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Executive Summary of White Paper (5000 character limit)

Building on Canadian expertise in studies of massive star clusters, we outline outstanding prospects in this field to which we can make fundamental contributions in the next decade and beyond. These include (1) understanding cluster formation in the early Universe and interpreting future observations of globular cluster progenitors at high redshifts, (2) settling the question of the presence of intermediate-mass black holes in the cores of globular clusters, (3) mapping the kinematics and abundances in the outer parts of Galactic globular clusters to understand their formation and the interplay with Galactic tides, (4) solving the puzzle of multiple stellar populations in globular clusters, (5) unveiling and characterizing compact objects in dense clusters and their implications of gravitational-wave astrophysics, and (6) bringing studies of cluster populations as fossil records of the formation and evolution of external galaxies to the next level with large statistical samples. We highlight synergies between these science goals and upcoming and proposed ground- and space-based facilities.

Following up on globular cluster progenitor candidates at high redshift (identified by JWST) with a 30-m class ground-based telescope and adaptive optics will be crucial to characterize these systems and will provide important clues on the relative timing of GC formation in the context of galaxy assembly as well as the possible role of GCs in cosmic reionization. In the meantime, we have reached a stage where our computational methods can model GC formation, and these models will be important to interpret observations. The hydro+dynamics simulations needed are however very expensive, and will require Compute Canada to have capacity for such intensive simulations for our community to take full advantage of its expertise in the field of (massive) cluster formation and evolution.

Extreme Multi-Conjugate Adaptive Optics (MCAO) on a 30-m class telescope also promises important breakthroughs in this field. It is the most promising option for reaching a definitive answer on the presence of IMBHs in globular clusters and their importance in the growth of supermassive black holes. It would provide order-of-magnitude improvements in angular resolution and in the precision of proper motion measurements needed for dynamical analyses. Imaging and spectroscopy with 30-m class telescopes would also enable careful studies of the companions of compact objects in clusters, especially accreting BHs, allowing to study of the link between black holes in globular clusters and gravitational sources.

Important questions in the field can be tackled with deep, space-based, wide-field imaging at HST-like resolution, preferably in the blue optical/UV region. CASTOR represents a unique opportunity to fill this niche. The statistical samples of proper motion measurements over large regions that this would enable would be ideal to map the plane-of-the-sky kinematics of nearby clusters over their entire extent, for example to measure velocity anisotropy and its impact on the inferred mass/presence of IMBHs, or map the kinematics of clusters near the tidal boundary and disentangle scenarios about their formation and interaction with the Galactic tidal field. Moreover, CASTOR imaging would offer opportunities to probe the host environments of neutron star mergers and constrain their dynamical formation in GCs. At larger distances, CASTOR's UV and blue-optical coverage would complete the SED coverage of other missions over the critical UVOIR region, allowing complete photometric characterization of potentially many tens of thousands of galaxies and their cluster systems in the local volume.

MSE with its large field of view, would also be ideally suited for mapping the kinematics (line-of-sight

velocities) in the outskirts of globular clusters, out to the tidal radius. But crucially, it would yield detailed chemical composition for large samples of stars in globular clusters, significantly improving upon current surveys. As such, it would be the most important next-generation facility to address the origin of multiple (chemical) populations in these systems, a great unsolved problems in the study of stellar populations. MSE would also make it possible to build large spectroscopic databases of star cluster populations in external galaxies.

Finally, upcoming radio facilities like ngVLA and SKA will provide a significant step forward towards a better determination of BH populations in GCs, with substantial improvement in sensitivity that would allow the identification of typical weakly-accreting black hole candidates in clusters, as well as thoroughly test the presence of weakly-accreting intermediate-mass black holes. Significant improvements in the study of compact objects in clusters will also be possible with future advanced X-ray telescopes with higher spectral resolution and sensitivity, such as ESA's Athena and NASA's Lynx missions.

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1 Introduction

Canadians have long played a leading role in star cluster studies, from deep photometry of their stellar content, to stellar evolution codes, studies of chemical abundances, cluster formation, dynamical evolution, and investigations of cluster populations in galaxies. The study of star clusters is connected to a wide range of astrophysical questions, including galactic structure and mass profiles, the assembly history of galaxies, star formation in extreme conditions, stellar dynamics, stellar/binary evolution, compact objects, and intermediate-mass black holes.

