European Organisation for Astronomical Research in the Southern Hemisphere

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Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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1. Title — Category: **X–0**

The Physics and Mass Assembly of Galaxies out to $z \sim 6$

2. Abstract

We propose to obtain ELT spatially resolved spectroscopy of a sample of a thousand massive galaxies at $2 < z < 6$, selected from future large area optical-nearIR surveys. These observations will yield direct kinematics of stars and gas in the first generation of massive galaxies (in the range $0.1 < M < 5 \times 10^{11} M_{\odot}$), as well as their stellar population properties. One will be able to derive dynamical masses, ages, metallicities, star-formation rates, dust exinction maps, to investigate the presence of disk and spheroidal components and the importance of dynamical processes (e.g. merging, in/outflows) which govern galaxy evolution. These data will also allow one to study the onset of well known scaling relations at low redshifts, and to witness the gradual shift of star formation from the most massive galaxies in the highest density regions to less massive galaxies in the field. The whole program is designed to provide the ultimate test of galaxy formation theories.

3.

Run	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	Multi-IFU	30n	jun	n	$\leq 0.8''$	CLR	v

4. Principal Investigator: **Piero Rosati** (ESO, ESO, prosati@eso.org)

CoI(s): Mathieu Puech (ESO, ESO), Andrea Cimatti (Bologna, I), Sune Toft (ESO, ESO), Marijn Franx (Leiden, NL), Jacqueline Bergeron (IAP, F)

5. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

Yes / N/A / mid-course

6. Description of the proposed programme

A) Scientific Rationale: Over the last decade, the synergy of 8-10m class telescopes with HST has strongly reinvigorated the field of galaxy formation and evolution by unveiling very distant galaxies ($z \sim 6$), by allowing the first determination of the global star formation history since redshift $z \sim 6$ and by providing the first insights on the stellar mass assembly history out to $z \sim 3$. Despite this recent progress, the outstanding question remains on *how and when* galaxies assembled their *baryonic* mass across cosmic time. The ΛCDM standard model has provided a satisfactory scenario describing the hierarchical assembly of dark matter halos, in a bottom-up sequence which is now well-established over the whole mass structure spectrum. In contrast, little progress has been made in the physical understanding of the formation and evolution of the baryonic component because the conversion of baryons into stars is a complex, poorly understood process. As a result, all intellectual advances in galaxy formation and evolution over the last decade have been essentially empirical, often based on phenomenological (or "semi-analytical") models which heavily rely on observations to describe, with simplistic rules, such processes as star formation efficiency, energy feedback from star formation and AGN, chemical evolution, angular momentum transfer in merging, etc. Cornerstones observations in this empirical framework are the (total and stellar) mass of galaxies and their physical properties, including age and metallicities of their underlying stellar populations, dust extinction, SF rate, structural/morphological parameters. The study of well-established scaling relations involving a number of these physical parameters (e.g. mass-metallicity, fundamental plane, color-magnitude, morphology-density) are essential for understanding the physical processes driving galaxy evolution. However, with the current generation of 10m-class telescopes, we have been able to construct for example the fundamental plane of early-type galaxies, or to measure the Tully-Fisher relation of late types over a wide range of masses only at low redshifts, whereas only the brightest or most massive galaxies have been accessible at $z > 1$, and a direct measuremnt of masses has been almost completely out of reach at $z > 2$. Thus, our ability to explore the evolution and origin of the aforementioned scaling relations has rapidly reached the limit of 10m-class telescopes. As a result, most of the outstanding questions arisen from recent observational galaxy evolution studies which have pushed the VLT to its limit call for an ELT, specifically to extend the spectroscopic limit by at least two magnitudes with near-diffraction limit angular resolution. HST/Nicmos imaging studies have shown that massive galaxies with disk-like morphologies exist at least out to $z \sim 2.5$ (see Fig.3). IFU spectrographs on 9-10m class telescopes (e.g., VLT/SINFONI and Keck/Osiris) are currently able to distinguish merging from rotating disks in star-forming (SFR$= 100 - 200$ M$_\odot$/yr) massive galaxies ($v \gtrsim 200$ km/s, or $\sim 10^{11} M_\odot$) out to $z \approx 2$ (Genzel et al. 2006; Förster Schreiber et al. 2006; Wright et al. 2007, Shapiro et al. 2008). Spatially resolved metallicity maps have been attempted only for a few very bright late-type galaxies at $z \sim 2$ (Förster Schreiber et al. 2008, in prep.). In addition, observations of bright Ly-break galaxies at $z \sim 3$ and their sorrounding IGM have revealed very large and ubiquitous outflows which play a crucial role for the energy feedback and metal enrichment of the IGM (Steidel et al. 2007). To date, these studies have been confined only to the brightest and most massive galaxies at $z \lesssim 2.5$, thus providing a limited and biased view on galaxy formation.

