Listening to the Universe through Einstein's waves

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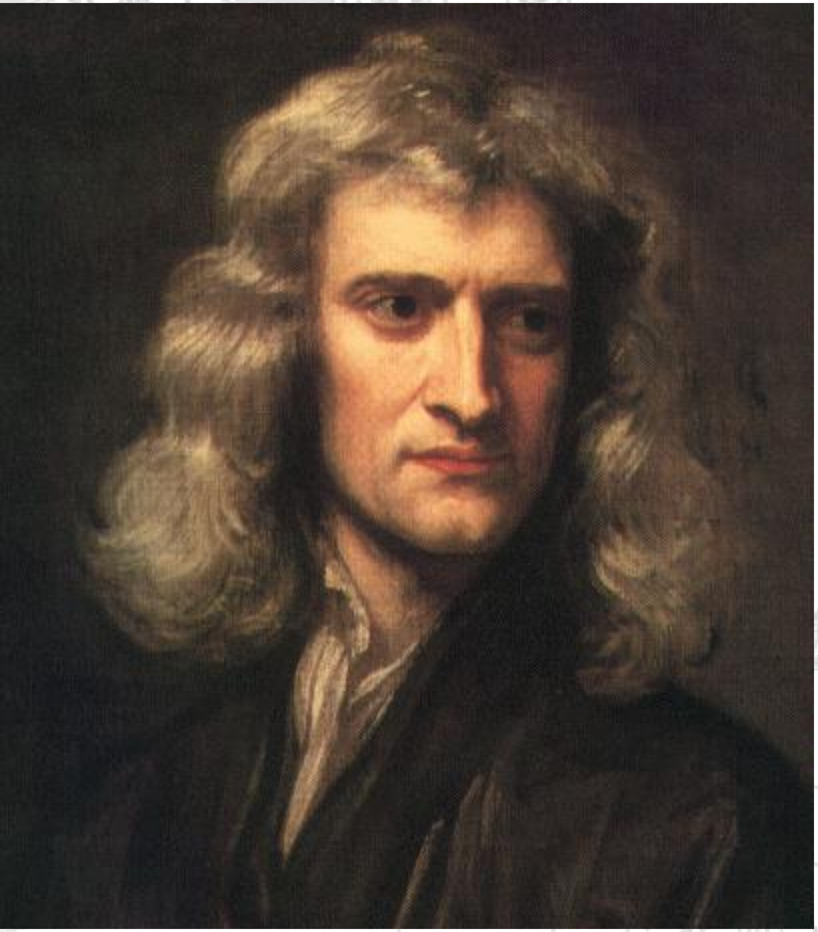
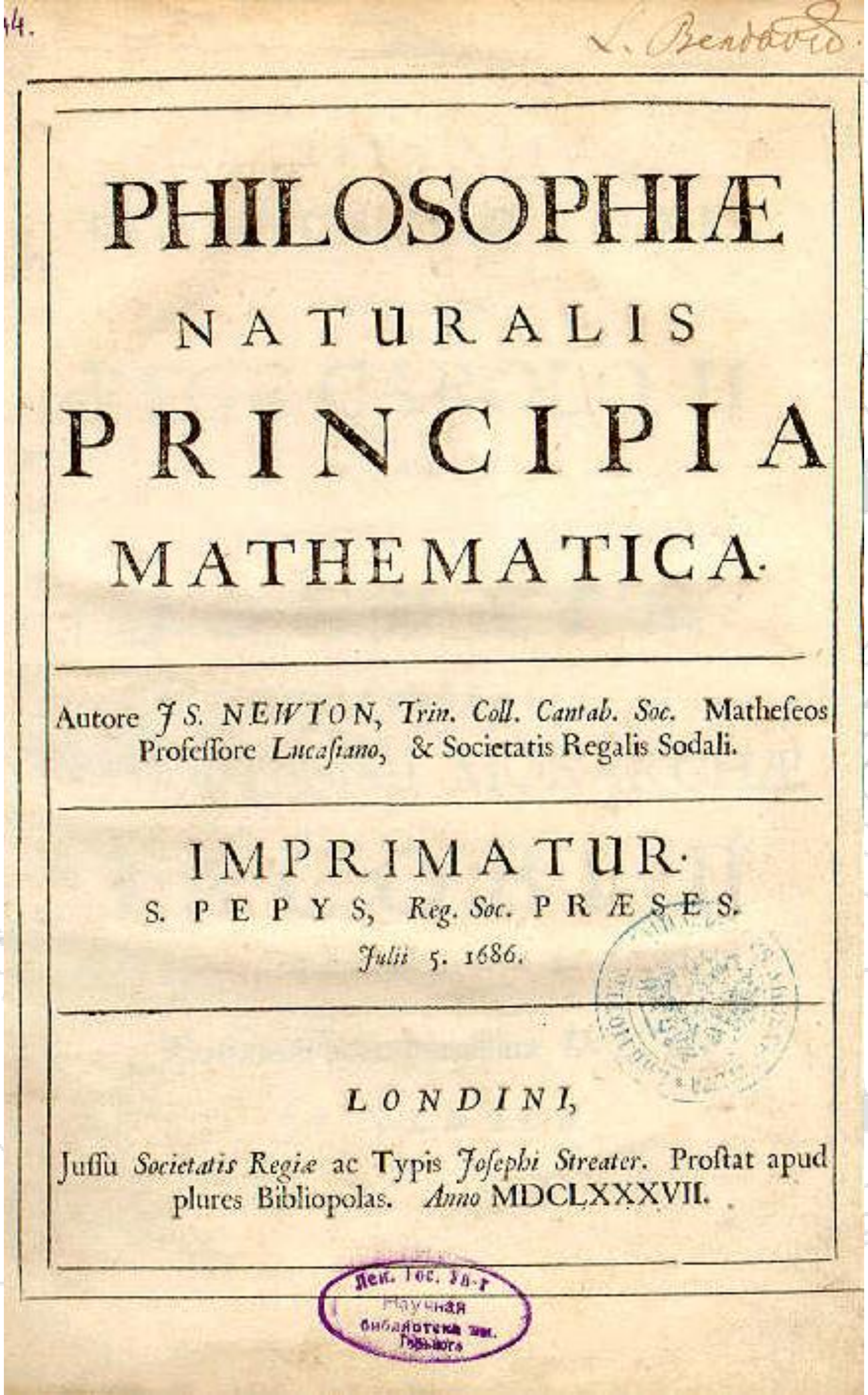
Newton’s Theory of Gravity (1686)





PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

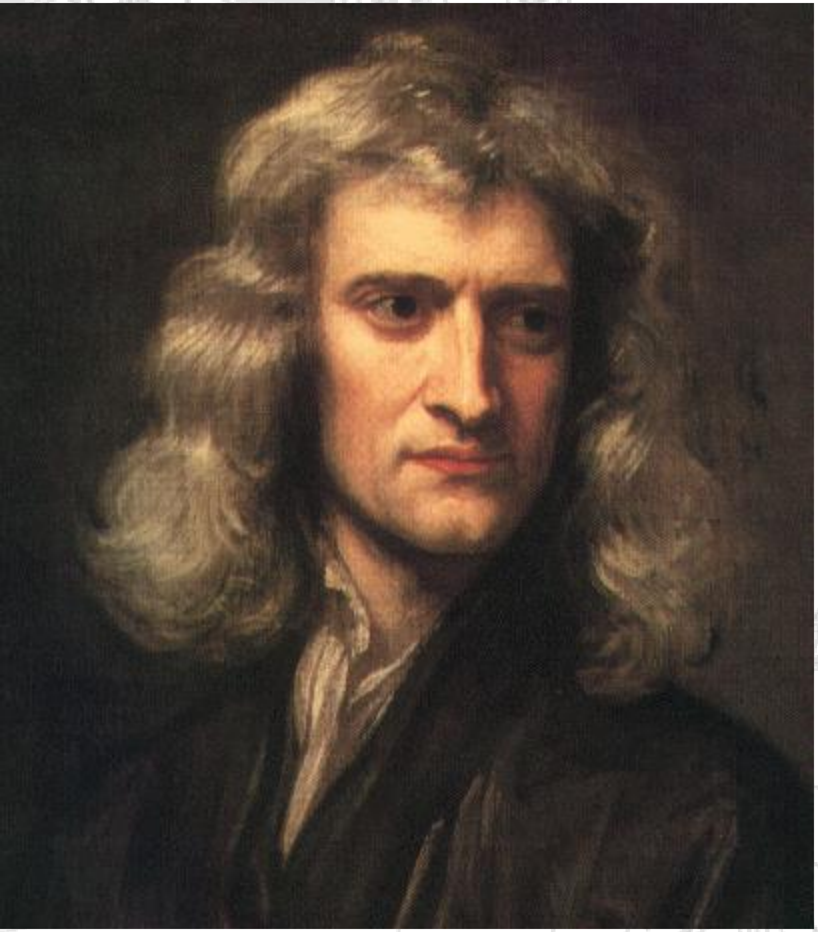
Autore *JS.* NEWTON, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

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

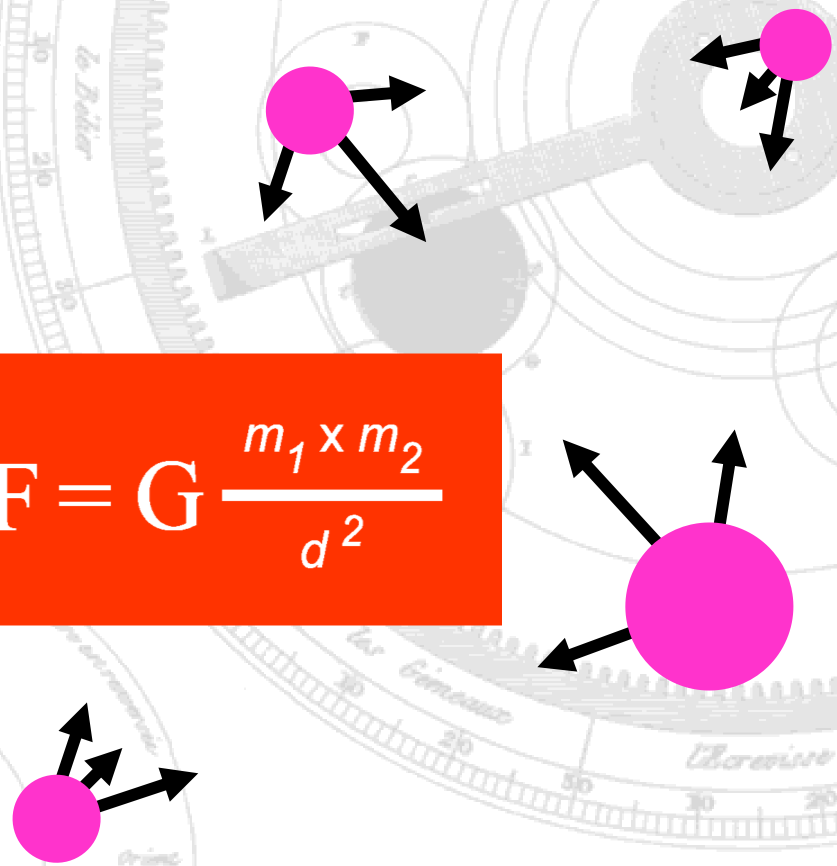
LONDINI,

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

Newton's Theory of Gravity (1686)

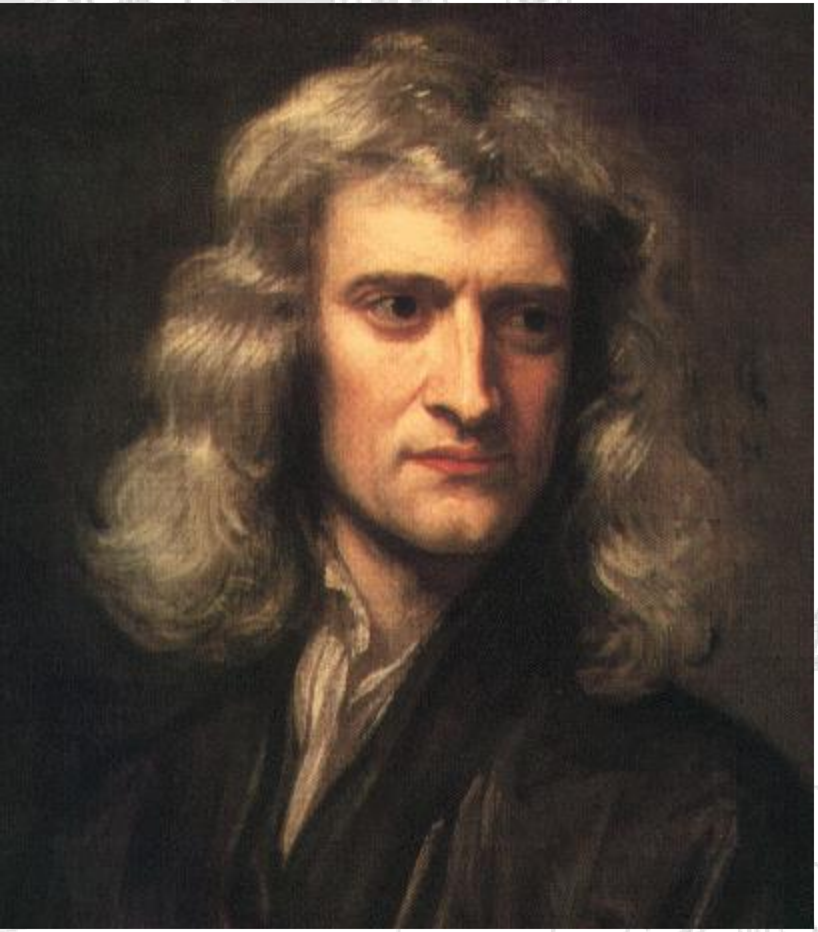


- Equal and opposite forces between pairs of bodies



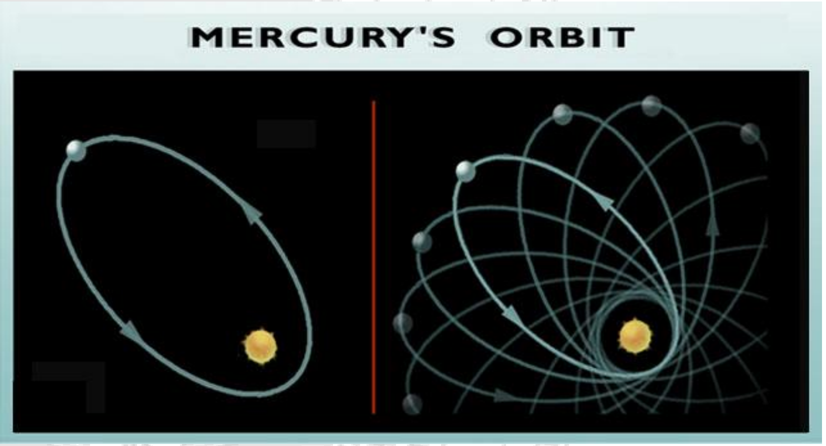
$$F = G \frac{m_1 \times m_2}{d^2}$$

Newton’s Theory of Gravity (1686)



- Extremely successful theory
- Solved most known 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

However, One Unexplained Fact and Two Mysteries



Astronomers observed perihelion of Mercury advances by 43”/century compared to Newton’s theory

What causes the mysterious force in Newton’s theory ?

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

General Relativity
A Radical Idea

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

Equazione di Einstein

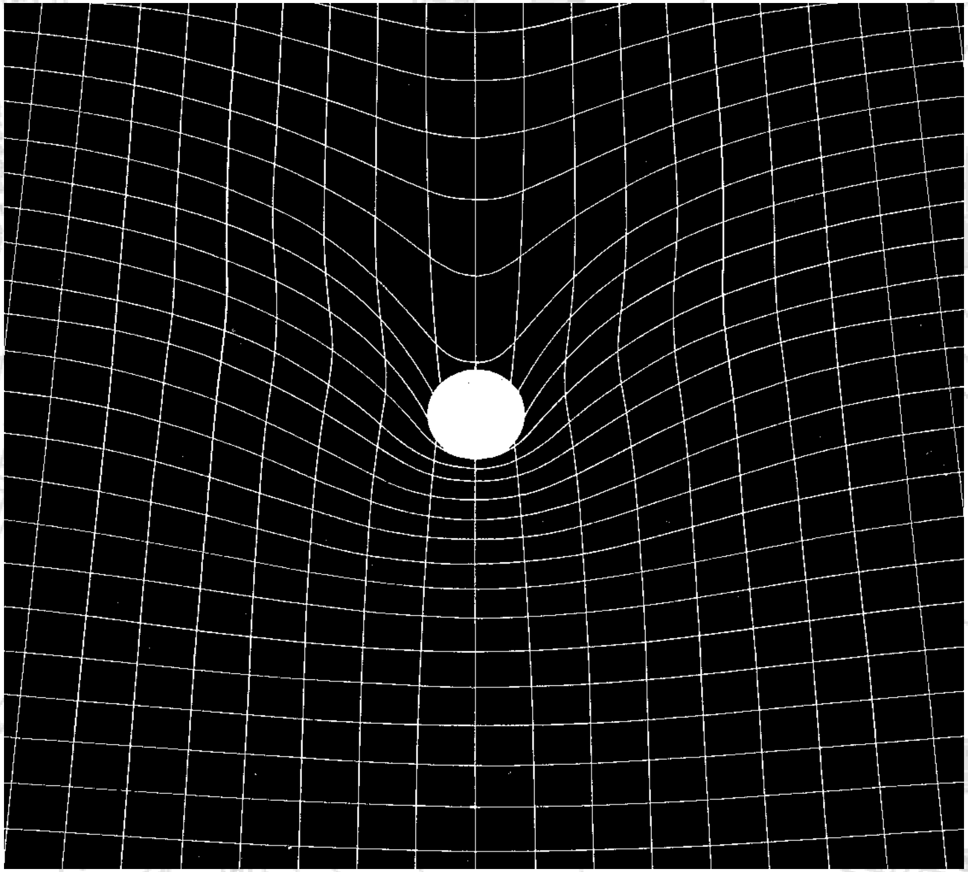
$$R_{\mu\nu} - \frac{1}{2} R \cdot g_{\mu\nu} = \frac{8\pi G}{c^2} T_{\mu\nu}$$

Spazio-tempo Materia

- La materia definisce la geometria dello spazio-tempo
- La geometria determina il moto della materia
- La distribuzione di materia ed il suo moto non possono essere descritti indipendentemente dal campo gravitazionale da essi prodotto

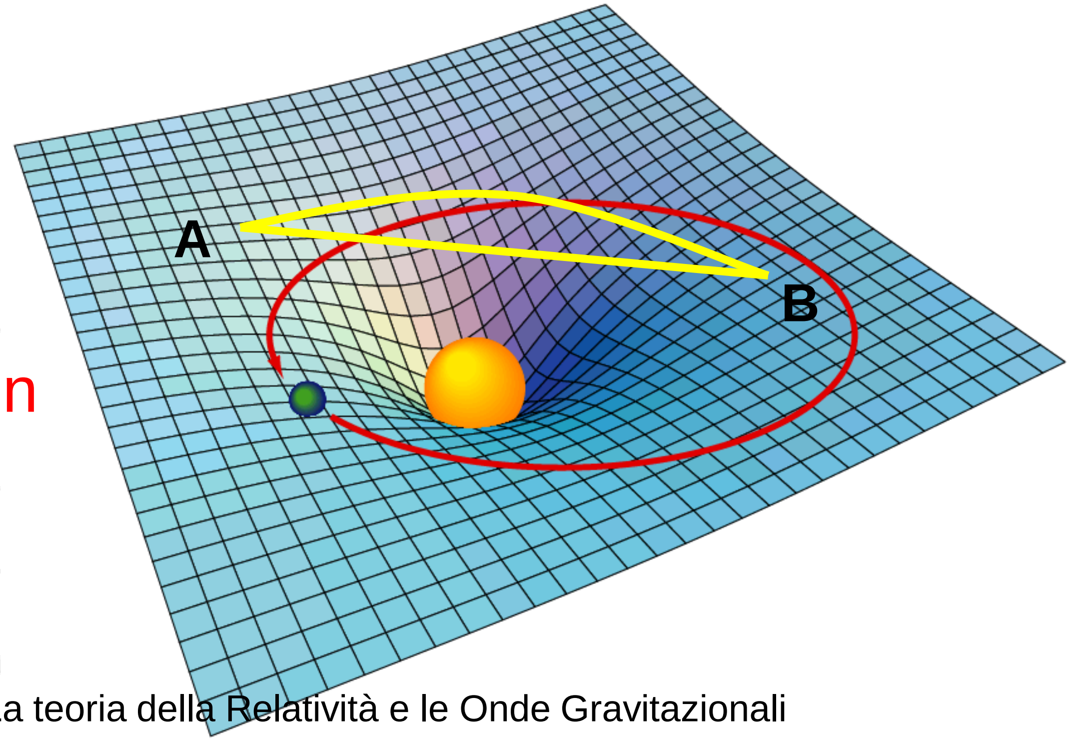
spaziotempo dice alla materia come muoversi; materia dice allo spaziotempo come distorcersi

