Gravitational wave astronomy

past, present and future

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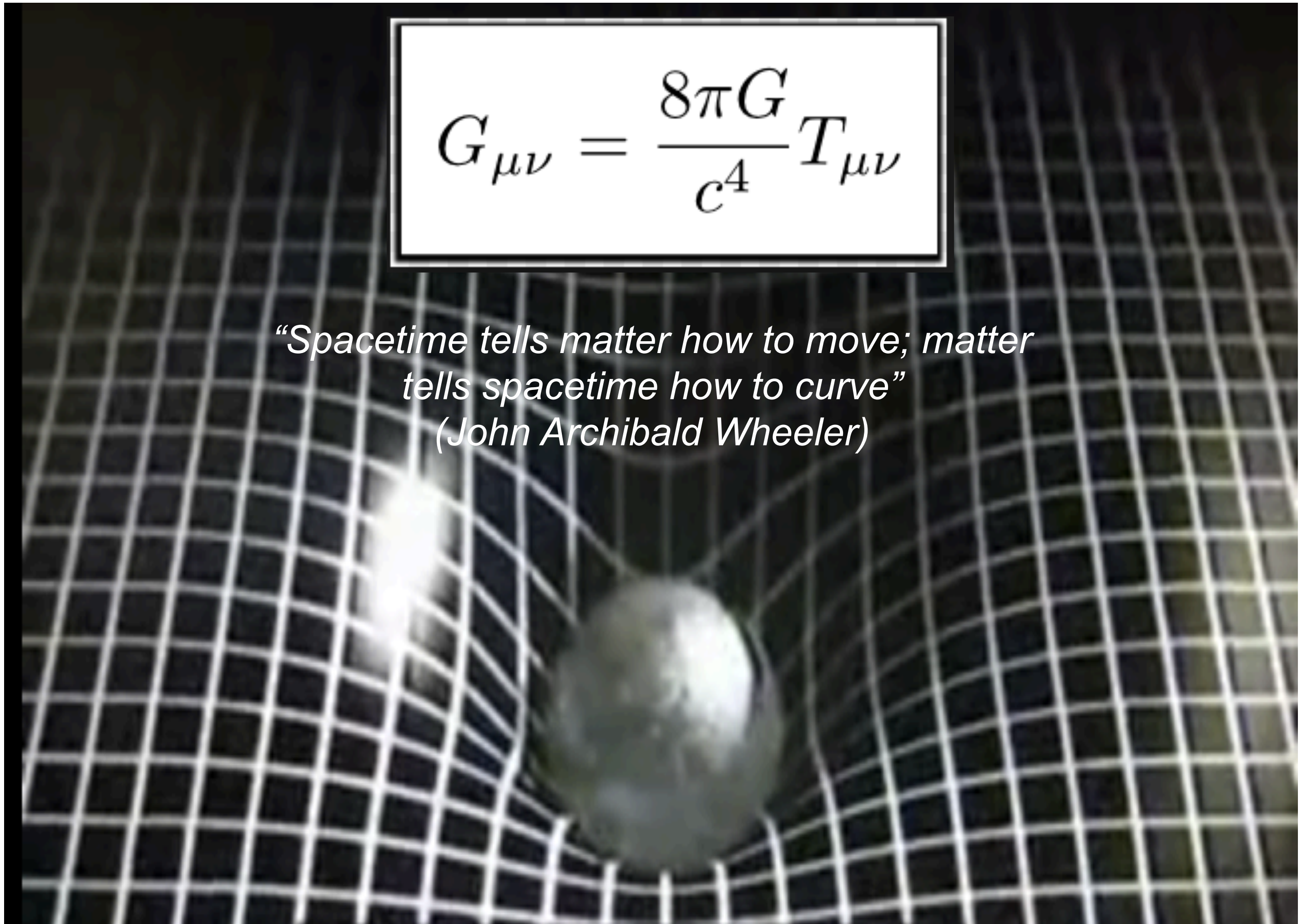
SciNeGHE 2016
High-energy gamma-ray experiments at the dawn of gravitational wave astronomy
Pisa,18 October 2016

Einstein's Theory of Gravitation

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



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

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

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

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

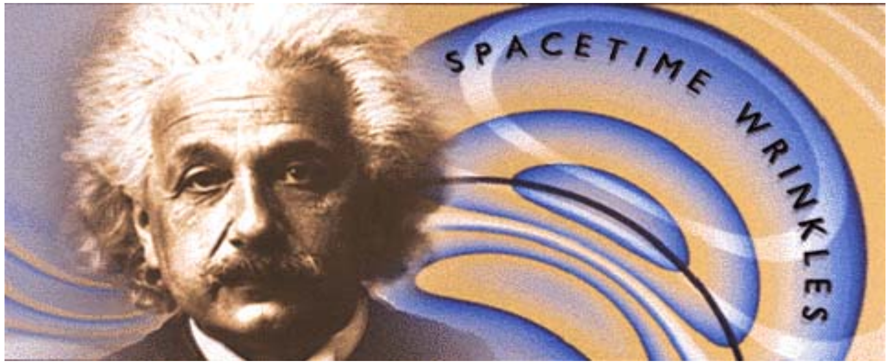
The Einstein equation in vacuum becomes

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

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**

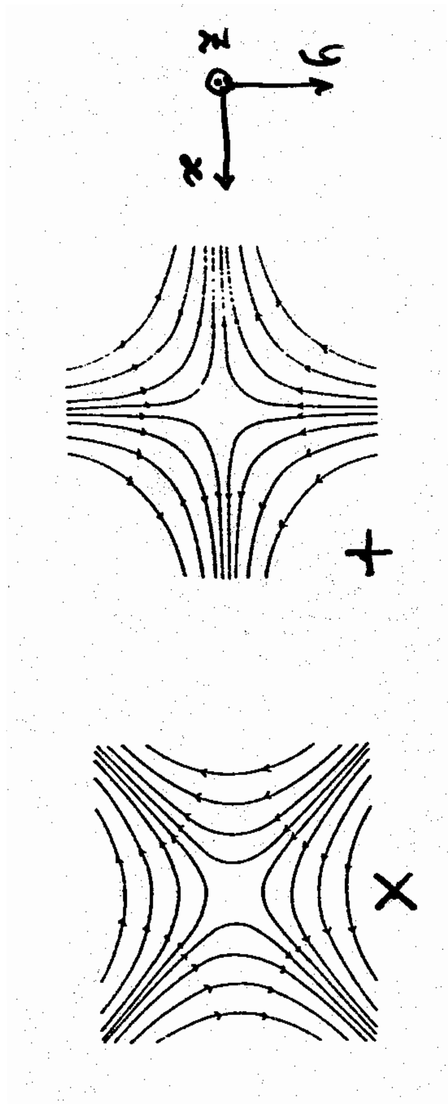
- **Associated with massless, spin 2 particles (gravitons)**

- **Emitted by time-varying quadrupole mass moment**
  no dipole radiation because of conservation laws

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

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

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



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

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

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

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 ~ W^{1/2}d^{-1}; source in the Galaxy ***h ~ 10^{-18}***, in VIRGO cluster ***h ~ 10^{-21}***

($h \sim W^{1/2} d^{-1}$; $h \sim 10^{-18}$; $h \sim 10^{-21}$)

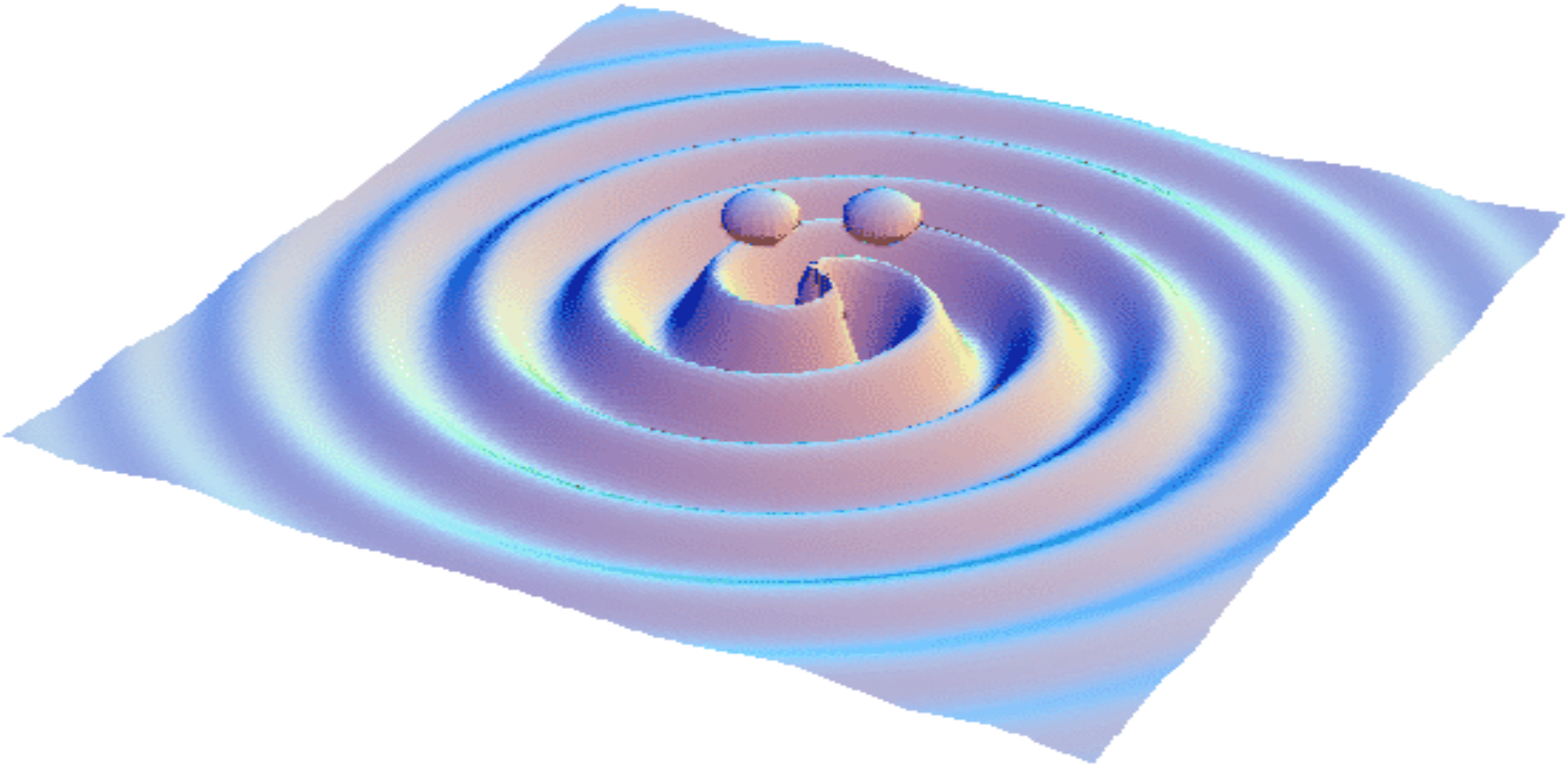
Fairbank: "*...a challenge for contemporary experimental physics..*"

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \qquad (21)$$

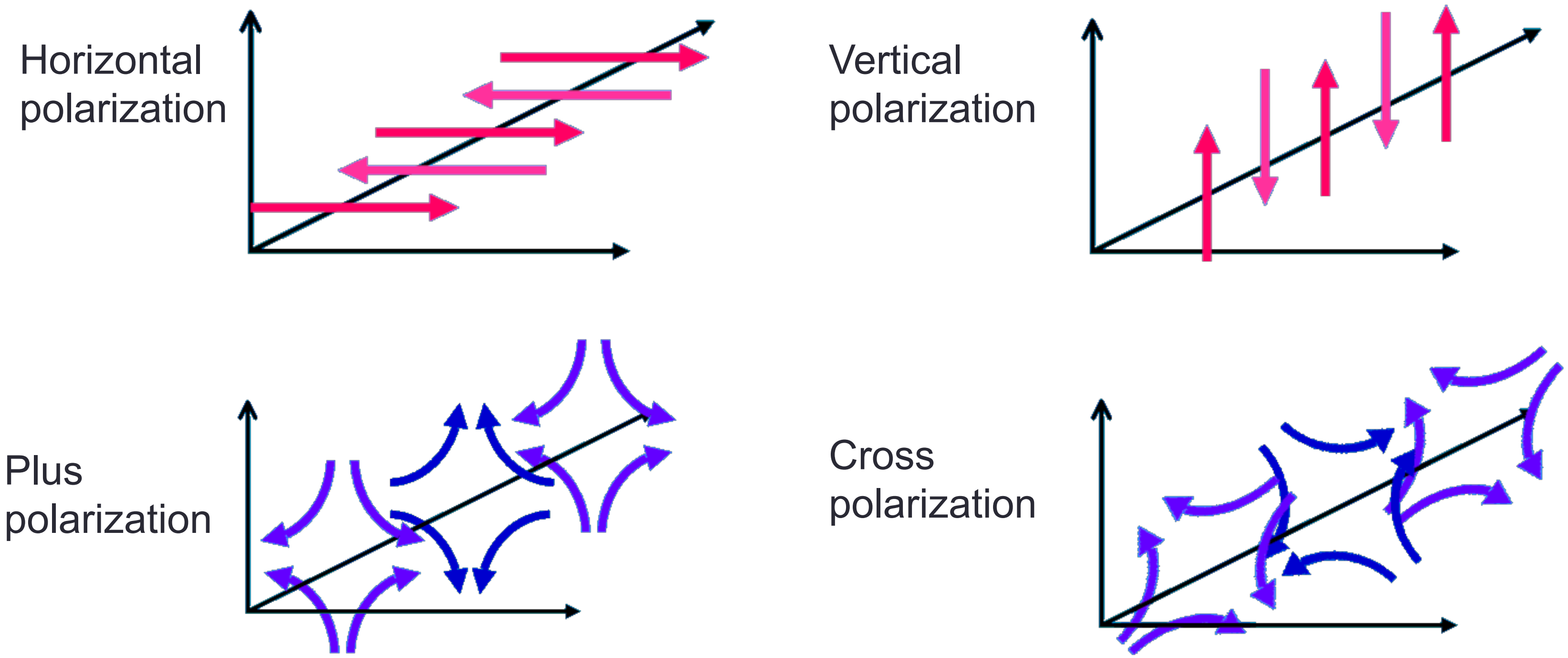
Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

"…..in any case one can think of A will have a practically vanishing value."

