INTRODUCTION

Gravitational microlensing is one of the few means of finding primordial black holes (PBHs), if they exist. Recent LIGO detections of 30 $M_\odot$ black holes have re-invigorated the search for PBHs in the 10-100 $M_\odot$ mass regime. Unfortunately, individual PBH microlensing events cannot easily be distinguished from stellar lensing events from photometry alone. However, the distribution of microlensing timescales ($t_E$, the Einstein radius crossing time) can be analyzed in a statistical sense using models of the Milky Way with and without PBHs. While previous works have presented both theoretical models and observational constrains for PBHs (e.g. Calcino et al. 2018; Niikura et al. 2019), surprisingly, they rarely show the observed quantity – the $t_E$ distribution – for different abundances of PBHs relative to the total dark matter mass ($f_{PBH}$).

MODEL FOR PRIMORDIAL BLACK HOLE LENSES

We present a simple calculation of how the $t_E$ distribution changes between models with and without PBHs. We utilize PopSyCLE (Lam et al. 2019) to simulate microlensing events for a 3.74 deg$^2$ field towards the Galactic bulge that includes stars and stellar-mass compact objects, but not PBHs. PopSyCLE output is then modified to add PBH lensing events via the procedure below. Several simplistic assumptions are made when injecting PBHs:

- The spatial and velocity distribution of PBHs follows the stellar halo.
- The mass distribution of PBHs is Gaussian with $m_{PBH} = 30 M_\odot$ with a spread of $\sigma_{M_{PBH}} = 20 M_\odot$.
- The total mass of the dark matter halo (including PBHs) is $M_{DM} = 10^{12} M_\odot$.
- The total mass of the stellar halo is $M_{H\star} = 10^9 M_\odot$.

Microlensing rates depend on the number of lens objects. On average, the total number of primordial black holes in the Milky Way, $N_{PBH}$, is

$$N_{PBH} = \frac{f_{PBH} M_{DM}}{m_{PBH}}$$

where $m_{PBH}$ is the mean mass of a PBH and $f_{PBH}$ is the fraction of the halo mass in PBHs, which is a free parameter. The number of halo stars in the Milky Way is

$$N_{H\star} = \frac{M_{H\star}}{m_{H\star}}$$

where $m_{H\star}$ is the mean mass of a halo star. The PopSyCLE synthetic microlensing survey covers a small fraction of the sky towards the Galactic Bulge, in a similar direction as OGLE and MOA on-sky surveys. Thus we need to convert the all-sky $N_{PBH}$ into the number of PBHs that are lensed in some survey, $N_{PBH,S,L}$. For a survey, $S$, with a survey duration of $T_S$, the number of lensed objects of any type is (Paczynski 1986),

$$N_{S,L} \approx \frac{2 T_S}{\pi t_E} \tau N_{\star,S}$$

where $t_E$ is the mean Einstein crossing time, $\tau$ is the lensing optical depth, and $N_{\star,S}$ is the number of source stars monitored in the survey typically coming from the bulge, disk, and a small number of stars from the halo. Given that

$$f_{PBH} \approx \frac{N_{PBH}}{N_{H\star}}$$
PopSyCLE tells us the number of lensed halo stars in our survey, \( N_{H^*,S,L} \), we need only consider the ratio of events, 
\[
\frac{N_{PBH,S,L}}{N_{H^*,S,L}} = \left( \frac{\tau_{PBH}}{\tau_{H^*}} \right) \left( \frac{\tau_{E,PBH}}{\tau_{E,H^*}} \right). 
\]
(4) 

The Einstein crossing time, \( t_E \), is given by 
\[
t_E = \frac{\theta_E}{\mu_{rel}} \text{PBH}
\]
is the angular Einstein radius and \( \mu_{rel} \) is the source-lens relative proper motion. Assuming that the distance and proper motion distribution is identical for halo stars and PBHs, the \( t_E \) ratio gives \( \left( \frac{\overline{m}_{H^*}}{\overline{m}_{PBH}} \right)^{1/2} \). The optical depth ratio is 
\[
N_{PBH,S,L} = N_{H^*,S,L} \left( \frac{N_{PBH,S}}{N_{H^*,S}} \right) \left( \frac{\overline{m}_{PBH}}{\overline{m}_{H^*}} \right)^{1/2}
\]
(6) 
and 
\[
N_{PBH,S,L} = N_{H^*,S,L} \left( \frac{f_{PBH} \cdot M_{DM}}{M_{H^*}} \right) \left( \frac{\overline{m}_{H^*}}{\overline{m}_{PBH}} \right)^{1/2}
\]
(7) 

