

Limits on primordial black hole evaporation from H.E.S.S. observations.

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Primordial Black Holes are expected to be formed in the early Universe by the gravitational collapse of overdense regions, among other mechanisms. They are also expected to lose their mass over time by the Hawking radiation process. As the rates of this radiation increase with temperature, the PBH evaporation should result in a violent explosion. The current upper limits on explosion rates are on the order of $10^4 - 10^5 pc^{-3} yr^{-1}$. In this contribution we'll present the results of a search for TeV γ -ray burst within timescale of few seconds, using nearly 5000 hours of H.E.S.S. data. The search algorithm and statistical estimation strategy will be presented as well as cosmological implications of this measurement.

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1. Introduction

Primordial black holes (PBH) have been predicted to form in the early Universe via a variety of mechanisms [1]. Popular mechanisms include the gravitational collapse of overdense regions with significant density fluctuations [2] or pressure reduction during cosmological phase transitions [3]. PBHs could have masses ranging from 10^{-5} g for PBHs created at the Planck time up to several tens of M_{\odot} for PBHs created during the QCD phase transition. No PBH candidate has been unambiguously detected, although there has been claims of such detections, notably progenitors of recent black hole merging events [4] and MACHOs [5].

Black holes were predicted by Hawking [6] to radiate off particles with a black body spectrum of energies. The emission can be described by an effective temperature

$$T_{\text{BH}} = \frac{M_p^2}{8\pi M_{\text{BH}}}, \quad (1)$$

where M_p and M_{BH} are the Planck mass and the PBH mass respectively.

Black holes lose their mass by Hawking radiation at a rate inversely proportional to their squared mass.

A popular method for constraining the density of low-mass PBHs is searching for their γ -ray emission. Searches have attempted to detect a diffuse photon signal from a distribution of PBHs [7] or to look directly for the final stage emission of an individual hole [8–10]. The latter strategy is adopted in this contribution, using data from H.E.S.S.

2. Dataset

H.E.S.S. is an array of five imaging atmospheric Cherenkov telescopes dedicated to observing very-high energy (VHE) γ -rays (energies above 50 GeV) from astrophysical sources, located in the Khomas Highland of Namibia at an altitude of 1800 m above sea level. The first four telescopes have been installed in 2003 (H.E.S.S.-1 phase of the experiment) and have been operational since 2004. A fifth telescope with a reflective area of 596m² and a camera of 2048 photo multipliers has started its operations in 2012.

The data used for this analysis are all the H.E.S.S.-1 observations taken between January 2004 and January 2013. One H.E.S.S. observation run consists of data taken towards the same position on the sky during ~ 28 minutes. Some regions of the sky (Crab, LMC, SMC, region of SN 1006) were excluded from this analysis as well as runs of poor quality, affected for instance by bad weather or technical problems. The data set comprises 11494 runs, corresponding to 4924 hours of observations. The data have been processed by two independent calibration and reconstruction chains. The ImPACT analysis [11] was applied to all the runs in order to suppress the background of hadronic cosmic rays and reconstruct the direction and energy of the gamma-ray candidates. The arrival times of these so-called “gamma-like” events are extracted together with their reconstructed parameters. For each run, gamma-like events with a distance to the center of the camera larger than 2 degree are excluded. The results were cross-checked with the Model analysis [12].

3. Data analysis and results

The signature of PBH explosion is a short burst with a small number (2 to 15) of gamma-like events (photon cluster) which arrive in coincidence in angular space and time. The clustering method used in this paper is based on the OPTICS (Ordering Points To Identify the Clustering Structure) algorithm [13]. The statistical background was directly estimated from the data, by using the same photon list, but with randomized ("scrambled") times of arrival. The average value of the number of clusters distribution obtained by time scrambling 200 times the photon list of each run is taken as the background.

