When Black Holes Collide

SEA and Coffee, 2020

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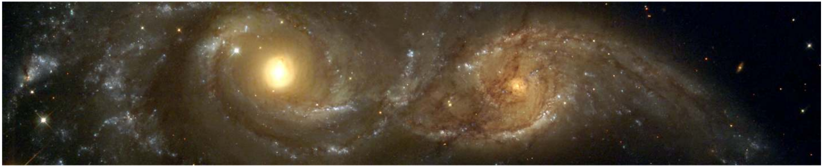
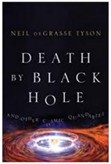
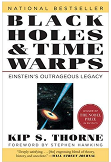
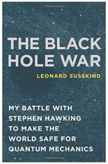
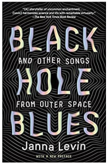
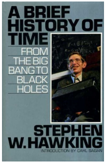


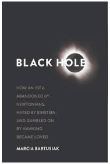


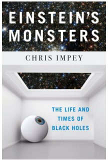






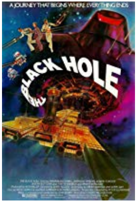


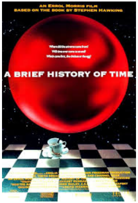


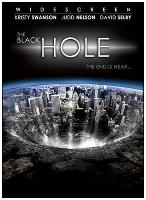


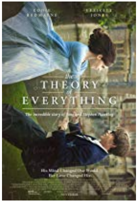
Black Holes in Film

- The Black Hole, 1979
- A Brief History of Time, 1992
- Event Horizon, 1997
- The Black Hole, 2006
- Star Trek, 2009
- Interstellar, 2014
- The Theory of Everything, 2014

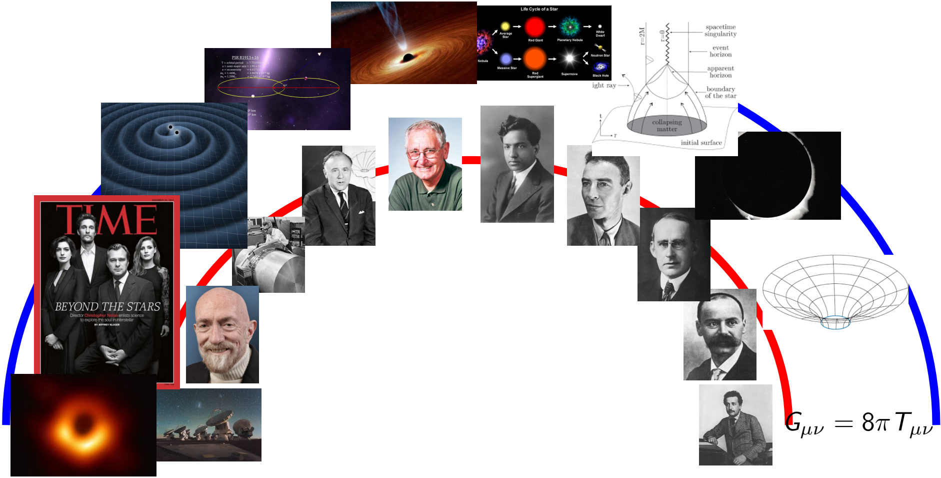








At a Glance



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

Outline

1. Gravitation
2. Einstein's Relativity Theories
3. Black Hole Geometry
4. Stellar Collapse
5. Search for Gravitational Waves
6. First Picture of a Black Hole
7. Summary

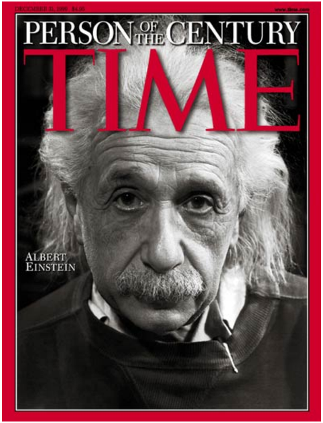


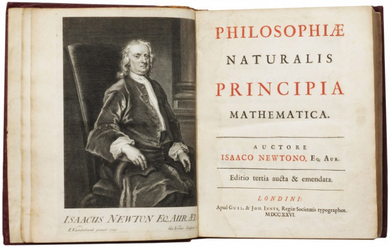
Figure: Person of the Century.

Isaac Newton (1642-1727)

In 1680s Newton sought to present derivation of Kepler's planetary laws of motion.

- Principia 1687.
- Took 18 months.
- Laws of Motion.
- Law of Gravitation.
- Confirmed 1759, Halley's Comet

Objects on the Earth feel same force as the planets orbiting the sun.



John Michell (1724-1793) - restored from obscurity

- Natural philosopher, clergyman
- Applied Newton's Corpuscular Theory.
- *Philosophical Transactions of the Royal Society of London*, 27 November 1783.
- A star's gravitational pull might be so strong that the escape velocity would exceed the speed of light! - **Dark Stars**
- Pierre-Simon Laplace, 1796, *Exposition du Système du Monde*
- Consider **escape velocity**

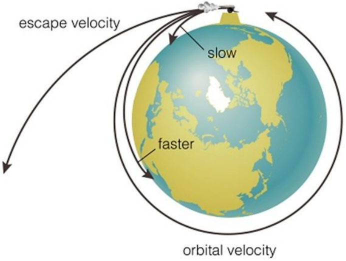


Figure: Firing projectiles.

Common Escape Velocities, $v = \sqrt{\frac{2GM}{R}}$,

From Newtonian theory: Escape rates for some celestial bodies
$G = 6.67 \times 10^{-11} Nm^2/kg^2$

	Mass M (kg)	**Radius** R (m)	**Escape Velocity** v (m/s)
Moon	7.348×10^{22}	1.737×10^{6}	2,376 (5,300 mph)
Earth	5.972×10^{24}	6.378×10^{6}	11,176 (25,000 mph)
Jupiter	1.898×10^{27}	7.1492×10^{7}	59,511 (133,000 mph)
Sun	1.989×10^{30}	6.957×10^{8}	617,567 (1.38 million mph)

For light, $R = \frac{2GM}{c^2}$ where $c = 186,000$ mi/s $= 3.0 \times 10^8$ m/s.

- Earth, $R = .0088$ m.
- Sun, $R = 2.9$ km,

$$\frac{\text{Sun Mass}}{\text{Earth Mass}} = \frac{1.989 \times 10^{30}}{5.972 \times 10^{24}} = 3.3 \times 10^5$$

But, light is a wave!

