Processing and analyzing the GW150914 data and their possible physical interpretations

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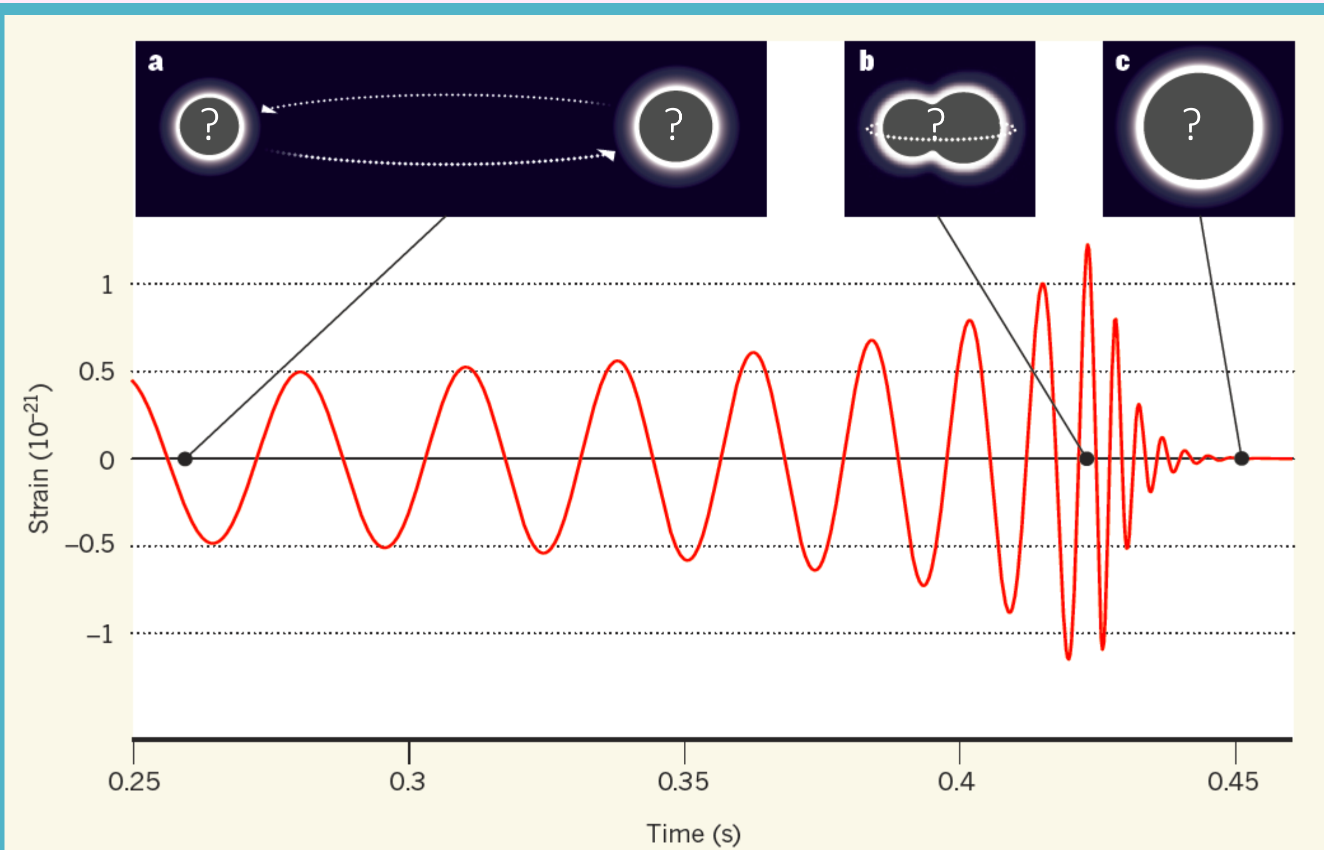
Sofia University Foundation TCPA & BLTF, JINR, Dubna

BAN, Sofia, 11 April 2016



GRAWITATIONAL WAVES

Down to a new astronomy

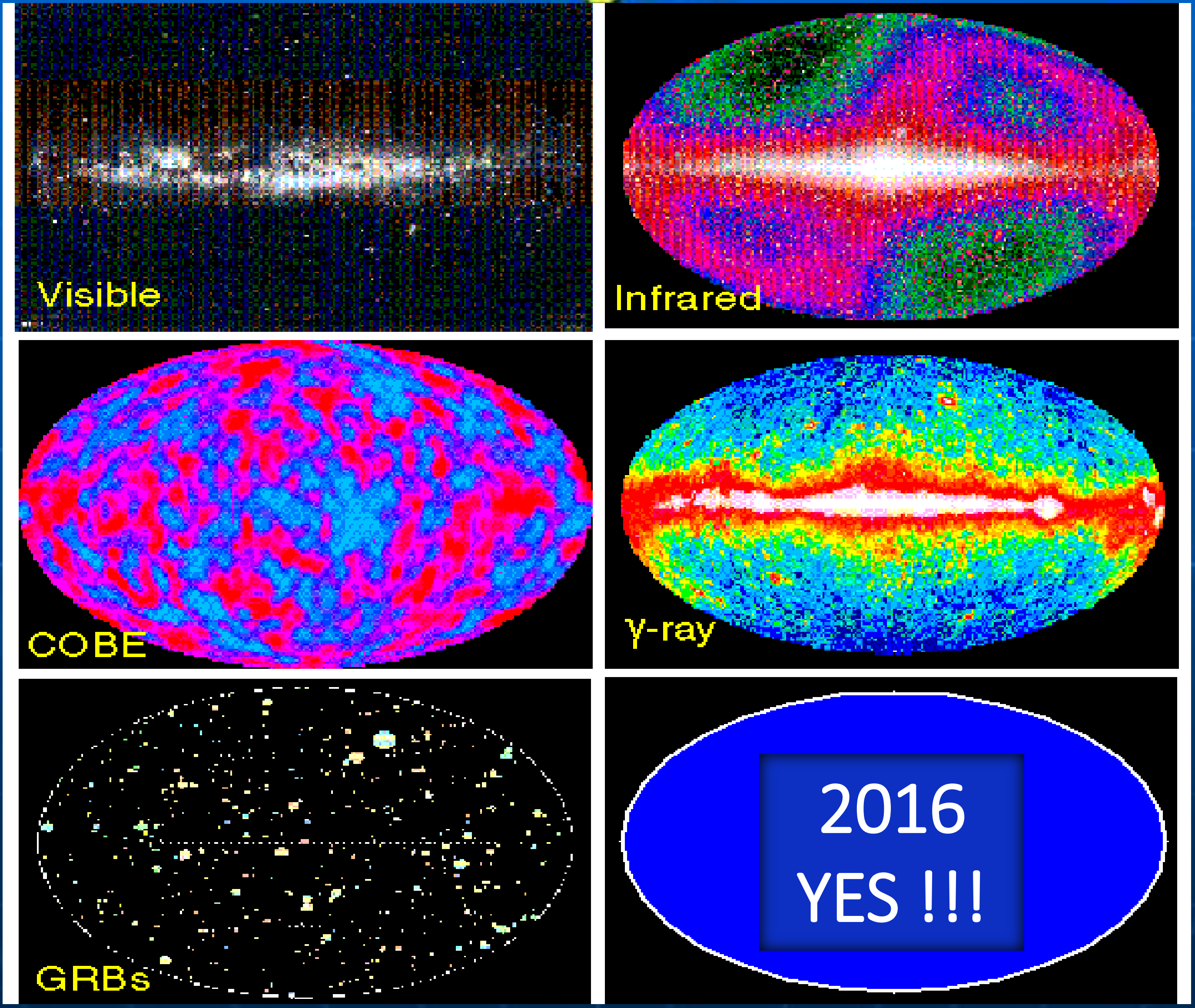
M. COLEMAN MILLER

40 | NATURE

VOL 531

3 MARCH 2016

The Universe as seen in different wave lengths



Plan of the talk:

1. History and basics of theory of GW.

2. **First indications for existence of GW:** Huls-Taylor (1993).

3. **The development of Numerical Relativity.**

4. **GW150914 announcement and its announced features.**

5. **The real data for GW150914 and their analysis.**

6. **The problems with QNM analysis.**

7. **Possible alternative explanations and models of GW150914 and their problems.**

10. Some basic conclusions.

The **existence of gravitational waves (GW)** was hypothesized on the basis of general considerations for the first time by **Oliver Heaviside (1893)** (in his book ***Electromagnetic theory***),

and independently by

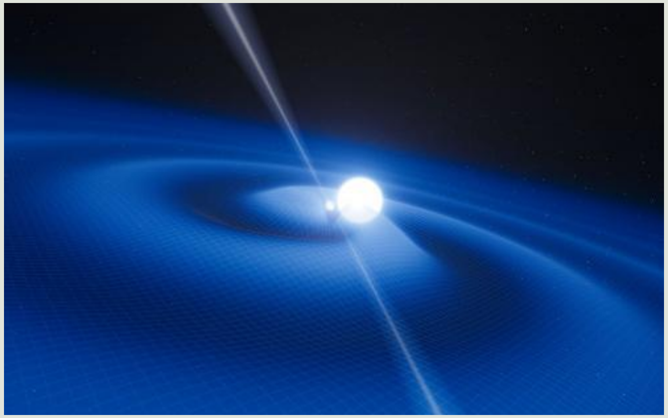
Hendric A. Lorentz (1900),

and by

Henri Poincare (1905).

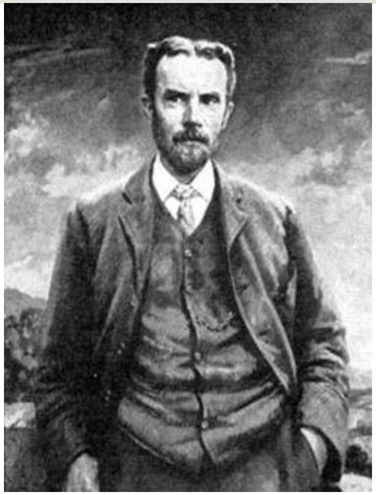
Leading idea: finite velocity of spreading of

Electromagnet interaction in vacuum:



$$c_0 = 299\ 792\ 458 \text{ m/s}.$$

No specific theory of GW was proposed at that time, or at least is not known.

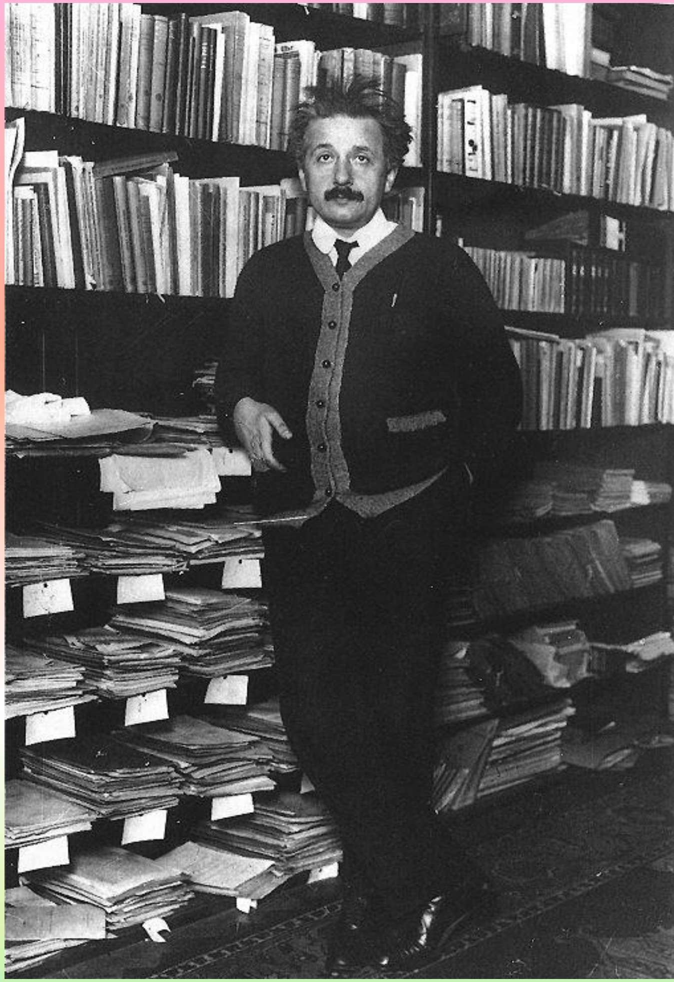


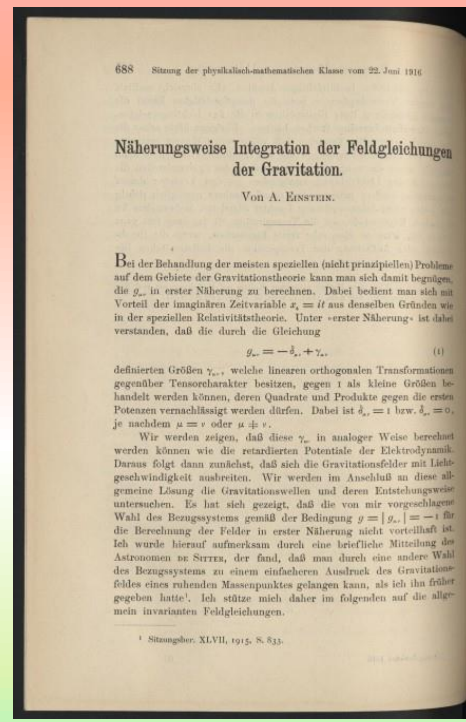
Oliver Heaviside

Hendric A. Lorentz

Henri Poincare

GW were predicted in 1916 by Albert Einstein to exist on the basis of his theory of general relativity, gravitational waves theoretically transport energy as gravitational radiation.





Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

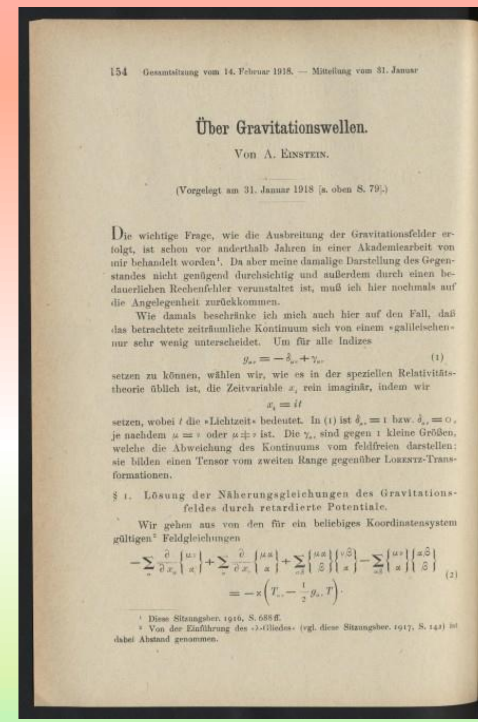
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen de Sitter, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

[1] Sitzungsber. XLVII, 1915, S. 833.



Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. 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.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu}\begin{Bmatrix}\mu\alpha\\ \alpha\end{Bmatrix} + \sum_{\alpha\beta}\begin{Bmatrix}\mu\alpha\\ \beta\end{Bmatrix}\begin{Bmatrix}\nu\beta\\ \alpha\end{Bmatrix} - \sum_{\alpha\beta}\begin{Bmatrix}\mu\nu\\ \alpha\end{Bmatrix}\begin{Bmatrix}\alpha\beta\\ \beta\end{Bmatrix} = -\kappa\left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T\right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

Albert Einstein:
First theory of GW – 1916-18

A. Einstein, Sitzungsber. preuss. Akad. Wiss.,
B. 1916, S. 688; 1918, S. 154.

Remember that the basic PHYSICAL Einsten's idea for inventing GR was also the finite speed of spreading of gravity! The geometry was only a tool!