Gravitational Waves

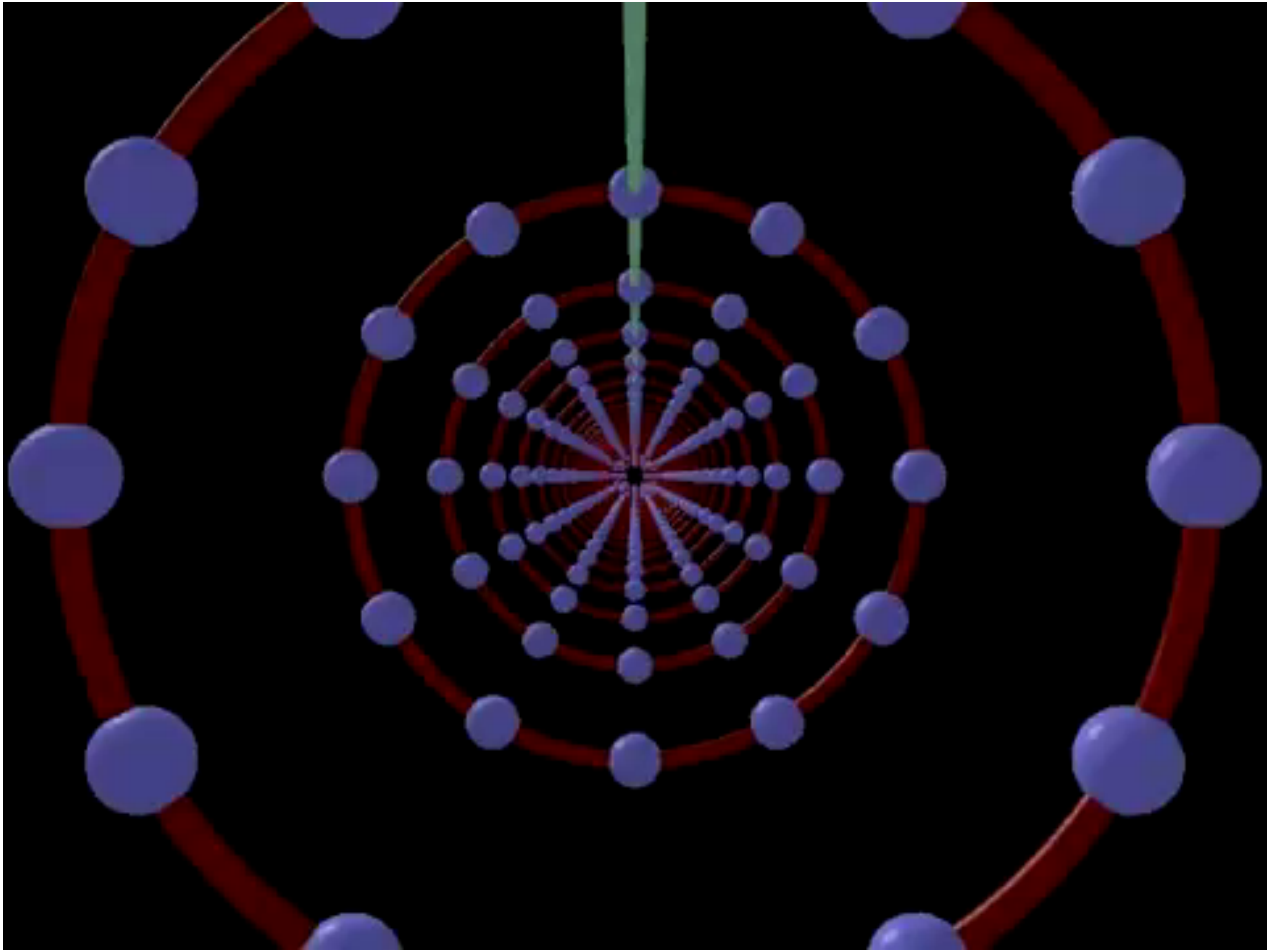


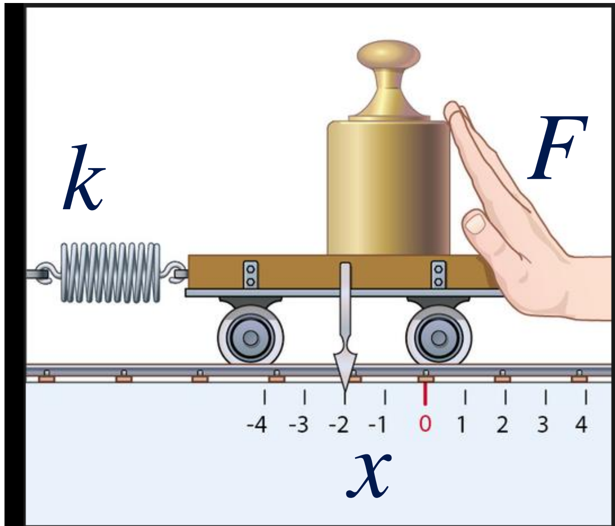
Comparison with electromagnetic waves

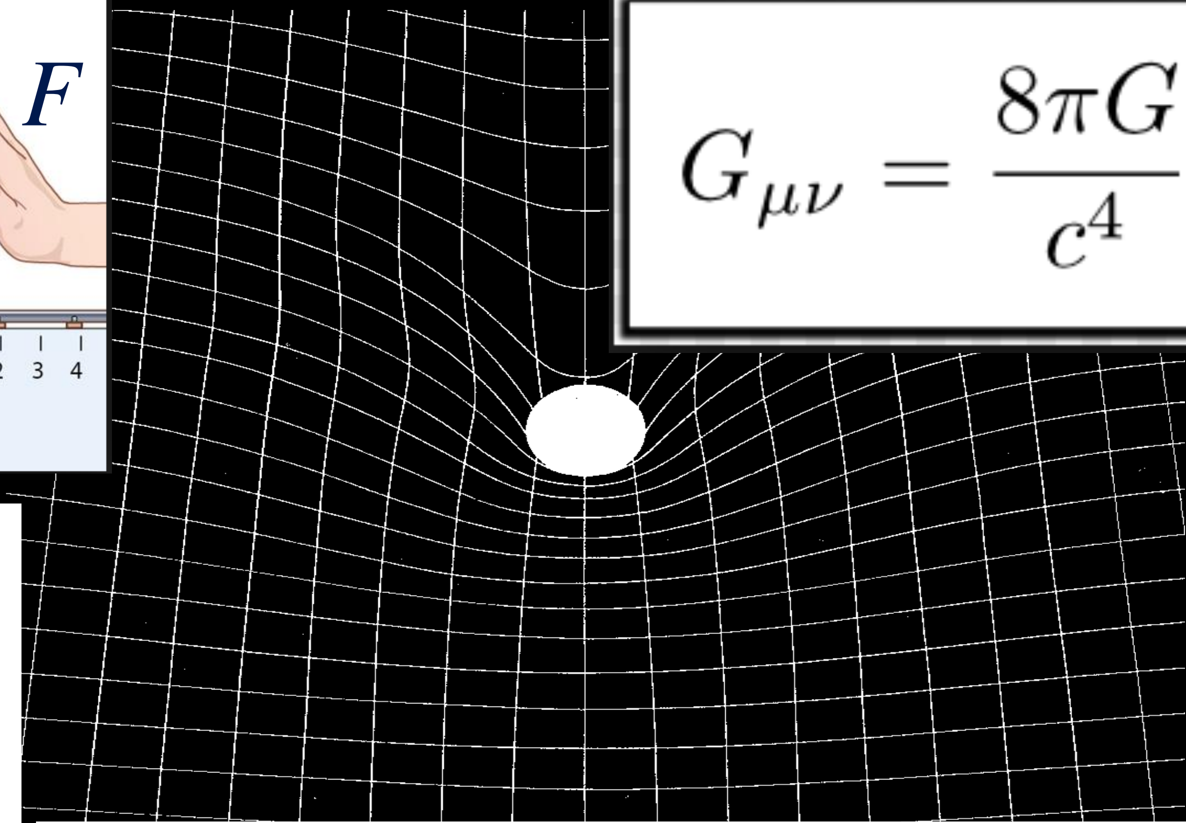


The so-called "electromagnetic theory of light" has not helped us hitherto . .
it seems to me that it is rather a backward step . . . the one thing about it that seems intelligible to me, I do not think is admissible . . That there should be an electric displacement perpendicular to the line of propagation'

Lord Kelvin







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

$$F = -kx$$

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

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

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

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

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

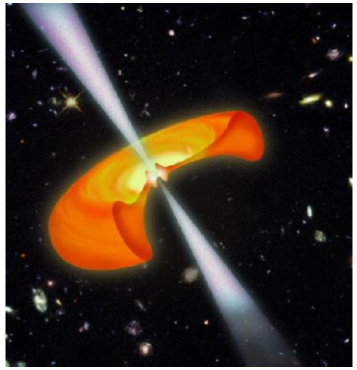
$$k \approx 10^{45}\ \frac{kg}{s^2} \qquad STIFF!$$

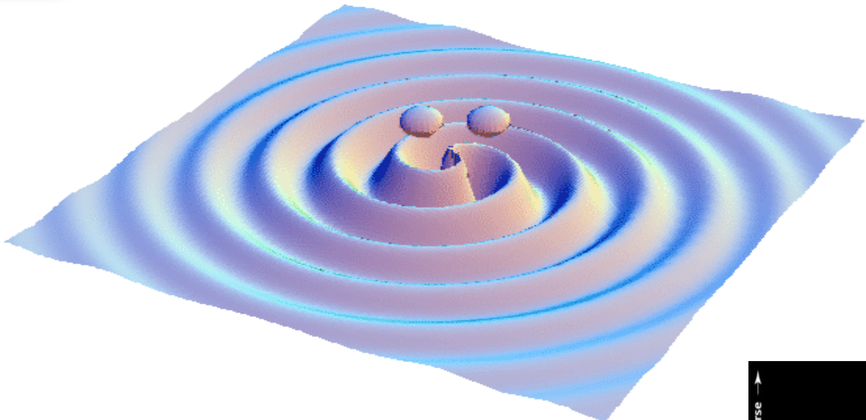
GW OBJECTIVES

FIRST DETECTION
test Einstein prediction

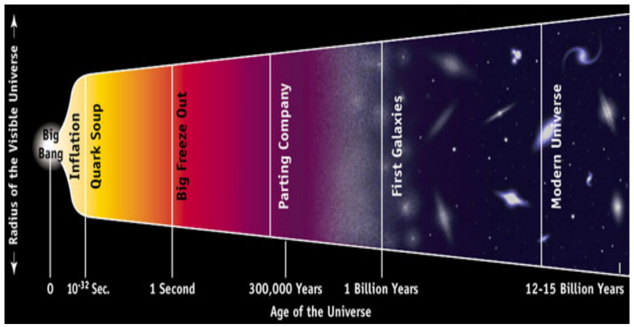
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

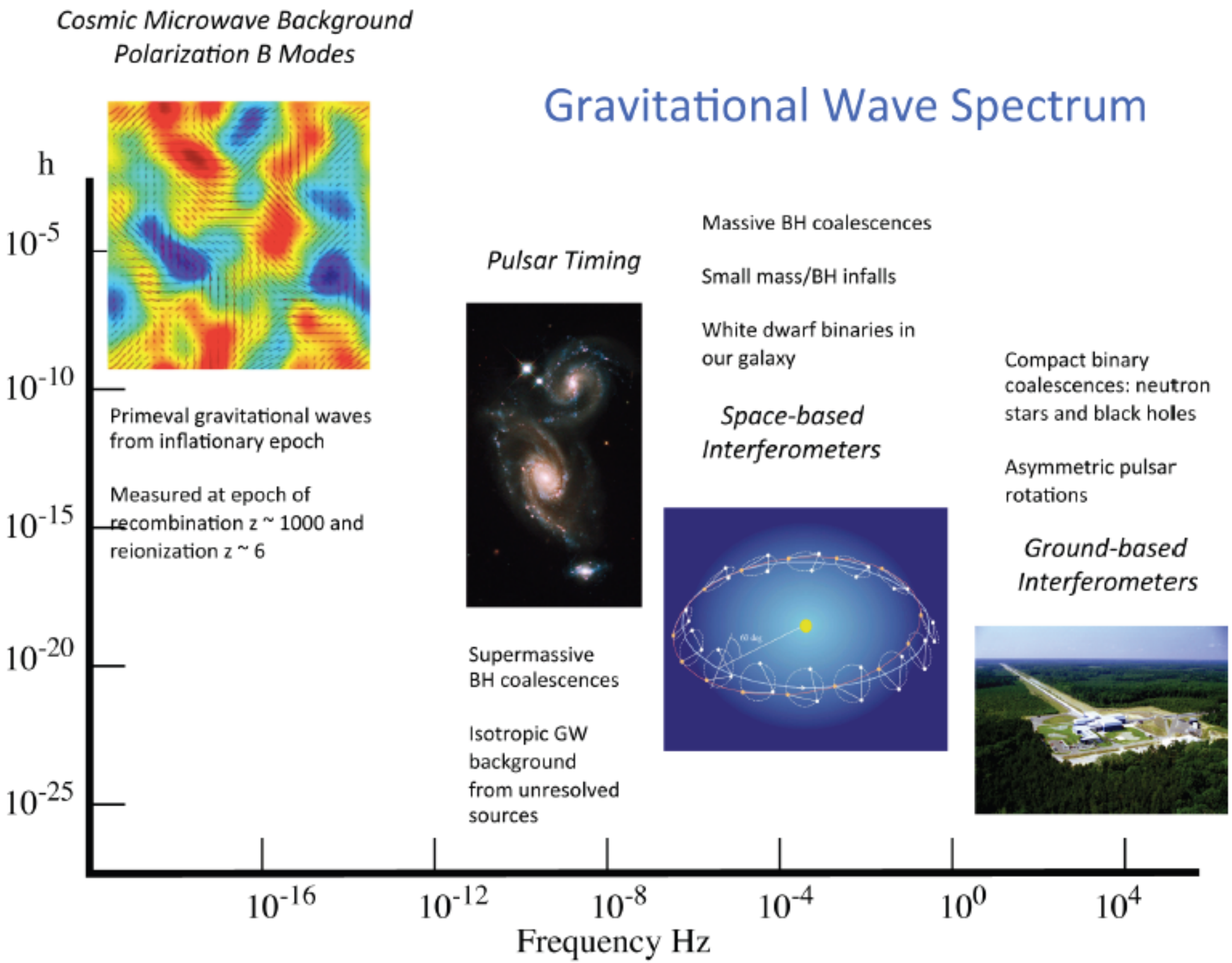
ASTRONOMY & ASTROPHYSICS
look beyond the visible,
understand Black Holes,
Neutron Stars and supernovae
understand GRB

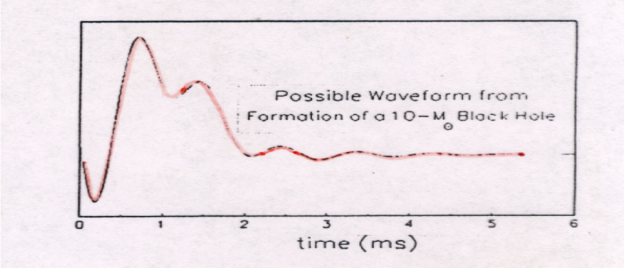




COSMOLOGY
the Planck time:
look as back in time as theorist can conceive

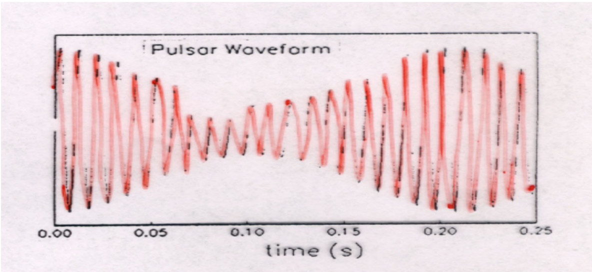



Gravitational Wave Spectrum
Cosmic Microwave Background
Polarization B Modes
h
10-5
10-10
10-15
10-20
10-25
Primeval gravitational waves
from inflationary epoch
Measured at epoch of
recombination z ~ 1000 and
reionization z ~ 6
Pulsar Timing
Supermassive
BH coalescences
Isotropic GW
background
from unresolved
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



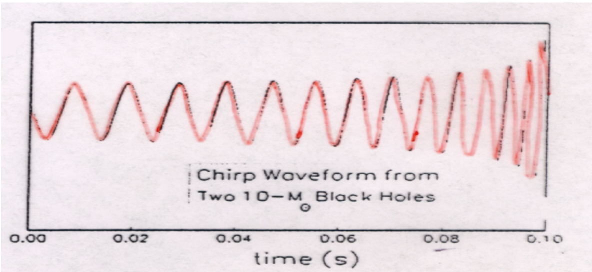
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

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



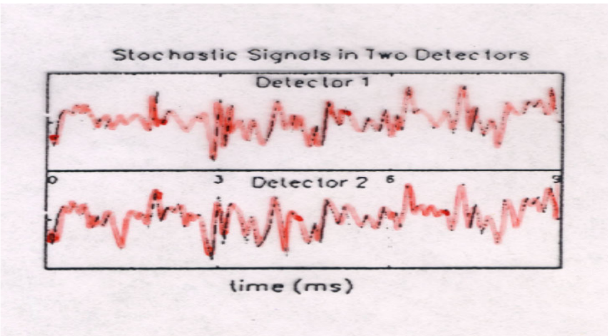
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

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



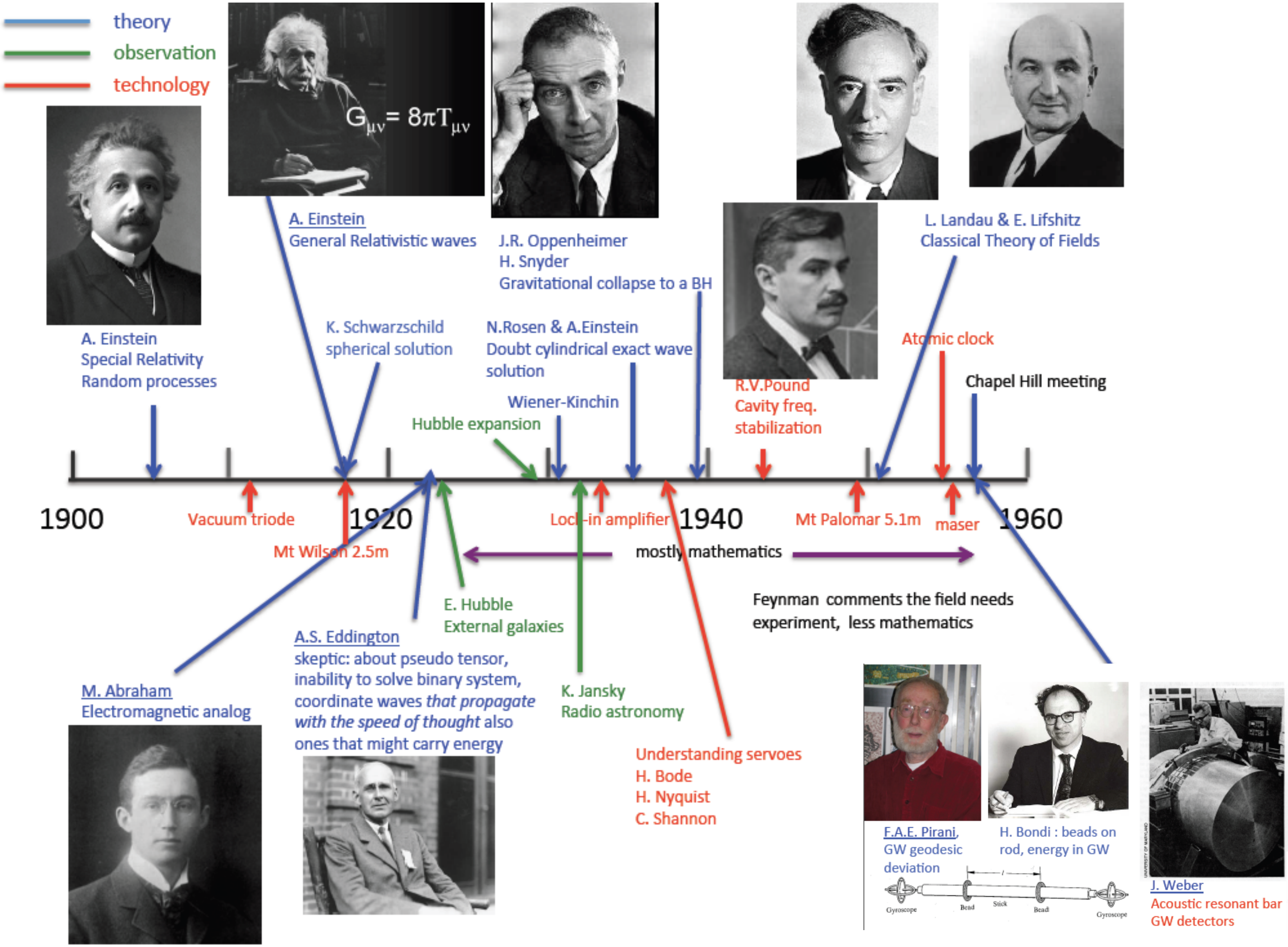
COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

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


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
R.V.Pound
Cavity freq.
stabilization
Chapel Hill meeting
Wiener-Kinchin
Hubble expansion
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
F.A.E. Pirani,
GW geodesic deviation
H. Bondi : beads on rod, energy in GW
Gyroscope
Bead
Stick
Bead
Gyroscope
J. Weber
Acoustic resonant bar GW detectors

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

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

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

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

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

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

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?

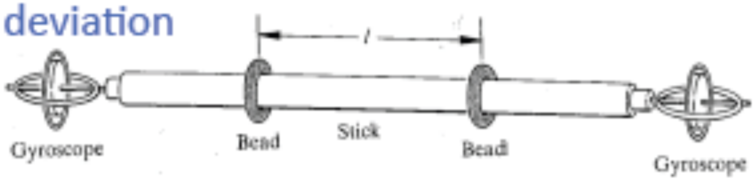
PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

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.

