Analyzing the viability of primordial black holes as a significant component of cosmological dark matter

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Abstract

Dark matter is a clear and necessary component of our Universe today, yet no candidate in any mass range has yet been discovered. Thus, in light of gravitational wave observations of the surprisingly high mass black hole binary coalescences in recent years, the old theory of primordial black holes (PBHs) has been revived, and these objects have become a prime leading candidate for dark matter. While there are many current constraints that rule out PBHs as making up the dark matter in the higher mass windows, one lower mass window remains. Upcoming higher-sensitivity gravitational wave observatories will have the ability to discriminate through their gravitational wave signals if they are seeing normal astrophysical or primordial black coalescences, giving us hints on whether PBH do make up all, or any, of the dark matter.

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1 Introduction and Overview

Since almost the end of the 19th century we have had various indirect gravitational lines of evidence that have conflicted with our calculation of the mass of total matter in the Universe estimated from the summed up light from stars and galaxies, and knowing the mass estimates for these objects. These range from observations of individual galaxy rotation curves to velocity dispersions of massive galaxy clusters, and all show more than the sum of the luminous mass is needed explain these phenomena. They all point to the idea that the Universe should contain extra mass that is not luminous, and that we cannot see or observe in any other way than gravity (either completely or almost so). What we find is that the various lines of evidence point to the fact it this mass makes up about 25% of the total mass-energy content of the Universe, while that of ordinary matter makes up about 5%.

The leading candidate for many decades for a dark matter candidate has been the existence a hypothetical particles called a WIMP (weakly interacting massive particle) which does not interact through electromagnetic or strong nuclear force interactions, but primarily only through gravity. However in most models, WIMPS do typically have a very small residual weak interaction cross-section with normal matter. In the 1970's the idea of WIMPs became initially very popular especially thanks to theory of everything (ToE) models which unify the four known forces. These ToE models often incorporate supersymmetry, which then generically result in WIMPs as the lightest supersymmetric particle, which has little to no cross-section with ordinary matter.

However – until now, for over 5 decades, no hint whatsoever of WIMPs has been seen in direct detection experiments on the Earth, indirect detection astrophysical observations, or missing mass or momentum observations at colliders such as the LHC.

Because of the failure of detecting WIMPs and further, the detection in 2015 of gravitational wave (GW) events at LIGO/VIRGO due to massive black hole coalescenses, an old theory that had been considered obsolete has in recent years received much more scrutiny: the existence of primordial black holes (PBHs).

PBHs are hypothetical black holes that may have been created in the very early instants of the Universe, in the first fraction of the first second. They occur in multiple types of models, due to extreme density fluctuations in the inflationary phase of the radiation-dominated Universe. PBHs evade the stringent Big Bang nucleosynthesis bounds on the baryonic (i.e. normal matter) component of the Universe being less than 5% of the total matter-energy content, as they are created far before particles themselves come into being. If they exist, PBHs could still make up all of the dark matter mass of the Universe.

Because they emit no direct bright EM radiation, a priori, black holes are difficult to find, and we do not know exactly their exact population across the whole mass spectrum. Thus, the hidden PBH population that comes from the early Universe could be the mass we are searching for. Indeed, what has really reopened the discussion on PBHs as DM has been the results of the LIGO-Virgo-Kagra (LVK) collaboration in recent years,

