Intensive Course in Physics
Gravitational Waves

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Chapter 0: Introduction to Gravitational Waves

November 7, 2016

Curriculum Vitae

Assistant Professor
PI Gravitational-Wave Group

Postdoc
CBC searches; test of GR; nuclear EOS

PhD
Test of GR; nuclear EOS; cosmology

MSci & BA
Experimental & Theoretical Physics

Direct Detection of Gravitational Waves

Discoveries

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.

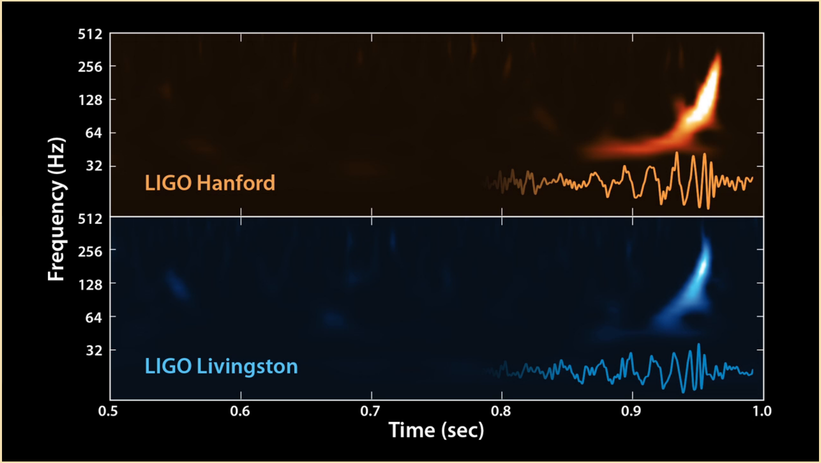
Discoveries

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

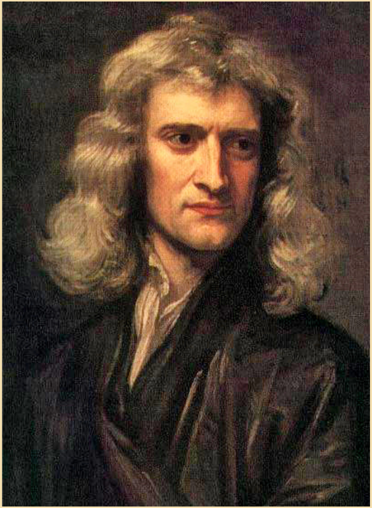
We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

GW150914


Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Newtonian Gravity

- Newton: Same force that causes an apple to fall from a tree and the Earth to orbit the Sun.



Newtonian Gravity

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- The *attractive* force is proportional to the mass of the two objects

$$F_g = G\frac{m_1 m_2}{r^2} \qquad (1)$$

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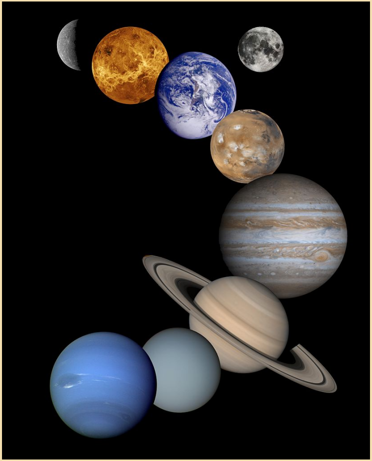
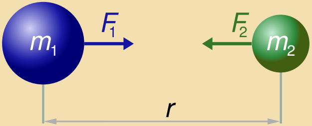
$$F_g = G\frac{m_1 m_2}{r^2} \qquad (1)$$

⇒ Accurately describes the motion of most celestial objects in our solar system.

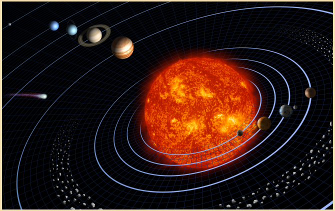


Newtonian Gravity – Problems

- Does not describe *how* the interaction occurs
  - How does the Earth know about the apple?
- Instantaneous interaction
  - Force felt is instantaneous
- Unexplained phenomena
  - Orbit of Mercury
  - Bending of light

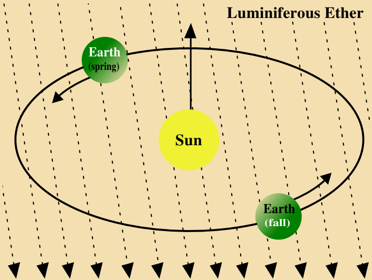


$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$



Special theory of relativity

- 1887: Michelson and Morley showed that the speed of light is always the same



Special theory of relativity

- 1887: Michelson and Morley showed that the speed of light is always the same
- 1905: Assistant examiner at Swiss patent office formulates new law of motion: **special relativity**
  - The speed of light is the same for all observers
  - Nothing can go faster than the speed of light

