Characterising the ISM of bright, lensed star-forming galaxies across cosmic time with the SPIRE FTS

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Science Category: Extra Galactic: High-z galaxies
Observing Modes: PACS Photometer, SPIRE Spectrometer
Hours Requested: 94.1

Abstract:
We have shown that Herschel is capable of exploring high-redshift galaxies spectroscopically, provided those galaxies are sufficiently bright.

Here, we propose to exploit the wide wavelength coverage of the SPIRE FTS to study the powerful diagnostic rest-frame FIR cooling lines from a unique and complete sample of 25 bright, gravitationally-lensed - but intrinsically typical - submm galaxies (SMGs). We can thus perform the first detailed analysis of their ISM, tracing their density structure and searching for variations in line strengths compared to local counterparts.

Our targets span $1 < z < 3.1$ (where [C II] is not accessible to ALMA) and a good range of L(FIR) (12 < log L(FIR) < 13.5), and are selected from panoramic Herschel imaging surveys that are uniquely capable of providing a large, reliable sample at S(350um) > 200mJy, with excellent ancillary data.

We will detect or place sensitive limits on the key atomic cooling lines, e.g. [C II], [O I], [O III], and combine these with ground-based observations of 12CO, 13CO, C I and dense-gas tracers to model their ISM and thence understand their energetics and evolution. Using these data we will:

1) map the evolution of the gas content as a function of redshift, via the sensitivity of [C II]/L(FIR) to M(H2);
2) search for changes in the properties of the star-forming gas as a function of redshift and L(FIR);
3) coadd the spectra in the rest frame to delve up to 5x deeper still, to search for faint lines, e.g. H2O and [O I]145.5, allowing a complete characterisation of the average emission;

4) conclusively address the issue of the contribution of AGN to the immense luminosities of submm galaxies.

Goals 1–3 drive the requirement for a sample of 25 SMGs. All our goals require Herschel and cannot be addressed by other facilities.

We stress that the scientific legacy of ISO and Spitzer has in large part been based on the wealth of data in their spectroscopic archives and the same is likely to be true for Herschel.

1. Description of the proposed programme (max. 3 pages)

1.1 Scientific Goals:

Summary: We propose to exploit the spectroscopic capabilities of *Herschel*, in particular the wide wavelength coverage of the SPIRE FTS, to study the powerful diagnostic rest-frame FIR cooling lines from a unique and complete sample of 25 bright, gravitationally-lensed – but intrinsically typical – submm galaxies (SMGs). We can thus perform the first detailed analysis of their ISM, tracing their density structure and searching for variations in line strengths compared to their local counterparts. Our targets span $1 \lesssim z_{\rm CO} < 3.1$ (where [C II] is not accessible to ALMA) and a good range of $L_{\rm FIR}$ ($12 \lesssim \log L_{\rm FIR} \lesssim 13.5$), selected from panoramic *Herschel* imaging surveys that are uniquely capable of providing a large, reliable sample at $S_{350\mu m} > 200$ mJy, with excellent ancillary data. We will detect or place sensitive limits on the key atomic cooling lines, e.g. [C II], [O I], [O III], and combine these with ground-based observations of ^{12}CO, ^{13}CO, C I and dense-gas tracers to model their ISM and thence understand their energetics and evolution. Using these data we will:

1) map the evolution of the gas content as a function of redshift, via the sensitivity of [C II]/$L_{\rm FIR}$ to $M(H_2)$;
2) search for changes in the properties of the star-forming gas as a function of redshift and $L_{\rm FIR}$, referenced to z=0 observations, which may indicate changes in the primary mode of star formation;
3) coadd the spectra in the rest frame to delve up to 5× deeper still, to search for faint lines such as H_2O, [O I]145.5 and high-J CO lines, allowing a complete characterisation of the average emission;
4) conclusively address the issue of the AGN contribution to the immense luminosities of submm galaxies.

Goals 1–3 drive the requirement for a sample of 25 SMGs. All our goals require *Herschel* and cannot be addressed by other facilities. We stress that the scientific legacy of *ISO* and *Spitzer* has in large part been based on the wealth of data in their spectroscopic archives and the same is likely to be true for *Herschel*.

Our total request for the proposed programme is 94.1 hours.

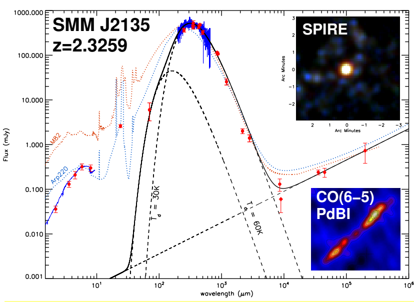
The power of gravitational lensing...

Gravitational lensing has played an important role in IR and submm studies of high-redshift galaxy and AGN populations since the discovery of *IRAS* FSC 10214 (Rowan-Robinson et al. 1991). This demonstrated the existence of a population of $z \sim 2$ ultraluminous IR galaxies (ULIRGs), widely expected to be the progenitors of the "red and dead" spheroidal systems seen at $z \sim 0$ (e.g. Swinbank et al. 2006). The subsequent discovery of an energetically-significant FIR/submm cosmological background (e.g. Puget et al. 1996; Fixsen et al. 1998) underlined the importance of obscured star formation and AGN activity in the evolution of young galaxies and drove an urgent need to resolve the background and understand the physical processes which created it.

The steep FIR/submm source counts make lensing a powerful tool to help identify and study examples of the high-redshift populations which are expected to dominate the extragalactic background in these wavebands (Blain 1996). The lensing boosts the sensitivity of observatories and improves their spatial resolution (which can otherwise result in high confusion limits) to reach the populations responsible for the bulk of the background (e.g. Blain et al. 1999; Hopwood et al. 2010). The lack of emission in these wavebands from the typical foreground lens population – the same "red/dead" elliptical galaxies which are thought to have evolved from high-redshift ULIRGs (SMGs) is also a substantial benefit. The boon provided by lensing has been seen particularly in the submm waveband, where it aided many advances in our understanding of SMGs, alleviating the photon starvation, facilitating their identification, the measurement of redshifts and hence their confirmation as massive gas-rich, star-forming galaxies at $z \sim 2$–3 (Ivison et al. 1998; Frayer et al. 1998).

...combined with the power of FIR diagnostics

One of the most striking recent discoveries is that of the $z = 2.3$ ULIRG, SMM J2135 (Swinbank et al. 2010), which is amplified by $(32.5 \pm 4.5)\times$ to produce a source with $S_{350\mu m} \sim 430$ mJy. SMM J2135 is an otherwise "typical" SMG yet it has been possible to assemble a comprehensive dataset of powerful diagnostic lines (Fig. 1).