James Clerk Maxwell (1831-1879) - Light = EM Wave

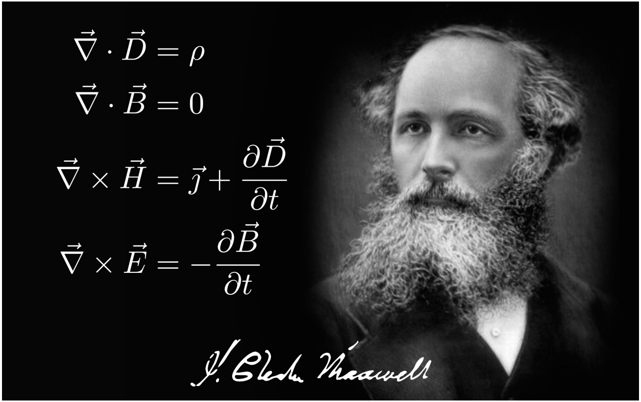


Figure: Equations of Electricity and Magnetism
Gauss' Law, No magnetic monopoles, Maxwell-Ampere Law, Faraday's Law.

... and then came A. Einstein!

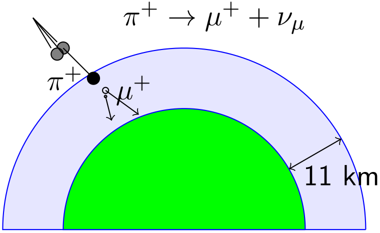
1905 - Einstein's Miracle Year

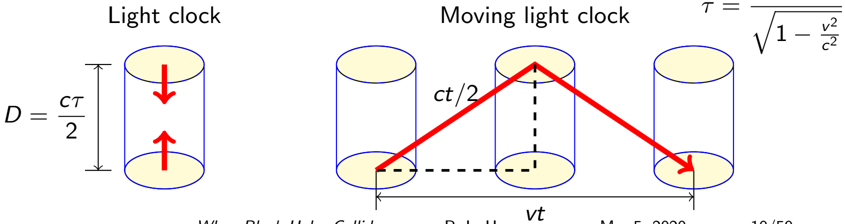
- Photoelectric effect (March/June).
- Brownian motion (May/July).
- Special Relativity (June/September).
  - Inspired by Maxwell's Theory.
  - Two Postulates
    - Physics is same for all inertial observers.
    - Speed of light same for everyone.
  - Consequences.
    - Time dilation.
    - Length contraction.
    - Space and Time relative.
- $E = mc^2.(September/November)$

Figure: Einstein (1879-1955)

Time Dilation - Moving clocks tick slower.

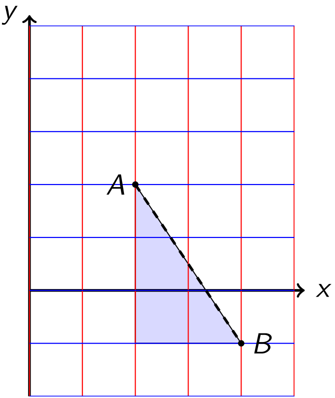
- Examples -
  - Plane trip
    - 620 mph (277 m/s)
    - Lose 3 ns/hr.
  - Muon
  - Cosmic rays collide with nuclei.
  - Pions decay into muons.
    - Lifetime 2.2 μs
    - At 0.995c, travels 660 m



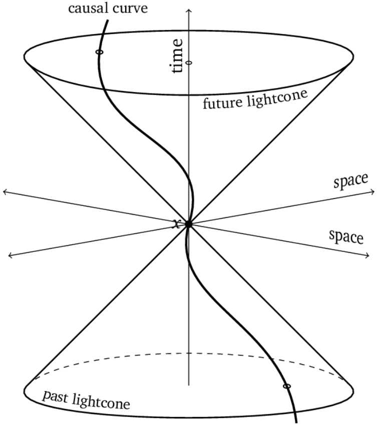


Space, Time, and Spacetime

From René Descartes:



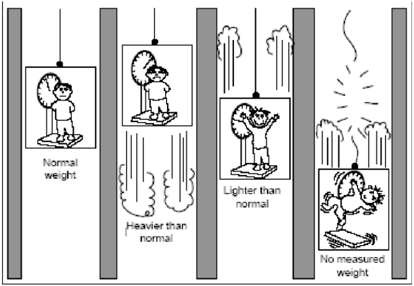
From Hermann Minkowski:



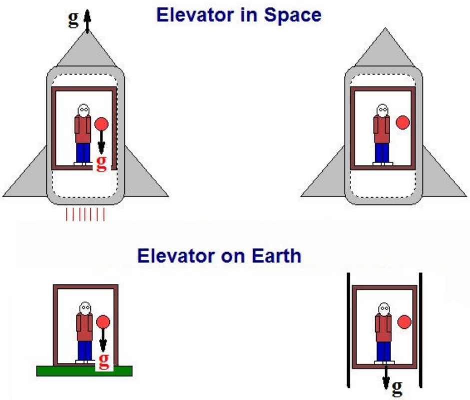
Particles move in straight lines to maximize lifetime.

Einstein's Happiest Thought

- Einstein spent years generalizing
- Galileo Galilei - Everything falls at the same rate.
- Einstein - When you fall freely, gravity disappears.
- Led to the Equivalence Principle



The Equivalence Principle



There are no (local) experiments which can distinguish non-rotating free fall under gravity from uniform motion in space in the absence of gravity.

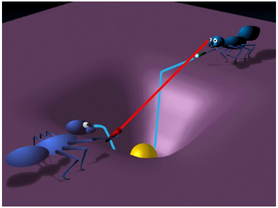
General Relativity - 1915

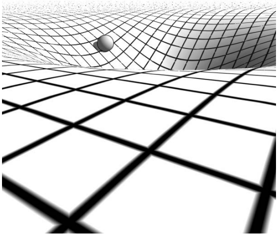
Einstein generalized special relativity to Curved Spacetime.

- Einstein's Equation
- Gravity = Geometry

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

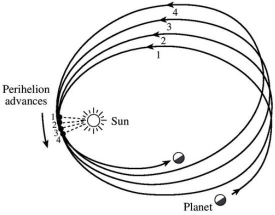
- Mass tells space how to bend and space tell mass how to move.
- Predictions. (Wheeler)
  - Perihelion Shift of Mercury.
  - Bending of Light.
  - Time dilation.





