Gravitational wave science

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LIGO Scientific Collaboration

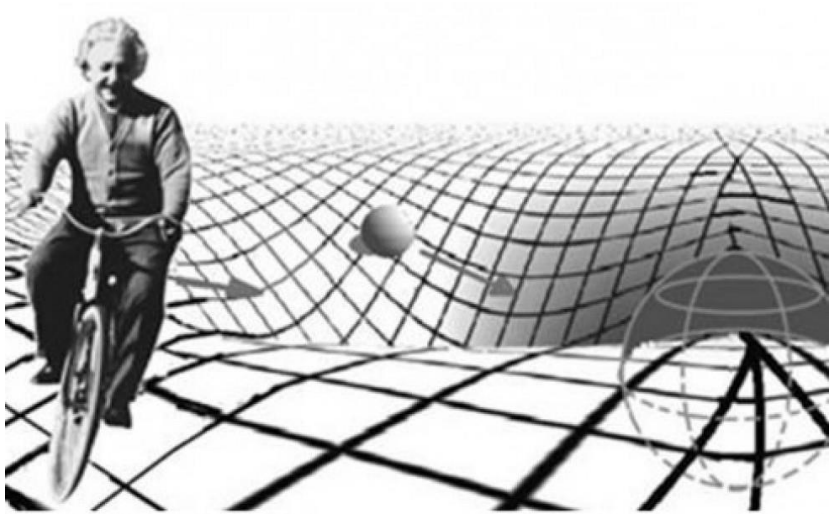
Advanced Virgo

Einstein’s theory of general relativity

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

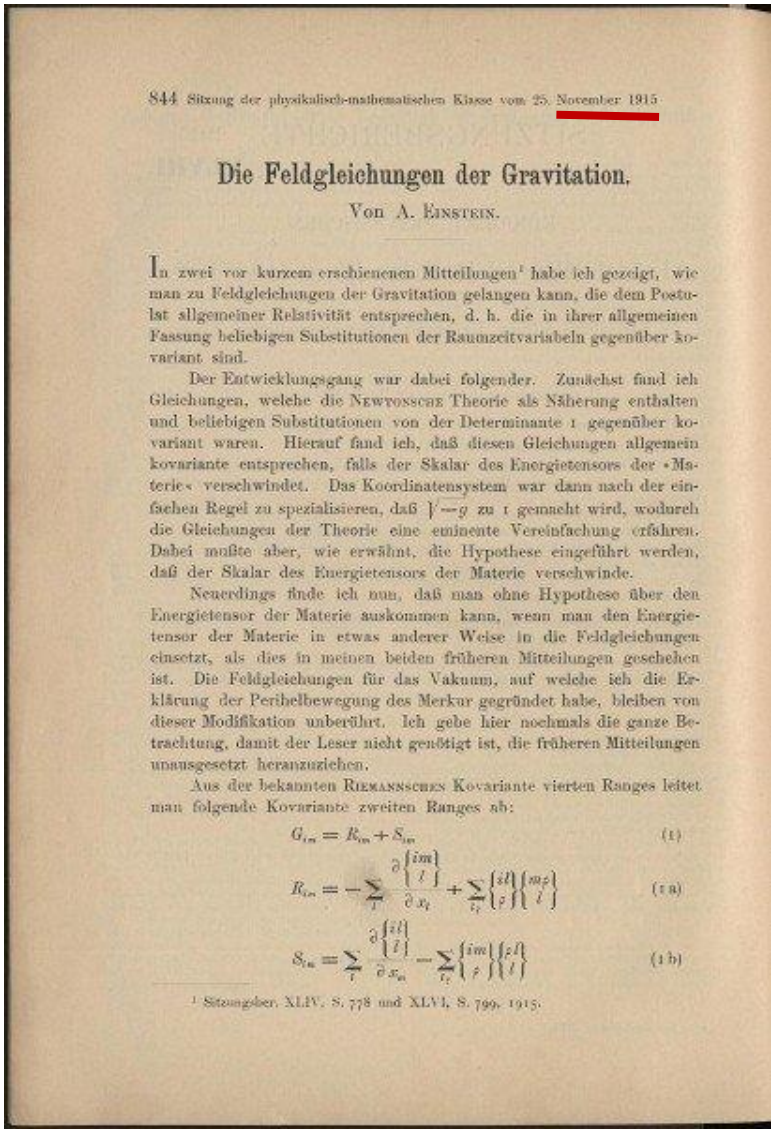
Einstein’s Gravity

- 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, wormholes, structure formation, …
- Gravitational waves: curvature perturbations in the spacetime metric



844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten und beliebigen Substitutionen von der Determinante 1 gegenüber kovariant waren. Hierauf fand ich, daß diesen Gleichungen allgemein kovariante entsprechen, falls der Skalar des Energietensors der »Materie« verschwindet. Das Koordinatensystem war dann nach der einfachen Regel zu spezialisieren, daß $\sqrt{-g}$ zu 1 gemacht wird, wodurch die Gleichungen der Theorie eine eminente Vereinfachung erfahren. Dabei mußte aber, wie erwähnt, die Hypothese eingeführt werden, daß der Skalar des Energietensors der Materie verschwinde.

Neuerdings finde ich nun, daß man ohne Hypothese über den Energietensor der Materie auskommen kann, wenn man den Energietensor der Materie in etwas anderer Weise in die Feldgleichungen einsetzt, als dies in meinen beiden früheren Mitteilungen geschehen ist. Die Feldgleichungen für das Vakuum, auf welche ich die Erklärung der Perihelbewegung des Merkur gegründet habe, bleiben von dieser Modifikation unberührt. Ich gebe hier nochmals die ganze Betrachtung, damit der Leser nicht genötigt ist, die früheren Mitteilungen unausgesetzt heranzuziehen.

Aus der bekannten Riemannschen Kovariante vierten Ranges leitet man folgende Kovariante zweiten Ranges ab:

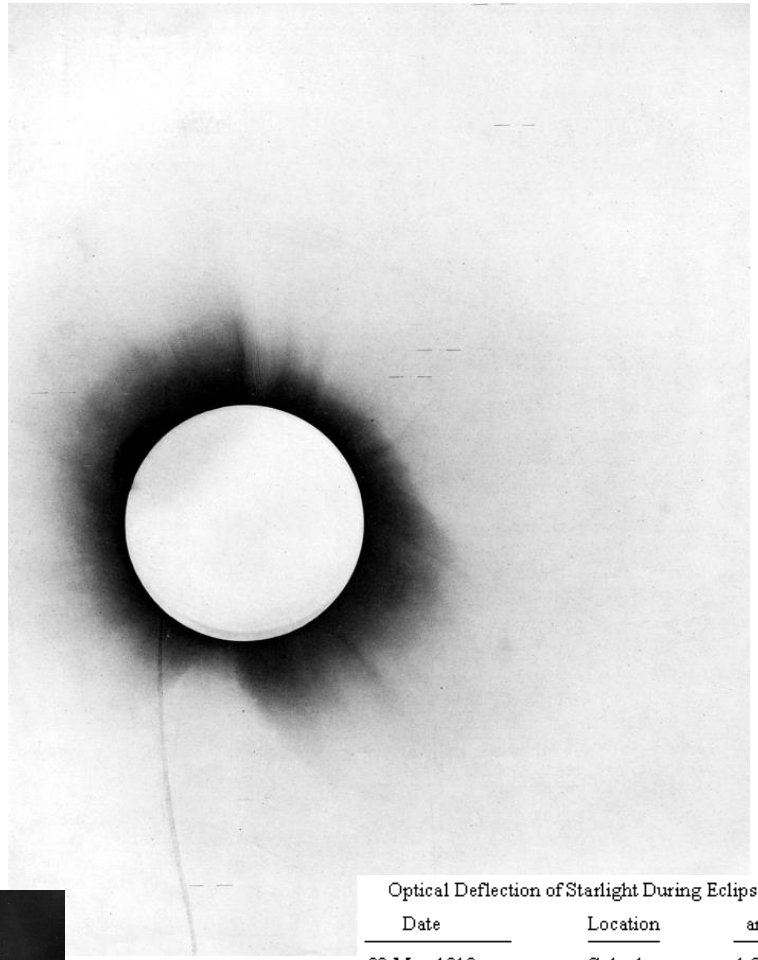
$$G_{in} = R_{in} + S_{in} \tag{1}$$

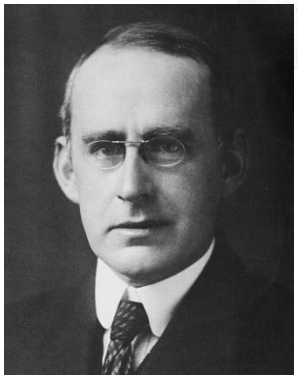
$$R_{in} = -\sum_{l} \frac{\partial \begin{Bmatrix} im \\ l \end{Bmatrix}}{\partial x_l} + \sum_{l\tau} \begin{Bmatrix} il \\ \tau \end{Bmatrix} \begin{Bmatrix} m\tau \\ l \end{Bmatrix} \tag{1a}$$

$$S_{in} = \sum_{l} \frac{\partial \begin{Bmatrix} il \\ l \end{Bmatrix}}{\partial x_m} - \sum_{l\tau} \begin{Bmatrix} im \\ \tau \end{Bmatrix} \begin{Bmatrix} \tau l \\ l \end{Bmatrix} \tag{1b}$$

[1] Sitzungsber. XLIV, S. 778 und XLVI, S. 799, 1915.

Arthur Eddington observes bending of light in May 1919





Optical Deflection of Starlight During Eclipses

Date	Location	arc secs
29 May 1919	Sobral	1.98 ± 0.16
	Principe	1.16 ± 0.40
21 Sep 1922	Australia	1.77 ± 0.40
		1.42 to 2.16
		1.72 ± 0.15
		1.82 ± 0.20
9 May 1929	Sumatra	2.24 ± 0.10
19 June 1936	USSR	2.73 ± 0.31
	Japan	1.28 to 2.13
20 May 1947	Brazil	2.01 ± 0.27
25 Feb 1952	Sudan	1.70 ± 0.10
30 Jun 1973	Mauritania	1.66 ± 0.19

LIGHTS ALL ASKEW IN THE HEAVENS

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

EINSTEIN THEORY TRIUMPHS

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

A BOOK FOR 12 WISE MEN

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

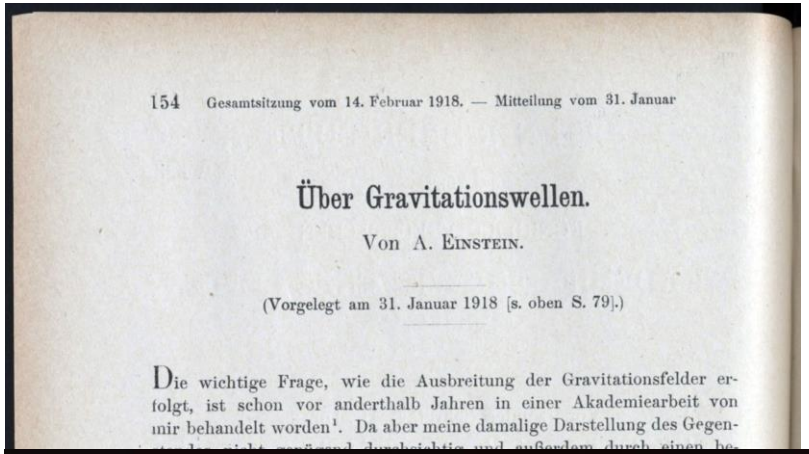
New York Times, November 10, 1919

Einstein arrives in New York

Einstein is now world famous

Einstein predicts existence of gravitational waves

Einstein publishes his discovery in Sitzungberichte Preussische Akademie der Wissenschaften, 22 June 1916 and on 14 February 1918



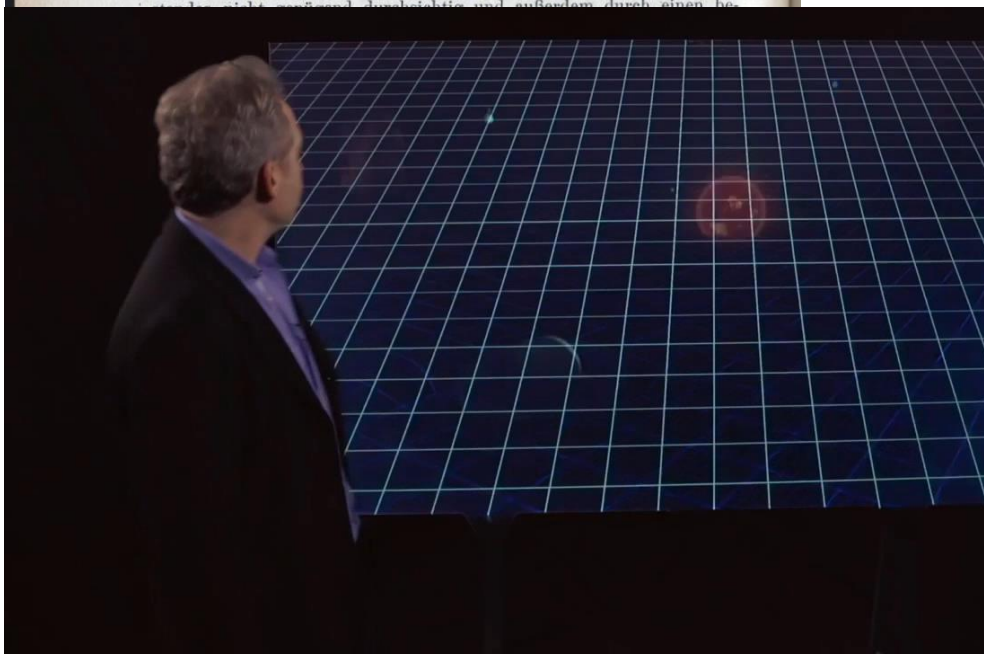
154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

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 Gegen-



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

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

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.

Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die Maxwellsche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

Gravitational radiation exists: PSR B1913+16

Russell A. Hulse
Joseph H. Taylor, Jr.
In 1974 discovery of the first pulsar in a binary system

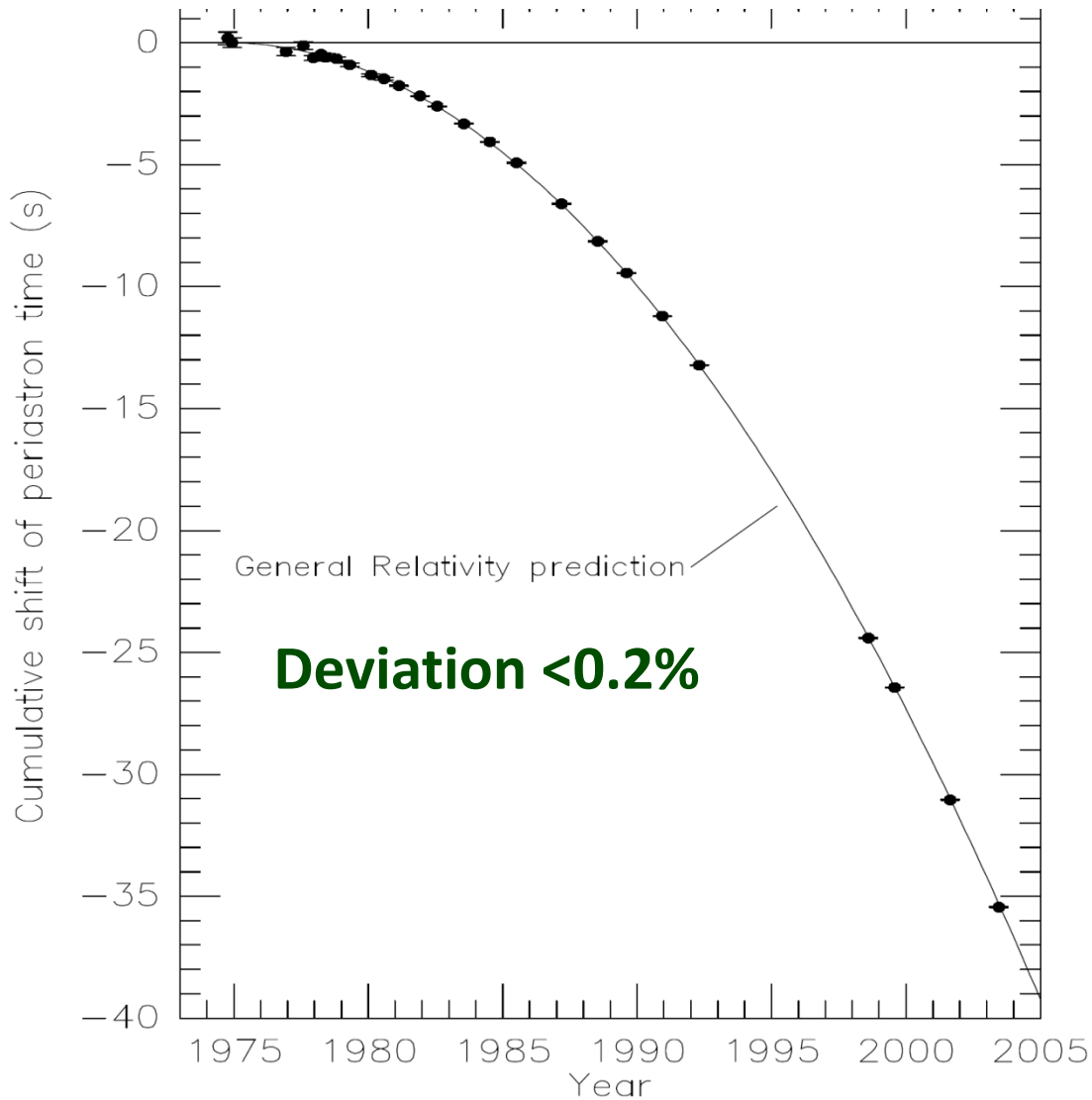
Period ~ 8h

GW emission shortens the period

Indirect detection of GWs

Nobel 1993

Δt_P [s] Periastron advance



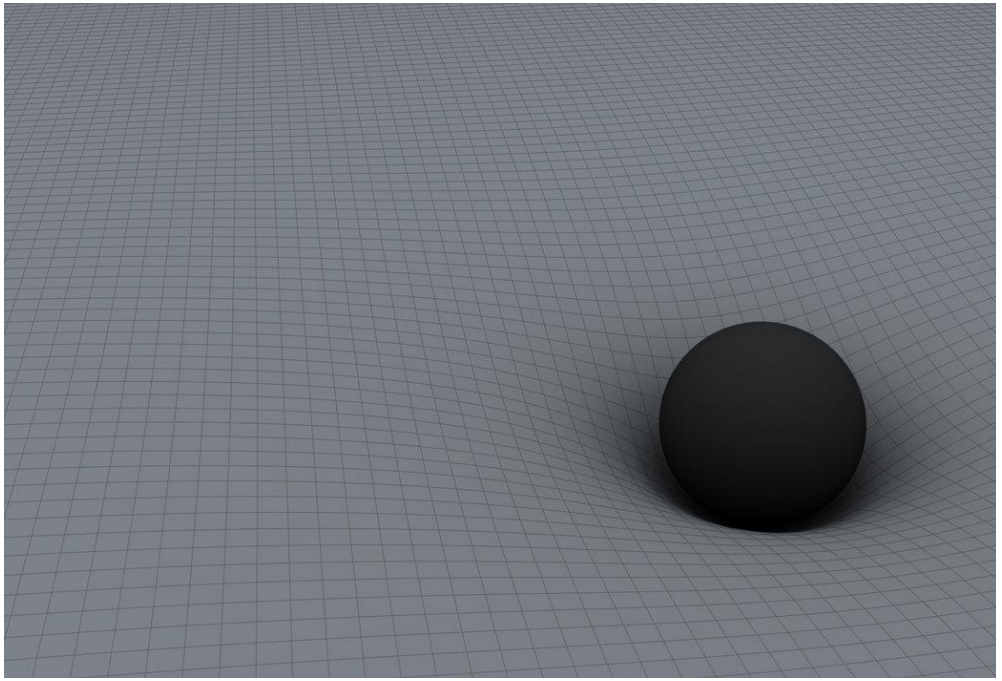
Robert Oppenheimer predicts existence of black holes

Together with Snyder he predicts in 1939 the creation of black holes for neutron stars with masses above approximately $3M_{\odot}$ (Tolman-Oppenheimer-Volkoff limit)

Black holes are made of spacetime. According to GR all matter has disappeared in a singularity

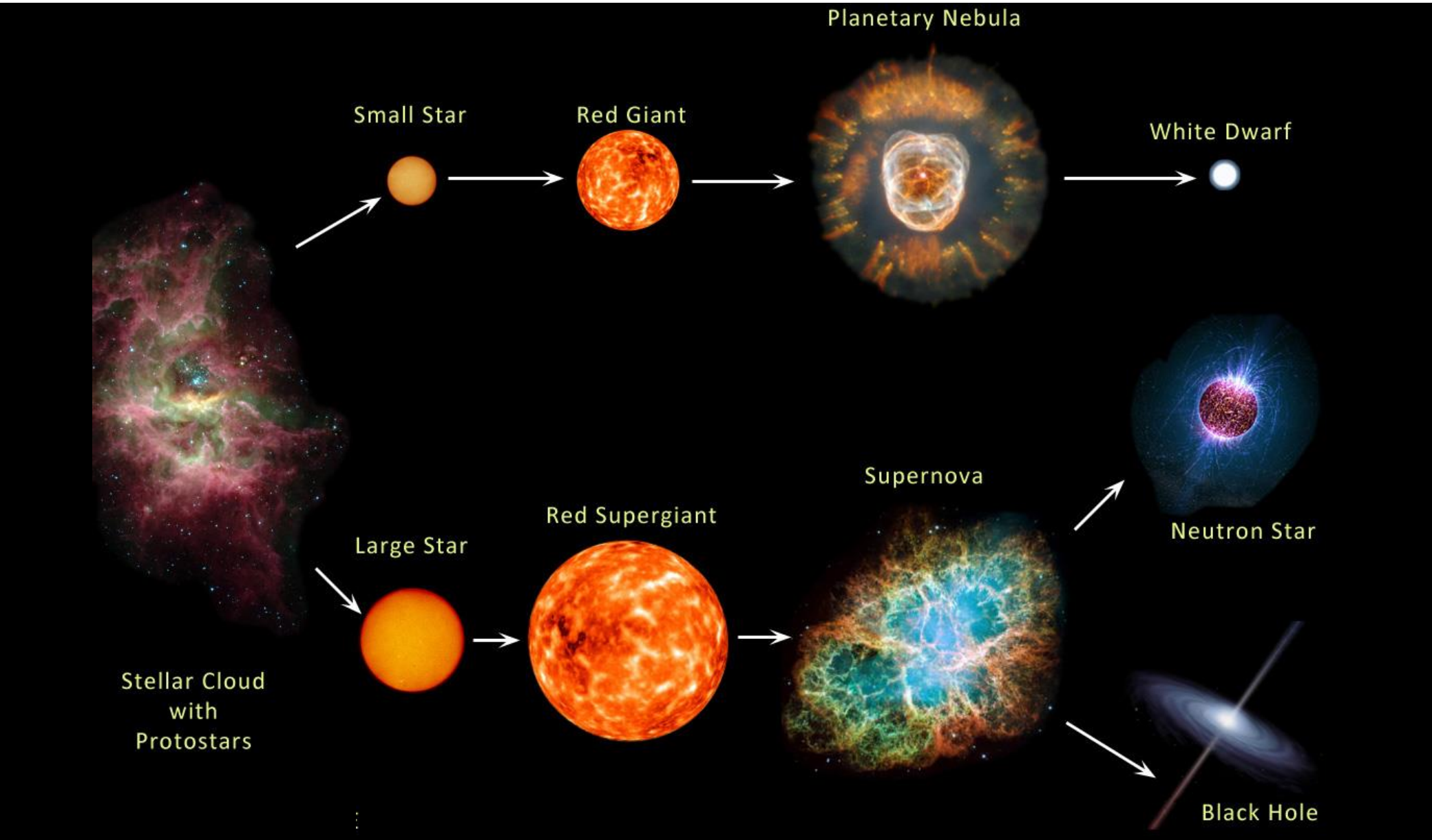
Finkelstein (1958) identified Schwarzschild surface as an event horizon

Discovery of pulsars (1967) and identification as neutron stars (1969)



Evolution of stars

Compact objects are the product of stellar evolution: white dwarfs, neutron stars, and black holes



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

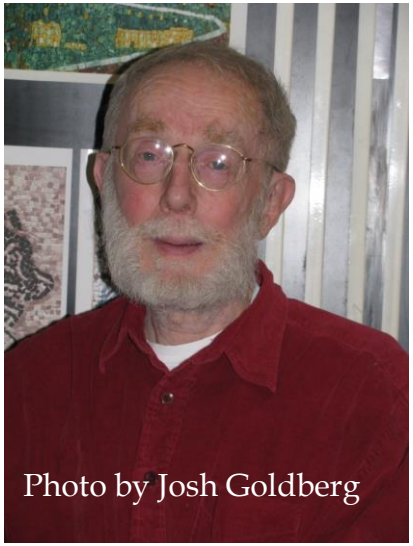


Photo by Josh Goldberg

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

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

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.

