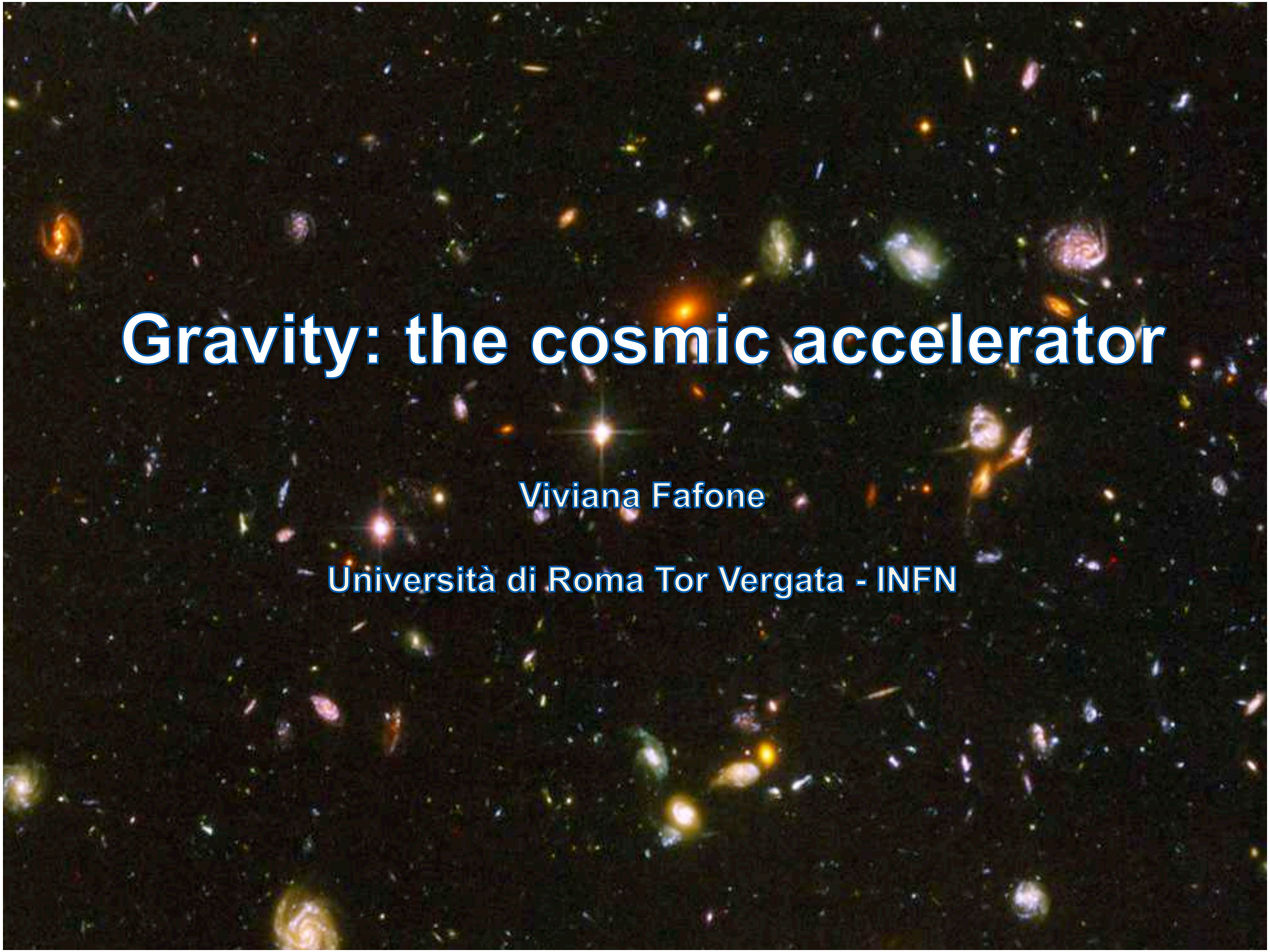


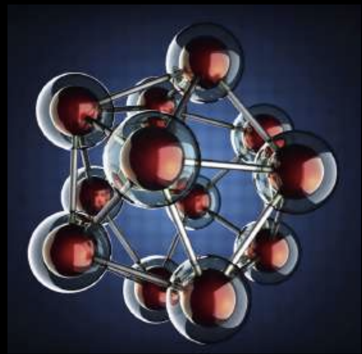
Gravity: the cosmic accelerator

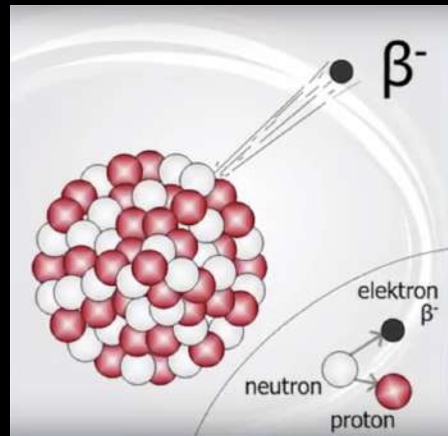
Viviana Fafone

Università di Roma Tor Vergata - INFN

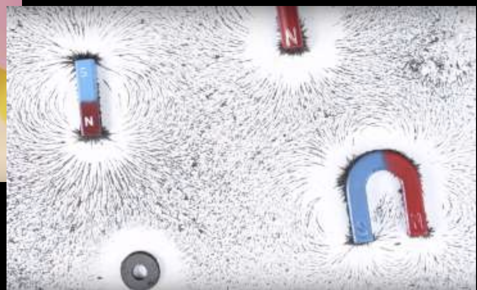
The Four Fundamental Forces

- Strong





- Weak



- Electromagnetism

- Gravity

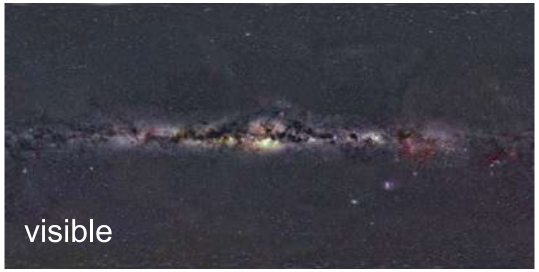
Many violent phenomena, driven by gravity, happen in the universe

Which tools do we have to investigate the Universe?


1564 – 1642

E.M. Astronomy

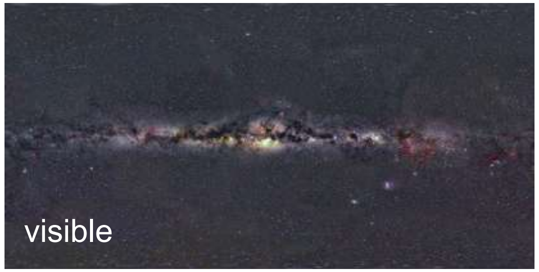
- Current e.m. telescopes are mapping almost the entire Universe

