



## Photon spectra from final stages of a primordial black hole evaporation in different theoretical models

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**Abstract:** Possibilities of an experimental search for gamma-ray bursts from primordial black hole (PBH) evaporations in space are reconsidered. It is argued that the corresponding constraints which can be obtained in experiments with cosmic ray detectors strongly depend on theoretical approach used for a description of the PBH evaporation process. Predictions of several theoretical models for gamma-ray spectra from final stages of PBH life (integrated over time) are given.

### Introduction

Direct searches for the bursts of gamma rays from the evaporations of PBHs have been carried out in several works during last decade [1, 2, 3, 4, 5]. PBHs are a unique probe of general relativity, cosmology and quantum gravity [6]. They could have been formed in the early universe, e.g., from direct gravitational collapse of primordial density perturbations. It was shown in numerous works that PBHs can be produced due to specific features of the inflationary potential or due to perturbation amplification during preheating phase. For direct searches of PBHs their spatial clustering properties are very essential. It was shown recently [7] that the local clustering enhancement of PBH number density in our galaxy can be very large, up to  $\sim 10^{22}$ , i.e., many orders of magnitude larger than the factors  $\sim 10^7$  predicted earlier in some works. Due to this, the limits from direct searches of PBHs can be much stronger than indirect limits from measurements of diffuse gamma ray extragalactic background.

### PBH evaporation models

#### Model of MacGibbon and Webber

In first calculations of photon spectra from BH evaporations it had been shown that this spectrum

is far from being thermal simply because emitted elementary particles such as quarks fragment into hadrons, photons, neutrinos, etc, and just this fragmentation and decay of unstable hadrons produces the final photon spectrum [8]. It was assumed that the radiation evaporated from the BH interacts too weakly and all emitted quarks propagate freely and fragment independently of each other.

The resulting time-integrated spectrum (for the case  $T_H \gg m_\pi$ ) can be parametrized in the simple form

$$\frac{dN}{dE_\gamma} \approx 3 \times 10^{20} \begin{cases} \left(\frac{E_0}{T_H}\right)^3 \left(\frac{T_H}{E_\gamma}\right)^{3/2}, & E_\gamma < T_H; \\ \left(\frac{E_0}{E_\gamma}\right)^3, & E_\gamma \geq T_H, \end{cases}$$

where  $E_0 = 10^5$ , and all energies are measured in GeVs. The parametrization is valid for  $E_\gamma > m_\pi/2$ . The average energy of this distribution is

$$\begin{aligned} \bar{E}_\gamma &\approx 2T_H \frac{3 - 2\sqrt{\frac{E_{min}}{T_H}}}{4\sqrt{\frac{T_H}{E_{min}} - 3}} \approx 15\sqrt{T_H} \approx \\ &\approx 1300\Delta t^{-1/6}, \end{aligned} \quad (1)$$

where we used, just for example,  $E_{min} = 100\text{GeV}$ , and  $\Delta t$  is the remaining PBH lifetime (in seconds), which is connected with initial Hawking temperature by the simple relation:

$$\Delta t = 4.7 \times 10^{11} T_H^{-3}. \quad (2)$$

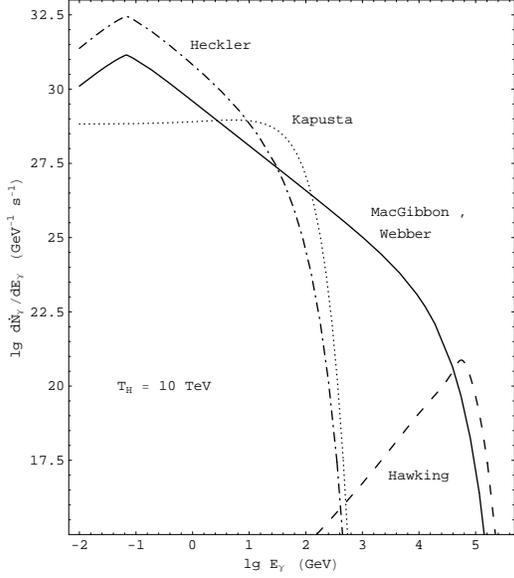


Figure 1: Instantaneous photon spectra from a black hole with Hawking temperature  $T_H = 10$  TeV.

