Binary Stars, Black Holes and Gravitational Wave Astronomy.

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- Gravitational waves from binary black hole (BH) coalescence has been discovered recently by LIGO (Abbott et al., 2016).
- In this connection, formation mechanisms for compact BH binaries with merging time shorter than Hubble time ($14 \cdot 10^9$ years) should be investigated.

- Lipunov, Postnov and Prokhorov (1997) calculated binary evolutionary tracks using Scenario Machine Code (Kornilov and Lipunov, 1983, Lipunov et al., 1996) to theoretically predict that LIGO should first discover coalescing binary BHs and not neutron stars (NS).

- The idea to use the optical laser Michelson interferometer to register gravitational waves was put forward by Gertsenstein and Pustovoit (1962). This idea was developed by Braginsky and Thorne.
- Gravitational wave research by Gertsenstein, Pustovoit, Braginsky was constantly supported and inspired by Vitaly Lazarevich Ginzburg.

- By analogy with X-ray binary systems discovered by X-rays from accreting relativistic objects, close binary systems (CBS) discovered by gravitational wave radiation can be called as gravitational wave (GW) binary systems.

- Masses of BHs in three LIGO GW binary systems (GW150914, GW151226, LVT151012) as well as the progenitor star masses

$$\frac{M_{OB}}{M_\odot} \simeq 8 \cdot \left(\frac{M_{BH}}{M_\odot}\right)^{0.7}$$

are presented in Table 1.

- Here M_{BH} is taken to be equal to the mass of Si core of massive star (Massevich and Tutukov, 1988)

$$\frac{M_{Si}}{M_\odot} \approx 0.05 \cdot \left(\frac{M_{OB}}{M_\odot}\right)^{1.4}$$

Table 1.

LIGO GW binaries with BHs.

System	Type of the comp.	BH masses ($M_\odot$)	Initial masses of stars ($M_\odot$)
GW150914	BH+BH	36+29	100+80
GW151226	BH+BH	14.2+7.5	50+30
LVT151012	BH+BH	23+13	75+50

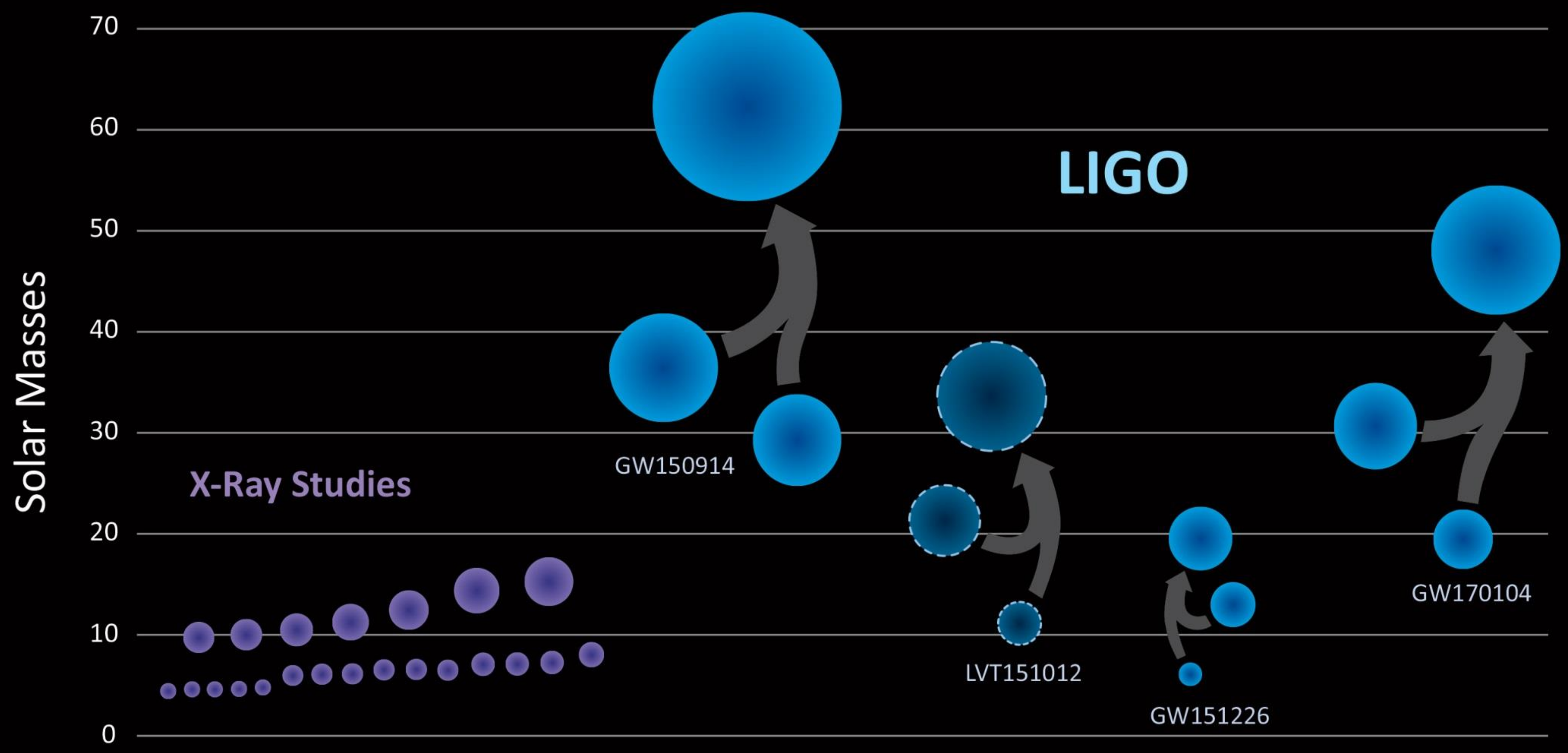
Massive BH X-ray binaries.

