

# The Maunakea Spectroscopic Explorer: the science-driven design rationale

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## ABSTRACT

The Maunakea Spectroscopic Explorer (MSE; previously, the Next Generation CFHT) will fill a missing link in the international suite of optical-infra-red facilities in the 2020s, and will provide a key capability for multi-wavelength science, namely: fully dedicated, 10m-class, wide-field spectroscopy of thousands of objects per hour at spectral resolutions ranging from  $R = 2000$  to  $\geq 20000$ . This facility will be provided by upgrading the existing CFHT and expanding the partnership. A Project Office has been established to lead the continued scientific, technical and partnership development and complete a Construction Proposal for the facility. Here, we review the current status of the science development, in particular discussing the mechanisms by which the principal science drivers flow into the technical design, and we discuss how the facility will be optimized to satisfy demanding scientific specifications.

**Keywords:** Maunakea Spectroscopic Explorer; multi-object spectroscopy; astronomical facilities; surveys; Next Generation Canada-France-Hawaii Telescope;

## 1 INTRODUCTION

The Maunakea Spectroscopic Explorer (MSE; formerly, the Next Generation Canada-France-Hawaii Telescope, NGCFHT) is a project to expand the partnership of the CFHT and upgrade the existing 3.6m telescope with a 10m, segmented-mirror telescope equipped with a dedicated wide-field, highly multiplexed fibre spectrograph capable of carrying out transformational spectroscopic surveys of the faint universe. The scientific capabilities of such a facility are well documented, having been discussed almost continuously for more than a decade now.<sup>1-4</sup> The scientific need for such a facility has only sharpened with time, particularly in light of the many wide-field imaging and astrometric surveys scheduled for the coming decade (e.g., Pan-STARRS, VISTA, VST, Hyper-SuprimeCam, GAIA, the Dark Energy Survey, Skymapper, LSST, SKA, Euclid and WFIRST).

The idea of replacing the 3.6m CFHT with a much larger telescope is not a new one.<sup>5-9</sup> Uniquely, upgrading the Observatory on its current site is foreseen by, and consistent with, the Mauna Kea Comprehensive Master Plan\*. An early, comprehensive, report on CFHT redevelopment is that of Grundmann et al.,<sup>10</sup> who concluded that a  $\geq 10$  m segmented mirror alt-az telescope similar to the Keck 10m design would be able to fit on the pier inside the CFHT dome. At the time, a major motivation for “upgrading” CFHT was to identify options for building large aperture facilities that would surpass the power of the new 8-10m class telescopes. This desire ultimately led the partners to engage in the forthcoming Extremely Large Telescopes (ELTs), and took the focus off CFHT redevelopment for over a decade.

MSE began as a grassroots movement within the CFHT user communities in 2010. During 2011-2012, an international Feasibility Study was initiated to explore the facility’s scientific capabilities and requirements, its technical feasibility and readiness, and - crucially - to engage at an early stage with new partners, ensuring that all subsequent development of the facility takes place within this new and expanded consortium. The Feasibility Study reports were submitted to the CFHT Science Advisory Committee (SAC) and Board in November 2012 and are publicly available<sup>†</sup>. Following an international

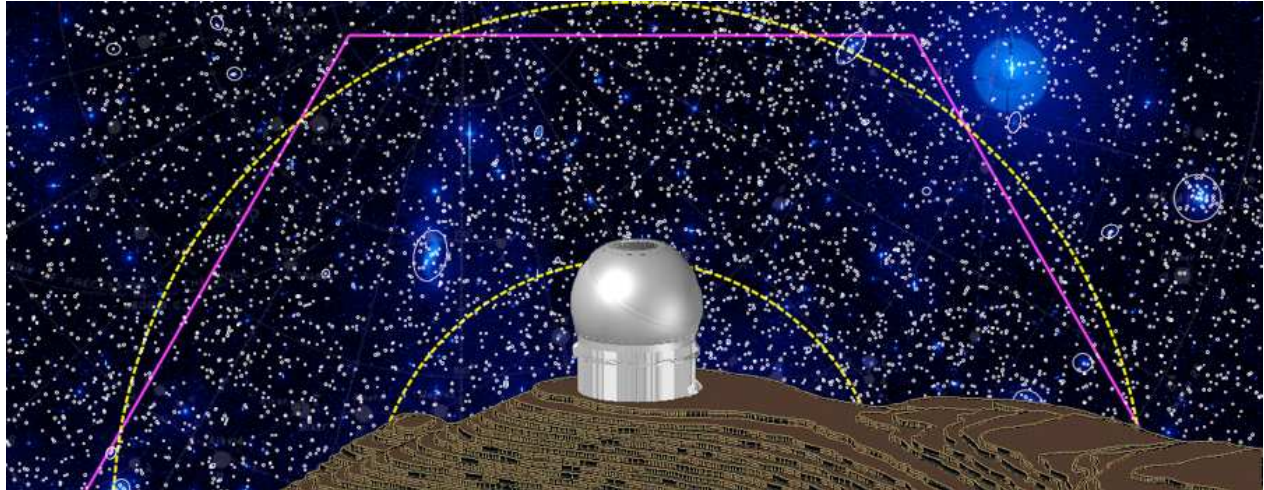
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\*<http://www.malamamaunakea.org/management/comprehensive-management-plan>

†<http://mse.cfht.hawaii.edu/documents.php>



**Figure 1:** The Maunakea Spectroscopic Explorer (*rendering by Dynamic Structures Ltd; montage by L. Ferrarese*)

workshop discussing the facility in March 2013<sup>‡</sup>, plans for the formation of a Project Office were submitted to the SAC. In September 2013, the SAC recommended to the Board that they support the proposal to create a Project Office. The launch of the Project Office was officially announced in May 2014. It is charged with developing a Construction Proposal for MSE over the next  $\sim 3$  years. The aim of this proposal is to provide the partners and potential partners with the information necessary to decide to proceed with the upgrade of CFHT and to transform it into the new facility, that will be operated by a new and expanded partnership. The Project Office announcement and more information is available on the MSE webpages<sup>§</sup>. A rendering and visualization of MSE atop Maunakea is shown in Figure 1.

