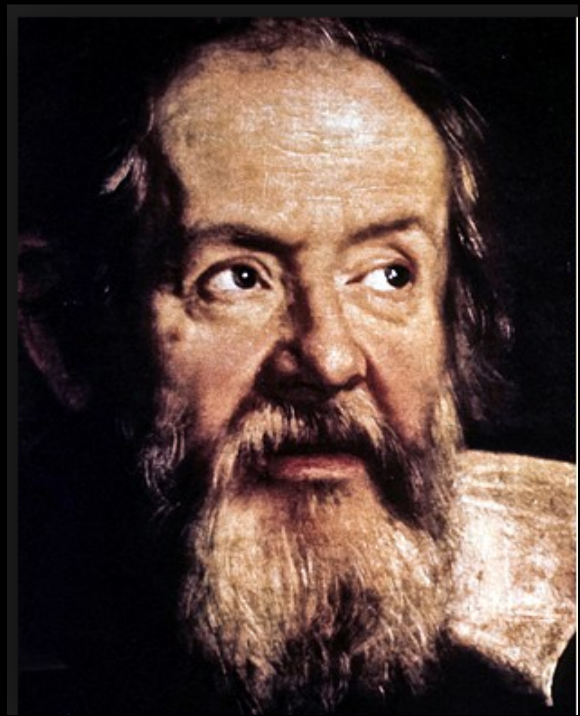
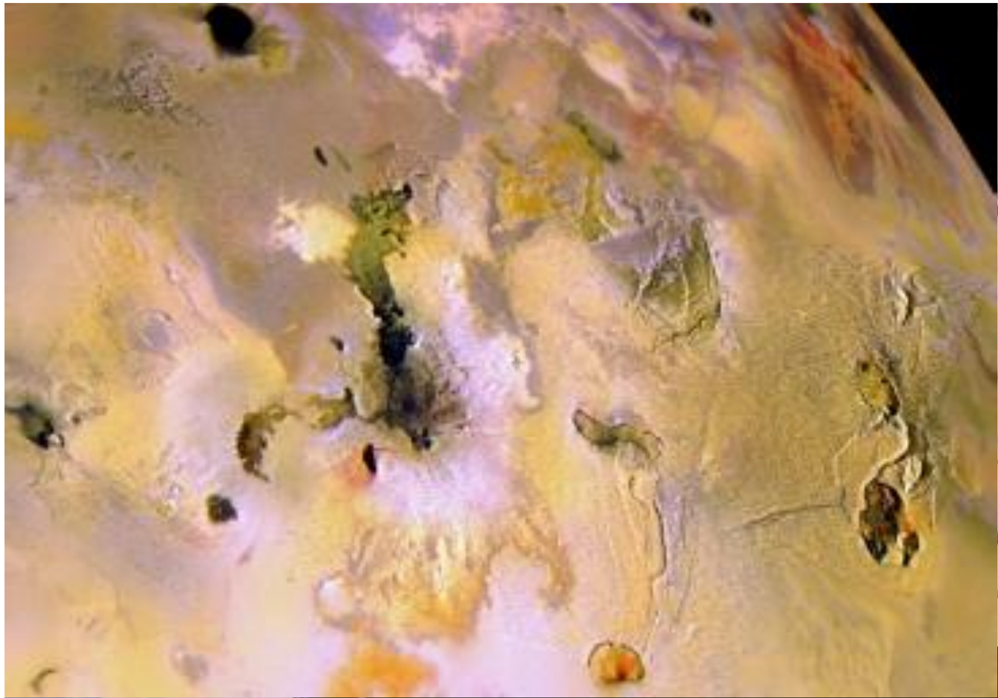
OPENING THE GRAVITATIONAL WAVE WINDOW TO THE UNIVERSE

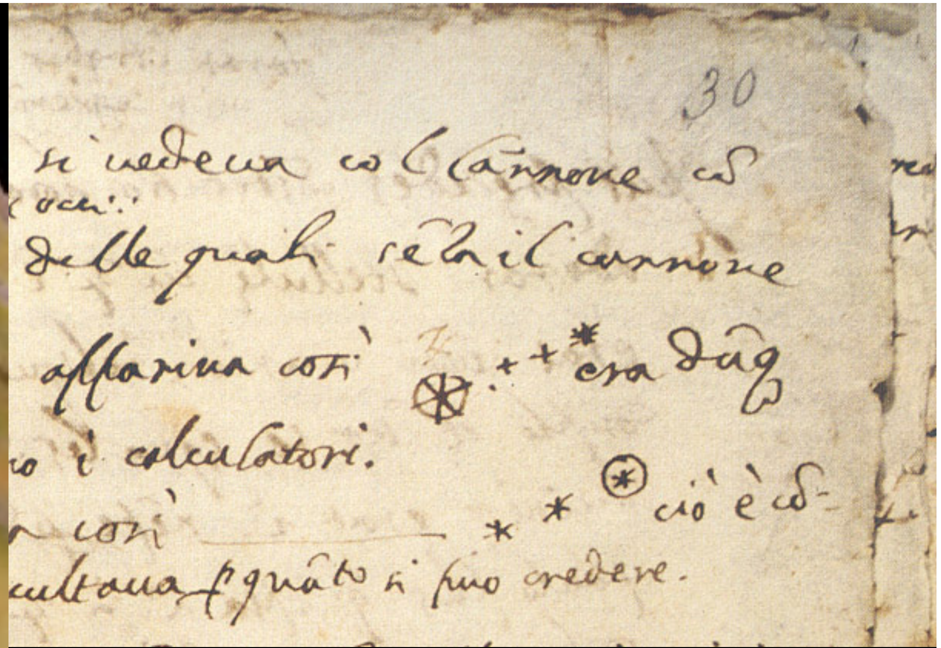
Eugenio COCCIA
University of Rome "Tor Vergata"
and Gran Sasso Science Institute, INFN

Barcelona, February 18 2016



GALILEO





30

si vedeva col cannone co

delle quali se bene il cannone

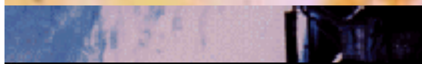
appariva così ... era dunq

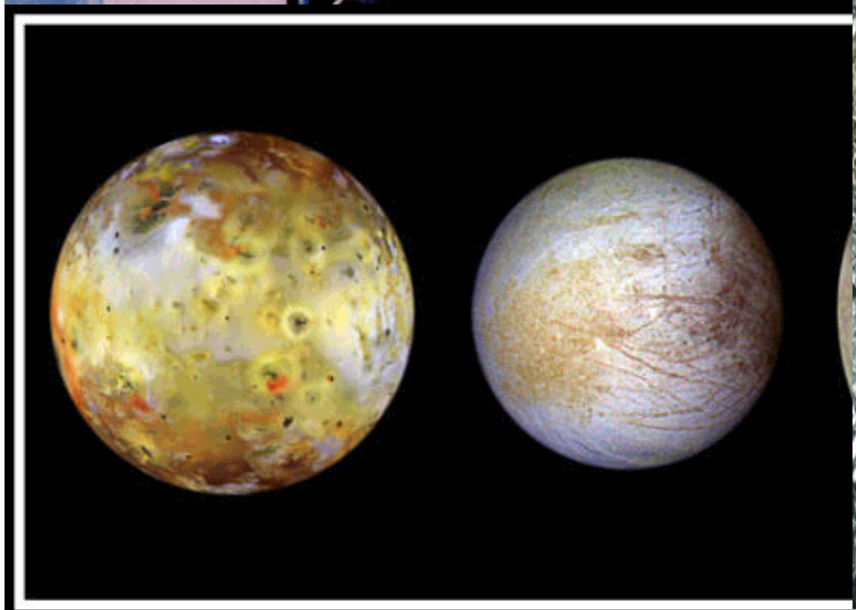
i calculatori.

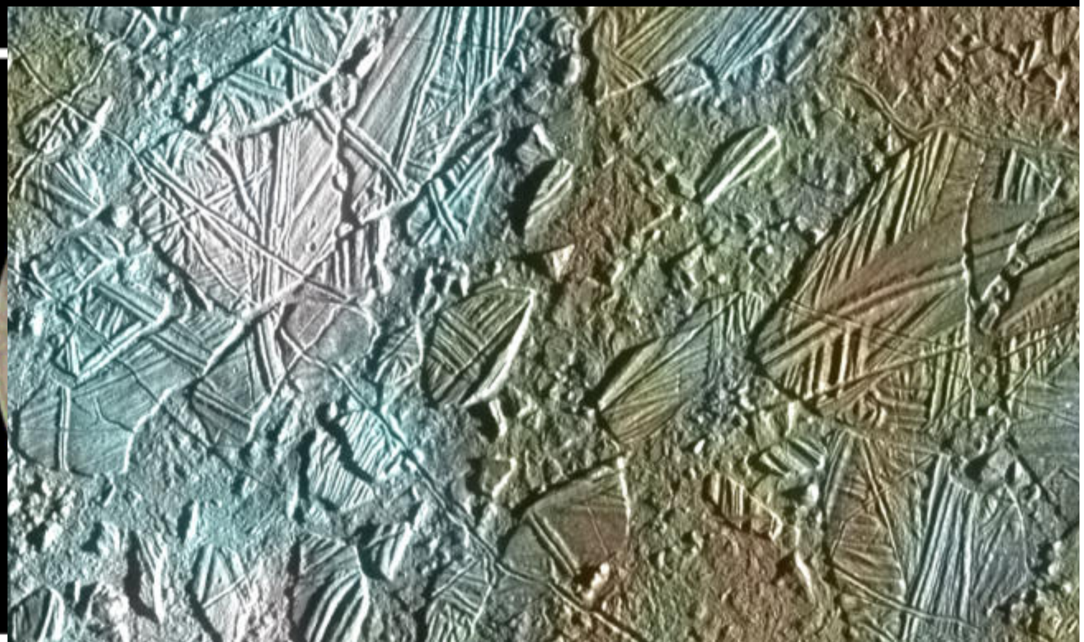
ciò è co-

così

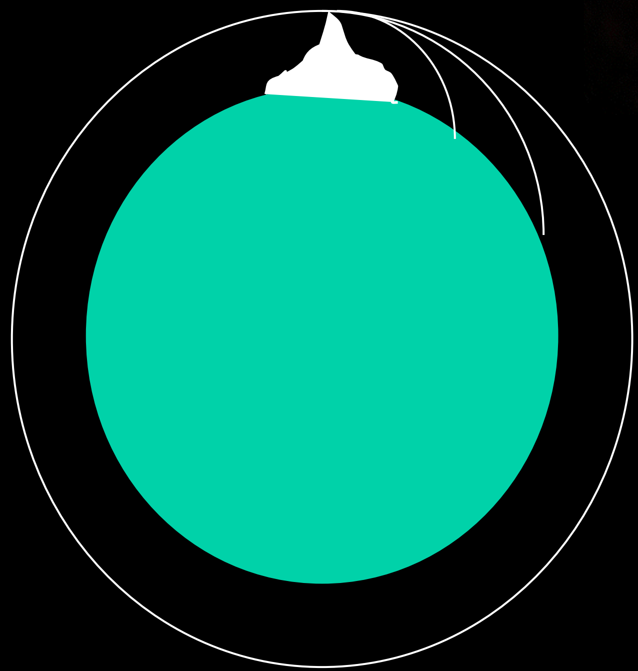
multava quanto si può credere.

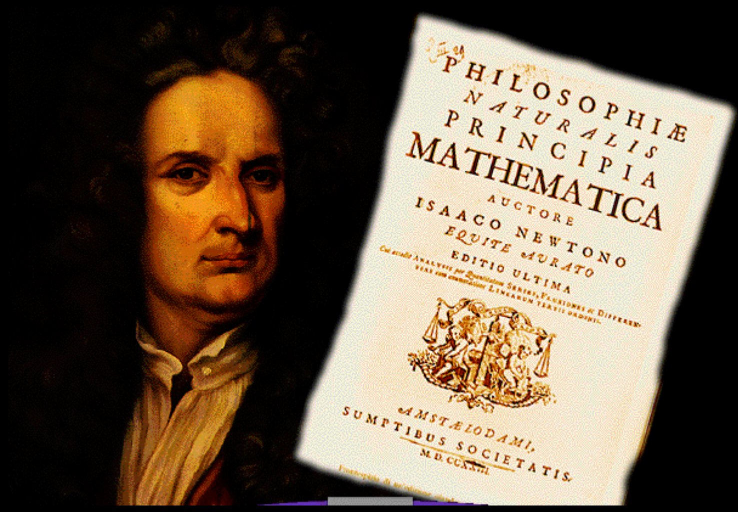


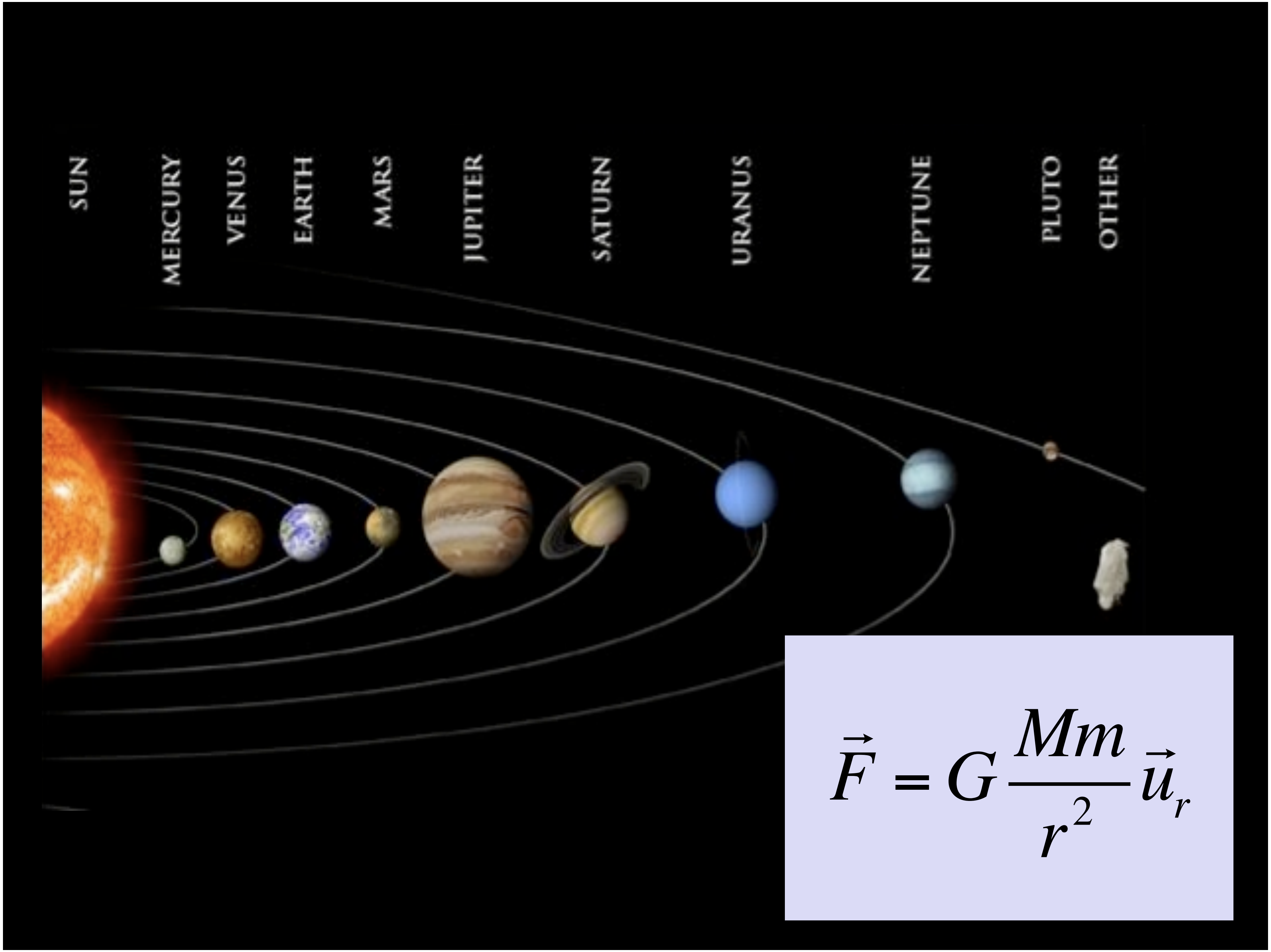




Newton



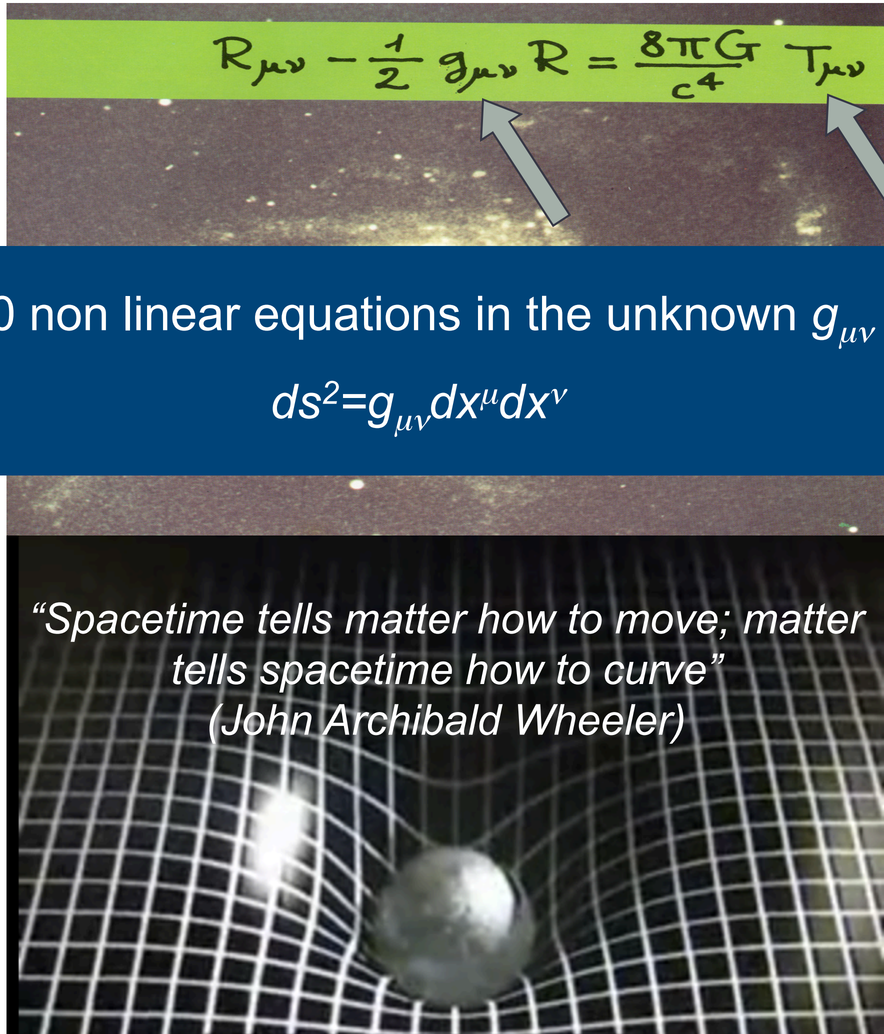

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA
AUCTORE
ISAACO NEWTONO
EQUITE AURATO
EDITIO ULTIMA
AMSTÆLODAMI,
SUMPTIBUS SOCIETATIS.



$$\vec{F} = G\frac{Mm}{r^2}\vec{u}_r$$

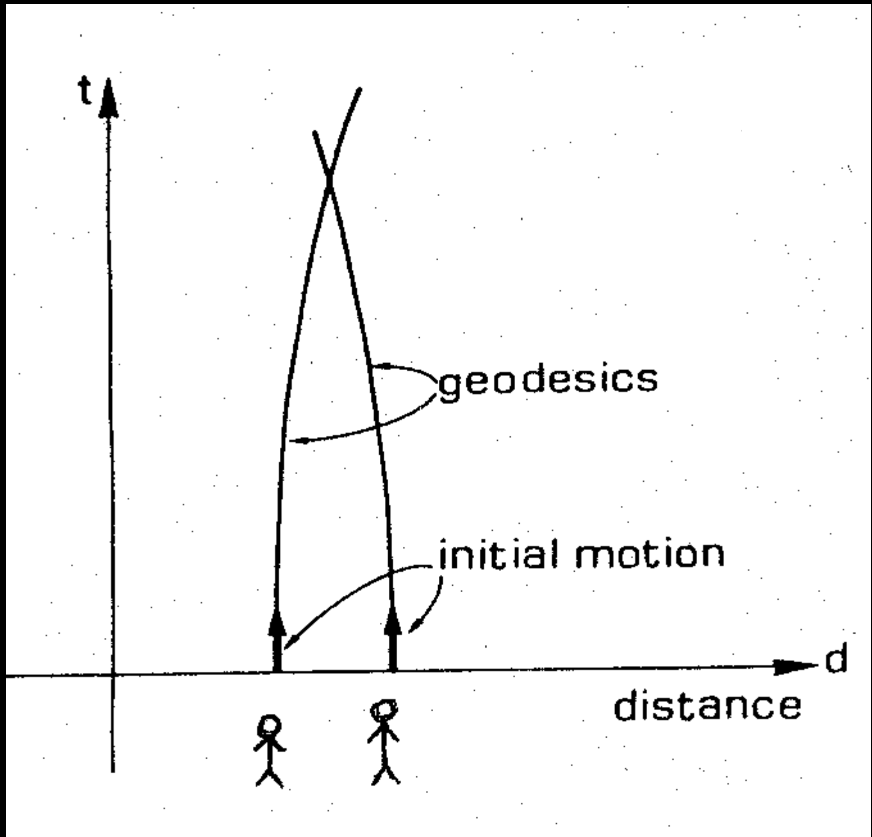
Einstein's Theory of Gravitation

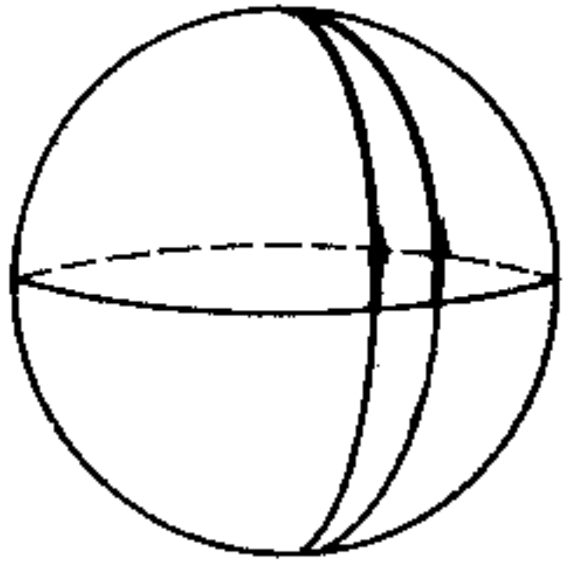
Gravity is a manifestation of spacetime curvature induced by mass-energy



10 non linear equations in the unknown $g_{\mu\nu}$

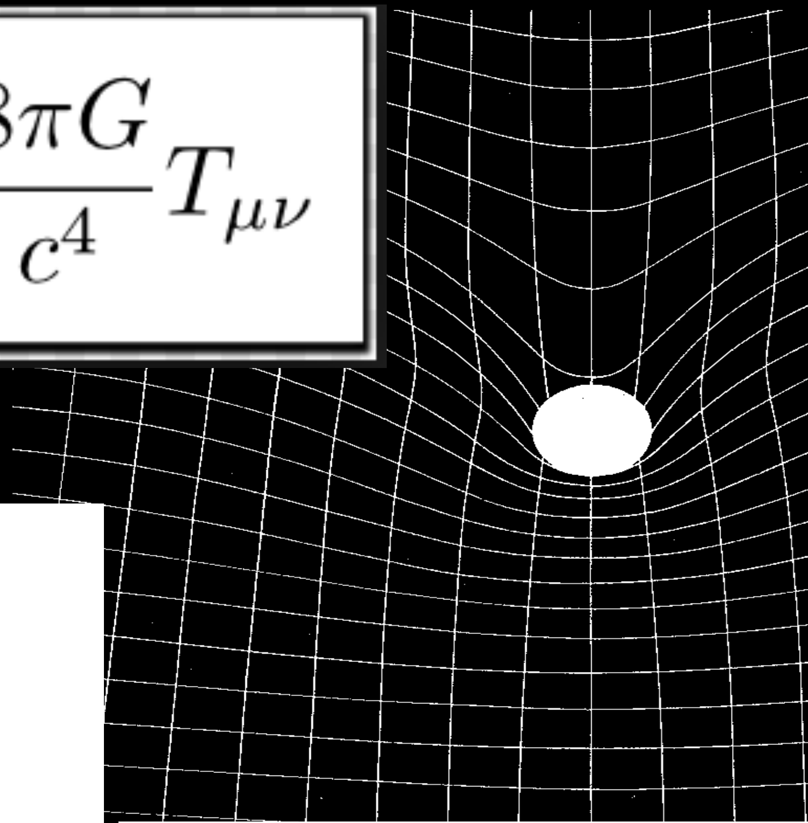
$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

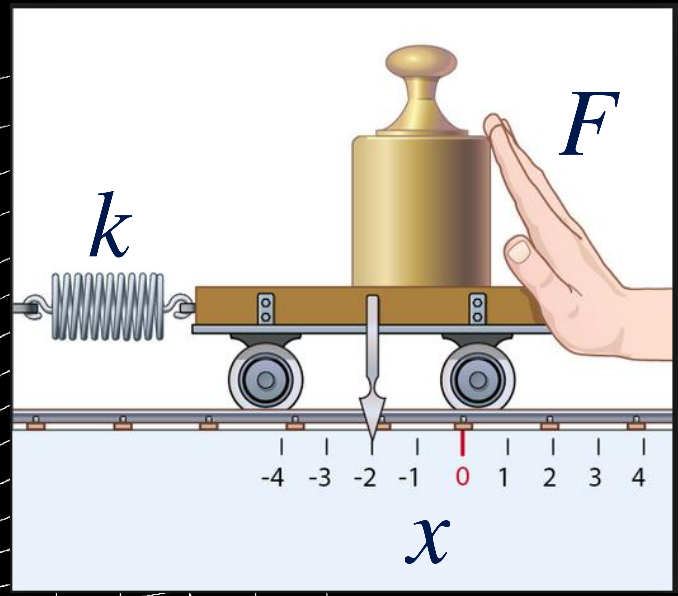

t
geodesics
initial motion
d
distance



( )

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$





$$F = -kx$$

$$F \Leftrightarrow T_{\mu\nu}$$

$$x \Leftrightarrow G_{\mu\nu}$$

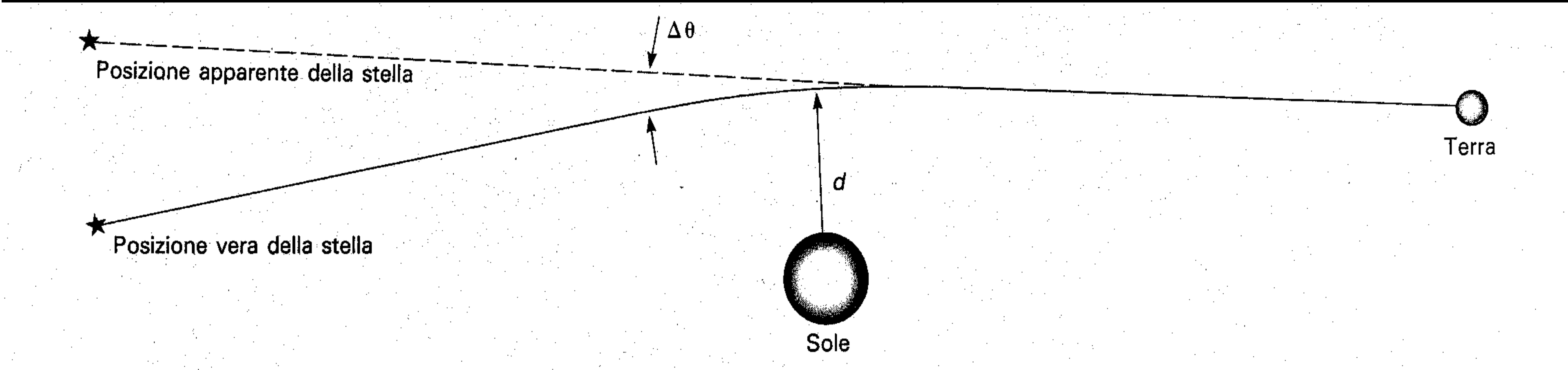
$$k \Leftrightarrow \frac{c^4}{8\pi G}$$

$$c = 299\ 792\ 458\ \ m/s = 3\times 10^8\ \ m/s$$

$$G = 0{,}000\ 000\ 000\ 066\ 7\ \frac{m^3}{kg\ s^2} = 6{,}67\times 10^{-11}\ \frac{m^3}{kg\ s^2}$$

$$k \approx 10^{45}\ \frac{kg}{s^2} \qquad STIFF!$$

Funziona?



