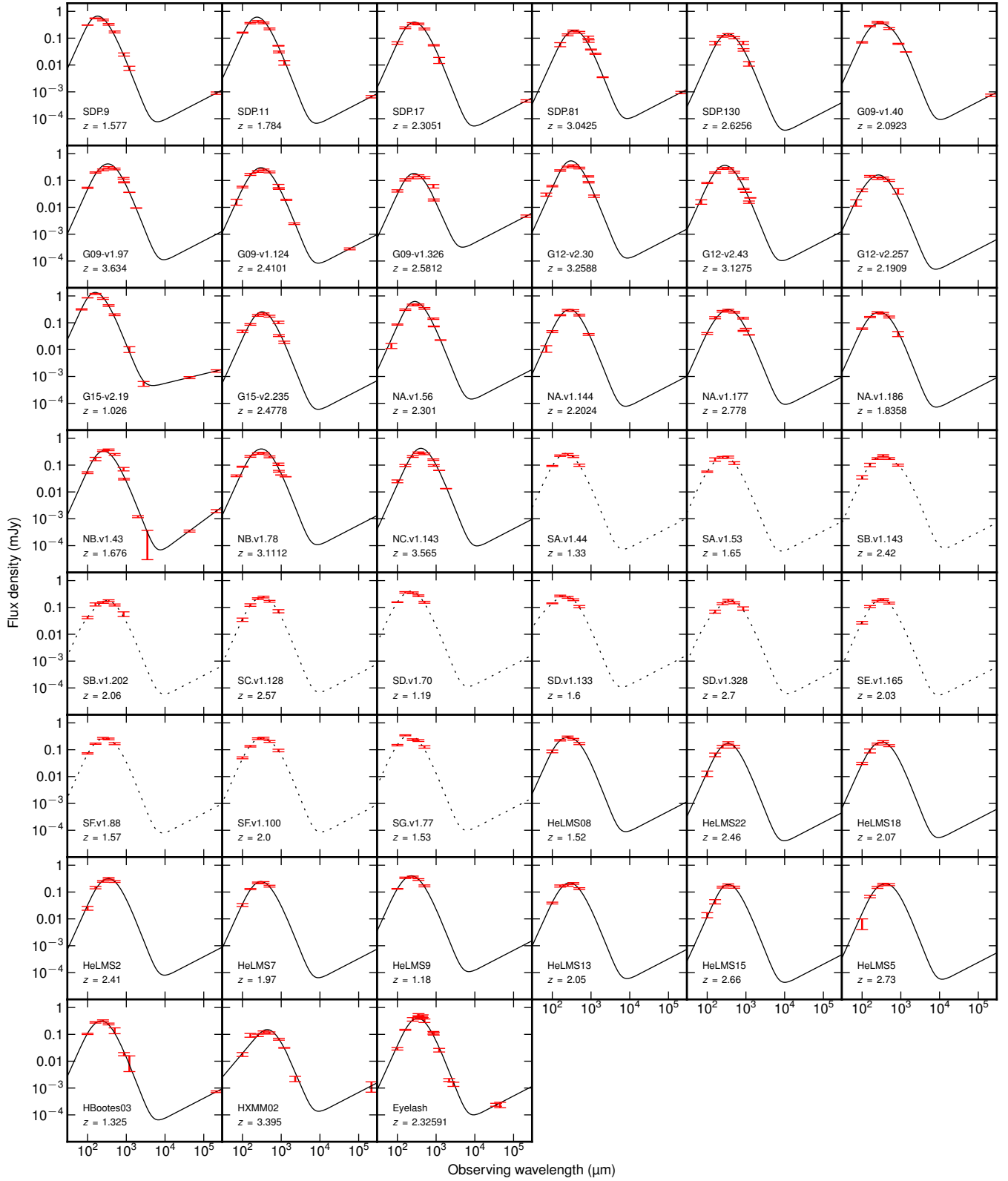


Figure 3. SED fits to available FIR–radio photometry for objects in the sample, using the power-law dust temperature distribution model of Kovács et al. (2010). Sources selected from the *H*-ATLAS SGP field do not have secure redshifts, and fits for these sources are performed assuming a best-fit photometric redshift and are shown as a dotted line.

Source	[C II] 158 μm $10^{-18} \text{ W m}^{-2}$	[N II] 122 μm $10^{-18} \text{ W m}^{-2}$	[N II] 205 μm $10^{-18} \text{ W m}^{-2}$	[O III] 88 μm $10^{-18} \text{ W m}^{-2}$	[O III] 52 μm $10^{-18} \text{ W m}^{-2}$	[O I] 63 μm $10^{-18} \text{ W m}^{-2}$	[O I] 145 μm $10^{-18} \text{ W m}^{-2}$	OH 119 μm $10^{-18} \text{ W m}^{-2}$
SDP.9	3.5±0.6	<2.8	<2.5	4.8±1.5	–	–	<1.5	<4.6
SDP.11	6.1±0.4	<1.5	<2.1	4.9±1.0	–	–	<1.4	–2.0±0.7
SDP.17	<2.1	<1.0	–	<2.88	–	<3.6	2.1±0.5	<1.4
SDP.81	2.9±0.6	<2.6	–	2.9±0.5	<3.7	2.1±0.7	<2.7	<2.3
SDP.130	<1.3	<2.6	–	<1.6	–	<3.9	<1.7	<1.4
G09-v1.40	2.5±0.9	<1.4	<2.1	<2.0	–	<6.7	<1.0	<1.3
G09-v1.97	–	<1.7	–	<1.1	3.5±0.6	<2.7	–	<2.2
G09-v1.124	3.0±1.0	<1.3	–	<3.0	–	2.1±0.7	<1.5	<1.1
G09-v1.326	<1.7	<1.2	–	<2.0	–	<4.3	<1.9	<0.8
G12-v2.30	–	<1.5	–	<1.1	<2.6	<2.3	<1.4	<1.7
G12-v2.43	<2.9	<2.1	–	<1.1	<4.3	<4.3	<2.8	<2.3
G12-v2.257	3.4±0.6	<1.1	–	<2.6	–	<4.0	<1.5	<1.1
G15-v2.19	7.9±1.0	<5.2	<1.8	–	–	–	<6.6	<8.0
G15-v2.235	<2.2	<1.5	–	<4.1	–	–	3.5±1.2	<1.4
NA.v1.56	<1.5	<0.7	–	2.3±0.6	–	<3.9	3.0±0.6	<0.9
NA.v1.144	<1.8	<1.2	–	<2.6	–	<3.1	<1.4	<1.4
NA.v1.177	<1.2	<0.8	–	<1.5	<5.1	<3.3	<1.5	<0.8
NA.v1.186	4.2±0.4	<1.7	<1.5	<2.0	–	–	<1.0	<1.7
NB.v1.43	8.8±0.5	<2.6	<2.6	<3.4	–	–	<1.2	<3.3
NB.v1.78	<2.5	<2.6	–	<1.6	<3.9	<3.1	<2.5	<2.2
NC.v1.143	–	<1.7	–	<1.3	<2.2	<1.7	–	<5.5
SA.v1.44	<2.0	<3.0	<1.8	<5.3	–	–	<2.0	<4.0
SA.v1.53	3.7±0.4	<2.8	<2.7	<5.1	–	–	<1.6	<2.8
SB.v1.143	3.9±1.0	<0.8	–	<4.4	–	<2.8	<1.6	<0.9
SB.v1.202	3.1±0.6	<1.0	<2.1	–	–	<9.2	<0.9	<0.8
SC.v1.128	1.5±0.5	<1.2	–	<3.2	–	<3.3	<2.5	<1.2
SD.v1.70	<2.5	<2.4	<1.8	<2.2	–	–	<0.9	<1.2
SD.v1.133	4.1±0.6	<2.7	<2.1	<4.6	–	–	<1.6	–3.4±1.1
SD.v1.328	<1.2	<1.6	–	<1.6	–	<2.7	<1.4	<1.3
SE.v1.165	–	<1.7	–	<1.1	<3.6	<2.0	<1.3	<1.3
SF.v1.88	<1.4	<1.4	<2.4	<3.1	–	–	<1.0	<1.3
SF.v1.100	<2.1	<0.9	–	<2.0	<5.1	<2.9	<2.0	<0.9
SG.v1.77	<1.3	<1.5	–	<2.1	–	<3.8	<1.5	<1.3
HeLMS2	<2.2	<0.6	–	<2.2	–	<2.3	<1.5	<0.9
HeLMS7	<1.3	<1.0	–	<2.3	–	<4.2	<1.8	<0.9
HBootes03	3.1±1.4	<4.0	<3.3	3.1±1.6	–	–	–	<3.8
HXMM02	–	<1.6	–	<0.7	–	<2.0	<2.6	<1.8
Eyelash	5.0±0.7	1.8±0.2	–	–	–	–	<1.5	–2.8±0.4

Table 3. Far-IR line fluxes of individual galaxies, measured by fitting Sinc-Gaussian profiles to each line. The uncertainties are from the propagation of the fitting error and from bootstrapping in the neighbouring $\pm 5000 \text{ km s}^{-1}$ velocity range around the targeted lines, to get the ‘local’ noise level.

cal starbursts (see Kovács et al. 2010); the dust spectral emissivity index, β , is fixed at 1.8, the true value of which likely varies inversely with temperature (Knapp et al. 1993; Mennella et al. 1998; Dunne et al. 2000); the characteristic photon cross-section to mass ratio of particles κ_0 is assumed to be $\kappa_{850\mu\text{m}} = 0.15 \text{ m}^2 \text{ kg}^{-1}$ (see Kovács et al. 2010); the conversion from L_{IR} to star formation rate follows Kennicutt & Evans (2012) with a Kroupa initial mass function (IMF) (Kroupa & Weidner 2003); the synchrotron spectral index, α , is fixed as -0.75 for objects with less than two photometric measurements at $\lambda_{\text{rest}} > 4 \text{ mm}$ (e.g. Ibar et al. 2010b).

Total infrared luminosities and dust masses are comparable to those estimated for these galaxies via other methods, such as MAGPHYS (Negrello et al. 2014), or a single grey-body component (Bussmann et al. 2013). However, the fitted SFRs are higher than those suggested by MAGPHYS, which is likely due to the different adopted calibrations. To compare the total IR luminosity ($S_{\text{IR}}^{8-1000\mu\text{m}}$) with the radio continuum observations, we also calculate q_{IR} , following Ivison et al. (2010a,b), as $q_{\text{IR}} = \log_{10}[(S_{\text{IR}}/3.75 \times 10^{12} \text{ W m}^{-2})/(S_{1.4\text{GHz}}/\text{W m}^{-2} \text{ Hz}^{-1})]$, where $S_{1.4\text{GHz}}$ is K -corrected assuming $S_\nu \propto \nu^\alpha$, again with

$\alpha = -0.75$. Finally, we list the derived properties, such as L_{IR} , SFR, M_{dust} and $T_{\text{d}}^{\text{cutoff}}$ in Table 4.

In Fig. 4 we plot correlations and distributions for a few of the parameters we have fitted. It is not surprising that the gravitational amplification factor, μ , is weakly anti-correlated with the intrinsic infrared luminosity, L_{IR} , after correcting the lensing magnification. This is because correspondingly higher μL_{IR} is required for higher-redshift sources to reach our $S_{350\mu\text{m}} > 200 \text{ mJy}$ flux-density threshold.

We find a tentative trend of decreasing q_{IR} with increasing redshift, indicating a potential variation of the IR-radio correlation with redshift. This is consistent with the decreasing trend found recently in the 3-GHz survey in the COSMOS field (Delhaize et al. 2017). However our results indicate much shallower slope index, whose significance is very limited by the current sample size.

The total infrared luminosity L_{IR} shows an good increasing correlation with fitted dust mass, M_{d} , over two orders of magnitude, which is also expected since all targets in the sample show similar dust temperatures and far-IR colors. The correlation shown in the targets with lensing correction seems consistent with that shown in targets without lensing corrections.

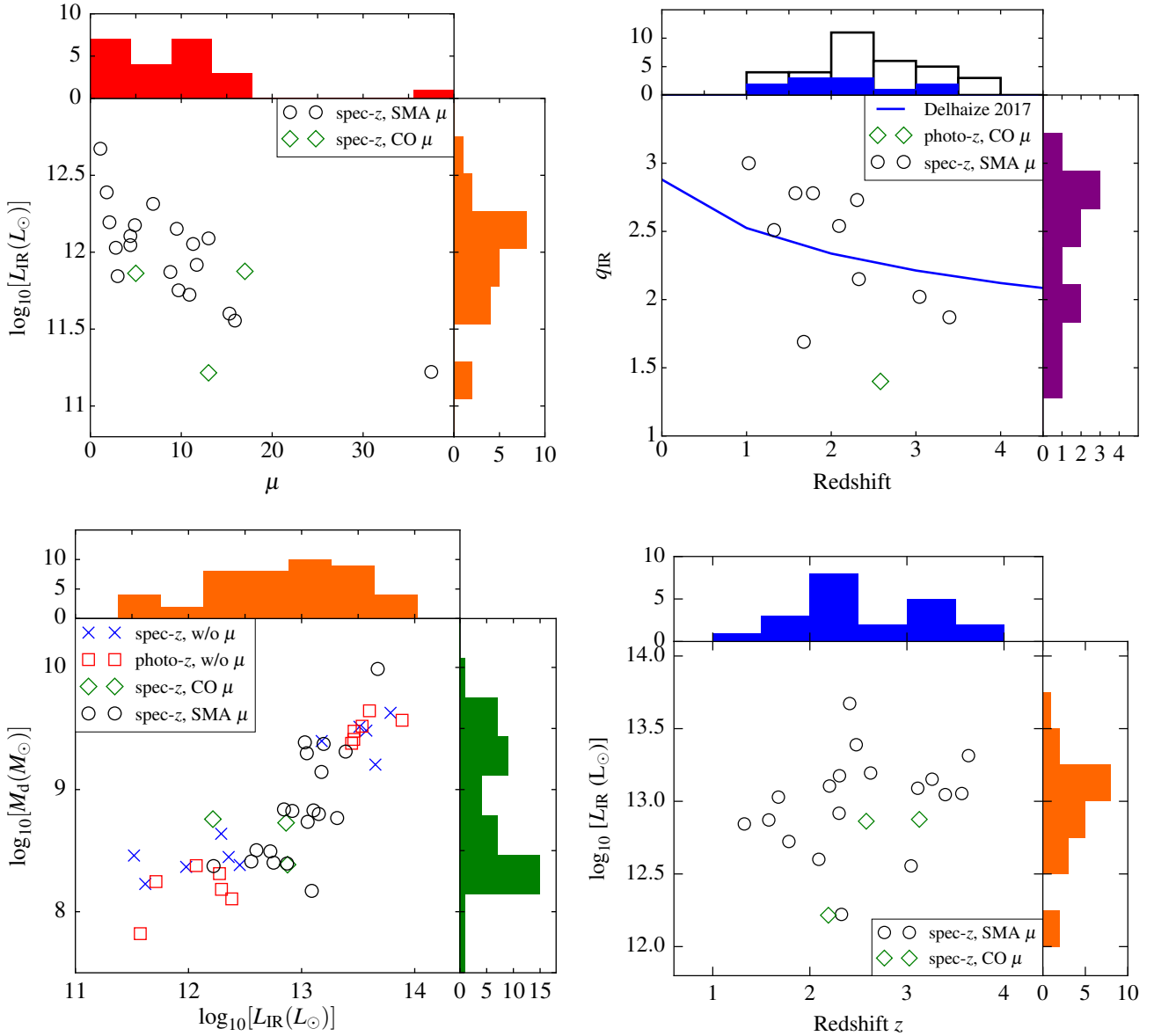


Figure 4. Distributions and correlations of SED fit parameters. *Upper left:* The distributions of gravitational amplification factor μ and the total infrared luminosity, L_{IR} (8–1000 μm). *Upper right:* The distribution of redshift and the total infrared to radio correlation factor q_{IR} . The blue line shows the infrared-radio correlation fitted in star-forming galaxies in the COSMOS field (i.e. Delhaize et al. 2017): $q_{\text{TIR}}(z) = (2.88 \pm 0.03)(1+z)^{-0.19 \pm 0.01}$. The open histogram (black) shows the redshift distribution of the whole sample. *Lower left:* The distributions of total infrared luminosity and the fitted dust mass M_{d} , after lensing amplification corrections. For targets without amplification factors (blue cross and red squares), we have divided by a factor of five for both axes, in order to compare with the de-lensed results. *Lower right:* The distributions of redshift and the total infrared luminosity after lensing correction. Filled histograms (in color) show the distribution of the sample. Open circles represent systems with known redshifts and lens models, primarily from Bussmann et al. (2013). Green diamonds represent targets with known redshifts, but with estimates of gravitational amplification factors only from their CO line characteristics (Harris et al. 2012). Blue crosses represent sources with known redshifts, with no existing lens model. Red squares represent sources with photometric redshifts, as shown in Table 2.

The median redshift (including both photo- z and spec- z) for the whole sample is 2.5 ± 0.6 , with a redshift range spanning $z = 1.0$ – 3.6 . The intrinsic L_{IR} spans from 10^{12} to $10^{13.5} L_{\odot}$, with a median of $\sim 10^{13} L_{\odot}$, indicating their starburst natures.

In the end, we find that the redshift does not show significant correlation with the intrinsic L_{IR} , indicating that our sample is not potentially biased to more luminous targets at higher redshifts, although they are selected with flux cutoffs.

4.3 Magnification factors

Gravitational amplification values are primarily taken from Bussmann et al. (2013) that are derived from SMA data in preference to values derived from Near-IR imaging (e.g. Calanog et al. 2014; Dye et al. 2014), due to the likelihood of a physical separation (and hence amplification difference) of the starburst and existing stellar population (Fu et al. 2012; Dye et al. 2015; Hodge et al. 2016; Oteo et al. 2017). Most galaxies in the sample are strongly lensed, with

a median amplification of around 10 \times , distributed between 1–15 \times . SMM J2135–0102 is an outlier with its very high amplification factor.

When fitting dust SED and measuring lines ratios, we neglect the possibility of differential lensing at different wavelengths, which may bring in extra uncertainties (e.g. Hezaveh et al. 2012; Serjeant 2012; Yang et al. 2017). The lensed status of this sample could complicate the modelling of their SEDs, particularly the low-temperature dust components which may not be co-spatial with hotter dust near the starburst. This similar effect could also be important for optical and near-IR flux density measurements and modeling (e.g. Negrello et al. 2014; Ma et al. 2015).

The different origins of the fine-structure ionised lines make differential lensing more severe. Resolved observations have shown that the [N II] emission is more extended than the [O III] emission in local galaxies (e.g., Hughes et al. 2015). Besides, [C II] originates from multiple gas phases, making it more extended than the [N II] emission, which has been seen in the Milky Way galaxy, local galaxies and galaxies at high redshift (e.g., Goldsmith et al. 2015; Lapham et al. 2017; Pavesi et al. 2016). However, the line ratios of the same species at the same energy level, e.g., the two [N II] lines and the two [O III] lines, are expected to be not as severe as those of species from different origins. Detailed studies on the differential lensing effect need very high-quality high-resolution images at all studies wavelengths, and are highly dependent on the model interpretation, which is beyond the scope of our study.

5 SPECTROSCOPY RESULTS

Herschel spectra of all our targets are presented in Appendix D. In galaxies with known spectroscopic redshifts, we report individual detections of nine [C II] 158- μ m emission lines, four [O III] 88- μ m lines, three [O I] 145- μ m lines, two [O I]-63 μ m lines, one [O III]-52- μ m line, one [N II]-122- μ m line, and one OH 119- μ m line in absorption. For galaxies without spectroscopic redshifts, we estimate their photometric redshift based on the FIR-based photometric redshifts fitting method (for details see Ivison et al. 2016), which fits FIR templates of different high- z galaxies. We adopt the best fits using the ALESS template and add the difference between different templates to the final error. We then search for lines within a range of $z_{\text{phot}} \pm 0.5$ ($\sim 3\sigma$), and find five possible [C II] emission lines at $z_{\text{phot}} \pm 0.5$ (one of these, SD.v1.133, with a possible OH 119- μ m absorption feature), thus yielding five plausible new spectroscopic redshifts. These redshifts need to be confirmed with follow-up observations before they are considered robust.

We also compare the [C II] spectra of SDP.11 and NA.v1.186 obtained with *Herschel* and those observed with APEX, which are shown in Fig. 5. For SDP.11, the velocity-integrated [C II] flux obtained with APEX is $265 \pm 65 \text{ Jy km s}^{-1}$, fully consistent with our *Herschel* detection, $269 \pm 30 \text{ Jy km s}^{-1}$. This is also close to the [C II] flux measured with the second-generation z (Redshift) and Early Universe Spectrometer (ZEUS-2) on APEX (Ferkinhoff et al. 2014). We note that the [C II] line profile of SDP.11 is resolved into two velocity components, separated by $\sim 300 \text{ km s}^{-1}$, which were not resolved by either the *Herschel* or ZEUS-2 observations. We also overlay the CO $J = 4 \rightarrow 3$ spectrum with the [C II] lines, and find that the twin-peaked profile of the APEX [C II] line is consistent with CO (also for HCN) detections in Oteo et al. (2017), likely indicative of a merger. For NA.v1.186, our APEX observations give a [C II] flux of $310 \pm 90 \text{ Jy km s}^{-1}$, around 60% higher than that ob-

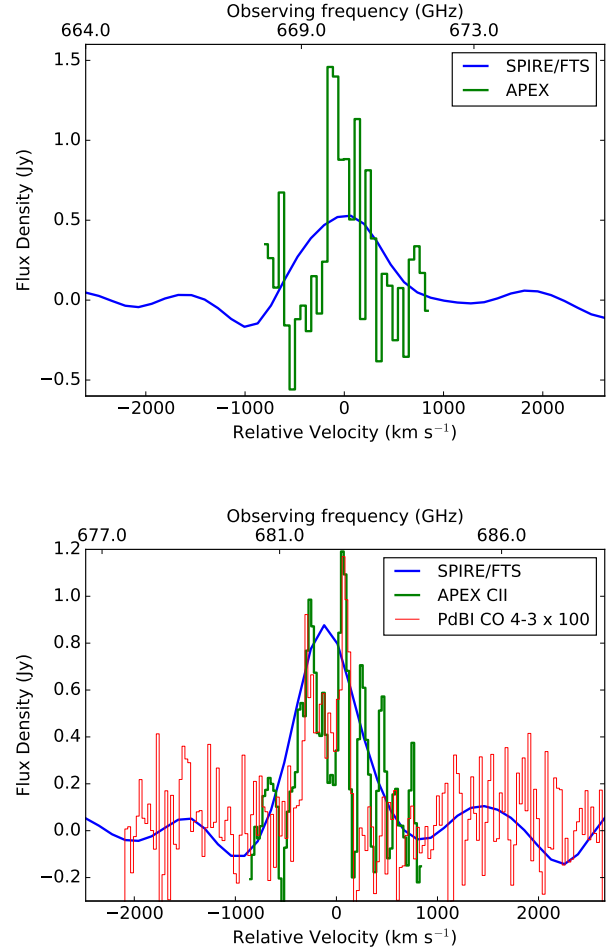


Figure 5. Upper: [C II] spectra of NA.v1.186. The blue line shows the un-apodised *Herschel* FTS spectrum, and the green line shows the APEX spectrum. Lower: [C II] and CO $J=4-3$ spectra of SDP.11. The blue line shows the un-apodised *Herschel* FTS spectrum, the green line shows the APEX spectrum, and the thin red line shows the CO $J=4-3$ spectrum (multiplied by 100 \times) obtained with the PdBI (Oteo et al. 2016).

tained from *Herschel* ($190 \pm 40 \text{ Jy km s}^{-1}$), but in agreement within the uncertainties.

