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The accreted nuclear clusters of the Milky Way

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ABSTRACT

A number of the massive clusters in the halo, bulge, and disc of the Galaxy are not genuine globular clusters (GCs) but instead are different beasts altogether. They are the remnant nuclear star clusters (NSCs) of ancient galaxies since accreted by the Milky Way. While some clusters are readily identifiable as NSCs and can be readily traced back to their host galaxy (e.g. M54 and the Sagittarius Dwarf galaxy), others have proven more elusive. Here, we combine a number of independent constraints, focusing on their internal abundances and overall kinematics, to find NSCs accreted by the Galaxy and trace them to their accretion event. We find that the true NSCs accreted by the Galaxy are: M54 from the Sagittarius Dwarf, ω Centari from *Gaia*-Enceladus/Sausage, NGC 6273 from Kraken, and (potentially) NGC 6934 from the Helmi Streams. These NSCs are prime candidates for searches of intermediate-mass black holes (BHs) within star clusters, given the common occurrence of galaxies hosting both NSCs and central massive BHs. No NSC appears to be associated with Sequoia or other minor accretion events. Other claimed NSCs are shown not to be such. We also discuss the peculiar case of Terzan 5, which may represent a unique case of a cluster–cluster merger.

Key words: globular clusters: general – galaxies: nuclei – galaxies: star clusters: general.

1 INTRODUCTION

Nuclear star clusters (NSCs) are some of the densest and most massive clusters known and occupy the central parts (i.e. nuclear region) of many galaxies. For galaxies with stellar masses above 10^8 $M_{\odot}$, the majority have readily identifiable nuclear clusters (for a recent review, see Neumayer, Seth & Böker 2020), and for galaxies with masses as low as 10^6 $M_{\odot}$, the occupation fraction of NSCs remains above 10 per cent. NSCs are unique among star clusters as they are the only type (including open clusters, globular clusters (GCs), and young massive clusters) that hosts clear evidence for multiple generations of star formation within them or extended star formation histories (SFHs; see the recent review by Bastian & Lardo 2018). While some NSCs display clear evidence of extended *in situ* star formation (e.g. Seth et al. 2006; Walcher et al. 2006; Feldmeier-Krause et al. 2015), others may be formed by the merging of in-spiralling GCs (e.g. Capuzzo-Dolcetta 1993; Lotz et al. 2001) due to dynamical friction (Tremaine, Ostriker & Spitzer 1975).

The result of these processes, either extended SFHs or the merging of GCs, is that NSCs are expected to host significant spreads in Fe-peak elements and/or extended SFHs. Such spreads are readily observable in resolved colour-magnitude diagrams (CMDs) and/or spectroscopy, as well as with integrated spectroscopy (e.g, Kacharov et al. 2018). Heavy element spreads are rare among Galactic GCs, unlike the light elements (e.g. He, C, N, O, Na) abundance spreads, often referred to as 'multiple populations', which appear to be universally present in old and massive stellar clusters (e.g. Gratton, Carretta & Bragaglia 2012a; Martocchia et al. 2018).

Due to the exquisite measurements provided by the *Gaia* satellite, it has become possible to dynamically trace the origin of the majority of GCs within the Milky Way (MW – Massari, Koppelman & Helmi 2019, hereafter MKH19). Using the integrals of motion, the authors were able to assign GCs to either an *in situ* origin or one of the known galactic accretion events, i.e. *Gaia*–Enceladus/Sausage (G-E/S), the Sagittarius dwarf galaxy, the progenitor of the Helmi streams, and the Sequoia galaxy. Additionally, they found a collection of GCs, which they term the 'Low-energy' group, without (at the time) any known accretion event. This group is likely to be associated with the Kraken merger event, an early and relatively massive accretion event that has been postulated based on the kinematics and age-metallicity distribution of GCs (Kruijssen et al. 2019a, b, 2020; Pfeffer et al. 2020; Forbes 2020).

The inferred stellar masses of these accreted dwarf galaxies ($\sim 10^8$ $M_{\odot}$) imply that many of them would be expected to host an NSC, based on the occupation fraction distribution observed today (Sánchez-Janssen et al. 2019). The goal of the present work is to use the updated sets of constraints available to uncover the NSCs brought in as part of these accretion events and assign them to their host galaxy.

There has been much previous work done to uncover the accreted NSCs within the Milky Way GC population (e.g. see the review by Da Costa 2016). The most clear-cut case in the Galaxy is that of the GC M54, which hosts an extended SFH and large Fe-spread (e.g. Alfaro-Cuello et al. 2019) and is physically associated with the central regions of the Sagittarius dwarf galaxy (Ibata, Gilmore & Irwin 1995). However, as will be explored later in the paper, even in this clear case, there has been some confusion about the actual abundance spread (see Section 2.3.2). The best studied example of

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a GC hosting a large Fe-spread that is likely an accreted NSC is ω Centauri (e.g. Lee et al. 1999; Hilker & Richtler 2000; Bekki & Freeman 2003), although which accretion event it is associated with is still debated.

While finding Galactic GCs with Fe-spreads is a promising and powerful way to identify accreted NSCs within the Galaxy, the picture has been somewhat complicated by the growing number of Galactic GCs with alleged Fe-spreads (see Da Costa 2016). If all of these GCs would be accreted NSCs, then we would be missing a large fraction of galactic accretion events (of massive satellites), which is unlikely given the *Gaia* results to date (e.g. Helmi 2020). However, follow-up studies of a number of clusters with claimed Fe-spreads suggest that some may not be true, as the abundances measured from Fe I and Fe II give conflicting results (e.g. Mucciarelli et al. 2015b). In the present work, we will critically assess the claims of Fe-spreads present in Galactic GCs, and for the likely NSC candidates, we will attempt to associate each one with their host (accreted) satellite galaxy.

This paper is organized as follows: in Section 2, we first discuss constraints obtained through abundance spreads. The kinematical constraints are explored in Section 3. Finally, in Section 4, we combine all of the constraints in order to identify the accreted NSCs within the Milky Way, as well as which accreted satellite they were brought in with.

2 CONSTRAINTS FROM IRON SPREADS

2.1 Background on spectroscopic methods

There are a number of ways that spreads in the [Fe/H] content in stars within a GC can be inferred. There have been several studies that used relatively low-resolution spectra of a number of stars within a GC and looked for variations in the CaT lines, as a proxy for [Fe/H] spreads (e.g. Husser et al. 2020). This can be an efficient way to find such spreads, but a number of caveats exist, so some care must be taken. The most direct way to infer spreads in [Fe/H] is through the analysis of high-resolution spectra (typically done for red giant branch – RGB – stars) to measure [Fe/H] directly. However, even this direct method has some caveats, as in some cases (which will be discussed below), the measurements for Fe I and Fe II disagree.

2.2 Background on photometric methods

Recently, due to the extensive survey of Galactic GCs with the *Hubble Space Telescope* (Piotto et al. 2015), exquisite photometry for thousands of GC members exists from the UV to the optical. Milone et al. (2017) have combined the photometry into pseudo-colours to create the so-called 'chromosome maps'. These maps are extremely efficient in separating out the light element abundance patterns, a.k.a. 'multiple populations', with the P1 (normal, or field-like) stars offset from the P2 populations (those with enhanced N, Na, and Al and depleted O and C).

