Einstein's waves: a new tool to explore the Universe

Viviana Fafone

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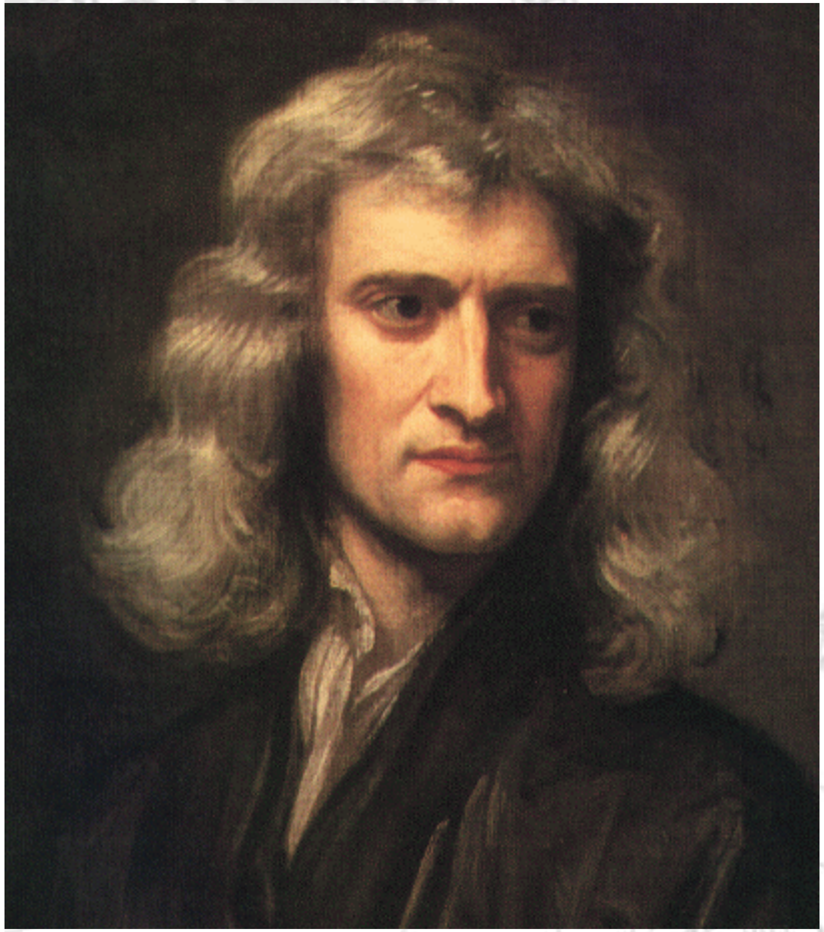
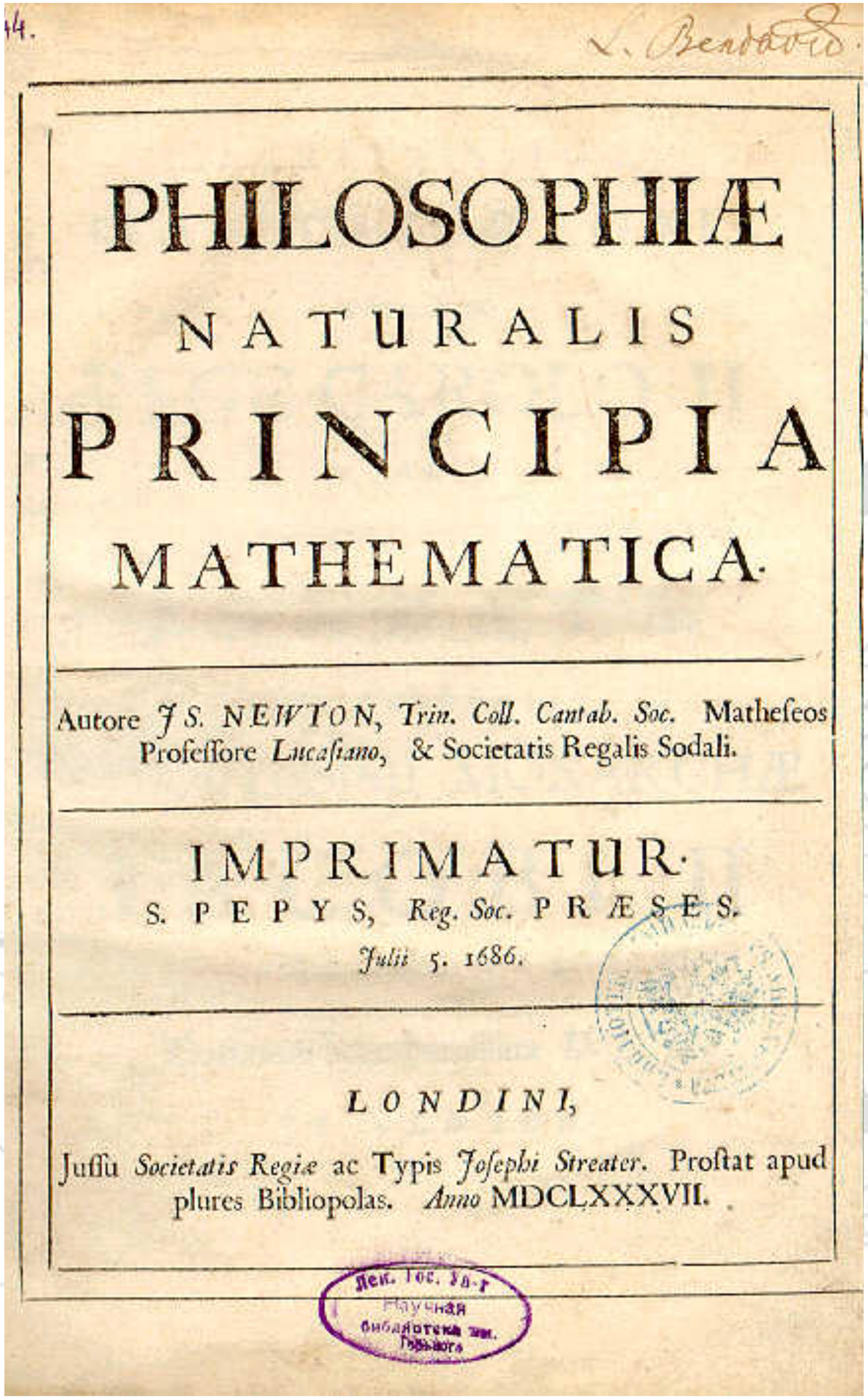
Newton’s Theory of Gravity (1686)





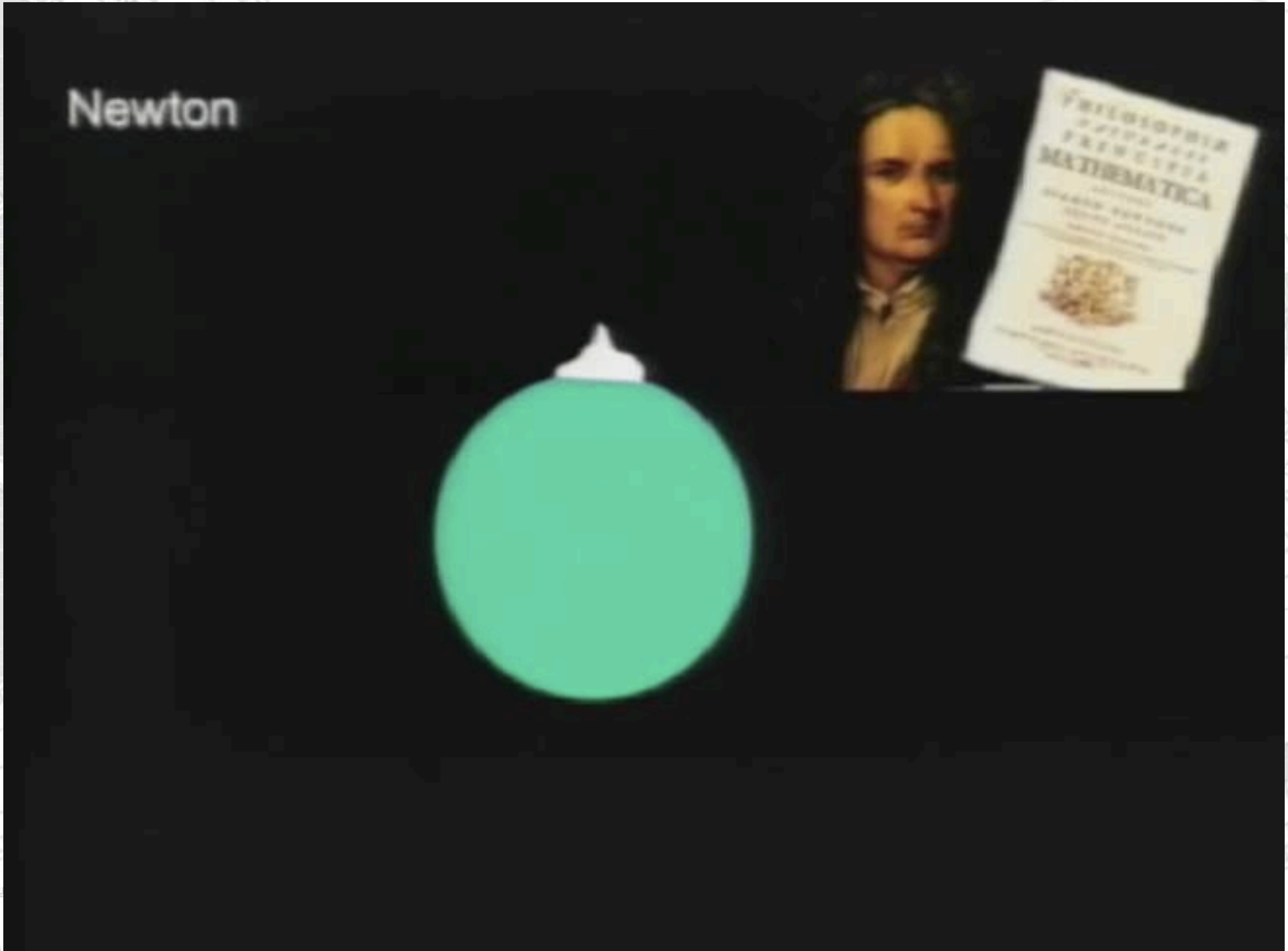
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

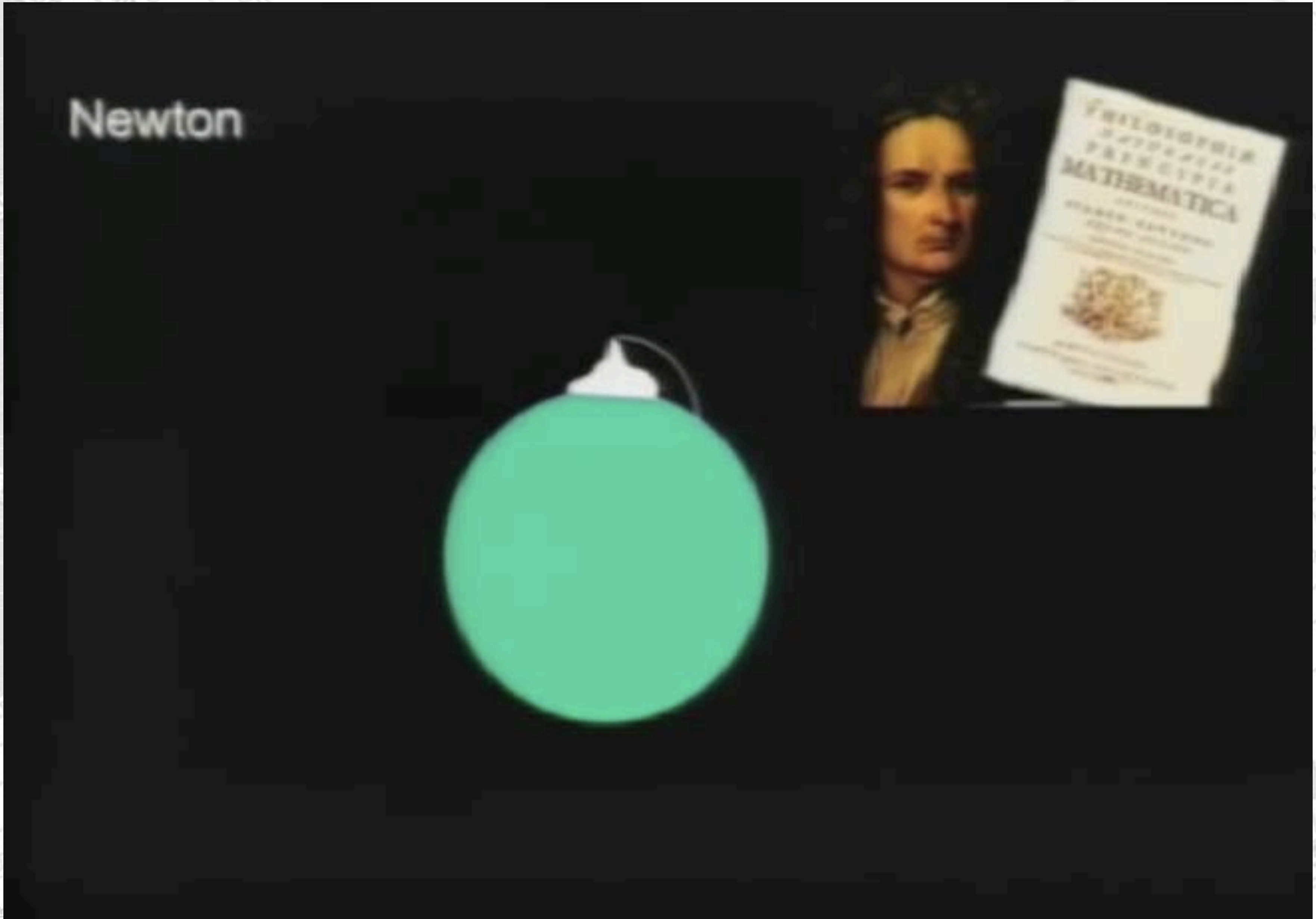
Autore *JS. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.


Newton
MATHEMATICA



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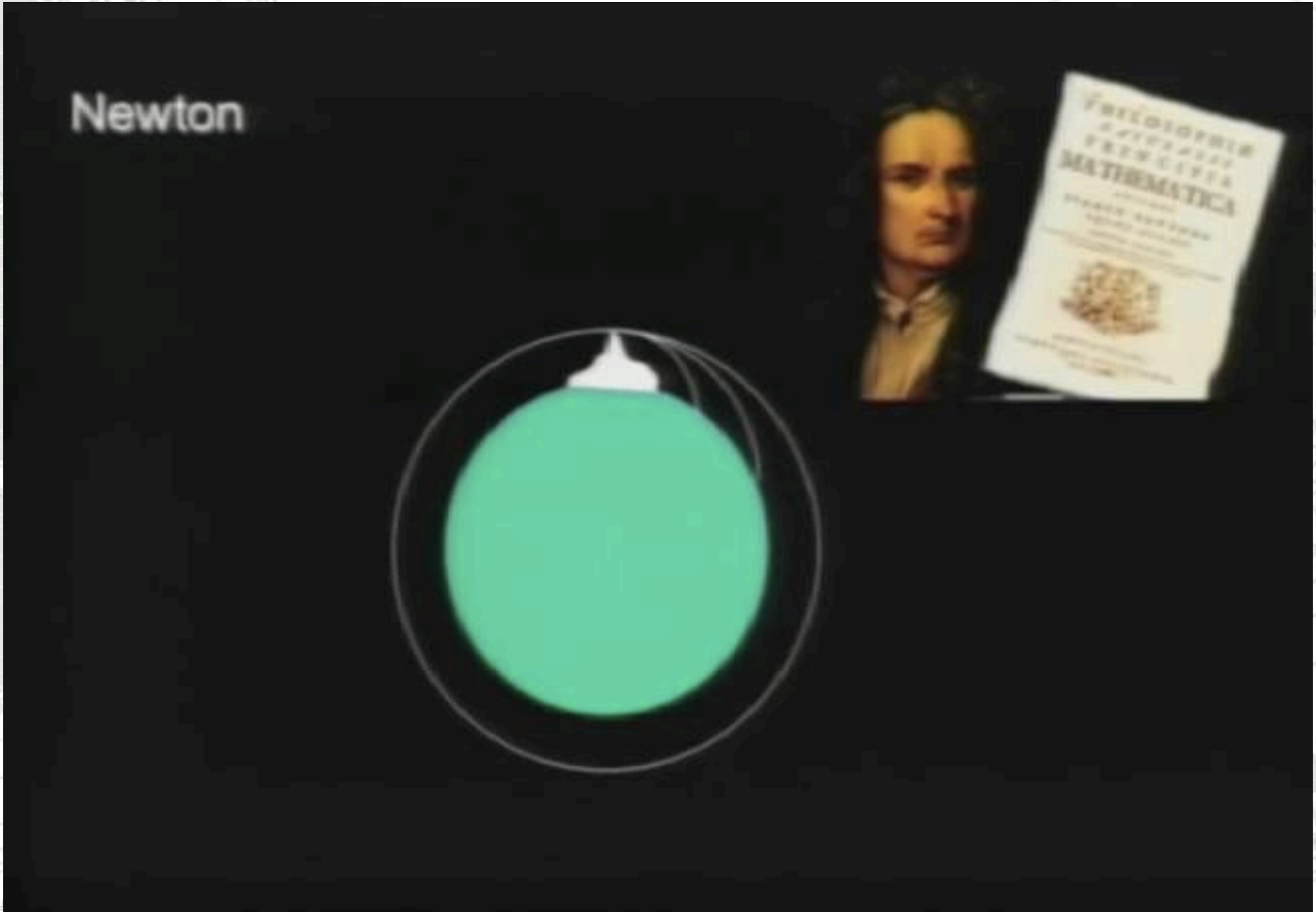
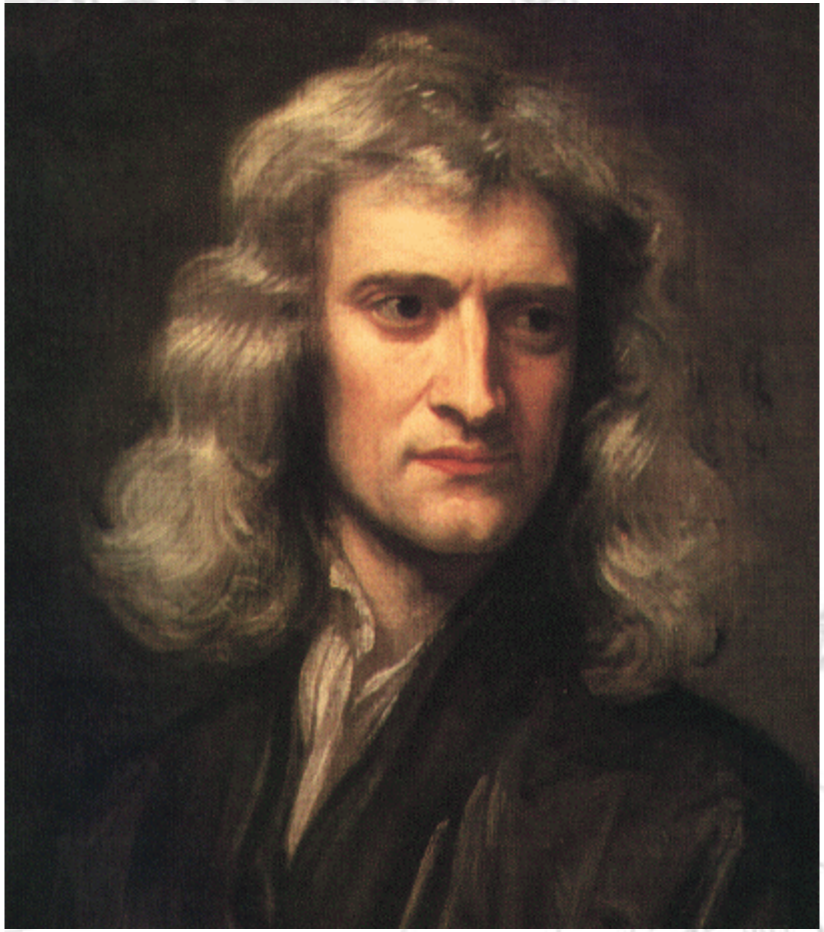
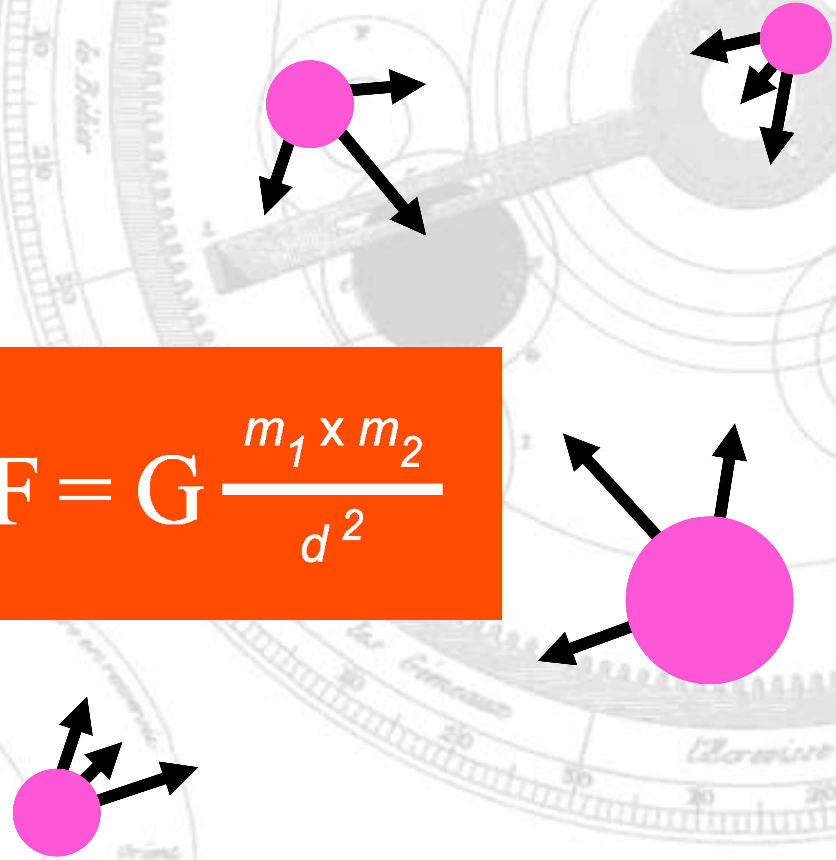

