Primordial Black Holes evaporating on the neutrino floor

Roberta Calabrese
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
E-mail: rcalabrese@na.infn.it

Abstract. Primordial Black Holes (PBHs) are Black holes formed in the early universe. They evaporate emitting all the elementary particles whose mass is lower than the PBHs temperature. We focused on PBHs whose mass is in the range \([5 \times 10^{14}, 8 \times 10^{15}] \) g. We studied their neutrinos emission. These neutrinos can interact via coherent elastic neutrino-nucleus scattering (CEνNS) producing a signal in multi-ton DM direct detection experiments. We show that is possible to set bounds on the PBHs abundance. This talk is based on Ref.[1].

1. Introduction
There are many Dark Matter (DM) candidates in the literature. Some of them predict the existence of new particles beyond the Standard Model (BSM), for instance, WIMPs, WIMPzillas, and Axions. Other DM candidates are extensive objects such as MACHOS, MACROS, and PBHs. In this talk, we will focus on PBHs. They could be originated from the collapse of large overdensities in the Very Early Universe. Due to the fact that they do not come from the collapse of stars, they can have any mass. PBHs abundance is often indicated with

\[
f_{\text{PBH}} = \frac{\rho_{\text{PBH}}}{\rho_{\text{DM}}},
\]

PBHs evaporate emitting Hawking Radiation that consists of the emission of all the elementary particles whose mass is smaller than the PBHs temperature. The emission is blackbody-like. PBHs’ temperature is inversely proportional to their mass, thus PBHs with a higher mass are further from the complete evaporation than the lighter ones. PBHs with masses around \(10^{15} \) g are near the complete evaporation.

2. Neutrinos emitted by PBHs.
In our analysis, we considered a monochromatic mass distribution for PBHs in the range \([5 \times 10^{14}, 8 \times 10^{15}] \) g. We considered them to be non-rotating and neutral. We obtained the neutrino emission from PBHs using the publicly available BlackHawk code [4]. We considered Majorana neutrinos since Dirac neutrinos would produce faster evaporation having twice the degrees of freedom of the Majorana ones. It has been estimated that the effect of having Dirac neutrinos is around 10% [3].
Neutrino fluxes from PBHs. The solid colored lines represent the neutrino primary flux three benchmarks for different PBHs masses, while the dashed ones represent the secondary neutrino flux. The Black dashed lines represents the background due to DSNB, solar, and atmospheric neutrinos. The figure is an update of a figure present in Ref. [1].

Neutrino emission consists of two components: neutrinos emitted directly by the PBHs (primary emission), and neutrinos deriving from the hadronization of strongly-interacting constituents and decay of unstable particles produced by the evaporation (secondary component). Due to some uncertainties on the secondary component, we decided to use only the primary one.

The Galactic differential neutrino flux is given by

$$\frac{d\phi_{\nu}^{MW}}{dE_{\nu}} = \int d\Omega \frac{d^2 N}{4\pi dE_{\nu}dt} \int dt \frac{f_{PBH} \rho_{MW} [r(l, \psi)]}{M_{PBH}},$$  \hspace{1cm} (2)

where

$$r(l, \psi) = \sqrt{r_\odot^2 - 2lr_\odot \cos \psi + l^2},$$  \hspace{1cm} (3)

and $r_\odot$ is the distance between the sun and the galactic center, $l$ is the distance to the PBH, and we employed a Navarro-Frenk-White (NFW) density profile [2].

The Extra-Galactic differential flux is given by

$$\frac{d\phi_{\nu}^{EG}}{dE_{\nu}} = \int_{t_{min}}^{t_{max}} dt \left[ 1 + z(t) \right] \frac{f_{PBH}\rho_{DM}}{M_{PBH}} \frac{d^2 N_{\nu}}{dE_{\nu}dt} E_{\nu} = [1 + z(t)] E_{\nu},$$  \hspace{1cm} (4)

where $t_{min}$ is taken to be the matter-radiation equality, and $t_{max}$ is the minimum between the Universe lifetime and the PBHs lifetime. Since none of the PBHs we are considering is already evaporated, $t_{max}$ is always the Universe lifetime. The total neutrino flux is plotted in Fig. 1 for three benchmark values of $M_{PBH}$ and $f_{PBH}$.

3. Coherent scattering of neutrinos.

CE\nuNS differential cross-section is given by

$$\frac{d\sigma_{\nu N}(E_{\nu}, E_R)}{dE_R} = \frac{G_F^2 m_N Q_w^2}{4\pi} \left( 1 - \frac{m_N E_R}{2E^2_{\nu}} \right) F^2(q),$$  \hspace{1cm} (5)

where $G_F$ is the Fermi constant, $Q_w = [N - Z(1 - 4\sin^2 \theta_W)]$, $Z$ and $N$ are the number of proton and neutron in the atom, $m_N$ is the nucleus mass, $\theta_W$ is the Weinberg angle, $E_R$ and $E_{\nu}$ are the...
Figure 2. Upper bounds on PBHs. In grey it is shown the total background. The solid colored lines represent the same benchmark cases showed in Fig. 1. The solid vertical line represents the threshold recoil energy used in our analysis. The figure is an update of a figure present in Ref. [1].

nucleus recoil and neutrino energy respectively. \( F(q) \) is the nuclear form factor. The differential rate of event can be computed as follows

\[
dR_{\nu N}/dE_R dt = N_T \epsilon(E_R) \int dE_\nu d\sigma_{\nu N}/dE_R(d\phi_\nu dE_\nu \Theta(E_{\nu}^{\text{max}} - E_R),
\]

where \( N_T \) is the number of target nuclei in the detector, \( \epsilon(E_R) \) is the detector efficiency and \( \Theta \) is the Heaviside step function. In Fig. 2 are shown the differential rate of event for the same benchmarks as Fig. 1. To fully exploit the fact that the shape of the differential rate of event is different than the background, we performed a binned analysis.

