The detection of gravitational waves.

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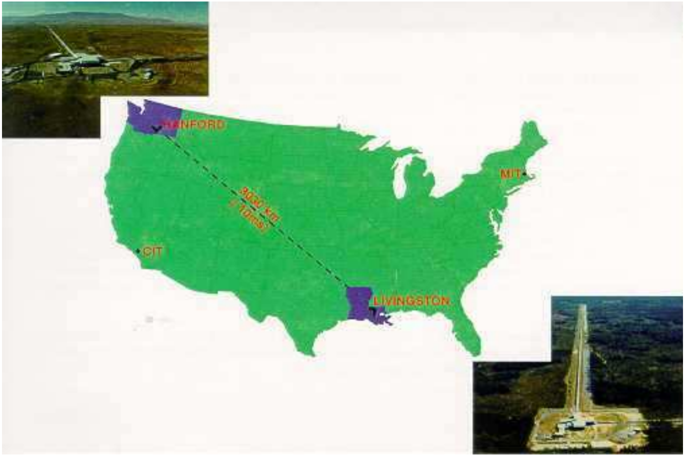
Press conference

February 11, 2016: Gravitational wave detection. David Rietze. PI LIGO: We did it, we have detected gravitational waves

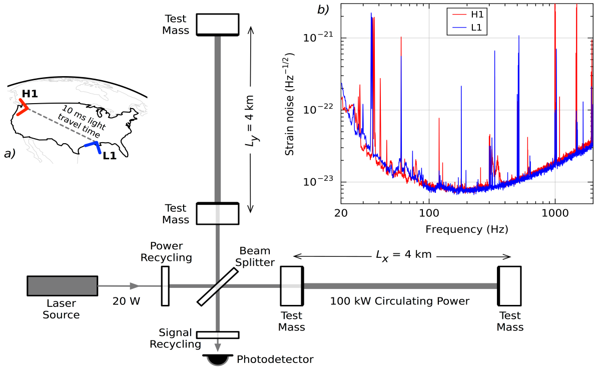
Advanced LIGO made the first detection of a gravitational wave signal GW150914, a successful confirmation of a prediction by Einstein's theory of general relativity.
The signal was clearly seen by the two LIGO detectors located in Hanford and Livingston.
The black holes were each of approximately $35 M_\odot$, orbiting each other as close as ~ 350 km apart and subsequently merged to form a single spinning black hole.

Gravitational waves are produced by accelerating masses, and like electromagnetic waves, they travel at the speed of light. As they travel, the waves squash and stretch spacetime in the plane perpendicular to their direction of propagation.
Detecting them, however, is exceptionally hard because they induce very small distortions: even the strongest gravitational waves from astrophysical events are only expected to produce relative length variations of order $h \sim 10^{-21}$

Advanced LIGO consists of two detectors, one in Hanford, Washington, and one in Livingston, Louisiana. Each detector is a Michelson interferometer, consisting of two 4-km-long optical cavities, or arms, that are arranged in an L shape.



The interferometer is designed so that, in the absence of gravitational waves, laser beams traveling in the two arms arrive at a photodetector exactly 180 out of phase, yielding no signal. A gravitational wave propagating perpendicular to the detector plane disrupts this perfect destructive interference. During its first half-cycle, the wave will lengthen one arm and shorten the other; during its second half-cycle, these changes are reversed



Gravitational waves

Let us will write a small perturbation $h_{\mu\nu}$ on a flat background spacetime $\eta_{\mu\nu}$ as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \ , \qquad |h_{\mu\nu}| << 1 \tag{1}$$

* There are some degree of the freedom in choice of gauge. It is known that the transverse-traceless (TT) gauge defined by

$$h_{0\mu}^{\mathrm{TT}} = 0; \qquad \eta^{ij} h_{jk}^{\mathrm{TT}} = 0; \qquad \eta^{ij} h_{ij}^{\mathrm{TT}} = 0, \tag{2}$$

is convenient for discussion of GWs.
* In this gauge, the Einstein equation outside the source, where $T_{\mu\nu} = 0$,is reduced to a wave equation

$$(\partial_{tt}^2 - \nabla^2) h_{ij}^{\mathrm{TT}} = 0 \tag{3}$$

Gravitational waves

The wave equation has **a plane wave solution:**

$$h_{ij}^{\mathrm{TT}}(t,z) = A_{ij}^{\mathrm{TT}}\cos(\omega(t-z)) \ , \tag{4}$$

here we set the direction of the wave propagation as z-axis.

