Neutrino and positron constraints on spinning primordial black hole dark matter

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(Dated: December 4, 2019)

Angular momentum is a fundamental property of a black hole and is known to have a strong effect on its evaporation rate. It has recently been postulated that primordial black holes can have substantial spin. We conduct a comprehensive study of the detectability of primordial black holes with non-negligible spin, via the searches for the diffuse supernova neutrino background and observation of the 511 keV gamma-ray line from positrons in the Galactic center, setting competitive constraints. Spinning primordial black holes are probed up to a slightly higher mass range compared to non-spinning ones. Our constraint using neutrinos is slightly weaker than that due to the diffuse gamma-ray background. We find that the positron constraints are typically weaker in the lower mass range and stronger in the higher mass range for the spinning primordial black holes compared to the non-spinning ones. They are generally stronger than those derived from the diffuse gamma-ray measurements for primordial black holes having masses greater than a few $10^{16}$ g.

Introduction – Astrophysical observations provide unambiguous evidence of a non-relativistic, collision-less, and weakly interacting matter, known as dark matter (DM), constituting $\sim 26\%$ of the total energy density of the Universe [1–3]. Many well-motivated DM candidates have been proposed and decades of experimental searches conducted, yet the microscopic identity of DM remains unknown. One of the earliest proposed DM candidates is a population of primordial black holes (PBHs) [4–10]. There exist numerous observational constraints on the fraction of DM comprised of PBHs [11–48], however, there still exists parameter space where PBHs can form all of the DM [38, 44, 45]. Multiple techniques have been advocated in order to probe PBHs in various mass ranges [38, 49–53]. Given this increased scrutiny of PBHs (which started after the direct detection of gravitational waves [54, 55] and the subsequent proposal that these BHs are primordial in nature [56–59]), it is obvious to ask if we have explored all the properties of BHs in our searches for PBHs. Typically, it has been assumed that PBHs have low spins [60–62], however, there exist viable cosmological scenarios where PBHs are born with a high spin [63–70]. Angular momentum is a fundamental property of BHs and it is crucial to explore its implications [71–74]. Here, we study the impact of angular momentum on the observability of PBHs.

PBHs with masses $\lesssim 10^{-16} M_\odot$ can be discovered via the observation of particles produced through Hawking radiation. The lifetime of PBHs with masses less than $2.5 \times 10^{-19} M_\odot$ ($3.5 \times 10^{-19} M_\odot$) for non-rotating (maximally rotating) black hole is less than the age of the Universe and it cannot contribute to the DM density [75–78]). The leading constraints on low-mass PBHs arise from the observation of photons [22, 30, 48], cosmic rays [79], and the 511 keV gamma-ray line [46, 47]. Astrophysical observations of neutrinos have been used to constrain particle DM [80, 81] and here we study its implications for PBHs. Earlier analyses of the positron and the neutrino observations have focussed on non-spinning PBHs [82–88]. Using the latest experimental inputs, we thoroughly investigate the constraints on spinning and non-spinning PBHs.

The origin of the 511 keV gamma-ray line from the Galactic centre (GC) is one of the enduring mysteries of astrophysics [89–92]. Many models have been proposed to explain this observation [93–104], yet none are confirmed. Our constraints are agnostic of these models and robust. The diffuse supernova neutrino background (DSNB) is the accumulation of all neutrinos emitted by core-collapse supernovae over the history of the Universe [105–107]. The current upper limits on the $\bar{\nu}_e$ flavour of DSNB are due to the observations in Super-Kamiokande [108], KamiLAND [109], and Borexino [110]. We probe the DM fraction of non-spinning and spinning PBHs by considering neutrino and positron emission and possible detection by Super-Kamiokande (Super-K) and INTEGRAL, respectively. By considering a log-normal mass distribution, we can probe further into a previously unexplored mass window. At low masses, our results constrain the possibility that PBHs make up all the DM.

Methods & Results – PBHs can have wide range of masses depending on its formation time [22]. An uncharged rotating BH radiates with a temperature [75, 76, 111–113]

$$T_{\text{PBH}} = \frac{1}{4\pi G_N M_{\text{PBH}}} \frac{\sqrt{1 - a_*^2}}{1 + \sqrt{1 - a_*^2}},$$

(1)

where $M_{PBH}$ denotes the mass of the PBH, $G_N$ is the gravitational constant, $a_* \equiv J/(G_N M_{PBH}^2)$ is the reduced spin parameter, and $J$ is the angular momentum of the PBH. Fig. 1 shows $T_{\text{PBH}}$ as a function of $a_*$ for various values of $M_{PBH}$. For a given PBH mass, the temperature can vary by orders of magnitude as the PBH spin...
approaches its extremal value, \( a_* \to 1 \).

