Three messengers from the sky: light, neutrinos and gravitational waves

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1564 – 1642

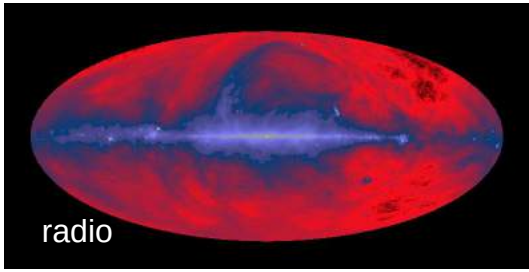
E.M. Astronomy

- Current e.m. telescopes are mapping almost the entire Universe

Galileo's telescope

E.M. Astronomy

- Current e.m. telescopes are mapping almost the entire Universe
- Keywords:
  - Map it in all the accessible wavelenghts



Arecibo

VLA

Radio Telescopes

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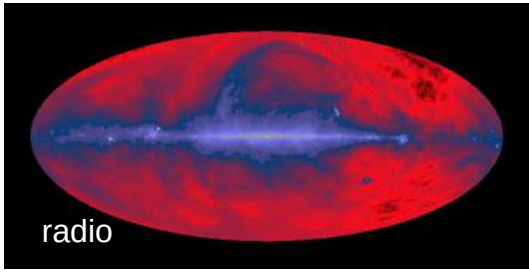
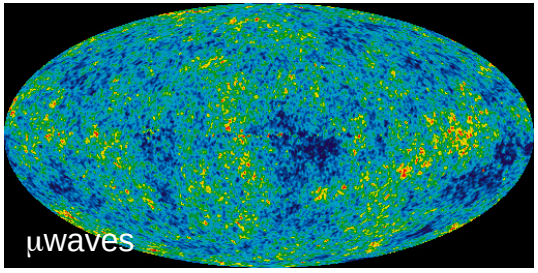
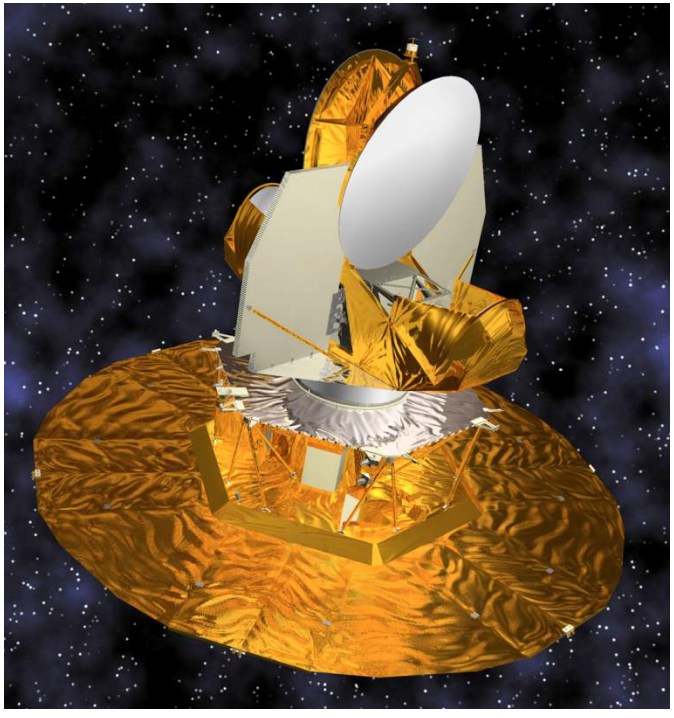
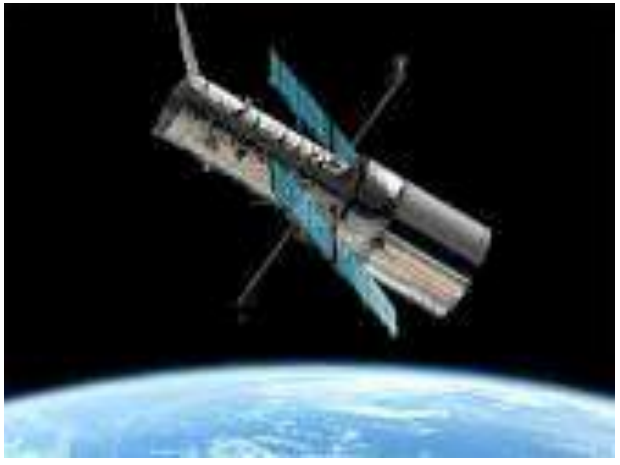






WMAP



Hubble

Microwaves telescopes

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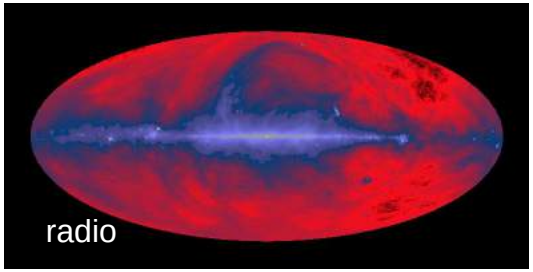

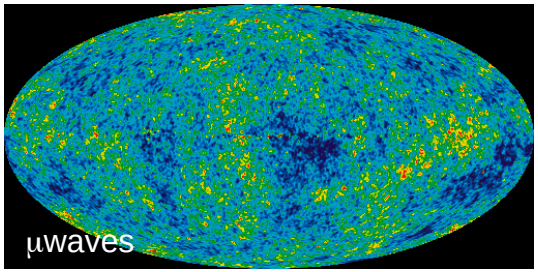

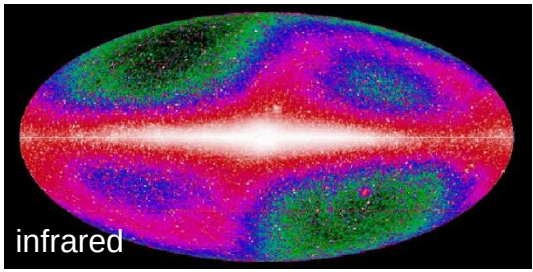

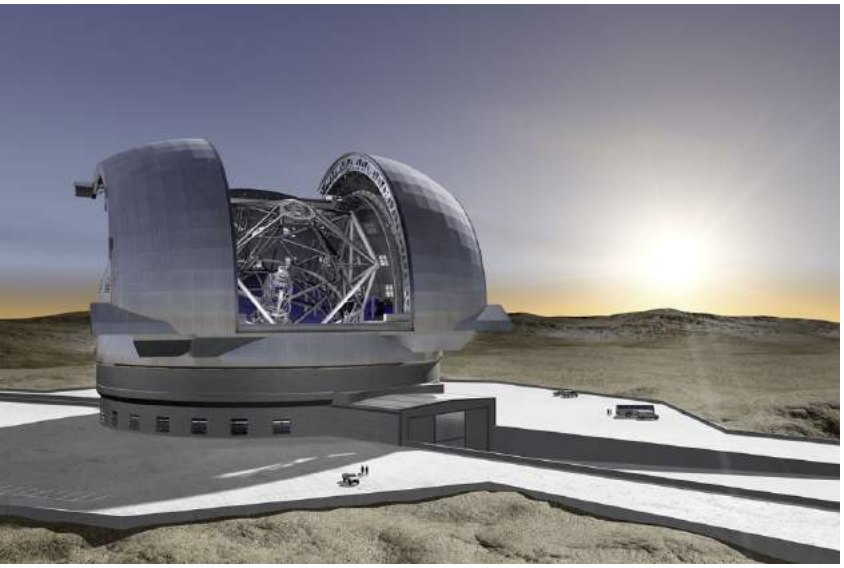

E-ELT (infrared telescope)

E.M. Astronomy

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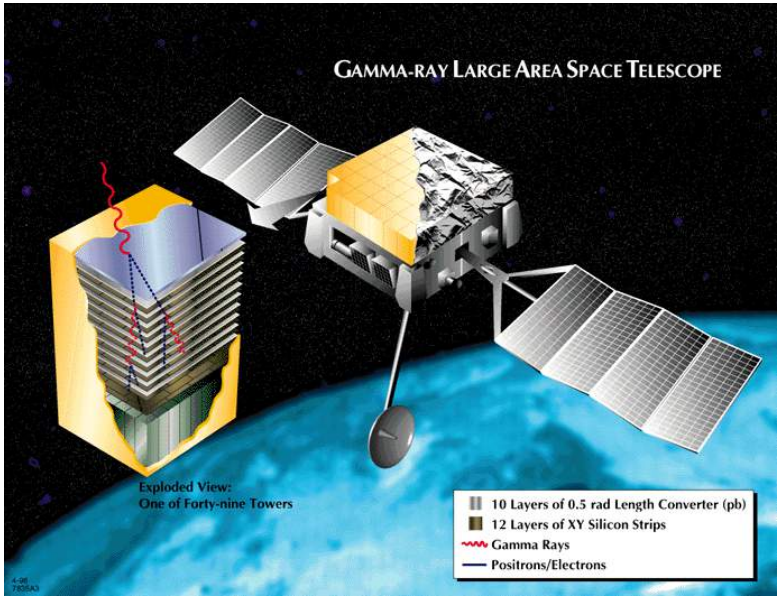
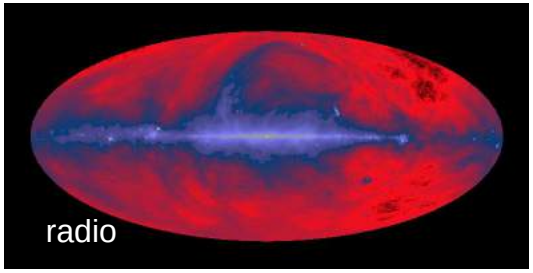
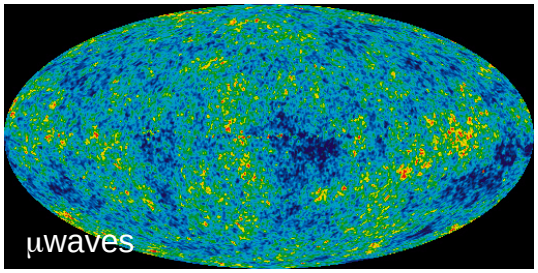
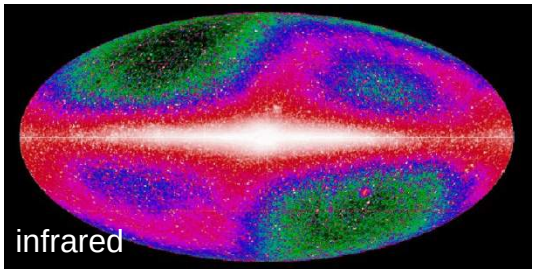
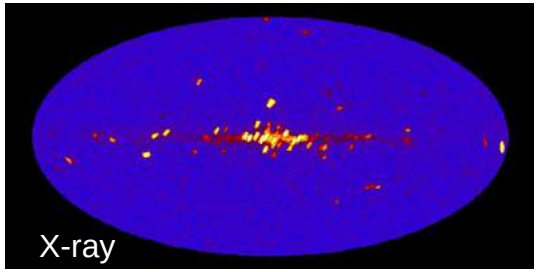


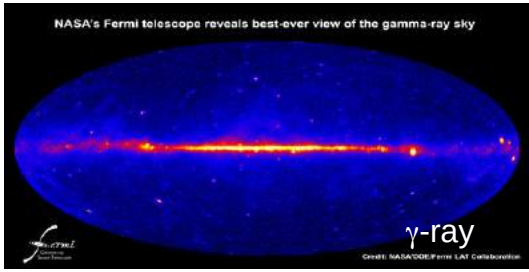
Fermi (GLAST) telescope

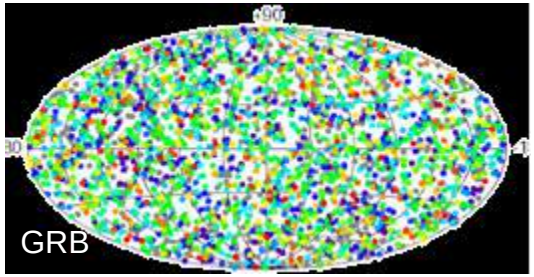








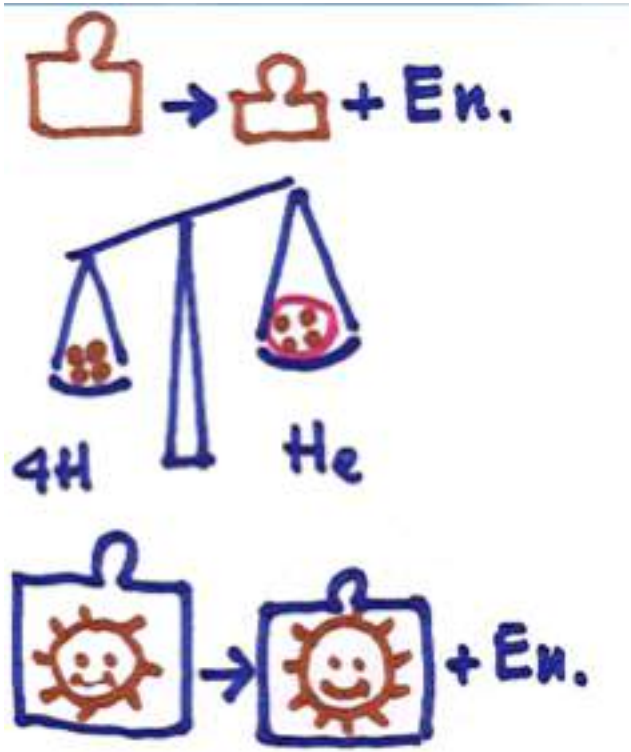




How do we know what happens inside the sun?

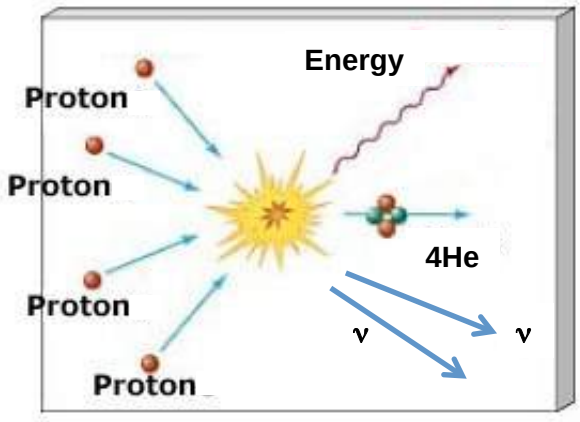
How do we know what happens inside the sun?

