OPENING THE GRAVITATIONAL WAVE WINDOW TO THE UNIVERSE

Eugenio Coccia

University of Rome "Tor Vergata"

INFN, Gran Sasso Science Institute

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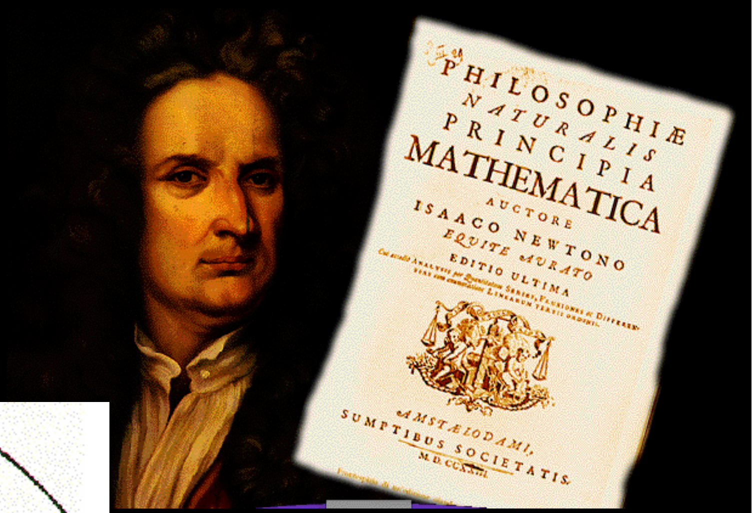
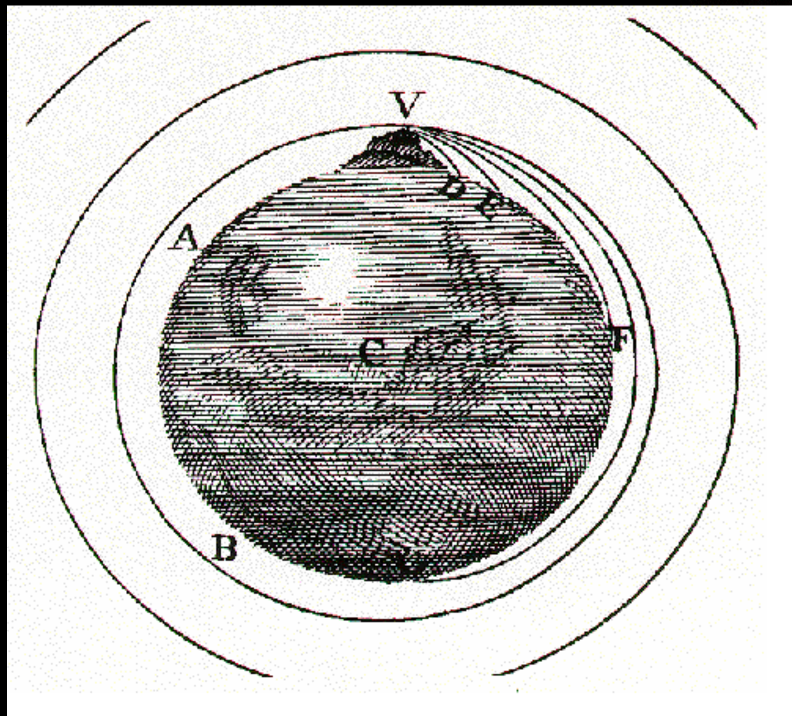
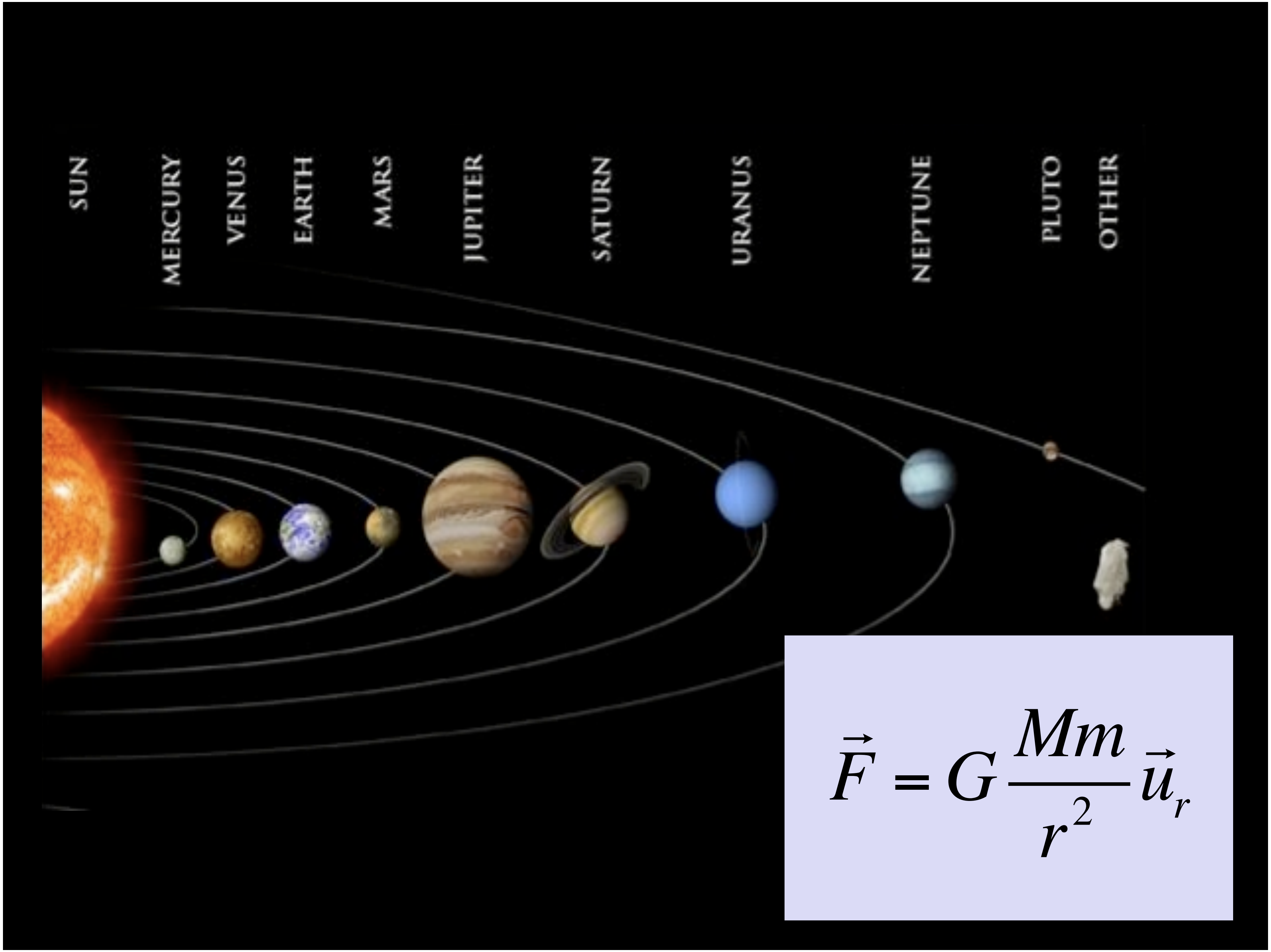
Newton


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

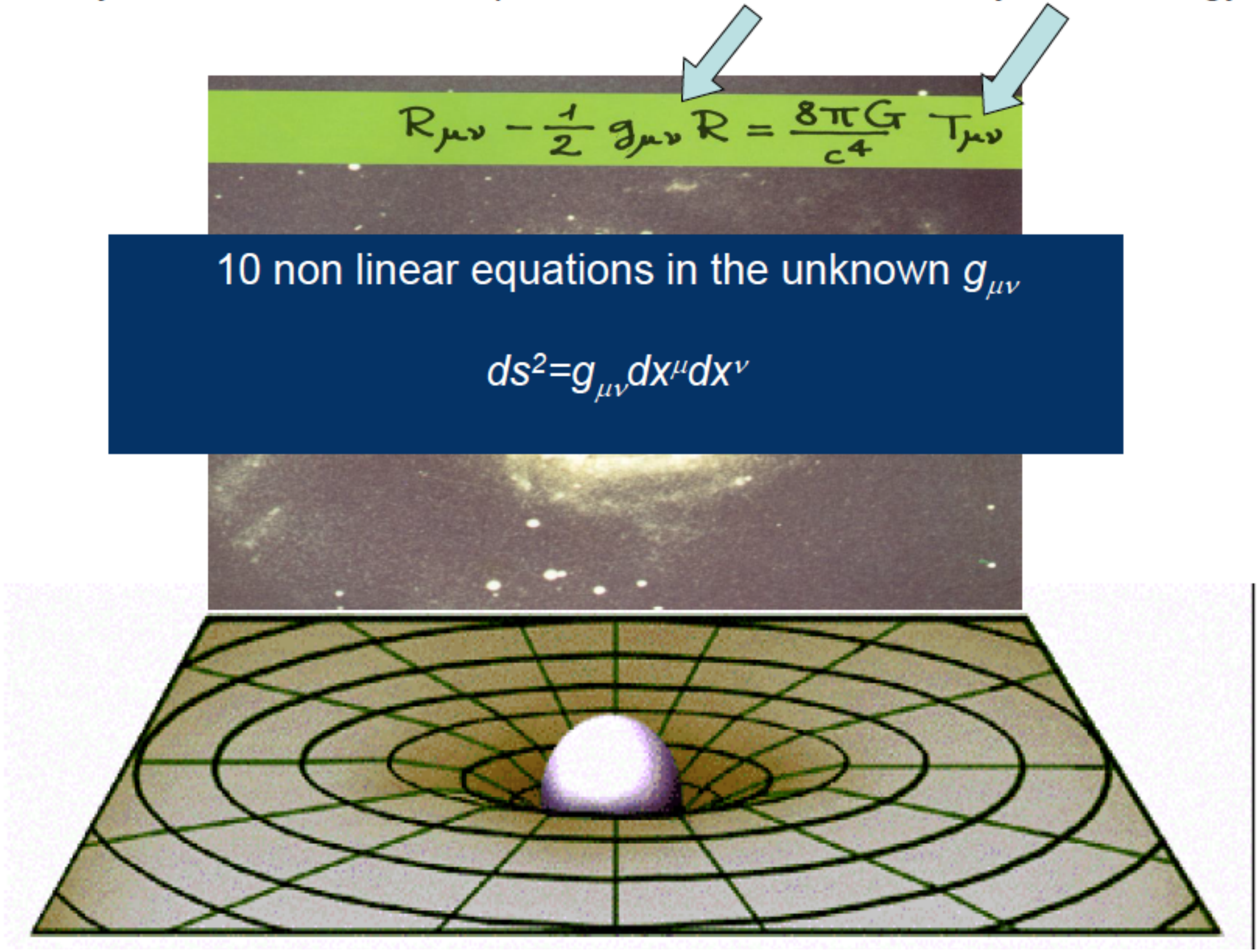

V
D
E
A
F
C
B



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

General Relativity (1915)

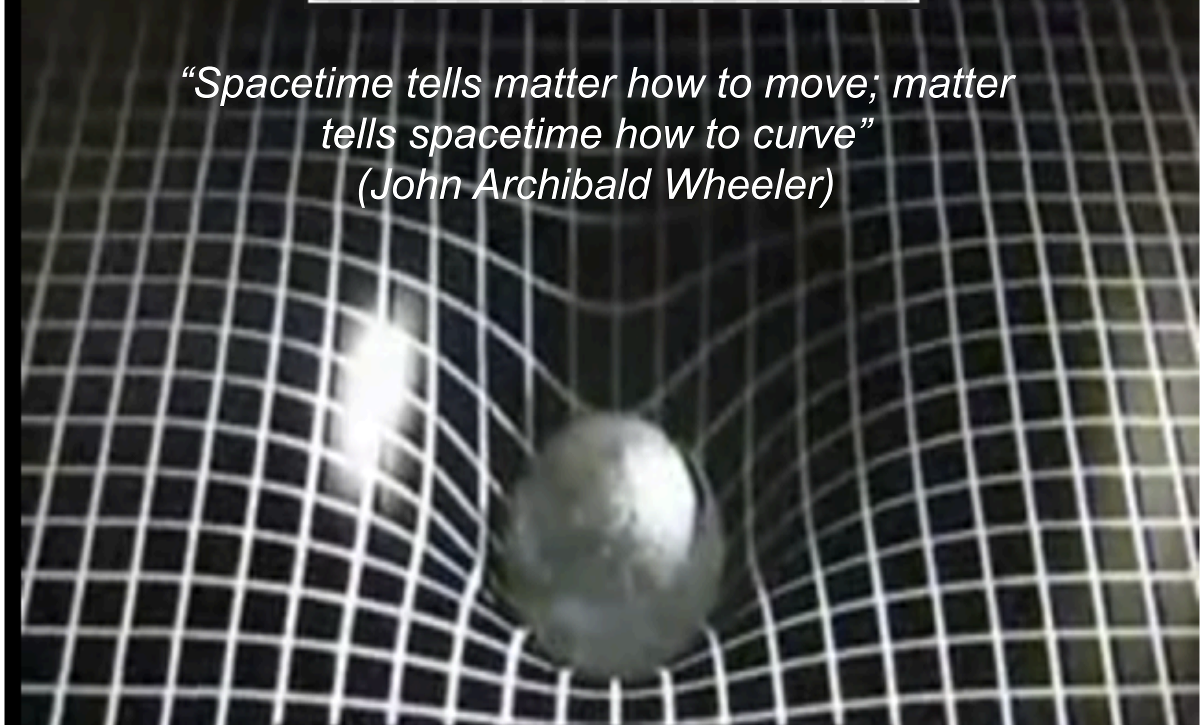
Gravity is a manifestation of spacetime curvature induced by mass-energy

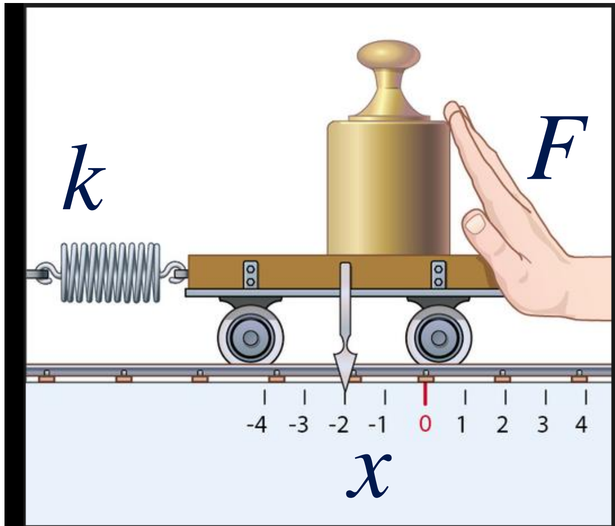


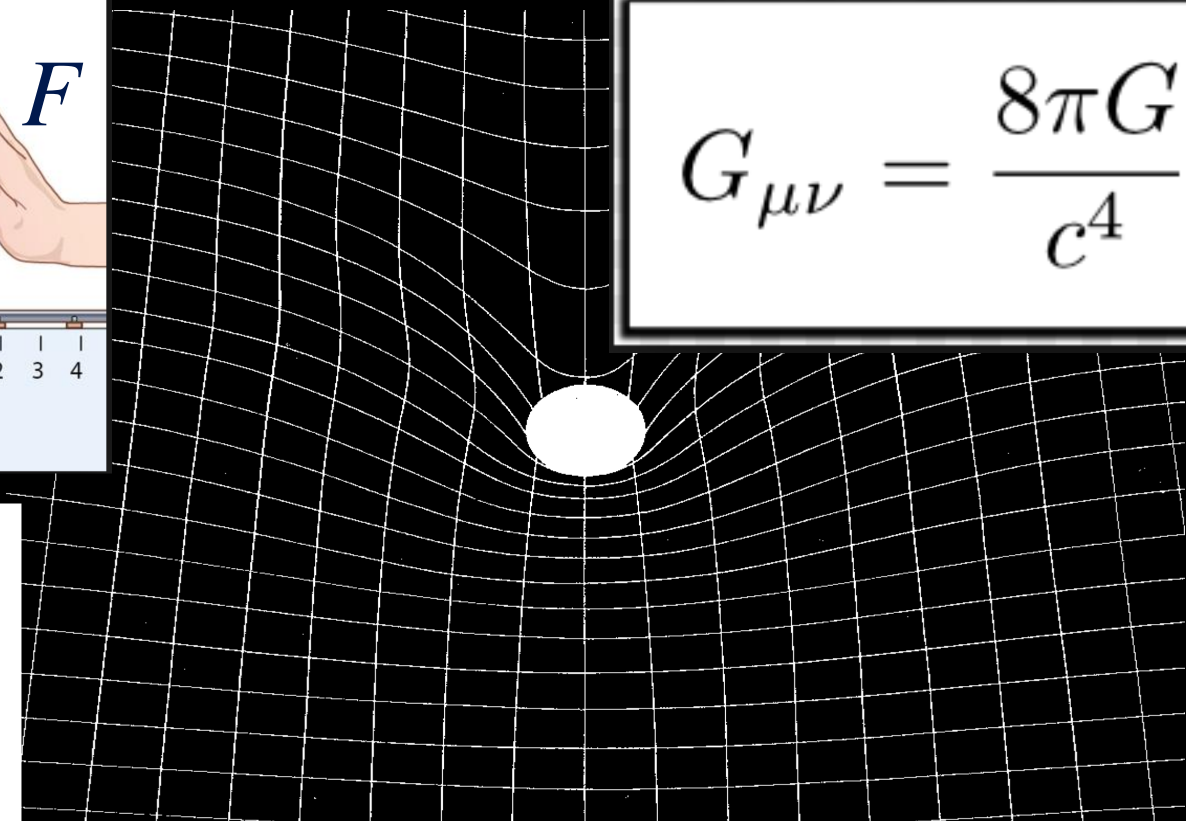
Einstein's Theory of Gravitation

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

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







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

$$F = -kx$$

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

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

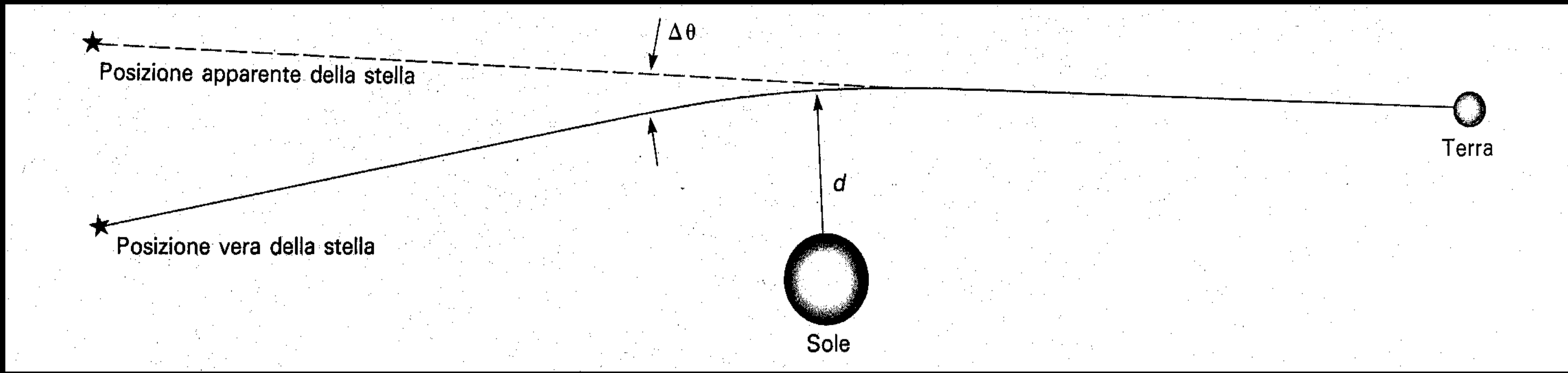
$$k \Leftrightarrow \frac{c^4}{8\pi G}$$

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

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

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

Light deflection



Eddington

LIGHTS ALL ASKEW IN THE HEAVENS

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

EINSTEIN THEORY TRIUMPHS

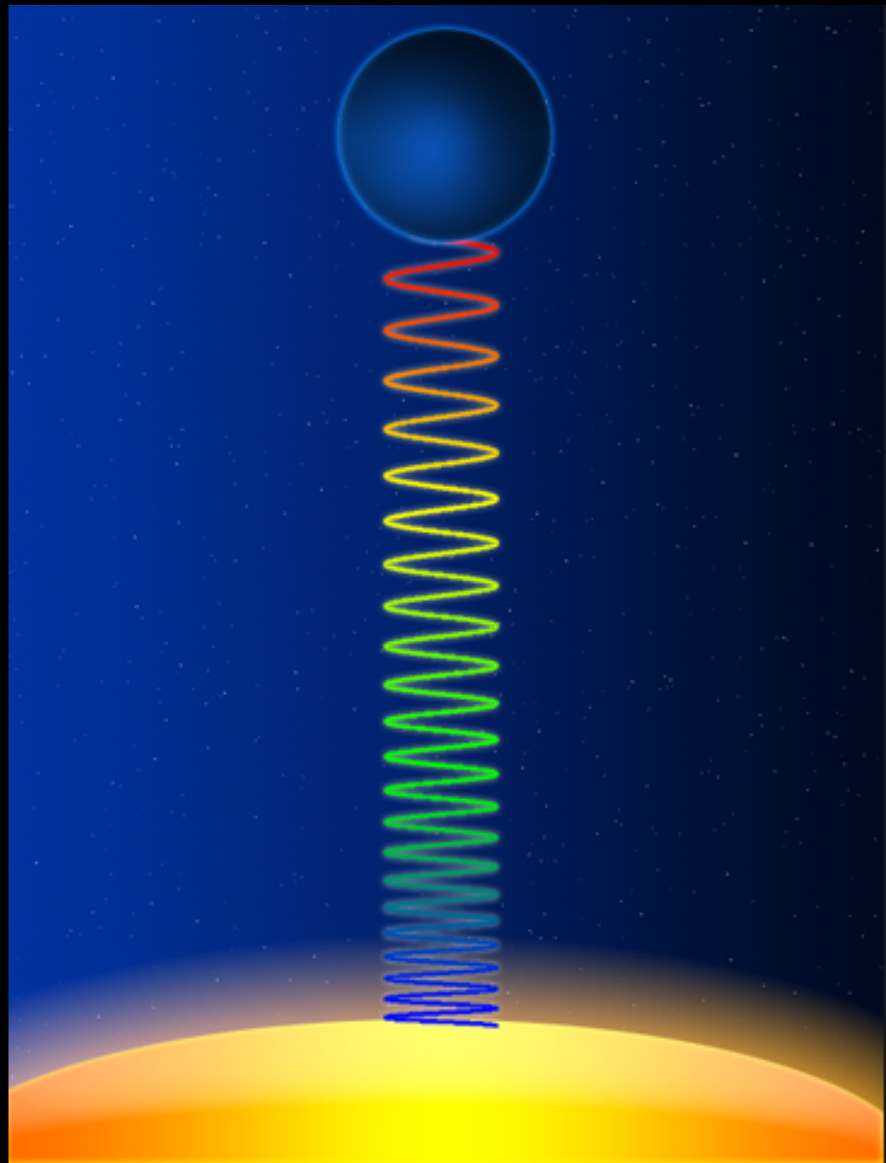
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

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.