The analysis was performed for 4 values of the timescale Δt , namely 10, 30, 60 and 120 seconds, using the 4924 hours data-set described in section 2. An hypothetical PBH signal is discovered or constrained by comparing the observed data to the expected background (hypothesis H0). If an evaporation signal exists in the data, both the evaporation signal and the background will be observed (hypothesis H1).

The theoretical number of expected PBH bursts of size b to be detected in the data for an observation run i is:

$$n_{sig}^i(b, \Delta t, \rho_{PBH}) = \rho_{PBH} V_{eff}^i(b, \Delta t) \quad (2)$$

where ρ_{PBH} is the local PBH explosion rate and the effective space-time volume of PBH detection is defined by

$$V_{eff}^i(b, \Delta t) = T_i \int d\Omega_i \int_0^\infty dr r^2 P_i(b, N_\gamma), \quad (3)$$

where the index i goes over each run of the H.E.S.S. dataset, T_i and $d\Omega_i$ being the corresponding run live time and observation solid angle respectively.

The effective volume can be written explicitly as

$$V_{eff}^i(b, \Delta t) = T_i \Omega_i \frac{(r_0 \sqrt{N_0})^3}{2} \frac{\Gamma(b - 3/2)}{\Gamma(b + 1)} \quad (4)$$

where N_0 is the observed number of photons from a PBH at r_0 .

The PBH density is estimated by maximizing a likelihood ratio with ρ_{PBH} as the only free parameter, following the procedure of Feldman-Cousins [14]. The likelihood ratio is given by:

$$\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} = \prod_i \frac{\mathcal{P}(n_{ON}^i | \lambda = n_{OFF}^i + n_{sig}^i(b, \Delta t, \rho_{PBH}))}{\mathcal{P}(n_{ON}^i | \lambda = n_{OFF}^i)} \quad (5)$$

where \mathcal{P} is the Poisson probability, $n_{sig}^i(b, \Delta t, \rho_{PBH})$ is defined in eq. 2, n_{ON}^i is the number of clusters found in the data and n_{OFF}^i is the corresponding mean number of clusters found in the OFF data.

The corresponding test statistics is given by:

$$TS = -2 \ln \left(\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} \right) = 2 \times \sum_i n_{sig}^i + n_{ON}^i \left(\ln(n_{OFF}^i) - \ln(n_{OFF}^i + n_{sig}^i) \right) \quad (6)$$

The maximum value obtained for the test statistics (TS, eq. 6) at any Δt is $\sim 10^{-4}$. No significant signal was found in the data. Upper limits on the PBH evaporation rate $\dot{\rho}_{\text{PBH}}$ with confidence levels (CL) of 95% and 99% were derived and are shown in Fig. 1.

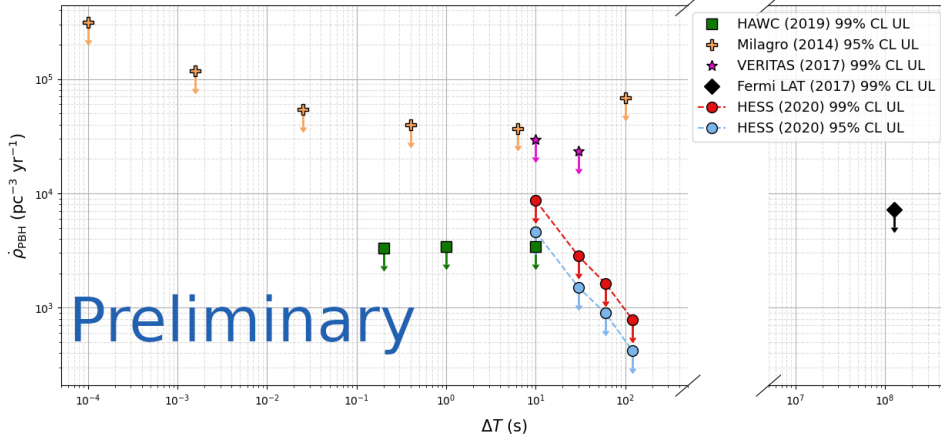


Figure 1: Upper limits on the PBH evaporation rate $\dot{\rho}_{\text{PBH}}$ for time scales of 10, 30, 60 and 120 seconds measured by H.E.S.S.. Upper limits from HAWC [10], Veritas [8], Milagro [15] and Fermi LAT [9] are also shown.

