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Observational signatures of massive black hole progenitor pathways: could Leo I be a smoking gun?

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ABSTRACT

Observational evidence is mounting regarding the population demographics of massive black holes (MBHs), from the most massive cluster galaxies down to the dwarf galaxy regime. However, the progenitor pathways from which these central MBHs formed remain unclear. Here, we report a potentially powerful observational signature of MBH formation in dwarf galaxies. We argue that a continuum in the mass spectrum of MBHs in (fossil) dwarf galaxies would be a unique signature of a heavy seed formation pathway. The continuum in this case would consist of the usual population of stellar mass black holes, formed through stellar evolution, plus a smaller population of heavy seed MBHs that have not yet sunk to the centre of the galaxy. Under the robust assumption of initial fragmentation of the parent gas cloud resulting in a burst of heavy seed production, a significant fraction of these seeds will survive to the present day as off-nuclear MBHs with masses less than that of the central object. Motivated by the recent discovery of an MBH in the relatively low central density Leo I galaxy, we show that such a continuum in MBH seed masses should persist from the lightest black hole masses up to the mass of the central MBH in contrast to the light seeding scenario where no such continuum should exist. The detection of off-centred MBHs and a central MBH would represent strong evidence of a heavy seeding pathway.

Key words: black hole physics – galaxies: individual: Leo I – galaxies: star formation – early Universe.

1 INTRODUCTION

Dwarf galaxies are typically defined as having stellar masses below 3×10^9 M$_\odot$. In a cosmological context, they have become increasingly important in recent years as they resemble the earliest galaxies formed at high redshift, and some may be the fossil remnants of these very early galaxies (e.g. Bovill & Ricotti 2011; Frebel, Simon & Kirby 2014; Collins et al. 2022). Additionally, whether or not these small galaxies host central massive black holes (MBHs) has been a topic of focused investigation over the last decade or so. Initial research into using (fossil) dwarf galaxies to understand the formation mechanisms of MBHs at high redshift was pioneered by Volonteri, Lodato & Natarajan (2008) and van Wassenhove et al. (2010) with a significant observational focus now taking place on determining the occupation fraction of MBHs in dwarf galaxies in the present-day Universe (e.g. Baldassare et al. 2020).

Detecting and determining the occupation fraction of MBHs in dwarf galaxies remains a significant challenge, with the occupation fraction and the active fraction currently unknown and debated (Pacucci, Mezcua & Regan 2021). Most searches of dwarf galaxies thus far have focused on using optical narrow emission line diagnostic diagrams to identify active galactic nucleus (AGN) emission and broad emission lines to estimate the MBH mass (Greene & Ho 2004, 2007; Reines, Greene & Geha 2013; Moran et al. 2014; Chilingarian et al. 2018). Additional searches in the X-ray have also revealed numerous candidate AGNs in dwarf galaxies out to much higher redshift (Pardo et al. 2016; Mezcua et al. 2018; Mezcua, Suh & Civano 2019; Mezcua & Domínguez Sánchez 2020). However, these and similar techniques are subject to high systematic uncertainties, and a cleaner method for determining the existence and mass of MBHs in dwarf galaxies comes from the kinematics of stars. Unmediated by gas dynamics, stellar velocity measurements can give an unbiased probe of the gravitational potential in the central parsecs of the host galaxy. Resolving the gravitational effect of an MBH requires kinematic measurements within its sphere of influence (Peebles 1972), which has been limited to relatively nearby galaxies. The pioneering work of Kormendy & Richstone (1995) has been extended to additional, nearby galaxies by, for example, McConnell et al. (2012) and Liepold et al. (2020).

The kinematic method does not measure the MBH mass directly but rather the total gravitational potential of the host and any MBH within the host galaxy (den Brok et al. 2014; Thater et al. 2017; Nguyen et al. 2018, 2019). Hence, kinematics at several radii, a luminosity profile, and dynamical modelling are necessary to separate the mass components of the galaxy (e.g. van der Marel

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et al. 1998; Gebhardt et al. 2000, 2003; Cappellari et al. 2002; Rusli et al. 2013). One of the few systematic uncertainties of the method is in the dynamical modelling procedure – the most computationally expedient methods (e.g. Jeans analysis) assume a known form for the velocity anisotropy and dark matter profile. In principle, these restrictions are avoidable with non-parametric modelling, albeit at a much higher computational cost. Using this methodology, Bustamante-Rosell et al. (2021) recently determined that the Leo I dwarf galaxy contains an MBH with a mass ($M_{\rm MBH}$) of $(3.3 \pm 2) \times 10^6$ M$_\odot$.

