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# Primordial Black Hole as Dark matter with $\gamma$-ray emissions

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Primordial black holes (PBHs) as a dark matter (DM) candidate become popular again recently. Through their Hawking radiation, we can analyze their signal by $\gamma$-ray emissions. Our work focuses on cross-correlating the MeV $\gamma$-ray emissions and the cosmic microwave background shear to projectedly constrain the fraction of PBHs as DM. Near-future data can provide a tight constraint on the fraction of the Schwarzschild PBHs in the mass range around $10^{17}$ g, like CMB-S4 project and the $\gamma$-ray telescope e-ASTROGAM. Some astrophysical sources also contributed to the observed emission in the MeV energy band. Furthermore, the constraining ability can be improved by another order of magnitude when taking the PBHs model with spins into account. This technology with proper coming data could importantly fill the gaps with PBHs fraction limits in the asteroid mass range.

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## 1. Gamma-ray signals from PBHs

Primordial black holes (PBHs) within the asteroid mass range ($1\times10^{16}-10^{23}$g) as Dark matter (DM) candidates, still possess significant uncertainty regarding their fraction, namely $f_{\rm PBH}\equiv\Omega_{\rm PBH}/\Omega_{\rm DM}$. Formed during the early universe, PBHs have been constrained by many different techniques under the theoretical hypothesis, like gravitational-lensing, dynamical effects, accretion, gravitational waves, and Hawking Evaporation (HE) [1].

Following the idea of Hawking Evaporation, PBHs can emit standard model particles, which include photons. The $\gamma$-ray emissions in the MeV range produced by PBHs could trace the density field of the Universe. We can define the window function of PBHs along the line of sight direction, which is given by

$$W_{\rm PBH}(\chi)=\frac{f_{\rm PBH}\Omega_{\rm DM}\rho_c}{4\pi M_{\rm PBH}}\times\int_{\delta E}\int_{t_{\rm min}}^{t_{\rm max}}\left[\frac{{\rm d}^2N}{{\rm d}t{\rm d}E_\gamma}\right]_{\rm tot}E_\gamma(\chi)e^{-\tau[\chi,E_\gamma(\chi)]}{\rm d}E_\gamma{\rm d}t\;, \tag{1}$$

where ${\rm d}^2N/{\rm d}t{\rm d}E_\gamma$ denotes the number of particles $N$ emitted per units of energy and time, both primary and secondary spectra are considered, with the latter being generated from processes such as decay or hadronization of primary particles. $\chi=\chi(z)$ represents the comoving distance, and $\tau[\chi,E_\gamma(\chi)]$ is the optical depth. The time integral runs from $t_{\rm min}=380,000$ years at the last scattering of the CMB to $t_{\rm max}=\min(t(M),t_0)$, where $t(M)$ is the PBHs lifetime with mass $M$ and $t_0$ is the age of the Universe. Additionally, we give a mild $a_*=0.5$ and an extreme spin $a_*=0.9999$ for comparison with the $a_*=0$ case. In our calculations, we adopt the public software `BlackHwak` [2] to generate the photon spectra with these three spin conditions, $a_*=\{0,\ 0.5,\ 0.9999\}$.

Besides, the clusters of galaxies, AGNs and galaxies can also provide the significant contributions to the MeV $\gamma$-ray emission of the sky. We cross-correlating the CMB shear as the MeV $\gamma$-ray tracer, and the equation is given by:

$$C_\ell^{\kappa,{\rm PBH}}=\int\frac{{\rm d}z}{c}\frac{H(z)}{\chi^2(z)}W_\kappa(z)W_{\rm PBH}(z)P_{\kappa,{\rm PBH}}(k=\ell/\chi,z), \tag{2}$$

where $P_{\kappa,{\rm PBH}}$ is the 3D power spectrum of cross-correlation between CMB lensing and the $\gamma$-ray emissions from PBHs, which consists of two parts in the halo model, $P_{\kappa,{\rm PBH}}=P^{\rm 1h}_{\kappa,{\rm PBH}}+P^{\rm 2h}_{\kappa,{\rm PBH}}$, and the mass integral runs from $M_{\rm min}=10^7M_\odot$ to $M_{\rm max}=10^{18}M_\odot$. For the model choices, see more detail in [3], the example results are shown in left of Fig.1.