Classical Tests - Perihelion Shift of Mercury

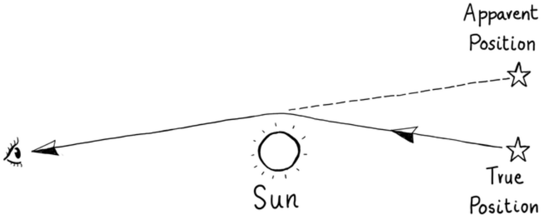
- First noted by Le Verrier, 1859
  38″ (arc seconds) per century
- Re-estimated by Newcomb, 1882.
- Ellipse axis shifts 43″ per century.



arcsec/cent	Cause
532.3035	Gravitational tugs by other bodies
0.0286	Oblateness of Sun
42.9799	General Relativity
-0.0020	Lense-Thirring
575.31	Total Predicted
574.10 ± 0.65	Observed

Classical Tests - Deflection of Light

- Deflection of light - when light passes near a large mass its path is slightly bent.
- 1919 Eclipse observed an island near Brazil and near the west coast of Africa.

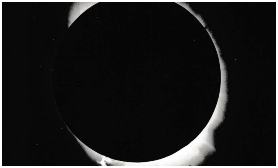


LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

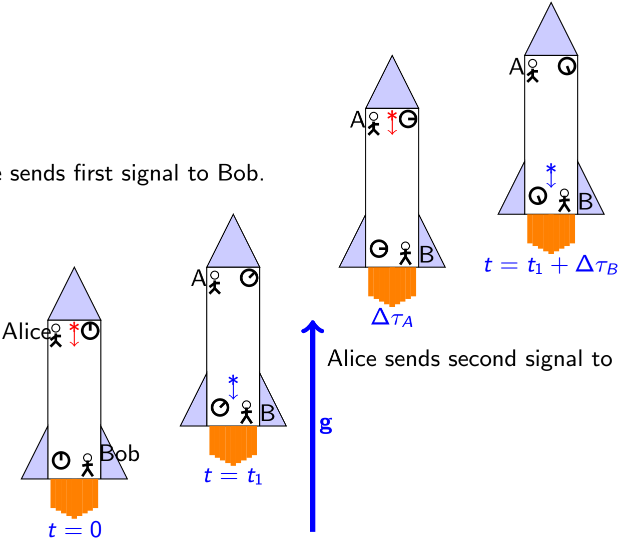
EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.



Classical Tests - Gravitational Time Dilation

Alice sends first signal to Bob.



Alice sends second signal to Bob.

Time Dilation and GPS

Gravitational redshift - clocks in a gravitational field observed from a distance tick slower. (1960s, Pound-Rebka-Snider experiments)

- Special Relativity.

$$\delta t = \frac{\delta\tau}{\sqrt{1-\frac{v^2}{c^2}}}$$

- General Relativity.

$$\delta t = \delta\tau\sqrt{1-\frac{2GM}{rc^2}}$$

- Application - GPS

GPS Satellites

- Global Positioning System
- 32 Satellites (max)
- Semi-synchronous orbits
  - 20,200 km,
  - 11 hours 58 min
  - Cesium or Rubidium clocks
- At least 4 over each location
- SR: Lose 7,200 ns/day
- GR: Gain 45850 ns/day
- Net, 39 μs/day [or, 500 m/hr]

Triangulation

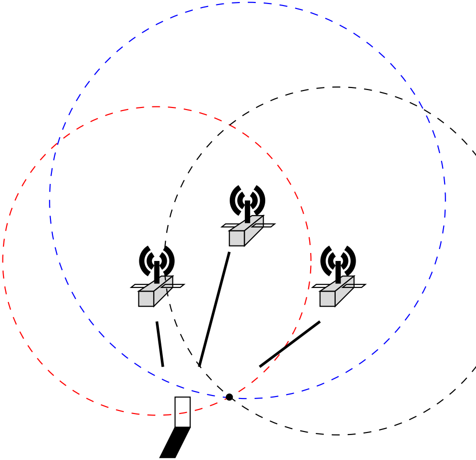
Equations of intersecting circles:

$$\begin{aligned}(x-14)^2+(y-45)^2 &= 39^2\\ (x-80)^2+(y-70)^2 &= 50^2\\ (x-71)^2+(y-50)^2 &= 29^2\end{aligned}$$

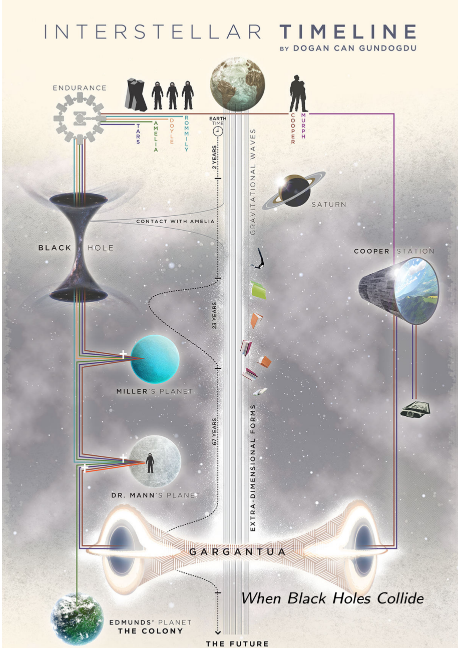
Solve

$$x = 50, y = 30$$

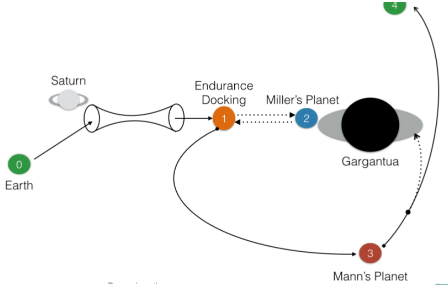
For satellites, use intersecting spheres and vertical coordinate, z.



Interstellar - The Movie



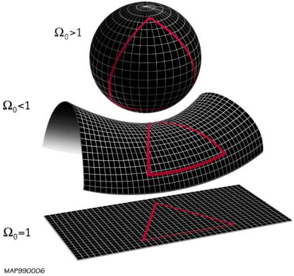
When Black Holes Collide



GR Applied to Cosmology - 1920s

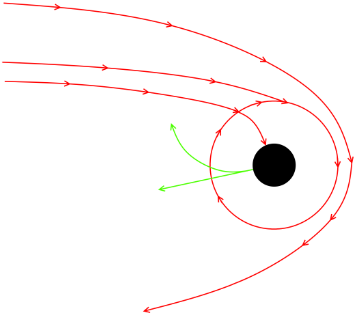
- Karl Schwarzschild (1873-1916)
  Spherical solution
- Einstein Applied GR to Cosmology (1917).
- Alexander Friedmann (1888-1925)
  Curved spacetime: Positive, negative, flat
- Georges Lemaitre (1894-1966)
  Expanding universe.
- Hubble - Expanding universe data.
- Einstein's greatest blunder.