In this paper, we use the Leo I result together with analytical arguments and findings from high-z simulations to argue that dwarf spheroidal galaxies, as well as similar low-density dwarf galaxies, potentially host a previously unexplored signature of MBH seeding pathways.

Light seeds [those emerging from the remnants of the very first stars (Madau & Rees 2001)] could be the progenitors for MBHs – in order to do so, they would have to grow extremely efficiently – something that so far appears challenging to achieve in practice (e.g. Smith et al. 2018). *Heavy* seeds, on the other hand, are thought to be born with masses, possibly via an intermediate stage as a supermassive star (Woods et al. 2017), in the range $M_{\rm seed} \simeq 10^3$–10^5 M$_\odot$ in high-z galaxies that resemble today's dwarfs.

For the purposes of this paper, we use the term heavy seed for all masses greater than 10^3 M$_\odot$. We are cognizant that this is in tension with some nomenclature that would instead refer to black holes with masses of approximately 10^3 M$_\odot$ as 'medium'-weight seeds and only those greater than approximately 10^4 as heavy seeds. The mass of the medium-weight seeds is a robust prediction of dynamical models of MBH formation (e.g. Miller & Davies 2012; Katz, Sijacki & Haehnelt 2015; Stone, Küpper & Ostriker 2017; Schleicher et al. 2022) that either through runaway stellar collisions or through the repeated mergers of lighter black holes produce black holes with masses of approximately 10^3 M$_\odot$. However, more recently this distinction (in resulting black hole masses) is becoming blurred with simulations by both Chon & Omukai (2020) and Regan et al. (2020) predicting initial black hole masses in the range of 10^3–10^4 M$_\odot$ due to certain environmental dependences, which previously were thought to produce heavy seeds. Perhaps the more fundamental difference between the scenarios is that in the model scenarios of Chon & Omukai (2020) and Regan et al. (2020) a significant number (and spectrum) of black hole masses are predicted due to fragmentation of the parent gas cloud. In contrast, the dynamical pathways predict a single MBH with a mass of approximately 10^3 M$_\odot$. Therefore, the signature we postulate here should be a unique signature of a scenario in which multiple heavy seeds are formed from fragmentation.

In summary, our proposition here is that heavy seeds born at high redshift, through either rapid halo assembly or similar processes, are typically formed in multiples, due to modest fragmentation of the parent gas cloud. In fossil dwarf galaxies that do not have overly dense central structures [i.e. they are below the density typical of nuclear star clusters (NSCs)], a significant number of these initial fragments will survive and constitute a robust observational signature of the initial seeding pathway.

In Section 2, we discuss the characteristics of the Leo I galaxy and its MBH. In Section 3, we outline models for MBH growth through both the light and heavy seed channels, showing how the different pathways may be distinguished given sufficiently sensitive observations of MBH demographics in fossil dwarf galaxies. In Section 4, we discuss the broader implications of our postulates and give our conclusions.

2 THE MASSIVE BLACK HOLE IN THE DWARF GALAXY LEO I

The recent detection of an MBH at the centre of the dwarf spheroidal galaxy Leo I by Bustamante-Rosell et al. (2021) represents one of the most remarkable MBH discoveries to date. Its mass was estimated at $M_{\rm MBH} = (3.3 \pm 2) \times 10^6$ M$_\odot$, lifting it significantly above the standard $M_{\rm MBH}$–σ relation (Kormendy & Ho 2013; Baldassare et al. 2020; Greene, Strader & Ho 2020) for both very massive and dwarf galaxies alike.

