VIRGO

Programma

- **Introductive talk (30 min)**

- **Control room, central interferometer visit (45 min)**

- **Tunnel visit: West arm at 1500 m (45 min)**

VIRGO

A gravitational-wave detector

(http://public.virgo-gw.eu)

Istituto Nazionale di Fisica Nucleare

Firenze-Urbino
Napoli
Perugia
Pisa
Roma
Roma Tor Vergata

Centre National de la Recherche Scientifique

Annecy
Lyon
Nice
Orsay
Paris

from 2006 Amsterdam 

from 2009 Budapest 

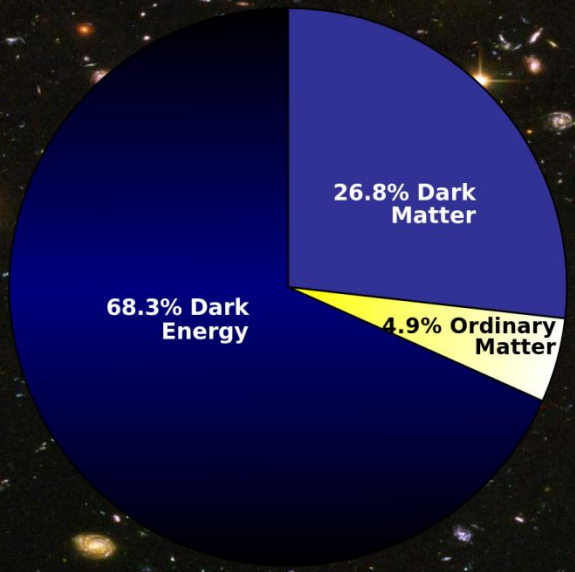
Warszawa 

> 200 physicists, engineers, technicians !

EGO – European Gravitational Observatory

Dark Matter and Dark Energy

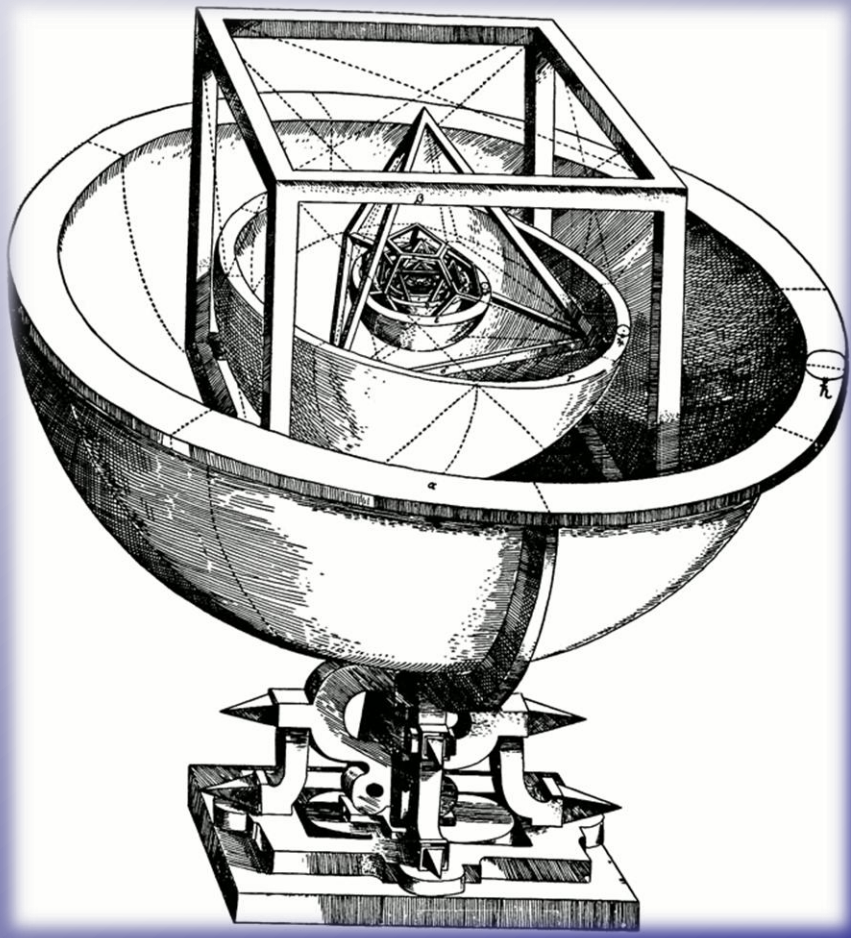
Only 5% of visible celestial objects is constituted by ordinary matter !!



Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team STScI-PRC04-07a

Musica universalis



- **J.Kepler** wrote in *Harmonice Mundi* (1618) that every planet produce a musical note during its motion around the Sun.

- During Kepler's times, it was thought that the Earth and other planets orbited around the Sun inside each own sphere (like in Dante's *Divina Commedia*)

- It was also thought that the ratios between the radii of the spheres were similar to the musical intervals (musica universalis).

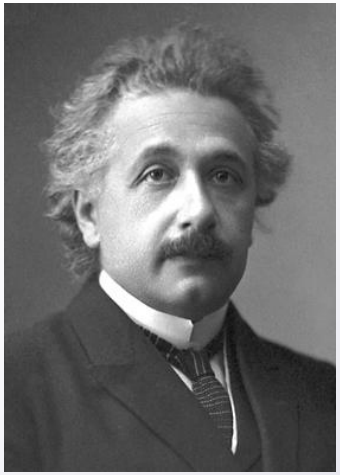
For completely different reasons universe actually generates sounds!!

- The sky has been studied, up to now, essentially through EM radiation, originated by temperature, electric charge, magnetic properties of the stars.

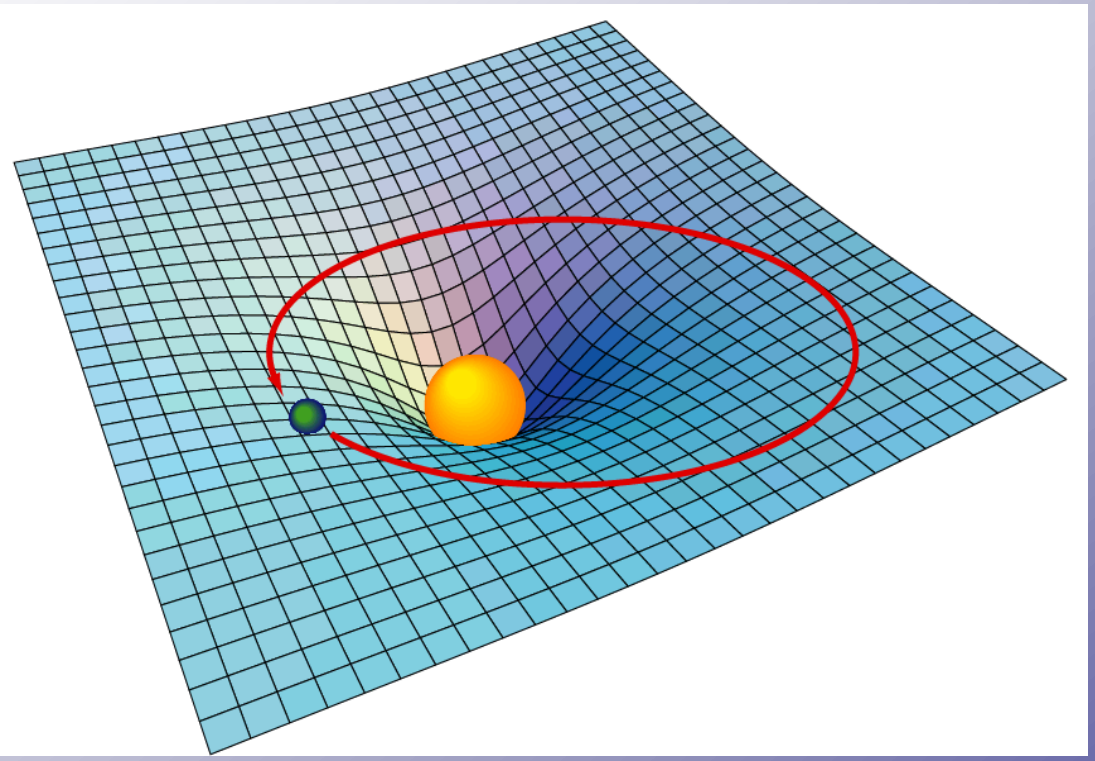
- Gravitational Waves have a completely different nature, since they are due to the moving mass of celestial bodies.

- Hence GW's may give new information, completely independent with respect to EM radiation; in particular about dark matter.

Space-time geometry



Einstein predicted that low mass bodies tend to move towards big mass bodies, not because they are "attracted“ by a force, but because low mass bodies move inside the space-time deformed by big mass bodies.

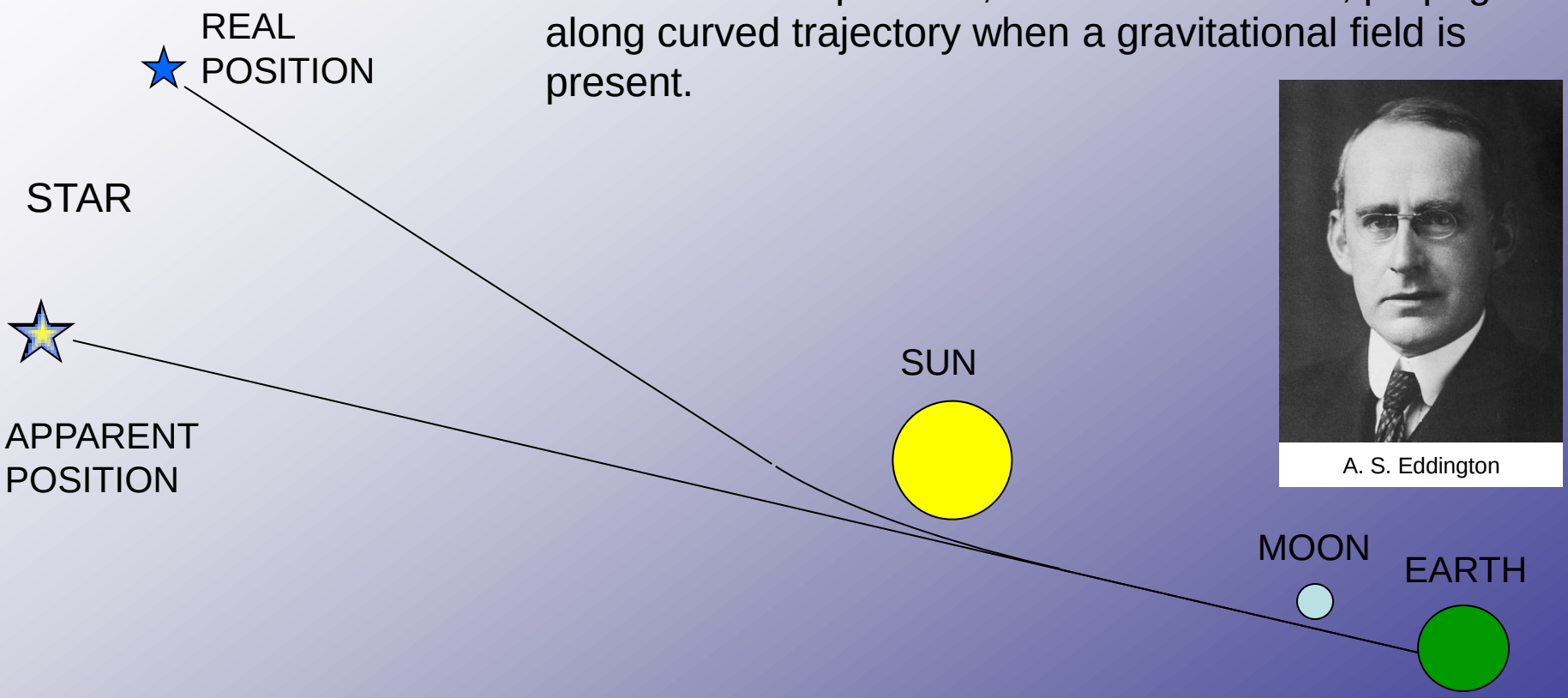


- Imagine the space-time as a rubber sheet.
- A mass on its surface will generate a deformation.
- A smaller mass placed on the sheet will slip towards the bigger mass.