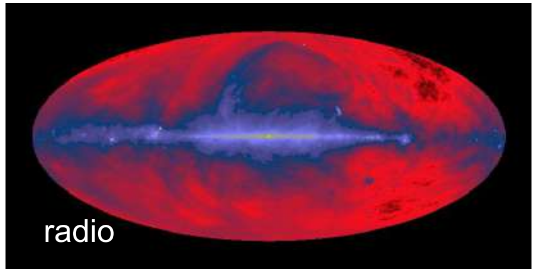



Galileo's telescope

E.M. Astronomy

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





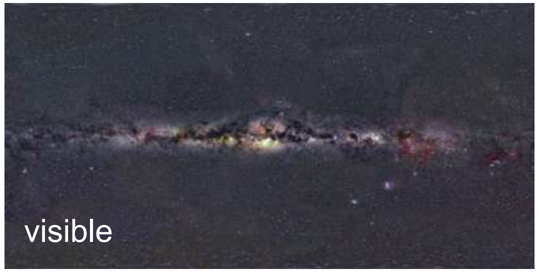
Arecibo

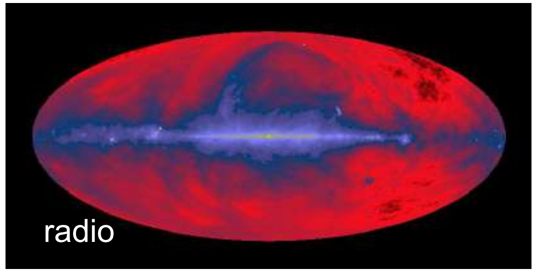
Radio Telescopes

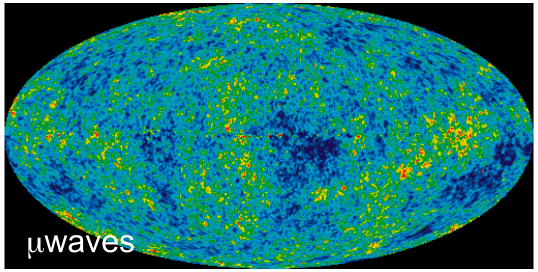
VLA

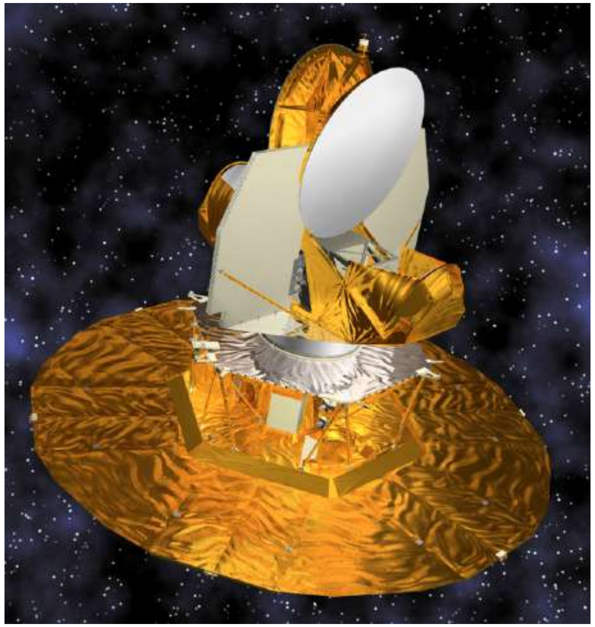
E.M. Astronomy

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



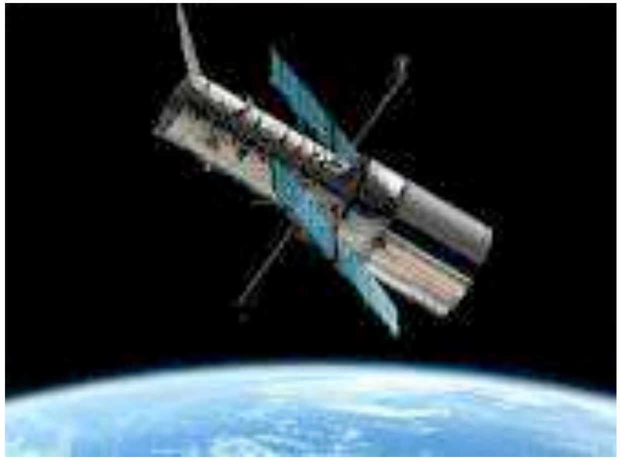






WMAP

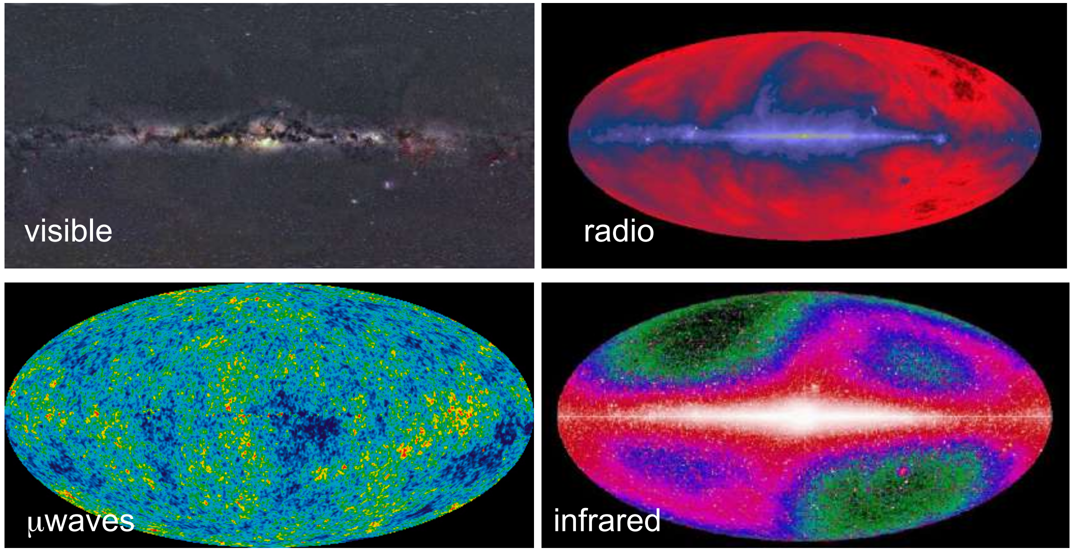
Hubble

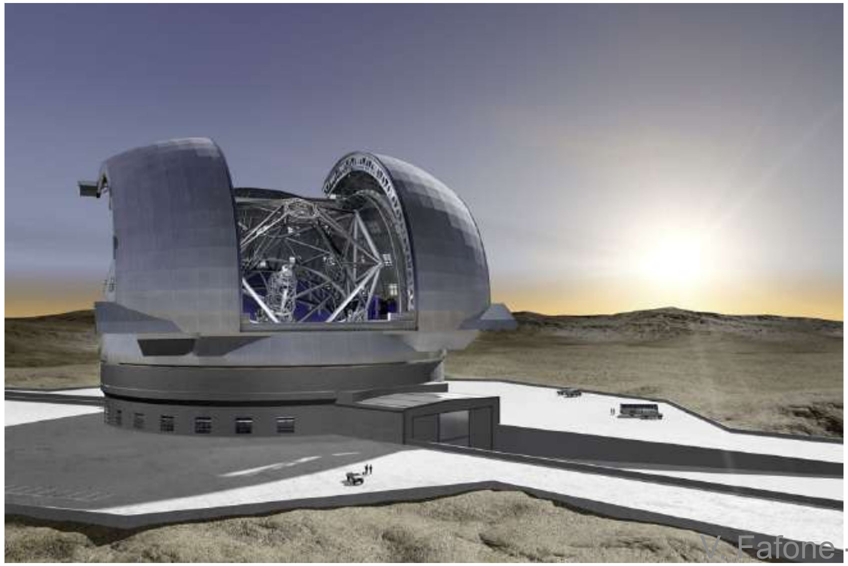


Microwaves telescopes

E.M. Astronomy

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

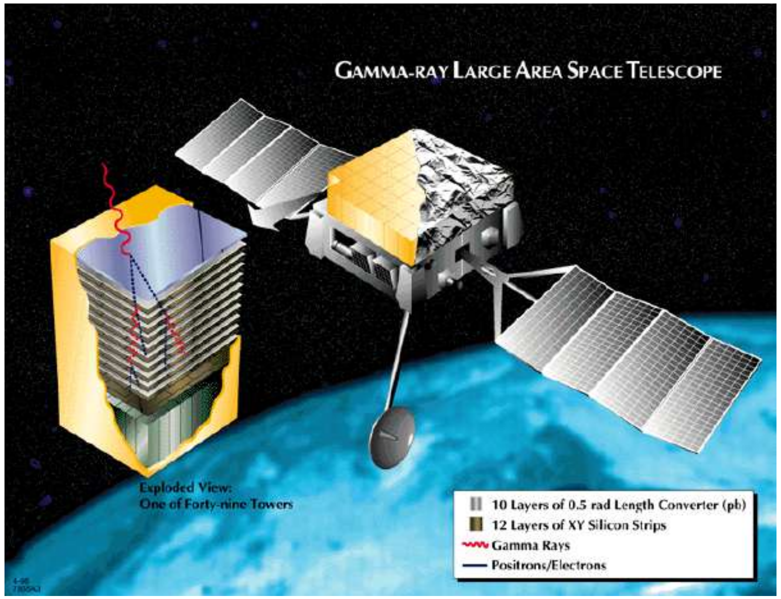




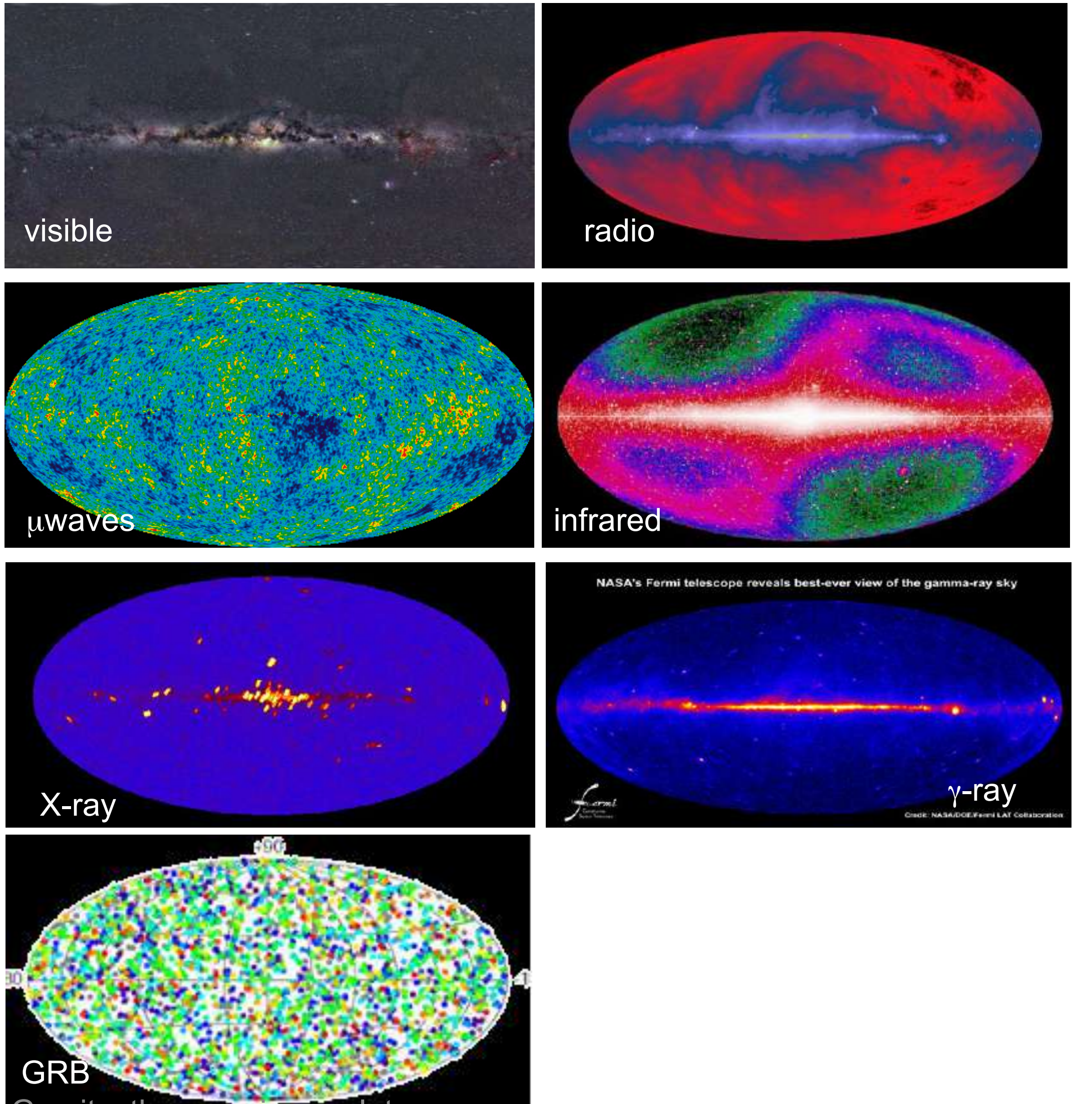
E-ELT (infrared telescope)

E.M. Astronomy

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



Fermi (GLAST) telescope

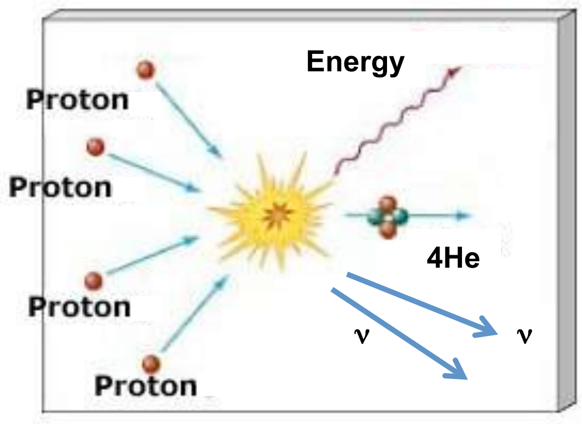


So, we “see the light” emitted from the stars …

… and what else?

We have neutrinos as well

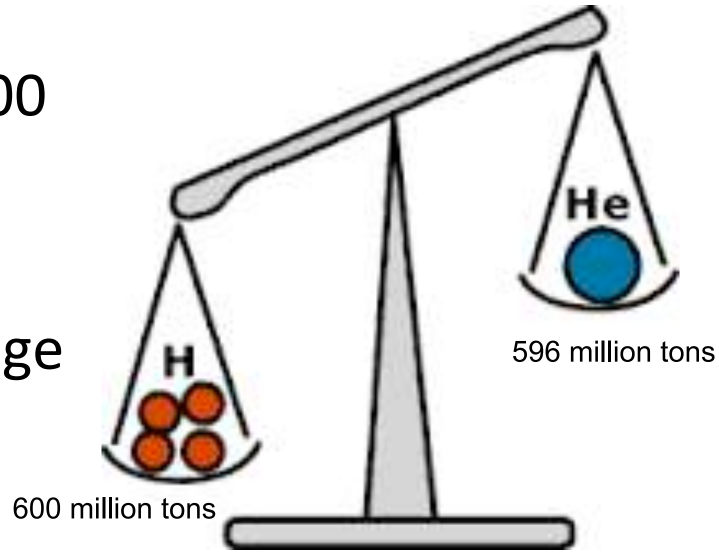
- We now that in the Sun nuclear reactions take place



- 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!

Neutrinos 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.

νs from Supernovae

- In a SN explosion ~ 10^{53} erg are emitted on a very short time scale (~1 s)
- Only 0.1% of the emitted energy is through e.m. radiation
- 99.9% is emitted as neutrinos

Crab Nebula

Distance: 6000 light year, diameter 10 light year, 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

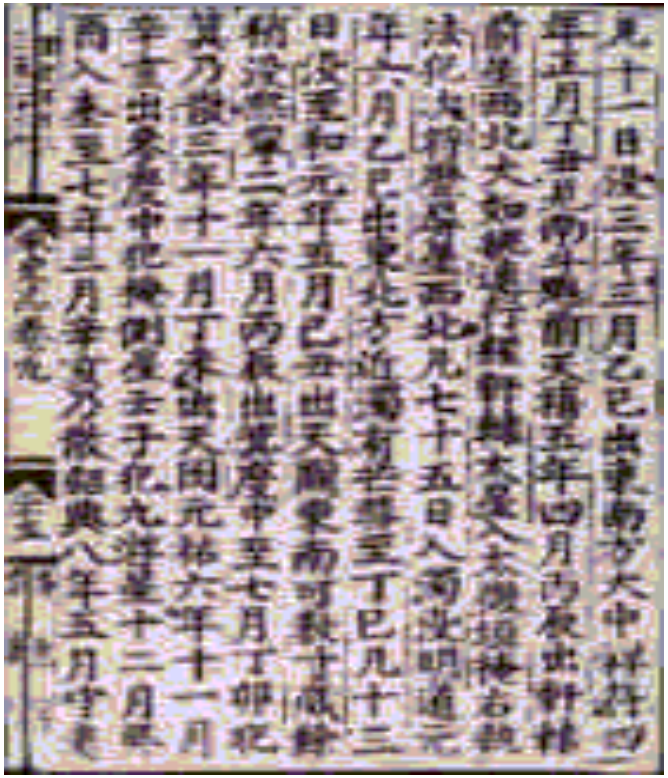
In the center there is a Pulsar (not visible in the picture) rotating at a frequency of 30Hz

νs from Supernovae

From the original engraving by the chinese astronomers:

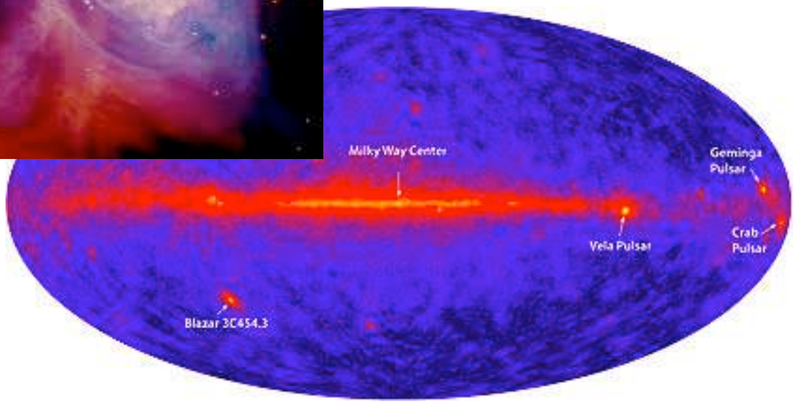
1054年 7月 4日 [宋會要]中記有：「 元年三月，司天监言客星没，客去之兆也。初， 至和元年五月，晨出東方，守天關。晝如太白，芒角四出，色赤白，凡見二十三日。」

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”



νs from Supernovae

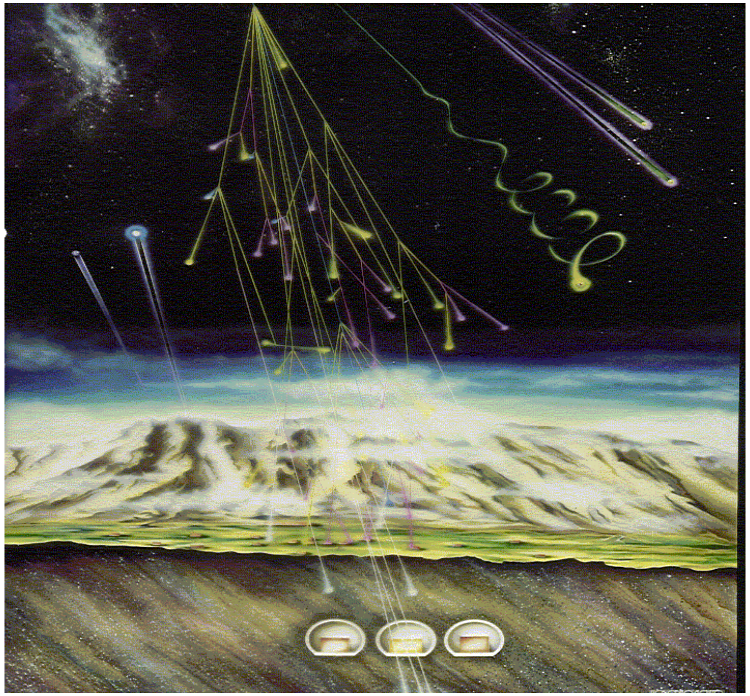
SN1987A: The Vela Pulsar (PSR J0835-4510)
A radio, optical, X-ray- and gamma-emitting pulsar associated with the Vela SN Remnant in the constellation of Vela.



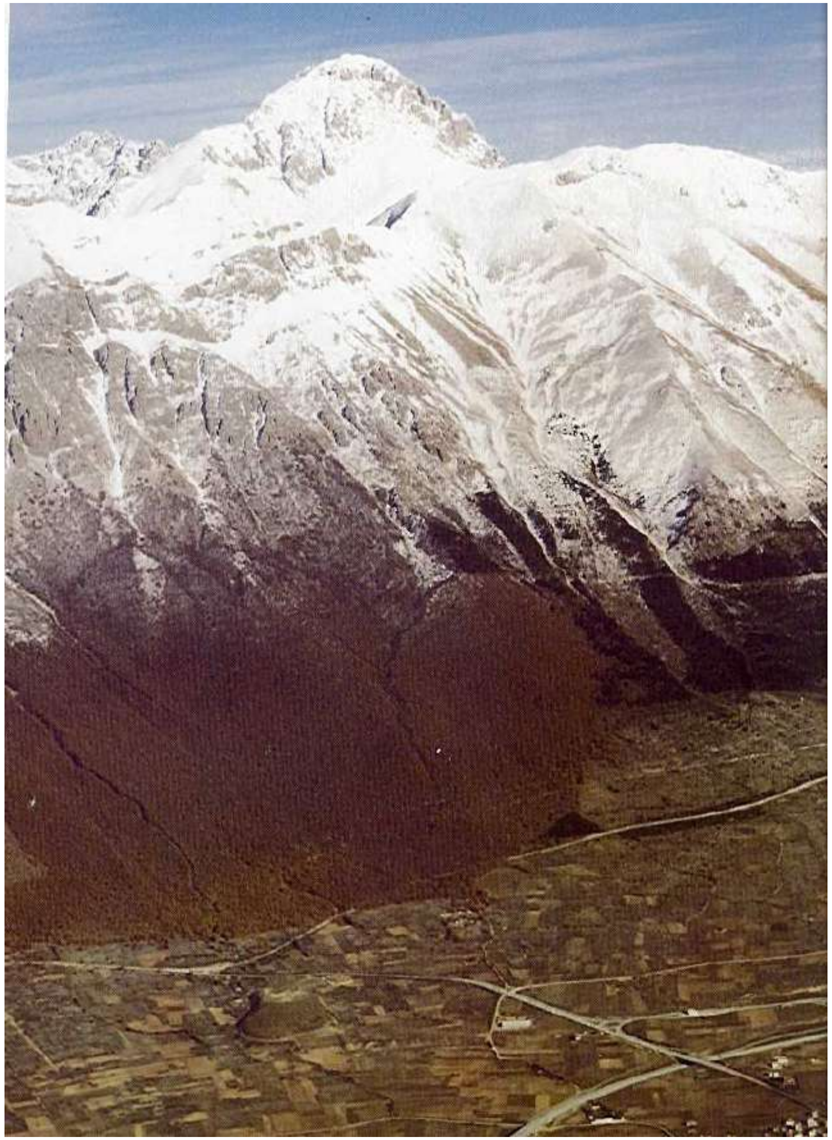
How can we detect neutrinos?