Weak field approximation in GR

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1.$$

$$h_{\mu\nu}(x,t) = \frac{4G}{c^2}\int \frac{S_{\mu\nu}(x', t - \frac{|x-x'|}{c})}{|x-x'|}\, \mathrm{d}^3x'$$

$$S_{\mu\nu} = T_{\mu\nu} - 1/2\, g_{\mu\nu} T^{\lambda}{}_{\lambda}$$

Flat waves: $h_{\mu\nu} = \varepsilon_{\mu\nu} \exp(\mathrm{i}k_\lambda x^\lambda) + \varepsilon^*_{\mu\nu} \exp(-\mathrm{i}k\lambda x^\lambda).$

Wave equation: $\boxed{k^\mu k_\mu = 0}$

Harmonic gauge: $k_\mu \varepsilon^\mu{}_\nu = 1/2\, k_\nu \varepsilon^\mu{}_\mu \quad \varepsilon_{\mu\nu} = \varepsilon_{\nu\mu}$

Gauge transformations:

$$x'^\mu = x^\mu + \xi^\mu(x),$$

$$h'_{\mu\nu} = h_{\mu\nu} - \xi_{\mu,\nu} - \xi_{\nu,\mu}$$

$$\varepsilon'_{\mu\nu} = \varepsilon_{\mu\nu} + k_\mu e_\nu + k_\nu e_\mu.$$

$$\xi^\mu(x) = \mathrm{i}\, e_\mu \mathrm{e}^{\mathrm{i}kx} - i\, e^*_\mu \mathrm{e}^{-\mathrm{i}kx}$$

Flat GW along axes Oz:

$$k^3 = k^0 \equiv k(>0), \quad k^1 = k^2 = 0$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_{11} & h_{12} & 0 \\ 0 & h_{12} & -h_{11} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

only the two states $\varepsilon_{11} \pm \mathrm{i}\varepsilon_{12}$ exist, with $J_z = \pm 2$

Rotation around axes Oz:

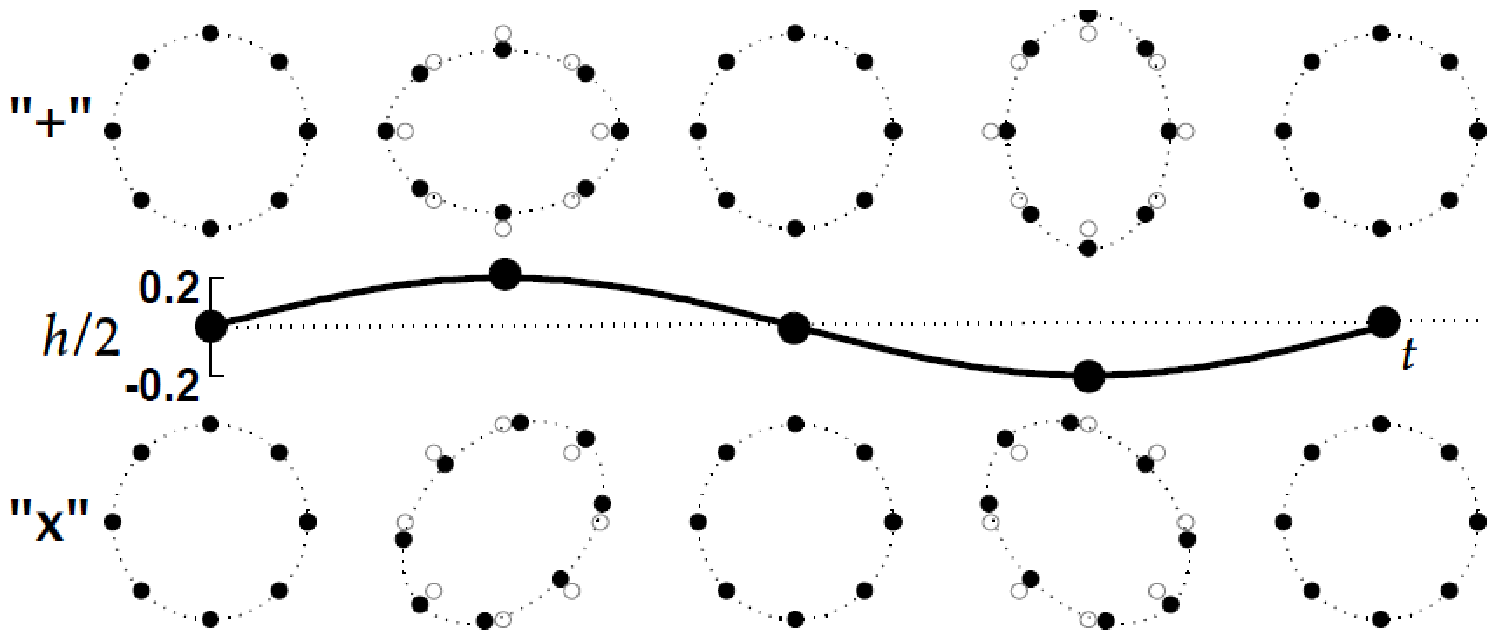
$$R(\theta) = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

The graviton is particle with spin 2

$$\varepsilon_{11}{}' - \mathrm{i}\varepsilon_{12}{}' = \underline{\mathrm{e}^{2\mathrm{i}\theta}}(\varepsilon_{11} - \mathrm{i}\varepsilon_{12})$$

The two types of GW in GR:

$$V_{GW} = c$$



$$h = 2\frac{\delta \ell}{\ell}.$$

Polarization of GW in modified theories of gravity (f(R), MDG, Hordensky model...)

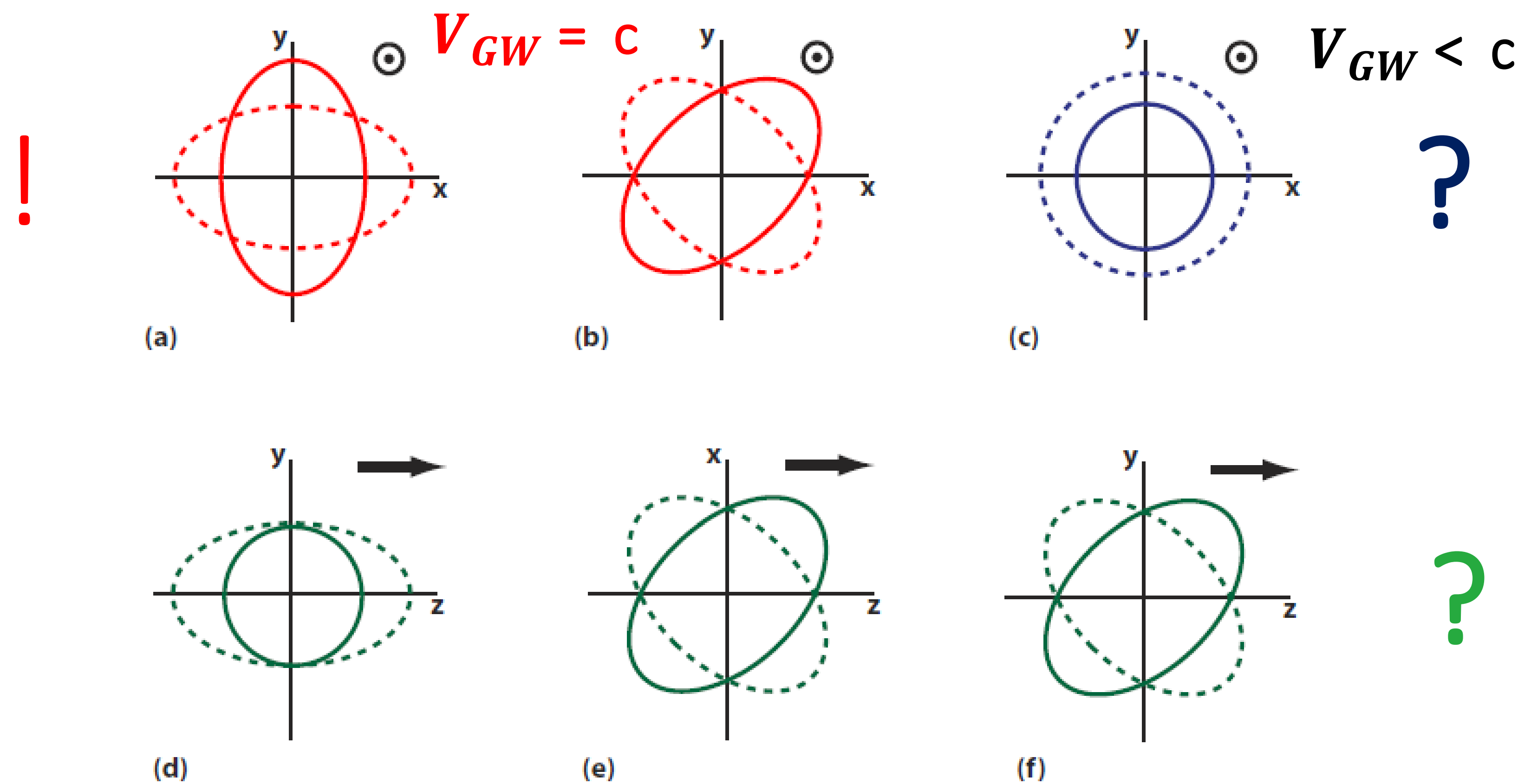
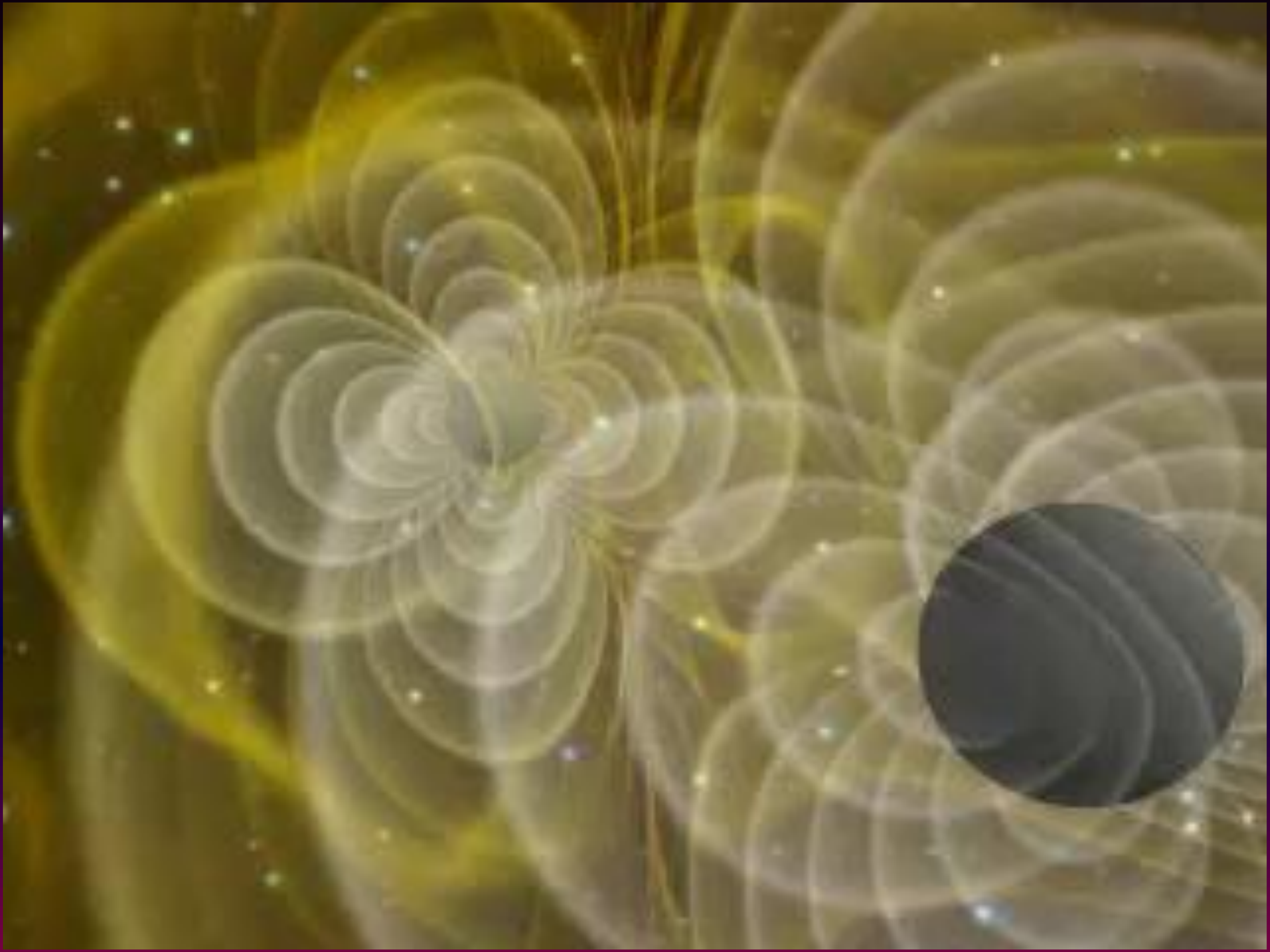


Figure 4: Effect of the six possible GW polarization modes on a ring of test particles. The GW propagates in the z-direction for the upper three transverse modes, and in the x-direction for the lower three longitudinal modes. Only modes (a) and (b) are possible in GR. Image reproduced by permission from [471].

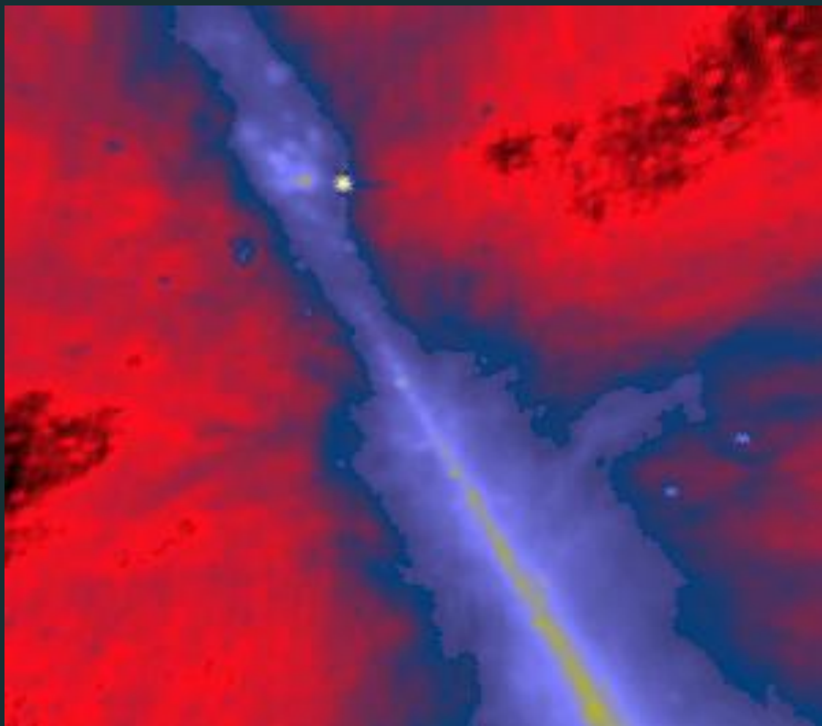
Quadrupole character of GW (NASA Goddard)



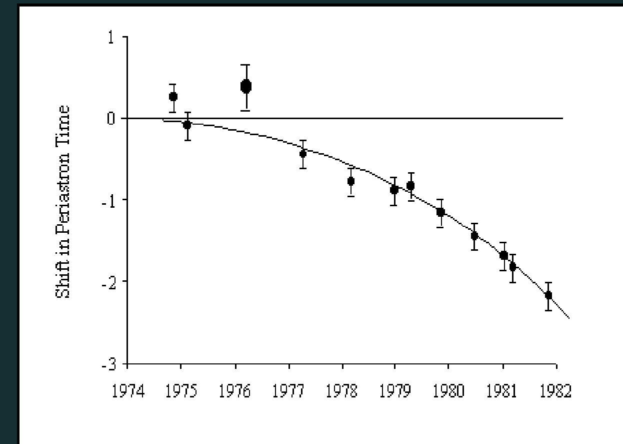
First indirect evidences for gravitational waves

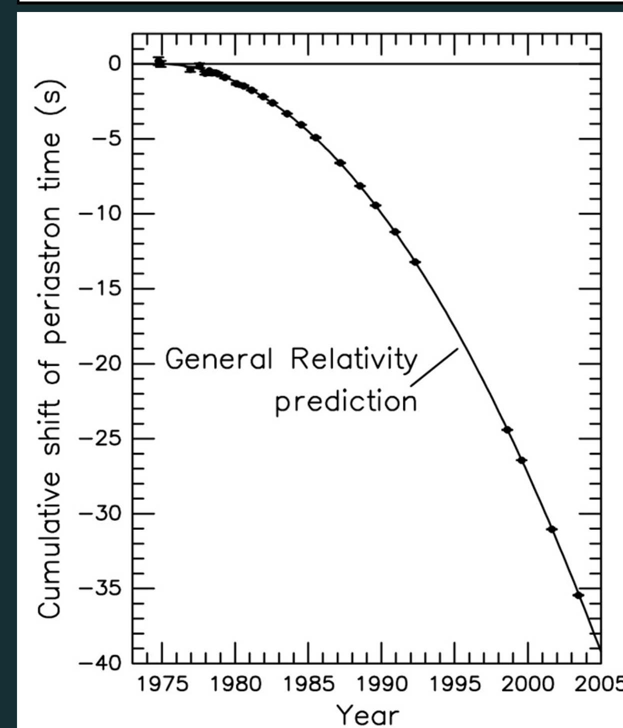
$$P = \frac{\mathrm{d}E}{\mathrm{d}t} = -\frac{32}{5}\frac{G^4}{c^5}\frac{(m_1 m_2)^2(m_1+m_2)}{r^5}$$

$$\frac{\mathrm{d}\tau}{\mathrm{d}t} = (-2.422 \pm 0.006) \times 10^{-12}$$



$$\frac{\mathrm{d}\tau}{\tau} = -\frac{48\pi}{5}\left(\frac{GM}{Rc^2}\right)^{5/2}$$





Indirect detection

of

gravitational waves

1993 Nobel Price:

Hulst &Taylor

BH merger:

The collision of two BH will produce a ringing single final BH (Stephen Hawking,+...)

