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О ДЕТЕКТИРОВАНИИ ВЫСОКОЧАСТОТНЫХ РЕЛИКТОВЫХ ГРАВИТАЦИОННЫХ ВОЛН *

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Рассмотрена специфика спектра реликтовых гравитационных волн, формирующихся на инфляционном и постинфляционном этапах эволюции ранней Вселенной, для космологических моделей, основанных на модифицированных теориях гравитации и гравитации Эйнштейна. Рассматривается возможность обнаружения высокочастотных реликтовых гравитационных волн с помощью процесса преобразования гравитонов в фотоны в постоянном и переменном магнитном поле. Проводится сравнение чувствительности детекторов этого типа с чувствительностью других существующих и перспективных детекторов высокочастотных гравитационных волн. На основе анализа оценки чувствительности различных типов детекторов высокочастотных гравитационных волн делается вывод о перспективах прямой верификации моделей космологической инфляции с помощью гравитационно-волновых антенн.

Ключевые слова: Общая теория относительности, модифицированные теории гравитации, гравитационные волны, гравитационно-волновые антенны.

ON THE DETECTION OF HIGH-FREQUENCY RELIC GRAVITATIONAL WAVES

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The specificity of the spectrum of relic gravitational waves formed at the inflationary and post-inflationary stages of the evolution of the early universe is considered for cosmological models based on modified theories of gravity and Einstein gravity. The possibility of detecting high-frequency relic gravitational waves by using the process of converting gravitons into photons in a constant and alternating magnetic field is considered. The sensitivity of detectors of this type is compared with the sensitivity of other existing and prospective detectors of high-frequency gravitational waves. Based on the analysis of the sensitivity assessment of various types of high-frequency gravitational wave detectors, a conclusion is made about the prospects for direct verification of cosmological inflation models using gravitational-wave antennas.

Keywords: General relativity, modified gravity theories, gravitational waves, gravitational-wave detectors.

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Introduction

Since the first detection of the emission of gravitational waves in 2015 [1] General Relativity (GR) has once again demonstrated its correctness in describing the large-scale structure of the Universe

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and the validity of the geometric interpretation of gravitational interaction. Notwithstanding, General Relativity does not answer all the questions relating to the current accelerated expansion of the Universe and how to solve the problem of dark matter and dark energy. Various types of modifications of GR are considered to solve these types of problems, e.g. adding scalar fields to GR [2, 3] or modifying GR by adding dependencies of higher orders of space-time curvature [4, 5]. Although these frameworks may yield some interesting mathematical results, they require experimental verification.

The nature of the transition from the inflationary stage to the post-inflationary stage of the evolution of the universe has a significant impact on the spectrum of relict gravitational waves. Deviations of the state parameter of matter at the post-inflationary stage from the value corresponding to radiation $w_\gamma = 1/3$ during this transition corresponding to the presence of an additional stage of stiff energy domination, induce a significant increase in the energy density of relict gravitational waves in the high frequency range.

The value of the state parameter of the post-inflationary matter field can be determined as follows

$$w = -1 + \frac{4}{3}\left(1+\beta\right), \tag{0.1}$$

where $\beta = 0$ for the slow-roll inflation based on GR with post-inflationary radiation domination [6], $\beta = 1/2$ for quintessential inflation based on GR with post-inflationary domination of kinetic energy of a scalar field [7], $0 \leq \beta \leq 1/5$ for inflationary models based on the scalar-tensor gravity with the power-law connection between coupling function and the Hubble parameter [8], $0 \leq \beta \leq 1/2$ for the inflationary models based on the scalar-torsion gravity with the power-law connection between coupling function of a scalar field and torsion scalar and the Hubble parameter [9] and $-1/2 \leq \beta \leq 0$ for inflationary models based on the Einstein-Gauss-Bonnet gravity, where $\beta = \alpha_{GB}$ is a coupling constant between scalar field and the Gauss-Bonnet term [10, 11].

We also note that quintessential inflationary models based on Einstein gravity imply only one value of the stiff matter state parameter $w = 1$, while modified gravity theories imply a wider range of values for this parameter $1/3 < w \leq 1$. For this reason, analysis of the spectrum of relict gravitational waves leads to the possibility of determining the influence of modifications of Einstein gravity at the inflationary stage of the evolution of the universe.

