Deep Infrared Surveys and their Cosmological Implications

SINCE THE RECENT DISCOVERY BY THE COBE MISSION OF A COSMIC BACKGROUND IN THE INFRARED CONTAINING ROUGHLY HALF OF THE GLOBAL COSMIC RADIATIVE BUDGET, ONE OF THE IMPORTANT THEMES IN COSMOLOGY HAS BEEN THE DETECTION AND CHARACTERIZATION OF ITS SOURCES. WE REPORT HERE ON THE FIRST ATTEMPTS IN THIS SENSE CARRIED OUT THROUGH DEEP MID- AND FAR-IR SURVEYS WITH THE INFRARED SPACE OBSERVATORY, AND WE DETAIL ON THE OBSERVATIONAL CAMPAIGNS OF OPTICAL FOLLOW-UP USING VARIOUS ESO TELESCOPES. THIS RESULTED IN THE IDENTIFICATION OF A POPULATION OF LUMINOUS AND ULTRA-LUMINOUS MASSIVE STAR-FORMING GALAXIES, STRONGLY EVOLVING IN COSMIC TIME. THESE RESULTS SET THE SCENE FOR THE FORTHCOMING DEEPER EXPLORATIONS USING THE SIRTF OBSERVATORY AND THE LATEST GENERATION OF ESO INSTRUMENTS.

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ONE OF THE KEY THEMES for observational cosmology is the study of the build up with cosmic time of stellar populations and the progressive assembly of galaxies, a fundamental process from the primordial diffuse plasma to the highly structured present-day universe. These investigations are usually performed through observations in the UV/optical/near-IR with large ground-based optical telescopes. In the last couple of decades, however, it has become more and more evident that a lot of further independent information may be obtained from selecting faint galaxies at longer infrared wavelengths. By these means not only are the effects of dust extinction minimized (dust absorption is a strongly decreasing function of wavelength), but also the dust re-radiation in the mid- and far-infrared and the sub-millimeter (between $\lambda\sim10$ and 1000 μm) can be detected.

While only ~30% of the light from normal galaxies is absorbed by dust, this fraction becomes much higher when we consider the most active star-forming regions in galaxies and phases of enhanced generations of stars which are episodically triggered in galaxies.

There is also evidence that these active phases in galactic evolution were quite more frequent in the past, not strange if we consider the much larger fractions of diffuse gas and dust in galaxies during the early evolutionary phases, hence the more abundant fuel available to form stars. A spectacular achievement for cosmology during the 1990s was the discovery by the COBE mission of a diffuse airglow with peak emission at $\lambda\approx200$ μm (the Cosmic IR Background, CIRB) attributed to the integrated emissions by primeval galaxies and Active Galactic Nuclei (Puget et al. 1996; Hauser et al. 1998).

Unfortunately, the IR and sub-millimeter domain is very difficult to access by astronomical observations, possible from ground only in a few narrow spectral windows, between 2.5 and 30 μm (the VISIR instrument on VLT will soon exploit some of these windows) and at $\lambda>300$ μm (accessible by large millimetric telescopes). Observations from space platforms are then mostly required. The combined use of deep observations from space by the ESA Infrared Space Observatory (ISO) for selecting high-z active galaxies (both starbursts and AGNs) and the VLT for high-resolution optical studies to physically characterize them turned out to be particularly powerful.

Another important step is being achieved with the infrared observatory SIRTF successfully launched by NASA on August 25. ESO is currently involved in systematic campaigns (mentioned later in this paper) of complementary optical imaging and spectroscopic observations for a best exploitation of the data from space. We summarize in this paper results of some exploratory long-wavelength surveys and optical follow-up studies that have involved the use of ESO telescopes.

THE MAIN INFRARED SURVEYS

The Infrared Space Observatory (ISO, Kessler et al 1996), operative from 1995 to 1998, included two focal-plane instruments of cosmological interest: a mid-IR array camera (ISOCAM), and a far-IR imaging photometer from 60 to 200 μm

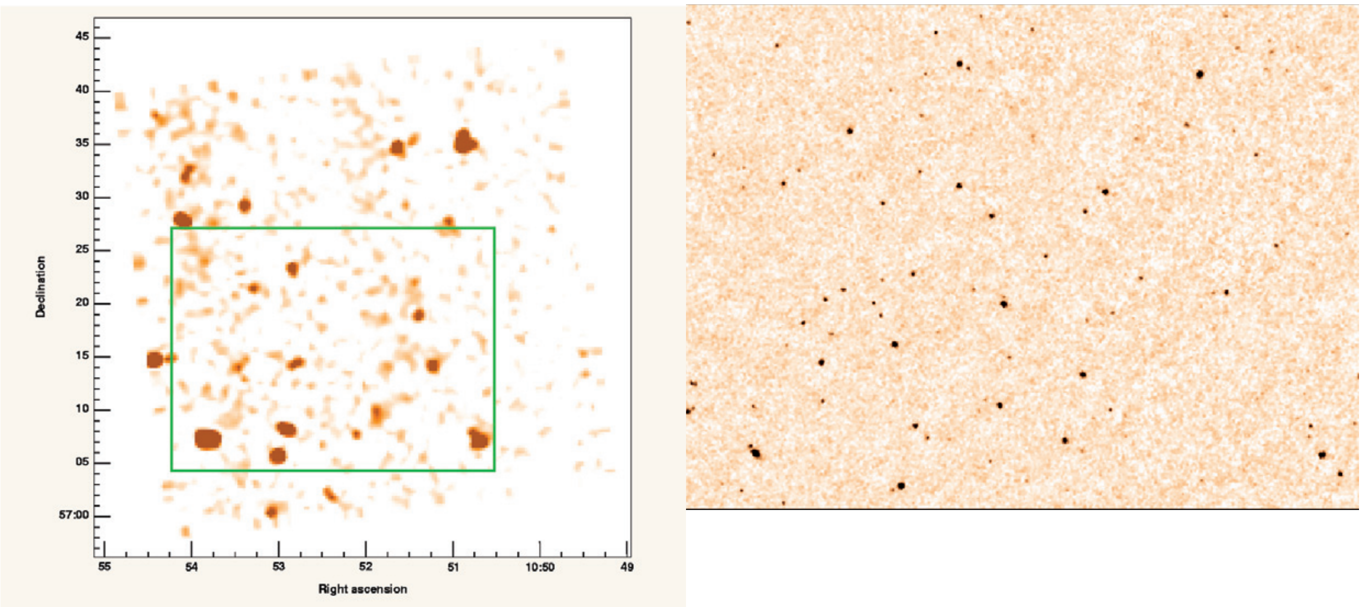


Figure 1: Left panel: ISOPHOT 90 μm map in the Lockman Hole region (Rodighiero et al. 2003). This is likely the deepest far-IR image ever obtained and contains sources with fluxes down to ~20 mJy. The area within the green box is expanded in the right panel, as seen by ISOCAM at 15 μm (Fadda et al., 2003, in preparation).

