Primordial Black Hole Dark Matter evaporating on the Neutrino Floor

Roberta Calabrese,1 Damiano F.G. Fiorillo,1 Gennaro Miele,1,2 Stefano Morisi,3 and Antonio Palazzo3,4, ∗

1 Università degli Studi di Napoli “Federico II”, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy, and INFN - Sezione di Napoli, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy
2 Scuola Superiore Meridionale, Università di Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy
3 Dipartimento Intereateneo di Fisica “Michelangelo Merlin”, Università degli Studi di Bari, Via Amendola 173, 70126 Bari, Italy
4 Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Via Orabona 4, 70126 Bari, Italy

Primordial black holes (PBHs) hypothetically generated in the first instants of life of the Universe are potential dark matter (DM) candidates. Focusing on PBHs masses in the range $[5 \times 10^{15} - 5 \times 10^{16}]$g, we point out that the neutrinos emitted by PBHs evaporation can interact through the coherent elastic neutrino nucleus scattering (CEνNS) producing an observable signal in multi-ton DM direct detection experiments. We show that with the high exposures envisaged for the next-generation facilities, it will be possible to set bounds on the fraction of DM composed by PBHs improving the existing neutrino limits obtained with Super-Kamiokande. We also quantify to what extent a signal originating from a small fraction of DM in the form of PBHs would modify the so-called “neutrino floor”, the well-known barrier towards detection of weakly interacting massive particles (WIMPs) as the dominant DM component.

Introduction. The identity of dark matter (DM) is one of the most puzzling mysteries in contemporary astroparticle physics and cosmology. In spite of enormous efforts, no uncontroversial non-gravitational signal of DM has emerged so far. In this context, the recent detection of gravitational waves from binary black hole mergers by LIGO/Virgo [1, 2] has strongly revamped the attention [3–7] towards the hypothesis that DM may be composed of primordial black holes (PBHs). As first recognized in the seventies, these objects can be generated in the early Universe from the collapse of large overdensities [8–14], and may constitute a fraction of the observed amount of DM [10, 13] (see [15–19] for recent reviews). PBHs emit Hawking radiation [20], and for large enough masses ($M_{PBH} \gtrsim 5 \times 10^{14}$g), have a lifetime longer than the age of the Universe. The evaporation process can give rise to observable signals. In fact, bounds (present or prospective) on PBHs have been obtained from X-rays [21, 22], γ-rays [21, 23–27], 511 keV γ-ray line from galactic center [28–30], galactic e+ [31], cosmic microwave background (CMB) [32–34], radio signals from inverse Compton scattering on CMB photons [35] and synchrotron radiation [36], and heating of the interstellar medium [37, 38]. The possibility to constrain PBHs using the emitted neutrinos was discussed long ago in [39–41]. More recently, limits on PBHs have been obtained in [29] exploiting the null searches of the diffuse supernova neutrino background (DSNB) performed by Super-Kamiokande [42]. Also, prospective bounds from the experiment JUNO have been discussed in [43].

In this Letter, we entertain a novel possibility, never addressed before in the literature, proposing to detect the emitted neutrinos from PBHs by coherent elastic neutrino nucleus scattering (CEνNS). It is only recently that the CEνNS process, predicted long time ago [44], has been successfully observed by COHERENT [45], where a few kilograms detector was exposed to an intense neutrino flux of artificial origin. The very same process involving neutrinos of natural origin, such as the solar, DSNB and atmospheric ones, constitutes an irreducible background [46–52] (forming the so-called “neutrino floor” [52]) towards detection and identification of WIMPs as DM candidates in next-generation direct detection experiments. Here we show that neutrinos from PBHs with masses in the range $[5 \times 10^{14}, 5 \times 10^{15}]$g, which emit neutrinos with peak energy between 10 MeV and 100 MeV, may emerge as a signal on top of such a familiar background. As a consequence, it is possible to set prospective bounds on the PBHs fraction $f_{PBH}$ of DM in this mass range. As an interesting byproduct of our study, we show how the neutrino floor gets modified by the presence of a hypothetical signal from PBHs.