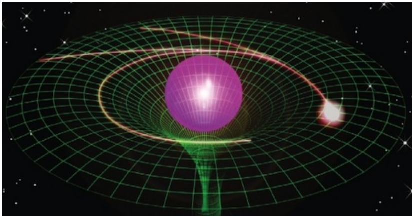
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu}.$$



Karl Schwarzschild (1873-1916)

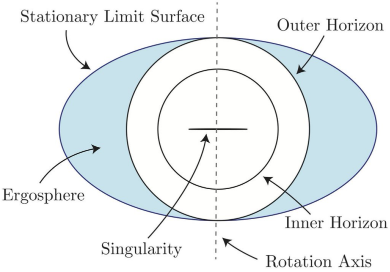
- Spherically symmetric solution. 1916
- Schwarzshild radius - point of no return.
- Later - black hole solutions.
- Add Charge Reissner-Nordström





Kerr Black Hole

- Roy Kerr (1963) - Rotating black holes
- B. Carter (1971) - Only need Mass, Charge, Angular momentum.



Eddington-Finkelstein Diagram

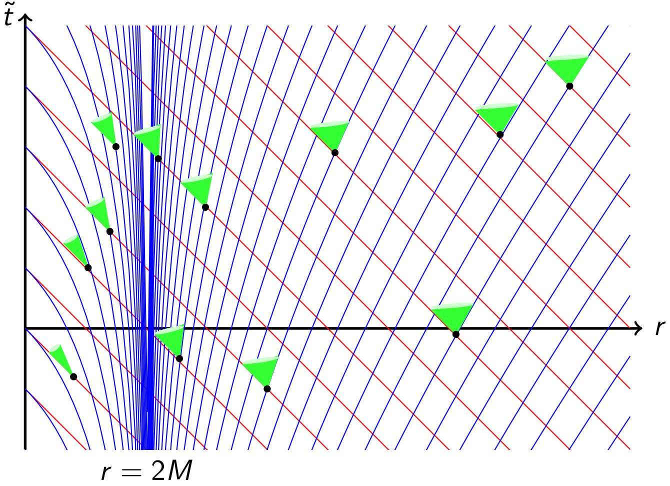


Figure: Light rays in Eddington-Finkelstein coordinates with future light cones.

Kruskal Diagram

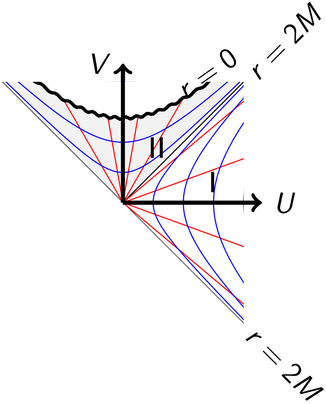


Figure: The coordinates are mapped to a Kruskal diagram. The singularity is denoted by the wavy black curve. The white region is the black hole exterior.

Extended Kruskal Diagram

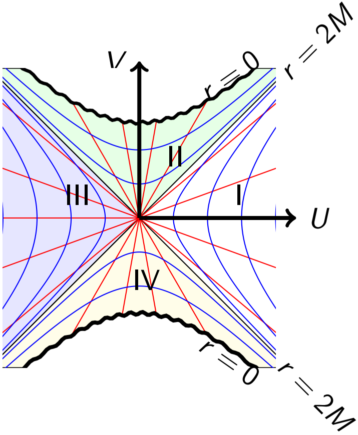


Figure: The extended Kruskal diagram to Regions III and IV often interpreted as another universe connected to the first by a wormhole.

Map of the Universe - Roger Penrose

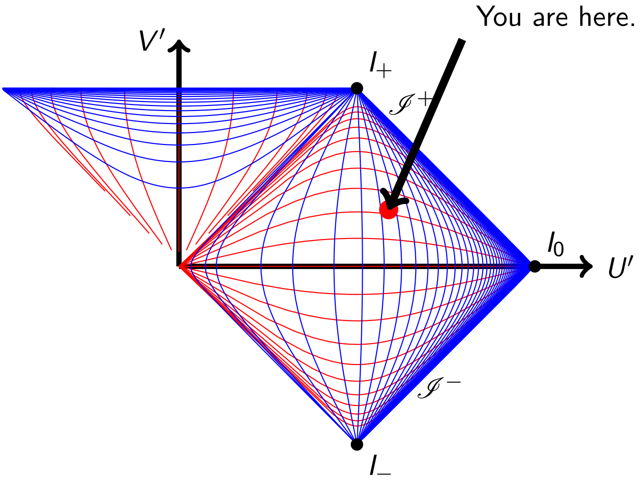
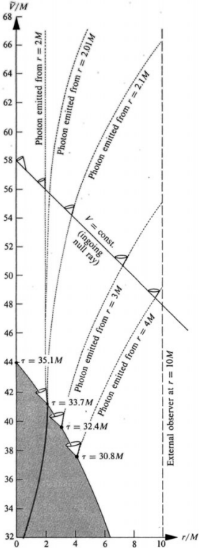


Figure: Penrose diagram for the Schwarzschild Geometry.

- White dwarf quantum statistics
  - 1924 Eddington - e^{-}-pressure
  - 1930 Chandrasekhar (19 yr)
    - Mass Limit (1.4 Solar masses)
- 1939 Einstein - Renewed
  - Can a spherical star cluster collapse into a stable star of radius R_s?
- R. Oppenheimer and Students
  - 1938 R. Serber and G. M. Volkoff
    - neutron star limit (now 1.5-3)
  - 1939 Snyder - Star collapse $< R_s$?
- Progress on the fate of stars not until 1960s: quasars, pulsars and compact x-ray sources



The Search for Black Holes

- 1963 Quasars
- 1964 Black Hole in print,
  Science Magazine Issue: Vol. 85 No. 3, Jan 18, 1964
- 1972 Cygnus X-I (Hawking & Thorne made a bet)
- 1972 Jacob Bekenstein - Black Hole Temperature $T = \dfrac{\pi A k c^3}{2hG}$
- 1974 Hawking Radiation
- 1974 Radio Waves from Milky Way Sagittarius A*
  Supermassive BH, 4 million solar masses
- 1978 Black hole in M87 (Messier 87)
- 2008 Event Horizon Telescope
- 2016 Gravitational Waves - Advanced LIGO
- 2019 First black hole picture, M87

Falling into a Black Hole

Figure: Artistic view of black hole devouring a star forming accretion disk and central jets.

