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Dirac and Majorana neutrino signatures of primordial black holes

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Abstract. We study Primordial Black Holes (PBHs) as sources of massive neutrinos via Hawking radiation. Emphasizing that black holes emit neutrino mass eigenstates, we describe quantitatively how the PBH evolution and lifetime is affected by the mass and fermionic — Dirac or Majorana — nature of neutrinos. In the case of Dirac neutrinos, PBHs radiate right-handed and left-handed neutrinos in equal amounts, thus possibly increasing the effective number of neutrino species, $N_{\rm eff}$. Considering the full system of Friedmann equations, and the current constraint on $N_{\rm eff}$, we derive a novel bound on the initial PBH fraction β' for black hole masses 4×10^7 g $\lesssim M_i \lesssim 10^9$ g. Future measurements of $N_{\rm eff}$ may be able to constraint the initial fraction for black hole masses as low as 1 g. If an excess in $N_{\rm eff}$ is found, PBHs with Dirac neutrinos could provide a minimal explanation of it. For example, for 10^7 g $\lesssim M_i \lesssim 10^9$ g and $\beta' \gtrsim 10^{-13}$, an excess radiation at the level of $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.37$ is produced, which can alleviate the tension of the Hubble parameter measurements. Finally, we obtain the diffuse flux of right-helical neutrinos from PBHs at the Earth, and show that their detection in a PTOLEMY-like detector (using neutrino capture on Tritium) would be difficult.

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Contents

1 Introduction

The existence of black holes (BHs) in the Universe is now well established. The 2016 discovery of gravitational waves from the merger of stellar-mass BHs [1] is a direct evidence of it, and has stimulated a wide range of studies of BH phenomenology. In this context, various mechanisms to explain the origins of BHs in astrophysics and cosmology have been considered. One possibility is that BHs might be produced in the early Universe shortly after inflation, as a result of the gravitational collapse of density fluctuations [2–6]. These *primordial black holes* (PBHs) can have masses exceeding the Planck mass, and their Schwarzschild radius can be small enough for quantum effects to be important. They could constitute (part of) the Dark Matter (DM); a possibility that has gained attention recently [7–11].

As Hawking demonstrated in early seminal papers [12, 13], black holes evolve with time – and eventually vanish out of existence – by losing mass via particle radiation. For PBHs, this evaporation process can have observable effects, which allow to place constraints on PBH models and parameters [6, 14]. Interestingly, a number of phenomenological effects of PBH evaporation are related to their neutrino emission, which can be primary (direct emission as Hawking radiation) or secondary (via the decay of leptons and hadrons) [6, 15–21].

Constraints from neutrino emission have focused on PBHs with masses $M_i \gtrsim 10^9$ g [15, 18–20, 22]. Limits from atmospheric and solar neutrino experiments [19, 20] and from the search of astrophysical $\bar{\nu}_e$ at SuperKamiokande [23] have been considered, however they are weaker than BBN or γ-ray limits [6]. The kilometer-scale detector IceCube is sensitive to the high-energy neutrinos emitted in the last $\sim 10^3$ s before the PBH disappearance [22], and could provide constraints on PBH parameters at a level similar to γ-ray bounds [18]. Very recently, the production of light non-interacting states (such as sterile neutrinos) via the Hawking radiation in a possible BH dominated era has been analysed, finding that it could alleviate the tension between the measurements of the Hubble parameter [24].

While most literature so far has considered neutrinos as massless, initial conceptual studies have pointed out the potential importance of including neutrino mass effects. As early as 1970's, it was pointed out that the helicity suppression present in the weak interactions (see, e.g. [25–28]) is absent in the Hawking radiation [29]. Later, effects of neutrino masses on the BH evaporation have been considered qualitatively [21, 30]. These early works left open the question of how these effects could possibly impact the diverse PBH phenomenology and cosmology. The time is now mature to address this question, in the light of the greatly advanced picture we now have of neutrino masses and mixing (e.g., [31–33]), and also in the context of the renewed attention for PBH physics. In this paper, assuming that the PBHs were formed after inflation, we want to address carefully the imprint of neutrino masses and fermionic nature on the PBH phenomenology and possible cosmological implications. Furthermore we will show that the case of Dirac neutrinos provides a minimal realization of the scenario of Ref. [24], with PBHs radiating light, non-interacting right-handed neutrinos.

This manuscript is organized as follows. In Sec. 2, we discuss the general neutrino emission from Schwarschild BHs and the impact on their evaporation of nonzero neutrino masses and of the two possible fermionic natures, Dirac or Majorana. Supposing the minimal extension of the Standard Model (SM) to accommodate neutrinos as Dirac particles, in Sec. 3 we derive a constraint on the initial PBH fraction, given the possibility of emitting additional radiation in form of right-handed neutrinos. The implications of Dirac neutrinos for reconciling measurements of the Hubble parameter are briefly presented as well. In Sec. 4, the diffuse neutrino flux at Earth and its detectability are discussed. Finally, in Sec. 5 we draw our conclusions. We will consider natural units in which $c = \hbar = k_B = 1$ throughout this article.

2 Primary neutrino emission from primordial black holes

In this section we summarize the main features of the emission of *massive* neutrinos from PBHs. We will mainly focus on the primary neutrino emission, where effects of the neutrino mass can be strong. Due to the emphasis on mass effects, secondary neutrino production from the decay of leptons or hadrons, where mass effects are negligible, will not be discussed. We will also limit the discussion to Schwarzschild black holes (i.e., black holes with zero charge and zero angular momentum). This is justified, because possible non-zero charge and/or angular momentum initially present in a BH would evaporate much faster than the mass, ultimately leading to a Schwarzschild BH [12, 13, 34–36] .

2.1 Massive neutrinos from Schwarzschild black holes

The Hawking radiation is a consequence of the ambiguity of the concept of particle in a curved spacetime. Namely, an observer in the far future relative to the BH formation finds a nonzero expectation value of the number operator of the vacuum state of an observer in the far past [12, 13]. Therefore, the first observer measures a steady flux of particles from the BH. These particles have a thermal spectrum, with the temperature that depends on the BH mass M (and on the gravitational coupling constant, G), as [12, 13, 37]

$$T = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13}\ \mathrm{g}}{M}\right)\ \mathrm{GeV}\ . \tag{2.1}$$

Neutrinos produced by the Hawking process have different properties compared to the familiar case of production via the weak interaction. In the SM neutrinos are massless Weyl particles with three weak interaction eigenstates (flavors): ν_α ($\alpha = e, \mu, \tau$). However, from oscillation experiments we have learned that neutrinos are massive, and the flavor states are superpositions of states with definite masses, ν_a ($a = 1, 2, 3$), the free Hamiltonian eigenstates. The free neutrino field operator creates or annihilates a mass eigenstate ν_a from the vacuum state, thus *black holes emit mass eigenstates.*

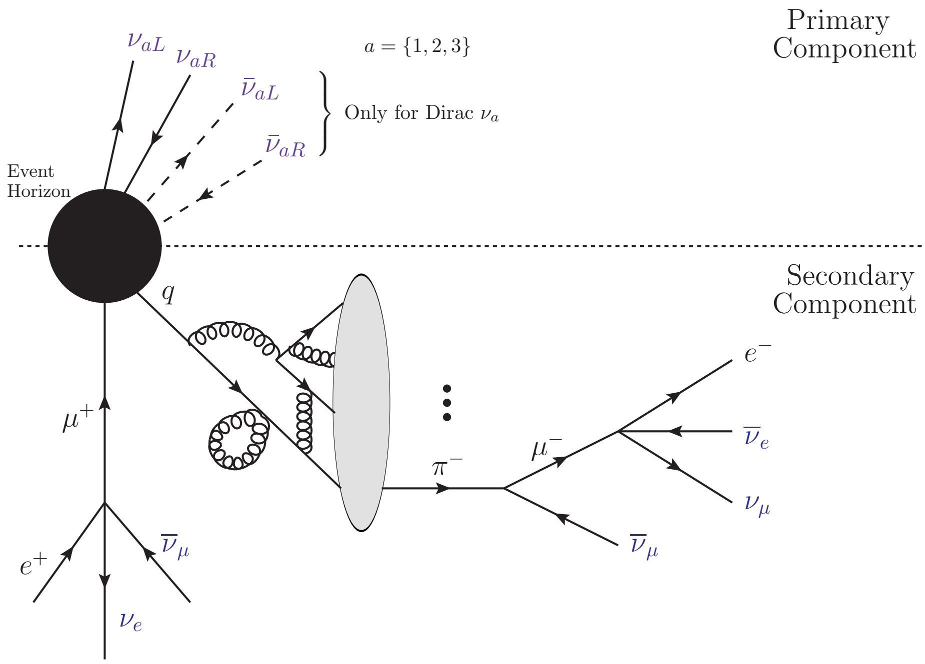

Figure 1: An illustration of the two different types of neutrino emission, primary and secondary, from a PBH.