Intermezzo

Geometry

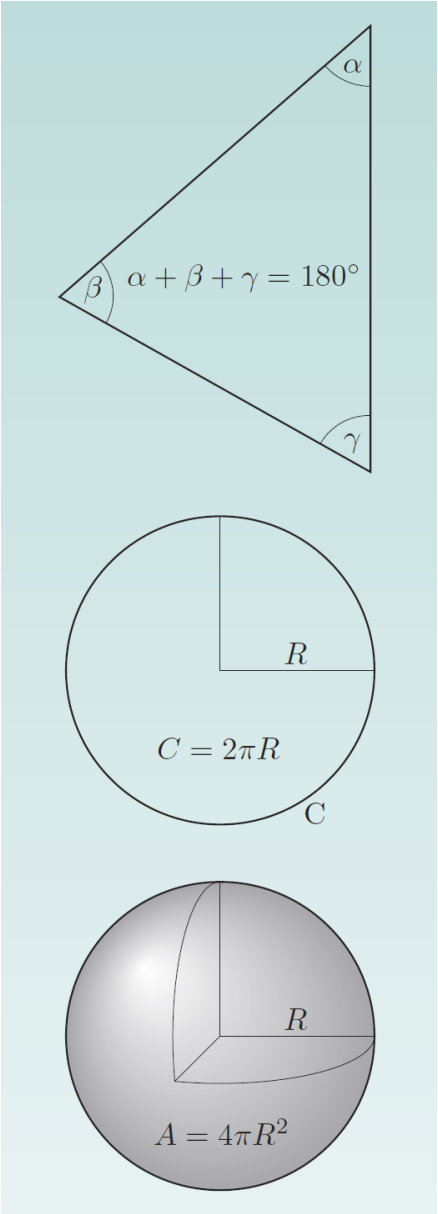
Geometry is the study of shapes and spatial relations

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. They defined *differential geometry*

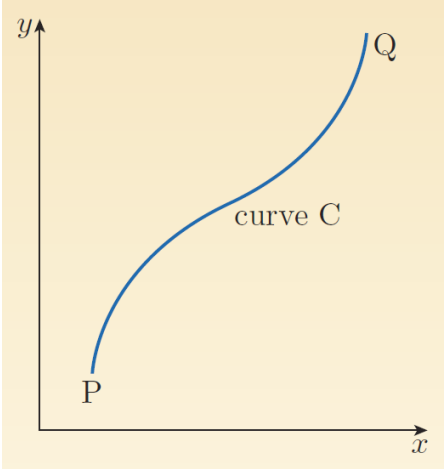
Determining the geometric properties of the space (or spacetime) is an <u>experimental</u> enterprise. It is not the subject of pure mathematics



Differential geometry and the line element

Line element is the central element of any geometry

Example: length of a curve in Euclidean 2D plane



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

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)*

<u>Example</u>: the function $y = x^2$ gives $x(u) = u,\, y(u) = u^2$

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

<u>One has</u>

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

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

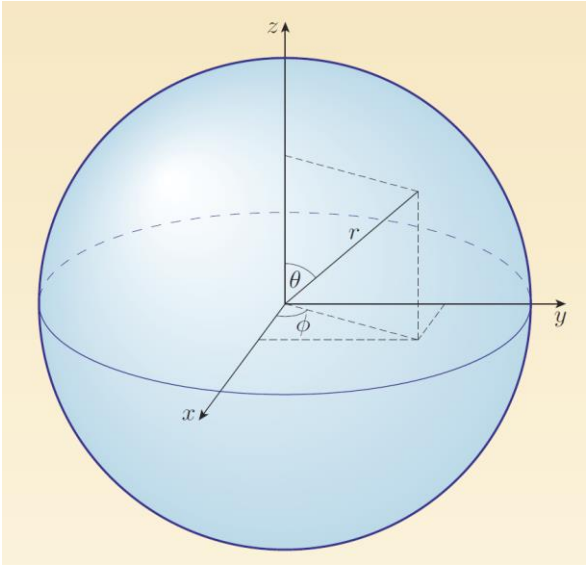
$$L_{\mathrm{C}}(\mathrm{P},\mathrm{Q}) = \int_{\mathrm{P}}^{\mathrm{Q}} \mathrm{d}l \Rightarrow L_{\mathrm{C}}(\mathrm{P},\mathrm{Q}) = \int_{\mathrm{P}}^{\mathrm{Q}} \mathrm{d}l = \int_{u_{\mathrm{P}}}^{u_{\mathrm{Q}}} \left(\left(\frac{\mathrm{d}x}{\mathrm{d}u}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}u}\right)^2\right)^{1/2}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

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

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

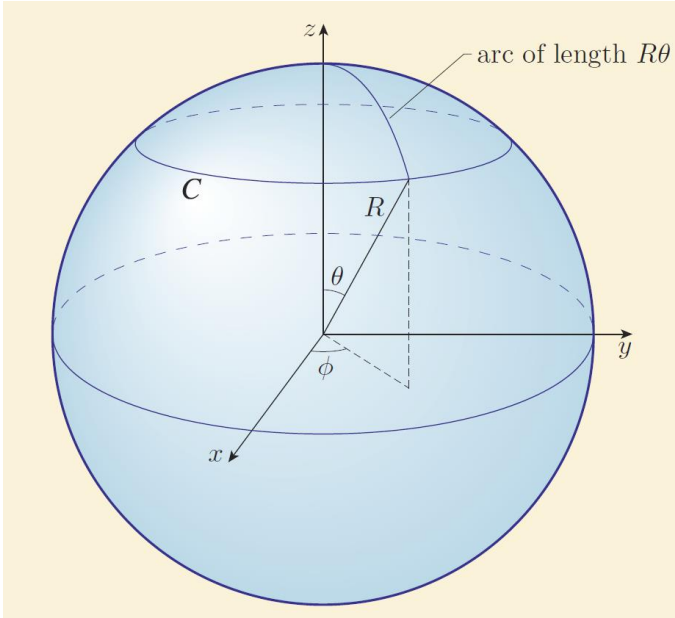
Curved spaces

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



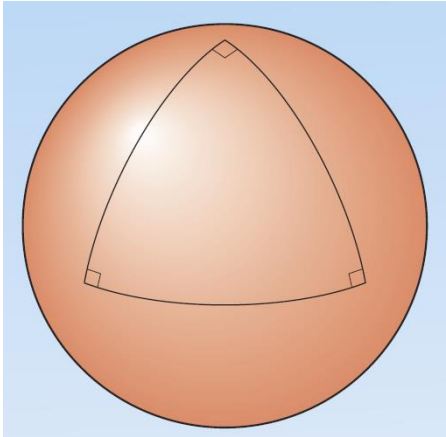
<u>Example</u>: calculate the circumference of circle *C*

<u>Answer</u>: 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

SRT derived from Minkowski metric of spacetime

SRT derived from Minkowski metric of spacetime

For Cartesian coordinates ST has global metric

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Line element $ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2$

Line element represents the time elapsed between two events for an observer O1 at rest with respect to these events, $ds^2 = -c^2d\tau^2$

For an observer O2, moving with respect to O2 at a constant velocity *v*, the two events occur at a time difference *dt* and take place at two different positions

$$c^2d\tau^2 = c^2dt^2 - dx^2 - dy^2 - dz^2 \quad \Rightarrow \quad d\tau = \pm\sqrt{1-\left(\frac{v}{c}\right)^2}dt \quad \rightarrow \quad d\tau = \frac{dt}{\gamma}$$

Lorentz contraction can be found in a similar manner

Which transformation leave the line element invariant?
Question: which functions solve the following equation? Thus $t' = t'(t,x,y,z), x' = x'(t,x,y,z), \ldots$

$$c^2dt^2 - dx^2 - dy^2 - dz^2 = c^2dt'^2 - dx'^2 - dy'^2 - dz'^2$$

Answer: displacements, rotations and Lorentz transformations. For example

$$\left.\begin{aligned} cdt' &= \gamma\left(cdt - \left(\tfrac{v}{c}\right)dx\right) \\ dx' &= \gamma(dx - vdt) \\ dy' &= dy \\ dz' &= dz, \end{aligned}\right\} \rightarrow \begin{pmatrix} dx^{0'} \\ dx^{1'} \\ dx^{2'} \\ dx^{3'} \end{pmatrix} = \begin{pmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} \rightarrow dx^{\mu'} = \Lambda^{\mu'}{}_{\nu}dx^{\nu}$$

See also “The path to Special Relativity”, Gideon Koekoek et al., arXiv:2109.11925

Metric perturbations and gravitational waves

General Relativity

Metric is determined by the energy momentum tensor

Spacetime is not flat and we can write the line element as $ds^2 = g_{\alpha\beta} dx^\alpha dx^\beta$

In local Lorentz frame at $\wp$, we have $g_{\alpha\beta}(\wp) = \eta_{\alpha\beta}$ and $g_{\alpha\beta,\gamma}(\wp) = 0$ with $\eta_{\alpha\beta} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

A freely falling particle always along a geodesic $\boxed{\frac{d^2 x^\mu}{ds^2} + \Gamma^\mu{}_{\alpha\beta} \frac{dx^\alpha}{ds} \frac{dx^\beta}{ds} = 0}$

Christoffel symbols $\Gamma^\mu{}_{\alpha\beta} = \frac{1}{2} g^{\gamma\mu} \left(g_{\gamma\alpha,\beta} + g_{\gamma\beta,\alpha} - g_{\alpha\beta,\gamma} \right)$

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

Riemann tensor tensor $R^\alpha{}_{\beta\mu\nu} = \frac{1}{2} g^{\alpha\sigma} \left(g_{\sigma\nu,\beta\mu} - g_{\sigma\mu,\beta\nu} + g_{\beta\mu,\sigma\nu} - g_{\beta\nu,\sigma\mu} \right)$

What generates curvature of spacetime?

General Relativity to the rescue …

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

John A. Wheeler: “spacetime tells matter how to move; matter tells spacetime how to curve”

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

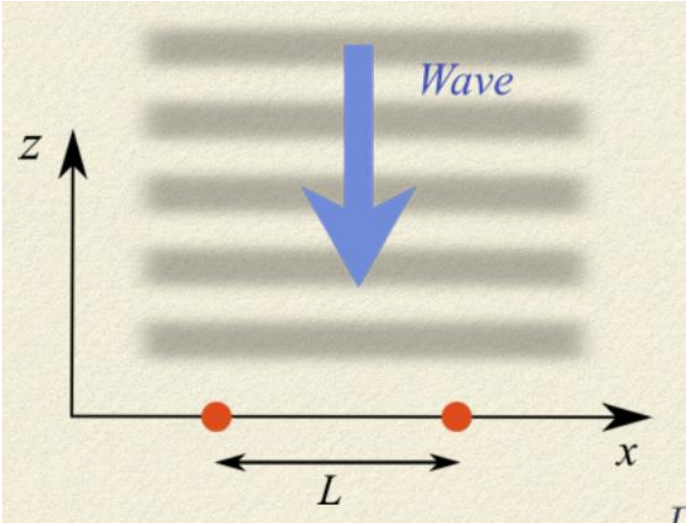
General solution for a wave traveling along the *z*-axis is $\epsilon_{\alpha\beta} e^{-ik_\rho x^\rho} = \left(h_+ \epsilon^+_{\alpha\beta} + h_\times \epsilon^\times_{\alpha\beta}\right) e^{-ik_\rho x^\rho}$

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

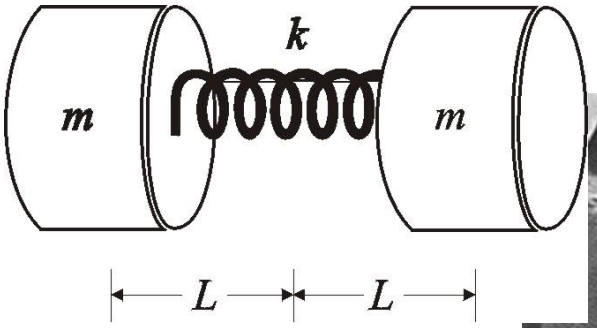
End of intermezzo

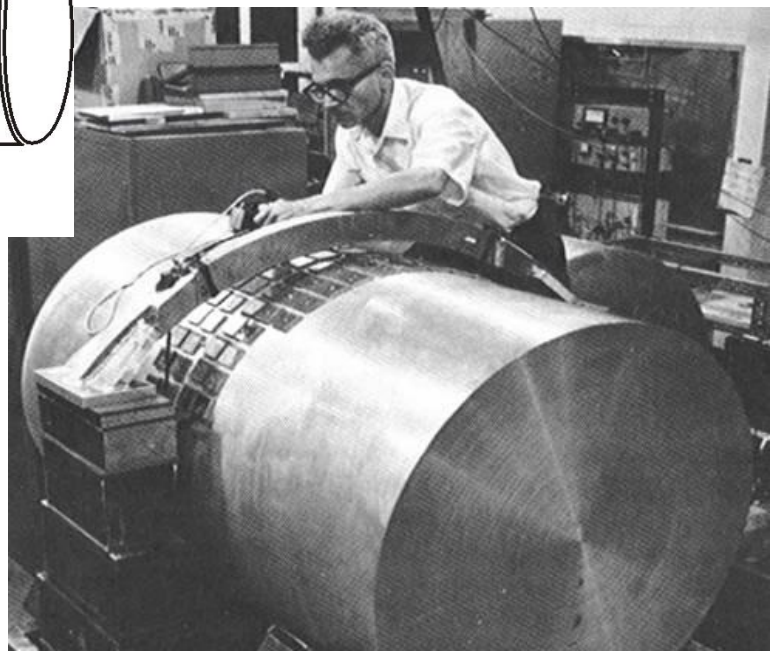
Weber bars

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



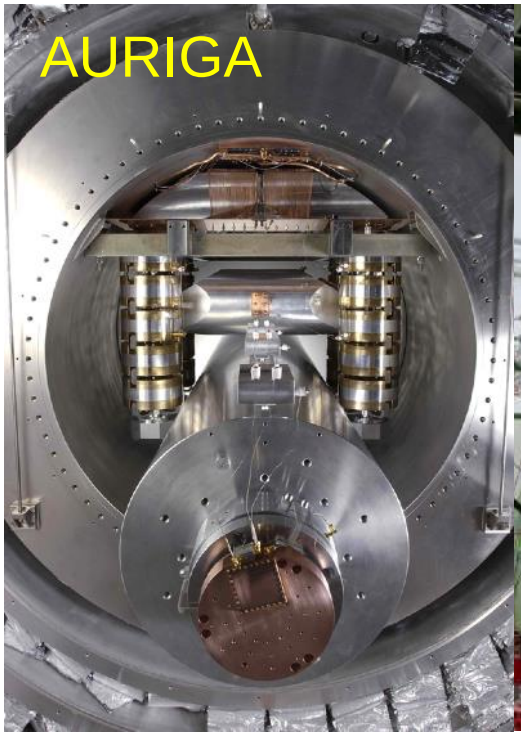


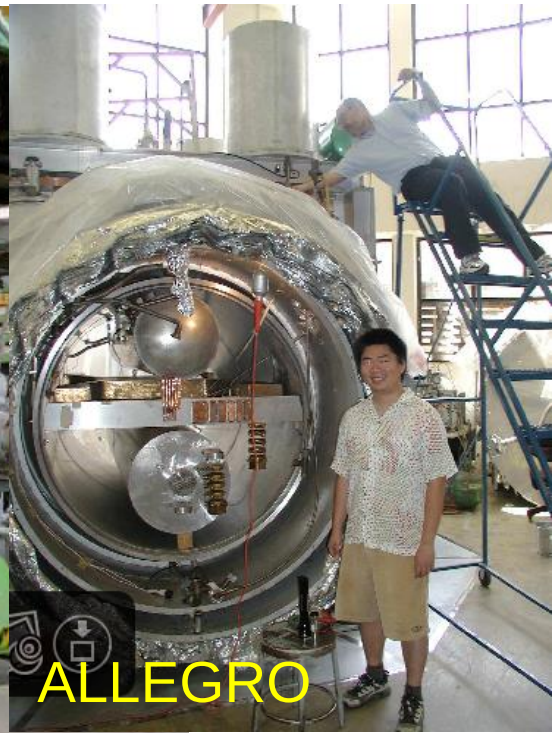
Resonant bar detectors

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(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

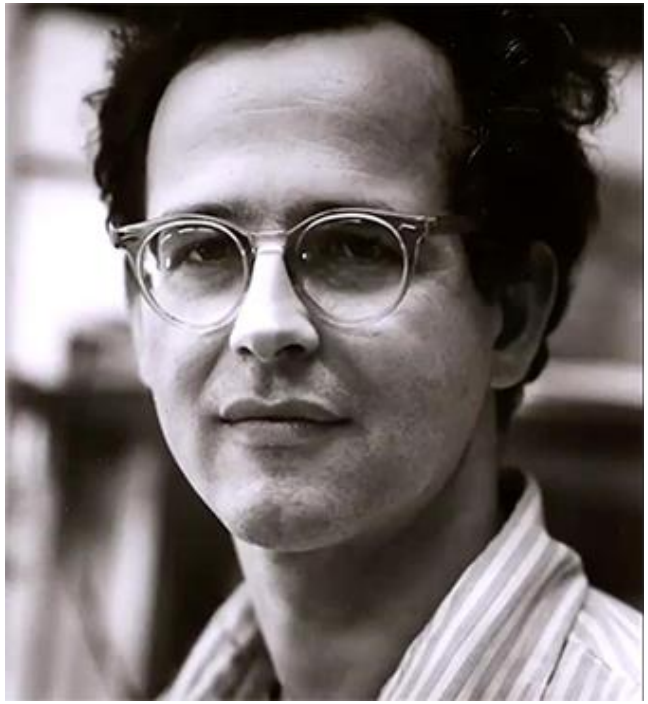
In the early ‘60’s, he spent two years working with Bob Dicke at Princeton on gravity experiments

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



Gravitational waves: a 50 year quest

GW research started with Joseph Weber in the late 1960s with the use of resonant bars

GW resonant bar antenna's

- Weber published various detections
  - *"Gravitational radiation", Phys. Rev. Lett.* ***18,*** *498 (1967)*
  - *"Gravitational-wave-detector events", Phys. Rev. Lett.* ***20****, 1307 (1968)*
  - *"Evidence for discovery of gravitational radiation", Phys. Rev. Lett.* ***22,*** *132 (1969)*
  - *"Gravitational Radiation Experiments", Phys. Rev. Lett.* ***24****, 276 (1970)*
  - *"Anisotropy and Polarization in the Gravitational-Radiation Experiments", Phys. Rev. Lett.* ***25****, 180 (1970)*
  - *"New Gravitational Radiation Experiments", Phys. Rev. Lett.* ***31****, 779 (1973)*
- Discredited
  - IBM, Levine and Garwin (1973)
  - Bell Labs, Tyson (1973)
- Room-temperature and cryogenic bars
  - RT12: Russia, US, UK, Japan, Germany, Italy, China, France
  - CT06: Stanford, LSU, UK, Rome, Regina, Legnaro
  - Triple (94%) and fourfold operations (57%): 2005 - 2007
  - Plans: TIGA, GRAVITON, (mini)GRAIL and SFERA
- Further claims
  - SN1987A: Rome, Maryland with neutrino's
  - P. Astone et al., Class. Quantum Grav. **19** (2002) 5449

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Featured in Physics

Evidence for Discovery of Gravitational Radiation

J. Weber
Phys. Rev. Lett. 22, 1320 – Published 16 June 1969

Physics See Focus story: A Fleeting Detection of Gravitational Waves

Article References Citing Articles (214) PDF Export Citation

ABSTRACT

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.

