Typical detectors and to-date observations of Gravitational Waves

A new physical frontier

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High Energy Seminar

Experimental Physics PhD (*Cycle XXXVI*)

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CONTENTS

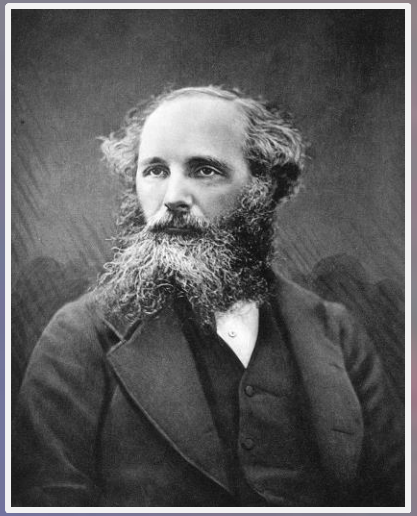
NEWTONIAN TROUBLES...

Changing inertial reference frame, the velocities add up (Addition Theorem) as our common sense suggests

"RELATIVE MOTION"

G. Galilei (https://www.uffizi.it/)

VS



J. C. Maxwell (https://fineartamerica.com/)

Electric and magnetic fields are linked, and related vibrations travel at $c \approx 300\,000$ km/s

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If one moves anyhow with respect to light ("Ether"), a different speed is expected to be measured

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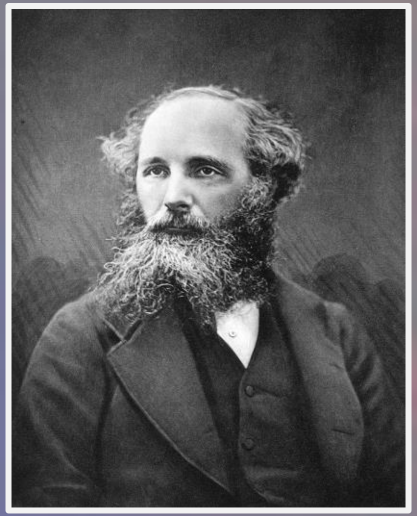

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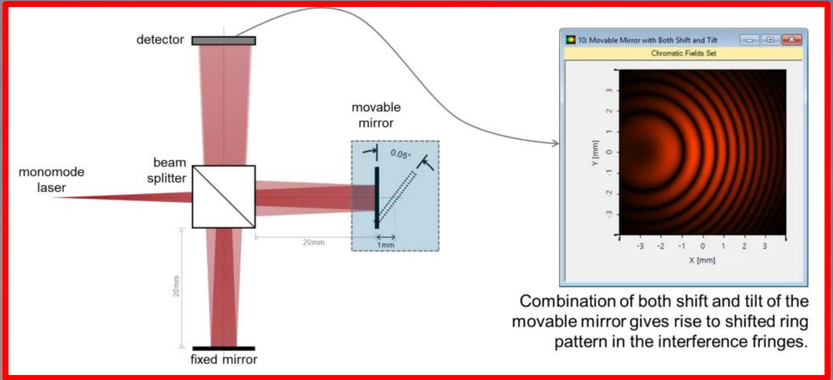

Combination of both shift and tilt of the movable mirror gives rise to shifted ring pattern in the interference fringes.

https://atomstalk.com/blogs/theory-of-relativity/

Michelson-Morley experiment (1887) showed no signal of any change for c!

NEW SHOCKING PHYSICS

$E = mc^2$

https://library.ethz.ch/

In 1905 Albert Einstein proposed a revolutionary solution (Special Relativity):

the speed of light c is invariant for any inertial observer!

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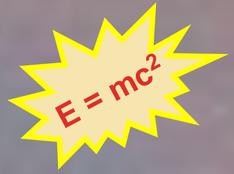

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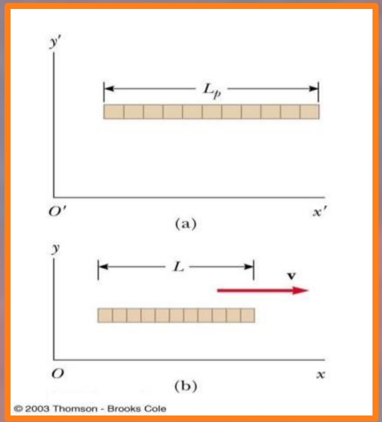
In 1905 Albert Einstein proposed a revolutionary solution (Special Relativity):

the speed of light c is invariant for any inertial observer!

Combining it with both inertia and relativity principle, the very concepts of space and time, as well as that of simultaneity, changed for ever...

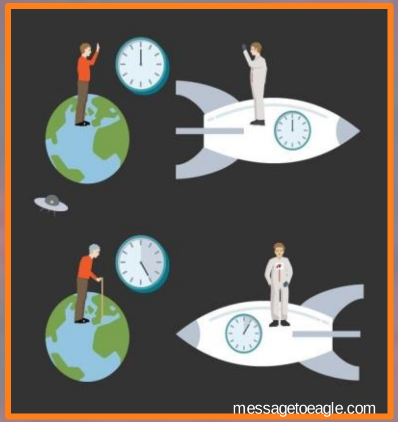
L' = L / γ



$$\gamma_v = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

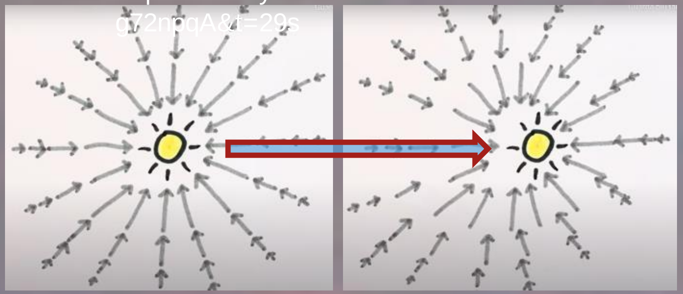
$$p = \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix} \Rightarrow \begin{aligned} t' &= \gamma_v\left(t - \frac{v}{c^2}x\right) \\ x' &= \gamma_v(x - vt) \\ y' &= y \\ z' &= z \end{aligned}$$

T' = γ T



A MORE COMPLETE VIEW

https://www.youtube.com/watch?v=YHS9g72npqA&t=29s

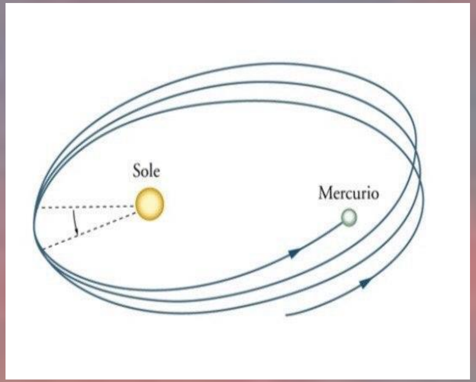


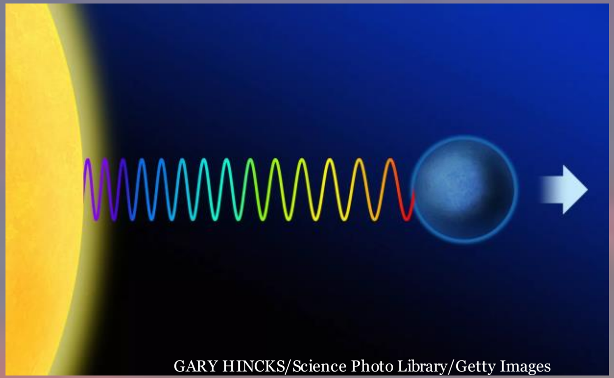
GENERAL RELATIVITY (1916)

