Gravitational waves

a short introduction

A.N. Baushev

Gravitational field equations

1) The index agreement:

The greek indexes (α, β, γ etc.) take values (0, 1, 2, 3). 0 is the time coordinate, the rest are the space coordinates
The latin indexes (a, b, i, j etc.) take values (1, 2, 3), these are the space coordinates.
Repeating indexes imply summation.

The metrix

$$ds^2 = g_{\alpha\beta} dx^\alpha dx^\beta \equiv \sum_{\alpha=0}^{3} \sum_{\beta=0}^{3} g_{\alpha\beta} dx^\alpha dx^\beta$$

The metrix

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

$$dl^2 = dx^2 + dy^2 + dz^2$$

$$\eta_{\alpha\beta} \equiv \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$ds^2 = g_{00}dt^2 + 2g_{01}dtdx + 2g_{02}dtdy + 2g_{03}dtdz +$$

$$+ g_{11}dx^2 + 2g_{12}dxdy + 2g_{13}dxdz + g_{22}dy^2 + 2g_{23}dydz + g_{33}dz^2$$

$$g_{\alpha\beta} = g_{\beta\alpha}$$

$$g_{\alpha\beta} = \begin{pmatrix} g_{tt} & g_{tx} & g_{ty} & g_{tz} \\ g_{xt} & g_{xx} & g_{xy} & g_{xz} \\ g_{yt} & g_{yx} & g_{yy} & g_{yz} \\ g_{zt} & g_{zx} & g_{zy} & g_{zz} \end{pmatrix}$$

A change of coordinates

$$(x^0, x^1, x^2, x^3) \to (\tilde{x}^0, \tilde{x}^1, \tilde{x}^2, \tilde{x}^3)$$

Spherical coordinates

$$(t, r, \theta, \phi)$$

$$g_{\alpha\beta} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & r^2 \sin^2\theta \end{pmatrix}$$

Rotating cylindrical coordinates

$$(t, z, r, \phi)$$

$$g_{\alpha\beta} = \begin{pmatrix} -1 + \Omega^2 r^2/c^2 & -\Omega r^2 & 0 & 0 \\ -\Omega r^2 & 1 & 0 & 0 \\ 0 & 0 & r^2 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Общая теория относительности в общем виде

Символы Кристофеля (в некотором смысле, силы)

$$\Gamma^{\alpha}{}_{\beta\gamma} = \frac{1}{2}\, g^{\alpha\mu} \left(\frac{\partial g_{\mu\beta}}{\partial x^{\gamma}} + \frac{\partial g_{\mu\gamma}}{\partial x^{\beta}} - \frac{\partial g_{\beta\gamma}}{\partial x^{\mu}} \right)$$

Тензор Римана (тензор кривизны)

$$R^{\alpha}{}_{\beta\gamma\delta} = \frac{\partial \Gamma^{\alpha}{}_{\beta\delta}}{\partial x^{\gamma}} - \frac{\partial \Gamma^{\alpha}{}_{\beta\gamma}}{\partial x^{\delta}} + \Gamma^{\alpha}{}_{\mu\gamma}\Gamma^{\mu}{}_{\beta\delta} - \Gamma^{\alpha}{}_{\mu\delta}\Gamma^{\mu}{}_{\beta\gamma}$$

Тензор Риччи

$$R_{\alpha\beta} \equiv R^{\gamma}{}_{\alpha\gamma\beta}$$

Уравнения Эйнштейна для пустоты

$$R_{\alpha\beta} = 0$$

Weak gravitational field

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, |h_{\alpha\beta}| \ll 1$$

$$\eta_{\alpha\beta} \equiv \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$h_{\alpha\beta} = \begin{pmatrix} -2\Phi & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Newtonian limit

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$

$$ds^2 = -(1 + 2\Phi)dt^2 + (1 - 2\Phi)(dx^2 + dy^2 + dz^2)$$

$$ds^2 = -(1 + 2\Phi)dt^2 + (dx^2 + dy^2 + dz^2)$$

The linearized theory in the weak field case

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, |h_{\alpha\beta}| \ll 1$$

The Chrisloffel symbols (forces, in some sense)

$$\Gamma^{\alpha}{}_{\beta\gamma} = \frac{1}{2}\, g^{\alpha\mu} \left(\frac{\partial g_{\mu\beta}}{\partial x^{\gamma}} + \frac{\partial g_{\mu\gamma}}{\partial x^{\beta}} - \frac{\partial g_{\beta\gamma}}{\partial x^{\mu}} \right)$$

$$\Gamma^{\alpha}{}_{\beta\gamma} = \frac{1}{2}\, \eta^{\alpha\mu} \left(\frac{\partial h_{\mu\beta}}{\partial x^{\gamma}} + \frac{\partial h_{\mu\gamma}}{\partial x^{\beta}} - \frac{\partial h_{\beta\gamma}}{\partial x^{\mu}} \right)$$

The Einstein equation for empty space

$$R_{\alpha\beta} = \frac{1}{2} \left(\eta^{\gamma\delta} \left[\frac{\partial^2 h_{\alpha\gamma}}{\partial x^{\beta} \partial x^{\delta}} + \frac{\partial^2 h_{\beta\gamma}}{\partial x^{\alpha} \partial x^{\delta}} - \frac{\partial^2 h_{\alpha\beta}}{\partial x^{\gamma} \partial x^{\delta}} \right] - \frac{\partial^2 h}{\partial x^{\alpha} \partial x^{\beta}} - \right.$$

$$\left. -\eta^{\alpha\beta} \left[\eta^{\gamma\mu} \eta^{\delta\nu} \frac{\partial^2 h_{\mu\nu}}{\partial x^{\gamma} \partial x^{\delta}} - \eta^{\mu\nu} \frac{\partial^2 h}{\partial x^{\mu} \partial x^{\nu}} \right] \right) = 0$$

$$R_{\alpha\beta} = \frac{1}{2}\left(\eta^{\gamma\delta}\left[\frac{\partial^2 h_{\alpha\gamma}}{\partial x^\beta \partial x^\delta} + \frac{\partial^2 h_{\beta\gamma}}{\partial x^\alpha \partial x^\delta} - \frac{\partial^2 h_{\alpha\beta}}{\partial x^\gamma \partial x^\delta}\right] - \frac{\partial^2 h}{\partial x^\alpha \partial x^\beta} - \right.$$

$$\left. -\eta^{\alpha\beta}\left[\eta^{\gamma\mu}\eta^{\delta\nu}\frac{\partial^2 h_{\mu\nu}}{\partial x^\gamma \partial x^\delta} - \eta^{\mu\nu}\frac{\partial^2 h}{\partial x^\mu \partial x^\nu}\right]\right) = 0$$

We make a change

$$\hbar_{\alpha\beta} \equiv h_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}h, \quad \hbar \equiv \eta^{\alpha\beta}\hbar_{\alpha\beta} = -h$$

$$h_{\alpha\beta} = \hbar_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}\hbar$$

$$\eta^{\gamma\delta}\left[\frac{\partial^2 \hbar_{\alpha\gamma}}{\partial x^\beta \partial x^\delta} + \frac{\partial^2 \hbar_{\beta\gamma}}{\partial x^\alpha \partial x^\delta} - \frac{\partial^2 \hbar_{\alpha\beta}}{\partial x^\gamma \partial x^\delta}\right] - \eta^{\alpha\beta}\eta^{\gamma\mu}\eta^{\delta\nu}\frac{\partial^2 \hbar_{\mu\nu}}{\partial x^\gamma \partial x^\delta} = 0$$

Infinitesimal coordinate changes

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, |h_{\alpha\beta}| \ll 1$$

$$y^\alpha = x^\alpha + \xi^\alpha, |\xi^\alpha| \ll 1 \qquad T(y^\alpha = a^\alpha) = T(x^\alpha = a^\alpha) - \frac{\partial T}{\partial x^\alpha}\xi^\alpha$$

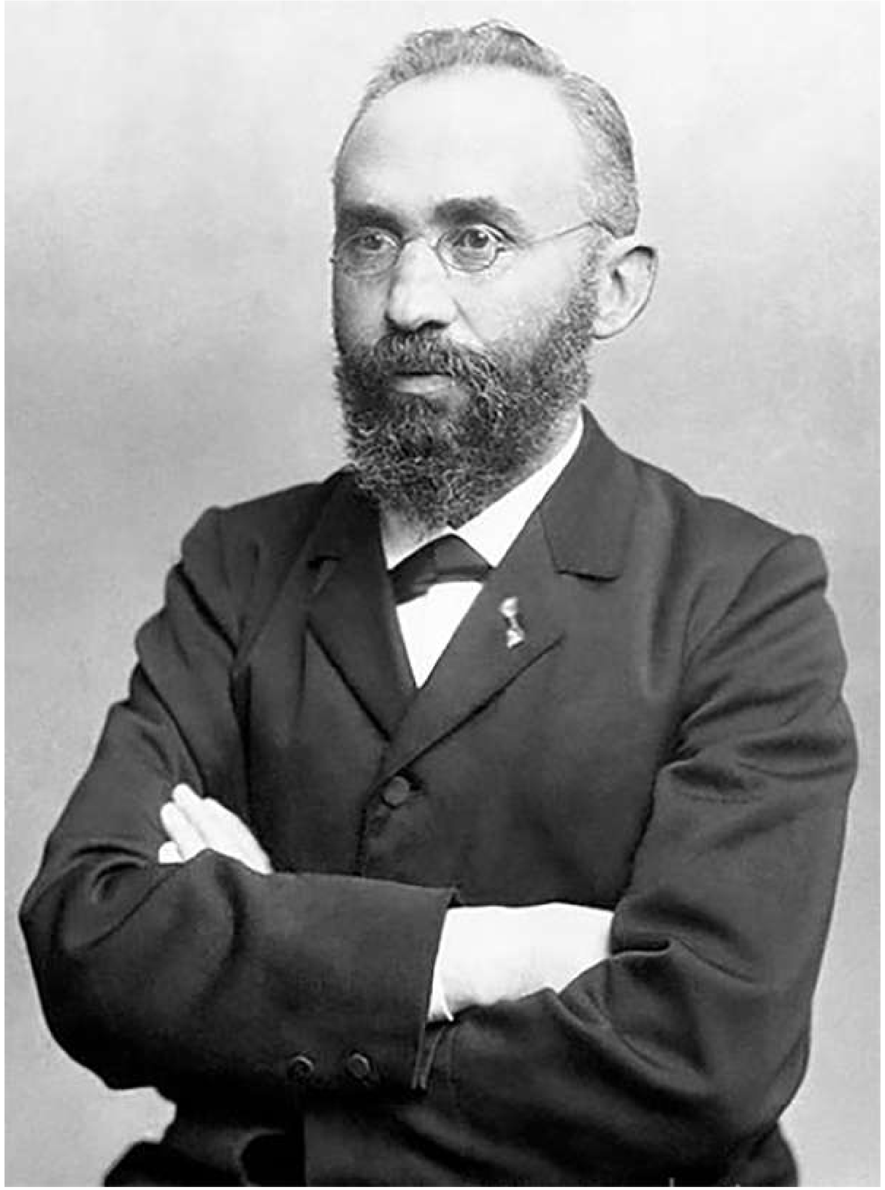
$$\tilde{\bar{h}}_{\alpha\beta} = \bar{h}_{\mu\nu}\frac{\partial x^\alpha}{\partial y^\mu}\frac{\partial x^\beta}{\partial y^\nu} \simeq \bar{h}_{\alpha\beta} - \frac{\partial \xi^\alpha}{\partial x^\beta} - \frac{\partial \xi^\beta}{\partial x^\alpha}$$

Lorenz gauge $$\frac{\partial \bar{h}^{\alpha\beta}}{\partial x^\beta} = 0$$

$$\eta^{\gamma\delta}\frac{\partial^2 \bar{h}_{\alpha\beta}}{\partial x^\gamma \partial x^\delta} = 0 \qquad -\frac{\partial^2 \bar{h}_{\alpha\beta}}{\partial t^2} + \frac{\partial^2 \bar{h}_{\alpha\beta}}{\partial x^2} + \frac{\partial^2 \bar{h}_{\alpha\beta}}{\partial y^2} + \frac{\partial^2 \bar{h}_{\alpha\beta}}{\partial z^2} = 0$$

$$\Box \bar{h}^{\alpha\beta} = 0$$ *The last dirty trick* $$\Box \xi_2^\alpha = 0$$

Lorenz or Lorentz?



Hendrik Antoon Lorentz

invented the Lorenz transformation

Ludvig Valentin Lorenz

invented the Lorenz gauge condition

$$\bar{h}_{\alpha\beta} = \Re[A_{\alpha\beta} \exp(ik_\mu x^\mu)] \qquad \omega \equiv k_0 = \sqrt{k_1^2 + k_2^2 + k_3^2}$$

$$\Box \bar{h}_{\alpha\beta} = 0, \quad \frac{\partial \bar{h}_{\alpha\beta}}{\partial x^\beta} = 0 \to k^\alpha k_\alpha = 0, \quad A_{\alpha\beta} k^\beta = 0$$

$$\Box \xi_2^\alpha = 0 \qquad y^\alpha = x^\alpha + \xi^\alpha \qquad \xi^\alpha = -iC^\alpha \exp(ik_\alpha x^\alpha)$$

So we may put four more conditions! $$A_{\alpha 0} = 0$$

But these are three conditions, not four, since: $$A_{\alpha\beta} k^\beta = 0 \to A_{0\alpha} k^\alpha = 0$$

Then we put the fourth $$\eta^{\alpha\beta} A_{\alpha\beta} \equiv A_\alpha{}^\alpha = 0$$

Итого $$A_{\alpha\beta} k^\beta = A_{\alpha 0} = A_\alpha{}^\alpha = 0$$

Thus, the TT-calibration

$$\bar{h}_{\alpha}{}^{\alpha} \equiv \bar{h} = \bar{h}_{\alpha\beta}k^{\beta} = \bar{h}_{\alpha 0} = 0$$

$$h_{\alpha\beta} = \bar{h}_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}\bar{h} \quad \rightarrow \quad h_{\alpha\beta} = \bar{h}_{\alpha\beta}$$

$$h_{\alpha}{}^{\alpha} \equiv h = h_{\alpha\beta}k^{\beta} = h_{\alpha 0} = 0$$

Let us consider a flat wave propagaing along OZ axis:

$$k_{\alpha} = (\omega, 0, 0, \omega)$$

$$h_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{xx} & h_{xy} & 0 \\ 0 & h_{xy} & -h_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \underbrace{h_{xx}dx^2 - h_{yy}dy^2}_{h_{+}} + \underbrace{2h_{xy}dxdy}_{h_{\times}}$$

Two polarizations of gravitational waves

$$h_+ = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{xx} & 0 & 0 \\ 0 & 0 & -h_{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad h_\times = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & h_{xy} & 0 \\ 0 & h_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

A bit of history...

- 1900 — Lorentz supposed that the gravitation may propagate with a speed, not exceeding the speed of light;

- 1905 — Henri Poincaré introduced the term «gravitational wave» (fr. onde gravitique). Laplace objected against the existence of the gravitational waves showing that they would make corrections of the order of v/c to the Newtonian law of gravitation, which contradicted to observations. Poincaré showed that the corrections mutually cancel each other;

- 1916 — Einstein showed that a mechanical system should emit gravitational waves within the framework of general relativity, although under normal conditions energy losses are of the order of $1/c^4$, being negligible and practically unmeasurable (in this work, he still mistakenly believed that a mechanical system that constantly retains spherical symmetry can emit gravitational waves).

