The cosmological and astrophysical sources of MHz gravitational waves

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The sources of MGz gravitational waves

- The early universe
- Primordial black holes
- Exotic compact objects
- Topological defects

Some publications: Analysis of cosmological models

1. S. Chervon, I. Fomin, V. Yurov, A. Yurov, Scalar Field Cosmology, Series on the Foundations of Natural Science and Technology, Vol. Volume 13. 13 (WSP, Singapur, 2019). https://doi.org/10.1142/11405.

2. S.V. Chervon, I.V. Fomin, A. Beesham, Eur. Phys. J. C 78, 301 (2018). The method of generating functions in exact scalar field inflationary cosmology. https://doi.org/10.1140/epjc/s10052-018-5795-z.

3. I.V. Fomin, S.V. Chervon, Eur. Phys. J. C 78, 918 (2018). Non-minimal coupling influence on the deviation from de Sitter cosmological expansion. https://doi.org/10.1140/epjc/s10052-018-6409-5.

4. I.V. Fomin, S.V. Chervon, Phys. Rev. D 100, 023511 (2019). Reconstruction of general relativistic cosmological solutions in modified gravity theories. https://doi.org/10.1103/PhysRevD.100.023511.

5. S.V. Chervon, I.V. Fomin, E.O. Pozdeeva, M. Sami, and S.Yu. Vernov, Phys. Rev. D 100, 063522 (2019). Superpotential method for chiral cosmological models connected with modified gravity. https://doi.org/10.1103/PhysRevD.100.063522.

6. I.V. Fomin, S.V. Chervon, A.V. Tsyganov, Eur. Phys. J. C 80, 350 (2020). Generalized scalar-tensor theory of gravity reconstruction from physical potentials of a scalar field. https://doi.org/10.1140/epjc/s10052-020-7893-y.

7. I.V. Fomin, Eur. Phys. J. C 80, 350 (2020). Gauss-Bonnet term corrections in scalar field cosmology. https://doi.org/10.1140/epjc/s10052-020-08718-w.

Some publications: The detection of the high-frequency GWs

1. Fomin I.V., Chervon S.V., Morozov A.N. Gravitatsionnye volny rannej Vselennoj [Gravitational waves of the early Universe]. Moscow: BMSTU Publ., 2018. 154 p.

2. Gladyshev V.O., Morozov A.N. Low-frequency optical resonance in a multiple-wave Fabry- Perot interferometer. Pisma v Zhurnal Tekhnicheskoj Fiziki [Technical Physics Letters], 1993, vol. 19, no. 14, pp. 38-42.

3. Esakov A.A., Morozov A.N., Tabalin S.E., Fomin I.V. Application of low-frequency optical resonance for detection of high-frequency gravitational waves. Vestnik MGTU im. N.E. Baumana. Ser. Estestvennye nauki [Herald of the BMSTU. Ser. Natural Sciences], 2015, no. 1, pp. 26-35.

4. Golyak I.S., Dvoruk S.K., Esakov A.A., Morozov A.N., Pustovoit V.I., Strokov M.A., Tabalin S.E. Development and creation model to registration high-frequency gravitational waves. Fizicheskie osnovy priborostroeniia [Physical Bases of Instrumentation], 2016, vol. 5, no. 3, pp. 40-47. DOI: 10.25210/jfop-1603-040047

5. I.S. Golyak, A.A. Esakov, A.N. Morozov,A.L. Nazolin, S.E. Tabalin, I.V. Fomin Information-measuring complex for registration high frequency gravitational waves. Radiostroenie [Radio Engineering], 2021, no. 2, pp. 13-23. DOI: 10.36027/rdeng.0221.0000190.

6. Fomin I.V., Morozov A.N., The high-frequency gravitational waves in exact inflationary models with Gauss-Bonnet term. 2016, Journal of Physics: Conference Series 798 (1), 012088. https://doi.org/10.1088/1742-6596/798/1/012088.

