Primordial Black Holes (PBHs) with a mass $M \lesssim 10^{17} \text{g}$ are expected to inject sub-GeV electrons and positrons in the Galaxy via Hawking radiation. These cosmic rays are shielded by the solar magnetic field for Earth-bound detectors, but not for VOYAGER-1, which is now beyond the heliopause. We use its data to constrain the fraction of PBHs to the dark matter in the Galaxy, finding that PBHs with $M < 10^{16} \text{g}$ cannot contribute more than 0.1% (or less for a lognormal mass distribution). Our limits are based on local galactic measurements and are thus complementary to those derived from cosmological observations.


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1. As well as generated more recent incarnations in the same vein, involving other macroscopic candidates, see e.g. [4, 5] and references therein.

2. Galactic ones [29] are also relevant but less competitive.

3. In the same range of masses, recent bound have been derived using Planck data [31] as well as the latest EDGES measurements of the 21 cm absorption at high redshift [32]. The former are subdominant with respect to the EGB ones, while the latter could be stronger. Since, however, they are still subject to large uncertainties, we will mostly compare with the EGB.
at about 0.5 GeV. They will therefore be relevant for models where the $e^\pm$ are significantly accelerated during the propagation process.

The rest of this Letter is organized as follows. We first review the production of $e^\pm$ from PBH evaporation and their propagation in the local galactic environment. Then, we derive the constraints comparing with the experimental data, both for a unique PBH mass and for a mass distribution. We also compare with existing constraints. We finally briefly discuss the results and conclude.

**Methodology** — A BH with mass $M$ has a temperature [24, 25]

$$T = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13} \text{ g}}{M}\right) \text{ GeV},$$

with $G$ the Newton constant and $h = c = k_B = 1$. BHs lose mass radiating particles at a rate

$$\frac{dM}{dt} = -5.34 \times 10^{25} f(M) \left(\frac{\rho}{M}\right)^2 \text{ g/s},$$

where $f(M)$ is the number of emitted particle species normalized to unity for $M \gg 10^{17} \text{ g}$. The spectrum of emitted $e^\pm$ is

$$\frac{dN_{e^-}}{dt \, dE} = \frac{\Gamma_e}{2\pi} \left[ \exp \left(\frac{E}{T}\right) + 1 \right]^{-1},$$

where $\Gamma_e$ is the electron absorption probability which, in the geometric optics limit (high energy), reads $\Gamma_e \approx 27 G^2 M^2 E^2$ [41]. Assuming that PBHs constitute all of the DM, the number of electrons injected at the position $\vec{x}$ in the Galaxy per unit of time, energy and volume is

$$Q(E, \vec{x}) = \frac{\rho(\vec{x})}{\rho_\odot} \int_{M_{\text{min}}}^{\infty} dM \, \frac{g(M)}{M} \frac{dN_{e^-}}{dt \, dE},$$

where $\rho(\vec{x})$ is the DM density and $g(M) = M dN_{\text{PBH}}/dM dV$ is the mass distribution of PBHs normalized to $\rho_\odot$. We consider two spherically symmetric DM halos: a Navarro-Frenk-White (NFW) [42] halo scaling like $1/r$ in the center of the Galaxy and a cored halo featuring a constant density at small galactocentric radii. We use the kinematically constrained parameters provided in Table 6 of [43] where the DM density at the Sun position $R_\odot \approx 8.2 \text{ kpc}$ is $\rho_\odot \approx 0.4 \text{ GeV/cm}^3$ and, for the cored profile, the core radius is $7.7 \text{ kpc}$.

