

## Searching for Very-High-Energy Gamma-Ray Bursts from Evaporating Primordial Black Holes

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**Abstract**—Temporal and energy characteristics of the very-high-energy gamma-ray bursts from evaporating primordial black holes have been calculated by assuming that the photospheric and chromospheric effects are negligible. The technique of searching for such bursts on shower arrays is described. We show that the burst time profile and the array dead time should be taken into account to interpret experimental data. Based on data from the Andyrchy array of the Baksan Neutrino Observatory (Institute for Nuclear Research, Russian Academy of Sciences), we have obtained an upper limit on the number density of evaporating primordial black holes in a local region of space with a scale size of  $\sim 10^{-3}$  pc. Comparison with the results of previous experiments is made.

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## Introduction

Primordial black holes (PBHs) can be formed in the early Universe through the gravitational collapse of primordial cosmological density fluctuations. Therefore, the formation probability of PBHs and their observational manifestations depend significantly on how the primordial density fluctuations emerged and developed. The pattern of black hole formation is determined not only by the cosmology and physics of the early Universe. Theoretical predictions of the PBH formation probability depend strongly on the adopted theory of gravitation and, which is also important, on the adopted model of gravitational collapse. The evaporation of black holes on which their experimental search is based has not been completely studied either. Thus, PBH detection will provide valuable information about the early Universe and can be a unique test of the general theory of relativity, cosmology, and quantum gravity (Carr 2003). Knowledge of the spatial distribution of PBHs is important for their direct

search. As was shown by Chisholm (2006), the local PBH number density in our Galaxy could be many orders of magnitude higher than the mean PBH number density in the Universe (the density ratio could reach  $\sim 10^{22}$ , which is much larger than the previously predicted value of  $\sim 10^7$ ). Therefore, the constraints on the PBH number density imposed by direct searches can be more stringent than those imposed by diffuse extragalactic gamma-ray background measurements.

The high-energy gamma-ray bursts (GRBs), i.e., significant and time-localized excesses of gamma radiation above the background, are generated at the final PBH evaporation stage. Since the calculated temporal and energy characteristics of such bursts depend on the theoretical evaporation model (Bugaev et al. 2007), the technique of an experimental search and, accordingly, the constraints imposed on the PBH number density in the local Universe are modeldependent. PBHs can be searched for in experiments on arrays designed to detect extensive air showers (EASs) from cosmic rays with effective primary gamma-ray energies of 10

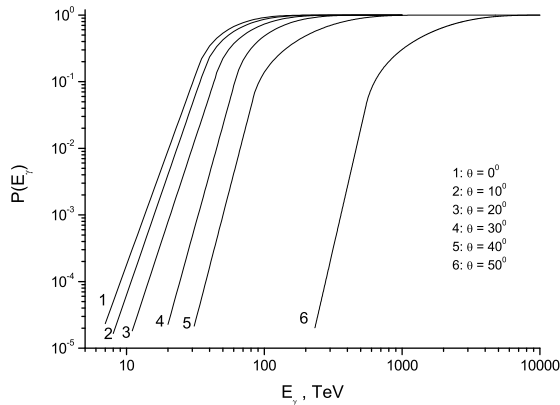


Figure 1: Probability of EAS detection by the Andyrchy array versus primary gamma-ray photon energy for various zenith angles  $\theta$ .

TeV or higher only within the framework of the evaporation model without a chromosphere (MacGibbon and Webber 1990). The duration of the high-energy GRBs predicted by chromospheric evaporation models is too short, much shorter than the dead time of EAS arrays.

It should be noted that the duration of the high-energy GRBs is fairly short in the evaporation model without a chromosphere as well. Therefore, the effect of the array dead time on the burst detection probability should be taken into account when interpreting the experimental data from EAS arrays with a high threshold energy of the primary gamma-ray photons.