- Einstein (1905): Formulated Theory of Special Relativity, with that came $E=mc^2$
- Aston (1920): Found that the atomic mass of Helium was one part in 120 less than four Hydrogen atoms
- Eddington (1920): Stated that Sun burns Hydrogen into Helium producing heat and light
- Bethe (1939): Explained "CNO" cycle responsible for Sun's energy production



How do we know what happens inside the sun?

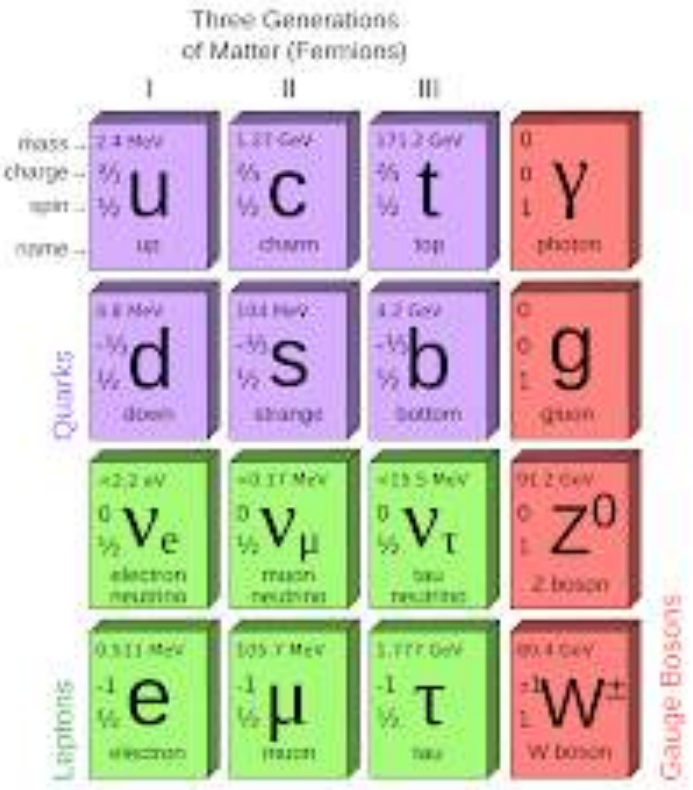
- We think that in the Sun we have nuclear reactions



- How can we prove this is the reaction taking place inside the Sun?

- Neutrinos are the signature we have to say there are nuclear reactions inside the Sun, differently from light which comes from the outer regions
- Detect solar νs!

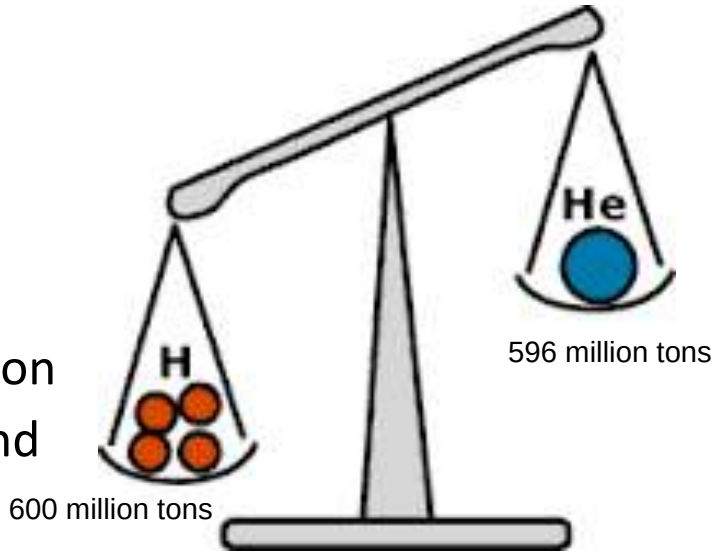
How do we know what happens inside the sun?



How do we know what happens inside the sun?

How can we measure νs coming from Sun?

1. How many νs come from the Sun?
   - Each second, in the center of the Sun, 600 million tons of Hydrogen become 596 million tons of Helium → 4 tons of mass per second become energy and νs → huge flux



each second 60 billions of neutrinos cross a surface of 1 cm^2 i.e. a surface like a thumb nail.

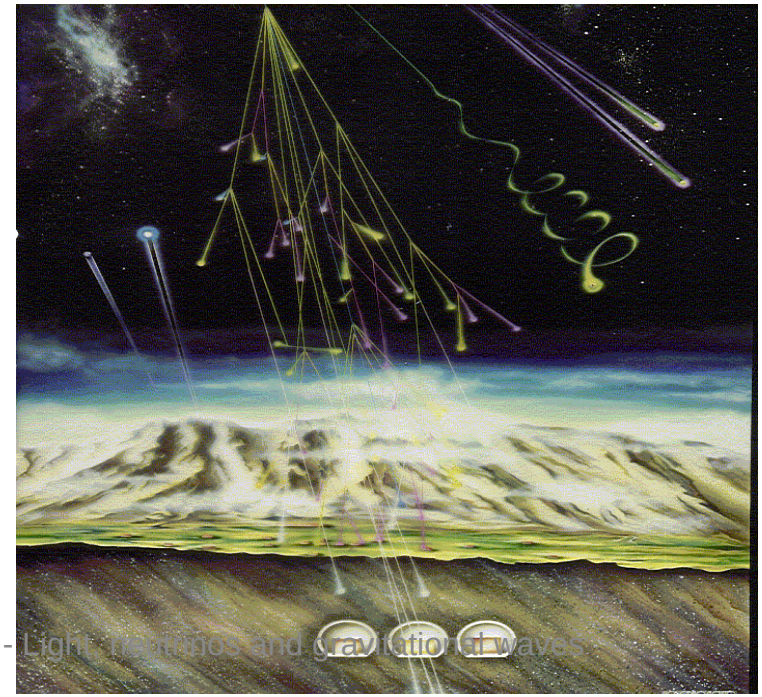
How do we know what happens inside the sun?

How can we measure νs coming from Sun?

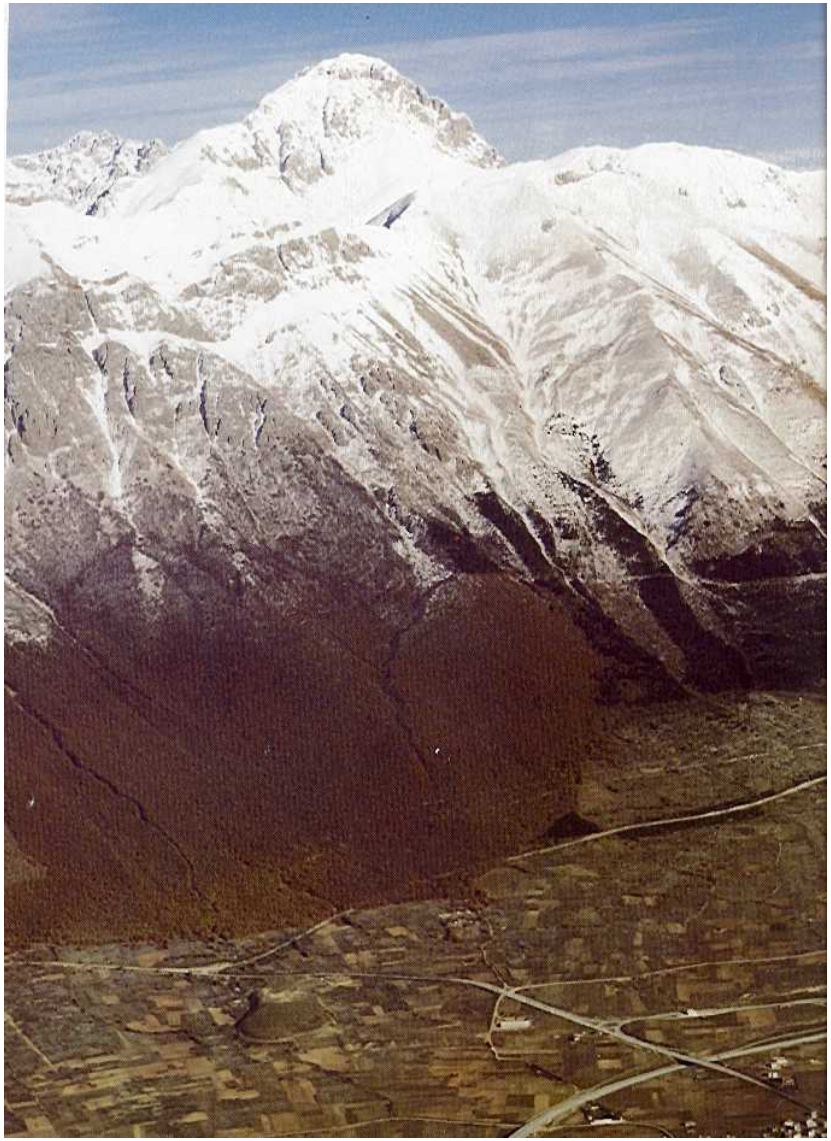
2. How can we measure them?

- νs are very elusive and penetrating → we need to shield the detector from other types of radiation (e.g. cosmic rays)

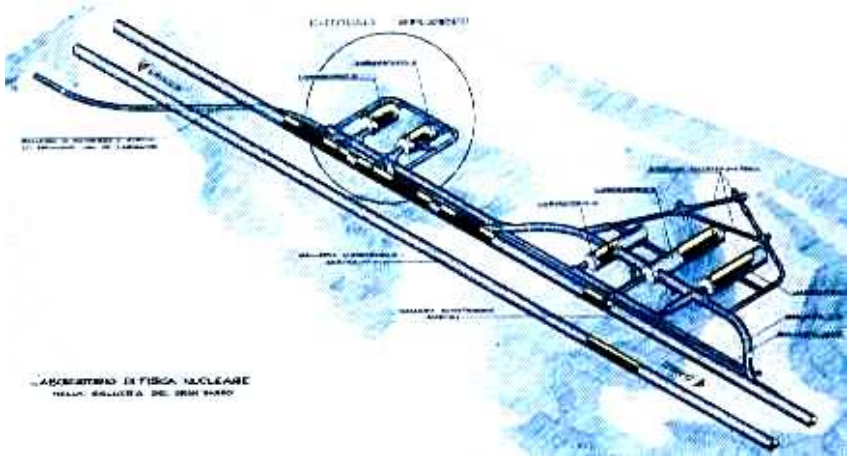
→ Underground detectors!