Special theory of relativity

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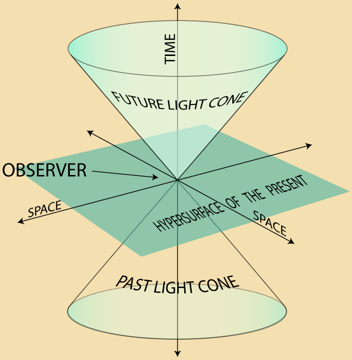
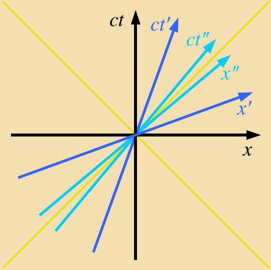
⇒ Space and time are related and depend on the observer



General theory of relativity I

- Newton theory of gravity incompatible with special relativity
  - Gravity must be bound by the speed of light
  - Special relativity only describes constant motion, not acceleration



General theory of relativity I

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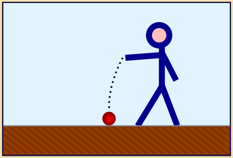
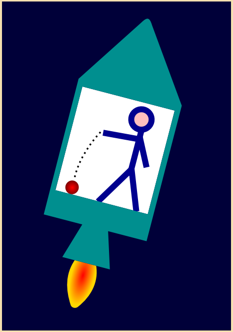
- Einstein's thought experiment
  - Cannot distinguish floating in space from free fall in a closed compartment
  - Gravity is just an acceleration





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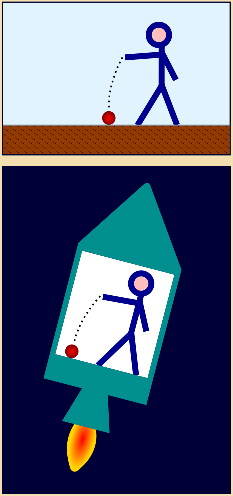
⇒ The cause of this acceleration is *mass*

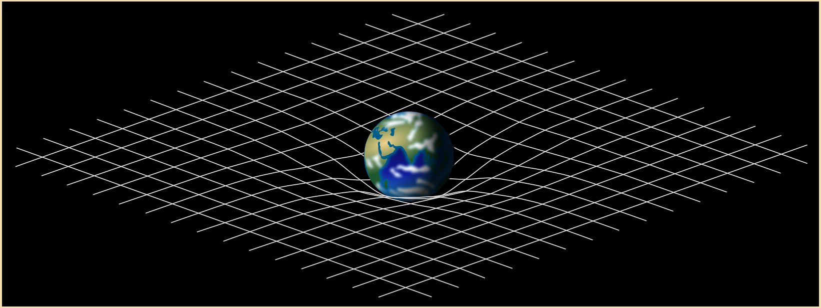


General theory of relativity II

Spacetime tells matter how to move; matter tells spacetime how to curve.

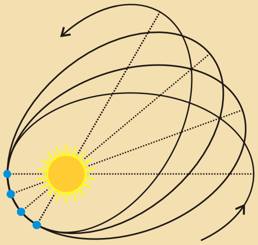
John A. Wheeler

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



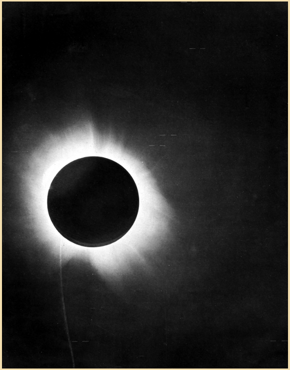
Predictions from General Relativity

- Precession of the orbit of Mercury
  - Discovered by Le Verrier in 1859
  - First attributed to unknown planet
  - Predicted by General Relativity

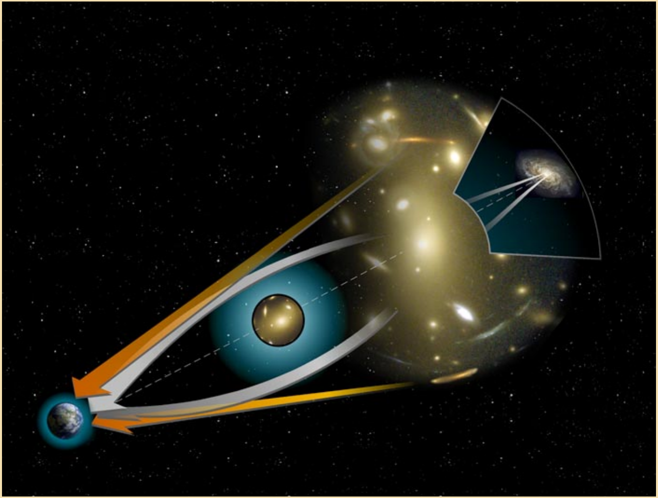


Predictions from General Relativity

- ✓ Precession of the orbit of Mercury
- Bending of light
  - Observing background stars during solar eclipse
  - Predicted by General Relativity