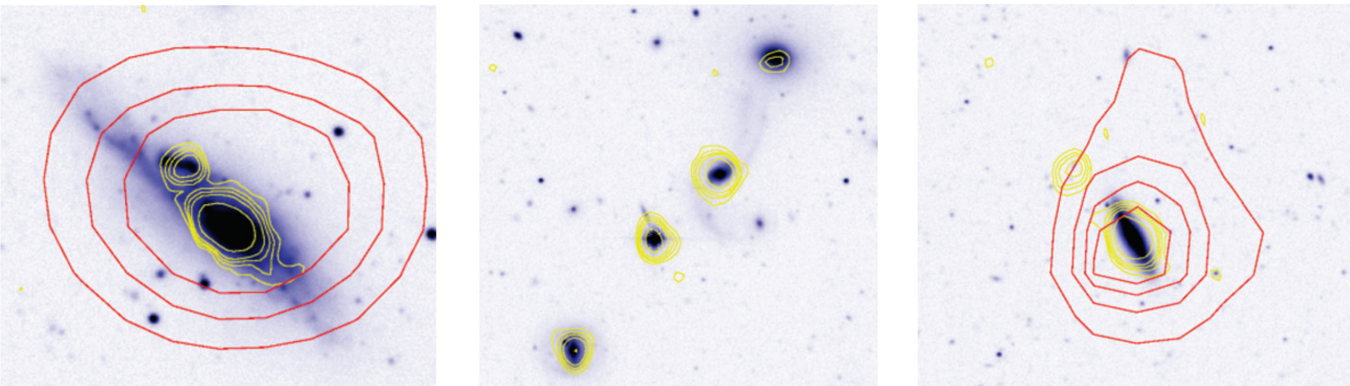


Figure 2: Optical R-band images of IR sources in the Lockman Hole (taken from Rodighiero et al. 2003 and Fadda et al. 2003 in preparation). Yellow contours are the 15 μm detections, red contours are from the 90 μm map.

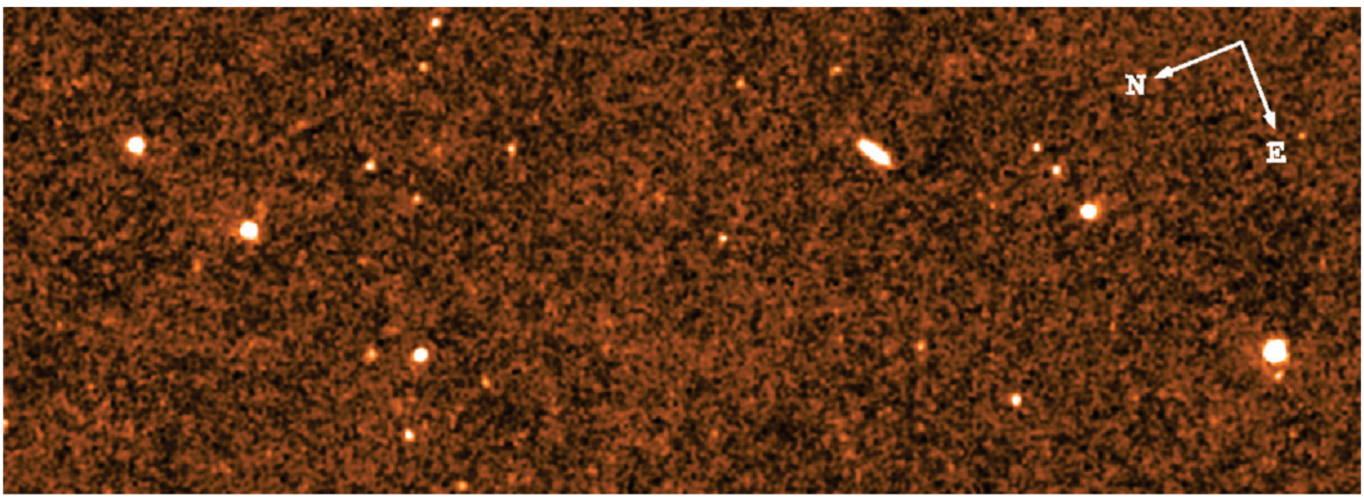


Figure 3: An ISO 30′ × 10′ region at 15 μm of the ELAIS N2 field (Vaccari et al., 2003, in preparation).

(ISOPHOT). The main extragalactic results from the 30-month ISO mission have been summarized by Genzel & Cesarsky (2000). The most important ISO surveys have been performed with a wide-band filter at 12-18 μm and two far-IR (λ=90 and 170 μm) channels. Due to the different diffraction-limited spatial resolution, ~4.6 arcsec FWHM at 15 μm and ~50 arcsec at 100 μm, ISO sensitivity limits in the mid-IR are three orders of magnitude deeper in flux than at the long wavelengths (0.1 mJy versus 100 mJy). Illustrative examples of deep images at 15 and 90 μm are reported in Figs. 1 to 4.

Source counts analyses

Faint IR-selected sources show extremely high rates of evolution with redshift, exceeding those measured for galaxies at other wavelengths and comparable to, or larger than, those of quasars (Elbaz et al. 2002, Franceschini et al. 2001). This is shown by the differential counts of extragalactic sources at 15 μm based on seven independent datasets, displaying a strong departure from an Euclidean law characteristic of a local non-evolving population (see Fig. 5).

An attempt to reproduce these source counts through modelling (but also involving data on the z-distributions, luminosity functions, and data at other IR and sub-mm wavelengths) was described in Franceschini et al. (2001). The model assumes the existence of two basic source populations with different physical and evolutionary properties: quiescent spirals (long dashed line in Fig. 5) and a population of fast evolving sources (dotted line, including starburst galaxies and type-II AGNs). The local fraction of the evolving starburst population is ~10% of the total. In this scenario, the active starbursts and the quiescent galaxies belong to the same population. Each galaxy is expected to spend most of its lifetime in the quiescent state, but occasionally interactions or merger events with other galaxies trigger a short-lived (few to several 10^7 years) active starbursting phase. The inferred cosmological evolution for the latter may be interpreted as an increased chance to detect a galaxy during the active phase back in the past, following the higher probability of interactions during the past denser epochs, and the larger gas masses available to form stars at higher z increasing the rate of star formation (SFR) and the starburst's luminosity. By exploiting the observed correlations of mid-IR, far-IR and radio luminosities, Elbaz et al. (2002) have found that the galaxies detected in the ISOCAM deepest 15 μm surveys are responsible for about two-thirds of the in-