(J. Wheeler)



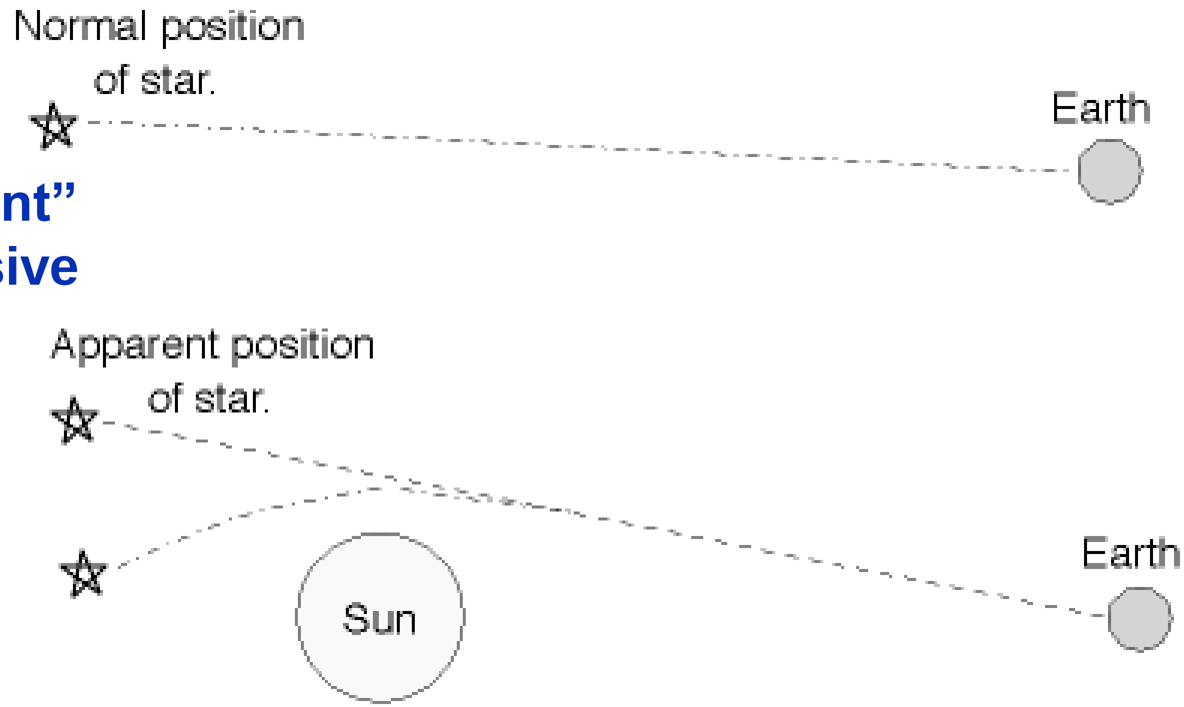
General Relativity
A Radical Idea

- 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



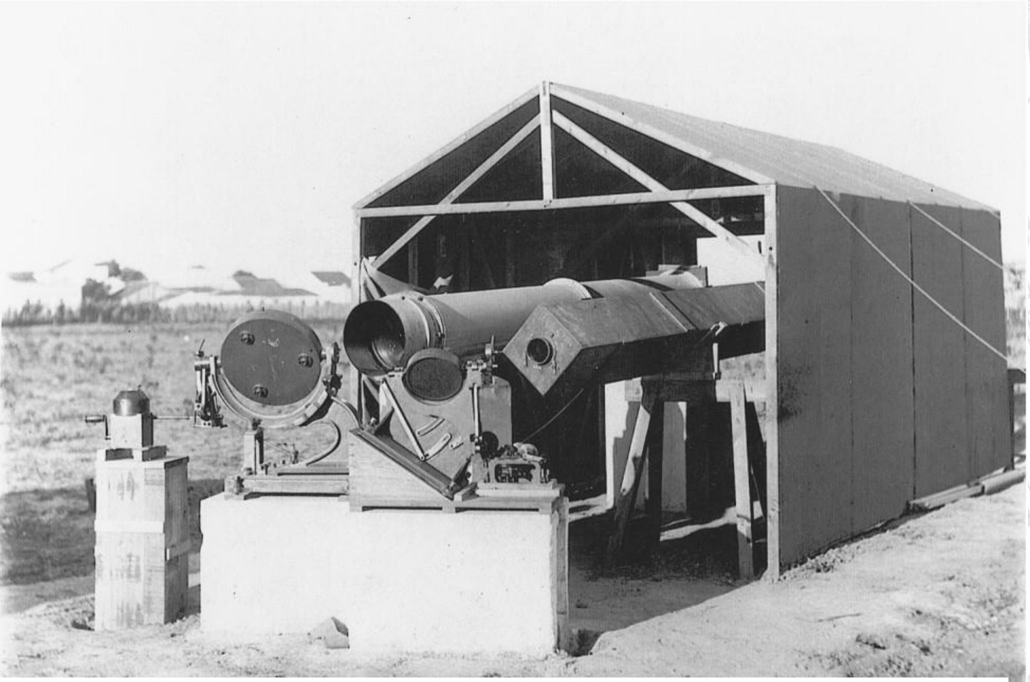
The path of light will be "bent" when it passes near a massive object (like the sun)

Inversely proportional to angle between sun and star

Could only be seen during eclipse

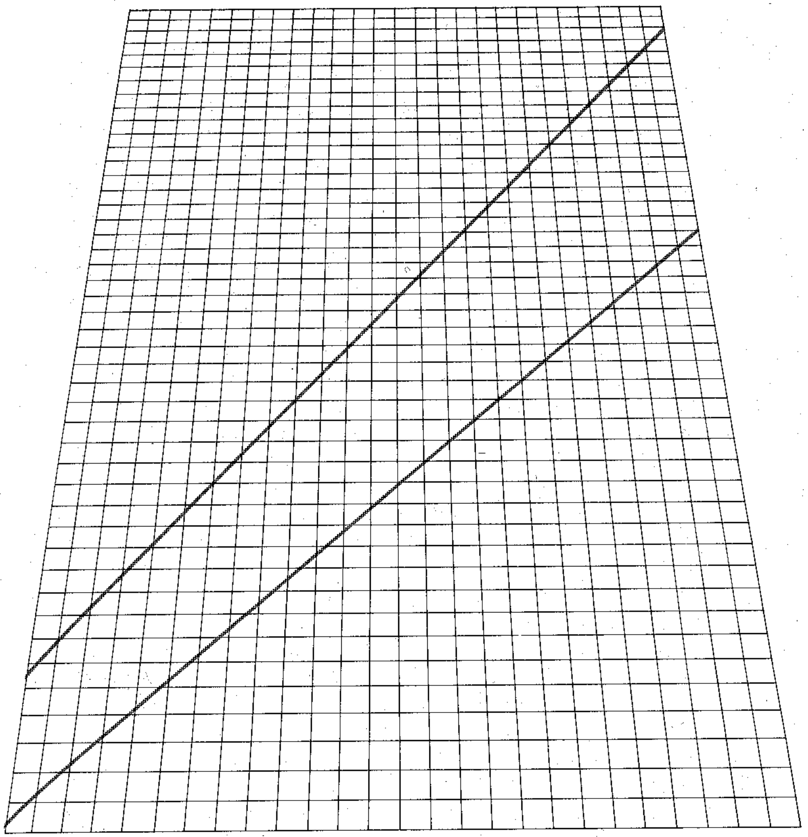
Confirming Einstein ….

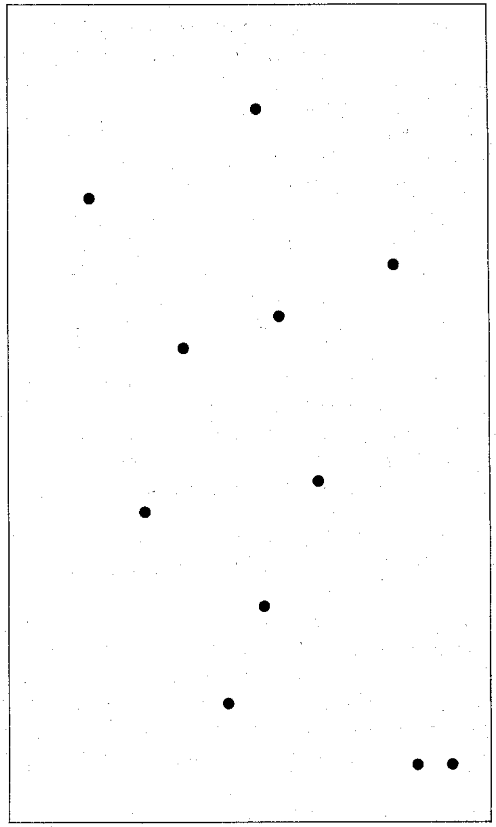
- Famous British astronomer Sir Arthur Eddington led an expedition to photograph the solar eclipse of 29 May 1919 against Hyades star cluster



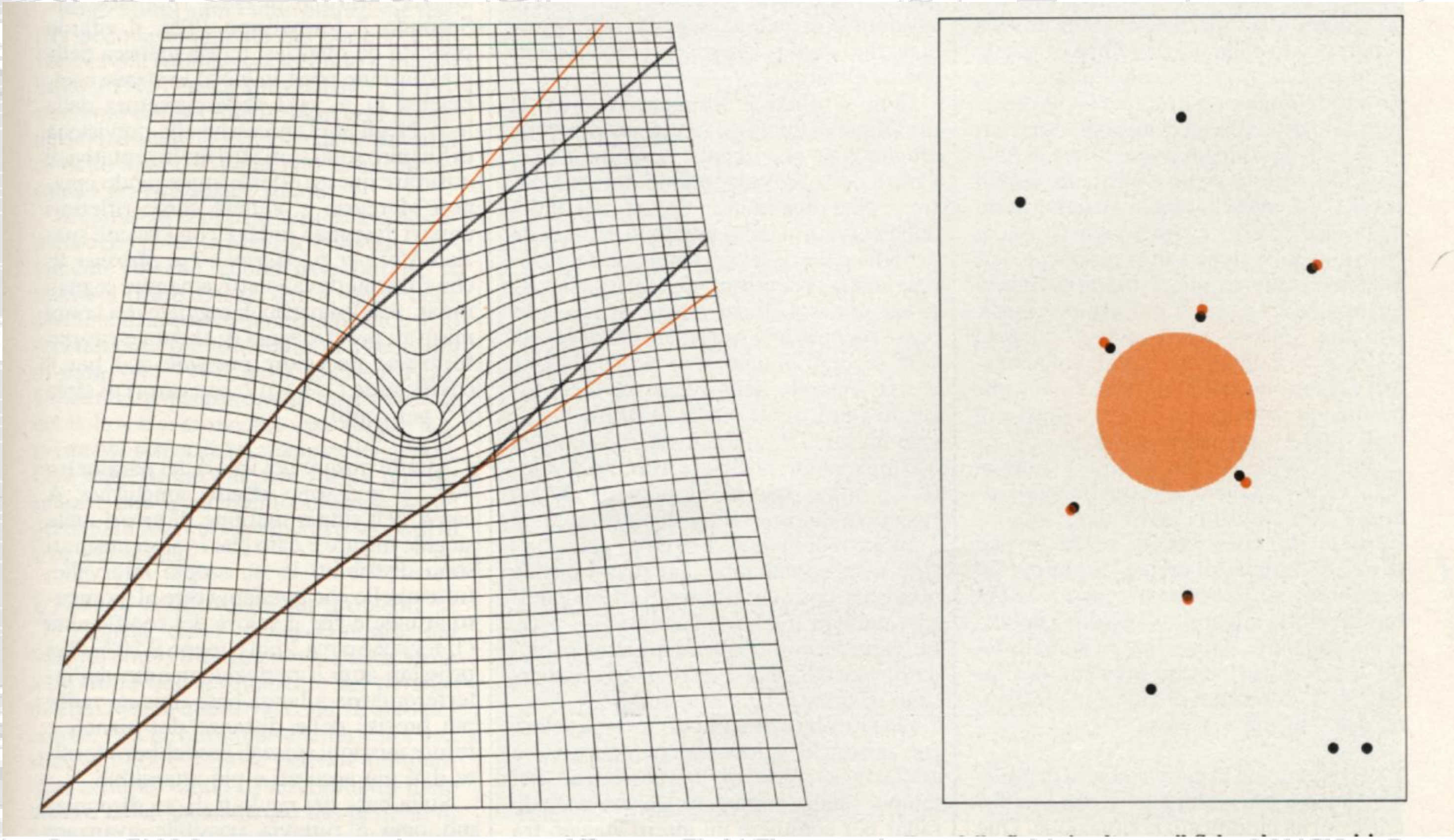
	Measured Deflection
No Deflection	**0**
Einstein	**1.75”**
Principe	**1.61” ± 0.30”**
Sobral	**1.98” ± 0.12”**

Confirming Einstein ….





Confirming Einstein ….



Stunning Confirmation for Relativity

REVOLUTION IN SCIENCE.

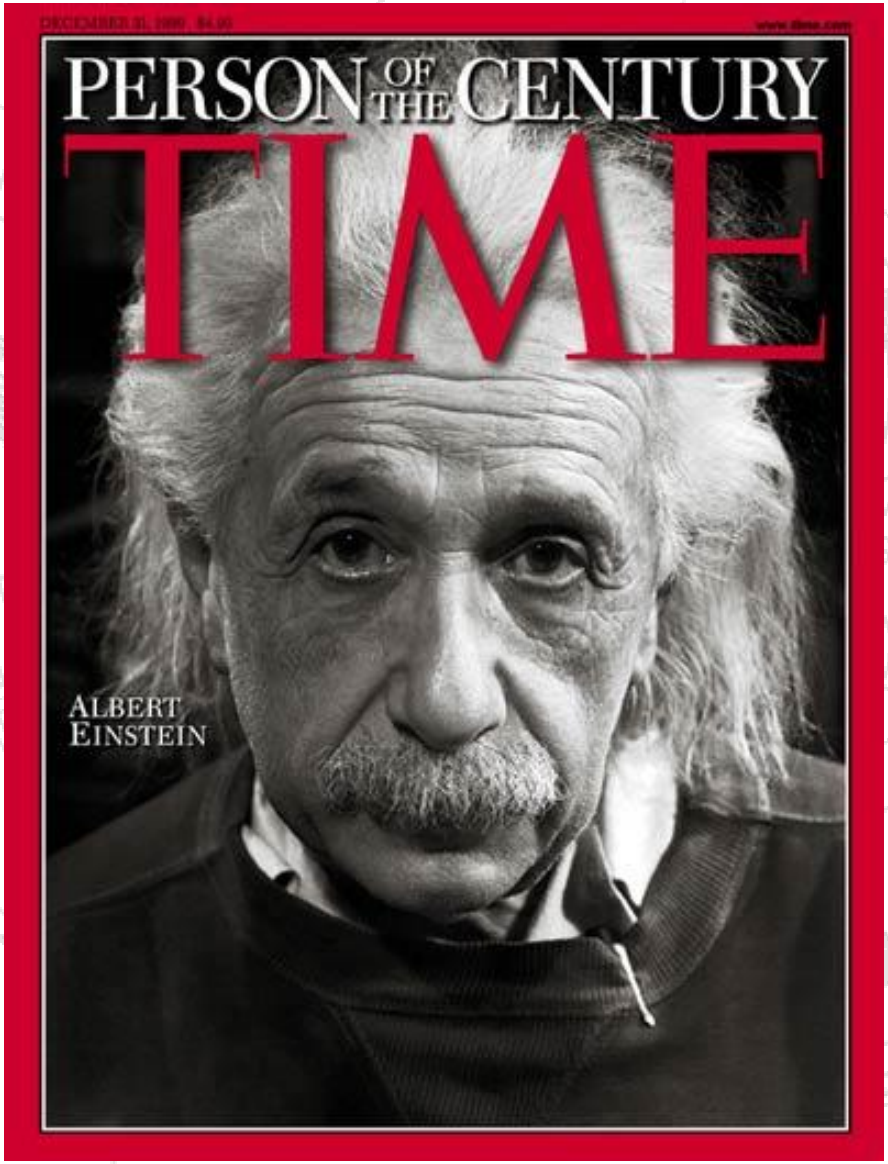
NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

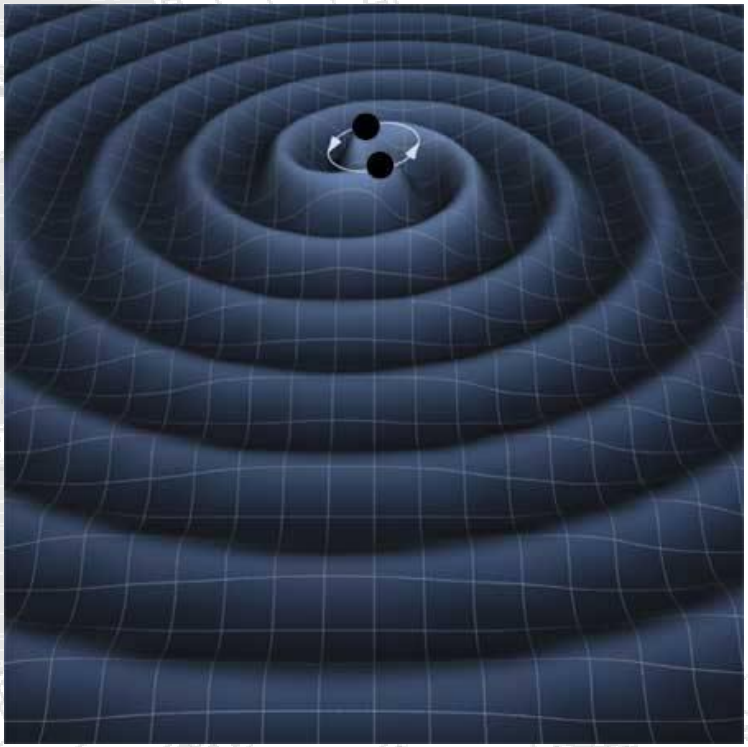
Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

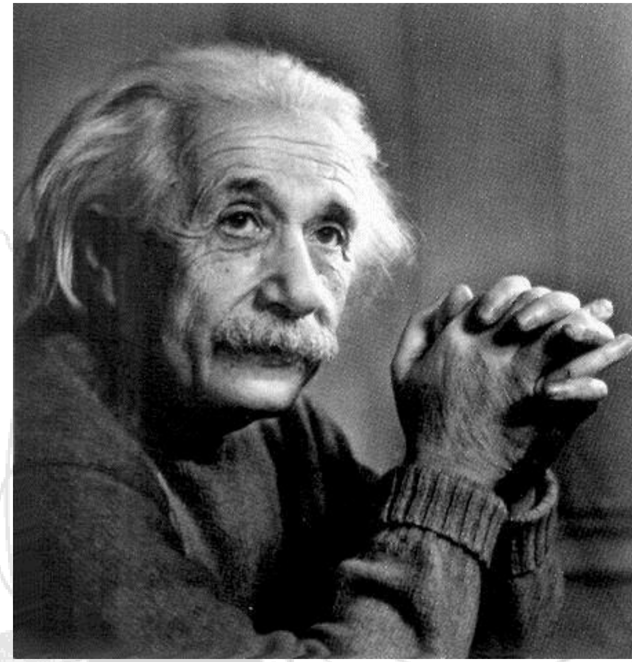
The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying 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



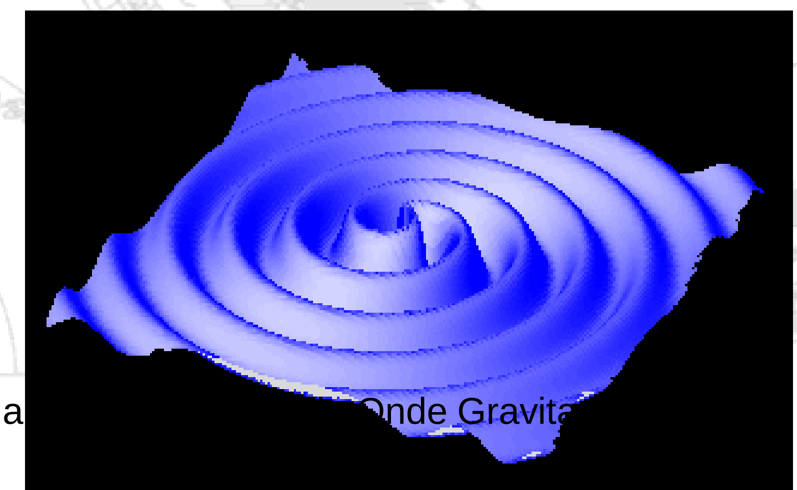
Una nuova predizione: le onde gravitazionali