Relativistic treatment of gravitation, basis for all cosmological models

- **c is the maximum speed** that any object or signal can actually reach, so the classical instantaneous interaction between distant bodies is not possible anymore!
- **Gravitational field <=> geometric distorsion of Minkowski space-time** (newtonian limit for ≈ flat metric, and low velocities)

https://astroaristofane.blog/





GARY HINCKS/Science Photo Library/Getty Images

X-ray: NASA/CXC/UA/J.Irwin et al; Optical: NASA/STScI

FIELD EQUATION

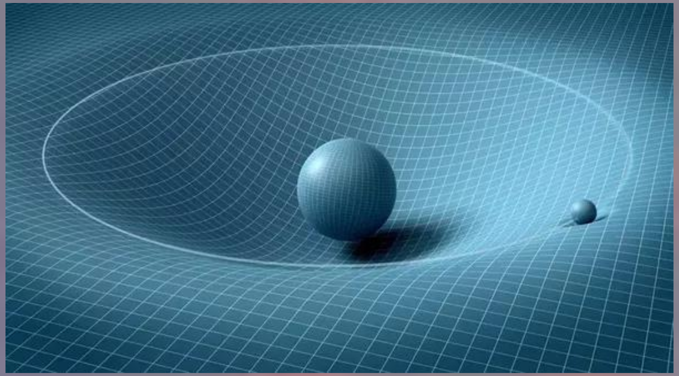
$ds^2 = g_{\mu\nu}(x)\, dx^\mu\, dx^\nu$

"*Space-time tells matter how to move, matter tells space-time how to curve*" (J. A. Wheeler)

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature (Einstein Tensor)

Mass-Energy (Stress-Energy Tensor)



http://www.alfinito.it/

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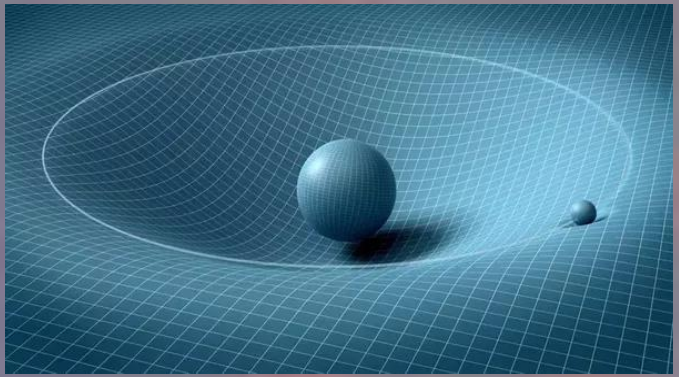

http://www.alfinito.it/

Ten-component tensorial field, with no linear equations (superposition principle not valid!)

Known solutions:

i. **Weak field (linear approximation, even not static)**

ii. Spherical simmetry (Schwarzschild)

iii. Cosmological evolution (Friedmann-Lemaître)

GRAVITATIONAL WAVES

Ripples in space-time fabric caused by accelerated masses, propagating as waves at the speed of light

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Linearization and investigation on oscillating solutions over t

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + \varepsilon h_{\mu\nu}(x)$$

$\varepsilon \longrightarrow 0$

Harmonic frame in vacuum (invariant gauge)

$$\Box h_{\mu\nu} = 0$$

Laplace-Beltrami Operator

$$\Box = g^{\alpha\beta}\left(\frac{\partial}{\partial x^\beta}\frac{\partial}{\partial x^\alpha} - \Gamma^\mu_{\alpha\beta}\frac{\partial}{\partial x^\mu}\right)$$

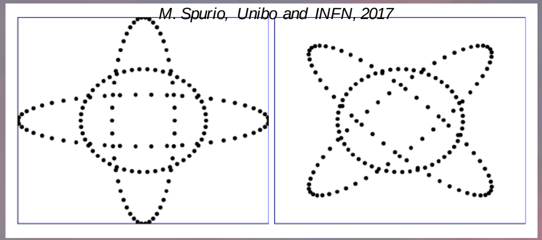
$$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \nabla^2\right)$$

Plane wave with related vector k // z axis

$$h_{\mu\nu}(\mathbf{x}) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{[i(\vec{k}\cdot\vec{x}-\omega t)]}$$

(h_+, h_x) constant amplitudes -> polarizations

GRAVITATIONAL WAVES



Effect on a ring-shaped set of masses in the (x,y) plane; to relate GWs to source, $T_{\mu\nu}$ + proper assumptions must be considered (see field eq.)

h := adimensional "strain" referring to measurable GW amplitude ≈ ΔL/L (distance rhytmically changing between objects)

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EXPECTED SIGNAL

Many doubts about the very detectability (by Einstein himself)…as extremely small incoming wave!

Fundamental emission condition:

Inhomogeneous mass distribution
(no spherical simmetry)

↓

Quadrupole moment

Source distance

$$h_{ij} \simeq \frac{4G}{rc^4}\frac{d^2Q_{ij}}{dt^2}$$

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Angular Speed

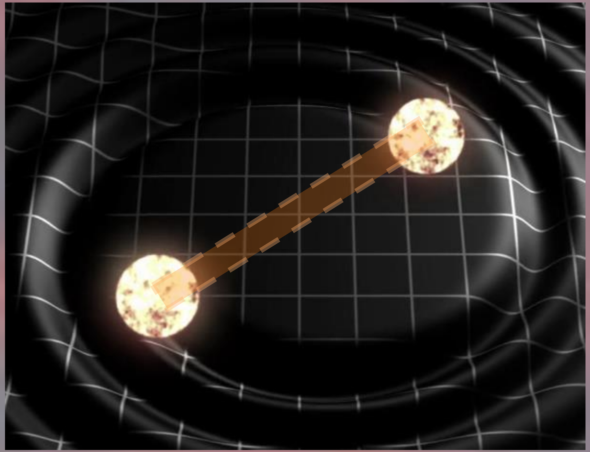
Inertia Moment

Gravitational Constant

$$P = \frac{32\Omega^2 I^2 G}{5c^2}$$

Light Speed

Spinning Bar Power



https://www.storyblocks.com/

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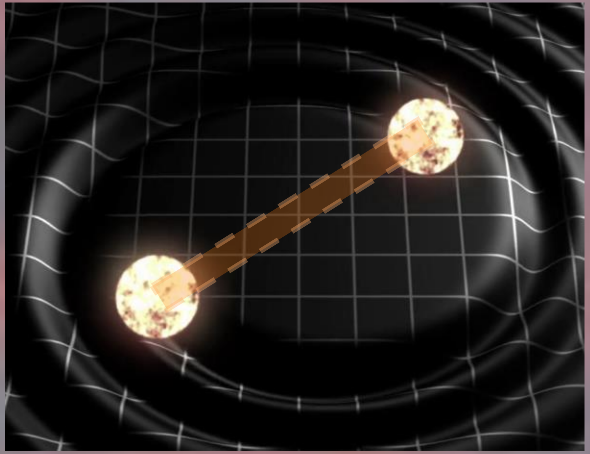
Tipically, strong GWs expected from massive objects changing their *Q* moment very rapidly

Binary NSs/BHs, flattened pulsars, SNe are the best (but far...!) candidates

Tiny quantities, e.g.:

P negligible also for Sun-Jupiter system

Typical ΔL/L ~ atom size for Sun-Earth distance!