## The Experiment

The Andyrchy array to detect EASs from cosmic rays is located on the flank of Mount Andyrchy at an altitude of  $\sim 2060$  m above sea level; its geographical coordinates are  $43.28^\circ$  N and  $42.69^\circ$  E. The array consists of 37 scintillation detectors based on plastic scintillator, each with an area of  $1 \text{ m}^2$ . The separation between the detectors in the horizontal plane is  $\sim 40$  m and the total area of the array is  $5 \times 10^4 \text{ m}^2$ . The EAS trigger becomes active when  $\geq 4$  array detectors are triggered simultaneously; the trigger rate is  $\sim 9 \text{ s}^{-1}$ . The effective angular resolution of the array for such events is  $3.8^\circ$ . The array dead time per EAS event does not depend on the EAS power and is 1 ms. The array and its operating parameters were described in detail previously (Petkov et al. 2006).

The detection probabilities  $P(E_\gamma, \theta)$  of the EASs generated by primary gamma-ray photons with energy  $E_\gamma$  incident on the array at zenith angle  $\theta$  were determined by simulating electromagnetic cascades in the atmosphere and the detector (Smirnov et al. 2005; Smirnov 2005). The CORSIKA code (version 6.03, the QGSJET model) (Heck et al. 1998) was used to simu-

late electromagnetic cascades in the atmosphere. The characteristics of the secondary particles that reached the array level were used as input parameters in the code for calculating the detector response, in which the energy release and the triggering time of each array detector were calculated. For the event simulated in this way, the arrival direction of the simulated EAS was reconstructed on the basis of a standard technique used in processing the recorded events. In Fig. 1, the EAS detection probability is plotted against the primary gamma-ray photon energy for several zenith angles. Since the detection probability of primary gamma-ray photons is a relatively smooth function of the photon energy, the median energy of the primary gamma-ray photons detected by the array depends on their energy spectrum. Following Alexandreas et al. (1993), we will take the median energy of the primary gamma-ray photons when the source is located at zenith and the gamma-ray spectrum is a power law with an index of  $-2.7$  as the effective energy of the gamma-ray photons detected by the array. For the EASs detected by the Andyrchy array, this energy is 60 TeV.

For each of the events selected by the EAS trigger, we reconstructed the EAS arrival direction, i.e., the zenith and azimuth angles  $(\theta, \phi)$  in the array coordinate system. Based on our processing, we created an archive of preprocessed information for the period 1996–2001 (the net accumulation time is  $\sim 1100$  days and the total number of events is  $\sim 6.22 \times 10^8$ ), which contains the absolute event time (with an accuracy of 1 ms) and the EAS arrival direction. Searching for GRBs over the celestial sphere (without referencing to the already detected bursts) is, in fact, searching for spatiotemporal concentrations of events (clusters). Since we take fairly short time intervals, spatial concentrations of events are searched for in the horizontal coordinate system. For each event  $i$  with an absolute time  $t_i$  and arrival angles  $(\theta, \phi)_i$ , we search for a cluster of such events  $i, i+1, \dots, i+n-1$  that the EAS arrival directions differ by less than  $\alpha_r$  from the weighted mean direction. Thus, each cluster is characterized by multiplicity  $n$ , duration  $\Delta t$ , absolute time  $T$ , and arrival direction  $(\theta, \phi)$ .

Previously, data from the Andyrchy array (Smirnov et al. 2005; Smirnov 2005) were used to search for cosmic GRBs over the celestial sphere. Groups of EASs arrived from one angular cell  $\alpha_r = 4.0^\circ$  in radius were selected; the minimum and maximum time differences in the cluster were taken to be 10 ms and 10 s, respectively. For each multiplicity ( $n \geq 2$ ), the dependences of the number of clusters with a given multiplicity on the interval  $\Delta t$  were derived. The background of chance coincidences (the formation of clusters with a given multiplicity  $n$ ) was calculated using a similar processing of the simulated events. The EAS arrival angles  $(\theta, \phi)$  and the time between the EAS arrivals were simulated using experimental distributions. The experimentally measured detection rates of such clus-

ters are in agreement with those expected from the background of chance coincidences (within the limits of one standard deviation).