The transport of cosmic ray (CRs) $e^\pm$ in the Galaxy is described by a phenomenological diffusion model [44–49] with a rigidity ($R$) dependent diffusion coefficient $K(R) = K_0 \beta (R/GV)^{\delta}$. CRs $e^\pm$ lose energy through synchrotron emission and inverse Compton scattering on the interstellar radiation field as well as interacting with the gas of the interstellar medium (ISM) (ionisation, Coulomb interaction and bremsstrahlung). They also undergo convection because of the galactic wind (leading to additional energy losses because of adiabatic expansion) and diffusive reacceleration induced by the Alfvén waves propagating in the interstellar plasma. The velocity of the galactic wind is assumed to be constant in modulus, $V_c = \text{sgn}(z) \, V_c \, e_z$, and the reacceleration is linked to the spatial diffusion through $D(R) \propto V_c^2 / K_0(R)$, the exact functional form depending on the propagation model adopted.

The galactic geometry is described by the two-zone diffusion model (disc and diffusive halo) with the galactic radius $R = 20 \text{ kpc}$ and the vertical extension of the Galactic disc $2h = 0.2 \text{ kpc}$. The half-height $L$ of the diffusive halo is of the order of a few kpc and is discussed further below. The transport equation is solved following the semi-analytical method introduced in [50] and extended for sub-10 GeV $e^\pm$ while accounting for all propagation processes by the pinching method [51].

The propagation parameters are determined from the data of secondary to primary CRs ratio. We make use of two benchmark sets of parameters, dubbed hereafter models A and B. Model A is the model MAX of [50, 52] where $L = 15 \text{ kpc}$, $K_0 = 0.0765 \text{ kpc}^2/\text{Myr}$, $\delta = 0.46$, $V_c = 117.6 \text{ km/s}$ and $V_c = 5 \text{ km/s}$, derived from HEAO-3 Boron/Carbon (B/C) data [53]. We checked in [51] that these parameters are consistent with AMS-02 $e^+$ data. For model B, we adopt the best fit parameters of ref. [54], which makes use of the new AMS-02 B/C data [55] to update the propagation parameters: we use $L = 15 \text{ kpc}$, $K_0 = 0.125 \text{ kpc}^2/\text{Myr}$, $\delta = 0.507$, $V_c = 0 \text{ km/s}$, $V_c = 1.3 \text{ km/s}$, $R_b = 275 \text{ GV}$, $\Delta \delta = 0.157$ and $s = 0.074$, where $R_b$, $\Delta \delta$ and $s$ parameterize a break in the diffusion coefficient [56]. Ref. [54] only determined the ratio $K_0/L$ but also obtained indications that $L > 4.1 \text{ kpc}$ from the AMS-02 $e^+$ flux. Hence, we will vary $L = 4.1 \rightarrow 20 \text{ kpc}$ for model B. Model A features a strong diffusive reacceleration, possibly required by the antiprotons flux measured by AMS-02 [54], while there is none in model B. Since sub-GeV CRs $e^\pm$ are more sensitive to reacceleration than CR nuclei, we anticipate that the flux of $e^\pm$ produced by radiating PBHs will be drastically different for A and B. The two models are therefore quite diverse, and allow to quantify the impact of the CRs propagation uncertainty on our results.

**Results** — Assuming all DM of the Galaxy is made of single mass PBHs (monochromatic mass function), we represent in Fig. 1 the flux of $(e^++e^-)$ at solar position produced by radiating PBHs with mass $10^{15} \text{ g}$, $10^{16} \text{ g}$ and $10^{17} \text{ g}$.

The spectra obtained with model B drop very quickly above the PBH temperature. Indeed, since there is no diffusive reacceleration for B, the transport of sub-GeV $e^\pm$ is dominated by energy losses (mainly ionization of the ISM) and CRs $e^\pm$ continue to cool down as they propagate. As a consequence, the bulk of $e^\pm$ measured at Earth are produced locally in a few kpc radius sphere around the Sun and their flux is approximatively given by

$$\Phi_{e^\pm}(E, \odot) \simeq \frac{c}{4\pi b(E)} \int_{E}^{\infty} \frac{dE_s \, Q(E_s, \odot)}{E},$$

where $b(E)$ is the energy loss rate. For energies much smaller than the PBH temperature, the flux can be approximated by the analytical expression $\Phi_{e^\pm}(E, \odot) \simeq$
(11Gσ⊙ζ(3)T²)/(4π²b(E)) where ζ is the Riemann function. Therefore, the e± spectrum follows the energy dependence of the energy loss rate and scales as T² (or equivalently M⁻²). Fig. 1 shows that VOYAGER-1 data probe PBHs with masses M ≲ 10¹⁶ g.

