Localization of gravitational waves as a test of gravitation theories

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Outline

Gravitation theories and polarization of gravitational waves

Einstein's geometrical approach:

Gravitational potentials: metric tensor of the curved Riemannian spacetime.

- **General Relativity** (GR, "geometrodynamics"), *Einstein (1916)*
  $\Rightarrow$ only tensor "plus" and "cross" GWs
- **Modified GR**: scalar-tensor metric theories, e.g. Brans-Dicke Theory
  reviews: Will (2014); Clifton et al. (2012)
  $\Rightarrow$ tensor and scalar GWs

Feynman's field approach:

Gravitational potentials: symmetric second rank tensor field in the flat Minkowski spacetime.

- **Field Gravitation Theory** (FGT, "gravidynamics"), *Feynman (1971)*
  modern reviews: Sokolov and Baryshev (1980); Baryshev (2017)
  $\Rightarrow$ tensor and scalar longitudinal GWs.

Sources and polarization of gravitational waves

Sources and polarization states of GWs

- **coalescing compact binaries** (CBC) $\Rightarrow$ tensor transverse GWs;
- **core-collapse supernovae** (CCSN):
  asymmetric $\Rightarrow$ tensor transverse GWs;
  spherically-symmetric $\Rightarrow$ scalar GWs.

Expected waveforms

In both cases – a sinusoidal waveform with changing frequency.

Polarization states in scalar-tensor theories of gravitation

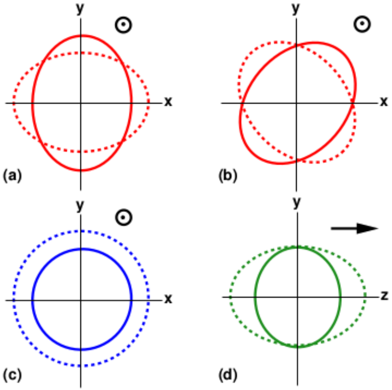


Рис.: Response of test masses on a polarization state of an incoming GW (Will (2014))

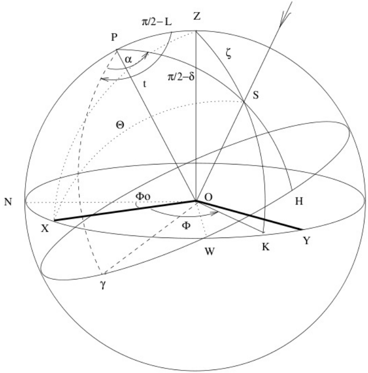


Рис.: Equatorial and horizontal coordinate systems of an interferometric antenna for a GW source S

Antenna-response functions of an interferometric antenna

A general strain of an incoming GW of different polarization states:

$$\bar{h} = F_{+}(\zeta,\Phi,\Psi)h_{+}(t) + F_{\times}(\zeta,\Phi,\Psi)h_{\times}(t) + F_{\mathrm{SL}}(\zeta,\Phi)h_{\mathrm{SL}}(t) + F_{\mathrm{ST}}(\zeta,\Phi)h_{\mathrm{ST}}(t) \quad (1)$$

Z is the zenith,
P – the northern pole,
γ defines the sidereal time,
α – the right ascension (RA), δ – the declination (DEC), ζ – the zenith angle. The reference direction of the detector is the direction OX with the azimuth Φ_0.

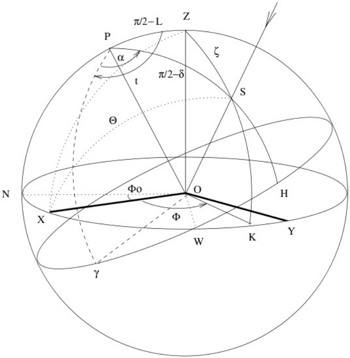


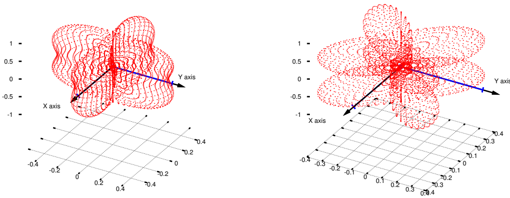
Рис.: Equatorial and horizontal coordinate systems of an interferometric antenna for a GW source S

