Keck spectroscopy of $z = 1 - 3$ ULIRGs from the Spitzer SWIRE survey

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ABSTRACT

Context. High-redshift ultra luminous infrared galaxies contribute the bulk of the cosmic IR background and are the best candidates for very massive galaxies in formation at $z > 1.5$.

Aims. It is necessary to identify the energy source for their huge luminosities, starburst or AGN activity, in order to correctly interpret the role of ULIRGs in galaxy evolution, and compute reliable estimates of their star formation rates, stellar masses, and accretion luminosities.

Methods. We present Keck/LRIS optical spectroscopy of 35 $z \geq 1.4$ luminous IR galaxies in the Spitzer Wide-area Infra-Red Extragalactic survey (SWIRE) northern fields (Lockman Hole, ELAIS-N1, ELAIS-N2). The primary targets belong to the “IR-peak” class of galaxies, having the 1.6$\mu$m (restframe) stellar feature detected in the IRAC Spitzer channels. The spectral energy distributions of the main targets are thoroughly analyzed, by means of spectro-photometric synthesis and multi-component fits (stars + starburst dust + AGN torus).

Results. The IR-peak selection technique is confirmed to successfully select objects above $z = 1.4$, though some of the observed sources lie at lower redshift than expected. Among the 16 galaxies with spectroscopic redshift, 62% host an AGN component, two thirds being type-1 and one third type-2 objects. The selection, limited to $r' < 24.5$, is likely biased to optically-bright AGNs. All IR-peakers without emission lines have a non negligible continuum detection, and are likely to be very powerful starbursts, heavily extinguished by dust ($A_V \geq 5$ mag). The SEDs of non-AGN IR-peakers resemble those of starbursts ($SFR = 20 - 500 M_\odot/yr$) hosted in massive ($M > 10^{11} M_\odot$) galaxies. The presence of an AGN component provides a plausible explanation for the spectroscopic/photometric redshift discrepancies, as the torus produces an apparent shift of the peak to longer wavelengths. These sources are analyzed in IRAC and optical-IR color spaces. In addition to the IR-peak galaxies, we present redshifts and spectral properties for 150 objects, out of a total of 301 sources on slits.

Key words. Galaxies: distance and redshifts - Galaxies: active - Galaxies: starburst - Galaxies: high redshift - Galaxies: fundamental parameters - Infrared: galaxies

1. Introduction: distant starbursts in the SWIRE survey

Locally rare, Ultra-luminous ($L_{IR} > 10^{12} L_\odot$, ULIRGs) and Hyper-luminous ($L_{IR} > 10^{13} L_\odot$, HLIRGs) infrared galaxies dominate the energy budget in the distant Universe (e.g. Franceschini et al. 2001; Elbaz et al. 2002).
Extragalactic surveys with ISO, SCUBA, MAMBO\(^1\) (e.g. Franceschini et al. 2003; Genzel & Cesarsky, 2000; Ivison et al. 1998 see Lonsdale et al., 2006, for a review), and now Spitzer have shown that the number of dusty, IR-luminous galaxies at \(2 < z < 3\) is several orders of magnitude higher than in the local Universe. The analysis of the statistical properties of high-\(z\) ULIRGs has shown that they contribute substantially to the cosmic infrared background (CIRB), discovered by COBE in the late '90s (Puget et al. 1996; Hauser et al. 1998; Elbaz et al. 2002; Dole et al. 2006).

The currently most successful models for galaxy formation all invoke a “biased” hierarchical buildup within a \(\Lambda\)CDM cosmology (e.g. Cole et al. 2000; Hatton et al. 2003; Granato et al. 2004) to assemble galaxies, suggesting that the most massive objects (e.g. \(M_{\text{stars}} > \text{several } 10^{11} M_\odot\)) may assemble earlier, more quickly and in richer environments than less massive ones. This may occur in short-lived, intense bursts of star formation at \(z > 2\) (Somerville et al. 2001; Nagamine et al. 2005). This theoretical framework has enjoyed great success in describing many observational results from the local Universe, and at moderate redshifts (e.g. Cole et al. 2005).

The sternest tests of these models, however, come from observations at \(z > 1\), where the earliest formation stages of massive galaxies and rich clusters are predicted to occur. Several pieces of evidence exist that fully formed massive galaxies were already in place at redshift \(z > 1.5\) (e.g. Ellis et al. 1997; van Dokkum et al. 2003).

Analyses of the ultra-luminous submillimeter galaxy (SMG) population at \(z > 1.5\) (e.g. Chapman et al. 2004) support extreme star-formation rates in rare massive objects. These distant IR sources, with implied \(SFR > 500 M_\odot/\text{yr}\) (e.g. Farrah et al. 2002), are the best candidates to be the progenitors of ellipticals which formed most of their stars rapidly at \(z \sim 2 - 4\).

Nevertheless, whether the huge luminosities of ULIRGs and SMGs are powered by starburst emission, AGN accretion or a combination of the two has been often, and is still, a matter of debate. Discriminating between starburst and AGN power is fundamentally important for properly measuring their star formation rates, stellar masses, accretion rates, and also for understanding the connection between bulge and black hole building.

Spitzer (Werner et al. 2004) holds the key to this major question, because the IR broadband spectral energy distributions (SEDs) and IRS (Houck et al. 2004) spectra of \(z > 1\) sources can discriminate warm AGN-dominated emission, characterized by a power-law (torus-like) SEDs, from emission dominated by stars (e.g. Weedman et al. 2006). Lacy et al. (2004) and Stern et al. (2005) have demonstrated a strong segregation of AGN-dominated systems from starburst-dominated galaxies in the IRAC color-color space.

The first major IRS surveys of the 24\(\mu\)m-brightest, optically-faint galaxies from Spitzer surveys have shown that they tend to be dominated by warm AGN-heated dust (Houck et al. 2004; Yan et al. 2005). Polletta et al. (2006) and Lonsdale et al. (in prep.) have used the added power of SED analysis to distinguish the main energy source and estimate photometric redshifts for high redshift ULIRGs in the Spitzer Wide-area InfraRed Extragalactic Legacy survey (SWIRE Lonsdale et al. 2003, 2004), and find that the AGN/starburst fraction decreases rapidly with decreasing 24\(\mu\)m flux, until starburst-dominated systems far exceed AGN-dominated ones as \(f_{24}\) drops below 500\(\mu\)Jy (Lonsdale et al.). Weedman et al. (2006) have confirmed these broadband AGN vs. starburst classifications, by exploiting IRS spectroscopy of 17 \(z \sim 2\) ULIRGs and finding that the broadband classifications are correct in 90\% of the cases.

Finally, Farrah et al. (2006) have found evidence for significant clustering in \(z = 2 - 3\) SWIRE starburst-dominated ULIRGs, suggesting that powerful star formation might indeed be taking place preferentially within high density environments. Identifying powerful ULIRGs in the distant Universe is particularly important, not only because they may be the most massive galaxies in the process of formation, but also because they may trace the rarest, most massive dark matter halos at \(z \sim 2\) (\(M > 10^{13} M_\odot\), density \(< 10^{-7} \text{ Mpc}^{-3}\) at \(z = 2\)). SWIRE has sufficient volume to include about 85 halos with mass \(> 10^{14} M_\odot\) in the redshift range \(z = 2 - 3\) (Jenkins et al. 2001; Mo & White 2002), which will evolve to host extremely rich clusters of the Perseus class in the local Universe. For comparison, all the Spitzer deep surveys (extended-GOODS, S-COSMOS, GTO Deep, Dickinson et al. 2003; Sanders et al. 2007; Fazio et al. 2004a) together potentially sample about 9 such haloes. The First Look Survey (FLS, Soifer et al. 2004) and GTO-Bootes survey (Eisenhardt et al. 2004) potentially sample 24 similar haloes, but they are shallower than SWIRE, thus the number of IRAC-selected detectable sources is smaller. Finally, the sub-mm surveys to date have sampled a volume too small to identify even one halo with \(M > 10^{14} M_\odot\).

We have therefore selected from SWIRE the brightest mid-IR examples of starburst-dominated ULIRG candidates in the \(z = 1.5 - 3\) range for spectroscopic observation at Keck, to confirm their redshifts and characterize their nature. Our selection of these systems is based on the detection within the Spitzer IRAC bands of the redshifted stellar emission peak at \(\sim 1.6\mu\m\) in galaxies (Sawicki 2002; Simpson & Eisenhardt 1999). We name these kind of sources “IR-peakers”, or “IR-peak sources”.

We present here Keck/LIRIS multi-object spectroscopy of 35 IR-peaked systems in SWIRE northern fields. This instrument provides a nearly contiguous wavelength coverage from the 3000 \(\AA\) atmospheric cutoff to the \(Z\) band (\(\lambda_c = 9100 \ \AA\)). The UV-optical throughput is larger than 50\% in the \(U\) to \(g\) bands. This represents a great advan-
tage over optical-only spectroscopic surveys: Lyα can be probed to \( z \geq 1.7 \) and \([\text{O}ii] \ (\lambda = 3727 \ \text{Å})\) can be detected at \( z \leq 1.4 \). Basically, only a very narrow redshift desert exists for IR-peak galaxies observed with LRIS. Moreover, on the 10m Keck telescope, LRIS allows the detection of \( r' \approx 24 \) galaxies in reasonably fast exposure times (<2h).

Several other categories of interesting SWIRE targets have been included in the observations, in order to fill slitlet masks: X-ray, radio, power-law, extremely red, and 24\( \mu \)m sources.

Section 2 describes the sample selection and the available data in the SWIRE fields; Sect. 3 deals with observations and data reduction. Spectroscopic results are presented in Sect. 4, where we also discuss photometric redshifts. Details on the IR-peak population are given in Sect. 5, including spectroscopy and modeling of broadband SEDs. Section 6 includes the description of some additional interesting objects: high redshift quasars and X-ray sources. Finally, Sects. 7 and 8 discuss our findings and summarize our conclusions. Throughout this paper we adopt a \( H_0 = 71 \ [\text{km s}^{-1} \ \text{Mpc}^{-1}] \), \( \Omega_m = 0.27 \), \( \Omega_\Lambda = 0.73 \) cosmology.

2. Sample Selection

The SWIRE Legacy survey (Lonsdale et al. 2003, 2004; Surace et al. 2004) covers 49 deg\(^2\) in all seven Spitzer imaging bands, and has detected over 2 million galaxies up to \( z > 3 \). This sensitivity means that SWIRE can detect tens of thousands of star-forming galaxies with SFR \( \sim \) hundreds \( M_\odot/\text{yr} \), such as typically found in blank-field submm surveys, in at least two Spitzer bands at \( z \sim 1-3 \). Such a large ULIRG sample will include not only systems similar to the sub-millimeter galaxy class (SMGs), but also objects dominated by significantly warmer dust than typical of the submm- and mm-selected systems.

2.1. Spitzer data

The SWIRE northern fields benefit from extensive multiwavelength coverage, over the whole electromagnetic spectrum from the X-rays to radio frequencies. The SWIRE datasets are widely described by Surace et al. (2004).

The SWIRE Lockman Hole field is centered at RA=10h45m00s, DEC=+58d00m00s, with a total area of 10.6 deg\(^2\). Observations with the Infrared Array Camera (IRAC, Fazio et al. 2004) were obtained in April 2004, and the Multiband Imaging Photometer (MIPS, Rieke et al. 2004) data were collected in May 2004.

The SWIRE ELAIS-N1 field is centered at RA=16h11m00s, DEC=+55d00m00s, and covers 9 deg\(^2\); Spitzer observations were carried out during January and February 2004.

The SWIRE ELAIS-N2 field is centered at RA=16h36m48s, DEC=+41d01m45s, over 4 deg\(^2\) and was observed in July 2004.