Δθ
Posizione apparente della stella
Posizione vera della stella
d
Terra
Sole

Eddington

.IGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

LIGHTS ALL ASKEW IN THE HEAVENS

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

EINSTEIN THEORY TRIUMPHS

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

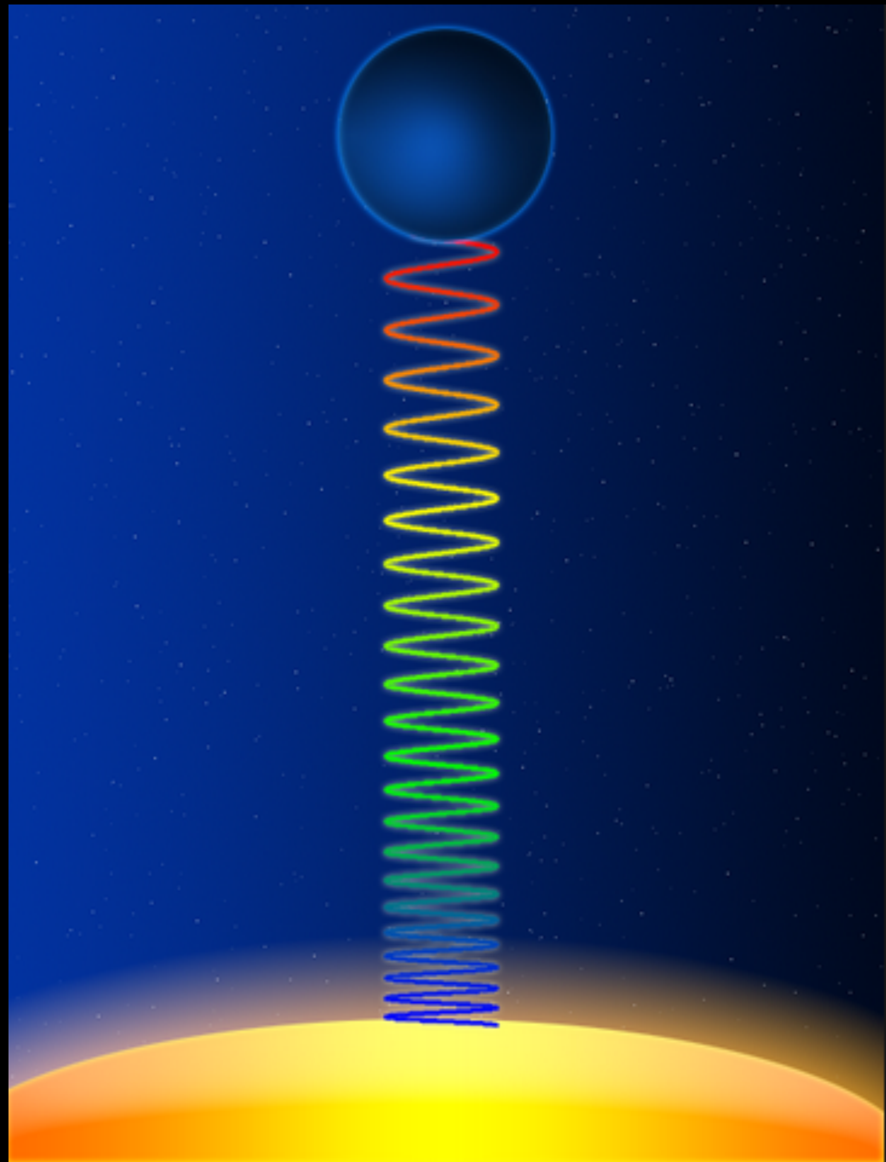
A BOOK FOR 12 WISE MEN

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

New York Times headline of November 10, 1919.

Harvard

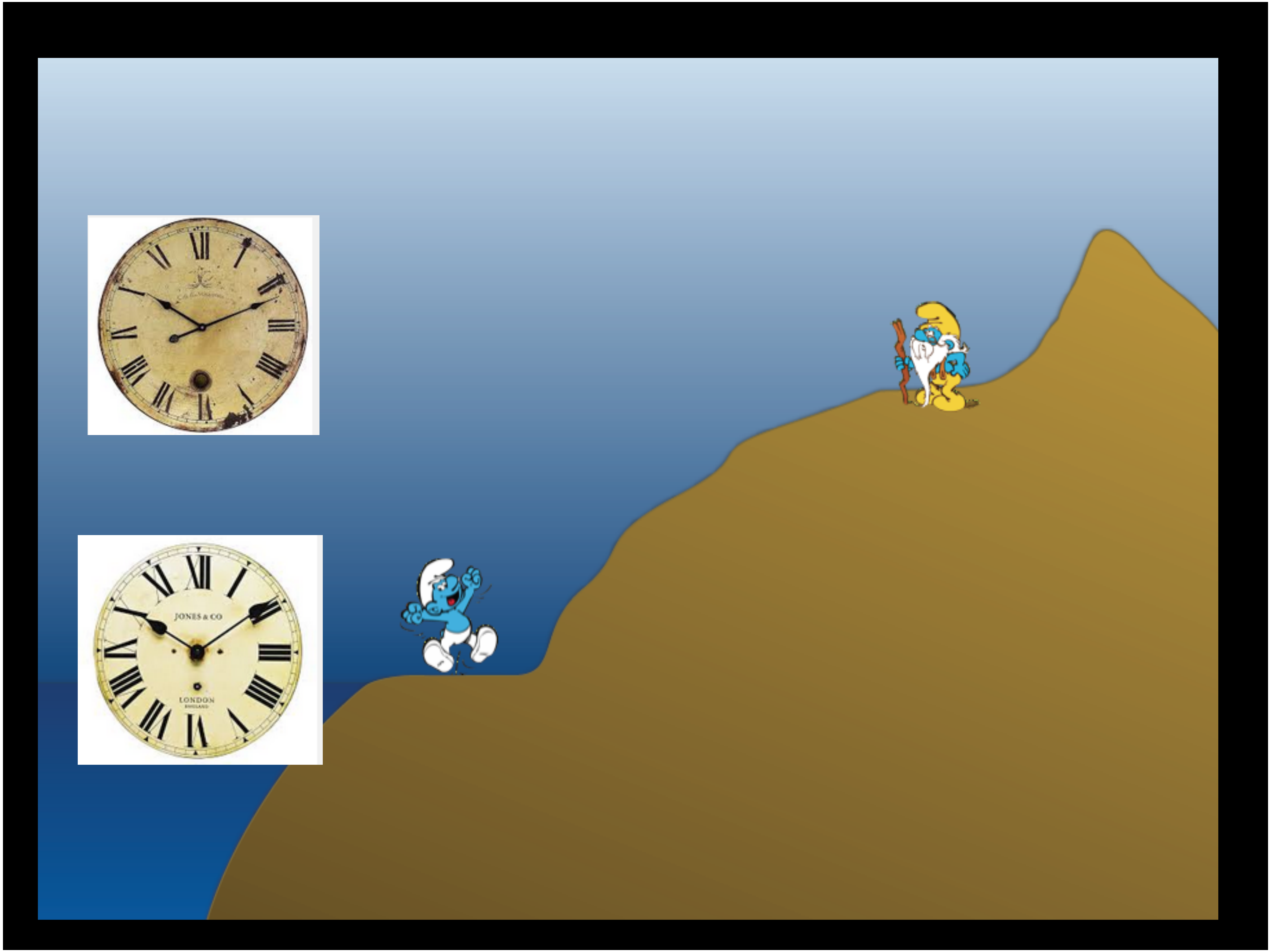
$$\frac{\Delta\nu}{\nu} = -\frac{v}{c} = -\frac{gh}{c^2}$$



Redshift

Pound and Rebka

1959


JONES & CO
LONDON

KINETIC Energy POTENTIAL Energy

$$\frac{1}{2}mv^2 \geq G\frac{mM}{R}$$

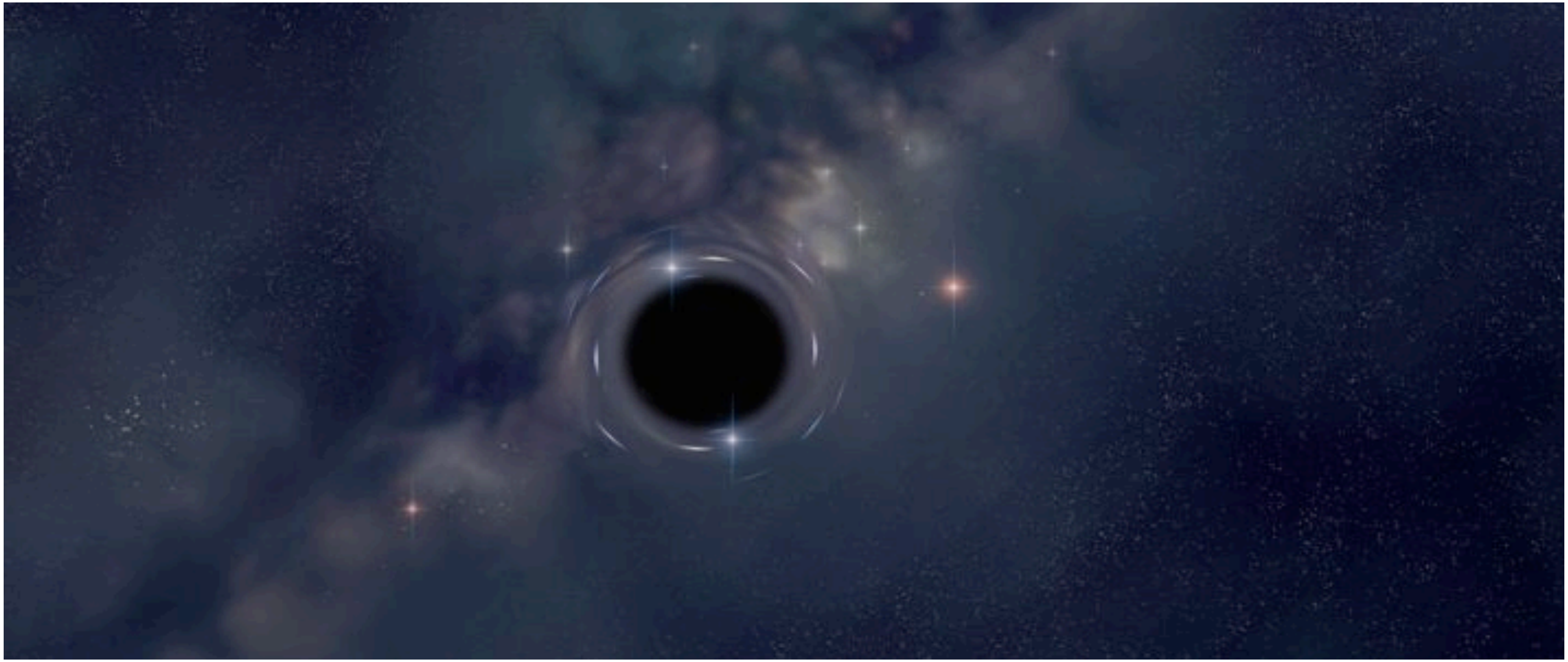
$$v_f = \sqrt{\frac{2GM}{R^2}}$$

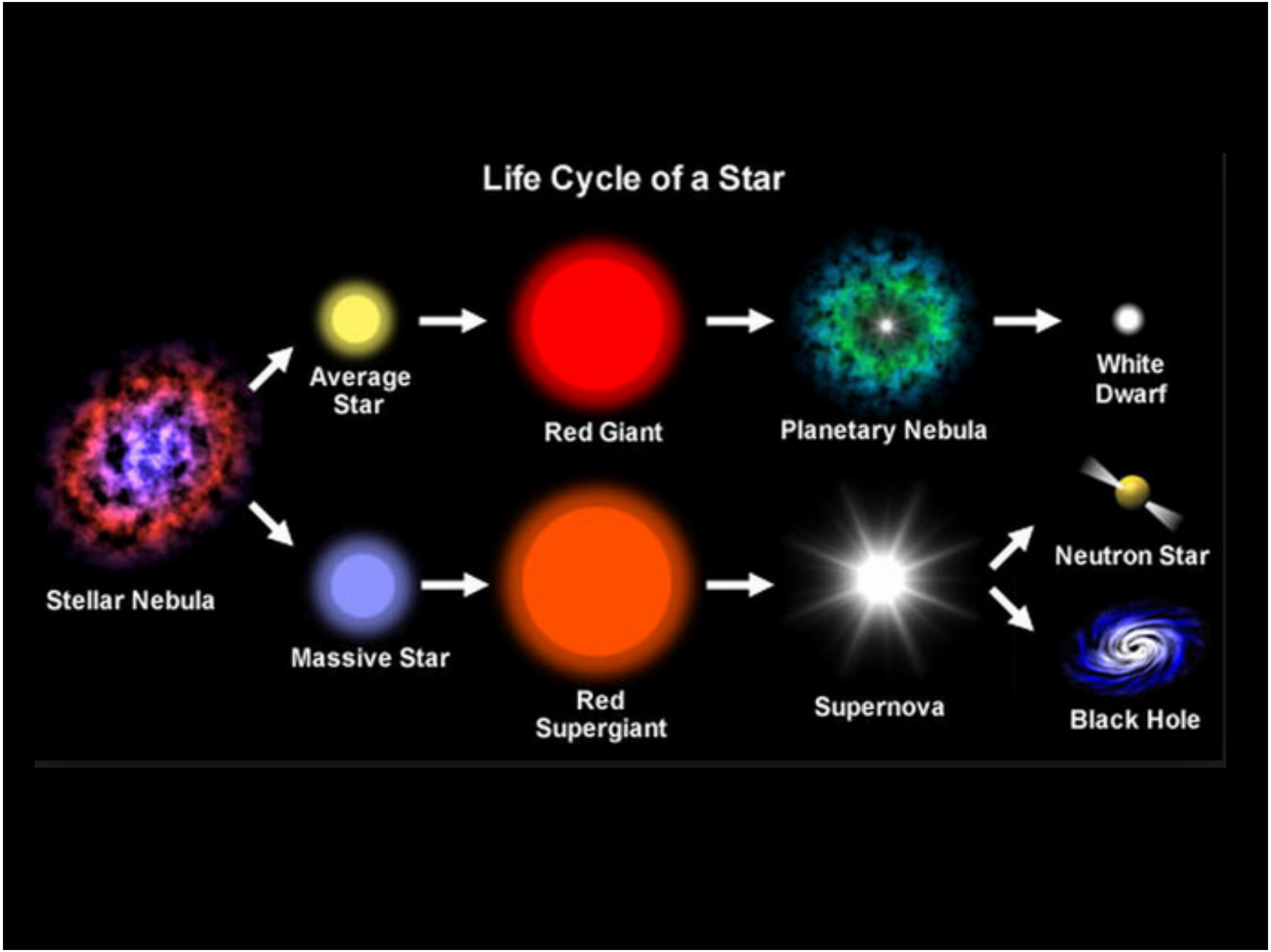
Escape velocity

Escape velocity is the speed of light if matter in squeezed into a sphere of radius

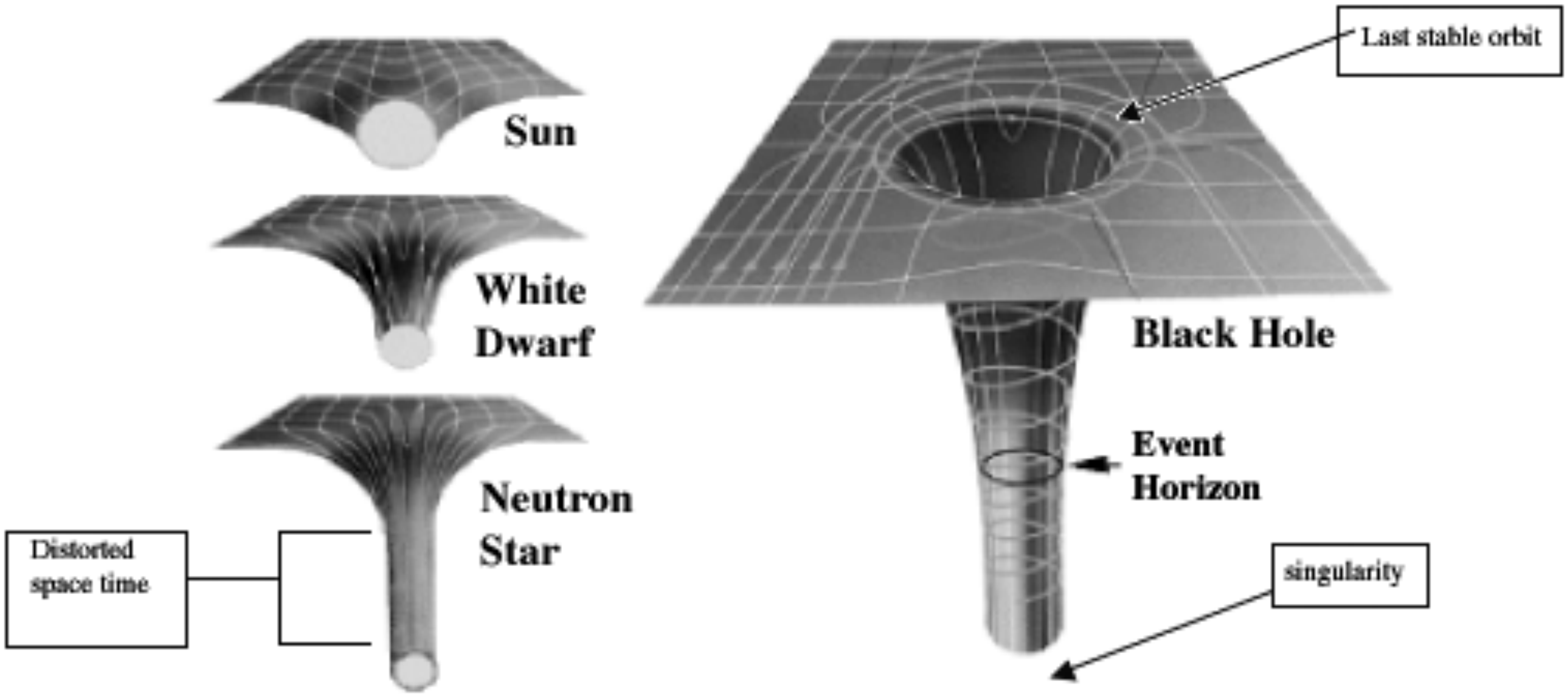
$$R = R_s = \sqrt{\frac{2GM}{c^2}}$$

BLACK HOLE



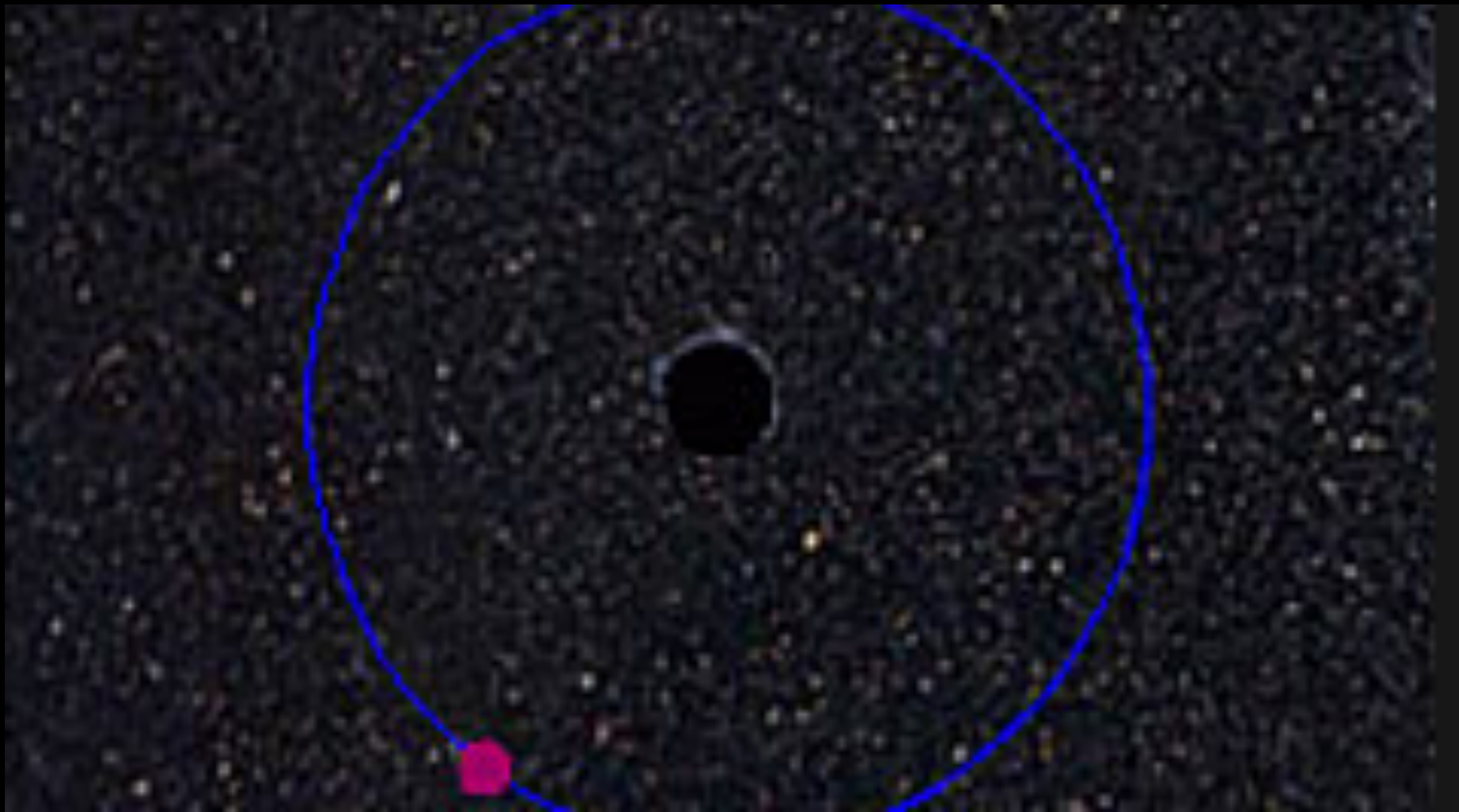

Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole

Sn 1987a

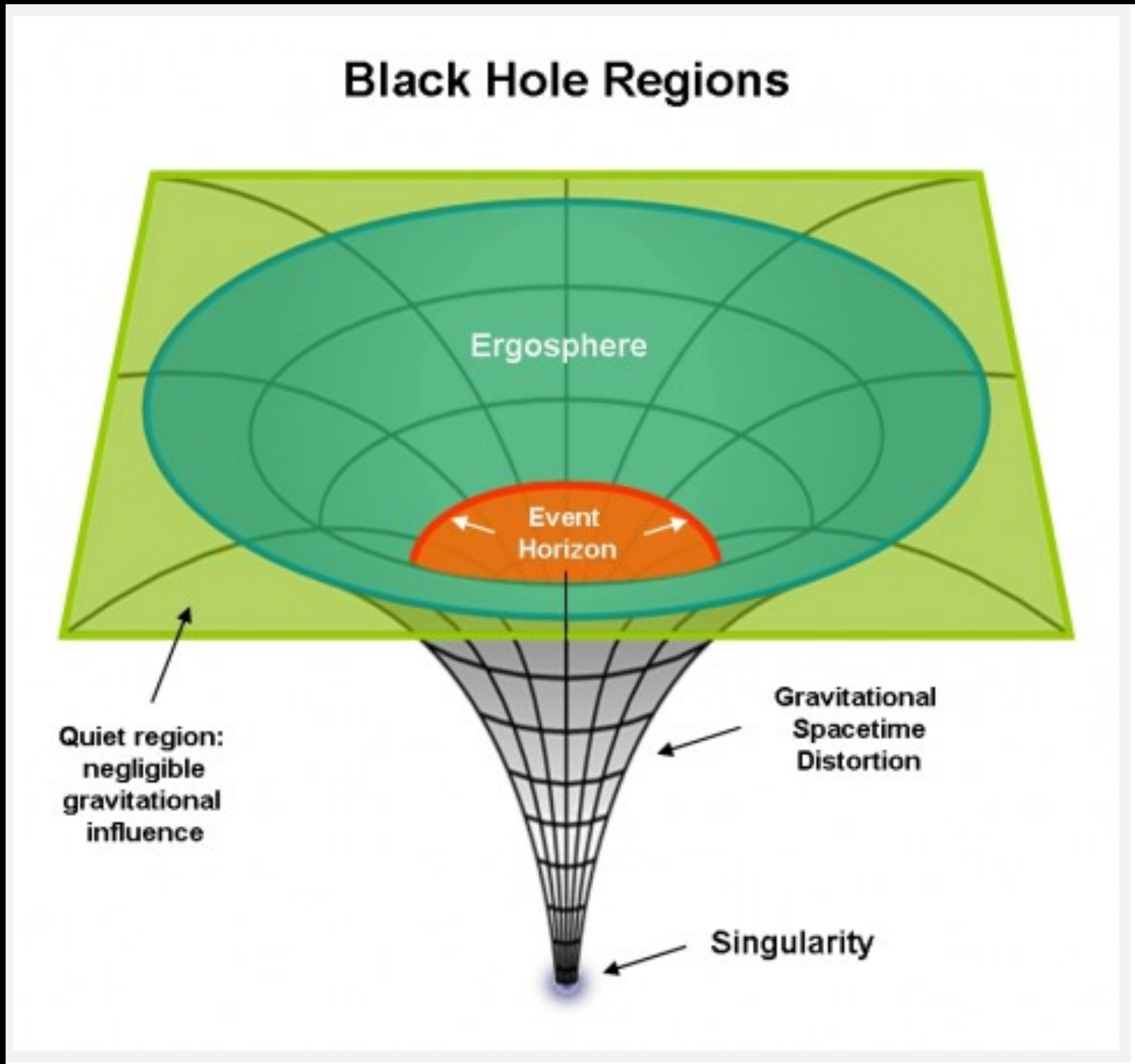

Sun
White
Dwarf
Neutron
Star
Distorted
space time
Last stable orbit
Black Hole
Event
Horizon
singularity

Spaghettification!