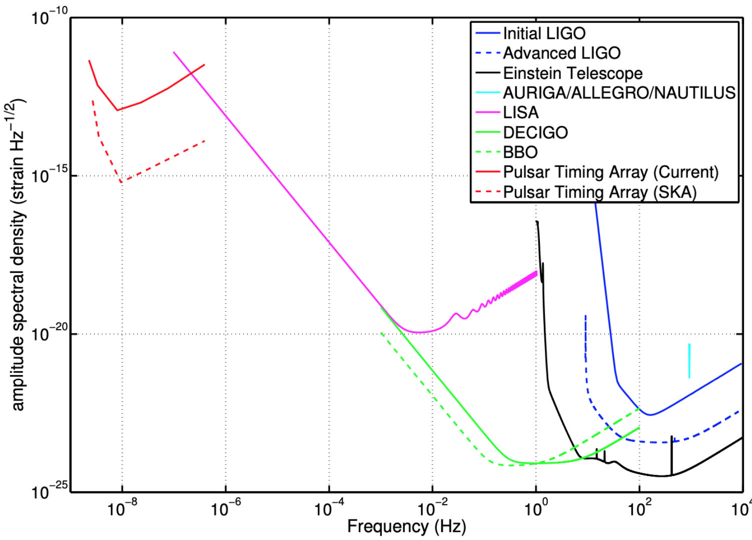

Figure 1: Current and projected GW detector sensitivities – shown is sensitivity vs. frequency.

which have shown a very different, and generally much more massive, population of stellar mass range black holes from the ones we have detected more locally through X-rays from their accretion disks, or in binaries with main sequence or other bright stars.

In the future, we hope a new generation of interferometers will be able to detect GWs with more sensitivity. In particular, the most prominent planned projects are the upgrades of LVK, the Cosmic Explorer (CE) interferometer planned to be 40km per arm and built in the USA, and the Einstein Telescope (ET) interferometer planned to be underground and built in Europe, and ultimately, LISA, a space-based configuration of spacecraft, with 2.5 million km arm lengths. Figure 1 shows a plot of the sensitivity versus frequency for some current and upcoming interferometric detectors [1].

In the rest of this short article we review why cosmologists are sure that DM exists in some form (Sec.2), the idea of PBHs as DM (Sec.3), current constraints on how much of the DM can be made by PBHs, and how these can be improved in the future (Sec.4), and we conclude in Sec.5.

2 Need for (DM) in modern cosmology

The history of DM stretches far back into the late 1800's, as the first scientist to make a conjecture about unseen mass in the Universe appears to have been Lord Kelvin, in 1884 [2]. Kelvin calculated the mass of the Milky Way from the observed dispersion velocity of stars orbiting around the centre of the galaxy, coming from the virial theorem, as

$$M_{vir} = \frac{\sigma_v^2 R_{vir}}{G} \tag{1}$$

where σ_v is the observed velocity dispersion of the stars, and R_{vir} is the radius at which the velocity dispersion is measured.

Kelvin stated the mass needed to create such a high dispersion velocity must be higher than the total mass of the visible stars. This then led to him theorizing there were some dark bodies present responsible for this mass discrepancy . Several other scientists in the years after this worked on the topic, including Kapteyn, Lundmark, and Oort.

Then, in 1933, Fritz Zwicky, an astrophysicist working at the California Institute of Technology, calculated the kinetic energy of the Coma Cluster of galaxies also from the virial theorem and found evidence of an invisible mass holding the cluster together that did not interact with the electromagnetic radiation, which he called "dark matter". From his early observations, he calculated that this hypothetical component should have been at least 400 times heavier than all visible matter.

Skipping ahead several decades, in the 1960's and 1970's, significant evidence was provided by Vera Rubin, Kent Ford and Ken Freeman in the form of galaxy rotation curves. This piece of evidence comes from the calculation of angular velocity of objects in nearly circular orbits due to simple Newtonian gravity. The calculation shows that as the distance from the centre of the galaxy increases and the included luminous mass increases, the angular velocity of the stars should decrease. However this does not occur, in every galaxy observed, implying a need for more included mass. This is what we identify as dark matter.

Further current lines of evidence indicating the existence dark matter are:

- Velocity dispersion: The virial theorem with the measured velocity distribution allows us to calculate the mass distribution in a bound system like an elliptical galaxy or a globular cluster. Again, repeatedly, estimates of velocity dispersion of elliptical galaxies are too high for the amount of luminous matter seen.
- Galaxy clusters: galaxy clusters are specifically relevant for DM as there are three different types of observations that indicate its existence: through X-rays emitted by hot gas in the clusters, through the scatter in the radial velocities of galaxies within clusters and through their gravitational lensing of objects behind the clusters. Gravitational lensing: Gravitational lensing is one of the results of Einsteinian General Relativity (GR), and it implies that massive objects (such as BHs) in between a more distant source and an observer bend the light that arrives to the observers from its initial direction.

