# 1 Ultra-VISTA: an Ultra Deep Survey with VISTA

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## 1.1 Abstract:(10 lines max)

The near-IR survey speed of VISTA will be unmatched until the JWST mission. We propose to exploit this capability for a combined ultra-deep broad-band YJHK$_s$ (1408 hr), ultra-deep narrow-band (180 hr), and wider YJHK$_s$ (212 hr) imaging survey of the COSMOS field. The ultra-deep survey, covering 0.73 deg$^2$ will open up the study of the universe between $z = 6.5$ and $z = 10$, producing a sample of $> 1000$ galaxies with $z > 6.5$. This will enable the study of the sources causing reionization, and delineation of the $z > 6.5$ galaxy luminosity function and its evolution well before JWST. The narrow-band survey is expected to find $\simeq 30$ Ly-$\alpha$ emitters at $z = 8.8$. The wide survey will complete the coverage of the full 1.5 deg$^2$ field, allowing the construction of mass-selected samples over $2 < z < 5$, complete to $M_{stars} \simeq 10^{10}$ M$_\odot$. This will allow the build-up of stellar mass in galaxies to be followed through the peak epoch of star-formation activity. This survey will have unprecedented legacy value, and will be a key resource for follow-up studies with VLT, ALMA, ELTs, and JWST.

# 2 Description of the survey: (Text: 3 pages, Figures: 2 pages)

## 2.1 Scientific rationale

Since VISTA was first conceived, our understanding of galaxy formation and evolution has been revolutionized by a series of major surveys. However, as a result of this progress, it is now clear that VISTA is *the premier facility* in the world for addressing the key outstanding questions concerning the formation and evolution of galaxies in the young universe. There are four main reasons for this.

**The first galaxies**. We now stand at the final frontier in our quest to understand the end of the dark ages and the formation of the first galaxies. The current situation is tantalizing; we know of several hundred galaxies at $z \simeq 6$ and we have good evidence that reionisation took place at $z \leq 10$, but there currently exist only three credible galaxy candidates at $z > 6.5$. Why do we know so little about the crucial epoch $6 < z < 10$ ? The reason is that the discovery of high-redshift galaxies via Lyman-break or Lyman-$\alpha$ emission selection can only be achieved via *optical* imaging out to $z \simeq 6$. To probe to higher redshifts requires near-infrared imaging of sufficient *area and depth* to enable effective Lyman-break and Lyman-$\alpha$ selection of galaxies over the redshift range $6 < z < 10$. Prior to JWST in 2015 this can only be achieved with VISTA.

**Tracing the growth of stellar mass.** At more moderate redshifts $z \simeq 1 - 5$, the potential advantages of the infrared for tracing the mass-dominant component of the stellar populations of galaxies have long been understood. However, no existing survey has the necessary area, depth, and supporting multi-frequency data to explore a wide dynamic range in mass over the redshift range $1 < z < 5$. Even the UKIDSS UDS survey now underway lacks the deep HST imaging required to clarify the link between the mass and morphological evolution of the galaxy population. Only the unique VISTA survey proposed here will achieve this.

**Dust-obscured star formation.** The follow-up of SCUBA and Spitzer surveys has demonstrated that the near-infrared is the wavelength of choice for identifying and studying the properties of the high-redshift galaxies which host extensive, dust-enshrouded, star-formation activity. The next generation of sub-mm/far-infrared surveys, to be undertaken with SCUBA2, Apex and Herschel will provide ultra-deep imaging over a few square degrees, including the COSMOS field as a high priority. The deep near-infrared survey proposed here is thus central to our future understanding of the role of dust-enshrouded star-formation in cosmic history.

**Representative volumes.** VISTA offers a uniquely powerful probe of galaxy formation/evolution, because its large areal coverage allows the study of a representative volume of the high-redshift universe, comparable to what could be surveyed spectroscopically when JWST will be operating. Our proposed ultra-deep VISTA survey thus offers the only currently-feasible route to quantify the evolution of the high-mass end of the galaxy mass function through this most crucial epoch in cosmic history.

VISTA therefore has the unique potential to complete our picture of the cosmic history of galaxy and star formation. However, for this potential to be realized we must ensure that: (i) a coordinated Y,J,H,$K_s$ + narrow-band survey, of sufficient area, can be completed to the necessary depth, and (ii) this survey is undertaken in an accessible field, with the very best available deep multi-frequency supporting data, for which all the necessary time can be scheduled within the overall VISTA survey program.

To achieve this goal, this proposal brings together four, originally-separate, deep VISTA proposals, in a co-ordinated effort to maximize the scientific return of VISTA via deep/ultra-deep near-infrared imaging of the COSMOS field. The COSMOS field is the largest field ever imaged with HST, reaching a depth $I_{AB} = 27$ ($10\sigma$) allowing a quantitative measurement of galaxy morphologies over a wide range in redshift (Scoville et al., 2006). Data are already assembled in the X-ray, optical, mid-IR (Spitzer) and radio wavelengths, with sub-mm (SCUBA2) and far-infrared (Herschel) data expected from 2008. More than 30000+ optical redshifts are being measured with VIMOS on the VLT (Lilly et al., 2006). By adding deep YJH$K_s$ photometry, our proposed ultra-deep Vista survey will unlock the full power of this unique dataset, and in particular will provide photometric redshift coverage, and galaxy stellar mass estimates over the redshift range $0 < z < 10$.

## 2.2 Immediate objective:

Here we propose to perform an ultra-deep imaging survey with VISTA, surpassing all previous and ongoing surveys in its combination of depth and area. We propose to spend 1408 hours of observing time in the COSMOS field in the Y, J, H, and $K_s$ bands. More than 0.73 deg$^2$ will be imaged in four $60\times11$ arcmin rectangles separated by 10-arcmin wide gaps (see Figure 1), enabling to reduce cosmic variance effects to below a few percents. The 5-$\sigma$ point-source depths are 26.7, 26.6, 26.1, 25.6, in Y, J, H and $K_s$ respectively (in AB magnitudes, as used through the full text).

Shallower imaging will be taken in the area between the columns of the deep exposure, for a total observing time of 212 hours. This will reach 5-$\sigma$ depths of 25.7, 25.5, 25.1, and 24.5 respectively.

To search for Ly-$\alpha$ emitters at $z = 8.8$, we propose narrow-band (NB1185) imaging for 180 hours, reaching a sensitivity of 24.07 (AB, $5\sigma$), equivalent to a flux-density limit of $3.7 \times 10^{-18}$ ergs/sec/cm$^2$.

