1. Executive Summary

The high sensitivity and survey capabilities proposed for MSE will make it a powerful facility for resolving many outstanding questions about galaxy evolution, dark matter, and star cluster formation. The nearby Universe affords a unique opportunity to study these objects in exquisite detail, and in many cases is the only way to connect statistical population parameters at higher redshift with the underlying physical mechanisms. To take advantage of this ability, MSE will be most powerful if it can support a range of spectral resolutions. As many of the nearby targets are relatively sparse on the sky, they will be most efficiently observed as part of general surveys that tackle a wide range of science objectives. In order for this to work well it will be important to observe with multiple resolutions at once. Most nearby objects are considerably extended on the sky, and MSE's primary role here will be to obtain more detailed information not accessible at higher redshift. Most of the science cases described here are greatly enhanced (or indeed, only possible) if spatially resolved spectroscopy can be obtained. Ideally done with multiple IFU arms or fiber bundles, a good intermediate solution can be found if individual fibers can be brought close together, and if spectrophotometric and wavelength calibration is good from fiber to fiber.

2. Science Overview

Understanding the growth of structure in the universe must necessarily proceed through two complementary paths. Studies of the high redshift universe provide an integrated, statistical picture of galaxy evolution over cosmic time. On the other hand, by probing a mass regime and spatial resolution unattainable at higher redshifts, studies of galaxies and star clusters in the local universe uniquely enable a detailed understanding of the role played by gas dynamics, radiative cooling, star formation, and stellar/AGN feedback in the hierarchical assembly of baryonic substructures. MSE will make important contributions on both fronts, and there is substantial overlap in science and potential survey design between them. In particular, the combination of high fiber density, large field-of-view, sensitivity and survey capability, MSE will be unparalleled in its ability to map the properties of galaxies relative to the surrounding large scale structure. Here we address some of the most compelling problems that MSE will address, through observations of the Universe between the Local Group and redshifts of about ~0.1.

Evolution of Galaxies Halos and Structure Over 12 Gyrs (S1 of MSE-highz-SRO1): One of the most compelling astrophysical problems today is the relationship between starlight and dark matter; how they are distributed relative to one another today, and how their structures have developed over time. A low-resolution, highly complete, spectroscopic survey of large areas of the sky allow us to measure the dark matter halo occupation distribution over a wide range of redshifts, and therefore measure directly the efficiency of galaxy formation over unprecedented scales. As with the SDSS and GAMA surveys, for example, the spectra will be used to address many other science cases, including scaling relations between galaxy properties like stellar mass, star formation rates and metallicities over a wide range of mass scales. Taking advantage of the high fiber density of MSE, it will be possible to efficiently achieve a high spectroscopic completeness, important for understanding the links between galaxy formation and large-scale structure, and the role of galaxy-galaxy interactions. The S1 survey described in MSE-highz-SRO1 will provide a transformational picture of our local universe in this respect.

Galaxies and galaxy clusters (MSE-lowz-SRO1): A multiobject spectrograph is the perfect instrument with which to observe galaxies in nearby groups and clusters. In particular, the field-of-view and fiber density of MSE makes it an efficient instrument with which to study the low-redshift systems which are large on the sky, and for which we can probe well down the mass function of galaxies. A survey of nearby clusters and groups will inform our understanding of cosmology, dark matter halo structure, and galaxy evolution.

The physical drivers of dwarf galaxy evolution (MSE-lowz-SRO2): One of the primary advantages of a telescope as sensitive as MSE is the ability to measure the properties of galaxies with very low stellar masses – the building blocks of structure. It is important to understand how these dwarf galaxies interact with each other and their environments, build up their metals and stars, and are affected by the energetic processes of star formation and supermassive black hole accretion. By observing the most nearby galaxies for which a significant volume is available, we will learn how the smallest galaxies form, grow and evolve. The Virgo and Coma clusters are ideal places to begin this work, as they are nearby and contain rich concentrations of dwarf galaxies. To decouple environmental effects, a comparably sized control sample of non-cluster galaxies is also required.

The link between stellar nuclei and black holes (MSE-lowz-SRO3): The Virgo cluster also affords us an opportunity to study the internal structure of galaxies in great detail. While there are numerous scientific advantages to having resolved spectroscopy with some sort of IFU, even single fiber spectroscopy of galaxies will be illuminating. In particular Virgo is close enough that we can study the chemical abundance and dynamics of the nuclei in galaxies with masses ranging from $4\mathrm{x}10^{10}M_{Sun}$ to $\sim 2\mathrm{x}10^{6}M_{Sun}$, ultracompact dwarfs, and other compact stellar systems. This is an important step in understanding the connection between central star clusters and supermassive black holes, which themselves play a fundamental role in the evolution of galaxies. An IFU that covers the central few arcseconds of galaxies can probe the interplay between the output from accreting supermassive black holes and their host galaxies, which must play a major role in producing the supermassive black hole scaling relations.

Extragalactic Globular Clusters and UCDs (MSE-lowz-SRO4): The small velocity dispersions of compact objects (2-20 km/s) requires high resolution spectroscopy to allow measurement of their kinematics, and to gain access to a large number of critical spectral lines that can uncover the enrichment and star formation histories of these important objects.

There are numerous other worthy science goals that we have not fully developed into SROs. These include:

Star cluster evolution: Star clusters are useful and ubiquitous tracers of star formation, and MSE provides the first opportunity to capitalize on this, uncovering the stellar populations of all galaxies within a distance of 20 Mpc. High-resolution spectroscopy, combined with high-resolution imaging and sophisticated *N*-body simulations will allow us model the initial conditions for cluster formation, their evolution, and conclusively address the shape of the stellar initial mass function in young massive clusters.

At even moderate resolution of only ~5000 it is still possible to break key degeneracies in the photometry and thus obtain useful measurements of cluster ages, metal content and masses. Such spectra far outperform photometry on that front, but spectroscopic studies have so far been limited to either a handful of nearby galaxies or the brightest clusters observable.

Furthermore, it remains an open question whether or not globular clusters contain a dark matter component. Accurate stellar velocities in the dynamically cold outer regions of distant Milky Way clusters are needed to determine this, requiring high-resolution (R~40,000) spectroscopy of stars with g~20.

The structure and dynamics of massive galaxies:
Faint objects around galaxies – low surface brightness dwarfs, globular clusters, planetary nebulae and ultra compact dwarf galaxies – can be used to probe the external structural properties of their massive host and thus provide insight on their formation mechanism. In particular they can be used to trace their outer kinematics up to large galactocentric distances, provided that their systemic velocity is known. While on-going and planned deep imaging surveys (e.g. NGVS, MATLAS, LSST, Euclid) have the sensitivity to detect these faint tracers, their spectroscopic follow-up proves to be particularly time consuming and inefficient with current spectroscopic facilities. MSE will be the ideal instrument to carry out this crucial task. Planetary nebulae are very useful tracers identifiable through their [OIII]5007 nebular emission line, but contamination with background Lyα emitters is a problem. To sufficiently distinguish the two requires moderately high spectral resolution of ~20,000

Globular clusters have also been proven to be useful as tracers of galaxy interactions and mergers, a developing methodology that requires complete spectroscopy of many objects at once.

Finally, the sensitivity of MSE will make it a powerful facility for studying the low-surface brightness outskirts of giant galaxies in integrated stellar light, particularly if equipped with

IFU capabilities. With facilities like MUSE we are only beginning to appreciate the wealth of information about galaxy formation that is contained in these regions; in particular the tidal tails that result from interactions with other galaxies or larger-scale structures.

3. Science synergies with other facilities

Ground-based imaging capabilities have largely outstripped spectroscopy at the present time, and the depths reached by surveys at almost all wavelengths are much greater than any existing spectroscopy. The combination of moderate resolution spectroscopy with all these data, ranging from radio to X-ray wavelengths, will provide needed insight into the complex process of galaxy formation and evolution.

Deep, high-resolution imaging is a requirement for many of the science cases described here, and of great benefit to all of them. The exquisite NIR imaging of EUCLID will be perfectly suited for this purpose; in turn MSE spectroscopy will extend the scientific capabilities of EUCLID itself. A similar synergy exists with LSST, which (unlike EUCLID) will have no spectroscopic capability at all. The multicolour optical data from LSST (and other imaging surveys like DES and HSC) will be essential for SED characterization and may be useful for relative flux calibration of MSE spectra.

The galaxy cluster and group science would certainly benefit from the X-ray data provided by eROSITA. In the first instance, however, there is no lack of targets at low redshift from existing data. The synergy is likely stronger for clusters at higher redshift, where MSE spectroscopy would be of great benefit to identify and characterize the fainter detections.

It is clear that galaxy formation and evolution can only be understood with a multiwavelength approach. The combination of LSST and Euclid data will be essential to trace the optical/IR spectral energy distribution of starlight. The active phase of galaxies produce radio jets as well as feedback between the black hole processes and star formation. Finally, the distribution and mass of neutral and molecular gas reservoirs of galaxies, together with the warm dust distribution, must be understood to uncover the link between large scale structure and stars. ALMA and SKA will both provide an unparalleled look at these components; with survey-like capabilities at submillimetre wavelengths CCAT will be a well-suited complement to MSE.

4. Competition

The Prime Focus Spectrograph (PFS) on Subaru is the most serious competitor to MSE, and may well have the first opportunity to make advances on some of the topics considered here. MSE, however, has two critical advantages over PFS: its dedication to surveys, and the higher spectral resolution mode (~20000). Only MSE will therefore be able to tackle the most ambitious projects and perform detailed abundance analysis (e.g. MSE-lowz-SRO3).

WEAVE and MS DESI have similar capabilities to MSE but are mounted on smaller telescopes. They will be able to address some of the science topics described here; but the greater sensitivity of MSE opens up a mass range and survey volume that is not accessible to those instruments. To maintain the advantage over these 4-m class survey instruments, it is essential to maximize the throughput of the whole system. The biggest primary mirror that can fit within the CFHT footprint and satisfy other technical constraints should be considered.