Polarization

From the TT condition

$$h_{0\mu}^{\mathrm{TT}} = 0; \qquad \eta^{ij} h_{jk}^{\mathrm{TT}} = 0; \qquad \eta^{ij} h_{ij}^{\mathrm{TT}} = 0, \tag{5}$$

the non-zero components are

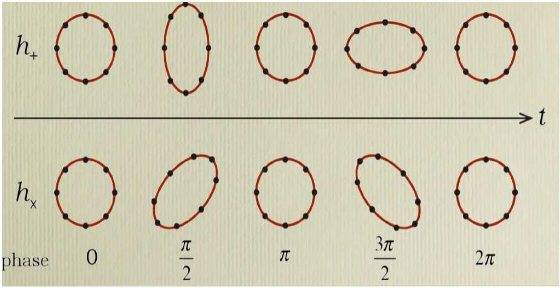
$$h_{xx}^{\mathrm{TT}} = -h_{yy}^{\mathrm{TT}} = h_{+}^{\mathrm{TT}} = A_{+}^{\mathrm{TT}} \cos(\omega(t-z)) \ , \tag{6}$$

$$h_{xy}^{\mathrm{TT}} = h_{yx}^{\mathrm{TT}} = h_{\times}^{\mathrm{TT}} = A_{\times}^{\mathrm{TT}} \cos(\omega(t-z)) \ , \tag{7}$$

* There are only two independent components h_+ and $h_\times$.

Polarization

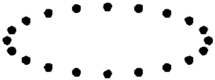
GW of h_+ and $h_\times$ traveling in a direction perpendicular to the screen will cause particles to move like this:



Polarization

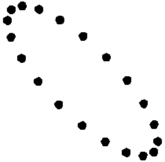
The $+$ (plus) mode

$$h_+^{\mathrm{TT}} \neq 0, \qquad h_\times^{\mathrm{TT}} = 0 \qquad (8)$$



The $\times$ (cross) mode

$$h_+^{\mathrm{TT}} = 0, \qquad h_\times^{\mathrm{TT}} \neq 0 \qquad (9)$$



If only $+$ mode or $\times$ mode wave comes, each particle oscillates along a straight line.
The $\times$ mode is the same as $+$ mode if rotated by 45 degrees.
These modes correspond to the linear polarization of light.

Polarization

* the circular polarization

$$h_+^{\mathrm{TT}} = h_+^{\mathrm{TT}} \neq 0 \tag{10}$$

In case of wave containing both $+$ and $\times$ modes with the same amplitude, each particle moves along a circle.
It corresponds to the circular polarization.
* If their amplitude are not same, each particle moves along a elliptic. It corresponds to the elliptic polarization.

Properties of GWs

Like EM waves

- GWs are transverse.
- GWs propagate with the speed of light.
- Amplitude decreases as $1/r$.

While the lowest mulipole of EM waves is the dipole

- The lowest allowed multipole of GWs is the quadrupole;
- no monopole radiation as a result of mass conservation
- no dipole radiation as a result of momentum conservation

Quadrupole Formula

On the assumption that

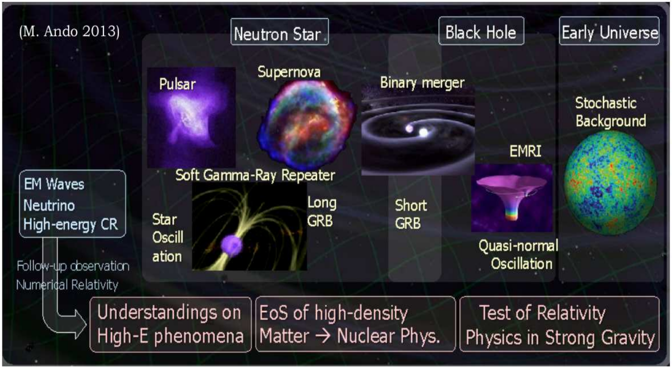
- (week field) the gravitational field generated by the source is sufficiently small
- (low velocity) the typical velocities inside the source are small compared to the speed of light,

gravitational waves generated by the source are given by **the quadrupole formula;**

$$h_{ij}^{\mathrm{TT}}(t,x) = \frac{1}{r}\frac{2G}{c^4}\partial_{tt}Q_{ij}^{\mathrm{TT}}(t-r)\ ,$$