Data processing is described by Surace et al. (2004) and Shupe et al. (in prep.), and consists of Basic Calibrated Data (BCD) by the SSC pipeline plus post-processing aimed at artifact removal, mosaicking and source extraction. The mosaicking was performed with the SSC routine MOPEX, and source extraction with SExtractor (Bertin & Arnouts 1996). IRAC fluxes were extracted through a 1.9" diameter aperture and corrected to total fluxes following SSC prescriptions; MIPS fluxes were extracted by means of PRF fitting (see Surace et al., and MIPS Data Handbook 2006). The 5\( \sigma \) depths (consistent with the 90% completeness levels) of the Spitzer data are on average 3.7, 7.4, 43, 46, and 195 \( \mu \)Jy at 3.6, 4.5, 5.8, 8.0, and 24 \( \mu \)m, respectively (Surace et al., in prep.), with field to field variations. None of the primary targets is detected at 70 and 160 \( \mu \)m in the SWIRE survey, at the average 5\( \sigma \) flux limits of 17.5 and 112 mJy respectively.

2.2. Available optical data

The Lockman Hole field was observed in the \( U, g', r' \), and \( i' \) bands with the MOSAIC Camera at the Kitt Peak National Observatory (KPNO) Mayall 4m Telescope, February 2002 (\( g', r' \), and \( i' \)) and January 2004 (\( U \) band). The scale of the Camera is 0.26"/pix and the field of view is 36' \times 36'. The astrometric mapping of the optical MOSAIC data is good to less than 0.4" and the seeing varied between 0.9 and 1.4 arcsec. Data reduction was performed with the Cambridge Astronomical Survey Unit (CASU, Irwin & Lewis 2001) pipeline, following the procedures described in Babbedge (2004). Fluxes were measured within a 3" aperture (diameter) and corrected to total fluxes using growth curves. Typical 5\( \sigma \) magnitude limits are 24.1, 25.1, 24.4 and 23.7 in \( U, g', r' \) and \( i' \) respectively (Vega), for point-like sources.

The ELAIS-N1 and EN2 fields were observed in the \( U, g', r', i' \) and \( Z \) bands, as part of the 2.5m Isaac Newton Telescope (INT, Roque de Los Muchachos, La Palma, Spain) Wide Field Survey (WFS, McMahon et al. 2001). The data were processed with the CASU pipeline; the average limiting magnitudes (Vega, 5\( \sigma \)) across the fields are 23.40 (\( U \)), 24.94 (\( g' \)), 24.04 (\( r' \)), 23.18 (\( i' \)) and 21.90 (\( Z \)). The overall photometric accuracy of the INT WFS survey is 2\%. Further details are given in Babbedge (2004) and Surace et al. (2004).

2.3. X-ray and Radio data

A 0.6 deg\(^2\) sub-area of the Lockman hole field, centered at RA=10h46m, DEC=59d10m was observed with the Chandra Advanced CCD Imaging Spectrometer (ACIS-I, Weisskopf et al. 1996) in the X-rays, during September 2002. Description of observations and data analysis is provided in Polletta et al. (2006). The total exposure time was 70 ks, reaching 3\( \sigma \) fluxes of \( \sim 10^{-15}, 5 \times 10^{-16} \), and \( 10^{-14} \) [erg cm\(^{-2}\) s\(^{-1}\)] in the broad (0.3–8 keV), soft (0.3–2.5 keV) and hard (2.5–8 keV) bands respectively.

As part of the ELAIS Deep X-ray Survey (EDXS), a sub-region of ELAIS-N1 was targeted by the
Chandra ACIS instrument. Observations and data analysis are described in Manners et al. (2003, 2004) and Franceschini et al. (2003). The Chandra field is centered at RA=16h10m20.11s, DEC=+54d33m22.3s (J2000.0) and the total net exposure time is 71.5 ks (after flare cleaning). Sources were detected to flux levels of $2.3 \times 10^{-15}$, $9.4 \times 10^{-16}$ and $5.2 \times 10^{-15}$ [erg cm$^{-2}$ s$^{-1}$] in the 0.5–8 keV, 0.5–2 keV and 2–8 keV bands.

Finally, a deep, 1.4 GHz radio survey, centered at RA=10h46m, DEC=59d01m covers 40′ × 40′ in the Chandra/SWIRE Lockman Hole field. These data were obtained in multiple Very Large Array (VLA) runs, obtained in Dec. 2001, Jan.-Mar. 2002, and Jan. 2003 (Owen et al., in prep.) with configurations A/B/C and D. The total integration time spent on source is 500 ks. The r.m.s. noise at the image center is 2.7 μJy (see also Polletta et al. 2006).

### 2.5. Mask fillers

LRIS masks can host as much as 30 slitlets, the exact number depending on the positions of the selected targets on the sky.

In addition to the primary IR-peakers included in each mask, the remaining slitlets were filled with sources from the SWIRE catalogs showing interesting photometric multi-wavelength properties, such as red optical-NIR colors ($i - 4.5 \geq 5$), consistent with $z \sim 1$ systems, X-ray or radio detection, IRAC red power-law (AGN-like) with a monotonic slope, and finally generic 24 μm detection.

Column eight in Tabs. 5 and 6 reports a rough classification of the most interesting sources, based on their photometric properties. In particular, we distinguish: 4.5μm- and 5.8μm-peak galaxies (P2, P3, P3L), X-ray and radio sources (X and R in column 8), and objects with a monotonic power-law like IRAC SED (pow).

The total number of mask is 4 in the Lockman Hole field, which have been observed during the first three hours of each night, three in ELAIS-N1 and one in ELAIS-N2. A total of 235 slits were defined. Figure 1 shows all targets detected in the mid-IR, in the r′-band vs. 24μm space.

These masks include 35 IR-peak targets (9 4.5μm and 26 5.8μm peakers), 7 X-ray sources, 12 radio sources, 19 IRAC power-law objects and 139 objects detected in the MIPS 24μm channel. Figure 2 shows the distribution of the selected targets in the IRAC color-space (Lacy et al. 2004; Stern et al. 2003; different symbols refer to different photometric (and spectroscopic) properties: IR-peak sources (filled circles), power-law IRAC SEDs (crosses), broad-line objects (open squares). It is already worth noting that the power-law and broad-line classifications are ~100% consistent with each other, these targets lying in the locus of AGNs in the IRAC color space (Lacy et al., See also Sect. 5).

### 3. Observations and data reduction

Observations were carried out in multi-object mode with the Low Resolution Imaging Spectrometer (LRIS, Oke et al. 1995) at the Cassegrain focus of the Keck-I telescope, during the nights of May 27th and 28th, 2006.

The LRIS instrument makes use of a dichroic to split the incoming light into a blue and red beam. Gratings, grisms and filters can be changed independently for the two beams. We have adopted the dichroic designed to split light at 5600 Å.

As far as the blue arm is concerned, in order to obtain a maximum throughput in the spectral range 3200-5000Å, we used the 400 lines/mm grism, blazed at 3400 Å, pro-

2 P3L sources have IRAC 3.6, 4.5, 5.8 μm detection, but only an upper limit at 8.0 μm.
viding a good throughput from the atmospheric cutoff at 3000 Å to the dichroic 5600 Å limit.

On the red arm, we used the 400/8500 grating, blazed at 7400 Å, providing wavelength coverage up to \( \sim 9550 \) Å. This configuration was chosen in order to optimize spectral coverage of simultaneous LRIS red and blue observations, as well as wavelength calibration with Hg, Cd, Zn, Ar arc lamps. The effective spectral coverage depends on the positioning of slits in the mask, relative to the telescope focal plane.

The dispersion in the blue and red arms is 1.09 Å/pix and 1.86 Å/pix. A 1.2 arcsec slit was adopted, resulting in an instrumental resolution (measured as the FWHM of arc lines) of \( \sim 10.5 \) Å. This corresponds to 750 and 420 [km s\(^{-1}\)] at 4200 and 7500 Å, respectively. The seeing varied between \( \sim 1.0 \) and \( \sim 1.3 \) during the two observing nights.

The slit masks cover an effective area of \( 6 \times 8 \) arcmin\(^2\) on the sky; between 15 and 30 slits with variable length were placed per mask, this number depending on the sky distribution of the selected targets. A total of 10 masks was observed during the two night run, with exposure times between 3600s and 5400s, split into three exposures per mask. Table 1 lists the position of the pointings on the sky, as well as exposure times, number of slitlets and number of IR-peak targets included.

Spectro-photometric standard stars Feige34 and BD+28D4211 were observed during the nights, taking care to have as close an airmass as possible to the science pointings. Flat field and arc lamp frames were taken at the same telescope position (ALT,AZ) as the science spectra, in order to reproduce the same instrumental flexures and shifts and avoid troublesome corrections during data reduction. Arc-frames were obtained using Hg, Cd, Zn, Ar lamps, ensuring bright calibration lines over the whole spectral range from 3000 Å to 9500 Å, with a gap between 5500 and 6500 Å only.

Data reduction was carried out by using the standard tasks in the IRAF\(^3\) environment. Bias, dark and flat field corrections were performed in the standard manner, by using the overscan CCD regions and the dome flat field corrections ware performed in the standard manner, by using the overscan CCD regions and the dome flat field corrections. Wavelength and flux calibration were performed on the two-dimensional spectra, after background subtraction.

Extraction of spectra was performed in all cases where a continuum trace was detected; lines were identified on non-flux-calibrated frames, in order to avoid losses of spectral coverage due to the relative position of slits with respect to the standard star spectrum. Line properties were measured after flux calibration.

The lines detected for the IR-peak galaxies are listed in Tabs. 3 and 4 where we list observed wavelengths, equivalent widths, FWHMs (corrected in quadrature for the instrumental resolution) and derived redshifts.

Spectroscopic redshifts of all the observed targets are listed in Tabs. 5 and 6 where we include also the number of emission/absorption lines detected for each object.

4. Results

The full sample of targeted sources includes 233 objects\(^5\), distributed in the Lockman Hole, ELAIS-N1 and ELAIS-N2 SWIRE fields.

We have computed redshifts on the basis of the presence of emission lines, both in the ultraviolet and optical restframe domains, such as Lyman-\(\alpha\) (\(\lambda = 1216\) Å), Niv (\(\lambda = 1240\) Å), Oi (\(\lambda = 1304\) Å), Silv, Otv (\(\lambda = 1400\) Å), Niv (\(\lambda = 1486\) Å), CIV (\(\lambda = 1548, 1551\) Å), HeII (\(\lambda = 1640\) Å), CIII (\(\lambda = 1909\) Å), MgII (\(\lambda = 2796, 2803\) Å), FeII and FeIII lines (\(\lambda = 2000 - 3000\) Å), [OIII] (\(\lambda = 3726, 3729\) Å), as well as Balmer Hydrogen emission and absorption, CaII-HK, [OII], [NII], and [SII] lines for lower redshift sources. We do not have adequate resolution to resolve the [OIII], CIV and MgII doublets.

The spectroscopic success rate per mask strongly depends on the observing conditions, such as presence of cirrus, seeing and airmass. The last column in Tab. 1 lists the number of redshifts obtained for each mask, without accounting for serendipitous sources.

Lockman Hole masks were observed during the first hours of each night, at increasing airmass, with relatively poor results (see Tab. 1). During the first night, 6/21 and 15/26 sources have a successful redshift estimate for masks LH\(_{427597}\) and LH\(_{575325}\) respectively\(^6\). Masks LH\(_{128777}\) and LH\(_{579894}\), observed on the second night, turn out to have 11/29 and 9/24 good spectroscopic redshifts, without taking into account serendipitous sources.

It is worth to note that mask LH\(_{579894}\) has a success rate as low as LH\(_{128777}\) (\(\sim 38\%\)), despite the lower airmass (1.36 vs. 1.56). The main reason for this effect is that the former contains fewer 24μm-bright targets than the latter (45% vs. 60% of the objects in slit), resulting in a lower emission lines detection rate.

The ELAIS fields were observed at lower airmasses, hence the success rate is higher for these areas, being 73% on average, with a 80% peak in the best case. A total of 139 redshifts have been derived for the targeted objects.

The redshift uncertainty depends on the number of detected spectral features. In the case that only one emission line is detected, the sources of uncertainty on the redshift estimate are given by the wavelength calibration of the spectrum (having a typical r.m.s of 0.7 - 1.0 Å) and the centroid uncertainty in positioning during the gaussian fit

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3 The package IRAF is distributed by the National Optical Astronomy Observatory which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4 http://www2.keck.hawaii.edu/inst/lris/

5 Note that a couple of targets were observed twice, in distinct masks, therefore the effective number of targets is 233 in 235 slitlets.