Einstein’s changing attitude to gravitational waves

- **19 Feb 1916, letter to Schwarzshild:** *“Es gibt also keine Gravitationswellen, welche Lichtwellen analog wären”*
- **22 Jun 1916, article:** *“...so sieht man, daß A (die Ausstrahlung des Systems durch Gravitationswellen pro Zeiteneinheit) in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.”* Nährungsweise Integration der Feldgleichungen, *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 688*
- **31 Jan 1918, article:** *“Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.”* *Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften (Berlin), 1916 154*
- **1936 undated letter to Max Born:** *“Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they have been assumed a certainty to the first approximation.”*
- **1936 Princeton lecture:** *“If you ask me whether there are gravitational waves or not, I must answer that I do not know. But it is a highly interesting problem.”*

Herrn John T. Tate
Editor The Physical Review
University of Minnesota
Minneapolis, Minn.

Sehr geehrter Herr:

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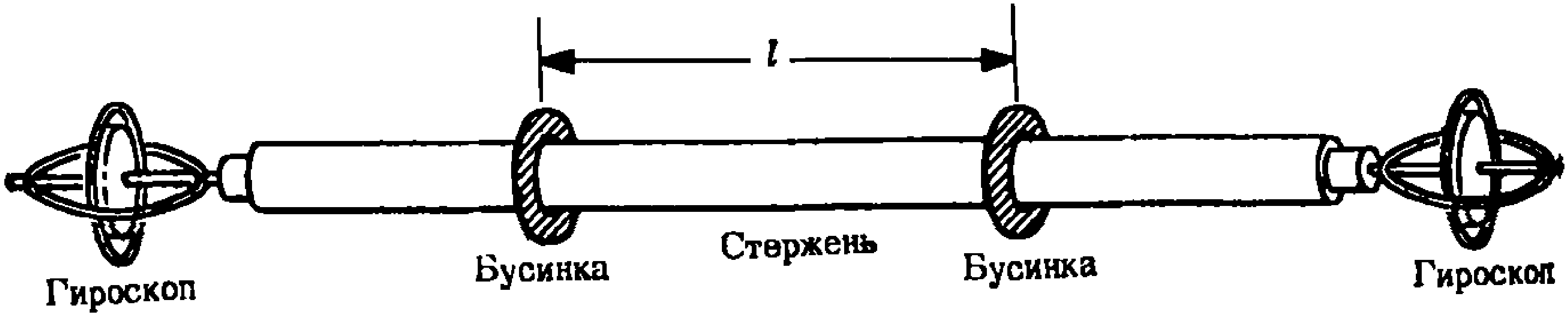
Mit vorzüglicher Hochachtung

P.S. Herr Rosen, der nach Sowjet-Russland abgereist ist, hat mich autorisiert, ihn in dieser Sache zu vertreten.

Bondi, Feinman, 1957



Consider a plane wave along the OZ axis. Then a unit vector along the bar is

$$\vec{n} = (\sin\theta\cos\phi; \sin\theta\sin\phi; \cos\theta)$$

Then the vibration amplitude of the beads is

$$l = l_0(1 + \frac{1}{2}h_{xx}\sin^2\theta\cos 2\phi + \frac{1}{2}h_{xy}\sin^2\theta\sin 2\phi)$$

Misner, Thorne, Wheeler, Gravitation, Vol 2

$$a^i = \sum_{j=1}^{3}\frac{\ddot{h}_{ij}^{TT}l^j}{2}$$

The Feynman's opinion about the conference

“I am not getting anything out of the meeting. I am learning nothing. Because there are no experiments this field is not an active one, so few of the best men are doing work in it. The result is that there are hosts of dopes here and it is not good for my blood pressure...

...Remind me not to come to any more gravity Conferences!”

R. Feynman, What Do You Care What Other People Think? P91, 1988 (Warsaw meeting 1962)

Emission of gravitational waves

$$h \sim m\frac{da}{dt}$$

$$m_1 a_1 = -m_2 a_2 \quad \rightarrow \quad m_1\frac{da_1}{dt} + m_2\frac{da_2}{dt} \simeq 0$$

$$\left(\left(\frac{v}{c}\right)^3 \frac{r_g}{r}\right)^2$$

$$r_g = \frac{2Gm}{c^2}$$

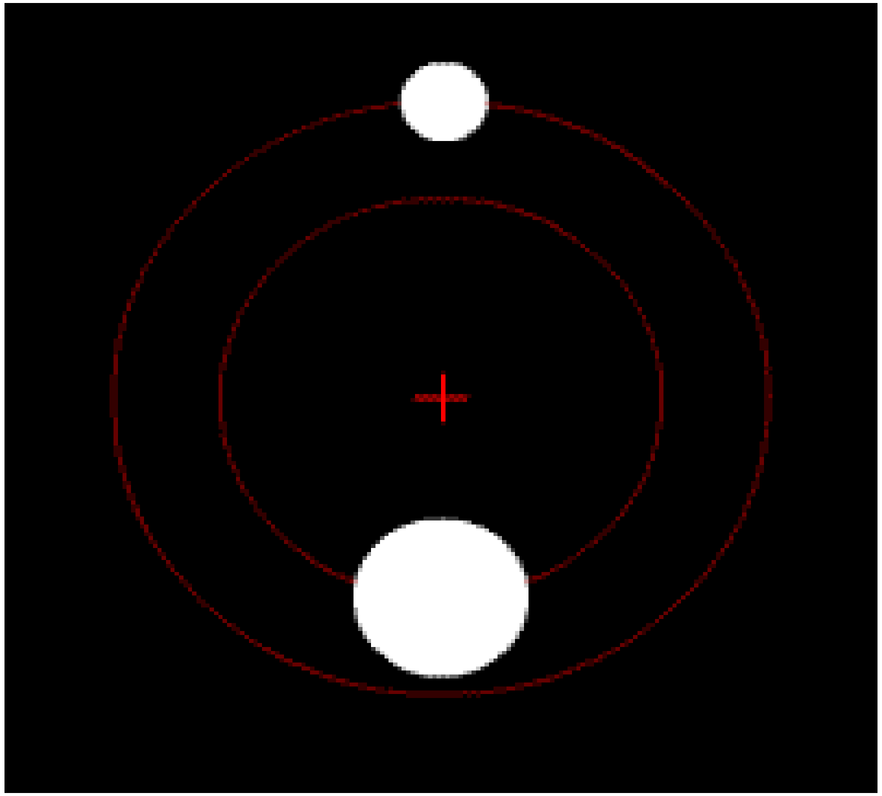
$$D_{ij} = \int \rho(3x_i x_j - r^2\delta_{ij})dV$$

$$-\frac{dE}{dt} = \frac{G}{45c^5}\dddot{D}_{ij}\dddot{D}^{ij}$$

Potential sources of gravitational waves

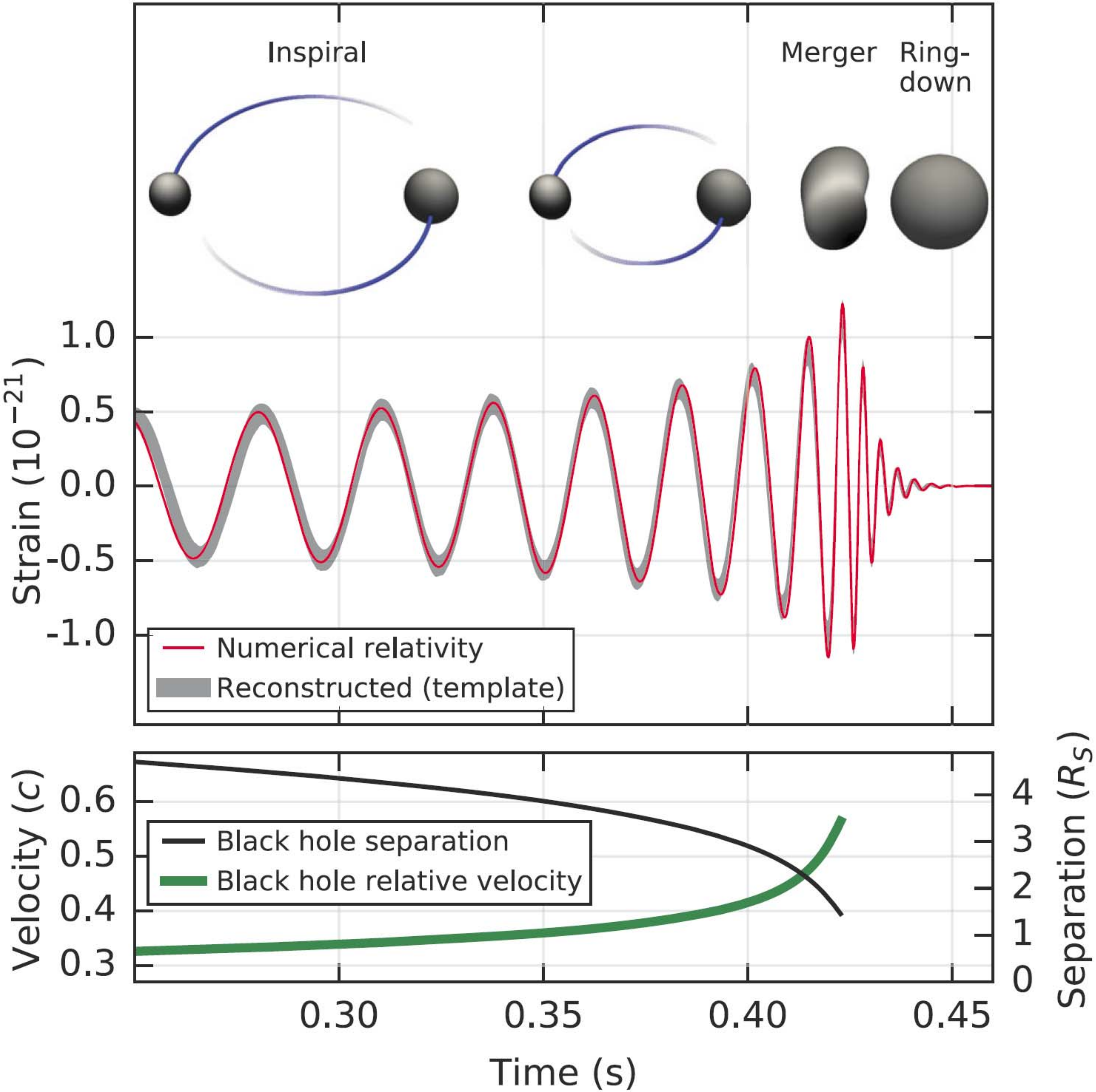
- Binary compact objects (neutron stars, black holes, white dwarfs)
- Collisions of galaxies and their clusters
- Asymmetric collapse of stars
- Cosmological gravitational waves
- In general, almost any accelerated motion of masses (except for a spherically-symmetric one)

