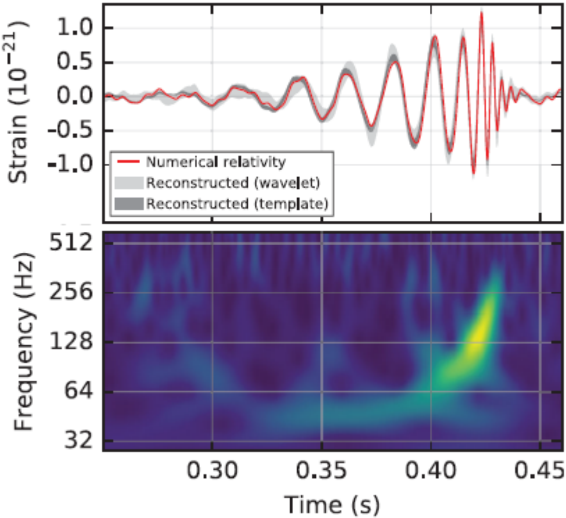
GW170104 optical counterpart and possible scenarios of gravitational waves generation

Liudmila Fesik
Saint Petersburg State University

The International Conference
SN 1987A, Quark Phase Transition in Compact Objects and Multimessenger Astronomy
2–8 July 2017

Outline

GW events detected by LIGO



GW150914 data:
$h \sim 0.6 \times 10^{-21}$
$f_0 \sim 100$ Hz
$\lambda = c/f_0 =$
$3 \times 10^8 \mathrm{cm} = 3\,000 \mathrm{km}$

What's wrong with a GW energy in GR

General Relativity, *Einstein (1916)*
Landau–Lifshitz pseudotensor: does not preserved under common coordinate transformations ⇒ non-localizability of the energy-momentum of grav. field.
To avoid the problem: the effective stress-energy (or Isaacson) tensor:

$$T^{\mathrm{GW}}_{\alpha\beta} = \frac{c^2}{32\pi G} \left\langle h^{\mathrm{TT}}_{\mu\nu;\alpha} h^{\mathrm{TT}\,\mu\nu}_{\phantom{\mathrm{TT}\,\mu\nu};\beta} \right\rangle \qquad (1)$$

The energy-momentum carried by GW cannot be localised in the region smaller than the wavelength λ (Misner et al. (1973)).
$\lambda = c/f_0 = 3 \times 10^8\,\mathrm{cm} = 3\,000\,\mathrm{km}$ **vs** length of an arm of a LIGO antenna: 4 km.
Field Gravitation Theory, *Feynman (1971)*
The energy density of a GW is obtained from the true energy-momentum tensor in the flat Minkowski spacetime ⇒ localizability of the energy-momentum carried by GW.

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.

Compact Binary Coalescence (CBC)

Only tensor radiation due to coalescing relativistic compact objects (RCOs) with dimensions close to the gravitational radius $R_G = GM/c^2$:

- with events horizon in the frame of GR: BH–BH, BH–WD, WD–WD.
- without events horizon in the frame of FGT.

GW Event	150914	151226	151012	170104
Chirp-mass $\mathfrak{M}/M_\odot$	28.1	8.9	15.1	21.1
Total mass $M/M_\odot$	65.3	21.8	37	50.7
Primary mass $m_1/M_\odot$	36.2	14.2	23	31.2
Secondary mass $m_2/M_\odot$	29.1	7.5	13	19.4
Final mass $M_f/M_\odot$	62.3	20.8	35	48.7
Luminosity dist. $r/$ **Mpc**	420	440	1000	880
Source redshift z	0.09	0.09	0.20	0.18
Radiated energy $E_{GW}/M_\odot c^2$	3.0	1.0	1.5	2.0
Peak luminosity $L_{max}/10^{56}$ erg/s	3.6	3.3	3.1	~ 3.0

Core-Collapse Supernova (CCSN)

Possible core-collapse mechanisms and GW polarizations

- **Asymmetric** ⇒ tensor transverse GWs, difficult to make estimations due to poorly known internal physical processes;
- **Imshennik-Nadezhin scenario**: a strong rotation of the core ⇒ formation of an RCO binary radiating tensor transverse GWs, following by a merging into a single RCO with scalar GWs radiation;
- **Spherically-symmetric** (pulsations) in scalar-tensor metric theories and FGT ⇒ scalar GWs.