The INFN Gran Sasso Laboratory

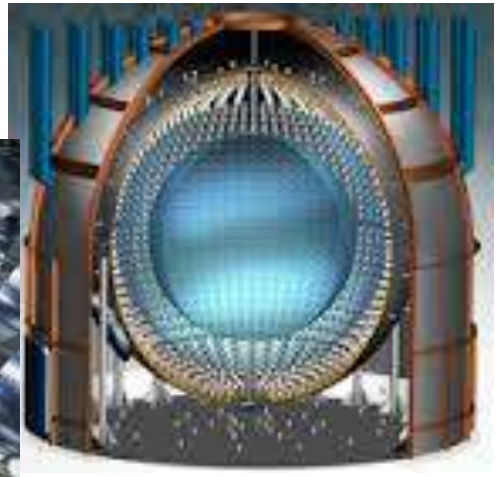


The lab of cosmic silence

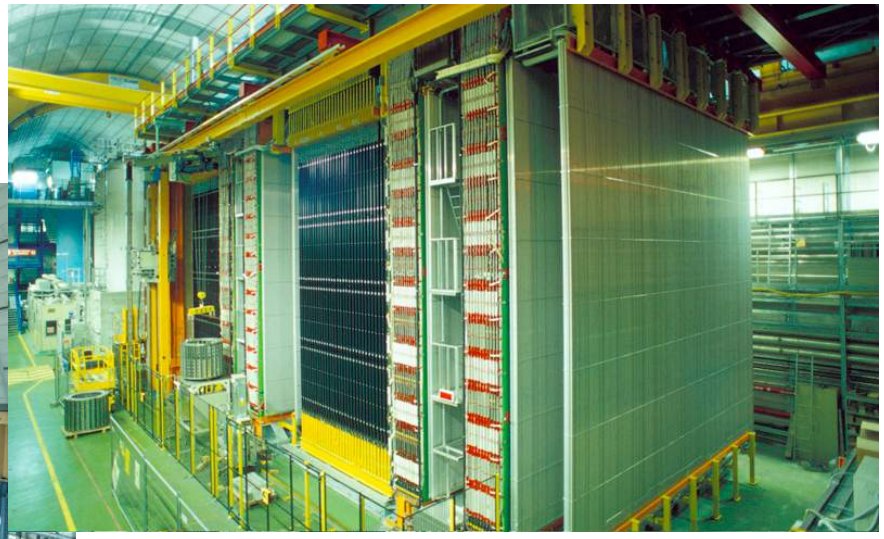


The INFN Gran Sasso Laboratory

Borexino

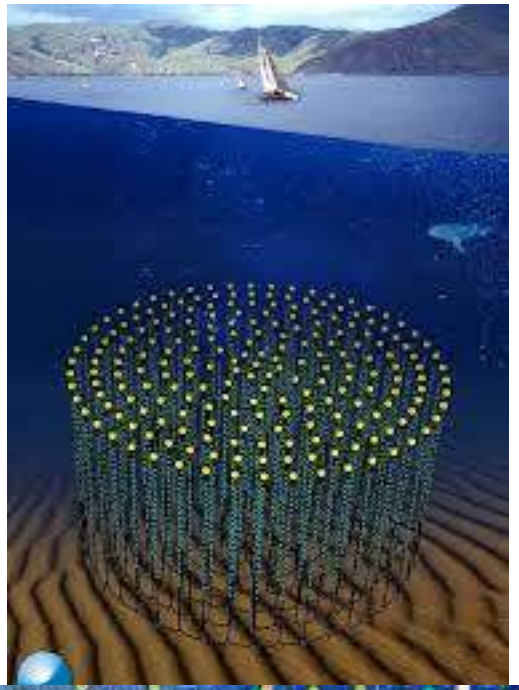


Opera



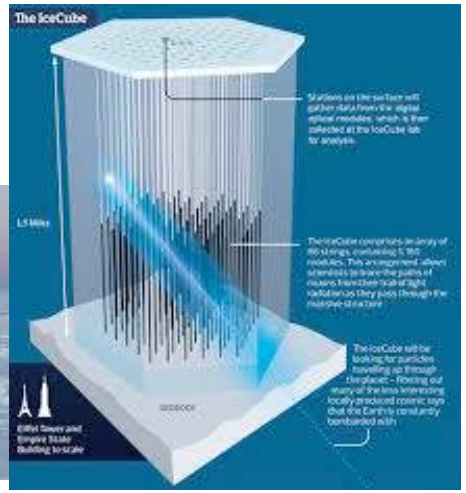
LVD

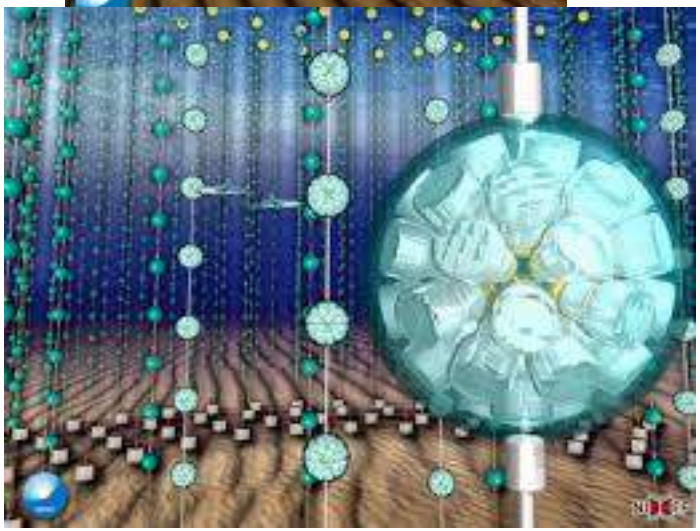
Underground Labs



KM3NET

IceCube

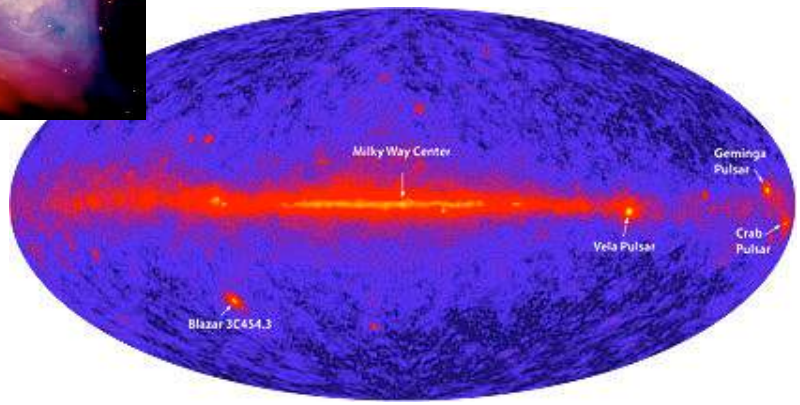




νs from Supernovae

- Only 0.1% of the emitted energy in a SN is through e.m. radiation
- 99.9% is emitted as neutrinos
- νs are the tool to investigate the internal structure, the dynamics of the collapse

The Vela Pulsar (PSR J0835-4510)
A radio, optical, X-ray- and gamma-emitting pulsar associated with the Vela SN Remnant in the constellation of Vela.



νs from Supernovae

Crab Nebula

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。」

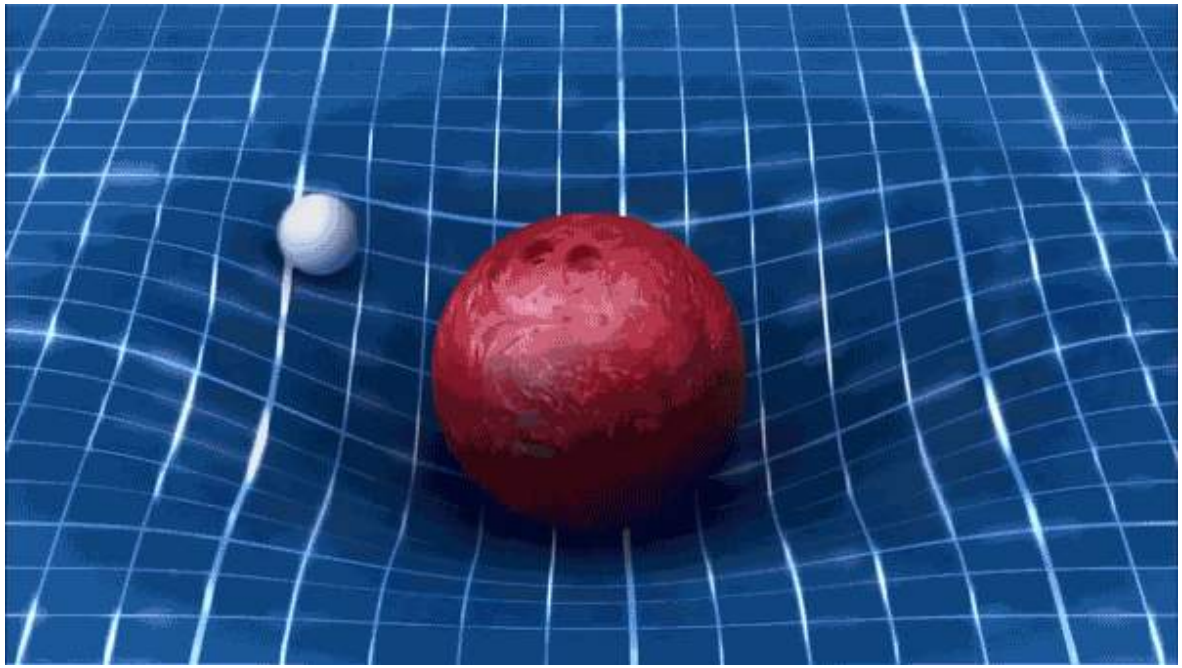
In the “ShongHuiYao” book, which means “Collection of the Shong dinasty” it is written: “In month March of year ZhiHe (May 1054), the astronomer noticing that the KeXing star was decreasing its intensity, foresees that the star will disappear. In the morning of May 13th of the same year (July 4th, 1054) 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”

That’s all, Sir?

Do not forget gravity

General Relativity: a new theory of Gravity

- Einstein (1915): 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



General Relativity: a new theory of Gravity

REVOLUTION IN SCIENCE.

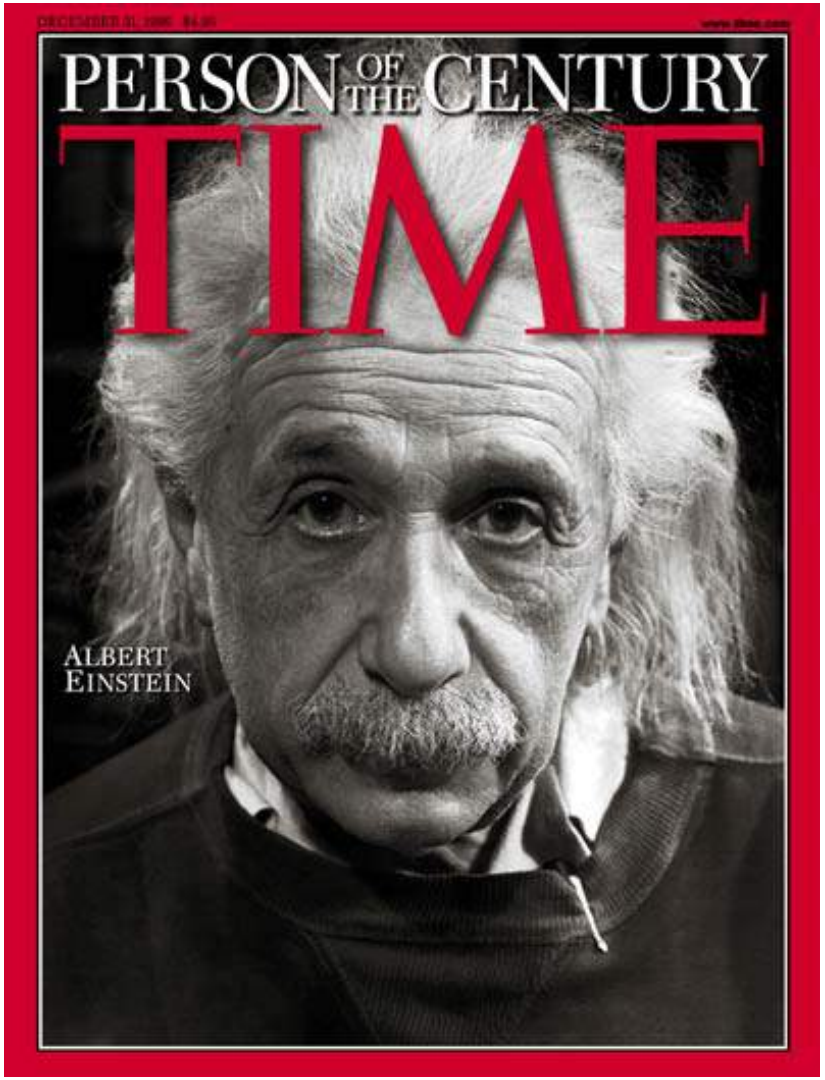
NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

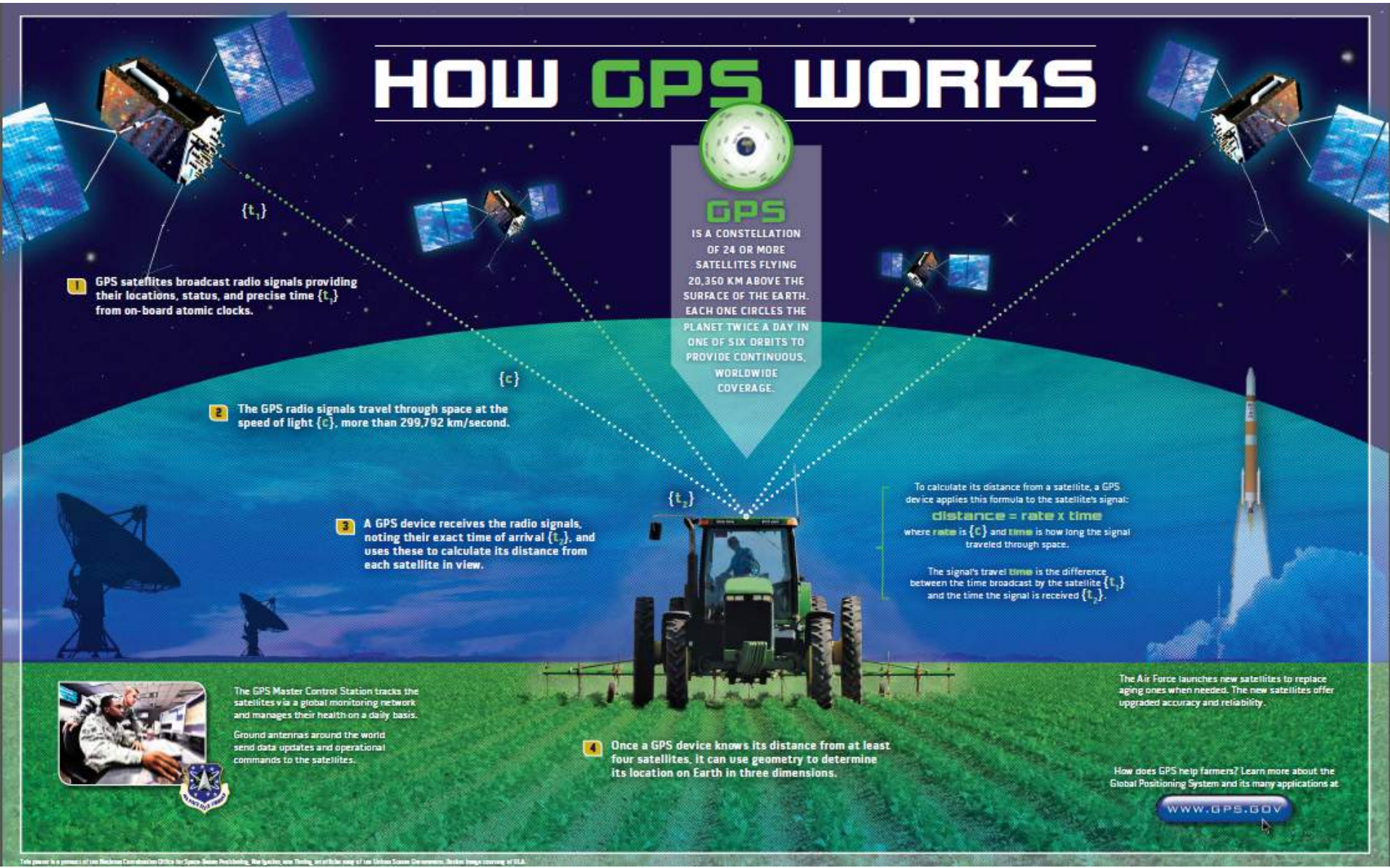
Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