Newton
MATHEMATICA

Newton's Theory of Gravity (1686)

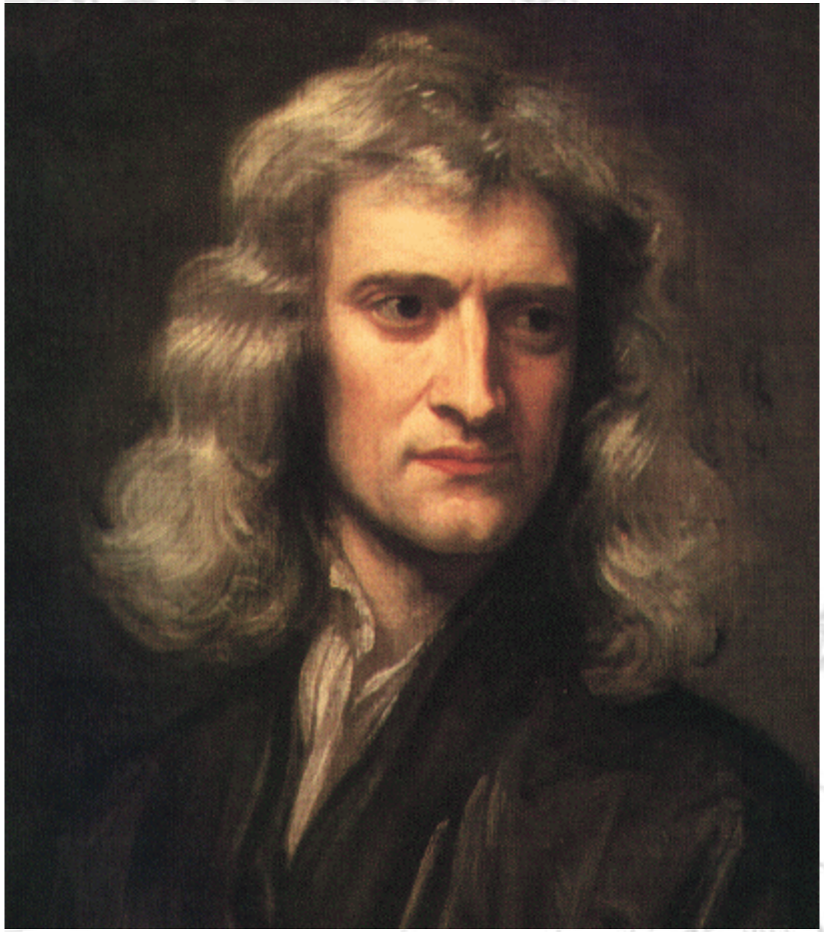


- Equal and opposite forces between pairs of bodies



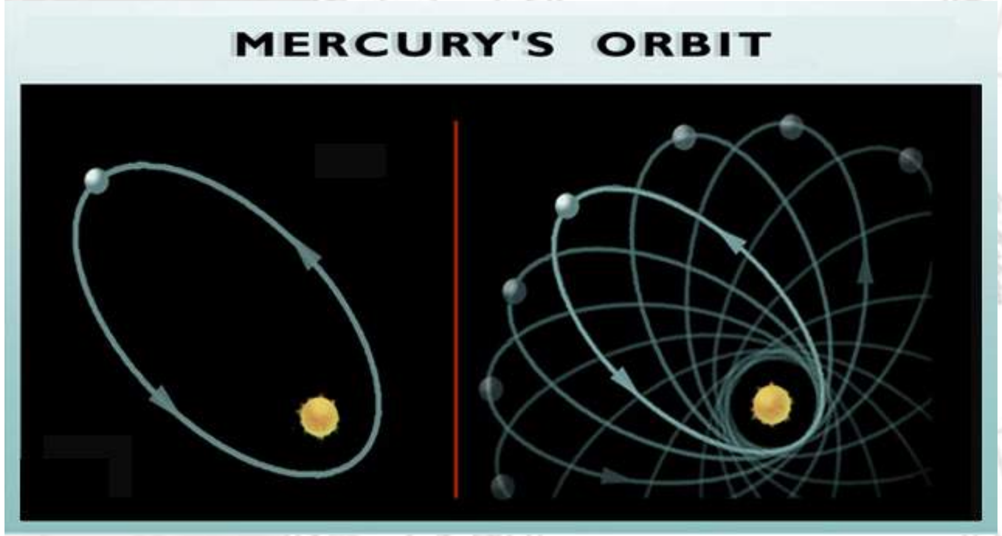
$$F = G\frac{m_1 \times m_2}{d^2}$$

Newton's Theory of Gravity (1686)



- Extremely successful theory
- Explained most unsolved problems of astronomy and terrestrial physics
  - eccentric orbits of comets
  - tides and their variations
  - the perturbation of the motion of the moon by gravity of the sun
- Unified the work of Galileo, Copernicus and Kepler

Something not convincing in Newton's theory…



(1) Astronomers observed a difference in the precession of the perihelion of Mercury of 43"/century with respect to Newton's theory

(2) How can a body know the instantaneous positions of all the other bodies in the Universe?

(3) How can this interaction be transmitted "through" vacuum?

Einstein Relativity

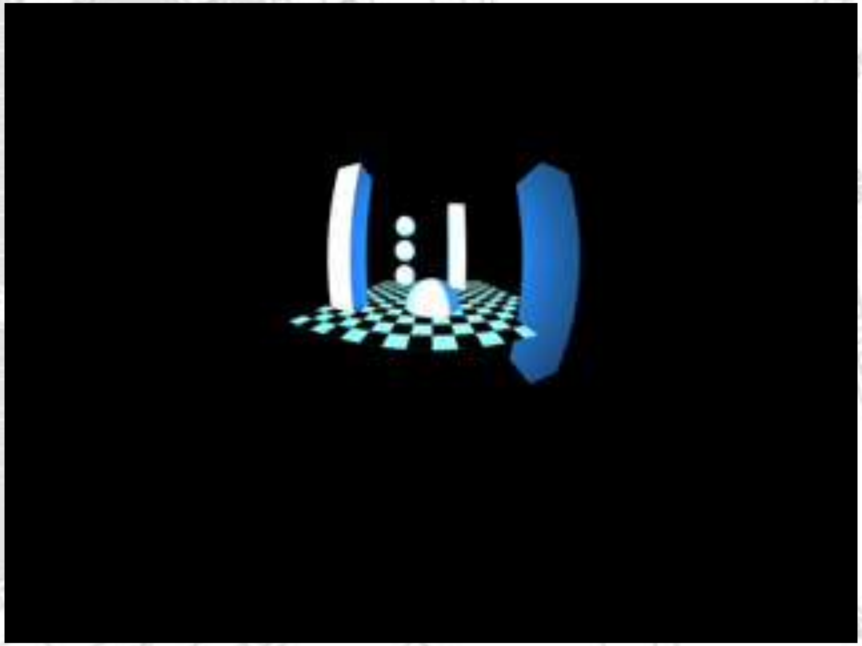
- Definitely overthrew the 19th-century concepts of absolute space and time
- Spacetime = 3 spatial dimensions + time
- Perception of space and time is relative

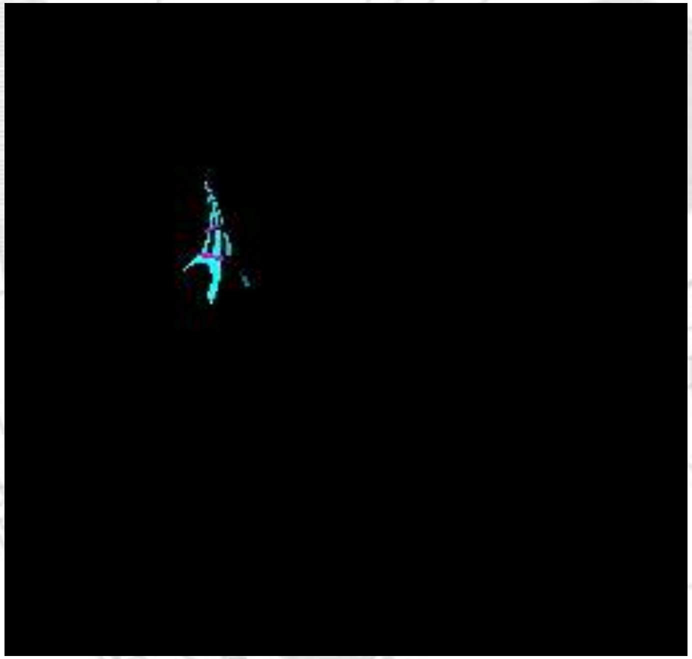
Einstein Relativity

- In 1905 he published a treatise
  On the Electrodynamics of Moving Bodies
  - This introduced the theory of Special Relativity which extended the classical theory of relativity by Galileo
  - * The physical laws are the same in all reference systems moving with mutual constant velocity (inertial systems). This statement is the same as the Galilean relativity
  - * The speed of light is independent from the reference frame: it is constant

Einstein Relativity

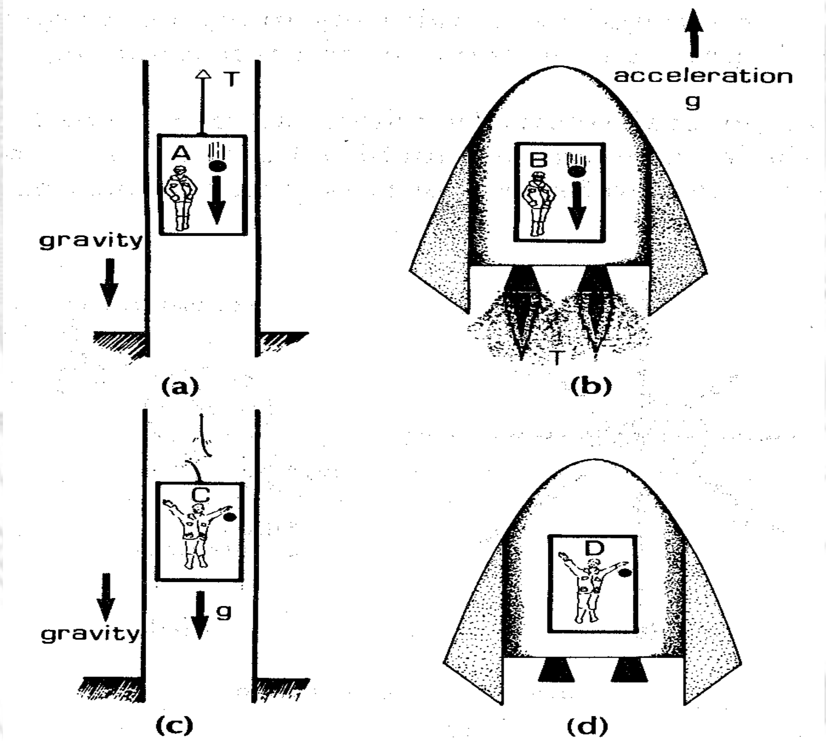
- Consequences of special relativity





Einstein Relativity

- Special Relativity was not the end of the story: accelerated reference frames were not included
- Einstein’s question: how can we include also the acceleration?
- A first hint came from a famous “gedanken” experiment: the Einstein’s elevator

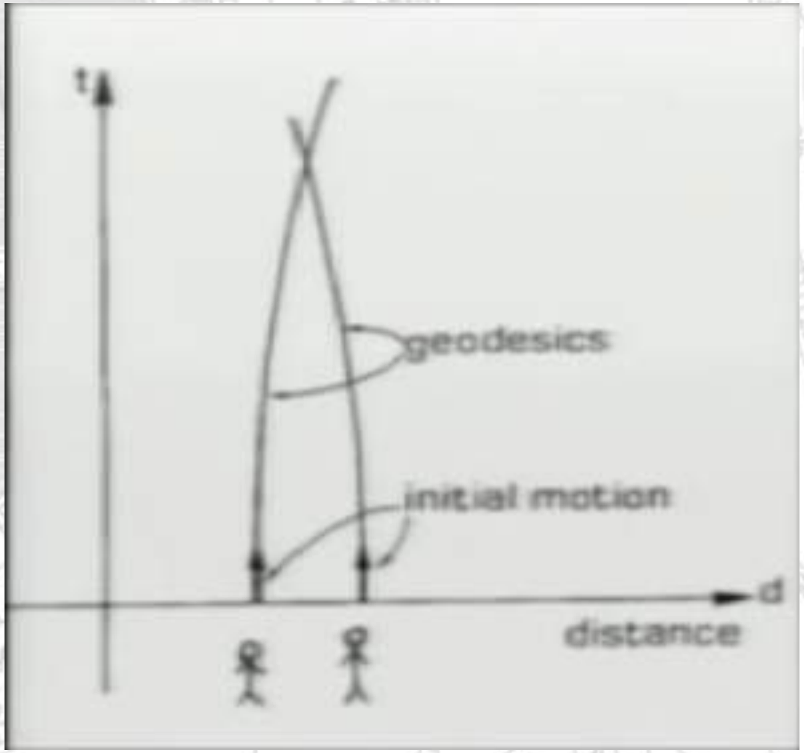


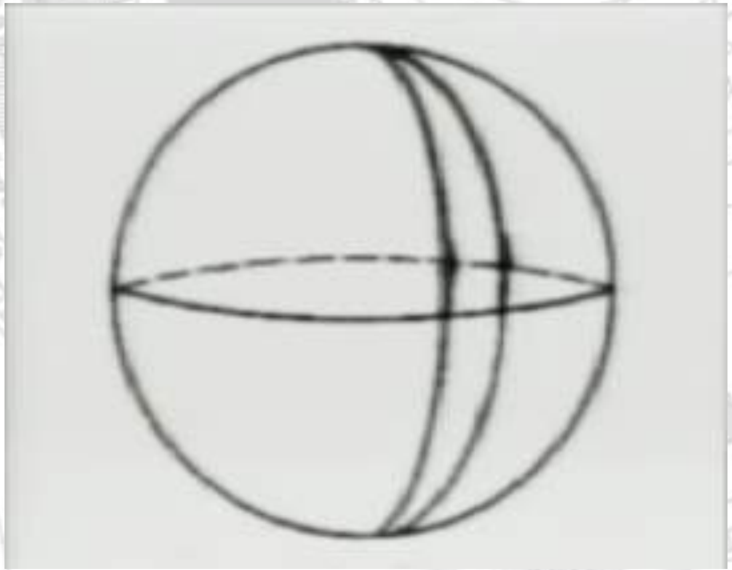
Einstein Relativity

- So, acceleration is equivalent to gravity.
- Einstein spent about 10 years to understand how to organize a theory which could include the gravitational field and be compliant with the special relativity
- This effort ended in 1915 with the publication of the theory of General Relativity

General Relativity
A Radical Idea

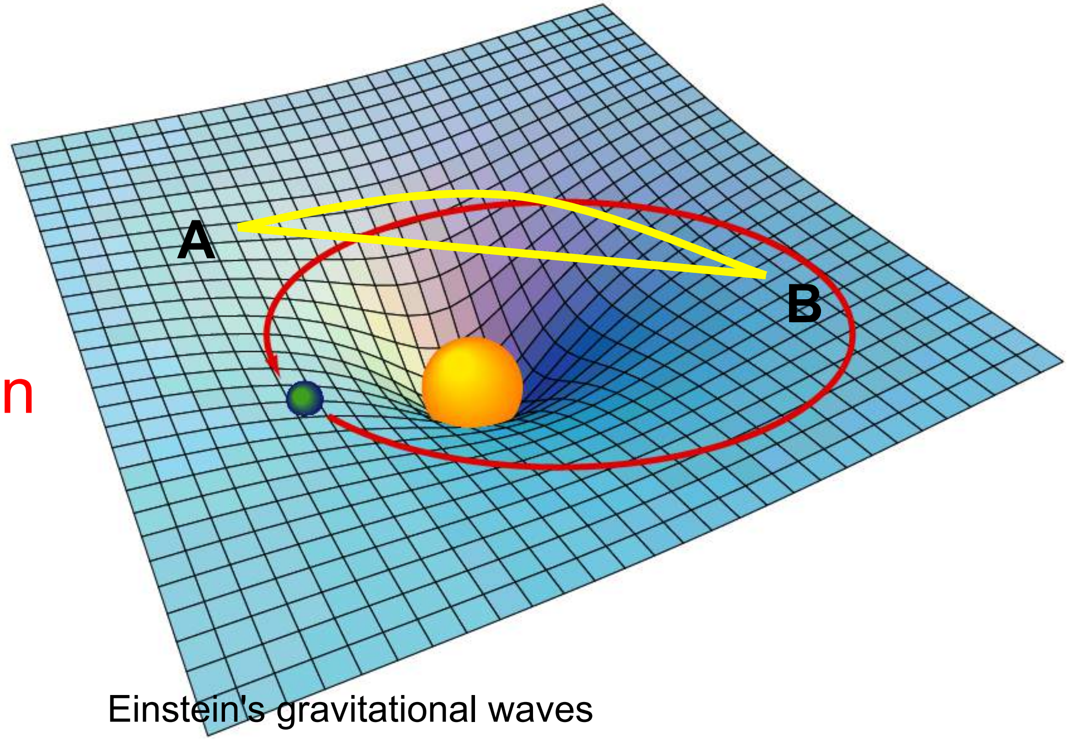
- Gravity is not a force, but a property of space & time





