4MOST – 4-metre Multi-Object Spectroscopic Telescope

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ABSTRACT

4MOST is a wide-field, high-multiplex spectroscopic survey facility under development for the VISTA telescope of the European Southern Observatory (ESO). Its main science drivers are in the fields of galactic archeology, high-energy physics, galaxy evolution and cosmology. 4MOST will in particular provide the spectroscopic complements to the large area surveys coming from space missions like Gaia, eROSITA, Euclid, and PLATO and from ground-based facilities

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like VISTA, VST, DES, LSST and SKA. The 4MOST baseline concept features a 2.5 degree diameter field-of-view with ~2400 fibres in the focal surface that are configured by a fibre positioner based on the tilting spine principle. The fibres feed two types of spectrographs; ~1600 fibres go to two spectrographs with resolution R>5000 (λ~390–930 nm) and ~800 fibres to a spectrograph with R>18,000 (λ~392-437 nm & 515-572 nm & 605-675 nm). Both types of spectrographs are fixed-configuration, three-channel spectrographs. 4MOST will have an unique operations concept in which 5 year public surveys from both the consortium and the ESO community will be combined and observed in parallel during each exposure, resulting in more than 25 million spectra of targets spread over a large fraction of the southern sky. The 4MOST Facility Simulator (4FS) was developed to demonstrate the feasibility of this observing concept. 4MOST has been accepted for implementation by ESO with operations expected to start by the end of 2020. This paper provides a top-level overview of the 4MOST facility, while other papers in these proceedings provide more detailed descriptions of the instrument concept[1], the instrument requirements development[2], the systems engineering implementation[3], the instrument model[4], the fibre positioner concepts[5], the fibre feed[6], and the spectrographs[7].

Keywords: Wide-field multi-object spectrograph facility, VISTA telescope, tilting-spine fibre postioner, wide field corrector, facility simulator, science operations, Gaia, eROSITA

1. INTRODUCTION

The need for wide-field, high-multiplex spectroscopic survey facilities has been identified in a number of strategic documents like the Science Vision for European Astronomy[9], the ASTRONET Infrastructure Roadmap[10], their updates and several others[11][12]. In response, ESO selected in 2011 the MOONS[13] and 4MOST projects to conduct Concept Design Studies for Multi-Object Spectroscopic (MOS) facilities in the near-infrared and the optical, respectively. Both projects went through their Concept Design Reviews in spring 2013 and were selected for implementation. For budget profile reasons at ESO the start of 4MOST was delayed by a year and the official kick-off of the Preliminary Design Phase with ESO is now expected in January 2015.

While preparing for the Preliminary Design Phase, 4MOST is going through an Optimization Phase. During this phase the consortium is re-evaluating the science and system requirements with their proper flow down, seeking cost reductions from the Concept Design, consolidating the consortium and management structure and securing the required capital costs funding and labour resources beyond what is provided by ESO.

The goal of 4MOST project is to create a general-purpose and highly efficient spectroscopic survey facility useful for many (for most?) astronomers in the ESO community. The 4MOST design philosophy is based on the notion that 4MOST is not just an instrument, but is a *survey facility*, meaning that:

- **4MOST runs all the time**: there will be minimal instrument changes, 4MOST will be running almost all of the time on the telescope during its main two times 5 year surveys,
- **4MOST provides a total package**: the target selection, operations and survey strategy, instrument capabilities, and high level data product delivery are all part of facility and are optimally tuned to compliment each other,
- **One design fits many science cases**: the design and operations will minimize the constraints on science cases that need optical spectroscopy, but the number of observing modes (e.g., spectrograph configurations) should be kept to a minimum (preferably one). The goal is to deliver a general-purpose, reliable, but simple instrument, operations concept and data analysis software that is well suited to most science cases. To increase efficiency all science cases will be running at the same time in parallel, all the time.

The Project Office of the 4MOST project is located at the Leibniz-Institut für Astrophysik, Potsdam (AIP). During the Conceptual Design Phase the technical development was carried out by the AIP, Universität-Sternwarte München, Max-Planck-Institut für extraterrestrische Physik, Landessternwarte Heidelberg in Germany, the University of Cambridge and Rutherford Appleton Lab in the United Kingdom, the Observatoire de Paris à Meudon in France, ASTRON in the Netherlands, and the European Southern Observatory. Additional science support was provided by the Uppsala and Lund Universities in Sweden and the University of Groningen in the Netherlands. The consortium structure for the following phases is described in Section 7.

In Sections 2 and 3 we describe the main science drivers and the operations concept of 4MOST, which together drive the instruments specifications laid out in Section 4. In Section 5 we present an overview of the instrument concept and the

4MOST facility simulator and its results are described in Section 6. In Section 7 describes the consortium structure, and we conclude we conclude with the further schedule and summary in Section 8.

2. SCIENCE DRIVERS

We live in an era of ever larger and deeper sky surveys, covering a broad range of wavelengths. A number of surveys are completed/on-going (e.g., VISTA-surveys, VST-surveys, Pan-STARRS, SDSS, GALEX, WISE, 2MASS, DES, SkyMapper, Gaia) others are on the verge of being started/launched (e.g., eROSITA, ASKAP), while yet others have been approved for construction (e.g., Euclid, LSST, SKA). To reach their full potential and their most ambitious science goals, all these surveys are in strong need of large-area, high-multiplex spectroscopic complement in order to identify and characterize detected sources. While current facilities are used to conduct large spectroscopic surveys (e.g., RAVE, Gaia-ESO, Sloan/SEGUE/BOSS/APOGEE), the new flood of imaging surveys requires a next generation of spectroscopic survey instruments. The 4MOST facility aims to bring this capability to the ESO community.

To derive the instrument requirements for a facility that runs both large dedicated surveys and is a general purpose tool for a large ESO community we decided to develop a number of Design Reference Surveys (DRSs) that 4MOST should be able to run in parallel. The DRSs are those key science projects that are strongly supported by the European scientific community and at the same time put the tightest limits on the design. These DRSs will now be further developed into real 4MOST Consortium Surveys, while additional surveys from both the community and consortium will be added at a later time approximately three years before the start of operations. Below we first describe the key 4MOST Extra-galactic and Galactic Surveys that the consortium will implement, then indicate some other surveys that could be conducted by 4MOST, and finally present a list of top-level science requirements derived from our DSRs.