- νs are very elusive and penetrating
  → 1: they are a good tool to investigate the internal structure, the dynamics of the collapse
  → 2: we need to shield the detector from other types of radiation (e.g. cosmic rays)

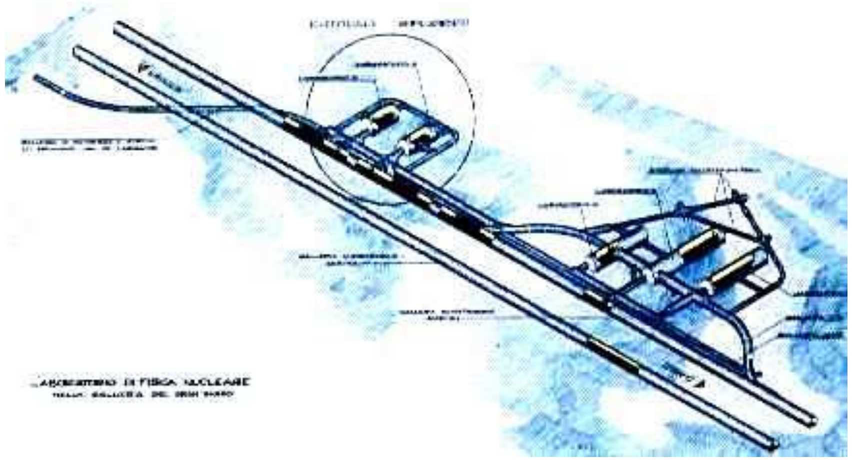
→ Underground detectors!



The INFN Gran Sasso Laboratory

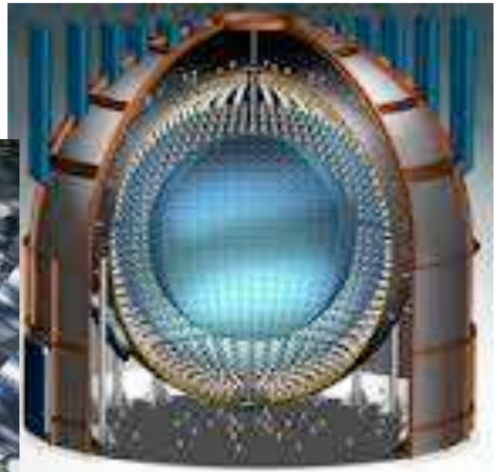


The lab of cosmic silence



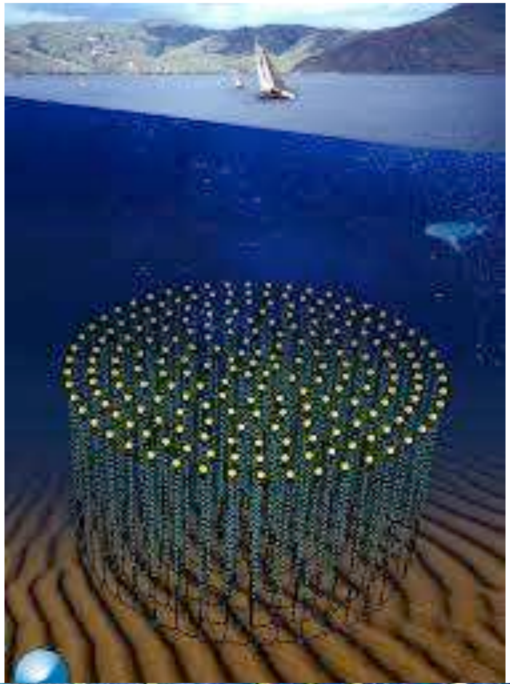
The INFN Gran Sasso Laboratory

Borexino

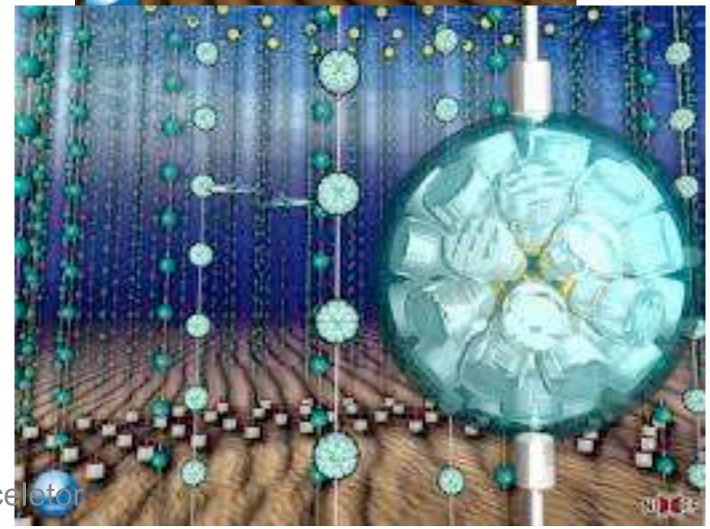


LVD

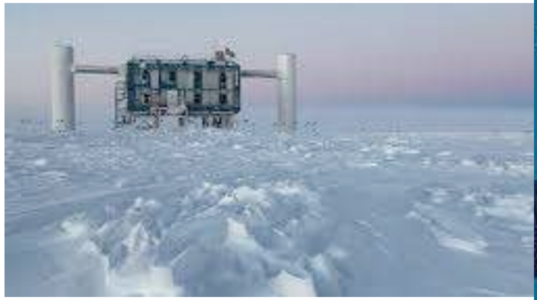
Underground Labs

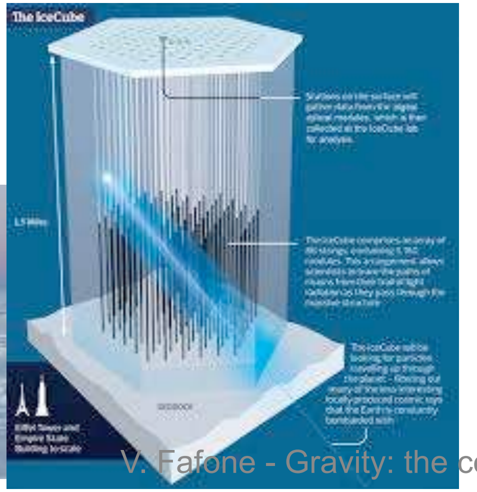


KM3NET



IceCube





So, we “see the light” emitted from the stars …

… and the neutrinos

Anything else?

Yep: Gravitational Waves!

Predicted by General Relativity

Ripples in spacetime moving at the speed of light

Sources of GW

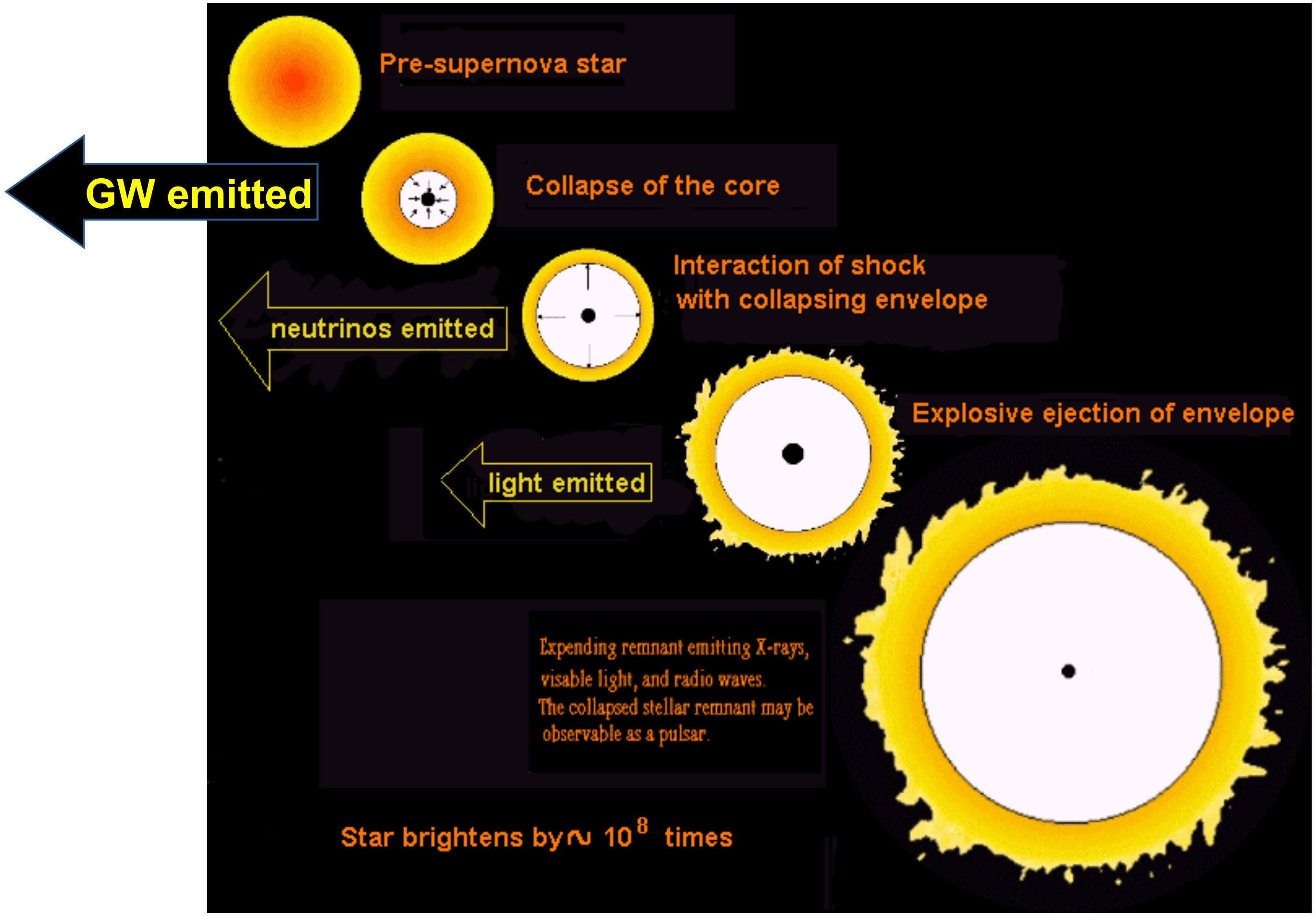
- Gravitational collapse

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)

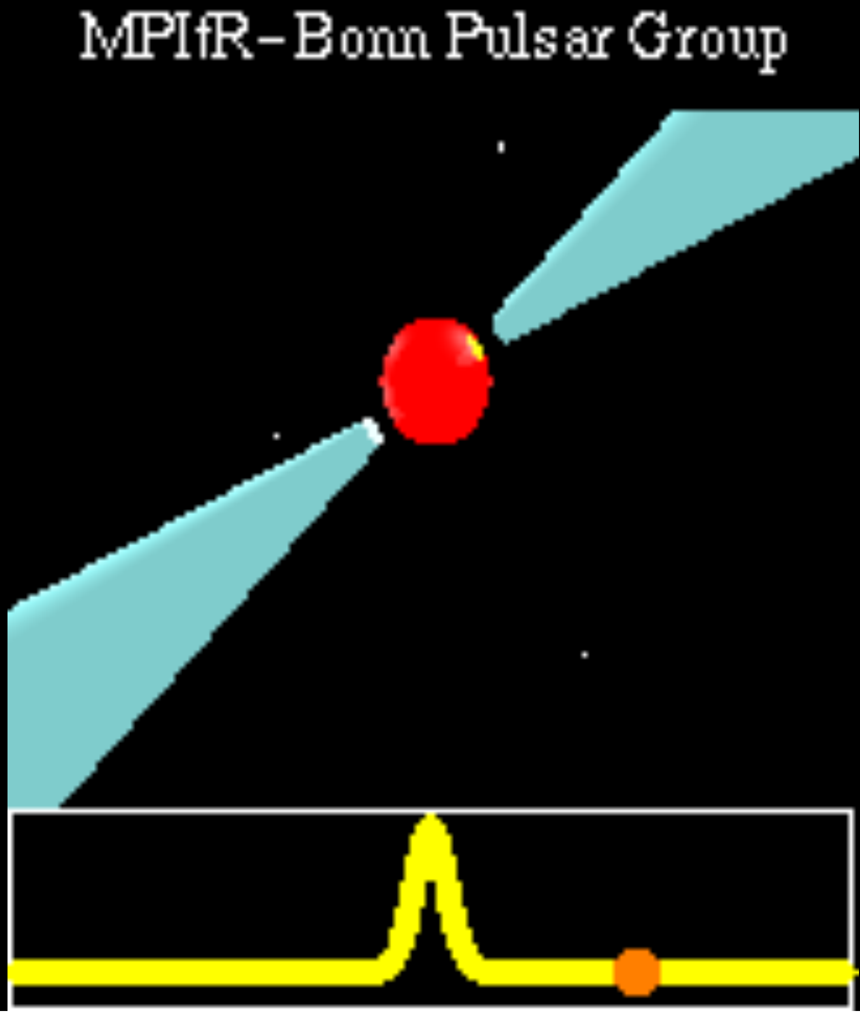
Very compact objects (R~10 km) made by neutrons. Very high density (10^{12} - 10^{14} g/cm^3). The estimated number rotating of NS in our Galaxy is about 10^9; about 1000 are observed as pulsars.

f=10-100 Hz

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

=

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



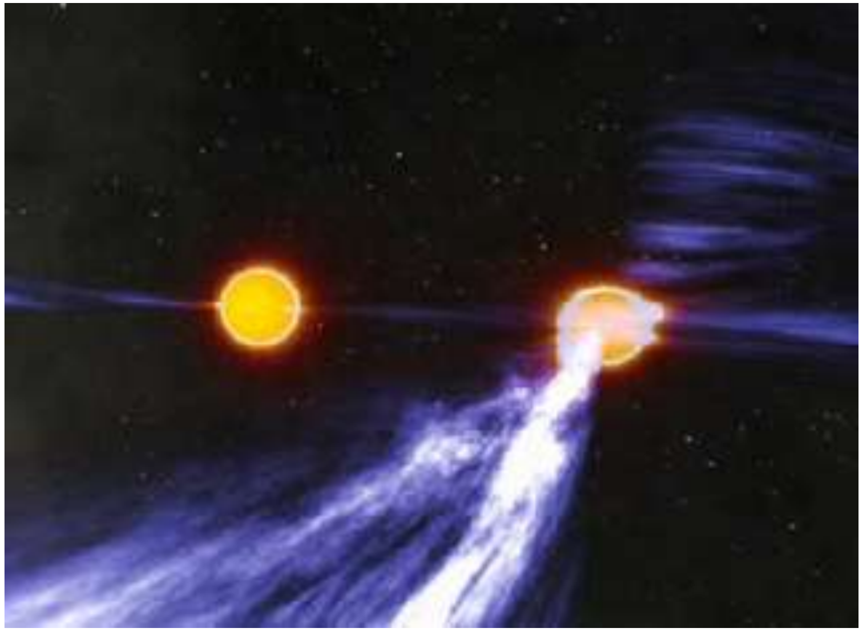
Sources of GW

- 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.