- Cosmic microwave background (CMB): While DM does not affect CMB directly through the electromagnetic interaction, it still has a gravitational potential effect and an effect on the density and velocity of ordinary matter.
- Structure formation: In the early Universe density perturbations collapsed into clusters, galaxies and stars. But with only baryonic matter in the Universe, the time for density perturbations to grow would not have been sufficient to form the structures we see now. Hence, dark matter that is not affected by radiation as baryonic matter is provides a solution.
- Bullet Cluster: In the case where dark matter does not exist, the problem then is with GR itself. However the Bullet Cluster (the consequence of a collision of two galaxy clusters) provides a real problem for theories of modified gravity, as its centre of mass is distant from the baryonic centre of mass. On the other hand, dark matter would explain perfectly this system.
- Type Ia supernova distance measurements: Thanks to these bright standard candles we can measure the history of the expansion rate of the Universe. Using the notation of Ω_x being the fraction of matter-energy density in X to the total matter-energy density of the Universe. This requires an amount of dark energy density of $\Omega_\Lambda \approx 0.7$, while the amount of baryonic matter is $\Omega_b \approx 0.05$, therefore leaving a missing $\Omega_{DM} \approx 0.25$, which still behaves like matter gravitationally, and clusters (unlike dark energy). These proportions of mass and energy density are called the ΛCDM concordance model, and is our current working picture of the contents of the Universe. These results support the ΛCDM model.
- Sky surveys and baryon acoustic oscillations: Thanks to baryon acoustic oscillations which are acoustic oscillations in the photon–baryon fluid of the early Universe, and the CMB we can estimate the Hubble constant and therefore the average density of mass in the Universe.
- Redshift-space distortions: Through redshift we can build a model of the galaxy distribution. Because of their mass superclusters appear flattened, while voids stretched. This results, like all those above, ΛCDM model.
- Lyman-alpha forest: In astronomical spectroscopy, the Lyman-alpha forest is the sum of the absorption lines arising from the Lyman-alpha transition of neutral hydrogen in the spectra of distant galaxies and quasars. Lyman-alpha forest observations can also constrain cosmological models.

Each of these methods above when analyzed carefully results in a cosmological ratio of dark matter to baryonic matter of about 5 to 1, and all support the ΛCDM model.

3 The idea of primordial black holes

The idea of primordial black holes(PBHs) was most clearly stated in the work of Stephen Hawking and Bernard Carr in 1970s, building on previous work by other physicists in the 1960's [3]. Hawking and Carr theorized that on the smallest scales in the first fraction of a second of the Universe's existence there should have been strong density fluctuations in the dense energy fluid continuum. These fluctuations would have created zones with high spacetime curvature due to energy significantly more or less concentrated than other areas, during the inflationary phase of cosmology. There are various theories on how these curvature fluctuations that formed PBHs have occurred such as: Quantum diffusion, Phase transitions, Curvaton and stochastic spectator fields, Primordial magnetic fields, Early matter era, Single-field inflation, Multi-field inflation, Cosmic strings domain walls, and Preheating.

However they arise, once in existence, PBHs present modern-day characteristics such as non-relativistic velocities, being nearly collisionless and stable that make them good candidates for DM.

Here are some of the pieces of evidence that are leading us to believe that PBHs make up all or most of the DM of the Universe [4], [5]:

Spin: As PBHs are formed due to the collapse of Gaussian energy overdensities in the early Universe, their spin should originally be very small, however this could be increased by mass accretion, or by mergers with other compact objects. In the case of matter accretion the spin expected for something that was originally a PBH is around $\chi_{effective} \simeq 0.8$. However LIGO mergers have spin values averaging on $\chi_{eff} \simeq 0$.