Sources of Gravitational Waves

Man made gravitational radiation: undetectable Compact and high-energy astronomical phenomena: for terrestrial detectors (observation band ~ 10Hz-1kHz)



Radiation from a Binary System

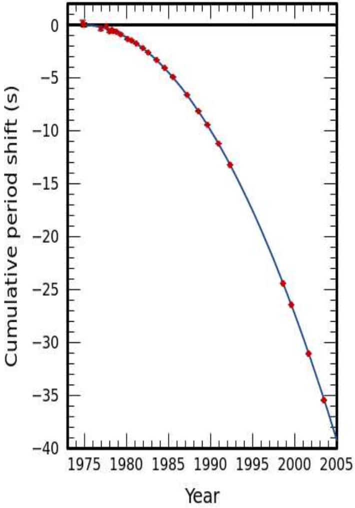
We must consider astronomical sources. The most promising one is a compact binary system.
For a binary system consisting of neutron stars or black holes, the radiation of energy by the orbital motion causes the orbit to shrink to make an inspiral orbit and finally two stars merge into one.

PSR B1913+16 (the Hulse-Taylor Pulsar)

In 1974, Russell Hulse and Joseph Taylor discovered a binary pulsar at Arecibo Observatory.

The GWs by the inspiral of PSR B1913+16 (distance $= 6,400$pc)

- amplitude: $h \sim 10^{-23}$
- frequency: 7×10^{-5} Hz
- wavelength: $4 \times 10^{14} cm \sim 3,000$ AU
- It is impossible to detect them at present by grand-base interferometer (LIGO, VIRGO, KAGRA) or space interferometer (eLISA).
- Time to coalescence: ~ 250 Myr



PSR B1913+16 (the Hulse-Taylor Pulsar)

- First discovery of a binary pulsar
- First observational evidence for GWs
- First accurate determinations of NS masses
- Confirmation of general relativity as an accurate description of strong-field gravitational interaction

Nobel Prize for Taylor and Hulse in 1993

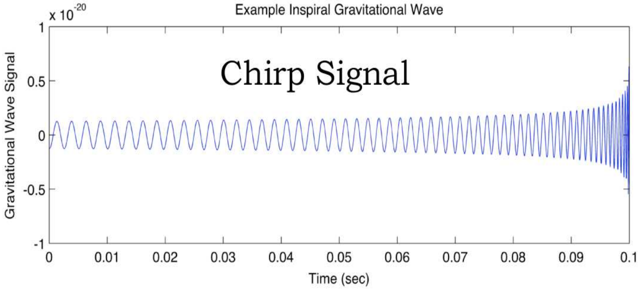
Compact Binary Coalescence

Compact binary coalescence is the most promising source of GWs for terrestrial and space interferometers. Compact binary: a binary system consisting of neutrons stars and/or black holes.

- NS/NS binaries
- NS/BH binaries
- BH/BH binaries

A Chirp Signal

Frequency and amplitude of GWs:

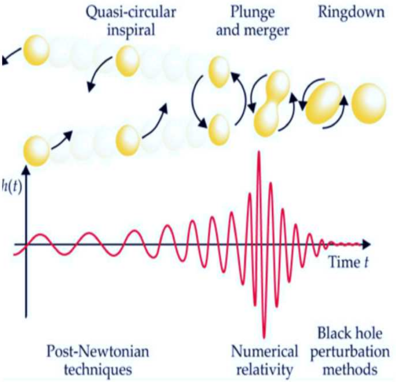


The shrinking will make GWs increase in frequency and amplitude.
This is called a chirp signal.

Compact Binary Coalescence

Three phases of waveform from CBC:

- a gradual inspiral
- a rapid merger
- ringdown of the resulting black hole or neutron stars



The two body problem in GR. 1964 the first Numerical relativity computation.

ANNALS OF PHYSICS: 29, 304-331 (1964)

The Two-Body Problem in Geometrodynamics

SUSAN G. HAHN

International Business Machines Corporation, New York, New York

AND

RICHARD W. LINDQUIST

The numerical calculations were carried out on an IBM 7090 electronic computer. The parameters a and μ_0 were both set equal to unity; the mesh lengths were assigned the values $h_1 = 0.02$, $h_2 = \pi/150 \approx 0.021$, yielding a 51 × 151 mesh. The calculations of all unknown functions, including a great number of input-output operations and some built-in checking procedures, took approximately four minutes per time step. Different check routines indicated that results close to the point $\mu = 0$, $\eta = 0$ lost accuracy fairly quickly. Since these would, in the long run, influence meshpoints further away, the computations were stopped after the 50th time step, when the total time elapsed was approximately 1.8. Some of the results are shown in Table I.

