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Title of White Paper The Maunakea Spectroscopic Explorer

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Executive Summary of White Paper (5000 character limit)

The Maunakea Spectroscopic Explorer (MSE) is a project to design and construct a wide-field spectroscopic telescope at a site with excellent natural seeing, and in so doing to continue the tradition of Canadian leadership in wide-field astronomy established with the Canada-France-Hawaii Telescope. MSE is an end-to-end science platform for the design, execution and scientific exploitation of transformative, high-precision spectroscopic surveys at low-, medium-, and high-resolution from 0.37 to 1.8 microns. It will unveil the composition and dynamics of the faint Universe and impact nearly every field of astrophysics across spatial scales from individual stars to the largest scale structures in the Universe.

Major pillars in the MSE science program include:
(i) high spectral resolution Gaia follow-up to understand the chemistry and dynamics of the distant Milky Way in unprecedented detail;
(ii) a revolutionary study of galaxy formation and evolution over billions of years back to `cosmic noon' when the Universe was at its peak of star formation;
(iii) a large-volume, redshift survey to constrain inflationary physics and determine the mass of the neutrino;
(iv) high fidelity measurements of the density profiles of the dark matter halos of Milky Way satellites; and (v) the largest sample yet of quasars with black hole masses measured from reverberation mapping, used to calibrate relationships enabling black hole mass estimates for millions of quasars.

The MSE design features an 11.25m aperture telescope dedicated to multi-object spectroscopy over a 1.5 square degree field of view. A total of 3249 fibers will feed spectrographs operating at low (R ~= 3000) and moderate (R ~= 6000) spectral resolution, and an additional 1083 fibers will simultaneously feed high resolution spectrographs (R ~= 20,000-40,000). It is expected that 80% of useful observing time will be dedicated to large, multi-year Legacy Surveys proposed by MSE partners and chosen in a competitive, peer-reviewed process. The remaining 20% of observing time will be allocated to the partners, based on their relative share in MSE, for smaller Strategic Surveys. All MSE data will be available to all partners, with a proprietary period of several years before becoming publicly available. A set of Design Reference Surveys will be created and iterated during the design and construction phases so that the MSE science community is ready to propose surveys that take full advantage of all of the capabilities of MSE.

Numerous international studies have concluded that the capabilities provided by MSE would be a critical hub in the emerging international network of front-line astronomical facilities over the coming decades, naturally complementing and extending the scientific power of TMT, SKA, Euclid, LSST, and many other facilities. High rankings in ongoing national reviews and success in peer-reviewed funding competitions will pave the way for detailed design of MSE in 2021-2025, construction in 2026-2031, and operation in the 2030s and well beyond.

The cost to build the MSE conceptual design is US$420M, including risk margins, and the cost to operate the facility is estimated at US$25M/year, all in 2018 dollars. A model with several roughly equal major partners instead of one dominant partner is anticipated. The current MSE partnership

consists of Canada, France, U. Hawaii, Australia, China, and India, plus observers from Texas A&M University, the US National Optical Astronomy Observatories, and a consortium of UK universities and research institutes. The MSE Science Team consists of approximately 400 scientists worldwide, including about 36 from Canada and an equal number from France, exceeded only by the number of members from the US.

Recommendations:
It is not realistic to expect that Canada can be a part of every single scientifically exciting astronomical facility that exists, will be built, or is proposed. Projects and facilities undertaken at a national level in Canada therefore need to be strategic investments that increase scientific and industrial capacity, build upon strengths, leverage past investments, and provide collaborative and leadership opportunities within the worldwide community. The MSE project fulfills those criteria and fills a major missing link in the future international network of multi-wavelength astronomical facilities. In that context, and given the benefits of an MSE facility to the Canadian community, we recommend:

1) that the community prioritizes continued Canadian involvement in the MSE project through its preliminary design phase, its final design phase, and its construction and operation on a suitable site, subject to successful design reviews and successful funding by an international partnership.

2) that the community supports a Canadian share in an MSE facility of at least 20%, ensuring that Canada has a significant voice in the project as one of the top 3 or 4 partners.

Lead author and affiliation Pat Hall, York University

Email address of lead author phall@yorku.ca

Other authors and affiliations

Michael Balogh (University of Waterloo),
Pauline Barmby (Western University),
John Blakeslee (NRC / Gemini Observatory),
Jo Bovy (U. Toronto),
Colin Bradley (U. Victoria),
Terry Bridges (Okanagan College),
Jan Cami (Western University),
Scott Chapman (Dalhousie University),
Francois Chateauneuf (INO),
Nick Cowan (McGill University),
Patrick Côté (NRC),
Ivana Damjanov (Sant Mary's University),
Maria Drout (U. Toronto),
Gwendolyn Eadie (U. of Toronto),
Sara Ellison (U. Victoria),
Laura Ferrarese (NRC),
Wesley Fraser (NRC),
Bryan Gaensler (Dunlap Institute / U. Toronto),
Sarah Gallagher (Western University),
Daryl Haggard (McGill University),
Vincent Henault-Brunet (Saint Mary's University),
Falk Herwig (U. Victoria),
Alexis Hill (MSE Project Office),
Julie Hlavacek-Larrondo (U. de Montr'eal),
Mike Hudson (U. Waterloo),
Matt Johnson (York University / Perimeter Institute),
Viraja Khatu (Western University),
Chervin Laporte (U. Victoria),