Finally, in the near future our knowledge of the nearby Universe will be greatly increased with data from ambitious IFU surveys. Surveys done with the SAMI instrument on the AAT have already transformed the field. With the recent arrival of MUSE on the VLT, MaNGA at APO, and the anticipation of HECTOR (a possible successor to SAMI), the study of nearby galaxies is entering a new era. By the time MSE sees first light, the scope for single fiber spectroscopy of nearby galaxies to make transformational discoveries will have been reduced. Most of the science cases we have developed benefit enormously from the ability to obtain some form of integral field spectroscopy. This can be achieved even in the baseline design, by reobserving galaxies multiple times and moving the fiber location. While normally inefficient, this might work reasonably well in surveys where a patch of sky is being continually reobserved; a few nearby objects could be targeted in this way. Even better would be the ability to close-pack two or more fibers, ideally forming fiber bundles that can be placed on objects – again possibly within the context of a larger survey. One or more dedicated IFU arms would be better still, with survey efficiency increasing in proportion to the number of IFUs available.

5. Key Capabilities for MSE to deliver transformative science

From the science cases presented above and in the Appendix, we identify several key capabilities that will enable transformative science. In approximate order of priority:

1. All science cases exploit the sensitivity of MSE resulting from its large aperture and high throughput. The baseline design allows transformational science to be done in all science cases we have described, though in many cases (e.g. MSE-highz-SRO1) these require long campaigns which may prove difficult to coordinate with other surveys. Increased sensitivity (by increasing the mirror diameter for example) would allow such surveys to be done more quickly; an important consideration given the scope and number of proposed campaigns in the MSE Science case.
2. Dedicated survey capability is essential to carry out these ambitious programs on a competitive timescale.
3. An important aspect of most of the proposed science is analysis of stellar populations, for which good relative flux calibration is crucial. In addition, the wavelength and spectrophotometric calibration from fiber to fiber must be good enough to reliably measure the spatial gradients across galaxies, either by close-packing fibers or by moving fibers between exposures.

4. The ability to close-pack at least some fibers would enable efficient study of the spatially resolved properties of low mass and/or distant (z~0.1) galaxies whose spatial extent is limited to a few arcsec. Full IFU capabilities, or at a minimum the ability to place a fiber bundle that contiguously samples an area of ~20 sq arcsec or more, are required to fully exploit one of the biggest advantages the nearby Universe holds for understanding the physics of galaxy formation and evolution: the large angular size of stellar systems. In particular, an IFU capability will allow MSE to take full advantage of its aperture and significantly outperform SAMI and HECTOR. Additional IFU units within the MSE field of view would increase the efficiency/grasp proportionally. IFUs that cover fields larger than 20 sq arcsec will allow MSE to capitalize on its sensitivity and probe the outskirts of nearby galaxies.
5. A range of available spectral resolutions is paramount. Strong science cases exist for R~2000 (redshifts of faint galaxies and measurements of nebular emission line strengths); R~5000 (dynamics of galaxies); and R~20,000 (absorption line abundance analysis and dynamics of globular clusters). Higher resolution still (R~40,000 or more) would enable extending study of star clusters to lower masses. It is important to have flexibility in the choice of resolution, and the maximum survey efficiency would be achieved if the resolution could be selected for each fiber individually.
6. A high fiber density (>1 per $arcmin^2$) within the largest possible field of view, 1 deg^2 or higher, is needed to maximize efficiency and allow multiple science programs to be served at once.
7. Broad optical wavelength sensitivity is required. In particular it is crucial to maintain sensitivity to light over 360-750 nm, to enable measurement of the [OII]3727 emission line for the measurement of metal abundance, and the Hα emission line out to z~0.1. Extending the wavelength coverage to cover Paβ (1.282 mic) would permit a more accurate determination of the dust attenuation (and thus star formation rate) in the gaseous component of galaxies. This is a desirable feature, though all our proposed science goals would be achievable without it.

The Table below shows how these requirements map on to the science cases presented above. Green boxes indicate requirements that are essential for the corresponding science case, while yellow boxes represent desirable capabilities.

	Dedicated Survey	High fiber density	FOV	Close-pack fibers	IFU	Sensitivity	R=2000	R=5000	R=20000	R=40000	Blue (370nm)	NIR (>1000nm)	Relative flux calibration
Evolution of galaxy haloes and structure	green	green	green	green		green	green				green	yellow	green
The physics of dwarf galaxies	yellow		green	yellow	green	green	green				green	yellow	green
Stellar nuclei, AGN and compact objects	yellow			yellow	green	green		yellow	green		green	yellow	green
Galaxy clusters	green	green	green	yellow	green	green	green	green			green	yellow	green
Milky Way star clusters		green		yellow		green		green	green	green			green
Extragalactic star clusters and UCDs			yellow	yellow		green			green				
Massive galaxy dynamics				yellow	yellow	green		green	yellow		green	yellow	

6. Avenues for future work

The preliminary mapping between requirements and science cases in the previous section needs to be more quantitatively justified and specified. The science cases for studying the outer regions of massive galaxies and Milky Way star clusters are promising and may be developed more fully into SROs. Once the options for close-packing fibers, or providing some IFU capability, become clear, the relevant science cases can be further developed. Some of the SROs need further work to better justify requirements, as well as general polishing (adding references, for example). There is considerable overlap between many of the SROs, and the current presentation may not be the most efficient way to link scientific goals to technical requirements. As MSE is a dedicated survey instrument, however, attention should soon turn to specifying survey specifics in more detail so that the efficiency of exploring these science cases can be maximized.

7. Appendices (SROs)

Below we include four science reference observations. MSE-highz-SRO1 is included as part of the high-redshift science case, and has a particularly broad scope including a low-redshift survey S1.

MSE-lowz-SRO1-3 all include observations of Virgo and/or Coma clusters as part of the survey. In practice, these obvious targets will require a different survey strategy, and future work should focus on designing a Virgo-specific (and Coma-specific) survey that embraces as much of this science as possible. SRO1&2 in particular have very similar goals and future work will consider how best to merge them.

MSE-highz-SRO1. Evolution of Galaxies Halos and Structure Over 12 Gyrs

MSE-lowz-SRO1. Clusters of galaxies as probes of galaxy evolution

MSE-lowz-SRO2. The physical drivers of dwarf galaxy evolution

MSE-lowz-SRO3. The link between galaxy nuclei and black holes

MSE-lowz-SRO4. Extragalactic Globular Clusters and UCDs

MSE-lowz-SRO1: Clusters of galaxies as probes of galaxy evolution

I. Abstract

Galaxy groups and clusters are extraordinarily important astrophysical laboratories, as they are the only places in the Universe where we have good observational constraints on all relevant components: dark matter, hot gas, cold gas and stars. Because of their large potential wells, the most massive clusters galaxies act as (nearly) closed boxes, retaining the entire thermal and gravitational history of their assembly and growth. These environments allow us to observe the interactions between galaxies and large scale structure assembly, thus establishing an important link between predictive ΛCDM theory and the complex (but observable) process of galaxy formation. The field of view and multiplex capability of MSE makes it perfectly suited to studying these environments in the local Universe, providing new insight into the galaxy evolution process and dark matter properties, and helping to constraint cosmological models.

II. Science Justification

The evolution of structure in the Universe is dominated by dark matter, which gives rise to the cosmic web of filaments and haloes we see in the galaxy distribution. The mechanisms by which galaxies grow and evolve with time are closely connected with this large-scale structure, and this poses an observational problem because detailed information on kpc scales or smaller, associated with star formation and galactic winds for example, must be coupled to structure on scales of several Mpc and larger. The precision needed on both fronts cannot be achieved photometrically, and only through spatially complete spectroscopy over very wide areas can this problem be understood observationally. MSE will be unique in its ability to address this, as described in detail in MSE-Lowz-SRO1. Of particular interest, though, is a detailed study of galaxies residing in the most massive dark matter haloes: galaxy groups and clusters.

For galaxies that are dominant in their dark matter halo, their evolutionary history is strongly correlated with their total stellar mass at the epoch of observation (e.g. Brinchmann et al. 2004, Salim et al. 2007, Noeske et al. 2007, Daddi et al. 2007, Rodighiero et al. 2011, Whitaker et al. 2012, Sobral et al. 2014, Speagle et al. 2014). However, satellite galaxies of a given stellar mass appear to have ceased forming stars at an earlier epoch, and this leads to the well-established correlation between galaxy properties (age, star formation rate, and perhaps morphology) and environment (e.g. Peng et al. 2010). There is no shortage of physical mechanisms that may influence the evolution of satellite galaxies. Low accretion rates, gas stripping, tidal disruption, mergers and high-speed interactions all likely play a role.

Distinguishing which effects are dominant, and where, remains a challenge. The complexity means we are unlikely to put the question to rest from consideration of global galaxy properties alone: ultimately, spatially resolved spectroscopic data for large samples of galaxies will be required. The relevant physics, and its effect on galaxies, is likely to be a function of galaxy mass. Because of their shallow potential well, dwarf galaxies are very fragile objects, which can easily be perturbed even in moderate environments like groups and the periphery of massive clusters (Boselli & Gavazzi 2014). This makes it particularly important to extend studies of environment to the lowest stellar masses possible.

Galaxy clusters have been a testbed for studies of galaxy evolution for over 30 years, often anticipating discoveries that have been found to be universal several years later. They are the tail of a continuum distribution of halo masses, and the most extreme environments where galaxy formation proceeded at an accelerated pace compared to the rest of the universe. Clusters accrete individual galaxies and larger subclumps from their outskirts. As the cluster grows in mass, and the background density drops, the virial radius grows. Thus the earliest accreted galaxies are found near the core, while the most recently arrivals are predominantly near the virial radius. In this way, investigating the galaxy population as a function of clustercentric distance provides a way to read the history of structure assembly and its effect on galaxies (e.g. Balogh et al. 2000; McGee et al. 2009).