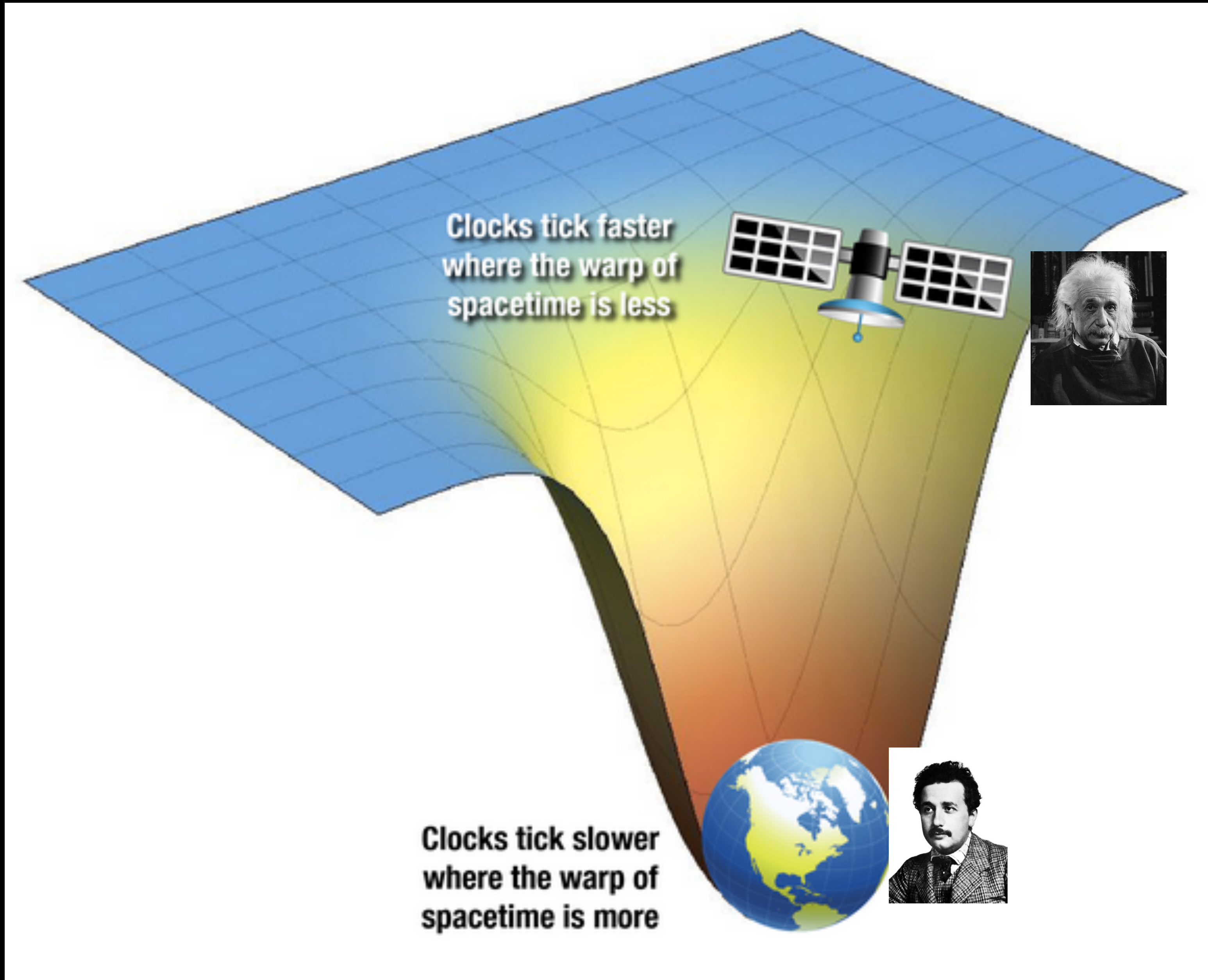
Harvard



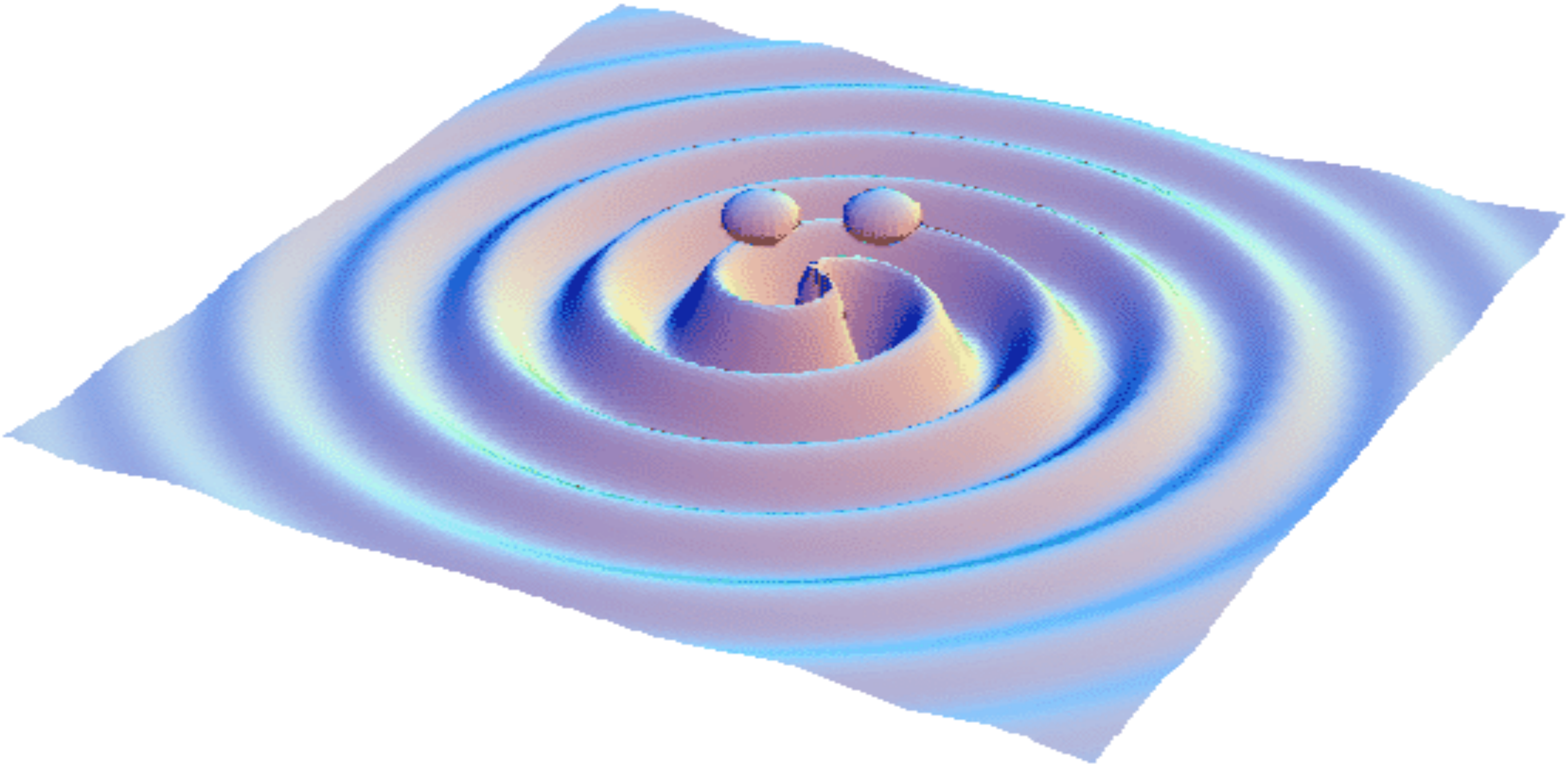
Redshift

Pound and Rebka

1959


Clocks tick faster where the warp of spacetime is less
Clocks tick slower where the warp of spacetime is more

Gravitational Waves



1916

Über Gravitationswellen.

Von A. Einstein.

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

La prima pagina di un lavoro di Albert Einstein del 1918 in cui per la prima volta vengono dedotte le equazioni della propagazione ondosa del campo gravitazionale.

Weak field approximation

$$g_{\mu\nu} = g^{o}_{\mu\nu} + h_{\mu\nu}$$

$$|h_{\mu\nu}| << 1$$

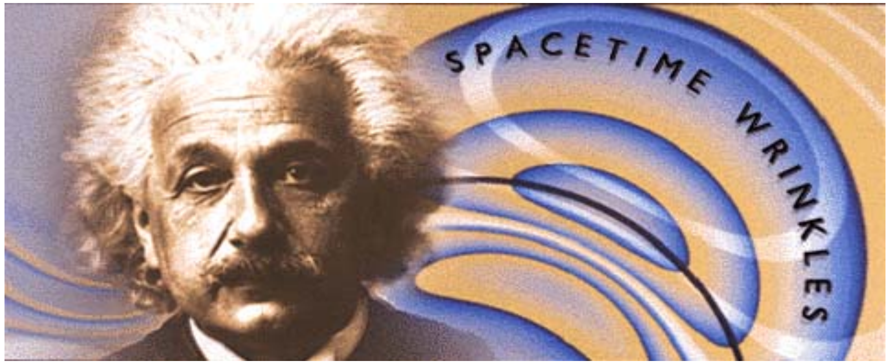
The Einstein equation in vacuum becomes

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

Having solutions

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

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



Gravitational waves are strain in space propagating with the speed of light

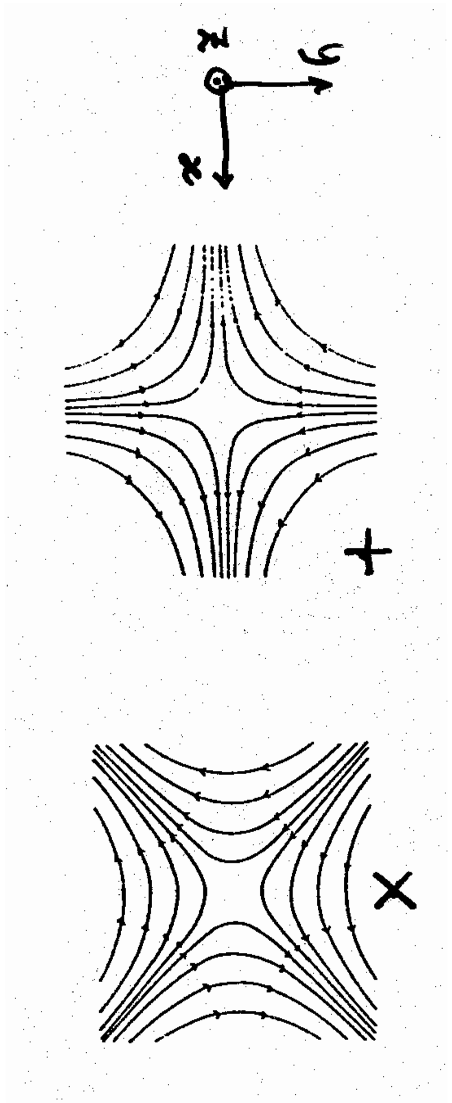
Main features

- **2 transversal polarization states**
- **Associated with massless, spin 2 particles (gravitons)**
- **Emitted by time-varying quadrupole mass moment**
  no dipole radiation because of conservation laws

$$-\frac{dE}{dt} = \cancel{\frac{2G}{3c^3}\left(\ddot{d}\right)^2} + \frac{G}{45c^5}\left(\dddot{Q}\right)^2 + \ldots$$

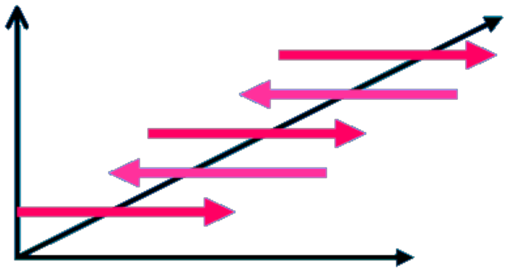
$$\dot{d} = \sum_i m_i \dot{x}_i \Rightarrow \ddot{d} \equiv 0 \qquad Q_{ij} = \int \rho x_i x_j d^3x$$

$$h_{ij}(t) = \frac{2G}{rc^4}\ddot{Q}_{ij}(t - r/c)$$

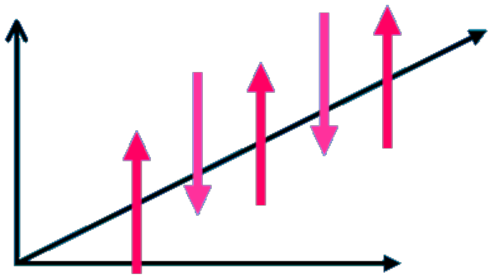


Comparison with electromagnetic waves

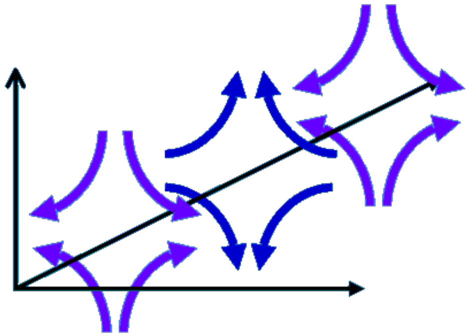
Horizontal polarization



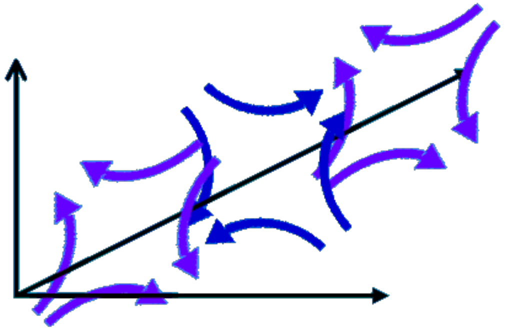
Vertical polarization



Plus polarization

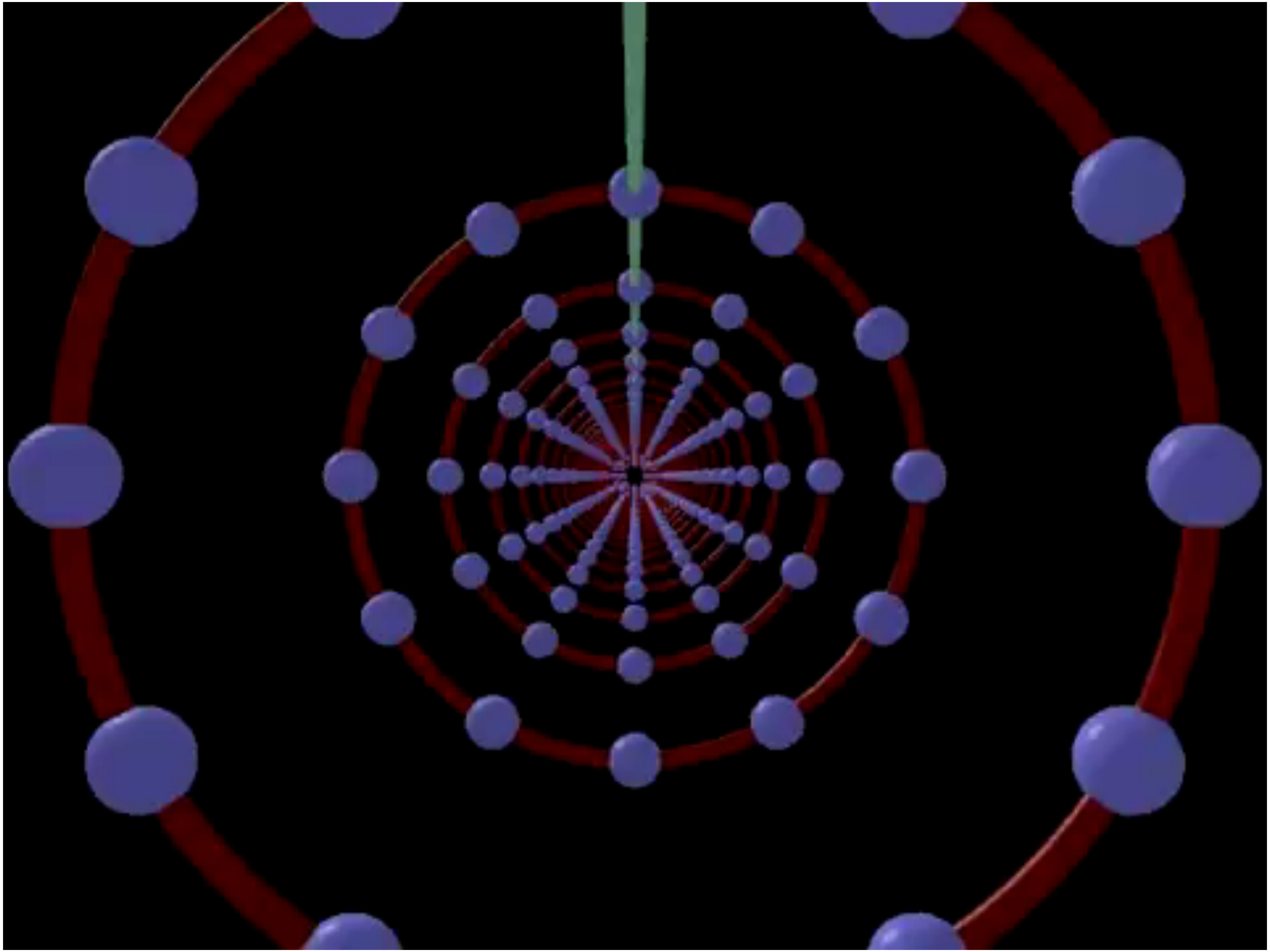


Cross polarization

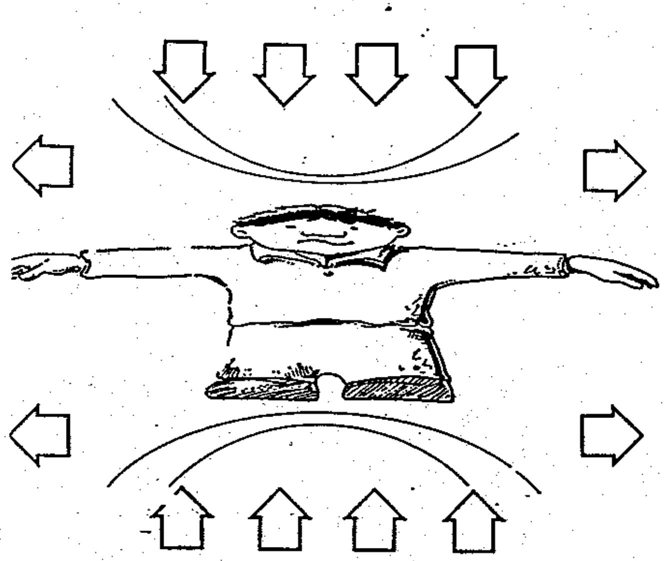


The so-called “electromagnetic theory of light” has not helped us hitherto . .
it seems to me that it is rather a backward step . . . the one thing about it that seems intelligible to me, I do not think is admissible . . That there should be an electric displacement perpendicular to the line of propagation’

Lord Kelvin

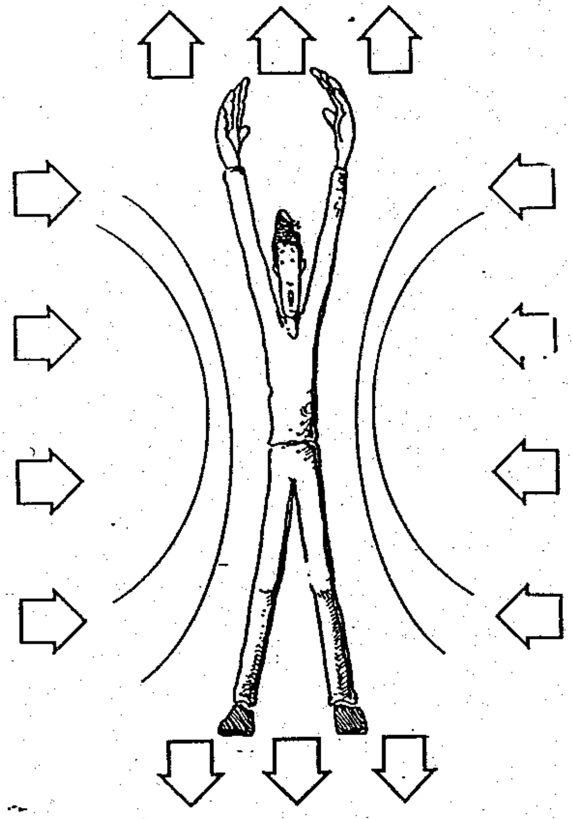


CAUTION: GRAVITATIONAL RADIATION



MAY BE DANGEROUS
TO YOUR HEALTH

CAUTION: GRAVITATIONAL RADIATION



MAY BE DANGEROUS
TO YOUR HEALTH

- **No laboratory equivalent of Hertz experiments for production of GWs**

Luminosity due to a mass M and size R oscillating at frequency $\omega \sim v/R$:

$$L = \frac{2G}{5c^5}\left\langle \dddot{Q}^2 \right\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin\omega t$$

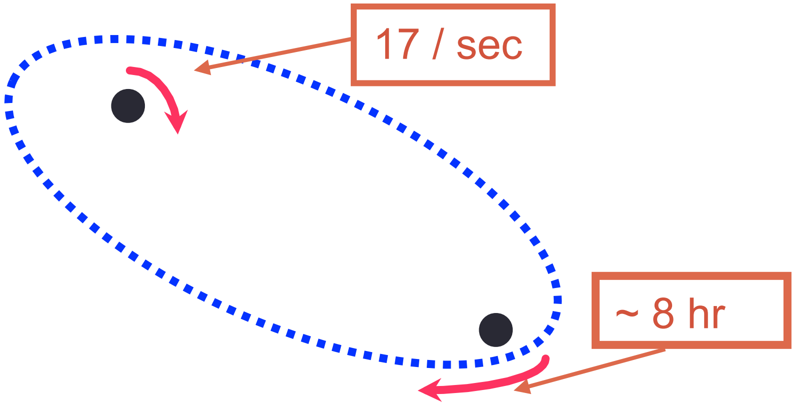
M=1000 tons, steel rotor, f = 4 Hz ⟹ L = 10^{-30} W
Einstein: " *.. a pratically vanishing value…*"

Collapse to neutron star 1.4 M_o ⟹ L = 10^{52} W

$h \sim W^{1/2} d^{-1}$; source in the Galaxy ***$h \sim 10^{-18}$***, in VIRGO cluster ***$h \sim 10^{-21}$***
Fairbank: "*...a challenge for contemporary experimental physics..*"