## Searching for GRBs from PBHs for the Evaporation Model Without a Chromosphere

The spectrum of the gamma-ray photons emitted by PBHs,  $dN_\gamma/dE_\gamma$ , depends on the time  $t_l$  left until the end of black hole evaporation. In the evaporation model without a chromosphere (MacGibbon and Webber 1990), the numerically calculated and time-integrated photon spectrum can be fitted by a piecewise power function (for a black hole temperature  $T_H \gg m_\pi$  and gamma-ray energies  $E_\gamma > m_\pi/2$ ):

$$\frac{dN_\gamma}{dE_\gamma} = N_0 \begin{cases} \left(\frac{E_0}{T_H}\right)^3 \left(\frac{T_H}{E_\gamma}\right)^{3/2}, & E_\gamma < T_H \\ \left(\frac{E_0}{E_\gamma}\right)^3, & E_\gamma \geq T_H \end{cases}$$

(Bugaev et al. 2007), where  $E_0 = 10^5$  and all energies are measured in GeV. The parameter  $N_0$  is

$$N_0 \approx \nu_0 \times 7 \cdot 10^{19},$$

while  $\nu_0$  includes the effective number of degrees of freedom of the quarks and gluons used in calculating the photon spectrum. A simple estimate for  $N_0$  includes the  $u$  and  $d$  quarks, their antiquarks, and all gluons; in this case,  $\nu_0 = (1/3)(3 \cdot 2 \cdot 2 \cdot 2 + 8 \cdot 2) = 40/3$  ( $1/3$  is the ratio of the number of  $\pi^0$  mesons to the total number of  $\pi$  mesons). The corresponding value of  $N_0$  is  $9 \times 10^{20}$ . The lower limit for the parameter  $\nu_0$  can be obtained by taking into account only one type of quarks ( $\nu_0 = 4$ ); in this case,  $N_0 \approx 3 \times 10^{20}$ .

The time until the end of PBH evaporation  $t_l$  (in seconds) is related to the black hole temperature  $T_H$  (in GeV) by

$$t_l = 4.7 \times 10^{11} T_H^{-3}.$$

Since the array detects the EASs generated by primary gamma-ray photons with energy  $E_\gamma$  incident at zenith angle  $\theta$  with probability  $P(E_\gamma, \theta)$  and since the spectrum of the gamma-ray photons emitted by PBHs  $dN_\gamma/dE_\gamma$  depends on  $t_l$ , the spectrum recorded by the array (its response function)  $P(E_\gamma, \theta)dN_\gamma/dE_\gamma$  also depends on  $t_l$ . Here,  $\theta$  is the zenith angle at which the PBH is seen from the array. Figure 2 shows the photon spectra and response functions of the Andyrchy array for the vertical direction and for  $t_l = 1$  s and 1 ms, with  $N_0 = 3 \times 10^{20}$ .

The total number of gamma-ray photons emitted by PBHs that can be detected by the array,

$$N_\gamma(\theta, t_l) = \int_0^\infty dE_\gamma P(E_\gamma, \theta) dN_\gamma/dE_\gamma,$$

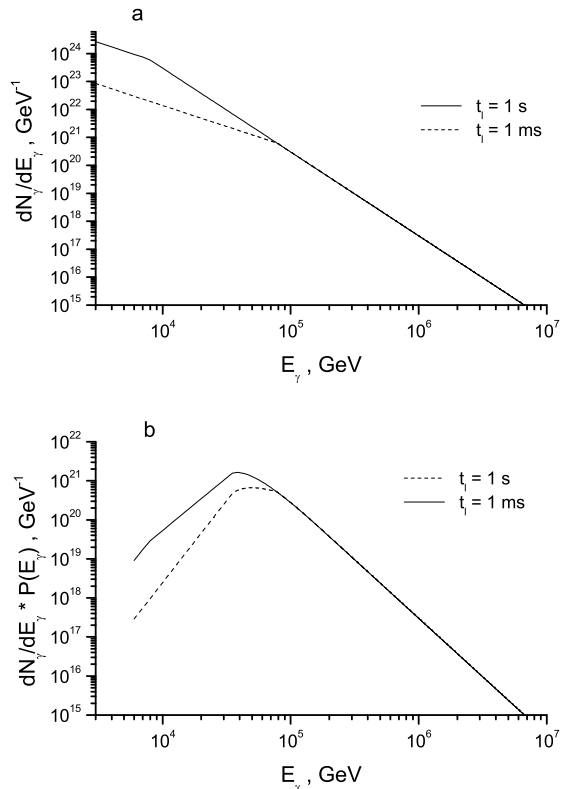


Figure 2: (a) Photon spectrum from evaporating PBHs. (b) Response functions of the Andyrchy array for the vertical direction at two values of  $t_l$ .