From the ring-down waves we can infer the mass, the spin and surface area of the final BH.

Kip Thorne, in The Future of Theoretical Physics and Cosmology, Cambridge, 2003:

"If the total area does not increase, Stephen is wrong, Einstein's GR laws are wrong, and we will have a great crisis in physics... Since the 1970's these remarkable predictions have remained untested. They seem to be an unequivocal consequence of Einstein's GR laws,

but relativity might be wrong or (much less likely)

we might be misinterpreting its mathematics."

BH merger (NR)

Several Orbits: NR is not what it was!

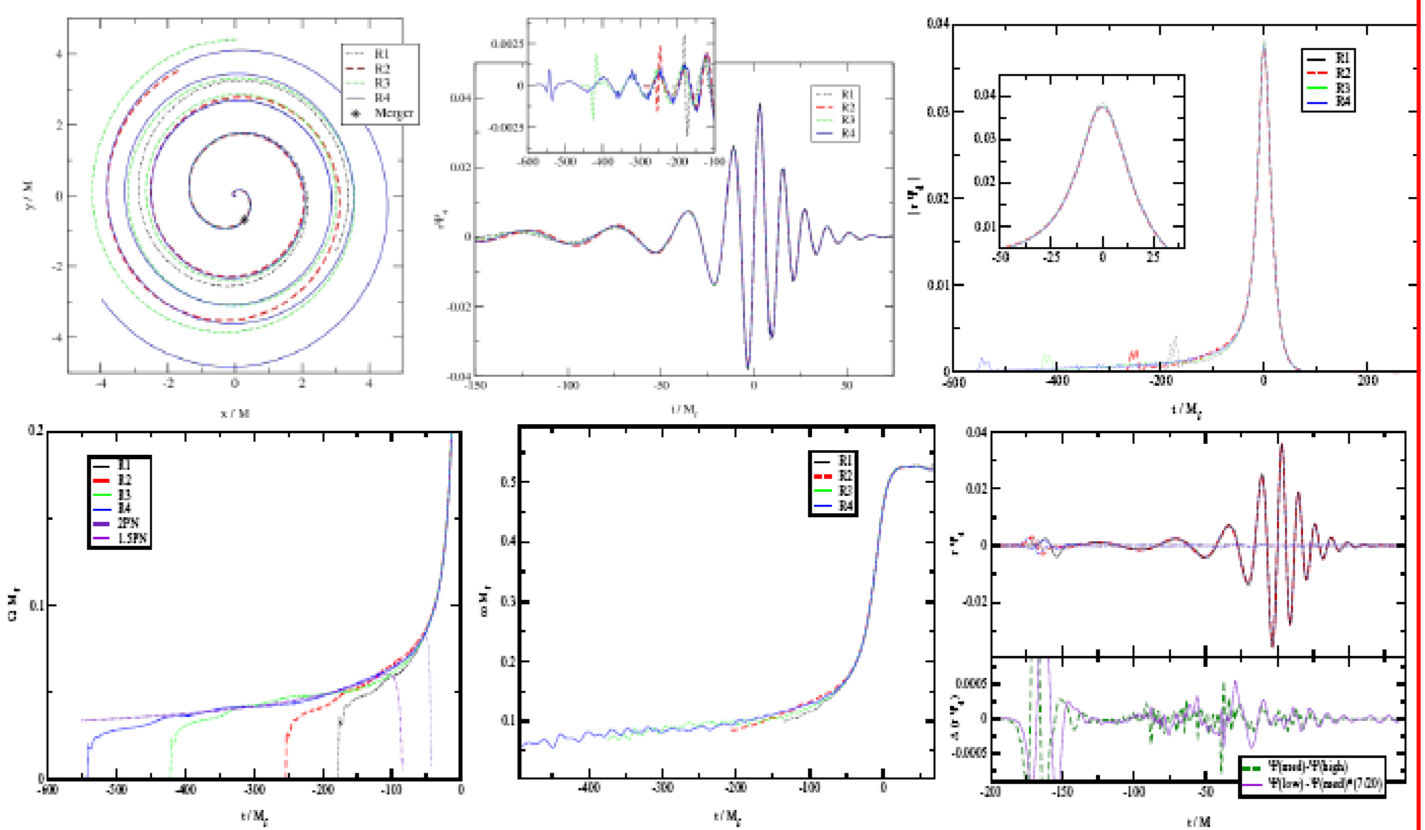


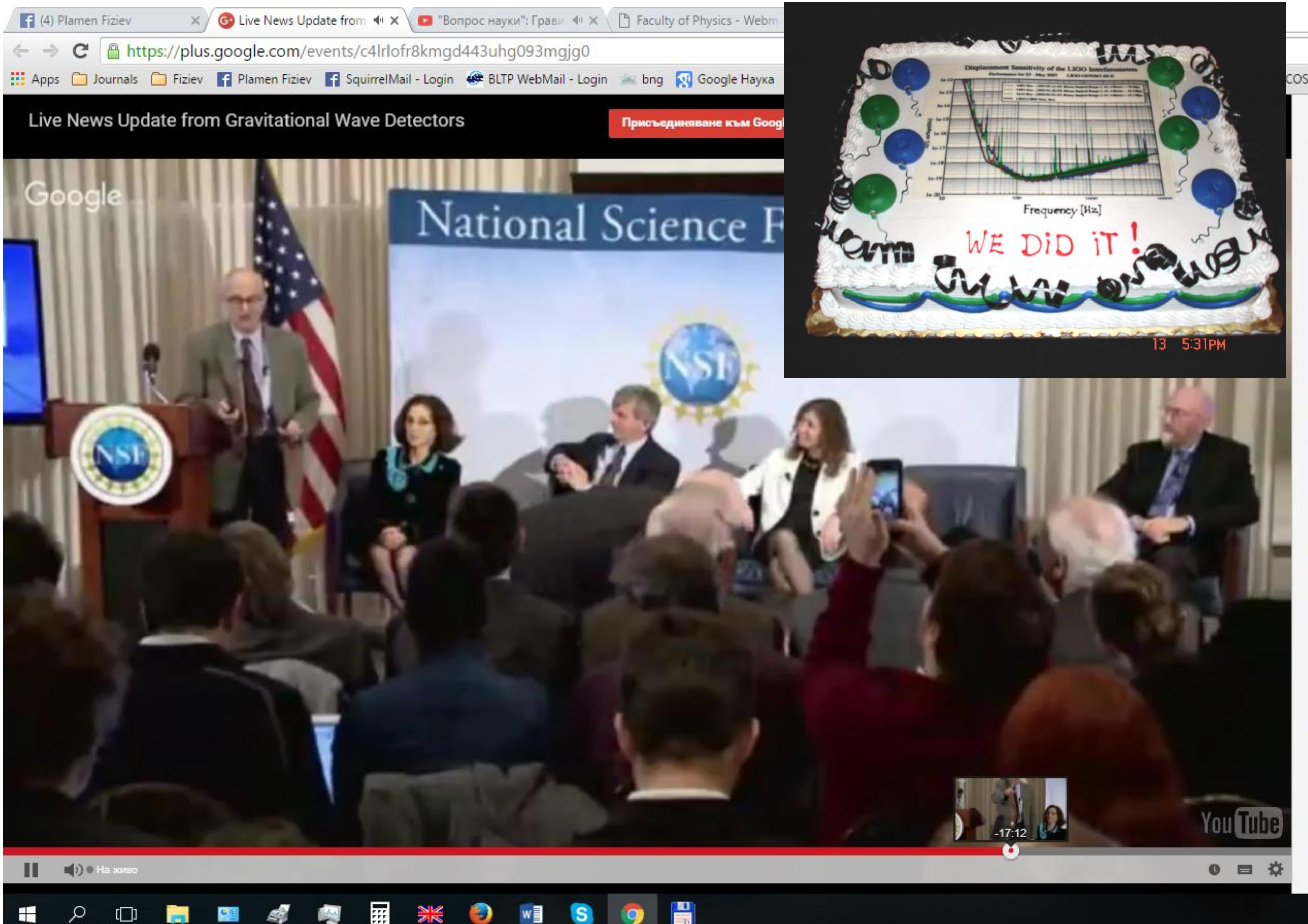
Figure: Success after 30 years: 4.2 Orbits and waveforms, NASA Goddard.

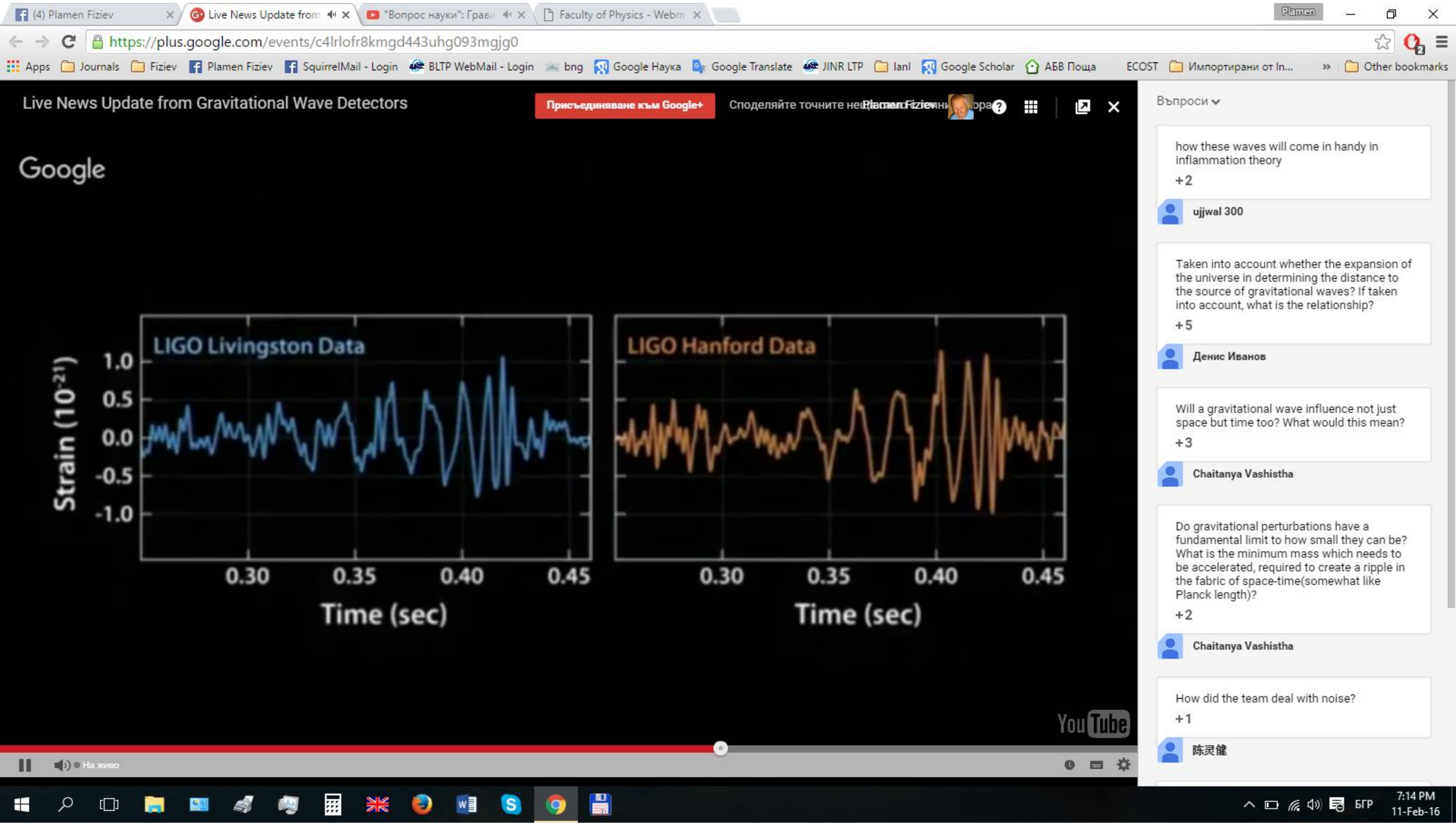
Radiated energy: 3.6 – 3.9%, final $a/M \approx 0.7$.

NR Problems:

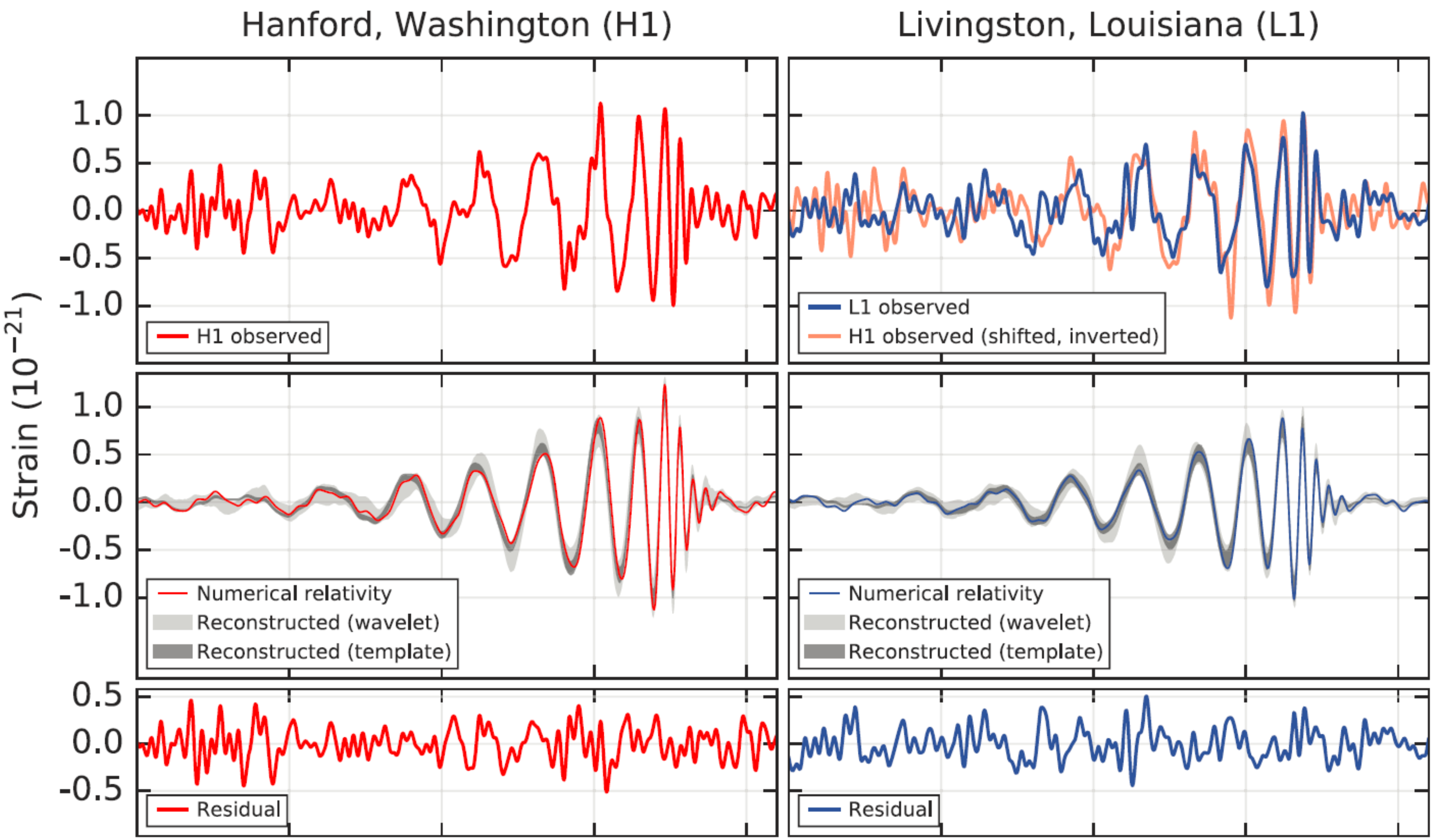
1. We have No resolution of the GR constraints.
2. Superluminal Signals and waves.
3. Singularities are not resolved but just put under carpet.
4. Too expensive and CPU time consuming ➡ only a few exact NR waveforms are available.
5. Works only for restricted domain of BH masses
6. Eccentricity and spin effects for higher GW modes, are not taken into account.

