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Primordial Black Holes as dark matter candidates: Constraints from the diffuse MeV emission

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Abstract. For more than 20 years, the Compton telescope had provided the best measurements of the Galactic diffuse MeV spectrum. Recently, our analysis of 16 years of data from the SPectrometer on INTEGRAL (SPI) measured this emission with a higher signal-to-noise ratio. At MeV energies, the dominant contribution to the diffuse emission comes from inverse Compton scattering. Nonetheless, sub-dominant emission from Primordial Black Hole (PBH) Dark Matter (DM) can be searched for in these data. Hypothetically formed from the collapse of over-densities before Big Bang nucleosynthesis, PBHs are interesting candidates for DM in the ΛCDM model of cosmology. PBHs of masses between 10^{16} and 10^{18} g, in the so-called asteroid mass range, are currently unconstrained and can saturate the DM cosmological abundance. MeV emission from PBH in this mass range is expected to come from PBH evaporation. We searched for the PBH signal with 16 years of SPI data, and demonstrated that PBHs cannot account for all the DM if their mass is smaller than 4×10^{17} g.

1 Introduction

Black holes (BHs) are objects so compact that nothing can escape from their gravitational influence. Unlike stellar BHs that form from the gravitational collapse of stars in the late Universe, primordial BHs (PBHs) are thought to be formed from over dense regions in the early universe, before Big Bang nucleosynthesis. Therefore, they could contribute to the dark matter (DM), which accounts for about 27% of the energy density of the Universe according to the ΛCDM model of cosmology

Figure 1 shows the existing constraints on f_{PBH}, the fraction of DM in the form of PBHs, as a function of M_{PBH}, the monochromatic PBH mass. For masses larger than 10^{22} g or smaller than 10^{17} g, PBH DM is well constrained by various observations but between these two values, a mass window remains where PBHs could still saturate the DM cosmological abundance. The lower part of this mass window, the asteroid mass range, can be probed by looking for the Hawking evaporation signal of PBHs in Galactic diffuse MeV data.

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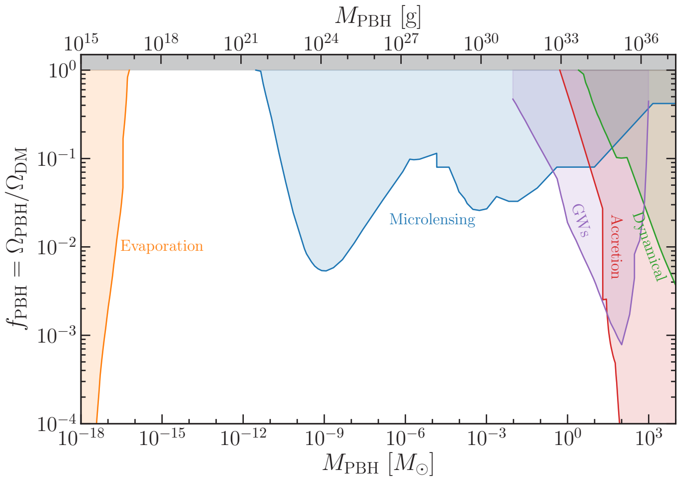

Figure 1. Constraints on PBH DM [1]. The possible fraction of DM in the form of PBHs $f_{\rm PBH}$ depends on the PBH mass $M_{\rm PBH}$. The shaded regions are excluded by various observations (see [1] for details) but the mass window between 10^{17} and 10^{22} g remains unconstrained.

2 Hawking evaporation

S. Hawking demonstrated [2], by applying quantum field theory effects to BHs, that a radiation could be released outside their event horizon, reducing then the BH mass. This radiation spectrum follows an almost blackbody distribution and for photons, it writes:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}t} = \frac{1}{2\pi}\frac{\Gamma(E, M_{\rm PBH})}{e^{E/T_{\rm PBH}} - 1} \tag{1}$$

where $T_{\rm PBH} = M_P^2/(8\pi M_{\rm PBH})$ with M_P being the Planck mass and $\Gamma(E, M_{\rm PBH})$ is the greybody factor. This effect is not significant for stellar BHs but only for the lightest PBHs. However, it can be shown that PBHs formed with $M_{\rm PBH} < 5 \times 10^{15}$ g should already have evaporated by now. The PBH photon flux is calculated as follows:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E}(l,b) = \frac{f_{\rm PBH}}{4\pi M_{\rm PBH}}\frac{\mathrm{d}^2 N}{\mathrm{d}E\mathrm{d}t}\int_{\rm l.o.s.} \mathrm{d}s\, \rho(r(s,l,b))\,. \tag{2}$$

where $\rho(r(s,l,b))$ is the DM density profile and s, l, b are the line of sight (l.o.s.), galactic longitude, and galactic latitude, respectively. In the following, the DM density profile is assumed to be a NFW profile [3]. For $M_{\rm PBH} = 10^{16-18}$ g, the PBH signal peaks at MeV energies and can be looked for in Galactic hard X-ray diffuse emission.

3 Galactic diffuse MeV emission

3.1 The MeV gap

Despite its major scientific interest, the Galactic diffuse MeV emission is poorly studied. The continuum sensitivity of high-energy photon telescopes and detectors worsen by several orders of magnitude around MeV energies and the only measurement of the Galactic diffuse MeV emission was performed by the Compton Telescope (COMPTEL) more than 20 years ago [4]. Bounds on $f_{\rm PBH}$ have been set using COMPTEL data [5], but more recent data from SPI, the SPectrometer on INTEGRAL, can also be used.

