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Proceeding Paper

Escaping the Pair-Instability Mass Gap with the Help of Dark Matter †

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Abstract: Black Holes are not expected to form in the mass range of 60 $M_\odot$ to 130 $M_\odot$ because of the Pair-Instability Supernova (PISN). However, the recent observational evidence of GW190521 does not comply with the existing theory. Here, we have looked into the effects of Dark Matter (DM) in the progenitors of PISN in terms of luminosity, lifetime and temperature and have shown that in the presence of DM particles, the progenitors can overcome the PISN stage to collapse into a black hole (BH) as a remnant.

Keywords: dark matter; black hole mass gap; pair-instability supernova; gravitational waves

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1. Introduction

On 21 May 2019, the Laser Interferometer Gravitational-wave Observatory (LIGO) and a Virgo interferometer observed the largest binary black hole merger to date. The merger involved two black holes with masses of 85 $M_\odot$ and 66 $M_\odot$. The mass of the remnant black hole is about 142 $M_\odot$ [1]. One of the primary black holes (85 $M_\odot$) in the merger lies within the PISN mass gap. Non-rotating models with ZAMS ranging from 140 $M_\odot$ to 260 $M_\odot$ end their lives by exploding as PISN [2,3]. PISN occurs when Carbon–Oxygen (C-O) core reaches a mass ranging between 60 $M_\odot$ to 130 $M_\odot$, [4–7] at sufficient temperature ($T \sim 3 \times 10^9$ K) and density ($\rho < 5 \times 10^5$ g cm^{-1}), and the photon energy rises such that an electron–positron pair starts to form. The pair production phenomenon occurs at 1.2×10^{10} K, but even at 10^9 K, appreciable pair creation happens because of high-energy photons [8–10]. The formation of an electron–positron pair lowers the radiation pressure, thereby causing the star to become unstable. Once explosive oxygen burning takes place, the dynamical instability leads the C-O core to explode, leaving no compact remnant behind. Hence, no black holes between 60 $M_\odot$ and 130 $M_\odot$ in mass range are expected to form, but the GW190521 remains a contradiction.

There are a few alternative explanations for GW190521. One is the merger of black holes [11], stellar progenitors [12] or primordial black holes [13]. Another alternative extends the Standard Model [14], while another approach considers a gas accretion-driven mechanism that can build up black hole masses, which can reach up to any intermediate-mass black holes [15]. Another alternative says that the event may have occurred due to instantaneous collision in a dense and crowded galactic environment [16]. Another alternative says that if an extra energy source is added, other than nuclear fusion, then the star might avoid the PISN stage and leave a BH remnant behind. The extra energy source comes from DM annihilation [17]. However, we suggest that even the presence of DM particles in the progenitors can affect their evolution and leave a BH as remnant.

The evidence from the anisotropies in the cosmic microwave background [18], galaxy cluster velocity dispersions [19], large-scale structure distributions [20], gravitational lensing studies [21] and X-ray measurements from galaxy clusters [22] show that the universe is not dominated by ordinary baryonic matter, but by a form of non-luminous matter called dark matter. DM is non-baryonic matter which is about five times more abundant than ordinary baryonic matter. DM normally interacts only via gravity and is dynamically cold. Weakly Interacting Massive Particles (WIMPs) are hypothesized to be DM particles, which are the thermal relics of the early universe [23,24]. Recent studies have shown that the stellar structure and evolution could be affected by the admixture of DM particles and baryonic matter, especially in the formation of stars in the early universe [25]; white dwarfs [26]; neutron stars [27]; and in the evolution of low-mass red giants [28]. In this work, we extend this idea and study how DM admixture can affect the progenitor of PISN. We also show that the presence of DM can help the progenitor to escape the PISN phase and form a black hole.

2. Method

From the hydrostatic equilibrium relation [29],

$$T_c \propto \frac{M}{R} \tag{1}$$

It is clear that the core temperature (T_c) increases as the mass (M) increases. If more DM fraction is present in the star, then the star's core temperature will increase, thereby the star will burn faster and brighter to maintain equilibrium. Using the relations between the mass and parameters such as temperature, lifetime, and luminosity, we can analyze how DM particles of different mass and different fractions can affect the progenitor of PISN.

3. Results and Discussion

3.1. Effect of Dark Matter on the Temperature of the PISN Progenitors

Whether a C-O core becomes degenerate or not depends upon its mass. For simplicity, we neglect radiation pressure, as well as the creation of electron–positron pairs, which can also lead to partial degeneracy of electrons at very high temperatures and low densities. Thus, from the equation of state, we arrive at the relation between the maximum core temperature and the core mass as [29]:

$$T \propto M^{1.3} \tag{2}$$

To analyze how DM admixture alters the progenitor, we take the ratio of mass in the presence of DM particles to the mass in absence of DM particles, which is given as:

$$\frac{M_{DM}}{M_0} = \frac{f m_{DM} + (100 - f) m_B}{100 m_B} \tag{3}$$

where f is the fraction of dark matter particles, m_B is the mass of baryonic matter (mass of proton, $m_p \approx 1$ GeV) and m_{DM} is the mass of DM particle. Based on (2) and (3), the ratio of temperature in the presence of DM particles (T_{DM}) to the temperature in the absence of DM particles (T_0) can be given as:

$$\frac{T_{DM}}{T_0} = \left(\frac{M_{DM}}{M_0} \right)^{1.3} \tag{4}$$

The plot for increasing fractions of DM particles, with the ratio of the temperature in the presence of DM particles (T_{DM}) to the temperature in the absence of DM particles (T_0), can be seen in Figure 1.