5.1 [C II] 158- μ m as a diagnostic of ISM properties

The 158- μ m [C II] fine-structure transition is often the brightest observed FIR emission line. With the Atacama Large Millimeter/submillimeter Array (ALMA) now operational, interest in the interpretation of [C II] 158- μ m emission from high-redshift galaxies has increased in recent years.

[C II] has been reported to have an apparent relative decrease in the gas cooling efficiency with increasing radiation field intensity, dust temperature, and/or SFR (e.g. Abel et al. 2009; Stacey et al. 2010; Díaz-Santos et al. 2013a, 2014; Herrera-Camus et al. 2018a,b). The fraction of energy transmitted via this line is not constant, however, exhibiting a well-known decrease in the $L_{\text{line}}/L_{\text{FIR}}$ ratio with increasing L_{FIR} in the local Universe (Luhman et al. 2003). This results in the brightest (ultra-)luminous infrared galaxies (ULIRGs) exhibit the highest deficits. Compared with nearby

Source	Amplification	μM_{H_2} $10^{11} M_{\odot}$	μL_{IR} $10^{12} L_{\odot}$	L_{IR} $10^{12} L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	$M_{\text{d}}^{\text{tot}}$ $10^8 M_{\odot}$	$T_{\text{d}}^{\text{cutoff}}$ K	q_{IR}
SDP9	8.8 ± 2.2	1.9 ± 0.5	71.5 ± 2.4	8.1 ± 1.9	1200 ± 300	2.2 ± 1.0	36.1 ± 3.4	2.78 ± 0.10
SDP.11	10.9 ± 1.3	2.4 ± 0.3	68.9 ± 2.3	6.3 ± 0.7	900 ± 100	3.8 ± 0.9	34.9 ± 1.6	2.78 ± 0.10
SDP.17	4.9 ± 0.7	4.3 ± 0.6	76.7 ± 3.1	15.7 ± 2.2	2300 ± 300	13.5 ± 4.2	27.8 ± 1.7	2.73 ± 0.12
SDP.81	15.9 ± 0.7	3.8 ± 0.2	58.0 ± 4.0	3.7 ± 0.3	550 ± 50	2.6 ± 0.5	38.9 ± 3.8	2.02 ± 0.13
SDP.130	2.1 ± 0.3	1.7 ± 0.2	31.8 ± 2.8	15.1 ± 2.5	2300 ± 400	29.6 ± 6.6	24.1 ± 1.4	–
G09-v1.40	15.3 ± 3.5	3.3 ± 0.8	65.1 ± 2.1	4.3 ± 0.9	600 ± 130	7.4 ± 1.0	43.5 ± 2.9	2.54 ± 0.11
G09-v1.97	6.9 ± 0.6	5.0 ± 0.4	212.0 ± 6.0	30.8 ± 2.0	4600 ± 300	5.3 ± 1.9	50.7 ± 1.6	–
G09-v1.124	1.1 ± 0.1	2.2 ± 0.2	64.5 ± 4.9	58.6 ± 5.9	8800 ± 900	82.0 ± 12.6	24.4 ± 1.6	2.40 ± 0.22
G09-v1.326	$5.0 \pm 1.0^{\text{H}}$	2.7 ± 0.5	47.2 ± 1.9	9.4 ± 1.5	1400 ± 200	4.5 ± 1.7	30.8 ± 4.4	1.40 ± 0.12
G12-v2.30	9.5 ± 0.6	7.1 ± 0.5	202.0 ± 7.0	21.3 ± 1.2	3200 ± 170	5.6 ± 1.8	37.3 ± 1.2	–
G12-v2.43	$17.0 \pm 11.0^{\text{H}}$	1.3 ± 0.8	150.0 ± 3.8	8.8 ± 4.8	1300 ± 700	2.8 ± 1.6	31.7 ± 3.0	–
G12-v2.257	$13.0 \pm 7.0^{\text{H}}$	1.4 ± 0.8	34.0 ± 1.2	2.6 ± 0.9	400 ± 100	2.7 ± 3.7	24.8 ± 2.3	–
G15-v2.19	9.0 ± 1.0	2.9 ± 0.3	58.1 ± 2.0	6.0 ± 0.5	900 ± 100	2.4 ± 0.8	35.2 ± 1.9	$3.0. \pm 0.07$
G15-v2.235	1.8 ± 0.3	3.5 ± 0.6	49.8 ± 1.8	27.7 ± 4.2	4100 ± 600	23.3 ± 6.0	35.3 ± 1.8	–
NA.v1.56	11.7 ± 0.9	5.8 ± 0.4	109.0 ± 4.4	9.3 ± 0.8	1400 ± 110	7.3 ± 1.8	31.1 ± 1.7	–
NA.v1.144	4.4 ± 0.8	1.8 ± 0.3	54.8 ± 2.1	12.5 ± 2.4	1900 ± 300	6.9 ± 2.2	40.1 ± 3.7	–
NA.v1.177	–	4.2	94.1 ± 3.0	18.8 ± 2.8	2800 ± 600	1.6 ± 0.4	34.7 ± 3.2	–
NA.v1.186	–	3.6	32.7 ± 1.3	6.5 ± 1.4	1000 ± 200	7.4 ± 2.1	28.8 ± 2.2	–
NB.v1.43	2.8 ± 0.4	3.6 ± 0.5	31.2 ± 1.3	11.1 ± 1.6	1700 ± 400	24.7 ± 4.9	23.8 ± 1.2	1.67 ± 0.09
NB.v1.78	13.0 ± 1.5	4.6 ± 0.5	156.0 ± 7.2	12.0 ± 1.4	1800 ± 400	2.5 ± 0.5	49.7 ± 4.4	–
NC.v1.143	11.3 ± 1.7	6.2 ± 0.9	153.0 ± 6.1	13.5 ± 1.9	2000 ± 300	9.6 ± 2.3	35.2 ± 3.7	–
SA.v1.44	–	–	18.2 ± 0.9	3.6 ± 0.8	540 ± 120	5.5 ± 1.7	26.1 ± 2.1	–
SA.v1.53	–	–	22.9 ± 0.8	4.6 ± 0.8	680 ± 90	5.7 ± 1.2	27.3 ± 1.9	–
SB.v1.143	–	–	55.5 ± 3.2	11.1 ± 1.5	1700 ± 250	14.6 ± 4.3	30.9 ± 3.7	–
SB.v1.202	–	–	35.1 ± 3.1	7.0 ± 2.5	1000 ± 200	5.5 ± 2.1	29.9 ± 4.5	–
SC.v1.128	–	–	54.4 ± 2.4	10.9 ± 1.3	1600 ± 230	9.1 ± 2.3	31.7 ± 3.2	–
SD.v1.70	–	–	23.5 ± 2.8	4.7 ± 1.1	700 ± 200	6.7 ± 1.1	27.0 ± 2.6	–
SD.v1.133	–	–	25.3 ± 3.9	5.1 ± 0.4	760 ± 200	3.8 ± 0.7	28.9 ± 2.0	–
SD.v1.328	–	–	42.4 ± 2.7	8.5 ± 1.3	1300 ± 240	13.1 ± 1.5	29.3 ± 3.4	–
SE.v1.165	–	–	37.2 ± 3.3	7.4 ± 1.7	1100 ± 300	7.3 ± 0.9	29.6 ± 2.9	–
SF.v1.88	–	–	34.8 ± 1.4	7.0 ± 1.3	1000 ± 300	7.0 ± 1.3	29.3 ± 2.3	–
SF.v1.100	–	–	51.2 ± 2.8	10.2 ± 2.4	1500 ± 400	12.4 ± 2.6	30.6 ± 2.8	–
SG.v1.77	–	–	49.4 ± 1.7	9.9 ± 1.3	1500 ± 400	3.3 ± 0.8	33.6 ± 2.4	–
HeLMS08	–	–	14.1 ± 0.6	2.8 ± 0.3	420 ± 100	10.7 ± 2.4	23.3 ± 1.9	–
HeLMS22	–	–	32.6 ± 2.2	6.5 ± 1.1	970 ± 180	9.1 ± 1.8	28.3 ± 3.8	–
HeLMS18	–	–	40.9 ± 1.8	8.2 ± 1.2	1200 ± 200	6.5 ± 1.4	30.5 ± 3.0	–
HeLMS2	–	–	75.3 ± 4.4	15.1 ± 2.0	2300 ± 300	11.5 ± 1.9	33.5 ± 3.0	–
HeLMS7	–	–	53.9 ± 1.9	10.8 ± 2.5	1600 ± 340	6.8 ± 1.3	32.3 ± 2.8	–
HeLMS9	–	–	33.1 ± 1.0	6.6 ± 1.1	1000 ± 290	6.8 ± 1.3	29.1 ± 2.0	–
HeLMS13	–	–	70.7 ± 2.6	14.1 ± 2.1	2100 ± 300	3.8 ± 1.0	27.2 ± 2.9	–
HeLMS15	–	–	30.1 ± 1.6	6.0 ± 9.6	900 ± 140	13.0 ± 3.4	35.1 ± 4.1	–
HeLMS5	–	–	82.3 ± 7.5	16.5 ± 3.3	2500 ± 500	7.5 ± 2.0	37.9 ± 3.3	–
HBoötes03	3.0 ± 1.5	1.0 ± 0.5	20.8 ± 0.9	6.9 ± 1.4	1000 ± 200	6.9 ± 1.9	23.8 ± 6.2	2.51 ± 0.09
HXMM02	$5.33 \pm 0.19^{\text{B}}$	3.4 ± 0.8	66.2 ± 6.5	15.1 ± 3.3	2300 ± 500	24.1 ± 7.0	23.0 ± 2.3	1.87 ± 0.22
Eyelash	37.5 ± 4.5	5.6 ± 0.7	62.3 ± 2.9	1.7 ± 0.2	250 ± 30	2.4 ± 0.6	33.3 ± 3.4	2.15 ± 0.26

Table 4. Properties from the SED fits described in Section 4.2. In addition, H₂ masses from CO measurements are shown, taken from Iono et al. (2006, 2012); Frayer et al. (2011); Fu et al. (2012); Harris et al. (2012); Lupu et al. (2012); Danielson et al. (2013); Ivison et al. (2013); Messias et al. (2014). These were converted to $L'_{\text{CO}1-0}$ where necessary by the brightness temperature ratios given in Bothwell et al. (2013), and then to a molecular gas mass via an α_{CO} conversion factor of $0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$. ^H Amplification estimate from CO line luminosity and FWHM from Harris et al. (2012).

^B Amplification estimate from ALMA 870- μm data (Bussmann et al. 2015).

normal quiescent star-forming spirals, the luminosity ratio between [C II] and the FIR continuum emission decreases by more than an order of magnitude in extreme star-forming systems (e.g. LIRGs and ULIRGs Díaz-Santos et al. 2013a, 2014). The relationship also hold in spatially-resolved measurements on scales of a few hundreds pc, e.g. surveys of KINGFISH (Smith et al. 2017b), GOALS (Díaz-Santos et al. 2014), SHINING (Herrera-Camus et al. 2018a), with lower values found in the nuclei of galaxies than in the extended disks, and the trend may be even more pronounced with $L_{\text{FIR}}/M_{\text{H}_2}$ (e.g. Graciá-Carpio et al. 2011).

Several theories have been proposed to explain this deficit.

The ionisation parameter, U , and hence dust temperature and SFR surface density, appear to be strongly correlated with the line-to-continuum ratio (Díaz-Santos et al. 2013a), with the most extreme values of all three parameters found in the dense merging nuclei of low-redshift ULIRGs. Resolved observations and detailed modelling (Herrera-Camus et al. 2018a,b) show that not only the high ionisation parameter, but also the reduction in the photoelectric heating efficiency make the [C II] line not able to trace the FUV radiation field. Dust grain charging in higher radiation fields, leading to a lower photoelectric gas-heating efficiency, may additionally play a role (Malhotra et al. 1997). Column density will also have

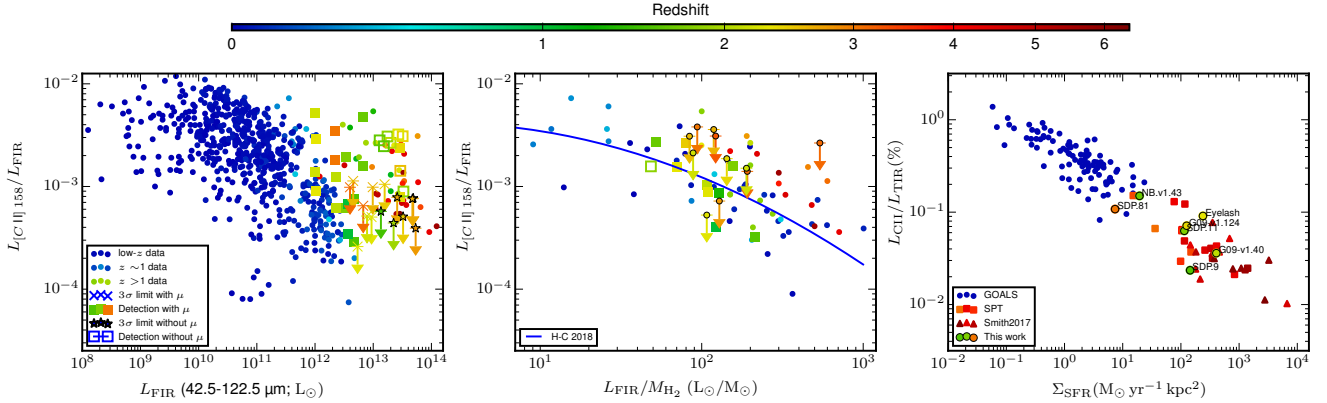


Figure 6. *Left:* The well-known $L_{[\text{C II}] 158 \mu\text{m}}/L_{\text{FIR}}$ deficit, locally and at high redshift in starburst-dominated galaxies. Data from this work are shown as squares, or downward arrows indicating 3σ upper limits. Filled points have FIR luminosities corrected for magnification, non-filled points use magnification estimates from SED fitting. Low-redshift data are taken from Brauher et al. (2008); Díaz-Santos et al. (2013a); Sargsyan et al. (2014); González-Alfonso et al. (2015); Ibar et al. (2015); Rosenberg et al. (2015). Data at $z \sim 1$ are from Stacey et al. (2010); Farrah et al. (2013); Magdis et al. (2014). Higher redshift data are taken from Cox et al. (2011); Swinbank et al. (2012); Wagg et al. (2012); Riechers et al. (2013); De Breuck et al. (2014a); Riechers et al. (2014); Rawle et al. (2014); Gullberg et al. (2015). Where necessary, luminosities have been scaled from literature measurements by the mean of the values from our SED fits $L_{\text{FIR}}(42.5\text{--}122.5 \mu\text{m}) = 0.60 L_{\text{IR}}(8\text{--}1000 \mu\text{m})$. *Middle:* The $[\text{C II}]/L_{\text{FIR}}$ ratio as a function of $L_{\text{FIR}}/M_{\text{H}_2}$, which should correlate more strongly than the continuum luminosity alone (e.g. Graciá-Carpio et al. 2011). Gas masses are determined from integrated-galaxy CO observations, converted to CO $J = 1 - 0$ luminosities where necessary. The blue line shows the scaling relation for $[\text{C II}]/\text{FIR} - \text{FIR}/M_{\text{H}_2}$ found in local star-forming galaxies (Herrera-Camus et al. 2018a). *Right:* The $[\text{C II}]/L_{\text{TIR}}$ ratio as a function of surface density of SFR, Σ_{SFR} . This expands the KINGFISH-GOALS-High- z compilation of Smith et al. (2017b), with additional data from Spilker et al. (2016). There are six new measurements from this work, which have both $[\text{C II}]$ detection and size estimate, labeled with inner-coloured black circles. This plot includes data from the Great Observatories All-sky LIRG Survey (GOALS) sample (Díaz-Santos et al. 2013b), South Pole Telescope (SPT) sample (Spilker et al. 2016; Gullberg et al. 2015), and high redshift galaxies collected from the literature (Walter et al. 2009a; Carniani et al. 2013; Riechers et al. 2013; Wang et al. 2013a; De Breuck et al. 2014b; Neri et al. 2014; Riechers et al. 2014; Yun et al. 2015; Díaz-Santos et al. 2016; Oteo et al. 2016; Smith et al. 2017b).

an effect as $[\text{C II}] 158\text{-}\mu\text{m}$ is primarily produced in PDRs, with a small contribution from H II regions for local galaxies (e.g. Abel 2006); the column density at which the $[\text{C II}]$ becomes luminous is then governed by the ionisation parameter and dust extinction. FIR continuum radiation, however, can also be produced by non-PDR sources. Lines of sight through high optical depth molecular material to a PDR and starburst will contain a substantial continuum contribution from the molecular region, as well as from the H II region close to the ionising source. This increases the FIR continuum emission and, at very high column densities, the optical depth to the lines may become large enough to reduce their observed flux. Croxall et al. (2012) found that the $[\text{C II}]/L_{\text{IR}}$ ratio decreases with increasing dust temperature traced by the $F_{70\mu\text{m}}/F_{100\mu\text{m}}$ color, while the $[\text{N II}]/L_{\text{IR}}$ ratio keeps unchanged. The $[\text{C II}]$ deficit was also found to have a relationship with the ionization state of small grains, revealed from polycyclic aromatic hydrocarbons (PAH) features (i.e. Croxall et al. 2012).

This effect appears to continue at high redshift, albeit potentially to a lower extent (e.g. Stacey et al. 2010). While the global SFRs in high-redshift DSFGs often equal or exceed those found in local ULIRGs, significant differences may exist in the distribution of gas and star formation within these two populations. In some systems, a larger volume of gas may be illuminated by a lower flux of ionising photons, producing both a smaller ionisation parameter, U , and a lower optical depth. Díaz-Santos et al. (2013a) and Gullberg et al. (2015) discuss the deficit and correlations with other parameters in further detail, in particular with emission area and molecular gas mass, for low- and high-redshift galaxies, respectively.

Our $L_{[\text{C II}] 158 \mu\text{m}}/L_{\text{FIR}}$ measurements are plotted in Fig. 6 along with values from local and high-redshift starburst galaxies. Gravitational lensing has allowed us to push intrinsic luminosities

towards or below those of local ULIRGs, and our sources occupy much of the space between the highest redshift ALMA detections (primarily with $L_{\text{FIR}} > 10^{13} L_{\odot}$) and low-redshift systems (typically with $L_{\text{FIR}} < 3 \times 10^{12} L_{\odot}$). We see a spread in $L_{[\text{C II}] 158 \mu\text{m}}/L_{\text{FIR}}$, from $\sim 3 \times 10^{-3}$ to 3×10^{-4} , suggesting that the local relation does not hold at higher redshifts; however, the non-detections may have lower ratios. These values appear to confirm other observations indicating that – for starburst-dominated systems at least – the deficit is lower for high-redshift ULIRGs than for their low-redshift cousins, likely resulting from a lower intensity of ionising radiation due to their similar total star formation occurring over a larger volume.

The line-to-continuum ratio is expected to correlate more strongly with $L_{\text{FIR}}/M_{\text{H}_2}$ (Graciá-Carpio et al. 2011) and our measurements – plotted in Fig. 6 using gas masses derived from CO luminosities – agree with this theory. Fig. 6 also shows that the overall scaling relation derived from local star-forming galaxies (Herrera-Camus et al. 2018a) and our data are also fully consistent with the same trend.

In addition to the total IR luminosity, the FIR lines – as coolants of star-formation-heated gas – may be used to trace the instantaneous SFR. Since it is often the brightest line, $[\text{C II}] 158\text{-}\mu\text{m}$ is of primary interest. The conversion is non-linear, however, due to the changing efficiency of these lines with increasing SFR. Sargsyan et al. (2014) and Herrera-Camus et al. (2015) discuss the effectiveness of $[\text{C II}] 158\text{-}\mu\text{m}$ as a tracer of SFR in the local Universe, noting that $[\text{C II}] 158\text{-}\mu\text{m}$ can provide measurements consistent with other star-formation tracers, such as PAH emission and MIR emission lines, but that any calibration may require additional corrections, applicable to more strongly star-forming sources, such that SFRs derived from continuum measurements may be superior.

Transition	rest wavelength μm	rest frequency GHz	ionisation energy eV (low-up)	critical density cm^{-3} (H_2)	critical density cm^{-3} (e)	E_{up} K	ref
$[\text{OIII}]^3\text{P}_2 - ^3\text{P}_1$	51.81	5786	35.12 – 54.94		3.6×10^3		Draine (2011)
$[\text{NIII}]^2\text{P}_{3/2} - ^2\text{P}_{1/2}$	57.32	5229	29.60 – 47.45		3.0×10^3		Malhotra et al. (2001)
$[\text{OI}]^3\text{P}_1 - ^3\text{P}_2$	63.18	4744.8	0 – 13.6	$4 \times 10^5 (T/100)^{-0.34}$		227.7	Draine (2011)
$[\text{OIII}]^3\text{P}_1 - ^3\text{P}_0$	88.36	3393	35.12 – 54.94		5.1×10^2		Draine (2011)
$\text{OH } \Pi_{3/2} - \Pi_{3/2} \frac{5}{2}^- - \frac{3}{2}^+$	119.23	2514.32	0 – 4.4	$\sim 1 \times 10^8$		120.7	LAMBDA
$\text{OH } \Pi_{3/2} - \Pi_{3/2} \frac{5}{2}^+ - \frac{3}{2}^-$	119.44	2509.95	0 – 4.4	$\sim 1 \times 10^8$		120.5	LAMBDA
$[\text{NII}]^3\text{P}_2 - ^3\text{P}_1$	121.90	2459.4	14.53 – 29.6		3.1×10^2		Draine (2011)
$[\text{OI}]^3\text{P}_0 - ^3\text{P}_1$	145.53	2060.1	0 – 13.6	$8 \times 10^4 (T/100)^{-0.34}$		326.6	Draine (2011)
$[\text{CII}]^2\text{P}_{3/2} - ^2\text{P}_{1/2}$	157.74	1900.4	11.26 – 24.4	3×10^3	50	91.21	Malhotra et al. (2001)
$[\text{NII}]^3\text{P}_1 - ^3\text{P}_0$	205.18	1461.1	14.53 – 29.6		44	70.10	Draine (2011)

Table 5. Physical properties of the observed lines. LAMBDA database: <http://home.strw.leidenuniv.nl/~moldata/> The critical densities are calculated with a kinetic temperature of 10,000 K for electrons, and a kinetic temperature of 100 K for collisions with the H_2 gas.

Literature calibrations from these local samples are presented in the form $\frac{\text{SFR}}{M_{\odot}\text{yr}^{-1}} = A \left(\frac{L_{[\text{CII}]158\mu\text{m}}}{L_{\odot}} \right)^B$, where $A = 1.22 \times 10^{-8}$, $1 \pm 0.2 \times 10^{-7}$ and 1.00×10^{-7} , and $B = 1.034$, 1 and 0.983 from De Looze et al. (2011), Sargsyan et al. (2014) and Herrera-Camus et al. (2015), respectively. For our highest signal-to-noise $[\text{C II}] 158\text{-}\mu\text{m}$ detection, that of SMM J2135–0102, these suggest SFRs of 40, 165 and $120 M_{\odot}\text{yr}^{-1}$, the range reflecting the inherent dispersion in the observed $L_{[\text{CII}]158\mu\text{m}}/\text{SFR}$ ratios. An equivalent calibration derived from high-redshift data has $A = 3.02 \times 10^{-9}$ and $B = 1.18$ (De Looze et al. 2014), with the higher exponent value accounting for the decreasing line-to-continuum ratio in galaxies with the high infrared luminosities discovered at such redshifts. For SMM J2135–0102, this calibration suggests a SFR of $230 M_{\odot}\text{yr}^{-1}$, fully consistent with the $250 M_{\odot}\text{yr}^{-1}$ that we estimate from our photometric L_{IR} fit.