In this paper, we consider the influence of stiff matter on the resulting spectrum of relict gravitational waves in the present era of the evolution of the universe and discuss the possibilities of direct registration of relict gravitational waves on the basis of the various detection methods.

To evaluate the possibility of direct detection, this paper discusses the classical and modified Gerzenshtein effect, which involves the conversion of gravitational wave (GW) emission into photons in the presence of constant and varying magnetic fields, respectively, as well as high-frequency gravitational-optical resonance in a multi-beam interferometer [12]. As it will be shown below, the latter is the most promising method for observing relic gravitational waves in laboratory conditions.

1. Energy contained in gravitational waves

The energy density of relic gravitational waves can be estimated [13] by a dimensionless value

$$\Omega_{\rm GW} \simeq \Omega^0_{\rm GW} \cdot \begin{cases} 1, & f < f_{\rm RD} \\ 1.27 \cdot \left(\frac{f}{f_{\rm RD}}\right)^{\alpha_S}, & f \geq f_{\rm RD} \end{cases} \tag{1.1}$$

where $\Omega^0_{\rm GW} = 10^{-15} \cdot r/h^2$, r is the tensor – scalar ratio, $h \simeq 0.68$ is the dimensionless Hubble constant, parameter α_S is defined as

$$\alpha_S = 2\frac{3w-1}{3w+1}, \tag{1.2}$$

where $f_{\rm RD}$ is the frequency of the mode that corresponds to the size of the horizon at the beginning of the epoch of radiation domination in the present epoch. Taking into account the LIGO sensitivity

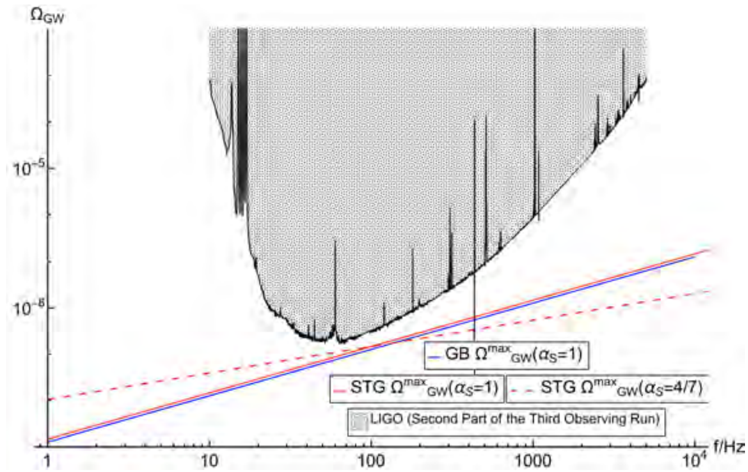

Рис. 1. Energy density of relic gravitational waves of the present models for different values of the post-inflationary matter state parameter in comparison with the region of operation of the LIGO gravitational-wave antenna [14]

it is not hard to obtain dependence between $f_{\rm RD}$ and parameter of matter state w. At 100Hz LIGO sensitivity is limited by dimensionless value $\Omega_{\rm GW} \lesssim \frac{1}{h^2}10^{-9}$ [14] (Fig.1) i.e.

$$f_{\rm RD}(w) = 100 \cdot \left(\frac{h^2 \cdot \Omega_{\rm GW}(100{\rm Hz})}{10^{-15} \cdot r}\right). \tag{1.3}$$

The cutoff frequency of the relic gravitational-wave background spectrum $f_{\rm cutoff}$ can be estimated taking into account the integral restriction on the energy density contained in relic gravitational waves [13]

$$\int_{f_{\rm BBN}}^{f_{\rm cutoff}} \Omega(f)\frac{df}{f} \lesssim 1 \times 10^{-6}, \tag{1.4}$$

where $f_{\rm BBN} < f_{\rm RD} < f_{\rm cutoff}$, $f_{\rm BBN} \simeq 1.8 \times 10^{-11}$Hz is the frequency of the mode corresponding to the size of the Universe, when primordial nucleosynthesis started. Given (1.1) and (1.4) it is not hard to obtain

$$f_{\rm cutoff}(w) \leq f_{\rm RD}(w)\left(\alpha_S \left[\frac{1 \times 10^{-6}}{1.27 \times \Omega^0_{\rm GW}} - \frac{1}{1.27} ln\left(\frac{f_{\rm RD}(w)}{f_{\rm BBN}}\right)\right] + 1\right)^{\frac{1}{\alpha_S}} \tag{1.5}$$

this dependency allows us to evaluate the maximal possible energy density for given frequency of relic gravitational waves (or in other way the maximal energy density for given state parameter of post-inflationary matter of the Universe) which in it's turn allows evaluate the possibility of direct detection based on detectors sensitivity.