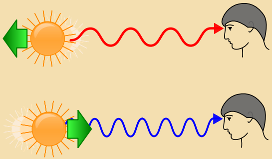


Bending of light



Predictions from General Relativity

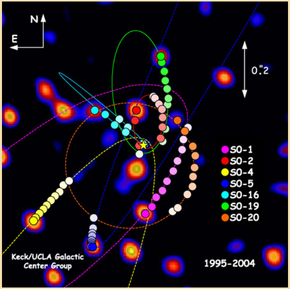
- ✓ Precession of the orbit of Mercury
- ✓ Bending of light
- Gravitational redshift
  - Wave changes frequency depending on preceding or recessing source
  - Gravity can also cause redshift/blueshift



Redshift/blueshift

Predictions from General Relativity

- ✓ Precession of the orbit of Mercury
- ✓ Bending of light
- ✓ Gravitational redshift
- ▸ Black holes
  - ▸ Calculate the curvature of spacetime around a mass
  - ▸ Existence of a horizon within where nothing can escape, not even light

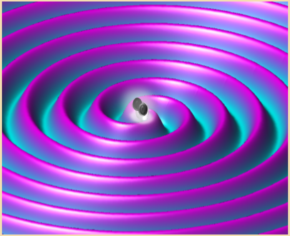


Predictions from General Relativity

- ✓ Precession of the orbit of Mercury
- ✓ Bending of light
- ✓ Gravitational redshift
- ✓ Black holes
- ▸ Expansion of the Universe
  - General Relativity predicts that the Universe is expanding
  - Must have started from a single point: Big Bang

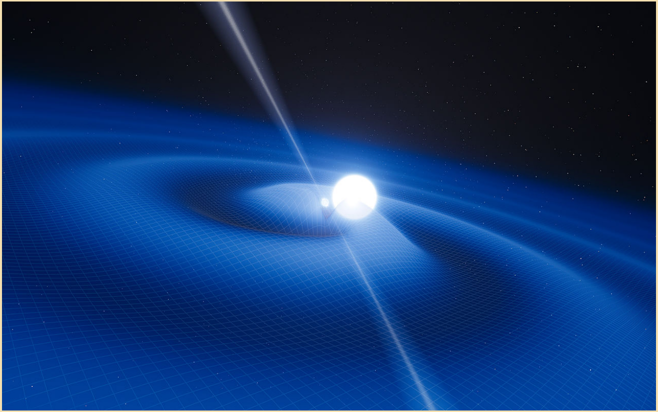
Predictions from General Relativity

- ✓ Precession of the orbit of Mercury
- ✓ Bending of light
- ✓ Gravitational redshift
- ✓ Black holes
- ✓ Expansion of the Universe
- Gravitational waves
  - Ripples in spacetime
  - Propagate at the speed of light
  - Last undiscovered prediction



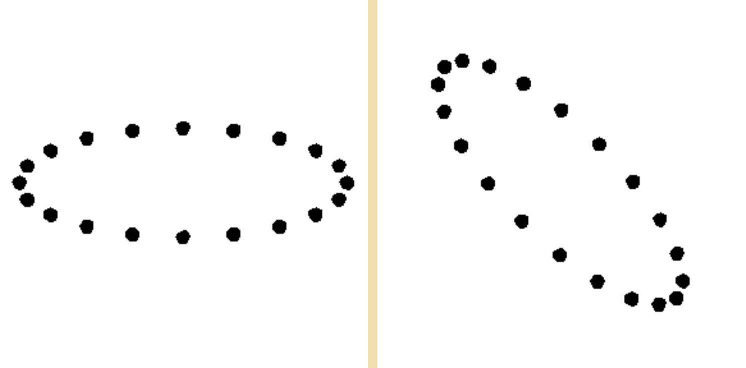
Gravitational Waves

- Ripples in spacetime that travel at the speed of light



Gravitational Waves

- Ripples in spacetime that travel at the speed of light
- Causes the contraction and expansion of space and time



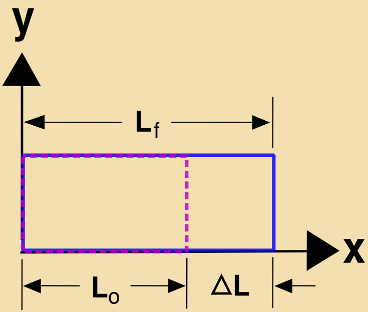
Effects of Gravitational Waves

1.3 billion lightyears away

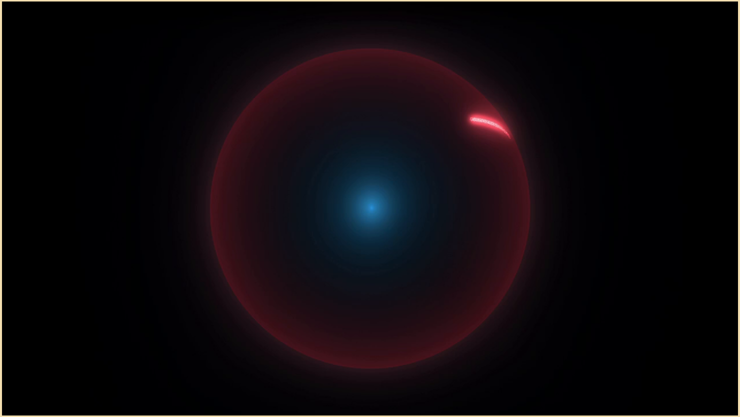
Measuring gravitational waves

- Measure gravitational waves by measuring *length changes*
- These changes are very small $\Delta L/L \approx 10^{-21}$
  - Similar to width of a hair over distance to the nearest star