Many different science applications can be tackled with this survey, only a few are listed below:

**Sources of reionization: the high redshift universe (z > 6.5).** Recent surveys have pushed the study of high-redshift galaxies out to $z = 6.5$ (e.g., Hu et al. 2002, Bunker et al. 2004, Giavalisco et al. 2004, Bouwens et al. 2006) and up to $z = 6.96$ (Iye et al., 2006). Bouwens et al. (2006) have identified $> 500$ i-dropout galaxies at $z \approx 6.5$, enabling a robust determination of the restframe UV luminosity function. Recent results on $z = 6.5$ quasars (Fan et al. 2003) and WMAP analysis (Spergel et al. 2006) suggest that reionization may have happened at slightly higher redshifts, $z = 7 - 9$. Today, the luminosity function at these redshifts remains very uncertain, because only very few $z > 6.5$ galaxy candidates are known. This is simply a result of the severe lack of area in existing deep near-infrared studies (e.g., Bouwens et al. 2004, Kneib et al. 2004, Labbé et al. 2006). However, recent results from the UKIDSS UDS have demonstrated the exciting potential of the new generation of near-infrared imagers to revolutionize this field (see Figure 2).

The unique wide-field capability of VISTA will allow us to find $z > 6$ galaxies very effectively when the VISTA imaging data are combined with existing ACS i-band, and CFHT z-band imaging. We propose to obtain ultra-deep VISTA imaging in the near-infrared, so that large numbers of i, z, Y, and J-dropouts can be selected. A key advantage of VISTA for performing such drop-out searches compared to other surveys (e.g. UKIDSS-UDS) is the superior sensitivity of up to 1.2 magnitudes in the Y and J bands. The dropout selection technique relies on the very strong 1216 Å break in $z > 6.5$ galaxies and AGN, with the selection criteria as shown in Figure 3. The relevant redshift intervals are $\delta z$ = 6-6.5,6.5-7.5, 7.5-9.5, and 9.5-11 for i, z, Y, and J-dropouts respectively. It is hard to predict the number of high-redshift galaxies which will be detected because, of course, the main goal of this proposal is to measure the (essentially unknown) evolution of the galaxy luminosity function at $z > 6$. Indeed, at $z = 6$ there is still a considerable spread in results, even when studies are based on the same data (c.f. Bouwens et al. 2006 with Beckwith et al. 2006). If we assume that the (conservative) luminosity function at $z = 6$ derived by Bouwens et al. (2006) applies at higher redshifts, we expect 560, 450, 180, and 6 galaxies at $z = 6.3$, 7.5, 8.5, and 10, corresponding to i, z, Y, and J-dropouts respectively. This demonstrates that we can obtain cosmologically meaningful samples, and obtain statistically meaningful constraints on the bright end of the luminosity function out to $z = 9.5$ ($Y$-dropouts). In addition, the large survey area is required to assemble the large number of sources necessary for a unique measurement of the projected angular correlation function $w(\theta)$, and its deprojection to compute the correlation length $r_0$.

The 5-$\sigma$ magnitude limits correspond to 0.7, 0.9, 1.5, 2.8 times $L_*$ at $z = 6.3$, 7, 8.5 and 9.5 respectively, assuming the Bouwens et al. (2006) $z = 6$ luminosity function. Hence the luminosity function will be well sampled, and can be accurately determined at these redshifts. The total field has a size of $195 \times 156$ comoving Mpc at $z = 8$, much larger than the scale of fluctuations. Hence the determination of the luminosity density will be mostly free from uncertainties introduced by "cosmic variance" in the distribution of large-scale structure.

**Narrow band search ($\mathbf{z = 8.8}$).** In addition to the continuum search described above, we will perform a narrow band search for $z = 8.8$ Ly-$\alpha$ emitters in the deepest 0.73 deg$^2$, for a total of 180h. Past Ly-$\alpha$ searches have been extremely successful in yielding spectroscopically confirmed samples (e.g., Steidel et al., 2000; Fynbo et al., 2001; Malhotra & Rhoads, 2004; Hu et al., 2004), including the discovery of the most distant galaxy spectroscopically identified to date ($z = 6.96$; Iye et al., 2006). Furthermore, they provide an important test of the epoch of reionization: the Ly-$\alpha$ Luminosity Function can be drastically altered through damped absorption by the neutral medium (Miralda-Escudé, 1998; Gnedin & Prada, 2004). The details of this evolution depend on the local ionization of the IGM by the Ly$\alpha$-emitting galaxies. The discovery of a large sample of Ly$\alpha$-emitting galaxies at $z = 8.8$ will also reveal information about the star-formation density at this epoch. We will be able to compare this with the recent results on emission-line galaxies at $z \simeq 7$ (e.g. Iye et al. 2006).

This narrow-band survey will yield large numbers of lower-redshift emission-line sources through the detection of H$\alpha$ ($z \approx 0.8$), H$\beta$ and [OIII]5007 ($z \approx 1.4$) and [OII]3727 ($z \approx 2.2$). The resulting samples will provide valuable insight into cosmic star-formation history over a wide range of redshifts.

The near-infrared sky spectrum is full of OH lines, which make it impossible to perform effective narrow-band searches at most redshifts. Here we propose to make use of the uniquely-empty region at 1180 nm. A narrow-band filter at this wavelength will be provided by the Dark Cosmology Centre. We propose to observe for 180 hours on the ultra-deep field, reaching a 5-$\sigma$ depth of $3.7 \times 10^{-18}$ ergs/s/cm$^2$. To this depth and area, we expect to find $\sim 15 - 30$ Ly$\alpha$-emitters, $\sim 6000$ H$\alpha$-emitters and a few hundred intermediate redshift emitters.

**The mass-selected galaxy population ($\mathbf{1.5 \leq z \leq 5}$).** The Lambda-CDM galaxy formation paradigm is central in our understanding of the processes by which galaxies in the Universe we see today were assembled from the initial fluctuations produced during inflation. The fundamental assertion is that all galaxy formation is driven by the gravitational growth of dark halos, their clustering and the dynamics of gas within those dark halos. Making a complete census of the galaxy population and associated stellar mass at all epochs is therefore mandatory before any attempt to understand galaxy evolution. This includes both star-forming galaxies and the earliest stellar populations formed in the Universe.

While the census of high-redshift galaxies with $z \geq 1.5$ based on UV rest-frame selection is now reasonably well established (e.g. VVDS, Le Fèvre et al., 2005), measuring stellar masses and obtaining mass-selected samples of galaxies at these redshifts is still very hard, as the rest-frame optical moves into the near-infrared. Deep near-infrared surveys are essential for a complete census of $z > 1.5$ massive galaxies, and in general, the masses of galaxies at $z > 1.5$ can only be estimated with help of such imaging. The deep near-infrared surveys have shown that the $z \geq 2$ samples defined on the basis of such imaging are very different from samples obtained through optical selection (e.g., Franx et al. 2003, Daddi et al. 2004a, b, van Dokkum et al. 2006), while the Ly-break galaxies (Steidel et al. 1996) contribute a small fraction of the mass at $2 < z < 3$. Some of the recent near-infrared surveys go deep enough to reach stellar masses of $10^{10}$ $M_\odot$ at $z = 3$, the typical mass of a Lyman-break galaxy at $z = 3$ (e.g., FIRE Survey). However, the areas covered are generally very small, from 5 sq. arcmin for the deepest part of the FIRE Survey to $10 \times 15$ arcmin for the shallower GOODS CDFS imaging.