A binary system

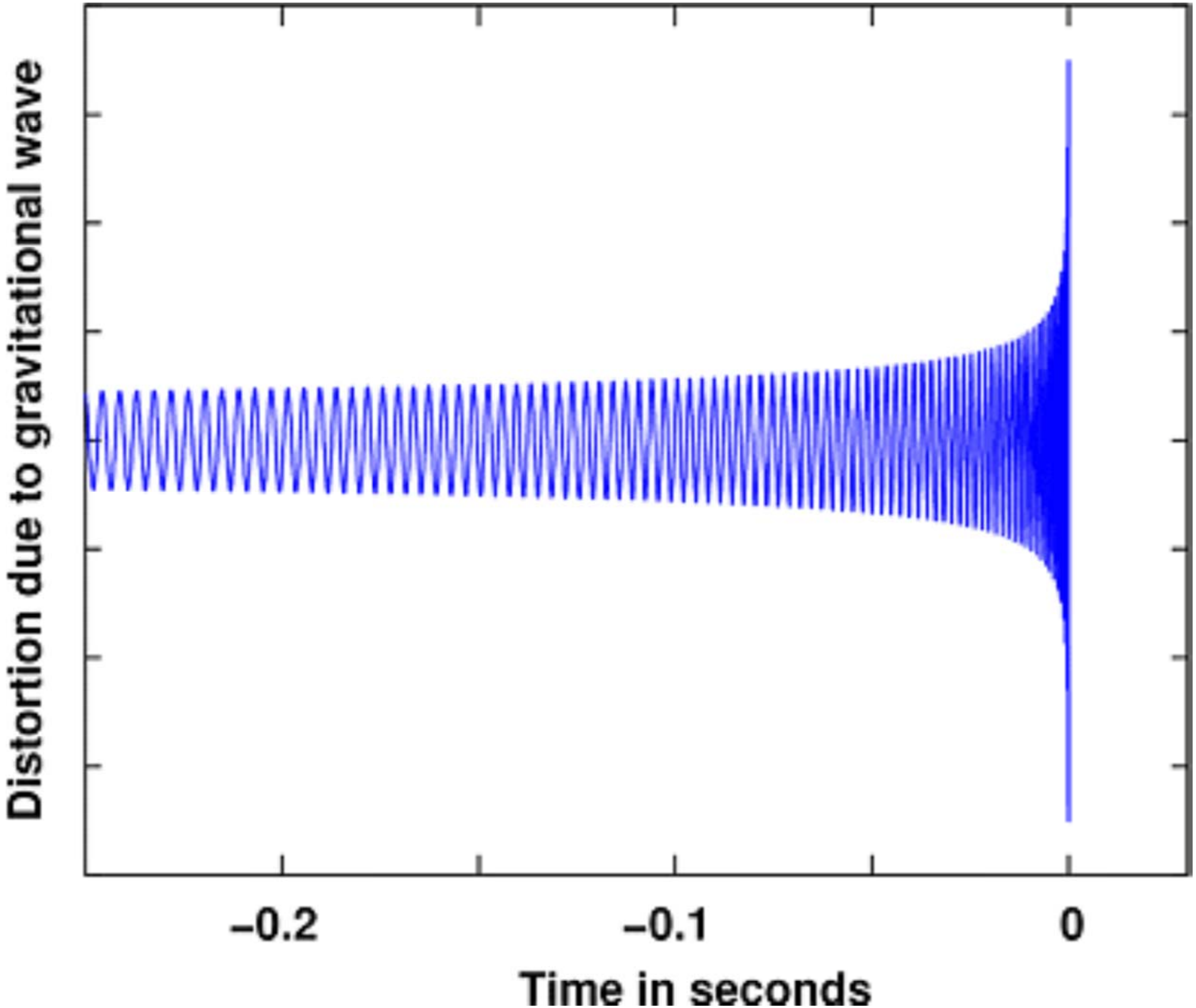


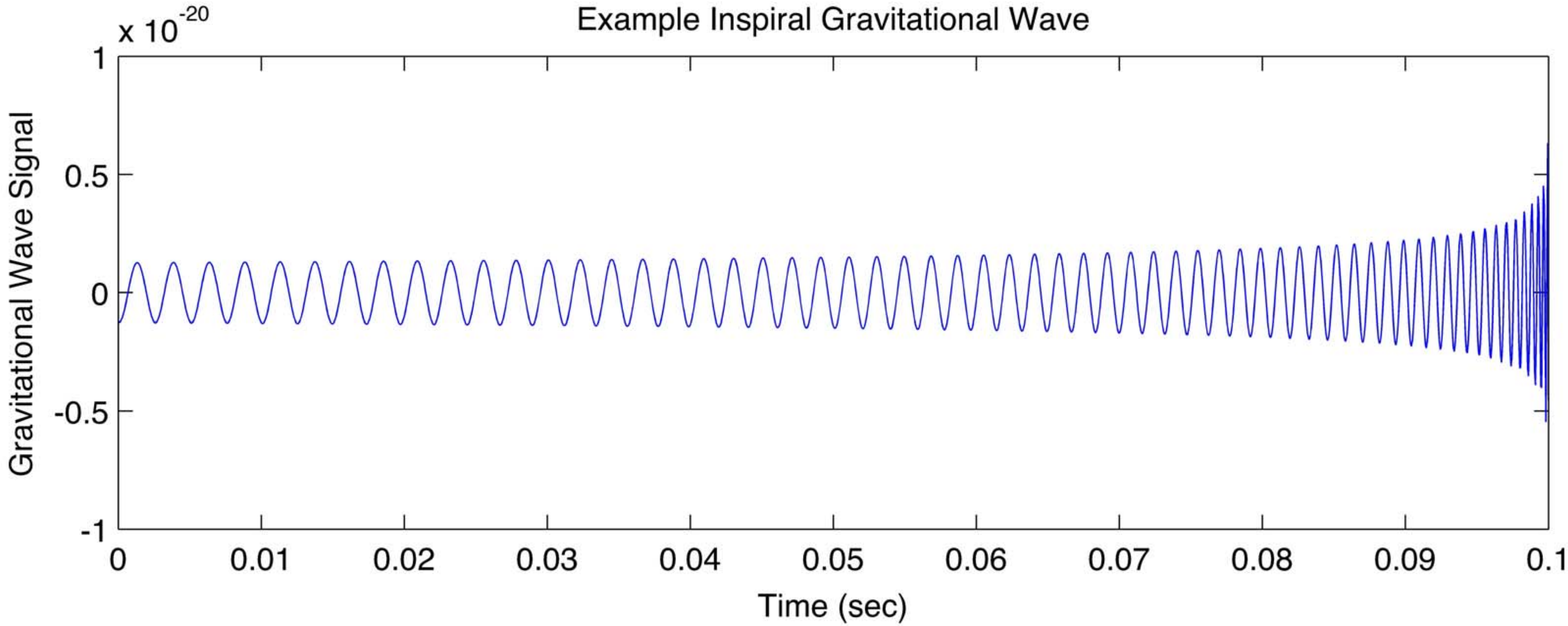
$$-\frac{dE}{dt} = \frac{32G^4 m_1^2 m_2^2 (m_1 + m_2)}{5c^5 r^5}$$

$$-\frac{dr}{dt} = \frac{64G^3 m_1 m_2 (m_1 + m_2)}{5c^5 r^3}$$


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

A chirp from neutron stars





Schutz (1986);

Cutler&Flanagan (1994)

arXiv:gr-qc/9402014

$$M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

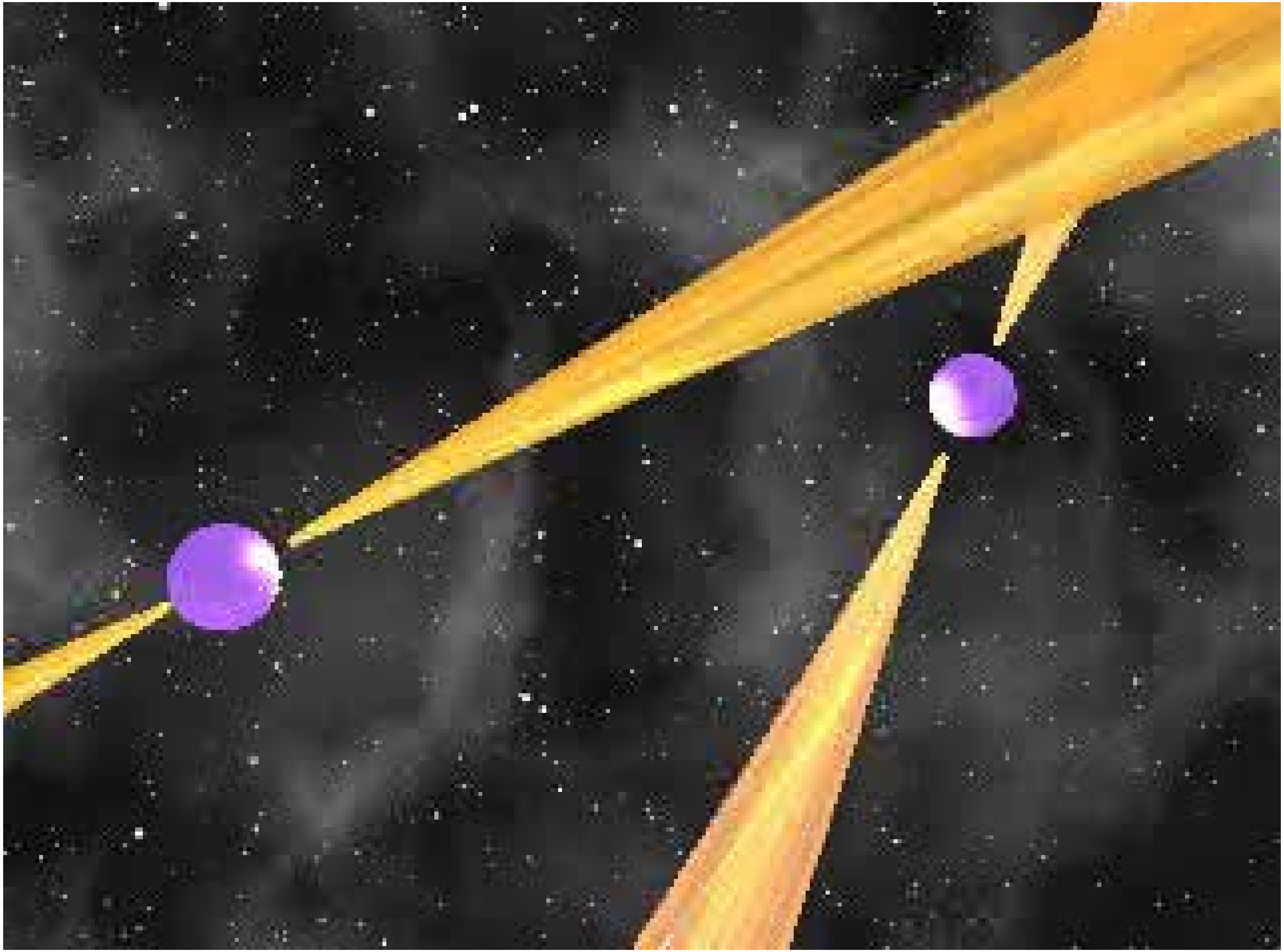
$$M_{chirp} = \frac{c^3}{G}\left(\frac{5\pi^{-8/3}}{96} f^{-11/3}\dot{f}\right)^{3/5}$$

Joseph Weber,

late 60'th

Resonant detector

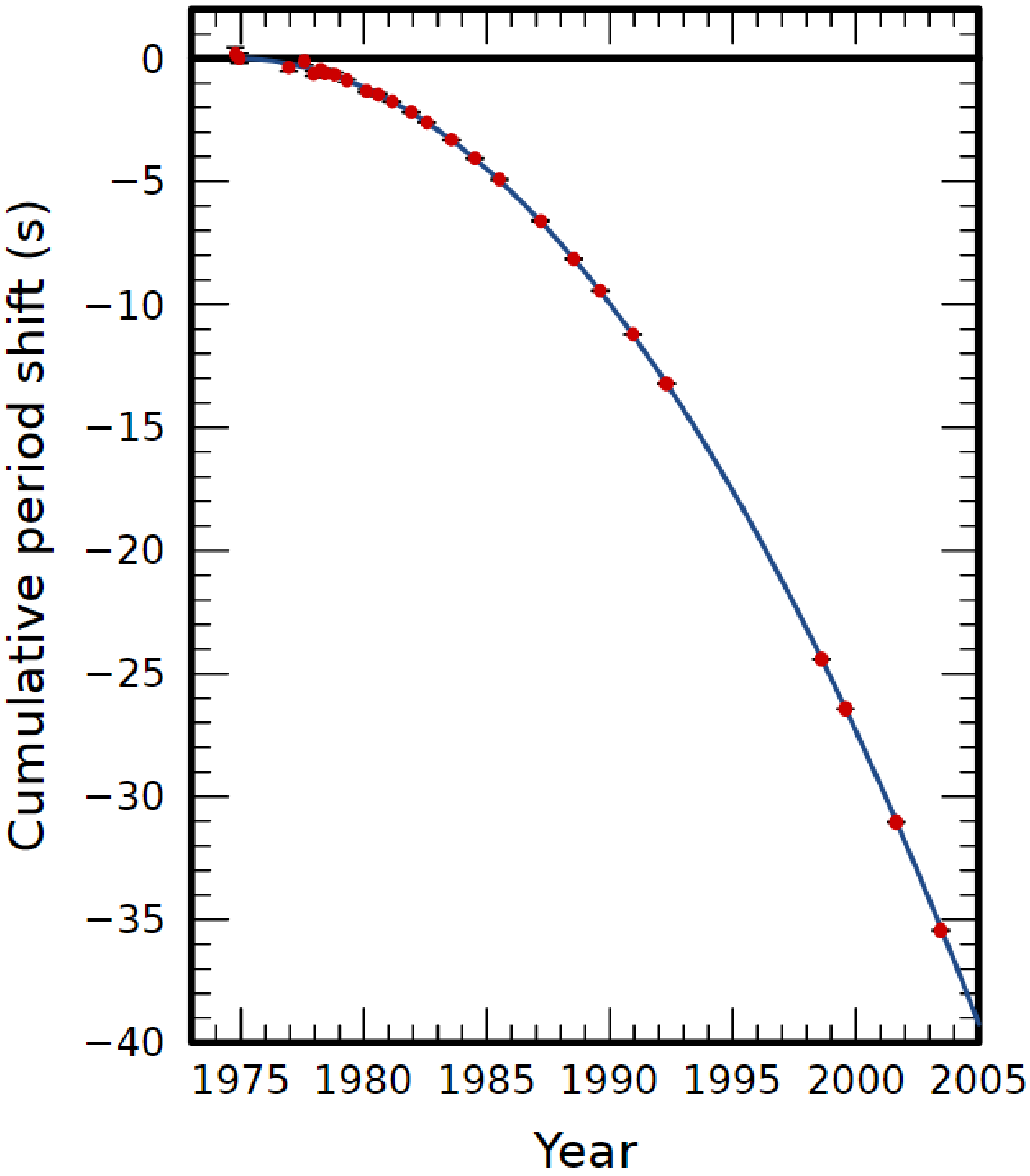
PSR J0737−3039

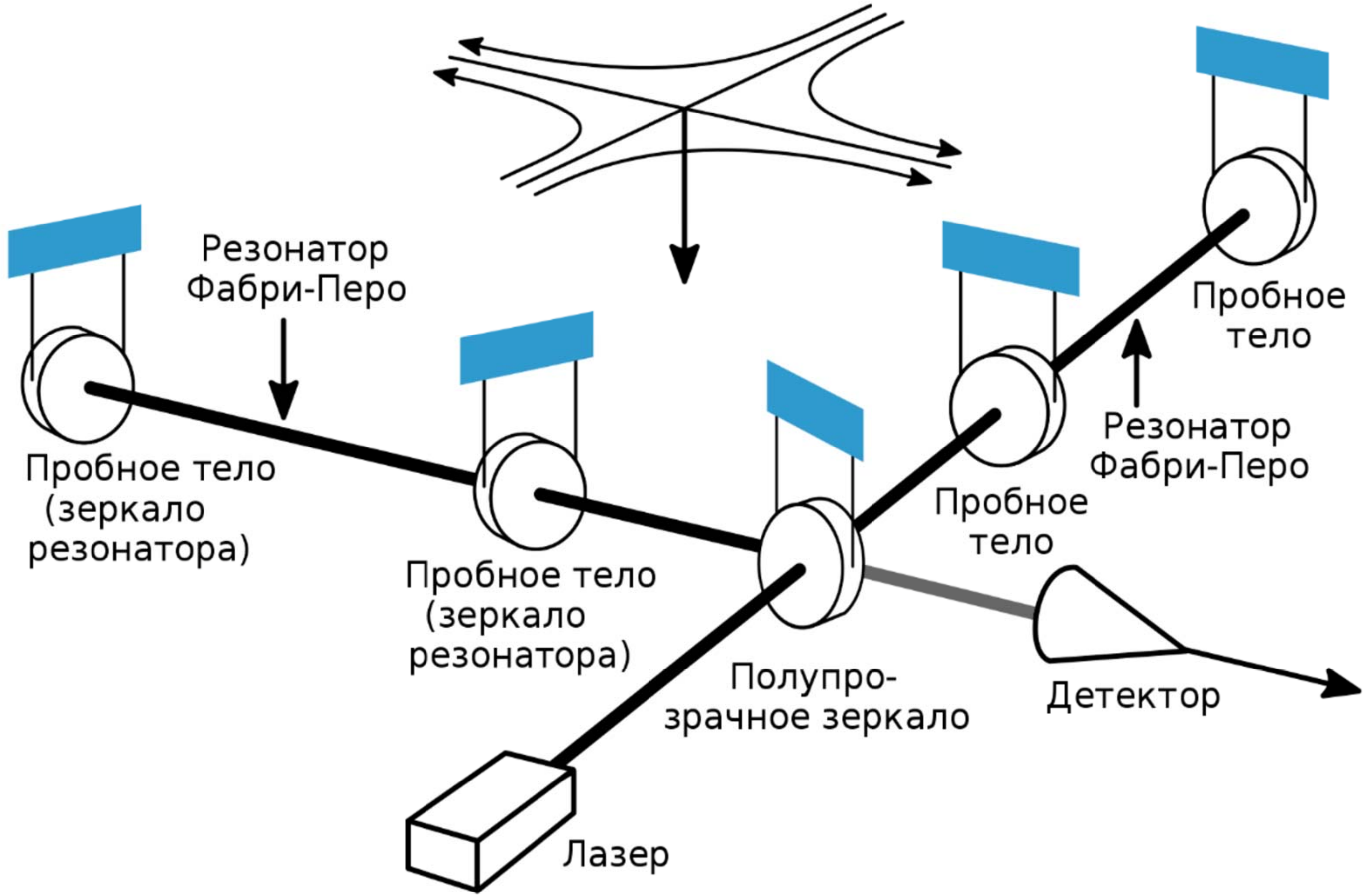


Hulse–Taylor binary pulsar PSR J1915+1606 (1974)