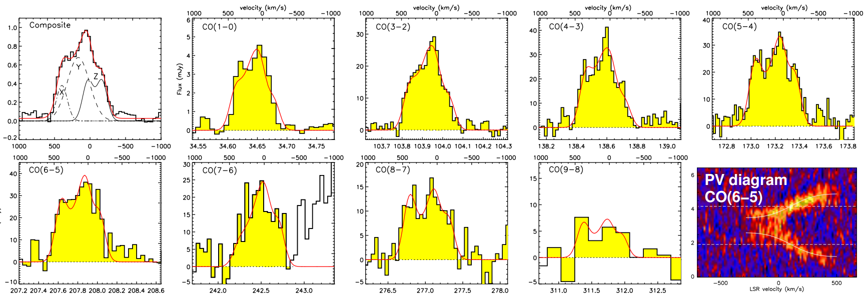


Figure 1 (left): SED of SMM J2135, with FTS data in blue, showing the accuracy of L(FIR) for such bright targets. Inset: image generated from the 250–, 350– and 500–micron data and a high–resolution IRAM PdBI image of 12CO J=6–5.

Figure 1 (right): The cornucopia of diagnostic emission lines detected at high SNR from SMM J2135 (these also include 13CO, HCN, C I J=2–1 and 1–0), possible only for SMGs with significant lensing amplification (Danielson et al. 2010). In the IRAM PdBI PV diagram we resolve 750 km/s of velocity shear across an 800–pc extent with 100–pc resolution, comparable to the best spatial resolution expected from the fully commissioned ALMA for unlensed SMGs.

Ivison et al. (2010) observed SMM J2135 for 7 ks using the SPIRE FTS (PV phase), detecting [C II] 157.7 ($1.7 \pm 0.4 \times 10^{-17}$ W m^{-2}) – a crucial cosmological tool to characterise galaxies – as well as providing tentative detections of [O I] 145.5 and [N II] 122.1. The subsequent analysis demonstrates that the ISM in this $z = 2.3$

1. Description of the proposed programme (cont.)

ULIRG is multi-phase, with an apparently low-metallicity, cool ($T \sim 25\,\mathrm{K}$) and extended component which contains the bulk of the gas mass and, in addition, a higher metallicity, warmer phase ($T \sim 45\,\mathrm{K}$) which more closely traces the regions of current star formation (Fig. 2, left).

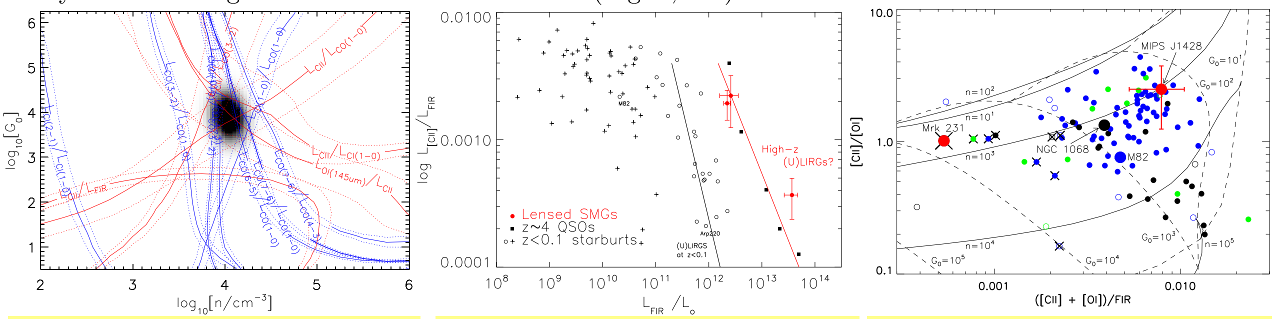


Figure 2 (left): powerful diagnostic line ratios for SMM J2135 from 12CO, 13CO, C I and [C II] as a function of density, n, and FUV flux, Go, from the PDR models of Kaufman et al. (1999) and Meijerink et al. (2007). From Danielson et al. (2010).

Figure 2 (middle): [C II]/L(FIR) vs. L(FIR) for local normal and starburst galaxies (black crosses; circles) and for high–redshift SMGs (red). Adapted from Maiolino et al. (2009). See text for discussion of several interpretations and their consequences.

Figure 2 (right): AGN diagnostics using the ratios of [C II], [O I] and L(FIR) with the models of Kaufman et al. (1999). AGN – black; H II galaxies – blue; LINERs – green; ULIRGs – points with crosses. Taken from Sturm et al. (2010).

Hence, by supplementing ground-based data with the critical rest-frame FIR atomic transitions covered by *Herschel*, it is possible to apply the same observational tools used on local star-forming galaxies (e.g. Wolfire et al. 1990; Hollenbach & Tielens 1990; Kaufman et al. 1999) to understand the processes of star formation at high redshift. *This has facilitated detailed investigations of the ISM at $z = 2.3$ in SMM J2135 which begin to rival our understanding of $z \sim 0$ galaxies – a striking demonstration of the opportunities which gravitational lensing provides to aid our understanding of the processes which drive galaxy formation and evolution.*

The [C II] emission from SMM J2135 is ∼10× more luminous than expected from local ULIRGs (e.g. Luhman et al. 2003; Brauher et al. 2008); indeed, the data currently available suggest that at a fixed $L_{\rm FIR}$, high-redshift SMGs generally have enhanced [C II] compared to low-redshift galaxies (Fig. 2, middle). It has been speculated that this supports the presence of a low-metallicity gas reservoir, more extended than those seen around the compact starbursts at $z \sim 0$ (Hailey-Dunsheath et al. 2010; Ivison et al. 2010), as has also been suggested by submm, radio and CO sizes and near- and mid-IR colours and spectra (e.g. Tacconi et al. 2008; Menéndez-Delmestre et al. 2009), i.e. lower dust content leads to lower attenuation to UV photons, which makes the [C II]-emitting region larger, whilst lowering $L_{\rm FIR}$ (Maiolino et al. 2009). However, [C II]/$L_{\rm FIR}$ is also high in local LIRGs and this is not due to extended low-metallicity gas, so whatever suppresses [C II] in ULIRGs does not operate in LIRGs. The most recent interpretation of the drop in [C II]/$L_{\rm FIR}$ in low-redshift ULIRGs (based on *Herschel* data – Hailey-Dunsheath et al., in prep) suggests [C II]/$L_{\rm FIR}$ is driven by $L_{\rm FIR}/M({\rm H_2})$: [C II]/$L_{\rm FIR}$ is low where $L_{\rm FIR}/M({\rm H_2})$ is high, and vice versa. This implies that measuring [C II]/$L_{\rm FIR}$ as a function of redshift will allow us to trace the evolution of the gas content, at fixed $L_{\rm FIR}$.