2.1 Extra-galactic Science and Cosmology

Constraining the origin of the accelerating universe is expected to be a significant driver of the observations that are going to be done with 4MOST. Depending on the point of view, the accelerating universe can be interpreted as a form of dark energy or as modified gravity. 4MOST will provide constraints on the models by measuring the cosmic expansion history and the growth of structure using several different probes:

1) *Baryonic Acoustic Oscillations (BAO) and Redshift Space Distortions (RSD)*: By carrying out a large redshift survey (>10 million galaxies) across a large area of the southern sky (>15,000 deg^2) 4MOST will measure the rate of expansion and structure growth of the universe. The surveys will concentrate on redshifts z<~1 samples to complement the higher redshift sample of Euclid, and maximize the area and number of targets suitable for a 4m telescope. Combining measurements of object populations with different biases (Luminous Red Galaxies, Emission Line Galaxies, Active Galactic Nuclei, Lα forest) and using their cross-correlation even better constraints can be obtained on cosmological parameters.

2) *Weak Lensing*: Weak lensing studies being carried out by imaging surveys like KIDS, DES, LSST and Euclid will be supported by providing large spectroscopic redshifts samples of galaxies to calibrate their photometric redshift techniques. Furthermore, by performing a redshift survey in the same area one can constrain the intrinsic alignment of galaxies that biases the weak lensing measurements. By cross-correlation the measurements of the foreground density field derived from a redshift survey using the RSD technique with lensing significantly improves the Dark Energy constraints, where 4MOST, being uniquely in the south, can improve constraints by another factor of 2–4x by spectroscopically surveying the same sky area as the above mentioned lensing surveys[14].

3) *Galaxy Clusters*: As a highly biased population, galaxy clusters provide a strong constraint on the growth rate of structure through measurements of the evolution of the galaxy cluster mass function. Galaxy cluster samples will be created through both optical and X-rays (see below) selection and in addition to a redshift 4MOST will provide velocity dispersions of a large fraction of the detected clusters to provide an independent cluster mass calibration.

4) *Supernovae Ia (SNe Ia)*: By using large numbers of standard candels in the form of SNe Ia strong constraints can be obtained on the expansion rate of the universe. 4MOST can initially obtain redshifts of Sne Ia host galaxies discovered earlier by DES. Later, once LSST is operational, any 4MOST observation will have been preceded by LSST in the last week and several 10s of LSST transients can be followed up per 4MOST pointing, resulting in >25k active transients followed up per year.

Next to the large dark energy surveys, 4MOST will perform a number of more dedicated extra-galactic surveys. In particular 4MOST will provide follow-up of the eROSITA X-ray mission. eROSTIA will in four years perform 8 independent all-sky surveys at the 0.5–10 keV energy range. Starting 2016 eROSITA's final combined survey will go to a limiting depth a factor 30 deeper than the ROSAT all-sky survey with broader energy coverage, better spectral resolution, and better spatial resolution. 4MOST will be used to survey the >50,000 Southern X-ray galaxy clusters that will be discovered by eROSITA, measuring 3–30 galaxies in each cluster. These galaxy cluster measurements determine the evolution of galaxy populations in clusters, yield the cluster mass evolution, and provide highly competitive constraints on Dark Energy evolution. 4MOST will provide spectroscopy for about one million eROSITA detected AGN, achieving completeness levels as high as 90% for targets selected in both the soft (0.5-2 keV) and the hard (2-10 keV) X-ray bands. In so doing, we will determine the physical properties of these X-ray selected AGNs, constraining the cosmic evolution of active galaxies, their clustering properties, and their connection with the large scale structure from z~0 all the way to z~3 (and possibly beyond). This will include (mildly) obscured objects, as well as bright AGN that are rare in current X-ray surveys because of volume limitations.

The 4MOST WAVES Survey is a massively multiplexed spectroscopic survey of ~2 million galaxies build upon the excellent imaging data provided by two of the European Southern Observatories ongoing Public Surveys: VST KiDS and VISTA VIKING. The current survey design is proposed to comprise of two distinct sub-surveys, DEEP-WAVES and WIDE-WAVES (Figure **1**). DEEP-WAVES will cover ~100 deg^2 to r < 22 mag and extend the power of SDSS-like population statistics out to z~1. The deep survey will yield ~1.2 million galaxies allowing for the detection of ~50k dark matter haloes (to $10^{12}M_\odot$) and 5k filaments, representing the largest group and filament catalogue ever constructed, and forming the first detailed study of galaxy evolution as a function of halo mass. The groups themselves will be used in turn as telescopes in their own right to probe to the most distance corners of the Universe using gravitational lensing. WIDE-WAVES will cover 750 deg^2 to r < 22 mag with photo-z pre-selection (z < 0.25). This will result in ~0.9 million galaxy targets and uncover a further 85k dark matter halos, allowing a detailed study of the halo occupancy in 10^{11} – $10^{12}M_\odot$ halos to a stellar mass limit of $10^7M_\odot$, and providing a field dwarf galaxy sample over a volume of > $10Mpc^3$. A key aim of the combined surveys will be to compare empirical observations of the spatial properties of galaxies, groups, and filaments, against numerical simulations in order to distinguish between Cold, Warm, and Self-Interacting Dark Matter models. They will enable an unprecedented study of the distribution and evolution of mass and energy in the Universe, probing structures extending from 1-kpc scale dwarfs galaxies in the local void to the morphologies of 200-Mpc long filaments at z=1.0.

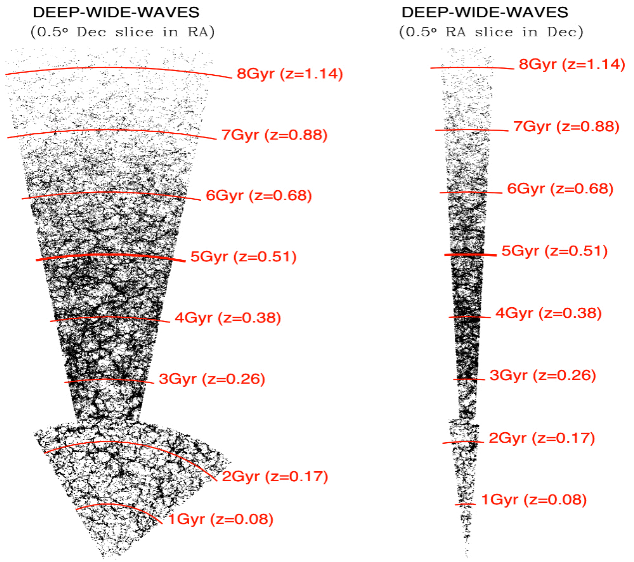

Figure 1: Cone plot sections of 0.5 degree thickness of the simulated redshift distribution of galaxies for the combined DEEP- and WIDE-WAVES survey. Based on early access to data from the Theoretical Astrophysics Observatory, courtesy Prof. Darren Croton (Swinburne).

