

Fermionic sub-GeV dark matter from evaporating primordial black holes at DarkSide-50

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We present a search for boosted dark matter from primordial black hole (PBH) evaporation using the DarkSide-50 ionization-signal-only dataset corresponding to the experiment's (12202 ± 180) kg d exposure. We focus on evaporation of PBHs with masses in the range $[10^{14}, 10^{16}]$ g producing Dirac fermionic dark matter particles with sub-GeV kinetic energy. These relativistic particles, with energies up to hundreds of MeV, can generate detectable signals for masses below $\mathcal{O}(100)$ MeV. The absence of a signal enables setting complementary limits to those derived from cosmological observations and direct detection searches for cosmic-ray-boosted dark matter.

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Astrophysical and cosmological observations over a wide range of length scales suggest the presence of dark matter (DM) in the Universe [1,2]. Despite being regarded as one of the backbones of the standard cosmological model, we have almost no information regarding its nature and interaction, apart from its gravitational effects. Among the detection techniques employed to discern DM properties, one finds direct detection experiments looking for DM-nucleon and DM-electron interactions [3]. The drawback of looking at these interactions is that the recoil energies induced by sub-GeV DM,¹ predicted by several mechanisms [4,5], are below the detection threshold of most direct detection experiments. Scenarios predicting a fraction of DM endowed with high kinetic energies overcome this experimental limitation [6–14]. In this paper, we focus on detecting boosted sub-GeV DM from evaporating primordial black holes (PBHs) using data from the DarkSide-50 experiment.

The DarkSide-50 experiment is a dual-phase liquid argon (LAr) time projection chamber (TPC). It operated underground in Italy at the INFN Gran Sasso Laboratories. Energy released by particle interactions in the 46.4 ± 0.7 kg active LAr volume results in two measurable quantities: scintillation light (S1) and ionization ion-electron pairs. The ionization electrons are drifted by a 200 V/cm electric field toward the upper part of the TPC, where they are extracted into a gas pocket by a stronger 2.8 kV/cm electric field, inducing a secondary electroluminescence light signal (S2) [15–19]. The 128 nm ultraviolet S1 and S2 photons are converted into 420 nm photons by a tetraphenyl butadiene wavelength shifter coating the internal surface of the TPC. Below the cathode and above the anode, the 420 nm photons are finally detected by two arrays of nineteen 3 in. photomultiplier tubes (PMTs). The TPC is contained in a stainless steel cryostat. The cryostat lies inside a 30 ton boron-loaded liquid scintillator equipped with 110 (8 in.) PMTs and is used as an active neutron veto. The neutron veto is finally enclosed in a 1 kt ultrapure water Cherenkov tank equipped with 80 PMTs that provides a passive shield against

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external backgrounds and that is used as a cosmic muon veto. Additional information on the DarkSide-50 detector is given in Refs. [20–24].

The DarkSide-50 experiment has searched for DM with masses ranging from hundreds of MeV to several GeV with the ionization-only and Migdal analyses [25,26]. Dark matter particles with lower masses could still be detectable by DarkSide-50 if they had sufficient kinetic energy. Evaporating PBHs could provide such a mechanism, as shown in Refs. [27,28]. PBHs, hypothetical black holes generated as a by-product of some inflationary (or more complex) scenarios [29,30], offer a broader mass range than ordinary black holes because of their nonstellar origin. Hawking’s studies on the quantum effects of PBHs revealed that they evaporate, emitting elementary particles with masses smaller than the PBHs’ temperature [31,32]. This unique property places several constraints on PBHs’ abundance [33–43].

According to Hawking’s calculations, spinless neutral PBHs with masses exceeding 5×10^{14} g survive up to the present time. Many phenomenological studies focused on the production of DM from PBH evaporation in the early Universe [44–53]. In contrast, we consider the production of DM up to the present time. Moreover, the generated DM constitutes a small contribution to the current DM abundance [27,28,54,55]. However, its presence yields interesting implications for direct detection facilities. The analysis implemented in this paper leads to constraints in the DM parameter space that are complementary with existing ones [10,12,56–58].