We do not attempt here to extensively review all these implications and the relevant work in this field, but rather choose to select a few outstanding and exciting scientific prospects, to which the Canadian astronomical community, with its existing expertise and involvement in different facilities, can make fundamental contributions in the next decade and beyond. From the vast parameter space spanned by cluster studies, we narrow down our focus to stellar systems which are dense ($r_{\rm eff} \sim$ few pc) and massive ($\sim 10^4 - 10^7$ M$_\odot$) enough to survive for a Hubble time in the tidal field of their host galaxy without dissolving completely (i.e. globular clusters both old and young). We outline the promises of studies of massive cluster formation in the early Universe, scientific opportunities linked to the chemo-dynamical evolution of star clusters, the study of compact objects in dense clusters and the potential to constrain the formation of gravitational wave (GW) sources via dynamical interactions in the dense environments of globular clusters, and discuss studies of cluster populations in external galaxies in the next decade and beyond.

2 Cluster formation in the early Universe

Globular clusters (GCs) were among the first baryonic structures to form in the Universe during the earliest phases of galaxy formation, but their origin is still shrouded in mystery. Given their ages, the old GCs of the Milky Way must have formed between redshifts $3 \lesssim z \lesssim 10$. Observing these nascent massive clusters in the early Universe is challenging, and modelling their formation involves the complex interplay of many physical ingredients. However, we are on the verge of major progress in the next decade. Giant Molecular Clouds (GMCs) can now be simulated at high enough resolution to identify the sites of star cluster formation and track their earliest evolution (Li et al., 2019; Gavagnin et al., 2017). In particular, one recent suite of radiative-hydrodynamic realizations of GMCs (performed by Howard et al., 2017, 2018) with the FLASH2.5 code is aimed directly at understanding how *massive* star clusters originate and grow within turbulent GMCs, starting from realistic large GMCs (10^4 to $10^7 M_\odot$).

Simulations like these yield several important new results that put our view of young massive cluster (YMC) formation into a new light and represent a clear step forward in our physical understanding of how globular clusters might have originated in the early universe. It appears to be the first few Myr that are the most important for cluster growth by the combination of direct gas infall and merging. Star cluster formation seems simple at low cluster mass ($\lesssim$ a few $10^4 M_\odot$): single-epoch, a short period of direct accretion of gas and then subsequent star formation. At higher mass the growth history of clusters becomes significantly more complex, in particular due to merging of substructures. For the highest-mass YMCs, the final mass is gained almost equally from direct gas accretion and from merging with many other, smaller clusters, extending the main period of star formation over the entire timespan of the simulations. The growth histories of the clusters also have a stochastic nature, especially because of the random initial nature of the turbulence spectrum and the details of the gas flows. They have *strongly contingent individual histories* that are very unlike a simple, isolated monolithic collapse. At low metallicity (as in old GCs), feedback on the surrounding gas is less important because of the much lower opacity, which makes it easier for clusters to grow to higher masses. In this low feedback regime, GMC masses of $10^7 M_\odot$ are needed to build YMCs at the level of GCs (with initial masses near $10^6 M_\odot$). It is precisely during the redshift epochs $z \gtrsim 2$ when such massive GMCs are most common. At their very most basic level, these recent modelling studies support one simple but important conclusion: that globular clusters over their entire mass range can form in the early stages of galaxies in a *normal manner*, by growth within GMCs. Exotic and semi-cosmological scenarios are (so far) not called for.

Observations of massive stellar clusters as they are forming in the early Universe are just starting to become available. Three very compact, young, and massive objects (GC progenitor candidates) were found beyond a redshift of 6 using the magnification effects of strong gravitational lensing of the Hubble Frontier Fields (Vanzella et al., 2017). When the James Webb Space Telescope (JWST) is launched in 2021, searches for GC progenitors at high redshifts are expected to yield a significant harvest of candidates (Renzini, 2017). **Following up the identified GC progenitor candidates with a 30-m class ground-based telescope will be crucial**. At these redshifts, the spatial resolution of JWST (NIRCAM) is ~ 200 pc, which is insufficient, for example to distinguish GC progenitors from star cluster complexes. With a 30-m class ground-based telescope and adaptive optics, we will be able to push the spatial resolution down to ~ 30 pc, allowing for a much better characterization of these systems. In addition to providing evidence on GC formation, the detection of GC progenitors, their clustering, and the presence or absence of a central galaxy already in place would **provide important clues on the relative timing of GC formation in the context of galaxy assembly and the possible role of GCs in cosmic reionization**. It will also help to quantify how much more massive GC progenitors were compared to present-day GCs.

