Low Mass Black Holes from Dark Core Collapse

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Unusual masses of the black holes being discovered by gravitational wave experiments pose fundamental questions about the origin of these black holes. Black holes with masses smaller than the Chandrasekhar limit \( \approx 1.4 M_\odot \) are essentially impossible to produce through stellar evolution. We propose a new channel for production of sub-Chandrasekhar mass black holes: stellar objects can catastrophically accrete non-annihilating dark matter in dense regions of the Universe, owing to interactions of dark matter and ordinary matter, and the dark core subsequently collapses. The wide range of allowed dark matter masses allows a smaller effective Chandrasekhar limit, and thus smaller mass black holes. We point out several avenues to test our proposal.

**Introduction** – A non-baryonic form of matter, known as dark matter (DM), forms a dominant component of our Universe [1]. Experimental searches have been trying to search for DM particles but no conclusive evidence has shown up yet. Primordial black holes (PBHs) are an alternate well-motivated DM candidate [2–5] that can constitute all of the DM density [6–11]. PBHs as a DM candidate have received renewed attention [12–15]. Numerous constraints exist on their density [9, 16–38] and many other tests have been proposed [6, 39–43]. However, there are no established formation mechanisms which naturally produce the correct abundance of PBHs. The initial abundance of PBHs is exponentially sensitive to the spectrum of density perturbations and the threshold for collapse; fine-tuning of parameters is required to achieve a non-negligible abundance.

With the remarkable advances in gravitational wave (GW) and multi-messenger astronomy, the detection of a sub-Chandrasekhar mass \( \leq 1.4 M_\odot \) BH may be just around the corner signaling new physics. Usual stellar evolution cannot lead to sub-Chandrasekhar mass BHs, and the most discussed alternatives are PBHs. The recent detections of GW190425 [50] and GW190814 [51], which are either the heaviest neutron stars (NSs) or the lightest BHs ever seen, have ignited interest in \( \mathcal{O}(1) M_\odot \) BHs [52–56]. These developments motivate our study on sub-Chandrasekhar and \( \mathcal{O}(1) M_\odot \) BHs.

The key question is, given the GW observation of a merger involving sub-solar-mass object(s), how can we pinpoint their identity? As pointed out in Refs. [57, 58], DM accretion in stars can in fact transmute them to such BHs. However, these models, employing dark quantum electrodynamics sector DM or a fermionic asymmetric DM with non-negligible self-interaction strength, are not generic. Transmutation of stellar objects to BHs due to core collapse has been extensively studied in order to set stringent constraint on DM-nucleon scattering cross section from the existence of old NSs [47–49, 59–66], from connection with type-Ia supernovae [7, 67–70] as well as connections to several other astrophysical phenomenon [71–75].

In this Letter, we propose a simple and generic mechanism to trigger dark core collapse and convert a sub-Chandrasekhar or \( \mathcal{O}(1) M_\odot \) stellar object to a comparable mass BH and propose several tests for the proposal. We show that non-annihilating DM with usual interactions with nuclei is sufficient for such transmutations. Continuous accumulation of non-annihilating DM particles in the core, followed by their gravitational collapse at a modified Chandrasekhar limit set by DM particle properties, can produce sub-Chandrasekhar or \( \mathcal{O}(1) M_\odot \) BHs and is a viable alternative to PBHs. We try to answer a few basic questions: what particle physics parameter space can these explore, how do we test the origin of these BHs, and especially, how to distinguish them from PBHs?

**Methods & Results** – Non-annihilating DM scatters with stellar nuclei, gets captured via single [76, 77] or multiple scattering [78–80], and accumulates inside a stellar object linearly with time. An estimate of the total number of captured DM particles inside a stellar object can be found in [81, 82] and [49], in the contact interaction approximation and for interactions mediated by any arbitrary mass mediators, respectively. Once the captured DM particles satisfies the collapse criterion, i.e., \( N_\chi \big|_{\text{age}} \geq \max \left[ N_{\text{Cha}}, N_{\text{self}} \right] \), transmutation occurs, where \( N_\chi \big|_{\text{age}} \) is the total number of accumulated DM particles within a celestial object throughout its age \( t_{\text{age}} \). \( N_{\text{Cha}} \) and \( N_{\text{self}} \) denote the Chandrasekhar limit (which depends on the DM particle spin) and the number of DM particles required for initiating the self-gravitating collapse. For bosonic (fermionic) DM, zero point energy is provided by the Heisenberg uncertainty principle (Pauli exclusion principle). The Chandrasekhar limit, \( N_{\text{Cha}} \), for bosonic DM, \( \sim 1.5 \times 10^{34} \, (100 \text{ GeV}/m_\chi)^2 \) can be met more easily than for its fermionic counterpart, \( \sim 1.8 \times 10^{51} \, (100 \text{ GeV}/m_\chi)^2 \), explaining an easier transmutation for bosonic DM [47, 68]. The required number of DM particles for self-gravitating, \( N_{\text{self}} \), does not depend on the spin statistics of the DM particles, and is set by the condition that DM density has to exceed the baryonic density within the stellar core.
Once the captured DM particles satisfy the collapse criterion, dark core collapse can ensue and a tiny BH is formed within the stellar object. This BH accumulates matter from the host star and transmutes the star into a comparable mass BH. For typical NS parameters, if this tiny BH is lighter than $\sim 10^{-20} M_{\odot}$, it evaporates faster than its mass accretion rate and cannot transmute the NS to a BH [9, 62]. For non-annihilating bosonic and fermionic DM, transmutation of a typical NS ceases due to efficient Hawking evaporation for masses $\gtrsim O(10^7)$ GeV and $\gtrsim O(10^{10})$ GeV respectively.