Binary neutron star

They will collide in ~300 mln. years

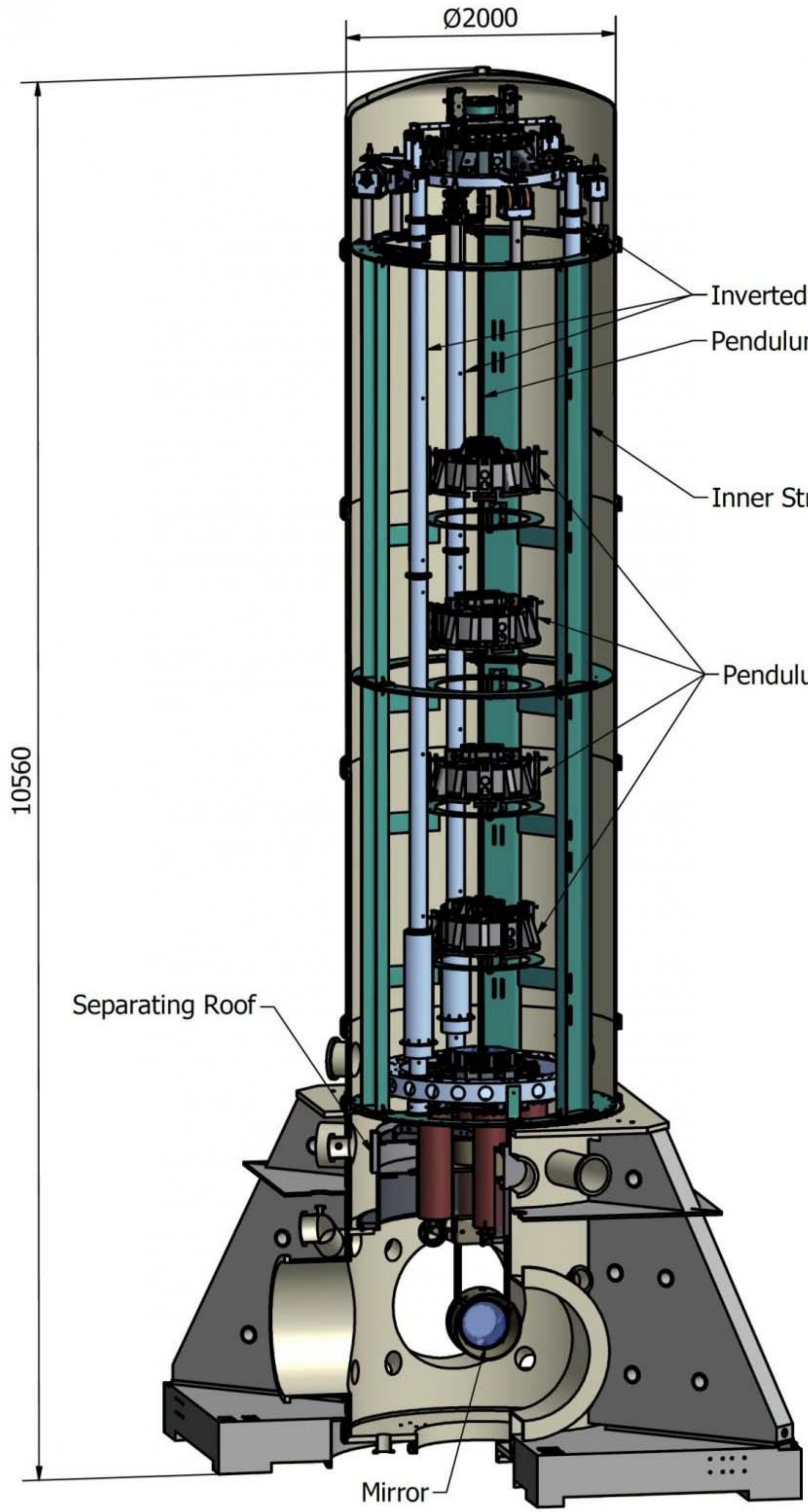



Резонатор
Фабри-Перо
Пробное
тело
Пробное тело
(зеркало
резонатора)
Пробное тело
(зеркало
резонатора)
Пробное
тело
Резонатор
Фабри-Перо
Полупро-
зрачное зеркало
Детектор
Лазер

VIRGO

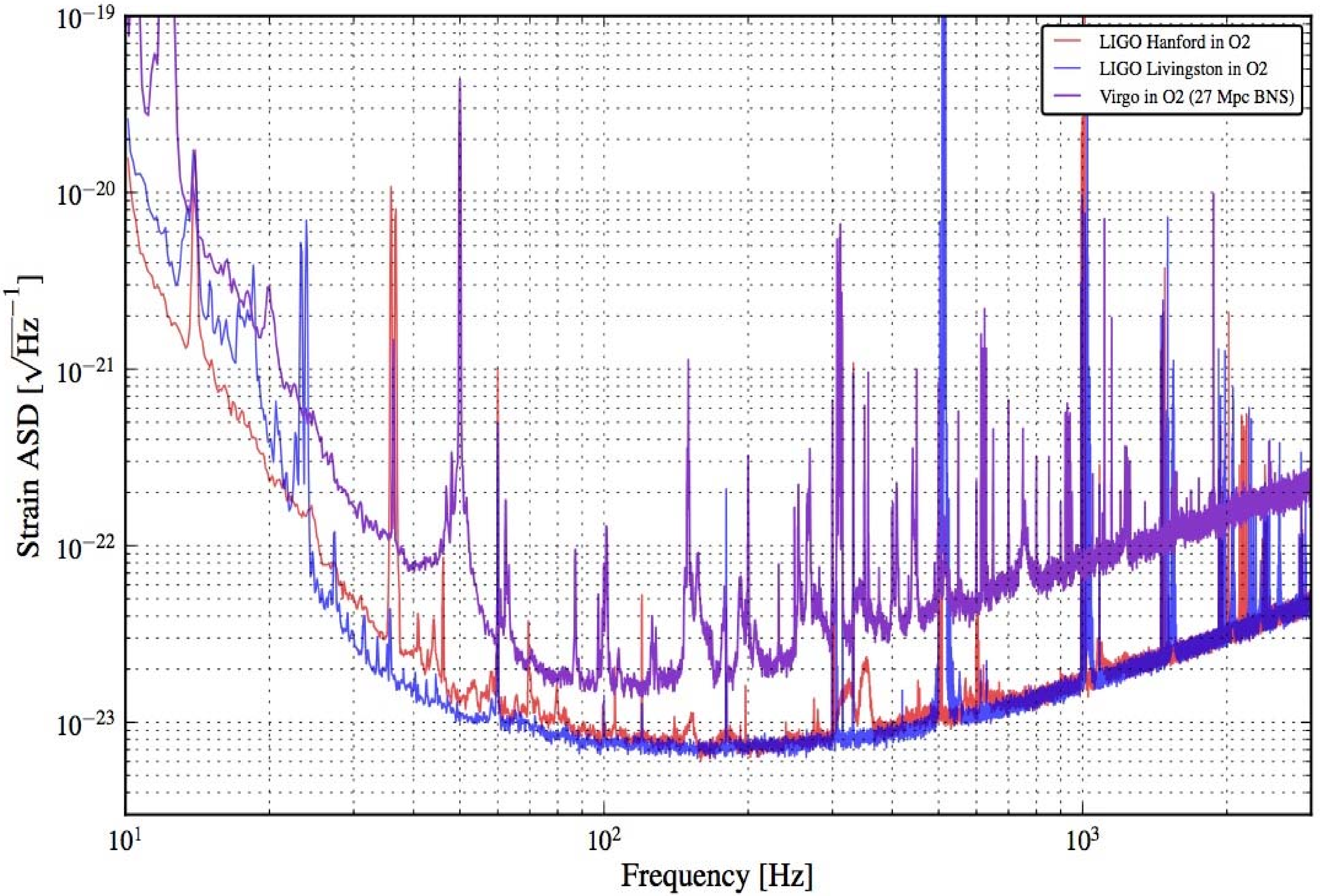
Mirror mount

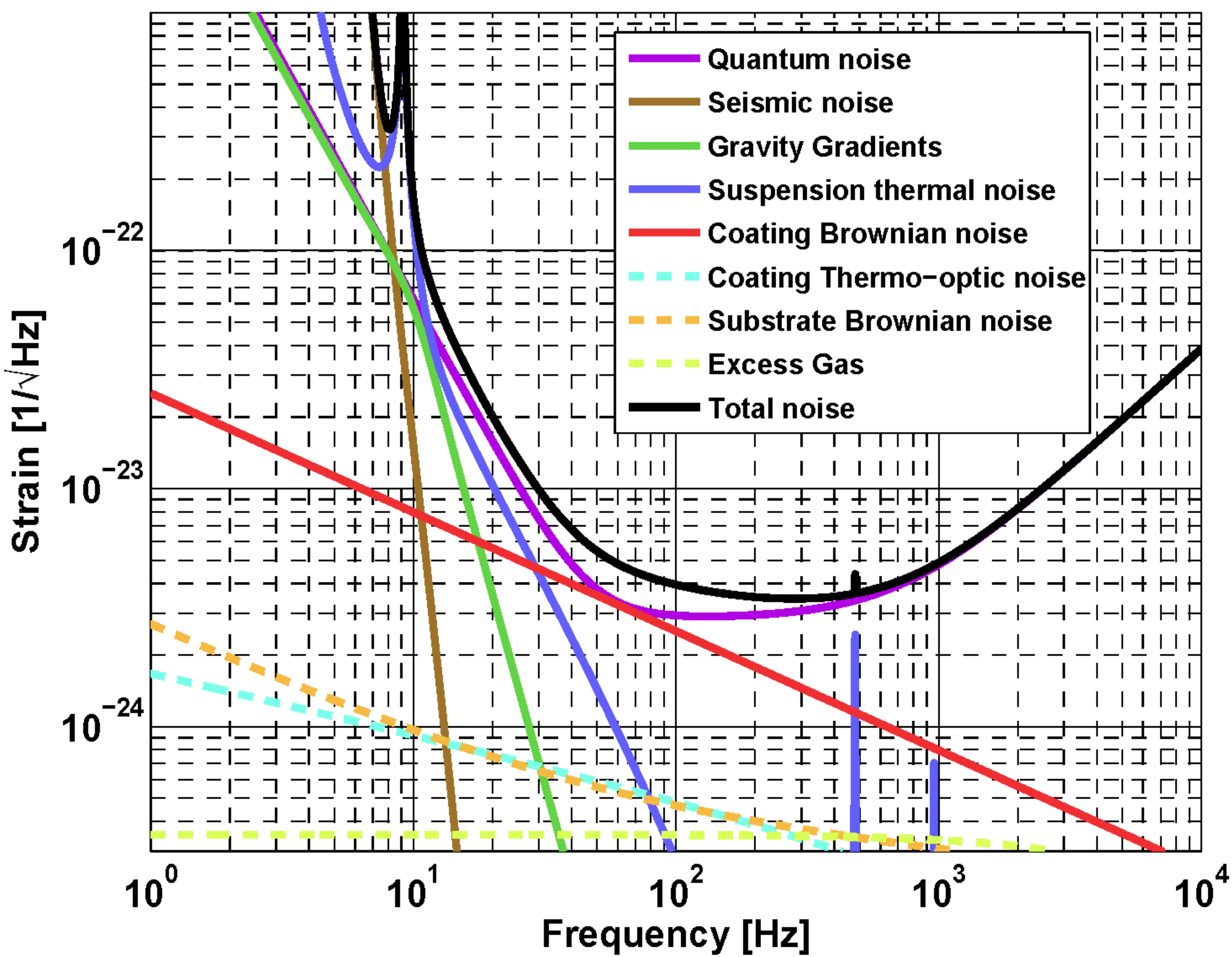
Adalberto Giazotto



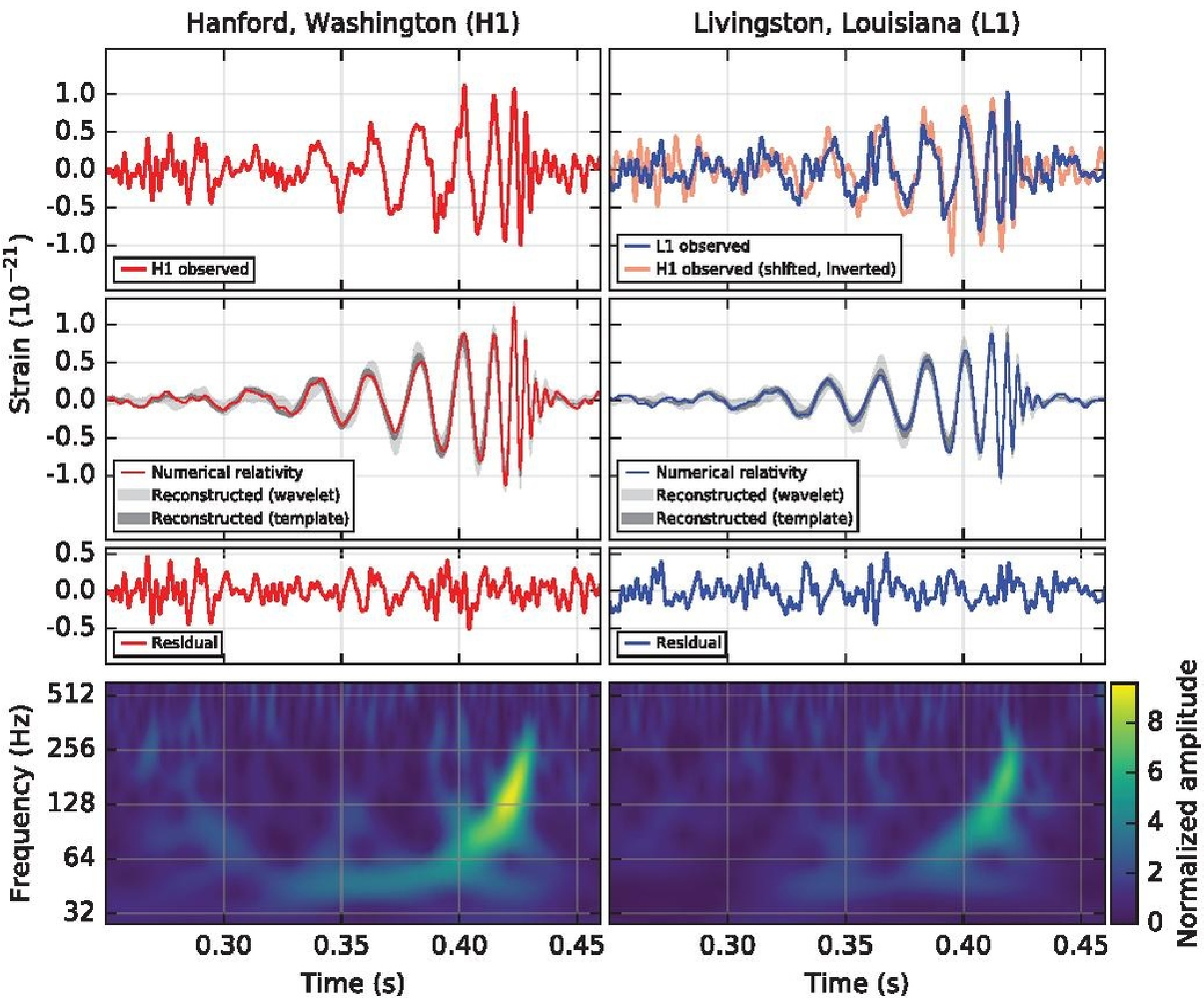
Earth

Sp


LIGO Hanford in O2
LIGO Livingston in O2
Virgo in O2 (27 Mpc BNS)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
Strain ASD [$\sqrt{\mathrm{Hz}}^{-1}$]
10^{1}
10^{2}
10^{3}
Frequency [Hz]

