SAGACE

Stellar Mass And GAlaxy CEnsus in the first two billion years of the Universe

ANR young researcher - Fundamental research	
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1 SUMMARY OF THE PROPOSAL

One of the primary frontiers in extragalactic astronomy is observing the build-up of the galaxies in the first 1–2 billion years of the universe. The first galaxies could appear 200 million years after the Big-Bang. These primordial systems will grow and they could end up into huge galaxies composed of several hundred billions of stars, such as our own Milky Way. We propose to measure at which rate the galaxies assembled their stellar populations in their infancy, i.e. by catching massive galaxies when the Universe was only 500 million years old. Then, we will follow their evolution over the following two billion years.

Numerous physical mechanisms play a crucial role in shaping the galaxy mass assembly, but their relative importance is unknown at $z>3$. For instance, some simulations show that the star formation could be boosted in the early Universe by dark matter filaments penetrating directly the galaxy, i.e. a process called "cold accretion". But the observational evidences of such mechanism are tiny. Major mergers could contribute in building the massive galaxies, but we do not know how often such events could occur at $z>3$. We also do not know when the supernovae and Active Galaxy Nuclei activities started to have a significant impact in regulating/quenching the star formation.

We need observables to constrain the relative importance of these physical processes and bring together a robust scenario of galaxy formation. We will produce statistical analysis extracted from the largest samples of massive galaxies at the current frontier in extra-galactic astronomy.

We propose to make measurements of unparalleled precision of the buildup of stellar mass and the star-formation rate at $3<z<6$ and produce the largest census of the massive galaxies at $6<z<8$. This project is nowadays possible thanks to the ongoing program SPLASH of 1700h with the IRAC camera onboard of the Spitzer telescope, the only instrument that probes the rest frame optical fluxes needed to measure the galaxy stellar masses at $z>3$. We will cover a large field of 2 deg2 to get tens of rare and massive galaxies at z ~ 7-8, a mass-selected sample of more than a hundred thousand of galaxies at $z>3$ and exquisite data to secure their distances (Hyper Suprime-Cam in optical and UltraVISTA in near-infrared). By comparing our results with semi-analytical and phenomenological models, we will quantify the relative importance of the different physical processes powering galaxy formation. Our work will provide a solid legacy for the forthcoming deep extra-galactic international surveys in which French laboratories are deeply involved, and a treasure of targets for the JWST and ELT to proceed later with detailed observations.

2 CONTEXT AND SCIENTIFIC OBJECTIVES

2.1 Scientific context

Galaxy growth within the dark matter structures

While baryonic matter represents just 5% of the mass-energy content in the Universe, it is the only component with a known nature. Our project aims to understand the journey of these baryons from the primordial Universe to their assembly into stars and galaxies.

The first galaxies could appear at redshift $z>10\text{-}20$ in dark matter halos more massive than $10^6\ M_\odot$ (Bromm et al. 2013). Then, dark matter (DM) halos grow along cosmic time under the action of gravity and the baryonic gas trapped into these DM halos fuel the star formation. These primordial systems will grow and they could end up into huge galaxies composed of several hundred billions of stars, as our own Milky Way.

However, only a small fraction of the gas is converted into stellar populations. Numerous physical processes break partially the link between the halo mass and the stellar mass, as shown in Figure 1. The complex interplay between numerous physical processes explains why our understanding of the galaxy formation and evolution is still incomplete. In this dynamic cycle of the baryons, several major aspects need to be considered:

The feeding of the galaxy in cold gas: new gas is continuously inflowing in the halo because of the hierarchical growth of the DM structures (see Figure 1). But only a small fraction of gas can cool radiatively and penetrate the galaxy (e.g. White et Rees 1978). Recently, a new mode of gas accretion has been identified in simulations: DM filaments could penetrate deeply the central galaxies and feed the star formation more efficiently in cold gas (Dekel et al. 2009). This “cold accretion” mode could be dominant at z>2, boosting the star formation in the early Universe. But observational evidences of cold accretion are still limited (e.g. Cresci et al. 2009).

The star formation efficiency: The internal conditions within a galaxy impact their efficiency in converting gas into stars. A large fraction of disk galaxies appear clumpy at z~2 (e.g. Foester-Screiber et al. 2009) and instabilities within these clumpy galaxies could enhance the star formation efficiency (e.g. Bournaud et al. 2007). These instabilities could result from a high gas fraction, which depends on the considered epoch. While such process is probably not relevant in the local Universe, we do not know its impact at z>3.

AGN and SN feedbacks: Energetic feedbacks from supernovae (SN) and active central nucleus (AGN) regulate the star formation activity. As shown in Figure 1, AGN feedback is believed to suppress the star formation in the most massive halos (Bower et al. 2006, Croton et al. 2006, Cattaneo et al. 2006) while SN feedback slow down star formation in low mass halos (e.g. Torrey et al. 2013). The energy released by AGN and SN could also create gas outflows reaching hundreds of $M_\odot$/yr (e.g. Lehnert et al. 1996). While such outflows are observed in several powerful star forming galaxies, the outflow rate depends on the galaxy and halo properties (e.g. Martin et al. 2012). In the primordial Universe, feedback of extremely massive POPIII stars could have a devastating impact on the formation of the first stellar populations (Bromm et al. 2011) and delayed the formation of the first galaxies. Massive black holes are already identified at z>6 showing that they could also impact the galaxy formation in the primordial Universe. Therefore, even in the primordial Universe, feedback could play a dominant role.

Merger between galaxies: mergers and interactions between galaxies will modify the star formation history by creating stochastic burst of star formation, and eject some material within the intergalactic medium. Mergers will modify the mass distribution of the galaxies along time, by merging several galaxies into one. The major merger rate is barely measured out to z~2 (e.g. Lopez-Sanjuan et al., 2013) and could depends on the mass as shown at z<1 (de Ravel et al. 2009). The tight relation between Star Formation Rate (SFR) and stellar mass (0.2-0.3 dex), well established at z<2-3 (Elbaz et al. 2007, Daddi et al. 2007) put a constrain on the maximum amount of stochasticity in the star formation history induced by major mergers (e.g. Rodiguiero et al. 2009). But we do not know how tight is the mass-SFR relation at z>3.

Objectives of this project: provide observational constrains at 3<z<7-8

Detailed analysis of small galaxy samples are crucial to demonstrate the existence of the physical processes described in the previous paragraph. However, statistical analysis extracted from large and representative galaxy samples are necessary to characterize their relative importance along cosmic time.

Our objective is to produce such statistical analysis in the first 2 billion years of the Universe. We plan to deliver simple and fundamental measurements, used since decades, which are powerful observables to characterize the relative importance of the various physical processes governing the star formation:

- The SFR Density (SFRD, $M_\odot/\mathrm{yr}/\mathrm{Mpc}^3$) which characterizes the stellar mass formed per year in a given comoving volume;
- The specific SFR (sSFR defined as SFR/M_{star}) characterize the growth rate of a galaxy, i.e. the stellar mass instantaneously created over the one cumulated along cosmic time;
- The Galaxy Stellar Mass Function (hereafter ***GSMF***) quantifies the distribution of the galaxies according to their stellar mass in a given comoving volume.

At z<3, we reach now a high degree of convergence between the various measurements of the SFR Density evolution (e.g. Cucciati et al. 2011, Karim et al. 2011, Gruppioni et al. 2013, Madau 2014), the ***GSMF*** (e.g. Fontana et al. 2006, Perez-Gonzalez et al. 2008, Ilbert et al. 2010 & 2013, Tomzac et al. 2014), or the sSFR (e.g. Elbaz et al. 2011, Rodiguiero et al. 2009).

At z>3-4, these fundamental statistical measurements are still inexistent or possibly affected by large systematic uncertainties. Our statistical knowledge of the galaxy population at z>3 is often limited to the UV luminosity function. Large and representative samples of massive galaxies at z>3 are still missing because they require the combination of: *1)* deep observations to reach z>3 galaxies; *2)* large fields to get a significant number of rare and massive galaxies; *3)* imaging data able to map the optical rest-frame light emitted by the $z>3$ galaxies; *4)* and finally exquisite data to secure their distances. We propose to make possible this new step. **We propose to measure at which rate the galaxies assembled their stellar populations in their infancy, i.e. by catching massive galaxies when the Universe was only 500 million years old. Then, we will follow their evolution over the following two billion years.** This project is nowadays possible thanks to the ongoing program SPLASH of 1700h with the IRAC camera onboard of the Spitzer telescope, the only instrument that probes the rest frame optical fluxes needed to measure the galaxy stellar masses at $z>3$.

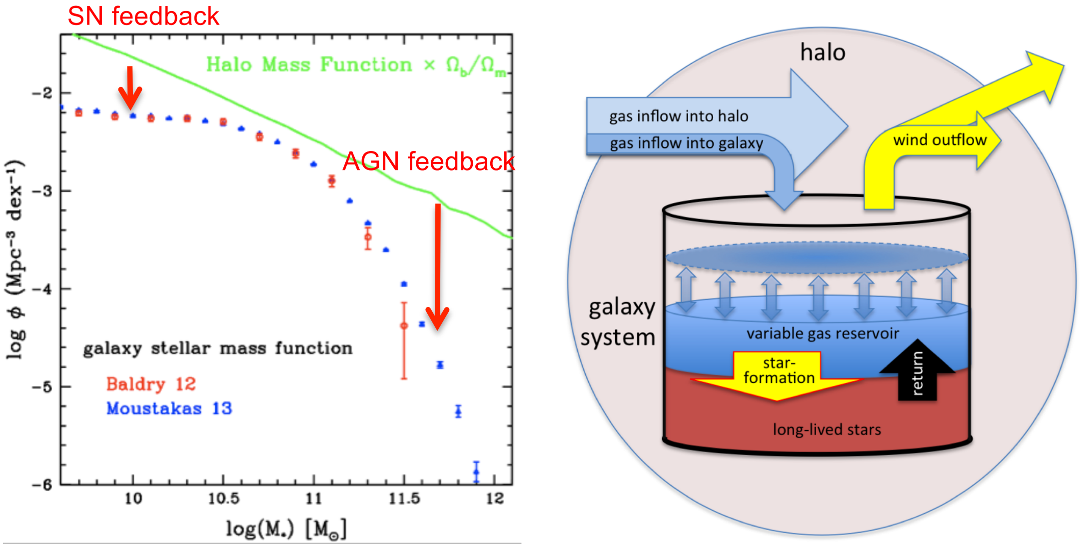

Figure 1 Left: comparison of the local DM halo mass function and the galaxy stellar mass function (hereafter GSMF) showing that the star formation needs to be completely suppressed in the most massive halos and reduced in low mass halos. AGN and supernovae feedbacks are possible candidates. Right: Simplified galaxy+halo system as seen by Lilly et al. (2013) showing the gas inflow coming from the hierarchical growth of the DM structure, the gas which is converted into old stars by star formation processes, and gas outflows created by SN or AGN. We want to constrain the relative importance of all these processes at $z>3$.