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



An application of GR to everyday life: the GPS



A prediction of GR: black holes

Sun

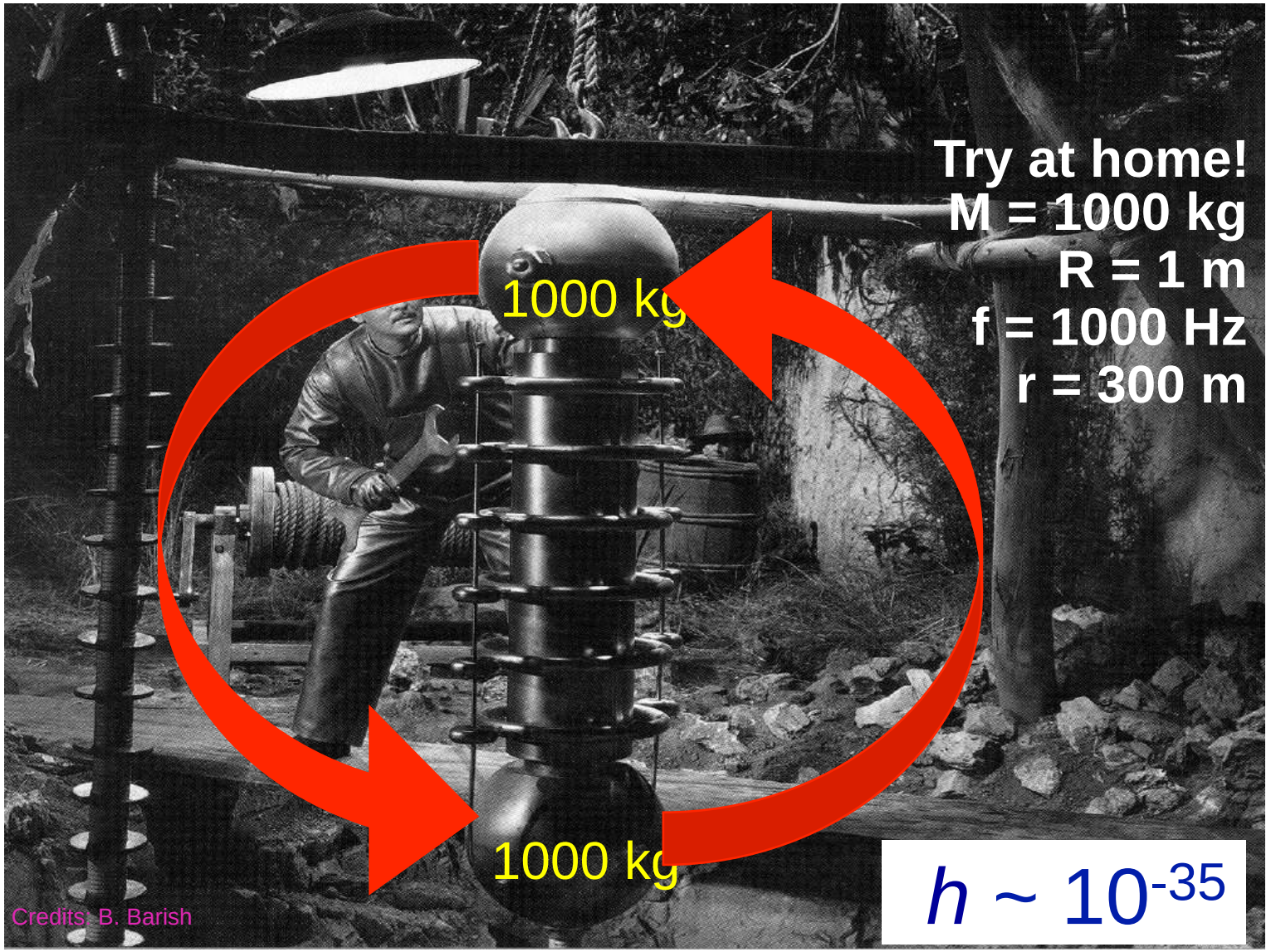
Neutron Star

Black Hole

A prediction of GR: gravitational waves

Ripples in spacetime moving at the speed of light

How to produce a GW?



Sources of GW

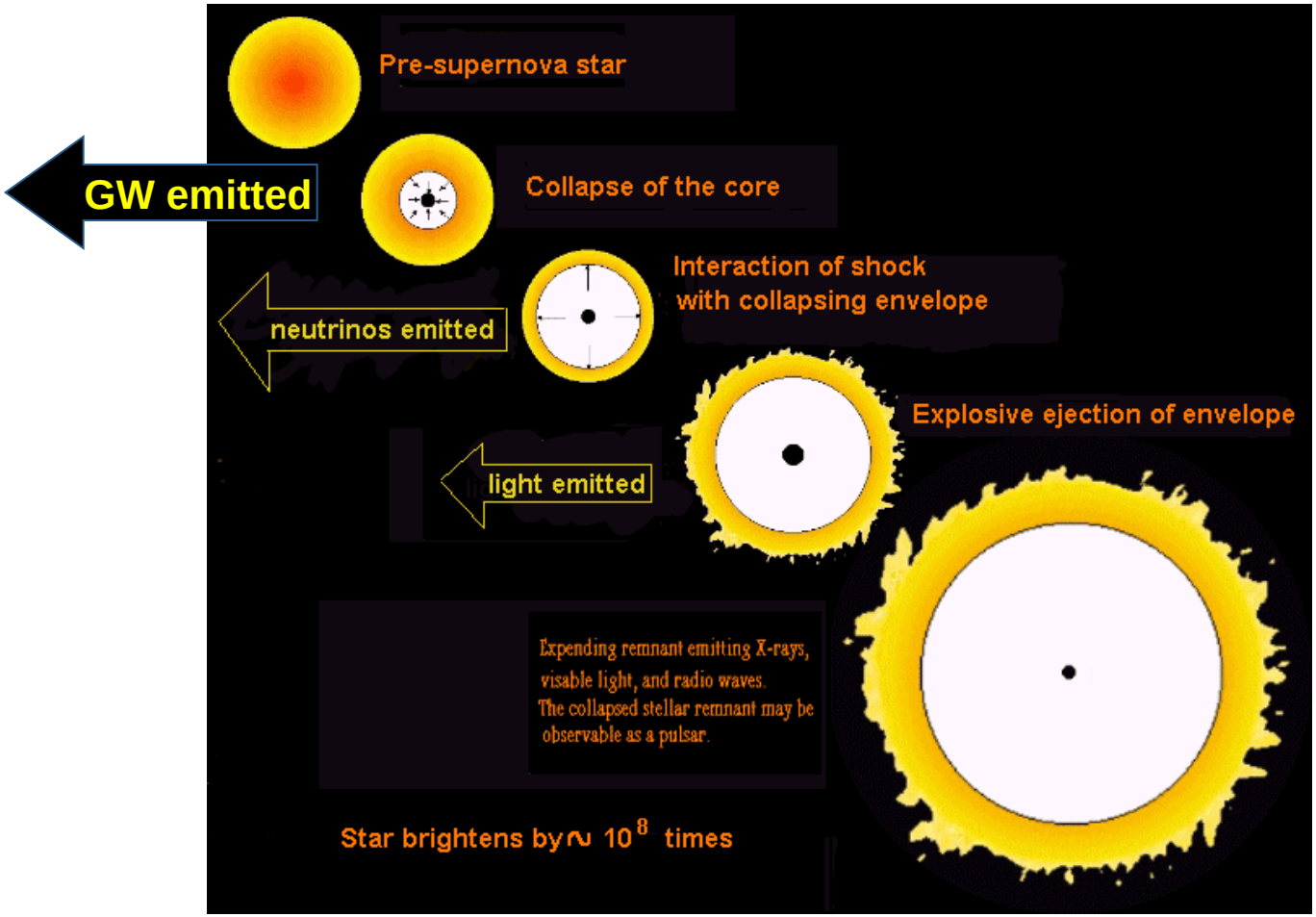
- Gravitational collapse

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.

Sources of GW

- Gravitational collapse



Sources of GW

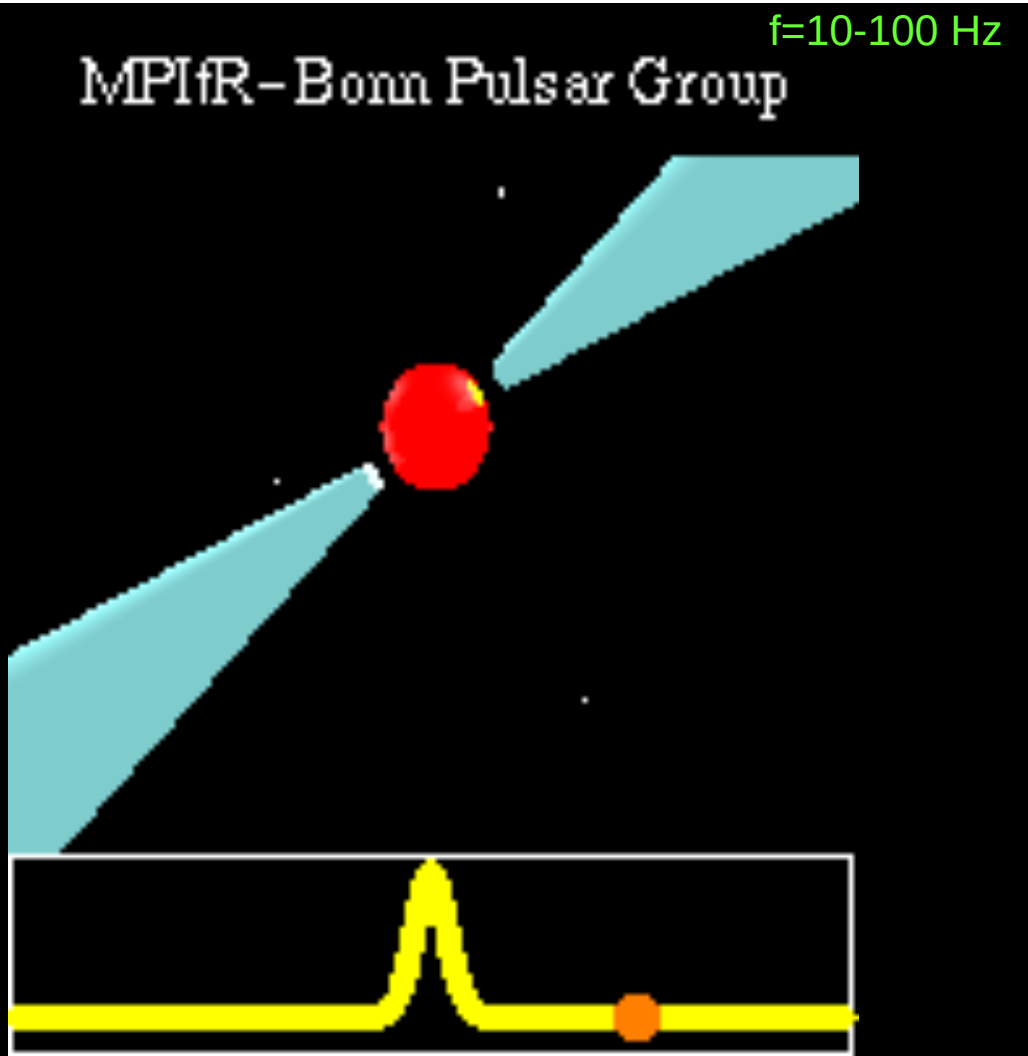
- Neutron stars (Pulsars)

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.

Very strong magnetic fields (10^9 Tesla)
+
Rapid rotation

=

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



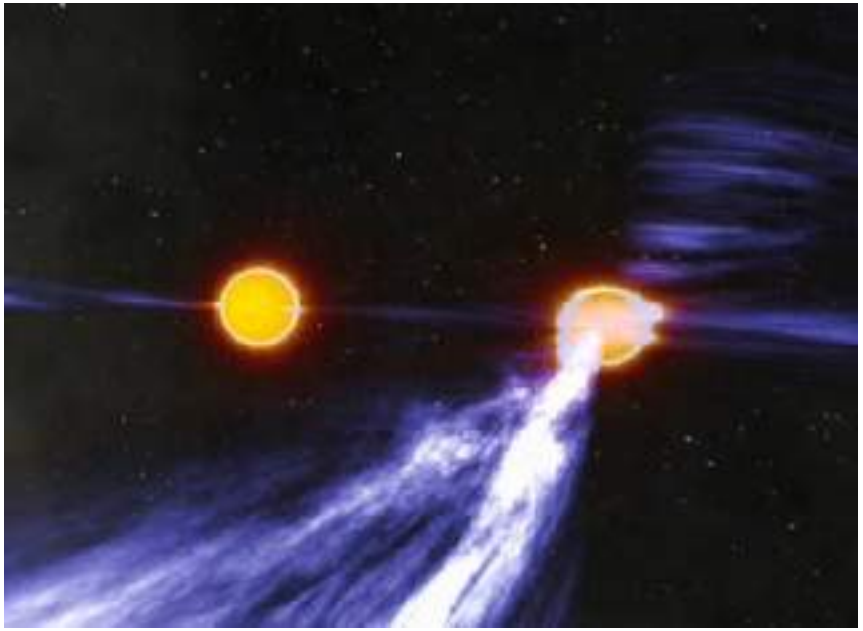
Sources of GW

- Binary systems

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.

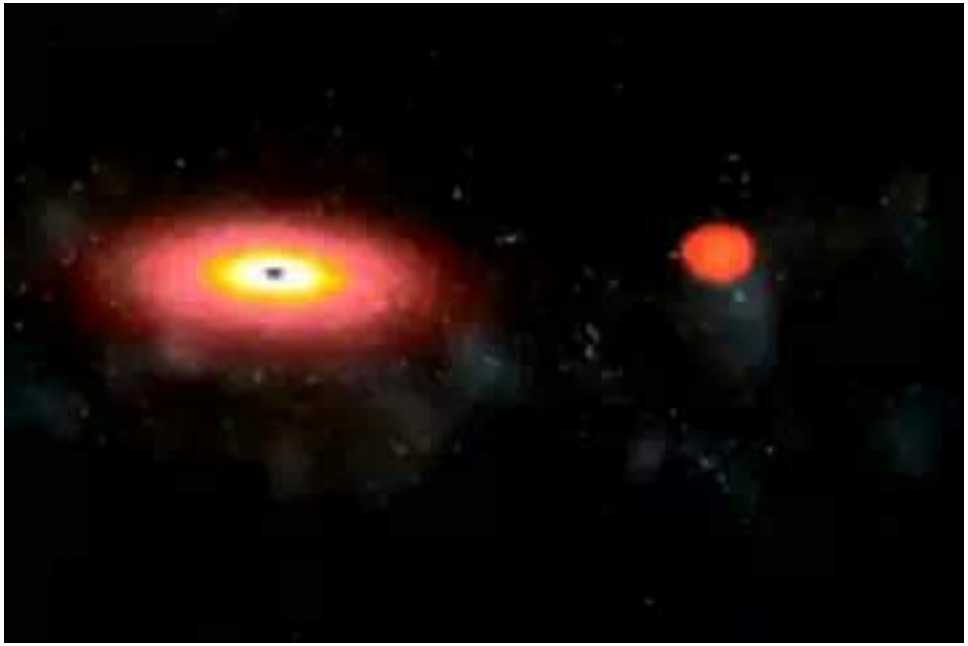
Sources of GW

- Binary systems (NS-NS)



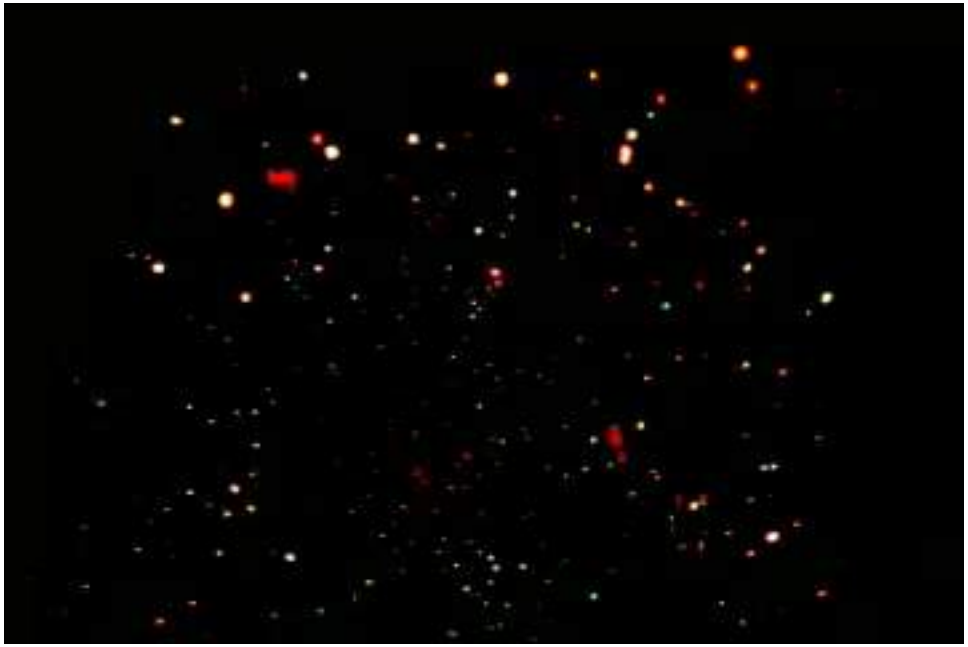
Sources of GW

- 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 (BH-BH)



This sequence begins with the Chandra Deep Field-North in X. 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.

