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Primordial Black Holes

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Abstract

In this report we analyze and review the current understanding of primordial black holes, first of all investigating their formation mechanism. We then focus the attention on the cosmological role of such objects, since the hypotesis of them providing a potential cold dark matter candidate became increasingly interesting from the detection of the LIGO merger event GW150914. We then try to summarize the main constraints on the mass windows permitted for primordial black holes. Moreover, we present the formation mechanisms of PBHs binaries, that allow us to investigate and test primordial black holes in deep detail.

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Chapter 1

Primordial Black Holes

1.1 Brief introduction

A black hole (BH) is a region of space-time where gravity is so strong that nothing -no particles or electromagnetic radiation- can escape from it. Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre-Simon Laplace. The first modern solution of general relativity that would characterize a black hole was found by Karl Schwarzschild in 1916, although its interpretation as a region of space from which nothing can escape was first published by David Finkelstein in 1958.

Essentially, there are three types of black holes, depending on the formation mechanism: stellar black holes, primordial black holes (PBHs) and supermassive black holes (SMBHs). The first class of black holes originates when a massive star ($M \gtrsim 25 M_\odot$) ends its evolutionary phase and eventually collapses. The formation of primordial black holes instead is based on the idea that a highly overdense region of inhomogeneities in the primordial Universe could directly undergo gravitational collapse to form BHs. It is still debated either the last class of black holes (i.e. SMBHs) has a different outset with respect to the other two classes, originating after galaxy formation, or it can be included in the PBHs theory.

Despite the fact that to date there is still no evidence for primordial black holes, this discovery is generally recognised as one of the key developments in 20th century in physics because it beautifully unifies general relativity, quantum mechanics and thermodynamics [1]. The history of primordial black holes started in the late sixties, when Zel'dovich and Novikov first showed that a black hole in the early Universe might grow catastrophically by accreting the surrounding radiation. The treatment of such objects was carried on by Hawking some years later, when he proposed the formation of BHs as a consequence of direct gravitational collapse of inhomogeneities in the primordial Universe [2]. This initiated the modern theory of the mechanism of PBHs formation.

Primordial black holes could have been produced due to various mechanisms, but the most natural possibility is the one of PBHs forming from primordial density fluctuations. However, the following results are still valid in most cases. We can thus consider a general reasoning in order to estimate a relation between the mass of the primordial black hole (M_{PBH}) and its time of formation t_f. At zero order approximation, assuming that the primordial black hole forms immediately after a perturbation enters the horizon, denoting with M_H the horizon mass at horizon crossing, we find an estimation of the time of formation t_f [3]:

$$M_{PBH} \sim M_H = \frac{4\pi}{3}\rho_H R_H = \frac{4\pi}{3}\frac{3H^2}{8\pi G}\left(\frac{c}{H}\right)^3 = \frac{c^3 t_f}{G} = 10^{15}\left(\frac{t_f}{10^{-23}\ s}\right)\ g$$

where we assumed a spatially flat Friedmann–Lemaitre–Robertson–Walker (FLRW) metric and we used the fact that $\mathrm{H} \propto 1/(2\mathrm{t})$ during the radiation domination era. In the equation, c is the speed of light, G is the gravitational constant, H is the Hubble constant, R_H is the Hubble radius and

ρ_H is the horizon energy density. We can see that, depending on their formation time, PBHs can have a wide range of masses: those formed at Planck time (10^{-43} s) would have the Planck mass (10^{-5} g), those formed at the QCD phase transition at t $\sim 10^{-6}$ s would have mass of order a solar mass, while those formed at 1 s would be as large as 10^5 $M_\odot$, comparable to the mass of the black holes thought to reside in galactic nuclei.

Furthermore, as realised by Hawking [4], primordial black holes radiate thermally and so evaporate on a timescale τ_{PBH} that depends on the mass of the PBH in the following way:

$$\tau_{PBH} \sim 10^{10} \left(\frac{M_{PBH}}{10^{15}\ g} \right)^3 Gyrs$$

From this relation we can thus see that PBHs with masses of 10^{15} g will be evaporating today, while heavier PBHs are stable and could be currently present in the Universe.

1.2 Formation mechanisms

To date, several mechanisms of primordial black hole formation in the early Universe have been proposed. These include primordial collapse of density fluctuations or spontaneous formation due to a phase transition, for example from domain walls, collapse of cosmic string or bubble collisions [3, 5]. However, the most frequently studied PBH formation scenario is the gravitational collapse of overdense regions in the early Universe. In this report we will briefly analyze only the most important ones.