Prior studies of Leo I used individual stellar kinematics and stellar counts to probe the gravitational potential of the dwarf spheroidal (Koch et al. 2007; Sohn et al. 2007; Mateo, Olszewski & Walker 2008). Bustamante-Rosell et al. (2021) showed that when concentrated in the central parsecs of the galaxy, individual stellar kinematics suffered from crowding, which biased this method towards inferring lower velocity dispersions, which in turn led to inferring lower enclosed masses. New integrated light kinematics, unaffected by this bias, confirmed these results, showing a steady rise in the velocity dispersion from 360 parsecs into the centre. Accounting for crowding in prior data sets gave velocity dispersions that matched the integrated light measurements.

An almost unambiguous signature of a black hole is a Keplerian potential dominating over the potential of the galaxy. Different assumptions for the shape of the dark matter halo and radius of tidal disruption for the galaxy were tested through orbit-based dynamical modelling, but all models consistently excluded the no black hole hypothesis at over 95 per cent significance.

Leo I represents an ideal environment in which to test our model. It is a dwarf spheroidal galaxy with a low gas content and a core stellar density at least two orders of magnitude less dense than that of a typical globular cluster. Ruiz-Lara et al. (2020) find that the core of Leo I has a central density of the order of 0.7 stars pc^{-3}, between 2 and 3 orders of magnitude less dense than the centres of typical globular clusters (Gratton et al. 2019). In terms of definitions, the core of Leo I can be (marginally) described as an NSC (see for example, fig. 2 from Stone et al. (2017). However, its central mass densities put Leo I at the very lowest end of the NSC spectrum and several orders of magnitude below that required for an NSC that can dynamically generate an MBH (e.g. Miller & Davies 2012; Stone et al. 2017).

3 MODEL

Our model for determining the progenitor seeds of MBHs explores the seeding and growth of light and heavy seeds.

3.1 Light seed growth and dynamics

Both semi-analytical models and numerical simulations attempting to model the growth over cosmic time of PopIII remnant black holes ($M_{\rm BH} \lesssim 10^3$ M$_\odot$) have consistently shown that these light seeds do not grow (Johnson & Bromm 2007; Volonteri et al. 2008; Alvarez, Wise & Abel 2009; Pacucci, Natarajan & Ferrara 2017; Smith et al. 2018). Light seed growth has been shown to be possible within more idealized settings – particularly where it is able to accrete within the confines of a dense stellar cluster at high redshift (Miller & Davies 2012). Pioneering work by Portegies Zwart et al. (2004) demonstrated that stellar collisions in dense clusters can produce massive stars that in turn collapse into MBHs – or perhaps also populating the pair instability mass gap with black holes (González et al. 2021). In a similar way, Miller & Davies (2012), Stone et al.

(2017), and Fragione et al. (2022) have identified NSCs with velocity dispersions of greater than 40 km s^{-1} as ideal sites in which to grow black holes (via tidal captures and tidal disruptions) past an initial bottleneck and up to a point where gas accretion can take over.

Others have investigated the growth of light seeds, predominantly via gas accretion within dense environments (e.g. Alexander & Natarajan 2014; Lupi et al. 2016; Natarajan 2021; Fragione et al. 2022) as a possible pathway to growing initially 'light' black holes.

However, of particular relevance to this paper, such a dense environment is not necessarily present in all dwarf galaxies and certainly not in the dwarf galaxy Leo I – the case study used in this paper.

None the less, we cannot exclude the possibility of light seed rapid growth (through accretion) even in the environs of dwarf spheroidal galaxies like Leo I. We quantify the probability of a PopIII remnant black hole growing through accretion in the core of a galaxy as follows. We first assume that the mass of the PopIII remnant is 500 $M_\odot$ (which is in itself an optimistic assumption), giving a Bondi–Hoyle radius (from which a cross-section can be calculated) ($R_{\rm Bondi}$) of $\sim 10^{-2}$ pc. First, the probability that a black hole finds itself in a sufficiently dense volume relative to the volume of the galactic core is

$$P_{\rm BH\_in\_cloud} = (R_{\rm cloud}/R_{\rm galcore})^3 , \quad (1)$$

where $R_{\rm cloud}$ is the radius of the gas cloud and $R_{\rm galcore}$ is the radius of the core of galaxy. We set $R_{\rm cloud} = 0.1$ pc and $R_{\rm galcore} = 20$ pc. We then multiply this number by the number of clouds expected in this region. For this purpose, we assume that 1×10^{-4} (1 per cent by volume) of $R_{\rm galcore}$ is filled with sufficiently dense gas giving $N_{\rm clouds} \sim 800$. The values used here are based on the properties of the gas-rich star-forming galaxy found in Regan et al. (2020).

