Snowmass2021 - Letter of Interest

Exploring Beyond-the-Standard-Model Physics with TeV Gamma Rays from Primordial Black Holes[*]

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

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

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Abstract: Primordial Black Holes may have been created by density fluctuations or phase transitions in the early Universe and could be as massive as $>10^9$ solar masses or as small as the Planck mass. It has been postulated that a black hole has a temperature inversely-proportional to its mass and will thermally emit all species of fundamental particles via Hawking Radiation. Primordial Black Holes in some mass ranges may be candidates for a non-negligible fraction of WIMP dark matter. A next-generation survey instrument such as the Southern Wide-field Gamma-ray Observatory (SWGO) would be ideal for searching for the evaporation signatures of Primordial Black Holes. While the mass expected to be evaporating today, producing short bursts lasting a few seconds of high-energy gamma radiation in the GeV–TeV energy range is not a WIMP dark-matter candidate, confirmed detection of a PBH burst of any initial mass would lend significant strength to the theory of PBHs as WIMP dark matter, as well as provide valuable insights into many areas of physics.

[*]This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;2]

Primordial black holes (PBHs) are theoretical black holes which may have been formed in the early stages of the Universe[3]. Their mass spectrum depends on the formation mechanism and spans a large mass range. Black holes with low-enough mass are expected to evaporate completely through the radiation of particles and energy at the Hawking temperature[4]. The lifetime of a PBH is

$$\tau \approx 4.55 \times 10^{-28} (M_{\rm BH}/1{\rm g})^3 \text{ s} \ . \tag{1}$$

That is, a PBH with an initial mass of $\sim 5 \times 10^{14}$ g that was formed in the first moments of the Universe would have an evaporation time of roughly the current age of the Universe[5], and thus might be detectable from Earth today. In the latest stage of evaporation, the PBH emits particles and radiation at increasingly higher energies which may be detectable by atmospheric or water Cherenkov detectors[6]. While PBHs with mass $\sim 5 \times 10^{14}$ g are expected to be evaporating today, producing short bursts lasting a few seconds of high-energy gamma radiation in the GeV–TeV energy range, they are not a WIMP dark-matter candidates[7]. However, confirmed detection of a PBH burst of any initial mass would lend significant strength to the theory of PBHs as WIMP dark matter by proving their existence, as well as allowing the determination of their relic density and rate-density of evaporation, and providing valuable insights into many areas of physics, including fundamental processes in the very early Universe and particle physics at energies higher than currently achievable by terrestrial accelerators[8].

Gamma-ray observatories can therefore search for PBHs by looking for bursts of high-energy gamma rays created by the last seconds of PBH evaporation. Upper limits on the local density of such evaporating PBHs have been reported by the High-Altitude Water Cherenkov (HAWC) Observatory[9]. These analyses—and related ones by atmospheric Cherenkov observatories—search for spatially-localized and short-time bursts of gamma-ray events unrelated to an astrophysical source. The choice of the time window for these searches is a compromise between signal and background, with typical time windows being 1–30 s.

In the present Universe, PBHs in certain mass ranges may constitute a non-negligible fraction of dark matter[7;10]. Since the existence of stellar-mass black holes was recently confirmed during the first observational run of Advanced LIGO[11], there has been a resurgence in support for a PBH component of the total dark matter energy density (e.g., Refs.[12–14]). Limits placed thus far indicate that $f(m)$, the fraction of dark matter that is made up of PBHs, is $\lesssim 10\%$ over a range of masses[7] (see Figure 1).