We note that our simple approximation that the PBH velocity distribution is identical to the halo distribution is only valid when the PBHs make up a small fraction of the halo mass and the gravitational potential is dominated by some other form of dark matter. Thus, we only consider \( f_{PBH} \lesssim 0.3 \).

We inject the above number of lensed PBHs into the PopSyCLE simulation. PBHs are injected by randomly drawing from other halo star lensing events and modifying the lens mass, \( m_L \), and Einstein crossing time, \( t_E \), using
\[
m_{L,PBH} = \text{Norm}(\mu = 30 M_{\odot}, \sigma = 20 M_{\odot}) 
\]
(8) 
and 
\[
t_{E,PBH} = t_{E,orig} \sqrt{m_{L,PBH}/m_{L,H^*}}. 
\]
(9) 

We adopt this mass distribution as recent detections of 30 \( M_{\odot} \) black holes with LIGO have renewed interest in this mass range (Carr et al. 2016).

### THE \( T_E \) DISTRIBUTION

The simulated 3.74 \( \text{deg}^2 \) field of view towards the inner Galactic Bulge contains \( 1.7 \times 10^9 \) stars when no observational cuts are applied. Within this field, there are \( 5 \times 10^5 \) microlensing events in a 1000 day survey before adding PBHs. PBH lenses contribute an additional \( 3.8 \times 10^4, 1.2 \times 10^5, \) and \( 2.3 \times 10^5 \) events for \( f_{PBH} = 0.05, 0.15, \) and \( 0.30, \) respectively.

The \( t_E \) distribution is shown in Figure 1 and is enhanced at long timescales as \( f_{PBH} \) increases. Also shown is the resulting \( t_E \) distribution after observational cuts are applied in a manner suitable for an OGLE (Udalski et al. 2008) or WFIRST (Penny et al. 2019) microlensing survey. Cuts are often made on the impact parameter \( (u) \), which is the closest on-sky separation normalized by the Einstein radius, the difference between the baseline and peak magnitude \( (\Delta m) \), the source flux fraction \( (f_{SFF}) \), which is the ratio of unlensed source flux divided by the baseline flux that includes neighboring stars in the beam, and the signal-to-noise at the peak (\( SNR_{\text{peak}} \)). OGLE observable events include only those with baseline magnitude of \( I < 22 \text{ mag}, u_0 < 1, \Delta m > 0.1, \text{ and } SNR_{\text{peak}} > 3 \). WFIRST observable events include only those with baseline magnitude of \( H < 26 \text{ mag}, u_0 < 2, \Delta m > 0.1, \text{ and } f_{SFF} > 0.1 \). The total number of non-PBH microlensing events is reduced, largely due to the magnitude cuts, from \( 5 \times 10^5 \) to \( 1.7 \times 10^2 \) and \( 9.5 \times 10^4 \) for OGLE and WFIRST, respectively. While the PBH signal is difficult to detect in older surveys such as MACHO and OGLE-III, the PBH signal is easily detectable when \( f_{PBH} > 0.05 \) in any multi-year microlensing surveys with \( > 10^4 \) total events, modulo long time-scale systematics that could decrease the sensitivity.

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Figure 1. The $t_E$ distribution when the Milky Way dark matter halo ($M_{DM} = 10^{12} M_\odot$) is composed of different fractions of primordial black holes (specified by $f_{PBH}$). The PBH masses are assumed to follow a normal distribution peaking at $30 M_\odot$ with a spread of $20 M_\odot$. Left: No observational cuts. Middle: OGLE-style observational cuts on a linear scale shows very little sensitivity to PBHs. Right: WFIRST-style observational cuts enable a strong detection of a PBH signal for $f_{PBH} > 0.05$.

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