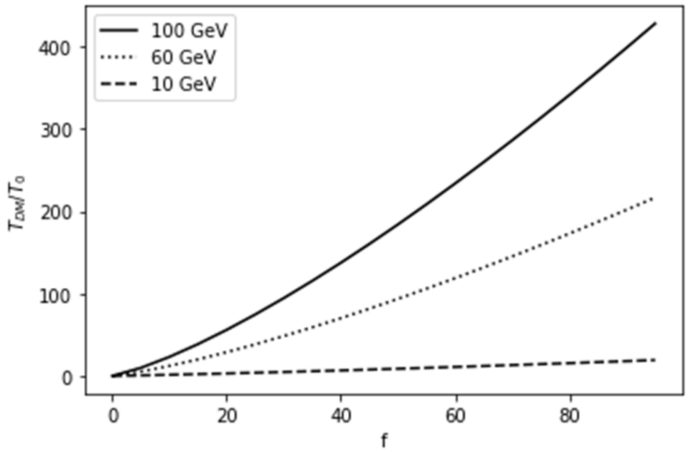

Figure 1. Variation of temperature with increasing dark matter fraction.

Thus, for a DM particle with a mass of 10 GeV, even a fraction of $f \sim 0.1$ (10% of DM admixture) will lead to a temperature increase by a factor of 2. Similarly, for a DM particle with a mass of 60 GeV, a fraction of $f \sim 0.1$ will lead to a temperature increase by a factor of 13 and for $1m_{DM}$ = 100 GeV, the temperature will increase by a factor of 24 for $f \sim 0.1$.

3.2. Effect of Dark Matter on the Lifetime of the PISN Progenitors

When the star burns more quickly to maintain the equilibrium, the rate of fusion in the core increases, which reduces the lifetime of the star. During the nuclear fusion phase in the star, the timescale is given by [30]:

$$\tau \approx \frac{M\epsilon c^2}{L} \tag{5}$$

where ϵ is the mass defect of the nuclear reaction and L is the luminosity output. The ratio of the lifetime of the progenitor in the presence of DM particles (τ_{DM}) to the lifetime of the progenitor in the absence of DM particles (τ_0) is given as:

$$\frac{\tau_{DM}}{\tau_0} = \left(\frac{M_{DM}}{M_0}\right)^{-0.45} \tag{6}$$

The plot for the increasing fraction of DM particles with the ratio of the lifetime in the presence of DM particles (τ_{DM}) to the lifetime in the absence of DM particles (τ_0) can be seen in Figure 2.

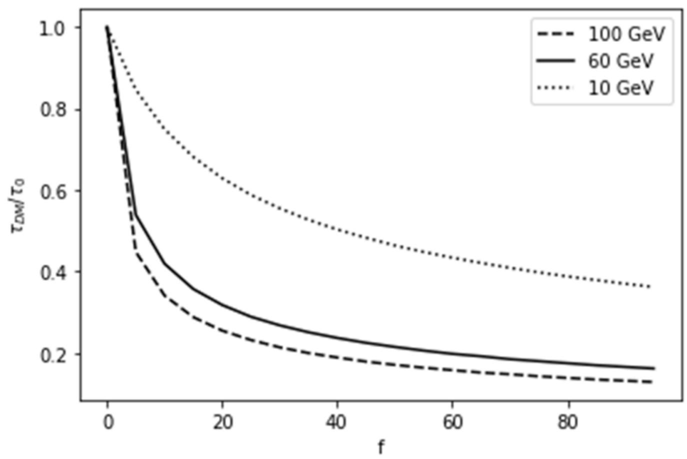

Figure 2. Variation in lifetime with increasing dark matter fraction.

Thus, for a DM particle with a mass of 10 GeV, a fraction of $f \sim 0.1$ will reduce the lifetime to 0.7 times that of the original lifetime (without the presence of DM). Similarly, for a DM particle with a mass of 60 GeV, a fraction of $f \sim 0.1$ reduces the lifetime to 0.4 times the original lifetime and for $1m_{DM}$ = 100 GeV, a 10% of DM admixture will result in lifetime reduced to 0.3 times.

3.3. Effect of Dark Matter on the Luminosity of the PISN Progenitors

Because of DM admixture, the star burns more brightly in order to maintain the equilibrium. The greater the rate of fusion in the core, the higher the luminosity of the star. Thus, the DM admixture contributes to a considerable increase in the luminosity of the star. The *M*/*L* relation for rotating massive stars at solar composition for ZAMS between 120 $M_\odot$ to 500 $M_\odot$ is given as [31]:

$$L \propto M^{1.45} \tag{7}$$

From (7), the ratio of luminosity in the presence of DM particles (L_{DM}) to the luminosity in the absence of DM particles (L_0) is given as:

$$\frac{L_{DM}}{L_0} = \left(\frac{M_{DM}}{M_0}\right)^{1.45} \tag{8}$$

The plot for the increasing fraction of DM particles with the ratio of the luminosity in the presence of DM particles (L_{DM}) to the luminosity in the absence of DM particles (L_0) is seen in Figure 3.