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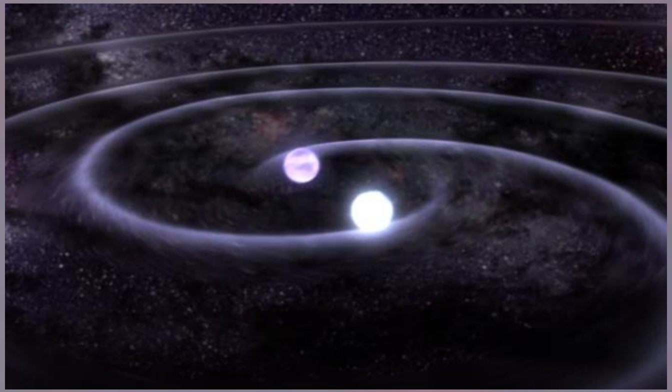
FIRST OBSERVATIONAL HINT



https://www.ligo.caltech.edu/

PSR 1913+16

First binary pair of pulsar-NS ever discovered, ≈ 21000 l.y. away, by R. A. Hulse and J. H. Taylor in 1974 (Nobel Prize in 1993)

Using the Arecibo Radio Observatory, a pulsed emission was found with T ≈ 59 ms (systematic variations of ≈ 8 h due to the companion)

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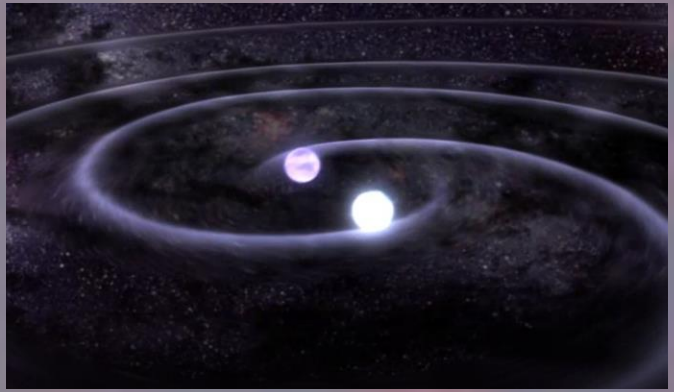

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Taylor & Weisberg, ApJ, 1982

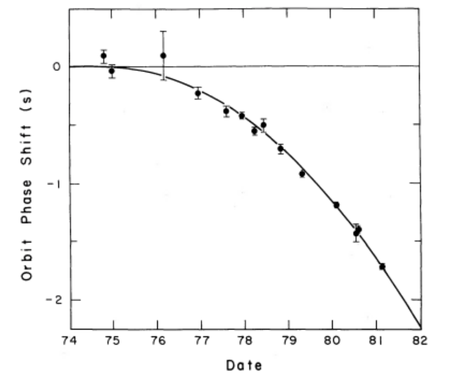


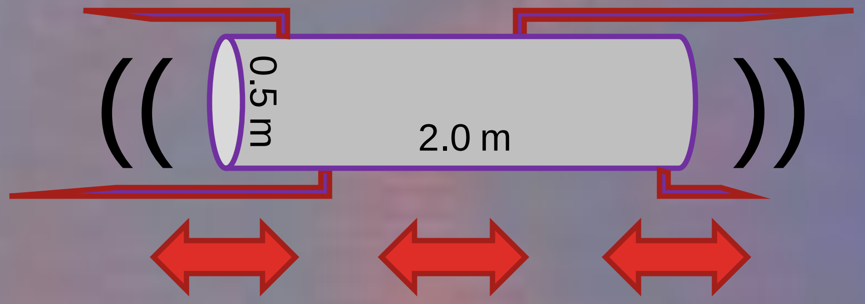
FIG. 6.—Orbital phase residuals, obtained from the data listed in Table 4. If the orbital period had remained constant, the points would be expected to lie on a straight line. The curvature of the parabola drawn through the points corresponds to the general relativistic prediction for loss of energy to gravitational radiation, or $\dot{P}_b = -2.40\times10^{-12}$.

Analyzing 6+ years of observations, the NSs were orbiting closer and closer around each other, approaching at precisely the rate expected in the hypothesis of energy loss due to GW emission!

Further confirmations came up in the following years, also from different binary sistems, so that GWs were not just theoretical anymore...

HOW TO DETECT GWs?

After F. Pirani studies showing that GWs actually transfer energy to matter (via tidal forces), in the '60s speculation on experimental detection started, mainly thanks to J. Weber



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But not enough sensitivity nor band width ☹

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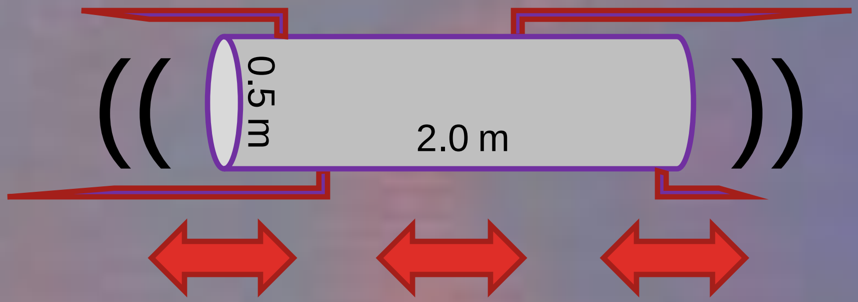

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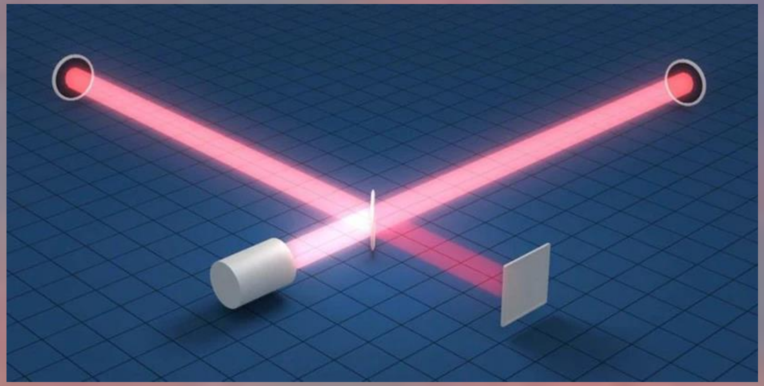


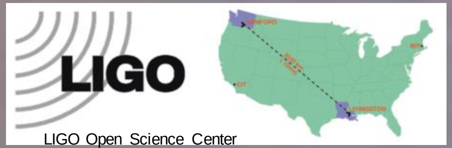
https://www.inverse.com

From new detailed models and calculations (on h, ν), <u>Laser Interferometers</u>, using special mirrors to perform light interference, became promising

Sufficiently sensible and wide-band technique ☺

LIGO

Laser Interferometer Gravitational Observatory



- Two identical detectors ≈ 3000 km apart in U.S.A., one in Hanford (Washington State), the other in Livingston (Louisiana)

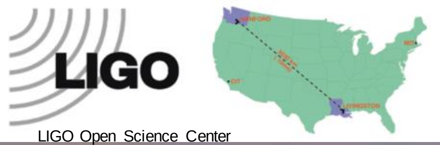
- 4 km-scale laser interferometers, built 1994-2002, with an improved Michelson L-type configuration ("iLIGO" until 2010, then "aLIGO" until 2017)

- Reachable strain and bandwidth 10^{-22} and 100 Hz respectively

- Together with Virgo (≈ 3 km, Pisa, Italy) and GEO (≈ 600 m, Sarstedt, Germany) is known as LVC or LSC

https://www.engineering.com (courtesy of LIGO Laboratory)

LIGO



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↳ *to exclude noise, attempt localization, and forward triggers!*

DETECTOR INSIGHT

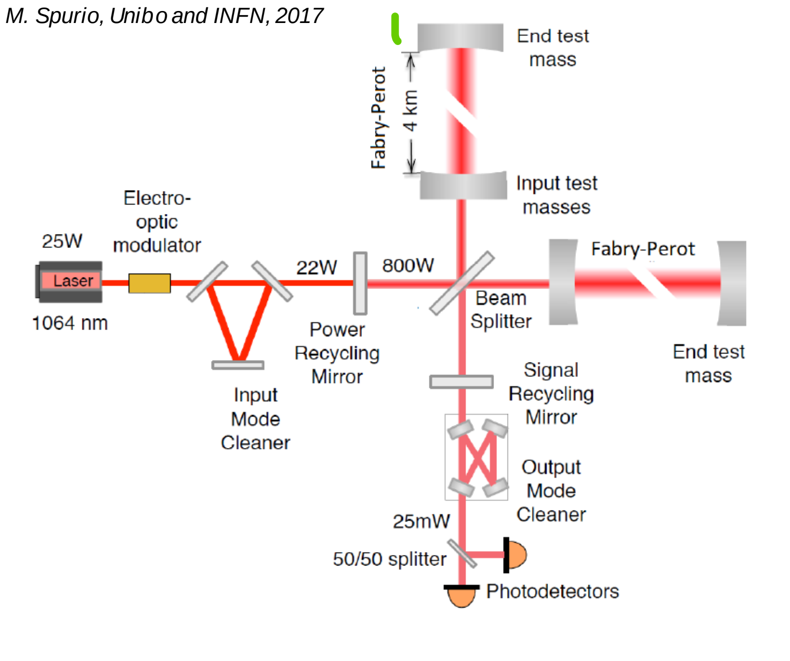


Figure 3: Layout of an aLIGO detector. Adapted from [14]. See text for details.