## 2. Gamma-ray from Future Experiments

In this study, we assess the potential of an instrument possessing the sensitivity of e-ASTROGAM to examine the projected constraining capabilities on the fraction of PBHs. The photon range of e-ASTROGAM is from 150 keV to 3 GeV [4]. We adapted the effective area, angular resolution, and flux sensitivity, to exhibit variations across different energy intervals as specified in Table III and IV of [5]. Employing an observational time of $10^6$ seconds, we focus our examination on a sky fraction of $f_{\rm sky}=0.23$, corresponding to a field of view of $\Omega=2.9$ steradians. The flux sensitivity of $1.1\times10^{-12}\,{\rm erg\,cm^{-1}\,s^{-1}}$ is adopted uniformly throughout the entire energy range, while the particle background registers a count rate of 1.4 counts ${\rm s^{-1}\,sr^{-1}}$. Finally, We choose the proper energy range for integration for each mass of PBHs, which is around the $E_{\mathrm{peak}}$ listed in the table I of [3]. For the peak energy $E_{\mathrm{peak}}$ exceeds the energy range capability of e-ASTROGAM, we solely considered lowest photons within the energy range of e-ASTROGAM, i.e., from 150 keV to 300 keV. We neglect the contribution from the clusters because the main contribution of the clusters appears in the energy band < 40 keV.

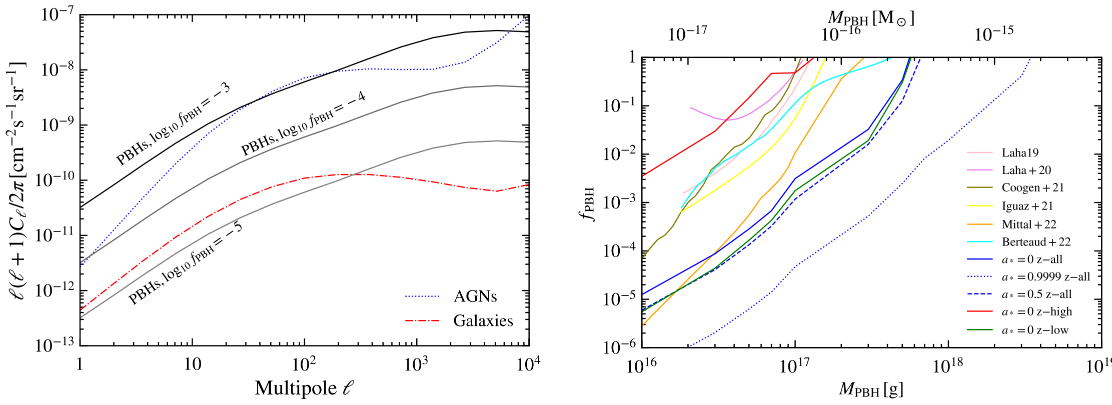


**Figure 1:** Left: Cross-correlation angular power spectra between the CMB lensing and AGNs (blue dotted line), galaxies (red dash-dotted line), and PBHs (black solid lines). Here, we choose the PBHs mass $M_{\mathrm{PBH}} = 10^{17}$ g, the spin $a_* = 0$. From top to bottom, we show power spectra from different values of the PBHs fraction: $f_{\mathrm{PBH}} = 10^{-3}$, $10^{-4}$, $10^{-5}$, respectively. Right: 95% C.L. bounds on the PBHs fraction as a function of the PBHs masses, when considering different cases. We plot some important PBHs works for comparison, the details of references can be found in Ref. [3].

In order to conduct CMB lensing studies, we adopt a CMB-S4 experiment [6], which features a telescope beam with a Full-Width-Half-Maximum (FWHM) of $1'$, with temperature and polarization white noise levels of 1 $\mu K'$ and 1.4 $\mu K'$, respectively. Our approach involves setting the primary CMB noise levels $N_\ell^{\mathrm{TT}}$ and $N_\ell^{\mathrm{EE}}$ as Gaussian noise distributions: $N_\ell^{\mathrm{XX}} = s^2 \exp\left(\ell(\ell+1)\frac{\theta_{\mathrm{FWHM}}^2}{8\log 2}\right)$, where XX stands for TT or EE, $s$ is the total intensity of instrumental noise in $\mu K$ rad, and $\theta_{\mathrm{FWHM}}^2$ is the FWHM of the beam in radians. For the CMB lensing reconstruction noise, we use the EB quadratic estimator method described in [7], implemented by the `QUICKLENS` software package [1].