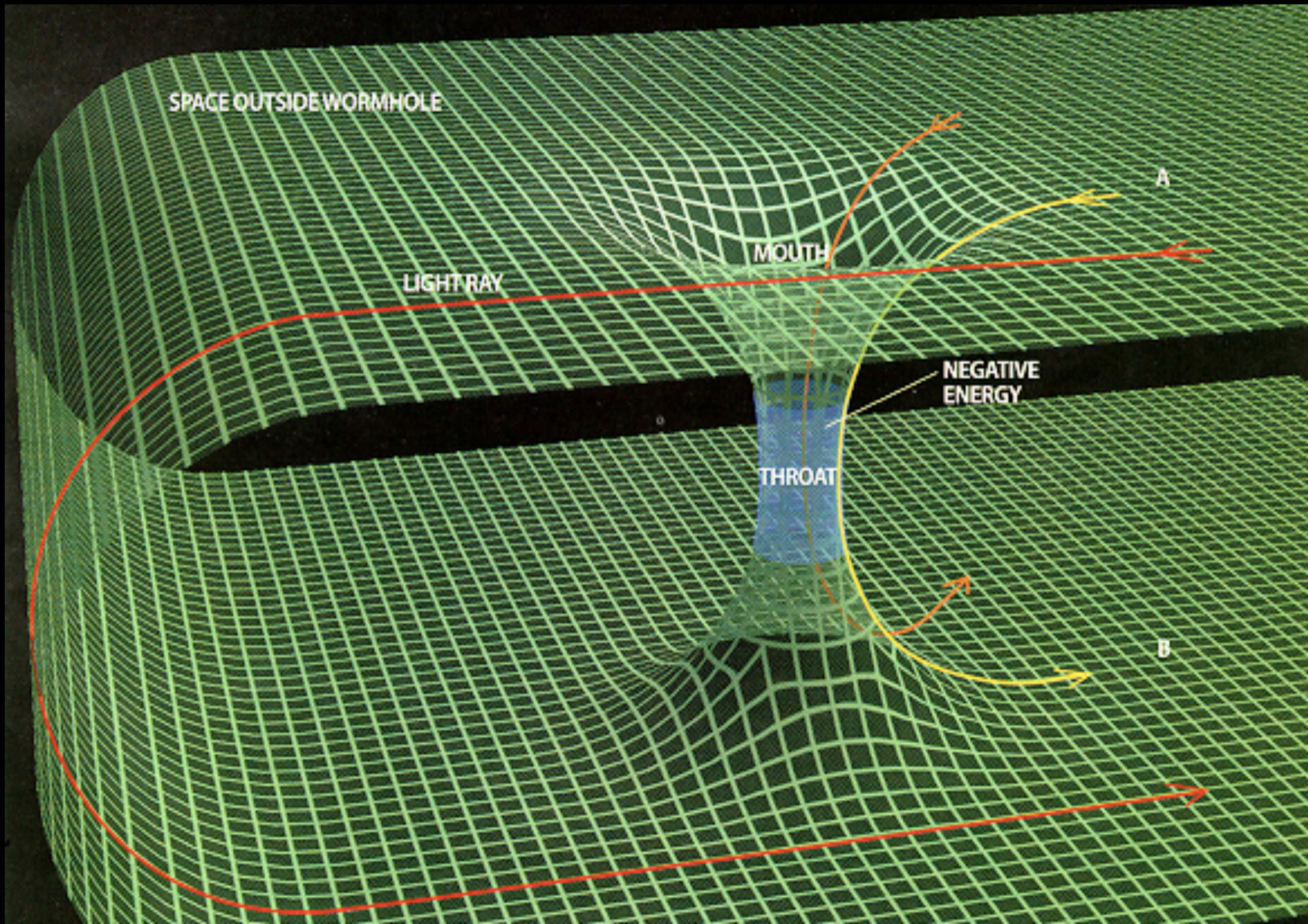
Viaggiare nel futuro

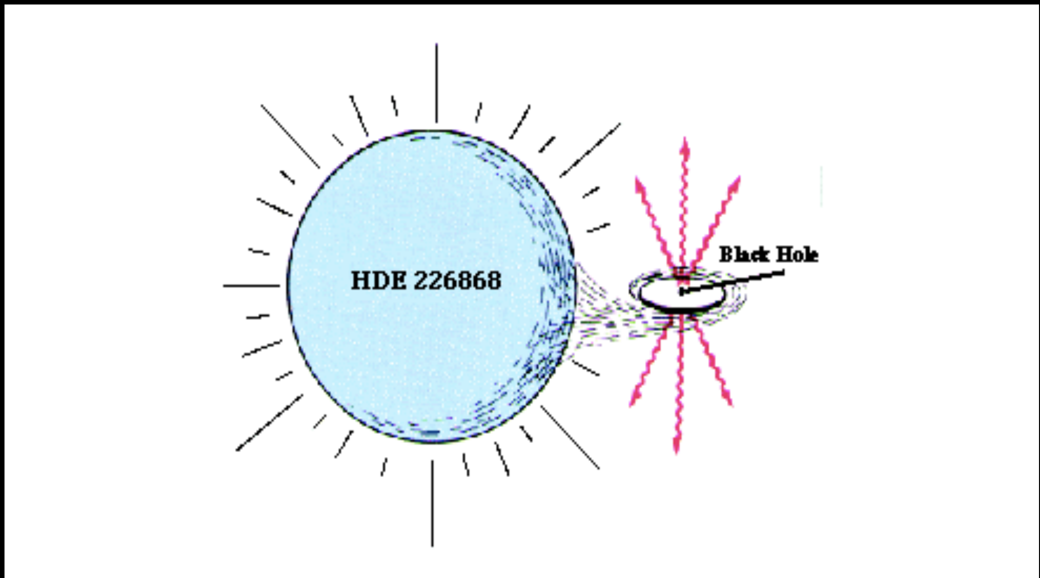


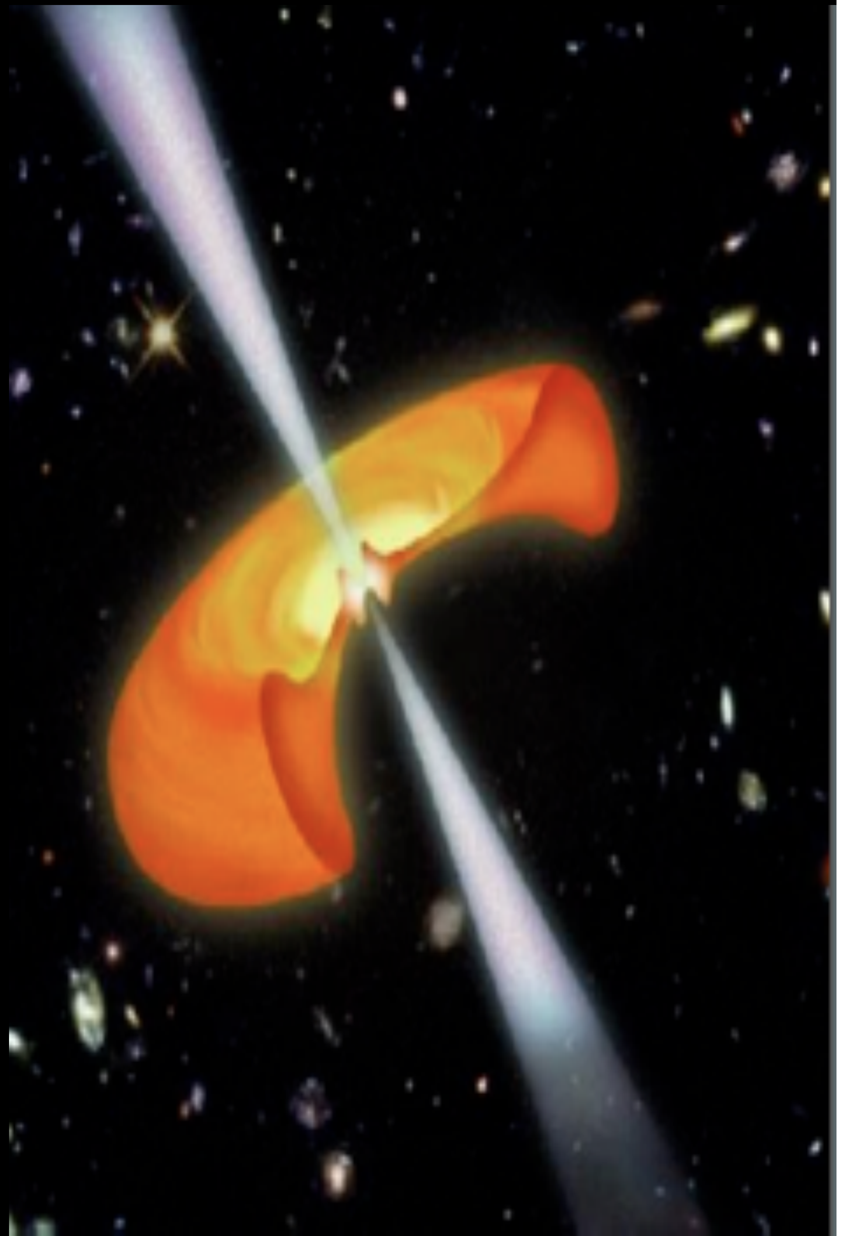
Estrarre energia

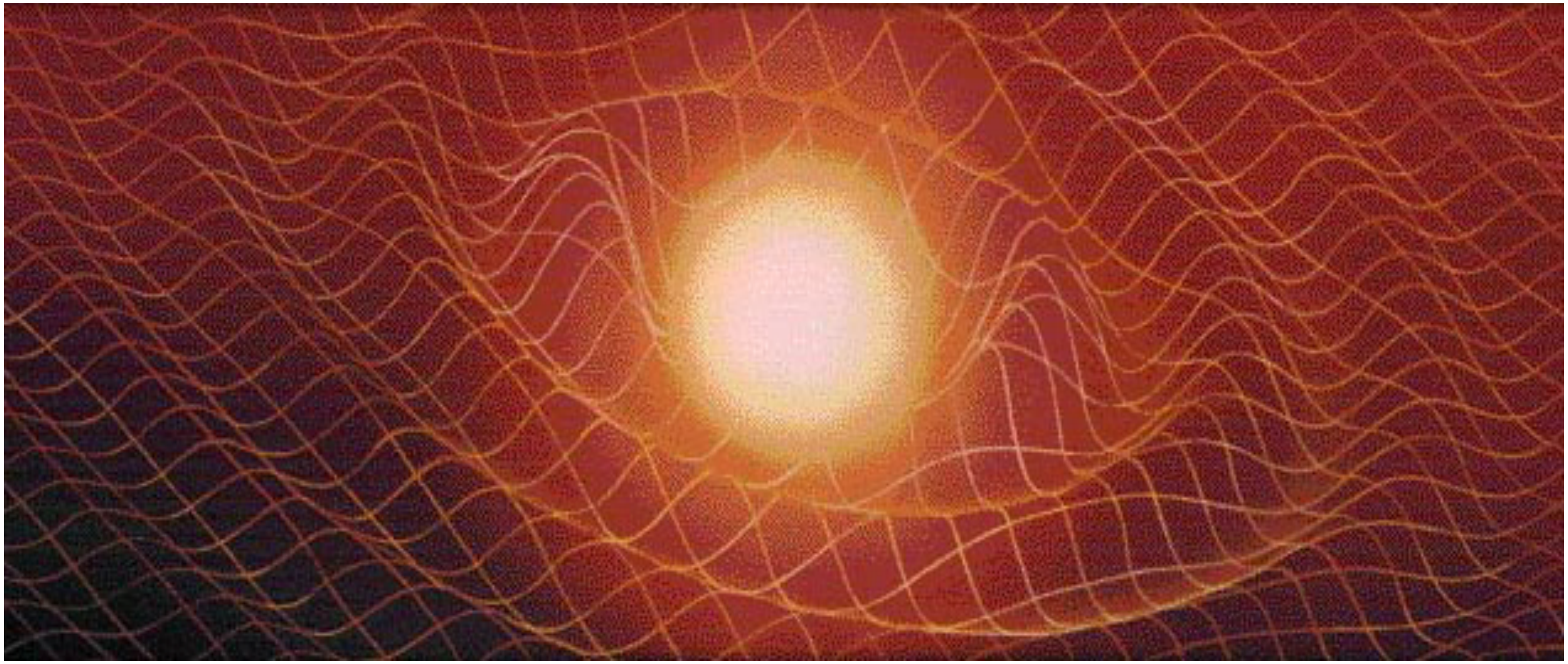


Andare oltre

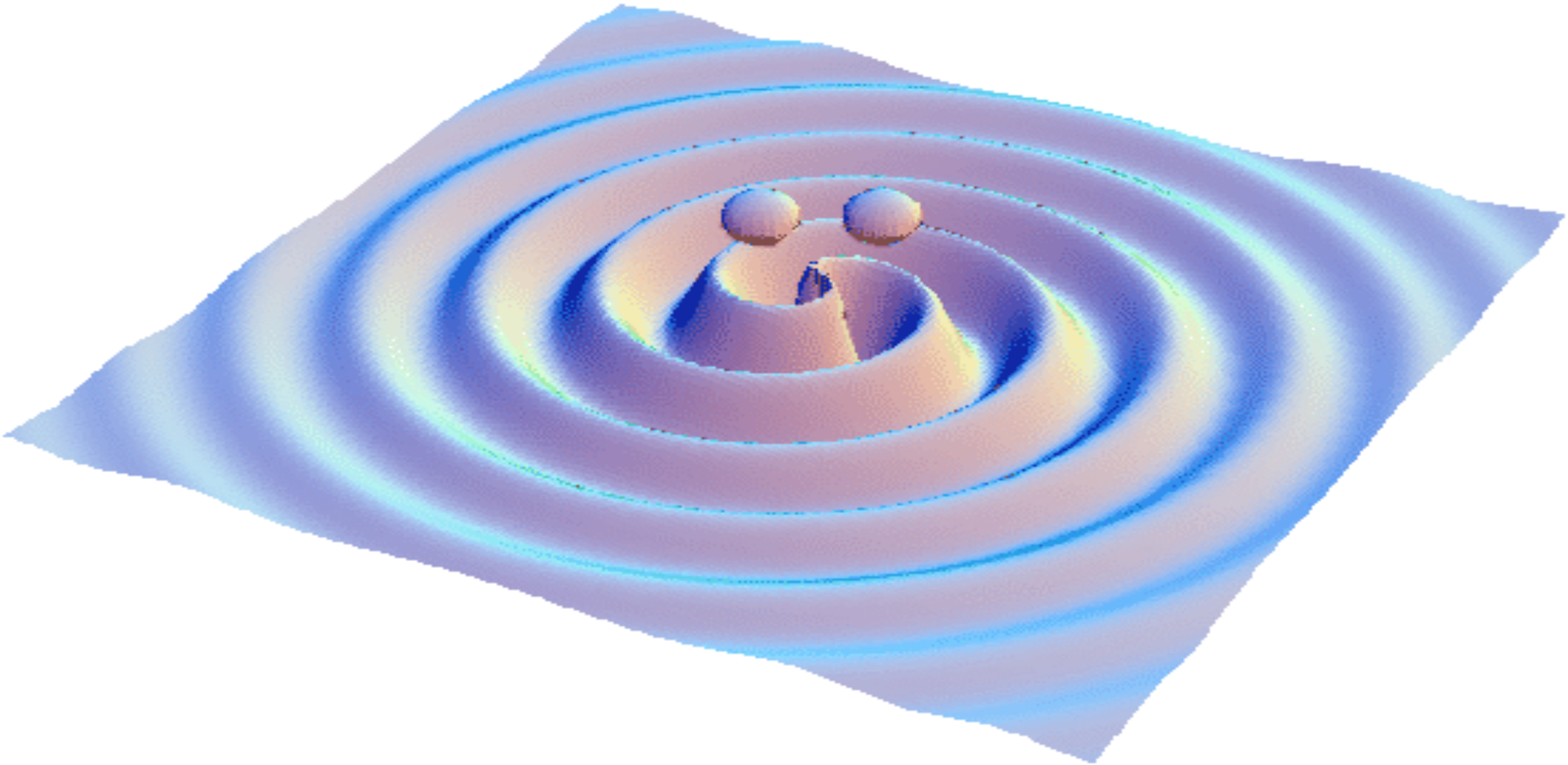



HDE 226868
Black Hole





Gravitational Waves



… and Gravitational Waves

• In the weak field limit, the field equation can be linearized. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$g_{\mu\nu} = g^{o}_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| << 1 \qquad (\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

• $h_{\mu\nu}$ takes the form of a plane wave propagating at the speed of light (c).

$$h_{\mu\nu} = h_{+}(t - z/c) + h_{x}(t - z/c)$$

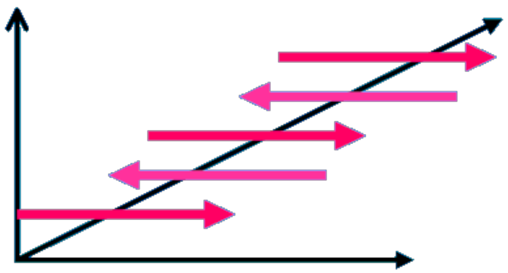
Spacetime perturbations, propagating in vacuum like waves, at the speed of light : gravitational waves

•Since gravity is spin 2, the waves have two components (polarizations), rotated by 45^0 (instead of 90^0, as e.m. waves) from each other.