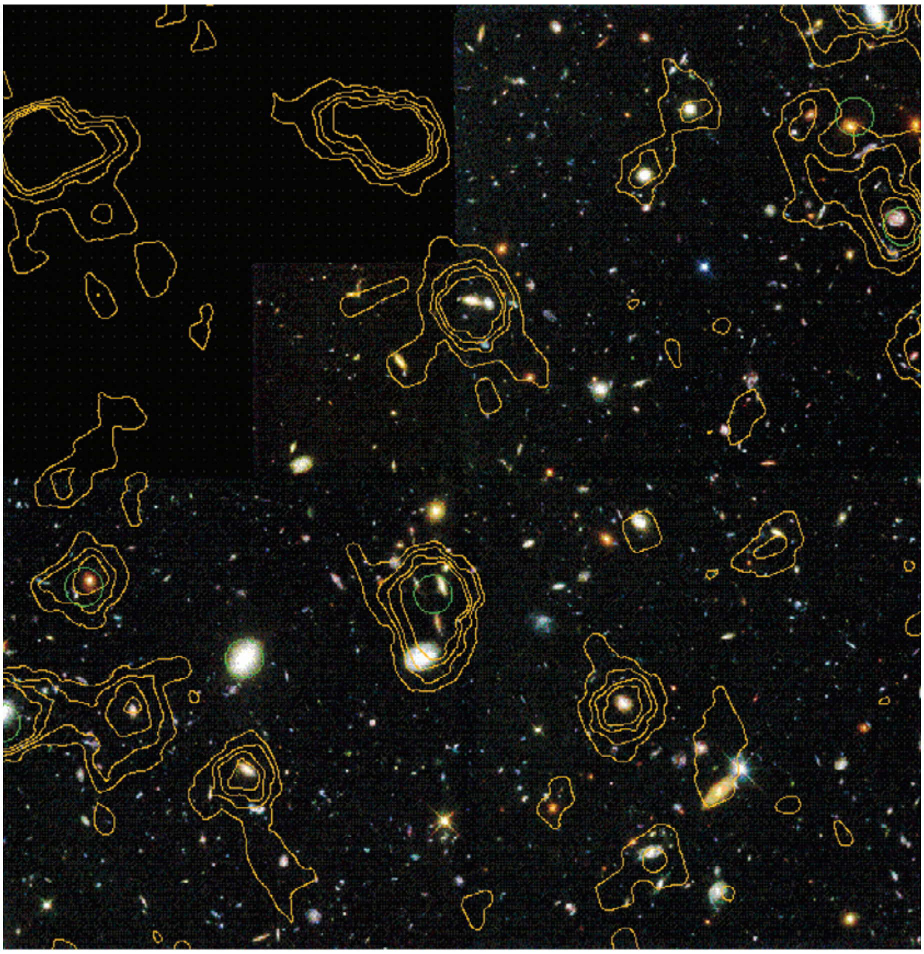


Figure 4: ISO 15 μm contours (yellow) overlayed on the WFPC2 HST image of the HDF North (Aussel et al., 1999).

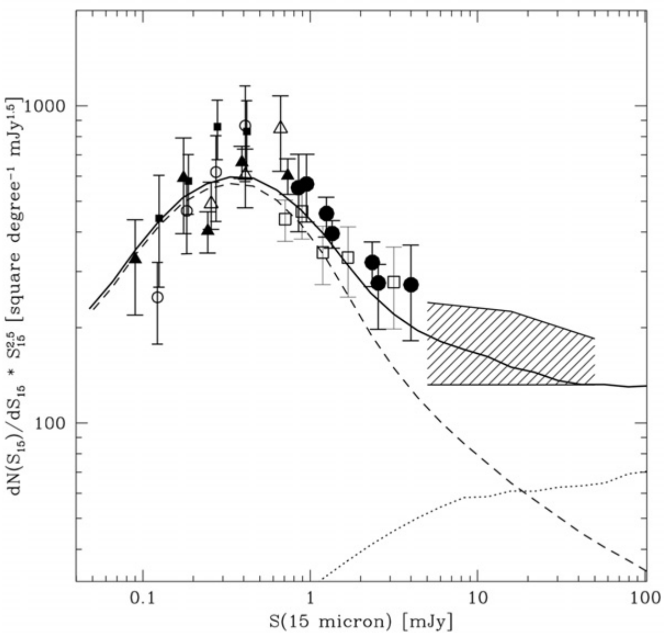


Figure 5: Differential counts at λ_{eff}=15 μm normalized to the Euclidean law ($N[S] \propto S^{-2.5}$). The dotted line are the expected counts for a population of non-evolving spirals. The short dashed line comes from our model population of strongly evolving starburst galaxies. See Franceschini et al. (2001) for more details.