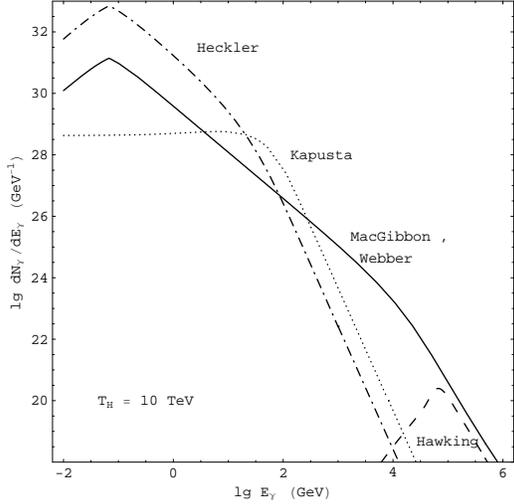


Figure 2: Time-integrated photon spectra from a black hole with initial Hawking temperature  $T_H = 10$  TeV.

### Heckler model

According to Heckler's idea [9], once a black hole, in course of an evaporation, reaches some critical temperature  $T_{crit}$ , the emitted Hawking radiation begins to interact with itself and forms a

nearly thermal chromosphere. This assumption is based on a simple argument: at relativistic energies, the cross section for gluon bremsstrahlung in a  $qq$  or  $q\bar{q}$  collision is approximately constant (up to logarithms of energy) while the density of emitted particles around the BH is proportional to BH temperature. The evaporation of BH creates a radiation shell which propagates outward at the speed of light. The quark and gluon spectrum in the observer rest frame is obtained by boosting a thermal spectrum at  $T_{crit} = \Lambda_{QCD}$  (and  $\Lambda_{QCD} = 200\text{MeV}$ ) with the Lorentz factor  $\gamma_{ch} \approx 0.22(T_H/\Lambda_{QCD})^{1/2}$  of the outer surface of the thermal chromosphere,

$$\frac{d\dot{N}_j}{dQ} = \sigma_j \frac{\gamma_{ch}^2 r_{ch}^2 Q^2}{2\pi^2} \times \int_0^1 \frac{(1 - \beta \cos \theta) \cos \theta d\Omega}{\exp[\gamma_{ch} Q(1 - \beta \cos \theta)/T_{ch}] - (-1)^{2s}} . \quad (3)$$

In this formula the integration over the surface of the chromosphere of radius  $r_{ch} = \gamma_{ch}/\Lambda_{QCD}$  has been carried out. The observed photon spectrum of the chromosphere is a convolution of the quark-gluon spectrum given by (3) with the quark-pion fragmentation function and the Lorentz-boosted spectrum from  $\pi^0$  decay.

The high energy behavior of time-integrated spectrum is ( $E_\gamma$  is in GeVs)

$$\frac{dN}{dE_\gamma} = 3 \times 10^{34} E_\gamma^{-4} . \quad (4)$$

The average energy of time-integrated spectrum is

$$\bar{E}_\gamma \approx 0.17 T_H^{1/4} \approx 1.6 \Delta t^{-1/12} . \quad (5)$$

### Kapusta & Daghigh model

This approach [10] differs from those of Heckler mainly in two respects. It is assumed that the hadronization of quarks occurs before the thermal freeze-out and the onset of free-streaming. It is assumed, further, that it happens suddenly at a temperature  $T_f$  in the range  $100 - 140$  MeV (it is the parameter of the model), and to this moment all particles whose mass is greater than  $T_f$  have annihilated leaving only photons, electrons, muons and pions. Photons emitted by BH come from two

sources. Either they are emitted directly from a (boosted) black-body spectrum or they arise from the  $\pi^0$ -decay.

The formula for particle spectrum from the outer edge of the chromosphere is analogous to (3). For the concrete calculation, we used  $T_f = 0.12$  GeV. The values of  $\gamma_{ch}$  and  $r_{ch}$  obtained in [10] are

$$\gamma_{ch} \approx 0.22 \sqrt{\frac{T_H}{T_f}}, \quad r_{ch} \approx \frac{0.89}{T_f} \sqrt{\frac{T_H}{T_f}}. \quad (6)$$

The gamma ray flux from the  $\pi^0$  - decay in the limit  $E_\gamma \gg m_\pi$  is given by the simple formula [10]

$$\frac{d\dot{N}^{\pi^0}}{dE_\gamma} = \frac{4r_{ch}^2 T_f^2}{\pi^2} \sum_{n=1}^{\infty} \frac{\exp(-nE_\gamma/2\gamma_{ch}T_f)}{n^2}, \quad (7)$$

and we used it to estimate photon flux from this channel even at  $E_\gamma \sim m_\pi$ .