Collapse of primordial inhomogeneities

First of all, in the early Universe after inflation the background spacetime can be well-described by the spatially-flat Friedmann-Lemaitre-Robertson-Walker metric (homogeneous and isotropic space):

$$ds^2 = -dt^2 + a(t)^2 \delta_{ij} dx^i dx^j$$

where a(t) is a scale factor. Against this background, characterised by the background energy density $\bar{\rho}$, we consider a locally perturbed region that would eventually collapse to a black hole. Such a region would be a very rare region in the space. The equation of state that relates the pressure (p) of the fluid with its energy density (ρ) is given by

$$p = w\rho$$

where w is a dimensionless constant. In particular, for the Universe dominated by (non-relativistic) matter w=0, whereas a radiation (or relativistic matter) dominated Universe corresponds to w=1/3. In this case, for gravity to overcome pressure at maximum expansion the region must be larger than the Jeans length. This leads to the requirement that the density contrast, defined as

$$\delta = \frac{\delta\rho}{\bar{\rho}} = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

at horizon crossing must exceed a critical value $\delta_c \approx$ w [5]. If this happens, a PBH forms. The criteria for PBH formation in a matter dominated Universe with w = 0 are somewhat different. In this case, because the pressure is zero, it is possible for PBHs to form well within the horizon.

Collapse of Cosmic Loops

Cosmic strings are one-dimensional topological defects which may form during phase transitions in the very early Universe. In the cosmic string scenario, one expects that as a cosmic string network evolves, long strings self-intersect and form cosmic string loops. There is a small probability that an oscillating cosmic string loop will be in a configuration where all of its dimensions are less than its Schwarzschild radius and hence it will collapse to form a primordial black hole with mass roughly equal to the horizon mass. The number of PBHs formed depends on the mass per unit length of the strings μ, which is related to the symmetry breaking scale. Cosmic string loops can collapse to form PBHs at any point during radiation domination, therefore the resulting PBHs have an extended mass function [5, 6].

Collapse through Bubble Collisions

Bubbles of broken symmetry might arise at any spontaneously broken symmetry epoch and various groups have suggested that primordial black holes could form as a result of bubble collisions. However, this happens only if the bubble-formation rate per Hubble volume is finely tuned: if it is much larger than the Hubble rate, the entire Universe undergoes the phase transition immediately and there is not time to form black holes; if it is much less than the Hubble rate, the bubbles are very rare and never collide. The holes should have a mass of order the horizon mass at the phase transition [6].

Collapse of Domain Walls

The collapse of sufficiently large closed domain walls produced at a 2nd-order phase transition in the vacuum state of a scalar field, such as might be associated with inflation, could lead to primordial black holes formation. These PBHs would have a small mass for a thermal phase transition with the usual equilibrium conditions. However, they could be much larger if one invoked a non-equilibrium scenario [6].

1.3 Mass functions

In principle, primordial black holes could have two types of mass functions: either it is monochromatic, so all the PBHs would form with nearly the same mass, or it is extended, and so we can have a large variety in the values of their masses. Most of the PBH dark-matter proposals assume that the mass function of the black holes is very narrow (i.e. nearly monochromatic). Even if this is the simplest approach, this is also the most unrealistic case and in most scenarios one would expect the mass function to be extended [7]. In principle, one could also have two distinct PBH populations, both monochromatic but with a different mass [8]. As we are going to see in the following chapter, depending on their mass functions, primordial black holes could play a variety of cosmological roles.

Chapter 2

Role of PBHs

2.1 PBHs as dark matter

Assuming general relativity is correct and according to the ΛCDM model, there is extensive astronomical and cosmological evidence that the majority of the matter in the Universe, about 26% of the entire energy content, is made of non-luminous matter, i.e. matter that does not interact with observable electromagnetic radiation and therefore extremely difficult to detect with standard astronomical equipment. This type of matter is non-baryonic and it is called cold dark matter (CDM). The nature of dark matter (DM) is one of the most longstanding and puzzling questions in physics. Cosmological measurements have now determined with exquisite precision the abundance of dark matter and from both observations and numerical simulations we know quite a bit about its distribution in galactic halos [9]. Still, the nature of dark matter remains a mystery. Even if there are different theories, the standard cold dark matter scenario is characterized by the assumption that the dark matter comprises some form of weakly interacting massive particle (WIMP). Given the efficacy with which weakly interacting massive particles have eluded detection, it may be warranted to consider other possibilities for dark matter.