With the advent of VISTA, it is now possible to combine depth and area for near-infrared surveys in a very efficient way, and fill this gap in wavelength coverage. The VISTA Y,J,H,$K_s$ data will make it possible to secure a large, volume-complete, census of stellar populations out to $z \simeq 4$, and to select galaxies by stellar mass. The proposed survey will probe more than one magnitude deeper in absolute luminosity than any other planned or on-going survey, reaching down to $0.1L_*$. The unprecedented multi-wavelength data from the u-band to $4.5\mu$m will provide very complete spectral energy distributions, from which galaxy stellar masses and accurate photometric redshifts can be computed, with very few catastrophic failures (Ilbert et al., 2006).

The proposed deep exposures reach $M_{stars} \simeq 10^{10}$ $M_\odot$ at $z = 3$, equivalent to the depth of the FIRE Survey, but over an area 400 times larger. The total volume between $z = 2$ and $z = 4$ will be $1.6 \times 10^7$ Mpc$^3$, sufficient for a representative sample of the universe, minimizing cosmic variance. The depth will be well-matched to the Spitzer-IRAC photometry ($\simeq$ 24.2(AB) at 3.5 $\mu m$; Sanders et al., in prep.) The shallower survey will reach stellar masses of $2.5 \times 10^{10}$ $M_\odot$, 3 times smaller than the existing observations of the COSMOS field with CFHT-WIRCAM. The evolution of the mass function can then be derived with unprecedented accuracy. The combination of large volume and accurate photo-$z$ information will allow the study of the evolution of the angular correlation function $w(\theta)$ or the $w_p(r_p)$ projection of the space correlation function $\xi(r_p, \pi)$. These measurements will be compared to predictions from, for example, halo-occupation models.

*Expected number of objects*

At the depth $Ks_{AB} = 24.6$ and matching z,Y,J,H bands proposed for the shallower survey, we expect to identify 30000/70000 of galaxies with $1.4 < z < 5$ based on extrapolations from the CDFS-GOODS survey and FIRES survey, respectively. This survey will be the first to study the high-redshift universe in such detail for complete *mass-selected* samples.

**High-redshift QSOs.** Deep near-infrared coverage will also be crucial for the selection of high-z AGN candidates especially, in combination with X-ray observations, for the identification of absorbed Type-2 QSOs (Maiolino et al., 2006). Large X-ray selected samples of $z > 3$ AGN are not presently available (only 20-30 are known from various inhomogeneous X-ray surveys), and deep, near-infrared photometry will be crucial for the selection of a large sample (50-100) of $z > 3$ QSOs (Hasinger et al. 2006). The near-infrared imaging will also allow exploration of the link between host-galaxy stellar mass, and black-hole mass at these high redshifts.

**Conclusion.** We believe that, in themselves, the key, unique science goals discussed above fully justify the proposed investment of telescope time. However, we also anticipate that this survey can be used for numerous other science applications. The wealth of data on the COSMOS field will make this a uniquely powerful resource, and additional studies which can be undertaken include: identification of AGN; studies of AGN hosts; evolution of the black-hole:bulge mass relation; the identification and characterization of sub-mm galaxies; comparison of star-formation rates derived from X-ray, UV, optical, IR, radio, sub-mm, and emission-line estimators; correlation functions of various classes of galaxies over a wide range in redshift; comparison of galaxy stellar mass estimates with CO-linewidth mass measurements to be undertaken with ALMA.

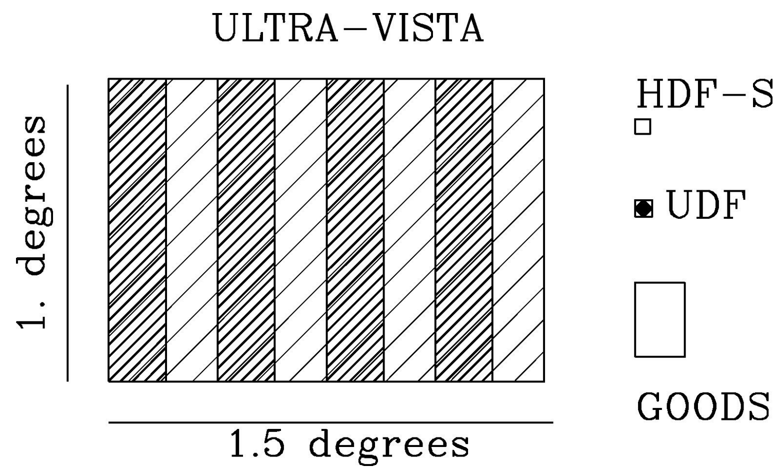


Figure 1: The field of view of the Ultra-Vista survey. The dark shaded area indicates the Ultra-Deep survey, with an integration time of 1408 hours. The shallow survey will cover the full field, leading to a deep image with a size of 1.5 x 1 degree. The HDF-S FIRES field and UDF fields are the only fields of comparable depth as our deep survey. The near-infrared NICMOS UDF imaging is indicated in black. These 2 fields are more than 400 times smaller than our deep survey area. The GOODS-South survey is larger than these 2 deep fields, but shallower by about 1.5 magnitudes.

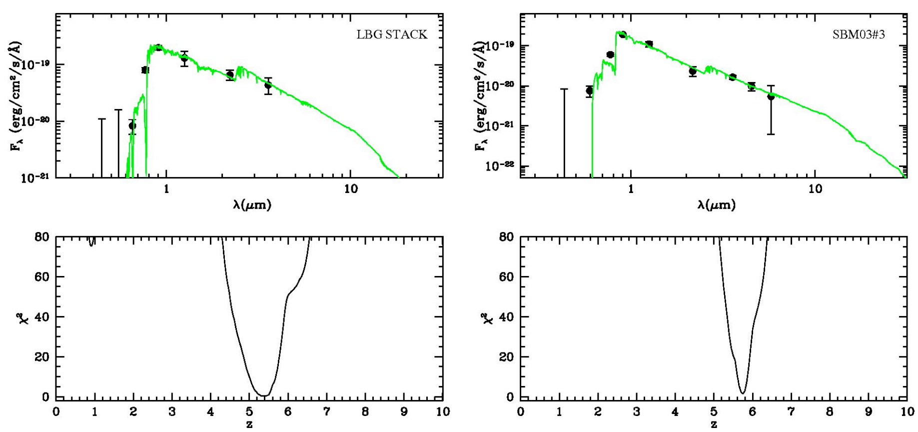


Figure 2: A recent demonstration that very high-redshift galaxies can indeed be uncovered with as much reliability from ground-based wide-field near-infrared imaging, as from space. The left-hand plot shows the stacked photometry, best fitting model spectrum, and chi-squared versus redshift (marginalized over galaxy age and dust reddening) for the nine galaxies at $z > 5$ recently isolated by McLure et al. (2006) from the Early Data Release imaging from the UKIRT UKIDSS UDS. For comparison, the right-hand plot shows the same information for the brightest $z > 5$ galaxy uncovered with HST in the GOODS CDFS field (SMB03#03, $z = 5.78$, Bunker et al. 2003). This comparison demonstrates that the necessary photometric dynamic range can be achieved to securely isolate very high-redshift Lyman-break galaxies with ground-based wide-field optical-IR imaging (and indeed that surveys approaching 1 square degree, are revealing the existence of significant numbers of massive galaxies at $z \simeq 6$). Our proposed final VISTA infrared imaging will be 30 times deeper than the data used to produce the left-hand plot, allowing the clean isolation of individual galaxies out to $z \simeq 9$ down to masses $M_{stars} \simeq 10^{10}$M$_{\odot}$.