Text Math Drawing Plot Animation Hide

```
> qload(schmidt);
Warning: grOptionMetricPath has not been assigned.
Calculated ds for schmidt (0.001000 sec.)
```

Default spacetime = schmidt

For the schmidt spacetime:

Coordinates

$x(up)$

$$x^a = [\, t \;\; x \;\; y \;\; z \,]$$

Line element

$$ds^2 = h11(t,x,y,z)\; dt^2 + 2\,h12(t,x,y,z)\; dt\; dx + 2\,h13(t,x,y,z)\; dt\; dy + 2\,h14(t,x,y,z)\; dt\; dz + h22(t,x,y,z)\; dx^2 + 2\,h23(t,x,y,z)\; dx\; dy + 2\,h24(t,x,y,z)\; dx\; dz + h33(t,x,y,z)\; dy^2 + 2\,h34(t,x,y,z)\; dy\; dz + h44(t,x,y,z)\; dz^2 \qquad (2)$$

```
> grcalcd ( G(up,dn) ):
Created definition for G(up,dn)
Calculated g(dn,dn,pdn) for schmidt (0.001000 sec.)
Calculated Chr(dn,dn,dn) for schmidt (0.001000 sec.)
Calculated detg for schmidt (0.001000 sec.)
Calculated g(up,up) for schmidt (0.017000 sec.)
Calculated Chr(dn,dn,up) for schmidt (0.083000 sec.)
Calculated R(dn,dn) for schmidt (9.253000 sec.)
Calculated Ricciscalar for schmidt (21.934000 sec.)
Calculated G(dn,dn) for schmidt (20.559000 sec.)
Calculated G(up,dn) for schmidt (171.596000 sec.)
```

CPU Time $= 223.451$

For the schmidt spacetime:

G(up,dn)

$G(up, dn)$

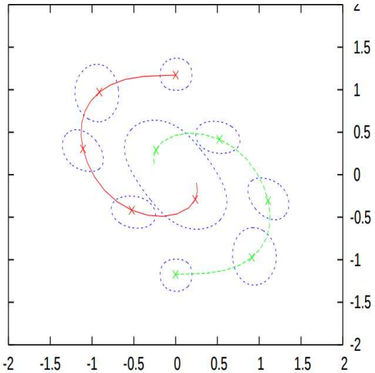
$G^{t}{}_{t}$ = *1240543 words. Exceeds grOptionDisplayLimit*

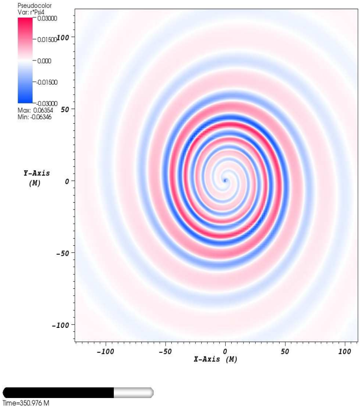
$G^{x}{}_{t}$ = *921284 words. Exceeds grOptionDisplayLimit*

$G^{y}{}_{t}$ = *921284 words. Exceeds grOptionDisplayLimit*

Black hole mergers

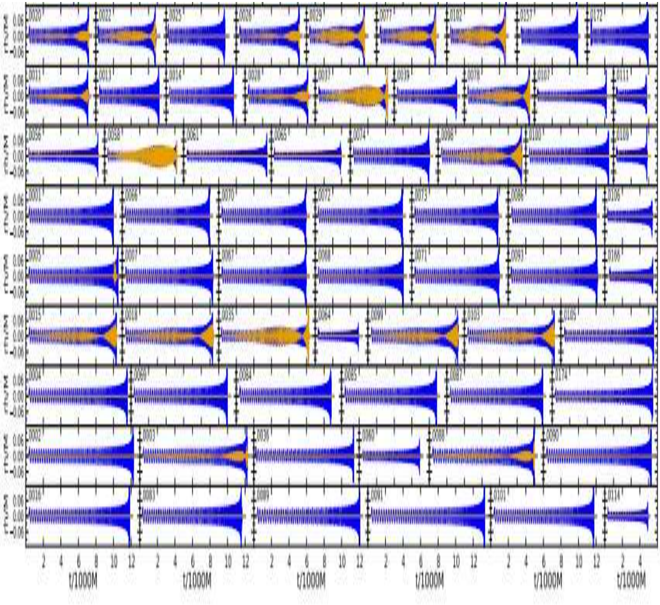
Two body problem in GR. Finally solved in 2005.