In our search strategy, we characterize the DM flux from PBHs with a monochromatic mass distribution. We consider nonrotating and neutral PBHs, as spinning PBHs exhibit an enhanced evaporation rate. Within this context, the Hawking temperature is [31,32,59–63]

$$T_{\text{PBH}} = 10.6 \left(\frac{10^{15} \text{ g}}{M_{\text{PBH}}} \right) \text{ MeV}, \quad (1)$$

where M_{PBH} is the PBH mass in grams. The differential spectrum of emitted fermion DM species χ from a PBH with Hawking temperature T_{PBH} reads

$$\frac{d^2 N_\chi}{dT_\chi dt} = \frac{g_\chi}{2\pi} \frac{\Gamma^\chi(T_\chi, T_{\text{PBH}})}{\exp(T_\chi + m_\chi)/T_{\text{PBH}} + 1}, \quad (2)$$

where m_χ , T_χ , and g_χ are the particle’s mass, kinetic energy, and degrees of freedom, respectively. This expression accounts for deviation from the blackbody radiation by means of the graybody factor Γ^χ , obtained from BlackHawk [64–66], a code that computes the Hawking emission. We assume our DM candidate to be a Dirac fermion ($g_\chi = 4$).

After estimating the differential spectrum, we quantify the flux of light DM reaching Earth. We divide the flux of

DM particles from PBHs into Galactic (gal.) and extragalactic (egal.) components

$$\frac{d^2 \phi_\chi}{dT_\chi d\Omega} = \frac{d^2 \phi_\chi^{\text{gal}}}{dT_\chi d\Omega} + \frac{d^2 \phi_\chi^{\text{egal}}}{dT_\chi d\Omega}. \quad (3)$$

We describe the Galactic component as

$$\frac{d^2 \phi_\chi^{\text{gal}}}{dT_\chi d\Omega} = \frac{f_{\text{PBH}}}{4\pi M_{\text{PBH}}} \frac{d^2 N_\chi}{dT_\chi dt} \int_0^{+\infty} ds \rho_{\text{NFW}}(r), \quad (4)$$

where $f_{\text{PBH}} \equiv \rho_{\text{PBH}}/\rho_{\text{DM}}$ is the fraction of the DM energy density composed of PBHs in the current cosmic landscape. The galactic component is proportional to the integral over the line-of-sight distance s of the Galactic DM density. Our analysis adopts the Navarro-Frenk-White DM density profile ρ_{NFW} [67], which is a function of the galactocentric distance $r = (r_\odot^2 + s^2 - 2r_\odot s \cos \ell \cos b)^{1/2}$, where $r_\odot = 8.5$ kpc is the distance between the Sun and the Galactic Center, and (b, ℓ) are the Galactic latitude and longitude.

We consider the following expression for the extragalactic differential flux:

$$\frac{d^2 \phi_\chi^{\text{egal}}}{dT_\chi d\Omega} = \frac{f_{\text{PBH}} \rho_{\text{DM}}}{4\pi M_{\text{PBH}}} \int_{t_{\text{min}}}^{t_{\text{max}}} dt [1 + z(t)] \frac{d^2 N_\chi}{dT_\chi dt}, \quad (5)$$

where $z(t)$ is the redshift, and we perform the integral from the time of matter-radiation equality (t_{min}) to the age of the Universe (t_{max}). As $z(t)$ increases, the contribution of boosted dark matter becomes progressively negligible due to the redshift. In contrast with the Galactic component, which is enhanced toward the Galactic Center, the extragalactic one is isotropic. In Fig. 1, we show the Galactic and extragalactic diffuse flux for a reference DM mass of