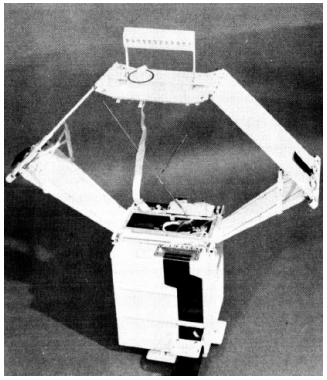
Received 29 April 1969

12. Lunar Surface Gravimeter Experiment

John J. Giganti,[a] J. V. Larson,[a] J. P. Richard,[a] and J. Weber[a†]

Apollo 17 Prelim. Sci. Rept. SP-330

The primary objective of the lunar surface gravimeter (LSG) is to use the Moon as an instrumented antenna (refs. 12-1 to 12-8) to detect gravitational waves predicted by Einstein's general relativity theory. A secondary objective is to measure tidal deformation of the Moon. Einstein's theory describes gravitation as propagating with the speed of light. Gravitational waves carry energy, momentum, and information concerning changes in the configuration of their source. In these respects, such waves are similar to electromagnetic waves; however, electromagnetic waves only interact with electric charges and electric currents. Gravitational waves are predicted to interact with all forms of energy.

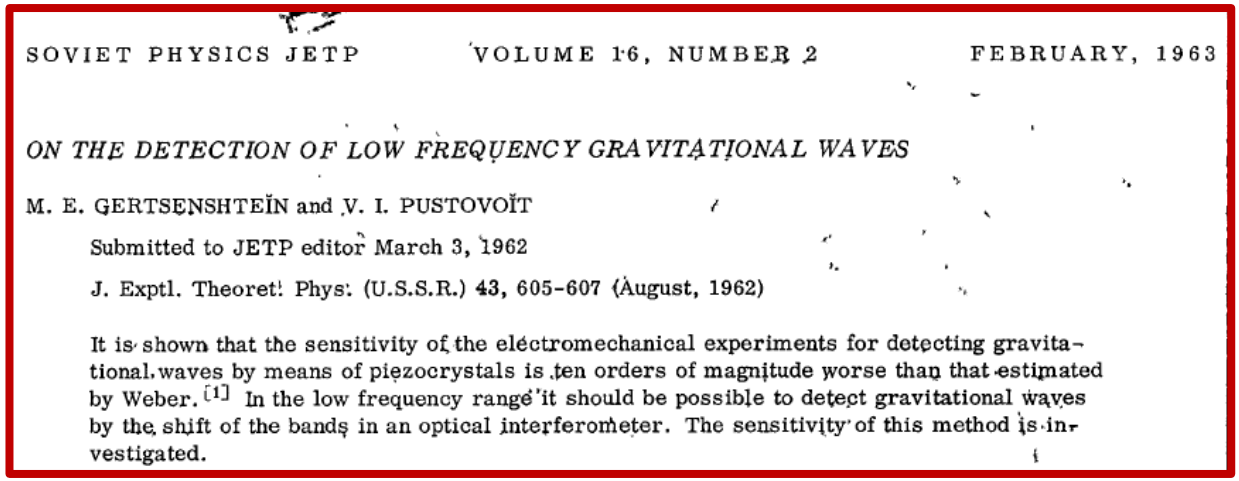


Interferometers as detectors for gravitational waves

Interferometric detectors were first suggested in the early 1960s and the 1970s

Interferometers

- First proposed by Gertsenshtein and Pustovoit (1962)
  - Sov. Phys. – JETP 878 16, 433 (1962) 879
- First built by Forward at Hughes Research Laboratories
  - G. E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. 880 10, 2495 (1971)
- A study of the noise and performance of such detectors
  - R. Weiss, Electromagnetically coupled broadband gravitational antenna, Tech. Rep. (MIT, 1972) Quarterly report of the Research Laboratory for Electronics. https://dcc.ligo.org/LIGO-P720002/public
- First interferometer studies
  - MPG Garching: early 1980s: a 3 m and later a 30 m ITF
  - UK: 1 m and later 10 m ITF with FP cavities
  - Caltech: 40 m ITF; later Japan
- LIGO
  - Caltech and MIT agreement 1984
  - Congress funding in 1991 for M$ 23
  - NSF funding in 1994 for M$ 395
- Virgo
  - Approved CNRS (1993) and INFN (1994)
  - Nikhef joined in 2007



SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

The first detection

LIGO: Laser Interferometer Gravitational Observatory

LIGO realized two interferometers with 4 km long arms in the USA (Livingston LA and Hanford WA)

Binary Neutron Stars (BNS)

We have observed over 2,000 pulsars (NS) in our Milky Way. Thus NS exist and there are probably billions of NS per galaxy. Before GW150914 many of us expected the first GW event would be a BNS

Astronomers discovered 17 binary neutron stars (BNS), *e.g.* Hulse Taylor BNS

J. G. Martinez et al
2017 *ApJL* **851** L29.
doi:10.3847/2041-8213/aa9d87

These systems undergo strong quadrupole-type acceleration

After a certain time, both NS will collide

In the process a black hole may be created

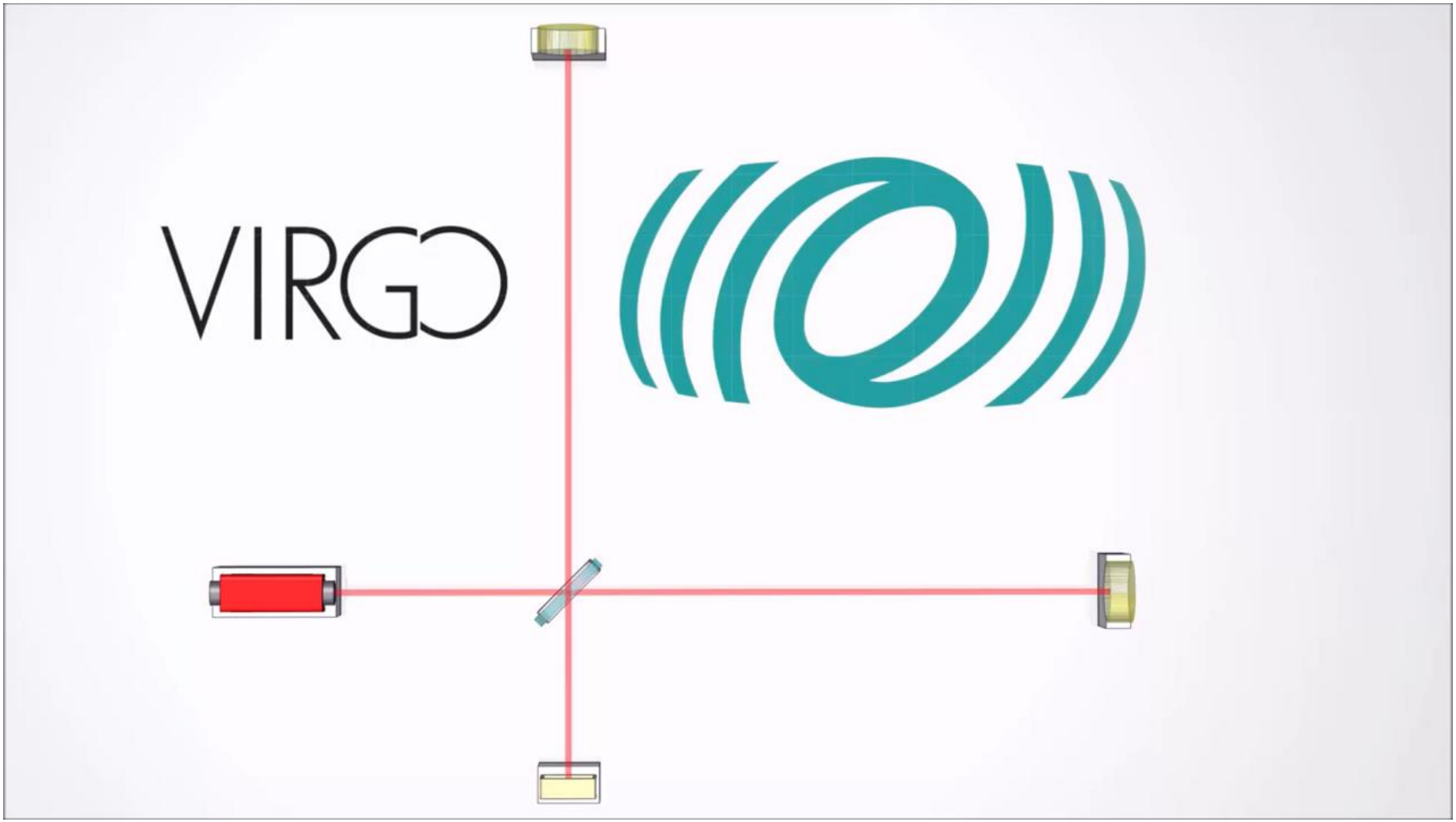
Numerical simulation representing the binary neutron star coalescence and merger which resulted in the gravitational-wave event GW170817 and gamma ray burst GRB170817A

Credits: Numerical Relativity Simulation: T. Dietrich (Max Planck Institute for Gravitational Physics) and the BAM collaboration

Scientific Visualization: T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics)

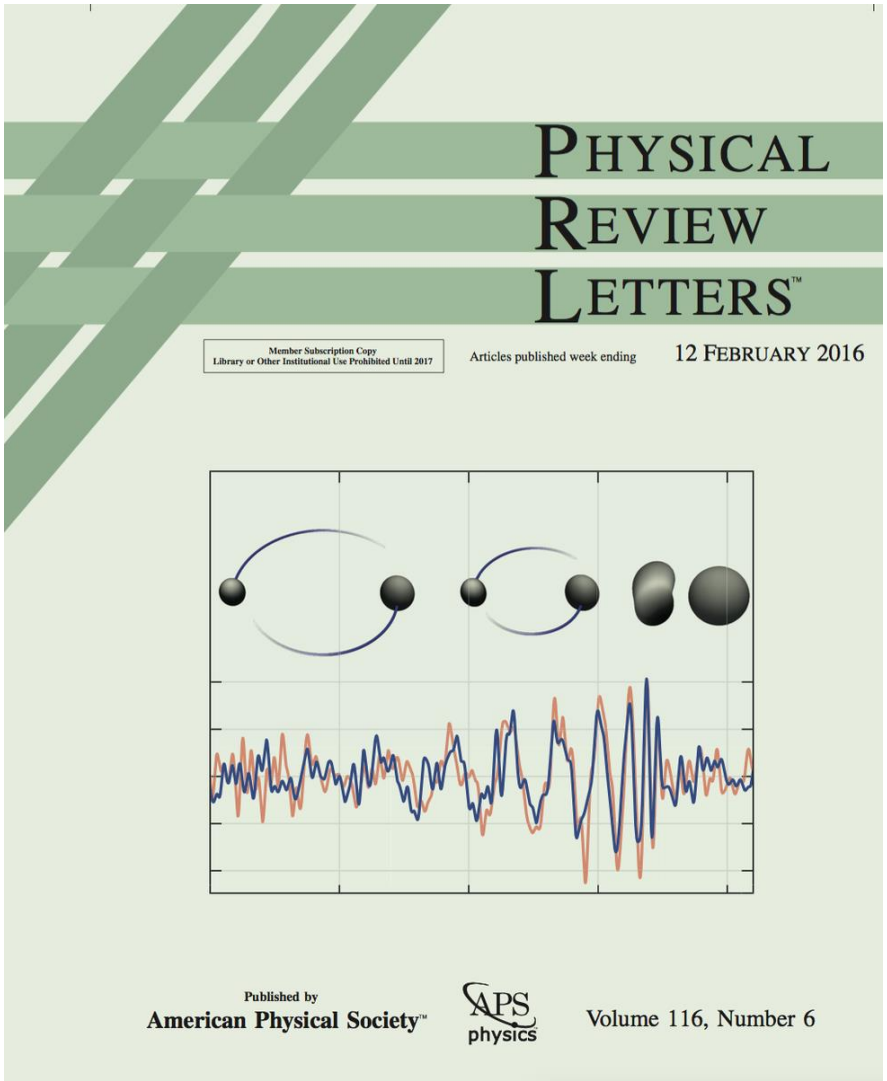
Interferometric gravitational wave detectors

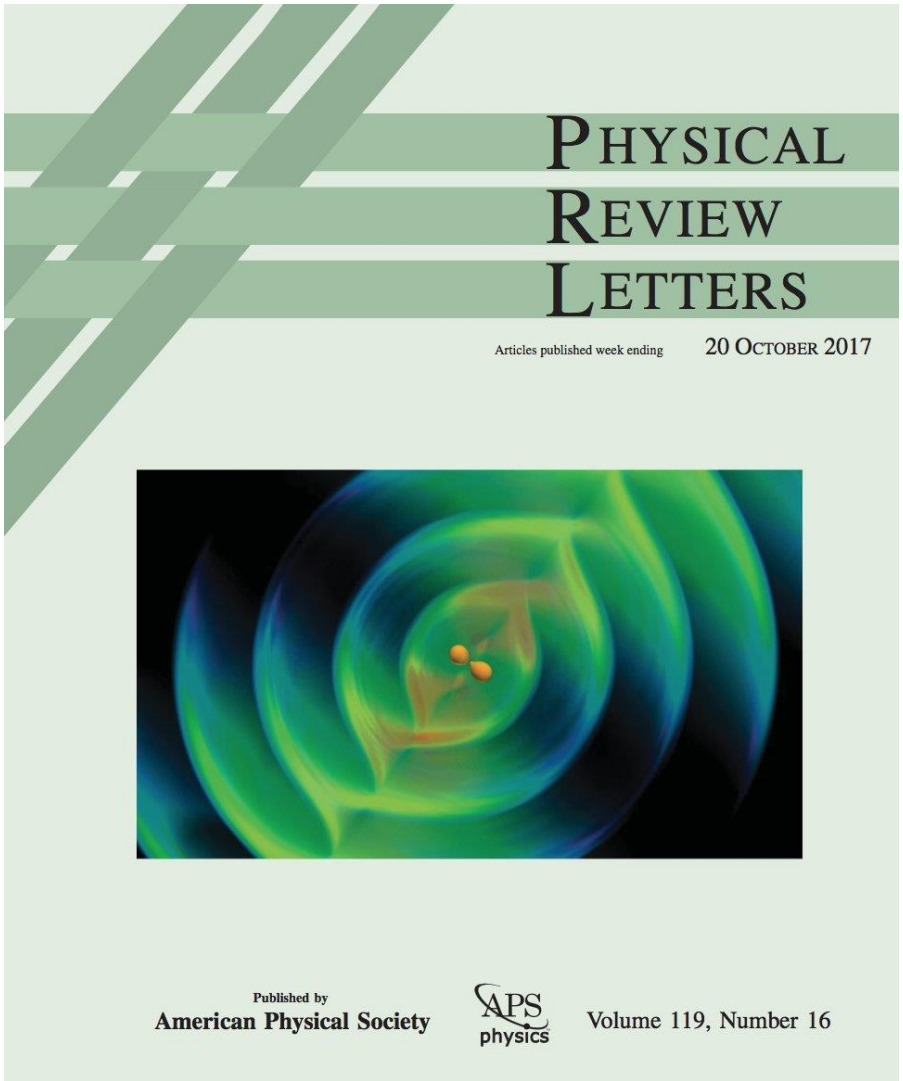
Tiny vibrations in space can now be observed by using the kilometer-scale laser-based interferometers of LIGO and Virgo. This enables an entire new field in science



About ninety detections…so far

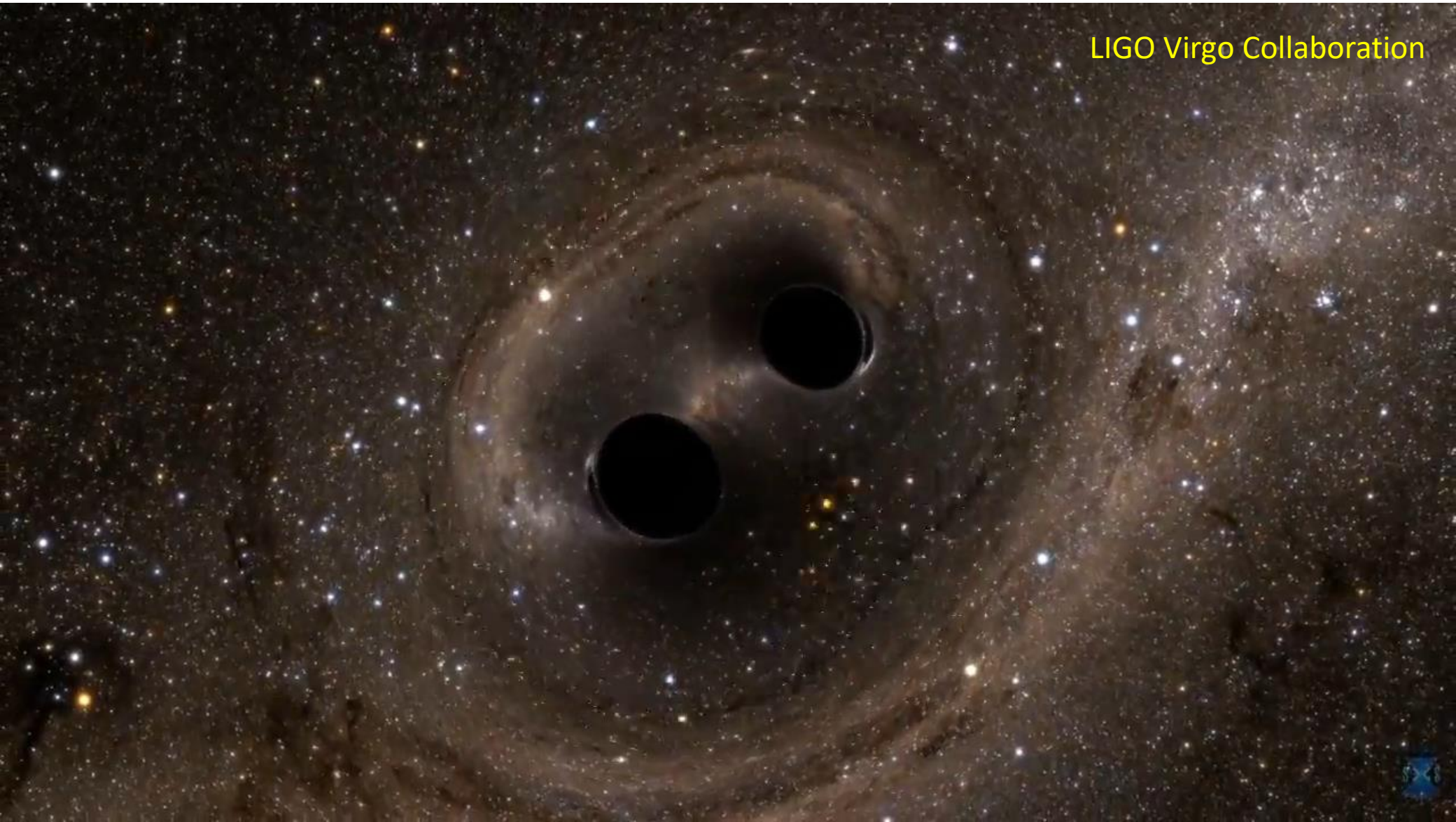
First gravitational wave detection with GW150914 and first binary neutron star GW170817





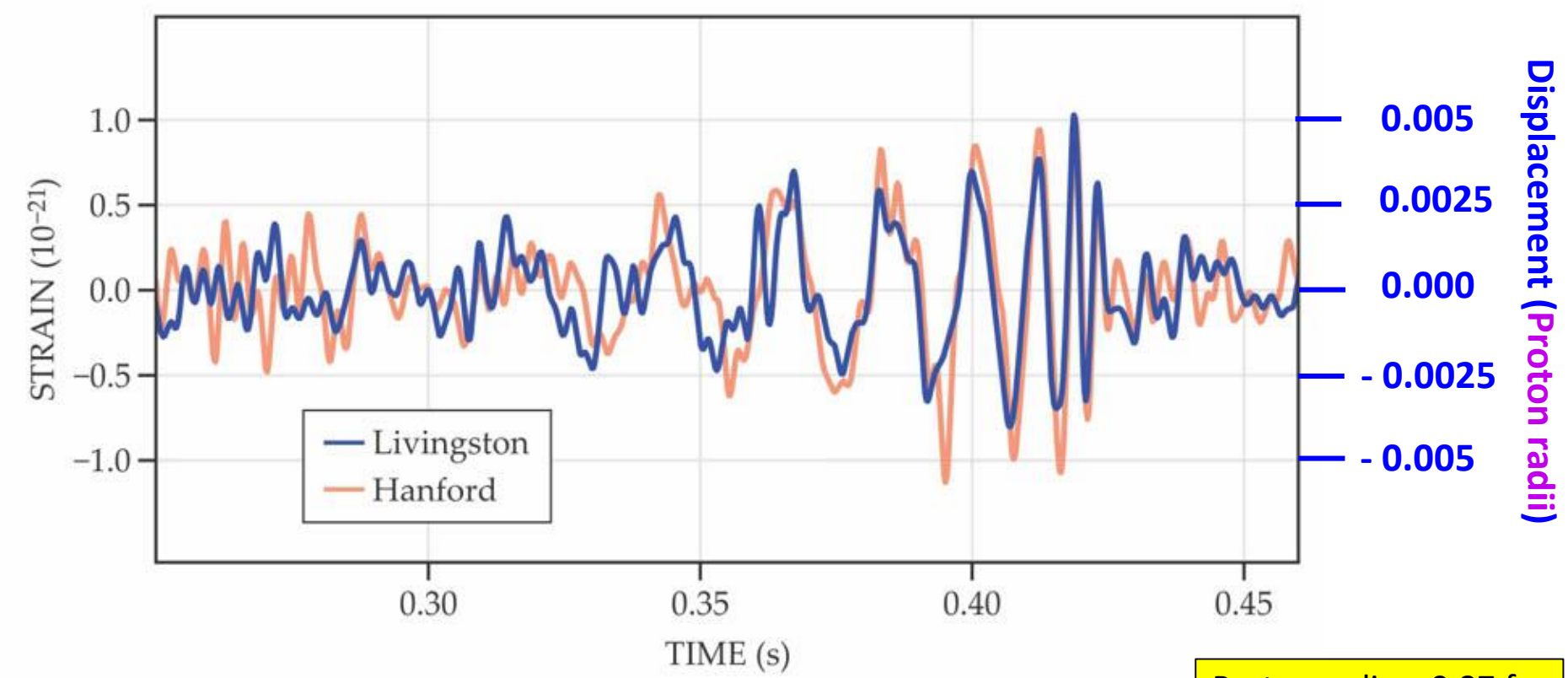
Event GW150914

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



Event GW150914

On September 14th 2015 the gravitational waves generated by a binary black hole merger, located about 1.4 Gly from Earth, crossed the two LIGO detectors displacing their test masses by a small fraction of the radius of a proton