Relic gravitational waves in cosmological models

• Inflation ⇒ cosmological perturbations ⇒ large-scale structure formation (by scalar perturbations) and relic gravitational waves (tensor perturbations)

• Scalar and tensor perturbations ⇒ CMB anisotropy and polarization ⇒ observational constraints

• For the case of GR these constraints restrict the possible types of potentials of inflaton

• For the case of modified gravity theories the models with arbitrary potentials can satisfy the observational constraints

• Restriction on modified gravity theories $|c_g - 1| \leq 5 \times 10^{-16}$

(detection of gravitational waves from neutron star merging)

The main parameters of relic GWs

The frequency f, the energy density

$$\Omega_{gw}(f) = \frac{1}{\rho_c} \frac{d\rho_{gw}}{d\log f} \qquad \rho_c = \frac{3H_0^2}{8\pi G}$$

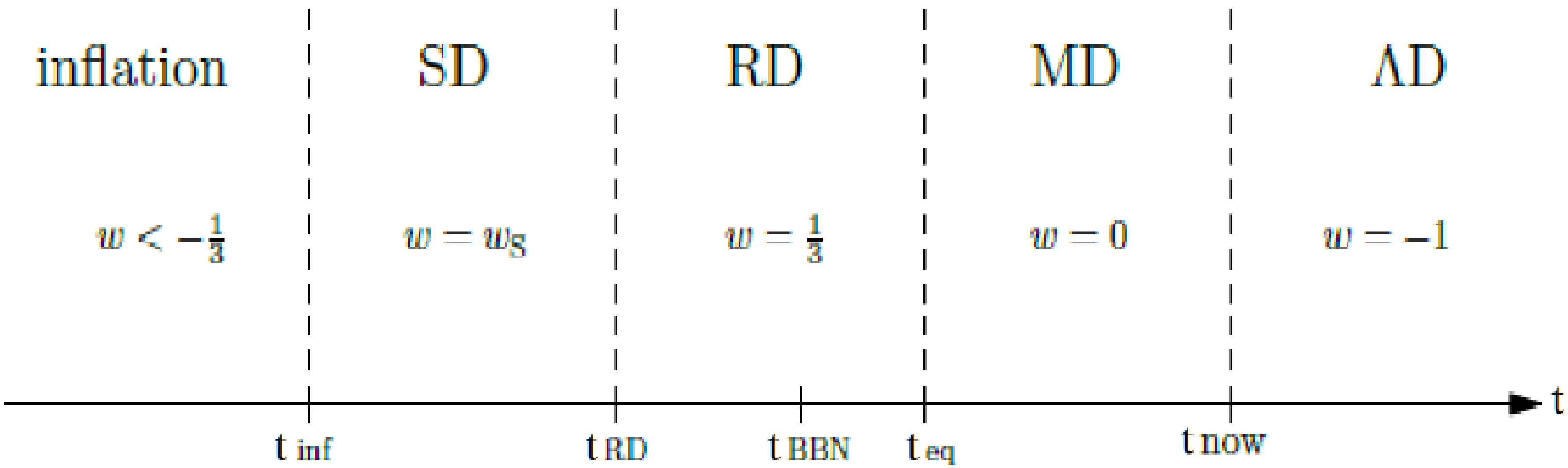
The dimensionless amplitude

$$h_{gw}(f) = 1.3\times 10^{-16}\sqrt{\Omega_{gw}(f)h_0^2}\left(\frac{Hz}{f}\right) \qquad h_0 \simeq 0.7$$

The BBN constrain

$$\int_{f_{BBN}}^{f_*} \Omega_{gw}(f)h_0^2 \simeq 1.12\times 10^{-6}$$

The stages of the universe's evolution



The spectrum of relic GWs at the modern era

$$\Omega_{GW}\left(f\right) \simeq 2\times 10^{-15}\times r\times \begin{cases} 1 & , \quad f \ll f_{RD} \\ 1.27\times\left(\dfrac{f}{f_{RD}}\right)^{2\left(\frac{3w_S-1}{3w_S+1}\right)} & , \quad f \gg f_{RD} \end{cases}$$