also depends on  $t_l$ . Figure 3 shows the dependences  $N_\gamma(\theta, t_l)$  (integrated burst profile) for several zenith angles  $\theta$ . It should be noted that the burst profile mainly determines the technique of searching for GRBs from PBHs on a specific array, in particular, the choice of a time interval  $\Delta t$  for the search for EAS clusters. Let us call the time left until the end of black hole evaporation during which 99% of the gamma-ray photons that can be detected by a given array are emitted the burst duration  $t_b$  for this array. In Fig. 4,  $t_b$  is plotted against the zenith angle for the Andyrchy array. We see from the figure that the array can record the events from evaporating PBHs in a limited range of zenith angles, because the expected GRB duration at large zenith angles is shorter than the array dead time per event  $t_d$ .

We searched for the groups of EASs arrived from one angular cell for time intervals of a given duration,  $\Delta t = t_b(\theta)$ . Because of the short time intervals (accordingly, the reduced background of chance coincidences), we used large angular cells:  $\alpha_r = 7.0^\circ$ ; such a cell contains 90% of the events from a point source. The distributions of the detected clusters in multiplicity were obtained for  $\Delta t = 40, 24, 11,$  and  $3$  ms, which correspond to the zenith angles  $\theta = 0^\circ, 10^\circ, 20^\circ,$  and  $30^\circ$ .

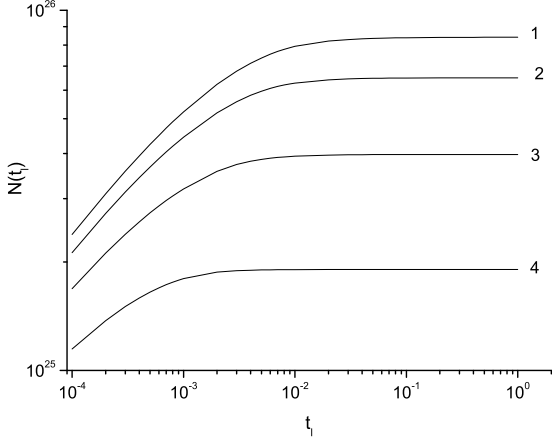


Figure 3: Total number of gamma-ray photons emitted by PBH that can be detected by the Andyrchy array versus the time  $t_l$  left until the end of black hole evaporation: 1,  $\theta = 0^\circ$ ; 2,  $\theta = 10^\circ$ ; 3,  $\theta = 20^\circ$ ; 4,  $\theta = 30^\circ$ .

The results of our search for two values of  $t_b$  are presented in Fig. 5. The maximum multiplicities  $n'(\theta)$  of the detected clusters are 4, 4, 3, and 2, respectively.

## Results

We obtained a constraint on the number density of evaporating PBHs using the technique described in Linton et al. (2006). Let a PBH be located at distance  $r$  from the array and be seen from it at zenith angle  $\theta$ . The mean number of gamma-ray photons detected by the array over the burst duration  $t_b$  is then

$$\bar{n}(\theta) = \frac{\epsilon N(t_b(\theta)) S(\theta)}{4\pi r^2},$$

where  $S(\theta)$  is the array area and  $\epsilon = 0.9$  is the fraction of the events from a point source that fell into an angular cell with a size of  $7.0^\circ$ . The number of bursts detected over the total observation time  $T$  can be represented as

$$N = \rho_{pbh} T V_{eff},$$

where

$$V_{eff} = \int d\Omega \int_0^\infty dr r^2 F(n(\theta), \bar{n}(\theta), t_b(\theta))$$

is the effective volume of the space surveyed by the array,  $\rho_{pbh}$  is the number density of evaporating PBHs, and  $F(n, \bar{n}, t_b)$  is the detection probability of a cluster of  $n$  EASs with the mean value of  $\bar{n}$  over the burst duration  $t_b$ . In turn, the total detection probability can be expressed as a product of the Poisson probability of  $n$  EASs falling on the array with the mean value of  $\bar{n}$