Space-time geometry

Space-time is distorted by any gravitational field: space geometry is not flat

Therefore even photons, that have no mass, propagate along curved trajectory when a gravitational field is present.

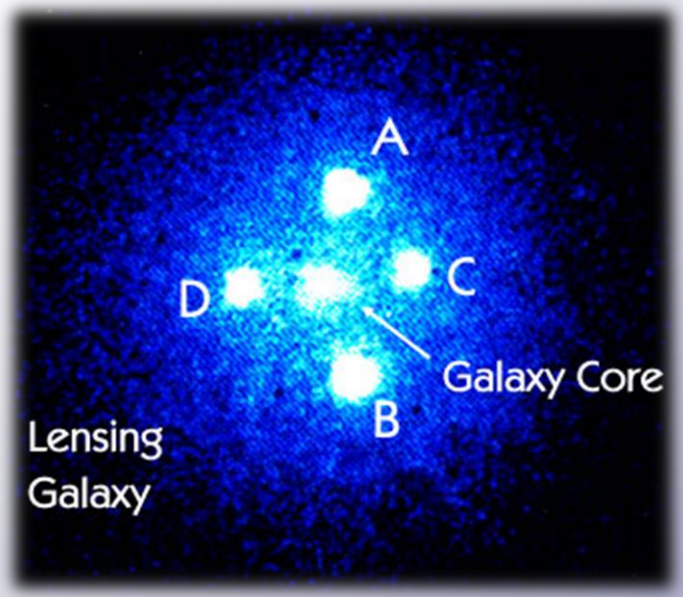


A. S. Eddington

This amazing effect of gravity on light was verified by Eddington with an expedition he organized to the island of Principe (off the west coast of Africa) in order to observe the total solar eclipse of May 29, 1919.

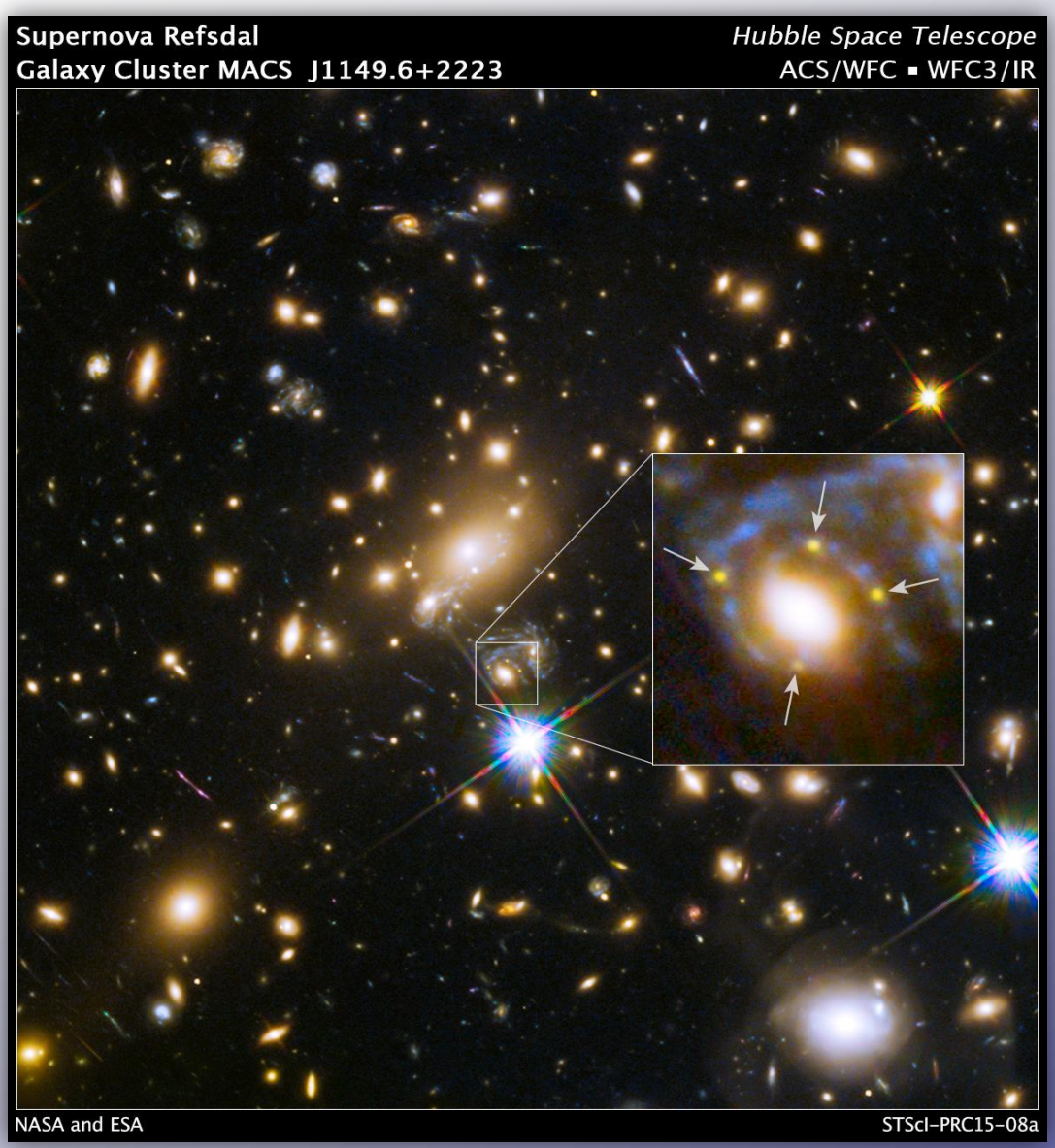
Gravitational lenses

Einstein's cross



- Gravity acts on light rays as a lens
- Einstein's cross, located in the Pegasus constellation, consists of 4 symmetric images of the same star, 8 billions light years from us, that is almost perfectly behind the nucleus of a galaxy distant ''only'' 500 millions light years
- Gravitational lenses can also be used as astronomical magnifying glasses !!

Gravitational lenses



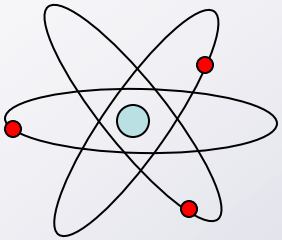
- First observation of the effect of gravitational lenses on the light of a supernova (March 2015).
- 4 simultaneous images of the same supernova are produced by the gravitational field of the galaxy inside the highlighted box.
- The galaxy and supernova distances are 5 billions and 9 billions light years respectively.

Two forces compared

ELETTROMAGNETISM

Electric charge (±)
Electric Force

$$F = C\frac{q \bullet Q}{R^2}$$



Atoms

Accelerated motion
Maxwell

ELECTROMAGNETIC WAVES

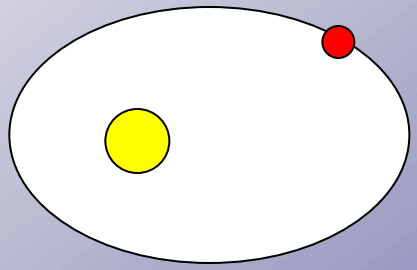
light
radio TV phone
microwaves
X-rays, γ-rays

c = 300 000 000 m/s

GRAVITATION

Mass
Gravitational Force

$$F = G\frac{m \bullet M}{R^2}$$



Solar System

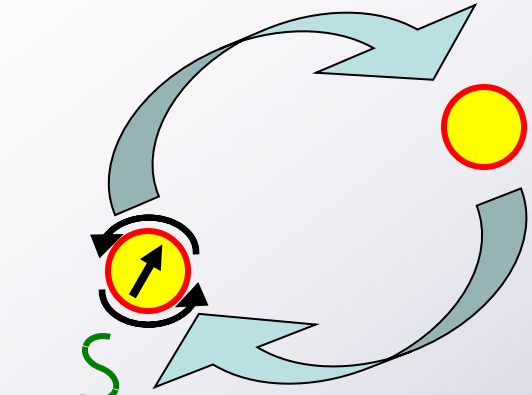
Accelerated motion
Einstein

GRAVITATIONAL WAVES

?

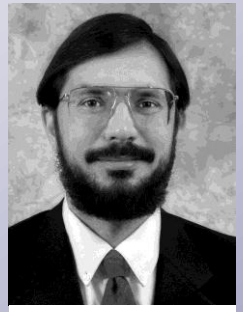
Now we know they exist !!