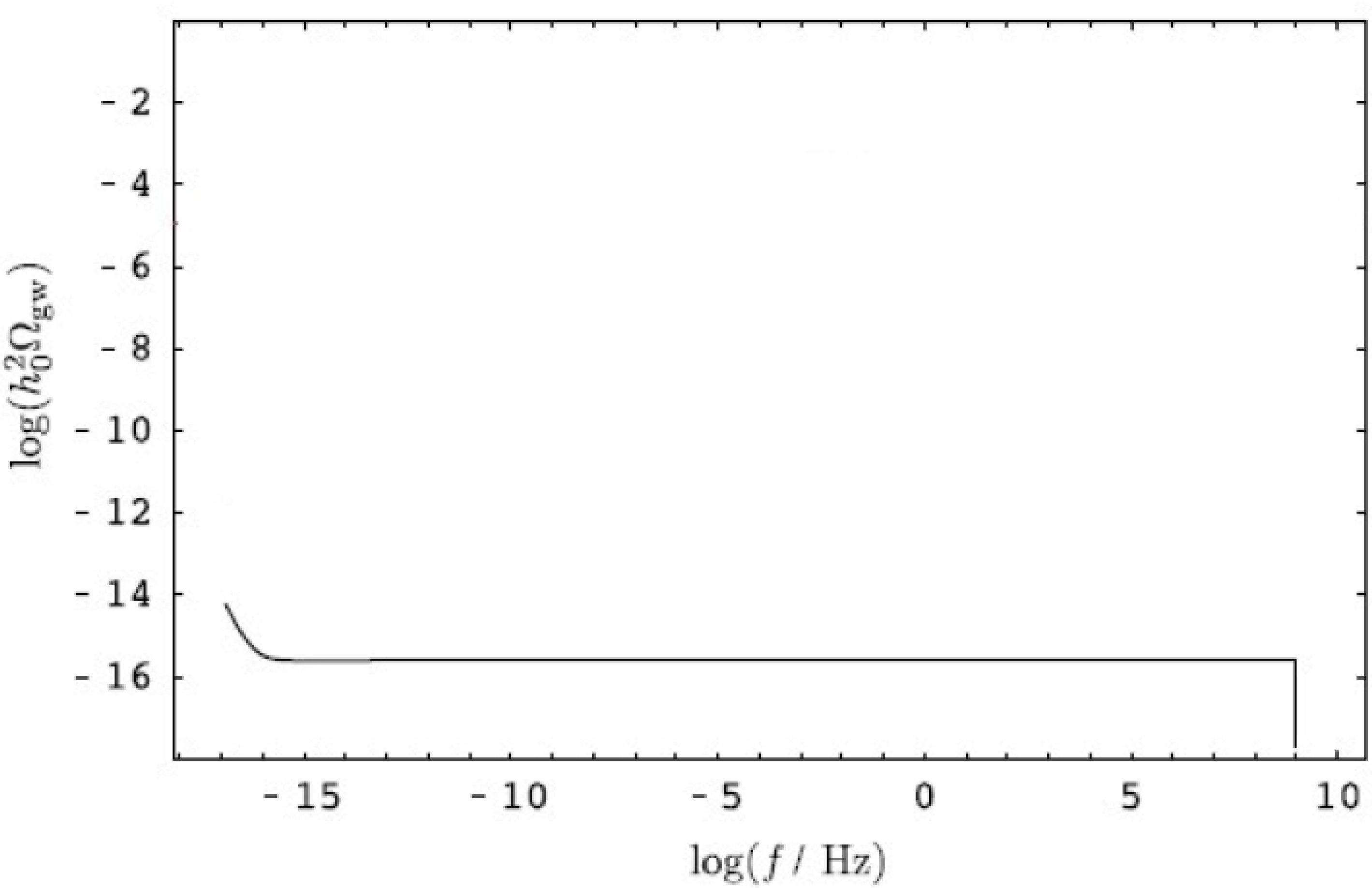
The value of tensor-to-scalar ratio and frequency of relic GWs at the radiation domination era depends on the type of the cosmological model