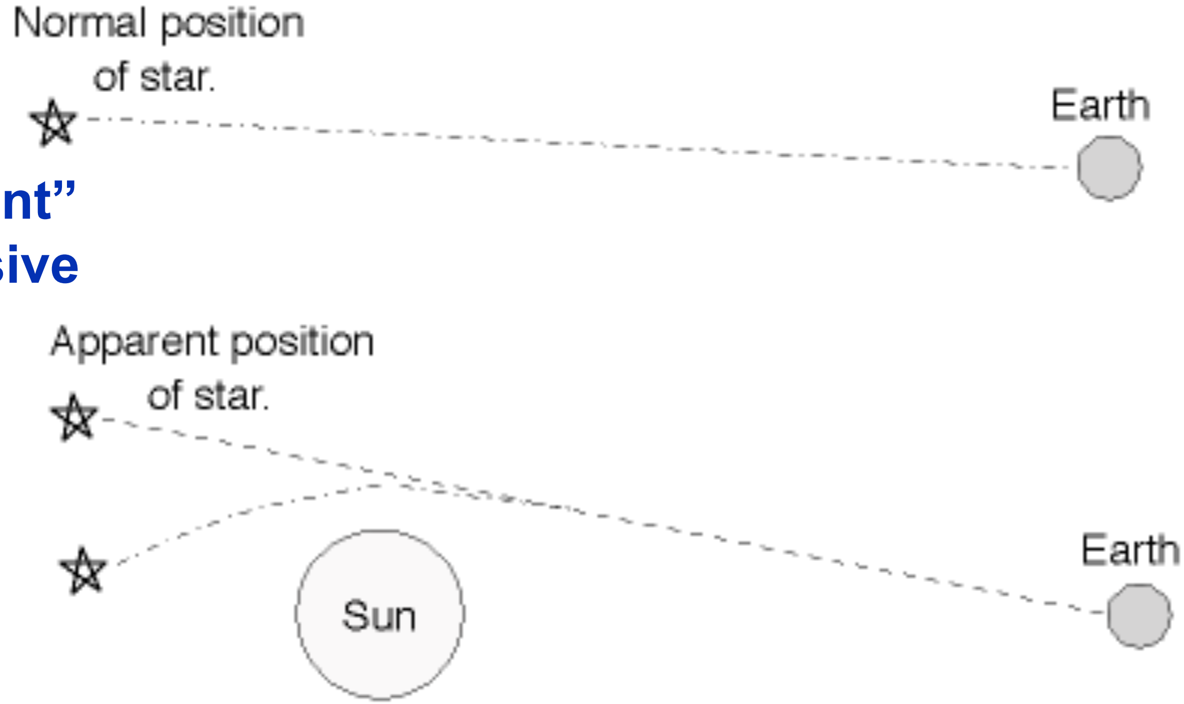
General Relativity
A Radical Idea

- Gravity is not a force, but a property of space & time
- Concentrations of mass or energy distort (warp) spacetime
- Objects follow shortest path through this warped spacetime



Explained the precession of Mercury

A New Prediction of Einstein’s Theory



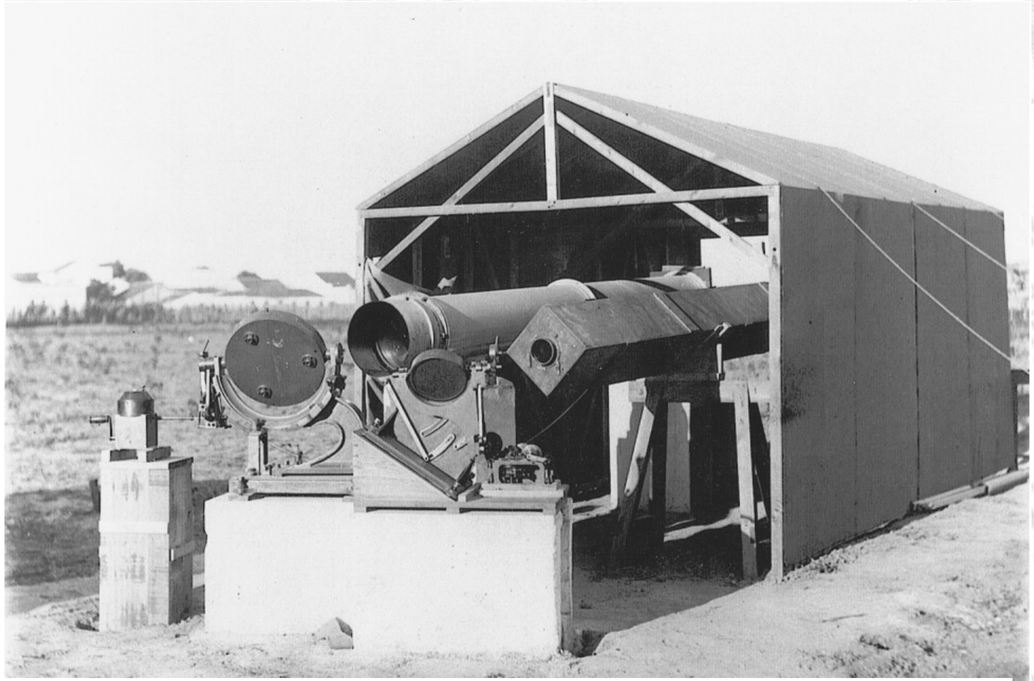
The path of light will be “bent” when it passes near a massive object (like the sun)

Inversely proportional to angle between sun and star

Could only be seen during eclipse

Confirming Einstein ….

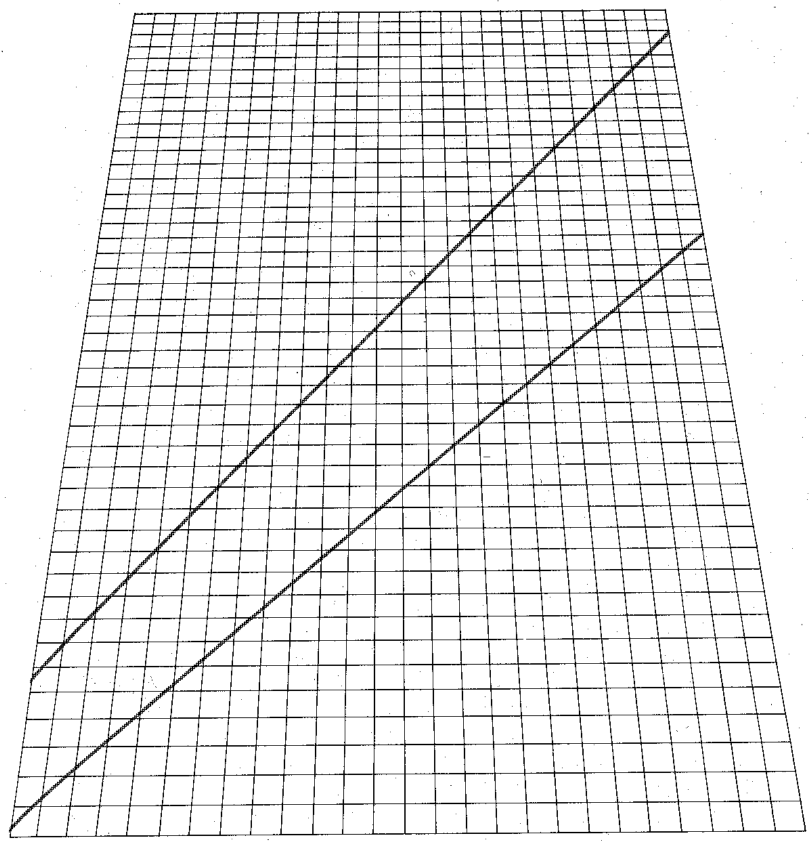
- Famous British astronomer Sir Arthur Eddington led an expedition to photograph the solar eclipse of 29 May 1919 against Hyades star cluster

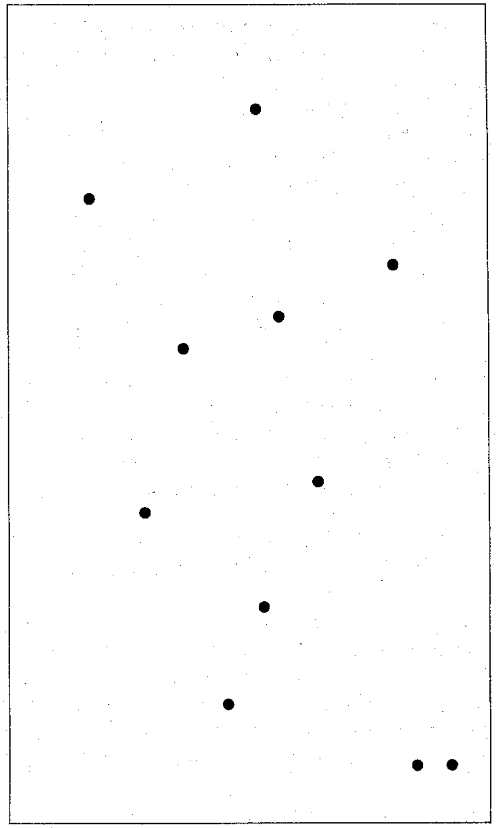


© Science Museum/Science and Society Picture Library

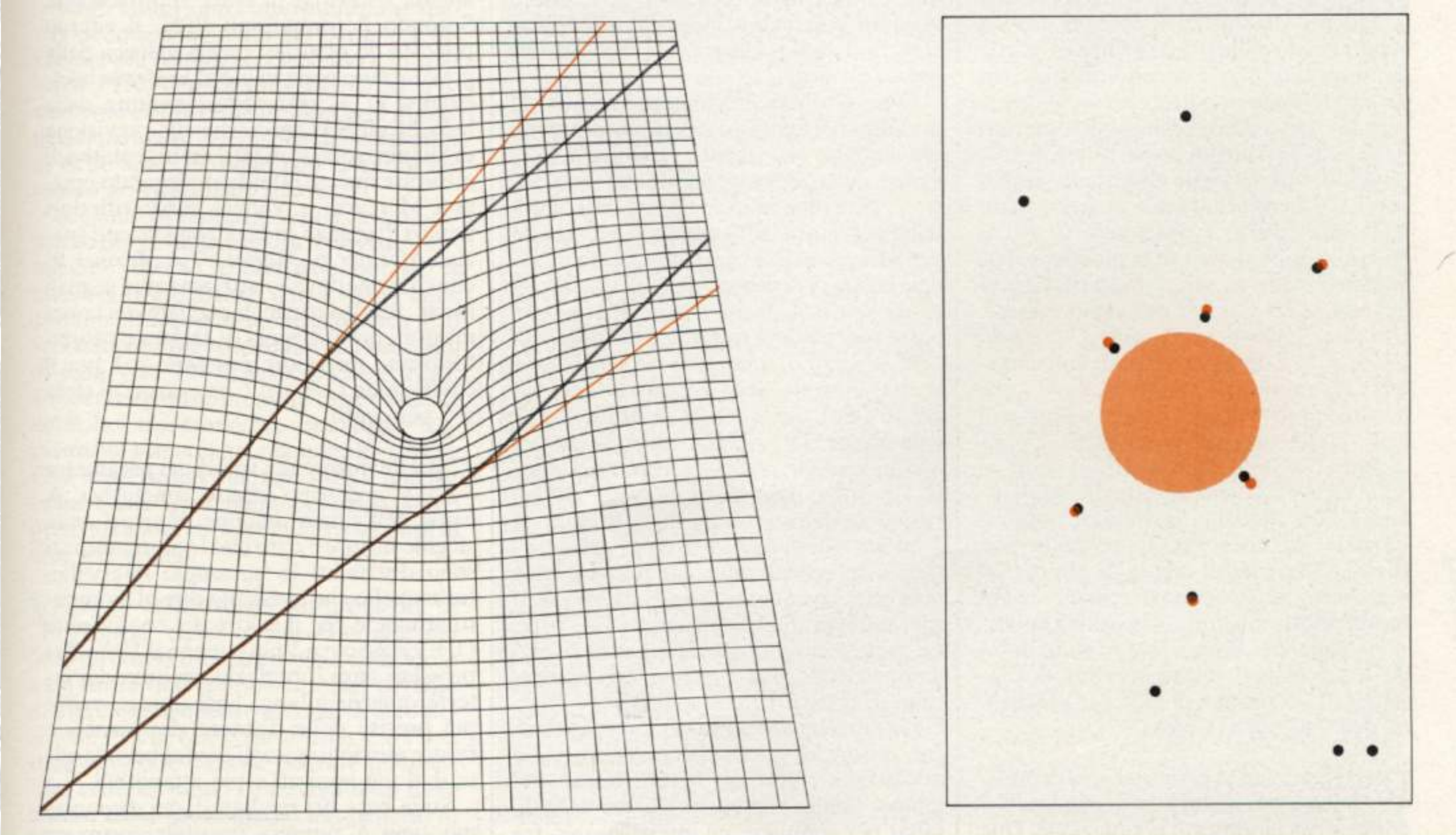
	Measured Deflection
No Deflection	0
Einstein	1.75”
Principe	1.61” ± 0.30”
Sobral	1.98” ± 0.12”

Confirming Einstein ….

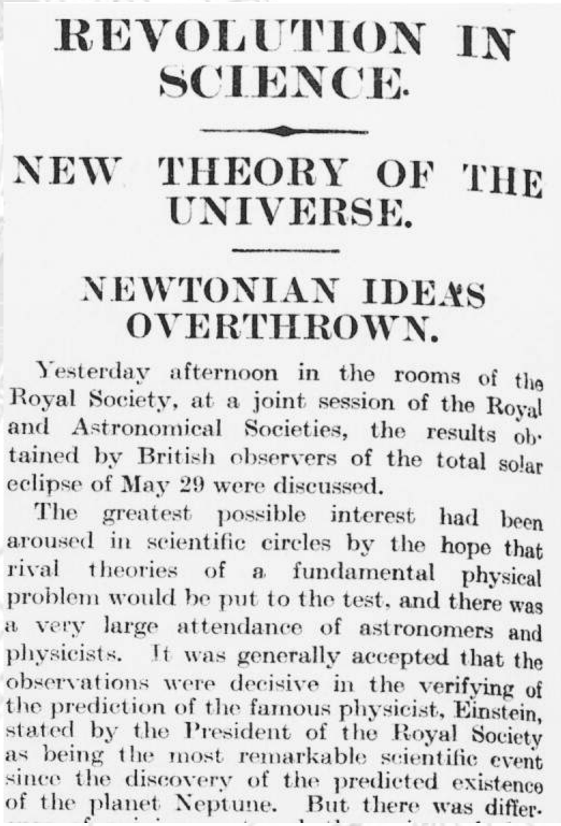




Confirming Einstein ….



Stunning Confirmation for Relativity



REVOLUTION IN SCIENCE.

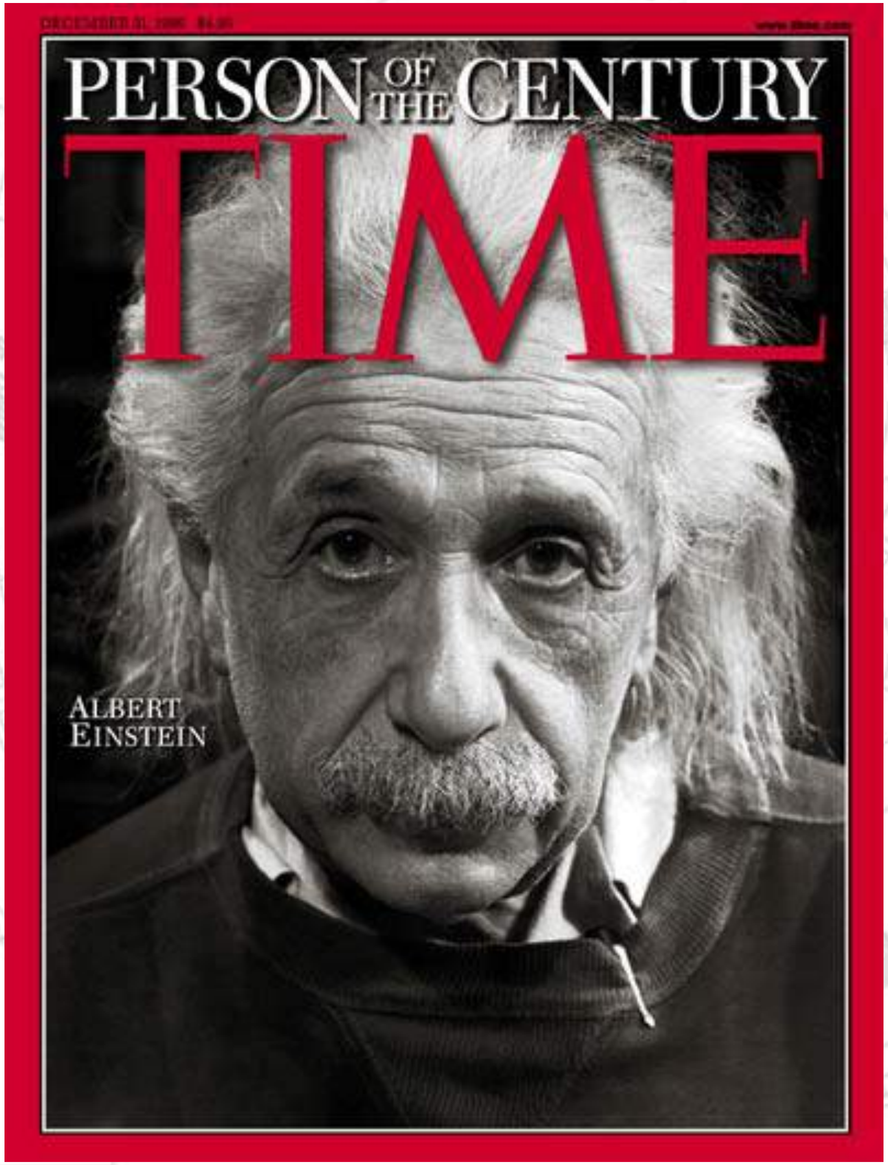
NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

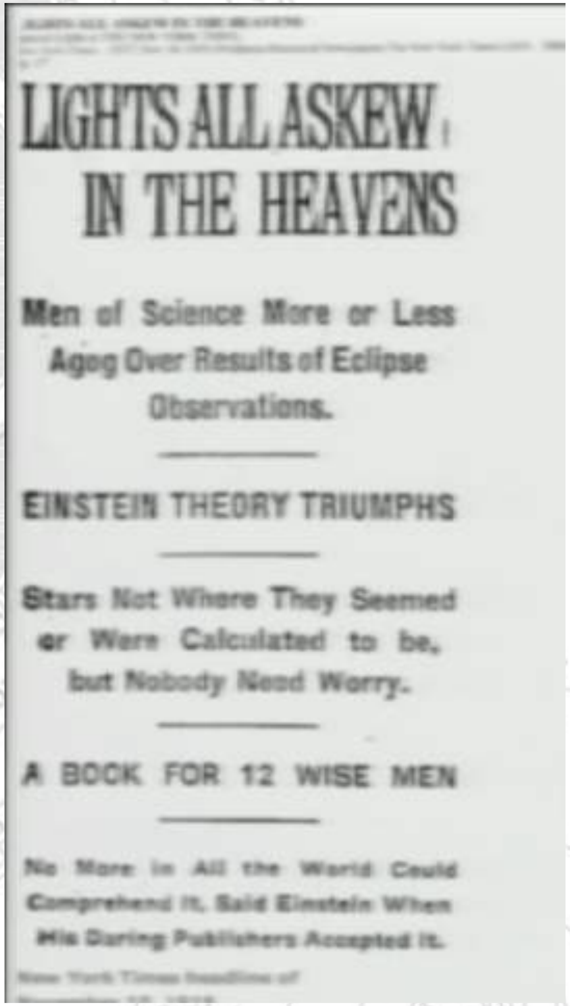
Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was differ-