However, when constructing the chromosome maps, Milone et al. (2017) found that while most clusters were similar, containing versions of the P1 and P2 populations (which they refer to as Type I clusters), a number of clusters (referred to as Type II) showed additional populations. Most of these Type II clusters showed an additional population of stars above and to the right of the nominal P2 stars in the chromosome maps. We will refer to these stars as the P2-anomalous population. Additionally, the true Fe-spread clusters (see below) also contained stars that were offset from the main P1 population (which we will refer to as the P1-anomalous stars).

As every GC studied in the necessary detail to date displays the P1 and P2 populations, a merger of two clusters (one of the pathways to form an NSC, likely to be the dominant process at dwarf galaxy masses – Neumayer et al. 2020) should show a spread in [Fe/H] as well as the two sub-populations P1 and P2. Likewise, if a GC is able to accrete material and form a second generation of stars within it, it would be expected to form a P1 population (and perhaps P2 populations) that is offset in [Fe/H] from the existing P1 and P2 populations. These stars would sit to the right and slightly down in the chromosome map if they are enhanced in [Fe/H] due to their cooler temperatures (e.g. Marino et al. 2019). Hence, we will use the available chromosome maps to look for both the anomalous P1 and P2 in determining if [Fe/H] spreads due to second generations of star formation or GC mergers were at play in the formation of the present-day GC.

The origin of the anomalous P2 populations within the Type II clusters without a corresponding anomalous P1 population is still unknown. The P2 anomalous stars are generally enhanced in the C+N+O sum (where this sum is consistent with being constant in most other clusters/populations) and enriched in s-process elements (see e.g. Bastian & Lardo 2018). In some cases, these P2 anomalous populations have led to the suggestion that spreads in [Fe/H] are present within the cluster, which will be discussed in detail in Section 2.3.

Unless otherwise noted, all of the chromosome maps discussed in this paper are from Milone et al. (2017).

2.3 Individual clusters

2.3.1 *NGC 5139 (ω Cen)*

The best studied GC with a clear [Fe/H] spread is ω Cen, which hosts an $\sim$1.2 dex spread in iron (Norris & Da Costa 1995; Norris, Freeman & Mighell 1996; Suntzeff & Kraft 1996; Johnson & Pilachowski 2010). The dominant population has [Fe/H] ~ -1.8 with subsequent minor peaks at -1.5, -1.1, and -0.8. Spectroscopic evidence for a centrally concentrated population of very metal-poor stars (between [Fe/H] $= -2.30$ and -2.52) was recently reported by Johnson et al. (2020). However, no such population is evident in the study of Husser et al. (2020), despite the larger sample size of their study. If confirmed, this population would be near the observed floor in GC metallicity in the Milky Way and other Local Group galaxies (Beasley et al. 2019; Kruijssen 2019).

The chromosome map of NGC 5139 is one of the most complicated observed to date, clearly reflecting the presence of significant Fe-spreads (Milone et al. 2017).

2.3.2 *NGC 6715 (M54)*

Carretta et al. (2010a) have presented [Fe/H] measurements for a large sample of stars within M54 and report an Fe-spread with a dispersion of $\sigma = 0.19$ dex. However, closer scrutiny reveals that this spread only refers to the oldest populations within the cluster. When the young and intermediate-age populations are also included, an Fe-spread of nearly 1.5 dex becomes apparent (Carretta et al. 2010a, b; Alfaro-Cuello et al. 2019). The associated age spread of the full stellar population of this cluster covers $\sim$10 Gyr from $\sim$2 Gyr ago to $\sim$12 Gyr ago (e.g. Bellazzini et al. 2008; Alfaro-Cuello et al. 2019).

When studying the internal metallicity spread of M54, one needs to account for the contribution of field stars from the Sagittarius dwarf, given the location of the cluster inside the stream of the disrupting galaxy. Indeed, Alfaro-Cuello et al. (2019) found that the intermediate-age population is the least centrally concentrated of the three and hence could be composed of Sagittarius field stars. On the other hand, the young metal-rich populations appear to be the most centrally concentrated and hence clearly associated with M54. This is also supported by the kinematics of the populations (see Alfaro-Cuello et al. 2020).

The chromosome map of NGC 6715 is correspondingly complicated, due to the spread in [Fe/H] as well as in age. Each of the two old stellar populations within the cluster displays the characteristic properties of multiple populations (Carretta et al. 2010b). While the intermediate-age (3–9 Gyr) and young components (∼2 Gyr) do not display strong evidence for MPs (Sills et al. 2019), this may be due to the observed correlation between a populations age and the strength of their MPs (e.g. Martocchia et al. 2018; Saracino et al. 2020) or association with the field star population of Sagittarius (Alfaro-Cuello et al. 2019).

2.3.3 NGC 6273 (M19)

Johnson et al. (2015) showed that NGC 6273 hosts three distinct stellar populations with an extended metallicity distribution. The metal-poor group has $\langle[\mathrm{Fe/H}]\rangle = -1.75$ ($\sigma = 0.04$), whereas the metal-rich component has $\langle[\mathrm{Fe/H}]\rangle = -1.51$ ($\sigma = 0.08$) and enhanced s-process content. They also detected a possible anomalous group with $\langle[\mathrm{Fe/H}]\rangle = -1.30$ (one star) and noticeably lower [X/Fe] ratios for nearly all elements. The two dominant populations are nearly equivalent in number, whereas the anomalous group constitutes only 6 per cent of the whole spectroscopic sample. The authors also note that other clusters (i.e. M2 and NGC 5286) host a minority population of anomalous stars with peculiar abundances that may indicate that these stars were originally part of a different system or accreted from a larger progenitor host.

These results were later confirmed by Yong, Da Costa & Norris (2016), who analysed a large sample of CaT spectroscopy of this cluster and found a range of [Fe/H] values spanning ∼1 dex ($\sigma = 0.17$). This was followed up by Johnson et al. (2017), who used a large sample of high- and medium-resolution spectra of NGC 6273 members, and found a dispersion in [Fe/H] of ∼0.2 dex, with a full range of values from [Fe/H] ∼ −2 to −1 dex.[1] Additionally, they find some evidence for three discrete sub-populations in metallicity space with each sub-populations exhibiting the classic signatures of MPs. They also identified a population of at least five peculiar 'low-α' stars that have [α/Fe] ∼ 0.0 and low [Na/Fe] and [Al/Fe] abundances.

2.3.4 Terzan 5

Ferraro et al. (2009) found evidence, based on a relatively small sample of stars, for a significant age and metallicity spread within Terzan 5. Origlia et al. (2011) provided an analysis of a much larger sample and confirmed that the cluster was made up of two major components, one with [Fe/H] ∼ −0.25 and another with [Fe/H] ∼ +0.27. The lower metallicity group is also significantly enhanced in [α/Fe] in line with expectations of galactic chemical enrichment if there is a significant age difference between the populations. More recently, Massari et al. (2014) confirmed the previously identified peaks in [Fe/H] and also identified a metal-poor component at [Fe/H] ∼ −0.8 dex, which accounts for ∼6 per cent of the stars in the cluster.

