Probing for Dark Matter using Gravitational Wave Interferometry

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With the recent detection of gravitational waves by Advanced LIGO (aLIGO), new limits have been set on the merging densities and rates of a predicted source of dark matter known as primordial black holes. Primordial black holes (PBHs) are a theoretical class of black hole that would have formed under the extreme conditions and high matter densities of the early universe rather than the core-collapse of a high-mass star or other processes associated with later evolutionary periods of the universe. PBHs have been hypothesized to partially or completely explain dark matter clusters and are also thought to be potential sources of gravitational waves. Here, I explore the possibility that PBH dark matter has been detected by aLIGO, and how future searches for gravitational waves (GW) by aLIGO and related classes of GW interferometers can be used to probe the large-scale distribution of PBH dark matter clusters within the universe.

One of the primary goals of gravitational wave interferometry is to investigate and directly observe gravitational waves (GW). In the process, the measurements and data supplied by GW detectors will permit the theorization into the large scale structure and dynamics of dark matter (DM). The existence of dark matter is well supported observationally through measurements in the cosmic microwave background (CMB) anisotropy, the distribution and dynamics of large scale structures in the universe, the stability of galaxies and galactic clusters, gravitational lensing, and much more. While the composition of dark matter is still not understood, there are several prevailing hypotheses. One such hypothesis concerns primordial black holes (PBHs) as either the sole source or one of several sources of dark matter. But before PBHs are discussed in reference to dark matter, it is first necessary to understand exactly what PBHs and GWs are.

Primordial black holes are non-relativistic, non-interacting black holes that would have formed in the very early universe where the high density of matter would permit the spontaneous creation of black holes due to chaotic density fluctuations. Being non-relativistic and non-interacting, PBHs are an ideal candidate used to match our observations with DM models. Primordial black holes have been given several mass constraints due to current cosmological theory and observations. It is known that PBHs must be massive enough to not evaporate in a time span shorter than the age of the universe, which constrains their mass to $m_{PBH} \gtrsim 5 \times 10^{11} kg$. For $m_{PBH} \lesssim 7 \times 10^{12} kg$, there should have been detections of gamma rays by NASA's EGRET and FERMI telescopes, however no such detections have been made. In addition to this, FERMI should have detected the gravitational lensing of gamma ray bursts for PBH masses between $5 \times 10^{14} kg$ and $5 \times 10^{17} kg$. Again, no such observations have been made by FERMI. For PBH masses between $10^{15} kg$ and $10^{21} kg$, PBHs should have destroyed neutron stars in globular clusters and an absence of microlensing events in globular clusters exclude PBHs in the mass range of $10^{23} kg$ to $10^{31} kg$. With the absence of specific spectral distortions of the CMB black body spectrum, we can also exclude PBHs as a candidate for dark matter if $m_{PBH} \gtrsim \mathrm{M}_{\odot}$. This presents a problem as this would render the possibility of PBHs as a candidate for dark matter invalid. However, if PBH mergers were highly efficient in the early universe such that PBHs of mass $m_{PBH} \lesssim \mathrm{M}_{\odot}$were not held to CMB distortion and microlensing constraints, we could expect to see galactic halos heavily populated with very massive PBHs.

Moving on to gravitational waves, (not to be confused with gravity waves) GWs are perturbations in space-time predicted by general relativity. These perturbations should be created by any motion through space-time, but are so immeasurably small that only the most cosmologically energetic events would produce gravitational waves with a large enough energy for GW interferometers to detect. These energetic events include mergers of neutron stars and black holes, supernovae, and the precession of neutron stars. It was not until 1974 that gravitational waves were first indirectly observed from a binary pulsar, the "Hulse-Taylor binary pulsar," PSR B1913+16 and directly observed from a binary black hole merger in September 2015, known as GW150914.

With the detection of GW150914 from Advanced LIGO (aLIGO), theoretical models have bounded the rate of black hole mergers that can be rectified with the PBH-DM models. These observations require specific galactic distributions for PBHs: a radially uniform distribution following an Einasta or Navarro-Frenk-White (NFW) profile or a clustered, non-uniform distribution that creates sub-halos of PBHs within a given galactic halo. Each of these distributions have their own merging rates and each model uses the same $m_{PBH} = 30\text{M}_{\odot}$mass, as this mass matches up with the masses of both black holes observed in the GW150914 merger. Note that while the mass is constrained to $m_{PBH} = 30\text{M}_{\odot}$, in the end this will not matter because PBH merging rates are independent of PBH mass, however the mass constraint is necessary in many other calculations that are of little concern in this analysis.