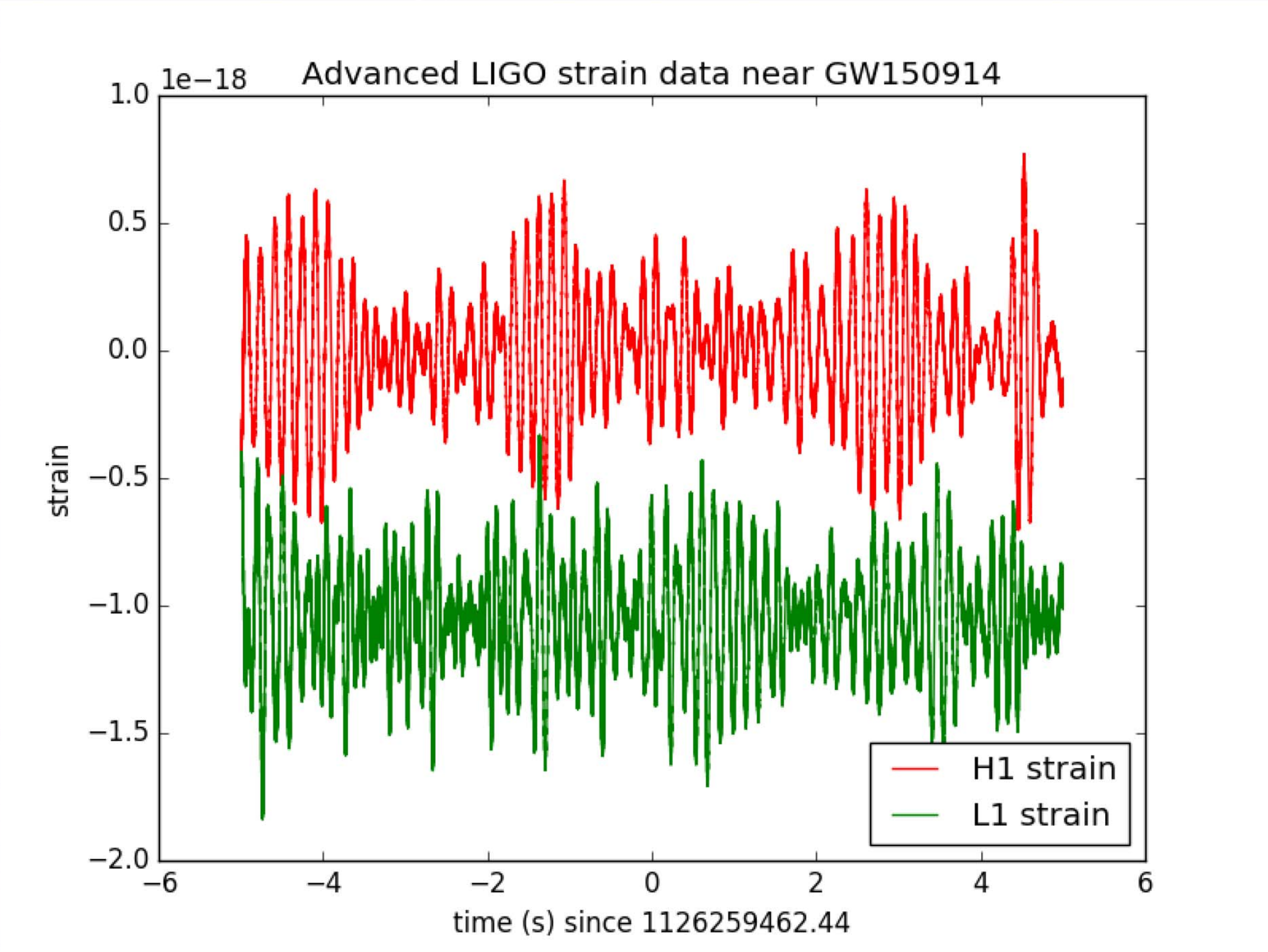


Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)

Data without whitening or band pass



Source: LOSC

26,768 views | Jun 16, 2017, 04:30pm

Was It All Just Noise? Independent Analysis Casts Doubt On LIGO's Detections

Starts With A Bang Contributor
Starts With A Bang Contributor Group ⓘ
Science

POST WRITTEN BY

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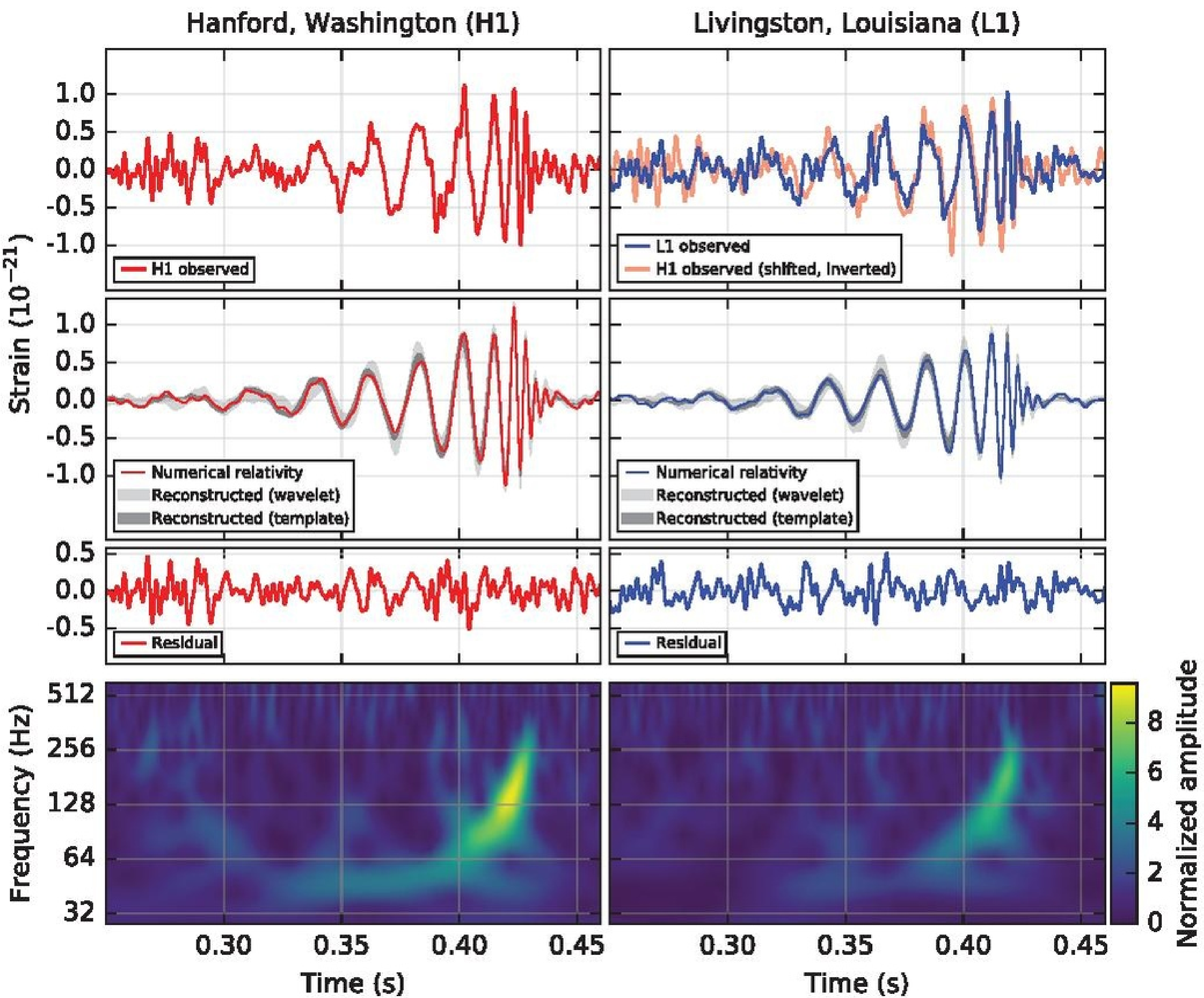
GW150914

- September 14, 2015 at 9:50:45 UTC, detected by the two LIGO detectors, first in Livingston, and 7ms later - in Hanford

- Merging of two black holes, $36_{-4}^{+5}\ M_{sun}$ and $29_{-4}^{+5}\ M_{sun}$

- A single black hole of mass $62_{-4}^{+4}\ M_{sun}$ was formed, and $3_{-0.5}^{+0.5}\ M_{sun}$ were gone with gravitational waves.

- The distance to the event is 410_{-140}^{+160}Mpc, ~1300 mln. light years



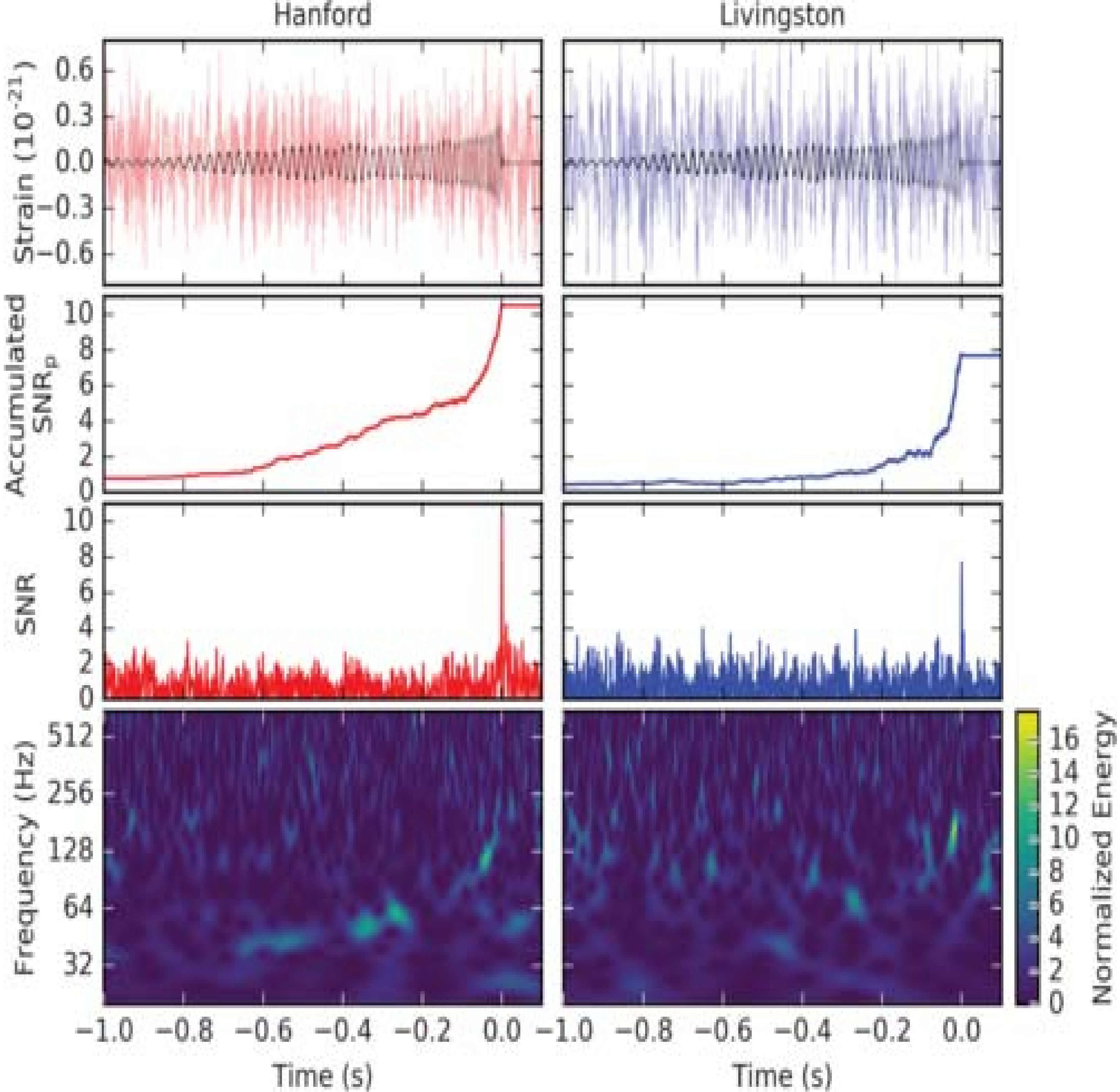
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
0
2
4
6
8
0.30
0.35
0.40
0.45
Time (s)

GW151226

- December 26, 2015, detected by the two LIGO detectors, first in Livingston, and 1.1 ms later - in Hanford

- Merging of two black holes, $14.2_{-3.7}^{+8.3}$ M_{sun} and $7.5_{-2.3}^{+2.3}$ M_{sun}. A single black hole of mass $20.8_{-1.7}^{+6.1}$ M_{sun} was formed, and $1_{-0.2}^{+0.1}$ M_{sun} were gone with gravitational waves.

- The distance to the event is 440_{-190}^{+180} Mpc, ~1400 mln. light years.

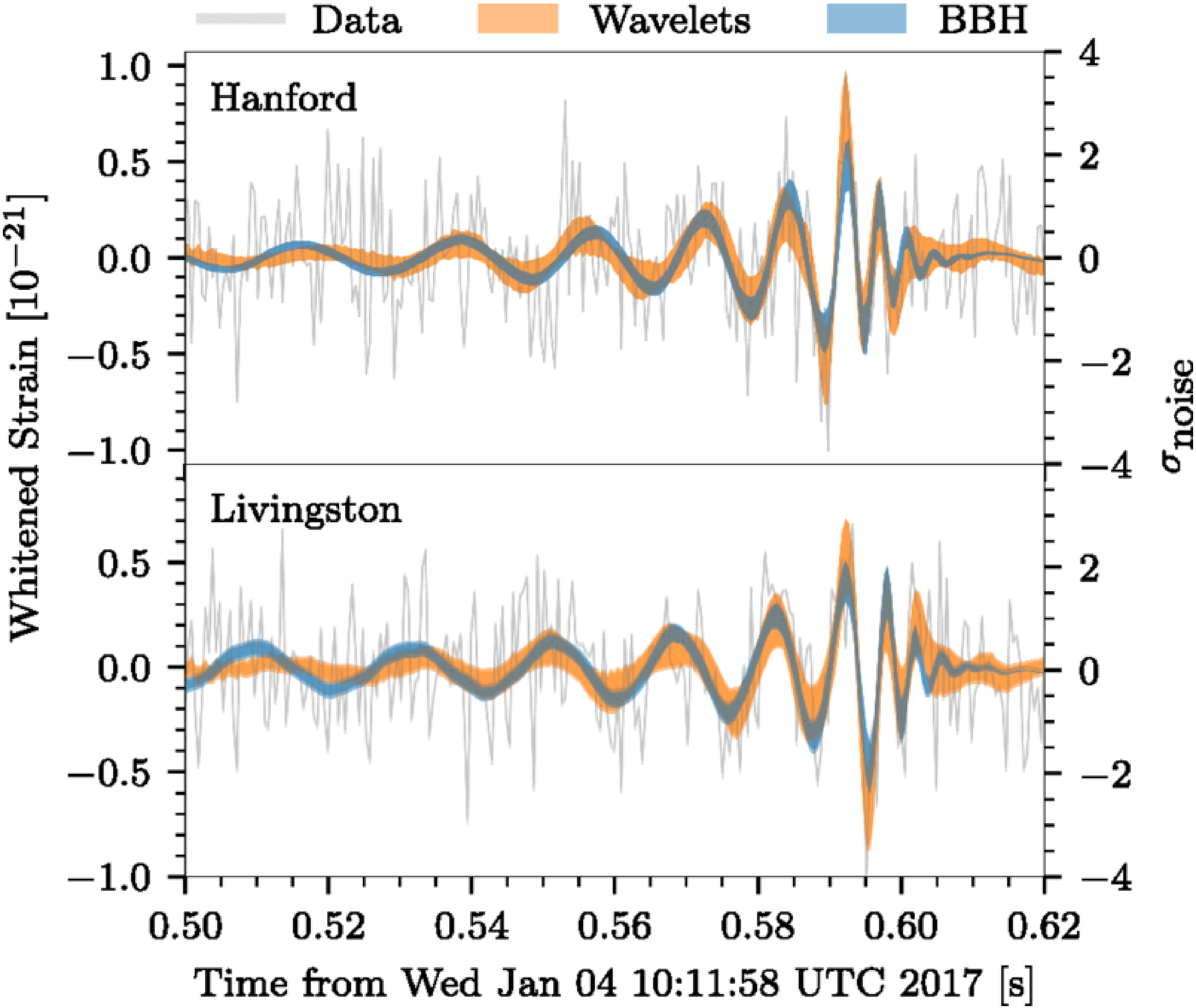

Hanford
Livingston
Strain (10^{-21})
Accumulated SNR$_p$
SNR
Frequency (Hz)
Normalized Energy
Time (s)
Time (s)

GW170104

- January 14, 2015 at 10:11:58,6 UTC, detected by the two LIGO detectors, first in Hanford, and 3 ms later - in Livingston

- Merging of two black holes, $31.2_{-6.0}^{+8.4}$ M_{sun} and $19.4_{-5.9}^{+5.3}$ M_{sun}. A single black hole of mass $48.7_{-4.6}^{+5.7}$ M_{sun} was formed, and 2 M_{sun} were gone with gravitational waves.

