Snowmass2021 - Letter of Interest

Electromagnetic probes of ultralight primordial black holes

Thematic Areas: (check all that apply □/■)

■ (CF3) Dark Matter: Cosmic Probes
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics & cosmology

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Abstract: Dark matter (DM) is omnipresent in the universe, from sub-Galactic scales to galaxy clusters. Despite its abundance, the nature of DM remains mysterious, as it has evaded all nongravitational direct and indirect probes thus far. Primordial black holes (PBHs), formed out of regular-matter overdensities in the early universe, provide an attractive alternative to new-physics models of DM. If these PBHs are ultralight (with masses $M_{\rm PBH} \lesssim 10^{18}$ g), their gravitational effects are indistinguishable from those of regular particle DM. However, due to their black-hole nature, ultralight PBHs Hawking evaporate over time, emitting high-energy particles that can be directly detected. Here we outline what next-generation MeV telescopes ought to do to better detect ultralight PBHs.

Background

Despite the precision to which we know the abundance of the cosmic DM, its nature remains one of the most puzzling questions in physics. One of the oldest and well-motivated candidate of DM is primordial black hole (PBH). PBHs could form in the very early Universe due to the gravitational collapse from Standard Model (SM) plasma, and are a possible solution to the DM puzzle that does not invoke any new particles[1–7]. The fraction $f_{\rm PBH}$ of DM in the form of PBHs is constrained to be below unity for PBH masses $M_{\rm PBH} \gtrsim 10^{23}$ g ($\approx 5 \times 10^{-11}$ $M_\odot$) via various observations, such as gravitational lensing[8–18], stellar dynamics[19–25], dwarf galaxy heating[26], gravitational waves[27–36], and the cosmic microwave background (CMB)[37–40]. The situation is different for lower-mass PBHs, as their classical gravitational signatures are not strong enough to cause a measurable effect in existing data. Low-mass PBH being captured by or to destroy white dwarfs[41] and neutron stars[42] can lead to rich astrophysical signatures[43–45]. Potential constraints set by these BHs are sensitive to the assumptions of the properties of each astrophysical systems, which have large observational uncertainties[46–50]. Ultralight PBHs can also lead to interesting multi-messenger astrophysical signatures with their effects on compact-object mergers[51;52].

Search for PBHs using gamma-ray telescopes

Non-spinning black holes (BHs), with mass $M_{\rm BH}$, evaporate over time, emitting particles roughly as a blackbody with temperature[53–58] $T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}}$. For reference, $M_{\rm BH} = 10^{17}$ g corresponds to a non-spinning BH temperature $T_{\rm BH} \approx 0.1$ MeV, and thus the Hawking emission from these BHs will predominantly consist of neutrinos and photons. This shows that sub-MeV range probes hold great promise to find PBHs as DM. For spinning PBHs (e.g.[59]) the emission spectrum can change[60].

A promising avenue to search for ultralight PBHs ($M_{\rm PBH} \lesssim 10^{18}$ g) consists of searching for their