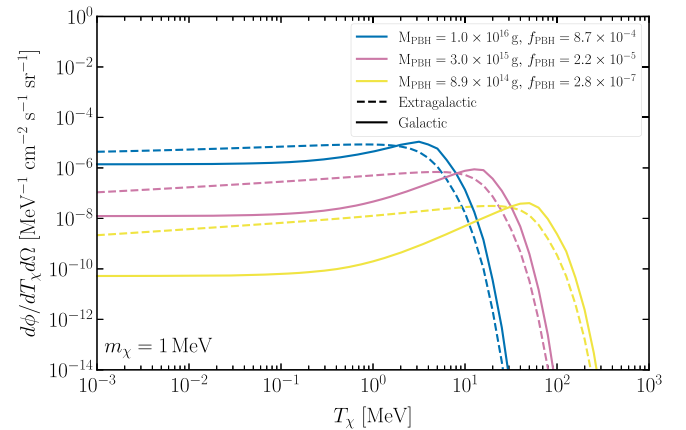


FIG. 1. Diffuse DM differential flux from evaporating PBHs as a function of its kinetic energy. The solid lines show the Galactic components, while the dashed lines the extragalactic ones. With different colors, we identify different PBH masses and abundances.

$m_\chi = 1$ MeV for different PBH masses assuming the largest allowed f_{PBH} by constraints of Refs. [41,68].

Direct detection facilities can detect DM via their interaction with nucleons and electrons. However, these processes are not only fundamental for detection but also for the attenuation of the DM flux at the DarkSide-50 due to propagation through Earth and its atmosphere [69–72].

In this analysis, we adopt the analytical approach described in Ref. [10], where the authors consider a ballistic DM propagation. However, as shown in Ref. [12], this approximation would not hold for light DM collisions with heavy nuclei. Instead, they consider a diffusive propagation that may lead to a larger energy loss, a possible reflection of DM, and a lower flux. To better understand the impact of the ballistic approximation, we also estimate χ flux under the most conservative assumption that any interaction depletes the particles completely. Even under this assumption, the expected event rate in DarkSide-50 is still detectable, as the difference in event rates is around 12%. Because of this, we do not expect that a more detailed model of the propagation of a light DM candidate would substantially alter our scenario; we simply use the ballistic approach.

For PBHs with masses greater than 5×10^{14} g, the Hawking temperature—and therefore the dark matter kinetic energy—remains below 100 MeV. Consequently, the impact of the nuclear form factor in the propagation through Earth, as well as the effects of quasielastic and inelastic scattering, can be safely neglected [73]. Within this approximation, the interaction length for propagation through Earth ($\ell_{\text{int}}^\oplus$) and the atmosphere ($\ell_{\text{int}}^{\text{atm}}$) is

$$\ell_{\text{int}}^i = \left[\sum_{\mathcal{N}} n_{\mathcal{N}}^i \sigma_{\chi\mathcal{N}} \frac{2m_{\mathcal{N}}m_\chi}{(m_{\mathcal{N}} + m_\chi)^2} \right]^{-1}, \quad (6)$$

where the sum is taken over the most abundant elements in Earth and in the atmosphere, $\mathcal{N} = \{\text{Fe, Al, N, O, Si, Ni, S, Mg, Ca}\}$, $n_{\mathcal{N}}$ is their abundance, and $m_{\mathcal{N}}$ is their mass.

Assuming χ couples equally to protons and neutrons—a common benchmark in searches for weakly interacting massive particles—the DM-nucleon cross section is

$$\sigma_{\chi\mathcal{N}} = \sigma_\chi^{\text{SI}} A^2 \left(\frac{m_{\mathcal{N}}(m_\chi + m_p)}{m_p(m_\chi + m_{\mathcal{N}})} \right)^2, \quad (7)$$

where A is the $\mathcal{N}$ mass number, m_p is the proton mass, and σ_χ^{SI} denotes the spin-independent cross section, the focus of our analysis. We highlight that spin-independent scattering is subject to a coherent enhancement. We indicate with T_0 the initial kinetic energy of a particle before entering the atmosphere, and with T_d the kinetic energy of a dark matter particle that traveled a total distance $d = d_{\text{atm}} + d_\oplus$, where d_{atm} is the thickness of the atmosphere traversed by the DM particle, and $d_\oplus$ is the depth of the DarkSide-50 experiment. The distances d_{atm} and $d_\oplus$ depend on the