System	Type of the comp.	Masses ($M_\odot$)	Orbital period (days)
Cyg X-1	O9.7Iab+BH	19.16+14.81	5.60
LMC X-1	O(7-9)III+BH	30.6+10.3	3.91
M33 X-7	O(7-8)III+BH	70.0+15.6	3.45

Massive classical binaries.

System	Type of the comp.	Masses ($M_\odot$)	Orbital period (days)	$\dot{M}$ ($M_\odot$/year)
WR20a	WN6h+WN6a	83+82	3.69	$\sim 10^{-5}$
NGC3603-A1	WN6a+WN6	116+89	3.77	$\sim 2 \cdot 10^{-5}$
R136-38 (LMC)	O3V+O3V	56+30	3.39	$\sim 10^{-6}$
R145 (LMC)	WN6h+O	>116+>48	158.8	$\gtrsim 2 \cdot 10^{-5}$
WR21a	O3f/WN6a+O4	>87+>53	31.67	$\gtrsim 10^{-5}$

Black Holes of Known Mass



- Table 1 shows that our Galaxy and other galaxies (e.g. LMC) contain CBS in which the mass of at least one of the components exceeds $\sim 100 M_{\odot}$ and could be real progenitors of the massive GW binary systems like GW150914 ($36 M_{\odot} + 29 M_{\odot}$).

- Data on BH masses and optical star masses in the most massive X-ray binary systems (CygX-1, LMCX-1 and M33X-7) are presented in Table 1.
- In these systems one BH is formed and further evolution of CBS should lead to the formation of secondary BH; so BH binary will be formed.

- These X-ray binaries reside in different galaxies, and their masses are insufficient to explain the masses of BHs in the system GW150914 (M_{BH}=36$M_\odot$ and 29$M_\odot$). But the masses of BHs in the system GW151226 (M_{BH}=14.2$M_\odot$ and 7.5$M_\odot$) fall within the range of BH masses in X-ray binary systems (4-16$M_\odot$).