$\Rightarrow$ Incredibly difficult to measure

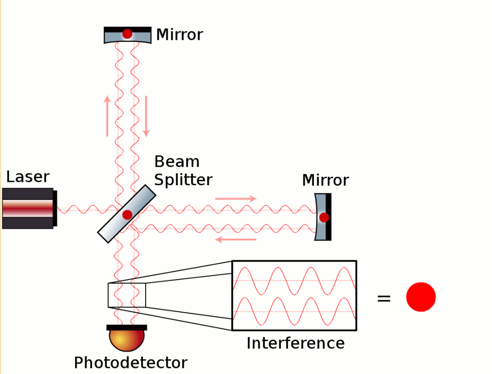


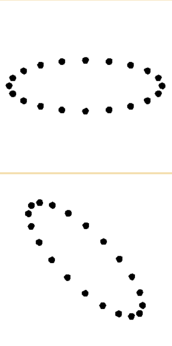
Measurement scale



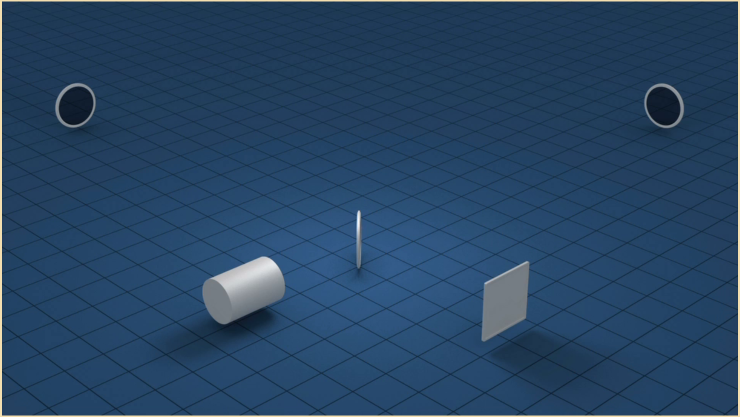
How can we detect gravitational waves?

- Measure strain through *laser interferometry*
- Gravitational waves changes the length of the arms
- Measure the change in light intensity

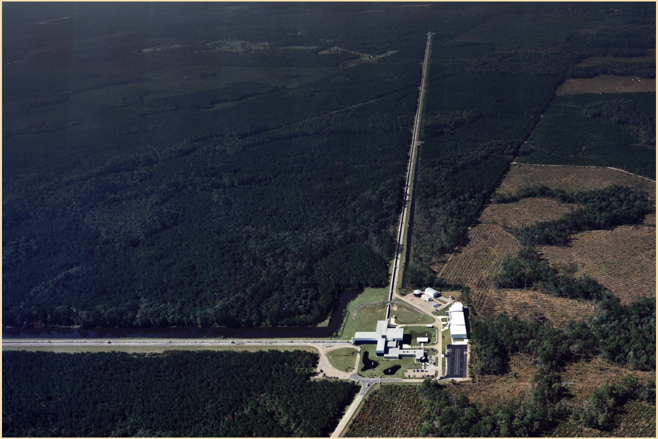




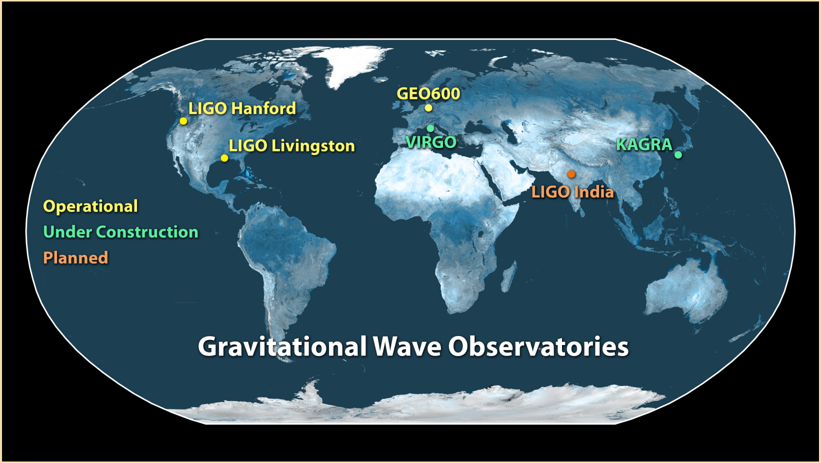
Interferometers



Laser Interferometer Gravitational-Wave Observatory



Laser Interferometer Gravitational-Wave Observatory



LIGO

LSC

LIGO Scientific Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
American University Washington, DC
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
R·I·T
University of Strathclyde
Michigan
Università degli Studi del Sannio
The University of Western Australia
UTRGV
ACU
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique theorique
NASA Goddard Space Flight Center
University of Cambridge
ICTP SAIFR
Max Planck Institute for Gravitational Physics
Albert Einstein Institute
The University of Mississippi
香港中文大學
The Chinese University of Hong Kong
Monash University
Southern University
Columbia University in the City of New York
The University of Chicago
Caltech
The University of Adelaide Australia
The University of Melbourne
University of Birmingham
University of Minnesota
Universitat de les Illes Balears
UIB
University of Wisconsin Milwaukee
University of Washington
Northwestern
Syracuse University
Cardiff University
Prifysgol Caerdydd
Monash University
INPE
UF University of Florida
Montana State University
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU
Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council
Rutherford Appleton Laboratory