The indirect detection: PSR 1916+13



E. M. Waves

J. Taylor



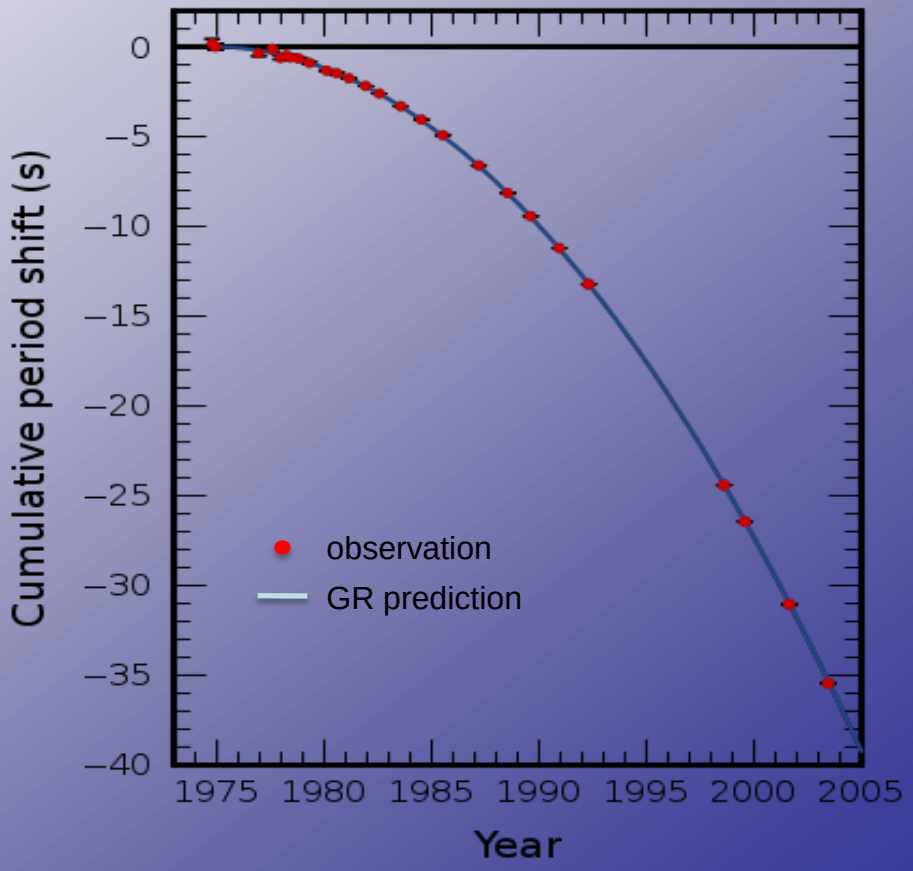
R.Hulse

Gravitational Waves

8 hour orbital period

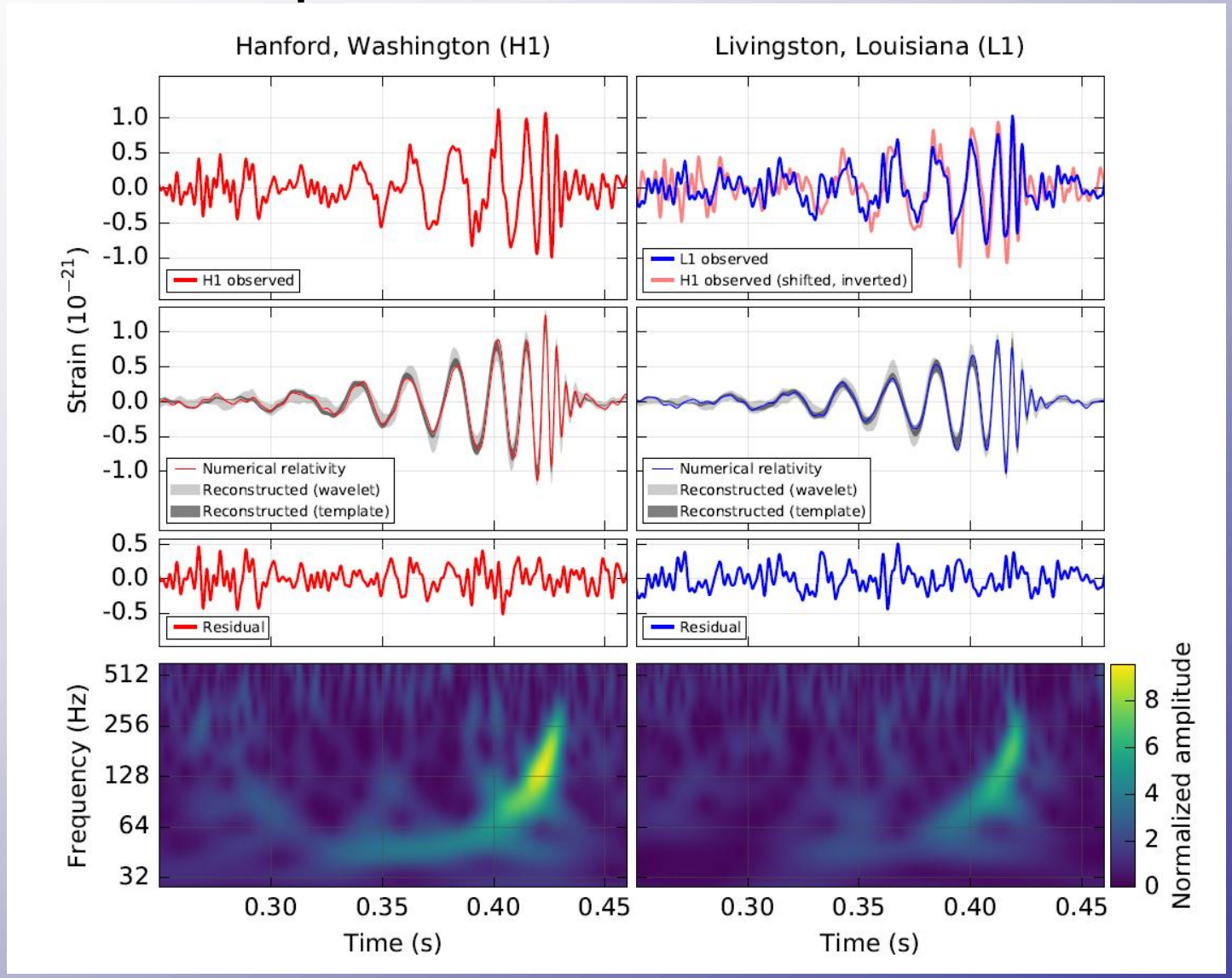
The system loses energy emitting gravitational waves, exactly as expected.

Coalescence in 400 millions years: the two stars will merge together



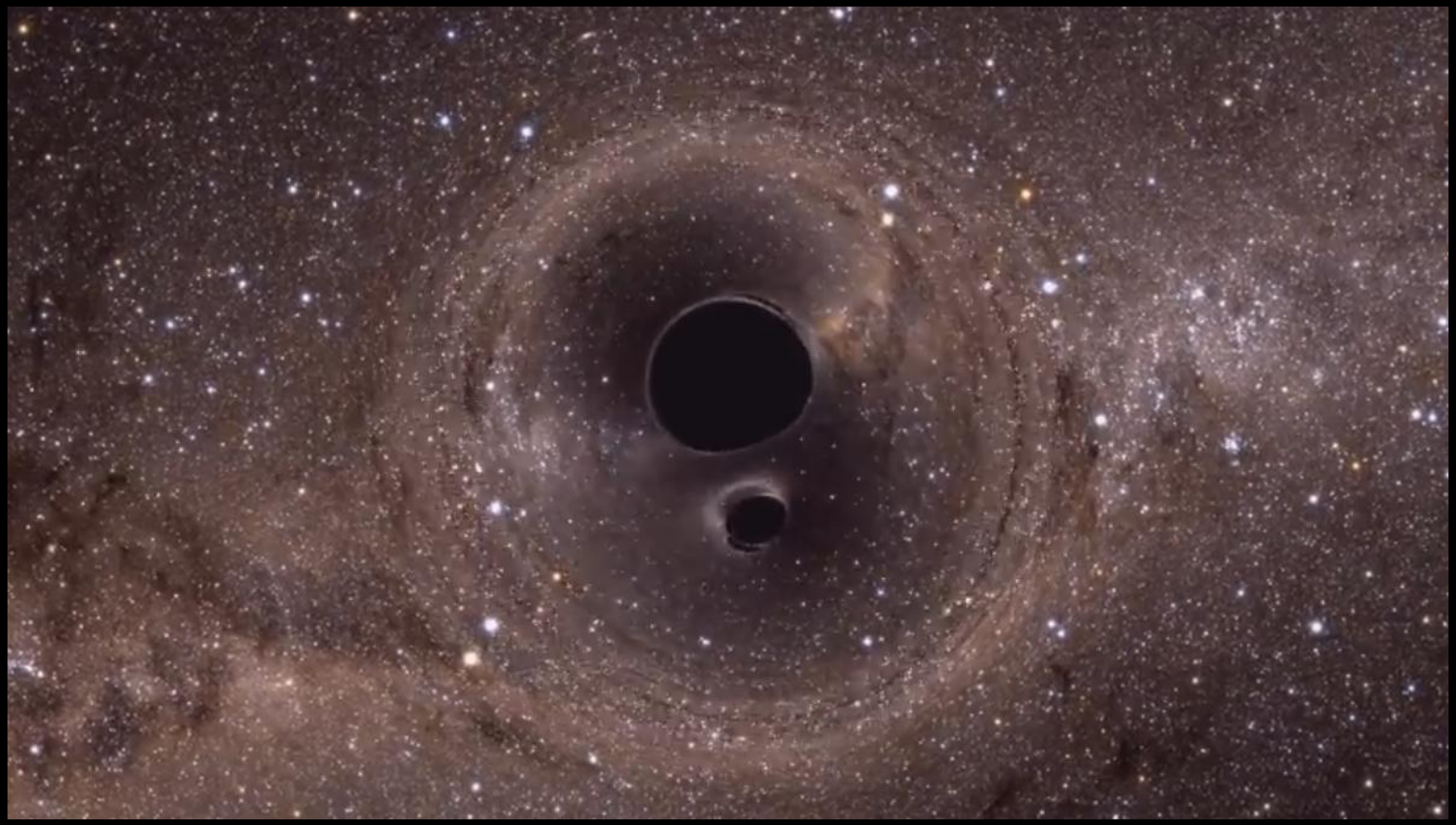
The ‘first detection’

September 14th 2015 at 11:50:45 CET

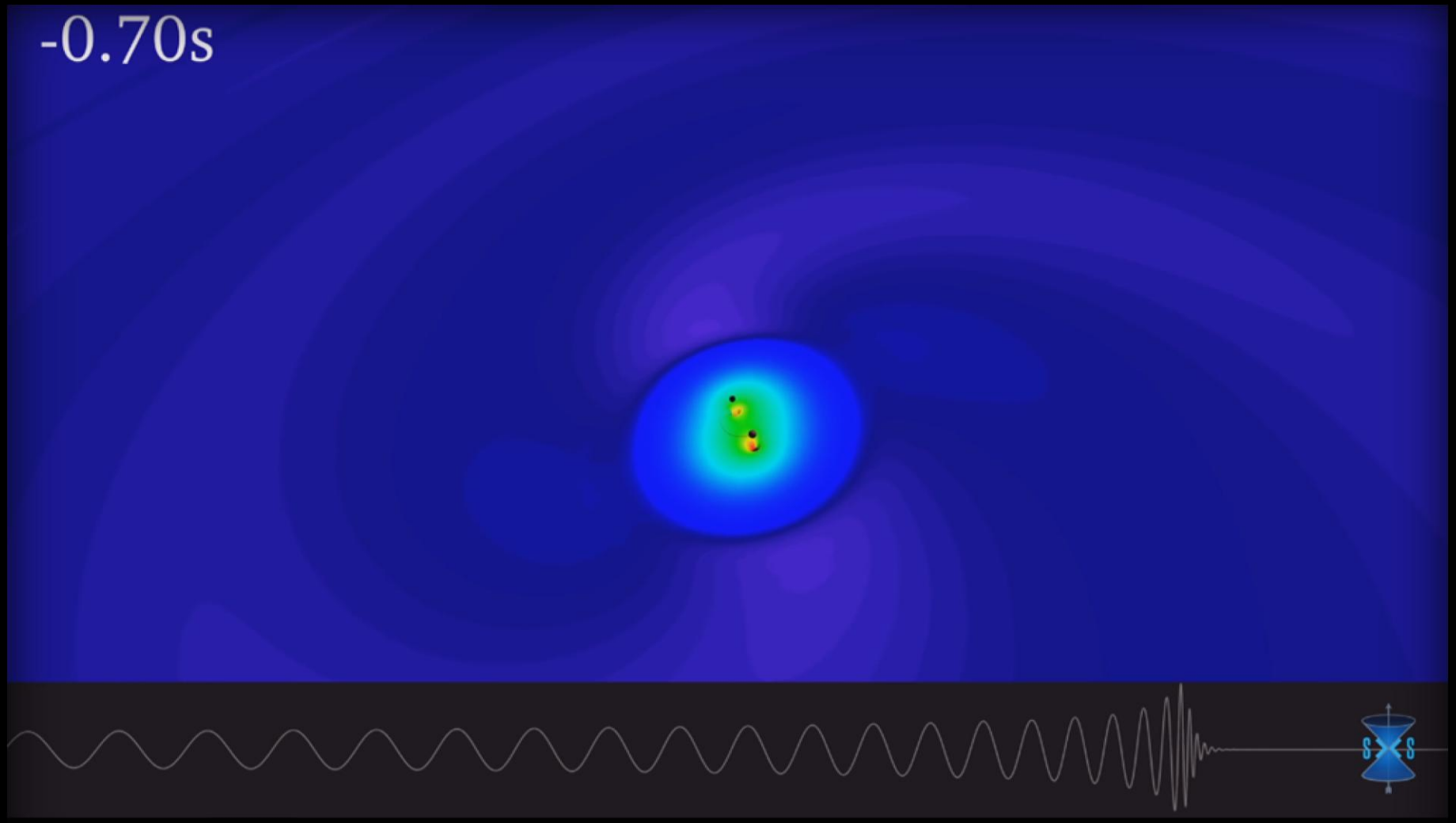


False alarm probability: 1/203000 years !!