Antenna-response functions on a tensor transverse GW

Antenna-response functions on tensor transverse "+" $F_+(\zeta, \Phi, \Psi)$ and "×" $F_\times(\zeta, \Phi, \Psi)$ GW of a two-arms interferometric antenna (Will (2014)):

$$F_+(\zeta, \Phi, \Psi) = \frac{1}{2}(1 + \cos^2 \zeta) \cos 2\Phi \cos 2\Psi - \cos \zeta \sin 2\Phi \sin 2\Psi \quad (2a)$$

$$F_\times(\zeta, \Phi, \Psi) = \frac{1}{2}(1 + \cos^2 \zeta) \cos 2\Phi \sin 2\Psi + \cos \zeta \sin 2\Phi \cos 2\Psi \quad (2b)$$



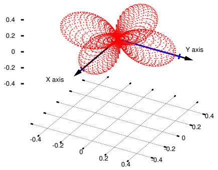
(a) on a tensor + GW (b) on a tensor "×" GW

Antenna-response functions on a scalar GW

Antenna-response functions on scalar longitudinal $F_{\mathrm{SL}}(\zeta,\Phi)$ and transverse $F_{\mathrm{ST}}(\zeta,\Phi,\Psi)$ GW of an interferometric antenna: with two-arms (2-arms mode) *(Will (2014))*:

$$F_{\mathrm{SL}}(\zeta,\Phi) = \frac{1}{2}\sin^2\zeta\cos 2\Phi \qquad (3a)$$

$$F_{\mathrm{ST}}(\zeta,\Phi) = -\frac{1}{2}\sin^2\zeta\cos 2\Phi \qquad (3b)$$

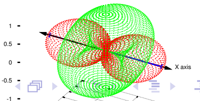


with one-arm (1-arm mode):

$$F_{\mathrm{SL}}(\zeta,\Phi) = \cos\Theta = \sin\zeta\cos\Phi \qquad (4a)$$

$$F_{\mathrm{ST}}(\zeta,\Phi) = \sin\Theta \qquad (4b)$$

The one-arm modification can distinguish between <u>longitudinal</u> and <u>transverse</u> scalar GW modes.



Description of the method

The method is based on:

- **time delay** Δ between a GW arrival;
- **antenna-response** on a polarization state of an incoming GW for each detector;
- **positions of the antennas** at the arrival sidereal time (ST);
- **the ratio of the detected strains** h_1/h_2 on the antennas couple:

$$h(t) = \frac{\Delta L(t)}{L_0} = h^0\, s(t)\, G(\zeta, \Phi, \Psi) \quad (5)$$

$$\frac{h_1}{h_2} = \frac{G_1}{G_2} = \frac{G(\zeta_1, \Phi_1, \Psi_1)}{G(\zeta_2, \Phi_2, \Psi_2)} \quad (6)$$

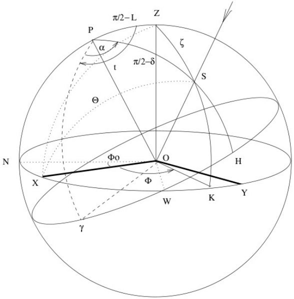


Рис.: Equatorial and horizontal coordinate systems of an interferometric antenna for a GW source S

Application of the method step-by-step

The order of application for a detected GW event:

1. Construction of an apparent circle (AC) of possible source positions on the sky by the arrival time delay Δ.
2. Calculation of G-factors $G(\zeta, \Phi, \Psi)$ for each point of the AC and each antenna in the network.
3. Selection such points at the AC where the calculated G-factors ratio G_1/G_2 corresponds the observed strains ratio h_1/h_2 within an observational error.

$$\frac{h_1}{h_2} \approx \frac{G_1}{G_2} \tag{7}$$

The GW events detected by aLIGO in 2015–2017

Таблица: Data of the LIGO events 2015–2017. ST is the sidereal time of the event, h^0 – the strain as a maximal amplitude normalized by 10^{-21}, $\Delta_{\rm LH}$ – the time delay between registrations at Livingston and Hanford antennas.