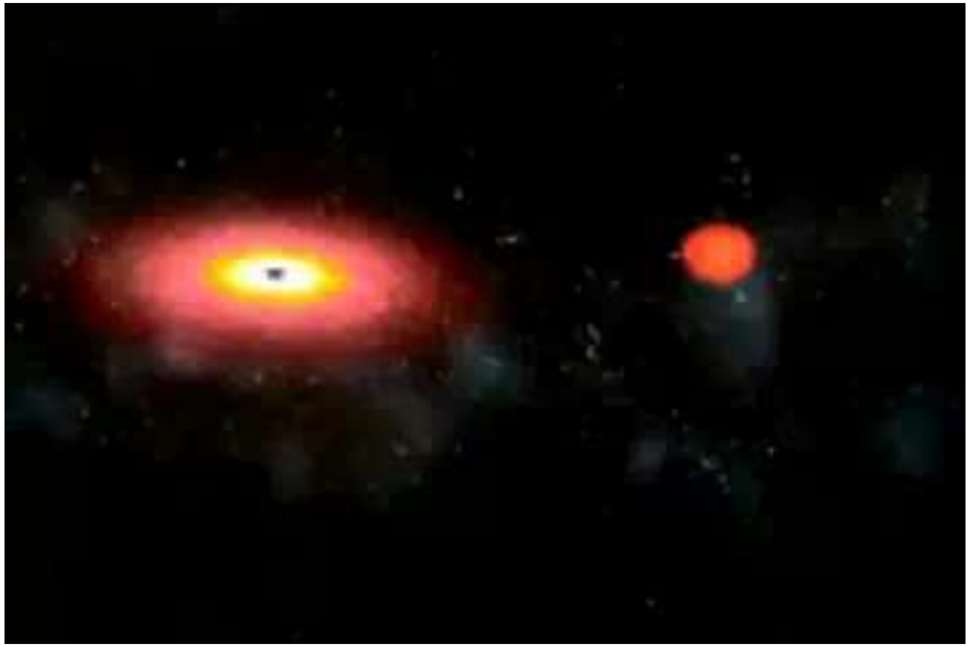
Sources of GW

- Binary systems (NS-NS)



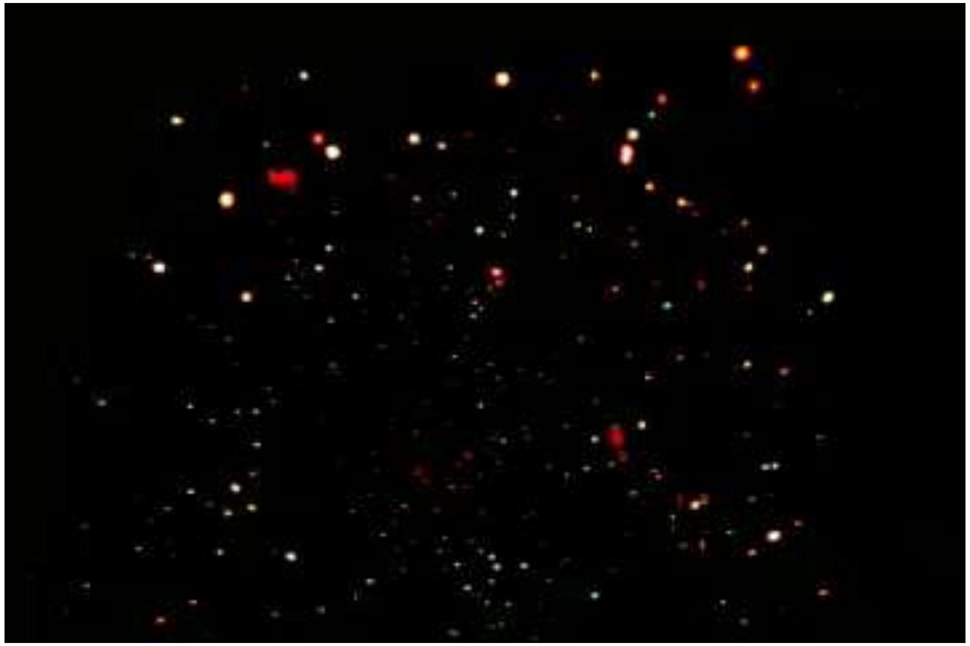
Sources of GW

- Binary systems (NS-BH)



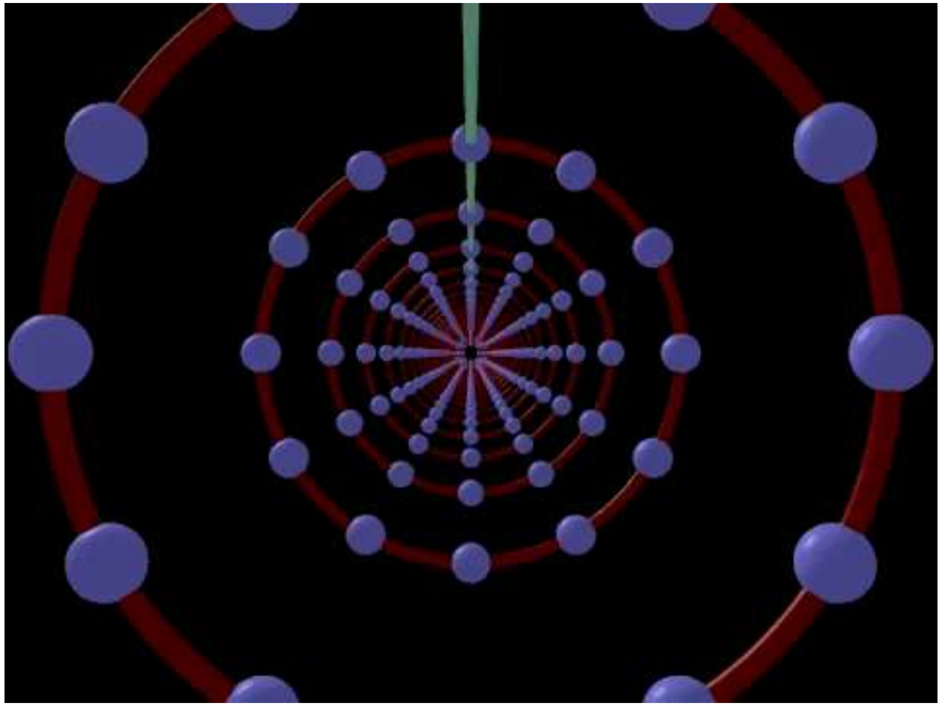
Scientists have seen tantalizing, first-time evidence of a black hole eating a neutron star: first stretching the neutron star into a crescent, swallowing it, and then gulping up crumbs of the broken star in the minutes and hours that followed.

- Binary systems (BH-BH)

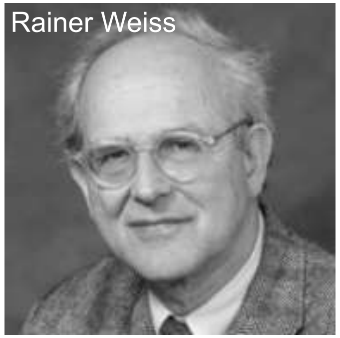


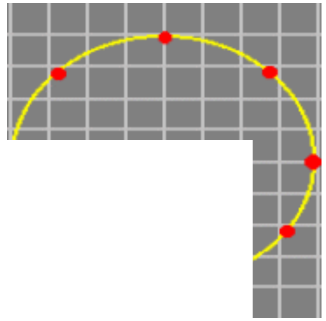
This sequence begins with the Chandra Deep Field-North in X. Black holes that are also found in submillimeter observations, indicating active star formation in their host galaxies, are then marked. The view then zooms onto one pair of particularly close black holes (known as SMG 123616.1+621513). Astronomers 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.

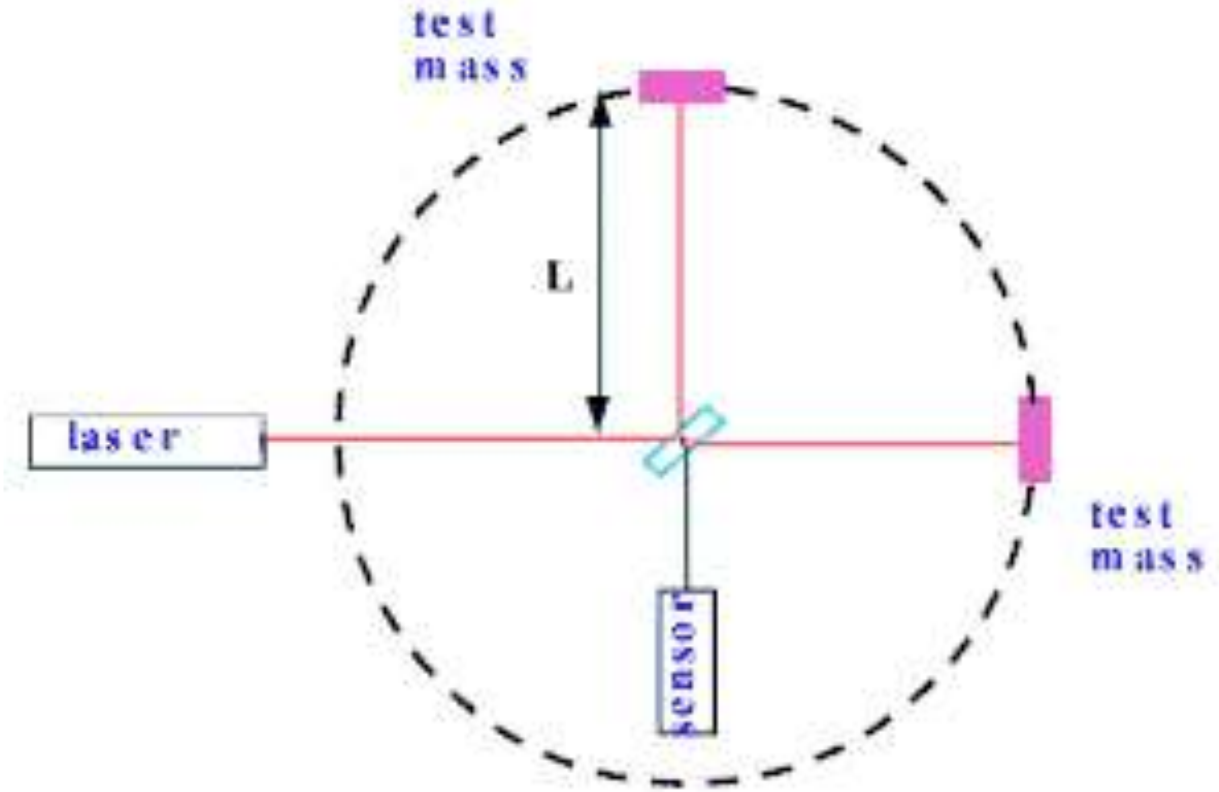
How can we measure a GW?



