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Microlensing searches for stellar mass black holes: a brief summary

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1. SOME OPEN QUESTIONS IN THE FIELD OF STELLAR MASS BLACK HOLES

The Milky Way has a stellar mass of $\sim 6 \times 10^{10} M_{\odot}$ (Licquia & Newman 2015), of which roughly 10^{8-9} $M_{\odot}$ (a fraction of $\sim 10^{-3} - 10^{-4}$) is thought to be in the form of stellar mass black holes (BHs) (Agol & Kamionkowski 2002). However, only a few dozen have thus far been observed, since at any given time, only a tiny fraction are actively accreting and producing X-rays. Detections of isolated BHs have been rare, with the only strong candidates coming from microlensing, a technique which is by nature suited to detecting dark objects. In particular, microlensing detections of a large sample of stellar mass BHs will help constrain the following questions, among others:

- What is the mass function of dark objects in the stellar mass BH range? Does the 2-5 $M_{\odot}$ mass gap between neutron stars and black holes actually exist, or is it a LIGO selection effect?
- What is the distribution of BH natal kick velocities?
- How does the population of *isolated* black holes compare with the population of binary black holes? What implications may this have for dynamical vs stellar-evolution-based binary formation scenarios?

2. WHERE WE ARE NOW, OBSERVATIONALLY

Interpreting microlensing detections can be challenging, but rewarding. This is perhaps best illustrated by the two strongest candidates for isolated BHs found thus far. Wyrzykowski et al. (2016) report two microlensing events detected with OGLE where multi-parameter model fitting says that they (1) have high probabilities for being dark objects, and (2) are likely in the mass range for black holes.

The first candidate has two possible solutions to its microlensing parameters. The first is one where the background source being lensed contributes 100% of the light and where the mass of the lens is $8.7^{+8.1}_{-4.7}$ $M_{\odot}$. In this case, the object is very likely a black hole, as it is completely dark and too massive to be a neutron star. The other scenario is one where the background source contributes 64% of the light. In this case, the mass is $9.3^{+8.7}_{-4.3}$ $M_{\odot}$. The other 36% may be from an unrelated star along the line of sight, or from the lens itself. If it is from an unrelated star, the lens is a BH by its mass and darkness. If it is not from an unrelated star, we have two possibilities once again. In case 1, the lens is at the best fit distance of 2.4 kpc. In this case its mass of $9M_{\odot}$ will be far brighter than the extinction corrected 16th magnitude object corresponding to the 36%. This case is ruled out. In case 2, it is actually far closer and happens to be moving in (projected) parallel with the bulge star being lensed. If for instance it is in the disk, it would be $\sim$1 $M_{\odot}$ and would be moving in a very coincidental manner (a projected proper motion of $\sim$0.9 mas/year). The authors say that this is extremely unlikely, and can be tested with precision astrometry in a few years. In total, this source remains the best candidate for an isolated black hole. The authors note that their detection efficiency above $\sim$6 $M_{\odot}$ is quite low, suggesting that there are many more of these systems out there. Additionally, the best fit mass of $\sim$ 9 $M_{\odot}$ is more massive than is typically found in X-ray binaries. This opens the door (along with LIGO mergers) for a much richer exploration of the mass distribution of black holes.

The second OGLE candidate has two degenerate solutions: $3.3^{+2.7}_{-1.5}$ $M_{\odot}$ and $4.8^{+4.0}_{-2.5}$ $M_{\odot}$. While the errorbars are large, a large fraction of the posterior probability distribution is within the mass gap between neutron stars and BHs. Along with the LIGO mass gap event, this provides a hint that objects may exist in this mass gap. The existence of this mass gap has been called into further question by a reanalysis of OGLE events using Gaia DR2 astometry (Wyrzykowski & Mandel 2020), who refine the mass estimate of the second event to be 4.5 $\pm$ 1.8 $M_{\odot}$ and further report 7 additional candidates in the mass gap, most of which have most likely masses between 2-3 $M_{\odot}$. Based on these events, they conclude that there is a lack of evidence *in support of* a mass gap, and strong evidence against a *wide* gap spanning the full 2-5 $M_\odot$. Due to degeneracies in fitting the mass, it is possible to drive these masses above 5 $M_\odot$ by increasing the relative proper motion between the lens and the source. However, this requires a substantial velocity for the black holes, implying natal kicks of 20-80 km/s. Either result (no mass gap or kicks) is interesting in the context of supernova modeling.

3. WHAT ROMAN WILL PROVIDE

Black holes are identified in microlensing through their high mass and lack of light. They are rare hard to identify: OGLE observes ∼2000 microlensing events per year, and over 8 years of operation, the number of candidate black holes is O(10). Interesting conclusions have already been drawn, but they would be made far more robust with a larger sample. The ideal survey to to achieve such a sample is a sensitive, wide field, high cadence search with precise and simultaneous astrometry. The sensitivity and wide field will ensure that faint and rare events will be detected. The high cadence is important in modeling the microlensing lightcurve in order to estimate masses. Finally, the simultaneous astrometry will eliminate the need for followup to determine parallaxes, another crucial ingredient in modeling microlensing parameters.

The Nancy Grace Roman telescope, scheduled to launch in 2025, will provide all of these factors except for the wide field (ironically, given its former name: the Wide Field Infrared Survey Telescope). In fact, the field will be ∼75x smaller than the OGLE field. However, the other factors are expected to far outweigh the lack of area. OGLE IV repeatedly observes ∼150 deg^2 of the Galactic bulge for 8-9 months out of the year with a cadence of ∼20 minutes to 2 days depending on the field. The observations are taken in I band, with a detection limit of 22nd mag, and the typical seeing is 1.3”. By contrast, the Roman microlensing survey (which is tuned for exoplanets) is expected to observe a single 1.97 deg^2 field of the Galactic bulge every 15 minutes over 6 observing session spanning 72 days each. It will achieve a sensitivity of $H < 26$, and it will be diffraction limited (∼160 mas). The high sensitivity is important, since only ∼10% of long duration lenses (i.e. black hole candidates) are high enough signal to noise to be modeled using their OGLE lightcurves (Lam et al. 2020). The high resolution of Roman allows for astrometry precise enough to determine microlensing parameters to be measured during the event itself. This is particularly important, because the best selector for black hole candidates relies on a parameter (π_E, the microlensing parallax) that does not become measurable until significantly after the photometric peak (and thus cannot be used for astrometric followup). With simultaneous astrometry, the need for followup is removed. An additional helpful effect of the high resolution is that far fewer unrelated stars are blended within in the PSF, thus limiting a primary source of uncertainty in the mass.

Lam et al. (2020) combine population synthesis modeling of compact objects with the survey parameters of OGLE and Roman in order to estimate the number of BHs that they will observe. They find a similar number to what was actually observed with OGLE, and with the same assumptions, estimate that Roman will detect O(1000) BH microlensing events with measurable mass. Given this many events, the mass distribution of lenses (and the presence of a mass gap or lack thereof) will become self evident (the authors estimate that this only requires O(100) BHs). The proper motion of the lenses may also be inferred, producing a distribution of natal kicks for black holes. Unusual structures indicative of binarity might be detected in the lightcurves themselves. This can constrain the multiplicity of black hole lenses. These measurements will be complementary with future iterations of GW observatories, X-ray missions, etc., since all of these have their own selection biases. Combining all their efforts, we will soon have a far more complete picture of the range of conditions where stellar mass black holes can be found.

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