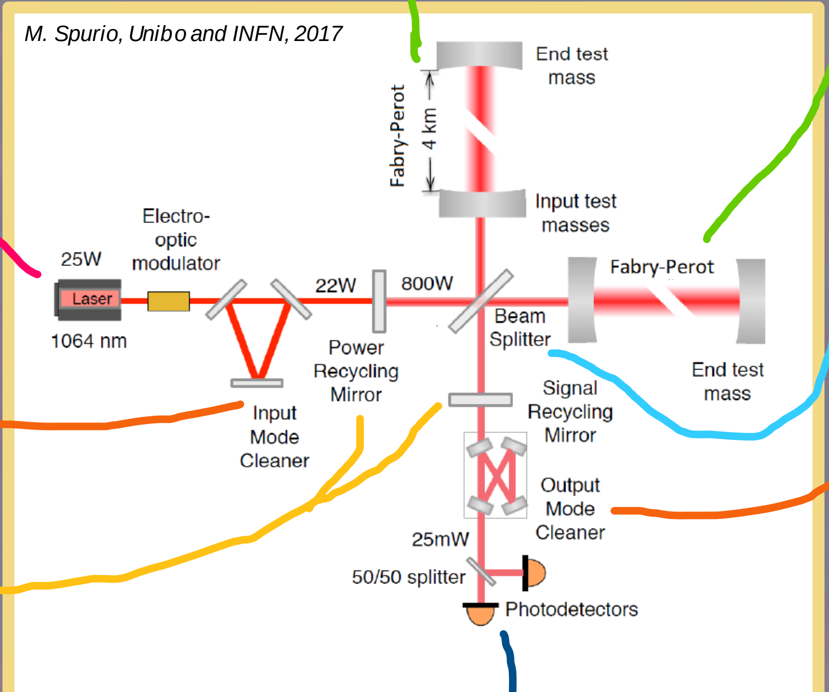
DETECTOR INSIGHT

Additional mirrors to continuously reflect parts of the laser beam back and forth within the arms (≈ 270 times => effective lenght ≈ 1080 km!)

Laser diode producing light beam which passes through some crystal devices to get amplified and refined (final λ ≈ 1064 nm, P > 35 W)

Separation into two identical beams at 90° travelling down to the arms, until mirrors ("test masses") reflect them back to merge into one beam again

Suspended Fabry-Perot cavity to clean up the beam spatial profile, improve polarization, and help stabilize the laser frequency



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Suspended Fabry-Perot cavity to reject unwanted spatial and frequency components of light before detection

Between laser source/signal and beam splitter to amplify the overall light ("recycled" photons add to the incoming ones, both for input/output)

Pattern of destructive interference of one splitted laser beam with the other (intensity change <=> some travelled L_{arm} change of at least one of them)

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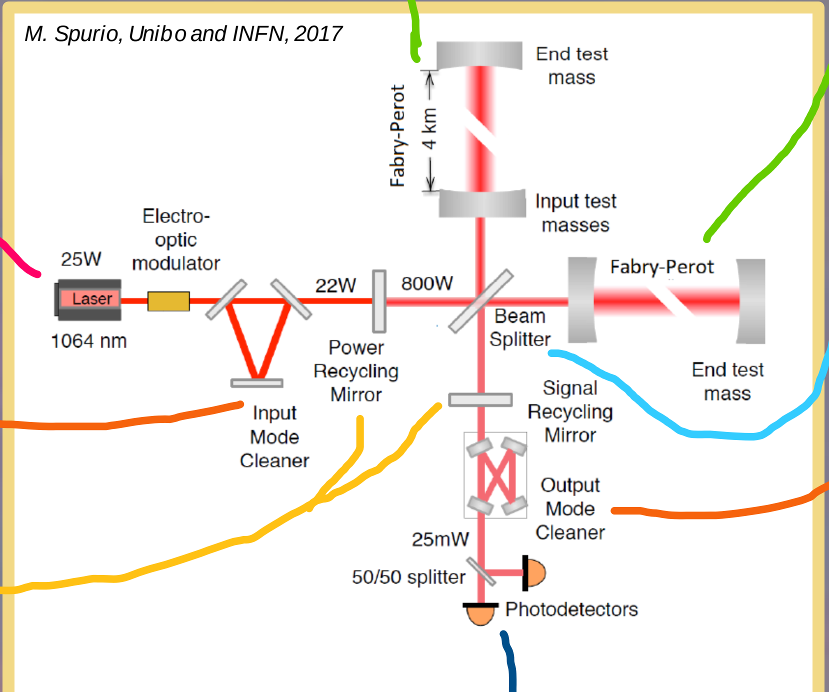

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Top quality mirrors: purity and atom-scale precision (abs. ≈ 10^{-6} to avoid heating and keep alignment)

klipartz.com

Pattern of destructive interference of one splitted laser beam with the other (intensity change <=> some travelled L_{arm} change of at least one of them)

FURTHER REFINEMENTS

All kinds of vibration sources (living beings, cars, earthquakes, etc.) easily cause tremendous noise, so *seismic isolation* is of paramount importance!

Damping systems

Active

Sensors able to feel ground movements, receiving a net counter-motion to react

Passive

"Quad" i.e. 4-stage pendulum with 0.4 mm thick glass fibers holding mirrors perfectly still

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Moreover, the laser beam travels in an excellent vacuum (≈ 10^{-6} Pa) to avoid degradation due to dust and air in the path and/or mirrors; also tubes were accurately heated and emptied to remove air molecules

ANALYSIS OVERVIEW

If data-taking underway, ~TB memory storage required daily (-> network of supercomputers)

N.B.: such GW detectors are sensitive to phase variations, not to energy flux!

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Time dependent wave amplitude for a two-body system (simple estimate)