London Times, 6 November 1919



Stunning Confirmation for Relativity


LIGHTS ALL ASKEW IN THE HEAVENS

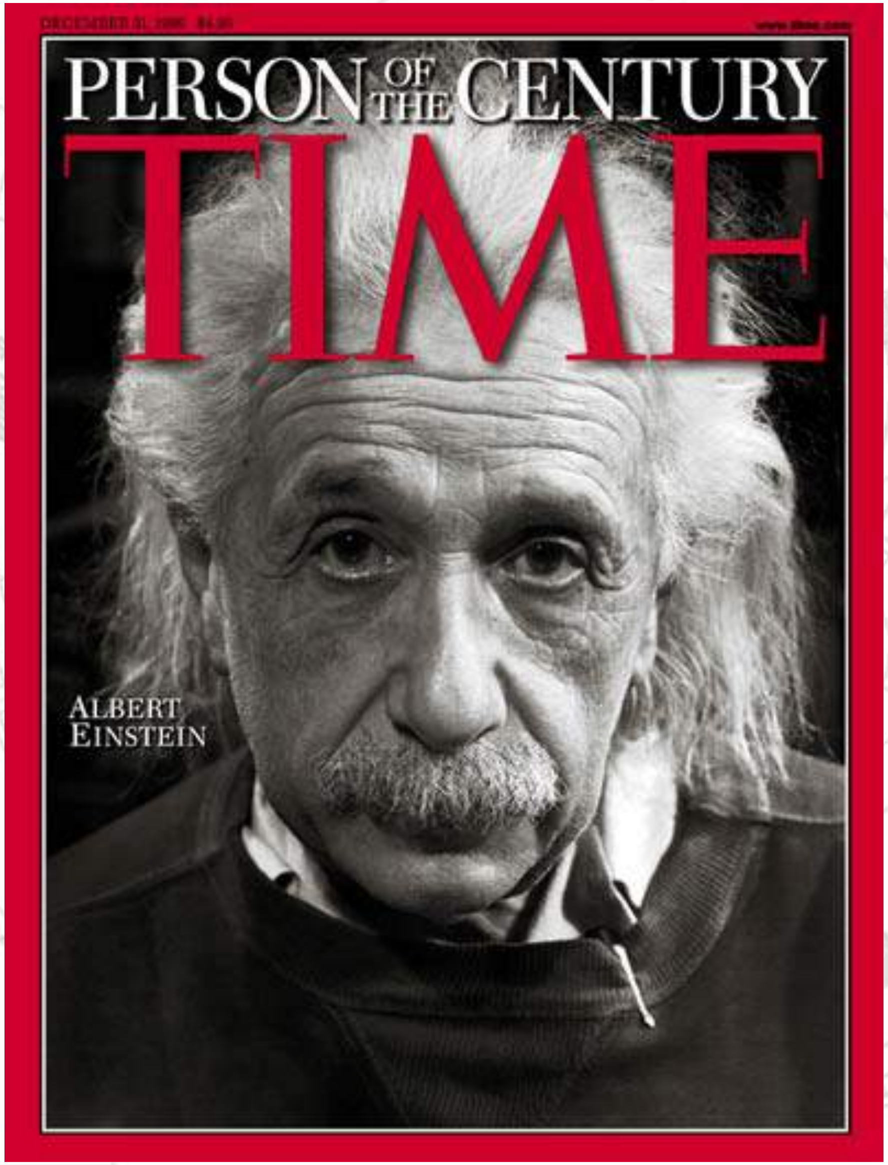
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

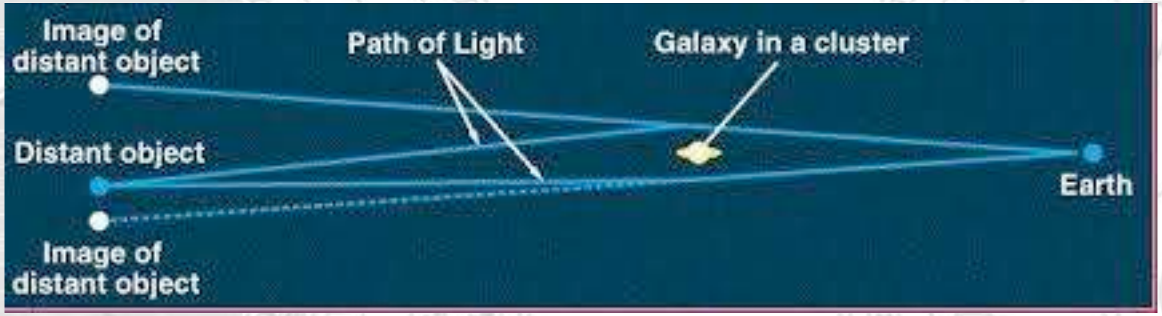
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

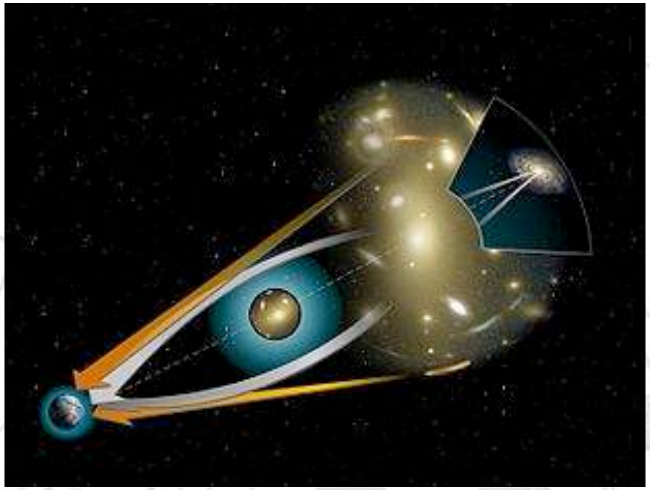
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

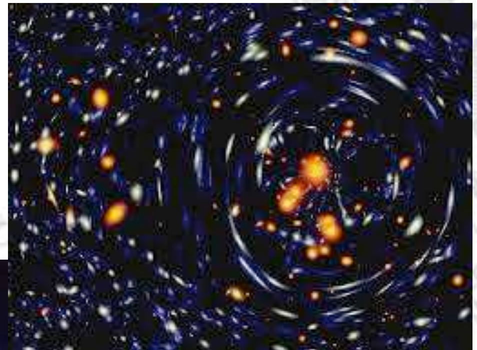


An application of light deflection: gravitational lensing



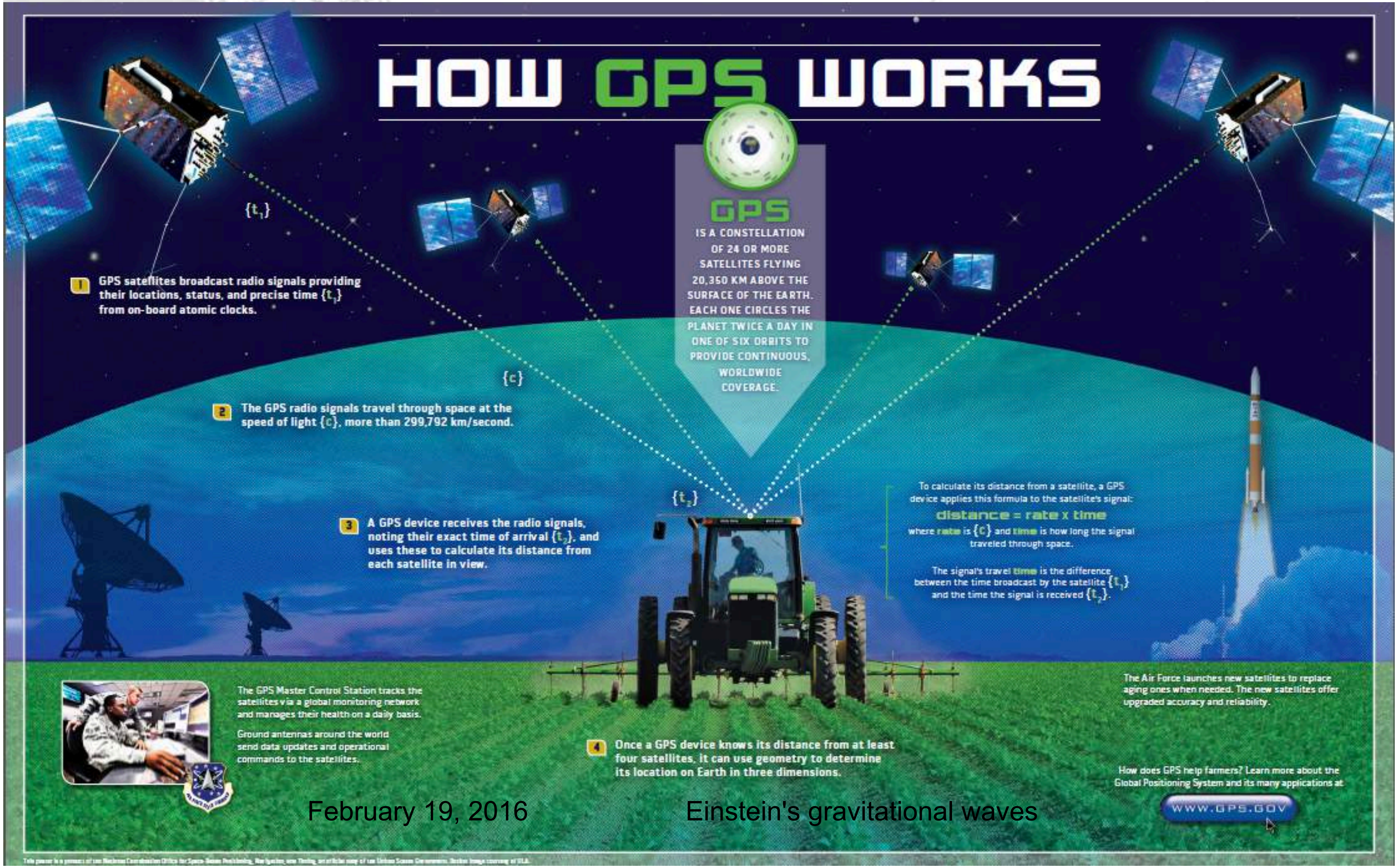


Different patterns depending on the position of the light source with respect to the gravitational lens

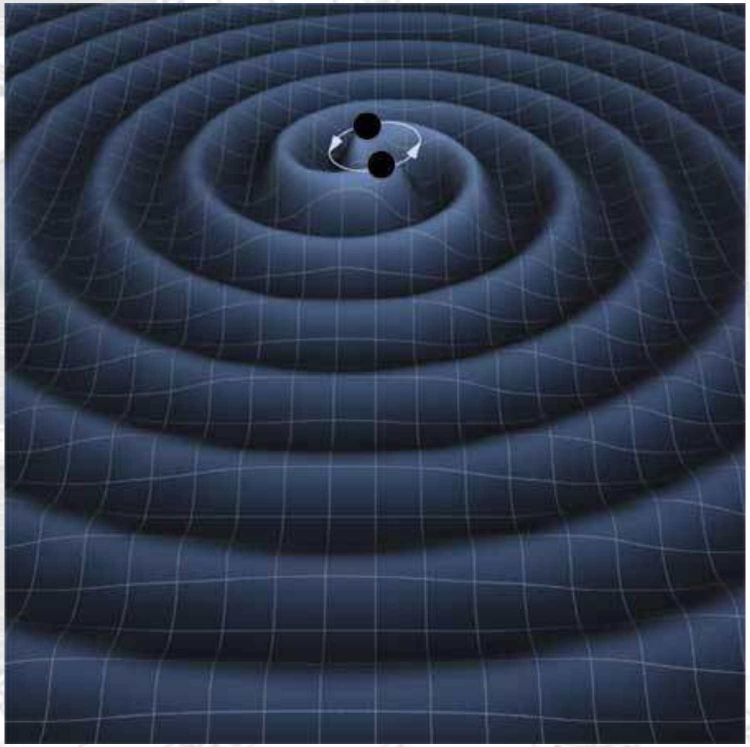


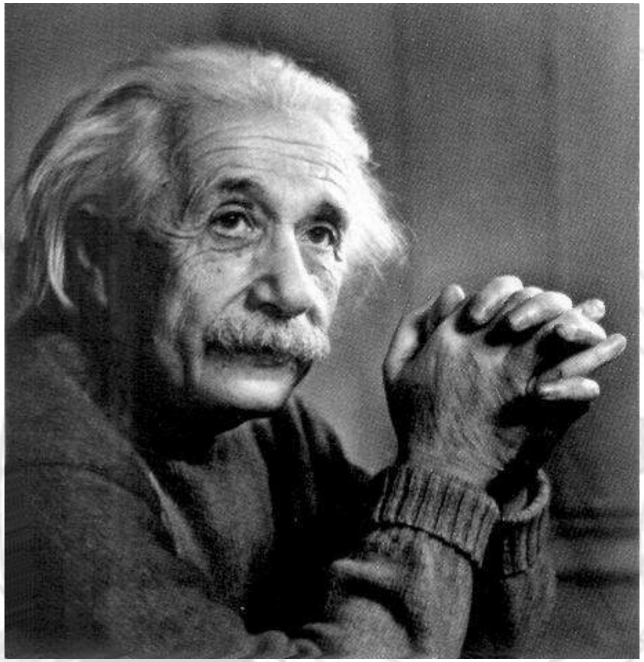
Simulation of the gravitational lensing of a Galaxy passing behind a black hole

An application of GR to everday life: the global positioning system

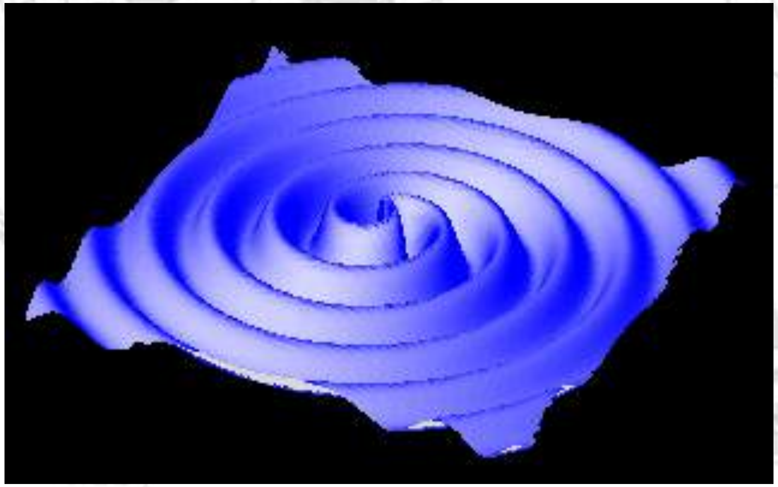


A New Prediction: Gravitational Waves

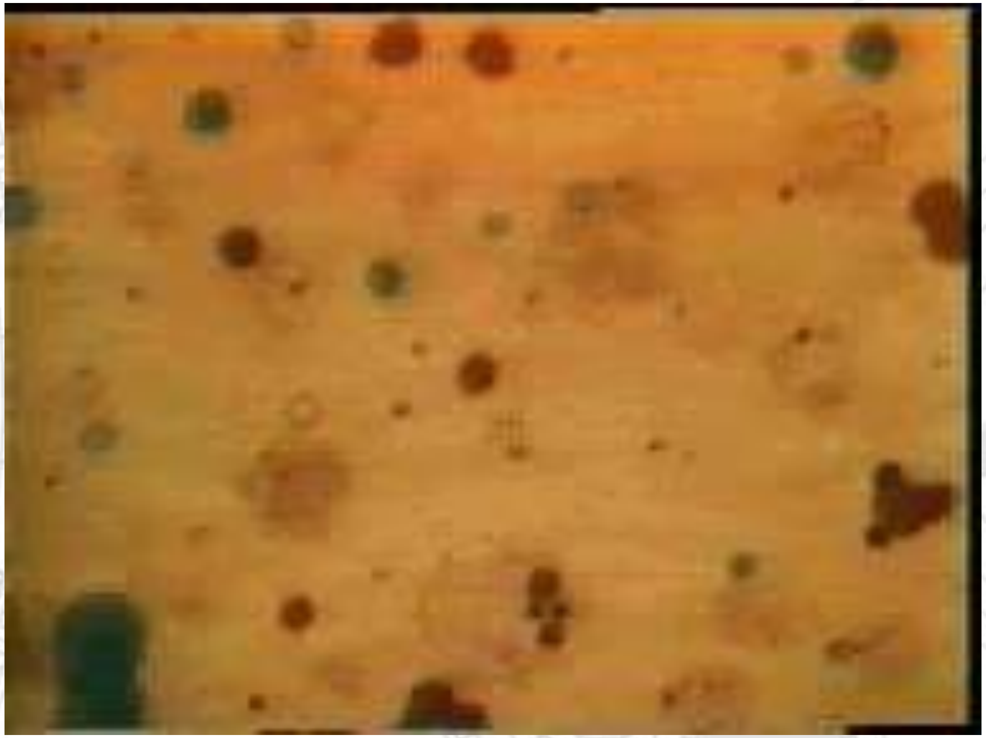




Photograph by Yousuf Karsh of Ottawa, courtesy AIP Emilio Segre Visual Archives



Ripples in spacetime moving at the speed of light



•GW are generated by accelerated masses; they propagate in the space-time at the speed of light

•They cannot be produced in laboratory with a measurable amplitude: it is necessary a big accelerated mass ➔ astronomical sources of GWs

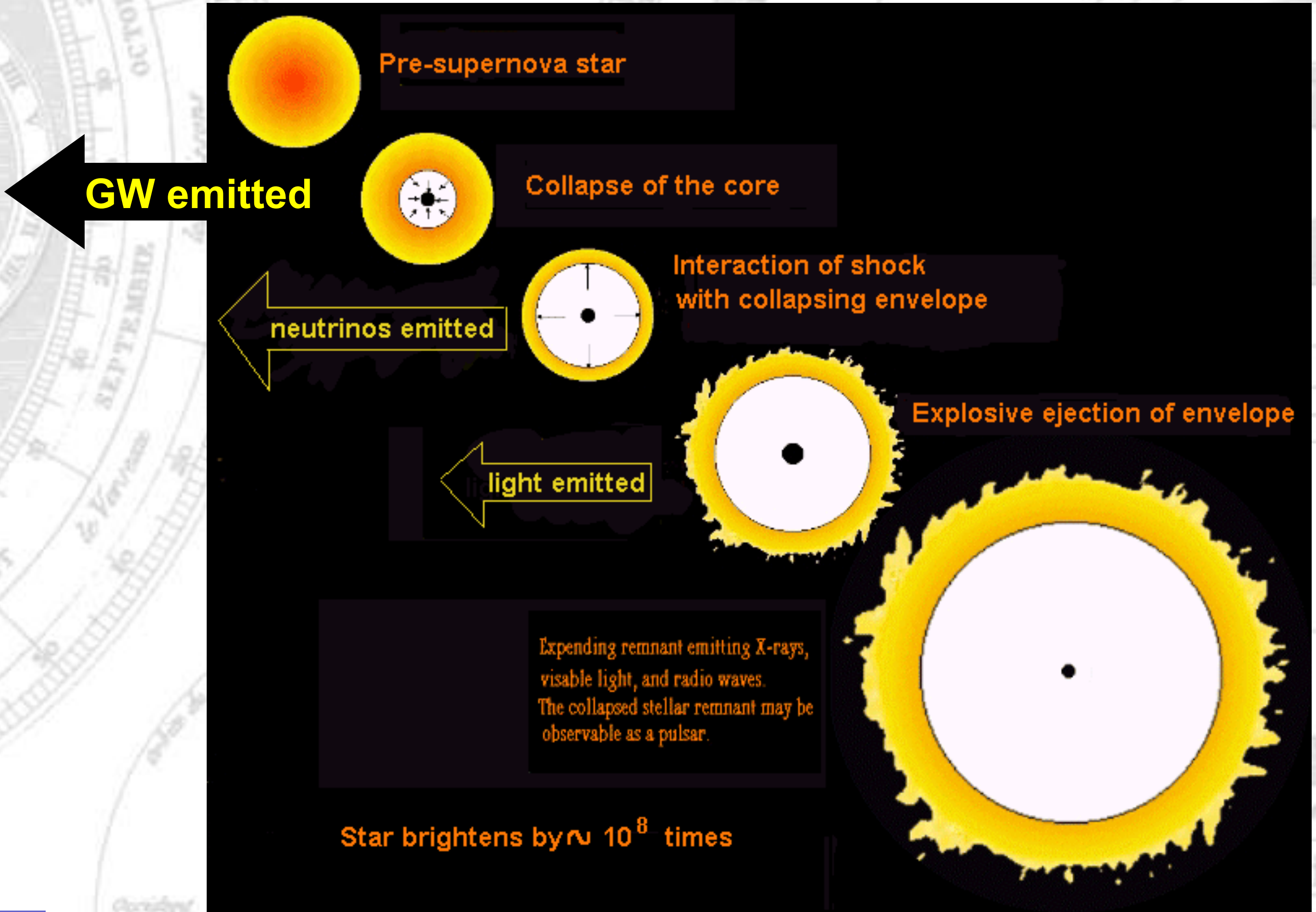
Sources of GWs

- Gravitational collapse

At the end of its life a star collapses → supernova
This event is accompanied by the emission of GWs.

