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LOW-MASS BLACK HOLES AS THE REMNANTS OF PRIMORDIAL BLACK HOLE FORMATION

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1. ABSTRACT

This article documents our ongoing search for the elusive "intermediate-mass" black holes. These would bridge the gap between the approximately ten solar mass ($M_\odot$) "stellar-mass" black holes (the end-product of the life of a massive star) and the "supermassive" black holes with masses of millions to billions of solar masses found at the centers of massive galaxies. The discovery of black holes with intermediate mass is the key to understanding whether supermassive black holes can grow from stellar-mass black holes, or whether a more exotic process accelerated their growth only hundreds of millions of years after the Big Bang. Here we focus on searches for black holes with $M_{\rm BH} \sim 10^4 - 10^6$ solar masses that are found at galaxy centers. We will refer to black holes in this mass range as "low-mass" black holes, since they are at the low-mass end of supermassive black holes. We review the searches for low-mass black holes to date and show tentative evidence, from the number of low-mass black holes that are discovered today in small galaxies, that the progenitors of supermassive black holes were formed as ten thousand to one-hundred thousand solar mass black holes via the direct collapse of gas.

2. THE BLACK HOLE MASS SCALE

Over the last decade we have come to understand that supermassive black holes, with masses of millions to billions of times the mass of the Sun, are very common in the centers of massive galaxies (Richstone et al. 1998). Black holes are found in the centers of most massive galaxies at the present time. We would like to understand when and how they formed and grew.

We cannot yet watch the first supermassive black holes form. They did so soon after the Big Bang, and light from those distant events is beyond the reach of today's telescopes. However, we do have two very interesting limits on the formation of the first black holes. The first comes from observations of the most distant known black holes: light is emitted by material falling into the deep gravitational potential of the black hole. These monsters are so bright that they must be powered by at least billion solar mass black holes. They had very little time to grow, as we see them only a few hundred million years after the Big Bang (Fan et al. 2001). Whatever process formed and grew the first massive black holes, it had to be very efficient.

At the other extreme, we can study the lowest-mass black holes in galaxy nuclei nearby to us, the left-over seeds that for some reason never grew to be a billion suns. As we describe below, conditions were best to make supermassive black hole seeds soon after the Big Bang. Therefore, black holes found in small galaxies today likely formed early and have not grown significantly since. If we assume that black holes form in a similar way in all galaxies, then the numbers and masses of black holes in small galaxies today contains clues about the formation of the first black holes (e.g., van Wassenhove et al. 2010). The sheer number of left-overs will indicate how commonly black hole seeds were formed, as well as inform future gravitational wave experiments that expect to see a large number of paired low-mass black holes as they spiral together and coalesce (Hughes 2002). Studying the energy output from low-mass black holes could tell us whether growing black holes at early times were important in shaping early star formation in the galaxies around them (e.g., Jeon et al. 2012).

Unfortunately, low-mass black holes are difficult to find. Because of their low mass, they only have gravitational influence over stars in a very small volume at the galaxy center. Therefore, we are often forced to wait until material falls into the black hole. We detect the black hole indirectly via the radiation energy that is released as matter falls in.

Here we document the last decade of searching for the elusive low-mass black hole population.

3. FORMATION PATHS FOR THE FIRST MASSIVE BLACK HOLES

To understand the growth of the first supermassive black holes, we first must determine how the black holes form to begin with. Theoretically, there are two possible answers. Either black holes are created as the end-product of stellar evolution, a process that continues to produce stellar-mass black holes today, or the black hole is made directly from the collapse of a gas cloud, which requires the high gas fractions and low metallicities of the early universe. Once the black hole is formed, it also must grow. There are likely many growth paths, but a rapid mechanism is required to explain the $\sim 10^9\ M_\odot$ black holes that are observed only hundreds of millions of years after the Big Bang (e.g., Fan et al. 2001). We first discuss the two formation routes, and then the possible growth mechanisms. Volonteri (2010) presents a very cogent and recent review of the leading theories for the formation of the first massive black holes. I will only briefly review the subject for completeness, with an emphasis on the observable consequences at the present day.

Stellar-mass black holes form when massive stars run out of fuel at the end of their life. The first black holes may have formed in the same way. The first stars were likely very massive (e.g., Bromm & Yoshida 2011). In order for stars to form, gas clouds need to contract; they are able to cool and shrink by emitting light predominantly in specific element transitions. Because there were no elements heavier than He and Li in primordial gas, it was hard for clouds to cool efficiently. As a result, proto-stars grew much larger before their gravitational attraction was strong enough to counteract the internal energy in the gas. In theory, the end-product of these massive first stars will depend on the mass. Stars with masses less than $\sim 100\ M_\odot$ or more than $\sim 260\ M_\odot$ will make a black hole with a mass approaching that of the star (e.g., Heger et al. 2003). For masses in between, it is thought that pair-instability supernova, in which pair production in the star center leads to a run-away stellar collapse, will leave no remnant (e.g., Barkat et al. 1967). Of course, the details of

