Gravitational waves

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Maratea, June 30, 2018

LIGO Scientific Collaboration

Advanced Virgo

February 2016: discovery of gravitational waves

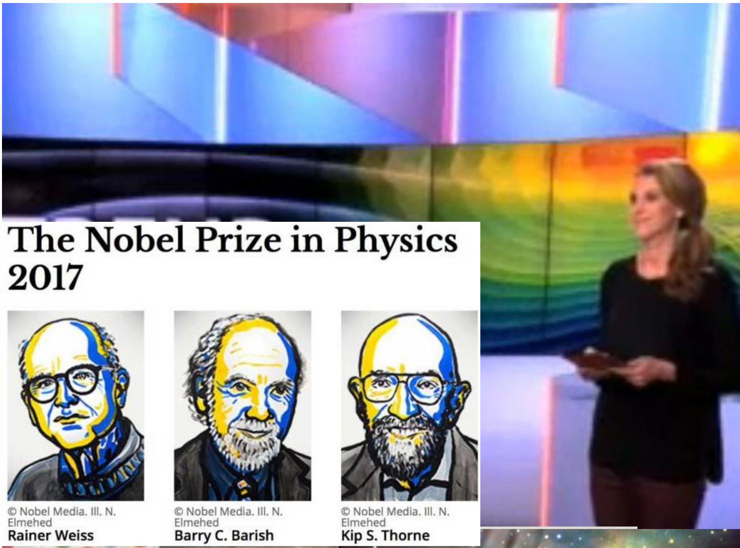
Tiny vibrations in space can now be observed by using the kilometer-scale laser-based interferometers of LIGO and Virgo. This enables an entire new field in science

José Antonio Font analiza en una conferencia el premio Nobel de Física de 2017

GABINETE DE PRENSA 22 de noviembre de 2017

José Antonio Font.

El director del Departamento de Astronomía y Astrofísica de la Universitat de València, José Antonio Font, analizó el premio Nobel de Física de 2017, en el MuVim. 'Arrugas del espacio-tiempo y estallidos de luz' era el título de la conferencia de Font dentro de els Debats del Magnànim. El acto fue presentado por el catedrático Vicent Martínez.



EL PAÍS | EL PAÍS SEMANAL

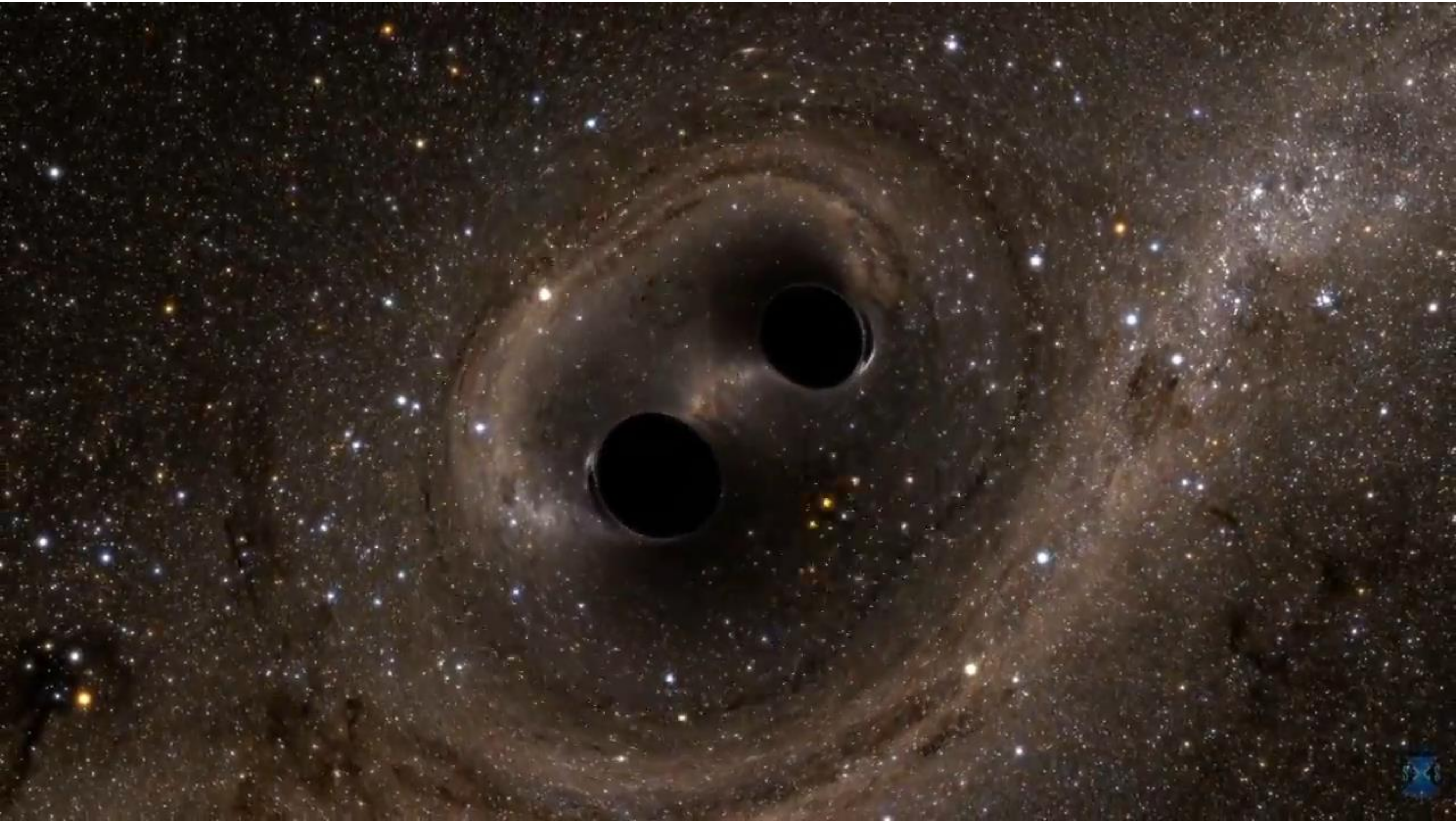
VISIONARIOS ›

Alicia Sintes, la física española que ganó parte del Nobel

Silvia Hernando

Event GW150914

Chirp-signal from gravitational waves from two coalescing black holes were observed with the LIGO detectors by the LIGO-Virgo Consortium on September 14, 2015



Intermezzo

Metric tensor and geometry

Geometry

Geometry is the study of shapes and spatial relations

Euclidean geometry

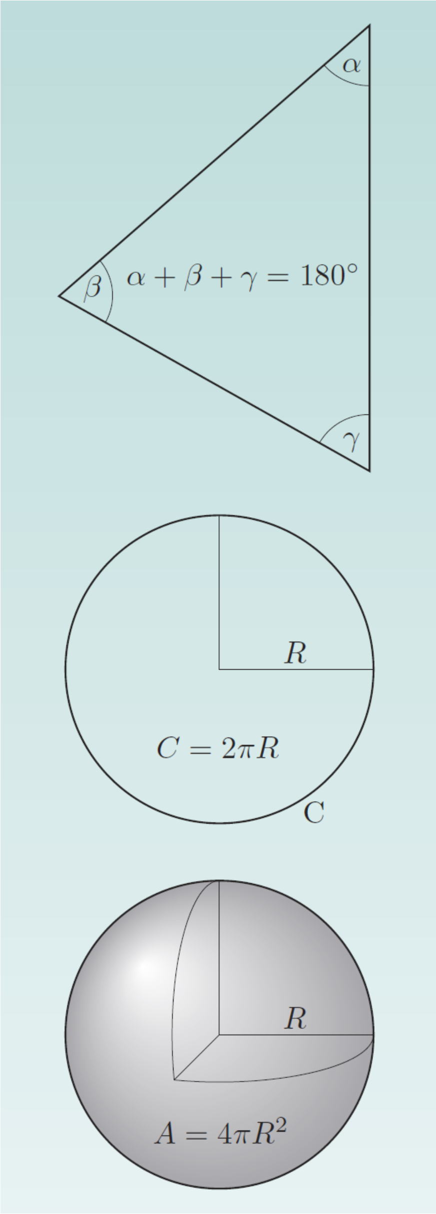
- sum of internal angles of a triangle is 180°
- circumference of a circle with radius R has length $2\pi R$
- a sphere with radius R has area $A = 4\pi R^2$
- Newton: space is Euclidean and time is universal
- Newton thus assumes a flat spacetime

Euclidian geometry is not the only kind of geometry

- Bolyai, Lobachevsky, Gauss discovered other geometries

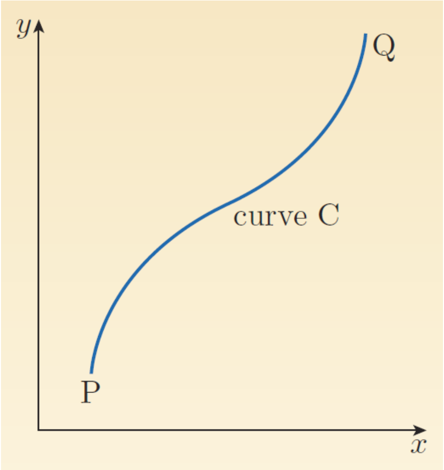
Especially, Carl Friedrich Gauss (1777 – 1855) and Bernhard Riemann (1826 – 1866) have made important contributions to the development of geometry. The defined *differential geometry*

Determining the geometric properties of the space (or even spacetime) around us is an experimental enterprise. It is not the subject of pure mathematics



Differential geometry and the line element

Line element is the central element of any geometry



Example: Length of a curve in Euclidean flat geometry in 2D

- Cartesian coordinates
- divide the curve in segments Δl_i
- use Pythagoras for each segment $(\Delta l)^2 = (\Delta x)^2 + (\Delta y)^2$
- sum in order to find the entire length of the curve

$$L_{\mathrm{C}}(\mathrm{P},\mathrm{Q}) \approx \sum_{i=1}^{n} \Delta l_i$$

Take the limit to infinitesimal elements

- this defines the line element

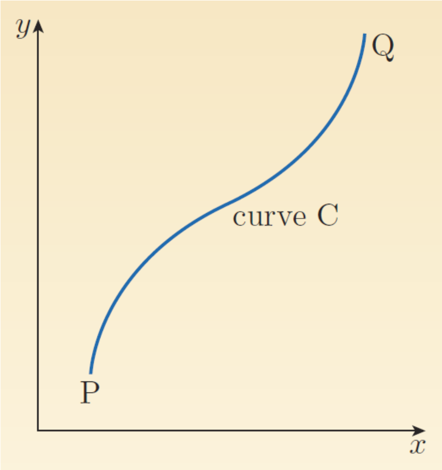
$$L_{\mathrm{C}}(\mathrm{P},\mathrm{Q}) = \int_{\mathrm{P}}^{\mathrm{Q}} \mathrm{d}l \quad \Rightarrow \quad \boxed{\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2 \quad \Rightarrow \quad \mathrm{d}l = (\mathrm{d}x^2 + \mathrm{d}y^2)^{1/2}}$$

Now we only need to know how to evaluate such an integral. When we add up the line elements, we need to account for the direction of the line element, since it gives different contributions d*x* and d*y*

Differential geometry and the line element

Line element is the central element of any geometry

Length of a curve in Euclidean 2D plane



The simplest solution is to make use of a parametrized curve. The coordinates become functions of a continuous varying parameter *u*

We then have *x(u)* and *y(u)*

Example: the function $y = x^2$ gives $x(u) = u, y(u) = u^2$

Example: the function $x^2 + y^2 = 1$ gives $x(u) = \cos(u), y(u) = \sin(u)$

One has

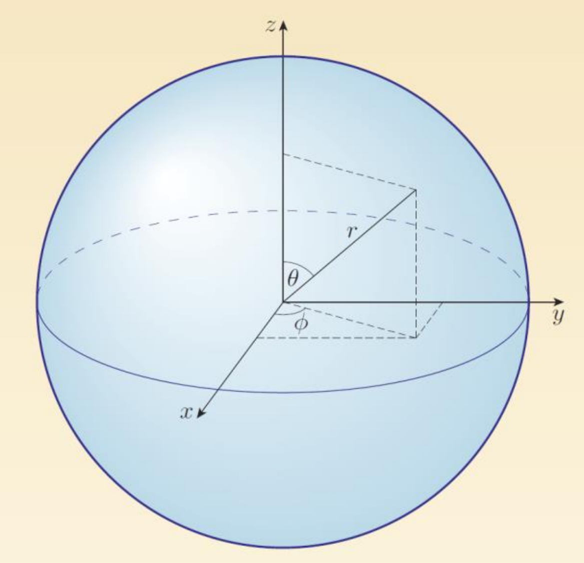
$$\left.\begin{aligned} \Delta x &= \frac{\Delta x}{\Delta u}\Delta u \\ \Delta y &= \frac{\Delta y}{\Delta u}\Delta u \end{aligned}\right\} \Rightarrow \quad \mathrm{d}x = \frac{\mathrm{d}x}{\mathrm{d}u}\mathrm{d}u, \quad \mathrm{d}y = \frac{\mathrm{d}y}{\mathrm{d}u}\mathrm{d}u,$$

$$\mathrm{d}l = (\mathrm{d}x^2 + \mathrm{d}y^2)^{1/2} \Rightarrow \quad \mathrm{d}l = \left(\left(\frac{\mathrm{d}x}{\mathrm{d}u}\right)^2 \mathrm{d}u^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}u}\right)^2 \mathrm{d}u^2\right)^{1/2} = \left(\left(\frac{\mathrm{d}x}{\mathrm{d}u}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}u}\right)^2\right)^{1/2} \mathrm{d}u$$

$$\Rightarrow \quad L_{\mathrm{C}}(\mathrm{P},\mathrm{Q}) = \int_{\mathrm{P}}^{\mathrm{Q}} \mathrm{d}l = \int_{u_{\mathrm{P}}}^{u_{\mathrm{Q}}} \left(\left(\frac{\mathrm{d}x}{\mathrm{d}u}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}u}\right)^2\right)^{1/2} \mathrm{d}u$$

Line element for different coordinates

Line element for the same geometry but in different coordinates



Consider 3D Euclidean (flat) space

Cartesian coordinates $\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2$

Spherical coordinates

$$\left.\begin{aligned} x &= r\sin\theta\cos\phi, \\ y &= r\sin\theta\sin\phi, \\ z &= r\cos\theta. \end{aligned}\right\} \Rightarrow$$

$$\begin{aligned} \mathrm{d}x &= \sin\theta\cos\phi\,\mathrm{d}r + r\cos\theta\cos\phi\,\mathrm{d}\theta - r\sin\theta\sin\phi\,\mathrm{d}\phi, \\ \mathrm{d}y &= \sin\theta\sin\phi\,\mathrm{d}r + r\cos\theta\sin\phi\,\mathrm{d}\theta + r\sin\theta\cos\phi\,\mathrm{d}\phi, \\ \mathrm{d}z &= \cos\theta\,\mathrm{d}r - r\sin\theta\,\mathrm{d}\theta, \end{aligned} \Rightarrow \boxed{\mathrm{d}l^2 = \mathrm{d}r^2 + r^2\,\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2}$$

Using this line element we can again determine the length of a curve in the 3D flat space. We then can build up the entire 3D Euclidean geometry. Gauss realized that the line element is the key concept

We can go further and also consider the geometry of 2D *curved* spaces in the 3D flat space. To this end we fix *r* = *R* and find for the line element

$$\mathrm{d}l^2 = R^2\,\mathrm{d}\theta^2 + R^2\sin^2\theta\,\mathrm{d}\phi^2$$

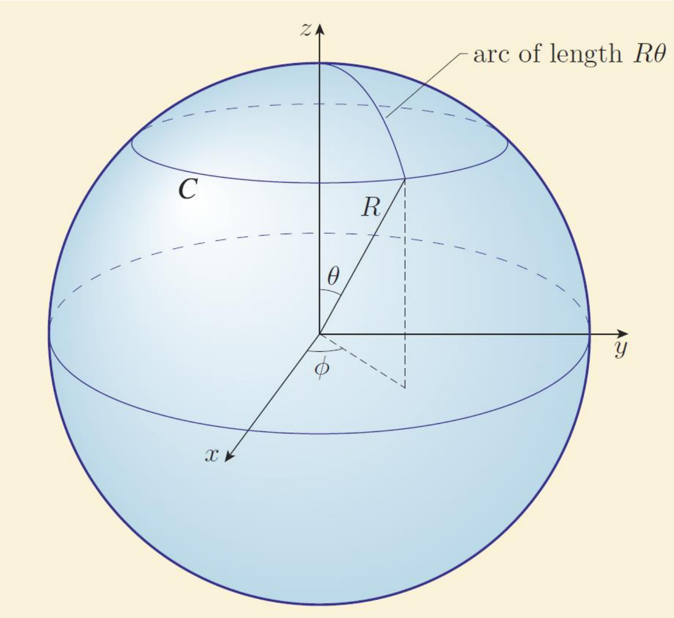
Curved spaces

Line element for curved surface leads to different geometry

Consider 2D curved surface (space) of a sphere

Line element $\mathrm{d}l^2 = R^2\,\mathrm{d}\theta^2 + R^2\sin^2\theta\,\mathrm{d}\phi^2$

Coordinates are θ and ϕ

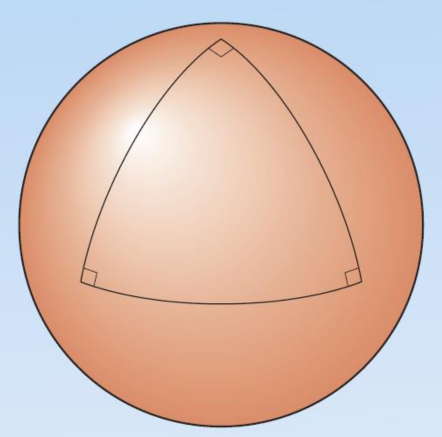


Example: calculate the circumference of circle *C*

Answer: θ is constant, thus

$$C = \int_0^{2\pi} R\sin\theta\,\mathrm{d}\phi = R\sin\theta\,[\phi]_0^{2\pi} = 2\pi R\sin\theta$$

When we measure the radius and circumference in the same curved surface, the we discover that the circumference is different than the Euclidean result



The sum of the internal angles of a triangle is larger than 180º

The shortest path between two points is the segment of a circle through both point, where the center of the circle coincides with the center of the sphere. This is a *great circle*

Note that curvature is an *intrinsic* property of the surface

Metric and Riemannian geometry

Line element is the starting point for any geometry

We have seen several line elements

$$\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2$$
$$\mathrm{d}l^2 = \mathrm{d}r^2 + r^2\,\mathrm{d}\phi^2$$
$$\mathrm{d}l^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2$$
$$\mathrm{d}l^2 = \mathrm{d}r^2 + r^2\,\mathrm{d}\theta^2 + r^2\sin^2\theta\,\mathrm{d}\phi^2$$
$$\mathrm{d}l^2 = R^2\,\mathrm{d}\theta^2 + R^2\sin^2\theta\,\mathrm{d}\phi^2$$

We deduced expressions for these line elements from the known properties of these spaces

Line element is expressed as the sum of the squares of coordinate differences, in analogy to the expression by Pythagoras

With the line element we can determine the lengths of curves and shortest paths, and with this the properties of circles and triangles, and in fact the entire geometry of a particular (curved) space

Riemann realized the one also can take the line element as starting point for a geometry (and not only as a summary)

An *n*-dimensional Riemann space is a space for which

$$\mathrm{d}l^2 = \sum_{i,j=1}^{n} g_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j$$

The functions g_{ij} are called the metric coefficients and must be symmetric $g_{ij} = g_{ji}$ so there are *n*(*n*+1)/2 independent coefficients

The set of metric coefficients is called the *metric*, sometimes also the metric tensor, and it determines the complete geometry of the space

Metric perturbations and gravitational waves

Metric of Special and General Relativity

Special Relativity uses the metric of flat spacetime: Minkowski metric

Line element measures the distance between two infinitesimally close events in spacetime

For the global Cartesian coordinates $ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$

With the Minkowski metric $\eta_{\alpha\beta}$ we can write the line element as $ds^2 = \eta_{\alpha\beta}dx^\alpha dx^\beta$

With $\eta_{\alpha\beta} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

In general spacetime is not flat and we write the metric as $g_{\mu\nu}$

The metric is a rank 2 tensor. The curvature is defined by the rank 4 Riemann tensor tensor $R_{\alpha\beta\gamma\delta}$, which depends on $g_{\alpha\beta}$, and also by its contractions, the Ricci tensor $R_{\alpha\beta}$ and curvature scalar R

What generates curvature of spacetime?

General Relativity to the rescue …

Einstein equations $R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$ with $T_{\mu\nu}$ the energy momentum tensor

Linearized gravity

Einstein field equations can be written as a wave equation for metric perturbations

We assume that the metric $g_{\mu\nu}$ can be described as flat $\eta_{\mu\nu}$ with a small perturbation $h_{\mu\nu} \ll 1$ encoding the effect of gravitation

Start from the Einstein equations $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$

Linearize by replacing $g_{\alpha\beta}$ with $\eta_{\alpha\beta} + h_{\alpha\beta}$ and removing higher order terms in $h_{\alpha\beta}$

The equivalent equation is still complicated: change variables $h_{\alpha\beta} \rightarrow \bar{h}_{\alpha\beta}$

The trace-reversed variables are defined by $\bar{h}_{\alpha\beta} \equiv h_{\alpha\beta} - \frac{1}{2} \eta_{\alpha\beta} h$

In GR physics does not depend choice of coordinates (gauge)

Choose a specific set of coordinates systems that meet the condition $\frac{\partial}{\partial x^{\alpha}} \bar{h}^{\alpha\beta} = \partial_{\alpha} \bar{h}^{\alpha\beta} = 0$

The field equations may now be written as $\Box \bar{h}_{\alpha\beta} = \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \bar{h}_{\alpha\beta} = -2 \left(\frac{8\pi G}{c^4} \right) T_{\alpha\beta}$

In vacuum the EFE reduce to a wave equation for the metric perturbation $h_{\alpha\beta}$

Gravitational waves

GW polarizations can be derived in Transverse Traceless (TT) gauge (coordinate system)

In vacuum we have $T_{\alpha\beta} = 0$ and the EFE reduce to the wave equation $\Box \bar{h}_{\alpha\beta} = \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\bar{h}_{\alpha\beta} = 0$

This wave equation obeys the gauge condition $\partial_\alpha \bar{h}^{\alpha\beta} = 0$

We consider solutions $\bar{h}_{\alpha\beta} = \mathbb{R}\mathrm{e}\left(\epsilon_{\alpha\beta} e^{-ik_\rho x^\rho}\right)$ with wave vector $k^\rho = \begin{pmatrix} \omega/c \\ k_x \\ k_y \\ k_z \end{pmatrix}$

Then satisfying the wave equation $\Box \bar{h}_{\alpha\beta} = 0$ implies $k_\rho k^\rho = 0$. This gives $\omega^2 = c^2 \left|\vec{k}\right|^2$ and thus a wave propagating at the speed of light *c*

Using the gauge condition $\partial_\alpha \bar{h}^{\alpha\beta} = 0$ leads to $k_\rho \epsilon^{\rho\sigma} = 0$ and we have 6 remaining independent elements in the polarization tensor

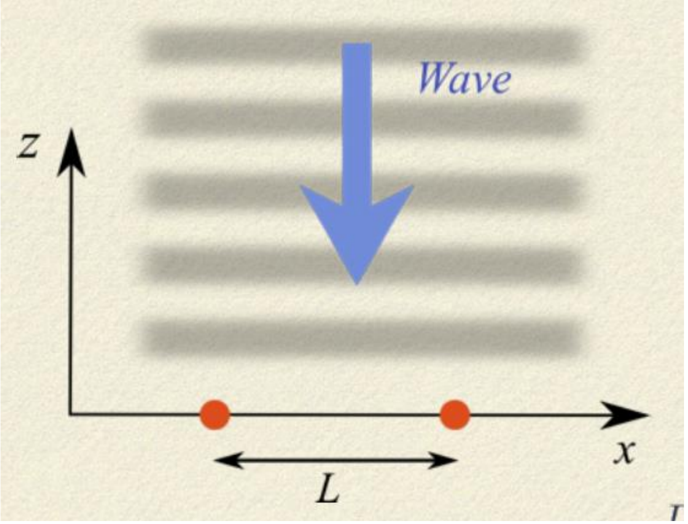
Among the set of coordinate systems, it is possible to choose one for which $\epsilon_{0\sigma} = 0$. This reduces the number of independent elements to 2 denoted “plus” and “cross” polarization

General solution for a wave traveling along the *z*-axis is $\epsilon_{\alpha\beta} e^{-ik_\rho x^\rho} = \left(h_+ \epsilon^+_{\alpha\beta} + h_\times \epsilon^\times_{\alpha\beta}\right) e^{-ik_\rho x^\rho}$

Here is $\epsilon^+_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ and $\epsilon^\times_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ are a basis for the polarization tensor

Gravitational waves: effect on two test masses

Metric perturbation *h* is the relative variation in proper length between the test masses



Consider the proper length between two test masses in free fall

Line element $ds^2 = g_{\alpha\beta} dx^\alpha dx^\beta$

Consider a plus-polarized gravitational wave

We only consider the x-direction and for proper length ($dt = 0$) we have $ds^2 = g_{xx} dx^2$

We have $L = \int_0^{\Delta x} \sqrt{g_{xx}}\, dx = \int_0^{\Delta x} \sqrt{1 + h_{xx}^{TT}(t, z = 0)}\, dx$

We find $L \approx \int_0^{\Delta x} \left(1 + \frac{1}{2} h_{xx}^{TT}(t, z = 0)\right) dx = \left(1 + \frac{1}{2} h_{xx}^{TT}(t, z = 0)\right) \Delta x$

The TT-coordinate system has coordinates “fixed” at the test masses

The proper length changes, because the metric changes. This is observable

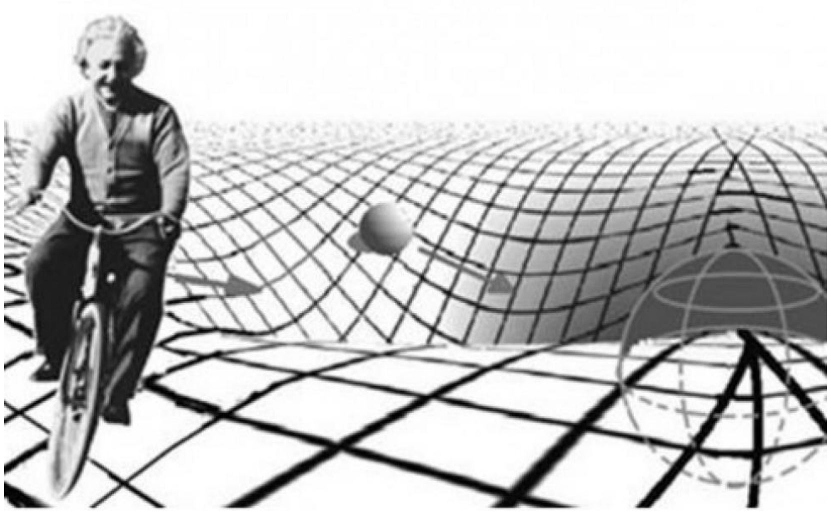
End of intermezzo

Einstein’s theory of general relativity

Einstein discovers deep connections between space, time, light, and gravity

Einstein’s Gravity

- Space and time are physical objects
- Gravity as a geometry



Predictions

- Gravitation is curvature of spacetime
- Light bends around the Sun
- Expansion of the Universe
- Black holes, worm holes, structure formation, …
- Gravitational waves

Einstein predicted gravitational waves in 1916

… but then doubted their existence for the rest of his life

The theory was so subtle, Einstein was never sure whether the waves were a coordinate effect only, with no physical reality

For decades relativists doubted whether GWs are real

Gravitational waves

In Eddington’s early textbook on relativity, he quipped that some people thought that “gravitational waves travel at the speed of thought”

Einstein proposed many experiments, including really hard ones, but never suggested a search for gravitational waves

The controversy lasted four decades, until the Chapel Hill Conference in 1957

Felix Pirani

Solved the problem of the reality of gravitational waves

He showed relativists that gravitational waves must have physical reality, because you could invent a (thought) experiment that could detect them