6 These numbers don’t include serendipitous sources.
to the line profile (which is a fraction of a pixel and negligible with respect to estimating redshifts). When dealing with multiple line detections, the average \( z \) is computed and the uncertainty is given by the dispersion of the average. Typical uncertainties on \( z \) are thus smaller than \( \Delta z = 0.01 \) for narrow lines. In the case of broad emission lines, a lorentzian fit to the lines was usually adopted, but the asymmetry and broadness of profiles cause the uncertainty of line positioning to be larger and dominate the \( \Delta z \). In this case, the redshift uncertainty can be as large as \( \Delta z = 0.03 \).

In addition to the formally targeted objects, 68 serendipitous sources were detected, and for 35 of these a redshift estimation was possible. We have identified these serendipitous objects by measuring their projected distance from the main target in the same slit, matching it to the SWIRE multi-wavelength catalog, and visually seeking for SWIRE counterparts on \( r' \) band and 3.6\( \mu \)m images. Only 15 were identified, while another 14 are detected in the optical but not by Spitzer. Among these, only 11 have a spectroscopic redshift. In Tabs. 5 and 6 we list only those serendipitous sources with a SWIRE/Spitzer counterpart.

The total number of redshifts available is 174, for a total of 301 objects in slits; 150 sources with redshift have a SWIRE identification.

### 4.1. Photometric redshifts

Taking advantage of the extensive multiwavelength coverage available in the observed areas, we have computed photometric redshifts for all the targeted sources, by using the Hyper-z (Bolzonella et al. 2000) and the Rowan-Robinson (2003) codes.

In the former case, we have adopted a semi-empirical template library including GRASIL (Silva et al. 1998) models of spiral and elliptical galaxies, M82 and Arp220 templates (Silva et al.) upgraded with observed PAH mid-IR features, a ULIRG template (IRAS 19254-7245, Berta et al. 2003), type-1 AGN and Seyfert templates by Polletta et al. (in prep.), obtained by averaging observed AGN SEDs. The fits were performed using only the optical and IRAC (3.6 – 8 \( \mu \)m) data, ignoring the MIPS 24\( \mu \)m flux. Tests including the 24\( \mu \)m data have been attempted as well, but they have shown a higher degree of degeneracy and aliases in the photometric redshift estimate.

The photometric redshifts thus obtained are compared to the spectroscopic Keck results in Fig. 4 (left panel). The dashed and dotted lines represent 10\% and 20\% uncertainty, respectively. Filled circles represent IR-peak sources, crosses are objects with power-law IRAC SEDs, and open squares indicate broad-line detections. All other cases are plotted as open circles.

Outliers are mostly AGNs (crosses or open squares in Fig. 4), typically showing a power-law spectral energy distribution from the optical to the mid-IR. In this kind of object, neither strong, nor sharp features are detected in the broad band SEDs, therefore the photometric redshift estimate often fails.

Accounting for all sources with a spectroscopic redshift, the r.m.s. of the distribution of \( \Delta (1+z) \) is 0.095. Excluding power-law sources, it decreases to 0.069. The semi inter-quartile range (s.i.q.r.) computed for all sources is 0.028.

The results obtained by using the Rowan-Robinson (2003) code are shown in the right panel of Fig. 4. As far as AGN-dominated objects are concerned, the results of this code show a much better consistency between photometric and spectroscopic redshifts for high-redshift sources, while it seems to fail for low-redshift ones. For the latter, the photometric redshift is overestimated. The adopted templates are those described in Rowan-Robinson et al. (2004), including AGN SEDs built on actual ELAIS data. The overall concordance of the photometric estimate and the spectroscopic measure of redshifts is similar to the one obtained with Hyper-z, having a \( \Delta(1+z) \) r.m.s. and s.i.q.r. of 0.091 and 0.043. The number of dramatic failures (outliers) is smaller than in the Hyper-z case, but the median scatter is slightly larger.

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\[ \Delta \] Here \( \Delta \) is the difference between the photometric and spectroscopic redshift estimates.
Finally, Fig. 3 reports the redshift distribution of our targets with spectroscopic redshift. The white histogram represents the distribution of spectroscopic redshifts for all sources, while the shaded histogram includes only IR-peak objects.

4.2. Spectroscopic classification

The last column in Tables 5 and 6 reports the spectral classification of targets, based on the detected lines. We classify as simply “emission line” galaxies (ELG), those sources with insufficient lines to apply any diagnostic technique, i.e. sources with only one or two lines detected. Similarly, “absorption line” galaxies (ALG) have only absorption lines detected.

When possible, emission line fluxes were corrected for extinction, as derived from the observed Balmer decrement (using the available Balmer lines and assuming case-B recombination, Hummer & Storey, 1987).

We classify starburst galaxies (SB) on the basis of different criteria:

- presence of strong emission lines (e.g. [OII], $\lambda = 3727$ Å) and young star absorption lines (e.g. type-A stars), such as the advanced Balmer series, from H$\delta$ down to H-10;

- conformity to optical diagnostic diagrams for AGN/starbursts, based on optical emission lines (Veilleux & Osterbrock 1987; Dessauges-Zavadsky et al. 2000; Baldwin et al. 1998), or on the basis of optical diagnostic diagrams (e.g. Veilleux & Osterbrock 1987; Baldwin et al. 1981) in some cases. Because only a few optical emission lines are available, a distinction between Seyfert-2 galaxies and LINERs is not possible, apart in one case (EN1,340460, at the boundary between starbursts and LINERs).

Type-1 AGNs (BLAGN flag) are recognized through the presence of broad emission lines (FWHM > 1000 [km s$^{-1}$]), both in the ultraviolet and optical restframe spectral domains.

Type-2 AGNs (NLAGN) are identified by the presence of high-ionization narrow emission lines (e.g. Nv, CIV, HeII, [NeV], $\lambda = 1240, 1549, 1640, 3426$ Å) in the observed spectra (e.g. Farrah et al. 2003; Villar-Martín et al. 1998; Allen et al. 1998), or on the basis of optical diagnostic diagrams (e.g. Veilleux & Osterbrock 1987; Baldwin et al. 1981) in some cases. Because only a few optical emission lines are available, a distinction between Seyfert-2 galaxies and LINERs is not possible, apart in one case (EN1,340460, at the boundary between starbursts and LINERs). It is worth specifying that ultraviolet emission lines such as CIV can be produced also by star forming activity, typically being heated by O stars, but are always associated with a P-Cyg profile, produced by stellar winds with velocities higher than 1000 [km s$^{-1}$] (e.g. Shapley et al. 2003; Farrah et al. 2003). Given the resolution of our spectra, when no P-Cyg profile is detected and the CIV ($\lambda 1549$ Å) line is observed as narrow emission only, a type-2 AGN explanation is favored.

Globally, 122 narrow-line emission galaxies have been classified. Among these, 44 have enough spectroscopic information to allow an unambiguous classification: 39 turn out to be starbursts and 5 type-2 AGNs, at least in the sampled optical range. Seven galaxies show only absorption lines (typically the CaT-HK doublet and some advanced Balmer Hydrogen lines), and 17 are type-1 AGNs. Finally, four stars were identified in our slitlets.

5. IR-peak galaxies

As far as IR-peak sources are concerned, a total of 35 targets were included in our 10 masks; among these, 11 galaxies have a confirmed spectroscopic redshift in the range $z = 1.5 - 3.0$, 5 lie between 1.0 < $z$ < 1.5, and one turned out to be a low redshift ($z < 1.0$) (confused, see below) interloper. For the remaining 18 IR-peak targets no spectral features were detected, but in all cases a non negligible continuum is present (columns 2-3 in Tabs. 3 and 4 specify if a continuum was detected in the blue and/or red LRIS arms and over which wavelength range).

Figure 7 shows the spectra and SEDs of IR-peak targets with spectroscopic redshifts, the distinction between 4.5μm- and 5.8μm-peak being obvious.

Tables 3 and 4 list the basic measured properties of the detected lines for IR-peak galaxies, including the equivalent width (EW), full width at half maximum (FWHM, corrected for the instrumental resolution), observed wavelength and identification. In the last columns of Tab. 2 spectroscopic and photometric redshifts for these targets are listed.

Infrared peakers lie in the fourth quadrant of the IRAC color space ([3.6 - 5.8] > 0, [4.5 - 8.0] < 0 in the right panel of Fig. 2 or [3.6 - 4.5] > 0, [5.8 - 8.0] < 0 in the left panel). Objects at the boundary between the IR-peak and AGN-torus loci (i.e. [4.5 - 8.0] ≃ 0.0, [3.6 - 5.8] > 0) display mixed properties. For example, found here are objects showing a power-law like IRAC SED, with a smooth 5.8μm-peak superimposed (filled circles with crosses). These can be interpreted as a 5.8μm peak diluted by AGN-torus power-law emission. Other composite galaxies show a clear IRAC peak shape, but their restframe UV spectra are dominated by broad-line emission (filled circles within open squares). The properties of individual IR-peakers are discussed below.

Fig. 5 presents the comparison between spectroscopic and photometric redshifts for IR-peakers only, obtained with the Bolzonella et al. (2000) (left hand side) and Rowan-Robinson (2003) (right) codes. The two principal outliers (in the Hyper-z case) are a Lockman Hole source with spectroscopic redshift of $z = 0.249$, which turns out to be a confused object (see below) and a broad-line object in ELAIS-N2. In the latter case, the Hyper-z code could not find a reliable redshift by adopting a QSO template, because of the almost featureless continuum, and then it completely underestimated the photometric $z$. The Rowan-Robinson et al. (2004) templates seem to solve these troubles, but underestimate the redshift of a 4.5μm-peak in ELAIS-N1 (EN1,202261) with a very red $r' - Z$ color (see Fig. 7), which probably was interpreted as a deep Balmer break at $z < 1$. 
5.1. 4.5 µm-peak sources

Eight 4.5 µm-peak galaxies were observed. Three of these sources have a confirmed spectroscopic redshift between \( z = 1.30 \) and \( z = 1.45 \), with narrow emission lines (EN1\textsuperscript{2102261}, EN2\textsuperscript{167372}, EN2\textsuperscript{166134}). The detected features are not enough to distinguish between starburst or AGN activity (see Sect. 4.2), therefore we put these sources in the general “ELG” class. For two of these targets the photometric redshifts agree with the measured spectroscopic values (see Tab. 2), while for source EN2\textsuperscript{167372} the two are not consistent with each other (\( z_{\text{phot}} = 2.120, z_{\text{spec}} = 1.445 \)). For this source, IRAC photometry is available only in channels 1 and 2, while both the 5.8 and 8.0 µm bands have only an upper limit. It is possible that the photometric estimate of redshift has been affected by the lack of near-IR restframe data.

A fourth 4.5 µm-peak object lies at \( z = 1.545 \) (target EN1\textsuperscript{2102260}) and is characterized by broad emission lines, which testify to the presence of a type-1 AGN component contributing to the UV-optical emission. This object is detected also in the X-rays. The IRAC spectral energy distribution shows a red 8.0 − 5.8 µm observed color (see Fig. 7), the 8.0 µm observed flux being likely dominated by hot dust heated by the AGN component. Photometric and spectroscopic redshift estimates are in agreement, the former having been obtained with a type-1 AGN template (Polletta et al., in prep.).

It is worth noting that a similar IRSED can be observed also in the case of starburst galaxies at redshift \( z = 0.3 - 0.5 \). Actually, in this case a 4.5 µm peak can be produced by the strong 3.3 µm Polycyclic Aromatic Hydrocarbon (PAH) feature lying in IRAC channel-2, while the 8.0 µm flux density is enhanced by mid-IR PAH dust features (6.2, 7.7 µm) at low redshift (\( z \leq 0.5 \)). A good example is given by source EN1\textsuperscript{2102683} (see Fig. 8), a starburst galaxy at \( z = 0.497 \). An advantage in breaking this kind of aliasing would be provided by J, H, K band data. In fact the observed \( (J - 3.6)_{AB} \) color of a typical starburst (e.g. M82) is \( \sim 0.3 \) at \( z = 0.4 \), while it increases to values \( > 1.5 \) at \( z > 1.4 \). Similarly, the \( (K_s - 3.6)_{AB} \) values are \( \sim -0.4 \) and \( \sim 0.6 \) at the same two redshifts (see Fig. 9). At \( z = 0.4 \), the 1.6 µm peak lies in the \( K_s \) band and the \( K_s \) flux is brighter than in the IRAC bands. The \( K_s \) band is gradually shifted blueward of the peak, at increasing redshift, and the \( (K_s - 3.6)_{AB} \) color changes sign at \( z \approx 0.6 \).