Finally, we compute, assuming that the black hole walks a random trajectory around that galaxy, that the fraction of the volume sampled by the black hole, $V_{\rm sampled}$, in a Hubble time, $\tau_{\rm Hubble}$, is given by

$$V_{\rm sampled} = \frac{\tau_{\rm Hubble} R^2_{\rm Bondi} v_{\rm BH}}{2R^3_{\rm galcore}} , \quad (2)$$

where $v_{\rm BH}$ is the average relative velocity of the black hole (set here to be equal to the sound speed of the gas, $\sim$10 km s^{-1}). The total probability of a single PopIII remnant accreting within a high-z galaxy (for which these numbers are derived) is then given by

$$P_{\rm growth} = P_{\rm BH\_in\_cloud} \times N_{\rm clouds} \times V_{\rm sampled} . \quad (3)$$

Using the canonical set of values noted above, which are consistent with gas-rich early galaxies, equation (3) gives a probability that a stellar mass black hole intersects a single dense gas cloud within a Hubble time as $P_{\rm growth} \sim 9 \times 10^{-8}$.

Given this estimate, the probability of two (or more) black holes within the same environment experiencing growth becomes infinitesimally small. This is just the probability of a single black hole encountering such a sufficiently dense environment once – when in reality a black hole must encounter such an environment on multiple (perhaps hundreds of) occasions.

In short, unless light seeds find themselves within a very dense environment in which growth becomes much more likely via dynamical processes, light seeds are extremely unlikely to grow.

3.2 Heavy seed growth and dynamics

Our assumptions on the mass of heavy seeds are given by state-of-the-art cosmological simulations undertaken by numerous groups. The general agreement is that MBH seeds within the range $M_{\rm seed} = 10^3$–10^5 $M_\odot$ are possible (Hosokawa et al. 2013; Latif et al. 2013; Inayoshi & Haiman 2014; Inayoshi, Omukai & Tasker 2014; Regan, Johansson & Haehnelt 2014; Latif, Schleicher & Hartwig 2016; Regan & Downes 2018a, b). In idealized settings, a single object (with masses up to 10^5 $M_\odot$) can be formed (Inayoshi et al. 2014), but for models in which more cosmologically consistent treatments are performed the formation and retention of multiple fragments are either moderate (e.g. Regan & Downes 2018a, b; Latif et al. 2022) or more widespread (Wise et al. 2019; Regan et al. 2020). While some of these fragments may eventually merge or be ejected from the halo, it is also likely that many will survive as isolated MBHs or in stable binaries.

Current models for heavy seed formation suggest that several heavy seeds could form at the same time. Here, we show that if this is the case, then it is unlikely that all of them will merge with the central MBH. Hence, we propose that a signature of heavy seed formation in quiescent (i.e. those who have had no major mergers) dwarf galaxies is the detection of off-centred, wandering MBHs (see Fig. 1) with masses in the range of $M_{\rm MBH} = 10^3$–10^5. These MBH 'leftovers' are the observational signature of a heavy black hole formation pathway in fossil dwarf galaxies. This signature does not apply to more massive galaxies in which MBHs can be incorporated through subsequent mergers over cosmic time, nor does it (likely) apply to dwarf galaxies with high central densities typical of NSCs (Stone et al. 2017). Although dynamical pathways (which straddle the definition of light and heavy seeds) may not create the continuum of MBHs, we outline next, with instead a single MBH predicted to form within a dense system (e.g. González et al. 2021). Instead, the signature of an initial burst of heavy seeds will be a radial continuum of black hole masses as we now outline.

We now explore through a simple analytical model how the impact of dynamical friction can lead to a fraction of the initial heavy seed population surviving within the fossil dwarf galaxy. Our goal is to demonstrate the existence of an MBH mass spectrum within a heavy seed environment. We do not attempt a detailed exploration of the dynamics of MBH evolution as this is outside the scope of this paper (but see McCaffrey et al., in preparation).