For the radially uniform distribution with Einasto profile given by

$$\rho(r) = \frac{\rho_{-2}}{e^{2n[(r/r_{-2})^{(1-n)}-1]}} \tag{1}$$

with density parameter $\rho_{-2} \equiv \rho(r_{-2})$, distribution radius r_{-2} where the logarithmic slope of the profile is equal to (-2), and number density n. Using the Milky Way as an example with $r_{-2} \approx 20\ kpc$, we get a number density of $4 \leq n \leq 7$. From here, the expected distance between any two PBHs becomes a function of radial distance from the galactic center and are on the order of a few kiloparsecs apart to approximate 100 kpc apart, respective to the distance from the galactic center with a higher PBH density as we approach the galactic core. Using a Newtonian approximation to calculate the individual merger rate for a single PBH,

$$\tau_{PBH}^{merg} = n_{PBH}(m_{PBH})^2 \left(\frac{3}{2\pi v^2}\right)^{3/2} \frac{8G\pi^2}{3} R_{PBH} v^2 \tag{2}$$

with PBH mass $m_{PBH} = 30\text{M}_{\odot}$, commoving velocity $v = 200 km/s$, and Schwarzschild radius R_{PBH}. From this, we can expect to see a total merging rate of the entire Milky Way $\tau_{gal}^{merg} \approx 5 \times 10^{-12} year^{-1}$. Very similar results are obtained from an NFW profile, both of which give us values nearly equal to the rate of direct star collisions within the galactic disk of the Milky Way. With this model, it would be fair to conclude that PBHs are nearly collision-less, which confirms PBHs as a suitable DM candidate. The issue with this model however, is that it does not match up with the observations and expectations of the aLIGO team, who inferred a much higher black hole merger rate between 2 – 400 $year^{-1} Gpc^{-3}$, which is where the clustered PBH distribution comes in.

The clustering of PBHs into sub-halos within a galactic halo is a valid path of structural evolution for dark matter within a larger galactic system. This structure would not be difficult to form, as cosmic inhomogeneities would create an intrinsic chaotic element within all galactic structures. Additionally, the clustering of PBHs may have naturally contributed to the formation of ultra-faint dwarf galaxies comprised almost entirely of dark matter. Current GW interferometers are able to detect merging events over a range of several hundred cubic Mpc, which is large enough to contain some of the largest structures in the known universe including galaxy clusters and filaments. This is where the aLIGO team developed their expected merger rate of 2 – 400 $year^{-1} Gpc^{-3}$, which is a big motivating factor for searching for the noted ultra-faint DM dominated dwarf galaxies that would otherwise be nearly invisible to electromagnetic observations. Using the number density from previous calculations and an extra enhancement factor E_{factor}, it was found that the total merging rate per cubic gigaparsec was $\tau_{tot} \approx 1.4 \times 10^{-8} f_{DM} E_{factor} year^{-1} Gpc^{-3}$, with a dark matter factor f_{DM} to account for the fraction of dark matter made of PBHs, of which f_{DM} is bound between $0 \leq f_{DM} \leq 1$. An enhancement factor of $10^9 \sim 10^{10}$ is required to match the expected rates set by the aLIGO team, which corresponds to a PBH number density with 1 to 10 PBHs per cubic parsec within a given cluster.

The models proposed here to explain the distribution of PBHs as dark matter require these predicted merger rates to be as accurate as possible, because the future of GW interferometry depends on continuous detections being made to secure further funding for more research into gravitational waves. By 2019, aLIGO will reach a sensitivity necessary to probe redshifts of $z < 0.75$, which would expand its observational capacity by about $500 Gpc^3$, and with our predictions, we could expect to see around 2×10^4 merger events over the following six years of aLIGO operation. With that many observed mergers, GW interferometry will have a much greater picture of how dark matter and PBHs are distributed. There is also the planned Einstein telescope, the Big Bang Observatory, and the Deci-hertz Interferometer Gravitational wave Observatory (DECIGO), all of which would expand the observational capacity of gravitational waves to lower frequency events and with much higher sensitivities. Additionally, the electromagnetic Gaia telescope will set more accurate bounds on PBH densities within the Milky Way and will be able to discern PBH distribution.

S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, A. G. Riess, Phys. Rev. Lett. 116, 201301 (2016), arXiv:1603.00464 [astro-ph.CO].

S. Clesse, J. García-Bellido, arXiv:1603.05234 [astro-ph.CO].

T. Wickramasinghe, M. Benacquista, DOI 10.1063/1.1419664, arXiv:astro-ph/0106087.

Y. Kurita and H Nakano, Phys. Rev. D 93, 023508 (2016), arXiv:1510.00893 [gr-qc].