Such low-z 4.5 µm-peak-like sources are not reported in Tabs. 3 and 4 since they do not conform to the IR-peak selection (because their peak is not due to the 1.6µm feature) and they are easily spectroscopically identified by using bright optical lines.

On the other hand, another source (EN2\textsuperscript{275226}) shows a clean 4.5 µm-peak, with \( S(8.0) < S(4.5) \) and no rise in IRAC channel 4, but the observed UV (restframe) spectrum shows that it hosts a type-1 AGN as well. This object lies at \( z = 1.710 \), in perfect accordance with the 4.5 µm-peak selection and the photometric redshift estimate. It is likely that the AGN component dominates the UV restframe spectrum, while the near-IR SED is powered mainly by star light.

Finally, source LH\textsuperscript{572243} lies at \( z = 1.820 \), having narrow lines detected in its spectrum. A bright, narrow CIV (\( \lambda = 1549 \) Å) emission line, without any P-Cyg profile, is detected, testifying to the presence of a type-2 AGN nucleus (e.g. Farrah et al. 2005), which is also confirmed by X-ray data.

The remaining 4.5 µm-peak targets (LH\textsuperscript{245782} and LH\textsuperscript{576281}) don’t have any spectroscopic redshift confirmation, although their continuum emission is detected by LRIS.

As a whole, 6 out of the 8 4.5 µm-peakers have a robust spectroscopic redshift, as derived from emission lines. Considering that LH\textsuperscript{245782} was included in one of the two masks observed at high airmass, this translates into a 87.5% successful detection for 4.5 µm peakers. Besides the presence of AGN components, our photometric estimates of redshift were consistent with the actual spectroscopic evidence in 80% of the cases, while for the remaining poor photometry is the main cause of discrepancy.

5.2. 5.8µm-peak sources

Our masks include 27 5.8 µm-peak targets, of which only 10 have a confirmed spectroscopic redshift. Thirteen out of the 17 without spectral lines detected lie in the Lockman Hole field, whose observing conditions were not optimal for optically-faint objects. The remaining four are all faint targets, having \( r' > 23.5 \).

In the 5.8 µm-peaker sample, we distinguish between sources having a clear stellar 1.6 µm peak detected in IRAC bands (e.g. object EN2\textsuperscript{172324}, see Fig. 7) and sources with a steep infrared SED (e.g. target EN1\textsuperscript{279954}, Fig. 7). The latter are likely to be composite sources, whose near-IR emission is not only due to low-mass stars, but also to an AGN component. The 1.6 µm restframe peak is produced by the stellar component, but it is diluted by the AGN emission, which reddens the 5.8 − 8.0 µm color. These sources are characterized by a very red 5.8 − 4.5 − 3.6 µm slope, with flux ratios of \( S(5.8)/S(4.5) \approx 1.4 − 1.8 \) and \( S(4.5)/S(3.6) \approx 1.3 − 1.5 \).

This group consists of targets EN1\textsuperscript{205467}, EN1\textsuperscript{279954} and EN2\textsuperscript{165986}. For the first one we were not able to derive any spectroscopic redshift, while the other two have very bright, broad ultraviolet emission lines (see Tabs. 3 and 4), confirming the presence of a type-1 AGN contributing to the optical observed fluxes. The two sources turn out to be at redshifts \( z = 2.409 \) and \( z = 2.163 \), respectively, consistent with the 1.6 µm SED feature lying in the 5.8 µm IRAC band. The photometric redshift estimate for this kind of source is carried out by adopting an AGN-like template (Polletta et al., in prep.), which leads to a 50% consistency with the actual spectroscopic measure (see Tab. 2). This problem can
be ascribed mainly to the lack of sharp features in the broad-band SEDs of these sources.

Sources EN1\_282078 and EN2\_273717 show a bluer slope, with \( S(5.8)/S(4.5) \approx 1.2 \) and \( S(4.5)/S(3.6) \approx 1.1 - 1.3 \) and a smooth 5.8\( \mu \)m peak. These sources turn out to have broad emission lines as well, at lower redshift, namely \( z = 1.685 \) and \( z = 1.800 \) respectively. The AGN contribution to the NIR SED of these sources is likely lower than in the previous case, but still non-negligible and clearly visible in the UV-optical domain (restframe). The inconsistency of the spectroscopic redshift value and the 5.8\( \mu \)m-peak selection — which implies that the restframe 1.6\( \mu \)m stellar feature is shifted to the IRAC channel 3 at \( z > 1.8 \) — is discussed below, and interpreted with a non-negligible AGN contribution to IRAC fluxes (Sect. 5.4).

Also in the case of source LH\_57436, the IRAC data define a smooth 5.8\( \mu \)m peak, but the \( S(8.0)/S(4.5) \) flux ratio is smaller than unity in this case (while it was larger than 1 in the two classes described above). Narrow Mg\( \text{II} \) and Fe emission lines are detected. The latter suggests the presence of a type-2 AGN. The smoothness of the peak suggests that this galaxy might lie at \( z < 1.5 \) with the 1.6\( \mu \)m feature falling shortward of the 5.8\( \mu \)m band center. In fact the spectroscopic redshift of this galaxy turns out to be \( z = 1.474 \), consistent with the photometric estimate.

The target EN1\_339960 is formally a 5.8\( \mu \)m-peaker, but its channel 2 and 3 fluxes are comparable, defining a very broad peak in the IRAC SED. The observed spectrum is dominated by a very strong C\( \text{IV} \) emission with a \( \sim 2000 \) [km s\(^{-1}\)] width, at \( z = 1.475 \), putting it in the AGN-1 spectroscopic class.

Three galaxies have a confirmed redshift between 1.7 and 2.0, narrow L\( \alpha \) and other emission lines and SED typical of high-redshift starbursts, i.e. EN1\_42445, EN2\_11091 and EN2\_172324. The latter shows a bright C\( \text{IV} \) narrow line, with no P-Cyg profile, that we interpret as produced by a type-2 AGN. A reddened torus contributes also to the IRAC SED, shifting the peak to the 5.8\( \mu \)m band (see Section 5.3). For the other two sources, not enough spectral features are detected, therefore they are simply classified as “emission line” galaxies.

The highest redshift IR-peaker detected is a \( z = 2.866 \) source, EN1\_340451, lying at the upper redshift limit of the 5.8\( \mu \)m-peak selection. This is a very faint optical source, with bright IRAC emission and a weak 24\( \mu \)m flux. We detect L\( \alpha \), He\( \text{II} \) (\( \lambda = 1640 \) \( \text{\AA} \)) and C\( \text{III}\) (\( \lambda = 1909 \) \( \text{\AA} \)) narrow lines. The wavelength coverage of the data has a gap in the range \( \lambda = 5500 - 6150 \) \( \text{\AA} \), where C\( \text{IV} \) (\( \lambda = 1549 \) \( \text{\AA} \)) would fall, but the presence of He\( \text{II} \) (with a ionization energy of 54.4 eV, four times that of H\( \text{II} \)) suggests the presence of a type-2 AGN component.

Finally, it is important to highlight the presence of one outlier: the low redshift interloper LH\_572257, at \( z = 0.249 \). This object is an X-ray source, with soft (0.3 – 2.5 keV), hard (2.5 – 8.0 keV) and broad (0.3 – 8.0 keV) fluxes of 11.01, 26.71 and 35.15 \( \times 10^{-16} \) [erg cm\(^{-2}\) s\(^{-1}\)]. By examining the optical and IRAC postage stamp images in Fig. one can notice that optically the source seems to consist of two different components: a point-like object (likely the X-ray low-z object) and a fuzzy galaxy, \( \sim 1.5'' \) to the north. It is possible that the latter dominates the IRAC SED and effectively is a high-redshift 5.8\( \mu \)m-peak galaxy lying underneath a low-z source, which instead dominates the optical fluxes. This is confirmed by the Ks band image, where the optically-faint galaxy dominates and the optically-brighter object is significantly fainter. Couples of white squares are over plotted on the z-band and K\( \_z \) band images, centered on the two distinct components.

### 5.3. Sources with no emission line detection

Apart from objects in the Lockman Hole, for which the observing conditions were not optimal (high airmass), there are four IR-peakers with no line detection in the ELAIS fields. In all cases continuum emission is detected; in Tabs. and\( ^3 \) and\( ^4 \) we report the wavelength range covered by the detected continuum for each source.

The IR-peakers without line detection lie at the faint end of the \( r' \) magnitude distribution of our targets (\( r' > 23.5 \)), see Tab.\( ^2 \). Nevertheless, for other comparably faint IR-peaker sources a measure of the spectroscopic redshift has been possible. In Figure\( ^3 \) (left panel) the \( r' \) and 24\( \mu \)m AB magnitudes of the ELAIS-N1, N2 IR-peakers are compared. The sources without line detection turn out to be those with brighter 24\( \mu \)m fluxes, of the order of 0.5 – 1.0 mJy.

The plot on the right shows that these galaxies are also those with the brighter mid-IR excess, i.e. the reddest (3.6 – 24) \( \mu \)m color. The two reddest ones lie close to a broad-line IR-peaker. One (EN1\_205467) of the two shows a power-law IRAC SED (plus 5.8\( \mu \)m-peak) and is a point-like object on optical images; its photometric redshift is \( z = 0.320 \), but it is not reliable because of the almost featureless broad-band SED.

The second one (EN2\_269695) is a fuzzy galaxy on optical images and shows a sharp 5.8\( \mu \)m peak. The photometric redshift is \( z = 1.800 \), which would allow UV emission lines (L\( \alpha \), M\( \text{gII} \)) to be detected in the covered spectral range (see Tab.\( ^2 \)). The huge mid-IR luminosity suggests that this is a powerful starburst, heavily extinguished by dust, which would also explain the lack of detected emission lines.

The remaining two objects (EN1\_341469 and EN2\_10334) are the two optically-reddest in the IR-peaker category, with (\( r' = 3.6\mu \)m) > 4.9 (in AB units, see Fig.\( ^4 \)). These two sources are also the two brightest 24\( \mu \)m emitters, with S(24) > 1.0 mJy.

The photometric redshifts are \( z = 1.54 \) and 2.01 respectively; by adopting a typical starburst template (e.g. M82), we derive bolometric infrared (8 – 1000 \( \mu \)m) luminosities of \( 5 \times 10^{12} \) L\( \odot \) for both sources, which would imply an SFR in excess of 800 M\( \odot \)/yr (Kennicutt\( ^1 \) 1998), if powered only by star formation. Such level of activity would produce a Ly\( \alpha \) emission of \( 2.5 \times 10^{41} \) L\( \odot \).
Unfortunately, for EN1_341469 no blue-arm spectrum is available and we cannot test a possible detection of Lyα. As far as EN2_10334 is concerned, at a redshift $z = 2.01$, that Lyα luminosity corresponds to a flux of $S$(Lyα) = $3.1 \times 10^{-14}$ [erg cm$^{-2}$ s$^{-1}$] and the line would fall at $\lambda = 3660$ Å. The continuum of source EN2_10334 is detected at a 2σ level with a flux of $2.0 \times 10^{-18}$ [erg cm$^{-2}$ s$^{-1}$ À$^{-1}$]. Adopting an intrinsic FWHM of 10 Å, in order not to detect the line at a 5σ level, the source must be extinguished by $A$(Lyα) = 5.75 magnitudes, corresponding to $A_V \simeq 2$ (using the Calzetti et al. 1994 extinction law).

In the case that a type-2 AGN plays a non negligible role in the emission mechanism, then these numbers would significantly change.

### 5.4. Modeling of observed SEDs

The spectral energy distributions (SEDs) of the IR-peak galaxies with spectroscopic redshifts are analysed here, by means of multi-component fitting.