Since the Hawking spectrum depends on the internal degrees of freedom, the neutrino emission depends on the neutrino fermionic nature. For Majorana neutrinos, a BH produces neutrinos with left (LH) and right (RH) helicities

$$\nu_{aL},\ \nu_{aR},$$

per mass eigenstate.[1] In the Dirac case, the antineutrino states are also emitted (see illustration in fig. 1):

$$\nu_{aL},\ \nu_{aR},\ \bar{\nu}_{aL},\ \bar{\nu}_{aR}.$$

Moreover, due to the absence of helicity suppression, both LH and RH neutrinos and their antineutrinos are produced with equal rates [29].

To fix the ideas, let us consider the neutrino mass spectrum with normal mass ordering and the lightest neutrino mass set to be $m_0 = 0.01$ eV. Using parameters from recent fits to neutrino oscillation data [33], the three masses, m_a, result to be $m_1 = m_0$, $m_2 \approx 1.32 \times 10^{-2}$ eV, $m_3 \approx 5.12 \times 10^{-2}$ eV. The emission rate of neutrinos with momentum between p and $p + dp$ by a Schwarzschild BH is [12, 13, 18]

$$\frac{d^2 N_\nu}{dp\, dt} = \sum_{a=1,2,3} \frac{g_a^N}{2\pi^2} \frac{\sigma_{\rm abs}^\nu(M, p, m_a)\, p^2}{\exp[E_a(p)/T] + 1}, \tag{2.2}$$

[1] Here, for sake of simplicity, we do not consider the origin of neutrino masses in detail to avoid extra assumptions in the present discussion. Nevertheless, we should notice that heavy right-handed Majorana neutrinos like those appearing in the Seesaw mechanism [38–44] could also be produced from the PBH evaporation. Thus, a nonzero initial abundance of RH neutrinos produced from the evaporation could lead to generation of matter-antimatter asymmetry, a PBH driven Leptogenesis, see [45–47].

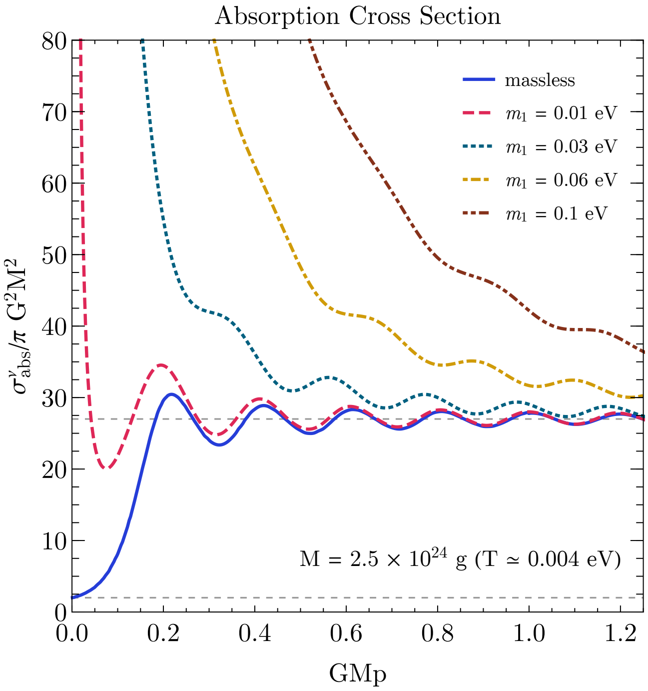

Figure 2: Absorption cross section of the lightest neutrino by a BH with $M = 2.5 \times 10^{24}$ g as function of the neutrino momentum (in units of $G^{-1}M^{-1}$) for 0 eV $\le m_1 \le 0.01$ eV. The horizontal dashed lines indicate the massless low momentum ($\sigma^{\nu}_{\rm abs} \simeq 2\pi G^2 M^2$) and high momentum ($\sigma^{\nu}_{\rm abs} \simeq 27\pi G^2 M^2$) limits, see text.

with E_a being the energy of a neutrino ν_a and g_a^N (N=Dirac or Majorana) the number of internal degrees of freedom. The quantity $\sigma^{\nu}_{\rm abs}$ is the cross section for the absorption of a state ν_a with momentum p by the BH, dependent on the gravitational coupling, $\alpha_g^a = GMm_a$. It presents a oscillatory behavior coming from the contribution of the different partial waves [48], see Fig. 2. In the low momentum limit, $\sigma^{\nu}_{\rm abs}$ is dominated by the first partial wave, taking a value of $\sigma^{\nu}_{\rm abs} = 2\pi G^2 M^2$ for massless neutrinos [29, 48]. For large momenta, the absorption cross section tends to the geometric optics limit, $\sigma^{\nu}_{\rm abs} \to 27\pi^2 G^2 M^2$.

The cross section approaches the classical limit in the case large gravitational couplings, $\alpha_g^a \gg 1$. Such limit takes place when $M \gtrsim 10^{28}$ g for all neutrino mass eigenstates. Nevertheless, neutrino emission from such PBHs will be extremely suppressed due to their small temperature. Besides, PBHs having

$$\mathcal{M}_\nu \equiv \frac{1}{8\pi G T_{{\rm C}\nu{\rm B}}} \approx 5.65 \times 10^{25} \text{ g}$$

would be in thermal equilibrium with the Cosmic Neutrino Background (CνB), so any PBH with larger masses absorbs more neutrinos from the CνB than it emits.[2]

In Fig. 3 we show examples of massless and Majorana mass eigenstate neutrino emission rate (in terms of the neutrino momentum, p) for values $M = 10^{22}$ g ($T \approx 1$ eV$-$ left) and $M = 10^{24}$ g ($T \approx 0.01$ eV$-$ right). As expected, in the first case Majorana and massless neutrino spectra fully coincide. For the higher mass, the spectra of the mass eigenstates

[2] A similar analysis could be done for PBHs in thermal equilibrium with the Cosmic Microwave Background (CMB). In such case, we have that $\mathcal{M}_\gamma \approx 4 \times 10^{25}$ g.