A companion paper discusses in more detail the overall development plans of CFHT, and provides technical details and discusses the partnership growth required to transform CFHT into MSE.<sup>11</sup> In this article, we discuss the previous and future science development of MSE, and describe the process by which we identify the science requirements and relate these to the technical flow-down. We begin in Section 2 by discussing the major facilities that will be in operation in the 2020s, and compare MSE to other multi-object spectroscopic capabilities in development. In Section 3, we discuss some of the science highlights for MSE based on the previous science development undertaken during the Feasibility Study. The plan for the continued scientific development process during this new phase is discussed in Section 4, and Section 5 summarizes all of these elements.

## 2 INTERNATIONAL CONTEXT AND DEFINING CHARACTERISTICS OF MSE

### 2.1 Motivation

The most productive astronomical survey of all time, the Sloan Digital Sky Survey (SDSS), demonstrated the scientific potential of very large sky surveys, in particular the combination of large area photometry and highly multiplexed spectroscopy. There are now a large number of either ongoing or planned photometric surveys which together will map the entire sky at optical and/or IR wavelengths. These include (but are not limited to) the DES, surveys with the VST (ATLAS, KIDDS) and VISTA (VIKING, VHS), PanSTARRS PS1, Skymapper and the Subaru HyperSuprimeCam. A key priority in the USA is the LSST, and in Europe is the forthcoming EUCLID space mission (with WFIRST happening in the USA). ESA has recently launched Gaia, which will image the entire sky to create an ultra-precise astrometric map, and obtain photometry for all objects down to  $V \sim 20$ . At longer wavelengths, too, there is significant need for optical spectroscopy. SKA, and its path-finders MEERKAT and ASKAP, will identify millions of objects for which analysis of their optical counterparts will be crucial. The HI stacking experiments that will be carried out cannot proceed without first identifying

<sup>‡</sup><http://ngcfht.cfht.hawaii.edu/>

<sup>§</sup><http://mse.cfht.hawaii.edu>

redshifts for large numbers of optical sources. At different wavelengths, eROSITA, CCAT and others will provide a comprehensive, wide field, multi-wavelength, perspective of the Universe. The cumulative result is that wide field astronomy is burgeoning.

Despite considerable efforts (discussed in the next section), wide field spectroscopic capabilities are not growing at a rate that will keep pace with increasing demands. The spectroscopic follow-up needs of LSST, Euclid, Gaia - and the plethora of other wide field facilities - is immense. Further, 10-m class MOS has an important role to play in terms of identifying, from these extensive wide-field datasets, those sources that are most interesting for follow-up by the “giants” - the Thirty Meter Telescope, the European Extremely Large Telescope, and the Giant Magellan Telescope. As both a follow-up capability and as a feeder capability, extreme MOS in the 2020s will be essential. These considerations are independent of the many other, “stand-alone”, science drivers enabled by wide field MOS, that are discussed below.

## 2.2 MOS in development

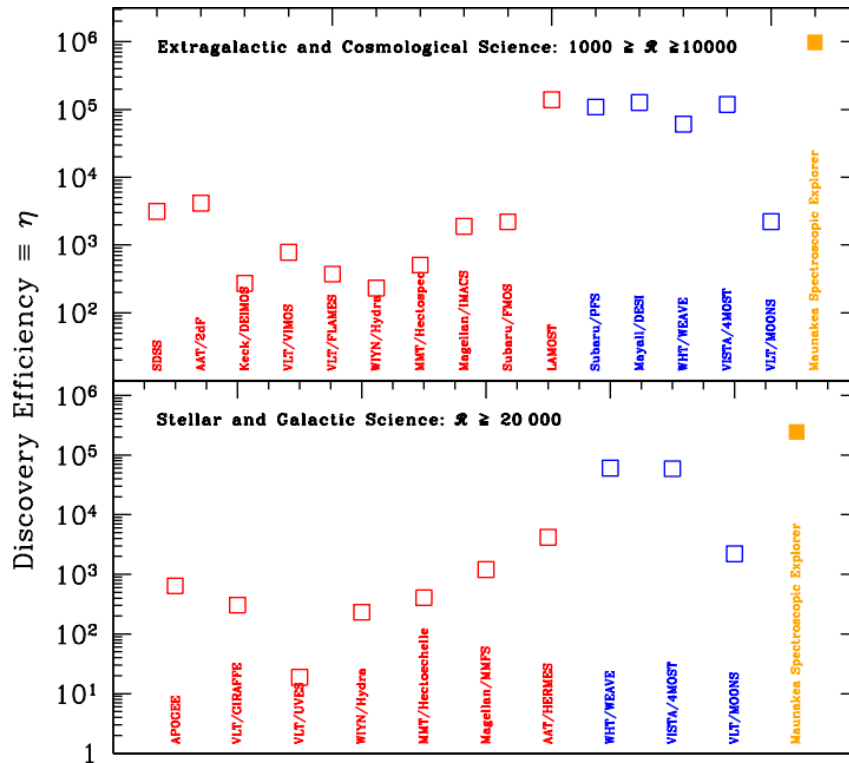
**Table 1:** Existing and planned multi-object spectroscopic capabilities, with defining characteristics. These include wavelength range, field of view, etendue, the number of simultaneous spectra per field, the spectral resolution, the fraction of time the capability is in use, the image quality, and the discovery efficiency (defined in the text)