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

Increspature nello spazio-tempo che si propagano alla velocità della luce

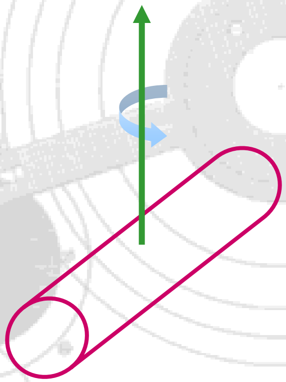


- GW are generated by accelerated masses; they propagate in the space-time at the speed of light
- They cannot be produced in laboratory with a large amplitude: it is necessary a big mass ➔ astronomical sources of GWs

- E’ possibile produrre onde gravitazionali in laboratorio? (Einstein)
  - Massa di acciaio, 1 metro di raggio, lunga 20 metri, ruotante alla velocità di 4.4 rivoluzioni/s

    $P = 10^{-30}$ W

Cilindro rotante di massa M e lunghezza L



Per confronto, in un’evento di Supernova, all’esplosione, puo’ essere emessa energia pari a **~ 10^{40} Joule in una frazione di secondo**
→ In laboratorio non si possono produrre onde gravitazionali di ampiezza sufficiente a poter essere misurate

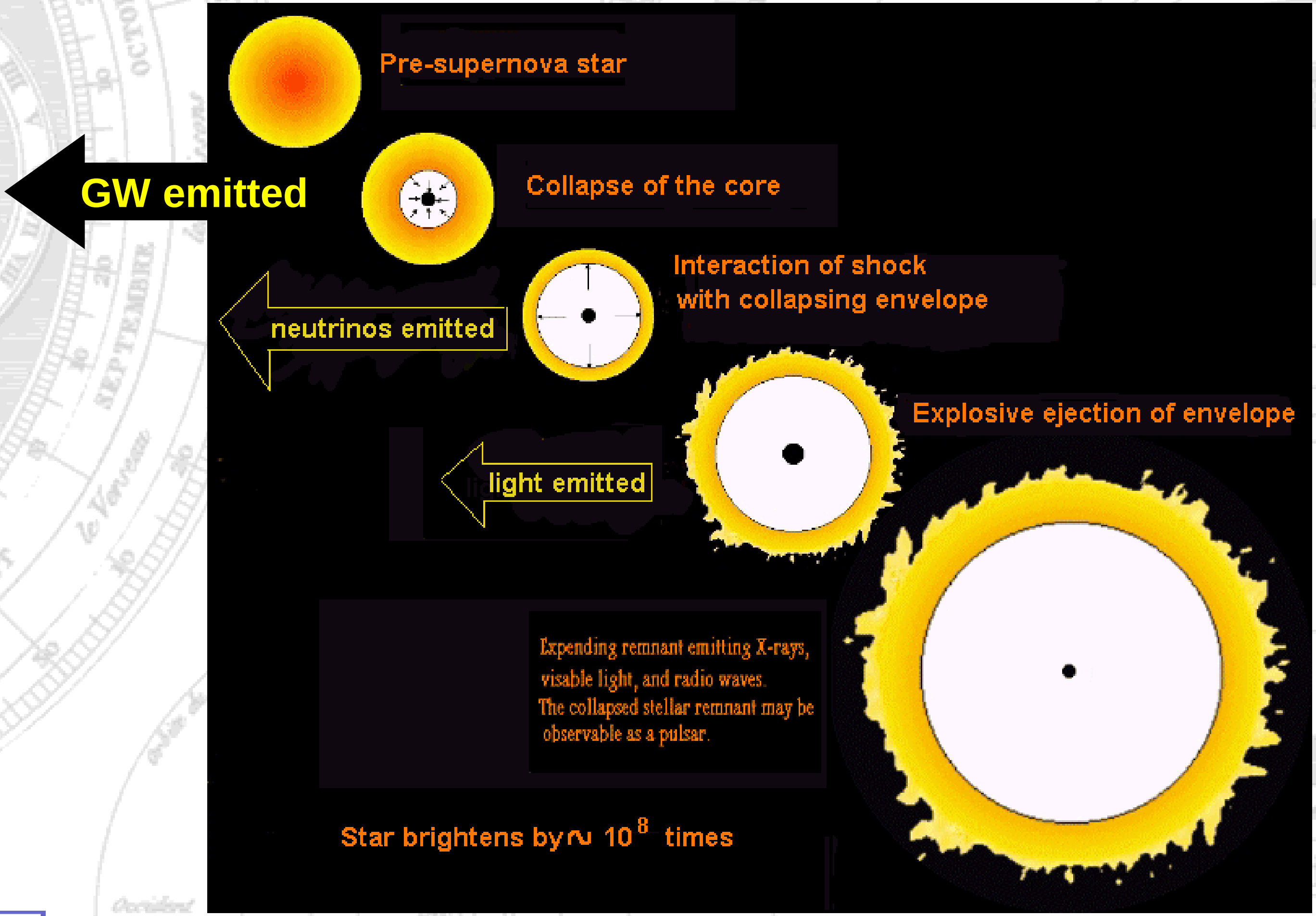
Sorgenti di onde gravitazionali

- Collassi gravitazionali

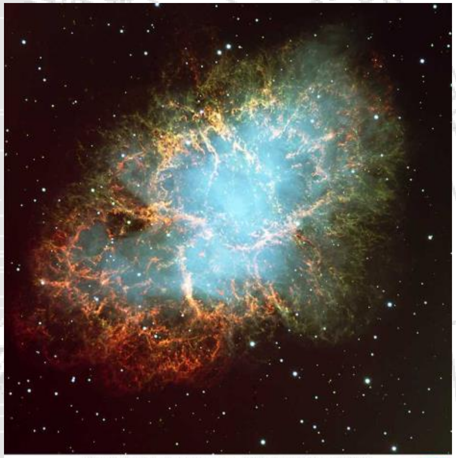
  Stella che ha esaurito il combustibile nucleare collassa sotto l'effetto della propria gravità. Il collasso del core della stella è accompagnato dall'espulsione degli strati più esterni della stella → supernova (SN)

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



SUPERNOVAE



The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999) © European Southern Observatory

Crab Nebula

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

SN remnants observed on July 4th 1054 in Cina e 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

La trascrizione dell'incisione originale degli astronomi cinesi e la sua traduzione

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。」

Nel libro "ShongHuiYao", che significa "Raccolta della dinastia Shong", si trova scritto: "Nel Marzo dell'anno ZhiHe Primo (Maggio 1054), l'osservatore astronomico vedendo che la stella KeXing (Stella temporanea) diminuisce di intensita' luminosa, prevede la scomparsa dell'astro. La mattina del 13 Maggio dello stesso anno (4 Luglio 1054), la nuova stella nasce ad est come un guardiano celeste. E' tanto luminosa di giorno, quanto la stella polare di notte, con una corona particolarmente luminosa e bianca, della durata di 23 gioni."

Sorgenti di onde gravitazionali

- Pulsars: oggetti compatti (R~10 km) composti da neutroni ad altissima densita' (10^{12} - 10^{14} g/cm^3) Il numero stimato di NS ruotanti nella Galassia e' di circa 10^9, di cui 1000 osservate come pulsar e di queste, 5 a meno di 200 pc.

f=10-100 Hz

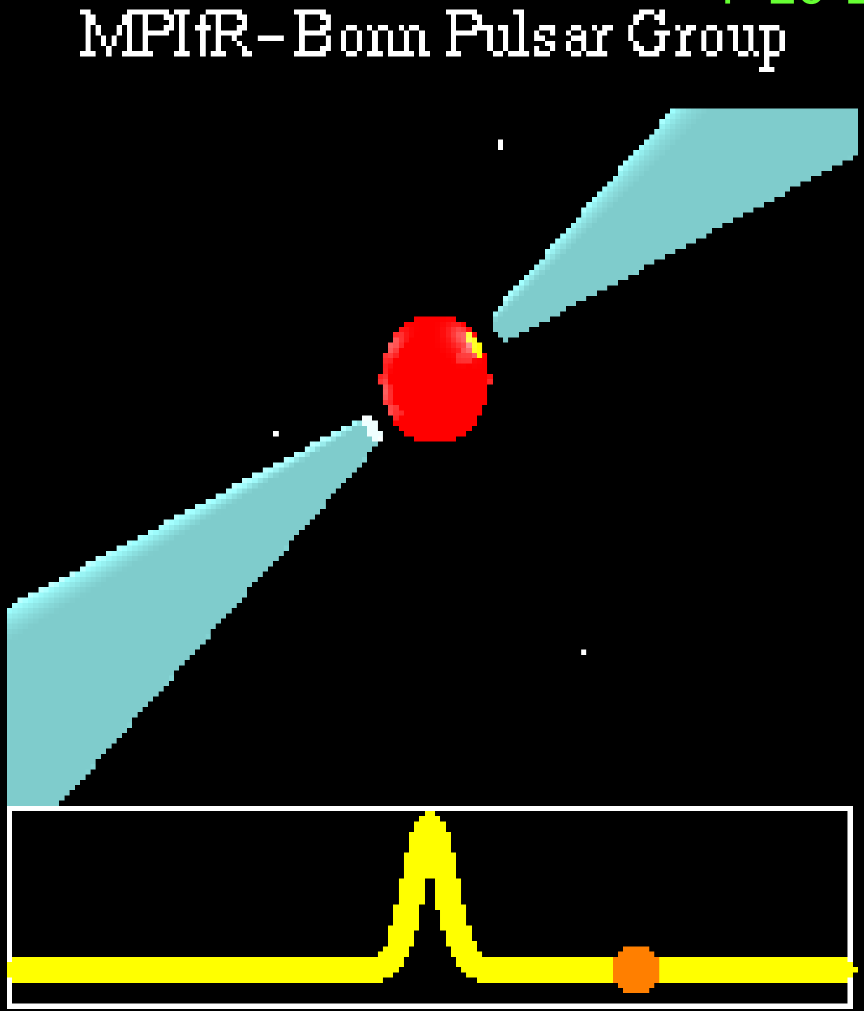
Campi magnetici molto forti (10^9 Tesla)

+

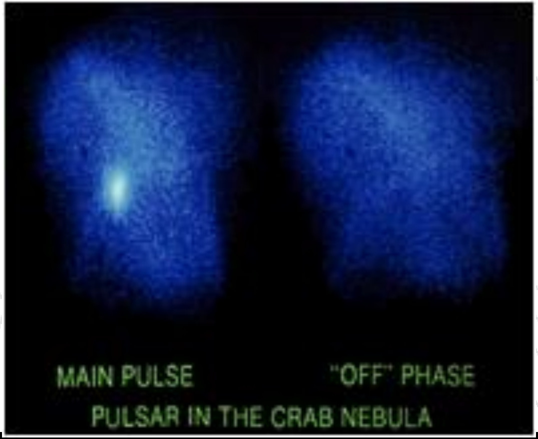
Rapida rotazione

=

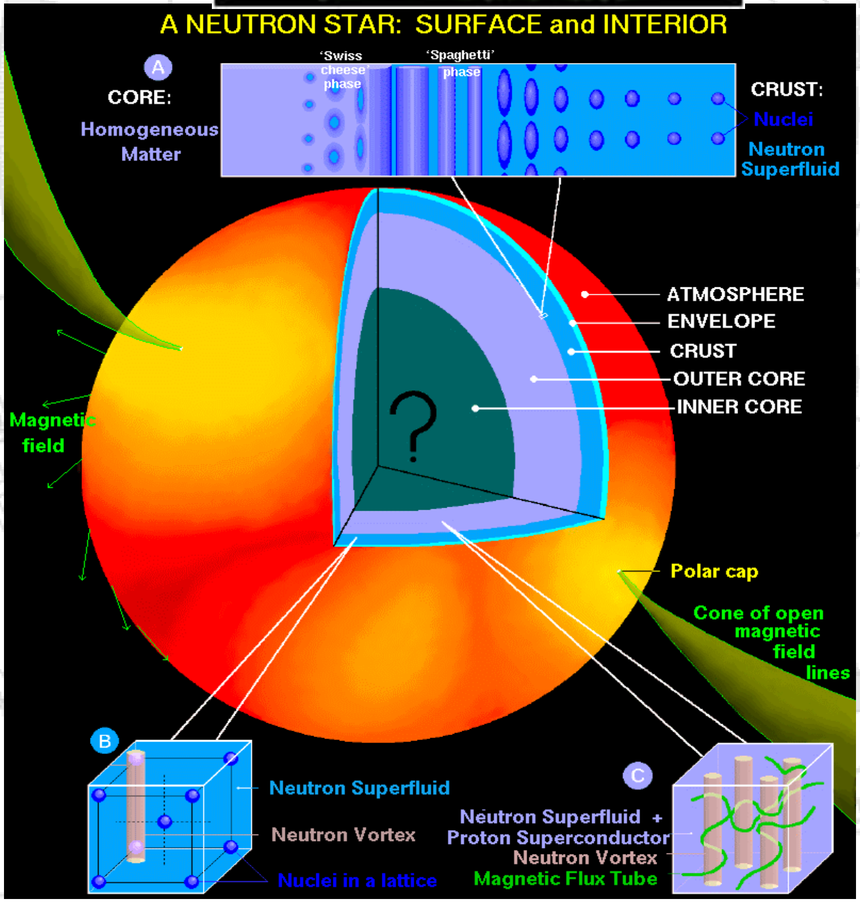
$\Rightarrow$ emissione di onde elettromagnetiche (luce, onde radio) e onde gravitazionali



Stelle di neutroni



- La fisica di queste stelle non e' ancora ben compresa
  - Dopo 40 anni non sappiamo cosa fa pulsare le pulsar.
  - Le proprieta' dell'interno non sono ben comprese: equazione di stato, superfluidita', superconduttivita',nucleo solido, sorgente di campo magnetico.
  - Potrebbero perfino non essere stelle di neutroni, ma composte di quark!



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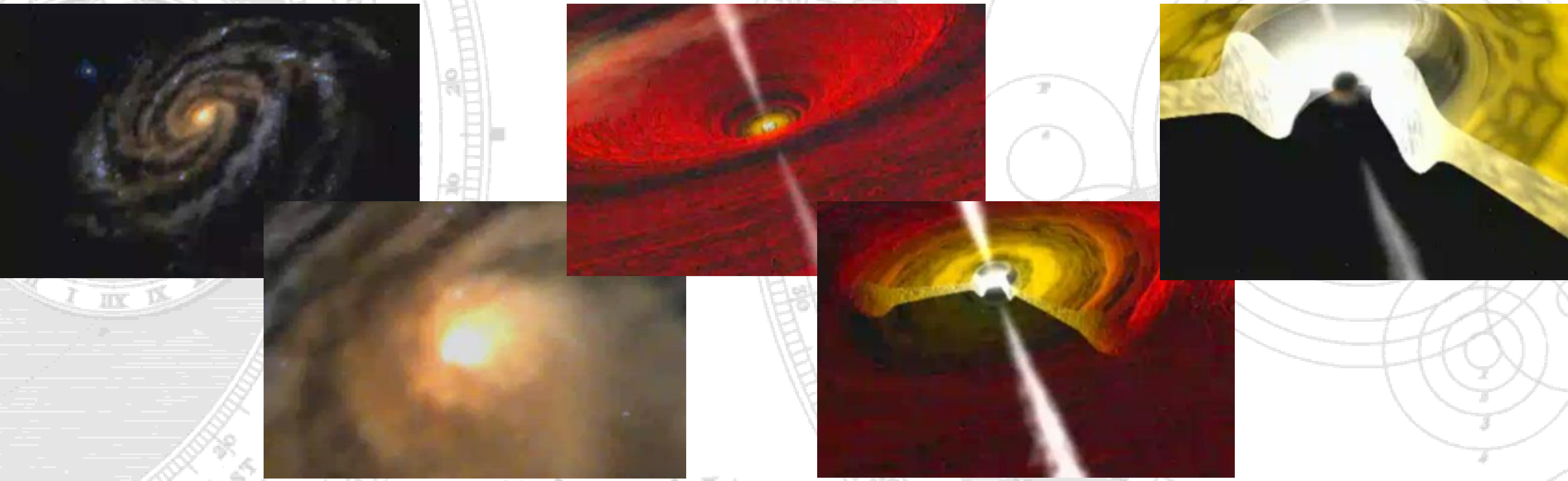
INFN Istituto Nazionale di Fisica Nucleare

Sorgenti di onde gravitazionali

- Buchi neri: stadio terminale della vita di una stella molto massiva (maggiore di 1.4 Masse solari)

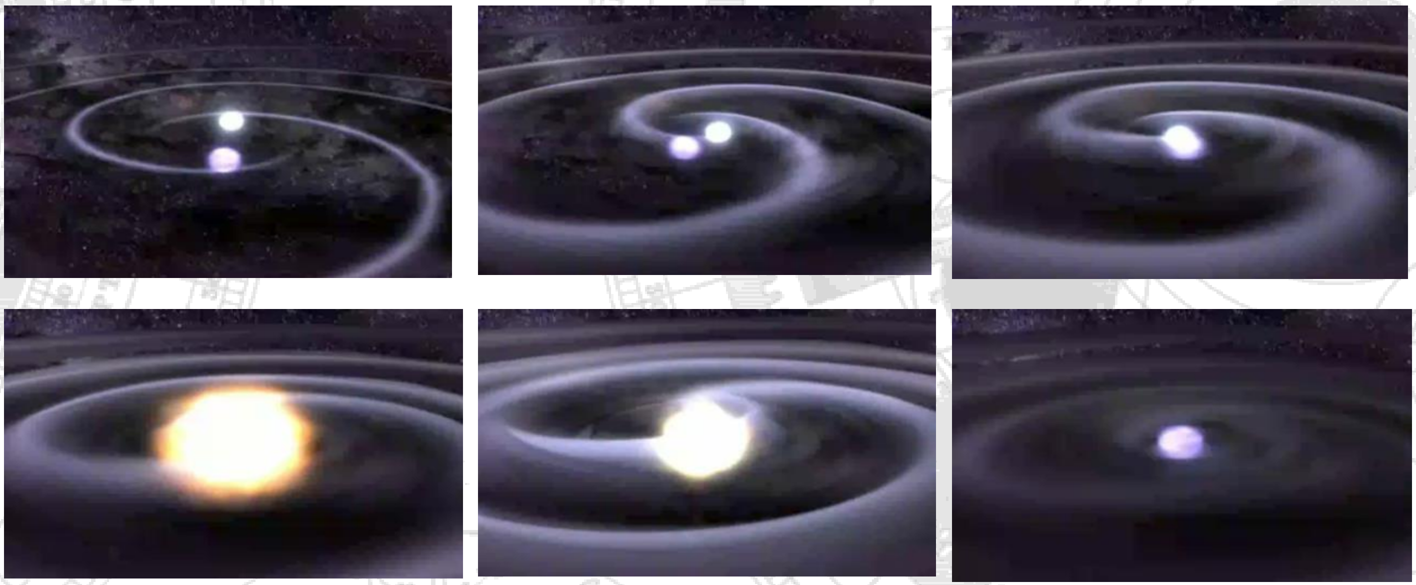


This animation illustrates the activity surrounding a black hole. While the matter that has passed the black hole's "event horizon" can't be seen, material swirling outside this threshold is accelerated to millions of degrees and radiates in X-rays. At the end of the animation, the black hole is shown 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.

Sorgenti di onde gravitazionali

- Sistemi binari (NS-NS / WD-WD)

Si stimano circa 10^{8-9} binarie galattiche con frequenze > 0.1mHz (la maggior parte 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.

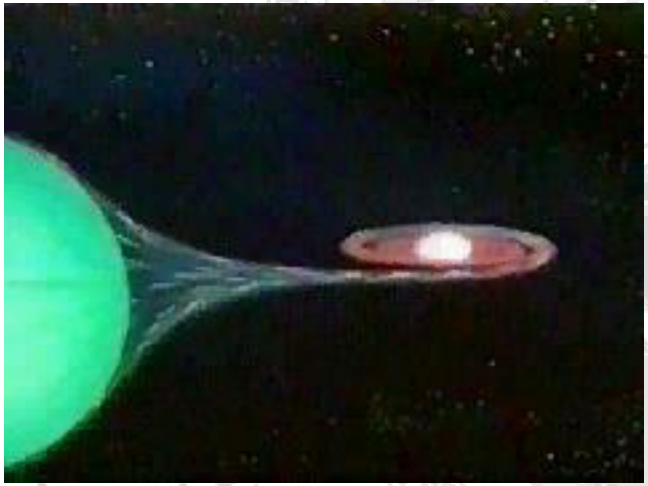
Sorgenti di onde gravitazionali

- Sistemi binari (BH-NS)

Scientists say they 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.