- The massive Main Sequence stars $(M \gtrsim 100 M_\odot)$ which can be considered as progenitors of BHs in GW binary systems have high values of radii:

$$R \approx \left(\frac{M}{M_\odot}\right)^{0.6} \approx 20\, R_\odot\,.$$

- Therefore, the initial value of the orbit radius of corresponding CBS should be

$$a \gtrsim 50\, R_\odot\,.$$

- Coalescence time for two BHs in GW binary system due to GW radiation (Landau and Lifshits, 1994)

$$\tau_c = 10^8 \left(\frac{a}{R_\odot}\right)^4 \frac{M_\odot^3}{M_1 M_2 (M_1+M_2)} \text{ years.}$$

- Formation of GW signal needs τ_c less than Hubble time (14·10⁹ years). Therefore, resulting binary BH should be sufficiently compact:

$$a \lesssim 40 \div 50\ R_\odot\ .$$

- However, due to strong radial stellar wind from massive stars ($\dot{M} \gtrsim 10^{-5}\, M_{\odot}$/years for stars with solar metallicity $Z_{\odot}$) evolution of a massive CBS goes with increasing separation ɑ between the components:

$$ɑ\,(M1+M2) = \mathrm{const}, \rightarrow$$

$$\frac{\Delta ɑ}{ɑ} = - \frac{\Delta(M_1+M_2)}{M_1+M_2}.$$

WR ($\dot{M} > 10^{-5}\, M_{\odot}$/years) and LBV ($\dot{M} \sim 10^{-2}\, M_{\odot}$/years) phenomena (Conti, 1976; Conti, Crowther and Leitherer, 2008).

- Due to strong radial mass loss by stellar wind, evolution of high mass

(e.g. $100\,M_{\odot} + 100\,M_{\odot}$) binary system can go without Roche-Lobe filling by the companions and with increasing separation $a > 50\,R_{\odot}$.

- As a result, wide resulting BH+BH binary ($a > 50\,R_{\odot}$) is formed for which merging time is longer than Hubble time.
- So gravitational-wave signal from such wide BH+BH binary system can not be observed.

- Because main cause of radial expansion of stellar wind is radiation pressure, mass loss rate for massive stars depends on metallicity z of matter which determines its opacity (e.g. Vink, 2006):

$$\dot{M} \sim z^{0.75} \quad 0.001 \lesssim \frac{z}{z_\odot} \leq 10 .$$

- Therefore, massive stars with low metallicity $(z < 0.1\ z_\odot)$ and weak stellar winds should be considered.
- For example, hydrogen – helium stars of population III $(M > 100\ M_\odot)$ that were formed at the early stage of the Universe evolution. Because coalescence time for binary BH system formed as a result of the evolution of massive CBS may reach many billions of years, progenitor stars can be related to this early epoch of the evolution of Universe $(T \simeq (1 \div 2) \cdot 10^9$ years).

- Also, some additional mechanisms of angular momentum loss are needed for description of evolution of massive CBS, leading to formation of compact BH binary systems ($a < 50\ R_{\odot}$): e.g. common envelope (CE) evolution, evolution due to natal Kick velocity for relativistic object, decreasing of separation a due to dynamical friction of the CBS stars in dense interstellar molecular clouds e.c. (e.g. Tutukov and Cherepashchuk, 2017).

- Up to now four basic evolutionary scenarios leading to formation of compact ($a < 50\ R_\odot$) BH+BH systems have been developed.

1) Scenario of evolution of primordial BH+BH binary systems formed at the early stage of the Universe evolution (e.g. Blinnikov, Dolgov, Porayko, Postnov, 2016).

- In this scenario masses of BHs in GW binary system do not restricted by any upper limit.
- This scenario can be easily applied for interpretation of high mass GW binaries like GW150914 ($M_1 = 36\ M_\odot$, $M_2 = 29\ M_\odot$).

2) Scenario of dynamical formation of massive CBS from hierarchical triple systems of stars – members of dense cores of stellar clusters through Lidov-Kozai mechanism (see e.g. Antonini et al., 2016). Triple star systems are expected to form frequently via close binary – binary encounters in the dense cores of clusters.