Detecting GWs with light



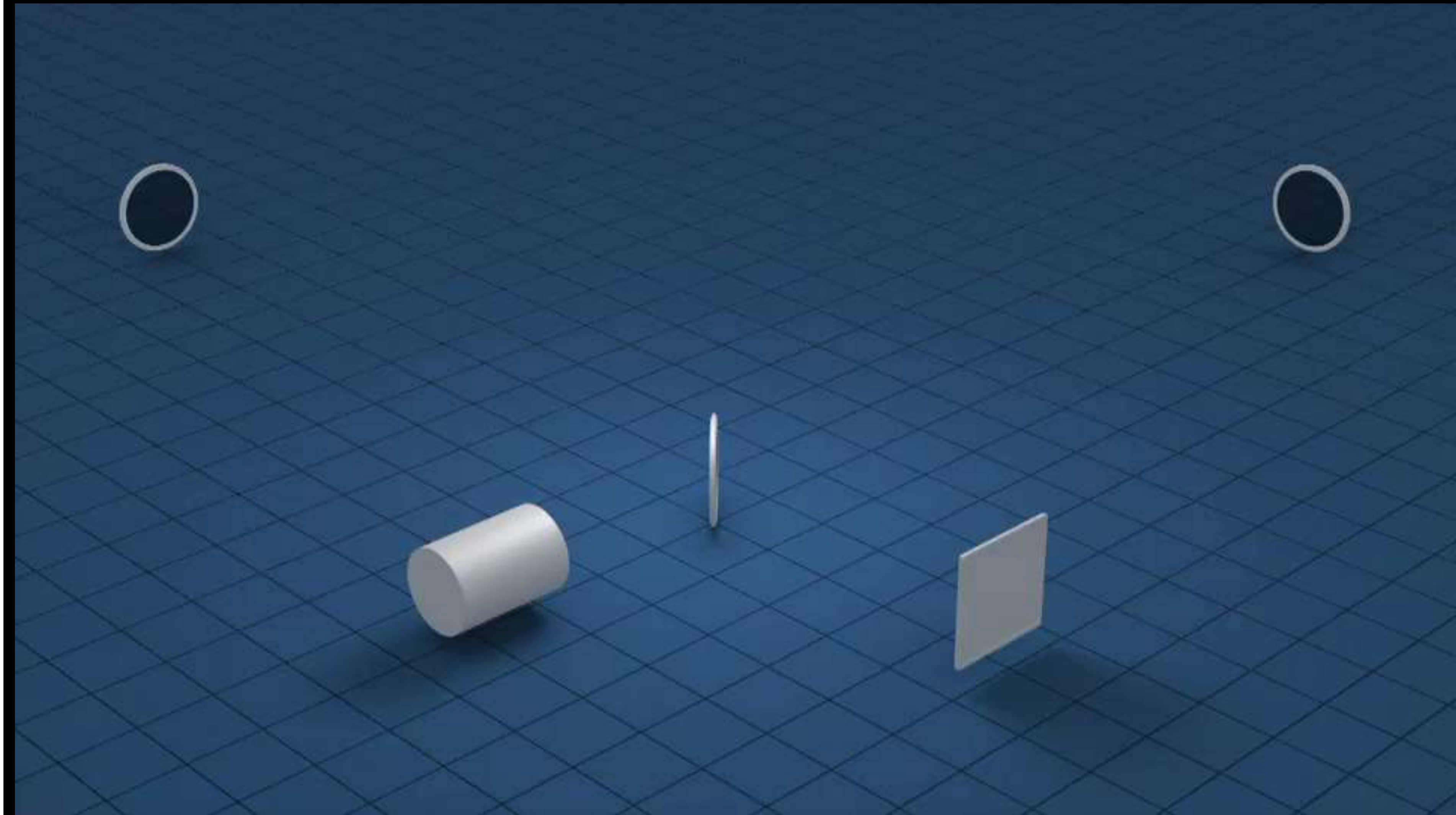




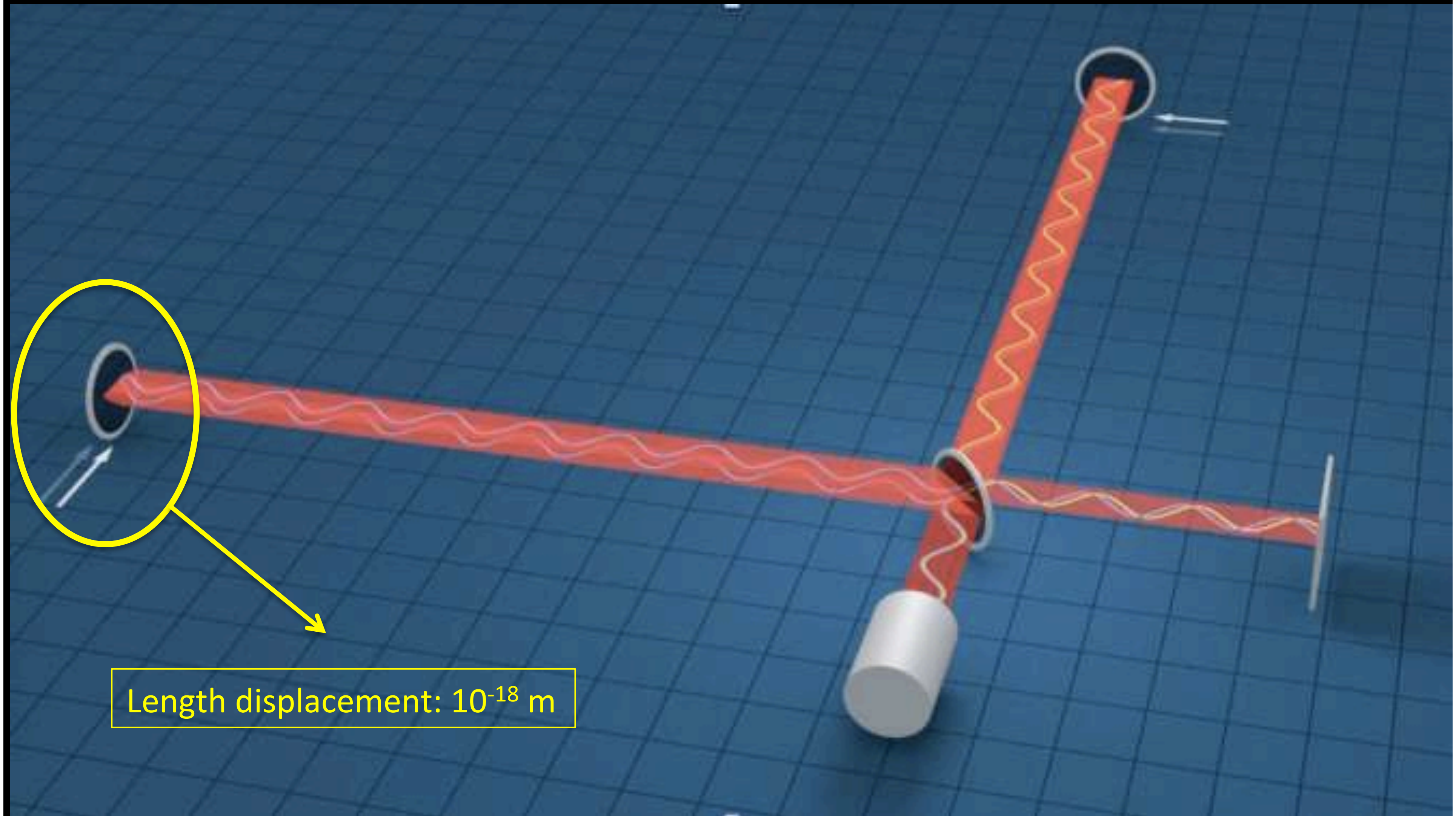
Michelson interferometer

I have greatly exaggerated the effect!