2. Detectors under consideration

First experimental scheme under consideration is one where detection is provided by the response of Gaussian beam (2.1) to high-frequency relic gravitational waves [15]

$$\psi = \frac{\psi_0}{\sqrt{1+(z/f)^2}}\left(-\frac{r^2}{W^2}\right) \exp\left[i\left((k_e z - \omega_e t) - tan^{-1}\frac{z}{f} + \frac{k_e r}{2R} + \delta\right)\right], \tag{2.1}$$

where ψ is the electric field, $r^2 = x^2 + y^2$, $k_e = 2\pi/\lambda_e$, $f = 2\pi W_0^2/\lambda_e$, $W = W_0\left[1+(z/f)^2\right]^{1/2}$, $R = z + f^2/z$, ψ_0 - maximum amplitude of the electric field, W_0 - beam radius, δ - phase additive. The following parameters are realized in the detector under analysis $W_0 = 0.05$m, $l = 0.1$m, $l_0 = 0.3$m, $\psi_0 = 3 \times 10^5$V/m, $\hat{B}_y^{(0)} = 30$T (constant magnetic field, applied to the region of space $-l/2 < z < l/2$).

As it is shown [15], the photon flux resulting from the interaction between the gravitational wave and the Gaussian beam is estimated to be

$$S^{\phi|(1)} = \frac{1}{\mu_0}\left(\tilde{E}_r^{(1)}\tilde{B}_z^{(0)}\right) = -\frac{1}{\mu_0}\left(\tilde{E}_x^{(1)}\tilde{B}_z^{(0)}\right)\cos\phi - \frac{1}{\mu_0}\left(\tilde{E}_y^{(1)}\tilde{B}_z^{(0)}\right)\sin\phi. \tag{2.2}$$

Above $S^{\phi|(1)}$ is the first order tangential photon flux, generated by perturbed electric field $\tilde{E}_r^{(1)}$ and constant magnetic field $\tilde{B}_z^{(0)}$ pointed radially and axially accordingly. In the case of $\omega_e = \omega_g$, and when considering the amplitude of the cross-polarisation of the gravitational wave in the plane $z = 0$, the average photon flux $S^{\phi|(1)}$ can be estimated as

$$\langle S_\times^\phi\rangle_{\omega_e=\omega_g}^{(1)} = \frac{h_\times \hat{B}_y^{(0)}\psi_0 lr}{4\mu_0 W_0^2} exp\left(-\frac{r^2}{W_0^2}\right)\sin^2\phi. \tag{2.3}$$

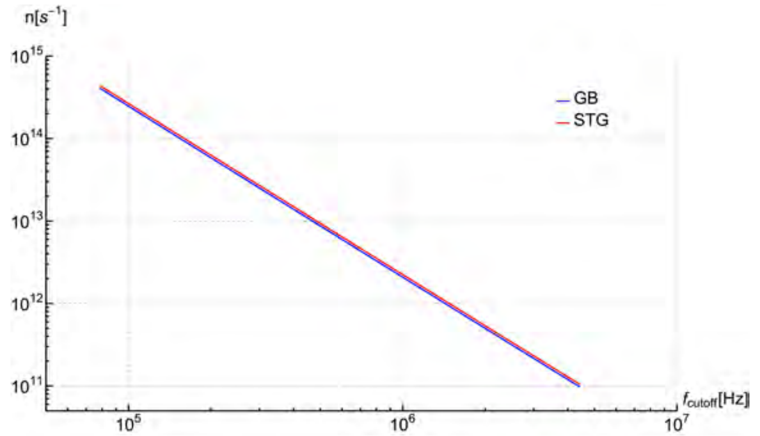

Рис. 2. Number of photons per second generated by the interaction of a Gaussian beam with a gravitational wave, for different cutoff frequencies $f_{\text{cutoff}}(w)$, corresponding to different values of the state parameter of matter in the post-inflationary universe.