time-dependent longitude of the experiment. We account for the DarkSide-50 detector located at a depth of about 1.4 km [74]. The flux of DM particles in DarkSide-50 is

$$\frac{d^2\phi_\chi^d}{dT_d d\Omega} \approx \frac{4m_\chi^2 e^\tau}{(2m_\chi + T_d - T_d e^\tau)^2} \left(\frac{d^2\phi_\chi}{dT_\chi d\Omega} \Big|_{T_0} \right), \quad (8)$$

where $\tau = d_{\text{atm}}/\ell_{\text{int}}^{\text{atm}} + d_\oplus/\ell_{\text{int}}^\oplus$, and the incoming DM flux is evaluated at

$$T_0(T_d) = \frac{2m_\chi T_d e^\tau}{2m_\chi + T_d - T_d e^\tau}. \quad (9)$$

We consider the average of Eq. (8) over a day.

After estimating the flux of DM at the detector, we can calculate the differential event rate. It quantifies the number of expected events at the detector due to the interaction of DM with the target material. In the case of DM-nucleon interaction, the differential event rate reads as

$$\frac{dR}{dE_r} = \sigma_{\chi\text{Ar}} \mathcal{N}_{\text{Ar}} \int dT_d d\Omega \frac{d^2\phi_\chi^d}{dT_d d\Omega} \frac{\Theta(E_r^{\text{max}} - E_r)}{E_r}, \quad (10)$$

where $\mathcal{N}_{\text{Ar}}$ is the total number of targets, Θ is the Heaviside function, E_r is the recoil energy, and

$$E_r^{\text{max}} = \frac{T_d^2 + 2m_\chi T_d}{T_d + (m_\chi + m_{\text{Ar}})^2/(2m_{\text{Ar}})} \quad (11)$$

is the maximum recoil energy allowed, with m_{Ar} being the argon mass. The spin-independent cross section $\sigma_{\chi\text{Ar}}$, including also the argon nuclear form factor [75,76], is defined as

$$\sigma_{\chi\text{Ar}} = \sigma_\chi^{\text{SI}} A^2 \left(\frac{m_{\mathcal{N}}(m_\chi + m_p)}{m_p(m_\chi + m_{\mathcal{N}})} \right)^2 F(q)^2, \quad (12)$$

where q is the three-momentum transfer and $F(q)$ is the Helm nuclear form factor.

In Fig. 2, we show the expected event rate vs recoil energy assuming $M_{\text{PBH}} = 1.0 \times 10^{15}$ g and the highest $f_{\text{PBH}} = 4.1 \times 10^{-7}$ compatible with existing limits [41,68]. Initially, the rate increases for higher cross sections, until attenuation effects become significant and shift the spectrum toward lower recoil energies. As the DM lose energy traveling through Earth's overburden, they arrive at the detector with reduced kinetic energy, which leads to a suppression of high-energy recoils but an enhancement of the rate at lower recoil energies. For even larger cross sections, this enhancement moves to recoil energies below the detector's threshold, ultimately causing the observed rate to decrease overall.

For the analysis described in this work, we consider only the S2 signal, regardless of the presence or absence of an

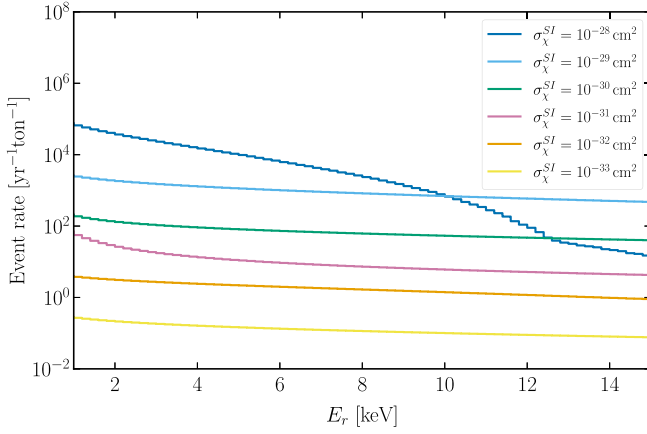


FIG. 2. Expected rate assuming $M_{\text{PBH}} = 1.0 \times 10^{15}$ g and $f_{\text{PBH}} = 4.1 \times 10^{-7}$ for different spin-independent cross sections.