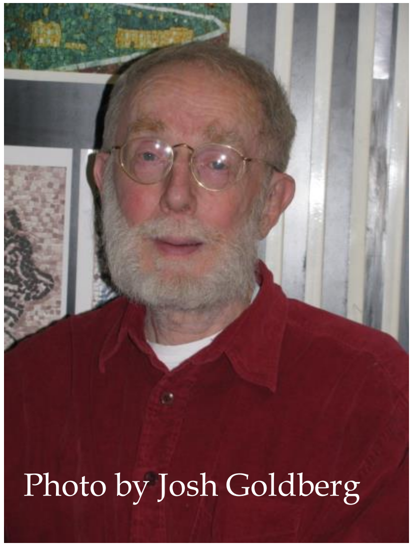
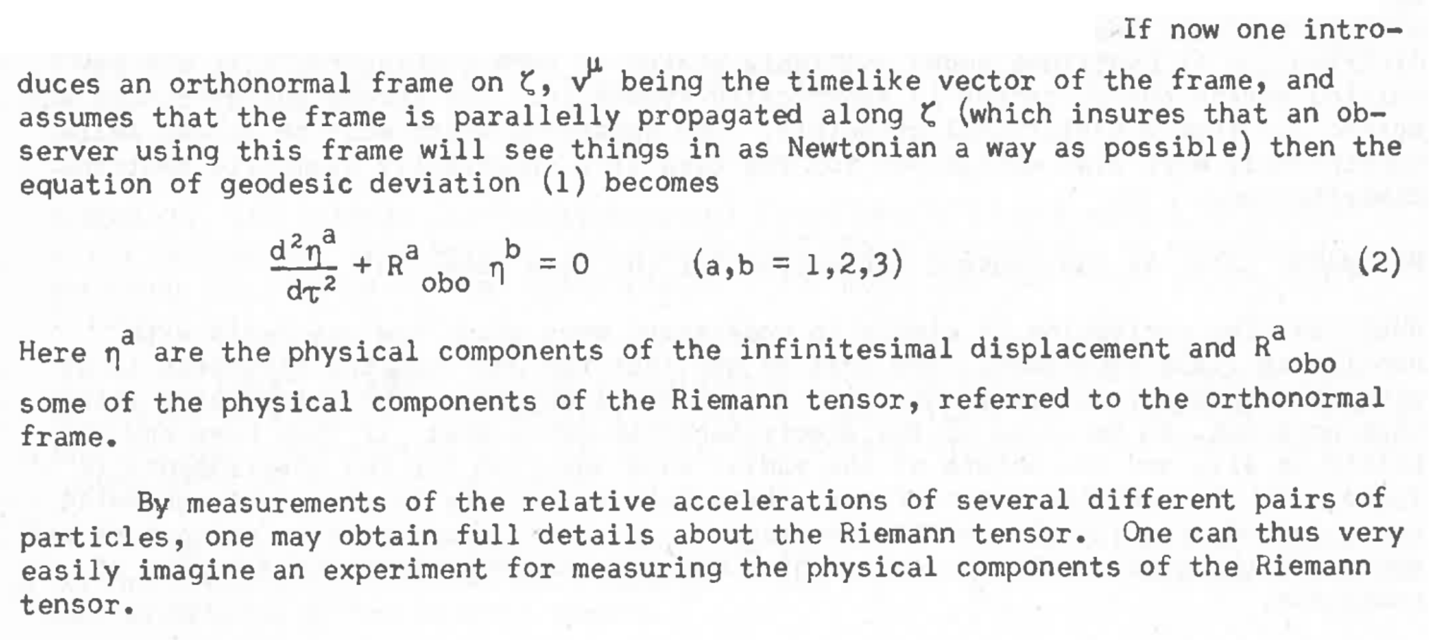


Photo by Josh Goldberg



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 (1) becomes

$$\frac{d^2\eta^a}{d\tau^2} + R^a{}_{obo}\,\eta^b = 0 \qquad (a,b = 1,2,3) \tag{2}$$

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

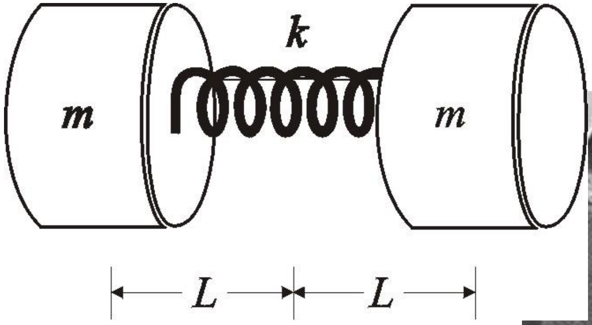
By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

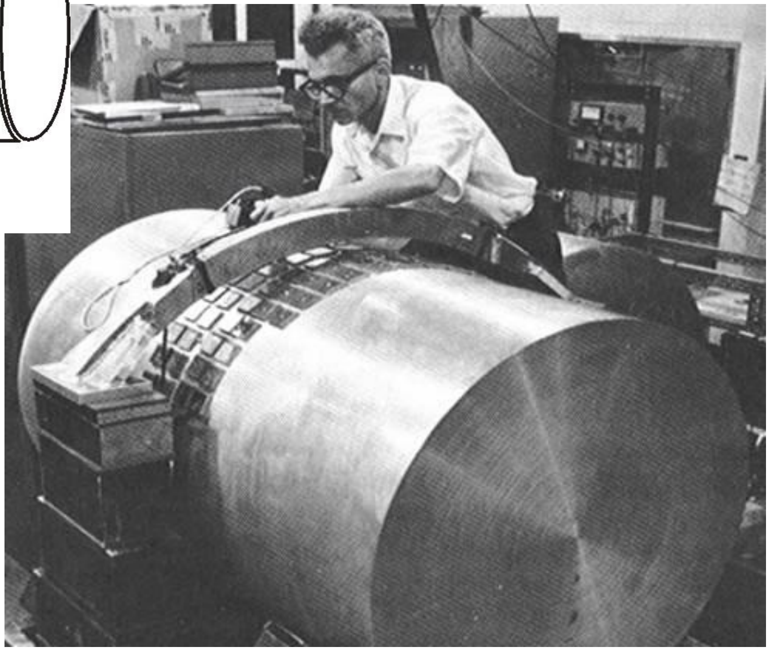
Weber bars

Joe Weber, co-inventor of the maser, was working with John Wheeler at Princeton on gravitational waves. The two of them were at Chapel Hill, and listened well to Pirani's talk

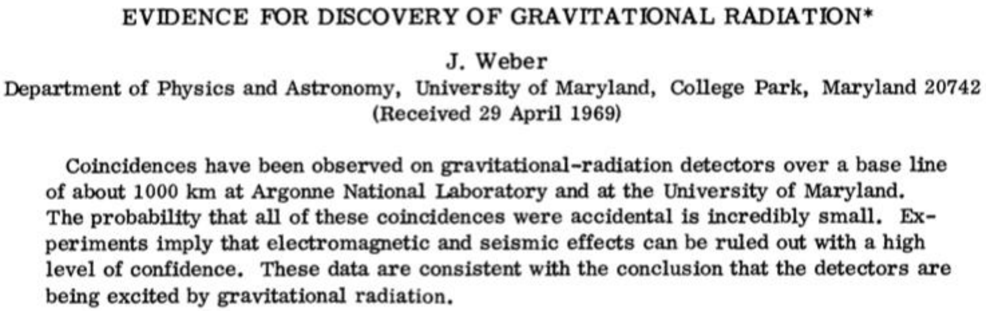
Weber's gravitational wave detector was a cylinder of aluminum. Each end is like a test mass, while the center is like a spring. PZT's around the midline are Bondi's dashpots, absorbing energy to send to an electrical amplifier

A massive (aluminum) cylinder. Vibrating in its gravest longitudinal mode, its two ends are like two test masses connected by a spring





Resonant bar detectors



EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

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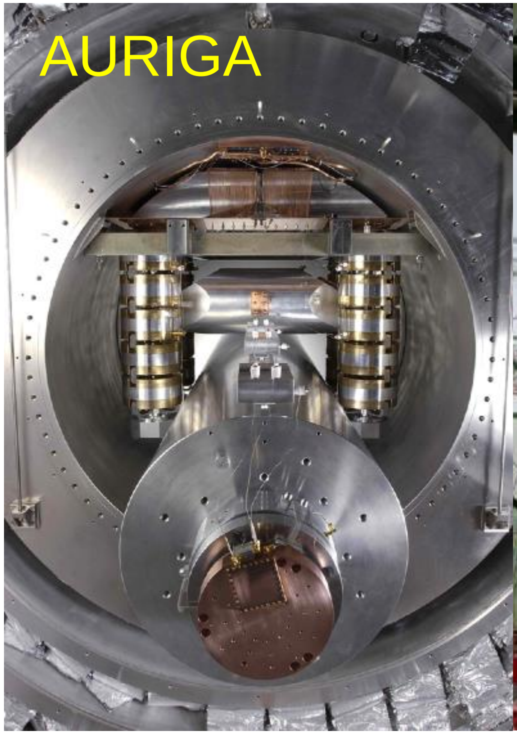
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.



Rainer Weiss

In 1957, Rai Weiss was a grad student of Jerrold Zacharias at MIT, working on atomic beams

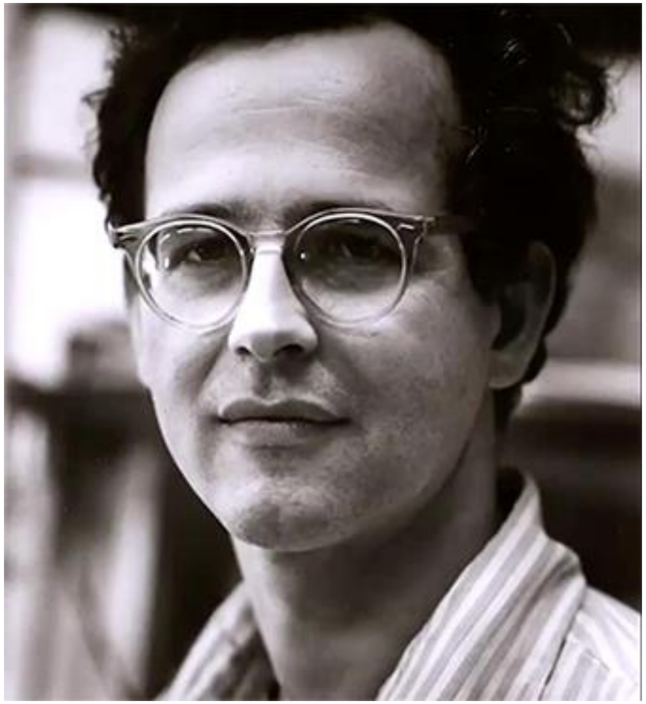
In the early ‘60’s, he spent two years working with Bob Dicke at Princeton on gravity experiments

In 1964, Rai was back at MIT as a professor. He was assigned to teach general relativity. He didn’t know it, so he had to learn it one day ahead of the students

He asked, What’s really measurable in general relativity? He found the answer in Pirani’s papers presented at Chapel Hill in 1957

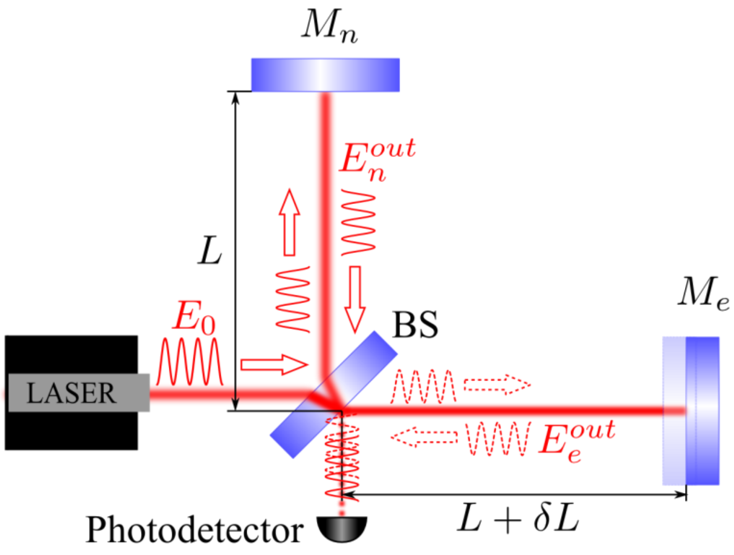
In Pirani’s papers, he didn’t “put in” either a spring or a dashpot between the test masses. Instead, he said: “It is assumed that an observer, by the use of light signals or otherwise, determine the coordinates of a neighboring particle in his local Cartesian coordinate system”

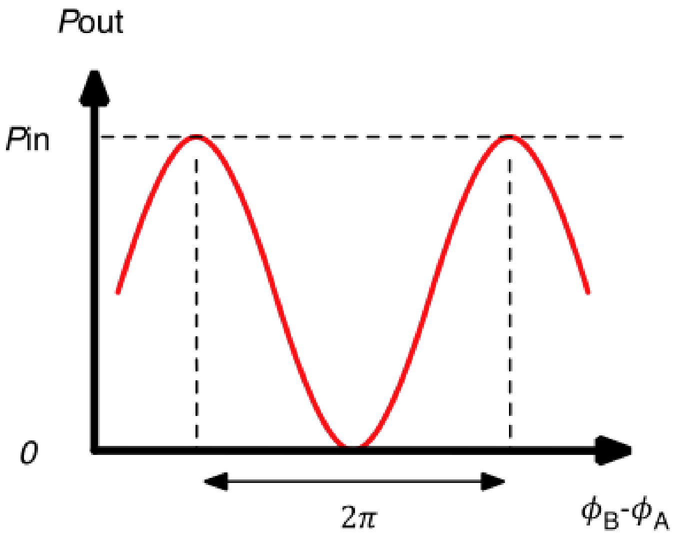
Zach’s lab at MIT was in the thick of the new field of lasers. Rai read Pirani, and knew that lasers could do the job



Laser interferometer

Michelson interferometer: at what working point would you operate it?





$$E_{out} = \frac{1}{2}\left(e^{-i\phi_A} - e^{-i\phi_B}\right)E_{in}$$

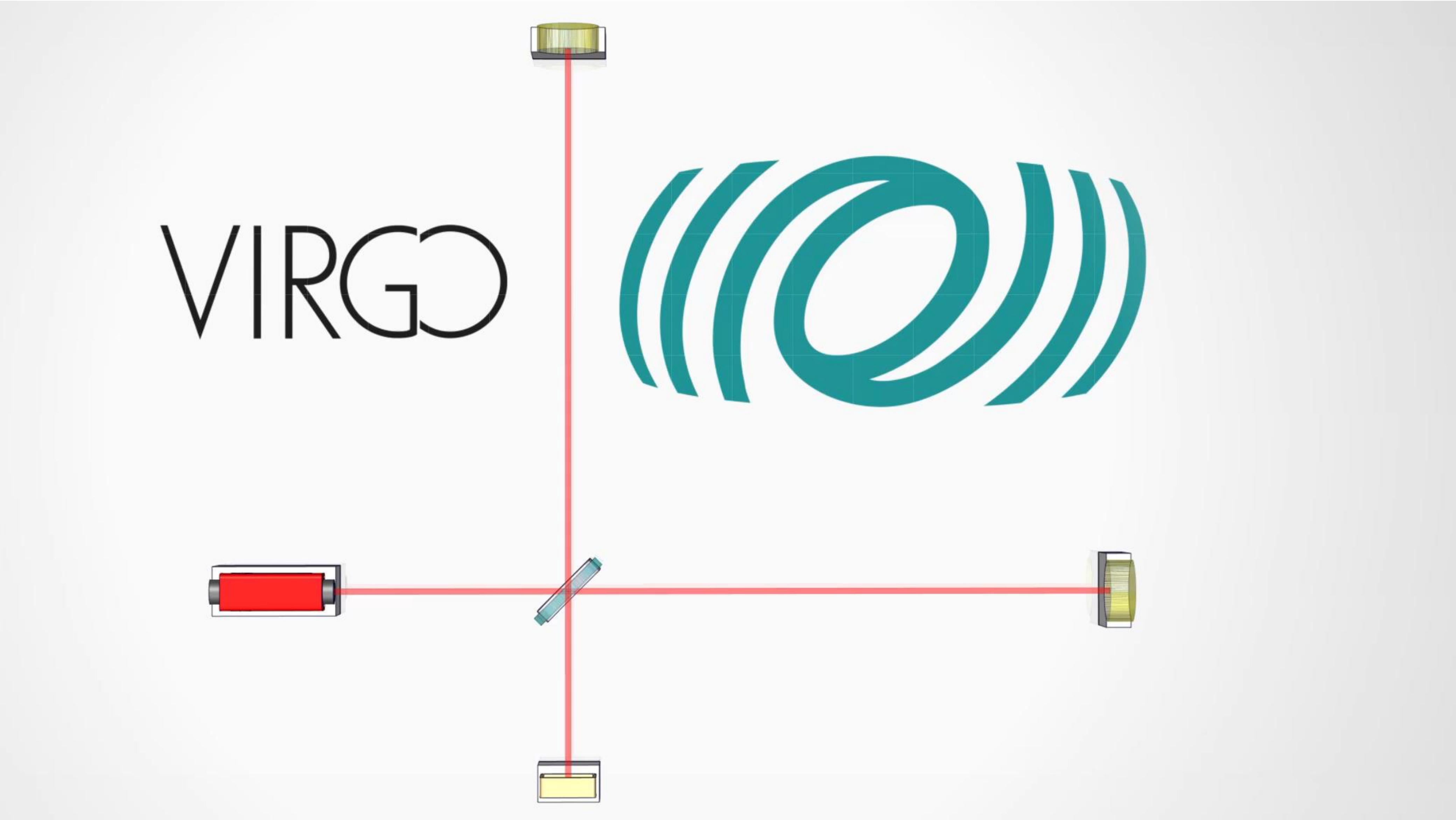
$$\boxed{\phi_i = \frac{4\pi}{\lambda}L_i}$$

$$E_{out} = \left[ie^{-i(\phi_A+\phi_B)/2}\sin\left(\frac{\phi_A - \phi_B}{2}\right)\right]E_{in}$$

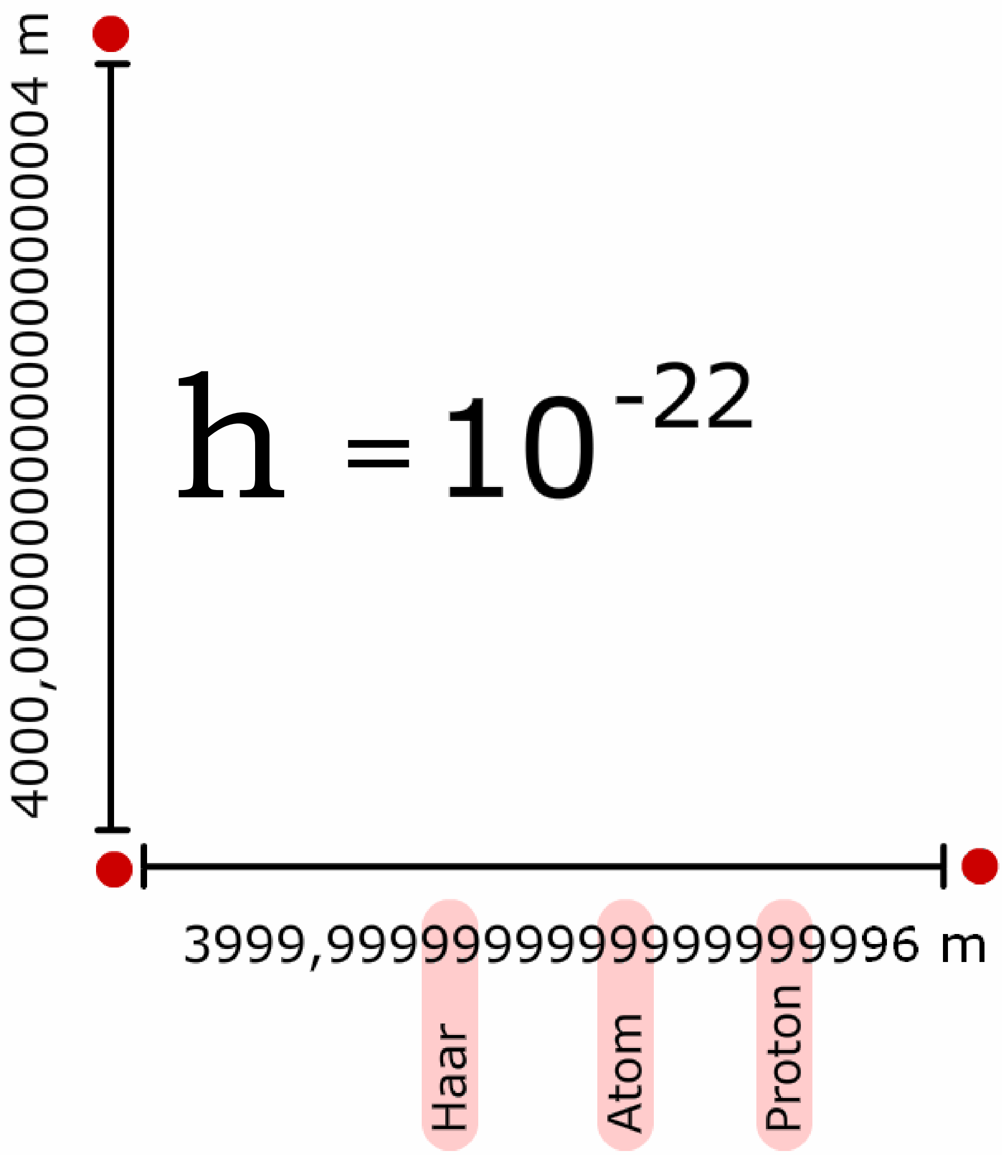
$$P_{out} = E_{out}E_{out}^* = P_{in}\sin^2\left(\frac{\phi_A - \phi_B}{2}\right) = \left[1 - \cos\left(\phi_A - \phi_B\right)\right]\frac{P_{in}}{2}$$

Detecting gravitational waves with an interferometer

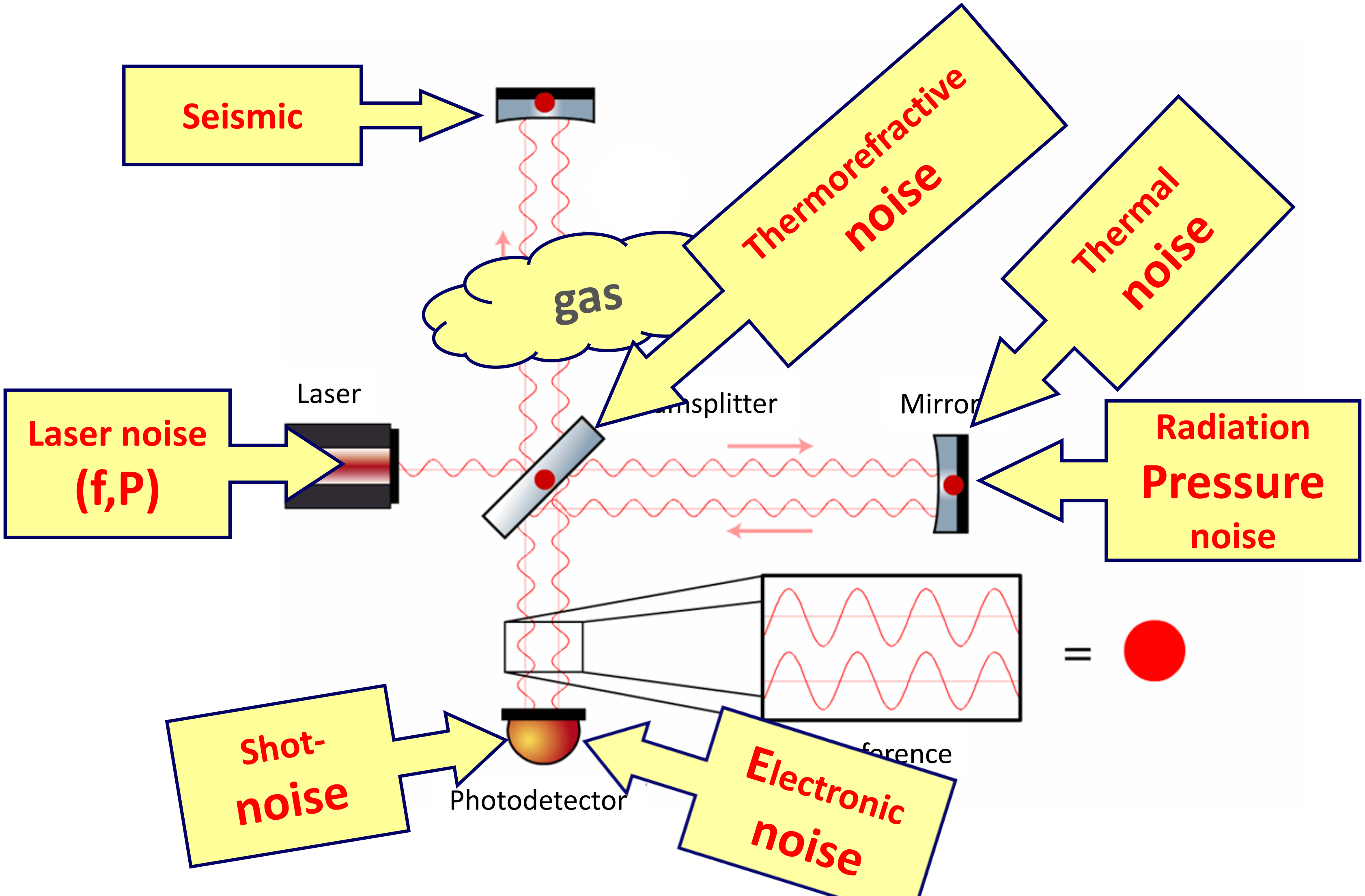
During our detection of GW150914 the mirrors moved by about 10^{-18} m