To interpret these observations, it will be important to understand what we expect the objects to look like – for example, small compact globular clusters could be more identifiable than their entire (diffuse) host galaxy (Zick et al., 2018). Making such predictions requires realistic simulations, and at long last, **we have reached a stage where our computational methods can model GC formation**. Computationally, the community has recently made breakthroughs in physically-motivated methods to allow simulations to work together across a range of size and time scales (e.g. the AMUSE framework Portegies Zwart & McMillan, 2018). However, the hydro+dynamics simulations we need to address these questions about GC formation are very expensive, and it is not clear that ComputeCanada can/will handle this level of computation (with runs that take of order 10^7 CPU-hours each). To follow the long-term dynamical evolution of GCs, GPUs are the main driver but the latest cluster on Compute Canada is limited to 2 GPUs per node and slow cross-talk between nodes. **It is therefore highly desirable for Compute Canada or the new organization that will take over to have the capacity for such intensive simulations for the Canadian community to take full advantage of its astrophysical expertise in the field of (massive) cluster formation and evolution. We also emphasize that major advances in software development are now on the horizon that will be needed to usher in an era of exascale computing, allowing the true multiscale nature of cluster formation and evolution to be fully explored.**

3 The chemo-dynamical evolution of globular clusters

Space-based missions and spectroscopic surveys are providing exquisitely detailed information about the structure, kinematics, and stellar populations of nearby globular clusters (e.g. Watkins et al., 2015; Kamann et al., 2018; Gaia Collaboration et al., 2018). Detailed spectroscopy of individual stars has also provided chemical abundances for stars in globular clusters that have complicated our understanding of their formation and evolution (e.g., multiple populations and r-process spreads possibly linked to rare neutron star mergers). While Gaia, the Hubble Space Telescope (HST), and current multi-object spectrographs (like VLT-MUSE and FLAMES, and soon GIRMOS on Gemini) are wonderful and complementary tools, they are still far from providing a complete chemo-dynamical picture of GCs and fall short of answering some key open questions about these systems, which we discuss below.

3.1 Cluster cores and intermediate-mass black holes

Extrapolating the relation between the mass of supermassive black holes and the central velocity dispersion of their host galaxy (the "$M - \sigma$" relation; Ferrarese & Merritt, 2000), to low masses, we may expect intermediate-mass black holes (IMBHs; $\sim 10^2 - 10^5$ M$_\odot$) to hide in the dense cores of GCs, where they could have formed by runaway collisions (e.g. Portegies Zwart et al., 2004). IMBHs could represent a missing link from which supermassive black holes could grow to masses as high as $10^9 - 10^{10}$ M$_\odot$ as early as redshift $z \sim 6$ (e.g. Fan, 2006). In particular, uncovering not only the existence but the mass distribution of IMBHs would reveal vital information about the viable formation channels for SMBHs in the high-z Universe (Mezcua, 2017). The search for accreting IMBHs in GCs with radio observations, however, has only yielded upper limits on their mass or null detections (see Section 4.1), but various claims of detections have been made in the last decades based on stellar kinematics in their innermost few arcseconds (e.g. Noyola et al., 2008; Lützgendorf et al., 2011) or on the gravitational accelerations of millisecond pulsars determined from long-term pulsar timing (e.g. Kızıltan et al., 2017). However, every claim has been followed by a rebuttal, either based on better data (e.g. van der Marel & Anderson, 2010; Lanzoni et al., 2013; Mann et al., 2019) or on alternative and more plausible interpretations (radial anisotropy in the velocity distribution or the presence of a concentration of dark stellar remnants, both of which can increase the central velocity dispersion; e.g. Illingworth & King, 1977; Zocchi et al., 2017; Hénault-Brunet et al., 2019).

In the next decade, convincing dynamical evidence for IMBHs (or very stringent upper limits on their masses) will require increased samples of precise stellar velocity measurements deep inside cluster cores. Proper motion measurements (e.g. with high-precision astrometry with adaptive optics on a 30-m class telescope and long time-baseline near diffraction-limited space-based imaging), in particular, have the advantage that fainter stars can be probed compared to line-of-sight velocity measurements from spectroscopy, yielding better statistics. With HST and its pixel scale of $40 - 130$ mas/pixel, precise proper-motion kinematic data deep in the cluster core are only available for a few (nearby) clusters with relatively sparse cores (e.g. van der Marel & Anderson, 2010; Mann et al., 2019). Stars in the crowded central fields of globular clusters are unfortunately also beyond Gaia's reach. Longer time baselines with HST-like resolution and spaced-based imaging beyond HST would increase the precision of proper motion measurements, in particular with a mission like CASTOR, where UV sensitivity allows to avoid contamination by bright RGB stars concentrated in the cluster core (as opposed, for example, to WFIRST).