The number of generated photons per second in this case can be estimated as

$$n_\phi = \frac{1}{\hbar\omega_e}\int_0^{W_0}\int_{-l/2}^{l_0}\langle S_\times^\phi\rangle_{\omega_e=\omega_g,\phi=\pi/2}^{(1)} dzdr. \tag{2.4}$$

The theoretical photon formation frequency Fig.2 is presented for the gravitational wave frequency corresponding to the cutoff frequency, i.e., for each frequency the maximum permissible (taking into account the integral restriction (1.4)) amplitude of relic gravitational waves is taken. The photon formation frequency, as it is easy to see, at 4.4×10^6Hz is $n_\phi|_{4DEGB} \approx n_\phi|_{STG} \approx 10^{11}$Hz.

As it was shown by Mitskievich and Nesterov [16] during the propagation of gravitational and electromagnetic waves in parallel, the production of phase-shifted photons in the electromagnetic waves does not occur. Similarly, when the gravitational wave propagates perpendicularly to the plane of EM wave propagation, a phase shift is expected in the electromagnetic wave, which can be estimated as

$$\Delta\alpha = h\,(\Lambda - \sin[\Lambda])\sin[\Lambda - \delta], \tag{2.5}$$

where $\Lambda = \omega_g L/c$, h - amplitude of gravitational wave, ω_g - circular frequency of the gravitational wave, L - effective size of the space at which the gravitational wave interacts with the electromagnetic wave, c - speed of light, δ - source wave phase. The geometric phase shift for the considered detector configuration is $\sim 2 \times 10^{-35}$ at 4.4×10^6Hz, which renders it impossible to record gravitational waves at laboratory-sized facilities. According to this, although the value $n_\phi|_{4DEGB} \approx n_\phi|_{STG} \approx 10^{11}$Hz is presented, the generated photons cannot be detected because of their small phase shift in respect to the alternating electromagnetic field available in the detector.

The second case considers a setup based on the modified Gertsenshtein effect, where it is implied that the gravitational wave interacts with the electromagnetic field inside a solenoid, where the magnetic field $\mathbf{B}^{(0)}$ is a superposition of the DC and AC components, namely [17]

$$\mathbf{B}^{(0)} = \overline{\mathbf{B}}^{(0)}(\mathbf{x}) + \tilde{\mathbf{B}}^{(0)}(\mathbf{x},t) = \begin{pmatrix} 0 \\ B_y^{(0)} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ -\tilde{B}_y^{(0)}\cos(\omega_B t) \\ 0 \end{pmatrix}, \tag{2.6}$$

where ω_B is the frequency of the alternating magnetic field oscillation.

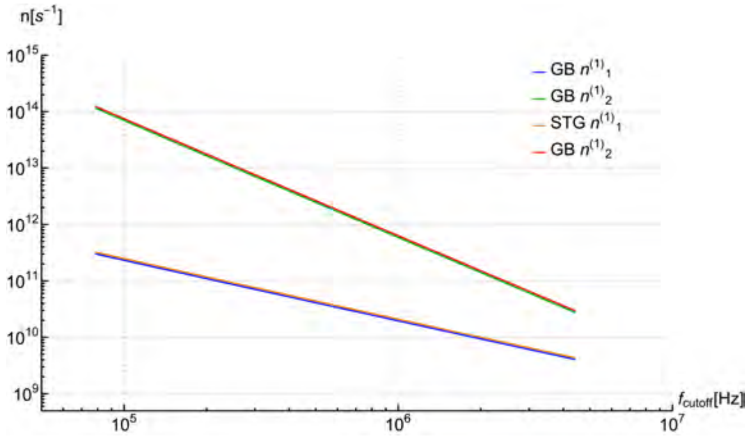

Рис. 3. Frequency of appearance of photons generated by the inverse Gertsenshtein effect.