For sources that do not show any AGN signature in their spectra or broad-band SEDs, we adopt the technique described in Berta et al. (2004) of mixed stellar population synthesis. The observed SEDs are reproduced by combining simple stellar populations (SSPs) of solar metallicity, built on the basis of the Padova 1994 isochrones (for more details on the SSP library see Berta et al. 2004). Each phase in the SSP history is extinguished by a different amount of dust, according to age-selective extinction (Poggianti et al. 2001). Since disc populations are on average affected by a moderate $A_V$ (< 1 mag, e.g. Kennicutt 1992), the maximum allowed absorption for stars older than 1 Gyr is $A_V = 0.3 \sim 1.0$ magnitudes. For younger populations the color excess gradually increases, but is limited to $A_V \leq 5$.

The 24μm flux is included in the fit and it is used for constraining the amount of dust extinguishing young stars in the ongoing starburst. The energy absorbed by dust at UV-optical wavelengths is reprocessed to the mid- and far-IR domain, by means of a prototypical starburst template.

An M82 template was adopted, built combining the Silva et al. (1998) model and the Förster Schreiber et al. (2001) observed mid-IR spectrum. Local ultra-luminous sources ($L_{IR} > 10^{12} L_{\odot}$) can be characterized by deep silicate 10μm self-absorption and “cold” SEDs (e.g. Arp220). Similar templates equally show the usual stellar 1.6μm peak.

Nevertheless, increasing observational evidence exists that high-z IR-peakers detected in the mid-IR resemble the M82 prototype. Spitzer mid-IR IRS spectra of $z \simeq 1.9$ IR-peak galaxies (Weedman et al. 2006) are dominated by bright PAH features and lack silicate 10μm self-absorption. Rowan-Robinson et al. (2003) studied and classified the SEDs of SWIRE sources over 6.5 deg$^{-2}$ in the ELAIS-N1 field. These authors find that M82-like starbursts are 3 times more numerous than colder Arp220-like objects. Based on the observed redshift distribution and on number counts modeling, they also infer that this ratio is even higher at $z \sim 1.5 - 2.0$. Lonsdale et al. (in press) performed 1.2 mm (250 GHz) observations of SWIRE 24μm-selected (H)ULIRGs with the Max Plank Millimeter Bolometer (MAMBO, Kryva et al. 1998) on the IRAM/30m telescope. As a result, they find that the 1.2mm/24μm flux ratio of these sources resembles that of M82, lower than for an Arp220-like population, and lower than what found for sub-mm selected galaxies (SMGs). It is worth noting, in fact, that their selection (similar to ours) favors 24μm-bright systems, instead of mm-bright objects. All of these recent findings drove the choice of the M82 template, as stated above.

As a further check, we have attempted stacking of far-IR (70 and 160 μm) SWIRE images at the position of the observed IR-peakers, but unfortunately no signal was detected on the stacked frames.

Also the detected spectroscopic features have been included in the fitting procedure, in order to provide additional constraints on the star formation history of these sources.

Table 7 reports the results of this analysis: for each source, the best fit stellar mass and ongoing star formation rate (SFR) are listed. The SFR is computed as an average on the last 10$^8$ yr in the life of the galaxy, in order to be comparable to the Kennicutt (1998) calibrations. We also report the derived extinction, as averaged over the whole galaxy life and over the last 10$^8$ yr, as well as the bolometric IR ($8-1000$ μm) luminosity, as computed with the adopted template. Finally, 3σ ranges, as computed from the exploration of the parameters space, are listed within parentheses. A detailed description of degeneracies is provided in Berta et al. (2004). The average number of SSPs effectively involved in the fit is 3-4, depending on redshift.

In Fig. 7 we show the fit to the observed SEDs. The blue-dashed and red-dotted lines represent the contributions of young (age < 10$^9$ yr) and old (age $\geq$ 10$^9$ yr) stars to the modeled SEDs. The green solid line is the total model, as stated above. The LRIS spectrum of source LH...
we classified source EN1_340451 as a type-2 AGN, on the basis of the HeII narrow line detected with Keck, but its broad-band SED is well fitted by a stellar model, with no need for additional components. Thus this source is best fitted by a moderate starburst (SFR= 56.1 $M_\odot$/yr) hosted in an extremely massive galaxy with M= 6.69 × 10^{11} M_\odot.

A detailed analysis of the stellar mass function of IR-peak sources is being carried out for the SWIRE survey, and is deferred to Berta et al. (in prep.), which will take into full account the spectroscopic results presented here.

As far as sources with an AGN spectral classification are concerned, a different fitting procedure was adopted. We reproduced the observed datapoints by means of the combination of a simple stellar population and a torus template [Fritz et al. (2006)]. The purpose, in this case, is to show how the detected IR-peak can be reproduced with multiple components, when the spectroscopic redshift is not fully consistent with what was expected for a pure stellar 1.6 $\mu$m peak.

We have therefore combined the Fritz et al. (2006) torus library, with the simple stellar population library used before [Poggianti et al. 2001; Berta et al. 2004]. The best fit is sought by $\chi^2$ minimization. The stellar component consists of one SSP, extinguished by a varying amount of dust. Again, extinction is also constrained through a far-IR starburst template. In combination to stars, the torus AGN emission is added, in order to fit the observed data.

The torus library by Fritz et al. spans several geometries of the toroidal dust distribution around the central AGN nucleus, varying the ratio between outer and inner radii ($R_{out}/R_{in} = 20 - 300$), and the aperture angle of the torus (measured starting from the equatorial plane, $\Theta = 40^\circ - 140^\circ$). We limit our analysis to a uniform dust distribution in the torus, because we do not have sufficient data points to constrain the entire library and because our purpose here is to get a general requirement on the level of AGN contribution to the mid-IR SED. The optical depth at the equator covers the range $\tau = 0.1 - 10.0$ at 9.7 $\mu$m. The spectrum emitted by the central engine is modeled with a broken power-law $\lambda L(\lambda) \propto \lambda^{\alpha}$, with indexes $\alpha = 1.2, 0, -0.5$ in the ranges $\lambda = 0.001 - 0.03, 0.03 - 0.125, 0.125 - 20 \mu$m respectively. Two different sets of models are included, differing for the UV-optical-IR slope of this power law, being $\alpha = -0.5$ or $\alpha = -1$. See Fritz et al. (2006) for more details of this model.

The results of this AGN+stars fit are in Tab. 8 and plotted in Fig. 7. The green dashed line represents the stellar component (including starburst dust), the blue dotted line is the AGN contribution to the global SED (red solid line).

The details of the best fit models are subject to strong degeneracies and are limited by the use of one single SSP, instead of a sophisticated model like in the starburst case. A unique best fit can not be achieved due to the limited photometry, therefore 3$\sigma$ ranges for the parameters are reported in Tab. 8 instead of best fit values. These fits have the illustrative purpose to point out how the shape of the broad band SED of IR-peak galaxies with AGN detection in the UV restframe spectra can be simply explained by two different physical components.

According to the unified scheme for AGN emission [Antonucci & Miller 1995], in the UV type-1 features emerge when the viewing angle does not intersect the dusty torus. At longer wavelengths, stellar and AGN spectral energy distributions are complementary, with the stellar component peaking around 1 $\mu$m and dominating the optical spectrum, while the torus warm dust emission increases longward and dominates the 3-10 $\mu$m range (see, for example, source EN1_282078). The warm component of the torus, coming from the inner regions closer to the central engine, can significantly contribute to the IR-peak itself, modifying its shape and apparently shifting it to a wavelength longer than 1.6$\mu$m (restframe). A good example of this effect is source EN1_282078, for which the IR-peak is detected in the restframe K band.

When a type-2 AGN is present, which in fact happens only in three of our sources, the UV-optical SED can be easily fitted by stars alone. In two cases (EN1_340451 and LH_572243) the whole SED, up to the mid-IR is reproduced with a simple starburst model (see above). Only in one case (EN2_172324) is a warm dust component needed in order to explain the near-IR fluxes. Nevertheless, in this latter case, our code cannot fully reproduce the observed shape of the IR-peak, even including the type-2 AGN.

Other effects might explain the observed SED of EN2_172324. Dust in AGB stars can significantly modify the shape of the IR-peak, changing its colors. The feature flattens, becoming bluer on the blue side and redder on the red side (see Piovan et al. 2003), and the H$^-$ feature is smoothed. Nevertheless these effects cannot explain a shift in the redshift of the peak of $\Delta z = 0.4$, as apparently observed in source EN2_172324.

At the observed redshift ($z = 1.739$), both Br$\gamma$ and Paa fall in the 5.8$\mu$m IRAC channel and could give a significant contribution to the observed flux, if very strong. Obviously, as a final source of uncertainty, photometry plays an important role.

Finally, blind tests on the sources listed in Tab. 7 (i.e. with no evidence for an AGN in their spectra) were carried out, using the multi-component approach. The fit confirm that a possible AGN would contribute less than 2% to the IRAC fluxes of these objects.

6. Other interesting sources

The multi-object mask geometry, and the low density of IR-peakers on the sky, allowed us to target several SWIRE/Spitzer sources having peculiar properties or multi-wavelength counterparts over a wide fraction of the electromagnetic spectrum.

The properties of some of these interesting sources are briefly described here, while a detailed analysis is deferred to subsequent papers.
6.1. High-redshift AGNs

The observed masks include three type-1 AGNs at redshift \( z > 2.5 \). Two of these AGNs (EN1\_282051 and EN2\_274735) were selected as \( z \sim 3 \) QSO candidates by their flux decrement in the U-band. We further required a red IRAC color \((m[3.6] − m[4.5] > −0.15)\) which eliminates contamination from main sequence stars (Siana et al. 2007, in prep.).

The third object (EN1\_202756) did not have any particular priority; it would have been selected as a \( z \sim 3 \) QSO but since it is fainter \((g' > 23.42, \text{Vega})\), the U band depth was insufficient to provide a red enough \( U − g' \) limit for selection. This AGN is not detected at 24\,\mu m, nor in IRAC channels 3 and 4, in the SWIRE survey.

EN1\_282051 is a bright quasar, with a 24\,\mu m flux of 740 \( \mu \text{Jy} \), lying at redshift \( z = 3.1 \). Four broad emission lines were detected: Ly\( \beta \), Ly\( \alpha \), C iv \(( \lambda = 1549 \AA \) and C iii\( \lambda \) \(( \lambda = 1909 \AA \)). Figure 10 shows the observed spectrum and theSED of this target. The latter has been superimposed with two different QSO templates differing in the FIR/optical luminosity ratio. The optical part of the templates belongs to the composite quasar spectrum from the Large Bright Quasar Survey (Brotherton et al. 2001) while the infrared section was obtained as the average SED of SWIRE quasars (Polletta et al. 2006; Hatziminaoglou et al. 2003). A detailed analysis of this object is being carried out by Siana et al. (in prep.).

Five broadband emission lines were detected for target EN2\_274735, Ly\( \alpha \), Si iv, O iv \(( \lambda = 1400 \AA \), C iv \(( \lambda = 1549 \AA \) and C iii\( \lambda \) \(( \lambda = 1909 \AA \)), at redshift \( z = 2.605 \), with several intervening systems producing absorption lines. This object is an optically-bright quasar that is not detected in the SWIRE 24\,\mu m survey (at the 200 \( \mu \text{Jy} \) limit) and has a FIR/optical color redder than in the previous case (see Fig. 10). Further analysis is deferred to Siana et al. (in prep.).

Finally, EN1\_202756 is a faint quasi-stellar object, with a \( r' \) magnitude of 22.95 (AB), detected only in the 3.6 and 4.5 \( \mu m \) channels, with a 16.65 and 17.12 \( \mu \text{Jy} \) flux respectively. Six emission lines are detected at \( z \sim 3.005 \): Ly\( \beta \), Ly\( \alpha \), C iv, He ii \(( \lambda = 1640 \AA \) ), N ii\( \lambda \) \(( \lambda = 1750 \AA \) ) and C iii\( \lambda \). The observed colors are redder than the QSO templates adopted (see Fig. 10).  

6.2. X-ray sources

Two masks were centered on the Lockman Hole and ELAIS-N1 regions which had been observed in the X-rays by Chandra (Polletta et al. 2006; Manners et al. 2003; Franceschini et al. 2005).