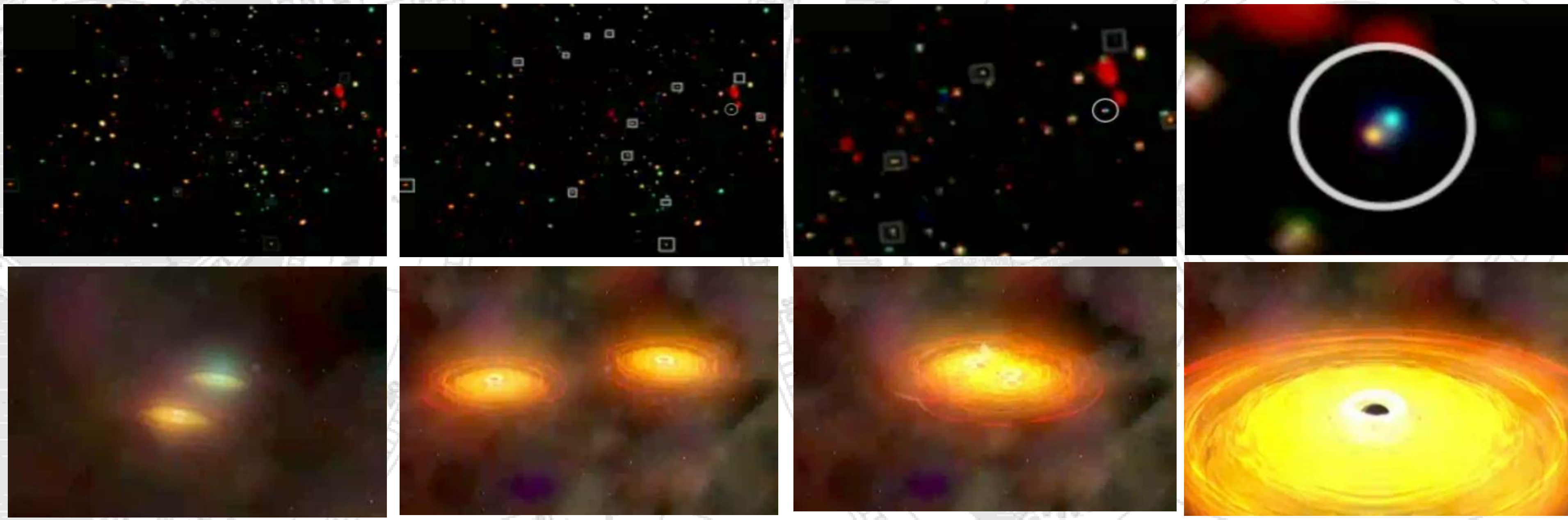
Sorgenti di onde gravitazionali

- Sistemi binari (BH-star / NS-star)

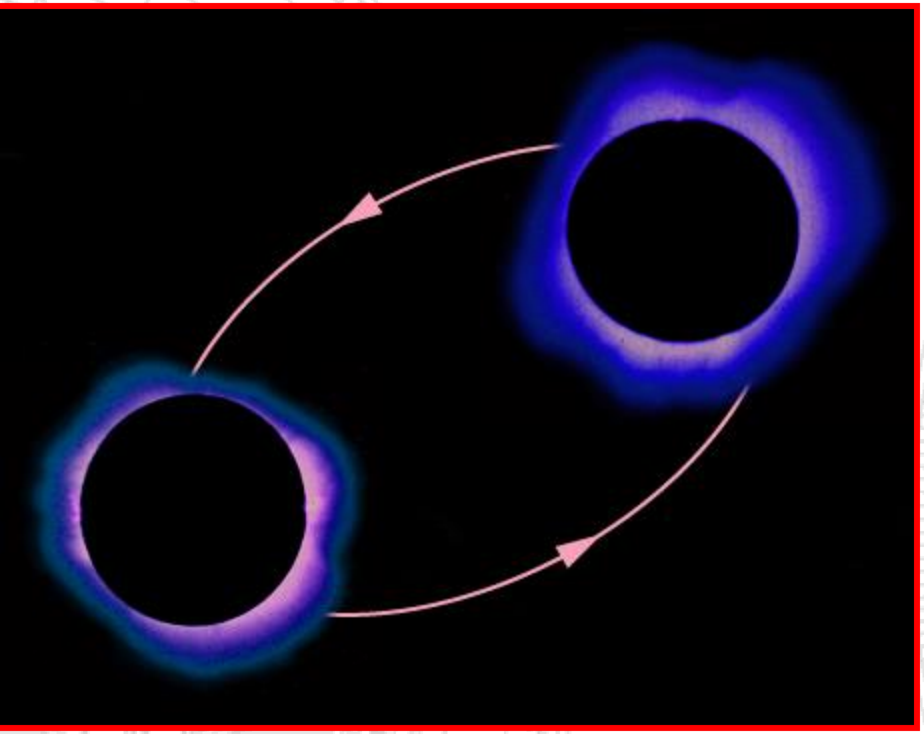


Sorgenti di onde gravitazionali

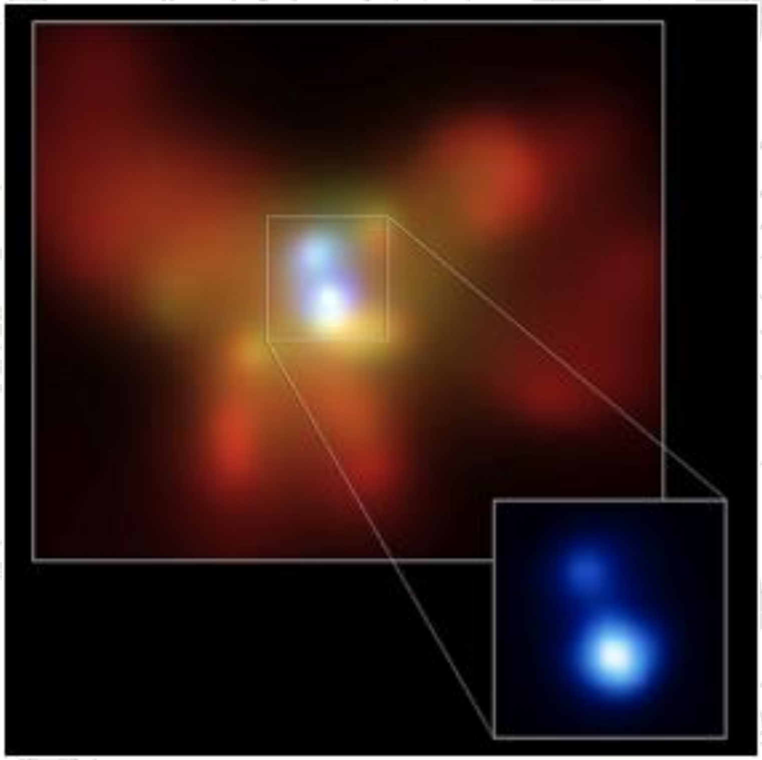
- Sistemi binari (BH-BH)



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.

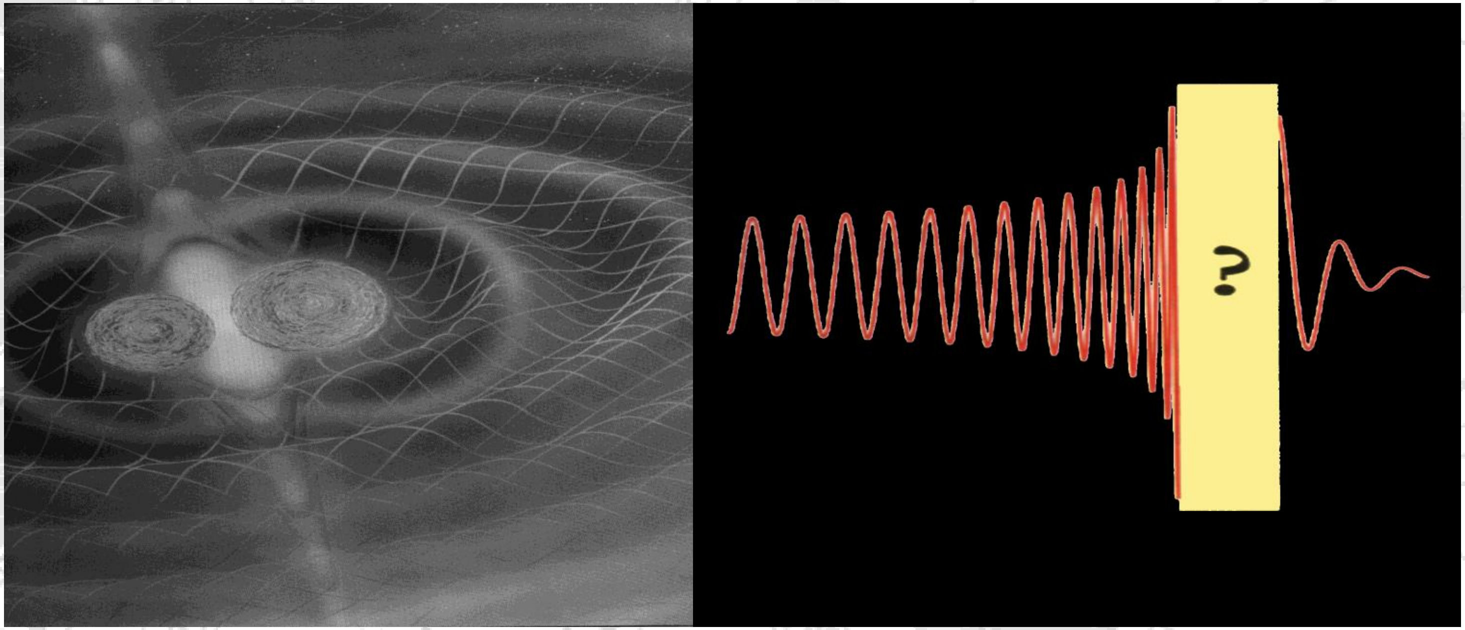


These systems can also be formed by galactic nuclei (10^4-10^6 solar masses)



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, Nobel prize in 1993)

No Evidence For Gravitational Waves Until 1974

Russell A. Hulse

Discovered and Studied Pulsar System PSR 1913 + 16

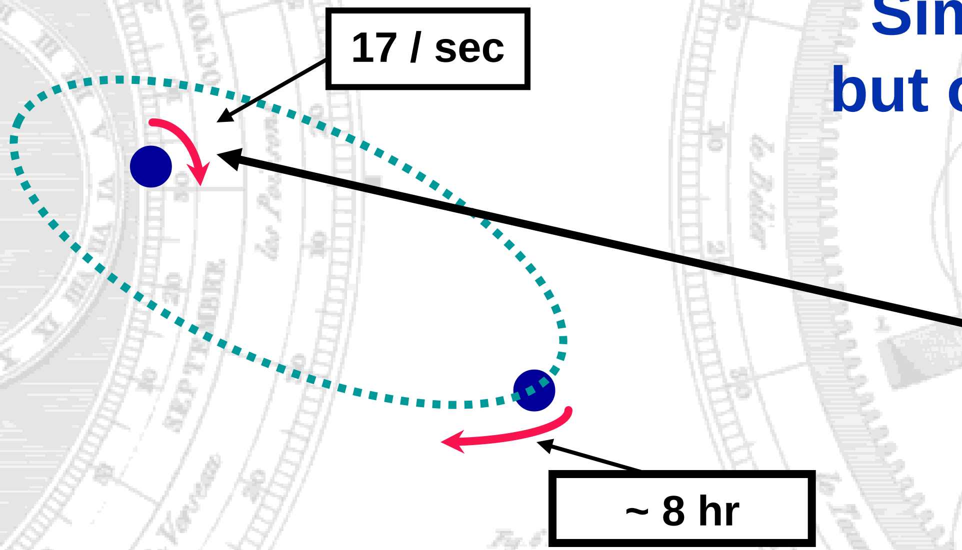
Joseph H.Taylor Jr

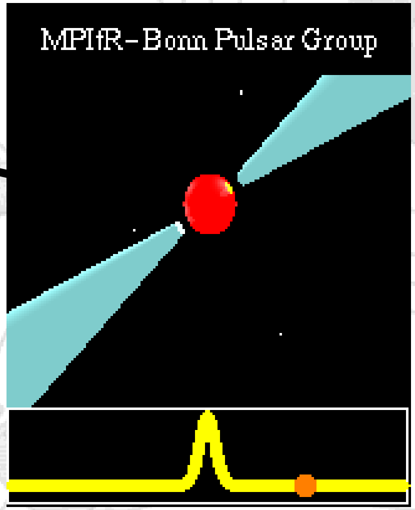
Source: www.NSF.gov

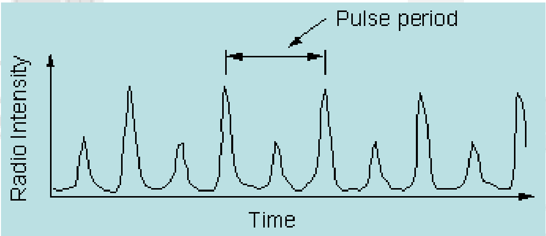
Neutron Binary System

PSR 1913 + 16

Similar mass to our sun but only 20 km in diameter







Two Neutron Stars in Orbit

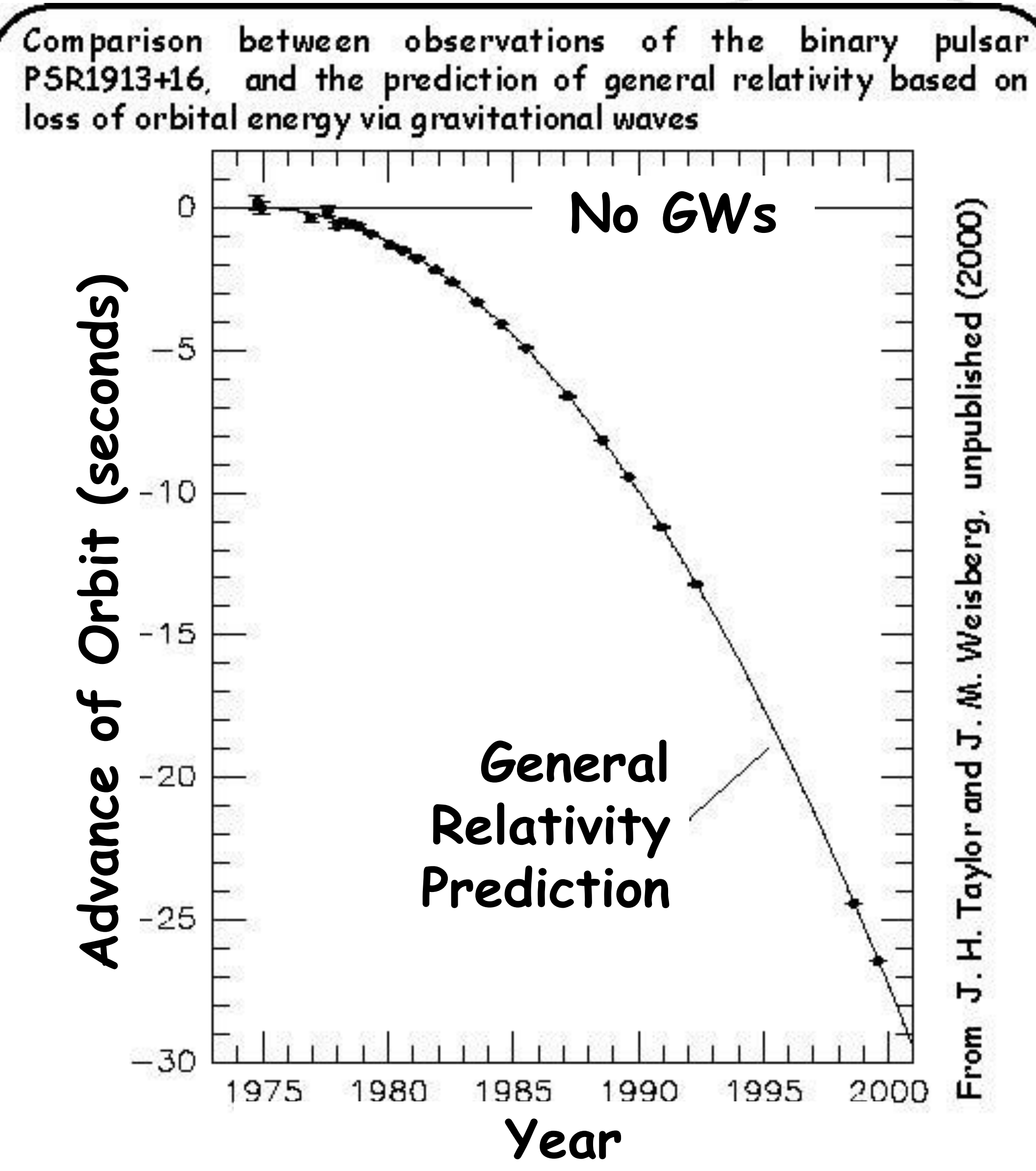
- **Separated by 1,000,000 km**

Prediction from General Relativity

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

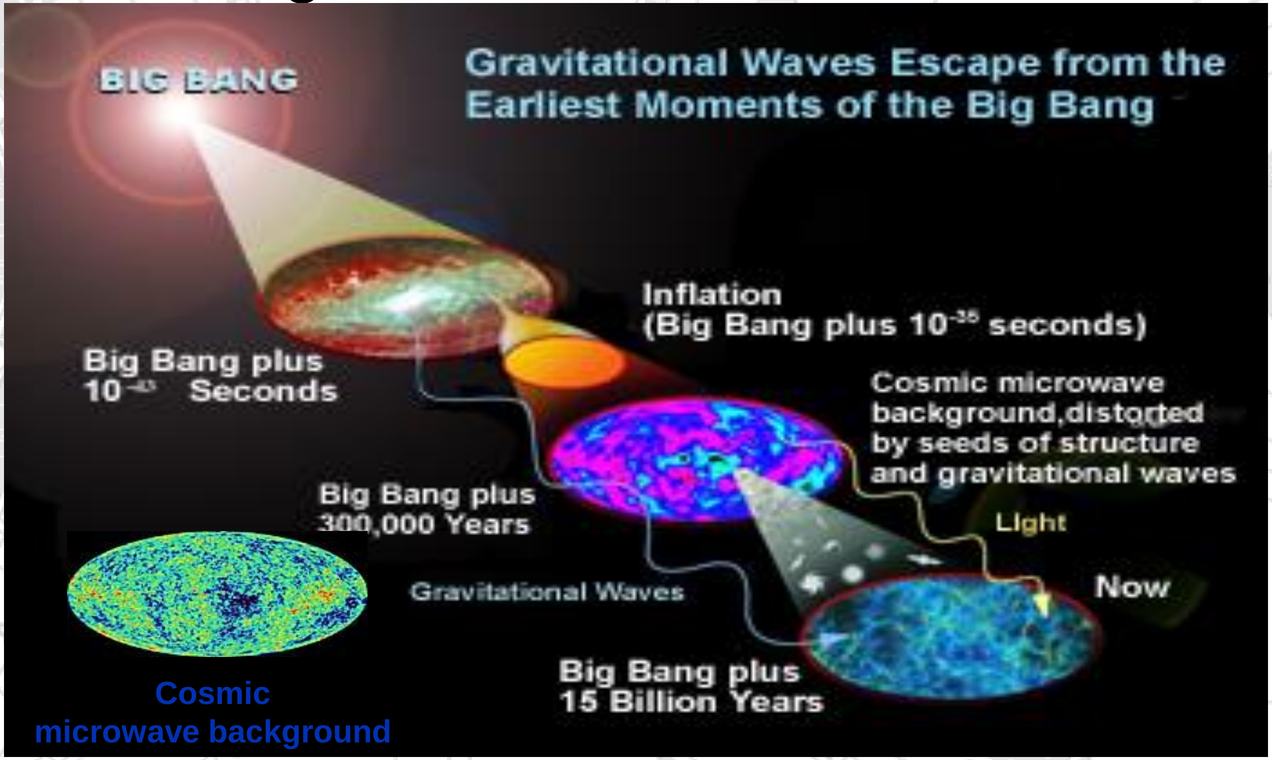
Evidence for gravitational waves!