$$\Delta L / L \approx \mathbf{h}(t) \approx h_0 \cos(\omega_{gw}\, t)$$

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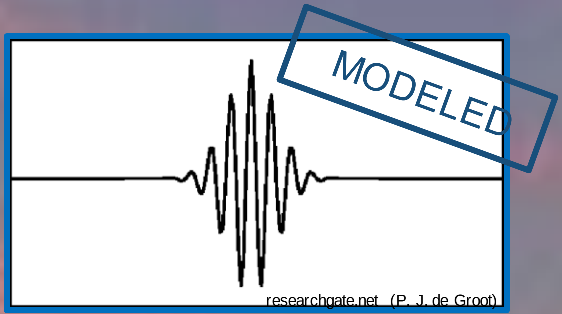
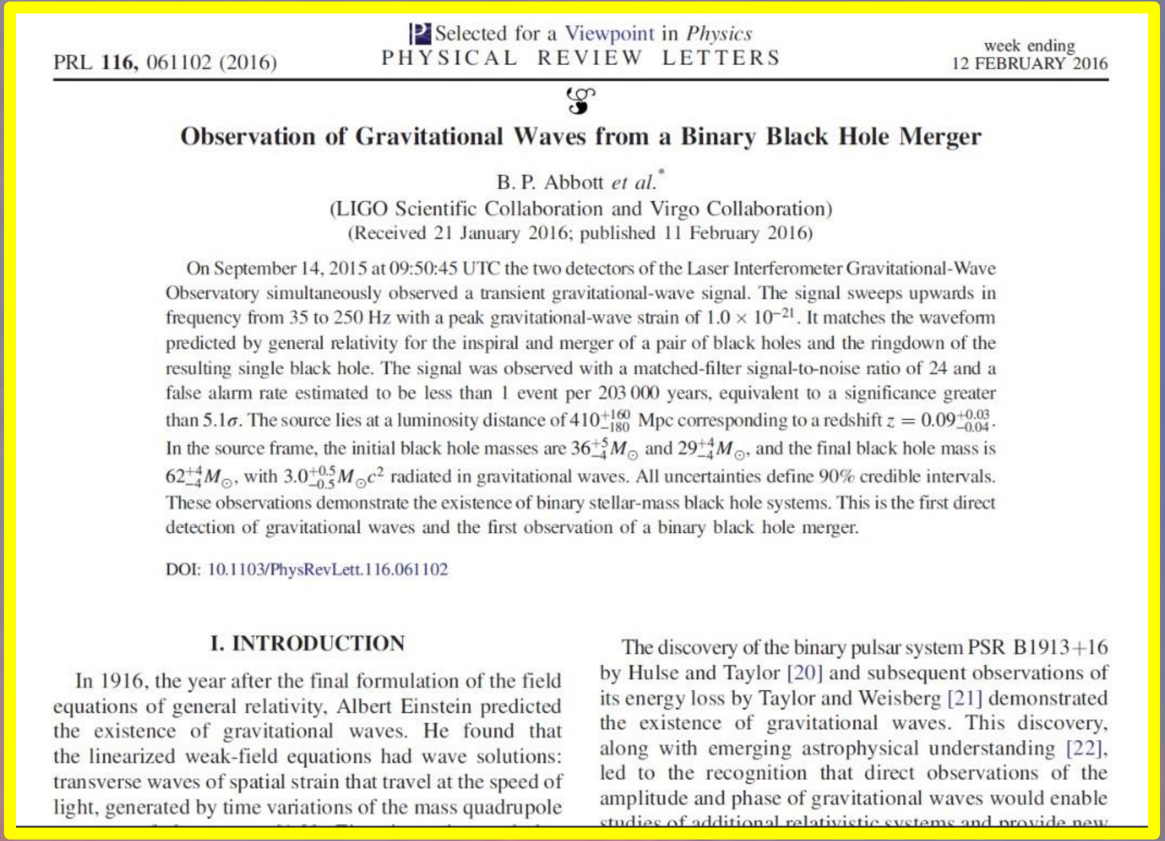
Matched-filter signal to noise ratio: pre-calculated template signals as input (accurate predictions by post-newtonian calculations and perturbation theory + numerical relativity)



Signal waveforms specific for expected binary sistems (e.g. $h \gtrsim 10^{-22}$, $M_{BH} = 1 \div 99\ M_{\odot}$, $\chi_{spin} \leq 0.99$)

FIRST DETECTION EVER

About 100 years after Einstein prediction, LIGO(+Virgo) finally revealed a Gravitational Wave!



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}M_{\odot}$ and $29^{+4}_{-4}M_{\odot}$, and the final black hole mass is $62^{+4}_{-4}M_{\odot}$, with $3.0^{+0.5}_{-0.5}M_{\odot}c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new

GW150914

- ✓ Detected on 14th September, 2015 and announced on 11th February, 2016 (*B. P. Abbott et al., Physical Review Letters*, related Nobel Prize in 2017)
- ✓ $h_{max} \approx 10^{-21}$, $\nu \approx 35 \div 250$ Hz, significance > 5.1σ
- ✓ Due to an inspiral and merger of two ≈ 30 $M_{\odot}$ black holes at about 1.2 billion light years away from Earth (first direct proof of such occurrences)

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PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole

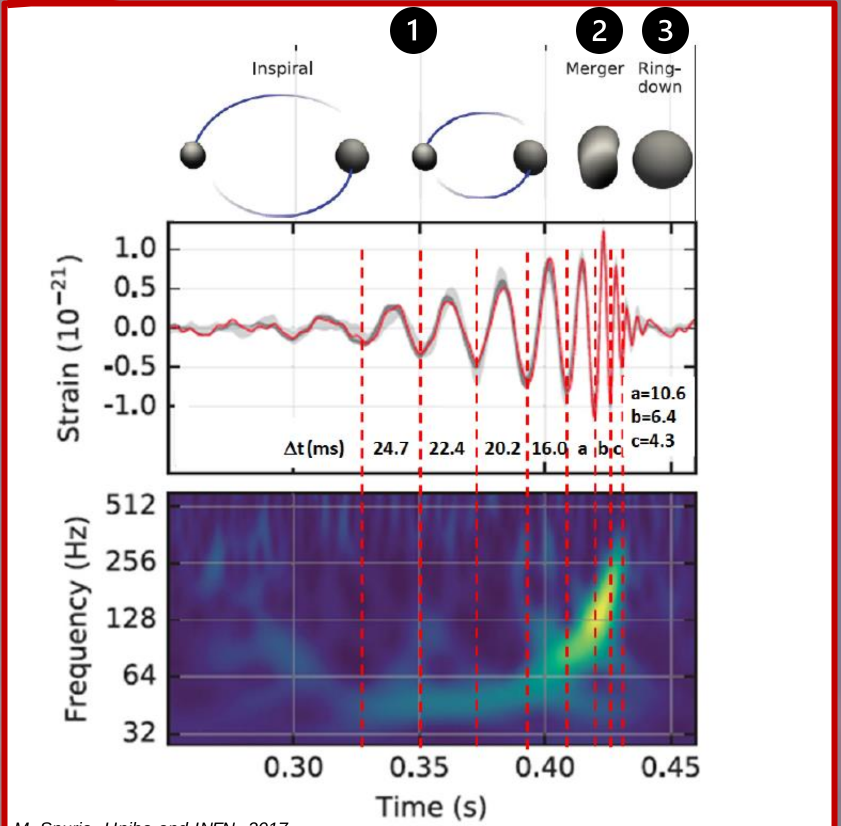
The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new

GW150914

- ✓ Detected on 14th September, 2015 and announced on 11th February, 2016 (*B. P. Abbott et al., Physical Review Letters*, related Nobel Prize in 2017)
- ✓ $h_{max} \approx 10^{-21}$, $\nu \approx 35 \div 250$ Hz, significance > 5.1σ
- ✓ Due to an inspiral and merger of two ≈ 30 $M_\odot$ black holes at about 1.2 billion light years away from Earth (first direct proof of such occurrences)

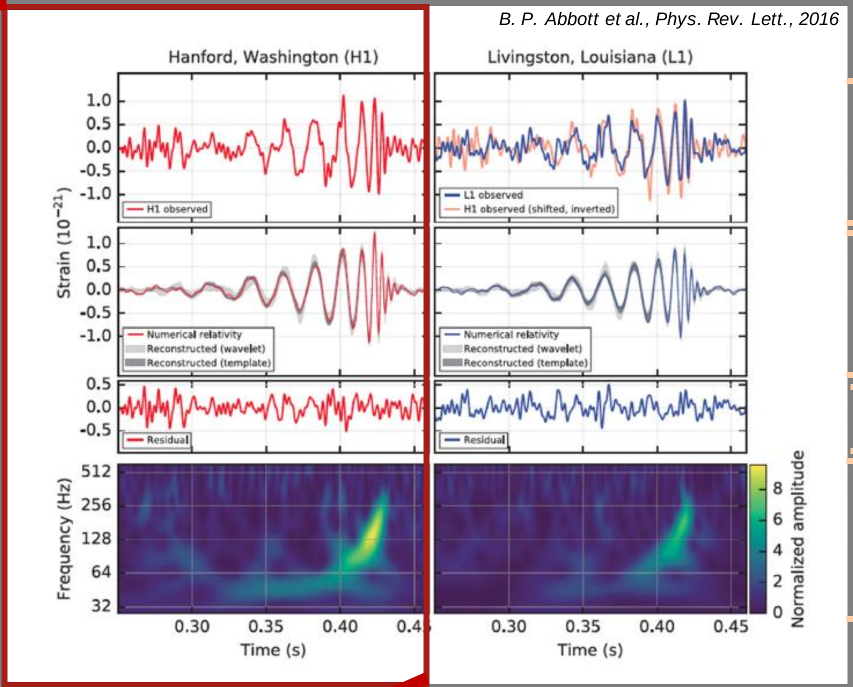
Major milestone for all humankind…and starting point of a new astrophysical field!