Radiated energy and distances to objects

Relationship for tensor waves:

$$h_0^{\text{tens}} \approx 6 \times 10^{-21} \left(\frac{\Delta E}{10^{-3}}\right)^{\frac{1}{2}} \left(\frac{0.1\text{s}}{\tau}\right)^{\frac{1}{2}} \left(\frac{100\text{Hz}}{f}\right) \left(\frac{1\text{Mpc}}{r}\right) \tag{2}$$

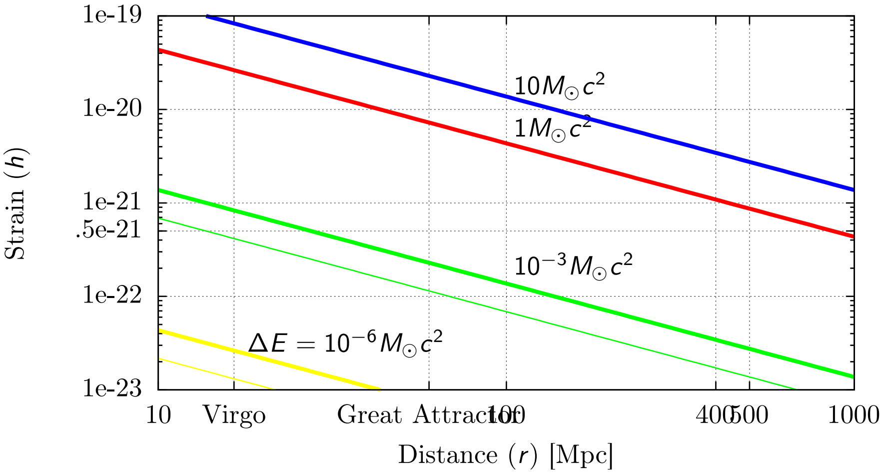
Relationship for scalar waves:

$$h_0^{\text{sc}} \approx 1.36 \times 10^{-20} \left(\frac{\Delta E}{10^{-3}}\right)^{\frac{1}{2}} \left(\frac{0.1\text{s}}{\tau}\right)^{\frac{1}{2}} \left(\frac{100\text{Hz}}{f}\right) \left(\frac{1\text{Mpc}}{r}\right) \tag{3}$$

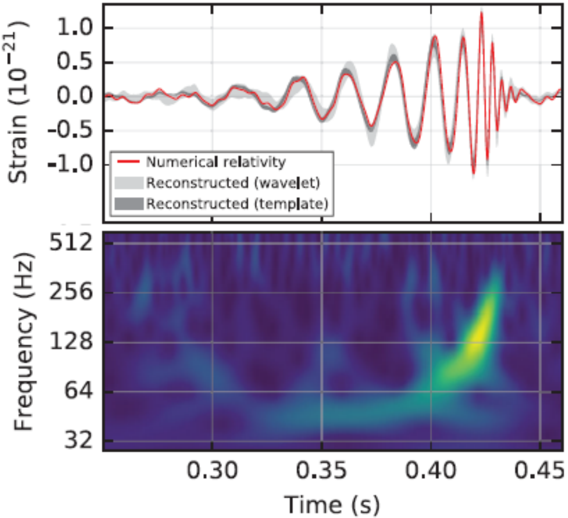
The upper limit on the radiated in GWs energy due to CCSN

- metric theories: $E_{\text{GW}} \leq 10^{-3} M_{\odot} c^2$.
- FGT: radiated energy is **limited only by a rest mass** of an object itself $\sim$ several $M_{\odot}$ (Baryshev 1999).

Radiated energy and distances to objects



CCSN parameters estimations in the FGT



GW150914 data:
$h_1 \sim 0.6 \times 10^{-21}$
$f_0 \sim 100$ Hz
GW170104 data:
$h_1 \sim 0.25 \times 10^{-21}$
$f_0 \sim 100$ Hz

CCSN parameters estimations in the FGT

Used data of a signal

- h – strain;
- $P_0 \sim 1/f_0$ – characteristic period of pulsations;
- f_0 – average frequency;

The gravitational radius $R_G = GM_0/c^2$.