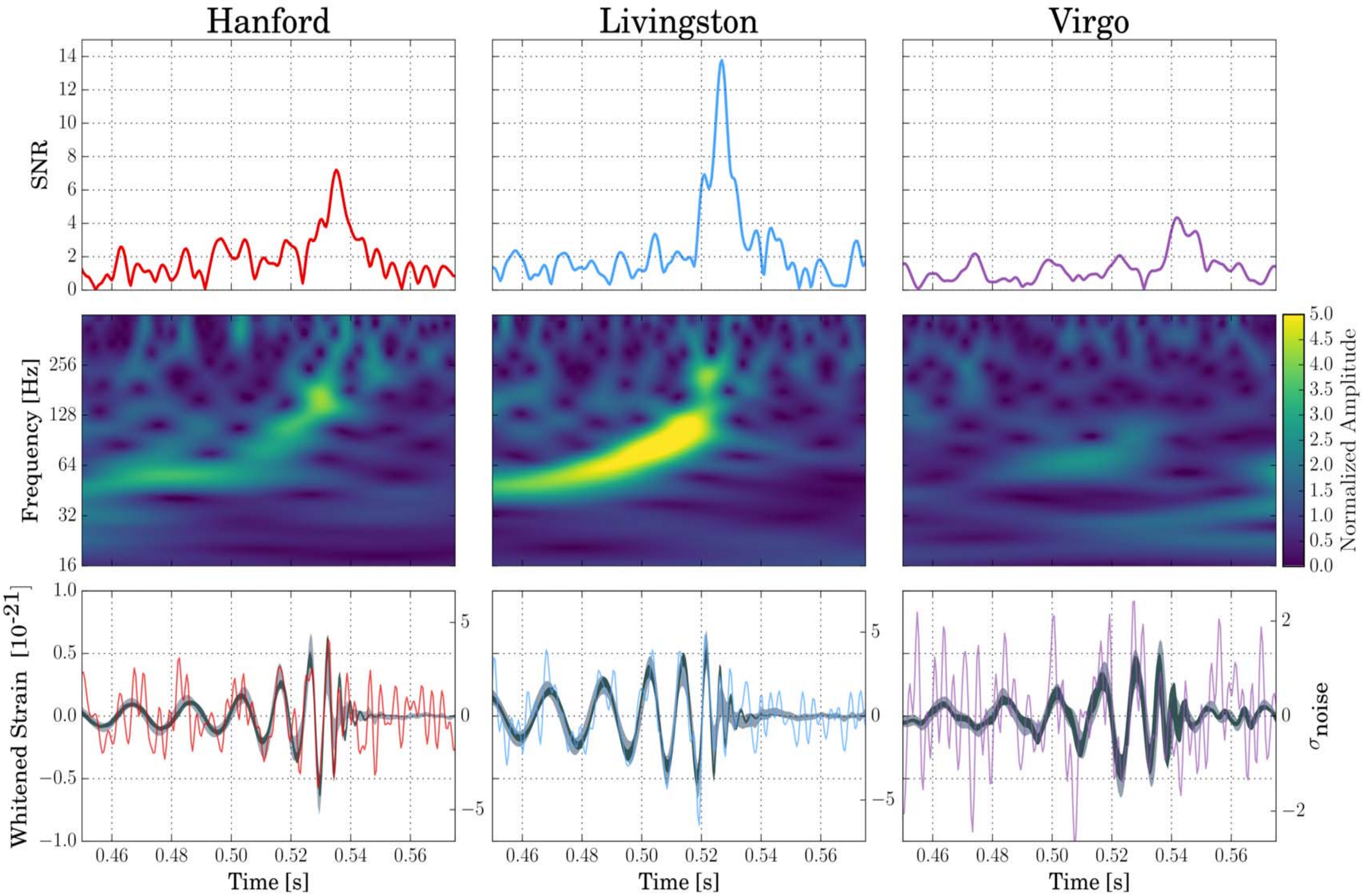
- The distance to the event is 880_{-390}^{+450} Mpc, ~2900 mln. light years.



Data
Wavelets
BBH
Hanford
Livingston
Whitened Strain [10^{-21}]
σ_{noise}
1.0
0.5
0.0
−0.5
−1.0
4
2
0
−2
−4
0.50
0.52
0.54
0.56
0.58
0.60
0.62
Time from Wed Jan 04 10:11:58 UTC 2017 [s]

GW170814

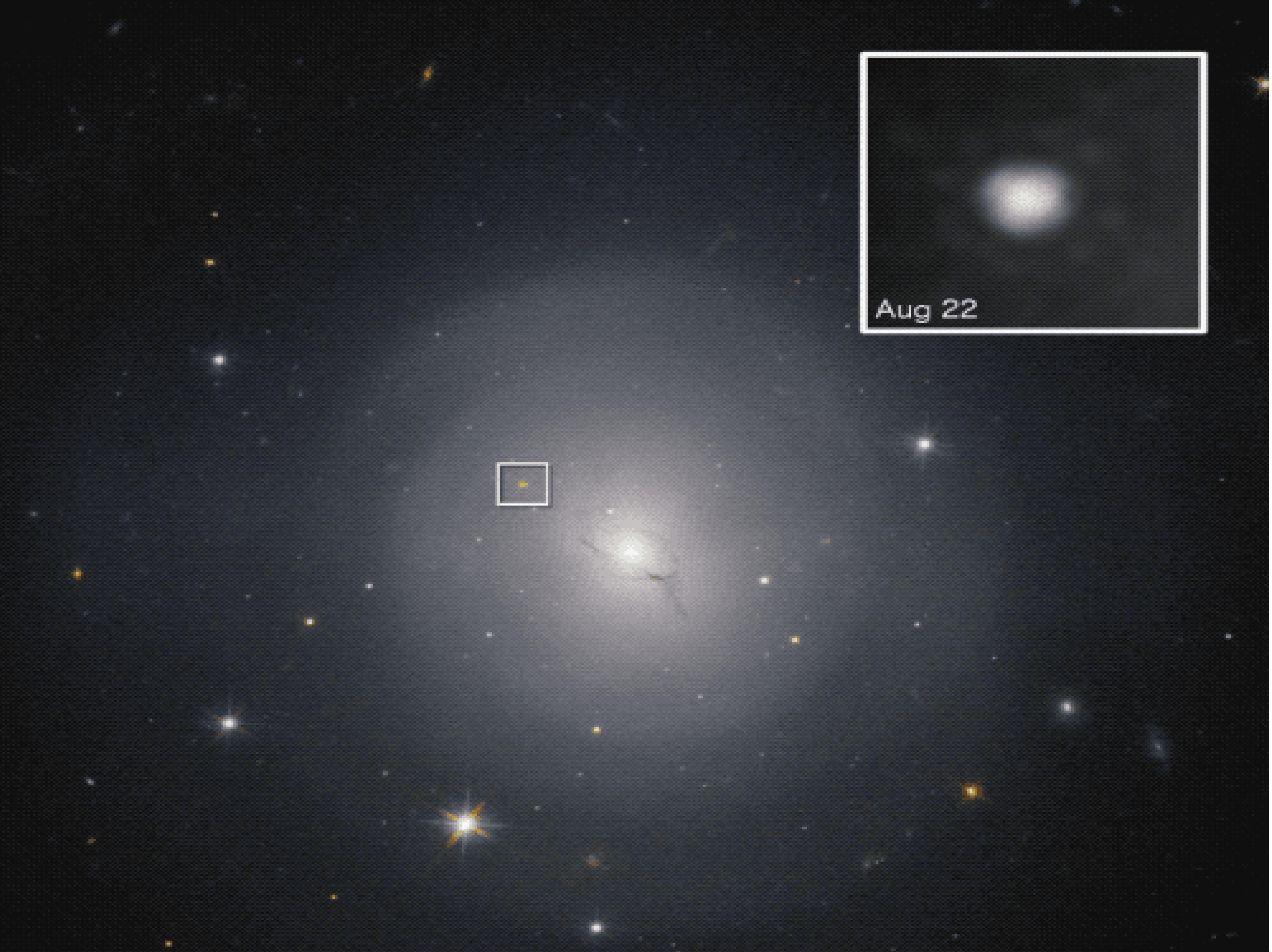
- August 14, 2017 at 9:50:45 UTC, detected by all three detectors, first in Livingston, and 8ms later - in Hanford, and 14ms later by VIRGO. The possible area of the event decreased from 1160 to 60 square degrees.
- Merging of two black holes, 31 M_{sun} and 25 M_{sun}. A single black hole of mass 53 M_{sun} was formed, and 3 M_{sun} were gone with gravitational waves.
- The distance to the event is 567 Mpc, ~1800 mln. light years.
- The first experimental estimation of the polarization of gravitational waves

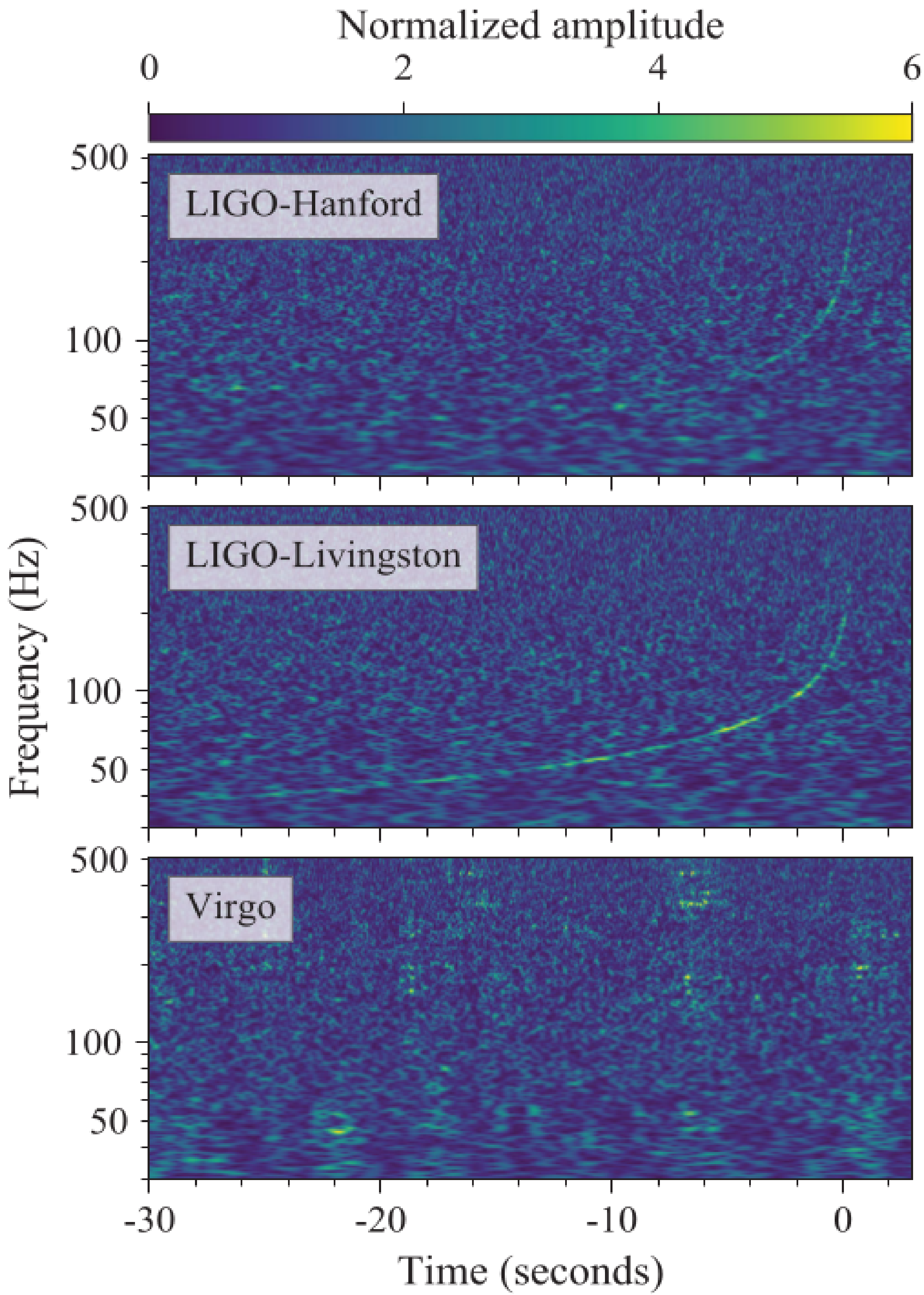


Hanford
Livingston
Virgo
SNR
Frequency [Hz]
Normalized Amplitude
Whitened Strain [10^{-21}]
σ_{noise}
Time [s]

