A Low-mass Cutoff of the Primordial Black Hole Mass Spectrum

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A modest violation in the conservation of mass during the merger of two Primordial Black Holes (PBHs) affects the PBH mass spectrum. We find that if the initial cosmological redshift is on the order 10^{12}, then the fraction of PBHs with masses greater than $10^3 M_\odot$ appears be close to what is required to provide the seeds for galaxies. Additionally, we note that as a result of rapid collisions and strong coupling to electromagnetic radiation for temperatures > GeV there will be an effective low mass cutoff in the mass spectrum for PBH masses less than a certain PBH mass less than than $0.1 M_\odot$. We also point out that this cutoff in the mass spectrum below $1 M_\odot$ could be probed by future microlensing surveys

Introduction

Primordial black holes (PBHs) provide an attractive explanation for dark matter (DM) in that they can not only provide the seeds for both galaxies and the large scale density inhomogenieties in the observed universe, but also because BHs can possess a large entropy, radiation of their entropy may explain the origin of the CMB [1]. In particular, if the cosmological redshift extends to z~10^{12} and the initial mass spectrum for PBHs is restricted to masses between 0.01 $M_\odot$ and < 1 $M_\odot$ then it appears the appearance of a CMB and large scale inhomogenous structure of the universe would necessarily follow [2]. The signature for this scenario is that today there is a sharp cutoff in the PBH mass spectrum somewhere in the range (0.01-0.1)$M_\odot$

Boltzmann Equation Model

Our approach to modeling the PBH mass spectrum is based on using the Boltzmann equation to model the changes in the spectrum due to close encounters between BHs which result in mergers of the two BHs [3]. Although in principle the masses of BHs in an assembly of BHs will continuously lose as due to gravitational radiation, we only take into account the change in mass due to the merger of two BHs. The Boltzmann equation we use has the form

$$\frac{dp(M)}{dt} = 27\pi\nu(t)\frac{\rho_{DM}}{\bar{M}(t)}\Bigg[\int_{M^*}^{M} \sigma_{cap}(M', M-M')p(M-M')p(M')dM' - p(M)\int_{M^*}^{\infty}\sigma_{cap}(M,' M)p(M')dM'\Bigg]$$

where the collision cross-section is calculated using the critical impact parameter [4] where gravitational radiation is sufficient to cause the BHs to spiral together and merge. In our previous paper [3] we only took into the masses of the merging BHs in calculating the mass of the new BH, while in this paper we used as a estimate of the fraction of the sum of masses lost due to gravitational radiation the estimates of this loss based on the LIGO observations [5].

Predictions

There are two obvious constraints on the PBH mass spectrum.

1) The observed abundance of seeds for galaxies as well as the required abundance of compact seeds needed by Frenk et al. to explain the observed large scale inhomogeneities in the distribution of matter
2) The contribution of PBHs to the LIGO events.

Because of the difficulty of numerically extending our Boltzmann equation solution to a redshift (say z < 100) where galaxies form, we cannot explicitly calculate the PBH mass spectrum where galaxies form. However, based on our results at z ~ 1000, which assume a typical merger mass loss for z > z* typical of what is inferred from LIGO [5] (see Figures below) we can provide an estimate of the fraction of PBHs with masses > 1000 $M_\odot$