Physicists found a curiosity in the detection at LIGO of event GW170104. The heaviest black hole spin orientation was anti-aligned with the orbital angular momentum. This would not be ordinarily expected for two black holes forming in the same originally spinning halo. However, it could happen if one object becomes a binary with another through gravitational capture. And this case of a black hole forming a binary system through a capture process is exactly what would be expected from a PBH.

Microlensing: Gravitational microlensing of stars of Andromeda and quasar bounds gives data supporting the presence of black holes which intriguingly exactly falls within the region obtained by the mass spectrum reconstruction with LVK events. These results are in apparent contradiction with the EROS survey towards the Large and Small Magellanic Clouds, however, the EROS survey has been recently reanalyzed making PBHs allowed again potentially in the LVK observed region.

Dynamics of UFDGs: The recent detection of numerous satellite ultra-faint dwarf galaxies (UFDGs) of our galaxy, in M31 or in the Local Group, actually provide not only one but several clues of PBHs as DM. Observations of mass-to-light ratios can be reproduced, at least qualitatively, in the PBH as DM scenario with such a simple toy model. In particular, PBH dark matter would explain the existence of a recently detected diffuse galaxy lacking any dark matter. With a radius of 2.2 kpc and a mass-to-light ratio of at most a few, it is not dense enough for PBH accretion to be efficient and so it differs from other dwarf galaxies like Crater 2 that are strongly DM dominated.

Stellar tidal streams: Perturbations on tidal streams in galaxies allow us to measure the microstructure of DM in the form of PBH clusters. Tidal streams are dwarf galaxies in an elongated stellar structure, stretched by tidal forces as the dwarf galaxies are consumed and stretched apart by the larger galaxies. These structure are very gravitationally sensitive to DM clumps. Especially for the smallest streams around 10^3 to $10^5 M_\odot$, omnipresent in the halo. PBHs would leave gaps in tidal streams, which have been found in the GD1 and Palomar-5 stellar streams.

Correlations between CXB and CIB: The PBH as DM scenario predicts that the high mass tails of the PBH mass distribution will correspond to very massive BHs that will act as seeds for gas to fall and initiate star formation at high redshifts.This generates a UV and gamma-ray background at high redshift ($z \simeq 20$) which could be seen today as it is redshifted into the infrared and soft X-rays, respectively. The recent measurement of strong spatial correlations between fluctuations in the Cosmic Infrared Background (CIB) and the diffuse Cosmic X-ray Background (CXB) suggests that a population of PBH could have initiated star formation and reionization at high redshift and also be responsible for the sources generating a fraction of the infrared and soft X-ray backgrounds today. Intriguingly, the required abundance of PBH to explain these correlations is compatible with the present DM abundance

Abundance of SMBHs: The Chandra X-ray Observatory discovered more than 5000 SMBHs (SuperMassive Black Holes) in 1/6 of a square degree area in the Southern Sky, in a deep image using more than a 7 million second exposure. This corresponds to over a billion SMBHs in the entire sky, at distances up to 12 to 13 billion light years from us. Chandra found evidence that SMBHs in the early Universe (when it was just one billion years old) grow mostly in bursts, rather than by slow accumulation of matter. The seeds could be massive PBHs that acquire mass very early (after decoupling) via gas accretion and merging, which then initiate a rapid growth of mass in bursts. These seeds would be responsible for an early and extended epoch of smooth (non-patchy) reionization, a scenario favored by Planck 2015 data . Finally, these early SMBHs could be precisely those seen by Chandra.

SGWB: It would be most enchanting to be able to hear the Stochastic Gravitational Wave Background (SGWB) of the formation of PBHs in the radiation era (which is a generic prediction of that era), in pulsar timing arrays. This is theoretically possible as the waves should not mix with generic stochastic backgrounds because of the extremely small size of the horizon of the early Universe.