Since primordial black holes form before nucleosynthesis, they are non-baryonic and therefore PBHs with $M_{PBH} > 10^{15}g$, that as we saw they have lifetime longer than the age of the Universe, are a potential cold dark matter candidate [5]. There are general arguments that PBHs rather than WIMPs may provide the dark matter: one is that the density of such black holes is not constrained by the limits on the baryonic density implied by Big Bang nucleosynthesis. Furthermore, this has the advantage that, unlike the situation for WIMPs or other particle candidates, there is no need to invoke new physics [8]. The PBH dark matter proposal has been emphasized from the earliest days of PBH research in 1975, but this hypotesis has become particularly popular recently, especially since the discovery of black hole coalescence by LIGO. As we are going to see in the following chapter, primordial black holes' masses are constraint by observations in specific mass windows and, inside these windows, there are only a few permissible mass windows in which PBHs could contribute significantly to the dark matter. However, this is still under debate and possibly we will better investigate this topic with new observations and experiments.

2.2 PBHs as generators of cosmic structures

Since there is clear evidence that SMBHs with mass $10^5 - 10^{10} M_\odot$ reside in the centres of most galaxies, with observations of quasars suggesting that these were already in place at very early times ($z > 6$), another proposal is that PBHs could provide seeds for SMBHs and, more in general, for galaxies. These scenarios are independent of the dark matter one and they depend on the mass functions of PBHs.

PBHs of mass m provide a source of fluctuations for objects of mass M in two ways [8]:

- via the seed effect, in which the Coulomb effect of a single black hole generates an initial density fluctuation m/M;
- via the Poisson effect, in which the $\sqrt{N}$ fluctuation in the number of black holes generates an initial density fluctuation $(fm/M)^{1/2}$ for a PBH dark matter fraction f.

Both types of fluctuations then grow through gravitational instability to bind regions of mass M.

One can place interesting upper limits on $f(M_{PBH})$ by requiring that various types of structure do not form too early. One can also take a more positive approach, exploring the possibility that primordial black holes may have helped the formation of these objects, thereby complementing the standard CDM scenario of structure formation. If the primordial black holes have a monochromatic mass function and provide all the dark matter ($f \sim 1$), then the Poisson effect dominates on all scales and various astrophysical constraints that we are going to discuss require $m < 10^2 M_\odot$. This implies that PBHs can only bind subgalactic masses but still allows them to play a role in producing the first bound baryonic clouds or the SMBHs which power quasars. For $f \ll 1$, the seed effect dominates on small scales and can bind a region of up to 4000 times the PBH mass. It is known that most galaxies contain central supermassive black holes with a mass proportional to the bulge mass and this correlation is naturally explained by the seed effect if the black holes are primordial, rather than forming after galaxies, with an extended mass function [1].

2.3 PBHs as dark matter and generators of cosmic structures

If the PBHs have an extended mass function, both the seed and Poission effects could operate on different scales. Indeed, in principle, one could have two distinct PBH populations, both monochromatic but with a different mass. In this case, one population may provide the dark matter and generate a Poisson effect, while the other may provide a low density of SMBHs which generate a seed effect. However, this seems rather contrived [8].

Chapter 3

PBH abundance constraints

Any proposed model of primordial black holes formation must be confronted with constraints in the mass range where the predicted PBH mass function peaks. Primordial black holes' abundance constraints are usually quoted in terms of the fraction of the energy density in the form of PBHs at the time they form, defined as

$$\beta(M_{PBH}) \equiv \frac{\rho_{PBH}}{\rho_{tot}}$$

The PBH density evolves as $\rho_{PBH} \propto a^{-3}$, while the radiation density varies as $\rho_{rad} \propto a^{-4}$. Therefore during radiation domination the fraction of the total energy density which is in the form of PBHs grows proportional to a(t). So, even if the fraction of the energy density of the Universe in PBHs is initially small, it can grow to be significant at late times [5].

We can define the fraction $f(M_{PBH})$ of the mass of primordial black holes as

$$f(M_{PBH}) = \frac{\Omega_{PBH}}{\Omega_{CDM}} \approx \left(\frac{\beta(M_{PBH})}{10^{-8}}\right)\left(\frac{M_{PBH}}{M_{\odot}}\right)^{-1/2}$$

where Ω_{PBH} and Ω_{CDM} are the fraction of the critical density (for which the geometry of the Universe is flat) in the form of PBHs and cold dark matter, respectively. $f(M_{PBH}) = 1$ corresponds to the fact that all the dark matter in the Universe is in the form of primordial black holes. For instance, we can estimate this value through lensing and dynamical constraints, which limit the fraction of the Milky Way (MW) halo in the form of compact objects, where we are assuming that the density of other compact objects is negligible and the Milky Way's dark matter composition is the same as the Universe as a whole (which is a reasonable assumption). In doing so, we can investigate the presence and the abundances of primordial black holes in the Universe. There are a lot of other useful constraints and now we are going to analyze the main methods. I decided to report only the reasoning and not the numerical values on the abundances of PBHs in order to give an overview of the proceedings without weighting down the treatment.