Rainer Weis, NSF Director France A. Córdova, David Reitze, Gabriela Gonzalez , Kip Thorn



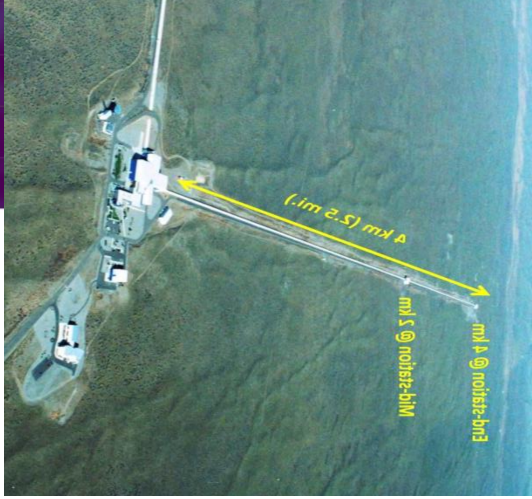

Live News Update from Gravitational Wave Detectors
Присъединяване към Google+
Google
LIGO Livingston Data
LIGO Hanford Data
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Въпроси
how these waves will come in handy in inflammation theory
+2
ujjwal 300
Taken into account whether the expansion of the universe in determining the distance to the source of gravitational waves? If taken into account, what is the relationship?
+5
Денис Иванов
Will a gravitational wave influence not just space but time too? What would this mean?
+3
Chaitanya Vashistha
Do gravitational perturbations have a fundamental limit to how small they can be? What is the minimum mass which needs to be accelerated, required to create a ripple in the fabric of space-time(somewhat like Planck length)?
+2
Chaitanya Vashistha
How did the team deal with noise?
+1
陈灵健
https://plus.google.com/events/c4lrlofr8kmgd443uhg093mgjg0
7:14 PM
11-Feb-16

Basic announced results according PRL 116, 061102 (2016)



GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)



first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

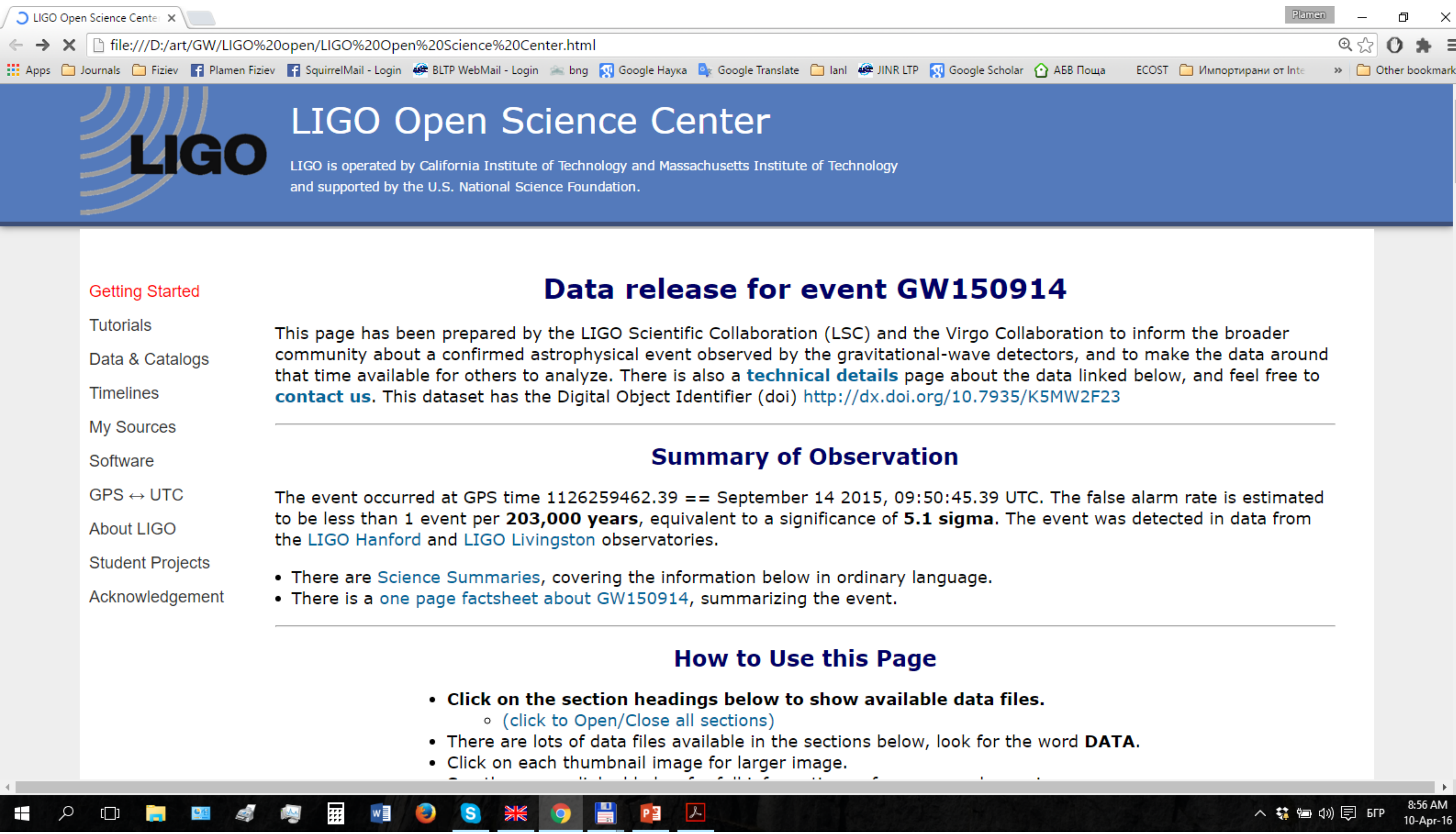
Parameter ranges correspond to 90% credible bounds. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

Peak GW luminosity:

$$L_{mreging} = Mc^2/_{R_g/c} \approx 3.6 \times 10^{56}\ erg/s$$

$$L_{\mathrm{Planck}} = E_{\mathrm{Planck}}/t_{\mathrm{Planck}} = c^5/_G \approx 10^{58}\ erg/s$$

Available Data for GW150914



LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

Getting Started
Tutorials
Data & Catalogs
Timelines
My Sources
Software
GPS ↔ UTC
About LIGO
Student Projects
Acknowledgement

Data release for event GW150914

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a **technical details** page about the data linked below, and feel free to **contact us**. This dataset has the Digital Object Identifier (doi) http://dx.doi.org/10.7935/K5MW2F23

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the LIGO Hanford and LIGO Livingston observatories.

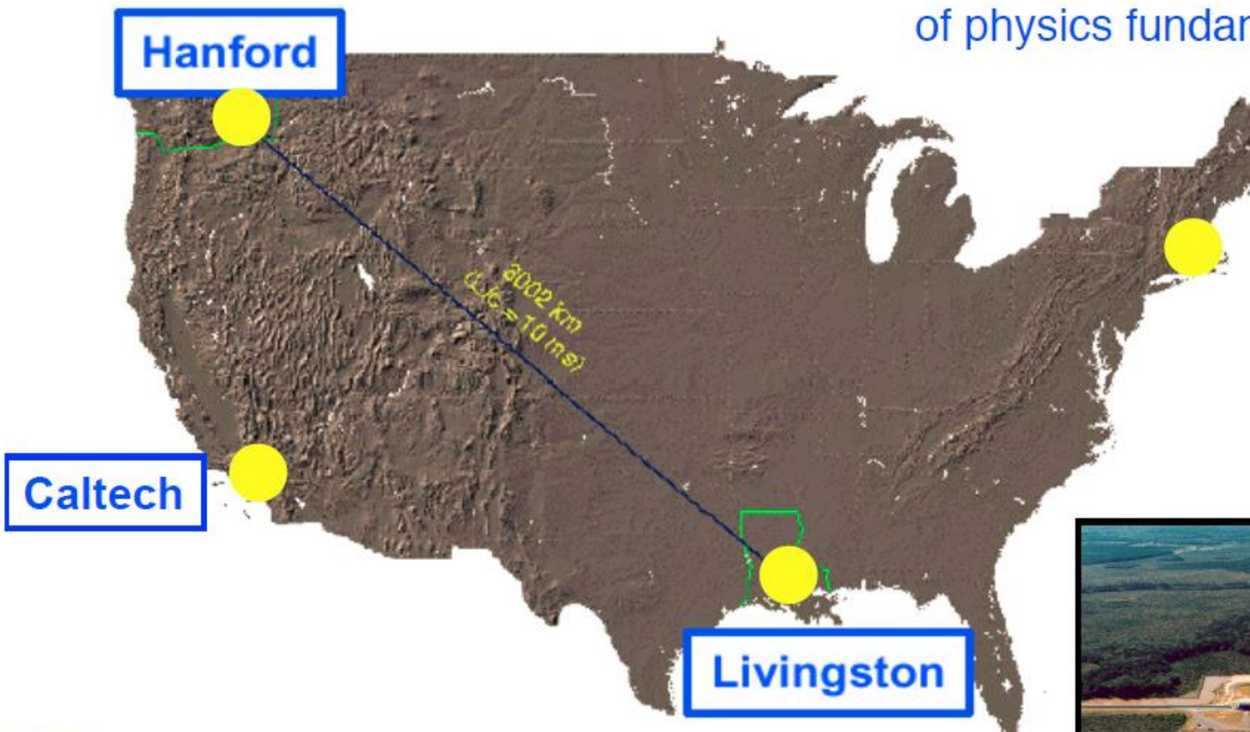
- There are Science Summaries, covering the information below in ordinary language.
- There is a one page factsheet about GW150914, summarizing the event.

How to Use this Page

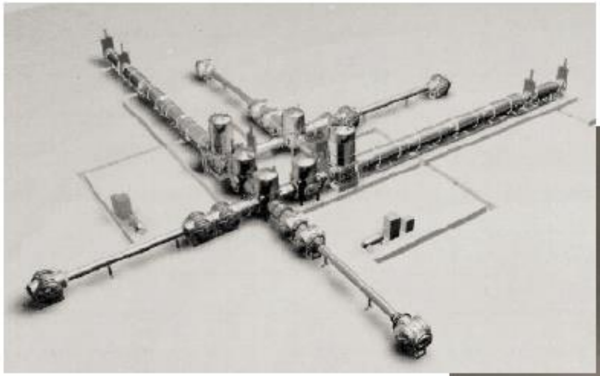
- **Click on the section headings below to show available data files.**
  - (click to Open/Close all sections)
- There are lots of data files available in the sections below, look for the word **DATA**.
- Click on each thumbnail image for larger image.

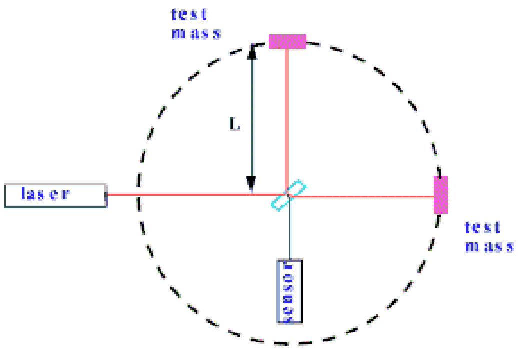
David Shoemaker
For the LIGO and Virgo Scientific Collaborations

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



Measuring $\Delta L = 4 \times 10^{-18}\, m$





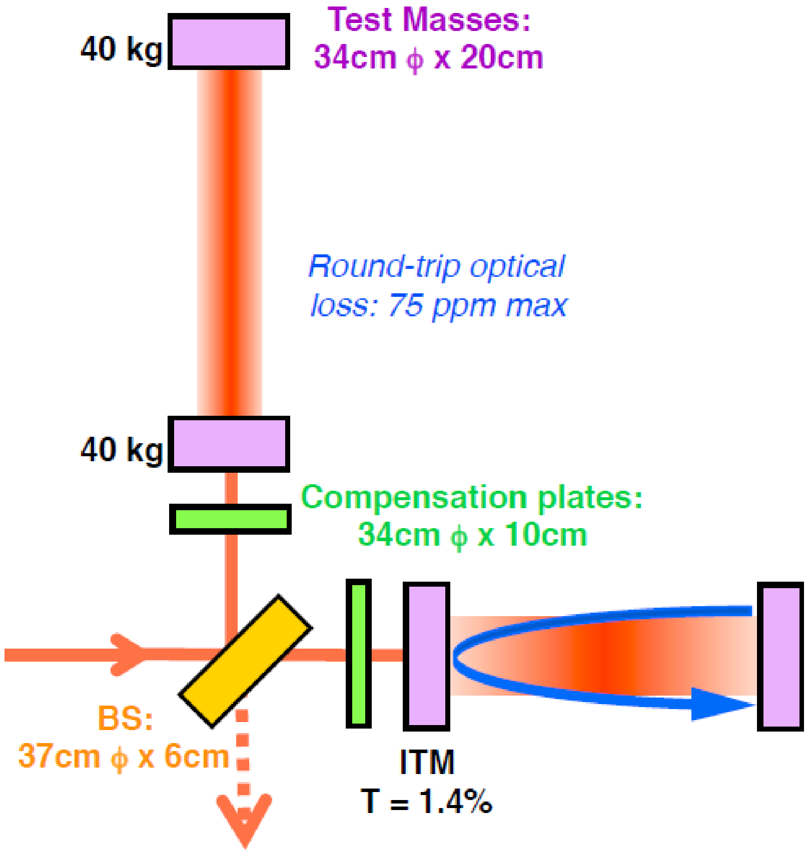
$$h \sim \frac{\Delta L}{L} \sim \frac{10^{-18}\,\mathrm{m}}{4\,\mathrm{km}}$$