- In a sufficiently inclined triple $(i > 39°)$, gravitational interactions between the inner and outer binary can cause large – amplitude oscillations in the eccentricity of the inner orbit (so called Lidov-Kozai Cycles), which can lead to a collision and merger of two inner components

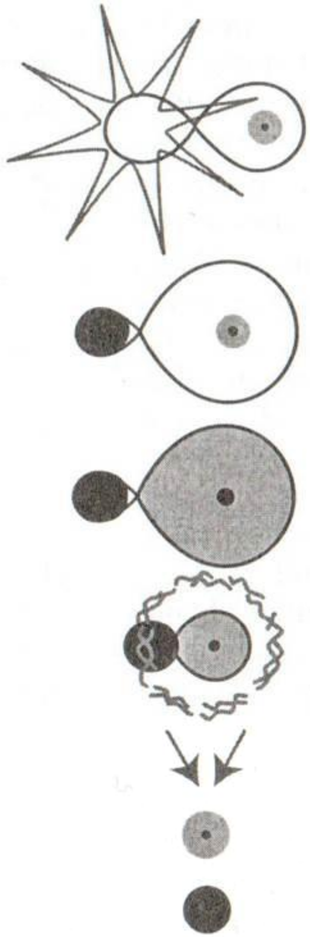
3) Scenario of evolution of chemically homogenous tidally distorted massive stars in very close, almost contact binary system (e.g. De Mink and Mandel. 2016).

- Due to meridional circulation of matter in such rapidly rotating stars they become homogenous helium stars and can produce massive BHs at the end of their evolution.

4) Classical evolutionary scenario with mass exchange in isolated massive CBS (Tutukov and Yungelson, 1973, 1993, Lipunov, Postnov, Prokhorov, 1997, Belczynski et al., 2016). In the papers of Abubekerov, Antokhina, Bogomazov and Cherepashchuk (2009), Bogomazov (2014) and Belczynski, Holz, Builk, O’Shaughnessy (2016) using Population Synthesis Codes classical evolutionary scenarios have been calculated for massive CBS which lead to formation of compact ($a < 50 R_{\odot}$) BH+BH binary system as well as Thorhe-Zytkov objects.