No evidence for GWs until 1974

Russell A. Hulse

Discovered and Studied
Pulsar System
PSR 1913 + 16

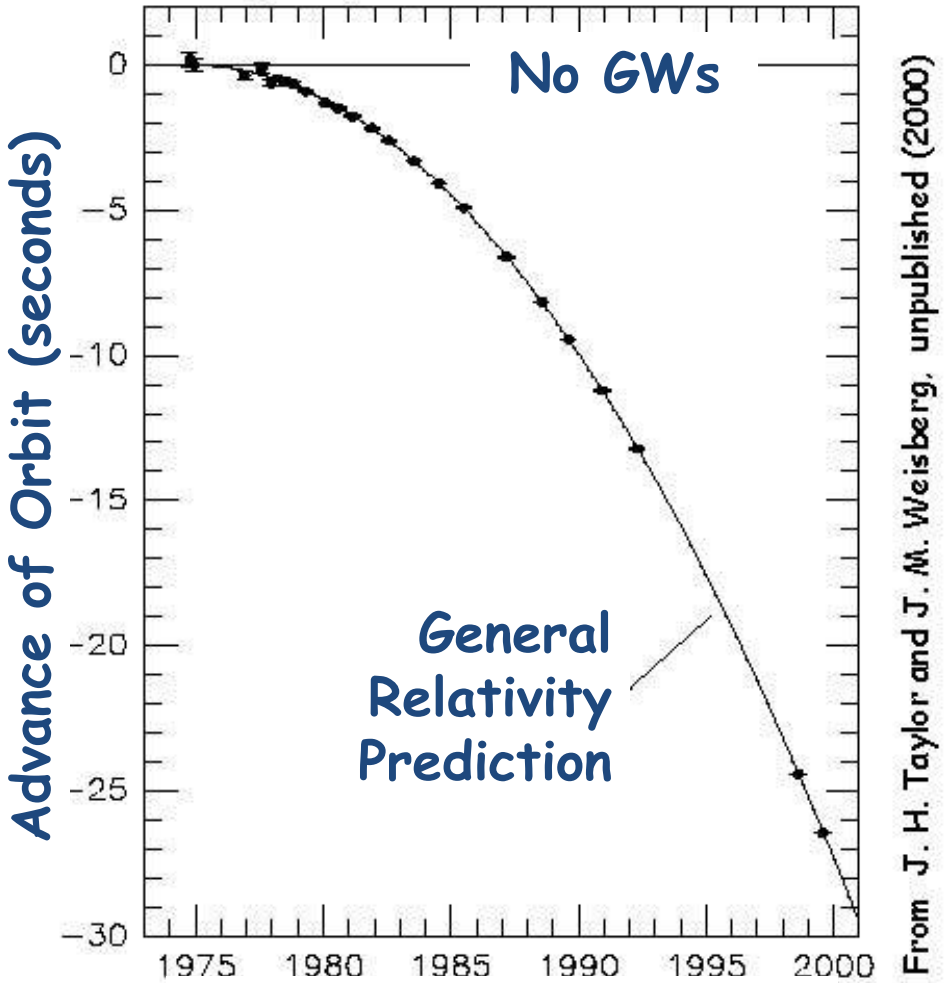
Joseph H.Taylor Jr

Source: www.NSF.gov

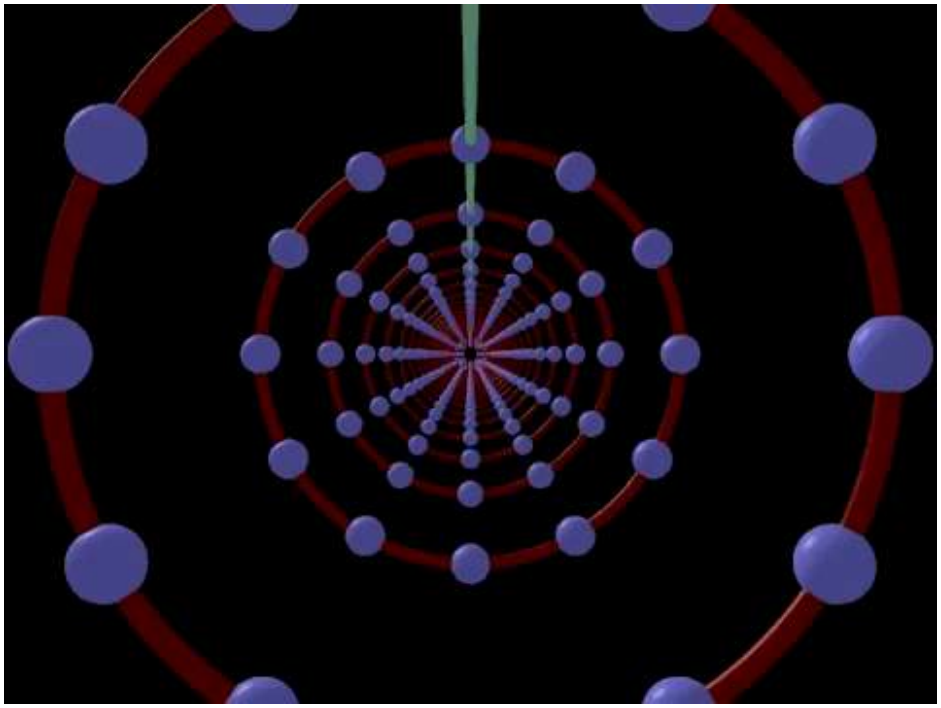
Evidence for gravitational waves!

Nobel Prize in 1993

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



How can we measure a GW?



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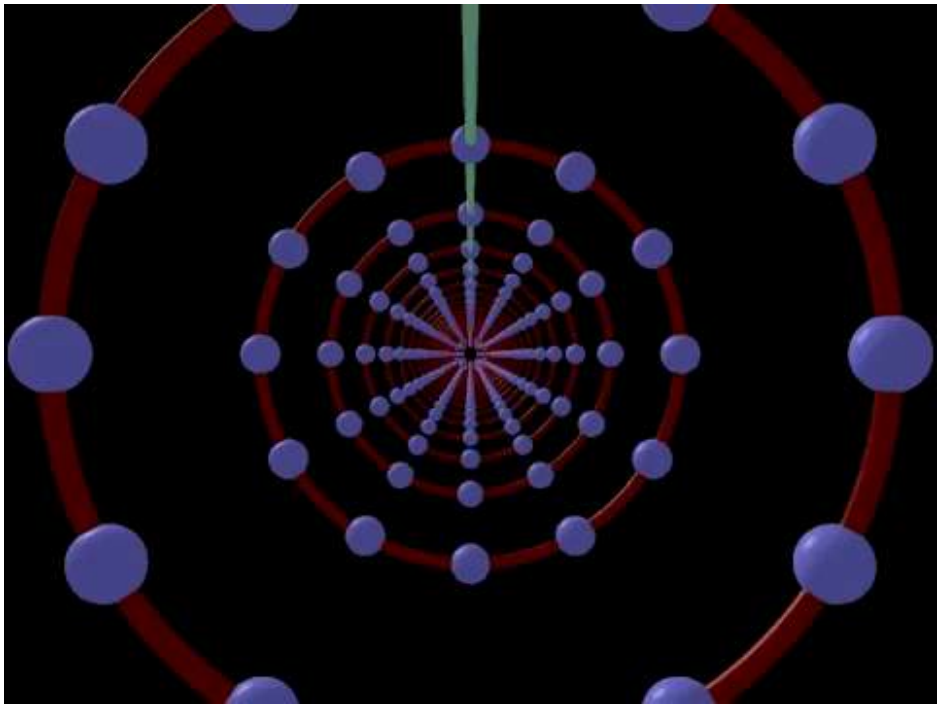
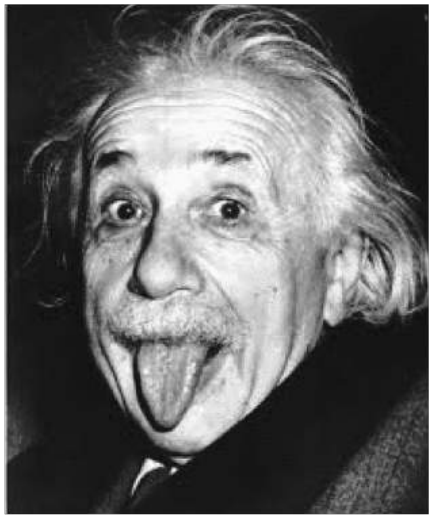
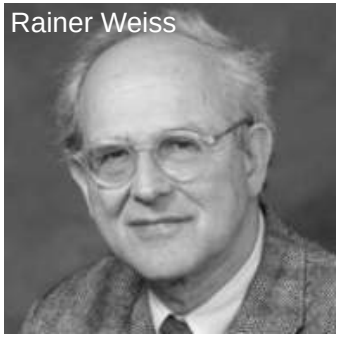
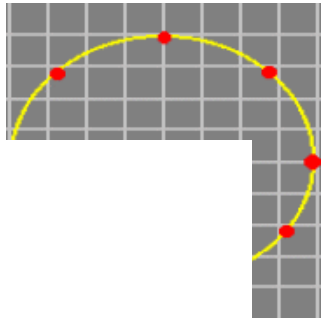
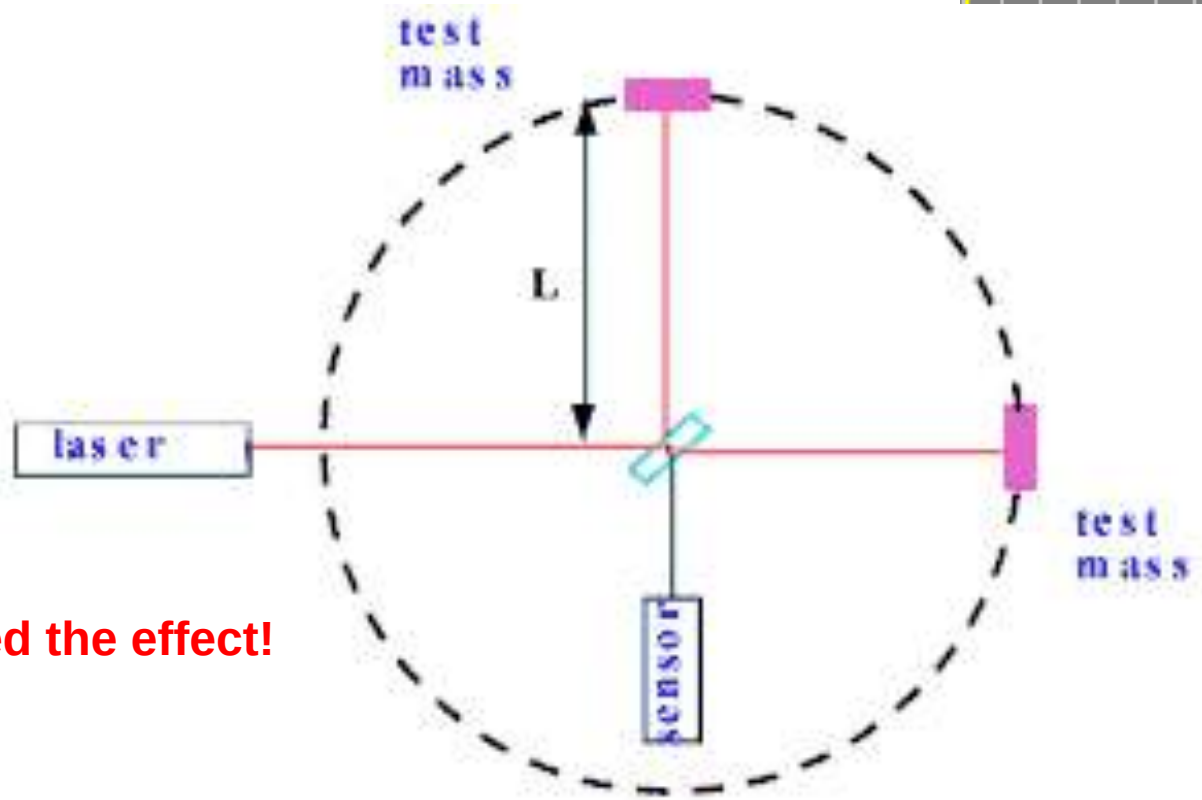