The ‘first detection’



The ‘first detection’



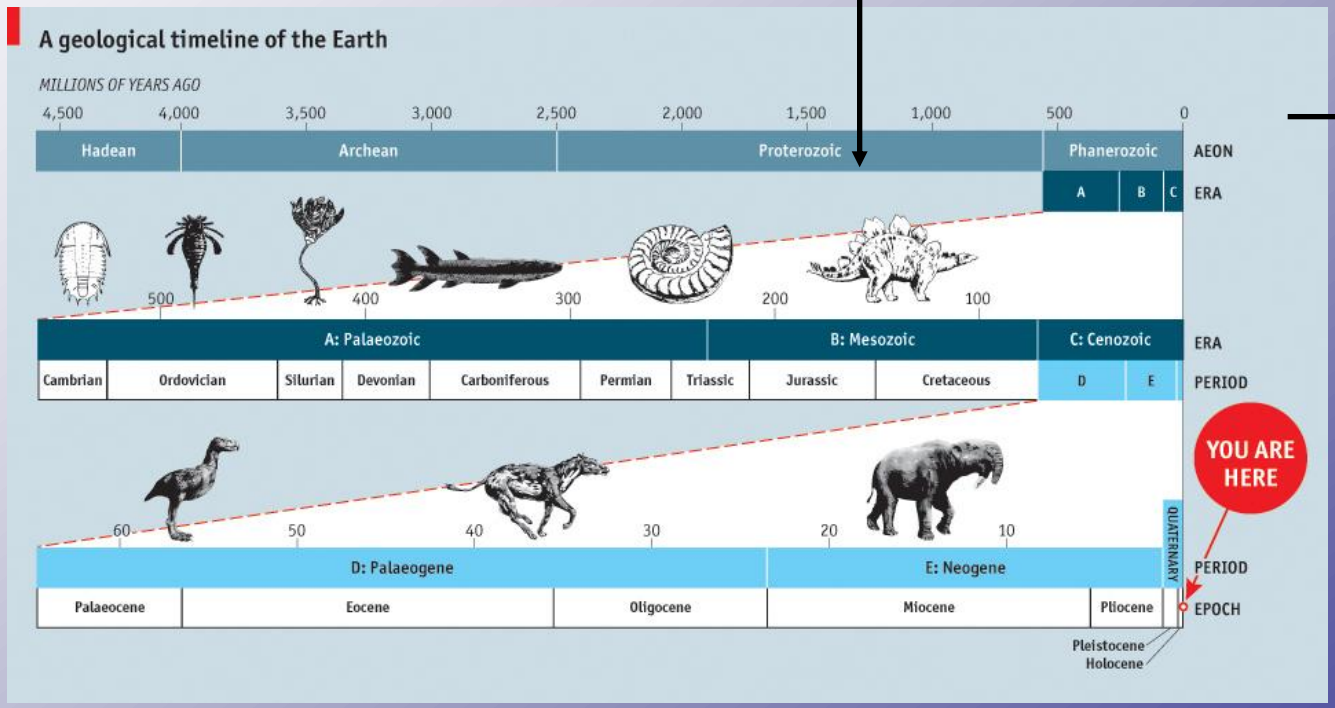
The ‘first detection’

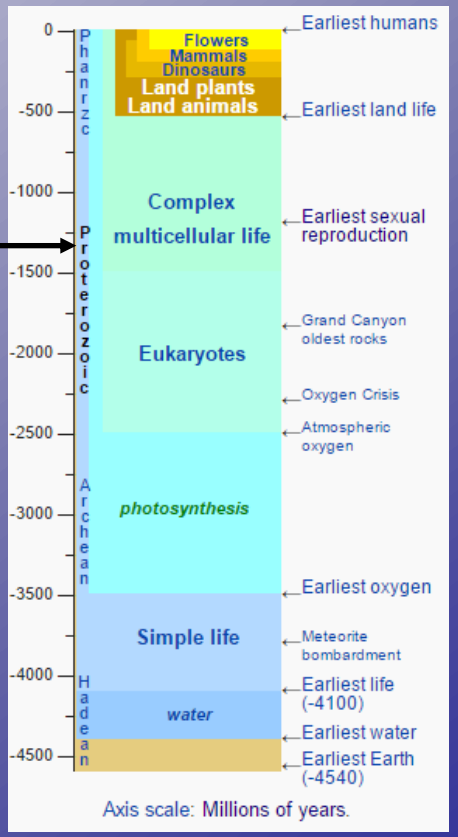
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

3 Solar Masses are converted in Gravitational Waves !!!

1.34 Billions light years !!!

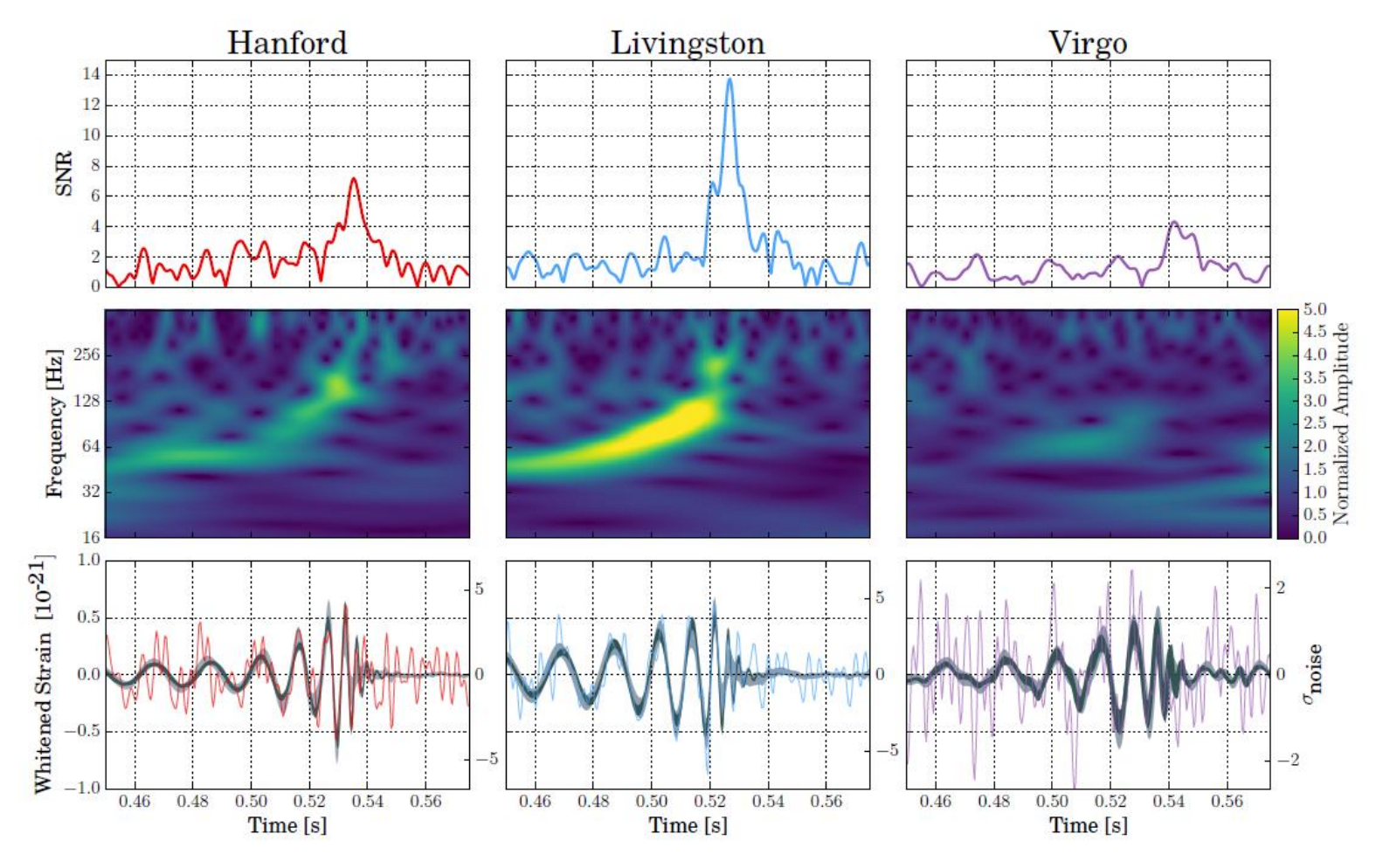
First detection





Virgo first detection

14th August 2017 at 12:30:43 CET



False alarm probability: 1/27000 years !!

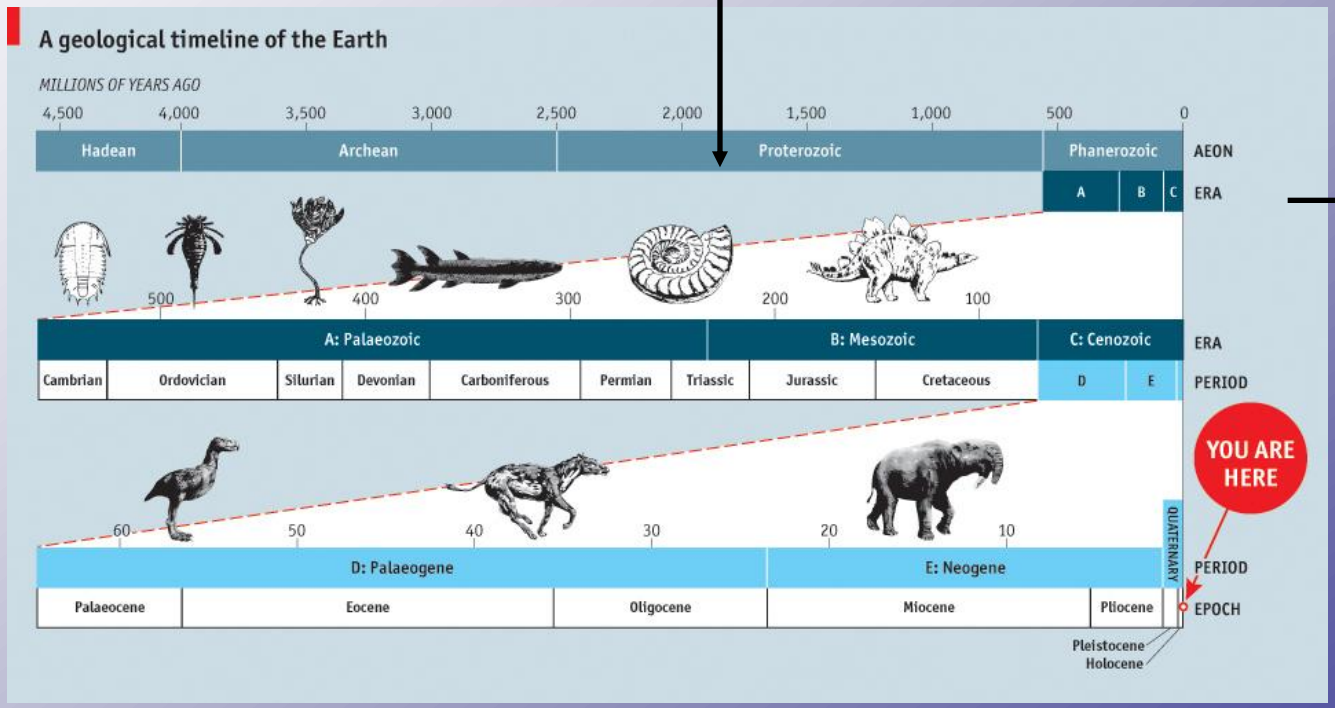
Virgo first detection

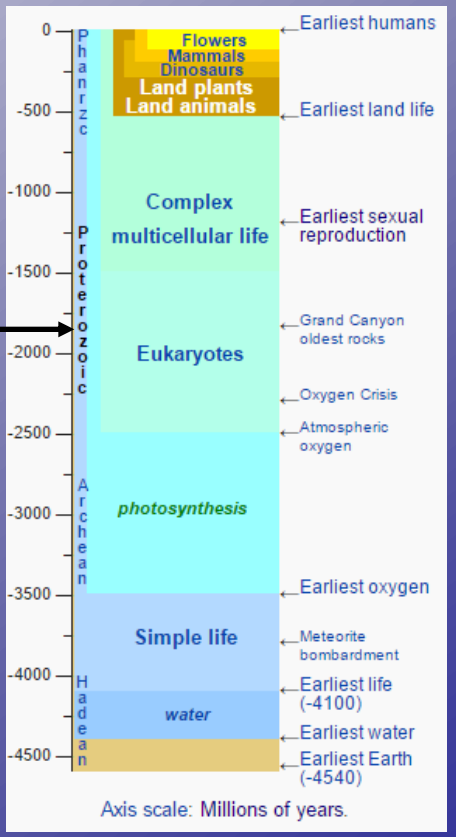
Primary black hole mass m_1	$30.5^{+5.7}_{-3.0}\,M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2}\,M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1}\,M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7}\,M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5}\,M_\odot$
Radiated energy E_{rad}	$2.7^{+0.4}_{-0.3}\,M_\odot c^2$