In this case, the high-energy behavior of time-integrated photon flux is similar to (4), but the flux is approximately 1.5 orders of magnitude larger:

$$\frac{dN}{dE_\gamma} = \frac{M_{Pl}^2 T_f}{26E_\gamma^4} = 6.9 \times 10^{35} E_\gamma^{-4}. \quad (8)$$

The average energy is given by

$$\bar{E}_\gamma \approx 0.36 \sqrt{T_H} \approx 32 \Delta t^{-1/6}. \quad (9)$$

## Experimental search of PBH bursts with ground based detectors

One can see from Fig. 3 that the average photon energy as a function of PBH lifetime is highly model dependent. Therefore, various methods should be used for the search. Up to now the search of high energy gamma radiation from PBH with ground-based arrays had been carried out using the predictions of the model of [8], and, specifically, data on distribution of events (extensive air showers (EAS)) in time and space were used. The results were reported in [1, 2, 3, 4, 5], time intervals used were from 1 to 10 seconds.

If the chromosphere models of black hole evaporation are close to reality the average photon energy at last instants of PBH life is rather low. In the model of hadronic chromosphere developed in

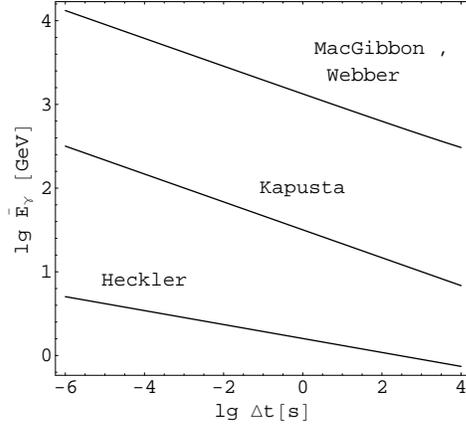


Figure 3: Average energy of gamma rays emitted from a PBH, as a function of left PBH lifetime. Upper curve corresponds to  $E_{min} = 100$  GeV.

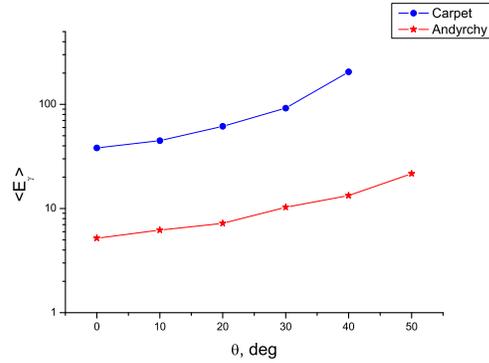


Figure 4: Average photon energy vs. zenith angle for model of [10].

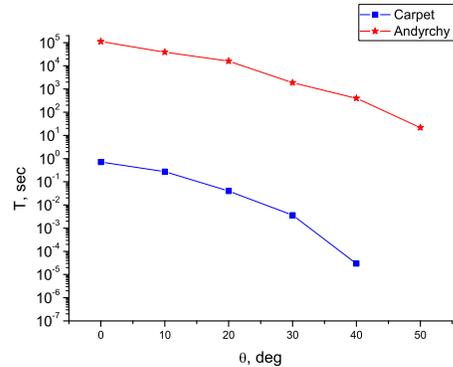


Figure 5: Time duration of gamma burst vs. zenith angle for model of [10].

[10] this energy is about 30 GeV for  $\Delta t \sim 1$ s. A search of PBH bursts in this case is possible using the method suggested in works of EAS-TOP collaboration [11] and Baksan group [12, 13]. Shower particles generated in atmosphere by photons with energy  $\sim 30 \div 100$  GeV are strongly absorbed before reaching the detector level, so, the average number of signals in the detector module is smaller than 1. Therefore, in this energy range PBH bursts can be sought for by operating with the modules in single particle mode, that is, by measuring the single particle counting rate of the individual modules. The primary arrival directions of photons are not measured, and bursts can be detected only as transients (short-time increases) of the cosmic ray counting rate.

Using the photon spectra from PBH bursts calculated above and registration efficiencies of photons (as functions of zenith angle, the array altitude and features of concrete modules) one can calculate the average energies of PBH bursts for a given array and, approximately, corresponding time durations of these bursts.

On Fig. 4 the dependencies of average photon energy on zenith angle in model of [10] for two arrays of Baksan observatory are shown. Andyrchy and Carpet arrays are situated practically on the same place (horizontal distance between them is about 1 km), but their altitudes above sea level are different: Andyrchy - 2060 m, Carpet - 1700 m. On Fig. 5, time duration of bursts as a function of zenith angle is given for the same arrays. One can see that duration of burst strongly depends on the zenith angle.

In summary, it is shown that predictions for high energy photon spectra from PBH burst depend rather strongly on the model used for description of final stage of PBH evaporation. In particular, chromosphere models predict too steep spectra in TeV region. It is argued that, if such models are correct, the practical search of PBH bursts can be carried out using the technique developed by EAS-TOP and Baksan groups for a search for  $\gamma$ -bursts at energies  $E > 10$  GeV. It is shown that in such search the average energy and time duration of the signal depend on the zenith angle of its arrival and on the altitude of the array above sea level.

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