4. Cosmological consequences

The initial mass distribution of PBH describing PBH production in the early universe by scale-invariant Gaussian density perturbations can be modelled by a simple power-law [16]:

$$\frac{d\rho_{\text{PBH}}}{dM_i} = \frac{\rho_0}{M_*} \left(\frac{M_i}{M_*} \right)^{-\beta} \quad (7)$$

where M_i is the initial mass of PBHs, M_* , the initial mass of PBHs at the final stage of evaporation at present time, and Ω_{PBH} is the fraction of the critical density ρ_c in PBHs with mass larger than M_* . ρ_0 is a normalization factor.

The current local rate of vanishing PBHs is given by [16]:

$$\dot{\rho}_{\text{PBH}} \simeq \frac{\alpha(M_*)}{M_*^3} \eta \rho_0, \quad (8)$$

where $\alpha(M)$ counts the degrees of freedom of the particles contributing to the energy loss as a function of the black-hole mass and η is the ratio between the global and local dark matter densities.

Taking for η and $\alpha(M_*)$ their 95 % CL limit values $\eta > 1.6 \times 10^4$ [17] and $\alpha(M_*) > 10^{17} \text{ kg}^3 \text{ s}^{-1}$, upper limits on the initial PBH mass fraction as a function of the index β can be obtained and are shown in figure 2.

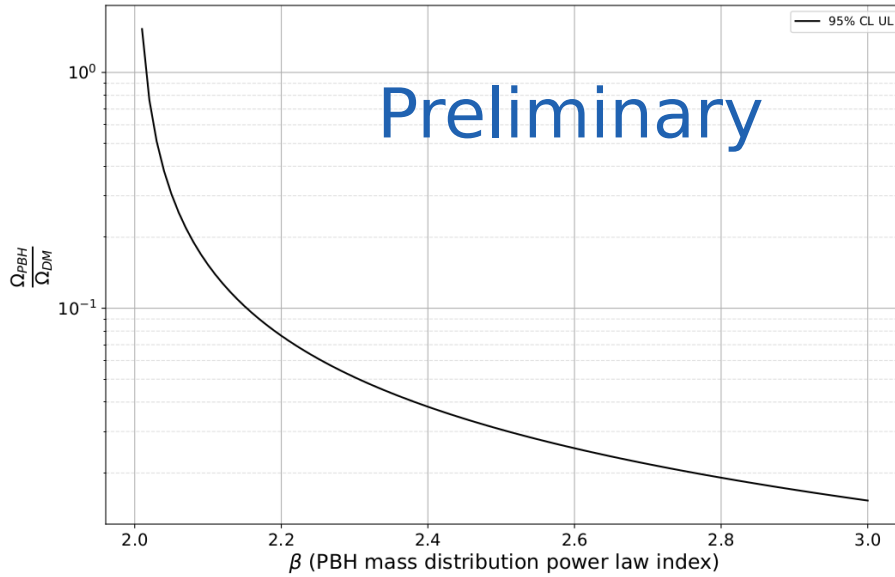


Figure 2: Upper limits on the initial PBH fraction of the critical density as a function of the PBH mass distribution index.

5. Summary

4924 hours of H.E.S.S. observations have been used to search for short time-scale (10 s to 120 s) clusters of photons corresponding to the expected PBH evaporation signal. The number of clusters found is fully compatible with statistical fluctuations. The most constraining 95% CL upper limit on the PBH evaporation rate was found to be $\dot{\rho}_{PBH} < 527 \text{ pc}^{-3} \text{ yr}^{-1}$. Strong constraints have been put on the initial fraction of the invisible mass in PBHs in the hypothesis of a PBH mass power-law distribution.

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