3 Solar Masses are converted in Gravitational Waves !!!

1.8 Billions light years !!!

Virgo detection



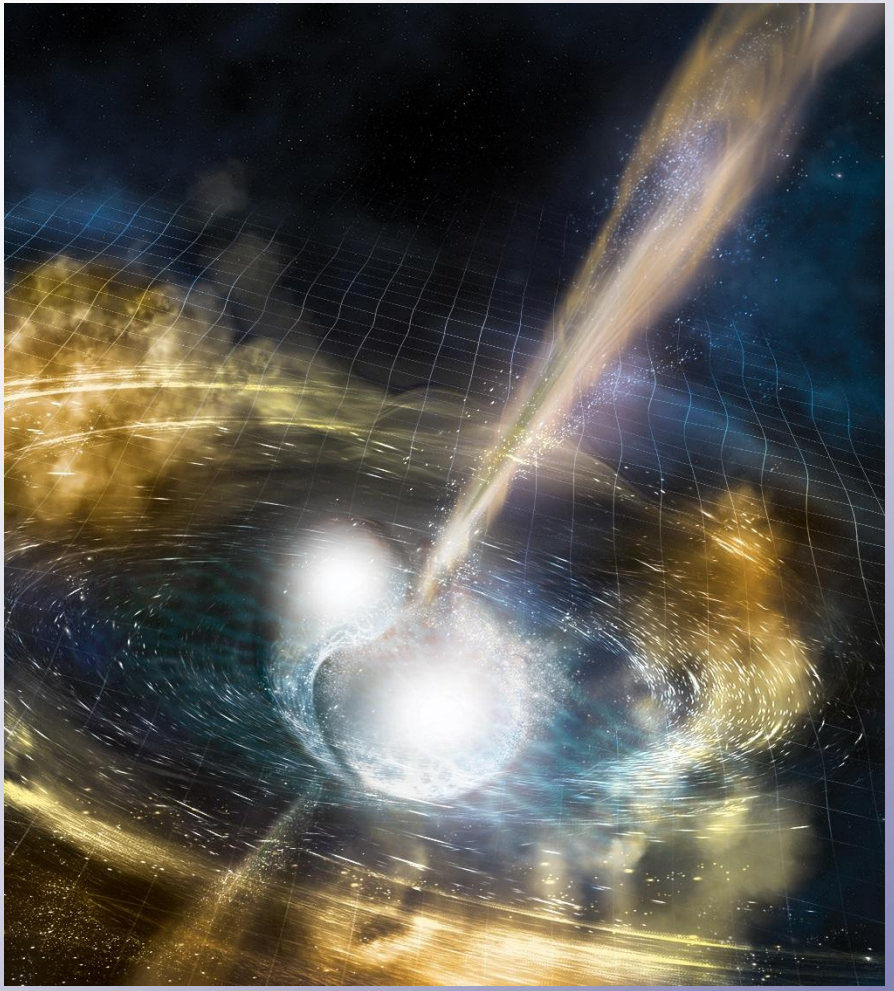


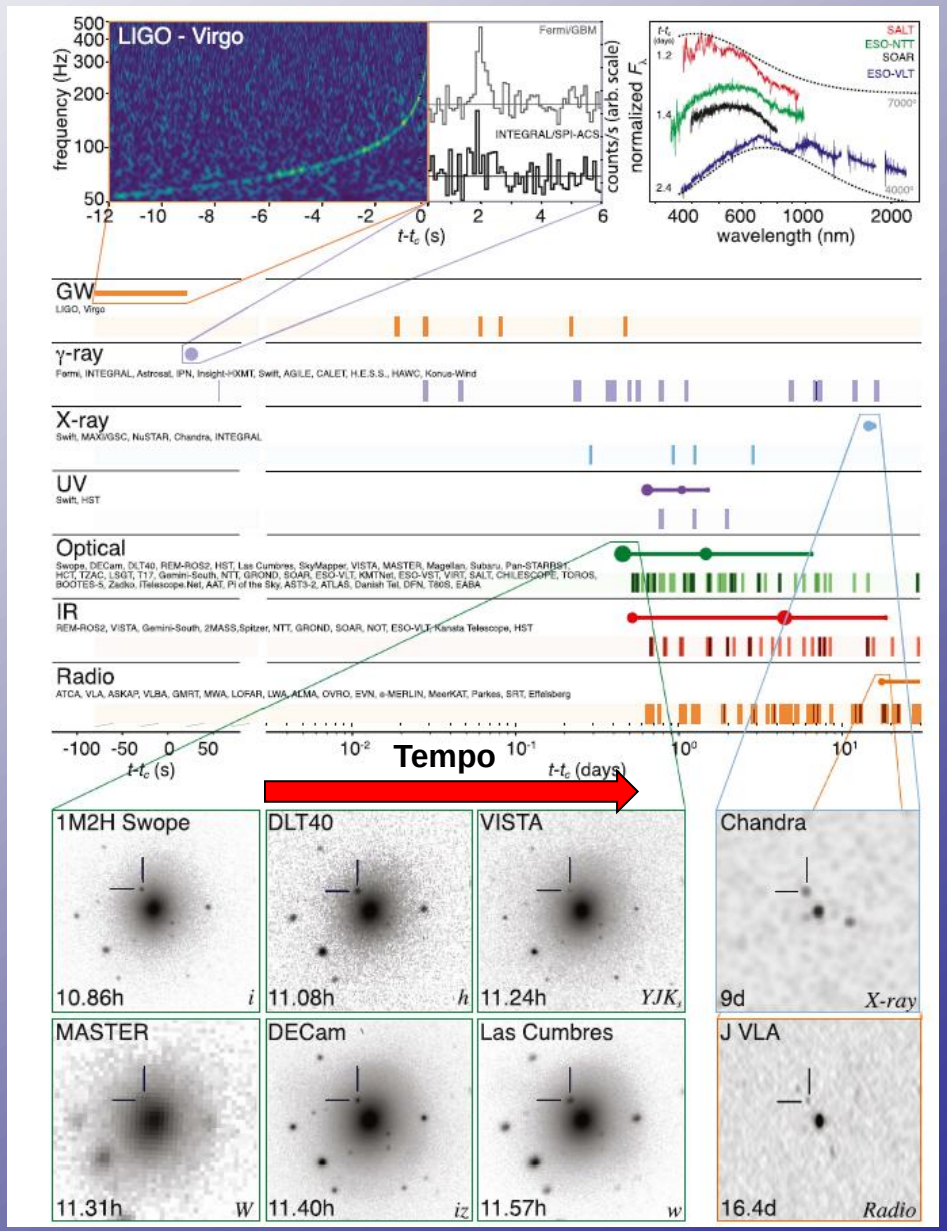
The birth of gravitational wave astronomy

17th August 2017 at 14:41:04 CET

The birth of gravitational wave astronomy

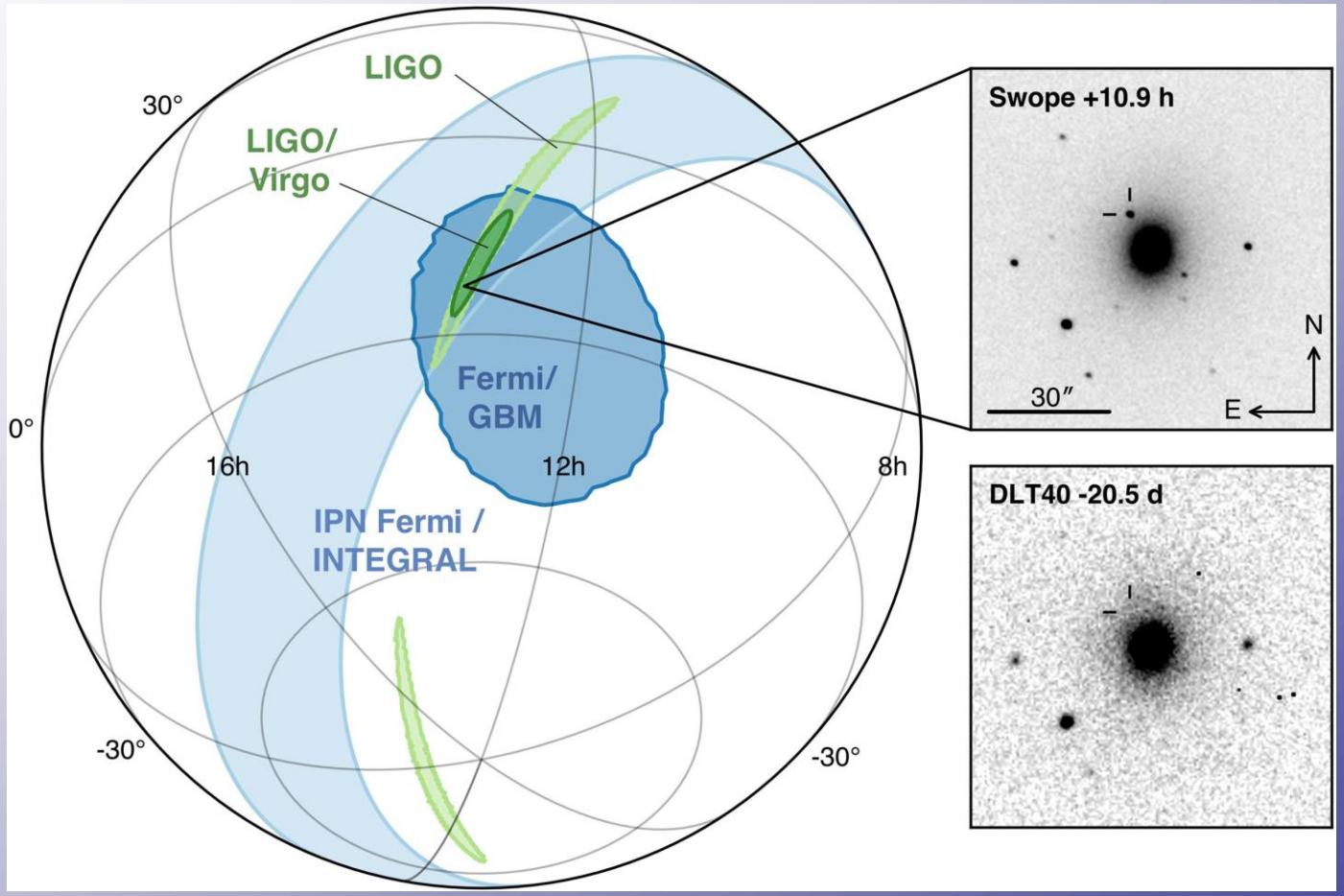
A Neutron star coalescing binary





The birth of gravitational wave astronomy

The kilonova localization



How GWs interact with matter ?

Gravitation Waves “stretch and compress” every body along their path along perpendicular directions at the wave frequency.