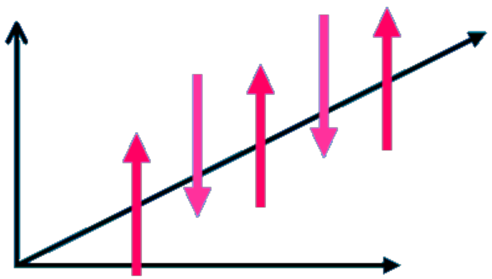
… and Gravitational Waves

Comparison with electromagnetic waves

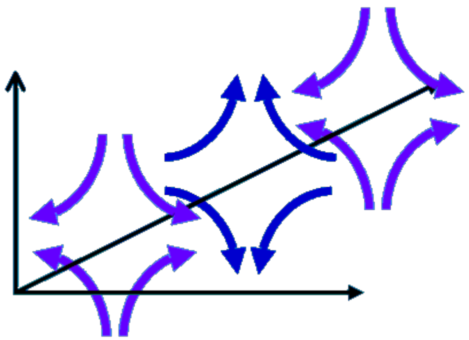
Horizontal polarization



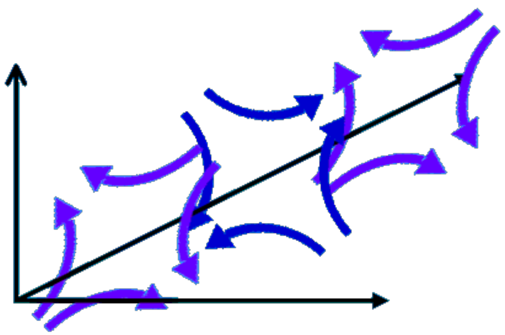
Vertical polarization



Plus polarization

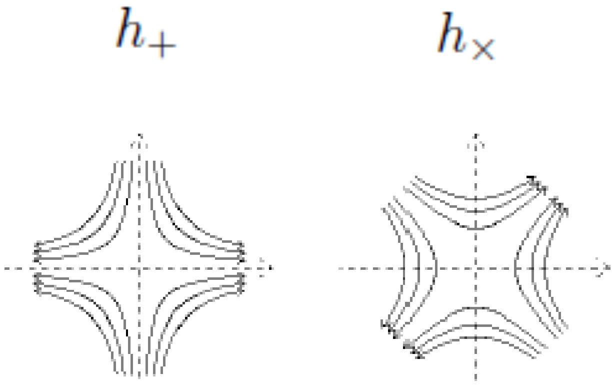


Cross polarization

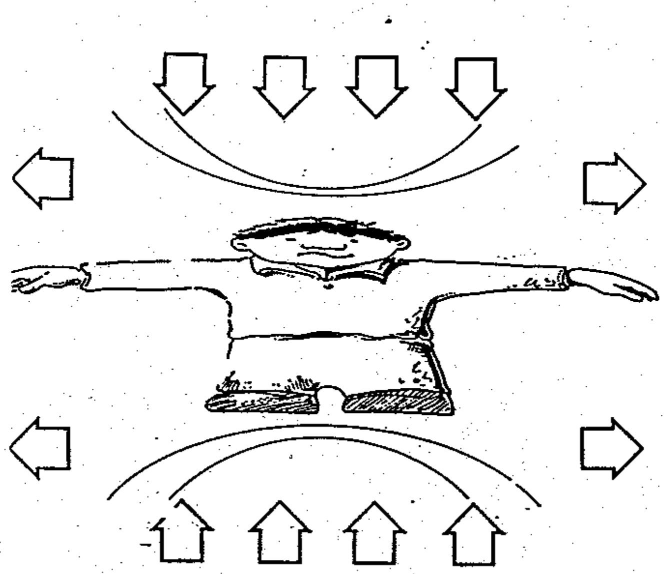


… and Gravitational Waves

$$h_{\mu\nu} = h_{+}(t - z/c) + h_{x}(t - z/c)$$

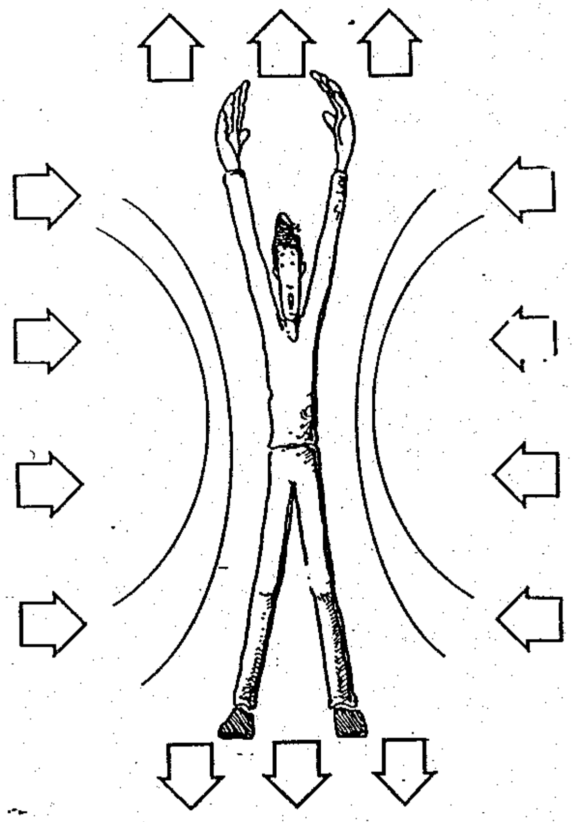


CAUTION: GRAVITATIONAL RADIATION

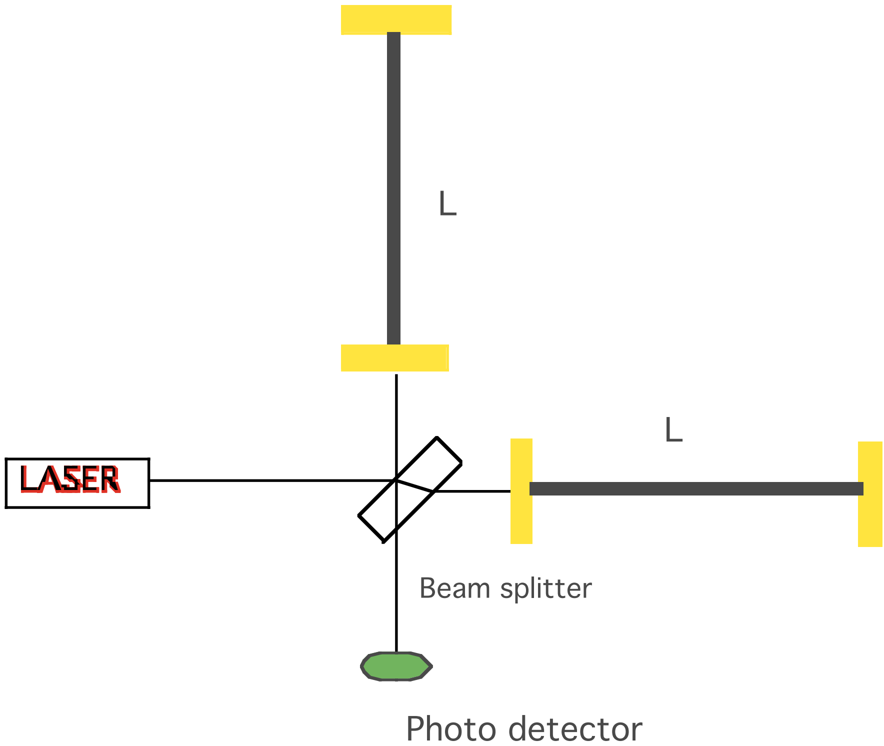


MAY BE DANGEROUS TO YOUR HEALTH

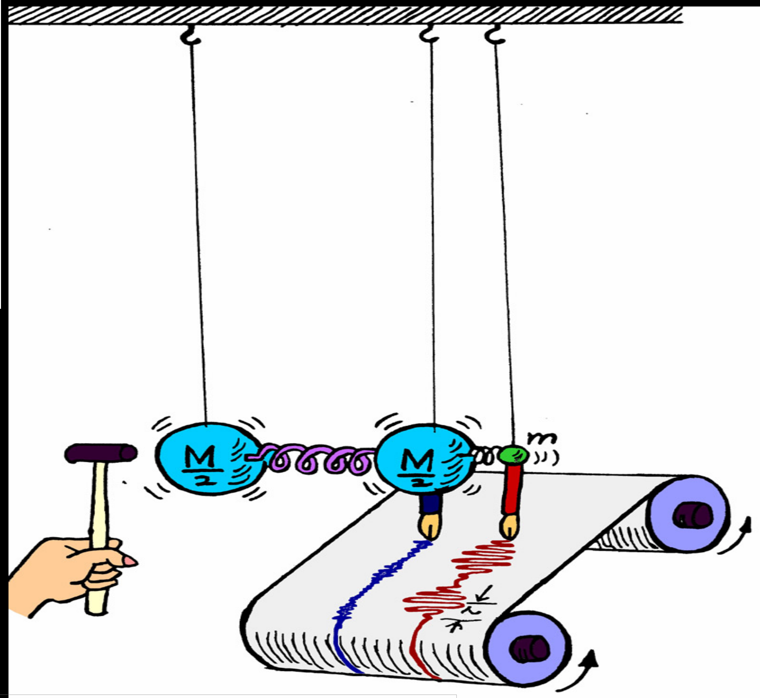
CAUTION: GRAVITATIONAL RADIATION



MAY BE DANGEROUS TO YOUR HEALTH



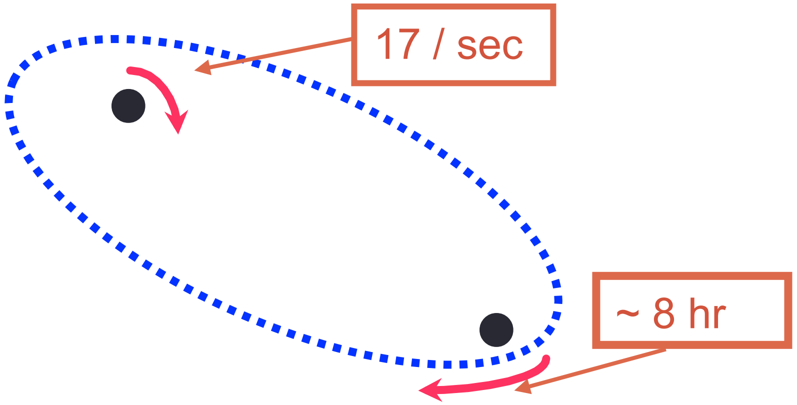
$$h = \frac{\Delta L}{L}$$



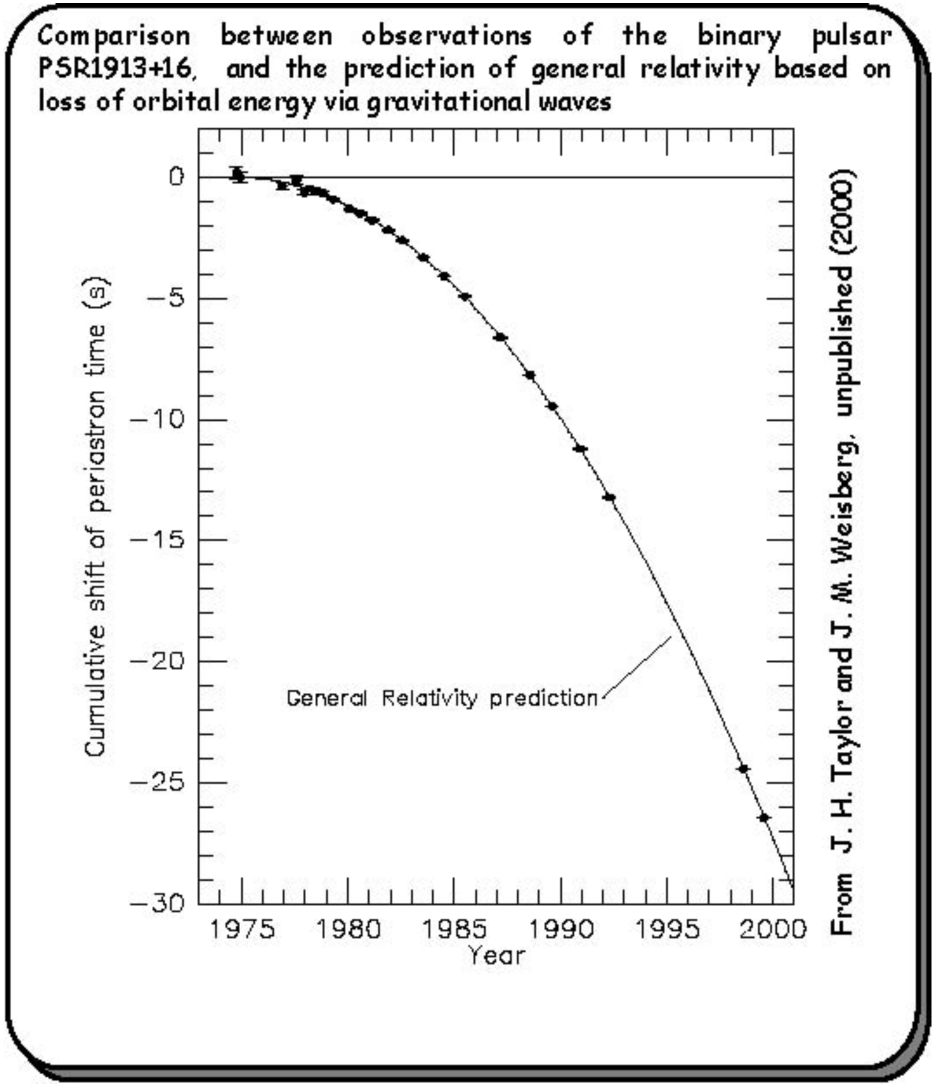
Impossibile visualizzare l'immagine. La memoria del computer potrebbe essere insufficiente per aprire l'immagine oppure l'immagine potrebbe essere danneggiata. Riavviare il computer e aprire di nuovo il file. Se viene visualizzata di nuovo la x rossa, potrebbe essere necessario eliminare l'immagine e inserirla di nuovo.

Indirect evidence for GWs: PSR 1913+16

Joseph Taylor Russell Hulse



They will merge in 300 million years



$dP_b/dt = -(2.40 \pm 0.01) \times 10^{-12}$ s/s

Advanced Virgo

The Binary Pulsar PSR 1913+16

Università di Roma Tor Vergata

INFN Istituto Nazionale di Fisica Nucleare

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release

13 October 1993

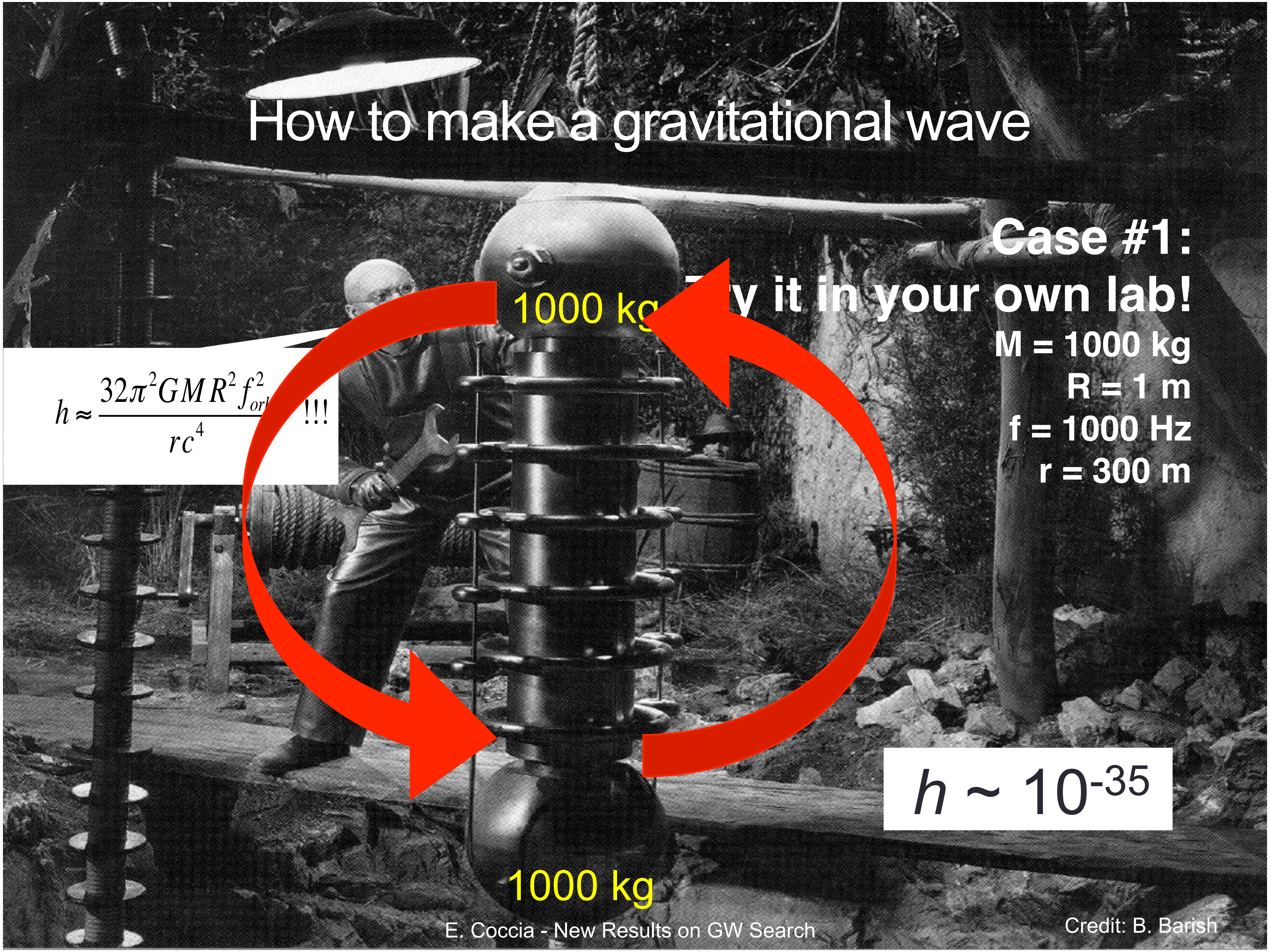
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize Physics for 1993 jointly to **Russell A. Hulse** and **Joseph H. Taylor, Jr**, both of Princeton University, New Jersey, USA **for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation**

Nobel Prize in 1983

Gravity investigated with a binary pulsar

The discovery rewarded with this year's Nobel Prize in Physics was made in 1974 by **Russell A. Hulse** and **Joseph H. Taylor, Jr** using the 300-m radiotelescope at Arecibo, Puerto Rico, West Indies. Taylor, then Professor at the University of Massachusetts, Amherst, and his research student Hulse were searching systematically for pulsars - a kind of rapidly rotating cosmic beacon with a mass somewhat greater than that of the sun and a radius of about ten kilometres. (A human being on the surface of a pulsar would weigh some hundred thousand million times more than on Earth.) The pulsar's "beacon light" is often within the radio wave region.

The first pulsar was discovered in 1967 at the radioastronomy laboratory in Cambridge, England (Nobel Prize 1974 to Antony Hewish). What was new about the Hulse-Taylor pulsar was that, from the behaviour of the beacon signal, it could be deduced that it was accompanied by an approximately equally heavy companion at a distance corresponding to only a few times the distance of the moon from the earth. The behaviour of this astronomical system deviates greatly from what can be calculated for a pair of heavenly bodies using Newton's theory. Here a new, revolutionary "space laboratory" has been obtained for testing Einstein's general theory of relativity and alternative theories of gravity. So far, Einstein's theory has passed the tests with flying colours. Of particular interest has been the possibility of verifying with great precision the theory's prediction that the system should lose energy by emitting gravitational waves in about the same way that a system of moving electrical charges emits electromagnetic waves.


How to make a gravitational wave
Case #1:
Try it in your own lab!
M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m
$h \approx \frac{32\pi^2 G M R^2 f_{orb}^2}{r c^4}$!!!
1000 kg
1000 kg
$h \sim 10^{-35}$
E. Coccia - New Results on GW Search
Credit: B. Barish

How to make a gravitational wave that might be detectable

- Consider 1.4 solar mass binary neutron star pair

  $M = 1.4\ M_\odot$

  $R = 20$ km

  $f = 400$ Hz

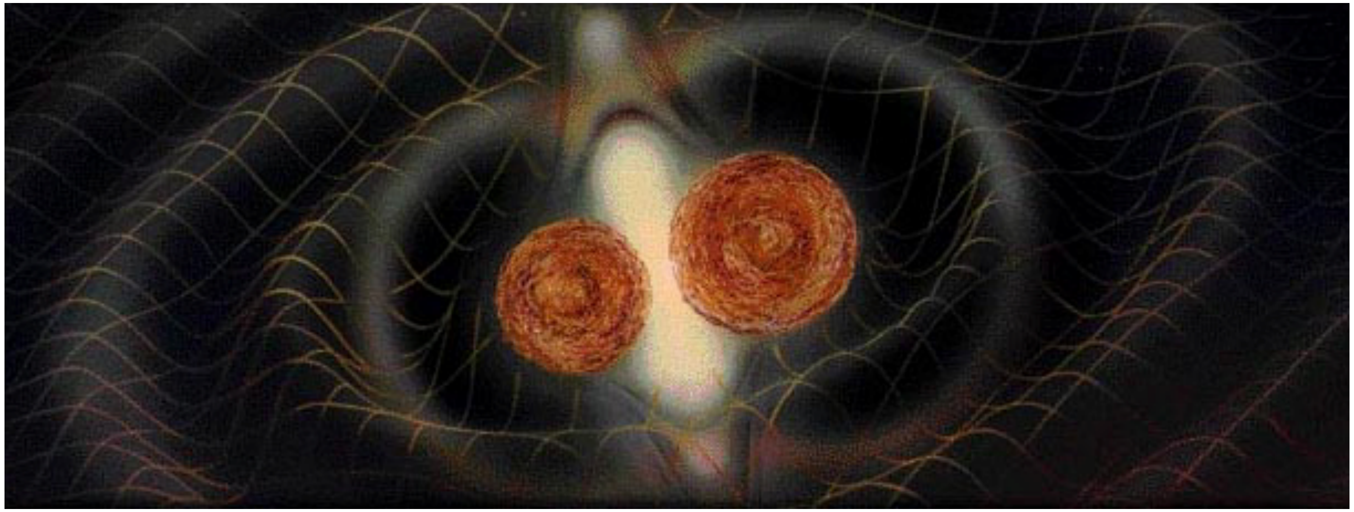
  $r = 5\ 10^{23}$ m (15Mpc)

$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

Credit: T. Strohmayer and D. Berry

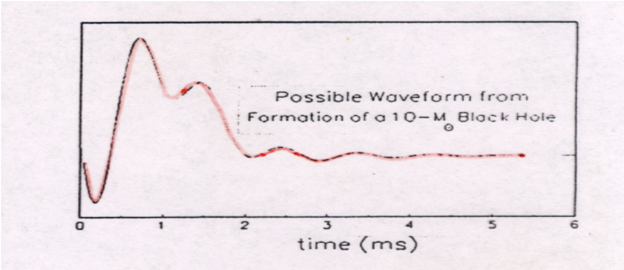
Gravitational radiation is a tool for astronomical observations

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



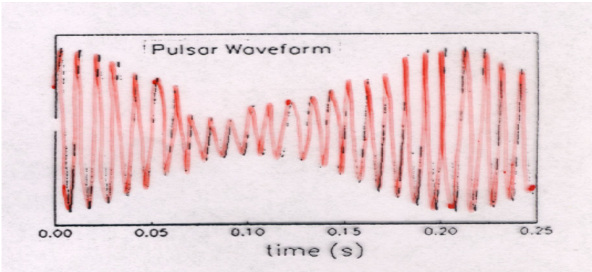
- GWs are emitted by coherent acceleration of large portion of matter

- GWs cannot be shielded and arrive to the detector in pristine condition



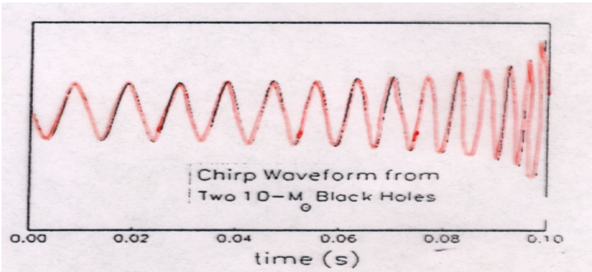
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density



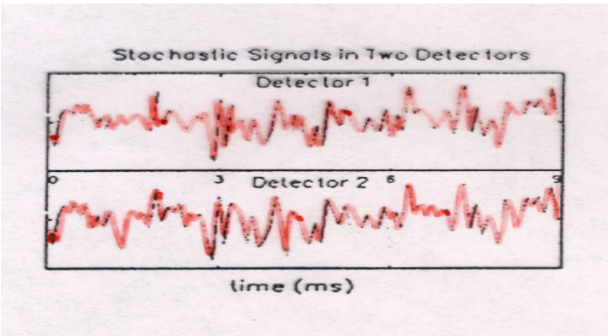
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution



COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

Una immagine di Joseph Weber, pioniere della ricerca delle onde gravitazionali, intento ad incollare le ceramiche piezoelettriche su una delle prime antenne a temperatura ambiente.

Weber started seeing things

In 1969, Weber made his first of many announcements that he was seeing coincident excitations of two detectors.

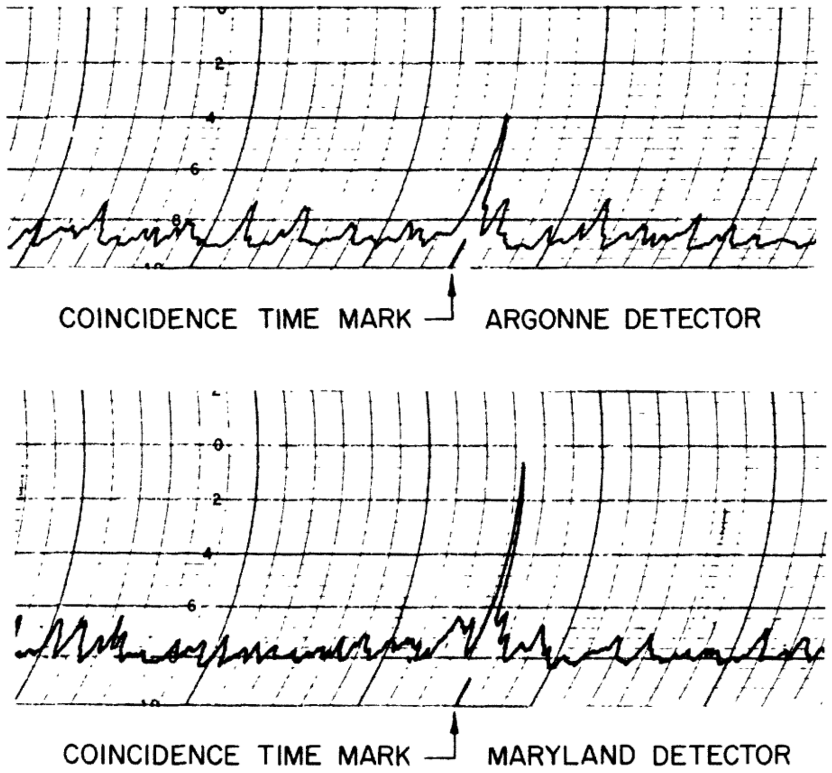


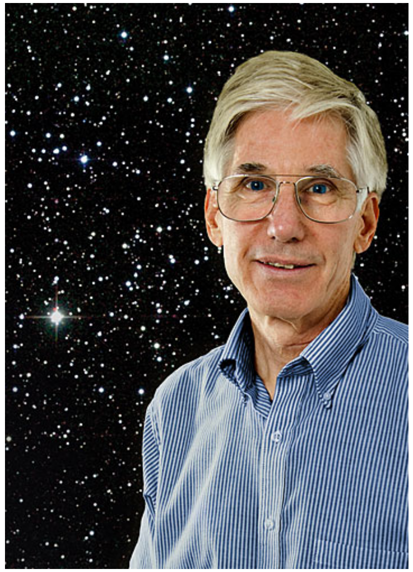
FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

Joining the quest …

Ron Drever and Jim Hough, Glasgow

Guido Pizzella, Rome

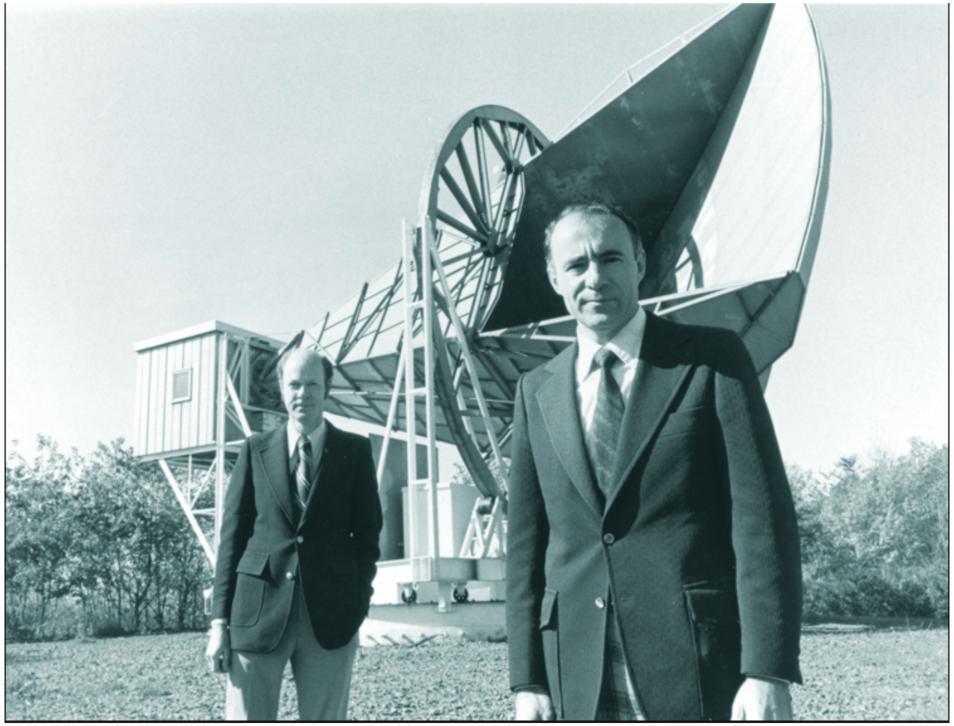
Richard Garwin, IBM



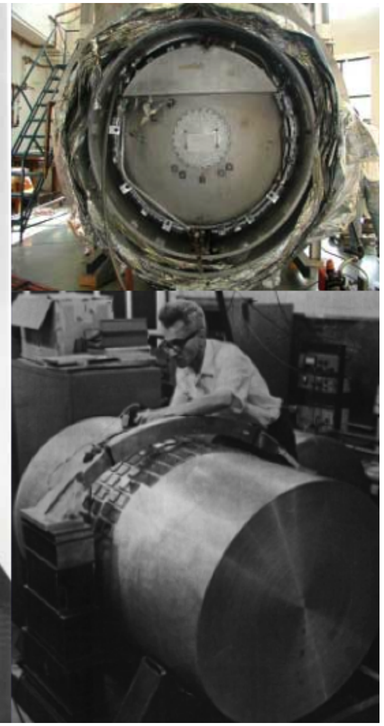
Tony Tyson, Bell Labs

During the sixties Amaldi tried to push the Italian physicists in the direction of new researches in the birth phase:

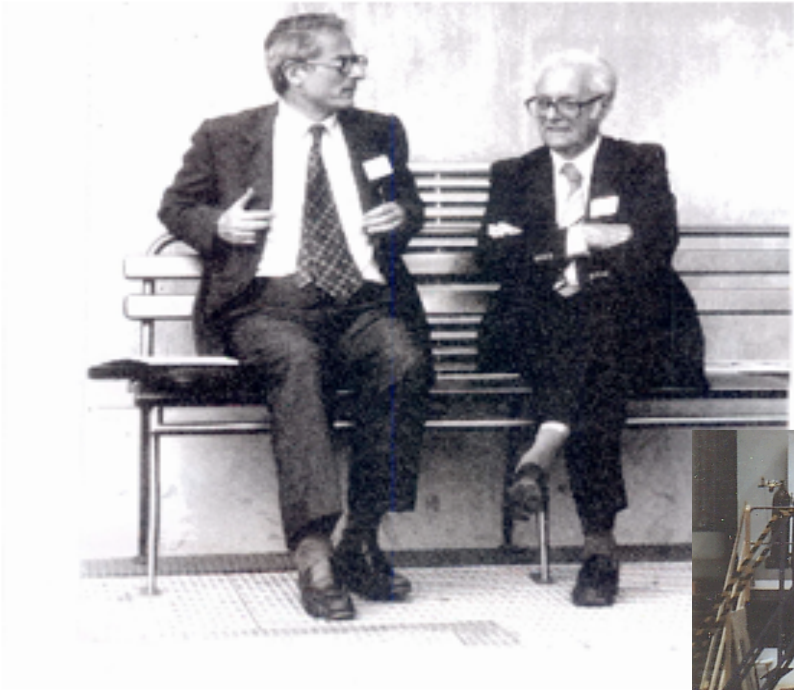
Infrared Background radiation and Gravitational Waves (after Penzias & Wilson and Weber's experiments).