Alan McConnachie (NRC),
Brian McNamara (U. Waterloo),
Faizan Mohammad (U. Waterloo),
Adam Muzzin (York University),
Hilding Neilson (U. Toronto),
James Nemec (Camosun College),
Christopher O'dea (U. Manitoba),
Laura Parker (McMaster University),
David Patton (Trent University),
Will Percival (U. Waterloo),
Jesse Rogerson (Canada Aviation and Space Museum),
John J. Ruan (McGill University),
Charli Sakari (U. Washington),
Marcin Sawicki (Saint Mary's University),
Doug Simons (CFHT),
Greg Sivakoff (U. Alberta),
Kei Szeto (MSE Project Office),
Solomon Tesfamariam (UBC),
Karun Thanjavur (U. Victoria),
Simon Thibault (U. Laval),
Guillaume Thomas (NRC),
Ludovic Van Waerbeke (UBC),
Kim Venn (U. Victoria),
Tracy Webb (McGill University),
Jon Willis (U. Victoria),
Joanna Woo (Simon Fraser University)

1 Authors

AUTHORS: **Pat Hall** (York University), **Michael Balogh** (University of Waterloo), **Pauline Barmby** (Western U.), **John Blakeslee** (NRC / Gemini Observatory), **Jo Bovy** (U. Toronto), **Colin Bradley** (U. Victoria), **Terry Bridges** (Okanagan College), **Jan Cami** (Western U.), **Scott Chapman** (Dalhousie University), **Francois Chateauneuf** (INO), **Nick Cowan** (McGill University), **Patrick Côté** (NRC), **Ivana Damjanov** (Sant Mary's University), **Maria Drout** (U. Toronto), **Gwendolyn Eadie** (U. of Toronto), **Sara Ellison** (U. Victoria), **Laura Ferrarese** (NRC), **Wesley Fraser** (NRC), **Bryan Gaensler** (Dunlap Institute / U. Toronto), **Sarah Gallagher** (Western U.), **Daryl Haggard** (McGill University), **Vincent Henault-Brunet** (Saint Mary's University), **Falk Herwig** (U. Victoria), **Alexis Hill** (NRC / MSE Project Office), **Julie Hlavacek-Larrondo** (U. de Montréal), **Mike Hudson** (U. Waterloo), **Matt Johnson** (York University / Perimeter Institute), **Viraja Khatu** (Western U.), **Chervin Laporte** (U. Victoria), **Alan McConnachie** (NRC), **Brian McNamara** (U. Waterloo), **Faizan Mohammad** (U. Waterloo), **Adam Muzzin** (York University), **Hilding Neilson** (U. Toronto), **James Nemec** (Camosun College), **Christopher O'dea** (U. Manitoba), **Laura Parker** (McMaster University), **David Patton** (Trent University), **Will Percival** (U. Waterloo), **Jesse Rogerson** (Canada Aviation and Space Museum), **John J. Ruan** (McGill University), **Charli Sakari** (U. Washington), **Marcin Sawicki** (Saint Mary's University), **Doug Simons** (CFHT), **Greg Sivakoff** (U. Alberta), **Kei Szeto** (NRC / MSE Project Office), **Solomon Tesfamariam** (UBC), **Karun Thanjavur** (U. Victoria), **Simon Thibault** (U. Laval), **Guillaume Thomas** (NRC), **Ludovic Van Waerbeke** (UBC), **Kim Venn** (U. Victoria), **Tracy Webb** (McGill University), **Jon Willis** (U. Victoria), **Joanna Woo** (Simon Fraser University)

2 Introduction

The Maunakea Spectroscopic Explorer (MSE) is an end-to-end science platform for the design, execution and scientific analysis of high-precision, optical and near-infrared spectroscopic surveys (McConnachie et al., 2016).

The MSE design features an 11.25m aperture telescope fully dedicated to multi-object spectroscopy over a 1.5 square degree field of view. A total of 3249 fibers will feed six 'LMR' spectrographs operating at low (R $\simeq$ 3000) and moderate (R $\simeq$ 6000) spectral resolution, and an additional 1083 fibers will simultaneously feed two 'HR' high-resolution spectrographs operating at high (R $\simeq$ 20,000 to 40,000) resolution. Both the LMR and HR spectrographs will simultaneously have access to the full field of view. The entire optical window from 370 nm to 950 nm and the near-infrared J and H bands will be accessible at low/medium resolution, and three windows in the optical range will be accessible at high resolution. The entire MSE system is optimized for high throughput, high signal-to-noise observations of the faintest sources in the Universe. High quality calibration and stability is ensured through the dedicated operational mode of the observatory, which will deliver the equivalent of more than 10 million fiber hours of 10m class spectroscopy for forefront science every year. The discovery efficiency of MSE is an order of magnitude higher than any other spectroscopic capability currently operating or in development. MSE builds on the success of the Sloan Digital Sky Survey (SDSS) concept, but is realized on a facility with a 20 times larger aperture to be located at a site with superior atmospheric seeing. Indeed, MSE will produce datasets equivalent – in number of objects – to an SDSS Legacy Survey every 7 weeks.

MSE began as a Canadian-led concept for a next-generation CFHT (ngCFHT) during LRP2010: *The LRPP recommends that Canada develop the ngCFHT concept (science case, technical design, partnerships, timing).* Over the next few years, a grassroots team prepared a Feasibility Study on a shoestring and promoted the project internationally. The CFHT Board established a Project Office in 2014 and the project was renamed the Maunakea Spectroscopic Explorer. From the LRP Mid-Term Review (MTR) in 2015-2016: *The MTRP thus strongly recommends that Canada continue to lead the development of the MSE project*. MSE passed a Conceptual Design Review in January 2018. A snapshot of the entire MSE observatory including technical designs at the end of the Conceptual Design Phase can be found in the MSE Book 2018 (Hill et al., 2018).