Proton radius=0.87 fm

Measuring intervals must be smaller than 0.01 seconds

Nobel Prize in Physics 2017

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/press.html

KUNGL. VETENSKAPS-AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release: The Nobel Prize in Physics 2017

3 October 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017 with one half to

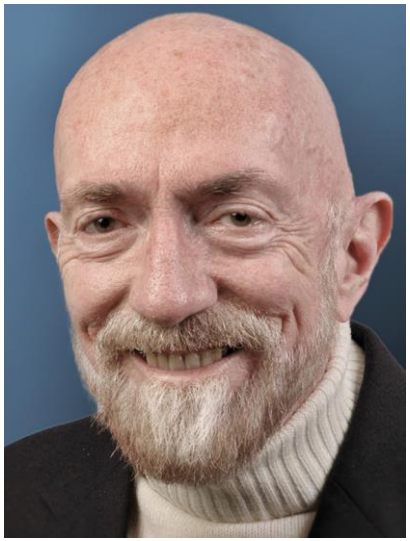
Rainer Weiss
LIGO/VIRGO Collaboration

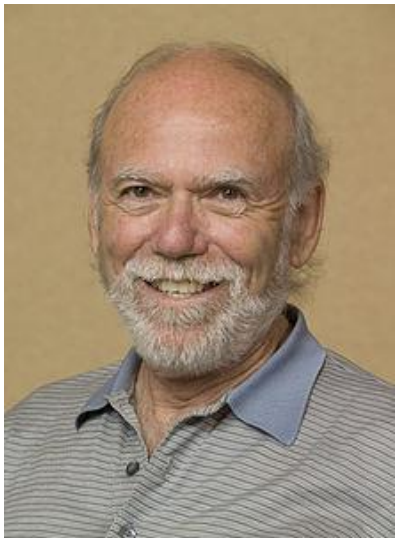
and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

Kip S. Thorne
LIGO/VIRGO Collaboration





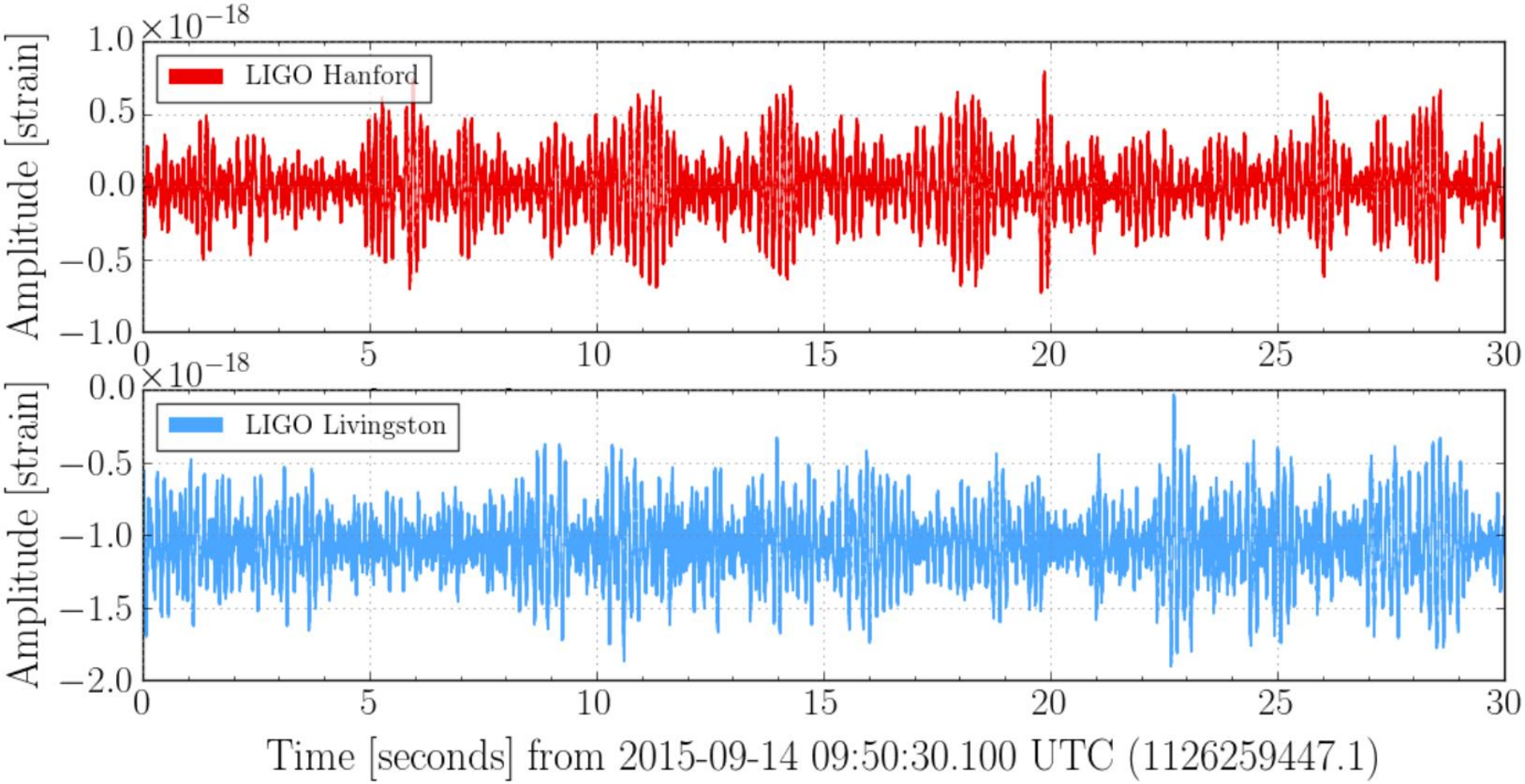
Special thanks to Virgo’s founding fathers

Alain Brillet and Adalberto Giazotto

Intermezzo: let’s have a very basic look at the actual data

Data analysis

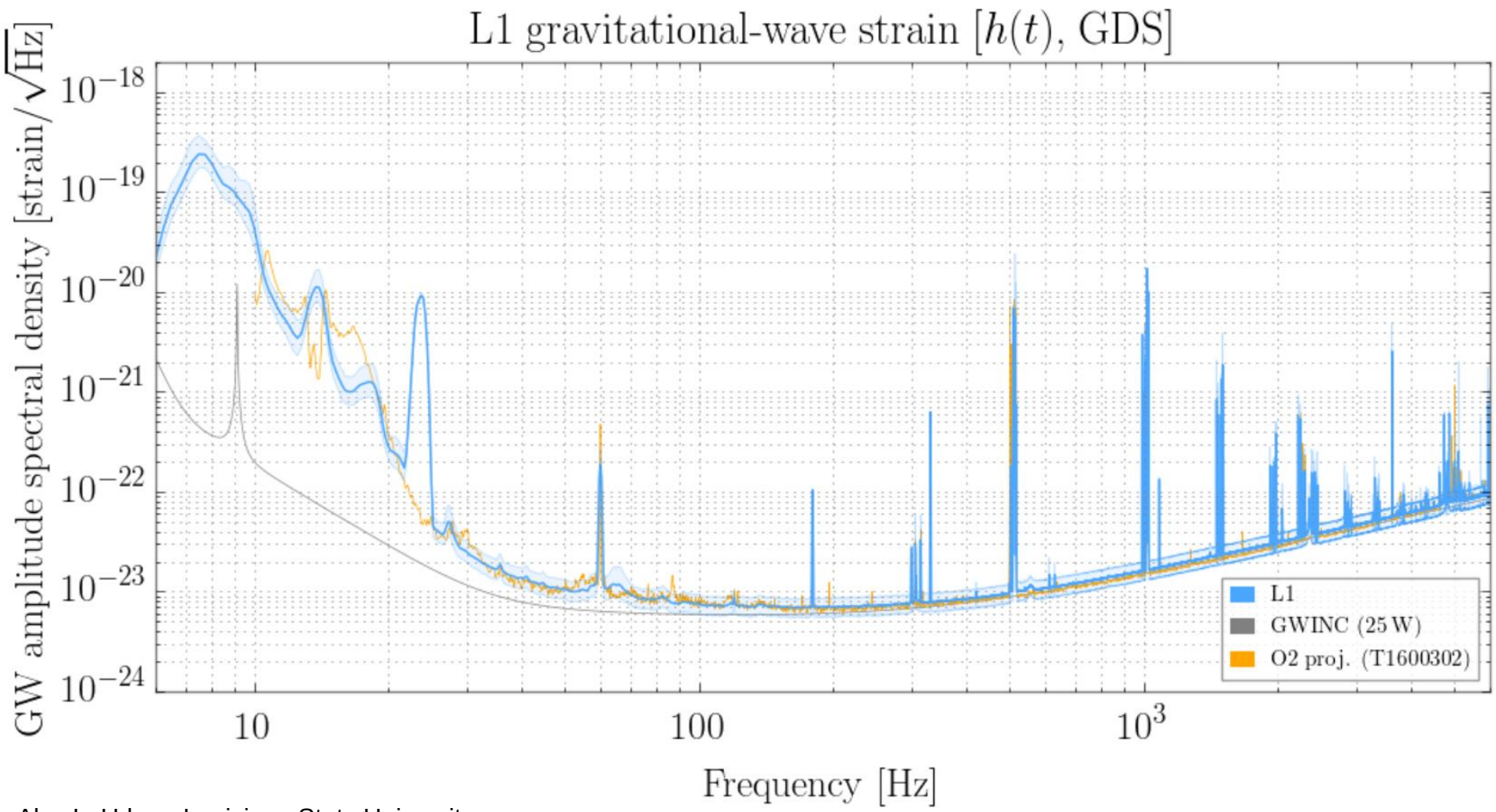
The interferometers produce a raw *h(t)* (so called “hoft”) time series. Note the scale of the amplitudes



Alex L. Urban, Louisiana State University
LIGO, DCC Document Number G1701155

Data analysis

In the frequency domain we have an amplitude spectral density (ASD). We whiten the data (i.e. divide out the median noise curve)



Alex L. Urban, Louisiana State University
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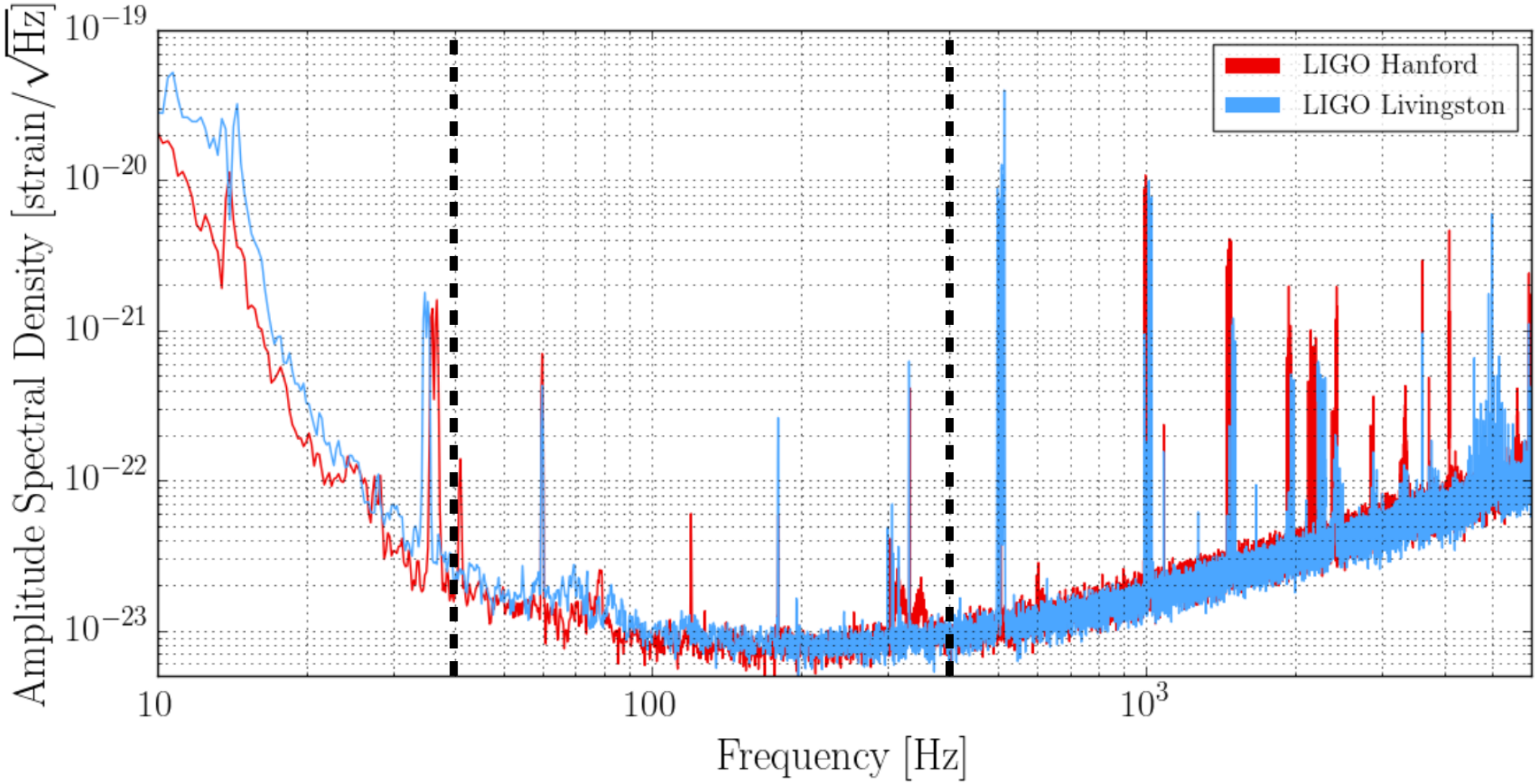
Data analysis

We can get rid of a lot of noise just by restricting where to look: this is called bandpassing



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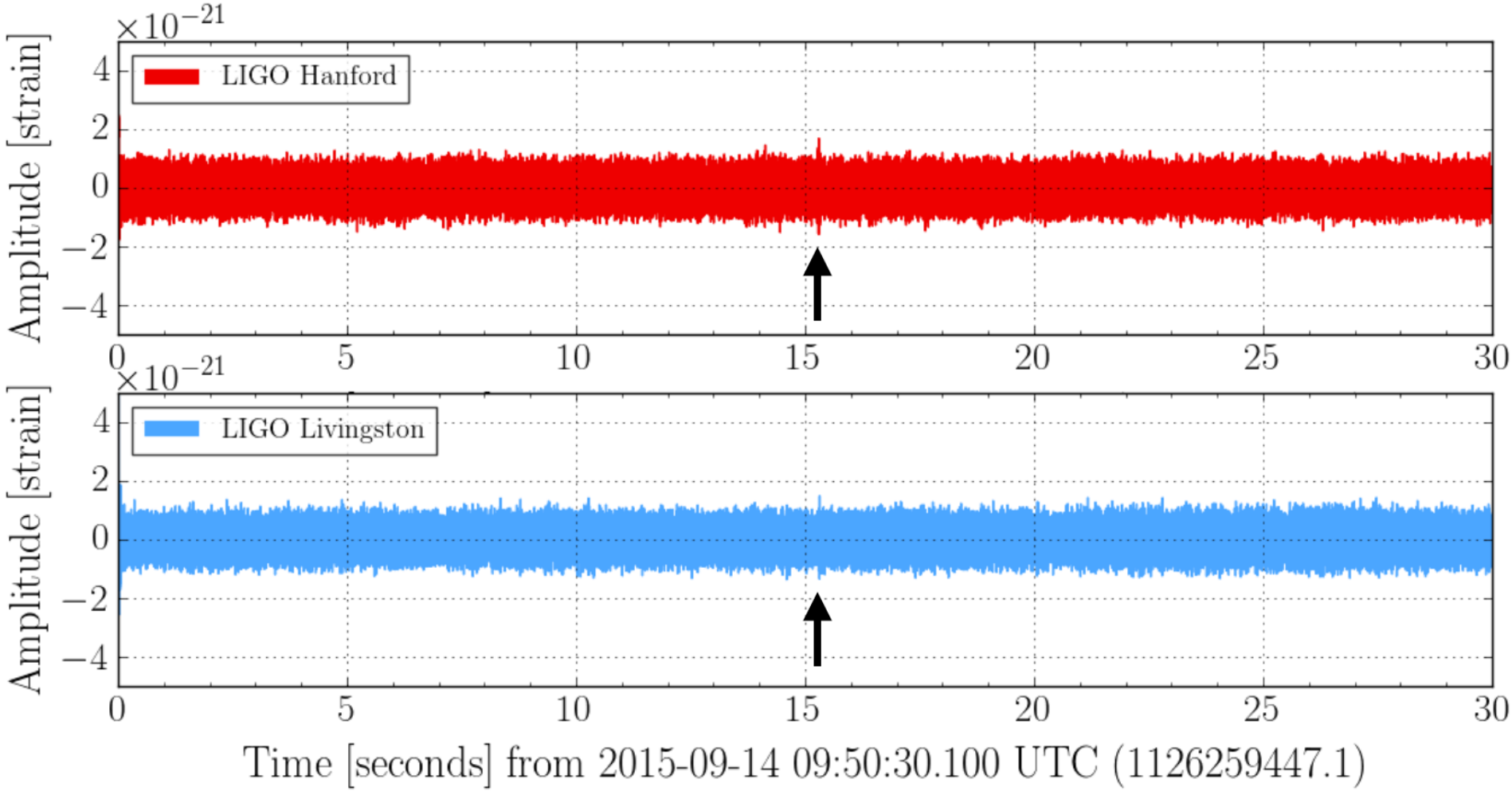
Data analysis

Back in the time domain the bandpassed data look much cleaner. Note the scale of the amplitude. However we observe some spiky-ness. This is indicated by the arrows



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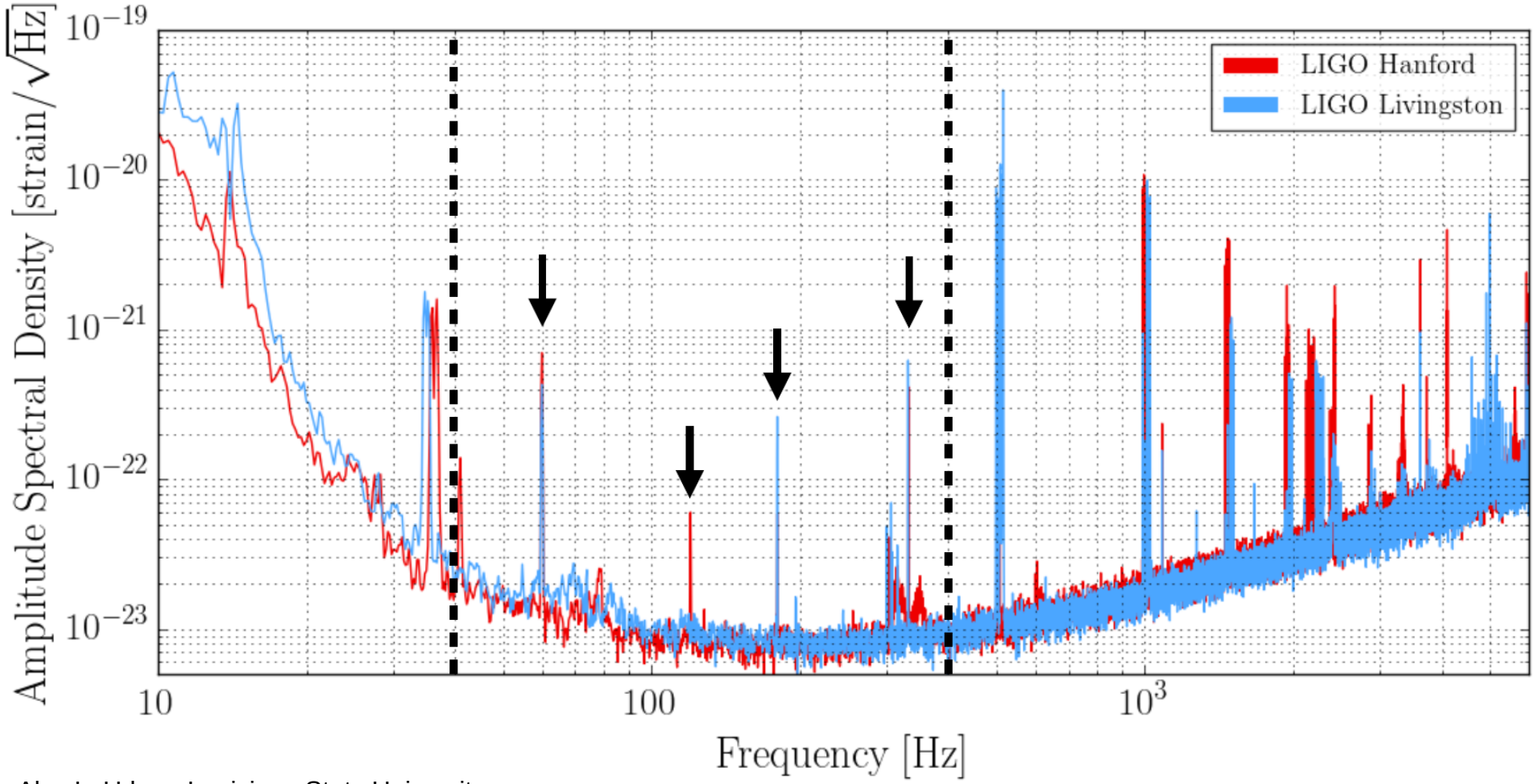
Data analysis

In the frequency domain, we observe some sharp lines. What do you think is the effect of these lines?