[C II] is also crucial for assessing the relative influence of starbursts and AGN in a galaxy. X-ray dissociation regions (XDRs) do not ionise the carbon or heat the dust efficiently, but they do heat the gas; for PDRs the situation is the opposite, so the combination of low [C II]/CO and high CO/$L_{\rm FIR}$ is characteristic of AGN excitation. This diagnostic is not unique – certain combinations of radiation field and gas density will also produce these results for PDRs – but other diagnostics can be used to assess the plausibility of those conditions, e.g. [O I]63.2 and high-J CO. [C II]/[O I] is low in XDRs, and an XDR begins to dominate the CO SLED at J = 8–7 (e.g. Mrk 231 – Van der Werf et al. 2010), which is often accessible from the ground (Fig. 1, right).

Our unique sample

Herschel's capability for panoramic FIR mapping provides a unique opportunity to select large samples of bright objects and undertake statistical studies to understand their properties. *Her*MES and *H*-ATLAS (Eales et al. 2010; Oliver et al., in prep) are mapping 70 + 550 deg^2 to around (or below) the SPIRE confusion limit. One of the most interesting outcomes has been the detection of a significant number of gravitationally lensed SMGs in the distant ($z > 1$) Universe (Negrello et al. 2010; see also Vieira et al. 2010). The FIR-bright sources comprise a mixture of these lensed, high-redshift SMGs, plus "contaminants" (from our perspective) – nearby ($z \lesssim 0.2$) spirals and blazars. The contaminants are very easily identified with our high-quality optical/NIR/radio data (§1.3), resulting in a clean sample of strongly-lensed, bright, yet intrinsically "typical" SMGs.

Together, *Her*MES and *H*-ATLAS will detect some ∼50 lensed SMGs with $S_{350\mu m} > 200$ mJy, with redshifts mainly in the $z \sim 1$–3.5 range, and a good range of $L_{\rm FIR}$ ($11 \lesssim \log L_{\rm FIR} \lesssim 12.5$) due to the range of amplifications (Negrello et al. 2007, 2010; Fig. 3). Selecting at (or beyond) 500 μm risks blending and would result in many sources with $z > 3.1$, shifting [C II] out of the FTS band; selecting at $S_{350\mu m} \lesssim 100$ mJy would require much longer integration times to achieve only tentative detections of [C II], let alone the fainter diagnostic lines, while providing little benefit in terms of the diversity (in e.g. $L_{\rm FIR}$) of the population being sampled.

Our sample selection is simple and straightforward: it will comprise 25 lensed SMGs with $S_{350\mu m} > 200$ mJy and $1 \lesssim z_{\rm CO} < 3.1$, where [C II] is not accessible to ALMA. Observations of two targets are complete (see §2.1), using the mode proposed here, leaving 23. *H*-ATLAS comprises 89% of our total sky coverage and is currently ∼20% complete, with the remainder (and hence ∼40 more targets to choose from) due in 2010. We have created AORs for the targets that satisfy our selection criteria at the time of writing; the remainder are dummies, in our remaining fields. For the known targets, CO-derived redshifts ($z_{\rm CO}$) have proved easy to obtain from the ground using CSO/Zspec (Fig. 3, right; $z = 1.58, 1.79, 2.65, 3.04$ – Lupu et al. 2010), GBT/Zpectrometer ($z = 2.32, 2.63, 3.04$ – Swinbank et al. 2010; Frayer et al. 2010) and IRAM ($z = 4.24$ – Cox et al., in prep), guided by FIR photometric estimates. So far, we have been able to measure accurate redshifts for every galaxy that satisfies our selection criteria, and all our fields are accessible to those facilities, or to APEX/Zspec.

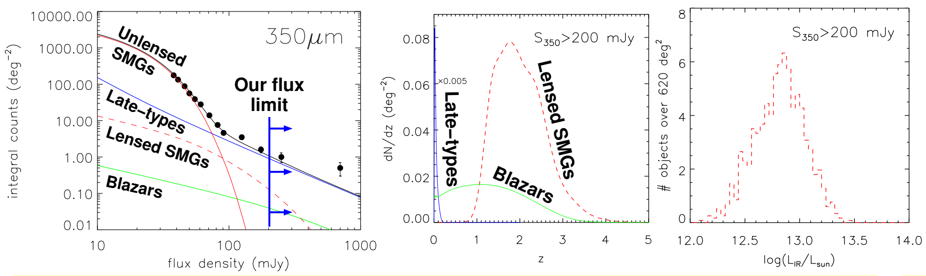


Figure 3 (left): 350–um counts (Clements et al. 2010) with lensing predictions from Negrello et al. (2007, 2010) overplotted in red (unlensed SMGs), dashed red (lensed SMGs), blue (local late–type galaxies) and green (blazars). Over the combined area of H–ATLAS and HerMES, we expect ~50 lensed SMGs, ~500 late–type galaxies (z <~ 0.2) and ~20 blazars. The latter two categories are easily separated from the lensed SMGs with our high–quality optical/NIR/radio data. Also shown: predicted distributions of redshift and L(FIR) for the lensed SMGs.

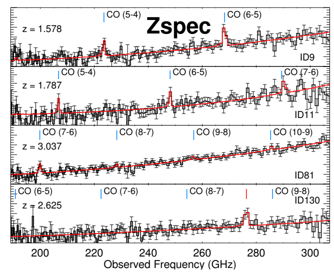


Figure 3 (right): CO redshifts have proved straightforward to acquire using Zspec (shown here; z=1.58, 1.79, 2.65, 3.04 – Lupu et al. 2010), with GBT/Zpectrometer (Swinbank et al. 2010; Frayer et al. 2010) and with IRAM (Cox et al., in prep).

1.2 Science Exploitation Plan:

For our unique sample of strongly lensed, high-redshift galaxies, we have demonstrated that it is possible to study their ISM using SPIRE's FTS. The requested spectroscopy covers 194–671 μm with resolution, $R = 372$–1289, with line sensitivities of 1.0, 1.6 and 1.3×10^{-18} W cm^{-2} (1σ at 250, 350 and 500 μm) and a continuum sensitivity at 350 μm of $1\sigma \sim 22$ mJy (if we degrade to $R = 20$). As outlined in §1.1, our targets will cover the redshift range $1 \lesssim z_{\rm CO} < 3.1$ (Fig. 3) where the FTS range corresponds to rest-frame 97–335 ($z = 1.0$) and 48–163 μm ($z = 3.1$). We thus expect to see the most prominent ISM cooling lines, including [C II] 157.7, [O I] 63.2 (perhaps [O I] 145.5), and also [O III] 88.4 and [N II] 122.1, which we can then combine with our well-constrained $L_{\rm FIR}$ and CO spectral-line energy distributions (SLEDs) obtained from GBT, CSO, JCMT, IRAM, APEX, EVLA and ultimately ALMA. The line-to-line as well as line-to-$L_{\rm FIR}$ ratios are some of the most powerful known diagnostics for the physical conditions of a galaxy and its star-forming regions. The ready availability of CO $J = 1$–0 data from GBT and EVLA mean we also have the key diagnostics required for XDR-based interpretation: CO $J = 1$–0, [O I] 63.2, [C II] 157.7 and $L_{\rm FIR}$ (see Fig. 2 and e.g. Hollenbach & Tielens 1990; Kaufman et al. 1999). The detection of even fainter lines, e.g. H_2O, [O I] 145.5 and high-J CO, may well prove possible when we coadd the full sample in the rest frame (see, e.g., Fig. 3 of Menéndez-Delmestre et al. 2009), going up to 5× deeper still, allowing a complete characterisation of the average emission.