Unfortunately, the envisaged pixel scale for CASTOR (~ 100 mas) may be too large for significant improvements in precision. We note that JWST is even less optimized for this task with its long-wavelength coverage and a pixel scale comparable to HST and CASTOR. **Extreme Multi-Conjugate Adaptive Optics (MCAO) on a 30-m class telescope (with a pixel scale of $4 - 5$ mas) thus appears to be the most promising option for reaching a definitive answer on the presence of IMBHs in GCs**. This would provide **order-of-magnitude improvements in angular resolution and in the precision of proper motion measurements needed for dynamical analyses**. Further down the line, the Large UV/Optical/IR Surveyor (LUVOIR) can potentially provide similar resolution to extreme MCAO on a 30-m class telescope, with the advantage of UV capability. These would not only constrain the presence of an IMBH, but also more generally the structure, dynamics, and evolution of GCs and their dense central regions. We refer to Woods et al. (LRP2020) for other aspects of IMBH searches, e.g., in nearby dwarf galaxies, and the broader impact which robust detections would have in understanding the evolution of SMBHs.

3.2 Internal kinematics, anisotropy, and the dynamical behaviour near the tidal boundary

The high-precision proper motions provided by MCAO on a 30-m class telescope or LUVOIR would be limited to a field of view of a few square arcminutes at most (similar to JWST or HST). These would not address the need for proper motions in the intermediate and outer parts of clusters (way beyond the field of view of HST), which will be key to measure the velocity anisotropy profile over the entire extent of a cluster. **Measurements of two components of the velocity in these regions are needed to break the well-known degeneracy between mass and velocity anisotropy (e.g. Binney & Mamon, 1982), which in the case of GCs can affect the central velocity dispersion and the inference about the presence of an IMBH or its inferred mass** (e.g. Zocchi et al., 2017).

There are several other motivations for mapping the kinematics of large samples of stars over the entire extent of GCs, with implications for cluster formation, evaporation, and destruction by the Galactic tidal field. Simulations demonstrate that the outskirts of GCs are very sensitive to the external tidal field, with improved observations offering the chance to measure the mass profile of the Milky Way, the GMC population of the disk (Gieles et al., 2006) and the properties of baryonic and non-baryonic substructure (e.g. Rossi et al., 2018; Webb et al., 2019), the latter of which will help validate the cold-dark matter framework.

Open questions also remain about the kinematics of (higher-energy) stars near the nominal tidal radius or escape velocity and the interplay with the Galactic tidal field in the outskirts of GCs. **Extended stellar halos have been discovered around several Milky Way globular clusters (e.g. Kuzma et al., 2018). These halos could naturally arise from the interaction of the GC with Galactic tides, or (for some GCs) originate from debris of a progenitor dwarf galaxy**. Although we reiterate the key point made in Section 2 that state-of-the-art hydrodynamical simulations of cluster formation show that GCs can form in a normal manner in the early Universe, we note that extended halos have sometimes been ascribed to a more exotic scenario where GCs formed and evolved in their own low-mass dark matter halo (e.g. Peñarrubia et al., 2017). **Kinematics (and abundance measurements see Section 3.3) in the outskirts of GCs are required to disentangle these scenarios**.

While Gaia has provided exquisite information about the structure, kinematics, and stellar populations of nearby star clusters (e.g. Gaia Collaboration et al., 2018), its magnitude limit yields poor statistics (e.g. Jindal et al., 2019) and small samples of proper motion measurements in the outskirts of GCs (due to being limited to RGB stars which are concentrated in the inner regions because of mass segregation and which are also intrinsically rare compared to main-sequence stars). **Deep, space-based, wide-field (~ 0.25 deg^2) imaging at HST-like resolution and proper motion measurements with a mission like CASTOR would represent a unique opportunity to fill this niche and address the questions above.**

The Maunakea Spectroscopic Explorer (MSE), or the MSE design at another facility, with its large field of view, would also be ideally suited for mapping the kinematics (line-of-sight velocities) in the outskirts of globular clusters out to the tidal radius ($\sim 40 - 60$ arcmin). The large number of fibres and a radial velocity precision better than 100 m/s (much smaller than the velocity dispersion in GCs), combined with membership information from Gaia or proper motions from another wide-field space-based imager, will allow observation of a large number of stars in clusters out to a distance of ~ 100 kpc.