Nobel Prize



Sorgenti di onde gravitazionali

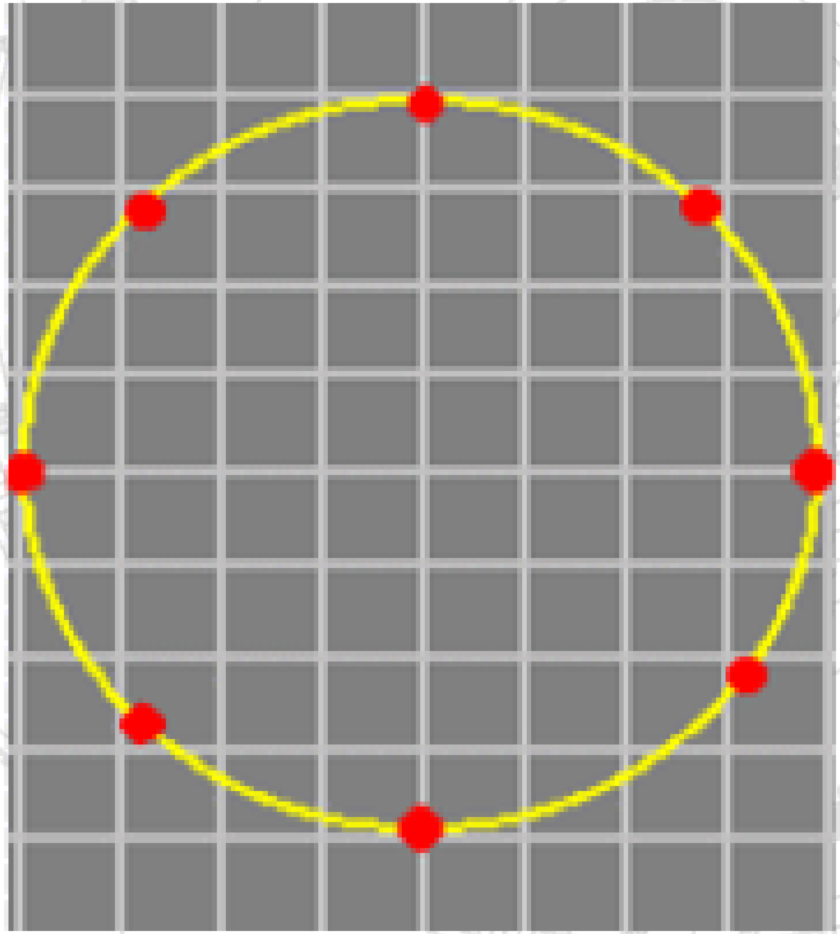
- Radiazione gravitazionale di fondo



La misura di questo segnale può fornire informazioni sui primissimi istanti di vita dell'universo

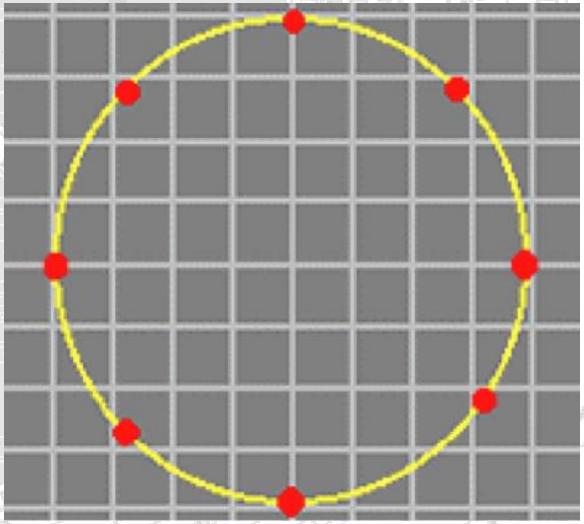
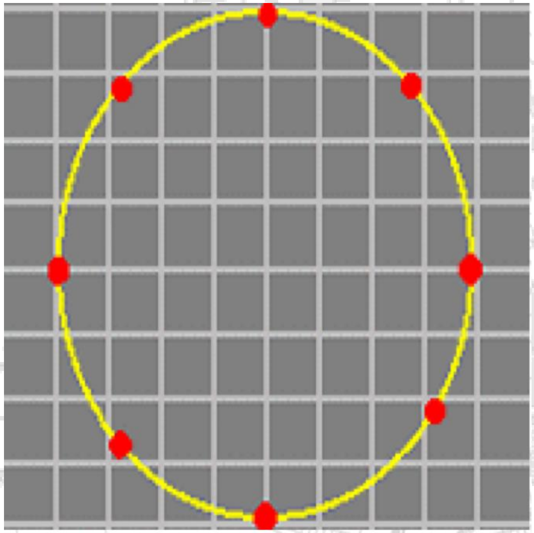
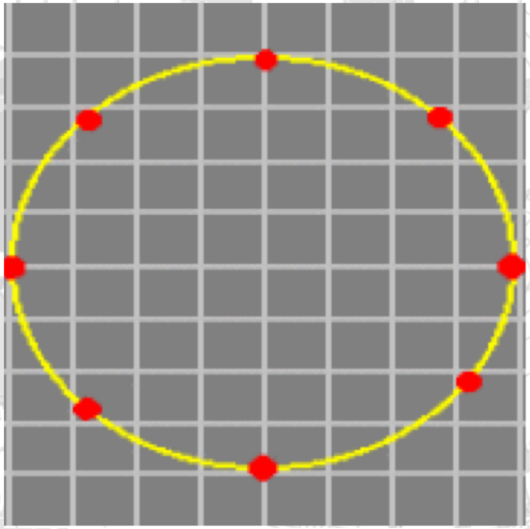
Effect of a Passing Gravitational Wave

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



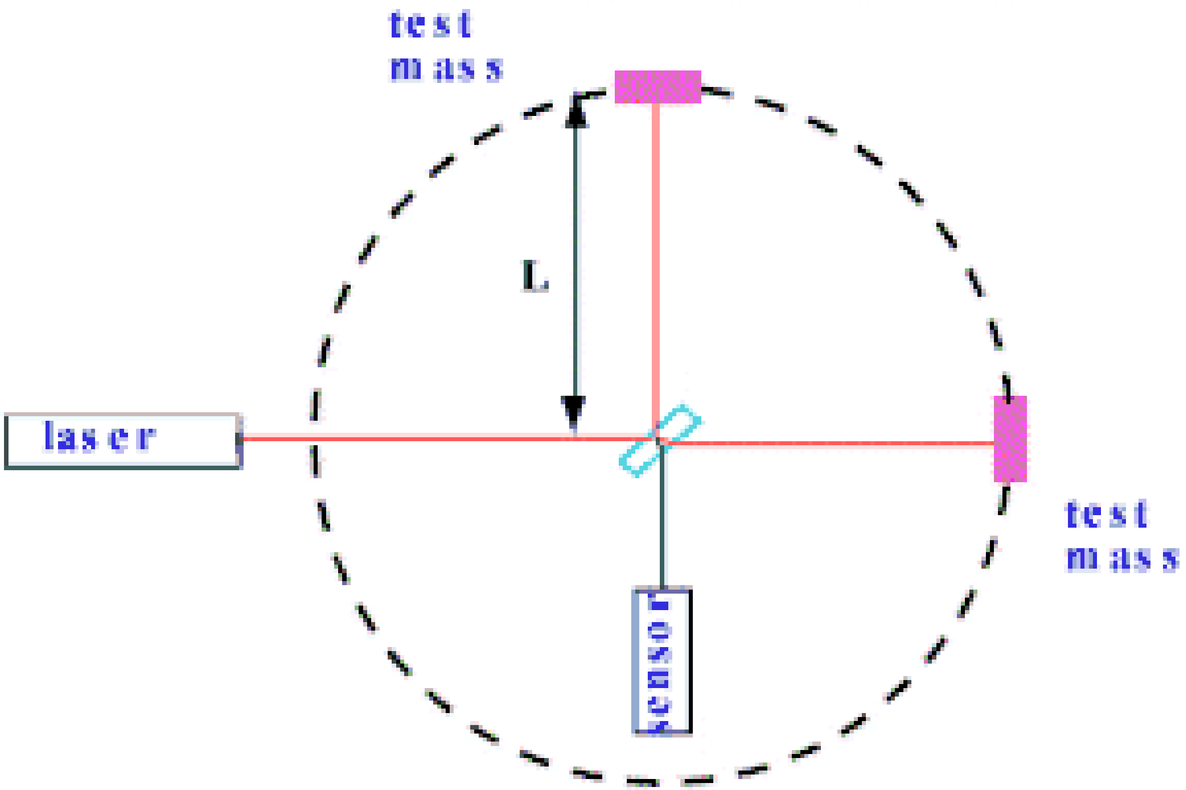
Effect of a Passing Gravitational Wave

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

Detecting a Gravitational Wave with Light

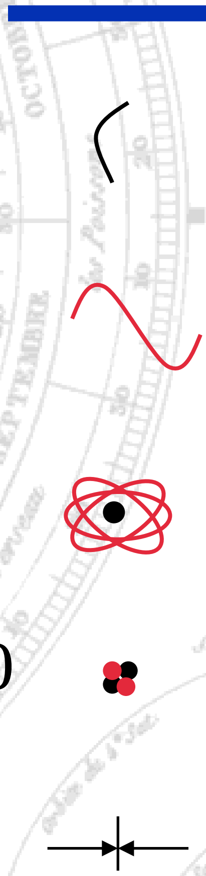
Michelson Interferometer



Strength ($\Delta L/L$) of a strong wave is about 10^{-21}

For L = 1 km, => $\Delta L = 10^{-18}$ m

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

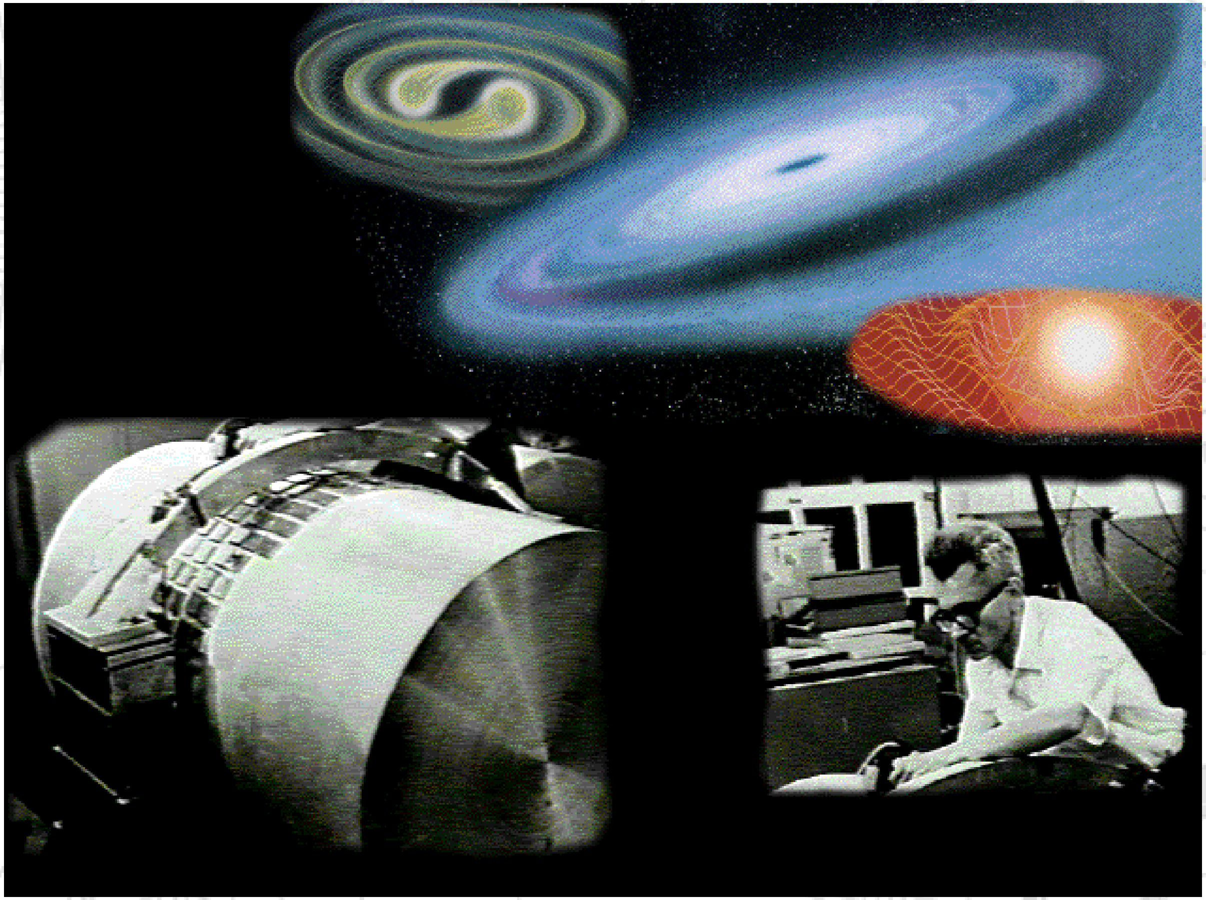
÷10,000 — Atomic diameter 10^{-10} m

÷100,000 — Nuclear diameter 10^{-15} m

÷1,000 — GW detector 10^{-18} m

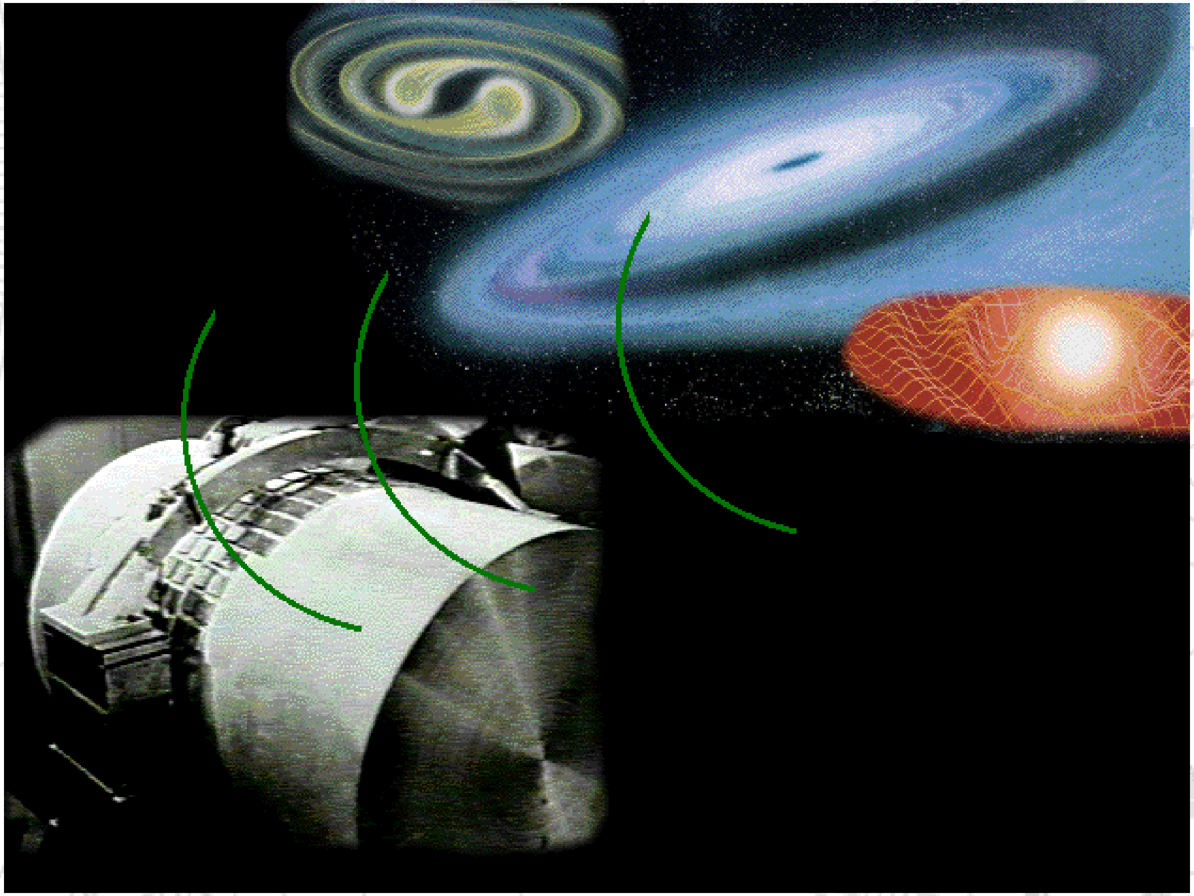
Detecting a Gravitational Wave with an Elastic Body

Bar detectors



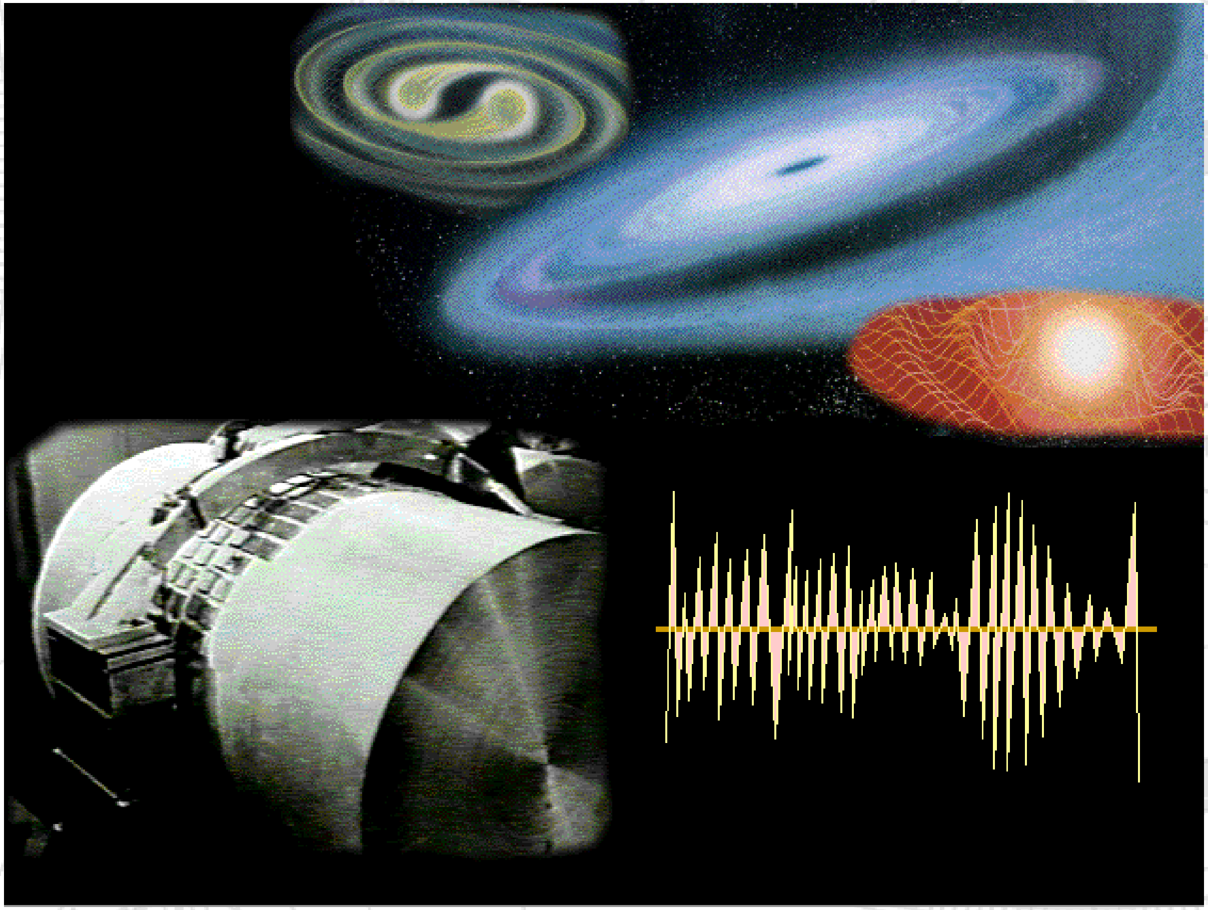
Detecting a Gravitational Wave with an Elastic Body