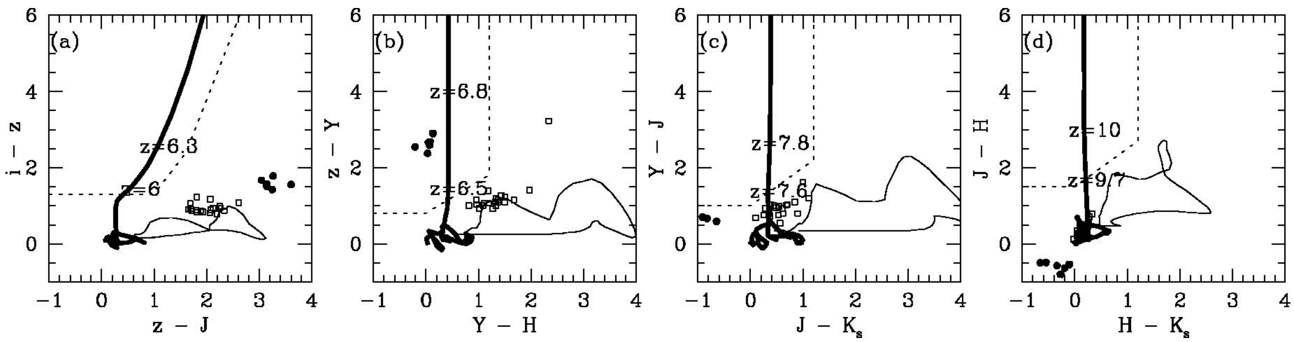


Figure 3: Color selection criteria for i, z, Y, and J-dropouts, respectively, in AB magnitudes. The thick curves show the expected colors for a starburst galaxy. The thin curves show the expected color for early-type galaxies at lower redshift. The selection boundaries (dashed) are chosen to minimize contamination by low redshift ellipticals (where the 4000Å break is mistaken for the 1216Å break), and stars (points). The stars plotted here are brown dwarfs, the main contaminants of concern. Note that T-dwarfs (solid symbols) produce some contamination for z-dropouts, but can be identified by their blue J-K$_s$ colors. The redshift labels refer to the color-space location of high-redshift starbursts on the (thick) tracks. Assuming the $z = 6$ luminosity function of Bouwens et al. (2006), we expect to find $\approx$ 600 i-dropouts at $z = 6.3$, 500 z-dropouts at $z = 7$, 200 Y-dropouts at $z = 8.5$, and 7 J-dropouts. Note that dust extinction will move the tracks for ellipticals and star forming low-redshift galaxies up and to the right in the 4 diagrams, and so genuine high-redshift dropouts can always be isolated from dusty lower-redshift contaminants, provided we have the deep long-wavelength imaging to isolate the objects with blue colours above the 1216 Å break.

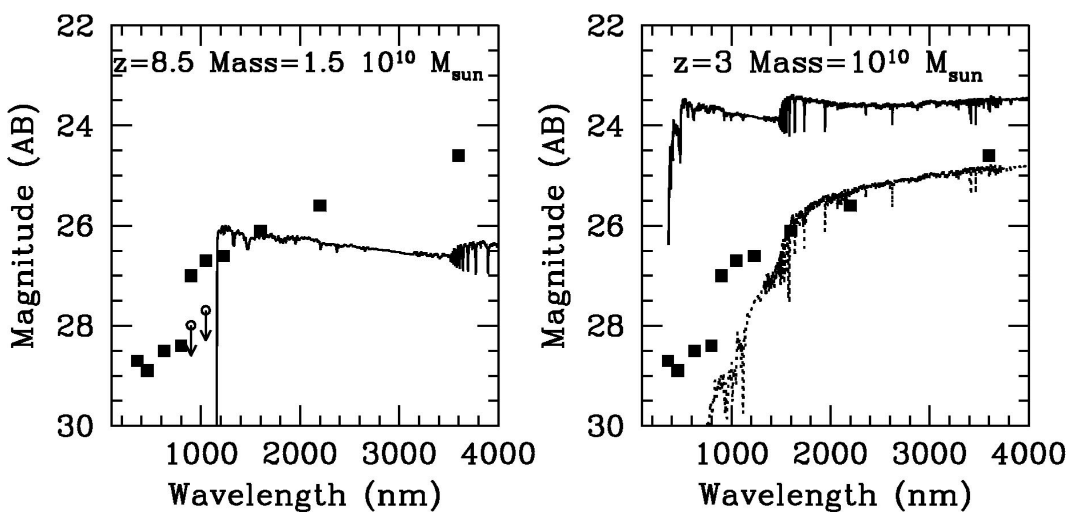


Figure 4: Limiting magnitude of the Deep Survey Field as a function of wavelength - the solid points indicate final $5-\sigma$ detection limits in each waveband. In the left-hand diagram, we have indicated the Spectral Energy Distribution (SED) of a galaxy with a mass of $1.5 \times 10^{10}$ M$_\odot$ at $z = 8$. As demonstrated by the $2-\sigma$ upper limits shown here for the z and Y bands, this galaxy would be selected as a Y-drop galaxy, with a strong ($\simeq$ 10-sigma) detection in J, and Y−J $> 2$. Crucially (see Figure 3) it can be seen here that this galaxy will also be detected in H (and marginally in K) with enough S/N to establish the colour longward of the break with sufficient accuracy to exclude low-redshift red galaxy interlopers, and galactic stars. In the right-hand panel we show two model SEDs of galaxies with a mass of $10^{10}$ M$_\odot$ at $z = 3$. The continuous curve is a model with a constant star-formation rate, the dotted curve is a model with a single burst population formed at $z = 5$. As is obvious from the plot, the old population is only detected in the reddest bands (H and Ks). Deep near-infrared imaging is crucial for the detection of such galaxies.