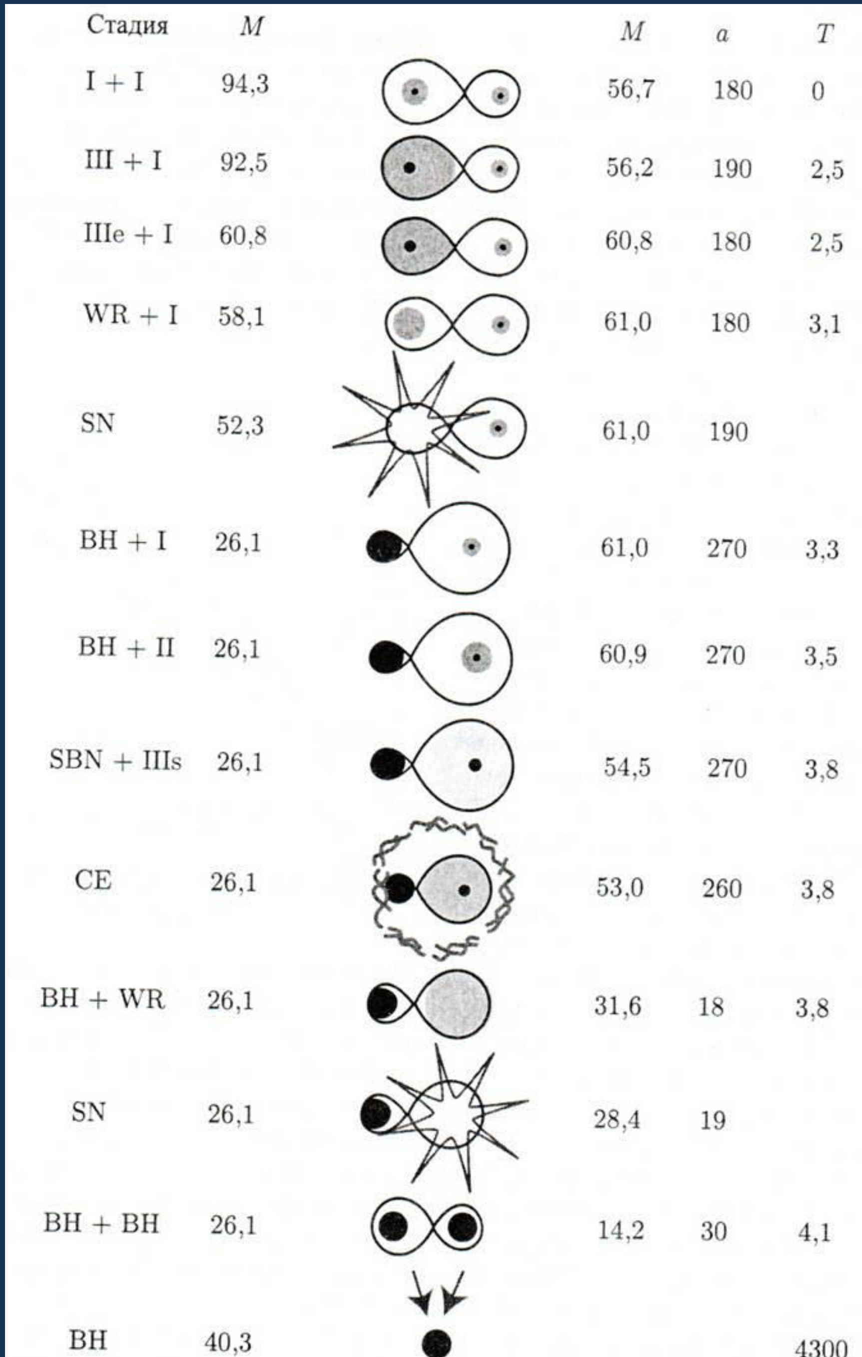
Evolutionary scenario for M33 X-7

(Abubekerov et al., 2009)



Стадия	M	M	a	T
I + I	113,2	41,4	34	0
III + I	108,3	37,8	36	2,4
WR + I	75,0	71,1	22	2,4
SN	52,5	69,6	26	
BH + I	15,8	69,9	46	2,6
SBN + IIIs	15,8	69,3	38	3,2
CE	15,8	64,4	22	3,2
TZ	55,3			3,2
BH	55,2			3,3

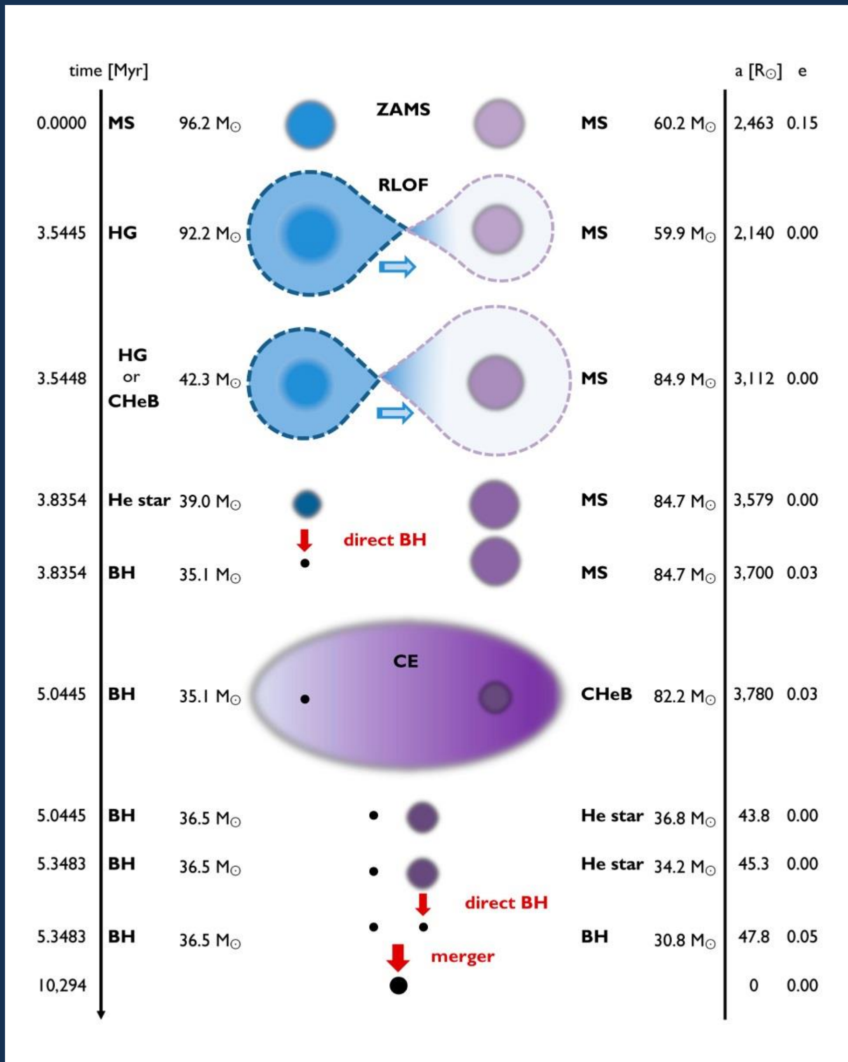
Evolutionary stages for the X-ray binary M33X-7 calculated by the Scenario Machine code. Shown are masses of the components M (in solar masses), the distance between the components α (in solar radii $R_\odot$), and the time T during which the binary system is at the corresponding evolutionary stage. CE (common envelope) is the common envelope stage. Nazin and Postnov (1995).