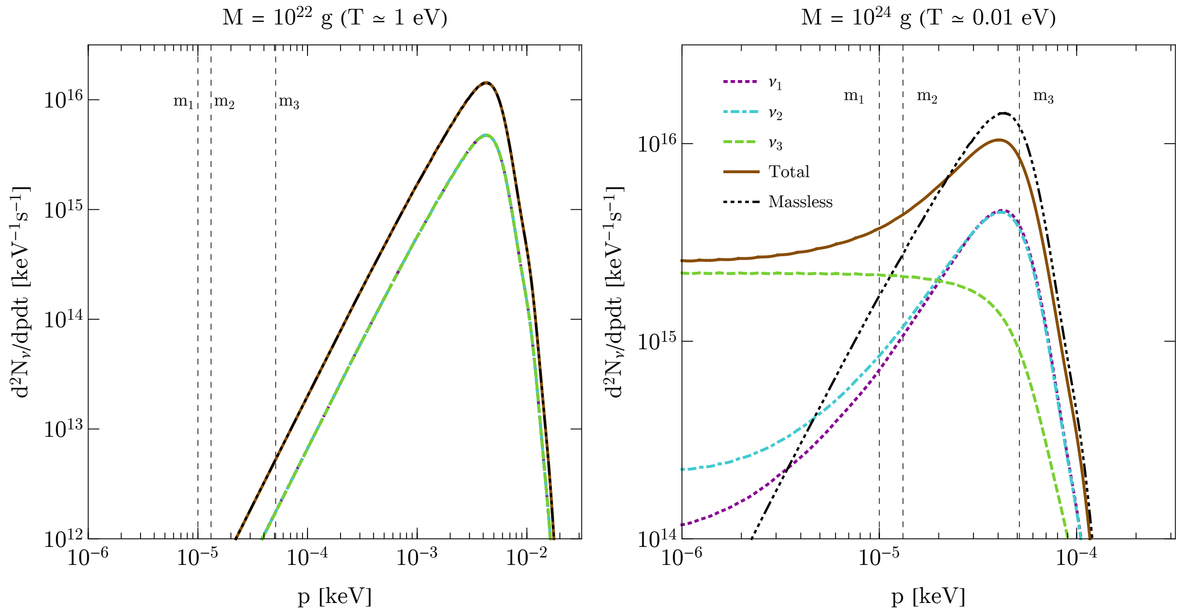

Figure 3: Primary Hawking emission spectrum for massless neutrinos and Majorana neutrinos with masses $m_1 = 10^{-2}$ eV, $m_2 \simeq 1.3 \times 10^{-2}$ eV, $m_3 \simeq 5 \times 10^{-2}$ eV and PBHs with $M = 10^{22}$ g (left) and $M = 10^{24}$ g (right). We also show the contribution of each mass eigenstate.

show large modifications, compared to the massless case, due to the mass effects from the absorption cross section (see fig. 2). Also, the emission rate becomes exponentially suppressed when $E_a \gtrsim T$, as expected from a Fermi-Dirac distribution.

Finally, we can summarize the effect of masses and the fermionic nature in the primary neutrino emission from a Schwarzschild BH as follows:

- *Majorana neutrinos*: Mass effects are important for the emission when $m_a \sim T$, and there are two degrees of freedom per mass eigenstate, LH and RH neutrinos that can be emitted, similar to the massless case.
- *Dirac neutrinos*: Mass effects are important for $m_a \sim T$, and there are four possible degrees of freedom per mass eigenstate that can be emitted, LH and RH neutrinos and antineutrinos.

2.2 Effects on the PBH evaporation

Let us now discuss how the primary emission of massive neutrinos affects the time evolution of a black hole. Due to evaporation, a PBH loses mass with a rate given by [6, 16, 17]

$$\begin{aligned}\dot{M} &= -\sum_j \frac{g_j}{2\pi^2} \int dp\, E_j(p) \frac{\sigma_{\rm abs}^{s_j}(M,p)\, p^2}{\exp[E_j(p)/T] - (-1)^{2s_j}} \\ &= -5.34 \times 10^{25}\ {\rm g\, s^{-1}}\, \varepsilon_N(M) \left(\frac{1\ {\rm g}}{M}\right)^2 , \end{aligned} \tag{2.3}$$

where the sum is done over all the particle species j ($j = l, q, a, g, W, Z, H$, corresponding to the SM set of particles: leptons, quarks, neutrinos mass eigenstates, gluons, W, Z and the

Higgs boson). For each species j, the quantities E_j, g_j, and s_j indicate the energy, internal degrees of freedom and spin; $\sigma^{s_j}_{\rm abs}(M,p)$ are the spin- and momentum-dependent absorption cross sections (see Sec. 2.1). In (2.3), $\varepsilon_N(M)$ is the evaporation function, which can be expressed as [17]:

$$\begin{aligned}\varepsilon_N(M) = 2f_1 + 4f^1_{1/2}&\left\{\sum_{\ell=e,\mu,\tau}\exp\left[-\frac{M}{\beta_{1/2}M_\ell}\right] + 3\sum_q \exp\left[-\frac{M}{\beta_{1/2}M_q}\right]\right\}\\ &+ 2\,\eta^N_\nu f^0_{1/2}\sum_{a=1,2,3}\exp\left[-\frac{M}{\beta_{1/2}M_a}\right]\\ &+ 16f_1\exp\left[-\frac{M}{\beta_1 M_g}\right]\\ &+ 3f_1\left\{2\exp\left[-\frac{M}{\beta_1 M_W}\right] + \exp\left[-\frac{M}{\beta_1 M_Z}\right]\right\} + f_0\exp\left[-\frac{M}{\beta_0 M_H}\right],\end{aligned} \tag{2.4}$$

where M_j is the mass of a PBH with a temperature equal to the mass of the particle j

$$M_j = \frac{1}{8\pi G m_j} \approx \left(\frac{1.06\ \text{GeV}}{m_j}\right)\cdot 10^{13}\ \text{g}\,,$$

and η^N_ν accounts for the difference between Dirac and Majorana degrees of freedom,

$$\eta^N_\nu = \begin{cases}2 & \text{for } N = \text{Dirac}\\ 1 & \text{for } N = \text{Majorana}\end{cases}.$$

The factors $f_{0,1,2}$, $f^{(0,1)}_{1/2}$ appearing in (2.3) describe the contribution to $\varepsilon_N(M)$ per degree of freedom depending on the spin and the charge of the emitted particle. The spin-dependent parameters $\beta_{0,1/2,1,2}$ are fixed such that the emitted power of a black hole with $M = \beta_s M_j$ is maximum at $p = m_j$ [16, 17]

$$\beta_s = \begin{cases}2.66 & \text{for } s=0\\ 4.53 & \text{for } s=\frac{1}{2}\\ 6.04 & \text{for } s=1\end{cases},\qquad f_s = \begin{cases}0.267 & \text{for } s=0\\ 0.060 & \text{for } s=1\\ 0.007 & \text{for } s=2\end{cases},\qquad f^q_{1/2} = \begin{cases}0.147 & \text{for } q=0 \text{ (neutral)}\\ 0.142 & \text{for } q=1 \text{ (charged)}\end{cases}.$$

Note that here $\varepsilon(M)$ is defined so that $\varepsilon = 1$ for massless neutrinos and in the high M limit ($M \gtrsim 10^{17}$ g, i.e., only neutrinos and photons emitted, see fig. 4).

By integrating the mass loss rate, eq. (2.3), we obtain the lifetime τ_N of a PBH of initial mass M_i [6, 17]. To illustrate its dependence on the mass and nature of the neutrino, in fig. 4 we show the ratio $\tau_N(M_i)/\tau_0(M_i)$ (with τ_0 being the lifetime in the massless neutrino case), and the function $\varepsilon_N(M)$ for massless, Dirac and Majorana neutrinos. In the figure, we observe three different regimes, depending on the initial PBH mass (or, equivalently, the initial temperature, T_i):

- The *low mass regime.* for $M_i \lesssim 10^{16}$ g ($T_i \gtrsim 1$ MeV), the neutrino emission is always accompanied by the emission of other SM particles. The emitted neutrinos are relativistic, so results for Majorana and massless neutrinos coincide. In the Dirac case, the additional degrees of freedoms enhance the evaporation function up to 10%, resulting in a comparable ($\sim$ 10% or less) shortening of the lifetime compared to the massless/Majorana case.