## 3. Results and Conclusions

We compute the covariance matrix as the following, by assuming the experiments are the power spectra of Gaussian random fields,

$$\Gamma_{\ell,\ell'}^{\gamma,\kappa} = \frac{\delta_{\ell\ell'}}{(2\ell+1)\, f_{\mathrm{sky}} \Delta\ell} \times \left[ C_\ell^{\gamma\kappa} C_{\ell'}^{\gamma\kappa} + \left( C_N^\gamma + \sqrt{C_\ell^\gamma C_{\ell'}^\gamma} \right) \left( C_N^\kappa + C_\ell^\kappa \right) \right], \tag{3}$$

where the photon noise term above is $C_N^\gamma = 4\pi f_{\mathrm{sky}} \langle I_{\mathrm{X}} \rangle^2 N_{\mathrm{X}}^{-1} W_\ell^{-2}$, and $\langle I_{\mathrm{X}} \rangle$ refers to the sky-averaged intensity observed by the telescope, which is assumed to contributed by default AGNs

[1] https://github.com/dhanson/quicklens/

and galaxies; $N_X = \langle I_X A_{\rm eff} \rangle t_{\rm obs} \Omega_{\rm FoV}$; the beam window $W_\ell = \exp\left(-\sigma_b^2 \ell^2/2\right)$ is a Gaussian point-spread function.

The upper limits on the parameter space of the PBHs fraction are derived at 95% confidence level by requiring $\chi^2 = 2.71$ with the estimator assumed to follow a $\chi^2$ distribution with one degree of freedom defined as, $\chi^2 = \sum_\ell \left(C_\ell^{\gamma,\kappa} \Gamma_{\ell\ell'}^{-1} C_{\ell'}^{\gamma,\kappa}\right)$, where the sum of multipoles is from $\ell_{\rm min} = 10$ to $\ell_{\rm max} = 10^3$, respecting the beam window function of e-ASTROGAM. It is important to highlight that in the signal part of the $\chi^2$ function, only the cross-correlation term involving the PBHs is considered. This assumption is made under the premise that we are capable of accurately extracting the background associated with the emitting AGNs and galaxies while disregarding model uncertainties in the astrophysical components. Additionally, we avoid summing up the energy bins due to the fact that for every PBH mass, the integration energy range will vary around the different $E_{\rm peak}$ values mentioned earlier.

In the right panel of Figure 1, the solid blue line represents our main result for standard Schwarzschild PBHs. The tight projected constraint that can be obtained from e-ASTROGAM is primarily due to its high sensitivity to flux, which is a crucial factor in the measurement of photon noise. The high sky-averaged intensity observed by the telescope leads to a suppression of the shot noise term in the covariance matrix (Eq.(3)) and improves the precision of the results on the PBHs fraction ($f_{\rm PBH}$).

We spit redshift ranges into 3 bins: $0-10$ ($z$-all), $0-1$ ($z$-low, green solid line), and $1-10$ ($z$-high, red solid line), from right of Figure.1, $z$-low case is very close to the $z$-all case, which indicates that the effect from astrophysical sources is mainly from the low-redshift Universe. In addition, from the results of $a_* = 0.5$ (blue dashed line) and $a_* = 0.9999$ (blue dotted line), we could know $f_{\rm PBH}$ is greatly enhanced by more than an order of magnitude when PBHs are extremely rotational.

By leveraging future projects such as e-ASTROGAM and CMB-S4, we are able to establish highly stringent limitations on the Schwarzschild PBHs fraction within the mass range of $10^{16} - 5 \times 10^{17}$ g. The future real data are promisingly addressing the gaps in the limits of PBHs fraction within the asteroid mass range.

## References

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