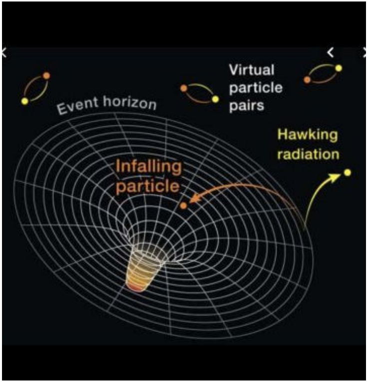
Black Holes Have a Temperature - Hawking Effect

- BH - 5 solar masses, 2.6×10^{69} years to evaporate.
- BH - center of our galaxy, about 4 million solar masses, 1.34×10^{87} years to evaporate.
- The most massive black hole known, 66 billion solar masses. It would require 6×10^{99} years to evaporate.
- Small primordial black hole, mass of 1.7 trillion kilograms, 13.8 billion years, or the age of the universe.

$$t = \frac{5120\pi G^2 M_{solar}^3}{\hbar c^4} = 6.617 \times 10^{74} \text{ s}$$

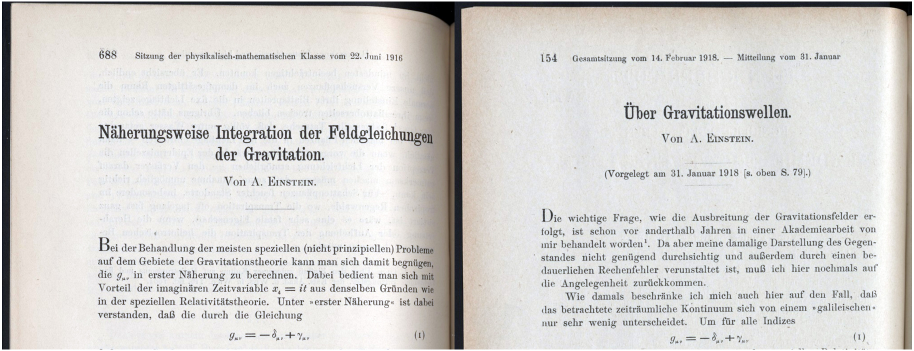
Black Hole Unsolved Problems

- 1991 Hawking-Thorne bet Preskill
  - Information that falls into a black hole gets lost.
  - Black Hole Information Paradox
  - 2004 Black Hole Complementarity
- 2012 Polchinski - Firewall at horizon
- Conflict between 3 principles
  - Equivalence Principle.
  - Information cannot be destroyed
  - Locality
- Need theory of quantum gravity
  - Entanglement
  - String Theory



Read more here.

Einstein Predicts Gravitational Waves - 1916, 1918



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

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

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

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

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.

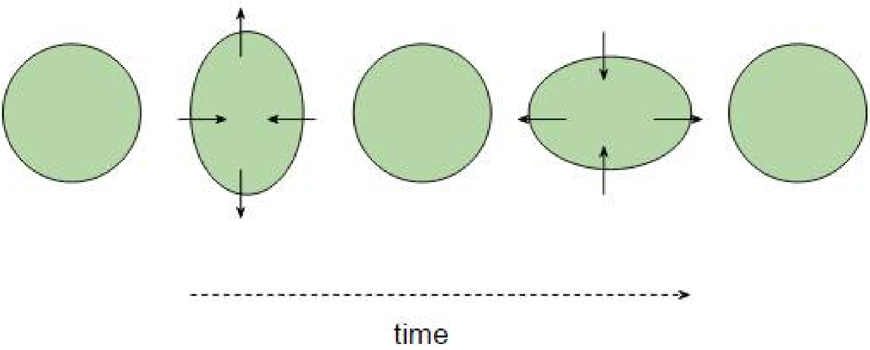
Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

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

1917 - Ripples in spacetime due to accelerating masses (like EM waves from antennae) or collisions.

Varied his opinion as to existence and ability to detect GWs.

Gravitational Waves

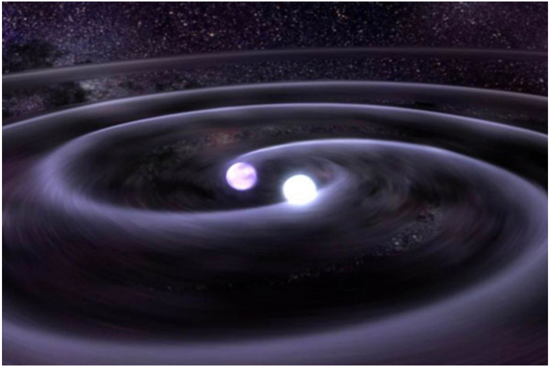


Waves stretch spacetime in one direction and compress in other direction.

Gravitational Wave Sources

Gravity is Weak and needs strong sources:

- Nonspherical Supernovae.
- Nonspherical Spinning stars.
- Binary Systems (Taylor-Hulse binary pulsar).
- Stellar Collapse - Oppenheimer and Snyder 1939.



Taylor-Hulse Binary Pulsar PSR B1913+16

Existence of gravitational waves - Joe Taylor and Russel Hulse - 1974.

- Pulsars: pulsating radio star. Rapidly rotating neutron star.
- Magnetic lighthouse.
- Regular flashing
  - 2x each cycle - 17 per second.
- Regular variations - 7.75 hrs and 3s differences due to elliptical orbit.
- 305 m Arecibo Radio Telescope in Puerto Rico.
- 1993 Nobel Prize

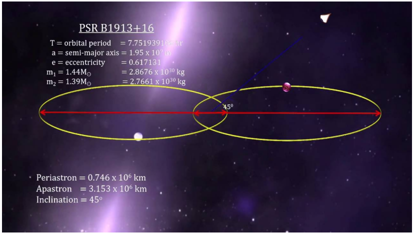


Figure: Binary Pulsar

Binary Pulsar PSR B1913+16 and General Relativity

- Tested Einstein's Prediction of radiation loss as gravitational waves.
- Calculated masses, periastron (closest distance), and apastron (furthest).
- Energy Loss: $\frac{dE}{dt} = 7.35 \times 10^{24}\text{W}.$
- Orbital period change: $\frac{dT}{dt} = 7.65$ milliseconds/yr.
- First indirect observation of gravitational waves.