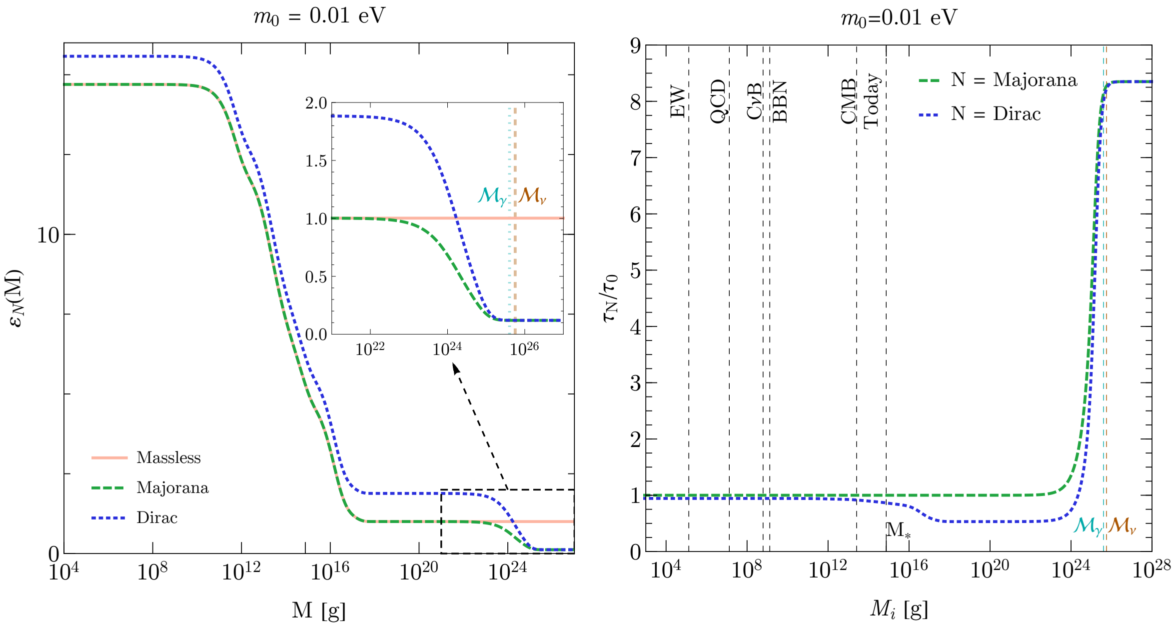

Figure 4: The evaporation function $\varepsilon_N(M)$ (left panel, with zoom-in inset) and the ratio of black hole lifetimes for massive and massless neutrinos (right panel), in the cases of Majorana and Dirac neutrinos. The evaporation function in the massless case is also presented in the left panel. The dashed lines in the right panel indicate the PBH mass for which the lifetime would be equal to the different epochs of the early Universe (assuming the standard cosmological model): Electroweak phase transition (EW), QCD phase transition, the neutrino decoupling (CνB), the beginning of the Big Bang Nucleosynthesis (BBN), and the age of the Universe, denoted by M_*. In both panels, $\mathcal{M}_\gamma(\mathcal{M}_\nu)$ indicate the PBH mass values for which the black hole is in thermal equilibrium with the CMB (CνB).

- The *intermediate mass regime.* for 10^{16} g $\lesssim M_i \lesssim 10^{24}$ g (10^{-3} eV $\lesssim T_i \lesssim 1$ MeV), a PBH only radiates neutrinos and photons for most of its life. The neutrinos are mostly relativistic, implying only minor differences between the Majorana and massless cases. For Dirac neutrinos, the extra degrees of freedom increase the initial emissivity by up to a factor of 2, relative to the massless case, with a corresponding reduction of the lifetime by almost half.

- The *high mass regime.* if $M_i \gtrsim 10^{25}$ ($T_i \lesssim 10^{-3}$ eV) a PBH evolution is dominated by photons, with strong mass-suppression of the neutrino emission. Due to the photon-domination, the evaporation function (and therefore the lifetime) is approximately the same for Dirac and Majorana neutrinos. As M_i increases, the lifetime ratio starts to converge to a value of 8.35. However, it should be noted that, as M_i approaches $\mathcal{M}_\gamma$, the PBH evolution is no longer described by evaporation only, as photon absorption from the CMB starts to dominate (see Sec. 2.1).

An important question is how the effect of the neutrino mass and nature on the PBH evolution could affect cosmology. To address it, in fig. 4 we show the values of M_i for which the PBH lifetime would be equal to the beginning of the different cosmological epochs (assuming the standard cosmological model, see figure caption). The PBH mass corresponding to a lifetime equal to the age of the Universe is found to be $M_i = M_* \approx \{7.5, 7.5, 7.8\} \times 10^{14}$ g, for massless, Majorana and Dirac neutrinos, respectively. It falls in the low M_i regime, where mass effects are negligible. Therefore, we conclude that the neutrino mass effect significant only for PBHs which are still present in the Universe today.

3 PBH evaporation in the early Universe: the case of Dirac neutrinos

3.1 Constraints on the initial PBH fraction

Dirac neutrinos can be introduced in the SM framework with the minimal addition of singlet right-handed states, ν_{aR}. The Yukawa interaction terms, $\mathscr{L}_Y = -Y_\nu^{ab}\overline{L_L^a}\widetilde{H}\,\nu_{bR}$, generate neutrino masses of $\sim \mathcal{O}(\mathrm{eV})$ after the Electroweak symmetry breaking if the Yukawa couplings Y_ν^{ab} are of order $\sim \mathcal{O}(10^{-12})$. Thus, RH states are not produced thermally in the Early Universe in the minimal scenario[3] [49, 50]. Nevertheless, PBH evaporation could emit an important population of RH neutrinos, modifying the evolution of the Universe. This could impose a limit on the initial PBH fraction since the effective number of neutrino species, $N_{\rm eff}$, has been constrained to be $N_{\rm eff} = 2.99 \pm 0.17$ ($\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM} < 0.28$ at 2σ C. L.) by CMB + BAO measurements [51]. Furthermore, future experiments that intend to measure $N_{\rm eff}$ with higher precision could improve the constraints [52]. These are the South Pole Telescope SPT-3G ($\Delta N_{\rm eff} < 0.12$ at 2σ C. L.) [53], the CMS Simmons Observatory ($\Delta N_{\rm eff} < 0.05 - 0.07$ at 1σ C. L.) [54] and the CMB Stage-4 (CMB-S4) experiments ($\Delta N_{\rm eff} < 0.06$ at 95% C. L.) [55].

Let us assume that a PBH population was formed, with a monochromatic PBH mass distribution, at a time when the Universe was radiation-dominated. Thus, the initial PBH mass depends on the particle horizon mass as $M_i = 4\pi\gamma\rho_{\rm tot}^i H^{-3}/3$, with $\rho_{\rm tot}^i$ the total energy density, H the Hubble parameter and $\gamma = (3\sqrt{3})^{-1}$, a dimensionless parameter related to the gravitational collapse [6, 56][4]. The temperature in which PBHs form is then

$$T_{\rm f} = \left(\frac{45}{16\pi^3 G^3}\right)^{\frac{1}{4}} g_*(T_{\rm f})^{-\frac{1}{4}}\gamma^{\frac{1}{2}} M_i^{-\frac{1}{2}}, \tag{3.1}$$

with $g_*(T_f)$ the number of relativistic degrees of freedom at the PBH formation time. We parametrize the initial PBH density fraction $\rho_{\rm PBH}^i$ to the total energy as [6]

$$\beta' = \gamma^{\frac{1}{2}} \left(\frac{g_*(T_{\rm f})}{106.75}\right)^{-\frac{1}{4}} \frac{\rho_{\rm PBH}^i}{\rho_{\rm tot}^i}. \tag{3.2}$$

In Fig. 5 we summarize upper limits on β' (taken from [6]) for massless neutrinos and for the mass region 1 g $\lesssim M_i \lesssim 10^{12}$ g. Constraints are strong for masses $M_i \gtrsim 10^9$ g, since the final stages of the evaporation would occur during the BBN [6]. For 10^6 g $\lesssim M_i \lesssim 10^9$ g, a model dependent bound has been obtained considering the production of the lightest superpartner (LSP) in a Supersymmetric scenario [57]. In the same region there exists a model independent but weaker constraint corresponding to the modification of the photon-to-baryon ratio by additional photons from the evaporation [58]. For lower PBH masses, $M_i \lesssim 10^6$ g, the possible production of Planck-mass relics introduces another constraint

[3] Furthermore, note that an initial non-thermal RH neutrino density cannot thermalize with the primordial plasma [49].