Recently, Herrera-Camus et al. (2018a,b) present new scaling relations based on several physical properties of galaxies and classifications, including separation from the main-sequence of star-forming galaxies, star-formation efficiency, and AGN/LINER/pure starburst categories. Using the calibration for galaxies above the main-sequence (Herrera-Camus et al. 2018a), the SFR of Eyelash is $\sim 160 M_{\odot}\text{yr}^{-1}$, slightly below our fitted SFR, but consistent with the values obtained in Sargsyan et al. (2014) and Herrera-Camus et al. (2015).

An extension to these $L_{[\text{CII}]158\mu\text{m}}/\text{SFR}$ relationships exploits local resolved galaxies to consider surface densities. Díaz-Santos et al. (2013a) derive a relationship for the nuclei of a large sample of LIRGs, which appears to hold for high-redshift objects (Díaz-Santos et al. 2014), and which can be re-arranged as:

$$\log_{10} \left(\frac{\text{area}}{\text{kpc}^2} \right) = \log_{10} \left(\frac{L_{\text{IR}}}{L_{\odot}} \right) + \frac{\log_{10} \left(\frac{L_{[\text{CII}]158\mu\text{m}}}{L_{\text{FIR}}} \right) - 1.21 \pm 0.24}{0.35 \pm 0.03} \quad (2)$$

The resulting surface areas suggested for our sample are typically within a factor of a few of the demagnified areas we have adopted (these can be fairly uncertain), primarily from the lens modelling of Bussmann et al. (2013), and are compatible with the low-redshift scatter. As shown in Fig. 6 (right panel), the $L_{[\text{CII}]158\mu\text{m}}/L_{\text{IR}}$ ratio shows a decreasing trend with surface density of SFR, Σ_{SFR} , following exactly the same trend found in local starbursts and high redshift galaxies in the literature (Smith et al. 2017b; Spilker et al. 2016). The compactness of the star-formation activities seems to be a very tight correlation with the $L_{[\text{CII}]158\mu\text{m}}/L_{\text{IR}}$ ratio. There seems to have a slight trend with red-

shift as well, possibly due to the selection biases – only the most intense, high surface-density starbursts can be selected in the more distant Universe. Highest lensing magnification occurs within a small angular area, so compact starbursts allow a higher fraction of the total luminosity to be located within the lensed area.

6 REST-FRAME STACKING

In individual spectra of the sample, only the brightest FIR cooling lines may be detected. Recently Wardlow et al. (2017); Wilson et al. (2017) stacked *Herschel*-PACS and *Herschel*-SPIRE spectra of DSFGs at high redshift and detected ionised fine-structure lines, such as $[\text{O IV}] 26\text{-}\mu\text{m}$, $[\text{S III}] 33\text{-}\mu\text{m}$, $[\text{OIII}] 52\text{-}\mu\text{m}$, and neutral lines, such as $\text{C I } 158\text{-}\mu\text{m}$, $[\text{OI}] 63\text{-}\mu\text{m}$. Here, we stack our *Herschel*-SPIRE spectra to probe the faint lines.

6.1 Spectral stacking

To search for fainter lines, and to determine the evolution of the average properties of the population as a whole, we stacked the observed spectra in the rest frame. In principle the noise should reduce as \sqrt{n} , where n is the number of stacked spectra, when weightings are not considered. Different stacking techniques have been adopted in the literature (e.g. Spilker et al. 2014; Wardlow et al. 2017; Wilson et al. 2017) for various scientific purposes, which give different weightings to the data. In the following sections, we present three different stacking methods to explore the average physical properties in the sample and the potential biases of the stacking techniques.

Before stacking, we applied apodisation to convolve the spectral response from a Sinc function to reduce sidelobes and generate a more ‘‘Gaussian-like’’ profile (i.e., Naylor & Tahic 2007, see also HIPE manual). To stack spectra with different redshifts (see Section 6), the spectra need to be blueshifted to the rest frame, where the widths of the Sinc function for each galaxy increases with redshift by $1+z$, i.e., from 2.6 GHz at $z = 1.2$ to 5.5 GHz at $z = 3.6$, compared to the 1.2-GHz width of the system response of the *Herschel*-SPIRE. If we simply add/average together the same line from different redshifted galaxies without apodisation, the sidelobes of the Sinc functions (of different widths) tend to cancel each other, which biases the stacked signal.

To match the velocity resolution across the sample at the rest frequency, we vary the Gaussian width of the apodisation with redshift, where width = $((z - 1.5)/2 + 1.1) \times 1.20671$ GHz, which

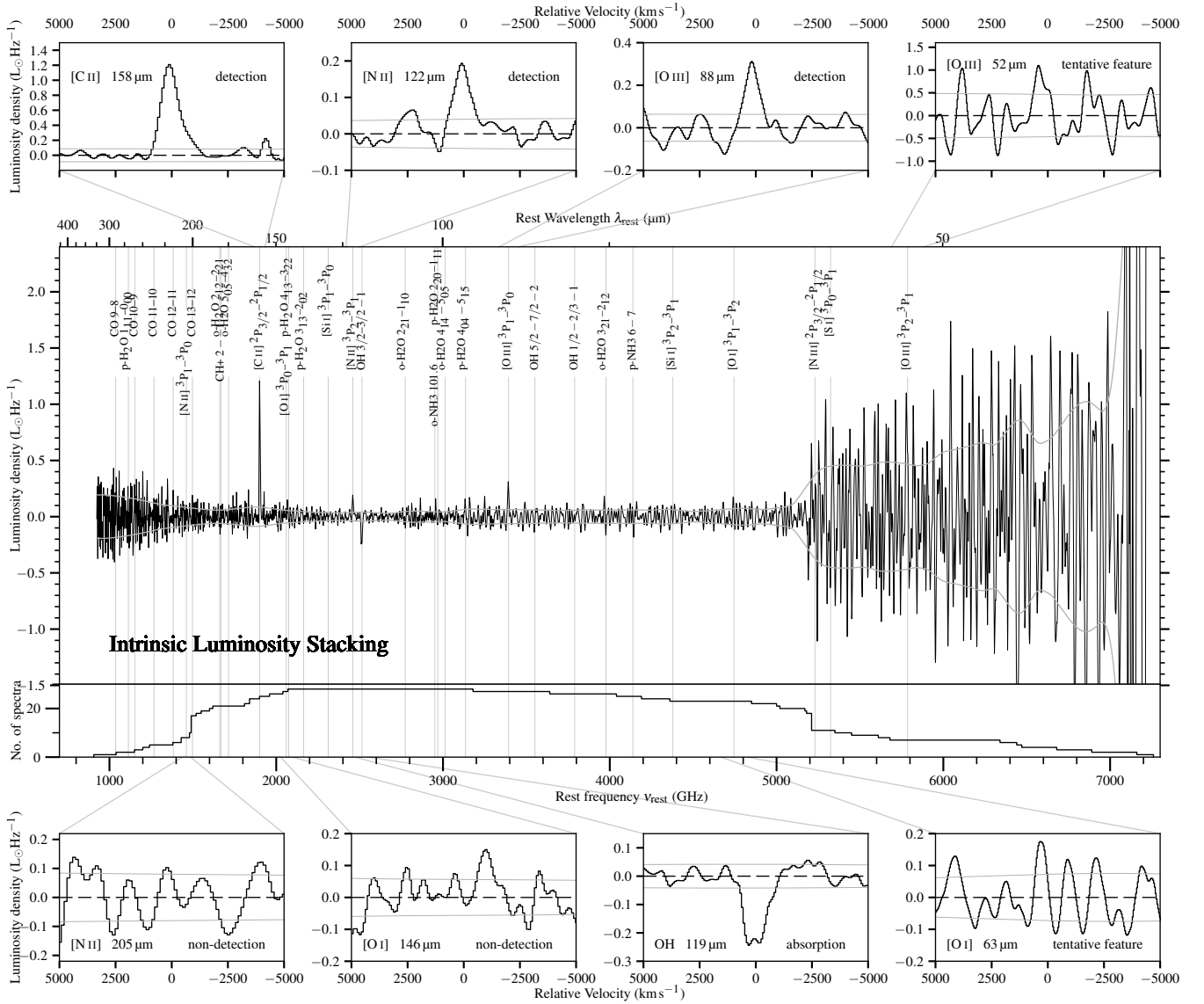


Figure 7. *Upper centre:* Rest-frame intrinsic (de-lensed) luminosity stack of all spectra where secure redshifts are in hand. Markers denote the positions of the primary spectral features expected. *Lower centre:* The number of spectra contributing to the stacked spectrum. *Upper and lower:* ± 5000 km s $^{-1}$ cuts around the positions of the primary atomic and ionic spectral lines analysed elsewhere in this work, plus the OH 119 μ m doublet.

ensures a roughly uniform velocity resolution at any given rest frequency. For the one galaxy at $z < 1.5$, G15-v2.19, we use a Gaussian width of 1.1 GHz. Converting from the Sinc function to the Gaussian function may raise the flux by 5% (e.g. Hopwood et al. 2015), which we consider as an extra source of error in the final flux estimate. To avoid the noisy edges of the spectra in both SLW and SSW, which are heavily affected by ripples, we do not include the very edge of the spectral ends in the stacking. For SLW, we exclude 30 channels at the low-frequency end and 120 channels at the high-frequency end; for SSW, we exclude 30 channels at both ends of the spectra.

The first method stacks spectra using their intrinsic de-lensed line luminosities. This can only be applied to the sources with both known spectroscopic redshifts and amplification factors. This method focuses on the intrinsic properties of the galaxies and mitigates the influence of the highly non-uniform lensing factors for different targets (and thus frequency coverage, since the targets all lie at different redshifts). However, the sample size is limited by

the numbers of galaxies with lensing models (23 out of 38 galaxies with *Herschel*-SPIRE spectra).

We blue shift all apodised spectra to the rest frame, then convert flux densities to luminosity densities (spectral luminosity) with their luminosity distances. To arrive at de-lensed intrinsic properties, we divide the luminosity by their amplification factors (from e.g. Bussmann et al. 2013). Then we create an empty output spectrum covering the total frequency range in the rest frame, with a frequency sampling step equivalent to the minimum of all individual spectra (to avoid under-sampling the high-redshift end). After re-sampling the rest-frame de-lensed spectra (in luminosity density) into the template output spectrum, we average all of them for each channel using $1/\sigma^2$ weighting, which is controlled by the noise level appropriate for this specific channel. The final output is a spectrum in de-lensed mean line luminosity density. The final noise level is a channel-based function. The spectra resulting from this intrinsic stacking method is displayed in Fig. 7.

The second method uses a similar stacking technique as

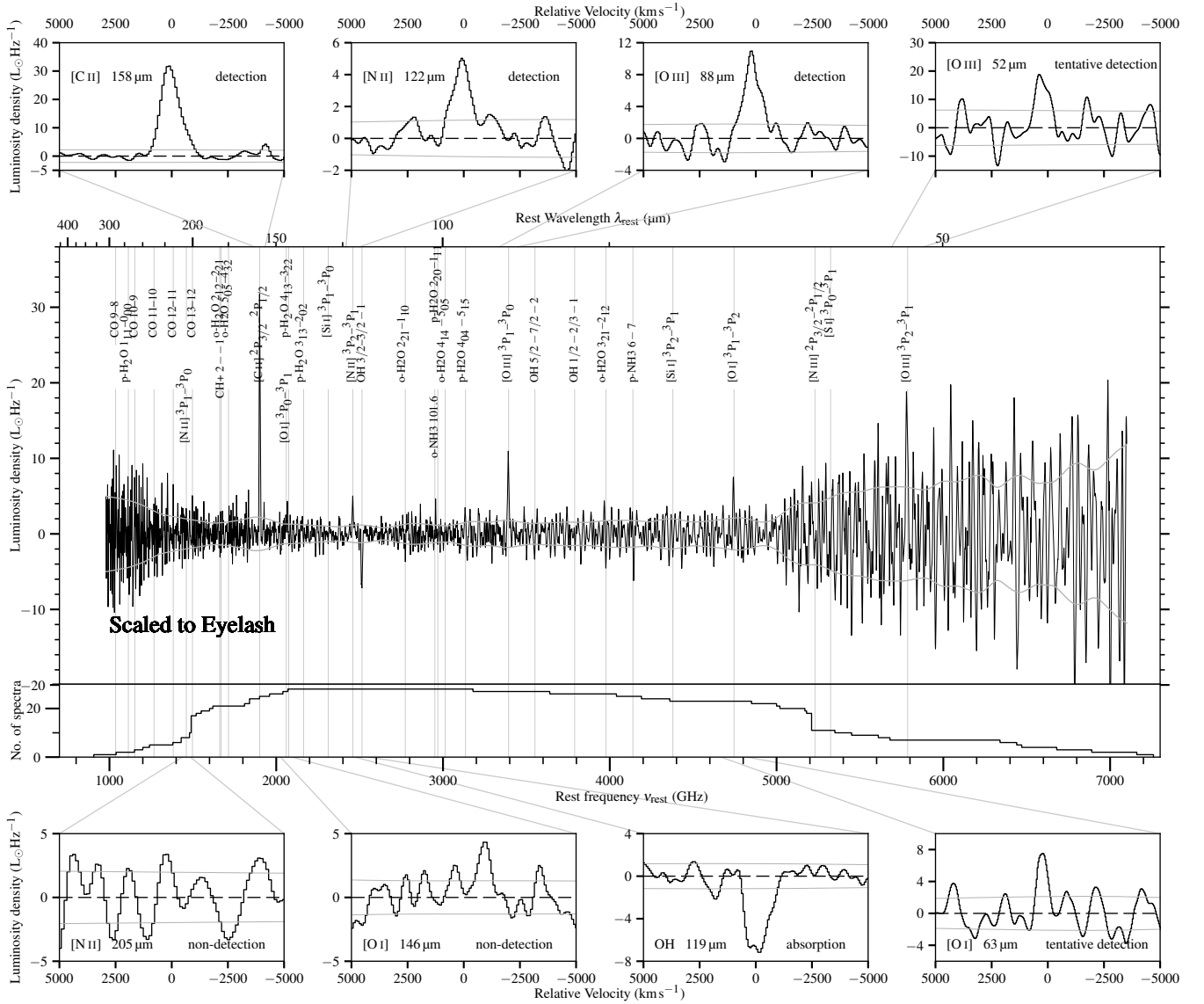


Figure 8. *Upper centre:* Scaling stacked spectrum, with all spectra scaled to the 500 μm flux of SMMJ2135–0102. Markers denote the positions of the primary expected spectral features. *Lower centre:* The number of spectra contributing to this stacked spectrum. *Upper and lower:* $\pm 5000 \text{ km s}^{-1}$ cuts around the positions of the primary atomic and ionic spectral lines analysed elsewhere in this work, plus the OH 119 μm doublet.

Spilker et al. (2014), taking advantage of the negative K correction in the submm wavelength regime. We use SMMJ2135–0102 as a ‘master’ template, and blue-shift (or red-shift for galaxies with $z < 2.326$) all measured spectra to its redshift ($z = 2.32591$). We then scale all spectra by their 500- μm continuum flux relative to the value measured for SMMJ2135–0102. In this way, the lensing factors for all of our spectra are scaled to a value similar to that of SMMJ2135–0102 at 500 μm , so the stacked spectrum should have a similar amplification factor as SMMJ2135–0102.

The blue-shifted and scaled spectra are then stacked together using $1/\sigma^2$ weighting. This stacking method does not require amplification factors, and thus avoids the associated uncertainties. All spectra with known redshifts can be used, regardless of lensing models, so this method can be applied for a relatively large sample of galaxies. Comparing to the results from the first stacking technique, this approach can reveal any potential bias in the different stacking methods. We present the spectrum obtained using this scaling method in Fig. 8.

The third method is based on median, instead of the mean, to avoid weightings that may bias to the more luminous or higher signal-to-noise spectra. We normalise all spectra with their infrared luminosities, L_{IR} , blueshift spectra to their rest-frames, and then calculate the median value across all spectra for each channel bin. When calculating the median values, we do not adopt weightings, i.e., equal weighting. Such a stacking method can avoid systematic biases by a few strong targets and is robust to test if the weakly detected lines are common (more than 50%) in the sample. We present the spectrum obtained using the median stacking method in Fig. 9. In principle, a straight (non-weighted) stacking would also be little biased by noise, but such method could only result in a detection of the [C II] line and a marginal detection of the [O III] 88 μm line.

From the line ratios of multiple far-IR lines, calculated between the intrinsic stacked spectrum and the scaling stacked spectrum, the amplification factor of the scaling stacking method is \sim

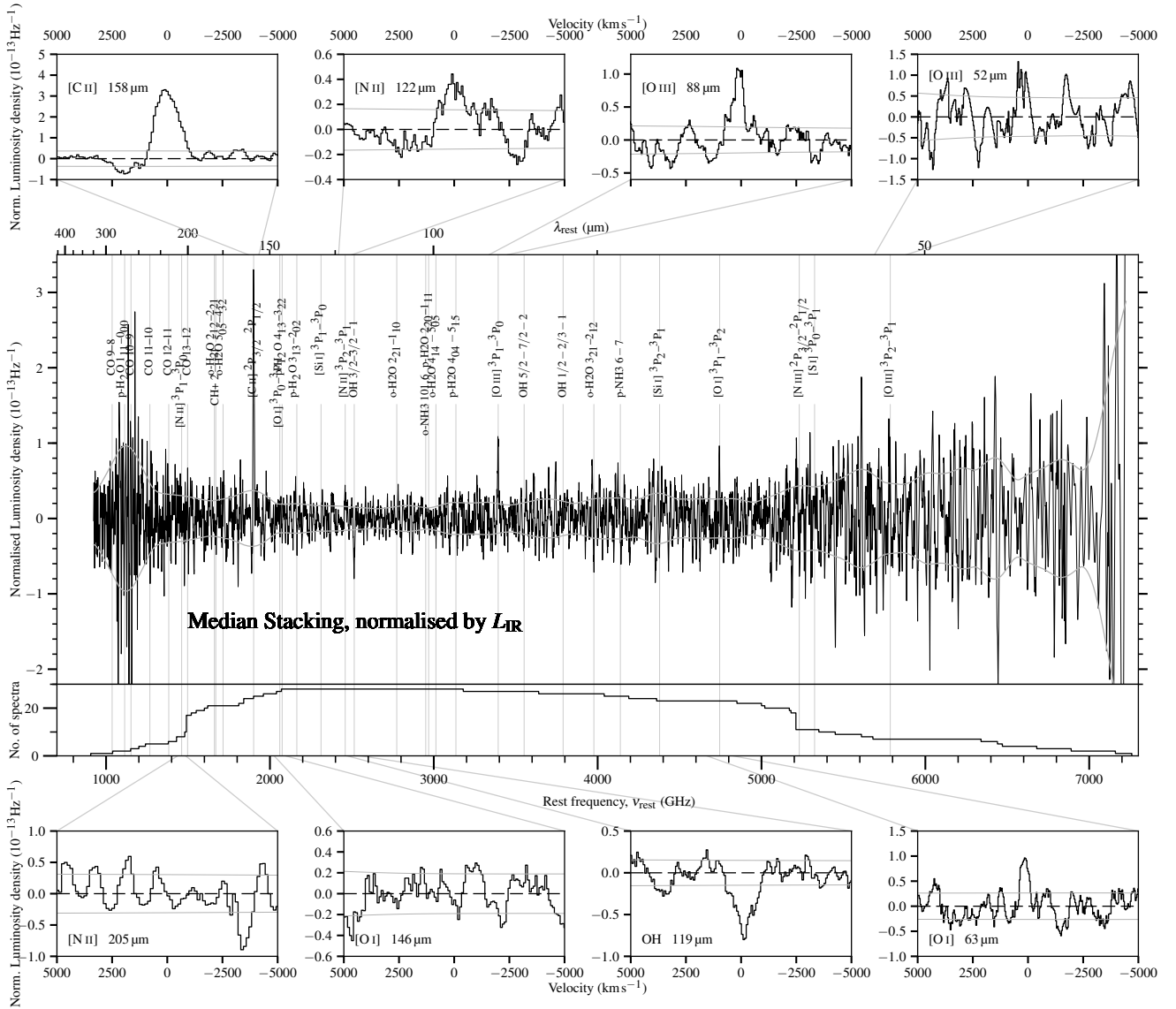


Figure 9. *Upper centre:* Median stacked spectrum, with all spectra normalised to their own L_{IR} . Markers denote the positions of the primary expected spectral features. *Lower centre:* The number of spectra contributing to this stacked spectrum. *Upper and lower:* $\pm 5000 \text{ km s}^{-1}$ cuts around the positions of the primary atomic and ionic spectral lines analysed elsewhere in this work, plus the OH $119 \mu\text{m}$ doublet.

15–30 (depending on the specific line), higher than the mean value of the amplification factors.

This is because the scaling stacking method has a systematic bias. We have scaled all spectra to the $500\text{-}\mu\text{m}$ flux of Eyelash, which actually has the highest flux in the sample. This would actually artificially bias all spectra to a higher amplification factor (compared to the mean value) for the final stacked spectrum. Furthermore, the higher S/N of Eyelash and its very high amplification factor (~ 37.5 Swinbank et al. 2011) may further bias the final amplification to high values.

6.2 SED stacking

To probe the average dust properties and the mean IR luminosity, we also stack the IR photometry data and generate a mean intrinsic SED. We combine all the IR photometry data for each target, blue

shift the PACS, SPIRE and 1.4-GHz radio fluxes to their rest frequencies, derive the luminosity for each band, and correct for the lensing magnifications. Then we fit a single MBB with a power-law synchrotron emission. The stacked mean SED and the rest-frequency luminosities of the continuum data are shown in Fig. 10. We fit the SED with a single MBB with a dust emissivity slope index of $\beta = 1.8$, resulting a dust temperature of $\sim 45 \pm 5 \text{ K}$, close to the SED modeling and dust temperatures measured in DSFGs at similar redshifts (e.g. Swinbank et al. 2014). The average dust mass is $3.7 \pm 0.5 \times 10^8 M_{\odot}$, which corresponds to an H_2 gas mass of $\sim 3.7 \pm 0.5 \times 10^{10} M_{\odot}$, when a typical dust-to-ISM mass ratio of ~ 100 is adopted for metal-rich galaxies (e.g. Swinbank et al. 2014; Scoville et al. 2017).