accompanying S1 signal. The advantage of considering the so-called “S2-only” dataset is that, without requiring S1, the low-energy threshold to nuclear recoils drops significantly. However, without S1, there is no possibility of discriminating between electronic and nuclear recoils, therefore requiring a rigorous treatment of the electron recoil background and its related systematic uncertainties. A rigorous definition of the background model can be found in Ref. [25]. The main background contributions are given by “external” γ background events, induced by the radioactivity of the PMTs and the cryostat, and by “internal” background events, induced by the decays of ^{85}Kr and ^{39}Ar isotopes within the active LAr volume. Other contributions, including solar and atmospheric neutrinos and cosmogenic or radiogenic neutrons, are negligible. The β decay spectra associated with the ^{85}Kr and ^{39}Ar background are computed including the atomic exchange and screening effects and are validated down to 200 eV [77,78]: below this threshold, we consider an additional symmetric systematic uncertainty on the spectral shape ranging linearly from 25% at 0 eV to 0% at 200 eV [25]. Moreover, the uncertainty on the Q value [79] is also taken into account as a systematic 1% uncertainty on the shape of the spectrum of ^{39}Ar and 0.4% on the one of ^{85}Kr . The other systematic effect acting on the shape of all the background spectra being considered is the uncertainty on the ionization response, modeled via Monte Carlo simulations and constrained by calibration measurements [80]. The external background spectra are computed by means of Monte Carlo simulations of the radioactivity of each component of the detector. The simulations use the initial activities and their associated uncertainties from material radiopurity measurements and account for their decay over the data taking period.

The dataset considered in this paper corresponds to the total (12202 ± 180) kg d exposure of the experiment, and we used the same data selection described in Ref. [25]. The analysis of the sensitivity of DarkSide-50 to a PBH induced

DM signal is carried out with the Bayesian analysis tool developed and presented in Ref. [81]. This method integrates the detector response model into the likelihood function, explicitly preserving the dependence on the quantity of interest, $\sigma_{\chi}^{\text{SI}}$. In particular, as done in Ref. [81], we assume a binned Poisson likelihood defined as

$$p(\{x_i\}|\theta) = \prod_i \frac{\lambda_i(\theta)^{x_i}}{x_i!} e^{-\lambda_i(\theta)}, \quad (13)$$

where λ_i is the intensity of the Poisson process in the i th bin of the data spectrum, x_i is the corresponding observed number of events, and θ indicates all the parameters of the fit related to the signal model and the detector response and background mode, i.e., the calibrations, the background rates, and the signal parameters. The data spectrum is expressed as a function of the number of detected primary ionization electrons N_{e^-} . This quantity, which is not necessarily an integer, is proportional to S2—and consequently to the nuclear recoil energy—through the parameter $g_2 = (23 \pm 1)$ photoelectrons/ e^- . This represents the mean number of photoelectrons produced per ionization electron extracted in the gas pocket [80]. The lower N_{e^-} threshold for this analysis is set at $N_{e^-} = 4$, where the contribution of correlated background events due to spurious single electrons is negligible. The upper threshold is defined by the maximum value at which detector response calibrations have been validated, specifically, $N_{e^-} = 170$ [25,26,81]. For this analysis, $\lambda_i(\theta)$ is given by