Ferraro et al. (2016) found evidence for two discrete main-sequence turn-offs within the cluster, suggesting an ∼8 Gyr delay between the formation of the dominant sub-solar component and the super-solar metallicity component.

Both its large metallicity spread and the absence of a measurable Al-O anticorrelation in each metallicity group have been used as arguments for Terzan 5 not being a 'true' GC (Origlia et al. 2011). However, variations in [Al/Fe] and [O/Fe] are expected to be extremely small in metal-rich GCs (Pancino et al. 2017; Nataf et al. 2019). Also, the five most metal-poor stars presented in Nataf et al. (2019) with metallicities between [Fe/H] = –0.66 and –0.46 show the usual CNO abundance variations, with sodium and potassium variations possibly detected as well. Thus, the light-element abundance variations among Terzan 5 stars are consistent with those seen in normal GCs at the same metallicity (Nataf et al. 2019).

While the evidence for significant age and [Fe/H] spreads is quite clear in Terzan 5, it remains a distinctive case, which we will discuss in more detail in Section 4.2.

2.3.5 NGC 6934

Marino et al. (2018) studied four stars with high-resolution spectra located on the split RGB of NGC 6934. They found intrinsic Fe variations with a difference in iron of the order of ∼0.2 dex. Importantly, the authors did not find evidence of s-process spreads. Given the lack of any star-to-star variations in s-process elements of NGC 6934 stars associated with the inferred changes in metallicity (as in the case for i.e. M 22 and NGC 1851; see below), we conclude that the measured [Fe/H] spread is likely real.

Looking at the chromosome map of this cluster, it does show a small population of stars with enhanced [Fe/H] that contains both the nominal P1 and P2 sub-populations (∼6.7 per cent, Milone et al. 2017). Hence, we conclude that NGC 6934 likely hosts an [Fe/H] spread and may be an NSC.

2.3.6 NGC 2419

NGC 2419 is among the most luminous ($M_\mathrm{V} = -9.5$; Bellazzini et al. 2012) and massive ($M \simeq 10^6$ $\mathrm{M}_\odot$; Ibata et al. 2013) GCs in the halo of the Milky Way. It is located at a galactocentric distance of $d = 87.5$ kpc (di Criscienzo et al. 2011). Its half-light radius is significantly larger than that of other GCs with similar luminosity, more akin to the nuclei of dwarf galaxies than to classical GCs (van den Bergh & Mackey 2004). This has led several authors to suggest that NGC 2419 could be the stripped core of a former dwarf galaxy (e.g. Mackey & van den Bergh 2005).

Cohen et al. (2010) measured [Ca/Fe] abundances for 43 bright giants in NGC 2419 from moderate-resolution spectra around the calcium triplet. They found a significant spread in their inferred [Ca/H] values, with a prominent peak at [Ca/H] ≃ −1.95 and a dispersion of ∼0.2 dex, which was larger than the measurement errors. Cohen, Huang & Kirby (2011) followed up this result with high-resolution spectra of seven luminous RGB stars of NGC 2419,

[1]We note that while Johnson et al. (2015) and Johnson et al. (2017) used the 'spectroscopic' approach to determine the Fe-spread within M 19, which can lead to an artificial broadening of the intrinsic Fe-spread (e.g. Lardo, Mucciarelli & Bastian 2016; Mucciarelli et al. 2016), the large spread found in M19 (∼1 dex) argues that a large and true Fe-spread exists within this cluster. Future work using the 'photometric' method on this cluster will be able to confirm this.

finding that NGC 2419 stars do not display any spread in [Fe/H] or [Ca/Fe] in excess to what is expected from the observational uncertainties. Additionally, they observed a star with a very low [Mg/Fe] ratio but being normal in all other element ratios except for a high [K/Fe]. This chemical anomaly was never reported before for GC stars (Cohen et al. 2011).

The lack of any intrinsic spread in [Fe/H], [Ca/H], and [Ti/H] was further confirmed by Mucciarelli et al. (2012), who also demonstrated that NGC 2419 indeed exhibits a large dispersion in Mg abundances (>1 dex). According to Mucciarelli et al. (2012), such a large spread in Mg abundances is the cause of the dispersion in [Ca/H] observed by Cohen et al. (2010), as the observed severe Mg depletion leads to an increase of the equivalent widths of the Ca triplet lines at a constant Ca abundance. Indeed, the strength of the CaT lines is sensitive not only to the abundances of Ca and Fe but also to the abundance of those elements that affect the H^- continuum opacity (e.g. α-elements) through their contribution to the free electronic density.

A large Mg depletion might in principle cause an apparent range in CaT line strengths that mimics a small abundance spread also in other clusters. However, significant star-to-star variations in Mg abundance have been found to date only in a few cases, mostly metal-poor and massive GCs (see Carretta et al. 2014, for a discussion). Thus, the case of NGC 2419 is clearly unique among stellar clusters in the Milky Way.

2.3.7 NGC 5824

Da Costa, Held & Saviane (2014) carried out a low-resolution (but large sample) study of this cluster, using the CaT as a proxy for [Fe/H]. They suggest that an iron spread likely exists within the cluster. Roederer et al. (2016) performed the first high-resolution study of a large sample of RGB stars in NGC 5824. In particular, they presented a detailed abundance analysis of 17 elements for 26 stars. The authors measured $\langle[\mathrm{Fe/H}]\rangle = -1.94 \pm 0.02$ (statistical) $\pm$ 0.10 (systematic). From their analysis, they were able to exclude the presence of an intrinsic metallicity spread at the 0.08-dex level. Similarly, Mucciarelli et al. (2018) followed up this result with high-resolution spectroscopy and did not find a substantial spread in [Fe/H].[2] NGC 5824 also displays a large range of [Mg/Fe] abundance, observed only in a few metal-poor and/or massive clusters (Mucciarelli et al. 2018). The [Fe/H] abundances (as derived from Ca II lines) are also mildly anticorrelated with [Mg/Fe] in the sense that NGC 5824 stars with low [Mg/Fe] have systematically higher [Fe/H] abundances. This led Mucciarelli et al. (2018) to conclude that such an unusual Mg depletion (down to [Mg/Fe] ~ -0.5) gave rise to a significant increase of the equivalent widths of the Ca II lines and that can be erroneously interpreted as a high Fe abundance. Thus, the metallicities inferred from Ca II lines could be overestimated in Mg-poor stars, as in the case of NGC 2419.