Telescope/Instrument	$D_{M1}$ (m)	Status	Available	$\lambda$ ( $\mu\text{m}$ )	$\Omega$ ( $\text{deg}^2$ )	$A\Omega$ ( $\text{m}^2 \text{deg}^2$ )	$N_{\text{mos}}$	$\mathcal{R}$	$f$	$IQ$	$\log \eta$
<i>Ground-Based</i>											
AAT/AOOmega	3.9	Existing	1996	0.37–1.00	3.14	37.5	392	1000–17000	0.5	1.5	3.5
SDSS	2.5	Existing	2000	0.38–0.92	1.54	7.6	640	1800	1.0	1.4	3.6
Keck/DEIMOS	10.0	Existing	2002	0.41–1.10	0.023	1.8	150	2500–5500	0.4	0.7	2.1
VLT/VIMOS	8.2	Existing	2002	0.37–1.00	0.062	3.3	600	180–2500	0.2	0.8	2.9
VLT/FLAMES	8.2	Existing	2003	0.37–0.95	0.136	7.2	8–130	5600–25000	0.2	0.8	1.3–2.6
MMT/Hectospec	6.5	Existing	2004	0.36–0.92	0.79	26.1	240–300	1000–40000	0.2	1.0	2.6–2.7
WIYN/Hydra	3.5	Existing	2005	0.37–1.00	0.79	7.5	90	800–40000	0.2	0.8	2.4
Magellan/IMACS	6.5	Existing	2008	0.36–1.00	0.16	5.3	400	1100–16000	0.2	0.6	3.3
SDSS/APOGEE	2.5	Existing	2011	1.51–1.70	1.54	7.6	300	27000–31000	0.5	1.4	2.8
Subaru/FMOS	8.2	Existing	2012	0.8–1.8	0.20	10.4	400	600–2200	0.2	0.7	3.3
LAMOST <sup>†</sup>	4.0	Existing	2012	0.37–0.90	19.6	247	4000	1000–10000	1.0	3.0	5.1
AAT/HERMES	3.9	Existing	2013	4 windows	3.14	37.5	392	28000	0.5	1.5	3.6
Subaru/PFS	8.2	Planned	2017	0.38–1.30	1.1	70	2400	1900–4500	0.3	0.7	5.0
WHT/WEAVE	4.2	Planned	2018	0.37–1.00	3.14	41	~1000	5000–20000	0.7	0.8	4.8
Mayall/DESI	4.0	Planned	2018	0.36–1.05	7.1	89	5000	3000–4800	0.5	1.5	5.1
VLT/MOONS	8.2	Planned	2018	0.8–1.8	0.14	7.3	1000	4000–20000	0.3	0.8	3.3
VLT/4MOST	4.1	Planned	2019	4 windows	3.0	40	1500	3000–20000	1.0	0.8	5.1
MSE	10.0	Planned	2021	0.37–1.30	1.5	118	3200	2000	1.0	0.7	6.0
				0.37–1.00			3200,800	6500,20000	1.0	0.7	5.4
<i>Space-Based</i>											
Gaia	$2 \times (1.4 \times 0.5)$	Existing	2014	0.85–0.87	all sky survey ( $V < 17$ )			11500			
Euclid	1.2	Planned	2020	1.10–2.00	0.55	0.62		250			
WFIRST	1.5	Planned	2025:	1.10–2.00	0.5	0.89		75–320			

<sup>†</sup> – Also known as the Guo Shou Jing Telescope (GSJT).

In response to the emerging void in ground based astronomy caused by the lack of clear avenues towards massive spectroscopic datasets, several spectroscopic projects are in advanced stages of development. All of these take the form of either instruments for 4-m and 8-m class telescopes, or 4-m class spectroscopic facilities (i.e., dedicated usage). Table 1 presents a list of current and future MOS capabilities, along with their basic characteristics. These include the aperture of the facility, the wavelength range, field of view, etendue, the number of simultaneous spectra per field, the spectral resolution, the fraction of time the capability is in use, the image quality, and the discovery efficiency. This latter quantity is defined as  $\eta = A\Omega N_{\text{mos}} f / IQ^2$ .

Several of the projects listed in Table 1 are at an advanced stage of development, or have recently come on-line. In this group, AAT/HERMES<sup>12</sup> stands out as the only instrument that is geared exclusively towards high resolution (and consequently targets mostly stellar populations in the Milky Way). HERMES is now beginning to undertake the GALAH survey with this instrument, observing  $\sim 10^6$  stars and measuring the abundances of  $> 15$  elements per star to around  $V \sim 14$ . Also in the 4 m class, DESI ( $N = 4000$ ;  $R5K^{13}$ ) stands in contrast to HERMES in terms of its focus on low resolution science, with well developed plans for a survey targeting baryonic acoustic oscillations (BAO). DESI is a merger of two former projects, BigBOSS and DECSpec, and is targeted to go on the Mayall telescope.



**Figure 2:** “Discovery efficiency” for spectroscopic capabilities that currently exist (red) and that are in development (blue). MSE is shown for comparison. The top panel is for instruments and facilities that operate at low resolution (for which extragalactic and cosmological science applications are common) and the bottom panel is for high spectral resolution capabilities (for which stellar and Milky Way science applications are common). The discovery efficiency is defined in the text and is listed for each instrument and facility in Table 1. It is based on the aperture of the facility, the field of view, the degree of multiplexing, the image quality, and the fraction of time the capability is in use.