Advanced LIGO

- Advanced LIGO began operations in September 2015

Telescopes

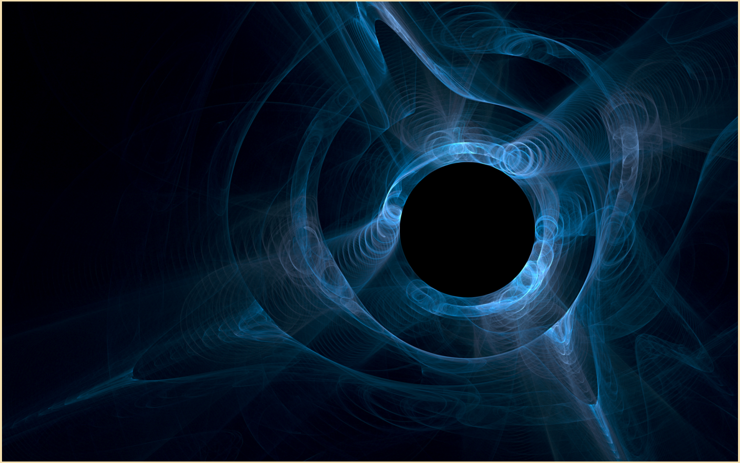
- 1609: Galileo used a *telescope* to view the stars

Amazing discoveries

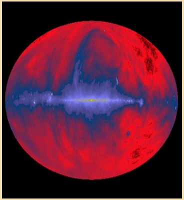
- Since then, we have made amazing discoveries

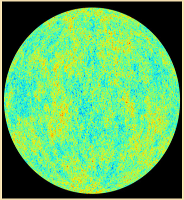
The dark Universe

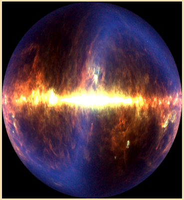
- Many astronomical phenomena are *dark*