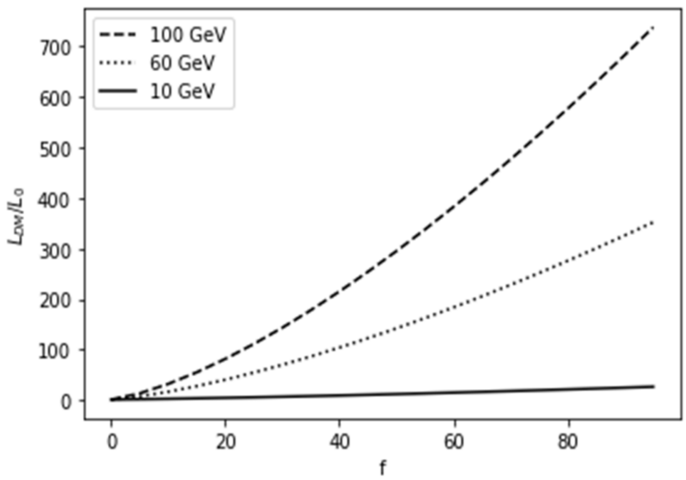

Figure 3. Variation in luminosity with increasing dark matter fraction.

For a DM particle with a mass of 10 GeV, a fraction of $f \sim 0.1$ will lead to an increase in the luminosity by a factor of 2.5. As the mass of the DM particle is increased to 60 GeV, a fraction of $f \sim 0.1$ will lead to an increase in luminosity by a factor of 16. For $1m_{DM}$ = 100 GeV, the luminosity of the progenitor will increase by a factor of 31 for $f \sim 0.1$.

3.4. Overcoming the PISN Stage

In massive stars, carbon burning occurs at temperatures around T = 0.6–1.0 $\times$ 10^9 K. Oxygen burning occurs around T = 1.5–2.7 $\times$ 10^9 K and T = 3–4 $\times 10^9$ K in explosive environments [32]. A temperature rise by a factor of 10 (from 0.5 $\times$ 10^9 K to 5 $\times$ 10^9 K) will lead to the progenitor vanquishing the explosive oxygen burning stage by burning faster and brighter. The lifetime of carbon burning is about 10^2–10^3 years [30]. For a DM particle with a mass of 10 GeV, a fraction of $f \sim 0.1$ will reduce the lifetime to 0.7 times the original lifetime (without the presence of DM). So, the lifetime of the carbon burning phase reduces from 1000 years to 700 years.

From Figure 4, we can infer that for the temperature to increase by a factor of 10, we need a fraction of $f \sim 0.5$ for a DM particle with a mass of 10 GeV and a fraction of $f \sim 0.06$ for a DM particle with a mass of 80 GeV. For a DM particle with a mass of 60 GeV, a fraction of $f \sim 0.08$ is enough to raise the temperature by a factor of 10, reaching $T \sim 5 \times 10^9$ K, thereby avoiding the explosive oxygen burning phase and collapsing into a black hole in the PISN mass gap region. Similarly, for a DM particle with a mass of 100 GeV, a fraction of $f < 0.05$ is enough for the progenitor to collapse into a black hole.

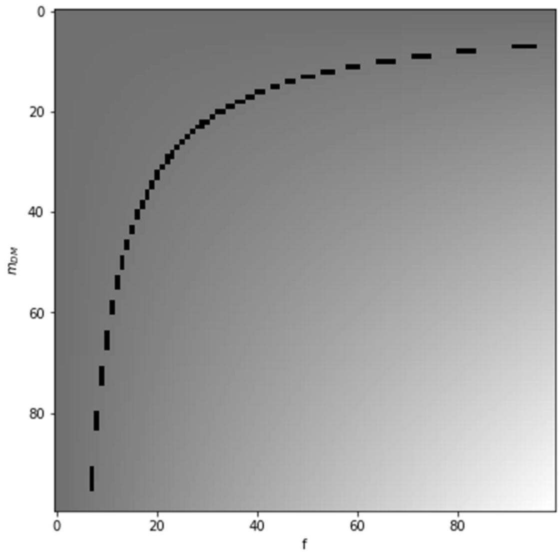

Figure 4. DM fraction versus DM mass for a change in temperature by a factor of 10.

4. Conclusions

We have used DM particles of different masses to explain the discrepancy of the black hole's existence in the PISN mass gap. From the results, we can conclude that when the core mass rise in the presence of DM, the brightness and temperature also rise. The increased brightness and temperature cause the lifetime of the PISN progenitor to drop by around half, even in the presence of relatively small fractions of DM. The admixture model is extensively used to show that the PISN progenitors could collapse into a black hole in the PISN mass gap by burning faster and brighter.

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