2.2 Observational context: the SPLASH survey of the COSMOS field

The SPLASH survey

The only instrument able to trace the rest-frame optical at $z>3$ is the IRAC camera on board of the Spitzer telescope which is sensitive at $\lambda>3.5\mu m$. Such coverage is required to perform a stellar mass census at $z>3$. We are building a unique dataset with a new deep IRAC coverage of the 2 deg^2 COSMOS field. SPLASH (PI: P. Capak, cycles 9 and 10), is an **ongoing survey of 1700h with IRAC to cover the full COSMOS field** (Scoville et al. 2007). This imaging survey is carried on in two bands: 3.6μm and 4.5μm. 3/4 of the data have been already acquired on the COSMOS field (see Figure 2). The observations should be ending in August/September 2014. The survey will reach a magnitude limit of 0.25μJy - four times deeper than the current IRAC coverage on the COSMOS field (Sanders et al. 2007, Ilbert et al. 2010) - which is crucial to study $z>6$ sources. We will cover a contiguous field of 2 deg^2 (45 times larger than the GOODS field) which is crucial to reveal rare massive sources at high redshift and perform exquisite statistical analysis.

This field has a treasure of ancillary dataset. In addition to SPLASH, we have extremely deep NIR data with UltraVISTA in four bands YJHK, matching the depth of the IRAC SPLASH survey. The second year of UltraVISTA DR2 data are already reduced and are available, reaching a depth of ~25 in Y,J,H,K. These data will become deeper and deeper along our project, with the end of the survey planned in 2017. New visible data from Hyper suprime-cam (HSC) at Subaru will be available at the project start, imaging to ~27-28 mag across the 0.4−1.0μm range over the full field. We already have deep observations (mag~26-27) in more than >25 bands from Subaru and CFHT (Capak et al. 2007, Ilbert et al. 2009) and 1.4 deg^2 of coverage with ACS. We have an intensive spectroscopic follow-up with the best MOS spectrograph including VIMOS@VLT, DEIMOS@Keck, MOSFIRE@Keck, FMOS@Subaru (e.g. Lilly et al. 2009, Silverman et al. 2014). In particular, the VUDS project already obtained 3000 spectra of galaxies at z>3 in the COSMOS field (Le Fèvre et al. 2014).

Finally, we were also awarded of additional 1200h to cover a second field (the SXDS field) with IRAC in cycle 10 with SPLASH. By combining the UDS, HSC and SPLASH data, we will extend our study later in order to double the size of our sample and reduce the cosmic variance. We will study the SXDS field as a second priority.

Observational Challenge: obtain accurate distances and stellar masses at z>3

Our main challenge is to measure the distances and stellar masses for sources with a really faint emission in optical. Indeed, massive galaxies at z>6 should not be detected in i-band because of the absorption of the UV light by the Inter Galactic Medium. We estimate that almost 70% of the galaxies at z>3 will have an optical counterpart fainter than i>26 in the SPLASH survey. **Even if most of the sources are not detected in optical, we will deliver photometric redshifts with a precision of 4%, by having four deep NIR bands with the UltraVISTA data (YJHK), two deep bands in IRAC (3.6 and 4.5 μm) and deep upper-limits in optical with HSC.** In order to reach such precision, we will need:

1. a clean estimate of the upper-limits in the deepest optical bands (HSC). We need to estimate the upper-limits locally and develop new methods to deal with upper-limits in a robust way in the photo-z;
2. an accurate estimate of the galaxy colors despite the PSF variation between UltraVISTA (0.7") and IRAC (1.6"). While several softwares are developed for such task (EM, TFIT, Convphot), extensive work is required to provide satisfactory results;
3. a specific work on the galaxy templates, IGM and emission lines to deliver accurate photo-z at z>3.

Finally, we will compute the physical parameters for the full sample, including the galaxies at z>6. We will need a careful analysis of the uncertainties which propagate into the physical parameters (e.g. the photo-z uncertainties). We will also extensively test possible systematic uncertainties introduced by underlying assumptions on the stellar population synthesis models used to obtain the stellar masses.

Based on simulations, we can build a mass-selected sample at z>3 with no equivalent: we expect to get >100000 galaxies at z>3 with a mass limit at $>10^9 M_\odot$. The total sample of one million galaxies will be of an enormous interest for the community working in observational cosmology, and therefore we organize a timely schedule to release our data (see Section 5).

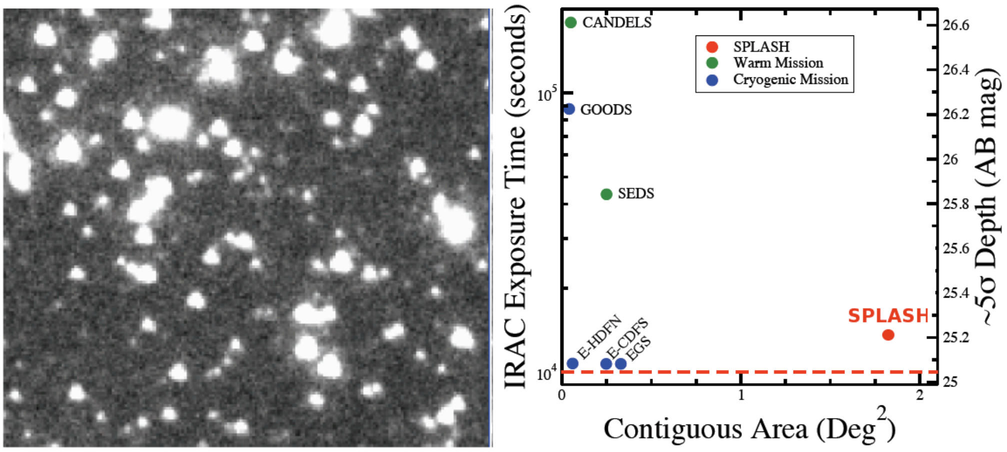

Figure 2 : 0.02% of the current SPLASH mosaic on the left (1/4 of the final integration time/px) and SPLASH versus other IRAC surveys on the right. The SPLASH survey include two fields of 2 deg^2(COSMOS and SXDS). Our project is focused on the COSMOS field which can be combined with UltraVISTA. SXDS will be considered in a second step.

2.3 Searching the most massive galaxies at z>6

An accurate census of the primordial galaxy is of key importance for improving our knowledge of the earliest phases of galaxy evolution and the process of cosmic reionization. The unique NIR sensitivity of WFC3 camera installed on HST since 2009 makes feasible the detection of z>6 galaxies. The first 450-900 million years in the Universe represents the current frontier in cosmic history (e.g. Bouwens et al. 2010). The z>6 galaxies were intensively tracked in the last 5 years and up to a thousand of candidates are now selected from WFC3 data (e.g. McLure et al. 2013). First samples of candidates at 8.5<z<10 are even extracted from the Hubble Ultra Deep Field 12 (Ellis et al. 2013). While these data are extremely deep (mag~29-30 for the HUDF, mag~27 for CANDELS), their covered areas are limited to few hundred of arcmin^2 (4.5 arcmin^2 for the HUDF, 200 arcmin^2 for CANDELS). These data are extremely powerful to study the distribution of the faint star-forming galaxies, but the small covered area prevents for gathering massive and rare sources.

We need to survey much larger fields to catch the most massive galaxies (Bowler et al. 2012). The improvement of the NIR detector allow us to use ground-based facilities to cover >deg^2 fields and get the brightest and most massive sources at z>6. Such massive galaxies are extremely interesting since are probably the first systems to be formed. In less than 700 million years (between z=20 and z=6), these massive galaxies could have already formed several billions of stars. By catching the most massive galaxies at z>6, we can:

1. study at which maximum rate the gas is converted into stellar populations in these early stages of the Universe;
2. characterize when the first galaxies appeared based on the age of their stellar populations;
3. quantify how the massive sources contribute in completing the reionization of the neutral intergalactic hydrogen, providing more detailed information on how reionization proceeded.

Several massive candidates have been published at z>6 (e.g. Mobasher et al. 2005 with a $6\times10^{11} M_\odot$ source at z~6.5 or Capak et al. 2011), but later on, each of them has been confirmed to be dusty interlopers at z~2-3 (Dunlop et al. 2007, Dunlop et al. 2013). Bowler et al. (2012, 2014) already use the UltraVISTA data to select ~30 galaxies at z>6. We will pursue this effort using data which will be almost 1 mag deeper over the full wavelength range: the final SPLASH data, deeper UltraVISTA data and new HSC data. **One main objective is to extract hundreds of massive candidates at z>6-7 with a robust photometric redshift estimated with 6 bands on the COSMOS field.** Based on the semi-analytical simulation of Wang et al. (2008), we could expect one hundred z>6 galaxies and ten z>7 galaxies more massive than $10^{10} M_\odot$ (see Figure 3). This sample will be by far the largest sample of massive galaxies at z>6. We will organize a spectroscopic follow up for our best candidates with current NIR facilities (e.g. KMOS@VLT, MOSFIRE@Keck). Since these galaxies are the brightest, they are also the easiest to follow in spectroscopy.

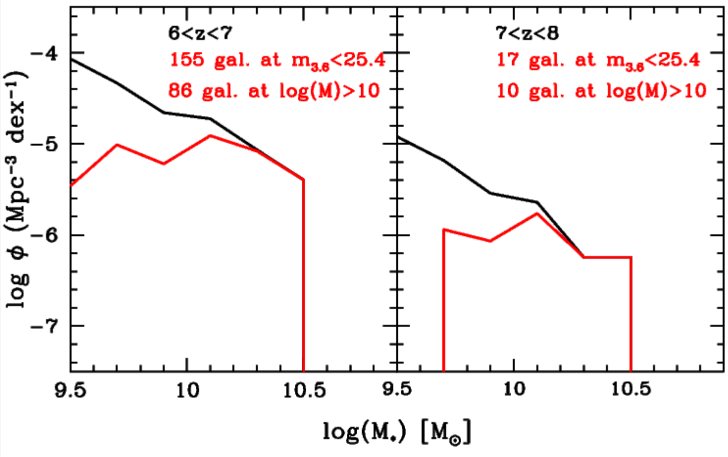

Figure 3: Stellar mass distribution of 6<z<7 and 7<z<8 galaxies, as predicted by the Wang et al. (2008) semi-analytical model. Black lines correspond to the full simulation while the red correspond to a cut at 3.6μm>0.25μm expected for the SPLASH survey.

2.4 Characterizing the star formation history from z=3 to z=6

Our second objective is to characterize the Star Formation History (herafter SFH) in the first 2 billion years. We will measure the stellar mass created instantaneously as well as the stellar mass created along the galaxy history, which constrains the relative importance of the various physical processes governing the star formation.

Using direct tracers of the SFH

The most direct way to characterize the SFH is to measure the instantaneous SFR for a large and representative sample of galaxies. For a given galaxy, the total light emitted by the most massive stars with a short lifetime can be converted into instantaneous SFR with standard relations (e.g. Kennicutt 1998). The most common tracers of the SFR are: *1)* the emission lines, in particular Hα; *2)* the UV light directly emitted by the massive stars; *3)* the far-IR light corresponding to the UV light absorbed and reemitted by dust; *4)* the radio data corresponding to the synchrotron emission by SN.

The various tracers show that the SFRD is decreasing steadily since the last 7-10 billion years, i.e. from z=2 to z=0 (see Figure 4), as well as the sSFR (see Figure 5). At 2<z<4, the situation is already confused as shown in Figure 4. We observe systematic differences reaching a factor 2 between the SFRD derived from the UV (Cucciati et al. 2012) and from the far-IR (Gruppioni et al. 2013).