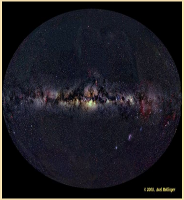


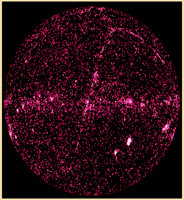
A new window on the Universe

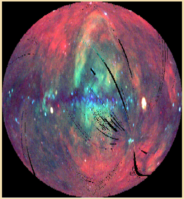

radio

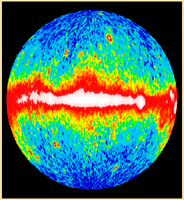

microwave


infrared


visible


ultra-violet

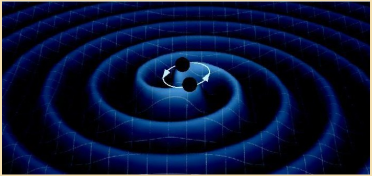

x-ray


γ-ray

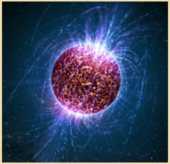
gravitational

Astrophysical sources of gravitational waves

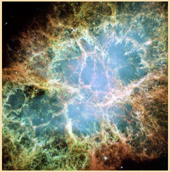
Binary mergers

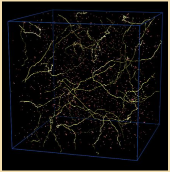


Continuous waves

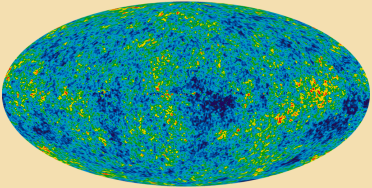


Burst



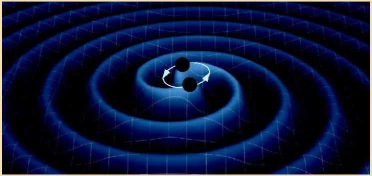


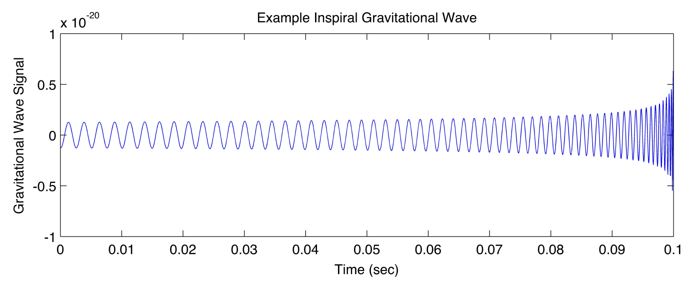
Stochastic background



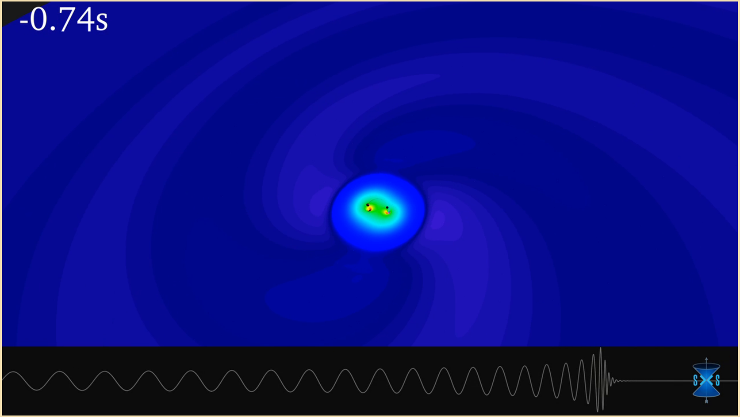
Binary mergers

- Radiate GWs as components orbit each other
- Loss of energy/momentum causes separation to shrink
- Ultimately merge and form single black hole





GW150914

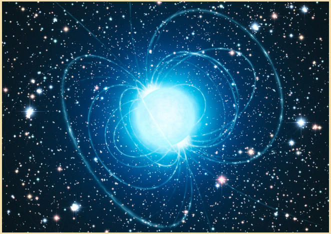


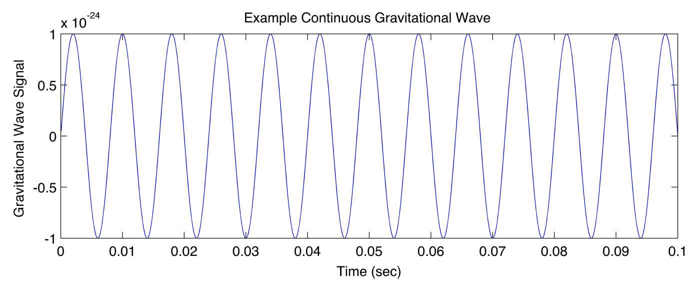
29 solar mass black hole + 36 solar mass black hole