F.A.E. Pirani, GW geodesic deviation

H. Bondi : beads on rod, energy in GW



The main point of this presentation was that it is relative accelerations of neighboring free particles that are the physically meaningful (i.e.,measurable) ways to observe gravitational effects. Pirani points out the transparent connection between the equation of geodesic deviation and Newton's Second Law, as long as one identifies $\mathbf{R}_{\mathbf{a}0\mathbf{b}0}$ with the second derivative of the Newtonian potential (i.e., as the tidal field.)

To make sure everyone sees how important and simple this is, he remarks, "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".

from: P. Saulson, Gen Relativ Gravit (2011) 43:3289–3299

Joe Weber at Chapel Hill

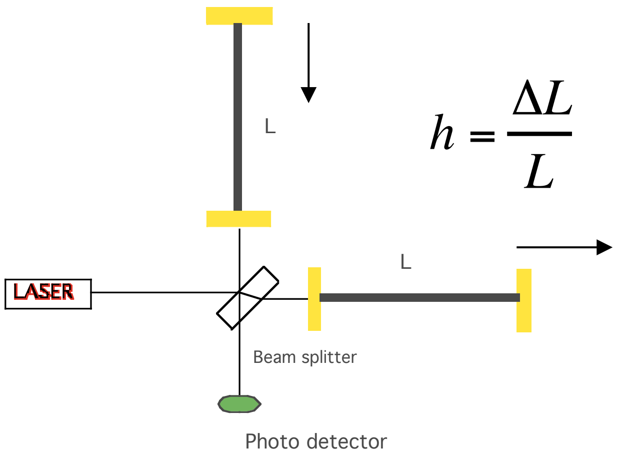
Joe Weber, co-inventor of the maser, was a U Md professor, on sabbatical in 1956 -57 with John Wheeler at Princeton.

At the Chapel Hill conference in Jan 1957, they heard the key talk by Pirani that clarified that GW's were real, because they could (in principle) be detected.

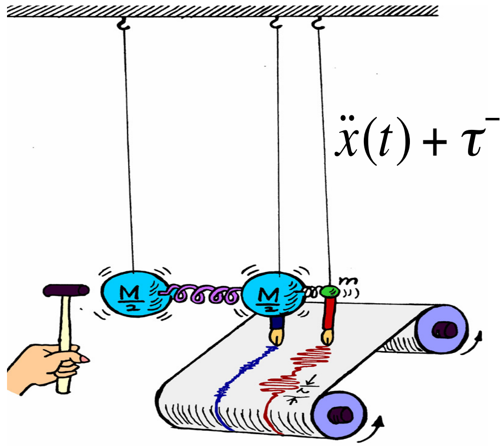
- **GWs are detectable in principle**
  The equation for geodetic deviation is the basis for all experimental attempts to detect GWs:

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

- **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

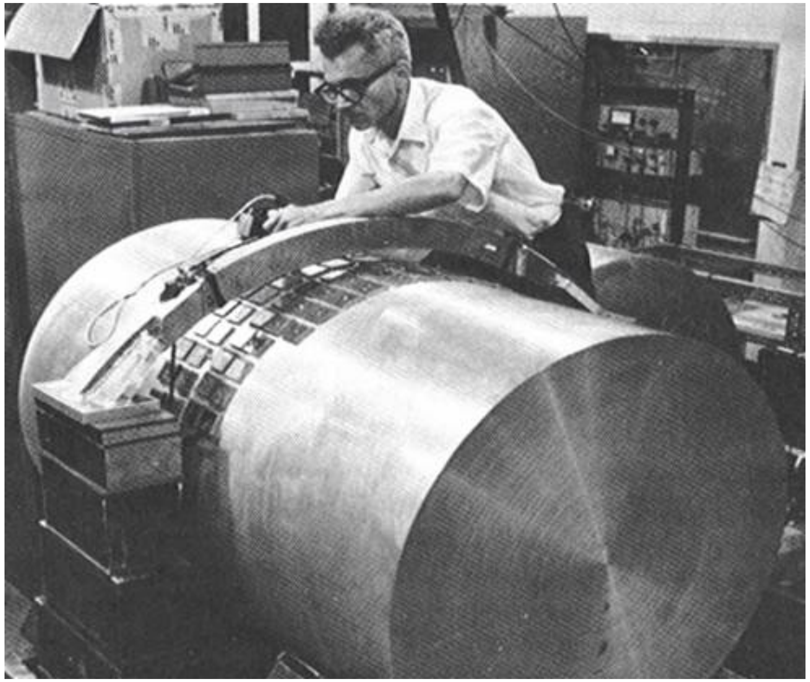


$$h = \frac{\Delta L}{L}$$



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

Weber's bar



Weber's detector embodied Pirani's *gedankenexperiment*.

It was a cylinder of aluminum, each end of which is like a test mass, while the center is like a spring. PZT's around the midline absorb energy to send to an electrical amplifier.

Weber invented us from scratch

It was an act of genius (and/or madness) to transform a *gendankenexperiment* into a working apparatus and an observing program.

Along the way, Weber developed:

- Sensitivity calculation and noise analysis
- Thermal noise minimization by high Q
- Seismic isolation
- Coincidence for background rejection
- Time slides for background estimation
- Inverse False Alarm Rate detection statistic

Weber started seeing things

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

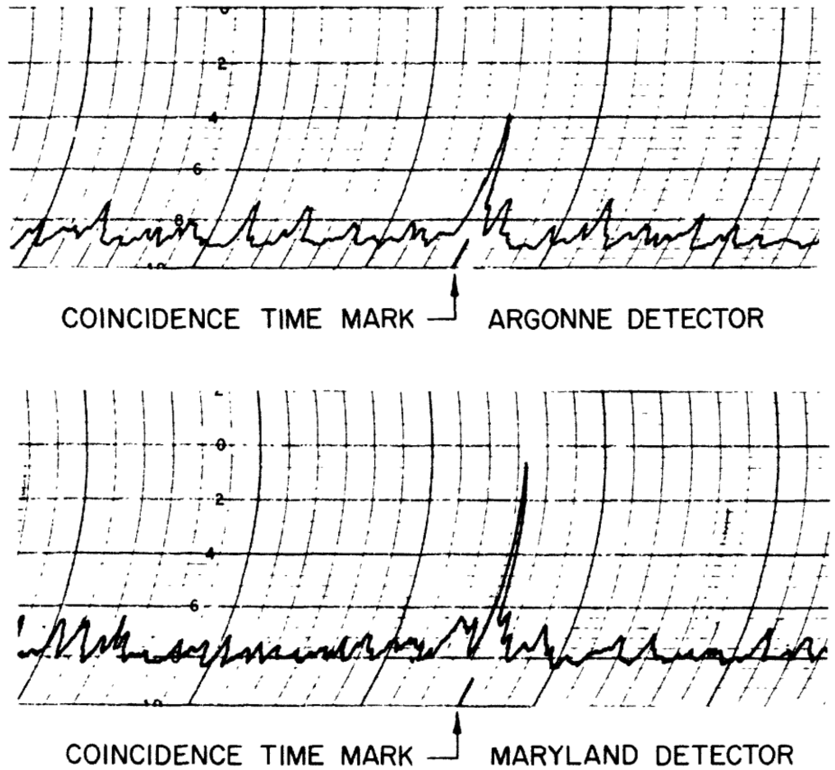


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

Acoustic bar GW
Detector groups


R. Garwin


W. Fairbank


G. Pizzella, E. Amaldi

1965-1975
Room T bars

Bell Labs
Frascati
Glasgow
IBM
Rochester
Max Planck
Rome

1975-1990+
Cryogenic bars

Frascati
Louisiana
Moscow
Perth
Rochester
Stanford

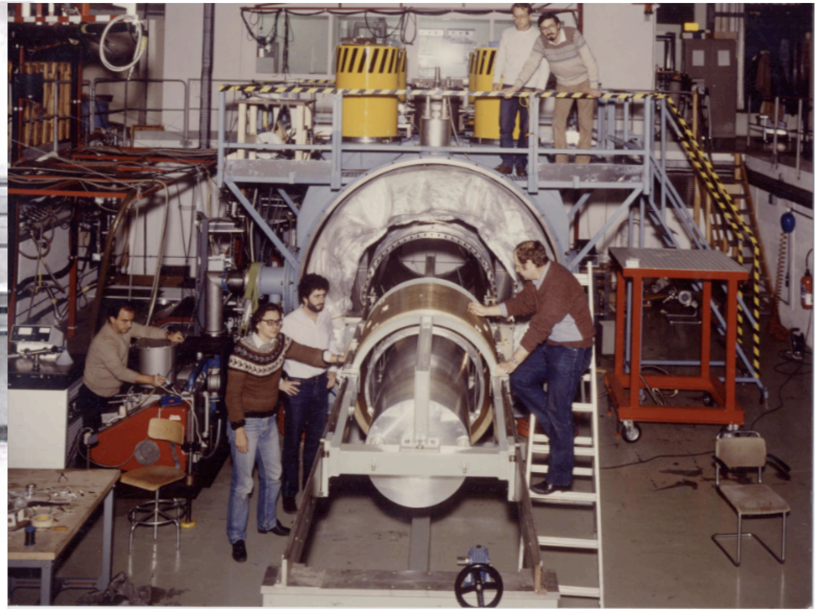
2000 ->
Spherical cryogenic detectors

Brazil
Netherlands


A. Tyson

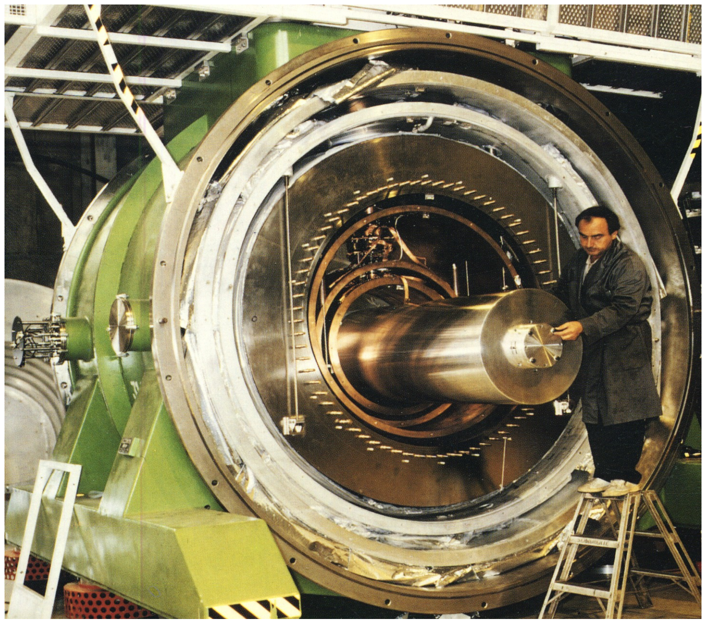

W. Hamilton

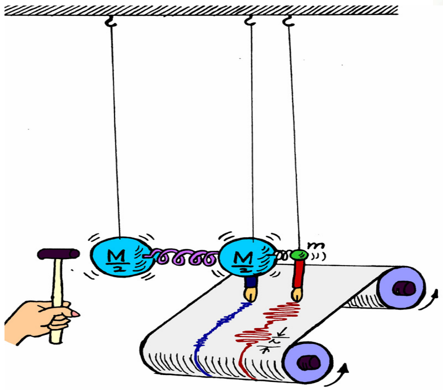

P. Michelson



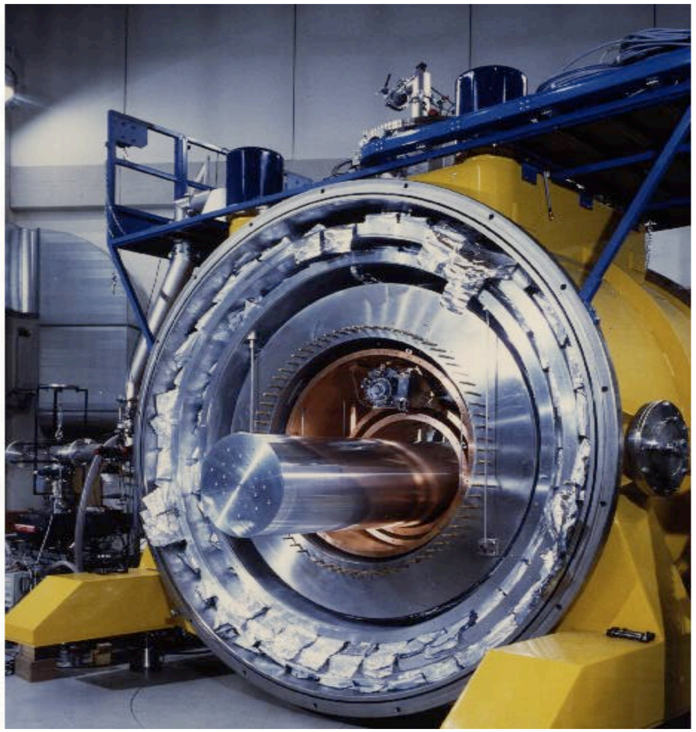
Explorer, CERN

Nautilus, LNF



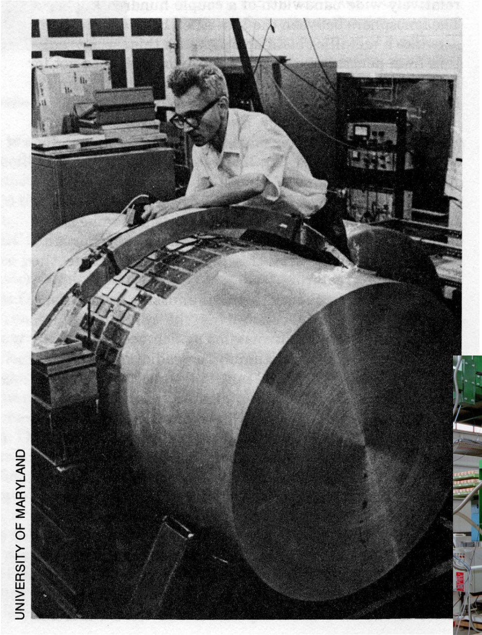


Auriga, LNL

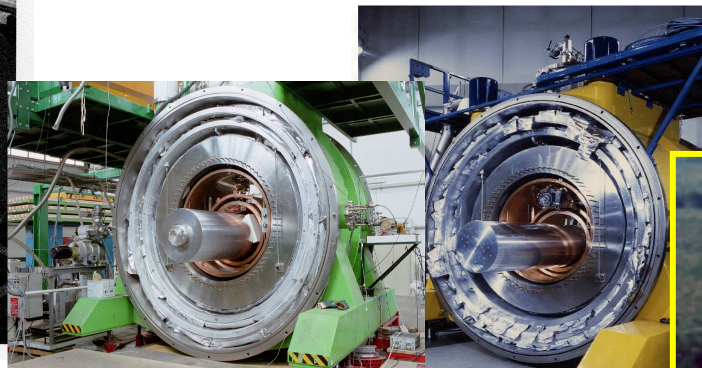


Some perspective: 50 years of attempts at detection:

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

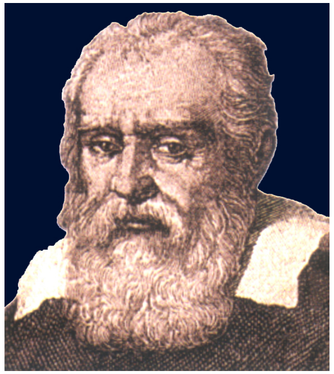


90’: Cryogenic Bars

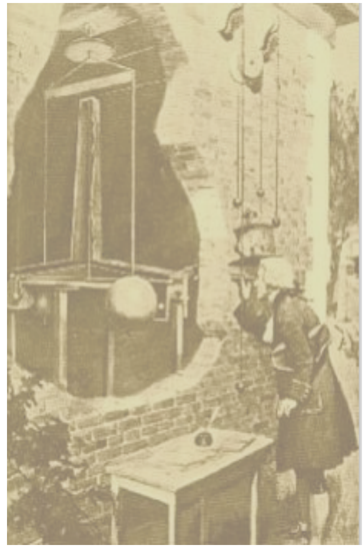
2000’ - : Large Interferometers

1997: GWIC was formed

GWIC thesis prize named after Stefano Braccini



Experimental gravitational physicists are heirs to several great traditions:

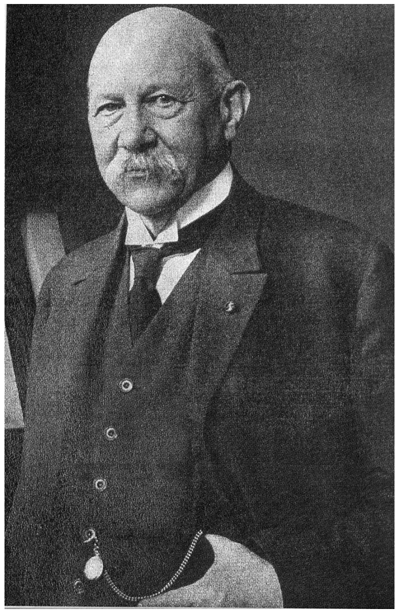


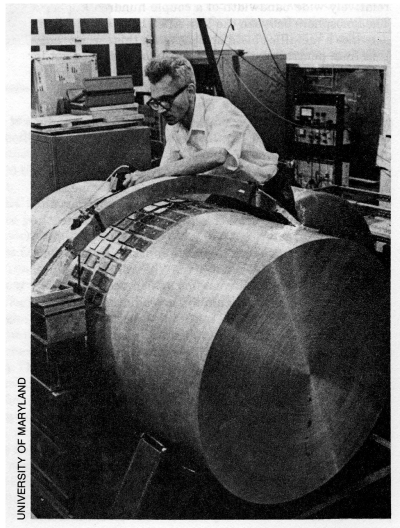
- High precision mechanical experiments (Cavendish, Eotvos, Dicke..)
  detection of weak forces applied on mechanical test bodies

