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Black Holes' Dark Dress: The impact of local Dark Matter halos on the mergers of primordial black hole binaries

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① PBHs and Gravitational Waves

Shortly after the first observation of gravitational waves (GWs) by LIGO, it was suggested [1, 2] that the signal could be produced by the mergers of Primordial Black Holes (PBHs). PBHs may be produced in the very early universe, for example, from the direct collapse of large density fluctuations after inflation [3].

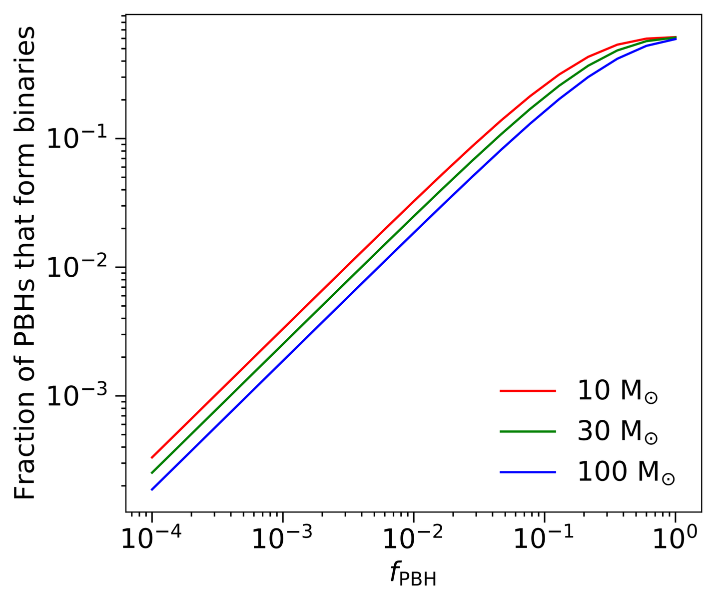
If a pair of PBHs form sufficiently close together, they may decouple from the Hubble flow before matter-radiation equality and form a binary. This turns out to be the dominant mechanism for the formation of PBH binaries [4].

The properties of the binary orbits – their semi-major axis a and eccentricity e (or equivalently angular momentum $j = \sqrt{1-e^2}$) – can be calculated from the spatial distribution and tidal influences of the PBHs. The merger time of a PBH pair is then given by [5]:

$$t_\mathrm{merge} = \frac{3\,c^5}{170\,G_N^3}\,\frac{a^4 j^7}{M_\mathrm{PBH}^3}\,.$$

From this, it turns out that the rate of PBH mergers which would be observed *today* far exceeds that observed by LIGO-Virgo if the PBHs make up a significant fraction f_PBH of the Dark Matter (DM) in the Universe.

The LIGO-Virgo events can still be explained, however, if the PBHs are **sub-dominant**. In this case, fewer binaries are formed and fewer mergers would be observed today:



In this case, though, the PBH binaries may be affected and disrupted by the particles making up the dominant DM component. Here we concern ourselves with *local* DM halos which form around the PBHs.

PBH binaries may produce observable GW signals today, but their orbits could in principle be disrupted by local Dark Matter halos.

② Dark Dresses

PBHs evolving in a sea of DM will begin to accrete a *local* DM halo before matter-radiation equality, z_eq. This **Dark Dress** of DM is formed as the density of the Universe decreases and the gravitational pull of the PBH begins to dominate over the Hubble flow.

The size of the Dark Dress grows with time as the 'sphere of influence' of the PBH expands in the diluting Universe. The 'truncation radius' of the halo is given by [6]:

$$r_\mathrm{tr}(z) = 0.0063\left(\frac{M_\mathrm{PBH}}{M_\odot}\right)\left(\frac{1+z_\mathrm{eq}}{1+z}\right)\mathrm{pc}\,.$$

If the PBHs pass through each other's DM halos during their orbit, **dynamical friction** may affect the size (a) and shape (e) of the orbit, changing the merger time and the observed merger rate today.