1.3 Relation to observations with other facilities:

The *H*-ATLAS and *Her*MES fields were originally chosen largely because of their wealth of existing ancillary data. For *H*-ATLAS, these include many thousands of spectroscopic redshifts as well as deep panchromatic images. For *Her*MES, the ancillary data are of a quality befitting the most intensively studied extragalactic "deep fields" on the sky. Follow-up proposals for these lensed targets have been successful on *HST*, *Spitzer*, EVLA (continuum and CO $J = 1$–0), GBT, IRAM PdBI+30m, SMA, ESO/VLT and CSO/APEX/Zspec. For many of the proposals, the observations have already been executed, processed and analysed, e.g. at GBT, CSO/Zspec, SMA and IRAM, all cases where the staff and/or instrument teams are very active in the project.

References: Blain 1996, MNRAS, 283, 1340 • Blain et al. 1999, ApJ, 512, L67 • Brauher et al. 2008, ApJS, 178, 280 • Clements et al. 2010, A&A, 518, L8 • Danielson et al. 2010, www.roe.ac.uk/∼rji/dan.pdf • Eales et al. 2010, PASP, 122, 499 • Fixsen et al. 1998, ApJ, 508, 123 • Frayer et al. 1998, ApJ, 506, L7 • Frayer et al. 2010, ApJL, submitted • Hailey-Dunsheath et al. 2010, ApJ, 714, L162 • Hollenbach & Tielens 1990, Rev. Mod. Phys., 71, 173 • Hopwood et al. 2010, ApJ, 716, L45 • Kaufman et al. 1999, ApJ, 527, 795 • Ivison et al. 1998, MNRAS, 298, 583 • Ivison et al. 2010, A&A, 518, L35 • Luhman et al. 2003, ApJ, 594, L758 • Lupu et al. 2010, Science, www.roe.ac.uk/∼rji/lupu.pdf • Maiolino et al. 2009, A&A, 500, L1 • Meijerink et al. 2007, A&A, 461, 793 • Menéndez-Delmestre et al. 2009, ApJ, 699, 667 • Negrello et al. 2007, MNRAS, 377, 1557 • Negrello et al. 2010, Science, www.roe.ac.uk/∼rji/neg.pdf • Puget et al. 1996, A&A, 308, L5 • Rowan-Robinson et al. 1991, Nature, 351, 719 • Sturm et al. 2010, A&A, 518, L36 • Swinbank et al. 2006, ApJ, 371, 465 • Swinbank et al. 2010, Nature, 464, 733 • Tacconi et al. 2008, ApJ, 680, 246 • Van der Werf et al. 2010, A&A, 518, L42 • Vieira et al. 2010, ApJ, arXiv:0912.2338 • Wolfire et al. 1990, ApJ, 358, 116

2. Technical Implementation (max. 1 page)

2.1 Observations Strategy:

SPIRE FTS observations

These are spectroscopic follow-up observations of galaxies discovered using *Herschel* photometric imaging. The strategy is straightforward because we know the broad-band flux density of the targets in the SPIRE photometer bands, and have demonstrated during PV and GT that observations of $S_{350} > 200$-mJy targets are feasible (e.g. Ivison et al. 2010). Our proposed targets are point-like sources at *Herschel* resolution and we plan to obtain point-source observations with sparse spatial sampling. The target spectra will be extracted from the central SPIRE FTS detectors, which are also those that have been best calibrated in terms of flux and instrumental responses. The telescope reference will be taken from coordinated calibration-time dark-sky observations.

We will spend twice as much time as the observation of SMM J2135, which used 50 repetitions (7 ks) and was obtained during SPIRE PV, prior to optimisation of the mode (see Ivison et al. 2010). With 100 repetitions, our sensitivities are $1\sigma \sim 1.0, 1.6$ and 1.3×10^{-18} W m^{-2} at 250, 350 and 500 μm. We have tested the mode proposed here by acquiring FTS data for two lensed SMGs, at $z = 3.04$ and 2.63, which form part of our sample of 25. These targets were 2× fainter than SMM J2135, yet we detect [C II] 157.7 as well as [O III] 88.4 and [N II] 122.1 (Valtchanov, Ivison et al. in prep).

100 repetitions should result in >5-σ detections of [C II] 157.7 for all our targets, and ∼10-σ detections for those targets as bright as SMM J2135, well matched to the 10% accuracy with which we have been able to determine the amplification of SMM J2135 via high-spatial-resolution CO imaging.

In addition, we can create low-resolution ($R = 20$) spectra and detect the continuum with a SNR of ∼10 to better constrain the SED peak.

PACS observations

Our wide surveys utilise the SPIRE+PACS Parallel mode and our bright, high-redshift SPIRE sources are not detected a 100–160 μm due to the modest depth of our PACS imaging.

We therefore propose to obtain two consecutive orthogonal mini scan-maps per target with PACS (nominal 3-arcmin scan legs) around each source, going down to 2.7 and 5.1 mJy (1σ) at 100 and 160 μm, respectively, to characterise the blue region of the SED, which can make a substantial contribution to $L_{\rm FIR}$ (the $L_{\rm FIR}$ calculated for SMM J2135 by Ivison et al. 2010 is ∼2× that determined by Swinbank et al. 2010, because the latter ignored the blue region of the SED).

2.2 Observing Time Requirements:

The time estimates and sensitivity levels are given below, in Table 1.

Table 1. Time estimation and sensitivity for the proposed observations.

Time for SPIRE FTS, 100 high-resolution repetitions:	13932s
Line sensitivity at 250, 350 and 500 μm (1σ):	1.04, 1.59 and 1.25 $\times 10^{-18}$ W m^{-2}
Continuum sensitivity (for $R = 20$, at 350 μm, 1σ):	22 mJy
Time for PACS mini scan-map, 2 repetitions:	456s (plus 335s, concatenated)
PACS sensitivity (1σ):	2.7 mJy at 100 μm; 5.1 mJy at 160 μm
Total time, 23 targets:	$\mathbf{(23 \times 13932) + (23 \times (456 + 335)) = 94.1\,hours}$

2.3 Other Special Requirements or Constraints:

The PACS nominal and orthogonal mini scan-maps are concatenated.