Major reports in the USA, Europe, and elsewhere all recognise that wide-field spectroscopic survey capabilities such as those MSE will provide are an essential missing component of the world-wide astronomy portfolio (Elmegreen et al 2015, Najita et al. 2016, Ellis et al. 2017). Thanks in large part to Canadian astronomers, MSE is currently the most advanced design for this type of facility, and the CFHT Board have officially recognised it as the scientific future of CFHT.

3 Science with MSE

The MSE Detailed Science Case (DSC; The MSE Science Team et al. 2019) forms the foundation for the Science Requirements Document (SRD).[1] The Science Requirements for MSE are defined as the capabilities necessary to conduct the high impact science programs outlined in the DSC that are uniquely possible with a dedicated spectroscopic facility at an excellent site. These capabilities include:

• High survey speed and sensitivity: The etendue of MSE is more than twice as large as its only 8m competitor (149 vs. 66 m^2 deg^2 for Subaru/PFS). MSE's sensitivity allows efficient observation of sub-L* galaxies out to high redshift and high resolution studies of stars in the distant Galaxy. The excellent site image quality is essential for efficiently observing the faintest objects and to ensure the spectrograph optics are a reasonable size given the multiplexing demands.

• Dedicated and specialized operations: Dedicated operations with no instrument exchanges enables very large surveys to be conducted and increases the stability of the observing systems, yielding more accurate calibration. Specialized observing mode capabilities are being built into the MSE design to enable time domain programs such as quasar reverberation mapping, high-value transient targeting, and precision stellar radial velocity monitoring,

• Spectral performance: The extensive wavelength coverage of MSE from the UV to H-band uniquely enables the same tracers to be used to study galaxy and black hole growth at all redshifts to beyond cosmic noon. Chemical tagging with MSE can be conducted across the full luminosity range of Gaia targets, and operation at R=40,000 enables the use of weak lines in the blue to access species sampling a diverse range of nucleosynthetic sites.

The MSE Science team is currently formed into nine Science Working Groups illustrating the range of science possible with MSE. One group is focused on what is envisioned as a second-generation MSE capability: Integral Field Unit development. Here we highlight a very few of the most notable science cases from the other eight groups. For more details and for other science cases, see the MSE Detailed Science Case.

3.1 Chemical Nucleosynthesis

Our knowledge concerning the emergence of the elements of the Periodic Table remains limited. Although the basic processes for the synthesis of the chemical elements in stars are known, debate continues on the dominant environments (low-mass stars, high-mass stars, merging neutron stars, etc.) and the dominant times (during main sequence evolution, in the dying stages, etc.) at which those processes occur, and therefore on the relative contributions of each process to the abundances of individual elements over cosmic time. Much more precise measurements of the composition of stars ('chemical tagging') provides an exceptionally powerful probe of the spatial and temporal distributions of the various possible element production processes in the Galaxy.

For example, the most metal-poor stars can provide great detail on the dominant processes of the formation and assembly of the major populations of the Milky Way. The very first stars in the Milky Way were likely much more massive than the sun ($M > 10M_\odot$), and have long since exploded. Nonetheless, we can study them: chemical elements produced by the first stars were returned to the gas clouds from which a second generation of stars formed. That second generation included some low-mass stars ($M < M_\odot$) which still live today, and their atmospheres retain the chemical composition of the interstellar gas at the time and place of their birth. As the DSC puts it, "the oldest and most chemically primitive stars are fossils, which contain the nuclear ashes of the first stars to be born in the universe."

There are few, if any, suitable lines of heavy elements created by rapid or slow neutron capture available in the infrared. Hence, optical surveys are required to constrain the origin of such r- and s-process elements. MSE stands alone as a large aperture multi-object spectroscopic facility with sufficiently high spectral resolution in the optical to address this and other key questions relating to the origin and evolution of the chemical elements. For example,

[1] The SRD is available at `https://mse.cfht.hawaii.edu/?page_id=15`.

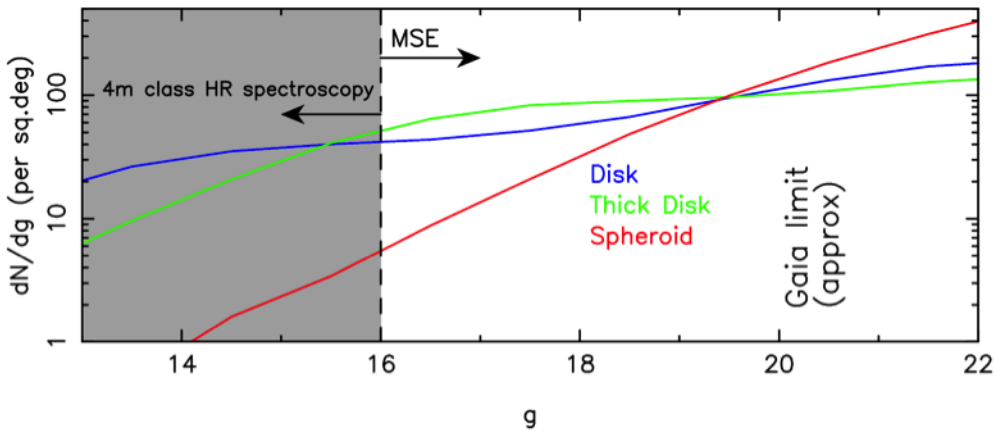

Figure 1: Differential star counts as a function of magnitude for the three main Galactic components, based on the Besancon model of the Galaxy (Robin et al. 2003, A&A, 409, 523) for a 100 square degree region in the vicinity of the north Galactic cap. The shaded region indicates the magnitude range accessible to 4m class spectrographs at high resolution (R $\simeq$ 20 000 – 40 000). At such resolutions, MSE is the only facility able to access the thick disk and spheroid *in situ*; that is, in the regions of the Galaxy in which they are the dominant components. MSE targets at high resolution span the full luminosity range of targets that will be identified with Gaia.