The study of smaller galaxy groups, and the outer regions of clusters, is also vitally important environments, as these are the environments where galaxies make the important transition from central galaxies in their own halo, to gas-starved satellite galaxies subject to a wide range of new, external forces. Cosmological hydrodynamical simulations predict a depletion of both hot and cold gas and a decline in the star-forming fraction of galaxies as far out as 5 virial radii (e.g. Bahé et al. 2013). Observations have proved that the cluster outskirts and groups do host galaxy populations that differ from the general field (e.g. Lewis et al. 2002, Pimbblet et al. 2002, Treu et al. 2003, Balogh et al. 2004, Moran et al. 2007). But for nearby clusters, observations that extend to such large distances are limited to a handful of clusters or superclusters (e.g. Merluzzi+ 2010, Mahajan+ 2011, Smith+ 2012, Haines+ 2011). Groups – both within the cluster infall regions and more isolated systems – represent an earlier stage in the hierarchy and thus also hold clues about the first central-to-satellite transformations. The vast majority of stellar mass at the present day is contained in galaxy groups, yet we know very little about the galaxy dynamics, stellar populations or the transformational physics that drives their evolution. In addition, dynamically young groups discovered through deep imaging (through the lack of tidal features) offer the potential to study the very coming together of galaxy groupings, before they grow to their more massive counterparts.

Local cluster galaxy populations also represent an important link to the higher-redshift Universe, z=1-3, where observations are largely confined to massive galaxies (stellar masses > $10^{10.5}$ M_{Sun}). The stellar ages and masses of these galaxies indicate an early formation and assembly, and their evolution from z=3 to z=0 is a major focus of extragalactic studies today. In particular, the evolution of their sizes represents a challenge for current models of galaxy formation, and is sensitive to the relative role of in-situ star formation and external accretion (Valentinuzzi et al. 2010, Poggianti et al. 2013). According to simulations, the majority of galaxies that are already massive and evolved at z>=2 will end up in haloes with masses $>10^{14}$ M_{sun} today (Poggianti et al. 2013). Rich clusters at low-z are therefore the repository of the majority of the descendants of the massive galaxy population studied at high-z, and it is where we should look to trace their evolution.

Rich galaxy clusters are also good places to study more general aspects of galaxy evolution, for which high-quality spectroscopy is required. Because of the high number density of galaxies on the sky, a massively multiplexed instrument like MSE can efficiently obtain such spectra for thousands of galaxies at once. An important example would be a precision measurement of the initial mass function (IMF) in galaxies. The role of the IMF for studies of galaxy formation and evolution can hardly be overstated, as the assumptions regarding its slope and mass range are the basis for the interpretation of most galaxy integrated observables at any redshift. Evidence has accumulated that the IMF is indeed non-universal, and varies with galaxy mass (van Dokkum & Conroy 2010; Capellari et al. 2012; Smith et al. 2012a; see also sec. 2.5.4.3. of the Feasibility Study). But this evidence remains controversial, and it remains unknown to what extent the IMF depends on galaxy type, mass, redshift or environment. MSE will have the capability to address this important issue, and a survey of rich clusters would efficiently provide a measurement of IMF-sensitive line indices for galaxies as a function of their mass, morphology and environment. Of course, similar measurements of field galaxies would also be required. Since galaxies that are bright enough will have a low density on the sky, these observations would best be obtained by coordinating with other surveys, borrowing a few fibers per configuration.

Finally, highly complete observations of galaxy clusters can also provide an important look at properties of the dark matter itself. Determining structural properties of dark matter haloes is one of the fundamental goals of modern cosmology, and galaxies can be used as tracers to measure the mass and velocity anisotropy profiles. Precise measurements of the mass distribution provide insight into the nature of dark matter, and constrain alternative theories of gravity (Biviano et al. 2013). Measurements of the halo concentration, mass density profiles and velocity anisotropy profiles provide strong constraints on the halo formation process and history (e.g. Klypin et al. 2014). Dynamical mass estimates of clusters also play an important role in understanding the relationship between various observational mass tracers (e.g. X-ray, SZ, optical richness) and the mass of the underlying dark halo. This improves the accuracy with which the galaxy cluster abundance evolution can be measured and related to the predicted evolution of the dark matter halo mass function. As described in the MSE Feasibility Study (2.5.4.2), this is critical for cosmological tests of dark energy and alternative gravity models, which rely on such evolution. Finally, detailed cluster dynamical analysis is also fundamental for understanding the interactions between galaxies, the intracluster gas and the dark matter halo.

III. Current status:

Nearby galaxy clusters have been studied for a long time, but it is really only since the SDSS that we have achieved the survey homogeneity and control of systematics to begin to understand the interplay between galaxies and their environments. In fact, most of our modern understanding about nearby galaxy clusters comes directly from the SDSS and 2dFGRS, which have the statistical power to decouple the various complex processes at work. SDSS also set a new standard for data quality and calibration fidelity, which was an essential component of its success. However, SDSS has some important limitations, including:

- Relatively bright limiting magnitude, due to the small aperture of the telescope. This limits our ability to study dwarf galaxies at distances large enough to acquire large statistically-useful samples.
- Moderate signal-to-noise ratio and spectral resolution, which require follow-up work for more detailed stellar population or dynamical analysis.
- Single fiber spectroscopy, limited to the central regions of nearby galaxies. This is one of the biggest challenges of drawing broad conclusions from SDSS spectroscopy.
- The need to avoid fiber collisions means close-pairs of galaxies, and dense environments, are undersampled. While this can be modeled and corrected for statistically at some level, it is not ideal when the goal is to study exactly those regions.

The GAMA survey was designed to reach a very high spectroscopic completeness, making it well-suited to studying dense environments. However its relatively small area (~300 square degrees) means it does not include a large sample of the most massive clusters. Other targeted cluster surveys have probed deeper than SDSS, and/or obtained higher S/N spectroscopy, but only for a small number of systems.

The biggest leap forward since SDSS is likely to come from the ongoing and planned IFU surveys, with instruments like SAMI, MaNGA and MUSE. The surveys planned to date are not tailored toward massive galaxies in clusters, however. Moreover, only a 10m telescope can reach the low surface brightness required to sample the spatially resolved galaxy history over the whole galaxy.

IV. Survey design:

Significant progress on all the problems described above can be achieved with a comprehensive, spectroscopic survey of galaxy groups and clusters. Some of the objectives can be achieved with a redshift survey, requiring only single-fiber, relatively low signal-to-noise spectroscopy of moderate resolution (R~2000) or so. Others, particularly those related to the complex physics of galaxy evolution, will require much better quality spectra and, in some cases, spatially resolved spectra.

For kinematical analysis of dwarf galaxies – critical for distinguishing between the various physical processes operating in dense environments – higher resolution spectra will be required (R~6500). We anticipate that a synergy can be found to optimize the strategy for these various objectives, which in some cases can make use of the same spectrum, or use the redshift as pre-selection for deeper studies.

Cluster sample:

a) MSE will observe a sample of X-ray selected clusters at $0.05<z<0.1$, with masses 10^{14} M_{Sun} and higher (corresponding to velocity dispersions of $\sigma>500$ km/s). Suitable X-ray catalogues already exist, and will be further improved by eROSITA, though access to the latter remains uncertain.

At a given halo mass, clusters display a range in X-ray gas properties and dynamical status (merger history, amount of substructure). A large number of clusters is needed to cover the whole range of cluster masses with sufficient statistics to determine the dependencies of galaxy properties on these other cluster properties. A sample of ~40 clusters will deliver ~5 clusters per 0.2dex of cluster mass bin. This is the minimum number needed to identify robust correlations and comparisons with simulations, disentangling halo mass effects from dynamical status.

b) While it will be most efficient to observe clusters at $z>0.05$, where the angular extent of the clusters is on the order of 1 degree, it is imperative to also include our nearest neighbours Virgo and Coma. These massive systems afford us the best opportunity to study the lowest-mass galaxies, and the structure and low surface-brightness regions of massive galaxies. Because of their large extent on the sky, these will need a different observational strategy.

At a distance of 16.5 Mpc and with a gravitating mass of $M_{200}= 4.2 \times 10^{14}$ $M_\odot$, the Virgo Cluster is the dominant mass concentration in the local universe, the centre of the Local Supercluster, and the largest concentration of galaxies within ~ 35 Mpc. The cluster has been extensively studied at virtually all wavelengths. In the optical, a new catalogue of likely cluster members (based on photometric and morphological criteria) reaching $g=-7$ mag (stellar masses ~ 5×10^5 $M_\odot$) has been (almost!) published by the NGVS collaboration. Detailed structural parameters, reaching surface brightnesses of 30 mag arcsec^{-2} (g-band), exist for all cluster members. A 90% complete census of globular clusters, as well as many ultracompact dwarf galaxies, is available within one virial radius. Virgo presents a unique opportunity to study the galaxy population in its totality (from quiescent to star forming galaxies), across a wide mass range, on all spatial scales, in a controlled environment in which all other baryonic substructures are also well characterized.

A factor ~5 farther away than Virgo, Coma is an attractive target because it is much more massive, yet subtends a smaller area on the sky, so the target density is much larger. MSE could observe most of the virialized region in a single pointing, and this greater efficiency nearly compensates for the longer integration times needed to reach the same physical depth.

c) For lower-mass galaxy groups, X-ray selection is not viable and we must turn to other methods. In MSE-Lowz-SRO1 we describe a highly complete redshift survey, which will identify many thousands of group-mass haloes at low redshift, from redshift clustering. Many of the science goals described here can be reached from those data. For the more detailed studies, requiring higher S/N or spatially resolved spectroscopy, follow-up observations would be required. Galaxy groups are more dynamically heterogeneous than clusters, due to stochasticity in accretion histories (McGee et al. 2009). In order to sample the full distribution of group mass and dynamical state, a sample of several hundred groups would be required.