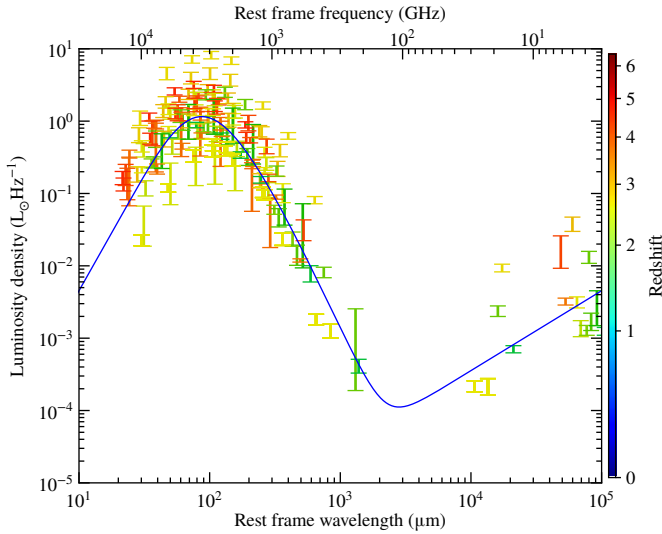


Figure 10. The rest-frame stacked SED (blue line) derived from fitting the power-law dust temperature distribution model (i.e., Kovács et al. 2010) to all demagnified photometric points (colourful dots) of the members of the sample for which lensing model and spectroscopic redshift are available. Colours show the different redshifts of the sources.

Transitions	$L^{\text{intrinsic}}$	$M_{\text{H}^+}^{\text{min}}$	L^{scale}	$\mu M_{\text{H}^+}^{\text{min}}$
Unit	$10^9 L_{\odot}$	$10^8 M_{\odot}$	$10^9 L_{\odot}$	$10^8 M_{\odot}$
[O III] 52- μm	14 ± 2	0.36 ± 0.1	200 ± 25	5 ± 1.4
[O I] 63- μm	1.7 ± 0.3		79 ± 8	
[O III] 88- μm	3.3 ± 0.3	0.9 ± 0.1	87 ± 5	24 ± 1.4
OH 119- μm^{\dagger}	-2.9 ± 0.6		-66 ± 8	
[N II] 122- μm	1.5 ± 0.3	7.4 ± 1.5	36 ± 5	180 ± 25
[C II] 158- μm	7.6 ± 0.2		216 ± 4	
[N II] 205- μm	< 0.9		< 18	

Table 6. Measured line properties in the stacked spectra. $M_{\text{H}^+}^{\text{min}}$ is the estimated minimum ionised gas mass calculated from [N II] 122- μm and [O III] 88- μm lines, following the method used in Ferkinhoff et al. (2010). \dagger : The OH flux is combined from two velocity components. μ is the stacked amplification factor for each line, which ranges about 15–30, depending on the specific line and weighting adopted (see Section 6.1).

6.3 Molecular absorption features

In the two weighted stacked spectra, we find clear absorption corresponding to the OH 119- μm feature, with robust individual detections seen in the spectra of G09-v2.19 and SMM J2135–0102, the latter presented first by George et al. (2014). If we remove SMM J2135–0102 and G09-v2.19 from the sample then the OH absorption feature remains after re-stacking. In the median stacked spectrum, the OH 119- μm absorption feature is still clearly detected. This indicates that this OH 119- μm absorption feature is likely common for the DSFGs in our sample, and is not dominated by a few strong targets.

Blueshifted OH 163- μm line has also been observed in emission towards high-redshift galaxies (Riechers et al. 2014). This feature provides further evidence that out-flowing molecular gas may be common within the high-redshift DSFG population, despite being difficult to observe. However, further analysis of this detection is beyond the scope of this work.

To derive the equivalent width of the OH absorption line, we create another stack designed to include both the line emission and the continuum. We take the SED models derived in Section 3.1, in-

terpolate the SED to the observed frequency of the absorption line, then add the continuum intensity. We then stack the spectra with the added continuum contribution, adopting the same weighting scheme as in Section 6 for consistency. Finally, we fit a second-order polynomial baseline to the continuum and normalise the spectra to unity to derive the equivalent width. These continuum-adjusted, stacked spectra are shown in Fig. 11. The uncertainties on the integrated opacities were estimated as $\Sigma_{\tau} \sqrt{\delta V \Delta V_{1/2}}$ where Σ_{τ} is the r.m.s. uncertainty on the opacity for the velocity resolution δV and $\Delta V_{1/2}$ is the half-maximum velocity width.

The critical densities of the two OH ${}^2\Pi_{3/2} J = 5/2-3/2$ transitions are very high (Table 5) and their upper level energies are ~ 120 K. This makes it difficult to excite these transitions to high- J levels – we can anticipate that most of the OH molecules are in the ground state and well mixed in the low-density gas along the line of sight. This assumption is supported by the fact that we do not detect any obvious signals of another ground transition of OH $J = 3/2-2/1$ at 79- μm , nor the other high lying doublet of OH ${}^2\Pi_{3/2}-{}^2\Pi_{1/2} J = 3/2-2/1$ at 84.6- μm (see Fig. 11). These transitions were detected in absorption or emission in nearby local compact (U)LIRGs, e.g., Mrk 231, NGC 4418 and Arp 220, where multiple transitions of OH have been detected with absorption depths comparable to their 119- μm OH features (e.g. Sturm et al. 2011; González-Alfonso et al. 2012; Spoon et al. 2013).

We follow the method in González-Alfonso et al. (2014) to calculate the theoretical ratios of the equivalent width between OH 119- μm , OH 84- μm and OH 79- μm . For optically thin absorption and ignoring any possible emission components and assuming a uniform filling factor of unity (i.e. recovering all of the continuum emission in the line of sight), the equivalent width of the absorption lines is given by:

$$W_{\text{eq}} = \lambda^3 g_u A_{\text{ul}} \frac{N_{\text{OH}}^l}{8\pi g_l}, \quad (3)$$

where λ is the wavelength, A_{ul} is the Einstein coefficient for spontaneous emission, g_u and g_l are the statistical weighting factors of the upper and lower levels and N_{OH}^l is the OH column density in the lower transition, which is ${}^2\Pi_{3/2} J = 3/2$ for OH 119- μm .

In the optically thin limit, the OH119-to-OH84 equivalent width ratio is ~ 0.84 . Although the OH 84- μm absorption line is often seen in local (U)LIRGs at similar equivalent width as the 119- μm line (González-Alfonso et al. 2015, 2017), we have only a non-detection for the OH 84- μm line in our stacked spectra. This indicates that the OH population at the ${}^2\Pi_{3/2} J = 5/2$ energy level is much less than that on the ground level, ${}^2\Pi_{3/2} J = 3/2$. This means that the average excitation of OH in our lensed DSFGs is low, with most OH molecules in the ground energy level, and there are much fewer OH molecules in the $J = 5/2$ level than the $J = 3/2$ level, compared to what has been found in local ULIRGs.

On the other hand, the OH119-to-OH79 equivalent width ratio is ~ 39.3 , which is consistent with the non-detection of the OH 79 μm absorption line in our stacked spectrum, supporting the relatively optically thin assumptions. However, in local (U)LIRGs, both lines are often detected at similar equivalent widths, which show optically thick conditions (e.g. González-Alfonso et al. 2017).

Unfortunately, our spectral resolution (around ~ 400 km s $^{-1}$ at 119- μm) hinders attempts to identify any P-Cygni profiles, or to set constraints on the maximum velocity of the OH lines, given the signal-to-noise ratio of our stacked spectrum, even without apodisation applied. For nearby local ULIRGs and QSOs, Veilleux et al.

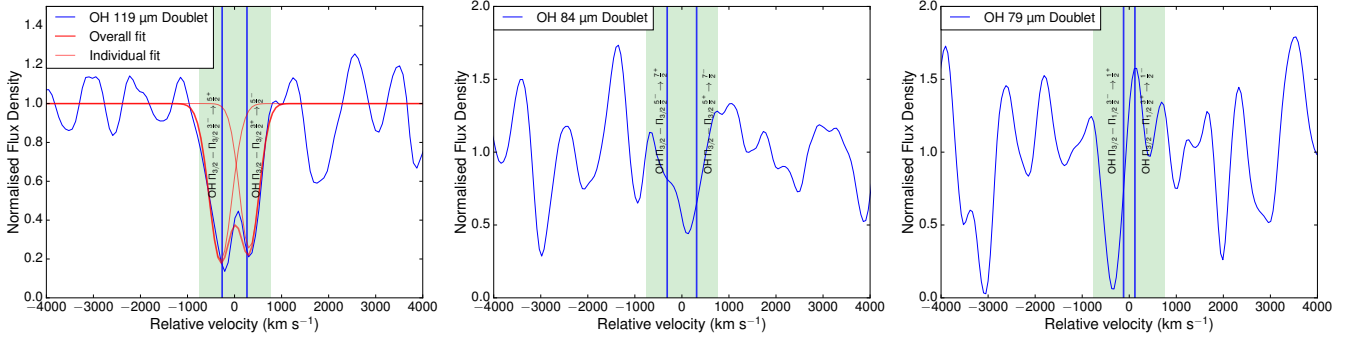


Figure 11. Normalised OH line profile of the stacked spectrum, using their intrinsic luminosity and continuum contribution interpolated from SED fitting. *Left:* stacked OH 119 μm spectrum. The absorption feature is fitted with two Gaussian components, centered at the rest frequencies of the OH doublet transitions, $\nu_{\text{rest}} = 2514.31$ GHz for OH $\Pi_{3/2} - \Pi_{3/2} \frac{5}{2}^+ - \frac{3}{2}^+$ and $\nu_{\text{rest}} = 2509.95$ GHz for OH $\Pi_{3/2} - \Pi_{3/2} \frac{5}{2}^+ - \frac{3}{2}^-$. *Middle:* stacked OH 84- μm spectrum. *Right:* stacked OH 79- μm spectrum.

(2013) found a median outflow velocity of around -200 km s^{-1} . Such a velocity for the DSFGs would not be resolved by our data. We fit identical Gaussian profiles to both transitions of the OH absorption doublet and find their line centres to be consistent with their rest frequencies.

Following George et al. (2014), we can estimate an upper limit for the OH column density assuming optically thin OH absorption. To derive the optical depth of the absorption lines, we assume that the filling factor of the continuum source and the foreground molecular gas is unity. The line optical depth, $\tau(\nu)$, is given by:

$$\tau(\nu) = -\ln\left(\frac{I(\nu) - I_{\text{cont}}}{I_{\text{cont}}}\right), \quad (4)$$

where $I(\nu)$ is the depth of the absorption relative to the continuum level as a function of velocity ν and I_{sat} is the continuum intensity. The equivalent width of the OH 119- μm absorption features is estimated to be $\sim 1050 \text{ km s}^{-1}$. We calculate the total OH column density following Mangum & Shirley (2015) and George et al. (2014):

$$N_{\text{total}}^{\text{OH}} = \frac{4\pi}{h\nu} Q(T_{\text{ex}}) \frac{1}{B_{21} g_u} \frac{\exp\left(\frac{E_u}{k_B T_{\text{ex}}}\right)}{\exp(-h\nu/k_B T_{\text{ex}}) - 1} \int \tau dV \quad (5)$$

where we assume optically thin lines and a filling factor of unity. E_u is the upper level energy of this transition, $Q(T_{\text{ex}})$ is the partition function (where we adopt the Q values given by the JPL database⁷), $g_1 = 3$ for an ortho level and $g_1 = 1$ for all any other cases. $B_{21} = A_{21}/(2h\nu^3/c^2)$, where $A_{ul} = \frac{64\pi^4\nu^3}{3hc^3} |\mu|^2$ is the Einstein coefficient for spontaneous emission, μ is the electric dipole moment and ν is the rest frequency of the line.

As shown in aforementioned discussion, the non-detection of 84- μm and 79- μm lines indicates that the OH excitation is low. We therefore adopt a low excitation temperature of 9 K (comparable to the cosmic microwave background temperature, T_{cmb} , at $z = 2.5$) and derive an estimate of the OH column density: $\sim 2 \times 10^{15} \text{ cm}^{-2}$. Assuming the OH abundance is the same as the Galactic value, $X_{\text{OH}} = 5 \times 10^{-6}$ (e.g. Goicoechea & Cernicharo 2002), the average H_2 column density is $\sim 4 \times 10^{20} \text{ cm}^{-2}$, which is considerably lower than the typical H_2 column densities found in SMGs (e.g. Simpson

et al. 2017), which indicates that either the OH abundance in DSFGs is much lower than that found in local galaxies or, more likely, that the observed OH is associated with out-flowing gas and does not trace the total column of H_2 .

7 ATOMIC AND IONISED LINES

The [C II] 158- μm and [O I] 63- μm lines often dominate the cooling of neutral gas in starburst galaxies: and ionic fine-structure lines like [N II] and [O III] normally dominate the FIR cooling of the ionised gas, which is mostly in H II regions (e.g. De Looze et al. 2014; Hughes et al. 2015). The [O III], [N II], and [O II] lines at optical wavelengths have the strongest cooling in H II regions (e.g. Osterbrock & Ferland 2006), but most of the optical cooling lines are absorbed by dust gains in the dusty starburst galaxies. Dust grains re-emit most of the incident FUV and optical radiation in the FIR and as a result the luminosity ratio, [O I]/FIR, [O III]/FIR, and [C II]/FIR, typically $\sim 0.01 - 0.1 \%$ in high-redshift DSFGs (see Fig. 6) provides an estimate of the efficiency of gas heating. This value is, however, affected by the non-negligible fraction of [C II] 158- μm produced in H II regions, the strong dependence of the carbon ionisation front upon metallicity (e.g. Croxall et al. 2017) and the optical depths of the lines, in particular $\tau_{[\text{O I}] 63 \mu\text{m}} \sim 1-3$ (e.g. Liseau et al. 2006; Hughes et al. 2015). The [O III] and [N II] lines come only from the ionised gas phase – the [N II] lines originate from both diffuse and dense H II gas phases – offering an excellent estimate of the total mass of ionised gas (e.g. Liseau et al. 2006; Zhao et al. 2016a,b). With similar critical densities, but different ionisation potentials, the ratio [O III] 88- μm /[N II] 122- μm provides a good tracer of the stellar effective temperature of the ionising source.

7.1 Ionised gas mass

The extreme starburst conditions in the SMG sample supplies enormous amount of heating power to ionise neutral gas, mostly due to the feedback of star-formation through UV radiation, X-rays, outflows, and shocks, etc. It has been claimed that some high redshift starburst galaxies have very high mass ratios between ionised gas and molecular gas, $M(\text{H}^+)/M(\text{H}_2) \gtrsim 10 - 20\%$, in SMMJ02399 and Cloverleaf (Ferkinhoff et al. 2011), by calculating the minimum ionized gas mass, $M_{\text{H}^+}^{\text{min}}$, traced by the [N II] and [O III] lines. Following the method used in Ferkinhoff et al. (2010, 2011), we

⁷ <http://spec.jpl.nasa.gov/ftp/pub/catalog/doc/d017001.cat>

assume that nitrogen in H II regions is singly ionised and the [N II] emission could represent all the diffuse low-density ionised gas, neglecting other energy levels (e.g. [N III] or [O II], [O V] and higher). The minimum ionised gas mass can be estimated from:

$$M_{\text{H}^+}^{\text{min}} = F_{\text{line}} \cdot \frac{4\pi \cdot D_L^2 \cdot m_{\text{H}}}{g_{\text{upper}}/g_{\text{tot}} A_{10} h \nu_{\text{line}} X_{\text{line}}}, \quad (6)$$

where F_{line} is the line flux in Jy km s^{-1} , D_L is the luminosity distance in Mpc, m_{H} is the mass of a Hydrogen atom, A_{10} is the Einstein spontaneous A coefficient, g_{upper} is the statistic weighting of the upper energy level ($= 3$ for [N II] 122- μm and [O III] 88- μm lines), $g_{\text{tot}} (= \sum g_i \exp(-\Delta E_i/kT))$ is the partition function, h is the Planck constant, ν_{line} is the rest frequency of the emission line and X_{line} is the relative abundance of the studied ionised atoms (N or O) relative to ionised hydrogen (H^+). For the minimum mass estimate, we assume that $X_{\text{NII}} = \text{N}/\text{H}$, $X_{\text{OIII}} = \text{O}/\text{H}$, and we adopt the relative abundances (comparing to H) of N and O to be 9.3×10^{-5} and 5.9×10^{-4} (i.e. the H II region abundances in [Savage & Sembach 1996](#)).

We calculate $M_{\text{H}^+}^{\text{min}}$ using the [N II] 122- μm [O III] 88- μm and [O III] 52- μm lines for both kinds of stacked spectrum and list them in Table 6. We find that $M_{\text{H}^+}^{\text{min}}$ derived using only the [O III] 88- μm lines are about 12–13% of those derived using the [N II] lines, likely because the [O III] 88- μm lines trace highly ionised gas and the [N II] lines probe almost all phases of H^+ , including the diffuse phase as well as gas ionised by less energetic UV photons. Similarly the $M_{\text{H}^+}^{\text{min}}$ derived using [O III] 52- μm lines are 20%–30% of that derived using [O III] 88 μm , likely due to the much higher critical density of [O III] 52- μm , which is almost solely contributed by the dense gas phase ($n_e > 10^3 \text{ cm}^{-3}$).

We derive a $M_{\text{H}^+}^{\text{min}}$ of $\sim 7.4 \pm 1.5 \times 10^8 M_{\odot}$ for the intrinsic stacked spectrum and $180 \pm 25/\mu \times 10^8 M_{\odot}$ for the scaled spectral stack. The relative ratio between the [O III]-derived $M_{\text{H}^+}^{\text{min}}$ and the [N II]-derived $M_{\text{H}^+}^{\text{min}}$ are similar for the two different stacked spectra. We list their $M_{\text{H}^+}^{\text{min}}$ values in Table 6.

7.2 [N II] lines

The two lines of [N II] are particularly interesting since they are excited solely in ionised gas (H II) given their ionisation potential of 14.53 eV, i.e. a value just above the ionisation energy of hydrogen, 13.6 eV, which indicates that they are potentially related to star-forming activity. Both lines have relatively low critical densities (44 cm^{-3} for [N II] 205- μm and 300 cm^{-3} for [N II] 122- μm , see Table 5), meaning they are easily excited in the diffuse ionised ISM. Both lines are normally optically thin at FIR wavelengths, even for high column densities and extreme conditions (e.g. [Goldsmith et al. 2015](#)). Given their long wavelengths, they are much less affected by dust extinction compared to their optical/NIR transitions. As such, these lines are independent extinction-free indicators of the current SFR (e.g. [Zhao et al. 2013](#)).

Both [N II] lines lie at high frequencies that are inaccessible from ground-based telescopes. Only FIR space telescope missions (e.g. *ISO* and *Herschel*) could detect the line in the Milky Way and some local galaxies (e.g. [Wright et al. 1991](#); [Goldsmith et al. 2015](#); [Zhao et al. 2016a](#); [Herrera-Camus et al. 2016](#); [Croxall et al. 2017](#)). The [N II] lines, especially the [N II] 205- μm line, are found to be usually 10–50 \times weaker than the [C II] 158- μm line, making it difficult to detect from redshifted galaxies. After some early searches in the distant Universe (e.g. [Ivison & Harrison 1996](#)), ALMA has

begun to observe these lines in high-redshift galaxies (e.g. [Ferkinhoff et al. 2015](#); [Pavesi et al. 2016](#)). Self-absorption may also play a role in the [N II] line ratio, which will be discussed in Section 8.3.

In Fig. 12, we plot the theoretical line ratio between the [N II] 122- μm and [N II] 205- μm lines ($R_{122/205}$) following [Rubin \(1985\)](#) and ([Draine 2011](#)). We find that the minimum value of $R_{122/205}$ is around unity at relatively low electron densities ($\sim 1\text{--}10 \text{ cm}^{-3}$); at high electron densities ($\geq 10^{4\text{--}5} \text{ cm}^{-3}$), $R_{122/205}$ saturates at around 10. We present $R_{122/205}$ models for three electron temperatures ($T_e = 5,000, 10,000$ and $30,000 \text{ K}$) in Fig. 12, showing $R_{122/205}$ as a monotonically increasing function of electron density for each temperature. $R_{122/205}$ is not sensitive to T_e , but is very sensitive to n_e . Clearly, this makes the $R_{122/205}$ ratio an excellent tracer of n_e , with little degeneracy in T_e . Furthermore, the ratio of $R_{122/205}$ seems sensitive across a wide range of n_e between 10 and 10^4 cm^{-3} .

We over-plot a few representative data points measured from the same far-IR [N II] pair from the literature, trying to compare different n_e results obtained using the same tracer. In our Milky Way, an average n_e of 22 cm^{-3} was found using observations made by the *Cosmic Background Explorer* (COBE, [Wright et al. 1991](#); [Bennett et al. 1994](#)). Using *Herschel*, [Goldsmith et al. \(2015\)](#) observed [N II] lines along roughly 100 sight lines across the Galactic disk, mostly close to the inner parts of our Galaxy ($\pm 50^\circ$ of Galactic longitude), and they found most to have n_e between 10 and 100 cm^{-3} (see their Figure 19). In Fig. 12, the average conditions of the warm ionised medium (WIM) are plotted as a gray box in the bottom-left corner. The electron density of the WIM is quite uncertain, and is often taken to be $\sim 0.01\text{--}0.1 \text{ cm}^{-3}$ (e.g. [Taylor & Cordes 1993](#); [Goldsmith et al. 2015](#); [Persson et al. 2014](#)). [Heiles et al. \(1996\)](#) found a low volume filling factor and a relatively high n_e of 5 cm^{-3} , using 1.4-GHz radio recombination lines in the Galactic plane. In our plot we set this value as the highest plausible n_e value for the WIM, and use an arrow showing that it might also be much lower than the gray box.

We also plot the n_e range measured in NGC 891 ([Hughes et al. 2015](#)), as the representative value found for nearby quiescent spirals and in the Milky Way ([Goldsmith et al. 2015](#)). A similar n_e range has been found in the starburst region, 30 Doradus, in the Large Magellanic Cloud (LMC, [Chevance et al. 2016](#)). For local normal galaxies (e.g. [Herrera-Camus et al. 2016](#)) and LIRGs (e.g. [Zhao et al. 2016a](#); [Díaz-Santos et al. 2017](#)) most n_e values range between 10 and 100 cm^{-3} , too. For most local ULIRGs, although higher SFR densities are expected, they lie in the same region as spiral galaxies with the maximum, $n_e \sim 120 \text{ cm}^{-3}$ found in UGC 05101 ([Spinoglio et al. 2015](#)) via [N II] lines. Higher n_e values have also been found in a few spatially resolved regions in our Galaxy and in some nearby starburst regions. In the central regions of IC 342 ([Rigopoulou et al. 2013](#)) and M 82 ([Petuchowski et al. 1994](#)), n_e values are much higher than the average for the disks. Interestingly, the n_e measured in Sgr A* ([Goicoechea et al. 2013](#)) and the ionising peak of the Orion bar ([Bernard-Salas et al. 2012](#)) show the highest values, indicating high-density H II regions compared to the lower densities found to represent the average conditions in galaxies.