2.2 Galactic Science

With the successful launch of the Gaia mission in Dec 2013, the field of Galactic Archeology and Near-Field Cosmology, i.e. the study of the formation and evolution of the Milky Way and its satellite system in a cosmological context, is expected to go through a dramatic development soon. Gaia will provide distances from parallaxes and tangential velocities from proper motions for more than one billion Milky Way stars down to m_V~20 mag. Gaia will also provide radial velocities and astrophysical characterization for about 100 million stars from its spectrograph, but its sensitivity to measure radial velocities is limited to m_V~12–16 mag depending on spectral type (Figure **2**). The exact limits are subject to further testing following the scattered background light anomaly. Obtaining good stellar parameters or even chemical element abundances with Gaia is limited to much brighter objects and here 4MOST will provide the complimentary measurements in the form of radial velocities with ~1km/s accuracy to the depth of Gaia's astrometric limits and detailed abundances to m_V~16 mag for millions of stars. These kind of measurements allows one to determine the three-dimensional Galactic potential, measure the influence of the Milky Way's bar and spiral arms on disk dynamics, determine the Galactic assembly history through chemo-dynamical substructure and abundance pattern tagging, and find 1000s of extremely metal-poor stars to constrain earliest galaxy formation and stellar evolution.

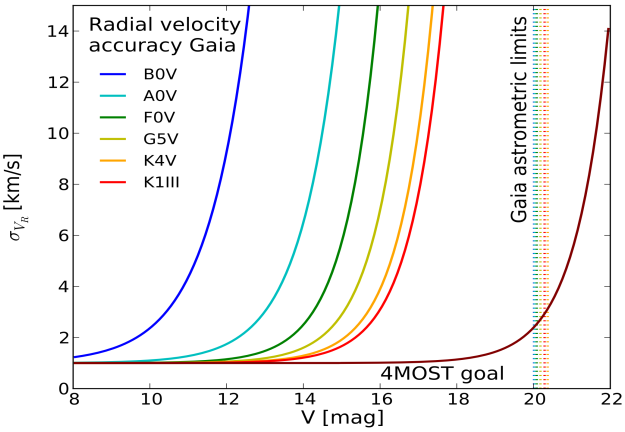

Figure 2. The 4MOST goal radial velocity accuracy compared to the Gaia end of mission accuracy as function of stellar apparent magnitude. Our aim is to match the spectroscopic magnitude limits of 4MOST to the astrometric limits of Gaia, thereby enabling 6D-phase space studies to Gaia's limits.

Large area surveys of faint Galactic stellar objects will enable us to elucidate the formation history of the Milky Way. Models of hierarchical galaxy formation predict large amounts of dynamical substructure in the Milky Way halo that 4MOST can detect through measuring radial velocities of Red Giant Stars. With the same data set we will be able to determine the three-dimensional Galactic potential and constrain the mass power spectrum of the dark matter halos by measuring the kinematics of the streams of stars that are the remnants of tidally disrupted dwarf galaxies surrounding the Milky Way.

With 4MOST we also envision to trace back in time the origin and evolution of essentially all the dominant stellar components of the Milky Way: the thin and thick disks *and* the bulge. Some of the key questions in this area are: How did the thin and thick disks form and evolve? How did the Galactic bar and spiral structures influence these components? Did the bulge form through dynamical instabilities or via accretion events?

Physical conditions of star formation suggest that most of the stellar material is produced in a finite number of large clumps, each characterized by chemical homogeneity. Various dynamical processes that act upon these stellar aggregates (perturbations from spiral arms, the central bar, and mergers, as well as accreted debris) can erase the kinematical imprint of objects born together. Indeed, comparison between a range of dynamical models and the observed velocity field for an unprecedentedly large disk area will allow us, for the first time, to unambiguously quantify the bar and spiral structure dynamical parameters, as well as the disk merger history. Loss of information due to stellar diffusion processes will be recovered by accurate metallicity and α-element measurements, thus allowing us to distinguish substructure *both* dynamically and chemically. Four mock catalogs were created from a Milky Way simulation "observed" with Gaia-like accuracy to test the feasibility of 4MOST observations (Figure **3**): 1) *Extended Solar Neighbourhood (ESN)* sample – With this sub-catalogue we aim at sampling in great detail the velocity substructure to distances where Gaia provides the most precise parallaxes (d < 2 kpc). 2) *Dynamical disk* sample – In plane sample to detect velocity resonance structures in the disk. 3) *Sparse disk Giants* sample – Sparser, higher *S/N* sample above and below the plane to study the chemo-dynamical structure of the Milky Way disk, and 4) *Bulge sample* – Dedicated Giants sample to study the formation of the bulge using both chemical and dynamical tracers.