$$0 < r \leq 0.065 \qquad\qquad f_{RD} \sim 10^{-11} - 10^{-9}\, Hz$$

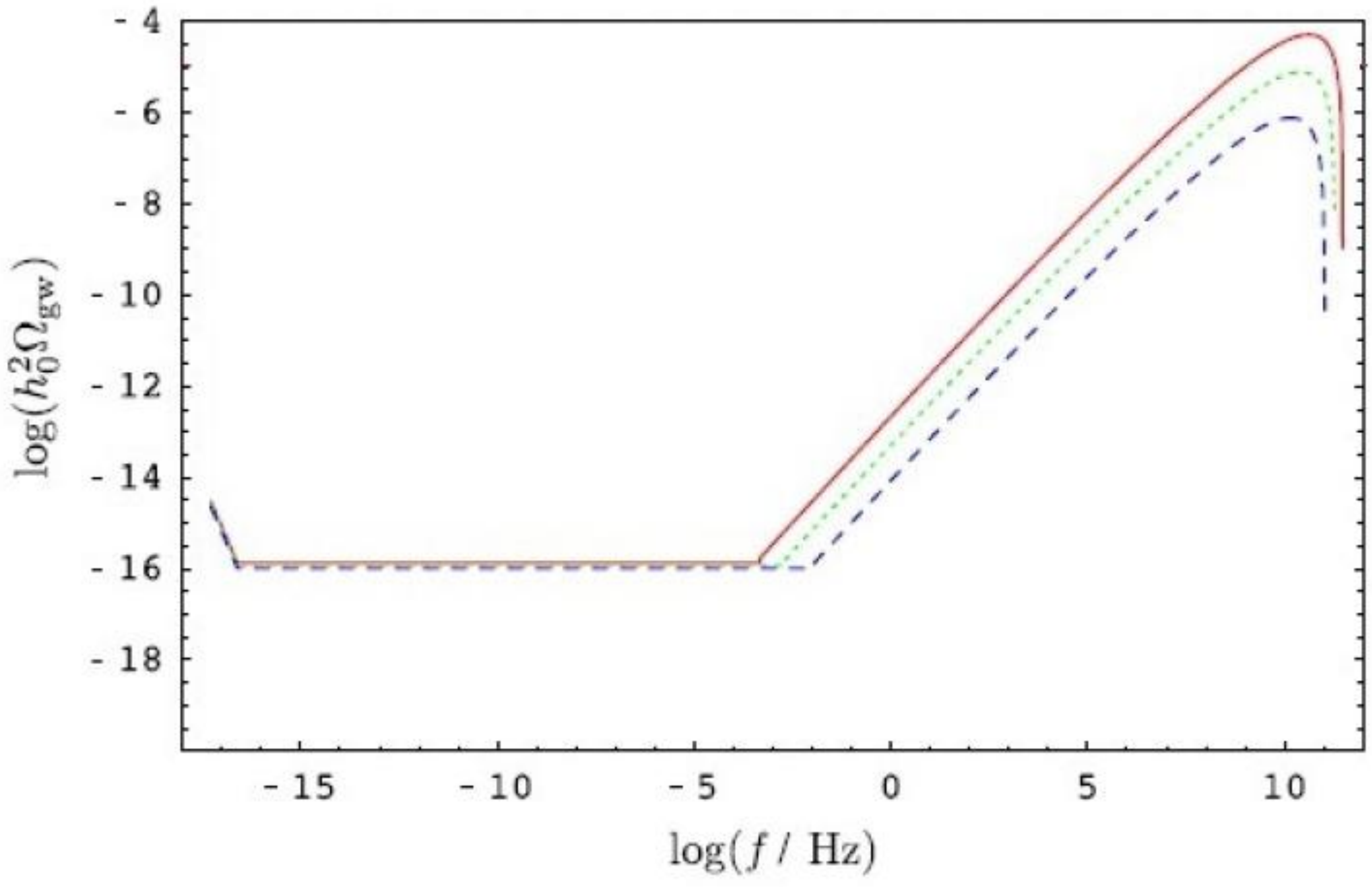
The state parameter for SD stage is $\dfrac{1}{3} < w_S \leq 1$

For standard slow-roll inflation one has $w_S = w_{RD} = \dfrac{1}{3}$ (SD stage is absent).

The spectrum of relic GWs for standard slow-roll inflation



The spectrum of relic GWs for inflation with additional SD stage



Primordial black holes

- Primordial binaries

$$h_{max} \approx 1.7\times10^{-22}\left(\frac{m_{PBH}}{M_{\odot}}\right)^{0.7} \approx 4.2\times10^{-20}\left(\frac{Hz}{f}\right)^{0.7}$$

- Capture in primordial BH haloes

$$h_{max} \approx 2.8\times10^{-23}\left(\frac{m_{PBH}}{M_{\odot}}\right) \approx 6.1\times10^{-20}\left(\frac{Hz}{f}\right)$$

with frequencies from kHz up to GHz.

Exotic compact objects: boson star binaries

For inspiral phase

$$f \simeq C^{3/2}\left(\frac{6\times10^{-3}M_{\odot}}{M}\right)10^{6}\ Hz$$

$C = GM/Rc^2$ is the compactness parameter.

The GW amplitude for a boson star binary formed by equal mass objects is

$$h_{gw} \simeq 1.72\times10^{-20}\,C\left(\frac{M}{M_{\odot}}\right)\left(\frac{Mpc}{D}\right)$$

where D is the distance between the source and the observer.