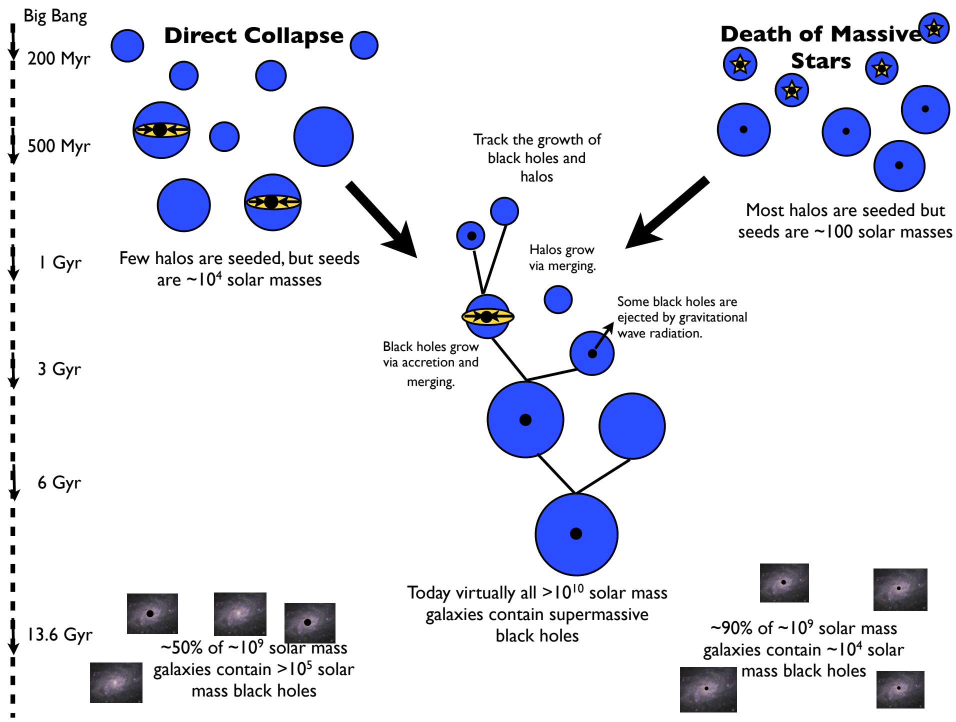


FIG. 1.— Schematic of the evolution of seed black holes assuming two different formation mechanisms (the death of the first generation of massive stars vs. the direct collapse of gas into a black hole). Dark matter halos and the galaxies in them grow through merging. Black holes grow both via merging and by accreting gas. One additional complication is that after merging, gravitational radiation "recoil" (see §3.1) may send the black hole out of the galaxy. At present, we can distinguish between the two scenarios based on the fraction of small galaxies that contain massive black holes (we call this the "occupation fraction").

early stellar evolution are very difficult to test observationally. There are many uncertain details, such as whether the first stars formed in pairs, and how much mass they lose at late stages of evolution. We will assume the first stars left behind standard $\sim 100\, M_{\odot}$ remnants.

Alternatively, conditions in the early universe may have allowed gas clouds to collapse *directly* into black holes (e.g., Haehnelt & Rees 1993). Direct collapse requires very low angular momentum gas that only existed in large quantities soon after the Big Bang. In this scenario, only a very small fraction of halos will manage to form a black hole, and only for a short period of time soon after the Big Bang.

With these two formation paths in mind, the next question is whether the black holes created via either path can grow into the very luminous sources that are observed hundreds of millions of years after the Big Bang. With direct collapse models, even in the halos with low angular momentum content and low molecular hydrogen fraction (and thus inefficient cooling) the gas will likely settle into a disk, and require some sort of instability to condense further (Lodato & Natarajan 2006). Once sufficiently condensed, the central $10^4 - 10^5\, M_{\odot}$ of material may very efficiently gain mass as a dense and round "quasi-star", (e.g., Begelman et al. 2006).

It is marginally possible for a stellar-mass seed to grow into a billion solar mass black hole in hundreds of millions of years, but only if the black hole manages to grow continuously at the maximal allowed rate. Above the so-called "Eddington" limit, radiation pressure forces will exceed gravitational attraction and blow apart the accretion disk. In practice, it is difficult for black holes to grow continuously at their Eddington limit, since the emission from accretion will heat the gas around the black hole and slow down subsequent accretion (e.g., Milosavljević et al. 2009). One way to speed up the growth of black holes created via stellar death is to merge many smaller seeds into a more massive seed (e.g., Li et al. 2007). Dense clusters of stars contain many small seeds that may sink to the center of the cluster and merge to form a more massive seed with $M_{\rm BH} \approx 10^4\, M_{\odot}$ that can then grow further into a supermassive black hole (e.g., Miller & Davies 2012). Similarly, stars may merge first, forming a supermassive star and then create a more massive seed (e.g., Portegies Zwart et al. 2004; Devecchi & Volonteri 2009).

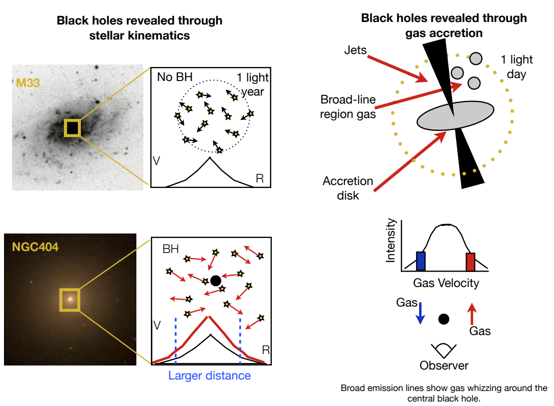
3.1. *Observational Consequences*

These different formation scenarios are only interesting if they predict differences in observations of the real universe. Eventually, perhaps with the successor to the *Hubble Space Telescope*, called the *James Webb Space Telescope*, we will detect the earliest growing black hole seeds (e.g., Bromm & Yoshida 2011). In the meantime, we can look for clues in how black holes inhabit galaxies today. Just looking at supermassive black holes in massive galaxies provides few insights, because all memory of their humble beginnings has been erased through the accretion of gas and smaller black holes. However, if we focus on the "left-over" seeds in small galaxies (those with stellar masses $M_{\rm gal} < 10^{10}\, M_{\odot}$), the black holes that never grew, we get a more direct view of the original seed population (e.g., van Wassenhove et al. 2010).

Volonteri and collaborators construct models of dark matter halos merging and growing from the early universe to the present day. They put seed black holes into the halos using different prescriptions depending on how the seeds were formed (see Figure 1). Then, they watch the black holes evolve along with the halos. There are still many uncertainties associated with these models. For instance, as black holes merge, they emit gravitational radiation. In general, the gravitational radiation will have a preferential direction. When the black holes finally merge, the remnant black hole will receive a kick from the gravitational radiation that may, in extreme cases, send the black hole out of the galaxy completely, called gravitational "recoil" (e.g., Merritt et al. 2004). Since it is theoretically uncertain how effective gravitational radiation will be at ejecting black holes, there is additional uncertainty added to the models. Also, the models assume seeds are formed either via direct collapse or via star death, when in reality there is likely a mixture.