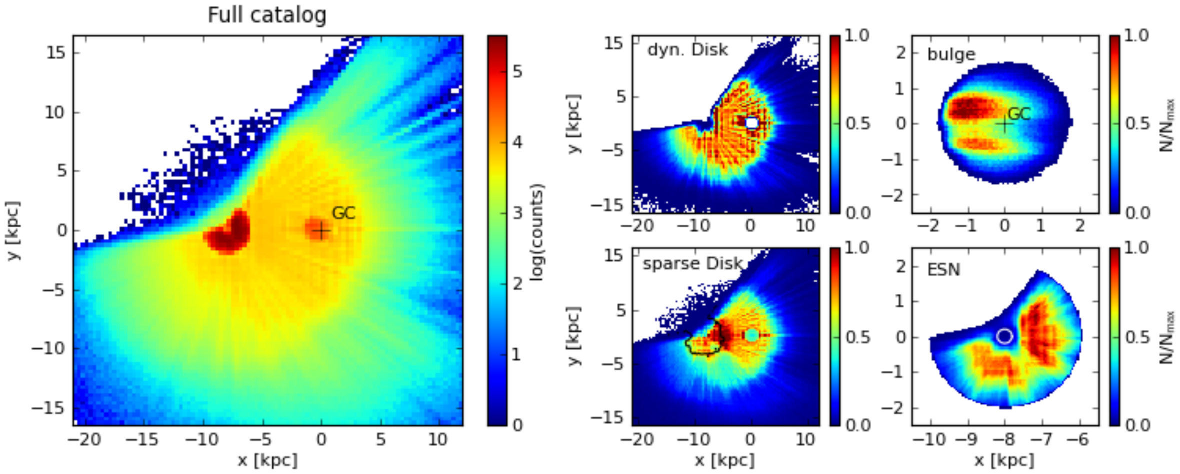

Figure 3. Distribution in the (x,y) plane of the disk/bulge mock catalog. The left panel shows the projected target density of the complete catalog. Color-coding is in logarithmic scale. In the right panels, color-coding is linear. They show the different samples from which the catalog was constructed in order to a) cover most of the disk/bulge, and b) to meet the high density of targets required to address dynamic questions (dynamical disk and ESN), while for the chemo-dynamical ones (sparse disk) a sparser sample is enough. On the other hand the dynamical sample requires much lower S/N than the chemo-dynamical one. Note the different spatial scale of the panels. The black line in the sparse disk panel indicates where the number of observed dwarfs equals the number of giants. In the ESN panel the white circle has a radius of 200 pc and thus corresponds to the Hipparcos sphere of current state of the art. The Galactic Center is at (0,0).

2.3 Other Science

Many other science goals can be achieved with 4MOST thanks to its high multiplex, two spectroscopic modes, and its flexible, general-purpose operations concept (see next Section). The operations concept allows for surveys ranging from scarce targets all-sky to high target densities in specific areas to be accommodated. Other examples expected to come from the ESO community are a survey of 100k White Dwarf discovered by Gaia to constrain the star formation history of the Milky Way, reverberation mapping of AGN, complement PLATO observations to characterize exo-planet host star and abtain accurate ages of astro-seismology objects, chemo-dynamics of the Magellanic Cloud System, redshifts for strong lensing candidates from Euclid, characterization of SKA radio sources, high resolution spectroscopy survey of Milky Way Open Clusters, constraining stellar evolutionary channels by following up eROSITA Milky Way point sources, spectroscopy of a large range of variable, binary, and transient objects to be discovered by DES, LSST, SKA, etc, dynamics of Globular Clusters and their tidal streams, and Planetary Nebulae and HII regions in the Milky Way and nearby galaxies.

2.4 Top-level Science Requirements

To address the science questions raised above the following requirements were derived. 4MOST shall be able to obtain:
–*Redshifts* of AGN and galaxies (also in clusters): R~5000 spectra of 22 r-mag targets with S/N=5 per Å in 2 hours and the capability to observe >3 targets in ⌀=2' per pointing,
–*Radial velocities* of ≤2 km/s accuracy *and Stellar parameters* of <0.15 dex accuracy of any Gaia star: R~5000 spectra of 20 r-mag stars with S/N=10 per Ångström in <2 hours,
–*Abundances* of up to 15 chemical elements: R~20000 spectra of 15.5 r-mag stars with S/N=140 per Å in 2 hours.

Furthermore, in a 5 year survey 4MOST shall be able to obtain:
– *15 (goal 30) million targets* at R~5000,
–*1.0 (goal 3.0) million targets* at R~20,000,
–*16,000 (goal 23,000) degree^2* area coverage on the sky, at least two times with 1 hour total exposure time each.

3. OPERATIONS CONCEPT

As a general-purpose spectroscopic survey facility serving many communities, the planned science operations of 4MOST is unique and will be different from normal ESO operations, where each observing program gets planned and executed sequentially on the telescope. For 4MOST, there are a few science cases that have high enough target densities to fill all fibres in a 4MOST field-of-view (these are termed Key Surveys), but there are many important science cases that need only a few targets in each field-of-view but have large numbers of targets spread over the entire sky (Add-on Surveys). To efficiently fill all fibres and to make surveys of targets with low density possible, all 4MOST surveys will be merged in one survey and observed simultaneously. The results of the 4MOST Facility Simulator demonstrate that the following straw man common survey strategy enables simultaneous and successful observing of the galactic and extragalactic science programs:

- Each sky location is observed with a sequence of nominally 20 minute exposures, in typically two visits of 3x20 minutes. Exposure times from 20 minutes to 2 hours are feasible depending on brightness and signal-to-noise needs of the targets, and, if needed, even longer in more often visited special areas (Galactic Bulge, deep fields, etc.), by reconfiguring only those fibres to new targets that have reached their total required exposure time.
- The sky is subdivide into areas that will be preferentially observed under certain circumstances (predominantly moon phase), such that, with the predefined exposure time limits from the point above, magnitude ranges of targets can be set that ensure the S/N requirements of each science goal are met.

The 4MOST consortium Key Surveys are designed to fully exploit the 4MOST capabilities and make sure all fibres can be used, yet these surveys have low enough completeness requirements such that they leave many fibres free for additional surveys. Community consultation during survey design, peer review during Phase 1, and yearly data release schedules similar to ongoing large programs (Gaia-ESO, PESSTO), will make sure that the large Key Surveys are in the interest of the entire community.

To enable this scheme, Phase I becomes a two-tiered process. First the large Key Surveys of 5-year duration are defined that ensure that enough targets are available at any pointing across the sky. These Key Surveys will set the survey strategy boundaries, such that next ESO users can plan their Community Surveys (also of 5-year duration) using a 4MOST Survey Simulator tool. The selected Community Surveys can either be all-sky surveys or more targeted special area surveys (high target density areas in the Bulge or Magellanic Clouds, deep fields, time series fields, etc.). Once all surveys have submitted their target catalogs, exposure requirements, and total survey figure-of-merit requirements, Phase II gets completed by merging all surveys in one big program from which joint telescope Observing Block (OB) commands are created using the 4MOST Observer Support Software. These OBs are then scheduled for observation and executed using the current VISTA operation scheme.

The merging of surveys in one OB results also in merged data reduction treatment. The Consortium Data Management System will process all raw data to calibrated 1D spectra. Given that all Consortium Surveys are Public Surveys, it is assumed that all Community Surveys are also Public Surveys, with similar data release policies. Data Management is also involved in quality control on same-night (technical failures), few-days (spectra of sufficient S/N and quality) and ~yearly time scales (are enough spectra produced for the science goals of the different surveys).

4. INSTRUMENT SPECIFICATION

The instrument specification was derived from the science requirements and the operations concept. The main 4MOST Instrument Specifications are listed in Table 1.

Table 1. Main 4MOST instrument specifications.