2.3.8 NGC 6656 (M22)

This cluster has been the subject of some debate about whether it hosts [Fe/H]-spreads within it. Hesser, Hartwick & McClure (1977) were the first to note the similarities of M22 and ω Cen. Norris & Freeman (1983) showed that the CH and CN variations in M22 were correlated with Ca II H and K line variations, indicating that both C and N are overabundant in a high fraction of the stars in M22, which also appear to be enriched in Ca (i.e. more metal-rich). Numerous studies of this cluster over the last decades have yielded conflicting results: depending upon the sample and the adopted analysis techniques, some authors measure no significant variations whereas others find significant iron variations up to ∼0.5 dex (e.g. Cohen 1981; Gratton 1982; Lehnert, Bell & Cohen 1991; Brown & Wallerstein 1992). More recently, Da Costa et al. (2009) analysed intermediate-resolution spectra around the Ca II triplet to trace Fe variations and found an iron abundance distribution that is substantially broader than that expected from the observed errors alone, with a peak at [Fe/H] ~ -1.9 and a broad tail to higher abundances. The authors also note that the abundance distribution among M 22 stars bears a qualitative similarity to that for ω Cen, although the ranges of the chemical variations in M22 are considerably smaller.

Based on a sample of high-resolution spectra, Marino et al. (2009) report the presence of two sub-populations, with a difference in their [Fe/H] content of ∼0.14 dex. They also found a significant spread in s-process elements, with stars with higher [Fe/H] values also having large s-process abundances.

Mucciarelli et al. (2015b) argued that the intrinsic iron spread measured from high-resolution spectra by Marino et al. (2009) was due to differences in the measured values of Fe I and Fe II (which should ideally give the same results; see also Ivans et al. 2004). In particular, Mucciarelli et al. (2015b) re-analysed the sample of 17 RGB stars discussed in Marino et al. (2009). In contrast to Marino et al., who derive atmospheric parameters following a standard fully spectroscopic approach, Mucciarelli et al. (2015b) used two different methods to constrain effective temperatures and surface gravities. When atmospheric parameters are derived spectroscopically, they measure a bimodal metallicity distribution that well resembles that by Marino et al. (2009). However, the metallicity distribution from Fe II lines strongly differs from the distribution obtained from Fe I features when photometric gravities are adopted. The Fe I distribution still mimics the [Fe/H] distribution obtained using spectroscopic parameters, whereas the Fe II shows the presence of a single stellar population, which is internally homogeneous in iron. The authors suggest that the difference may be caused by non-local thermodynamical equilibrium (NLTE) effects or over-ionization mechanisms, and such differences have now been found in other clusters. Interestingly, in all such cases, the GCs show spreads in their s-process elements, which is atypical for GCs. Indeed, the analysis presented in Mucciarelli et al. (2015b) confirms the presence of the two s-process element groups found by Marino et al. (2009). The significant range in Ca II triplet line strengths seen among the red giants in M 22 remains to be explained. Indeed, because of the relatively modest Mg variations and the higher overall metallicity of the cluster, it seems unlikely that star-to-star Mg variations are driving the Ca triplet variations observed by Da Costa et al. (2009).

Finally, in contrast to the results of Alves-Brito et al. (2012), who argued for a ∼0.4 dex intrinsic iron spread in this cluster based on high-resolution infrared spectra, Mészáros et al. (2020) did not find any compelling evidence for significant Fe variations in M22 from the spectroscopic analysis of 80 RGB stars from the SDSS-IV APOGEE-2 survey.

The chromosome map clearly shows an anomalous population of stars above the standard P2 population. However, no such stars are seen corresponding to an Fe-enriched P1 population. This is further evidence against actual [Fe/H] spreads within the cluster.

We conclude that M 22 is not likely to host significant spreads in [Fe/H]; hence, it is not a candidate NSC.

[2]In particular, Mucciarelli et al. (2018) measured a mean metallicity of $[\mathrm{Fe/H}] = -2.12 \pm 0.01$ with an intrinsic scatter of 0.00 ± 0.02 from the analysis of the 66 RGB stars in common with Da Costa et al. (2014).

2.3.9 NGC 1851

NGC 1851 is a relatively massive GC characterized by a double sub-giant branch (SGB) in its CMD (Milone et al. 2008). Its shows a range in C+N+O abundance among RGB stars (e.g. Yong, Grundahl & Norris 2015) and star-to-star variations in s-process elements (Yong & Grundahl 2008; Carretta et al. 2011; Lardo et al. 2012; Gratton et al. 2012b). The cluster is surrounded by a symmetric, diffuse stellar halo that extends more than 250 pc in radius, with no evidence of tidal tails (Olszewski et al. 2009; but see Sollima et al. 2012; Carballo-Bello et al. 2018). The presence of this stellar system surrounding NGC 1851 has led some to speculate that the cluster might have been originally formed in a dwarf galaxy, which is now tidally disrupted (Marino et al. 2014; Simpson, Martell & Navin 2017; Kuzma, Da Costa & Mackey 2018).

Carretta et al. (2011) measured the [Fe/H] abundance, along with a number of other elements, in 124 giant stars within this cluster. They report a spread in [Fe/H] of $\sigma = 0.07$ dex, which is larger than their nominal uncertainties in the measurements of individual stars (∼0.03 dex). The authors find a larger abundance spread if they analyse Fe and Ba together, as the nominally Fe-rich populations are also rich in Ba. One potential problem with this analysis is that Ba is an s-process element, and clusters that show s-process element abundance variations have been associated with spurious claims of Fe-spreads (see also Husser et al. 2020). Villanova, Geisler & Piotto (2010) presented a chemical abundance analysis of a sample of 15 RGB stars in this cluster. They found that the Ba distribution is bimodal, whereas the iron abundance for the two Ba groups is the same within the errors. Given the small (and still disputed) [Fe/H] spread and the associated s-process variations, we do not consider NGC 1851 to be a strong candidate accreted NSC.

2.3.10 NGC 7089 (M2)

A case that is similar to M22 and NGC 1851 is that of M2. Yong et al. (2014) analysed CaT and high-resolution spectroscopy of a large sample of RGB stars within M2 and inferred a significant spread in [Fe/H] with three peaks; a large peak at [Fe/H] = −1.7 and two smaller metallicity components at [Fe/H] = −1.5 and −1.0.

Lardo et al. (2016) followed up these results and found a similar behaviour as was found in M22 for the two main peaks (Mucciarelli et al. 2015b). Specifically, they found that the two peaks at [Fe/H] = −1.7 and −1.5 merged into a single peak when using photometric gravities and treating Fe I and Fe II separately. However, the small sub-population at [Fe/H] = −1.0 remained. This population makes up ∼1 per cent of the stellar population in the cluster. The presence of the sparse, metal-rich component, which shows neither evidence for sub-populations nor an internal spread in light-elements, is confirmed by the study of Milone et al. (2015).

Due to the extremely low fraction of [Fe/H] enhanced stars, we do not consider M2 to be a strong candidate to be an NSC and instead suggest that these stars may constitute a rare accretion event from one GC to another (e.g. Khoperskov et al. 2018) or the accretion of a small cluster on M2.

However, the origin of this cluster (and its large Fe-spread within a small minority of cluster members) is still uncertain as the likelihood of each investigated formation channel is low.