# 3 Are there ongoing or planned similar surveys? How will the proposed survey differ from those? (1 page max)

To our knowledge there are no other on-going surveys with similar depth and area combination. The proposed survey is unique because of the following:

**1. New data complementary to existing data**

The COSMOS field benefits from an exceptional dataset for which the added scientific return of near-infrared photometry will be very high. The COSMOS field has become one of the most widely surveyed areas in the sky in the framework of the COSMOS survey (http://www.astro.caltech.edu/cosmos). The core observations available in this field are deep HST-ACS imaging over the full 2 deg$^2$ in i-band, reaching $i(AB) = 27$ ($10\sigma$). A wealth of deep photometry is available in uBgriz from Subaru and CFHT (Taniguchi et al., in preparation), from 3.6 to 8 microns with Spitzer-IRAC (observations completed), and Galex 150 and 225 nm observations (Schiminovich et al., in preparation). Even deeper optical observations are in progress from the CFHTLS, reaching $u_{AB} = 28.7$ to $i_{AB} = 28.4$ (http://www.cfht.hawaii.edu/Science/CFHLS/cfhtlsgoals.html). A major redshift survey of $\simeq 35000$ galaxies is underway using 600h of observations at the VLT with VIMOS (Lilly et al., 2006). Near-infrared K-band photometry is only available today at a depth $K_s(AB) = 21$, and observations are in progress to reach $K_s(AB) = 23.5$. We are aiming to go one magnitude deeper in the full field and more than 2.5 magnitudes deeper in the ultra-deep 0.73 deg$^2$. The XMM-COSMOS survey has imaged the 2 deg$^2$ COSMOS area for 800 ksec reaching flux limits of 0.7, 3.3 and 10 $\times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ in the [0.5-2], [2-10], [5-10] keV bands respectively (Hasinger et al. 2006). The number of detected X-ray sources should reach $\sim 2000$ when the additional 600 ksec XMM-Newton time granted to the project is completed (A04). The central 0.7 deg$^2$are also going to be imaged with Chandra (1.8 Msec), reaching $4-5$ times deeper than XMM. VLA 1.4-GHz data have been taken over a large part of the field, to a 5-$\sigma$ limit of 40 $\mu$Jy.

**2. Survey Legacy Value for the community:**

The only facility able to meet these ambitious goals today is VISTA, and we are offering to carry out a public survey for the community. We will produce unprecedented data of long-lasting Legacy value. The 5-year time-scale of this survey will allow the productions of hundreds of very high-redshift candidates, which will be available for immediate VLT, ALMA and JWST follow-up. Once the time is awarded, the field will become the standard near-infrared deep field. We and others will propose for a variety of follow-up with other instruments (see Section 7).

**Other efforts**

The most obviously similar survey to the deep VISTA survey proposed here is the UKIDSS Ultra Deep Survey (UDS). This survey, with WFCAM on UKIRT, commenced in late 2005 and is scheduled to run for 7 years. The aim is to complete a 0.8 deg$^2$ survey of the Subaru-XMM deep field, to 5-$\sigma$ (AB) depths of K= 25, H= 25.3, J= 25.5. Our proposed VISTA survey therefore differs from the UDS in several key respects. First, the ultra-deep component is substantially deeper, especially in $J$ where the additional factor of 3-4 in depth is absolutely crucial for probing to the highest redshifts. Second, the UDS has no Y-band imaging, absolutely central to our strategy to search for Lyman-break galaxies at $z \simeq 7-8$. Third, the shallower component of the VISTA survey covers twice the area of the UDS. Fourth the supporting optical and Spitzer data in the COSMOS field are significantly deeper. Finally, the UDS field lacks the complete HST ACS i-band imaging which is unique to the COSMOS field, and allows the crucial connection between galaxy spectral and morphological evolution to be explored (as well as enormously aiding star-galaxy separation).

Near-infrared imaging of a sub-section of the COSMOS field also forms part of a J,H,K survey of CFHT Legacy fields now underway with WIRCam on the CFHT. However, because of the relatively small field of view of WIRCam ($20 \times 20$ arcmin), and the modest depth goals of this survey (K(AB)$\simeq$ 23.5), the currently-planned WIRCam imaging is clearly not competitive with the VISTA imaging proposed here.

Recently, the project DAzLE (The Dark Ages z Lyman-$\alpha$ Explorer; Horton et al., 2004) has been awarded 10 nights at the VLT to find $z = 7.7$ and $z = 8.8$ Ly$\alpha$-emitters. However, DAzLE could only cover several % of our field size to the depth proposed here. Hence there is no real overlap.

## 4 Observing strategy: (1 page max)

We propose to observe the COSMOS field, exposing only in a single $1.5 \times 1$ degree field. In order to reach our required depth, we propose to take very deep exposures of just 4 columns. This can be achieved in a homogeneous way by taking 3 pointings separated in the vertical direction by 1/3 of a detector size. Each position in the deep columns will be observed for 2/3rd of the exposures. The total observing time will be 1408 hours. The proposed geometry of 4 deep columns is a compromise between the desire to go as deep as possible on the one hand, and to have large contiguous coverage on the other hand for correlation studies. We note that full coverage of the $1.5 \times 1$ degree field to the required depth would take too much observing time, whereas coverage of a single pawprint would seriously hamper correlation studies, given the decreased pair separations between 10 and 15 arcmin.

The area between the 4 deep columns will be imaged to a shallower depth, with a total observing time of 212 hours. The narrow-band imaging will be performed on the very deep columns, for a total time of 180h.

All observations will be taken using the following strategy. The observations will be split up in Observing Blocks of 1 hour, exposing a single pawprint. Jitters in a box of 30 arcsec will be used to allow for the correction of bad pixels, structure in the dark, and reliable sky subtraction. These 1-hour observations will be straightforward to reduce. Three sequential Observing Blocks offset vertically by 1/3rd of a detector width will be executed to obtain full coverage of a column in a single band and, after that, the filter will be changed. This process will build up a homogeneous dataset over the years of the survey.

We note that the brightness of the near-infrared sky depends on the time of night and filter band. In the $K_s$-band, observations can be started by the time the sky is dark enough for the telescope to operate. The $K_s$-band sky brightness is sufficiently low around true sunset/sunrise, and hence observations can start well before astronomical twilight, if the telescope and ESO allows. The H-band sky behaves similarly, but it is known that the J-band sky continues to decrease strongly well after astronomical twilight, so for an optimal survey, these exposures are reserved for the middle of the night. The same undoubtedly holds for the Y band. *We request that ESO takes these considerations into account when planning for operations. The effectiveness of the telescope can be greatly increased if observations can start well before astronomical twilight.*

The choice of the COSMOS field was driven by the auxiliary data available for this field. It is optimal for a variety of reasons. One of the most important datasets available is the deep HST ACS i-band imaging. This imaging goes to a depth of 27.7 (5 $\sigma$) over the full field, and is absolutely unique. It can be used to select $i$-dropouts in combination with our dataset and the CFHT Legacy survey $z$-band imaging. The most important auxiliary observations are listed in the table below. The COSMOS field is the only field in the sky of the size of the VIRCAM with this kind of auxiliary imaging. Furthermore, it is accessible for future ALMA observations.