All our targets lie within a small number of large fields; only one "dark sky" scan is required in each field.

Following SPIRE ICC and HSC policy, the SPIRE FTS "dark sky" scans will be carried out in calibration time.

2.4 Duplication analysis:

We request a new 100-repetition scan of SMM J2135. This was the first high-redshift target observed in SV for 7 ks with the FTS, prior to the optimisation of the mode (Ivison et al. 2010).

3. Data Processing Plans (max. 1 page)

3.1 Data Processing and Analysis Plans:

SPIRE FTS data processing

The FTS observations will be processed by two groups of experts, in friendly competition – one at the *Herschel* Science Centre, the other at the SPIRE Instrument Control Centre at STFC-RAL. We may use an improved FTS pipeline (see below) – allowing the subtraction of the off-position reference spectrum – to produce the final spectrum from the central (target) SPIRE FTS detectors from both spectrometer arrays.

FTS data reduction for faint sources presents a number of challenges that – at present – cannot be met within the capabilities of HIPE. Therefore, the analysis of the proposed spectra may involve use both of HIPE routines and specially developed routines (mostly in IDL) based on expertise acquired from previous space missions, e.g. *ISO*.

The expectation is that by the time the observations are carried out, optimised SPIRE FTS pipeline developments now underway will have resulted in currently specialised data-processing techniques being incorporated into HIPE.

The new detector-temperature-based FTS pipeline is also expected to be in use at this stage, and will be especially suited to this programme.

As with any new instrument, the processing continues to improve with time as one better understand the instrument. The current situation is that the noise in the interferogram domain reduces as $\sqrt{N}$, where N is the number of scans, but this is not the case for the resulting spectrum despite the fact that the Fourier transform is linear. A team led by Naylor is working on a sophisticated line-fitting tool (Naylor et al. 2010, SPIE, in press – www.roe.ac.uk/∼rji/n10.pdf) which exploits our detailed knowledge of the instrumental line shape (ILS). By using the ILS, we can exploit the many 10s of independent spectral data points surrounding a line, which contain coherent information about the spectral line (but incoherent in the noise) to improve our sensitivity. So while the instrument performance is not expected to change, our understanding of it will.

This proposal team includes FTS experts from the SPIRE team, and the team as a whole will ensure that the data processing is optimised and that any new techniques are fed back to SPIRE to allow all users to benefit.

PACS mini scan-maps data processing

These observations will be processed in Edinburgh by the experienced *H*-ATLAS PACS DR team (see e.g. Ibar et al. 2010, MNRAS – www.roe.ac.uk/∼rji/i10.pdf). We will use the latest HIPE pipeline for PACS and the latest PACS calibration tree in order to derive the best possible photometry in the two PACS bands, 100 and 160μm.

3.2 Product Generation Methods:

See §3.1.

4. Management and Outreach Plans (max. 1 page)

4.1 Team Resources and Management Plan:

The team has the expertise necessary to plan for optimal observations, and to process the data beyond the standard *Herschel* data processing scripts, and to analyse the science data. We have already demonstrated a very strong publication record with *Herschel* data, e.g. the PI has written two first-author *Herschel* Special Issue papers and the team has over 20 first-author *Herschel*-based papers.

SPIRE FTS: processing, extraction of the final calibrated spectra and low-resolution continuum will be performed by Bruce Swinyard, Ivan Valtchanov and David Naylor. Iterations using improved processing for the telescope background removal as well as alternative FTS pipelines will be attempted to squeeze the most out of the data (see §3). Validation of the data products will be carried out by Rob Ivison, Dimitra Rigopoulou and Chris Pearson. Once validated, the data products will be distributed to the team.

PACS mini scan-maps: pipeline processing and extraction of PACS photometry at 100 and 160 μm will be handled by Eduardo Ibar. Validation of the data products will be carried out by Rob Ivison, Antonio Cava and Hervé Aussel. Once validated, the data products will be distributed to the team.

A small team comprising Rob Ivison, Ivan Valtchanov, Paul Van der Werf, Mark Swinbank and Bruce Swinyard will manage the team and enforce a merit-based publication policy.

A related proposal has been submitted by Aprajita Verma et al. to acquire PACS spectroscopy of a sample which overlaps in large part (but not entirely) with the sample proposed here. These two teams are well integrated.

Asantha Cooray will serve as US-based PI. He will submit this proposal to the NASA Herschel Science Center (NHSC) requesting financial support for data analysis for all US-based investigators. He is responsible for the scientific and administrative conduct of the US teams participation in this proposal.

4.2 Outreach Activities:

Our outreach team will be coordinated by Haley Gomez, and will also contain Rob Ivison, Matt Griffin and Stephen Serjeant.

This research project lends itself easily to outreach since the concept of lenses is relatively approachable and the question of how galaxies change with time is fundamental and intriguing. The institutes listed in this proposal already have vigorous outreach, media and education projects in place which we will capitalise on in relation to *Herschel*. A number of co-Is on this proposal are active members of the *Herschel* Outreach Group (HOG, led by Matt Griffin, PI of SPIRE) which meets on a regular basis. Examples of the successful projects run by this group are London Science Museum events, the Royal Society Summer Exhibition, the Big Bang Fair in Manchester, the Wrexham Science Festival and Science@Eisteddfod, interacting with tens of thousands of members of the public. Members of our team have also undergone Media training sessions held by the Royal Society.

HOG has also had a number of successful funding awards related to *Herschel* outreach and education including high definition vodcasts on *Herschel* science (`teapotsfromspace.org`) and a strong partnership with the award-winning outreach company, Science Made Simple (SMS), who have constructed a popular interactive *Herschel* show. We will continue to work closely with SMS and will incorporate our exciting results in their "latest highlights" part of the show.

We will utilise the advice and resources provided by the UK *Herschel* Outreach Officer (HOO), who is responsible for coordinating UK-wide outreach activities. This involves coordinating efforts of *Herschel* Team members across the UK, liaising with the press and media, and providing opportunities to present *Herschel* science to schools and other public groups. We will work closely with HOO to add our images to the incredibly popular Chromoscope astronomy tool at `www.chromoscope.net` (with millions of visitors since its launch in 2009 October). The proven track record of the success of the HOG activities will be invaluable to our outreach programme.

We will produce press releases in coordination with the ESA PR office, suitable for the general public, and the results will be incorporated into display material used at future exhibits and exhibitions.

We will provide suitable FITS images for ESA's Online Showcase of *Herschel* Images.

In Edinburgh, we are linking our *Herschel* outreach to E-ELT and JWST – see `www.bigtelescopes.org.uk`. We are also running a Deep Space programme for early secondary schools, wherein students do group work with data on galaxies and exo-planets. We will make a video about our work with *Herschel* and schools will then be able to view this as part of their work with the Deep Space resources.