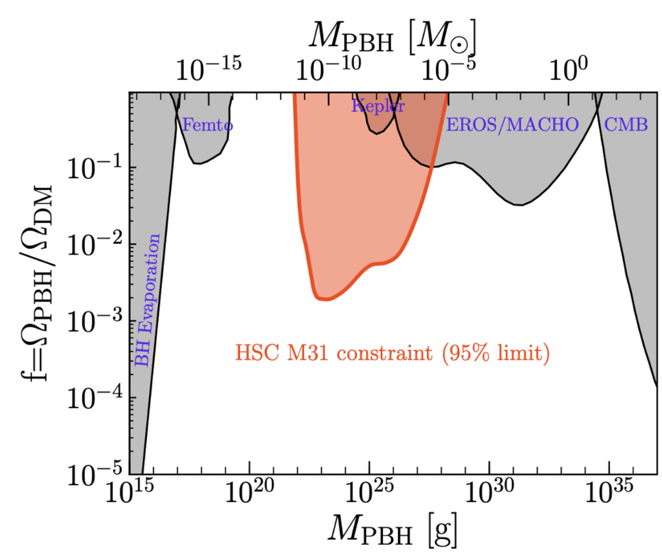

Figure 1: Dark matter fraction with respect to PBHs[15].

The luminosity of a PBH burst decreases as the squared distance to the PBH. However, at larger distances, the number of PBHs with given luminosity is expected to *increase* as the cube of the distance.

Therefore, an observatory's sensitivity to PBHs scales as the 3/2 power of its gamma-ray sensitivity. The sensitivity of the Southern Wide-field Gamma-ray Observatory (SWGO; www.swgo.org) is expected to be roughly ten times better than the current HAWC observatory. Assuming no PBH burst detection, the upper limit on the local rate of PBH evaporation would thus be expected to improve by more than a factor of 30 compared to the HAWC limits, reaching the level of $\lesssim 130\,\mathrm{pc}^{-3}\mathrm{yr}^{-1}$, as shown in Table 1 and Figure 2.

Experiment	Burst Rate Upper Limit	Optimal Search Duration	Reference
Milagro	$36000\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1s	16
VERITAS	$22200\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30s	17
HESS	$14000\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30s	18
Fermi-LAT	$7200\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1.26×10^8s	19
HAWC 3 yr.	$3400\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	10s	9
SWGO 10 yr.	$\lesssim 90\ \mathrm{pc}^{-3}\mathrm{yr}^{-1}$	10s	Estimated

Table 1: The strongest limits on the burst rate density of PBHs from the current generation of experiments, compared to the capabilities of a next-generation observatory, SWGO, with 10 times better sensitivity than HAWC. Note that the optimal search duration specifies the methodology of the search (optimizing for signal while minimizing background) rather than being a physical PBH parameter.

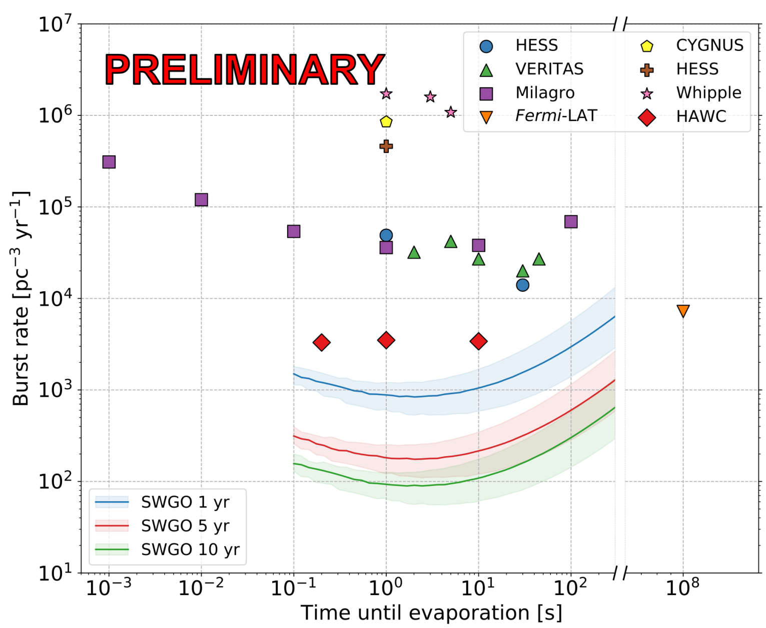

Figure 2: Sensitivity curve predicted upper limits for PBHs with SWGO (based on the HAWC limits from Ref. 9), with the upper limits from Whipple[20], CYGNUS[21], the Tibet Air Shower Array[22], H.E.S.S.[18], VERITAS[17], *Fermi*-LAT[19], Milagro[16], and HAWC[9].

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