The situation is probably worse at z>4, despite the apparent convergence seen in Figure 4. Indeed, all the z>4 studies rely on the ultraviolet (UV) light to trace the SFR (e.g. Bouwens et al. 2009). But correcting the UV light from dust absorption is extremely challenging and uncertain, in particular for massive star-forming systems (Heinis et al. 2014). The impact of dust extinction could be lower at z>4, as shown in Cucciati et al (2010) and Bouwens et al. (2009). Still, extreme star-forming galaxies with most of their light emitted in IR are discovered at z>5 (e.g. Capak et al. 2011), showing a population of powerful IR galaxies already present in the young Universe. One possibility is to rely on the SED fitting to estimate the SFR. Such estimate is extremely sensitive to the assumed attenuation curve, metallicity, etc. For instance, the sSFR values could increase by a factor 2 when emission lines are taken into account in the SED fitting procedure at z>4 (e.g. Stark et al. 2009 and 2013 in Figure 5, see Schaerer et al. 2009, De Barros et al. 2014).

Despite the difficulty of relying on the UV-optical tracers of the SFR at z>3, we still propose to measure the SFRD and sSFR evolution with these standard methods, since our dataset presents several key advantages. We still have the advantage of covering the largest field ever used for this kind of studies at z>4, we will rely on accurate and well tested photo-z using large VIMOS/VUDS (Le Fèvre et al. 2014) and Keck/DEIMOS/MOSFIRE (Capak et al., in prep) spectroscopic samples. We will also have a large λ rest-frame baseline from the UV to the rest-frame optical to constrain the SED fitting and derive the dust correction.

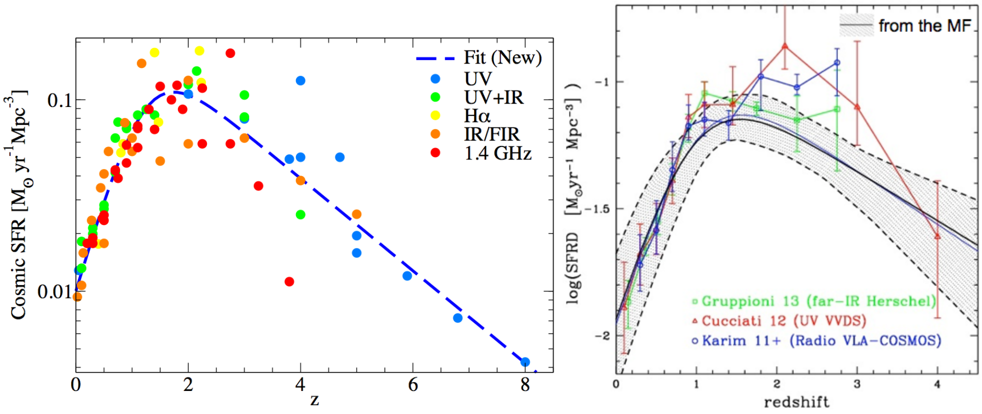

Figure 4 : Left: *direct measurements of the SFRD compiled by Behroozi et al. (2013). At z>4, the SFRD rely on the UV light, which could be affected by large systematic uncertainties due to the dust correction.* Right: *The black solid line and dashed area correspond to the star formation history inferred from the UltraVISTA mass density, a method that we propose to extend out to z~6. The other points show determinations from the literature including SFRD derived from the UV and IR luminosity functions from Cucciati et al. (2012) and Gruppioni et al. (2013) (brown triangles and green squares, respectively) and stacking in radio radio from Karim et al. (2011).*

<u>The galaxy stellar mass census as a complementary probe</u>

Since direct tracers of the SFR are associated to large systematic uncertainties at z>3, we propose a complementary method based on the galaxy stellar mass census to study the SFH. The stellar mass of a galaxy corresponds to its star formation history integrated over time. By comparing the amount of stellar mass accumulated at different epochs, we can directly reconstruct the star formation history (Wilkins et al. 2008, Ilbert et al. 2013) and the sSFR evolution (Ilbert et al. 2013 and Figure 4).

The advantage is that the stellar masses are measured in a different and complementary way. While the stellar masses are also derived from SED fitting, their estimate rely on the optical rest-frame light which is less affected by assumptions on the dust attenuation. We do not dispose yet of any accurate census of the ***GSMF*** at z>4. Caputi et al. (2010) produced a measurement at 4<z<5 but the uncertainties are quite large. Lee et al. produce a ***GSMF*** at 4<z<6 but limited to the extremely blue population, selected in UV.

Thanks to the new IRAC data that we are currently gathering on the COSMOS field, we are in a position to construct several complete mass-selected samples with >100000 galaxies at z>3 and to extend our work out to z~6. Using the same method as Ilbert et al. (2013), we will provide a complementary and independent view of the global star formation history and of the evolution of the galaxy growth rate in the first 2 billion years. We expect to nail down the uncertainties on the SFRD and sSFR below 25% at 3<z<6, which are currently dominated by much larger systematic uncertainties on how to correct the UV light into SFRD.

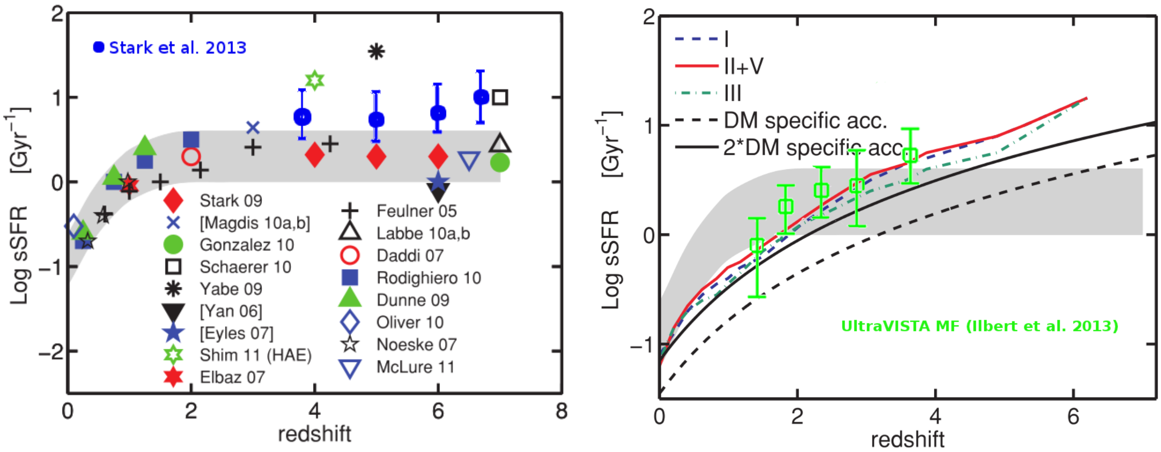

*Figure 5: **Left:** Compilation of galaxy growth rate (sSFR=SFR/M$_{star}$) from Weinmann et al. (2011). The grey area corresponds to the most likely sSFR positions according to direct measurements published before 2011. We added the updated values of Stark et al. (2103). Above z>3, there is a large dispersion in the sSFR, explained by the difficulty to measure the SFR using UV light. **Right:** SAM model by Weinman et al. (2011), which is not able to reproduce the plateau in sSFR. The green points are our own estimates from Ilbert et al. (2013) based on the UltraVISTA stellar mass census, which do not exhibit any plateau. We propose to extend this measurement out to z~6 with this new and complementary method to be applied for the first time at z>3-4.*

2.5 Isolate the dominant physical mechanisms which regulate the star formation in the first 2 billion years

We will measure the star formation history in the first 2 billion years of galaxy evolution. Such measure will provide new constrains on the dominant physical mechanisms which regulate the mass assembly. Indeed, many physical mechanisms impact the star formation, and their relative importance is unknown at such early cosmic times: e.g. the accretion mode of the gas into the galaxy (e.g. Dekel et al. 2009), the impact of mergers, the impact of supernovae and AGN feedback. We will provide state-of-art statistical measurements with the largest and most robust mass-selected samples at z>3.

Comparisons with models will allow us to quantify the relative importance of different physical processes which power galaxy formation.

This galaxy growth rate is deeply related to the growth rate of the underlying DM structures (e.g. Bouché et al. 2010, Lilly et al. 2013). The growth rate of the dark matter halos is governed by the content and the initial conditions of the Universe, well measured by numerous experiments since decades and independent probes (SN, Cosmic Microwave Background, cluster counts, or the Baryonic Acoustic Oscillations). Based on these estimates of the cosmological parameters, large N-body simulations predict the evolution of dark matter halos masses and their spatial distribution. Numerous methods exist to populate the DM with galaxies. We can reasonably assume that the baryonic gas is proportional to the DM halo mass. **The expected properties of the galaxies will depend on the physical processes introduced to convert this baryonic gas into stellar populations. By comparing these expected properties with observed galaxy samples, we bring some insight on our knowledge of these physical processes.**

In practice, we will first use extremely simple analytical recipes to interpret the evolutions of our observables (mass density, SFRD, sSFR). Recent papers have even provide recipes to characterize the evolution specific DM halo accretion rate (M'_{DM}/M_{DM}), with relations as simple as $0.036(M_{DM}/10^{12}M_{\odot})^{0.15}(1+z)^{2.35}$ (e.g. Neistein & Dekel 2008). Following Bouché et al. (2010), or Lilly et al. (2013), we can parametrize the fraction of gas penetrating the galaxy, the star formation efficiency, the outflow rate, or the considered halo mass in which the star formation is possible. These simple models, as illustrated in Figure 1, are easy to develop and we will use such tools to interpret our results. Such tools are really flexible and we will be able to change basic recipes to interpret our results.

In a second step, we will use Semi Analytical Models (SAM). In these more complex models, analytical recipes are implemented to reproduce the numerous physical processes participating to the galaxy building. We will work with the prediction of GALICS (Hatton et al. 2003). We can easily extract the galaxy SFR and masses from this model. We will also be in a position to include different recipes in this semi-analytical model and adjust some relevant parameters to test their impact on our observables. As shown in Figure 1, the comparison of the DM halo mass function and the ***GSMF*** is a fundamental constraint for AGN feedback and SN feedback theories. We want to provide the same diagnostic at z>3. For instance, such comparison will tell us if quenching was already in action at high redshift and if the impact of feedback implemented in the SAM reproduces the same trends. We will also look in detail the evolution of the sSFR predicted with the SAMs models. Indeed, the sSFR evolution is closely related to the specific DM increase rate (Bouché et al. 2010, Lilly et al. 2013), which links the galaxy growth with the hierarchical growth of DM structures. Weinmann et al. (2011) underline the difficulty of having a sSFR evolution different from the specific DM growth rate even in the SAMs (see Figure 5), specially at z>3. We will investigate this problem with our new estimate of the sSFR at z>3 and modifying our own SAMs if necessary.

2.6 Synergy with other surveys

Our team participates to numerous photometric and spectroscopic surveys in the next decade. Our project is a key to prepare all these future missions and surveys.

JWST-ELT

We plan to assemble the largest sample of massive galaxies in the early Universe, with tens massive galaxies at z>6 and tens of thousands at z>3. This sample will be a treasure trove of targets for JWST and the ELT. Our institute is part of the consortium which built MIRI. We are also proposing second generation instruments for the ELT with MOS capabilities. Our project will enable us to take firmly positions in the future highly competitive high-redshift projects with JWST or the E-ELT. The COSMOS field is visible to all the 20−39m telescopes that will be operating in Hawaii and Chile by the end of the decade enabling spectroscopy to the 27-28 mag_{AB} depth. An obvious goal of our project is to identify the most interesting targets that we can follow in spectroscopy and understand in detail how the first galaxies formed.