$$\begin{aligned} \lambda_i = \frac{\mathcal{E}}{\mathcal{E}_{\text{DS}}} [& r_{B,\text{Ar}} S_i^{\text{Ar}}(\theta_{\text{nuis}}) + r_{B,\text{Kr}} S_i^{\text{Kr}}(\theta_{\text{nuis}}) \\ & + r_{B,\text{PMT}} S_i^{\text{PMT}}(\theta_{\text{nuis}}) + r_{B,\text{cryo}} S_i^{\text{cryo}}(\theta_{\text{nuis}}) \\ & + S_i^{\chi}(\sigma_{\chi}^{\text{SI}}, \theta_{\text{nuis}}, f_{\text{PBH}})], \end{aligned} \quad (14)$$

where S_i^{src} , with $\text{src} \in \{\text{Ar}, \text{Kr}, \text{PMT}, \text{cryo}, \chi\}$, are the expected background and signal spectra for the nominal total exposure $\mathcal{E}_{\text{DS}}$ as a function of the detector response nuisance parameters θ_{nuis} and the cross section $\sigma_{\chi}^{\text{SI}}$. The variables $r_{B,\text{src}}$ are proportional to the rate of the internal and external background components. Here we use the same normalization of Ref. [81], where the spectra are normalized in such a way that $r_{B,\text{src}} = 1$ corresponds to the nominal DarkSide-50 exposure $\mathcal{E}_{\text{DS}}$. The quantity f_{PBH} is not treated as a parameter of the fit but it is fixed, depending on $\mathcal{M}_{\text{PBH}}$, to the highest value allowed by existing constraints derived from extragalactic γ -ray data [41] and from isotropic x-ray observations [68]. For smaller values of f_{PBH} , the corresponding upper bound on the cross section derived in this work can be obtained as $\sigma_{\chi}^{\text{SI,new}} = \sigma_{\chi}^{\text{SI,old}} f_{\text{PBH}}^{\text{old}} / f_{\text{PBH}}^{\text{new}}$. This approximation remains valid until the cross section becomes large enough for the Earth shielding effect to significantly limit the detector’s sensitivity. In that regime, the fit must be repeated using the correct signal spectrum. A rigorous

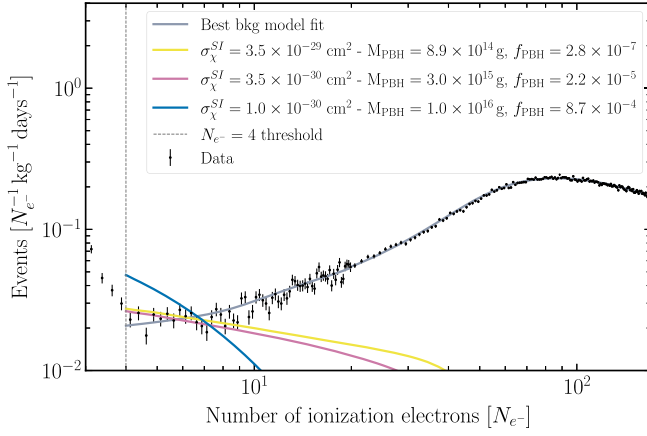


FIG. 3. The data spectrum (black points) and the best background-only fit result (gray line). As an example, signal spectra for three different values of σ_χ^{SI} and M_{PBH} at $m_\chi = 1$ MeV are shown by the yellow, purple, and blue lines. As shown in Fig. 1, lighter PBHs result in harder DM spectra.

description of the detector response model is described in Ref. [25], while its implementation in this analysis framework is given in Ref. [81]. The prior probability density function associated with the θ_{nuis} and the $r_{B,\text{src}}$ parameters corresponds to the constraints coming from the calibration, while a flat prior in the $[0, 10^{-28}]$ cm² range is used for σ_χ^{SI} . The quantity $\mathcal{E} = (12202 \pm 180)$ kg d represents the total exposure, with a prior uncertainty of 1.5% [25].