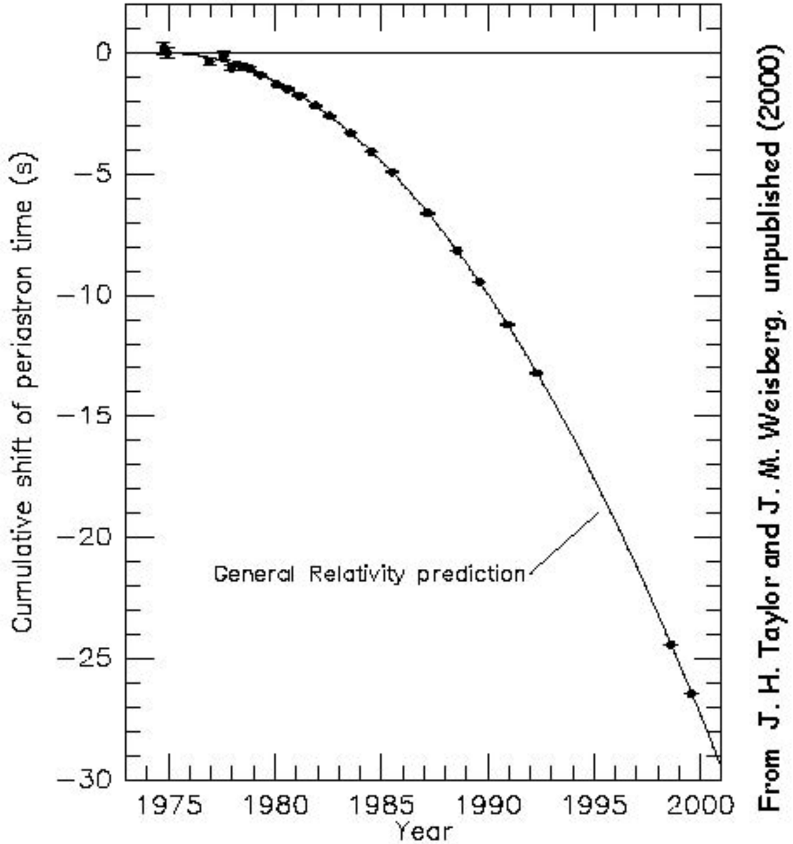
Indirect evidence for GWs: PSR 1913+16

Joseph Taylor Russell Hulse

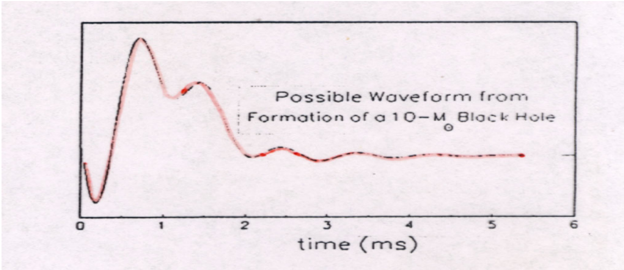


They will merge in 300 million years

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

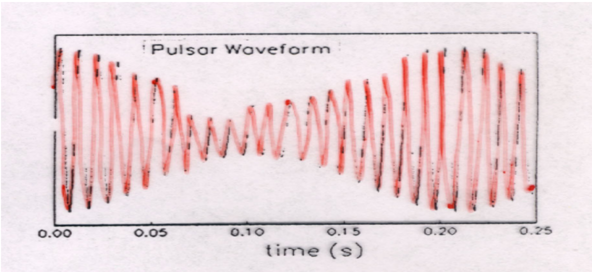


$dP_b/dt = -(2.40 \pm 0.01) \times 10^{-12}$ s/s



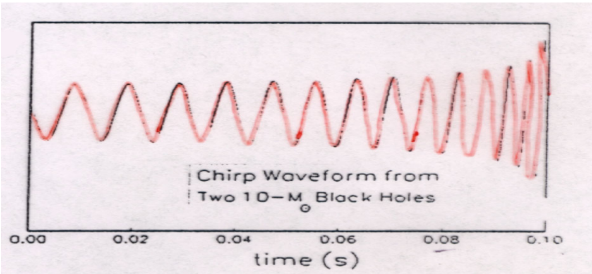
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

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



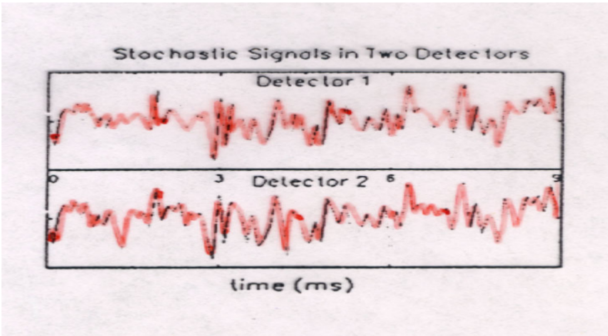
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

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

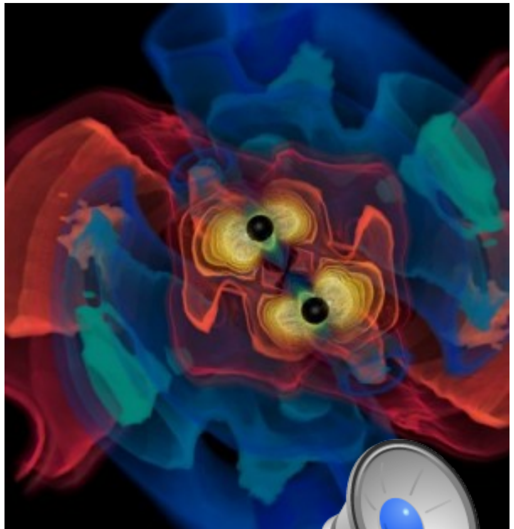
Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



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.

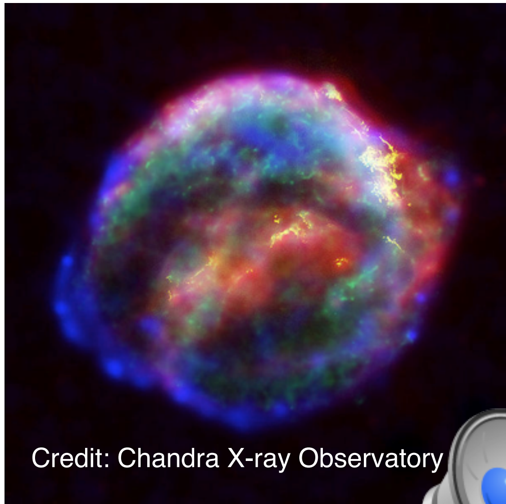
Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

Astrophysical sources of gravitational waves



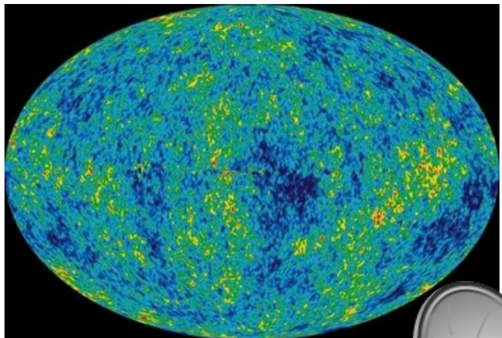
Credit: AEI, CCT, LSU

Compact Binaries



Credit: Chandra X-ray Observatory

Supernovae



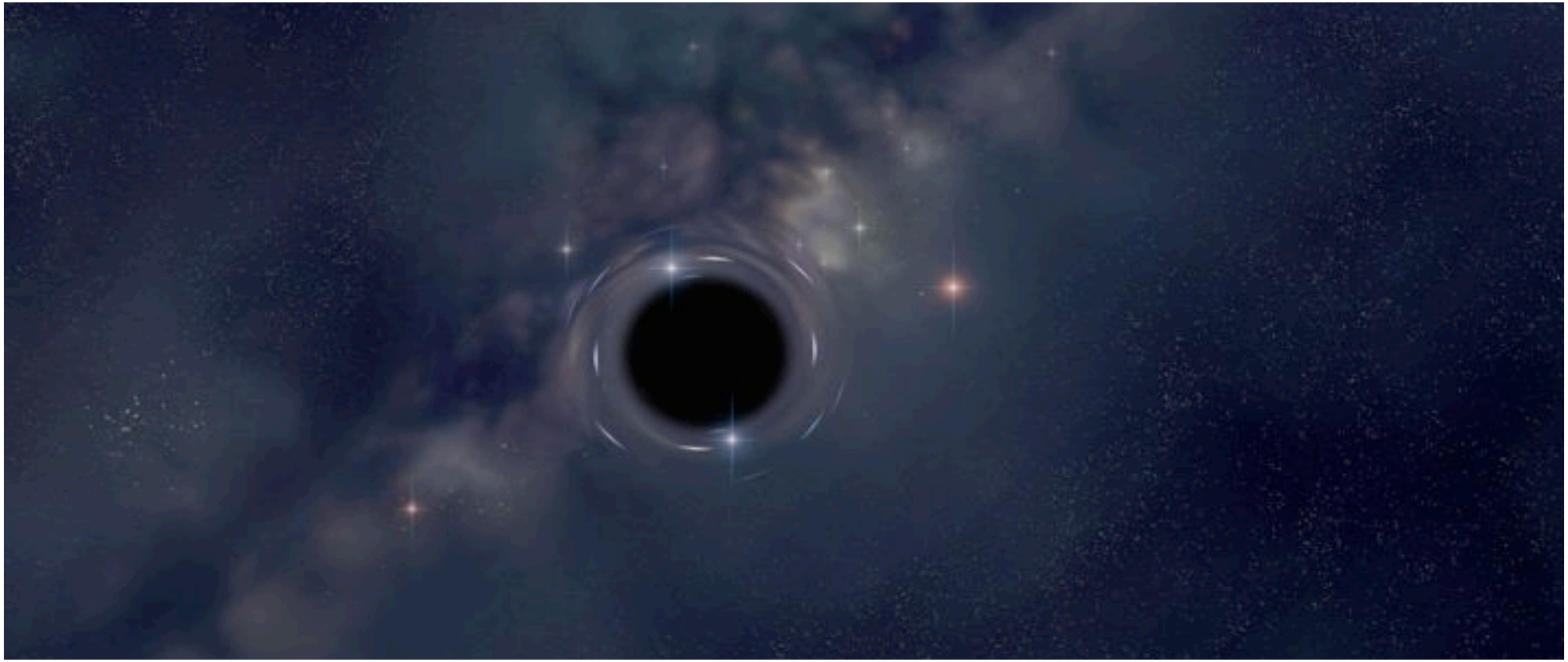
NASA/WMAP Science Team

Cosmic Gravitational-wave Background

Casey Reed, Penn State

Spinning neutron stars

BLACK HOLE



KINETIC Energy POTENTIAL Energy

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

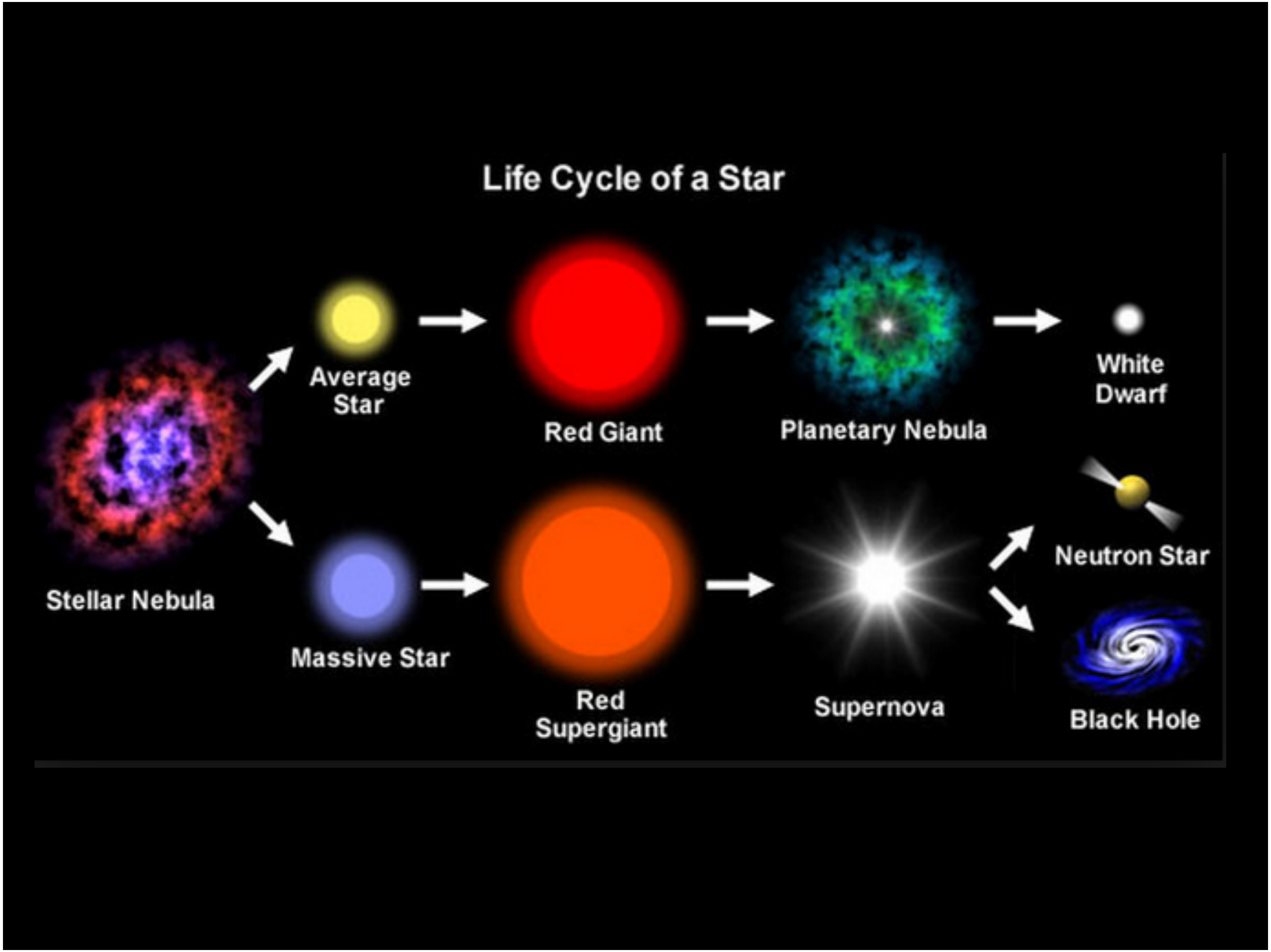
$$v_f = \sqrt{\frac{2GM}{R^2}}$$

Escape velocity

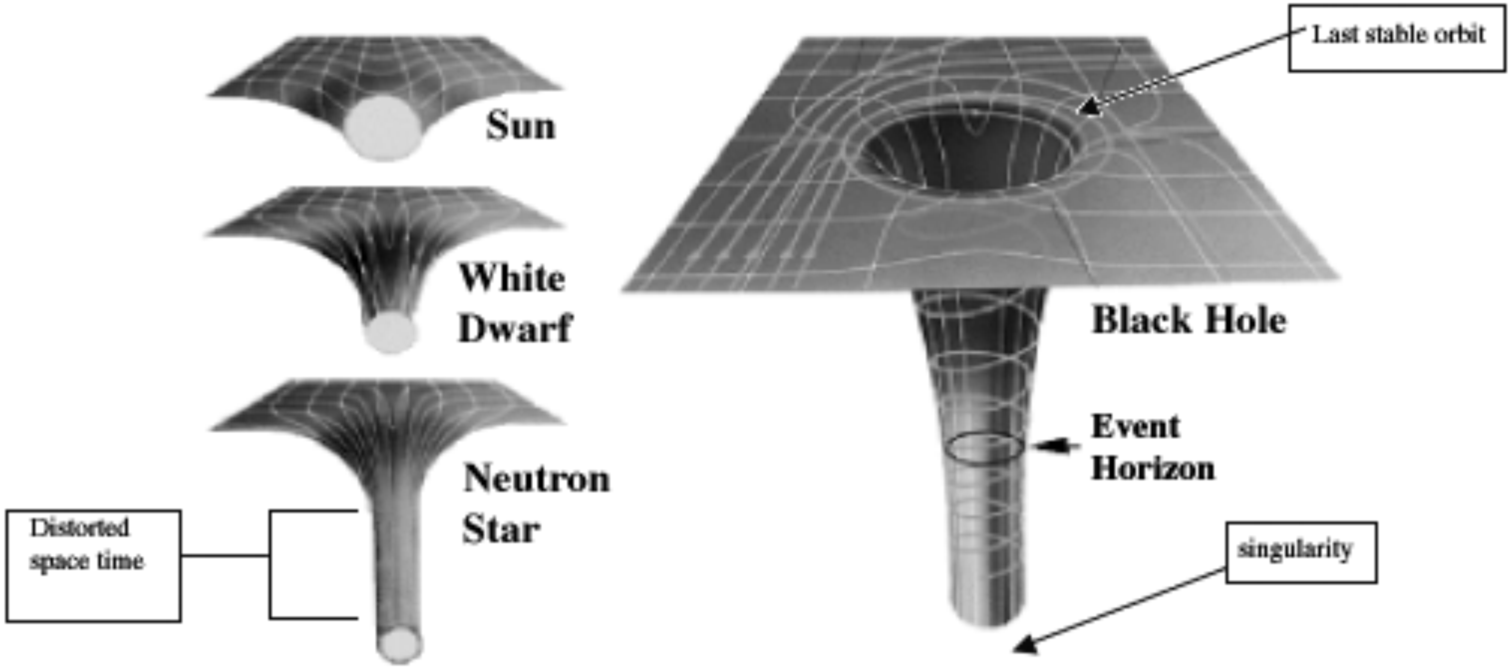
The escape velocity is equal to the speed of light if matter in squeezed into a sphere of radius