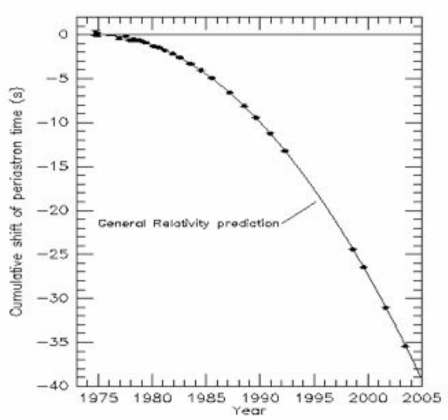


Figure: Binary Pulsar Data

Joseph Weber (1919-2000)

To detect gravitational waves (GWs) one needs a detector and right frequency range.
First attempt: Joseph Weber's mass resonators (1960).

- University of Maryland.
- Announced detection of 1968-9.
- Weber bars: aluminium cylinders, 2 meters in length, and
  1 meter in diameter,
  Like antennae for detecting gravitational waves.
- GWs Interact with matter – compressing and stretching.
- Never duplicated!

Co-founders of LIGO - 50 years in the making

- Rainer Weiss (1932)
  - MIT, Experimentalist.
  - invented the interferometric gravitational wave detector (1972).
- Ronald Drever (1931-2017)
  - Glasgow, Experimentalist.
  - recycle of laser light to increase optical path length.
- Kip Thorne (1940)
  - Caltech, Theoretical Physics.
  - *Gravitation*, Misner, Thorne, Wheeler.
  - Wormholes
  - *Contact* (Sagan), *Interstellar*.
- 2017 Nobel Prize Weiss, Thorne, Barish

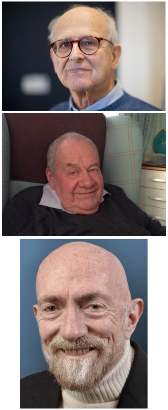


Figure: Weiss, Drever, Thorne

The Interferometer

Laser beam splits into two beams in each arm.
Beams recombine resulting in interference patterns.

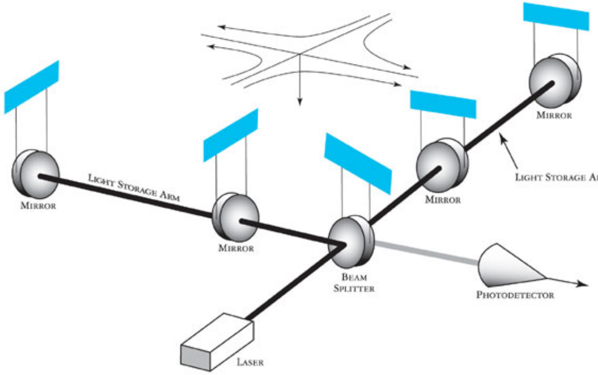


Figure: Interferometer - Interference of laser beams to detect small distortions.

LIGO Locations

- Laser Interferometer Gravitational-Wave Observatory (LIGO) located in Livingston, Louisiana, and Hanford, Washington, USA.
- Funded by the National Science Foundation (NSF) and others.
- Conceived, built, and operated by Caltech and MIT.
- 1,000+ scientists from universities in United States and 14 other countries; 90+ universities and research institutes; $\approx$ 250 students.

Figure: Hanford, WA site.

Figure: Livingston, LA site.

LIGO Locations

- Arms 4 km long ($\approx$ 2.5 miles) 1.2 m diameter tube - sensistivity.
- Far apart - eliminates background events.
- Largest sustained ultra-high vacuum (8x the vacuum of space)
- 300,000 cubic feet (about 8,500 cubic meters) at one-trillionth the pressure of Earth's atmosphere.
- International detectors include VIRGO in Italy, GEO in Germany, CLIO and KAGRA in Japan, AIGO in Australia.

Figure: Hanford, WA site.

Figure: Livingston, LA site.

Physics Event 1 Announced: GW150914

LIGO announced its 1st detection of gravitational waves 2/11/2016.

- September 14, 2015 at 5:51 a.m. Eastern Daylight Time
  - 1st detection gravitational waves
  - 1st confirmation binary black holes exist
  - Livingston ... 7 milliseconds later – Hanford
- Displacement $4-5\times 10^{-18}$ m
  - 4000-5000 times smaller than a proton!

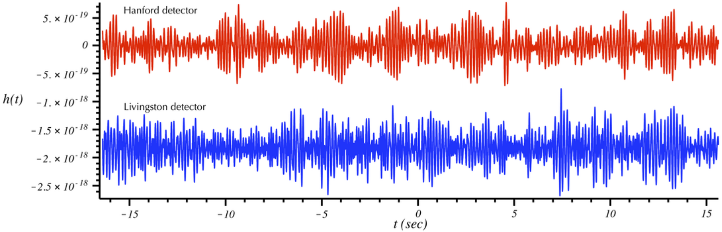


Figure: Signals from Livingston and Hanford.

Time Series

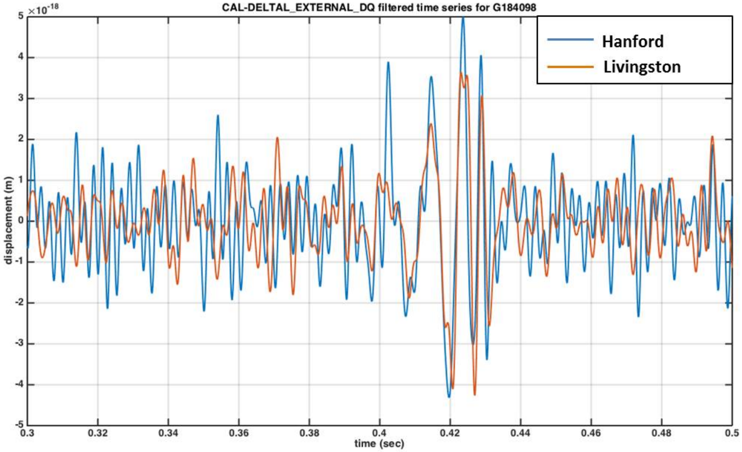
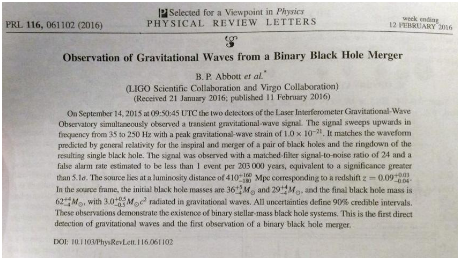


Figure: Time series.