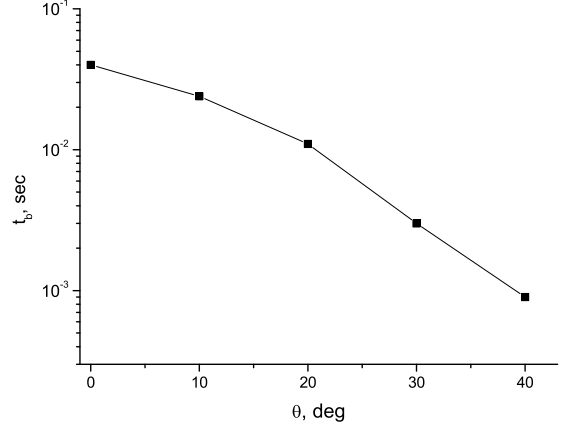


Figure 4: Burst duration versus zenith angle for the Andyrchy array.

and the probability to detect all  $n$  EASs over the burst duration  $t_b$  with the array dead time per event  $t_d$ :

$$F(n, \bar{n}, t_b) = f(n, t_b, t_d) \frac{e^{-\bar{n}} \bar{n}^n}{n!}.$$

In calculating the effective volume, we take  $n(\theta) = n'(\theta) + 1$  (this means that the distributions of the detected clusters in multiplicity can be explained by the background of chance coincidences). The probabilities  $f(n, t_b, t_d)$  of detecting  $n(\theta)$  EASs over the burst duration  $t_b(\theta)$  with the array dead time per event  $t_d$  were calculated by the Monte Carlo method by taking into account the burst time profile for a given zenith angle. The effective volume of the space surveyed by the array,  $V_{eff}$ , is  $1.88 \times 10^{-9} \text{ pc}^3$ , with  $N_0$  being  $9 \times 10^{20}$ . If the evaporating PBHs are distributed uniformly in the local region of the Galaxy, then the upper limit  $\rho_{lim}$  on the number density of evaporating PBHs at the 99% confidence level can be calculated from the formula

$$\rho_{lim} = \frac{4.6}{V_{eff} \cdot T};$$

in our case,  $\rho_{lim} = 8.2 \times 10^8 \text{ pc}^{-3} \text{ yr}^{-1}$ .

## Comparison with the Results of Previous Studies and Conclusions

Previously, the high-energy GRBs from evaporating PBHs were searched for in experiments on the CYGNUS (Alexandreas et al. 1993; the threshold energy of the primary gamma-ray photons is  $E_{th} \sim 30 \text{ TeV}$ ), HEGRA (Funk et al. 1995;  $E_{th} \sim 30 \text{ TeV}$ ), and Tibet (Amenomori et al. 1995;  $E_{th} \sim 10 \text{ TeV}$ ) EAS arrays for fixed one-second time intervals without taking into account the burst duration (and its dependence on the zenith angle for the specific array).

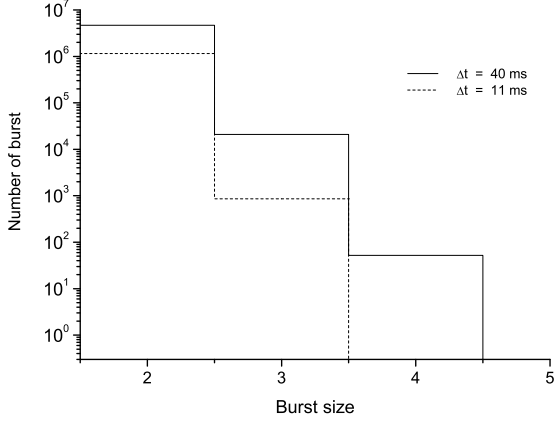


Figure 5: Measured number of clusters versus cluster size for two time intervals,  $\Delta t = 40$  ms and  $\Delta t = 11$  ms.