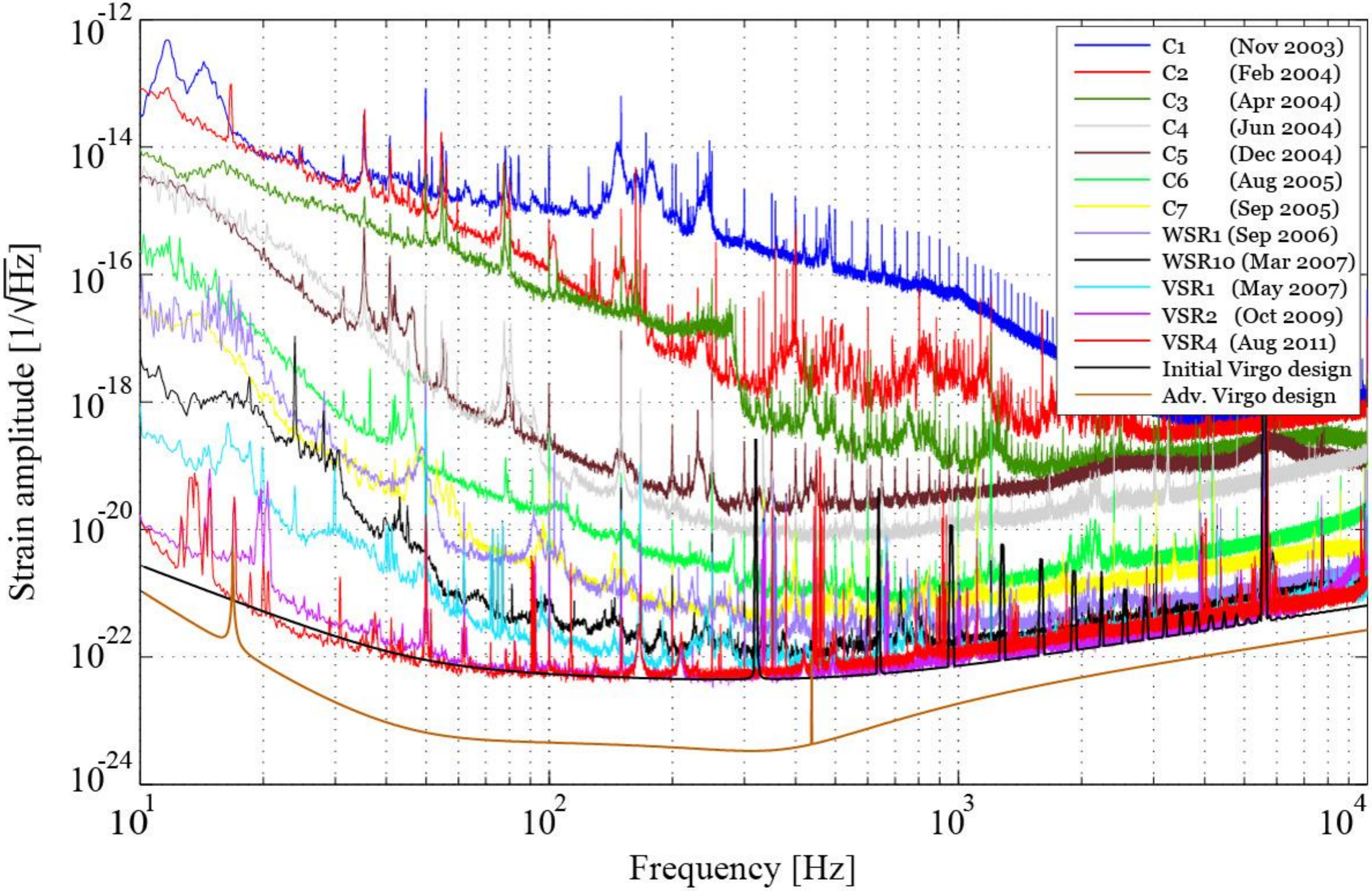
Effect of a strong gravitational wave



Interferometer: noise sources



Virgo: sensitivity evolution



Detecting gravitational waves with an interferometer

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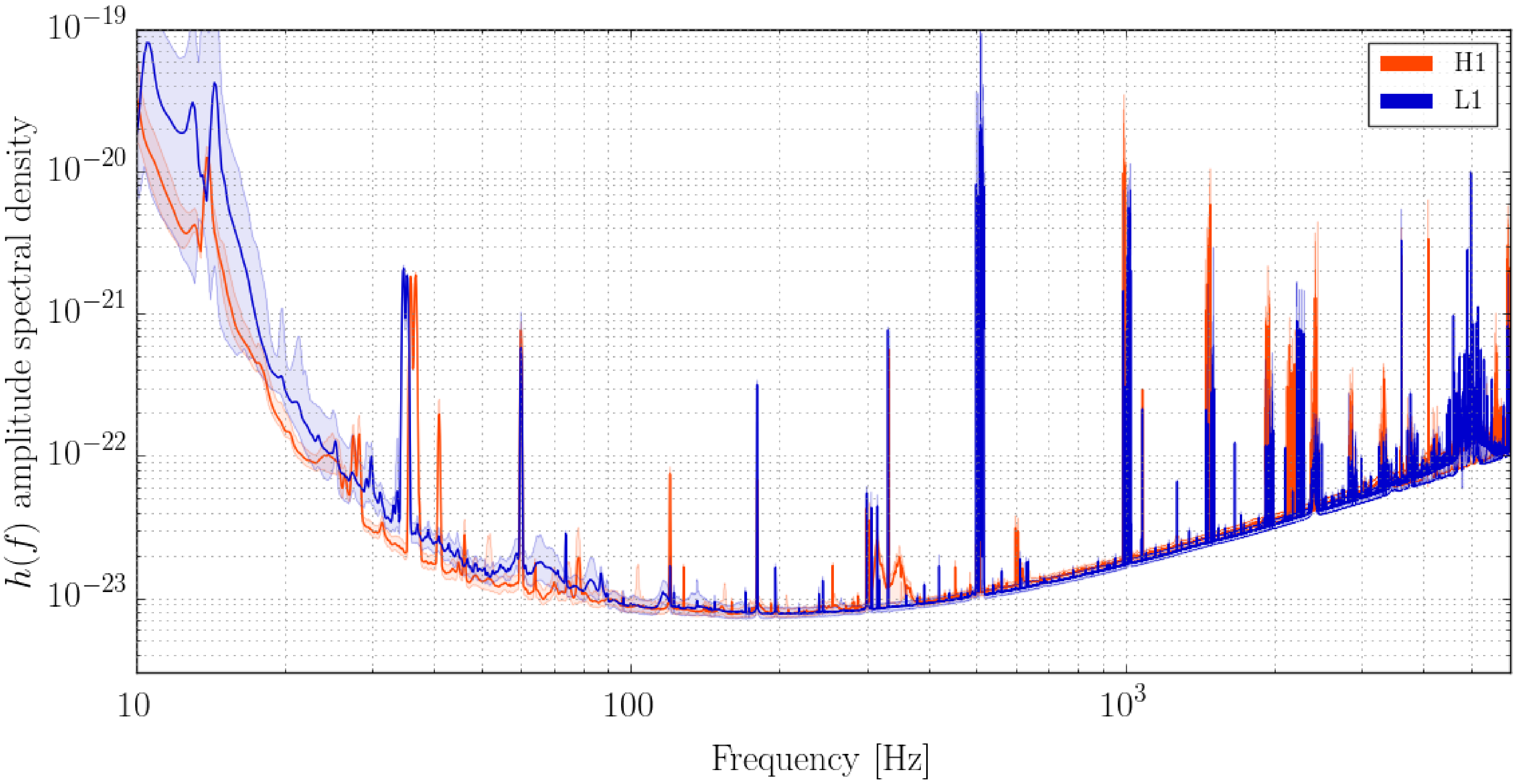

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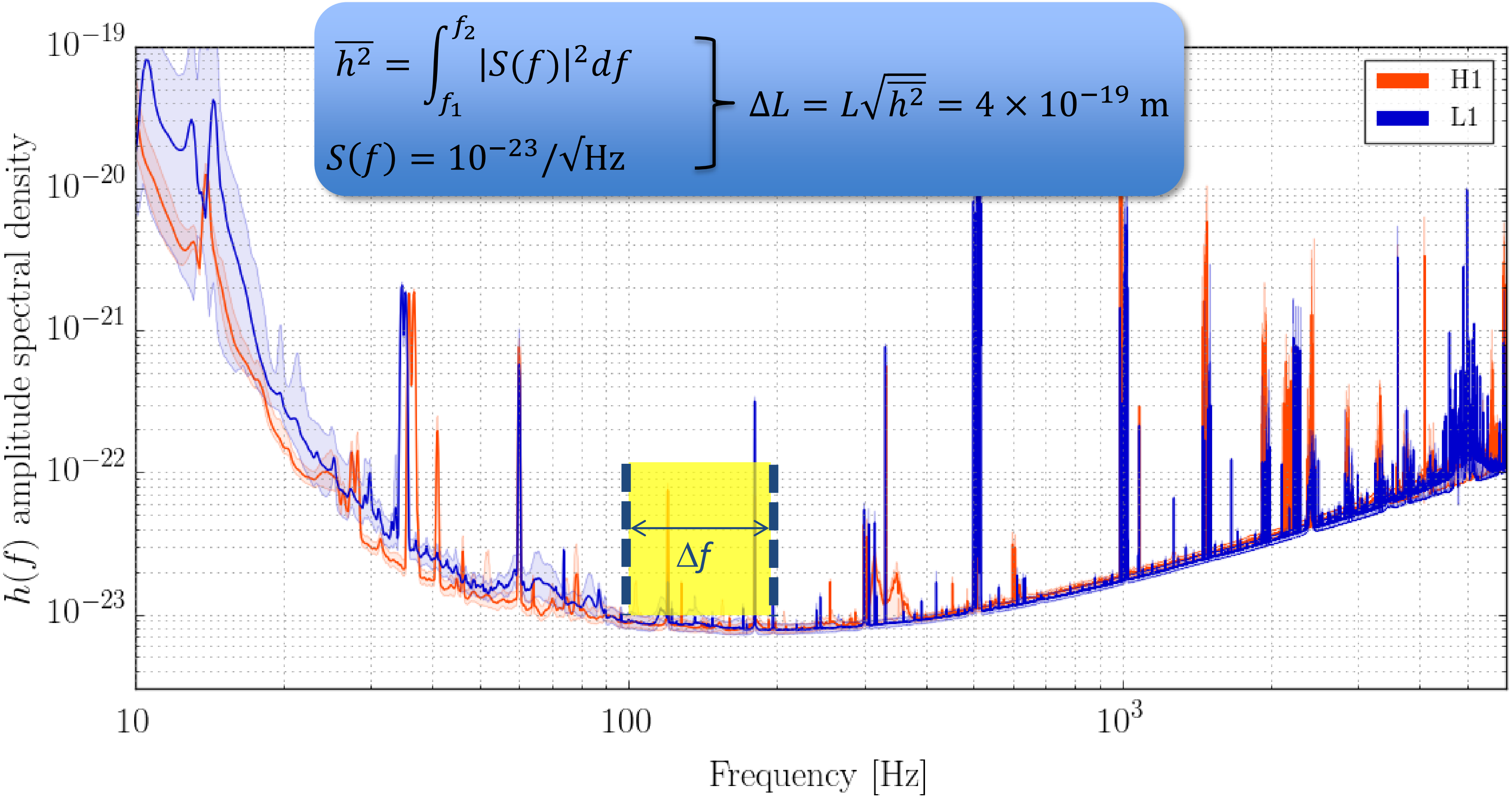
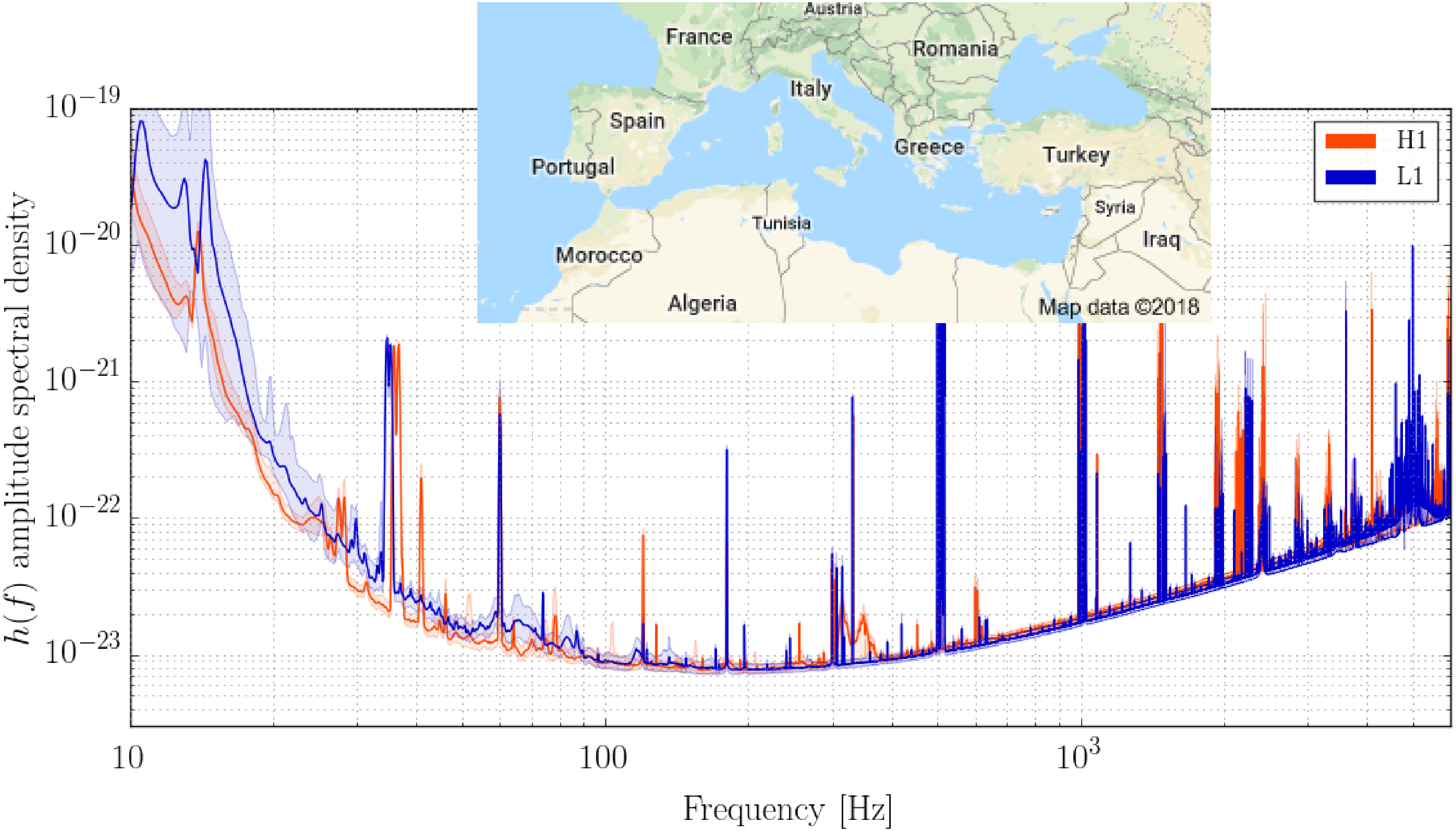


$$\left.\begin{aligned} \overline{h^2} &= \int_{f_1}^{f_2} |S(f)|^2 df \\ S(f) &= 10^{-23}/\sqrt{\text{Hz}} \end{aligned}\right\} \Delta L = L\sqrt{\overline{h^2}} = 4\times10^{-19}\ \text{m}$$

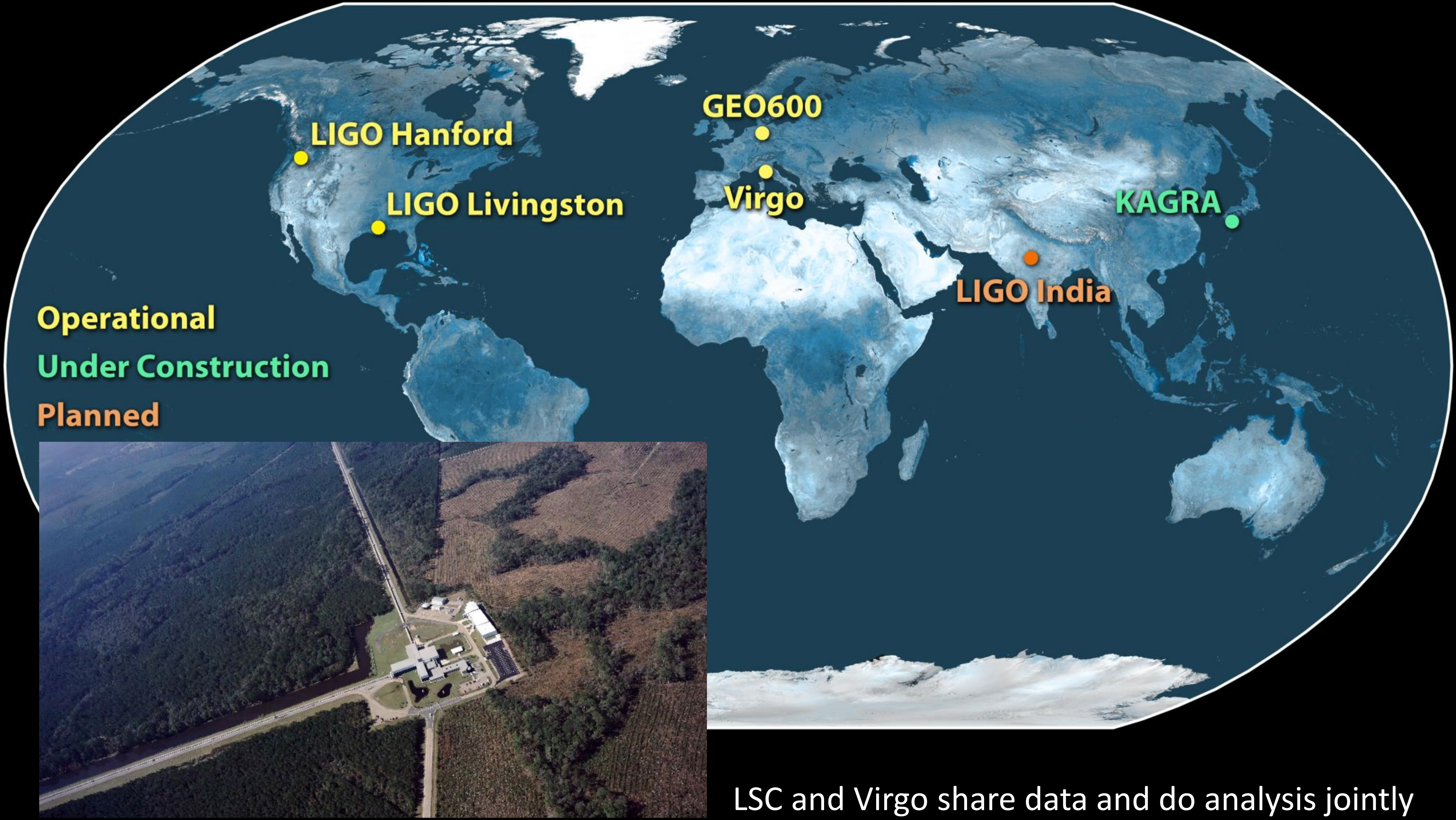
Detecting gravitational waves with an interferometer

During the measurement of GW150914 our mirrors moved by about 10^{-18} m



Gravitational wave science

Towards a global GW research infrastructure



LSC and Virgo share data and do analysis jointly

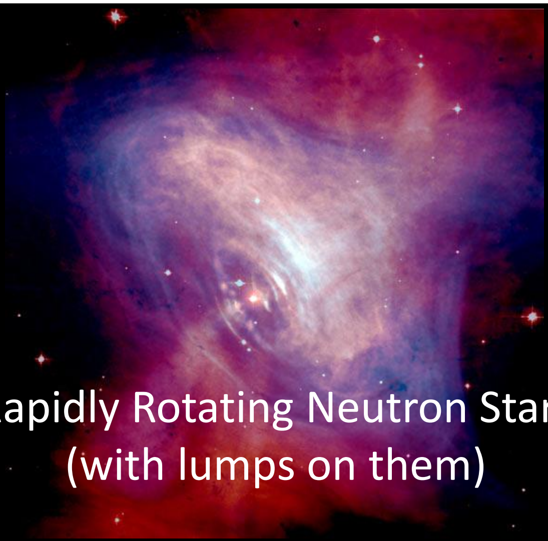
Sources of detectable gravitational waves

Sources can be transient or of continuous nature

Slide credit: J. Kissel, LIGO Hanford Observatory

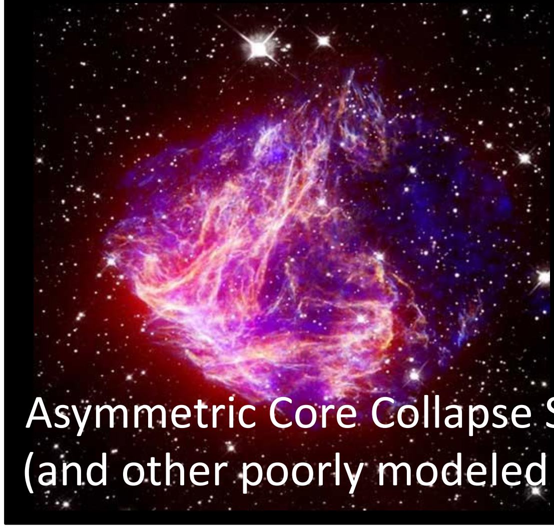
Colliding Binary Systems
(Galaxies, Black Holes, Neutron Stars)

Image: NASA/GSFC/D. Berry

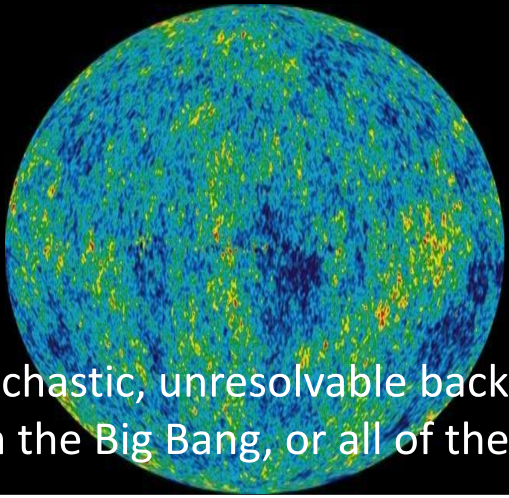


Rapidly Rotating Neutron Stars
(with lumps on them)

Anything with a time-dependent mass quadrupole!



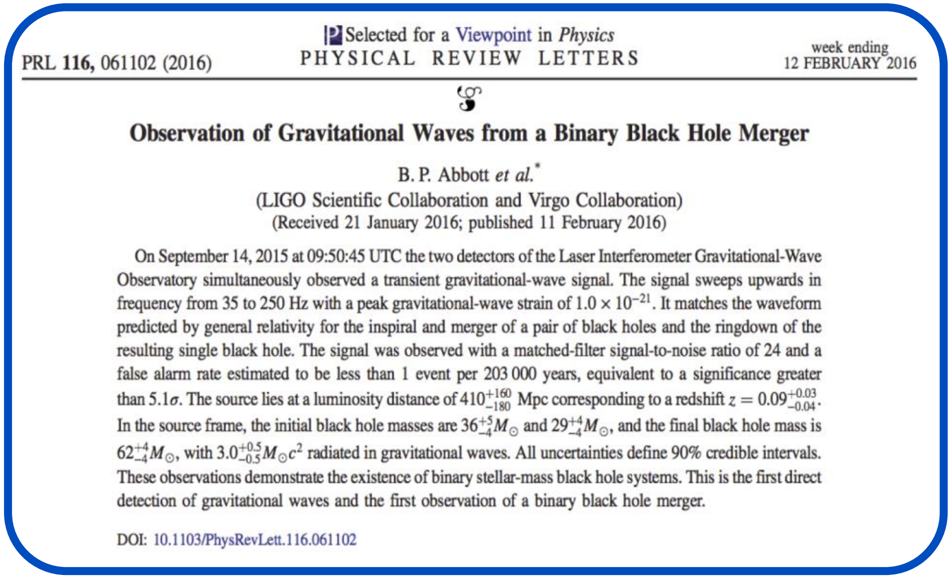
Asymmetric Core Collapse Supernovae
(and other poorly modeled explosions)



A stochastic, unresolvable background
from the Big Bang, or all of the above

Event GW150914

Collision of two stellar mass black holes



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 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 5.1σ. 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 $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ 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.

DOI: 10.1103/PhysRevLett.116.061102

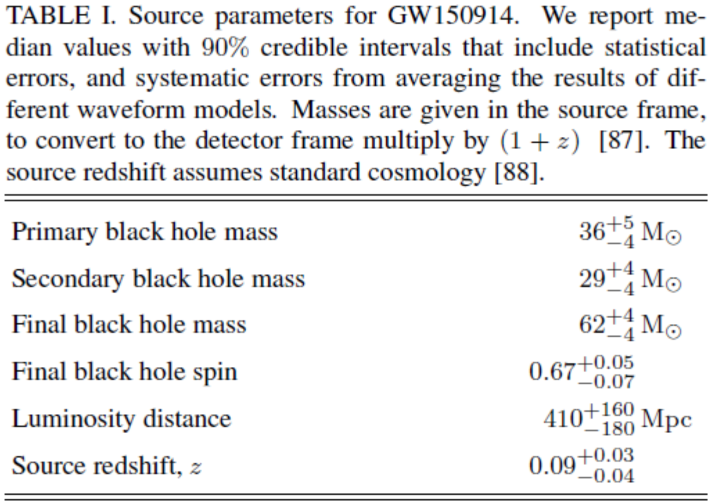
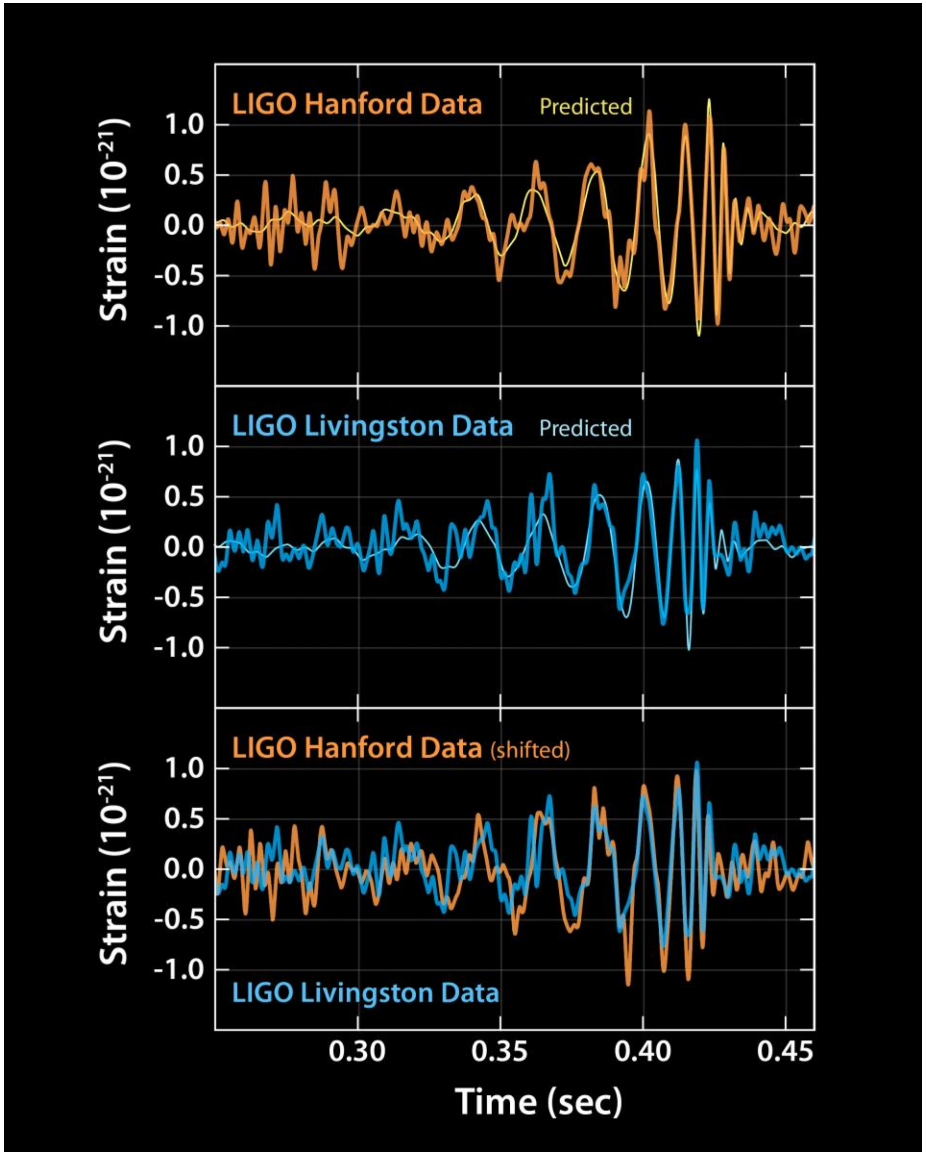


TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame, to convert to the detector frame multiply by $(1 + z)$ [87]. The source redshift assumes standard cosmology [88].