Transit of a tiny PBH through a compact object and subsequent conversion of the host to a BH can produce sub-Chandrasekhar and $O(1) M_{\odot}$ BHs [71, 83]. The estimated capture rate of a tiny PBH by a NS was revisited in [7, 84], which showed that the actual capture rate is quite small, $\sim 10^{-17} \text{ yr}^{-1}$ for a NS residing in a Milky-Way-like galaxy with ambient DM density, $\rho_{\chi} = 1 \text{ GeV cm}^{-3}$. The capture rate scales linearly with the ambient DM density and has a strong dependence on the velocity dispersion, $\langle \bar{v} \rangle^{-3}$. An $O(1)$ Gyr old NS in a DM dense region ($\rho_{\chi} = 10^3 \text{ GeV cm}^{-3}$) inside a globular cluster...
(\bar{v} \sim 10^{-5}) can in principle implode due to a PBH transit. However, such over-dense DM cores in a globular cluster are quite speculative and not yet well established. It has in fact been shown that globular clusters do not have any DM over-densities [85–88]. Hence, the explanation of a sub-Chandrasekhar or \(O(1) M_\odot\) BH due to a PBH transit hinges on the contentious assumption of a high DM density in globular clusters, and remains uncertain until the provenance of globular clusters is settled.

Fig. 1 shows the parameter space where a sub-Chandrasekhar mass NS (1.3 \(M_\odot\)) can transmute to a comparable mass BH for both bosonic and fermionic DM. DM-nucleon interactions mediated by an infinitely heavy mediator (light mediator of mass 10 MeV) is assumed in the top (bottom) panel. Exclusion limits from underground direct detection experiments PANDAX-II [44] and XENON1T [45] (similar limits also exist from the LUX collaboration [89]) as well as from the existence of an old nearby pulsar PSR J0437-4715 [47–49] are also shown along with the required parameter space for dark core collapse for two given ambient DM densities. In the contact interaction approximation, asymmetric bosonic DM of mass \(O(100)\) GeV in a DM dense environment with a non-zero interaction strength with nuclei is sufficient to explain a sub-Chandrasekhar mass BH. On the other hand, \(O(1)\) PeV asymmetric fermionic DM can also explain the same. For DM-nucleon interaction mediated via lighter mediators, transmutation of compact objects is more economical as exclusion limits weaken and implosions can be achieved with wider range of parameters. Similar analysis can also be performed for transmutation of a white dwarf (WD) due to dark core collapse. However, because of the lower baryonic density compared to a NS, the implosion criterion is harder to achieve for a WD. The required parameter space for transmutation turns out to be narrower with respect to that obtained from a NS: in order to implode a solar mass WD with ambient DM density \(10^3\) GeV cm\(^{-3}\), the scattering cross section has to be \(\gtrsim 10^{-44}\) cm\(^2\) for a 10 PeV asymmetric bosonic DM, whereas, the corresponding cross-section for a NS with the same ambient DM density is \(\sim 10^{-48}\) cm\(^2\).

The ambient DM density around a sub-Chandrasekhar or \(O(1) M_\odot\) BH plays a pivotal role to determine its origin. It is a simple yet powerful probe to determine the origin of the BH, more specifically, to distinguish a transmuted BH from a PBH. Since the DM rich environment favors implosion of stellar objects, detection of a sub-Chandrasekhar or \(O(1) M_\odot\) BH in a low DM dense region will prefer a primordial origin. Coexistence of a sub-Chandrasekhar or \(O(1) M_\odot\) BH and an NS of similar age can be a smoking gun signature of its primordial origin, as the required parameter space for such transmutation will be disfavored by the existence of the companion NS.