MSE will enable a large scale study of lithium abundances down to the lowest metallicities to understand why such stars are depleted in lithium below the abundance predicted from big bang nucleosynthesis.

In summary, MSE is uniquely tailored to understanding the cosmic formation and evolution of the elements of the periodic table. It will trace different nucleosynthetic processes, sites and timescales through the measurement of a large number of chemical species, including in the crucial blue/UV region of the spectrum.

3.2 The Milky Way

MSE will be vital for understanding the faint and distant regimes of our Galaxy where the outer disk, thick disk and stellar halo are dominant (Figure 1). MSE is the only survey spectrograph planned that will be able to observe millions of the faintest Gaia stars at high resolution. In addition, MSE radial velocities will give access to the full 6D position/velocity space for Gaia stars.

Chemical tagging will help us understand the origin of the elements, as discussed above, but also enables us to identify stars with common origins which are now dispersed across the sky, and to distinguish stars from environments with different star-formation histories. As noted by Freeman & Bland-Hawthorn (2002), "the major goal of near-field cosmology is to tag individual stars with elements of the protocloud" from which the star formed. MSE will provide abundance ratios for 20 to 30 elements formed through multiple nucleosynthetic channels to enable chemical tagging of many millions of targets in the halo, thin disk, thick disk and bulge. For any spectroscopic survey, the more distinct nucleosynthetic pathways that can be measured, the better we can trace and distinguish the distinct evolutionary paths of different stellar populations. The insights gained on stellar populations in our Galaxy also have immediate applications for extragalactic populations.

3.3 Cosmology

Percival et al. (2019) outline an MSE High-z Cosmology Survey of candidate galaxies and quasars at $1.6 < z < 4$ pre-selected using UNIONS and Euclid imaging. The survey is designed to probe a large volume of the Universe with a galaxy density sufficient to constrain primordial non-Gaussianity and therefore inflation. The parameter f_{NL} is a measure of local non-Gaussianity, and a detection of $f_{NL} > 1$ would rule out classes of slow-roll inflation models. The current constraint (from Planck) is $\sigma(f_{NL})$=5.7. A 10,000 deg^2 MSE survey (625 nights over 6 years, e.g.) can constrain f_{NL} to a precision $\sigma(f_{NL})$ = 0.4. That is an improvement over the value quoted in Percival et al.

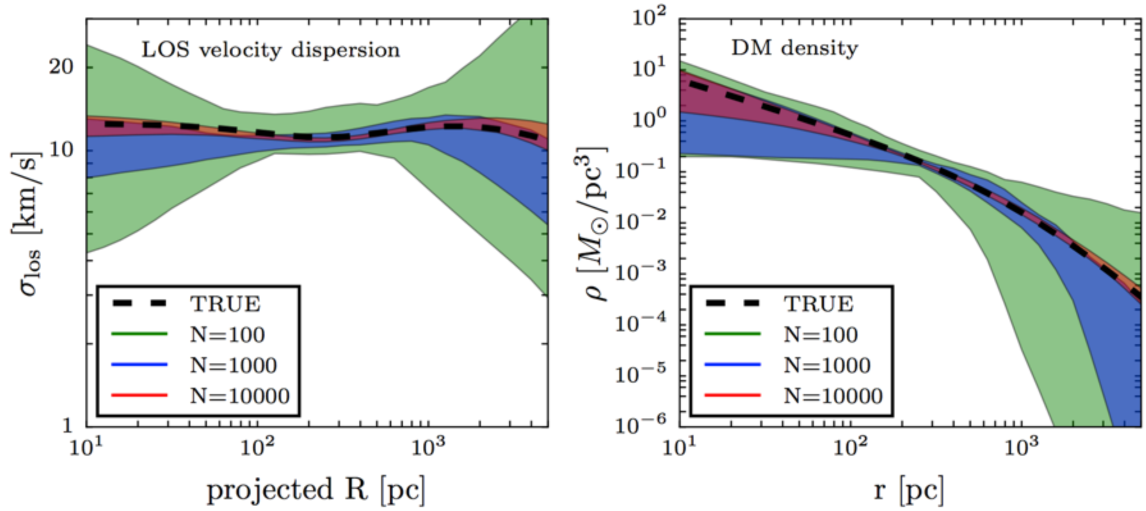

Figure 2: Recovery of intrinsic line-of-sight velocity dispersion (left) and inferred dark matter density (right) profiles as a function of spectroscopic sample size. Shaded regions represent 95% credible intervals from a standard analysis (based on the Jeans equation) of mock data sets consisting of line of sight (LOS) velocities for $N = 10^2$, 10^3 and 10^4 stars (median velocity error $2\,\mathrm{km}^{-1}$), generated from an equilibrium dynamical model for which true profiles are known (thick black lines, which correspond to a model having a cuspy NFW halo with $\rho(r) \propto r^{-1}$ at small radii). From Li et al. (2019).

(2019) because it includes measurements of the mass bispectrum (the three-point correlation function of Fourier modes) accounting for redshift-space effects; see Table 11 of Karagiannis et al. (2018).