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

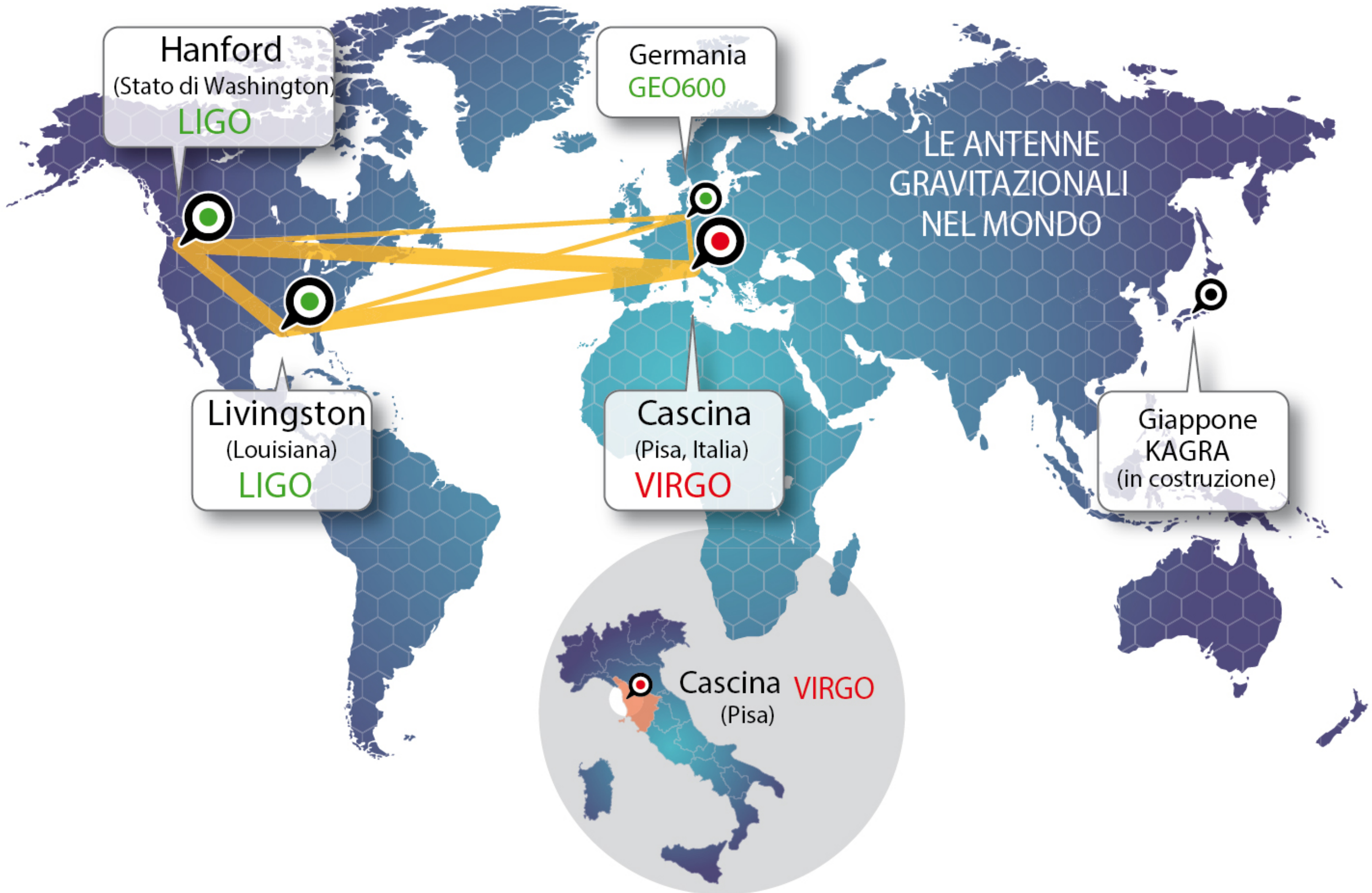
- Operation of ultraprecise e-m measurement systems (microwave pioneers of World War II)

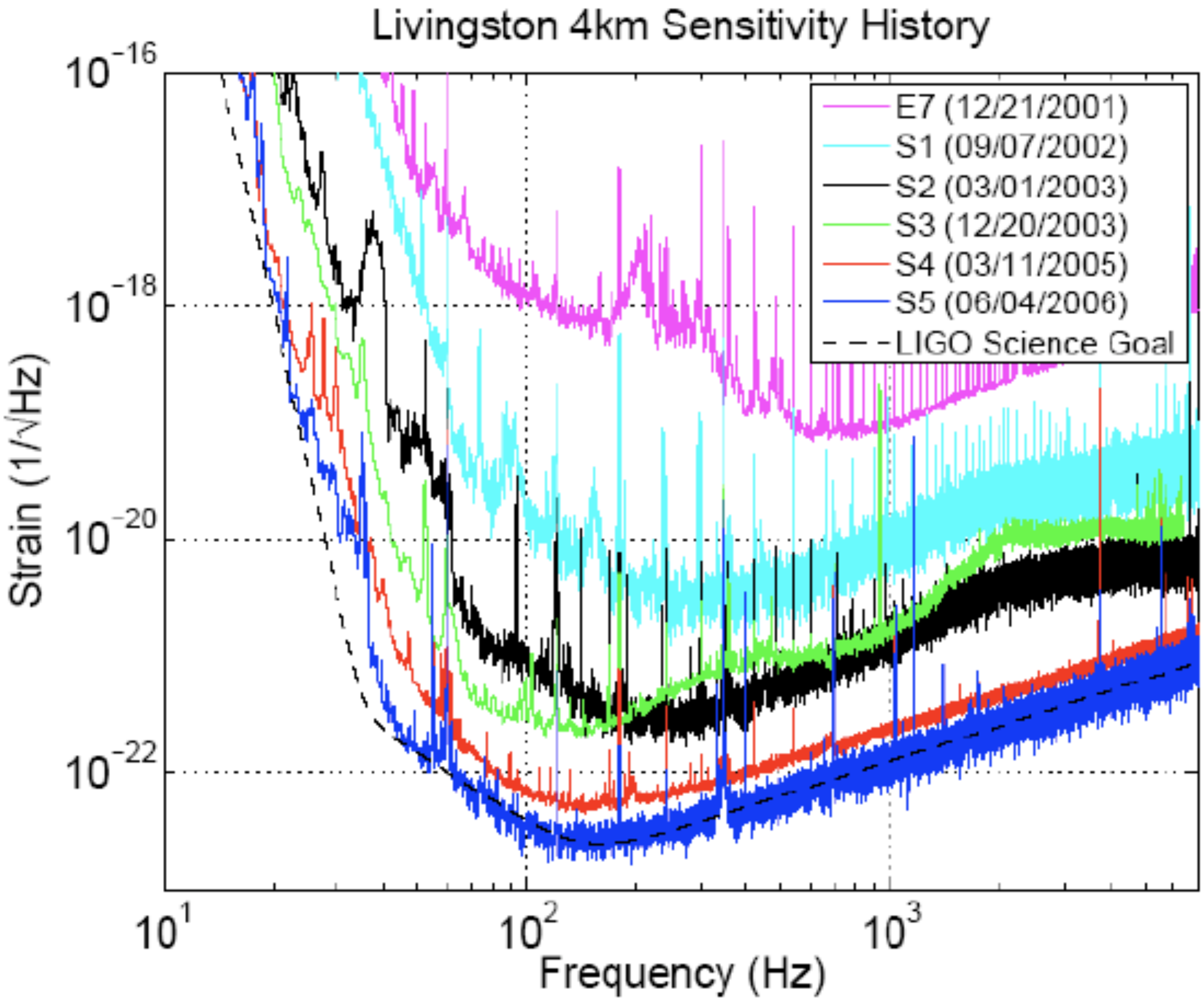
- Low temperature physics (K. Onnes)
  superfluids and superconductors technology

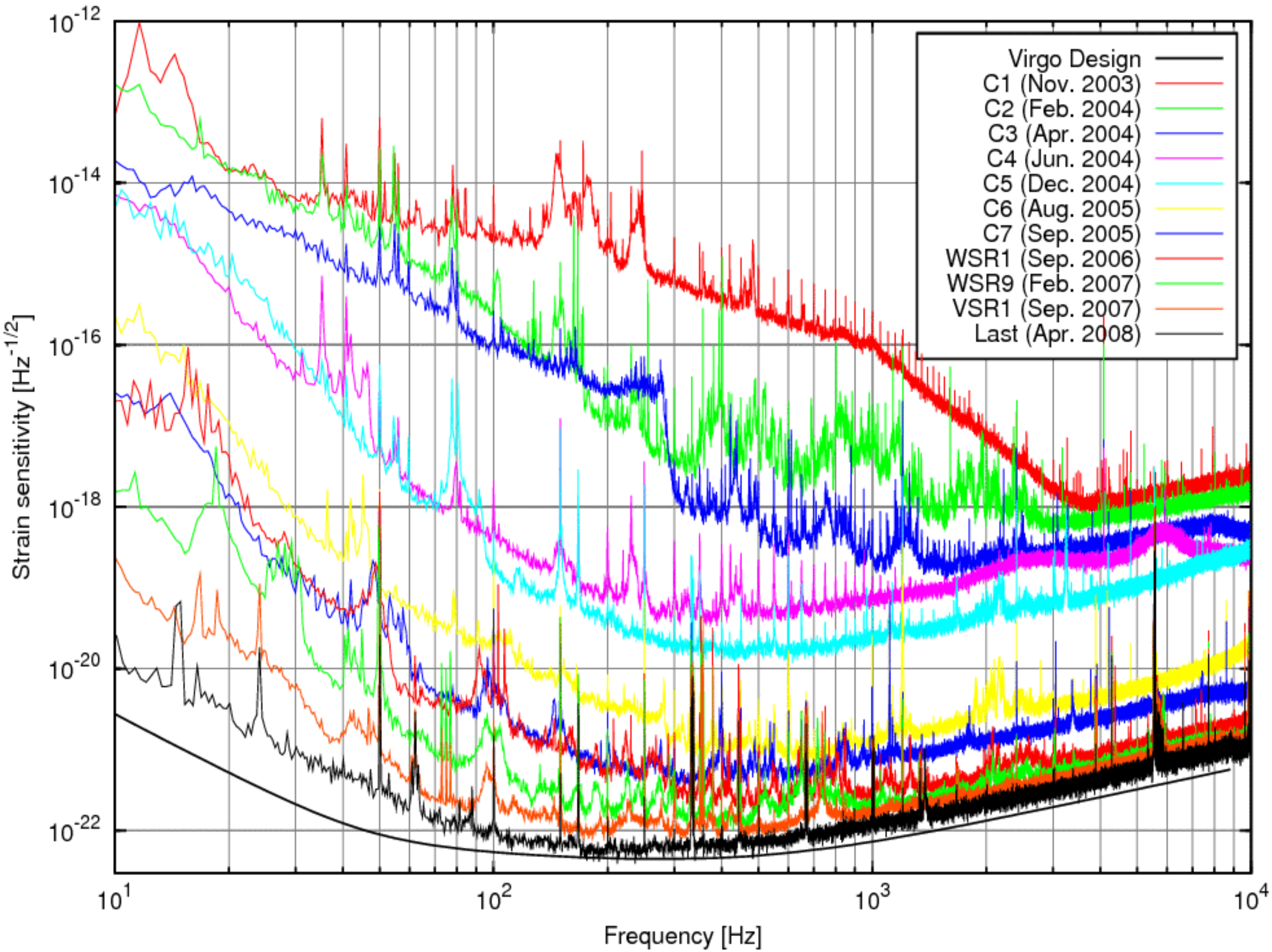




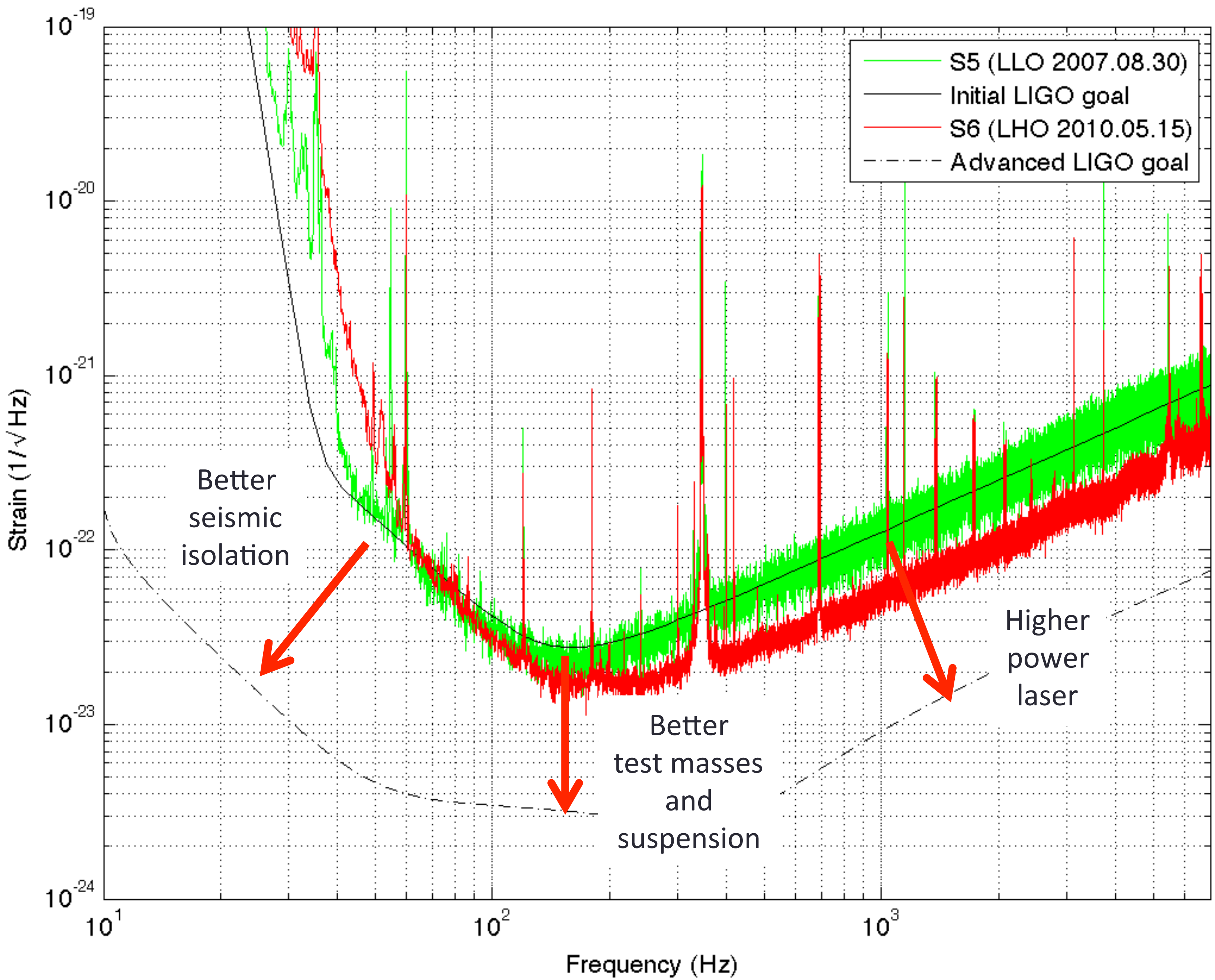
Global Network of Detectors



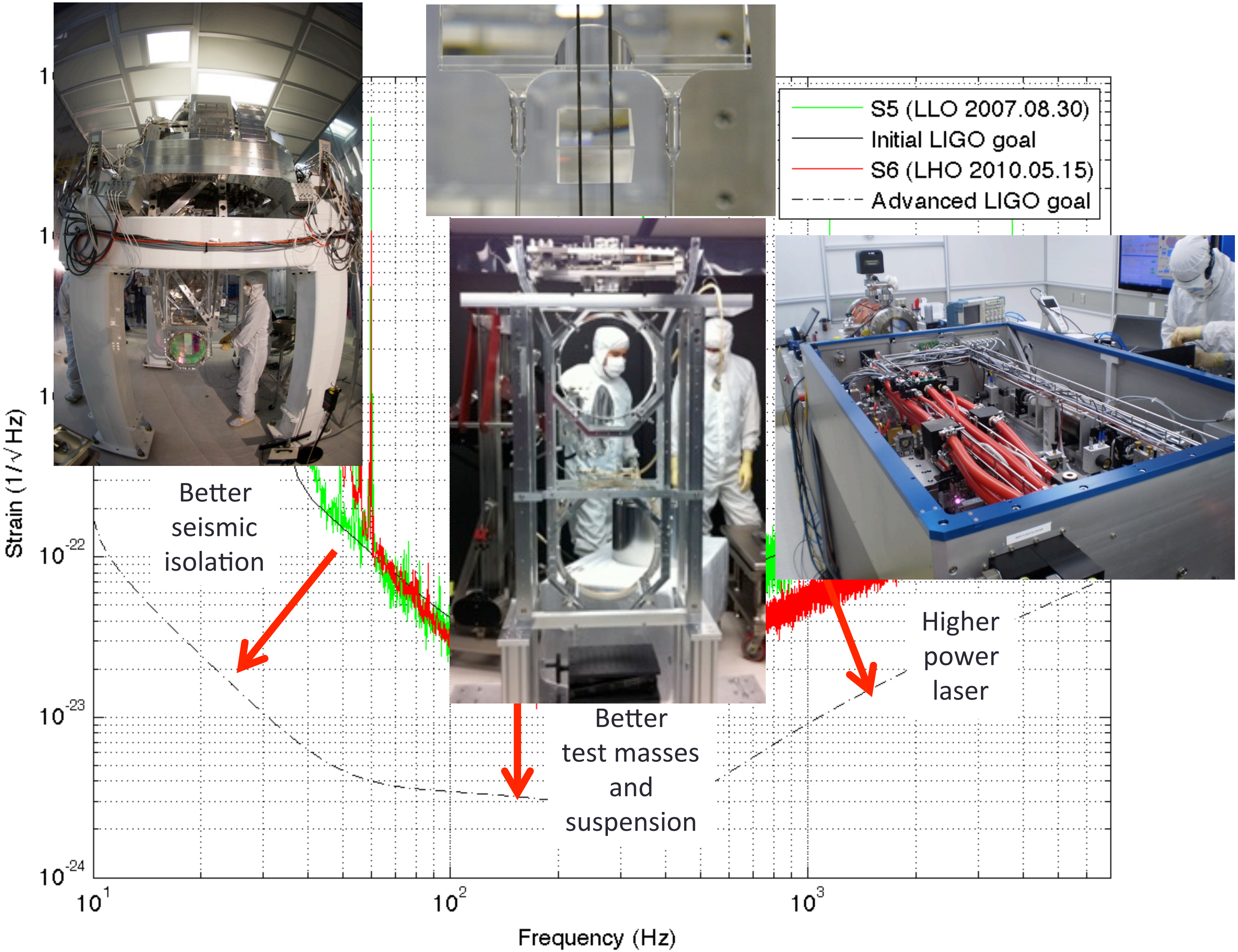

Livingston 4km Sensitivity History
E7 (12/21/2001)
S1 (09/07/2002)
S2 (03/01/2003)
S3 (12/20/2003)
S4 (03/11/2005)
S5 (06/04/2006)
LIGO Science Goal
Strain (1/√Hz)
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{1}
10^{2}
10^{3}
Frequency (Hz)