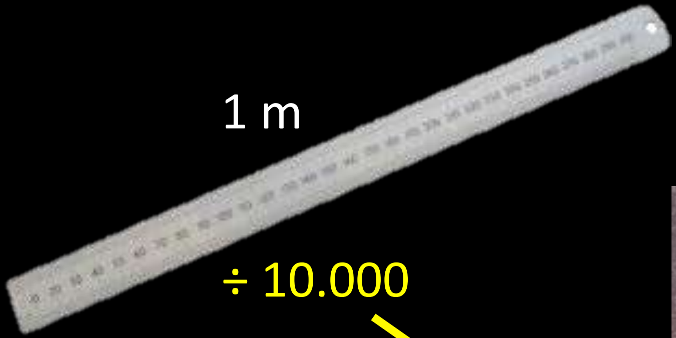
Detecting GWs with light



Detecting GWs with light



1 m



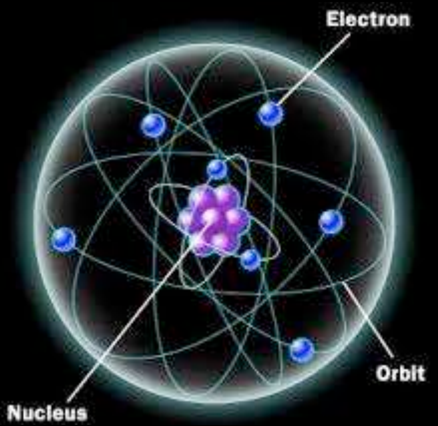
÷ 10.000

10^{-4} m

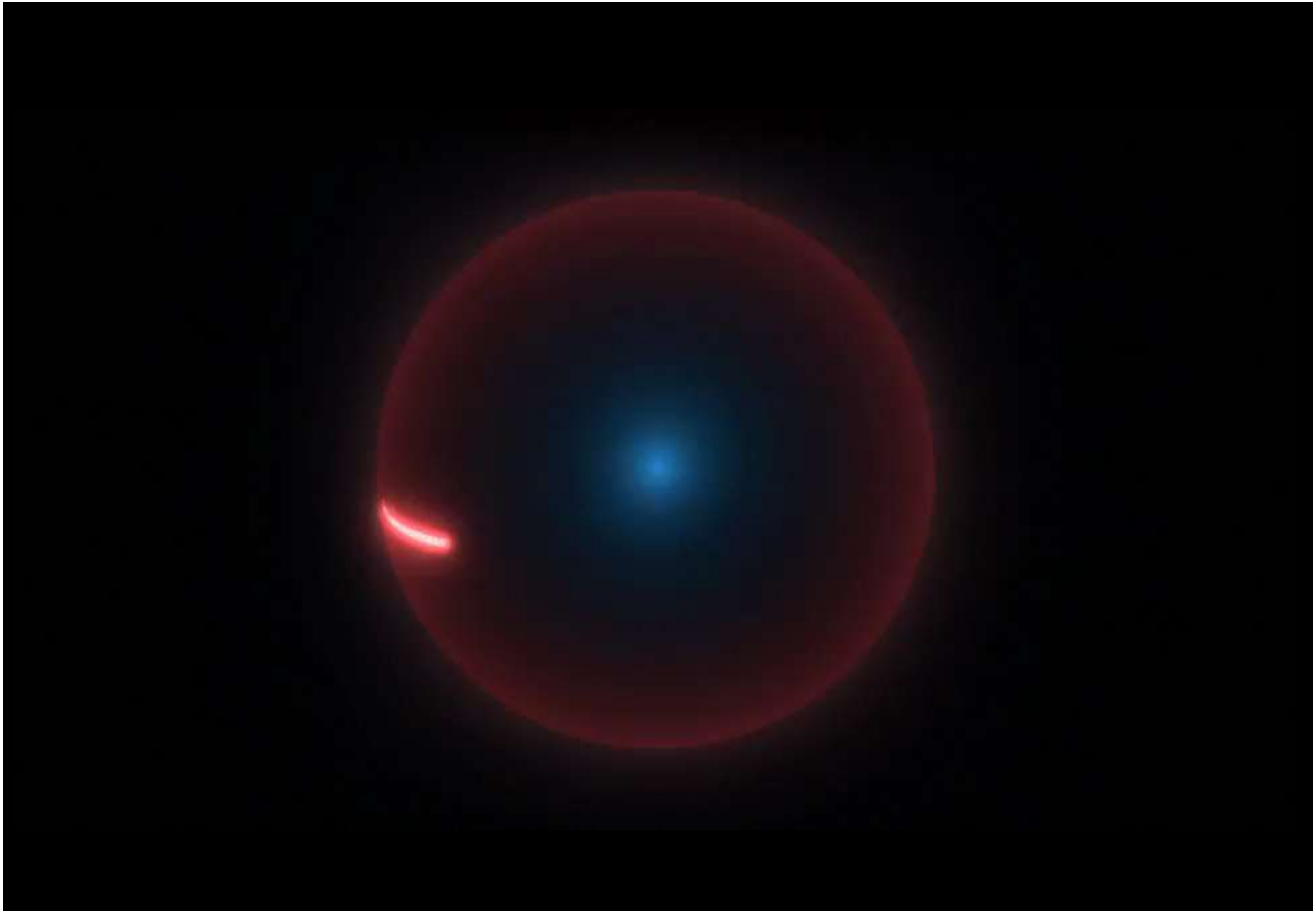
÷ 100

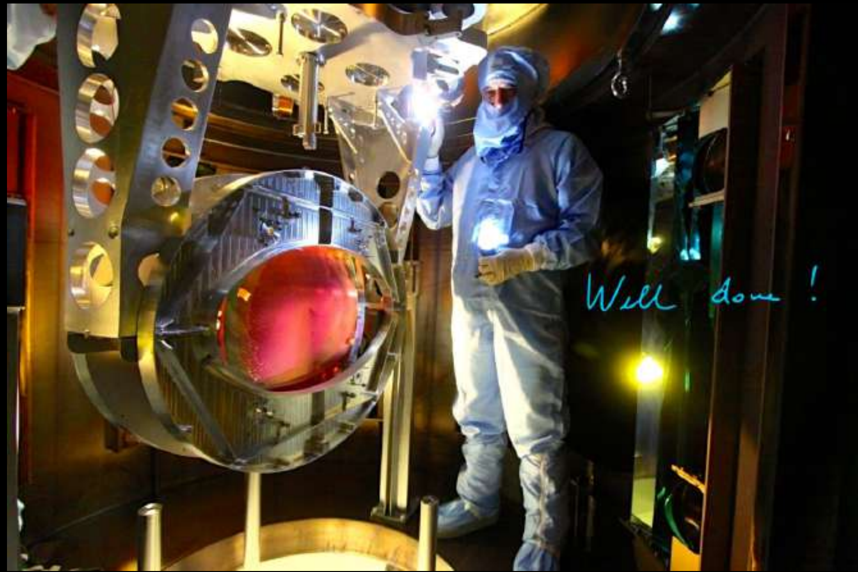
10^{-6} m

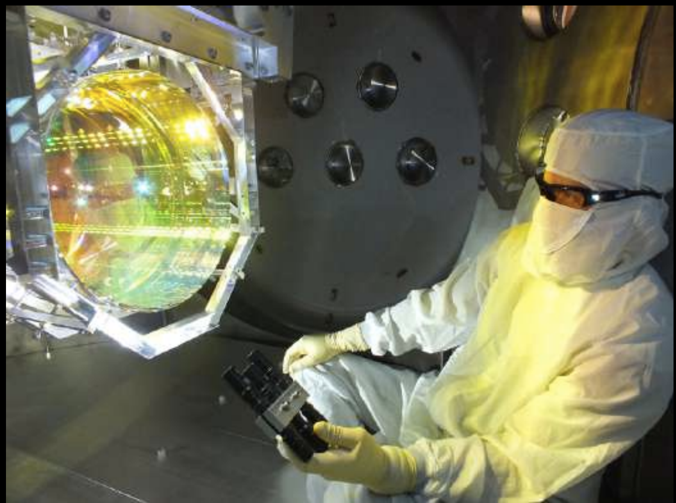
÷ 10.000

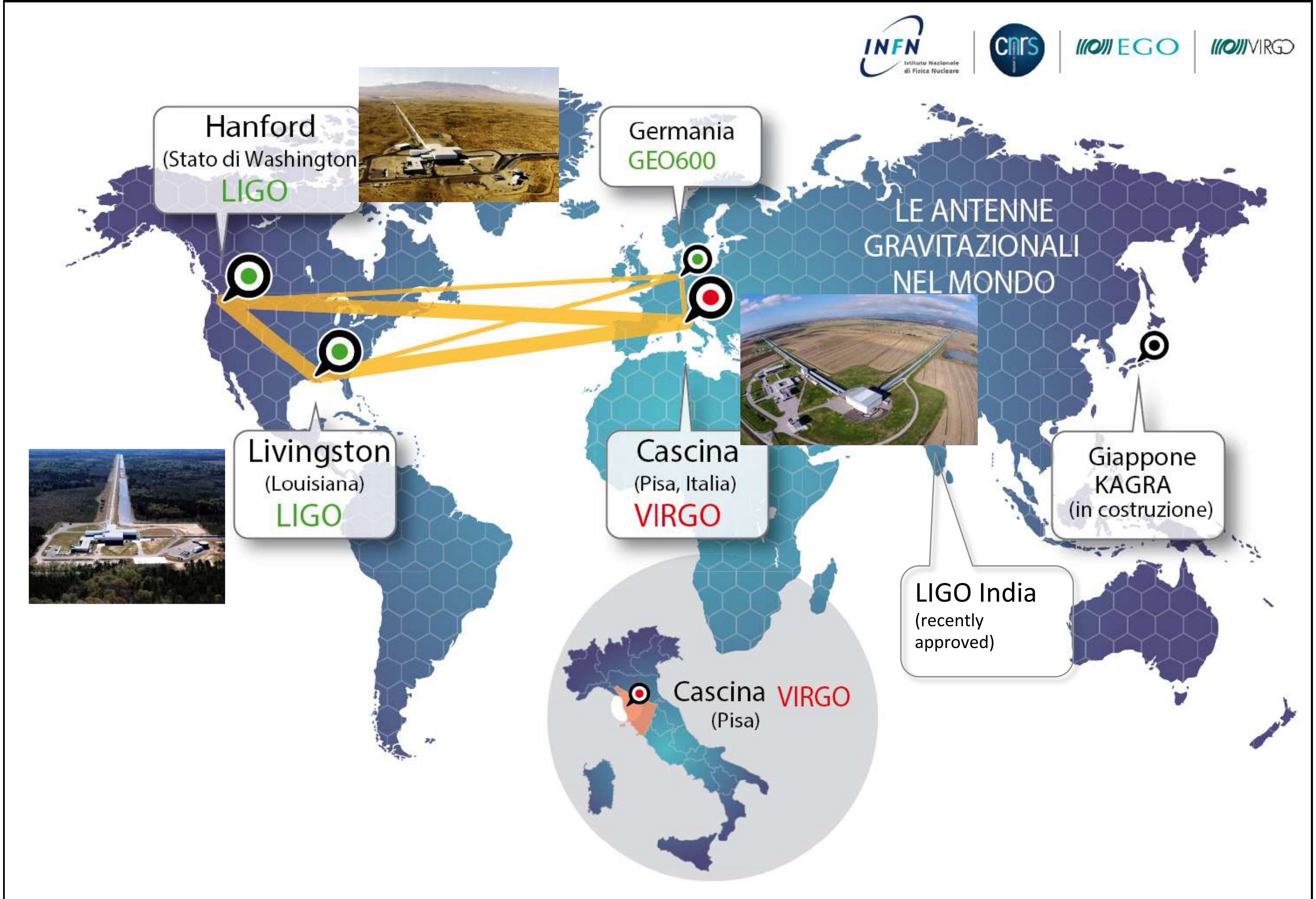


10^{-10} m



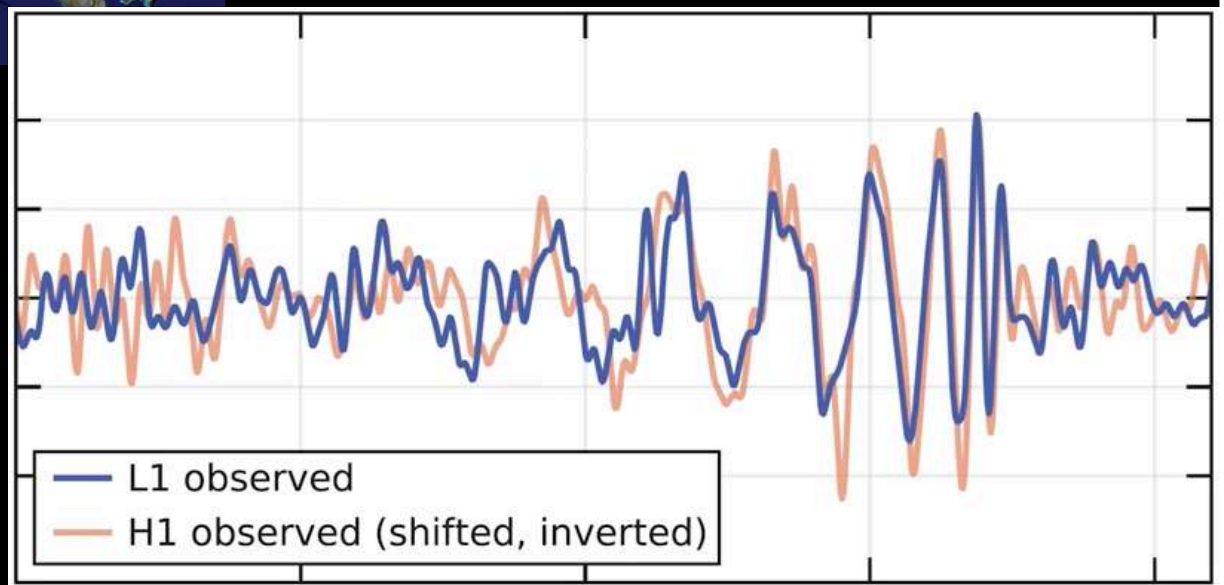

Well done !



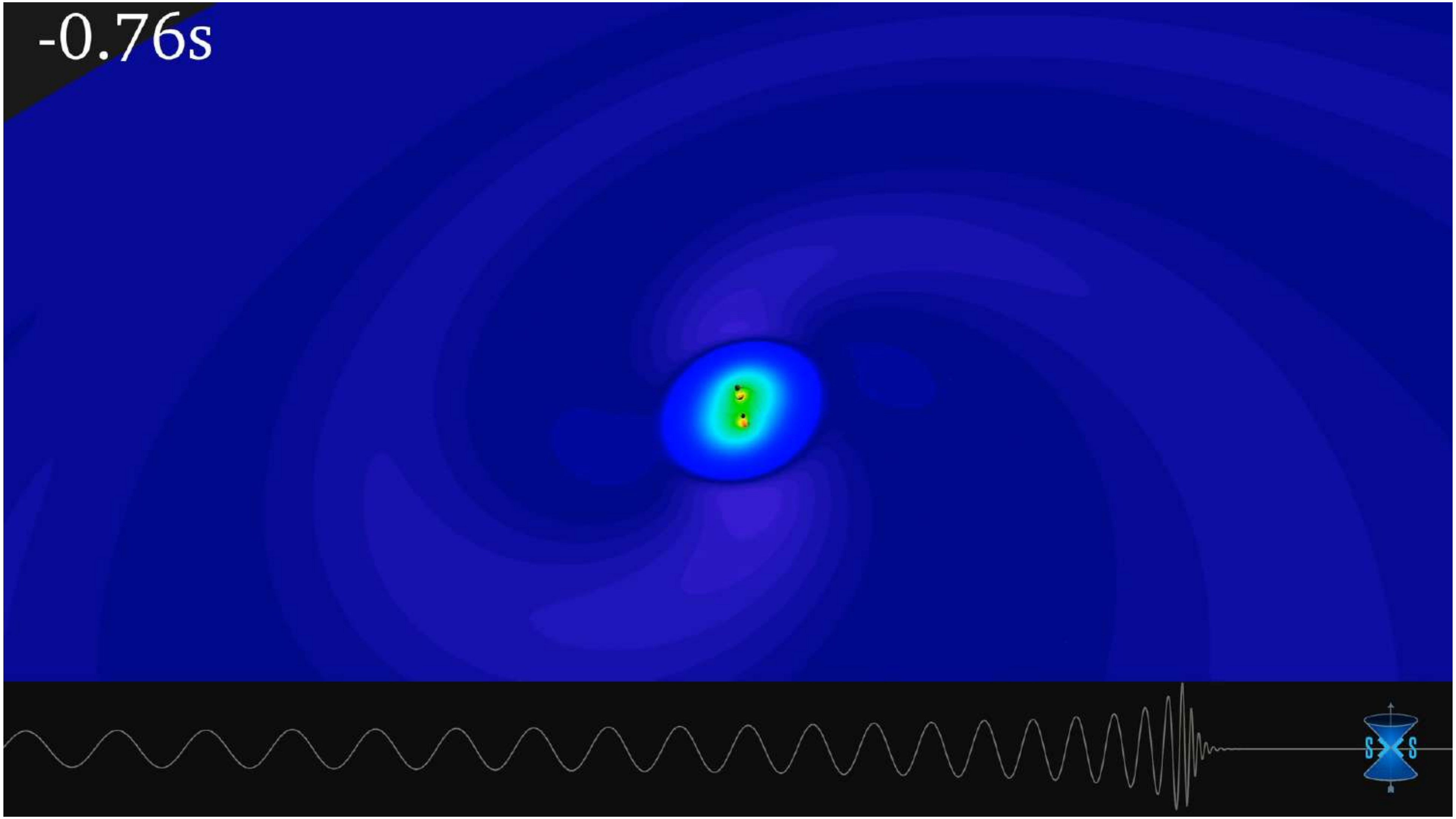


LE ANTENNE GRAVITAZIONALI NEL MONDO
Hanford
(Stato di Washington)
LIGO
Germania
GEO600
Livingston
(Louisiana)
LIGO
Cascina
(Pisa, Italia)
VIRGO
Giappone
KAGRA
(in costruzione)
LIGO India
(recently approved)
Cascina
(Pisa)
VIRGO

September 14th 2015 11:50:45 am



GWs emitted by a binary system



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

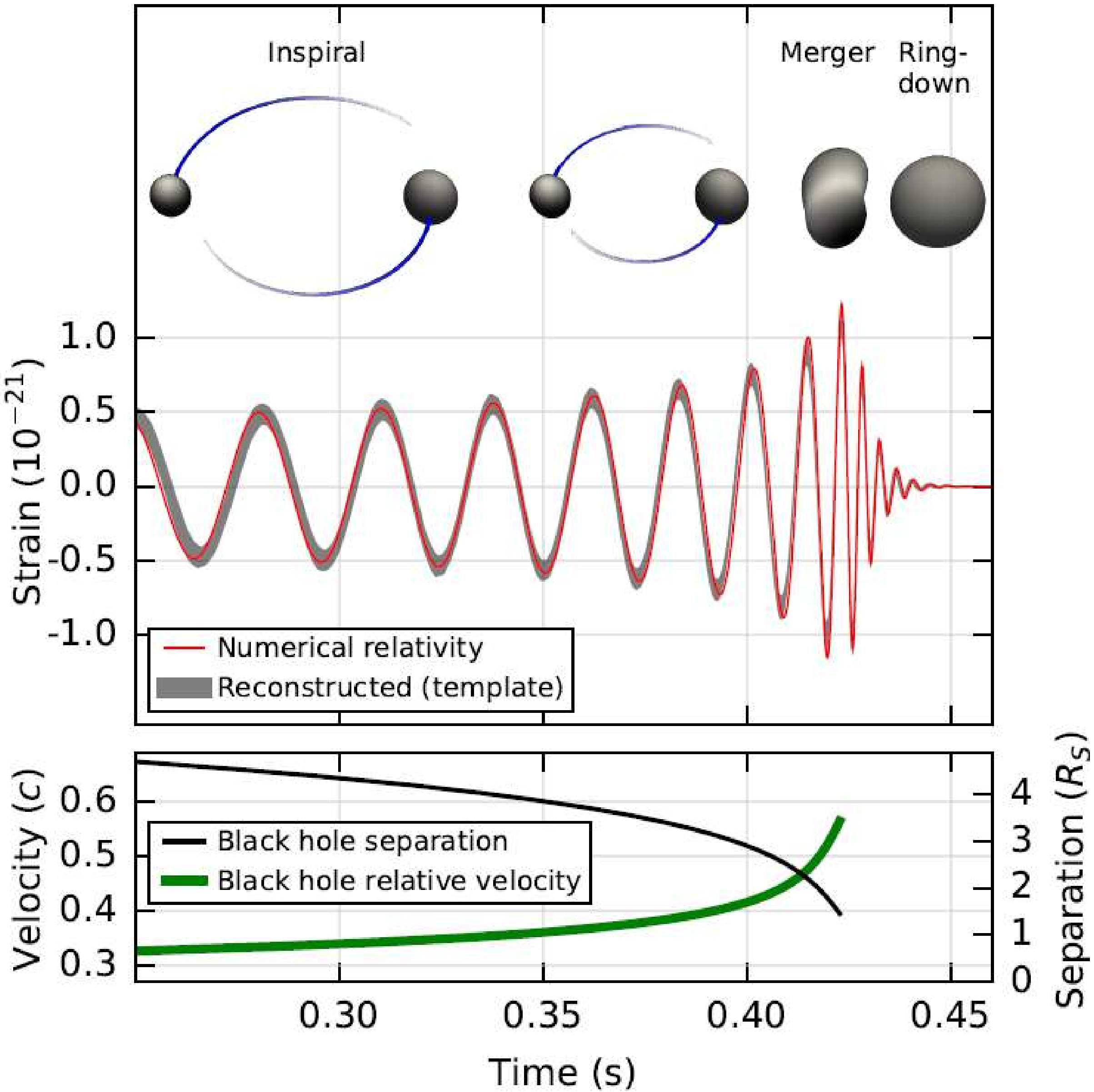
- 3 solar masses have been converted in gravitational energy

$$E = mc^2$$

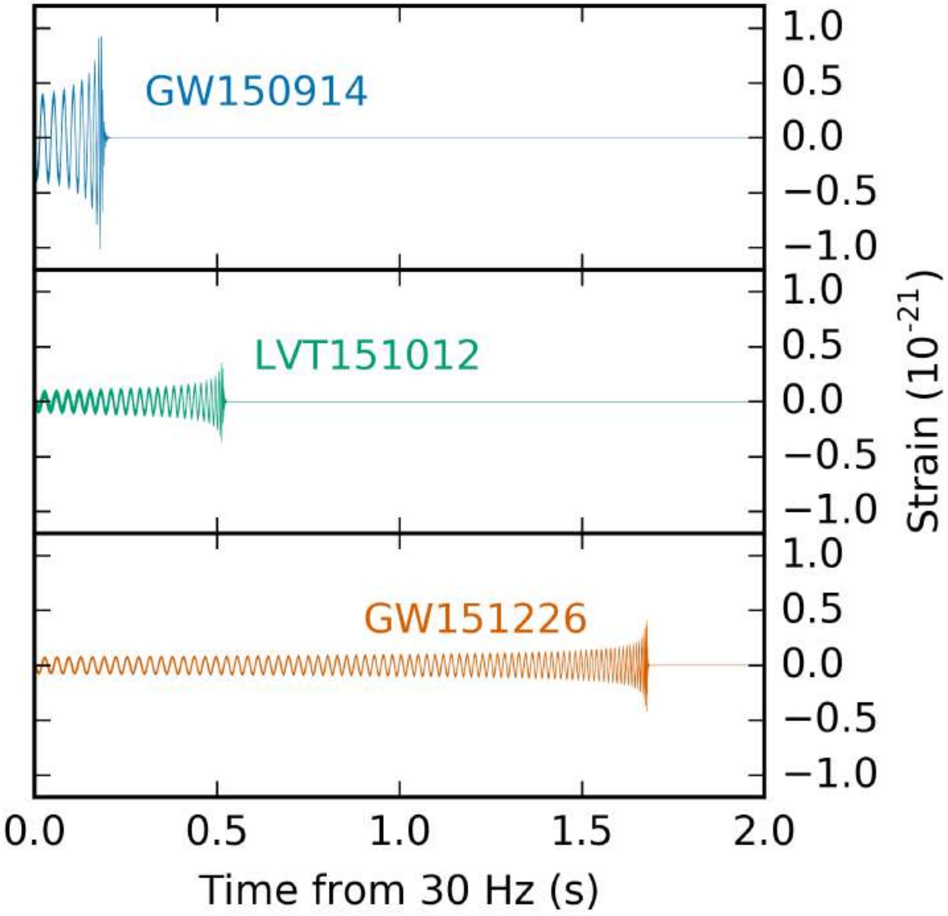
50 x light emitted by all the stars in the Universe