The number of emitted particles with spin \( s \) in the energy interval \( E \) and \( E + dE \) and in a time interval \( dt \) from a PBH is

\[
d^2N/dEdt = \frac{1}{2\pi} \frac{\Gamma_s(E, M_{\text{PBH}}, a_*)}{\exp[E/T_{\text{PBH}}] - (-1)^{2s}}, \tag{2}
\]

where \( \Gamma_s \) is the greybody factor \([72, 75–77, 112–114]\) and \( E' \) is the total energy of the emitted species including the rotational velocity. For the rest of our analysis, we will use BlackHawk to compute the spectra of the emitted particle \([73]\). We have checked this emission rate using the semi-analytical formulas from Ref.\([75–77, 112]\).

As the temperature of a PBH becomes comparable to the rest mass of a particle, such a particle is emitted in significant numbers \([75–77]\). We first focus on the emission of neutrinos from PBHs. In order to derive bounds from the DSNB, we need to take into account the Galactic and extragalactic contribution of PBHs. The Galactic contribution is given by

\[
F_{\text{Gal}} = \int d\Omega \int dE d^2N/dEdl \int dl f_{\text{PBH}} \rho_{\text{DM}}(r(l, \psi)) M_{\text{PBH}}, \tag{3}
\]

where \( r \) is the Galactocentric distance, \( \rho_{\text{DM}}(r) \) denotes the DM profile of the Milky Way (MW), \( l \) is the distance from the observer, \( \psi \) is the angle between the line of sight and the observer, \( \Omega \) is the solid angle under consideration, and the fraction of DM composed of PBHs is denoted by \( f_{\text{PBH}} \). The upper limit of the line of sight integral, \( l_{\text{max}} \), depends on the MW halo size and \( \psi \) \([115]\). We use the NFW and the isothermal DM profiles using the parametrization in Ref.\([115]\). For the extragalactic contribution, the differential flux is \([22, 72]\)

\[
F_{EG} = \int dt dE (1 + z(t)) f_{\text{PBH}} \rho_{\text{DM}} d^2N/dEdt E=1+z(t)E, \tag{4}
\]

where the time integral runs from \( t_{\text{min}} = 1 \text{ s} \), the neutrino decoupling time, to \( t_{\text{max}} \), the smaller of the PBH lifetime and age of the Universe. The average DM density of the Universe at present time is denoted by \( \rho_{\text{DM}} \). We use the cosmological parameters determined by the Planck observations \([1]\).

In addition to a monochromatic mass function for PBHs, we also consider a log-normal mass function, as predicted by many inflation models \([116–126]\):

\[
dN_{\text{PBH}}/dM_{\text{PBH}} = \frac{1}{\sqrt{2\pi}\sigma M_{\text{PBH}}} \exp \left[ -\frac{\ln^2(M_{\text{PBH}}/\mu_{\text{PBH}})}{2\sigma^2} \right], \tag{5}
\]

where \( \mu_{\text{PBH}} \) and \( \sigma \) are the average mass and width of the distribution, respectively.

The upper limit on \( f_{\text{PBH}} \) is obtained by comparing the total Galactic and extragalactic flux due to PBHs, with the current upper limit on the DSNB flux from different experiments. Neutrinos are emitted as mass eigenstates during PBH evaporation \([127]\). So, for \( T_{\text{PBH}} \gg m_\nu \), the \( \bar{\nu}_e \) flux is approximately equal to that of any one of the mass eigenstates. Current upper limits on the DSNB flux are 2.9 \( \bar{\nu}_e \text{ cm}^{-2}\text{s}^{-1} \) (139 \( \bar{\nu}_e \text{ cm}^{-2}\text{s}^{-1} \)) in the energy \( (E_\nu) \) range of 17.3 MeV to 91.3 MeV (8.3 MeV to 31.8 MeV) respectively \([108, 109]\). We find that the Super-Kamiokande and the KamLAND data help us probe the physical region of \( f_{\text{PBH}} < 1 \). We only show the upper limit obtained using the Super-Kamiokande data, as it is stronger at all PBH masses we consider.