For comparison, Ferraro & Wilson (2019) and Wilson & White (2019) advocate a 14,000 deg^2 survey yielding $\sigma(f_{NL})$ = 0.11 due to a larger estimated improvement from bispectrum constraints. The value of $\sigma(f_{NL})$ is expected to improve with the square root of the survey volume rather than with the number of galaxies observed; thus, the MSE cosmology survey would yield $\sigma(f_{NL}) \simeq 0.13$ if the bispectrum improvement factor from the above references is applicable. Rigorous calculations are obviously needed, but it is clear that an MSE cosmology survey can tighten constraints on models of inflation by delivering at least an order of magnitude improvement in $\sigma(f_{NL})$.

Furthermore, combining data from the MSE High-z Cosmology Survey, a next generation CMB stage 4 experiment, and DESI data will provide the first 5σ confirmation of the neutrino mass hierarchy from astronomical observations. The MSE Cosmology Survey will also tightly constrain baryon acoustic oscillations and large-scale mass fluctuations (σ_8) at high redshift, testing our understanding of the effects of dark matter and dark energy.

3.4 Astrophysical Tests of Dark Matter

Li et al. (2019) outline how MSE will advance our understanding of dark matter on scales from the Milky Way and its satellites to distant galaxy clusters. Across nearly all mass scales, the improvements offered by MSE in comparison to other facilities mean that the relevant analyses are limited by systematics rather than statistics.

MSE will enable measurement of the density profiles of the dark matter halos of Milky Way dwarf galaxies. To quantify this constraint, consider that an MSE survey of Local Group galaxies would increase the available spectroscopic samples by more than an order of magnitude in most cases. Ultrafaint satellites with $M_V \gtrsim -5$ would have stellar samples of several hundred to a thousand members each. 'Classical' Milky Way dwarf spheroidals ($-7 \gtrsim M_V \gtrsim -13$) and more luminous distant objects (e.g., NGC 185, NGC 205 and NGC 6822) would have samples from a thousand to tens of thousands of member stars each. The effects of stellar sample size on inferences about dark matter are illustrated in Figure 2.

And with an expected systematic velocity uncertainty in the high resolution mode of $100\ \mathrm{m\,s}^{-1}$, MSE will be able to detect substructures of masses 10^5-10^7 $M_\odot$ via their effects on the dynamics of Milky Way stellar streams.

In the low redshift Universe, MSE redshifts will improve measurements of the faint end of the luminosity function. For galaxies fainter than $M_r \sim -14$, the uncertainty in the global low-redshift luminosity function is large, due to incompleteness in both photometric and spectroscopic surveys. The result is a large uncertainty in the galaxy–halo connection for halo masses below $10^{10} M_{\odot}$. Reducing this uncertainty will either remove or confirm inconsistencies between small-scale observations and model predictions (Bullock & Boylan-Kolchin, 2017) that may provide concrete evidence for the need for non-cold dark matter.

3.5 Exoplanets and stellar astrophysics

Space photometry missions such as TESS are expected to discover tens of thousands of transiting Jupiter-mass planets in the 2020s (Barclay et al., 2018). These yields vastly outnumber the available follow-up resources on single-object spectrographs. MSE spectroscopy of large samples of transiting planet-host stars will test the mass-radius relation for objects near the boundary between planets and stars and help to improve the accuracy of exoplanet radii measurements by reducing uncertainties in limb darkening coefficients.

In addition, MSE will provide direct measurements of the bulk composition of thousands of exo-planetesimals, through spectroscopy of white dwarfs polluted by planetary debris.

3.6 Active Galactic Nuclei and supermassive black holes

A multi-epoch optical/near-IR reverberation mapping campaign with MSE will yield ∼2500 robust time lags of quasar broad-line regions from lines of different ionization in each object, extend lag detections to lower luminosities, and extend SDSS campaigns to detect lags in more luminous, slowly varying quasars at high redshift. The resulting accurate SMBH mass measurements, based on the same broad line at all redshifts, are needed to calibrate the radius - luminosity relation used to estimate SMBH masses from single-epoch quasar spectra, and to search for additional parameters in that relationship. In addition, deep AGN luminosity functions will trace the connection between AGN and the star-forming (and other) properties of their host galaxies over cosmic time.

3.7 Galaxy formation and evolution

A fundamental measurement for MSE will be the extension of the galaxy stellar mass function to masses below $10^8\ M_{\odot}$ using a cosmologically representative, unbiased, spatially complete spectroscopic sample over ∼100 deg^2, which could be obtained in conjunction with quasar reverberation mapping campaigns. This and other extragalactic surveys with MSE will provide a high-completeness, magnitude limited sample of optical and near-IR galaxy spectra spanning the epoch of peak cosmic star-formation (1.6$<z<$3). The outstanding sensitivity of MSE will dramatically increase our ability to study stellar populations over cosmological time. MSE surveys will cover the diverse range of environments probed by surveys such as SDSS and GAMA (groups, pairs, mergers, filaments, voids), back to an epoch when the Universe was 20% of its current age. The insights resulting from such surveys are difficult to predict given the relatively scarce amount of information we currently have in these regimes (thousands of spectra, vs. millions with MSE). Furthermore, the field of view and sensitivity of MSE will enable comprehensive mapping of the outer halo in the most massive galaxies within the Local Volume out to distance of 30 Mpc (~ 30 times larger than the volume where resolved stellar population studies are feasible with current instrumentation). MSE will thus have a generation-defining impact on our understanding of how galaxies evolve and assemble their mass over 12 billion years of cosmic time.

3.8 Time domain astronomy and the transient Universe

Any MSE program requiring multiple visits to a field to build up deep spectroscopic observations will also enable time domain studies of known variable quasars and stars, as well as transients localized by other facilities and targeted using dynamic fiber placement. And at least at the start of wide-field, single-visit surveys, there will be considerable freedom to target interesting transients localized by other observations. Out of all potential pointings, the one whose footprint includes the most interesting current transient (or variable) can be chosen for observation and a single fiber can be reassigned to observe the transient.