Bar detectors



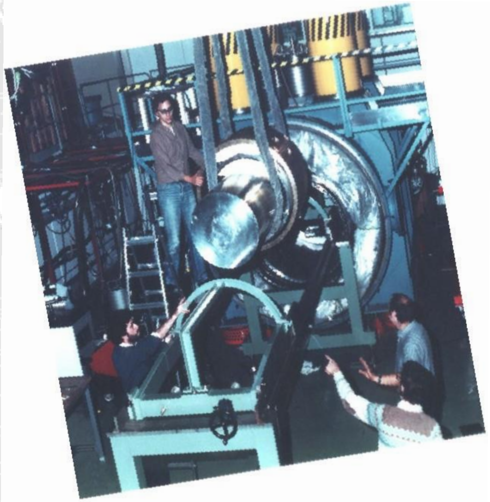
Detecting a Gravitational Wave with an Elastic Body

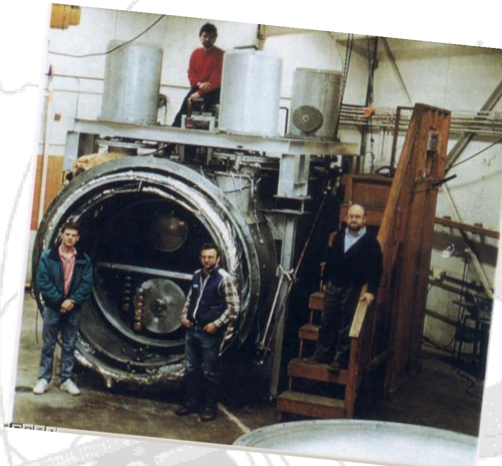
Bar detectors



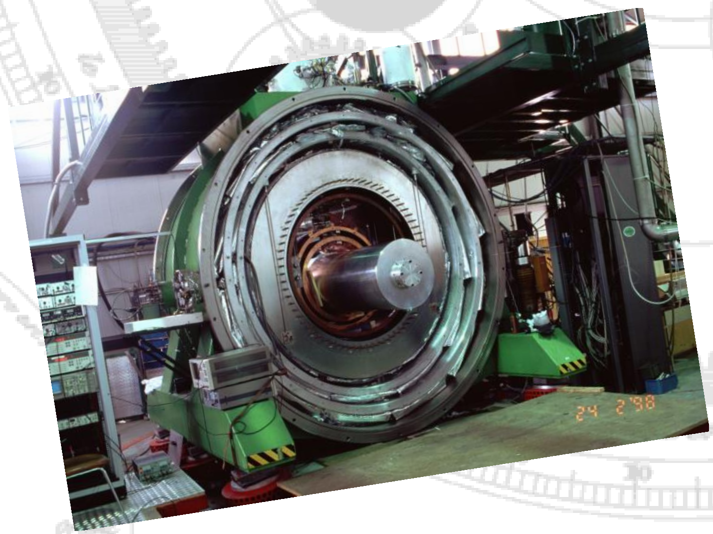

Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
MINIGRAIL
GEO
AURIGA
EXPLORER
VIRGO
NAUTILUS
TAMA
LCGT
LIGO
ALLEGRO
LIGO
MARIO SCHENBERG
AIGO
gravitational wave research

The network of bar detectors





ALLEGRO AURIGA EXPLORER NAUTILUS



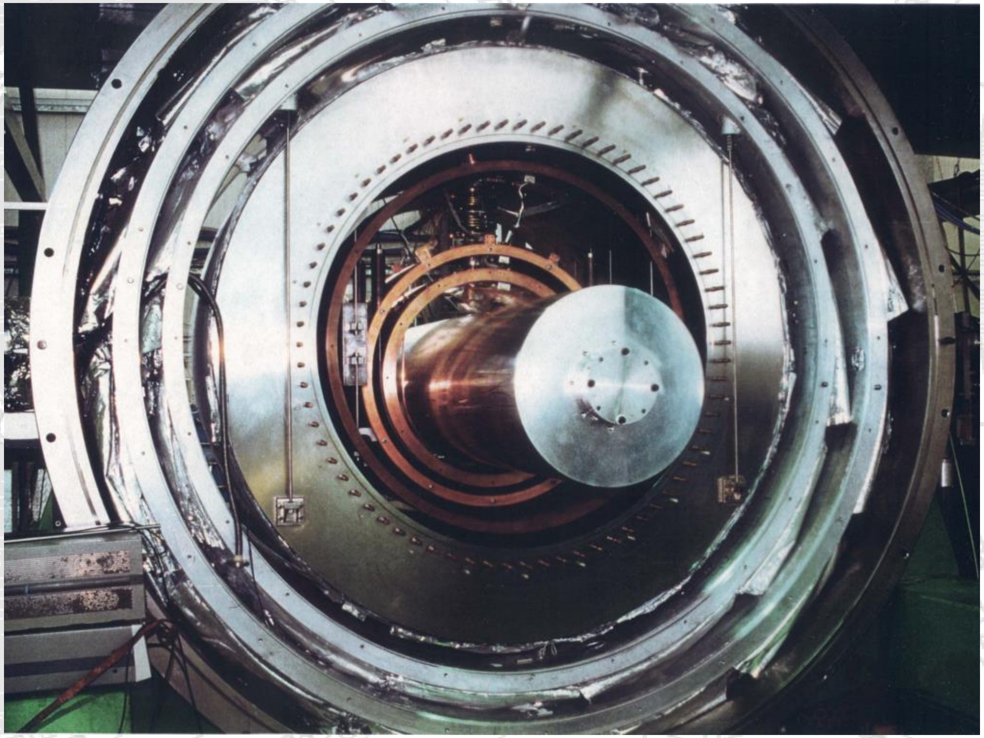
•Lo scambio d’energia tra Onde Gravitazionali e Materia è debolissimo.
L’Onda Gravitazionale attraversa la Materia senza essere significativamente attenuata.

•Il Sole , la Terra ed in generale i corpi celesti sono trasparenti alle Onde Gravitazionali.

•L’effetto dell’onda e’ comunque proporzionale alle massa → sono necessari rivelatori di grande massa per mettere in evidenza questo effetto

•Inoltre, e’ necessario isolare il rivelatore dai disturbi sismici con efficienti sistemi di filtri meccanici e raffreddarlo a bassa temperatura per ridurre l’incidenza del rumore termico.

Il rivelatore Nautilus presso i LNF

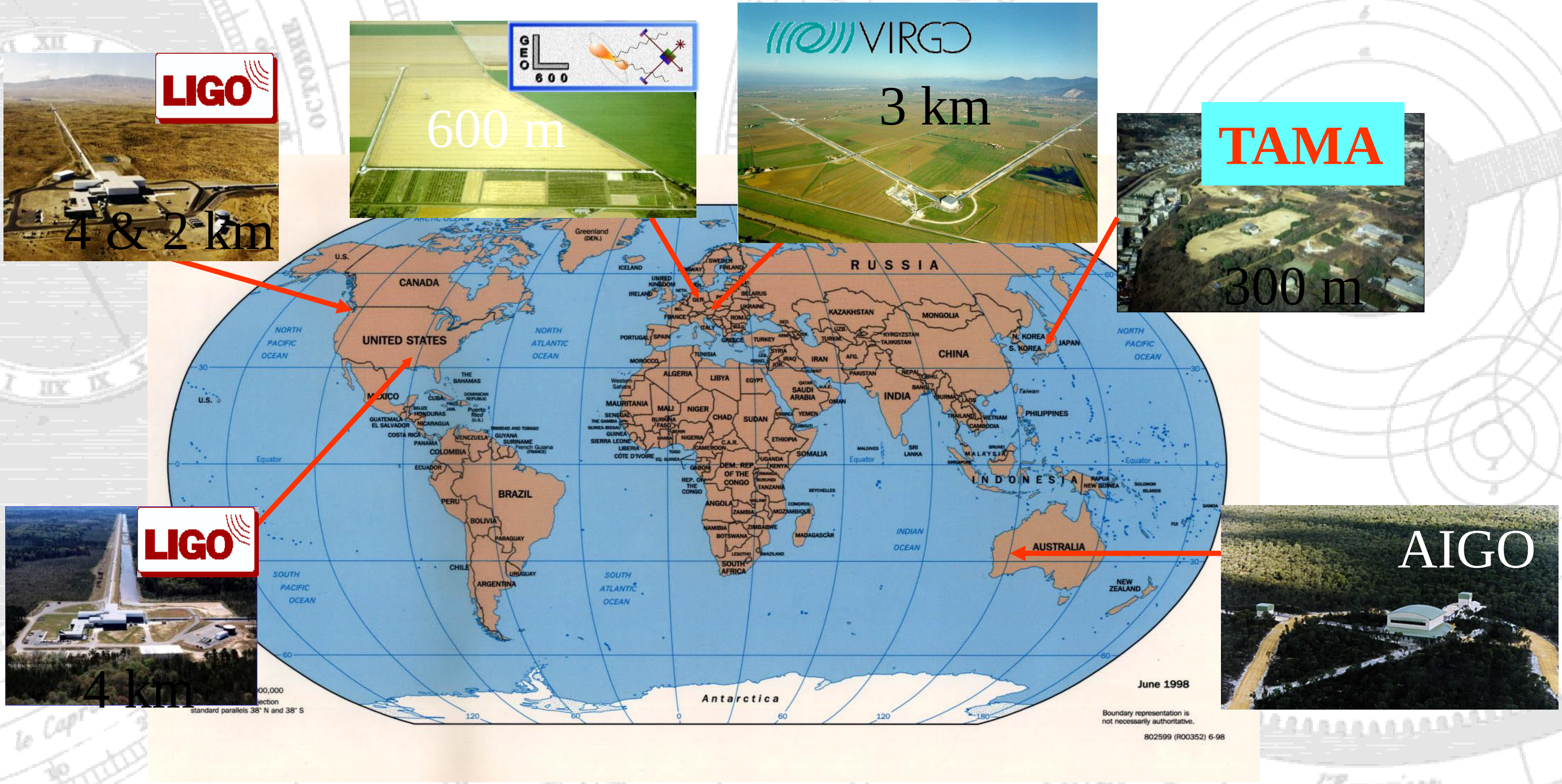


Length = 3 m

$h \sim \delta L/L \sim 10^{-21} \rightarrow \delta L=10^{-21}$ m

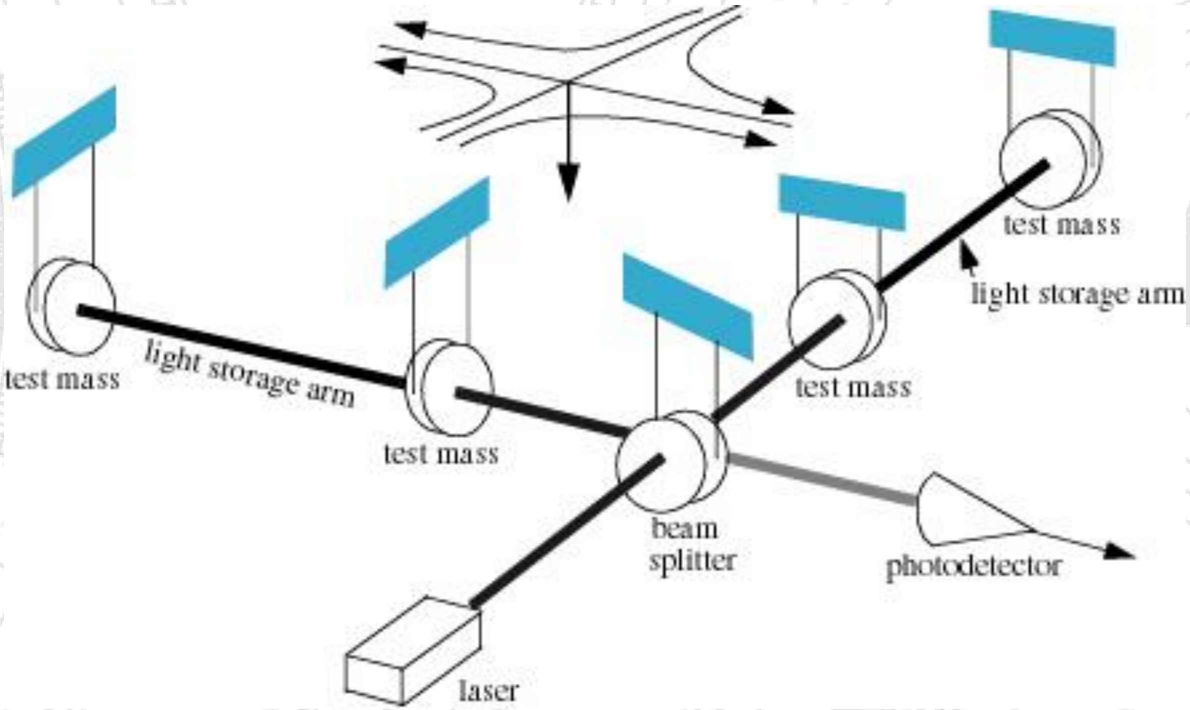
Thousand million times smaller than the dimensions of a proton!!!!

The network of interferometers



The Virgo detector

The effect of the GW is proportional to the length of the interferometer arms ➔ long arms are needed (3 km)

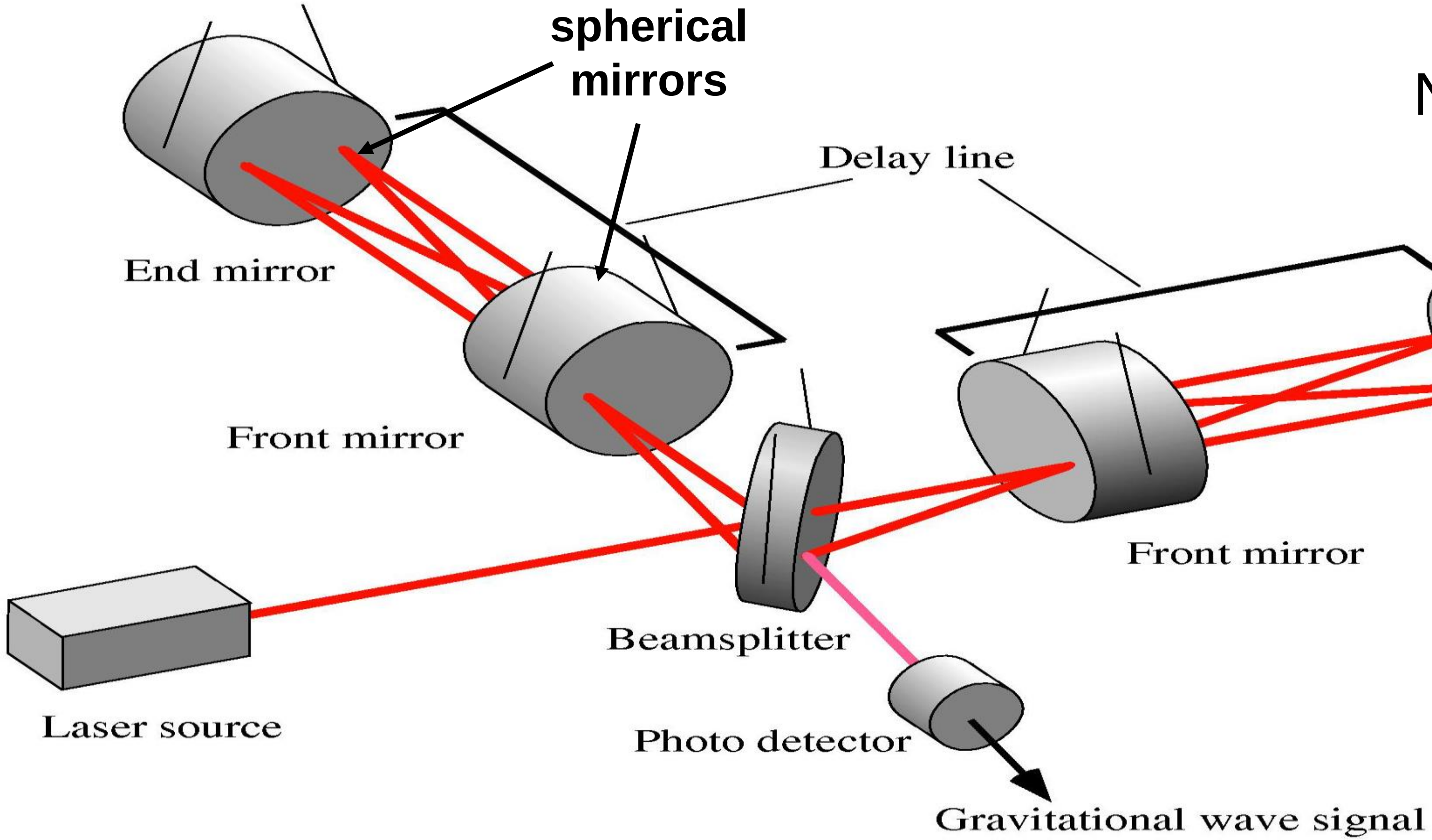


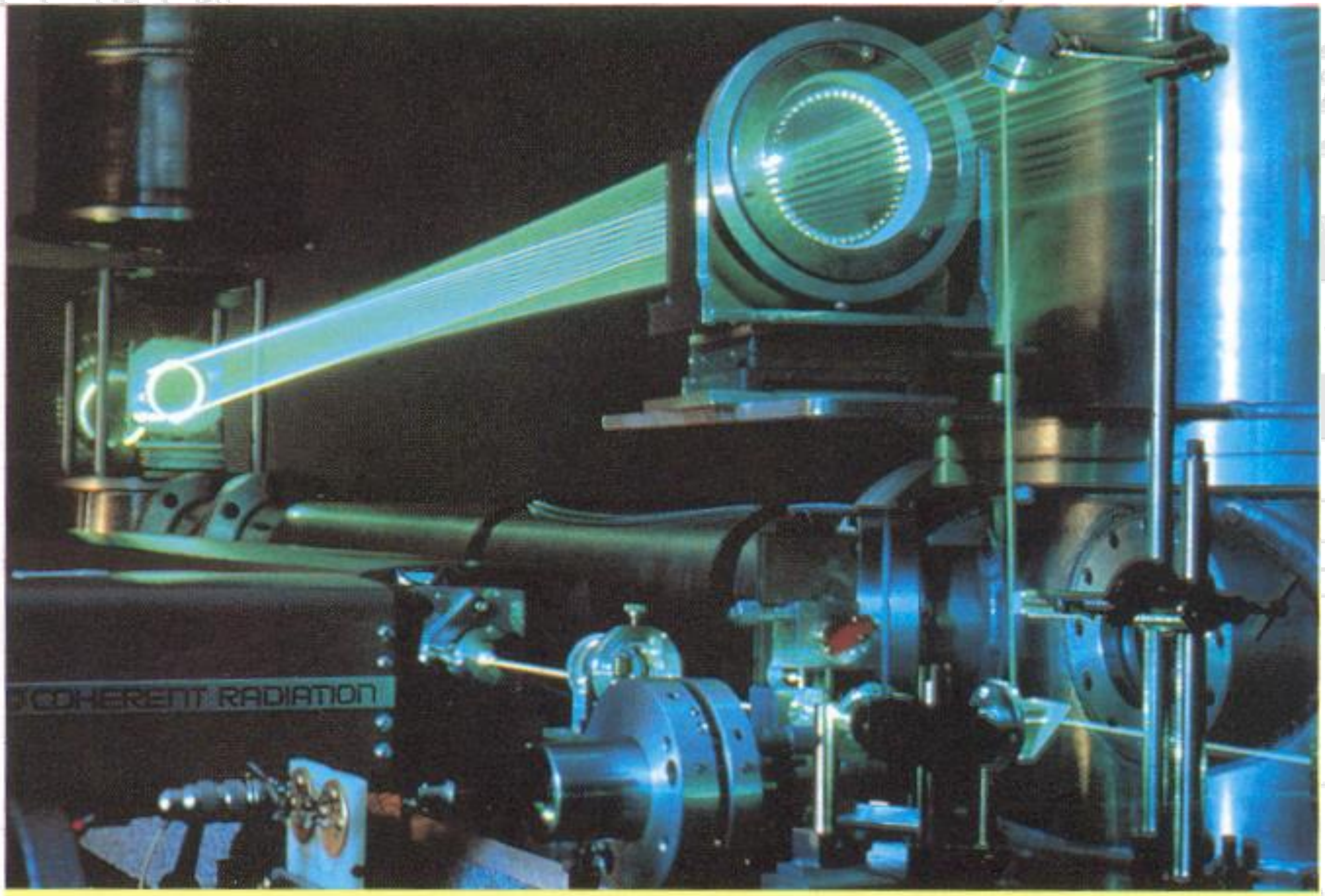
Also with L=3 km the displacement of the mirrors is 3 x 10^{-18} m: One million times smaller than the dimensions of a proton!!!!

Is it possible to increase the length traveled by the light?