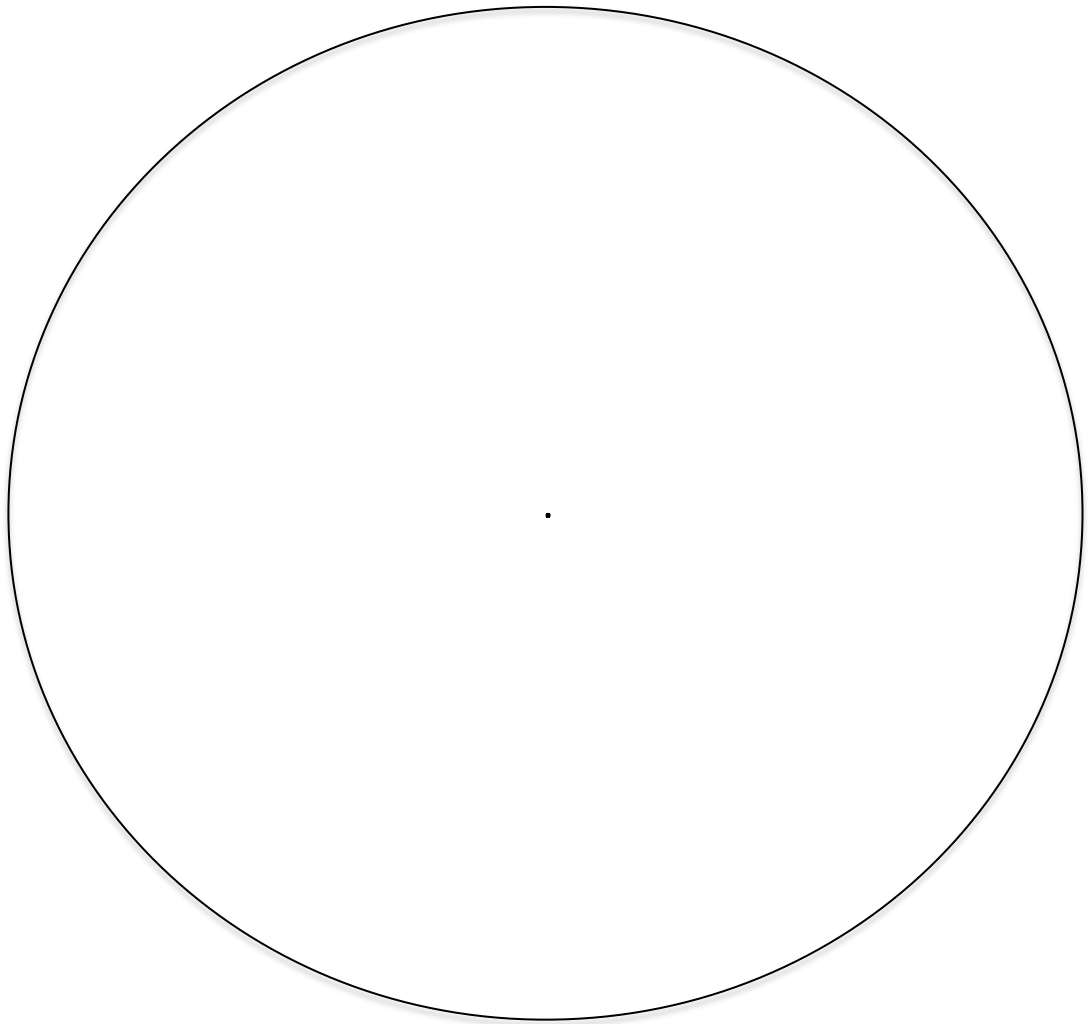
$$R = R_s = \sqrt{\frac{2GM}{c^2}}$$

Schwarzschild radius

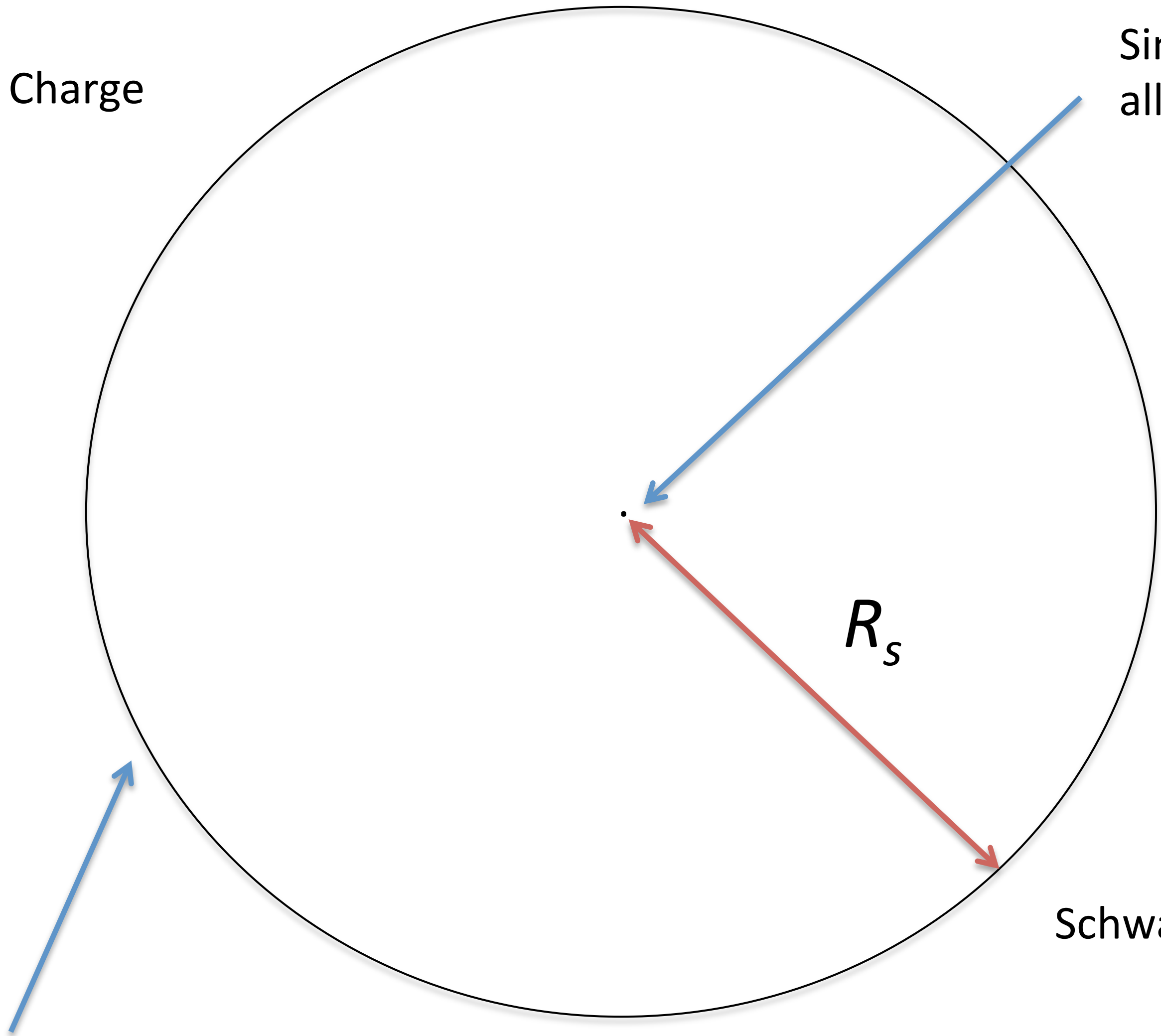


Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole

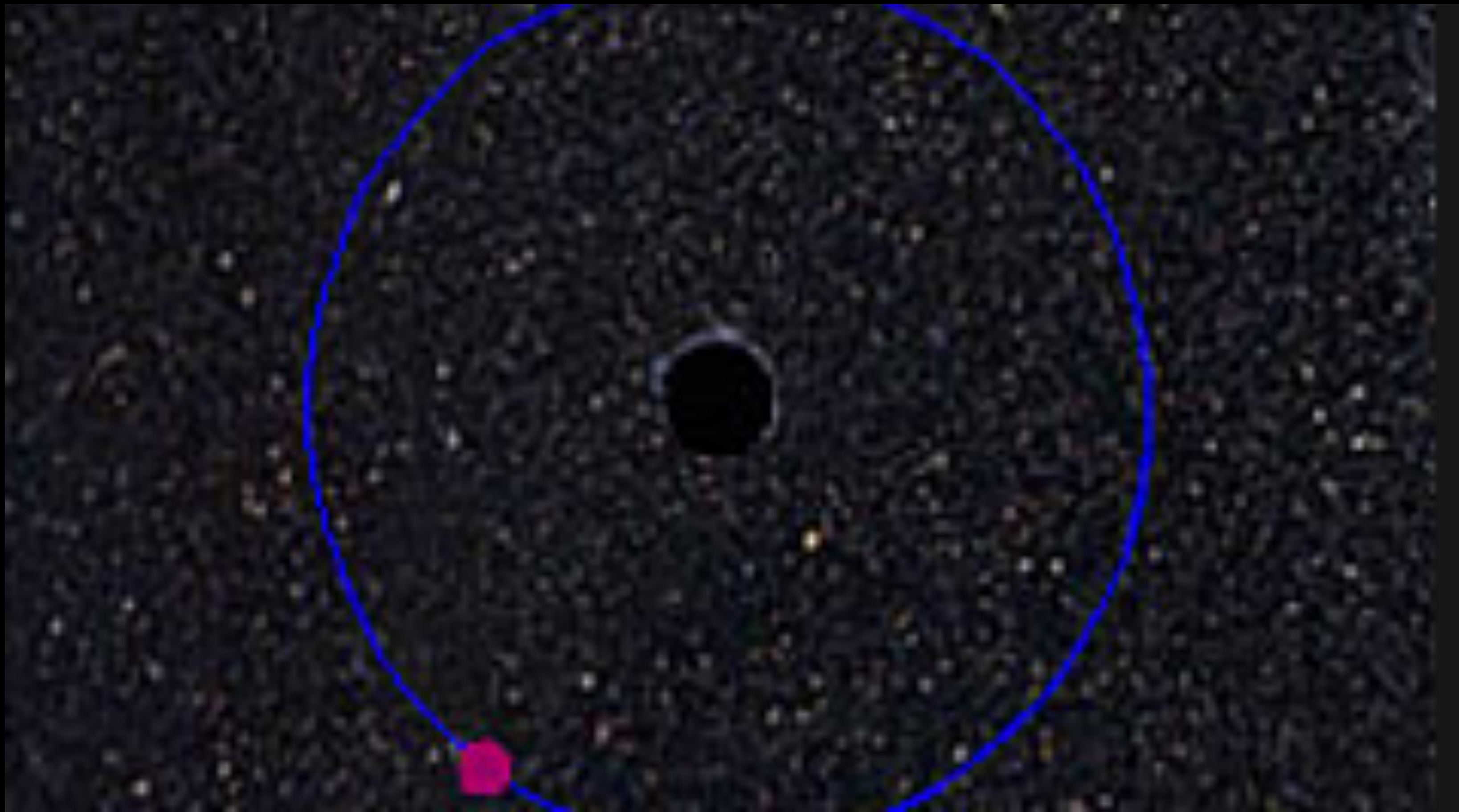

Sun
White
Dwarf
Neutron
Star
Distorted
space time
Last stable orbit
Black Hole
Event
Horizon
singularity

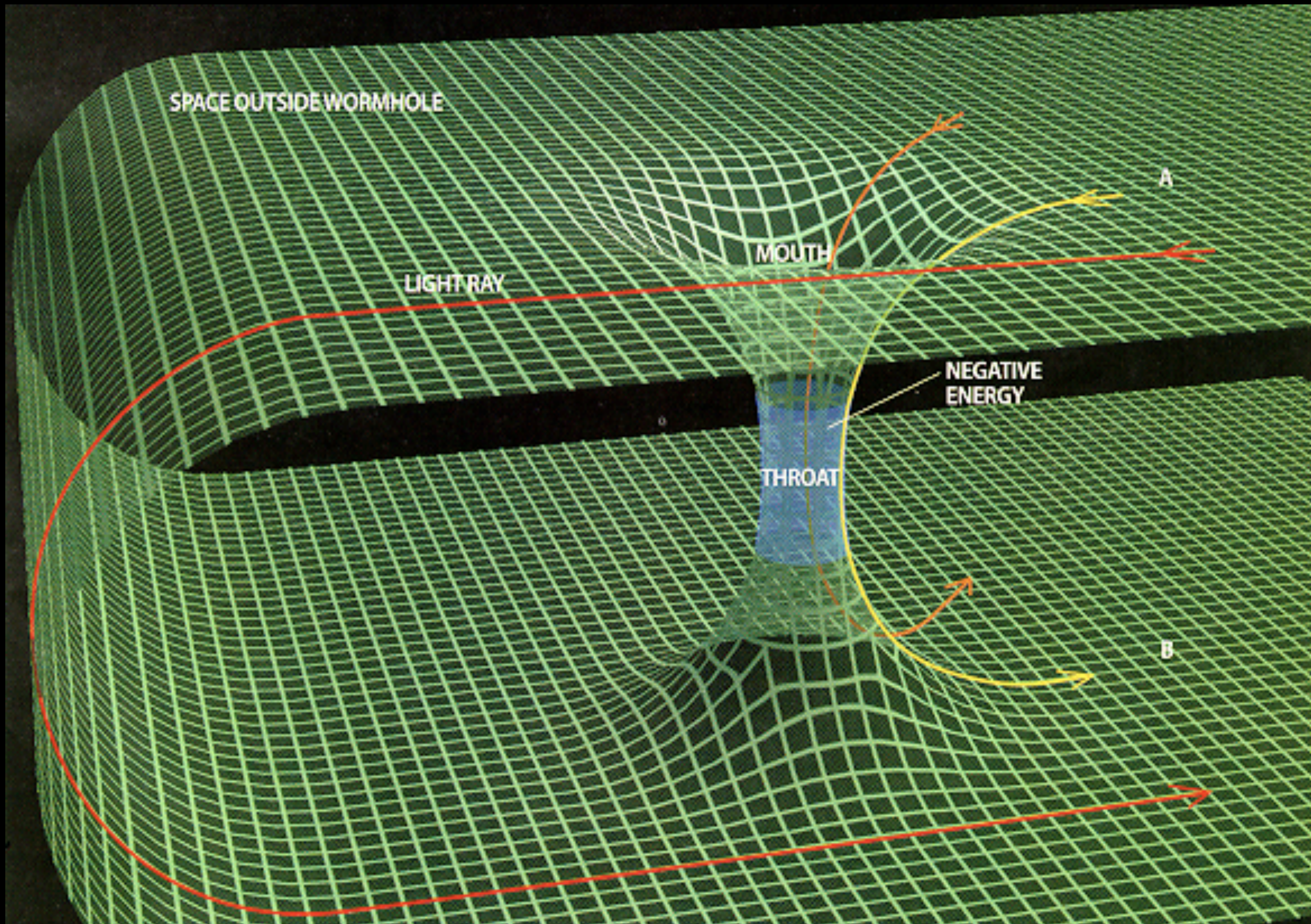


- Mass
- Spin
- Electric Charge



Time traveling



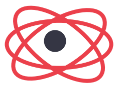


SPACE OUTSIDE WORMHOLE
A
MOUTH
LIGHT RAY
NEGATIVE
ENERGY
THROAT
B

How Small 10^{-18} meter is?

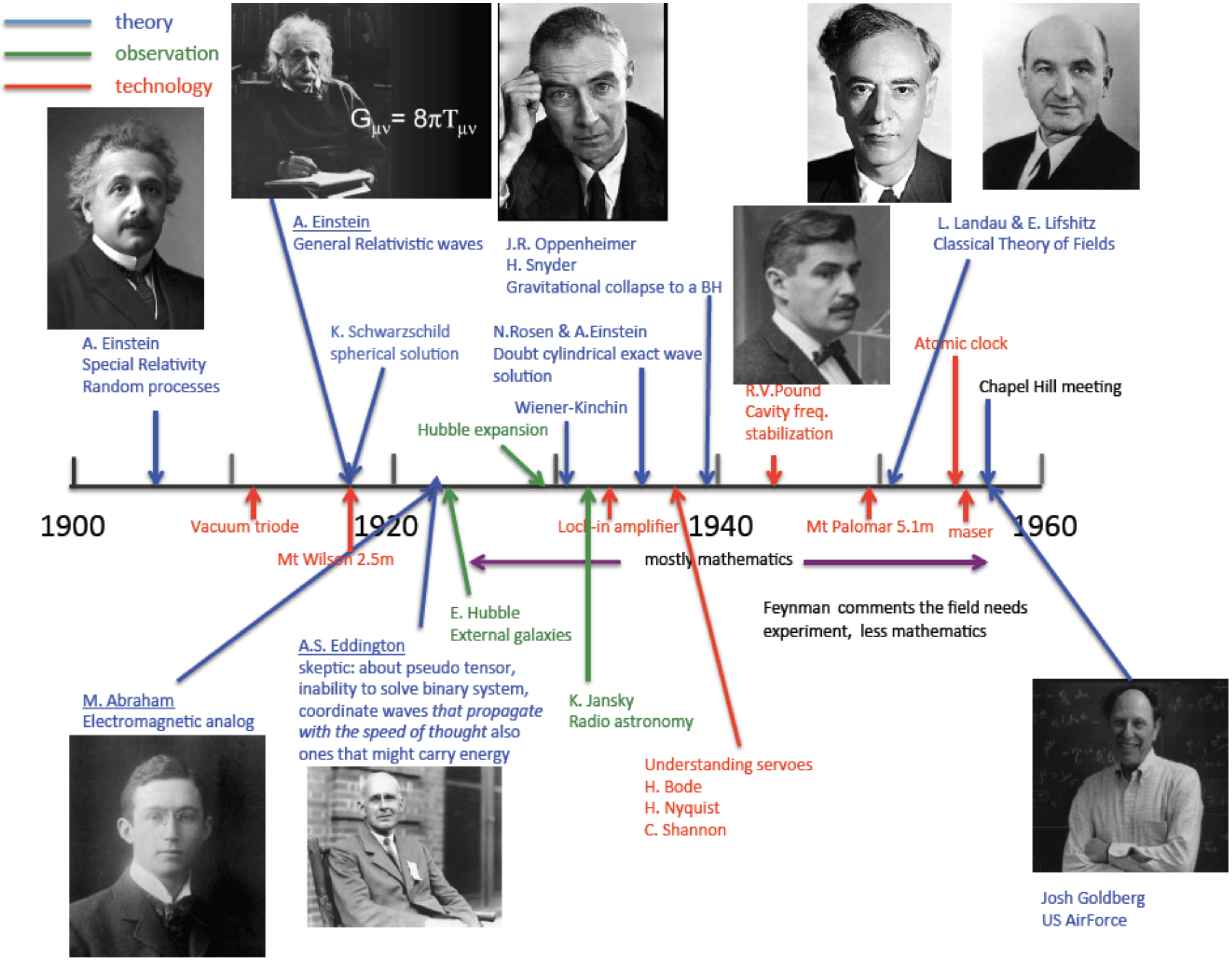
One meter

÷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**


theory
observation
technology
$G_{\mu\nu} = 8\pi T_{\mu\nu}$
A. Einstein
General Relativistic waves
J.R. Oppenheimer
H. Snyder
Gravitational collapse to a BH
L. Landau & E. Lifshitz
Classical Theory of Fields
A. Einstein
Special Relativity
Random processes
K. Schwarzschild
spherical solution
N.Rosen & A.Einstein
Doubt cylindrical exact wave
solution
Atomic clock
Chapel Hill meeting
Wiener-Kinchin
Hubble expansion
R.V.Pound
Cavity freq.
stabilization
1900
Vacuum triode
1920
Mt Wilson 2.5m
Lock-in amplifier
1940
Mt Palomar 5.1m
maser
1960
mostly mathematics
Feynman comments the field needs
experiment, less mathematics
E. Hubble
External galaxies
A.S. Eddington
skeptic: about pseudo tensor,
inability to solve binary system,
coordinate waves *that propagate*
with the speed of thought also
ones that might carry energy
M. Abraham
Electromagnetic analog
K. Jansky
Radio astronomy
Understanding servoes
H. Bode
H. Nyquist
C. Shannon
Josh Goldberg
US AirForce

Chapter 14
Measurement of Classical Gravitation Fields

Felix Pirani

Because of the principle of equivalence, one cannot ascribe a direct physical interpretation to the gravitational field insofar as it is characterized by Christoffel symbols $\Gamma^{\mu}_{\nu\rho}$. One can, however, give an invariant interpretation to the variations of the gravitational field. These variations are described by the Riemann tensor; therefore, measurements of the relative acceleration of neighboring free particles, which yield information about the variation of the field, will also yield information about the Riemann tensor.

Now the relative motion of free particles is given by the equation of geodesic deviation

$$\frac{\partial^2\eta^\mu}{\partial\tau^2}+R^{\mu}_{\nu\rho\sigma}v^\nu\eta^\rho v^\sigma=0 \quad (\mu,\nu,\rho,\sigma=1,2,3,4) \tag{14.1}$$

Here η^μ is the infinitesimal orthogonal displacement from the (geodesic) worldline ζ of a free particle to that of a neighboring similar particle. v^ν is the 4-velocity of the first particle, and τ the proper time along ζ. If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (14.1) becomes

$$\frac{\partial^2\eta^a}{\partial\tau^2}+R^{a}_{0b0}\eta^b=0 \quad (a,b=1,2,3,) \tag{14.2}$$

Here η^a are the physical components of the infinitesimal displacement and R^{a}_{0b0} some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One

can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

Now the Newtonian equation corresponding to (14.2) is

$$\frac{\partial^2\eta^a}{\partial\tau^2}+\frac{\partial^2 v}{\partial x^a\partial x^b}\eta^b=0 \tag{14.3}$$

It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence $R^{a}_{0b0}\sim\frac{\partial^2 v}{\partial x^a\partial x^b}$ between equations (14.2) and (14.3), for the respective empty-space equations may be written $R^{a}_{0a0}=0$ and $\frac{\partial^2 v}{\partial x^a\partial x^b}=0$. (Details of this work are in the course of publication in *Acta Physica Polonica.*)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

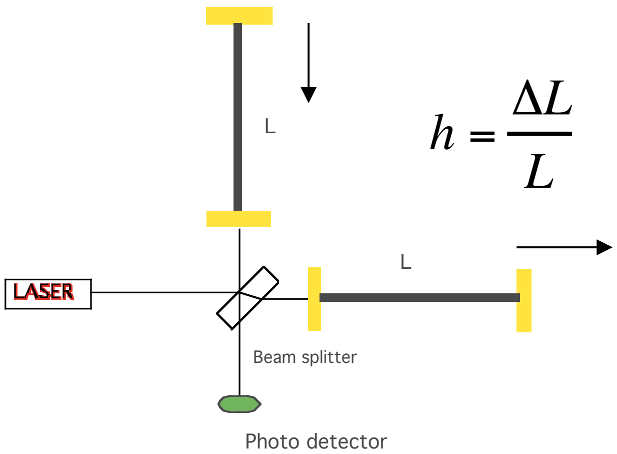
LICHNEROWICZ: Is it possible to study stability problems for η?

PIRANI: It is the same as the stability problem in classical mechanics, but I haven't tried to see for which kind of Riemann tensor it would blow up.

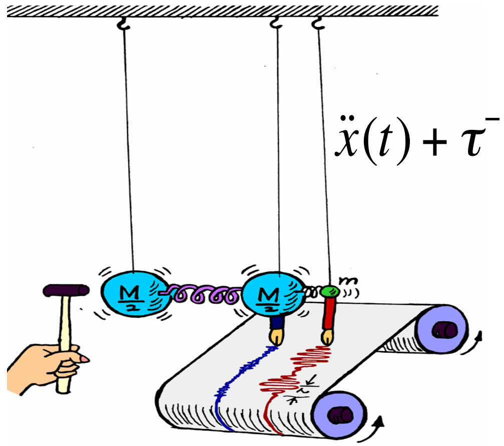
- **GWs are detectable in principle**
  The equation for geodetic deviation is the basis for all experimental attempts to detect GWs:

$$\frac{d^2\delta l^j}{dt^2} = -R_{joko} l^k = \frac{1}{2}\frac{\partial^2 h_{jk}}{\partial t^2} l^k$$

- **GWs change (δl) the distance (l) between freely-moving particles in empty space.**
  They change the proper time taken by light to pass to and fro fixed points in space
  In a system of particles linked by non gravitational (ex.: elastic) forces, GWs perform work and deposit energy in the system



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



$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{l}{2}\ddot{h}(t)$$

Weber

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.

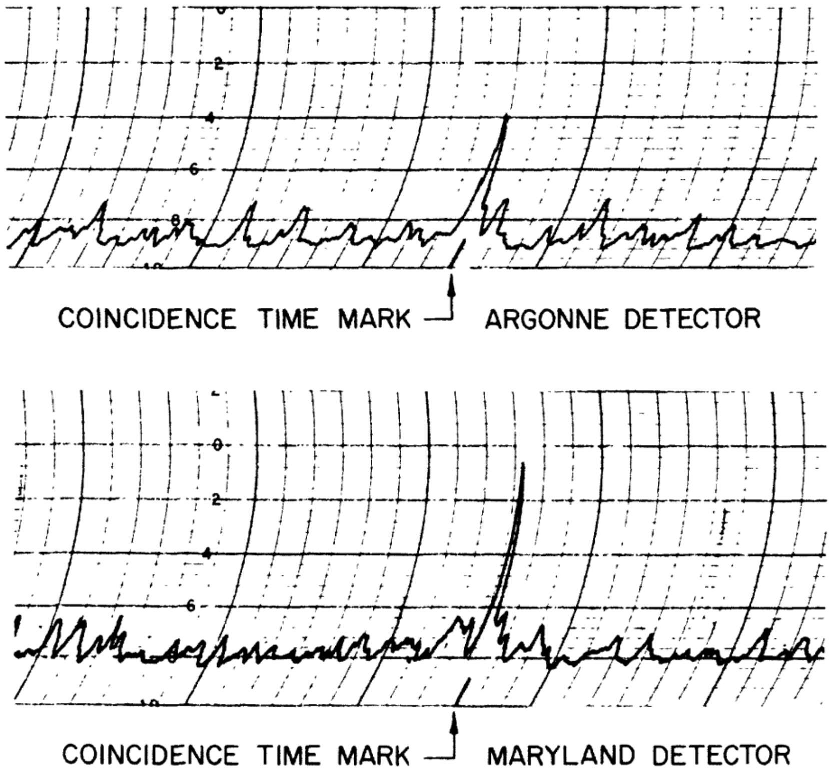


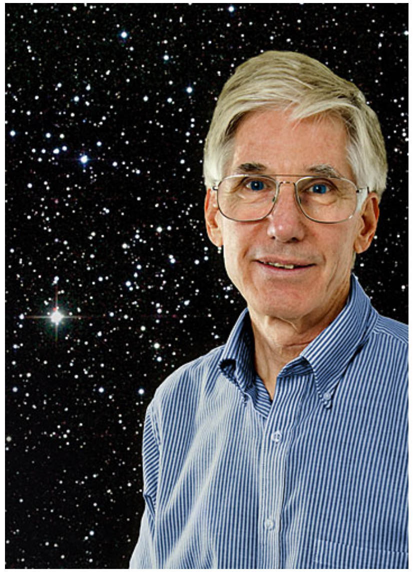
FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