[4] We have checked that our results are only mildly dependent on the value gravitational collapse factor.

[6, 59–66]. Nevertheless, such bound relies on the assumption that BHs do not evaporate completely, and it can introduce additional complications [67]. Although any consideration on the BH evolution when its mass gets closer to the Planck mass is certainly precarious, here we assume that PBHs evaporate completely.

To consistently model the production of RH neutrinos by PBHs, and its impact on the Universe evolution, we consider the set of Friedmann equations for the energy densities of PBH ($\rho_{\rm PBH}$), SM radiation ($\rho_{\rm R}$) and RH neutrinos ($\rho_{\nu_{\rm R}}$) [24, 68]

$$\dot\rho_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{\dot M}{M}\rho_{\rm PBH}, \tag{3.3a}$$

$$\dot\rho_{\rm R} + 4H\rho_{\rm R} = -\frac{\varepsilon_{\rm SM}(M)}{\varepsilon_{\rm D}(M)}\frac{\dot M}{M}\rho_{\rm PBH}, \tag{3.3b}$$

$$\dot\rho_{\nu_{\rm R}} + 4H\rho_{\nu_{\rm R}} = -\frac{\varepsilon_{\nu_{\rm R}}}{\varepsilon_{\rm D}(M)}\frac{\dot M}{M}\rho_{\rm PBH}, \tag{3.3c}$$

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm PBH} + \rho_{\rm R} + \rho_{\nu_{\rm R}})\ , \tag{3.3d}$$

with the standard definition $H = \dot a_t/a_t$, $a_t = a(t)$ the scale factor at the time t, $\varepsilon_{SM}(M)$ the evaporation function for the SM degrees of freedom only, and $\varepsilon_{\nu_{\rm R}} = 6f^0_{1/2}$, the contribution of the 6 (2 per mass eigenstate) neutral additional states in the case of Dirac neutrinos. Note that the system of equations (3.5) is fully general. It accounts for the possibility that, depending on the initial PBH fraction, the PBHs dominate the energy density before the final stages of their evaporation, changing the evolution of the Universe and leading to a non-standard cosmology [24].

Since PBH evaporation changes the radiation energy density, the entropy is no longer conserved. Therefore, to describe the evolution of the temperature in the Universe, we use the evolution of the entropy density [69, 70]

$$\dot s_{\rm R} + 3Hs_{\rm R} = -\frac{\varepsilon_{\rm SM}(M)}{\varepsilon_{\rm D}(M)}\frac{\rho_{\rm PBH}}{T}\frac{\dot M}{M}\ , \tag{3.4}$$

which gives an evolution equation for the temperature,

$$\frac{\dot T}{T} = -\frac{1}{\Delta}\left\{H + \frac{\varepsilon_{\rm SM}(M)}{\varepsilon_{\rm D}(M)}\frac{\dot M}{M}\frac{g_*(T)}{g_{*S}(T)}\frac{\rho_{\rm PBH}}{4(\rho_{\rm R}+\rho_{\nu_{\rm R}})}\right\}\ . \tag{3.5}$$

Here the Δ parameter describes the dependence of the entropic relativistic degrees of freedom on the temperature [69, 70]:

$$\Delta = 1 + \frac{T}{3g_{*S}(T)}\frac{dg_{*S}(T)}{dT}\ . \tag{3.6}$$

Thus, we have to solve the full system of the Friedmann equations eqs. (3.3), together with the temperature evolution eq. (3.5) and the mass lose rate, eq. (2.3) from the initial temperature until $T_{\rm EV}$, the temperature at which the PBH disappearance occurs. After their complete evanescence, we want to quantify the modification of the effective number of neutrino species at the matter-radiation equality. To do so, we relate the SM radiation and RH neutrino energy densities between the evaporation and the matter-radiation equality considering their dependence on the scale factors at such epochs, $a_{\rm EV}$, $a_{\rm EQ}$, respectively [24],

$$\frac{\rho_{\nu_{\rm R}}(T_{\rm EQ})}{\rho_{\nu_{\rm R}}(T_{\rm EV})} = \left(\frac{a_{\rm EV}}{a_{\rm EQ}}\right)^4 , \tag{3.7a}$$

$$\frac{\rho_{\rm R}(T_{\rm EQ})}{\rho_{\rm R}(T_{\rm EV})} = \frac{g_*(T_{\rm EQ})T_{\rm EQ}^4}{g_*(T_{\rm EV})T_{\rm EV}^4} = \left(\frac{g_*(T_{\rm EQ})}{g_*(T_{\rm EV})}\right)\left(\frac{a_{\rm EV}}{a_{\rm EQ}}\right)^4\left(\frac{g_{*S}(T_{\rm EV})}{g_{*S}(T_{\rm EQ})}\right)^{\frac{4}{3}} . \tag{3.7b}$$

with $T_{\rm EQ} \approx 0.75$ eV. Here the factors of g_*, g_{*S} account for the possible reheating of the thermal bath due to particle decays. Now, using the definition of $\Delta N_{\rm eff}$

$$\Delta N_{\rm eff} = \frac{\rho_{\nu_{\rm R}}(T_{\rm EQ})}{\rho_{\nu_{\rm L}}(T_{\rm EQ})} ,$$

with $\rho_{\nu_{\rm L}}(T_{\rm EQ})$ the active neutrino energy density, we have [24]

$$\Delta N_{\rm eff} = \left\{\frac{8}{7}\left(\frac{4}{11}\right)^{-\frac{4}{3}} + N_{\rm eff}^{\rm SM}\right\}\frac{\rho_{\nu_{\rm R}}(T_{\rm EV})}{\rho_{\rm R}(T_{\rm EV})}\left(\frac{g_*(T_{\rm EV})}{g_*(T_{\rm EQ})}\right)\left(\frac{g_{*S}(T_{\rm EQ})}{g_{*S}(T_{\rm EV})}\right)^{\frac{4}{3}} , \tag{3.8}$$

with $N_{\rm eff}^{\rm SM} = 3.045$ the effective number of relativistic species in the SM [71]. Note that the expression in eq. (3.8) is valid for any value of the initial PBH fraction, as the solutions of the Friedmann equations (eqs. (3.3)) are directly dependent on the initial condition on β'. In the scenario in which there was a PBH-dominated era, the entire population of SM particles plus RH neutrinos would come from the evaporation [24]. A PBH-dominated era would occur if the initial fraction is in the range [24]

$$\beta' \gtrsim 2.5 \times 10^{-14}\left(\frac{g_*(T_{\rm f})}{106.75}\right)^{-\frac{1}{4}}\left(\frac{M_i}{10^8 \text{ g}}\right)^{-1}\left(\frac{\varepsilon_D(M_i)}{15.35}\right)^{\frac{1}{2}} . \tag{3.9}$$

We present the constraint and future sensitivities on the initial PBH fraction assuming neutrinos as Dirac particles in Fig. 5. We find that the constraint on β' is improved by ~ 10 orders of magnitude in the region 4×10^7 g $\lesssim M_i \lesssim 10^9$ g. For smaller values of M_i, the final phase of the PBH evaporation would have occurred before the QCD phase transition. Thus, the relative RH neutrino contribution to the total radiation becomes smaller. This explains the sharp cut on the bound at around $M_i \sim 4 \times 10^7$ g. In fact, in the case of a PBH-dominated era, the minimum value of $\Delta N_{\rm eff}$ is $\Delta N_{\rm eff} = 0.14$, corresponding to values of M_i that evaporated before the EW phase transition. Smaller values of $\Delta N_{\rm eff}$ will indicate that PBH could not dominate the Universe in this specific scenario. This is in agreement with the results of [24]. Moreover, future experiments will be able to constraint the PBH-domination scenario with RH neutrinos in a larger region of the parameter space, even reaching PBH initial masses as low as ~ 1 g and initial fractions of $\beta' \gtrsim 10^{-6}$.