3.1 Evaporating constraints

The current picture of PBH evaporation is that they directly emit all particles which appear elementary at the energy scale of the PBH and have rest mass less than the black hole temperature. Therefore if the black hole temperature exceeds the QCD confinement scale, quark and gluon jets are emitted directly. The quark and gluon jets then fragment and decay producing astrophysically stable particles: photons, neutrinos, electrons, protons and their anti-particles [5].

The photons emitted by PBHs with $M_{PBH} < 10^9$ g will thermalize and contribute to the baryon to photon ratio. The requirement is that this ratio must not exceed the observed value of $\sim 10^9$ [5].

It has been argued that black hole evaporation could leave a stable Planck mass relic, in which case the present day density of relics must not exceed the upper limit on the present day CDM density [5].

PBHs with mass in the range $10^9 g < M_{PBH} < 10^{10} g$ have lifetime $\tau \approx 10^{-2} - 10^{-3} s$ and the mesons and anti-nucleons they emit would increase the neutron/proton ratio and hence the abundance of ^4He. Similarly, for masses in the range $10^{10} g < M_{PBH} < 10^{12} g$ the lifetime is between $10^{-2} s$ and $10^2 s$ and the high-energy hadrons produced dissociate the light elements, reducing the abundance of ^4He and increasing the one of the other elements. The tightest constraints are from deuterium and from non-thermally produced ^6Li.

PBHs with masses in the range $10^{13} g < M_{PBH} < 10^{15} g$ will have evaporated between redshift $z \sim 1000$ and the present day and can contribute to the diffuse extragalactic gamma-ray background. Slightly more massive PBHs, that have not evaporated completely by the present day, can also emit a significant flux of gamma-rays. Their abundance is limited by EGRET (Energetic Gamma Ray Experiment Telescope). For PBHs with $10^{15} g < M_{PBH} < 10^{17} g$ the gamma-ray constraints require the fraction of the dark matter in the form of PBHs to be less than one. In other words, primordial black holes in this mass range can not make up all of the dark matter [5].

3.2 Lensing constraints

The outstanding virtue of gravitational lensing is that the individual lensing signal is solely based on the gravitational physics, and does not suffer from the uncertainties that exist in studying electromagnetic signals resulting from the interaction between PBHs and surrounding matter. Gravitational lensing is a very powerful method to constrain/detect primordial black holes. If there is a cosmologically significant density of compact objects then there is a high probability that a distant point source is lensed, as we can see from Figure 3.1.

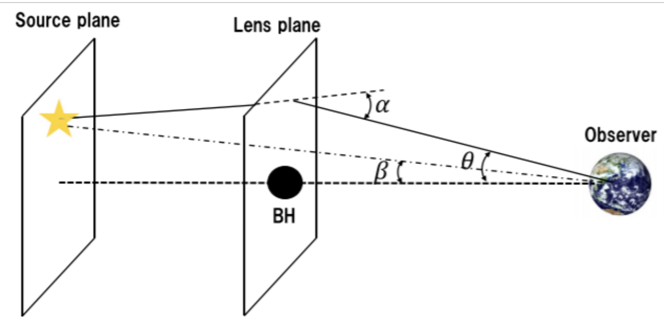

Figure 3.1: Trajectory of light ray bent by the lens object (BH). [2]

We can utilize the so-called femtolensing techinque, since for $10^{17} g < M_{PBH} < 10^{20} g$ the image separation is of order femto (10^{-15}) arc-seconds. However the time delay between images, $10^{-17} - 10^{-20} s$, is approximately equal to the period of a gamma-ray. Compact objects of this mass could therefore be detected by the interference pattern in the energy spectrum of a gamma-ray burst.

We then have the galactic microlensing method, that occurs when a compact object with mass in the range $10^{24} g < M_{PBH} < 10^{34} g$ crosses the line of sight to a star. The image separation is too small (of order micro arc-seconds, $10^{-6} arcsec$) for multiple images to be resolved and the lensing leads to a temporary amplification of the star's flux. Compact objects with $10^{30} g < M_{PBH} < 10^{35} g$ can also microlens quasars, amplifying the continuum emission without affecting the line emission. Limits on the number of small equivalent width quasars place a constraint on COs in this mass range.

In addition, it is possible to use the radio source millilensing technique, since massive compact objects with $10^{39} g < M_{PBH} < 10^{41} g$ can millilens radio sources, producing multiple images which can be resolved with Very Long Baseline Interferometry [5].