Joining the quest …

Ron Drever and Jim Hough, Glasgow

Guido Pizzella, Rome

Richard Garwin, IBM



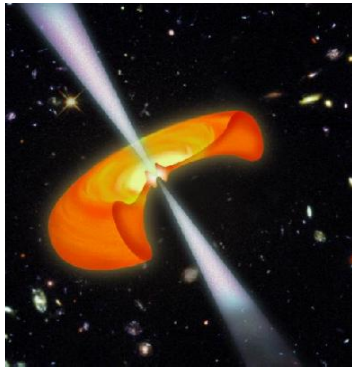
Tony Tyson, Bell Labs

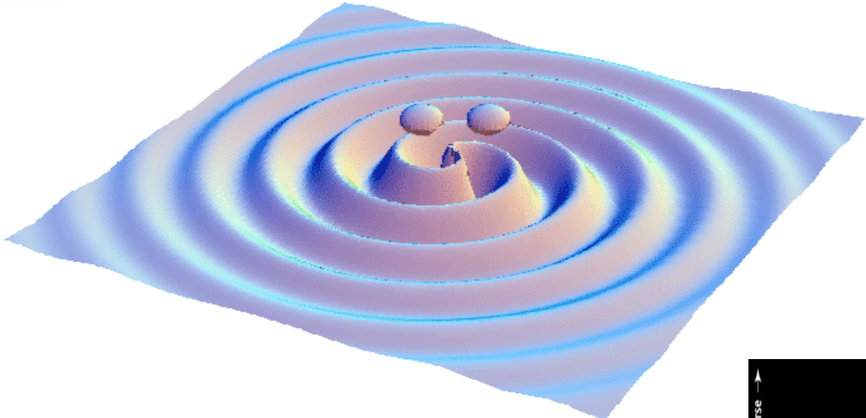
GW OBJECTIVES

FIRST DETECTION
test Einstein prediction

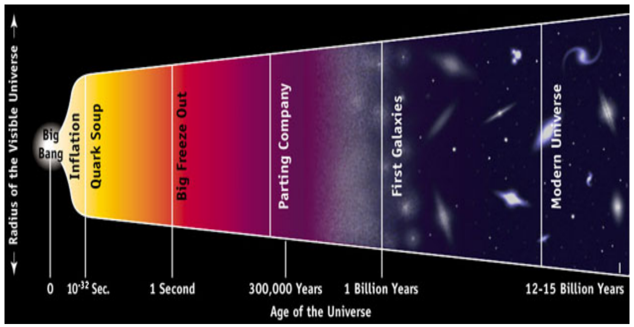
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

ASTRONOMY & ASTROPHYSICS
look beyond the visible,
understand Black Holes,
Neutron Stars and supernovae
understand GRB

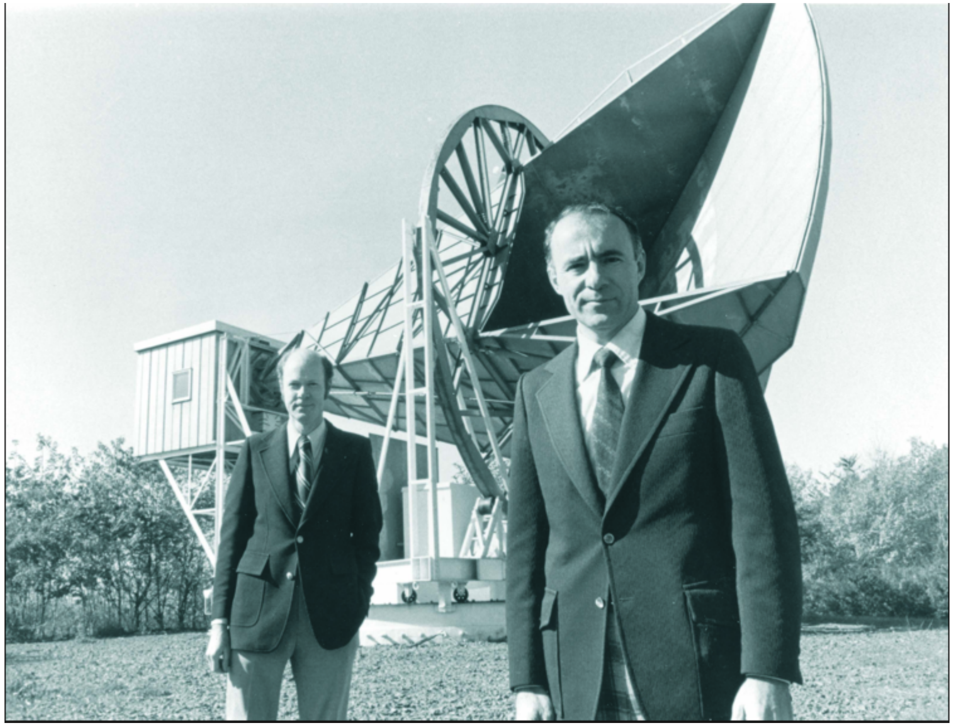




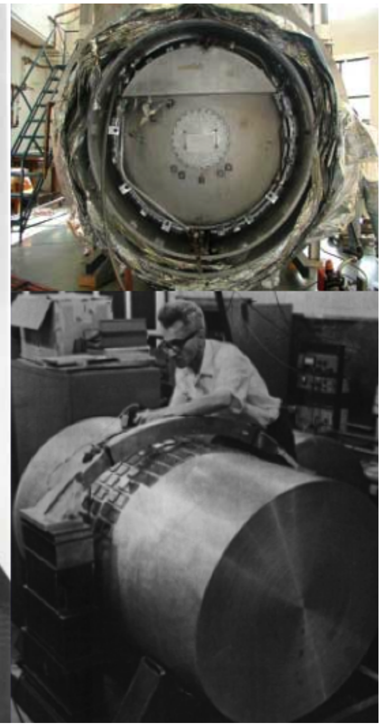
COSMOLOGY
the Planck time:
look as back in time as theorist can conceive

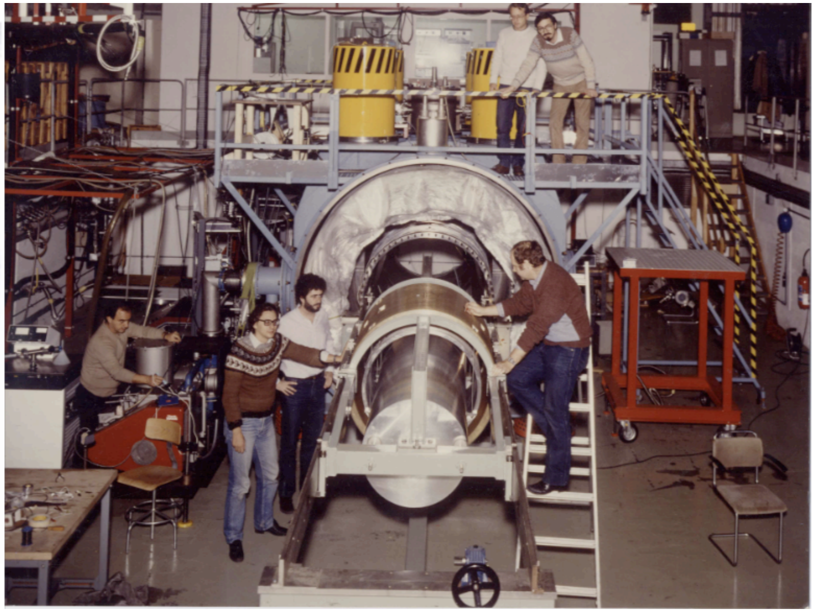


Durante gli anni sessanta Amaldi ha cercato di spingere i fisici italiani nella direzione di nuove ricerche, allora nella fase nascita:
la radiazione di fondo infrarosso e le onde gravitazionali (dopo gli esperimenti di Penzias e Wilson e di Weber).



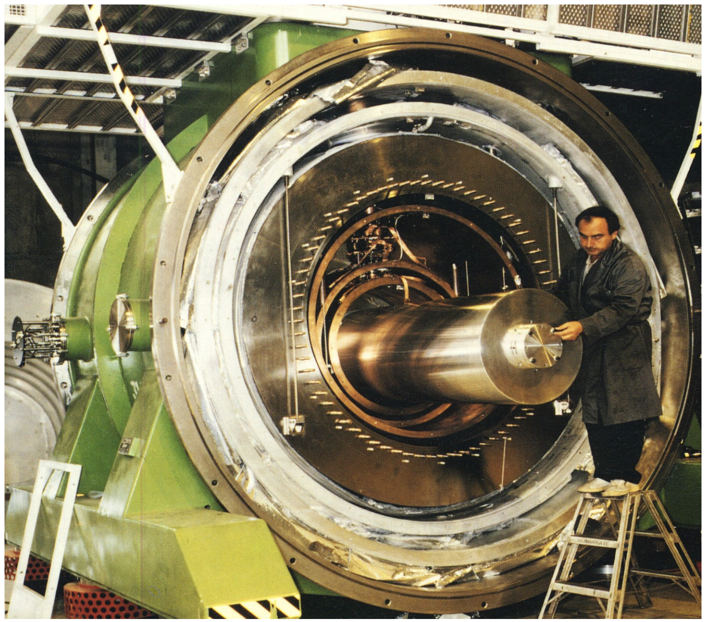
Joseph Weber 1919-2000

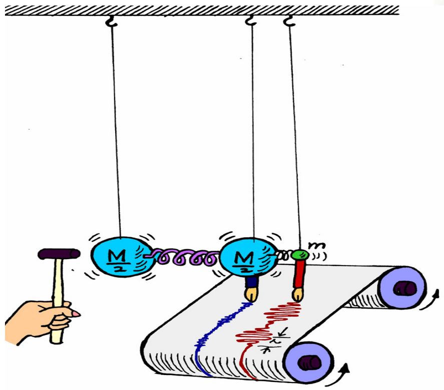




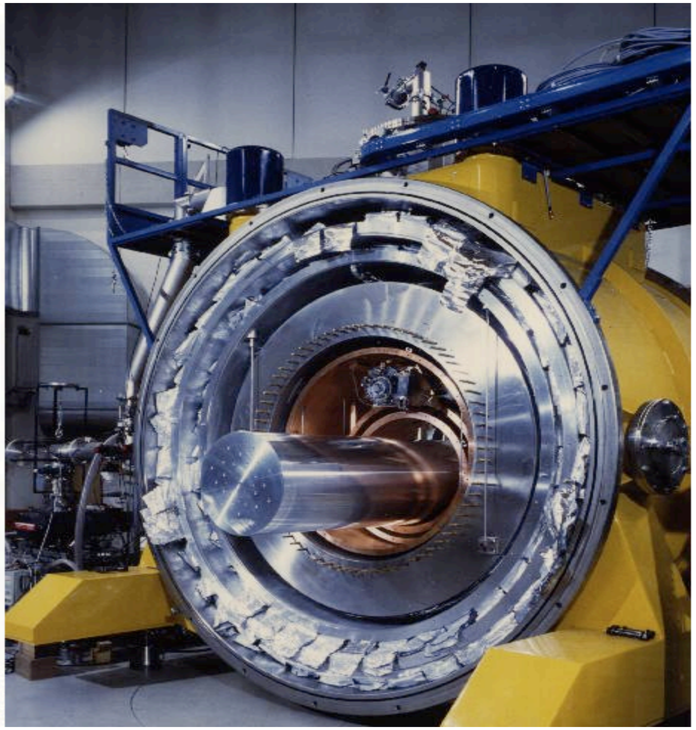
Explorer, CERN

Nautilus, LNF



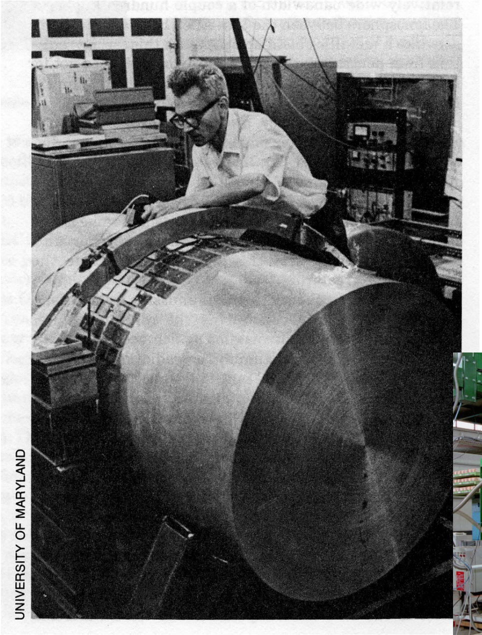


Auriga, LNL

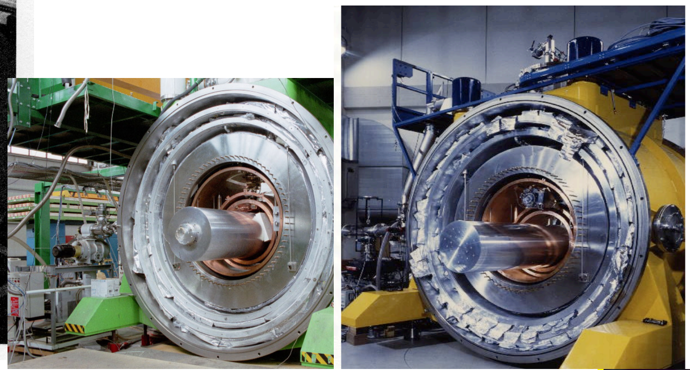


Some perspective: 50 years of attempts at detection:

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

1997: GWIC was formed

2000’ - : Large Interferometers

GWIC
Gravitational Wave International Committee

https://gwic.ligo.org/

The Gravitational Wave International Committee:

GWIC, the Gravitational Wave International Committee, was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. It is associated with the International Union of Pure and Applied Physics as its Working Group WG.11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC).

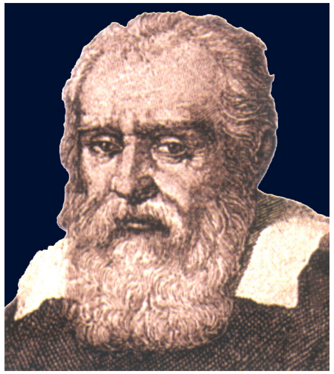
GWIC's Goals:

- Promote international cooperation in all phases of construction and scientific exploitation of gravitational-wave detectors;
- Coordinate and support long-range planning for new instrument proposals, or proposals for instrument upgrades;
- Promote the development of gravitational-wave detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics;
- Organize regular, world-inclusive meetings and workshops for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and foster research and development of new technology;
- Represent the gravitational-wave detection community internationally, acting as its advocate;
- Provide a forum for project leaders to regularly meet, discuss, and jointly plan the operations and direction of their detectors and experimental gravitational-wave physics generally.

iety.

News

- GWIC is now an IUPAP Working group (WG11)
- GWIC thesis Prize named after Stefano Braccini
- EC elected GWIC Chair for two more years



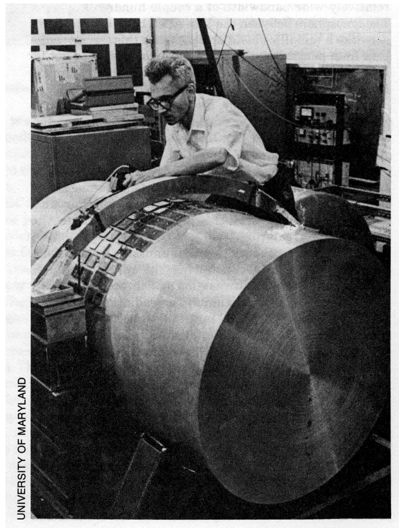
Experimental gravitational physicists are heirs to several great traditions:

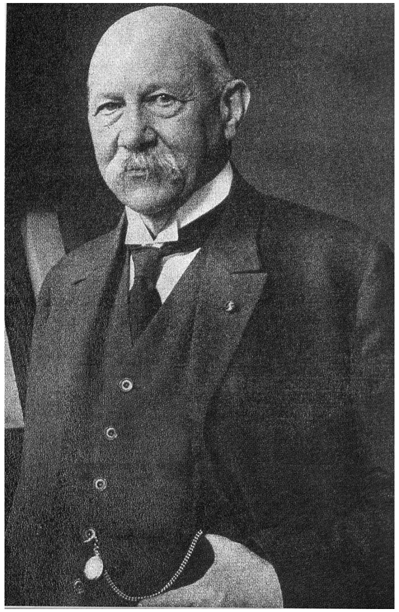
- High precision mechanical experiments (Cavendish, Eotvos, Dicke..)
  detection of weak forces applied on mechanical test bodies

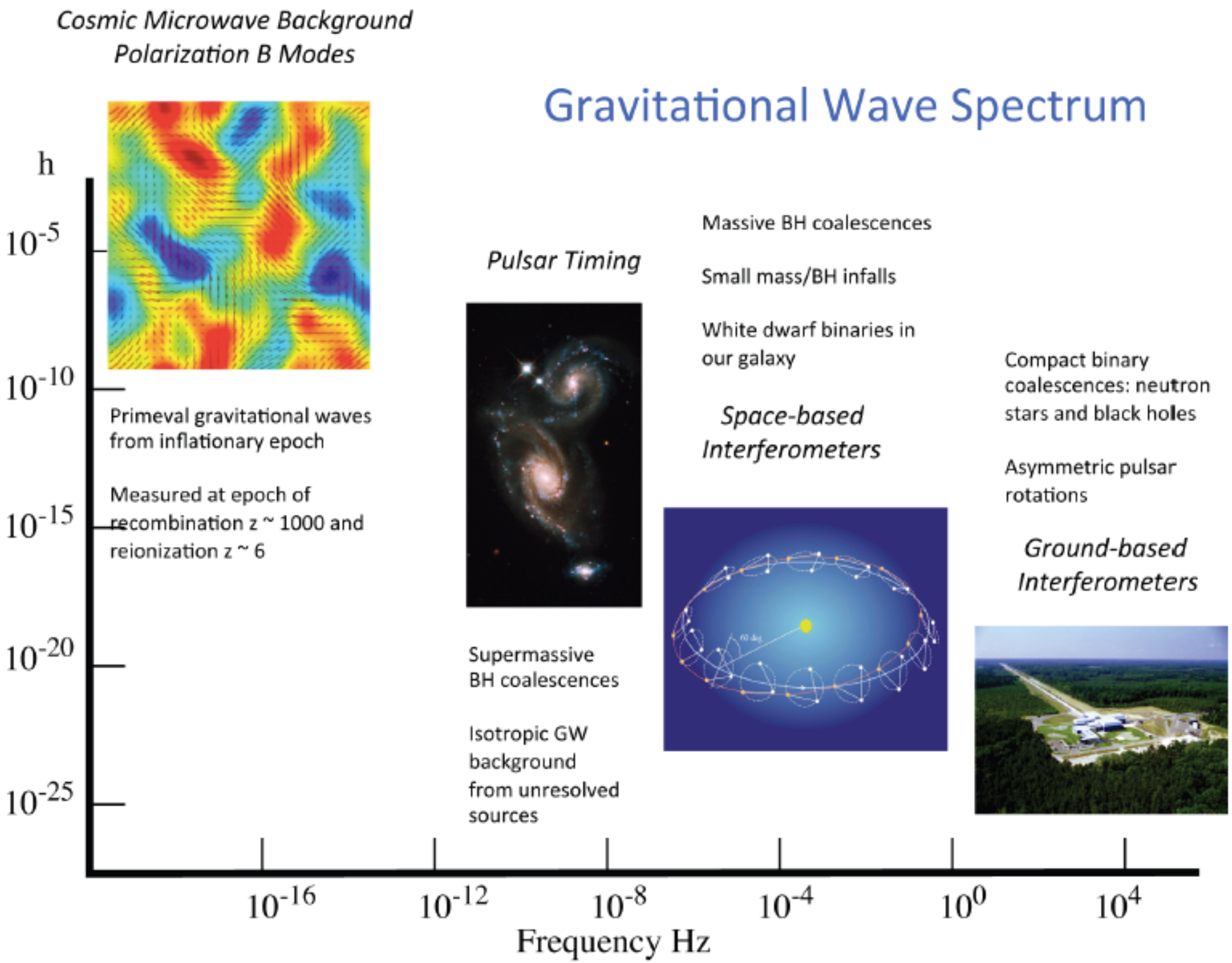
- High precision optical measurements (Michelson, laser developers…)

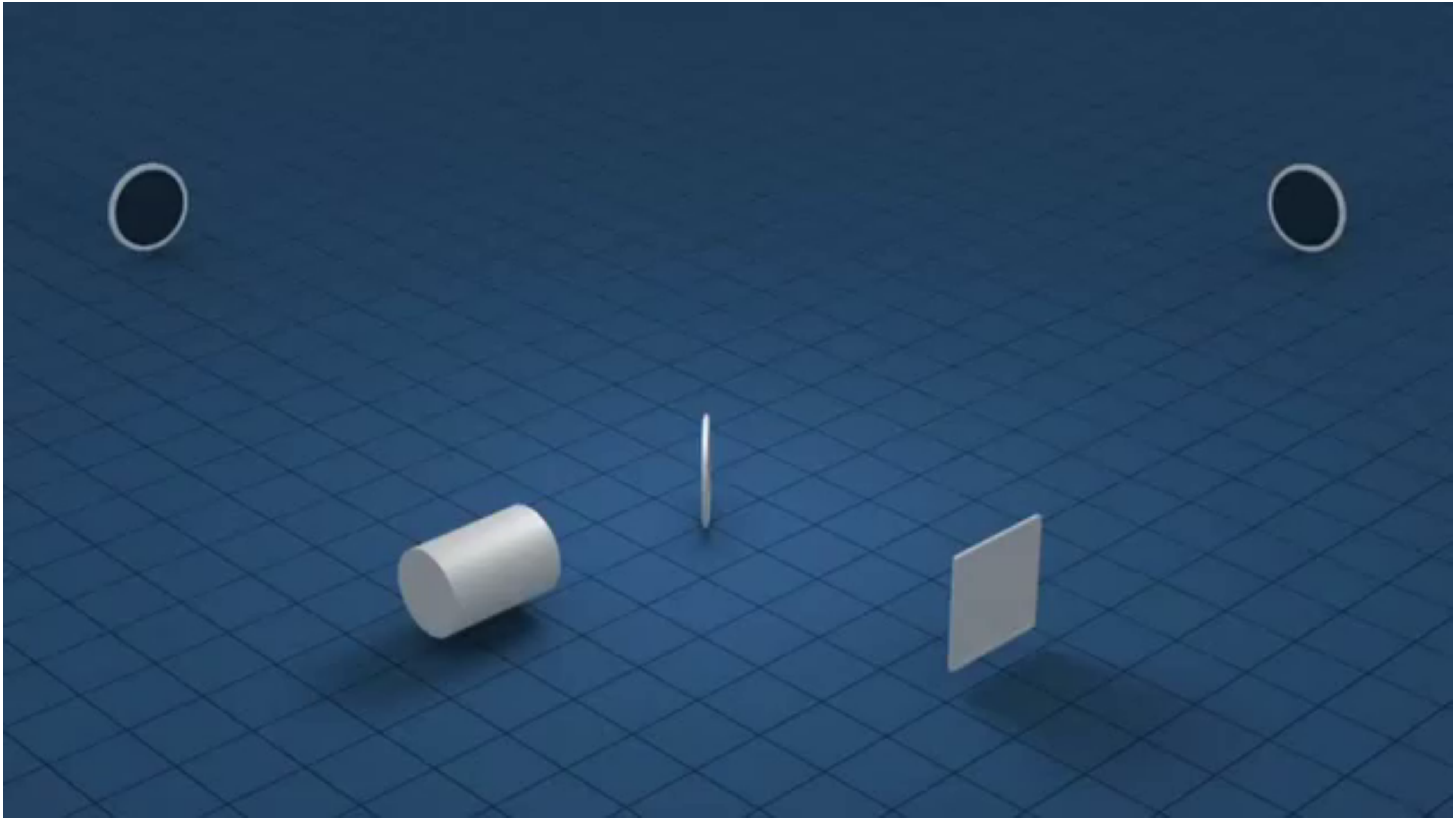
- Operation of ultraprecise e-m measurement systems (microwave pioneers of World War II)