GW event	UTC	ST [hrs]	$\Delta_{\rm LH}$ [ms]	h^0
GW150914	09:50:45	3.3315	$6.9^{+0.5}_{-0.4}$	0.6
LVT151012	09:54:43	5.2377	-0.6 ± 0.6	0.3
GW151226	03:38:53	3.8851	1.1 ± 0.3	0.3
GW170104	10:11:59	11.1	$-3.0^{+0.4}_{-0.5}$	0.3

The main selection condition

for the current GW events detected by Livingston (L) and Hanford (H) antennas:

$$\frac{h_L}{h_H} \approx \frac{G_L}{G_H} \approx 1 \pm 10\% \qquad (8)$$

An example of a source position selection

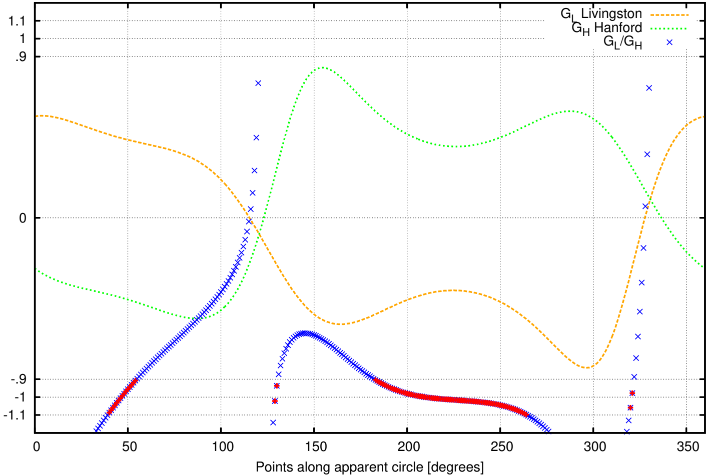
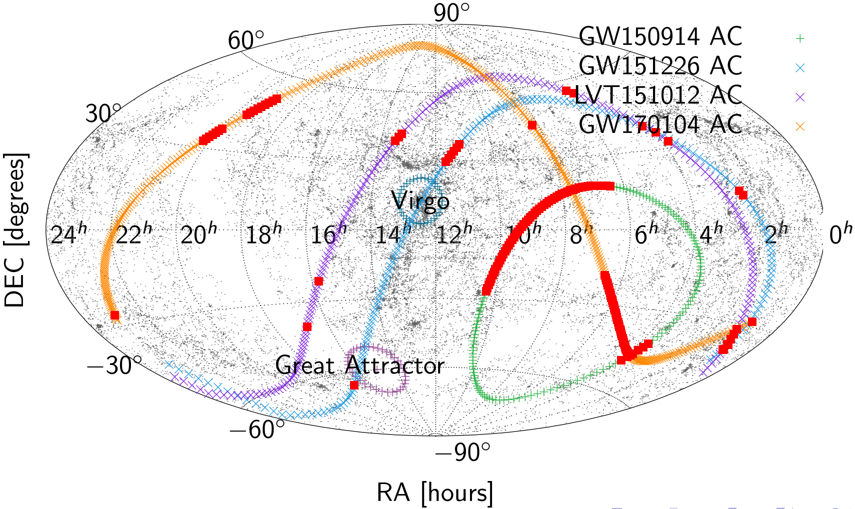


Рис.: Calculated G-factors along the AC for the GW150914 in the case of a tensor "+" incoming GW.