3.3 Dynamical constraints

To a certain degree, primordial black holes affect any astrophysical system by gravitational interaction. By appropriately evaluating the impact of PBHs on astrophysical systems, and making comparison with observations, it is possible to put an upper limit on the PBH fraction for a wide range of PBH mass. To date, various astrophysical systems have been considered in this context [2]. The abundance of massive compact objects in the Milky Way halo is constrained by their dynamical effects on the constituents of the MW. Here we briefly summarise the constraints which place the tightest limits on the halo fraction in COs.

Encounters with massive compact objects can disrupt or change the orbital parameters of wide binary stars. Observations of wide binaries therefore constrain the halo mass fraction of PBHs. In addition, compact objects will be dragged into the centre of the MW by the dynamical friction of spheroid stars and the population of COs themselves. Constraints on the central mass of the Milky Way limit the halo fraction of compact objects. Furthermore, massive compact objects traversing the Galactic disk would heat it, increasing the velocity dispersion of the disk stars [5]. This leads to a limit, from the observed stellar velocity dispersions, on the halo fraction in COs. Moreover, if a PBH is captured by a neutron star, the star will be accreted and destroyed in a short time. The existence of neutron stars in globular clusters (GCs) limits the abundances of primordial black holes. Finally, it was pointed out that the passage of a PBH through a white dwarf can ignite the thermonuclear runaway that eventually makes a white dwarf well below the Chandrasekhar limit explode. Thus, if there were too many PBHs above a certain mass, the white dwarfs with corresponding mass could not exist in the present Universe. Conversely, we can constrain the abundance of the PBHs by using the observational confirmation of white dwarfs. We expect this argument to constrain a certain PBH mass range: light PBHs do not give sufficient heat to the white dwarfs, simply because of the weakness of their gravitational effect; and white dwarfs do not encounter many heavy PBHs, simply because of their rareness [2].

3.4 CMB constraints

After decoupling, massive primordial black holes can accrete material and the subsequent radiation can affect the thermal history of the Universe. Baryonic gas around the primordial black hole is attracted to the PBH by its gravity. As the gas falls into the central region, the gas is compressed, increasing its density and temperature. During the infall, the gas can be fully ionized, either by the internal collisions of gas particles or by the outgoing radiation. Near the black hole horizon, the gas temperature is enormous and intense radiation from the ionized gas emanates outward [2]. X-rays emitted by gas accreted onto primordial black holes modify the cosmic recombination history, producing measurable effects on the spectrum and anisotropies in the Cosmic Microwave Background (CMB) radiation, which have been constrained using the FIRAS and WMAP data [5]. Another important limit comes from the dissipation of density fluctuations between 10^6 and $10^9 s$ by Silk damping [8]. This results in a μ-distortion in the CMB spectrum: when PBHs form abundantly, the dispersion of primordial fluctuations is also expected to be large, so Silk damping would produce unacceptably large μ-distortions. Non-detection of such features is translated into an upper limit on PBH abundance.

3.5 LSS constraints

Sufficiently massive primordial black holes would affect large scale structure formation due to the Poisson fluctuations in their number density, which enhance the dark matter power spectrum. Based on this observation their impact on the Lyman-alpha (Lyα) forest observations was investigated. The basic idea is the following. Spectra of distant quasars and galaxies show many absorption lines known as the Lyα forest. This arises due to the intervening neutral hydrogen in the intergalactic medium between the quasars and the Earth (typically $z \sim 2-5$), which absorbs photons from quasars by the Lyα transition (n=1 to n=2, where n is the principal quantum number of the hydrogen atom). Although this epoch is after reionization, there is still a tiny fraction of neutral hydrogen in the intergalactic medium because of the balance between the photoionization by the surrounding UV radiation and the recombination, and this tiny amount of neutral hydrogen is sufficient to produce the Lyα forests. Lyα absorption is more efficient in the site where baryonic matter is denser. Because of this, many absorption lines in the spectra reflect the inhomogeneous distribution of baryonic matter. Given that baryon perturbations are affected gravitationally by dark matter perturbations, the statistical properties of the optical depth encode those of the dark matter perturbations. Conversely, observational analysis of the optical depth makes it possible to probe the matter perturbations on small scales down to $\sim$Mpc. Lyman-alpha forest observations constrain then the fraction of the dark matter in PBHs [2, 5].