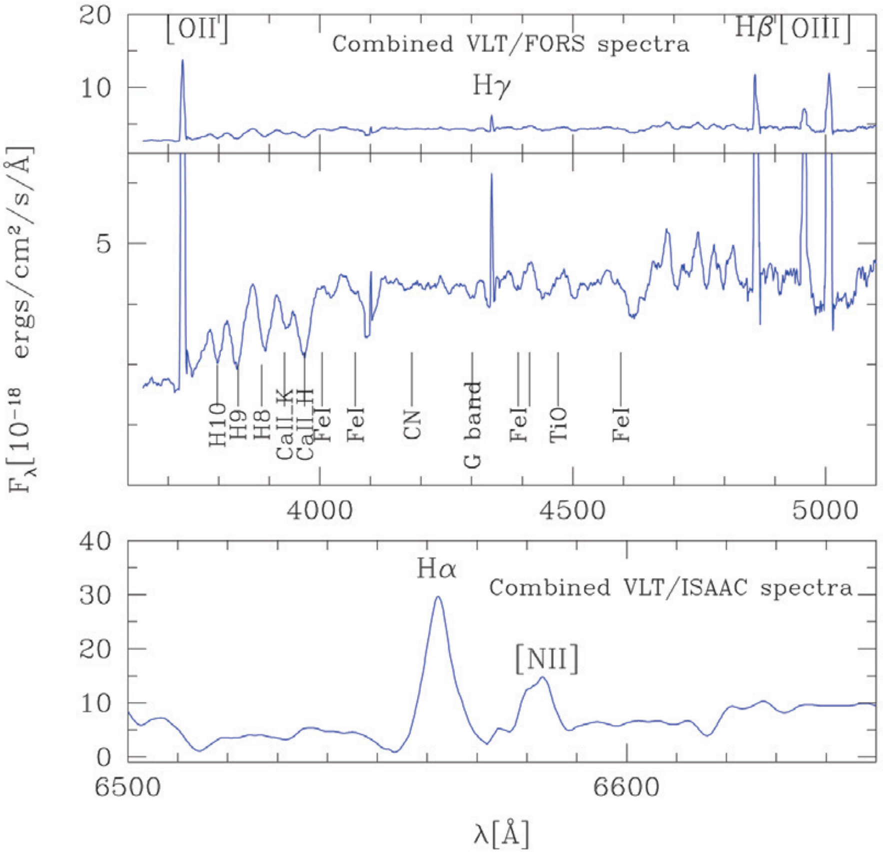
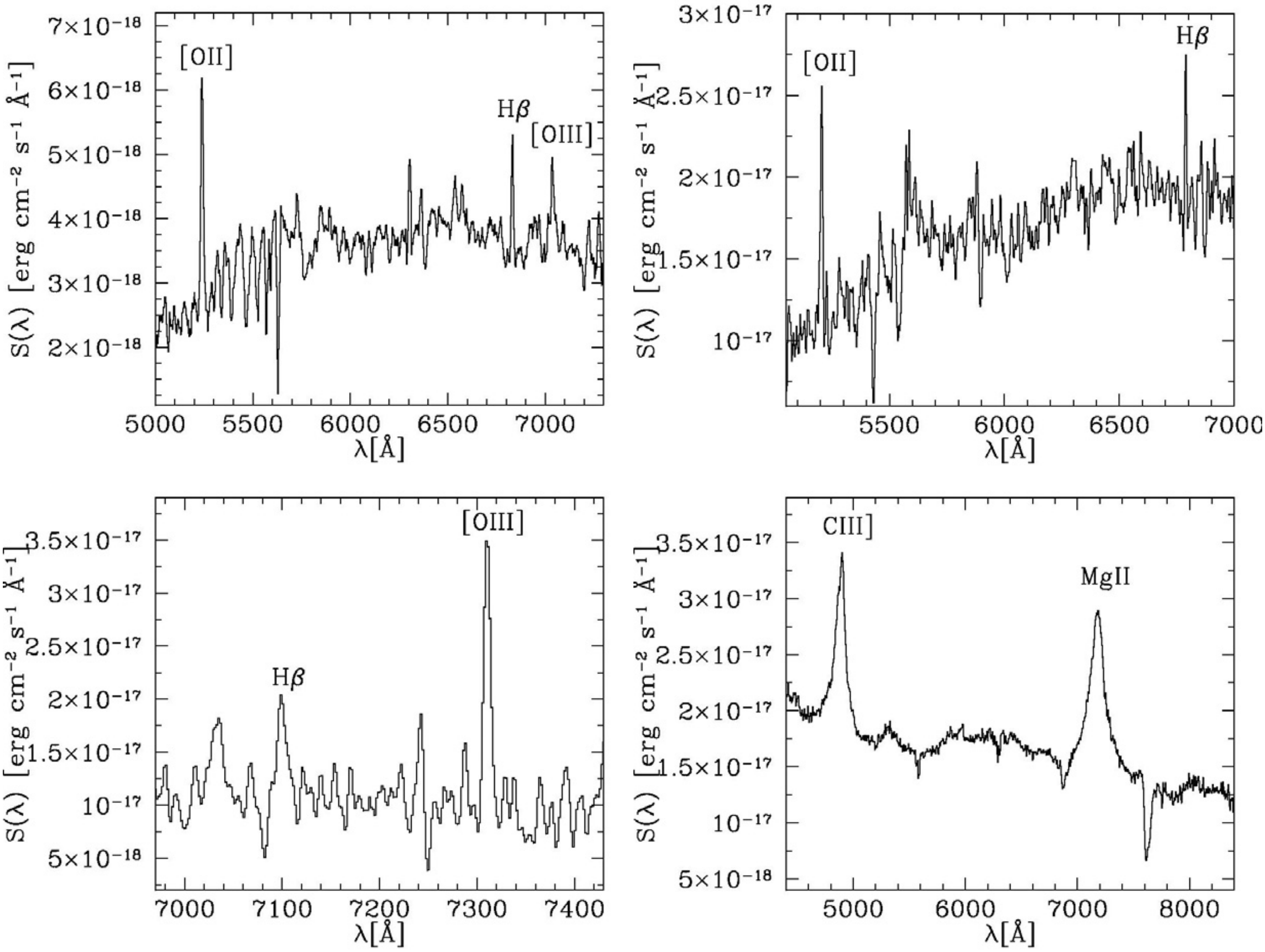


Figure 6: *Combined VLT FORS+ISAAC spectra of eight distant LIRGs (z~0.7) detected in the CFRS 03hr field. A zoom of the spectra revealing metallic and Balmer absorption lines combined with intense emission lines is shown in the central panel (the main absorption lines are indicated, Flores et al., 2003 in press).*

▼ ***Figure 7:*** *Observed optical spectra: panels (a) to (c) show 15 µm sources observed with NTT/EMMI. Panel (d) represents the QSO s19 from a FORS1/VLT spectrum. The spectra are taken from Franceschini et al. (2003)*



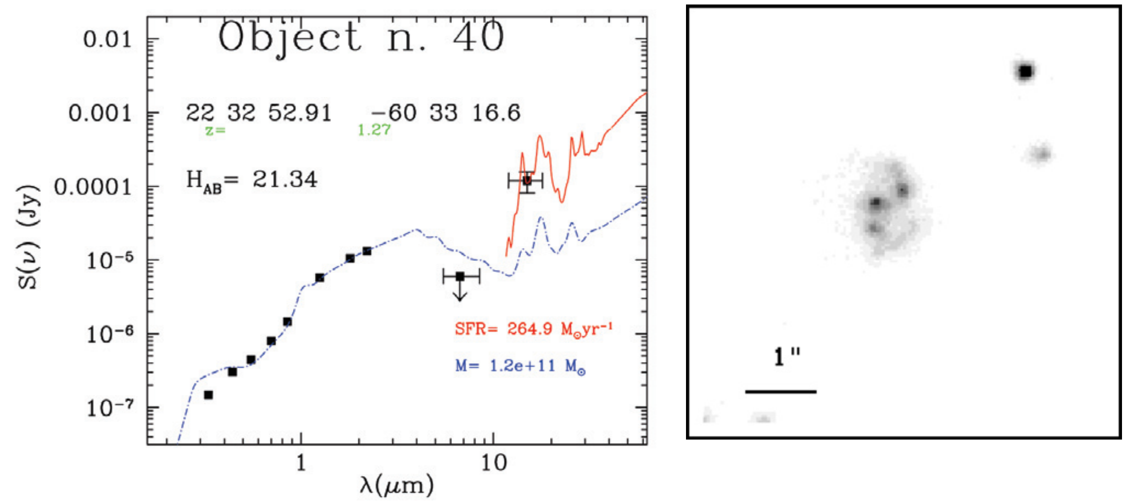


Figure 8: HDFS source S40. Left panel: the observed spectral energy distribution (square dots) compared with the best fit spectrophotometric model (dot-dash blue line) and the template SEDs of M82 (thick solid red line). Right panel: the WFPC-2 F814W image of S40 reveals a very complex and disturbed structure, possibly characterized by different regions of ongoing star formation or multiple nuclei (Franceschini et al. 2003).