Very few single targets of opportunity will have sufficient scientific impact to dictate where MSE will point (though MSE will be ready with targets for the other fibers if that happens). Rather, by assigning 1 fiber out of 4332 whenever possible to the most interesting transient or variable target in each field scheduled for observation, MSE can function as a full-time time-domain telescope at minimal impact to its other science goals.

4 Partnership and Survey Design & Operations Model

As of this writing, the MSE partnership consists of voting participants Canada, France, U. Hawaii, Australia, China, and India. Several groups have non-voting observer status while they explore options for joining as voting participants: Texas A&M University, the National Optical Astronomy Observatories, and a consortium of UK universities and research institutes (MSE:UK).

A Statement of Understanding on governance for the Preliminary Design Phase has been signed by Canada, CFHT, and Australia in the last few months, with other signatures expected soon. Cash and in-kind contributions to the project will continue to be tracked by the partnership to establish each partner's 'Beneficial Interest' in MSE. A partner's share in the governance of MSE will reflect the level of its Beneficial Interest in MSE. In other words, every partner will have two representatives on the MSE Board, but the votes of those representatives will be weighted to match each partner's Beneficial Interest.

The current *draft* MSE partnership concept envisions that 80% of the available observing time will go toward large, typically multi-year Legacy Surveys, while 20% will be dedicated to Strategic Surveys. Each MSE partner will contribute 80% of its time share to Legacy Surveys and receive 20% of its time share to allocate to Strategic Surveys as it sees fit. Scientists from all partners will be able to form collaborations to propose Legacy Surveys. The Legacy Surveys to be carried out will be chosen through a competitive, peer-reviewed process. All MSE partners will have access to all MSE data and data products. This *draft* partnership concept envisions that partners' cash plus in-kind contributions to the project will scale with their community size. A partner choosing not to contribute at the expected level would secure access to MSE for only a subset of its community. The MSE data and data products would be proprietary to the partnership for a period of several years at least.

Optimizing the design of MSE surveys is non-trivial, but will be accomplished via multiple iterations of Design Reference Surveys created using sophisticated survey design software, informed by experience from spectroscopic surveys on smaller telescopes since the 1990s.

MSE will operate in a queue-based mode enabled by sophisticated scheduling software known as the Observing Matrix Generator (OMG, Flagey et al., 2018). Survey teams will provide the OMG with lists of observing fields, exposure sequences, fiber allocations for LMR and HR fibers, and additional targets. Two examples will illustrate the envisioned OMG capabilities. For deep surveys of a few pointings (e.g., quasar reverberation mapping plus faint galaxy and stellar spectroscopy), after each night a survey metric can be measured from the accumulated data on each object. If a satisfactory value of that metric is reached (e.g., a certain redshift reliability), the object can be declared a success and its fiber reassigned in future. For wide surveys such as cosmology and in situ Galactic stellar population studies, after each exposure a survey metric (e.g., average SNR) can be estimated from quick-look reductions and used to automatically decide whether to obtain another exposure or to declare the field complete.

Each day, the OMG will produce an observing schedule for that night (and future nights), using information on weather, survey priorities, field availability, etc. The schedule will be recalculated during each exposure, if needed. For example, if a night's first exposure does not reach the required SNR as expected and another exposure on the same field is started, the OMG will recalculate the schedule for the rest of the night during that second exposure.

Thus, MSE observation scheduling is a challenging real-time optimization problem. Fortunately, cutting-edge computing techniques such as deep learning and artificial intelligence algorithms can be brought to bear on these problems. The MSE partnership takes the view that software must be an integral part of MSE design efforts, not an afterthought. Design of software for MSE survey design and observation scheduling has already begun during conceptual design and is a significant part of the CFI proposal for preliminary design funding (see next section).

5 Cost and Timeline

The cost to build the MSE conceptual design is US$420M in 2018 dollars. It is expected that a partnership agreement would cover construction and the first five years of operations. A model with several roughly equal major partners instead of one dominant partner is anticipated. Based on initial studies, we assume operating costs of 6% of the cost of the facility per year.

Thus, a Canadian share of 20% of MSE would require an investment of C$110M in the 2020s (mostly from 2025-2030) plus C$6.6M/year for operations in the 2030s, all in 2018 dollars. For comparison, Canada's shares of operations costs are approximately C$4.3M/year for CFHT and C$6.75M/year for Gemini, again in 2018 dollars.

Securing funding from the international partnership to proceed with preliminary design (estimated at US$25M) has required a delay to the start of this phase as partners develop funding plans to proceed. A C$24M funding proposal for the 2020 CFI round is being submitted by a Canadian industry and academia consortium to strengthen Canadian expertise and advance design work on the enclosure, telescope structure and top end, fiber-optic transport system, spectrographs, calibration systems, and software for survey planning and data reduction. A proposal for on the order of twice that amount to a subsequent CFI round is anticipated as a means to secure a large part of Canada's share for funding construction of MSE.

MSE is being actively considered in national reviews in Canada, France, the United States, and Australia. High rankings in these planning exercises will pave the way for sufficient funding to complete the preliminary design phase by 2023. We anticipate final design being complete and construction beginning in 2026, leading to science commissioning in 2031.

For a perspective on US partnership, see the Astro2020 white paper by Marshall et al. (2019). In particular, the costs required to secure a 25% share in MSE for the United States are appropriate for funding via a combination of NSF's mid-scale innovation program, supplemental in-kind contributions by US institutions, and NOAO/NCOA operations funding via integration of MSE's science data products into the NOAO Data Lab science platform.