Area coverage: All the cluster science objectives require coverage out to at least the virial radius; to understand the transformation of galaxies requires probing the outskirts, to at least 3 virial radii. At the redshifts of interest, the virial radius of massive clusters is between 1 and 3 Mpc. The MSE baseline FOV will thus cover the virial radius of all clusters at z=0.1. At lower redshifts, a mosaic of a few pointings will be required for the most massive clusters. The largest possible field of view is of great benefit for this science, increasing the efficiency with which the necessary range in environments can be studies. This is particularly true of Virgo, which will require many tens of pointings to cover an appreciable area.

The target density of massive clusters (at least beyond Virgo) is perfectly suited to MSE, with thousands of sufficiently bright galaxies lying within the field-of-view, on average. However the target density variation is large: the cluster cores are hundreds of times more dense than the outskirts, and throughout the cluster are subclumps and groupings of galaxies. The ability to close-pack fibers helps to achieve an unbiased sample of cluster galaxies; but with any realistic fiber spectrograph it will be necessary to observe each system with at least two configurations to sufficiently sample the densest regions.

V. Key astrophysical observables

Most of the cluster science objectives can be totally or partially reached with the instrument baseline configuration. The efficiency will be improved with increasing field of view (keeping fiber density constant) and sensitivity. The ability to close-pack fibers permits sampling galaxy pairs and high-density regions efficiently.

As a redshift machine, MSE will be unparalleled and it will be possible to obtain redshifts for galaxies with central surface brightness as low as μ_r=26.5 mag/arcsec^2 in ~2h. A redshift requires low S/N, about 3 integrated over a typical absorption line. Velocities need to be measured with a precision of ~50 km/s, in order to identify substructures and obtain a robust dynamical description. This precision (or better) is especially important for the sample of lower mass groups, which may have velocity dispersions of only a few hundred km/s. For redshifts it is useful, though not essential, to include the [OII]3727 emission line. While redshifts of cluster members will be identified from features with λ<700nm, redder coverage is desirable. This is particularly true for faint where there is substantial "contamination" from high-redshift galaxies; of course these contaminants are of interest in their own right, and a survey strategy would be developed to take advantage of this.

In principle, such low S/N spectra can also be useful for studying the underlying stellar populations, at least from the nebular emission lines which trace star formation rate and gas-phase metallicity. For this it is essential to include [OII]3727 through Hα. Extending to Paβ (1.282 mic) would enable an accurate determination of the dust attenuation in the gaseous component, and thus a more accurate measurement of the star formation rate, since it is much less attenuated than the Balmer lines. It is also possible, from such spectra, to learn more about the average stellar population in classes of galaxies, by stacking spectra from hundreds or thousands of individual galaxies. In this case, sufficient S/N can be obtained to measure absorption line strengths with sufficient precision to estimate galaxy ages to within ~1 Gyr. Wide wavelength coverage (at least 350nm-700nm) is essential for accurate modeling. In order to decouple the roles of stellar mass from halo mass (environment) it is essential to obtain good measurements of the stellar populations in galaxies with masses well below M^*, at least $M_{star}>10^9 M_{Sun}$. This corresponds to V~22 at these redshifts (Kroupa IMF).

However, at these redshifts any realistic fiber diameter will only cover the very central region of all but the lowest-mass dwarf galaxies (see Fig.1: galaxies with stellar masses > $10^{11} M_{Sun}$ at these redshifts have an effective radius R_e~3kpc, thus ~3 arcsec). For Virgo and Coma, of course, the problem is much more severe. It will be very challenging to make robust inferences about physical galaxy properties (star formation rates, metallicities) from such spectra. Moreover it will be impossible to learn about the role of stripping and tidal interactions, which are likely strong in clusters and lead to strong spatial variations across galaxies. It will be therefore essential to obtain observations at multiple physical locations within a galaxy. The best way to do this is with a fiber bundle or some other IFU capability. With moderate-resolution spectroscopy capable of measuring velocities <50 km/s this provides the opportunity to measure galaxy dynamics and thus gain insight into the roles of tides, past merger events, and stripping processes that likely play a role in cluster galaxy evolution. An alternative strategy exists, at least for a subset of clusters. To obtain sufficiently high S/N to measure stellar population parameters in the faintest galaxies will require integrations of ~6h or more. In addition, to achieve spatial completeness will require at least 2, preferably 3 or more fiber configurations per pointing. An individual exposure time of, say, 30 min would achieve sufficient S/N on the higher surface-brightness galaxies. On a subset of those, therefore, the fiber could be strategically moved around between exposures, allowing up to ~30 positions in the course of the 6h exposure. This would be adequate to construct a crude map of the spatial extent of young stars, for example. The number of positions could be doubled (or more) if at least two fibers can be positioned close together, so they can be both allocated to the same galaxy in a single configuration.

The Virgo cluster provides the best opportunity to observe a large sample of the lowest-mass dwarf galaxies (see MSE-Lowz-SRO2). In order to fully exploit this and push as far as possible down the luminosity function, it will be necessary to use small, closely packed fiber bundles (or similar IFU) in order to collect all the galaxy light and increase the integrated S/N. In order to study the kinematics of these galaxies, necessary to distinguish between gas stripping and tidal disruption effects, for example, moderate resolution spectroscopy of R~6500 will be required. The effective radius of galaxies fainter than g~18 mag in Virgo is 5 -10 arcsec. A closely packed configuration of at least 10×10 ~1 arcsec fibers would therefore be sufficient to cover the central regions of higher surface brightness. According to the exposure time calculator, coadding the signal from all fibers would allow to obtain a spectrum with S/N of 5 for a galaxy with average surface brightness of 27 mag/arcsec^2 (which essentially represents the limit of the current photometric catalogue) in a six hour integration. With 3000 fibers, configurable in 30 bundles, it will be possible to target all probable Virgo dwarfs in the outskirts in a single configuration; fields within the cluster core would require 2 to 3 configurations.

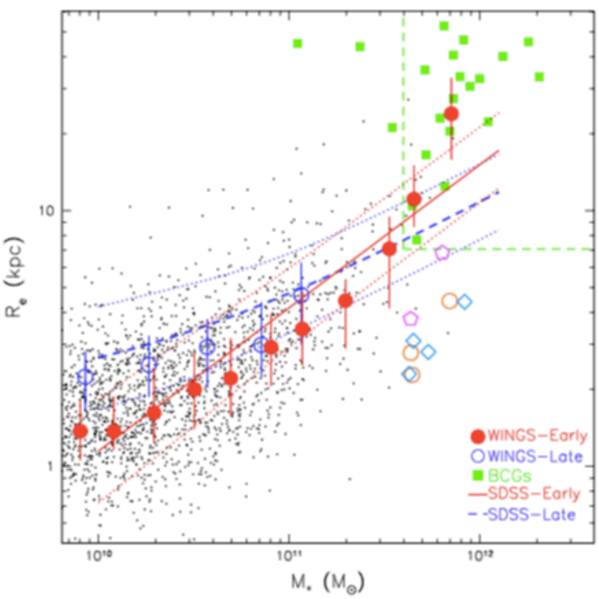


Figure 1 – Galaxy stellar mass – size (circularized effective radius) diagram of galaxies in rich clusters at z=0.04-0.07 from the WINGS survey (black dots). The median mass-size relations for early- and late-type galaxies are shown as red and blue circles, respectively. Brightest Cluster Galaxies are green. The SDSS relations for the field are shown as lines.

The most challenging observations, but arguably the most important, would be the measurement of tracers of the initial mass function shape in a large sample of galaxies. This requires very high S/N (>200) spectroscopy of dwarf-sensitive lines such as TiO4770, CaH 6380, Na I 8183 A, 8195A and FeH 9916 A (Wing-Ford) lines (Spiniello et al. 2014; van Dokkum & Conroy 2010). A higher resolution (R~5000) is required to deblend these weak lines from their neighbours. This would be most efficiently done if a subset of fibers with higher resolution could be assigned to the target galaxies, allowing the exposure time to build up as a cluster field is observed multiple times.

VI. Target selection:

Galaxies will be selected from deep, multicolour imaging. The colour information is essential to identify likely cluster members; particularly at the faintest magnitudes the background population becomes dominant. Good spatial resolution is needed to distinguish low-mass galaxies from stars, though stars are not dominant at the magnitudes of interest. The number of clusters with sufficiently good imaging data is not large, and we will require overlap with LSST, DECam, Euclid or other large imaging surveys to identify targets.

VII. Cadence and temporal characteristics

None

VIII. Calibration requirements

For stellar population work, accurate relative spectrophotometry is required. This should be at least as good as for the SDSS, at the level of 1-2% over the wavelength range covered.

In the absence of an IFU, we will rely on repositioning fibers, and/or allocating multiple fibers to a single galaxy, to extract spatial information. This requires good repeatability and fiber-to-fiber calibration of spectrophotometry and wavelength calibration. These systematic uncertainties should be subdominant to those of a single fiber observation; i.e. 1-2% spectrophotometry and wavelength calibration accurate to ~10km/s. For the same reasons, the position of each fiber must be known to within a fraction of a galaxy scale radius, <0.1". This precision is also needed to accurately place fibers on faint galaxies.

Good sky subtraction is essential for faint object spectroscopy, and can be challenging with fibers. Residuals from sky subtraction can make redshifts of faint objects challenging, and could limit the ability to do more detailed stellar population studies (e.g. IMF variations). Sky residuals should therefore be no more than a few percent of the Poisson noise.

IX. Data processing

A data processing pipeline that produces calibrated, sky-subtracted spectra is necessary to make large spectroscopic surveys tractable. The pipeline should also measure a reliable redshift and provide a quality flag; redshifts flagged as high quality should be correct >99.9% of the time. It is also useful, though not essential, for the pipeline to provide strengths of common nebular emission lines and spectral features (e.g. 4000A break).