| COSMOS | | | | |
|---|---|---|---|---|
| Observatory | Band | Coverage | Depth ($5\sigma$) | Status |
| XMM | 7 keV | Full | 1.4 Msec | Completed |
| GALEX | 150 nm, 225 nm | Full | 25.0 (AB) | Completed |
| HST/ACS | $i$ | Full | 28.5 (AB) | Completed |
| Subaru | B,V,r',i',z' | Full | 27.4,26.9,26.9,25.6 (AB) | Completed |
| Spitzer | 3.6, 4.5, 5.8, 8.0 $\mu$m | Full | 160 hrs | Completed |
| Spitzer | 24, 70, 160 $\mu$m | Full | 16 hrs | Completed |
| VLA | 1.4 GHz | Full | 40.0 ($\mu$Jy) | Completed |
| CFHT | u*g'r'i'z' | Full | 28.7,28.9,28.5,28.4,27.0 (AB) | In progress |
| VLT/VIMOS | — | — | Multi-slit spectroscopy | In progress |
| CFHT/WIRCAM | J,H,K | Sub-region | 23.5 (AB) | Planned |
| SCUBA-2 | 450, 850 $\mu$m | 1 sq. degree | 2.5, 0.75 mJy | Planned |
| Herschel | 110 - 500 $\mu m$ | Full | 30 - 65 mJy | Planned |

# 5 Estimated observing time:

| Period | Time (h) | Mean RA | Moon | Seeing | Transparency |
|---|---|---|---|---|---|
| P79 | 68 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P80 | 292 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P81 | 68 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P82 | 292 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P83 | 68 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P84 | 292 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P85 | 68 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P86 | 292 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P87 | 68 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |
| P89 | 292 | 10h | Y: dark; Y+J+NB not near astr. twilight; H K: all conditions | <0.8 | clear |

We note that observations in H and $K_s$ can be taken between true sunset/sunrise and astronomical twilight. Dark time might be needed for Y-band observations. The dependence of the Y-band sky on moon phase is not documented on the ESO website, but as we observe in all moonphases anyway, this is likely the best approach. When commissioning data come in, the strategy will be adapted. We will still be able to make use of all moonphases effectively.

We request a seeing better than 0.8 arcsec as measured on the detector. According to the seeing statistics for Paranal, this corresponds to the best 75% of the time. The average seeing for the best 75% of the time is 0.68 arcsec. We used this value to calculate our magnitude limits. Our statistics are based on the DIMM statistics for 2005, and the conversion of DIMM seeing to seeing on the detector.

The ratio of time over even and odd periods (detailed in the table above) is chosen under the assumption that we are allocated a fixed fraction of all the time when the field is visible (above airmass 2). The survey is expected to run for 5 years, from mid 2007 to mid 2011.

The distribution of integration time over the fields and filters is given in the Table below.

| | **Ultra Deep Survey** | | | | **NarrowB** | **Deep Survey** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Y | J | H | $K_s$ | NB1185 | Y | J | H | $K_s$ |
| **Time & depth** | | | | | | | | | |
| Total Integration Time over field (h) | 320 | 320 | 320 | 320 | 170 | 48 | 48 | 48 | 48 |
| Depth (5 $\sigma$) AB | 26.7 | 26.6 | 26.1 | 25.6 | 24.1 | 25.7 | 25.5 | 25.1 | 24.5 |
| **Observing strategy per 1-hour OB** | | | | | | | | | |
| Detector Integration Time (DIT) (sec) | 60 | 30 | 10 | 10 | 120 | 60 | 30 | 10 | 10 |
| Exposure co-adds (Ndit) | 2 | 4 | 12 | 12 | 1 | 2 | 4 | 12 | 12 |
| Jitters (NJitter) | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| **Total time and efficiency** | | | | | | | | | |
| Time including overhead (h) | 337 | 343 | 364 | 364 | 180 | 51 | 51 | 55 | 55 |
| Observing efficiency | .947 | .933 | .878 | .878 | .955 | .947 | .933 | .878 | .878 |

## 5.1 Time justification: (1 page max)

The first goal of this survey is to go deep enough to be able to detect high-redshift galaxies (out to $z = 10$, if they exist), and put useful constraints on the evolution of high-redshift galaxies. Second, we wish to reach a depth comparable to, or better than that of the deepest current survey to study mass-selected galaxies at $z = 2 - 5$ to a stellar mass of $10^{10}$ $M_\odot$ at $z = 3$, over a much larger area. Investing a large amount of observing time is further justified as the final result is expected to be significantly better than other surveys by more than an order of magnitude in a combined area-depth comparison.

In order to select the high-redshift galaxies, we will use the well-established dropout technique. The flux below 1216 Å is suppressed so effectively by the IGM at $z > 6$ that it can be used as a very effective selection criterion. The galaxies are selected by using 3 bands: they should be red in band1-band2, and blue in band2-band3, where the 1216 Å break lies between band1 and band2. The requirement that galaxies are blue in band2-band3 avoids contamination by early-type galaxies or dusty galaxies at much lower redshifts. Additionally, it is required that the galaxies are not detected in bands bluer of band1.

These considerations lead to the conclusion that one requires to have more depth in the bluer bands, since the criterion that the galaxy has a drop-off can only be established if the bluest band (band1) is deep enough. On the other hand, one does not wish to have differences which are too big, since otherwise one does not go sufficiently deep in the reddest bands (J, H, K) to effectively select the highest redshift galaxies ( J-dropouts at $z = 10$). In short, there are two opposing requirements: to go deep in the bluer bands for effective dropout selection, and to go deep in the reddest bands to go sufficiently deep at the highest redshift.

Hence we propose to spend equal amounts of observing time in all bands. We calculated the following 5 $\sigma$ limits using the VISTA ETC version 1.2: 26.8, 26.6, 26.2, 25.6, in Y, J, H and $K_s$ respectively (complemented by the limit of 27 in the z, and 27.8 in i from CFHT and HST). These limits will allow us to find sufficient numbers of high-redshift galaxies, and are as deep, or deeper than the deepest ground-based survey, which is the FIRE Survey (Franx et al. 2003, Labbe et al. 2003). The total required integration time is 1280 hours, spread equally over the 4 bands. With overheads, 1408 hours are required.

The combined CFHT-VISTA survey reaches to 0.7, 0.9, 1.5 and 2.8 times $L_*(z = 6)$ at $z$ =6.3, 7, 8.5 and 9.5 respectively, assuming the Bouwens et al. (2006) $z = 6$ Luminosity Function. We expect substantial numbers of galaxies: 560 at $z = 6.3$, 450 at $z = 7.5$, 180 at $z = 8.5$, and 6 at $z = 10$. At $z = 3$, our depth in the $K_s$-band reaches to $M_{star} = 10^{10}$ $M_\odot$, as required. This allows us to construct mass-selected samples to the typical mass of UV-selected galaxies at the same redshift. As shown in Figure 4, our depths are well matched to the depth of the CFHT Legacy survey, and the ACS-COSMOS imaging.