Given these uncertainties, we focus on the qualitative aspects of the models. They predict a higher fraction of low-mass galaxies to contain nuclear black holes if seeds are created via stellar deaths (see Volonteri et al. 2008 and the purple solid and green dashed lines, respectively, in Figure 2). We are trying to measure the fraction of galaxies that contain low-mass black holes, particularly in host galaxies with $M_{\rm gal} < 10^{10}\,M_{\odot}$. As I will show, this work is still in progress.

4. *TEXT BOX: FINDING SUPERMASSIVE BLACK HOLES*



4.1. *Direct Detection with Stellar Dynamics*

The most direct way to demonstrate that a supermassive black hole exists at the center of a galaxy is to look for the evidence of the gravity of the black hole from the motions of gas or stars at the galactic nucleus. Just like planets going around the sun, we can use the laws of gravity to translate the average velocities of stars around the black hole into a mass. At the center of our own Milky Way galaxy, researchers have charted the motions of individual stars whipping around at the galaxy center for over a decade. The star motions provide unambiguous evidence for a 4×10^6 solar mass black hole (Ghez et al. 2008; Gillessen et al. 2009).

In other galaxies, we cannot study individual stars. We can, however, still see the signature of the black hole in the average star motions near the galaxy center. Stars move much faster on average if there is a black hole at the center of the galaxy then if there is not. The bigger the black hole, the faster the average motions of the stars. Because the black hole comprises only a fraction of a percent of the total mass of the galaxy, only the stars or gas very near the galaxy center can feel the gravitational attraction of the black hole. To detect these fast-moving stars requires either the high spatial resolution of the *Hubble Space Telescope* or adaptive optics from the ground. In addition to stars, orbiting gas clouds can also be used to weigh the black hole, using very similar principles (e.g., Barth et al. 2001; Herrnstein et al. 2005; Kuo et al. 2011).

It is only possible to detect the gravity of big black holes that are in relatively nearby galaxies. As shown in the bottom panel of Figure 4, the signal from the gravity of the black hole is strongly concentrated towards the galactic center. When the galaxy is further away, the motions of stars near the black hole are blurred together with more distant stars that don't feel the black holes gravity, making its influence imperceptible. Similarly, as the black hole mass gets smaller, the high velocity stars become more and more difficult to detect. To study low-mass black holes, we are generally forced to wait until matter falls into the black hole and forms an accretion disk, which we can detect.

4.2. *Detecting accretion onto black holes*

Occasionally, gas will make its way into the galaxy nucleus and into the black hole. However, the gas must dissipate its energy and angular momentum to fall into the deep gravitational potential of the black hole. Nature uses accretion disks to funnel matter into black holes; accretion disks are many hundreds to thousands of times smaller than the gas disks described in §4.1. Accretion disks are also hot, and radiate most of their energy in the ultraviolet. While we cannot see the peak of the radiation from the accretion disk, we can recognize the following signatures of an accreting black hole:

• Unresolved X-ray emission at the galaxy nucleus is a sign of an accreting black hole. High-energy interactions between photons and electrons form an X-ray corona above the accretion disk. Because the corona region is very compact, the light signals propagate from one side of the corona to the other rapidly, enabling variability on short timescales. Other processes can create X-rays in galaxies, but the X-rays are generally of lower energy, relatively fainter, and do not tend to vary on the rapid timescales seen in accreting black holes.

• Sometimes accretion onto central black holes is accompanied by jets of accelerated particles that emit radio waves. Jet emission often accompanies accretion disks, although the exact mechanisms responsible for launching the jets in accreting supermassive black holes are not fully understood.

• Outside the accretion disk is gas that orbits the black hole and emits spectral line transitions: for instance hydrogen atoms emit optical light when electrons fall into the second energy level. Intrinsically, light from electron transitions are emitted at a specific frequency. However, because the gas is moving towards and away from us, the frequency we observe is shifted to the blue or the red via the Doppler shift. The faster the gas is moving, the wider is the range of velocities that we observe in line emission. The fast-moving gas that orbits close to the black hole but outside the accretion disk is called the "broad-line" region because of the high observed velocities.

• The gas in the galaxy on larger scales is also illuminated by emission from the accretion disk. Because the accretion disk emits strongly in the ultraviolet and X-ray, the gas in the galaxy is excited to a wide range of temperatures. Gas that is excited by accretion shows specific fingerprints in the ratios of different atomic transitions. These emission line fingerprints can be observed in the ultraviolet, optical, near-infrared and mid-infrared wavelengths (e.g., Ho et al. 1997). For instance, emission lines from quadrupley ionized Ne are typically only excited in the vicinity of an accreting black hole (Satyapal et al. 2007).

4.3. *Using accretion to determine black hole mass*

In cases for which we cannot determine a black hole mass directly using the motions of stars or gas, we can get an approximate idea of the mass by observing the motions of gas clouds in the broad-line region. We use the gas clouds in a very similar way to the stars: the faster the gas moves on average, the wider the range of velocities we observe in the gas. The wider the range of observed velocities, the more massive the black hole. However, we need to know not only how fast the gas clouds are moving, but also how far away they are from the central black hole. Thinking about the planets in the solar system as an analogy, we know that Pluto moves much more slowly around the Sun than the Earth just because it is at a much larger distance from the Sun. In the case of the gas clouds, it is actually quite challenging to determine their distances from the black hole. In some cases the time delay in variable emission from the accretion disk itself, and from the broad-line region further away, provides a size scale for the emission region, because the distance is just the delay time times the speed of light. Using this technique, the mass of the black hole in NGC 4395 is found to be $M_{\rm BH} \approx 10^5\ M_\odot$ (Peterson et al. 2005; Edri et al. 2012). Measuring these time delays is very time consuming. Usually, we do not measure the broad-line region size directly. Instead, we use a correlation between the luminosity of the black hole and the broad-line region size to estimate a radius for the broad-line region gas.