3.2 PBHs and indications of excess radiation

Until now, we have discussed experimental results on $N_{\rm eff}$ from the perspective of restricting the allowed PBH parameter space. But what would be the implications if an excess in $N_{\rm eff}$ (i.e., $\Delta N_{\rm eff} > 0$) is established? In that case, an attractive explanation could be found in PBHs, under the sole, minimal assumption that neutrinos be Dirac fermions.

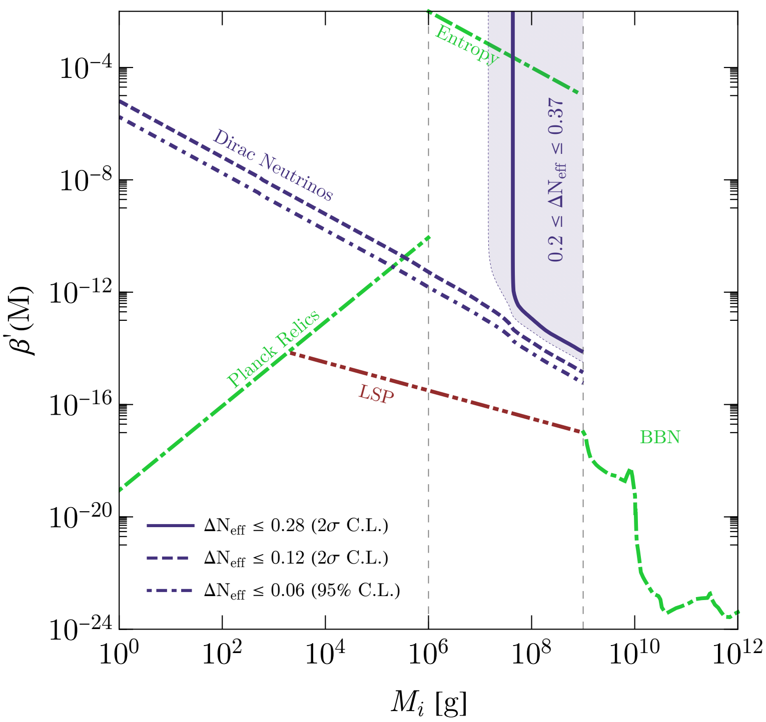

Figure 5: Constraints on the initial PBH fraction β' as a function of the initial PBH mass, M_i, due to the emission of RH states in the case of Dirac neutrinos. We consider limits stemming from constraints on $\Delta N_{\rm eff}$ (see legend): (i) the current limit of $\Delta N_{\rm eff} \leq 0.28$, and the expected sensitivities of future experiments, specifically, (ii) the South Pole Telescope/CMS Simmons Observatory, $\Delta N_{\rm eff} \leq 0.12$ and (iii) the CMB Stage-4, $\Delta N_{\rm eff} \leq 0.06$ (see text). The shaded region corresponds to the PBH parameters that produce $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.37$, values that can ease the tension on the Hubble measurements, see [24, 51, 72, 73]. Bounds from entropy generation, the production of a 100 GeV Lightest Supersymmetric Particle (LSP), Planck relics and BBN have been taken from [6] (legends on curves).

As an illustration, let us consider the recent claims that extra radiation, at the level of $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.5$, can alleviate the tension between measurements of the Hubble parameter at early and late times [24, 51, 72, 73]. In our specific scenario in which RH neutrinos are produced from PBH evaporation, a contribution up to $\Delta N_{\rm eff} \sim 0.37$ can be generated while satisfying all the other constraints on β'. Specifically (see fig. 5), $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.37$ is possible for PBH masses in the range $10^7 \lesssim M_i \lesssim 10^9$ g and $\beta' \gtrsim 10^{-13}$.

Interestingly, in the region of the parameters where PBH evaporation with Dirac neutrinos contributes significantly to $\Delta N_{\rm eff}$, models involving PBHs and new (non-neutrino) light degrees of freedom would be restricted (compared to the case of massless neutrinos). This, however, has some caveats: if new models assume Majorana neutrinos or Dirac neutrinos with other interactions, the limits derived here would be different.

4 Diffuse neutrino flux from PBHs

An interesting question is if the diffuse flux of neutrinos from PBHs at Earth is detectable. To answer, let us discuss how the radiated neutrinos evolve to the present time. When

PBHs are first formed, the average energy of their emitted neutrinos is (see Eq. (2.1)) $\langle E_\nu \rangle \sim T \sim \mathcal{O}(10^{21})$ eV $(1 \text{ g}/M_i)$. Thus, for PBHs with $M_i \gtrsim 10^{21}$ g, neutrinos are emitted as non-relativistic or semi-relativistic fermions of LH and RH helicity. Because helicity is conserved in their propagation, the neutrinos remain helicity eigenstates at all times. At their arrival at Earth, all the neutrino states would then have a left-chiral component, and they would interact weakly, allowing for a possible detection.

For $M_i \lesssim 10^{21}$ g, neutrinos are emitted as ultrarelativistic particles, for which helicity and chirality coincide. The RH neutrino states propagate by free streaming, and – due to helicity conservation – arrive at Earth as RH helicity eigenstates, suffering only redshift of energy. If they are non-relativistic at arrival (for $M_i \lesssim 10^6$ g), their non-zero left-chiral component will make them detectable via the weak interaction. A similar fate applies to the neutrinos produced as LH helicity eigenstates, provided that they are always decoupled from the plasma (i.e., $M_i \gtrsim 10^9$ g, corresponding to emission after neutrino decoupling, see Fig. 4). If that is not the case ($M_i \lesssim 10^9$ g), then the emitted LH neutrinos would equilibrate with the CνB, and be effectively lost to detection.

Previous works on detecting neutrinos from PBHs [15, 18–20, 22] have considered the active neutrino flux with energies $E_\nu \gtrsim 1$ MeV, and have included both primary and secondary emissions. Here, we will consider only the regimes where secondary emission is absent or suppressed, so primary emission dominates. This the case for:

- the flux of Dirac (LH + RH) neutrinos and antineutrinos or Majorana (LH + RH) neutrinos from PBHs that are still present in the Universe today ($M_i > M_* > 10^9$ g). These PBHs would contribute to a fraction of the dark matter (DM), which is subject to several constraints (see e.g., [6, 14, 74]). However, since our purpose is to consider the possible observational effects of nonzero neutrino masses in the evaporation and possible constraints on β' from neutrino measurements, we will assume that all DM is constituted by PBHs.
- the RH Dirac neutrino flux for PBH that have already completely evaporated ($M_i < M_*$, including the regime $M_i < 10^9$ g). For this scenario we will assume that the Universe had a PBH-dominated era at some point, corresponding to the region of the parameters space in Eq. (3.9).