When a massive star explodes, it creates a shell of hot gas that glows brightly in X-rays. These X-rays reveal the dynamics of the explosion.

- Gravitational collapse



Crab Nebula

SUPERNOVAE

Distance: 6000 year-light, diameter 10 year-light, expansion velocity 1800 km/s

SN remnants observed on July 4th 1054 in Cina and in America, visible also during the day for 23 days

In the center there is a Pulsar (not visible in the picture) rotating at a frequency of 30Hz

Below you can see the original engraving by the chinese astronomers and its translation

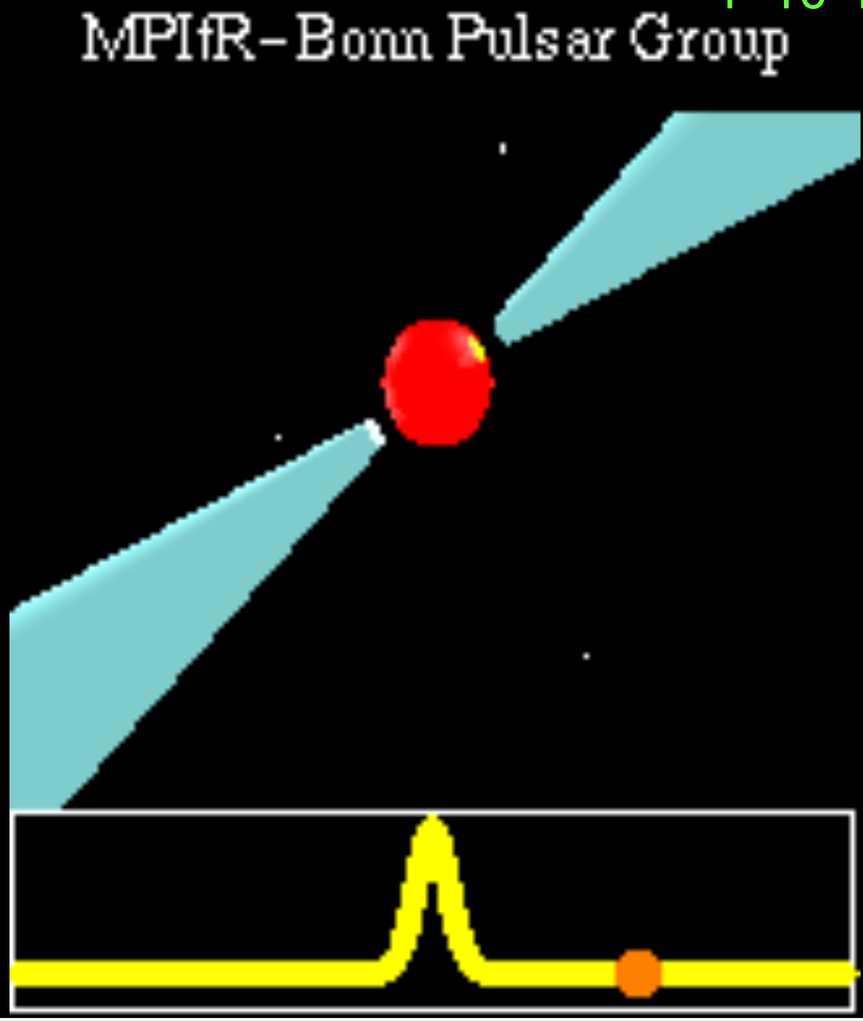
1054年 7月 4日 [宋會要]中記有：「 元年三月，司天监言客星没，客去之兆也。初， 至和元年五月，晨出東方，守天關。晝如太白，芒角四出，色赤白，凡見二十三日。」

In the “ShongHuiYao” book, which means “Collection of the Shong dinasty” it is written: “In month March of year ZhiHe (May 1054), the astronomer noticing that the KeXing star was decreasing its intensity, foresees that the star will disappear. In the morning of May 13th of the same year (July 4th, 1054) a new star is born at east like a celestial guardian. The star is so bright during daylight as the polar star is during the night, with a particularly bright and white corona, for 23 days”

- Neutron stars (Pulsars)

- Very compact objects (R~10 km) made by neutrons. Very high density (10^{12} - 10^{14} g/cm^3). The estimated number rotating of NS in our Galaxy is about 10^9; about 1000 are observed as pulsars (5 within 200 pc).

f=10-100 Hz



Very strong magnetic fields (10^9 Tesla)

+

Rapid rotation

=

⇒ emission of electromagnetic waves (light, radio waves) and gravitazional waves

- Black Holes
  - Final stage of a very massive star (more than 1.4 solar Masses)

This animation illustrates the activity surrounding a black hole. While the matter that has passed the black hole's "event horizon" can't be seen, material swirling outside this threshold is accelerated to millions of degrees and radiates in X-rays. At the end of the animation, the black hole is shown shrouded in a cloud of gas and dust, obscuring it from most angles at wavelengths other than the X-rays picked up by the Chandra X-ray Observatory.

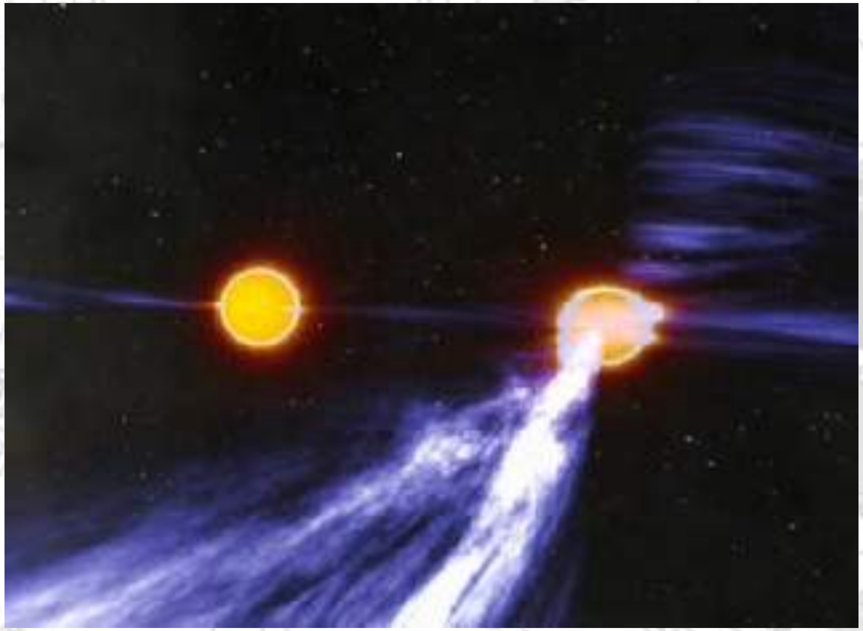
- Binary systems (NS-NS / WD-WD)

There should exist about 10^{8-9} binaries in our Galaxy with a frequency > 0.1mHz (mostly WD/WD).

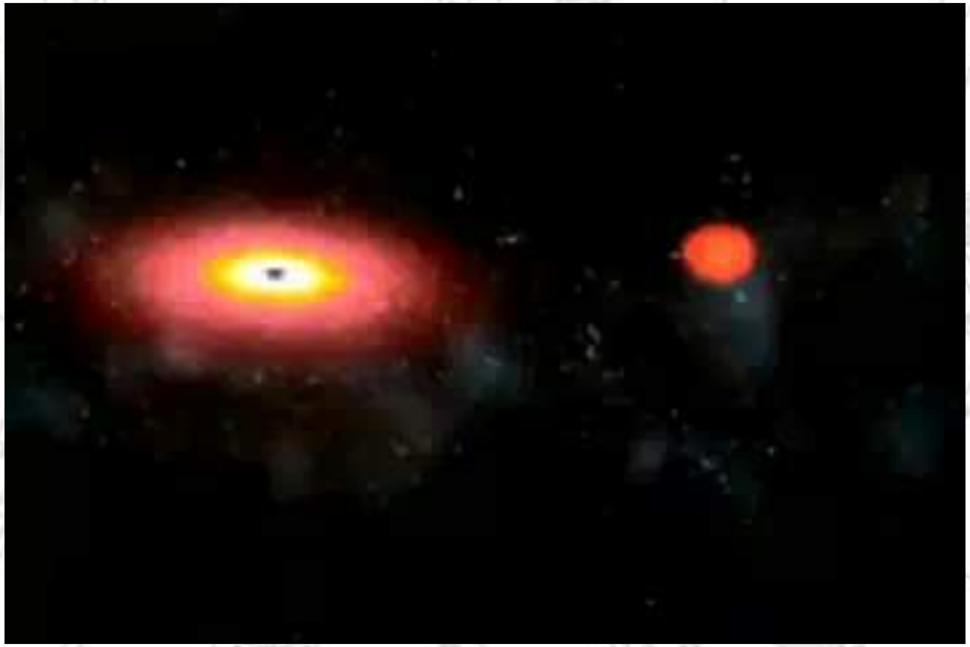
This artist concept depicts two white dwarfs called RX J0806.3+1527 or J0806, swirling closer together, traveling in excess of a million miles per hour. As their orbit gets smaller and smaller, leading up to a merger, the system should release more and more energy in gravitational waves. This particular pair might have the smallest orbit of any known binary system. They complete an orbit in 321.5 seconds - barely more than five minutes.

- Binary systems (NS-NS / WD-WD)

There should exist about 10^{8-9} binaries in our Galaxy with a frequency > 0.1mHz (mostly WD/WD).

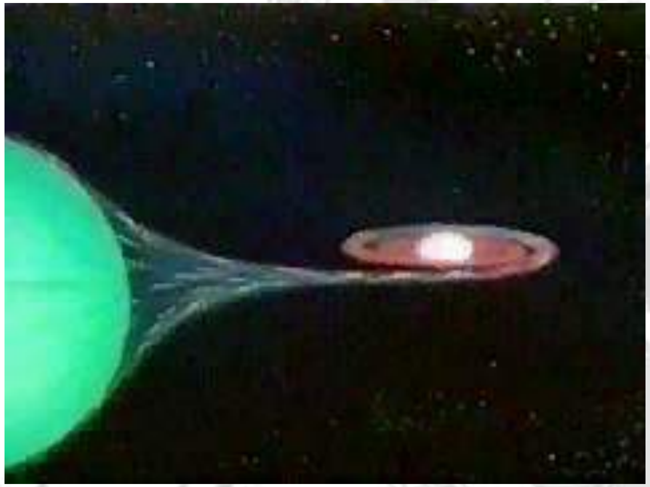


- Binary systems (NS-BH)

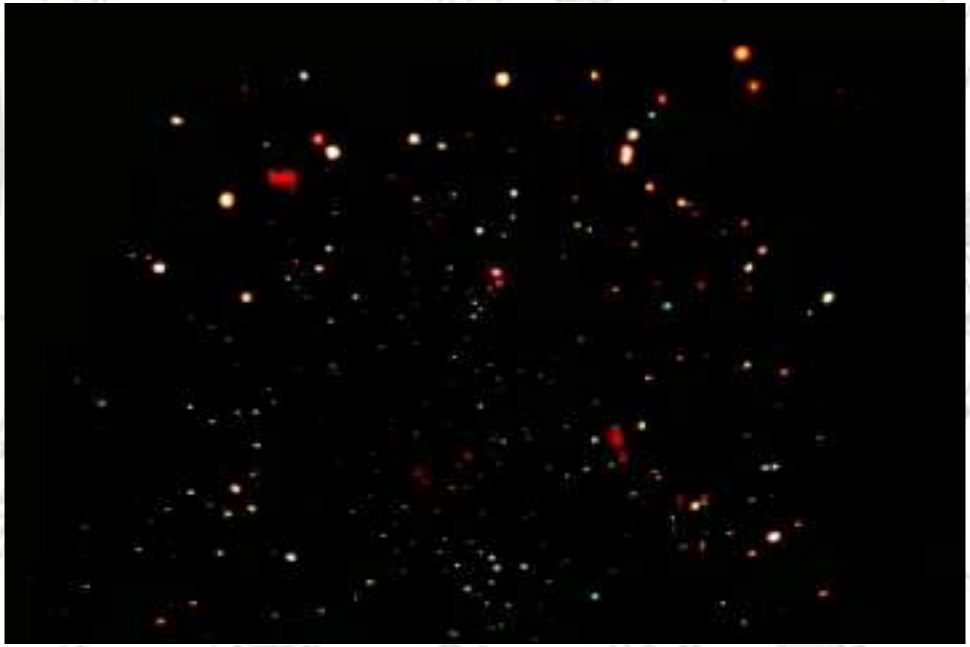


Scientists have seen tantalizing, first-time evidence of a black hole eating a neutron star: first stretching the neutron star into a crescent, swallowing it, and then gulping up crumbs of the broken star in the minutes and hours that followed.

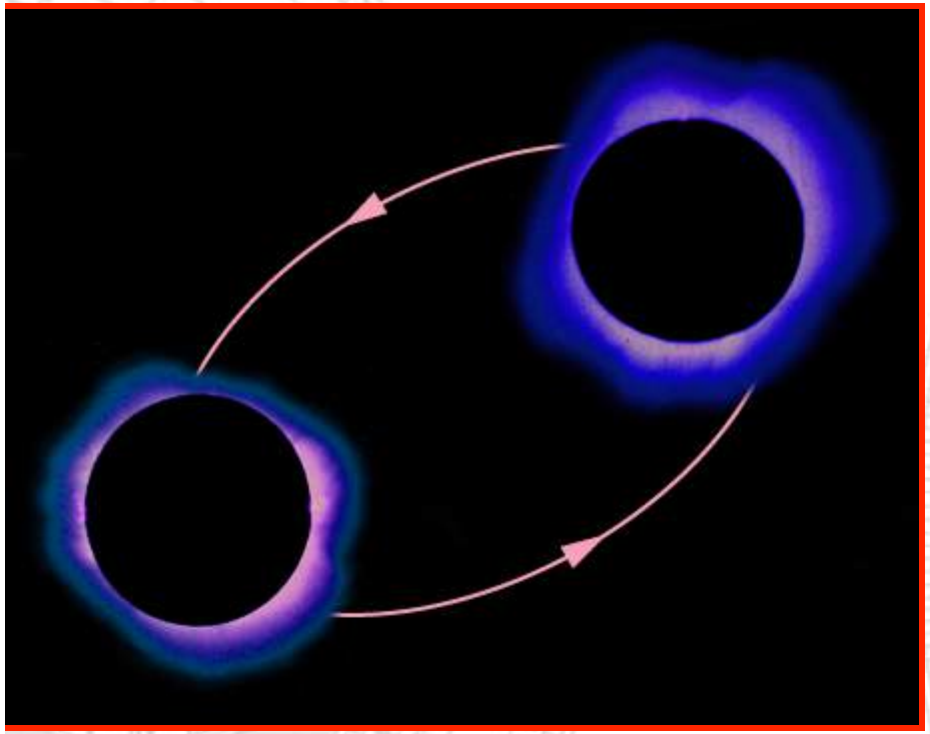
- Binary systems (NS-WD)



- Binary systems (BH-BH)

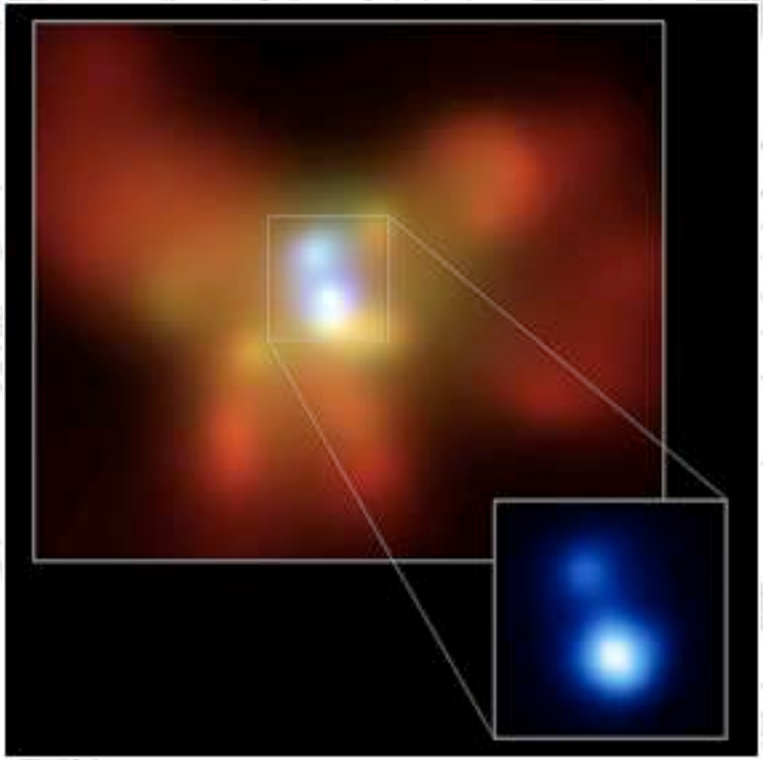


This sequence begins with the Chandra Deep Field-North, the deepest X-ray image ever taken. Black holes that are also found in submillimeter observations, indicating active star formation in their host galaxies, are then marked. The view then zooms onto one pair of particularly close black holes (known as SMG 123616.1+621513). Astronomers believe these black holes and their galaxies are orbiting each other and will eventually merge. The sequence ends by showing an animation of this scenario.