4. PBHs at next-generation detectors.

We implemented a \( \chi^2 \) statistic, that is

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

where \( \theta^T = [M_{PBH}, f_{PBH}] \), 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 \( hep \), DSNB, atmospheric) with respect to their best theoretical estimates. \( \Sigma = \text{diag}(\sigma^2_{\alpha_1}, \sigma^2_{\alpha_2}, \sigma^2_{\alpha_3}) \) is the covariance matrix, which we take diagonal.

For the uncertainties, we have assumed 30\%, 50\% and 20\%, respectively for solar \( hep \) [6], DSNB [7], and atmospheric neutrinos [8]. \( \chi^2(\theta, \alpha) \) is defined as

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

where

\[
L_0 = \prod_i P(x = N_{Bck}^i; \lambda = N_{PBH}^i(\theta) + N_{Bck}^i(\alpha)),
\]

and

\[
L_1 = \prod_i P(x = N_{Bck}^i; \lambda = N_{Bck}^i).
\]
**Figure 3. Upper bounds on PBHs.** Exclusion contours drawn at 90% confidence level for 1 d.o.f. The stars represent the three benchmark cases used in the previous plots. The colored regions represent existing constraints [9, 10, 11].

$P(x, \lambda)$ is the Poisson distribution, $N^i_{\text{Bck}}$ and $N^i_{\text{PBH}}(\theta)$ are the number of background events and the number of events due to PBHs in the $i^{th}$ bin respectively, while $N^i_{\text{Bck}}(\alpha) = \sum_j \alpha_j N^i_{\text{Bck},j}$. In our statistical analysis, we employed 10 bins in the recoil energy range [5 - 50]keV. In Fig. 3 are shown 90% CL exclusion limit that can be put from a Xenon detector with three benchmark exposures.

5. **Impact of PBHs on the neutrino floor.**
The neutrino floor is the irreducible background in DM direct searches due to neutrinos originating from the sun, diffuse supernovae, and Earth’s atmosphere. Since the signal that PBHs would produce lies on top of the standard background for certain PBHs abundance, we have a modification of the Neutrino floor due to the existence of a small fraction of PBHs. Here we quantify this effect by calculating the floor following the prescription of [5]. In Fig. 4 it is shown the modification of the neutrino floor for the same benchmark cases shown in the previous plots.

6. **Conclusions**
We pointed out that neutrinos produced by the evaporation of PBHs can interact via CE$\nu$NS and produce a signal in multi-ton DM direct detection experiments. We have shown that it will be possible to set constraints on PBHs abundance with the new generation facilities and improve the existing neutrino limit obtained by Super-Kamiokande. Lastly, we computed how the neutrino floor would be affected by the existence of a small fraction of PBHs. It is important to stress out that there would not be any changes if we had considered the highest $f_{\text{PBH}}$ allowed considering all the constraints.

7. **Acknowledgments**
We acknowledge partial support by the research grant number 2017W4HA7S “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).

**References**
[1] R. Calabrese, D. F. G. Fiorillo, G. Miele, S. Morisi and A. Palazzo, [arXiv:2106.02492 [hep-ph]].
Figure 4. Impact of PBHs on the Neutrino floor. The black line represents the Standard Neutrino floor, while the upper borders of the colored region represent the modification of the neutrino floor for three benchmark cases, the same as Fig. 1. The figure is an update of a figure present in Ref. [1].

[2] J. F. Navarro, C. S. Frenk and S. D. M. White, Astrophys. J. 490, 493-508 (1997) doi:10.1086/304888 [arXiv:astro-ph/9611107 [astro-ph]].
[3] C. Lunardini and Y. F. Perez-Gonzalez, JCAP 08, 014 (2020) doi:10.1088/1475-7516/2020/08/014 [arXiv:1910.07864 [hep-ph]].
[4] A. Arbey and J. Auffinger, Eur. Phys. J. C 79, no.8, 693 (2019) doi:10.1140/epjc/s10052-019-7161-1 [arXiv:1905.04268 [gr-qc]].
[5] J. Billard, L. Strigari and E. Figueroa-Feliciano, Phys. Rev. D 89, no.2, 023524 (2014) doi:10.1103/PhysRevD.89.023524 [arXiv:1307.5458 [hep-ph]].
[6] N. Vinyoles, A. M. Serenelli, F. L. Villante, S. Basu, J. Bergström, M. C. Gonzalez-Garcia, M. Maltoni, C. Peña-Garay and N. Song, Astrophys. J. 835, no.2, 202 (2017) doi:10.3847/1538-4357/835/2/202 [arXiv:1611.09867 [astro-ph.SR]].
[7] J. F. Beacom, Ann. Rev. Nucl. Part. Sci. 60, 439-462 (2010) doi:10.1146/annurev.nucl.010909.083331 [arXiv:1004.3311 [astro-ph.HE]].
[8] G. Battistoni, A. Ferrari, T. Montaruli and P. R. Sala, Astropart. Phys. 23, 526-534 (2005) doi:10.1016/j.astropartphys.2005.03.006.
[9] S. W. Li and J. F. Beacom, Phys. Rev. D 91, no.10, 105005 (2015) doi:10.1103/PhysRevD.91.105005 [arXiv:1503.04823 [hep-ph]].
[10] B. Carr, F. Kuhnel and M. Sandstad, Phys. Rev. D 94, no.8, 083504 (2016) doi:10.1103/PhysRevD.94.083504 [arXiv:1607.06077 [astro-ph.CO]].
[11] B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, [arXiv:2002.12778 [astro-ph.CO]].