Delay lines

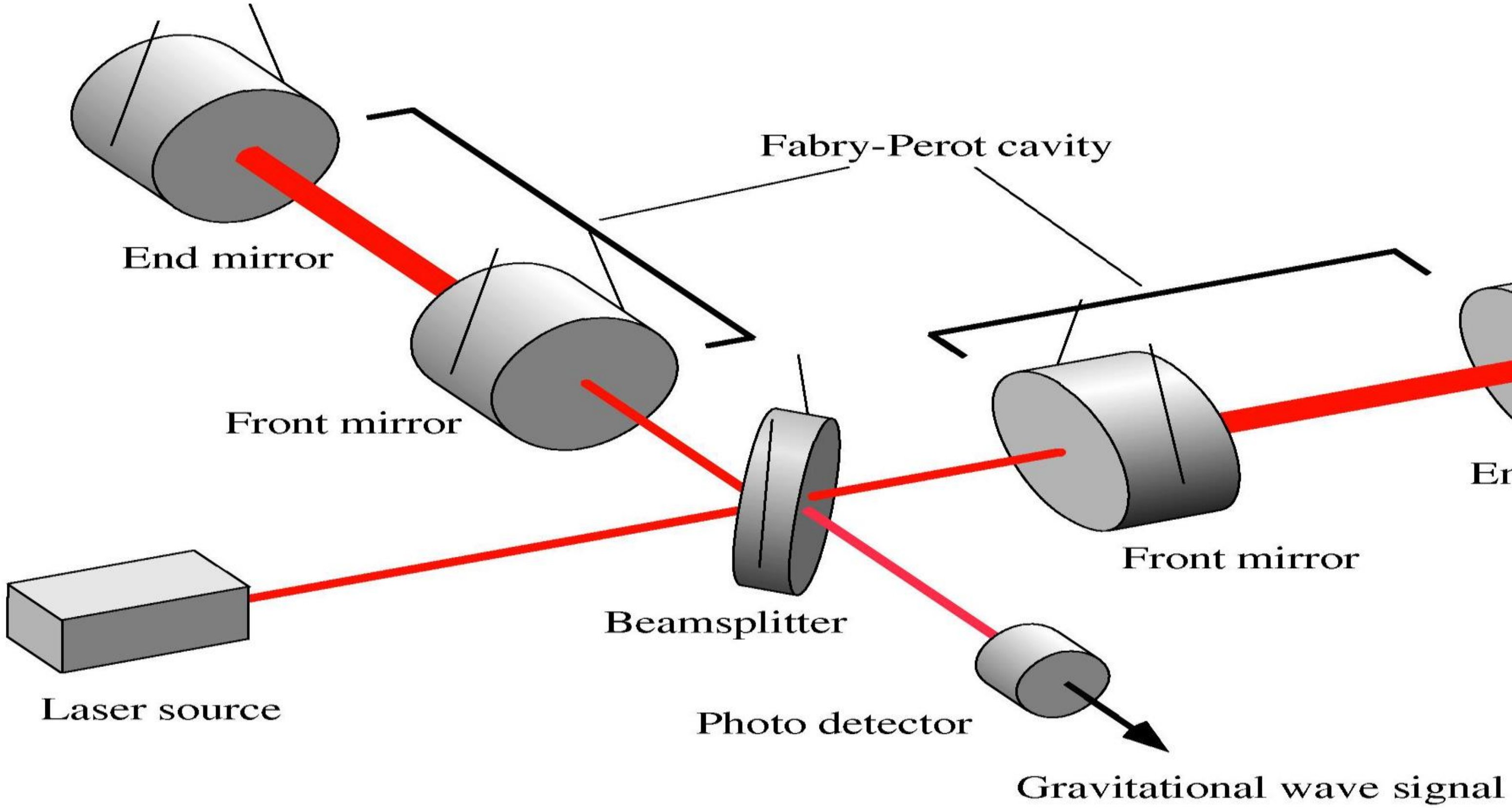
N=4

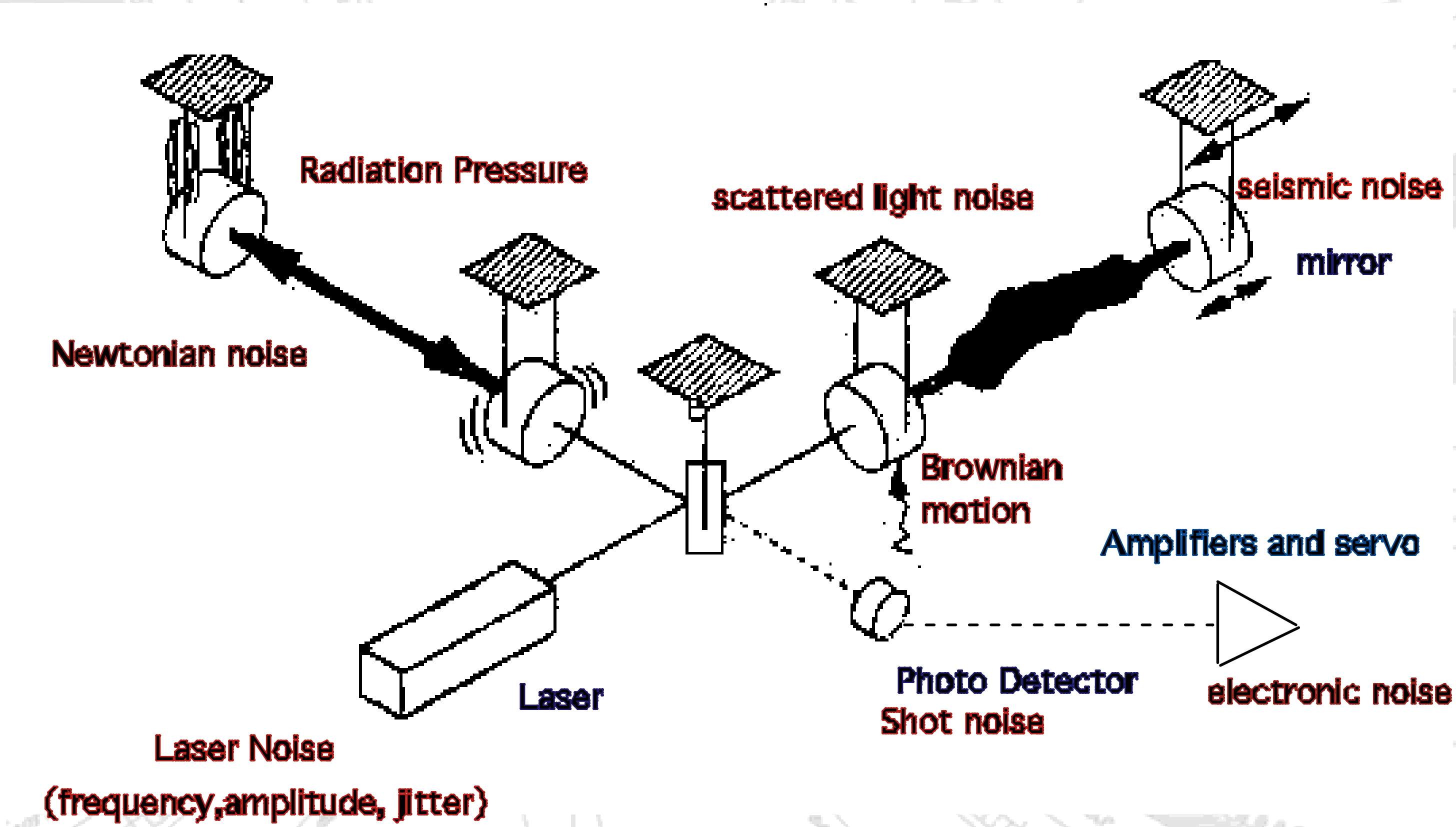




Un prototipo di antenna interferometrica sviluppato al Max Planck Institute di Garching (Germania).

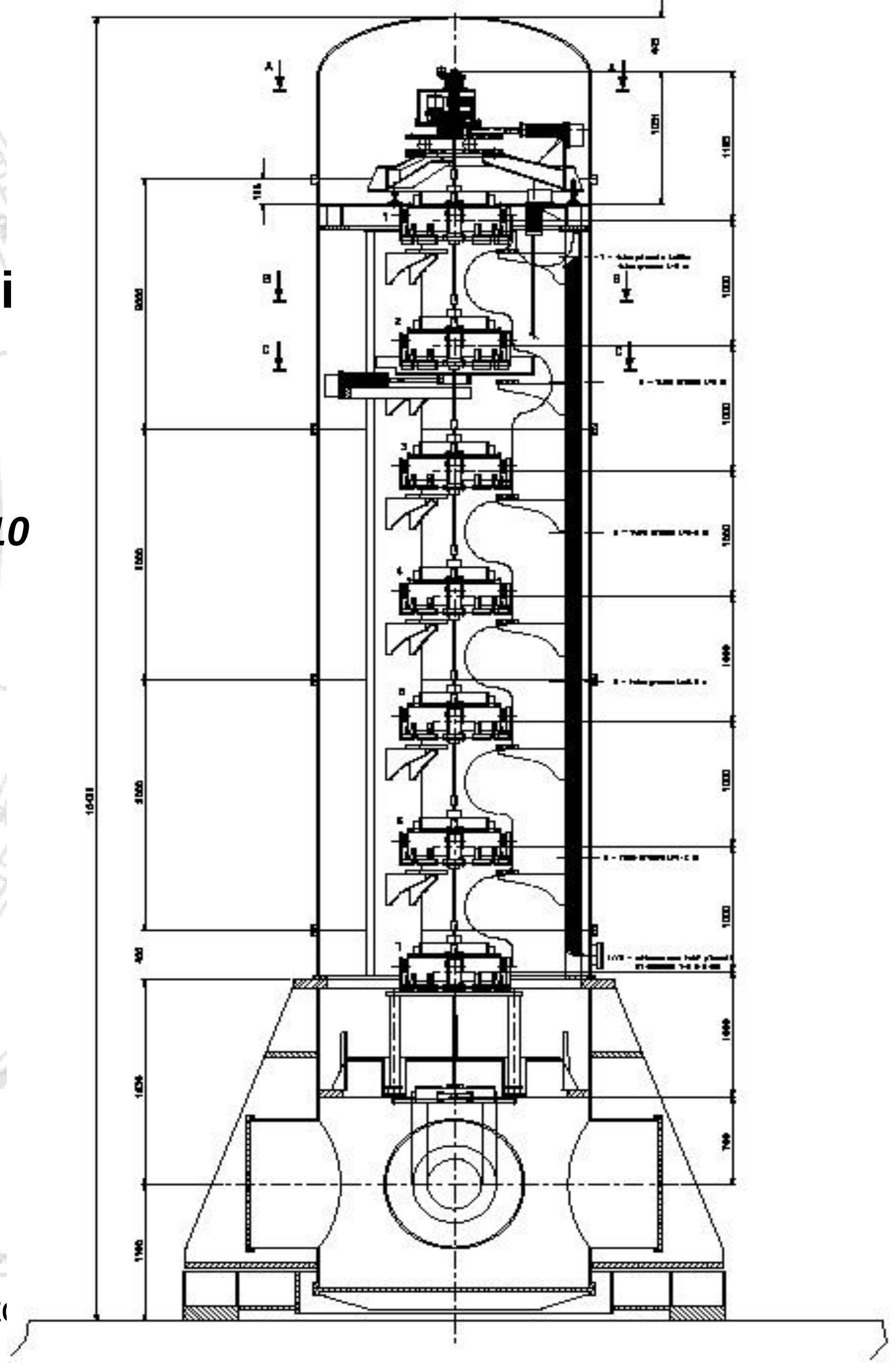
Fabry-Perot cavities




Radiation Pressure
scattered light noise
seismic noise
mirror
Newtonian noise
Brownian motion
Amplifiers and servo
Laser
Photo Detector
Shot noise
electronic noise
Laser Noise
(frequency,amplitude, jitter)

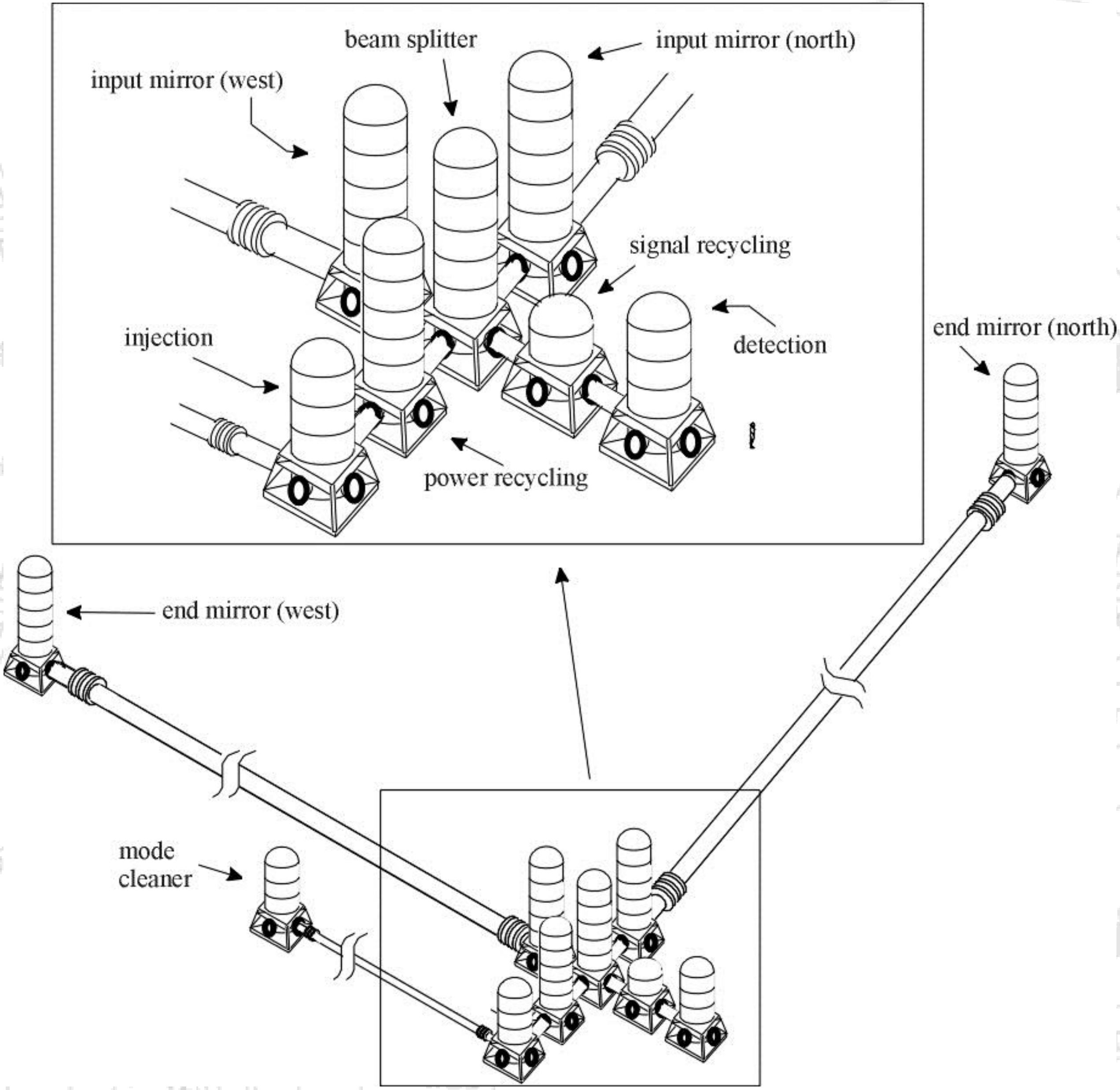
Riduzione del rumore sismico: Superattenuatori

- E' necessaria un'attenuazione di 10^{11} attenuation @ *10 Hz*



Virgo

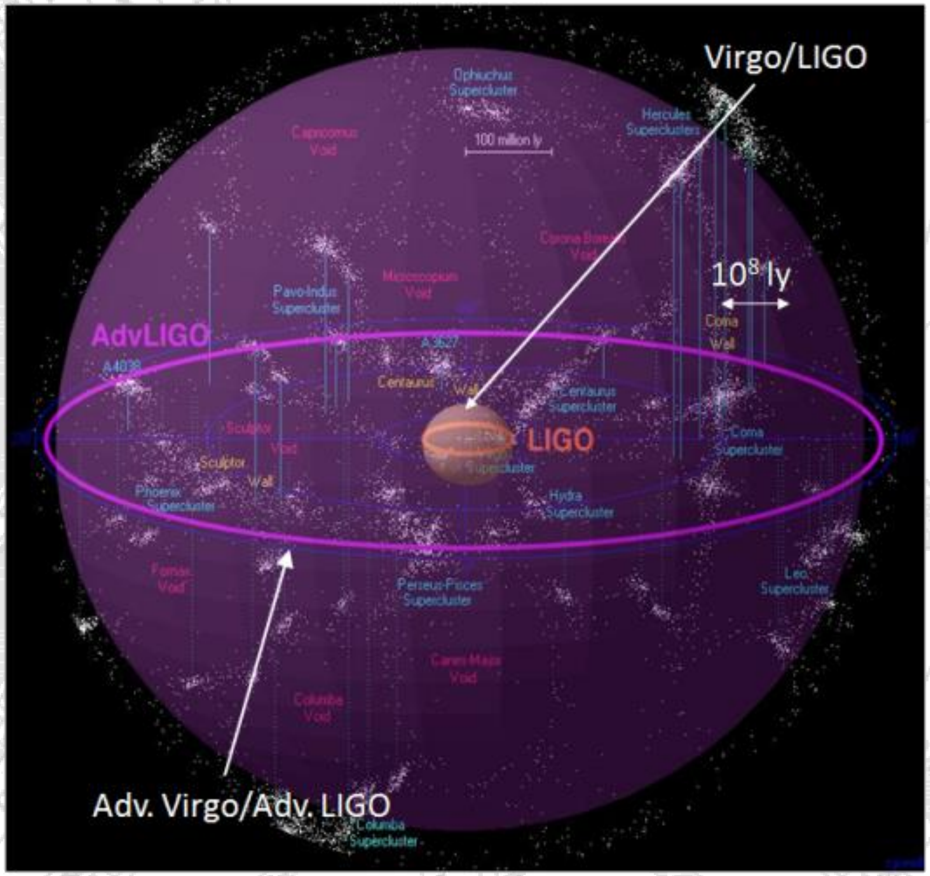
Sistema da vuoto e superattenuatori



Virgo - all'interno dell'edificio centrale

Virgo: a section of the 3 km vacuum pipe

Da Virgo ad Advanced Virgo



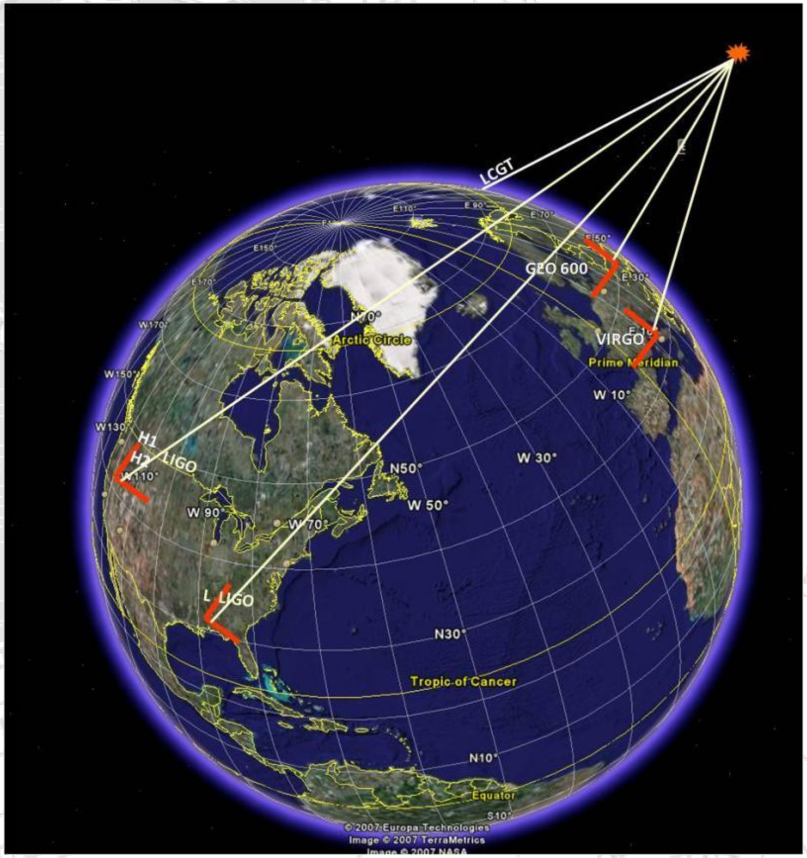
Credit: R.Powell, B.Berger

ADVANCED VIRGO is at present under construction

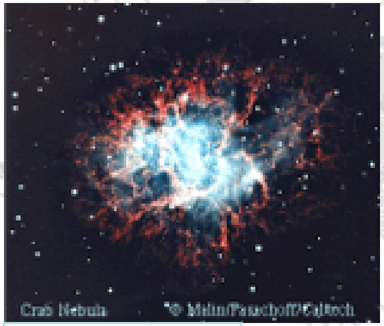
- It will be able to detect GW sources at a distance up to hundreds of Mpc
- Detection rate: ~1000x better than previous detectors
- Many GW events per year expected