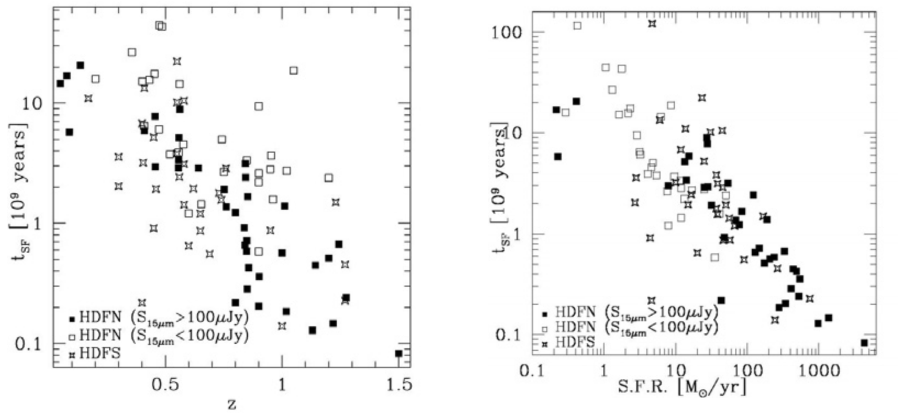


Figure 9: The timescale of star formation t_{SF}=M/SFR [in units of 10^9 yrs] of faint 15 μm ISO sources as a function of redshift (panel a) and star formation rate SFR (panel b). An Ω_m=0.3, Ω_Λ=0.7 cosmology is assumed.

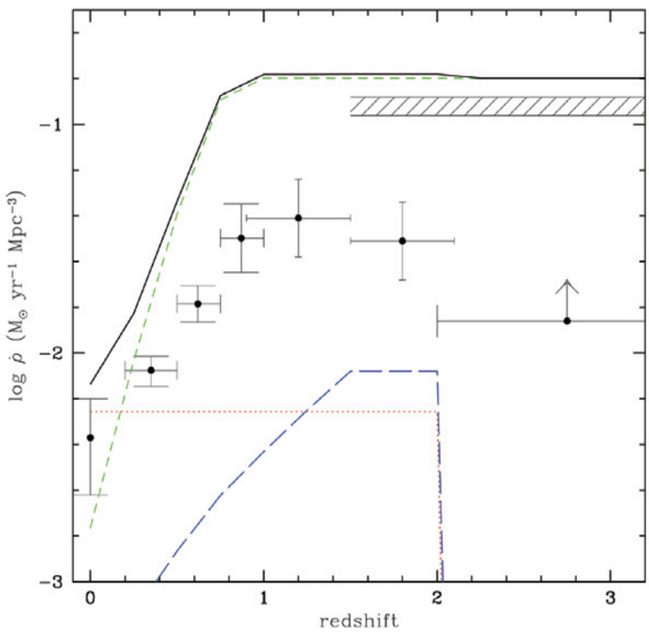


Figure 10: Evolution of the comoving SFR density for the IR-selected population based on our model of IR evolution, compared with data coming from optical observations. Dotted line: quiescent non-evolving population. Short-dash line: evolving starbursts. Long dashes: type-I AGNs. The shaded horizontal region is an evaluation of the average SFR in spheroidal galaxies to reproduce the observed metal abundance in clusters.

tegrated intensity of the CIRB at the peak wavelength of 140 μm.

ESO FOLLOW-UP OF IR-SELECTED SOURCES

The faint ISO-selected sources display various distinct features compared with other optically selected galaxy populations. They are very luminous on average ($L_{bol} \geq 10^{11}$ $L_\odot$), with the bulk of their emission coming out in the far-IR, in a similar way as the IRAS-selected galaxies include the most luminous systems in the local universe. Their areal density (a few sources/square arcmin at the faintest limits detectable by ISO) is much lower than found for faint galaxies in the optical. We have investigated the characters of IR emission in galaxies between z~0.2 and 1.5 detected by ISO in the Hubble Deep Fields North and South (HDFN and HDFS) and in the CFRS 03hr fields. We have in particular exploited the mid-IR flux as a most reliable tracer of star-formation. This study made use in particular of the near-infrared ISAAC and optical FORS spectrographs on VLT for a representative and unbiased subsample of 21 objects selected in HDFS (Franceschini et al. 2003).

Fairly intense redshifted Hα+[NII] emission is detected by ISAAC in virtually all the observed sources. The comparison with the Hβ, Hγ and [OII] line emissions observed with FORS2 (see Figs. 6 and 7), as well as the analysis of the spectral energy distributions of these sources, indicate typically high extinction values between 1.5 and almost 3 magnitudes in V, much larger than found for local normal spirals. The intrinsic (de-reddened) Hα flux then comes out to be strong in these objects. The SFR values estimated from the Hα measurements are fairly consistent with those based on the IR bolometric flux, if care is taken to appropriately correct the former for the large dust extinction. However, the latter is very difficult to assess based on slit spectroscopy: sensitive Integral Field IR spectrographs, like SPIFFI and SINFONI on VLT, will be needed to measure it more reliably. Typical values of SFR turn out to be ~10 – 300 $M_{\odot}$/yr for the IR-selected galaxies.

The analysis of VLT spectra show that distant LIRGs detected by ISO have solar or higher metallicities, revealing metallic and Balmer absorption lines combined with intense emission lines (Fig. 7), indicating a particularly complex star formation history.

Figure 8 shows the spectral energy distribution of the ISO-selected HDFS source S40 and its HST WFPC-2 I-band image. This object has been identified as a ULIRG at z=1.27, showing very strong Hα emission and mid-IR excess. Its optical SED has been fitted through a spectrophotometric synthesis code (dot-dashed line), while the mid-IR flux has been reproduced with an M82 template (thick red line).