Continuous waves

- Assymetric neutron stars

- Weak emitters
- Monotonic waveforms
- Long duration

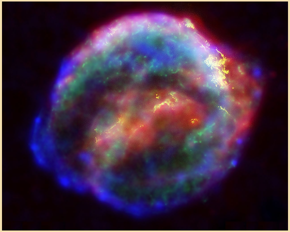


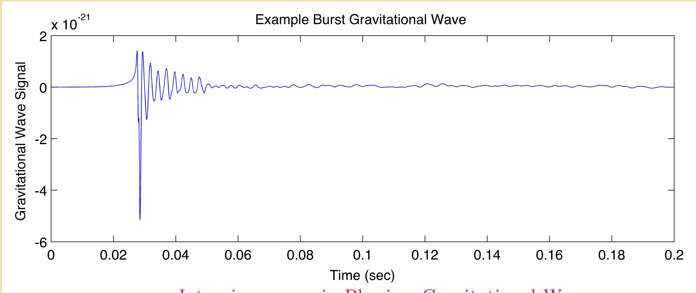


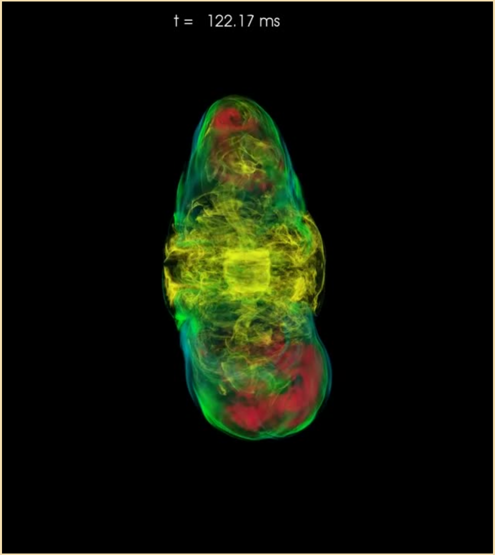
Burst

- Supernovae
- Cosmic strings

- Weak emitters
- Poorly modelled
- Short duration, transient



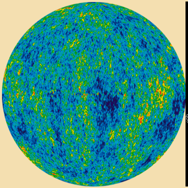


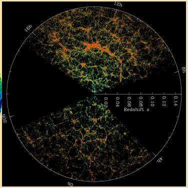

t = 122.17 ms

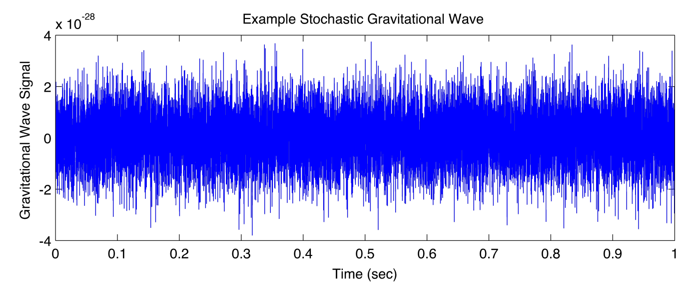
Stochastic

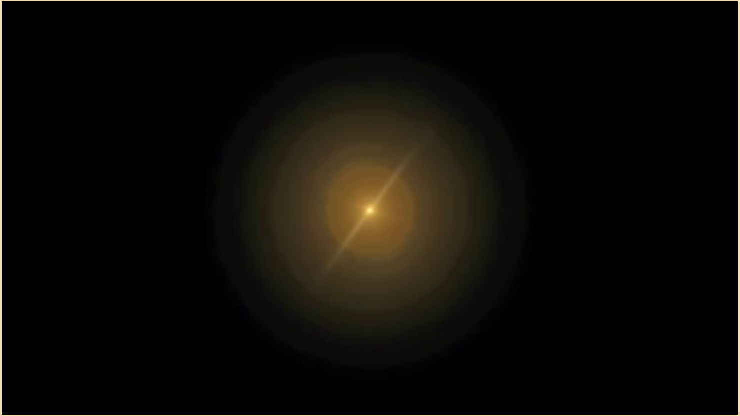
- Big Bang
- Unresolved binaries

- Weak emitters
- Well-modelled (statistically)
- Long duration



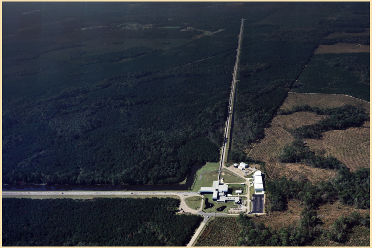






What can we learn from gravitational waves?

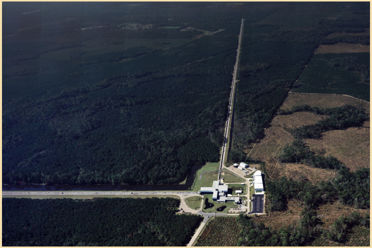
- Fundamental physics
  - Testing general relativity
  - Properties of black holes
  - Extra dimensions (string theory)
- Stellar/galactic evolution
  - End of stellar evolution
  - Galactic evolution
- Relativistic astrophysics
- Cosmology
  - Content of the Universe
  - Nature of dark energy/matter



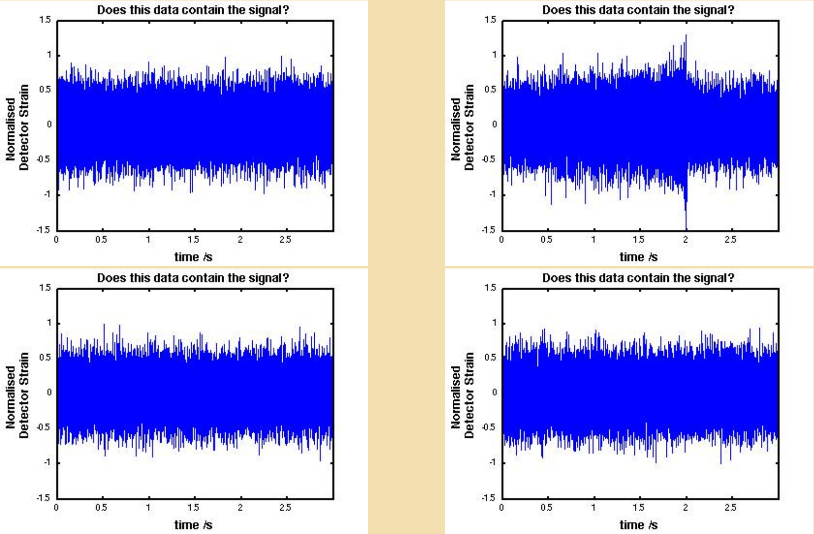
Concluding remarks

- LIGO is providing us with a new way to see the Universe
- Gravitational waves will teach us about astrophysical phenomena
- Discover things scientists have yet to envisage