Finally, we are involved in a STFC Small Award programme, with Susan Rodrigues, Professor of Science Education at the University of Dundee, to develop support for teachers to engage early secondary pupils with *Herschel*. The approach promotes active learning through the use of Comic Life, a trademarked software package which pupils can use to storyboard digital material such as from the *Herschel* website, `herschel.cf.ac.uk`. This is a fully piloted new approach to engaging with secondary pupils, incorporated into another secondary school programme, "Big Telescopes for Big Questions" and with GLOW (the intranet for Scottish schools).

5. List of Team Members

Ivison, Rob UK Astronomy Technology Centre, Royal Observatory Edinburgh – UK, Professor. Role: **PI**, validation of PACS and FTS data; management team leader; outreach team member; scientific interpretation. Relevant qualifications: leading the *H*-ATLAS PACS DR; author of two *Herschel* Special Issue papers, including one presenting FTS observations of a bright submm galaxy; co-discovered SMGs via lensing technique, pioneered their study in the radio waveband and thence characterised their properties across the full observable spectrum; leading the EVLA and co-leading the IRAM PdBI follow-up of the lensed SMGs in *H*-ATLAS and *Her*MES; SPIRE Associate Scientist; member of *H*-ATLAS executive.
Van der Werf, Paul Leiden Observatory – Netherlands, Associate Professor. Role: XDR diagnostics and algorithm development; management team member. Relevant qualifications: PI of *Herschel* KP, HerCULES, the programme that uses the SPIRE FTS most; developing special-purpose routines for the reduction of deep FTS spectra which will be available for use in our programme; more than a decade of experience with IR (*ISO* and *Spitzer*) and submm spectroscopy (JCMT) of star-forming galaxies.
Swinbank, Mark Durham University – UK, Postdoc. Role: reconstruction of source plane using lens modeling tools; management team member. Relevant qualifications: expert in analysis of lensed galaxies at high redshift.
Swinyard, Bruce STFC-RAL and University College London – UK, Professor. Role: observation planning, FTS data processing/calibration; management team member. Relevant qualifications: SPIRE Instrument Scientist, SPIRE Co-I.
Valtchanov, Ivan *Herschel* Science Centre, ESAC – Spain, SPIRE instrument and calibration scientist. Role: observation planning; FTS data processing; management team member. Relevant qualifications: co-I in *H*-ATLAS, *Her*MES, HLens, with deep knowledge of the SPIRE instrument and in particular the Fourier Transform Spectrometer, has extensive experience with multi-wavelength observations and data analysis.
Smail, Ian Durham University – UK, Professor. Role: Interpretation. Relevant qualifications: actively working on the gas properties of high-redshift galaxies, experience in exploiting gravitational lensing in the sub-millimetre.
Cox, Pierre IRAM – France, Director. Role: co-leading the follow-up of the lensed SMGs at IRAM PdBI and APEX. Relevant qualifications: many years of interferometric expertise.
Griffin, Matt Cardiff University – UK, Professor; Role: participation in observation planning, calibration, data analysis; outreach team member . Relevant qualifications: SPIRE PI, familiarity with instrument calibration, etc.
Eales, Stephen Cardiff University – UK, Professor. Role: target selection. Relevant qualifications: PI of *H*-ATLAS, member of the team that is following up the bright *H*-ATLAS sources.
Ibar, Eduardo UK Astronomy Technology Centre, Royal Observatory Edinburgh – UK, Postdoc. Role: PACS data reduction and EVLA follow-up. Relevant qualifications: key member of PACS data reduction team for *H*-ATLAS; first author on the *H*-ATLAS PACS DR paper.
Negrello, Mattia Open University – UK, Postdoc. Role: modeling of gravitational lenses. Relevant qualifications: expert in the modeling of the statistical properties of submm galaxies; his models of the effect of lensing on submm source counts predicted correctly that the yield of gravitational lenses in samples of bright *Herschel* sources should be high; joint leader of the *H*-ATLAS lensing team.
Naylor, David University of Lethbridge – Canada, Professor. Role: FTS data processing. Relevant qualifications: expert in Fourer transform spectroscopy; Canadian SPIRE co-I; leading Canadian role in SPICA/Safari; delivered Fourier spectrometer (FTS-2) for use with the SCUBA-2 camera at the JCMT; developing spectral fitting tools that will be used to analyse SPIRE FTS spectra, and advanced line-mapping software to intepret the results; research interests in the physics of the ISM.
Wright, Gillian UK Astronomy Technology Centre, Royal Observatory Edinburgh – UK, Professor. Role: AGN/starburst diagnostics. Relevant qualifications: expertise in ultra-luminous starburst galaxies, galaxy interactions, near-IR spectroscopy and diagnostics in galactic nuclei; European PI for MIRI, the mid-IR instrument for JWST; SPIRE co-I.
Dunne, Loretta University of Nottingham – UK, Faculty. Role: interpretation of SEDs. Relevant qualifications: expert in submm/FIR galaxy studies, both in the local and distant Universe; she led the SCUBA Local Universe Galaxy Survey, which produced the first direct measurements of the submm luminosity and dust mass functions; co-PI of *H*-ATLAS, with responsibility for the scientific leadership of Programme A.
Dye, Simon Cardiff University – UK, Postdoc. Role: Modeling of strong lens systems. Relevant Qualifications: joint leader of the *H*-ATLAS lensing team; expertise in submm data analysis and strong lens reconstruction methods.
Rigopoulou, Dimitra Oxford and STFC-RAL – UK, Research Lecturer. Role: data processing. Relevant qualifications: SPIRE/FTS data reduction/analysis/interpretation expertise, member of SPIRE-ICC, member of SPIRE-FTS pipeline group, expertise in interpreting/modeling far-infrared fine-structure lines.
Gomez, Haley Cardiff University – UK, Lecturer. Role: outreach team leader. Relevant qualifications: experience in *Herschel* outreach activities. Also experienced in chemical modeling of galaxies and reducing ground-based FIR/submm data, including SCUBA/LABOCA and SHARC II.
Frayer, Dave NRAO – USA, Staff. Role: leading follow-up ground-based CO observations with GBT/Zpectrometer. Relevant qualifications: PI of the ultra-deep *Spitzer* 70-μm surveys of the GOODS-N+S fields, key member of *Spitzer* COSMOS, SWIRE, XFLS, and FIDEL teams, extensive experience in high-redshift CO studies. Member of PACS DR group for *H*-ATLAS.
Bock, James Jet Propulsion Laboratory – USA, Sr. Research Scientist. Role: follow-up with the Zspec instrument on the CSO and APEX. Relevant qualifications: SPIRE co-I, co-coordinator of *Her*MES, Zspec team member, familiarity with SPIRE and Zspec instruments.
Verma, Aprajita University of Oxford – UK, Postdoc. Role: optical/near-IR follow-up. PI of complementary PACS spectroscopy proposal. Relevant qualifications: experience in the analysis of IR surveys and the multi-wavelength follow-up of IR galaxies, both locally and at high redshift; member of the PACS GTKP spectroscopy team, SHINING.
Thomson, Alasdair University of Edinburgh – UK, PhD student. Role: diagnostics involving CO(1–0). Relevant