Detecting GWs with light





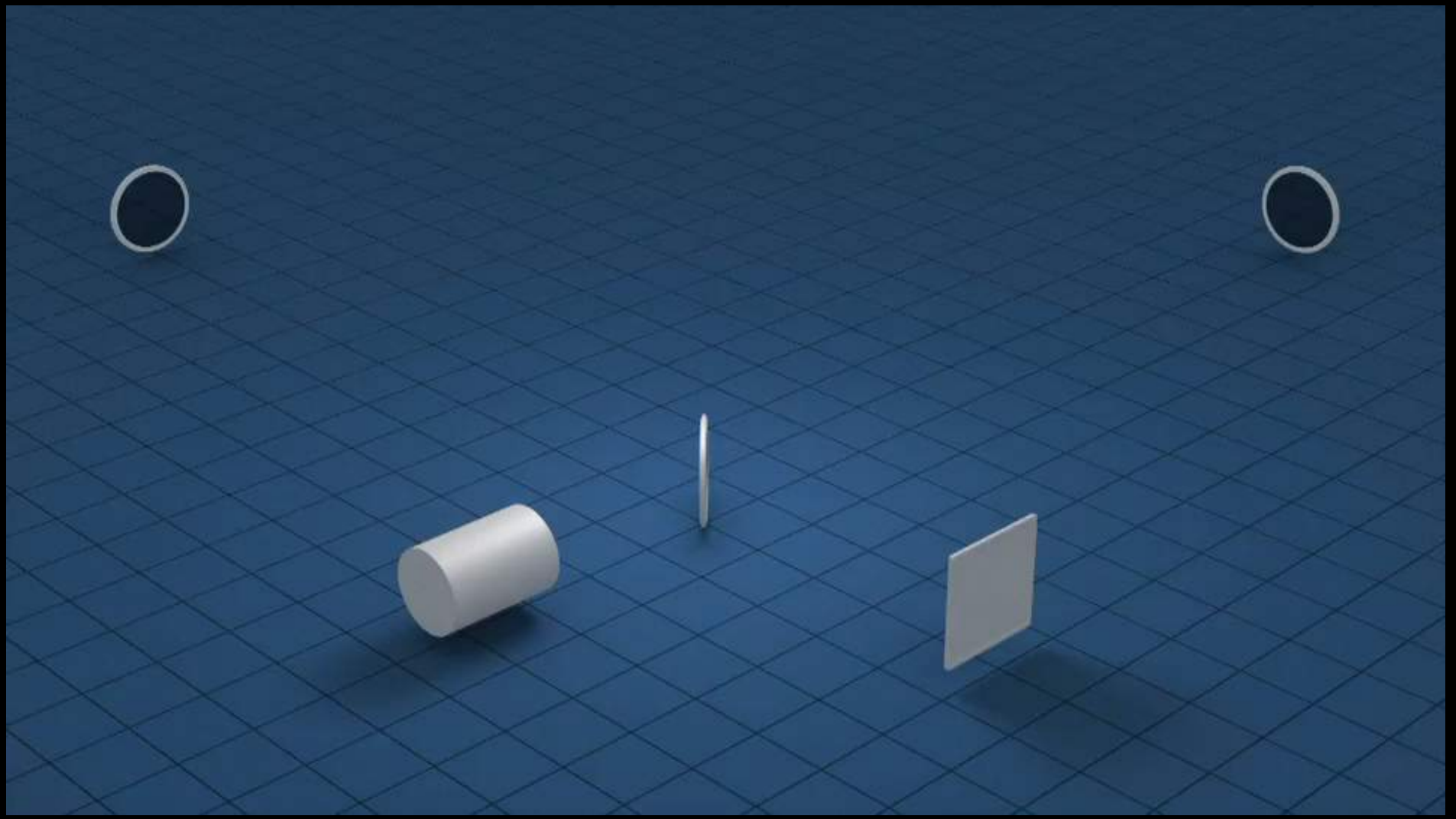


Michelson interferometer

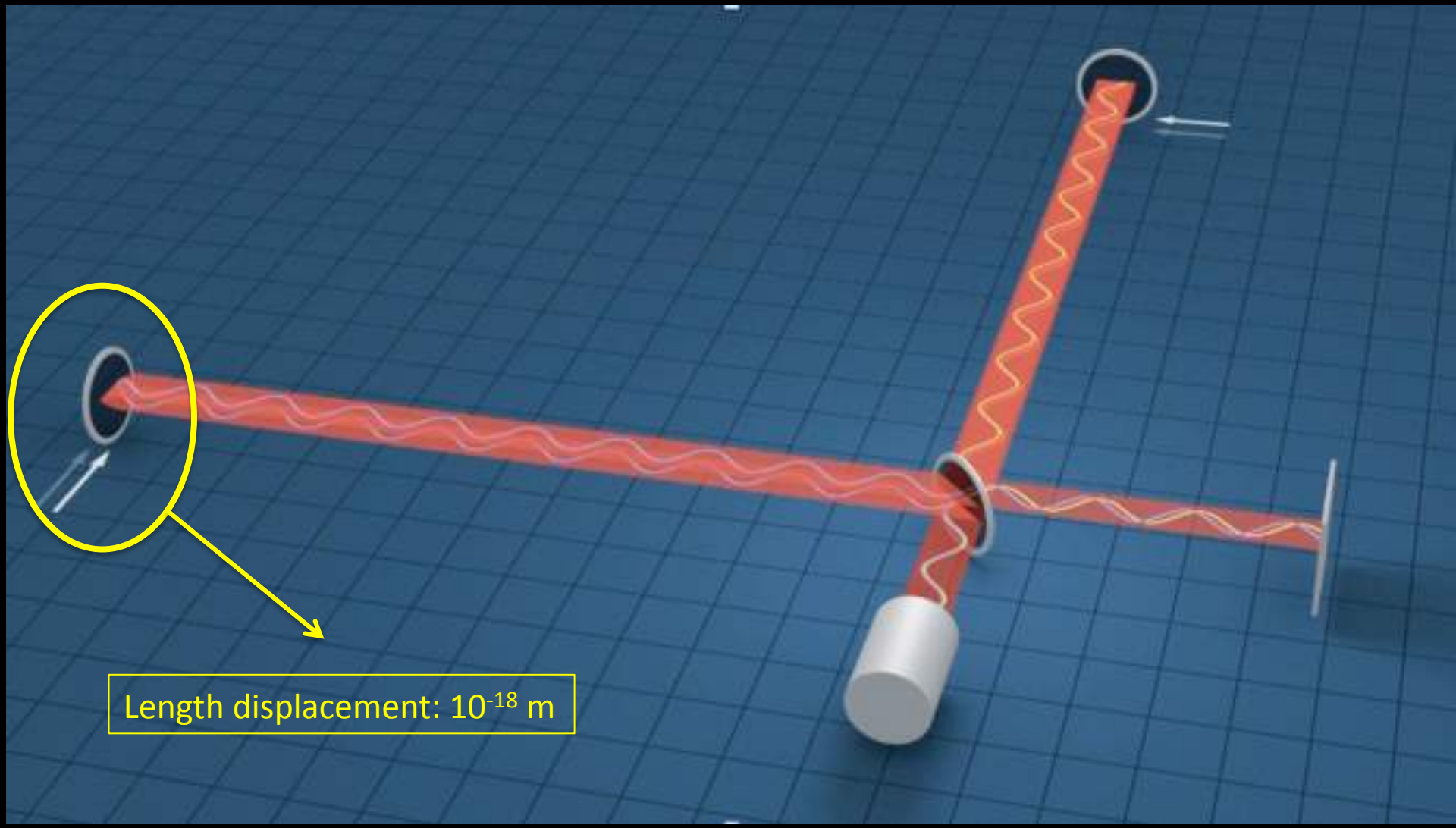
I have greatly exaggerated the effect!

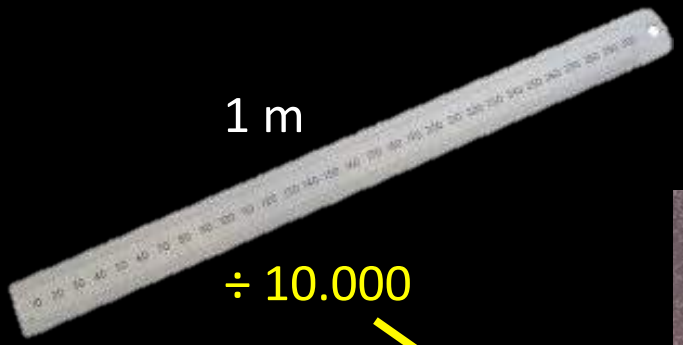
- **Amplitude of a strong wave is about 10^{-21}**
- **The effect of the GW is proportional to the length of the interferometer arms ➔ long arms are needed (of the order of a few km)**
- **For L = 1 km, => $\Delta L \sim 10^{-18}$ m ➔ 1/1000 dimension of a proton**