Specification	**Requirement**	**Goal**
Spectral resolution		
Low Resolution Spectrograph	R>5000 over full λ range	R>7000 @ 800 nm, R>5000 over full λ range
High Resolution Spectrograph	R>18,000 over full λ range,	R>18,000 over full λ range, R>20,000 average over full λ range

Specification	**Requirement**	**Goal**
Wavelength coverage Low Resolution Spectrograph High Resolution Spectrograph	 390–900 nm 392–437 & 515–572 & 605–675 nm	 380–940 nm 392–437 & 515–572 & 605–675 nm
Photon detecting percentage	>10% in 1.1 arcsec seeing	>15% in 1.1 arcsec seeing
Fibre aperture diameter	1.4″±0.1″	1.4″±0.1″
Field-of-View in hexagon	>4 deg^2	>5 deg^2
Fibre multiplex per pointing Low Resolution Spectrograph High Resolution Spectrograph	 >1400 >700	 >1600 >800
Observing efficiency	Overhead < 20%	Overhead < 10%
Available sky area	Zenith angle: 10°–52°	Zenith angle: 2°–55°

5. INSTRUMENT DESIGN

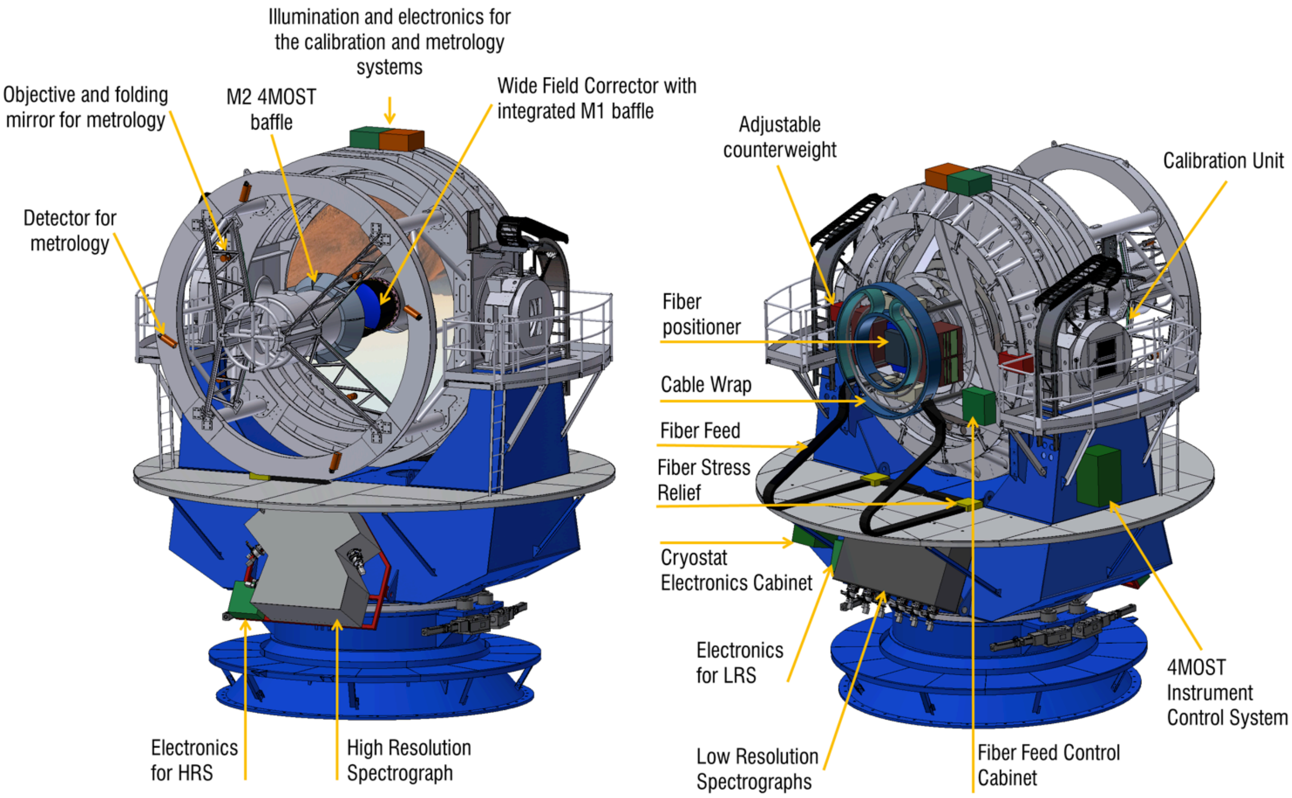

Figure 4. Layout and location of the 4MOST hardware.

Figure **4** provides an overview of the 4MOST instrument system mounted on the VISTA telescope. Seeing limited image quality in a 2.5-degree diameter field-of-view is provided by a new Wide Field Corrector (WFC) which includes an Atmospheric Dispersion Corrector (ADC), supported by three Acquisition and Guiding Units, two Low-Order and one High-Order Wave-Front Sensing Units. Two options are currently being considered for the WFC; a traditional WFC with two doublets with inclined interfaces between the two glasses providing an ADC and a WFC with a laterally moving lens providing the ADC (Figure **5**, see [8] for details, see also [15] for a similar design considered earlier for a 4MOST implementation on the New Technology Telescope (NTT)).