Unfortunately, our stacked spectra only give an upper limit for the [N II] 205- μm line flux, so we can provide only a lower limit for $R_{122/205} (> 2$, for a 3- σ limit), which corresponds to an n_e of $> 100 \text{ cm}^{-3}$, i.e., considerably higher than the global average conditions of most local star-forming galaxies. In Section 6.2, we find an average intrinsic IR colour of $S_{70}/S_{100} \sim 0.8$, which

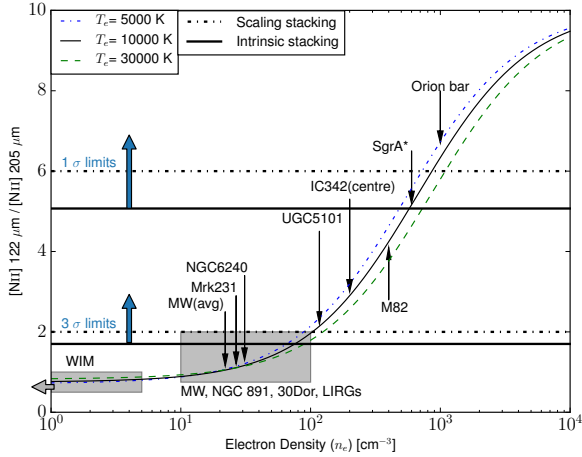


Figure 12. Theoretical line luminosity (in L_{\odot}) ratio between the [N II] 122- μm and [N II] 205- μm lines ($R_{122/205}$) as a function of electron density (n_e), following Rubin (1985) and (Draine 2011). We present $R_{122/205}$ models for electron temperatures $T_e = 5,000$ K (blue dotted), 10,000 K (black solid) and 30,000 K (green dashed). The thick solid and dash dot lines show the 1- σ and 3- σ lower limits of the observed line ratios of $R_{122/205}$, derived from intrinsic stacking and scaling stacking, respectively. We also overplot typical ranges of n_e measured with the same $R_{122/205}$, in the disks of nearby galaxies, in the central regions of galaxies, in the Galactic Centre, and for a few Galactic H II regions.

corresponds to ~ 1.15 in $\nu S_{70}/\nu S_{100}$. Our n_e limit is roughly consistent with the correlation found between $\nu S_{70}/\nu S_{100}$ and n_e by Herrera-Camus et al. (2016). Derived from Equation 6 in Herrera-Camus et al. (2016), n_e is $\sim 90 \text{ cm}^{-3}$, which lies at the high end of their galaxy sample, and has a wide dynamical range of n_e and $R_{122/205}$ for comparison. Most local star-forming galaxies, active star-forming regions in the LMC (e.g., 30 Dor), normal spirals (e.g., NGC 891), LIRGs and ULIRGs (e.g., Mrk 231 and NGC 6240), have a global average n_e between 10 cm^{-3} and 100 cm^{-3} , and show no obvious relations with the global SFR, or L_{IR} . The high n_e found for our stacked DSFG spectrum indicates higher pressure conditions for the ionised gas in their star-formation regions, more like M 82, SgrA*, IC 342 centre and that found in the Orion bar. On the other hand, the electron temperature is not expected to change dramatically (see also Sect. 7.5), so higher n_e values indicate higher pressures of the ionised gas phase.

In our Milky Way, younger H II regions (hyper-compact H II and ultra-compact H II, UCH II) are found to have higher n_e (e.g. Churchwell 2002), however the high n_e likely cannot be attributed to the age of the H II regions because the typical lifetime of an UCH II region is only $\sim 10^5$ years, too brief to play an important role here. Moreover, the extremely high SFRs found in DSFGs produces a prodigious flux of cosmic rays, $\sim 100\text{--}1000\times$ the Galactic value, which efficiently heats up the dense cores that are protected by the dust from UV photons, thereby increasing the Jeans mass of the dense cores (e.g. Papadopoulos 2010). The most massive dense cores can maintain their pressure via self-gravity, helping to confine H II to relatively small regions, such that the average n_e is systematically higher.

7.3 [O III] lines

The [O III] 88- μm and 52- μm lines are important coolants of the ionised phase of ISM in DSFGs because of the high abundance of oxygen. The ionisation potential of [O III] is 35.12 eV, which corresponds to very energetic physical conditions, e.g. the UV radiation from very hot massive stars (O and B stars), X-rays or shocks (e.g. Stasińska et al. 2015). As with the [N II] lines, [O III] line ratios are not sensitive to the electron temperature. The critical densities of the [O III] 88- μm and 52- μm transitions are ~ 500 and 3600 cm^{-3} , respectively, making them a sensitive probe of n_e in relatively dense H II regions.

In Fig. 13, we plot the theoretical line ratio of the [O III] 52- μm and 88- μm ($R_{52/88}$) lines, following Rubin (1985). The range where these lines are relatively sensitive to electron density is between 10^2 and 10^5 cm^{-3} , corresponding to line ratios, $R_{52/88}$, of ~ 0.7 and ~ 10 , respectively. Similar to Fig. 12, we plot $R_{52/88}$ with n_e of 5,000, 10,000 and 30,000 K, which shows that $R_{52/88}$ is not sensitive to T_e .

The [O III] 52- μm and 88- μm transitions have been observed from both Galactic targets and external galaxies. The grey box in the bottom left corner of Fig. 13 shows the n_e range measured with the same [O III] pair in the central region of the Milky Way (i.e. Rodríguez-Fernández & Martín-Pintado 2005), nearby Seyfert galaxies (e.g. Spinoglio et al. 2015) and normal galaxies (e.g. Negishi et al. 2001). These values are consistent with the n_e range measured from the [N II] lines, though [O III] lines are not very sensitive to n_e below a few hundred cm^{-3} . We also label the measured $R_{52/88}$ in the centres of a few typical nearby star-forming galaxies (e.g. M 82, NGC 253; see Duffy et al. 1987; Carral et al. 1994) and the average $R_{52/88}$ measured in Sgr B2 (Goicoechea et al. 2004), which are somewhat higher than the average value measured in galaxies as a whole. This indicates a higher average n_e in the centre of galaxies, consistent with the trend found in M 51 and NGC 4449 using optical observations (e.g. Gutiérrez & Beckman 2010).

We also overplot the $R_{52/88}$ values found in Galactic sources, including the range found in the H II regions of NGC 2024 (Orion B Giannini et al. 2000), G333.6-0.2 (Colgan et al. 1993), and Sgr B2(M) (Goicoechea et al. 2004). These targets show the highest n_e , especially Sgr B2(M) where several ultra-compact H II regions reside in a very small volume.

In Section 7.2 we estimated n_e using [N II] 122- μm and the upper limit from [N II] 205- μm , finding that the n_e found in our DSFGs is higher than 100 cm^{-3} . From the $M_{\text{H}^+}^{\text{min}}$ and n_e derived from [O III] lines, at least 10% of the ionised gas has a very high n_e , $\sim 10^3\text{--}10^4 \text{ cm}^{-3}$. The n_e derived from [N II] and [O III] are both higher than the densities found in local star-forming galaxies (e.g. 30 cm^{-3} Herrera-Camus et al. 2016, see also Figs 12 and 13), where the derived n_e values are consistent with measurements using optical lines (e.g. Zaritsky et al. 1994).

More recent evidence from optical and near-IR studies suggest that n_e in star-forming galaxies at $z \sim 2$ seem to be systematically higher than in local star-forming galaxies, by up to two orders of magnitude (e.g. Bian et al. 2016; Sanders et al. 2016). These studies find a median n_e of $\sim 250 \text{ cm}^{-3}$, consistent with our lower limit for n_e from the [N II] lines, indicating an increase of n_e with redshift for both normal star-forming galaxies and DSFGs.

As revealed in resolved studies of nearby galaxies, n_e tends to be higher in the centres of galaxies, likely due to the strength of the radiation field and the density of the local ISM (e.g. Herrera-Camus et al. 2016). High-redshift DSFGs may have both a higher radiation field, revealed by the [O III] to [N II] ratio, and a denser ISM, which

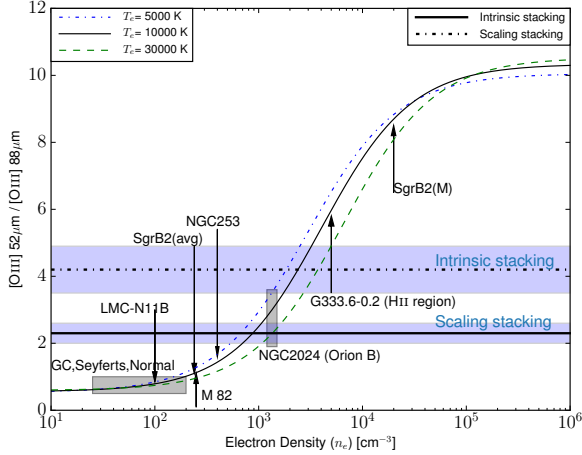


Figure 13. Theoretical line luminosity (in L_{\odot}) ratio between the [O III] 52- μm and [O III] 88- μm lines ($R_{52/88}$), as a function of n_e , following Rubin (1985). We present $R_{52/88}$ models for electron temperatures, $T_e = 5,000$ K (blue dotted line), 10,000 K (black solid line) and 30,000 K (green dashed line). The thick solid line and dash dot line show the observed $R_{52/88}$ ratios derived from intrinsic stacking and scaling stacking, respectively. The blue shadow regions show the 1σ error bar of the observed ratios. We also overplot typical ranges of n_e found in the disks of nearby normal galaxies, the LMC, the central regions of our Galaxy, and a few Galactic H II regions.

confines the expansion of H II regions and keeps n_e relatively high. However, optical measurements in both galaxy populations from the Sloan Digital Sky Survey (SDSS) and local analogs of high-redshift star-forming galaxies find that those with higher SFR surface densities (Σ_{SFR}) tend to have lower n_e (Bian et al. 2016); this is not consistent with far-IR [N II] results, which show a tight correlation between Σ_{SFR} and n_e (Herrera-Camus et al. 2016).

7.4 [C II] emission from ionised gas

To trace the origins of the [C II] 158- μm emission, it is important to separate between the [C II] luminosity fraction contributed by the neutral gas and that contributed by the ionised gas. The fraction from ionised gas is normally small $\sim 20 - 40\%$ (Croxall et al. 2017), but is not negligible, especially given the uncertainty in the C/N abundance ratios. The [C II]/[N II] line ratio is sensitive to the ionised gas fraction that contributes the [C II] emission, because [N II] lines come only from the ionised gas, and should pick up the majority of it, given their low critical densities.

In the ionised gas phase, both the [N II] and [C II] lines are excited by collisions with electrons, and neither line is sensitive to electron temperature. Using the line ratio between [N II] lines and [C II] 158- μm , one can probe the contribution to the observed [C II] intensity from the ionised gas phase with little dependence on n_e and T_e (e.g. Oberst et al. 2006, 2011; Hughes et al. 2015; Pavesi et al. 2016).

Although the [N II] 122- μm line has a higher critical density ($\sim 300 \text{ cm}^{-3}$) than that of the [C II] line, the ratio dependency on the electron density can be well modeled. We can use the upper limit of n_e derived from the two [N II] lines to set a further constraint. In Fig. 14, we plot the theoretical line ratio between [C II] 158- μm and [N II] 122- μm in the ionised gas phase. The observed [C II]/[N II] ratios include [C II] emission with contribution from neutral gas phase, so the ratio is always above the theoretical curves

(for the ionised gas phase only). The line ratio of [C II] 158- μm to [N II] 122- μm does depend on n_e . However, if the electron density is higher than a few hundred cm^{-3} (well above the critical densities of both lines), both the [N II] 122- μm and the [C II] 158- μm lines will be excited efficiently. For the abundances of N/H and C/H, we adopt 7.76×10^{-5} and 3.98×10^{-4} , respectively – typical H II region values (Savage & Sembach 1996). Because the [C II]/[N II] ratio is sensitive to abundances, we overplot the ratio using typical Galactic abundances found in diffuse clouds (7.94×10^{-5} for N; 1.38×10^{-4} for C – Savage & Sembach 1996) for comparison, and to present the uncertainty. More detailed discussion on the abundances will be presented in Section 8.4.

We plot the [C II] 158- μm /[N II] 122- μm line ratio curves at $T_e = 5,000$ K, 10,000 K and 30,000 K, which are consistent with each other, showing that these ratios are not sensitive to the electron temperature. The [C II] 158- μm /[N II] 122- μm ratio has a stronger dependency on the electron density, which can be constrained from the line ratio of the two [N II] lines. All line ratios decrease monotonically with electron density, and saturate at the high density end ($\geq 1000 \text{ cm}^{-3}$), where n_e is much higher than the critical densities of both lines.

The observed ratio of [C II] 158- μm and [N II] 122- μm in our stacked DSFG spectrum is 5.1 ± 1.0 , which is plotted as the shaded area. We find a lower limit for the electron density of 100 cm^{-3} , derived from the 3σ limit for the [N II] line ratios; the upper limit for n_e is 2000 cm^{-3} , derived using the [O III] lines, which are from the more energetic and denser H II regions. If we use the Galactic diffuse gas abundances (Savage & Sembach 1996), the contribution from ionised gas to the [C II] line is $\sim 10-15\%$. However, if H II region abundances are adopted (Savage & Sembach 1996), the ionised gas could contribute up to 60% of our [C II] emission. The ratios derived from the diffuse gas abundances is about $3\times$ less than those derived from abundances in H II regions. If an electron density of 100 cm^{-3} and an electron temperature of 10,000 K are assumed; this contribution drops to 30–40% for an n_e of 1000 cm^{-3} .

7.5 Radiation field

The [N II] 122- μm and [O III] 88- μm lines have similar critical densities $\sim 300-500 \text{ cm}^{-3}$, but their ionisation potentials differ by $\times 2$ from 14.5 to 35 eV. Both lines are normally optically thin, and are insensitive to the electron temperature. Their ratio is sensitive only to the abundance and radiation field, which is mainly controlled by the relative fraction of UV photons at different energies (e.g. Ferkinhoff et al. 2011).

Following Ferkinhoff et al. (2011), we can probe the stellar effective temperature using the ratio between the [N II] 122- μm and [O III] 88- μm lines in our stacked DSFG spectrum. We adopt the H II region models calculated by Rubin (1985), who derived the theoretical intensities of the ionised lines with different metal abundances, electron densities and stellar effective temperatures. Model ‘K’ in Rubin (1985) has elemental abundances close to the values in Galactic H II regions (e.g. Savage & Sembach 1996). The line intensity is proportional to abundance for optically thin lines, so we correct the line ratio map with the Galactic H II region abundances (Savage & Sembach 1996, see also Section 7.4), to provide a more consistent and realistic comparison. With the H II region abundances, the [O III]/[N II] ratio is about $1.15\times$ higher than those in Rubin (1985) – this does not influence our conclusions. The ratios between [O III] 88- μm and [N II] 122- μm from both our stacking methods are $\sim 2.2 \pm 0.5$ (intrinsic stacking) and 2.4 ± 0.3 (scaling

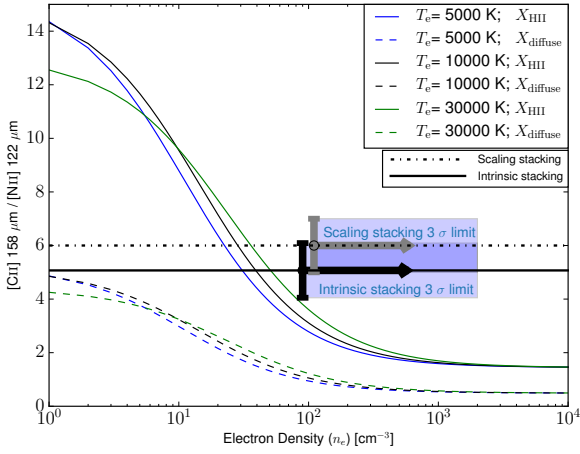


Figure 14. Theoretical line luminosity (in L_{\odot}) ratio of [C II] 158- μm and [N II] 122- μm as a function of electron density. This calculation considers the [C II] 158- μm emission that is excited by collisions with electrons only. We plot the [C II] 158- μm /[N II] 122- μm line ratios for 5000 K (blue), 10,000 K (black) and 30,000 K (green). Solid curves show the ratio using the Carbon and Nitrogen abundances measured in Galactic H II regions; dashed curves show the ratio with abundances in diffuse gas (e.g. [Savage & Sembach 1996](#)). The observed ratios between [C II] 158- μm and [N II] 122- μm in our stacked DSFG spectrum are plotted as thick black line and dash dotted line, for intrinsic stacking and scaling stacking, respectively. The blue shadow regions show the 1σ error bar of the observed [C II] 158/[N II] 122- ratios. The two arrows in the x-axis show the lower 3σ limits of electron density derived from $R_{122/205}$ ratios derived from the two stacking methods. The maximum allowed electron density is 2000 cm^{-3} , which is the n_e derived from [O III] lines.

stacking), fully consistent with each other. These values correspond to a stellar effective temperature of $\sim 35,000\text{ K}$, which corresponds to O8–O9 stars, according to [Vacca et al. \(1996\)](#). These values are less than that obtained from the resolved compact starburst center in a local ULIRG, Arp299, but are more consistent with the resolved results in most local LIRGs and AGN hosts on (sub-)kpc scales ([Herrera-Camus et al. 2018a,b](#)).

However, the global ratio of [N II]/[O III] is not just affected by abundances and the hardness of the radiation fields, but also sensitive to variation in the filling factors of the observing beam. The lower ionisation potential of [N II] makes it expected to be more extended than the [O III] 88 μm line. Only O stars can emit powerful UV photons to excite this line. This means that our [N II] emission is contributed from both O stars and B stars. On the other hand, [N II] lines have a very low critical densities, so its collisional excitation saturates in H II regions well before [O III] lines. If we zoom into smaller [O III] emitting regions, the [O III]/[N II] ratio would be higher than that obtained from global average. The combination of the two leads to [N II] dominating the extended, diffuse, ionized gas. So, our derived stellar effective temperature is actually a lower limit for that in the dense H II regions with [O III] emission.

To generate the observed [N II] 122- μm emission, $\sim 3 \times 10^7$ or $\sim 5 \times 10^7$ O8 or O9 stars are needed, respectively, assuming an n_e of 1000 cm^{-3} in the [Rubin \(1985\)](#) model. From the same models we can also derive the ionised gas mass from the [N II]122- μm emission. We find that different values of n_e give similar ionised gas masses (intrinsic), ranging between $1\text{--}2 \times 10^9 M_{\odot}$, consistent with the $M_{\text{H}^+}^{\text{min}}$ derived in the previous section. This is about $10\times$ less than that estimated for SMM J2135–0102 by [Ferkinhoff](#)

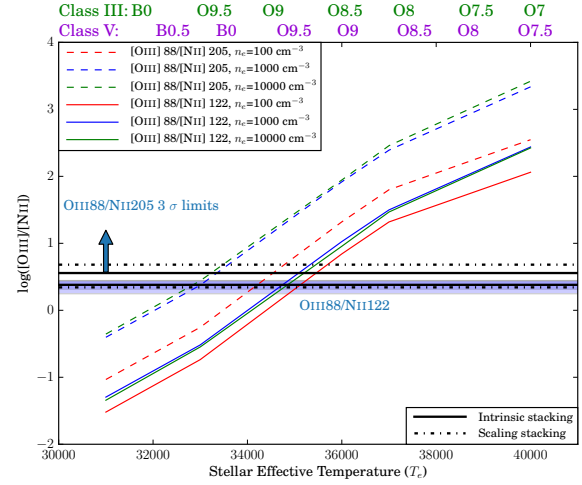


Figure 15. Theoretical line luminosity (in L_{\odot}) ratio of [O III] 88- μm and the [N II] lines as a function of the effective stellar temperature, derived from the [Rubin \(1985\)](#) H II models. We plot the observed [O III] 88- μm to [N II] 122- μm ratios and the upper limits of the observed [O III] 88- μm to [N II] 205- μm ratios, derived from for intrinsic stacking (black thick line) and scaling stacking (dash dotted line), respectively. The upper axis labels show stellar types of OB stars of corresponding electron temperature for luminosity class III (Green) and luminosity class V (Purple) stars, according to the classification of [Vacca et al. \(1996\)](#).

[et al. \(2011\)](#). However, for the galaxies with CO detections, the H_2 gas mass ranges from 1×10^{11} to $5 \times 10^{11} M_{\odot}$. The ionised gas mass fraction is estimated to be less than 2% of the molecular gas mass, assuming an α_{CO} conversion factor of 0.8 (typical value for ULIRGs [Bolatto et al. 2013](#)). This is consistent with the ionised gas fraction found in local galaxies (e.g. [Brauer et al. 2008](#); [Ferkinhoff et al. 2011](#)), but much less than the fractions found in two high-redshift DSFGs (35% for Cloverleaf quasar and 16% for SMM J2135–0102; [Ferkinhoff et al. 2011](#)). On the other hand, active galactic nuclei (AGNs) can increase the UV radiation and bias the hardness of the radiation field (e.g. [Groves et al. 2004](#)), which shows that a high [O III]/[N II] ratio can be easily achieved in the high-pressure narrow-line region of AGNs.

Using the [Si II] 34- μm and [S III] 33- μm lines in the stacked PACS spectra for a similar sample of high redshift lensed starbursts, [Wardlow et al. \(2017\)](#) found that SMGs on average contain AGNs, followed the method proposed by [Dale et al. \(2006, 2009\)](#). However, statistical studies based on X-rays and mid-infrared spectroscopy studies find that the fraction of DSFGs harbouring powerful AGN is small, thus they are unlikely to dominate the gas heating (e.g. [Alexander et al. 2005](#); [Coppin et al. 2010](#); [Wang et al. 2013b](#)). On the other hand, in the stacked PACS spectrum [Wardlow et al. \(2017\)](#) found non-detection for [O IV], which is expected to arise from AGNs due to the high ionisation potential. Thus we conclude that the AGN contamination to the far-IR lines should be negligible for our stacked results.

7.6 [O I] lines

We detect [O I] 63- μm emission in our stacked spectrum, with an upper limit for the [O I] 145- μm transition. These two lines have identical energy potentials for further ionisation, but they have different upper level energies, $\Delta E/k$, of 228 and 327 K above the ground state. The critical densities of the 145- and 63- μm transi-

tions are $\sim 10^4$ and $\sim 10^5 \text{ cm}^{-3}$, respectively, so both lines are sensitive to dense and warm neutral gas. Their line ratio is a powerful diagnostic of the density and temperature of the emitting regions, under the optically thin assumption (e.g. Liseau et al. 2006; Tielens & Hollenbach 1985). The heating of [O I] lines could be powered by radiative shocks (e.g. Hollenbach & McKee 1989; Draine & McKee 1993) or FUV photons from massive stars, given the high SFRs of these galaxies.

Given the non-detection of the [O I] 145- μm transition, we can get an upper limit for the ratio of [O I] 63/145 > 6 (1σ) or > 1.3 (3σ). These exclude a cold ($< 50 \text{ K}$) and optically thick scenario (see, e.g., Figure 4 of Liseau et al. 2006). If [O I] 63- μm is indeed optically thin, then the [O I] 145- μm emission is expected to be even further below our detection limit.

If the [O I] 63- μm emission is dominated by dissociative shocks, its intensity is proportional to the mass-loss rate, which is caused by the dominance of the cooling via [O I] 63- μm (Draine & McKee 1993; Hollenbach & McKee 1989). However, the excitation from PDRs is another strong power source for [O I] lines. The [C II]158- μm /[O I]63- μm luminosity ratio provides a way to discriminate between PDRs and shocks: this ratio is generally ≤ 10 in PDRs and ≥ 10 in shock-dominated regions (Hollenbach & McKee 1989). Our stacked DSFG spectrum shows [O I]63- μm /[C II]158- μm ~ 4 , on the high end of the resolved local starburst regions or AGN centres, and much higher than the values measured in normal galactic disks (Herrera-Camus et al. 2018a). Our global average ratios indicate that the [O I] emission must have some contribution from shocks, but shock is also not dominant. Moreover, the [O I] 63- μm emission often suffers from self-absorption effects (see Section 8.3), which has been seen both in the Milky Way molecular clouds (e.g. Ossenkopf et al. 2015), and in local starbursts (Luhman et al. 2003; Rosenberg et al. 2015). If the [O I] self-absorption also plays a role, the intrinsic ratio of [O I]63- μm /[C II]158- μm should be even higher.