Detecting GWs with light



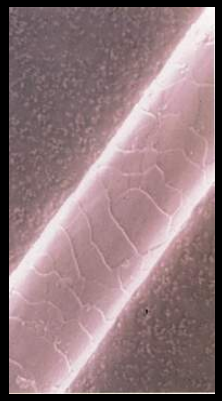
Detecting GWs with light





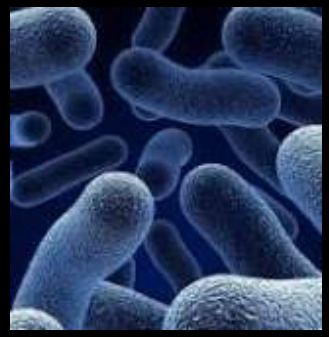
1 m

÷ 10.000



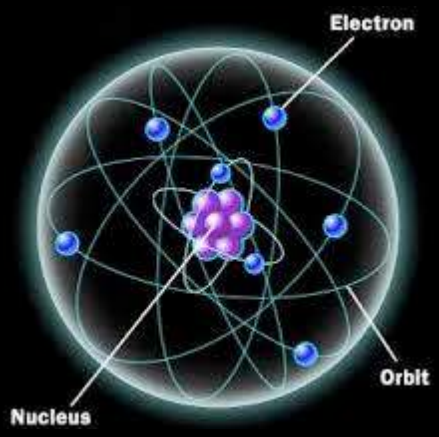
10^{-4} m

÷ 100

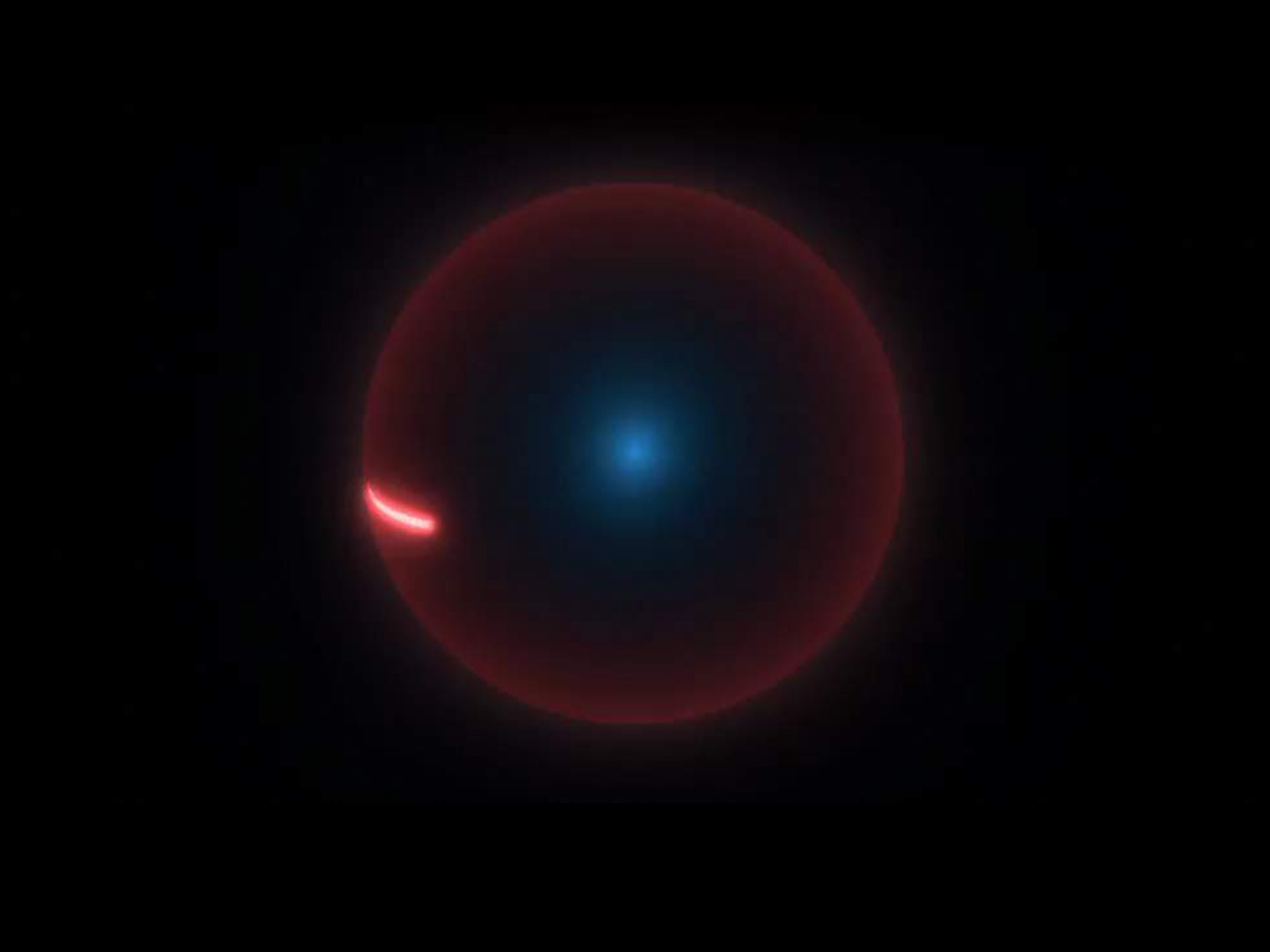


10^{-6} m

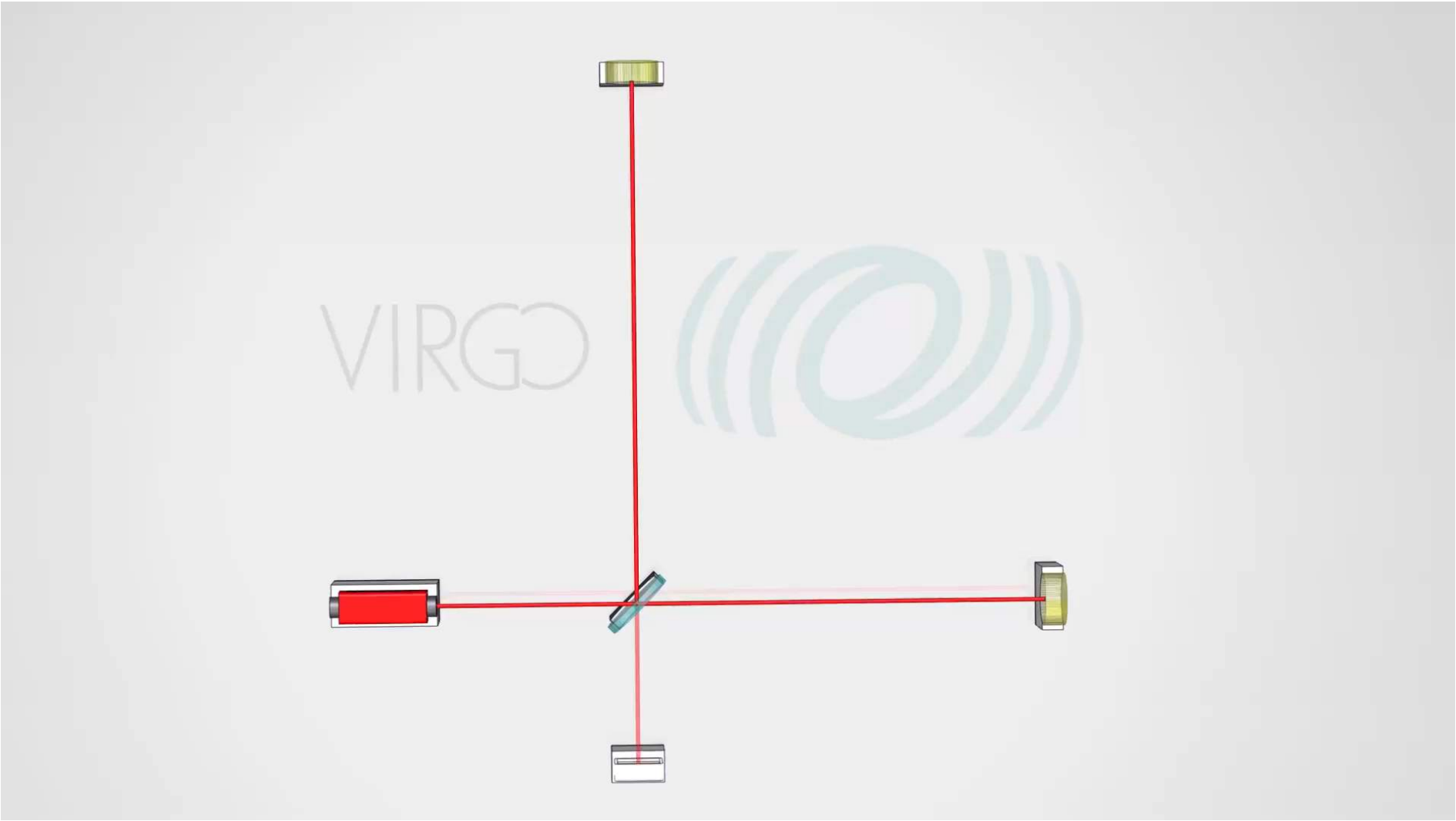
÷ 10.000



10^{-10} m



How to build a GW detector



LE ANTENNE GRAVITAZIONALI NEL MONDO

Hanford
(Stato di Washington
LIGO

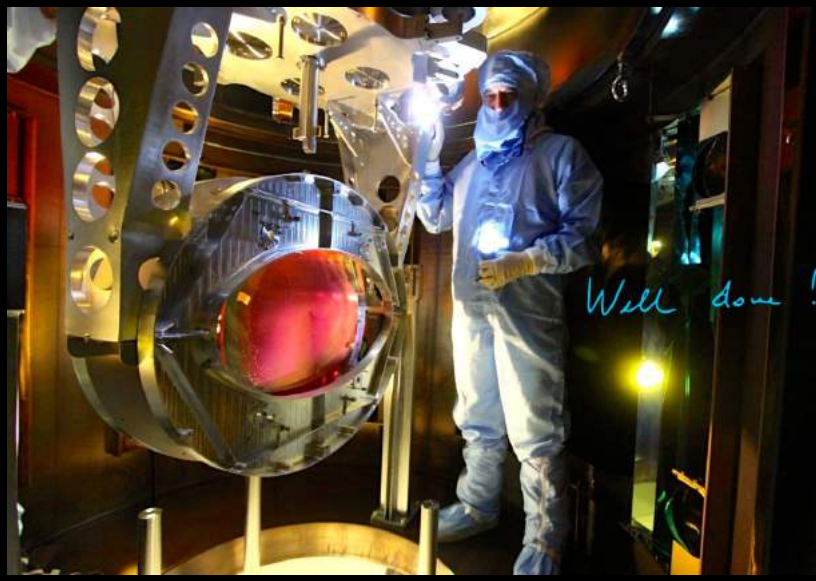
Germania
GEO600

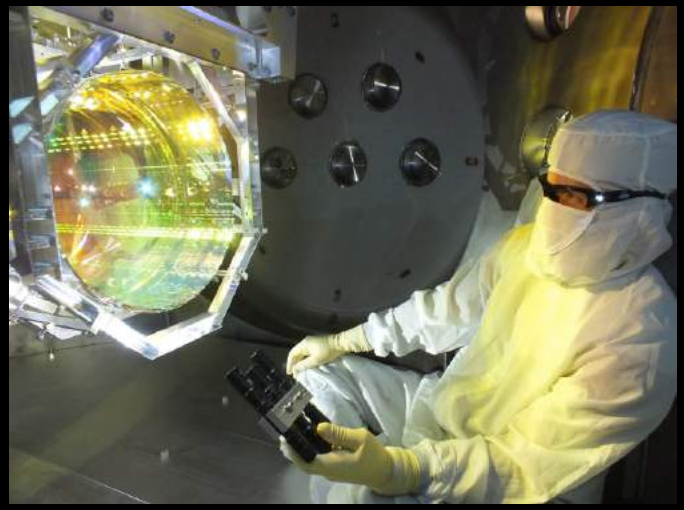
Livingston
(Louisiana)
LIGO

Cascina
(Pisa, Italia)
VIRGO

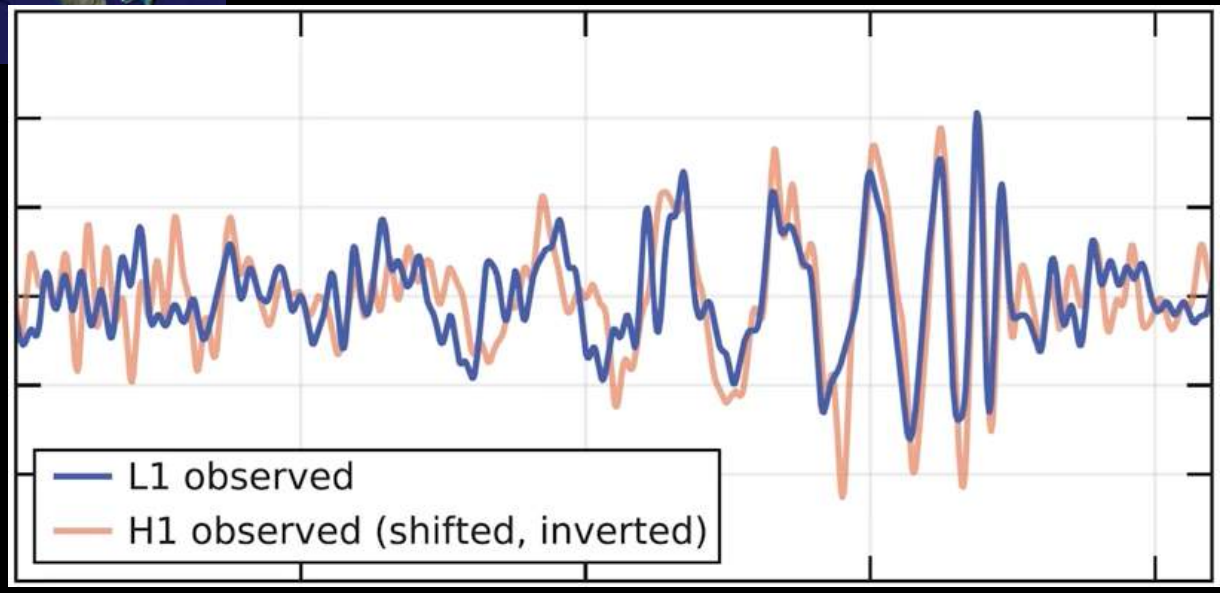
Giappone
KAGRA
(in costruzione)

LIGO India
(recently
approved)

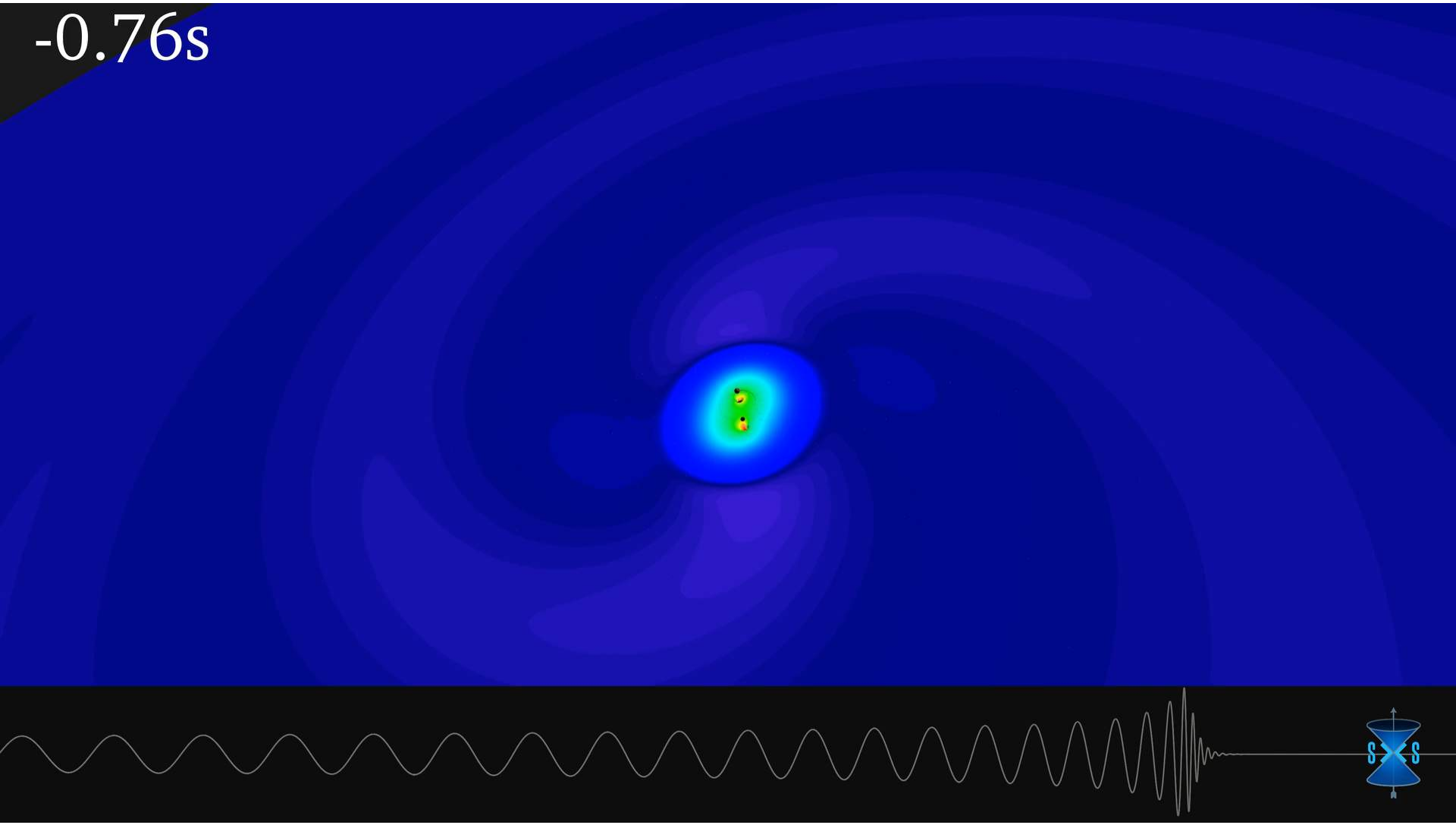

Well done !



September 14th 2015 11:50:45 am



Modeling the GW source



- Initial masses of the two BHs: 36 M_{sol} and 29 M_{sol}
- Final mass = 62 M_{sol}