An ELT, equipped with an optical-nearIR AO-assisted MOS, will remove these limitations, by directly probing physical properties of galaxies as a function of their masses and environment over 90% of the age of the Universe. Specifically, we will extend current studies of massive galaxies to $z \sim 5$ and extend the accessible mass range by more than a factor of 10 at $z \sim 2$. This will provide crucial information on the baryon physics in galaxy evolution models and will drive the transition from current phenomenological models to a physical understanding of galaxy formation and evolution.

B) Immediate Objective: The proposed experiment consists of spatially resolved ELT spectroscopic observations of a sample of ~ 1000 galaxies over the redshift range $2 < z < 6$. Specific requirements on the telescope/instrument system to reach the scientific objective discussed here are discussed in the following section. Specific science goals and measurements for this project include:

– High spatial resolution spectroscopy will provide direct kinematics of stars and gas in the first generation of massive galaxies in the range ($0.1 < M_{star} < 5 \times 10^{11} M_\odot$). The resolution will be of the order of FWHM= 0.01 arcsec in the H band, corresponding to 80pc at $z = 3$. This will allow one to assess the relative importance of different dynamical processes (e.g. merging, in/out-flows) in governing galaxy evolution at different cosmic times. Thus, it will be possible to quantify the role, physics and rate of merging in modulating star formation, mass assembly and morphology evolution.

– The evolution of the galaxy mass function will be traced by measuring dynamical masses (accurately derived from kinematic maps) of the first massive galaxies, i.e. 10 times more massive of the Milky Way ($M \sim 10 M_{MW}$), at virtually any redshift and as well as lower mass galaxies ($\sim 0.1 M_{MW}$) over 90% of the age of the Universe. This will require moderate-to-high resoution ($R > 1000$) integral field or multi-object spectroscopy to measure rotation curves from emission lines in disk-like systems and velocity dispersions from absorption-lines in early-type galaxies.

– The cosmic epochs over which the mass assembly of spheroids and disks occured will be determined. Current observations suggest that the build-up of spheroids was largely over by $z \sim 1$, just when the major build-up of disks was ramping up to dominate later on.

6. Description of the proposed programme (continued)

– Dust extinction is currently very difficult to estimate because the Balmer lines are redshifted in the near-IR, where the current sensitivity is often not enough to detect lines such as Hβ. With ELT spectroscopy, it will be possible to derive dust extinction maps from Balmer line ratios. Such a knowledge is essential to reliably derive physical parameters and to break the complex degeneracies due to dust extinction.
– The star formation rate (SFR) will be derived from the extinction-corrected emission line luminosity (e.g. Hα to $z \sim 2.5$, [OII] to $z \sim 5$), and compared with other indicators coming from multi-wavelength observations (e.g. ALMA, Herschel, JWST). The knowledge of the dynamical masses will constrain the specific star formation rates (SSFR=SFR/Mass) and the mass growth history in galaxies.
– The detailed properties of the stellar continuum, absorption and emission lines will be used to derive the age, metallicity and star formation history of the stellar population and to break the degeneracies between these quantities that affect the interpretation of the current results.
– The relative velocity of emission and absorption lines of different species will place important constraints of the ISM physical state and dynamics. This will also allow to identify the sources of feedback processes (energy injection into ISM, superwinds, outflows, AGN) and the origin of the SF quenching in massive halos and its possible link with the onset of the massive black hole - bulge relation and galaxy/AGN co-evolution.
– Current determination of the stellar mass function and its evolution is based on the model dependent method of "photometic masses" from multi-wavelength surveys, whose reliability remains largely untested. The ELT will provide crucial calibration of this method by allowing masses to be determined, via dynamical methods or strong gravitational lensing, for galaxies over the widest range of redshifts and morphological type.
– The transition of massive star formation from high-density environments to the field will be observed (current evidence tentatively places the epoch of such transition at $z > 4-5$).
– The migration of star formation rate from high to low masses as galaxies evolve ("downsizing effect") will be studied, by measuring M/L ratios of distant galaxies over a wide range of masses (only the most massive galaxies can be probed today out to $z \sim 1$).
– The evolution of velocity distribution function of satellites of nearby galaxies down to ~ 30 km/s (Loeb & Peebles 2003) will be observed as a direct probe of DM halo properties and as a test of CDM predictions.