3.3 Chemical evolution and the puzzle of multiple populations

Our understanding of stellar populations in GCs has been revolutionized in the past decade. Once thought to be simple chemically homogeneous systems of coeval stars, GCs have been revealed to display multiple sequences in their colour-magnitude diagram (in particular with HST; e.g. Piotto et al., 2015) and associated chemical signatures in the form of anti-correlations of light-element abundances based on high-resolution spectra with 8-m class telescopes (e.g. Gratton et al., 2012). **The origin of these multiple populations is shaping up as one of the great unsolved problems in the study of stellar populations** (Bastian & Lardo, 2018). A variety of scenarios have been put forward to explain the chemical abundance anomalies, but none of them can satisfyingly match all the different observational constraints. Many different sources of pollution have been considered: fast-rotating massive stars (e.g. Decressin et al., 2007), massive interacting binaries (de Mink et al., 2009), AGB stars (e.g. Ventura et al., 2001), and supermassive stars (Denissenkov & Hartwick, 2014; Gieles et al., 2018). Most recently, Howard et al. (2018) modelled the origin of multiple populations by rapid self-enrichment within a massive protocluster while both young stars and large amounts of gas are simultaneously present. This model builds on the growth of YMCs within the large reservoir of gas provided by their host GMCs. On the computational front, these models must, and can, be made more quantitative.

MSE would be the most important next-generation facility to tackle this problem, as it would not only obtain high-quality radial velocities for stars in Galactic GCs, but it would also crucially yield detailed chemical composition. These observations would be pivotal to provide new constraints on future models for self-enrichment and improve upon current surveys. The magnitude limits of the current large-scale spectroscopic surveys mean that they only observe the most luminous evolved stars in each cluster. MSE would have the ability to observe main-sequence stars in Galactic GCs, making it possible to study abundance patterns over a range of evolutionary phases (to distinguish primordial and evolutionary abundance effects) and significantly increase sample sizes. The combination of detailed chemical abundances and kinematics in the outer parts of GCs, where the relaxation time is long and memory of the initial conditions (kinematics and spatial distribution) of different chemical stellar populations has not been completely erased by two-body relaxation, can become a powerful tool to study the formation of multiple populations and confront model predictions (e.g. Hénault-Brunet et al., 2015).

4 Compact objects in dense clusters in the era of gravitational-wave astrophysics

Globular clusters are thought to be one of the main sites where GW-emitting systems are born (e.g. Sigurdsson & Hernquist, 1993; Portegies Zwart & McMillan, 2000; Abbott et al., 2016; Rodriguez et al., 2016). To better understand these systems, we need to better understand the population, dynamics, and the nature of compact objects in globular clusters. The high density of globular clusters, combined with challenges in high-resolution sensitive imaging (especially in X-rays), has made the study of compact objects (and their counterparts in other bands) in these environments extremely difficult. Advancements in instrumentation (i.e., Chandra) have enabled significant progress in the study of these objects.

4.1 Black holes

The presence of black holes in GCs (both stellar- and intermediate-mass) has been a central question in the study of compact objects and their evolution in clusters. All bright ($L_X > 10^{35}$ erg/s) X-ray binaries in Galactic GCs have been found to be accreting neutron stars (NSs; e.g., Bahramian et al., 2014; Sanna et al., 2018). This conformed with early theoretical predictions that all stellar-mass black holes (BHs) formed in GCs would be ejected from the cluster (e.g., Sigurdsson & Phinney, 1993). However, improved evolutionary dynamical models such as N-body and Monte Carlo simulations have shown that the dynamical ejection rate of BHs in GCs is lower than what was generally assumed (Breen & Heggie, 2013; Morscher et al., 2013). And indeed, advancements in multi-wavelength studies of GCs over the past decade have led to the discovery of strong BH candidates in globular clusters in other galaxies. Namely, deep Chandra and HST observations led to the discovery of ultraluminous X-ray sources in extragalactic GCs (likely to be stellar- or intermediate-mass black holes; e.g., see Maccarone et al., 2007)).