- 3 solar masses have been converted in gravitational energy

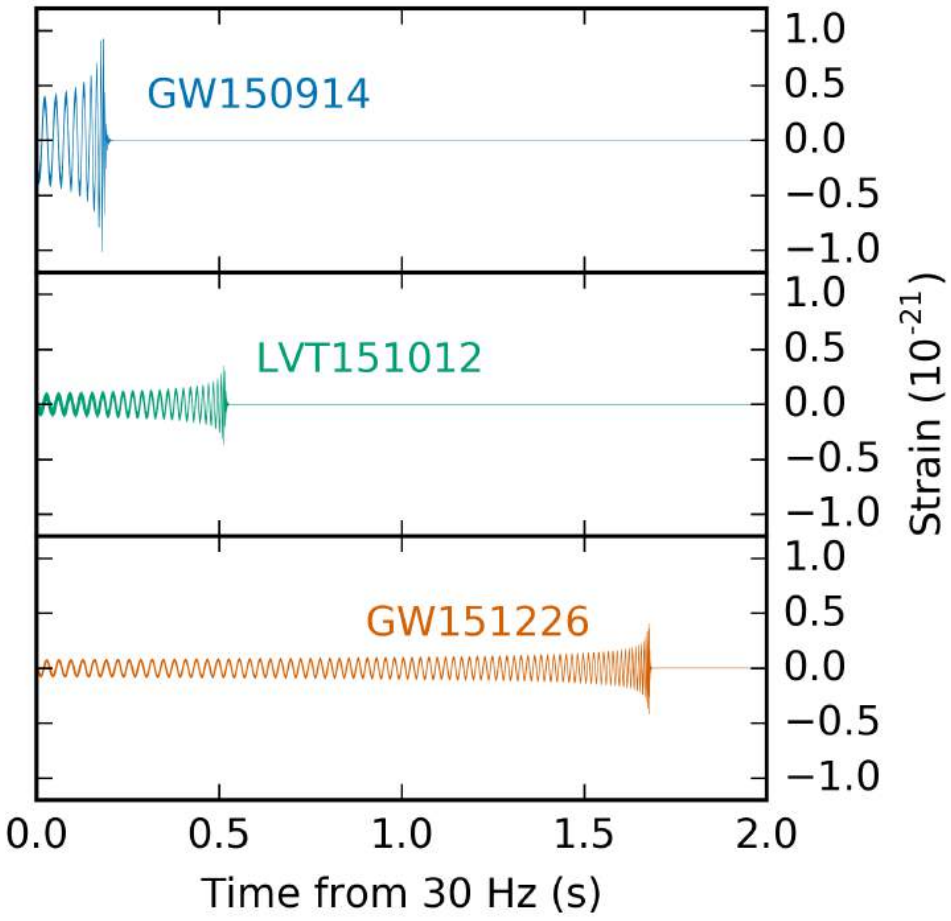
$$E = mc^2$$

50 x light emitted by all the stars in the Universe

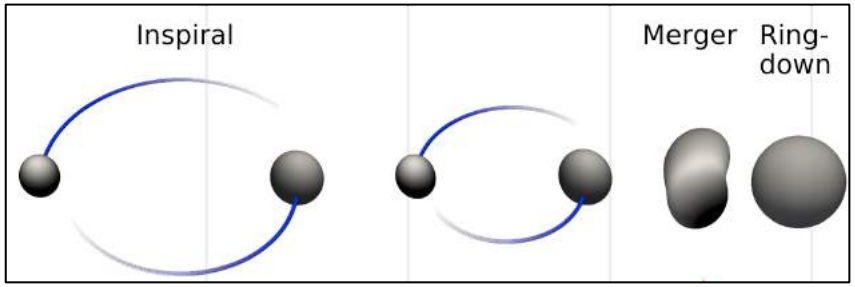
in a few tenths of seconds

- Distance = 1,3 billions light years

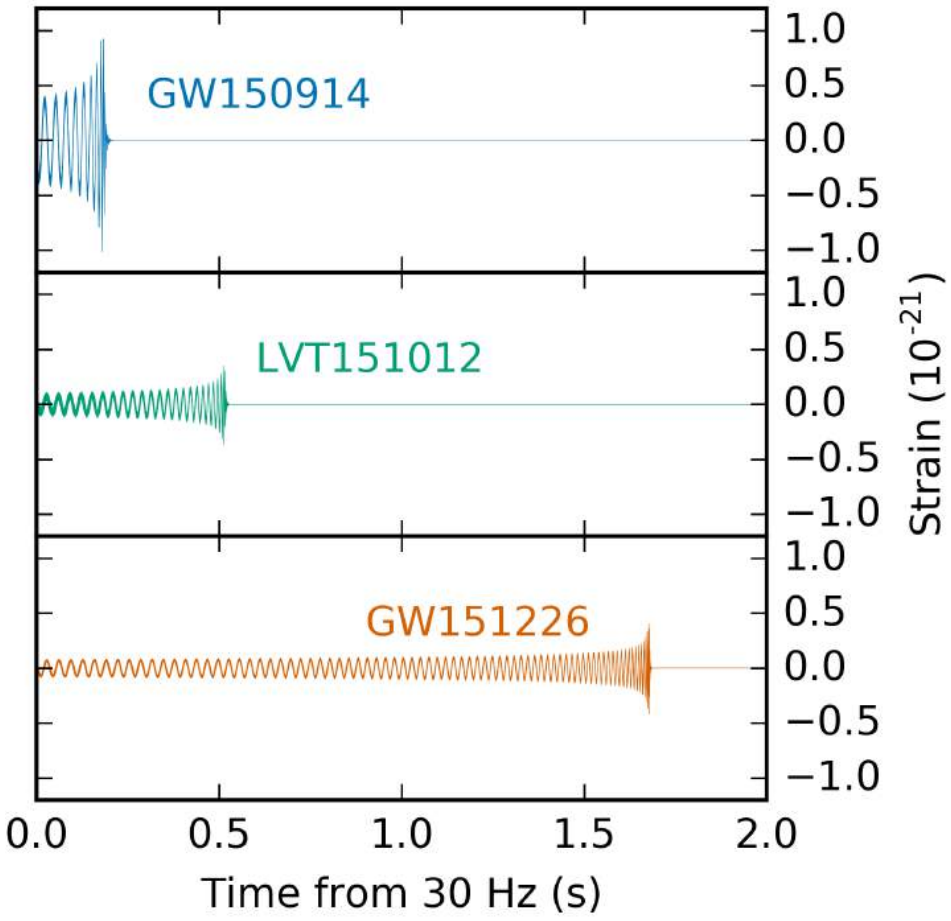
More signals detected



Evolution of a BH-BH binary system



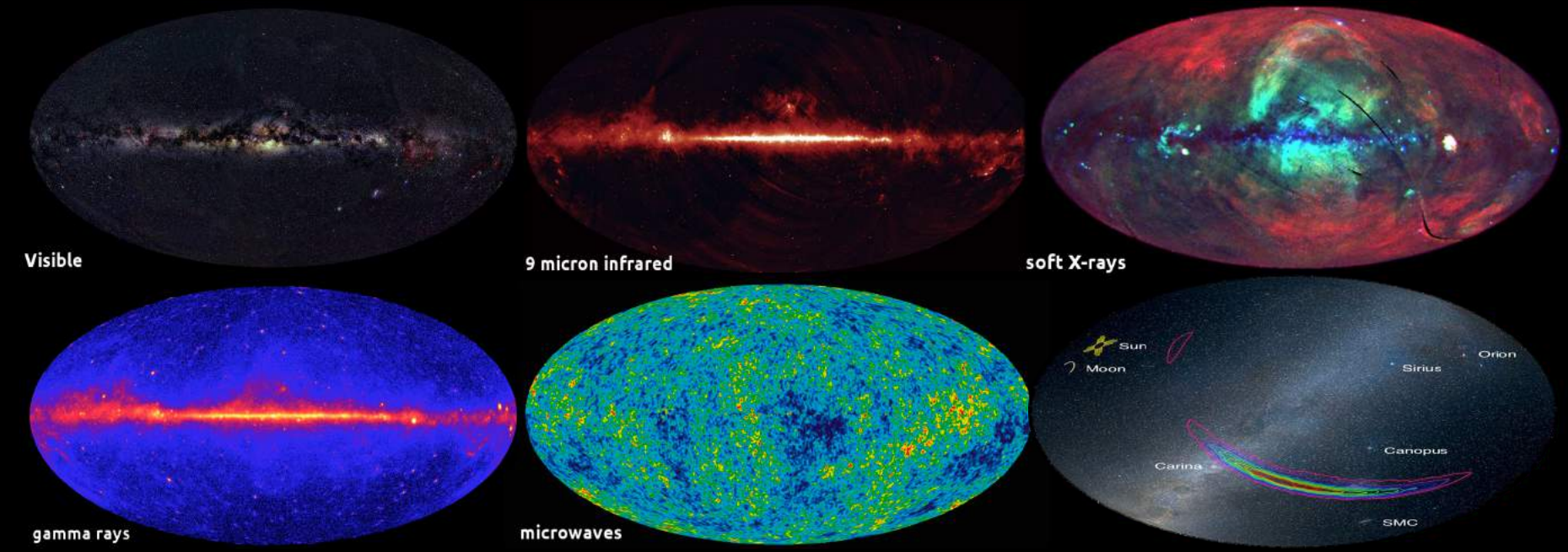
More signals detected



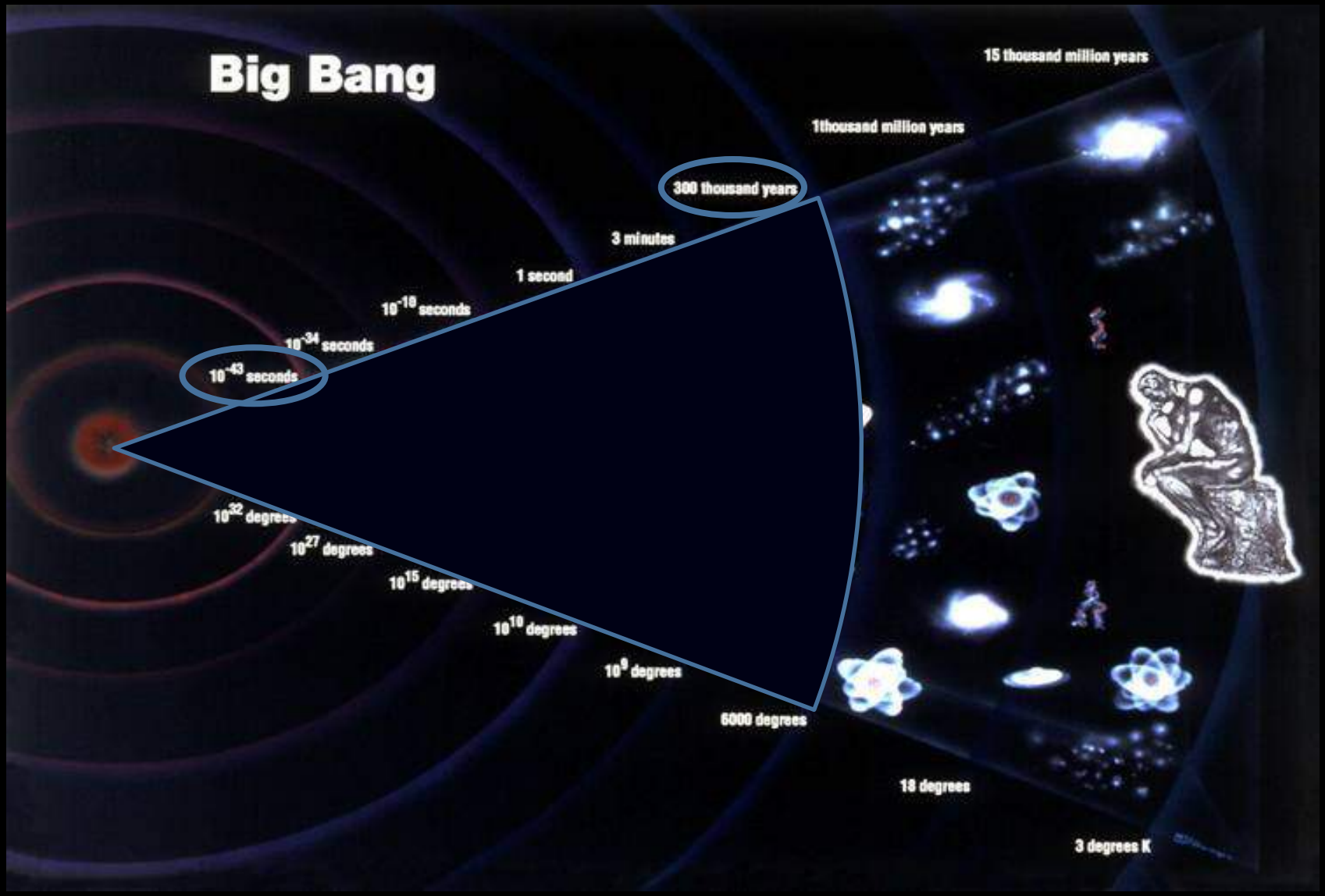
Masses of the BH progenitors

Main	Companion
$36^{+5}_{-4}\,M_\odot$	$29^{+4}_{-5}\,M_\odot$
$23^{+18}_{-6}\,M_\odot$	$13^{+4}_{-5}\,M_\odot$
$14^{+8}_{-4}\,M_\odot$	$7.5^{+2}_{-2}\,M_\odot$

GW astronomy

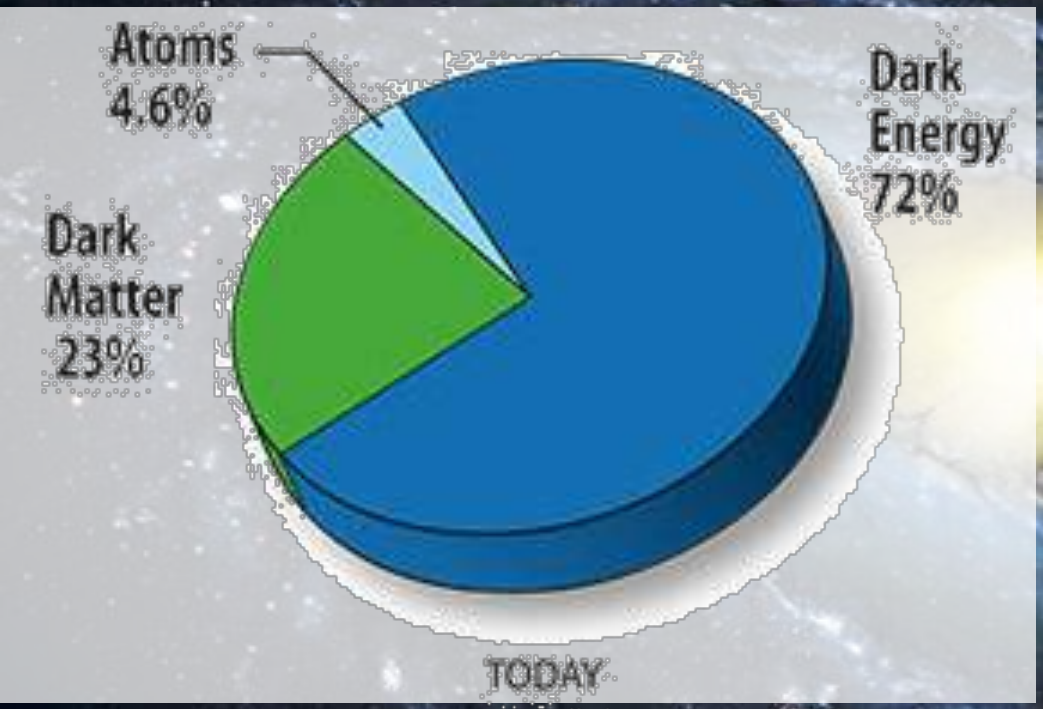


GWs can bring us info unaccessible to all other messengers: light, neutrinos and cosmic rays


Big Bang
15 thousand million years
1thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K

Multimessenger Science

- Current (lack of) understanding of the Universe



- To re-compose a photograph of the Universe we need to observe it with several “eyes”:
  - E.M. astronomy
  - Neutrino astronomy
  - Cosmic rays
  - Gravitational waves

Multi-messenger observation!

The most incomprehensible thing about the Universe is that it is comprehensible.

- Albert Einstein

The Universe is comprehensible because it is governed by scientific laws; that is to say, its behaviour can be modelled.

- Stephen Hawking

The End