MSE-lowz-SRO2: The physical drivers of dwarf galaxy evolution

I. Abstract

The lowest mass galaxies, those with stellar mass $M<10^9 M_{Sun}$ or so, can only be studied in detail in the nearby Universe, with highly sensitive instruments. The galaxies are the building blocks from which more massive galaxies are built. They also represent some of the greatest challenges to our theories of galaxy formation. Because of their shallow potential wells, star formation is readily disrupted by dynamical interactions and energetic events like supernova explosions or supermassive black hole accretion. A better understanding of these galaxies is vital for understanding how baryons and dark matter became so decoupled during the process of galaxy formation. To make progress, large statistical samples of galaxies with deep spectroscopy are required. MSE will make an important contribution here, especially if equipped with IFU capabilities.

II. Science Justification

In the past decade, imaging and spectroscopic surveys of large, unbiased samples of local galaxies, both in clusters and in the field, have revealed the existence of morphological and dynamical relations linking galaxies across a wide range of morphologies and masses. In particular, these surveys have established scaling relations, such as those between stellar mass, SFR and metallicity, and how these depend on other parameters, such as morphology, AGN activity and environment (Brinchmann et al. 2000; Kauffmann et al. 2003; Tremonti et al. 2004; Balogh et al. 2004), which in turn inform and constrain theoretical models. However, the extension of large statistical studies into the dwarf regime is largely uncharted, due to the flux-limited nature of most surveys.

The study of large, homogeneous samples of the lowest mass galaxies ($M<10^9$ M_{Sun}) is therefore of particular interest. With spectroscopic observations of faint galaxies in the very nearby Universe (<100 Mpc or so), we will be able to address, among others, the following questions:

- *Do the scaling relations seen in star-forming galaxies extend into the low mass regime?* At low masses, we expect chemical enrichment to become increasingly stochastic and sensitive to factors such as winds, infall and environment (Kirby et al. 2013), potentially with a metallicity `floor' where self-enrichment is driven by a few generations of stars (Sweet et al. 2014). Quantifying the role of these issues requires individual metallicity measurements for a statistical sample of dwarfs. Moreover, outliers in mass-metallicity space can help us quantify the fraction of dwarfs that have a tidal origin (e.g. Croxall et al. 2009), which may represent a significant (but currently poorly constrained) fraction of the dwarf population (e.g. Ploeckinger et al. 2014 and references therein). Large samples that span a range of environments are germane here, since the tidal dwarf fraction is likely to depend on cluster or group membership.

- *Do dwarf galaxies host AGN?* The canonical view of AGN is that they are hosted by massive galaxies, where the black hole mass scales with the mass of the bulge component. However, populations of low mass and/or bulgeless galaxies have recently been discovered (e.g. Greene & Ho 2004; Reines et al. 2013; Satyapal et al. 2014). Large samples of these populations will offer the opportunity to study the occupation fraction of AGN in low mass galaxies, determine whether SBHs relate more closely to the spheroidal (bulge) component or other properties of the host (e.g. total gravitational mass), and discover how the AGN affects the structure (on both global and nuclear sclaes) of the host galaxy (see also MSE-lowz-SRO3).
- *The role of feedback and environmental effects on the evolution of dwarf galaxies.* Models and simulations indicate that two major phenomena might have shaped galaxy evolution through cosmic time: AGN and stellar feedback, with different sorts of interactions happening in high-density environments. The feedback of AGNs has been proposed as a possible origin of the quenching of the star formation activity in massive galaxies (Bluck et al. 2014), while that of supernovae and massive stars in dwarf systems. The kinetic energy injected in the ISM by the nuclear black hole in massive galaxies and by stellar winds in dwarfs is able to remove the gaseous component feeding the star formation process. In high-density environments, such as clusters and groups, the gravitational interactions or the interactions with the hot and dense ICM trapped within the potential well of the over-density region (such as ram pressure stripping and thermal evaporation) can efficiently remove the gaseous component of the ISM of galaxies, transforming star forming systems into quiescent objects. The study of these physical processes is thus crucial for understanding galaxy evolution.

III. Current status

The mass-metallicity relation derived from SDSS galaxies extends only to log $M_* \sim 8.5$ (Tremonti et al. 2004). Pushing to lower masses has previously only been possible with either a handful of nearby galaxies (e.g. Lee et al. 2006) or stacking analyses (Andrews & Martini 2012), and has extended this relation down by a further factor of ten in mass, to suggest that the metallicity continues to fall with mass. However, at low masses, the chemical enrichment is likely to become increasingly stochastic, necessitating large samples of individual measurements that are carefully modeled (and not just stacked) to account for, e.g. varying levels of nitrogen abundance, which can be elevated in dwarfs (Berg et al. 2011). Intriguingly, the lowest mass Lyman Break Galaxies currently detectable at z~2 also have anomalously high N/O abundances, so that understanding the origin for these chemical deviations has a potentially broad impact. Large samples are also required in order to study dwarfs in different environments. Whereas the mass-metallicity relation in massive galaxies is not much affected by environment on average (Ellison et al. 2009), evidence from the local group indicates that dwarfs can be very sensitive to environment (e.g. Cole et al. 2014). Therefore, the determination of a large number of metallicity measurements in local dwarfs can be used to address a number of science questions that are germane to galaxy evolution near and far.

The role of black holes in galaxy formation is probably one of the most debated topics in the field (see, for example, the annual review by Kormendy & Ho 2013). However, current observations are largely limited to high mass galaxies, where the majority of galaxies are considered to host a black hole. However, several hundred low mass and/or bulgeless galaxies are now suspected of hosting a central black hole (e.g. Greene & Ho 2004; Reines et al. 2013; Satyapal et al. 2014). As demonstrated by the work at higher masses, large samples are required to study the demographics of this population. Current work is focusing on fine-tuning selection techniques and obtaining follow-up observations to confirm successful identification of an AGN (e.g. Secrest et al. 2015). The coming years promise to pin down the optimal selection techniques, likely through a combination of optical spectroscopy and mid-IR imaging (e.g. from WISE). However, new, large spectroscopic samples of low mass galaxies, with good quality imaging, will be needed to exploit this groundwork.

IV. Survey design

To achieve a full understanding of the stellar populations, and the effects of feedback and environment on dwarf galaxies requires a sample of several thousand galaxies in the mass range $10^7 < M_*/M_{Sun} < 10^9$, spanning a range of environment (from rich cluster cores to filaments and voids) and including all morphological classes. Galaxies should be selected using similar and well-defined criteria to minimize any possible selection bias.

While the relatively low S/N ratios achieved with redshift surveys are useful for probing gas-phase metal abundances and relatively high star formation rates (from nebular emission lines), a significant advance on our current understanding will require high quality data to measure the star formation and enrichment histories of the stellar populations. The long exposure times required to reach low stellar masses, at distances which afford sufficient volume to compile statistically useful samples, will impose requirements somewhat different from MSE-highz-SRO1 and MSE-lowz-SRO1, which otherwise pursue similar goals.

The most observationally efficient way to observe large numbers of dwarf galaxies is to target nearby, massive clusters. In MSE-lowz-SRO1 we describe a survey of galaxy clusters and groups that includes our nearest neighbours, Coma and Virgo. Here we emphasize the technical requirements needed to probe the lowest mass galaxies in those structures. However, galaxy clusters are rare and special places in the Universe, and to understand the formation history of more typical galaxies requires a survey of field dwarfs. The space density of such objects is low, however, and a practical MSE survey would integrate these observations within another survey. For example, in survey S1 of MSE-highz-SRO1, a few fibers could be allocated to very nearby dwarf galaxies, and repeated in multiple configurations to build up exposure time.

In Virgo, the density of galaxies in the mass range of interest varies between 300 in the cluster core and 30 at one virial radius. In Coma, which is 5 times more distant (~100Mpc vs 16.5 Mpc), the limiting stellar mass observable will be more than an order of magnitude higher than in Virgo, for a given flux limit. However, this will be largely compensated by the fact that the target density is also higher, since the entire virialized region of the cluster will fit into a single MSE FOV (Kubo et al. 2007). Both clusters (which differ substantially in their total mass and degree of relaxation) should therefore be targeted; while a Virgo survey would under-utilize the multiplexing and would be more naturally designed as part of other surveys (e.g. MSE-lowz-SRO3), a Coma survey would make optimal use of MSE multiplexing.

V. Key astrophysical observables

In Virgo the effective radii of galaxies in the mass range of interest are ~10 to 20 arcsec; in Coma they are 2 to 4". Therefore, even in MSE's baseline configuration (single 1.2" fibres) it would be possible to obtain a useful estimate of the metallicity (in absorption and emission, for the stars and gas respectively) and stellar populations. Using a small number of closely packed fiber bundles, however, would prove very beneficial, either by increasing the signal-to-noise ratio by integrating the signal from all fibers or, for the more massive galaxies, by providing spatially resolved information. The required exposure time is determined by requirements to measure continuum features (absorption lines and spectral breaks); nebular emission lines, useful for estimating star formation rates and gas phase metallicities, are less challenging to observe. To break the age-metallicity degeneracy and so obtain more precise ages of the dominant red population, one needs absorption line indices from high continuum S/N (> 25) spectra, with resolution ~5000 or greater. For red galaxies, mean stellar ages and metallicities can be determined to 20% and 0.1 dex respectively, at this depth. This will be possible in 1h exposures for galaxies with r<21.