Estimated parameters of a CCSN

- ρ_0 – average density;
- R_0 – radius;
- v_0 – velocity of pulsations;

CCSN parameters in the case of scalar radiation in FGT

Relationship between physical parameters of a pulsating CCSN and observed data of a GW signal in the case of scalar radiation in FGT:

$$h_0 \sim \frac{4}{3}\pi c \cdot \frac{P_0}{r} \cdot \alpha^5, \quad \alpha = \frac{\mathrm{v}_0}{c} \tag{4}$$

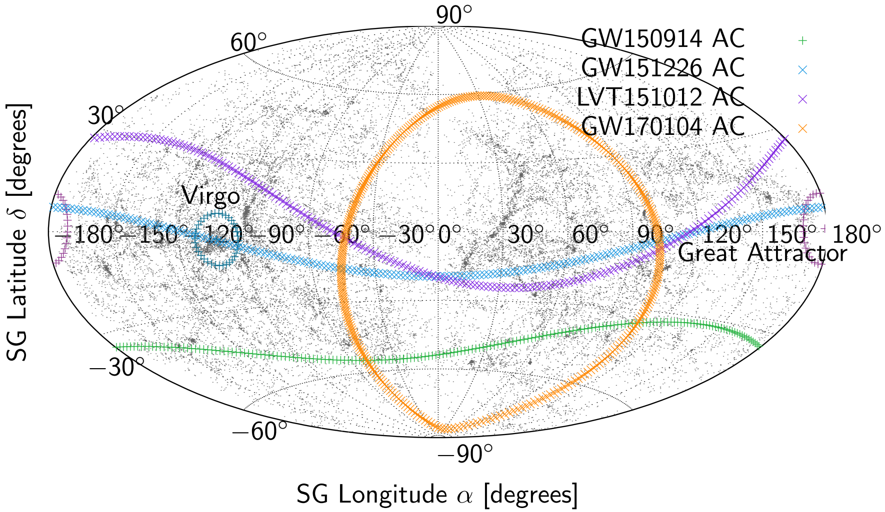
Compatibility condition

$$\frac{\gamma}{\beta} = \frac{4}{3}\pi\alpha^2, \; \beta = \frac{R_0}{R_G}, \quad \gamma = \frac{\rho_{\text{eff}}}{\rho_0} \tag{5}$$

Calculations for: $h_1 = 0.6 \cdot 10^{-21}$ and $h_2 = 0.25 \cdot 10^{-21}$. If parameter $\gamma = \rho_{\text{eff}}/\rho_0 \equiv 1 \Rightarrow$ an effective density $\rho_{\text{eff}} = 0.15 \cdot 10^{12}$ g/cm^3.

$\Delta E\,[M_\odot c^2]$	r_1 [Mpc]	r_2 [Mpc]	v_0/c	R_0/R_G	$M_0/M_\odot$
10^{-6}	0.72	1.74	0.06	58.44	2.22
10^{-3}	22.88	54.92	0.13	14.68	17.64
1	723.57	1736.57	0.25	3.69	140.08

ACs for LIGO events in the Supergalactic CS



Simulated statistics of the events

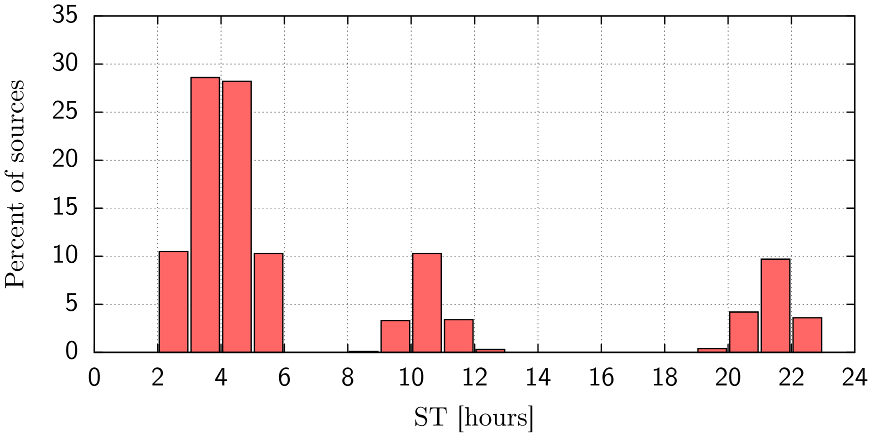


Рис.: Statistics of occurrence ACs along the SG plane within ±30° SGB

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 $l = 47.37^\circ$, $b = 6.32^\circ$ (**?**).