Furthermore, the established connection between accretion in the X-rays and radio jet outflow in the radio (Fender et al., 2003) has motivated sensitive radio continuum imaging with the VLA and ATCA that has detected accreting stellar-mass BH candidates in Galactic GCs (Strader et al., 2012; Chomiuk et al., 2013; Bahramian et al., 2017). **Upcoming radio facilities like ngVLA and SKA will provide a significant step forward towards a better determination of BH populations in GCs. The substantial improvement in sensitivity would allow identification of typical weakly-accreting BH candidates** (rather than just the brightest, as is the case now), and would provide the capabilities to distinguish them from background AGNs through precise proper motions.

The most reliable method for identifying stellar-mass BHs is through measurement of radial velocities of their binary companions. Recently, sensitive optical studies of globular clusters with the advanced IFU instrument MUSE have enabled the discovery (and mass estimation) of multiple stellar-mass BHs in the GC NGC 3201 (Giesers et al., 2018, 2019). These studies are currently most feasible for low extinction GCs with low densities (like NGC 3201). However, the population of such systems is significantly more intriguing in denser clusters where the formation rate of binaries with compact objects are substantially higher. The recent installation of ground-layer adaptive optics for sensitive optical IFUs like MUSE, along with upcoming high-resolution imaging and spectroscopy in the infrared with the Canadian-led Gemini Infrared Multi-Object Spectrograph (GIRMOS) will pave the way to deep studies of BH populations (and other compact objects) in more GCs. Further into the future, the promise of infrared and optical **imaging and spectroscopy with 30-m class telescopes would allow careful studies of the companions of compact objects, especially accreting BHs. These studies together would provide a complete picture of BH populations in GCs and enable studies about the link between GC BHs and GW sources.**

Besides stellar-mass black holes, direct detection of accreting IMBHs in GCs would also impact our understanding of GW sources. So far, evidence for the presence of IMBHs in GCs is inconclusive (see also Section 3.1 for efforts to detect their dynamical signature). Radio surveys with VLA and ATCA did not find any evidence of massive ($\gtrsim$ 2000 $M_\odot$) weakly-accreting IMBHs in Galactic GCs (Tremou et al., 2018). **Upcoming radio facilities like ngVLA and SKA will provide the capabilities to thoroughly test the presence of weakly-accreting IMBHs in GCs**, the results of which can be combined with the dynamical searches outlined in Section 3.1.

4.2 Neutron stars

In contrast with the elusive population of BHs, numerous accreting neutron stars (NSs) and their descendants, millisecond radio pulsars, have been identified in Galactic GCs. These large populations allow us to tackle a variety of science questions that are difficult to address in the rest of the Galaxy. For instance, targeted surveys for millisecond pulsars (MSPs) in GCs have identified over 100 MSPs, including key MSPs that led to breakthroughs in our understanding how MSPs are created. These include the first "redback" MSPs (e.g., Ferraro et al., 2001), the first confirmed transitional MSP (switching between a MSP and an accreting X-ray binary state; Papitto et al., 2013), and MSPs that are likely to set new, extreme records for the maximum mass of neutron stars (Freire et al., 2008). Measurements of the acceleration of MSPs allow precise measurements of the gravitational potential of GCs, probing the stellar and dark (including IMBH) mass distribution (e.g. Freire et al., 2017; Prager et al., 2017). Studies of both the accreting NS and MSP populations shed light on the paths by which MSPs are recycled (e.g., Heinke et al., 2005; Ye et al., 2019). Spectroscopic studies of accreting NSs in periods of quiescence can constrain the neutron star radius, and thus the properties of matter at densities well above terrestrial laboratories. Using the well-constrained distance to GCs, some quiescent accreting NSs have provided strong constraints on the neutron star radius (e.g. Rutledge et al., 2002; Guillot et al., 2013; Bogdanov et al., 2016; Steiner et al., 2018). **Significant improvements will be possible with future advanced X-ray telescopes with higher spectral resolution and sensitivity, such as ESA's Athena mission and NASA's proposed Lynx mission**.