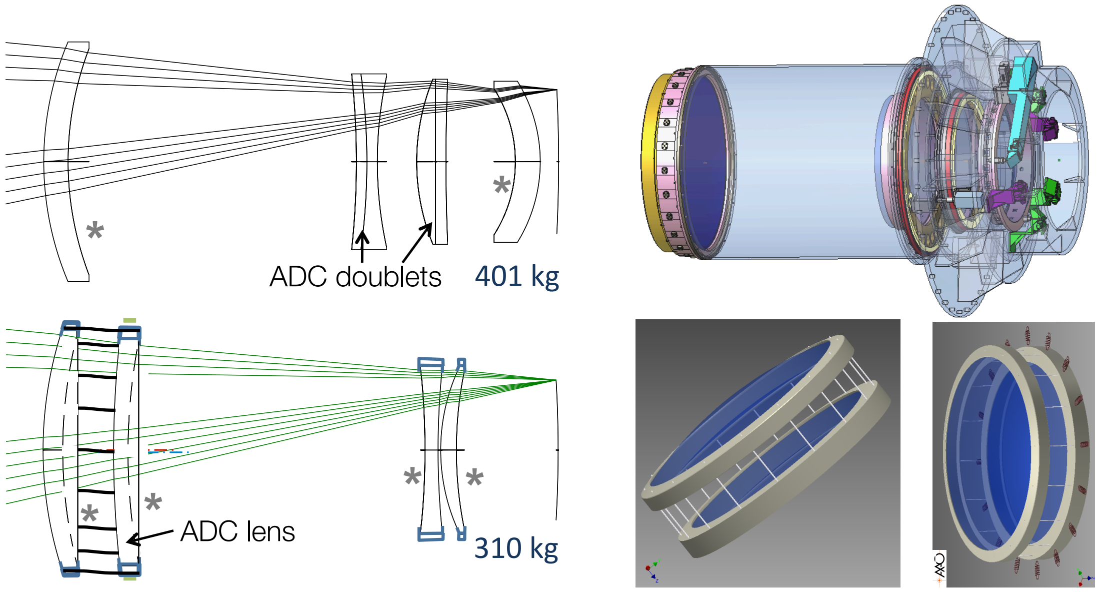

Figure 5. *Left)* Two VISTA Wide Field Corrector (WFC) design options being considered for 4MOST. At top a traditional WFC design with a counter rotating lens doublets that provide the Atmospheric Dispersion Correction (ADC) developed by IoA, Cambridge and at bottom a design with lateral lens displacement providing the ADC developed at AAO[8]. Aspheric surfaces are indicated by an *. *Top right)* mechanical layout of the IoA design with the positions of the A&G (green) and WFS (purple and cyan) units. *Bottom right)* A possible mechanism to provide passively through gravity the required lateral lens movement of the ADC in the AAO design (see [8] for details).

The light is collected in the Focal Surface into 85µm fibres, which are arranged to match sky target positions by the *AESOP Fibre Positioner*. AESOP is based on a tilting spine principle with design heritage from the Echidna positioner for Subaru/FMOS[16]. The Positioner holds 2436 fibres arranged in a hexagonal pattern of which 1624 are feeding two Low Resolution Spectrographs and 812 are feeding a High Resolution Spectrograph. The tilting spine design of the positioner is highly cost effective, modular, collision robust, and very efficient in target allocating because of its large fibre patrol radius compared to other grid-based positioner designs. Accurate fibre positioning is done by a feedback loop using a metrology camera looking through the WFC at the fibre tips that are back-illuminated from the spectrographs. A set of fixed spines around the field with back-illuminated fibres provide a reference frame that behaves identical to the moving spines in the changing gravity field of the telescope. Reference lights are also attached to the Autoguiders and the base of the fibre modules to tie the positioner reference frame to sky coordinates. The control system allows repositioning of all spines in parallel and experience with a prototype 4MOST spines shows that the required <10 µm accuracy can be achieved in less than 30s with a fast metrology system.

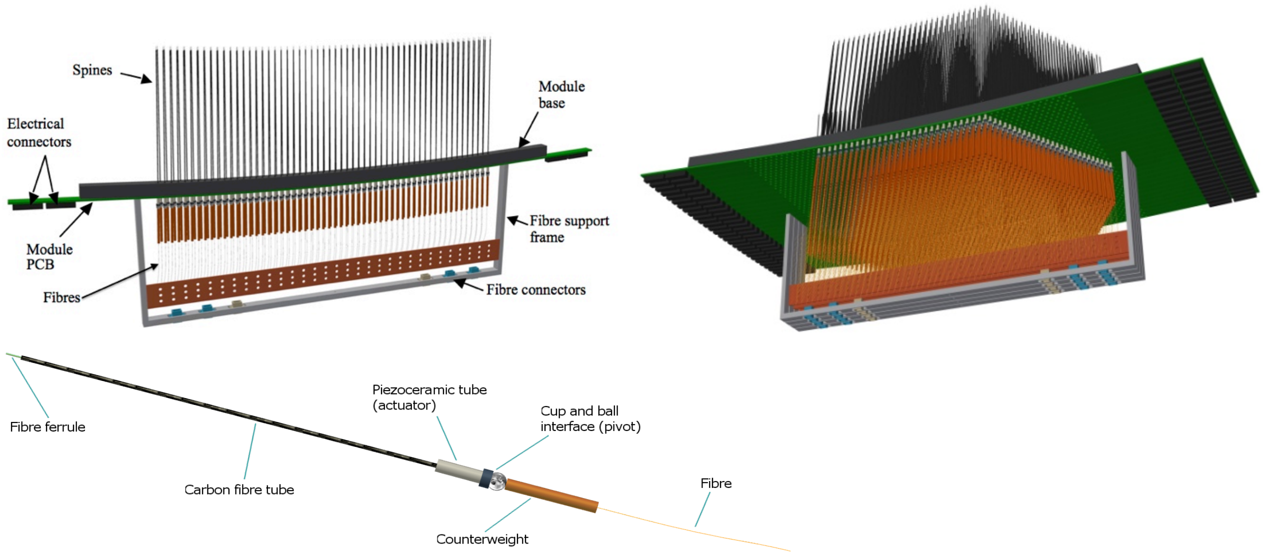

Figure 6. *Left)* One actuator module fitted with two rows of spines with 113 spines total. Fibre connectors are at the bottom, electronics connectors to the left and right. *Right)* Populated modules laid out in a hexagonal shape with 2436 spines assembled into 28 modules. All modules are identical, but populated with different numbers of spines to form a hexagon. The modules are slightly curved to follow the focal surface. Note that fibre support frames are only shown for the central four modules. *Bottom)* Layout of one spine consisting of a carbon fibre tube, a magnetically coupled ball joint and a piezo actuator tube.

To provide space for the AESOP Positioner, the current VISTA cable-wrap de-rotator is removed and replaced with a 4MOST de-rotator that is used by both the Fibre Feed and services. COTS multi-fibre connectors that have been demonstrated to have low losses are used to connect the *Fibre Feed* to the Positioner. The Fibre connectors in the Fibre Feed allow independent testing of the positioner and the spectrographs. Both the Fibre Feed and the Positioner are highly modular to simplify assembly, testing and repair. By placing the spectrographs on the telescope fork a short Fibre Feed of 16–18m length is enabled that runs through the new cable de-rotator, two altitude chains, and strain relief boxes to the spectrographs. All spectrographs are single-configuration, three-channel spectrographs with VPH gratings as dispersive elements and with identical 4k x 4k or 6k x 6k CCDs. Two *Low Resolution Spectrographs* handling 812 fibres each, cover a wavelength range from 390–930 nm and have a spectral resolution of R≈5000–7000. One *High Resolution Spectrograph* accepts 812 fibres and has a simultaneous wavelength coverage of 392–437 nm, 515–572 nm, and 605–675 nm at a resolution of R≈18000–21000.