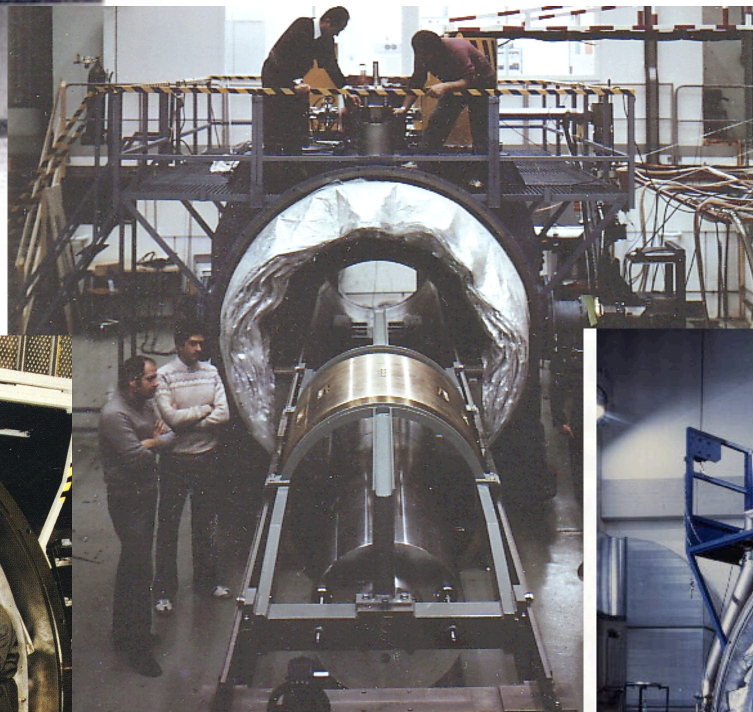
Joseph Weber 1919-2000



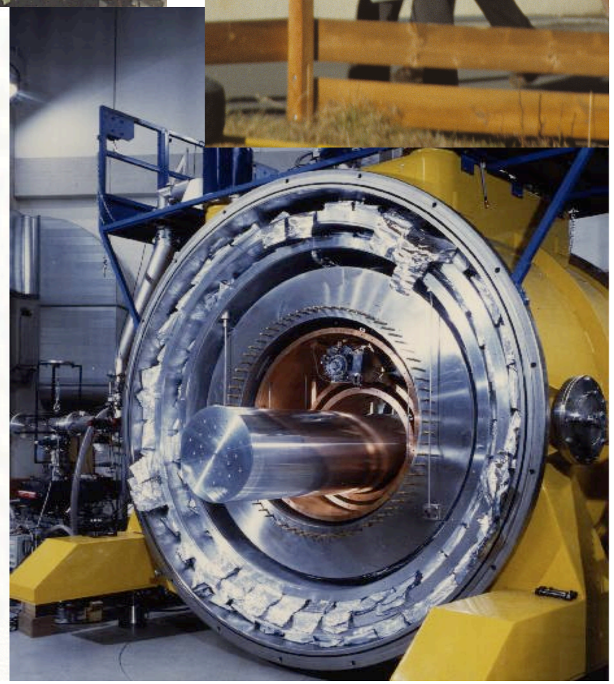
Guido Pizzella was Amaldi’s assistant and wanted to change its activity from space research (he worked with Van Allen in USA) to a more fundamental field. His decision was: Gravitational Waves (Francesco Melchiorri later choose the infrared background).



Nautilus, LNF



Explorer, CERN

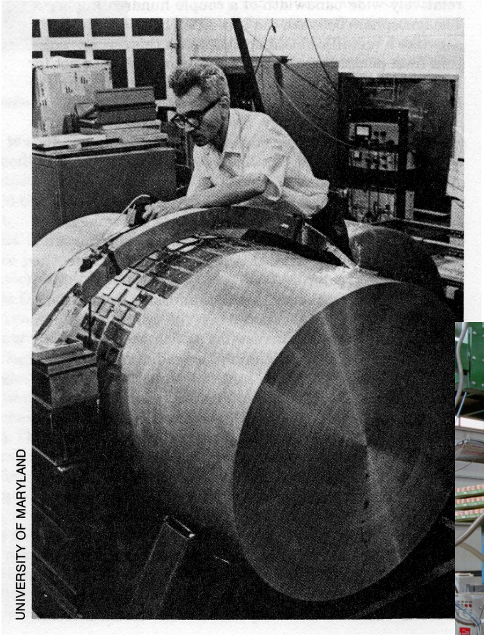


Auriga, LNL

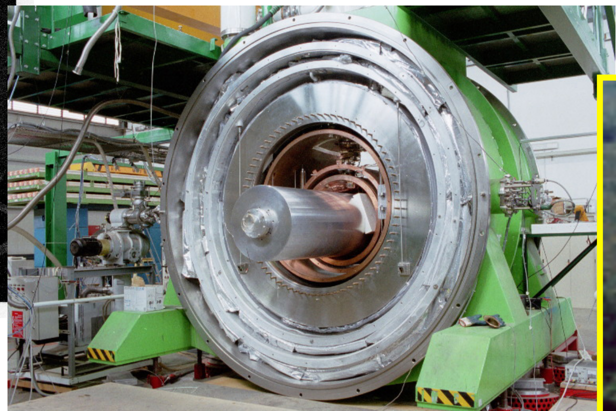
1988

Some perspective: 50 years of attempts at detection:

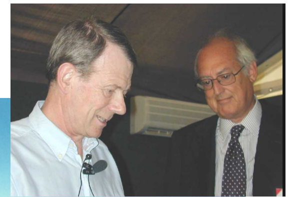
Since the pioneering work of Joseph Weber in the ‘60, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



60’: Joe Weber pioneering work

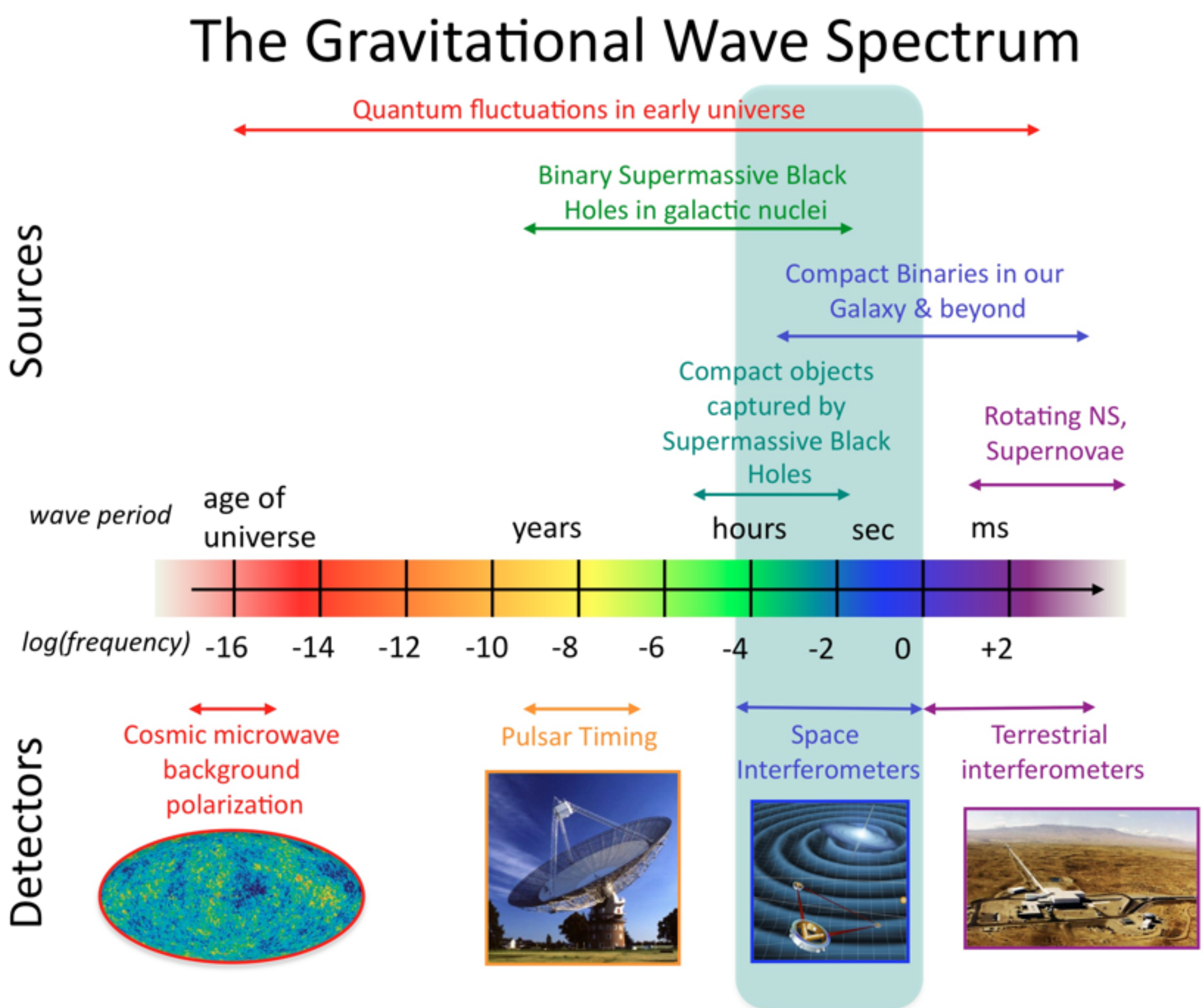


90’: Cryogenic Bars



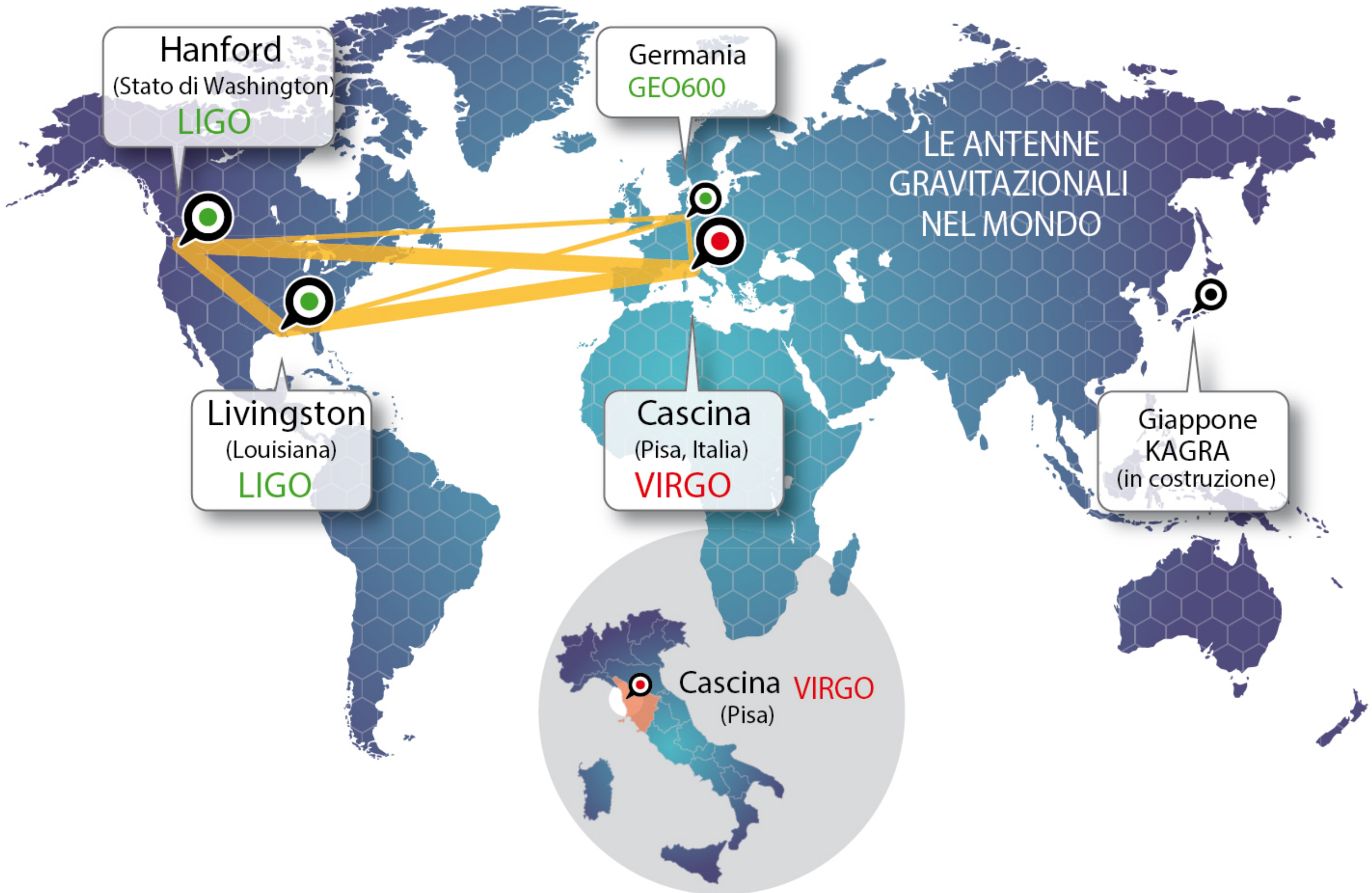
2000’ - : Large Interferometers

1997: GWIC was formed



The Gravitational Wave Spectrum
Sources
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

Global Network of Detectors



LIGO Scientific Collaboration

www.ligo.org

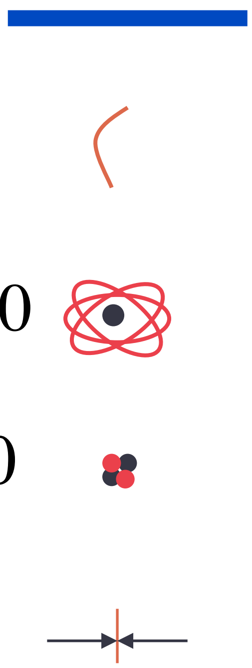
900+ members, 80+ institutions, 16 countries

Virgo Collaboration

- 5 European countries, 19 labs, ~250 members
- Scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary

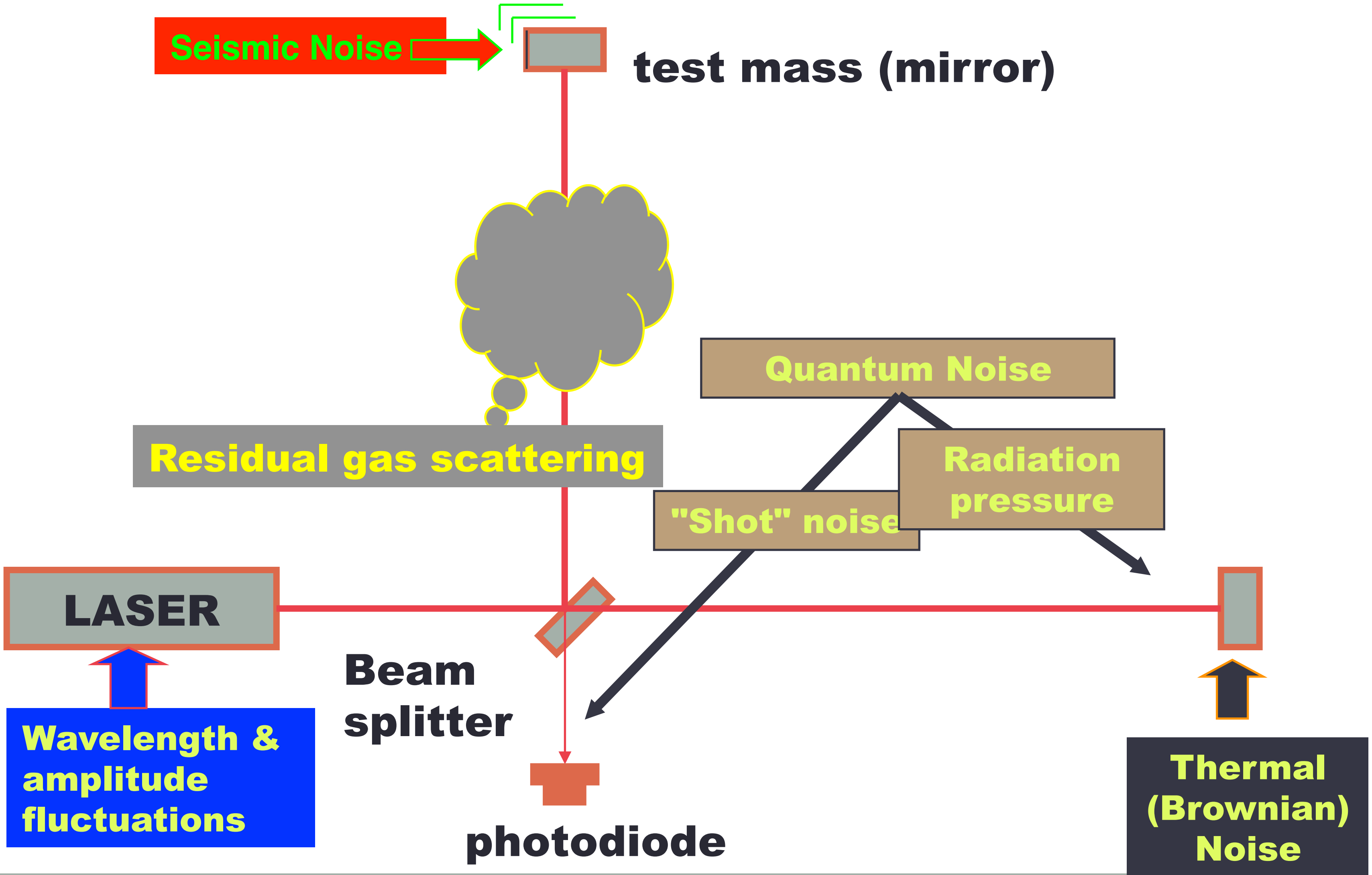
APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RADBOUD Uni. Nijmegen
RMKI Budapest

How Small 10^{-18} meter is?



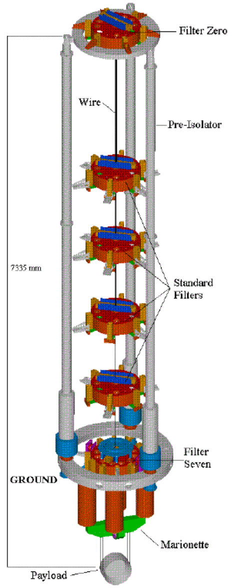
- **One meter**
- ÷10,000 — **Human hair ~ 10^{-4} m (0.1 mm)**
- ÷1,000,000 — **Atomic diameter 10^{-10} m**
- ÷100,000 — **Nuclear diameter 10^{-15} m**
- ÷1,000 — **GW detector 10^{-18} m**