In the Lockman Hole, three X-ray sources were put on a slit, a 4.5\,\mu m-peaker (already discussed in Sect. 5.1), the troublesome 5.8\,\mu m-peak object LH\_572257, which turned out to be a low-redshift confused interloper (see Sect. 5.2), and finally the low-redshift \(( z = 0.355) \) type-1 AGN LH\_575325, discussed in Wilkes et al. (in prep.). As far as ELAIS-N1 is concerned, four X-ray sources have a confirmed spectroscopic redshift. Two sources have typical type-1 AGN spectra (EN1\_204120 and EN1\_202260, \( z = 1.475 \), 1.545), consistent with the classification by Franceschini et al. (2005); EN1\_203962 is a type-2 AGN at \( z = 0.874 \), while finally EN1\_201165 has a starburst spectrum with [O ii] and [Ne v] detected at \( z = 0.762 \). Franceschini et al. (2005) classify both targets as Seyfert-2 galaxies, although the latter (target 92 in their work) shows a lack of X-ray photons with respect to the AGN prediction.

7. Discussion

When neither broad lines, nor type-2 lines are present in the spectra of the observed IR-peakers, a pure stellar spectro-photometric synthesis was performed (Berta et al. 2004). Seven sources satisfy these requirements; their luminosities are in (or close to) the ULIRG regime \(( L_{IR} \geq 10^{12} L_\odot )\), and their bright IR fluxes turn out to be powered by strong obscured starburst activity. The median rate of star formation is \( \sim 90 \, M_\odot/\text{yr} \); the median extinction of the stars in the starburst (age \( \leq 10^8 \) years) is \( A_V = 1.65 \) magnitudes (see Tab. 7).

The host galaxies of these starbursts are extremely massive, \( M(\star) = 1−6 \times 10^{11} M_\odot \), at redshifts \( z = 1.3−2.8 \). Consequently, the median derived timescale for star formation \( t_{SF} = \frac{M(\star)}{SFR} \) turn out to be \( 2.6 \times 10^9 \) years, requiring many such episodes of star formation in order to form the whole assembled mass (provided that the typical duration of a starburst episode is \( \sim 10^7 \) yr). The two most active objects, with \( SFR \) of the order of \( 500 M_\odot/\text{yr} \), have \( t_{SF} \sim 2−3 \times 10^8 \) yr, fast enough to form the bulk of the total stellar mass in one single extreme burst of star formation.

A different approach to SED fitting is followed, when dealing with sources that show AGN signatures in their spectra or SEDs (seven out of 16 targets). In this case, we combine a single SSP and a torus model (Fritz et al. 2000).

The results show how warm dust from an AGN torus can be a significant contributor to IRAC fluxes, especially to channels 3 and 4, for example providing a fraction > 50% of the total emission at 8.0\,\mu m. It is very interesting to point out that in these cases the AGN component not only dilutes the infrared stellar peak, but also produces an apparent shift of the peak to longer wavelengths. This effect is basically due to the shape of the Planck emission of warm dust at temperatures of few to several hundreds Kelvin. The presence of an AGN is sufficient to explain the inconsistency between spectroscopic and photometric redshifts of IR-peakers.

In type-1 objects, the AGN component dominates the UV restframe emission, producing bright broad lines in the observed spectra; in the optical-near-IR domain stars and torus SED are complementary, and stars provide the bulk of the observed fluxes. The torus component again emerges at longer wavelengths, in the near-mid infrared, with warm
dust from the inner regions dominating between 3-10 µm restframe.

The best fit solutions preferentially require a small torus distribution of dust around the central AGN, with $R_{\text{out}}/R_{\text{in}} = 30 - 100$. The AGN component dominates in the IRAC observed frame, but the fraction of flux due to the AGN decreases at longer wavelengths. In more than 50% of cases, the torus usually does not significantly contribute to MIPS fluxes (e.g. at 24µm) and the contribution to the total IR (8 – 1000 µm) luminosity is $\sim 15\%$ for the majority of sources (see Tab. 5). Therefore the mid-IR spectrum of IR-peak galaxies is expected to be characterized by bright PAH features. Weedman et al. (2006) confirm the presence of bright 7-13 µm PAHs in the IRS spectra of optically-faint 5.8µm-peak galaxies, with no evidence of dilution by AGN torus dust in 90% of the examined cases. This suggests that the mid-IR emission of Weedman’s galaxies is dominated by starburst activity. Nevertheless, their sources lie at $z \approx 1.9$, on the lower bound of the 5.8µm selection; even in the case of these optically-faint sources, it is possible that an AGN (torus) component provides a non negligible contribution to IRAC fluxes, without being identified in the mid-IR.

All the sources with type-1 AGN broad lines detected in the Keck spectra require a non negligible contribution of torus warm dust to their IRAC SEDs (see Tab. 5), while two objects with type-2 AGN classification can be fitted with a stellar component only, with no needs of any torus to reproduce the observed IRAC fluxes. Conversely, all sources showing a significant excess in the IRAC domain, with respect to pure stellar emission, show AGN signatures in their UV-optical restframe spectra (either type-1 or 2).

Figure 12 shows the distribution of the IR-peak galaxies with a confirmed spectroscopic redshift, in optical-IRAC color space. The points belonging to IR-peakers are color coded by redshift (left panels) and by torus contribution at 8.0µm (right panels). Redshift tracks for a Seyfert-1 (Mrk231, Fritz et al. 2006), a Seyfert-2 (IRAS 19254-7245, Berta et al. 2003) and a starburst (M82, Silva et al. 1998) template are shown.

At comparable IRAC fluxes, the observed sources need to be increasingly optically blue with redshift (bottom left panel), in order to be detected by Keck/LRIS, with reasonable exposure times. IRAC colors (top left) change in the same direction as the starburst track (which is dominated by stars in the near-IR), but show a significant scatter, due to the torus contribution to the SEDs. At the highest redshift end ($z \geq 2.4$), the IRAC SED becomes flatter and resembles a power-law with a very diluted 1.6µm peak. The $S(8.0)/S(4.5)$ flux ratio exceeds unity and sources transit to the AGN locus in the IRAC color space (triangles in the top left plot of Fig. 12).

As far as the torus contribution to the 8.0µm observed flux is concerned (right panels), the properties of the observed sources are not easily identified with the use of broad band colors only. No clear trend of the AGN fraction is seen in the IRAC color plot (top right, Lacy et al. 2004), for IR-peak galaxies, nor is segregation of different type of sources seen. Apart from a couple of sources with power-law like SEDs (compare to. Fig. 2), the IR-peak galaxies hosting an AGN tend to lie in the same locus of starburst galaxies in the IRAC color space. The AGN contribution to IRAC SEDs has been identified:

1. through the presence of broad emission lines in their UV-optical spectra;
2. thanks to spectroscopic redshifts lower than expected, requiring a non negligible torus component taking part in the near-IR emission of IR-peakers.

In the optical, sources with 8.0µm torus fraction larger than 50% seem to be preferentially bluer than the others, as expected when the type-1 AGN component increasingly emerges at UV wavelengths (restframe). Type-2 AGNs show optical-IR colors similar to starbursts, as their SEDs can even be fitted by stars alone.

The “AGN IR-peak population” contaminates the overall sample and is difficult to identify on the basis of broad band photometry alone. Extreme care should be taken in the analysis of sources in the fourth quadrant of the IRAC color plot, the best way to break degeneracies and aliases being — of course — spectroscopic confirmation of their physical properties.

8. Conclusions

High redshift galaxies can be identified on the basis of their restframe near-IR spectral energy distribution. In this spectral domain, low-mass stars dominate galaxy emission, and produce a peak at 1.6µm (restframe), which is further enhanced by a minimum in the H$^-$ opacity in stellar atmospheres. The stellar peak is detected in the IRAC channels 2 and 3 at redshifts between 1.5 and 3.0.

We have performed Keck/LRIS optical spectroscopy of high-z “IR-peak” galaxies, selected in SWIRE northern fields. In order to be observable with Keck/LRIS, the sample was restricted to the optically brightest sources among the IR-peak population. A total of 35 such object were targeted, and 16 have a spectroscopic confirmation, in the $z = 1.3 - 2.8$ range. Among these, six are 4.5µm-peakers, and the remaining 10 peak at 5.8µm.

By combining the spectroscopic analysis and broad band SED fitting, we have extended our knowledge in the emission properties of IR-peak objects. The main results that have been described throughout this paper are summarized below and in Tab. 9:

- The IRAC IR-peak galaxies turn out to lie in the redshift range $z = 1.3 - 2.8$, broadly confirming expectations. Photometric and spectroscopic redshift are in better accordance for 4.5µm-peak objects than for 5.8µm peaks, which turn out to be at slightly lower redshift than expected.
- Low-redshift starburst interlopers represent a significant source of contamination of the 4.5µm-peak sample. A bright 3.3µm PAH feature can significantly
contribute to the IRAC channel 2 flux, for $z \sim 0.4$. Nevertheless, JHK data can break this aliasing, sources with $(K_s - 3.6)_\text{AB} \leq 0$ being at $z \leq 0.6$.

- The optically-faintest IR-peakers that have very bright $24\mu$m fluxes turn out to be heavily extinguished starbursts, with $SFR > 500 \, M_\odot/\text{yr}$ and $A_V \geq 2$ mag. No emission line are detected in these cases.

- 69% (11/16) of the IR-peakers with spectroscopic confirmation show AGN signatures in their spectra; 64% (7/11) of these are broad-line type-1 objects, the remaining are type-2’s. The observed sample biased to the optically-brightest IR-peakers in the sky, likely favoring those which host optically-bright AGN.

- The AGN torus component is important in the IRAC $\sim \mu$m domain, but it usually does not contribute significantly to longer wavelength mid-IR fluxes; hence the mid-IR spectrum of these sources is dominated by PAH features, as confirmed by Weedman et al. (2006) IRS spectroscopy.

Finally, multi-object spectroscopy allowed us to include many other SWIRE sources on slits, for a total of 301 objects. Among these, 174 objects have a spectroscopic redshift; 150 targets with redshift have a SWIRE counterpart. Our slits include 7 X-ray sources, 12 radio sources and 19 IRAC power-law galaxies. On the basis of spectral properties, we have identified 122 narrow-line targets ALT,AZ positions. We are grateful to M. Meneghetti for tests on a supposed gravitational lens (which turned out not to be). We thank A. Bressan and C. Chiosi for useful discussions on UV and near-IR spectral features, S. Ciroi for suggestions on optical spectral classification, F. Di Mille and S. Siviero for elucidation on spectrographs and optical paths.