Analyzing Data and Reporting Results

- 5 months of silence!
- Compared signal to templates.
- 1 out of 200,000 templates.
- 1st est: 20-40 solar masses.
- 2nd round – narrowing of masses.
- 3rd round - Numerical relativity using parameter estimates.
- Now the evidence was in.
- Paper Nov-Jan 21 sent for peer review.
- Press conference, Feb 11, 2016, 10:30 A.M. EST.


Selected for a Viewpoint in *Physics*
PRL **116**, 061102 (2016) 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

Figure: First publication Feb. 11.

First Sounds of Black Hole Merger

Analysis of signal - removing background noise and locating signs of event.

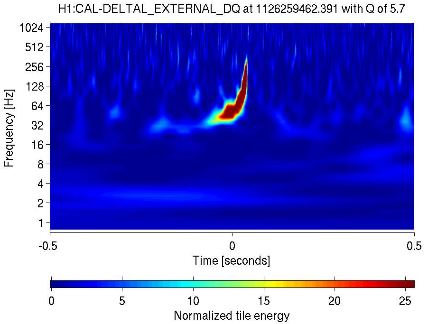


Figure: Hanford chirp.

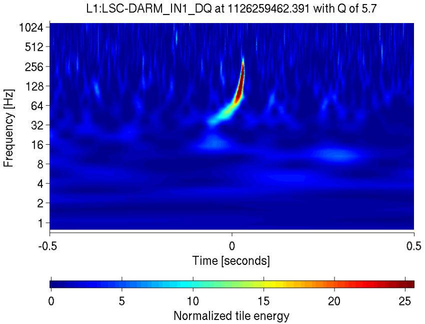


Figure: Livingston chirp.

Chirps

Chirp - the frequency increases or decreases with time. Sign of binary system merger.

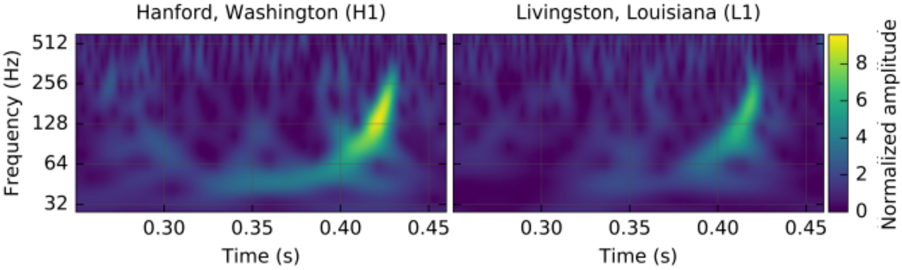


Figure: Chirps.

Listen: `https://www.ligo.caltech.edu/video/ligo20160211v2`

Numerical Relativity Template

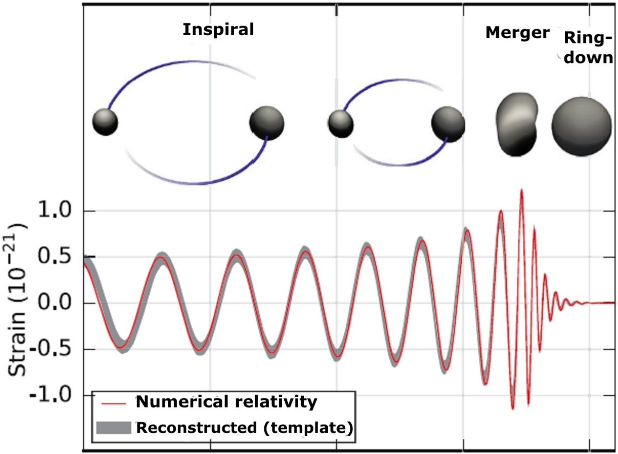
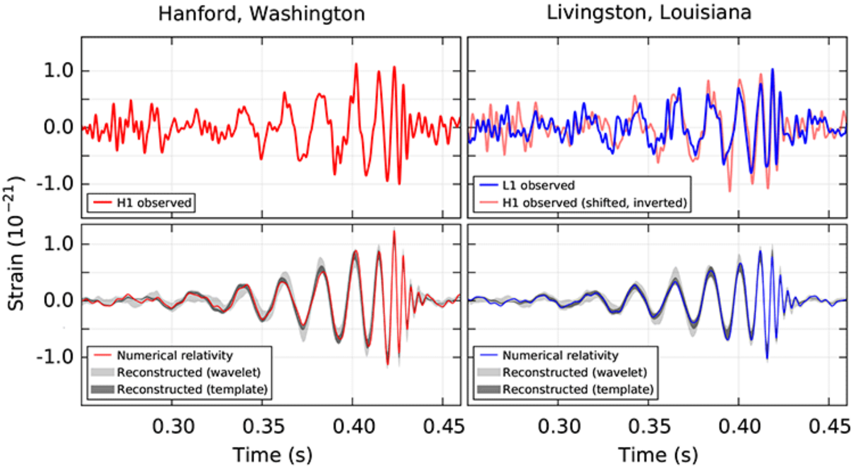


Figure: Black hole inspiral.

Numerical Relativity Template Comparison



Determining the Black Hole Masses

- Merger of 29 and 36 solar mass objects.
- Detected over 2-hundredths of second.
- Over 0.2s frequency changed from 35 to 350 Hz over 8 cycles.
- Schwarzschild radii $\geq$ 210 km and 350 km apart.
- 1.3 billion years ago.
- Frequency of signal indicated black holes.

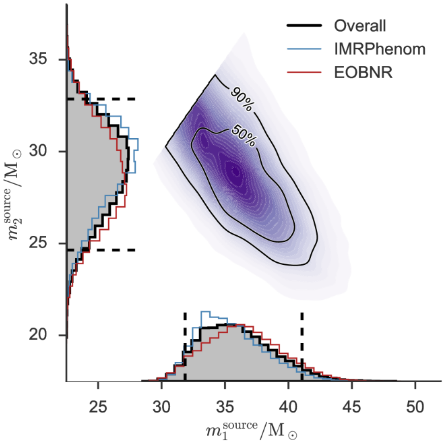


Figure: Final mass.