PFS-SUMIRE

The LAM is the only europeen institute part of the PFS-SUMIRE project. This spectrograph should be installed on the Subaru telescope in 2017. This MOS with 2300 fibers covers the 380nm<λ<1260nm wavelength range. The survey contains a color selected survey of 1<z<2 galaxies over 16 deg^2 to J≈23.4 and a ultra-deep part to observe galaxies at 3<z<6-7 (Takada et al. 2014). The targets will be selected from HSC imaging. The COSMOS and SXDS fields – our two SPLASH fields - are the two ultra-deep fields from HSC. Therefore, all the work that we are doing in our project to build the catalogues, measure the photo-z, define the color-color selection of high redshift source will benefit to the PFS project.

EUCLID

Euclid is a mission to map the geometry of the Universe. The core science of EUCLID is to study the nature of the dark matter and dark energy. We will need a billion of photometric redshifts and 2 millions of spectroscopic redshifts over 15000 deg^2. Our project will help in defining the EUCLID mission since:

- We propose to improve the photo-z technique, in particular when only upper-limits are available in optical. Indeed, EUCLID rely on the photo-z to perform the weak lensing tomographic analysis and we need to work with an optical multi-color coverage which is shallow (DES).
- COSMOS is a calibration field for Euclid.
- Our new photo-z catalogue will be used to generate simulated catalogue and test the spectroscopic data reduction pipleline.

We are all members of the EUCLID consortium and we share numerous responsabilities at various levels (O. Le Fèvre is part of the EUCLID board, and most of us are responsible of WPs in the different OUs and Science Working Groups).

3 SCIENTIFIC AND TECHNICAL PROGRAMME, PROJECT ORGANISATION

3.1 Project structure

O. Ilbert will coordinate this ANR “young researcher” project. The participants to the project work at the *Laboratoire d'Astrophysique de Marseille* (their contributions are listed in Table 1). However, our project is inserted in a more general context - the COSMOS survey - a collaboration of more than 100 scientists (Europe, US, Japon). Therefore, we need to coordinate our work with this collaboration and we include two external collaborators in our project: P. Capak, the lead of the SPLASH & COSMOS teams and H.J. McCracken, the responsible of the UltraVISTA data reduction. O. Ilbert will organize regular meetings and telecons, including these two external close collaborators. We also participate to the annual COSMOS/SPLASH team meetings to insure a good interaction with the full collaboration. Several participants of the ANR project are members of the COSMOS survey and are strongly involved since many years in the building of this dataset.

We split our project in several Work Packages, as shown in Figure 6. We can divide the WPs in two groups. The objective of the first group (WP 1 to 5) is the create the galaxy sample: we will generate the multi-color photometric catalogue in WPs 1 & 2 and we will use this catalogue to estimate the galaxy distances and the physical parameters in WPs 3, 4, 5. We estimate that after 1.5yr, we will be in a position to start the scientific analysis of our sample. The second group of WPs corresponds to the scientific exploitation. Based on the sample prepared during the first 1.5yr, we will study primordial galaxies, the galaxy star formation history of the first 2 billions years of the Universe, and we will interpret our results using flexible models. We detail each WP in section 3.2.

Name	Position[1]	Laboratory	#PM[2] 2014	#PM 2015	#PM 2016	#PM 2017
Ilbert O.	AA	LAM	4	9	9	5
Tresse L.	A	LAM	1	2	5	4
Arnouts S.	CR	LAM	1	4	4	3
Cattaneo A.	MCF	LAM	1	2	5	4
Le Fèvre O.	A	LAM	0.5	1.5	2	2
Cuby J.G.	A	LAM	0	1	2	2
	postdoc ANR	LAM	0	12	12	0
Capak P. (3)	DR	Caltech				
McCracken H.J. (3)	AA	IAP				

1. [1] (PR, DR, MCF, CR, PhD, PD=postdoc,…)

[2] #PM = number of person.months = number of months spent for each year on the project

[3] External collaborators, not counted in this project

Table 1: People involved in the project and their contributions. The postdoc financed by the ANR contributes at 25% of the total.

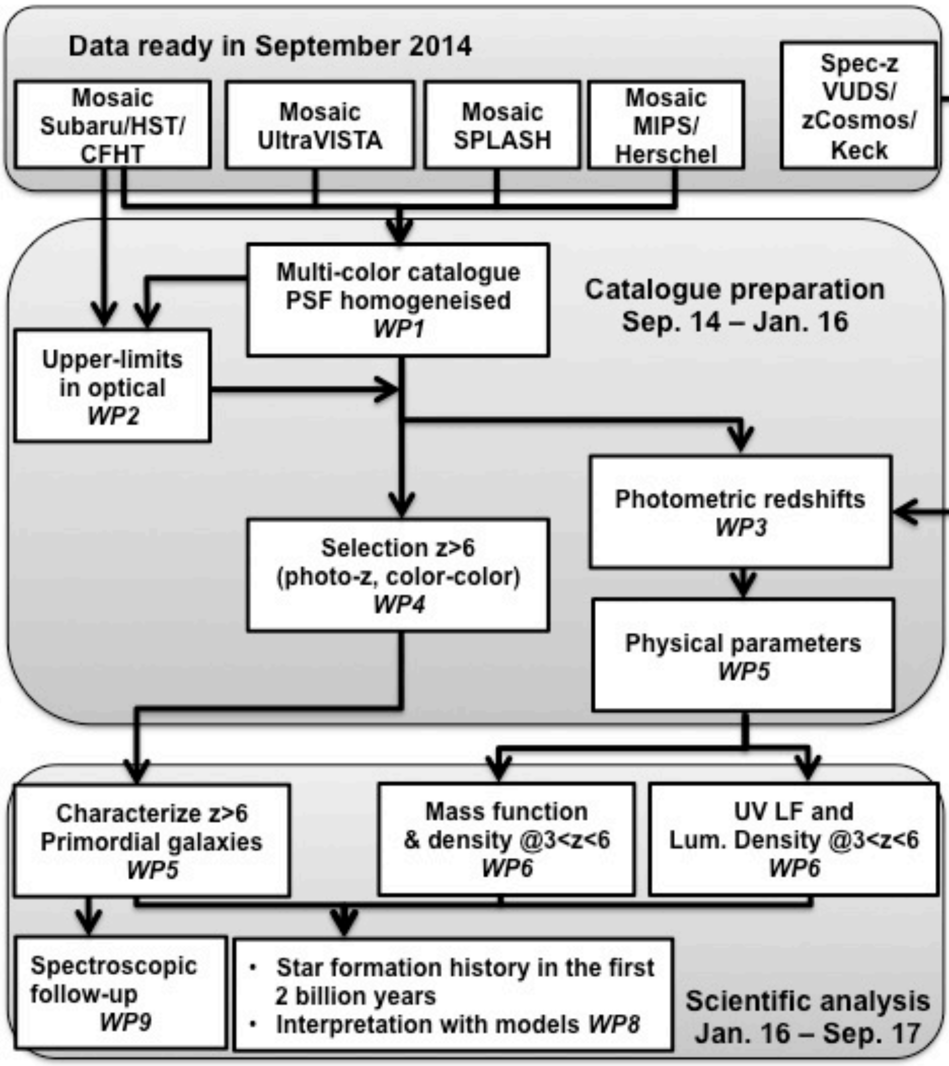

Figure 6: *Project organization in WPs.*

We have in total 9 WPs. We balanced the WP responsibilities according to the participation in month of each member to the project (table1). The choice of the WP leader is naturally driven by his/her expertize, as described in section 3.3. Ideally, the ANR postdoctoral researcher would have a background in the study of the high-z Universe (z>6). With such profile, the postdoc could take in charge three linked WPs (2, 4, 7) and have an important and coherent role in our project.

We list below the various WPs, their responsible, as well as the task schedule (see Figure 7). More details are given in 3.2.

- ***WP1 "Multicolor catalogue", lead: O. Ilbert.*** This task could start in September 2014. We aim to finish this work in 6-8 months, which would be spring 2015.
- ***WP2 "Upper-limits", lead: postdoc.*** This work would requires 3-4 months, and should start when the postdoc arrives at LAM. In order to not delayed the photo-z work, the postdoc should start as soon as possible.
- ***WP3 "Photometric redshifts", lead: O. Ilbert***. Some changes in our method/code are necessary to better deal with upper limits and get 3% photo-z at z>3. Since this work is based on the multi-color catalogue, we could start in March 2015. The work will take 6-8 months.
- ***WP4 "Identify z>6 galaxies", lead: postdoc.*** We expect the work to start immediatly after the work on the upper-limits WP2 (May 2015) and to extend over 6-8 months.
- ***WP5 "Physical parameters", lead: S. Arnouts.***This work requires a first preliminary photometric redshift catalogue, i.e. 3 months after the beginning of WP3. Therefore, we will start this work in May 2015. We expect a first robust version after six months (end of 2015) and we need six additional months to estimate systematic uncertainties.
- ***WP6 "Scientific exploitation: the star formation history", lead: O. Ilbert.*** This work can start when the first catalogue including the physical parameters will become available, i.e. after 6 months of WP5. We will start Nov. 2015 and the work extends out to the end of our project.
- ***WP7 "Scientific exploitation: analysis of the z>6 sources", lead: postdoc.*** The work will start after the first selection of the z>6 sources, i.e. beginning of 2016. Therefore, the postdoc will have one year to exploit scientifically its z>6 sample.
- ***WP8 "Scientific exploitation: comparison with theory", lead: A. Cattaneo.*** This work can be started as soon as the first statistical measurements are ready, i.e. beginning of 2016.
- ***WP9 "spectroscopic follow-up of the massive sources at z>6", lead: L. Tresse.*** We can start to prepare the spectroscopic follow-up as soon as the selection of the z>6 candidates is ready, beginning of 2016.

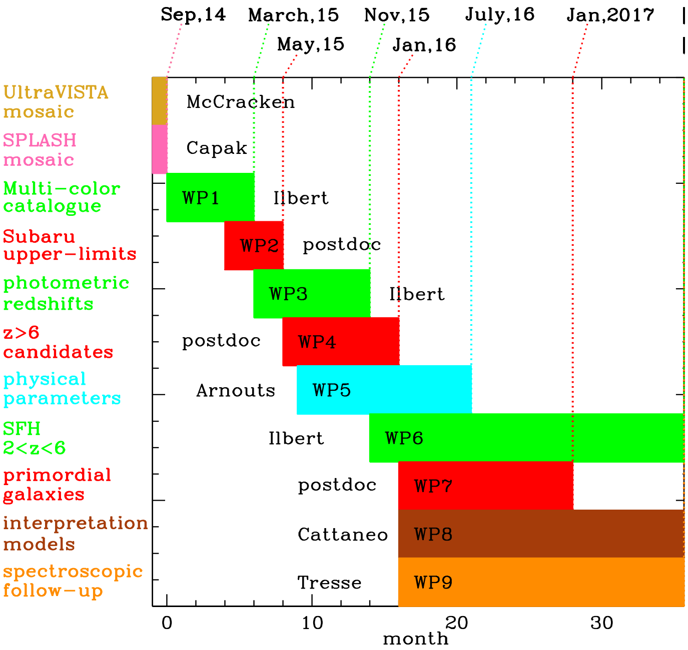

Figure 7: Task schedule and responsibilities.