In order to determine gas-phase metallicities and AGN contributions, the minimum wavelength range must cover from Hβ (4863 A) to [NII] 6583 A. However, while this encompasses the minimum number of lines required to make a dust correction (Hα and Hβ) and use strong line metallicity diagnostics (e.g. [OIII] 4959, 5007, Kewley & Ellison 2008), there is considerable benefit to extending to bluer wavelengths. At lower masses (and metallicities) "direct" chemical abundances can be determined, without recourse to string line calibrators, based on the weak [OIII] 4363 auroral line. Furthermore, coverage of [OII] 3727 is required for a direct oxygen abundance, and is particularly valuable in galaxies where there may be non-standard N/O ratios, as has previously been shown by Berg et al. (2011). These same emission lines can be used for standard AGN classification (e.g. Kauffmann et al. 2003). However, a slight extension redward to the [SII] doublet at 6717, 6731 is additionally useful for metallicity measurement. The moderate resolution required for the continuum measurements (MSE's baseline R~6500 would be ideal) is more than adequate for emission line measurements (e.g. for resolving doublets and determining the underlying continuum contribution to Hβ).

A complemetary approach aimed specifically at constraining the role of environment in the evolution of galaxies would be provided by spatially resolved, medium resolution spectroscopy (R=6500) covering the low-surface brightness regions of galaxies out to several effective radii, i.e. the regions where environmental perturbations are most efficient. In some cases, for instance in late-type galaxies with extended gas tails (cold, hot, or ionised), observations could be necessary also outside the stellar disc. Gravitational perturbations are expected to strongly perturb the gaseous and stellar components, producing asymmetric, distorted morphologies. Interactions with the hot ICM are expected to perturb mainly (if not only) the gaseous component. They produce truncated radial profiles in the gaseous disc, and, as a consequence of the stopping of the star formation, in the stellar disc in the young stellar populations. The comparison of 2D-spectroscopic observations with tuned models of galaxy evolution, with hydrodynamic simulations, or simply with SED fitting codes, can be used to date the age of the interaction and understand the effects of the perturbation on the stellar population (stellar continuum plus absorption lines) and, in late type systems, also on the gaseous component of the ISM (emission lines). Studies of this type would necessarily require full IFU capabilities.

VI. Target selection

Galaxies must be selected from deep, multicolour imaging. The colour information is essential to identify likely cluster members; particularly at the faintest magnitudes the background population becomes dominant. Good spatial resolution is needed to distinguish low-mass galaxies from stars, though stars are not dominant at the magnitudes of interest. For field dwarfs we will rely on wide-field surveys like LSST, DECam and Euclid. Preferably the observations here would be follow up to a lower S/N redshift survey, such as MSE-highz-SRO1. Sufficiently good imaging exists to select targets from Virgo (NGVS, Ferrarese et al. 2012, see MSE-lowz-SRO3) and Coma (Carter et al. 2008).

High spatial resolution imaging will provide morphological information, which is crucial for identifying possible triggers for changes in stellar populations, such as tidal interactions and stripping events. Such imaging is also required to identify the bulge component, closely-linked to supermassive black hole activity. In particular for dwarf galaxies it will provide the opportunity to identify bulgeless AGN.

As galaxy formation and evolution is a complex, multiscale process, it is desirable to have as much multi-wavelength data as possible. Of particular value are measurements of the gas content (from ALMA or CCAT) to couple with all the metrics we will obtain from the spectra and imaging (SFRs, O/H, M* etc.).

VII. Cadence and temporal characteristics

None

VIII. Calibration requirements

For stellar population work, accurate relative spectrophotometry is required. This should be at least as good as for the SDSS, at the level of 1-2% over the wavelength range covered.

In the absence of an IFU, we will rely on repositioning fibers, and/or allocating multiple fibers to a single galaxy, to extract spatial information. This requires good repeatability and fiber-to-fiber calibration of spectrophotometry and wavelength calibration. These systematic uncertainties should be subdominant to those of a single fiber observation; i.e. 1-2% spectrophotometry and wavelength calibration accurate to ~10km/s. For the same reasons, the position of each fiber must be known to within a fraction of a galaxy scale radius, <0.1". This precision is also needed to accurately place fibers on faint galaxies.

Good sky subtraction is essential for faint object spectroscopy, and can be challenging with fibers. Residuals from sky subtraction can make redshifts of faint objects challenging, and could limit the ability to do more detailed stellar population studies (e.g. IMF variations). Sky residuals should therefore be no more than a few percent of the Poisson noise.

IX. Data processing

A data processing pipeline that produces calibrated, sky-subtracted spectra is necessary to make large spectroscopic surveys tractable. The pipeline should also measure a reliable redshift and provide a quality flag; redshifts flagged as high quality should be correct >99.9% of the time. It is also useful, though not essential, for the pipeline to provide strengths of common nebular emission lines and spectral features (e.g. 4000A break).

X. Any other issues

The depth of the survey is clearly limited by the total collecting area and instrument throughput. For faint dwarf galaxies, the possibility of increasing the former parameter is of course beneficial.

MSE-lowz-SRO3: The link between galaxy nuclei and black holes

I. Abstract

Stellar nuclei are present in as many as 80% of galaxies less massive than a few $\times 10^{10}$ $M_\odot$. All evidence – including the surprising finding that nuclear masses represent an approximately constant fraction of the total host galaxy mass, the same fraction observed for supermassive black holes in the more massive systems – suggests that their dynamical and stellar population properties are shaped by the processes that drive the global evolution of galaxies. Yet, the origin of stellar nuclei is still poorly understood, with most current knowledge based on imaging survey. MSE would allow a complete census of ages, metal abundances, recent star formation and AGN activity, as well as internal velocity dispersion measurement for a magnitude limited sample of hundreds of nearby nuclei, hosted in galaxies with masses as small as $\sim 2\times 10^6$ $M_\odot$.

II. Science Justification

High resolution imaging and spectroscopy over the past decade have revealed not only that the structural and dynamical properties of galaxies vary smoothly over a wide range in mass, from giant to dwarf systems, but also that in any given galaxy the structural properties of the innermost regions – on tens of parsec scale – appear to be causally connected to the large, kpc-scale, properties of the host. The most massive ($M > 4\times 10^{10}$ $M_\odot$) early-type galaxies, for instance, are characterized by shallow density cores (tens to hundreds of parsecs across) believed to result from the evolution of supermassive black holes (SBHs), in ways that are are yet to be be fully understood (e.g. Bekki & Graham 2010; Milosavljevic & Merritt 2006; Capuzzo-Dolcetta 1993). SBHs are known to exist in all (massive) galaxies, and to play (through a process that has become known as "AGN feedback") an important role in their global evolution, as evidenced by the existence of a number of scaling relation linking SBH masses to the large, kpc-scale properties (mass, luminosity, velocity dispersion) of the host. In less massive galaxies, the shallow cores transition to high-density central nuclear structures, or "stellar nuclei" (Ferrarese et al., 2006b; Cote et al., 2006) whose properties (sizes, luminosities, masses, and, to a lesser extent, colours) also correlate with the global properties of the host galaxies. Although SBHs and stellar nuclei are not mutually exclusive (e.g. Filippenko & Ho 2003; Seth et al. 2008a; Shields et al. 2008; Graham & Spitler 2009, Gebhardt et al. 2001; Valluri et al. 2005; Cote et al. 2006; Ferrarese et al. 2006b), different lines of evidence indicate that the fraction of galaxies hosting SBHs decreases with decreasing galaxy mass (e.g. Gallo et al. 2008; Baldassare et al. 2014), while the opposite is true for stellar nuclei (at least down to the limit currently probed, $M(g) \sim -15.5$ mag, Ferrarese et al. 2006b). Perhaps even more suggestive is the fact that stellar nuclei in low-mass galaxies comprise about 0.2% of the total galaxy mass, the same fraction of the total mass that is enclosed in SBHs in more massive systems (Ferrarese et al. 2006b; Wehner & Harris 2006; Rossa et al. 2006, but see also Graham 2012; Leigh, Boker & Knigge 2012).

"Central Massive Objects" (CMOs, i.e. SBHs in the most massive galaxies, and stellar nuclei in the less massive ones) therefore appear to be universal by-product of galaxy evolution. This suggests that the structure, kinematics, and/or stellar populations of stellar nuclei might be determined by (and therefore hold information about) the complex interplay between secular evolution, environment, AGN and Supernova feedback that drive the global evolution of galaxies: understanding CMOs is an integral part in the ultimate quest to understand galaxy evolution. A related, important question in the physics of accreting supermassive black holes or active galactic nuclei (AGN) is why most accreting black holes produce low kinetic-power synchrotron jets that are quenched well within their host galaxies, while a few produce bulk-relativistic high kinetic power jets that extend to scales of nearly a Mpc. The feedback could occur by AGN heating the surrounding gas, thereby quenching star formation, and/or by the jet mechanical power inducing star formation.

The study of SBHs requires spatial resolutions that will only be attainable by the next generation of 30m, AO-assisted optical/NIR facilities. The study of stellar nuclei, however, is ideally suited to MSE. In very nearby AGN, it will be possible to measure the effects of AGN photoionization and shock ionization of the gas surrounding the AGN.

III. Current status

How stellar nuclei form, and how they relate (if at all) to SBHs is a very active field of research. In particular, two leading (although not mutually exclusive) theories for the formation of stellar nuclei have emerged: coalescence of globular clusters that spiral to the center through dynamical friction; and dissipation following mergers/interactions and the resulting inflow of gas towards the galaxy center.

Based on analysis of the ACSVCS/FCS imaging data, Turner et al. (2012) conclude that "for the low-mass galaxies in our sample, the most important mechanism for nucleus growth is probably infall of star clusters through dynamical friction, while for higher mass galaxies, gas accretion triggered by mergers, accretions, and tidal torques is likely to dominate, with the relative importance of these two processes varying smoothly as a function of galaxy mass." The idea that globular clusters can sink towards the centre of the host galaxy through dynamical friction goes back to the work of Tremaine, Ostriker & Spitzer (1975); in more recent work, Capuzzo-Dolcetta & Miocchi (2008) and Arca-Sedda & Capuzzo-Dolcetta (2014) show that subsequent merging leads to a nuclear star cluster whose properties and scaling relations are consistent with observational constraints. At the same time, the role of dissipation is also being confirmed observationally through detailed spectroscopic studies for a handful of individual galaxies. Such studies are challenging, due to the small angular size of stellar nuclei, but are painstakingly being assembled. Seth et al. (2008) suggest that the stellar nucleus in the edge-on spiral galaxy NGC 4244 was formed by episodic accretion of material from the galaxy disk, a mechanism that seems to be consistent with the observations of other late type galaxies (Seth et al. 2006; Walcher et al. 2006; Neumayer & Walcher 2012). Dissipation is also important in the formation of the stellar nucleus of the early-type galaxy NGC 404, although here the origin appears to be external, via multiple merging episodes, the most recent of which likely resulted from the accretion of a gas rich dwarf galaxy ∼1 Gyr ago (Seth et al. 2010).