As shown in [18], in the configuration when $\omega_g = \omega_B$ photon generation occurs at both the resonant and the dual frequency of the GW with characteristic frequency of formation

$$n_1^{(1)} = \frac{B_y^{(0)}\tilde{B}_y^{(0)} l \Xi}{4\mu_0\hbar} h_+, \tag{2.7}$$

and

$$n_2^{(1)} = \frac{3\left(\tilde{B}_y^{(0)}\right)^2 c\Xi}{4\mu_0\hbar\omega_g} h_+, \tag{2.8}$$

correspondingly, where l is the effective distance traveled by the GW in the solenoid electromagnetic field, Ξ is the area of the detector located so that the normal to its surface is $\mathbf{n}_\Xi \parallel \mathbf{k}_g$. In particular, we consider the setup in which the conditions $B_y^{(0)} = 30$T, $\tilde{B}_y^{(0)} = 0.1 B_y^{(0)}$, $l = 0.1$m, $\Xi = 0.05\text{m}^2$ are realized. Here teoretical photon formation frequency for $\omega_g = 2\pi \times 4.4 \times 10^6$Hz is $n_1^{(1)}\Big|_{\text{STG}} \simeq n_1^{(1)}\Big|_{\text{4DEGB}} \simeq 4.1 \times 10^9$Hz and $n_2^{(1)}\Big|_{\text{STG}} \simeq n_2^{(1)}\Big|_{\text{4DEGB}} \simeq 2.8 \times 10^{10}$Hz (Fig.3).

The geometric phase shift of the generated photons (2.5) is $\sim 4.5 \times 10^{-35}$ making detection impossible despite the fact that antennas sensitivity [17] defined by minimal detectable GW amplitude (2.9) is enough for registration Fig.4.

$$h^{min} = \frac{1}{2\mathbb{S}}\left[\frac{\hbar\omega}{\Xi\tau} + 2\frac{\hbar\omega^2\Delta\omega}{2\pi c^2}\frac{1}{e^{\hbar\omega/k_B T}-1} + \sqrt{\left(\frac{\hbar\omega}{\Xi\tau}\right)^2 + \frac{4}{\Xi\tau}\frac{\hbar^2\omega^3\Delta\omega}{2\pi c^2}\frac{1}{e^{\hbar\omega/k_B T}-1}}\right], \tag{2.9}$$

where $\mathbb{S} \approx \hbar\omega_g(n_1^{(1)} + n_2^{(1)})/h$, detector responce time $\tau = 10 \times 2\pi/\omega_g$, $\Delta\omega$ represents detector's sensitivity bandwidth.

Weak interacting small particle (WISP) detectors can also be considered as detectors of gravitational waves, since part of their design is well suited for registration of HFGW based on the inverse Gertsenshtein effect (in literature also appears as graviton-photon conversion (GRAPH)) [19].

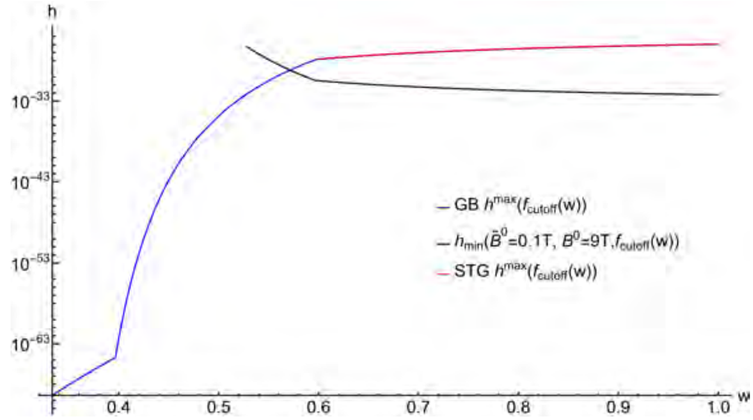

Рис. 4. The minimum GW amplitude h_{min} required for registration based on the modified inverse Gertsenshtein effect and the maximum relic gravitational wave amplitude h^{max} depending on the parameter of the post-inflationary matter state of the universe.