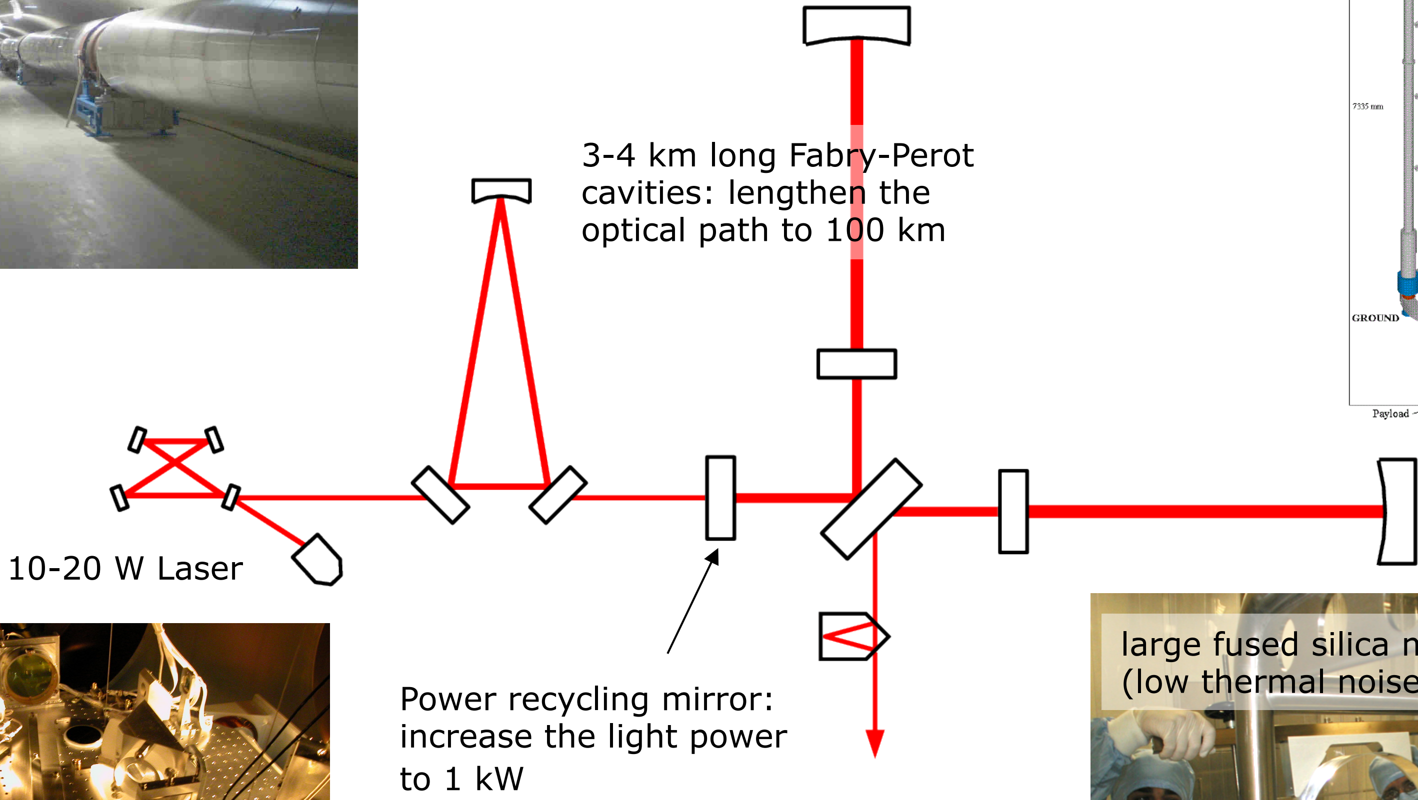
Interferometer Noise Limits

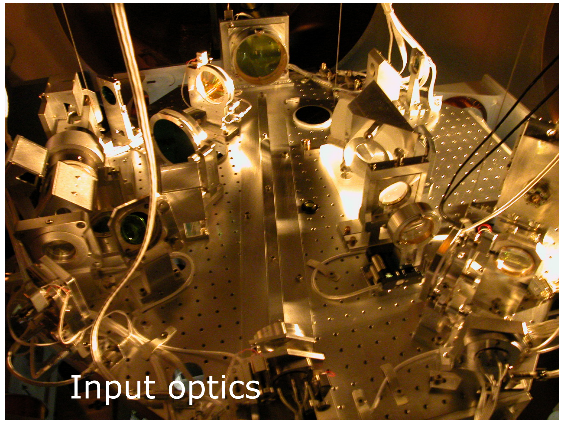


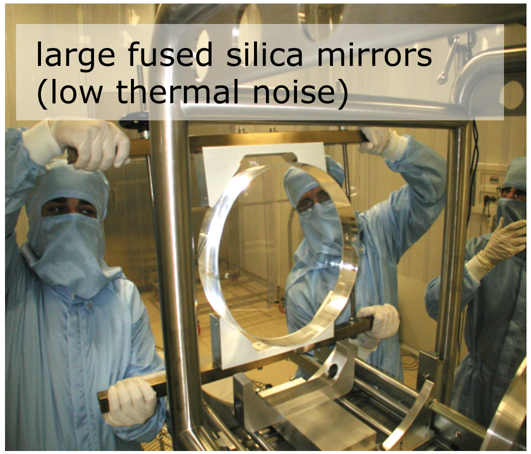
A real detector scheme

Isolation from ground vibrations

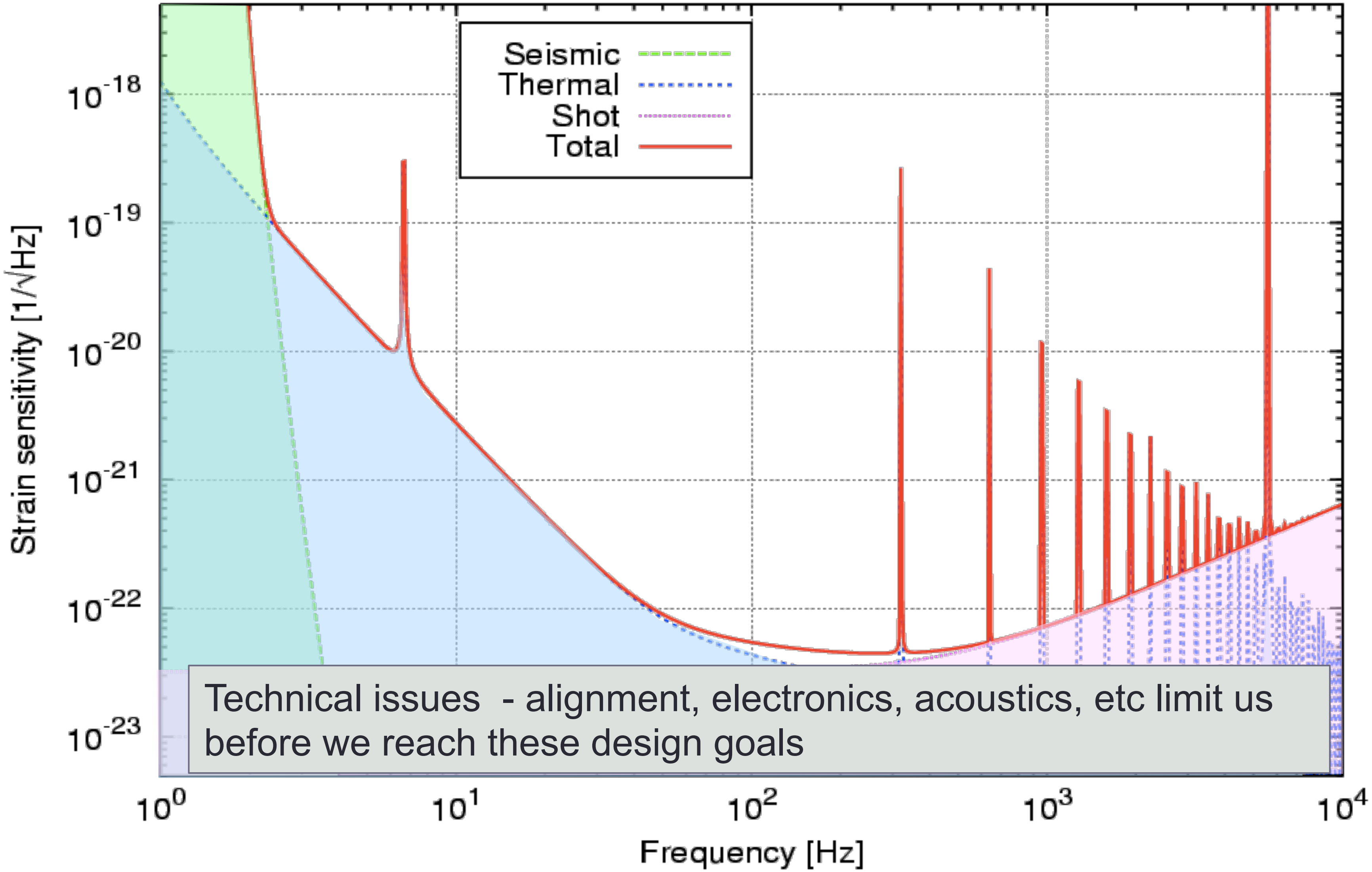






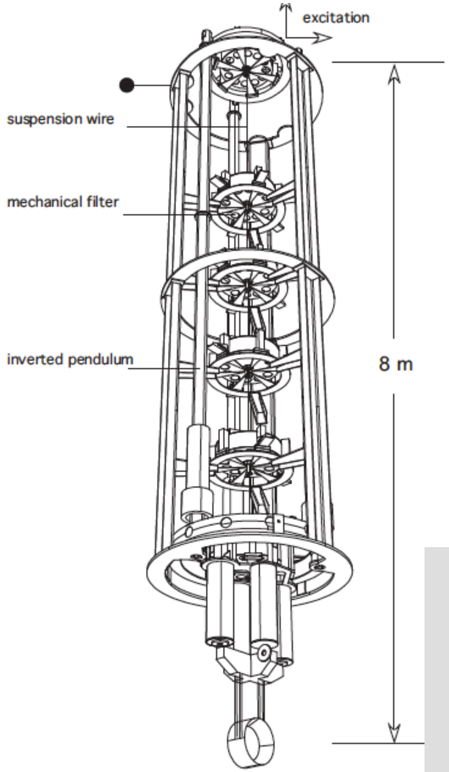


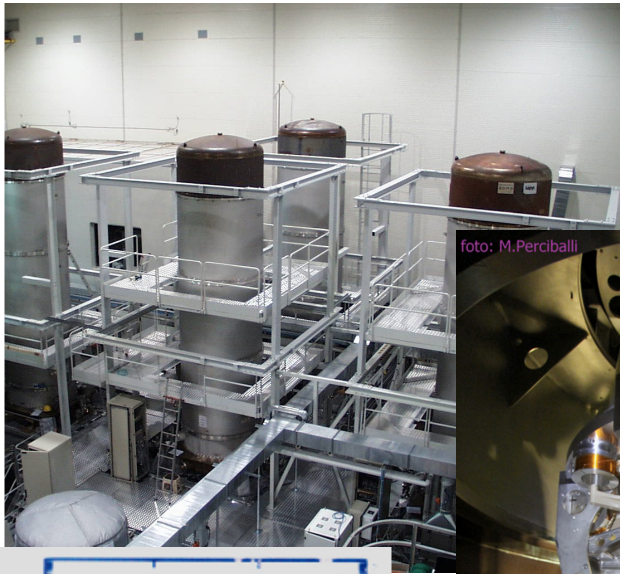
Sensitivity

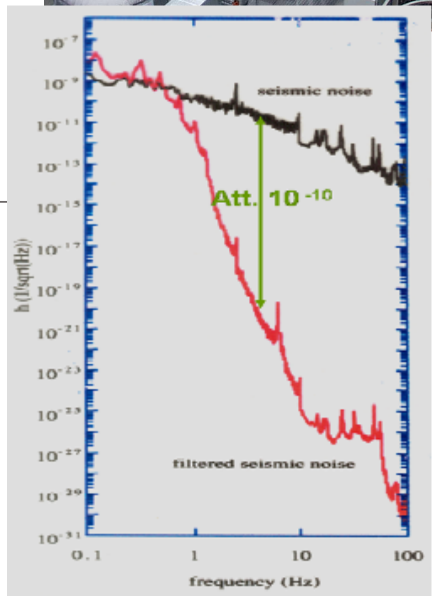


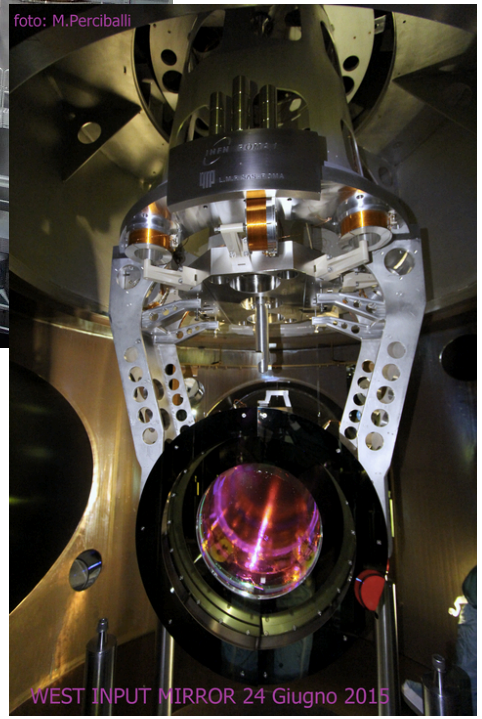
Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

Vibration isolation system



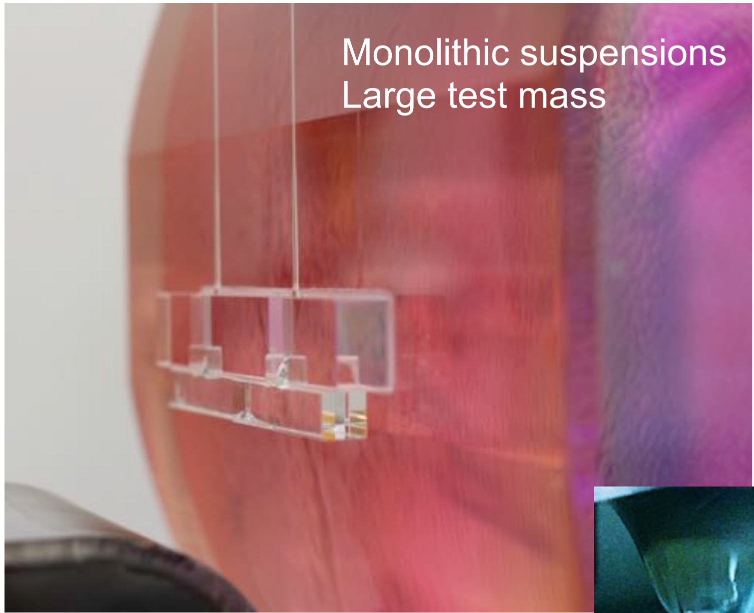


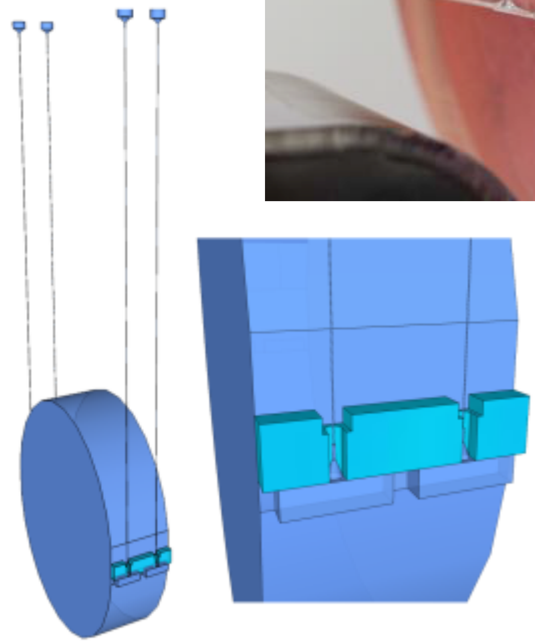


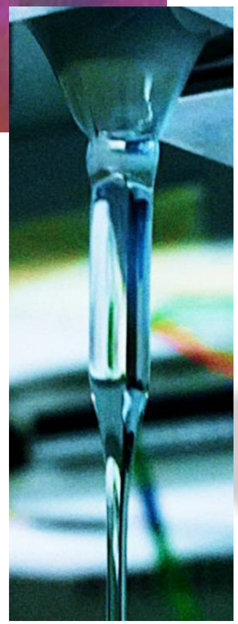


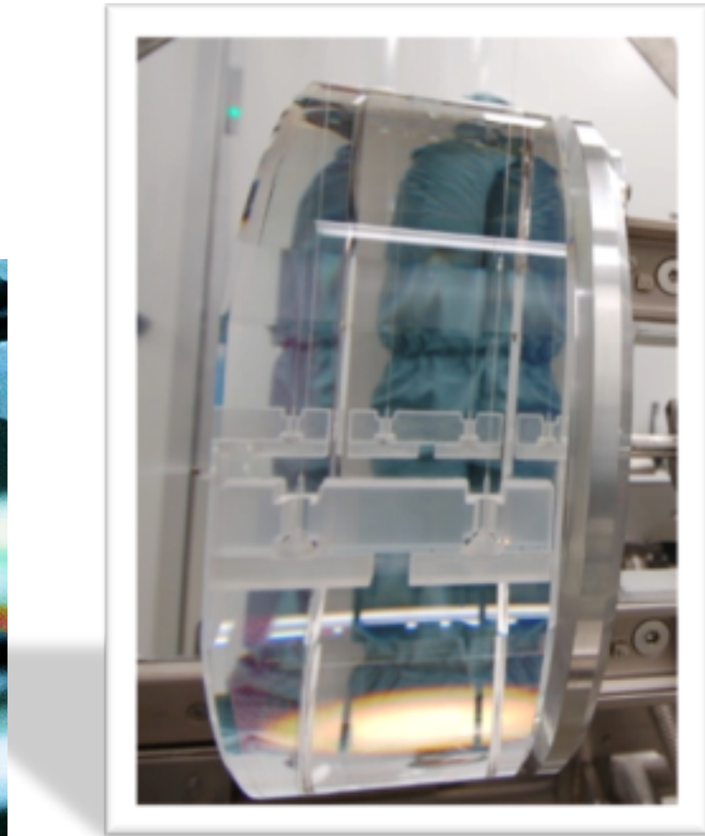
Reduce in-band seismic motion by 10 orders of magnitude

Monolithic suspension

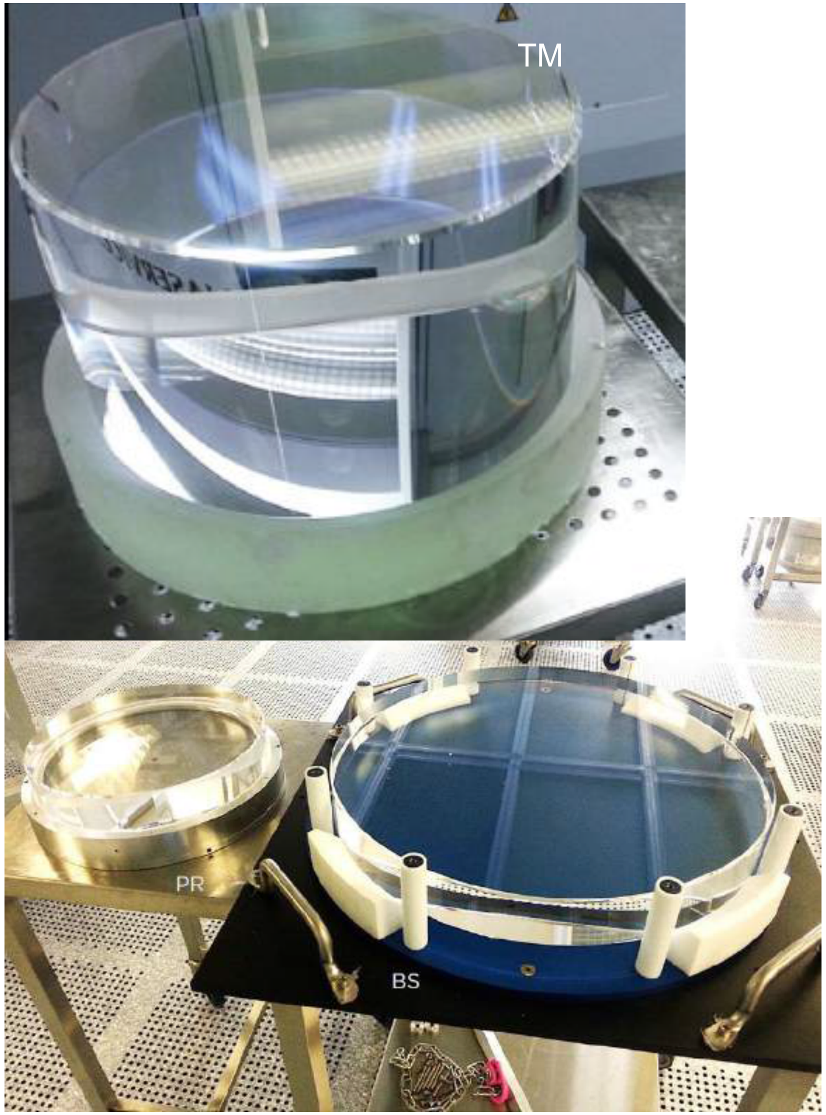




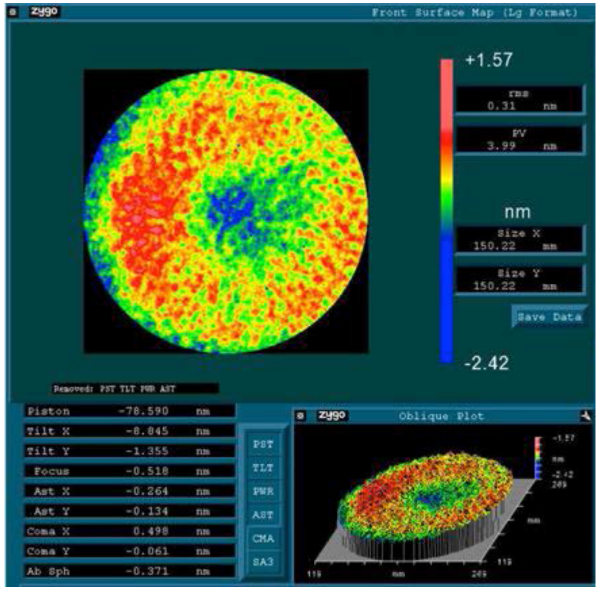




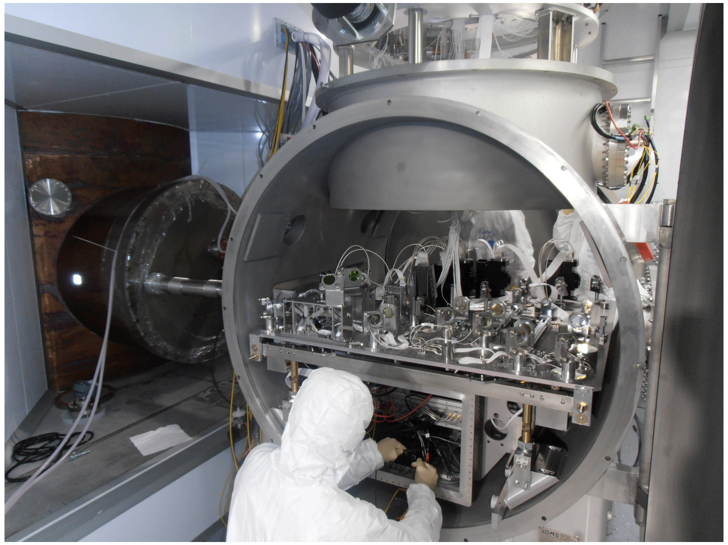
Mirrors



- Surface uniformity < 0.2 nm rms
- Scatter < 50 ppm
- Absorption < 0.2 ppm
- Internal mode Q's > 2 x 10^6

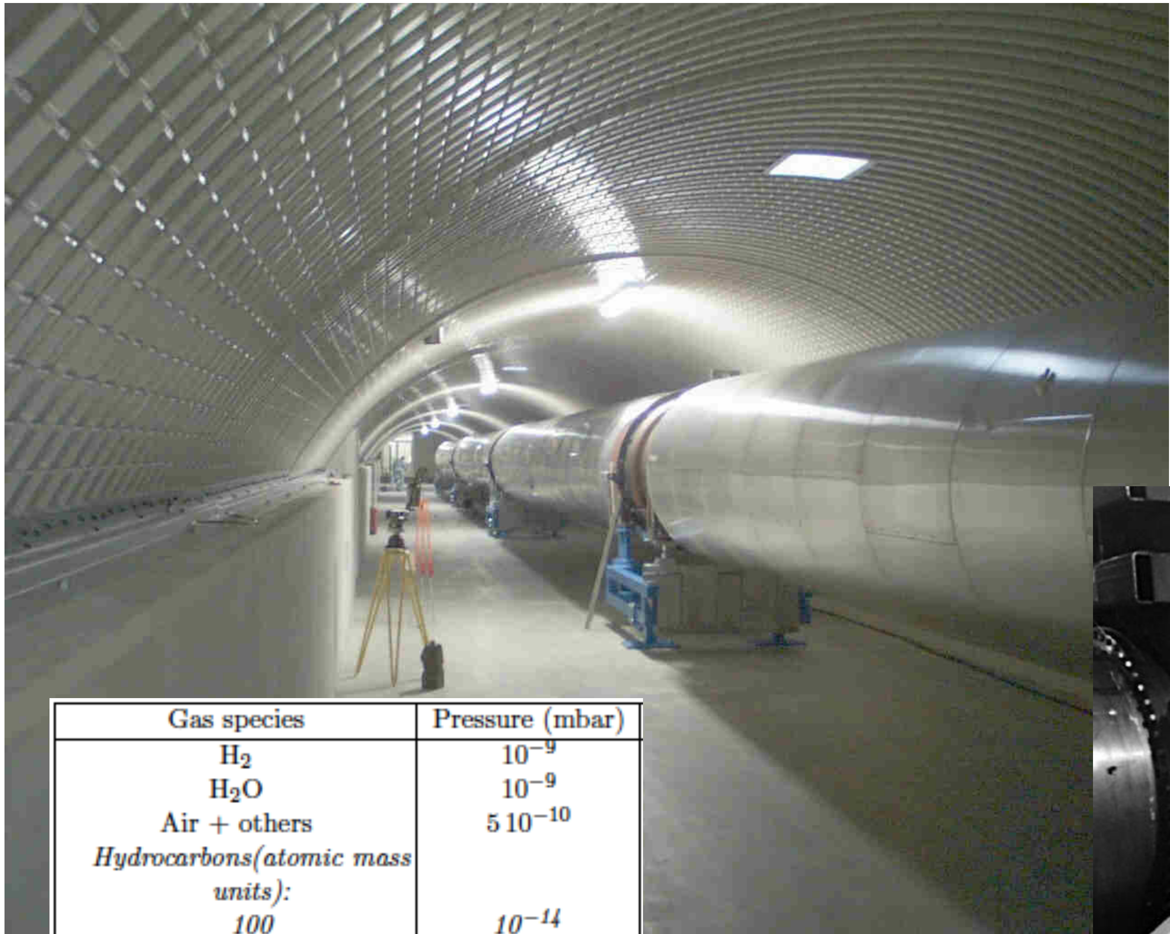


High precision optical systems



Virgo vacuum system

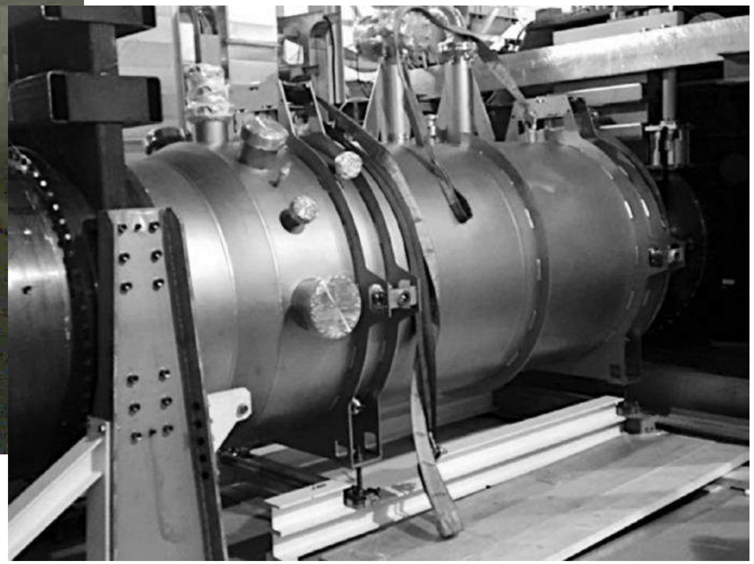
Largest ultra-high-vacuum system in Europe



Gas species	Pressure (mbar)
H_2	10^{-9}
H_2O	10^{-9}
Air + others	$5\,10^{-10}$
Hydrocarbons(atomic mass units):	
100	10^{-14}
300	
500	
Total	$2.5\,10^{-9}$