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Table 2. Data for IR-peak sources included in slit, sorted by field: basic photometric information, photometric flag, spectroscopic classification and redshift are listed. See Tab. 3 for more details on flags.

| ID | RA [J2000] | DEC [J2000] | r mag | S(3.6) | S(4.5) | S(5.8) | S(8.0) | S(24) | flag | Class | z | spec | spec | z |
|----|------------|-------------|-------|--------|--------|--------|--------|--------|------|-------|---|------|------|---|
| #  | (2000) | (2000) | &mu; | | | | | | | | | | |
| EN1 | 242.42930 | 54.697529 | 23.40 | 36.37 | 55.60 | 83.10 | 70.62 | 488.24 | P3,X, pow | - | - | 0.370 |
| EN2 | 242.42930 | 54.697529 | 23.40 | 36.37 | 55.60 | 83.10 | 70.62 | 488.24 | P3,X, pow | - | - | 0.370 |
| EN2 | 242.42930 | 54.697529 | 23.40 | 36.37 | 55.60 | 83.10 | 70.62 | 488.24 | P3,X, pow | - | - | 0.370 |
| EN2 | 242.42930 | 54.697529 | 23.40 | 36.37 | 55.60 | 83.10 | 70.62 | 488.24 | P3,X, pow | - | - | 0.370 |

Table 3. Detected lines for IR-peak targets, sorted by mask (first night). For each source, we report the observed wavelength, equivalent width (EW), full width at half maximum (FWHM, corrected for the instrumental resolution) and identification of the detected spectral features. For each detected line, the spectroscopic redshift is computed (last column).
| ID    | SWIRE blue range [Å] | Detected lines | λ [Å] | EW [Å] | FWHM [Å] | line | z |
|-------|---------------------|----------------|-------|--------|----------|------|---|
| LH_126546 | 3500-5600  6000-8300 | – – – – – – | – – | – – | – – | – – | – |
| LH_128777 | – | – – – – | – – | – – | – – | – – | – |
| LH_77722 | – | 5600-7600 | – – | – – | – – | – – | – |
| LH_778261 | 3500-5600  5600-8600 | – – | – – | – – | – – | – – | – |
| LH_774368 | 4800-5000 | – | – – | – – | – – | – – | – |
| LH_577298 | – | 6000-8500 | 6521.87 | -39.66 | <10.50 | Fe | – |
| EN1_141469 | 341469 | – | – | – | – | – | – |
| EN1_142445 | 3300-5500  5600-8500 | – | – | – | – | – | – |
| EN1_140451 | – – | 6 | – – | – | – | – | – |
| EN1_39960 | 3600-5600  5700-8500 | 3634.78 | -101.9 | 27.66 | CIV (1549) | 1.476 |
| EN1_20334 | 10334 | 4000-5600  6000-8500 | 3581.76 | <60 | 5.75 | Lyα (1216) | 1.946 |
| EN1_20334 | 10334 | 4000-5600  5700-8200 | 3333.35 | -68.92 | 7.36 | Lyα (1216) | 1.741 |
| EN1_72326 | 3100-5700  5700-8500 | 4520.45 | -41.4 | 25.17 | CIV (1549) | 1.744 |
| EN1_160196 | 165986 | 3200-5700  5600-8700 | 9112.03 | -134.7 | 19.06 | OII (3727) | 1.145 |
| EN2_167372 | 3200-5600  6000-9200 | 3872.52 | -499.2 | 146.83 | Lyα (1216) | 2.185 |
| EN2_168364 | 165986 | 3200-5700  5600-8700 | 3872.52 | -499.2 | 146.83 | Lyα (1216) | 2.185 |
| EN2_168364 | 165986 | 3200-5700  5600-8700 | 3872.52 | -499.2 | 146.83 | Lyα (1216) | 2.185 |
| EN2_167372 | 3200-5600  6000-9200 | 3872.52 | -499.2 | 146.83 | Lyα (1216) | 2.185 |

Table 4. Detected lines for IR-peak targets, sorted by mask (second night).
### Table 5. Results for first night

| ID$^*$ | SWIRE RA 2000 | DEC 2000 | Det. Lines | z spec | z phot | Note‡ | Class‡ |
|-------|----------------|----------|------------|--------|--------|-------|--------|
| LIh027170 | 161.7666800 | 57.7988530 | 0 | 0 | 0.720 | ELG |
| LIh04141 | 162.9474900 | 57.8128240 | 1 | 0 | 1.017 | 0.890 | ELG |
| LIh03572 | 162.9537900 | 57.8163990 | 1 | 0 | 0.935 | 0.890 | ELG |
| LIh04996 | 162.9557500 | 57.8022500 | 0 | 0 | 1.240 | ELG |
| LIh04478 | 162.9599600 | 57.7954600 | 0 | 0 | – | 0.590 | ELG |
| LIh04759 | 163.0052200 | 57.8525550 | 0 | 0 | – | 1.130 | P3L |
| LIh04888 | 163.0071900 | 57.8170200 | 2 | 0 | 0.700 | 1.030 | ELG |
| LIh047704 | 163.0361100 | 57.8389550 | 1 | 0 | 0.419 | 0.500 | ELG |
| LIh04801 | 163.0237900 | 57.8167370 | 0 | 0 | – | 1.420 | ELG |
| LIh04973 | 163.0228400 | 57.7955510 | 0 | 0 | – | 2.840 | P3L |
| LIh048065 | 163.0620100 | 57.8371960 | 0 | 0 | – | 1.000 | ELG |
| LIh04661 | 163.0397000 | 57.7906430 | 1 | 0 | 0.927 | 0.400 | ELG |
| LIh047660 | 163.0540000 | 57.7978250 | 0 | 0 | – | 2.780 | ELG |
| LIh047451 | 163.0705900 | 57.8112640 | 0 | 0 | – | 1.790 | P3 |
| LIh047463 | 163.0602000 | 57.7662620 | 0 | 0 | – | 1.130 | ELG |
| LIh047782 | 163.0663800 | 57.7654230 | 0 | 0 | – | 1.590 | P2 |
| LIh047597 | 163.0960800 | 57.8022120 | 0 | 0 | – | 1.780 | P3 |
| LIh047245 | 163.1034000 | 57.7950170 | 0 | 0 | – | 2.780 | ELG |
| LIh047717 | 163.1172000 | 57.7946130 | 1 | 0 | 1.026 | 1.000 | ELG |
| LIh048867 | 163.1425500 | 57.8190800 | 0 | 0 | – | 1.130 | ELG |
| LIh047477 | 163.1239900 | 57.7627410 | 0 | 0 | – | 4.410 | ELG |

Note‡: ELG = emission lines; SB = starburst diagnostics; BLAGN = broad line AGN; NLAGN = narrow-line AGN; star = star; ALG = absorption lines only; nc = no continuum detected (but emission lines yes).

‡: (a) indicates serendipitous sources;

*: pow = IRAC power-law SED; P3 = 5.8µm peak; P2 = 4.5µm peak;

L: = upper limit at 8.0µm; R = radio source; X = X-ray source

$^*$: ELG = emission lines; SB = starburst diagnostics; BLAGN = broad line AGN; NLAGN = narrow-line AGN; star = star; ALG = absorption lines only; nc = no continuum detected (but emission lines yes).

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The measured spectroscopic redshift is in Column 6, while column 7 lists the photometric estimate of $z$, as obtained with the Hyper-z code [2000].
| ID$^+$ | RA 12000 | DEC 12000 | Det. Lines | z spec | z phot | Note$^*$ | Class† |
|-------|--------|--------|-----------|--------|--------|--------|--------|
| EN1 25279 | 244.2631600 | 55.5667400 | 1 0 | 1.135 | 0.810 | ELG |
| EN1 248486 | 244.2396200 | 55.6035190 | 0 2 | 0.800 | 0.810 | ALG |
| EN1 281518 | 244.2629100 | 55.5971790 | 0 2 | 0.798 | 0.920 | ALG |
| EN1 218928 | 244.1426400 | 55.5922250 | 4 0 | 3.100 | 0.210 | pow BLAGN |
| EN1 218186 | 244.1489000 | 55.5828820 | 1 0 | 0.732 | 0.900 | ELG |
| EN1 282887 | 244.1957600 | 55.5805400 | 0 0 | - | 1.370 | - |
| EN1 283544 | 244.2381300 | 55.5712430 | 1 0 | 1.119 | 0.970 | ELG |
| EN1 282211 | 244.1892700 | 55.5671650 | 1 0 | 1.103 | 1.120 | ELG |
| EN1 282263 (s) | 244.2012600 | 55.5621000 | 1 0 | 0.808 | 0.720 | ELG |
| EN1 281866 | 244.2005200 | 55.5582820 | 0 2 | 1.211 | 0.970 | ELG |
| EN1 282870 | 244.1957600 | 55.5805400 | 0 0 | - | 0.910 | - |
| EN1 281341 | 244.2031100 | 55.5371650 | 1 0 | 0.878 | 0.860 | ELG |
| EN1 279813 | 244.1436800 | 55.5324780 | 1 0 | 0.808 | 0.720 | ELG |
| EN1 279984 (s) | 244.1844600 | 55.5128000 | 2 0 | 0.718 | 0.700 | ELG |

‡: (s) indicates serendipitous sources;  
*: pow = IRAC power-law SED; P3 = 5.8 µm peak; P2 = 4.5 µm peak;  
L = upper limit at 8.0 µm; R = radio source; X = X-ray source.  
†: ELG = emission lines; SB = starburst diagnostics; BLAGN = broad line AGN; NLAGN = narrow-line AGN; star = star; ALG = absorption lines only; nc = no continuum detected (but emission lines yes).

Table 5. Continued.
Table 6. Results for second night.
| ID         | RA      | DEC      | Det. Lines | z     | z spec | Note  | Class                  |
|------------|---------|----------|------------|-------|--------|-------|------------------------|
| EN2_1561   | 250.406220 | 40.777615 | 0          | 0     | 0.950  | pow   | ELG                    |
| EN2_1560   | 250.402020 | 40.774158 | 0          | 0     | 1.210  | –     | –                      |
| EN2_1438   | 250.426320 | 40.783157 | 2          | 3     | 0.430  | 0.510 | SB                     |
| EN2_1147    | 250.440830 | 40.762694 | 0          | 2     | 1.561  | 1.010 | ALG                    |
| EN2_1554   | 250.451480 | 40.817425 | 1          | 4     | 1.866  | 0.970 | SB                     |
| EN2_10334  | 250.438280 | 40.763359 | –          | –     | 2.010  | –     | –                      |
| EN2_1850   | 250.450692 | 40.803145 | 0          | 0     | 1.270  | –     | –                      |
| EN2_17775  | 250.460620 | 40.805050 | –          | –     | 0.000  | star  | –                      |
| EN2_1745   | 250.440690 | 40.755573 | 1          | 0     | 1.086  | 1.190 | ELG                    |
| EN2_11691  | 250.464570 | 40.791348 | 1          | 0     | 1.946  | 2.140 | ELG                    |
| EN2_1749   | 250.480210 | 40.812843 | 1          | 7     | 0.776  | 1.150 | SB                     |
| EN2_10301  | 250.480990 | 40.773952 | 1          | 3     | 0.673  | 0.960 | SB                     |
| EN2_0278   | 3250.493590 | 40.753378 | 5          | 0     | 1.720  | 1.020 | pow                   |
| EN2_1495   | 250.492500 | 40.747240 | 6          | 7     | 0.362  | 0.110 | SB                     |
| EN2_10015  | 250.509500 | 40.786121 | 0          | 7     | 0.737  | 0.710 | ALG                    |
| EN2_0634   | 250.514040 | 40.789330 | 0          | 0     | –      | 1.200 | –                      |
| EN2_2017   | 250.519000 | 40.765450 | 0          | 2     | 0.802  | 0.710 | ALG                    |
| EN2_0768   | 250.525380 | 40.750540 | 2          | 0     | 0.479  | 0.330 | ELG                    |
| EN2_0885   | 250.539170 | 40.796650 | 1          | 8     | 0.875  | 0.780 | SB                     |
| EN2_0977   | 250.547850 | 40.796260 | 0          | 0     | –      | 0.100 | –                      |
| EN2_0936   | 250.550190 | 40.781242 | 1          | 3     | 0.718  | 0.880 | SB                     |
| EN2_0835   | 250.536800 | 40.729000 | 1          | 0     | 1.400  | 1.320 | ELG                    |
| EN2_2702   | 250.542790 | 40.728800 | 1          | 3     | 0.916  | 0.980 | SB                     |
| EN2_2702   | 250.568700 | 40.784460 | 1          | 7     | 0.671  | 0.590 | SB                     |
| EN2_27234  | 248.621380 | 41.059710 | 4          | 0     | 1.739  | 2.070 | P3                    |
| EN2_272031 | 248.632660 | 41.059530 | 4          | 7     | 0.558  | 0.780 | SB                     |
| EN2_272031 | 248.635380 | 41.030450 | 0          | 0     | 1.150  | –     | –                      |
| EN2_27032  | 248.687560 | 41.053230 | 1          | 0     | 0.912  | 1.070 | ELG                    |
| EN2_269844 | 248.625580 | 41.015610 | 1          | 8     | 0.581  | 0.380 | SB                     |
| EN2_269626 | 248.697450 | 41.042477 | 0          | 0     | –      | 0.300 | –                      |
| EN2_268961 | 248.688440 | 41.026176 | 0          | 0     | –      | 0.490 | –                      |
| EN2_268666 | 248.676200 | 41.017720 | 1          | 0     | 1.265  | 0.990 | ELG                    |
| EN2_268545 | 248.693830 | 40.993660 | 1          | 0     | 0.952  | 0.490 | ELG                    |
| EN2_163772 | 248.650680 | 40.979750 | 1          | 0     | 1.445  | 2.120 | P2L                   |
| EN2_163772 | 248.651750 | 40.978490 | 0          | 0     | –      | 1.270 | –                      |
| EN2_162732 | 248.696300 | 40.997400 | 5          | 8     | 0.522  | 0.290 | SB                     |
| EN2_166533 | 248.657490 | 40.973550 | 1          | 4     | 0.909  | 0.890 | SB                     |
| EN2_166134 | 248.678600 | 40.958790 | 1          | 0     | 1.085  | 1.470 | P2L                   |
| EN2_165986 | 248.712040 | 40.989090 | 4          | 0     | 2.163  | 0.430 | P3,pow                 |
| EN2_165893 | 248.722850 | 40.983250 | 0          | 0     | 0.990  | –     | –                      |
| EN2_165571 | 248.725800 | 40.979890 | 1          | 5     | 0.797  | 0.100 | –                      |

1: (s) indicates serendipitous sources; pow: IRAC power-law SED; P3 = 5.8µm peaker; P2 = 4.5µm peaker; L = upper limit at 8.0µm; R = radio source. X = X-ray source.