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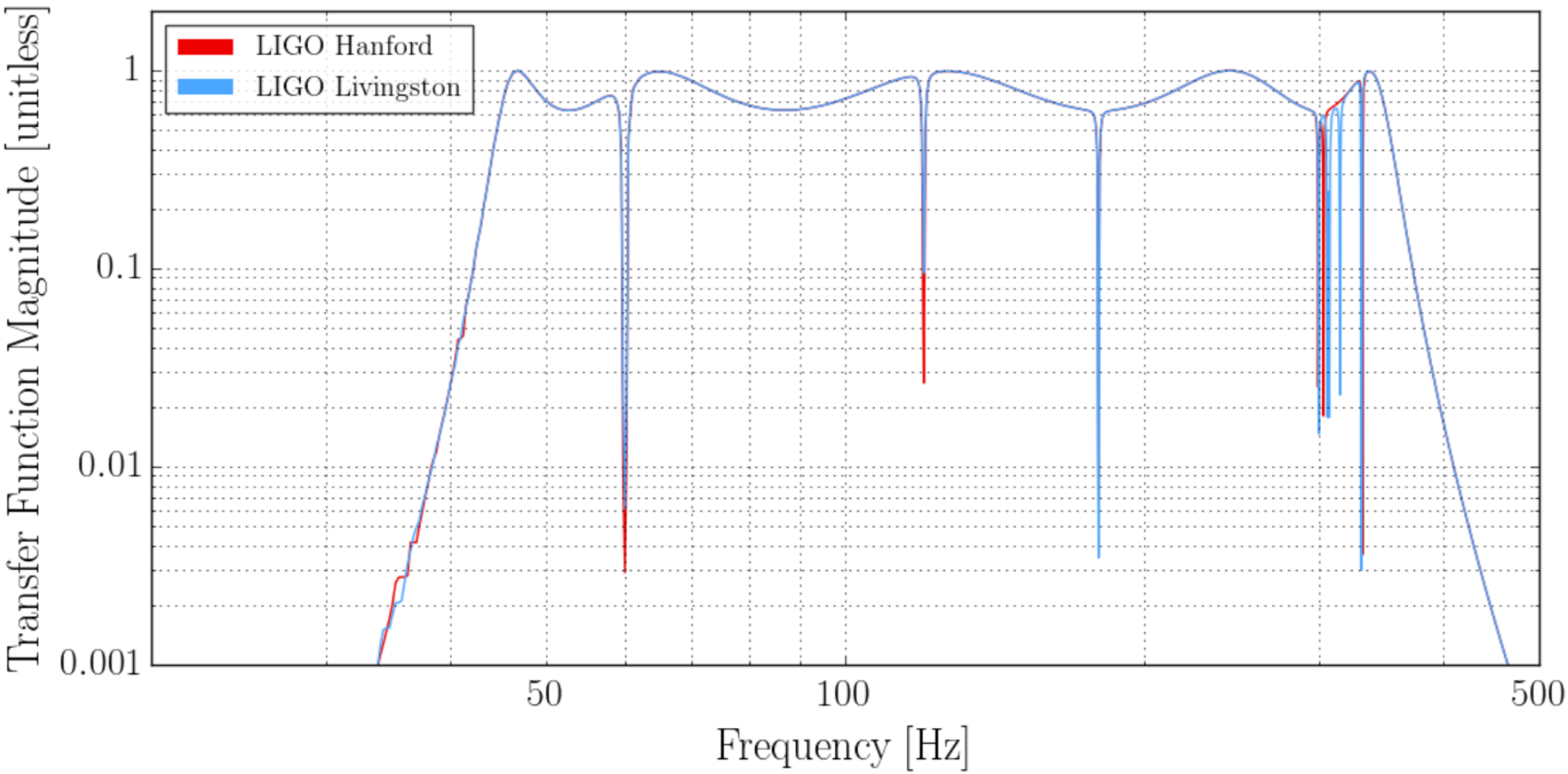
LIGO, DCC Document Number G1701155

Data analysis

The sharp lines are due to instrumentation effects. Let's get rid of them by using the following transfer function



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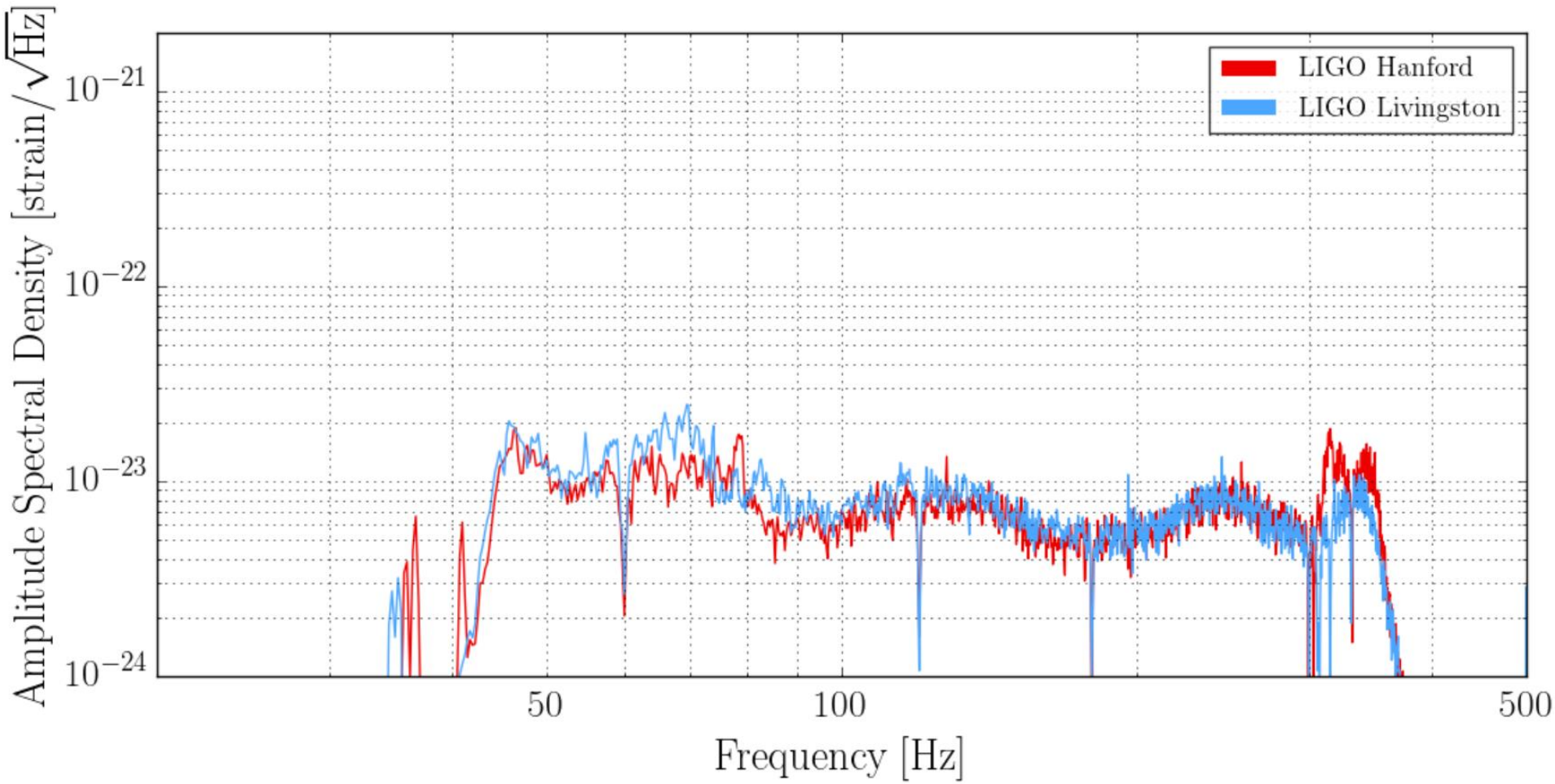
LIGO, DCC Document Number G1701155

Data analysis

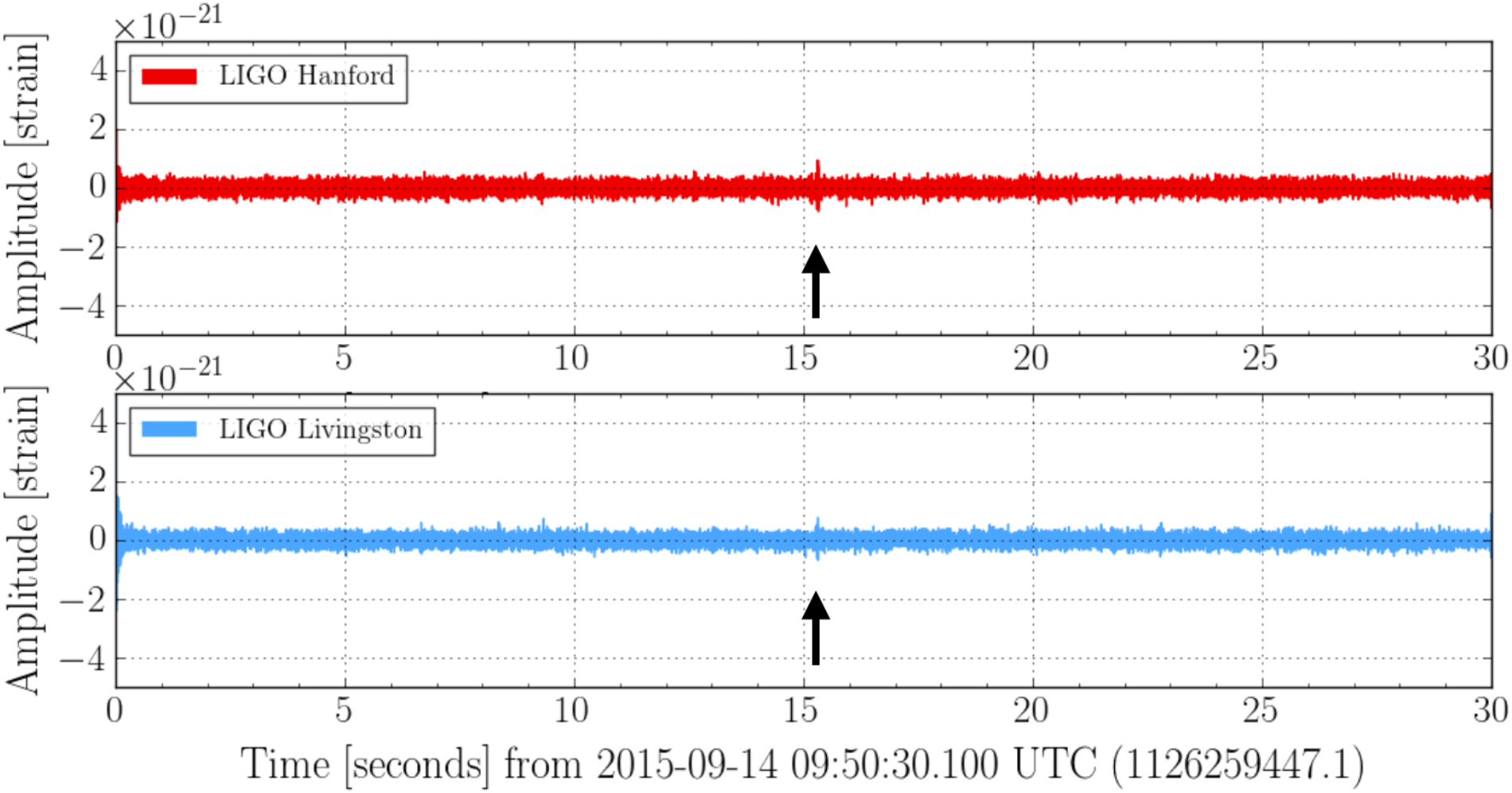
Data in the frequency domain affter applying a collection of notch files and one bandpass filter



Alex L. Urban, Louisiana State University
LIGO, DCC Document Number G1701155

Data analysis

Back in the time domain, the data look much cleaner! But those spikes are still there. Let's zoom in …



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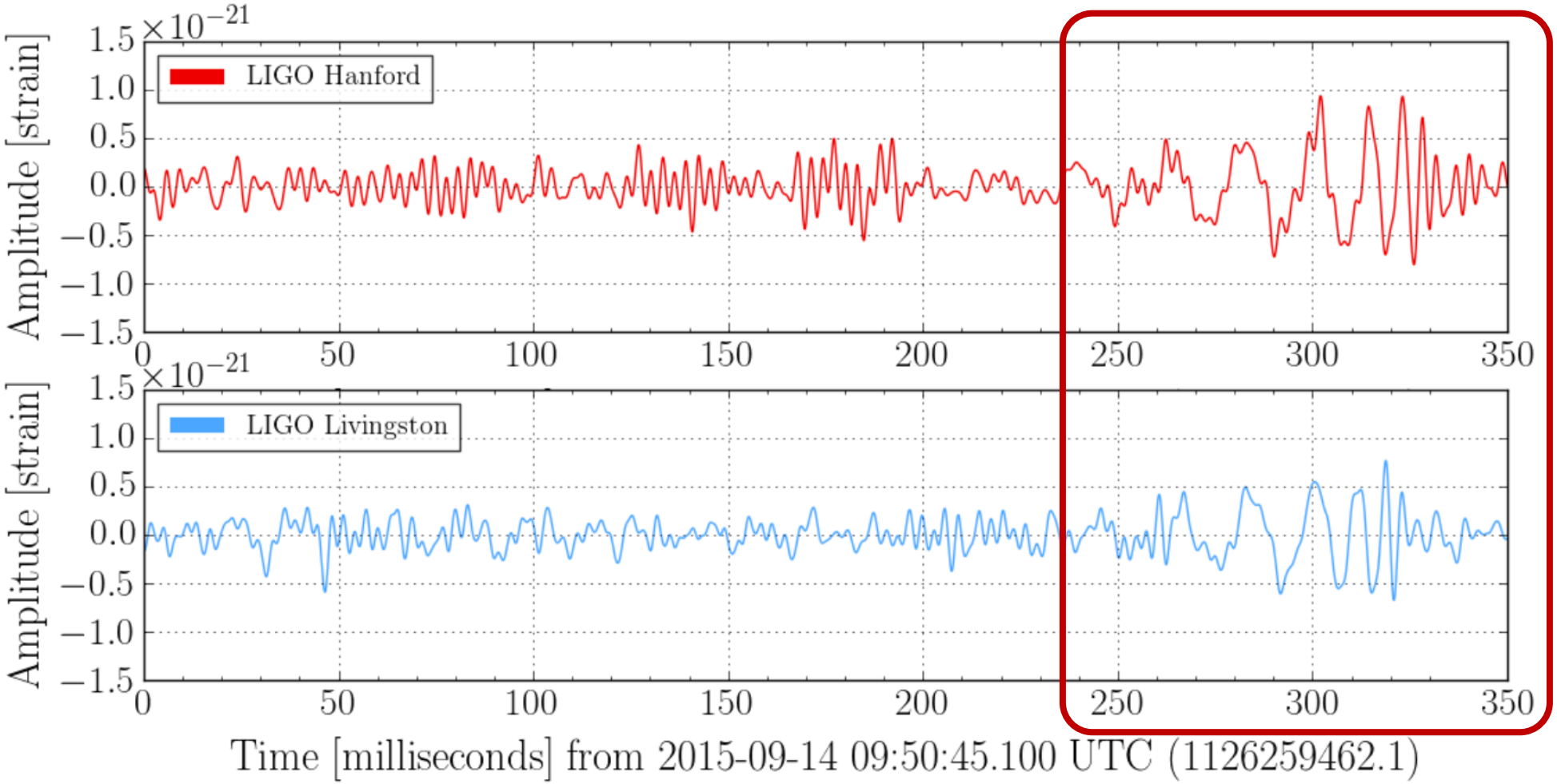
LIGO, DCC Document Number G1701155

Data analysis

After these basic filtering steps we clearly see the first detected gravitational wave event in the raw data streams



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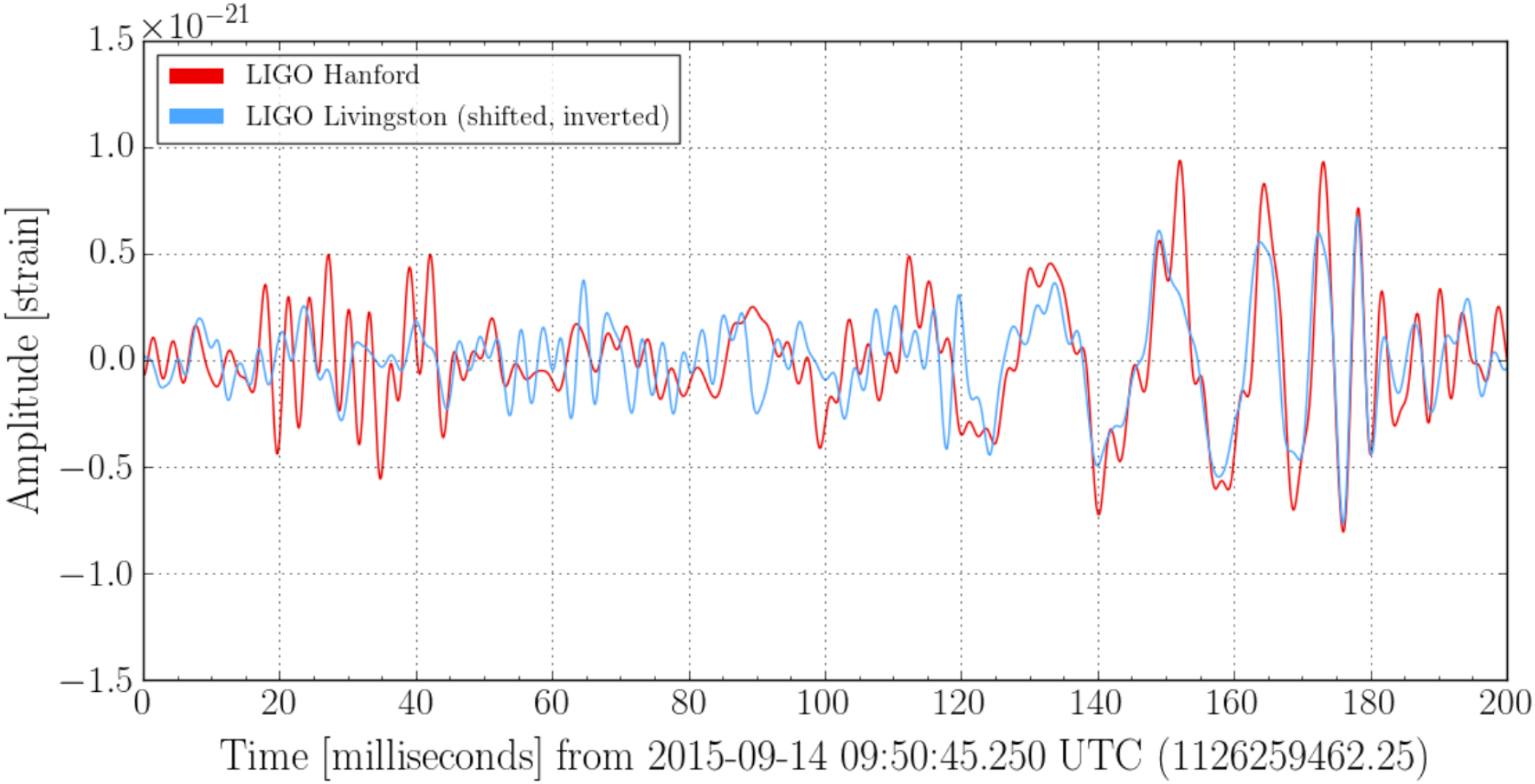
LIGO, DCC Document Number G1701155

Data analysis

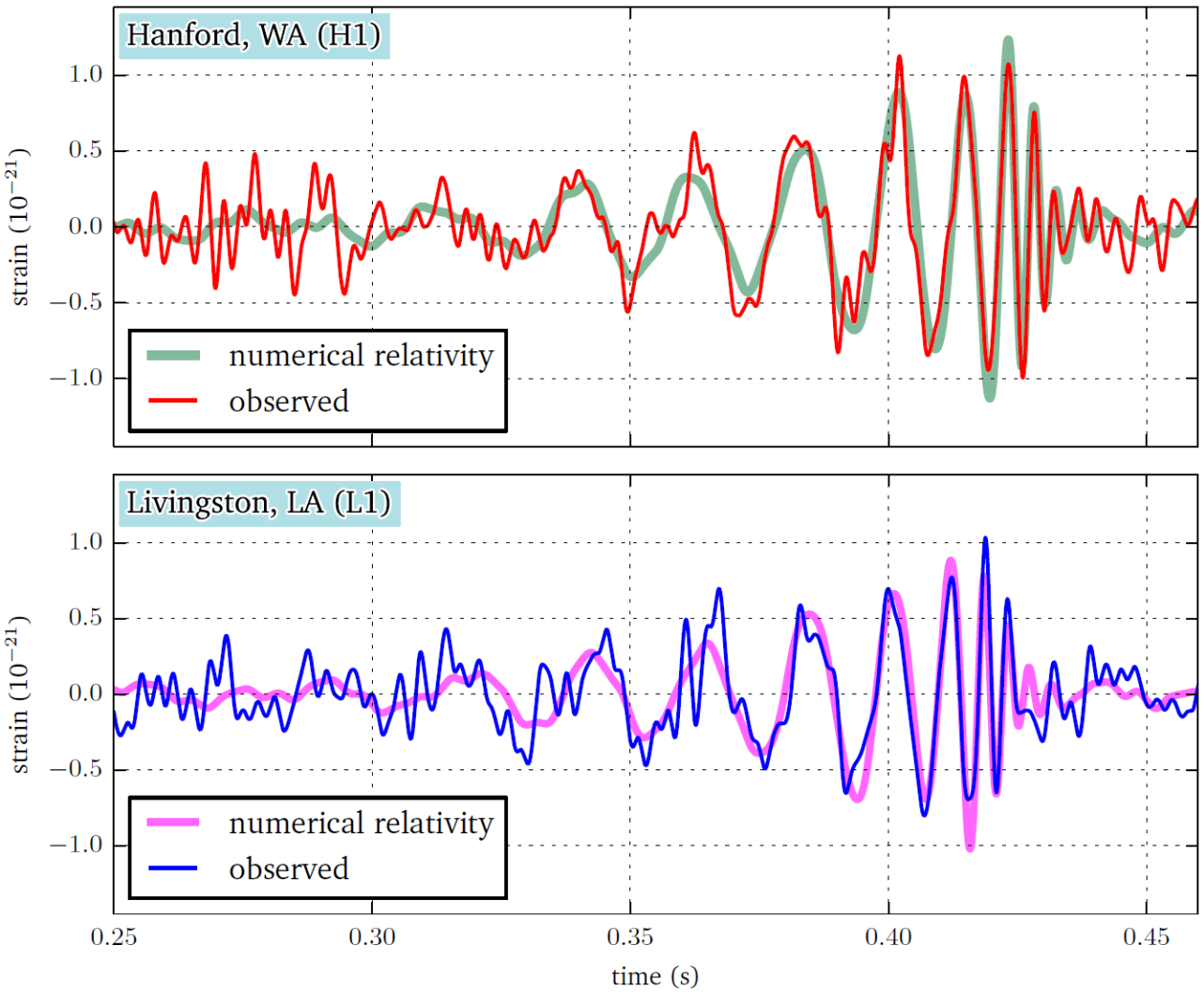
There is a coherent signal in both detector streams at this time