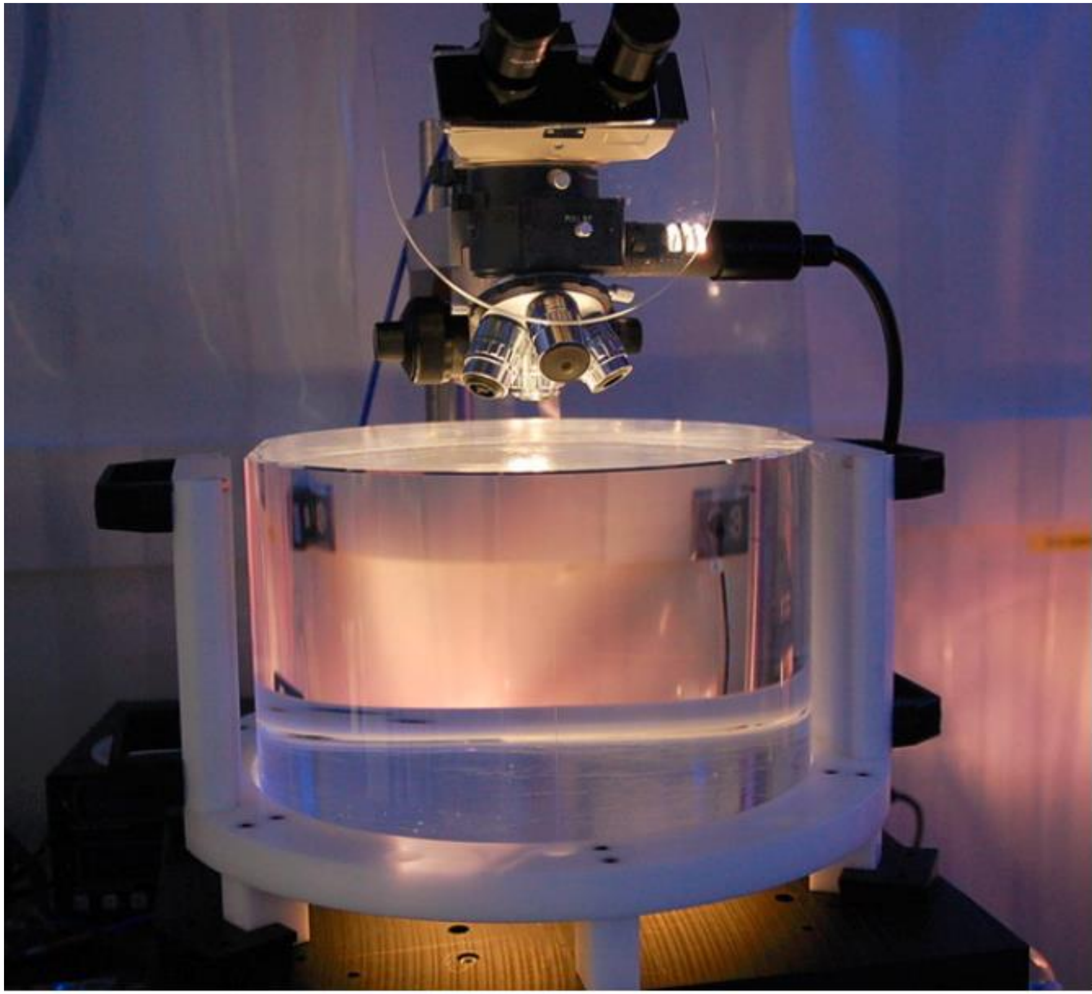
wave amplitude (Strain $\sim 10^{-22}$)

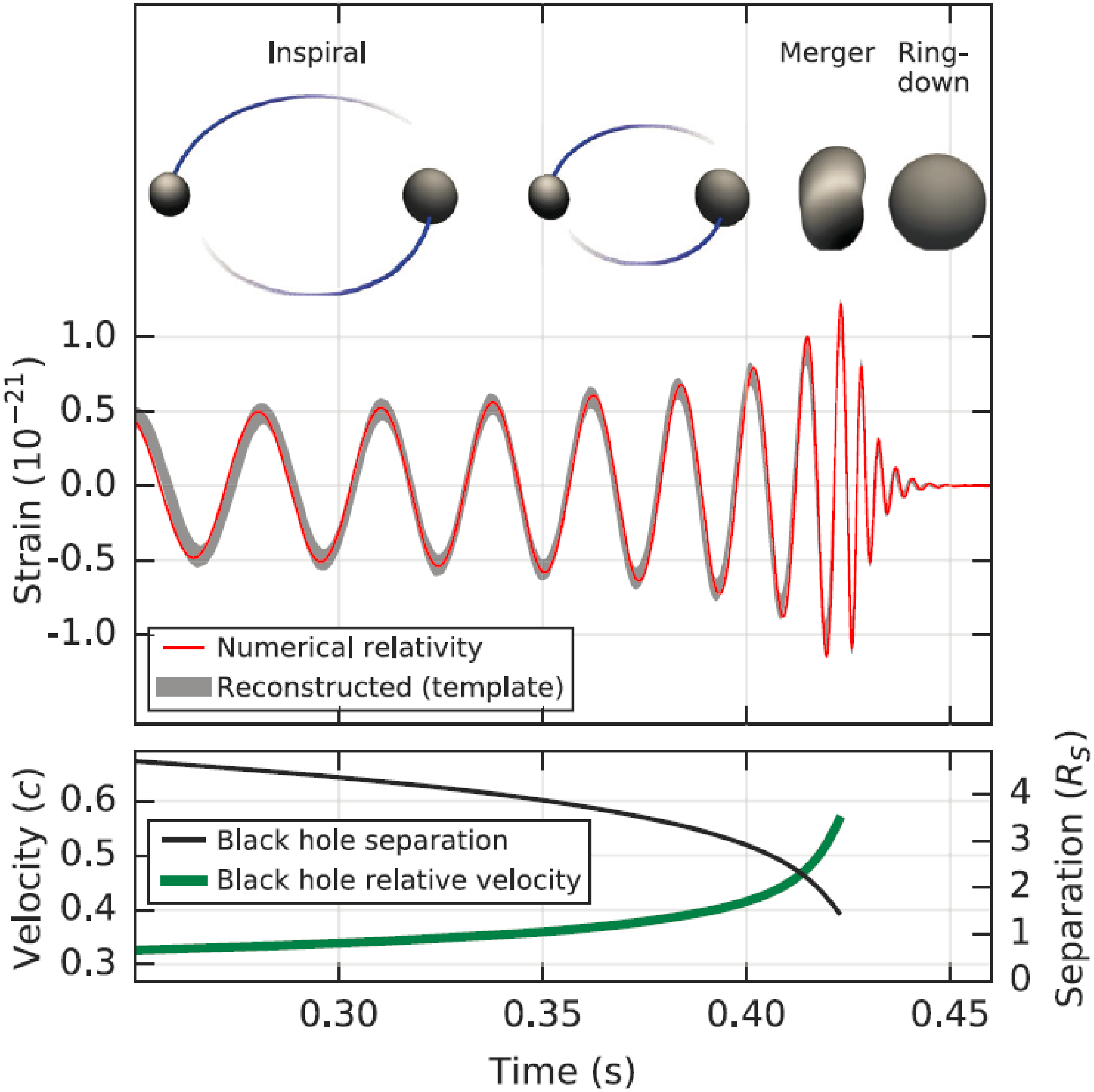
David Shoemaker

For the LIGO and Virgo Scientific Collaborations

- Requires the state of the art in substrates and polishing
- Pushes the art for coating!
- Sum-nm flatness over 300mm







Parameter space of the initial bodies:

a) $m_{1,2}$ $\boldsymbol{S}_{1,2}$

b) luminosity distance D_L,

ascension α

declination δ

orbital inclination ι,

polarization ψ

time t_c

phase ϕ_c of coalescence,

the eccentricity

(two parameters)

$$m = (1+z)m^{\text{source}}.$$

All together 17 parameters

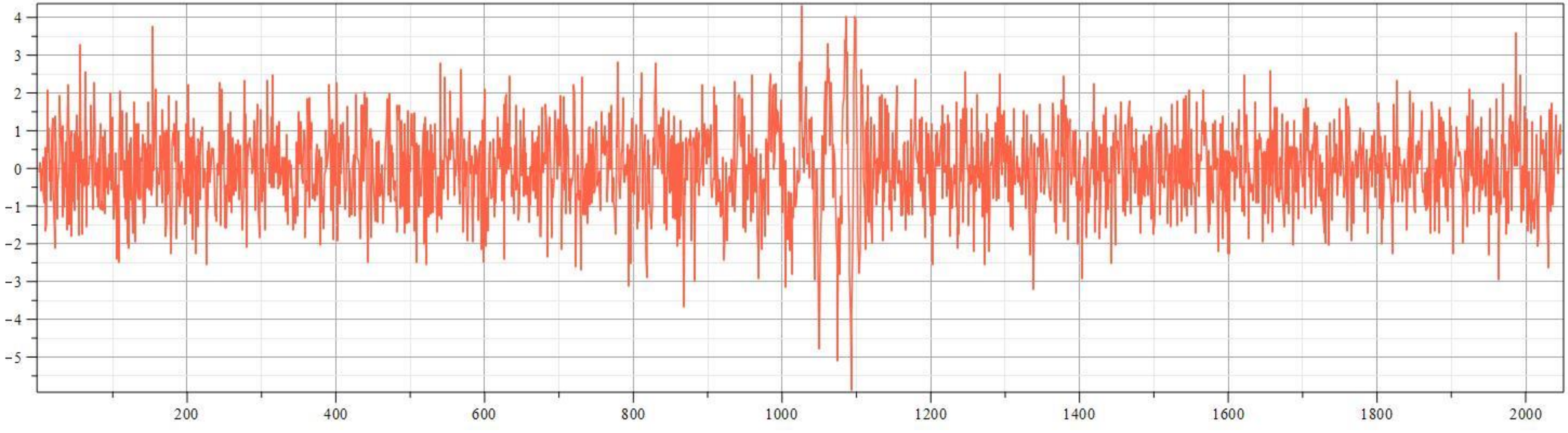
There are not enough data to find all of them for GW150914!

LIGO publications about GW150914 at LIGO side:

1. **About the Instruments and Collaborations**
2. Observing Gravitational-Wave Transient GW150914 with Minimal Assumptions
3. GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO (**PRL 116, 061102 (2016)**)
4. Properties of the binary black hole merger GW150914
5. The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
6. Astrophysical Implications of the Binary Black-Hole Merger GW150914
7. Tests of general relativity with GW150914
8. GW150914: Implications for the Stochastic Gravitational-Wave Background from Binary Black Holes
9. Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
10. Characterization of Transient Noise in Advanced LIGO Relevant to Gravitational Wave Signal GW150914
11. High-energy Neutrino Follow-up Search of Gravitational Wave Event GW150914 with IceCube and ANTARES
12. GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
13. Localization and broadband follow-up of the gravitational-wave transient GW150914

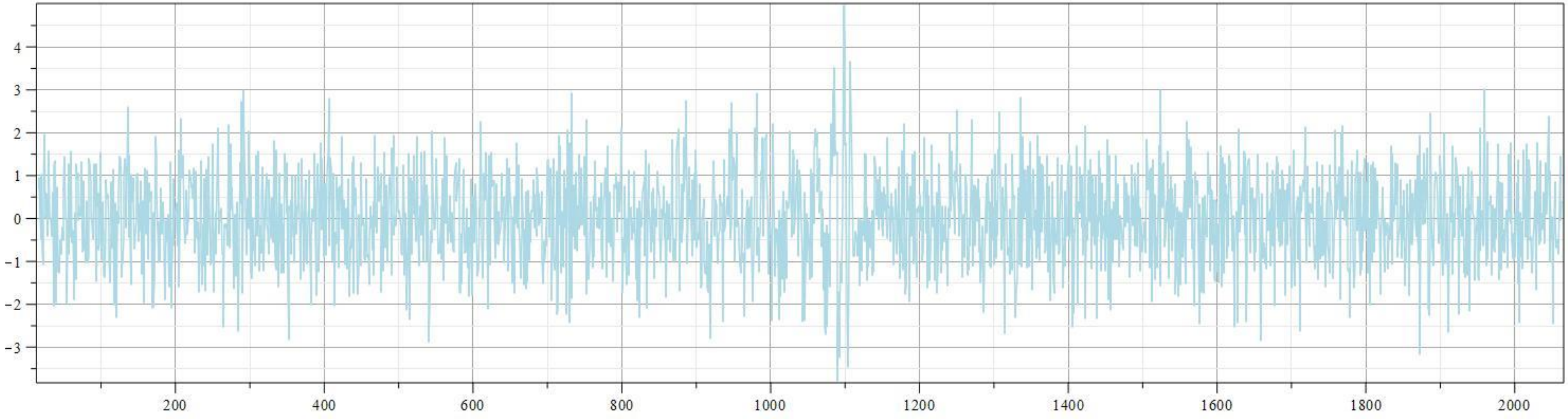
The real signal from GW150914 - Coherent Wave Burst (CWB)

Hamfoird



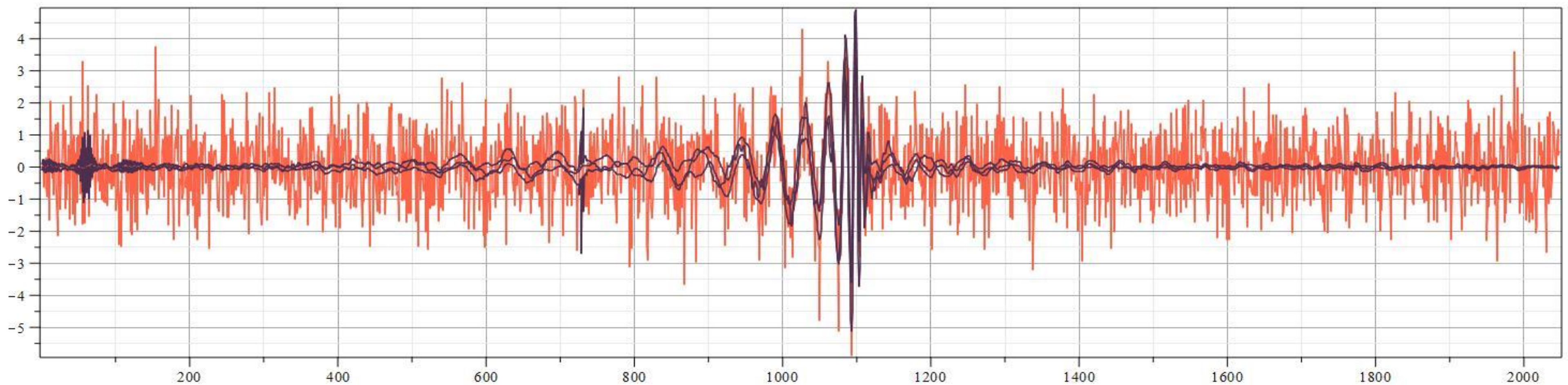
2048 points, Corr_Coeff (H5,L5) = -0.0458151661

Luisiana

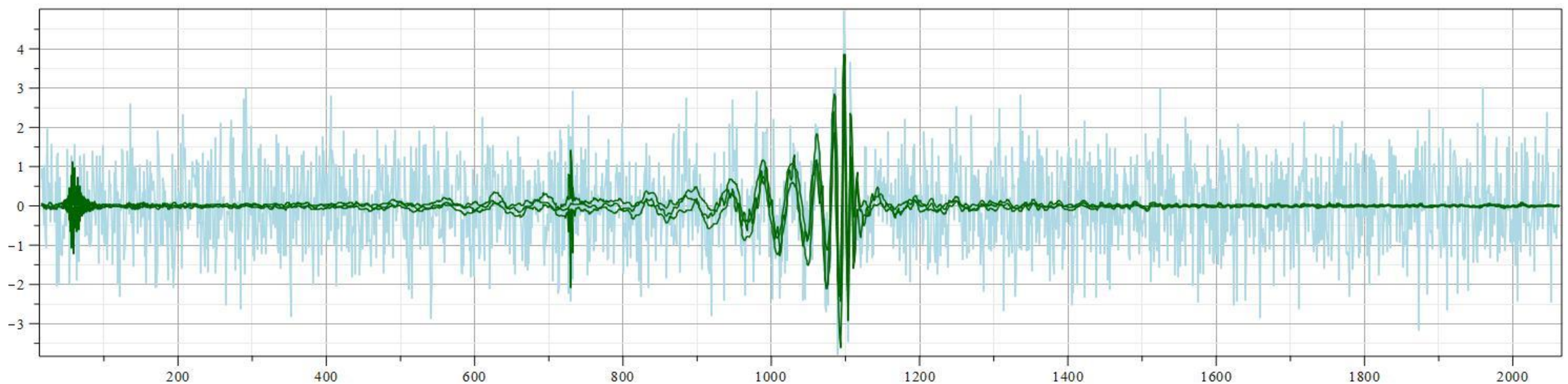


The GW150914 – CWB results:

The CWB pipeline searches for a broad range of GW transients in the LIGO frequency band **without prior knowledge of the signal waveforms**, and reconstructs the GW signal associated with these events using a likelihood analysis (arXiv:0802.3232 +…). Results for 2048 points:



2048 points, Corr_Coeff (H4,L4) = -0.0512823348

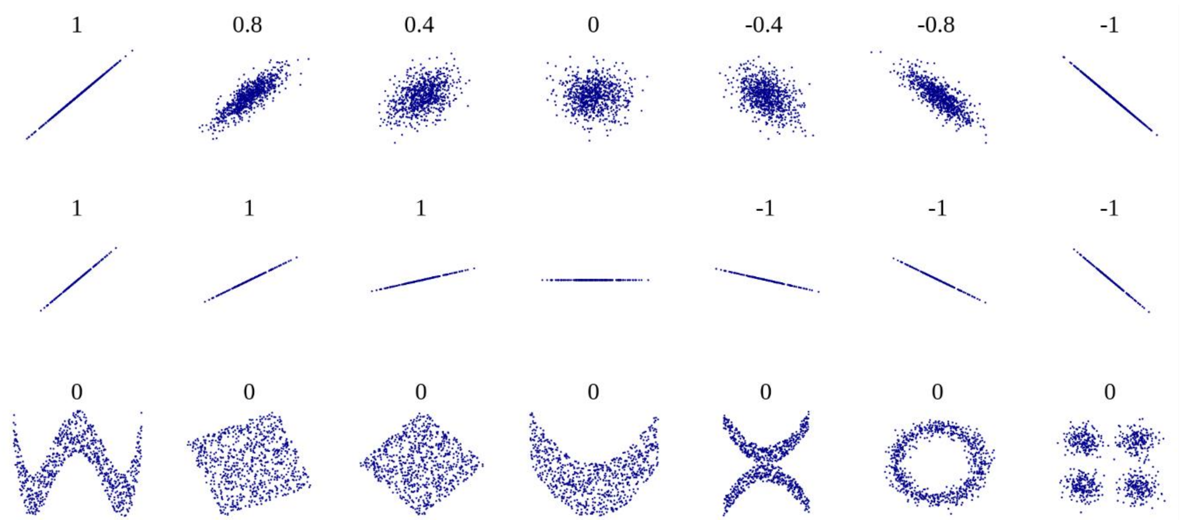


GW150914 is not from cosmic strings or Supernovae, but from binary merger

The Pearson correlation coefficient : definition and examples

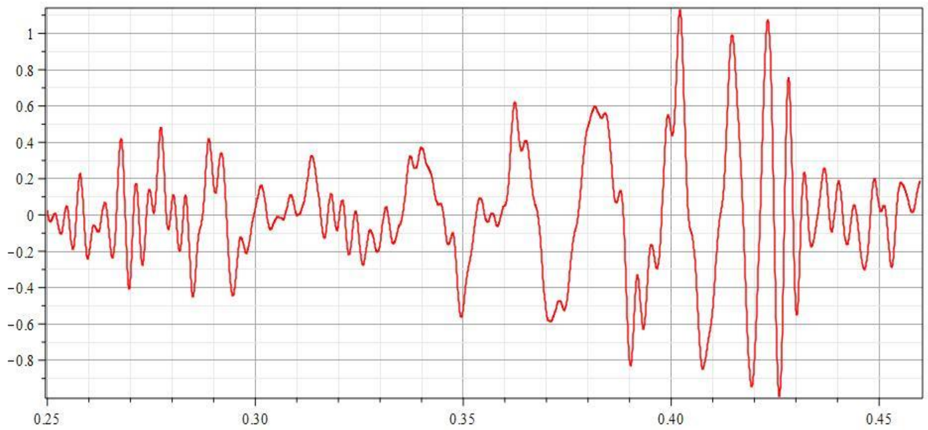
$$r_{xy} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

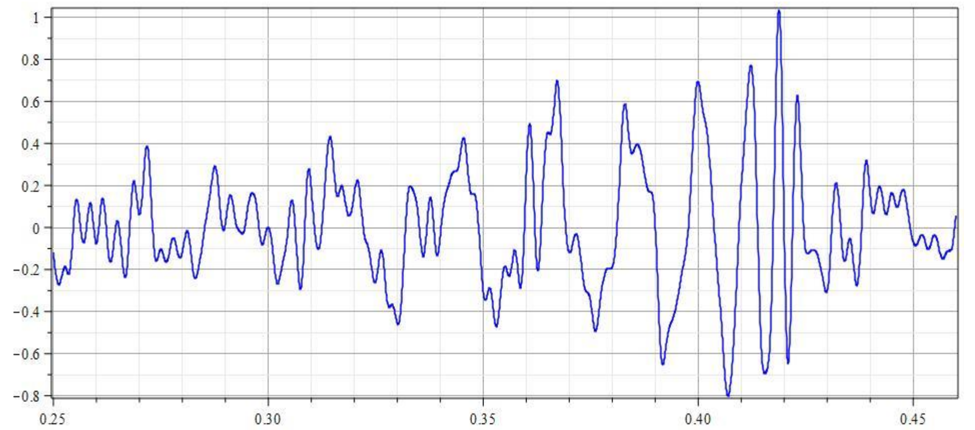
A measure of the strength and direction of the linear relationship between two variables that is defined as the (sample) covariance of the variables divided by the product of their (sample) standard deviations.



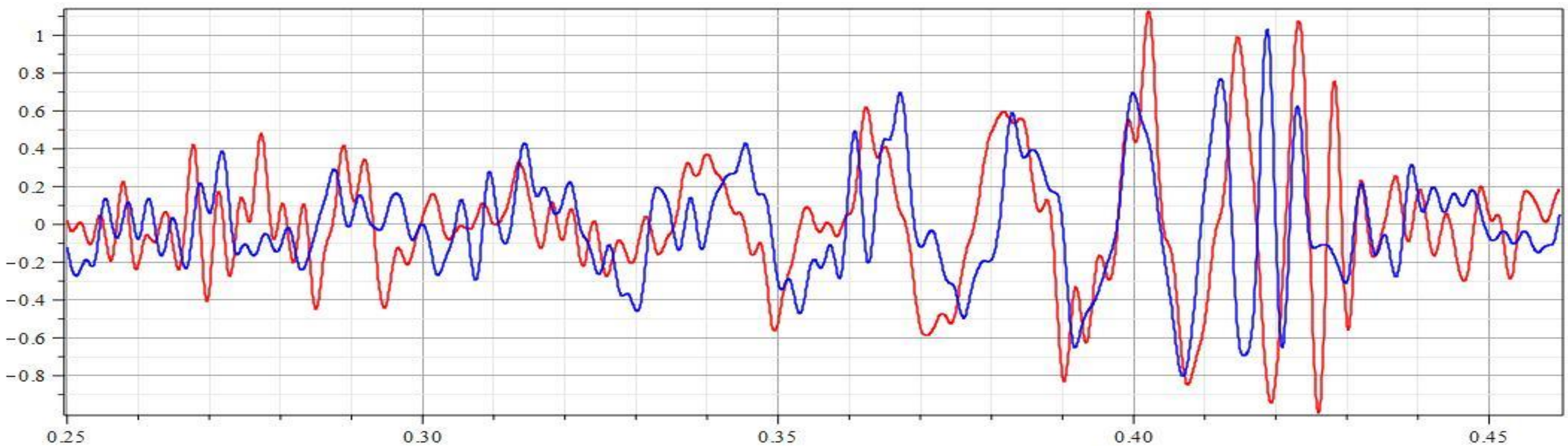
The GW150914 – Observed WF (PRL 116, 061102 (2016)):

Time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines

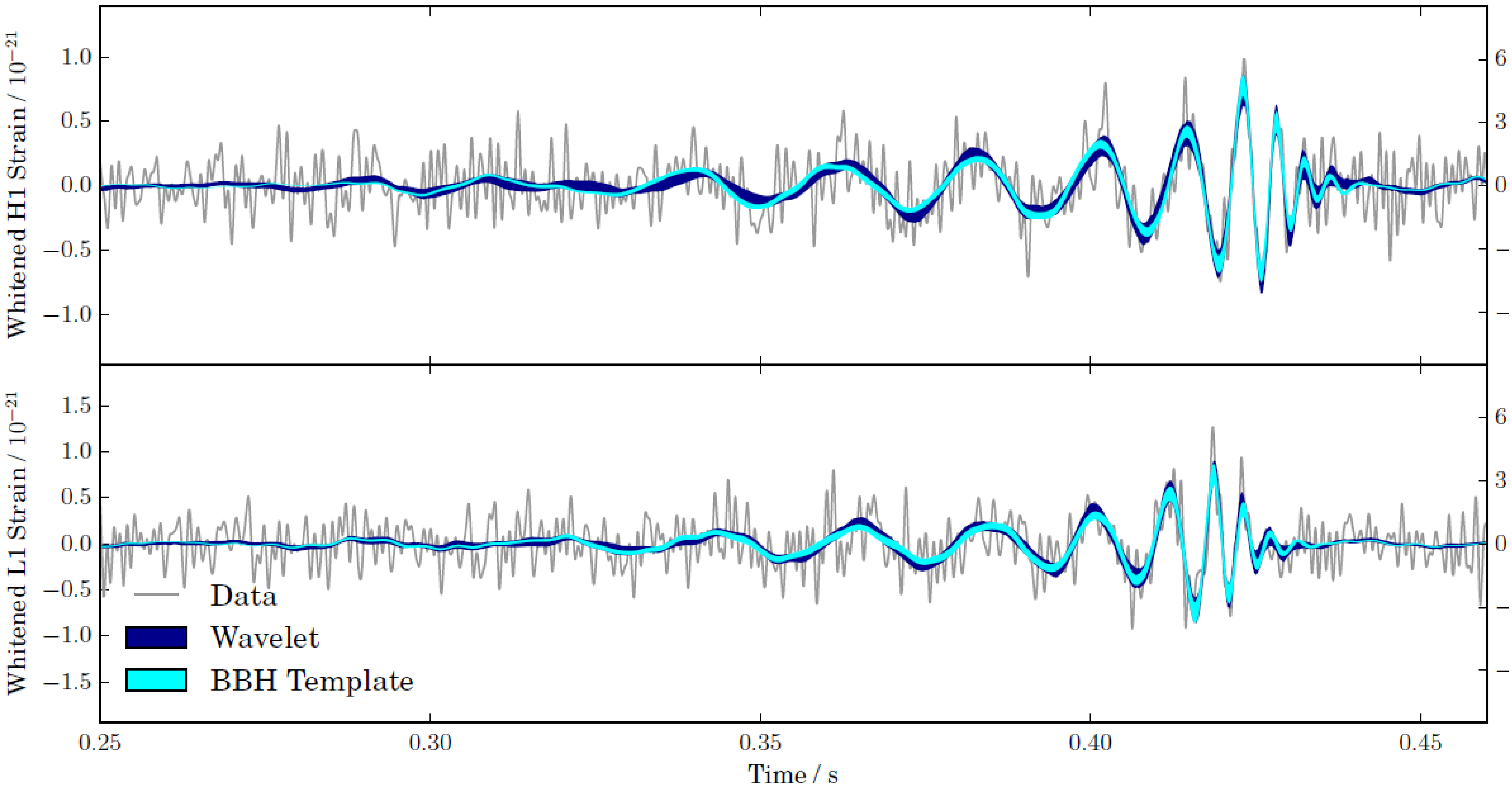




3441 points   Corr_Coeff (H1,L1) = 0.28833   (too low ?)



Properties of the binary black hole merger GW150914 :

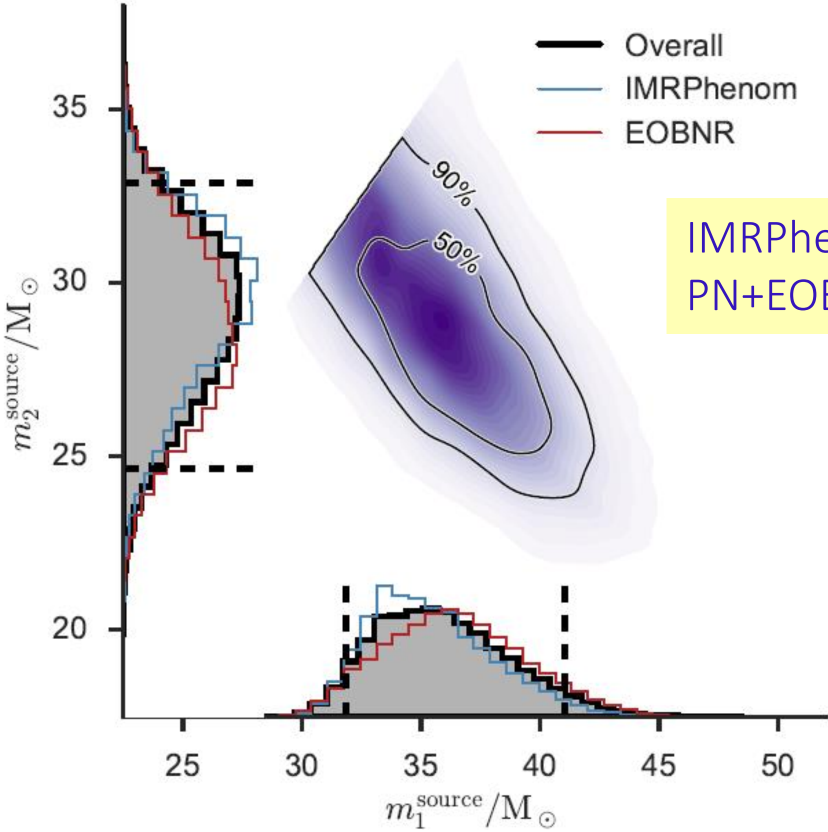


Time-domain data (sampled at 2048 Hz) and reconstructed waveforms of GW150914, whitened by the noise power spectral density.

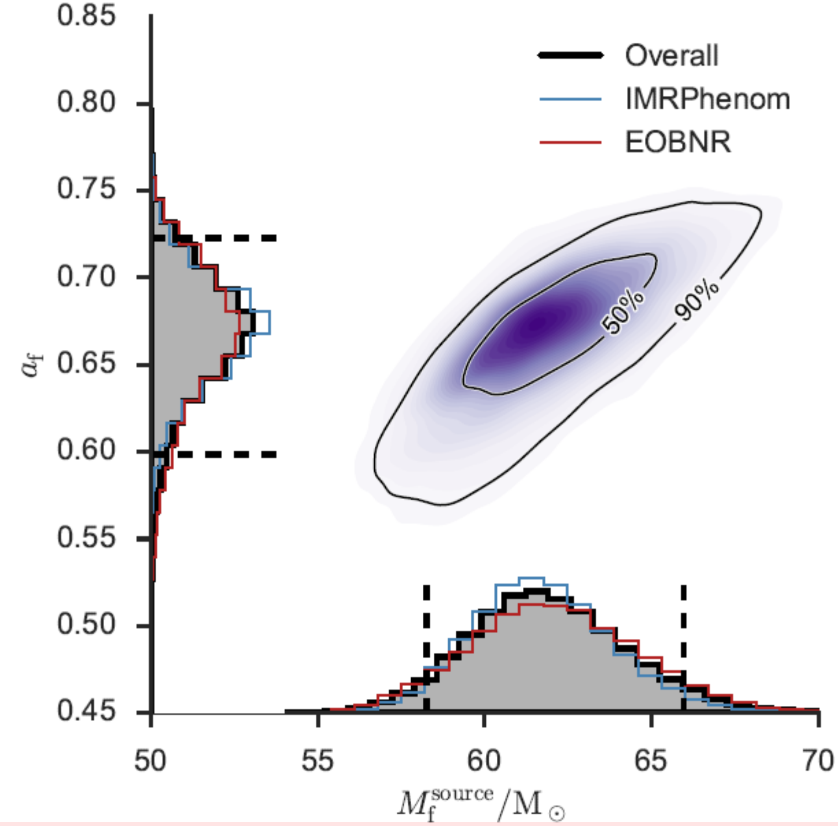
In the Figure the data are band-passed and notched filtered.

Shaded regions correspond to the 90% credible regions for the reconstructed waveforms.

Properties of the binary black hole merger GW150914 :



IMRPhenom = PN+EOB+NR



Initial masses distributions:

Overall (solid black), IMRPhenom (blue) and EOBNR (red) PDFs;

The dashed vertical lines mark the 90% credible interval for the Overall PDF.

The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a colour-coded posterior density function.

Source-frame mass and spin of the remnant BH produced by the coalescence of the binary. In the 1-dimensional marginalised distributions we show the Overall (solid black), IMRPhenom (blue) and EOBNR (red) PDFs; the dashed vertical lines mark the 90% credible interval for the Overall PDF. The 2-dimensional plot shows the contours of the 50% and 90% credible regions plotted over a colour-coded PDF.