In summary, though none of these hints are yet a smoking gun, they are all pieces of circumstantial evidence pointing at PBHs as forming most of the DM of our Universe.

4 Current and future prospects for constraining PBHs as DM

4.1 Current Constraints

There are a number of constraints already on how many PBHs could be allowed at any given mass monochromatically as seen in Figure 4.1 above. (The red peaks on the left are predictions of the PBH mass spectrum in a specific early Universe inflation model.) Going from left to right these constraints are:

Lifetime: Hawking radiation implies the release of photons from just outside the event horizon of a BH, due to matter-antimatter pair creation, with a higher emission rate the lower the mass of the black hole. Any BHs with masses below $\simeq 10^{15}$ g created just after the Big Bang would have a lifetime of a Hubble time or less, and thus would now have evaporated away. Thus this edge forms the lower allowed limit for PBHs surviving until today.

γ EG bkg: As black holes evaporate away their mass-energy through Hawking radiation, they make more and more gamma-rays (through positron emission and annihilation) ending in a final burst of gamma-rays which could be observations by instruments such as the Fermi Gamma-Ray Burst Monitor. If these existed, we should have been able to see such final explosions by PBHs near us in the Milky Way. Thus this is what creates the low mass yellow exclusion region.

Lensing of GRBs Because of the gravitational lensing effect, compact objects, such as PBHs, passing close to the line of sight to a gamma-ray burst (GRB) will induce in an increase in the observed brightness of the GRB. Previous work showed that there were not enough brightened events if the DM was made fully of PBHs in the 10^{17} to $10^{2}0$ g range (thus the blue Femtolensing exclusion region), but later analyses have indicated holes in this argument. [6]

WD Survival: When a PBH passes through a carbon-oxygen white dwarf, it might ignite the carbon therefore producing an explosion. The non-detection of these explosions give us a limit in the abundance of PBHs in the low-ish mass region shown in green.

Allowed region: note the lack of constraints in the region from about $10^{19} - 10^{22}$ g

Nearby micro-lensing: The HSC (Hyper Suprime Cam), Kepler telescope and EROS blue regions or from analyses indicating lack of enough observed lensing from individual stars in Andromeda or the Magellanic Clouds, shown in different shades of blue.

UFD: Dynamical constraints from Ultra Faint Dwarf galaxies, thus the high mass green region

CMB: Very massive PBHs would have disrupted the pattern of the CMB that we see today, thus the very high mass red region

In sum, there are various handles on that severely constrain many mass regions for PBHs, and there is really at this point only one mass

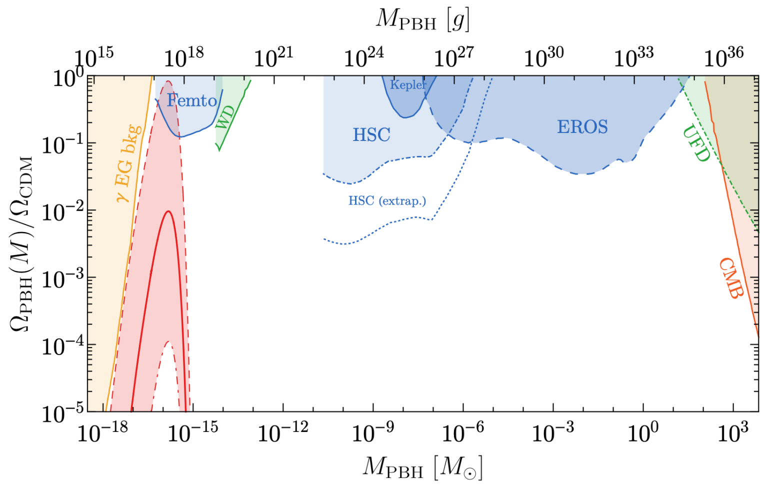

Figure 2: Current constraints on the fraction of DM that could be made at each specific mass by DM.

window that is still generally allowed for the PBHs to make up all the DM. This window is generally in the range where PBHs would have masses of approximately asteroid-size, so it is often called the "asteroid window".