The examples of the boson star models on the basis of modified gravity theories:
S. V. Chervon, J. C. Fabris, I. V. Fomin, Black holes and wormholes in f(R) gravity with a kinetic curvature scalar. 2021, Class. Quantum Grav. 38, 115005. https://doi.org/10.1088/1361-6382/abebf0.

Topological defects: Cosmic strings

A cosmic string loop oscillates relativistically under its tension and emits GWs in a series of harmonics with frequencies which depend only on the length of the loop L_S and the harmonic mode n.

The frequency of gravitational waves is

$$f_n = \frac{2nc}{L_S}, \quad n = 1,2,3,...$$

For the frequencies $f \sim 10^{-5} - 10^{9}$ Hz the spectrum of GWs is flat and the value of the energy density is estimated as follow

$$\Omega_{GW} \simeq 8 \times \Omega_{rad,0} \sqrt{\frac{G\mu}{\Gamma}} \leq 10^{-8}$$

where Gμ is the dimensionless tension of the string and Γ is the dimensionless total power emitted by the loop.

MHz gravitational waves detection

Application of gravitational-optical resonance in Fabry-Perot interferometers for detection of the high-frequency gravitational waves.

Gravitational-optical resonance in a multibeam interferometer occurs if the condition is fulfilled that an integer number of half-waves of gravitational radiation fits into the cavity length L, namely

$$f_n = \frac{nc}{2L}, \quad n = 1, 2, 3, ...$$

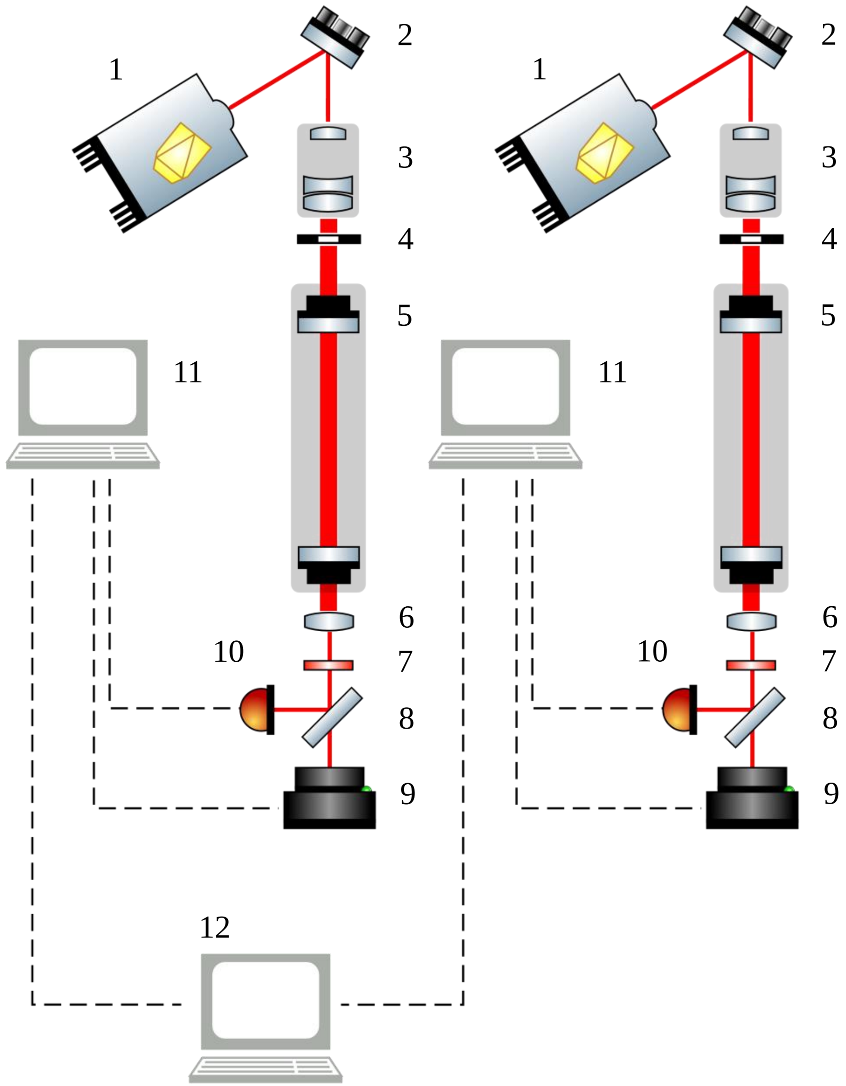
For n = 1, the relative variations in the power of laser radiation in the field of a gravitational wave

$$\frac{\delta W}{W} = \frac{QL}{\lambda_e} h_{gw}$$

The maximum sensitivity $\Omega_{GW}(f) \sim 10^{-8} - 10^{-6}$ can be achieved for GWs with frequencies of 5-10 MHz.