We compute the flux by integrating the Hawking spectrum of a PBH with initial mass M_i over the time t, including redshift effects, as follows [19, 75]:

$$\frac{d\Phi^\nu_{\rm PBH}}{dp_0} = \int_{t_i}^{\min(t_0,\tau)} dt\, \frac{d\Omega}{4\pi}\, \frac{a_0}{a_t} \left(\frac{a_i}{a_0}\right)^3 \frac{\rho^i_{\rm PBH}}{M_i}\, \frac{d^2 N_\nu}{dp\, dt}(M(t), p_0\, a_0/a_t), \tag{4.1}$$

with a_0, a_i the scale factor at the present and at the PBH formation time, respectively; p_0 is the neutrino momentum today, redshifted from the initial momentum p. The integration is performed between t_i (the formation time) and over the black hole lifetime (that is, until the time $t_i + \tau \simeq \tau$), or until the present time, t_0, if the PBH has not completely evaporated yet. The ratio (a_i/a_0) (and, analogously, a_0/a_t) can be found using the equation:

$$\begin{aligned} \frac{a_i}{a_0} &= \left(\frac{a_i}{a_{\rm EV}}\right)\left(\frac{a_{\rm EV}}{a_{\rm EQ}}\right)\left(\frac{a_{\rm EQ}}{a_0}\right) \\ &= \left(\frac{a_i}{a_{\rm EV}}\right)\left(\frac{g_{*S}(T_{\rm EV})}{g_{*S}(T_{\rm EQ})}\right)^{\frac{1}{3}}\left(\frac{T_{\rm EV}}{T_{\rm EQ}}\right)(1+z_{\rm EQ})\,, \end{aligned} \tag{4.2}$$

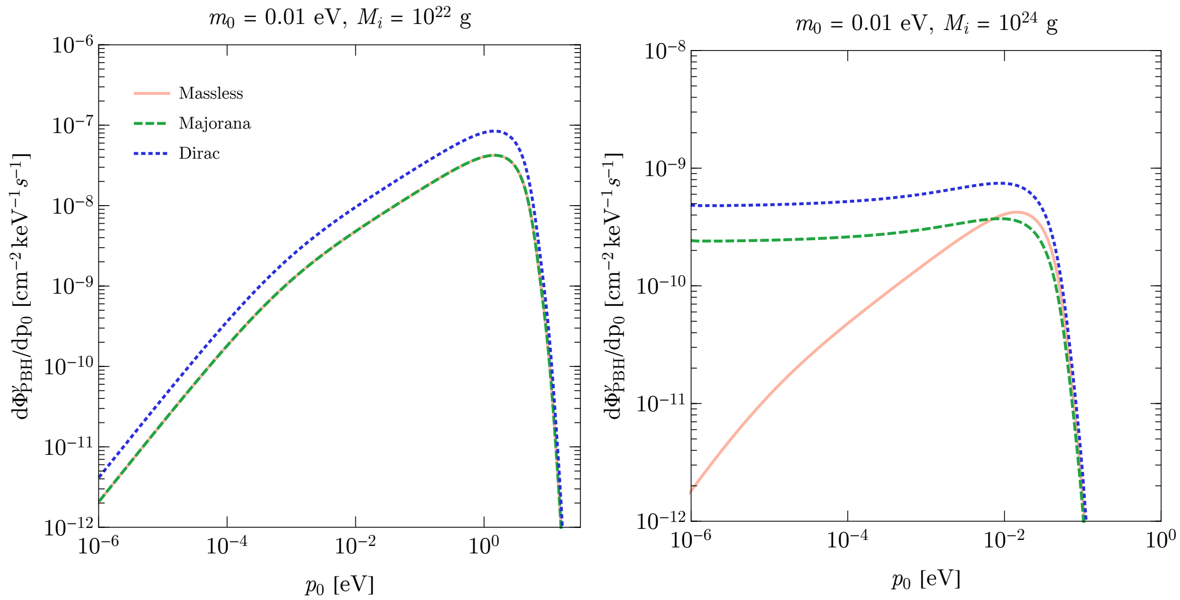

Figure 6: Spectrum of the PBH neutrino flux (considering all DM as made of PBH) for a PBH mass of $M_i = 10^{22}$ g (left) and $M_i = 10^{24}$ g (right).

with $z_{\rm EQ}$ being the redshift corresponding to $a_{\rm EQ}$. To obtain the ratio $a_i/a_{\rm EV}$, we use the solutions of the Friedmann equations (eqs. (3.3)).

As a first step, we would like to understand if a measurement of the diffuse fluxes could shed some light on the neutrino nature. In Fig. 6 we show the spectrum of the total neutrino diffuse flux for PBHs in the intermediate mass regime (see Sec. 2.2): $M_i = 10^{22}$ g and $M_i = 10^{24}$ g. As expected, the fluxes in the Dirac and Majorana scenarios differ by a factor of 2. For the case $M_i = 10^{24}$ g, the differences in the low momenta with respect to the massless case are due to effects of the absorption cross section, see Fig. 3. Thus, the diffuse fluxes contain the information of the neutrino mass and nature. Nevertheless, other neutrino fluxes would constitute a background to searches of neutrinos from PBHs. When we compare the Majorana neutrino diffuse flux for PBHs that still exist today with fluxes from other sources (see fig. 7), we find that the latter dominate, making a possible detection difficult in this case.

Coming now to the case $M_i \leq M_*$, results for the RH neutrino flux are shown in Fig. 8. For 10^{10} g $\lesssim M_i \lesssim 10^{14}$ g, we find that such flux is suppressed due to the bounds on the PBH initial fraction from BBN and gamma ray fluxes, see Fig. 5. For masses $M_i \lesssim 10^8$ g, the RH neutrino fluxes are comparable to, or even exceed, the fluxes from other sources for 3×10^{-3} eV $\lesssim p_0 \lesssim 1$ keV. Therefore, we identify this region of the parameter space as the most promising for detection. In this context, let us consider the detectability at a realistic facility. PTOLEMY [87] is a proposed experiment with the capability to detect non-relativistic neutrinos (with the cosmic neutrino background being the main candidate, see also [88–90]) via capture on tritium, $\nu_a + {}^3{\rm H} \to {}^3{\rm He} + e^-$ [91–93].

Following refs. [88, 92, 93], we have estimated the capture rate for neutrinos from PBHs to be $\Gamma^{\nu}_{\rm PBH} \sim 10^{-2}$ $[{\rm kg-year}]^{-1}$, for $M_i = 1$ g (the most optimistic case shown in Fig. 8). Considering that PTOLEMY will operate with 0.1 kg of tritium, detection appears impractical for the time being. Still, it may be worth to explore other possible detection