To illustrate the existence of an MBH mass spectrum, we first calculate the dynamical friction (Chandrasekhar 1943) time-scale of a sample of heavy seed masses born at different radii from the galactic centre. Using the formalism from Bar, Danieli & Blum (2022) (which was originally applied to globular cluster sinking time-scales in dwarf galaxies), we estimate the time for an MBH to sink to the centre of a dwarf galaxy as

$$\tau_{\rm DF} = \frac{v^3_{\rm MBH}}{4\pi G^2 \rho M_{\rm MBH} C} \quad (4)$$

$$\approx 2\left(\frac{v_{\rm MBH}}{10\ {\rm km\ s^{-1}}}\right)\left(\frac{3\times10^6\ {\rm M_\odot\ kpc^{-3}}}{\rho}\right)\left(\frac{3\times10^5\ {\rm M_\odot}}{M_{\rm MBH}}\right)\frac{2}{C}\ {\rm Gyr} , \quad (5)$$

where ρ is the background density of the medium inducing the dynamical friction, $M_{\rm MBH}$ is the mass of the MBH, $v_{\rm MBH}$ is the relative velocity of the MBH, and C is a dimensionless factor accounting for the velocity dispersion of the medium and the Coulomb logarithm (Hui et al. 2017).

Using this value for the dynamical friction time, $\tau_{\rm DF}$, the radius, R, to which the MBH sinks after a time t (assuming a core halo profile), can be estimated from Bar et al. (2021) using

$$R = r_0 \exp\left(-\frac{t}{2\tau_{\rm DF}}\right) , \quad (6)$$

where we set $r_0 = 200$ pc (as an approximate virial radius for a canonical dwarf galaxy) and $t = \tau_{\rm Hubble}$. Finally, using the value of

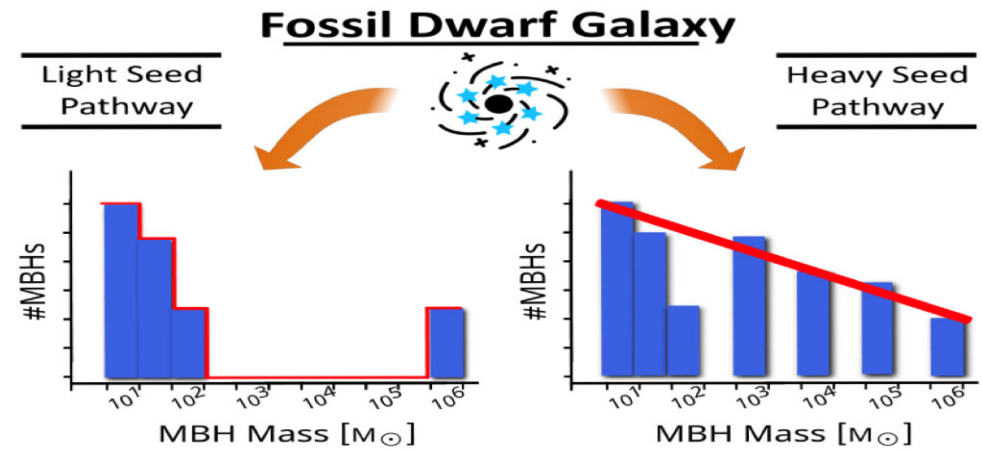

Figure 1. The spectrum of black hole masses inside a fossil dwarf galaxy. For the light seed pathway (left-hand side), only one (central) MBH is expected with a large mass gap between the mass of the central MBH and that of the stellar remnant black holes that will populate the galaxy. For the heavy seed channel on the other hand (right-hand side), an MBH continuum is expected as the gas initially fragments during the initial seeding process, leaving behind a number of heavy seed fragments. Some fragments will merge with the central objects – other fragments will remain in the core of the galaxy as passive MBHs. The detection of a continuum in black hole masses – particularly masses in the range of 10^3–10^5 M$_\odot$ – would represent very strong evidence of heavy seeding channel.