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

Energy radiated: 3.0 ± 0.5 solar masses

Peak power at merger: 200 solar masses per second



Inspiral of two black holes

The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from this inspiral phase

- Total mass $M = M_1 + M_2$
- Reduced mass $\mu = M_1 M_2 / M$
- Chirp mass $M_S^{5/3} = \mu M^{2/3}$

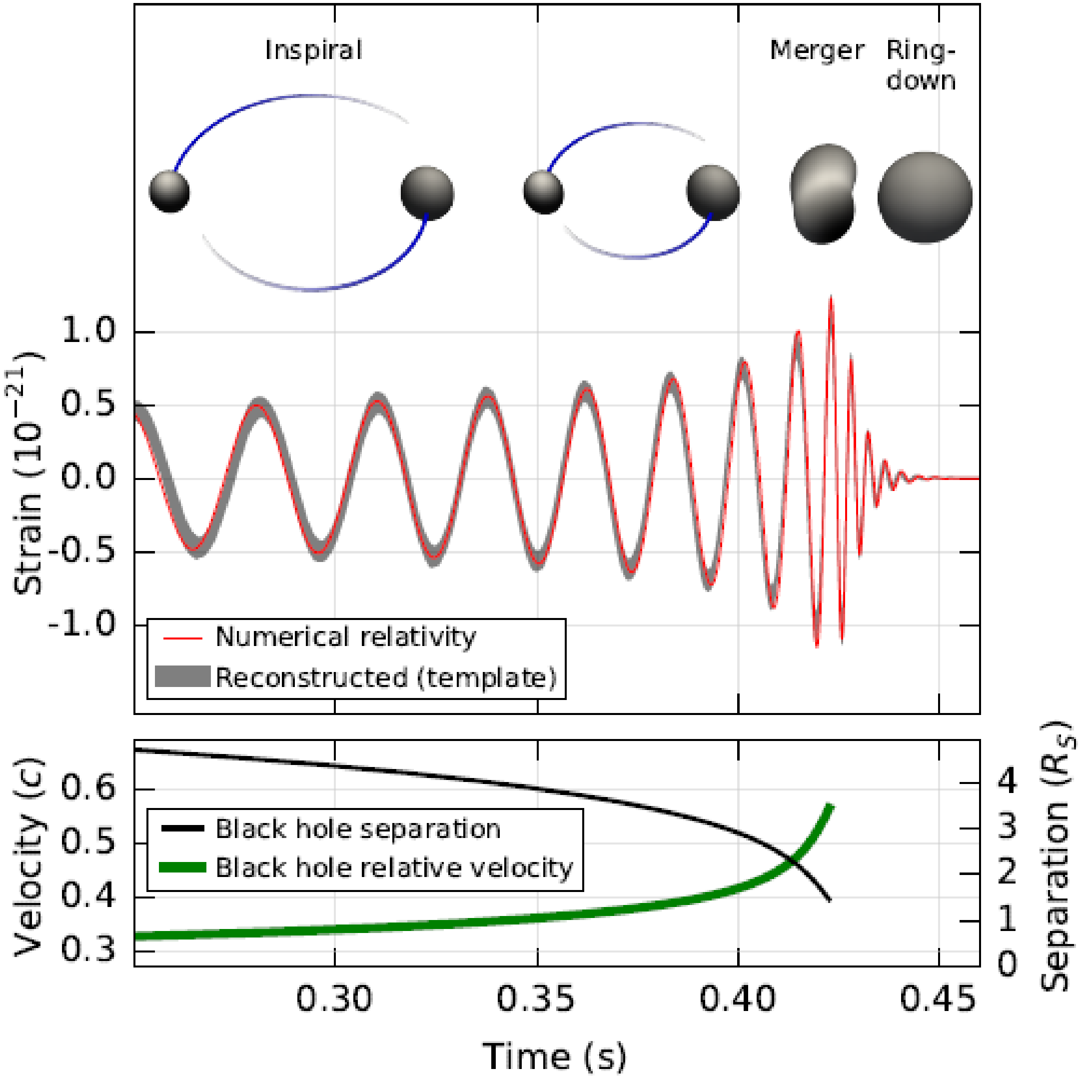
- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$

- Speed $\frac{v}{c} = \left(\frac{GM\pi f}{c^3}\right)^{1/3}$
- Separation $R_S = \frac{2GM}{c^2}$

- Orbital phase (post Newtonian expansion)

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$



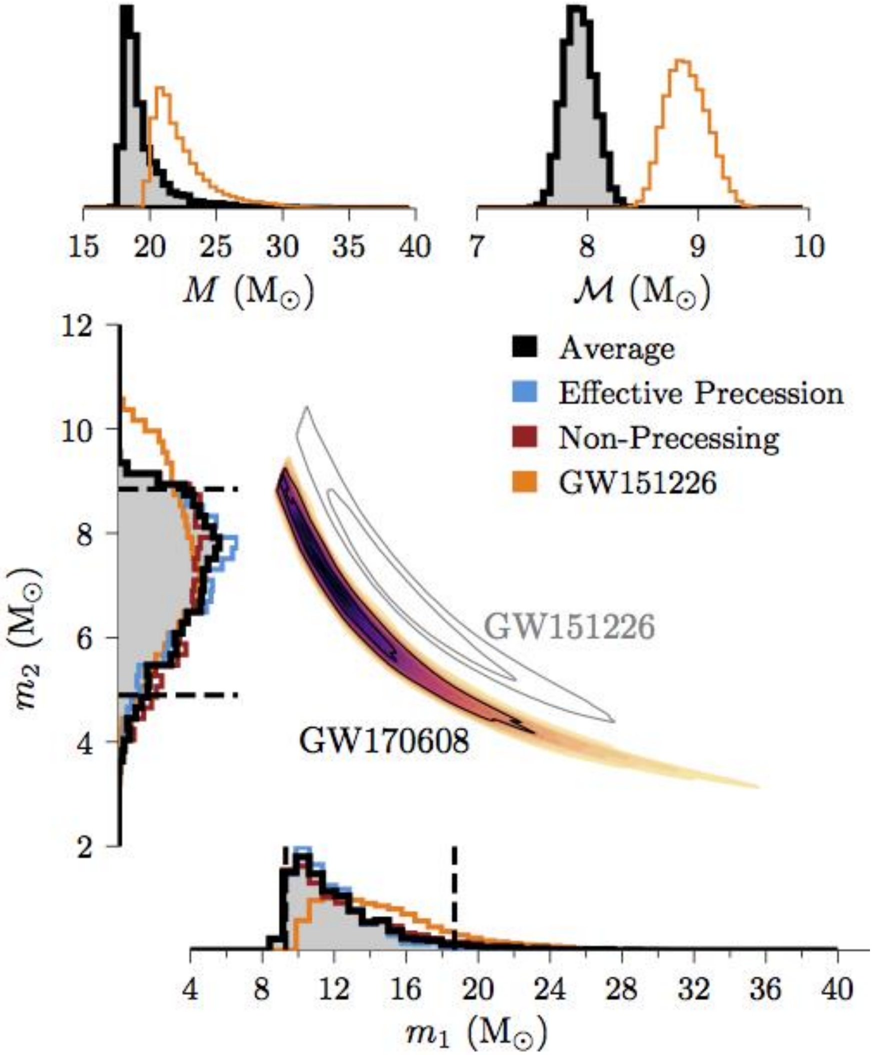
Scientific achievements: properties of black holes

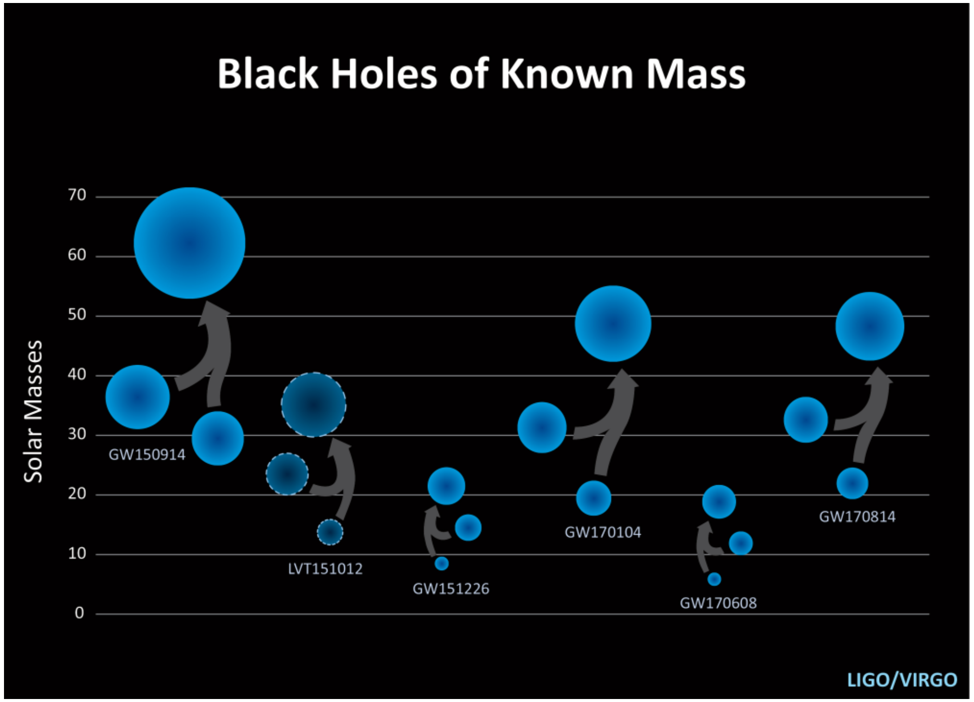
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

LVC reported on 6 BBH mergers

Fundamental physics, astrophysics, astronomy, and cosmology

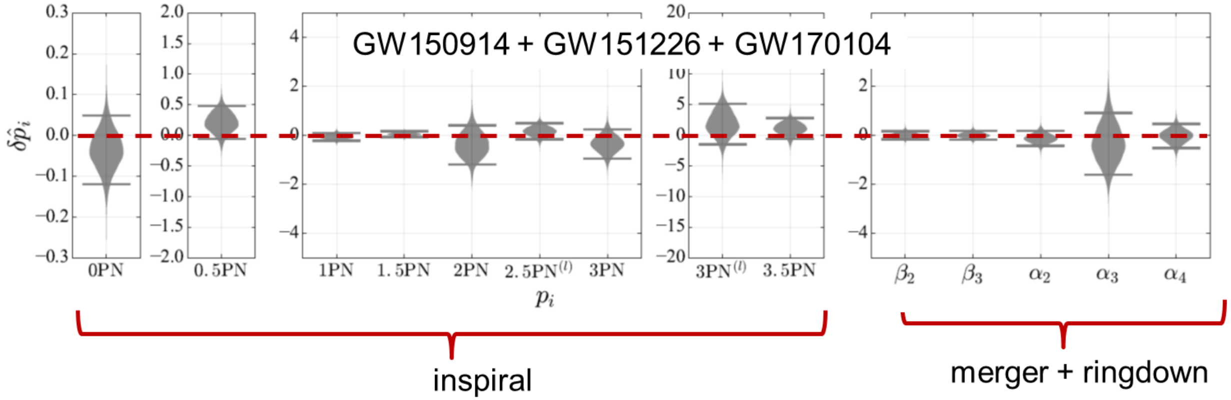
Testing GR, waveforms (with matter)





Precision tests of GR with BBH mergers

Bayesian analysis increases accuracy on parameters by combining information from multiple events



Inspiral and PN expansion

Inspiral PN and logarithmic terms: Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

Merger terms: numerical GR

Ringdown terms: quasi-normal modes; do we see Kerr black holes?

Towards high precision tests of gravity

Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

Our collaborations set ambitious goals for the future

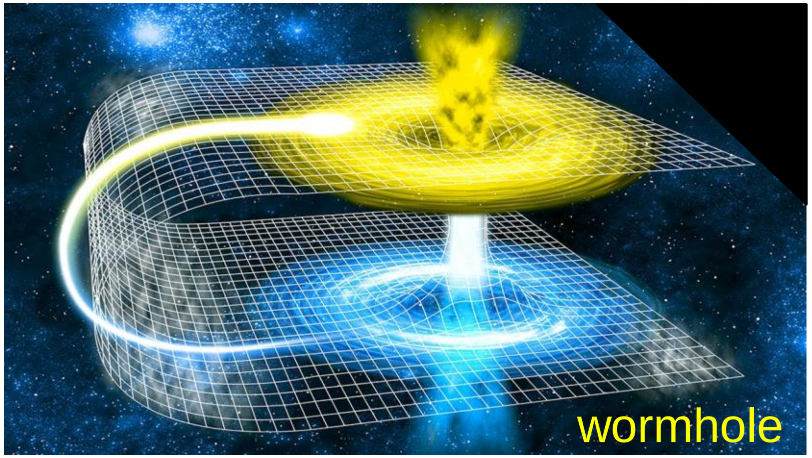
We need to improve:

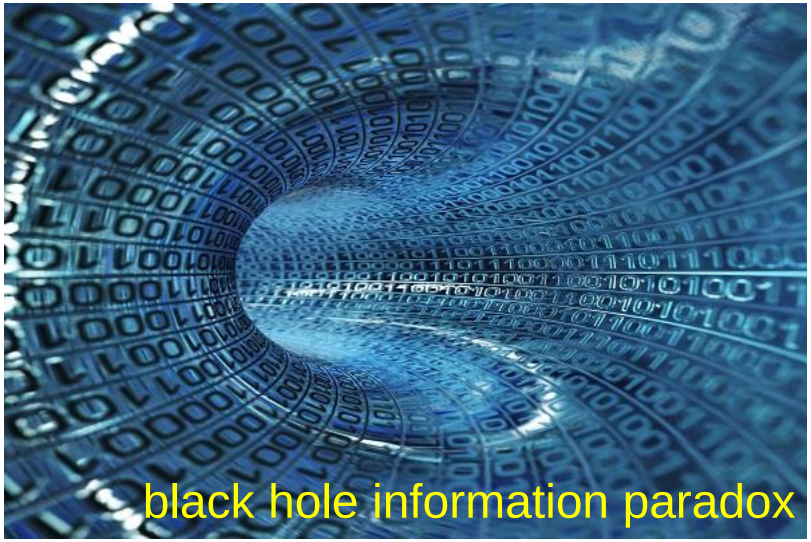
- sensitivity of our instruments over the entire frequency range
- improve of data exchange with the global community (e.g. Open Public Alerts)
- optimize our computing and analysis
- improve our source modeling (NR)

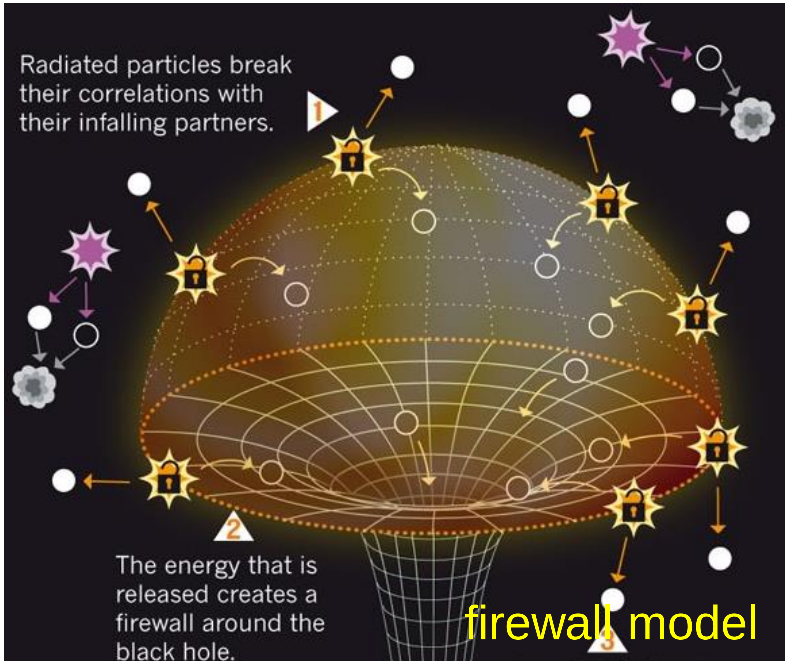
We are not done yet!

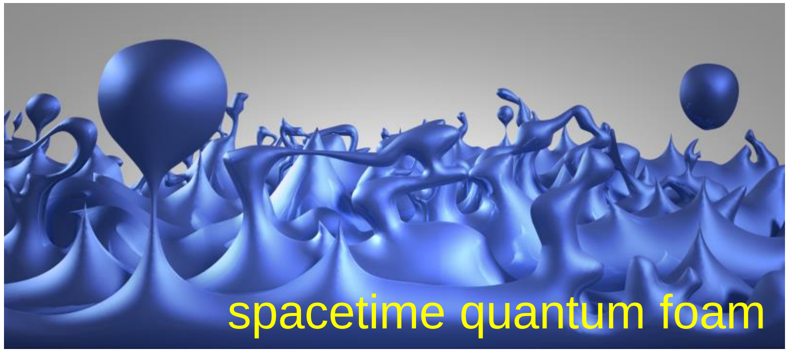
Fundamental physics: did we observe black holes?

Our theories “predict” the existence of other objects, such as quantum modifications of GR black holes, boson stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



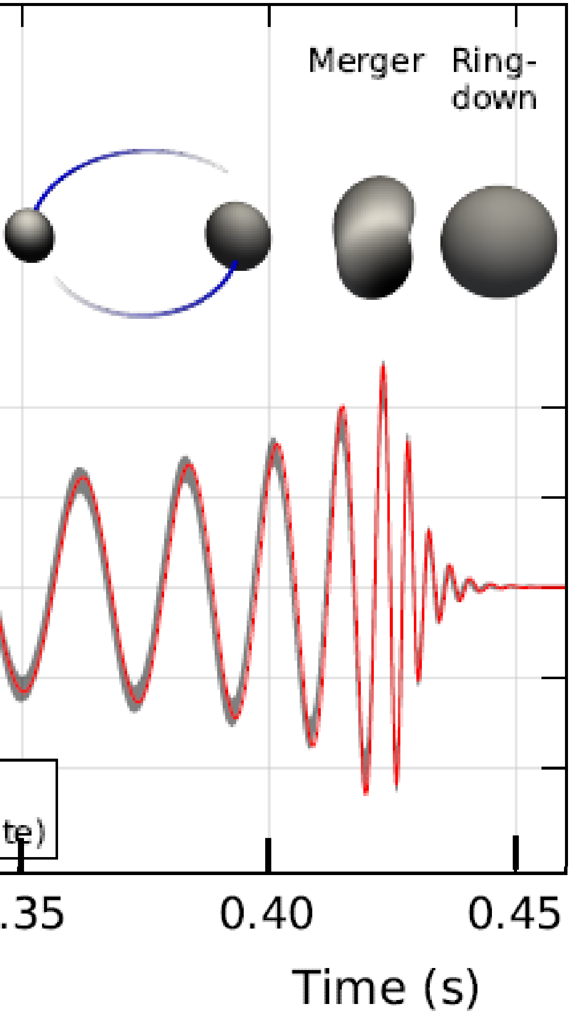


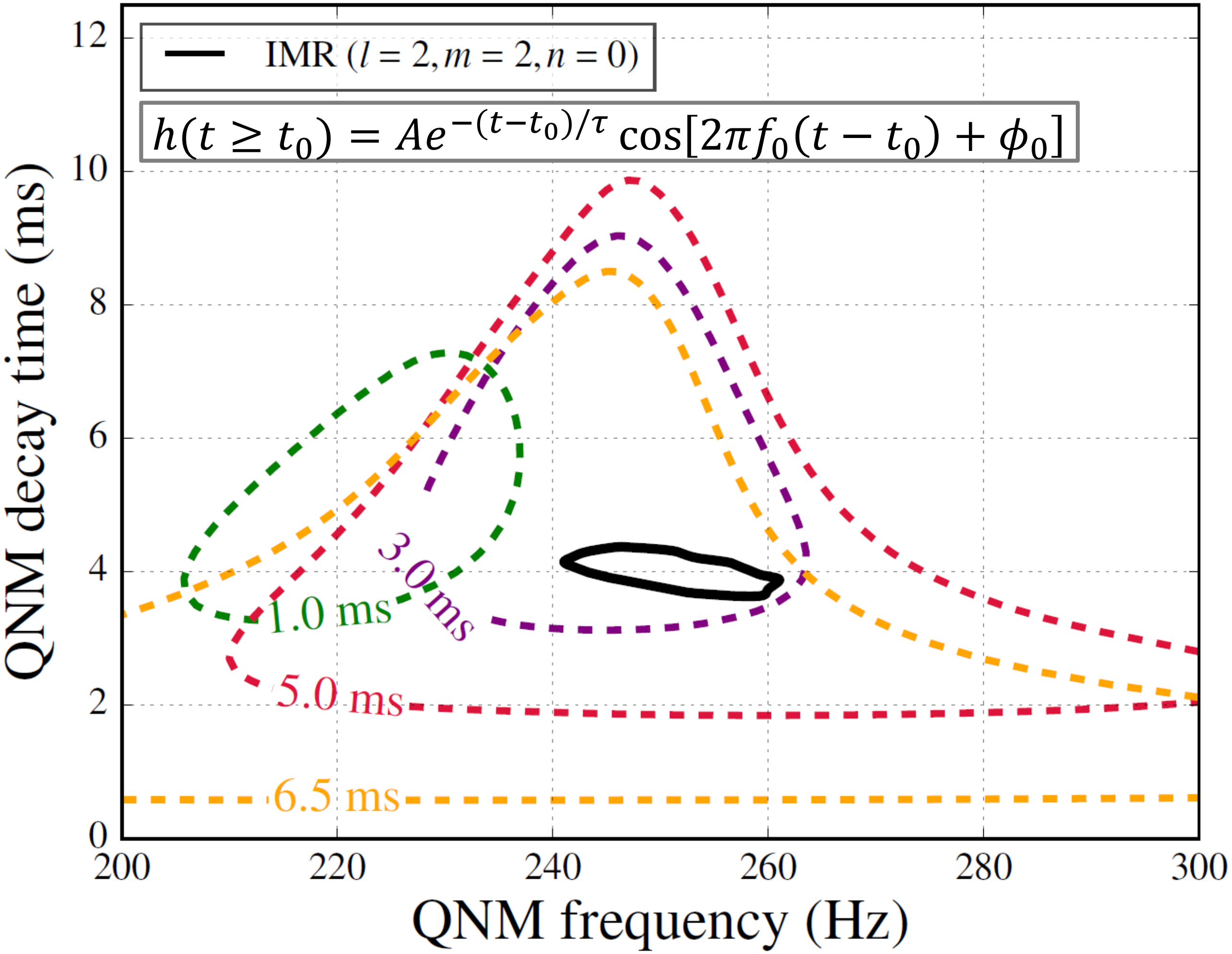




Is a black hole created in the final state?

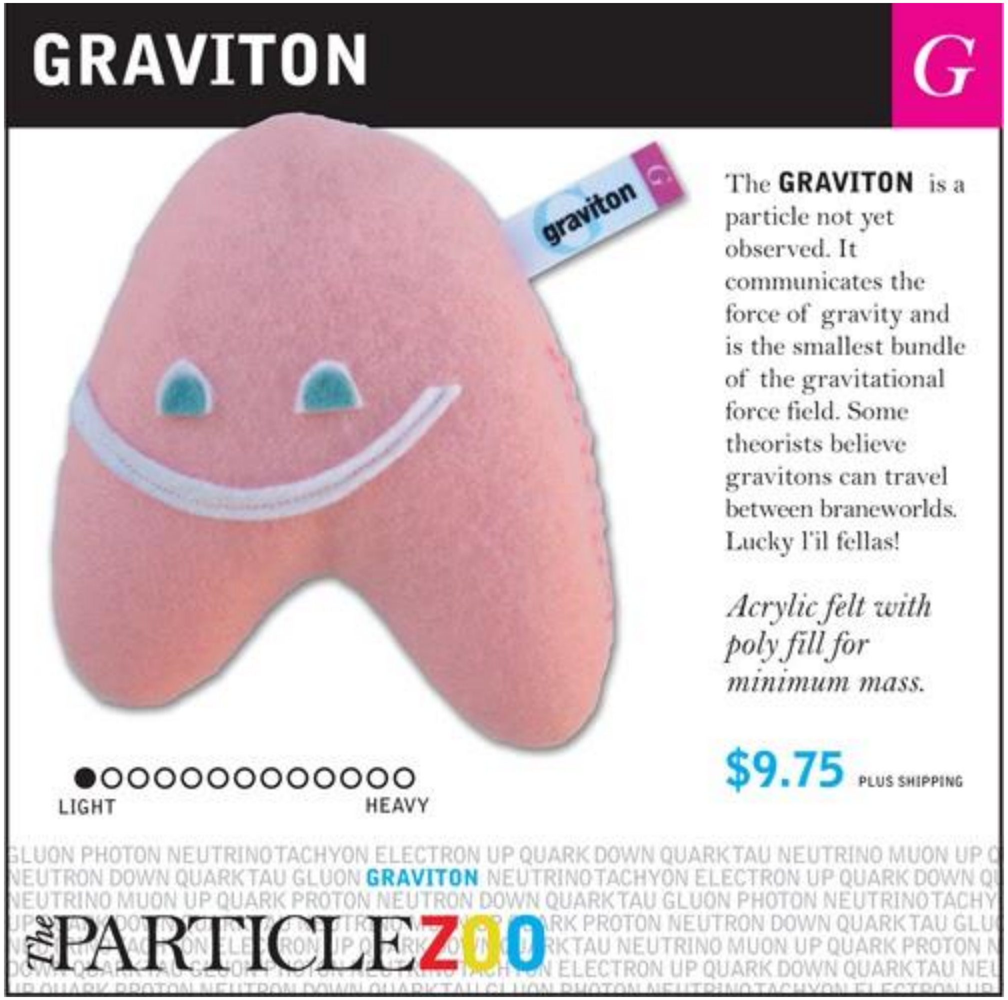
From the inspiral we can predict that the ringdown frequency of about 250 Hz and 4 ms decay time. This is what we measure (http://arxiv.org/abs/1602.03841). We will pursue this further





Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/{}_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



GRAVITON

The **GRAVITON** is a particle not yet observed. It communicates the force of gravity and is the smallest bundle of the gravitational force field. Some theorists believe gravitons can travel between braneworlds. Lucky l'il fellas!

Acrylic felt with poly fill for minimum mass.