6 LRP Criteria

1: How does the proposed initiative result in fundamental or transformational advances in our understanding of the Universe?

The MSE facility design enables optical/near-IR spectroscopic surveys an order of magnitude (or more) larger than conducted by previous facilities, and at magnitudes within reach of an 11.25-meter diameter mirror. See section 3 for a selection of science highlights, and the Detailed Science Case for many more.

2: What are the main scientific risks and how will they be mitigated?

The only other 8-m class, wide-field, massively multiplexed spectroscopic instrument being actively pursued is the Subaru Prime Focus Spectrograph. Subaru/PFS will be on-sky by 2022, but the scientific goals of MSE go beyond what can be achieved with Subaru/PFS even in a decade of observations, due to MSE's larger aperture, dedicated operations, greater multiplexing, and high-resolution and H-band capabilities. The same is true for massively multiplexed spectroscopic instruments currently being constructed for 4-m class telescopes (DESI, 4MOST, SDSS-V, WEAVE, etc.). The large aperture and high multiplexing of MSE means that it can carry out surveys which cannot be accomplished in any feasible length of time by similar instruments on smaller telescopes or by instruments with smaller multiplexing factors on similar size telescopes. Nonetheless, there is a scientific risk that delaying progress on MSE will enable new facilities to be built and conduct some surveys currently envisioned for MSE before MSE itself can do so. ESO has identified a wide-field 10-12 meter class dedicated spectroscopic facility ('SpecTel') as their top priority after E-ELT (Ellis et al., 2019). SpecTel in the southern hemisphere and an MSE facility on Maunakea would together offer near full-sky coverage, with obvious possibilities for collaboration if both are built. MSE will likely have a ten-year lead when design work on SpecTel begins in earnest. Translating that lead to being the first to actually conduct groundbreaking surveys on the sky requires continued progress on MSE. As another example, the MegaMapper concept (Schlegel et al., 2019) for a 6.5-m telescope feeding 20,000 fibers over 7 deg^2 could reach the same non-Gaussianity constraint $\sigma(f_{NL})$ as MSE in about half the time. However, MegaMapper would be a dedicated cosmology facility and would not have high-resolution or near-infrared spectroscopic capabilities.

Fortunately, because the MSE design is for an observing facility and not a pre-defined set of surveys, the long-term scientific impact of MSE is not at risk. An evolving set of Design Reference Surveys prepared by the community during the lead-up to operations, along with competitive survey selection, will ensure that the large surveys conducted by MSE are the best use of its capabilities possible given the future scientific landscape.

3: Is there the expectation of and capacity for Canadian scientific, technical or strategic leadership?

The MSE project is a Canadian initiative dating from LRP2010. Canada has been deeply involved in the MSE Project Office, Management and Science Advisory Groups, and Science Team. Canadian scientists and engineers have filled the roles of Project Manager, Project Engineer, Deputy Project Engineer, Project Scientist (through 2018), Project Spokesperson, and Management Group Chair. The great scientific interest in MSE in Canada means that Canadians are interested in helping to lead the project, not just participating in it.

4: Is there support from, involvement from, and coordination within the relevant Canadian community and more broadly?

The MSE Science Team includes about 36 Canadians, more than any other country except the USA, and this white paper has over 50 co-authors. There is considerable overlap between communities in Canada interested in wide-field imaging (e.g., UNIONS, LSST, CASTOR) and those interested in wide-field spectroscopy with MSE. The entire Canadian community will be able to propose to MSE, enabling synergies involving science at other wavelengths or with other facilities (e.g., spectroscopy of SKA radio source counterparts).

5: Will this program position Canadian astronomy for future opportunities and returns in 2020-2030 or beyond 2030?

Finalizing the MSE design, using it to construct a facility, and operating that facility will provide Canadian scientists a leading role in a premiere spectroscopic survey observatory that will generate scientific returns throughout the 2030s and beyond. The experience gained by Canadian industry through this program will position it to contribute to other spectroscopic and astronomical initiatives proposed for the 2020s and 2030s. The capabilities of MSE are highly desirable world-wide and could position Canada to leverage involvement in other facilities through science partnerships, time exchanges, or industrial partnerships.

6: In what ways is the cost-benefit ratio, including existing investments and future operating costs, favourable?

In terms of the surveys it will conduct, MSE looks to SDSS as the example to emulate, and the cost-benefit ratio of SDSS is outstanding. For MSE, as for SDSS, providing all data to the user community will enable scientific advances above and beyond those envisioned in the survey proposals.

Purely in terms of monetary costs, the cost-benefit ratio of MSE re-using much of the CFHT structure on Maunakea is higher than the cost-benefit ratio of building MSE at another site. Building MSE on the Big Island of Hawaii also enables continued access to scientific and technical staff familiar with the CFHT structure and the CFHT site. Building MSE as a partnership evolving from the CFHT partnership builds on 40 successful