5. THE SEARCH FOR LOW-MASS BLACK HOLES

Astrophysical supermassive black holes were first discovered as "QSOs" – quasi-stellar objects with very high intrinsic luminosities and very small sizes (e.g., Schmidt 1963). By the late 1970s there was compelling evidence that QSOs are powered by accretion onto a supermassive black hole. They were called "active galactic nuclei" (AGN) because they were shining via the energy released as material falls into (or is accreted by) the central supermassive black hole (Lynden-Bell 1969). The existence of real supermassive black holes, with masses of hundreds of millions of times the mass of the sun became commonly accepted, but it was far less clear whether these "monsters" represented a rare and long-lived phenomenon, or whether all galaxies contained supermassive black holes with short-lived bright episodes.

Twenty years later we finally learned that supermassive black holes are common. In fact, we believe that most massive galaxies contain a central supermassive black hole. The evidence came from both stellar dynamics and accretion (see text box). A survey by Ho, Filippenko, & Sargent (Ho et al. 1997) searched the centers of nearby, "normal" galaxies for subtle evidence that trace amounts of gas was falling into a central black hole. Amazingly enough, most ($\sim 70\%$) massive galaxies showed clear signs of accretion onto a supermassive black hole (see review in Ho 2008). At the same time stellar dynamical work was providing increasing evidence that every bulge-dominated galaxy harbors a supermassive black hole (e.g., Richstone et al. 1998). It became clear that black holes were preferentially associated with galaxy bulges[1]. Furthermore, the ratio of black hole to bulge mass was apparently constant to within a factor of two to three (Tremaine et al. 2002).

Unfortunately, understanding the black hole population becomes increasingly challenging as one considers lower and lower-mass galaxies. Low-mass galaxies typically contain more cold gas, more dust, and higher levels of ongoing star formation. The dust obscures emission from accretion, while the star formation masks it. Furthermore, if the correlation between BH mass and bulge mass applies, the BHs in smaller galaxies are less massive, which makes their emission weaker. Lower-mass black holes also exert a smaller gravitational force, so that it becomes more and more challenging to detect stars moving under the influence of the black hole.

5.1. *Dynamical Evidence for Black Holes in Low-mass Galaxies*

For the handful of bulgeless galaxies nearest to us, it is possible to search for the gravitational signature of a central black hole. In stark contrast to bulge-dominated galaxies, these nearby bulgeless galaxies show no evidence for a central massive black hole, with an upper limit of 1500 $M_\odot$ for the galaxy M33 (Gebhardt et al. 2001) and of $10^4\ M_\odot$ for NGC 205 (Valluri et al. 2005). Lora et al. (2009) and Jardel & Gebhardt (2012) find that the black hole masses of two very low-mass dwarf galaxies in our local neighborhood cannot be larger than $\lesssim 10^4\ M_\odot$. While massive, bulge-dominated galaxies contain black holes (an "occupation fraction" close to unity), clearly the occupation fraction drops in galaxies without bulges. But, do 50% of dwarf galaxies contain black holes or only 1%? And how does that fraction change with the mass of the galaxy?

Apart from M33 and NGC 205, there are very few galaxies near enough to place interesting limits on the presence or absence of a black hole based on the motions of stars or gas at the galaxy center (see text box above). Barth et al. (2009) studied the nuclear kinematics of the bulgeless galaxy NGC 3621. This galaxy also shows some evidence for accretion (see §3.3). They place a very conservative upper limit of $3 \times 10^6\ M_\odot$ on the mass of a central massive black hole, which would be improved by better measurements of the stellar ages in the star cluster surrounding the black hole. Seth et al. (2010) used the motions of a gas disk in the center of the small S0 galaxy NGC 404 to find a likely black hole mass of $\sim 5 \times 10^5\ M_\odot$. Neumayer & Walcher (2012) find upper limits of $\sim 10^6\ M_\odot$ for nine bulgeless spirals, confirming that such galaxies contain low-mass black holes if they contain a central black hole at all.

5.2. *Bulgeless Galaxies with Active Nuclei*

M33 taught us that not all low-mass galaxies contain central supermassive black holes. The galaxy NGC 4395, a galaxy very similar in mass and shape to M33, shows that some galaxies without bulges do contain nuclear black holes (Filippenko & Sargent 1989). Like M33, NGC 4395 is small and bulgeless. Unlike M33, NGC 4395 contains unambiguous evidence for a central massive black hole (see text box), including extremely rapid variability in the X-rays (Shih et al. 2003) and a radio jet (Wrobel & Ho 2006). While we do not know precisely, the black hole mass is likely $10^4 - 10^5\ M_\odot$ (Filippenko & Ho 2003; Peterson et al. 2005; Edri et al. 2012).

NGC 4395 highlights the utility of using nuclear activity as a fingerprint of low-mass black holes when their gravitational signature is undetectable. In 2004, Aaron Barth reobserved the forgotten active galaxy POX 52 (Kunth et al. 1987; Barth et al. 2004), which has a near-identical optical spectrum to NGC 4395. POX 52 also appears to contain a $\sim 10^5\ M_\odot$ black hole. NGC 4395 went from being an unexplained oddball to the first example of a class of objects, with POX 52 being the

[1] Bulges are ellipsoidal in shape and comprised of mostly old stars that move on random orbits through the galaxy. In contrast, disks are flat components of galaxies, where stars all orbit the galaxy on coplanar circular paths. Disks contain gas and ongoing star formation. If a bulge component contains no disk, we call it an elliptical galaxy.