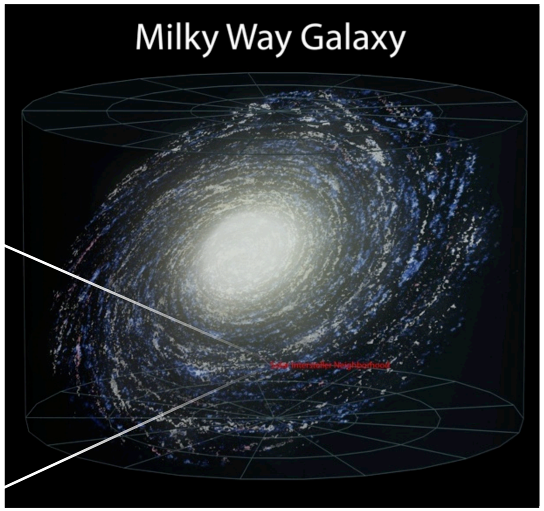
Pressures required for Advanced Virgo

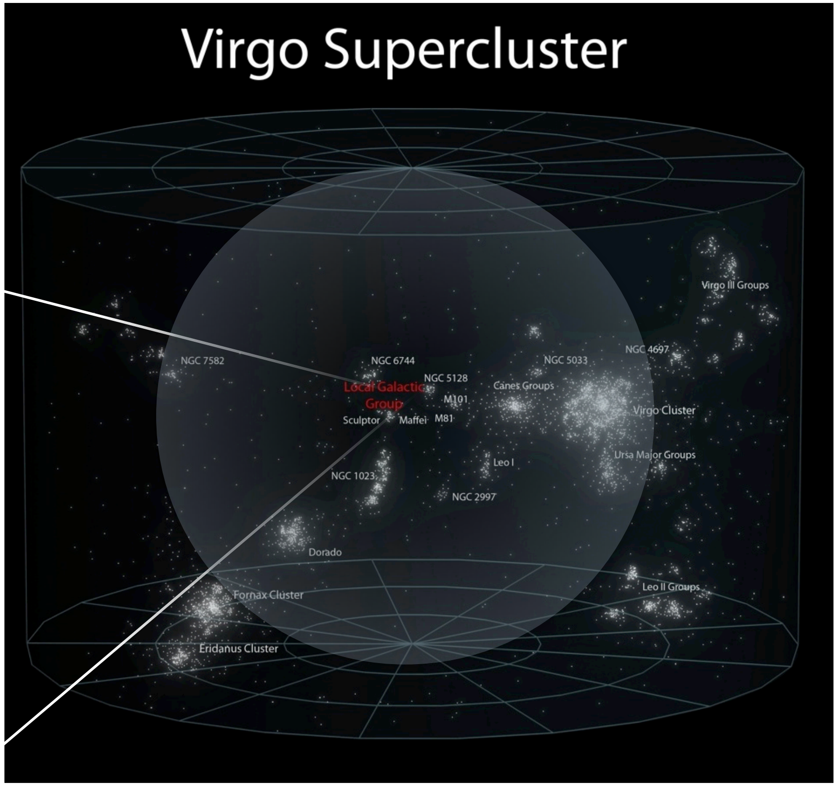
Liquid Nitrogen cryotraps



First generation detectors

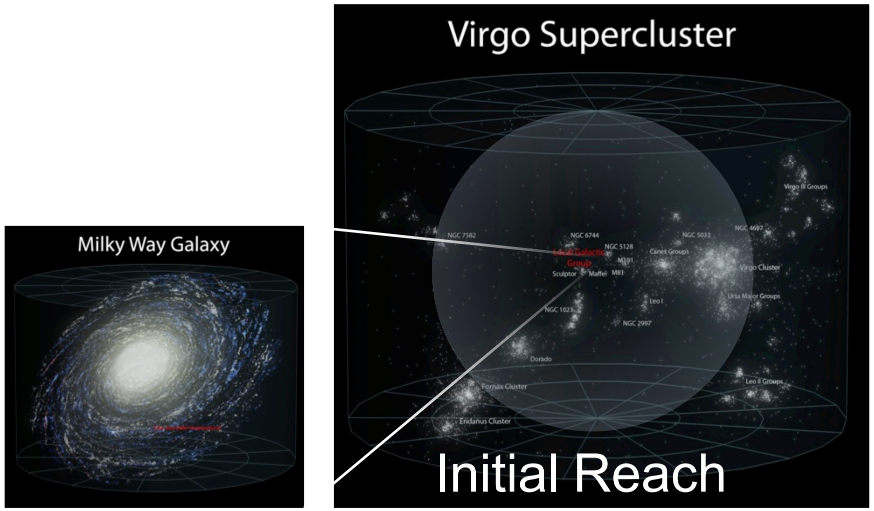
- First generation detectors and infrastructure built from mid-’90s to mid-2000; commissioned to design sensitivity; and observed for several years
- In case of NS-NS coalescence:
  - Sensitivity sufficient to reach about 100 galaxies; however…
  - Expected rate is low: events happen once every 10,000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

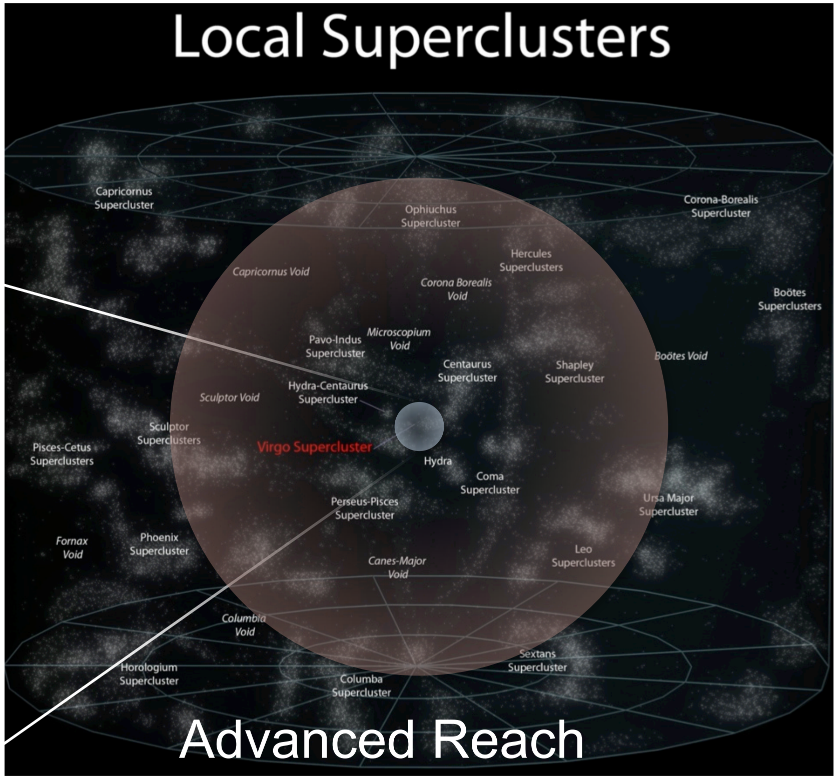




Advanced Detectors Sensitivity: a *qualitative* difference

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

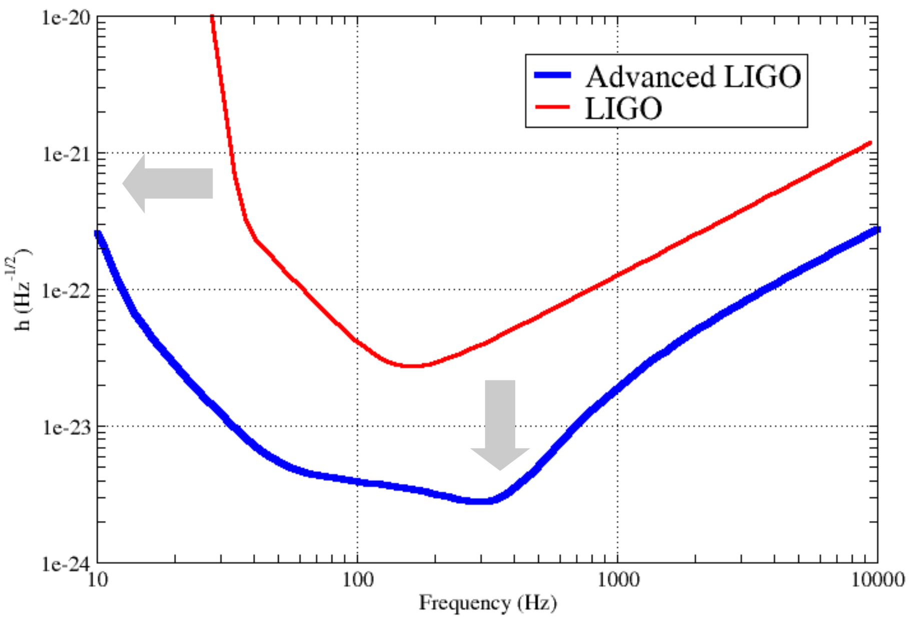


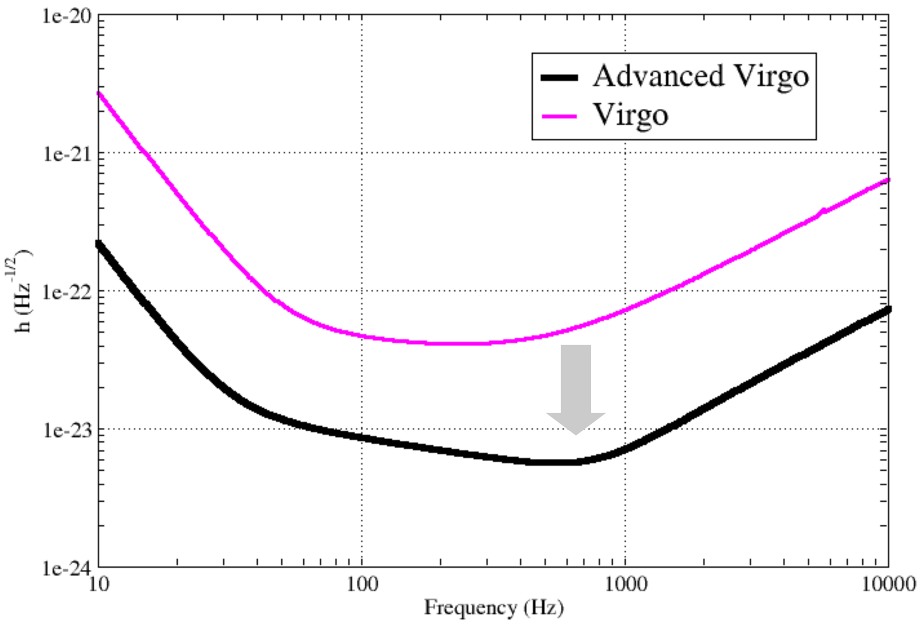


Advanced LIGO / Advanced Virgo

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

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

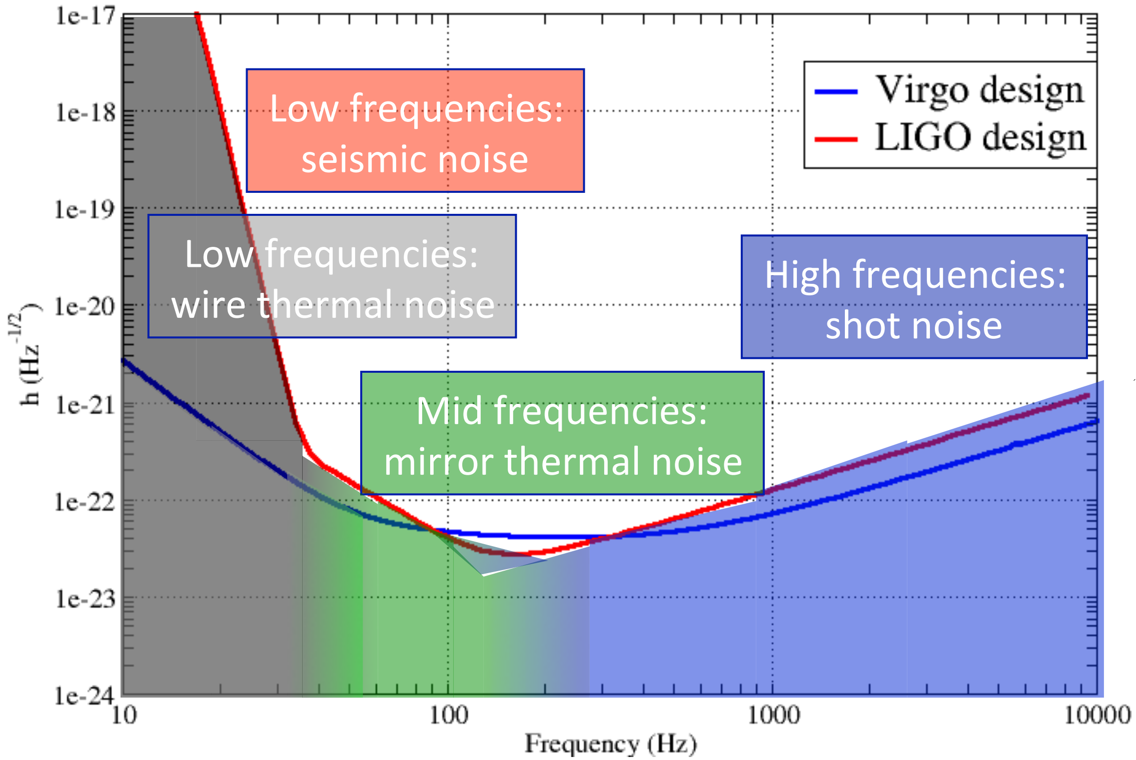


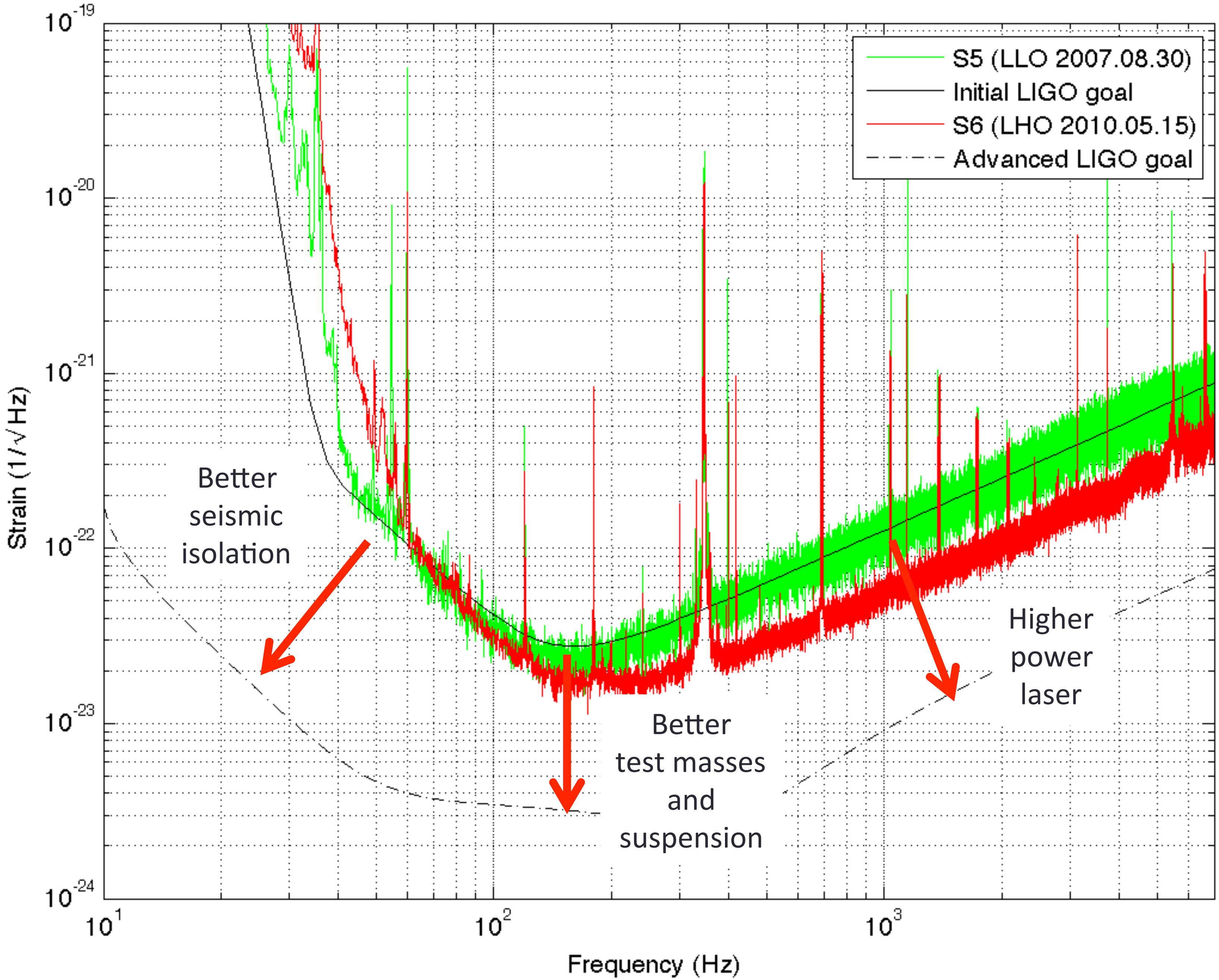


Achieving the Sensitivity Goal

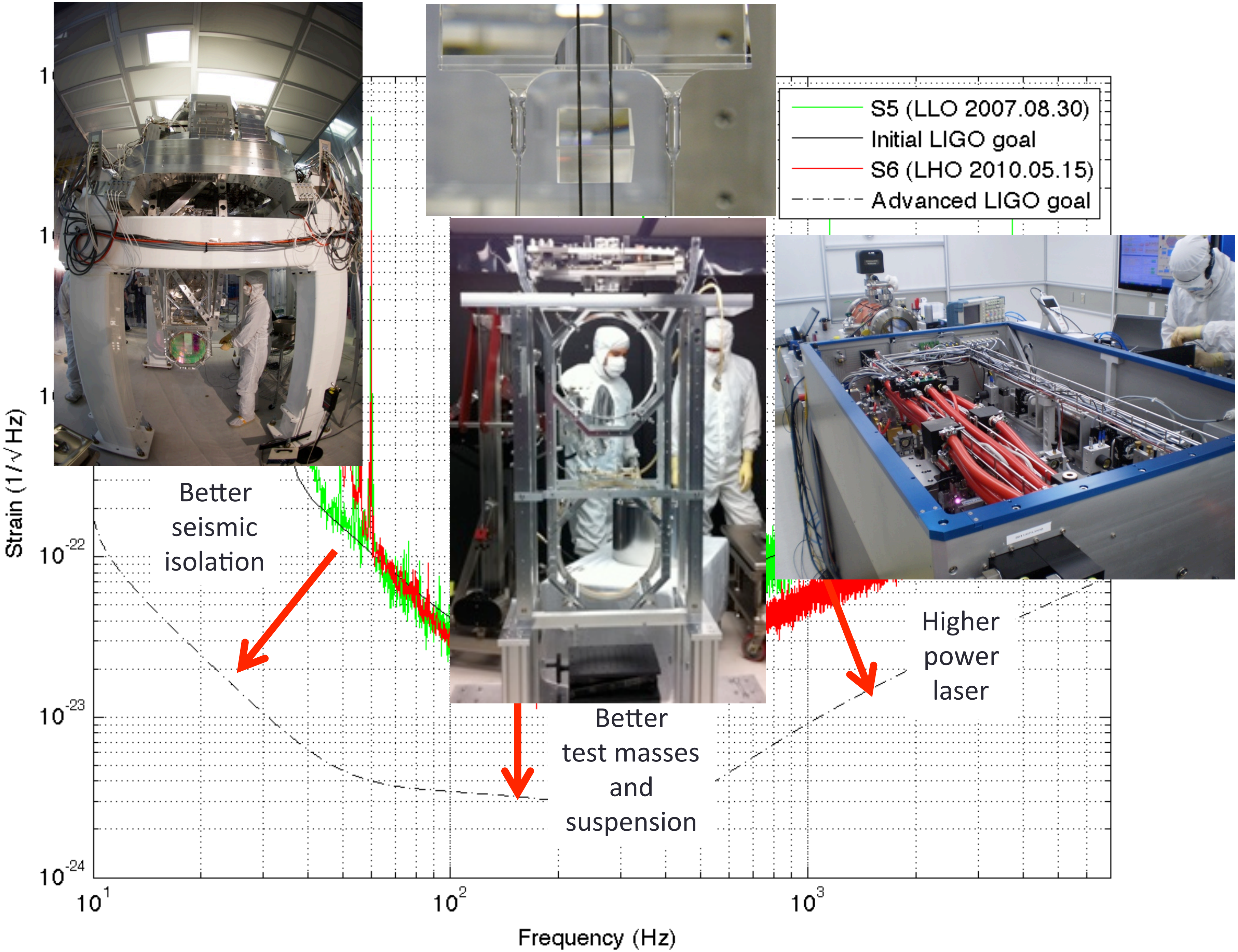
Achieving a sensitivity 10x better is ambitious.

Act on different noise sources: new ideas and a wide R&D program have been necessary





S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Better seismic isolation
Better test masses and suspension
Higher power laser



S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
10^-22
10^-23
10^-24
10^1
10^2
10^3
Frequency (Hz)
Better seismic isolation
Better test masses and suspension
Higher power laser

The Discovery Paper

Observation of Gravitational Waves from a Binary Black Hole Merger

The LIGO Scientific Collaboration and The Virgo Collaboration

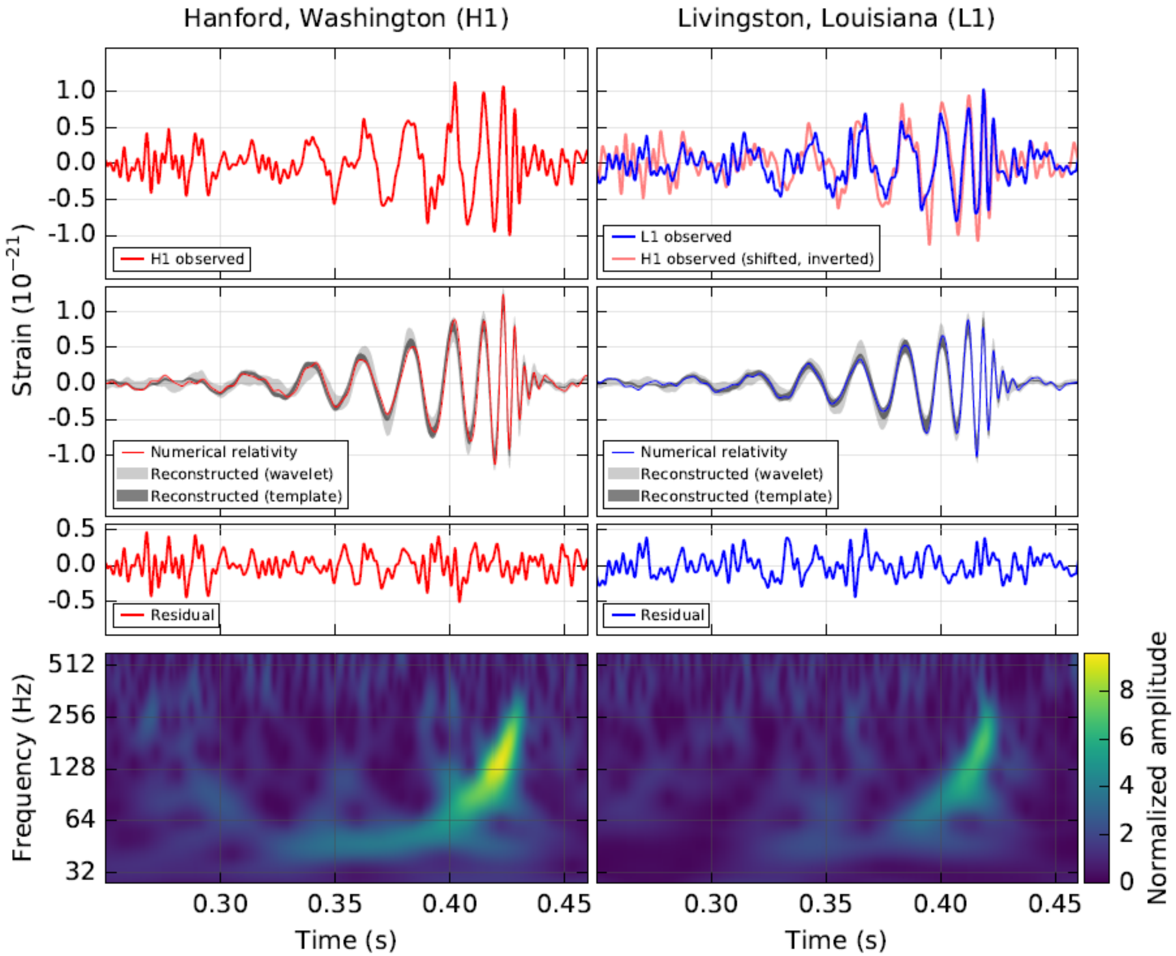
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 Hz to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than $5.1\,\sigma$. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}\,\mathrm{M}_\odot$ and $29^{+4}_{-4}\,\mathrm{M}_\odot$, and the final black hole mass is $62^{+4}_{-4}\,\mathrm{M}_\odot$, with $3.0^{+0.5}_{-0.5}\,\mathrm{M}_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

Phys. Rev. Lett. 116, 061102 – Published 11 February 2016

GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)