3.2 Detailed description of the work packages

TASK WP1 Multi-color catalogue for SPLASH

Responsible: O. Ilbert

Participants: S. Arnouts and several external collaborators (H. McCracken and P. Capak)

Objective: create a multi-color catalogue with >35 bands, despite the PSF variations between the several dataset.

Deliverable: a multi-color catalogue including CFHT/Subaru/VISTA/Spitzer/Herschel data with >2 millions of sources.

Method:
The final IRAC mosaics at 3.6μm and 4.5μm of the SPLASH survey should be ready at the ANR start (August-September 2014, end of Spitzer cycle 9 and 10). Our external collaborator P. Capak in Caltech (PI of SPLASH) will create the IRAC mosaics. In the meantime, H.J. McCracken at IAP leads the effort with the TERAPIX team to reduce the UltraVISTA data and provides us deeper and deeper mosaics (currently scheduled to finish in 2017). The second year of UltraVISTA DR2 data are already available, reaching a depth of ~25 in Y,J,H,K. More than >25 bands from Subaru and CFHT as deep as mag~26 are already available (Capak et al. 2007, Ilbert et al. 2009). The new visible data from Hyper suprime-cam at Subaru will be available at the project start. Some HSC data are already taken by our external collaborator, G. Hasinger at IfA, for the COSMOS team. Deeper HSC data will be taken by the HSC collaboration and should be available to the SPLASH team.

Our first task will be to create the multi-color catalogue in more than 35 filters with an accurate photometry, despite the PSF variations between the various dataset. We will homogenize all optical and NIR data to a common PSF, using the "PSFex" software developed by E. Bertin at IAP. This method can reliably deal with seeing variations of around 20% (Bertin 2010), which will ensure the measurement of flux densities within the same physical aperture across all wavebands and therefore most precise photometric redshifts. This method has already been partially applied to the first year of UltraVISTA data (Ilbert et al. 2013) and this effort is still ongoing with UltraVISTA DR2 data by our external collaborator H.J. McCracken. Depending on the progresses before the beginning of the ANR, such effort could be minimum for our ANR project.

We will combine all the ground based data (Subaru and CFHT) with the infrared data taken with the Spitzer and Herschel telescopes, in particular the IRAC/SPLASH data which are central for our project. We cannot degrade the optical/NIR images to the PSF of IR images (between 6"-35" for Herschel data). We developed a specific code (Called "EM") to perform the photometry of a low resolution image using a high resolution image as a prior. This code was developed by S. Arnouts and B. Milliard for GALEX data. This code uses a high resolution image as a prior (in this case, the UltraVISTA images) to perform the photometry in a low resolution image (here the mid and far IR images). This method extracts a K-band postage-stamp image of each UltraVISTA source and convolves it with the appropriate kernel to match the quality of the low-resolution image (in the first case the SPLASH IRAC data). The rescaling of the convolved stamp to match the observed low resolution image at the source position corresponds the source flux. We have already tested this method with the current IRAC images. Because of the depth of the new IRAC SPLASH data, this method will be absolutely necessary. We will apply the same procedure at longer wavelength (MIPS/Spitzer and Herschel data). We will generate a band-merged catalogue from the UV to the far IR.

Timescale: All the mosaics will be available in September 2014 (HSC, UltraVISTA, SPLASH in all bands). The depth of the VISTA coverage will also improves with time but we can already work with the current data. Therefore, we will start our work at the beginning of our ANR project. We aim to finish this work in 8 months, which would be spring 2015.

TASK WP2 Upper-limit measurement

Responsible: Postdoc

Participants: O. Ilbert, S. Arnouts

Objective: Estimate the upper-limits locally in our deepest optical images for all the sources not detected in optical.

Method: Our scientific objective is to study the Universe at z>3 and to select the most massive galaxies at z>6. Therefore, we need to secure the distance measurements for these populations. With the absorption of the IGM at $\lambda_{\text{rest-frame}} < 1216$Å, the UV rest-frame light is heavily absorbed. The galaxies at z> 3,4,5,6 will be undected in the bands bluer than B, g, r and i. The source detection in WP1 is based on the χ^2 image combining z^+, Y, J, H and K band. Thanks to this detection in NIR, we will not miss the high redshift sources, but they will be undetected in the bluest optical bands. Even if they are undetected, we can still use this information. Figure 8 shows two sources at z=4.15 and z=5.56 not detected in blue Subaru bands. By using the information on the upper-limits, we can eliminate the low redshift solutions.

Therefore, we absolutely need to keep the information that the source has been undetected in the optical bands. The detection limit will depend on the depth of the visible image at the location of the detected source, which is not kept when we construct the multi-color catalogue. The goal of this WP is to measure the detection limit at the position of the detected sources, as well as the uncertainty linked to the detection limit. We need to insure that the non-detection is not due to a default in the image (e,g. saturation, fake detection, etc). Given the small fraction of z>3-4 sources compared to the z~1 sources, any problem in associating detection limits could create a large contamination of bright sources in our z>3 sample. Therefore, such work is crucial for the selection of the z>6 sources but also for our full scientific project at z>3.

We will keep only the most sensitive images to perform this work. The Subaru data are already extremely deep. We already work with the u* (CFHT megacam), $BVRi^+z^+$ with a 5σ sensitivity at mag_{AB} ~ 26.5, 26.6, 26.8, 26.2, 26 respectively (Capak et al. 2007, Ilbert et al. 2009, Salvato et al. 2009). Currently, we do not use a local estimate of the upper-limits, but only a global approximated value. The HSC mosaic will be available at the beginning of our project and should be one magnitude deeper. These data are crucial to secure the high redshift candidates.

Timescale: The postdoc will be mainly in charge of the z>6 analysis. Since this task is crucial for the high-z analysis, the postdoc will be in charge of this WP. This work would requires 3-4 months, and should start when the postdoc arrives at LAM.

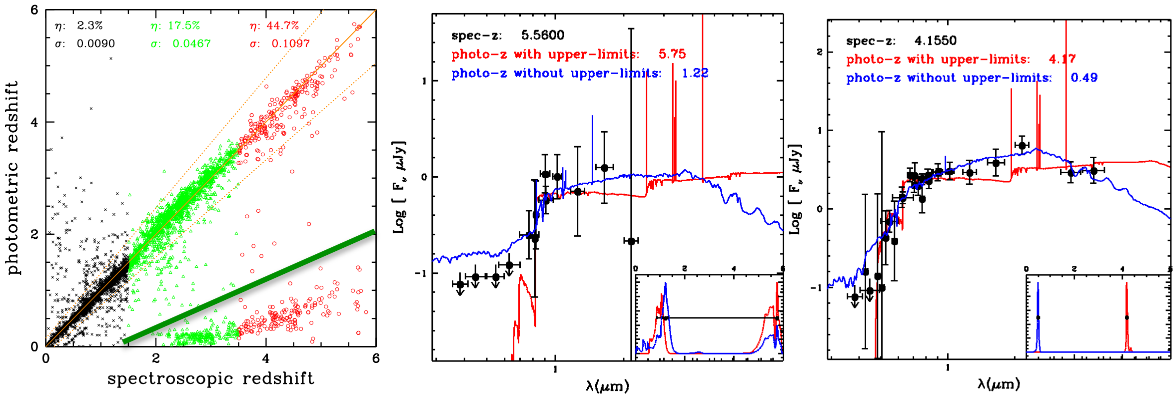

Figure 8: Left: *Photometric versus spectroscopic redshifts for an update of the i*-selected catalogue on COSMOS from Ilbert et al. (2009). The catastrophic failures below the green line is partially explained by the lack of NIR constrain for some sources and an approximate treatment of the upper-limits.* Middle and right panels: *Two examples of best fit templates and PDF. The cases with and without taking into account the upper-limits are shown in red and blue respectively. The upper-limits are imposed very approximatively with the same values over the full field. In this project, we will provide a clean local estimate of the upper-limits with 1 mag deeper HSC data.*

TASK WP3 Photometric redshifts

Responsible: O. Ilbert

Participants: S. Arnouts, postdoc

Objective: 3-5% accurate photometric redshifts at z>3 for hundred thousands of galaxies for the UltraVISTA and SPLASH surveys, along with associated uncertainties.

Deliverable: a photometric redshift catalogue and their Probability Distribution Functions (PDF) for all sources detected in WP1 (not limited to z>3). We expect one publication in a peer-reviewed journal describing this new catalogue.

Method: Photometric redshifts (photo-z) provide a distance estimate based on broad and medium band photometry. Whilst less accurate than a spectroscopic redshift, photo-z can be estimated for *all* galaxies in a catalogue. We will compute photometric redshifts using the "Le Phare" code (Arnouts & Ilbert, www.cfht.hawaii.edu/~arnouts/LEPHARE). This code is based on a SED fitting procedure and photo-z are "trained" using spectroscopic redshifts. Hildelbrandt et al. (2010) demonstrated that Le Phare has "best in class" performance among many photo-z codes. We have already produced a photometric redshift catalogue for the COSMOS catalogue including 30 bands (Ilbert et al. 2009) and an update of this catalogue based on UltraVISTA DR1 release (Ilbert et al. 2013). *YJHK* data from UltraVISTA allow us to reach a redshift accuracy of 3% at 1.5<z<3 (see Figure 8).

Our challenge is to produce accurate photometric redshifts at 3<z<6+. As show in Figure 8, the quality of the current photometric redshifts is much lower at z>3, with 40% of galaxies being at a wrong redshift (|photo-z - spec-z| > 0.15*(1+spec-z)). The challenge will be to reach also a 3% accuracy in the photo-z estimate at z>3 with less than 10% of catastrophic failures. This will become possible in our project since we get:

1. deeper NIR data (UltraVISTA and SPLASH) and optical data (HSC), allowing to sample the SED around the Lyman break for 3<z<6 galaxies for a larger fraction of sources and secure the position of the Lyman break. Having a local estimate of the upper-limits to be applied with HSC in WP2 is crucial in the redshift range.
2. a sample of 3000 spectroscopic redshifts at 2.5<z<7 from the VUDS survey (PI: O. Le Fèvre) is currently built, which will be crucial to test and to improve high-z photometric redshifts. Moreover, MOSFIRE spectra are currently acquired by the COSMOS team at z>4 (P. Capak).
3. We will improve our photo-z by a work on the method: we will try to varies the IGM (Thomas et al. in prep), include a better treatment of the emission line prescription (Schearer et al. 2009), take into account the significance of the upper-limits, improve our SED templates if necessary.

Timescale: This will require at least six months full time work to obtain the optimum templates and configuration to avoid biases and reach the expected photo-z accuracy of 3% at z>3 with less than 10% of catastrophic failures. Some changes in our method/code are necessary to better deal with upper limits. We will need to use the multi-color catalogue, which should be available en March 2015.

TASK WP4 Identify the z>6 galaxies

Responsible: Postdoc

Participants: J.G. Cuby, O. Le Fèvre, O. Ilbert

Objective: define several robust criteria to select the z>6 galaxies and create a catalogue of well checked candidates.

Deliverable: positions of the z>6 candidates and the confidence level in their selection.

Method: Our field allows us to combine several criteria to select the z>6 galaxies:

- *Color-color selection.* This method is extensively used in numerous surveys, in particular in the last few years using the new HST/WFC3 data (e.g. Bouwens et al. 2009). Such standard criteria have already been applied with the UlraVISTA data (Capak et al. 2007, Bowler et al.