In these experiments, constraints on the number density of evaporating PBHs were obtained by assuming the absence of any fluctuations in the number of EASs falling on the array (it was assumed that  $n = \bar{n}$ ) and by disregarding the effects of the burst time profile and the array dead time on the burst detection probability. The latter is particularly important for arrays with a high gamma-ray detection threshold (i.e., with a short burst duration  $t_b$ ) and a relatively long dead time  $t_d$ . Disregarding the effects of the array dead time and the burst time profile on the burst detection probability when interpreting the data will lead to an appreciable overestimation of this probability (i.e., the factor  $F$  in the above expression for the effective volume  $V_{eff}$ ) and, as a result, to an underestimation of the upper limit on the PBH number density. For example, in this case, a constraint of  $3.1 \times 10^6 \text{ pc}^{-3} \text{ yr}^{-1}$  instead of the real  $8.2 \times 10^8 \text{ pc}^{-3} \text{ yr}^{-1}$  is obtained for the Andyrchy array. In the limiting case, the array can be insensitive to the high-energy GRBs from PBHs altogether, since for  $t_d \geq t_b$  no more than one gamma-ray photon can be detected over the burst duration and a burst of  $n$  gamma-ray photons can be detected if  $nt_d < t_b$ .

Figure 6a presents the results of the studies listed above as they are given by their authors. This figure also shows the constraint obtained at  $E_\gamma \sim 1$  TeV in an experiment on the Whipple Cherenkov telescope (Linton et al. 2006) for a time interval of 5 s. In addition, for comparison, it also shows our constraint that we obtained in the approximation of a zero array dead time and by disregarding the burst time profile. The effective energy of the detected gamma-ray photons is along the horizontal axis. Two constraints obtained for different event selection conditions are given for the HEGRA array.

The upper limits on the number density of evaporating PBHs with allowance made for the burst time

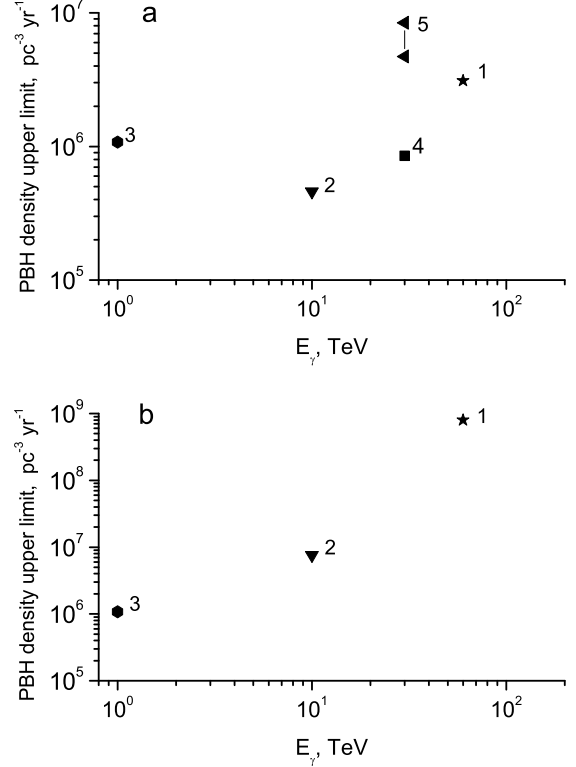


Figure 6: Upper limits on the number density of evaporating PBHs for the evaporation model without a chromosphere versus effective energy of the detected gamma-ray photons. Panel (a): 1, the Andyrchy array (this paper, without the effects of the burst time profile and the array dead time on the burst detection probability); 2, original data from the Tibet array (Amenomori et al. 1995); 3, the Whipple Cherenkov telescope (Linton et al. 2006); 4, original data from the CYGNUS array (Alexandreas et al. 1993); 5, original data from the HEGRA array (Funk et al. 1995). Panel (b): 1, the Andyrchy array (this paper, with the effects of the burst time profile and the array dead time on the burst detection probability); 2, recalculation of the Tibet data (see the text); 3, the Whipple Cherenkov telescope (Linton et al. 2006).

profile and the array dead time are shown in Fig. 6b. We obtained the constraint for the Tibet array ( $7.6 \times 10^6 \text{ pc}^{-3} \text{ yr}^{-1}$ ) by recalculating the data from Amenomori et al. (1995) using the technique described above (the dead time of this array is 5 ms per event). For the CYGNUS array, the expected burst duration is no more than 40 ms for a source at zenith, while the dead time estimated from the data in Alexandreas et al. (1993) is  $\sim 30$  ms per event. Since these two times are of the same order of magnitude, the real constraint on the PBH number density cannot be calculated. For the HEGRA array, we also disregarded the effect of its dead time, because no dead time is given in Funk et

al. (1995). Finally, estimates show that taking into account the dead time is unimportant at relatively low gamma-ray photon energies ( $\sim 1$  TeV). Therefore, the result of the Whipple array (Linton et al. 2006) remains essentially unchanged.