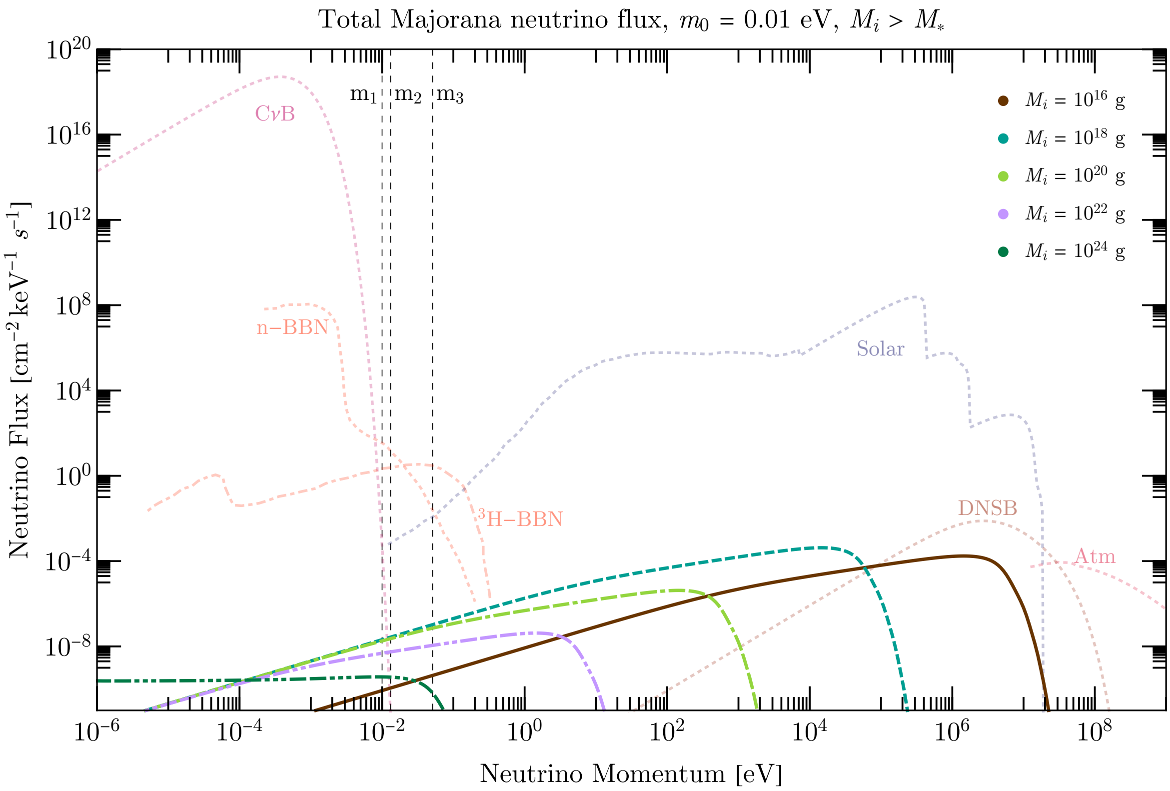

Figure 7: Diffuse Majorana neutrino flux for values of β' that saturate current limits (see Fig. 5) for PBHs with $M_i > M_*$. For comparison, we also present the solar neutrino flux [76–78], low-energy atmospheric flux [79, 80], the diffuse supernova neutrino background (DSNB) [81], the CνB flux [82–85], and neutrinos from decays of neutron and tritium produced at the BBN [86]. The dashed vertical lines indicate the assumed neutrino masses.

mechanisms beyond the simplest ones. This is left for future work.

5 Conclusions

After the discovery of gravitational waves, the astrophysics of PBHs has seen a renewed interest in the literature. In this work, we have studied the phenomenology of neutrinos from PBHs, in the light of the recent advances in neutrino physics. The neutrino emission from BH is completely different from the familiar weak interaction production, given that the Hawking process is a purely quantum effect in a gravitational background. Thus, neutrinos are not be emitted as flavor eigenstates, but as states with definite masses. Moreover, the primary neutrino emission is different in the case of Dirac and Majorana fermions since the particle emission from PBHs depends on the internal degrees of freedom.

We have obtained that the PBH lifetime depends on the neutrino fermionic nature and mass, in such a way that for PBHs masses of 10^{18} g $\lesssim M_i \lesssim 10^{24}$ g, the lifetime in the Dirac case is half the one for Majorana neutrinos. For larger masses, the lifetimes becomes ~ 8.35 times the value in the case of massless neutrinos. However, such dramatic effect can not be tested directly, because black holes in the mass region $M_i \gtrsim 10^{15}$ g have not completely evaporated yet, and thus are still present in the Universe. For masses smaller than 10^{12} g,

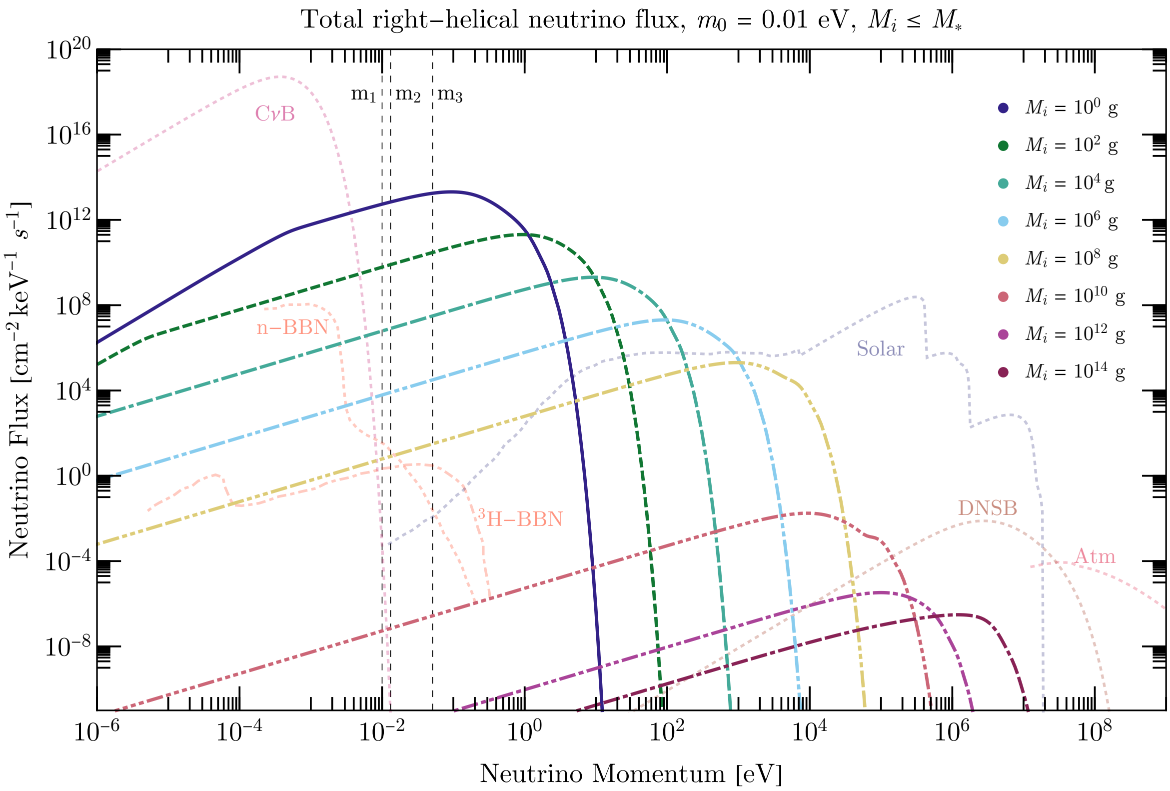

Figure 8: Same as Fig. 7, but for right-helical neutrinos and PBH with masses $M_i \leq M_*$.

the difference in the PBH lifetime between Dirac and Majorana is reduced to be ∼10 %, because the other SM particles are emitted, and the relative neutrino contribution is small.

If neutrinos are Dirac particles, a significant non-thermal population of RH neutrinos can be present at the BBN or the CMB production epoch, so that $N_{\rm eff}$ can be larger than its standard value. By imposing the current cosmological bound on $\Delta N_{\rm eff}$, we have derived a novel constraint on the initial fraction of PBHs for initial black hole masses 4×10^7 g $\lesssim M_i \lesssim 10^9$ g. Future experiments could improve this constraint, and extend it to masses as low as ~ 1 g.

We have identified an interesting region of the parameter space – masses $10^7 \lesssim M_i \lesssim 10^5$ g, and initial fraction of $\beta' \gtrsim 10^{-13}$ – where $\Delta N_{\rm eff}$ could be large enough to ease the tension between early and late measurements of the Hubble constant: $0.2 \lesssim \Delta N_{\rm eff} \lesssim 0.37$. This last result is a minimal realization of a recently discussed scenario where PBHs emit light, sterile particles [24].

Taking into account all the existing constraints, we have estimated the largest possible diffuse flux of neutrinos from PBHs at Earth. We found that the most promising scenario for detectability is for black holes with mass $M_i \sim \mathcal{O}(1)$ g. If the PBHs dominated the evolution of the Universe, they could cause a flux of non-relativistic right-helical neutrinos that exceeds all other neutrino fluxes in the momentum window $p_0 \sim 3 \times 10^{-3}$ – 10^3 eV. These neutrinos have a non-zero left chiral component, so in principle they are detectable. Considering detection via absorption on Tritium, as in the proposed PTOLEMY experiment, we find that for the most optimistic PBH parameters, a detection rate of one event per decade would require 1 kg of Tritium, which is currently unrealistic. Moreover, it may be difficult to distinguish a signal due to PBHs from the one due to the CνB. Nevertheless, we think that investigating experimentally achievable methods of detection of RH neutrinos from PBHs would be an interesting direction to pursue.

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