2.3.11 NGC 362

NGC 362 was observed at high resolution by Carretta et al. (2013). They collected spectra for 92 RGB stars in this cluster and found no evidence for an internal metallicity dispersion (see also Mészáros et al. 2020). Moreover, Carretta et al. (2013) discovered the presence of an additional, poorly populated (e.g. accounting for only ∼6 per cent of the total cluster population), red RGB sequence, which appears to be enriched in s-process elements, similar to that observed in M 22, NGC 1851, and in the bulk of giant stars in M2. More recently, Husser et al. (2020) measured a small metallicity variation of ∼0.12 dex among NGC 362 stars. This result is based on low-resolution spectra centred around the Ca triplet feature. Even if the observed dispersion in metallicity is statistically significant, the latter result is based on the analysis of 22 stars in the s-process rich population (i.e. the population of anomalous P2 stars present above the nominal P2 population in the chromosome map). For comparison, the authors observed 797 stars along the main RGB body.

Overall, the observational evidence would support the notion that NGC 362 is not characterized by an intrinsic iron spread and that the slightly higher [Fe/H] abundance observed in the s-process rich group of stars is likely to be introduced artificially by how atmospheric parameters and metallicities are derived in the spectroscopic analysis (e.g. Mucciarelli et al. 2015b; Lardo et al. 2016).

2.3.12 NGC 5286

Marino et al. (2015) report an [Fe/H] spread in this cluster, with two peaks separated by 0.2 dex, along with significant variations in s-process elements. This is very similar to what was found for M2 and the two main populations of M22. The analysed sample includes stars observed at different resolution with UVES and GIRAFFE. Unfortunately, Fe abundances from neutral and ionized Fe are available only for the UVES spectra, which offers both higher resolution and larger spectral coverage. Similarly, to the case of M 22, when spectroscopic gravities are used for the analysis of UVES spectra, the distributions of [Fe I/H] and [Fe II/H] are very similar and broad, pointing to an intrinsic iron scatter. On the other hand, the metallicity distribution derived from Fe II lines and photometric gravities is narrow and points out a lack of iron spread (Mucciarelli et al. 2016).

Like was the case for M2, the chromosome map of NGC 5286 shows the anomalous population above and to the right of the nominal P2 sub-population, typical of the ‘Type II’ clusters (Milone et al. 2017). However, in this cluster, we do not see the corresponding anomalous P1 stars that would be expected if the [Fe/H] spread was real.

Hence, we conclude that NGC 5286 is unlikely to host a significant [Fe/H] spread within it.

2.3.13 NGC 6864 (M75)

Kacharov, Koch & McWilliam (2013) used high-resolution spectroscopy of 16 giant stars within NGC 6864 to derive detailed abundances. They report a small [Fe/H] spread ($\sigma = 0.07$ dex). Like the clusters discussed above with small [Fe/H] spreads (NGC 1851; M2), this cluster appears to also have spreads in s-process elements (e.g. Ba). Like with M2, M22, and NGC 5286, we do not consider NGC 6864 to be a strong NSC candidate.

2.3.14 NGC 3201

Simmerer et al. (2013) report a spread of [Fe/H] = 0.4 dex from minimum to maximum. Using the measurements presented in their paper, we find a dispersion in [Fe/H] of 0.10 dex, which is only marginally larger than their average error on an individual measurement (0.09 dex). Mucciarelli et al. (2015a) re-analysed their spectra to show that the metal-poor component claimed by Simmerer et al. (2013) is composed by asymptotic giant branch stars that could be affected by NLTE-effects driven by iron overionization. Such NLTE effects have an impact on the iron abundances measured from Fe I lines (by 0.1–0.2 dex) but leave the abundances from Fe II lines unchanged. Thus, Mucciarelli et al. (2015a) conclude that the observed iron spread is not intrinsic but rather due to the inclusion of AGB stars in the sample (see also Ivans et al. 2001; Lapenna et al. 2014, 2016). Hence, we conclude that this GC does not host large [Fe/H] spreads.

2.3.15 NGC 6229

Johnson et al. (2017) report a small spread in [Fe/H] ($\sigma = 0.06$ dex) in the massive outer halo cluster NGC 6229. The authors note that such a spread is only marginally significant with respect to the uncertainties. They compare the [Fe/H] distribution to NGC 1851 and find them to be similar. However, as discussed above, NGC 1851 likely does not host a significant spread in [Fe/H]. The authors find that, like NGC 1851, NGC 6229 also shows s-process variations. Hence, it is likely to be a Type II cluster, although a chromosome map does not currently exist for this cluster.

We conclude that, like NGC 1851, NGC 6229 is unlikely to be an accreted NSC.

2.3.16 NGC 6388

We found an additional cluster in the Milone et al. (2017) catalogue that based on its chromosome map may be an additional candidate NSC. This is NGC 6388, a Type II cluster with a number of stars that may represent an anomalous P1 population. However, we note that this bulge cluster displays significant differential extinction. The apparent anomalous P1 population overlaps with the nominal P1 population and is extended along the reddening vector.

Carretta et al. (2007) presented a detailed chemical analysis of this peculiar bulge cluster based on the analysis of high-resolution spectra of seven RGB stars. They found an average value [Fe/H] = $-0.44 \pm 0.01 \pm 0.03$ dex with no evidence of intrinsic spread in metallicity. The absence of any star-to-star Fe variations was also confirmed in subsequent studies from the same authors based on larger sample of giant stars observed at high resolution (see Carretta & Bragaglia 2019, and references therein). Through low-resolution spectra, Husser et al. (2020) recently analysed a sample of RGB stars, claiming for the presence of a metallicity spread of $\sim$0.22 dex in the cluster. This finding is based on stars lying on top of the C+N+O and likely s-process rich population in the chromosome map, and, as stated by the authors, it may be affected by problems with the underlying photometry.[3]

Hence, until further confirmation, we conclude that this is likely a Type II cluster without an Fe-spread.

3 KINEMATICAL CONSTRAINTS

Based on the above literature review, we find that there are six clear cases of large [Fe/H] spreads within the MW GC population. They are (in order of mass, Baumgardt & Hilker 2018): ω Cen, M54, NGC 6273, Terzan 5, NGC 7089, and NGC 6934. In this section, we will use kinematical information to associate these NSC candidates with MW accretion events.

3.1 Individual clusters

3.1.1 NGC 5139 (ω Cen)

ω Cen has been recently suggested to be the former NSC of either G-E/S or Sequoia. Myeong et al. (2019) suggest that it is associated with the Sequoia accretion event based on the actions, inclination, and eccentricity of its orbit, while MKH19 suggest that it is associated with G-E/S based on the binding energy of its orbit within the MW. Similarly, Forbes (2020) assigned ω Cen and NGC 1851 as the NSCs of Sequoia and G-E/S, respectively.