GW150914 INTERPRETATION



M. Spurio, Unibo and INFN, 2017

Time progression of coalescence



B. P. Abbott et al., Phys. Rev. Lett., 2016

h as a function of time with filtered noise features

sine-Gaussian wavelets, template waveform, numerical relativity fit

Residuals := filtered – numerical

Time-frequency representation

1 Inspiral

Tighter and tighter circular orbits around common center of mass (energy loss as GWs)

2 Merger

"Blending" of the two objects into a single final BH

3 Ringdown

Relaxation into equilibrium state (Kerr BH)

MAIN INFERENCES

1 **Inspiral:** newtonian approach still valid, i.e. **dE_{gw} / dt = - dE_{tot} / dt** and **R-ω_s relation (Keplero's 3rd law)**

$$\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \equiv \mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3}\nu_{gw}^{-11/3}\,\dot{\nu}_{gw}\right)^{3/5}$$

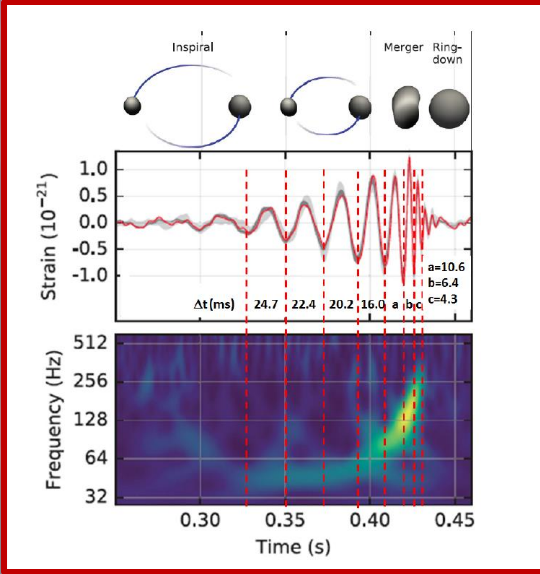
"Chirp Mass" → Look at the observed *t* and h_{min} values for an indication about combined masses!

2 **Merger:** advanced approach needed, starting when **R ~ $R_{schw,1}$ + $R_{schw,2}$**

$$M = \frac{1}{\pi\sqrt{8}}\frac{c^3}{G\nu_{gw}^{max}} \quad + \quad M = \frac{\mathcal{M}}{[(\alpha(1-\alpha)]^{3/5}}$$

$M := m_1 + m_2$ $\alpha := m_1 / M$

$\nu_{em} = (1+z)\,\nu_{obs}$ → **$m_1 \approx 36\ M_\odot$**, **$m_2 \approx 29\ M_\odot$** → Luminosity Distance for GWs → **$D_L \approx 0.4$ Gpc**



M. Spurio, Unibo and INFN, 2017

3 **Ringdown:** relativistic approach requested, to incorporate **BH spin ($\bar{S}$) effects**

$$\chi_{spin} = \frac{c}{G}\frac{|\vec{S}|}{m^2}$$

(**R_{schw}** modified) → inspiral data modelization → **$\chi_1 \lesssim 0.7$**, **$\chi_2 > 0$** → damped ringing signal numerical analysis → **$\chi_{rel} \approx 0.67$**

MAIN INFERENCES

$E_{gw} \approx 3\ M_\odot c^2$ in ≈ 0.1 s !

1 Inspiral: newtonian approach still valid, i.e. $dE_{gw} / dt = - dE_{tot} / dt$ and **R-ω_s relation (Keplero's 3rd law)**

$$\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} \equiv \mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3}\,\nu_{gw}^{-11/3}\,\dot{\nu}_{gw}\right)^{3/5}$$

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$M := m_1 + m_2$

+

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$\nu_{em} = (1+z)\ \nu_{obs}$ → $m_1 \approx 36\ M_\odot$, $m_2 \approx 29\ M_\odot$ → (Luminosity Distance for GWs) → $D_L \approx 0.4$ Gpc

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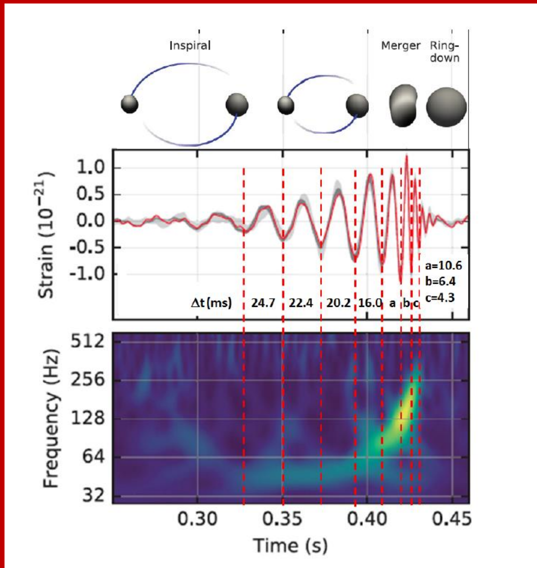
(R_{schw} modified) → (inspiral data modelization) → $\chi_1 \lesssim 0.7$, $\chi_2 > 0$ → (damped ringing signal numerical analysis) → $\chi_{rel} \approx 0.67$



M. Spurio, Unibo and INFN, 2017

ANOTHER INTRIGUING CASE

About 2 years after the first detection, an important GW signal came onto the scene!

PRL 119, 161101 (2017)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

I. INTRODUCTION

On August 17, 2017, the LIGO-Virgo detector network observed a gravitational-wave signal from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger. This discovery comes four decades after Hulse and Taylor discovered the first neutron star binary, PSR B1913+16 [1]. Observations of PSR B1913+16 found that its orbit was losing energy due to the emission of gravitational waves, providing the first

will observe between one BNS merger every few years to hundreds per year [14–21]. This detector network currently includes three Fabry-Perot-Michelson interferometers that measure spacetime strain induced by passing gravitational waves as a varying phase difference between laser light propagating in perpendicular arms: the two Advanced LIGO detectors (Hanford, WA and Livingston, LA) [22] and the Advanced Virgo detector (Cascina, Italy) [23].

Advanced LIGO's first observing run (O1), from

GW170817

- ✓ Detected by Ligo(+Virgo) on 17th August, 2017 and announced on 16th October, 2017 (*B. P. Abbott et al., Physical Review Letters*)
- ✓ $\nu \approx 30 \div 250$ Hz, significance $\gtrsim 5$, combined SNR ≈ 32.4
- ✓ Due to an inspiral and merger of two ≈ 1.17÷1.60 $M_\odot$ neutron stars at about 40 Mpc away (-> NGC 4993)
- ✓ Followed (~ 1.7 s) by a short Gamma-ray Burst seen by Fermi-GBM, providing the first direct link between them

GW170817 MASSIVE CAMPAIGN

Similar physical explanation for the merger:

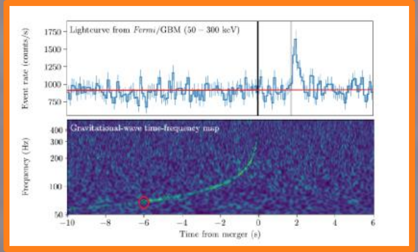
i) "newtonian" inspiral (stronger and stronger GW emission)

ii) relativistic inspiral (accelerated by spin but also tidal effects...)

iii) coalescence, final compact remnant (NS or BH) [+ ringdown]

GW170817 MASSIVE CAMPAIGN

M. Spurio, Unibo and INFN, 2017



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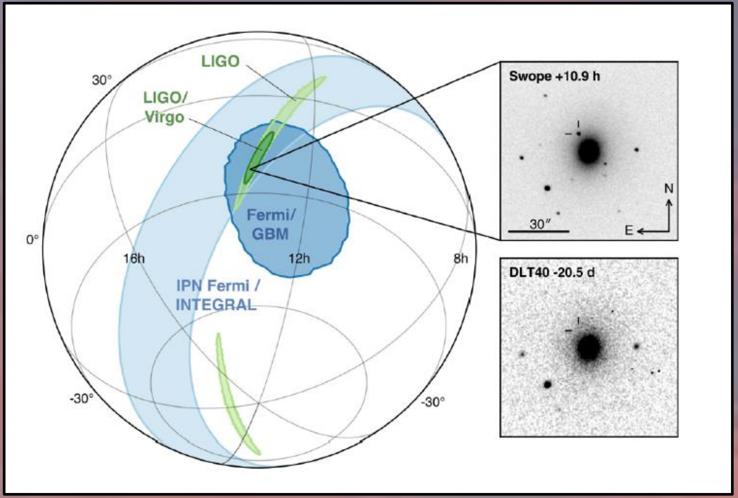

B. P. Abbott et al., The Astrophysical Journal Letters, 2017

But in particular...