8 CAVEATS

8.1 Statistics in the line ratios

In this paper, we have stacked *Herschel* SPIRE FTS spectra and derived the average physical conditions of the fine-structure lines using their relative ratios. We have to note that the average of ratios (e.g., $\langle [\text{N II}] 205\text{-}\mu\text{m} / [\text{N II}] 122\text{-}\mu\text{m} \rangle$) are not necessarily the same as the ratio of the averages $\langle [\text{N II}] 205\text{-}\mu\text{m} \rangle / \langle [\text{N II}] 122\text{-}\mu\text{m} \rangle$, which introduces an extra uncertainty in the statistics (e.g., Brown 2011).

For most lines, we do not have individual detections of the lines in the SPIRE spectra, so it is not possible to directly measure individual line ratio and get the average. Although a ratio of line flux averages (observational constraint) might be similar to an average of ratios (physical condition), the expectation – the average of the ratio – would always be larger than the ratio of the averages. Thus, our line ratios from stacked spectra are underestimated (Brown 2011). The derived n_e and radiation hardness are likely more extreme than those we derived. Furthermore, this speculation is especially true when the undetected lines are upweighted when adopting average weighted by noise levels.

8.2 Biases in stacking

We have stacked a sample of ~ 40 galaxies at a redshift range between 1.5 to 3.6. The *Herschel* SPIRE FTS has a fixed observing frequency range so the final line coverage is not uniform. Thus, the stacked averaged lines are actually from different galaxies, which makes another potential bias to the final line ratios. This effect is obvious at both the low- and high-frequency ends, especially for the [O III] 52- μm and [O I] 63- μm lines, which are more contributed by galaxies at higher redshifts. Moreover, the spectra are noisier in the band edges, which makes the S/N even lower for these lines.

Our first two stacking methods (intrinsic luminosity and scaling to Eyelash) both adopt weights of $1/\sigma^2$, which preferentially weight galaxies with better S/N levels (Eyelash) and smaller redshifts. The intrinsic luminosity weighting is relatively more biased to higher S/N targets, whilst the scaling method is more biased to higher luminosity targets. Although a straight (equally weighted) stacking could avoid weighting biases, such stacking will be highly dominated by non-Gaussian noises, especially the edges of both bands that cover across the whole frequency range. A median stacking of the L_{IR} normalised spectra is less biased by galaxy properties, and it can test if some weak features are common for the sample, e.g., the OH 119- μm absorption line. However, the median stacked spectrum is noisier and seems still contaminated by the noisy edges of individual band. This method also does not allow to calculate median of the dust continuum or L_{IR} using the same weighting from spectral line stacking.

8.3 Absorptions to the fine-structure lines

During our analysis, we accounted for the integrated line luminosities and neglected self-absorptions. This might be severe for the [O I] lines, which have been found in various Galactic and extra-galactic conditions (Fischer et al. 1999; Liseau et al. 2006; González-Alfonso et al. 2012; Fischer et al. 2014). The [C II] 158- μm line also often shows self-absorption features in Galactic studies (e.g. Gerin et al. 2015; Graf et al. 2012), and it might also affect extra-galactic studies as well (Malhotra et al. 1997), which is very difficult to identify with limited angular resolution (Ibar et al. 2015).

We also examine the possibility of the differential self-absorption to the [N II] line pair, due to the relatively lower excitation energy of the 205- μm line compared to the 122- μm line. Following Equation 6.3, the equivalent width ratio between the two lines are $W_{\text{eq}}(205)/W_{\text{eq}}(122) \sim 1.026$, indicating that their theoretical absorption depths are similar. Only a high optical depth can produce biased self-absorption to eliminate the observed [N II] 205- μm line flux. However, due to the small abundance of nitrogen, it is unlikely that the [N II] 205- μm line can be optically thick (Langer et al. 2016). Furthermore, self-absorption has not been found in local galaxies in our Milky Way galaxy, where [C II] and [O I] have been found to have self-absorption in some cases (Gerin et al. 2015). We conclude that our high $R_{122/205}$ is unlikely to be caused by self-absorption, but more detailed observations are needed to further support this conclusion.

Another, possible contamination that may bias the line measurement is an absorption against strong background continuum emission. This has been seen in [C II] absorption in high-redshift galaxies (e.g., Nesvadba et al. 2016) against strong continuum sources powered by intense star-formation or AGNs. Although this may not be a dominant bias for the fine-structure lines, such an

effect could contribute very high level of ‘line-deficit’ (Nesvadba et al. 2016).

On the other hand, the upper energy levels of the [N II] lines are 70-K and 188-K for the $^3P_1 - ^3P_0$ (205- μm) and $^3P_2 - ^3P_1$ (122- μm) lines, respectively. Therefore, the WIM component of them can be easily absorbed against background sources with high brightness temperatures. Using high-spectral-resolution observations from the HIFI instrument onboard *Herschel*, Persson et al. (2014) detected absorption features of the [N II] 205- μm lines toward a few massive Galactic star-forming regions. They found that [N II] emission from ionised gas in the dense and hot H II regions is likely absorbed by widespread low-density and relatively low-temperature WIM gas in the foreground.

Because the upper level temperature of [N II] 205- μm is relatively lower than that of [N II] 122- μm , the former is easily to get absorbed. The $R_{122/205}$ ratio obtained from global volume average observations can be biased by the differential absorptions, and may further bias the final derived n_e to lower values (suggestive of more diffuse gas) and this has possibly already influenced observational results in local galaxies (e.g., Zhao et al. 2016a; Herrera-Camus et al. 2016). Observations at high-angular and high-spatial resolution of the [N II] lines are needed to avoid the confusion from the absorption of the [N II] line in low-density gas and any WIM contribution.

We have neglected the optical depth of dust throughout this study. Dust can have non-negligible optical depths at mid- to far-IR wavelengths, especially for the compact starbursts, e.g. Arp220 has an optical depth of ~ 1 even at the 3-mm band (Scoville et al. 2017), i.e. it is optically thick at far-IR. Lutz et al. (2016) found that local ULIRGs generally have compact sizes and their optical depths in the FIR can be close to optically thick on average. It is difficult to estimate the accurate dust attenuation of the lines, but this effect may contribute to the line deficit over the sample (Fischer et al. 2014).

8.4 Elementary abundances

Our study adopted line ratios between different elements to derive physical conditions, e.g., [C II]/[N II] for the contribution of ionised gas, and [O III]/[N II] for the hardness of the radiation field. These are based on the assumption of the elementary abundances, which are actually fairly uncertain, due to unclear nucleosynthesis and galactic chemical evolution processes (e.g., Matteucci 2001).

The C/N abundance ratio is still largely under debate. Based on Galactic stellar determinations for the variations with metallicity (Nieva & Przybilla 2012), Croxall et al. (2017) find a decreasing C/N abundance ratio with increasing metallicity traced by [O/H]. This is partially consistent with the results found in dwarf galaxies, which show a C/N–[O/H] curve similar to a negative parabola shape (Garnett et al. 1995). Furthermore, recent work by Peña-Guerrero et al. (2017) shows that the C/N abundance ratio linearly increases with [O/H] in starburst galaxies with top-heavy IMFs, contradictory to the findings of Croxall et al. (2017). This indicates that the primary element channel for the N production is not negligible in metal poor conditions, and this effect is more severe for the top-heavy IMF conditions, which have more massive stars to supply the primary N yields (Coziol et al. 1999; Peña-Guerrero et al. 2017). It seems that it is likely not appropriate to adopt the Galactic chemical evolution and Galactic chemical abundances to starburst galaxies, which have systematically different evolution tracks and IMFs (Zhang et al. 2018).

On the other hand, the O/N abundance ratio that adopted in the

[O III]/[N II] line ratios also have large uncertainties. Using Galactic H II regions, Carigi et al. (2005) find a solo increasing trend of N/O ratio with [O/H], which is consistent with the results found using optical spectra measured from Galactic B-stars Nieva & Przybilla (2012). However, local starburst galaxies have systematically biased N/O ratios from the trend found in the Milky Way (Coziol et al. 1999). More confusingly, Contini (2017) shows that the N/O abundance ratios in gamma-ray and supernova host galaxies at $z < 4$ can not be explained by stellar chemical evolution models calculated for starburst galaxies, nor for the Milky Way, which suggests that different evolutionary tracks need to be applied for various galaxy types and redshifts.

9 SUMMARY AND CONCLUDING REMARKS

We present *Herschel* SPIRE FTS spectroscopy and PACS photometry of a sample of 45 gravitationally lensed DSFGs at $z = 1.0$ – 3.6 , targeting the [C II] 158- μm , [N II] 205- and 122- μm , [O III] 88 and 52- μm , [O I] 63- and 145- μm , and OH 119- μm lines. We obtained 17 individual detections of [C II] 158- μm , five detections of [O III] 88- μm , three detections of [O I] 63- μm , and three detections of OH 119- μm in absorption.

We find that the [C II]/ $L_{\text{IR}} - L_{\text{IR}}$ ratio shows a deficit at high FIR luminosities, high star-formation efficiency ($L_{\text{IR}}/M_{\text{H}_2}$) and higher surface densities of star formation rates, consistent with the trends found in local star-forming galaxies, ULIRGs, SPT sources and high-redshift starburst galaxies found in the literature.

To determine the average conditions of the ionised gas in our high-redshift DSFG sample, we stack the SPIRE spectra using three different methods, each with a different bias. We derive physical properties of the ionised gas from the stacked spectra using un-lensed intrinsic luminosity, and from the spectra scaled to a common redshift. In the stacked spectrum we detected emission lines of [C II] 158- μm , [N II] 122- μm , [O III] 88- μm , [O III] 52- μm , [O I] 63- μm , and OH in absorption at 119- μm . Median stacking has lower S/N but provides further evidences for the weak line detections.

Using the [N II] 122- μm detection and the upper limit for [N II] 205- μm , we derive a lower limit for the electron density of $> 100 \text{ cm}^{-3}$, which is higher than the average conditions found in local star-forming galaxies and ULIRGs using the same [N II] line pair. From the [O III] 63- and 145- μm detections, the electron density is found to be 10^3 – 10^4 cm^{-3} , which is one-two orders of magnitude higher than that found in local star-forming galaxies using the same [O III] lines. We also use [N II] 122- μm to derive the ionised gas contribution to [C II] 158- μm and find the fraction of ionised gas to be 10–15%. If we adopt the N and C abundances found in Galactic H II regions, this fraction can be as high as 60%. The [O I]/[C II] ratio indicates that the [C II] emission is likely dominated by PDRs rather than by large-scale shocks. Finally, we derived the OH column density from the OH 119- μm absorption feature, which we find likely traces outflows driven by the star formation.

The physical conditions derived for the sample seem to be systematically more extreme than for local star-forming galaxies and ULIRGs, i.e., in star-formation rates, in electron densities derived from both total ionised gas and dense ionised gas. We use the [N II]/[O III] ratio to derive an average radiation hardness of the sample, which indicates that the star-formation is dominated by massive stars with masses higher than O8.5, modulo the potential

biases from diffuse ionised gas and uncertainties in the N/O abundance ratio.

ACKNOWLEDGEMENTS

The authors are grateful to the referee for the constructive suggestions and comments. ZYZ thanks J.D. Smith, Justin Spilker for sharing data. ZYZ thanks Donatella Romano for very helpful discussion. ZYZ, RJI, LD, SM, IO, RDG and AJRL acknowledge support from the European Research Council (ERC) in the form of Advanced Grant, 321302, COSMICISM. RDG also acknowledges an STFC studentship. YZ thanks the support from the NSFC grant numbers 11673057 and 11420101002. CY was supported by an ESO Fellowship. US participants in *H-ATLAS* acknowledge support from NASA through a contract from JPL. *Herschel* was an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. PACS has been developed by a consortium of institutes led by MPE (Germany) and including UVIE (Austria); KU Leuven, CSL, IMEC (Belgium); CEA, LAM (France); MPIA (Germany); INAF-IFSI/OAA/OAP/OAT, LENS, SISSA (Italy); IAC (Spain). This development has been supported by the funding agencies BMVIT (Austria), ESA-PRODEX (Belgium), CEA/CNRS (France), DLR (Germany), ASI/INAF (Italy), and CICYT/MCYT (Spain). SPIRE has been developed by a consortium of institutes led by Cardiff University (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); and Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNES, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC, UKSA (UK); and NASA (USA). We thank Drew Brisbin for providing machine readable forms of the H II models presented in Rubin (1985).

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Source	Instrument	Time s	Date	Proj.	Notes
	PACS	90	2011-10-18	OT1	
	PACS	90	2011-10-18	OT1	
SDP.17	SPIRE	13320	2012-11-18	OT2	
	PACS	90	2011-12-02	OT1	
	PACS	90	2011-12-02	OT1	
SDP.81	SPIRE	13320	2010-06-01	GT1	Valtchanov et al. (2011)
	PACS	90	2010-06-03	GT1	70- and 160- μ m maps
	PACS	90	2010-06-03	GT1	70- and 160- μ m maps
SDP.130	SPIRE	13320	2010-06-01	GT1	Valtchanov et al. (2011)
	PACS	90	2010-06-03	GT1	70- and 160- μ m maps
	PACS	90	2010-06-03	GT1	70- and 160- μ m maps
G09-v1.40	SPIRE	13320	2011-11-06	OT1	
	PACS	90	2012-04-24	OT1	
	PACS	90	2012-04-24	OT1	
G09-v1.97	SPIRE	13320	2011-11-08	OT1	
	PACS	90	2011-11-10	OT1	
	PACS	90	2011-11-10	OT1	
G09-v1.124	SPIRE	13320	2012-11-18	OT2	
	PACS	90	2012-04-13	OT1	
	PACS	90	2012-04-13	OT1	
G09-v1.326	SPIRE	13320	2011-11-07	OT1	
	PACS	90	2011-11-28	OT1	
	PACS	90	2011-11-28	OT1	
G12-v2.30	SPIRE	13320	2012-07-07	OT1	
	PACS	90	2011-11-27	OT1	
	PACS	90	2011-11-27	OT1	
G12-v2.43	SPIRE	13320	2012-07-07	OT1	
	PACS	90	2011-07-14	OT1	
	PACS	90	2011-07-14	OT1	
G12-v2.257	SPIRE	13320	2012-07-07	OT1	
	PACS	90	2011-07-14	OT1	
	PACS	90	2011-07-14	OT1	
G15-v2.19	SPIRE	13320	2012-02-04	OT1	
	PACS	90	2011-07-09	OT1	
	PACS	90	2011-07-09	OT1	
G15-v2.235	SPIRE	13320	2012-02-04	OT1	
	PACS	90	2012-01-12	OT1	
	PACS	90	2012-01-12	OT1	
NA.v1.56	SPIRE	13320	2012-07-22	OT1	
	PACS	90	2011-11-27	OT1	
	PACS	90	2011-11-27	OT1	
NA.v1.144	SPIRE	13320	2012-08-03	OT1	
	PACS	90	2011-12-03	OT1	
	PACS	90	2011-12-03	OT1	
NA.v1.177	SPIRE	13320	2012-08-03	OT1	
	PACS	90	2011-11-27	OT1	
	PACS	90	2011-11-27	OT1	
NA.v1.186	SPIRE	13320	2012-06-18	OT1	
	PACS	90	2011-07-11	OT1	
	PACS	90	2011-07-11	OT1	
NB43	SPIRE	13320	2012-08-02	OT1	George et al. (2013)
	PACS	90	2011-11-27	OT1	
	PACS	90	2011-11-27	OT1	
NB.v1.78	SPIRE	13320	2012-08-02	OT1	
	PACS	90	2011-12-03	OT1	
	PACS	90	2011-12-03	OT1	
NC.v1.143	SPIRE	13320	2012-07-21	OT1	
	PACS	90	2011-07-11	OT1	
	PACS	90	2011-07-11	OT1	
SA.v1.44	SPIRE	13320	2012-12-03	OT2	
	PACS	90	2012-11-27	OT2	
	PACS	90	2012-11-27	OT2	
SA.v1.53	SPIRE	13320	2012-12-02	OT2	
	PACS	90	2012-11-27	OT2	
	PACS	90	2011-11-27	OT2	
SB.v1.143	SPIRE	13320	2012-12-29	OT2	
	PACS	90	2012-12-12	OT2	
	PACS	90	2012-12-12	OT2	
SB.v1.202	SPIRE	13320	2012-12-03	OT2	
	PACS	90	2012-12-12	OT2	
	PACS	90	2012-12-12	OT2	
SC.v1.128	SPIRE	13320	2012-12-03	OT2	
	PACS	90	2012-12-12	OT2	
	PACS	90	2012-12-12	OT2	

APPENDIX A: OBSERVING DATES

Basic information of the <i>Herschel</i> observations					
Source	Instrument	Time s	Date	Proj.	Notes
SDP.9	SPIRE	13320	2011-11-07	OT1	
	PACS	90	2011-12-02	OT1	
	PACS	90	2011-12-02	OT1	
SDP.11	SPIRE	13320	2012-11-18	OT1	

Source	Instrument	Time s	Date	Proj.	Notes
SD.v1.70	SPIRE	13320	2012-12-28	ot2	
	PACS	90	2012-12-25	ot2	
	PACS	90	2012-12-25	ot2	
SD.v1.133	SPIRE	13320	2012-12-28	ot2	
	PACS	90	2012-12-11	ot2	
	PACS	90	2012-12-11	ot2	
SD.v1.328	SPIRE	13320	2012-12-29	ot2	
	PACS	90	2012-12-11	ot2	
	PACS	90	2012-12-11	ot2	
SE.v1.165	SPIRE	13320	2012-12-29	ot2	
	PACS	90	2012-12-25	ot2	
	PACS	90	2012-12-25	ot2	
SF.v1.88	SPIRE	13320	2012-07-08	ot2	
	PACS	90	2012-07-15	ot2	
	PACS	90	2012-07-15	ot2	
SF.v1.100	SPIRE	13320	2012-07-08	ot2	
	PACS	90	2012-07-15	ot2	
	PACS	90	2012-07-15	ot2	
SG.v1.77	SPIRE	13320	2012-07-17	ot2	
	PACS	90	2012-06-25	ot2	
	PACS	90	2012-06-25	ot2	
HeLMS05	PACS	90	2013-01-06	ot2	
	PACS	90	2013-01-06	ot2	
HeLMS06	PACS	90	2013-01-06	ot2	
	PACS	90	2013-01-06	ot2	
HeLMS09	PACS	90	2013-01-11	ot2	
	PACS	90	2013-01-11	ot2	
HeLMS44	SPIRE	13320	2013-01-08	ot2	
	PACS	90	2013-01-01	ot2	
HeLMS45	PACS	90	2013-01-01	ot2	
	SPIRE	13320	2012-12-29	ot2	
HeLMS49	PACS	90	2013-01-06	ot2	
	PACS	90	2013-01-06	ot2	
HeLMS51	PACS	90	2013-01-06	ot2	
	PACS	90	2013-01-06	ot2	
HeLMS61	PACS	90	2013-01-01	ot2	
	PACS	90	2013-01-01	ot2	
HeLMS62	PACS	90	2012-12-26	ot2	
	PACS	90	2012-12-26	ot2	
HBöotes03	SPIRE	13320	2012-02-05	ot1	
	PACS	90	2011-11-27	ot1	
	PACS	90	2011-11-27	ot1	
HXMM02	SPIRE	13320	2012-02-05	ot1	
	PACS	90	2012-02-14	ot1	
	PACS	90	2012-02-14	ot1	
Eyelash	SPIRE	13320	2011-04-24	ot1	George et al. (2014)
	SPIRE	13320	2012-11-17	ot2	as above
	SPIRE	13320	2012-11-24	ot2	as above
	SPIRE	13320	2012-11-24	ot2	as above
	SPIRE	13320	2012-12-01	ot2	as above
	SPIRE	13320	2012-12-02	ot2	as above
	PACS	90	2011-11-17	ot1	
PACS	90	2011-11-17	ot1		

Herschel observations of the sample of strongly lensed DSFGs. SPIRE spectrometer observations consist of 100 forward and 100 reverse scans of the SMEC mirror. The two PACS photometer observations of each source consist of $10 \times 3'$ scan legs oriented at 70° and 110° respectively, and combined during processing into a single mini scan map.

APPENDIX B: PACS IMAGING

APPENDIX C: BASELINE SUBTRACTION AND SIGNAL RECOVERY

In this section we compare different background subtraction methods in the data reduction of *Herschel* SPIRE/FTS data. To remove the overall baseline profile, and especially the low-frequency ripple features produced by the imperfect calibration, we perform a convolved baseline fitting. To do so we first mask the frequency ranges of a few strong lines ([C II], [O III] $88\text{-}\mu\text{m}$, OH), each with a 2 GHz width, to avoid contaminations from the lines. Then we convolve the masked spectra with a Gaussian profile with 15 GHz (FWHM), which ensures a local baseline feature but without fitting the relatively narrower line features. We then subtract the baseline

profiles from the original spectra to get the final output spectra for each target.

Figure C1 presents an example of the baseline subtraction method. The thin lines show the pipeline produced spectra in the two central pixels of the *Herschel* FTS, SLW03 and SSW04. Thick lines show the baselines produced by convolving the masked spectra (the line free part) and Gaussian profile with 15 GHz in FWHM. The blue shadowed regions show the frequency ranges of the masked line features, which may potentially bias the baseline fitting. The red line shows an artificial Sinc function response with a peak of 0.3 Jy and a FWHM width of 1.2 GHz convolved with a 500 km s^{-1} Gaussian FWHM.

To fully verify the robustness of this method, we make a sanity test by randomly inserting artificial spectral signals to the raw data, subtract the baseline, and test if we can recover the line flux. We perform the test by randomly insert artificial signals in the spectra. We find that, if the signal is higher than 0.5 Jy (peak) and if the line width is less than 2000 km s^{-1} , the line flux can be recovered on very high confidence with an average error level of less than 20% of the real fluxes. Figure C2 presents a histogram of measured fluxes for 10000 times random test. The distribution shows a very well centralised flux corresponding to the inserted artificial noise, with relatively small span. This indicates that the baseline subtraction method does not alter the general flux measurement, and the ripple baseline feature likely not influence much on the high frequency (in Fourier domain) scales.

We fit a Gaussian to the histogram distribution, and find the σ to be ~ 0.05 Jy. However we also find that the distribution does not follow a Gaussian profile very well, especially for both the high and the low ends. We also examine how much does the recovered flux distribution deviate from normal distribution, and find that both K-S test and P-test gives $\sim 10^{-8}$, which mean that the histogram is likely not following a normal distribution. This is likely because the noise is not uniform across the whole spectral range, that may bias the noise distribution. Another reason could be that the noise between channels is correlated, and is not a white noise. It seems that the noise of the spectra is spiky that enlarges the histogram distribution at both ends with some extreme values. Overall, the test indicates a robust flux measurement can be recovered after the baseline subtraction.