Evolutionary scenario for IC10 X-1

(Abubekerov et al., 2009)

Evolutionary stages for the X-ray binary system IC10X-1 calculated by the Scenario Machine code. The notation is the same as in next Fig.



Evolutionary scenario for GW150914 (Belczynski et al., 2016)

Example binary evolution leading to a BH-BH merger similar to GW150914. A massive binary star ($96 + 60\ M_\odot$) is formed in the distant past (2 billion years after Big Bang; $z \sim 3.2$) and after five million years of evolution forms a BH-BH system ($37 + 31\ M_\odot$). For the ensuing 10.3 billion years this BH-BH system is subject to angular momentum loss, with the orbital separation steadily decreasing, until the black holes coalesce at redshift $z = 0.09$. This example binary formed in a low metallicity environment ($Z = 3\%\ Z_\odot$).

- Calculations of Belczynski et al. (2016) for classical evolution of isolated massive binary systems predict detection of about 1000 BH+BH mergers per year with total masses of 20-80 solar masses once second-generation ground-based gravitational-wave observatories reach full sensitivity.
- Other scenario for formation of merging BH+BH systems give values of merging rate less than 1000 BH+BH mergers per year: for the scenario of dynamical formation of massive CBS from hierarchical triple systems of stars

  ~1 Gpc^{-3} $year^{-1}$; for the scenario of evolution of chemically homogenous rapidly rotating massive stars

  ~500 Gpc^{-3} $year^{-1}$.
- The BH+BH mergers rate inferred from the 16 days of O1 LIGO observations are in the range

  (9 – 240) Gpc^{-3} $year^{-1}$ (Abbott et al., 2016), which is in qualitative agreement with theoretical prediction.

- In recent paper by Pavlovskii, Ivanova, Belczynski and Van (2017) physics of mass transfer in binaries with massive donors and compact companions was investigated in more details. It is shown that for a large range of binary orbital separations this mass transfer is stable and common envelope can not be formed. This allows to provide more accurate comparison theory and observations. In particular, it is possible to exclude in population synthesis a channel that predicts a BH+BH merger rate above 1000 Gpc^{-3} $year^{-1}$.
- Furthermore, the stability of the mass transfer leads to the formation of ultraluminous X-ray sources.