in a few tenths of seconds

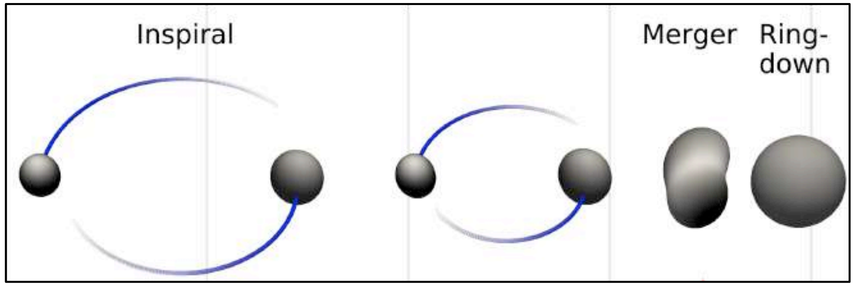
- Distance = 1,3 billions light years


Inspiral
Merger
Ring-
down
1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
4
3
2
1
0
Separation (R_S)
0.30
0.35
0.40
0.45
Time (s)

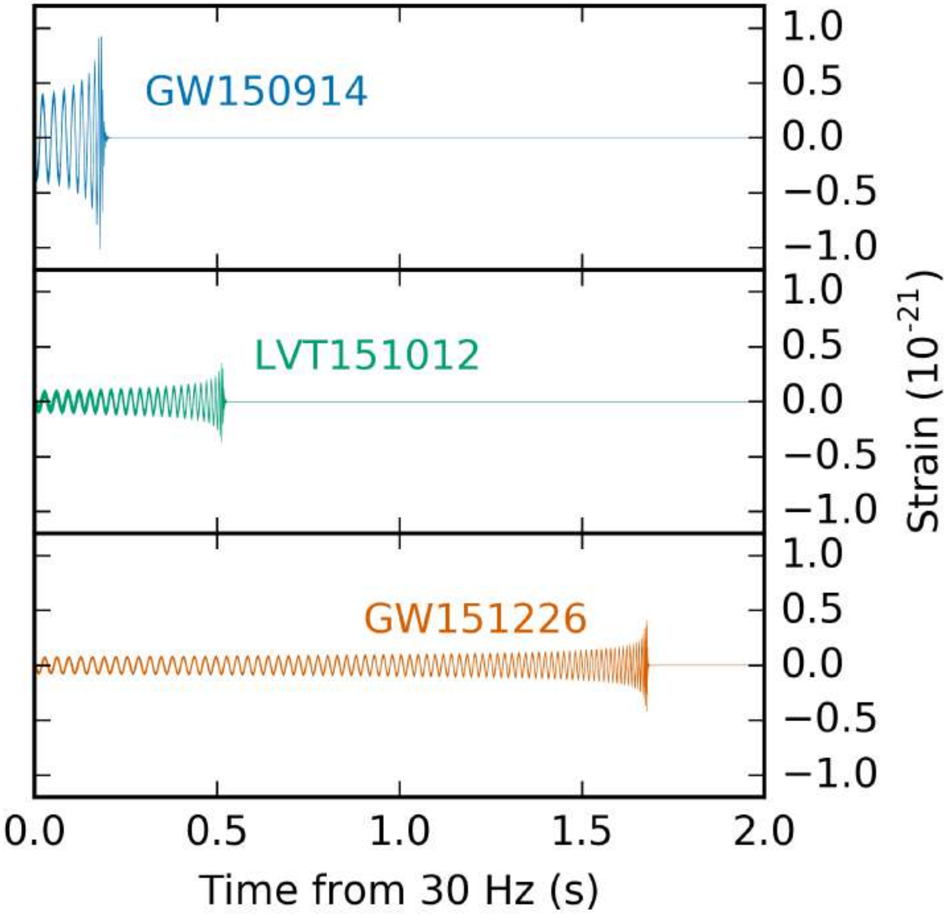
More signals detected



Evolution of a BH-BH binary system



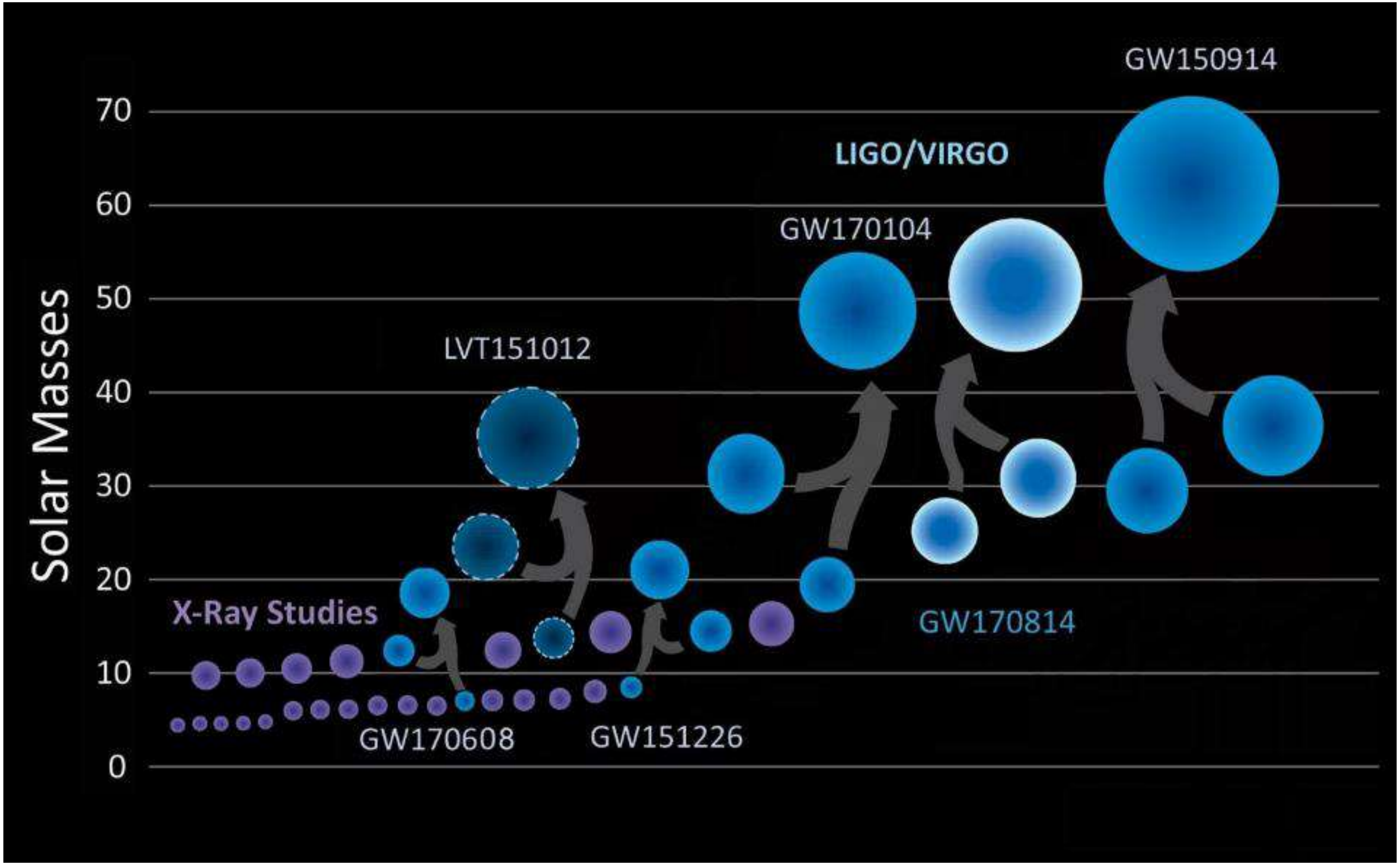
More signals detected



Masses of the BH progenitors

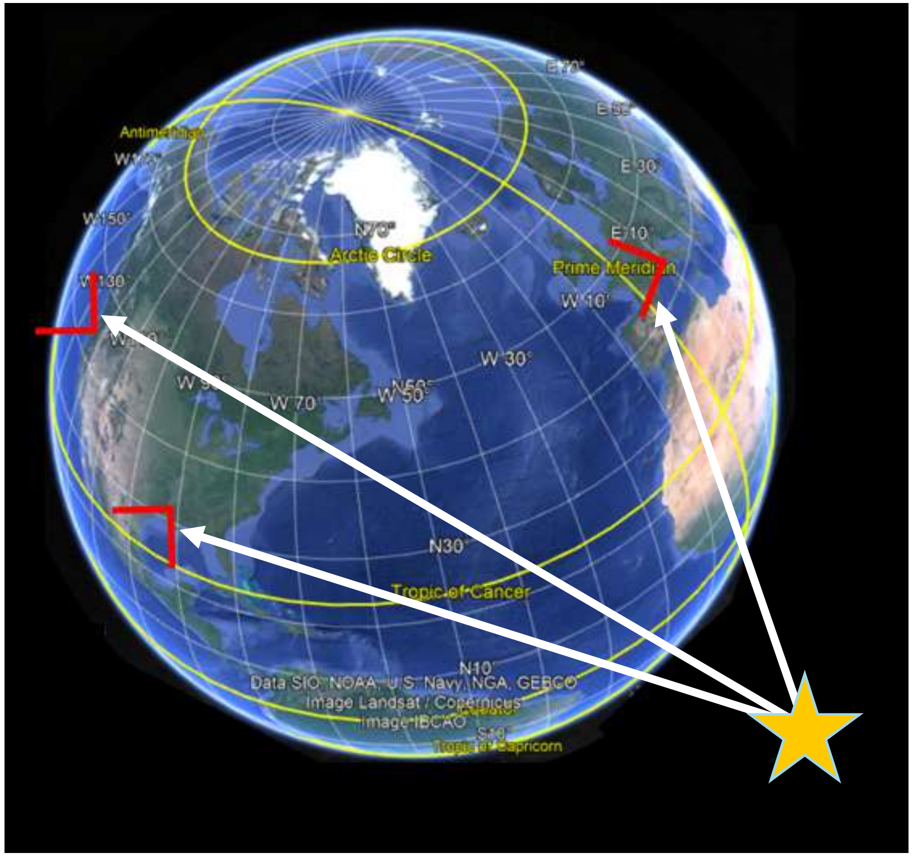
Main	Companion
$36^{+5}_{-4}\ M_\odot$	$29^{+4}_{-5}\ M_\odot$
$23^{+18}_{-6}\ M_\odot$	$13^{+4}_{-5}\ M_\odot$
$14^{+8}_{-4}\ M_\odot$	$7.5^{+2}_{-2}\ M_\odot$