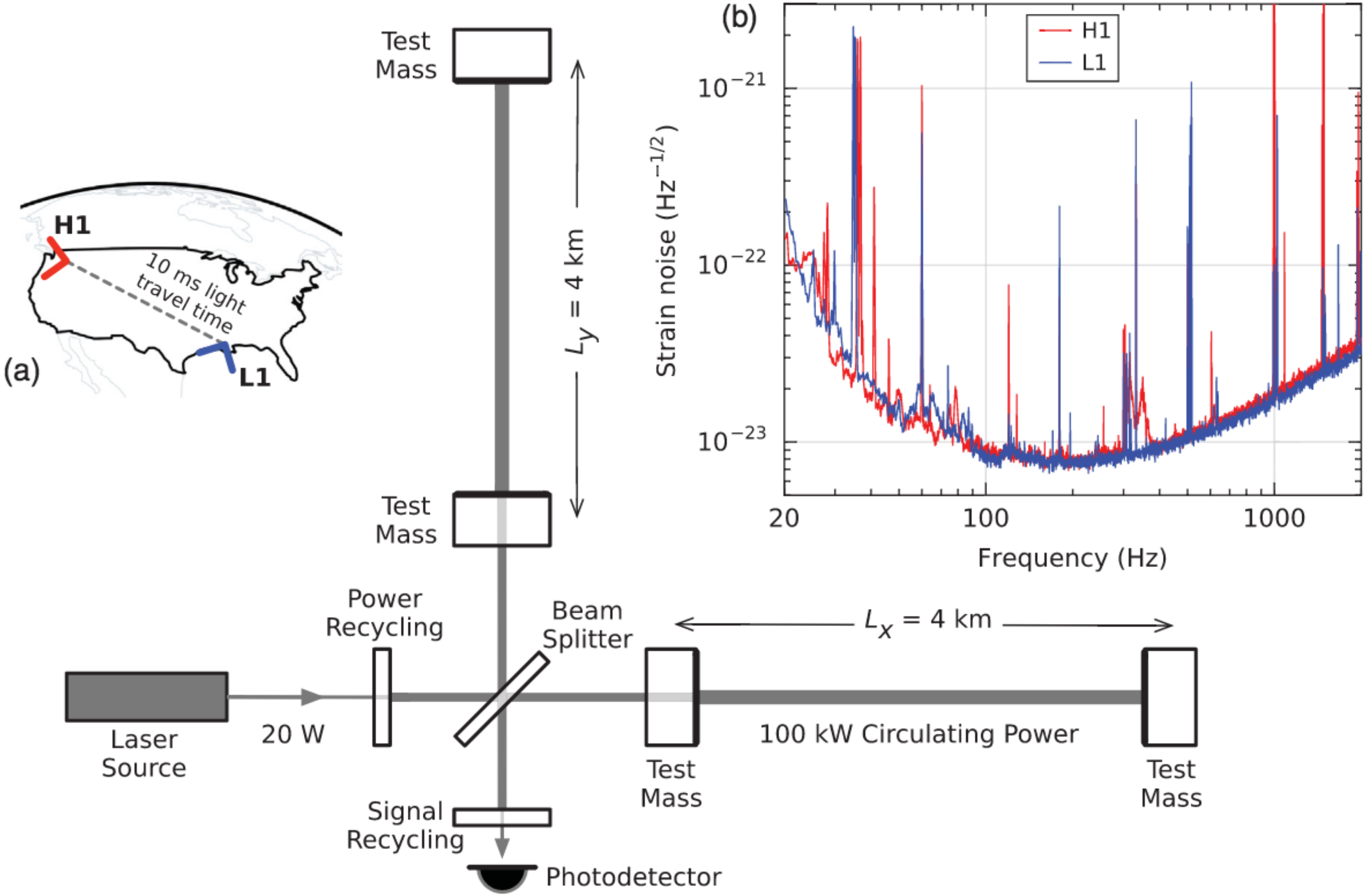


Virgo Design
C1 (Nov. 2003)
C2 (Feb. 2004)
C3 (Apr. 2004)
C4 (Jun. 2004)
C5 (Dec. 2004)
C6 (Aug. 2005)
C7 (Sep. 2005)
WSR1 (Sep. 2006)
WSR9 (Feb. 2007)
VSR1 (Sep. 2007)
Last (Apr. 2008)
Strain sensitivity [Hz^-1/2]
Frequency [Hz]
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^1
10^2
10^3
10^4



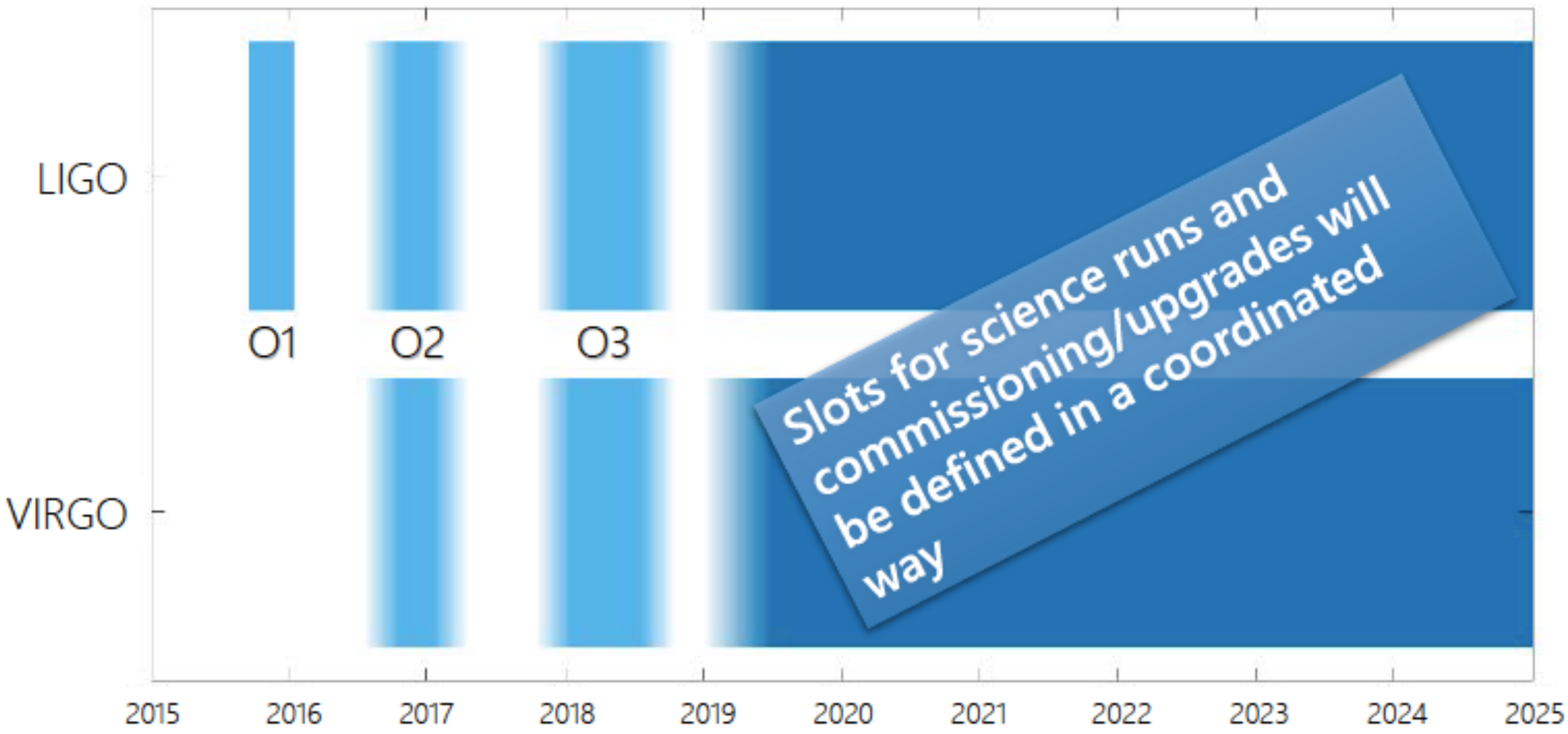
S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}


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


(a)
H1
L1
10 ms light travel time
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
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)

ADVANCED DETECTORS TIMELINE

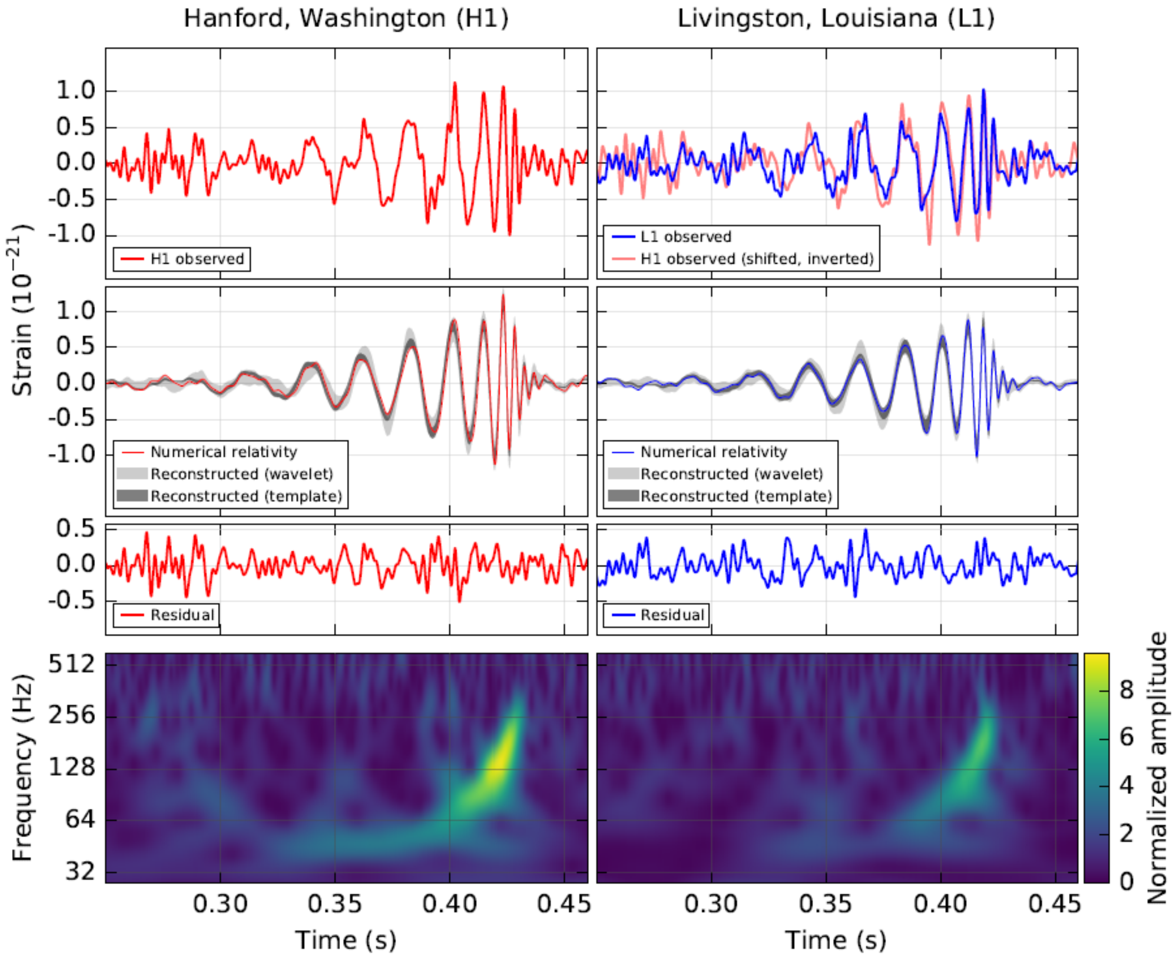
foreseen at the end of 2015



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



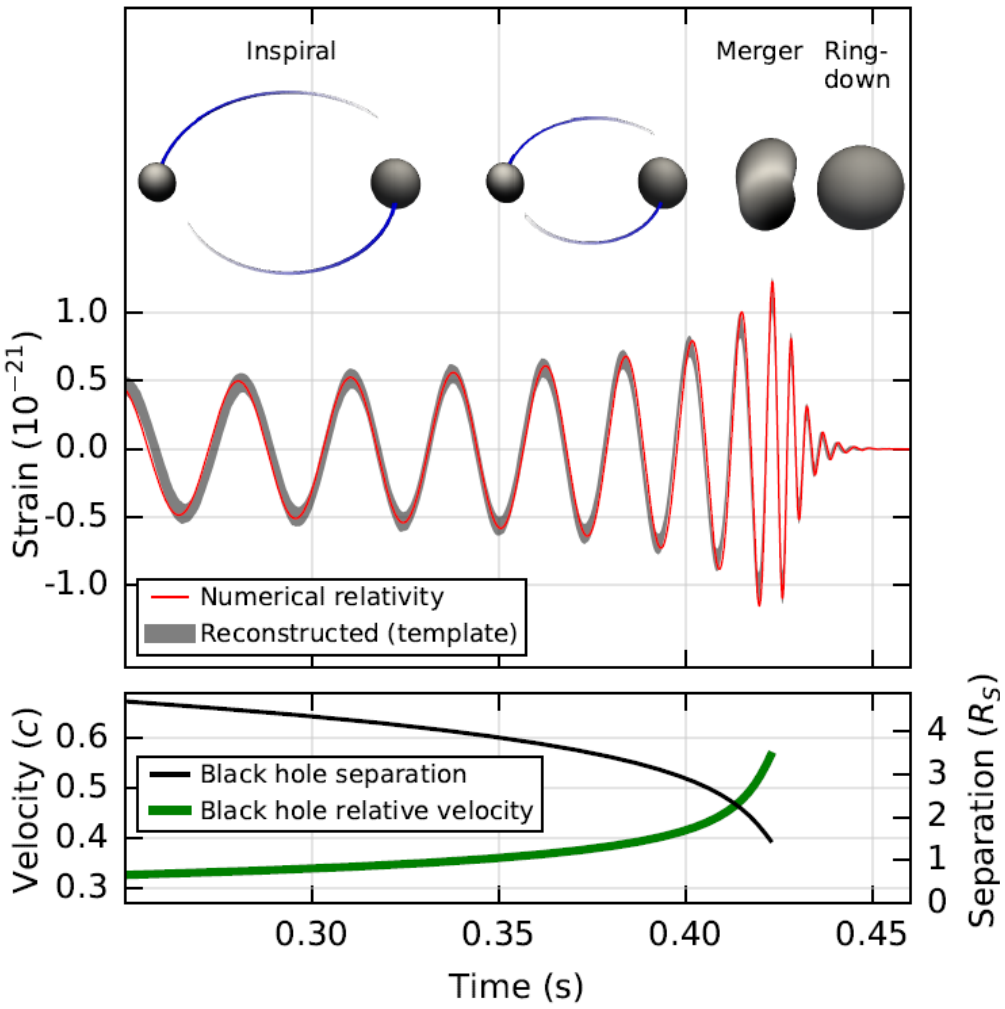
GW150914: Estimated Strain Amplitude

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

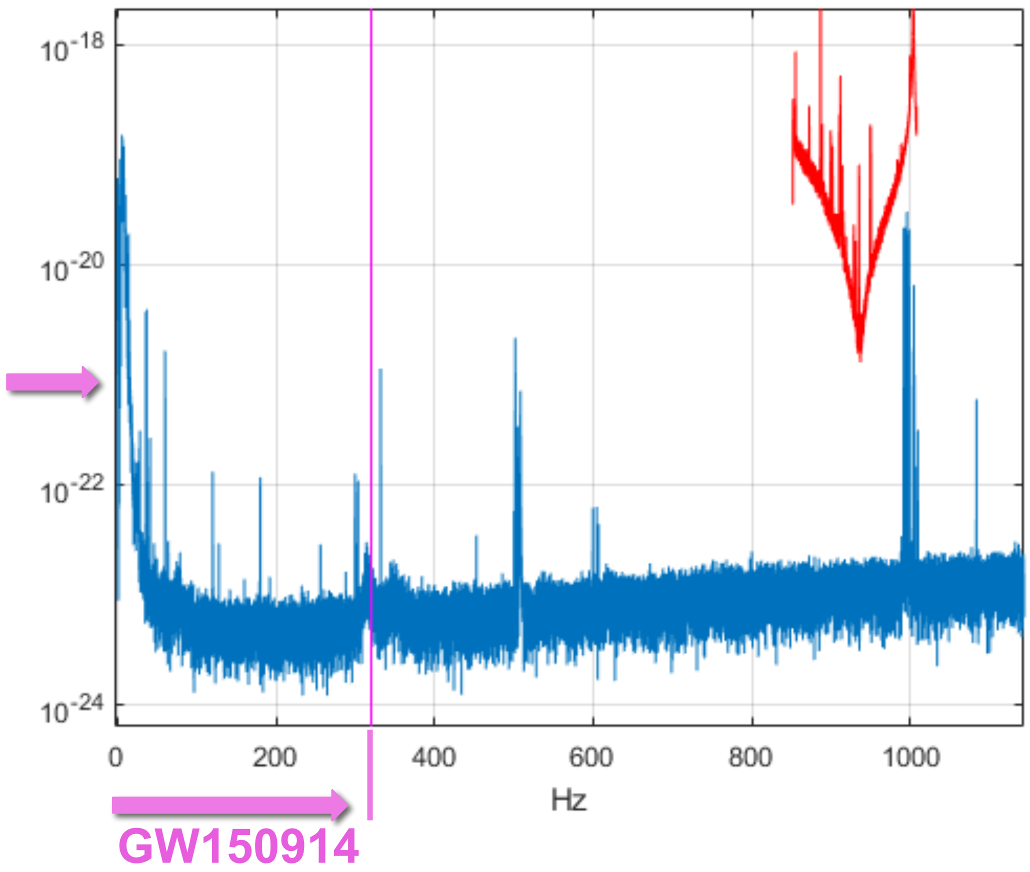
- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius ($R_s = 2GM_{tot}/c^2 = 210$km); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_{tot}\pi f_{GW}/c^3)^{1/3}$