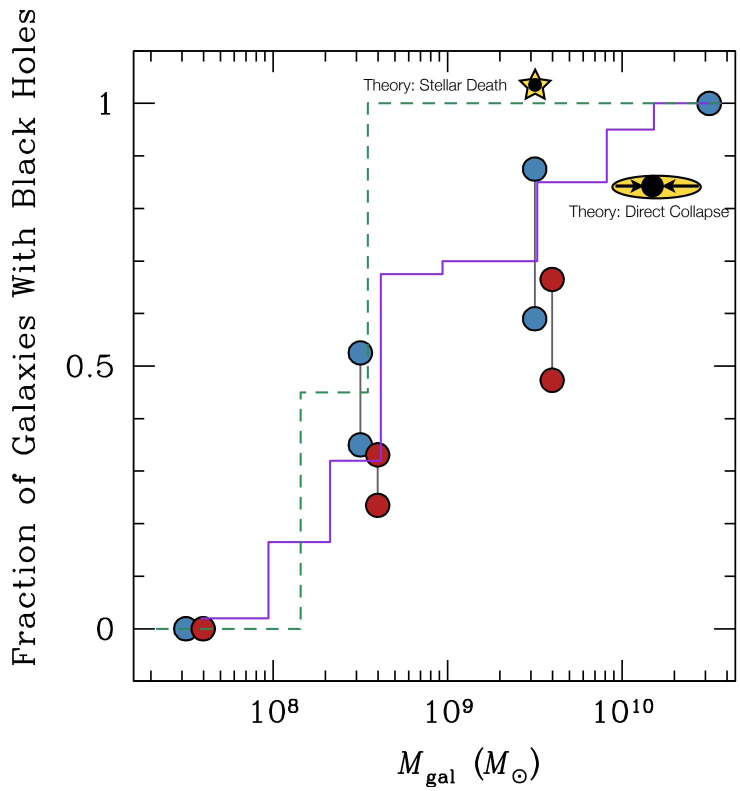


FIG. 2.— We show the expected fraction of galaxies with $M_{\rm gal} \lesssim 10^{10}\ M_\odot$ that contain black holes with $M_{\rm BH} \gtrsim 3\times10^5\ M_\odot$, based on the models of Volonteri et al. (2008), as presented in Volonteri (2010), for high efficiency massive seed formation (solid purple line) , as well as stellar deaths (greed dashed line). From data in the literature, in large circles we show the fraction of galaxies containing black holes greater than $10^6\ M_\odot$ (lower points) and greater than $3\times10^5\ M_\odot$ (higher points) based on the paper by Desroches & Ho (2009) (blue) and Gallo et al. (2010) (red). See text for details. Although the uncertainties are very large, we find tentative evidence in support of the efficient massive seed models (purple solid line).

second example. But are there more? We were inspired to perform the first large systematic search for this new class of "low-mass" accreting black holes.

In 2003, the Sloan Digital Sky Survey (SDSS York et al. 2000) had just started to provide pictures and spectra of objects over one-quarter of the sky, exactly what we needed to search for the rare and elusive low-mass black holes. We decided to find accreting black holes and use the motions of gas very close to the black hole to trace the black hole mass (see §4.2). We went through hundreds of thousands of galaxy spectra to pick out the accreting black holes with fast-moving gas (§4.2). We then picked out the ~ 200 systems with masses $< 10^6\ M_\odot$ (Greene & Ho 2004, 2007a). We chose this mass because it is similar to the mass of the black hole at our Galaxy center, and serves as the anecdotal low-mass cut-off of supermassive black holes. Dong et al. (2012) also searched through the SDSS for low-mass black holes with similar criteria, increasing the total sample by $\sim 30\%$.

Subsequent searches of the SDSS have adopted different approaches. While looking for galaxies with pristine, metal-free gas, Izotov & Thuan (2008) present evidence for accreting black holes in four vigorously star forming galaxies, again based on the detection of fast-moving gas that is most likely orbiting a black hole with $M_{\rm BH} \sim 10^4 - 10^6\ M_\odot$ (see Fig. 4). In contrast, a number of groups are now first selecting low-mass galaxies, and then searching for signatures of accretion (e.g., Barth et al. 2009).

5.3. *Multiwavelength Searches*

Searches for low-mass black holes using the SDSS were an important first step, and allowed us to comb through hundreds of thousands of galaxies. However, they are fundamentally limited in two ways. Firstly, in galaxy nuclei with ongoing star formation, dust obscuration and emission from star formation hides the evidence of nuclear activity. Secondly, the SDSS takes spectra of a biased sample of relatively bright galaxies, which makes it very difficult to calculate a meaningful occupation fraction (Greene & Ho 2007b).

An obvious way to circumvent these biases, and complement the original optical searches, is to use other wavebands. X-rays, for instance (see text box), are such high-energy photons that they can only be hidden by very large quantities of gas. Radio and mid-infrared wavelengths are also relatively unaffected by dust absorption. On the other hand, multiwavelength searches to date have been restricted to small samples.

The fraction of low-mass ($M_{\rm gal} < 10^{10}\ M_\odot$) galaxies with X-ray emission coming from the nucleus has been studied both as a function of stellar mass (Gallo et al. 2010; Miller et al. 2012) and galaxy morphology (Desroches & Ho 2009; Ghosh et al. 2008). The former studies focused on galaxies comprised of old stars, while the later focused on star-forming galaxies. Less than 20% of non-starforming galaxies with $M_{\rm gal} < 10^{10}\ M_\odot$ have nuclear X-ray sources with $L_X \gtrsim 2.5\times10^{38}$ erg s^{-1}, while in star forming galaxies of similar mass, $\sim 25\%$ of galaxies contain X-ray nuclei above the same luminosity. The difference in detection rate is likely due to a lack of gas to consume in the red galaxies. In §6, I will use these detection fractions to estimate the occupation frac-