1: ELG = emission lines; SB = starburst diagnostics; BLAGN = broad line AGN; NLAGN = narrow-line AGN; star = star; ALG = absorption lines only; nc = no continuum detected (but emission lines yes).

Table 6. Continued.
| ID     | Type | Class | z     | Mass(×10^11 M_☉) | SFR(10^8 M_☉/yr) | A_V (mean) | A_V (10^8 yr) | L_IR(8–1000 µm) |
|-------|------|-------|-------|-------------------|-------------------|------------|---------------|-----------------|
| SWIRE | phot. | spec. | spec. | [M_☉]             | [M_☉/yr]          | [mag]      | [mag]         | [10^11 L_☉]     |
| EN1   | 202261 | P2   | ELG   | 1.389             | 1.47 (1.41–2.36)  | 489 (349–421) | 1.68 (1.29–1.73) | 1.82 (1.94–1.88) | 10.81 (8.48–12.84) |
| EN1   | 342445 | P3L  | ELG   | 1.917             | 1.04 (0.91–1.84)  | 426 (268–480) | 1.10 (0.57–1.17) | 1.40 (0.96–1.49) | 9.37 (6.89–12.81) |
| EN1   | 340151 | P3   | NLAGN | 2.866             | 6.69 (6.12–7.29)  | 561 (29.6–108) | 0.63 (0.41–0.76) | 2.14 (1.43–3.20) | 36.79 (29.55–50.58) |
| EN1   | 340451 | P3L  | ELG   | 1.337             | 1.40 (1.35–3.86)  | 17.0 (9.90–200) | 0.79 (0.50–0.89) | 1.65 (1.20–2.02) | 9.08 (5.82–12.41) |
| LH1   | 340451 | P2   | NLAGN | 1.928             | 0.91 (0.88–0.92)  | 34.4 (27.9–91) | 0.82 (0.79–0.90) | 2.09 (1.99–2.28) | 9.27 (9.04–10.81) |

Table 7. Results of spectro-photometric fitting for sources with no AGN component. The five columns on the right contain the stellar masses of galaxies, their ongoing (within the last 10^8 yr) star formation rate, two values of the intrinsic extinction, and the IR (8–1000 µm restframe) luminosity produced by the ongoing starburst, estimated assuming an M82-like template. The two A_V values are computed by averaging over the whole galaxy life and over the last 10^8 yr (representing the amount of dust affecting the ongoing burst). In parenthesis the 3σ ranges derived from the exploration of the parameter space are reported.

| ID     | Type | Class | z     | B Laud. | Θ | r0,7 | L_BH | α     | age | E(B–V) | Mass | L_IR | % AGN | 8.0µm | IR |
|-------|------|-------|-------|---------|----|------|------|-------|-----|--------|------|------|------|-------|-----|
| SWIRE | phot. | spec. | spec. | R_out  | Ψ  | Θ    | Ψ    | L_IR  | α   |         |      |      |      |       |
| EN1   | 202261 | P2,X | BLAGN | 1.545   | 100–300 | 100–140 | 0.6–2.0 | 0–30 | 0.79–1.58 | -1.0 | 50–300 | 0.2–0.4 | 3.98–10.0 | 4.23–7.05 | 53–71% | 10–62% |
| EN1   | 282078 | P3   | BLAGN | 1.685   | 20–100  | 60–100  | 0.6–10.0 | 0–60 | 1.38–16.0 | -1.0 | 50–100 | 0.6–0.8 | 3.98–6.31 | 10.4–23.7 | 53–65% | 2–40% |
| EN1   | 279954 | P3,pow | BLAGN | 2.400   | 30–100  | 60–140  | 0.6–3.0 | 0–50 | 0.20–0.32 | -0.5 | 50–500 | 0.2–0.6 | 2.51–15.8 | 15.4–27.1 | 49–63% | 5–31% |
| EN1   | 199050 | P3   | BLAGN | 1.475   | 30–100  | 60–140  | 0.6–1.0 | 0–50 | 0.20–0.32 | -1.0 | 10–50  | 0.6–1.0 | 2.51–15.8 | 15.4–27.1 | 53–65% | 5–31% |
| EN1   | 275226 | P2   | BLAGN | 1.710   | 30–100  | 100–140 | 1.0–6.0 | 0–20 | 0.32–1.58 | -0.5 | 10–50  | 0.6–0.8 | 3.98–25.1 | 15.3–26.1 | 57–64% | 1–20% |
| EN1   | 273717 | P3   | BLAGN | 1.739   | 30–100  | 100–140 | 0.3–3.0 | 0–20 | 1.00–3.16 | -1.0 | 50–100 | 0.4–0.6 | 15.8–25.1 | 16.4–23.4 | 32–45% | 3–39% |
| EN1   | 165986 | P3,pow | BLAGN | 2.163   | 20–100  | 80–140  | 3.0–10.0 | 40–90 | 1.00–3.16 | -1.0 | 10–100 | 0.2–0.6 | 1.00–10.0 | 11.5–18.6 | 64–80% | 20–53% |

Table 8. Results of SED fitting for IR-peakers requiring an AGN component. The fit consists in the combination of a simple stellar population and a torus model [Fritz et al. 2006]. The 3σ ranges for the main geometrical and dust properties of the torus are reported, as well as stellar population ages, extinctions and masses.
Table 9. Summary of results.

| Category               | No. | %   |
|------------------------|-----|-----|
| Observed slits         | 235 | –   |
| Original targets       | 233 | –   |
| Serendip. targets      | 68  | –   |
| Total targets          | 301 | –   |
| Tot. measured redshifts| 174/301 | 58% |
| Serendip. redshifts    | 35/68 | 52% |
| SWIRE redshifts        | 150 | –   |
| Absorption line glxs   | 7/150 | 5%  |
| Emission line glxs     | 122/150 | 81% |
| Starbursts             | 39/150 | 26% |
| Type-2 AGNs            | 5/150 | 3%  |
| Type-1 AGNs            | 17/150 | 11% |
| z > 2.5 QSOs           | 3/150 | 2%  |
| Obs. IR-peakers        | 35  |     |
| Obs. 4.5\(\mu m\)-peakers | 8/35 | 23% |
| Obs. 5.8\(\mu m\)-peakers | 27/35 | 77% |
| IR-p. with redshift    | 16/35 | 46% |
| 4.5\(\mu m\)-p. with redshift | 6/8 | 75% |
| 5.8\(\mu m\)-p. with redshift | 10/27 | 37% |
| AGN IR-peakers         | 11/16 | 69% |
| Type-1 AGN IR-peakers  | 7/11 | 64% |
| Type-2 AGN IR-peakers  | 4/11 | 36% |
| Type-1 AGN 4.5\(\mu m\)-peakers | 2/7 | 29% |
| Type-1 AGN 5.8\(\mu m\)-peakers | 5/7 | 71% |
| Type-2 AGN 4.5\(\mu m\)-peakers | 1/4 | 25% |
| Type-2 AGN 5.8\(\mu m\)-peakers | 3/4 | 75% |

Fig. 1. Selection of sources for our spectroscopic Keck observations: distribution of observed targets in the 24\(\mu m\) vs \(r'\) space.
Fig. 2. Distribution of the observed targets in IRAC color space (Stern et al. 2005; Lacy et al. 2004). We distinguish: IR-peak sources (filled circles), power-law targets (crosses), broad-line detections (open squares). All other cases are plotted as open circles.

Fig. 3. Redshift distribution of successfully detected sources (spectroscopic $z$). The empty histogram shows spectroscopic redshifts for all sources, while the shaded histogram represents IR-peak sources alone.
Fig. 4. Comparison between spectroscopic and photometric redshifts. Dashed and dotted lines represent ±10 and 20% uncertainties. Left panel: results obtained with Hyper-z [Bolzonella et al. 2000]. Right panel: results of the Rowan-Robinson (2003) code.

Fig. 5. Comparison between spectroscopic and photometric redshifts for IR-peak sources. Left panel: results obtained with Hyper-z [Bolzonella et al. 2000]. Right panel: results of the Rowan-Robinson (2003) code.
Fig. 6. Distribution of IR-peak targets in the optical-IR color space (ELAIS-N1 and N2 only). Open symbols belong to sources with a spectroscopic redshift, filled ones represent objects with no spectral features detected.
Fig. 7. IR-peak sources with spectroscopic redshift: broad band SEDs and spectra. Sources with no AGN detected in the UV-optical spectra are fitted with spectrophotometric synthesis (Berta et al. 2004). In these cases, the dotted lines represent old (age \( \geq 10^9 \) yr) stellar populations, dashed lines are younger stars, the dashed lines long ward 5\(\mu m\) (restframe) are the IR starburst template adopted (see text) and the solid lines are the total best fit. \(\chi^2\) values computed without accounting (“opt”) and accounting (“opt+FIR”) for the available 24\(\mu m\) flux are reported. If an AGN was detected, a multi-component fit is performed. In these cases, the dashed lines are the stellar + starburst dust component, the dotted lines represent the torus model and the solid lines are the sum of the two. A unique \(\chi^2\) value is derived, taking into account all the available data.
Fig. 7. Continued.
Fig. 7. Continued.
Fig. 8. Example of low-redshift starburst galaxy displaying an IRAC SED which resembles a 4.5\(\mu\)m peaker. Note that the 8.0\(\mu\)m flux density is higher than the 5.8\(\mu\)m, but note also that source EN1\_20260 (Fig. 7) has the same property but lies at \(z = 1.545\). The photometric data are compared to the prototypical M82 starburst template, normalized to the 5.8\(\mu\)m band.

Fig. 9. Trend of JK-IRAC colors, as a function of redshift, as computed for starburst (M82, Silva et al. 1998), seyfert-2 (IRAS 19254-7245, Berta et al. 2003) and seyfert-1 (Mrk231, Fritz et al. 2006) templates.
Fig. 10. Spectra and SEDs of high-redshift QSOs. The observed photometry is compared to three different templates. The standard template (dotted lines) is built with the optical composite quasar spectrum from the Large Bright Quasar Survey [Brotherton et al. 2001] and the average SED of SWIRE quasars [Hatziminaoglou et al. 2005]. The reddest (long-dashed lines) and bluest (short-dashed) differ from it only in their IR/optical luminosity ratio [Polletta et al. 2006].
Fig. 11. The 5.8μm-peak target LH.572257 at $z = 0.249$. White squares are drawn on the $z$ and $K_s$ band stamps, in order to guide the reader in finding the two physical components that contribute to the observed SED (see text for more details). Stamp size is 0.01 deg.
Fig. 12. Color-color plots of the targets with spectroscopic redshifts. The datapoints for IR-peak galaxies (detected in the required bands) are color-coded by redshift (left) and AGN torus contribution at 8.0µm (right). Three template tracks from $z = 1$ to $z = 3$ are shown: a starburst (dashed lines, M82, Silva et al., 1998), a seyfert-2 (dot-dash, IRAS 19254-7245, Berta et al., 2003) and a type-1 AGN (dotted, Mrk231, Fritz et al., 2006).