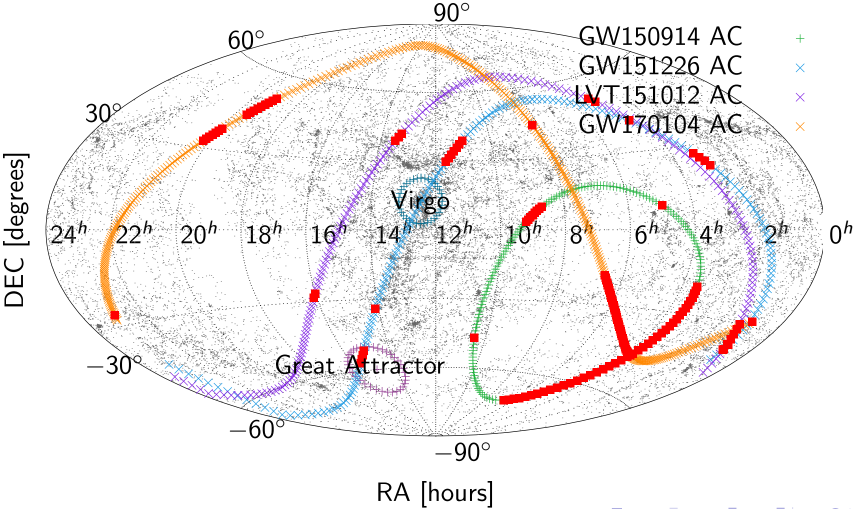
Localization of GW sources

in Equatorial CS for scalar polarization



Localization of GW sources

in Equatorial CS for tensor "+" polarization



2MRS catalogue and the Local Super-Cluster

The 2MRS catalogue

- the result of 2MASS all-sky IR survey;
- contains redshifts of 43 533 galaxies

The supergalactic coordinate system (SG) has the North Pole $SGB = 90^\circ$ with galactic coordinates $l = 47.37^\circ$, $b = 6.32^\circ$ (**?**).

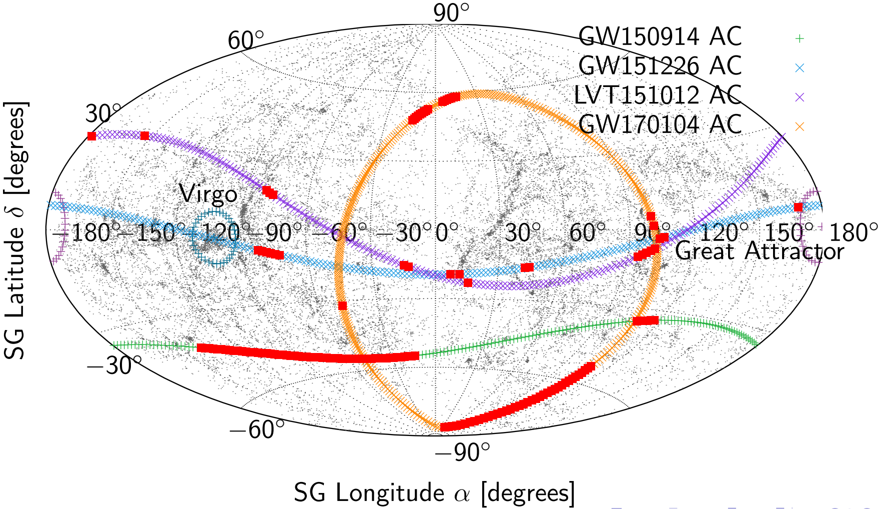
The Local Super-Cluster (LSC)

- a spatial distribution of galaxies within ~ 100 Mpc;
- a filamentary disc-like structure with the radius ~ 100 Mpc, thickness ~ 30 Mpc;
- the center roughly in the Virgo cluster ($SGL = 104^\circ$; $SGB = 22^\circ$);

The used sample covers 32 656 galaxies from the 2MRS with $z \leq 0.025$ (until 100 Mpc) corresponding to the LSC.