qualifications: in charge of DR for CO(1–0) survey of these targets with EVLA; data will comprise part of his thesis.
De Zotti, Gianfranco INAF-OAPd – Italy, Professor. Role: comparison with models. Relevant qualifications: experience with modeling (counts of strongly lensed sources, SEDs and FIR line emission).
Conversi, Luca European Space Agency, ESAC – Spain, Staff Scientist at *Herschel* Science Centre, SPIRE intrument and calibration scientist. Role: observation planning. Relevant qualifications: deep experience with SPIRE instrument data reduction, scientific background in CMB, SZ, Galactic dust, FIR background, multi-wavelength cosmological surveys, large-scale structure of the Universe and high-redshift galaxy clusters.
Cirasuolo, Michele UK Astronomy Technology Centre, Royal Observatory Edinburgh – UK, Staff. Role: and follow-up at optical/near-IR wavelengths and analysis of foreground lensing galaxy properties. Relevant qualifications: photometric redshift expertise.
Omont, Alain IAP – France, Faculty. Role: complementary observations of mm lines at IRAM and their joint analysis with SPIRE/FTS data. Relevant qualifications: worked for 15 years on mm studies of high-redshift QSOs and galaxies.
Glenn, Jason University of Colorado, Boulder – USA, Associate Professor. Role: Zspec follow-up of lensed SMGs on the CSO and APEX. Relevant qualifications: studies of high-redshift galaxies, the molecular ISM in nearby galaxies, and star formation in the Milky Way; extensive experience with submm instrumentation, including design and testing of aspects of the SPIRE bolometer arrays.
Asantha, Cooray U. of California – USA, Professor. Role: scientific interpretation. Relevant qualifications: Associate Scientist for SPIRE and US PI of *H*-ATLAS; interested in large-scale structure and high-redshift sources, including formation of first galaxies and dust in the Universe.
Aussel, Hervé AIM Paris-Saclay – France, Researcher. Role: PACS data validation. Relevant qualifications: expert in analysis of PACS images though direct measurement and stacking. Member of the PACS ICC.
Burgarella, Denis Laboratoire d'Astrophysique de Marseille – France, Astronomer. Role: scientific interpretation. Relevant qualifications: expertise in formation and evolution of galaxies.
Bridge, Carrie Caltech – USA, Postdoc. Role: Near-IR follow-up. Relevant qualifications: Co-I on *H*-ATLAS, HLens and *Her*MES and is working on the WISE mission. She has experience with reducing and analysing optical to submm data.
Serjeant, Stephen Open University – UK, Faculty. Role: high-resolution radio follow-up with eMERLIN and submm follow-up with SCUBA2; outreach team member. Relevant qualifications: co-lead of AGN working group in *H*-ATLAS, coordinator on the SCUBA-2 All-Sky Survey (SASSy), co-PI of the eMERLIN Gravitational Lensing legacy survey.
Pascale, Enzo Cardiff University – UK, Faculty. Role: data processing. Relevant qualifications: reduction lead of the SPIRE-HATLAS survey. extensive experience in reducing photometric and spectroscopic data in the mm and submm, in particular FTS data.
Bradford, Matt Caltech – USA, Faculty. Role: CSO/Zspec follow-up. Relevant qualifications: familiarity with Zspec.
Rowan-Robinson, Michael Imperial College – UK, Professor. Role: SED modeling. Relevant qualifications: many years of expertise in multi-wavelength SED modeling.
Pearson, Chris STFC-RAL – UK and University of Lethbridge – Canada, SPIRE ICC Scientist. Role: pipeline development specifically for the purposes of this experiment. Relevant qualifications: observations manager at the SPIRE Instrument Control Centre overseeing the SPIRE pipeline validation for scientific purposes including the FTS pipeline; scientific expertise in the area of galaxy evolution and source counts.
Valiante, Elisabetta UBC – Canada, Postdoc. Role: interpretation, regarding AGN. Relevant qualifications: expert in modeling starburst-AGN co-evolution.
Clements, Dave Imperial College London – UK, Lecturer. Role: general expertise. Relevant qualifications: experience of studying FIR-luminous galaxies with *IRAS, ISO, Spitzer*, SCUBA, *Herschel* and following up these surveys with a variety of observatories. Member of *Her*MES and *H*-ATLAS teams, member of SPIRE instrument team and ICC, led development of SPIRE data processing code for HIPE.
Vaccari, Mattia (University of Padova – Italy, Postdoc. Role: data processing. Relevant qualifications: SPIRE ICC Member and *Her*MES Multi-Wavelength Data Fusion lead.
Leeuw, Lerothodi SETI Institute – USA, Postdoc. Role: scientific analysis. Relevant qualifications: expert in radio, submm and FIR observations of early, merging, star-forming and related systems.
Chapman, Scott Camridge – UK, Associate Professor. Role: spectroscopic follow-up, analysis and interpretation. Relevant qualifications: spectroscopy expert; simulations of fine-structure lines for SPICA.
Oliver, Seb University of Sussex – UK, Professor. Role: Joint co-ordinator of *Her*MES. Relevant qualifications: extensive FIR/sub-mm survey experience.
Hurley, Peter University of Sussex – UK, PhD student. Role: Modeling of FIR SEDs and spectra. Relevant qualifications: working with Seb Oliver; data will form part of his thesis.
Magdis, Georgios CEA saclay – France, Postdoc. Role: data analysis. Relevant qualifications: developed IDL pipeline to reduce spectra.
Temi, Pasquale NASA–Ames – USA, Senior Scientist. Role: PACS imaging with MADMAP. Relevant qualifications: active member of *H*-ATLAS PACS DR group. Facility Scientist for SOFIA. Experience in infrared observations from ground-based observatories and space missions. Experience in observations and modeling of infrared emission from early-type galaxies.
Michałowski, Michal University of Edinburgh – UK, Postdoc. Role: SED modeling. Relevant qualifications: experienced in full spectral energy distribution modeling.
Franceschini, Alberto Padova University – Italy, Full Professor. Role: spectral synthesis and modeling of dust emission. Relevant qualifications: expertise in spectral synthesis and modeling of normal and active cosmological sources, dust emission in galaxies and AGNs. Co-I of SPIRE, with experience in IR astronomy, starting from analyses of *IRAS*