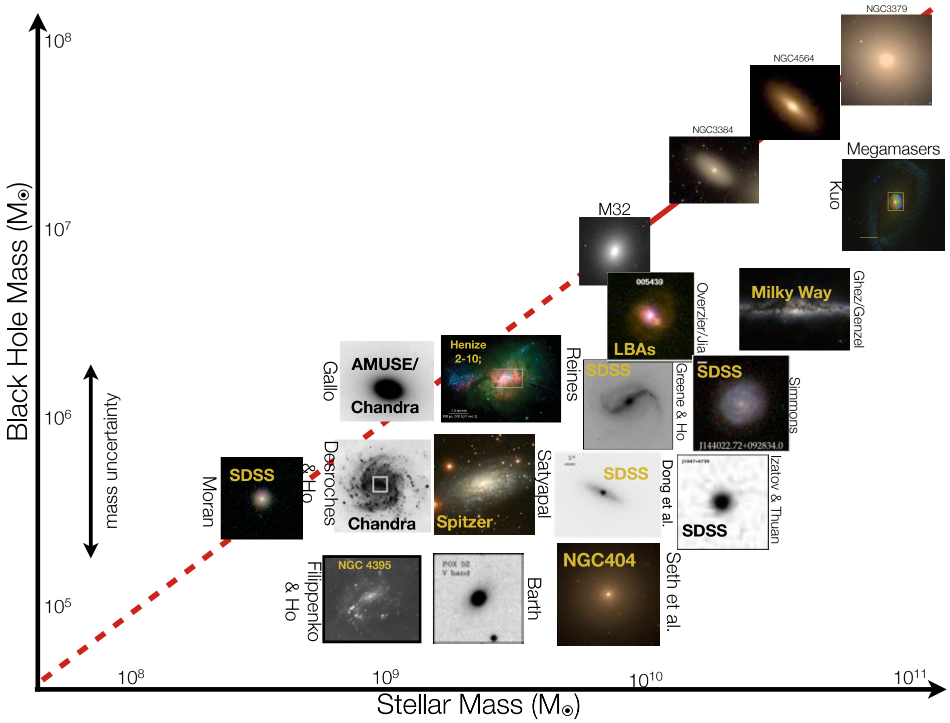


FIG. 3.— The relationship between galaxy bulge mass and black hole mass is linear for bulge-dominated galaxies, as shown by the solid red line in the upper right from Häring & Rix (2004). To guide the eye, we have extrapolated this relationship down to lower black hole masses with the dotted red line. However, in disk-dominated galaxies, particularly at low mass, there is no tight correlation between $M_{\rm BH}$ and properties of the galaxy. We illustrate the wide range of galaxy types hosting low-mass black holes, roughly placed in accordance with galaxy and black hole mass. However, note that only NGC 404 has a direct dynamical black hole mass measurement. In all other cases, the black hole masses are very approximate, as illustrated by the error bar to the left.

tion in galaxies with $M_{\rm gal} < 10^{10}\ M_{\odot}$.

The X-ray luminosities probed here are very low. If a $10^5\ M_{\odot}$ black hole has very little to accrete, it will only shine very weakly, in this case with an X-ray luminosity as low as $L_X \lesssim 10^{38}$ erg s^{-1}. However, stellar mass black holes can sometimes shine with this luminosity as well, although they are not very common; the best guess is that $\sim 10\%$ of the sources are actually powered by 10 $M_{\odot}$ black holes while the rest are powered $\sim 10^5\ M_{\odot}$ black holes (e.g., Gallo et al. 2010). However, as we look at less and less luminous X-ray sources, more and more of them will be powered by stellar-mass black holes, until for $L_X \lesssim 10^{37}$ erg s^{-1}, nearly all the sources will be stellar-mass black holes. Due to confusion about the nature of the detected objects, we are reaching the limit of what X-ray searches alone can tell us about the demographics of low-mass black holes. It is possible that including X-ray variability information will also help weed out the stellar-mass black holes (Kamizasa et al. 2012).

The high-ionization [Ne V] line, detected in mid-infrared spectroscopy, is a reliable indicator of AGN activity since starlight likely cannot excite this transition (e.g., Satyapal et al. 2007). Satyapal et al. (2008, 2009) focus on galaxies with little to no bulge component. In galaxies with very small bulges, they find a detection fraction similar to the X-ray studies ($\sim 20\%$; see also Goulding et al. 2010) but in the galaxies with no bulge whatsoever, their detection fraction drops nearly to zero (one galaxy out of 18 contains a [Ne V] detection). While the precipitous decline of detected bulgeless galaxies provides evidence for a dramatic decline in the occupation fraction of bulgeless galaxies, it is worth noting that the observations of the latter galaxies were not as sensitive.

Further progress requires observations at multiple wavelengths. For example, Reines et al. (2011) identified a likely $10^5 - 10^6\ M_{\odot}$ black hole in the center of the low-mass star-forming galaxy Henize 2-10. Radio or X-ray emission alone would have been unconvincing, since either could easily be explained by processes relating to star formation. However, the spatial coincidence of the radio and X-ray source, their relative brightness, and their distance from clusters of forming stars make a compelling case for a low-mass black hole in this galaxy. A larger sample of galaxies like Henize 2-10 (Overzier et al. 2009) also appear to have accreting black holes in some cases. Again, it is the combination of X-ray and radio detections that argues for black holes in these galaxies (Jia et al. 2011; Alexandroff et al. 2012).

6. PROPERTIES OF KNOWN LOW-MASS BLACK HOLES AND THEIR HOST GALAXIES

In addition to measuring the fraction of low-mass galaxies that contain black holes, it is of interest to determine whether black holes with lower mass emit a different spectrum than more massive accreting black holes. For instance, one naively expects that the accretion disk will get physically smaller and thus hotter as the black hole mass decreases. In turn, gas in the vicinity of the black hole will be heated by more energetic photons. Predictions of the impact of low-mass black holes on the gas conditions in the early Universe require empirical measurements of the radiation from low-mass black holes.

In practice, since accretion disk emission around supermassive black holes peaks in the ultraviolet, it is difficult to unambiguously measure changes in the disk temperature with mass (e.g., Davis et al. 2007). We have measured a few intriguing properties of the radiation from low-mass black holes, although thus far we have studied only the most luminous of them. First, they appear to have a very low incidence of jet activity (Greene et al. 2006). Second, we see indirect evidence that they have hotter accretion disks than their more massive cousins (Greene & Ho 2007c; Desroches et al. 2009; Ludwig et al. 2012; Dong et al. 2012) as expected from basic disk models (Done et al. 2012). As the accretion disk gets hotter, its impact on the surrounding gas will grow. Thus, growing black holes may well impact the formation of the first stars and galaxies (e.g., Jeon et al. 2012).