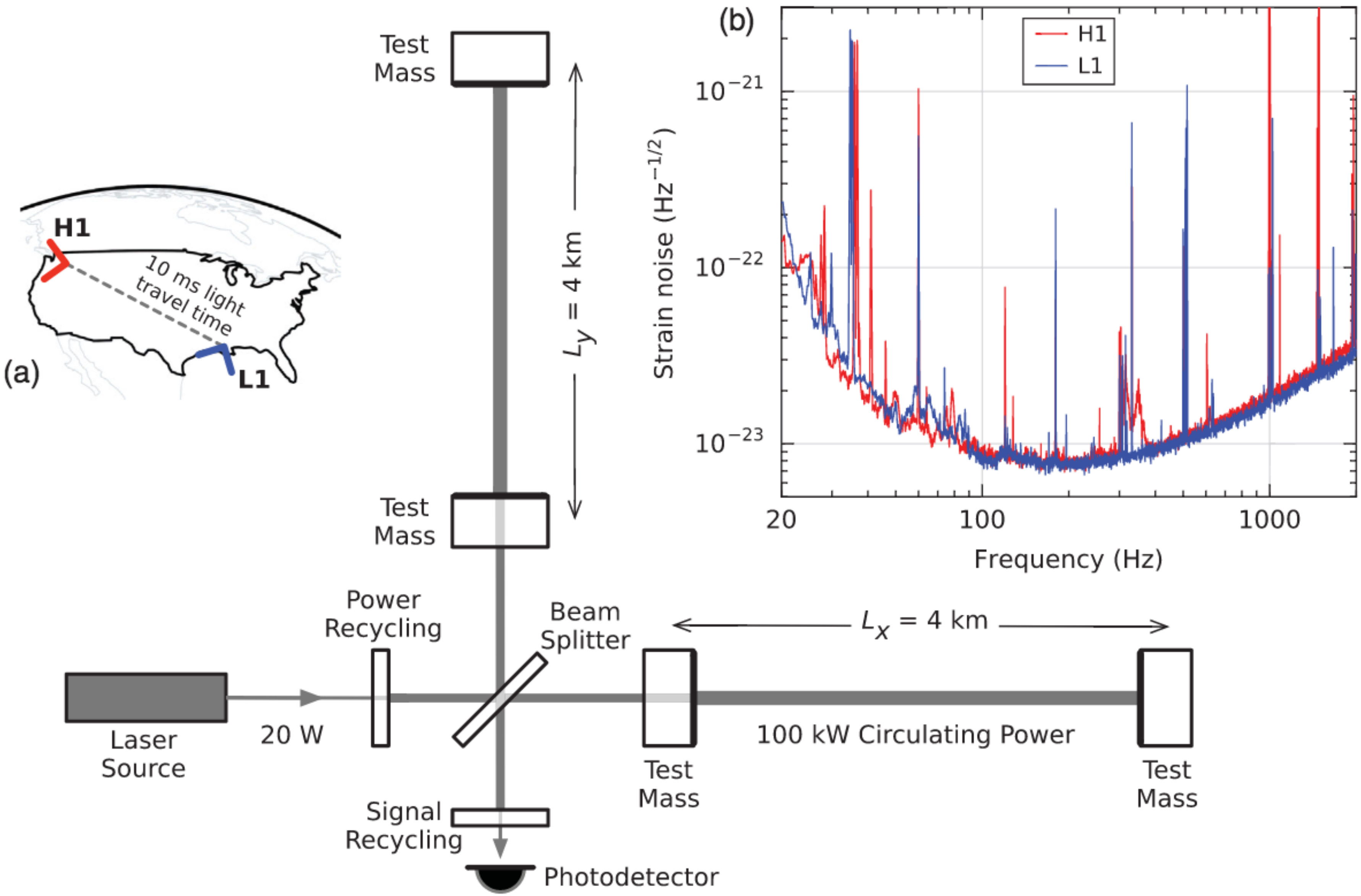
- Low temperature physics (K. Onnes)
  superfluids and superconductors technology





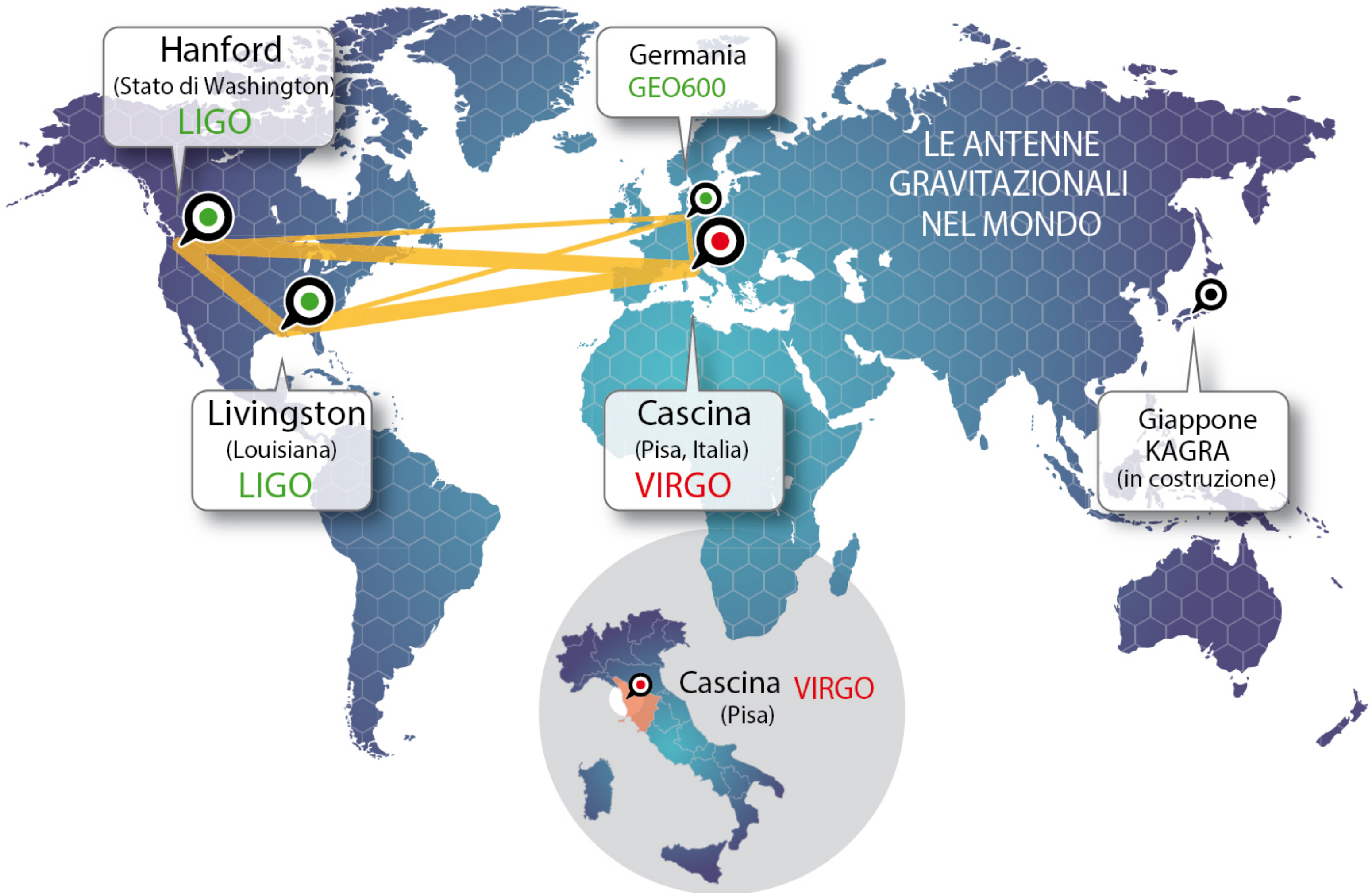

Gravitational Wave Spectrum
Cosmic Microwave Background
Polarization B Modes
h
10-5
10-10
10-15
10-20
10-25
Primeval gravitational waves
from inflationary epoch
Measured at epoch of
recombination z ~ 1000 and
reionization z ~ 6
Pulsar Timing
Supermassive
BH coalescences
Isotropic GW
background
from unresolved
sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in
our galaxy
Space-based
Interferometers
Compact binary
coalescences: neutron
stars and black holes
Asymmetric pulsar
rotations
Ground-based
Interferometers
10-16
10-12
10-8
10-4
100
104
Frequency Hz





(a)
H1
L1
10 ms light travel time
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector

Global Network of Detectors



LIGO Scientific Collaboration

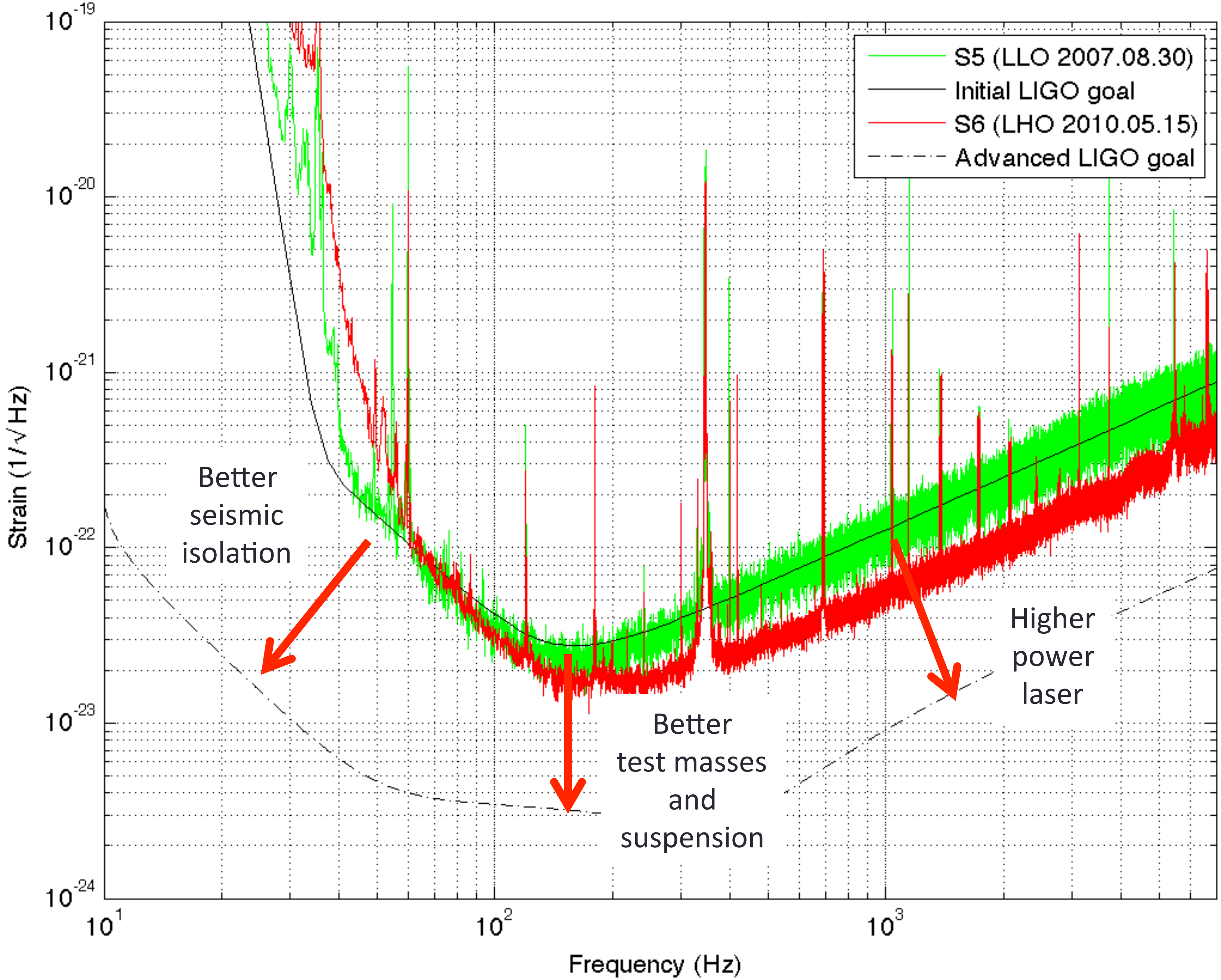
www.ligo.org

900+ members, 80+ institutions, 16 countries

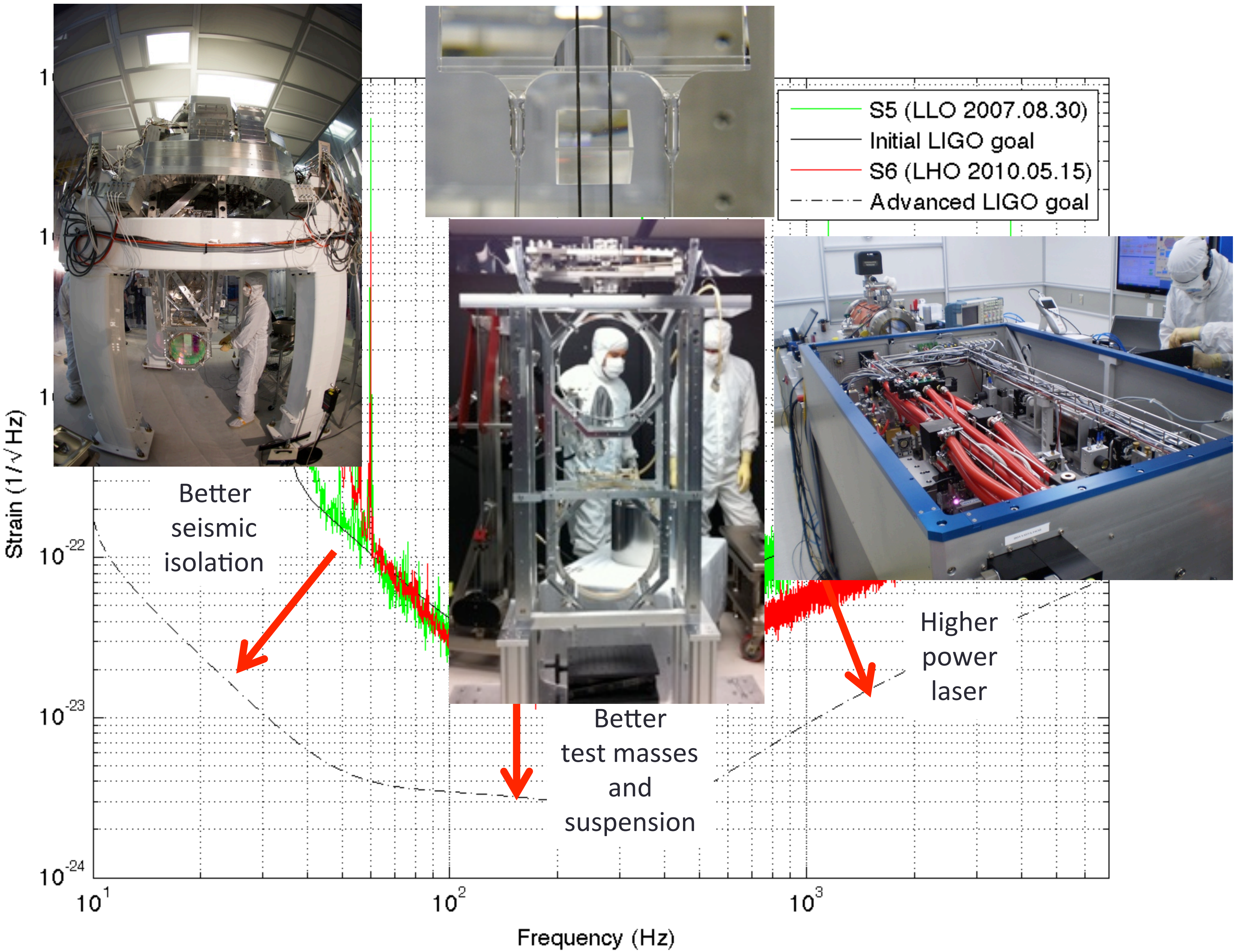
Virgo Collaboration

- 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



S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
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)
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

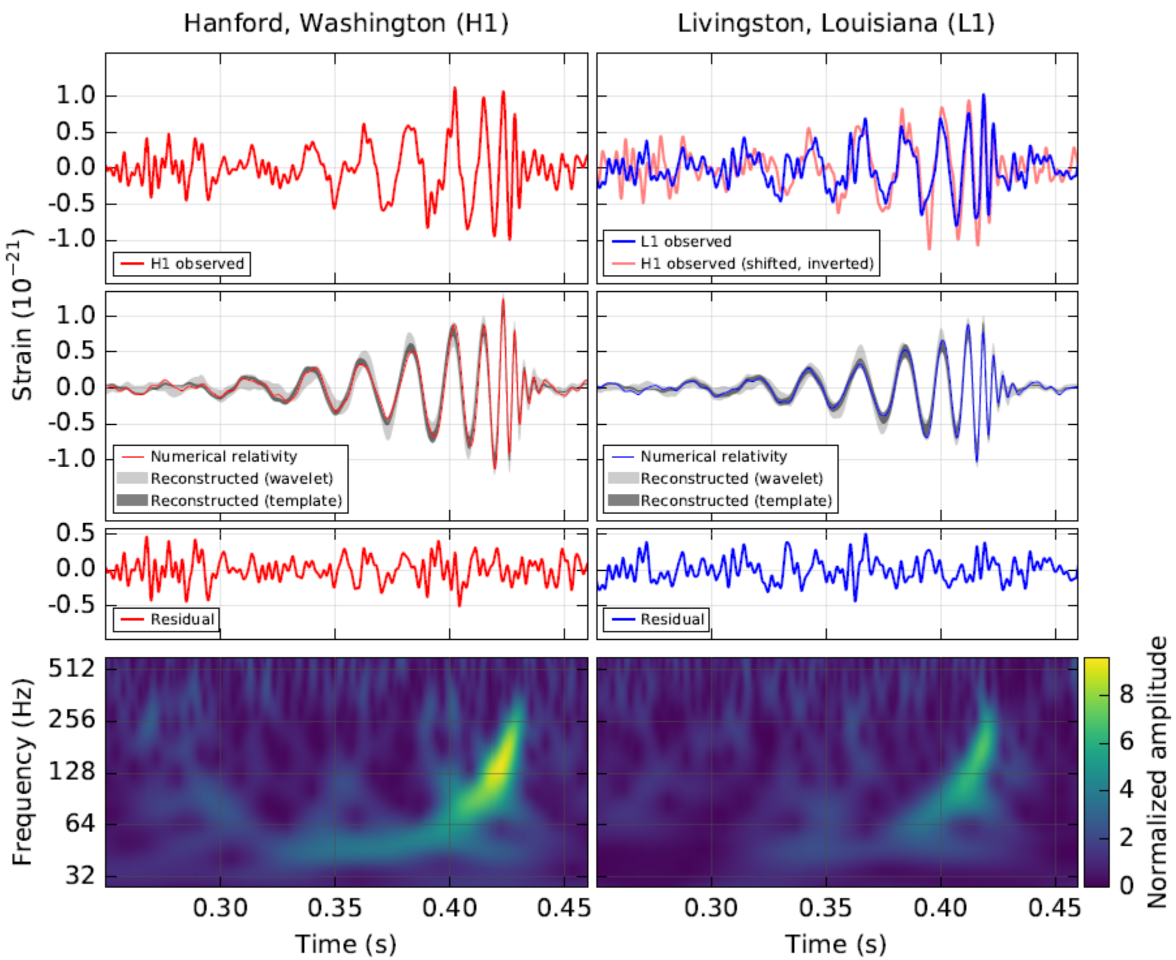
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 Hz to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It 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

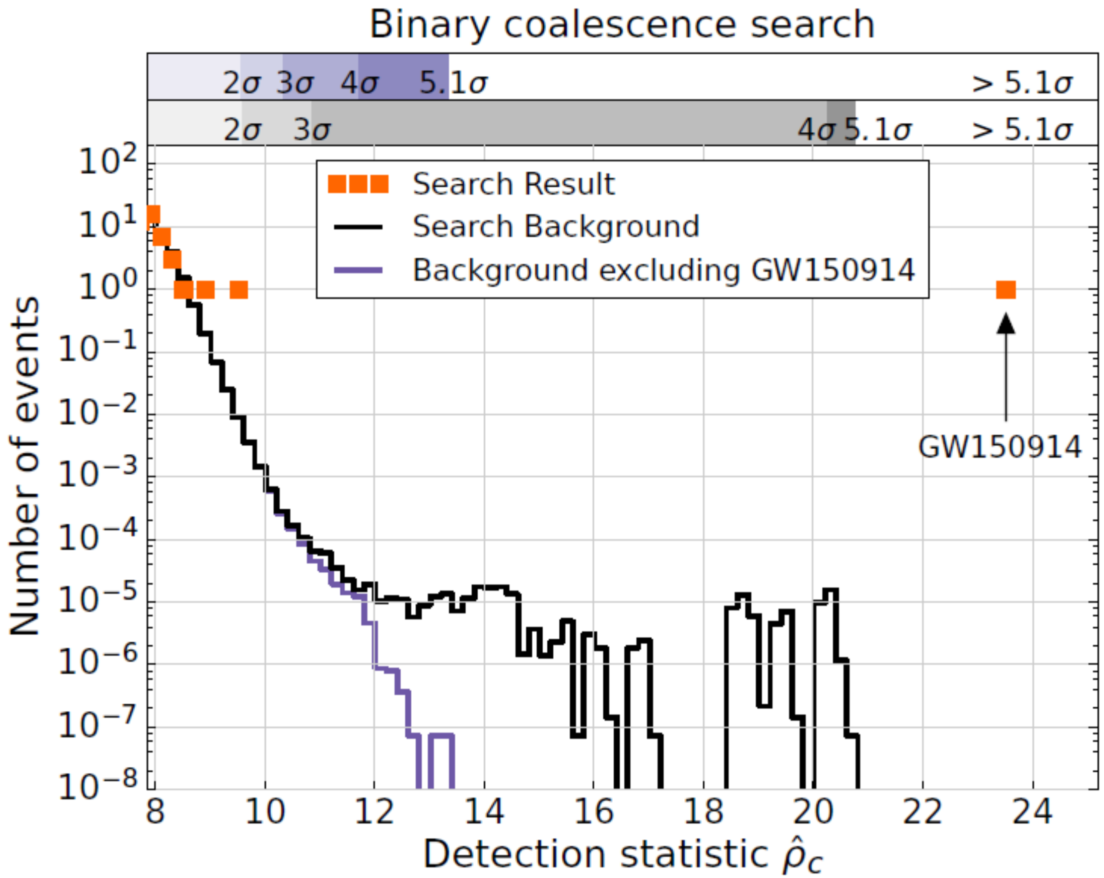
- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot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