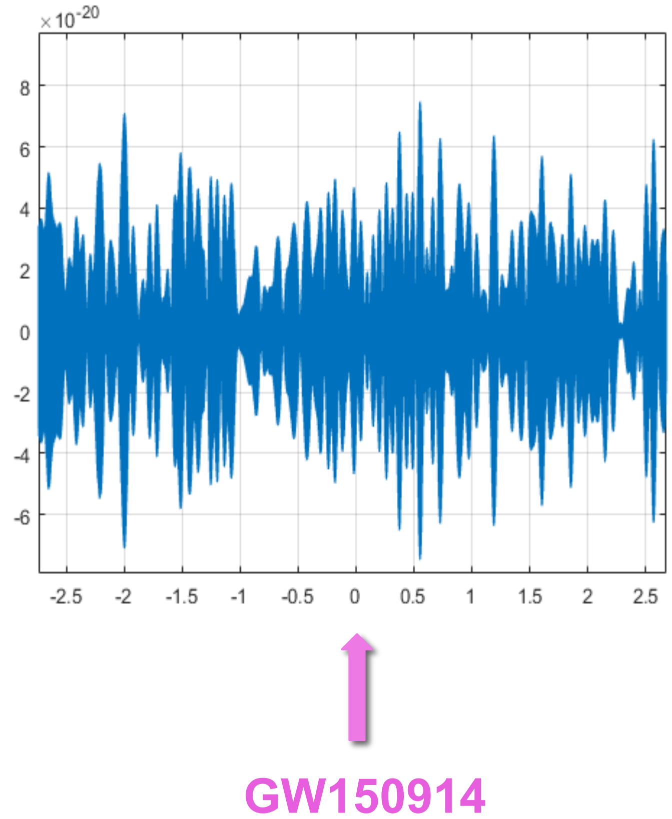
Binary Black Hole System

- 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)



Nautilus - September 14, 2015

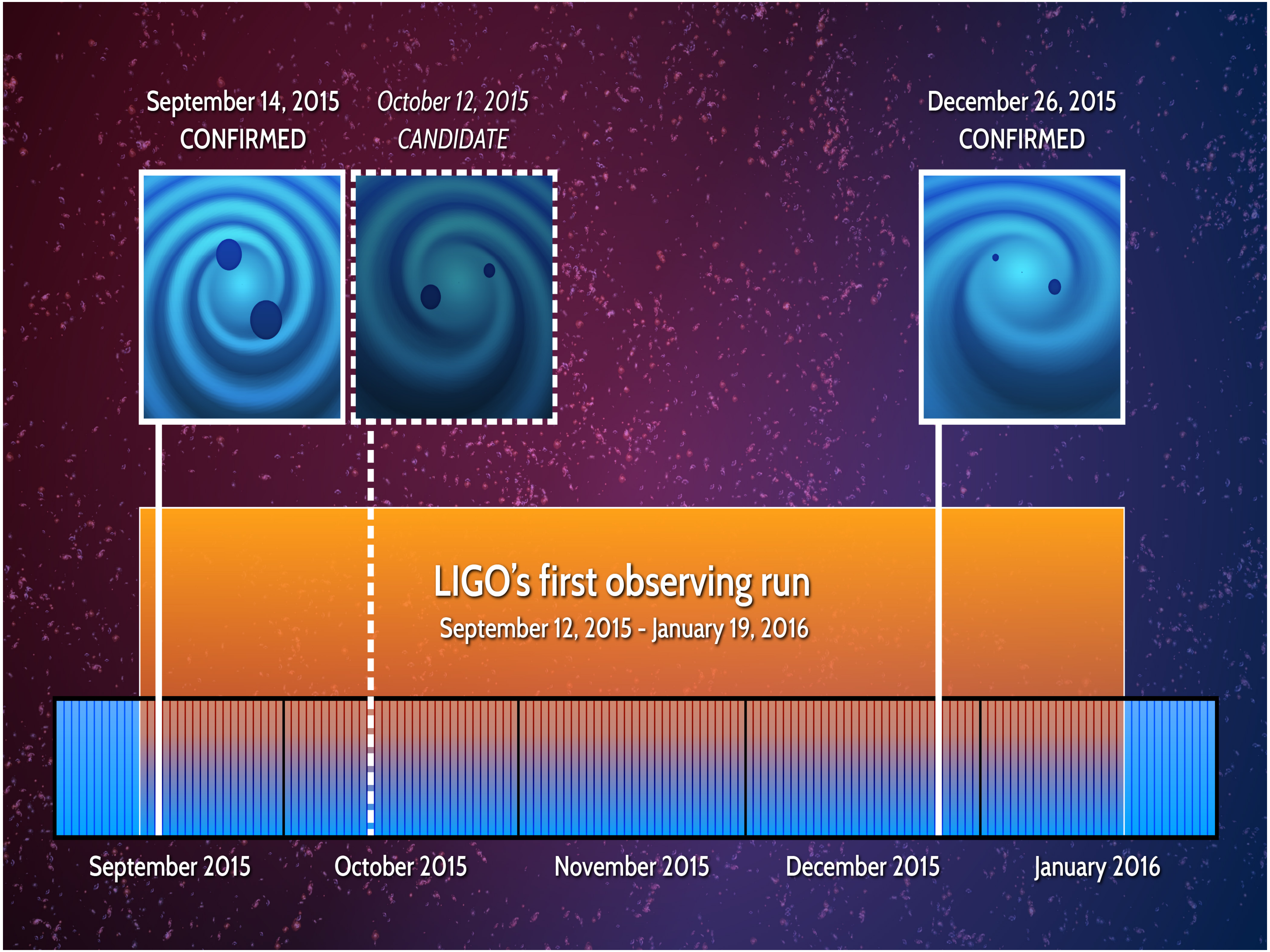




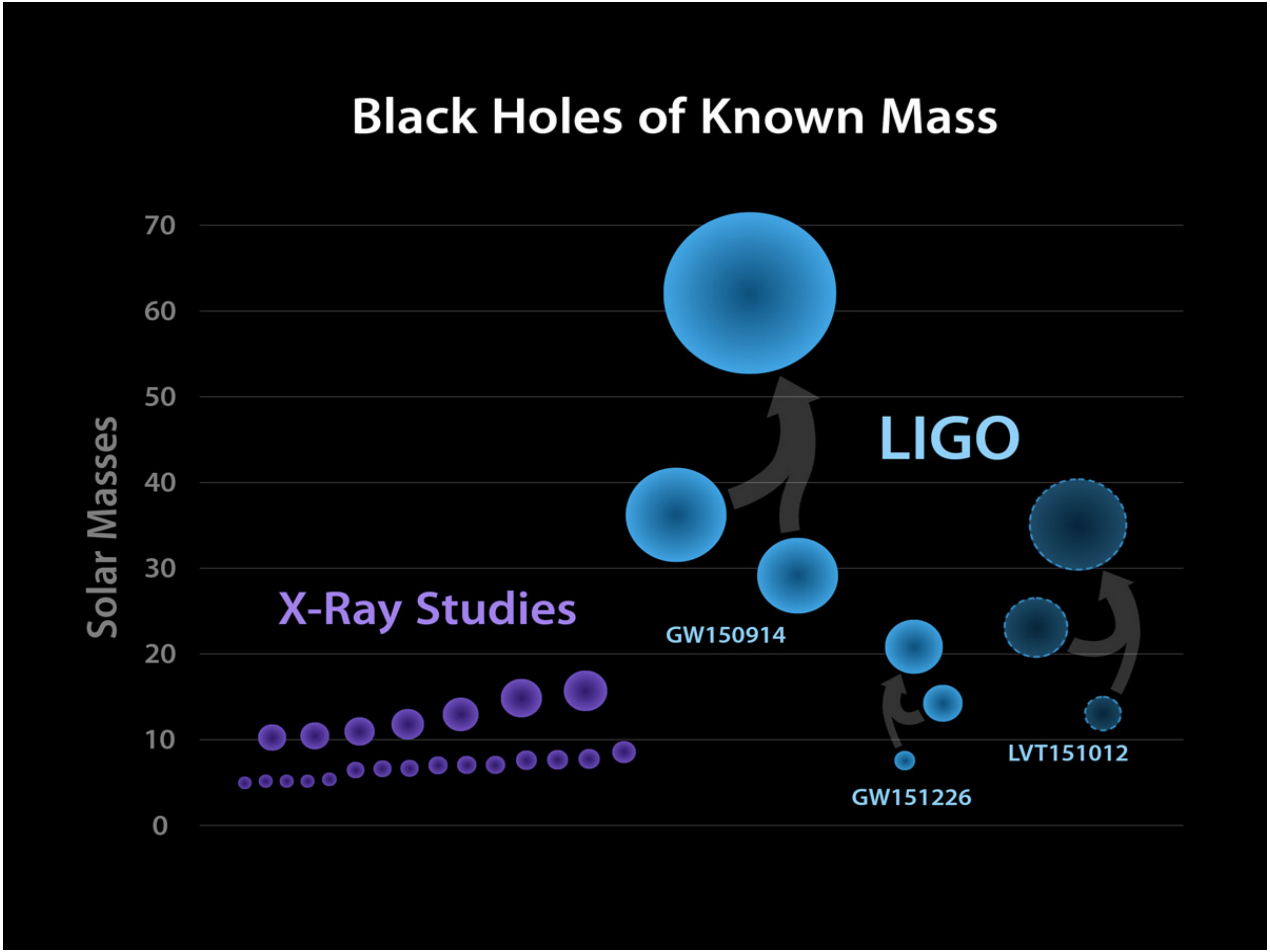
Source Parameters for GW150914

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

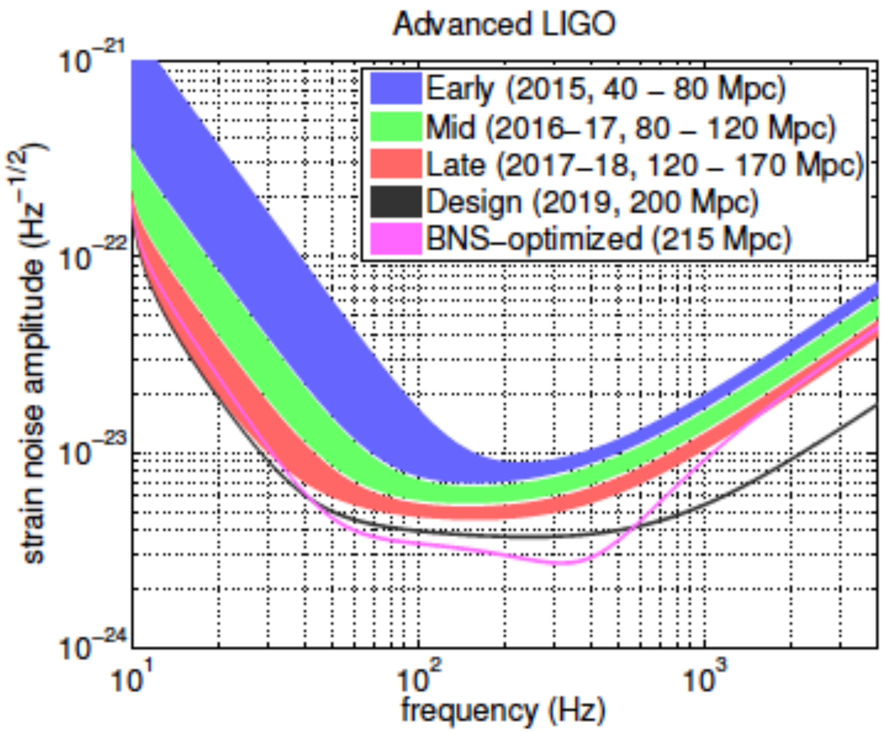


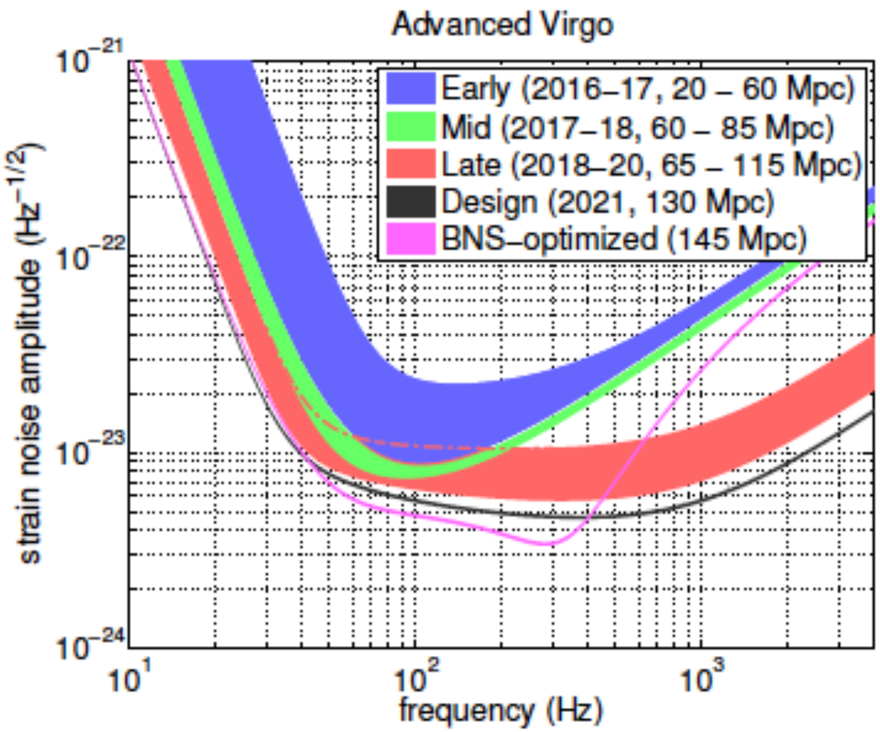
September 14, 2015
CONFIRMED
October 12, 2015
CANDIDATE
December 26, 2015
CONFIRMED
LIGO's first observing run
September 12, 2015 - January 19, 2016
September 2015
October 2015
November 2015
December 2015
January 2016



Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
GW151226
LVT151012

Plausible scenario
for the operation of the LIGO-Virgo network over the next decade





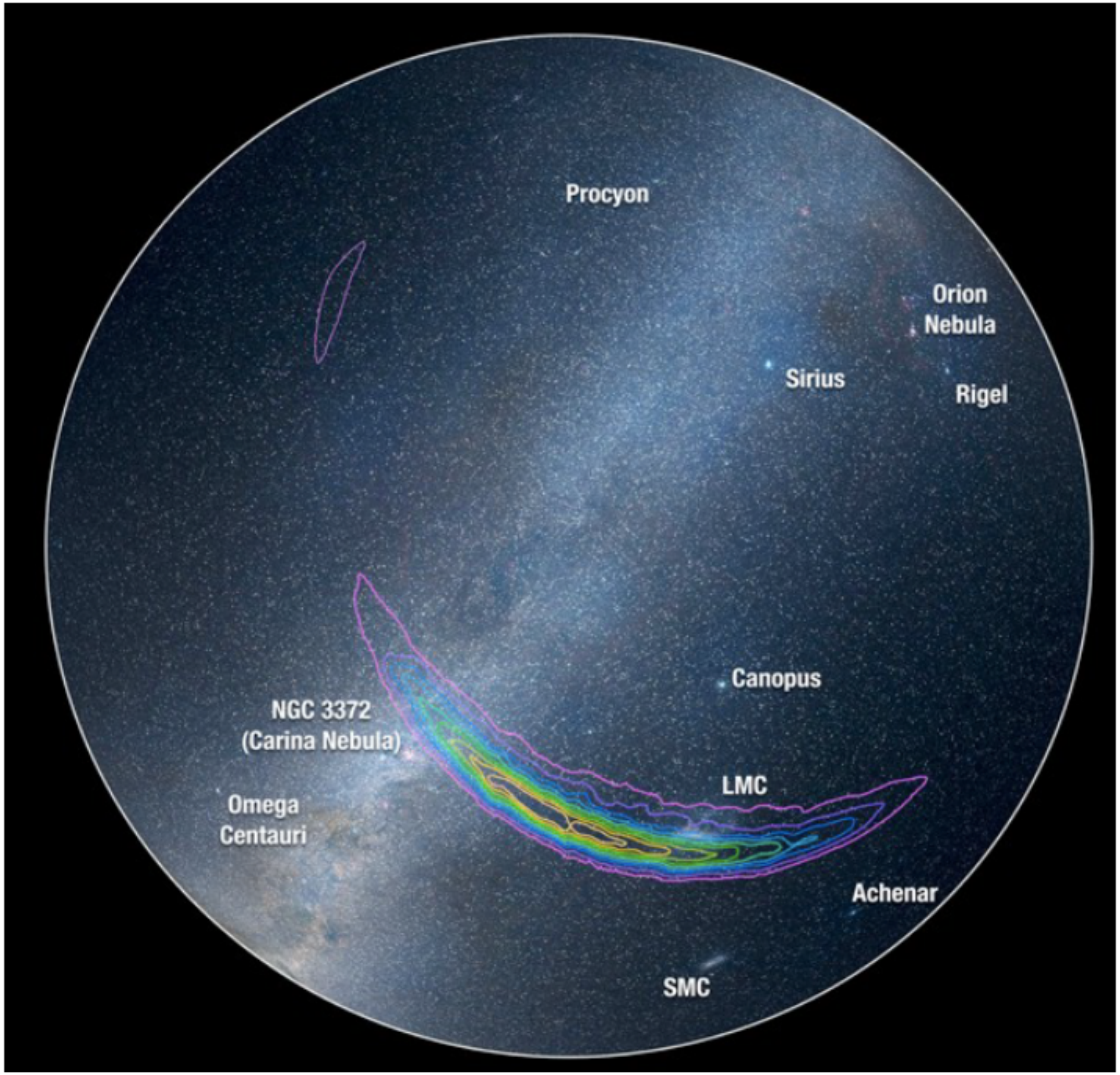
Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 $\deg^2$	20 $\deg^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Gravitational-Wave Sky Posteriors