Though there is significant overlap with the G-E/S debris, Sequoia field stars have typical energies $E \approx -1$ to -1.3×10^5 km^2 s^{-2} (Myeong et al. 2019) and an NSC of Sequoia would be expected to initially have a similar orbital energy, as galaxy accretion events deposit their GCs over a limited range in energies (Pfeffer et al. 2020). Thus, dynamical friction would need to act to reduce ω Cen to its present orbit with $E \approx -1.85 \times 10^5$ km^2 s^{-2}, or its apocentre would need to be reduced from an initial $\sim$30 kpc to its current value of 7 kpc. In contrast, dynamical friction could act on the host galaxy to deliver ω Cen to near its present apocentre (Bekki & Freeman 2003); however, the stellar debris from the merged galaxy would then be found at similar (small) apocentres.

Following Lacey & Cole (1993, their appendix B), we calculate the dynamical friction time-scale for the potential of an isothermal sphere, assuming a circular velocity of $V_c \approx 230$ km s^{-1} for the Milky Way[4] (Bland-Hawthorn & Gerhard 2016) and adopting an orbit circularity of 0.5, similar to ω Cen. For its present-day mass of 3.5×10^6 M$_\odot$ (Baumgardt & Hilker 2018), it would take >300 Gyr to reduce the apocentre of ω Cen from 30 to 7 kpc. For this to occur within a Hubble time, ω Cen would need a mass $\approx$50 times its present mass (i.e. a mass similar to that suggested for its host galaxy) without suffering mass loss through tidal effects. Similarly, starting at 20 kpc rather than 30 kpc still implies a time-scale $\approx$130 Gyr for the present-day mass of ω Cen. This simple analysis is in good agreement with the simulations from Bekki & Freeman (2003), who found that a nucleated dwarf galaxy infalling from 26 kpc on to a Milky Way-like galaxy can, through a combination of dynamical friction and tidal stripping of the host galaxy, result in a stripped nuclear cluster with an orbit similar to ω Cen.

The analysis also suggests that ω Cen was deposited by the merger of its host galaxy at an apocentre no further than $\approx$9–11 kpc (for a mass 1–3 times its present mass). This is consistent with the energy 'floor' found for G-E/S debris at $E \approx -1.8 \times 10^5$ km^2 s^{-2} (Horta et al. 2020b), very similar to the orbital energy of ω Cen of $E \approx -1.85 \times 10^5$ km^2 s^{-2} (assuming the potential from McMillan 2017), suggestive of a causal connection. The remaining uncertainty is why the orbit of ω Cen is less eccentric ($e \approx 0.68$, Baumgardt et al.

[3]Being located in the Bulge of the Galaxy, the photometry for this cluster is very problematic. This directly affects the extraction process of the spectra from the MUSE data cubes and therefore the quality of the spectra. As a consequence, large uncertainties are associated to the measured metallicities.

[4]Any reasonable value for the circular velocity does not affect these results since the dynamical friction time-scale approximately scales with V_c. Thus, the results are similar when adopting smaller circular velocities for the Milky Way at $z > 0$.

2019a) than the bulk of G-E/S stars ($e \approx 0.85$ Mackereth et al. 2019). However, we note that eccentricity may change during the course of a merger, such that merger debris at smaller apocentres becomes more/less eccentric than that at higher apocentres (e.g. fig. 4 in Pfeffer et al. 2020).

Other tentative evidence comes from the NSC-to-galaxy mass ratios of nearby galaxies. A mass of $M_{\rm NSC} = 3.5 \times 10^6$ M$_\odot$ suggests a host galaxy stellar mass of $\approx 10^9$ M$_\odot$ (Sánchez-Janssen et al. 2019, though with large scatter, and assuming that the NSC-to-galaxy mass relation holds at $z > 0$). Thus, the more massive of the two suggested that progenitors (G-E/S: Myeong et al. 2019; Matsuno, Aoki & Suda 2019; Kruijssen et al. 2020; Forbes 2020) appear the most likely candidate.

Therefore, we assign ω Cen to be the NSC of G-E/S.

3.1.2 M54

Numerous works have provided kinematic and spatial evidence linking M54 with the Sagittarius Dwarf galaxy, including Ibata, Gilmore & Irwin (1994), Sarajedini & Layden (1995), and most recently MKH19. M54 lies in the densest region of Sagittarius and has a distance and radial velocity consistent with the dwarf (Da Costa & Armandroff 1995; Ibata et al. 1995, 1997; Sarajedini & Layden 1995; Layden & Sarajedini 2000).

3.1.3 Terzan 5

Massari et al. (2015) were the first to measure a proper motion for Terzan 5, which they combined with the existing radial velocity measurements. Integrating the resulting orbit of the cluster led the authors to conclude that there was no evidence for an *ex situ* origin. This was later confirmed by MKH19, who found that Terzan 5 was kinematically associated with 'main-bulge' component of the galaxy. Hence, despite its characteristics of an age and metallicity spread, this appears to be an *in situ* cluster. We will discuss it in more detail in Section 4.2.

3.1.4 NGC 6273 (M19)

MKH19 unambiguously assign NGC 6273 to the 'low-energy' group of GCs. This group has subsequently been associated with the Kraken merger event (Kruijssen et al. 2019b, 2020; Pfeffer et al. 2020; Forbes 2020). Recently, Horta et al. (2020a) have reported the discovery of the stellar component of Kraken, based on a combination of abundances and kinematics, lending further support to the existence of this relatively massive accreted galaxy.

As there are no other NSC candidates for this group, we assign NGC 6273 to be the NSC for Kraken.

3.1.5 NGC 7089 (M2)

While the reported spread in [Fe/H] at low metallicity within NGC 7089 appears to be related to an enhanced C+N+O population within the clusters (i.e. not a true [Fe/H] spread), their existence of a small population of significantly enhanced [Fe/H] is present within the cluster.

MKH19 assign NGC 7089 to G-E/S based on its orbital properties. As we have argued, ω Cen is likely to be the NSC of this accreted galaxy; hence, it is unlikely that NGC 7089 is an NSC (see also the discussion in Section 3.2).

3.1.6 NGC 6934

Though it appears to have been accreted, MKH19 do not associate NGC 6934 with a progenitor galaxy (allocating it to the 'high-energy' group of presumably unrelated GCs). Its age and metallicity (11.5–12 Gyr, [Fe/H] = −1.55, Dotter et al. 2010; VandenBerg et al. 2013) place it within the 'accreted branch' of GCs, where a number of galaxy accretion events overlap in their age-metallicity relations (Massari et al. 2019; Kruijssen et al. 2020). NGC 6934 has an angular momentum (L_z) and energy close to that of GCs associated with the Helmi et al. (1999, hereafter H99) streams (MKH19). However, its very high eccentricity ($e \approx 0.9$ Baumgardt et al. 2019a) more closely matches GCs associated with G-E/S. If NGC 6934 was the NSC of the H99 streams progenitor, the question would remain of how it retained a higher energy than other H99 stream GCs (which would be unexpected for an NSC). Alternatively, NGC 6934 could be another case of GC mass transfer (like we propose for M2, Section 2.3.10) within its progenitor galaxy.

3.2 Other clusters

As discussed in Section 2, there have been claims in the literature that other clusters may also be accreted NSCs. After reviewing the evidence for each of these cases, we determined that most were not likely to be NSCs. Here, we look at the kinematic constraints from this group of clusters.

Below we list these clusters as well as the kinematic group they are associated with, taken from MKH19.