Black Holes of Known Mass



Not only gravitational waves from BHs detected, also from Neutron Stars

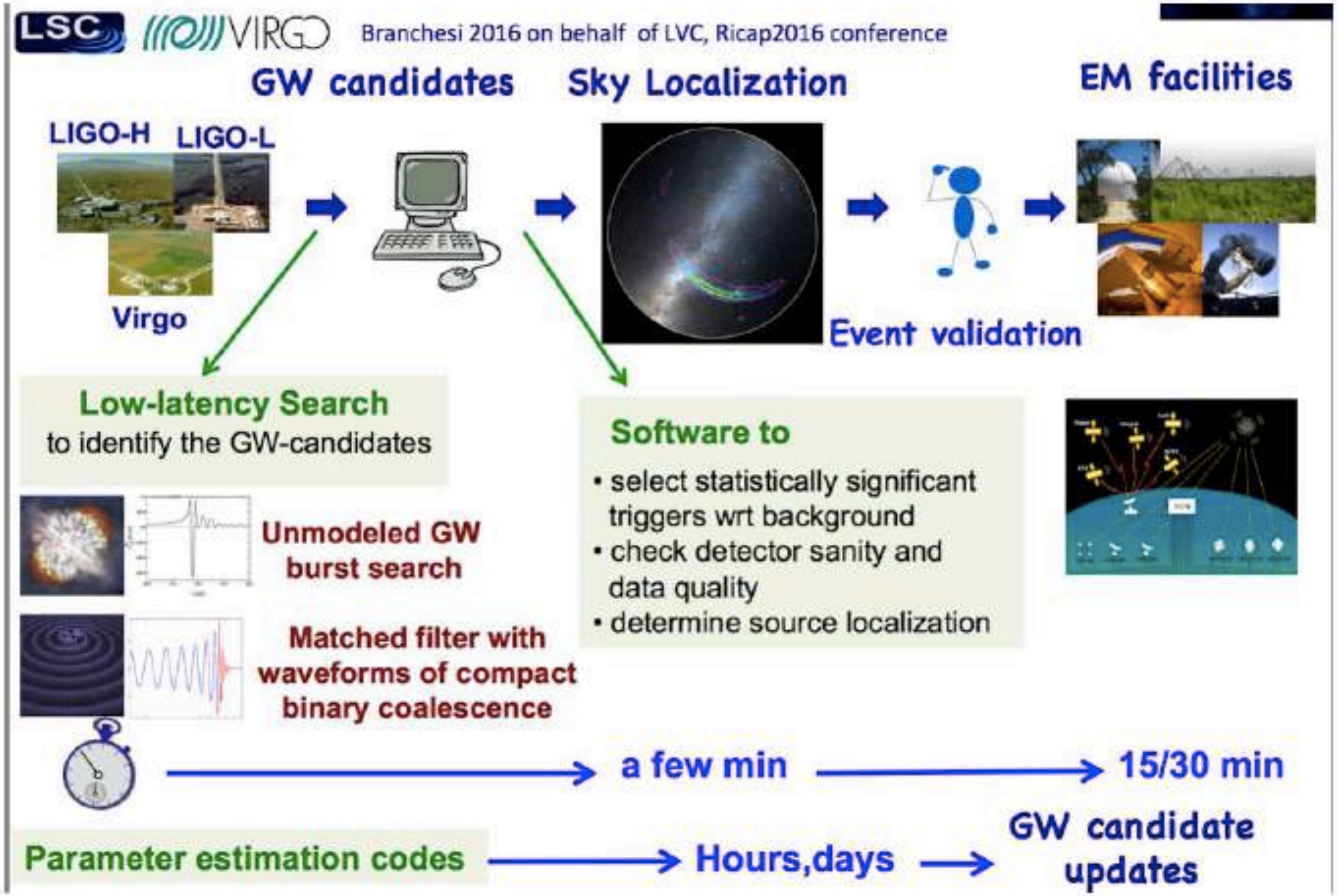
GW170817: localization



Multimessenger Astrophysics

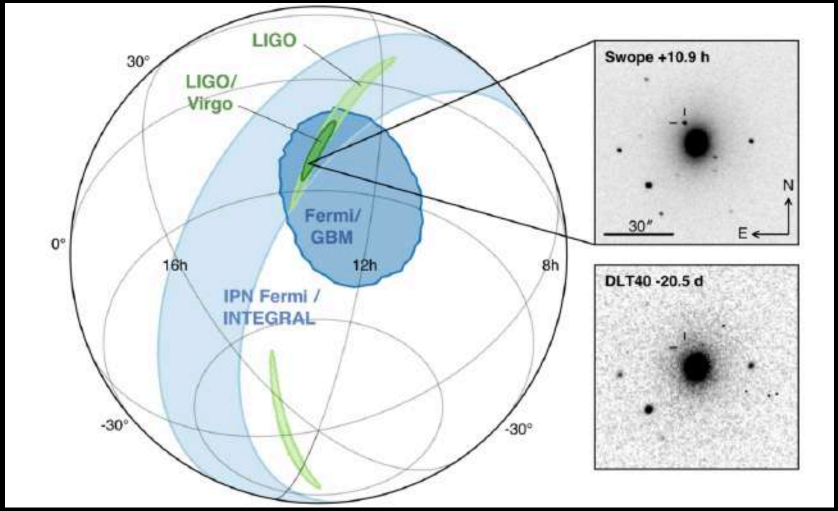
August 17th, 2017

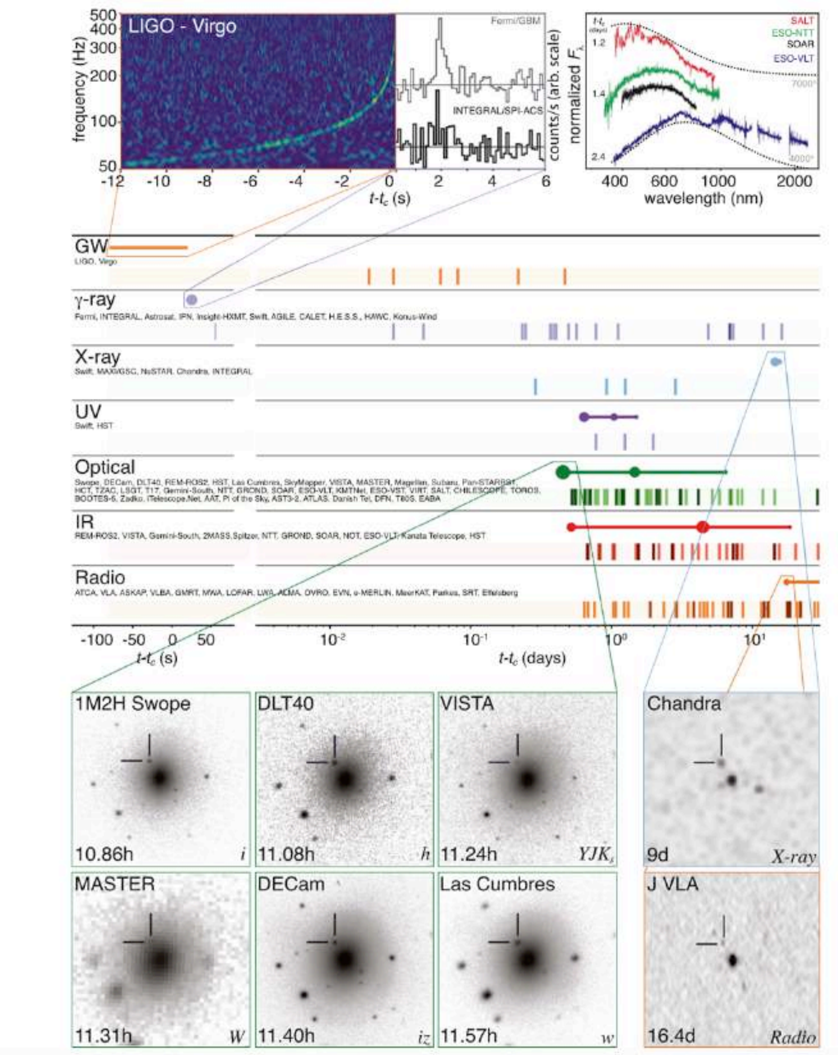
E.M. FOLLOW-UP



93 groups (>200 instruments) have signed the MoU with the LVC

The dawn of multi-messenger astrophysics





EM observation components:

(i) GW+prompt gamma-ray detection
→ BNS merger short gamma-ray burst progenitor

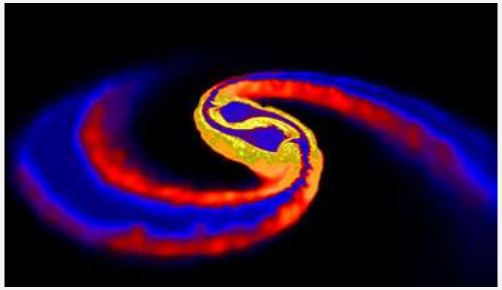
(i) an ultraviolet, optical, and infrared kilonova
→ heavy elements formed in the Universe

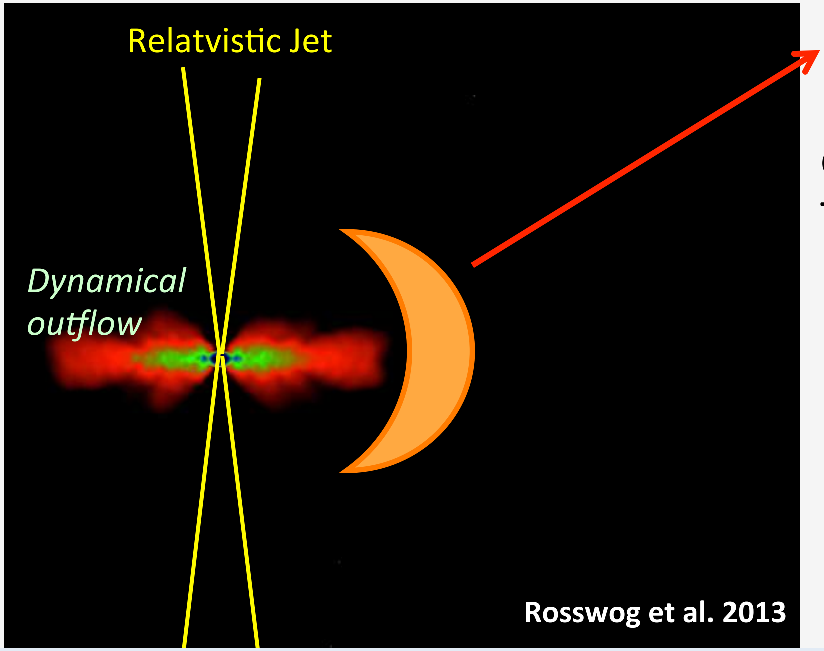
(iii) delayed X-ray and radio counterparts
→ first off-axis GRB

LVC + astronomers, ApJL, 848, L12

Macronova/Kilonova-Radio remnant

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected** during **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.3 c)**





r-process

Neutron capture rate much faster than decay, special conditions:
T > 10^9 K, high neutron density 10^{22} cm^{-3}

↓

nucleosynthesis of heavy nuclei

↓

radioactive decay of heavy elements

↓

Power MACRONOVA
short lived IR-UV signal (days)

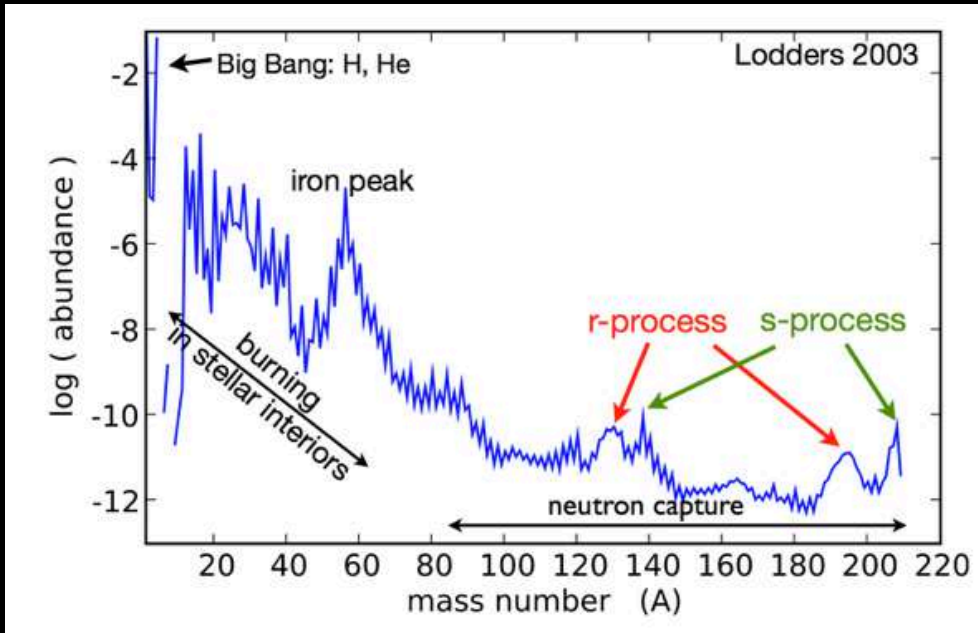
Accretion disc wind outflow

→winds unbind a fraction of the disk

→neutrino irradiation raises the electron fraction → No nucleosynthesis heavier element/high-opacity → brief (~ 2 day) **blue optical transient**

BNS and NS-BH mergers as factories of heavy elements in the Universe

Solar system abundances



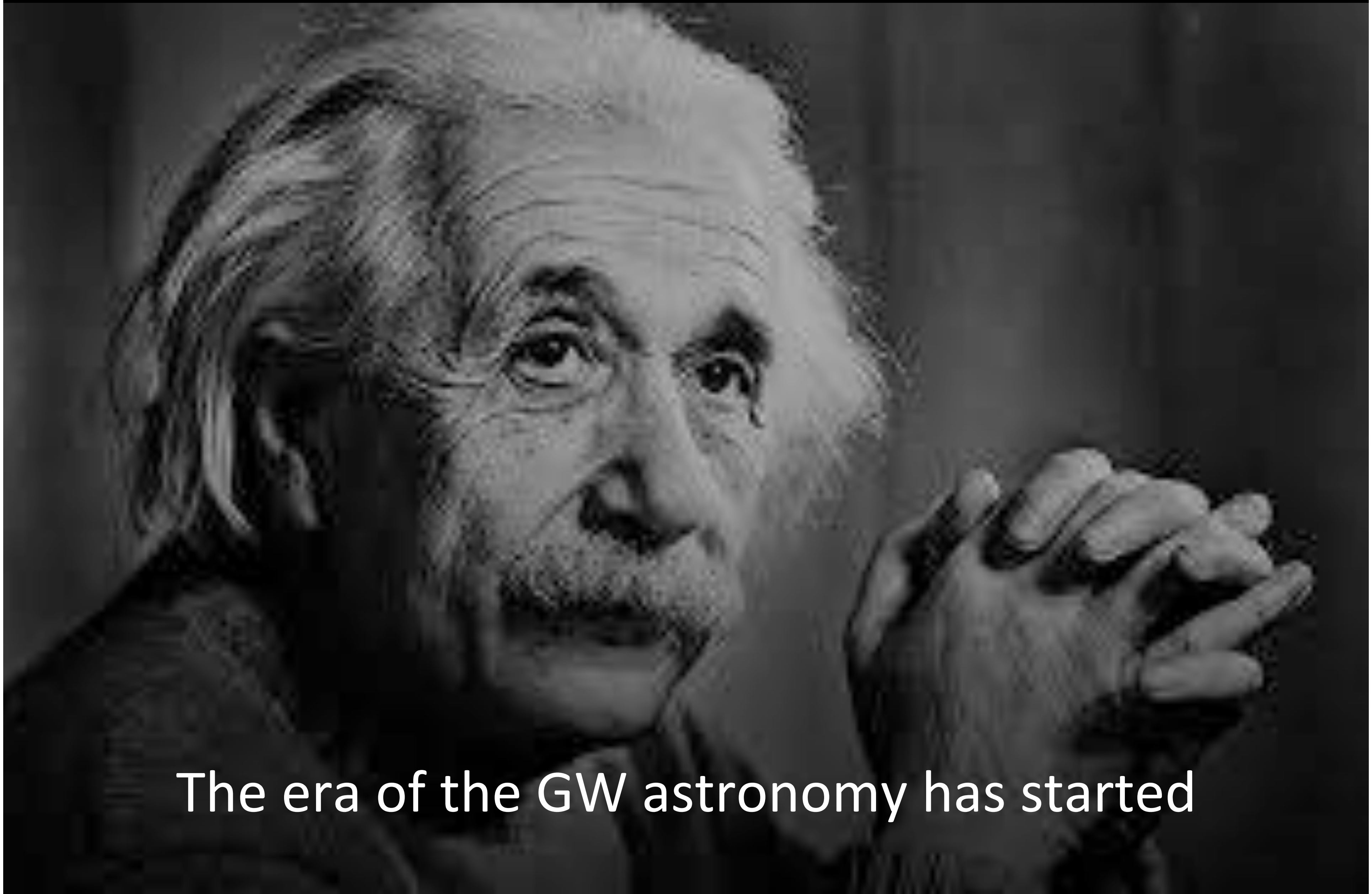
Examples of r-process elements

Iridium
Z= 77, A= 192

Platinum
Z= 78, A= 195

Gold
Z= 79, A= 197

Lead
Z= 82, A= 207



The era of the GW astronomy has started