$9.75 PLUS SHIPPING

●○○○○○○○○○○○○○

LIGHT HEAVY

$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2(1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2c^4$

We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed

$$\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2E^2)$$

$\lambda_g > 10^{13}\mathrm{km}$

$m_g \lesssim 10^{-22}\mathrm{eV/c^2}$

Michalis Agathos (Nikhef 2016)

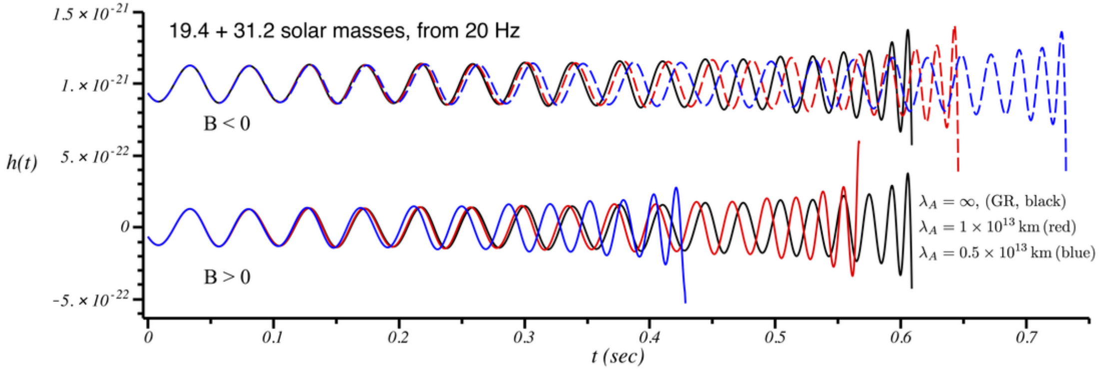
See “*Tests of general relativity with GW150914*” http://arxiv.org/abs/1602.03841

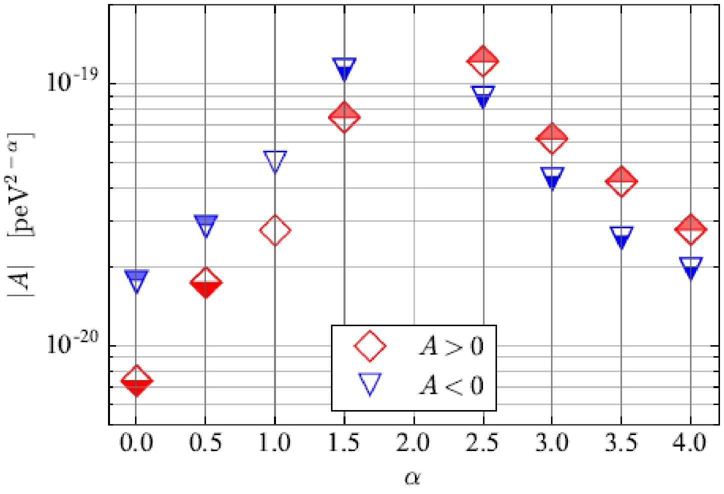
Bounds on violation of Lorentz invariance

First bounds derived from gravitational-wave observations, and the first tests of superluminal propagation in the gravitational sector

Generic dispersion relation
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0 \;\Rightarrow\; \frac{v_g}{c} \cong 1 + (\alpha - 1)AE^{\alpha-2}/2$$

Gravitational wave phase term
$$\delta\Psi = \begin{cases} \frac{\pi}{\alpha-1}\frac{AD_\alpha}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi AD_\alpha}{hc}\ln\left(\frac{\pi G\mathcal{M}^{det}f}{c^3}\right) & \alpha = 1 \end{cases} \qquad A \cong \pm\frac{MD_\alpha}{\lambda_A^2}$$





Several modified theories of gravity predict specific values of α:

- massive-graviton theories (α = 0, A > 0), multifractal spacetime (α = 2.5),
- doubly special relativity (α = 3), and Horava-Lifshitz and extradimensional theories (α = 4)

Exotic compact objects

Gravitational waves from coalescence of two compact objects is the Rosetta Stone of the strong-field regime. It may hold the key and provide an in-depth probe of the nature of spacetime

Quantum modifications of GR black holes

- Motivated by Hawking's information paradox
- Firewalls, fuzzballs, EP = EPR, …

Fermionic dark matter

- Dark matter stars

Boson stars

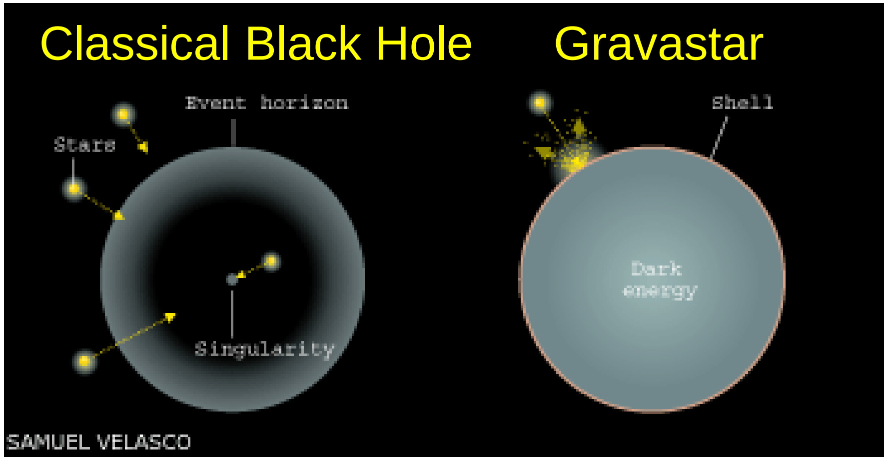
- Macroscopic objects made up of scalar fields

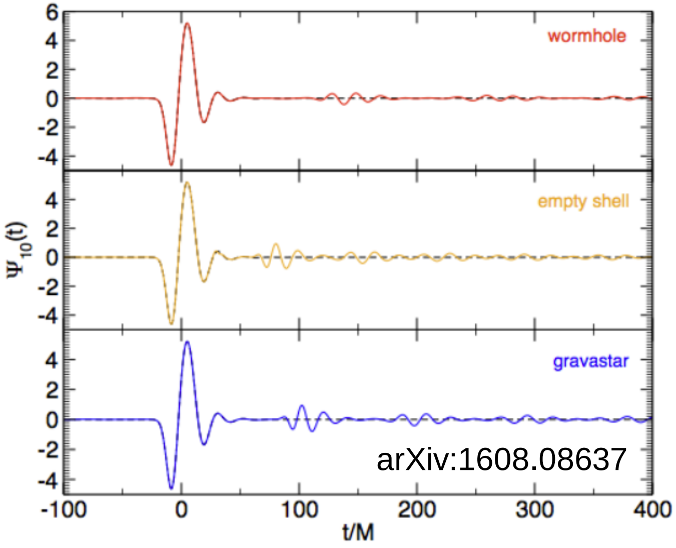
Gravastars

- Objects with de Sitter core where spacetime is self-repulsive
- Held together by a shell of matter
- Relatively low entropy object

GW observables

- Inspiral signal: modifications due to tidal deformation effects
- Ringdown process: use QNM to check no-hair theorem
- Echoes: even for Planck-scale corrections $\Delta t \approx -nM \log \frac{l}{M}$





arXiv:1608.08637

Virgo joins LIGO in August 2017

Advanced Virgo

Virgo is a European collaboration with about 280 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, The Netherlands, Poland, Hungary, Spain, Germany

- 20 laboratories, about 280 authors
  - 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
  - Univ. of Valencia
  - University of Jena

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

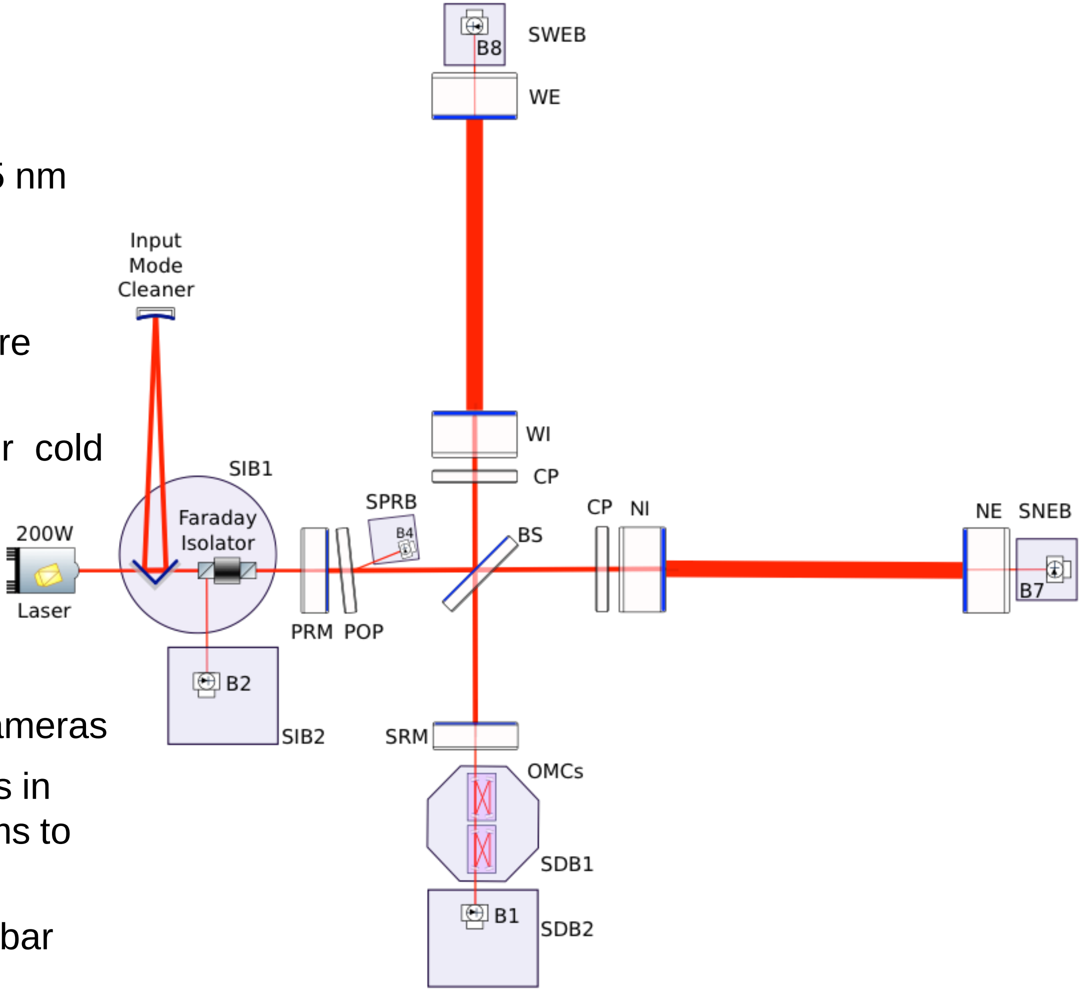
7 European countries

Advanced Virgo design

Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

For 2017

- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses: absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are 3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon CO2 actuators
  - CO2 central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: 10^{-9} mbar instead of 10^{-7} mbar

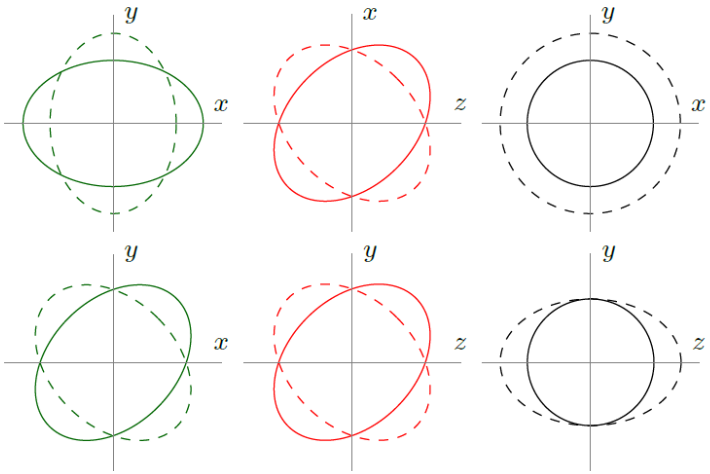


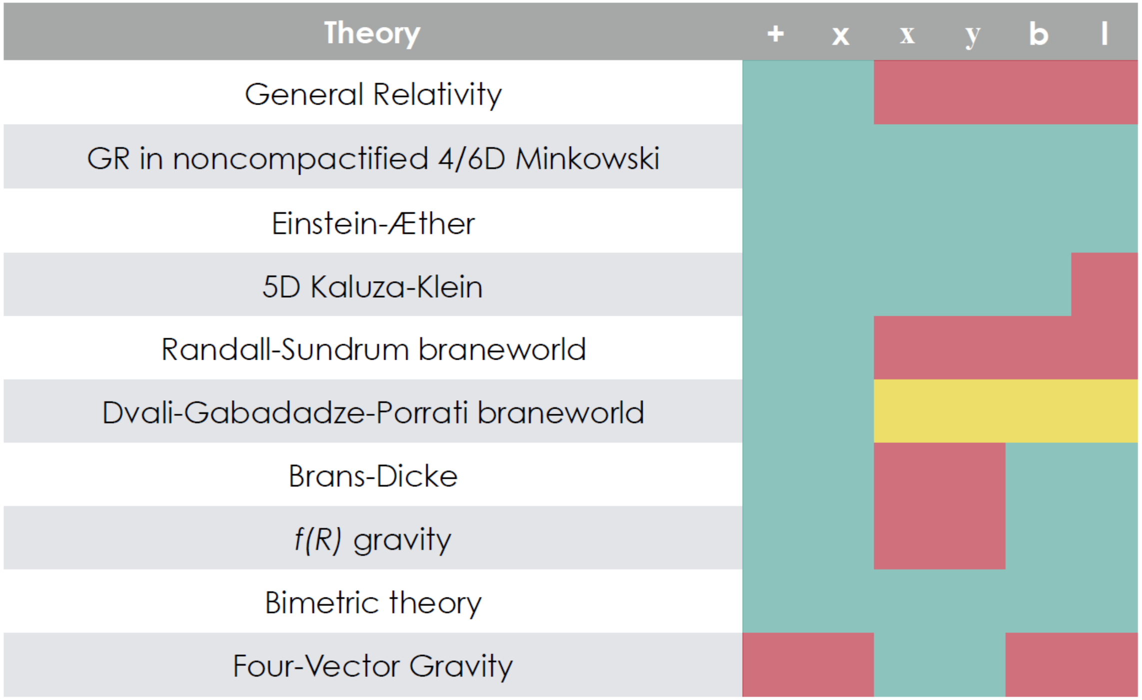
Polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know vector (V) and scalar (S) polarizations





Theory	+	x	x	y	b	l
General Relativity	🟩	🟩	🟥	🟥	🟥	🟥
GR in noncompactified 4/6D Minkowski	🟩	🟩	🟩	🟩	🟩	🟩
Einstein-Æther	🟩	🟩	🟩	🟩	🟩	🟩
5D Kaluza-Klein	🟩	🟩	🟩	🟩	🟩	🟥
Randall-Sundrum braneworld	🟩	🟩	🟥	🟥	🟥	🟥
Dvali-Gabadadze-Porrati braneworld	🟩	🟩	🟨	🟨	🟨	🟨
Brans-Dicke	🟩	🟩	🟥	🟥	🟩	🟩
f(R) gravity	🟩	🟩	🟥	🟥	🟩	🟩
Bimetric theory	🟩	🟩	🟩	🟩	🟩	🟩
Four-Vector Gravity	🟥	🟥	🟩	🟩	🟥	🟥

Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].

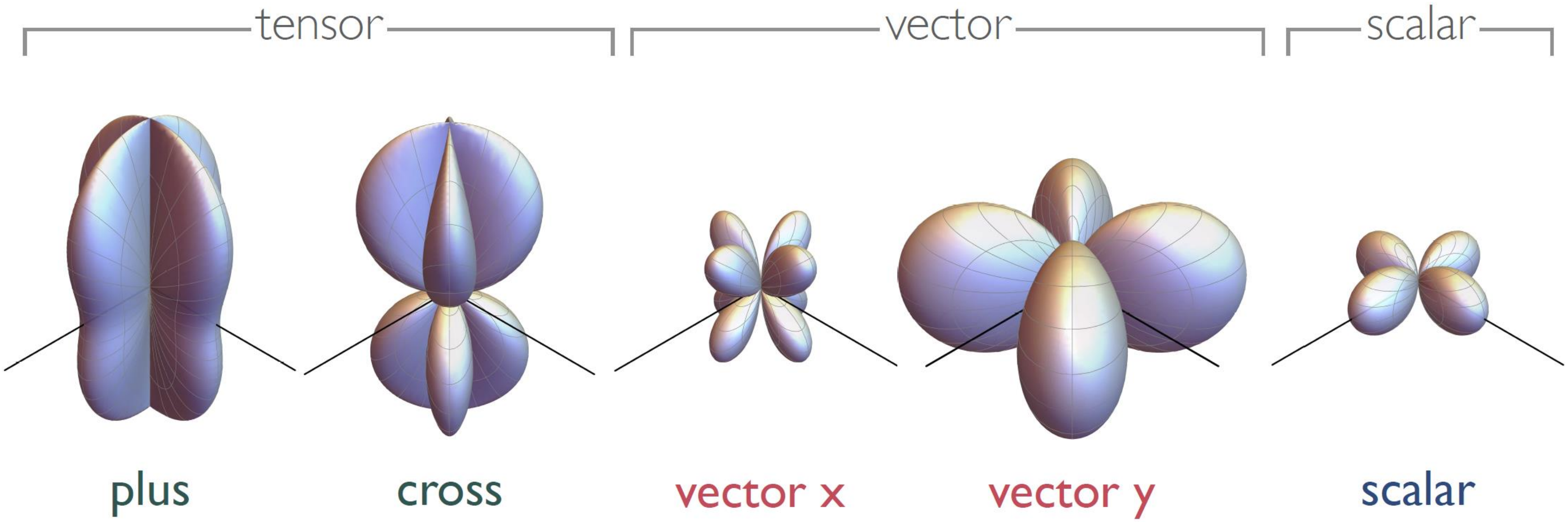
🟩 allowed / 🟨 depends / 🟥 forbidden

First test of polarizations of gravitational waves

According to Einstein's General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein's prediction

Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime



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Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime

Our analysis favors tensor polarizations in support of General Relativity

Our data favor tensor structure over vector by about a (Bayes) factor 200
And tensor over scalar by about a factor 1000

This is a first test, and for BBH we do not know the source position very well

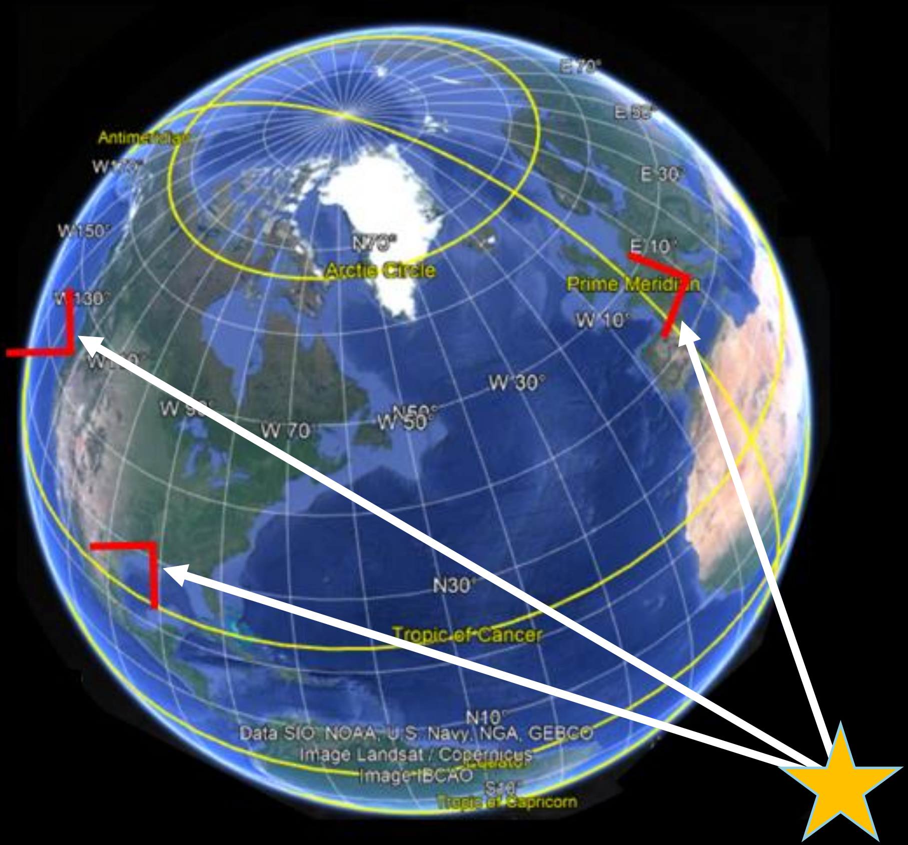
Virgo allowed source location via triangulation

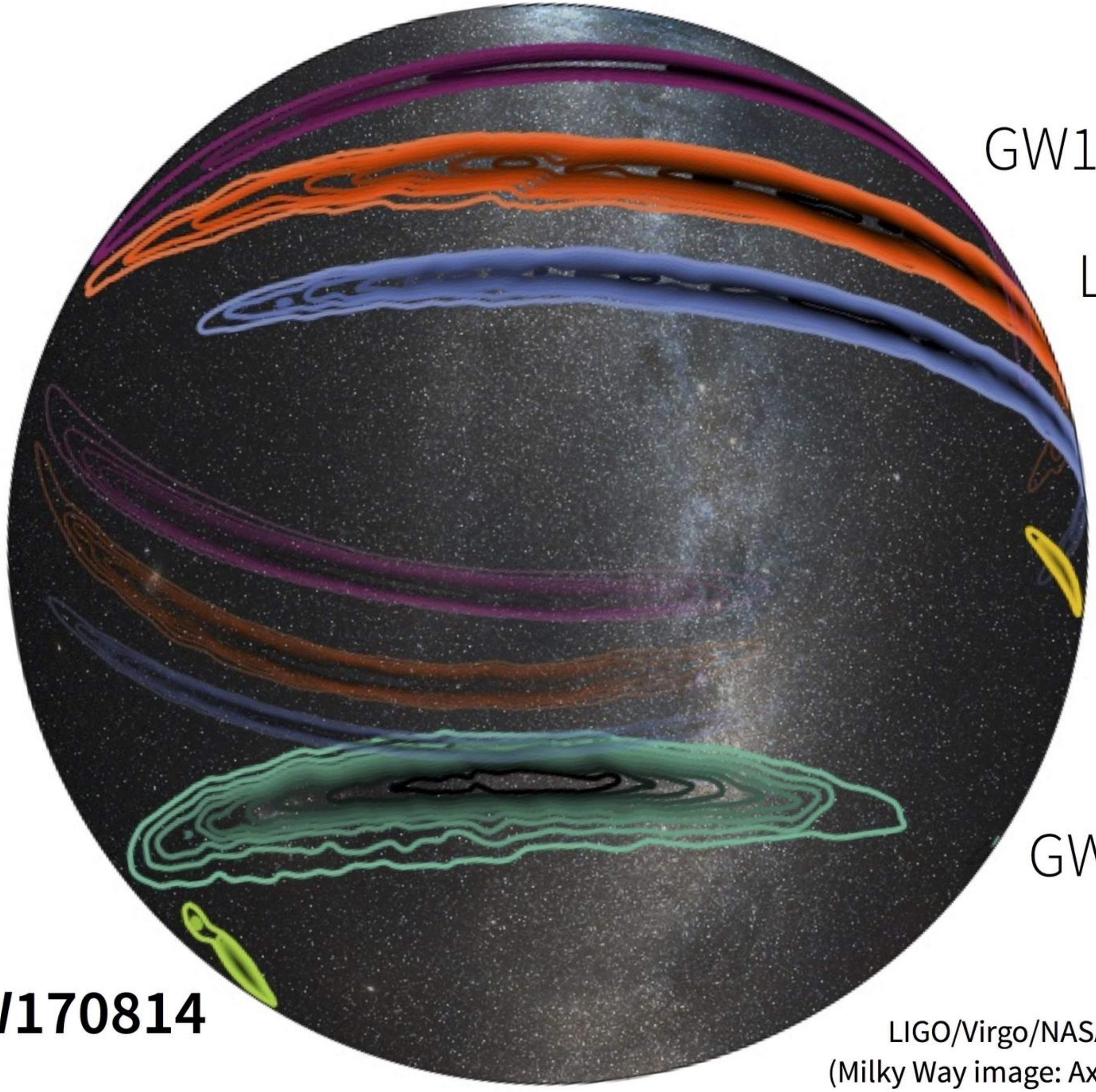
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

Virgo, Cascina, Italy

LIGO, Livingston, LA

LIGO, Hanford, WA

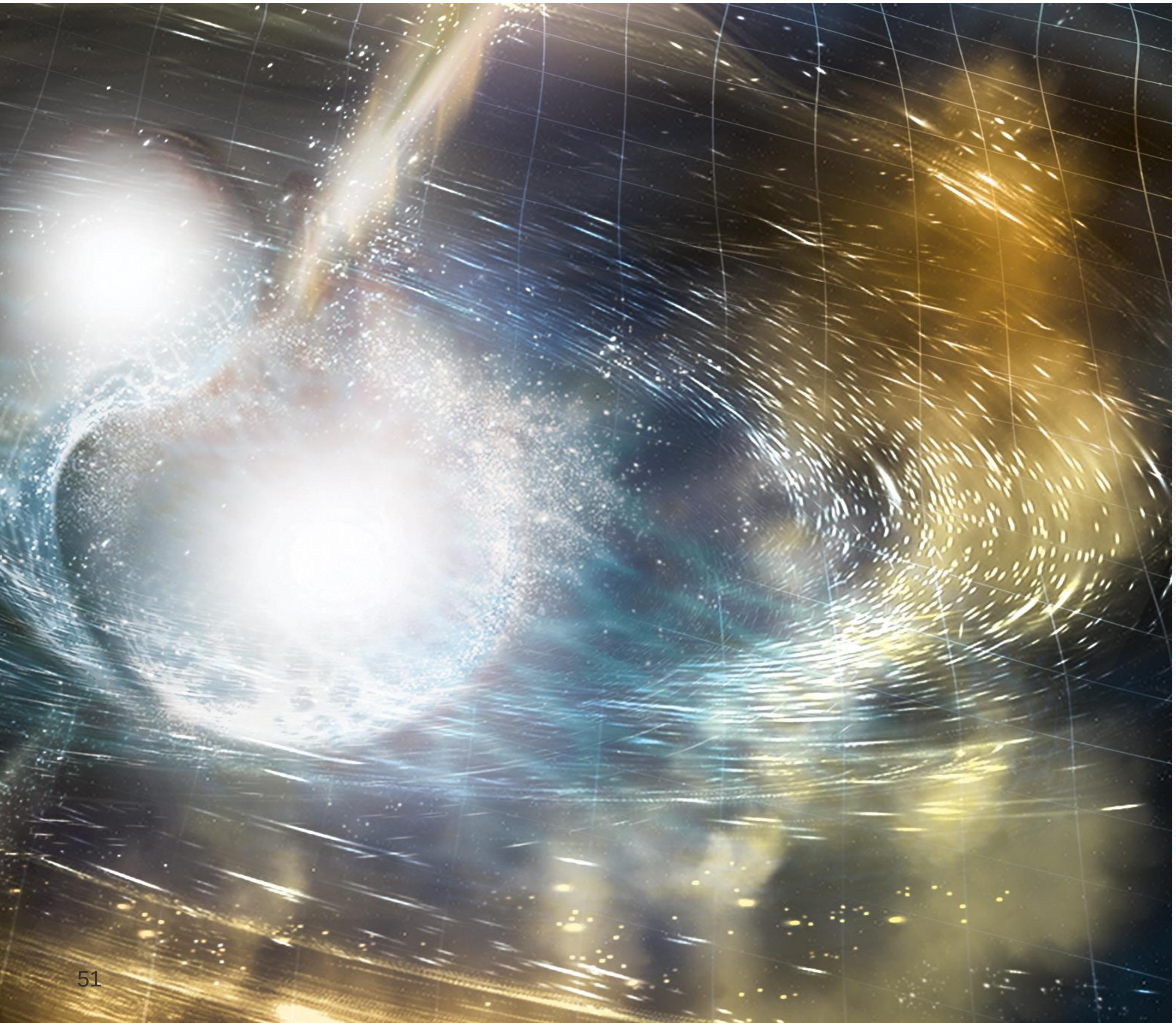


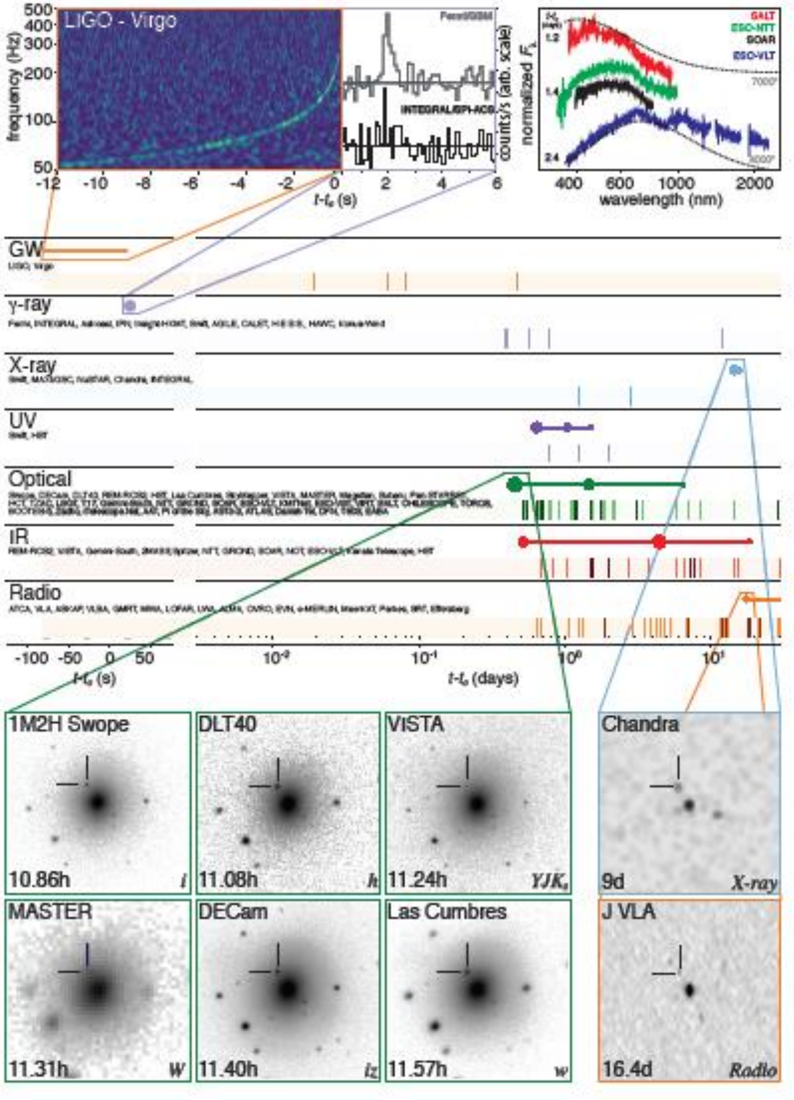


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

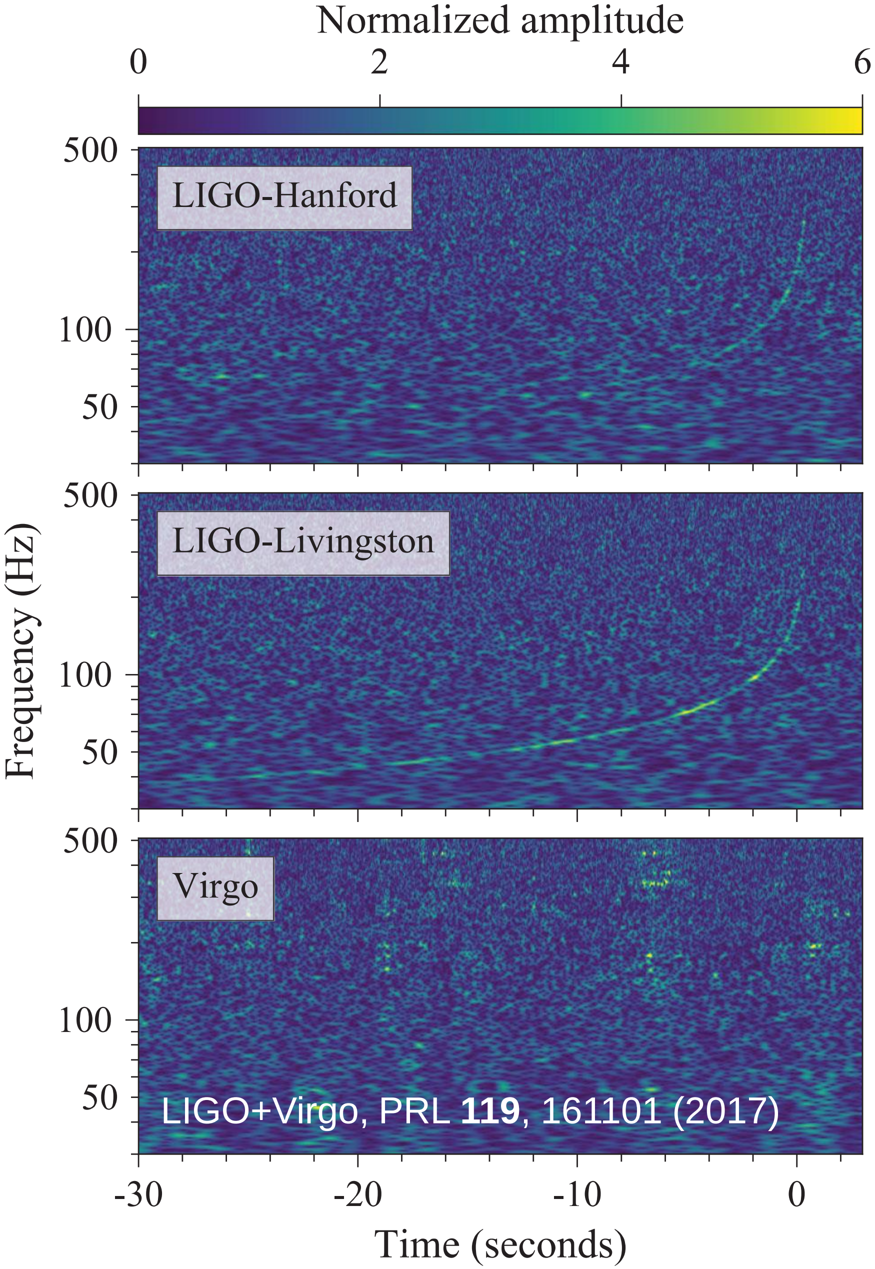
GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino's or other subatomic particles. Our three-detector global network allows identifying these counterparts