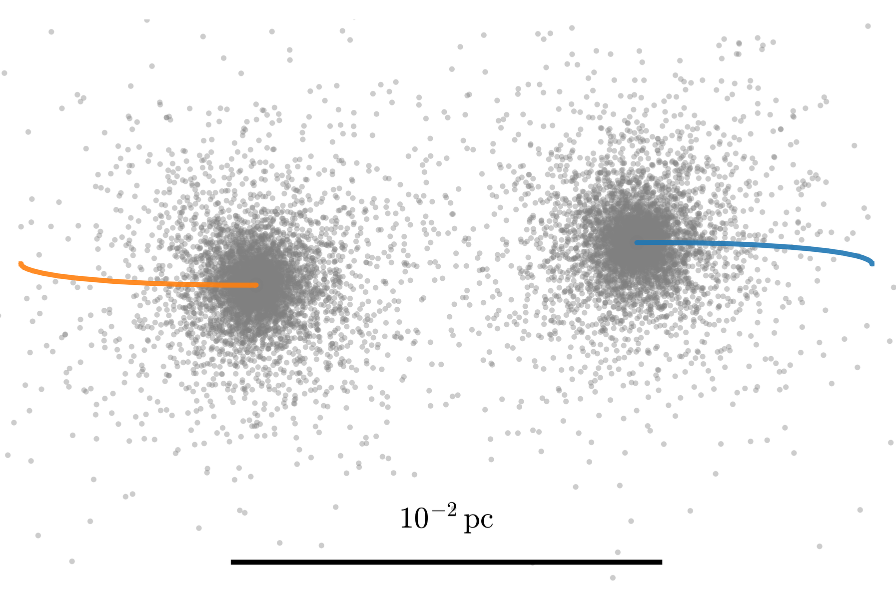
By the time PBH binaries have decoupled from the Hubble flow, they have typically accumulated a significant DM halo, whose dynamical friction may disrupt the orbit.

③ N-body Simulations

As the PBHs pass through each other's DM halos, dynamical friction will affect the orbit of the PBHs but it will also disrupt the DM halos themselves.

In the order to follow the self-consistent evolution of the PBHs and their dark dresses, we perform N-body simulations using the publicly available GADGET-2 code [7]. **Code and animations for the simulations and calculations in this work are available at github.com/bradkav/BlackHolesDarkDress.**

We begin each simulation at the time when the binary has decoupled from the Hubble flow and surround each PBH with an equilibrium DM halo. Below is a snapshot from a single simulation of two $30\,M_\odot$ PBHs during the first infall. Colored lines track the paths of the two PBHs, while the grey dots are DM pseudo-particles.

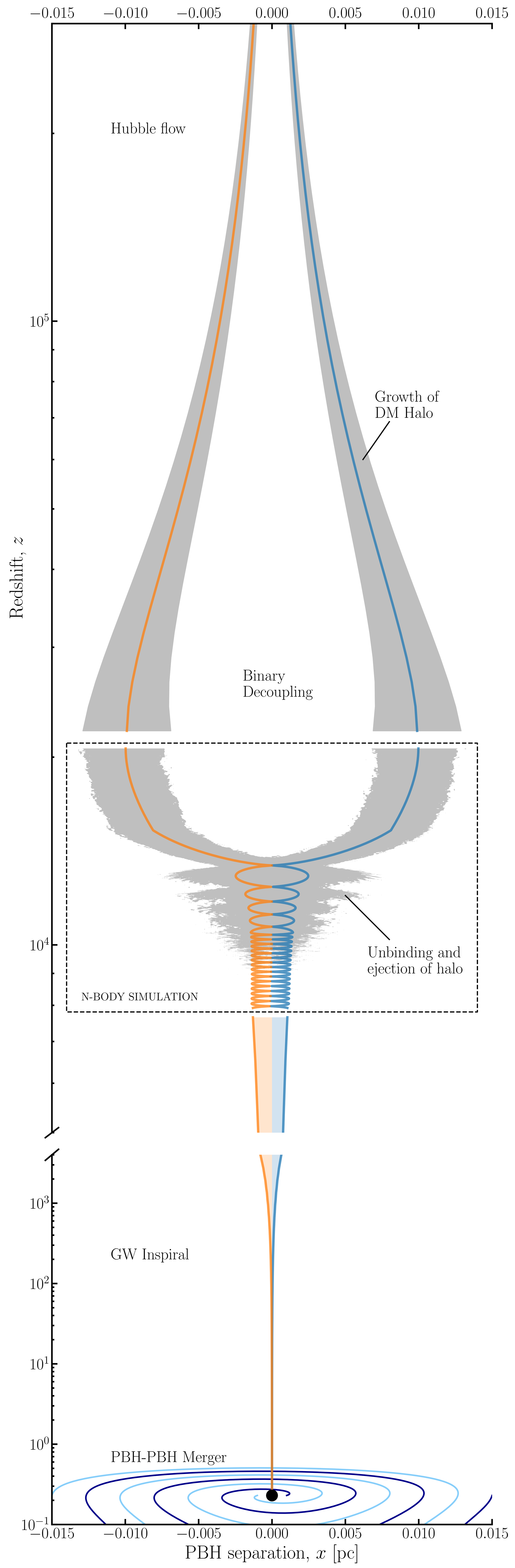


We end the simulation when the properties of the binary have stabilised.