Neutrinos emitted by PBHs. A black hole is believed to quantum evaporate [20], emitting radiation akin to a hot body. For a neutral non-rotating (Schwarzschild) black hole, the Hawking temperature is given by [20, 53–55]

$$k_B T_{PBH} = \frac{h c^3}{8 \pi G_N M_{PBH}} \approx 1.06 \left( \frac{10^{16} g}{M_{PBH}} \right) \text{MeV} , \tag{1}$$

where four fundamental constants appear, $k_B$ (Boltzmann), $G_N$ (gravitational), $h$ (Planck), and $c$ (speed of light). The differential flux per unit time of emitted particles depends on their spin. For spin 1/2 particles with mass negligible with respect to $T_{PBH}$ like neutrinos, it is given by

$$\frac{d^2 N_\nu}{dE_\nu \, dt} = \frac{1}{2 \pi} \frac{\Gamma_\nu (E_\nu, M_{PBH})}{E_\nu / k_B T_{PBH} + 1} , \tag{2}$$

where $E_\nu$ is the neutrino energy and $\Gamma_\nu$ is a graybody factor [53–55] encoding the imprint of the space-time geometry intervening between the event horizon and the
asymptotic observer. In our analysis, we employ the publicly available BlackHawk code [56] for calculating the energy spectra of the emitted neutrinos. BlackHawk provides the primary spectra for all fundamental Standard Model particles using the Hawking evaporation spectrum in Eq. (2). In addition, the code generates the spectra of secondary neutrinos deriving from hadronization of strongly-interacting constituents and decay of unstable particles. We sum up both kind of spectra in our analysis. In [57], it has been shown that Dirac neutrinos, having twice as many degrees of freedom as the Majorana ones, would affect the PBHs evaporation making it faster (see also (58, 59)). Although the additional Dirac degrees of freedom are sterile for the electroweak interactions and not detectable in the CEνNS process, their existence can alter indirectly the emission rate of the active degrees of freedom. For the PBHs masses considered in our work, this effect can be quantified around 10% [57]. For definiteness, we assume that neutrinos have Majorana nature. We ignore neutrino oscillations being irrelevant for the flavor-blind CEνNS process. We take into account both the contributions coming from the galactic and extragalactic PBHs. The galactic differential neutrino flux is given by

$$\frac{d\phi_{\nu}^{MW}}{dE_\nu} = \int d\Omega \frac{d^2N}{4\pi dE_\nu dt} \int dl \frac{f_{PBH} \rho_{MW}[r(l, \psi)]}{M_{PBH}} ,$$

(3)

where $\rho_{MW}(r)$ is the DM density of the Milky Way (MW), $r$ denotes the galactocentric distance

$$r(l, \psi) = \sqrt{r_\odot^2 - 2lr_\odot \cos \psi + l^2} ,$$

(4)

with $r_\odot$ being the distance of the Sun from the galactic center, $l$ the line-of-sight distance to the PBH, $\psi$ the angle between these two directions, and $\Omega$ the solid angle under consideration. For definiteness, we employ a Navarro-Frenk-White (NFW) profile [60]

$$\rho_{MW}(r) = \rho_\odot \left[ \frac{r}{r_\odot} \right]^{-1} \left[ 1 + \frac{r}{r_s} \right]^{-2} ,$$

(5)

where we take $\rho_\odot = 0.4 \text{GeV cm}^{-3}$ for the DM density in the solar neighborhood, $r_\odot = 8.5 \text{kpc}$, and $r_s = 20 \text{kpc}$ for the scale radius. We stress that the value $\rho_\odot = 0.4 \text{GeV cm}^{-3}$ lies at the lower end of its allowed range according to the latest estimates (see for example [61]). Therefore, the bounds we are going to derive will be conservative in this respect. For the extragalactic component, the differential flux integrated over the full sky is [16]

$$\frac{d\phi_{\nu}^{EG}}{dE_\nu} = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \left[ 1 + z(t) \right] \frac{f_{PBH} \rho_{DM}}{M_{PBH}} \frac{d^2N_{\nu}}{dE_\nu dt} |E_{\nu} = [1+z(t)]E_\nu| ,$$

(6)

$\rho_{DM}$ being the average DM density of the Universe at the present epoch, as determined by Planck [62]. The time integral runs from $t_{\text{min}}$ set to the era of matter-radiation equality to $t_{\text{max}}$, the minimum between the PBH lifetime and the age of the Universe. The overall neutrino flux from the sum of galactic and extragalactic contributions is plotted in Fig. 1 for three benchmark values of $M_{PBH}$ and $f_{PBH}$. As it will be discussed in the next section, these values are excludable at 90% C.L. from a xenon experiment with 200 t yr exposure, assuming a measurement compatible with the ordinary background. In the same plot, we represent the background which is formed from solar [63], DSNB [64] and low-energy atmospheric neutrinos [65, 66]. As expected from Eq. (1), smaller PBHs masses correspond to harder spectra of the emitted neutrinos with peak located at $\sim 4.2 T_{PBH}$ [67]. We see that PBHs neutrinos can be visible above the abrupt fall-off of the solar hep neutrinos, where the dominant contribution to the background is provided by DSNB and atmospheric neutrinos.