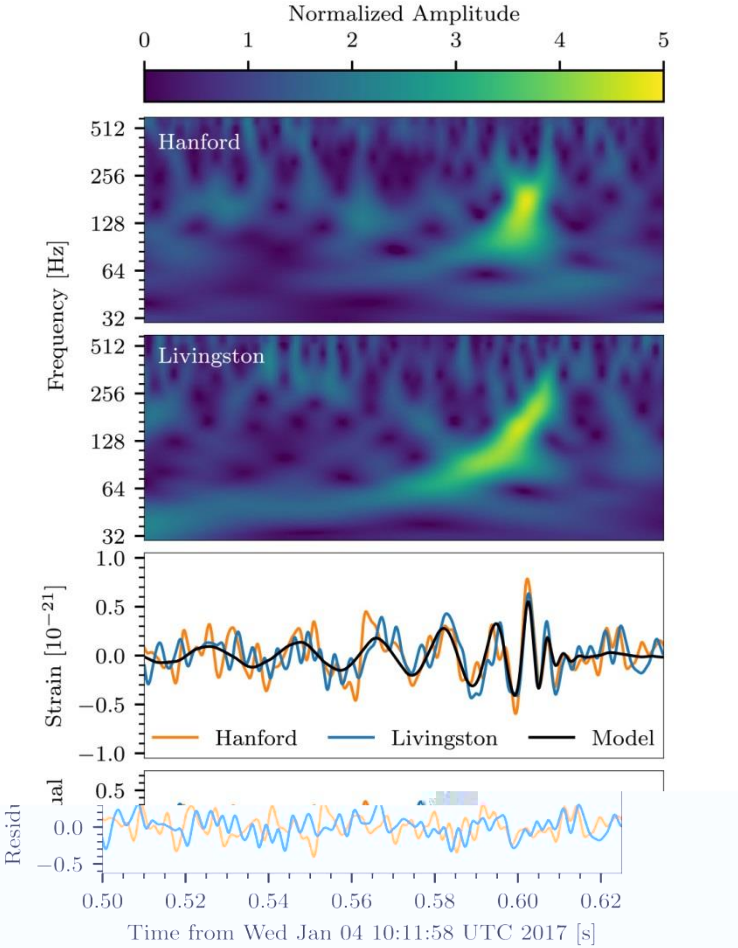


FIG. 1. Time–frequency representation [9] of strain data from
ford and Livingston detectors (top two panels) at the time of
170104. The data begin at 1167559936.5 GPS time. The
d panel from the top shows the time-series data from each
ector with a 30–350 Hz bandpass filter, and band-reject filters
uppress strong instrumental spectral lines. The Livingston
have been shifted back by 3 ms to account for the source's
location, and the sign of its amplitude has been inverted to
ount for the detectors' different orientations. The maximum-
lihood binary black hole waveform given by the full-pre-
ion model (see Sec. IV) is shown in black. The bottom panel
ws the residuals between each data stream and the maximum-
lihood waveform.

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- Just recently (2 June 2017) gravitational wave signal from new BH+BH binary GW170104 has been reported (B.P.Abbott et al., Phys. Rew. Letters, v.118, 221101, 2017).

Parameters of the new GW BH+BH binary system are the follow

Primary black hole mass m_1	$31.2^{+8.4}_{-6.0} M_\odot$
Secondary black hole mass m_2	$19.4^{+5.3}_{-5.9} M_\odot$
Chirp mass $\mathcal{M}$	$21.1^{+2.4}_{-2.7} M_\odot$
Total mass M	$50.7^{+5.9}_{-5.0} M_\odot$
Final black hole mass M_f	$48.7^{+5.7}_{-4.6} M_\odot$
Radiated energy $E_{\rm rad}$	$2.0^{+0.6}_{-0.7} M_\odot c^2$
Peak luminosity $\ell_{\rm peak}$	$3.1^{+0.7}_{-1.3} \times 10^{56} \mathrm{erg\,s^{-1}}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.12^{+0.21}_{-0.30}$
Final black hole spin a_f	$0.64^{+0.09}_{-0.20}$
Luminosity distance D_L	880^{+450}_{-390} Mpc
Source redshift z	$0.18^{+0.08}_{-0.07}$

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

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(LIGO Scientific and Virgo Collaboration)

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We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70 000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0} M_\odot$ and $19.4^{+5.3}_{-5.9} M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $\chi_{\rm eff} = -0.12^{+0.21}_{-0.30}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is 880^{+450}_{-390} Mpc corresponding to a redshift of $z = 0.18^{+0.08}_{-0.07}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g \leq 7.7 \times 10^{-23}\ {\rm eV}/c^2$. In all cases, we find that GW170104 is consistent with general relativity.