September 14th, 2015 at 09:50:45 UTC

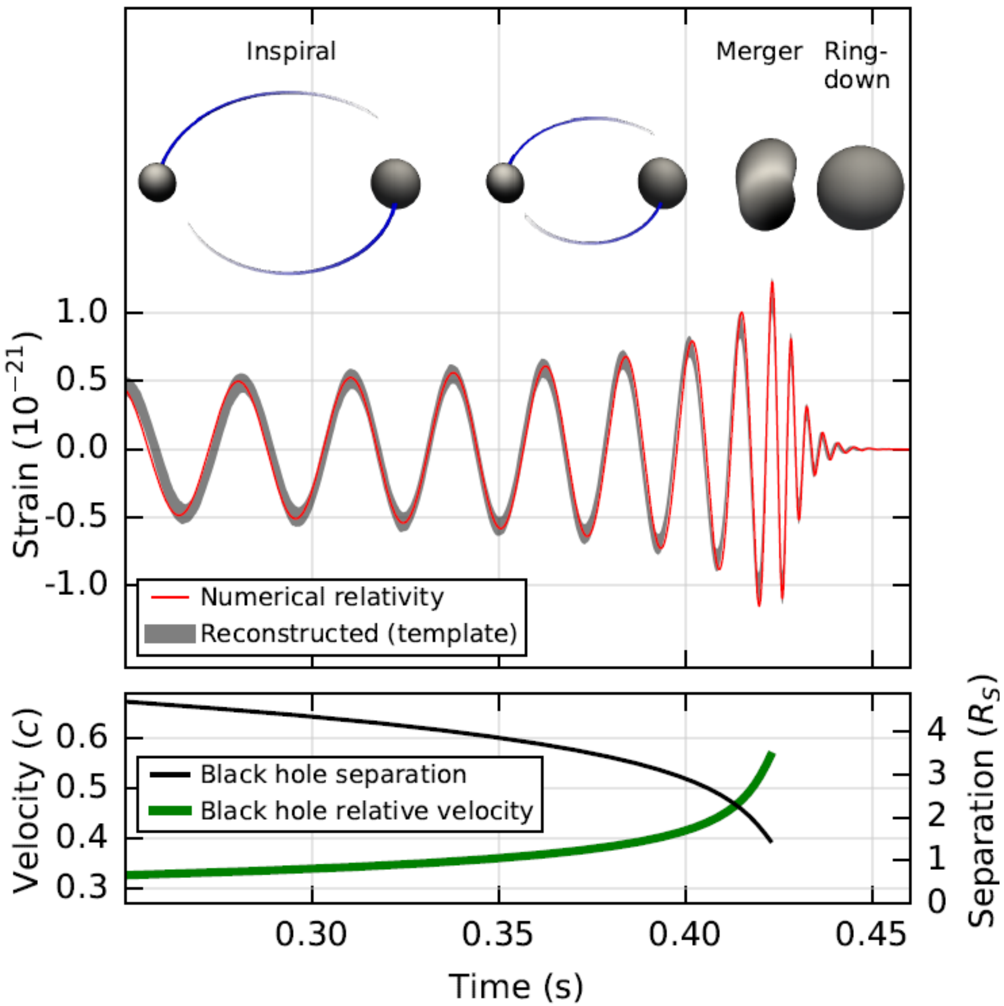


GW150914: Estimated Strain Amplitude

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

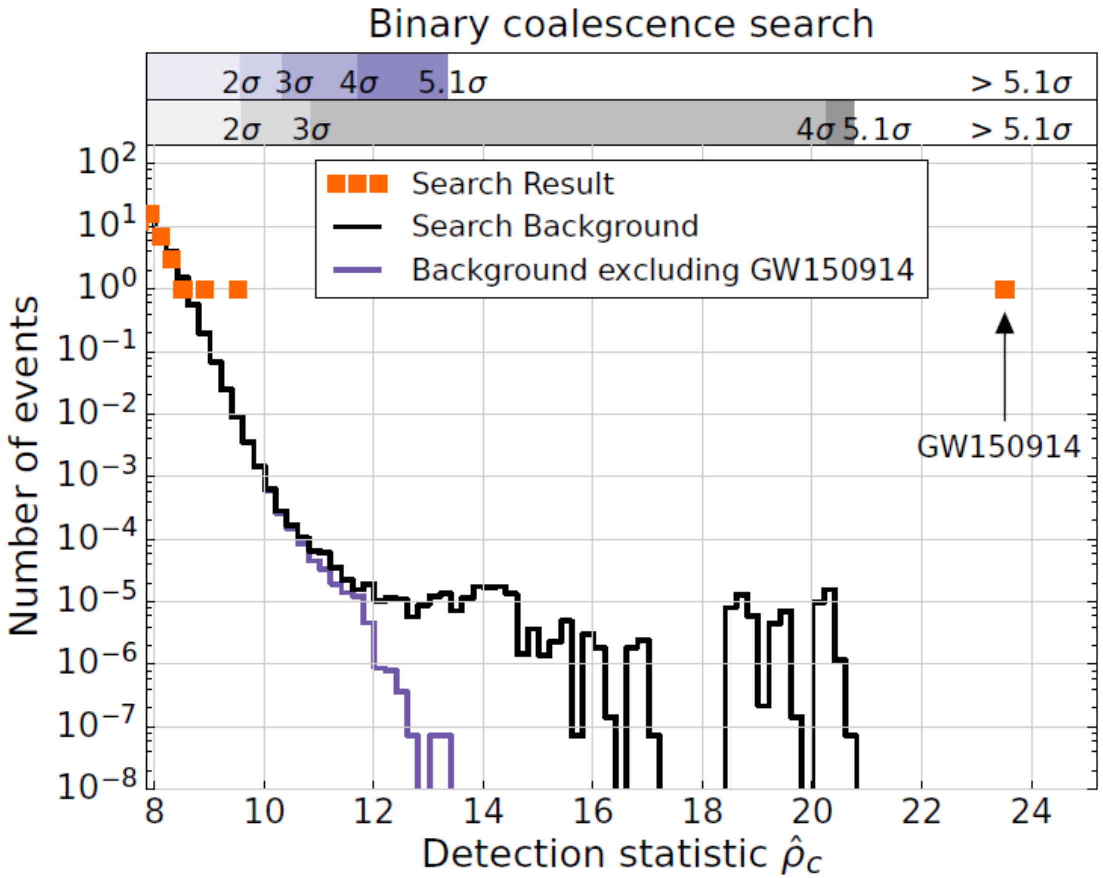
- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_{tot}/c^2 = 210$km); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_{tot}\pi f_{GW}/c^3)^{1/3}$

Binary Black Hole System
- M1 = 36 +5/-4 M_{sol}
- M2 = 29 +/- 4 M_{sol}
- Final Mass = 62 +/- 4 M_{sol}
- distance=410 +160/-180 MPc (redshift z = 0.09)



Statistical significance of GW150914

- number of candidate events (orange markers)
- number of background events (black lines)
- significance of an event in Gaussian standard deviations based on the corresponding noise background



- false alarm rate < 1 per 203,000 years,
- Poissonian false alarm probability < 2 x 10^{-7}
- Significance > 5.1 σ

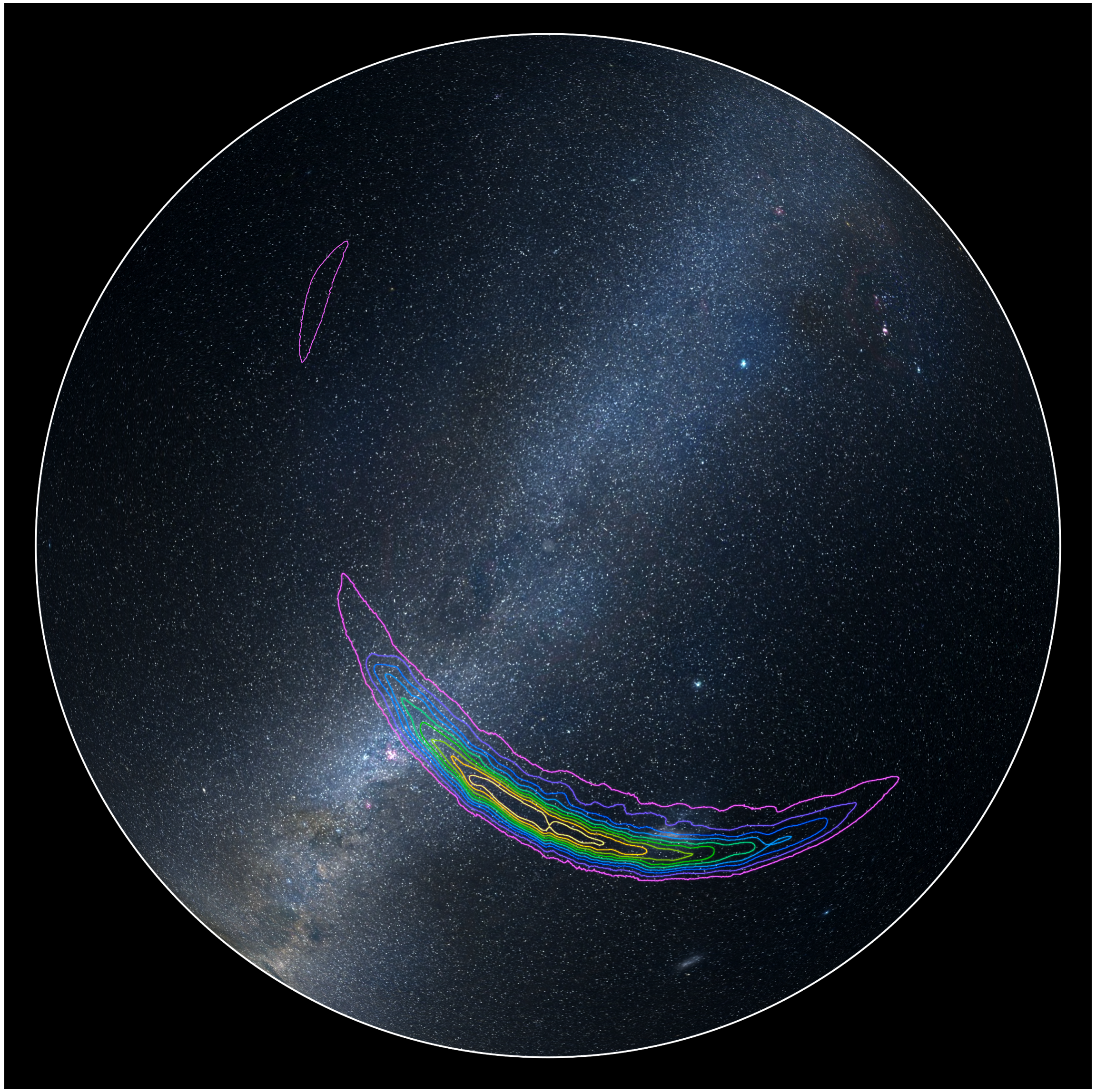
Source Parameters for GW150914

Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is 3.0±0.5 M_o c^2. The system reached a peak ~3.6 x10^{56} erg, and the spin of the final black hole < 0.7

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	$0.09^{+0.03}_{-0.04}$

Sky Localization for GW150914

- With only two detectors, the arrival time difference determines the source position to an annular region on the sky.
- GW150914 is localized to an area of approximately 590 deg^2 (90% credible region) in Southern emisphere



Bounding graviton mass

- If gravitation is propagated by a massive field, then the velocity of GWs (gravitons) will depend upon their frequency as

$$\frac{v_g}{c} = 1 - \left(\frac{c}{f\lambda_g}\right)^2$$

$\lambda_g = h/m_g c$ is the graviton Compton wavelenght.

- In the case of inspiralling compact binaries, GWs emitted at low frequency early in the inspiral will travel slightly slower than those emitted at high frequency later, resulting in an offset in the relative arrival times at a detector → the phase evolution of the observed inspiral gravitational waveform is modified.
- Matched filtering of the waveforms can bound such frequency-dependent variations in propagation speed →bound the graviton mass

Compton Wave-length of the Graviton

C. M. Will, Phys. Rev. D 57, 2061 (1998).

- We assume a modified dispersion relation for gravitational waves

$$(v_g /c)^2 = 1 - \{\hbar c /(\lambda_g E)\}^2$$

- In the massive graviton theory an extra phase term is added to the CBC evolution (formally a 1PN order term)

$$\phi_{MG}(f) = -(\pi D c) / [\lambda_g{}^2 (1 + z) f]$$

- Our constrain on the 1PN terms permit to derive a down limit for the Compton wavelength of the graviton

$$\lambda_g = 2 \pi \hbar / (m_g c) > 10^{13} \text{ km}$$

- It corresponds to a limit $m_g < 1.2 \times 10^{-22}$ eV/c^2.
  - limit better than that set by Solar System observations
  - thousand time better of the binary pulsar bounds
  - worse than bounds from dynamics of galaxy clusters and weak lensing observations (model- dependent bounds)

Companion Results

http://www.virgo-gw.eu/papers.html

Observation of Gravitational Waves from a Binary Black Hole Merger

Observation of Gravitational Waves from a Binary Black Hole Merger

ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914

Tests of general relativity with GW150914

The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914

W150914: Implications for the stochastic gravitational-wave background from binary black holes

Properties of the binary black hole merger GW150914

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

Observing gravitational-wave transient GW150914 with minimal assumptions

Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914

GW150914: First results from the search for binary black hole coalescence with Advanced LIGO

GW150914: The Advanced LIGO Detectors in the Era of First Discoveries

=11365

ASTROPHYSICAL IMPLICATIONS

DRAFT VERSION FEBRUARY 12, 2016
Preprint typeset using LaTeX style AASTeX6 v. 1.0

ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914

ABSTRACT

The discovery of the gravitational-wave source GW150914 with the Advanced LIGO detectors provides the first observational evidence for the existence of binary black-hole systems that inspiral and merge within the age of the Universe. Such black-hole mergers have been predicted in two main types of formation models, involving isolated binaries in galactic fields or dynamical interactions in young and old dense stellar environments. The measured masses robustly demonstrate that relatively "heavy" black holes ($\gtrsim 25\ M_\odot$) can form in nature. This discovery implies relatively weak massive-star winds and thus the formation of GW150914 in an environment with metallicity lower than $\simeq 1/2$ of the solar value. The rate of binary black-hole mergers inferred from the observation of GW150914 is consistent with the higher end of rate predictions ($\gtrsim 1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$) from both types of formation models. The low measured redshift ($z \simeq 0.1$) of GW150914 and the low inferred metallicity of the stellar progenitor imply either binary black-hole formation in a low-mass galaxy in the local Universe and a prompt merger, or formation at high redshift with a time delay between formation and merger of several Gyr. This discovery motivates further studies of binary-black-hole formation astrophysics. It also has implications for future detections and studies by Advanced LIGO and Advanced Virgo, and gravitational-wave detectors in space.

arXiv:1602.03846v1 [astro-ph.HE] 11 Feb 2016

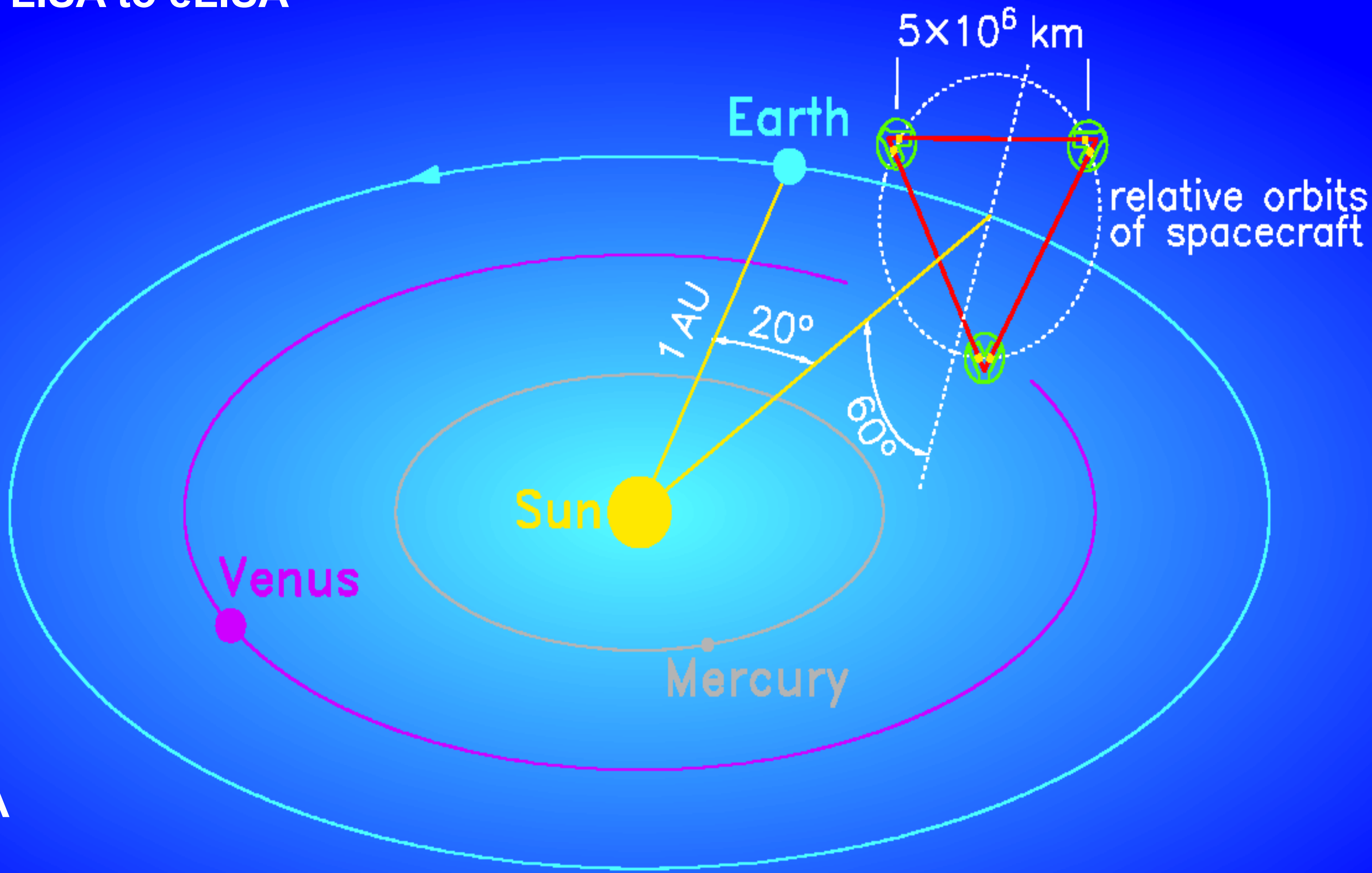
Conclusions

- Gravitational waves from the merger of two stellar mass black holes have been observed

- The detected waveforms match the prediction of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting black hole.

- **This observation is the first direct detection of gravitational waves and the first observation of a binary black hole merger.**

From LISA to eLISA



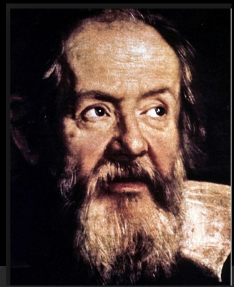
eLISA

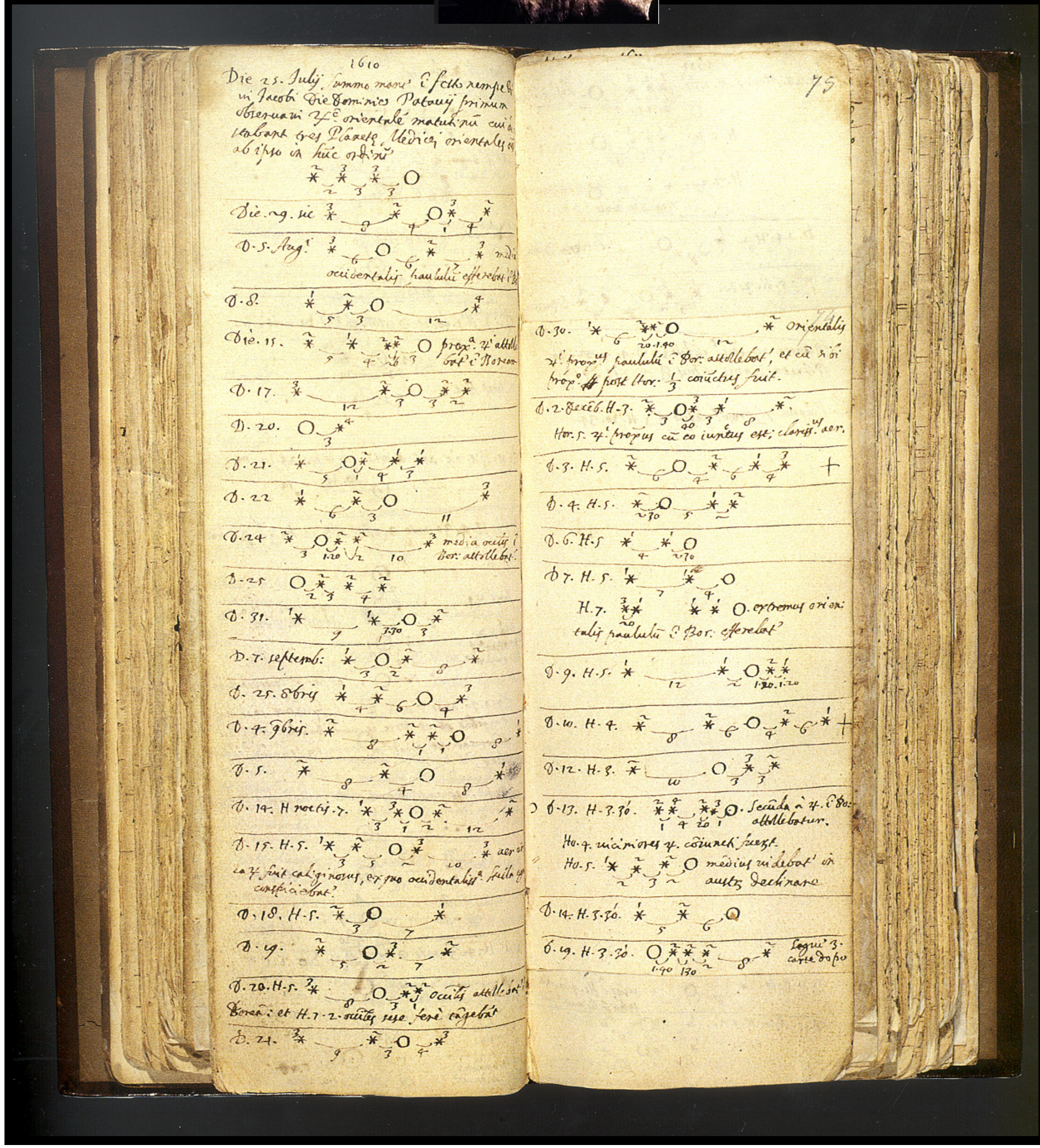
- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

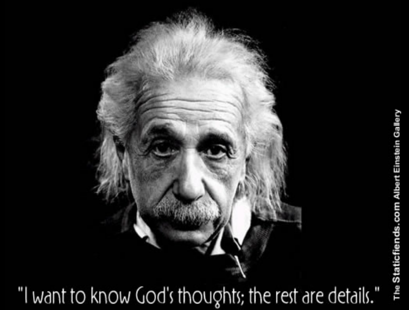
2030

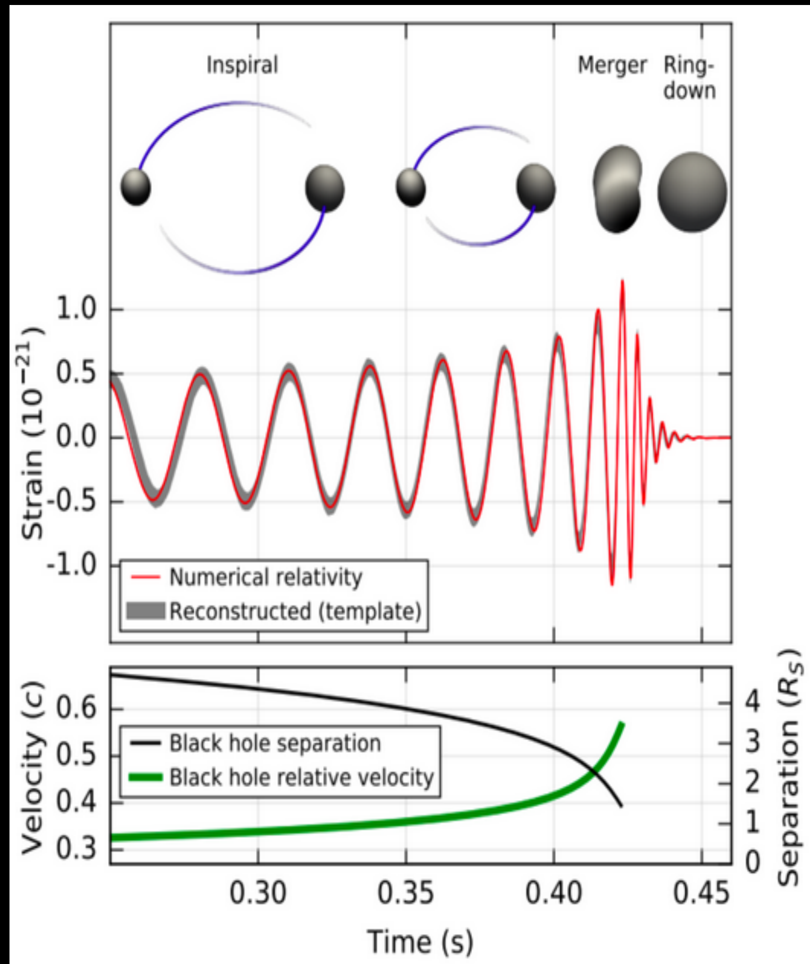
Every newly opened astronomical window has found unexpected results

Window	Opened	1st Surprise	Year
Optical	1609 Galilei	Jupiter's moons	1610
Cosmic Rays	1912	Muon	1930s
Radio	1930s	Giant Radio Galaxies CMB Pulsars	1950s 1964 1967
X - ray	1948	Sco X-1 X-ray binaries	1962 1969 Uhuru
γ - ray	1961 Explorer 11	GRBs	Late 1960s+ Vela






"I want to know God's thoughts; the rest are details."
The Staticfiends.com Albert Einstein Gallery


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


Le seul véritable voyage ... ce ne serait pas d’aller vers
de nouveaux paysages, mais d’avoir d’autres yeux
Marcel Proust