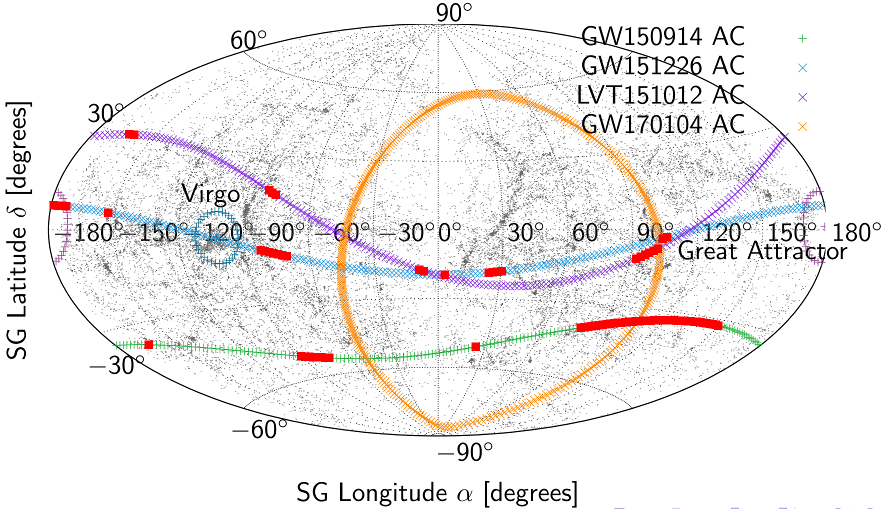
The Local Super-Cluster (LSC)

- a spatial distribution of galaxies within ~ 100 Mpc;
- a filamentary disc-like structure with the radius ~ 100 Mpc, thickness ~ 30 Mpc;
- the centre 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.

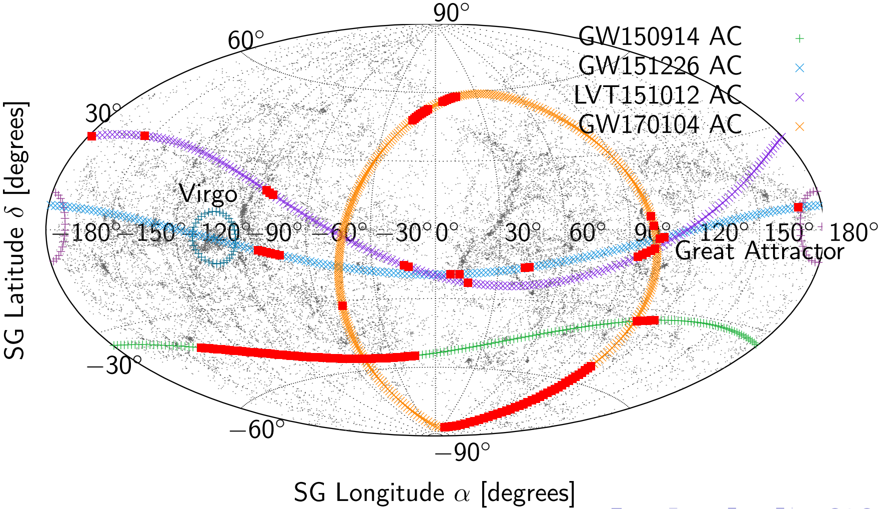
Localization of GW sources

in the Supergalactic CS for a tensor "+" polarization



Localization of GW sources

in the Supergalactic CS for a scalar polarization



Search for transients to GW150914 and GW151226

- **Pan-STARRS** – optical spectrum, 56 transients with 19 classified spectrographically;
- Global network **MASTER** – optical spectrum, 8 transients only one located close to the AC are SN;
- **Fermi** Gamma-ray Burst Monitor, a GRB was discovered 0.4 s after the registration of GW150914 with the energy $\sim 3 \times 10^{-7}$ erg giving the luminosity $\sim 2 \times 10^{49}$ erg/s at the distance 440 Mpc. Which is small for the coalescing objects such as BHs in GR.