In this paper we consider both already realized WISP detectors (ALPS [20], OSQAR [21], CAST [22]) and promising ones (ALPS IIc [23], JURA [24], IAXO [25]). The sensitivity of detectors ALPS, OSQAR, CAST can be rated as

$$h_{min}(f) \simeq 1.16 \times 10^{-16} \times \left(\frac{1\text{T}}{B}\right)\left(\frac{1\text{m}}{L}\right)\sqrt{\left(\frac{N_{\text{exp}}}{1\text{Hz}}\right)\left(\frac{1\text{m}^2}{A}\right)\left(\frac{1\text{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma}\right)}. \tag{2.10}$$

The above experiments were ultimately aimed at registration of N_{exp} photons in the frequency range Δf on detectors with a quantum efficiency ϵ_γ and a cross-sectional area of the photon generation region A. For the experimental setups considered above, these characteristics are given in Table 2, the quantum efficiency of the CCD matrices used as a function of the frequency of the incident radiation - in Fig.5

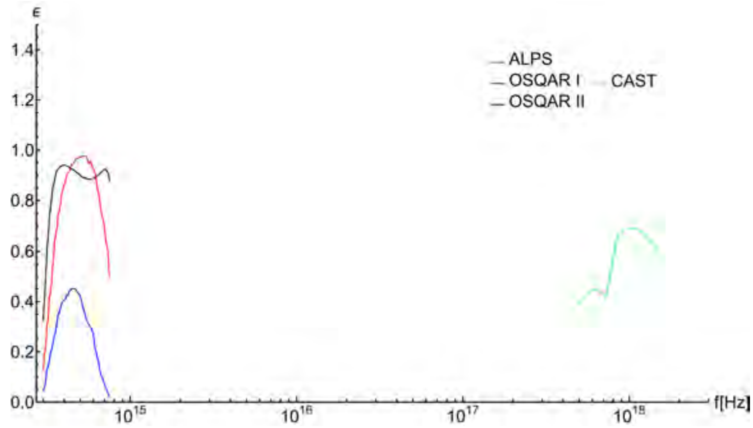

Рис. 5. Quantum efficiency of ALPS [20], OSQAR (2 matrices) [21] and CAST [22] CCD matrices used in the experiments as a function of radiation frequency.

The sensitivity of prospective detectors ALPS IIc, JURA, IAXO can be estimated as [19]

$$h_{min}(f) \simeq 2.8 \times 10^{-16}\left(\frac{1\text{T}}{B}\right)\left(\frac{1\text{m}}{L}\right)\sqrt{\left(\frac{1}{\mathcal{F}}\right)\left(\frac{N_{dark}}{1\text{Hz}}\right)\left(\frac{1\text{m}^2}{A}\right)\left(\frac{1\text{Hz}}{\Delta f}\right)\left(\frac{1}{\epsilon_\gamma}\right)}. \tag{2.11}$$

Table 2 presents all the necessary detector characteristics required for calculation. As the plants in this case have not yet been realized, we assume to use the theoretical value of quantum efficiency at wavelength 1024nm and the number of thermal photons N_{dark} instead of experimental values for quantum efficiency and frequency of photon formation.

	$N_{\exp}$(mHz)	A(m^2)	B(T)	L(m)	Δf(Hz)
ALPS	0.61	0.5×10^{-3}	5	9.00	9×10^{-14}
OSQAR I	1.76	0.5×10^{-3}	9	14.3	5×10^{-14}
OSQAR II	1.14	0.5×10^{-3}	9	14.3	1×10^{-15}
CAST	0.15	2.9×10^{-3}	9	9.26	1×10^{-18}

Таблица 1. Characteristics of the experimental setups ALPS [26], OSQAR (2 matrices) [27] and CAST [28], necessary for estimation of the minimum detectable GW amplitude on them

	$\epsilon_\gamma(\lambda = 1064\text{nm})$	N_{dark}(Hz)	A(m^2)	B(T)	L(m)	$\mathcal{F}$
ALPS IIc	0.75	$\approx 10^{-6}$	$\approx 2 \times 10^{-3}$	5.30	120	40 000
JURA	1	$\approx 10^{-6}$	$\approx 8 \times 10^{-3}$	13.0	960	100 0000
IAXO	1	$\approx 10^{-4}$	≈ 21	2.50	25	-

Таблица 2. Characteristics of the experimental facilities ALPS IIc [23], JURA [24] and IAXO [25] required for estimation of the minimum detectable GW amplitude on them

Thus, as can be seen in Fig.6, none of the considered WISP detectors has sensitivity for HFGW registration.