"kilonova" event followed by an unprecedented extensive worldwide observational effort!

≈ 70 observatories (ground/space-based) and 4000 physicists

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9
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Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_{\odot}$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of *r*-process nuclei synthesized in the ejecta.

Key words: gravitational waves – stars: neutron

1. Introduction

Over 80 years ago Baade & Zwicky (1934) proposed the idea of neutron stars, and soon after, Oppenheimer & Volkoff (1939) carried out the first calculations of neutron star models. Neutron stars entered the realm of observational astronomy in the 1960s by providing a physical interpretation of X-ray emission from

Heuvel 1975; Massevitch et al. 1976; Clark 1979; Clark et al. 1979; Dewey & Cordes 1987; Lipunov et al. 1987; for reviews see Kalogera et al. 2007; Postnov & Yungelson 2014). The Hulse-Taylor pulsar provided the first firm evidence (Taylor & Weisberg 1982) of the existence of gravitational waves (Einstein 1916, 1918) and sparked a renaissance of observational

ONLY THE BEGINNING...

"GW *yymmdd*"

=

analized

"S *yymmdd*"

=

not confirmed

B. P. Abbott et al., Phys. Rev. X 9, 2019

TABLE I. Search results for the 11 GW events. We report a false-alarm rate for each search that found a given event; otherwise, we display ···. The network SNR for the two matched-filter searches is that of the template ranked highest by that search, which is not necessarily the template with the highest SNR. Moreover, the network SNR is the quadrature sum of the detectors coincident in the highest-ranked trigger; in some cases, only two detectors contribute, even if all three are operating nominally at the time of that event.

		FAR $[y^{-1}]$			Network SNR		
Event	UTC time	PyCBC	GstLAL	cWB	PyCBC	GstLAL	cWB
GW150914	09:50:45.4	$<1.53 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<1.63 \times 10^{-4}$	23.6	24.4	25.2
GW151012	09:54:43.4	0.17	7.92×10^{-3}	···	9.5	10.0	···
GW151226	03:38:53.6	$<1.69 \times 10^{-5}$	$<1.00 \times 10^{-7}$	0.02	13.1	13.1	11.9
GW170104	10:11:58.6	$<1.37 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$<3.09 \times 10^{-4}$	$<1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
GW170729	18:56:29.3	1.36	0.18	0.02	9.8	10.8	10.2
GW170809	08:28:21.8	1.45×10^{-4}	$<1.00 \times 10^{-7}$	···	12.2	12.4	···
GW170814	10:30:43.5	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	$<2.08 \times 10^{-4}$	16.3	15.9	17.2
GW170817	12:41:04.4	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	···	30.9	33.0	···
GW170818	02:25:09.1	···	4.20×10^{-5}	···	···	11.3	···
GW170823	13:13:58.5	$<3.29 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.14×10^{-3}	11.1	11.5	10.8

TABLE II. Marginal triggers from the two matched-filter CBC searches. To distinguish events occurring on the same UTC day, we extend the YYMMDD label by decimal fractions of a day as needed, always rounding down (truncating) the decimal. The search that identifies each trigger is given, and the false alarm and network SNR. This network SNR is the quadrature sum of the individual detector SNRs for all detectors involved in the reported trigger; that can be fewer than the number of nominally operational detectors at the time, depending on the ranking algorithm of each pipeline. The detector chirp mass reported is that of the most significant template of the search. The concentration of our marginal triggers at low chirp masses is consistent with expectations for noise triggers, because search template waveforms are much more densely packed at low masses. The final column indicates whether there are any detector characterization concerns with the trigger; for an explanation and more details, see the text.

Date	UTC	Search	FAR $[y^{-1}]$	Network SNR	$\mathcal{M}^{det}$ $[M_\odot]$	Data quality
151008	14:09:17.5	PyCBC	10.17	8.8	5.12	No artifacts
151012.2	06:30:45.2	GstLAL	8.56	9.6	2.01	Artifacts present
151116	22:41:48.7	PyCBC	4.77	9.0	1.24	No artifacts
161202	03:53:44.9	GstLAL	6.00	10.5	1.54	Artifacts possibly caused
161217	07:16:24.4	GstLAL	10.12	10.7	7.86	Artifacts possibly caused
170208	10:39:25.8	GstLAL	11.18	10.0	7.39	Artifacts present
170219	14:04:09.0	GstLAL	6.26	9.6	1.53	No artifacts
170405	11:04:52.7	GstLAL	4.55	9.3	1.44	Artifacts present
170412	15:56:39.0	GstLAL	8.22	9.7	4.36	Artifacts possibly caused
170423	12:10:45.0	GstLAL	6.47	8.9	1.17	No artifacts
170616	19:47:20.8	PyCBC	1.94	9.1	2.75	Artifacts present
170630	16:17:07.8	GstLAL	10.46	9.7	0.90	Artifacts present
170705	08:45:16.3	GstLAL	10.97	9.3	3.40	No artifacts
170720	22:44:31.8	GstLAL	10.75	13.0	5.96	Artifacts possibly caused

O1 (Sep 2015 - Jan 2016)
\+ O2 (Nov 2016 - Aug 2017) run results

ONLY THE BEGINNING...

"GW *yymmdd*"

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"S *yymmdd*"

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B. P. Abbott et al., Phys. Rev. X 9, 2019

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GW170104	10:11:58.6	$<1.37 \times 10^{-5}$	$<1.00 \times 10^{-7}$	2.91×10^{-4}	13.0	13.0	13.0
GW170608	02:01:16.5	$<3.09 \times 10^{-4}$	$<1.00 \times 10^{-7}$	1.44×10^{-4}	15.4	14.9	14.1
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GW170817	12:41:04.4	$<1.25 \times 10^{-5}$	$<1.00 \times 10^{-7}$	···	30.9	33.0	···
GW170818	02:25:09.1	···	4.20×10^{-5}	···	···	11.3	···
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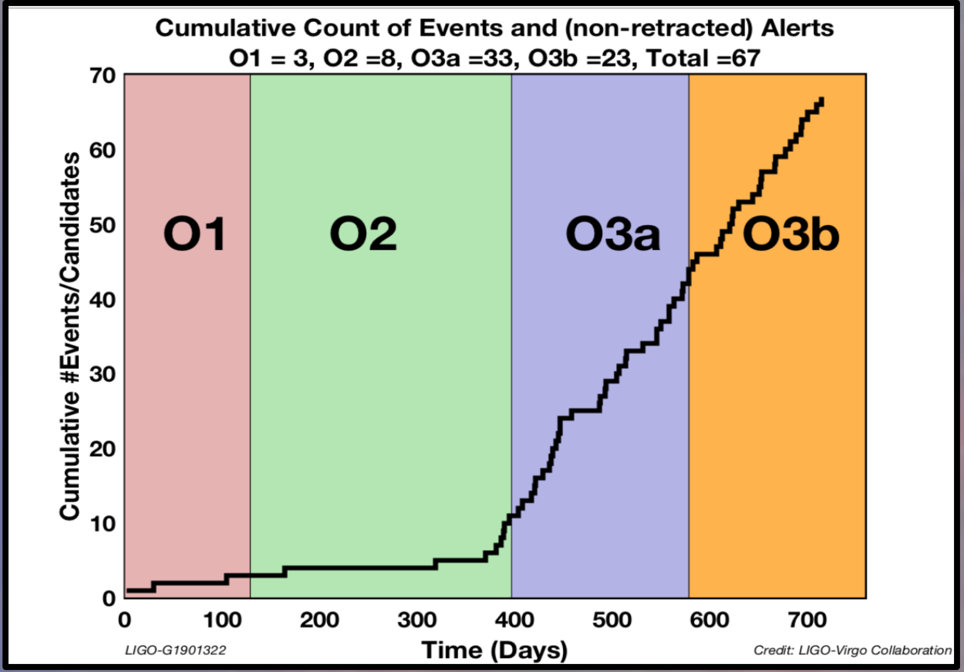
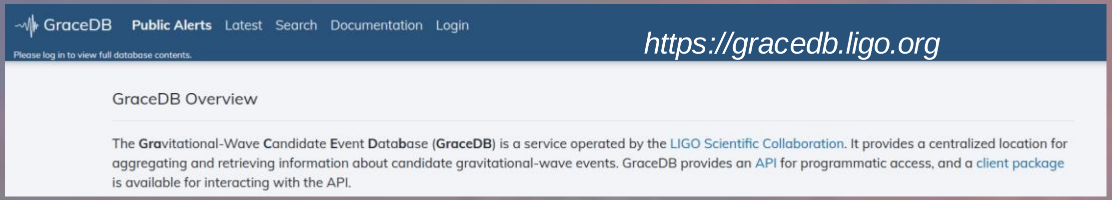
161202	03:53:44.9	GstLAL	6.00	10.5	1.54	Artifacts possibly caused
161217	07:16:24.4	GstLAL	10.12	10.7	7.86	Artifacts possibly caused
170208	10:39:25.8	GstLAL	11.18	10.0	7.39	Artifacts present
170219	14:04:09.0	GstLAL	6.26	9.6	1.53	No artifacts
170405	11:04:52.7	GstLAL	4.55	9.3	1.44	Artifacts present
170412	15:56:39.0	GstLAL	8.22	9.7	4.36	Artifacts possibly caused
170423	12:10:45.0	GstLAL	6.47	8.9	1.17	No artifacts
170616	19:47:20.8	PyCBC	1.94	9.1	2.75	Artifacts present
170630	16:17:07.8	GstLAL	10.46	9.7	0.90	Artifacts present
170705	08:45:16.3	GstLAL	10.97	9.3	3.40	No artifacts
170720	22:44:31.8	GstLAL	10.75	13.0	5.96	Artifacts possibly caused