The *Calibration System* feeds light from the M2 support spiders through the optical train to provide relative flux calibration of individual fibres ("flatfield") using a broadband light source and wavelength and resolution calibration by using a light source with narrow, well characterized emission lines. The emission line spectrum is also fed in dedicated calibration fibres permanently intermixed with the science fibres in the spectrograph.

The software development of 4MOST consists of three main parts:

- the *Science Operations System* implementing the Phase I tools –ETC and survey simulator– and the Phase II tools –Observer Support Software– that ingest survey target lists, make target-fibre assignment files, creates OBs of merged surveys, and tracks survey progress,
- the *Instrument Control Software* used for operating the instrument on Paranal. It coordinates the interactions between the different subsystems, and
- the *Data Management System* responsible for processing the raw data to higher-level data products and for quality control at both spectral and survey level.

Further details of the baseline instrument concept can be found elsewhere in these proceedings[1].

6. FACILITY SIMULATIONS

Detailed simulation tools have been developed to predict the performance of 4MOST and to help making science and engineering trade-offs. An ever more refined Top-Of-the-Atmosphere-to-Detector (TOAD) simulator simulates in detail how light travels through the atmosphere, the telescope and WFC, couples into the fibre (a significant point of throughput loss), through the fibre and the spectrograph onto the detector. The expected sensitivity for continuum flux is shown in Figure 7. Details of the TOAD simulator are described elsewhere in these proceedings[4].

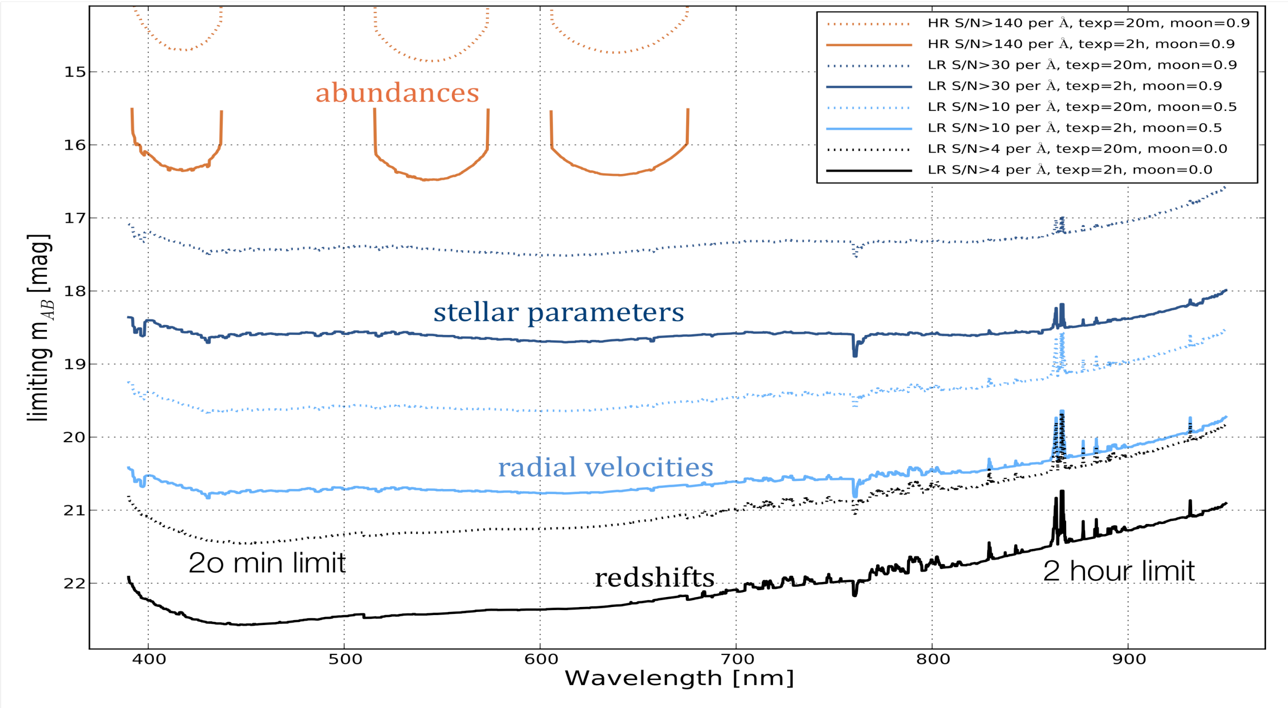

Figure 7. 4MOST limiting magnitudes for four typical science cases: obtaining stellar chemical abundances from high S/N R~20,000 spectra, determining accurate stellar parameters and chemical signatures from R~5000 spectra (both during bright time), obtaining stellar radial velocities from low S/N R~5000 spectra (grey time) and measuring galaxy redshifts from low S/N R~5000 spectra during dark time. The 2 hour exposure limits indicated by solid lines, the 20 minute exposure limits by dotted lines. These are conservative estimates based on >90 percentile limits in each step (i.e., seeing will be better in 90% of the cases than the 1.1 arcsec FWHM modeled here, the 90% worst position in field, fibre tilt angle, and position in spectrograph were used, etc.). In most conditions and for most fibres/spectra performance will be better.

The 4MOST Facility Simulator (4FS) was created to accurately determine the full science return possibilities of 4MOST. The simulator uses mock catalogues of target distributions and spectra created by the science teams, simulates the spectral throughput and detection of the objects, assigns the fibres at each telescope pointing, creates pointing distributions across the sky and simulates a 5-year survey (including overhead, calibration, downtime and weather losses), and finally does data quality analyses and computes the science Figure of Merits to assess the quality of science produced. These simulations have been run on a large number of instrument configurations with a number of different survey strategies. This has already led to a good understanding on how to optimize the survey strategy. The simulations prove the full feasibility of running different surveys in parallel with all progressing in well tuned balance using the appropriate weighting scheme between the different targets and field pointings. Figure 11 shows a fibre assignment for one pointing and the area coverage obtained in a 5-year simulation of the baseline configuration. In this figure, darker colours represent more shutter open time per field pointing, ranging from 20 to 260 minutes during dark/grey time and from 1 to more than 10 hours during bright time. Still further tuning is required to ensure full coverage of the southern galactic cap and the galactic disk.