APPENDIX D: SPIRE FTS SPECTRA OF ALL TARGETS

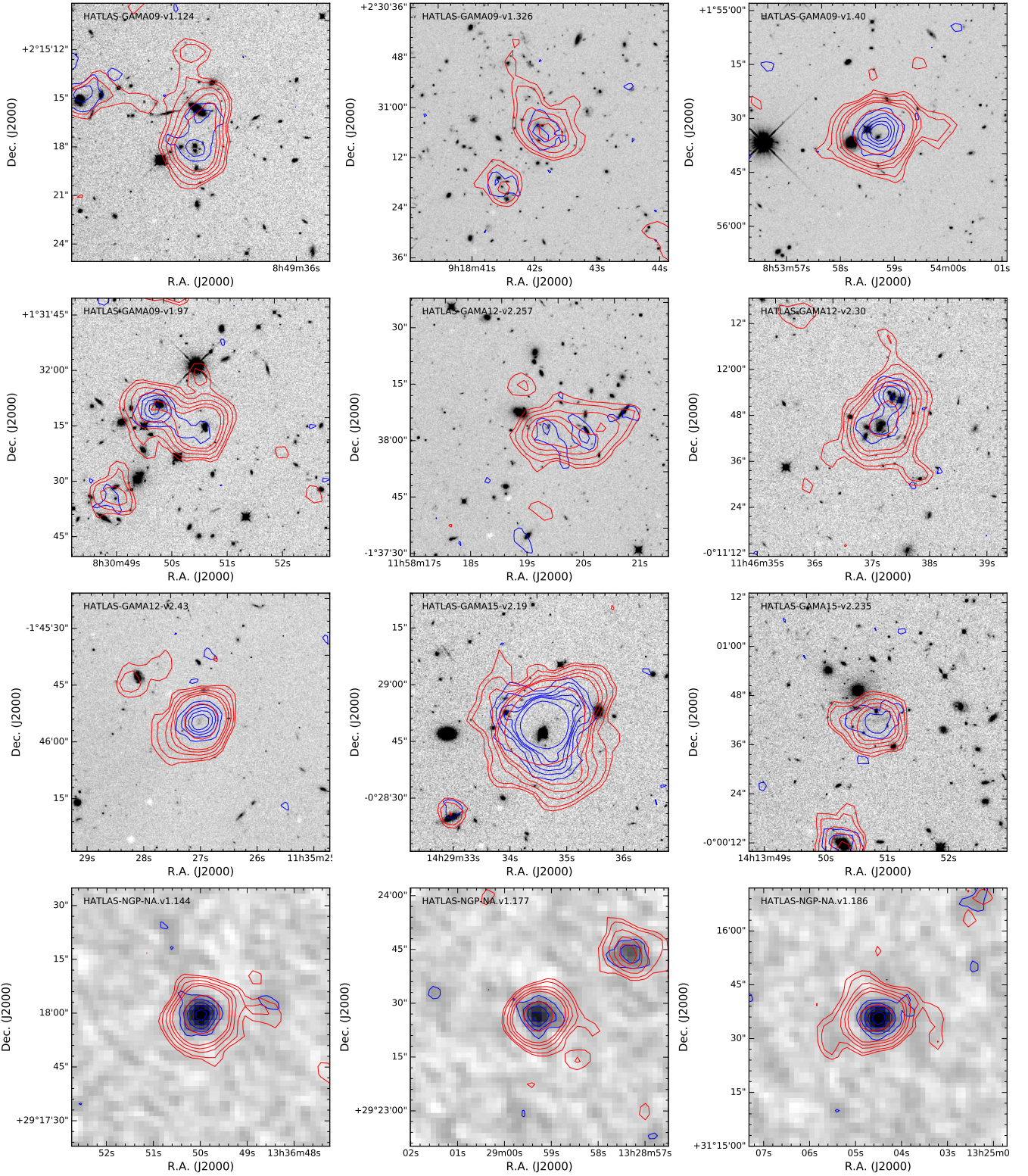
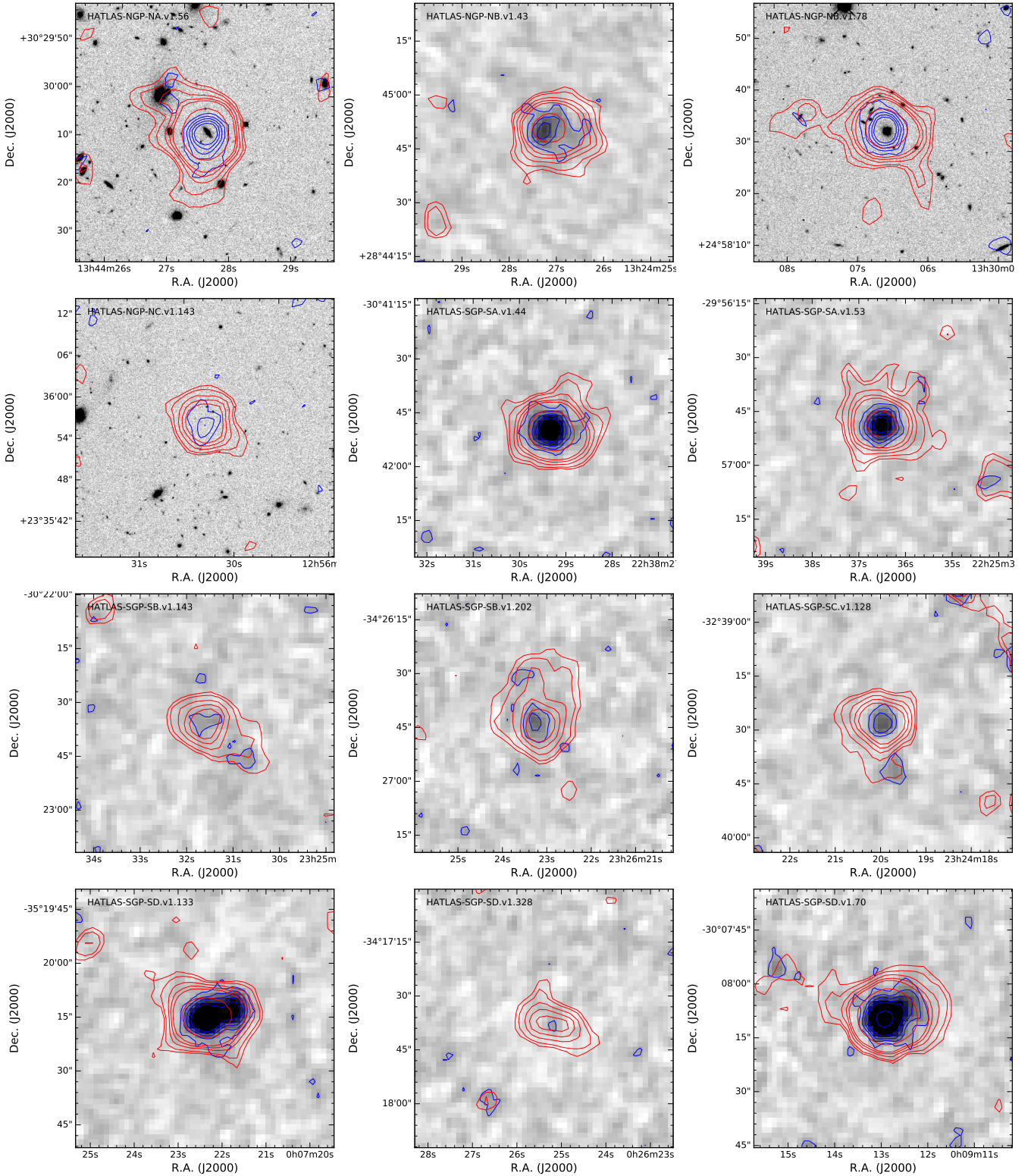


Figure B1. *Herschel* PACS images of the sample. The high resolution background images are HST F110W archival data. The low resolution background images are PACS 100 μm data. Red contours are PACS 160 μm data, with levels of 0.3, 0.4, 0.6, 0.8, 1.2 mJy/pixel. Blue contours are PACS 100 μm data, with levels of 0.2, 0.4, 0.6, 0.8, 1, and 2 mJy/pixel.

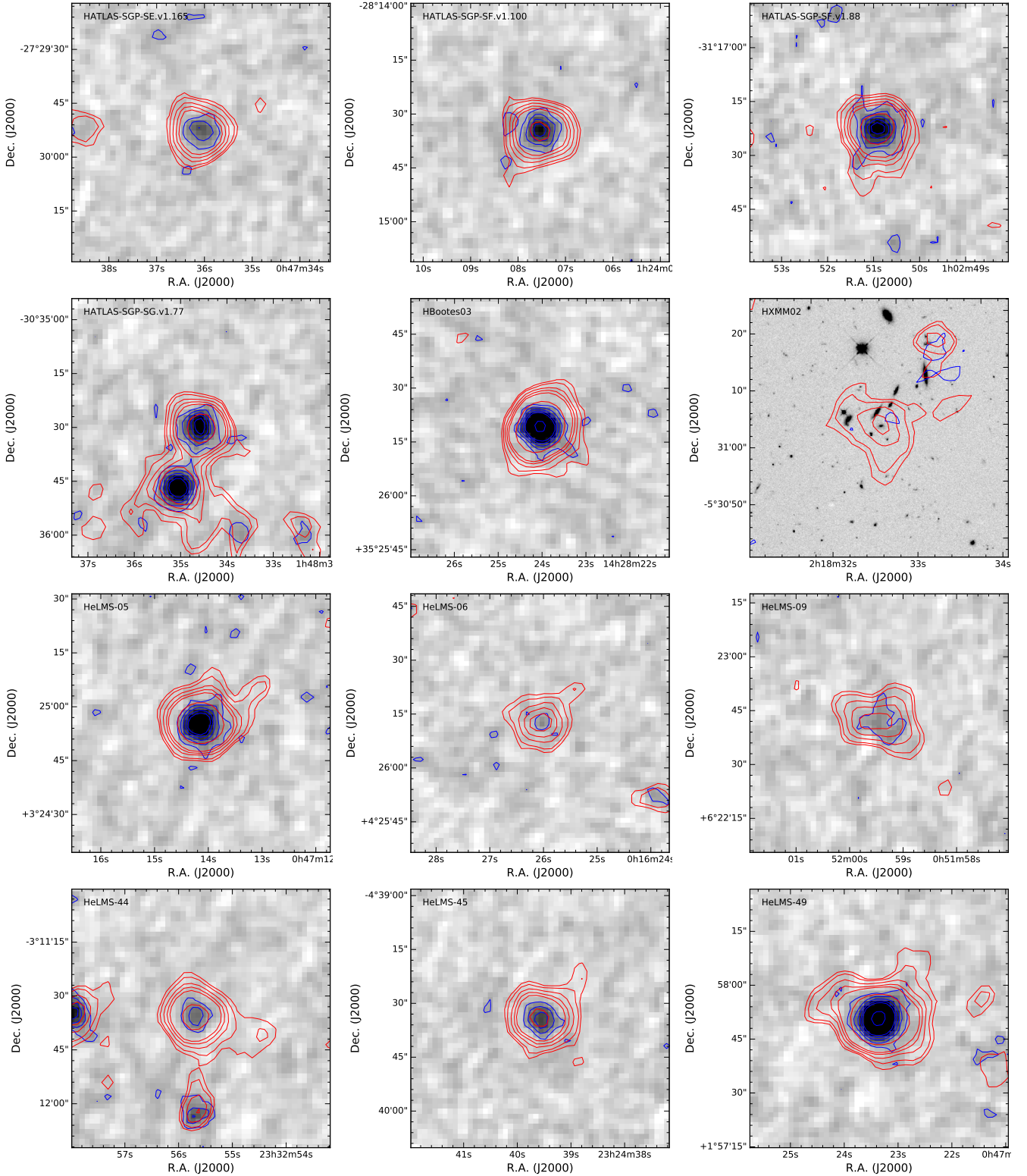


APPENDIX E: COMMENTS ON INDIVIDUAL OBJECTS

SDP.9 (J090740.0-004200): This is the lowest redshift and brightest of the original five strongly lensed DSFGs found in *H*-ATLAS (Negrello et al. 2010). NIR imaging suggests a nearly-complete Einstein ring (Negrello et al. 2014), however the dust emission is dominated by the SE region (Bussmann et al. 2013). Despite calculating

almost identical dust emission luminosities, the SFR we derive using our chosen calibration: that presented in Murphy et al. (2011) and recommended by the review of Kennicutt & Evans (2012); is a factor of 3 higher than value reported by Negrello et al. (2014). We find a relatively low $L_{[\text{C II}]158,\mu\text{m}}\text{-to-}L_{\text{FIR}}$ ratio of $2.5 \pm 0.9 \times 10^{-4}$.

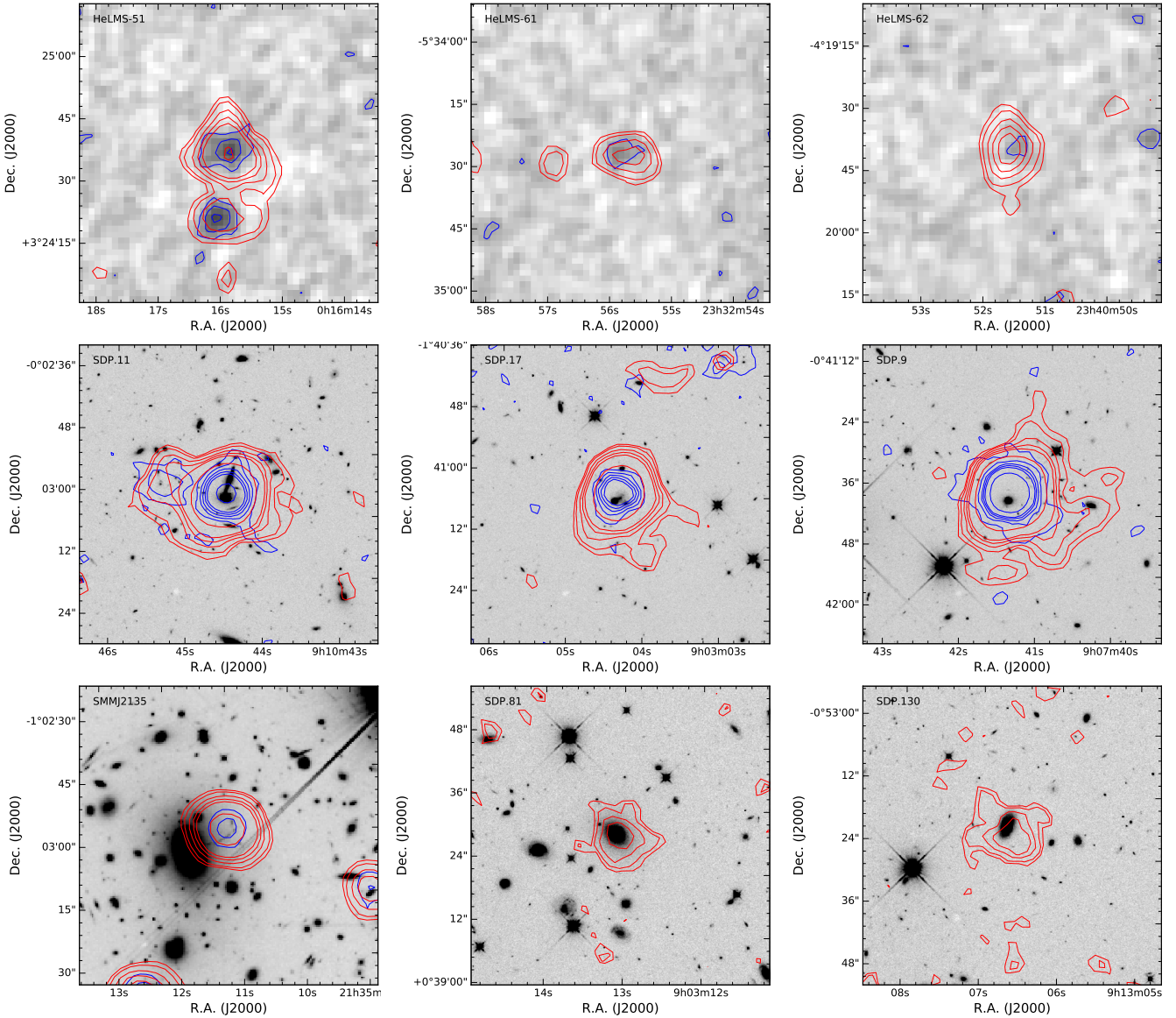
SDP.11 (J091043.0-000322): NIR imaging shows this object



as a full yet elongated Einstein ring. Dust emission does not exhibit the same brightness distribution, with the northern and southern regions dominant. A $7.5 \pm 2.3 \times 10^{-18} \text{ W m}^{-2}$ [O I] $63\text{-}\mu\text{m}$ line has been observed with PACS (Verma et al. in prep.). We find the [C II] $158\text{-}\mu\text{m}$ line to have a flux $9.7 \pm 0.9 \times 10^{-18} \text{ W m}^{-2}$. 50 %

higher than a recent measurement from ZEUS-2 on APEX (Ferkinnhoff et al. 2014).

SDP.17 (J090302.9-014127): With a complex NIR light profile, this system is difficult to separate into clear foreground and background components. The lensed image is not resolved into multiple components by the SMA in even the most extended con-



figuration, suggesting a relatively low amplification factor and hence high intrinsic luminosity. Despite this, the large emission area suggested by [Bussmann et al. \(2013\)](#) would indicate a comparatively modest star formation rate surface density, making our [C II] 158- μm non-detection interesting should that parameter be a key driver of the line-to-FIR continuum deficit.

SDP.81 (J090311.6+003906): This galaxy is lensed into two arcs, exquisitely revealed by recent long-baseline ALMA imaging ([ALMA Partnership et al. 2015](#)). These data have been used to produce a detailed reconstruction of the source-plane emission ([Dye et al. 2015](#)), which exhibits 200 pc-scale clumps. We use the amplification derived for the dust emission from this modelling effort: 15.9 ± 0.7 : which is higher than an estimate from lower resolution SMA data (11.1 ± 1.1 ; [Bussmann et al. 2013](#)), and also higher than the amplification estimated for the optical emission: 10.2 ± 0.5 ; which appears not to be co-spatial with the rest-frame FIR emission ([Dye et al. 2015](#)), as is common for starbursts (e.g. the Antennae Galaxies). An estimate of the source-plane emission radius from those data: 0.5 ± 0.2 kpc; is also used in our SED fitting. The SPIRE FTS spectrum is presented in [Valtchanov et al. \(2011\)](#) (pro-

gramme GT1_IVALTCHA_1), but for consistency we reprocess the data here. Due to the different method of background subtraction (off-axis vs. dark sky) we find a substantially lower [C II] 158- μm flux. However, as the off-axis method produced reduced noise over the dataset as a whole, and is used in the reduction of SPIRE spectra of other similarly faint targets (e.g. [Magdis et al. 2014](#); [Gullberg et al. 2015](#)), we use our measurement throughout this work. Despite the lower line flux, this object still appears to possess the highest $\mu L_{[\text{C II}] 158 \mu\text{m}}$ and $L_{[\text{C II}] 158 \mu\text{m}}/L_{\text{FIR}}$ values of our sample.

SDP.130 (J091305.0-005343): With a modest $\sim 2\times$ amplification this galaxy has significantly lower flux densities than the target threshold, and [Valtchanov et al. \(2011\)](#) found no lines in the FTS spectrum. Using newer calibration data, we find possible H II region emission, however the non-detection of [C II] 158- μm indicates these are likely noise.

G09-v1.40 (J085358.9+015537): This galaxy is visible in K_s band imaging as an almost-complete Einstein ring, consequently experiencing a high magnification factor of ~ 15 . The source-plane object may be highly elongated ([Calanog et al. 2014](#)). We detect [C II] 158 μm .

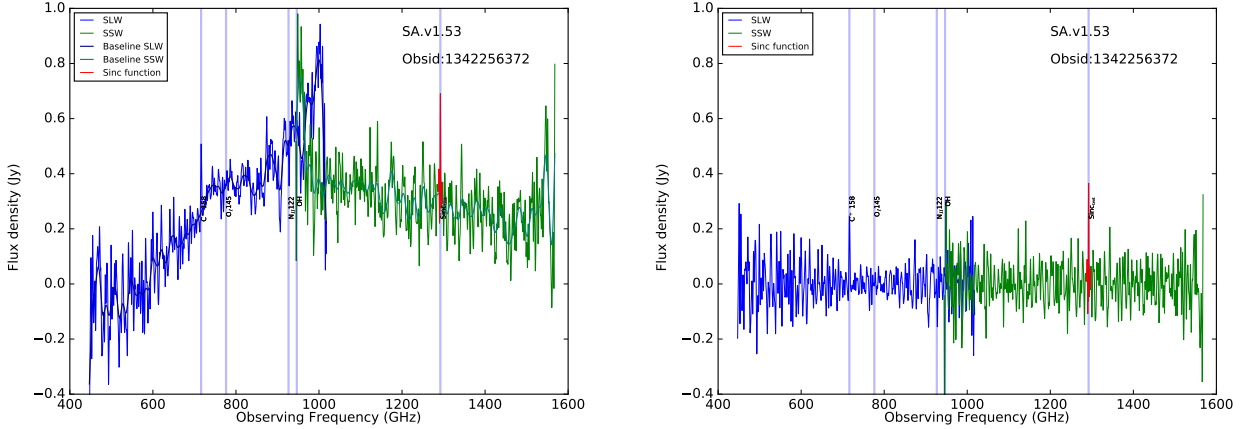


Figure C1. An example of our baseline subtraction method. *Left:* The observed *Herschel* FTS spectra of SA.v1.53, after standard calibrations. The thin blue line shows the spectrum obtained in the SLW-03 receiver, and the thin green line shows the spectrum obtained in the SSW-04 receiver. The thick lines show the baselines fitted using a 15 GHz Gaussian width, after masking the frequency ranges of potential line features. The blue shadowed regions show the masked frequency ranges potentially dominated by line emission or absorption features. Red line shows an artificial Sinc function response, which has a peak flux density of 0.3 Jy, a FWHM width of 1.2 GHz, and is further convolved with a Gaussian profile with a 500 km s^{-1} FWHM. *Right:* The FTS spectra after baseline subtraction. The line features (the [C II] line and the testing Sinc function) are still robust.