3.6 GWs constraints

The first effect that the primordial density perturbations seeding the PBHs causes are stochastic gravitational waves produced by the mode–mode coupling of the density perturbations. Density perturbations, which are classified as scalar-type, evolve independently of gravitational waves (GWs), which are classified as tensor-type, at the linear order in the perturbation. This independence no longer holds beyond the linear order and the gravitational waves are produced by the density perturbations at the second order by their mode–mode couplings. Assuming that primordial density perturbations existed on super-Hubble scales, the production of the GWs by the second-order effect happens predominantly at the time when the density perturbations re-enter the Hubble horizon. In other words, gravitational waves are mainly generated at the same epoch as the primordial black holes' formation. Once produced, those GWs freely propagate in the subsequent epochs and they are still permeating the present Universe. Combining that the typical frequency of such gravitational waves at the formation time is comparable to the Hubble horizon and that the horizon radius at that time is comparable to the size of the PBHs allows us to relate the PBH mass to the frequency of the GWs at present time. Thus, primordial density perturbations producing stellar-mass PBHs generate ultra-low frequency GWs in the nHz band. Quite interestingly, such low-frequency gravitational waves are severely constrained by pulsar timing experiments [2].

3.7 Summary of constraints

The constraints on $f(M_{PBH})$, the fraction of the halo in PBHs of mass M, are summarised in Figure 3.2, although some of them have now been revised. Here, primordial black holes of given mass M must lie below the various lines provided by the observations: this corresponds to constrain the maximum fraction $f(M_{PBH})$ for every mass. All the limits assume that the PBHs have a monochromatic mass function and cluster in the Galactic halo in the same way as other forms of CDM. The effects taken into account are extragalactic γ-rays from evaporation (EG), femtolensing of γ-ray bursts (F), white-dwarf explosions (WD), neutron-star capture (NS), Kepler microlensing of stars (K), microlensing of stars (ML) and quasar microlensing (ML), survival of a star cluster(E), wide-binary disruption (WB), dynamical friction on halo objects (DF), millilensing of quasars (mLQ), generation of large-scale structure through Poisson fluctuations (LSS) and accretion effects (WMAP, FIRAS).

As indicated by the arrows in Figure 3.2, the permitted mass windows for f$\sim$1, i.e. the mass windows for which primordial black holes could provide a non-negligible source of dark matter, are:

(A) the intermediate mass range ($10 - 10^3\ M_\odot$),

(B) the sublunar mass range ($10^{20} - 10^{24}\ g$)

(C) the asteroid mass range ($10^{16} - 10^{17}\ g$)

The constraints discussed above assume that the PBH mass function is monochromatic. However, there are many scenarios in which one would expect the mass function to be extended. In the context of the dark-matter problem, this is a two-edged sword [1]. On the one hand, it means that the total PBH density may suffice to explain the dark matter, even if the density in any particular mass band is small and within the observational bounds discussed above. On the other hand, even if primordial black holes can provide all the dark matter at some mass-scale, the extended mass function may still violate the constraints at some other scale. This is still an open issue and it is under investigation.

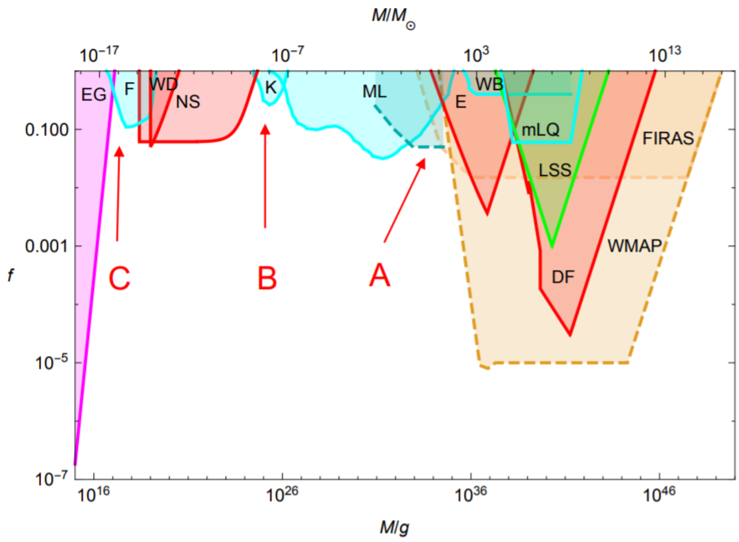

Figure 3.2: Summary of constraints on $f(M_{PBH})$. [1]

3.8 Claimed signatures

Most of the PBH literature has focused on constraints on their contribution to the dark matter, as discussed in the last section. However, a number of observations have been claimed as positive possible evidence for them, the masses ranging over 16 orders of magnitude, from $10^{-10}M_\odot$ to $10^6 M_\odot$ [6]. The first three are associated with lensing effects:

- microlensing events towards the Galactic bulge generated by planetary-mass objects, well above the expectations for free-floating planets;
- microlensing of quasars, including ones that are so misaligned with the lensing galaxy that the probability of lensing by a star is very low;
- the unexpected high number of microlensing events towards the Galactic bulge by dark objects in the so-called 'mass gap' between 2 and 5 $M_\odot$ where stellar evolution models fail to form black holes.