Sample Selection and Synergies with other facilities:
Most of the issues to be addressed with the ELT in the field of galaxy evolution will benefit greatly from the synergy with JWST, which will provide rest-frame optical imaging of galaxies with superp spatial resolution over the widest redshift range, as well as low resolution integrated spectroscopy. These space capabilities are likely to remain unmatched even in the era of ELT with LTAO. The galaxy samples needed for this science case will likely be drawn from the next-generation large field surveys in the optical (e.g. LSST and Pan-STARRS), near-IR (VISTA), and or sub-mm surveys with ALMA. Several mass selected samples of galaxies out to $z \sim 6$ will be available over the next decade, however the ELT observations proposed here will likely result into a flux-limited sample.

<u>References:</u>
Genzel R. et al., 2006, Nature, 442, 786
Grazian A. et al., 2006, A&A, 449, 951
Förster Schreiber N. M. et al., 2006, ApJ, 645, 1062
Loeb A. & P.J.E. Peebles 2003, Apj, 589, 29
Shapiro K.L et al. 2008, Ap.J, in press
Steidel C.C. et al. 2007, in proc. of "Cooling, Star Formation, and Feedback in High Redshift Galaxies", Gaching bei München
Toft S. et al., 2007, ApJ, 671, 285
Wright S.A. et al., 2007, ApJ, 658, 78

C) Telescope Justification:

Technical requirements for the telescope/instrument systems are derived as follows.
A sample of at least 1000 galaxies at $z < 2 < 5$ is required to properly sample galaxy diversity over the mass, redshift and "morphological type" (mergers, disks, spheroids). If we take a redshift range of $z = 1.5 - 5.6$, current observations suggest a K-band magnitude for L^* galaxies in this redshift range of $K^*_{AB} = 22 - 25$, with corresponding surface densities of $\Sigma(\text{gal/arcmin}^2) \approx 10, 1, \sim 0.1$, for $L > L^*$, at $z = 2, 4, 5$. Across the probed redshift range, the minimum mass accessible will vary from 0.1 to a few times M^*.
The sample size and surface densities imply a field of view of 20-100 arcmin^2 and a multiplex factor of at least 10, possibly up to 100. Spectral resolutions $R \sim 3 - 5000$ are required for adequate OH removal and detection of kinematic gradients. As a result, either a deployable IFU system with MOAO or a large monolithic IFU (LTAO) should be adequate for this project.
Required spatial sampling is of ~ 50 mas to resolve galaxies in at least 10 spatial bins given their effective radii of $R_E = [0.1 - 0.3]$ arcsec. This implies that AO performance are critical for this experiment, requiring an LTAO system, eventually MOAO.

6. Description of the proposed programme (continued)

Mapping physical properties (SFR, metallicity, dust) and dynamics requires mostly near-IR coverage, however to cover standard diagnostic lines, [OII]3727, [OIII]5007, Hβ, Hα, over the entire redshift range [1-5], one would need a wavelength coverage of $0.8 - 2.5\mu$, with trade-offs due to varying AO performance across this range.
Typical exposure times (see Sect.7 below) for M^* galaxies out to $z \sim 5$ are in the range 10-50 hours, making the whole program feasible in roughly 20-50 nights.
A first analysis of these requirements based on scaling arguments shows that no break points are apparent in achieving science goals, when considering a telescope diameter in the range of 30-42 meters. There is however a clear advantage for large apertures if one wants to access the highest redshift of galaxy assembly and an adequate range of galaxy masses (i.e. $0.1\,M^* < M < \text{a few}\,M^*$) over $2 < z < 5$.
Requirements and main parameters of targets are summarised in Table 1. below.