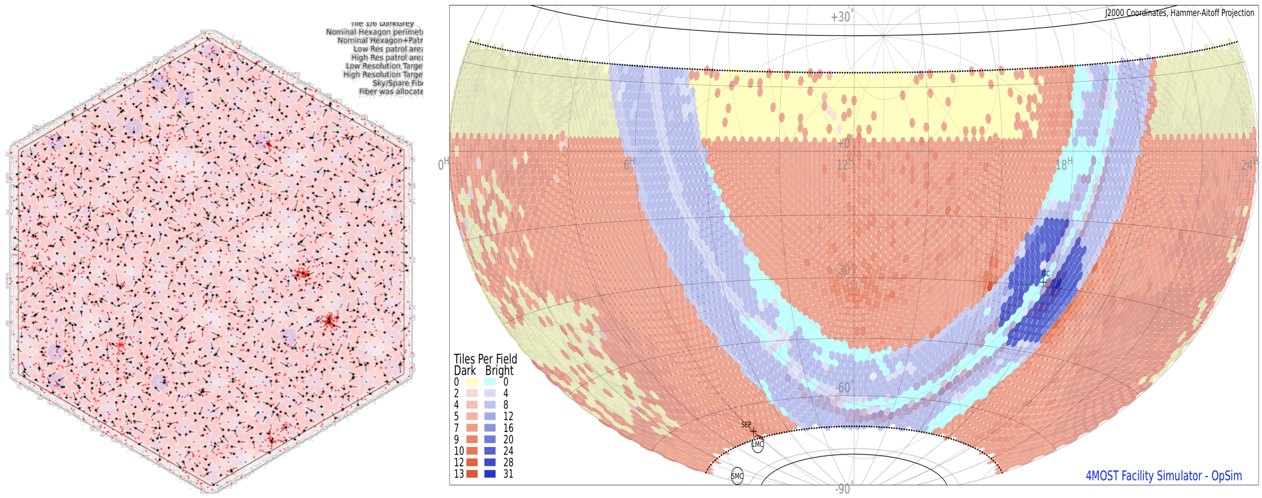

Figure 8. *Left)* A simulated 4MOST field with red dots indicating targets (note the highly clustered galaxy clusters) and fibre assignment indicated by a line and a black dot. *Right)* 4MOST Facility Simulator resulting sky coverage for bright (blue) and dark/grey (salmon) time. The legend lists the number of 20 minute exposures obtained.

Science case	**S/N per Å**	**r_{AB}-mags**	**Targets (Millions)**
Mliky Way halo HR	140	12–15.5	0.07
Milky Way halo LR	10	16–20.0	1.5
Milky Way disk/bulge HR	140	14–15.5	2.1
Milky Way disk/bulge LR	10–30	14–18.5	10.7
X-ray galaxy clusters	4	18–22.0	1.4
X-ray AGN	4	18–22.0	0.7
Cosmology galaxy redshifts	4	20–22.5	12.8
Total			**>27**

Table 1. 4MOST Facility Simulator results for a contemporaneous 5 year survey of the seven design reference science cases. Listed are the minimal Signal-to-Noise of each spectrum obtained, the magnitude range of objects observed, and the number of objects successfully observed.

Table 1 lists the total number of objects "successfully observed" by the simulator (i.e. that received enough exposure time to meet listed S/N requirements) after a 5 year combined survey of all the Design Reference Surveys that were implemented by the science team: studies of the Milky Way disk and halo at high and low spectral resolution, redshifts of galaxies in clusters and of AGN which where selected by eROSITA simulations of X-ray detections, and a massive galaxy redshift survey to obtain cosmological constraints. These simulations include realistic overheads, weather and maintenance losses, calibration exposure time, sky fibre allocations, etc., such that these are sensible expectations for the total number of objects that can be observed. More than 25 million objects were observed with the R~5000 spectrographs and more than 2 million with the R~20,000 spectrograph, still leaving enough free fibres for the large Community Surveys that need to be scheduled in parallel as well.

7. CONSORTIUM

After being adopted for construction by ESO, the 4MOST consortium is currently being consolidated for the following development, construction and operations phases. While not entire consolidated yet, provisionally the distribution of most of the technical work packages has been established as listed in Table 2. The full consortium will share the survey development and exploitation; however, Table 2 also lists which institutes have the lead responsibility for the different consortium surveys.

Table 2. 4MOST Consortium work package distribution.

Institute	Instrument responsibility	Science responsibility
Leibniz-Institut für Astrophysik Potsdam (AIP)	Management and System Engineering, Telescope interface (including WFC), Metrology, Fibre System, Calibration System, Instrument Control, Safety System, System MAIV and Commissioning	Milky Way Disk/Bulge LR
Australian Astronomical Observatory (AAO)	Fibre Positioner	Galaxy Groups Survey (WAVES)
Centre de Recherche Astrophysique de Lyon (CRAL)	Low Resolution Spectrographs	Galaxy Cluster Survey
European Southern Observatory (ESO)	Detectors System	
Institute of Astronomy, Cambridge (IoA)	Data Management System	Milky Way Halo LR
Ludwigs-Maximilians-Unversität München (LMU)	Instrument Control System	
Max-Planck-Institut für extraterrestrische Physik (MPE)	Science Operations System	X-ray selected Galaxy Clusters, X-ray selected AGN
Zentrum für Astronomie der Universität Heidelberg (ZAH)	High Resolution Spectrograph, Instrument Control System Software	Milky Way Halo HR
Rijksuniversiteit Groningen (RuG)		Milky Way Halo LR
Lunds Universitet (Lund)		Milky Way Disk/Bulge HR
Uppsala Universitet (UU)		
Laboratoire d'Etudes des Galaxies, Etoiles, Physique et Instrumentation (GEPI)		TBD

8. SUMMARY

4MOST will provide a wide-field, high-multiplex spectroscopic survey capability for the ESO community that has a broad range of applications, ranging from obtaining precision cosmological constraints to determining the formation history and structure of the Milky Way, and from studying the evolutionary connection between galaxies and their black holes out to high redshifts to characterizing host stars of exo-planets. The technical implementation with a 2.5 degree diameter field-of-view, and with ~2400 fibres feeding two R>5000 and one R>18,000 spectrographs enables a highly efficient surveying capability of a large fraction of the southern sky at high target density. The unique operation mode of 4MOST will ensure that both large and small surveys can be accommodated in the most efficient way. Following the approval of ESO, preliminary design will officially kick-off in January 2015 with an expected 4MOST first light by the end of 2020.

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