2012). However, we will use new data 1 magnitude deeper in IRAC with SPLASH, in NIR with new UltraVISTA releases, and in visible with HSC. Therefore, we will have more candidates at z>6 and a better constraint on their SEDs. We will be able to compare our color-color criteria to the ones commonly applied with HST/WFC3 on the CANDELS 0.2 deg^2 field in COSMOS.

- *Photometric redshifts*. This will be a natural extension of our WP3. We will combine all the multi-color data available. For massive galaxies at z>6, we expect to have at least a detection in UltraVISTA and SPLASH. Our best candidates will have measurements in 4-6 bands (YJHK and 3.6, 4.5 μm) and we will be able to use the clean work done on upper-limits in WP2. We will use our code Le Phare (Arnouts & Ilbert) and we will modify the IGM recipes and SED templates if necessary. We already have recipes to include emission lines into the templates (Ilbert et al. 2009) and we could modify them if necessary following Schearer et al. (2009). Our code could run with brown dwarfs and QSO templates which will help to discriminate possible contamination. Finally, we will obtain a PDF associated to our photo-z which will allows us to select the most secure z>6 candidates and attribute them a confidence level.
- *Narrow bands.* The COSMOS field has been observed in 3 narrow bands (2 from Subaru at 711 and 816 nm, and one with UltraVISTA at 1180 nm). It allows us to select high redshift candidates at z~5, z~6 and z~8).

By combining these different selection criteria, we will be able to insure a large number of candidates at z>6.

Timescale: We expect the work to start immediatly after the work on the upper-limits WP2 (May 2015) and to extend over 6-8 months. Since we want to keep the z>6 work as a common task, the postdoc should be in charge of this WP.

TASK WP5 Physical parameters

Responsible: S. Arnouts

Participants: O. Ilbert, postdoc

Objective: derive the physical parameters for the full photo-z catalogue, test their accuracy and possible systematic uncertainties for the z>3 populations.

Deliverable: physical parameters (at least stellar masses, SFR, sSFR, absolute magnitudes) for all the sources of the catalogue and associated uncertainties.

Method:
Galaxy physical parameters can be estimated with Le Phare starting from model spectra generated using stellar population synthesis models. The stellar mass estimate is driven by older stars emission at rest-frame optical / NIR wavelengths while the most recent (<10^7 yr) star formation is traced in the rest frame UV. At z>4, the Y,J,H and Ks-band from UltraVISTA will probe the rest-frame blue or UV, and the ultra-deep IRAC data from SPLASH will probe the optical rest-frame. As shown in Figure 9, we can not estimate the stellar masses at 4<z<6+ with the current data and only the combination of UltraVISTA and SPLASH will allow us to derive stellar masses with an accuracy better than 0.2 dex at such redshift.

We also need to estimate the SFR and sSFR. It implies to correct the UV light from the dust extinction. Such work is extremely challenging at z>3. Most of the works are using the UV slope but such correction could be strongly hampered by a degeneracy between the age and the metallicity (Heinis et al. 2014). Arnouts et al. (2013) developed a new method called *NRK* using M_{NUV}, M_R, M_K to estimate the SFR, corrected for dust extinction. However, this method is calibrated only at z<1.2. We are currently calibrating this method at z>2 using stacked Herschel data on the COSMOS field (Le Floc'h, Arnouts et al., in preparation). We will be able to measure the absolute magnitudes and rely on the *NRK* method calibrated at z>3 to derive the SFR.

Our main challenge will be to estimate accurate systematic errors for our physical parameters. We need to test the impact of our assumptions in deriving physical parameters by generating a large grid of possible models with different underlying physical properties. For instance, we will test several star formation histories (e.g. exponentially decreasing, increasing, random star formation bursts). We will test numerous extinction laws (e.g. Calzetti 2000, Prevot et al. 1984, Charlot & Fall 2001) and several stellar population synthesis codes (e.g. Fioc et al. 1997, Bruzual & Charlot 2003, Maraston 2005). We will use different IMF, some evolving with time. We will compute the physical parameters for all these different assumptions in order to assess possible systematic uncertainties.

Timescale: We need to wait at least 3 months to have a preliminary photo-z catalogue with robust distance measurement at z>3. Therefore, we will start this work in July-August 2015, and we will have a first robust version after six month (end of 2015). Then, we count 6 other months to quantify for possible systematic uncertainties. However, these last six months will not prevent us to work on the other scientific analysis.

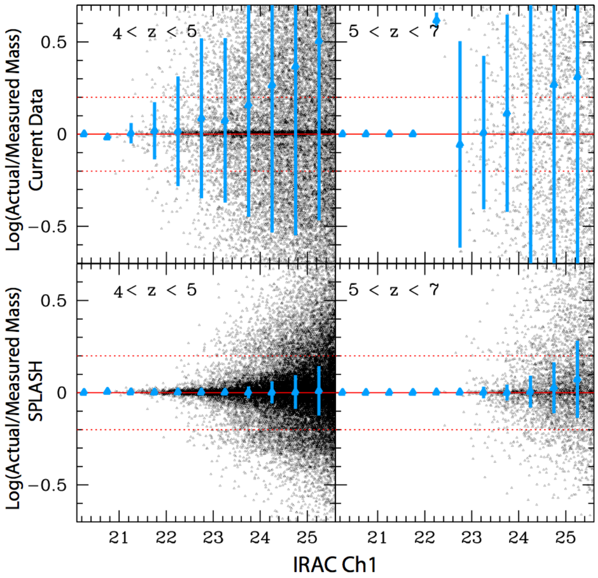

Figure 9 : a simulation showing the importance of the SPLASH/IRAC data in measuring accurate stellar masses. The two top panels show the recovered masses using current COSMOS data and the bottom panels represent the quality on the stellar mass we should get with our project.

TASK WP6 Scientific exploitation: the star formation history

Responsibles: O. Ilbert, L. Tresse, S. Arnouts
Participants: the full team

Objective: derive the star formation history in the first 2 billion years of galaxy evolution.

Deliverable: We expect several publications in peer-reviewed journals from this WP on the SFH at 3<z<6, using direct tracers of the SFR and complementary methods based on the mass function.

Method:
In this project, we propose to use two complementary methods to study the star formation history. One method is based on direct tracers of the SFR. We will also apply a complementary approach, by looking at the stellar mass growth.

The SFH from direct SFR tracers: L. Tresse and S. Arnouts will estimate the UV luminosity function at 3<z<6. While this method is sensitive to dust extinction, such estimate of the SFRD is the main method used at z>3 with direct SFR tracers. The UV rest-frame light is directly probed by the UltraVISTA data and photo-z are measured in WP2. The quality of the photo-z will be tested for star-forming galaxies using the VUDS survey (>2000 spec-z at z>3, Le Fèvre et al. 2014). We already developed our tool ALF (Ilbert, Tresse et al. 2005) to estimate the mass/luminosity function. We will integrate the UV LF to get the SFRD. A second step in this work will be to correct the UV light for dust extinction which should be done in WP3 using the new method by Arnouts et al. (2013).

The SFH from the stellar mass perspective: The stellar mass of a galaxy corresponds to its star formation history integrated over time. By comparing the amount of stellar mass accumulated at different epochs, we can directly reconstruct the star formation history (Wilkins et al. 2008, Ilbert et al. 2013 and Figure 4) and the galaxy specific SFR (Ilbert et al. 2013 and Figure 5). These methods provide a complementary view of the star formation history, since they do not rely on instantaneous SFR measurements but rather on the stellar mass. We already applied these methods on the first epoch of UltraVISTA data out to z~3 in Ilbert et al. (2013). Using the SPLASH sample, we will construct several complete mass-selected samples with >100000 galaxies at z>3 and we will extend our work out to z~6. Having the photometric redshifts and the stellar masses, we can derive the comoving density of galaxies at a given stellar mass, i.e. the ***GSMF***, using our tool ALF (Ilbert et al. 2005). We will integrate the ***GSMF*** to obtain the stellar mass density, i.e. the amount of stellar population already created in the early Universe. Then, we can apply our method from Ilbert et al. (2013) to derive the SFH and sSFR. In practice, we assume a function form for the SFH with several free parameters. We integrate this SFH to predict an evolution of the mass density. Then, we fit the free parameters to match the observed mass density. The result of this method on UltraVISTA DR1 is shown with the shaded area in Figure 4, but we do not have any constrain at z>4. We will be able to bring this new constrain with our project. The evolution of the ***GSMF*** can also be used to estimate the sSFR, as we did in Ilbert et al. (2013) and as shown in Figure 5. Because of the lack of convergence on the sSFR evolution at z>3 depending on the SFR tracer, it is important to get an estimate of the sSFR based on a complementary method, as we propose.

Timescale: This work can start when the first catalogue including the physical parameters will become available. Therefore, it can start beginning of 2016, in the middle of our ANR project. L. Tresse and S. Arnouts will lead the estimate of the UV LF and dust-corrected SFR, O. Ilbert will lead the mass function part. Such extensive work will require a minimum of one year and it will extend out to the limit of our project.

TASK WP7 Scientific exploitation: analysis of the z>6 sources

Responsible: Postdoc
Participants: the full team

Objective: analyse the physical properties of z>6 sources, analyse the impact of our estimate on the primordial Universe.

Deliverable: We expect at least one publication in a peer-reviewed journal about the z>6 massive galaxy population.

Method: We will select our z>6 sources in WP4. The strength of our survey is to cover a large area to detect the rare and massive sources at z>6. Therefore, we will focus on the sources detected with IRAC. These sources will be detected at least in UltraVISTA and IRAC, with upper-limits in deep optical HSC images. Therefore, we will be able to derive physical parameters from the SED fitting on these sources. We will take a special care in trying different options for the star-formation histories, emission line contributions, or assumed SSP models. We should estimate robust UV light and stellar masses. We will be able to assess the contribution of the massive galaxies to the star formation density at z>6, and the density of massive galaxies when the Universe was as young as 500-800 million years. We will estimate their contribution to the reionisation of the neutral gas, by computing their UV LF. If we estimate that the galaxy age and SFR are robust, we will have a clue on the epoch of the formation of the first galaxies.

Timescale: This scientific work will be lead by the postdoc who was already in charge of their selection. The work will start after the first selection of the z>6 sources, i.e. beginning of 2016. Therefore, the postdoc will have one year to exploit scientifically its z>6 sample.

TASK WP8 Scientific exploitation: comparison with theory

Responsible: A. Cattaneo

Participants: full team

Objective: interpret our results with simple phenomenological models but also with more complex physically motivated models as the semi-analytical models.

Method: We will produce accurate estimates of the stellar mass function, mass density, SFR density, sSFR for the 3<z<6 Universe in WP6 and we will provide also some constraints on primordial galaxies at 6<z<8 in WP7. We will first compare our results with predictions of semi-analytical models (SAMs). In the SAMs, the dark matter merger three is obtained with N-body simulations and the dark matter halos are populated using physically motivated analytical relations. The outputs from simulations provide direct access to the basic quantities (stellar mass, SFR, SFH, etc.) that permit to compute global galaxy properties to be compared directly with our data. We will fit the relevant free parameters in the SAMs to match our dataset and modify some recipes in the SAMs if needed.