The next three are associated with accretion and dynamical effects:

- unexplained correlations in the source-subtracted X-ray and cosmic infrared background fluctuations;
- the non-observation of ultra-faint dwarf galaxies (UFDGs) below the critical radius of dynamical heating by PBHs;
- the unexplained correlation between the masses of galaxies and their central SMBHs.

The last one is associated with gravitational-wave effects:

- the observed mass, spin and coalescence distributions for the black holes found by LIGO/Virgo.

Anyway, up to now, these are only *claimed* signatures and there is no certainty regarding the causes of the corresponding effects.

Chapter 4

PBHs binaries

The discovery at LIGO of the merger event (GW150914) of binary BHs triggered a renewed interest of PBHs, especially in the stellar mass range. The unexpectedly large mass of the detected black holes (around $30M_{\odot}$) brought us a new mystery about this component of the Universe. After the LIGO event, elucidating the origin of these BHs - and binary formation - has emerged as an important topic in cosmology and astrophysics. Explaining the LIGO event by the PBHs is non-trivial in two respects. First, since the GWs are emitted from BH binaries, the formation mechanism of the primordial black hole binary must be considered in order to test the PBH scenario with gravitational waves observations. Secondly, there are existing constraints on the primordial black holes' abundances for the mass around the observed BH masses. It needs to be checked whether the PBH scenario does not conflict with those constraints. Here, we will briefly review two distinct formation mechanisms for PBH binaries. It is important to remark here that the two mechanisms are not incompatible, but operate at different epochs in the cosmic history.

4.1 Formation mechanisms

Radiation dominance epoch

The first mechanism we are going to discuss operates in the epoch when the Universe was dominated by radiation. Just after the PBHs were formed in the very early Universe, they were distributed sparsely in space and the mean distance at that time was much longer than the Hubble horizon. Because of the rapid cosmic expansion, they were on the expansion flow and the mean distance grew in proportion to the scale factor $a(t) \propto t^{1/2}$. Since the Hubble horizon grows as $H^{-1}(t) \propto t$, the mean distance relative to the Hubble horizon decreases as the Universe expands. Thus, for the stellar-mass PBHs, unless f_{PBH} is extremely tiny, there is a period in the radiation-dominated epoch in which there are typically more than one primordial black hole inside the Hubble horizon. The cosmic expansion acts as a force that pulls two PBHs away from each other. Two PBHs are also pulled by the gravitational force acting between them. A primordial black hole pair satisfying a certain condition in distance decouples from the cosmic expansion and becomes gravitationally bound. As the two PBHs come closer, the surrounding PBHs, especially the nearest one, exert torques on the bound system [2]. As a result, the two PBHs avoid a head-on collision, and typically form a highly eccentric binary, as we can see in Figure 4.1.

Present epoch

In addition to the primordial black hole binary formation in the radiation-dominated epoch, PBHs can form binaries in the present Universe. Let us consider a situation where a primordial black hole travelling in space accidentally has a near-miss with another PBH. These PBHs may be concentrated in a local region, such as inside a larger dark matter halo, or simply moving freely in space. Near the periastron of the system (i.e. the point of closest approach between the two PBHs), the relative acceleration of the PBHs becomes maximal and dominant emission of gravitational

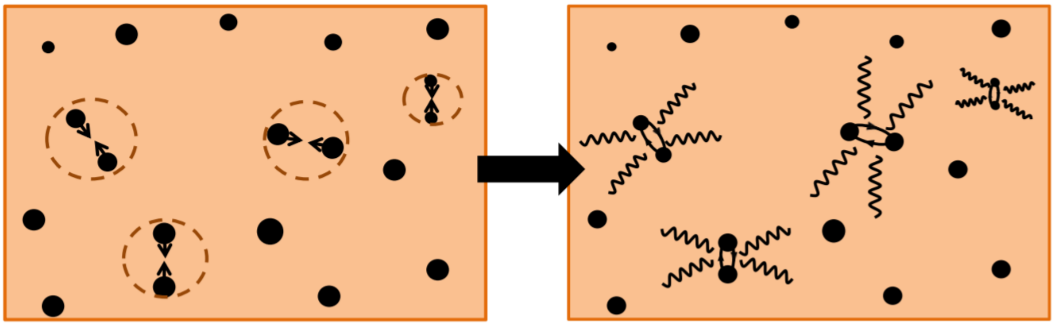

Figure 4.1: A schematic representation of the formation of PBH binaries in the radiation dominated epoch. [2]

radiation occurs. If the amount of energy of the emitted GWs is greater than the kinetic energy of PBHs, then the PBHs cannot escape to infinity any more and they form a bound system. Since a direct head-on collision is probabilistically unlikely, a binary typically results [2].