D) Strategy for Data Reduction and Analysis: The Puech et al. reduction pipeline used for the simulations described below (see Fig.2) will be well suited to reduce these data.

6. Attachments (Figures)

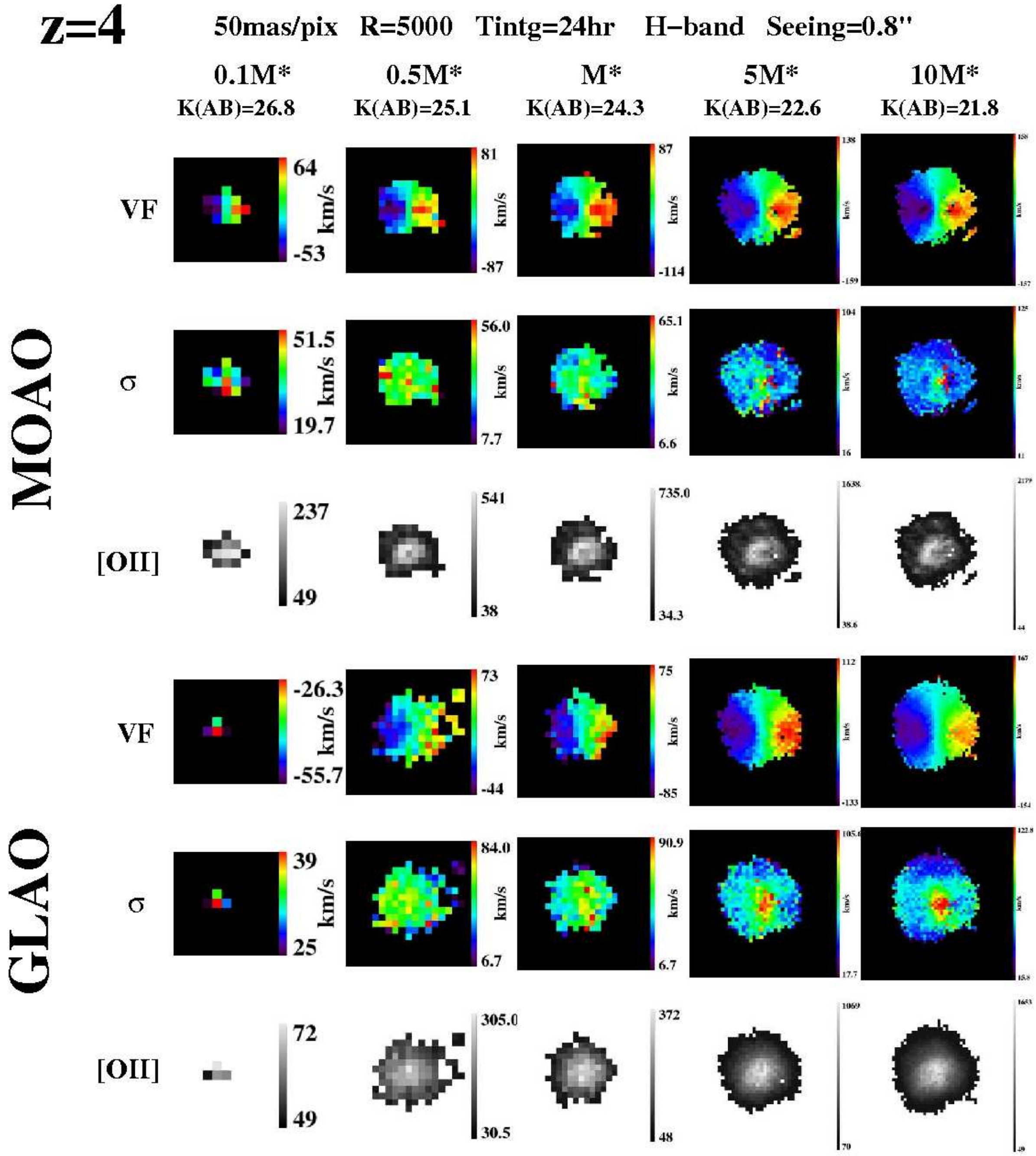

Fig. 1: Example of E-ELT simulation of spatially-resolved spectroscopic observations. An E-ELT equipped with a 3D spectrograph will provide kinematic maps of distant galaxies down to M* and up to $z \sim 4.5$. The M* galaxy case (central column) has $K(AB) = 24.4$ K and a line flux of 9×10^{-18} erg cm^2 s^{-1}. This figure illustrates the $z = 4$ case showing a rotating disk rescaled at different stellar masses (see Puech et al., in prep., for details). MOAO allows one to reach a better spatial resolution than GLAO (see the more curved isovelocities and the sub-structures in the [OII] emission map in the MOAO case), which is better suited for recovering the rotation curve of distant galaxies. However, GLAO already provides