The situation is different for model A since a fraction of sub-GeV e± gains energy from the diffusive reacceleration and populates the spectrum above the PBH temperature. This is remarkable as it means that CRs detectors can be sensitive to e± with energies above the maximum energy at which they had been injected in the Galaxy, namely the PBH temperature. In this specific situation, even AMS-02 is sensitive to signals produced by PBHs with M ≲ 10¹⁶ g. In the following, however, we will make only use of the VOYAGER-1 data since they turn out to be more restrictive than the AMS-02 ones for the PBHs abundance. We finally note that the spectra are rather insensitive to the choice between an NFW and a cored profile. This is expected since sub-GeV e± are produced in the local environment, where the profiles are similar. Constraints derived from e± on the PBHs local abundance will therefore be very robust regarding the uncertainty on the DM halo profile.

We thus use the VOYAGER-1 e± data to constrain the contribution of PBHs to the DM density in the Galaxy. The maximum fraction \( f = \rho_{\text{PBH}}/\rho_{\text{DM}} \) is determined requiring that the flux of e± emitted by PBHs does not overshoot any data point by more than 2σ. The limits for a monochromatic mass distribution are represented by the solid lines in the left panel of Fig. 2. The blue (red) solid line is obtained with model A (model B). Regarding model B, ionization of the ISM dominates the transport of e± measured by VOYAGER-1 and thus the main uncertainty comes from the size \( L \) of the diffusive halo (correlated with \( X_0 \) from the B/C analysis). Indeed, since sub-GeV e± almost do not lose energy in the diffusive halo, the larger the diffusive volume, the higher the signal from PBHs. This uncertainty affects the limits up to one order of magnitude as represented by the red band in Fig 2. For both propagation models, PBHs with masses smaller than 10¹⁶ g cannot contribute more than 0.1% to the DM density of the Galaxy.

Up to now we have not assumed any astrophysical background. There are however strong hints for the acceleration of Galactic e− by SNRs (see e.g.: [59]) and e± by PWNe (see e.g.: [60]). Secondary e± may also contribute to the background, up to 10% of the VOYAGER-1 flux [61]. Fitting the VOYAGER-1 data with a power law in energy, we find a spectral index of 1.31 (for \( \chi^2_{\text{ dof}} = 10.1/9 \)). Assuming negligible reacceleration, this translates into a spectral index at injection of \( \sim 2.1 \), as inferred from Eq. (5), consistent with the value predicted by diffusive shock acceleration simulations of SNRs and PWNe. This thus suggests that these objects are likely responsible for the acceleration of the leptons measured by VOYAGER-1. If we then assume a background for the VOYAGER-1 data modeled as 1.31 power law, the room for a DM contribution significantly shrinks and the corresponding limits are represented by the dashed lines in Fig. 2.

Our limits without background are at the same level as the EGB ones for masses smaller than 10¹⁶ g. On the other hand, taking into account a background probes, for M ≲ 10¹⁶ g, a fraction \( f \) between one and two orders of magnitude smaller than the EGB. In the most constraining scenario (model A with background) the limits almost reach the value M ≃ 10¹⁷ g probed by gamma ray burst lensing [62].