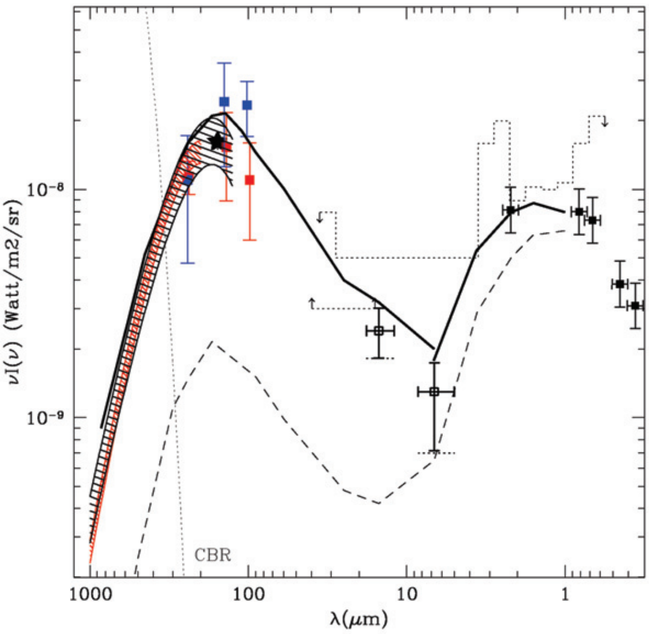


Figure 11: The Cosmic Infrared Background spectrum compared with estimates of the integrated optical light of faint galaxies in the HDF. The star marks the expected contribution of faint ISOCAM sources by Elbaz et al. (2002). The two mid-IR points are the resolved fraction of the CIRB by the deep ISO surveys IGTES (see Franceschini et al. 2001 for more details).

Details on another ISO galaxy in the HDFS, source S27, can be found in an ESO 2000 Press Release by Rigopoulou et al.; observed with the ISAAC mid-resolution spectrograph, it turned out to be one of the most massive galaxies known, with a mass of M≈10^{12} $M_{\odot}$.

We have looked for the evidence of the presence of Active Galactic Nuclei, as possibly responsible for the enhanced IR luminosities, by looking at the broadness of the Balmer lines, the low- to high-ionization line ratios, the HST morphologies, the slopes of the mid-IR spectra, and the ratio of the radio to IR fluxes. Clear evidence for nuclear activity has been found in 2 objects out of 21, while for two other objects the presence of AGN contributions is suspected. This AGN fraction is consistent with that estimated by Fadda et al. (2002) by combining deep mid-IR ISOCAM and Chandra and XMM-Newton X-ray observations in HDFN and the Lockman Hole: (17 ± 7)% of the mid-IR

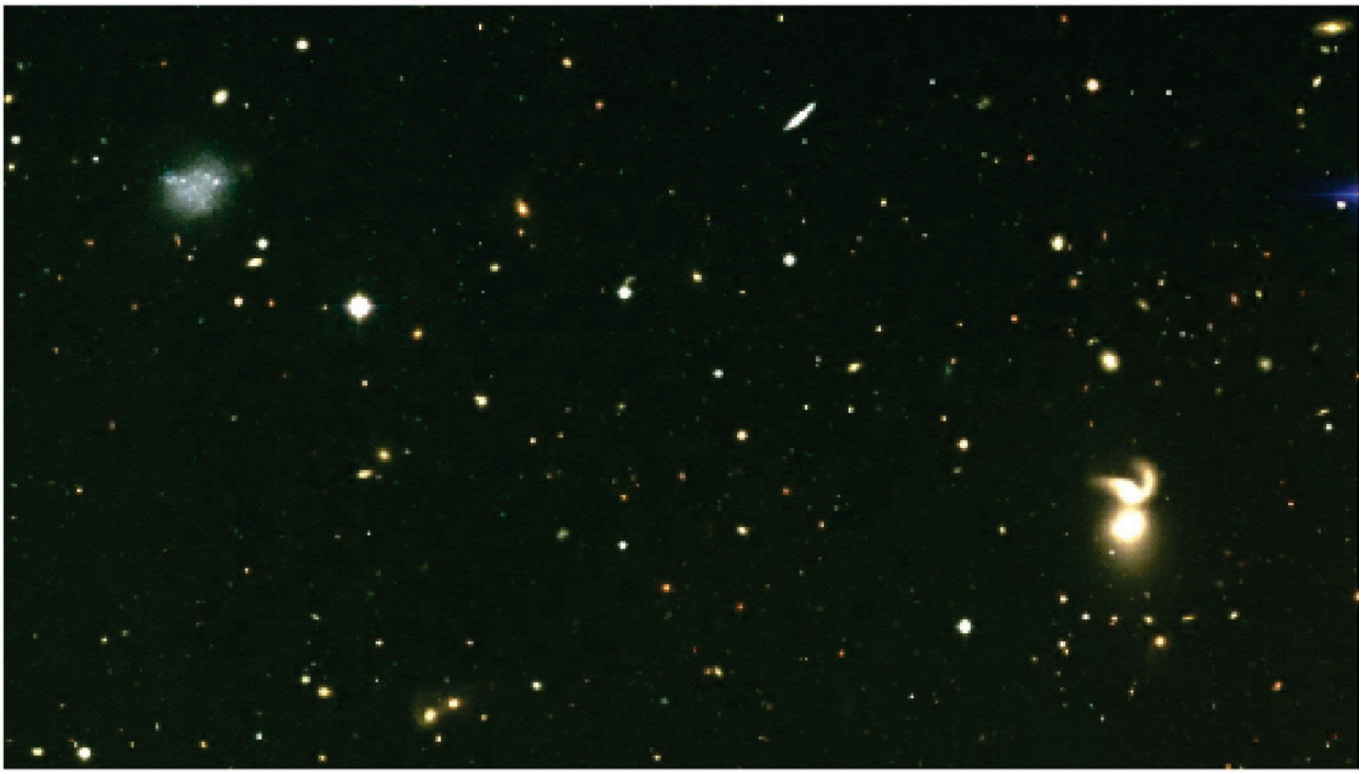


Figure 12: Combined BVR image of a 8×5 arcmin region in the ELAIS S1 region from the ESIS survey (Berta et al. 2003, in preparation). In the spirit of "Legacy Projects", all these data will have short proprietary periods and will become available to the community soon after the data reduction is completed.