Alex L. Urban, Louisiana State University
LIGO, DCC Document Number G1701155

Data analysis

Data in comparison to results of numerical relativity calculations



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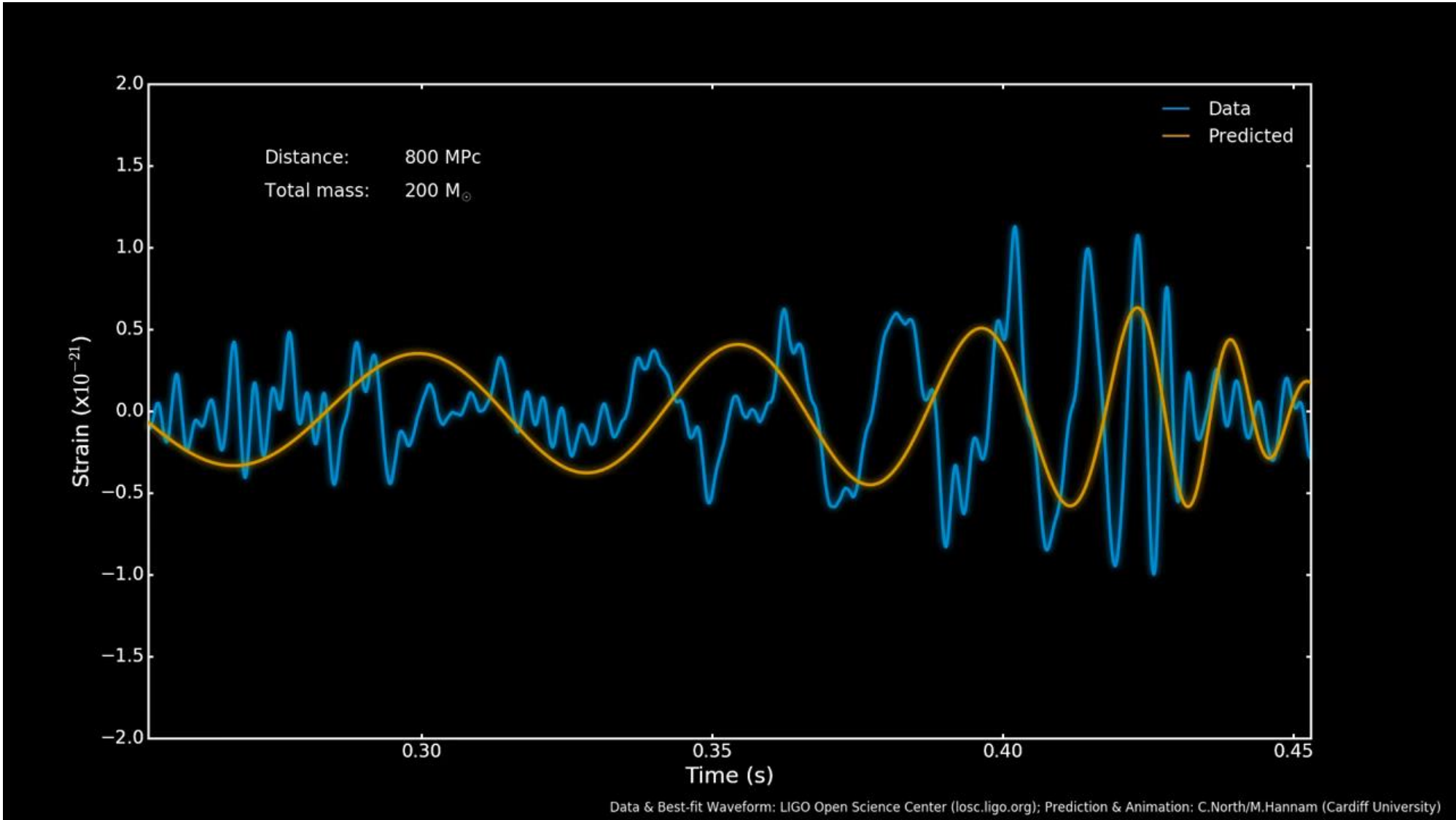
LIGO, DCC Document Number G1701155

Parameter estimation: GW150914

Once a gravitational wave signal has been identified in the our data, the next step is to measure the properties of the system. This is done by comparing the signal to millions of different waveforms predicted by general relativity and seeing which match the data



End of intermezzo

Gravitational wave science

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally, in ways it was never tested before?

Gravity

- Main organizing principle in the Universe
  - Structure formation
- Most important open problems in contemporary science
  - Acceleration of the Universe is attributed to Dark Energy
  - Standard Model of Cosmology features Dark Matter
  - Or does this signal a breakdown of general relativity?

Large world-wide intellectual activity

- Theoretical: combining GR + QFT, cosmology, …
- Experimental: astronomy (CMB, Euclid, LSST), particle physics (LHC), Dark Matter searches (Xenon1T), …

Gravitational waves

- Dynamical part of gravitation, all space is filled with GW
- Ideal information carrier, almost no scattering or attenuation
- The entire universe has been transparent for GWs, all the way back to the Big Bang

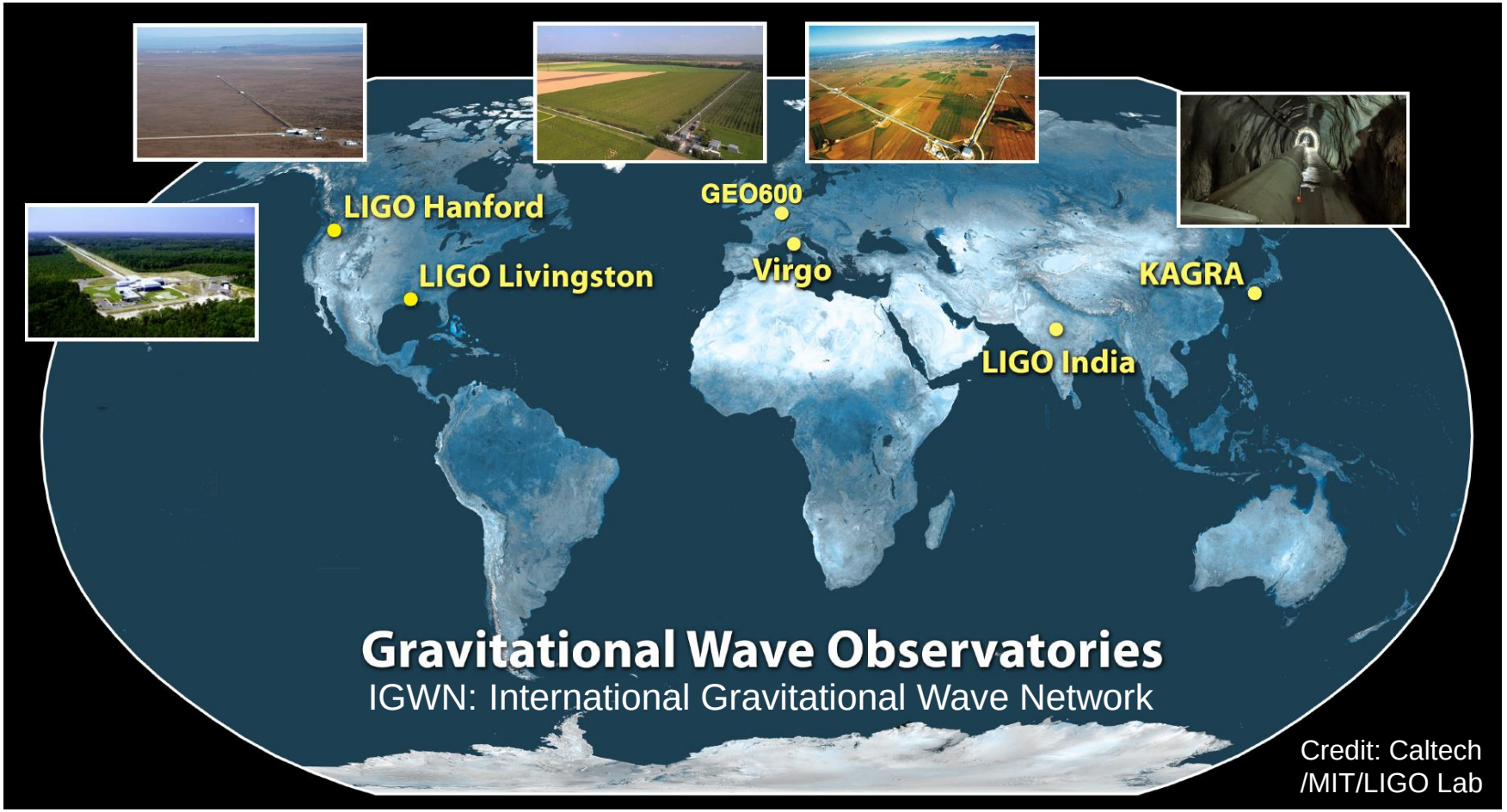
Gravitational wave science can impact

- Astronomy: compact objects, populations, transients, …
- Cosmology: Hubble parameter, Dark Matter, Dark Energy
- Fundamental physics: black holes, spacetime, horizons, matter under extreme conditions

LVK: LIGO Scientific, Virgo and KAGRA Collaborations

Observe together as a network of GW detectors. LVK have integrated their data analysis

LIGO and Virgo have coordinated data taking and analysis, and release joint publications
LIGO and Virgo work under an MOU already for more than a decade
KAGRA in Japan joined in February 2020



Virgo Collaboration

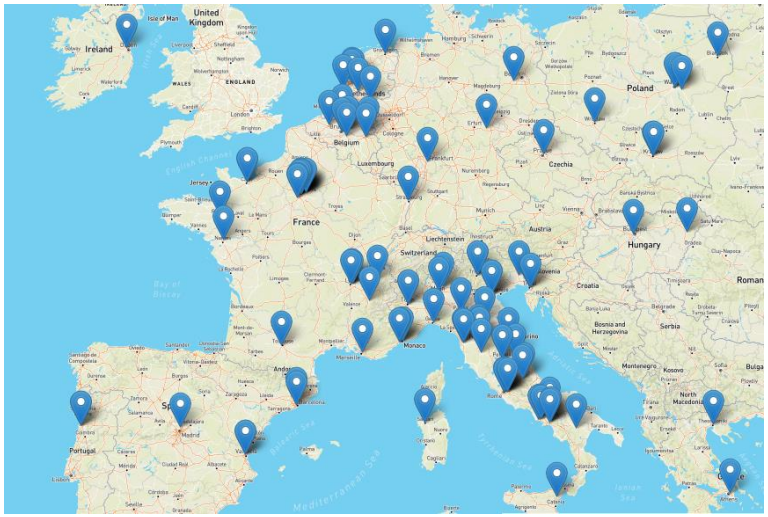
Virgo is a European collaboration with 782 members, 537 authors from 133 institutions in 15 different countries. Virgo has more that doubled its size in the last few years. See https://www.virgo-gw.eu/

Virgo is a 2nd generation GW detector in Europe

- EGO Council composed of France, Italy and the Netherlands
- Participation by scientists from Belgium, China, Czechia, Denmark, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Monaco, Poland, Portugal, Spain, The Netherlands

Gravitational wave science: steep learning curve

- Join gravitational wave science
- Learn about instrumentation and data analysis
- Path to third generation: Einstein Telescope
- Many members traditionally from CERN community



Virgo develops advanced and innovative technology

- Quantum technologies: frequency dependent squeezing
- Large test masses and advanced coatings
- Scattered light mitigation
- Low frequency risk reduction

14 European countries

LIGO – Virgo observation runs

LIGO and Virgo coordinate science data taking. In between the observation runs, the instruments are upgraded and commissioned to achieve better sensitivity

Observing run 1

- September 2015 to January 2016
- LIGO interferometers
- Most notable: first BBH GW150914
- Every few months

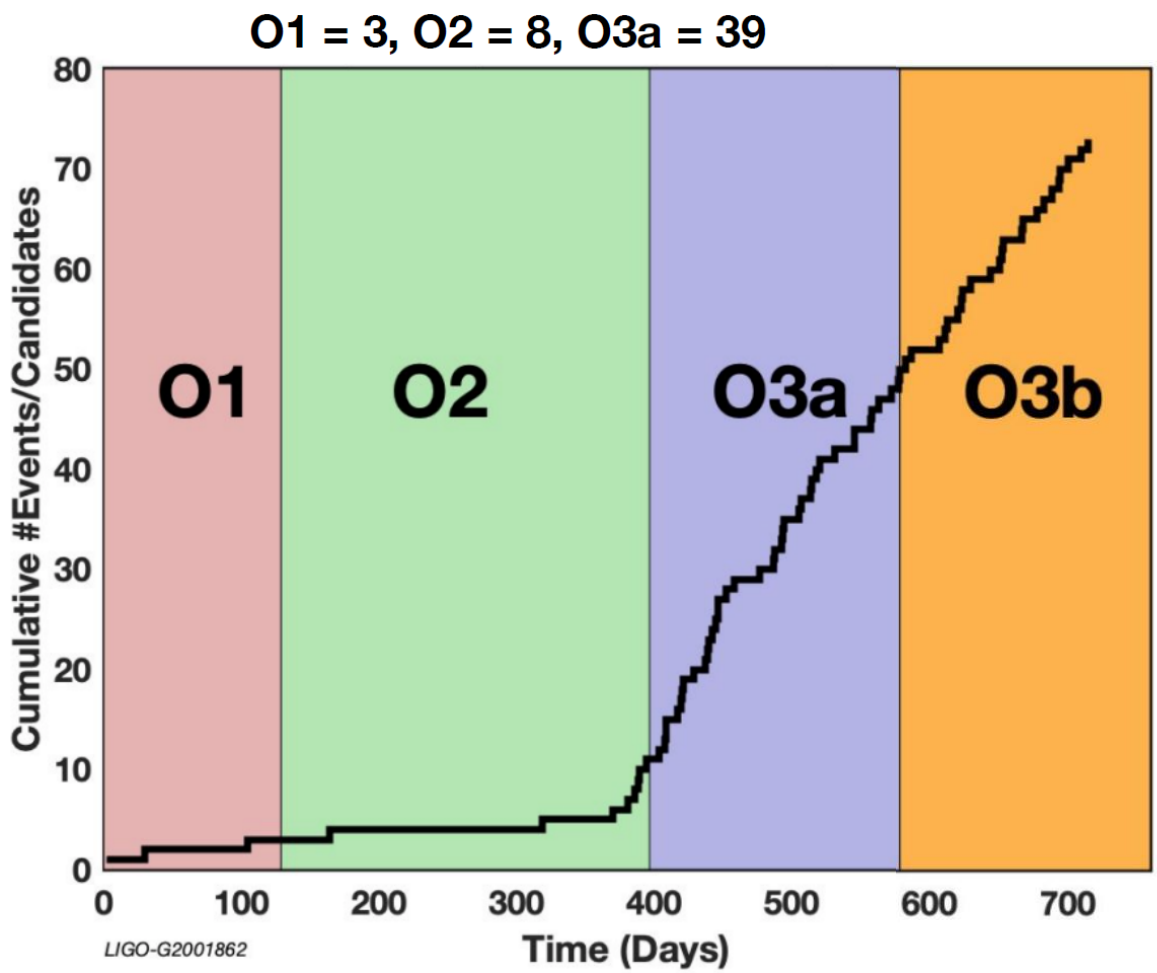
Observing run 2

- November 2016 to August 2017
- LIGO + Virgo (August 2017 only) ITFs
- Most notable: first BNS GW170817

Observing run 3

- April 2019 to March 2020
- LIGO + Virgo interferometers
- O1 - O3a: 50 significant detections

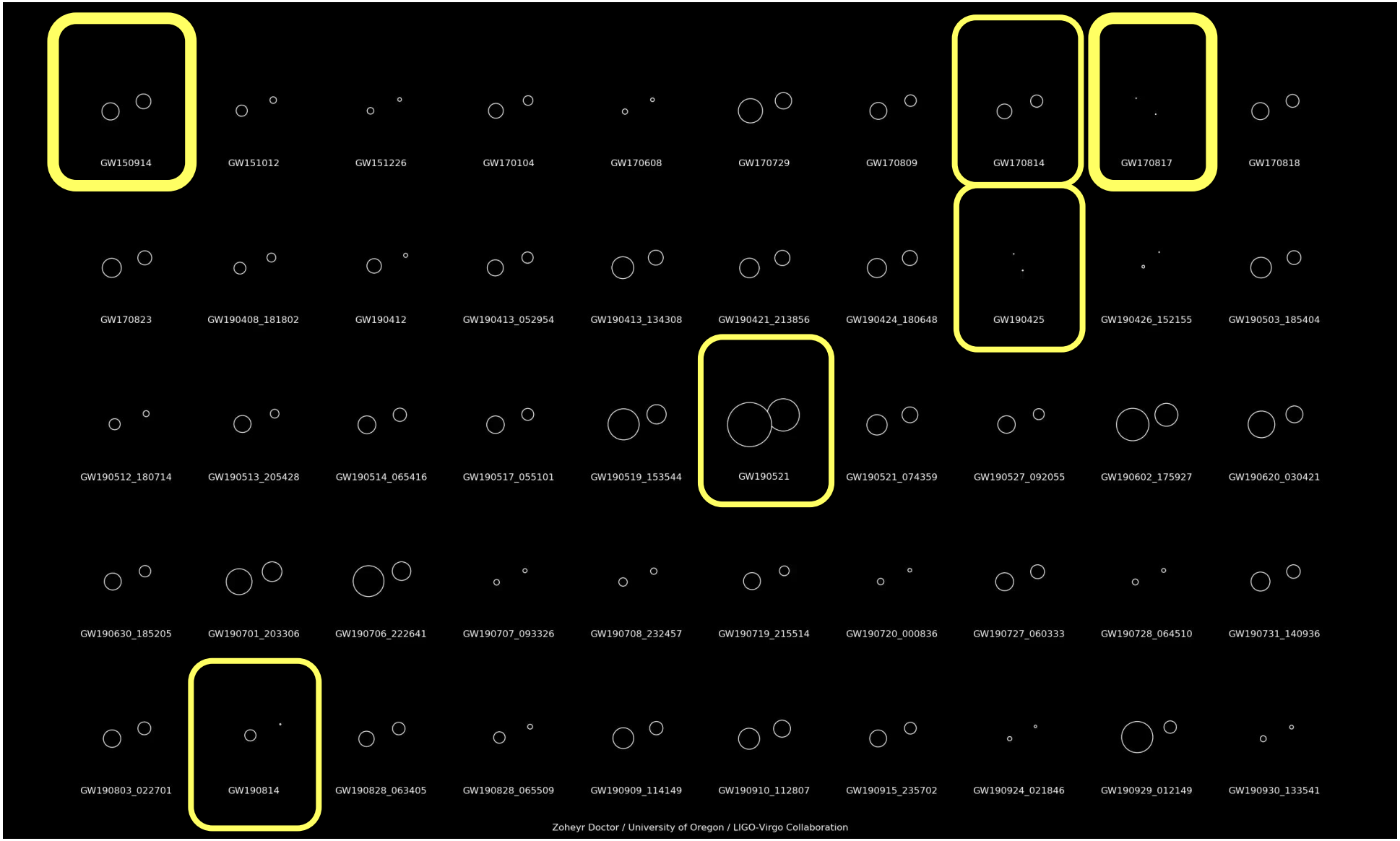
  Abbott et al. Phys. Rev. X 11, 021053 (2021)
- Weekly detections



Gravitational-Wave Transient Catalog, GWTC2

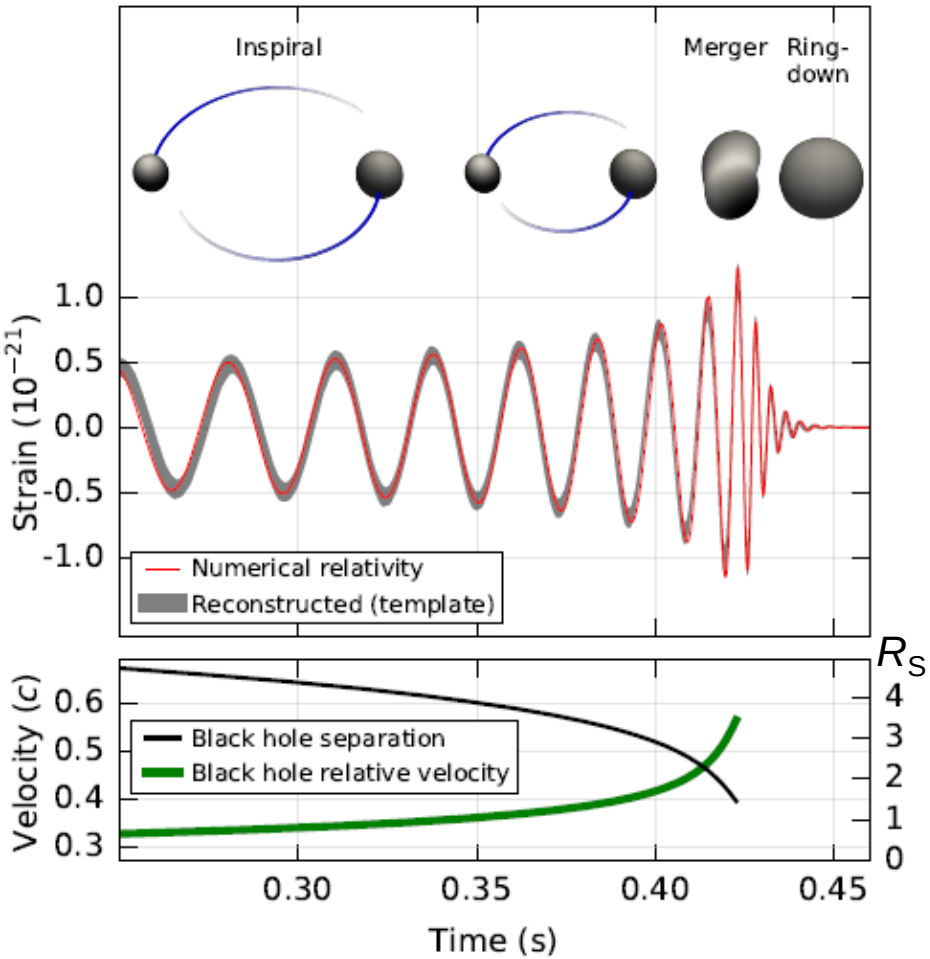
Compact binary coalescences observed by LIGO &Virgo during the first half of the third observing run