adequate spatially resolved kinematical information, which can be used to infer the dynamical nature of this source, e.g. a rotating disk. The latest AO PSF models (Feb 2008) have been used here.

6. Attachments (Figures)

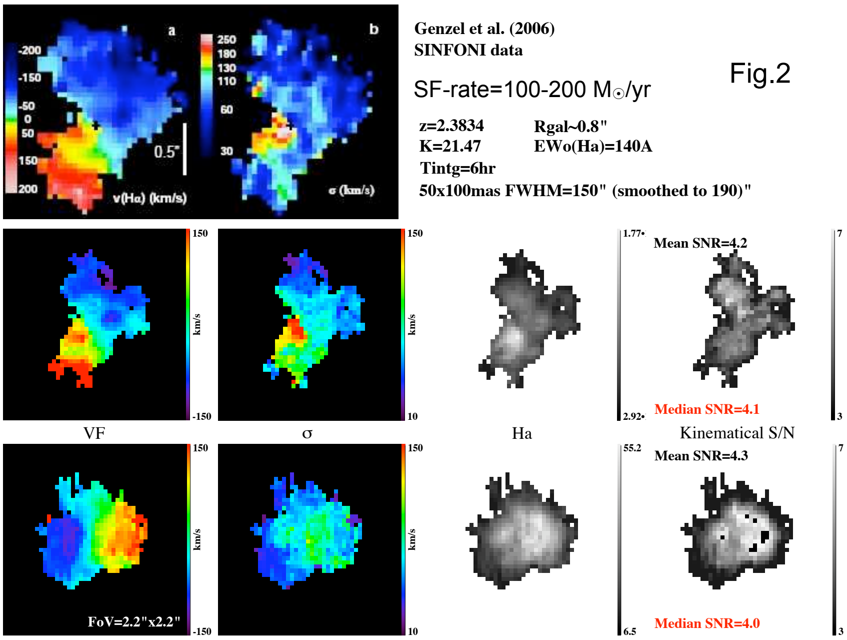

Fig.2

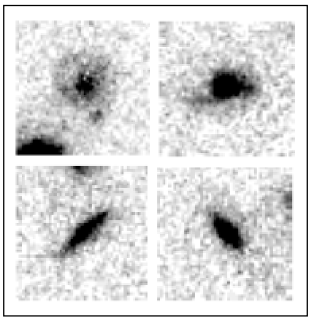
Fig.3

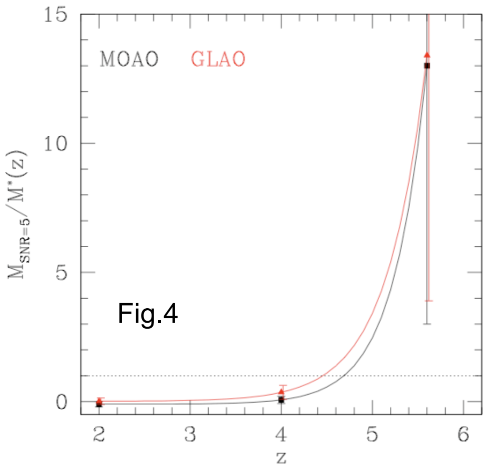

Fig.4

Fig. 2: Simulations of Genzel et al. observations of a massive star-forming galaxy at $z = 2.3$ with SINFONI on the VLT. *First line*: original Genzel et al. results; *second line*: re-analysis of the Genzel data cube with Puech's reduction pipeline (from left to right: velocity field, velocity dispersion, and Hα SNR; *third line*: simulation of VLT/SINFONI observations of a local disk galaxy rescaled to match physical parameters (mass, size, line EW, K-magnitude and kinematics) of Genzel's galaxy. Note how these simulations reproduce very well the observed signal-to-noise (rightmost images) in the Hα line.