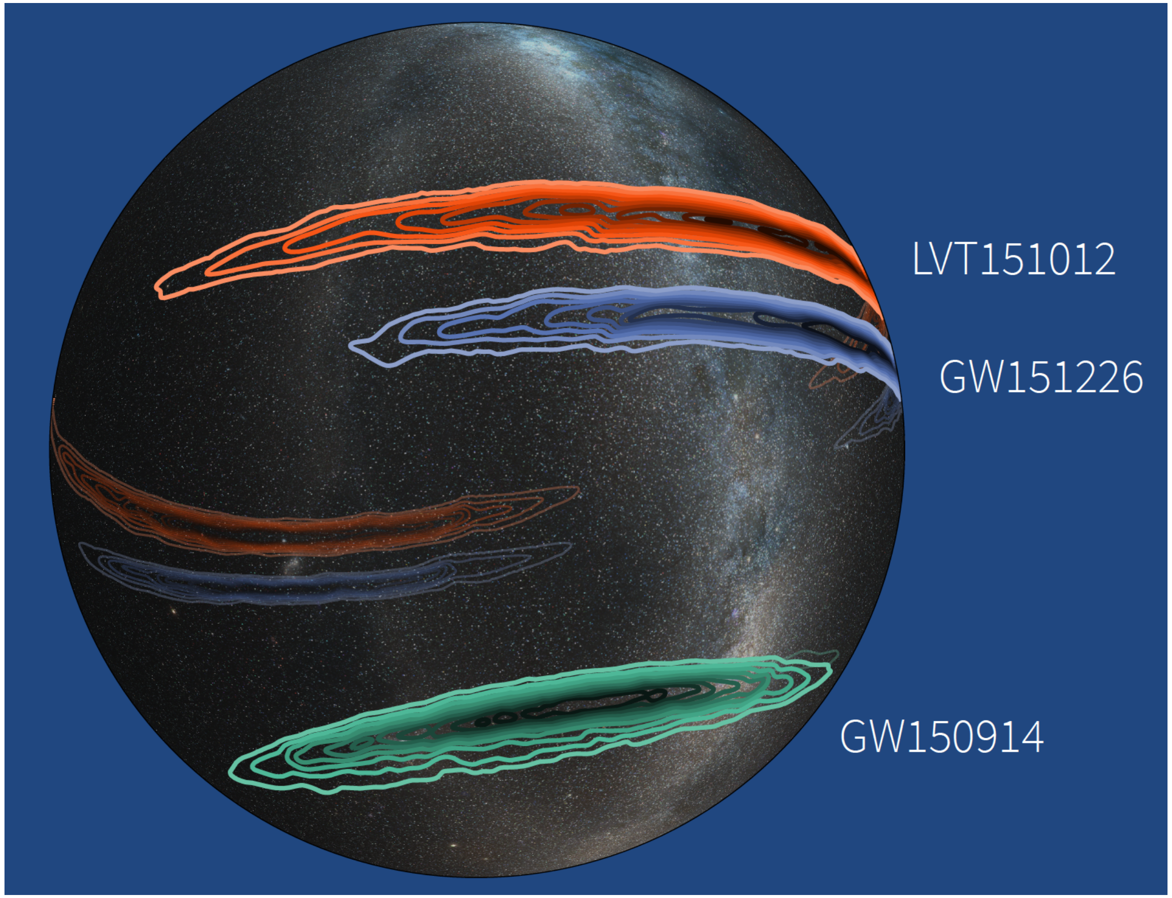
Sky areas broadly consistent with simply triangulation, and mostly cross-consistent

Triangulation ring consistent with time delay of about ~7 ms

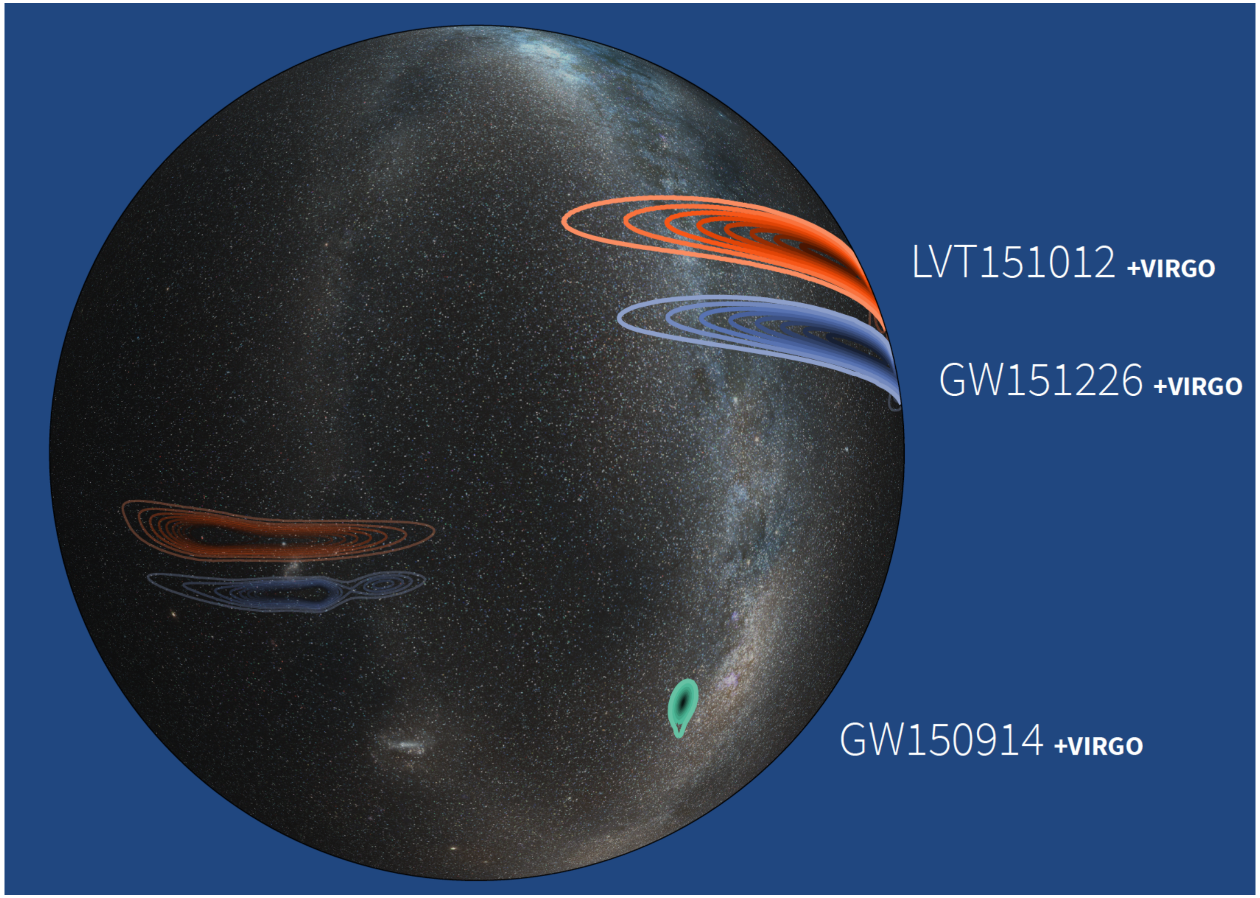
Search area: 620 sq. degrees to cover:

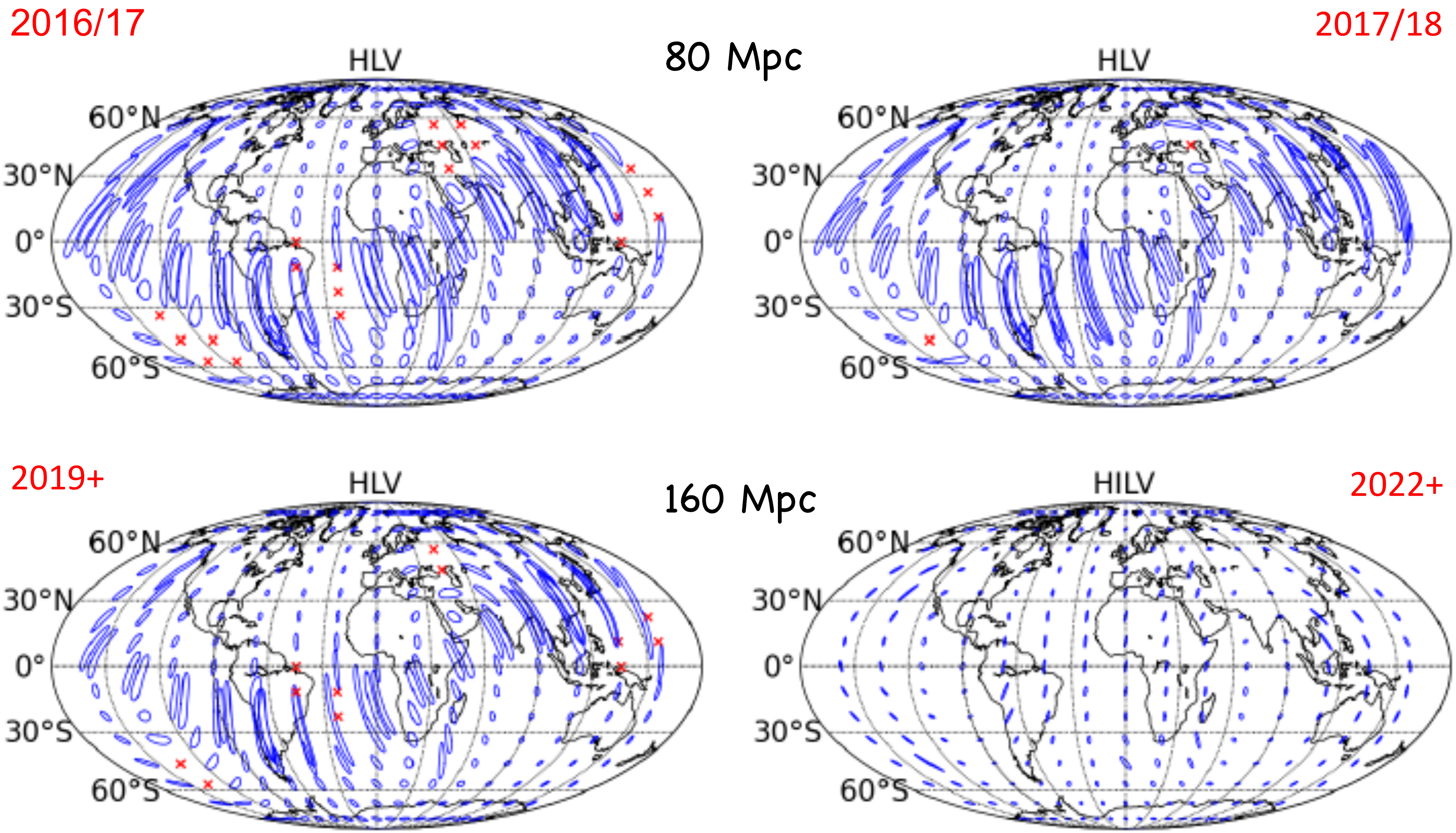


Sky Locations of Gravitational-wave Events GW150914, GW151226 and Candidate LVT151012



Simulated Sky Locations of O1 Events and Candidate Including the Virgo Interferometer

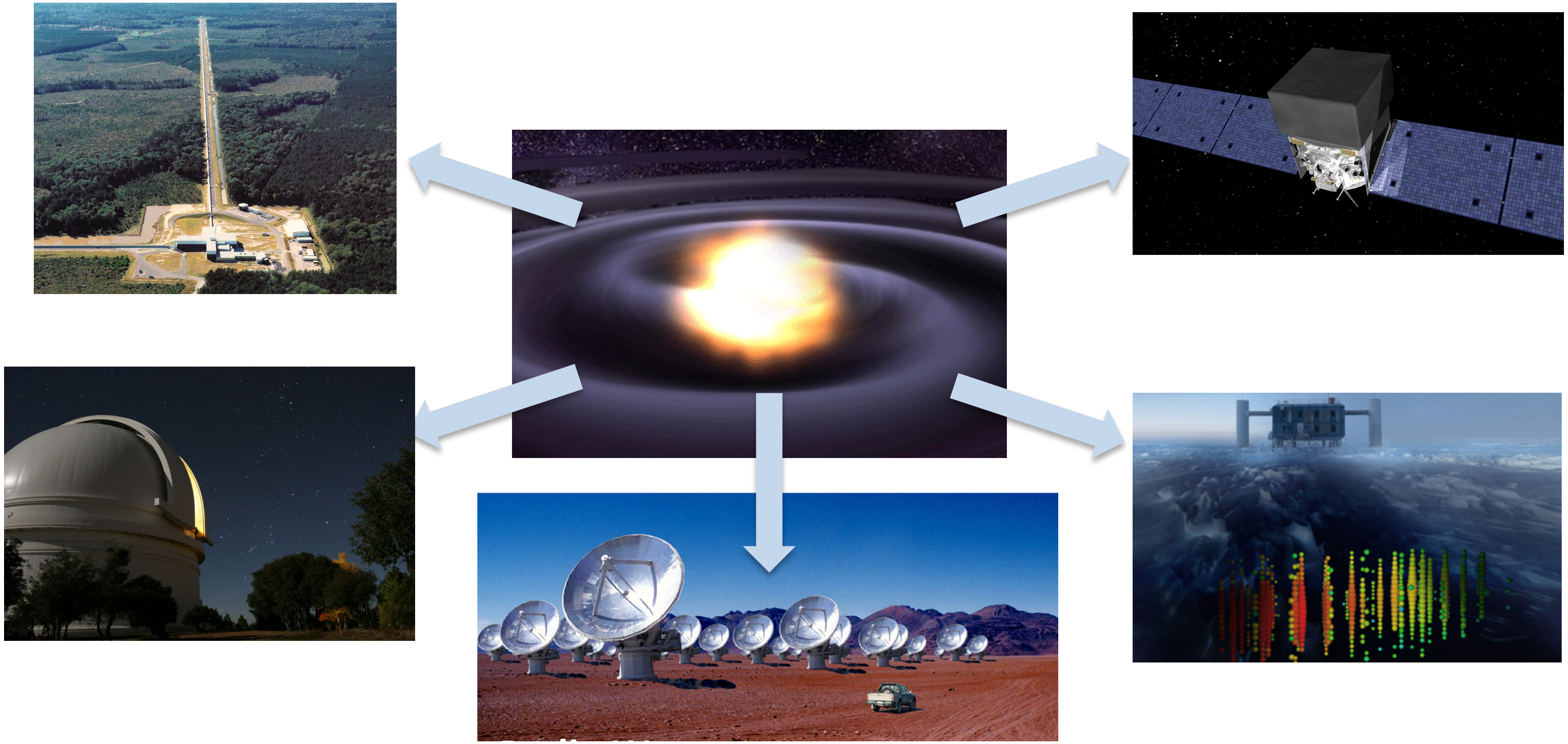


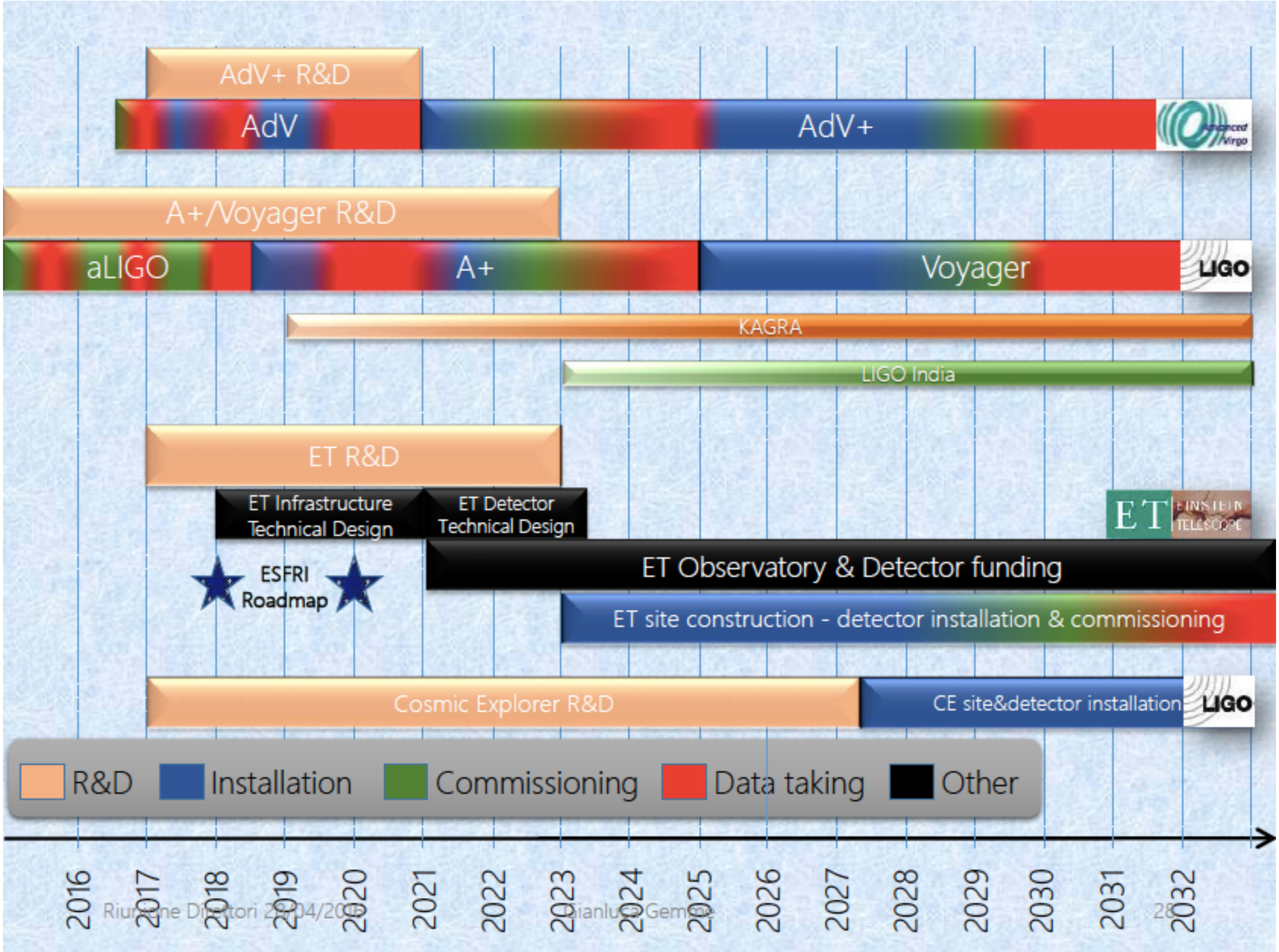


Localization expected for a BNS system

The ellipses show 90% confidence localization areas, and the red crosses show regions of the sky where the signal would not be condently detected.