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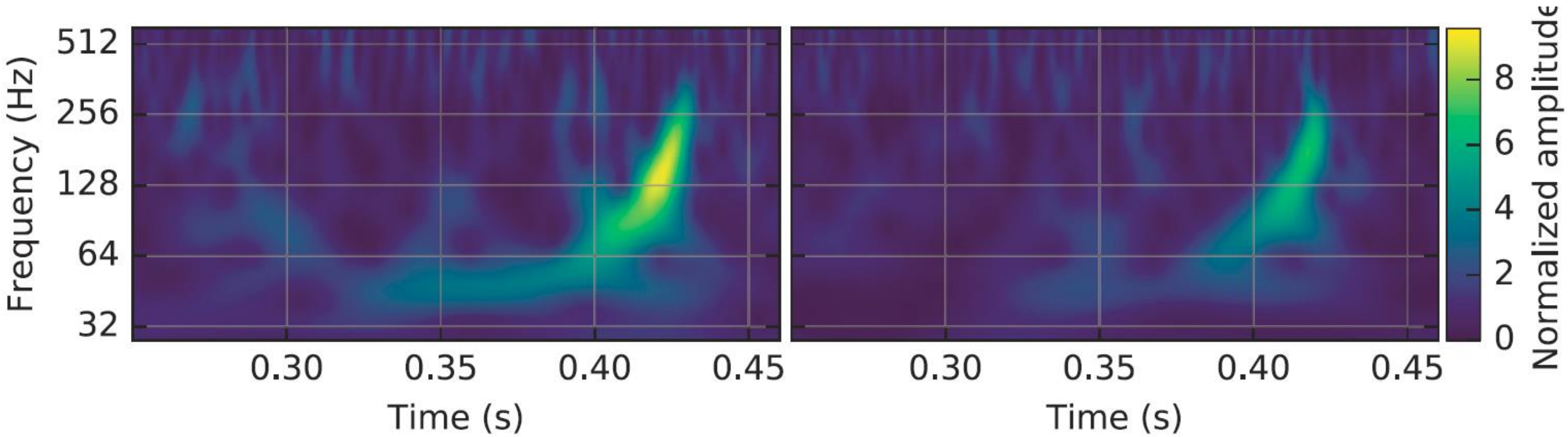
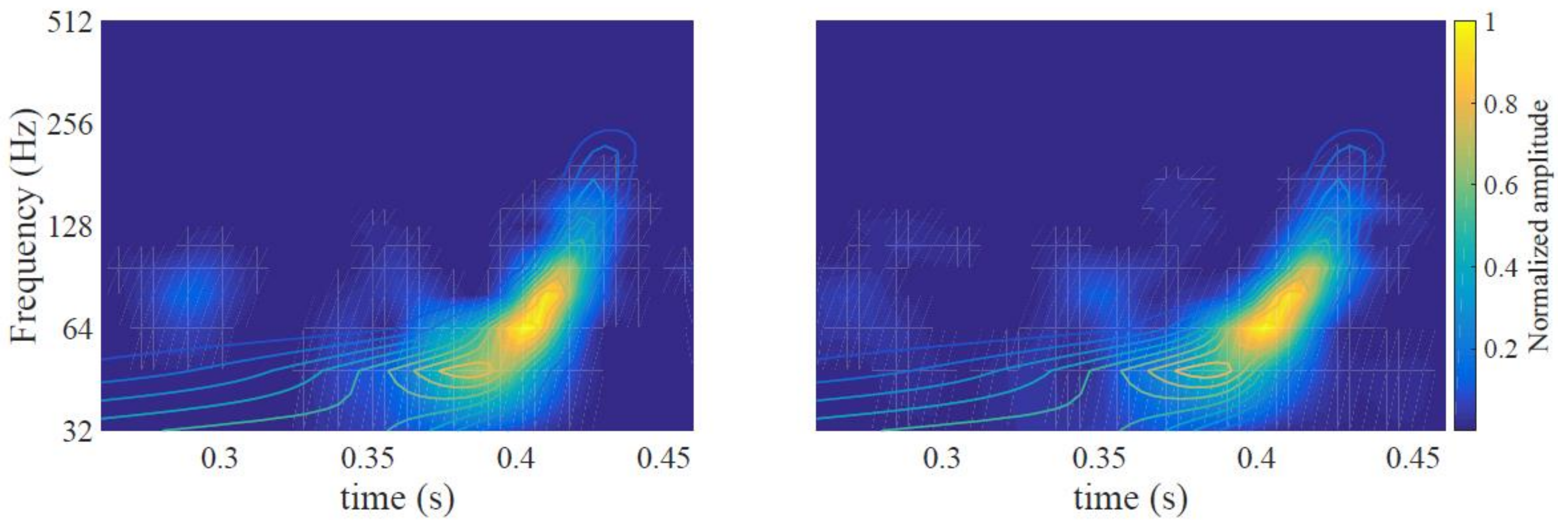
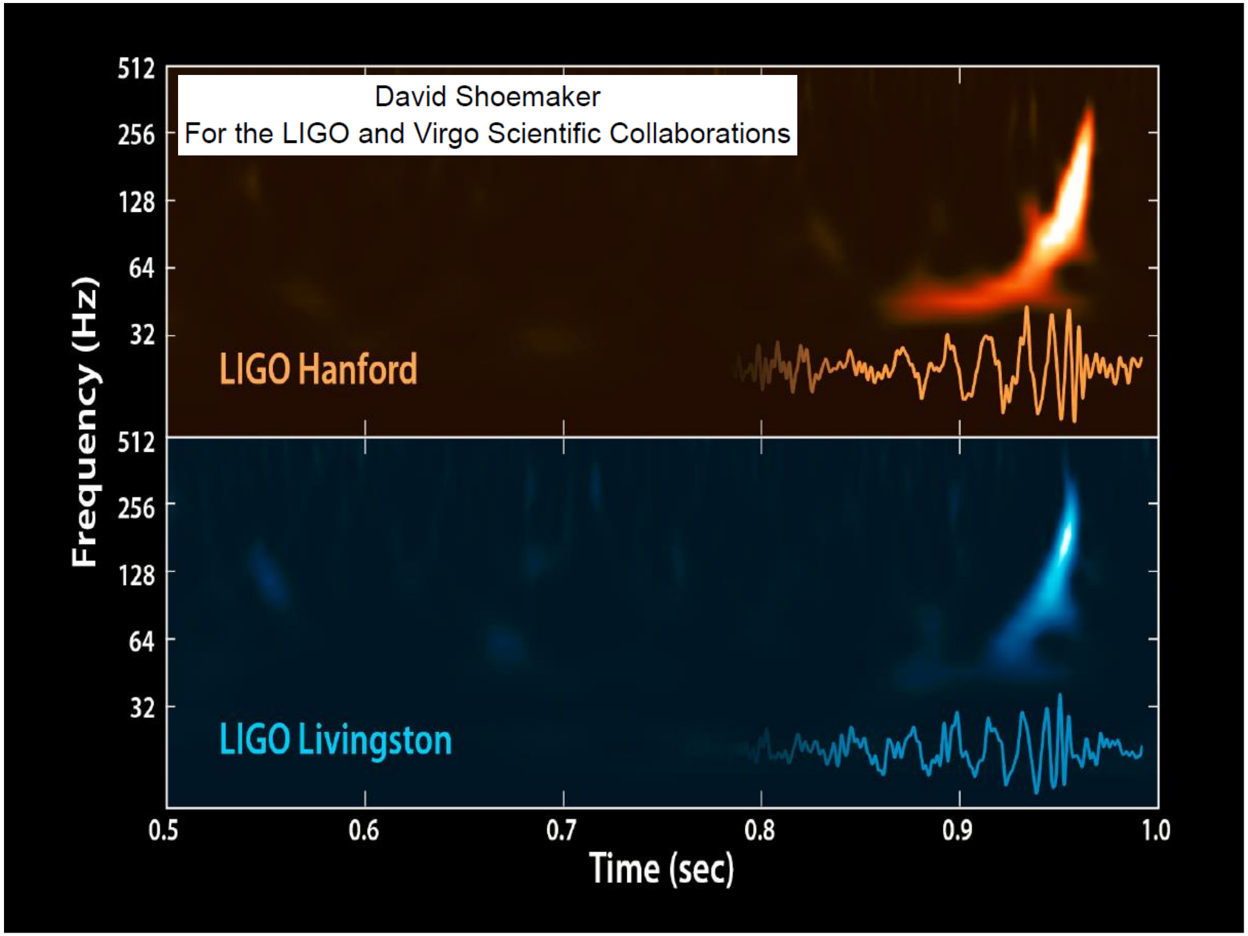


arXiv:1602.06833, A. Torres-Forn´e, A. Marquina, J. A. Font, and J. M. Ib´a˜nez
Denoising of gravitational-wave signal GW150914 via total-variation methods



Chirp Mass:

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$



1) HERE the consideration uses

ONLY

POINT PARTICLES

NOT BH

2) Newton gravity Is not able to explain observations, but GR AND modified theories can do this

$M = m_1 + m_2$ $\quad f$ is the GW frequency, $\dot{f}$ is its time derivative

BH NR fitting formula:

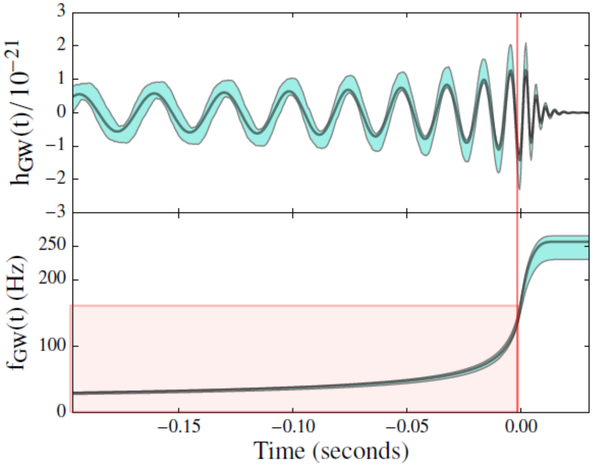
$$
\begin{aligned}
M\,\omega \;=\; & \frac{1}{8}\tau^{-3/8}\Bigg\{1+\left(\frac{743}{2688}+\frac{11}{32}\nu\right)\tau^{-1/4}-\frac{3}{10}\pi\tau^{-3/8} \\
& +\left(\frac{47}{40}\frac{S_\ell}{M^2}+\frac{15}{32}\frac{\delta M}{M}\frac{\Sigma_\ell}{M^2}\right)\tau^{-3/8} \\
& +\left(\frac{1855099}{14450688}+\frac{56975}{258048}\nu+\frac{371}{2048}\nu^2\right)\tau^{-1/2}+\left(-\frac{7729}{21504}+\frac{13}{256}\nu\right)\pi\tau^{-5/8} \\
& +\left[\left(\frac{101653}{32256}+\frac{733}{896}\nu\right)\frac{S_\ell}{M^2}+\left(\frac{7453}{7168}+\frac{347}{896}\nu\right)\frac{\delta M}{M}\frac{\Sigma_\ell}{M^2}\right]\tau^{-5/8} \\
& +\left(-\frac{720817631400877}{288412611379200}+\frac{53}{200}\pi^2+\frac{107}{280}C-\frac{107}{2240}\ln\left(\frac{\tau}{256}\right)\right. \\
& +\left.\left[\frac{25302017977}{4161798144}-\frac{451}{2048}\pi^2\right]\nu-\frac{30913}{1835008}\nu^2+\frac{235925}{1769472}\nu^3\right)\tau^{-3/4} \\
& +\left(-\frac{188516689}{433520640}-\frac{97765}{258048}\nu+\frac{141769}{1290240}\nu^2\right)\pi\tau^{-7/8}\Bigg\}\,,
\end{aligned}
$$

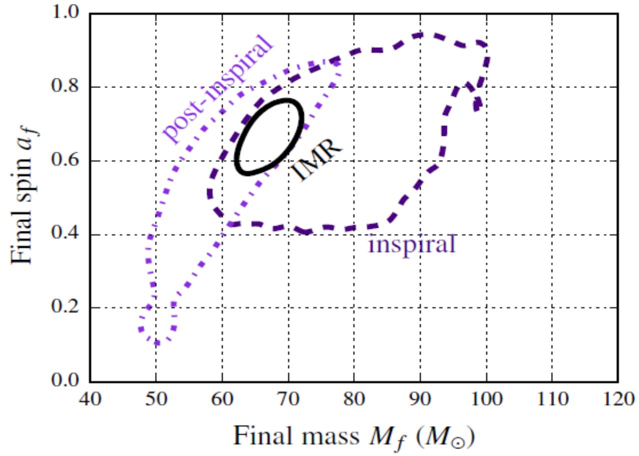
At present there is NO analogous formula for modified theories and for alternative models of GR150914

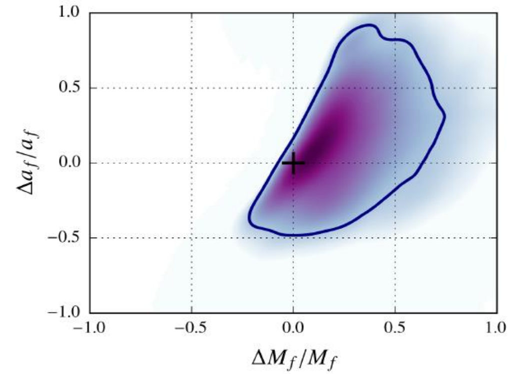
$$
\tau=\nu\,(t_c-t)/5M\,,\qquad \nu=\mu/M\,,\qquad \mu=m_1m_2/M\,,\qquad \delta M=m_1-m_2
$$

t_c is the time at which the orbital-frequency diverges , $\boldsymbol{\Sigma}\equiv M\left[\frac{\mathbf{S}_2}{m_2}-\frac{\mathbf{S}_1}{m_1}\right]$, $\mathbf{S}\equiv\mathbf{S}_1+\mathbf{S}_2$

Tests of general relativity with GW150914:



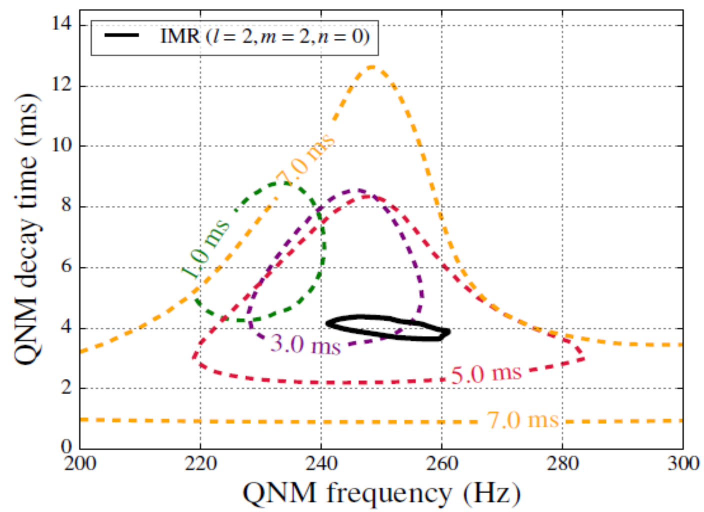




QNM of the Ker BH are well known (numerically) in the form

$\omega_{nlm}(M,a)$

The n = 0, l = 2, and m = 2 (i.e., the least damped) QNM obtained from the inspiral-merger-ringdown waveform for the entire detector's bandwidth.



Derived not from the **ringdown** tail !!!