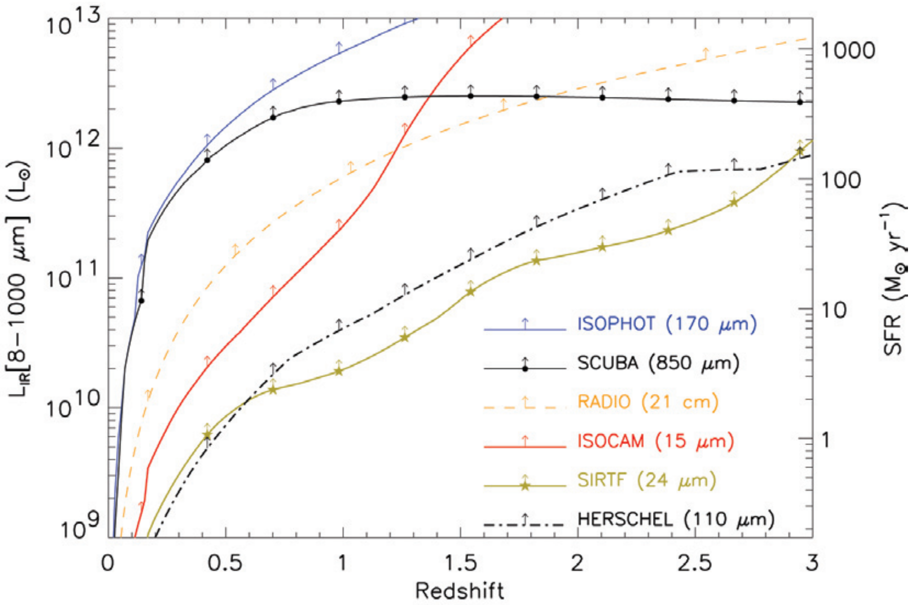


Figure 13: *IR luminosity (left axis) and star formation rate (right axis) as a function of redshift corresponding to the 5-σ sensitivity (S) limits at different wavelengths: ISOCAM (λ = 15 μm, S = 0.1 mJy), VLA (λ = 21 cm, S = 40 μJy), ISOPHOT (λ = 170 μm, confusion limit S = 120 mJy), SCUBA (λ = 850 μm, confusion limit S = 2 mJy), the MIPS camera on board SIRTF (λ= 24 μm, S = 22 μJy) and HERSCHEL-PACS (λ = 110 μm, S = 5.1 mJy). [Figure taken from Elbaz and Cesarsky 2003]*

sources are found to be AGNs. We estimate that the contribution of AGNs to the total extragalactic mid-IR background is of this same order.

To complement the dynamical mass estimates for faint IR galaxies based on ISAAC spectroscopy, we have estimated the stellar mass M by fitting the optical/near-IR photometric data with a detailed spectrophotometric model combining stellar populations with different ages and extinction (dot-dash line in Fig. 8). This analysis shows that the faint IR sources with fluxes S_{15} > 100 μJy are hosted by massive galaxies (M ≈ 10^{11} $M_\odot$). We have then estimated the timescale for the formation of stars in these galaxies as the ratio t_{SF} between the stellar mass M and the observed rate of SF. By these means t_{SF} has been found to span a very wide range of values between 0.1 and 10 Gyrs or more (see Fig. 9). When compared with the typical starburst duration (~10^8 yrs), this implies that the ongoing event of star formation can typically generate only a fraction of the stellar content in these galaxies, many of such repeated episodes during a protracted SF history being required for the whole galactic build-up. A trend towards a reduced level of star-formation activity in galaxies at decreasing redshifts is also apparent in the data (Fig. 9a). In summary, the 15 μm selection appears to emphasize sites of enhanced star formation inside massive galaxies, which are typically the brightest members of galaxy groups. These sources probably trace evolutionary phases, involving strong dynamical interactions and mergers, bringing to the formation of massive current-day galaxies.

The faint 15 μm selected galaxies in context

While ISO surveys do not allow sampling the optically-hidden SF at z>1.3 (emissions by small dust grains and PAH molecules are redshifted outside the ISO filters), constraints on higher-z sources come from ground-based sub-millimeter surveys with SCUBA and MAMBO on the JCMT and IRAM telescopes. Figure 10 shows an evolutionary model for the SFR density as a function of redshift based on ISO and SCUBA surveys. The contribution of IR-selected sources to the SFR significantly exceeds those based on optically selected sources. However the fast evolution inferred from the IR observations should level off at z>1, to allow consistency with the observed z-distributions for faint ISOCAM sources and with the observed CIRB spectrum (see Fig. 11).

As suggested by several authors (e.g. Lilly et al. 1999; see also Franceschini et al. 1994), the similar properties (bolometric luminosities, SEDs) between the SCUBA high-z population and local ultra-luminous IR galaxies argues in favour of the idea that these represent the long-sought “primeval galaxies”, those in particular leading to the local massive elliptical and S0 galaxies. The less extreme starbursts discovered by ISO at lower z may instead be related to the assembly of lower mass spheroids and spheroidal components in spirals.

The currently available data suggest an evolutionary scheme where star formation in galaxies has proceeded in two phases: a quiescent one taking place during most of the Hubble time, slowly building stars with standard IMF from the regular flow of gas in rotationally supported disks, and a transient actively starbursting phase, recurrently triggered by galaxy mergers and interactions. During the merger, violent relaxation likely redistributes old stars, producing de Vaucouleur profiles typical of galaxy spheroids. During this active phase, Franceschini et al. (2001) argue that young stars may be generated with a top-heavy IMF to allow consistency between the energy in the CIRB and optical backgrounds and the local stellar mass density in galaxies.

The SIRTF Legacy Surveys and the ESO Large Program ESIS

Relevant developments in this field are soon expected by the NASA Great Observatory SIRTF, with a primary mirror larger than ISO (85 vs. 60 cm) and superior detector assemblies. As part of its policy for the exploitation of the mission, NASA has promoted a set of six observing campaigns, the so-called SIRTF Legacy Program. Two of these are dedicated to deep cosmological surveys, the Great Observatory Origins Deep Survey (GOODS, a survey of 300 sq.arcmin in the HFD-North and Chandra Deep Field South) and the SIRTF Wide-Area In-