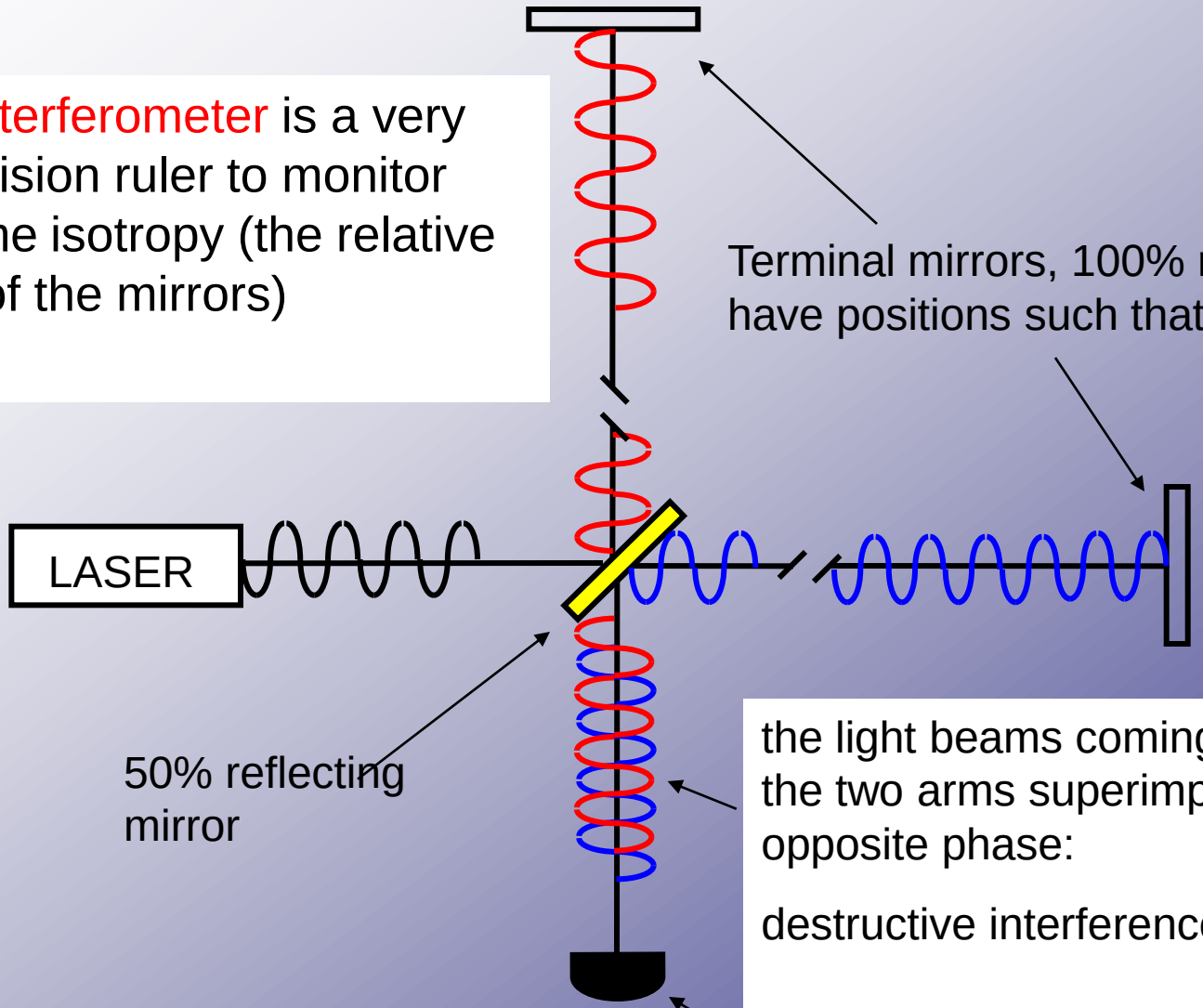
Leonardo’s Vitruvian man

The effect is extremely exaggerated !!
If the Vitruvian man was 4.5 light years tall, with the feet on the Earth and the head on the closest star, he will be stretched by a hair width

To detect Gravitational Waves directly, we therefore need an instrument capable to measure extremely small length variations.

Michelson Interferometer

A laser interferometer is a very high precision ruler to monitor space-time isotropy (the relative position of the mirrors)



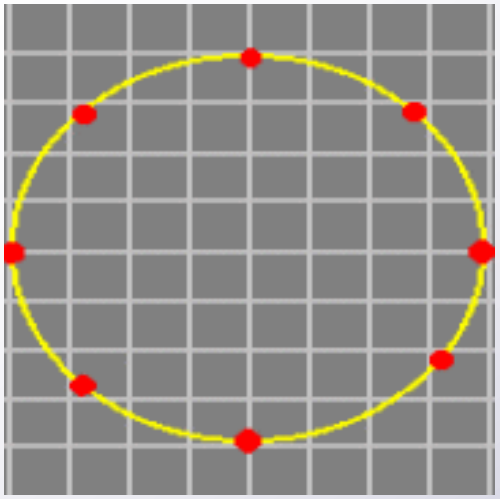
Terminal mirrors, 100% reflecting, have positions such that

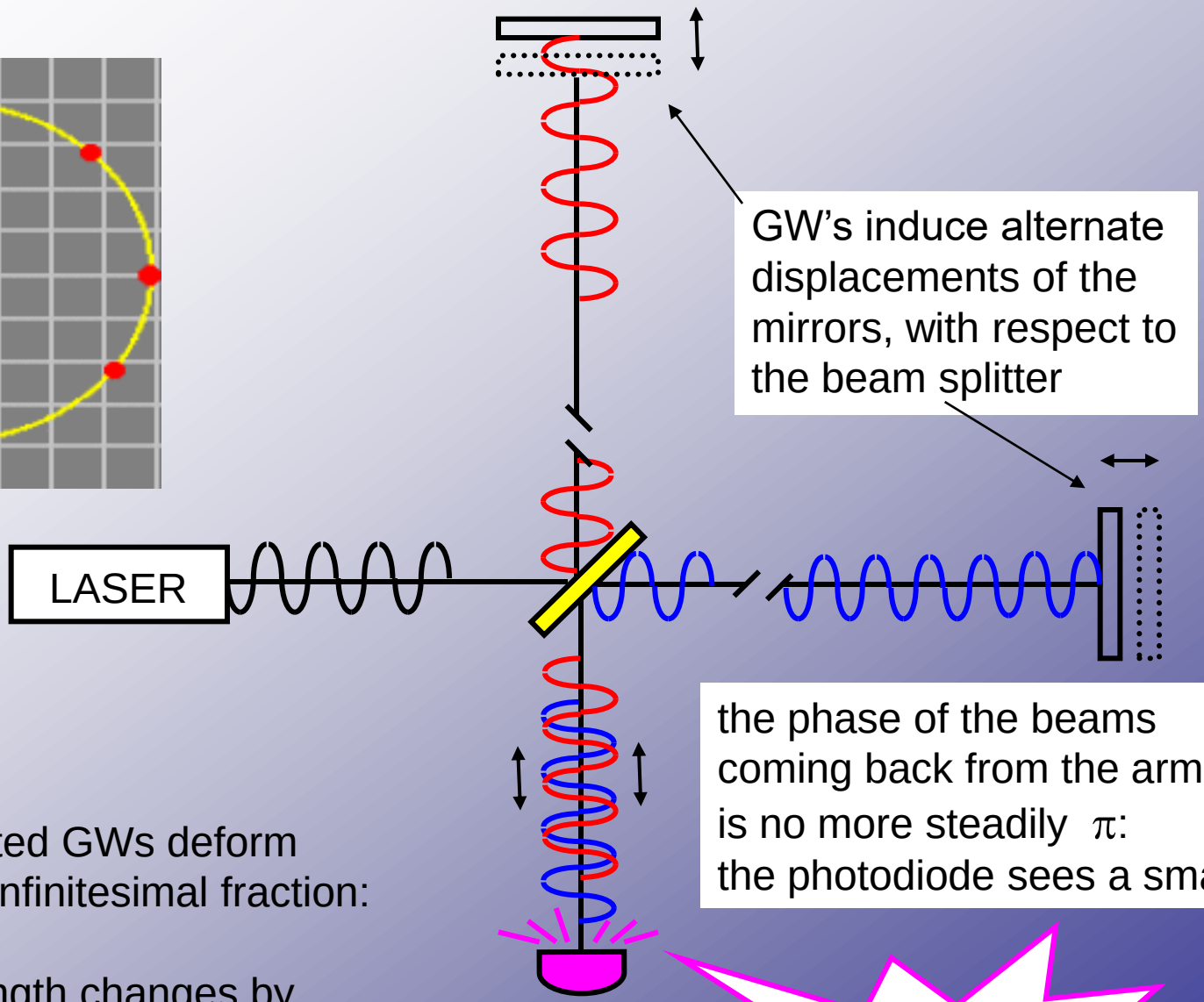
50% reflecting mirror

the light beams coming back from the two arms superimpose with opposite phase:

destructive interference

DARK:
the photodiode sees just noise





GW's induce alternate displacements of the mirrors, with respect to the beam splitter

the phase of the beams coming back from the arms is no more steadily π: the photodiode sees a small

oscillating light signal

The largest expected GWs deform space-time by an infinitesimal fraction:
10^{-21}

Virgo 3 km arm length changes by
3×10^{-18} m:
one thousands of a proton radius !!!

Noise sources

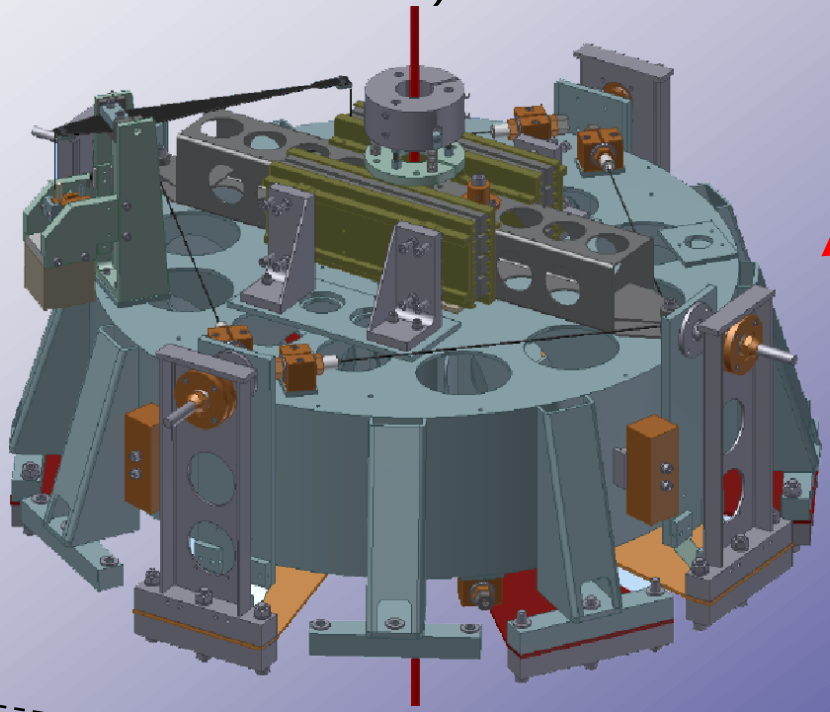
Detect 10^{-18} meters displacements *an extremely difficult measurement*

Several extreme technologies have been developed for **VIRGO** in order to beat the "**noises**" that can generate false signals, much bigger than those produced by gravitational waves:

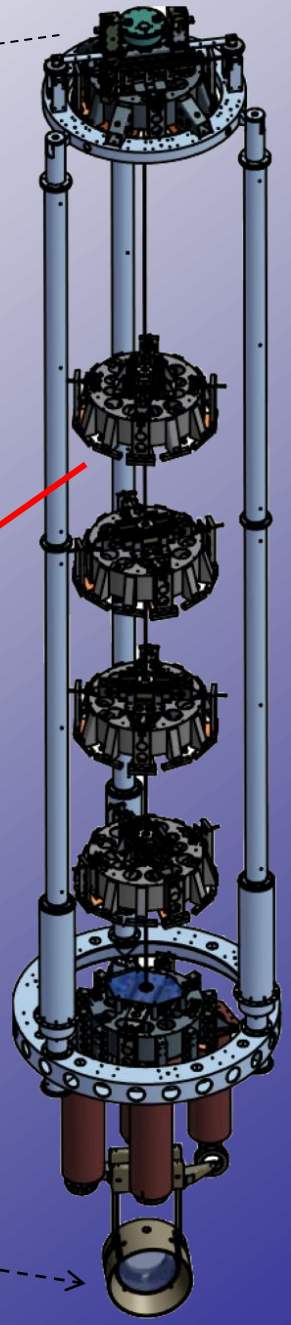
Problem	***Solution***	
Seismic vibrations	The superattenuator	**$x10^{-12}$**
Pressure fluctuations	Ultra high-vacuum	**$P = 10^{-12}$ bar**
Laser	$\nu = 10^{15}$ Hz	**$\Delta\nu = 10^{-6}$ Hz**
Mirrors	Surface roughness	**10^{-8} m**
Thermal Noise	Monolithic suspensions, cryogenic temperatures	

VIRGO superattenuator

It's able to attenuate the seismic motion of the mirrors by more than a factor 10^{12} (a million of a million times)