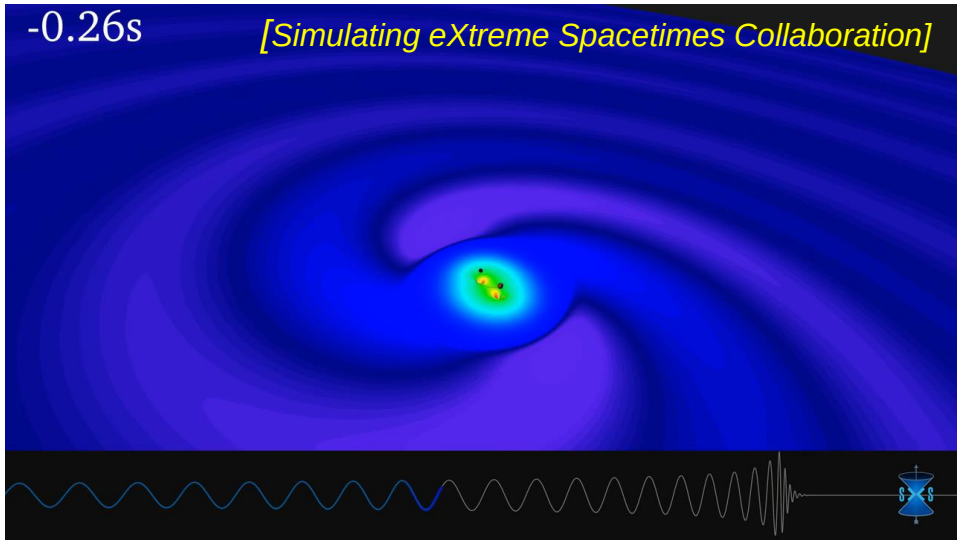
See Abbott et al. Phys. Rev. X 11, 021053 (2021)



Binary black hole merger GW150914

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 inspiral and ringdown phase





- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Orbital phase (post Newtonian expansion)

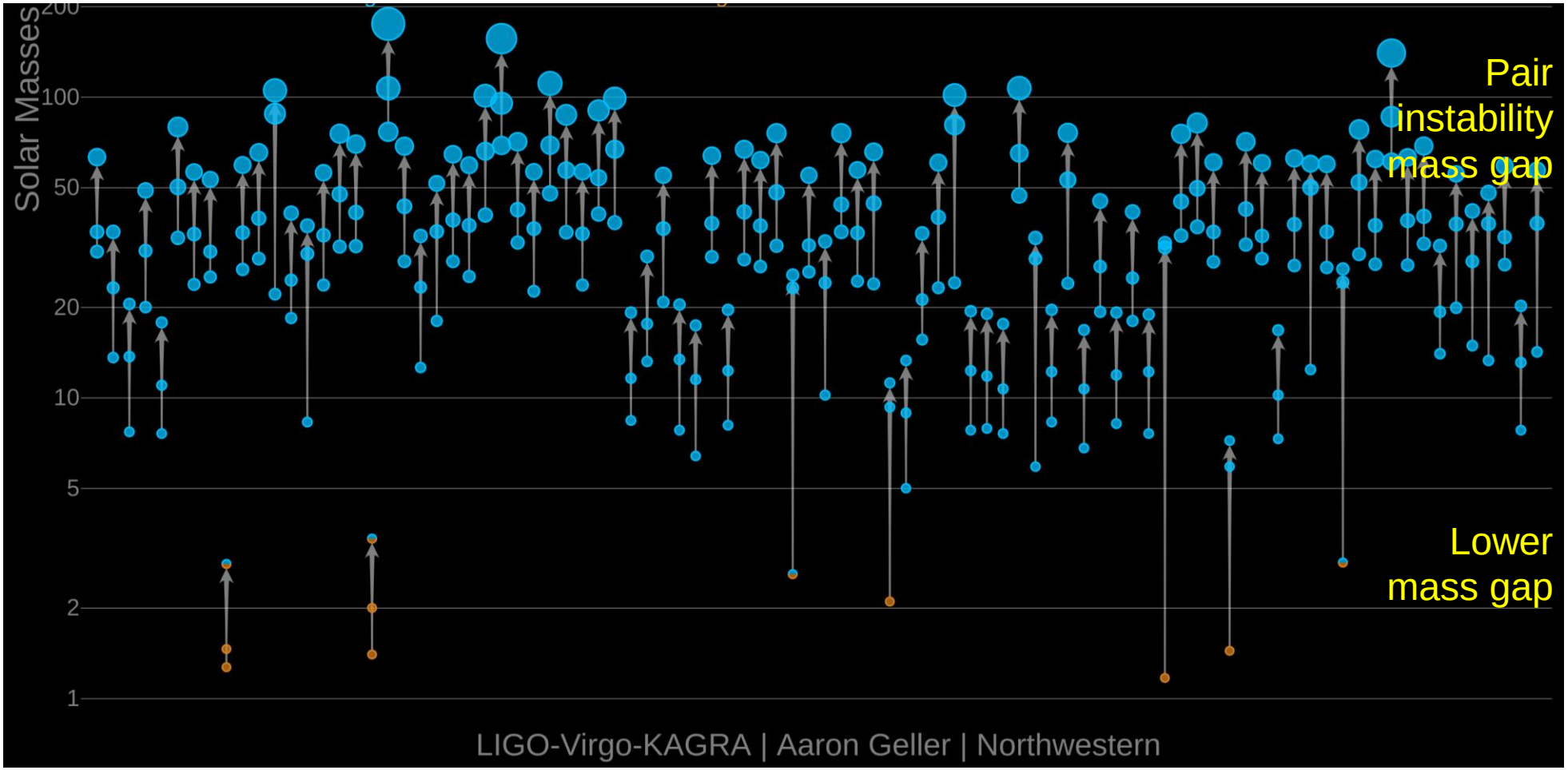
$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$

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

Population inference from GWTC3

Combine many observations to infer underlying properties. More sensitive than single-event inference. See Abbott et al. ApJ Lett. 913, L7 (2021)

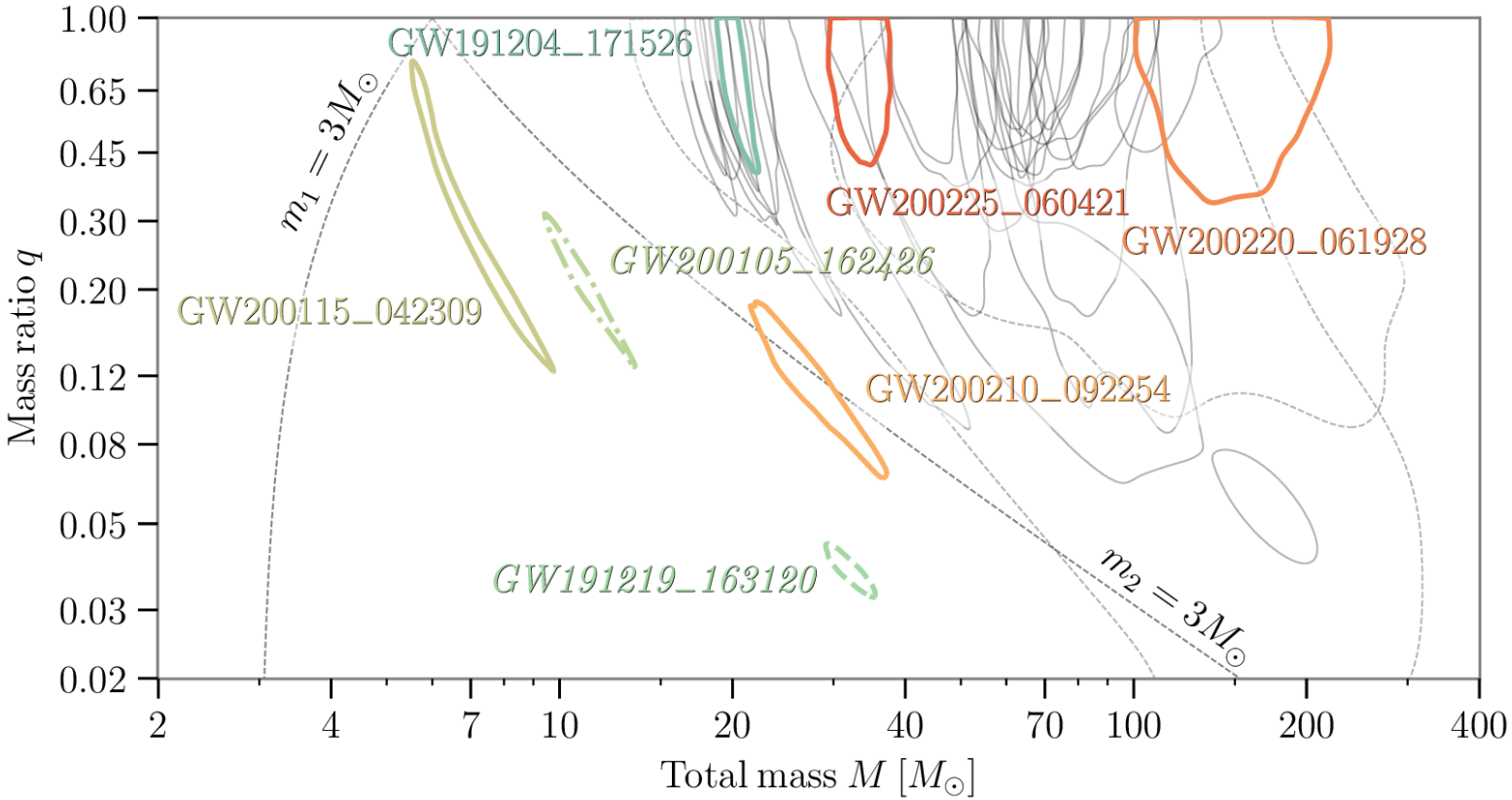
Note the presence of compact objects in the 2 – 5 and 60 – 120 $m_\odot$ mass gaps



Population inference from GWTC3

Estimates of the total mass (M) and mass ratio (q) between the least massive and most massive component. See arXiv:2111.03606

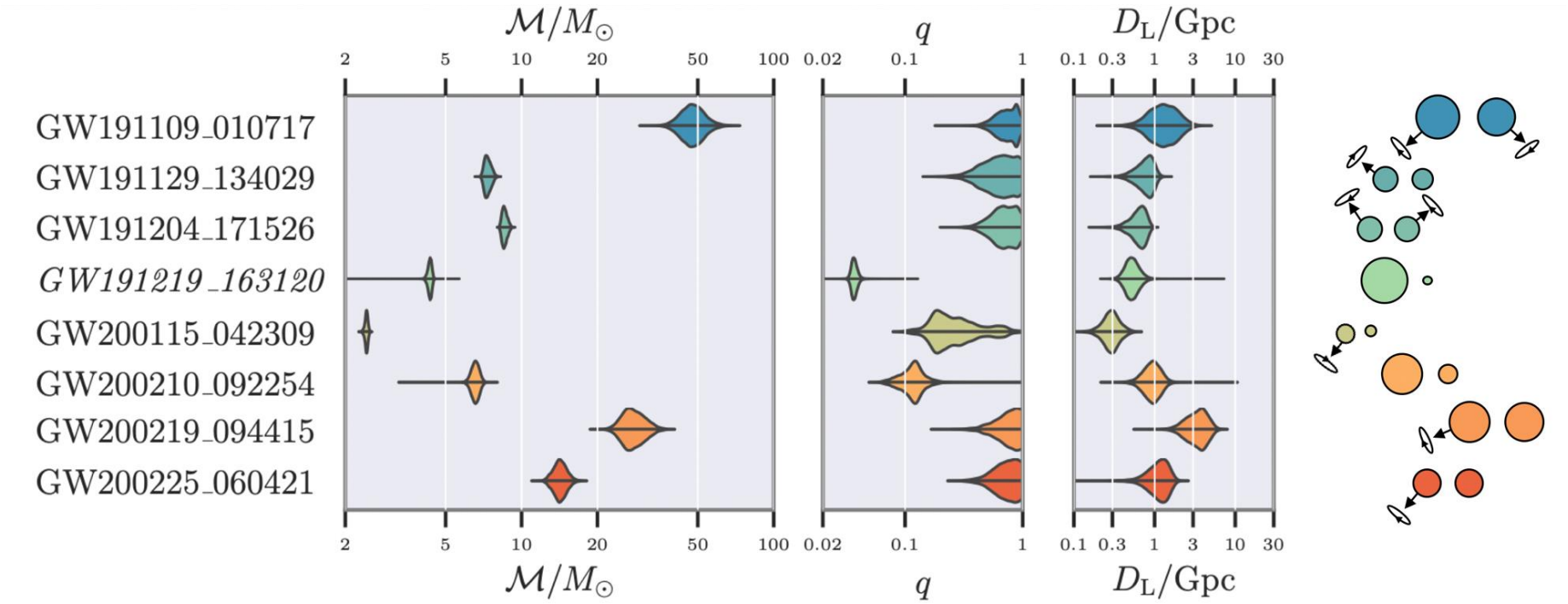
Each contour represents a different event and encloses the most probable values of the parameters at 90% probability (the 90% credible region)



Population inference from GWTC3

Most probable values of three key parameters of eight binary compact objects from GWTC-3: the binary chirp mass, M; the mass ratio, q, between the least massive and most massive component; and the luminosity distance, D_L. See arXiv:2111.03606

Each binary is illustrated to the right-hand side of the plot, with circle size representing mass and the component spins indicated (not to scale). Credits: LIGO-Virgo-KAGRA Collaborations/Isobel Romero-Shaw/OzGrav.

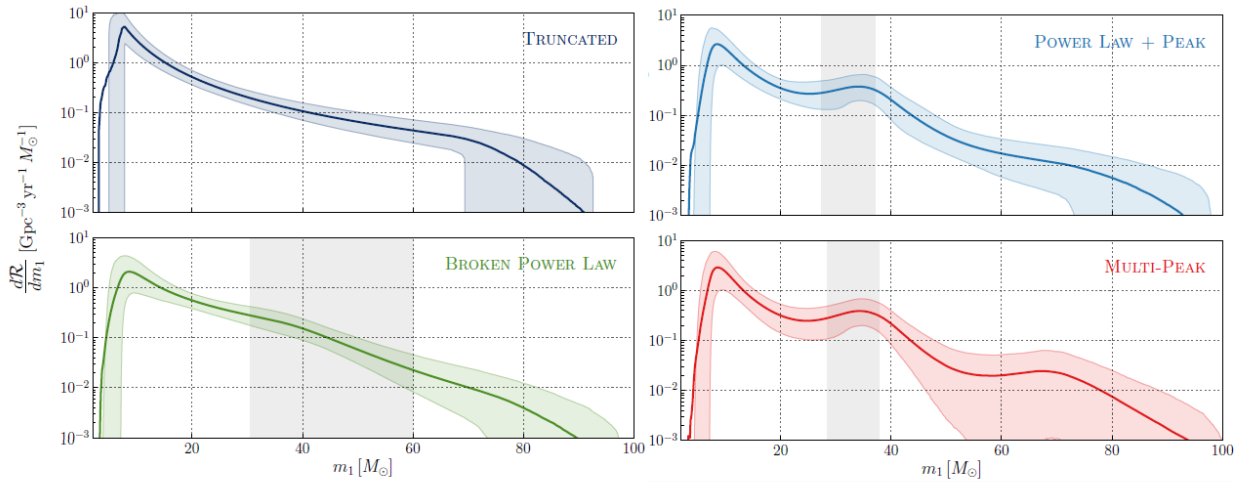


Binary black hole population inference from GWTC-2

Combine many observations to infer underlying properties. More sensitive than single-event inference. Spin maybe the key to formation channels Abbott et al. ApJ Lett. 913, L7 (2021)

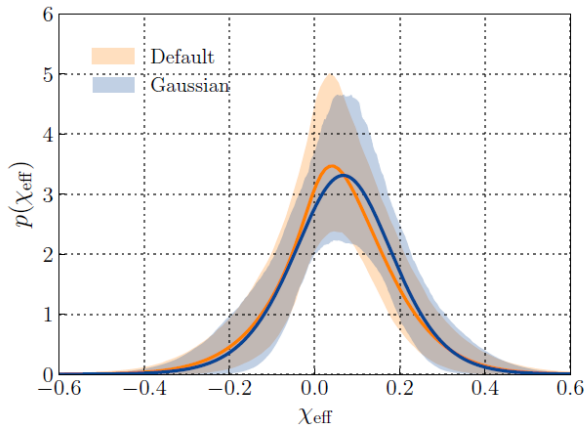
Mass distribution

- Used 47 BBH events
- FAR < 1 per yr
- Truncated model is not a good fit to the data
- Evidence of a feature around 35 - 40 M⊙



Spin distribution

- Mostly small components spin magnitudes
- Some BBH systems have spins misaligned with orbital angular momentum



Effective spin parameter

$$\chi_{\rm eff} = \frac{c}{GM}\left(\frac{\boldsymbol{S}_1}{m_1} + \frac{\boldsymbol{S}_2}{m_2}\right) \cdot \frac{\boldsymbol{L}}{|\mathbf{L}|}$$

Precision tests of GR with BBH mergers

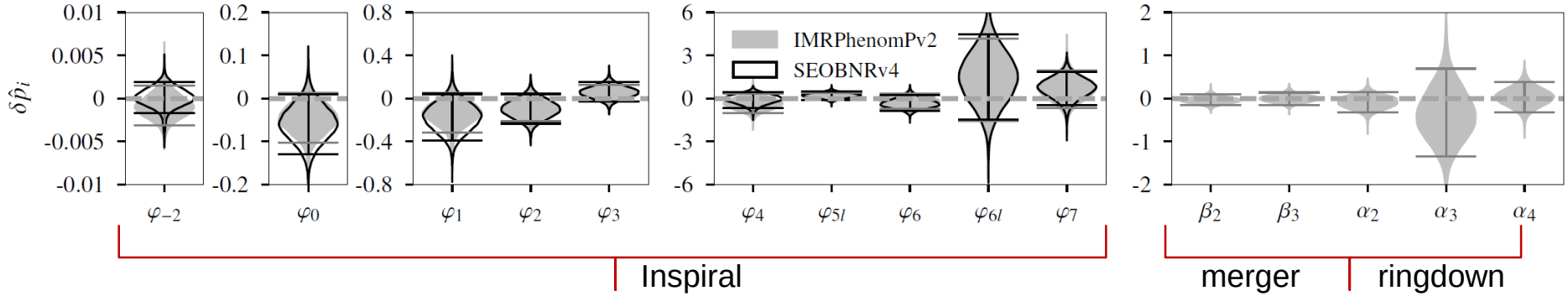
Bayesian analysis increases accuracy on parameters by combining information from multiple events

Inspiral and PN expansion

Inspiral PN and logarithmic terms:

Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

LIGO Virgo Collaboration
arXiv:1903.04467v2



Orbital phase (post Newtonian expansion): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

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

Towards high precision tests of gravity

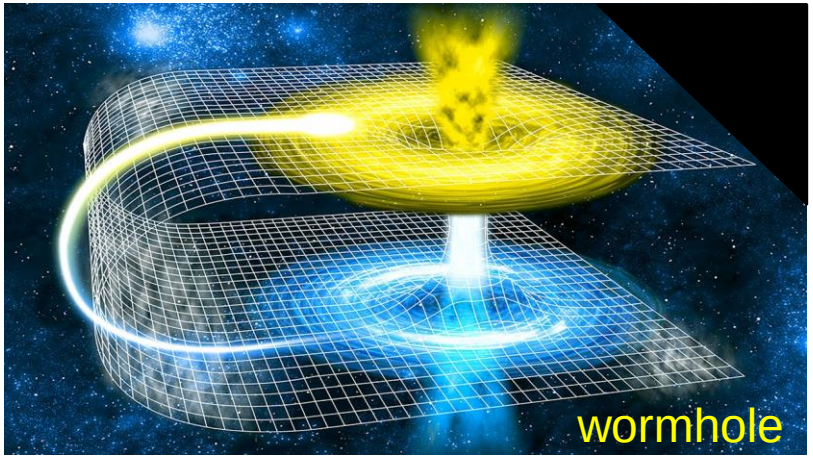
Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

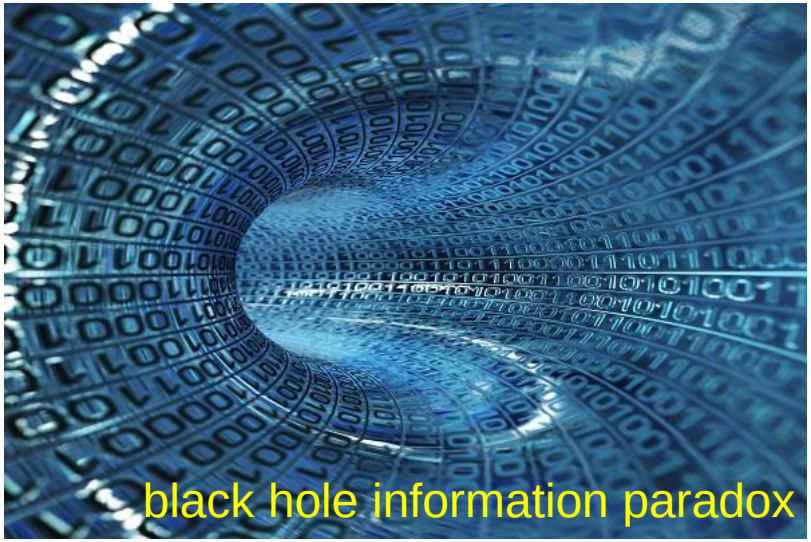
Ringdown terms

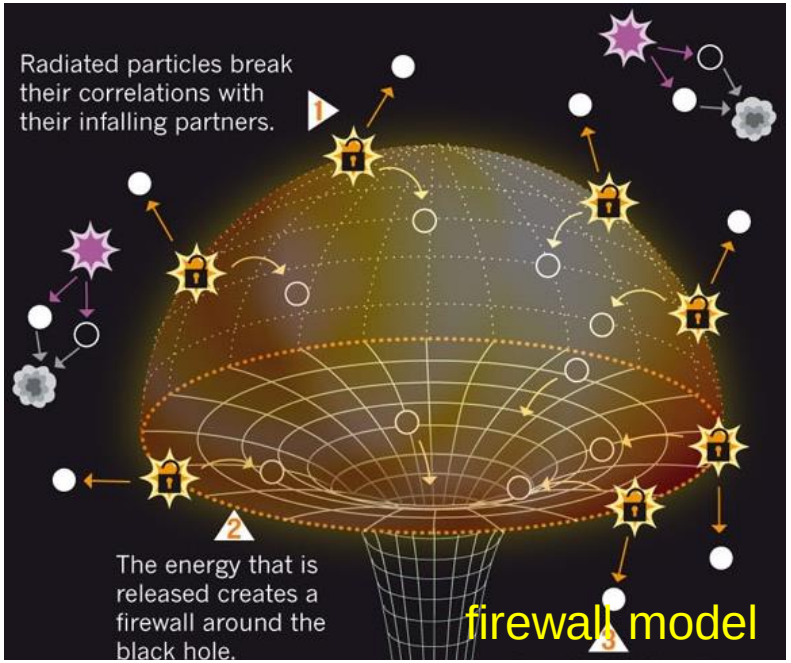
Quasi-normal mode analysis; do we see Kerr black holes?