17 August 2017: “It’s a binary neutron star!”



LIGO+Virgo, PRL **119**, 161101 (2017)

Gamma rays reached Earth 1.7 seconds after GW event

Implications for fundamental physics

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity

GWs and light propagation speeds

Identical speeds to (assuming conservative lower bound on distance from GW signal of 26 Mpc)

$$-3 \times 10^{-15} < \frac{\Delta v}{v_{EM}} < +7 \times 10^{-16}$$

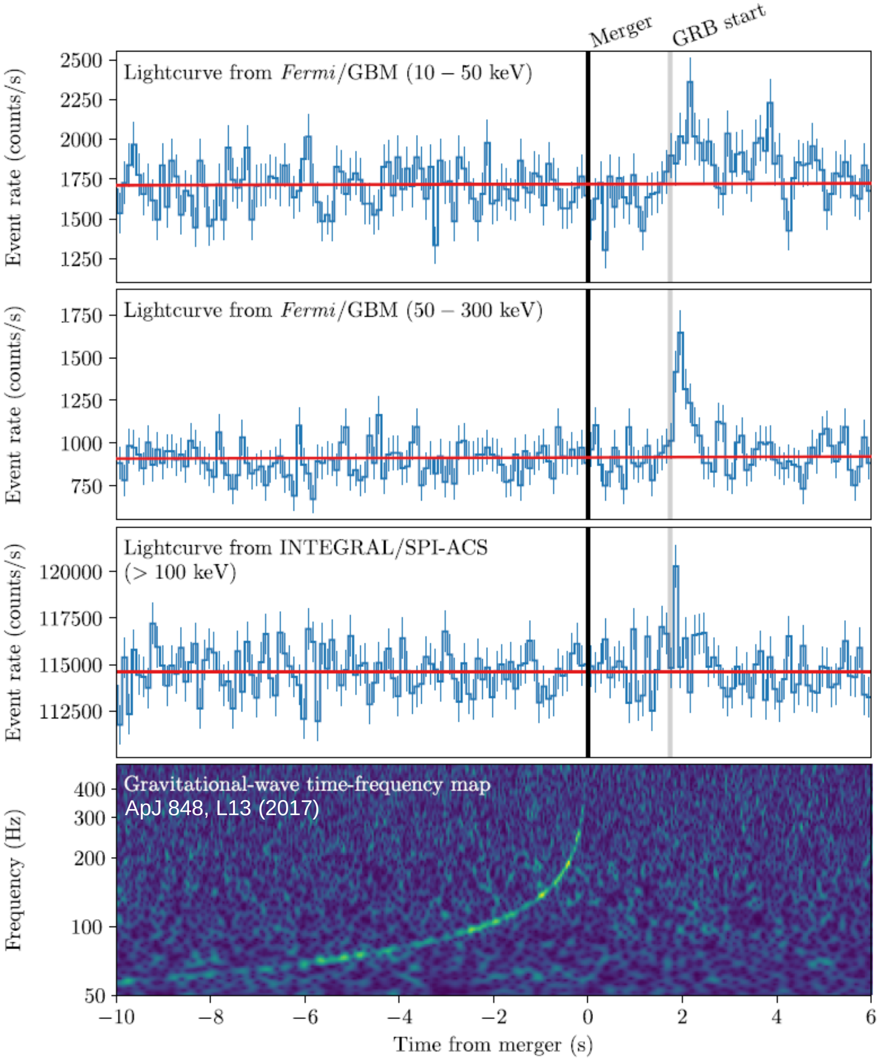
Test of Equivalence Principle

According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

$$\Delta t_{\text{gravity}} = -\frac{\Delta\gamma}{c^3}\int_{r_0}^{r_e} U(r(t);t)\,dr$$

Milky Way potential gives same effect to within $-2.6 \times 10^{-7} \leq \gamma_{\text{GW}} - \gamma_{\text{EM}} \leq 1.2 \times 10^{-6}$

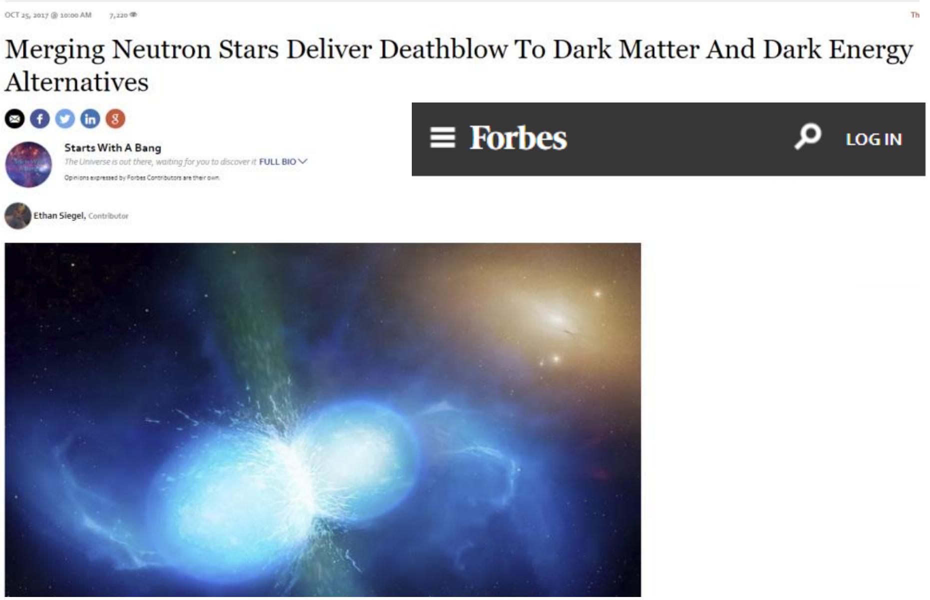
Including data on peculiar velocities to 50 Mpc we find $\Delta\gamma \leq 4 \times 10^{-9}$



ApJ 848, L13 (2017)

Dark Energy and Dark Matter after GW170817

GW170817 had consequences for our understanding of Dark Energy and Dark Matter



OCT 25, 2017 @ 10:00 AM 7,220

Merging Neutron Stars Deliver Deathblow To Dark Matter And Dark Energy Alternatives

Starts With A Bang

The Universe is out there, waiting for you to discover it FULL BIO

Opinions expressed by Forbes Contributors are their own.

Ethan Siegel, Contributor

GW170817 falsifies Dark Matter Emulators

No-dark-matter modified gravity theories like TeVeS or MoG/Scalar-Tensor-Vector ideas have the property that GW propagate on different geodesics (normal matter) from those followed by photons and neutrinos (effective mass to emulate dark matter)

This would give a difference in arrival times between photons and gravitational waves by approximately 800 days, instead of the 1.7 seconds observed (arXiv:1710.06168v1)

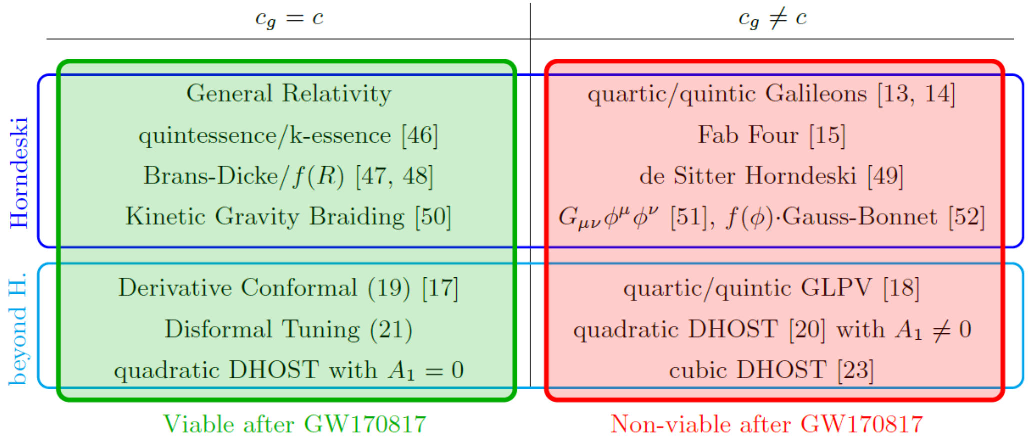
Dark Energy after GW170817

Adding a scalar field to a tensor theory of gravity, yields two generic effects:

1. There's generally a *tensor speed excess* term, which modifies (increases) the propagation speed of GW
2. The scale of the effective Planck mass changes over cosmic times, which alters the damping of the gravitational wave signal as the Universe expands

Simultaneous detection of GW and EM signals rules out a class of modified gravity theories (arXiv:1710.05901v2)

A large class of scalar-tensor theories and DE models are highly disfavored, e.g. covariant Galileon, but also other gravity theories predicting varying cg such as Einstein-Aether, Horava gravity, Generalized Proca, TeVeS and other MOND-like gravities



	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

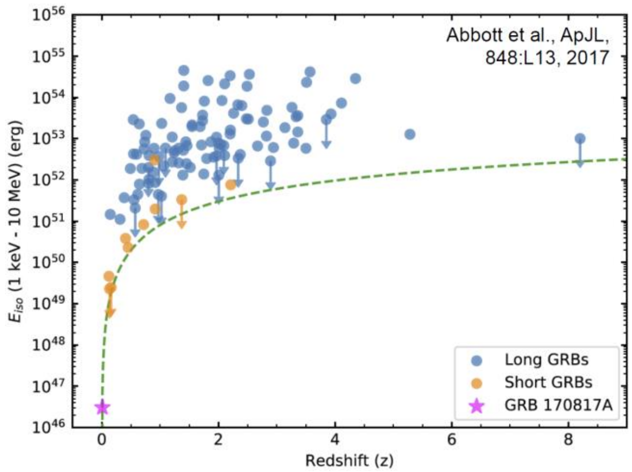
Looking into the heart of a dim nearby sGRB

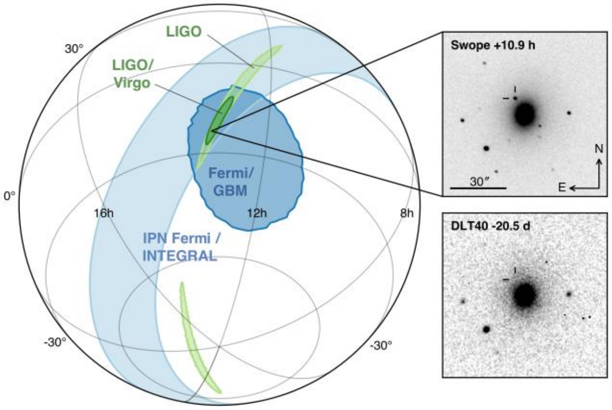
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

Closest by and weakest sGRB, highest SNR GW event

LIGO/Virgo network allowed source localization of 28 (degr)^2 and distance measurement of 40 Mpc

This allowed astronomers to study for the first time a kilonova, the r-process production of elements, a rapidly fading source

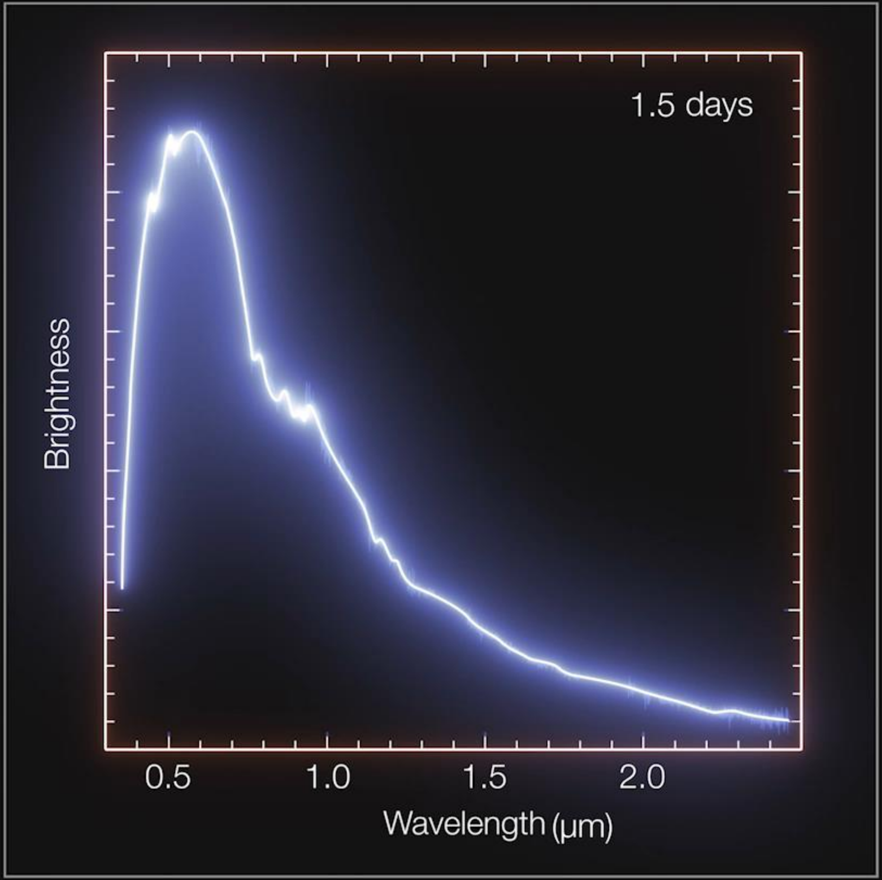

Abbott et al., ApJL, 848:L13, 2017



European Southern Observatory

About 70 observatories worldwide observed the event by using space telescope (e.g. Hubble and Chandra) and ground-based telescopes (e.g. ESO) in all frequency bands (UVOIR). We witness the creation of heavy elements by studying their spectral evolution

Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region



Kilonova description for GW170817

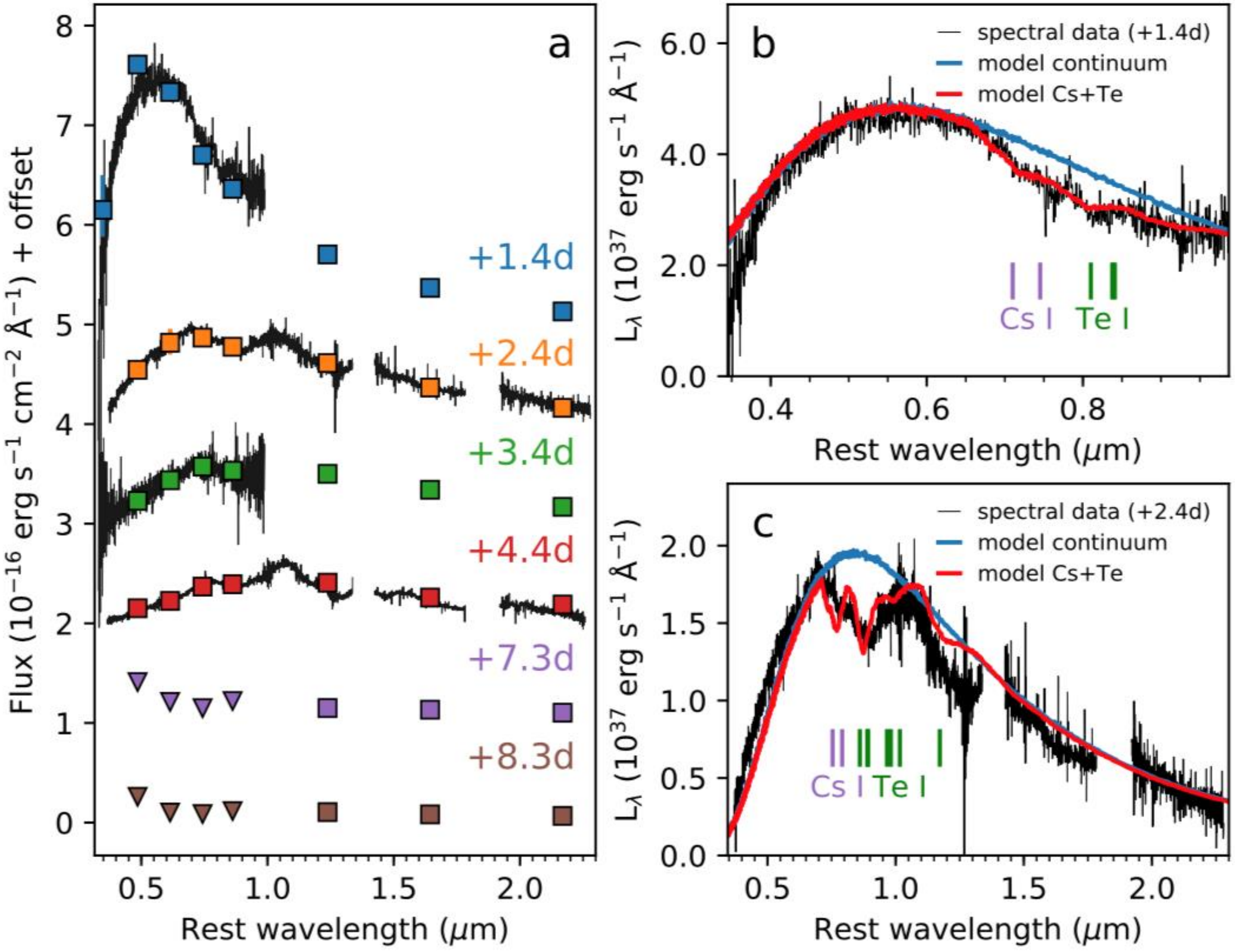
ePESSTO and VLT xshooter spectra with TARDIS radiative transfer models
See Smartt S.J. *et al*., Nature, 551, 75-79, 2017 for more details

The kilonova essentially has a black-body spectrum (6000 K; blue curve in panel C)

Data shows evidence for absorption lines due to tellurium and cesium (with atomic numbers 52 and 55)

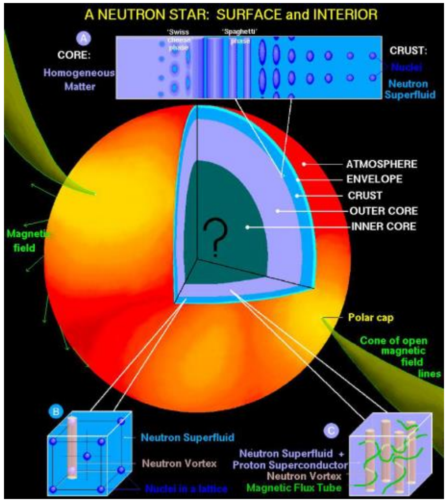
Formation of Cs and Te is difficult to explain in supernova explosions

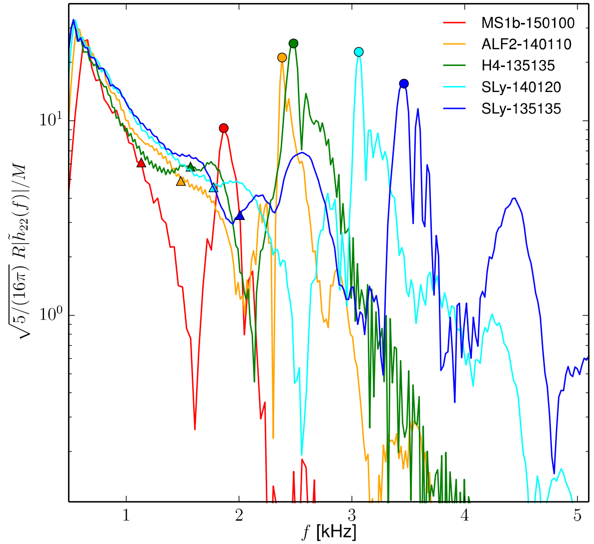
The lines are Doppler broadened due to the high speed of the ejected material (about 60,000 km/s)



Solving an astrophysical conundrum

Neutron stars are rich laboratories with extreme matter physics in a strong gravitational environment. Stability is obtained due to quantum physics



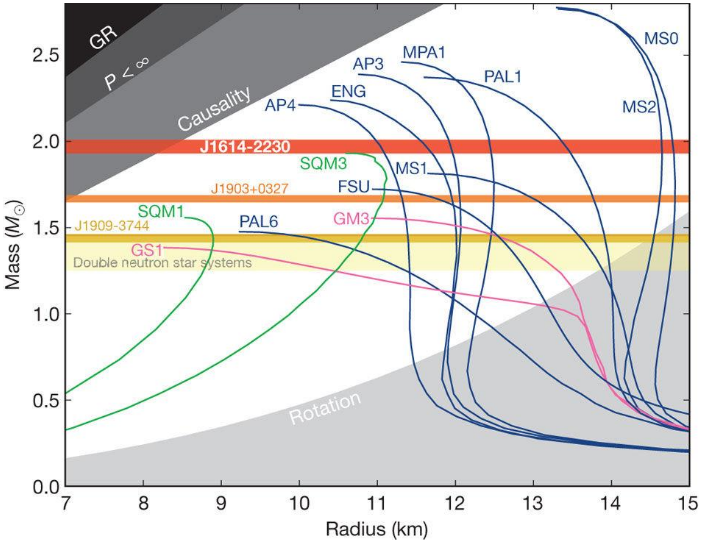


Structure of neutron stars?

- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?