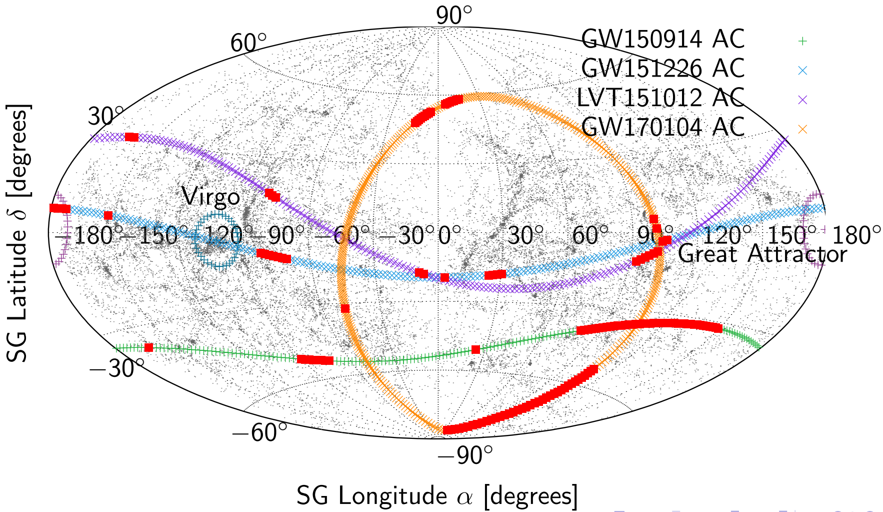
Localization of GW sources

in the Supergalactic CS for a scalar polarization



Localization of GW sources

in the Supergalactic CS for a tensor "+" polarization



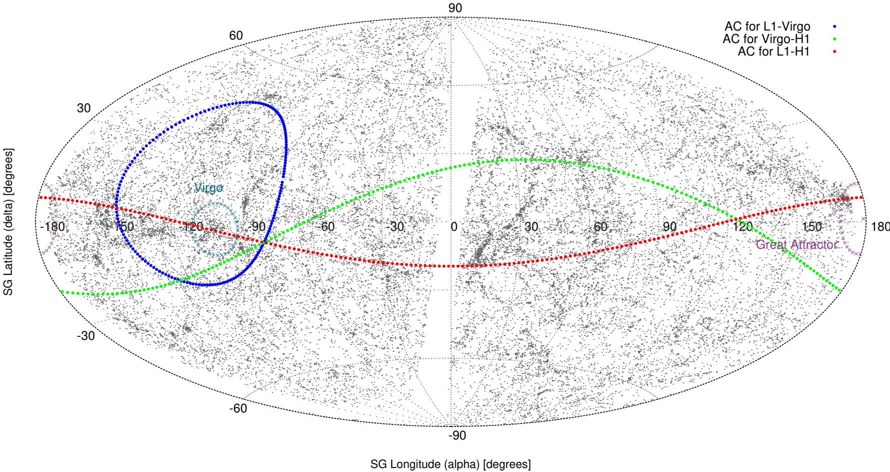
Method for determining a polarization state of a GW

Application of the method in the case of three operating anntennas: LIGO Livingston (L), LIGO Hanford (H) and Virgo (V) at the time of GW151226.

Polarization state	G_{L}	G_{H}	G_{V}	Δ_{LH}	Δ_{LV}	Δ_{VH}
RA $= 11.6^h$ DEC $= 30.3^\circ$				1.09	-23.35	-0.97
Tensor +, $\Psi = 0$	0.376	-0.356	-0.608			
Scal. long. or trans.	0.373	-0.346	-0.029			
Scal. long. (1-arm)	-0.933	0.384	-0.128			
Scal. trans. (1-arm)	0.359	0.924	0.992			
RA $= 18^h$ DEC $= 32^\circ$				-9.49	-11.53	-25.23
Tensor +, $\Psi = 0$	-0.525	0.468	0.190			
Scal. long. or trans.	-0.409	0.460	0.181			
Scal. long. (1-arm)	0.169	0.977	0.819			
Scal. trans. (1-arm)	0.985	0.212	0.574			