Accretion onto a central black hole has been found in low-mass galaxies of all shapes and with all levels of ongoing star formation. Miller et al. (2012) have found accreting black holes in galaxies comprised predominantly of old stars (see also Pellegrini 2010), while Izotov & Thuan (2008), Reines et al. (2011), and Jia et al. (2011) have reported evidence of accreting black holes in vigorously star forming galaxies. Some host galaxies are round (Barth et al. 2004), while others are pure disks (Filippenko & Ho 2003). We display the variety of host galaxy morphologies in Figure 3.

Supermassive black holes in bulge-dominated galaxies obey remarkably tight correlations between black hole mass and the properties of the host galaxy. For a long time it was simply unknown whether the correlations seen for bulges apply to disk-dominated galaxies; dynamical black hole mass measurements in disk galaxies are severely compromised by the presence of dust and young stellar populations. Early on, based on very indirect arguments, we saw evidence that the relationship between black holes and galaxies extended to low-mass and even bulgeless systems (Barth et al. 2005). However, as the number of available dynamical black hole masses in disk galaxies grows, it becomes increasingly clear that disk-dominated galaxies do not obey tight scaling relations with the central supermassive black hole (Hu 2008; Greene et al. 2010; Kormendy et al. 2011). Apparently the physical process that builds galaxy bulges (the merging of galaxies, we think), is also instrumental in growing black holes and establishing the scaling relations between black holes and bulges (e.g., Mihos & Hernquist 1996).

7. OCCUPATION FRACTIONS

Let us now determine whether existing observations of low-mass black holes favor a particular formation route for primordial seed black holes. I want to estimate the fraction of galaxies containing black holes as a function of galaxy mass: the occupation fraction. Based on previous work, we assume that all galaxies with stellar mass $M_{\rm gal} > 10^{10}\ M_\odot$ contain black holes. To study the occupation fraction in lower-mass galaxies, I will use the two X-ray studies discussed above from Desroches & Ho (2009) and Gallo et al. (2010) combined with Miller et al. (2012). Note that existing optical studies, while they include a larger number of objects, cannot be used for measuring occupation fractions because of their bias towards luminous host galaxies. While the samples with X-ray measurements are smaller, they should be unbiased.

Since we are using accretion to discover black holes (via X-ray emission), we will not detect all black holes. For instance, we may detect X-rays from 10% of galaxies with $M_{\rm gal} = 10^{11}\ M_\odot$, while they all contain supermassive black holes. If we then detect X-rays from 1% of galaxies with $M_{\rm gal} = 10^8\ M_\odot$, we can conclude that only 10% of $M_{\rm gal} = 10^8\ M_\odot$ contain black holes[2]. For each X-ray sample we need a comparison sample of more massive galaxies with similar X-ray observations. The Gallo et al. sample spans a wide range in stellar mass, so the comparison sample of bulges is built in. As a complementary sample of more massive disk galaxies to compare with the Desroches sample, I take the archival X-ray survey of Zhang et al. (2009). Given the existing X-ray surveys, we are not sensitive to black holes with masses $M_{\rm BH} \lesssim 3\times10^5\ M_\odot$.

The only additional complication is that lower-mass black holes are intrinsically more difficult to detect; their maximum luminosity gets lower as the black hole mass goes down. In other words, the Eddington limit (where the radiation pushing out balances the pull of gravity) increases linearly with black hole mass. At the luminosity limit of my survey, I can see massive black holes to a much lower fraction of their maximum luminosity than low-mass black holes. To remove this bias, I will normalize all the observed X-ray luminosities to the Eddington limit of that black hole ($L_X/L_{\rm Edd}$), and then only consider detections down to a fixed $L_X/L_{\rm Edd}$ limit. In most cases I do not have direct measurements of black hole mass. Galaxies with $M_{\rm gal} > 10^{10}\ M_\odot$ are assigned a black hole mass based on the correlation between galaxy mass and black hole mass, while I assume no such correlation holds for galaxies with $M_{\rm gal} < 10^{10}\ M_\odot$. Instead, I just assume that every black hole has a mass between 3×10^5 and $10^6\ M_\odot$. The limiting $L_X/L_{\rm Edd}$ is calculated accordingly in each case.

The results are shown in Figure 2. The Desroches & Ho limits are shown in blue, while the Gallo points are shown in red, for $10^6\ M_\odot$ (lower) and $3\times10^5\ M_\odot$ black holes (upper). We have no constraints on black holes of lower mass yet. The expectations from theory for seeds created via stellar death (green dashed) and direct collapse (solid purple) are shown as well. Obviously, the limits are not yet good enough to say anything definitive, but tentatively the data seem to prefer massive seed models.

Improving these limits will require a multi-pronged approach. As argued above, we are reaching the limit of utility of X-ray surveys because we run into confusion from stellar-mass black holes. However, X-ray surveys that stare at the same part of the sky for a very long time are starting to uncover accreting black holes in galaxies with $M_{\rm gal} < 10^9\ M_\odot$. At the same time, combining sensitive radio and X-ray surveys may yield interesting new constraints on black holes at much lower fractions of their Eddington luminosity.

8. *TEXT BOX: THINKING OUTSIDE THE NUCLEUS: OFF-NUCLEAR BLACK HOLES AND STELLAR CLUSTERS*

We focus here on black holes found at galaxy centers. However, we want to highlight two other very interesting locations that may harbor hitherto unknown low-mass black hole populations: the centers of dense stellar clusters, and in the outer parts of galaxies.