The σ_χ^{SI} cross section upper bound is computed as the so-called 90% credible interval (CI), defined as the 90% quantile of the marginalized posterior probability density function for σ_χ^{SI} . As done in Ref. [81], the spectrum below $N_{e^-} < 20$ is binned into $0.25N_{e^-}$ bins and the spectrum with $N_{e^-} \geq 20$ uses $1N_{e^-}$ bins. This choice is demonstrated to have a 5%–10% beneficial impact on the sensitivity with respect to a $1N_{e^-}$ binning on the whole spectrum when the signal rapidly falls with N_{e^-} [81]. The Earth shielding (ES) upper limit is defined as the value of the cross section at which the number of signal events above the $N_{e^-} = 4$ threshold goes to zero.² In Fig. 3, the data spectrum (black points), the best background-only fit result (gray line), and examples of signal spectra (blue, red, and orange lines) are reported. These spectra include all the smearing effects due to the detector response and are expressed as a function of N_{e^-} . Figure 4 shows the 90% CI expected (dashed lines) and the observed (continuous lines) limits on the σ_χ^{SI} cross section as a function of the DM mass. The expected limits are obtained on the so-called Asimov dataset, namely, the dataset generated using the nominal prefit best estimation of the θ_{nuis} ,

²Different definitions for the Earth shielding curve were tested, but given the rapidity with which, due to the Earth shielding effect, the spectrum above threshold falls to zero as the cross section increases, they are not appreciably different from the smallest value of σ_χ^{SI} at which there is no event above threshold.

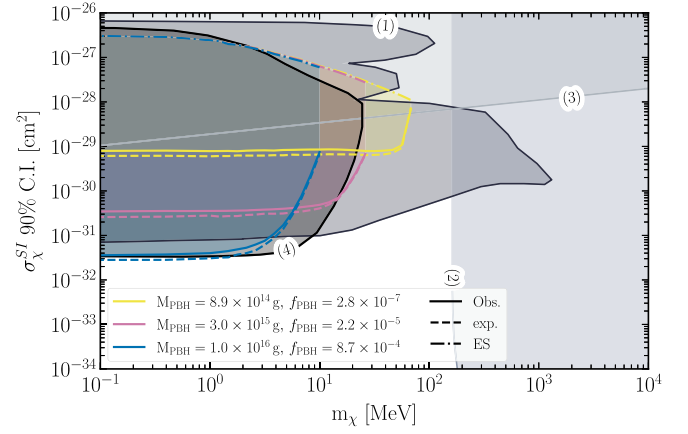


FIG. 4. The 90% CI observed (solid lines) and expected (dashed lines) limit on the DM cross section σ_χ^{SI} as a function of the DM mass, assuming a Dirac fermion DM candidate, and for three different values of the PBH mass for the final DarkSide-50 exposure of 12202 ± 180 kg d. The parameter f_{PBH} is fixed by the constraints of Refs. [41,68] (see the text for further details). For comparison, we report DM constraints from (1) cosmic-ray-boosted DM particles [10,12,56], (2) from the CRESST experiment (in the standard halo model scenario) [57,58], (3) from cosmology [82–85], and (4) from CDEX-10 [54], whose results were obtained in a similar scenario.

$r_{B,\text{src}}$, and $\mathcal{E}$ parameters. The observed limits are instead obtained on the real DarkSide-50 dataset. The difference between the two curves is due to the difference between the Asimov dataset and the real dataset, reflecting the variation of the pre- and postfit expected values for θ_{nuis} , $r_{B,\text{src}}$, and $\mathcal{E}$. However, all these variations are compatible with the prior expectations within calibration uncertainties [25,81].

In conclusion, we report on the search for boosted DM from PBH evaporation using the DarkSide-50 S2-only dataset. The analysis was performed in the Bayesian framework presented in Ref. [81], using the same dataset and the same detector and background model of the analyses presented in Refs. [25,26,81,86]. The constraints in Fig. 4 extend up to $M_{\text{PBH}} = 1.0 \times 10^{16}$ g and represent a complementary result with respect to the cosmological [82–85] and direct detection searches [57,58].

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DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

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