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



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

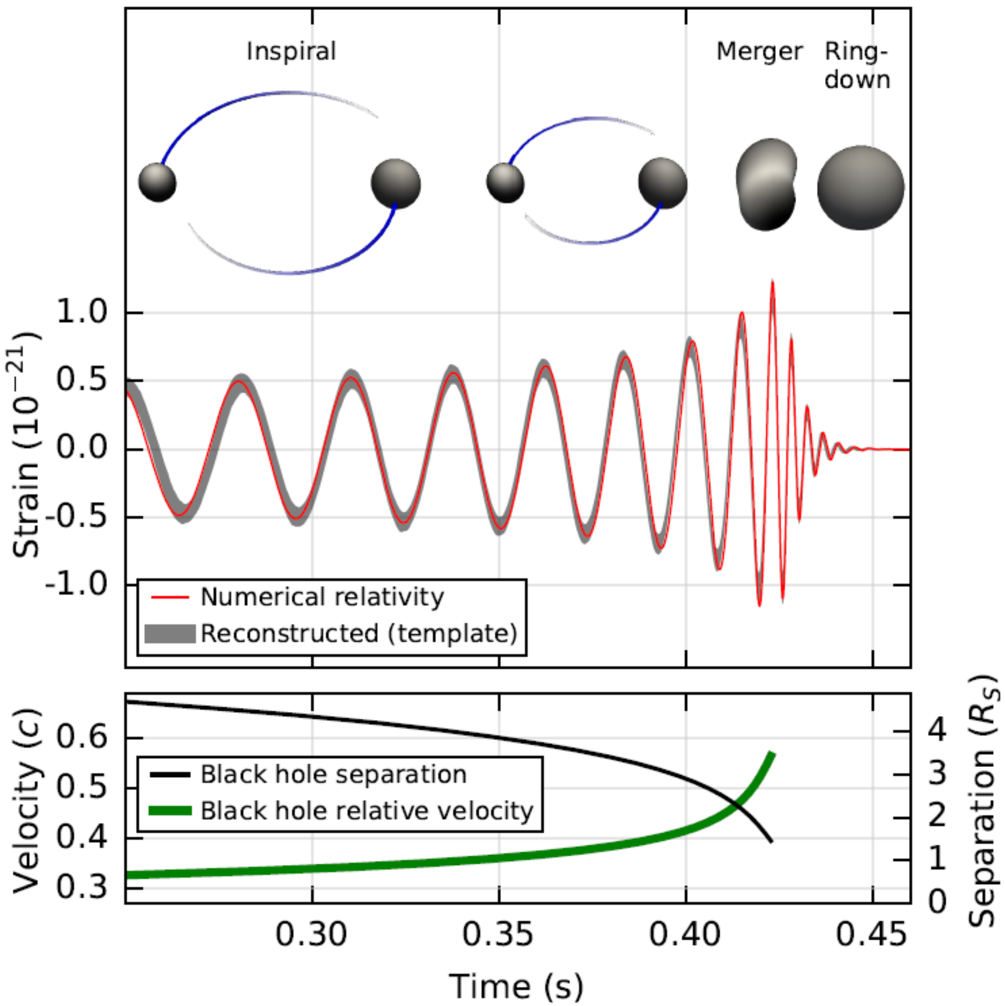
GW150914: Estimated Strain Amplitude

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

- 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 $v/c = (GM_{tot}\pi f_{GW}/c^3)^{1/3}$

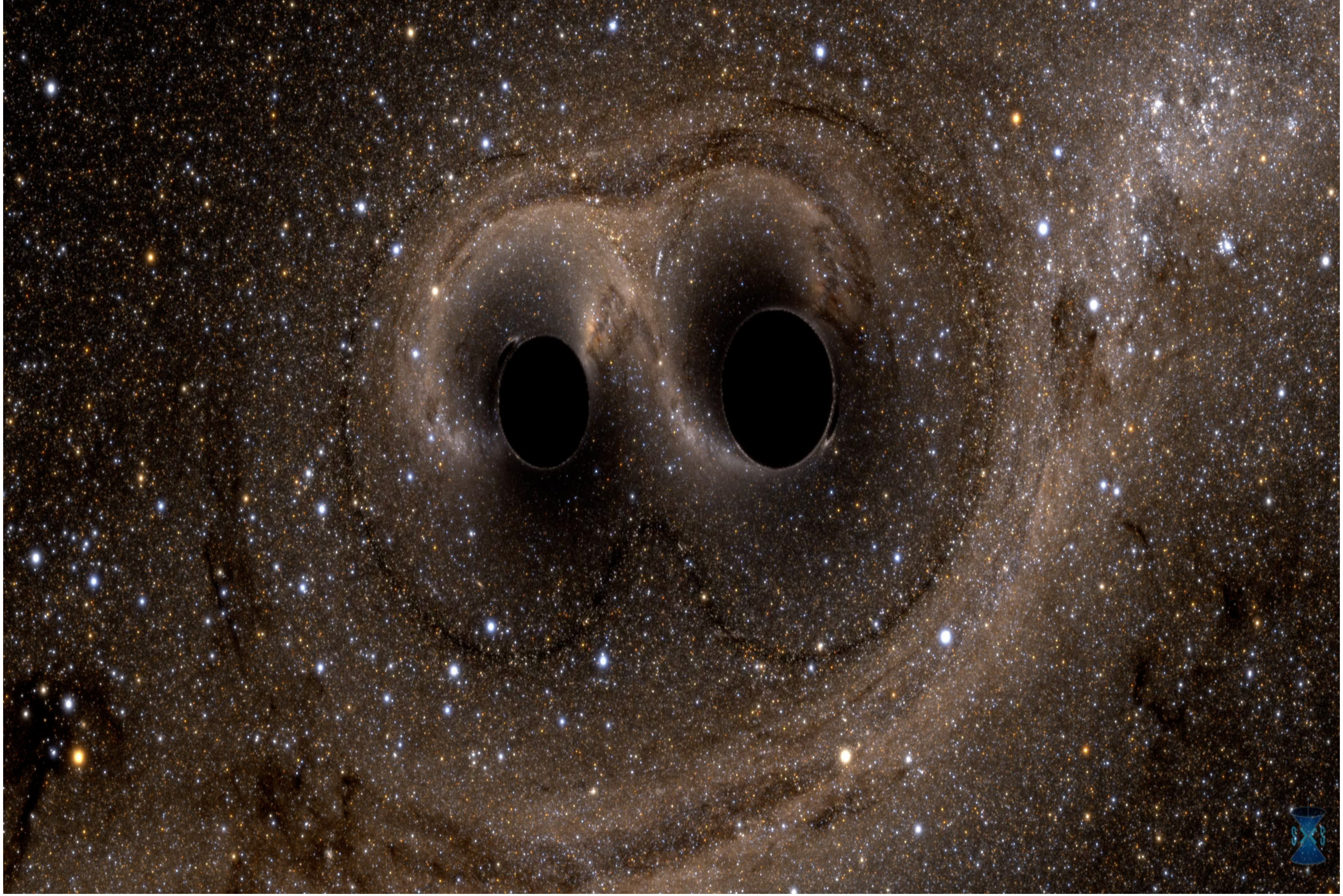
Binary Black Hole System

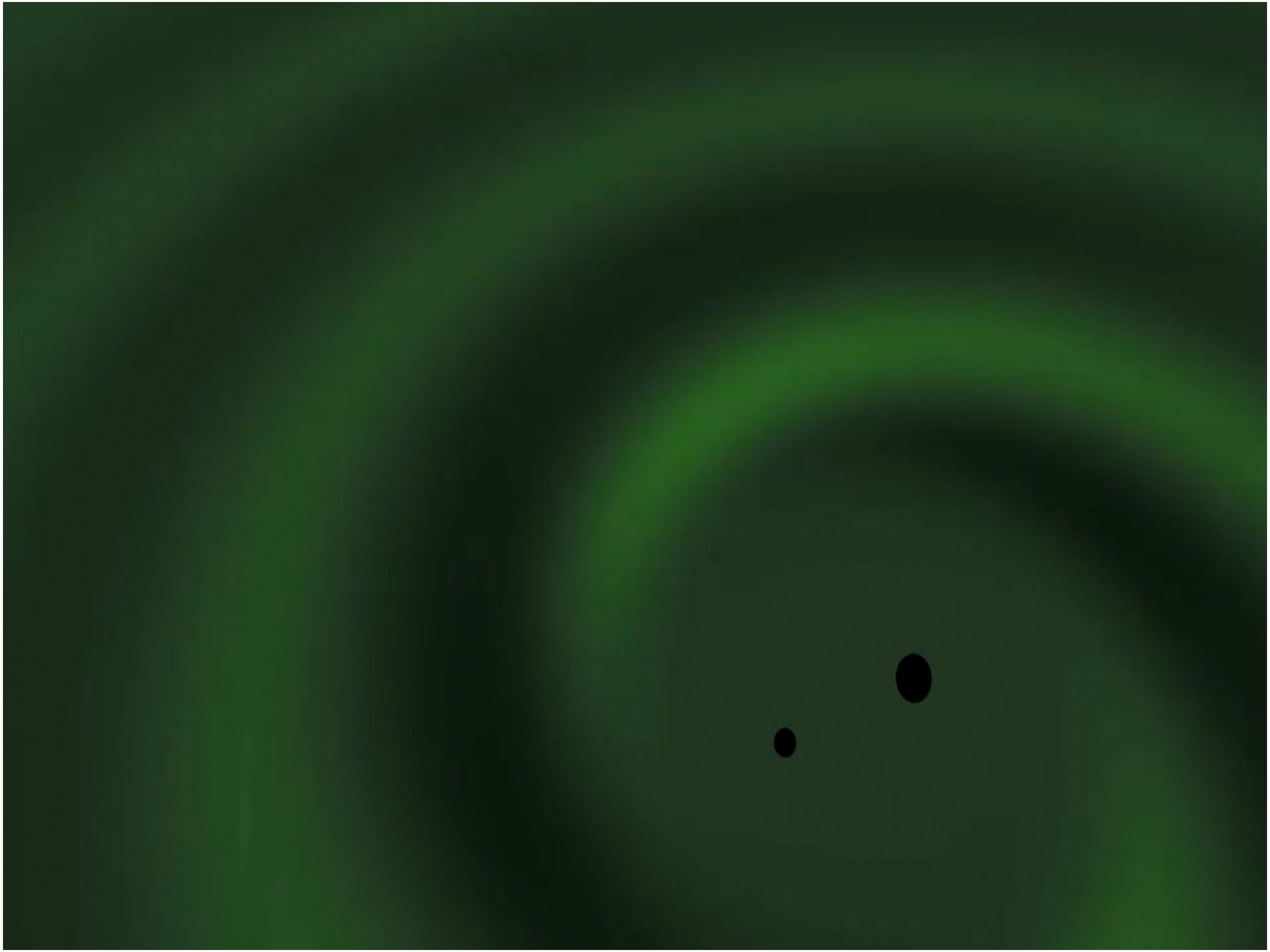
- M1 = 36 +5/-4 M_{sol}
- M2 = 29 +/- 4 M_{sol}
- Final Mass = 62 +/- 4 M_{sol}
- distance=410 +160/-180 MPc (redshift z = 0.09)

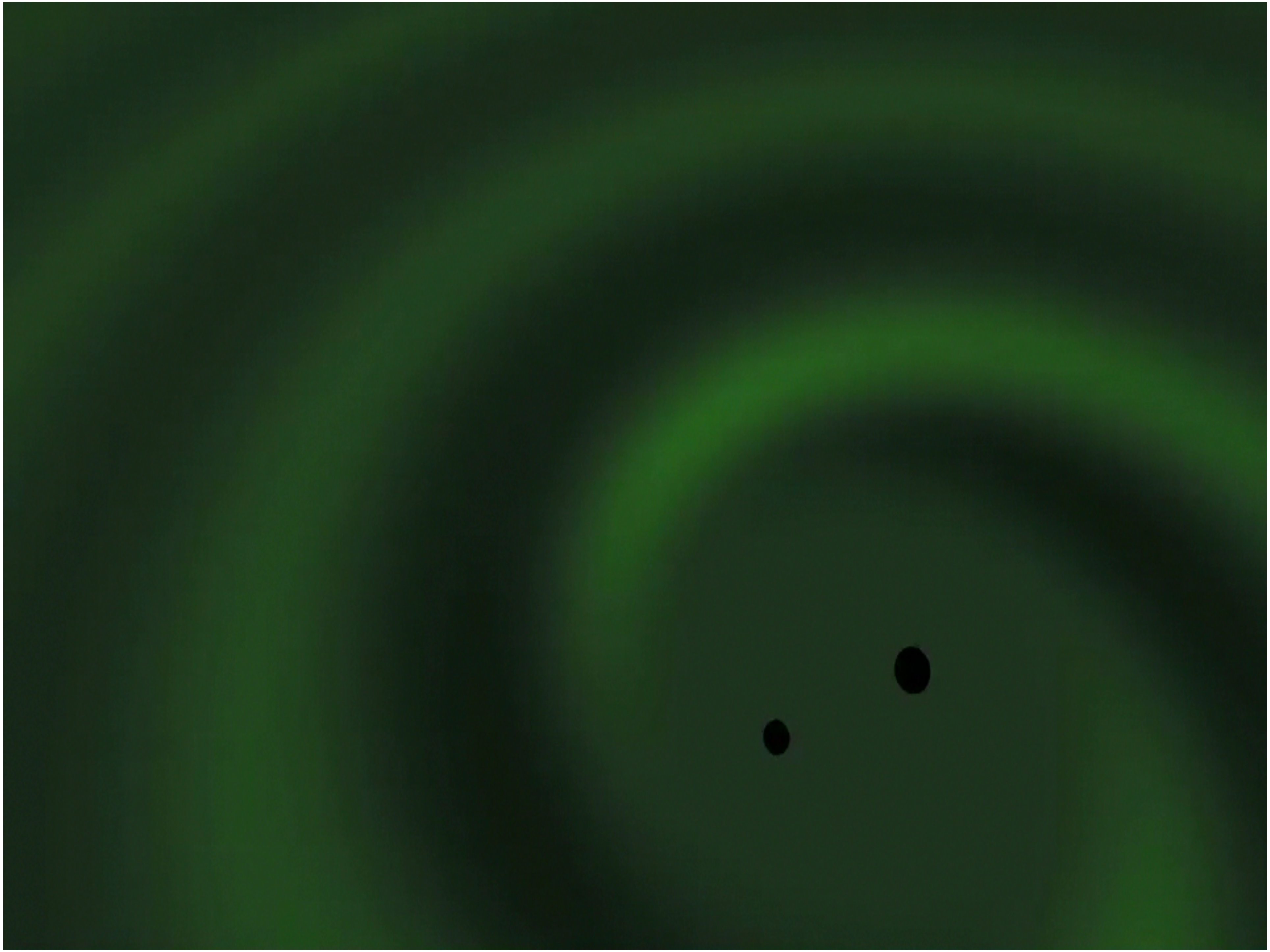


Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670







Measuring the parameters

- Orbits decay due to emission of gravitational waves
  - Leading order determined by "chirp mass"

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

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z)m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession
- Sky location, and binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

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 $\times 10^{56}$ erg, and the spin of the final black hole < 0.7

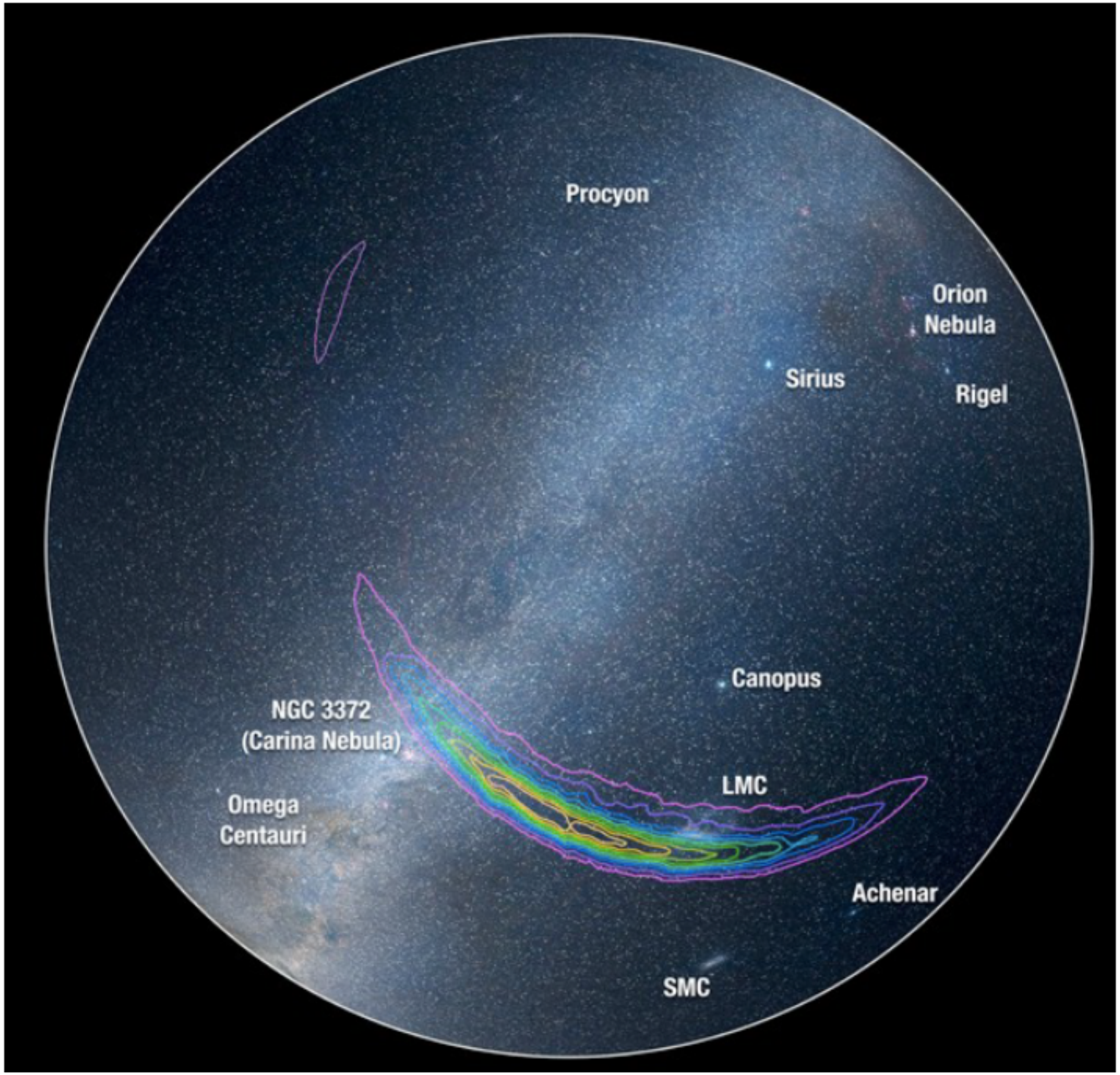
Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

Gravitational-Wave Sky Posteriors

Sky areas broadly consistent with simply triangulation, and mostly cross-consistent

Triangulation ring consistent with time delay of about ~7 ms

Search area: 620 sq. degrees to cover:




TRENTINO
ALTO ADIGE
Dobbiaco
Tarvisio
FRIULI
VENEZIA
GIULIA
Gorizia
Trieste
Domodossola
Sondrio
Trento
VALLE
D'AOSTA
Como
LOMBARDIA
Vicenza
Treviso
VENETO
Susa
Novara
Milano
Brescia
Verona
Padova
Venezia
Torino
Pavia
Cremona
Mantova
PIEMONTE
Piacenza
Parma
Modena
Ferrara
Cuneo
LIGURIA
EMILIA ROMAGNA
Genova
Bologna
Forlì
Rimini
Savona
La Spezia
Lucca
Firenze
Fano
Ventimiglia
Pisa
TOSCANA
Ancona
Livorno
Arezzo
MARCHE
Siena
Perugia
Tolentino
Civitanova Marche
Piombino
UMBRIA
Ascoli Piceno
Grosseto
Terni
Teramo
Pescara
L'Aquila
Civitavecchia
LAZIO
ABRUZZO
Termoli
Roma
Sulmona
MOLISE
Frosinone
Campobasso
Manfredonia
Foggia
Latina
Caserta
Benevento
Bari
Gaeta
CAMPANIA
PUGLIA
Brindisi
Olbia
Porto Torres
Napoli
Avellino
Potenza
Matera
Taranto
Sassari
Salerno
BASILICATA
Lecce
Nuoro
SARDEGNA
Oristano
CALABRIA
Iglesias
Cosenza
Cagliari
Crotone
Catanzaro
Messina
Palermo
Cefalù
Trapani
Reggio Calabria
SICILIA
Mazara del Vallo
Caltanissetta
Catania
Agrigento
Siracusa
Ragusa

GW150914 papers

- **Detection Paper**
  Phys. Rev. Lett. 116, 061102 (2016) arXiv:1602.03837
- **Astrophysics implications**
  ApJL, 818, L22, 2016
  arXiv:1602.03846
- **Test of GR**
  arXiv:1602.03841
- **Rates**
  arXiv:1602.03842
- **Stochastic Background**
  arXiv:1602.03847
- **EM follow-up**
  arxiv.org/abs/1602.08492
- **High Energy Neutrinos**
  arxiv.org/abs/1602.05411
- **CBC searches**
  arXiv:1602.03839
- **Unmodeled searches**
  arXiv:1602.03843
- **Parameter Estimation**
  arXiv:1602.03840
- **Instrument**
  arXiv:1602.03838
- **DetChar**
  arXiv:1602.03844
- **Calibration**
  arXiv:1602.03845
- **Public data release**
  https://losc.ligo.org/events/GW150914

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)

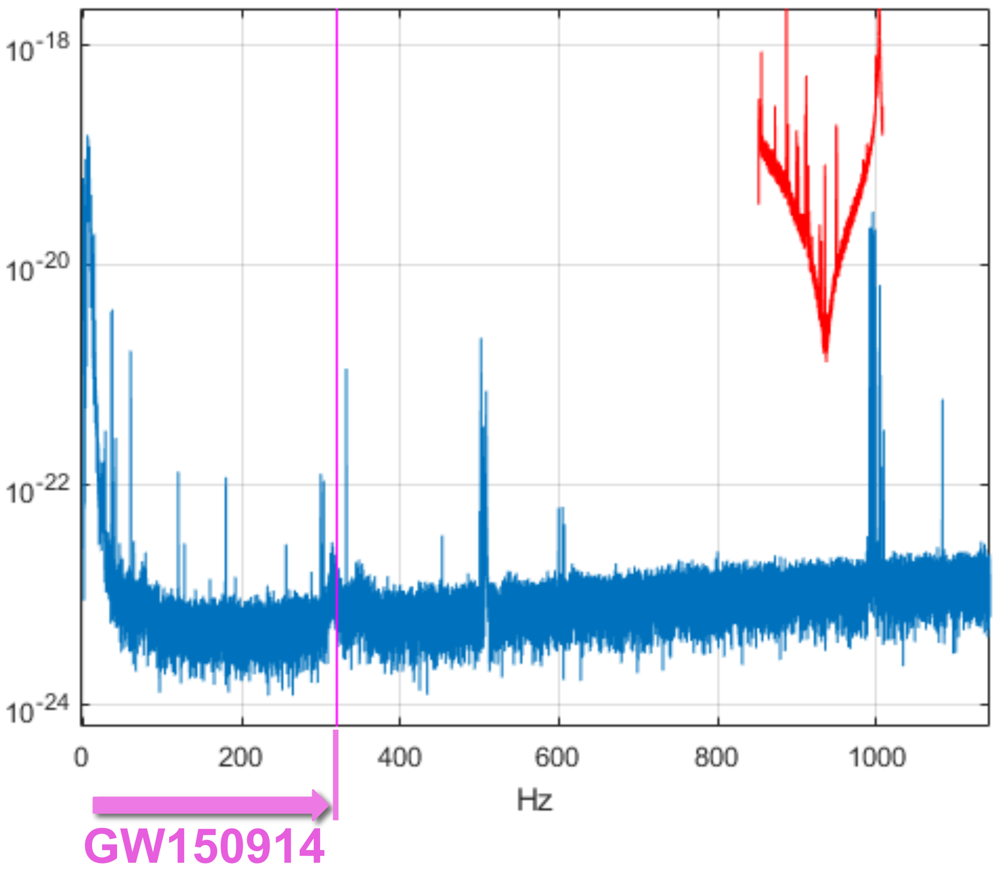
$$\phi_{MG}(f) = -(\pi D c) / [\ \lambda_g^{\ 2} (1+z) f\ ]$$