Fig. 2 shows the upper limits on \( f_{\text{PBH}} \) that can be derived from DSNB observations for various PBH mass distributions and spins. The left panel shows the constraints for the monochromatic mass distribution, whereas the middle and the right panels show the constraints for a log-normal distribution with \( \sigma = 0.5 \) and 1, respectively. For all these cases, we choose \( a_* = 0, 0.5, 0.9 \), and 0.9999 and the NFW profile to derive our limits. Since spinning BHs evaporate faster \([75–77]\), the limits for \( a_* = 0.5 \) and 0.9 are stronger than the non-spinning cases for the three mass distributions. For \( a_* = 0.9999 \), we find that the constraints are typically weaker than for \( a_* = 0.9 \). This can be understood by the rapid decrease in \( T_{\text{PBH}} \) as \( a_* \to 1 \) for a fixed value of \( M_{\text{PBH}} \). Due to the much smaller temperature, there are fewer neutrinos in the relevant energy interval, giving a weaker constraint. As we are searching for an all-sky signal, the limit has very little dependence on the DM profile of the MW.

For the detection of much lower energy neutrinos, PTOLEMY is a proposed experiment with the capability to detect the cosmic neutrino background \([128, 129]\). We found that the event rate of low energy neutrinos coming from the PBH evaporation is incredibly small in
FIG. 2. Upper limit on dark matter fraction of PBHs, $f_{\text{PBH}}$, from DSNB searches at Super-Kamiokande. The left, middle, and right panel corresponds to a monochromatic PBH mass function and log-normal PBH mass functions with $\sigma = 0.5$ and 1.0, respectively. In each plot, four different lines correspond to four different reduced spin parameters ($a_*=0, 0.5, 0.9, 0.9999$) of PBHs. Tiny dotted, dashed, dot-dashed, and solid lines correspond to $a_*=0, a_*=0.5, a_*=0.9, a_*=0.9999$, respectively. These constraints are derived using an NFW dark matter profile of the Milky Way.

FIG. 3. Upper limit on dark matter fraction of PBHs, $f_{\text{PBH}}$, from INTEGRAL 511 keV gamma-ray line measurement. The left, middle, and right panels correspond to a monochromatic PBH mass function and log-normal PBH mass functions with $\sigma = 0.5$ and 1.0, respectively. In each plot, four different lines correspond to four different reduced spin parameters ($a_*=0, 0.5, 0.9, 0.9999$) of PBHs. Tiny dotted, dashed, dot-dashed, and solid lines correspond to $a_*=0, a_*=0.5, a_*=0.9, a_*=0.9999$, respectively. These constraints are derived using an NFW dark matter profile of the Milky Way and assume that 80% of positrons within 3.5 kpc of the Galactic center annihilate to produce the 511 keV signal.

PTOLEMY and thus it will not be able to set useful limits [127].

The constraints from the GC positrons are derived following Ref. [47]. Given the plethora of astrophysical models to explain the GC 511 keV line, we derive the most conservative bound by simply requiring that the number of positrons injected via PBH evaporation is smaller than the number of positrons required to explain the observed 511 keV line. The major uncertainty in this technique arises from the unknown propagation distance of positrons in the GC [93, 130, 131].

The observed flux of 511 keV photons implies that the total production rate of positrons within the Galactic bulge is $\sim 10^{50}$ yr$^{-1}$ [91, 92, 132]. The limit on the PBH-fraction of DM ($f_{\text{PBH}}$) is obtained by requiring that positron injection rate from PBHs obeys this constraint:

$$f_{\text{PBH}} \leq \frac{10^{50} \text{ yr}^{-1}}{\int dE \int dM_{\text{PBH}} \int \frac{dN_{\text{PBH}}}{dE dM_{\text{PBH}}} d^{3}r \frac{\rho_{\text{MW}}(r)}{\rho_{\text{MW}}}} = \frac{10^{50} \text{ yr}^{-1}}{\int dE \int dM_{\text{PBH}} \int \frac{dN_{\text{PBH}}}{dE dM_{\text{PBH}}} d^{3}r \frac{\rho_{\text{MW}}(r)}{\rho_{\text{MW}}}}. \quad (6)$$

The energy interval in the above expression runs from 0.511 MeV to 3 MeV [133]. A careful astrophysical modeling of the sources can improve this limit by an order of magnitude [47]. In order to account for the propagation uncertainty of positrons, we consider two different cases: (i) all positrons injected within 1.5 kpc of the GC annihilate to produce the 511 keV signal and (ii) 80% of positrons injected within 3.5 kpc of the GC annihilate to produce the 511 keV signal [93, 130, 131].