So far we have considered a single PBH mass. Recent studies [30, 63–65] suggest however that realistic production mechanisms result in an extended mass function, well fitted by a lognormal distribution

\[
g(M) = \frac{\rho_\odot}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/\mu)}{2\sigma^2}\right),
\]

where \( \mu \) is the mass for which the density is maximal, \( \sigma \) is the width, we have normalized to DM density at the solar system position and we cut at 4 x 10¹⁴ g since all lighter PBHs have evaporated by today. The limits obtained in this case are represented in the right panel of Fig 2 for different value of the width \( \sigma \) in the range 0.1 – 2. We use here the propagation model B without any background for the VOYAGER-1 data. Considering this extended mass function enables to further constraint the fraction \( f \) with respect to a monochromatic distribution. This can be understood by the fact that the production rate of e± increases much more than the DM density as the PBHs mass decreases. Therefore the constraints are provided by the few light but very bright PBHs of the distri-

\[\begin{align*}
&10^{-9} \quad 10^{-7} \quad 10^{-5} \quad 10^{-3} \quad 10^{-1} \quad 10^1 \quad 10^3 \quad 10^5 \quad 10^7 \\
&\text{AMS-02} \\
&\text{VOYAGER-1} \\
&\text{Propagation A} \\
&\text{Propagation B} \\
&\text{NFW} \\
&\text{Cored}
\end{align*}\]

\(\begin{align*}
M &= 10^{17} \text{g} \\
E &= 10 \text{GeV} \\
\Phi_{\text{e}^+ e^-} &= \text{[cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}] \\
\end{align*}\)
Figure 2. Constraints on the fraction $f$ of PBHs to the DM as a function of the PBH mass, as obtained in this work (blue and red lines) and in related studies (black lines). The left panel assumes a single mass common to all PBHs, the right panel assumes a lognormal mass distribution.

Conclusions — To conclude, we have made use of the capability of VOYAGER-1 of measuring the interstellar low-energy flux of CRs $e^\pm$ to constraint the contribution of PBHs to the DM in the Galaxy. We computed the flux of CRs $e^\pm$ Hawking radiated by PBHs using the fully general diffusion-convection-reacceleration model of propagation, with the most up-to-date parameters adjusted on the AMS-02 data. Assuming that PBHs make up all the DM of the Galaxy, we found that VOYAGER-1 is sensitive to a signal from PBHs with $M \lesssim 10^{16}$g. AMS-02 is also sensitive to PBHs with $M \lesssim 10^{16}$g for a propagation model with strong diffusion reacceleration. We therefore constrained the fraction of PBHs to the DM density to be smaller than 0.1% for $M \lesssim 10^{16}$g. We also showed that considering a lognormal mass distribution (as predicted by inflationary models) significantly improves the constraints. Our limits are competitive with those derived from cosmological observations and they are even better below $10^{16}$g when assuming an astrophysical background for the VOYAGER-1 data. These limits are robust regarding the DM distribution in the Galaxy and they are not affected by solar activity, precisely because VOYAGER-1 data have been collected beyond the heliopause. We estimate the propagation uncertainty on our limits to be around one order of magnitude. We emphasize that these new limits are based on local measurements and do not depend on any cosmological parameters. PBHs clustering does not affect our results since the signal only depends on their density averaged on large scales in the Galaxy. They are therefore fully complementary to other limits derived from cosmological observations.

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[1] P. A. R. Ade et al. (Planck), Astron. Astrophys. 594, A13 (2016), arXiv:1502.01589 [astro-ph.CO].

[2] I. D. Zeldovich and I. D. Novikov, Soviet Astronomy 10, 602
[63] K. Kannike, L. Marzola, M. Raidal, and H. Veermäe, JCAP 1709, 020 (2017), arXiv:1705.06225 [astro-ph.CO].
[64] N. Bellomo, J. L. Bernal, A. Raccanelli, and L. Verde, JCAP 1801, 004 (2018), arXiv:1709.07467 [astro-ph.CO].
[65] J. Calcino, J. Garcia-Bellido, and T. M. Davis, (2018), arXiv:1803.09205 [astro-ph.CO].