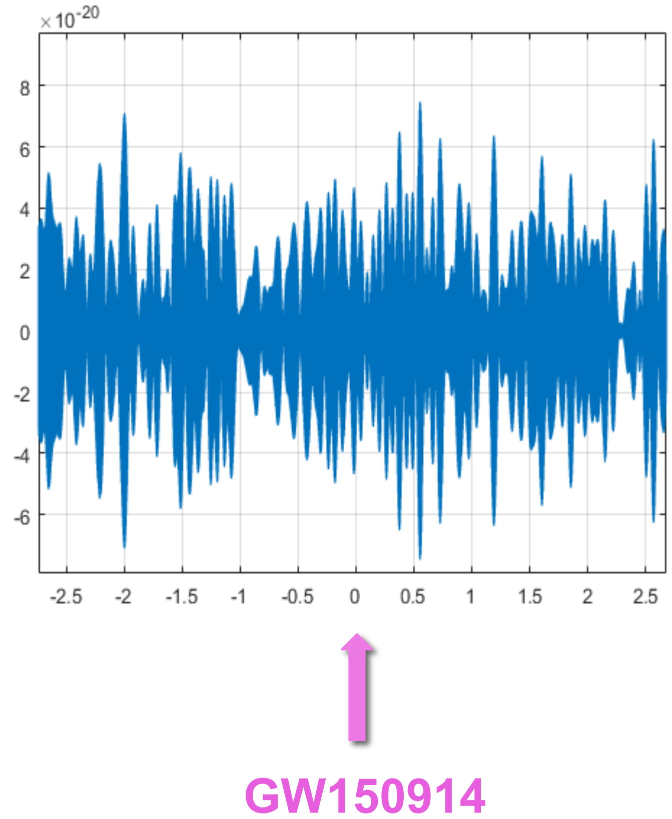
- Our constrain on the 1PN terms permit to derive a down limit for the Compton wavelength of the graviton

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

- 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)

Nautilus - September 14, 2015



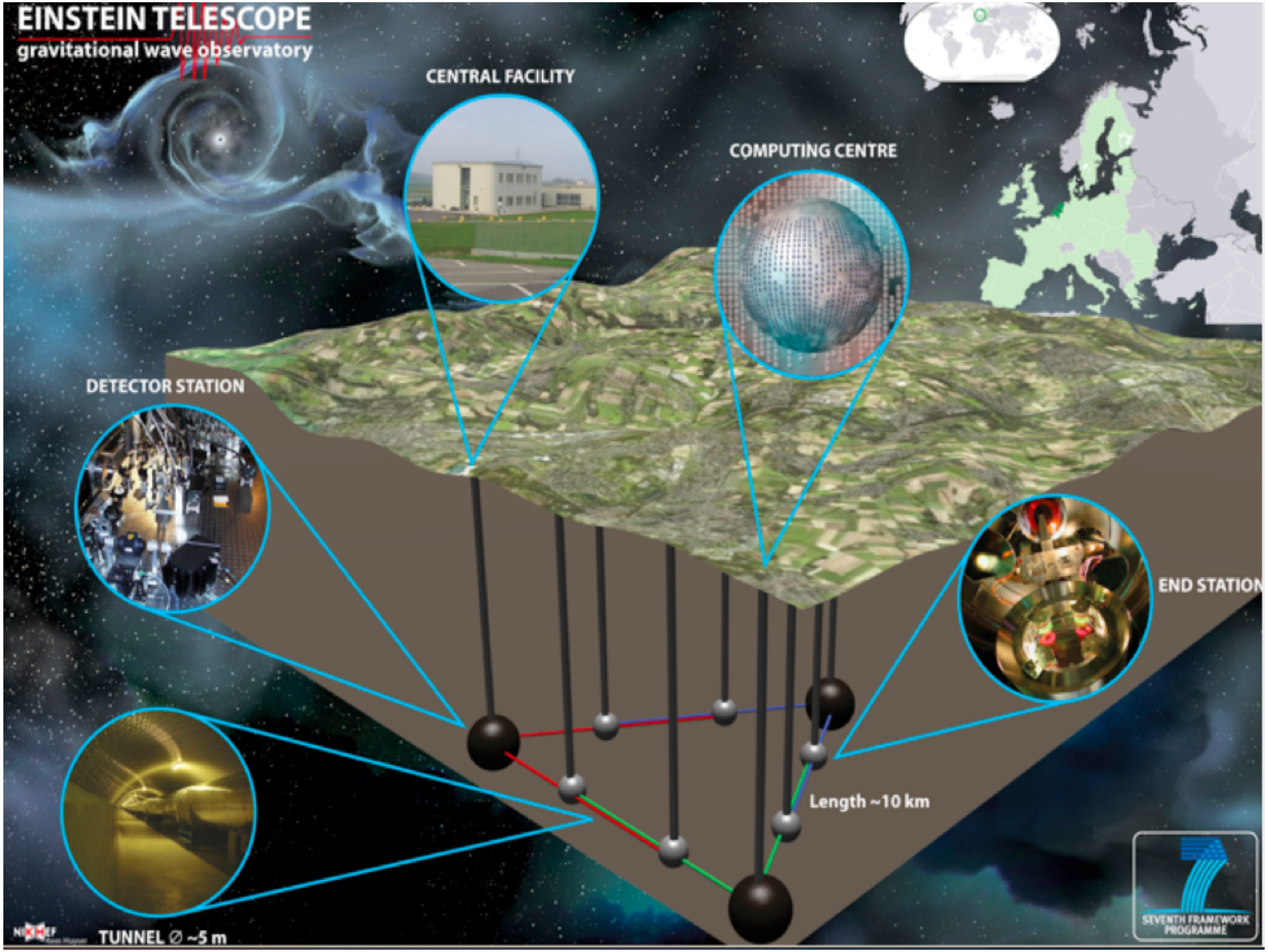


Conclusions

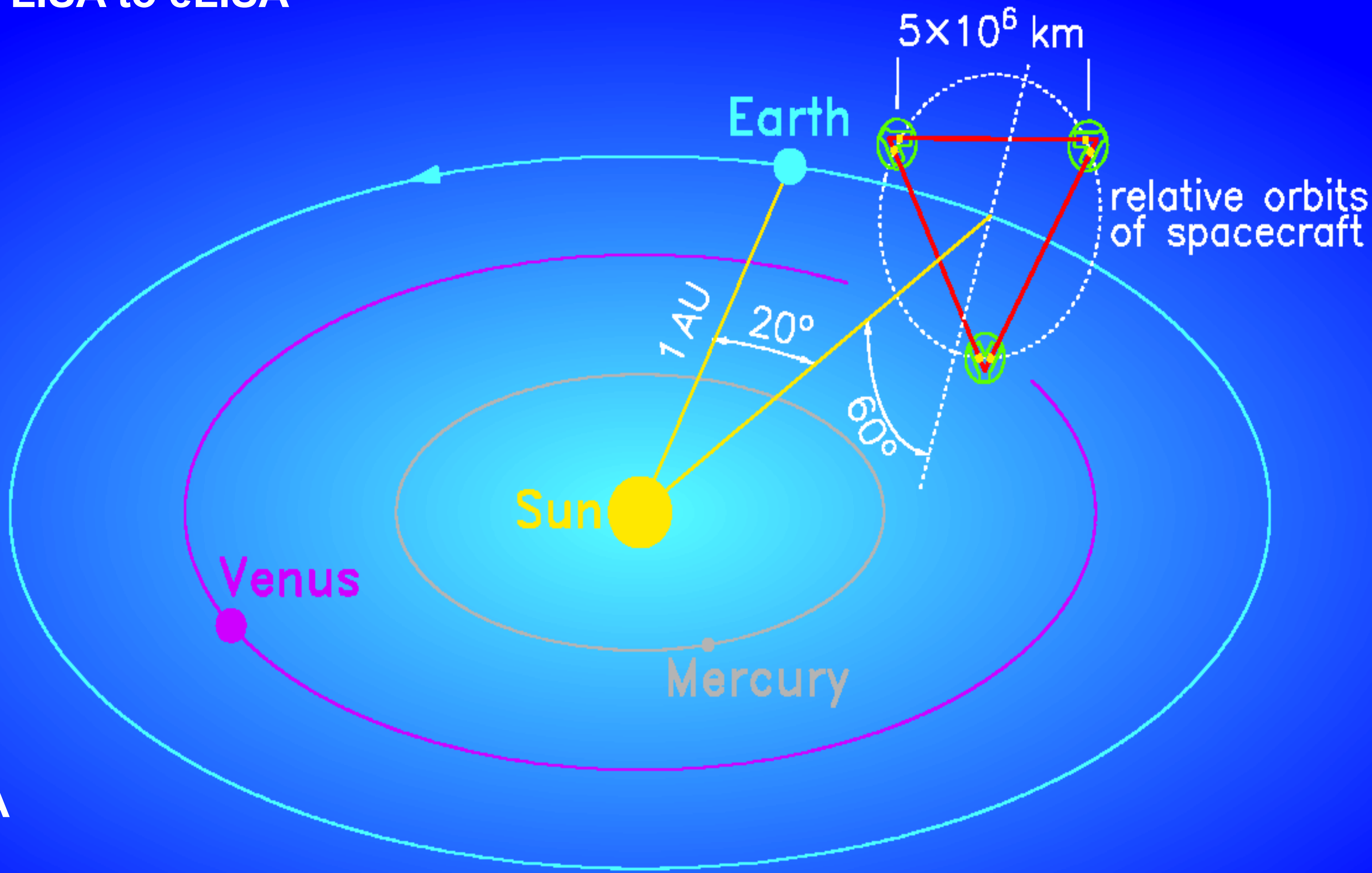
- Gravitational waves from the merger of two stellar mass black holes have been observed

- 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.**


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
SEVENTH FRAMEWORK PROGRAMME

From LISA to eLISA



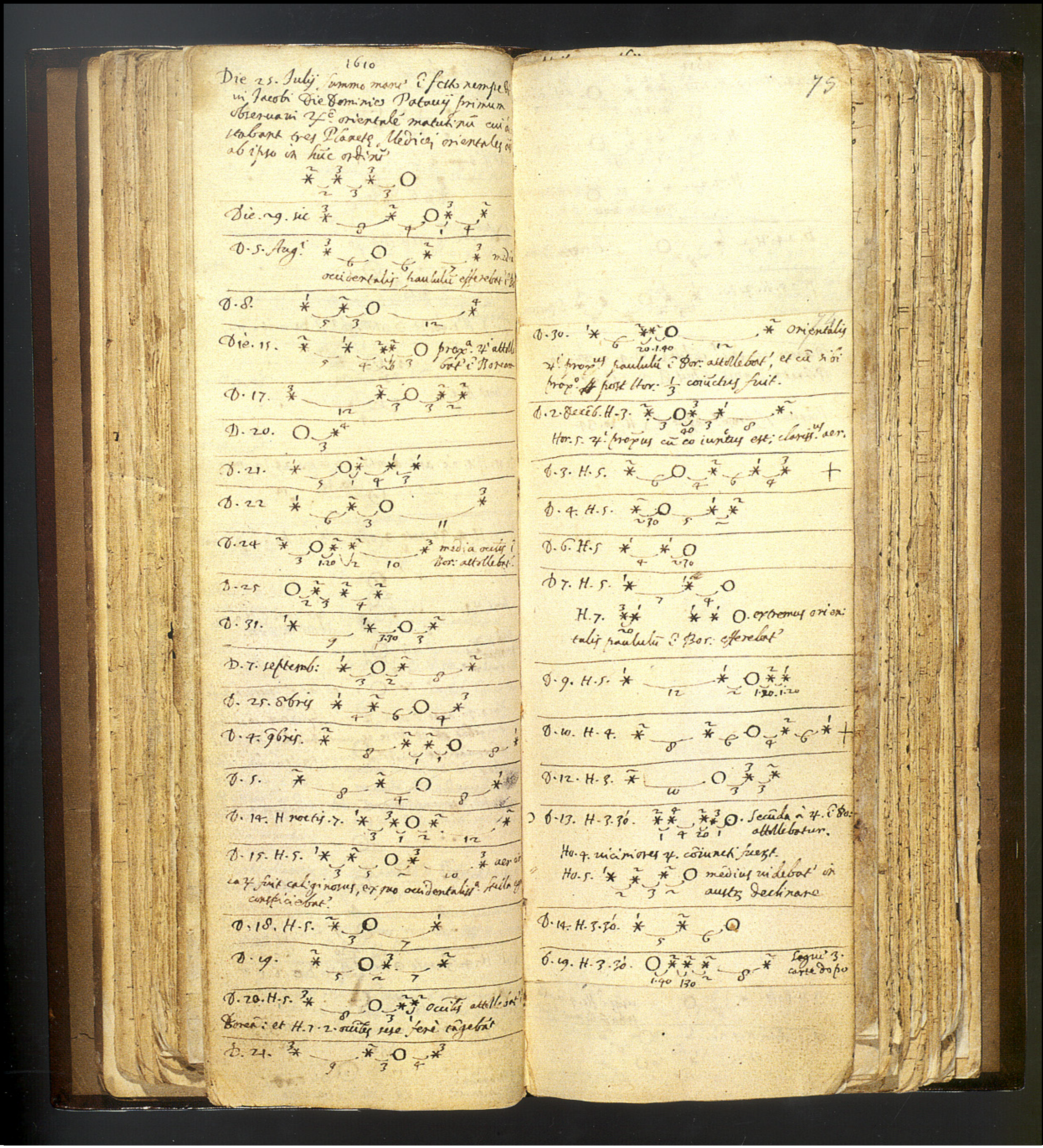
eLISA

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

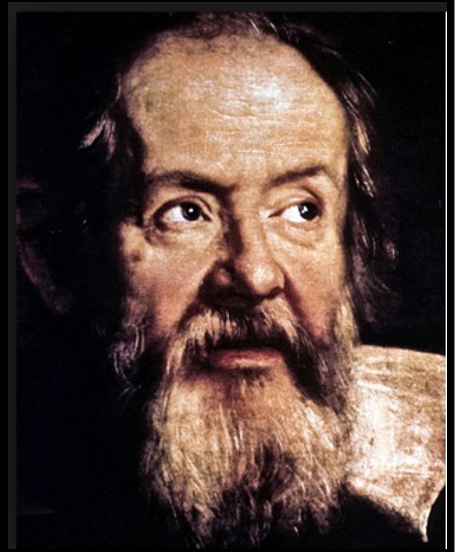
2030

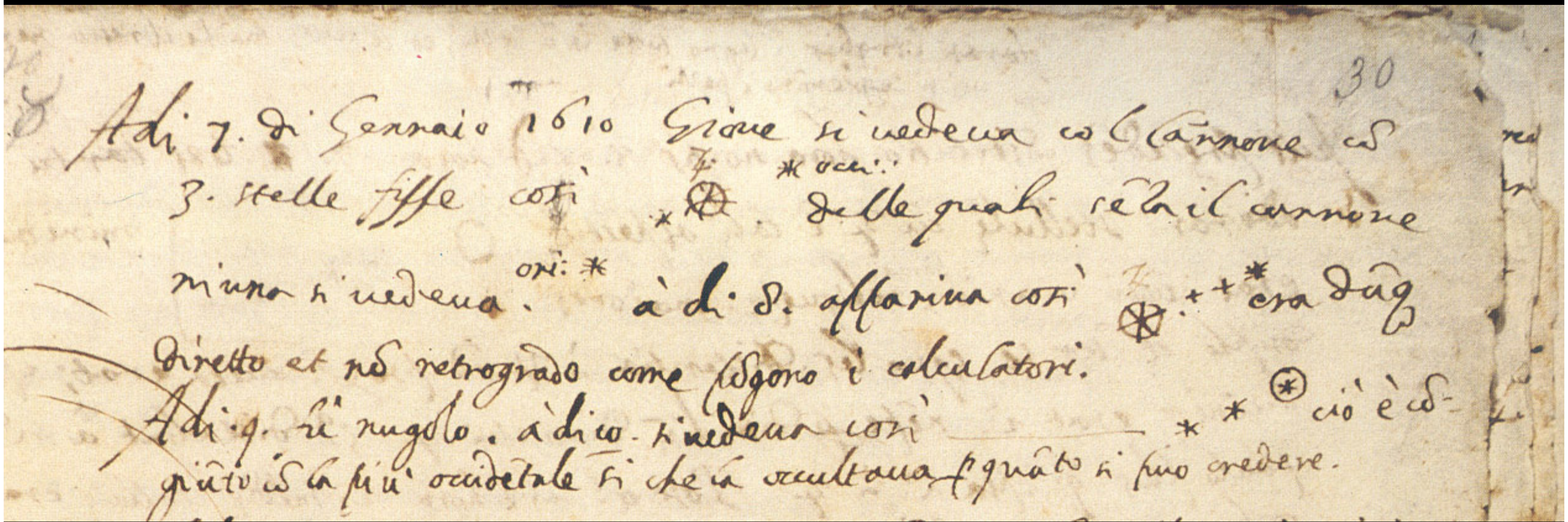
Every newly opened astronomical window has found unexpected results

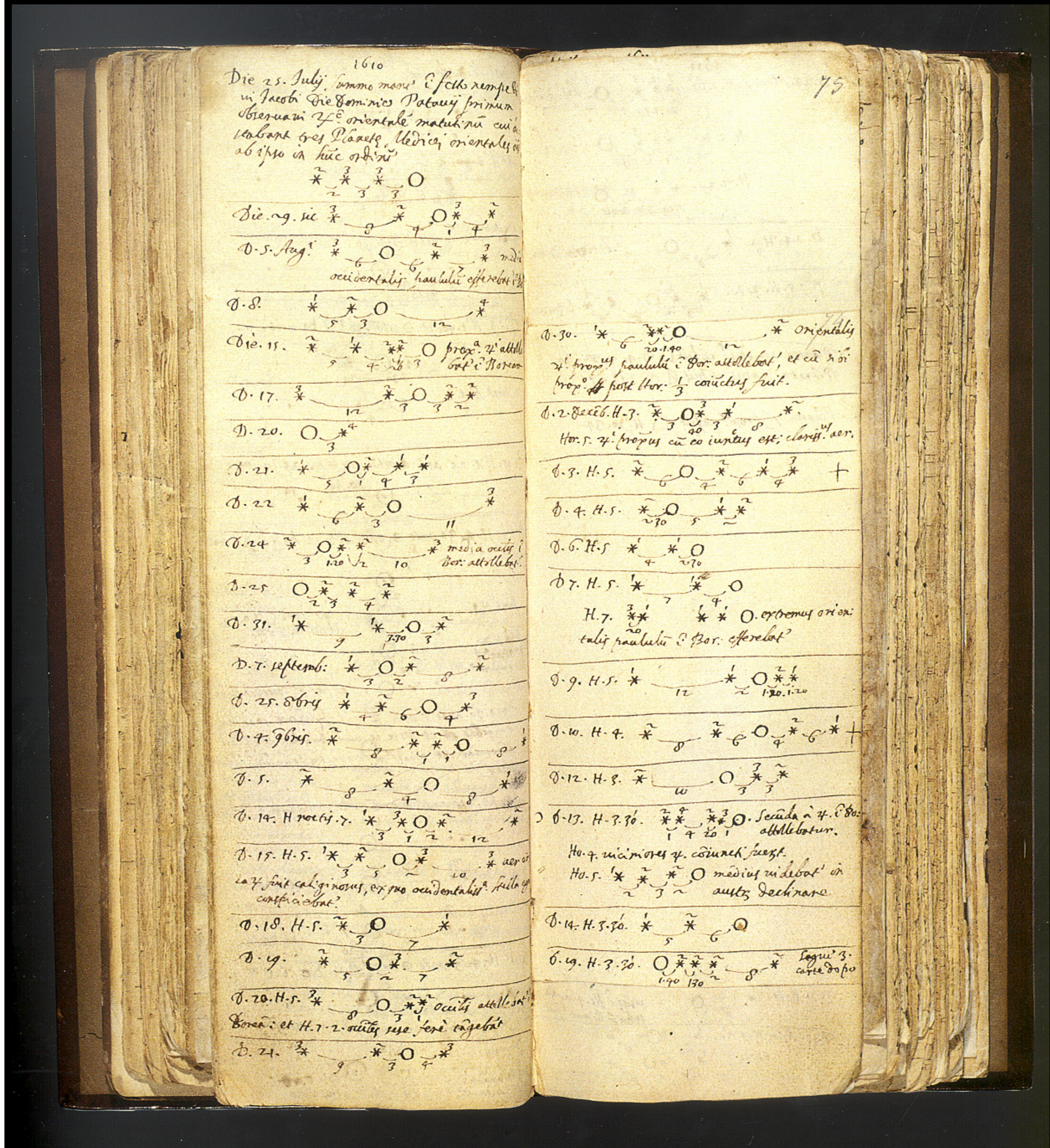
Window	Opened	1st Surprise	Year
Optical	1609 Galilei	Jupiter's moons	1610
Cosmic Rays	1912	Muon	1930s
Radio	1930s	Giant Radio Galaxies CMB Pulsars	1950s 1964 1967
X - ray	1948	Sco X-1 X-ray binaries	1962 1969 Uhuru
γ - ray	1961 Explorer 11	GRBs	Late 1960s+ Vela


1610
75
Die 25. Julij

Galilei




30
Adi 7. di Gennaio 1610 Giove si vedeva col Cannone con
3. stelle fisse così * ⊛ * delle quali senza il cannone
niuna si vedeva. à dì 8. appariva così ⊛ * * * era dunq
diretto et non retrogrado come vogliono i calculatori.
Adi 9. si nugolò. à dì 10. si vedeva così * * ⊛ ciò è con-
giunto con la più occidentale sì che la occultava per quanto si può credere.

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