A related topic of interest is the nature of "Ultra Compact Dwarf Galaxies", compact stellar systems discovered in dense environment and with properties intermediate between globular clusters and low-mass galaxies (e.g. Hilker et al. 1999, Drinkwater et al. 2000, Hasegan et al. 2005). The conjecture that the formation of UCDs might proceed through tidal and/or ram-pressure stripping of nucleated galaxies provides an additional reason why the study of stellar nuclei is an important element in understanding the evolution of structures in dense environments.

For studies of nearby AGN, resolved spectroscopy of the gas in the vicinity of the AGN has already proved valuable, using the WiFeS IFU on the Siding Spring 2.3m telescope, with a spectral resolution of ∼3000.

IV. Key astrophysical observables

As mentioned above, existing spectroscopic studies of stellar nuclei are rare. The game changer in this field will be a detailed kinematical and stellar population analysis of stellar nuclei in a statistically significant sample of galaxies representative of the galaxy population at large and spanning a range of environments. This would allow one to seek correlations between nuclei and the properties of globular cluster systems, UCDs, and the large scale properties of the host galaxies.

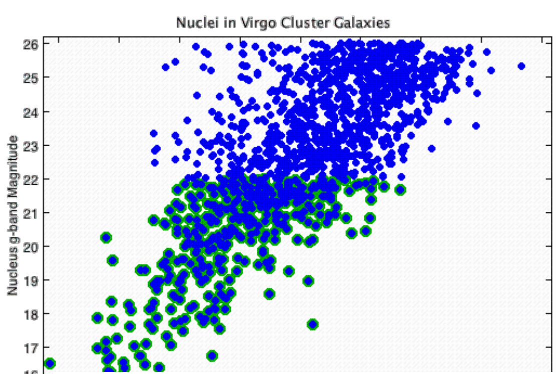
Abundance analysis requires high resolution spectra. This work would follow the lead of Colucci et al. (2014, arXiv1411.0696) who used HIRES at Keck with R=24,000, λ=3800-8600 Å, and S/N∼60, or Sakari et al. (2014, arXiv:1407.4120) who used HRS at HET with R=30,000, λ=5320−6290 Å and 6360-7340 Å, S/N=65-180. These modes are well matched by MSE's baseline highest resolution mode (R=20,000, Δλ =2000 Å), while MSE's baseline multiplexing capabilities (∼800 fibers at R=20,000) would represent a clear advantage over current studies. Emission lines – although not requiring nearly the same spectral resolution – would also be detected and can be used to diagnose on-going star formation and low level AGN activities: lines of particular interest are [OII]3727, Hβ, [OIII]5007, [OI]6300, [NII]6584, Hα, [SII]6717.

The central few arcseconds of a nearby galaxy hosting an AGN includes the extended narrow-line region ionised by the AGN as well as circumnuclear HII regions. The latter can be used to infer the abundance of the gas, and therefore the photoionizing spectrum. Spatially resolved spectroscopy can be used to study the kinematics of the narrow-line regions. The very same data cubes can also be used to study the kinematics of the narrow-line regions. Polarimetric radio imaging (VLA and GMRT and later LOFAR and even SKA) would then enable probing the interplay between the synchrotron jets and the NLR gas and the connection between excitation structure of the gas and the radio jet structures. Thus the possible locations of mass-loading and quenching of the synchrotron jets, as well as jet-induced star formation can be studied. The superior seeing of Mauna Kea combined with the proposed photon-collecting area of the MSE will enable identification of HII regions and spectroscopic mapping of the extended ionisation regions that will be unprecedented both in the number of galaxies and in the range of luminosities that can be probed. Thus, active galaxies with a range of central black hole mass and bulge mass as well as AGN power can be studied, which is essential to arrive at the fundamental driving parameters of the feedback mechanism.

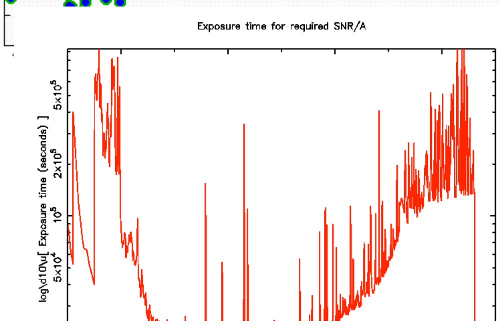
IV. Survey Design and Target Selection

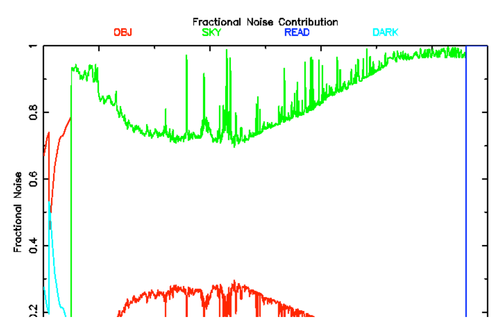
Because of their proximity and high density of targets, the Virgo, Fornax and Coma clusters are ideal to study large samples of galaxies, and their stellar nuclei. In what follows, Virgo will be used to define a strawman survey, given its Northern declination, proximity (16.5 Mpc vs. ~100 Mpc for Coma), and availability of ancillary data.

A complete census of nuclei in Virgo galaxies is being compiled by the Next Generation Virgo Cluster Survey (NGVS), a deep optical imaging survey covering the cluster out to one virial radius using MegaCam at CFHT (Ferrarese et al. 2012). Of the 3600 galaxies in the NGVS catalogue (most of which previously undetected), ~1300 are nucleated. The figure below shows a preliminary relation between *g*-band nuclear and galaxy magnitude for all nucleated Virgo galaxies identified in the NGVS.



As a reference, according to the exposure time calculator (ETC), in the baseline configuration, MSE can reach S/N~40 at 5000 Å and R=20,000 in a 6 hour exposure for a *g*=22 magnitude

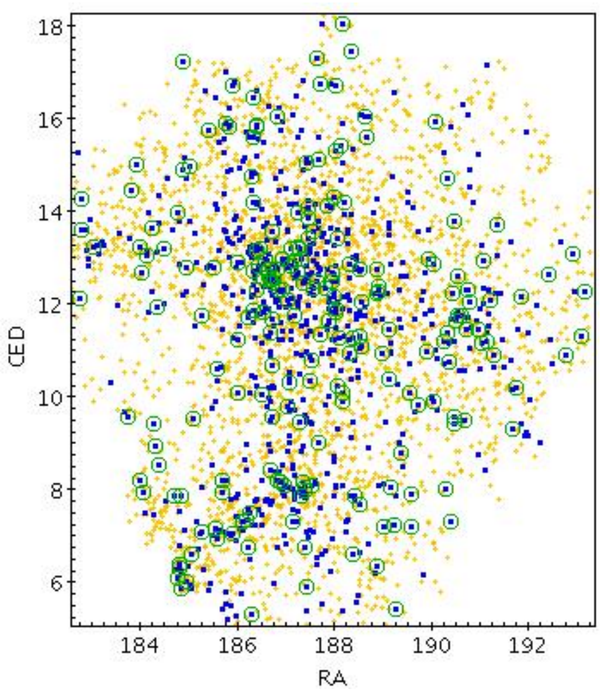




nucleus (highlighted in green in the figure), assuming a 0.7 arcsec seeing, a 50% sky brightness, 1.2 arcsec fibers and 25% overall throughput. The resulting spectrum, as simulated by MSE's ETC is shown below:

About 400 Virgo galaxies (as faint as $g\sim20$ mag, corresponding to an absolute g-band magnitude of −11.1 and a stellar mass of $\sim2\times10^6$ M$_\odot$) have a nucleus brighter than g=22 mag. The distribution of all (bona-fide) Virgo galaxies (yellow), nucleated Virgo galaxies (blue) and nucleated galaxies with a nucleus brighter than g=22 mag (green) is shown in the figure to the left.

For an MSE 1.5 deg^2 FOV, the number of targets (galaxies with a nucleus brighter than g = 22 mag) ranges between 1 at the outskirts and 40 in the core regions. The observations will additionally require a few sky fibers (which can be shared between galaxies) and, for the brighter galaxies, a fiber located on the galaxy's main body. This means that the number of fibers needed for the project would range from a couple to ~80 for each MSE field. A single configuration per field is therefore sufficient; covering 100 square degrees in Virgo (the area covered by the NGVS, extending out to one virial radius) would require ~400 hours.



The large number of fibers (at least 700) left unoccupied offers the unique opportunity to perform a similar study, but targeting the GC and UCD population within the cluster, thereby allowing one to probe the connection between these three types of baryonic substructures. The turnover magnitude of the GC luminosity function in Virgo is g~24 mag. There are ~750 GCs brighter than g~ 22 within a 1.5 square degree in the Virgo core, with the numbers being much lower around galaxies other than M87.

A single configuration per field would therefore yield systemic velocity and high resolution spectra for all stellar nuclei, GCs and UCDs brighter than g=22 mag, across Virgo, at the cost of approximately 400 hours of observing time. The galaxies targeted cover all Hubble types and extend well into the historic "dwarf" regime, reaching galaxies with masses as low as $\sim2\times10^6$ M$_\odot$, and located in regions of widely different densities, from the cluster centers to the outskirt (one virial radius).