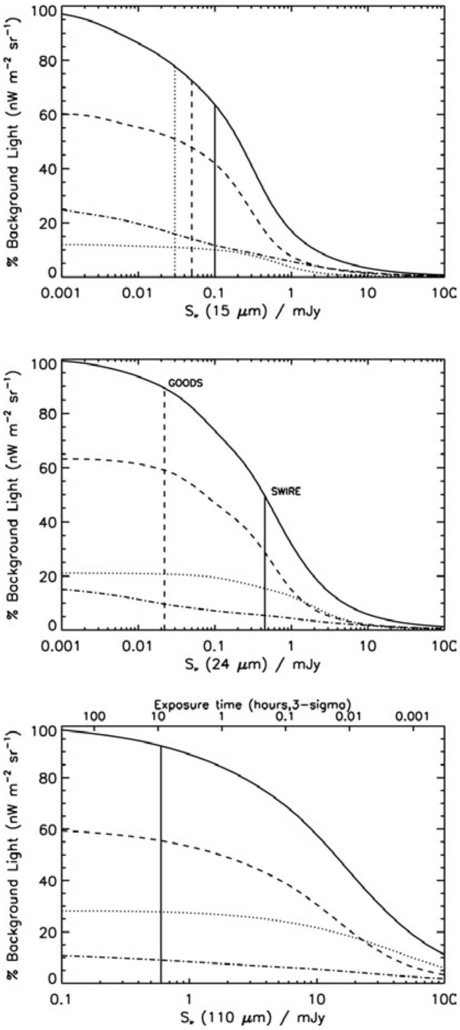


Figure 14: *The fraction of the extragalactic background light resolved into individual galaxies at 15, 24 and 110 μm by ISOCAM, SIRTF and HERSCHEL respectively down to the corresponding confusion limits. In the middle panel the two cosmological Legacy Programmes of SIRTF, GOODS and SWIRE, are indicated.*

frared Extragalactic (SWIRE) survey. The latter will observe a sky region of 67 sq.degrees split into 7 contiguous areas, 4 in the Northern and 3 in the Southern sky. In a formal letter issued by the Director General in 2001, ESO has committed itself to systematic optical/near-IR observing campaigns to complement the SIRTF observations, one of which (the Large Program ESO/SIRTF Imaging Survey, ESIS, P. I. A. Franceschini) has already started. The combined BVR image in Fig. 12 illustrates the imaging quality that we achieved with the ESO/MPG 2.2 m WFI in the area ELAIS-S1 (Berta et al. 2003, in preparation). The final ESIS survey will cover ~5.5 sq.deg. in BVR with WFI and in I with VIMOS, while a smaller overlapping area is being observed in Z. SIRTF SWIRE will observe this field in four mid-IR channels at 3.6, 4.5, 5.6, 8 μm and three far-IR channels at 24, 70 and 160 μm. Particularly the 24 μm channel promises to break the z~1.3 limit imposed on the ISO surveys.

Prospects for the long-term

Deep IR and sub-millimeter surveys have already demonstrated that a large fraction of present-day stars must have formed during one, and more probably several, dusty starburst events. As we have illustrated, the physics ruling IR emission of galaxies is extremely complex, and based on current observations we can just claim to have identified a new important area for cosmology. New instrumentation, both in space and on ground, will be needed to characterize these astrophysical and cosmogonical processes. Particularly the direct detection of the FIR emission is still missing and a detailed description of the evolution at $z > 1$ is missing. Also the origin of the infrared emission of these strong starbursts remains an issue: are they triggered by galaxy interactions? Are these interactions major mergers, minor mergers or simply tidal effets?

The challenge for future long wavelength surveys will be:

1. to increase the redshift range in which dusty starbursts can be detected in order to determine whether the cosmic density of star formation in the universe flattens, increases or decreases above redshift one;

2. to quantify the level of clustering of dusty starbursts;

3. to detect directly the far infrared emission of distant galaxies;

4. to study their morphology not only in the optical but also in the dust emission regime, thereby precisely quantifying the role of interactions in triggering these starbursts.

All these issues will be addressed in a complementary way by forthcoming infrared instrumentation, i.e. SIRTF, Herschel, ALMA and the JWST. SIRTF, and in particular the Legacy Program GOODS (Great Observatories Origins Deep Survey, Dickinson and Giavalisco 2001) will detect luminous IR galaxies up to z ~ 3 by pushing the IRAC and MIPS 24 μm instruments to their limits (see Fig. 13).

With its large field of view of 70 square degrees, the Legacy Program SWIRE (SIRTF Wide-area Infrared Extragalactic Survey), will quantify the level of clustering of these galaxies up to z~ 1. Later on, Herschel will allow for the first time the direct detection of the FIR luminosity of the distant dusty starbursts responsible for the CIRB (see Fig. 14), while SIRTF will be limited by confusion in this wavelength range. Large surveys with Herschel will also permit us to study the connection between the build up of large-scale structures and galaxy formation and evolution (see Elbaz and Cesarsky 2003). Finally, the James Webb Space Telescope (JWST) and the Atacama Large Millimeter Array (ALMA) will allow us for the first time to study the morphology of these galaxies directly in the infrared regime where they emit the bulk of their light.

Given the spatial complexity and optical faintness of these cosmic sources, an essential complement to the long-wavelength observations will be offered by the high-sensitivity integral-field spectrographs on VLT in the optical (GIRAFFE, VIMOS) and near-IR (SPIFFI, SINFONI). During the next decade our understanding of galaxy formation and evolution will see a decisive improvement.

References

Aussel, H., Cesarsky, C., Elbaz, D., Starck, J.L., 1999, *A&A*, 342, 313

Dickinson, M., Giavalisco, M., *ESO/UCM Meeting on the Mass of Galaxies at Low and High Redshift*, Springer-Verlag, ESO Astrophysics Symposia, R. Bender & A. Renzini, Eds, 2001, p. 324

Elbaz, D., Cesarsky, C., 2003, *Science*, 300-5617, 270

Elbaz, D., Cesarsky, C., Chanial, P., Aussel, H., Franceschini, A., Fadda, D. & Chary, R., 2002, *A&A*, 384, 848

Fadda, D., Flores, H., Hasinger, G., Franceschini, A., Altieri, B., Cesarsky, C. J., Elbaz, D., Ferrando, Ph., 2002, *A&A*, 383, 838

Franceschini, A., Mazzei, P., De Zotti, G., Danese, L., 1994, *ApJ*, 427, 140

Franceschini, A., Aussel, H., Cesarsky, C., Elbaz, D., Fadda, D., 2001, *A&A*, 378, 1

Franceschini, A., Berta, S., Rigopoulou, D., et al., 2003, *A&A*, 403, 501

Genzel, R., & Cesarsky, C.J.: 2000, *ARAA* 38, 761

Hauser, M.G., Arendt, R.G., Kelsall, T., et al., 1998, *ApJ*, 508, 25

Kessler, M.F., Steinz, J.A., Anderegg M.E., Clavel J., Drechsel G., et al., 1996, *A&A*, 315, 27

Lilly, S.J., Eales, S.A., Gear, W., et al., 1999, *ApJ*, 518, 641.

Puget, J.-L., Abergel, A., Bernard, J.-P., Boulanger, F., Burton, W. B., Desert, F.-X., Hartmann, D., 1996, *A&A* 308, L5

Rodighiero G., Lari C., Franceschini A., Gregnanin A., Fadda D., 2003, *MNRAS*, 343, 1155