I.S. Golyak, A.A. Esakov, A.N. Morozov, A.L. Nazolin, S.E. Tabalin, I.V. Fomin Information-measuring complex for registration high frequency gravitational waves. Radiostroenie [Radio Engineering], 2021, no. 2, pp. 13-23. DOI: 10.36027/rdeng.0221.0000190.

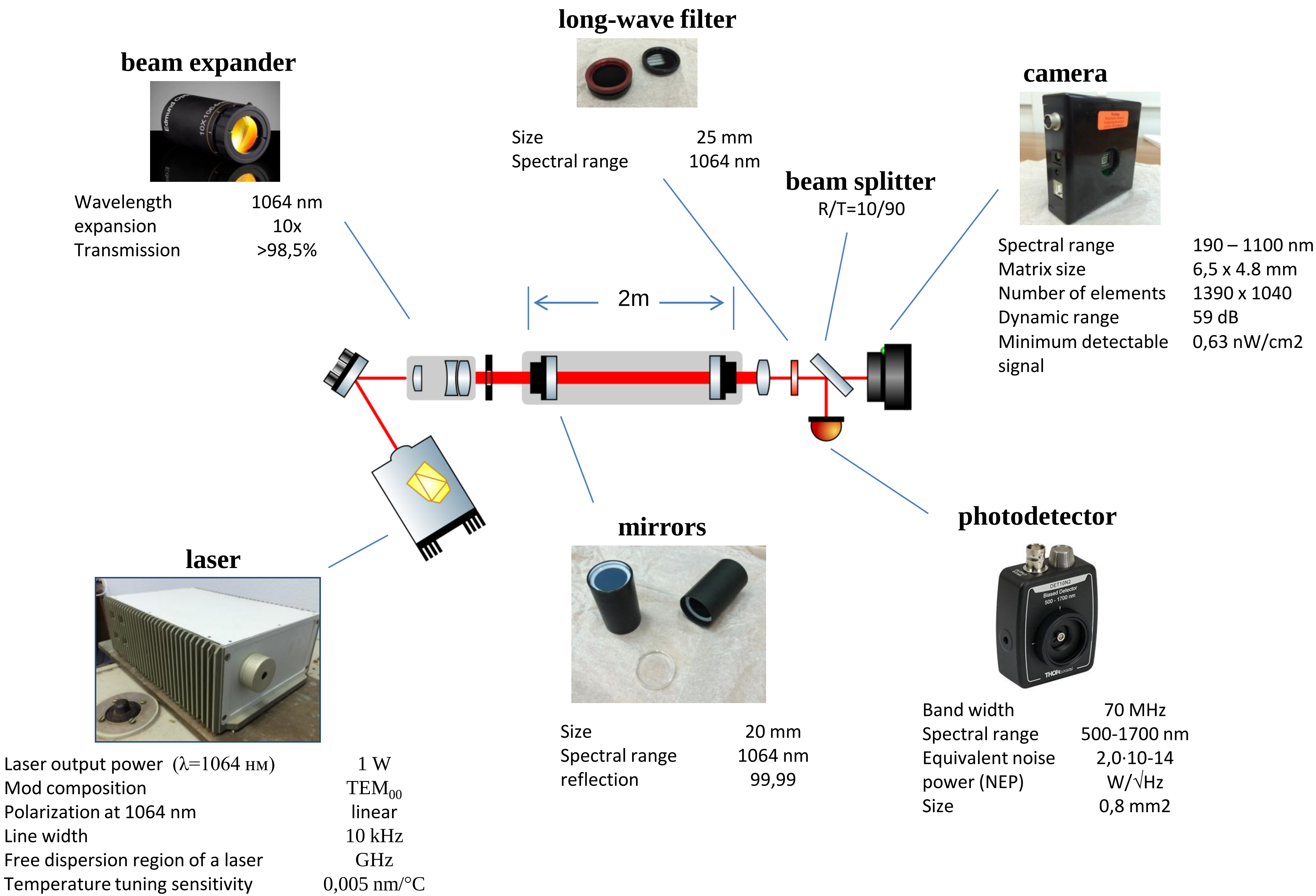
The developed scheme of the complex for testing the registration gravitational waves