Multi-Messenger Astronomy: Gravitational Wave + Electromagnetic +Neutrinos




AdV+ R&D
AdV
AdV+
A+/Voyager R&D
aLIGO
A+
Voyager
LIGO
KAGRA
LIGO India
ET R&D
ET Infrastructure Technical Design
ET Detector Technical Design
ESFRI Roadmap
ET Observatory & Detector funding
ET site construction - detector installation & commissioning
Cosmic Explorer R&D
CE site&detector installation
LIGO
R&D
Installation
Commissioning
Data taking
Other
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
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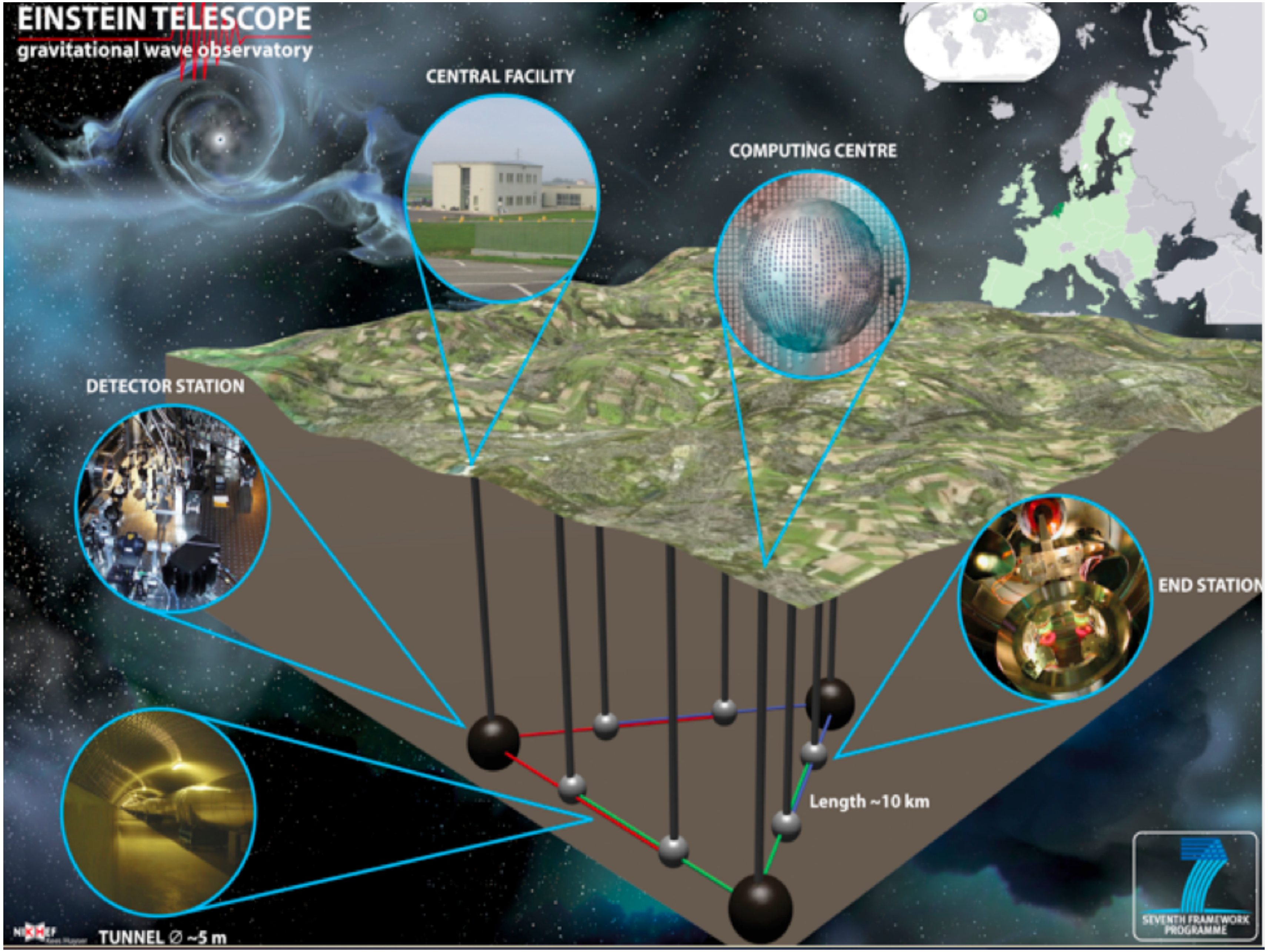
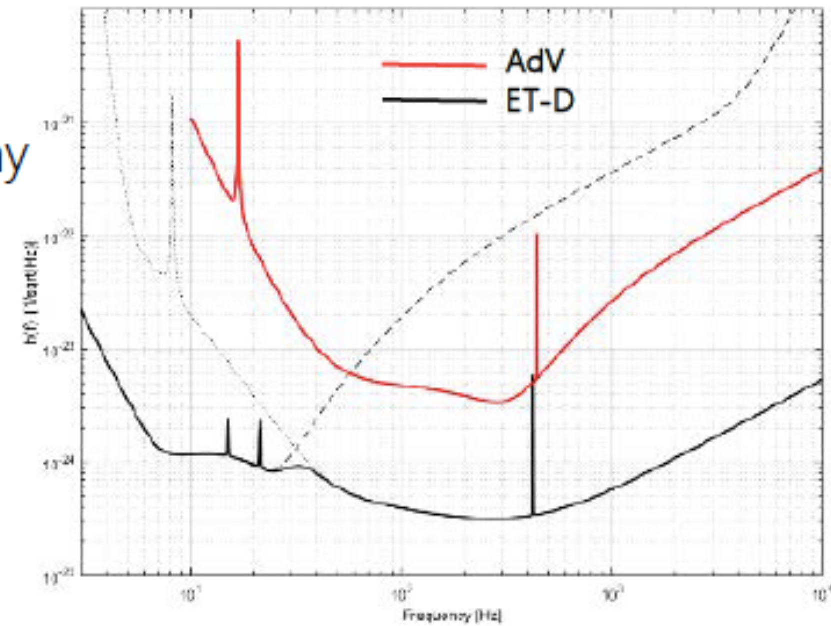
2029
2030
2031
2032


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

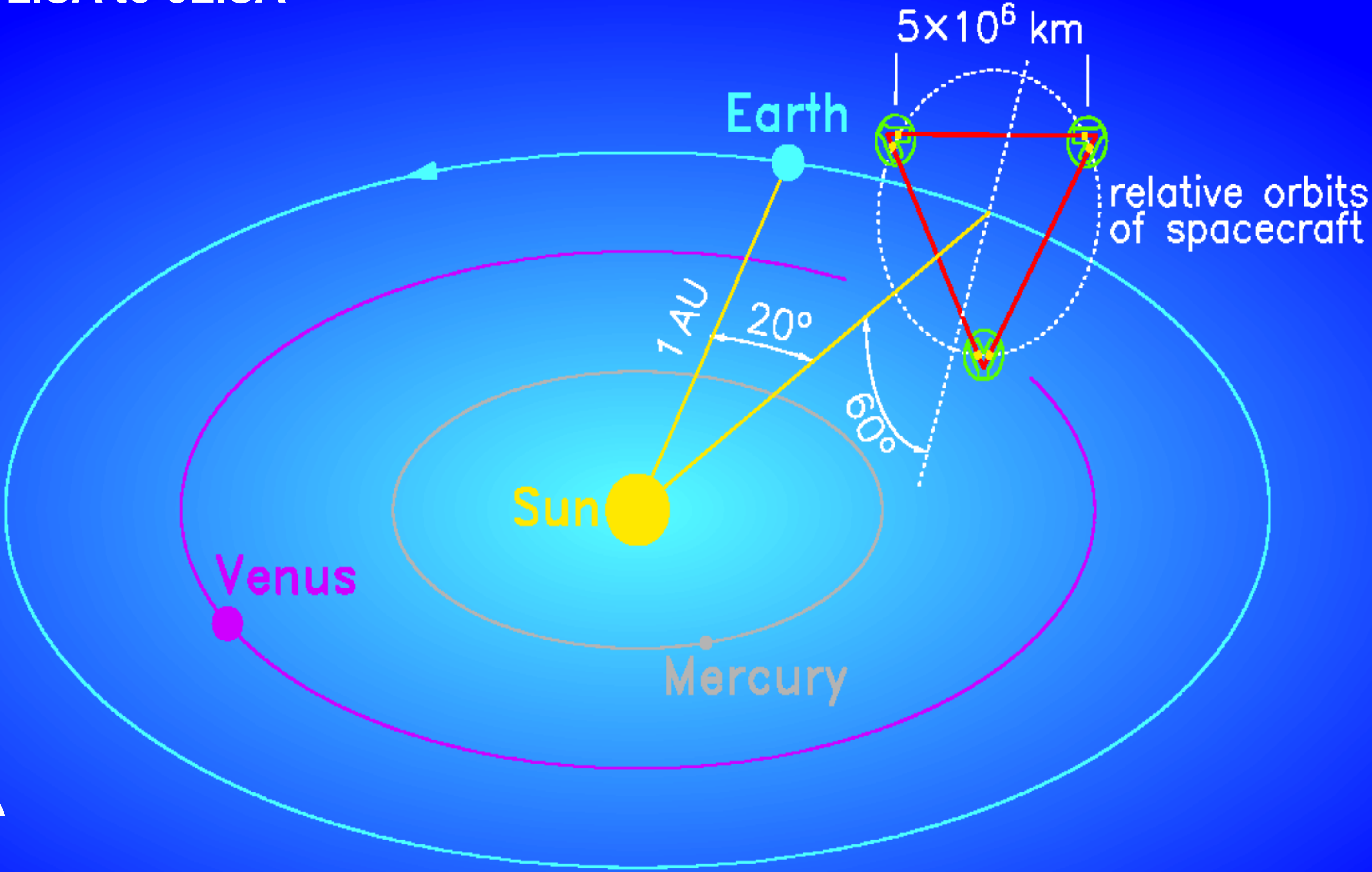
EINSTEIN TELESCOPE

✓ Design study of ET funded by the European Commission under FP7

- interest primarily focused on the Infrastructure rather than on the detector and its technologies
- The infrastructure should no limit the sensitivity of the future hosted detectors
  - Size
  - Environmental noises (seismic and NN)
- ET absorbed and developed many concepts in GW detectors:
  - Underground and cryo-compatible facility, pioneered in Japan by CLIO and KAGRA
  - Triangular geometry, concept used in LISA
  - Xylophone configuration



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;

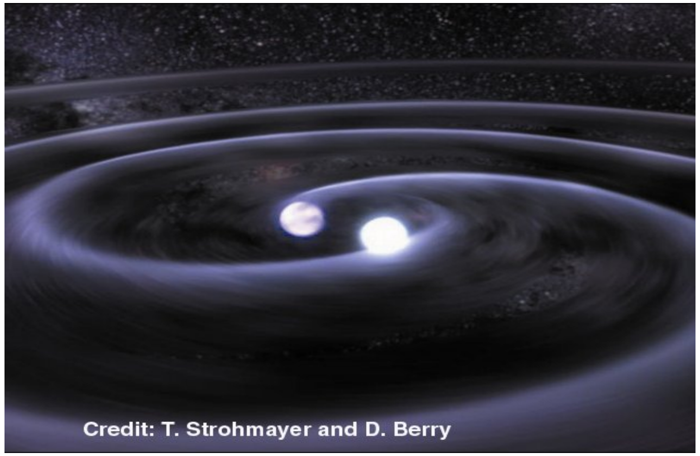
2029

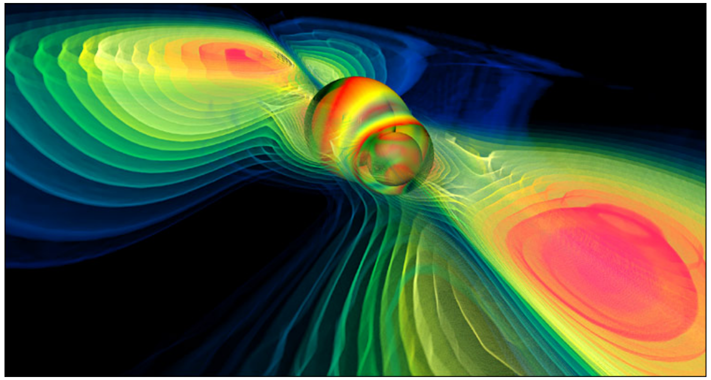
THE GLOBAL PLAN

- Advanced Detectors (LIGO, VIRGO) will initiate gravitational wave astronomy through the detection of the most luminous sources - compact binary mergers.

- Third Generation Detectors (ET and others) will expand detection horizons and provide new tools for extending knowledge of fundamental physics, cosmology and relativistic astrophysics.

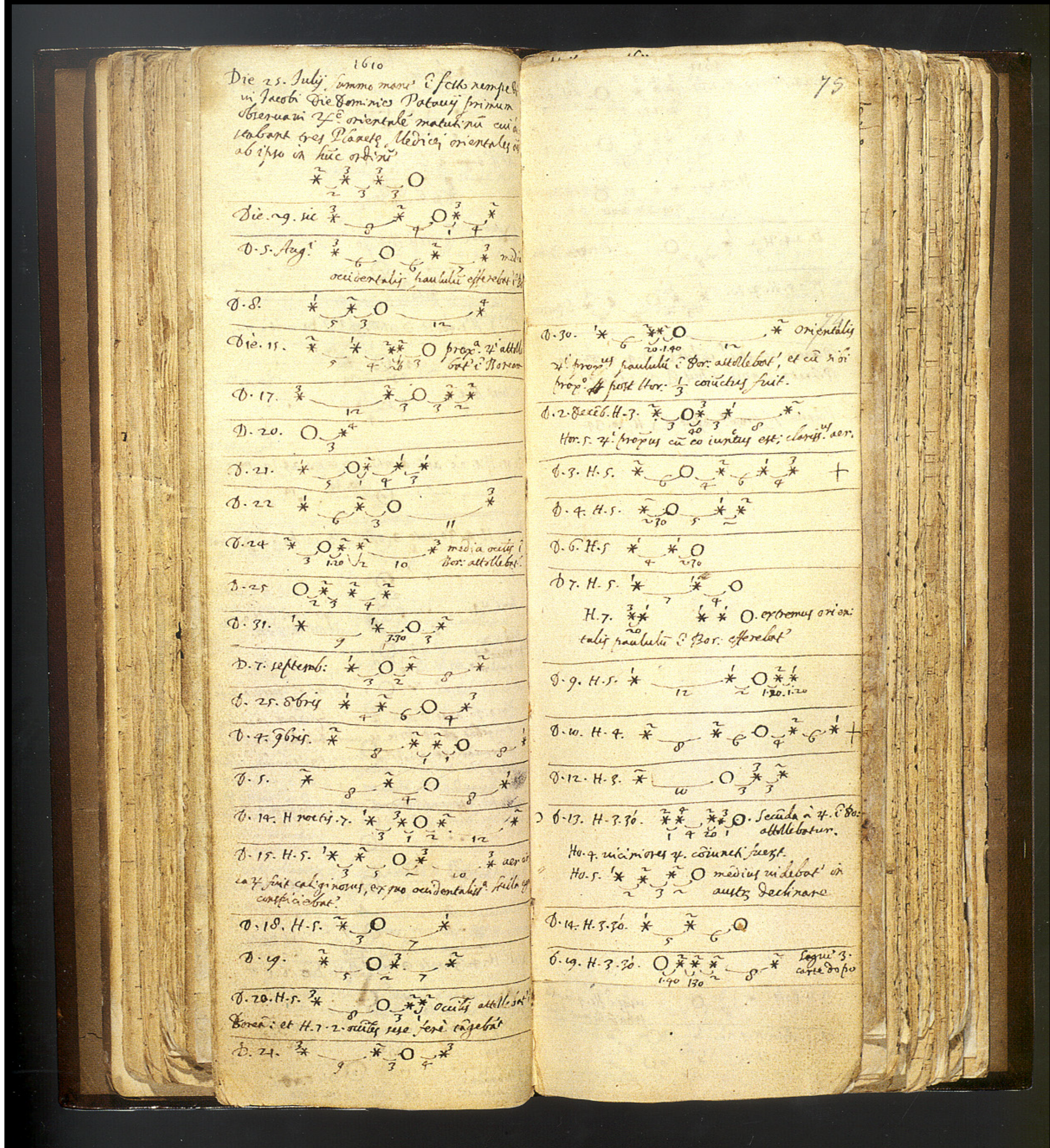
- Observation of low frequency gravitational wave with eLISA will probe the role of super-massive black holes in galaxy formation and evolution





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	GRBs	Late 1960s+ Vela
GW	2015	Binary BH mergers	2016

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