3.2 SPI data analysis method

At high energies, focusing photons becomes a hard exercise. Wolters telescopes, such as XMM-Newton, can be used up to keV energies, but for MeV and GeV photons, telescopes look like particle detectors. SPI is an instrument with a coded-mask made of transparent pieces that let the photons come in and opaque pieces absorbing them. On the germanium detector, located below the coded-mask, each source emitting photons casts a coded shadow, but the detected photons are not directionally tagged and this impacts the data analysis.

One analysis method is to assume spatial models for the photon emission, simulate what would SPI see through the coded-mask and compare the results to the SPI raw data, *i.e.* numbers of photons per observation, per energy and per detector. The best model is chosen with a maximum likelihood fit performed in each energy bin independently, which finally allows one to construct the total spectrum.

3.3 Galactic diffuse MeV spectrum from 16 years of SPI data

The major contribution to the diffuse MeV photons is known to come from Inverse Compton scattering (ICS) and we made a systematic study of this model component. The ICS spatial templates were created with `GALPROP` using one of the best-fit model *galdef* files from Fermi-LAT analyses [6]. Several alternative ICS models were created from our baseline model, such as a model with a thick halo or a model with a single cosmic-ray diffusion index. Additional templates, for unresolved sources, nuclear lines, and positronium annihilation, were included in the model. The significant instrumental background was also carefully studied.

Using the method previously described, we extracted the Galactic 0.5-8 MeV diffuse emission from 16 years of SPI data [7] from a $\sim 95^\circ \times 95^\circ$ region of interest. Our measurement (orange points in Figure 2 left) is in agreement with the old COMPTEL measurement (green points) but with a better signal to noise ratio (magenta points). Adding a NFW spatial template to the model led to no detection of a DM-origin signal. Therefore, upper limits can be put on $f_{\rm PBH}$.

4 Constraints on PBH DM

We used the newly extracted SPI spectrum to put constraints on PBH DM. We performed a Monte Carlo Markov chain spectral fit to adjust the various spectral parameters of the model component, namely the parameters $f_{\rm PBH}$ and $M_{\rm PBH}$ of the PBH spectrum, given by equation 1. The other model components are fitted with power-laws and Gaussians. We put the sampled values of $f_{\rm PBH}$ and $M_{\rm PBH}$ on a scatter plot and defined the 95% confidence level upper limit on $f_{\rm PBH}$ such as 95% of the samples falls below the limit for every mass bin.

Figure 2 right shows various constraints on PBH DM from the literature (colored broken lines) in the $10^{16} - 10^{18}$ g mass range, together with the bound we derived (solid black). We set the strongest constraints on PBH DM for $M_{\rm PBH} \gtrsim 10^{17}$ g and up to $M_{\rm PBH} \sim 4 \times 10^{17}$ g [8]. Above this value, PBH can still account for all the DM.

5 Conclusion

The DM is a major component of our Universe but its nature still hides its secret. PBH are non-particle DM candidates, and are by far the heaviest ones. These hypothetical objects could be detected for example, by observing their microlensing effects or by gravitational wave detectors, but the current non-detections allow one to set bound the abundance of PBH,

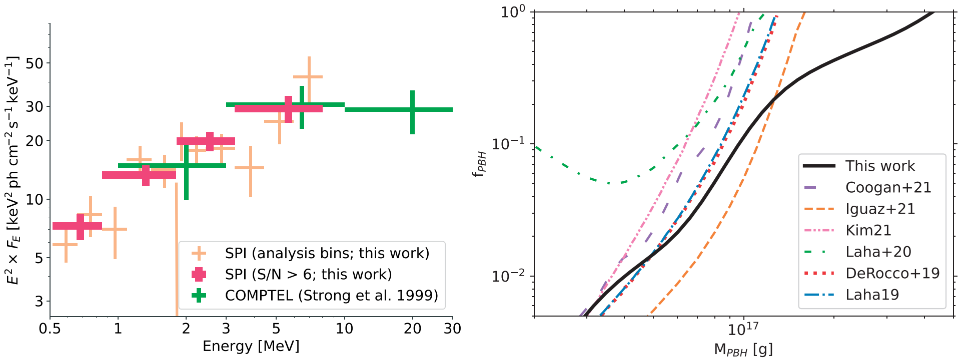

Figure 2. *Left:* Galactic diffuse MeV spectrum from 16 years of SPI data (orange) and from COMPTEL data (green). The SPI spectrum can be rebinned to obtain a signal to noise ratio larger than the COMPTEL measurement (magenta). *Right:* Upper limits on f_{PBH} as a function of M_{PBH} from the literature (colored broken lines) and from our analysis (black solid line). We showed that PBHs cannots saturate the DM cosmological abundance below $M_{\mathrm{PBH}} = 4 \times 10^{17}$ g.

i.e. on the fraction of DM in the form of PBHs. Light PBHs should be evaporating today in hard X-ray photons. We first extracted the Galactic diffuse MeV spectrum from 16 years of SPI data and then used it to put the strongest constraints on PBH DM in the asteroid mass range. We considered a simple model of non rotating PBH with a monochromatic mass distribution, and relaxing these constraints is expected to produce more stringent bounds.

A large PBH mass interval remains unconstrained and PBH could still saturate the DM cosmological abundance. Alternatively, our MeV spectrum can also be used to constrain decaying DM models, in which the DM candidates are axion-like particles or sterile neutrinos, as shown in [9].

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