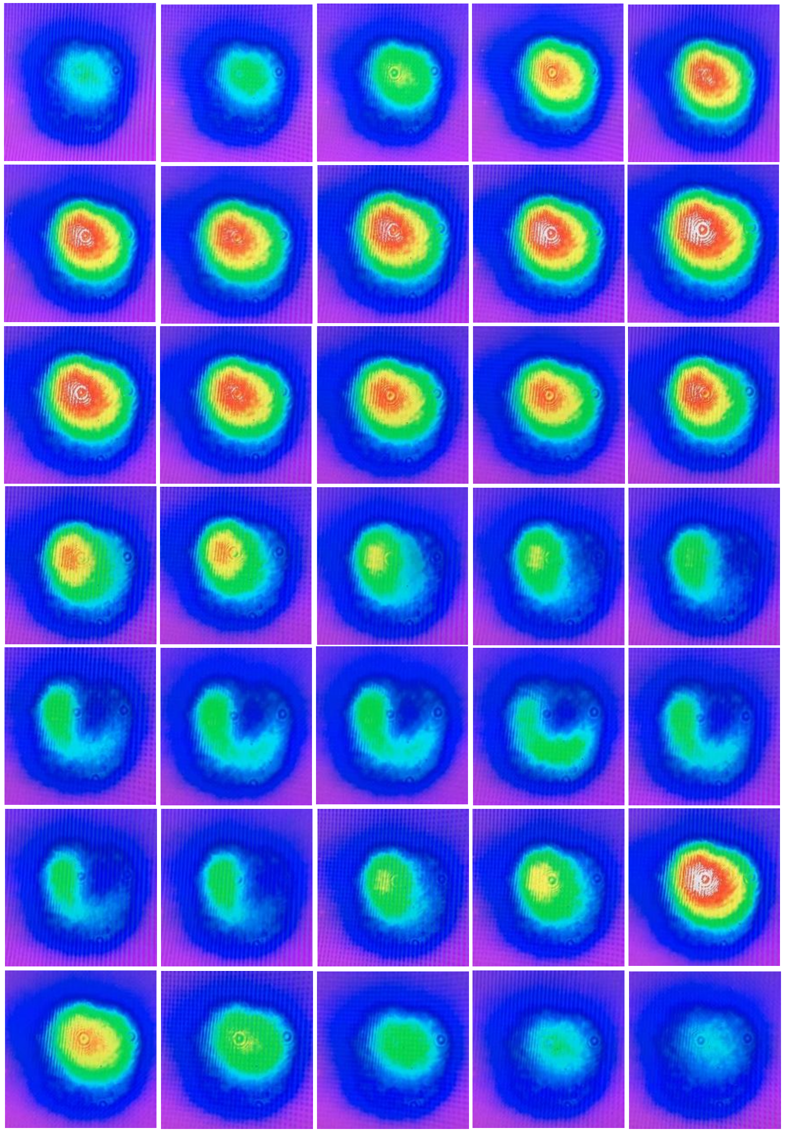
Main characteristics

Characteristics	**Value**
Cavity length	2 m
Pump laser wavelength	1064 nm
Laser power	1 W
Signal sampling frequency	till 20 MHz

1 – Nd:YAG laser1064 nm,
2 – mirror,
3 – beam expander,
4 – pinhole,
5 – Fabry-Perot interferometer ,
6 – focusing lens,
7 – long-wave filter,
8 – beam splitter,
9 – camera,
10 – photodetector DET10N2,
11 – data collection system,
12 – data processing system


beam expander
Wavelength 1064 nm
expansion 10x
Transmission >98,5%
long-wave filter
Size 25 mm
Spectral range 1064 nm
beam splitter
R/T=10/90
camera
Spectral range 190 – 1100 nm
Matrix size 6,5 x 4.8 mm
Number of elements 1390 x 1040
Dynamic range 59 dB
Minimum detectable signal 0,63 nW/cm2
2m
laser
Laser output power (λ=1064 нм) 1 W
Mod composition TEM00
Polarization at 1064 nm linear
Line width 10 kHz
Free dispersion region of a laser GHz
Temperature tuning sensitivity 0,005 nm/°C
mirrors
Size 20 mm
Spectral range 1064 nm
reflection 99,99
photodetector
Band width 70 MHz
Spectral range 500-1700 nm
Equivalent noise power (NEP) 2,0·10-14 W/√Hz
Size 0,8 mm2