There is

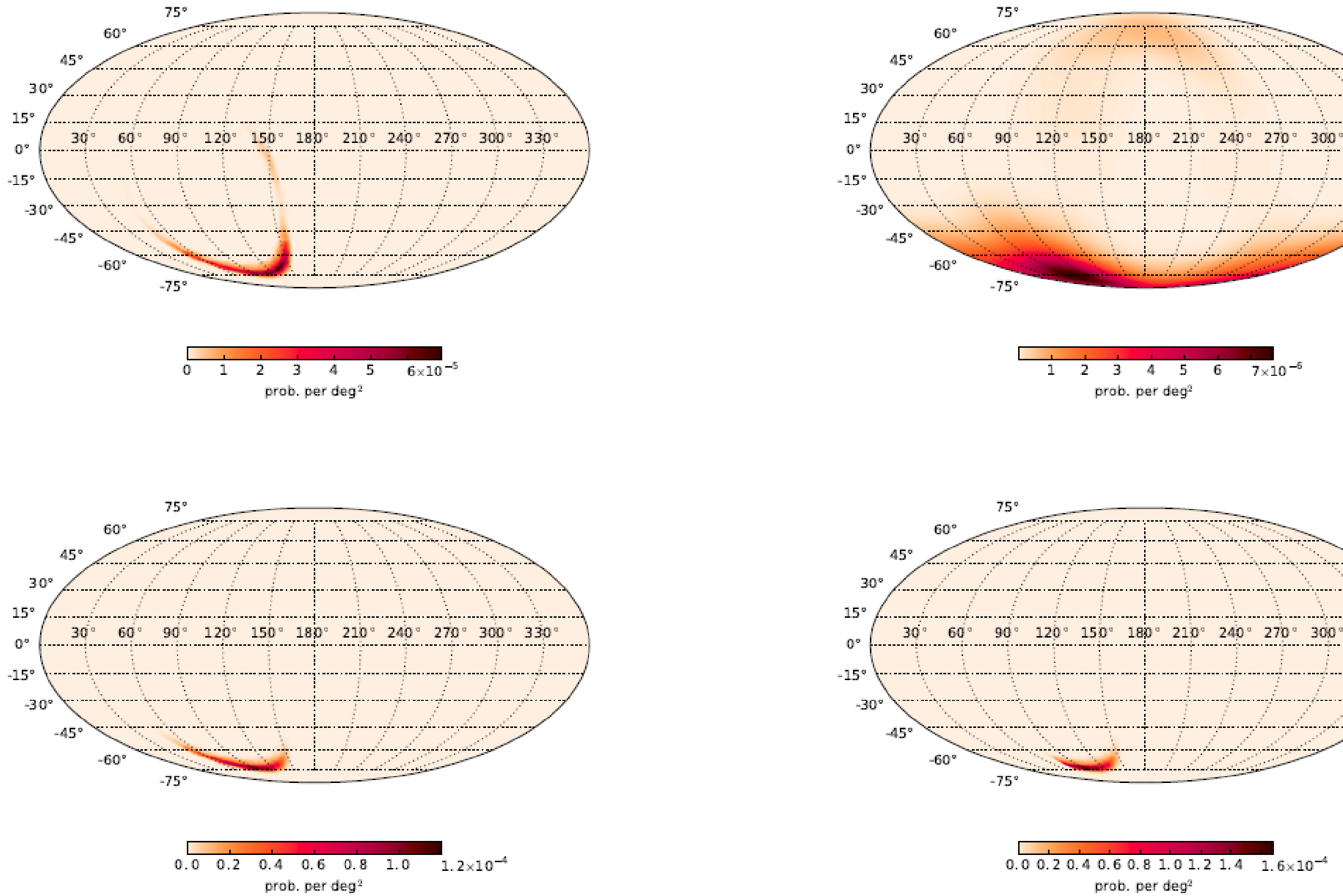
NO REAL PROOF

that the final object Is a BH

!!!

Fermi GBM Observations of LIGO Gravitational Wave event GW150914

arXiv:1602.03920

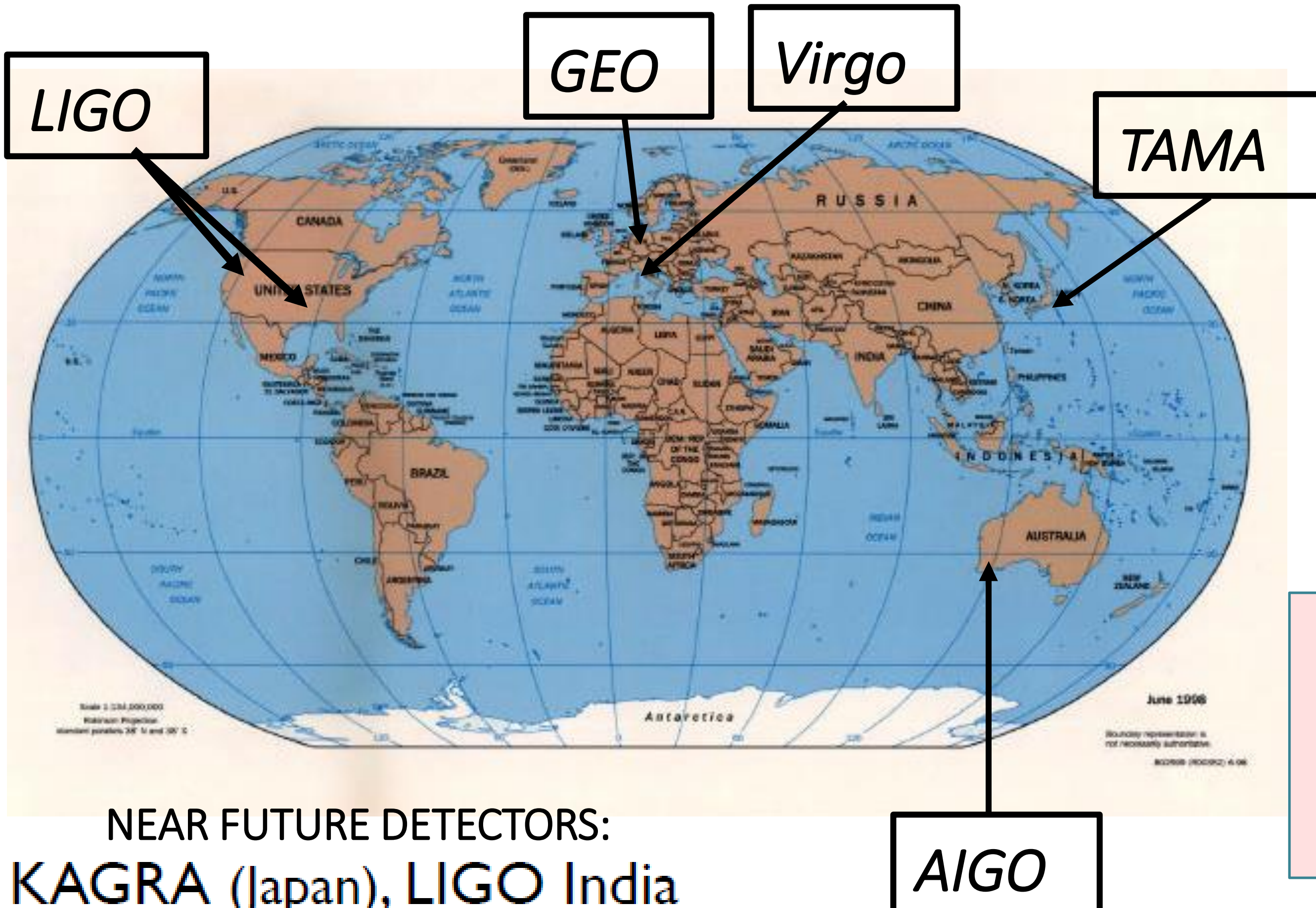


The LIGO localization map (top left) can be combined with the GBM localization map for GW150914-GBM (top right) assuming GW150914-GBM is associated with GW event GW150914. The combined map is shown (bottom left) with the sky region that is occulted to Fermi removed in the bottom right plot. The constraint from Fermi shrinks the 90% condence region for the LIGO localization from 601 to 199 square degrees.

The observed time-delay of GW150914 between the Livingston and Hanford observatories was $6.9^{+0.5}_{-0.4}$ ms. With only the two LIGO instruments in observational mode, GW150914's source location can only be reconstructed to approximately an annulus set to first approximation by this time-delay.

Interferometers - *international network*

'Simultaneously' detect signal (within msec)



detection confidence

locate the sources

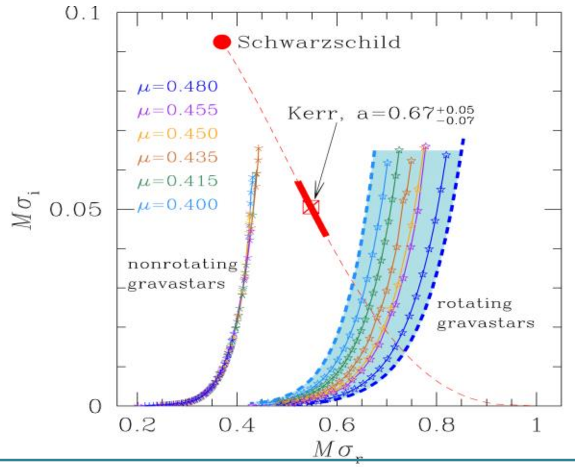
decompose the polarization of gravitational waves

NEAR FUTURE DETECTORS:
KAGRA (Japan), LIGO India
2020

Alternative explanations of GW150914

C. Chirenti and L. Rezzolla:
Did GW150914 produce a rotating gravastar?

arXiv:1602.08759



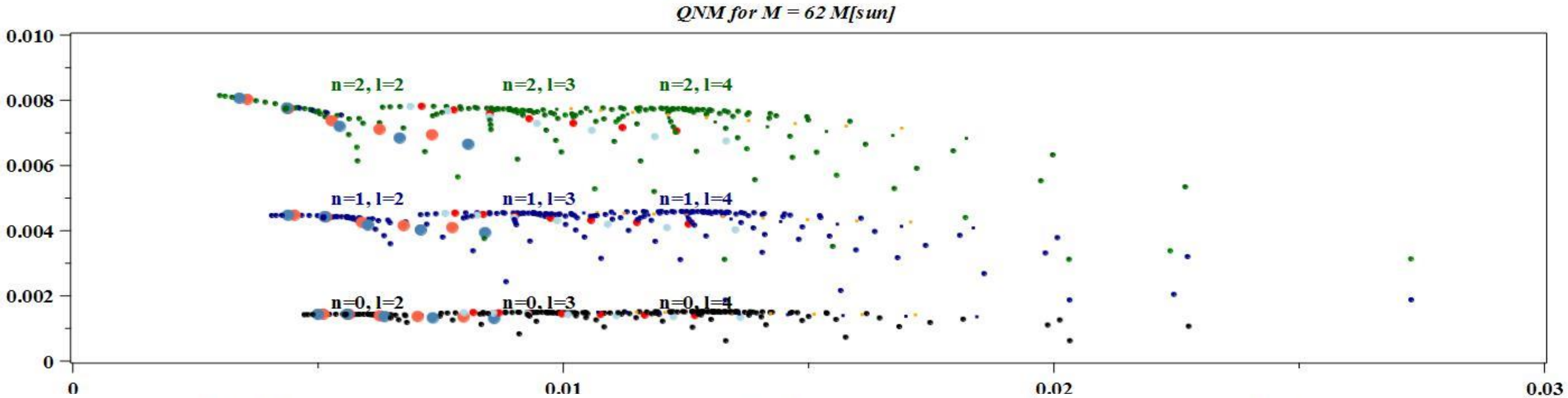
S.Bird, I.Cholis, J. B. Munoz, Y.Ali-Haimoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess: *Did LIGO detect dark matter?* arXiv:1603.00464

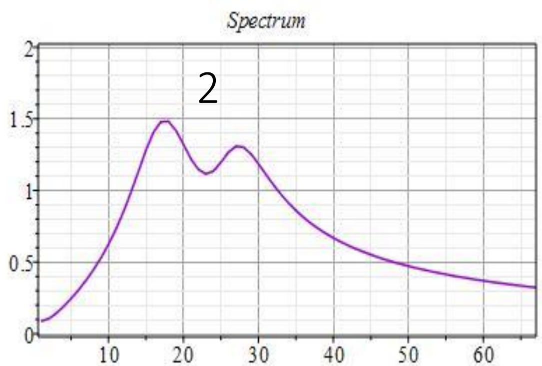
PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitationalwave background.

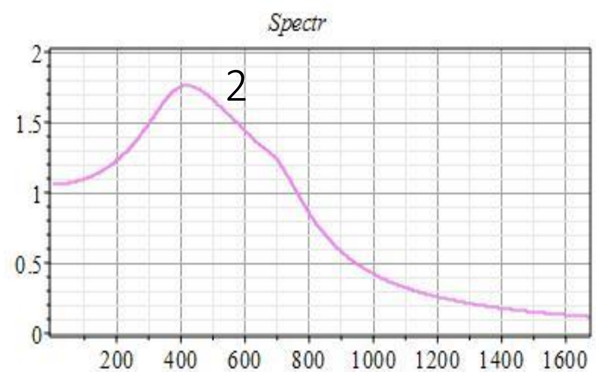
R.Konoplya, and A. Zhidenko: *Detection of gravitational waves from black holes: Is there a window for alternative theories?* arXiv:1602.04738

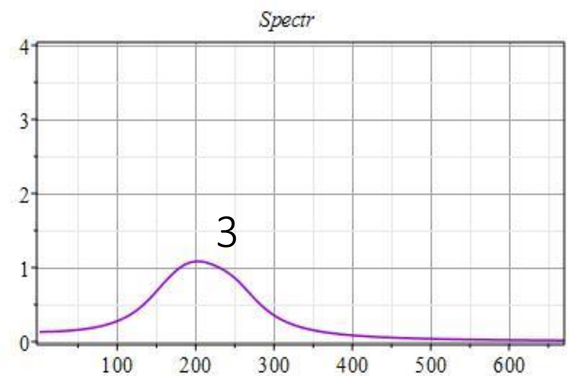
Here we shall show that this indeterminacy in the range of the black-hole parameters allows for some not negligible deformations of the Kerr spacetime leading to the same frequencies of black-hole ringing. This means that at the current precision of the experiment there remain some possibilities for alternative theories of gravity.

Problems in investigation of the tail of event GW150914 and QNM









V.Cardoso, E.Franzin, P. Pani*: Is the gravitational-wave ringdown a probe of the event horizon?* arXiv:1602.07309

If the final object is a BH, the ingoing condition at the horizon simply takes the ringdown waves and “carries” them inside the BH. In this case, the BH QNMs incidentally describe also the ringdown phase.

However, if the horizon is replaced by a surface of different nature (as, e.g., in the gravastar or in the firewall proposals) the relaxation of the corresponding horizonless compact object should then consist on the usual light-ring ringdown modes (which are no longer QNMs), followed by the proper modes of vibration of the object itself.

The Time, Energy and Temperature scales in the Universe

t	$\rho^{1/4}$	T	Event
10^{-42} s	10^{18} GeV	~ 0	Inflation begins ?
$10^{-36\pm6}\,s$	$10^{13\pm3}$ GeV	~ 0	Inflation ends, Cold Big Bang starts?
$10^{-18\pm6}$ s	$10^{6\pm3}$ GeV	$10^{6\pm3}$ GeV	Hot Big Bang begins ?
$10^{-10}\,s$	100 GeV	100 GeV	Electroweak phase transition ? (LHC)
$10^{-4}\,s$	100 MeV	100 MeV	Quark-hadron phase transition? (NICA)
$10^{-2}\,s$	10 MeV	10 MeV	γ, ν, $e^{\mp}$, n, p in thermal equilibrium
1 s	1 MeV	1 MeV	ν decoupling, $e^{\mp}$ annihilation
100 s	0.1 MeV	0.1 MeV	Nucleosynthesis
$10^4\,yr$	1 eV	1 eV	Matter-radiation equality
$10^5\,yr$	0.1 eV	0.1 eV	Atom formation, photon decoupling
$\sim\ 10^9$ yr	10^{-3} eV	10^{-4} eV	First bound structures forms
Now	$3\times\ 10^{-3}\ h^{1/2}(\Omega_0)^{1/4}$eV	**2.72548 ± 0.00057 K**	The present state of Universe

Some Conclusions

1. The GW150914 confirms the existence of some kind of GW at the 5.1 sigma level !

2. The absence of data about polarization of the GW in GW150914 does not permit us to distinguish GR from modified theories of gravity and to confirm validity of GR.

3. The basic hypothesis in the analysis of GW150914 – the validity of GR can not be true, since we know that GR plus Standard Particle Model are not enough to describe NATURE, and one needs peremptorily:
a) To introduce DARK ENERGY and DARK MATTER, which leads to possibility for alternative explanations of GW150914, or:
b) To consider modified theories of gravity which are able to give their own alternative explanations of GW150914. At present the modified theories are not developed enough.

4. The presence of BH in GW150914 is not well substantiate and follows from preliminary assumptions during the analysis of data! Actually, the GW150914 leads to a crisis in the theory of BH, because masses about 30-60 solar masses are not compatible with the evolution of the known stars.

5. The old theory (‘60) of the gravitational collapse must be reconsidered to take into account modern knowledge of matter EOS. The very theory of EOS is not complete and firmly establish.

5. A further analysis of the real data without any preliminary physical hypotheses is needed.

7. Only the analysis of QNM in the GW150914 tail may give us undisputable information about the nature of the final remnant. This is not done at present.

Thank YOU