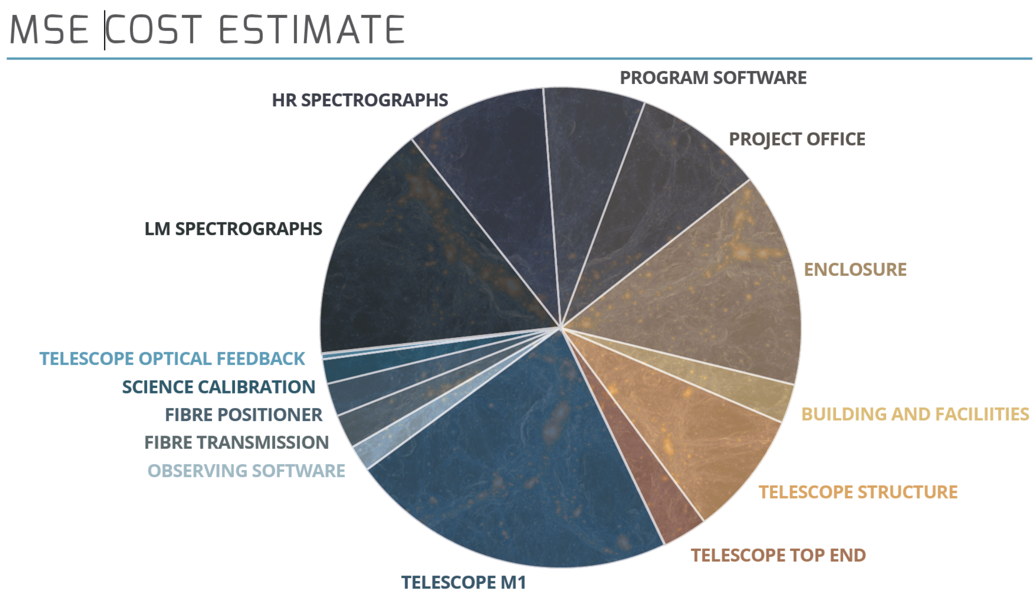

Figure 3: Distribution of the MSE conceptual design cost estimate (total cost US$420M in 2018 dollars).

years of collaboration between Canada, France, and University of Hawaii.

As for other sites that equal or exceed the quality of the CFHT site on Maunakea, the cost-benefit ratio of constructing an MSE-design facility from the ground up at an existing observatory is not as high, due to the added cost of the building. Construction at an unimproved site would lessen the cost-benefit ratio further.

7: What are the main programmatic risks and how will they be mitigated?

An obvious risk is the need for funding: building and operating an MSE-design facility is beyond the financial capacity of either Canada or the current CFHT partnership alone. This risk is being mitigated by partnership expansion, as the cost of MSE is within reach of an expanded partnership. The MSE design has some modular components which could enable certain cost-saving measures; e.g., near-IR arms could be installed on only two out of six LMR spectrographs without sacrificing full field near-IR coverage. However, no one component of the MSE budget dominates the cost (Figure 3).

A technical risk often mentioned is the accuracy of sky subtraction achievable with fiber spectroscopy, which sets the faint magnitude limit for observations. This risk is being mitigated through careful design including plans for accurate modeling and calibration of the instrument throughput in each fiber configuration. Furthermore, sky subtraction to the accuracy required for MSE science cases is possible: with careful attention to systematics, the existing MANGA fiber spectrographs have demonstrated a sky subtraction accuracy of $\pm 0.2\%$ (1σ) at 4000-5000 Å (Gu et al., 2018), much better than the accuracy they were designed to achieve.

A key programmatic risk regarding the Maunakea site is that demonstrations by opponents of siting TMT on Maunakea have affected operations of all Maunakea telescopes. Discussions are ongoing, but the final outcome is unknown. The MSE collaboration recognizes and acknowledges the cultural importance of the summit of Maunakea to a broad cross section of the Native Hawaiian community. Canadian astronomers within MSE are committed to considering telescope siting and indigenous rights issues through a pan-facility process that we expect to arise from the 2020 LRP, regardless of the final siting of TMT or MSE. Specifically relevant to MSE is that renewal of the Mauna Kea Science Reserve master lease is still pending, but clarity on the possibility of siting MSE on Maunakea is expected by the end of the MSE preliminary design phase. The CFHT and its staff have been a part of the Big Island community for 40 years, and MSE as a rejuvenation of the CFHT will not increase the physical footprint of astronomy on Maunakea, making the case of MSE significantly different from the case of TMT. Nonetheless, the MSE design itself is not tied to Maunakea; an MSE-design facility could be constructed at any site of comparable quality (mainly in terms of site seeing).

8: Does the proposed initiative offer specific tangible benefits to Canadians, including but not limited to interdisciplinary research, industry opportunities, HQP training, EDI, outreach or education?

Industry opportunities exist in designing and building the enclosure, telescope, spectrographs, fiber transport system, calibration facilities, software from survey design through to serving the final datasets, and more. Canada has particular expertise in enclosures, spectrographs, fiber bundling, and data archiving and serving.

Technical HQP opportunities exist for scientists and engineers participating in facility design, construction, and operations efforts. Scientific HQP including graduate students, postdocs, and faculty will participate in survey design, management, and scientific analysis. Participation in large survey projects by HQP is important to the advancement of their careers, given the increasing role played by large surveys in modern astronomy.

An MSE-design facility conducting large legacy surveys will follow current best practices in EDI, for example by establishing anti-harassment workplace standards, a collaboration code of conduct, and a committee on inclusiveness modelled on that of the SDSS.[a] If an equitable agreement is reached enabling the transformation of CFHT into MSE, MSE will continue CFHT's participation in the Maunakea Scholars Program to support aspiring young astronomers in Hawai‘i, through scholarships, enrolment in online astronomy courses, and competitive allocations of observing time to local students.

An MSE Education and Public Outreach (EPO) committee has already been established, including two Canadians, one from the Canada Aviation and Space Museum and one from the academic community. MSE EPO will build on the 40-year legacy of CFHT EPO, involving all partner communities as well as the local community at the telescope site.

[a]See `www.noao.edu/conduct/non-harassment.php`, `www.sdss.org/collaboration/coins/`, and `www.sdss.org/collaboration/the-sloan-digital-sky-survey-code-of-conduct/`.

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