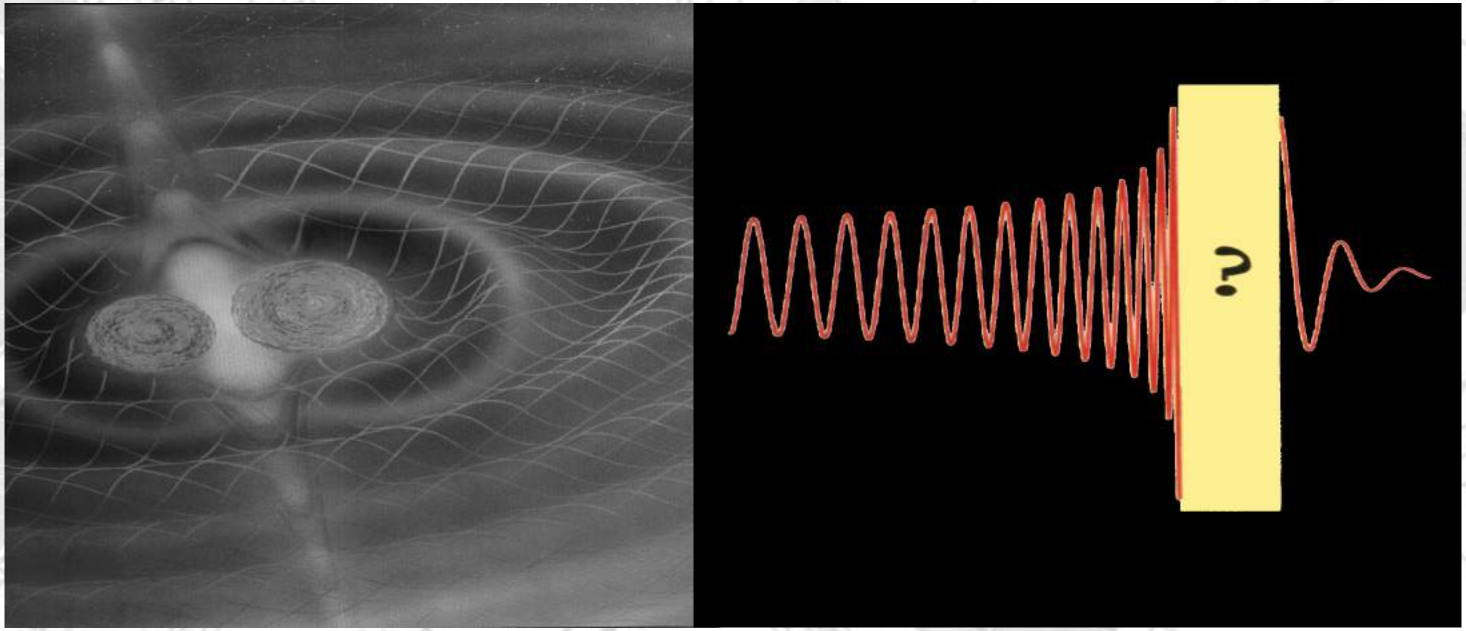


These systems can also be formed by galactic nuclei (10^4-10^6 solar masses)

NGC 6240, galassia massiva formata dal merger di due galassie piu' piccole. D~122 Mpc. I due BH distano circa 900 pc. Osservati da Chandra X-Ray



- Binary systems



The signal emitted has a very characteristic shape called chirp
The observation of a binary system confirmed the existence of GWs (Hulse e Taylor)

No Evidence For Gravitational Waves Until 1974

Russell A. Hulse

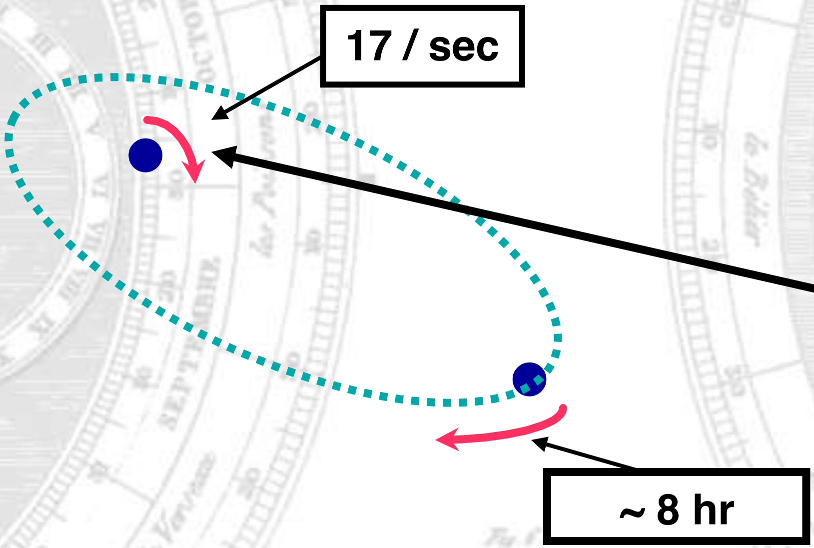
Discovered and Studied
Pulsar System
PSR 1913 + 16

Joseph H. Taylor Jr

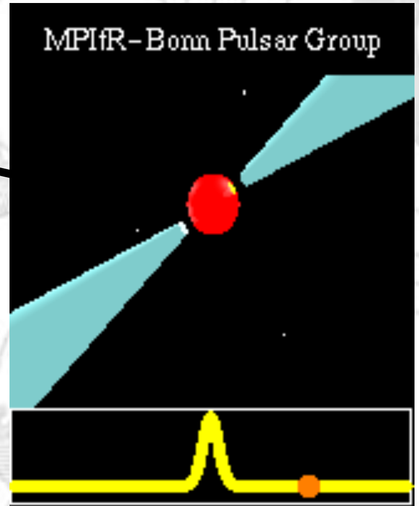
Source: www.NSF.gov

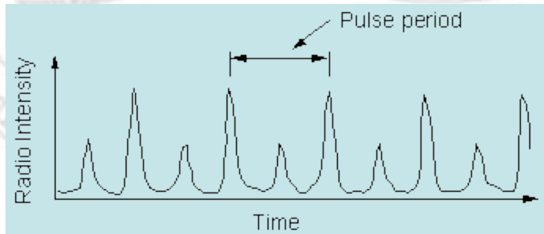
Neutron Binary System

PSR 1913 + 16



Similar mass to our sun but only 20 km in diameter





Two Neutron Stars in Orbit

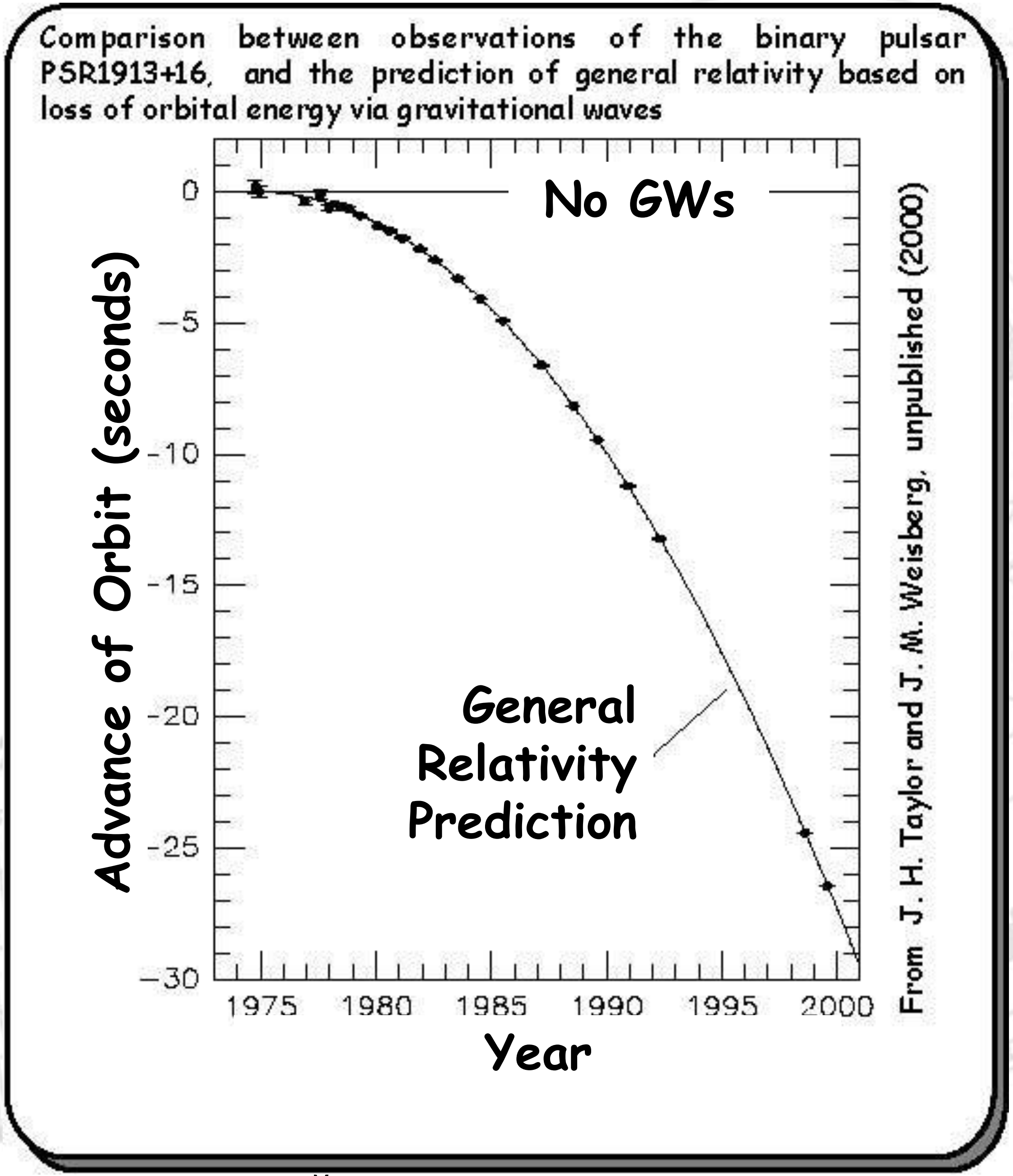
- **Separated by 1,000,000 km**

Prediction from General Relativity

- **Spiral in by 3 mm/orbit**
- **Rate of change orbital period**

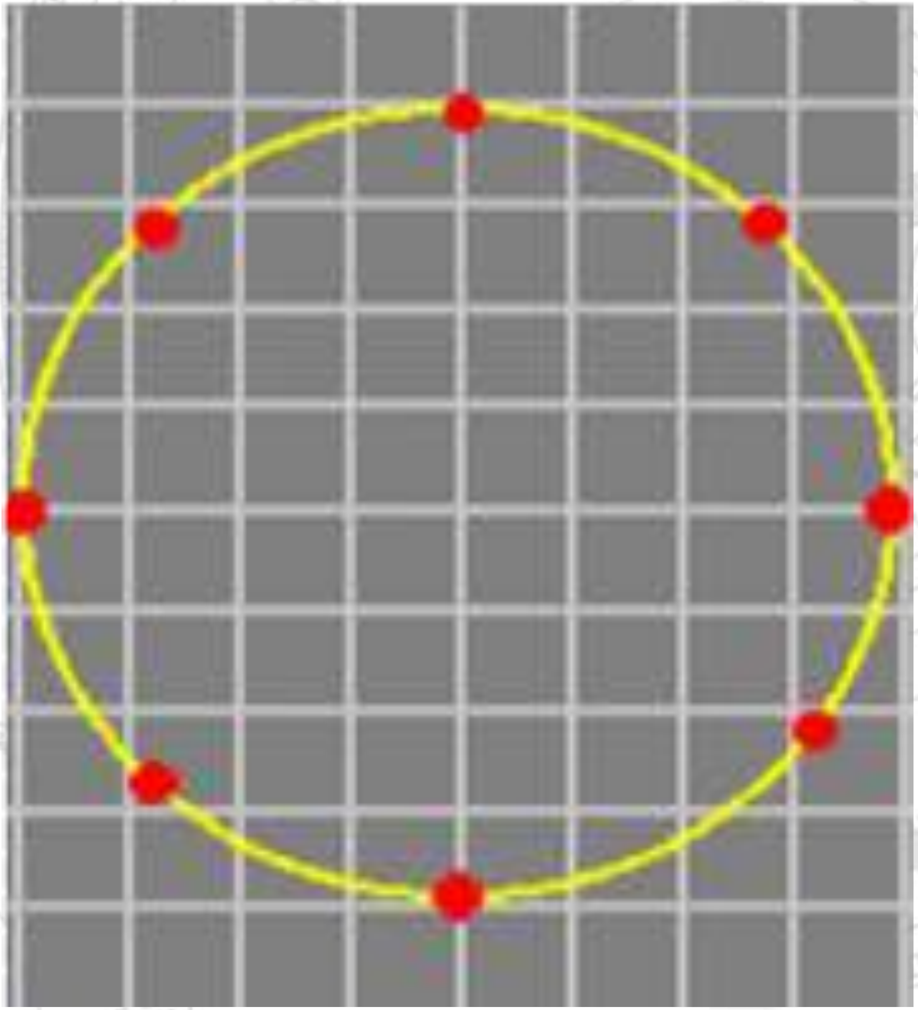
Evidence for gravitational waves!

Nobel Prize in 1993



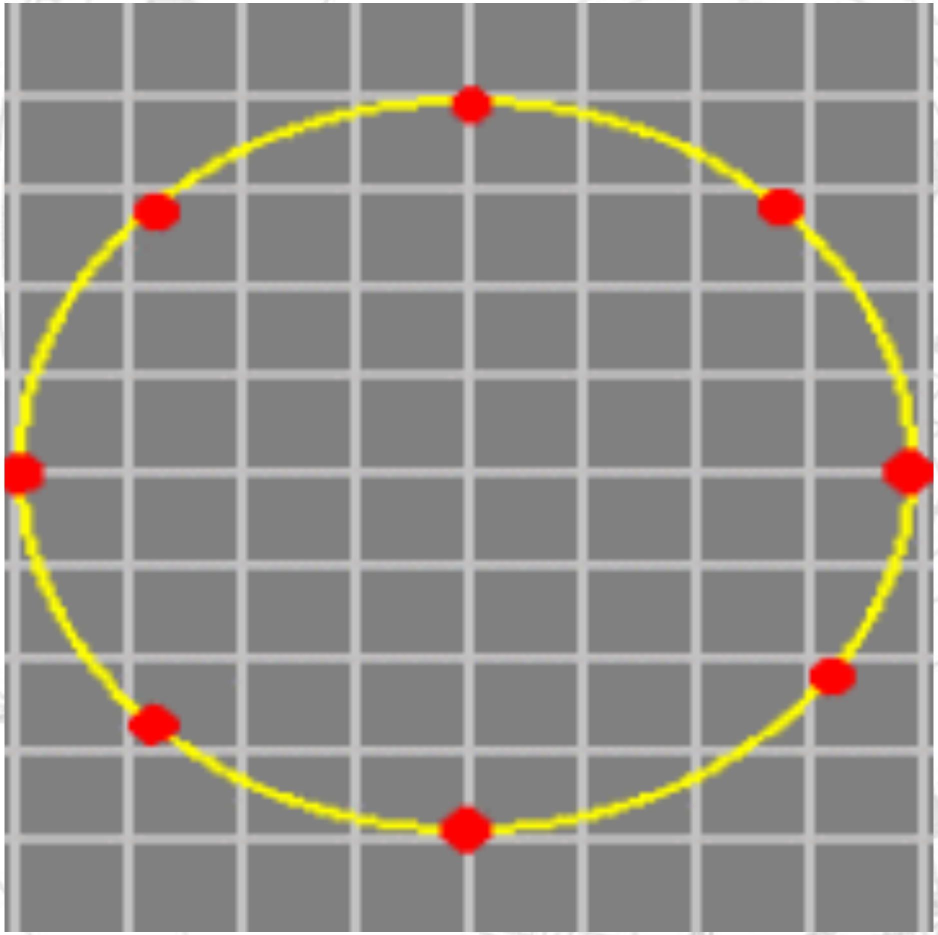
Effect of a Passing Gravitational Wave

- **Imagine a circle of masses in space**
  - **Free from all disturbances, except a gravitational wave**

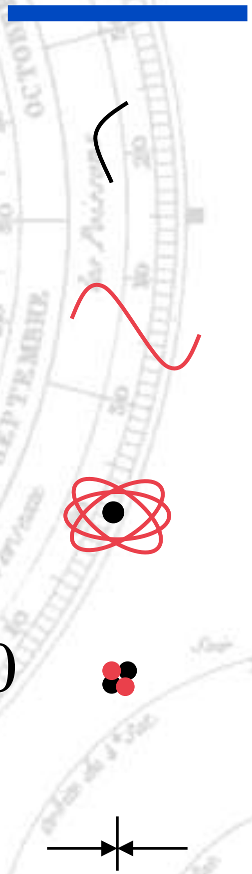


Effect of a Passing Gravitational Wave

- Gravitational wave traveling into the picture
- Change in separation (ΔL) proportional to initial separation (L)

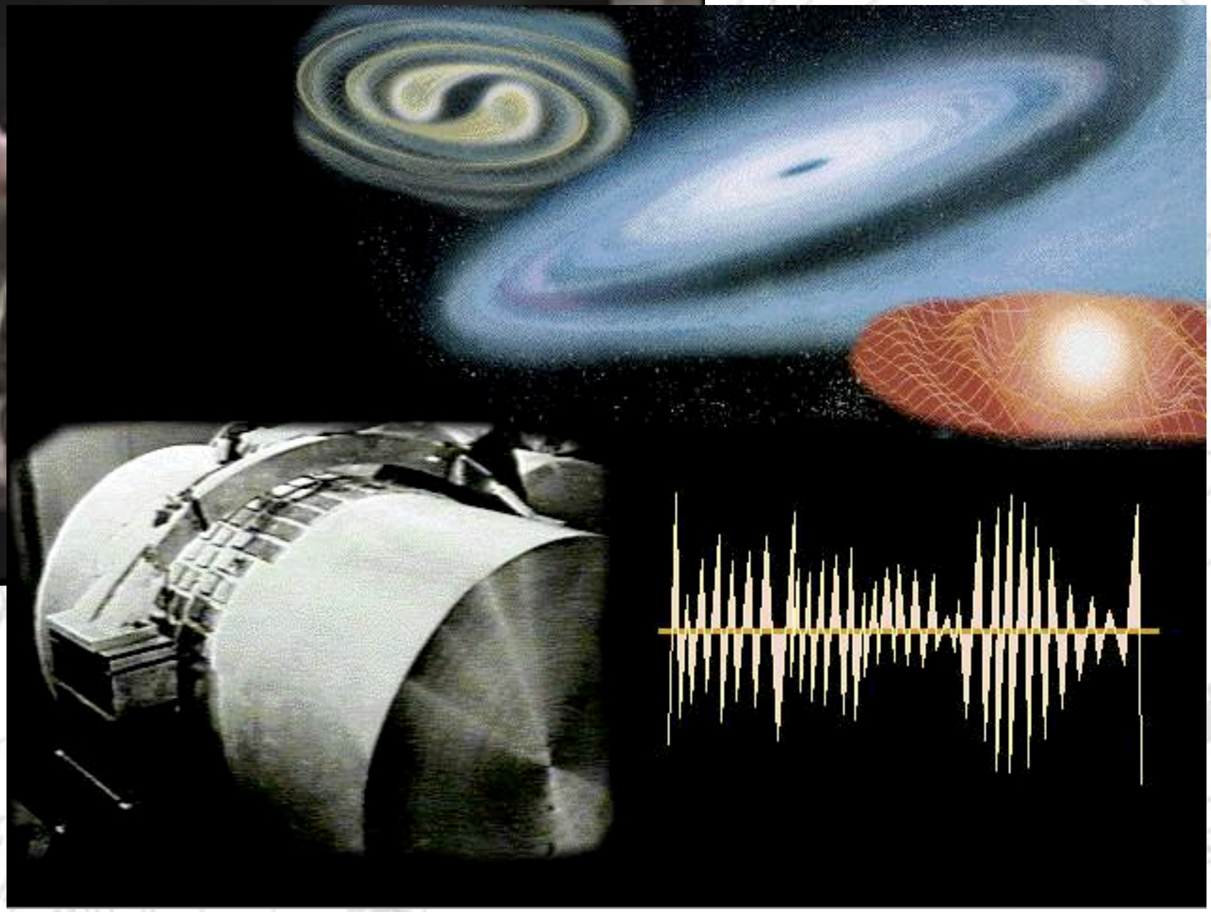


How Small is 10^{-18} Meter?