GW170817

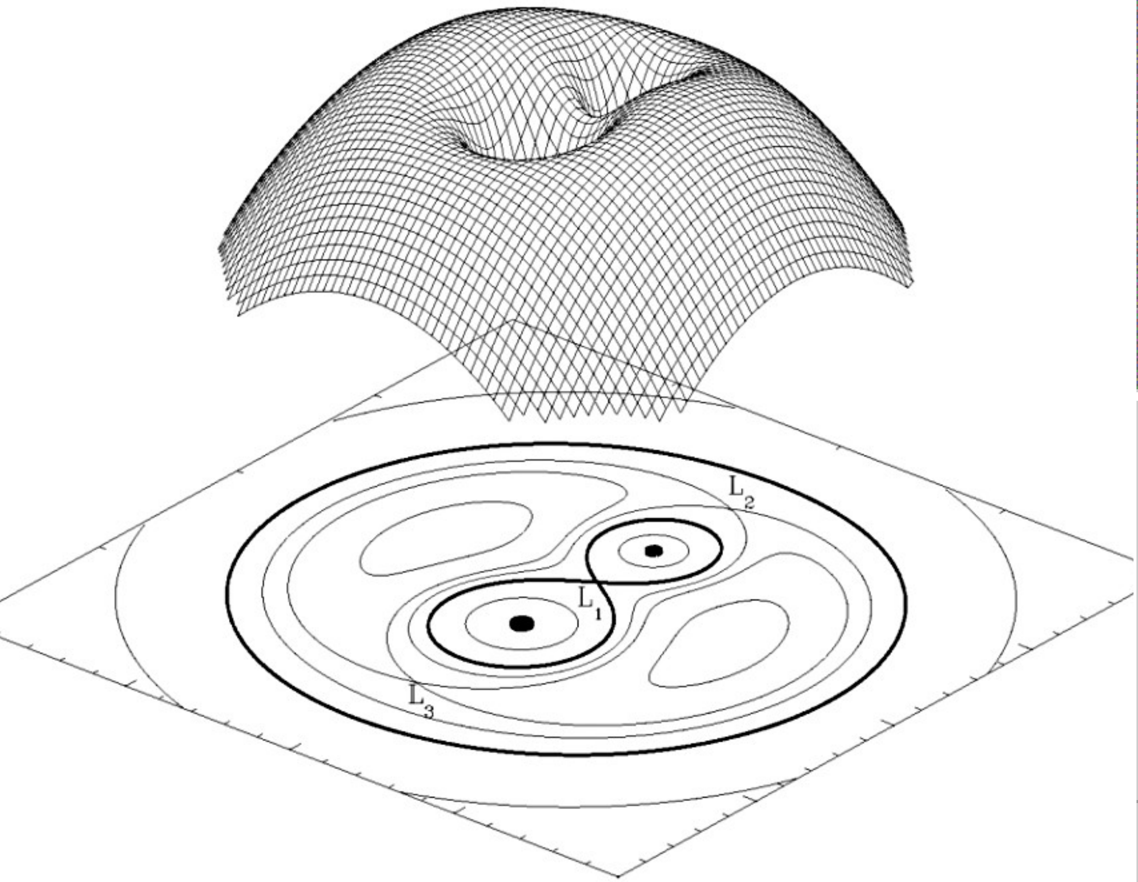
- August 17, 2017 at 12:41:04,4 UTC, by all three detectors.
- A merging of two neutron stars, 1.36–2.26 M_{sun} и 0.86–1.36 M_{sun}, more than 0.025 M_{sun} emitted as grav. waves
- NGC 4993 (Hydra constellation), distance 40_{-14}^{+8} Mpc, ~130 mln. light years
- The source was localized inside 28 square degrees
- First elecromagnetic component
- Short gamma-burst GRB 170817A in 1,74 ± 0,05 s after the maximum of the chirp
- Ultraviolet and infrared signals
- Radio and X-rays appeared only in a couple of days

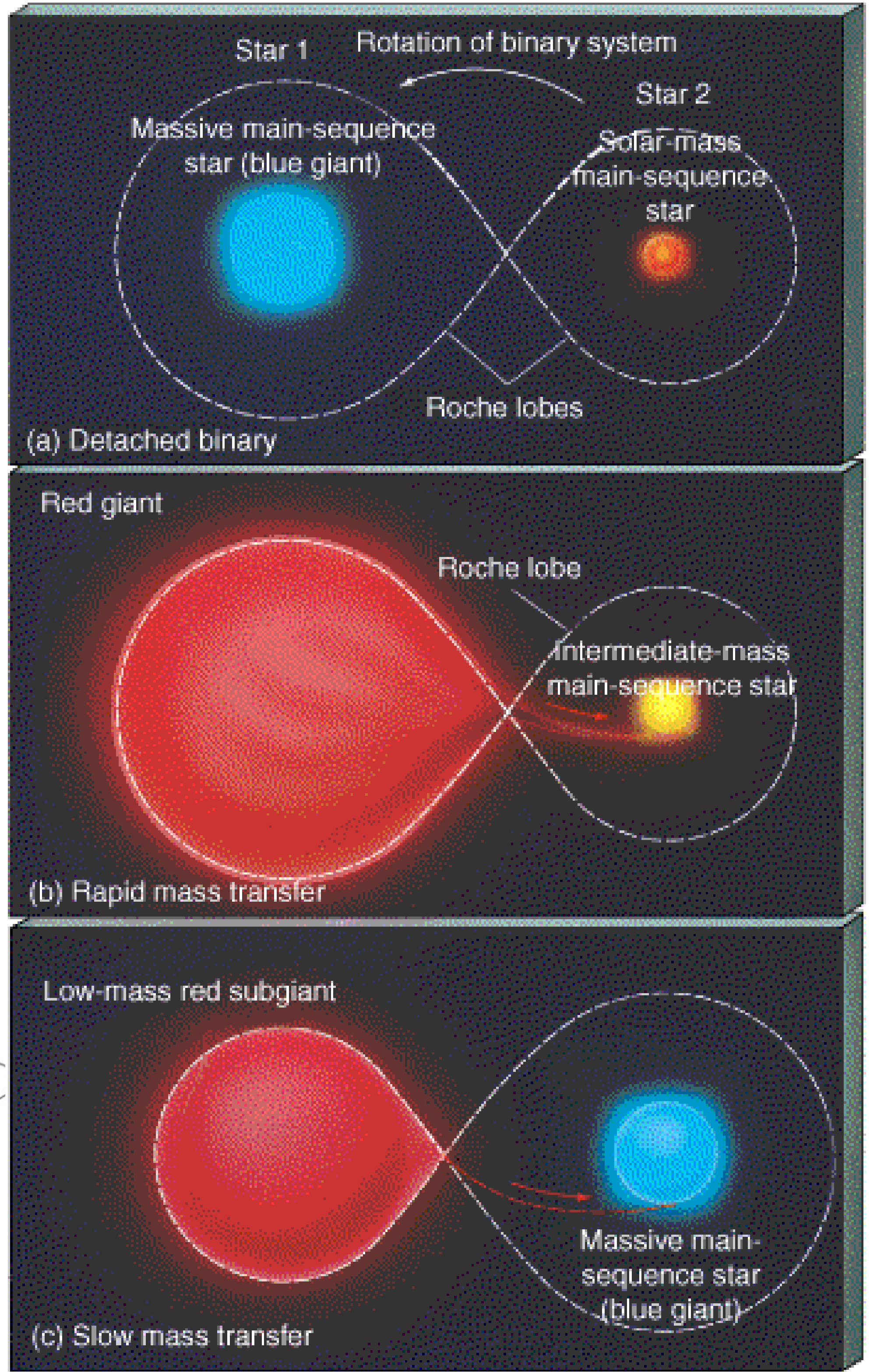

Aug 22

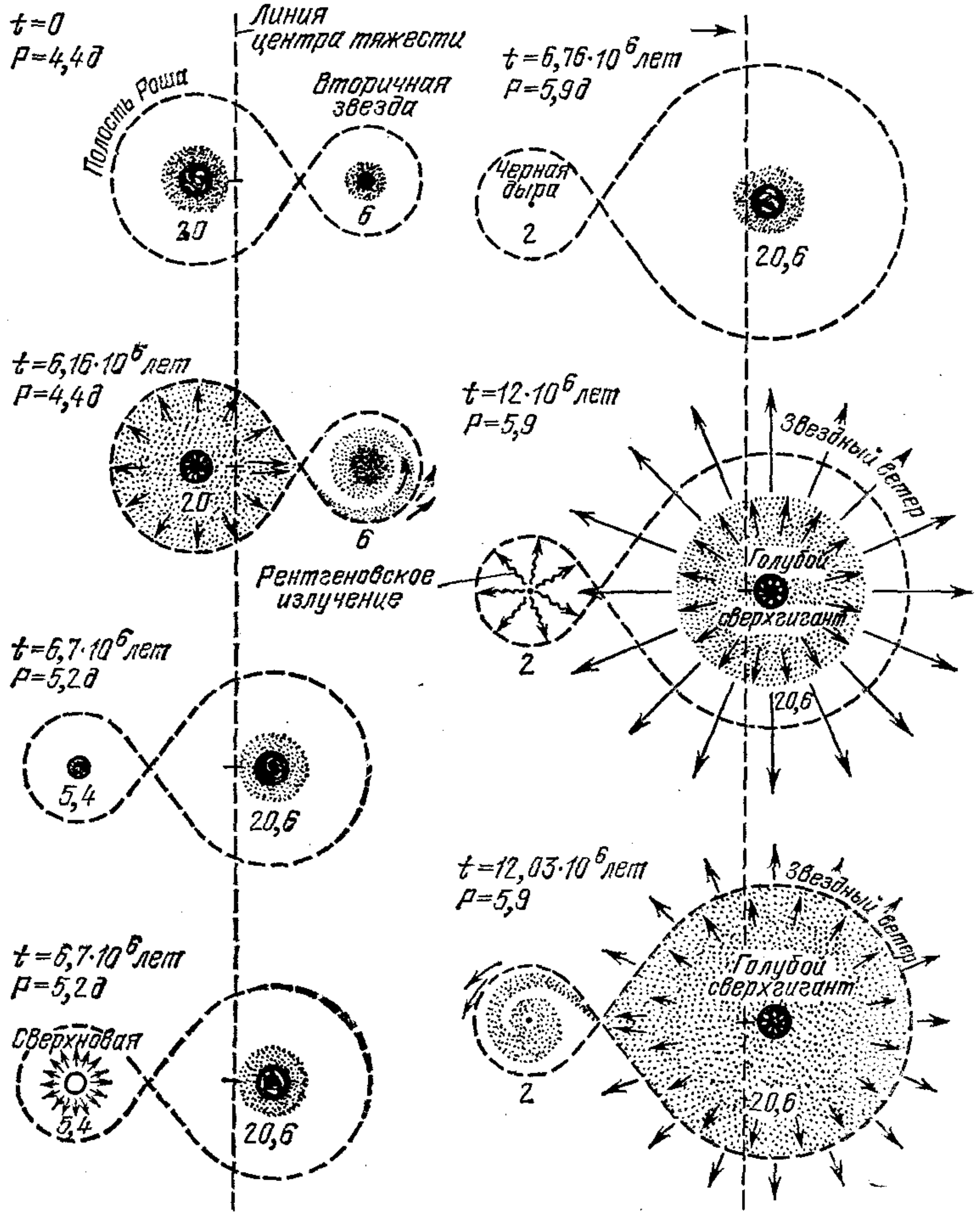


Normalized amplitude
0
2
4
6
500
100
50
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
-30
-20
-10
0
Time (seconds)

Evolution of a binary system

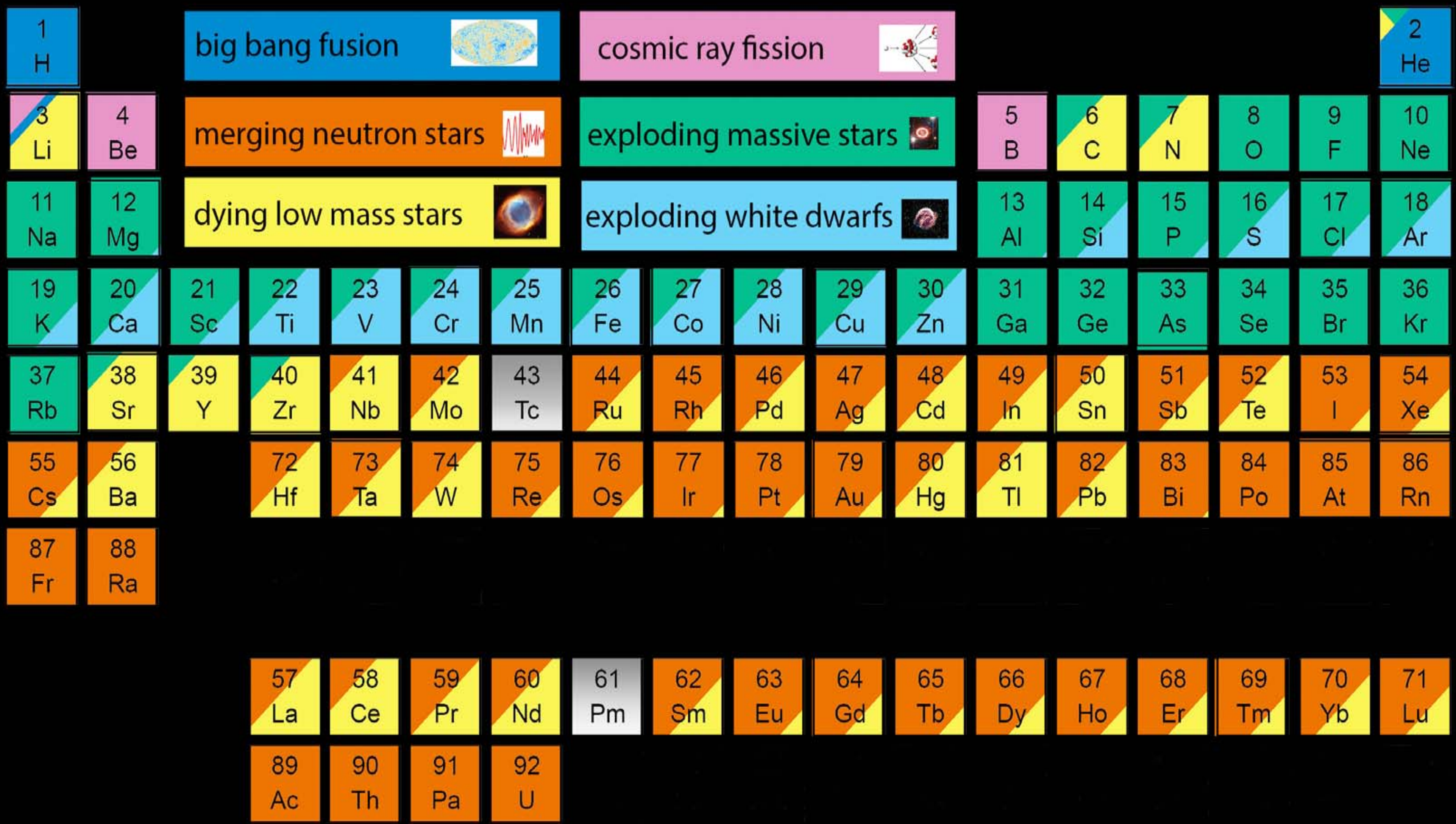






t=0
P=4,4д
Линия
центра тяжести
Полость Роша
Вторичная
звезда
20
6
t=6,76·10^6 лет
P=5,9д
Черная
дыра
2
20,6
t=6,16·10^6 лет
P=4,4д
20
6
t=12·10^6 лет
P=5,9
Звездный ветер
Голубой
сверхгигант
Рентгеновское
излучение
2
20,6
t=6,7·10^6 лет
P=5,2д
5,4
20,6
t=12,03·10^6 лет
P=5,9
Звездный ветер
Голубой
сверхгигант
2
20,6
t=6,7·10^6 лет
P=5,2д
Сверхновая
5,4
20,6