Comparison of Figs. 6a and 6b leads us to conclude that taking into account the burst time profile and the array dead time is very important at high energies of the detected gamma-ray photons.

How far are our constraints on the PBH number density from its actual estimates? If we make two assumptions: (1) the spectrum of the primordial density fluctuations is scale-invariant (in this case, the data obtained in measurements of the relic gamma radiation can be used to calculate the PBH mass spectrum and number density) and (2) the PBH accumulation factor in the Galaxy is equal to unity (i.e., there is no local increase in PBH number density in the Galaxy), then the predicted number density of evaporating PBHs is many orders of magnitude lower than the upper limits shown in Fig. 6b. However, there are many cosmological models in which the spectrum of the primordial density fluctuations is nonmonotonic on small scales (see, e.g., Bugaev and Klimai (2006) and references therein). The possible value of the accumulation factor has already been discussed above. In a word, we cannot rule out the possibility that the actual PBH number density is close to the already available experimental upper limits. In general, the predicted PBH number density in the Universe is determined by our views of the end of inflation. PBHs (even if they will not be discovered) are sources of unique information about this period in the history of the early Universe. Therefore, their searches will undoubtedly be continued.

As we see from Fig. 6b, the best (to date) constraint on the number density of evaporating PBHs ( $1.08 \times 10^6 \text{ pc}^{-3} \text{ yr}^{-1}$ ) was obtained in the experiment on the Whipple Cherenkov telescope (Linton et al. 2006). However, it should be noted that the effective gamma-ray photon energy in our experiment is two orders of magnitude higher than that in the Whipple one. Thus, our upper limit pertains not to black holes in general, but to black holes with certain properties (emitting 100-TeV gamma-ray photons at the end of their evaporation during bursts lasting  $\sim 10$  ms).

## Acknowledgements

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## References

- [1] D. E. Alexandreas, G. E. Allen, D. Berley, *et al.*, Phys. Rev. Lett. **71**, 2524 (1993).
- [2] M. Amenomori, Z. Cao, B. Z. Dai, *et al.*, in *Proceedings of the 24th International Cosmic Ray Conference, Rome, Italy, 1995*, Vol. 2, p. 112.
- [3] E. Bugaev, P. Klimai and V. Petkov, in *Proceedings of the 30th International Cosmic Ray Conference, Merida, Mexico, 2007*, arXiv:0706.3778 [astro-ph].
- [4] E. Bugaev and P. Klimai, arXiv:astro-ph/0612659.
- [5] B. J. Carr, Lect. Notes Phys. **631**, 301 (2003) [arXiv:astro-ph/0310838].
- [6] J. R. Chisholm, Phys. Rev. D **73**, 083504 (2006) [arXiv:astro-ph/0509141].
- [7] B. Funk, J. Gonzalez, H. Krawczynski, *et al.*, in *Proceedings of the 24th International Cosmic Ray Conference, Rome, Italy, 1995*, Vol. 2, p. 104.
- [8] D. Heck, G. Schatz, T. Thouw, *et al.*, Report FZKA 6019 (Forschungszentrum, Karlsruhe, 1998).
- [9] E. T. Linton, R. W. Atkins, H. M. Badran, *et al.*, JCAP **0601**, 013 (2006).
- [10] J. H. MacGibbon and B. R. Webber, Phys. Rev. D **41**, 3052 (1990).
- [11] V. B. Petkov, V. I. Volchenko, G. V. Volchenko, *et al.*, Instrum. Exp. Tech. **49**, 785 (2006) [Prib. Tekh. Eksp. **49**, 50 (2006)].
- [12] D. V. Smirnov *et al.*, Izv. Ross. Akad. Nauk, Ser. Fiz. **69**, 413 (2005).
- [13] D. V. Smirnov, Doctoral Dissertation in Mathematics and Physics (Institute for Nuclear Research, Russian Academy of Sciences, Moscow, 2005).

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