(i) NGC 1851 – G-E/S
(ii) NGC 2419 – Sagittarius Dwarf
(iii) NGC 5824 – Sagittarius Dwarf
(iv) NGC 6656 (M22) – Main-Disc (non-accreted)
(v) NGC 5286 – G-E/S
(vi) NGC 6864 – G-E/S
(vii) NGC 3201 – Sequoia or G-E/S (ambiguous)
(viii) NGC 6229 – G-E/S
(ix) NGC 6388 – Main-Bulge (non-accreted)

As noted by Milone et al. (2020), many of these clusters (mainly Type II) are associated with G-E/S. However, we do not expect G-E/S (or any other accreted system) to contribute more than one NSC to the Galaxy. Pfeffer et al. (2014) found that the number of accreted NSCs a galaxy is expected to host correlates with the galaxy's halo mass. G-E/S had an approximate stellar mass of $\approx 10^{8.5}$ M$_\odot$ (Kruijssen et al. 2020; Mackereth & Bovy 2020), which corresponds to a halo mass of $\approx 10^{11}$ M$_\odot$ (Moster, Naab & White 2018; Behroozi et al. 2019). We therefore expect G-E/S to contribute (on average) an additional ≈ 0.15 accreted NSCs with masses $> 10^5$ M$_\odot$ (equation 1, Pfeffer et al. 2014); i.e. dwarf galaxies will typically contribute only their own central NSC. This is consistent with the expectation that mergers are largely irrelevant for the formation and evolution of dwarf galaxies (e.g. Fitts et al. 2018; Davison et al. 2020; Martin et al. 2020). Therefore, under this interpretation, the other GCs associated with G-E/S are not likely to be NSCs.

Additionally, NGC 5824 and NGC 2419 belong unambiguously to the Sagittarius Dwarf, for which an NSC has already been identified (M54). Hence, we can rule these clusters out as NSC candidates, following the same reasoning above.

According to MKH19, M22 and NGC 6388 are kinematically associated with the Main-Disc and Main-Bulge, respectively, which would rule them out as accreted NSCs if they do not have an extragalactic origin. In the case of NGC 6388, some claims have been made in favour of an extragalactic nature (Horta et al. 2020b). However, as NGC 6388 has a metallicity [Fe/H] ≈ −0.5 (Carretta et al. 2007) and follows the *in situ* branch of the age-metallicity relation (Marín-Franch et al. 2009), as well as shows element abundances (e.g. Al, Carretta et al. 2007) higher than those typical of accreted objects (Das, Hawkins & Jofré 2020), we consider the *in situ* classification made by MKH19 as the most likely. M22 is a borderline case. It has a prograde orbit consistent with the disc (MKH19) but is on a moderately eccentric orbit ($e \approx 0.5$, Baumgardt et al. 2019a). It is also old and metal-poor ([Fe/H] = −1.5, age 12.7 Gyr, Forbes & Bridges 2010) and thus in a region of age-metallicity space where the *in situ* and accreted branches intersect. Therefore, it could either have been accreted or an *in situ* GC, which had its orbit disturbed by galaxy mergers (e.g. Pfeffer et al. 2020). Given the lack of corresponding merger debris or other clearly accreted GCs on similar orbits to M22 (e.g. MKH19), we currently favour the latter scenario (i.e. an *in situ* origin).

4 ANALYSIS – PULLING THE CONSTRAINTS TOGETHER

4.1 Accreted nuclear star clusters and their progenitor galaxies

By combining independent constraints obtained through stellar abundances and cluster kinematics, we have found three clear cases of NSCs within the Milky Way GC population that we have been able to associate with known satellite accretion events. The NSCs are NGC 5139 (ω Cen), NGC 6273 (M19), and NGC 6715 (M54), which were brought in by G-E/S, Kraken, and the Sagittarius Dwarf galaxy, respectively.

We found that the MW GC NGC 6934 displays some evidence for being an NSC, although further study is required to confirm its nature. This cluster is potentially kinematically associated with the H99 streams. Hence, it is possible that progenitor galaxy of these streams may have brought in NGC 6934 as an NSC.

We do not find any NSC candidate to be associated with the Sequoia accretion event. The Sequoia, G-E/S, Sagittarius Dwarf, and the H99 streams have estimated stellar masses (at the time of accretion) of ∼1–3 × 10^8 $M_\odot$ (e.g. Kruijssen et al. 2020). Neumayer et al. (2020) have compiled a list of NSCs in the local Universe, along with the properties of their host galaxies. They found that at these host galaxy stellar masses, 75–80 per cent of galaxies host NSCs (though this may be a lower limit, given the observational challenges in identifying NSCs). If we assume little evolution in the statistics (as the Neumayer et al. 2020 sample is collected at $z = 0$ while many of the MW satellites were accreted at $z > 1$), we would therefore expect ∼1 of the MW-accreted satellites not to host an NSC. Hence, it may not be surprising that the Sequoia did not host an NSC. The number of NSCs accreted by the MW is also consistent with the numbers expected from the assembly of MW-mass haloes (Pfeffer et al. 2014; Kruijssen et al. 2019b).

These results are summarized in Table 1.

4.2 The case of Terzan 5

As discussed above, Terzan 5 hosts a complex stellar population with (at least) two sub-populations separated by ∼0.5 dex. Additionally, Ferraro et al. (2016) find that these two populations are separated in age, with the dominant (60 per cent, sub-solar metallicity) one having an age of 12.5 Gyr and the minority component (40 per cent, super-solar metallicity) having an age of 4.5 Gyr.

Table 1. The candidate nuclear clusters and their most likely host galaxy.

Accretion event	NSC
Kraken	NGC 6273 (M19)
Gaia-Enceladus/Sausage	NGC 5139 (ω Cen)
Sequoia	none
Sagittarius	NGC 6715 (M54)
H99 streams(?)	NGC 6934

However, the kinematics of the cluster show that it is a member of the Bulge (MKH19) with an apocentre ≈2.8 kpc (Baumgardt et al. 2019a) and hence does not have an extragalactic origin.

We note that the age-metallicity relation of the main components of Terzan 5 follows the trend expected for Galactic enrichment (e.g. Snaith et al. 2015; Kruijssen et al. 2019b). This age-metallicity relation is also evidence against a galaxy accretion/NSC origin, since it would require a host galaxy of similar mass to the MW (the MW's nuclear cluster is similarly metal rich, Feldmeier-Krause et al. 2017) and a major merger <4.5 Gyr ago (i.e. more recent than the age of the youngest population) for which there is no evidence in the MW (e.g. Wyse 2001; Hammer et al. 2007; Stewart et al. 2008).

Origlia et al. (2013) found evidence for a small sub-population within the cluster with [Fe/H] = −0.79, which is also α-enhanced. Due to their small contribution to the total cluster mass, these stars may simply be accreted stars from the surrounding.

McKenzie & Bekki (2018) suggest that Terzan 5 may be the result of a bulge GC interacting with a GMC, accreting that gas and forming a second-generation *in situ*. This is possible, although if GC–GMC interactions were common, as suggested by the authors, then it is difficult to understand why more GCs in the Galactic central regions do not show such age/metallicity spreads.