In addition to the SAMs, we will also implement simple models. In the last few years, simple model like the "Bathtub" model (Bouché et al. 2010, Davé et al. 2012) or the "gas regulator" model (see Figure 1, Lilly et al. 2013, Peng et al. 2014) appeared as powerful tools to interpret the link between the growth rate of the dark matter halos and the stellar mass growth. With such models, we can simply link the specific mass accretion rate of the DM haloes, the sSFR, the gas fraction, the stellar mass growth of the galaxies. Peng et al. (2010) developed also a simple framework to link the quenching probability and the galaxy SFR. We will implement these analytical relations to interpret our results. In particular, the evolution of the sSFR at z>3 will be a crucial quantity to look at.

Timescale: This work can be started as soon as the first statistical measurements are ready. Beginning of 2016, we expect to have already a first selection of z>6 galaxies and preliminary measurement of the stellar mass function and luminosity function at z>3. The work will continue all along the project and will be extremely useful to interpret our results. A. Cattaneo who is an expert on SAMs will lead the project and S. Arnouts and O. Ilbert will develop the simple analytical models.

TASK WP9 spectroscopic follow-up of the massive sources at z>6

Responsible: L. Tresse

Participants: O. Le Fèvre, J.G. Cuby

Objective: spectroscopic follow-up of the massive sources at z>6

Method: At z>6-7 the Lα line is redshifted at λ>8512-9728Å. Therefore, we need instruments which are really sensitive in red and NIR. For the galaxies at z~6, we can envisage a follow up with current visible instrumentation like FORS2 or VIMOS. At z>6, we will propose a follow up with NIR powerful spectrographs which are now available, like X-SHOOTER, KMOS and MOSFIRE (through our Caltech collaborators). Since we are targeting the most massive galaxies at z>6, we increase our chance of confirming the redshifts of these galaxies. Some examples of z~7 spectroscopic redshifts exist already in the literature (Vanzella et al. 2011). Moreover, we will be in an excellent position to propose high redshift targets for JWST and PFS which will start their operations one-two years after the end of our project.

Timescale: We can start to prepare the spectroscopic follow-up as soon as the selection of the z>6 candidates is ready, beginning of 2016.

3.3 Team organisation

The participants to the project are listed in Table 1. We are members of the COSMOS survey and strongly involved since many years in the exploitation of this dataset. Our team gathers all the necessary expertise to execute the actions described in each WP. In the following, we describe the expertise of the participants and the complementarity with each WP. We also describe the qualification of the coordinator to lead this project. Finally, we describe the numerous projects at LAM in adequacy with this ANR.

EXPERTISE WITHIN THE TEAM AND ADEQUACY WITH THE WPs

Our first task (WP1, responsible: O. Ilbert) will be to create the multi-color catalogue with an accurate photometry, despite the PSF variation between IRAC and VISTA. O. Ilbert already produced the previous IRAC catalogue for the S-COSMOS survey (Sanders et al. 2007, Ilbert et al. 2010) and released it to the scientific community. S. Arnouts developed the code to perform the photometry of the GALEX sources, which is similar to the need we have for SPLASH. We will start this work with the "almost final" SPLASH mosaic in September 2014, which fit perfectly with the starting date of our project.

The next step will be to estimate the galaxy distances (WP3, responsible: O. Ilbert). O. Ilbert was already in charge of producing the photo-z for the COSMOS project (Ilbert et al. 2009, Ilbert et al. 2013). These photo-z are considered as the most accurate up to date and are widely used by the community (>400 citations). We will derive the photo-z for the SPLASH project. We will deliver the new photo-z catalogue before the end of our project. We have an excellent expertise in photo-z computation and we will use our own tool "*Le Phare*" to compute photometric redshifts and stellar masses (Arnouts et al. 2002, Ilbert et al. 2006). Based on these photometric redshifts, we will derive the physical parameters (WP5, responsible: S. Arnouts). In particular, we will derive the SFR using a new method, called *NRK*, developped and published in Arnouts et al. (2013), using the COSMOS data.

The postdoctoral researcher financed by the ANR will be in charge to study the massive primordial galaxies at z>6. Ideally, we would like to work with a young researcher having already a background on the high redshift Universe. With such profile, the postdoc could take in charge three related WPs and have an important role in our project. He/She will first work on the definition of the upper-limits with our deepest optical data (WP2, responsible: postdoc). This work is crucial to select z>6 galaxies. Then he/she will define robust criteria to select these sources (WP4, responsible: postdoc), analyse the physical properties of these sources (stellar masses and ages) and publish scientific analysis based on this sample (WP7, responsible: postdoc). While the postdoctoral researcher should have a background on primordial Universe studies, we already have an important expertise in our team in this domain. Indeed, O. Le Fèvre and J.G. Cuby, lead several projects to study the z>6 Universe (e.g. VUDS, CFHQIR) and they will be able to advice the postdoctoral researcher.

L. Tresse, O. Le Fèvre and J.G. Cuby are specialists in spectroscopy. They are part of the instrument team for JWST, PFS@Subaru and future MOS instrumentation for the ELT. O. Le Fèvre is the PI. of the VUDS project which will provide thousands of spectroscopic redshifts at z>3 in the COSMOS field. They will be in charge of the spectroscopic follow-up of the massive sources at z>6 (WP9, responsible: L. Tresse).

We will derive the star formation history in the first 2 billion years of galaxy evolution (WP6, responsible: O. Ilbert). We are all expert in this kind of analysis, and we leaded numerous reference studies in this domain in the last 10 years:

- on the mass assembly at z<2 using SWIRE/VVDS data (Arnouts et al. 2007) and using Spitzer/COSMOS data (Ilbert et al. 2010);
- on the link between the SFH/sSFR and the mass assembly measured at z<4 with UltraVISTA and Spitzer/COSMOS (Ilbert et al. 2013).
- using direct tracers of the SFRD using the UV light from GALEX/VVDS (Arnouts et al. 2005, Schiminovich, Ilbert, Arnouts et al. 2005) and VVDS data (Tresse, Ilbert et al. 2007 and Cucciati, Tresse, Ilbert et al. 2012).

While our studies are mainly linked to the z<2-4 Universe, we will be easily able to transfer our expertise to study an higher redshift domain, when the sample will be established.

Finally, we will interpret our results with simple phenomenological models but also with more complex physically motivated models as the semi-analytical model (WP8, responsible: A. Cattaneo). A.

Cattaneo is expert in this kind of model (e.g. Cattaneo et al. 2006, Cattaneo et al. 2009) and he participates to the development of a new version of GALICS (Hatton et al. 2003). Using SAMs, he mainly studied how AGN feedback regulate the star formation, which is closely related to our project.

QUALIFICATION OF THE PROJECT COORDINATOR

Associate astronomer at the *Laboratoire d'Astrophysique de Marseille* since 2009, Olivier Ilbert is internationally recognized for his work on deep imaging surveys. Over the last ten years, he has played a leading role in the exploitation of successively larger surveys. He has continuously worked in large international collaborations with tens of other scientists, with the largest spectroscopic surveys performed with VIMOS (VVDS, VIPERS and VUDS) which gathered >150000 spec-z out to z~6, and the largest multi-color catalogue to study the z>1 Universe including millions of sources (CFHTLS, COSMOS, WIRDS). He is also working on the future space mission Euclid, applying his expertize on multi-color surveys in several Operation Units.

Olivier Ilbert is also internationally recognized as an expert in measuring galaxy distances of very large samples with the photometric redshift technique. His two publications on photometric redshifts techniques have been cited more than 800 times in only a few years (Ilbert et al.2006 and Ilbert et al. 2009). Since ten years, O. Ilbert coordinates an effort to release the photometric redshifts for each new Terapix release of the CFHTLS survey (5 releases in total), with a first release in 2006 (Ilbert et al. 2006), in 2009 (Coupon, Ilbert et al. 2009) and the latest CFHTLS T007 release through the Terapix[1] web page and a dedicated web page on the CESAM[2] database. O. Ilbert is also in charge of producing the photometric redshifts and the physical parameters for the COSMOS survey since the last 7 years. He demonstrated the possibility to produce 1% accurate photo-z at z<1.3 using zCOSMOS bright and 3% accurate photo-z at z~2 using zCosmos faint. The COSMOS photo-z catalogues were also continuously updated (almost one release every year) with new data becoming available (first v1.5 release in 2008 described in Ilbert et al. 2009 and current release v2.0 including UltraVISTA and described in Ilbert et al. 2013). These COSMOS photo-z catalogues are the reference for the COSMOS collaboration, and are also used by a large community outside the COSMOS team. One goal of this project is to provide robust and well tested photo-z and physical parameters at z>3 using the new SPLASH data. **His experience in managing the photo-z estimates and the data release of millions of sources will insure a timely work on the new catalogue and its release.**

He developed the tool ALF (Ilbert et al. 2005) to compute the luminosity function, the mass function or the luminosity density for large-scale surveys, including several well tested estimators (Ilbert et al. 2004). With this expertise he took a leading role in computing the luminosity/mass functions for several surveys, like the VVDS with 10000 spectroscopic redshifts (Ilbert et al. 2005, Zucca, Ilbert et al. 2006, Tresse, Ilbert et al. 2007), the COSMOS survey with >200000 photo-z selected with IRAC (Ilbert et al. 2010, Ilbert et al. 2013), the VIPERS survey with >50000 spectroscopic redshifts at 0.5<z<1.5 (Fritz, Scodeggio, Ilbert et al. 2014). Therefore, he has the expertise to coordinate statistical analysis with this large galaxy sample.

He supervised two mater students (L. Cielsa in 2008 and G. Tramoy in 2010) and a PhD student (T. Moutard 2012-2015). He was part of several committees (referee for the ESO and Subaru Time allocation Committees, member of the *Conseil National des Universités* since 2013). He also managed several grants from PNCG (14k€), PICS (15k€), CNES (60k€).

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[1] http://terapix.iap.fr/article.php?id_article=841

[2] http://cesam.lam.fr/cfhtls-zphots/

ILBERT Olivier - Curriculum Vitae

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EDUCATION

- 2004 – Ph.D., *Galaxy formation and evolution at high z – luminosity functions of the VVDS survey* (Aix-Marseille University)
- 2001 – Master (DEA) in Astrophysics and Plasmas (Aix-Marseille University)

PROFESSIONAL EXPERIENCE

- Jan. 2009 – present Astronome-Adjoint at LAM
- Feb. 2006 – Jan. 2009 Postdoctoral fellow at the Institute for Astronomy, University of Hawaii
- Dec. 2004 – Jan. 2006 Postoctoral fellow at Bologna University
- Oct. 2001 – Dec. 2004 Ph.D. at LAM under the supervision of L. Tresse

SERVICES

- Teaching at University of Provence since 2001 (Licence and Master, >500hr)
- Referee of peer-reviewed publications in A&A, ApJ and MNRAS since 2005
- Referee for the ESO and Subaru Time Allocation Committee
- Member of the National Commission of French Universities (CNU 34)

PUBLICATIONS

• 206 refereed publications with >10300 citations since 2003 (source : NASA/ADS)

1. Ilbert, O**.**, et al., *Mass assembly in quiescent and star-forming galaxies since z ≃ 4 from UltraVISTA*, 2013, A&A, 556, 51, >56 citations
2. Ilbert, O**.**, et al., *Galaxy Stellar Mass Assembly Between 0.2 < z < 2 from the S-COSMOS*, 2010, ApJ, 709, 644, >290 citations
3. Ilbert, O**.**, et al., *Cosmos Photometric Redshifts with 30-Bands for 2-deg2*, 2009, ApJ 690, 1236, >430 citations
4. Ilbert, O., et al., *Accurate photometric redshifts for the CFHT legacy survey calibrated using the VIMOS VLT deep survey,* 2006, A&A, 457, 841, >400 citations
5. Ilbert, O., et al., *The VIMOS-VLT Deep Survey. Galaxy luminosity function per morphological type up to z = 1.2*, 2006, A&A, 453, 809, >59 citations
6. Ilbert, O., et al., *The VIMOS-VLT deep survey. Evolution of the galaxy luminosity function up to z =2 in first epoch data*, 2005, A&A 439, 833, >170 citations

THE HOST INSTITUTE

Our consortium is composed of researchers in the Laboratoire d'Astrophysique de Marseille (LAM), part of the cosmology team. The Laboratoire d'Astrophysique de Marseille has an internationally recognized expertise in deep surveys and participates or leads in many surveys either completed or in progress with the VIMOS instrument (built by a consortium led by LAM), totalling more than 100,000 spectra to z~6. The LAM is currently developing instruments for the EUCLID mission and for PFS. EUCLID will be the largest imaging multi-color survey from space covering 1/3 of the sky. EUCLID and PFS will acquired millions of spectra. The LAM is also involved in the MIRI camera for JWST, and participates to the study of second generation MOS instruments for the ELT. All these instruments or the planned surveys have among their objectives the study of the z>3 Universe and the detection of the primordial galaxies for JWST and the ELT.