Fig. 3 shows the upper limit on $f_{\text{PBH}}$, from the GC
FIG. 4. Variation in the upper limit on dark matter fraction of PBHs from INTEGRAL 511 keV gamma-ray line measurement, due to dark matter density profiles and positron propagation. This plot considers a PBH with $a_*=0.9$. The lines from top to bottom correspond to isothermal with 1.5 kpc, NFW with 1.5 kpc, isothermal with 3.5 kpc and NFW with 3.5 kpc region of interest respectively.

FIG. 5. Comparison of the limits derived from gamma-ray observations [72] (in various shades of orange) with that derived in this work (in various shades of blue) using the INTEGRAL 511 keV gamma-ray line measurements. For the latter, we have used an NFW dark matter profile and assumed that 80% of positrons injected via PBH evaporation with 3.5 kpc of the Galactic center annihilate. The line styles have the same meaning as in Fig. 3. The top (bottom) panel considers a monochromatic (log-normal distribution with $\sigma=1$) PBH mass distribution.

Fig. 4 shows the variation of the positron constraints on $f_{PBH}$ for a PBH with $a_*=0.9$, for different DM profiles and propagation distance of low-energy positrons in the GC. Since this variation is a multiplicative constant, as evident from eqn. 6, this uncertainty is the same for PBHs with different spins. The strongest constraint arises when we consider that the DM profile is NFW and that 80% of positrons injected within 3.5 kpc of the GC annihilate to produce the 511 keV signal. The weakest constraint arises when we consider the isothermal DM profile and 1.5 kpc region of interest around the GC.

Fig. 5 shows the comparison of our limits from INTEGRAL observations with that derived from gamma-ray measurements, for the monochromatic PBH mass distribution (top panel) and the log-normal mass distribution with $\sigma=1$ (bottom panel). The constraints derived from the INTEGRAL observations are stronger than those derived from the diffuse gamma-ray measurements, especially at PBH masses $\gtrsim$ few $\times 10^{16}$ g.

FIG. 6 shows the constraints on non-spinning PBHs, with a monochromatic mass function, over the entire viable mass range. We see that PBHs can form the entire DM density if it has a mass roughly in the range of $10^{17}$ g – $10^{23}$ g. These constraints depend on the underlying mass distribution [134–138], however, it is generally true that there exist multiple mass distributions for which PBHs can make up the entire DM density.

Near future observations can completely probe this mass...
FIG. 6. Constraints on non-spinning primordial black hole dark matter with a monochromatic mass distribution over the entire viable mass range. The various constraints are derived in this work (Super-K and INTEGRAL) and in Refs. [17, 19, 20, 22, 23, 26, 27, 31, 45, 79].

Summary & Outlook – Angular momentum, a fundamental property of BHs, can drastically change the evaporation rate of a BH. There has been a recent surge of interest in spinning PBHs and it is necessary to fully explore the parameter space of these exotic objects. Using DSNB searches and the INTEGRAL observations of the Galactic center 511 keV gamma-ray line, we probe the allowed parameter space of uncharged spinning PBHs. We show that nonzero angular momentum of a PBH allows us to probe higher mass PBHs. Our constraints using the DSNB (INTEGRAL) observations are weaker (stronger) than the existing limits from the diffuse gamma-ray background. Near future loading of gadolinium in Super-Kamiokande and Hyper-Kamiokande will further enhance their capability to search for the DSNB [139], and increase the prospect of PBH discovery via neutrinos. Improved modeling of the GC positrons will also allow us to probe PBHs more comprehensively.

Acknowledgements – We thank Jeremy Auffinger for help with the BlackHawk package. We are grateful to Jane MacGibbon for pointing us to relevant older literature. The work of B.D. is supported by the Dept. of Atomic Energy (Govt. of India) research project 12-R&D-TFR-5.02-0200, the Dept. of Science and Technology (Govt. of India) through a Ramanujan Fellowship, and by the Max-Planck-Gesellschaft through a Max Planck Partner Group. R.L. thanks the CERN Theory Group for support.

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