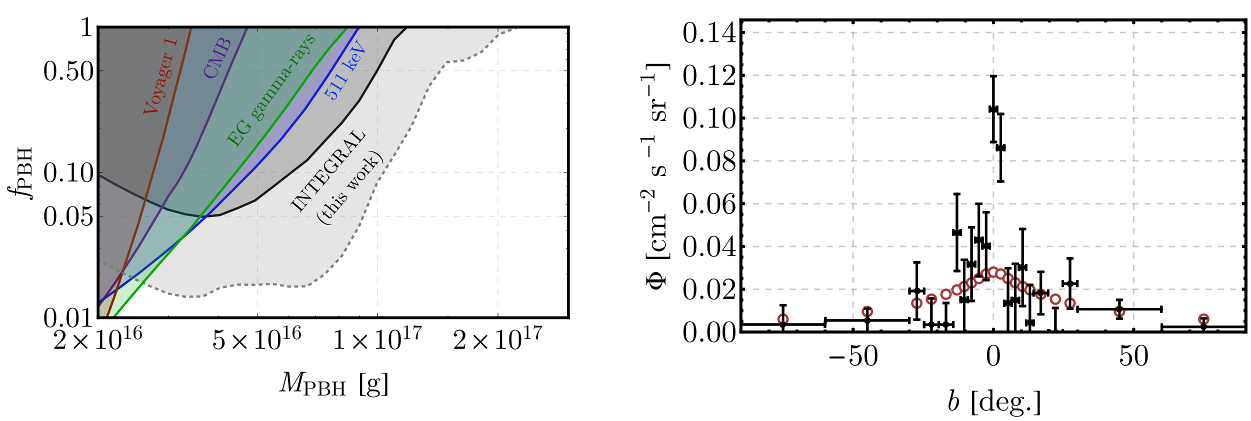

Figure 1: **Left:** Different constraints on the fraction $f_{\rm PBH}$ of DM that is composed of PBHs. The limit from detection of positrons with Voyager 1 is shown in red[61] (propagation model B without background), from the CMB in purple[62] (varying all parameters), from extra-Galactic gamma-ray emission in green[63] (assuming no AGN background), and from the flux of the 511 keV line in the MW in blue[64]. The strongest constraint, in black, uses the Galactic gamma-ray flux measured by INTEGRAL, from Laha et al. (2020)[65]. There are currently no robust constraints to the right of the plot until $M_{\rm PBH} = 10^{23}$ g[13;18;60;66;67]. **Right:** Galactic gamma-ray flux in the $0.2 - 0.6$ MeV energy band, from Laha et al. (2020)[65]. The black crosses show the INTEGRAL measurements as a function of Galactic longitude latitude b (integrated over $|l| < 23.1$ deg.)[68]. The red circles show the predicted emission from Hawking-evaporating PBHs with $M_{\rm PBH} = 1.5 \times 10^{17}$ g, if these PBHs make up the entirety of the MW DM.

Standard Model radiation as they Hawking evaporate[54–56;69;70]. This radiation would appear as electron-positron pairs[60;61;64;71–75], extra-Galactic gamma rays[63;76;77], and affect the CMB[62;78–80]. These studies have ruled out PBHs as the entirety of the DM for $M_{\rm PBH} \lesssim 10^{17}$ g. More recently, the strongest bound on the PBH mass has been raised to $M_{\rm PBH} \geq 1.2 \times 10^{17}$ g at 95% C.L., by using INTEGRAL MeV data[65]. The current constraints on ultralight PBH DM is shown in the left panel of Fig. 1. This constraint can be potentially be improved significantly by the next generation of gamma-ray telescopes. In the absence of a viable technique to detect keV-scale neutrinos, photons offer the only probe of detecting $\gtrsim 10^{17}$ g PBHs via Hawking radiation.

We show the flux from PBH DM with $M_{\rm PBH} = 1.5 \times 10^{17}$ g in the $0.2 - 0.6$ MeV band—where it peaks—in the right panel of Fig. 1. The Galactic emission from astrophysical backgrounds, as measured by INTEGRAL, is more concentrated towards the Galactic Center, as opposed to that from PBHs (or generic decaying DM), so a broad angular coverage will help us constrain decaying DM better.

Challenges and Opportunities

Heavier PBHs have lower temperatures as well as lower number densities. Therefore, the peak-energy flux of the emission from PBHs depends strongly on their mass, roughly as $1/M^3_{\rm PBH}$. This severely hampers searches of PBHs heavier than $M_{\rm PBH} \sim 10^{17}$ g. Recent work has cast doubt on PBH constraints due to femtolensing[66], and capture onto stars[67]. Thus, there is a large gap between the constraint from Laha et al. (2020)[65] and the next one: $M_{\rm PBH} > 10^{23}$ g, from Subaru microlensing data[13;18], where PBHs are currently allowed to make up all the DM.

Future gamma-ray observatories, such as AMEGO, will dramatically improve our understanding of the Galaxy in the energy range [200 keV – 10 GeV] [81]. AMEGO will be a wide field-of-view instrument which will have a higher energy and spatial resolution compared to earlier instruments in this energy regime. A search of PBHs using the diffuse Galactic and extra-galactic gamma-ray flux will benefit from the larger exposure which will be provided by AMEGO. The expected sensitivity of AMEGO will be approximately 20 times better than COMPTEL. Due to this improved sensitivity, AMEGO is expected to detect a number of new point sources which can lower the contribution of the undetected point sources to the Galactic and extra-Galactic gamma-ray background. The improved angular and energy resolution in AMEGO can also advance our understanding of the astrophysical background. This will lead to better search strategies, and therefore a detection or limits, on ultralight PBHs. Including observations of other multi-wavelength instruments, it is expected that we will better understand the contribution of cosmic-rays to the gamma-ray measurements. Since the AMEGO energy range covers the π^0 bump, it will be useful to disentangle this contribution to the astrophysical backgrounds [82]. A better understanding of the Galactic diffuse background in the energy range $\sim$200 keV to 500 keV holds great potential to probe PBHs with mass $\gtrsim 10^{17}$ g.

In addition to measuring the continuum gamma-ray component, AMEGO can also provide a sharper measurement of the 511 keV line in the Galactic center. If AMEGO is able to pin-point the sources responsible for the Galactic Center 511 keV line, then this will further constrain the viability of PBHs supplying the required number of positrons. A more precise measurement will help us go deeper into the $f_{\rm PBH}$ parameter space.

All of the above considerations make next-generation MeV telescopes, such as AMEGO, the best probes to search for ultralight PBHs as DM, and close the window that is current allowed for masses $10^{17} - 10^{23}$ g.

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