One of the intriguing sources of GWs are NS-NS mergers like the one that produced the GW event GW170817 and associated kilonova (KN) explosion (Abbott et al., 2017; Drout et al., 2017). Similar to BH mergers, these systems could be formed through dynamical encounters in GCs (Rodriguez et al., 2018). **Deep, wide-field, high-resolution imaging from space with a mission like CASTOR would offer unique opportunities to probe the host environments of NS-NS mergers and thereby constrain their formation in GCs**. Star formation histories near the location of the KN can set limits on the delay time between NS formation and coalescence, and thus constrain models for their progenitors (Blanchard et al., 2017; Fong & Berger, 2013; Pan et al., 2017). These delay times may also loosely constrain any kick velocity imparted on the system during the supernova explosions that produced the constituent NSs - a critical parameter for models of binary evolution. CASTOR would provide excellent localization of the GW source, allowing the merger environment to be studied on sub-parsec to kpc scales. If they formed from dynamical interactions in dense clusters, then NS-NS GW events may be associated with nearby or coincident GCs. With deep, multi-band, CASTOR images (obtained after the transient has faded) it would be possible to detect GCs out to a distance of ~ 100 Mpc, placing constraints on this formation channel. In the meantime, Canadian astronomers will soon have their first high-resolution spectrograph with high sensitivity below 500 nm from the Gemini GHOST spectrograph (Pazder et al., 2016); to be commissioned in January 2020. GHOST will be able to observe spectral lines of heavy neutron capture elements (there are only 6 spectral lines of these elements above 500 nm, i.e., the spectral range of the Gemini GRACES fibre). Observations of r-process element abundance spreads in globular clusters may be linked to rare neutron star binary mergers during formation (Roederer, 2011; Roederer & Sneden, 2011).

5 Cluster populations in external galaxies

The systems of star clusters in external galaxies are an imprint of the "fossil record" of the formation and assembly of their hosts. Since star clusters are a ubiquitous byproduct of galaxy formation (i.e., the most massive galaxies contain tens of thousands of clusters and all the but faintest dwarfs contain at least some clusters), they represent a diagnostic tool that can be applied to galaxies spanning wide ranges in mass, type and environment. During the past 15 years, thanks to advances in instrumentation and simulations, astronomers have begun to use star clusters to unravel the complex origins of nearby galaxies (i.e., star formation histories, chemical enrichment histories, merger histories, and mass budgets). On the observational front, arguably the largest gains have come through systematic imaging surveys of nearby galaxy clusters (Côté et al., 2004; Carter et al., 2008; Ferrarese et al., 2012) and targeted studies of individual massive galaxies (e.g. Brodie et al., 2014; Taylor et al., 2016). The former have been especially valuable, generating rich catalogues of up to tens of thousands of GC candidates and we look forward to results from similar campaigns aimed at the Fornax galaxy cluster (Iodice et al., 2016; Eigenthaler et al., 2018).

Despite the challenges involved, some important progress has been made on spectroscopic follow-up of photometric catalogues, albeit for individual galaxies. Because of the relatively large volumes occupied by GC systems, instruments with large fields-of-view and high multiplexing are required (e.g. Keck/DEIMOS, MMT/Hectospec). These programs provide information on the kinematics and stellar populations of GC systems, and allow us to constrain their membership (Forbes et al., 2017), kinemetry (Foster et al., 2016), distributions of metallicity and α-abundances (e.g. Sakari et al., 2015; Usher et al., 2015). One of the more important achievements unlocked by these efforts has been the measurement of dark matter halo masses around both massive and dwarf galaxies (Alabi et al., 2017; Toloba et al., 2016). It is even possible to constrain the anisotropy profile and merger histories of galaxies from extragalactic GC populations (e.g. Agnello et al., 2014; Webb et al., 2016). Owing to their richness and/or volumes, GC systems make for ideal tracers of the velocity fields of galaxies out to large galactocentric distances. Even more dramatic gains are expected for the coming decade, when a new suite of wide-field telescopes will make it possible to apply these techniques to large, statistical samples.

Powerful new imaging facilities will drive this revolution. On the ground, LSST and Subaru Hyper-SuprimeCam will provide deep, wide-field imaging in the green/red optical region while in space, Euclid and WFIRST will provide IR data with high angular resolution. **CASTOR, also operating with high resolution but in the UV and blue-optical wavelengths, would complete the SED coverage over the critical UVOIR region, allowing complete photometric characterization of potentially many tens of thousands of galaxies in the local volume.** The essential elements of these programs would be wide-field coverage, high angular resolution, and high photometric precision, so it is the space-based telescopes (Euclid, WFIRST, CASTOR) that will lead the way here.

Highly multiplexed, multi-object spectroscopy with a dedicated, 10-m class telescope like MSE would make it possible to build large spectroscopic databases of star cluster populations in external galaxies. MSE will be especially powerful because it would operate at both low and medium spectral resolution, making it possible to measure accurate radial velocities for star clusters that could then be used to explore the kinematics of individual galaxies (i.e., rotational support, anisotropy profiles, phase-space substructures) and measure dark matter profiles in even relatively low-mass systems.