Fig. 2 shows the spatial distribution of the NSs within a Milky Way like galaxy. Three components of the NS distributions, disk, bulge and the nuclear star cluster component are added together [90]. Since the DM dense inner regions potentially contain a large number of NSs, detection of an \(\sim O(1)\) Gyr old NS by the next generation radio telescopes like FAST [94] and SKA [95] will significantly strengthen the exclusion limits. As a consequence, the allowed parameter space for dark core collapse and subsequent transmutation of a stellar object will shrink and support the PBH scenario for a sub-Chandrasekhar or \(O(1) M_\odot\) BH.

Fig. 3 shows the cosmic evolution of the binary merger rate as well as mass distributions of the compact objects that can be used to determine the stellar or primumordial origin of BHs. Left panel of Fig. 3 shows the cosmic evolution of the PBH-PBH merger rate and rate of mergers involving one or more BHs which form out of a transmuted NS. The merger rate of a binary NSs peak at \(O(1)\) redshift as the star formation rate is maximum at that redshift, and the merger rate of binary NSs [97, 98, 101, 102] traces the cosmic star formation rate [97, 103]. On the other hand, the merger rate of PBH binaries keeps rising with higher redshift simply because of the fact that PBH binaries can form more easily in the early universe [15, 96, 104, 105]. This distinct redshift dependence of the merger rates, especially at higher redshifts, can be measured with the upcoming GW detectors like Cosmic Explorer [106] and space based GW detector Pre-DECIGO [107] which will distinguish the transmutation via implosion scenario from PBHs.

Mass distributions of the compact objects provide yet another powerful way to distinguish transmuted BHs from PBHs. Since, the transmuted BHs track the mass distribution of their progenitors, it can be compared
against well motivated PBH mass distributions to statistically determine the stellar or primordial origin of BHs. The last two panels of Fig. 3 correspond to the mass distribution of all observed NSs and white dwarfs. In fact, apart from mass distribution and redshift dependence of the merger rate, several other probes such as eccentricity measurement of binaries [108], the correlation between GW sources and galaxies [109, 110], which are typically used to distinguish PBH binaries from standard astrophysical binaries, can also be used to differentiate sub-Chandrasekhar mass or $\mathcal{O}(1)$ transmuted BHs from BHs of primordial origin. Extensive surveys for disappearing isolated NSs, though very challenging, may be a smoking gun of transmuted BHs.

With imminent ground and space based GW detectors, about one binary NS merger event is expected per week [111]. Considering the huge number of expected events, the greatly improved sky localization of the GW events with a multi-detector network [111], as well as the GW lensing [112], the implosion scenario can easily be tested in the near future. There also exist several ways to distinguish a transmuted BH binary from a binary NS. The peak signal frequency of a binary NS merger is much lower than that of a binary BH merger due to the less compact nature of NSs compared to the similar mass BHs [58]. Besides, the dimensionless tidal deformability parameter, which is zero for a BH and $\sim 100$ for a NS, can also be used to probe this implosion scenario [113]. More importantly, possible detection of an associated electromagnetic counterpart from radio wavelengths to gamma rays can also distinguish binary BHs from binary NSs or BH-NS merger.

Summary & Outlook – Sub-Chandrasekhar mass BHs cannot be explained by stellar evolution and will herald new physics. PBHs are the most discussed explanation of these objects. The notable alternative proposals, conversion of a compact object due to a PBH transit [83] and transmutation of compact objects due to dark core collapse [57, 58] are either not effective or appeal to baroque DM models. We study a simple mechanism for transmutation of compact objects that can naturally produce these sub-Chandrasekhar mass BHs without fine tuning. Non-annihilating DM with non-zero interaction strength with stellar nuclei, which is a vanilla DM model, already predicts such transmutation. For sub-Chandrasekhar mass progenitor, the imploded BH is a viable alternative to PBHs, whereas, for a heavier mass progenitor, it can possibly explains the lighter companions of recent anomalous GW events. Cosmic evolution of the merger rate and the mass distributions of the progenitors are simple yet powerful probes of our proposal. Observation of an associated electromagnetic counterpart along with a GW event, as well as a precise measurement of the tidal deformability parameter, can differentiate merger of such transmuted BHs from a binary NS merger or a BH-NS merger. Importantly, possible detection of any sub-Chandrasekhar mass BH in a DM deficient environment or accompanied by an old NS can falsify our proposal. Improved sky localization with multi-detector networks as well as sub-arc second precision of a GW event from GW lensing can also shed light on this topic in near future.

Note added – Ref. [114], which is on a similar topic, appeared on arXiv while this paper was being written. Our work differs in several respects and we do not consider PBH capture on stars due to the recent calculations [7, 84]. Both papers use different inputs but we agree on the general message: implosion scenarios can be
a viable alternative of PBHs, as well as can explain recent GW events and can easily be tested via several techniques in, and can be extensively tested in near future.

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