\+ O1 (Sep 2015 - Jan 2016)
O2 (Nov 2016 - Aug 2017) run results

O3a (Apr 2019 - Sep 2019)
O3b (Nov 2019 - Mar 2020) runs added



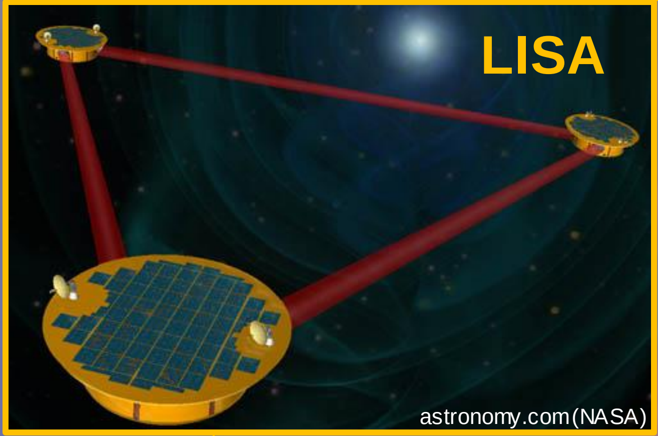
From O3, new **public system alert** for fast follow up:



And...O4 about to start (planned by this May)!

TOWARDS THE FUTURE

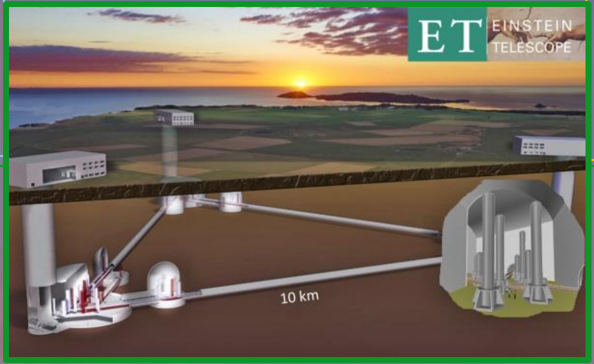
Kamioka Gravitational Wave Detector



Laser Interferometer Space Antenna

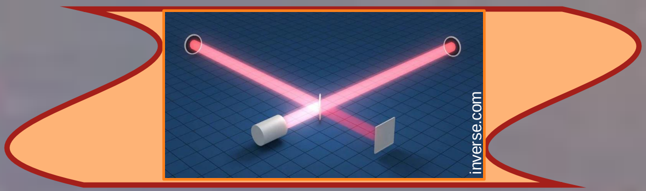
Isolated laser interferometer (≈ 3 km) at Kamioka Observatory (ICRR) in Hida, Japan, already operative in Feb-Apr, 2020, it will join LVC for O4 run ("LVK"); the first located underground, and with cryogenic mirrors

Pionieristic space-based laser interferometer (for ≈ 2030s), 3 spacecrafts in an equilateral triangle with ≈ 2 million km arms, following the Earth orbit (≈ 50 million km away); no terrestrial noise, and $\nu \approx 10^{-4} \div 1$ Hz

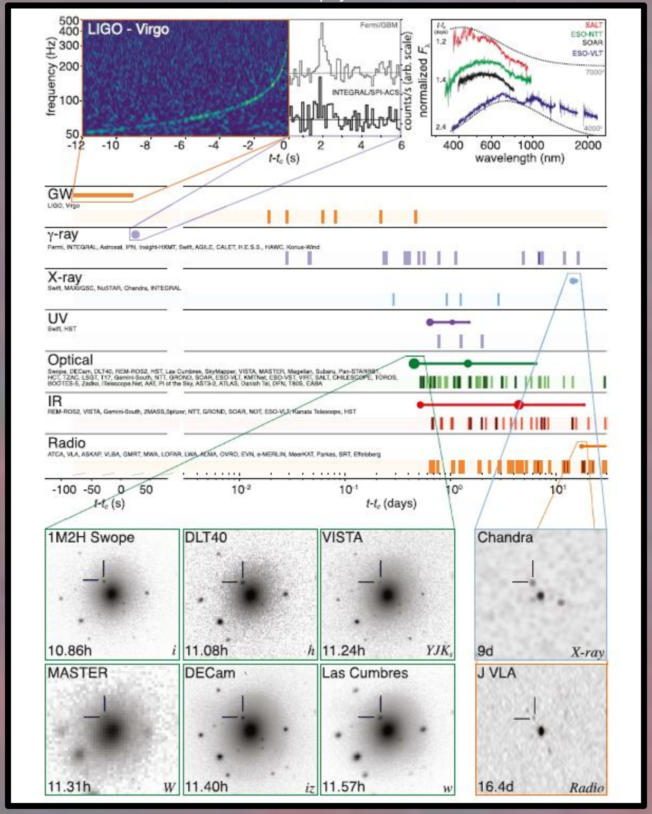
Einstein  **Telescope**

Proposed III generation underground-based large laser interferometer, triangle-shaped with ≈ 10 km arms and 2 detectors in each corner; reduced noise and improved cooling...maybe in Lula, Sardinia (Italy)!

CONCLUSIONS



B. P. Abbott et al., The Astrophysical Journal Letters, 2017



- Gravitational Waves (GWs) are space-time ripples moving at the speed of light, a natural consequence of Einstein's General Relativity Theory

- They are originated by massive objects accelerating around each other, or in general fastly changing their mass quadrupole moment

- Weak signal: main detectors are isolated Laser Interferometers, whose combined laser beams (void "arms" + reflecting mirrors) change their final pattern depending on the variable distance travelled due to GWs

- LIGO (two separated twin detectors in USA) announced the 1st GW revealed on 14th Sep, 2015 together with Virgo, from inspiral and merger of two distant BHs

- Many further detections: a new astrophysical means of observation was definitely born, which will help our future "Multi-messenger" comprehension of the Universe (see GW170817 figure)!

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Thanks for your attention!