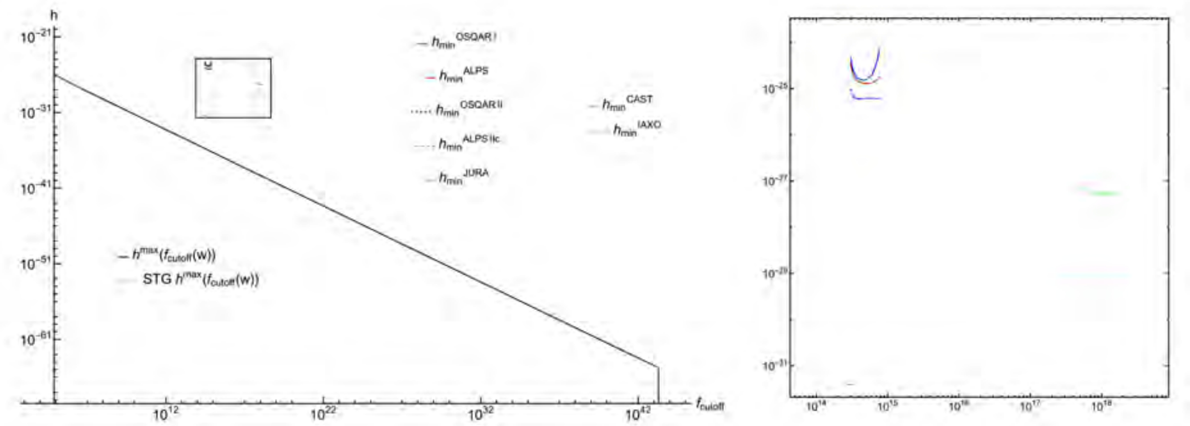

Рис. 6. Maximum amplitude of relic gravitational waves (h^{max}) and minimum GW amplitude required for registration at different WISP detectors (h_{min}).

The last discussed method of registering relic gravitational waves is gravitational-optical resonance. Gravitational-optical resonance in a multibeam interferometer is possible under the condition that an integer number of half-waves of GWs fit into the resonator length [29, 30]:

$$L = \frac{nc}{2f_g}, \quad n = 1, 2, 3, ..., \tag{2.12}$$

where L is the length of the resonator, c is the speed of light.

With such a resonator configuration that $L = c/2f_g$, the energy response of the Fabry-Perot interferometer to the passage of a gravitational wave can be estimated as [29, 30]

$$\delta W(t) = \frac{\mathcal{F}L}{\lambda_e} W_0 h_c(t), \tag{2.13}$$

where δW is the change in laser power transmitted by the interferometer, $\mathcal{F}$ is the quality factor of the Fabry-Perot interferometer, λ_e is the laser wavelength, and W_0 is the laser power at the input to the interferometer.

In terms of the spectral density of variation of the power generated by the passage of a GW through an interferometer, (2.13) can be written as [12]

$$S_{\delta W}(f) = \frac{\mathcal{F}^2 L^2}{\lambda_e^2} W_0^2 S_h(f), \tag{2.14}$$

where $S_h(f)$ is the spectral density of the gravitational-wave radiation. Taking into account the possibility of averaging the spectral density of the detector response over the time period T, it is shown [12] that for the described detection method, the minimum amplitude of the registered GW is estimated as follows

$$h_c = 2\left(\frac{\mathcal{F}}{T}\right)^{1/4} \left(\frac{\lambda_e}{\mathcal{F} W_0 c}\right) \sqrt{\tilde{S}_{\delta W}(f)} f^{5/4}, \tag{2.15}$$

where

$$\tilde{S}_{\delta W}(f) = \frac{\sqrt{cT}\mathcal{F}^{3/2} L^{3/2}}{\lambda_e^2} W_0^2 S_h(f) \tag{2.16}$$

is the time-averaged amplified spectral density of the Fabry-Perot interferometer response.

The shot photon noise, which determines the lower limit of detector sensitivity, is defined as [12]

$$h_{\text{Shot}} = 2f\left(\frac{\lambda_e}{\mathcal{F} W_0 c}\right) \left[\frac{\tilde{S}_{\delta W}(f)}{T}\right]^{1/2}. \tag{2.17}$$

For the setup in which the conditions $\lambda_e = 1.064\mu$m, $\mathcal{F} = 10^6$, $W_0 = 10^3$W are realized with signal averaging time $T = 1411$s and such a photodetector (DET10N2) that is able to detect $\tilde{S}_{\delta W} = 4 \times 10^{-28} W^2/Hz$, with $L = 27.5$m cavity is considered: Fig.7.