the new radius, R, we can now estimate the MBH merger rate, Γ, as (Bar et al. 2022)

$$\Gamma(R) \simeq \kappa_{\rm MBH}\, \sigma_{\rm MBH}\, v_{\rm MBH}\,, \tag{7}$$

where $\kappa_{\rm MBH}$ is the number density of initial heavy seeds calculated at the new radius R, $\sigma_{\rm MBH}$ is the cross-section for becoming gravitationally bound[1] ($\sigma_{\rm MBH} = \pi R^2_{\rm Bondi}$), and $v_{\rm MBH}$ is the relative velocity of the MBH (which we set equal to the sound speed). To calculate $\kappa_{\rm MBH}$, we divide the number of initial heavy seeds, $N_{\rm I}$, by the volume (i.e. $4/3\,\pi R^3$). We set $N_{\rm I} = 20$ based on the results of Regan et al. (2020). We are interested in the survivor fraction, ϵ, not in the number of mergers, $N_{\rm MBH} = \Gamma({\rm R}) \times N_{\rm I} \times \tau_{\rm Hubble}$. Specifically, ϵ, defined between 0 and 1, is the fraction of MBHs that survive and do not merge with another MBH and instead orbit the galactic centre at some radius R. ϵ is given by

$$\epsilon = 1 - \frac{N_{\rm MBH}}{N_{\rm I}}. \tag{8}$$

To illustrate this model, we run Monte Carlo simulations of the above scenario and plot the results in Fig. 2.

For our Monte Carlo model, we sample from a normal distribution of heavy seed masses with a mean of 1.5×10^4 M$_\odot$ and a standard deviation of 0.45. The distribution of heavy seeds is unknown (assuming they exist in the first place) and this distribution is chosen based on Regan et al. (2020). Our results are not sensitive to the details of the distribution but do rely on initial fragmentation and the production of multiple heavy seeds within the parent gas cloud. We modify the background density parameter, ρ, to illustrate how the survivor fraction, ϵ, can vary as a function of MBH mass and background density. An accurate calculation of the sinking time-scale is non-trivial and depends on detailed knowledge of the dwarf galaxy environment, including the cusp/core density profile and the time evolution of the galaxy (e.g. Sánchez-Salcedo, Reyes-Iturbide & Hernandez 2006; Weinberg et al. 2015; Shao et al. 2021; Sánchez-Salcedo & Lora 2022). As a result, we parametrize these unknown variables by varying the background density. The stellar density in LeoI is approximately 10^7 M$_\odot$ kpc^{-3} with other dwarf galaxies in the local group having values varying around this figure by several dex (McConnachie 2012). High-z dwarf galaxies tend to be more gas rich and can have densities at the higher end of our parametrization but their centres are also highly dynamic and simulations have consistently shown that MBHs struggle to sink towards the galactic 'centre' (e.g. Pfister et al. 2017; Lescaudron et al. 2022).

Fig. 2 shows the impact of different background densities on the survival fraction of MBHs. For background densities of $\rho \gtrsim 10^8$ M$_\odot$ kpc^{-3} (green line, similar to the density inside globular clusters), the survivor fraction drops rapidly above the heavy seed threshold ($M_{\rm MBH} \gtrsim 10^3$ M$_\odot$); i.e. most heavy seeds merge through mass seg-