Two projects listed in Table 1 are particularly useful to highlight for later comparison to MSE. The first is 4MOST,<sup>14</sup> a 4-m class dedicated spectroscopic instrument planned for VISTA. It would work in the optical and is baselined to operate in both low and high resolution modes. On an 8-m facility, Subaru/PFS ( $N = 2400, \sim R2K$ <sup>15</sup>) is under construction with first light around 2017. Upon completion, it will be the most powerful multiplexed spectrograph in the world at an exquisite site, and plans are underway for a Subaru Strategic Program to use this instrument over  $\sim 300$  nights. PFS emerged following the cancellation of the Wide Field Multi-Object Spectrograph, and is in some ways a spectroscopic complement to the Subaru/HyperSuprimeCam, which itself is poised to become the world’s premier optical imager.

### 2.3 Defining characteristics of MSE

MSE was conceived to fill the gap that has developed in the international network of astronomical facilities, and to become the premier facility for providing high quality spectroscopic data of the faint Universe for potentially millions of astronomical targets over thousands of square degrees. In doing so, MSE enables a very broad range of forefront science. In many respects, MSE is an evolution of the capabilities discussed above, all of which will be in operation before the end of this decade.

MSE is at a formative stage in its development. However, results from the Feasibility Study provide an informed baseline. In operation, it is envisioned that MSE will obtain efficiently very large numbers ( $> 10^6$ ) of low- ( $R \sim 2000$ ), moderate- ( $R \sim 6500$ ) and high-resolution ( $R \sim 20000$ ) spectra for faint ( $20 < g < 24$ ) science targets over large areas of the sky ( $10^3 - 10^4$  sq.deg) spanning blue/optical to near-IR wavelengths ( $0.37 - 1.3 \mu\text{m}$ ). At the highest resolutions, it would have a velocity accuracy of  $\ll 1$  km/s. At low resolution, complete wavelength coverage would be possible in a single observation.

Figure 2 shows the discovery efficiency for MSE in comparison to all other spectroscopic capabilities listed in Table 1 (where red indicates the instrument/facility exists, and blue indicated it is in development). The top panel is for low resolution capabilities, and the bottom panel is for high resolution capabilities. MSE appears in both panels, and in each panel the discovery efficiency of MSE is roughly an order of magnitude better than for the other instruments/facilities.

The discovery efficiency as shown in Figure 2 is indicative of the relative performances of the different instruments and facilities, but it clearly does not capture all of the salient considerations. For MSE, there are four key aspects of its design and operations that require highlighting, and that collectively distinguish it from all other astronomical facilities, current or planned. These are now discussed in more detail.

### 2.3.1 10 m aperture

MSE will utilize the full light-collecting power of a 10 m primary mirror. There are numerous excellent projects underway or under development that seek to develop MOS capabilities for 4 m class apertures. MSE science, however, is focused towards an understanding of the *faint* Universe - such as intrinsically faint stars, the distant Galaxy, low mass galaxies, and the high redshift Universe - that is not accessible with smaller apertures. This opens up extensive new areas of research, such as *in-situ* chemodynamical studies of the distant Milky Way stellar halo, enabling all Galactic components to be studied in an unbiased manner. Indeed, MSE is the only facility that will be able to conduct detailed chemical abundance studies across the full luminosity range of targets identified by the ESA/Gaia mission. Further, for extragalactic science, the dynamics and stellar populations of dwarf galaxies that fall below the detection threshold of smaller-aperture facilities at low and moderate redshifts will be easily accessible, and MSE will allow the analysis of sub- $L^*$  galaxies out to high redshift. Again, the light gathering power of the 10 m aperture is essential in allowing unbiased analyses of these galaxy populations that could not be achieved with smaller apertures.

### 2.3.2 Operation at a range of spectral resolutions

A core requirement of MSE is that it operates at a range of spectral resolutions. This is in contrast to the majority of spectroscopic instruments currently in development, that generally concentrate either on low ( $R \sim 2000$ ) or high ( $R \gtrsim 20000$ ) spectral resolutions. MSE is envisioned to operate with both low and high resolution settings, with the addition of an intermediate resolution mode ( $R \sim 5000$ ). At the March 2013 workshop discussing MSE science, a compelling case was made to enable a fourth, very high resolution mode ( $R \sim 40000 - 50000$ ) that will be investigated further to determine its feasibility.

A range of spectral resolutions is essential to MSE. Firstly, it enables a diverse range of scientific investigations, and MSE is expected to contribute equally to “Local Universe” science - where the brighter targets are more well-suited to high and intermediate spectral resolutions - and “Distant Universe” science - where the more distant faint targets require lower spectral resolutions. This diversity is essential to ensure success as a *facility*, in contrast to *instruments* (where a more limited range of capabilities is often acceptable due to a focus on a narrower range of science cases).

As well as promoting scientific diversity, operational efficiency is ensured by the availability of a range of spectral resolutions. In particular, MSE will observe throughout the lunar cycle, with higher resolution observations of bright targets dominating during bright time, and fainter extragalactic targets dominating the observing during dark time. Operating with high efficiency is important for all facilities, but is especially true for MSE where the accumulation of large datasets is an essential requirement for nearly all observing programs.

### 2.3.3 Dedicated operations

MSE provides a specialized technical capability, namely large-aperture wide field extreme MOS. MSE will conduct spectroscopy of a vast number of astronomical sources to produce homogeneously-calibrated, well-characterized, datasets. In comparison to instruments, specialized facilities are more easily able to achieve a higher level of data consistency and homogeneity. For instruments that move on and off telescopes at regular intervals, data issues such as calibration, stability and reproducibility can be problematic since the instrument is not being left in a stable configuration. This is in contrast to the situation for MSE, where the *basic operational philosophy* of specialization enables high quality and stable data (e.g., fibre coupling will be left in place all the time, no prime focus changes, WFC or ADC removals, etc.). Indeed, this allows for science cases that would otherwise be very difficult to address on other instruments (for example, time resolved high-resolution spectroscopy).