In high-resolution mode, MSE would open a new window into the chemical enrichment histories of galaxies via integrated-light, spectral synthesis studies. **Internal velocity dispersions measured with MSE for massive star clusters (and, similarly, for ultra compact dwarf galaxies and nuclear star clusters) — or with a 30-m class telescope for a handful of the most interesting systems — would allow the black hole content of these systems to be explored systematically for the first time**. Complementary radio and X-ray observations (from, e.g., SKA or Athena) would aid in the study of stellar- and possibly intermediate-mass black holes in these environments.

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

The program outlined addresses fundamental open questions about the Universe that can be (at least partly) tackled through studies of massive clusters: (1) Do GCs host IMBHs, and what are the implications for the growth of supermassive black holes? (2) How do GCs and cluster populations form in the early Universe, and what are the implications for cosmic reionization and galaxy assembly? (3) What are the dominant channels for forming GW-emitting sources, and are GCs one of the main sites where these systems are born? (4) What is the connection between cluster formation in the current universe with GC formation in the early universe?

2: Are the associated scientific risks understood and acceptable?

The program is based on the next generation of observatories (TMT, CASTOR, MSE, ngVLA, SKA, and Athena). Canadian participation in these projects is a necessary/acceptable risk. For participation in a 30-m class ground-based telescope, there is a risk that the high-angular resolution MCAO science described in this WP (GC progenitors at high z, IMBHs in GCs, faint companions of accreting BHs) is done first by the E-ELT if the telescope that Canada participates in gets on the sky much later. However, we note that for small-field AO observations, the TMT would still be expected to have greater point-source sensitivity than E-ELT (MAORY MCAO system) at wavelengths shorter than 1.4 μm as it achieves higher Strehl ratios.

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

Scientifically, Canada has a broad expertise and international leadership in all major topics outlined in this program: massive cluster formation, globular cluster dynamics and chemical evolution, observations of compact objects, studies of cluster populations in external galaxies. The program is largely based on projects in which Canada already has significant technical and strategic leadership (TMT, MSE, CASTOR, SKA, ngVLA) or opportunities (Athena), as described in other LRP2020 white papers.

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

Researchers from universities across Canada and at NRC are involved in this research theme. Many of the projects from which this science theme would strongly benefit also have industry partners (MSE, TMT, CASTOR) and broad support from the Canadian community across science topics, as well involvement/support from the Canadian Space Agency (CASTOR, Athena).

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

While tackling several key questions about massive star clusters, the program would position Canada to take advantage of the discovery space opened by extremely high precision astrometry through high angular resolution imaging with MCAO on a 30-m class telescope, as well as wide-field high-resolution multi-object spectroscopy (MSE) and wide-field space-based optical/UV imaging (CASTOR). Many of the facilities of interest to this program (30-m class telescope, CASTOR, SKA, ngVLA, Athena) open opportunities to follow up gravitational wave sources and/or understand their formation in GCs, positioning Canadian astronomy in the rapidly growing field of gravitational-wave astrophysics without direct involvement in a GW detector.

6: Is the cost-benefit ratio, including existing investments and future operating costs, favourable?

It is of course impossible for Canada to play a major role in all the facilities of interest to this program. We note two in particular (MSE and CASTOR), which fill a unique niche in the landscape of proposed facilities for the next decade, have strong Canadian leadership, simultaneously address many of the key questions in this science theme, and thus appear to present a very favourable cost-benefit ratio.

7: Are the main programmatic risks understood and acceptable?

N/A

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?

Interdisciplinary Research: Computationally intensive hydro/dynamical simulations to interpret cluster observations will present opportunities for interdisciplinary collaborations between astronomers and computer scientists.*HQP training:* Canadian involvement in the facilities and science outlined above would provide ample opportunities to develop transferable skills in computer programming and project management for the students and postdocs associated with these projects. *Education and Outreach:* Globular clusters are fascinating to the public and easily accessible. This program aims to solve remaining mysteries about these objects. The formation of black holes and gravitational-wave sources is also a dominant theme in this program, and related discoveries have a huge potential to capture the public's imagination. *Equity, Diversity, and Inclu-*

sivity: The timeliness and international interest in this science theme would allow us to attract students from underrepresented minorities as well as international students through collaborations.

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