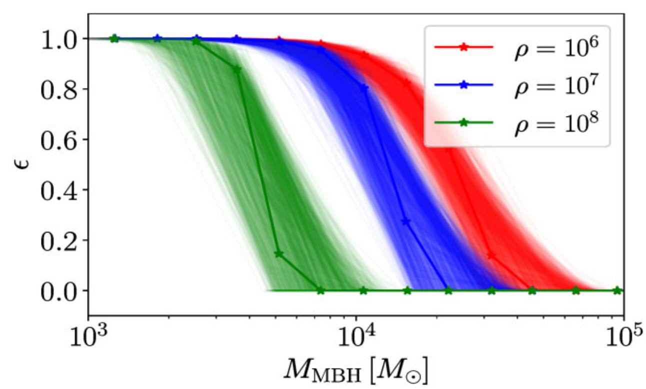

Figure 2. The survivor fraction, ϵ, as a function of the black hole mass, $M_{\rm MBH}$. The background density is varied from $\rho = 10^6$ M$_\odot$ kpc^{-3} up to $\rho = 10^8$ M$_\odot$ kpc^{-3} (we skip the units in the legend). Above $\rho = 10^8$ M$_\odot$ kpc^{-3}, the density starts to become close to that found in globular clusters and hence much denser than a typical dwarf spheroidal galaxy like Leo I. For the lower average density range (i.e. $\rho \sim 10^6$ M$_\odot$ kpc^{-3}), the survival rate of MBHs with $M_{\rm MBH} \lesssim 10^5$ M$_\odot$ is non-zero. As the background density increases, the dynamical friction force becomes stronger, gradually pulling all masses towards the centre.

[1]We note here that the approximation of being gravitationally bound does not imply that the black holes will necessarily merge (Begelman, Blandford & Rees 1980; Lodato et al. 2009) but is none the less a conservative approximation.

regation. However, for values of the background density parameter closer to that expected in typical dwarf spheroidal galaxies, the survivor fraction remains high ($\epsilon \gtrsim 0.5$) up to relatively high MBH masses ($M_{\rm MBH} > 10^4$ M$_\odot$). For background density parameters of $\rho \sim 10^6$ M$_\odot$ kpc^{-3} (red line, similar to the typical background density found outside the core of Leo I), the survivor fraction is non-zero out to $M_{\rm MBH} \gtrsim 6 \times 10^4$ M$_\odot$. Our model cannot account for the growth experienced by black holes over time and hence we are therefore assuming that these seeds do not grow. This is likely to be a very good assumption for all black holes with masses $M_{\rm MBH} \lesssim 10^5$ M$_\odot$ as numerical simulations with realistic seeding prescription show that black holes below this mass scale show little or no growth (e.g. Di Matteo et al. 2022). Above this mass scale, black holes may sink and grow more efficiently.

This admittedly simplified calculation shows that for density parametrizations typical of dwarf spheroidal galaxies, there is a large window in the heavy seed mass spectrum (10^3 M$_\odot \lesssim M_{\rm MBH} \lesssim 10^5$ M$_\odot$) for which the survivor fraction is non-zero. The most massive heavy seeds can readily sink to the centre – the estimated dynamical mass of the MBH at the centre of Leo I is $M_{\rm MBH} \sim 3 \times 10^6$ M$_\odot$ (see Section 2). Left behind on off-nuclear orbits are heavy seeds likely formed during the same formation epoch as the most massive seed but which have not yet sunk to the centre, due to their lower masses. In contrast to the wandering MBH paradigm typically discussed in the literature (e.g. Tremmel et al. 2018; Mezcua & Domínguez Sánchez 2020; Reines et al. 2020; Bellovary et al. 2021; Greene et al. 2021; Weller et al. 2022), these MBHs form *in situ* (i.e. not acquired via mergers) and slowly sink towards the centre of the galaxy. Their intrinsically different masses result in a diversity of time-scales to sink and merge; hence, their very existence results in a unique signature of their formation pathway. Additionally, we may in practice be somewhat conservative in our analysis here since we are assuming pure 'Chandrasekhar'-style dynamical friction. However, it is well known that the inspiral time may in fact be much longer (Goerdt et al. 2006; Read et al. 2006). In that case, our results will be a lower limit and the true survival fraction, ϵ, is likely to be higher. As a final note on the distribution of these survivors, it may be, depending on the composition of the core, that the mass distribution becomes inverted to what might be naively expected. Kaur & Sridhar (2018) have shown that core stalling can lead to positive mass dependence of radial sinking versus mass such that $R_{\rm s} \sim M_{\rm MBH}^{1/5}$, where $R_{\rm S}$ is the filtering radius. In this case, the more massive black holes may reside further from the centre (Kaur & Stone 2022).

4 DISCUSSION, CONCLUSIONS, AND FUTURE OBSERVATIONAL MARKERS

The discovery (Bustamante-Rosell et al. 2021) of an MBH at the centre of the dwarf spheroidal galaxy Leo I is remarkable in many ways. Leo I has an estimated virial mass ($M_{\rm vir}$) of $(7 \pm 1) \times 10^8$ M$_\odot$ (McConnachie 2012) and a stellar mass (M_*) of 5.5×10^6 M$_\odot$ (Mateo et al. 2008). With $M_{\rm MBH} = (3.3 \pm 2) \times 10^6$ M$_\odot$, this black hole is significantly overmassive, by a factor of $\sim 10^3$, compared to the virial mass of the halo. What are the consequences for the formation pathways of the central MBH?