Finally, the LAM includes a team of developers (CESAM) who implement databases for our projects. We will use this opportunity to deliver our data with a nice interface.

4 JUSTIFICATIONS OF THE REQUESTED RESSOURCES

The financial support requested for the realization of this project consists in:

- 24 months of post-doctoral contract: LAM, Marseille: 86.7k€
- Mission/travel expenses: 56k€
- Computing/small expenses: 24k€

Therefore, we request 173k€ in total, and we detail below the total aid requested.

Postdoctoral researcher

We would need a postdoctoral researcher for two years. Ideally, we would like to work with a young researcher having already a background on the primordial Universe. With such profile, the postdoc could take in charge the WP2, WP4 and WP7 and have an important role in our project. All these work packages form a coherent project, from the definition of the upper-limits (which are also useful for the photometric redshifts WP2) to the study of the most massive sources at z>6. Since this scientific domain is extremely competitive, we need a member of our project completely dedicated to the z>6 topics. Without the participation of a postdoc financed by the ANR, we will not have the resources to work on the primordial Universe. This project will enable us to take firmly positions in the future highly competitive high-redshift projects with JWST or the E-ELT for instance, and offer good opportunities for a young researcher.

Budget for the travel/missions

Given that our work is carried out in the framework of large international collaborations and given the highly competitive nature of our research, it is extremely important that we have sufficient resources for international travel. Our travel budget is also essential to ensure strong interactions with Caltech (P.Capak, PI of SPLASH) and Japon/Hawaii (HSC). We need to participate to international conferences and team meeting (once per year).

Total postdoc missions: 14k€. This provides 7k€/year, sufficient for one SPLASH/COSMOS team meeting (~3k€), one international conference (~3k€) and short missions in France (~1k€).
Total permanent researcher missions: 42k€. For travel costs we require 7k€/year per researcher to allow at least one week-long voyage either to or from Caltech (~2k€) and several shorter trips between Marseille and Paris (~1k€x2) and at least one trip to an International conference (~3k€). This provides 7k€/year. Given that the project is defined for three year, and that we count a minimum of mission for two researchers full time, we ask for a total of 7*3*2=42k€.

Equipment

We require 3k€/year/per researcher for computing (portable computers, monitors, storage and backup) and other small expenses: 3k€/year*2 (postdoc) + 3k€/year*3 *2 (2 researchers): 24k€

5 DISSEMINATION AND EXPLOITATION OF RESULTS, INTELLECTUAL PROPERTY

Data and catalog access

The COSMOS field is now one of the few reference fields studied in detail by the biggest ground and space telescopes. While a large part is covered with HST images (1.4 deg^2), it has been also observed by *XMM*, *GALEX*, *Spitzer*, *Chandra*, *Akari*, *Herschel, NuStar* from space and CFHT, VLT, SUBARU, KECK, VLA, IRAM, ALMA from ground. The COSMOS team is >100 researchers (Europe, USA, Japon). But the use of these data is extended well outside the COSMOS team. Hundreds of publications are using the public COSMOS data in their analysis. More than half of them are not published by the COSMOS team. Moreover, the COSMOS catalogues are used to prepare several large-scale projects developped in the next decade, as EUCLID (e.g. Jouvel et al. 2009) or BigBOSS (Schlegel et al., 2009, astro-ph/0904.0468).

Therefore, the data products of the WP 1-5 will be extremely useful to the astronomical community. The produced catalogues will be a reference for years to come. For the previous release of the photo-z catalogue in COSMOS (Ilbert et al. 2009), we proceeded in a two steps process with first a team release followed by a public release one year later. We will adopt the same policies regarding this new data release:

- The photo-z catalogue and the associated physical parameters will be released to the COSMOS team as soon as a stable and robust catalogue will be obtained, which should be January 2016 according to our task schedule. Numerous groups will have the opportunity the use this catalogue for their own scientific goals, including us, and provide feedback before the public release.
- One year after the team release, beginning 2017, we plan to release publicly our catalogues, i.e. the results of all WPs.

The catalogues will be released using several websites, as done in the past with CESAM[3], IRSA[4] and Terapix[5]. The CESAM database is developed in our institute. We will work closely with the CESAM team to provide added value products like the possibility to display the photo-z Probability Distribution Functions and the image stamps for each source of our catalogue.

Finally, the scientific community already benefits from the public SED fitting code LEPHARE[6]; we will provide regular updates to our template libraries and updated versions of the code, benefitting from the optimisations detailed here.

Scientific results

Our results will be promoted through the publication of refereed articles and presentations at international conferences, departmental seminars, collaboration meetings and workshops for the large international collaborations of which we are all a part.

We expect to publish at least >6 refereed papers based on our project in the next 4 years

- 1 paper describing the data and catalogue WP1-5;
- >2 papers on the SFH using the stellar mass function and the UV tracers from WP6;
- >1 paper on the high redshift universe and primordial galaxies;
- >1 paper on the comparison between models and the data;
- possible paper on the spectroscopic follow-up depending on the outcome.

We will also publicly release light-cones and mock catalogues from our simulations, if they can be useful for preparing for future surveys.

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[3] http://cesam.lam.fr/cesamdata/project_desc/hstcosmos/
[4] http://irsa.ipac.caltech.edu/Missions/cosmos.html
[5] http://terapix.iap.fr/article.php?id_article=844
[6] http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html

Outreach to the astronomical community and to the general public

A project website will be established, presenting our science to a large audience. Potential discovery of massive primordial galaxies will have an impact on the general public and we will communicate on these results using press releases.

6 BIBLIOGRAPHIC REFERENCES

Arnouts S. et al., 2005, ApJL, 619, 43
Arnouts S. et al., 2007, A&A, 476, 137
Arnouts S. et al., 2013, A&A, 558, 67
Behroozi P. et al. 2013, ApJ, 770, 57
Bouche N., et al., 2010, ApJ, 718
Bournaud et al., 2007, ApJ, 670, 237
Bouwens R.J. et al., 2009, ApJ, 705, 936
Bouwens 2011, ApJ, 737, 90
Bower R.G et al., 2006, MNRAS, 370, 645
Bowler R.A.A. et al. 2012, MNRAS, 426, 2772
Bowler R.A.A. et al. 2014, MNRAS, 420, 2810
Bromm V. & Yoshida N., 2011, ARAA, 49, 373
Burgarella D. et al., 2013, A&A, 554, 70
Capak P. et al., 2007, ApJ, 730, 68
Capak P.L. et al., 2011, Nature 470, 233
Caputi K.I. et al., 2011, MNRAS, 413, 162
Cattaneo A. et al. 2006, MNRAS, 370, 1651
Cattaneo A. et al. 2009, Nature, 460, 213
Croton D.J et al., 2006, MNRAS, 365, 11
Cucciati O. et al., 2012, A&A, 539, 31
Daddi et al. 2007, ApJ, 670, 156
Davé R. et al., 2012, MNRAS, 421, 98
de Barros S. et al., 2014, A&A, 563, 81
Dekel et al., 2009, Nature, 457, 451
de Ravel L. et al. 2009, A&A, 498, 379
Dunlop J. et al., 2007, MNRAS, 376, 1054
Dunlop J., 2013, ASSL, 396, 223
Elbaz et al. 2007, A&A, 468, 33
Elbaz D. et al., 2011, A7A, 533,119
Ellis R. et al., 2013, ApJ, 763, L7
Fontana A., et al., 2006, A&A, 459, 745
Förster-Schreiber N.M. et al., 2009, ApJ, 706, 1364
Gruppioni C.et al., 2009, MNRAS, 432, 23
Hatton et al. 2003, MNRAS, 343, 75
Hopkins & Beacom 2008, ApJ, 682, 1486
Heinis S. et al., 2014, MNRAS, 437, 1268
Hung C.L. et al., 2013 ApJ, 778, 129
Ilbert O. et al., 2005, A&A, 439, 863
Ilbert O. et al., 2009, ApJ, 690, 1236
Ilbert O. et al., 2010, ApJ, 709, 644
Ilbert O. et al., 2013, A&A, in press, arXiv:1301.3157
Karim A. et al., 2011, ApJ, 730, 61
Kennicutt, R.C., 1998, ARA&A, 36, 189
Lee K. et al., 2012, ApJ, 752, 66
Le Fèvre et al. 2014, submitted to A&A, astro-ph/1403.3938
Lehnert, M.D. & Heckman T.M., 1996, ApJ, 462, 651
Lilly et al., 1996, ApJ, 455, 1
Lilly et al., 2009, ApJS, 184, 218
Lopez-Sanjuan C. et al., 2013, A&A, 553, A78
Martin et al., 2012, ApJ, 760, 127
McLure, 2013, MNRAS, 432, 2696
Mobasher B. et al., 2005, ApJ, 635, 832
Noeske K.G. et al., 2007, ApJL, 660, L43
Pérez-Gonzalez et al., 2008, ApJ, 675, 234
Peng Y.-T. et al. 2010, ApJ, 721, 493
Pozzetti L et al., 2010, A&A, 523, 13

Rodiguiero et al. 2011, ApJ, 739, 40
Sanders et al., 2007, ApJ, 172, 86
Santini P. et al., 2012, A&A, 538, A33
Schaerer D. et al., 2009, A&A, 502, 423
Schiminovich D. et al., 2005, ApJL, 619, 47
Scoville N. et al., 2007, ApJS, 172, 1
Stark D. et al., 2009, ApJ, 697, 1493
Stark D. et al., 2013, ApJ, 763, 10
Takada et al., 2014, PASJ, 66, 1
Tresse et al. 2007, A&A, 472, 403
Vanzella et al. 2011, ApJ, 730, 35
Wang J. et al., 2008, MNRAS, 384, 1301
Weinmann S. et al., 2011, MNRAS, 417, 2737
White & Rees, 1978, MNRAS, 183, 341
Wilkins et al. 2008, MNRAS, 385, 687