*Coherent scattering of neutrinos.* Coherent elastic scattering of a neutrino $\nu$ (or antineutrino $\bar{\nu}$) on a nucleus $N$ can occur if $qR \ll 1$, where $q = |q|$ is the three-momentum transfer and $R$ is the nuclear radius [44]. The differential cross section can be expressed as [44]

$$\frac{d\sigma_{\nu N}(E_\nu, E_R)}{dE_R} = \frac{G_F^2 m_N}{4\pi} Q_\nu^2 \left( 1 - \frac{m_N E_R}{2E_\nu^2} \right) F^2(q) ,$$

(7)

where $G_F$ is the Fermi constant, $m_N$ is the nucleus mass, $Q_\nu = [N - Z(1 - 4 \sin^2 \theta_W)]$ is the weak vector nuclear charge, $Z$ and $N$ are the number of protons and neutrons, $\sin^2 \theta_W = 0.231$ [68] is the Weinberg angle, $E_R$ is the nucleus recoil energy, and $E_\nu$ is the neutrino energy. The recoil energy can assume the maximum value

$$E_{\text{max}} = 2E_\nu^2/(m_N + 2E_\nu) .$$

For the nuclear form factor $F(q)$, encoding the loss of coherence for $qR > 1$, we

![FIG. 1. Neutrino fluxes from PBHs.](image-url)

The black dashed contours represent the background fluxes originating from solar, DSNB and atmospheric neutrinos. The colored solid lines correspond to neutrinos from PBHs evaporation for three representative values of their mass and fraction of total DM content. These benchmark values lie on the 90% C.L. exclusion curve obtainable from a liquid xenon experiment with 200 t yr exposure (corresponding to the black stars in Fig. 3).
employ the Helm parametrization [69] using the recipes provided in [70]. The differential rate of events is given by

$$
\frac{dR_{\nu NN}}{dE_R dt} = N_T \epsilon(E_R) \times \int dE_\nu \frac{d\sigma_{\nu NN}}{dE_R} \frac{d\phi_\nu}{dE_\nu} \Theta(E_R^{\text{max}} - E_R),
$$

where \(N_T\) is the number of target nuclei in the detector, \(\epsilon(E_R)\) is the detector efficiency (assumed to be equal to one), \(d\phi_\nu/dE_\nu\) is the differential neutrino flux, and \(\Theta\) is the Heaviside step function. In Fig. 2, we show the differential rate of events as a function of the recoil energy window (dashed line), and for three benchmark values of the PBHs parameters (the same used in Fig. 1). The plots refer to an exposure of 200 t yr. One can observe that the shape of the spectrum induced by PBHs neutrinos appreciably changes with the value of the mass of the PBH. In particular, for smaller values of \(M_{\text{PBH}}\), which correspond to more energetic neutrino fluxes, the event spectrum is similar to the atmospheric background. In contrast, for larger values of \(M_{\text{PBH}}\) with flux peaked at lower energies, the PBHs event spectrum is quite different with respect to the background. For this reason, in the statistical treatment presented in the next section we employ a binned likelihood analysis, so as to exploit the information contained in the spectral shape.

**PBHs at next-generation detectors.** In order to derive prospective upper limits on the fraction of DM composed of PBHs, we implement the \(\chi^2\) test statistic defined as

$$
\chi^2(\theta, \alpha) = \min_{\alpha} \left[ \frac{1}{2} \chi^2 \left( \theta, \alpha \right) + (1 - \alpha)^T \Sigma^{-1} (1 - \alpha) \right],
$$

where \(\theta^T = [M_{\text{PBH}}, f_{\text{PBH}}]\), and \(\alpha^T = [\alpha_1, \alpha_1, \alpha_3]\) represent respectively the vector of the model parameters and that of the nuisance parameters associated to the normalization of the three backgrounds components (solar \(\text{hep}\), DSNB, atmospheric) with respect to their best theoretical estimates. The uncertainties on the backgrounds are encoded in the covariance matrix \(\Sigma_\alpha = \text{diag}((\sigma_{\alpha 1}^2, \sigma_{\alpha 2}^2, \sigma_{\alpha 3}^2))\), which we take diagonal because the three fluxes have completely independent origin. For the uncertainties, we have assumed 30\%, 50\% and 20\%, respectively for solar \(\text{hep}\) [63], DSNB [64] and atmospheric neutrinos [65, 66]. The first term in Eq. (9) is defined as