The shallower part of the survey is 1 magnitude less deep, and takes 212 hours including overhead to complete. This depth is comparable to the depth of the UKIDSS UDS, and we can detect galaxies with masses of $M_{stars} = 2.5 \times 10^{10}$ $M_\odot$ at $z = 3$.

The integration time for the narrow-band imaging is driven by the desire to detect a statistically useful number of sources (20-30). We predict the expected number of $z = 8.8$ Lyman-$\alpha$ emitters using the models of two theoretical groups (Thommes & Meisenheimer, 2005, and Le Delliou et al. 2006), and the observations at $z = 5.7$ by Hu et al. (2004). The models predict $\approx$ 15 objects, whereas the luminosity function of Hu et al. predicts $\approx$ 30 objects for our survey at $z = 8.8$.

The most important contaminants among the Ly-$\alpha$ candidates are [OII] ($z = 2.2$) and [OIII] ($z = 1.35$) emitters. These can be eliminated by combining a strong limit of the equivalent width, and the observed flux in the observed optical waveband which is expected for these interlopers but not for $z = 8.8$ galaxies. Hu et al. (2004) found that this technique resulted in a low contamination fraction at $z = 5.7$ ($< 30$ %).

Finally, we wish to emphasize that the depths requested here cannot be compromised by a smaller allocation of telescope time. Our survey is currently unique in terms of depth and area (being more than 400 times larger than the similar FIRE Survey, and $\geq$1 magnitude deeper than the UDS Survey). Diminishing the exposure time implies that the survey becomes much less unique, and the high-redshift galaxies will not be found in large numbers. The total observing time required for this proposal is 1800 hours.

# 6 Data management plan: (3 pages max)

## 6.1 Team members:

| Name | Function | Affiliation | Country |
|---|---|---|---|
| J. Dunlop | Co-PI | University of Edinburgh | UK |
| O. Le Fèvre | Co-PI | Lab. d'Astro. de Marseille | F |
| M. Franx | Co-PI | Leiden Observatory | NL |
| J. Fynbo | Co-PI | Dark Cosmology Centre | DK |
| | | | |
| Y. Mellier / H.J. McCracken | Pipeline processing | Terapix, IAP | F |
| Terapix team | Data quality control Terapix -I | Terapix, IAP | F |
| Le Fèvre/Le Brun | Data quality control Terapix -II | Lab. d'Astro. de Marseille | F |
| CASU (VDFS) team | Pipeline processing | University of Cambridge | UK |
| CASU (VDFS) team | Data quality control -I | University of Cambridge | UK |
| J. Emerson | VDFS Coordinator | QMU London | UK |
| WFAU | Science Archive | University of Edinburgh | UK |
| WFAU | Data quality control-II | University of Edinburgh | UK |
| Franx/Rix | Data quality control Casu output III | Leiden/Heidelberg | NL/D |
| Rix | Aperture-matched broad-band catalogs | Heidelberg | D |
| V. Le Brun | Aperture-matched broad-band catalogs | Lab. d'Astro. de Marseille | F |
| Freudling/Møller | Narrow-band pipeline processing | ESO | ESO |
| J.G. Cuby | Narrow-band quality control | Lab. d'Astro. de Marseille | F |
| K. Nilsson | Narrow-band catalogs | Dark Cosmology Centre | DK |
| W. Sutherland | VISTA Project Scientist | University of Cambridge | UK |
| UltraVista team Co-Is | Survey scientists | | |

The Ultra-Vista team Co-Is are listed on page 1. The team-members will participate in team meetings (to be held twice a year), assist with the various tasks, and participate in the scientific exploitation.

## 6.2 Detailed responsibilities of the team:

The Co-PI's will have the shared responsibility for leading this project. Dunlop, Le Fevre and Franx will lead the broad-band imaging component, Fynbo will lead the narrow-band imaging component.

The Co-PI's will construct the overall observing plan, the OB's will be constructed in Leiden and submitted to ESO twice a year. Progress of the observations will be monitored in Leiden and Marseille.

Basic image processing will be done by CASU as part of the VDFS, the VISTA Data Flow System. The VDFS is a collaboration between the UK Wide Field Astronomy Units at Edinburgh (WFAU) and Cambridge (CASU) coordinated by the VISTA PI (QMUL) and funded for VISTA by PPARC. It is a working system which is currently used for the UKIRT WFCAM surveys as a test bed for VISTA. It is designed to work for VISTA and is readiness will be reviewed mid-October.

Further image processing will be done using the infrastructure of the Omega-Cen and the Terapix facility in Paris, who are both collaborating in the Astro-Wise consortium (http://www.astro-wise.org). Both facilities provide software to co-add, and manipulate images, and to derive catalogs. It is foreseen that two parallel efforts will be undertaken at least in the first year, to provide redundancy, and to allow the determination of the best algorithms. This work will be under the responsibility of Franx (using Omega-Cen) and Le Fevre (using Terapix).

Quality control of the CASU output will be performed in several Co-PI institutions.

The pipeline for the narrow-band imaging will have to be adapted slightly, as the central wavelength varies slightly over the field. This will be done by Freudling and Møller under the responsibility of Fynbo.

The most important data products are the reduced 1-hour observing blocks, and the fully-stacked images. Catalogs will be based on these fully-stacked images. It is foreseen that catalogs will be produced in several locations, appropriate as the science applications vary. All of these activities will be under guidance and under the responsibility of the Co-PI's.

We note that we have extensive experience with very deep near-infrared imaging on the team. Franx was PI of the FIRE Survey, which provided ultra-deep imaging of the Hubble Deep Field South going to similar depth; Labbé performed the reduction of this survey; Almaini is PI of the UDS survey which is about 1 magnitude shallower than this survey. CASU is pipelining this survey, and Terapix is handling major survey data now being taken at the CFHT. Dunlop and his group at Edinburgh have published the first results on galaxies at $z = 6$ from the UKIRT UDS survey, and hence have extensive experience of catalog production and contamination issues from infrared imaging covering $\simeq 1$ sq. degree.

## 6.3 Data reduction plan:

Our observations are planned to produce 1-hour images of a single pawprint. Basic pipeline reductions will reduce these 1-hour images to a series of 30 sky-subtracted, cleaned and flat-fielded images, which will then be stacked into one astrometric image. These 1-hour astrometric images are distributed in the consortium, and are the basic "building blocks" for our survey. Since we keep re-observing the same field, we will produce images which are astrometrically identical, i.e., they cover exactly the same area on the sky. Hence they only need to be co-added to produce the final image.

As a result, a key part of the data reduction is the pipelining of the 1-hour observation blocks. This pipelining will be done at CASU as part of the VDFS. CASU has extensive experience already with this process, as it is testing the current pipeline on the UKIRT WFCAM data. The data will be distributed to the Terapix and Astro-Wise databases after basic pipelining.