Obvious synergies exist with other MSE science cases. In particular, estimate of the global metallicity, gas kinematics (if present), as well as a measure of the velocity field and degree of dynamical perturbations within the main body of the galaxy, would clearly lead to a complete picture of each system (see MSE-lowz-SRO1). Obvious complementarity also exists with stellar population and dynamical studies of star clusters, as discussed in MSE-lowz-SRO4.

For the study of AGN, target selection would be based on available radio imaging with sub-arcsecond resolution and large surface-brightness sensitivity in order to enable morphological comparison of the radio jets with the optical emission-line structure. The space density of these targets is low, and the observations would be incorporated within a larger survey.

VI. Cadence and temporal characteristics

None

VII. Calibration requirements

The calibrations requirements are standard for this kind of project. A number of red giant template stars (for velocity dispersion analysis) as well as telluric standards will need to be observed with the same instrumental configuration. There are no unusual requirements on flux or wavelength calibration constraints or pointing accuracy.

VIII. Data processing

Data processing is standard and not time critical (i.e. the data does not need to be reduced in real time).

IX. Any other issues

An increase in collective area would of course allow one to reduce the exposure times or, alternatively, to push further down the luminosity function and sample nuclei in lower mass galaxies than those described in the strawman survey above (while still requiring a single configuration per field, due to the relatively low target density). In Virgo, everything else being the same, a 12m aperture would reach nuclei ~0.2 mag fainter, and increase the sample size by 10%. While this would not be transformational, the project is nevertheless likely to benefit from a larger collective area, since the S/N~40 assumed in the previous section is likely on the low side of what is needed for the abundance analysis.

Additional factors that would help this program are:

- The ability to use unallocated fibers to feed a lower resolution mode (e.g. R=6500). This would allow one to measure radial velocities, integrated ages and metallicities for fainter GCs, and investigate, amongst other things, the distribution of dark matter within the cluster.

- The ability to closely pack a few fibers into small (several arcsec across) IFUs. This would lead, within the same program, to a complete view of the stellar population and kinematics of the host galaxy, and investigate the connection with the nuclear component.

MSE-lowz-SRO4: Chemical Abundances and Internal Kinematics of Extragalactic Globular Clusters and Ultra Compact Dwarfs

I. Abstract

II. Science Justification

Globular clusters: Globular clusters (GCs) are among the most prominent survivors of the earliest epochs of star formation. As single-age, single-metallicity, simple dynamical stellar systems that are thus relatively easy to interpret, the properties of globular clusters constrain not just their own formation and evolution, but the star formation and chemical enrichment history of the galaxies that host them, as well as the formation mechanisms of star clusters in general. Milky Way globular clusters have been studied in great detail, addressing fundamental issues in stellar evolution, stellar dynamics, and the formation history of the Galactic halo.

Moreover, these studies have formed the foundation for investigations of extragalactic GC systems, where the larger sample of galaxies available for study enables a more comprehensive approach to the investigation of GC systems and associated stellar spheroid formation, but where the distances involved require that the tools used are more crude (e.g, photometry and integrated low-resolution spectroscopy).

One area in which MSE can make a tremendous improvement on the status quo is in the spectral resolution typically used to study the integrated light of extragalactic GCs. The spectroscopic tools that are most commonly used to study extragalactic GCs are based on stellar population models and libraries designed mainly for the integrated light of distant galaxies (e.g. Worthey 1994; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003; Vazdekis et al. 2010). These galaxies often have large velocity dispersions (> 100 km/s) that limit the intrinsic resolution of their spectra, thus making it unnecessary to study them at spectral resolution higher than R ~ 2000. GCs, on the other hand, have much lower velocity dispersions (2–20 km/s) that can still be resolved with moderate to high resolution spectroscopy, enabling us to both measure their internal kinematics and gain access to a large number of spectral lines that are washed out in the integrated light of entire galaxies.

The large aperture and multiplexing advantage of MSE would allow us to extend detailed studies of globular clusters beyond the Milky Way and its satellites. The Andromeda Galaxy, M31, has the Local Group's largest globular cluster population and has been the target of numerous studies dating back to the first M31 globular cluster catalog of Hubble (1932). M31 GCs have already been studied at higher resolution to study their dynamical masses (Strader et al. 2011) and detailed chemical abundances (Colucci, Bernstein, & Cohen 2014).

III. Current status

Although [Fe/H] and [α/Fe] has been crudely measured in extragalactic systems using the well-known Lick/IDS system of broad spectroscopic indices (Worthey et al. 1994; Worthey & Ottaviani 1997), the Milky Way remains the only large galaxy in which detailed abundance patterns of elements in stars has been measured.

Globular clusters may turn out to be the sweet spot of extragalactic abundance measurements — up to 6 mag brighter than a typical red giant branch star, but with velocity dispersions that are still low enough to allow high resolution spectroscopic line work. Work by Colucci et al. (2014) with Keck/HIRES, who measured [Fe/H] and alpha-element abundances for 31 GCs in M31 shows the potential of this technique. Differences in abundance ratios have been found in globular clusters both within the Milky Way system and between the Milky Way and other galaxies in the Local Group. These abundance ratios trace the chemical histories of these systems, and given the diversity of merging histories of massive galaxies, we would expect that to be reflected in [Mg/Fe], [Ti/Fe] and possibly [Cr/Fe]. Variations in the Galactic globular clusters in their [Ti/Fe] ratios, perhaps as a function of Galactocentric distance, have been found (e.g. Lee et al 2005; Lee & Carney 2002) Old globular clusters in the Large Magellanic Cloud (Johnson et al. 2006) show lower [Ti/Fe] ratios than old Galactic globular clusters, but have similar [Mg/Fe] values. Pal 12, a cluster captured from the Sagittarius dSph, also shows anomalous abundances ratios in [Mg/Fe] and [Ti/Fe] although [Cr/Fe] is normal (Cohen 2004).

Milky Way globular clusters are known to follow scaling relations consistent with them being confined to a fundamental plane within the four-dimensional parameter space of general King (1966) models (Djorgovski 1995; McLaughlin 2000). These relations differ from the fundamental plane relations for early-type galaxies, and likely reflect the cluster formation process. Three parameters can be derived from high resolution surface brightness profiles — for example, r_0, the scale radius, $c = \log(r_t/r_0)$, the concentration parameter where r_t is the tidal radius, and L, the total luminosity. The last independent observable is σ_0, the central velocity dispersion, which gives the core mass-to-light ratio. In the Milky Way, globular clusters are described by a single mass-to-light ratio with little scatter, $M/L = 1.45 \pm 0.1$ (McLaughlin 2000), which is consistent with their universally old ages (> 8 Gyr). In the Milky Way then, this fact essentially removes M/L or σ as a free physical variable in the definition of the GC fundamental plane. In other galaxies (M31, field early-type galaxies), however, there is evidence that the metal-rich GCs may have ages 4-8 Gyr younger than the metal-poor GCs. If such an age spread exists, M/L will be smaller by a factor of two for the younger GCs (assuming a constant IMF), creating a tilt in the fundamental plane as a function of metallicity.

IV. Key astrophysical observables

In galaxies beyond the Milky Way satellites (D > 100 kpc), where individual old stars are too faint for high resolution spectroscopic work with today's technology, globular clusters are the only objects for which we can potentially measure detailed elemental abundances. Some of these elements when measured in old stars are very useful for understanding the chemical enrichment and nucleosynthetic processes in the early universe. Elements preferentially produced by Type II supernovae, the α-elements (of which Mg is one of the most commonly measured in extragalactic systems), should build up rapidly over the first billion years of star formation. Elements that are formed in both Type II and Type Ia supernovae, the iron-peak elements (which include Ti and Cr), should build up more gradually over time. Thus, the ratio of α to Fe-peak elements is a useful chronometer for the intensity and duration of star formation.

The optical spectra of GCs in the Mg triplet region (λλ5160-5300A˚) covers a large number (> 20) of strong FeI, TiII and CrI lines in addition to the MgI lines. With the high resolution (R~20,000) afforded by MSE, we can separately measure these feature and determine [Fe/H], [Mg/Fe], [Ti/Fe] and [Cr/Fe]. With several abundance ratios, in addition to an overall [Fe/H], MSE will allow us to compare extragalactic GC systems to each other and to the Galactic one in much finer detail. Lastly, by obtaining estimates of [Fe/H] independent of the low resolution methods that suffer from the age-metallicity degeneracy, studies with MSE will place corresponding constraints on the ages of extragalactic GCs.

In nearby galaxies, such as M31, M81, NGC 3379, and the Virgo cluster, MSE will be able to measure velocity dispersions for hundreds of globular clusters. The goal of a survey with MSE would be to obtain spectra of extragalactic globular clusters at high enough resolution to resolve the internal stellar velocity dispersion, and at high enough S/N to be able to constrain the abundances of Fe, Mg, Ti, and Ca. A MSE spectral resolution of R~20,000 corresponds to a velocity dispersion of 6 km/s, which means that with high enough S/N, we should be able to resolve the velocity dispersions of most GCs. This science case suffers significantly at lower R because many GC dispersions then become unresolved, and most GCs have dispersions on the low end. The abundance work could still be done at R~10,000, but would not be optimal.

V. Target selection

The first target for such a study would likely be M31. M31 has a system of over 500 GCs most of which are within the central 2 degrees. The number of targets is not sufficient to fill all the MSE fibers, but this program could be combined with other interesting M31 targets.The next best target would likely be the giant ellipticals, M87 and M49, in the Virgo Cluster. While more distant, there are hundreds of targets with g<21 that could be accessible for higher resolution studies.

VI. Cadence and temporal characteristics

No time-domain astrophysics foreseen.

VII. Calibration Requirements

TBD

VIII. Data processing

TBD

IX. Any other issues

None.