4.2 LIGO observations

Direct detection of gravitational waves by laser-interferometry is a completely novel method to search for primordial black holes that does not rely on electromagnetic waves. Soon after LIGO announced the first detection of GWs, caused by the merger of two BHs in a binary, several groups pointed out the possibility of the scenario that the observed BHs are primordial black holes. Thus, the exciting possibility has arisen that we might have discovered PBHs for the first time by the direct observation of gravitational waves (not just constraints!). From the observations made by interferometers it can be shown that $30M_{\odot} - 30M_{\odot}$ PBH binaries that are formed in the radiation-dominated era merge with frequency consistent with that estimated by the LIGO observations if $f_{PBH} \sim 10^{-3}$, and merge much more frequently if $f_{PBH} \sim 1$. This means that we can use the GW observations to place an upper limit on f_{PBH} irrespective of whether the observed mergers of BH binaries are attributed to PBHs or not. The derived constraint of $f_{PBH} \lesssim 10^{-3} - 10^{-2}$ excludes stellar mass PBHs as the dominant component of dark matter [2]. However, the detection does not exclude the primordial origin of the system and it still gives rise to a number of questions and possible scenarios. Indeed, we know that stellar mass PBHs seem not to be the dominant component of dark matter, but primordial black holes could still provide a source for dark matter in other mass windows. Even in the case in which PBHs do not contribute at all (or only by negligible quantities) to dark matter, they could still be important in generating cosmic structures as SMBHs and even galaxies. However, this result demonstrates that GW observations provide a novel tool to probe/constrain PBHs independently of electromagnetic observations.

Of course, the PBH scenario is not the only explanation of the LIGO events and there are several astrophysical scenarios that have been proposed as the origin of the LIGO events. So far, due to the small number of events detected, those scenarios are allowed observationally. Therefore, in principle, we are still not sure of the presence of primordial black holes. The next obvious task is to clarify how we can test the PBH scenario and discriminate it from the others by using future observations that will bring much more information.

4.3 Future constraints

We are at the dawn of the golden age of gravitational wave astronomy. In the future, ongoing experiments such as LIGO, Virgo and KAGRA will gain better sensitivity and be further upgraded and new types of experiment such as the Einstein telescope, Cosmic Explorer, LISA and DECIGO, each covering different frequency bands, will follow. Very likely, many more merger events will be detected and more statistical information on BHs and BH binaries such as mass, spin, eccentricity, redshift, spatial inhomogeneities, etc. will become available [2]. These new upcoming data will enable us to test the individual scenarios and possibly to pin down the best one.

Chapter 5

Summary

This report aimed to briefly review the present knowledge about primordial black holes. In the first chapter we started summarizing the historical background of such objects, analyzing then the most frequently studied formation scenarios, i.e. the gravitational collapse of overdense regions in the early Universe, the collapse of cosmic loops, bubble collisions and domain walls; finally we distinguished between the various types of mass functions. In the following chapter we reviewed the role of primordial black holes: we saw that in principle, depending on their mass functions, they could provide both potential cold dark matter candidates and seeds for cosmic structures, like supermassive black holes or galaxies. In chapter 3 we discussed a number of techniques in order to constrain the abundance of primordial black holes. For example, we saw the evaporating, lensing and dynamical constraints. All of these constraints give some well-accepted mass windows for PBHs in which, if they exist, they must lie. Among those, three mass windows remain in order to explain the dark matter problem: the asteroid mass range, the sublunar mass range and the intermediate mass range. We saw that, up to now, there are seven claimed signatures for primordial black holes, of which one was the merger detected by LIGO. Since there was a renewed interest in primordial black holes after the discovery at LIGO of the merger event GW150914 of binary BHs, in the fourth chapter we analyzed the formation mechanism of primordial black holes binary, distinguishing between two different epochs of formation in the cosmic history. We reviewed LIGO restrictions for the detected range of black holes binary, acknowledging that in the intermediate mass range PBHs can provide only a negligible fraction for dark matter. However, this does not exclude the primordial origin of the system and it could lead to mixed scenarios, in which either PBHs provide the entire content of the dark matter in different mass windows or they only produce little contributions to DM but they still play important cosmological roles. Furthermore, we can use the GW observations to place an upper limit on the fraction of PBHs irrespective of whether the observed mergers of BH binaries are attributed to PBHs or not. Since we know that gravitational wave astronomy has just begun, this leads to high hopes for the future. As GW astronomy progresses, it will continually bring us new findings and also it will stimulate related theoretical studies. Definitely, we will gain more knowledge about PBHs and the early Universe.

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