Experimental research

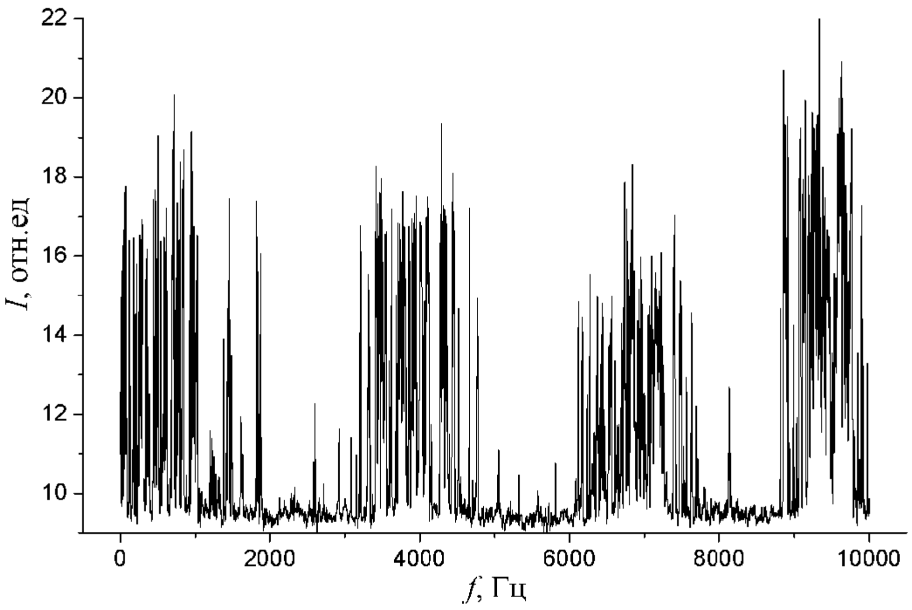


Images of the central spot recorded on a video camera for a short period of time. The signal measurement time was 3 s.

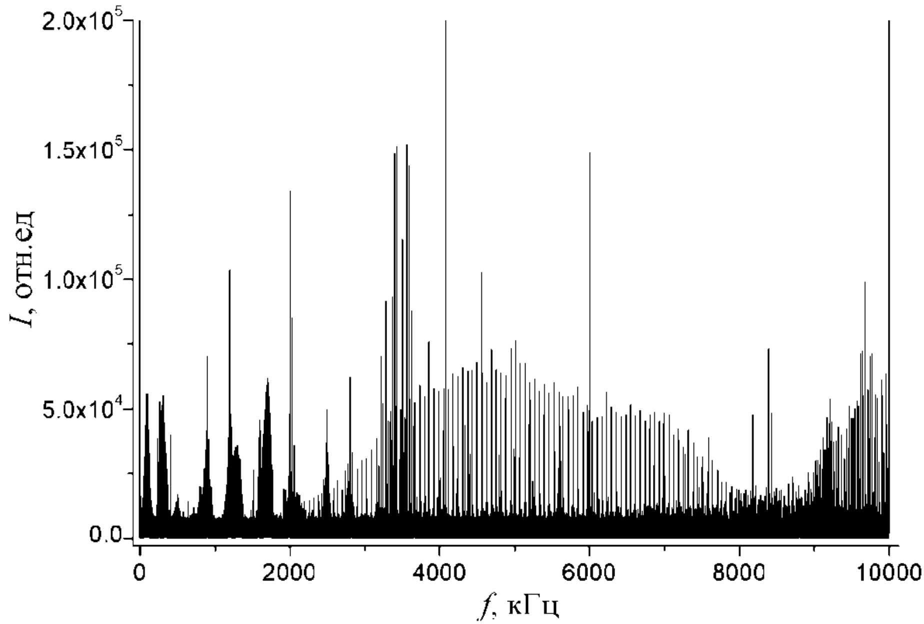
The temporal order of images goes from left to right and from top to bottom

Experimental research

Long-term signal recording on the photodetector with a frequency of 1 MHz. Duration 20 min.



Reconstructed spectrum of the signal



THANK YOU FOR ATTENTION!