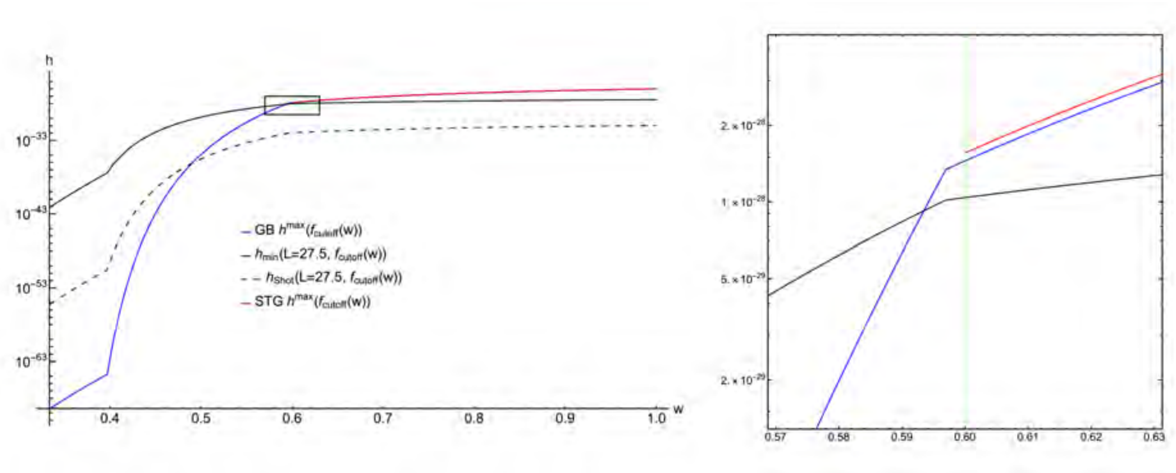

Рис. 7. The minimum detectable amplitude (black solid line) and limitation on the detector sensitivity from below, taking into account the shot photon noise (black hatched line), for the considered setup and the maximum GW amplitude depending on the parameter of the post-inflationary matter state of the Universe w. The green hatched line corresponds to 4.4 MHz.

From the presented analysis, it can be concluded that the high-frequency gravitational-optical resonance presents the most promising experimental scheme for detecting HFGWs. The gravitational-wave antenna based on the modified inverse Gertsenshtein effect is the next most promising option, provided that we can solve the issue of the small geometrical phase-shift between the generated and existing photons in the detection area.

3. Conclusion

Thus, when evaluating the possibility of directly registering relic gravitational waves, it has been established that detecting their interaction with a Gaussian beam at the frequency of 4.4MHz is impossible due to the small phase shift between the photons (with theoretical formation frequency $n_\phi \simeq 10^{11} s^{-1}$) of the Gaussian beam and those converted as a result of the GW-EM interaction. It was estimated that the theoretical frequency of photon formation, based on the modified inverse Herzenstein effect, is approximately $4.1 \times 10^9 s^{-1}$ for $\omega_e = \omega_g$, and $2.8 \times 10^{10} s^{-1}$ for $\omega_e = 2\omega_g$ at $\omega_g = 8.8\pi \times 10^6$rad/s. The considered setup based on the modified Herzenstein effect sets also a small $\left(\Delta\alpha \sim 4.5 \times 10^{-35}\right)$ geometric phase shift, which makes it technically impossible to register GW signals. Also has been shown that it is impossible to detect relic gravitational waves directly using the already created nor prospective WISP detectors. This is because, for the best of them, the minimum necessary amplitude of relic GW for detection is higher than predicted by the model by five orders of magnitude.

Among the considered installations for direct experimental verification of the correctness of the considered modifications of GR, it has been established that only the detector based on gravitational-optical resonance has the necessary sensitivity and is technically feasible (mirror mass is $M \simeq 6.4 \times 10^{-7}$kg, signal averaging time is $T \simeq 1411$s, cavity length is $L \simeq 27.5$m).

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