Another route to seed black hole growth may occur if the original seed is formed in the center of a dense cluster of stars. The black hole might grow to $10^4 - 10^6\ M_\odot$ by accreting smaller black holes at the centers of dense stellar clusters (e.g., Ebisuzaki et al. 2001). Then we may expect to find $\sim 10^4\ M_\odot$ black holes at the centers of globular clusters. These dense clusters of stars comprise some of the oldest stellar systems in the universe. Despite many searches

[2] We are making an assumption that the fraction of active black holes is always the same (in my example 10%), independent of the galaxy or the black hole mass. This is a strong assumption that we must make in order to proceed, but in detail it is probably incorrect. For instance, galaxies with less gas may be less likely to harbor an active black hole

[3] To calculate uniform stellar mass for all galaxies in both samples, I follow Gallo et al. (2010) and use correlations between galaxy $B-V$ color and the mass-to-light ratio of the stars from Bell et al. (2003).

for black holes in stellar clusters, both using dynamical techniques (e.g., van der Marel et al. 2002; Gerssen et al. 2003) and looking for signatures of accretion (e.g., Maccarone et al. 2005), there is not yet definitive evidence for black holes in globular clusters.

There is one exception. The most massive globular clusters, we believe, were formed not as isolated clusters of stars but rather as the nucleus of a galaxy that was then torn to shreds as it was eaten by a larger galaxy. These most massive clusters also tend to show a wider range of stellar age and chemical compositions than is seen in typical globular clusters, suggesting that they were formed gradually rather than as a single unit. The three prominent stripped galaxy candidates that are in our own local neighborhood all show dynamical evidence for a central 10^4 $M_\odot$ black hole (Gebhardt et al. 2005; Noyola et al. 2010; Ibata et al. 2009), although the detections are still controversial (van der Marel & Anderson 2010). Radiation from these putative black holes has not yet been detected (Wrobel et al. 2011; Miller-Jones et al. 2012).

Another suggestive line of evidence for black holes in the centers of star clusters come from the intriguing "Ultraluminous" X-ray sources. As the name implies, these targets have very high X-ray luminosities, so high that they exceed the maximum (Eddington) luminosity for a stellar-mass black hole. An easy way to explain the high luminosities is to power these X-ray sources with intermediate-mass black holes with masses of $100-10,000$ $M_\odot$. The evidence is not ironclad, however, since it is possible to reproduce the properties of ULXs with stellar-mass black holes in all but a few extreme cases (e.g., Socrates & Davis 2006). Unfortunately, determining the masses of black holes that power ULXs has proven impossible to date.

There is a spectacular ULX that deserves mention. ESO 243-49 HLX-1 has an X-ray luminosity greater than 10^{42}, the Eddington luminosity for a 10^5 $M_\odot$ black hole (Farrell et al. 2009). The X-ray source is found offset from the main body of the galaxy ESO 243-49, but at the same distance as the galaxy (Wiersema et al. 2010). HLX-1 is likely embedded in a stellar cluster with $M_{\rm gal} \approx 10^6$ $M_\odot$ (Farrell et al. 2012), perhaps the remnant of a galaxy that was eaten by ESO 243-49 in the past. ESO 243-49 HLX-1 is an intriguing source, but so far no other sources like it are known.

It is quite possible that many intermediate-mass black holes may reside outside of galaxy nuclei. As galaxies merge, they acquire black holes as well as stars. Many of these black holes may never reach the galaxy center, but reside in galaxy halos (e.g., Islam et al. 2003), where they would be very difficult to find. If the black hole is massive enough to sink to the galaxy center, then it may merge with an existing black hole; the resulting gravitational radiation could in principle eject the black hole from the galaxy (e.g., Merritt et al. 2004). At higher redshift, the number of infalling accreting black holes is high (Comerford et al. 2009), while at low redshift, systems like ESO 243-49 HLX-1 appear to be rare.

9. FUTURE PROSPECTS

How can we make progress on determining the space density of the lowest-mass black holes? At the moment, we are limited by the largest distances that we can probe in unbiased samples. Optical spectroscopic surveys such as the SDSS have yielded large samples, but with selection biases that are difficult to quantify. Searches in other wavebands, while cleaner in terms of selection effects, reach limited distances and thus contain small numbers of objects. I see multiple paths forward. The first is to look harder for black holes in local galaxies. We are reaching a fundamental limit in using X-rays, since stellar-mass black holes will dominate the emission in surveys that push an order of magnitude deeper (Gallo et al. 2010). On the other hand, the increased sensitivity of radio telescopes (particularly the Jansky Very Large Array; Jansky VLA) open the possibility of a combined radio and X-ray survey. While on an object-by-object basis there still may be complications (e.g., Miller-Jones et al. 2012), the combination of a radio and X-ray source will be compelling evidence for a low-mass black hole. Likewise, we may be able to rely on variability (both in the X-ray and in the optical) in the future (Kamizasa et al. 2012).

The second path is to try to find more accreting black holes in small galaxies by searching over larger distances rather than by looking for fainter sources. Very sensitive X-ray surveys (Xue et al. 2011) should allow such experiments, while the newly refurbished Jansky VLA could perform a very sensitive search using radio wavelengths. We also need better measurements of what fraction of more massive galaxies contain accreting black holes, as our comparison sample (e.g., Goulding et al. 2010).

Thirdly, even if a black hole is completely inactive, and thus undetectable by most of the methods discussed here, every once in a long while a star will wander too close to the event horizon and get disrupted. Many likely tidal disruption events have been observed (e.g., Gezari et al. 2012; Bloom et al. 2011), likely from stars falling into $\sim 10^6-10^7$ $M_\odot$ black holes. Since tidal disruption events are rare, with at most one every 10^5 years per galaxy expected (Magorrian & Tremaine 1999), we must monitor many galaxies every year to detect tidal disruption events. Ongoing and upcoming projects are designed to look at the same part of the sky again and again over years; with these surveys we can hope to detect many tidal disruptions per year, even around low-mass black holes (Strubbe & Quataert 2009). Eventually, as the surveys progress, we may be able to use the detection rate of tidal disruptions in small galaxies as a indicator of the occupation fraction. There are many surprises still to come.

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