N-body simulations allow us to self-consistently follow the evolution of the PBHs and DM halos and estimate the final merger time of the binary.

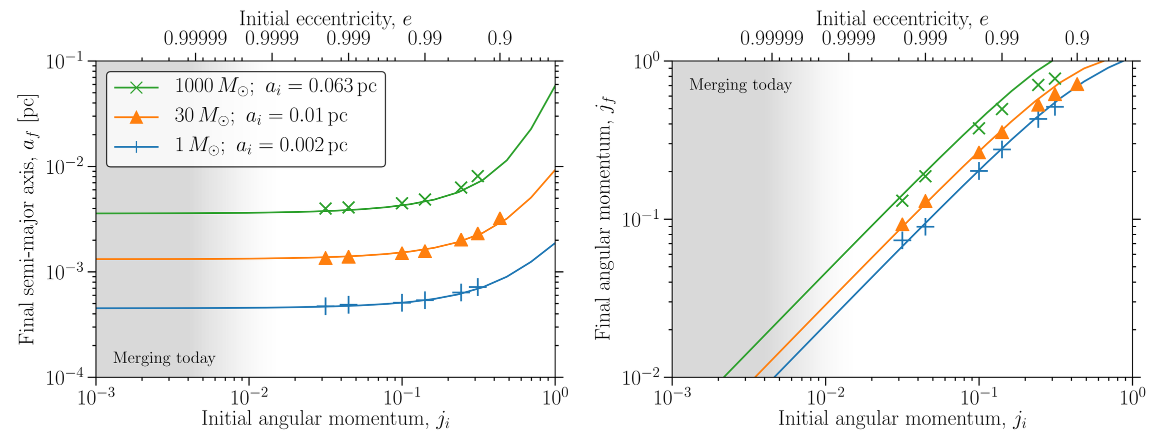
The Life of a PBH Binary

The evolution of two $30\,M_\odot$ primordial black holes (PBHs, orange and blue) which formed sufficiently close together so as to decouple from the Hubble flow and form a binary. If this binary is very eccentric, it may merge fast enough through the emission of gravitational waves (GWs) to be observed today by LIGO-Virgo. Grey bands show the Dark Matter (DM) halo which grows around each PBH and is subsequently expelled, shrinking and circularising the PBH binary.



④ Simulation Results

We performed N-body simulations for equal-mass PBHs of $1\,M_\odot$, $30\,M_\odot$ and $1000\,M_\odot$. We simulate a range of initial orbital parameters (a_i, e_i). The final orbital parameters (a_f, e_f) are plotted below as points. The solid lines are not fits to the simulation results but are instead analytic estimates, as described in the next section.



At the end of the simulations, the orbits have shrunk ($a_f < a_i$), in some cases by as much as a factor of 10. We observe in the simulations that the close passages of the two PBHs tends to unbind the DM halo; the binary stops shrinking when all of the DM has become unbound.

At the end of the simulations, the orbits are also more circular ($j_f > j_i$, recall that $j = \sqrt{1-e^2}$). While the shrinking of the orbits tends to decrease the merger time, the circularisation tends to increase it.

Dynamical friction unbinds the DM halo while shrinking and circularising the orbit of the PBH binary.

⑤ Impact on Merger Rate

PBH binaries which would merge today are very eccentric ($e > 0.9999$) and require very high resolution in the DM halo to simulate reliably. Unfortunately, this is not computationally feasible. However, the simulation results guide us in producing analytic estimates which we use to extrapolate to high eccentricity (solid lines above).

We find that dynamical friction shrinks the semi-major axis of the PBH binary. This injects energy into the DM halo, unbinding and ejecting it. In this way, orbital energy is converted into gravitational binding energy. Through **conservation of energy** we can thus relate the initial and final semi-major axis analytically, $a_i \to a_f$.

Dynamical friction may also generate a torque on the binary, changing its angular momentum. However, in simulations of the most eccentric binaries, the orbits are almost radial and we find very little exchange of angular momentum between the PBHs and the DM halos. This means that the **angular momentum of the PBHs and of the DM halos is separately conserved** allowing us to calculate the final angular momentum j_f given the initial orbital parameters.