Final Black Hole

- The final object was a 62 solar mass black hole.
- Mass difference (29+36=65) radiated as gravitational waves.
- Confirm's Einstein's Prediction from his quadrapole formula.

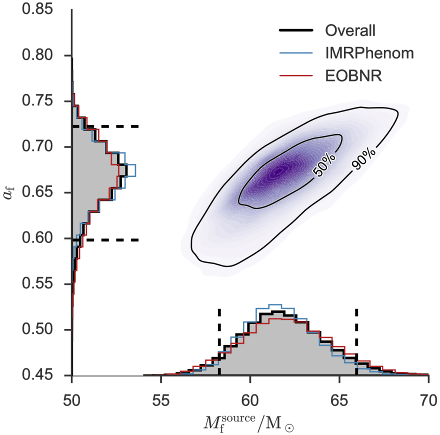


Figure: Final mass.

Event 2 Announced in 2016: GW151226

15 June, LIGO made a 2nd announcement of a GW detection.

- December 26, 2015 at 03:38:53 UTC.
- Merger of black holes 14, 8 solar masses, yielding 21 solar mass BH.
- 1.4 billion yrs ago.

Other detections? LIGO Press Releases

- LIGO and Virgo Detect Neutron Star Smash-Ups May 5, 2019
- Four New Detections, O1-O2 Catalog December 3, 2018
- GW170817 October 16, 2017
- 2017 Nobel Prize in Physics October 3, 2017
- GW170814 August 14, 2017
- GW170104 June 1, 2017
- GW151226 June 15, 2016
- GW150914 February 11, 2016

Event Horizon Telescope - Launched 2009

- 12 Radio Observatories
- A virtual telescope
- Data Processing Challenges
    - Hard Drives Failures 15000 ft
    - 900 TB/5 days
    - Flown to MIT - 800 CPUs and Max Planck Institute
- BH in Milky Way Galaxy: Sagitarius A*, 26 Mlyr
- M87 - supergiant elliptical galaxy in the constellation Virgo, 55 Mlyr, 6.5 billion solar masses
- Dec 2015 - Magnetic fields seen
- EHT turned on April 2017

Figure: EHT Network.

Picture of Black Hole - Released image April 10, 2019

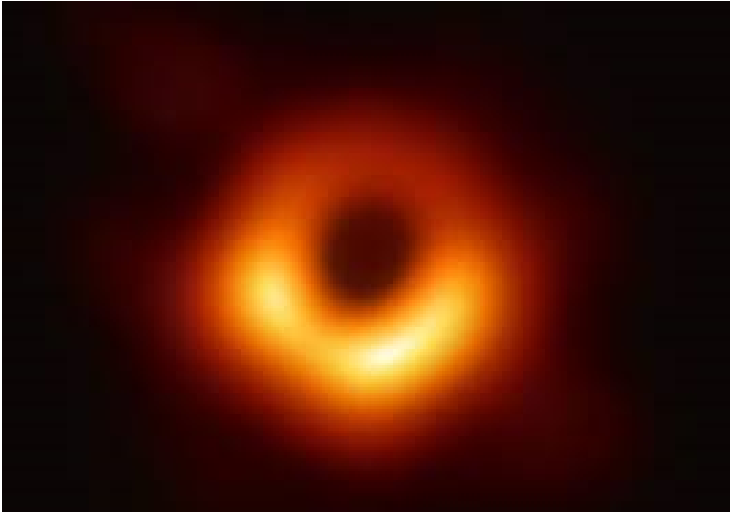
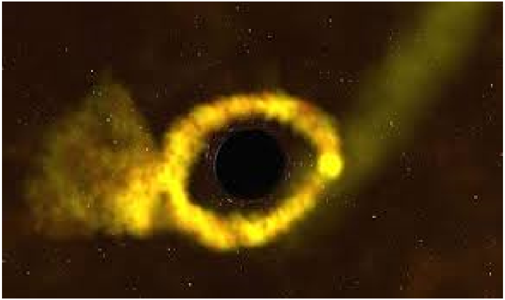


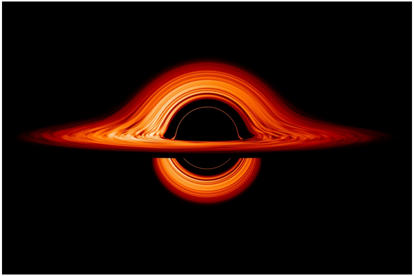
Figure: Supermassive black hole in M87.

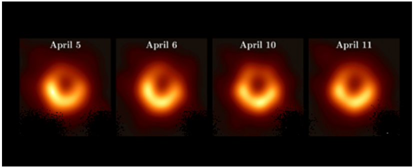
Other Pictures

Click links to movies:

- Black Hole Simulation
- Black hole captures star







Summary

- Einstein's prediction of gravitational waves in 1916 confirmed.
- Verification that black holes exist.
- The beginning of the new field of gravitational-wave astronomy.
- New observation tool vs optical, radio waves, x-rays.
- First picture of a black hole

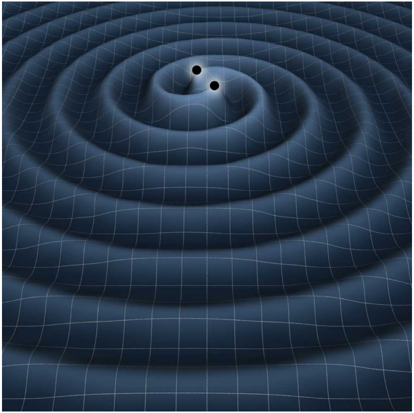


Figure: Black hole merger.

Further Reading

- *Black Hole Blues* - Janna Levin - Book (April 2016) on the story of gravitational wave detection
- *The Science of Interstellar* - Kip Thorne (The science behind the movie).
- *A Perfect Theory* - Pedro Ferreira (History of General Relativity).
- *Black Hole* - Marcia Bartusiak.
- *Einstein's Unfinished Symphony: Listening to the Sounds of Space-Time* - Marcia Bartusiak.
- *Black Holes and Time Warps: Einstein's Outrageous Legacy* - Kip Thorne.
- *No Shadow of a Doubt: The 1919 Eclipse That Confirmed Einstein's Theory of Relativity* - Daniel Kennefick

The End!
Thank you!
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