Fig. 3: Nicmos-3 images of 4 massive ($\sim 10^{11}\,M_{\odot}$) star-forming (with a typical star-formation rate of 100 $M_{\odot}$/yr) galaxies at $z = 2 - 3$. Images are $5''$across. (From Toft et al. 2007).

Fig. 4: Galaxy (stellar) mass corresponding to the minimum S/N needed for reliable kinematic measurements (see text) as function of redshift. The vertical bars cover a wide range of dynamical and morphological cases (Puech et al. 2008, in prep.). This plot shows that one can obtain reliable kinematically maps of galaxies down to M^*, out to $z \simeq 4.5$.

7. Justification of requested observing time and lunar phase

Lunar Phase Justification: Provide here a careful justification of the requested lunar phase.

Time Justification: (including seeing overhead) As a reference case, we consider a $z = 4$ star-forming galaxy with $H_{AB} = 24.3$ (or 22.9 Vega) which is a good estimate for an M^* galaxy from current stellar mass function studies. We assume an half-light radius of $R_H = 0.2$ arcsec. A robust assessment of the feasibility for this science case requires detailed 3D spectroscopy simulations, which were carried out using the Puech et al. methodology (Puech et al. MNRAS, submitted). Simulations were performed for a reference disk galaxy with a circular velocity of 230 km/s, size $= 4R_H = 0.8''(5.6\,kpc)$, observed in the [OII] line with $EW_0 = 30\,\AA$. We adopt a redshift dependence of the size as reported by Ferguson et al. 2004, and rescaled galaxy sizes as a function of mass following Courteau et al. 2007 (i.e. $R_{1/2} \propto M^{0.35}_{stellar}$). The S/N map peaks at $\sim$25 in the center, with a mean over the entire galaxy of $S/N = 12$. The sky model spectrum for Mauna Kea from the Gemini web pages was used (this corresponds to a mean sky brightness of 16.4 Vega-mag/arcsec^2). An MOAO correction was assumed giving 45% encircled energy within 100 mas). With this S/N one can recover the bidimension kinematics, in particular classify kinematically the galaxy (e.g. distinguish a disk from a merger) and reliably measure the rotation curve over the entire galaxy. A full grid of simulations (Puech et al. in prep., see example ein Fig.1) for different set up parameters (R, sky brightness, AO case, pixel scale), as well as physical parameters (R_H, mass, redshifts) have been run.
Results from these simulations suggest that to ensure robust kinematic measurements, we need a signa-to-noise over the galaxy size of at least 5, with the following scaling according to exposure time T, telescope diameter D, equivalent width EW, spectral resolution R, and pixel scale Δpix:

$$< S/N >_{min} = 5 \left(\frac{T}{24h}\right)^{0.5} \left(\frac{D}{42\,m}\right) \left(\frac{EW}{30\text{Å}}\right) \left(\frac{R}{5000}\right)^{-0.5} \left(\frac{\Delta pix}{50\,mas}\right)$$

The stellar mass that corresponds to such a minimal SNR increases with redshift z, according to

$$M_{lim}(z)/M^* = 0.1 + 3.3 \times 10^{-6} \exp(z/0.37)$$

For the characteristic stellar mass, M^*, we assumed $\log_{10} M^*(z) \approx 11.6 + 0.17z - 0.07z^2$, an empirical relation which describes the evolution of the observed mass function (Grazian et al. 2006).

Calibration Request: Special Calibration - None

8. Instrument requirements

Table 1. – **Main Technical Requirements and Target Parameters**

Requirements	Range of values (minimum/ideal)
Field of View	25–100 arcmin^2
Wavelength range	0.8–2.5 μ
Multiplexing	10–100
Spatial sampling	50–100 mas
Spectral resolution R	3–5000
50% enclosed energy diameter	< 250 mas (MOAO)
Target parameters	
Typical magnitude	22–25 (K_{AB})
Redshift range	2–6
Typical mass	$> 10^{10}$ $M_\odot$
Target density	0.1–10 arcmin^{-2}
Object size	0.1–0.5 arcsec
Typical Exptimes	10-50 hrs

9. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	UDF	3:32:39.0	-27:47:00	10-100	25	DM	ang diam(')	note

Target Notes: N/A