Simulated construction of ACs for the network L-H-V

for the source RA $= 11.6^h$; DEC $= 30.3^\circ$ in the Supergalactic CS



Summary and Outlook

- Source localization determined by an antenna-response is different depending on possible polarization states of incoming GWs.
- A network of LIGO-type two-arms antennas can distinguish between tensor and scalar, but not between scalar longitudinal and transverse polarizations, which is possible by means of one-arm interferometric detectors.
- For three aLIGO events: GW150914, GW 151226 and LVT151012, the AC of the allowed GW source positions are parallel to the supergalactic (SG) plane of the Local Super-Cluster of galaxies. If these GW sources are related to the LSC, then we have to consider distances to them within ~ 100 Mpc.
- There should be taken search for EM counterparts along a whole AC of a considered GW event.

Corresponding articles

- Fesik L.E., "*Polarization states of gravitational waves detected by LIGO-Virgo antennas*", 2017. arXiv:1706.09505 [gr-qc]
- Fesik L.E., Yu. V. Baryshev, V. V. Sokolov, G. Paturel, "*LIGO-Virgo events localization as a test of gravitational wave polarization state*", 2017. arXiv:1702.03440v2 [gr-qc]
- Yu. V. Baryshev and G. Paturel. "*Statistics of the detection rates for tensor and scalar gravitational waves from the local galaxy universe*" Astron. Astrophys., 371:378, 2001

Bibliography I

A. Einstein, "Approximative Integration of the Field Equations of Gravitation", *Preuss. Akad. Wiss. Berlin, Sitzber.* **688** (1916).

M. Will, "The Confrontation between General Relativity and Experiment", *Living Rev. Relativity* **17** (2014), no. 4, arXiv:1403.7377.

T. Clifton *et al.*, "Modified gravity and cosmology", *Phys. Rep.* **513** (2012) 1.

R. Feynman, "Lectures on gravitation", California Institute of Technology, 1971.

V. Sokolov and Y. Baryshev, "Field-theoretical approach to gravitation: energy-momentum tensor of the field", *Kazan State University* **17** (1980) 34.

Y. V. Baryshev, "Foundation of relativistic astrophysics: Curvature of Riemannian Space versus Relativistic Quantum Field in Minkowski Space", arXiv:1702.02020.

Thank you for your attention!

Simulated statistics of the events

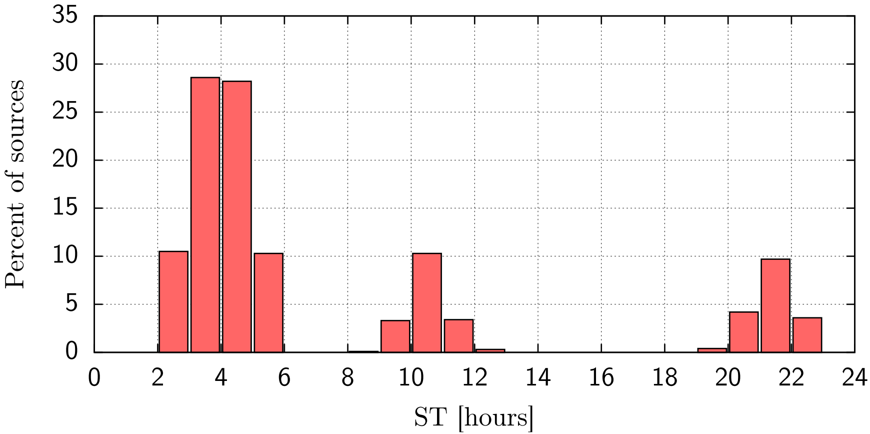


Рис.: Statistics of occurrence ACs by GW sources along the SG plane within