Widely differing theoretical predictions for equations of state

- Pressure as a function of density
- Mass as a function of radius
- Tidal deformability as a function of mass
- Post-merger signal depends on EOS
  - “Soft”: prompt collapse to black hole
  - “Hard”: hypermassive neutron star



Font *et al*, see https://www.uv.es/~jofontro/publications.html

Demorest *et al*., Nature 467, 1081 (2010)

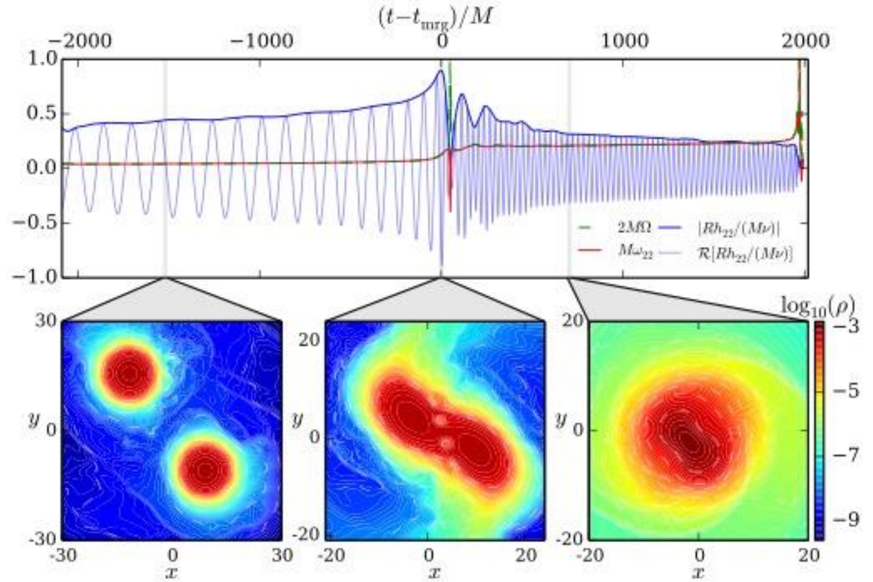
Bernuzzi *et al*., PRL 115, 091101 (2015)

Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

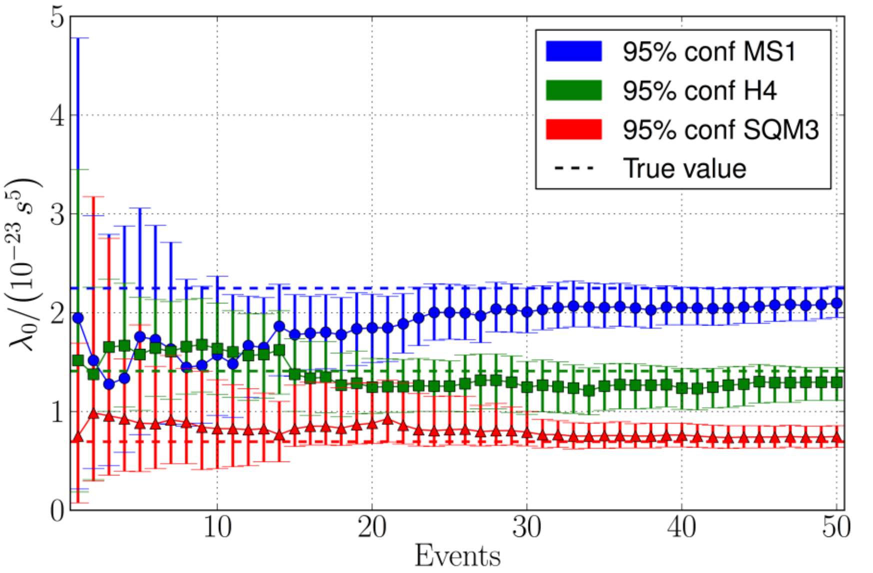
Gravitational waves from inspiraling binary neutron stars

- When close, the stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state



Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state

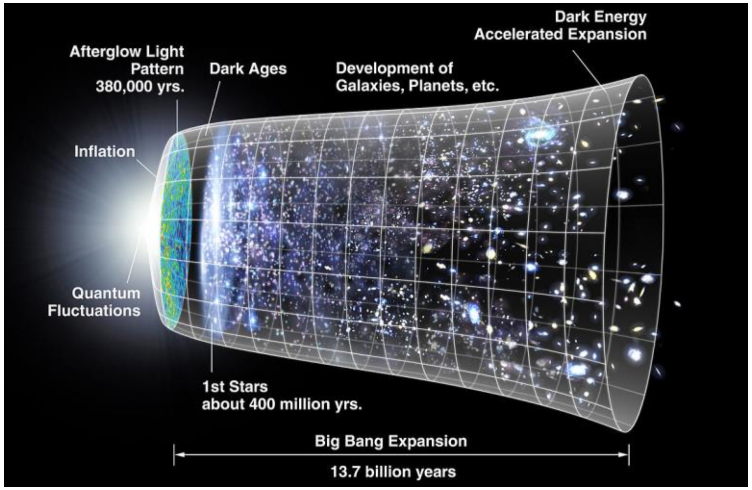


LIGO + Virgo, PRL 119, 161101 (2017)

Bernuzzi, Nagar, Font, …

A new cosmic distance marker

Binary neutron stars allow a new way of mapping out the large-scale structure and evolution of spacetime by comparing distance and redshift

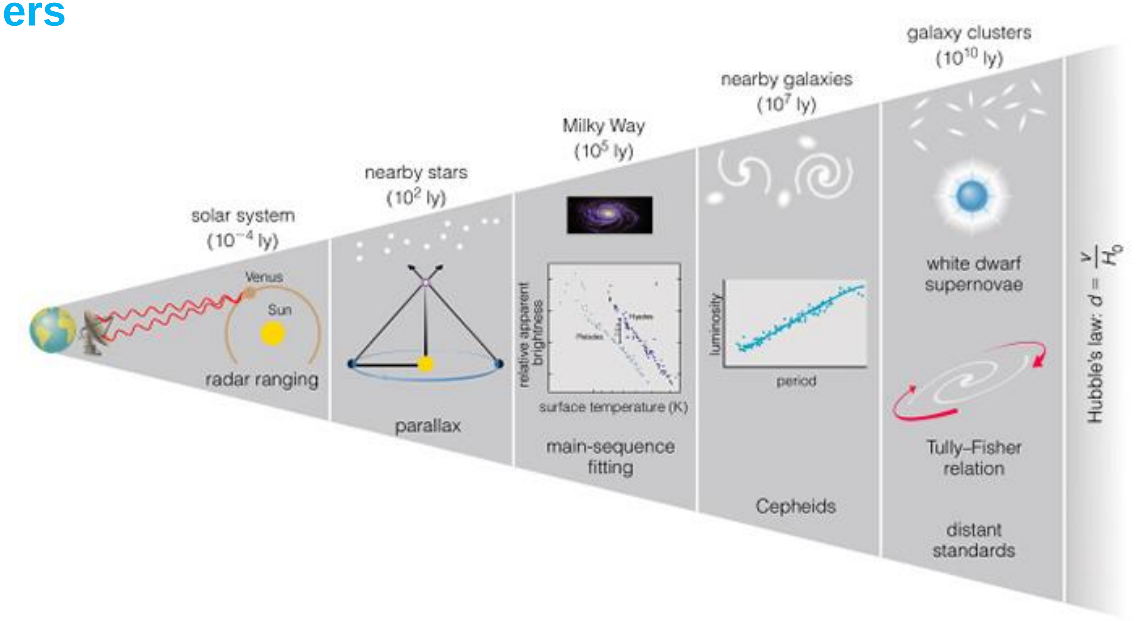


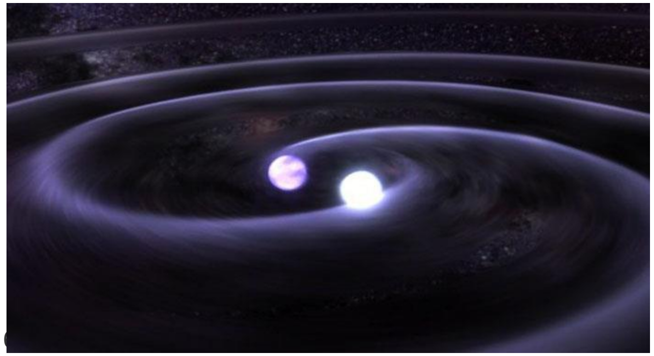
Current measurements depend on cosmic distance ladder

- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder

Gravitational waves from binary mergers

Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

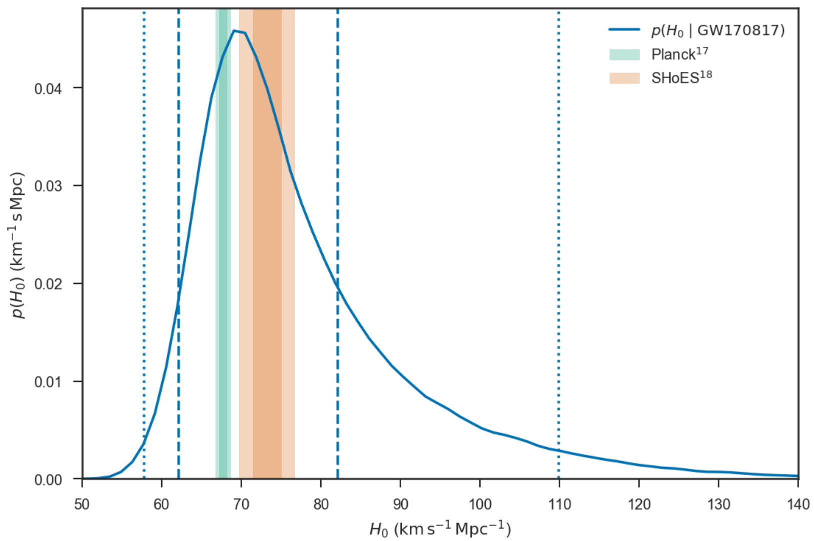
A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

Measurement of the local expansion of the Universe

The Hubble constant

- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

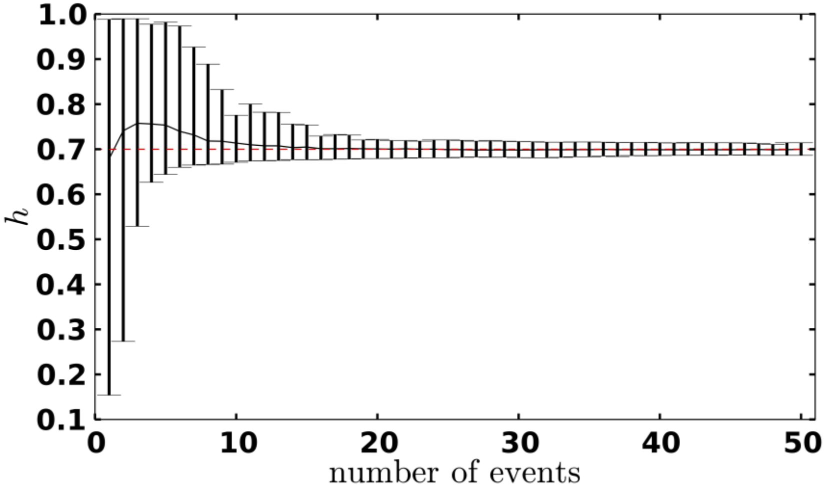
LIGO+Virgo *et al*., Nature 551, 85 (2017)



GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1-2%) accuracy

Del Pozzo, PRD 86, 043011 (2012)



Third generation observatories allow studies of the Dark Energy equation of state parameter

Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

Cosmology

Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy

Nuclear physics

Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

LVC will be back with improved instruments to start the next observation run (O3)

Next steps

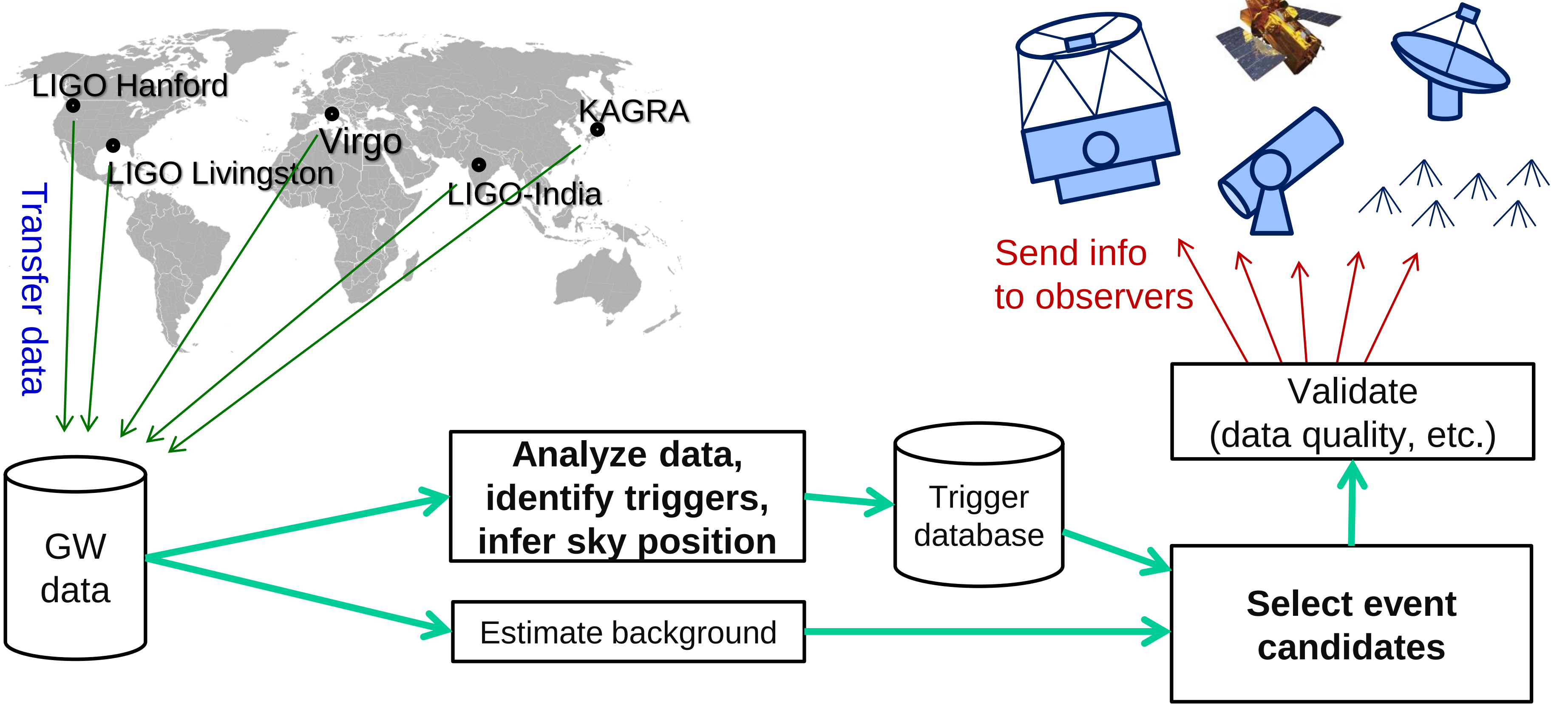
Observation run 3 (O3) expected to start early 2019

The LIGO-Virgo Collaboration is upgrading their instruments with the intention to achieve a doubling of the sensitivity and start multi-messenger astronomy (MMA). MMA requires rapid follow-up of interesting triggers and fast distribution of science data between partners distributed over the globe

Computing will become increasingly important as experiments mature

- GW event rate rapidly increases as sensitivity improves (note that GW-amplitude is measured; $\text{Rate} \sim S_{GW}^{3}$)
- Also computing needs grow as templates get longer

Moreover there is a strong push towards open data and an EU open science cloud



GW data

Analyze data, identify triggers, infer sky position

Estimate background

Trigger database

Select event candidates

Validate (data quality, etc.)

Send info to observers

Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

AdV+ and A+ as the next steps forward in sensitivity

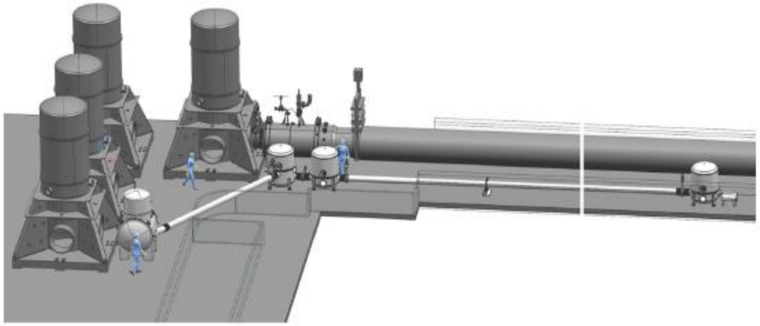
AdV+ is the European plan to maximize Virgo’s sensitivity within the constrains of the EGO site. It will be carried out in parallel with the LIGO A+ upgrade

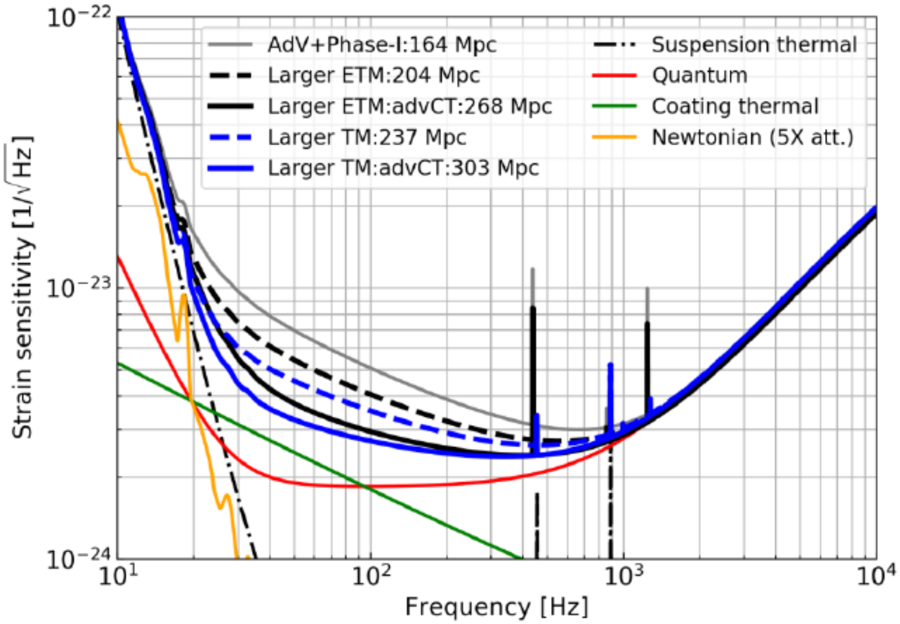
AdV+ features

- Maximize science
- Secure Virgo’s scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attract new groups wanting to enter the field

Upgrade activities

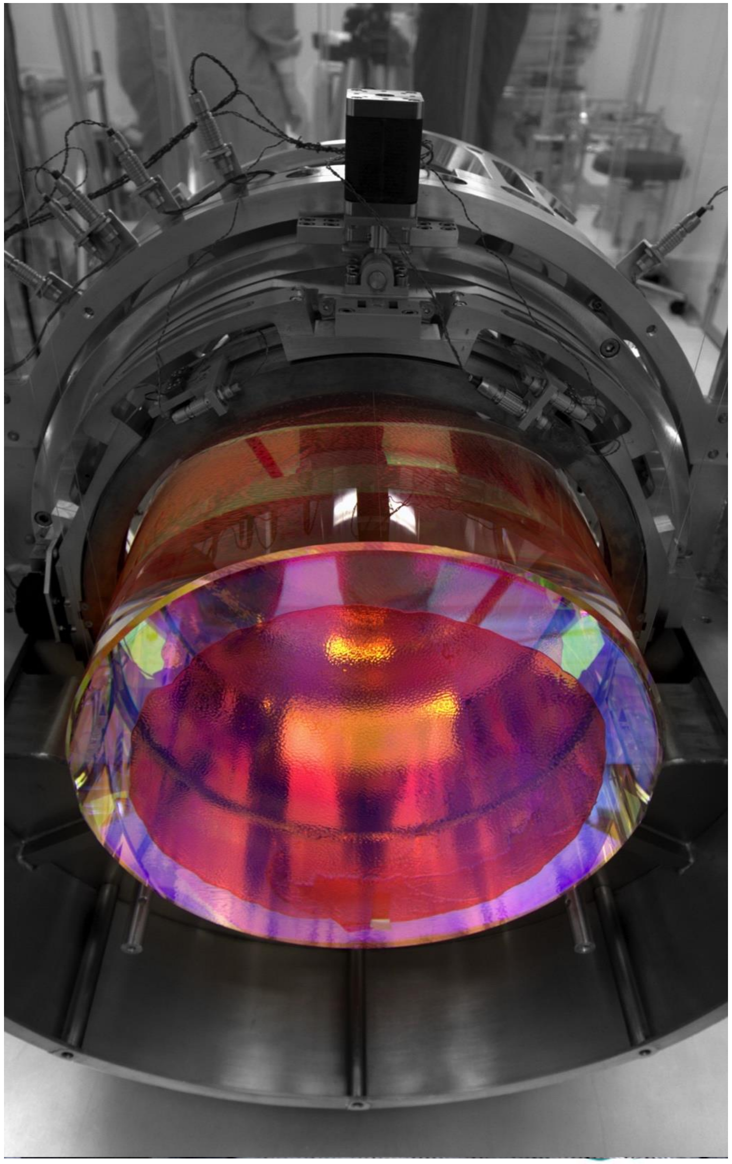
- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc





AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



Features

- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

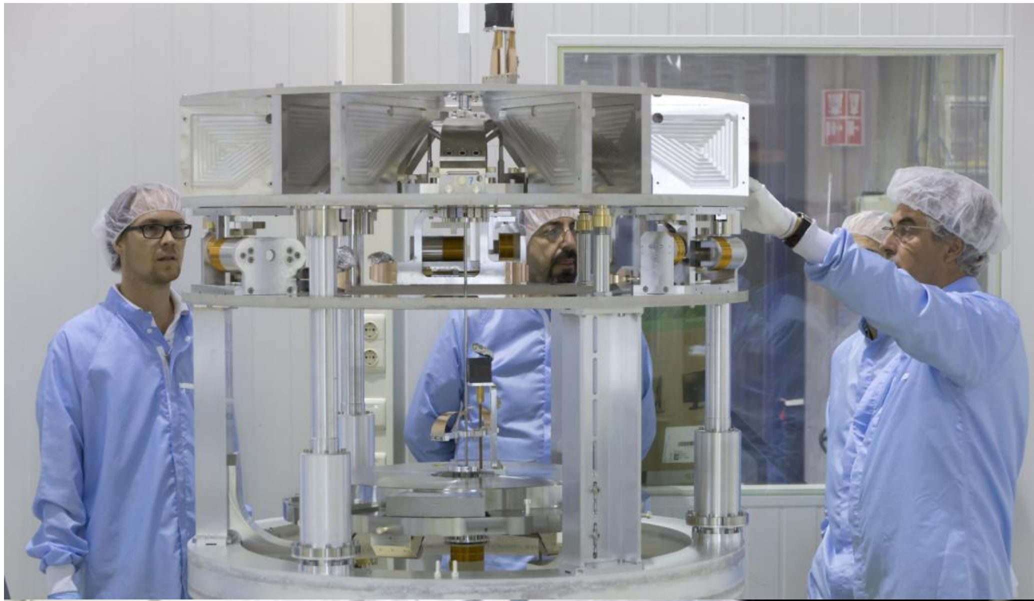
Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

Vibration isolation systems

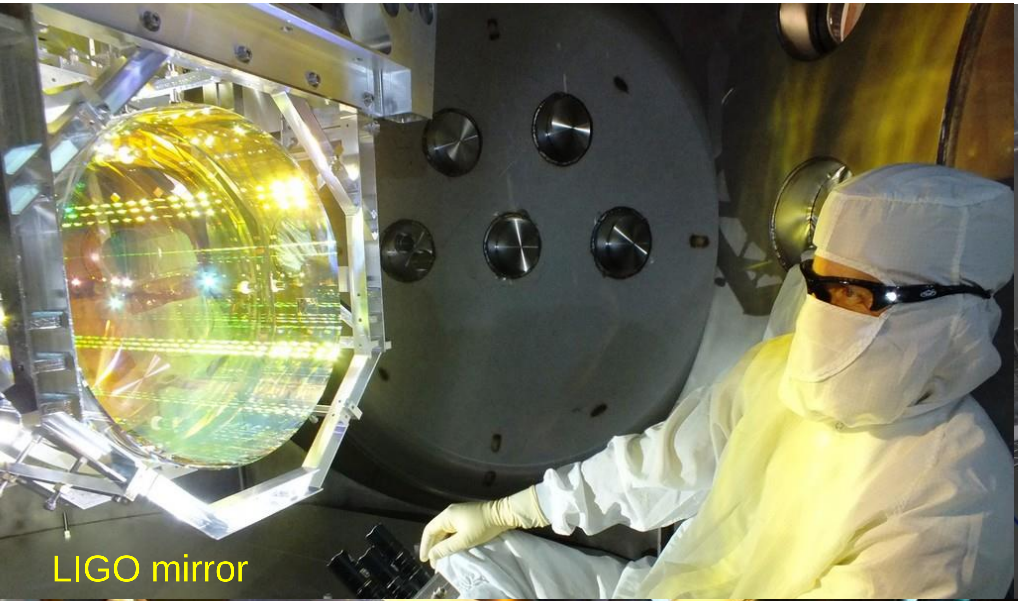
Optical systems for linear alignment, vibration isolation, PDs, QPDs, and phase camera’s, etc.

Detection bench



Advanced optical systems

Mirrors as test masses, beamsplitters, coating materials, suspended mode cleaners, …



LIGO mirror

Virgo beamsplitter

Virgo suspended injection bench

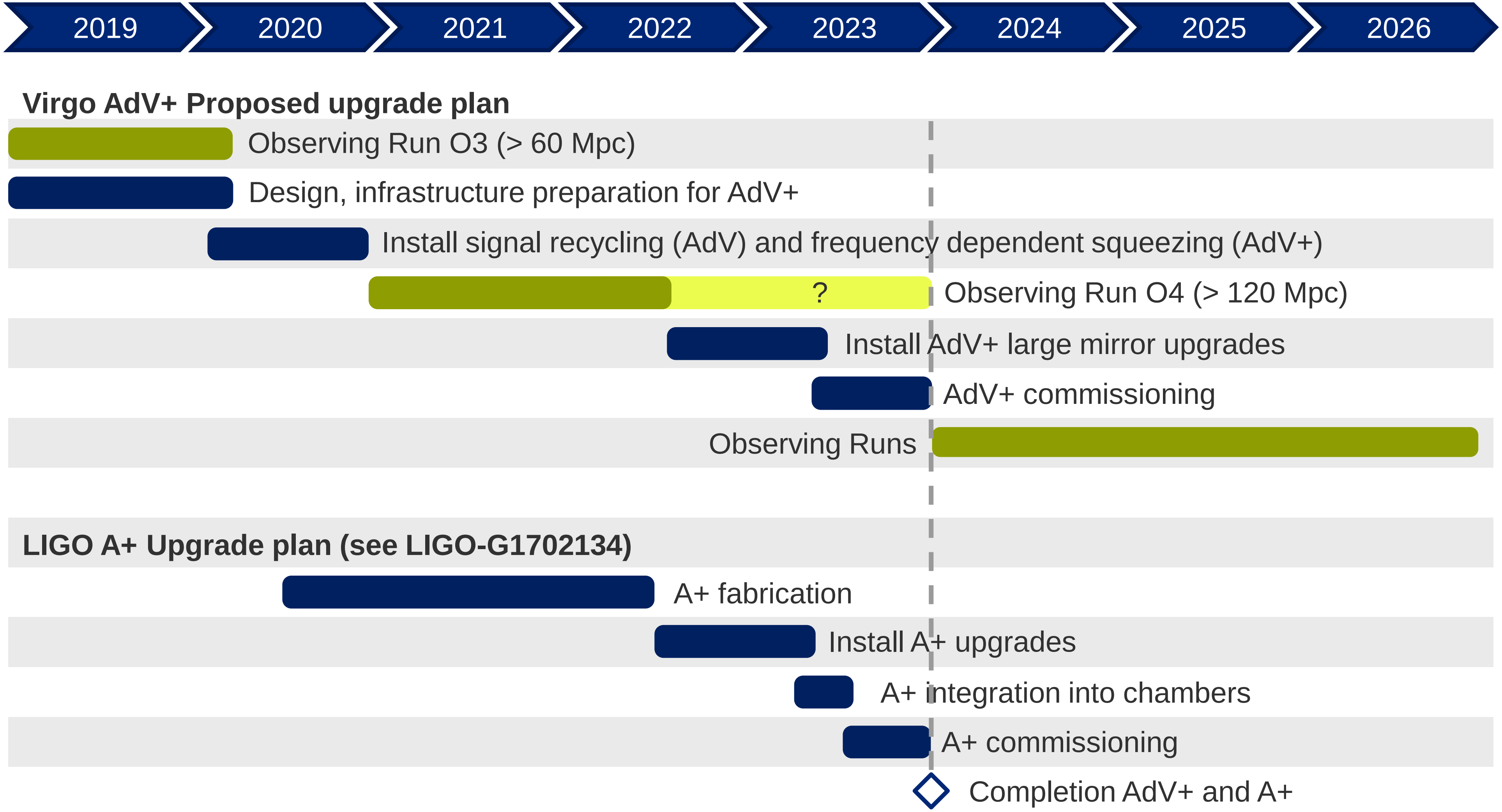
Lasers, quantum optics. Also controls: ML and deep learning

Ultra-stable laser systems. Not only 1 um, but also 1.55 and 2 um under investigation

Virgo squeezer from AEI

AdV+ to be carried out in parallel with LIGO’s A+ upgrade

Five year plan for observational runs, commissioning and upgrades



2019 2020 2021 2022 2023 2024 2025 2026

Virgo AdV+ Proposed upgrade plan

Observing Run O3 (> 60 Mpc)

Design, infrastructure preparation for AdV+

Install signal recycling (AdV) and frequency dependent squeezing (AdV+)

? Observing Run O4 (> 120 Mpc)

Install AdV+ large mirror upgrades

AdV+ commissioning

Observing Runs

LIGO A+ Upgrade plan (see LIGO-G1702134)