GW detectors network

- **A network of GW interferometers is in operation: besides Virgo, 2 large scale detectors in the US (+ shorter interferometers in Germany and Japan). Within a few years 2 large scale interferometers in India and Japan will start data taking**



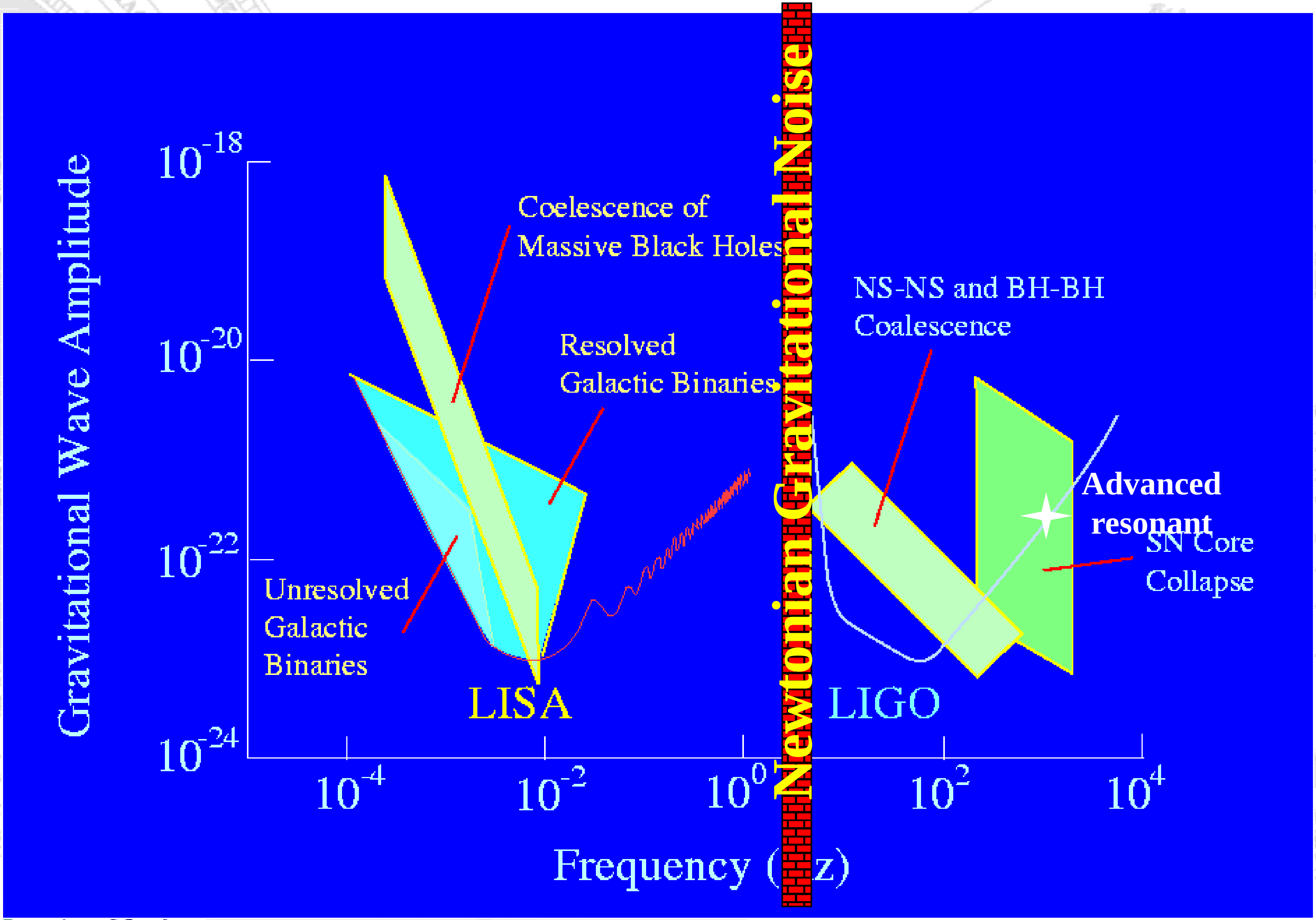
- Network detection capability: up to 200 Mpc for GW from binary neutron star systems. Detection rate: several events/year
- Other sources: binary black hole systems, isolated neutron stars, Super Nova collapses, stochastic background (associated with cosmological processes, e.g. inflation, cosmic strings, …)



Crab pulsar


SN 1987A

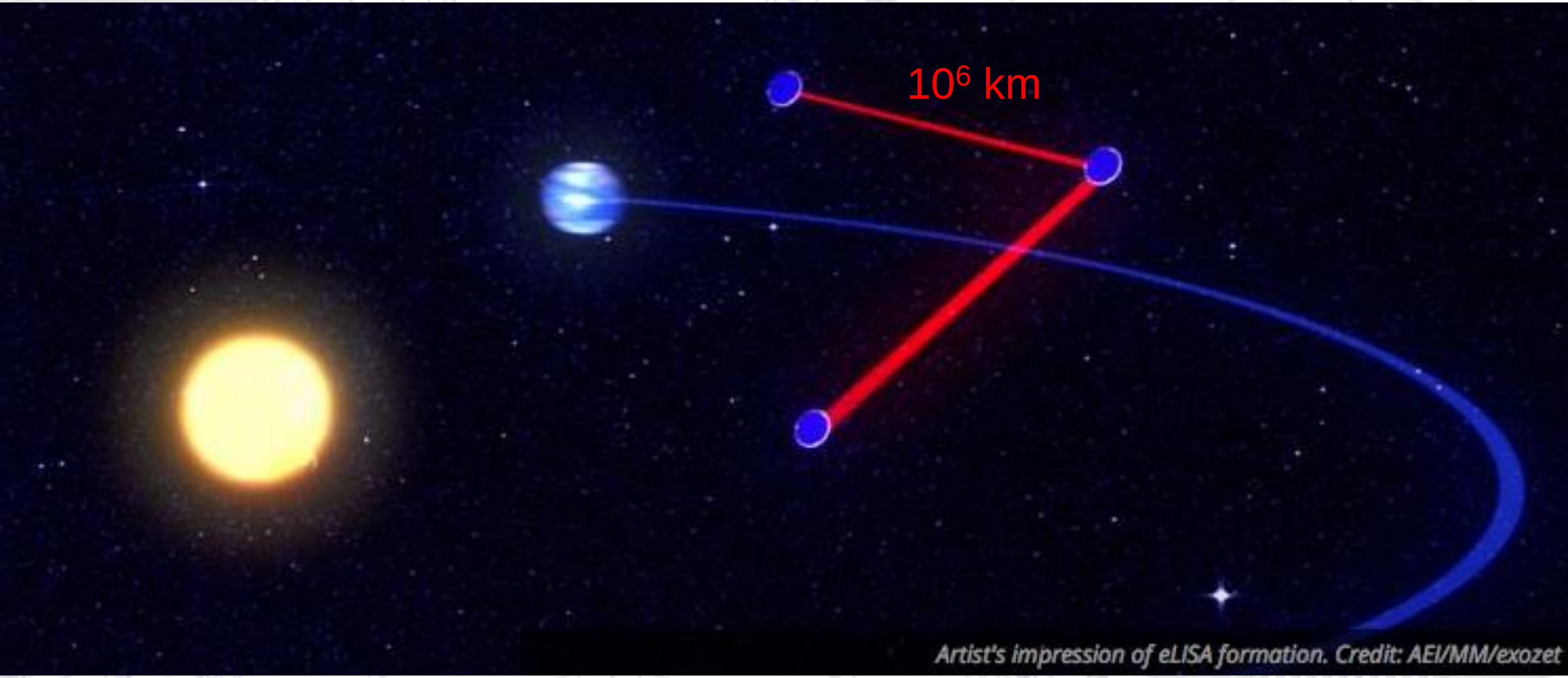
Strong connections with ν and EM detectors: a global network for MULTI-MESSENGER SCIENCE



Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coelescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
Newtonian Gravitational Noise
NS-NS and BH-BH
Coalescence
Advanced
resonant
SN Core
Collapse
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

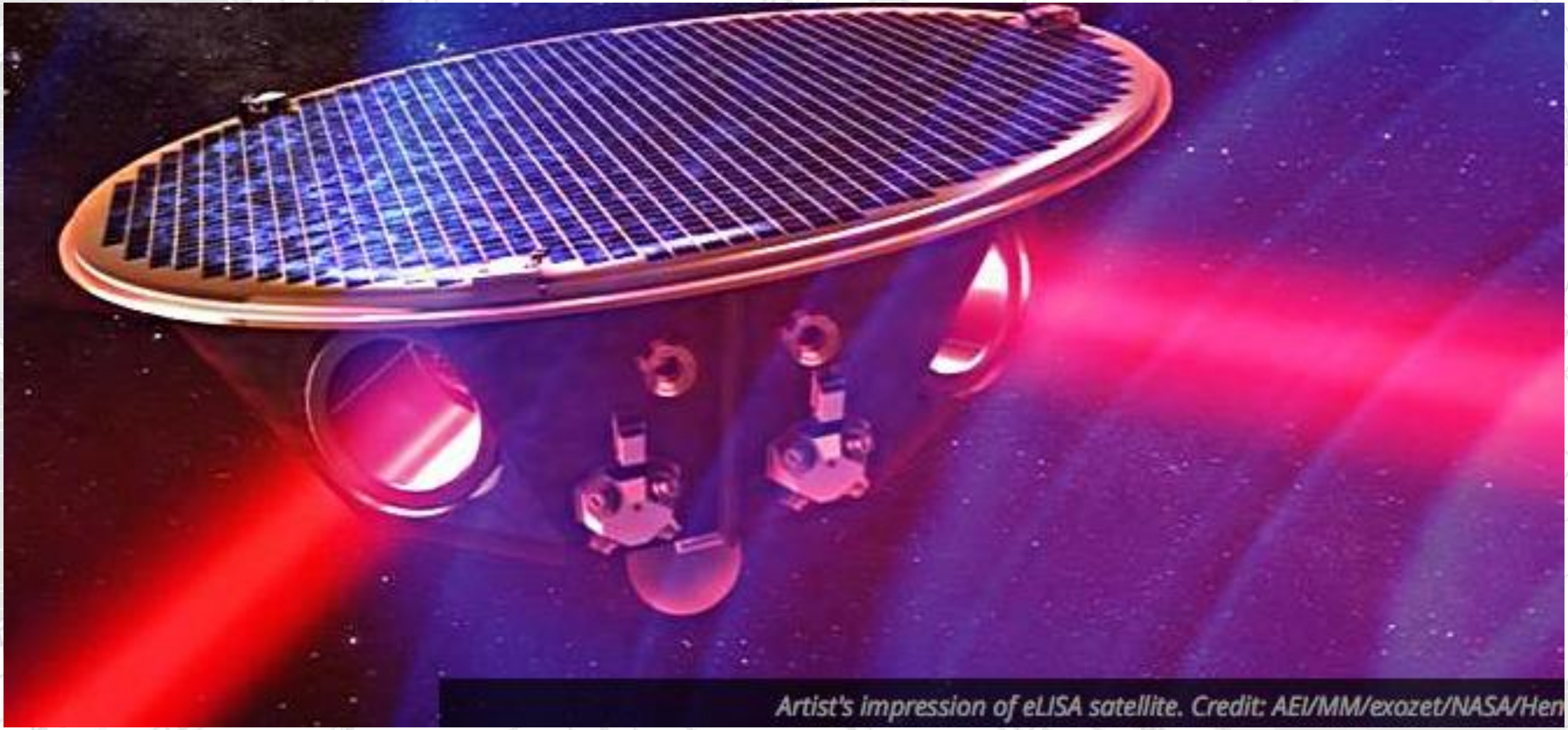
e-LISA

esa



A project for the future

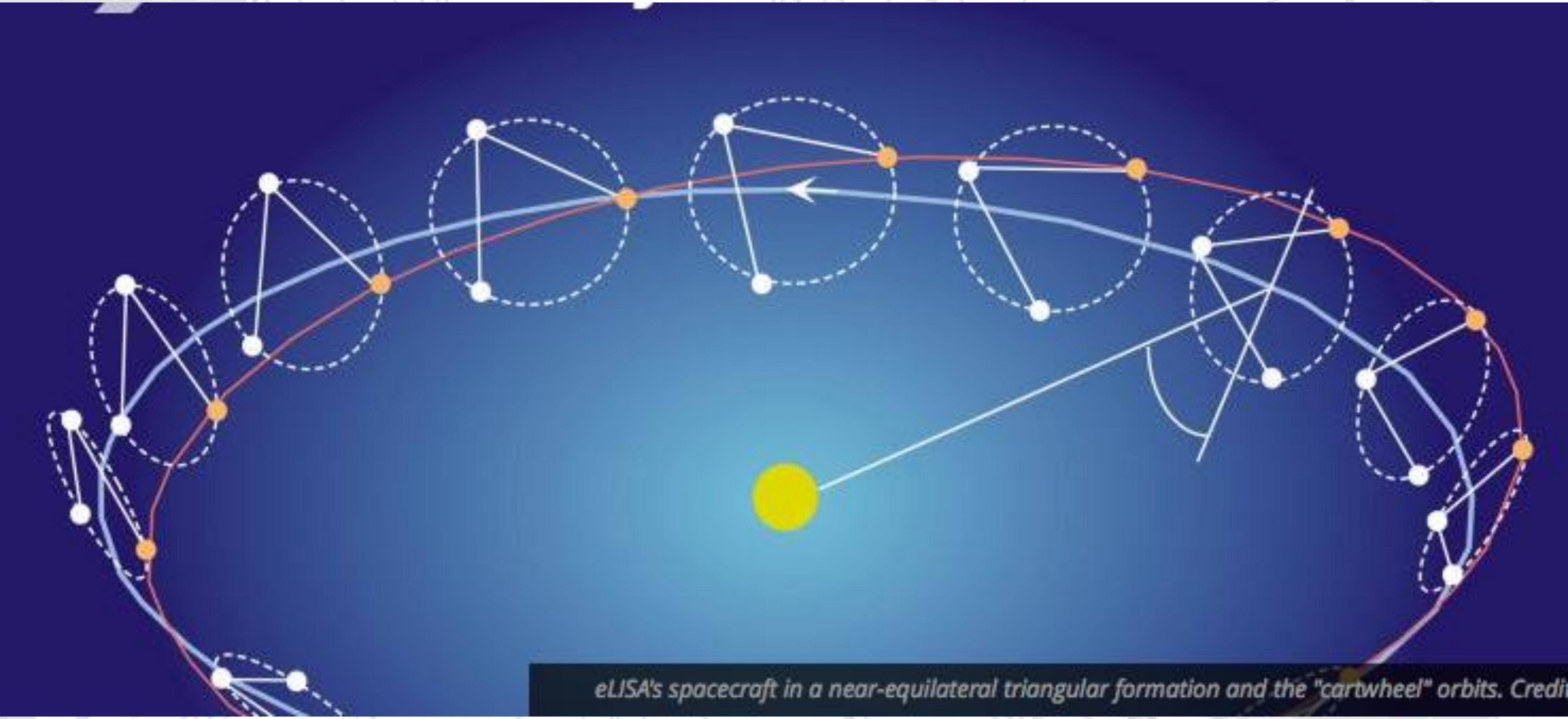
e-LISA



A project for the future

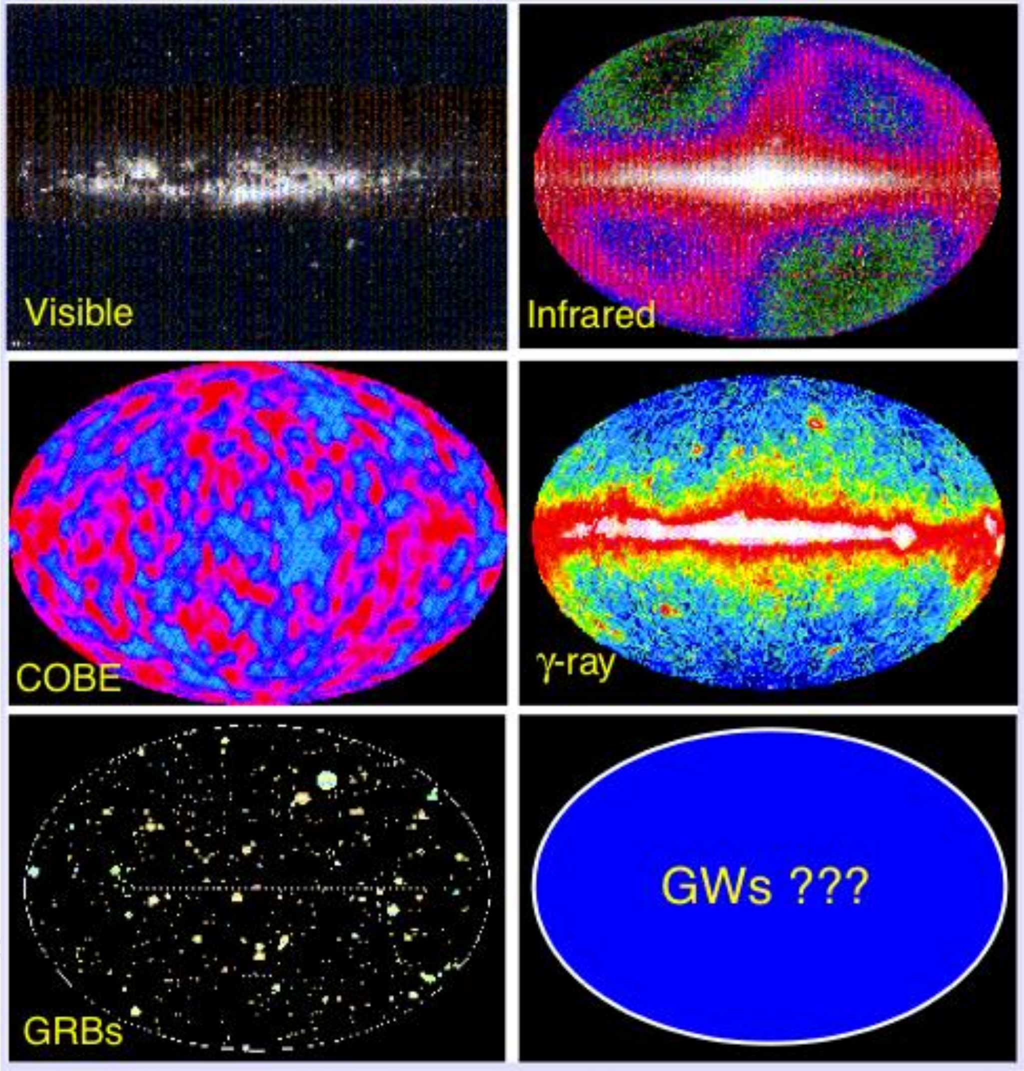
e-LISA

esa



A project for the future

1. Test of General Relativity
2. Beginning of gravitational astrophysiscs (pulsar, supernovae, binary systems, black holes)
3. From the study of the cosmic background→ "picture of the very early Universe" ~ 10^{-43} s after Big Bang



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

- **1915** Teoria della Relatività Generale
- **1916** Einstein predice le onde gravitazionali
- **1960** Weber realizza il primo rivelatore
- **1970** Inizia la costruzione dei rivelatori criogenici
- **1984** Taylor e Hulse trovano la prima prova indiretta delle onde gravitazionali (Premio Nobel nel 1993)
- **1990** rivelatori risonanti in misura
- **2005** Prima operazione di un grande interferometro
- **2015** interferometri avanzati in presa dati

Il 2016 sarà il centenario della pubblicazione della teoria della Relatività Generale: quale migliore occasione per festeggiare con la prima rivelazione diretta?

The End

Bibliografia

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- Fang Lizhi, Chu Yaoquan: From Newton's laws to Einstein's theory of relativity (Science Press/World Scientific)
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- Alcuni possibili testi "classici" sulla relatività generale:
- Misner, Thorne, Wheeler: Gravitation (Freeman and Company)
- Weinberg: Gravitation and Cosmology (Wiley & Sons)
- Kenyon: General Relativity (Oxford Science Publications)