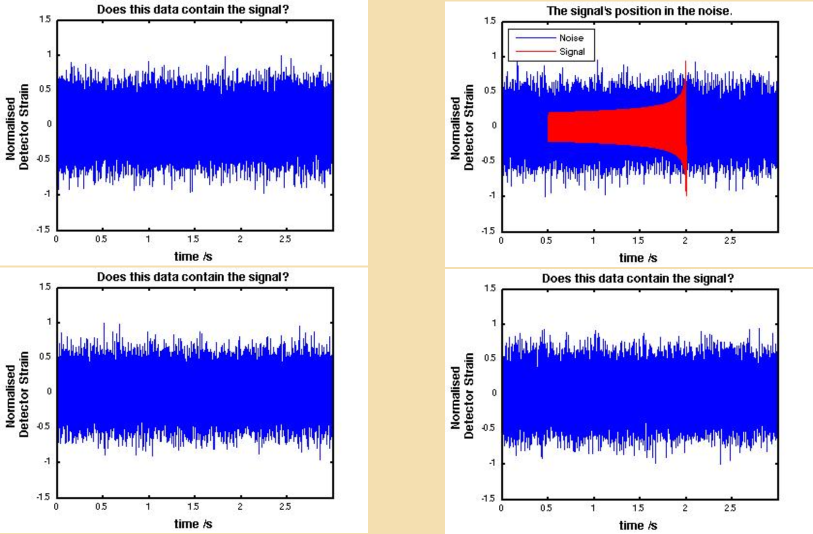
The beginning of a new era in astronomy



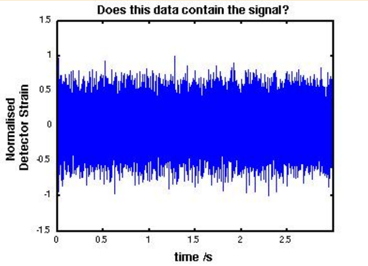
Black hole hunter – Easy

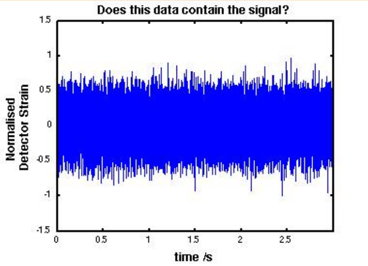


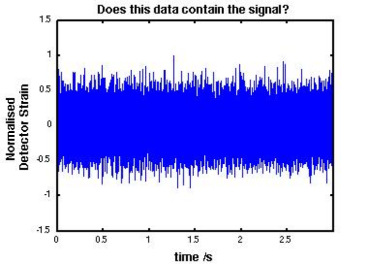
Black hole hunter – Easy

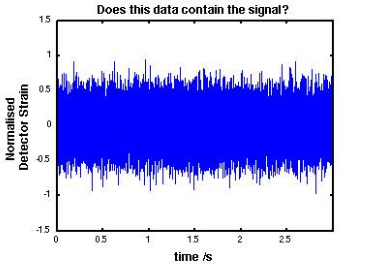


Black hole hunter – Intermediate

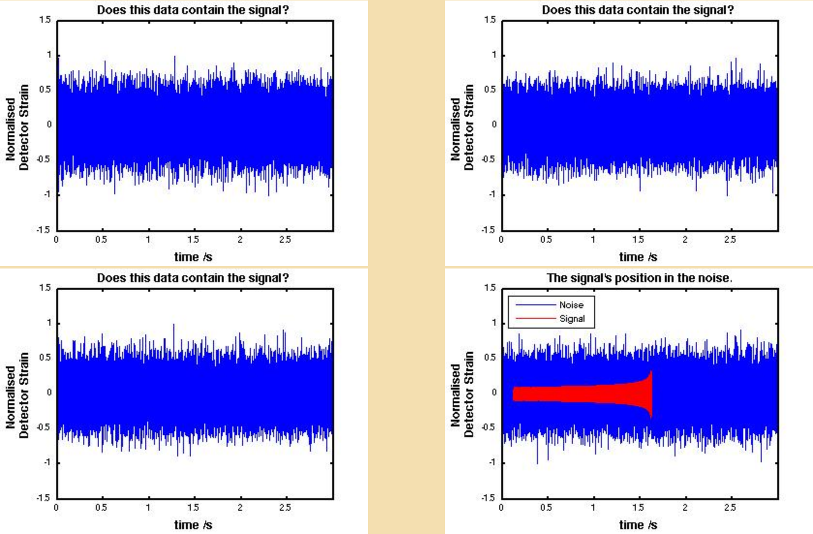




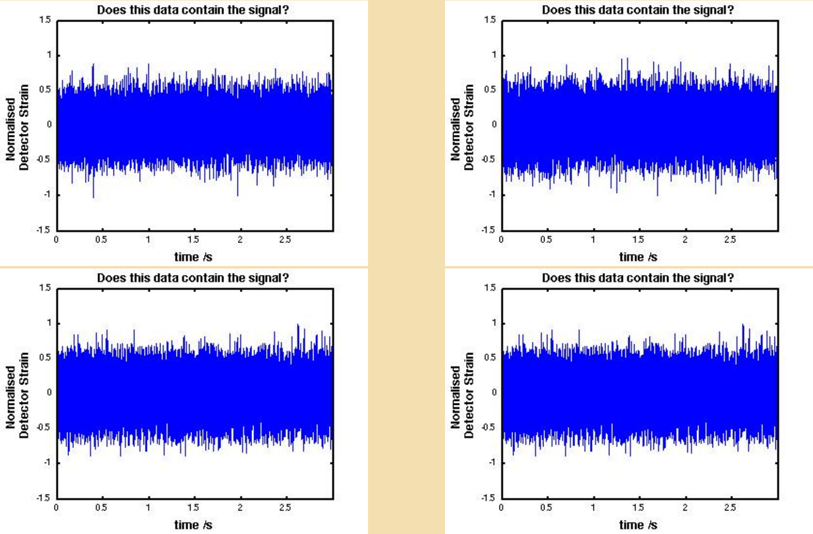




Black hole hunter – Intermediate



Black hole hunter – Advanced



Black hole hunter – Advanced