Mergers of GCs appear to be rare in major galaxies, given the high relative velocities of the individual clusters. However, Terzan 5 has a disc-like prograde orbit (Massari et al. 2015; Baumgardt et al. 2019a), and merger rates are likely to be enhanced inside discs. In their simulation of a GC population inside a Milky Way-like galaxy, Khoperskov et al. (2018) observed two major mergers of GCs inside the Galactic disc within 1.5 Gyr. Hence, it is conceivable that Terzan 5 represents a rare case of a cluster–cluster merger. Detailed studies of the internal structure and stellar kinematics of Terzan 5 may reveal further clues on the origin of this peculiar cluster. Gavagnin, Mapelli & Lake (2016) predict that in the case of a merger, the structure of the final cluster will depend sensitively on the properties of the merging entities.

We note that a number of young massive clusters appear to have formed at the end of the Milky Way's stellar bar where it intersects with the Scutum–Crux Arm (e.g. Davies et al. 2007; Alexander et al. 2009; see also fig. 3 in Portegies Zwart, McMillan & Gieles 2010). This is consistent with the high molecular gas densities and star formation rates often observed at the ends of bars in other nearby galaxies (e.g. Downes et al. 1996; Sheth et al. 2000, 2002). These clusters in the Milky Way have galactocentric distances of ∼3–5 kpc, close to the apocentre distance of Terzan 5 (Baumgardt et al. 2019a). Thus, if Terzan 5 happened to merge with a GMC or young massive cluster, which formed at the end of the stellar bar around 4 Gyr ago (or less), this would explain why it is such an outlier in the Galactic GC population.

We conclude that the origin of the complex stellar populations within Terzan 5 is still unknown, although it appears that we can confidently rule out the possibility of it being an NSC.

4.3 Intermediate-mass black holes

It is a long-standing question if intermediate-mass black holes (IMBHs, with masses $\sim 10^3 - 10^5$ $M_\odot$) reside in some GCs (see the recent review by Greene, Strader & Ho 2019). In light of the ubiquity of supermassive black holes (SMHs) in the centres of massive galaxies and the well-established scaling relations between SMBH masses and galaxy properties (e.g. McConnell & Ma 2013), the former NSCs of accreted galaxies appear as prime candidates to search for IMBHs. Further credibility for such a scenario comes from galaxies hosting both NSCs and SMBHs (see the review by Neumayer et al. 2020, and references therein) and the observation of SMBHs in massive ultra-compact dwarf galaxies (UCDs) observed around other galaxies (Seth et al. 2014; Ahn et al. 2017; Afanasiev et al. 2018), which are believed to be the remnants of accreted satellites (Bekki et al. 2003; Drinkwater et al. 2003; Pfeffer et al. 2016). However, evidence is still lacking for massive black holes in low-mass UCDs, which could be considered as extragalactic counterparts to ω Cen or M54 (Voggel et al. 2018). Confirming or refuting the presence of IMBHs in the former NSCs of the Galaxy is therefore crucial in order to understand if a lower mass limit for the formation of massive black holes in galactic nuclei exists.

For both, M54 and ω Cen, the presence of an IMBH has been suggested based on kinematic measurements (e.g. Noyola, Gebhardt & Bergmann 2008; Ibata et al. 2009). However, in particular, the case of ω Cen is still heavily debated (see Baumgardt et al. 2019b, and references therein). In both cases, further kinematic studies based on high-resolution data, such as *HST* astrometry or adaptive-optics assisted integral-field spectroscopy, will be required to answer the question if any of the clusters harbours an IMBH.

Alternatively, deep radio or X-ray observations can be used to search for signs of accretion of the intra-cluster medium on to an IMBH. To date, no such signals have been detected within the Galaxy (e.g. Haggard et al. 2013; Tremou et al. 2018), suggesting that IMBHs with masses $\gtrsim 1\,000$ $M_\odot$ are rare in GCs.

Our study suggests NGC 6273 and NGC 6934 as additional possible IMBH hosts. The central kinematics of both cluster have not been studied with high-resolution data so far. Another way of constraining the presence of massive black holes is by searching for signatures of gas accretion in deep radio data. While no IMBH was detected in NGC 6273 in previous radio surveys of Galactic GCs (e.g. Tremou et al. 2018), NGC 6934 has not been studied in this way so far. Hence it appears as a promising future target in the hunt for IMBHs.

Besides M54 and ω Cen, a number of Galactic GCs that we did not identify as likely former NSCs were suggested to host IMBHs (see compilations by Baumgardt 2017; Greene et al. 2019). However, all reported detections were not confirmed in follow-up studies and are therefore still controversial. We note that the detection of an IMBH in a GC does not necessarily imply that the cluster formed as an NSC, given that some of the mechanisms proposed to form massive black holes do not require the cluster to sit in the centre of a galaxy (e.g. Gieles et al. 2018).

5 SUMMARY

The goal of this study has been to find the NSCs that have been accreted by the Milky Way and associate them with their progenitor galaxy. We began with a sample of 15 GCs that have been claimed in the past as possible accreted NSCs. We have applied two independent constraints to assess the possibility of each cluster being an NSC, namely the internal abundance spreads (specifically [Fe/H]) and the orbital properties of the cluster.

From an analysis of the abundance spreads, we found six GCs with clear evidence of an internal [Fe/H] spread. They are ω Cen, M54, NGC 6273, Terzan 5, NGC 7089, and NGC 6934. Given the lack of detailed spectroscopic studies for many Milky Way GCs (particularly those nearest the Galactic centre), it is possible that more candidates will be discovered in the future. While NSCs are all expected to host Fe-spreads within their stellar population, a handful of known MW GCs, that are not strong NSC candidates, also host such spreads. The origin of these Fe-spreads is currently unknown and is a rich avenue for future studies.

By looking at the orbital properties (and their origin, either *in situ* or *ex situ*), we found four NSC candidates that can be associated with a galactic accretion event and hence are likely to be genuine NSCs. These are listed in Table 1. Of the five identified main accretion events (G-E/S, Sequoia, Kraken, Helmi-streams, and Sagittarius dwarf galaxy), we find an associated NSC for all except the Sequoia event (and possibly also the Helmi-streams). In the inferred mass range of the accreted satellites ($\sim 10^8$ $M_\odot$), NSCs are found in ~ 80 per cent of galaxies in the local Universe, in good agreement with the statistics implied by our results. These four former/current NSCs (ω Cen, M54, NGC 6273, and NGC 6934) are the best candidates for searches of IMBHs within star clusters of the MW.

We found that there were two GCs that host significant internal iron spreads that are unlikely to be accreted NSCs, namely Terzan 5 and NGC 7089 (M2). The origin of these iron spreads is currently unknown. Perhaps these clusters represent rare events of cluster–cluster mergers, collisions with molecular clouds, or the accretion of stars from one cluster to another due to a close passage.

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DATA AVAILABILITY

No new data were generated or analysed in support of this research.

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