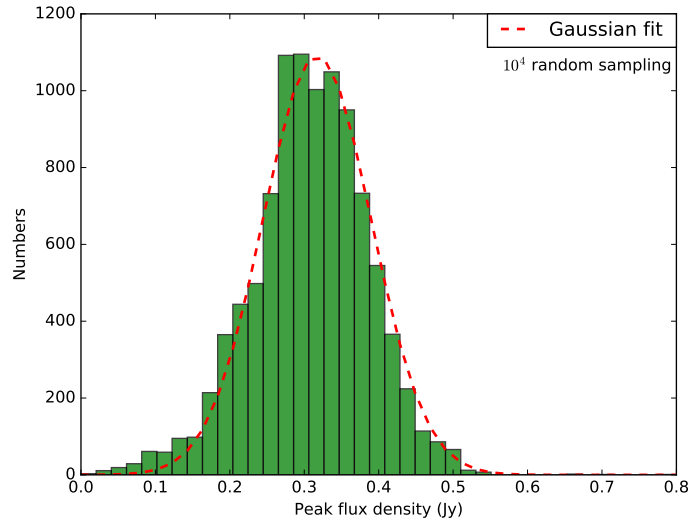


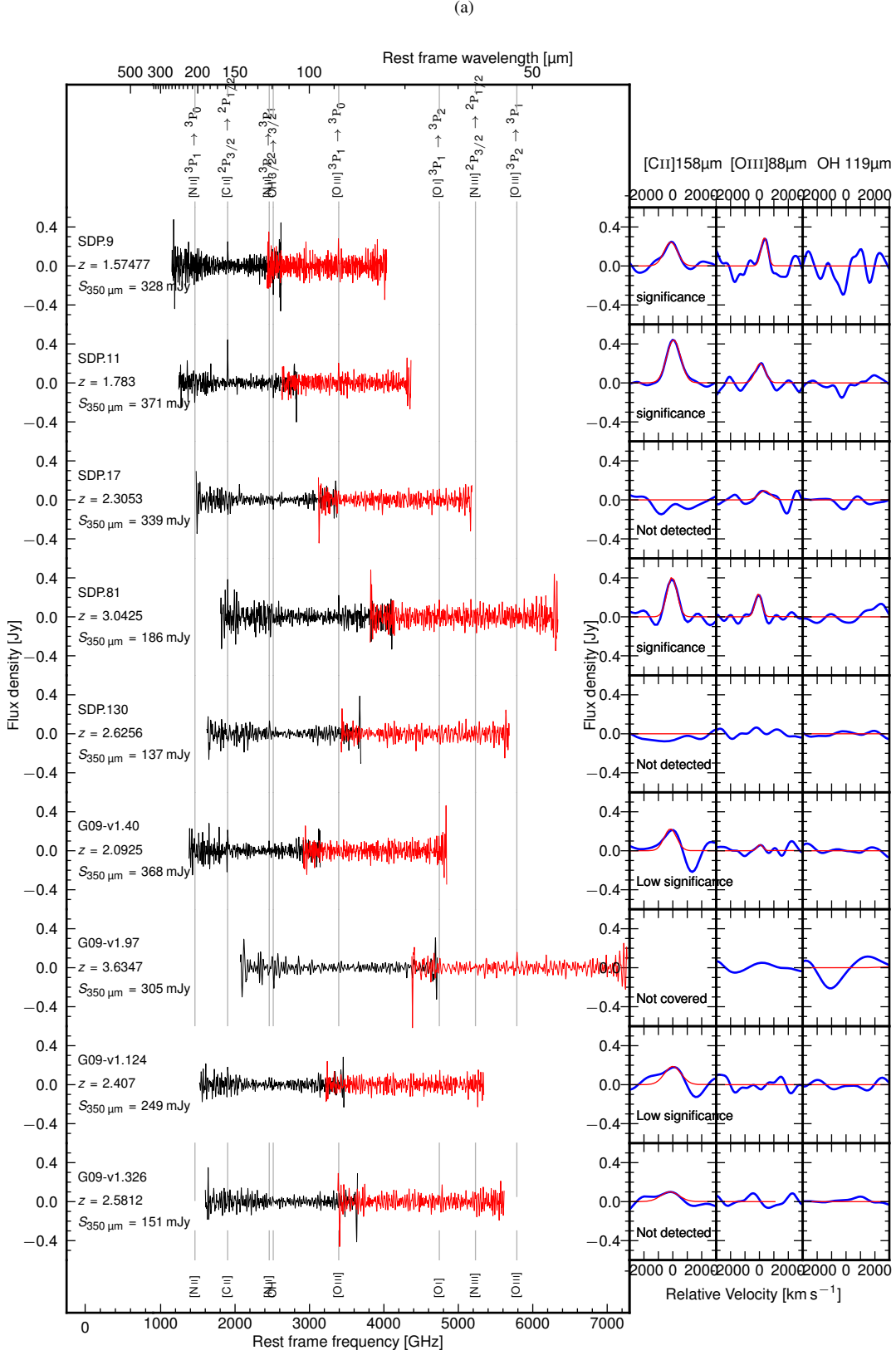
Figure C2. Distribution of the measured line fluxes, for a 10,000 times randomly sampled signal of 0.3 Jy Sinc function after baseline subtraction.

G09-v1.97 (J083051.0+013224): This source is lensed by two foreground galaxies at different redshift. While it possesses one of the largest μL_{IR} values of the sample, the high redshift means [C II] 158- μm is not covered by the FTS.

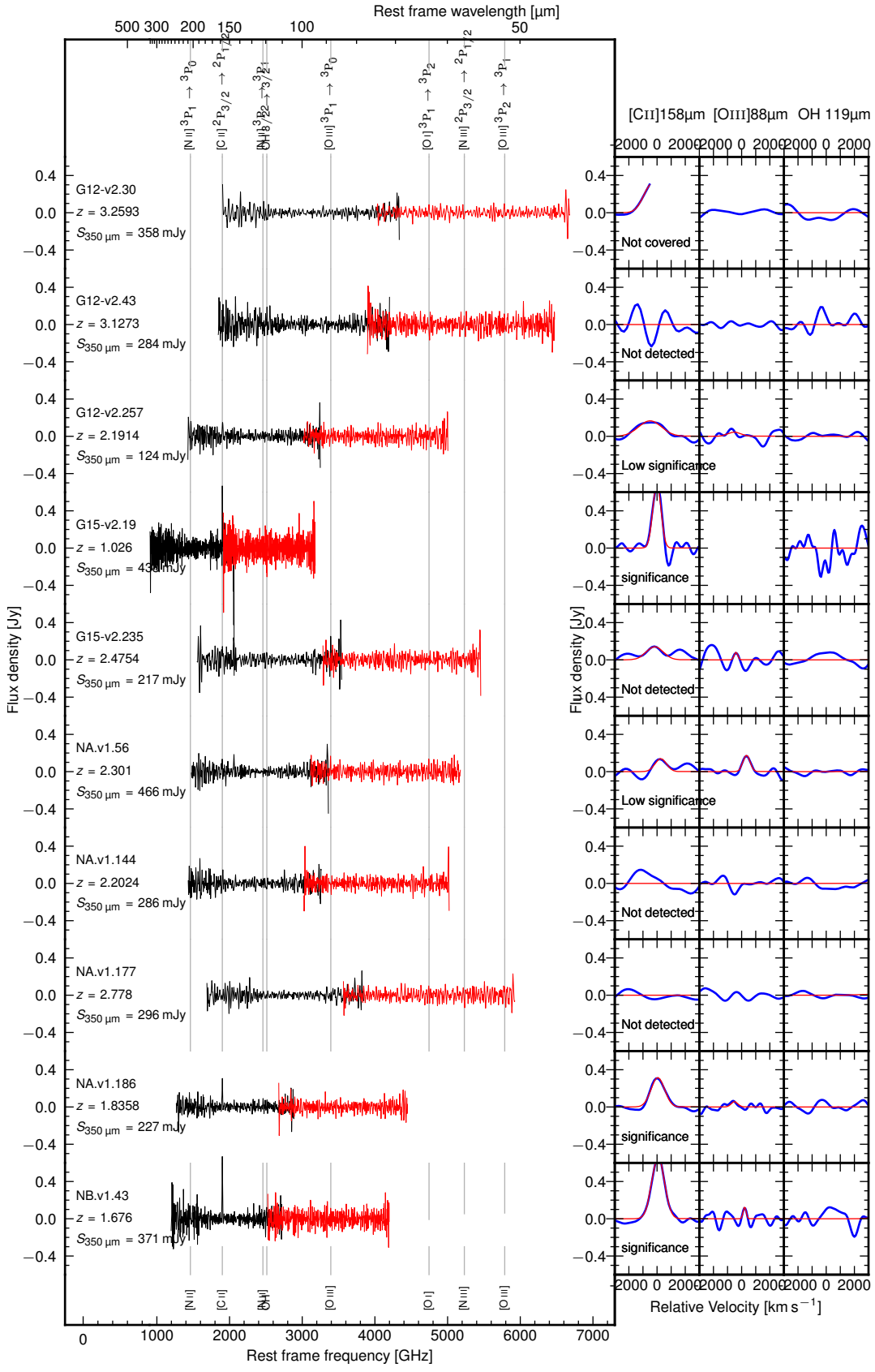
G09-v1.124 (J084933.4+021443): Uniquely within our sample this object is known to be essentially unlensed, its broad CO lines suggesting a very high intrinsic luminosity, confirmed by a range of follow-up observations which showed a system of four separate DSFGs, two of which are individually over the HyLIRG limit (Ivison et al. 2013). These two brightest are detected as separate point sources in our PACS imaging, but together only provide a low significance [C II]-158 μm feature. Recent NIR spectroscopy has revealed a broad-line AGN in this system (Oteo et al. in prep.), which will be responsible for some fraction of its FIR flux.

G09-v1.326 (J091840.8+023047): Available SMA imaging is consistent with a point source and no counterpart is found in *HST* or Keck imaging. Should this be an unlensed DSFG it would possess a SFR of $\sim 5000 M_{\odot} \text{ yr}^{-1}$, higher than any component of the known HyLIRG G09-v1.124, so we instead assume the amplification estimate of 5 ± 1 from Harris et al. (2012) derived from its CO luminosity and FWHM. No FIR cooling lines are observed in the FTS spectrum, however the flux densities lie below the target threshold.

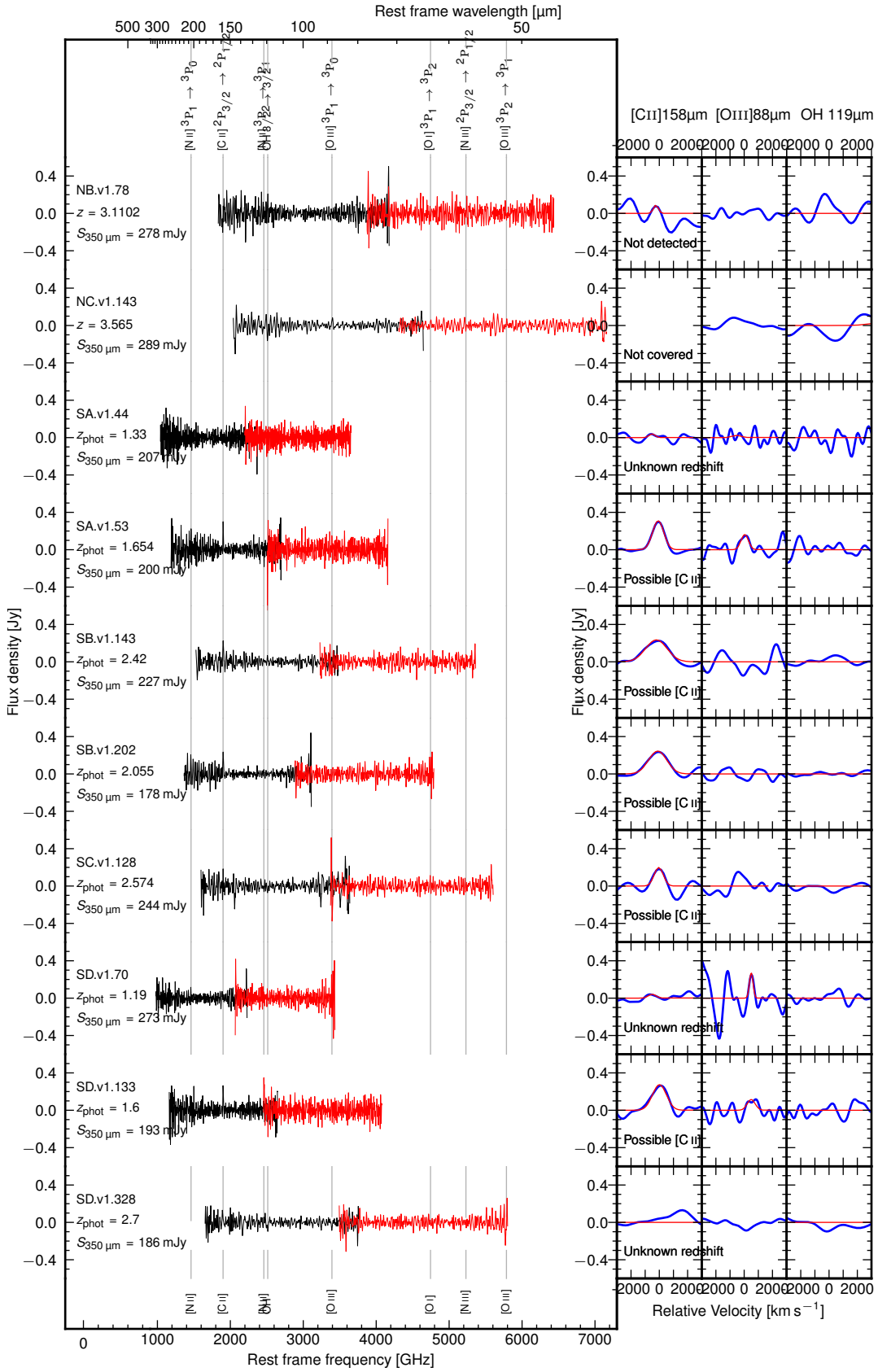
G12-v2.30 (J114638.0-001132): A detailed study of this galaxy is presented in Fu et al. (2012), indicating a complex system in which the existing stellar population is quadruply-lensed by a net factor of over $2\times$ that of the offset starburst, which provides some of the highest 500 and 880- μm flux densities in our sample. This

Figure D1. Spectra obtained using *Herschel* SPIRE/FTS, after subtracting the baselines


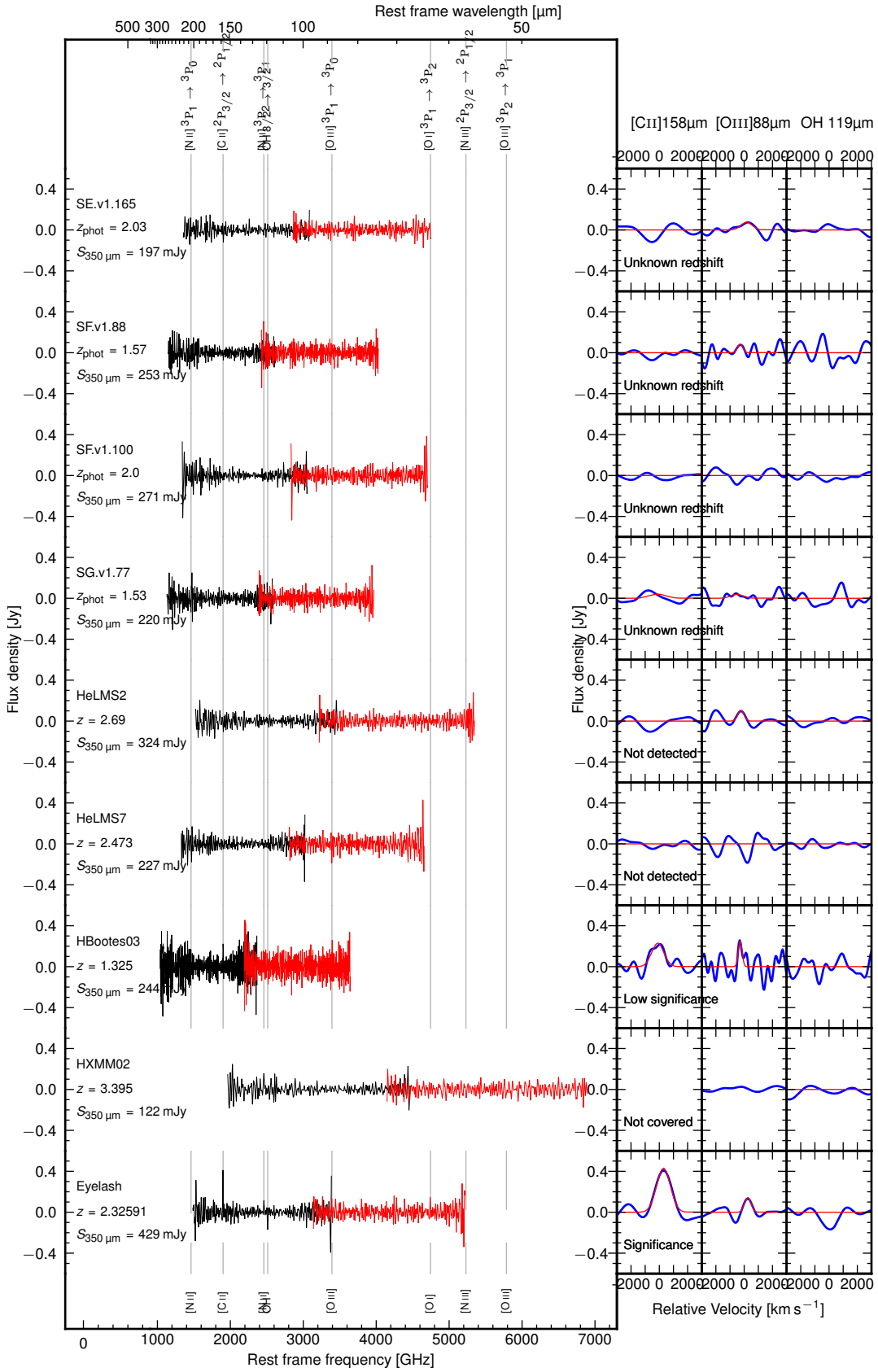
(b)



(c)



(d)



redshift represents the limit of the FTS coverage of the [C II] 158- μm line, which therefore lies in the noisiest region of the spectrum and is not detected.

G12-v2.43 (J113526.3-014606): Multiple lensed images are not resolved in the 880- μm SMA data, however a faint source visible in *HST* F110W and Keck/NIRC2 K_s imaging is likely a foreground lensing galaxy. With an apparent $\mu L_{\text{IR}} > 10^{14.1} L_{\odot}$, among the highest of our sources, we assume the large amplification estimate of Harris et al. (2012): 17 ± 11 . As with G12-v2.30, the [C II] 158- μm line lies within the high-noise end region of the spectrum, and no FIR lines are observed.

G12-v2.257 (J115820.1-013753): Two nearby spiral galaxies visible at 100- μm will be unresolved within the SPIRE beam but likely contribute very little to the measured flux densities at the longer wavelengths. No lensing model is available, though this object has one of the lowest 350- μm flux densities within our sample indicating a low μL_{IR} and likely $\mu \lesssim 5$. We however take the published amplification estimate of 13 ± 7 from Harris et al. (2012). As with the other low flux density sources, we do not find any emission line features.

G15-v2.19 (J142935.3-002836): This object is the brightest (and lowest redshift) within our sample. A detailed study is presented in Messias et al. (2014) indicating a gas-rich (25% of baryonic mass) merger of two source-plane components lensed into an almost complete Einstein ring. The redshift is too low for the spectrum to cover [O I] 63- μm and [O III] 88- μm , but a strong [C II] 158- μm feature is found. Additionally, we detect 119- μm OH $^2\Pi_{3/2} J = \frac{3}{2} \rightarrow \frac{5}{2}$ absorption.

With no strong evidence of an AGN (Messias et al. 2014) we, as with a similar detection within SMMJ2135 (George et al. 2014), attribute this to a SNe-driven outflow of molecular gas.

G15-v2.235 (J141351.9-000026): This galaxy is weakly lensed by a cluster with only a single elongated image visible, suggesting a high intrinsic luminosity. We find [C II] 158- μm and the second-highest $L_{[\text{C II}]158\text{-}\mu\text{m}}/L_{\text{FIR}}$ ratio of the sample.

NA.v1.56 (J134429.4+303036): This source has the highest 350 and 500 μm flux densities in our sample, visible as two well-defined arcs in SMA imaging. We detect [C II] 158- μm emission.

NA.v1.144 (J133649.9+291801): Available optical-NIR imaging is insufficiently deep to detect a lensing galaxy, however the 880- μm morphology indicates that this object is likely lensed with a small Einstein radius. A second tentative source at $z = 2.3078$ was suggested by a blind CO line search (Harris et al. 2012). We do not detect any spectral lines.

NA.v1.177 (J132859.3+292317): This source is resolved into a single elongated image in SMA data, and likely also responsible for a faint arc in Keck/NIRC2 K_s imaging. No lens models has been produced so far, and we do not detect any lines.

NA.v1.186 (J132504.4+311537): A feature suggestive of [C II] 158- μm at $z = 1.836$ found in our FTS spectrum was followed up with CARMA, extending the 3 mm spectrum below the nominal 85 GHz tuning range to detect CO $J = 2 \rightarrow 1$. A redshift of 1.8358 was confirmed, negating the previous estimate of $z = 2.635$. With no published deep NIR or interferometric FIR-mm imaging, a lens model has not been produced.

NB.v1.43 (J132427.0+284452): NIR images of this galaxy display an $\approx 10''$ long arc with little curvature: much more spatially extended than is visible in submillimetre data which arises from a small area towards the centre. Our FTS spectrum along with its detection of strong [C II] 158- μm emission was presented in George et al. (2013), however since publication of those data, a lensing model has been published. Lensing bodies are likely either

two galaxies or a nearby cluster (see Bussmann et al. 2013, for a discussion), with a (relatively uncertain) lensing amplification factor of 2.8 ± 0.4 derived for the dust emission. Calculations in this work utilise that value.

NB.v1.78 (J133008.4+245900): With > 200 mJy flux densities in all SPIRE bands, and at 160- μm despite a redshift above 3, this galaxy has the highest μL_{IR} of the sample and a warm dust temperature caused by its small radius and hence high SFR surface density. Coupled with the position of the [C II] 158- μm line within the spectrum, our non-detection of that transition is therefore perhaps unsurprising.

NC.v1.143 (J125632.7+233625): The lens has a redshift low enough for it to be visible in SDSS imaging and similarly to NB.v1.78, the background galaxy has a high μL_{IR} and an even higher dust temperature and SFR surface density, however the high redshift of this source means that [C II] 158 μm is not covered by the FTS spectrum.

H-ATLAS SGP sources: Without definite redshifts, it is difficult to glean much from these sources. Several have low significance SPIRE spectral features potentially corresponding to [C II] 158 μm , with the corresponding redshift listed in Table 2.

HeLMS sources: Only two of these galaxies were observed with the FTS, none of them exhibits [C II] 158 μm emission. Further follow-up of these objects needs to be done, rendering any conclusive determinations of their properties or lensing amplification difficult.

HBöotes03 (J142824.0+352619): This is a well-studied high-redshift DSFG (also known as MIPS J142824.0+352619) discovered before the wide area *Herschel* and SPT surveys (Borys et al. 2006; Swinbank et al. 2006). *Herschel* PACS detections of [O III] 52 μm ($3.7 \pm 0.8 \times 10^{-18} \text{ W m}^{-2}$) and [O I] 63 μm ($7.8 \pm 1.9 \times 10^{-18} \text{ W m}^{-2}$) are presented in Sturm et al. (2010), and a $19.8 \pm 3.0 \times 10^{-18} \text{ W m}^{-2}$ [C II] 158 μm detection with CSO/ZEUS in Hailey-Dunsheath et al. (2010). This latter value is particularly significant, being a factor of 5 higher than our measurement (fit shown in Fig. 3). We are unsure as to the reason for the magnitude of this discrepancy.

HXMM02 (J021830.5-053124): This object (also known as Orochi or SXDF1100.001) was included due to its previous in-depth study (Ikarashi et al. 2011; Iono et al. 2012). The small lens Einstein radius and amplification however give it the lowest 250 and 350 μm flux densities in our sample, which when coupled with its high redshift (such that the FTS spectrum does not cover [C II] 158 μm), mean no FIR lines are found. The dust mass temperature index of 7.2, used to fit all other galaxies is insufficient to account for the high PACS flux densities, with the best-fitting value being 5.7. This suggested additional mass of hot dust, coupled with the low FIRRC value (assuming a synchrotron spectral index of -0.75) indicates the presence of an AGN.

SMMJ2135 (J213511.6-010252): The Cosmic Eyelash is one of the most well-studied high-redshift DSFGs, its 37.5 ± 4.5 amplification factor enabling the spatial and spectral resolution of 3-4 massive star-forming clumps (e.g. Swinbank et al. 2010, 2011; Iverson et al. 2010c; Danielson et al. 2013). After a tentative detection of OH 119- μm absorption in the OT1 observation of this source, we included 5 repeat observations of that object in OT2. A detailed examination of that data is presented in George et al. (2014), however for consistency we reprocess that data again here. [C II] 158- μm appears at a higher velocity in the original spectrum than the repeats, however while individual spectra may exhibit slight noise-related velocity differences, the fit to the combined spectrum of all SMMJ2135 observations should be more reliable.