$$
\chi^2(\theta, \alpha) = -2 \ln \frac{L_0}{L_1},
$$

with likelihoods given by

$$
L_0 = \prod_i P(x = \overline{N}_{\text{Bck}}; \lambda = N_{\text{PBH}}^i(\theta) + N_{\text{Bck}}^i(\alpha)),
$$

and

$$
L_1 = \prod_i P(x = \overline{N}_{\text{Bck}}; \lambda = \overline{N}_{\text{Bck}}^i),
$$

where \(P(x, \lambda)\) is the Poisson distribution, \(i\) is the bin index, \(\overline{N}_{\text{Bck}}\) is the nominal number of background events expected in the \(i\)-th bin, whereas \(N_{\text{PBH}}^i\) is the number of PBHs events, and \(N_{\text{Bck}}^i = \sum_j \alpha_j \overline{N}_{\text{Bck},j}^i\) is the floating background. The second contribution in Eq. (9) is a penalty term gauging the statistical weight of the deviation of the background fluxes from their central values. We have neglected other possible backgrounds, in particular those arising from electron recoils of solar \(pp\) and \(^7\text{Be}\) neutrinos, since as shown in [71], these can be effectively suppressed through a statistical discrimination of the photon and ionization signals. In our statistical analysis, we employ ten bins in the recoil energy window \([5 - 50]\) keV. The choice of the threshold \(E_R^{\text{thr}} = 5\) keV is dictated by the position of the sharp cutoff of the \(\text{hep}\) neutrino event rate, which in this way has a marginal impact in our results. In view of the most recent theoretical evaluations of the DSNB [72–75], which point towards somewhat larger fluxes of the \(\overline{\nu}_e\) component with respect to previous findings, as a check, we have increased by a factor of two the nominal value [64] of the DSNB flux for both \(\nu\) and \(\overline{\nu}\) and for all three flavors. We find that the exclusion limits are basically unchanged because in the region of interest the DSNB has a subleading role, with the dominant contribution arising from the atmospheric neutrinos. Figure 3 displays the 90\% C.L. exclusion limits obtained from a xenon detector with the three benchmark exposures reported in the legend. The 20 t yr exposure should be attainable in LZ and XENON1T, while

**FIG. 2. Differential neutrino events rate.** The black dashed contour represents the total background rate (solar + DSNB + atmospheric). The colored solid lines correspond to neutrinos emitted from PBHs evaporation for three representative values of their mass and fraction of total DM content. These benchmark values are excludable at the 90\% C.L. by a liquid xenon experiment with 200 t yr exposure (corresponding to the black stars in Fig. 3). The grey vertical line indicates the threshold recoil energy used in the analysis.
the higher value of 200 t yr refers to the more ambitious project DARWIN. The third contour corresponds to 2000 t yr, which probably may be considered as an ultimate goal for liquid xenon detectors. Such high exposures seem to be less extreme for Argon based detectors [76]. In the same plot, for comparison, we report as a shaded grey region, the upper bounds obtained in [29] from the DSNB searches of Super-Kamiokande [42].

**Impact of PBHs on the neutrino floor.** Neutrinos originating from the Sun, diffuse supernovae and Earth’s atmosphere constitute an irreducible background in DM direct searches [46–51]. This background gives rise to the so-called “neutrino floor”, an ultimate limit to the discovery potential in the plane spanned by the WIMP mass $m_{\chi}$ and the spin-independent WIMP-nucleon cross section $\sigma_{\chi n}$. Of course, such a limitation holds for any kind of interaction, and can be generalized to other types of WIMP-nucleus effective field theory operators [77, 78], but is customary to adopt the case of spin-independent interaction as a benchmark. As a matter of fact, the running experiment XENON1T [79] is already surfacing the solar $^8$B neutrino background, which is dominant for WIMP masses around $m_{\chi} \sim 6$ GeV. The next-generation facilities with very high exposures will unavoidably encounter the neutrino floor also for larger WIMP masses, where the background from DSNB and atmospheric neutrinos is relevant. Going below such a floor will require exploiting timing structure of the signal [80], combining different targets [81], or using directional information [82–84]. Interestingly, the neutrino background can be affected by exotic neutrino interactions [85–88], with consequent modification of the standard neutrino floor [89–94], which can be influenced also by neutrinos originating from decay of massive particles [95, 96].