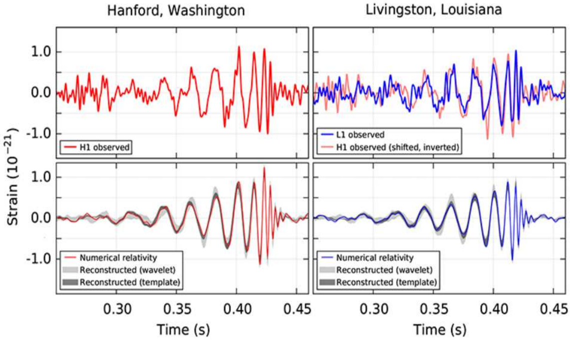


Eintein-Toolkit free available! (einsteintoolkit.org)

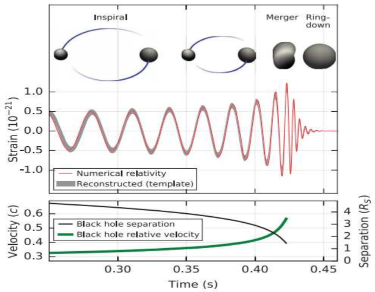
BBH catalogues



On September 14, 2015, similar signals were observed in both of LIGO's interferometers. The top panels show the measured signal in the Hanford (top left) and Livingston (top right) detectors. The bottom panels show the expected signal produced by the merger of two black holes, based on numerical simulations.

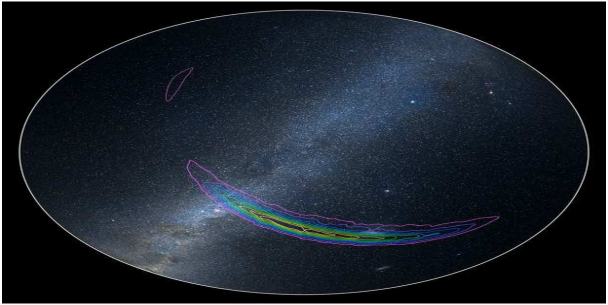


The most exciting conclusions come from comparing the observed signal's amplitude and phase with numerical relativity predictions, which allows to estimate parameters describing the gravitational-wave source. The waveform is consistent with a black hole binary system whose component masses are 36 and 29 times the mass of the Sun.



Moreover, no binary system other than black holes can have component masses large enough to explain the observed signal.

The binary was approximately 1.3 billion light years from Earth, or equivalently, at a luminosity distance of 400 megaparsecs (redshift of $z \sim 0.1$). The estimate is that about 4.6% of the binary's energy was radiated in gravitational waves, leading to a rotating black hole remnant with mass 62 times the mass of the Sun and dimensionless spin of 0.67.



Red Tematica Conacyt: Agujeros negros y ondas Gravitatorias

Several groups in NR

ICN-UNAM

Miguel Alcubierre (binaries)

Dario Nunez
(Post Mergers, multimessenger)

Marcelo Salgado (Neutron stars)

Cinvestav

Tonatiuh Matos
(Compact objects mimickers)

UMSH

Francisco Siddhartha
(binaries, accretion)

Jose Antonio Gonzalez
(binaries, accretion)

Oliver Sarbach
(Post mergers, Foundations)

UdG

Claudia Moreno
(Perturbation theory)

ICF-UNAM,

JCD
(Post mergers, multimessenger, BH instabilities)

INAOE

Omar Lopez
(Observation, EHT)

Post merger

Single perturbed black hole, fully characterized by its mass, angular momentum/charge. Quasinormal ringing. The final black hole oscillates with a particular frequency.

Multimessenger

Charged black holes accreting charged particles (plasma) both signals gravitational waves and electromagnetic counterpart.
Infalling particles cause perturbations in the black hole and it vibrates emitting radiation.
There is a correlation between the electromagnetic energy radiated and the gravitational waves. Still very small. Wait for the second generation of detectors

Conclusions

The upcoming network of Earth-based detectors, comprising Advanced Virgo Italy, KAGRA in Japan, and possibly a third LIGO detector in India, will help scientists determine the locations of sources in the sky. This would tell us where to aim âtraditionalâ telescopes that collect electromagnetic radiation or neutrinos. Combining observational tools in this way would be the basis for multimessenger astronomy.