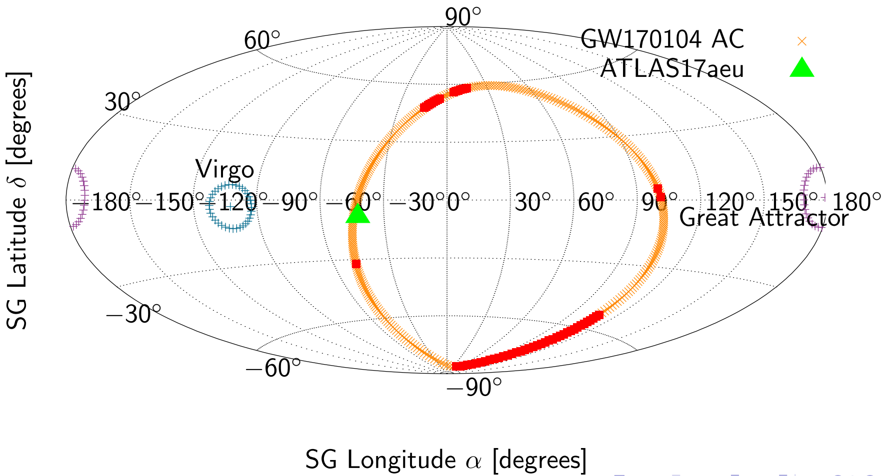
There is the possibility, in the frame of the FGT, to associate the GRB Fermi with GW150914 in the case of sources being a CBC comprising two relativistic compact objects without the events horizon.

Optical transient ATLASaeu

ATLAS is the Asteroid Terrestrial-impact Last Alert System
ATLAS17aeu was discovered in optics 23 hours after the registration of GW170104, also observed in x-ray by the Swift and in radio by the AMI.

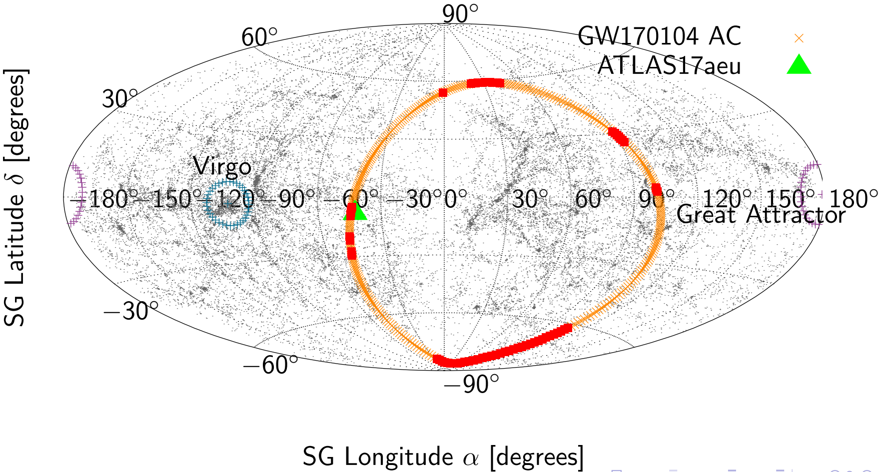
Localization of GW sources for GW170104

in the Supergalactic CS for a scalar polarization



Localization of GW sources for GW170104

in the Supergalactic CS for a mixture of tensor polarization: $G = 1.5F_{+} + \sqrt{2}F_{\times}$



Summary and Outlook

- Source localization determined by an antenna-response is different depending on possible polarization states of incoming GWs. There should be taken search for EM counterparts along a whole AC of a considered GW event.
- In the frame of scalar-tensor theories of gravitation, both metric and field, there is predicted the existence of a scalar GW radiation with a sinusoidal waveform due to spherically-symmetric CCSN (pulsations).
- For the discovered EM event **ATLAS17aeu** to be a transient for GW170104, there can be interpretation as a CBC of two RCOs with tensor GW radiation as well as a CCSN with scalar radiation.

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]
- Y. V. Baryshev, "*Foundation of relativistic astrophysics: Curvature of Riemannian Space versus Relativistic Quantum Field in Minkowski Space*", 2017, arXiv:1702.02020

Bibliography I

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

C. Misner, K. Thorne, and J. Wheeler, "Gravitation", Freeman and Company, Physics Series, 1973.

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

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.

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

Bibliography II

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

Y. V. Baryshev, "On a possibility of scalar gravitational wave detection from the binary pulsar PSR 1913 + 16", in "Gravitational wave experiments. Proceedings, 1st Edoardo Amaldi Conference, Frascati, Italy, June 14-17, 1994". 1999. arXiv:gr-qc/9911081.

Thank you for your attention!