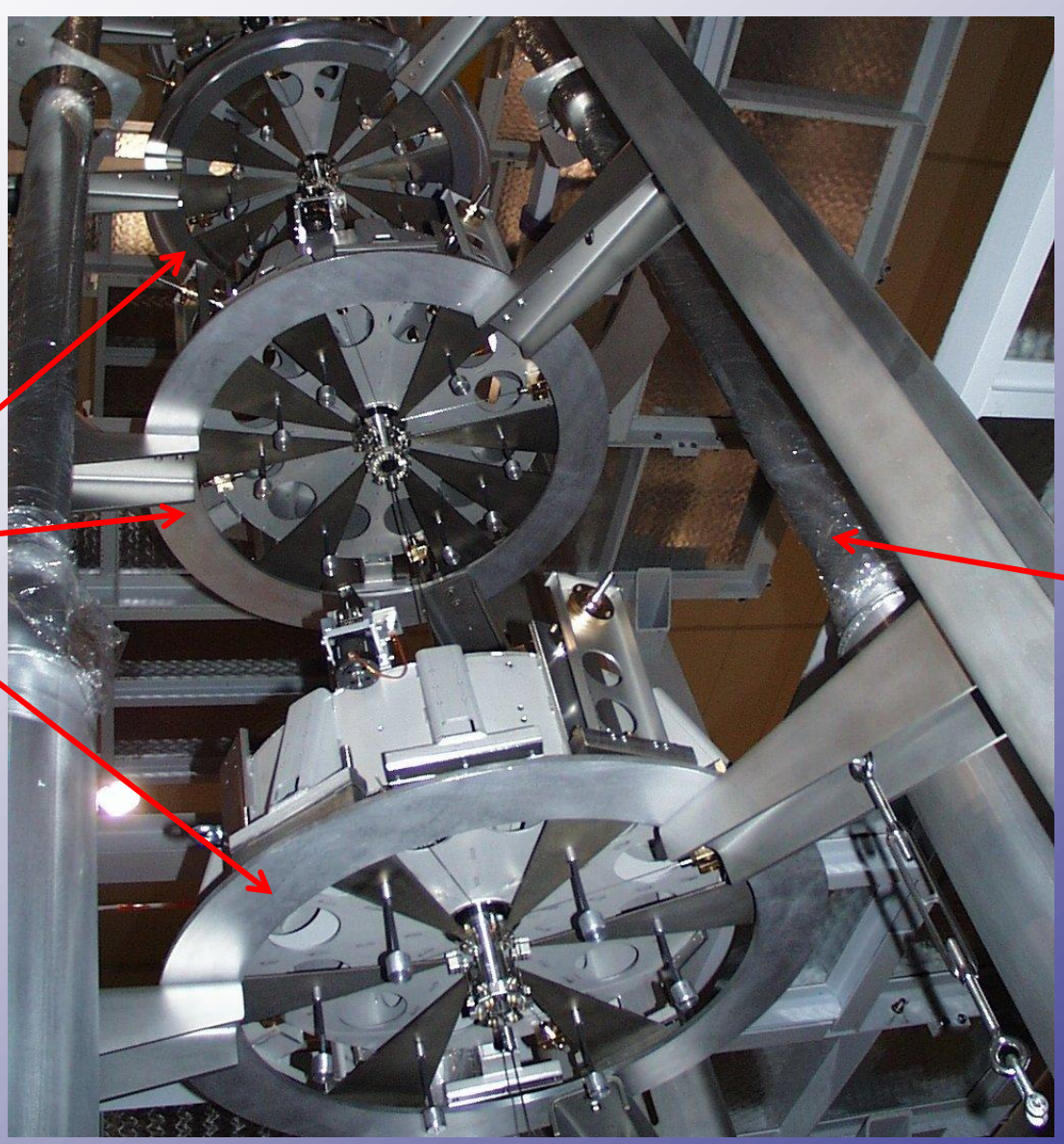


Standard filter

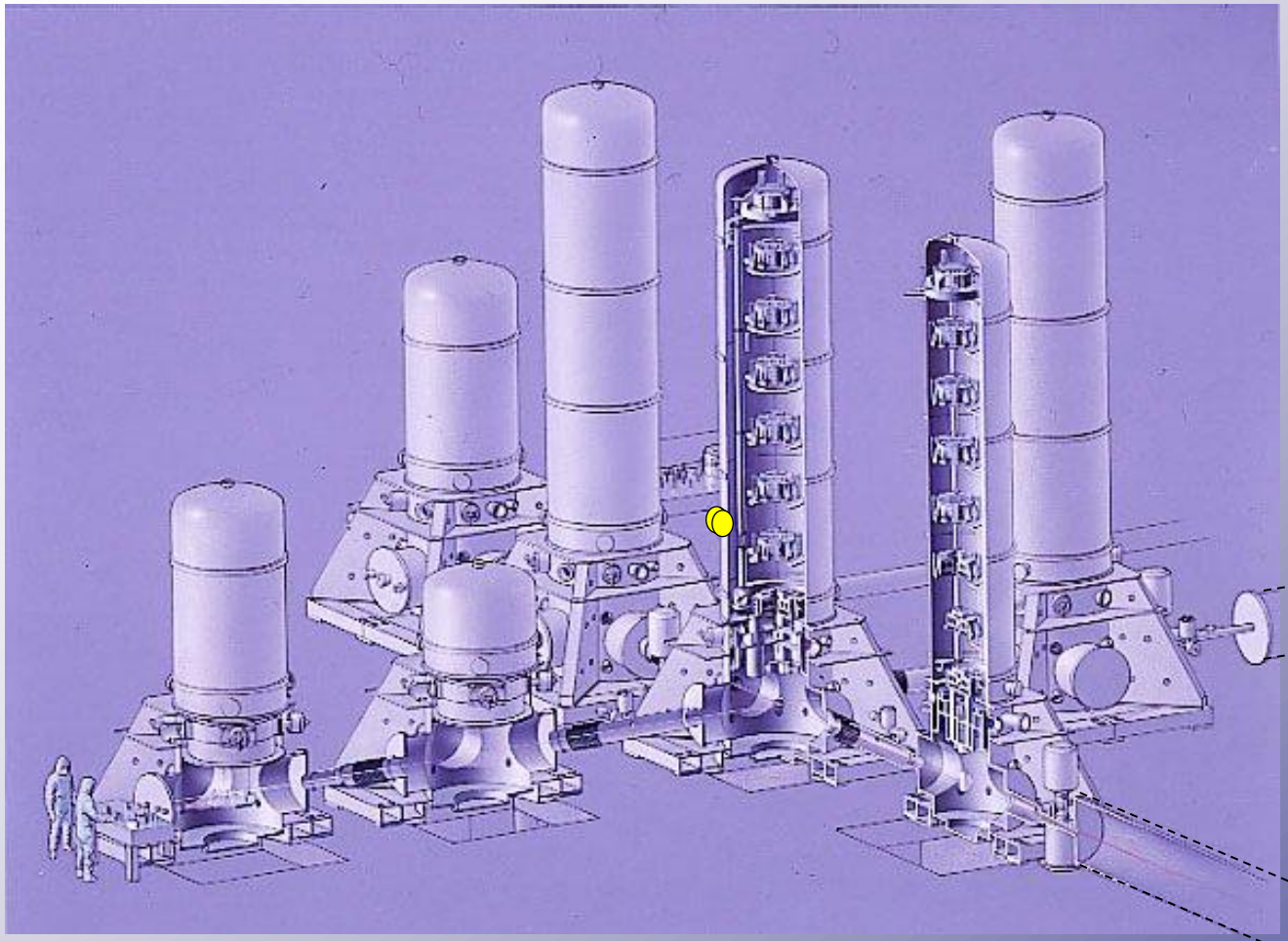


Suspended mirror

VIRGO superattenuator



VIRGO vacuum system



North Arm

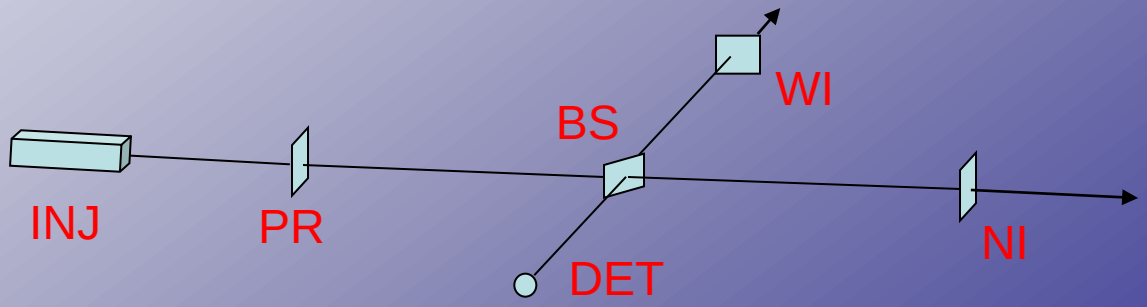
3 km

West Arm

3 km

A total volume of 7000 m^3 is kept at a millionth of a millionth of atmospheric pressure: it's the biggest "ultra-high-vacuum" (10^{-7} bar) system in Europe

The central building

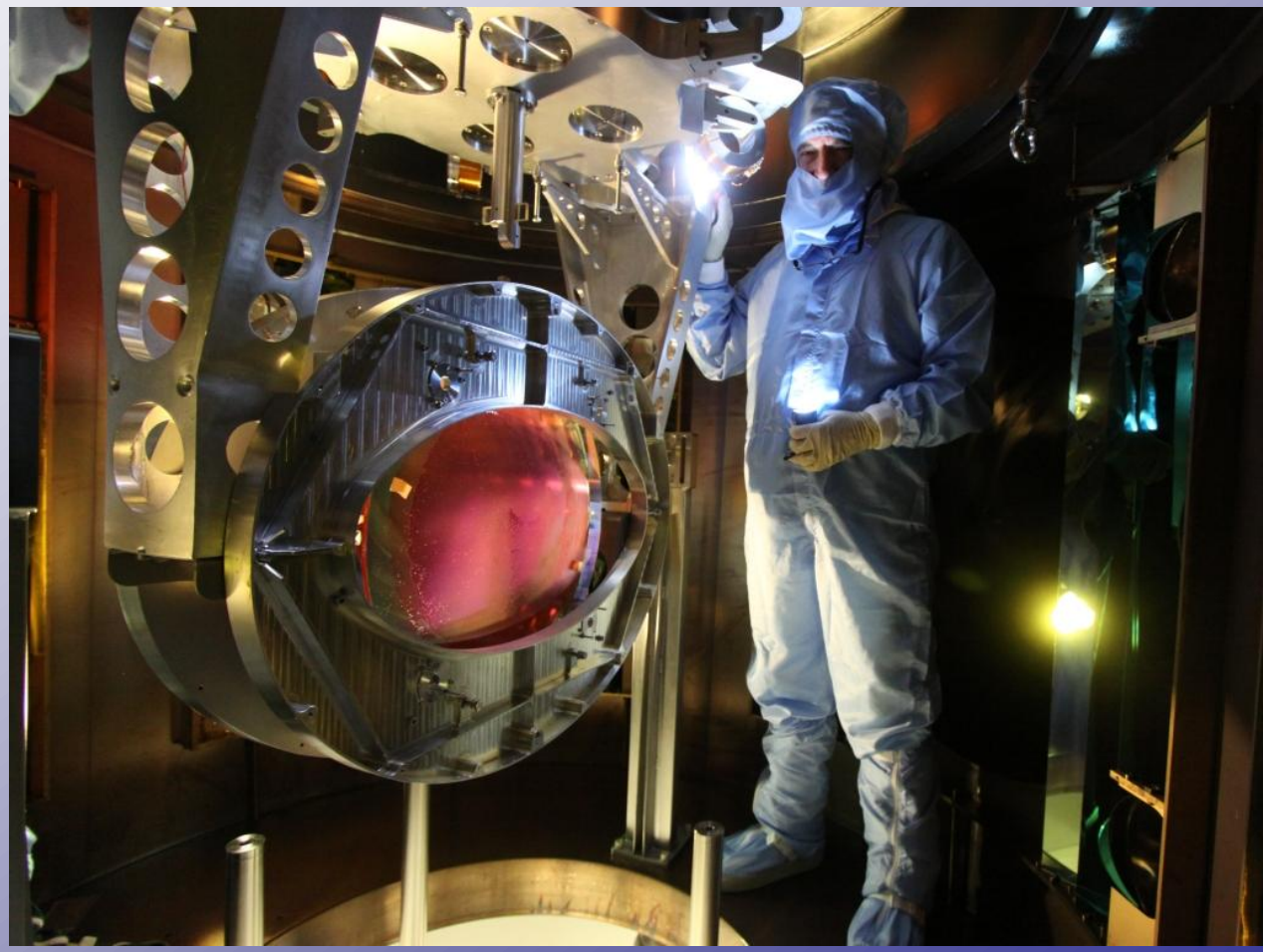


VIRGO Mirrors

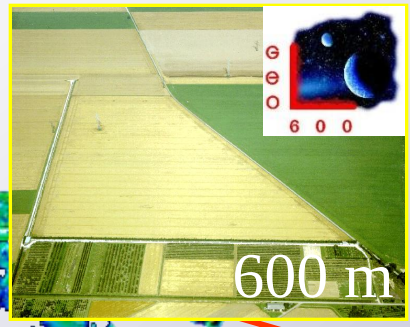
- **Mirrors** made of SiO2, **350 mm** of diameter, **200 mm** wide, surface roughness **< 10^{-8} m**.
- **Monolithic suspensions:** made with extremely thin SiO2 fibers (**400 µm** of diameter) to suspend mirrors of about **42 kg**.