A+ fabrication

Install A+ upgrades

A+ integration into chambers

A+ commissioning

Completion AdV+ and A+

Note: duration of O4 has not been decided at this moment

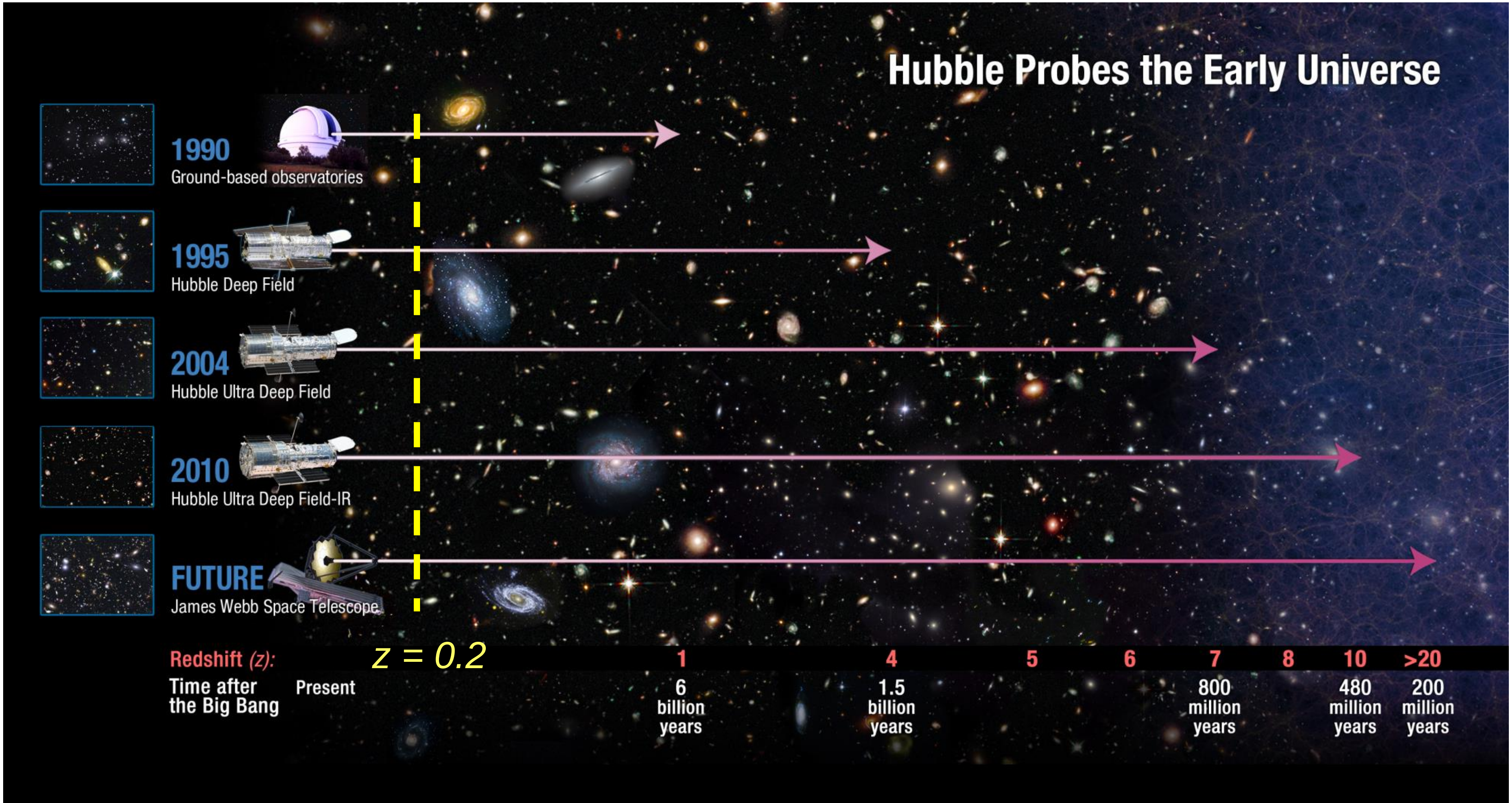
AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

Einstein Telescope: observing all BBH mergers in Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories

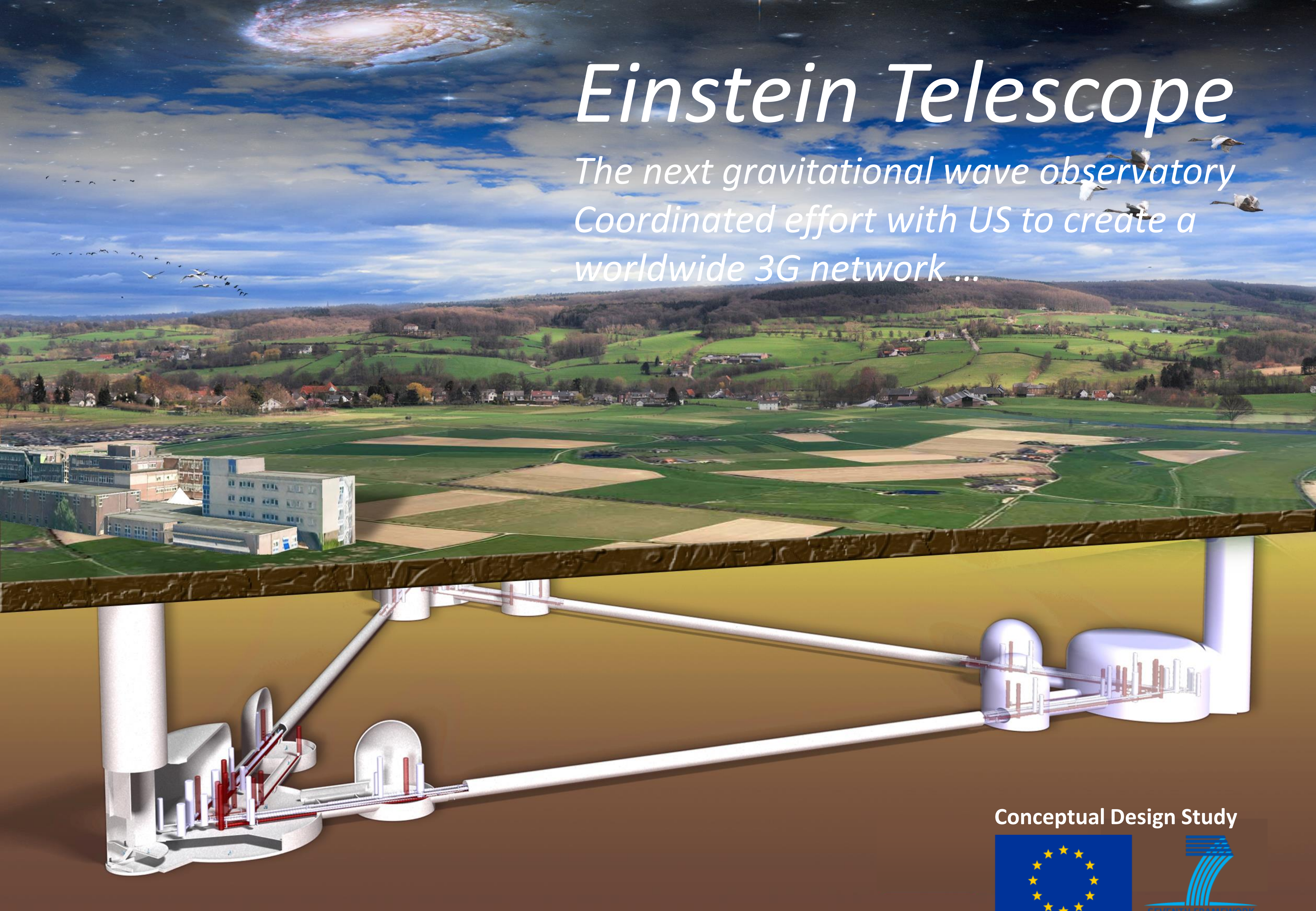
We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range ($z < 20$)

This allows sorting data versus redshift, mass distributions, *etc*. Early warning, IMBH, early Universe, CW, …



Einstein Telescope

The next gravitational wave observatory
Coordinated effort with US to create a
worldwide 3G network …



Conceptual Design Study

Studies of potential sites for Einstein Telescope

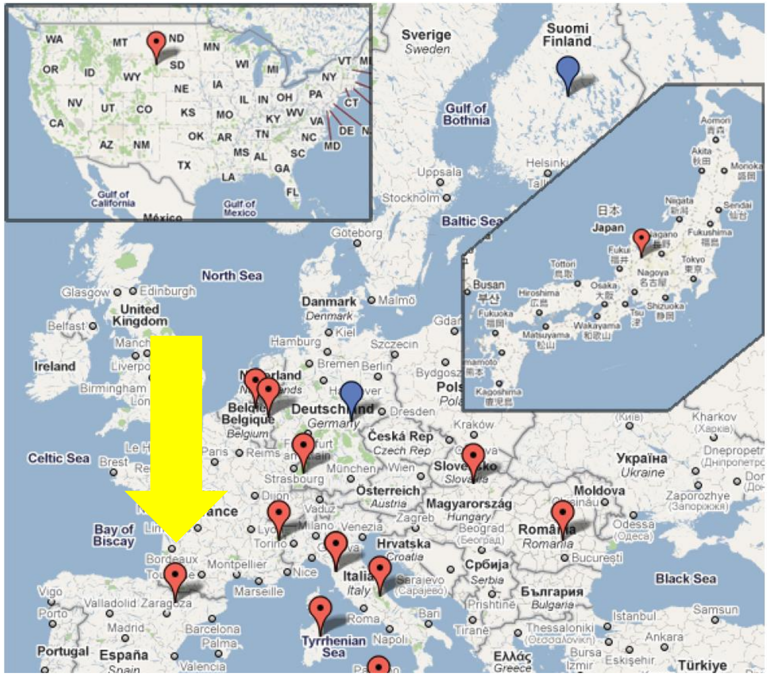
Canfranc underground laboratory in Spain features excellent site quality

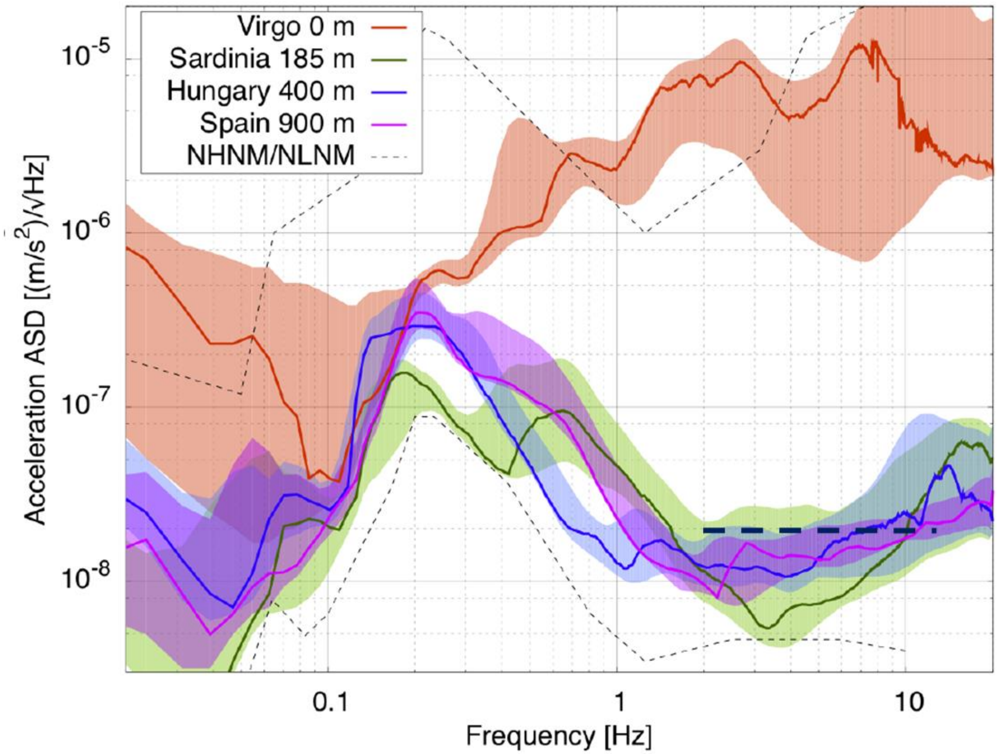
Lowest seismic noise level (complies with ET specs)

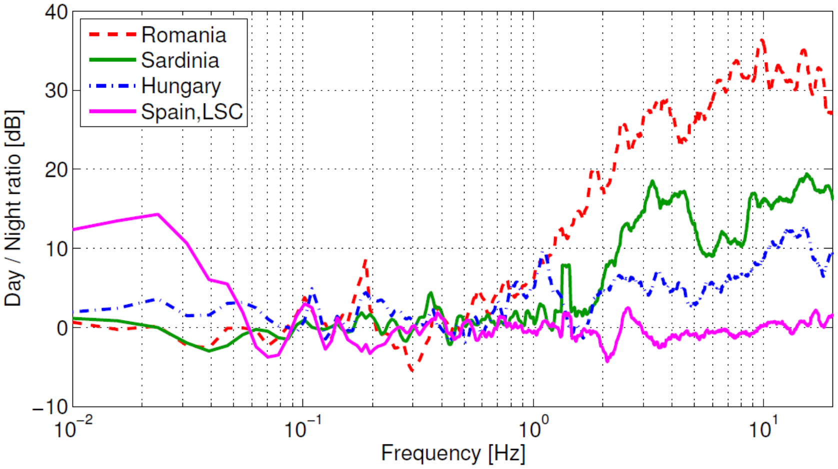
No diurnal dependence of seismic noise

Lowest population density (< 2 per km^2)

Large distance from ocean (120 km)

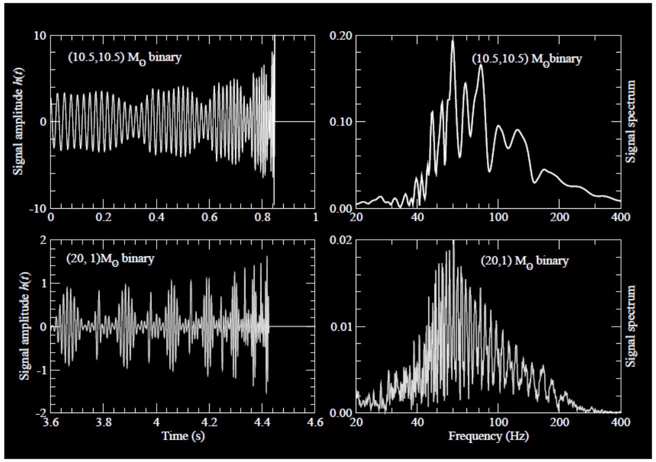


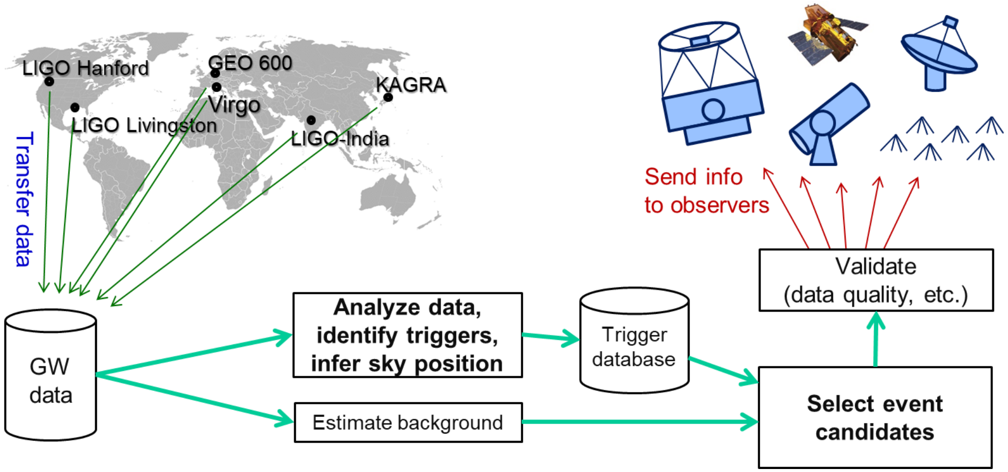




3G science

Detailed studies of gravity, near black holes. Early warning to EM follow-up community. Precision tests of detailed aspects of CBC. Cross correlation of the largest data sets. Access to early Universe





GW data

Analyze data, identify triggers, infer sky position

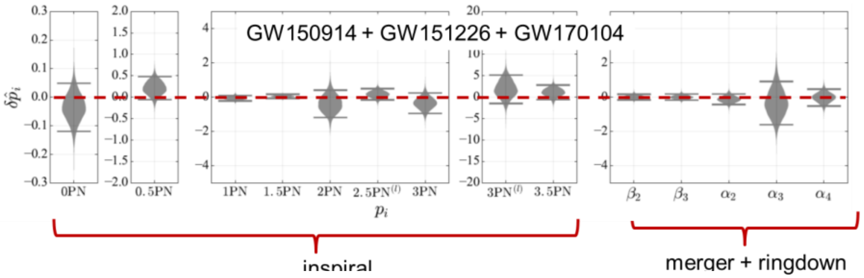
Trigger database

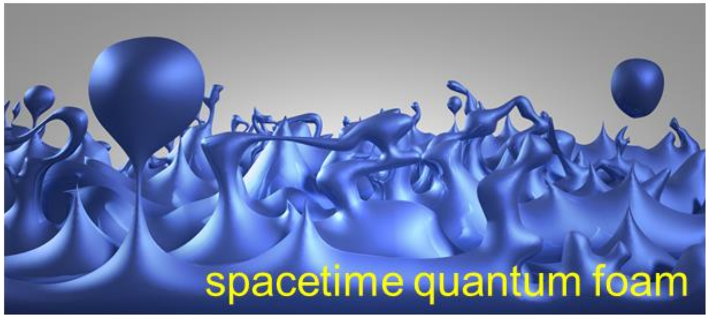
Estimate background

Select event candidates

Validate (data quality, etc.)

Send info to observers

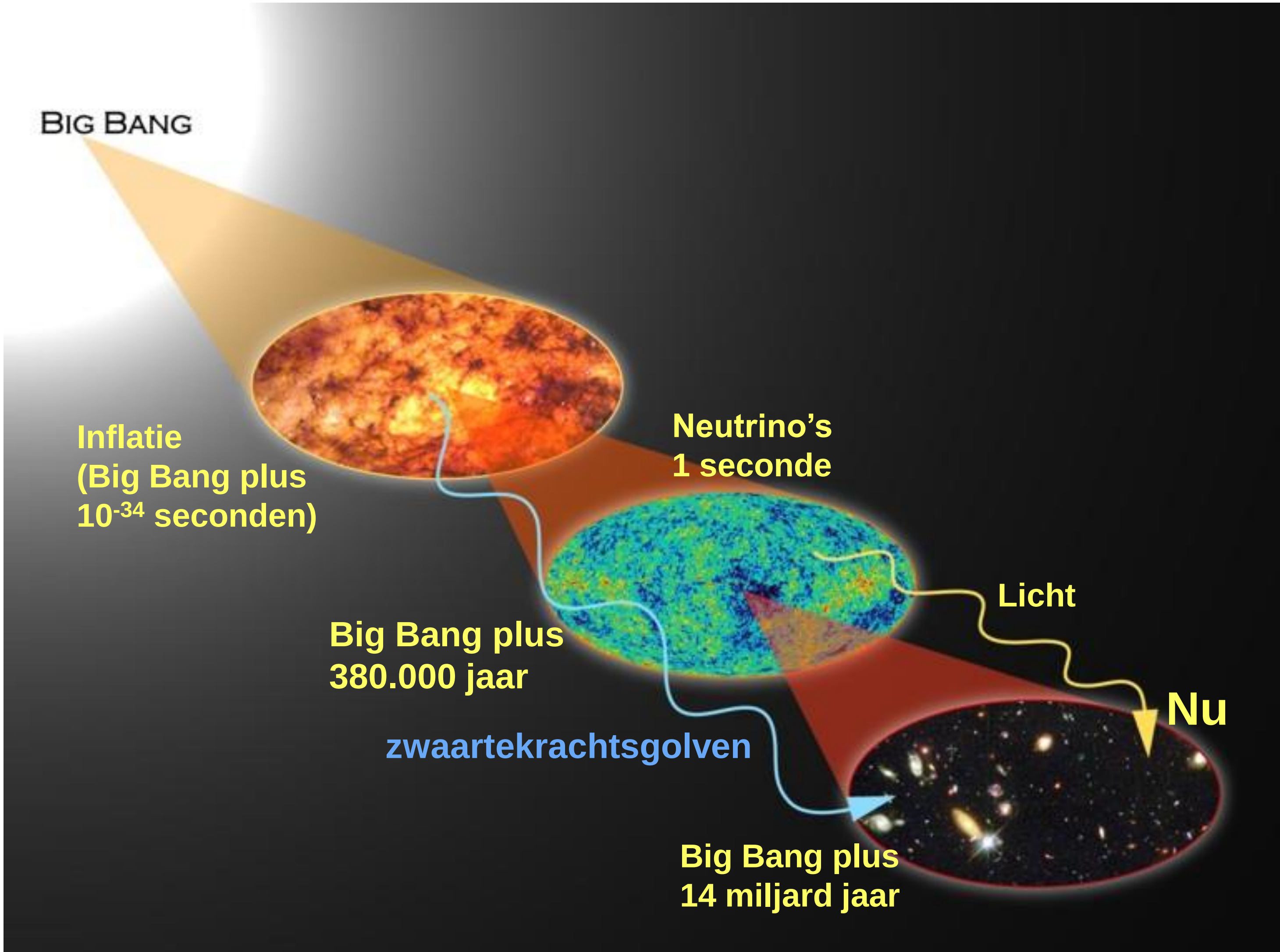




Einstein Telescope: early Universe

What is powering the Big Bang?

Gravitational waves can escape from the earliest moment of the Big Bang



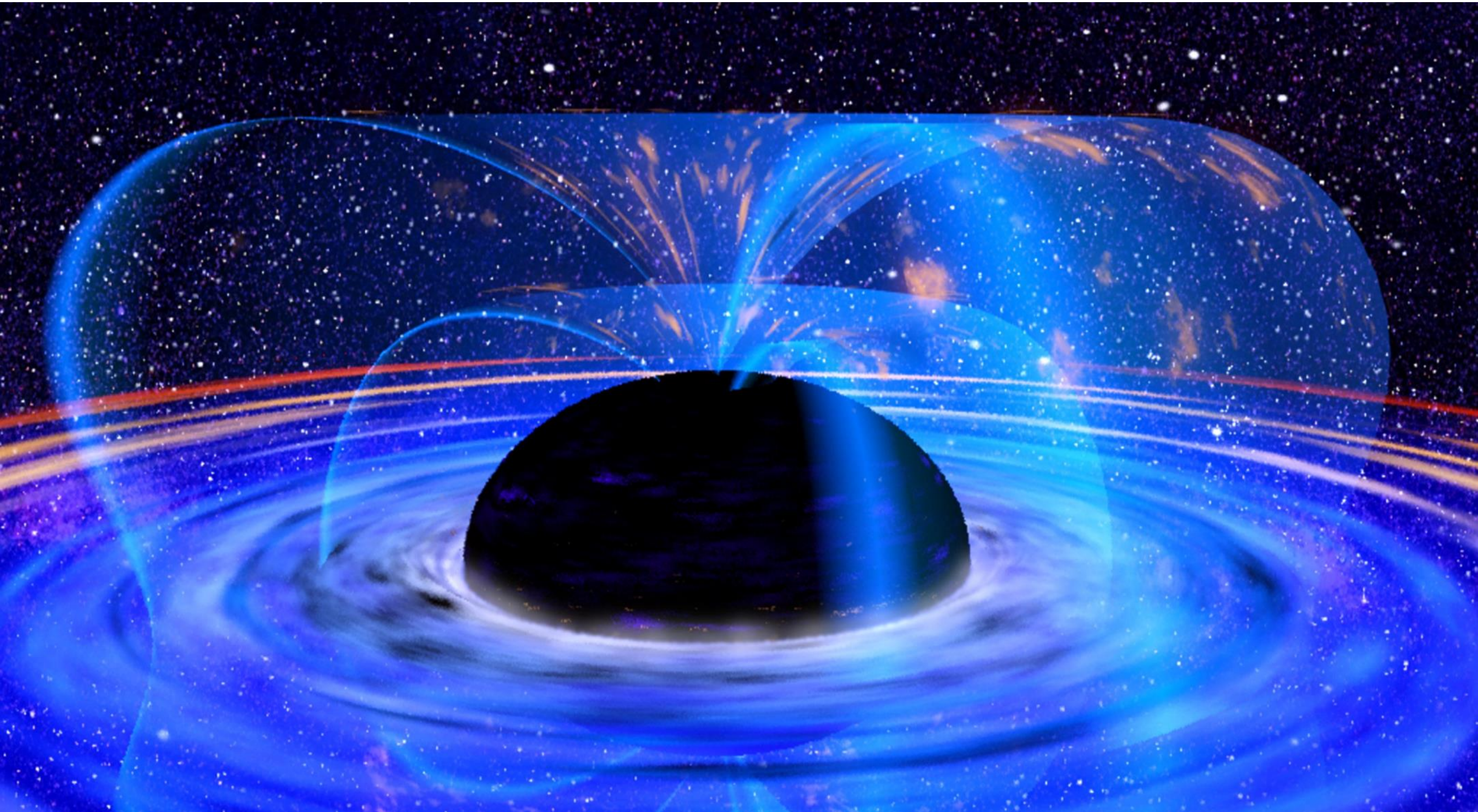
Einstein Telescope: cosmography

What is this mysterious dark energy that is tearing the Universe apart?
Use BNS and BBH as standard “candles” (so-called “sirens”)

Einstein Telescope: fundamental physics

What happened at the edge of a black hole?

Is Einstein’s theory correct in conditions of extreme gravitation? Of does new physics await?



Bright future for gravitational wave research

LIGO and Virgo are operational. LIGO-India and KAGRA in Japan under construction. ESA launches LISA in 2034. Einstein Telescope CDR financed by EU, strong support by APPEC

Gravitational wave research

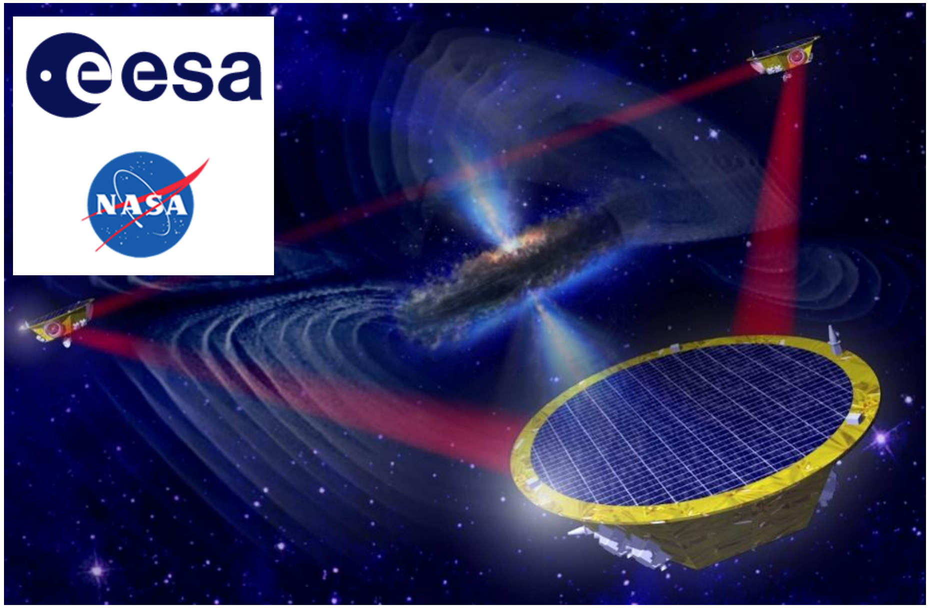
- LIGO and Virgo operational
- LIGO-India and KAGRA under construction
- ESA and NASA select LISA
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

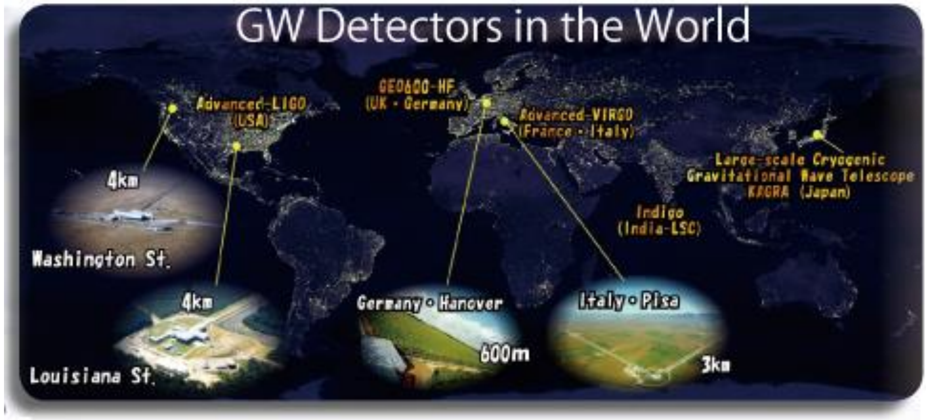
Einstein Telescope

- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2019)





Thank you for your attention!