It is worth considering what the specialized nature of MSE means in practice for the resulting science and impact of the facility, and here there is a clear analogy to SDSS. The SDSS telescope is a relatively small-aperture facility by modern standards, and it is located at a site that, while good, does not compete in terms of median image quality with a location like Maunakea, that is home to many much larger facilities. Nevertheless, SDSS is the most successful and high impact ground-based facility of all time. A search on the Astrophysical Data System for refereed astronomy publications that mention SDSS in their abstract - presumably those papers that either rely on SDSS data for analysis, interpretation or comparison - returns nearly 6000 papers with almost 1/4 million citations<sup>¶</sup>. A major reason for this overwhelming success is the extremely well-calibrated and well-characterized nature of the data. In some respects, MSE can be viewed as an evolution of the SDSS concept, realized on a facility that has  $\sim 25\times$  larger aperture and is located at one of the premier astronomical observatory location on the planet.

### 2.3.4 Long lifetime

Although many of the MOS instruments/facilities listed in Table 1 are built to address key missions, they will also undertake a range of ancillary science. For example, DESI is focused towards measurement of the BAO signature, and HERMES will obtain chemical abundance information for relatively bright stars in the Milky Way. In contrast, MSE is *not* built to address a single science case, and MSE is *not* built to conduct a single survey. Rather, MSE is built to provide *a single, missing, important, set of capabilities* (wide field MOS at a range of spectral resolutions), to provide astronomers with *certain types of astronomical data*. MSE is designed and optimized *to excel at providing these data*, and in so doing enables a vast range of science cases and strategic surveys.

MSE is expected to have a long lifetime. Like all such facilities, it is important that upgrades occur and that it is able to adapt to the changing scientific landscape. Throughout its evolution, MSE is envisioned to remain a *spectroscopic facility*, and will be the world's premier resource for exploitation of this important capability for frontier science. MSE will remain *a specialized technical capability, and a general science-purpose facility*.

## 3 SCIENCE HIGHLIGHTS FROM THE FEASIBILITY STUDY

The Feasibility Study for MSE began in 2011. The MSE facility has a broad, multi-national appeal, and the proposed redevelopment is beyond the scope of the existing CFHT partnership. As such, international science working groups (SWGs) were assembled (i.e., not limited to existing partner communities). The SWGs were chosen to cover the broadest possible range of science topics: the interstellar medium, stellar astrophysics and exoplanets, the Milky Way, the Local Group, nearby galaxies and clusters, galaxy evolution, QSOs and AGN, the intergalactic medium, and cosmology. In total, the SWGs included 60 astronomers representing many different communities that have a presence on Maunakea, either now or in the near future (Australia, Brazil, Canada, China, France, Hawaii, India, Japan, the Republic of Korea, Taiwan, the UK, and the USA).

The SWGs were presented with a baseline set of capabilities for MSE and were asked to identify what they considered the key science questions that should be addressed by the facility. This began an iterative process during which shortcomings in the capability suite were identified, and recommendations were put forward to better optimize MSE for the full range of key science drivers that were identified. This led to a refined set of capabilities (requirements) that together allowed for key science across the diverse range represented by the SWGs.

The full results of the Feasibility Study are available elsewhere<sup>||\*\*</sup>. A broad range of science topics emerged, and two major areas of investigation were highlighted as areas in which MSE would provide unprecedented scientific insights:

**Galactic Archaeology:** MSE would carry out the ultimate spectroscopic follow up of the Gaia mission. A baseline, multi-year, bright/grey-time survey was conceived during the Feasibility Study that would yield medium-resolution spectra for a sample of 20 million stars, 5 million of which would also have high-resolution data. Covering  $\sim 1/4$  of the sky to a depth of  $g \simeq 20 - 21$  mag, no planned or proposed survey could rival this baseline programme in its ability to characterize the halo metallicity distribution function, perform chemical tagging of Galactic stars, or explore the three-dimensional phase space structure of the Milky Way.

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<sup>¶</sup>5922 papers with 248561 citations, as of June 6 2014

<sup>||</sup>[http://mse.cfht.hawaii.edu/docs/Feasibility\\_Science\\_Final.pdf](http://mse.cfht.hawaii.edu/docs/Feasibility_Science_Final.pdf)

<sup>\*\*</sup>[http://mse.cfht.hawaii.edu/docs/Feasibility\\_Technical\\_Final.pdf](http://mse.cfht.hawaii.edu/docs/Feasibility_Technical_Final.pdf)

**Table 2:** Example science surveys developed as a baseline by the Science Working Groups during the Feasibility Study phase. These programs add up to more than 10 years of observing time. The actual science programs that MSE will conduct - that can range in size from a single exposure to several years of observing - will be decided through competitive time-allocation processes, but these baseline programs demonstrate the broad science appeal and the extensive usage that awaits the facility.