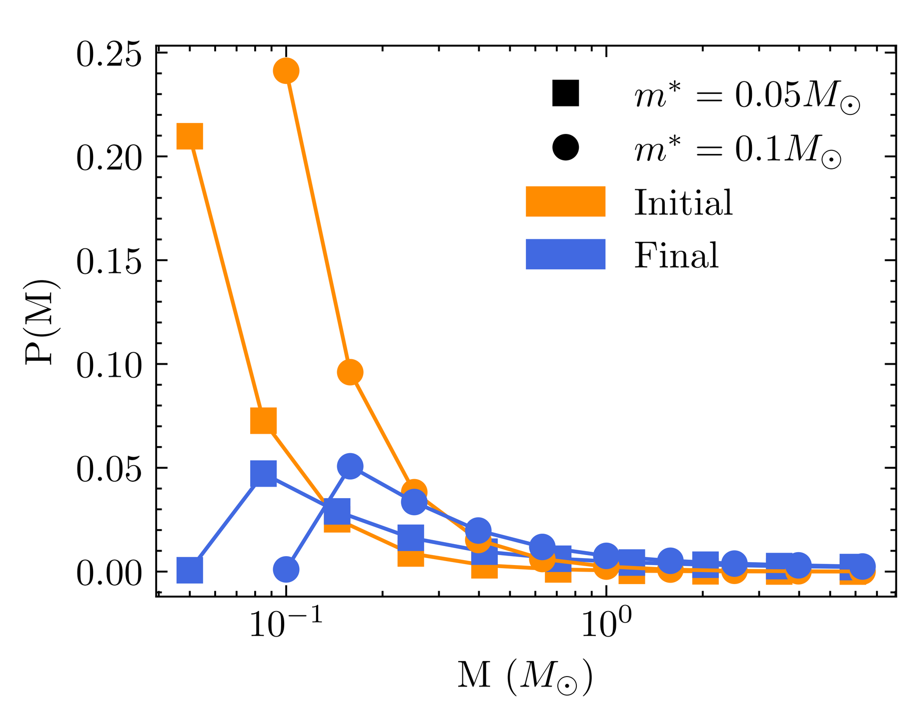

Figure 1. P(M) distributions - assuming no mass loss

For an initial red shift greater than 10^{12}, the total mass of PBHs with masses greater than 1000 $M_\odot$ will be less than the required fractio n of dark matter in galactic seeds. If we assume that there is ~ 1 $M_\odot$ of DM for every 5 times of visible matter, then the fraction of dark matter in the form of galactic seeds would be on the order 0.01%, which is not far from the total mass of present day PBHs with masses > 1000 $M_\odot$ that seems to be implied for an initial z*=10^{12} and an initial PBH mass on the order of 0.05 $M_\odot$. Due to the intrinsic difficulty of extending our calculation of the mass spectrum all the way to cosmological redshifts >1000 and concerns regarding the accuracy of our estimated merger rate when z* << 10^{12}, we cannot provide a precise value for the redshift where cosmological BHs first appear.

However, the curves in Fig. 2 do suggest that this limit cannot be much larger than ~10^{12}. Indeed, our mass spectra for z*=10^{12} do suggest that the fraction of dark matter represented by BHs with masses greater than 1000 $M_\odot$ is already approaching the expected 0.01%. for z*=10^{12}. For PBH < 0.05 $M_\odot$ the BH mass will be rapidly radiated away due to gravitational radiation produced by PBH collisions, as well as radiation of internal entropy, which becomes very strong when the ambient temperature exceeds ~ 1 GeV. [6].

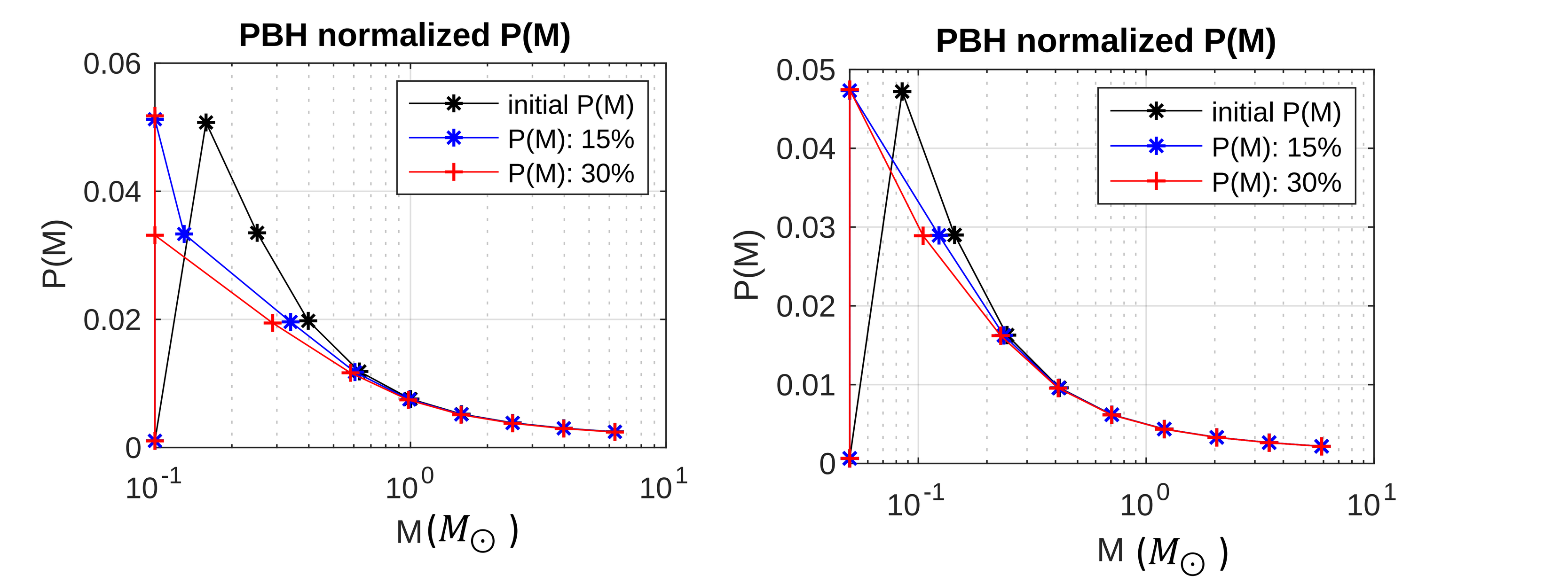

Figure 2. P(M) distributions - assuming 15% and 30% mass loss. Left m=0.1 $M_\odot$, and right m*=0.05 $M_\odot$*

Microlensing Constraints

Confirmation of a cutoff in the masses of of PBHs with masses < 0.05 $M_\odot$ ought to be possible in near future with high cadence observations with The Roman Space Telescope during the Galactic Bulge Time Domain Survey which can probe short-timescale microlensing events down to earth mass lenses [7]. Simultaneous photometric monitoring of events from spatially separated observatories such as the Roman Space Telescope at the second Lagrange point and ground-based surveys or future GEO missions will allow microlensing parallax to be measured for the free-floating planet mass ranges and will be a powerful direct probe of the substellar PBH mass spectrum. Finally, the sub-mas astrometric capabilities of the Roman Space Telescope may also provide a complimentary probe of substellar mass PBHs [8].

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