Numerous authors have argued that satellite galaxies irradiated by a nearby massive galaxy will host overmassive MBHs (Agarwal et al. 2013; Natarajan et al. 2017; Scoggins, Haiman & Wise 2022) formed via the heavy seed paradigm in which supermassive stars are one potential intermediate stage. For the case of Leo I, the heavy seed formation pathway may have been induced via an intense burst of Lyman–Werner radiation, the rapid assembly of the original Leo I galaxy component, baryonic streaming velocities, or a combination of one or more of these mechanisms. In either case, the result is broadly similar: a small number of MBHs are expected to form in the centre of the embryonic dwarf galaxy, Leo I in this case, with some surviving to the present epoch.

Dwarf galaxies are potential sites to search for the fossils of the very early stages of MBH formation (Volonteri et al. 2008; van Wassenhove et al. 2010). Here, we extend that idea by also suggesting that a specific observational signature of heavy seed MBH formation would be the existence of a continuum in mass of MBHs, from stellar mass to the mass of the central MBH, the continuum being made up of the population of stellar mass black holes formed from the end point of stellar evolution plus an additional, smaller, component made up from an initial burst of heavy seed formation. Fig. 1 illustrates this paradigm and its outcome. If the seed for the central MBH was a light seed, then no such continuum should exist, and there should be a clear gap in the black hole mass spectrum in fossil dwarf galaxies between the mass of the most massive black hole in the galaxy and the population of stellar mass black holes. In this case, a single light seed grows spectacularly through accretion but the process is sufficiently rare that only a single object emerges from the population of light seeds.

While the black holes carry no information of their accretion or merger history that is easily disentangled (Pacucci & Loeb 2020), there may be clues from the black hole demographics inside fossil dwarf galaxies like Leo I. Fragmentation, even in the heavy seed formation channel, is a robust prediction. As we demonstrate in Section 3, at least some of the original MBHs will survive as isolated or binary MBHs. It is these leftover MBHs, with masses lower than that of the central MBH, that we highlight as observational signatures of a heavy seed formation scenario.

It is essential to note that the absence of a continuum of black hole masses does not by itself falsify the heavy seed scenario, as mergers, ejections, or very low levels of fragmentation could equally be responsible. Instead, detecting a black hole mass spectrum would be strong evidence for a heavy seed formation channel.

A final unknown remains: what are the signatures of off-nuclear MBH in dwarf galaxies, and – most importantly – are they detectable at all? Electromagnetic emission from accretion on to MBHs in relic dwarfs such as Leo I is expected to be faint, because of the lack of gas. MBHs wandering outside the central regions of galaxies are now routinely discovered, also in dwarf galaxies (see e.g. Greene et al. 2020, 2021; Reines et al. 2020), with simulations showing that the presence of off-centred MBHs should be the norm in dwarfs (due to the long inspiral times; Bellovary et al. 2021). Recently, Seepaul, Pacucci & Narayan (2022) showed that wandering MBHs in the Milky Way galaxy, or in close-by galaxies such as Leo I, should be detectable in a wide range of frequencies, pending the presence of a minimum density of gas to trigger advection-dominated accretion flows (Pacucci & Loeb 2022). Alternatively, the merger of MBHs could be studied by third-generation gravitational wave observatories, such as the Einstein Telescope (Maggiore et al. 2020) and the Cosmic Explorer (Reitze et al. 2019), with the added advantage of a wide redshift range, crucial in building up the statistics necessary to probe demographics. In fact, Valiante et al. (2021) and Chen, Ricarte & Pacucci (2022) recently investigated the merger of MBHs in the mass range of our interest.

We encourage further in-depth observations and modelling of the dynamics inside Leo I and similar dwarf galaxies as an ideal environment in which to probe MBH seeding channels.

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DATA AVAILABILITY

Data generated in this research will be shared on reasonable request to the corresponding author.

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