Baseline Survey	Sky	Area (deg <sup>2</sup> )	Resolution	$\lambda$ (nm)	$g_{lim}$	T (nights)
<b>Multiplicity &amp; Exoplanets</b>	Bright	115	20000 2000	425 - 491 ; 585 - 675 370 - 1300	16.0	110
<b>ISM</b>	Bright	5000	20000	369 - 425 ; 761 - 879	16.0	140
<b>Galactic Archaeology I</b>	Bright/Grey	10000	20000	425-491 ; 585 - 675	20.4	1150
<b>Galactic Archaeology II</b>	Grey	10000	6500	381 - 439 ; 770 - 889	21.4	290
<b>Andromeda</b>	Grey/Dark	350	6500	436 - 504 ; 770 - 889	23.0	50
<b>LOWZ</b>	Dark	1000	2000	370 - 1300	$i = 22$	190
<b>Rich Clusters</b>	Dark	30	2000	370 - 1300	$r = 22$	45
<b>Virgo Cluster</b>	Dark	100	6500	436 - 504 ; 770 - 889	23.6	30
<b>Dark-Wide</b>	Dark	4300	2000	370 - 1300	$i = 23.5$	520
<b>Dark-Medium</b>	Dark	100	2000	370 - 1300	$i = 24.25$	480
<b>Dark-Deep</b>	Dark	1.5	2000	370 - 1300	$i = 26$	105
<b>Quasar Reverb. Mapping</b>	Dark	1.5	2000	370 - 1300	$i = 22.7$	105
<b>Cosmological Clusters</b>	Dark	750	2000	370 - 1300	$i = 23.5$	195
<b>BAO/Cosmology</b>	Dark/Grey	10000	2000	370 - 1300	$r = 23.7$	600

**Galaxy Evolution and Cosmology:** A baseline suite of dark-time surveys were identified that could cover many thousands of square degrees. These would yield spectra for more than 10 million galaxies, allowing a *study of galaxy evolution at seven distinct epochs between  $0.5 < z < 1.5$ , each with the same statistical power as the SDSS*. From a cosmological perspective, no planned or proposed spectroscopic survey would provide comparable constraints on the growth factor, the law of gravitation on large scales, or the shape of the power spectrum.

The impact of MSE would, however, be felt far beyond these fields. Its combination of large collecting area, wide field of view, high multiplexing, range of spectral resolution, and dedicated operations mode, would allow it to undertake transformational research across a wide range of subfields. A representative selection of other science results that the SWGs identified would be enabled by such a facility include:

- An extraordinary, three-dimensional map of the Galactic ISM, with the density structure and kinematics measured along hundreds of thousands of sight lines using high-resolution, absorption-line spectroscopy of molecular, atomic and ionized gas.
- The first panoramic, wide-field, time-domain spectroscopic surveys ever conducted, including unprecedented studies of stellar multiplicity, pulsating and eclipsing stars, novae and supernovae.
- The measurement of gravitational masses and density profiles for a complete sample of dark matter halos, down to the scales of dwarf galaxies, in a rich cluster environment based on radial velocities for hundreds of thousands of candidate baryonic substructures in the nearby Virgo cluster.

- A comprehensive study of the relationship between stellar and gravitational mass, baryon dynamics, and star formation efficiency in dark matter halos spanning a range of  $\sim 10^6$  in stellar mass. A baseline survey was proposed that would yield spectra for half a million galaxies within  $z \lesssim 0.15$ , covering an area four times larger than the GAMA survey, and reaching 2 magnitudes deeper.
- A baseline spectroscopic survey of  $\sim 100$  bright quasar fields would allow an order-of-magnitude improvement in our ability to probe the Galaxy-IGM connection based on  $\geq 40000 Ly\alpha$  absorbers. Spectroscopy for 1000 – 2000 damped  $Ly\alpha$  systems could be obtained that would dramatically improve our knowledge of early nucleosynthesis and the evolution of metals out to  $z \sim 4$ .
- A thorough study of AGN feedback through high-S/N, high-resolution, time-domain spectroscopy, as well as an independent determination of the redshift evolution of dark energy through BAOs in the  $Ly\alpha$  forest, and an AGN Hubble diagram calibrated through reverberation mapping.

Many of the SWGs suggested possible survey strategies to best enable their science goals. Table 2 provides a list of those baseline surveys which serve to demonstrate the range of science enabled and the diverse operational set-ups suggested. These example programs are well divided between lunar phase, spectral resolution and survey duration (ranging from a single field to multiple years of observing time). It is worth noting that even at this early stage, the example science programs add up to  $> 10$  years of observing time.

#### 4 SCIENCE DEVELOPMENT PLANS DURING THE CONSTRUCTION PROPOSAL PHASE

The science case for MSE, as developed during the Feasibility Study phase of the project, can be succinctly described as

**The Composition and Dynamics of the Faint Universe:** *Understanding the physical properties of the faint Universe from interstellar to cosmic scales*

and can be broken into four main science themes:

- The origin and diversity of stellar systems
- Milky Way archaeology at the earliest times
- Galaxy evolution across Cosmic Time
- Illuminating the Dark Universe

Figure 3 provides an illustration of example science that falls under each of these themes, from time-domain spectroscopic studies of stars in the Kepler footprint (top left), identification of tracers of different nucleosynthetic pathways in Milky Way stars (top right), mapping of galaxies and tracing cosmic structure (bottom left), to measurement of the gravitational potential of cluster-sized dark matter halos using every accessible luminous tracer over their entire extent (bottom right).