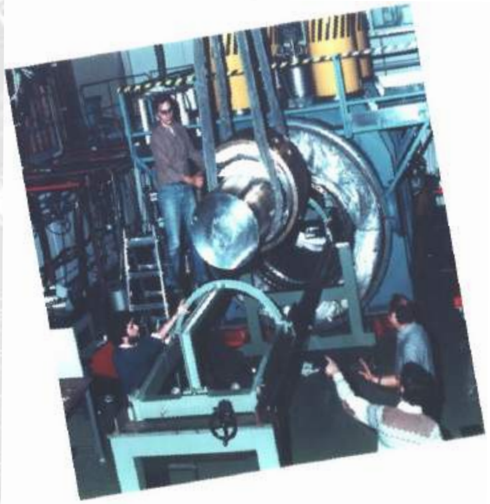


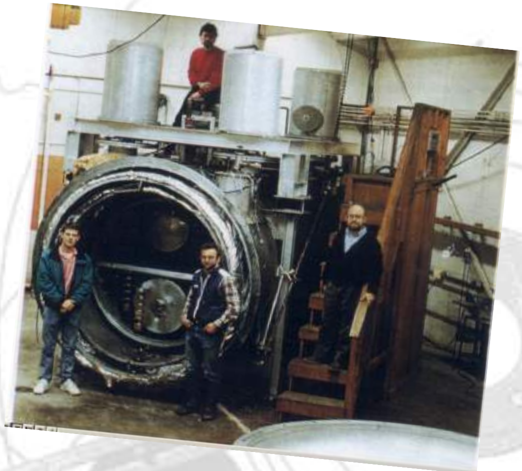
	One meter
÷10,000	**Human hair ~ 10^{-4} m (0.1 mm)**
÷100	**Wavelength of light ~ 10^{-6} m**
÷10,000	**Atomic diameter 10^{-10} m**
÷100,000	**Nuclear diameter 10^{-15} m**
÷1,000	**GW detector 10^{-18} m**

Bar detectors

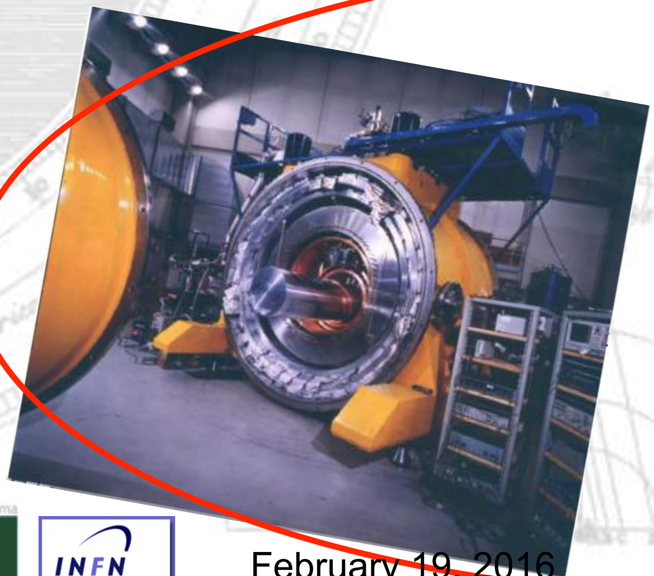


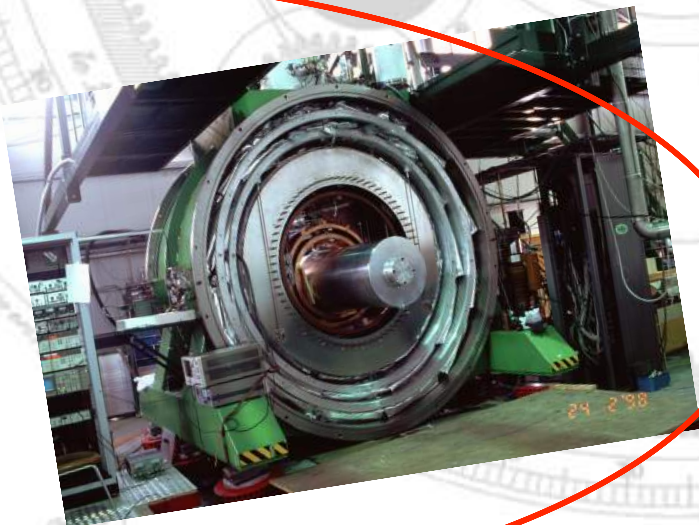
The network of bar detectors





ALLEGRO AURIGA EXPLORER NAUTILUS



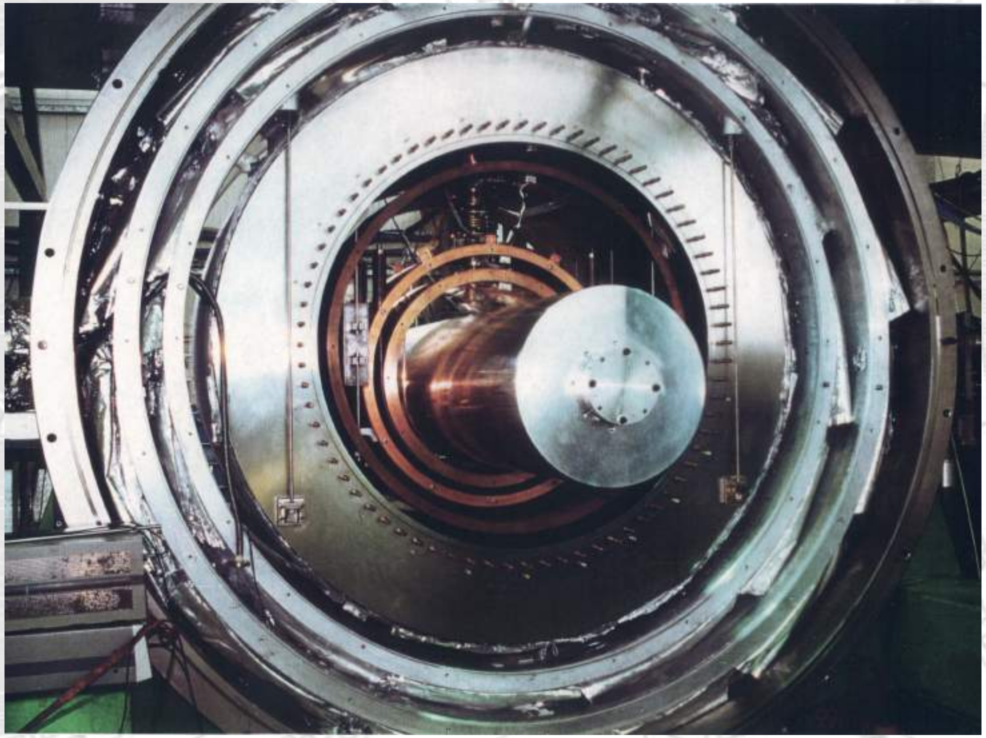


•The effect of the GW is proportional to the mass: large masses are needed (2 tons)

•The the small vibration induced by the GW would be hidden by the brownian motion of the detector (low T: -270 ^{o}C), by the seismic noise (mechanical filters) and by the amplifier noise (superconductive amplifier)

Bar detectors

- NAUTILUS



Length = 3 m

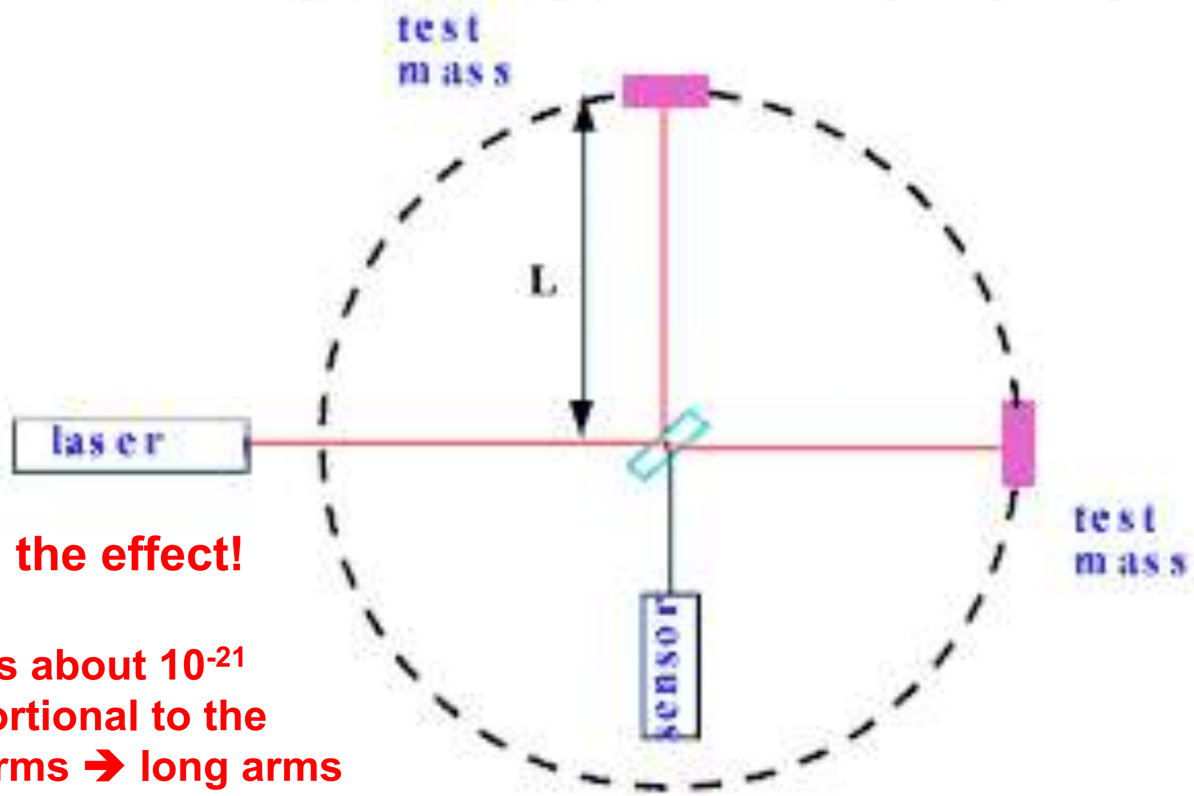
h ~ δL/L ~ 10^{-21} ➔ δL=10^{-21} m

Thousand million times smaller than the dimensions of a proton!!!!


Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
MINIGRAIL
GEO
AURIGA
EXPLORER
VIRGO
NAUTILUS
TAMA
LCGT
LIGO
ALLEGRO
LIGO
MARIO SCHENBERG
AIGO
gravitational wave research

Detecting a Gravitational Wave with Light

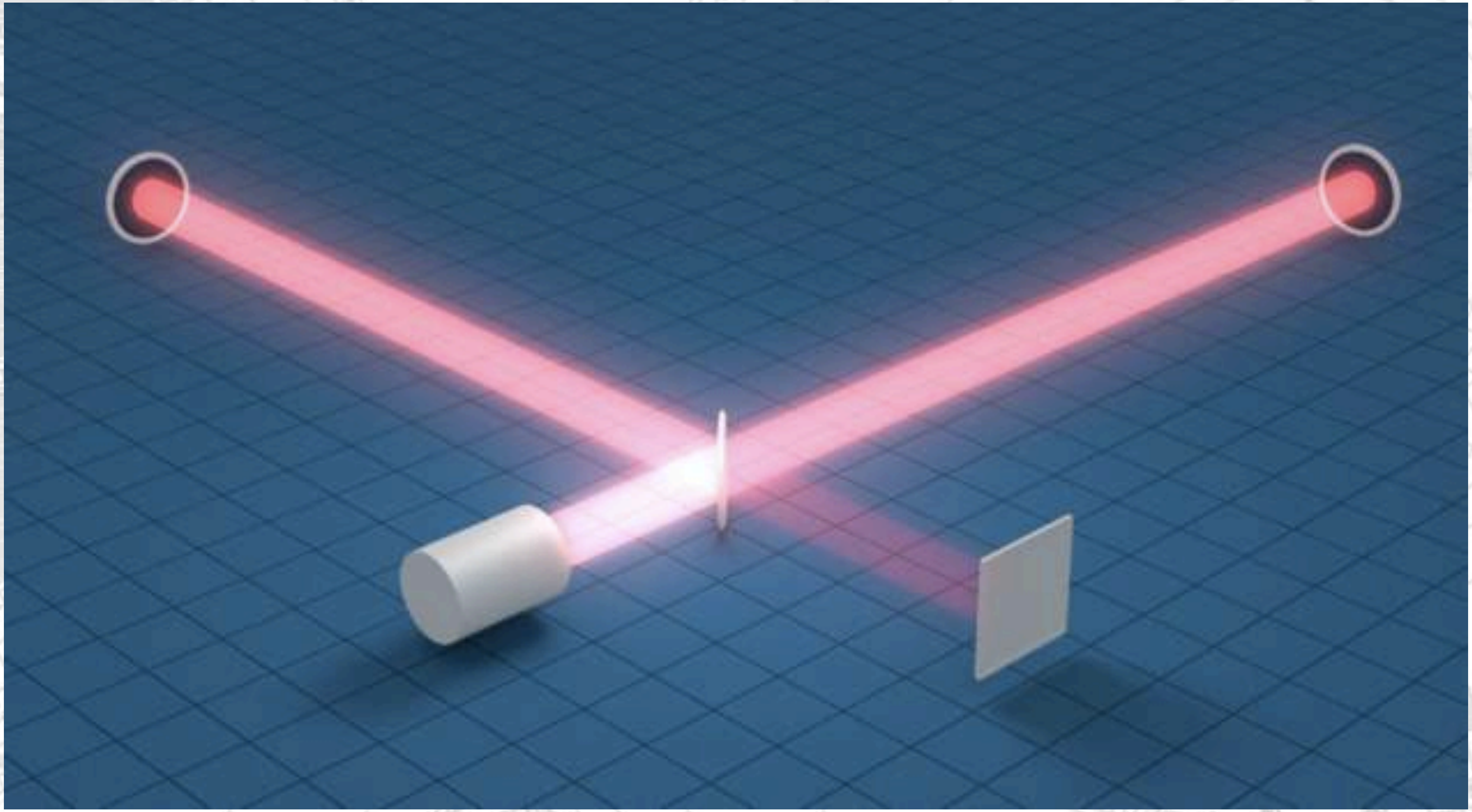
Michelson Interferometer



I have greatly exaggerated the effect!

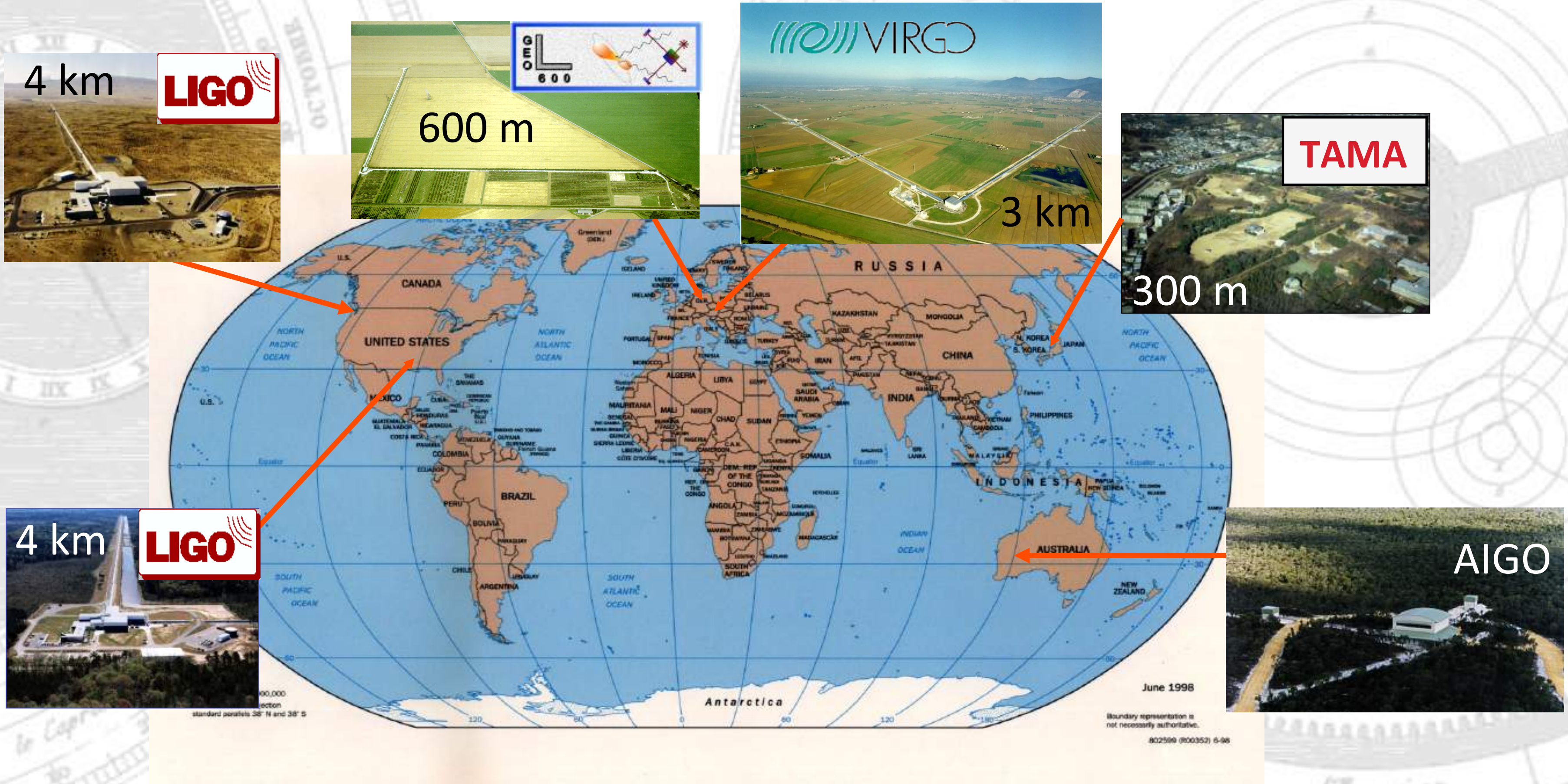
- **Amplitude of a strong wave is about 10^{-21}**
- **The effect of the GW is proportional to the length of the interferometer arms ➔ long arms are needed (of the order of a few km)**
- **For L = 1 km, => $\Delta L \sim 10^{-18}$ m**