A critical step in the reduction process is the quality control of the reduced and stacked 1-hour observation blocks. This is more than establishing that the frames contain data: careful checks will need to be done to make sure that the data are not limited by detector problems, sky subtraction problems, or other artifacts. Experience with VLT and UKIRT has shown that these problems can arise for substantial fractions of the data, and this will require early flagging, and potential adaptation of pipelines. We note that the survey which we are proposing is fairly uncommon for these telescopes as we will go very deep. Hence, in some sense, we are exploring new territory here, and we have to be ready to adapt our pipelines if necessary.

The narrow-band data will require additional reductions due to a small passband shift over the field. We plan to get access to science commissioning data for the VISTA narrow-band filter in order to investigate and prepare for the special corrections that may be necessary in the data reduction.

The final quality control for the CASU processed data will take place in Leiden, Heidelberg and Marseille.

Co-addition and catalog construction will be performed in Co-PI institutions, depending on the science application. For example: for the study of the $z = 2 - 5$ universe, one wishes to select objects in the $K_s$ band. On the other hand, Y-dropout studies will use J-band or H-band selected catalogs.

## 6.4 Expected data products:

Data products will include flux-calibrated astrometric 1-hour images, full co-added images, and multi-parameter catalogs coming from the SExtractor software and other programs. These data will be placed for public access in the ESO public archive.

Full multi-colour catalogs are more difficult to produce, but will be provided on a best-effort basis.

### 6.5 General schedule of the project:

T0: start of observations. Homogeneous coverage of the full area to the depth of the wide survey
T0+12months: start of deep survey
T0+13months: release of the first reduced data (from the first month of observing
T0+20months: release of the first year's data fully reduced (assuming that data taking lasts 8 months, and processing 1 year).

Thereafter we expect that we can deliver science products to ESO within 1 year after the observations have been done.

## 7 Envisaged follow-up: (1 page max)

The combined dataset on the COSMOS field will be a treasure for scientific exploration and follow-up observations. The following is already foreseen:

1) spectroscopic studies of the highest redshift galaxy candidates:
VLT spectroscopy with KMOS, X-Shooter and other spectrographs can detect Ly$\alpha$ from the high redshift galaxies. The detected emission line objects at $z = 8.8$ are prime candidates. For the continuum selected galaxies, continuum spectroscopy is beyond the capabilities of the VLT, but it is possible to do Ly-$\alpha$ spectroscopy of those galaxies with equivalent widths of more than 20 Åin the rest frame. Approximately 30% of the Lyman break galaxies have such strong emission out to $z = 6.5$ (Dow-Hygelund et al. 2006, submitted). This requires observations at 1 $\mu$ and beyond, which will become possible with KMOS on the VLT, EMIR on Grantecan, or Lucifer on the LBT. Integration times for the emission line objects will be 20-60 hours, integration times for the continuum detected objects will be longer, and will be done using the multiplex of KMOS.

2) ALMA follow-up of full field, and deep exposures in selected areas.
ALMA can go very deep, but has a small FOV for continuum imaging. Hence we foresee deep follow-up on selected objects, and shallower follow-up on larger areas. ALMA imaging will produce very accurate sub-mm fluxes. Star formation rates of 10 $M_{\odot}$/year can be detected in the continuum to $z = 8$ with integration times of 30 minutes. This will give star formation rates completely independent of the UV determined star formation rate, and will answer the question whether these galaxies had build up a reservoir of dust.

We note that the COSMOS field has a very suitable RA for follow-up with ALMA - many other extragalactic fields have RA around 0-4 hours giving much higher time pressure (and conflicting with SMC and LMC).

3) JWST follow-up of dropout galaxies.
Obviously, this field will be an ideal choice for JWST spectroscopy. The galaxies will be fairly bright for JWST standards. At the limit of our survey, it will take just $10^4$ seconds with Nirspec on JWST to get a R=100 spectrum with a S/N of 10 per resolution element in the continuum. These spectra will be of much higher quality than the ones currently available for $z \geq 2$ galaxies. An integration time of 1000 sec will be enough to measure the redshift of the faintest galaxies. Spectroscopy at R=1000 at the same S/N would take an integration of about $10^5$ seconds, and retrieve invaluable information about absorption lines, etc. The emission line galaxies selected with the narrow-band imaging can be confirmed within $10^4$ seconds with Nirspec on JWST. On our proposal, co-Is Bunker and Franx are members of the ESA JWST instrument team with 900h of GTO.

4) High spectral resolution studies with ELT.
ELT can perform very competitive high resolution spectroscopy, for kinematics and accurate linestrengths and lineprofiles. The integration times for continuum spectroscopy will depend on the sizes of the object, and will be comparable to the JWST integration times for 30-m class telescopes (around $10^4$ seconds). These integration times are perfectly reasonable, and we note that this is possible because we sample a wide area deeply.

5) Sub-mm and far-infrared follow-up
The COSMOS field is also one of the key fields which will be targeted for very deep sub-mm imaging at 850$\mu m$ and 450$\mu m$ as part of the SCUBA2 Cosmology Legacy survey (P.I.s Dunlop, Smail, van der Werf, and Halpern).

This survey is due to commence at the JCMT in late 2007. Over 5 years the central $\simeq 1$ square degree of this field will be mapped with SCUBA2 to rms depths of $\sigma_{450} = 0.5$ mJy, and $\sigma_{850} = 0.15$ mJy, with the deep $450\mu m$ imaging facilitating the deconvolution of the highly confused $850\mu m$ image.

In parallel with this sub-mm imaging, it is also planned (through a mix of guaranteed time and key project open time) to obtain deep far-infrared images of the COSMOS field with the PACS and SPIRE instruments on board Herschel. The current plan, commencing after launch in 2008, is to map 2 sq. degrees to r.m.s. depths of $\sigma_{110\mu m} = 6$ mJy, $\sigma_{170\mu m} = 6.5$ mJy, $\sigma_{250\mu m} = 9$ mJy, $\sigma_{350\mu m} = 11$ mJy, $\sigma_{500\mu m} = 13$ mJy. Ultra-deep imaging (a factor of 3 - 4 deeper) over the central 0.25 sq. degrees is also being proposed by J. Dunlop, as part of the Herschel Open Time Consortium.

# 8 Other remarks, if any: (1 page max)

Please note that this survey cannot be cut significantly in time or passbands used. Cuts in observing time will make it much less appealing, as the uniqueness will suffer, and the number of high redshift galaxies found will go down fast. No passbands can be cut, as the Y,J,H passbands are absolutely required for the I,Z,Y, dropouts, whereas the K band is absolutely required for the construction of mass selected samples out to $z = 4.5$, and for J dropouts.

**Comparison of VISTA and HAWK-I**: HAWK-I on the VLT will be faster per field, but the area is 36× smaller so that it will never be able to do this kind of large survey. Furthermore, much less telescope time is available on the VLT per instrument. Realistically, only a few very deep fields can be done per year on the VLT (e.g., FIRES, GOODS experience).

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