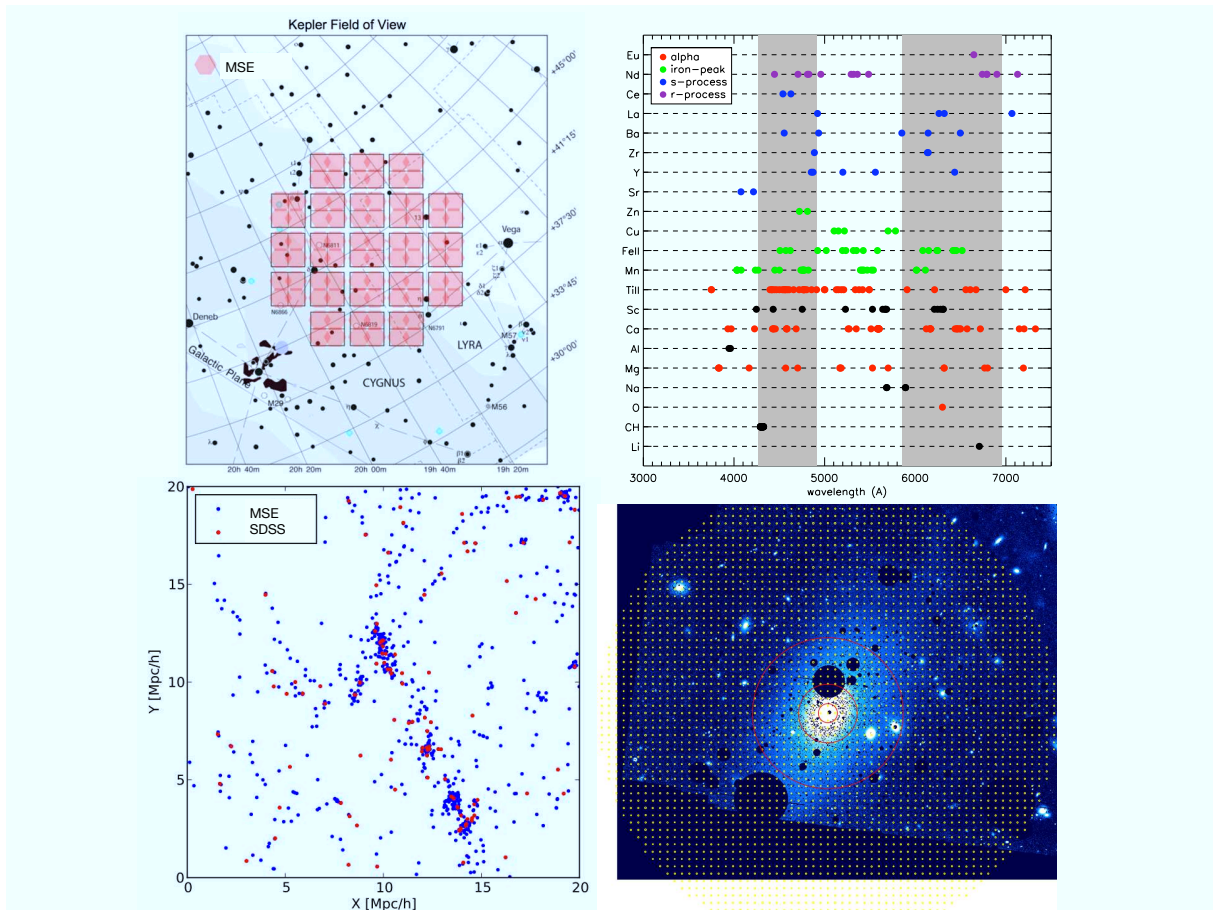
We now discuss the process for the future development of these science drivers, in particular with respect to the impact on the facility design and operations.

##### 4.1 Formation and structure of the Science Team

MSE is a multi-national facility and core to its success is the formation of a new and extended partnership. The science team is therefore essential not only for the scientific development of the facility, but also in terms of catalysing partnership formation. Through their role in the Feasibility Study, astronomers from Australia, Brazil, Canada, China, France, Hawaii, India, Japan, the Republic of Korea, Taiwan, the UK, and the USA have all helped develop MSE to its current phase. During the new Construction Proposal phase, this process continues through a restructured and “rebooted” Science Team.

MSE Science Team formation is taking place during June - July 2014. Membership is open all PhD astronomers whose scientific interests can be served by MSE. Particular emphasis is placed upon those communities previously involved in





**Figure 3:** The science case for MSE - The Composition and Dynamics of the Faint Universe: Understanding the physical properties of the faint Universe from interstellar to cosmic distance scales - can be broken into four main science themes: the origin and diversity of stellar systems (top left); Milky Way archaeology at the earliest times (top right); galaxy evolution across cosmic time (bottom left); illuminating the dark Universe (bottom right). Descriptions of each panel are given in the text.

the SWGs, and communities who currently have, or will have, a presence on Maunakea through existing and other future facilities. As discussed in previous sections, MSE is designed to fill a gap that is emerging in the international network of astronomical facilities, and it is advantageous for the partnership that delivers MSE to represent communities that are invested in other aspects of that network.

The governance of the Science Team is through the Science Executive. This panel is chaired by the Project Scientist (a member of the MSE Project Office). Each community that is working on the Feasibility Study, both from a scientific development perspective and from a technical design perspective, has a representative (or Contact Scientist) that sits on the panel. These Contact Scientists are the main contacts for their community on all aspects of MSE science development, and are expected to act as liaisons and advocates for the project. In addition to the Contact Scientists, the panel also consists of four Lead Scientists. These astronomers coordinate the work undertaken by the Science Team, and each Lead is responsible for the science development in the four main areas of the MSE science case. As the MSE science development evolves, it is expected that so too might the make-up of the Science Executive.