As illustrated in the previous sections, the neutrinos emitted by PBHs would lie on top of such a familiar background. Therefore, the existence of even a minute fraction of PBHs in the DM content would modify the neutrino floor, making it higher. Here we quantify this effect by calculating the floor following the prescription of [52]. For definiteness and consistency with the previous sections, we consider the case of a xenon target nucleus and adopt the same NFW profile as in Eq. (5). Following [70], we employ a galactic Maxwell-Boltzmann velocity distribution with most probable speed $v_0 = 220$ km/s, truncated at the escape velocity $v_{\text{esc}} = 544$ km/s and boosted into the laboratory frame with $v_{\text{lab}} = 232$ km/s. For a fixed value of the WIMP mass we calculate the cross-section $\sigma_{\chi n}$ that can be excluded at the 90% confidence level (corresponding to 2.3 DM events) selecting the exposure which leads to 1 CEνNS count. Then, varying over the energy threshold $E_{\nu R}^\text{br}$, we keep the value which minimizes the cross-section. By repeating such a procedure for a dense grid of WIMP masses in the range [1, 1000] GeV, we construct the contours shown in Fig. 4. The black upper border of the yellow region corresponds to the well-known ordinary floor. The upper edge of the colored regions corresponds to the case of PBHs with parameters reported in the legend, where for the sake of clarity, we use the same values and color convention adopted in Figs. 1 and 2.

Here, an important remark is in order. For sufficiently high PBH masses $M_{\text{PBH}} \gtrsim 10^{21} g \sim 10^{-12} M_\odot$ ($M_\odot$ being the solar mass), the existence of WIMPs as a dominant or subdominant component of DM, is incompatible even with a small fraction of DM made of PBHs [97–104]. This occurs because WIMPs are accreted by the PBH potential well, forming spiked ultracompact mini-halos, whose existence can be excluded by the non-observation of the expected products of WIMPs self-annihilation. However, for the low PBHs masses considered in our work, falling in the so-called evaporation range ($M_{\text{PBH}} \lesssim 10^{16} g \sim 10^{-17} M_\odot$), this phenomenon is negligible. In addition, one should note that DM may be asymmetric [105–107], and this may occur also for WIMPs [108], in which case self-annihilation is reduced (albeit not necessarily absent [109–112]). Therefore, we deem it interesting to consider how the neutrino floor would get modified by the presence of a minute DM frac-

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1 In [29], which considers both spinning and non-spinning PBHs, the upper limits are reported for masses above $10^{15} g$ because rotating black holes evapora-
ate faster than the non-rotating ones and can contribute to the present DM content for $M_{\text{PBH}} \gtrsim 7 \times 10^{15} g$. In our work, focused on non-rotating PBHs, we show the limits down to $M_{\text{PBH}} = 5 \times 10^{15} g$, as it is customary in the literature.
We have shown that with the high exposures envisaged of PBHs having mass in the range considered in this work.

Conclusions. We have explored a new avenue in constraining PBHs as Dark Matter with the neutrinos emitted in the Hawking radiation. Specifically, we have pointed out that neutrinos from PBHs can interact via the coherent elastic neutrino nucleus scattering (CEνNS) in multi-ton DM direct detection experiments. We have shown that with the high exposures envisaged for the next-generation facilities, it will be possible to set bounds on the fraction of DM composed of PBHs, improving the existing neutrino limits obtained with Super-Kamiokande. In addition, we have quantified how much a signal originating from PBHs would heighten the so-called “neutrino floor”, the ultimate barrier towards detection of WIMPs as the dominant DM component. For definiteness we have focused our study on liquid xenon detectors such as DARWIN [113], LZ [114], and XENON1T [115], but other targets such as liquid argon employed in DarkSide-20k [76] and ARGO [76], or archeological lead in RES-NOVA [116], should offer a similar opportunity provided that very high exposures are reached (see [117] for an extensive review of the experimental program of the direct detection facilities). Finally, we underline that, in the context of PBHs searches, the direct DM experiments would rather operate as indirect DM observatories. From this perspective, our study lends further support to the emerging role of such underground facilities as multi-purpose low-energy neutrino telescopes complementary to their high-energy “ordinary” counterparts, IceCube and KM3NeT.

ACKNOWLEDGMENTS

We thank B. Dasgupta and D. Montanino for helpful discussions. We acknowledge partial support by the research grant number 2017W4HAT7S “NAT-NET: Neutrino and Astroparticle Theory Network” under the program PRIN 2017 funded by the Italian Ministero dell’Istruzione, dell’Università e della Ricerca (MIUR) and by the research project TAsP funded by the Instituto Nazionale di Fisica Nucleare (INFN).

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