data; co-I of ISOCAM and the *Spitzer* wide-area Legacy programme, SWIRE.
Dunlop, James University of Edinburgh – UK, Professor. Role: follow-up in *Her*MES fields. Relevant qualifications: played a leading role in the study of galaxy/AGN evolution via surveys at radio, submm, IR and optical wavelengths. PI or co-PI of SHADES, the SCUBA2 Cosmology Legacy Survey, SpUDS and the UltraVista near-IR survey of COSMOS.
Farrah, Duncan University of Sussex – UK, Staff. Role: near- and mid-IR follow-up. Relevant qualifications: extensive experience with analysis of mid-IR spectroscopic data of low- and high-redshift ULIRGs. Member of several current large-scale extragalactic surveys, including deputy PI of SERVS.
Wang, Lingyu University of Sussex – UK, Postdoc. Role: near- and mid-IR follow-up. Relevant qualifications: experience working on large-scale structure using infrared data and galaxy formation and evolution using mid-IR spectra.
Pope, Alexandra University of Massachusetts Amherst – USA, Assistant Professor. Role: characterise IR SEDs and synthesis with spectral features, additional follow-up efforts. Relevant qualifications: experience with modeling and diagnostics from IR/mm spectra and broad-band SEDs of IR luminous galaxies, co-I on GOODS-*Herschel* OTKP.
Trichas, Markos CfA, Harvard – USA, Fellow. Role: X-ray follow-up. Relevant qualifications: experience in reducing and analysing FIR, submm, X-ray and optical spectroscopic data; member of the SPIRE ICC; involved in large multi-wavelength surveys such as SWIRE, *Her*MES, *H*-ATLAS AND ChaMP. He has worked on studies of AGN using IR, optical and X-ray photometry and spectroscopy.
Perez-Fournon, Ismael Instituto de Astrofisica de Canarias and Universidad de La Laguna – Spain, Lecturer. Role: hollow-up with the Gran Telescopio Canarias, IRAM and ALMA. Relevant qualifications: experience in extragalactic IR surveys (*ISO, Spitzer, Herschel*) and ground-based follow-up. Co-I of SPIRE, *Her*MES and *H*-ATLAS.
Ferrero, Patrizia Instituto de Astrofisica de Canarias and Universidad de La Laguna – Spain, Postdoc. Role: follow-up with the Gran Telescopio Canarias (GTC), IRAM and ALMA. Relevant qualifications: experience in photometry and spectroscopy (long-slit and 3D spectroscopy).
Gonzalez-Nuevo, Joaquin SISSA – Italy, Postdoc. Role: *Planck* liaison. Relevant qualifications: works on the statistical properties of radio and submm sources, focusing on simulations of the clustering of high-redshift proto-clusters and the development of detection methods for these kind of objects; *Planck* LFI Core Team Deputy; member of *H*-ATLAS.
Virdee, Jasmeer Oxford – UK, PhD student. Role: FTS data reduction. Relevant qualifications: supervised by Rigopoulou; data will form basis of thesis.
Blain, Andrew University of Leicester – UK, Professor. Role: follow-up with ALMA. Relevant qualifications: experience of observations and modeling of dust-enshrouded high-redshift systems.
Dannerbauer, Helmut Laboratoire AIM, CEA/DSM, CNRS and Université Paris Diderot – France, Postdoc. Role: radio follow-up. Relevant qualifications: expert in the identification of counterparts of dust-enshrouded high-redshift sources selected from submm/mm surveys.
Morrison, Glenn University of Hawaii and CFHT – USA; Associate Astronomer and Staff Astronomer. Role: follow-up from Mauna Kea. Relevant qualifications: experienced observer at CFHT, UKIRT.
Scott, Douglas UBC – Canada, Professor. Role: multi-wavelength modeling. Relevant qualifications: 15 years of experience in submm data reduction and analysis.
Cava, Antonio Instituto de Astrofisica de Canarias and Universidad de La Laguna – Spain, Postdoc. Role: PACS data validation. Relevant qualifications: PACS-ICC member with expertise in reduction and analysis of HERSCHEL. data; member of *Her*MES, PEP and *H*-ATLAS with interests in galaxies formation/evolution and clustering.
Hopwood, Ros Open University – UK, Postdoc. Role: algorithm development for FTS processing. Relevant qualifications: experienced with developing analysis software for *Herschel* DR.
Lupu, Roxana University of Pennsylvania – USA, Postdoc. Role: ground-based follow-up of lensed sources with Zspec. Relevant qualifications: carried out the redshift determination and analysis of the CO excitation for lensed *H*-ATLAS galaxies using Zspec data. Lead author of Science paper describing existing Zspec follow-up of lensed *H*-ATLAS SMGs. Extensive experience with modeling of molecular lines.
Aguirre, James University of Pennsylvania – USA, Assistant Professor. Role: coordinate Zspec follow-up. Relevant qualifications: broad background in bolometer-based instrumentation and data analysis, including major roles in TopHat, Bolocam, and Zspec; leads the U. Penn Zspec team.
Conley, Alexander University of Colorado, Boulder – USA, Postdoc. Role: Zspec follow-up. Relevant qualifications: familiarity with Zspec; member of the *Her*MES team, with experience in number counts.
López-Caniego, Marcos IFCA, CSIC-UC – Spain, Postdoc. Role: development of filtering techniques to detect and estimate the flux of compact sources at radio and submm frequencies. Modeling of gravitational lens systems. Relevant qualifications: Core Team Member of *Planck* LFI and the QUIJOTE-CMB experiment.
Jarvis, Matt Univ. Hertfordshire, Reader in Astrophysics. Role: optical follow-up. Relevant qualifications: leads the GMRT radio survey and a deep optical survey covering *H*-ATLAS; PI of the VISTA VIDEO survey.
Seymour, Nick University College London/MSSL – UK, Postdoc. Role: modeling and interpretation of IR SEDs. Relevant qualifications: Co-I of *Her*MES; experienced in the analysis of SPIRE data.
Gom, Brad University of Lethbridge – Canada, Staff. Role: migrating analysis code being developed for FTS-2/SCUBA-2 to the SPIRE FTS analysis. Relevant qualifications: responsible for the development of FTS-2, the imaging Fourier spectrometer recently delivered to the JCMT; 15 years experience working on FTS in the laboratory, at the JCMT and on *Akari*.

6. Observations Summary List

AOT	Time (hr)	AORs	SSOs	Timings	Groupings	Follow-up
SSpec	89.0	23	0	0	0	0
PPhoto	5.1	46	0	0	23	0

Notes (if applicable):

Observations of 2 targets are already complete (PI: Valtchanov), using the mode proposed here, leaving 23. *H*-ATLAS comprises 89% of our total sky coverage and is currently ∼20% complete, with the remainder of the data due by late 2010. We have inserted AORs for the targets that satisfy our selection criteria at the time of writing; the remaining 11 are dummies, spread over our remaining three large fields.