Detecting a Gravitational Wave with Light




Virgo aerial view

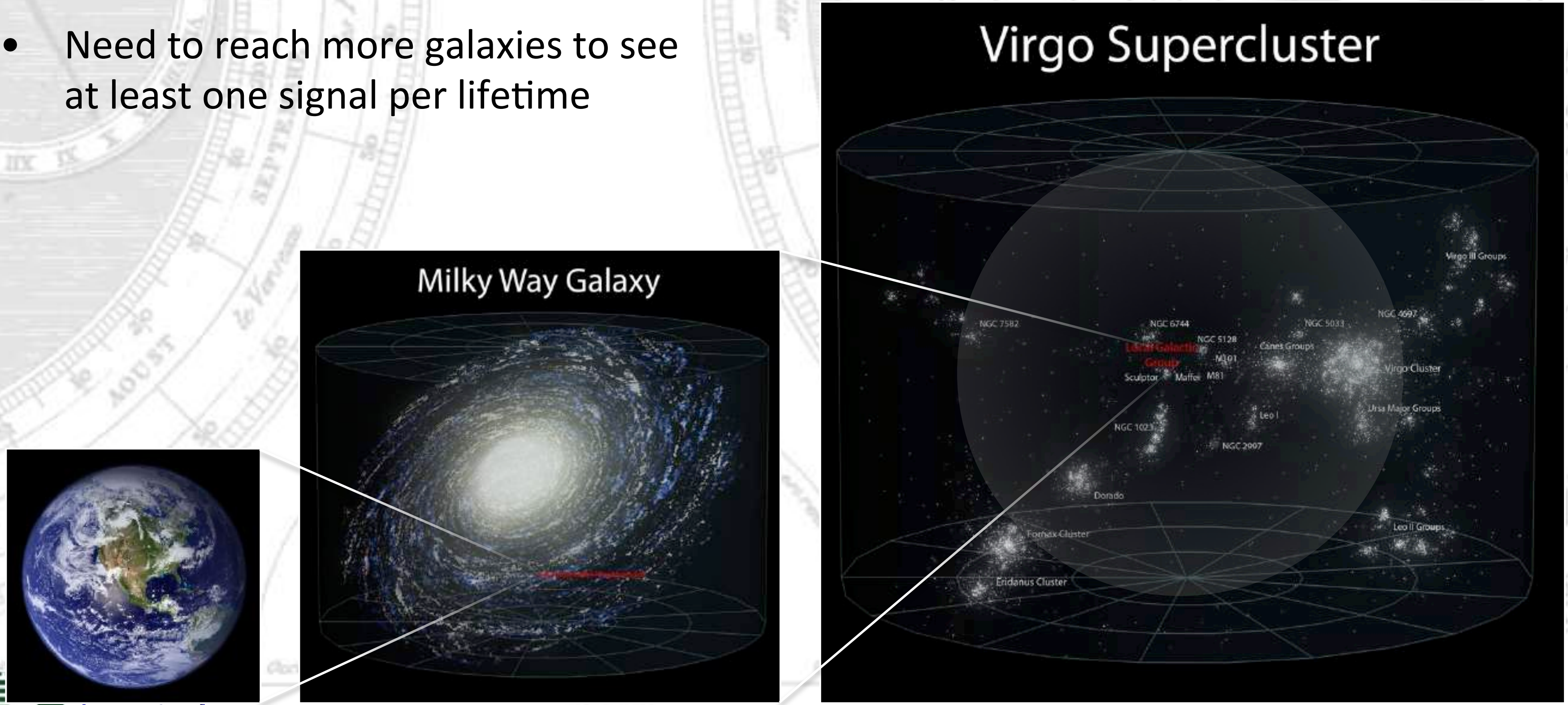
The network of interferometers



Virgo: a section of the 3 km vacuum pipe

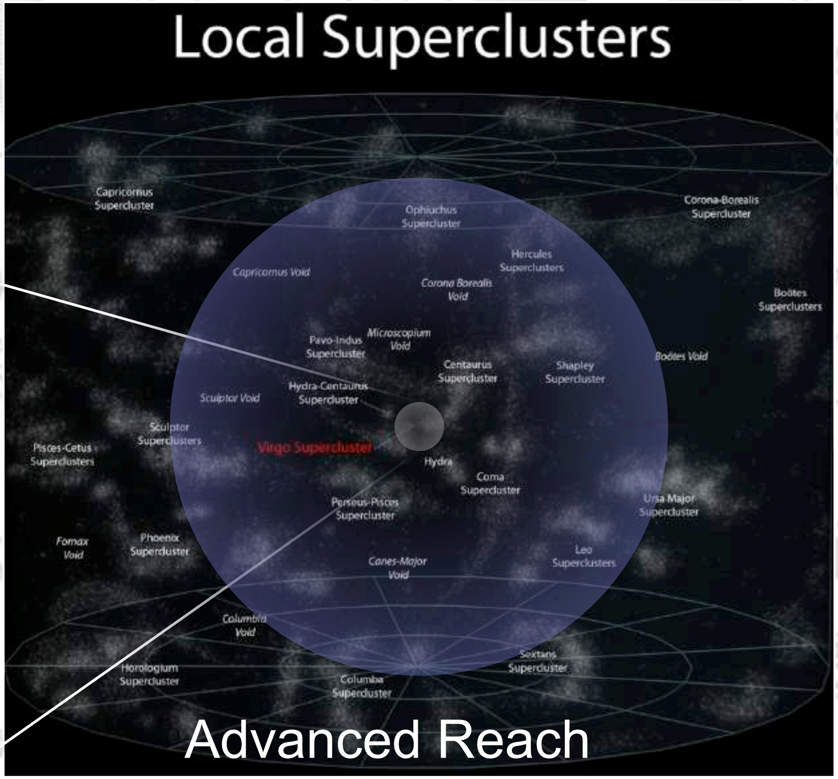
First generation detectors

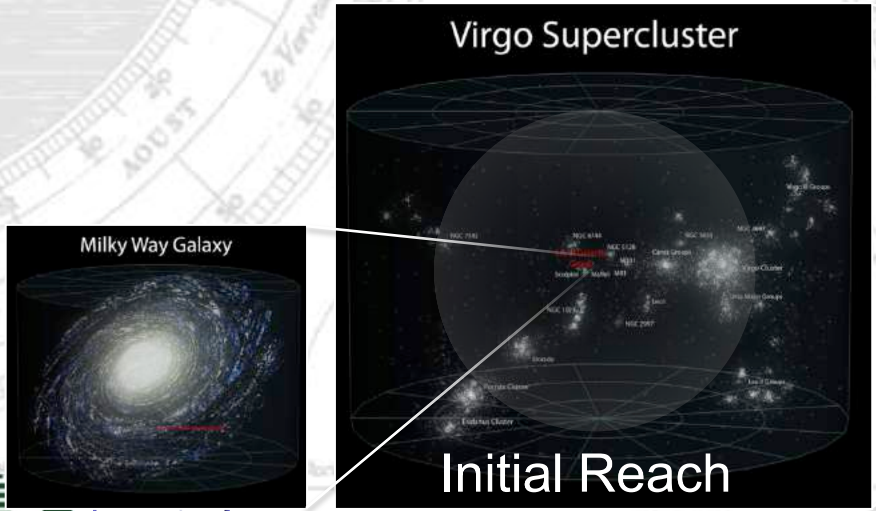
- First generation detectors and infrastructure built from mid-'90s to mid-2000; commissioned to design sensitivity; and observed for several years
- In case of NS-NS coalescence:
  - Sensitivity sufficient to reach about 100 galaxies; however…
  - Expected rate is low: events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see at least one signal per lifetime



Advanced Detectors Sensitivity: a *qualitative* difference

- While observing with initial detectors, parallel R&D led to better concepts
- 'Advanced detectors' are ~10x more sensitive
- → detection rate 10^3 larger
- NS-NS detection rate order of 1 per month (will reach about 100,000 galaxies)
- BH-BH detectable at cosmological distances (~1 Gpc)

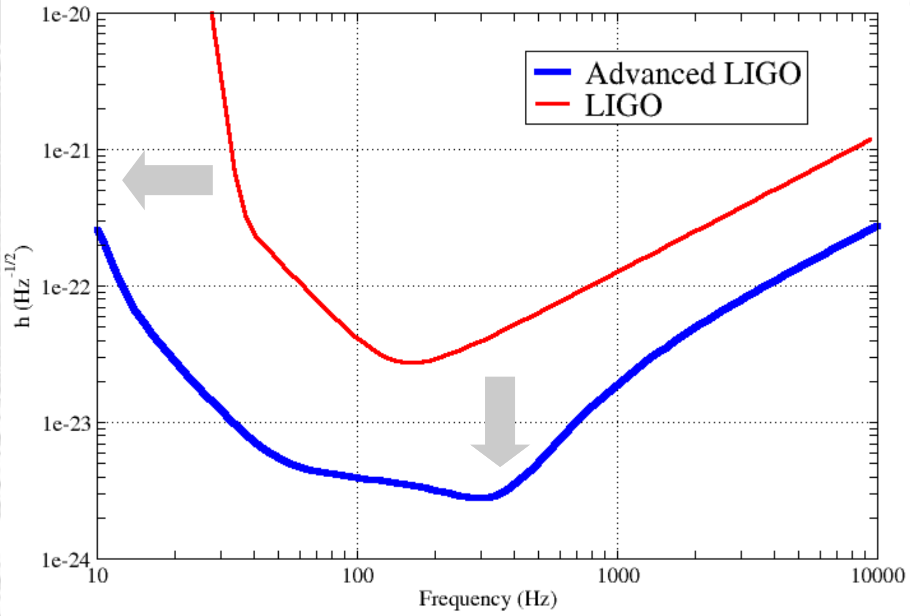


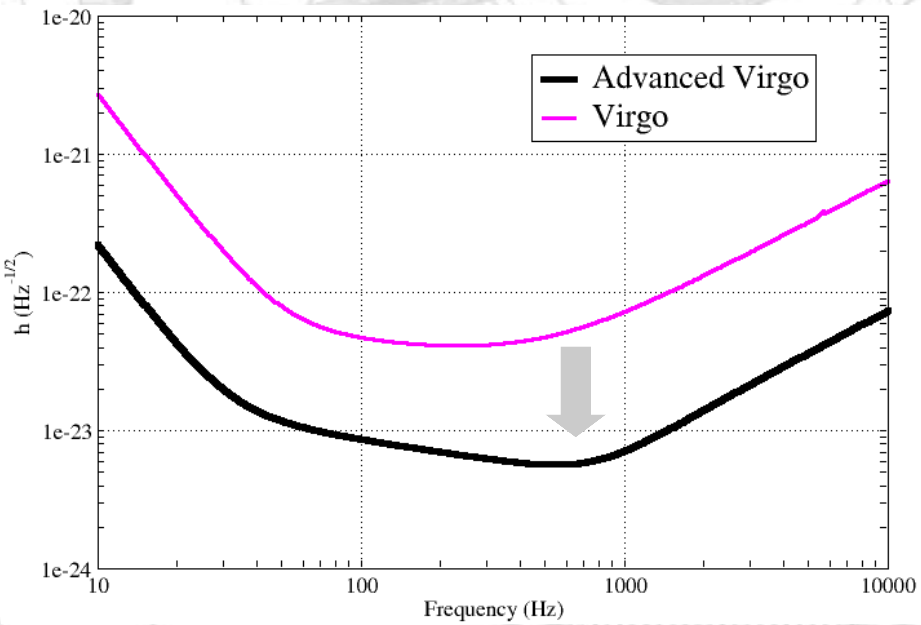


Advanced Virgo / Advanced LIGO

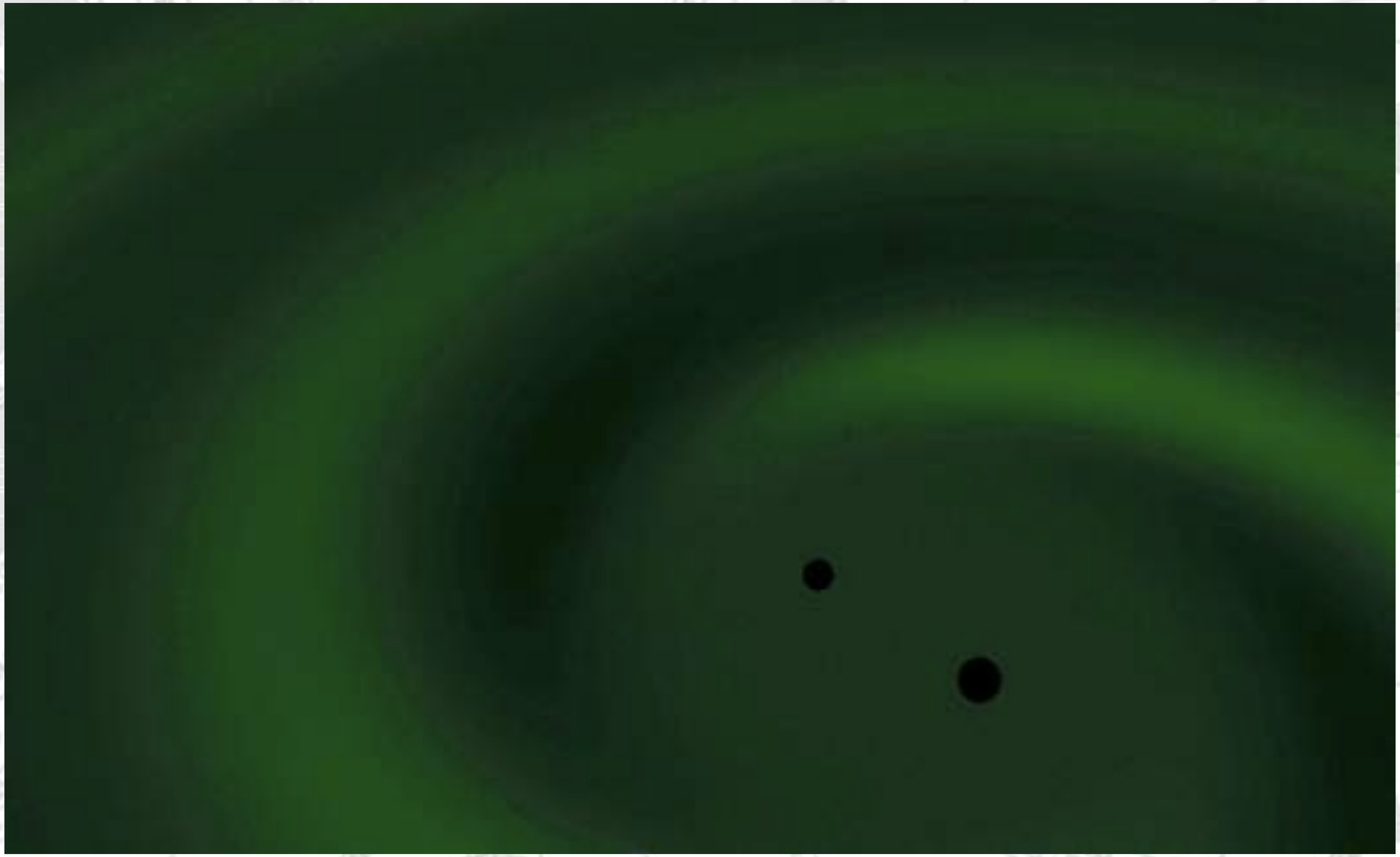
- Project start 2008 (NSF)
- Completed 2015
- First data taking run (O1) end 2015
- Commissioning toward final sensitivity underway

- Project start 2011 (INFN+CNRS)
- Construction almost completed
- Data taking start in 2016





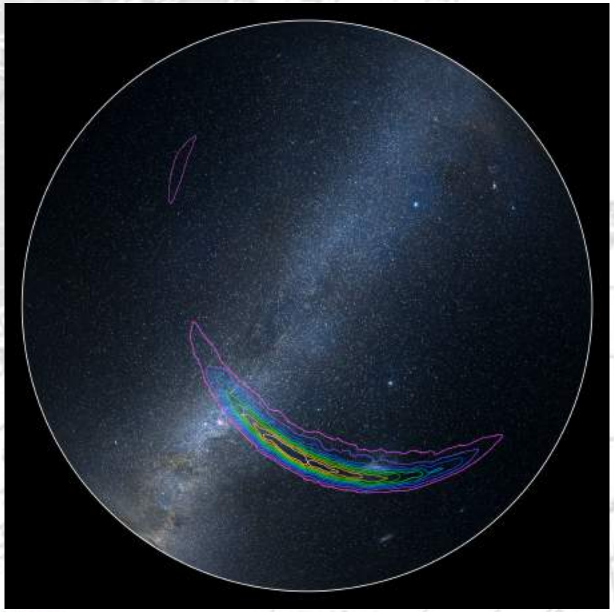
Simulation of BHBH merger

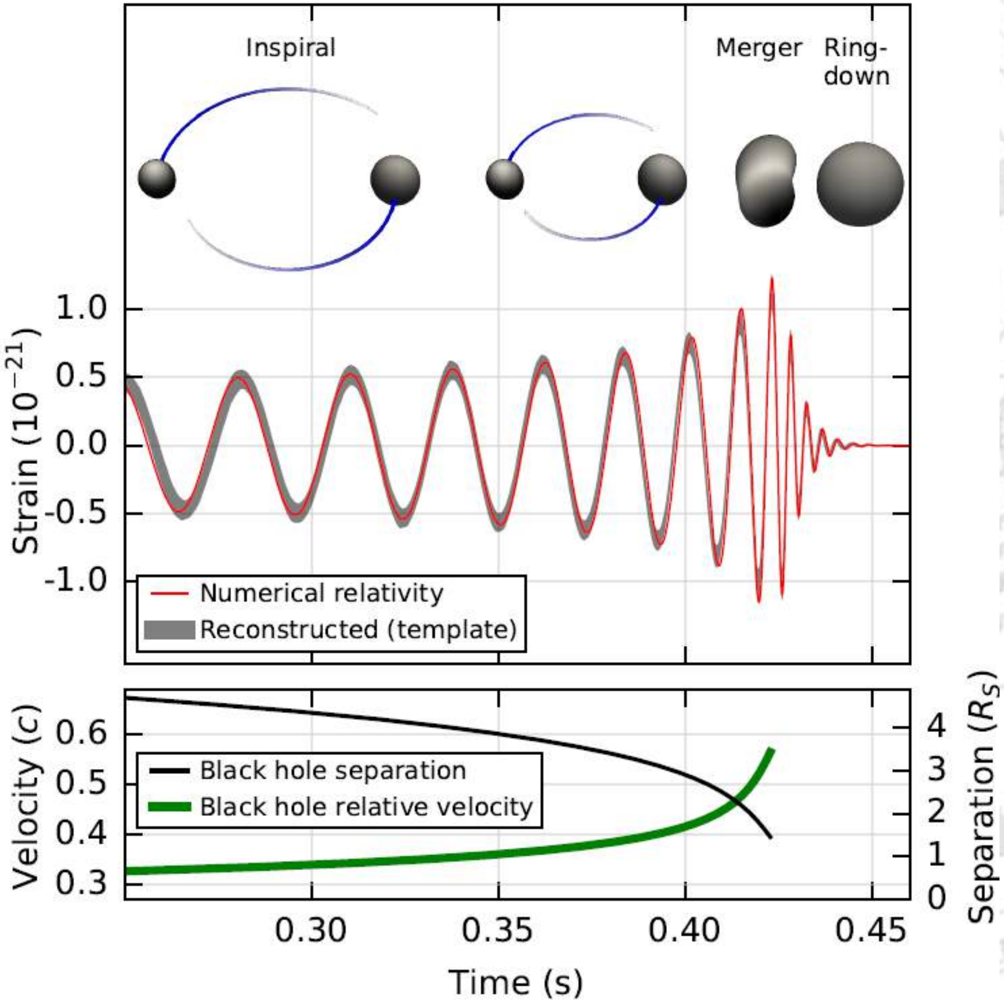


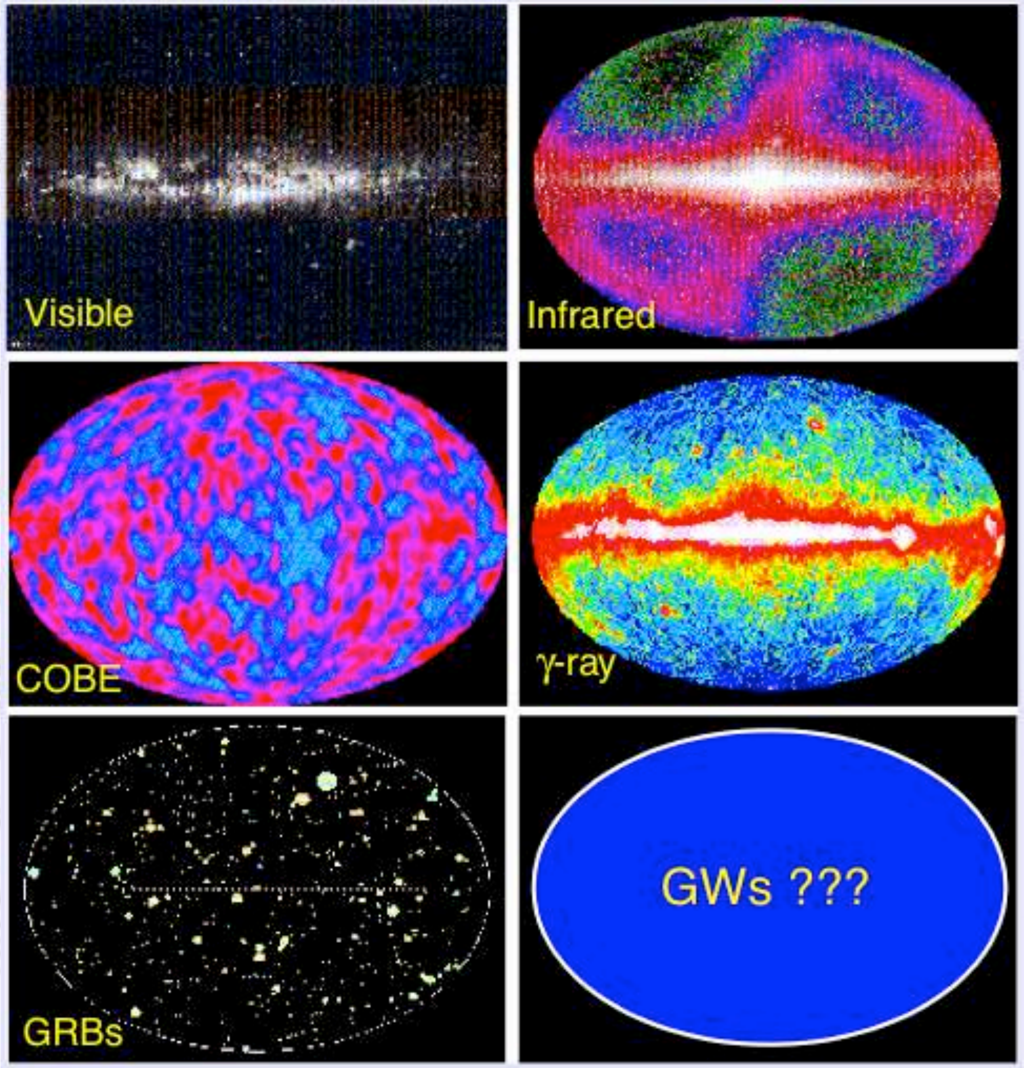
GW150914: Estimated Strain Amplitude

Binary Black Hole System

- $M1 = 36 +5/-4\ M_{sol}$
- $M2 = 29 +/- 4\ M_{sol}$
- Final Mass = $62 +/- 4\ M_{sol}$
- distance=410 +160/-180 MPc







GWs can reveal features of their sources that cannot be learnt by electromagnetic, cosmic rays or neutrino studies

- **1915** Einstein publishes his theory of General Relativity
- **1916** Einstein predicts the existence of GWs
- **1960** Weber builds the first GW detector
- **1984** Taylor e Hulse demonstrate the existence of GWs (Nobel Prize in 1993)
- **1990** Bar detectors start to operate
- **2005** Interferometers start to operate
- **2010** Construction of advanced interferometers starts
- **2015** Advanced interferometers in operation
- **2015, September** First GW detection

Great science in the next years!!!

The End