Guided by the results of our N-body simulations, we can now calculate *analytically* the final merger time of the binary, taking into account the effects of the local DM halo. We find that the final merger time t_f is related to the initial merger time t_i by:

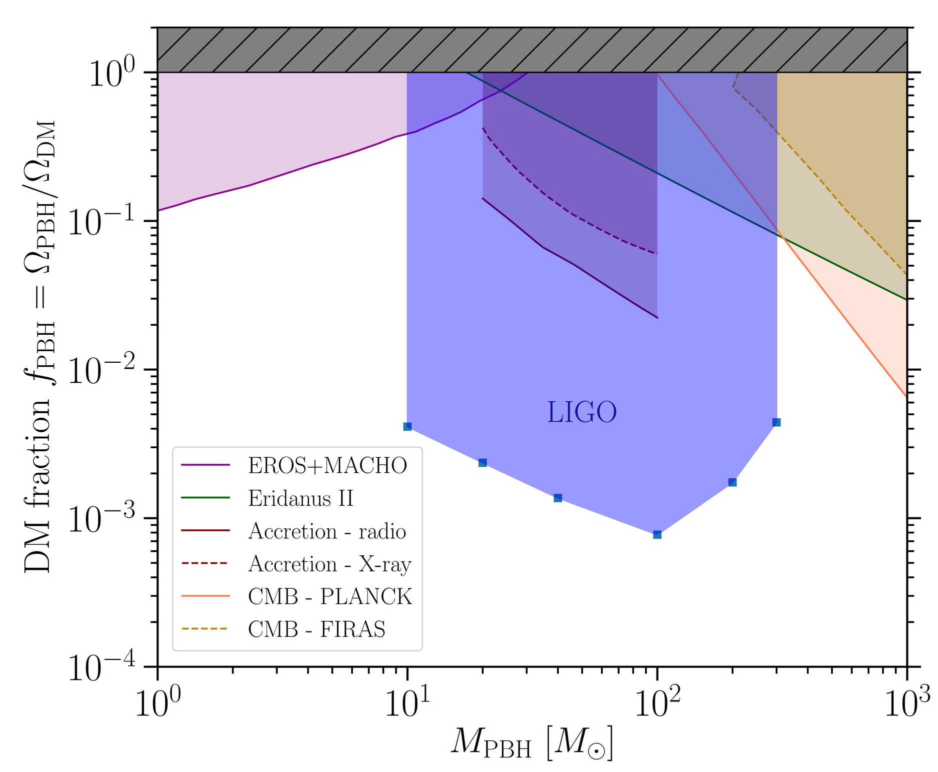
$$t_f = \sqrt{\frac{a_i}{a_f}}\,t_i\,.$$

The semi-major axis typically changes by no more than a factor of 10, leading only to a modest increase in the final merger time. The result is that the merger rate is increased by at most 50%.

For the most eccentric PBH orbits, the merger time is roughly conserved. The merger rate is therefore robust to the effects of local DM halos.

⑥ LIGO-Virgo Bounds

By calculating the number and properties of PBH binaries which are formed and **including the effects of DM halos** we can determine the rate of observable PBH-PBH mergers expected today. By comparing with limits on the merger rate published by LIGO-Virgo [8, 9], we can place a limit on the fraction f_PBH of DM in the form of PBHs:



We also show constraints on the PBH abundance from microlensing searches, from the disruption of stellar clusters, from X-ray and radio searches in the Milky Way, and from the CMB (see the paper for complete references).

Our bounds are roughly a factor of 2 stronger than previous constraints coming from the PBH merger rate [4]. This arises from the modest impact of the DM halo on the PBH orbits as well as a refined treatment of the LIGO sensitivity to PBH mergers.

LIGO observations provide the strongest bounds on the PBH abundance in the mass range $10-300\,M_\odot$. These are robust to the effects of local DM halos.

Summary

For Primordial Black Hole (PBH) binaries to produce observable Gravitational Wave (GW) signals today, they must survive undisrupted for the age of the Universe. We study the impact of **Dark Dresses** – *local* Dark Matter (DM) halos which accrete around PBHs – on the evolution of PBH binaries.

Using N-body simulations, we find that dynamical friction from the DM halos shrinks and circularises the PBH orbits. Guided by these simulations, we show analytically that while the physical properties of the orbits are changed drastically, **the merger time of the binaries is largely unchanged.**

Comparing the merger rate of PBHs – **including the effects of local DM halos** – with observations from LIGO-Virgo, we place the strongest bounds to date on the PBH abundance in the mass range 10 - 300 $M_\odot$.

These results not only place the bounds on more concrete ground but also demonstrate that feedback between DM and compact objects can have a dramatic effect on such systems. These effects should therefore also be included in the study of other GW signals, such as those from extreme mass ratio inspirals, when DM halos are present.

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