4.2 Future

The order to determine whether or not PBHs exist and there are enough to make up the DM in the asteroid window, we will need further observations in the future. There are a number of handles that we have on whether or not a given black hole or BBH (binary black hole) system is of astrophysical or primordial origin, and Figure 4.2 [7] summarizes the decision tree we might follow to determine whether a specific GW event we saw was of PBH origin or not (all of these observables can be determined from the GW signature).

From left to right the boxes in this decision tree are:

Redshift: There are no stars that have formed yet in the early Universe before a redshift of 30 (i.e. about 100 Myr after the Big Bang), and thus the only black holes that could exist at this time would be PBHs. If there are any GW events from BH coalescences seen in this time, it will be a smoking gun signature for the existence of PBHs.

Binary system eccentricity: PBH Binaries are highly circular and thus would have eccentricity very close to zero, whereas astrophysical binaries formed by capture might have much higher eccentricities

Deformability: If an object is not deformable at all then this is an indication that it is a compact object like a black hole. If it is highly deformable, it may be a massive brown dwarf, a white dwarf, or something else that is 'puffier' than a BH.

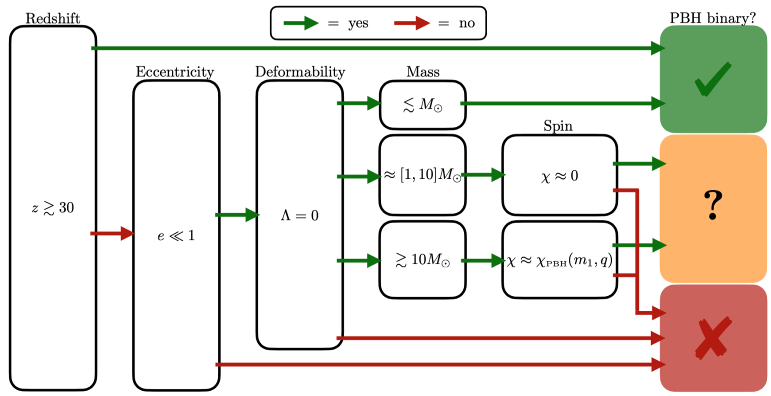

Figure 3: An observational plan to narrow down whether or not a specific event is from an astrophysical or primordial binary black hole system.

Mass: If a black hole is seen with less than one solar mass, it is a smoking gun that it is a PBH since we know of no astrophysical way to make any compact object (neutron star or BH) of this mass range. Whereas if a PBH is of a mass slightly greater than this, up to $5M_\odot$, it could have been in theory been formed by collisions of low mass neutron stars with other massive objects.

Spin: Spin is a final discriminant that can determine whether a signature is from PBH or not. In general PBHs are born with very little spin, whereas astrophysical black holes are born with significant spin. PBHs may grow in spin later by massive accretion or coalescence with other compact objects, so this is not necessarily a smoking gun signal but a very low observed spin would be indicative of a PBH system.

5 Conclusion

As we have seen in this article, dark matter is a necessary component of our Universe today, and it comprises 5 times as much mass as all the normal baryonic matter.

However, despite the compelling evidence for the existence of dark matter, and the theoretical prejudice that it would be in the WIMP mass range, no particle with mass in this range has ever been seen directly on the Earth, nor observed in indirect observations. Thus, in recent times cosmologists have been reaching for other explanations of what DM is actually composed of. PBHs have become a prime leading candidate in recent years for dark matter. While there are many current constraints that rule out PBHs as making up the dark matter in the higher mass windows, there is still one clear mass window left: the asteroid window. Upcoming gravitational wave observatories will have the ability to tell us whether any PBHs exist at all, and although these would generally be in the higher mass windows, if any exist, it would be a very strong signal that lower mass ones that can make up the dark matter also exist. It is an exciting time to be a cosmologist and have the ability to potentially resolve these decades-long mysteries in the coming years!

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