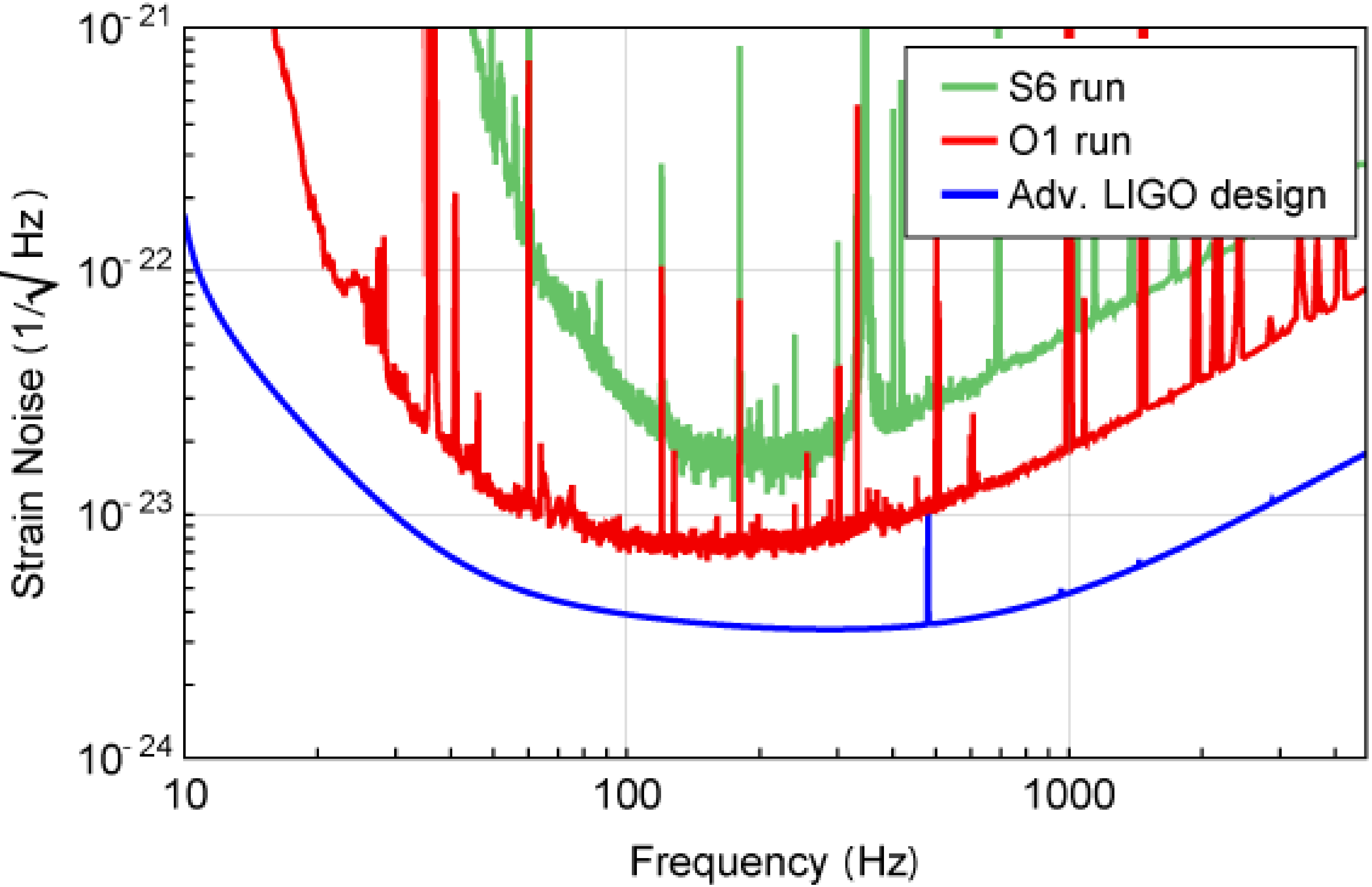
The Origin of the Solar System Elements

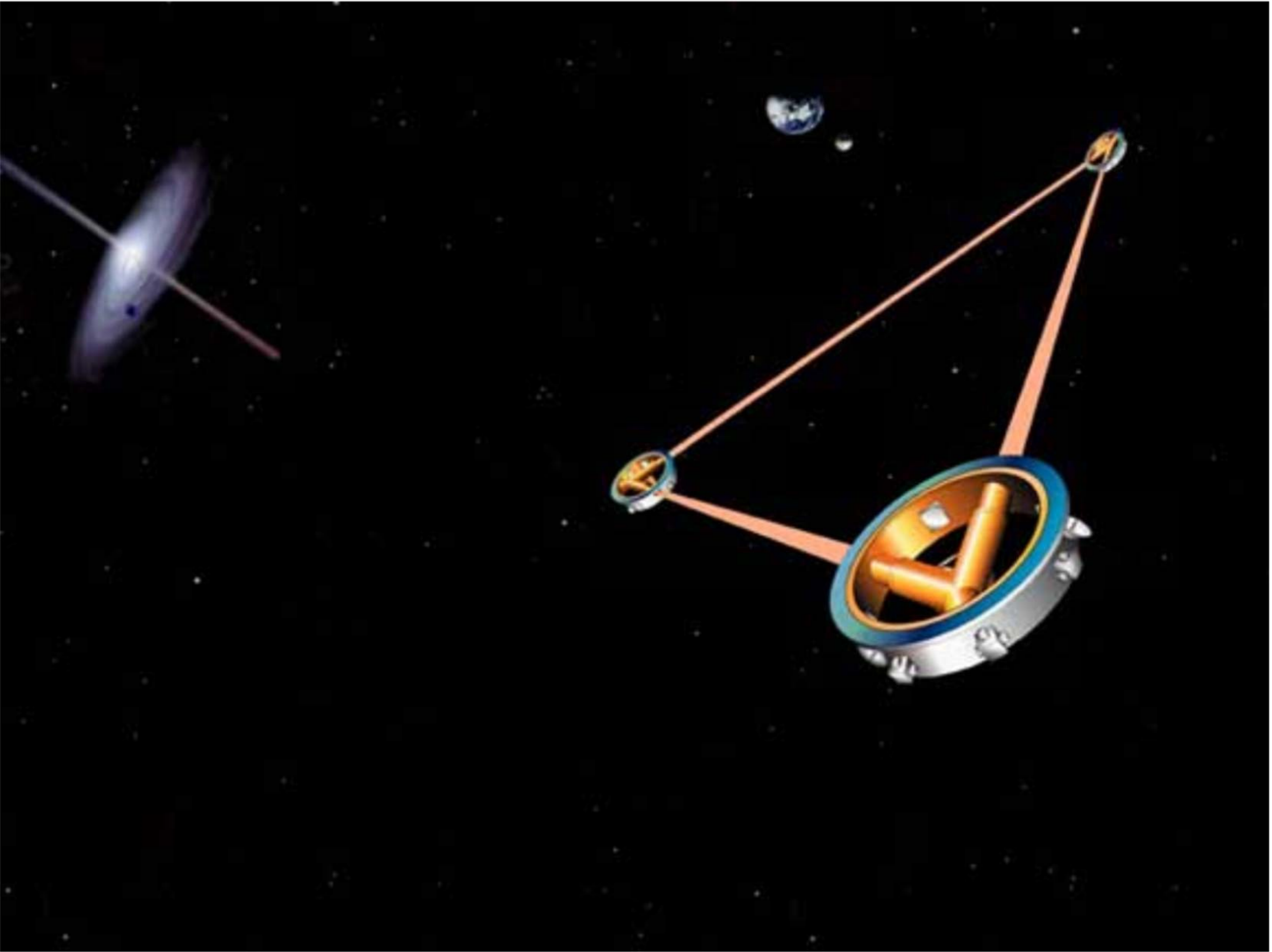


Astronomical Image Credits:
ESA/NASA/AASNova

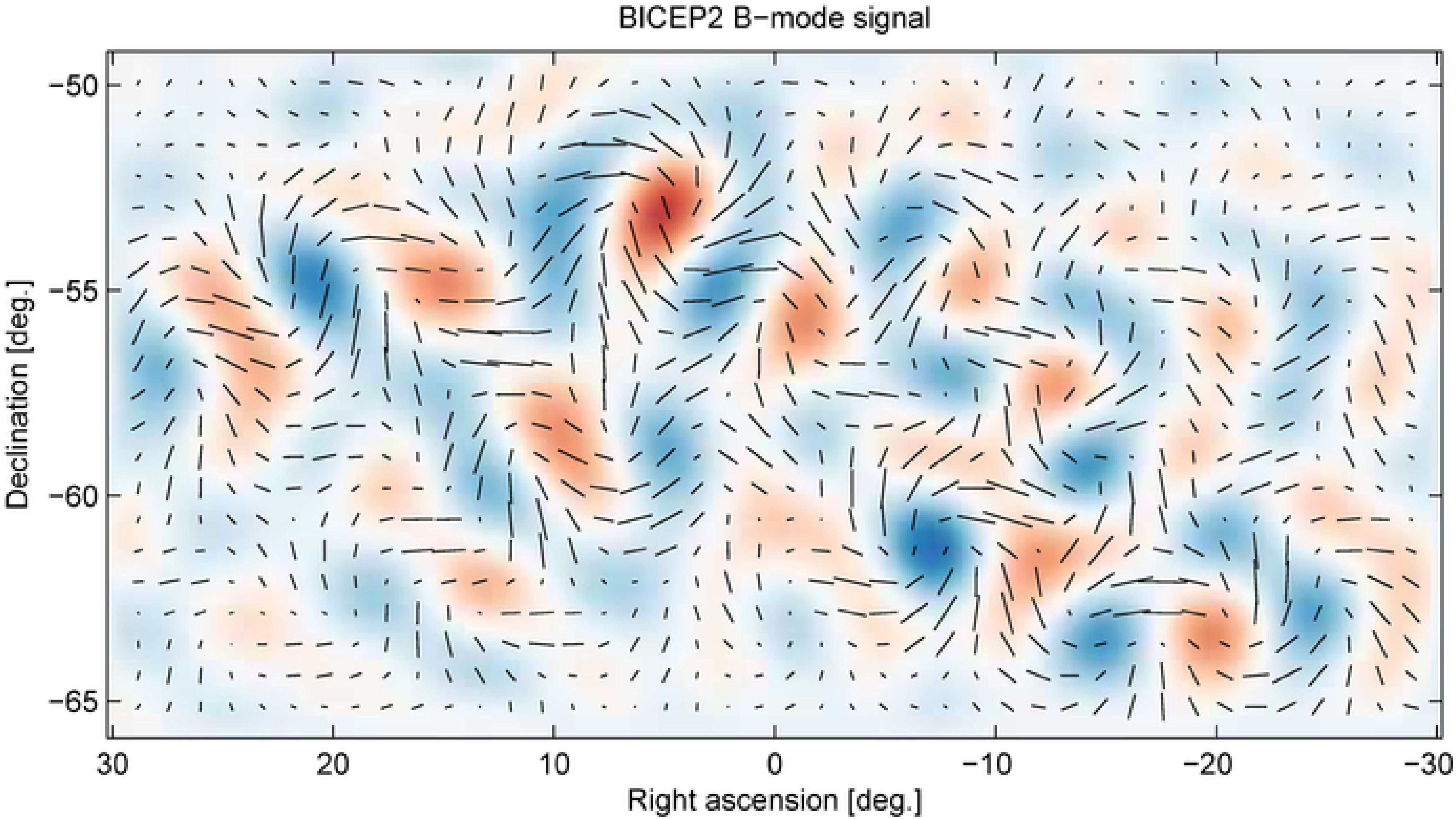
Graphic created by Jennifer Johnson

Advanced LIGO



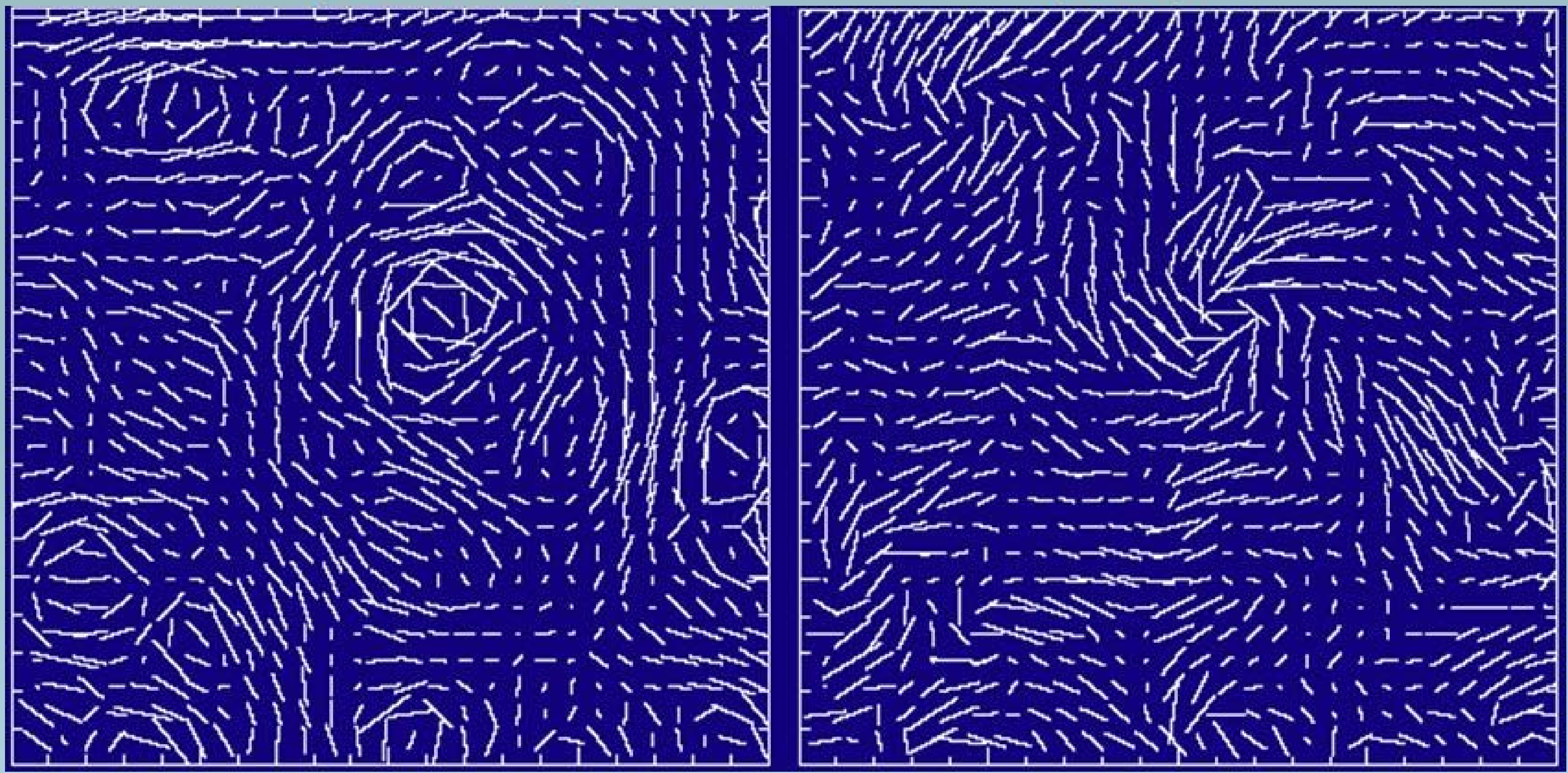


Cosmological gravitational waves



E-mode vs. B-mode

(curl-free) (curl)



Primordial tensors induce curl of CMB photons' polarization (B-mode).

Image: Seljak and Zaldarriaga