## 4.2 Science development process

In common with a large number of projects, key deliverables for the Science Team include the Detailed Science Case (DSC), Science Requirements Document (SRD) and the Operational Concept Document (OCD). Here, it is worth considering the DSC and the SRD in more detail:

- DSC: this is a key document in terms of describing the scientific landscape in which a facility will operate, and for identifying and describing the main scientific questions that need to be tackled by the facility. However, it can often lack the specificity that is required to identify the top-level requirements from which most other requirements flow. Indeed, if presented with a science case, it is very possible that a team of astronomers and engineers would develop quite different instruments based upon what they perceive as the main requirements. This implies that there is a linking stage between the DSC and SRD that is not captured by either of these documents in the traditional sense.
- SRD: It is worthwhile to give an example of what we mean by a Science Requirement, since even among astronomical instruments and facilities there is some variation as to the level at which these are defined. MSE is adopting the philosophy that they must stem directly from the DSC and be grounded in terms of the scientific measurements that are planned. As a result, a statement such as “MSE will operate at a spectral resolution of  $R = 2000$ ” is *not* a science requirement. This can be understood by considering why  $R = 2000$  might be necessary. For example, it might be that it is required in order to provide a certain accuracy in the determination of the cosmological redshift of a certain luminosity of galaxy. Note here that *it is the measurement of the redshift at a given accuracy that is the defining aspect of the measurement, and it is therefore the ability to conduct this measurement that is the top-level science requirement*. While  $R \sim 2000$  might be an appropriate and reasonable spectral resolution to operate at for this measurement, stating the spectral resolution as the top-level requirement neglects that fact that, for example, signal-to-noise could be traded against resolution, and operation at lower resolution might therefore be sufficient if the observations allow for higher signal-to-noise. Operation at  $R = 2000$  is therefore a design solution to the top-level requirement. It is not the requirement itself. Adopting this strategy ensures subsequent trade discussions are intimately linked to scientific measurements

To provide the link between the DSC and SRD, the MSE Science Team will develop “Science Reference Observations” (SROs). These SROs are baseline observing programs for the facility that are developed to a high level. All primary science cases described in the DSC have corresponding SROs, and they will collectively span the full range of observational set-ups and survey strategies that MSE is expected to support. An incomplete list of SRO aspects that will be developed include:

- Target selection (including spatial density and pre-imaging strategies)
- Identification of key astrophysical observables (e.g., line widths, velocities, specific spectral features, etc.) and required accuracies
- Observing cadence and any timing constraints (e.g., follow-up of transients)
- Required stability (temporal, spatial, spectral)

- Calibration measurements (including wavelength calibration, sky subtraction, spectrophotometric requirements, and any other non-standard requirements)
- Data processing plan, detailing the pathway from raw data to publishable results

The high level science requirements described in the SRD are directly connected to key astrophysical measurements that are expounded by the SROs and that are necessary to address the science drivers described in the DSC. This direct traceability to astrophysical measurements is essential for the trade studies that will inevitably arise during later stages of technical development, since it allows the scientific consequences of the proposed trade to be clearly understood in terms of delivered scientific performance.

The SROs, in addition to setting top-level science requirements, will also allow for a realistic operational concept to be developed. Aspects of MSE operations will be developed through an iterative process whereby baseline survey strategies and operational procedures are judged by their ability to integrate SROs into coherent and tractable observational programs. We stress that the SROs need not necessarily become actual observational programs on MSE, although there is clearly potential for this to occur. Ultimately, the challenge is to develop a suite of science-enabling capabilities through the development of the DSC, SROs, SRD and OCD that is sufficiently comprehensive and flexible to allow science applications that are not yet on the radar of the astronomical community.

## 5 Summary

The Maunakea Spectroscopic Explorer will be the premier astronomical facility for spectroscopy, with planned first light in the mid-2020s. It will provide a key capability that is currently missing from the future network of multi-wavelength astronomical facilities, by enabling powerful stand-alone science cases aimed at understanding the composition and dynamics of the faint Universe. MSE will be the major follow-up facility for the large number of wide field photometric and astrometric surveys in development, and a valuable “feeder” facility for the Extremely Large Telescopes in development. A Construction Proposal is underway, led by the MSE Project Office based in Waimea, Hawaii. This work builds on the extensive studies that were undertaken during the Feasibility Study phase and will continue the scientific, technical and partnership development that is essential to turn MSE into a reality. MSE is a new facility that will be designed and built by a new partnership. It will excel in its area of specialization, and in so doing will impact a vast swath of astronomical research, from the origin of stars and stellar systems, Galactic archaeology at the earliest times, galaxy evolution across cosmic time, to cosmology and the nature of dark matter and dark energy.

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## REFERENCES

- [1] Brown, M., and Dey, A. “Next Generation Wide-Field Multi-Object Spectroscopy,” in *ASP Conf. Series* **280** (2001)
- [2] Dey, A., et al., “KAOS: The Kilo-Aperture Optical Spectrograph” (2003)
- [3] Ellis, R., et al., “Wide-Field Fiber-Fed Optical Multi-Object Spectrometer WFMOS Study Summary” (2009)
- [4] Barden, S., et al., “WFMOS: A Feasibility Study for Gemini” (2009)
- [5] Richer, H., et al., “Illuminating the Dark Universe: Report of the Next Generation CFHT Committee” (1998)
- [6] Carlberg, R., et al. “A Wide-Field 8 Meter Telescope for Canadians” (1999)
- [7] Geyl, R., et al., “The New CFHT” (2000)
- [8] Burgarella, D., et al., “The Next Generation Canada-France- Hawaii Telescope” (2000)
- [9] Fahlman, G. G. 2003, The Proceedings of the IAU 8th Asian-Pacific Regional Meeting, Volume 1, 289, 3
- [10] Grundmann, W., “A CFH 12-16m Telescope Study” (1997)
- [11] Simons, D., et al., in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*

- [12] Barden, S. C., et al., "HERMES: revisions in the design for a high-resolution multi-element spectrograph for the AAT," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7735** (July 2010).
- [13] Levi, M., Bebek, C., Beers, T., et al. 2013, arXiv:1308.0847
- [14] de Jong, R., "4MOST: 4-metre Multi-Object Spectroscopic Telescope," *The Messenger* **145**, 14–16 (Sept. 2011).
- [15] Takada, M., Ellis, R. S., Chiba, M., et al. 2014, PASJ, 66, 1