VIRGO Mirrors

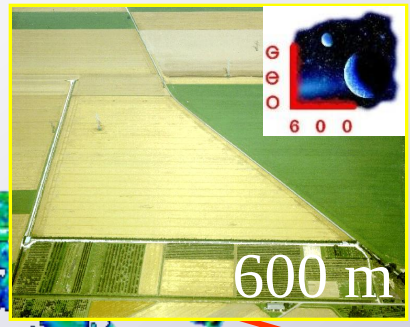
- **The first mirror of the ‘new generation’**
- 550 mm of diameter, 65 mm of width
- About 34 kg of total weight
- It’s the test mass supported by the Beam Splitter suspension

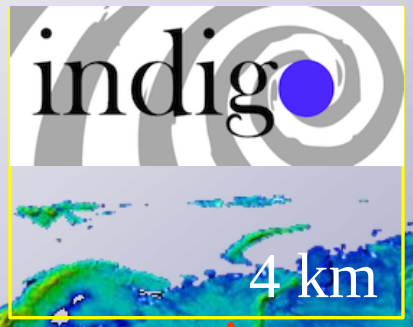


Competition & Collaboration (2018)

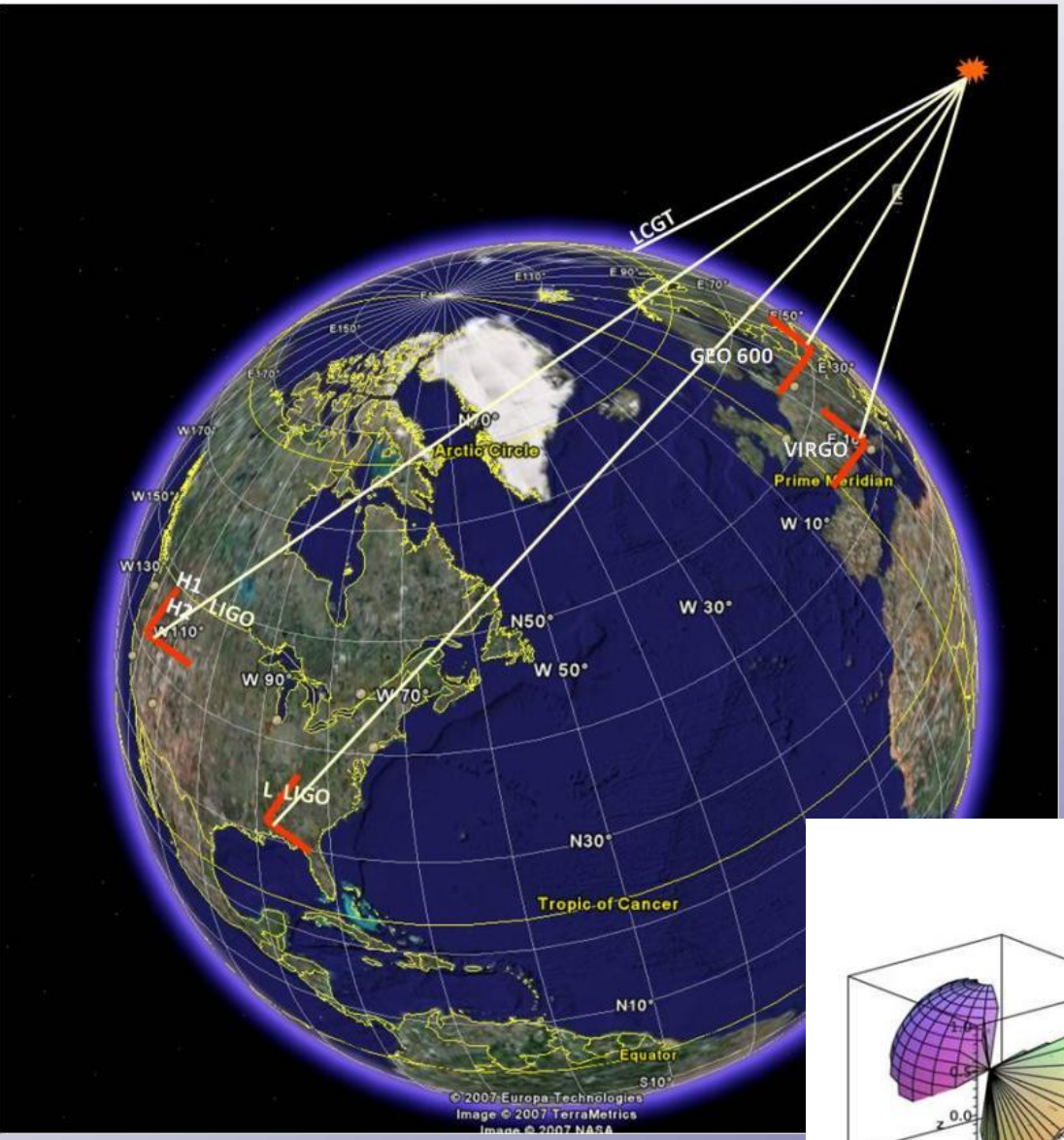


Competition & Collaboration (2020)



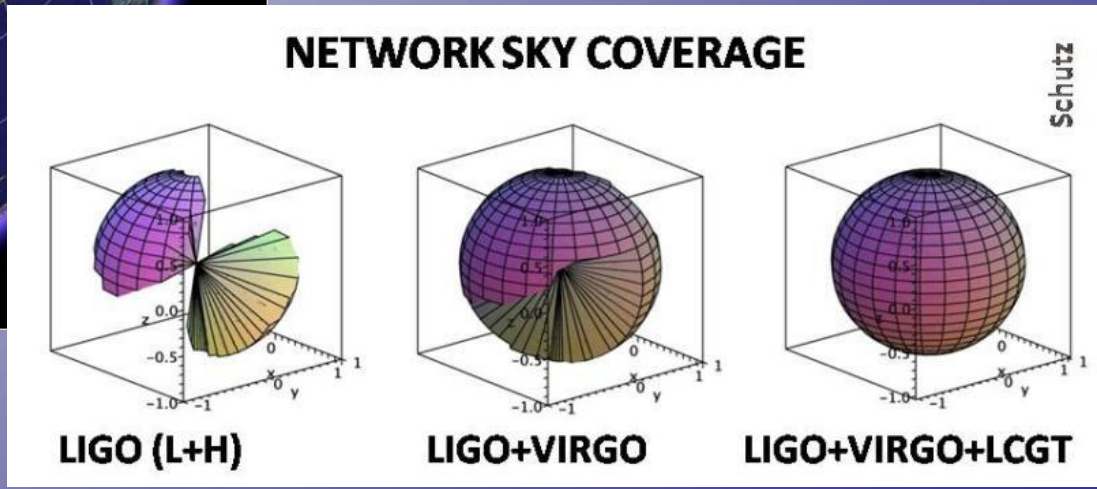


Competition & Collaboration



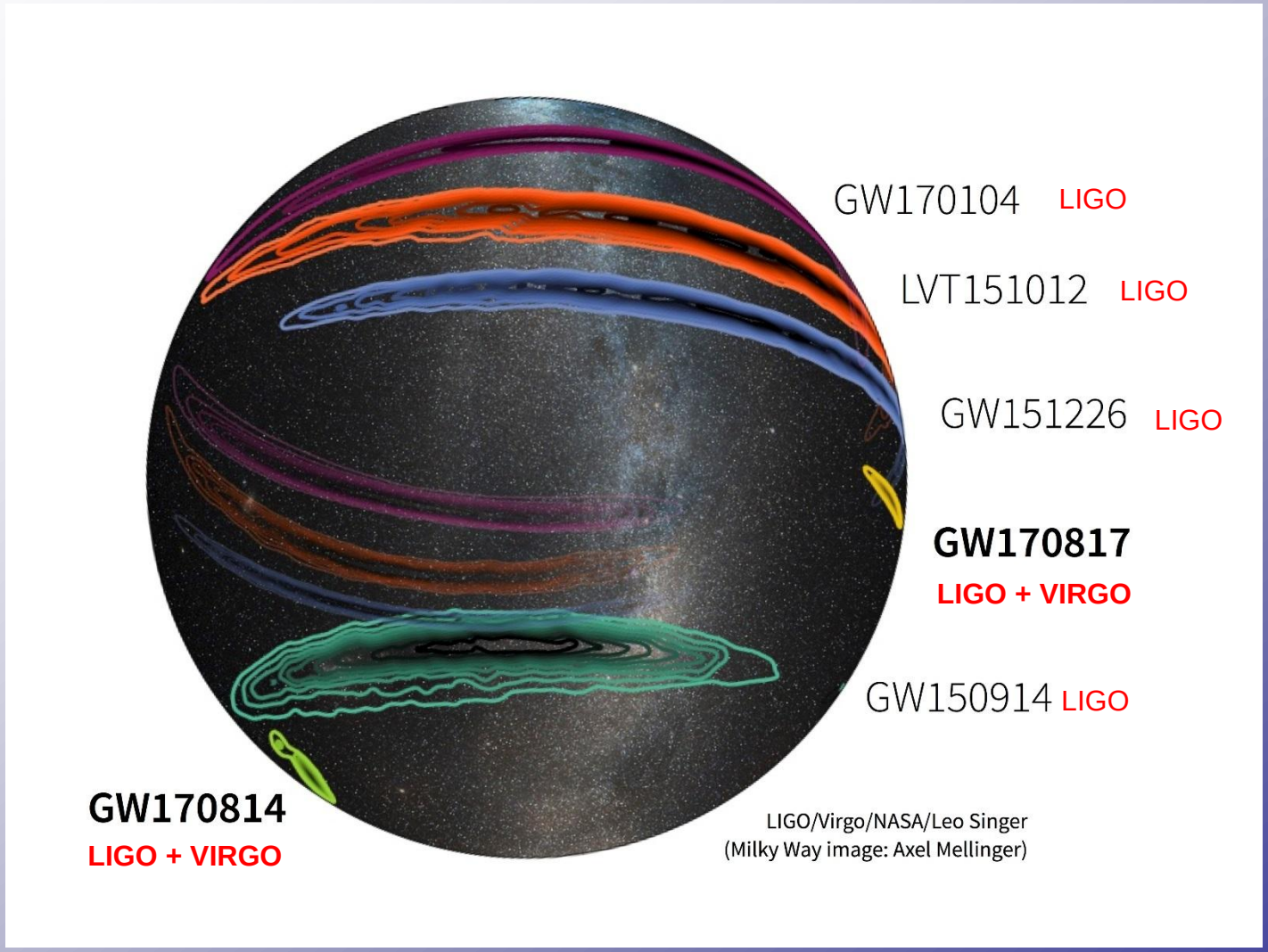
Advantages:

- Better event reconstruction
- Detection probability is increased
- The significance of each detected event is increased
- Sky coverage is increased



Competition & Collaboration

The impressive Virgo contribution to the localization of GW events!!



Thank you for your attention!!