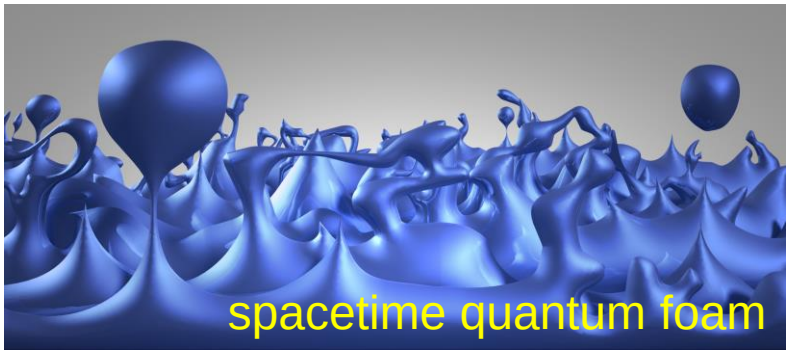
Fundamental physics: did we observe black holes?

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?



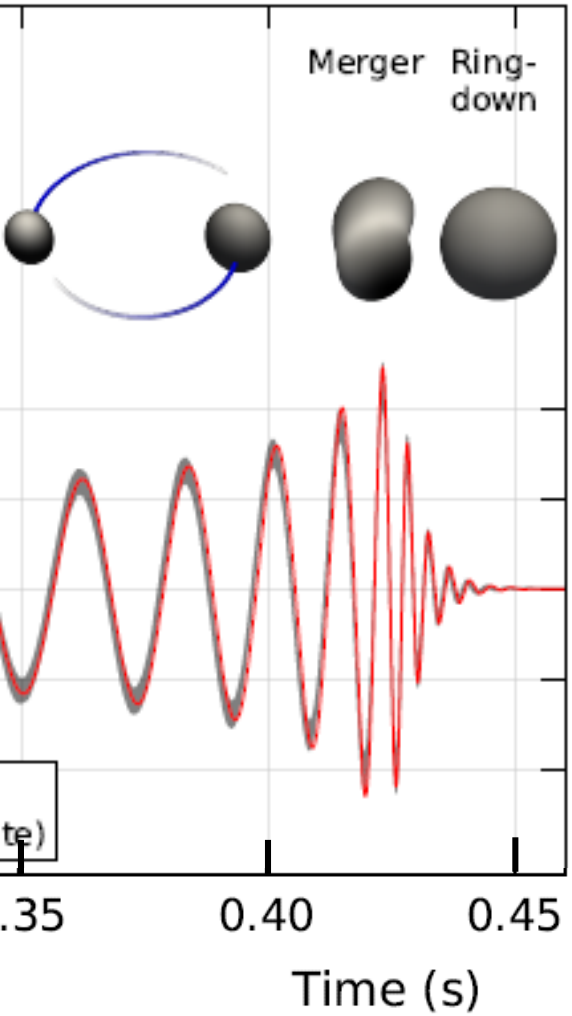


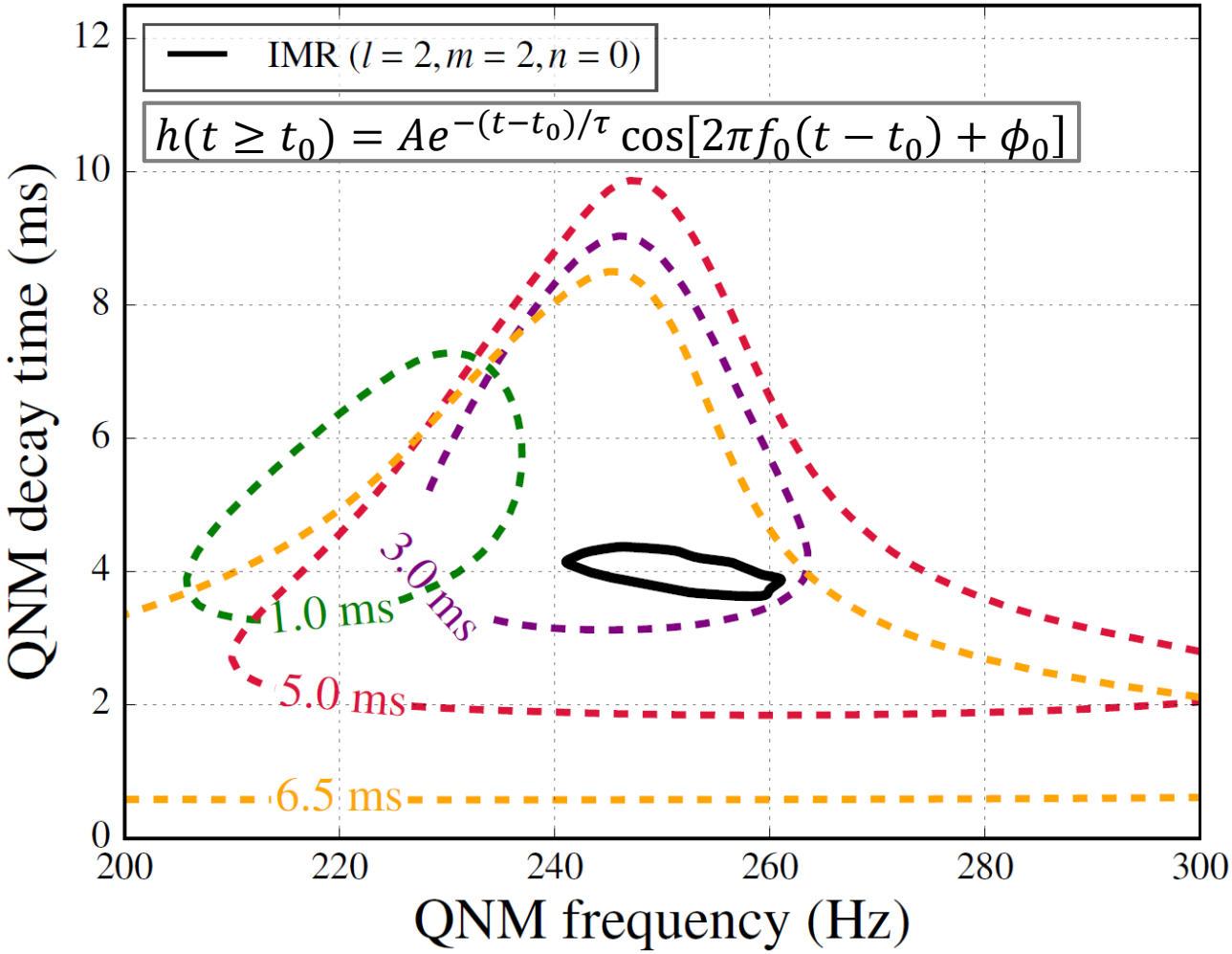




Is a black hole created in the final state?

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 and perform test of no-hair theorem. This demands good sensitivity at high frequency





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

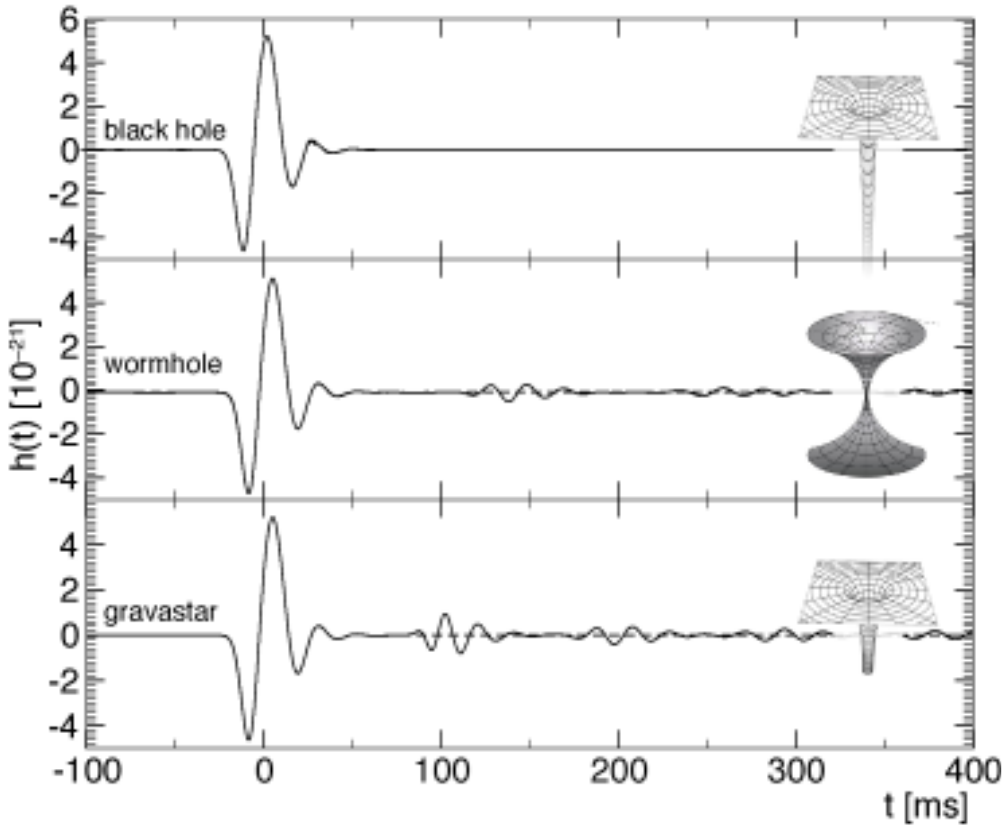
- Dark matter stars

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 $\Delta t \approx -nM \log \frac{l}{M}$
- Studies require good sensitivity at high frequency

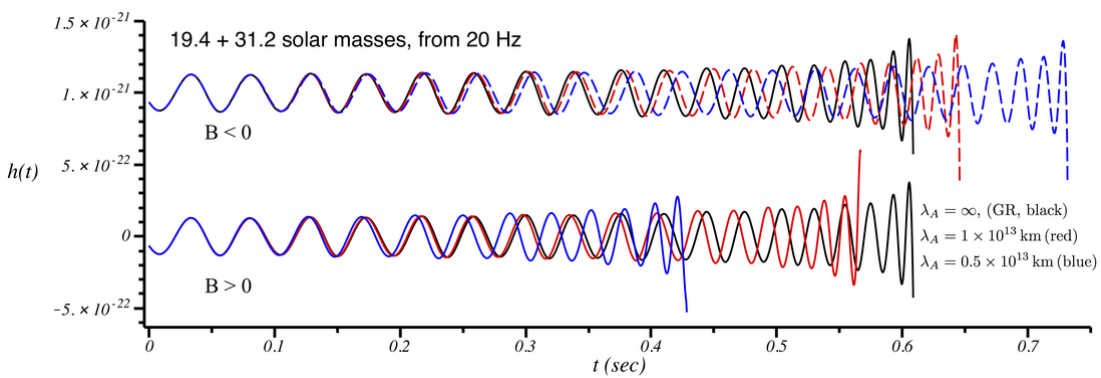
Bounds on violation of Lorentz invariance

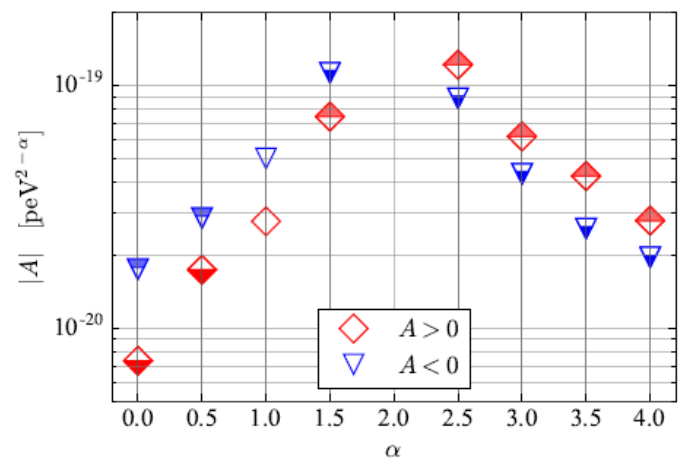
First bounds derived from gravitational-wave observations, and the first tests of superluminal propagation in the gravitational sector

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

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





Several modified theories of gravity predict specific values of α:
- massive-graviton theories ($\alpha = 0$, $A > 0$), multifractal spacetime ($\alpha = 2.5$),
- doubly special relativity ($\alpha = 3$), and Horava-Lifshitz and extradimensional theories ($\alpha = 4$)

Bound on mass of the graviton: $m_g \leq 1.76 \times 10^{-23}\mathrm{eV}/\mathrm{c}^2$

No evidence for deviations from general relativity

Learning about gravity with LIGO and Virgo
See Abbott et al. Phys. Rev D. 103, 122002 (2021)

Observations

- Residuals from best-fit waveforms consistent with noise ✓
- Consistency of parameters inferred from inspiral and merger-ringdown phases ✓
- No evidence for deviations from the PN coefficients predicted by GR ✓
- Consistency with no dispersion of GWs and massless graviton ✓
- BH spin-induced quadrupole moments are consistent with their Kerr values ✓
- Ringdown frequencies and damping times consistent with GR ✓
- No detection of echoes ✓
- No evidence for pure scalar or pure vector polarizations ✓

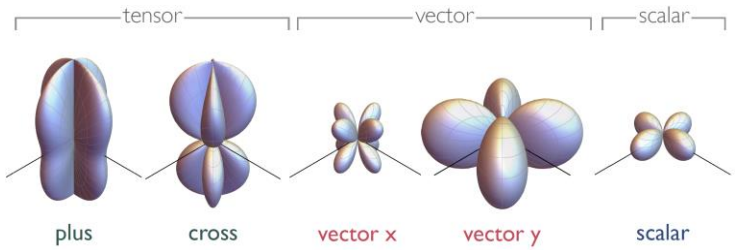
- New bound on mass of graviton: $m_g \leq 1.76 \times 10^{-23} \mathrm{eV/c^2}$

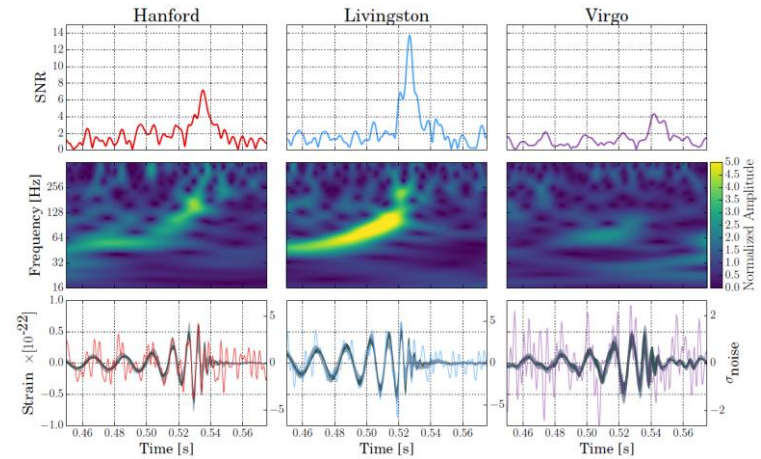
GW170814: first test of polarizations of GW

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 fundamental test of the polarizations of spacetime





Our analysis favors tensor polarizations in support of General Relativity

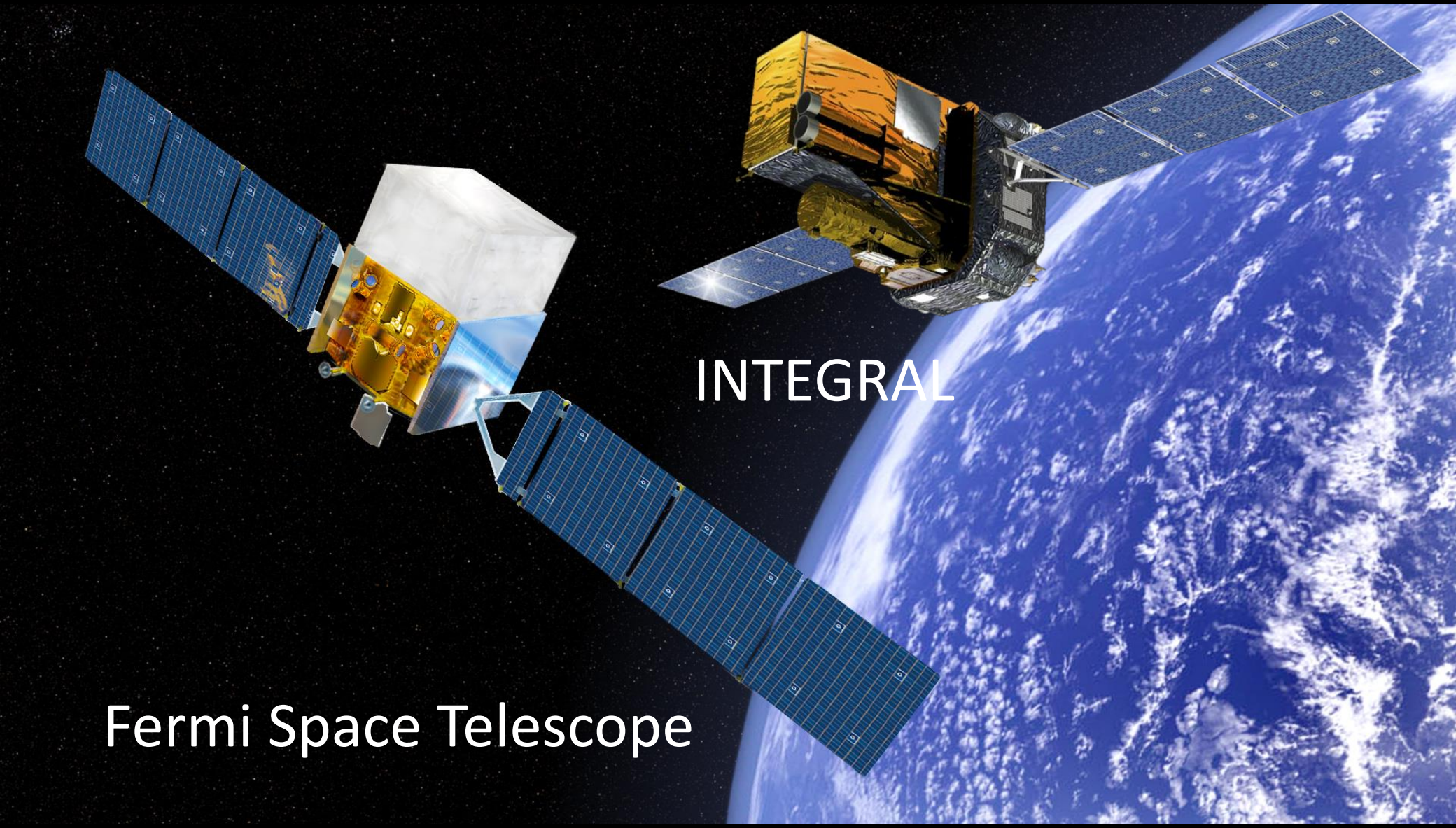
Our data favor tensor structure over vector by about a (Bayes) factor 200

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

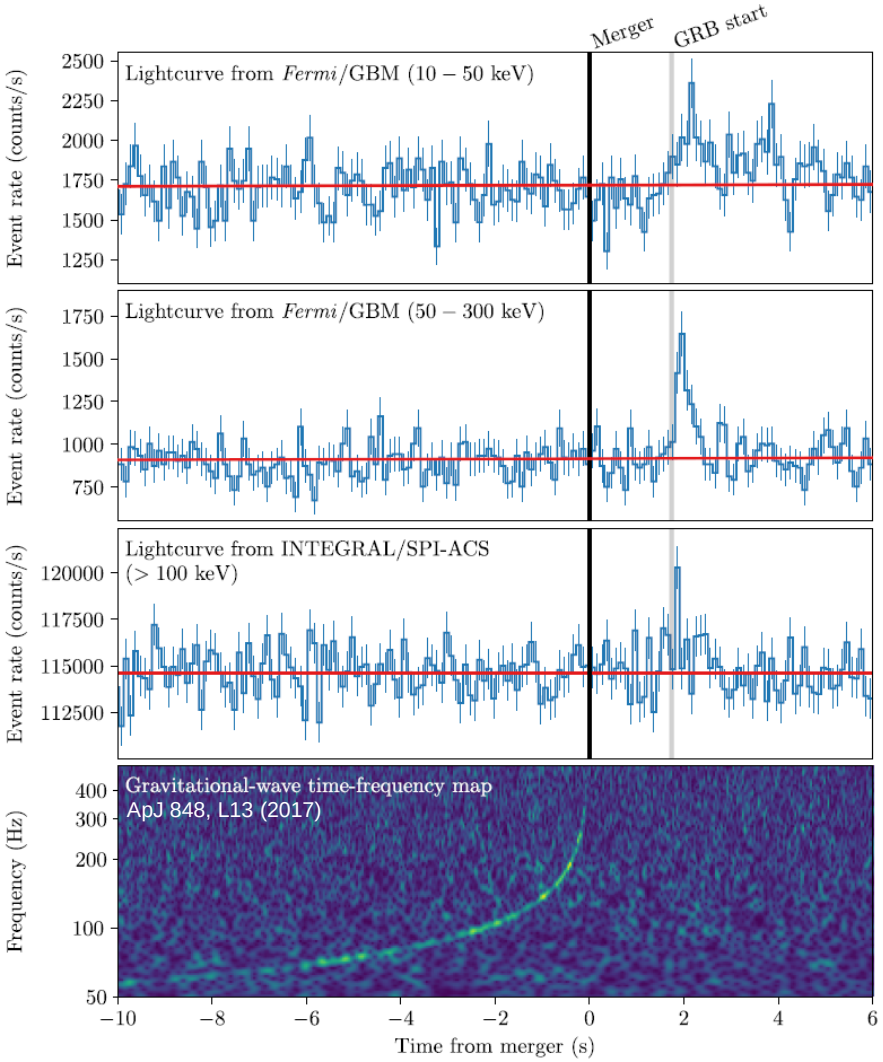
Some scientific highlights: neutron stars

GW180717: gamma rays emitted 1.7 seconds after merger



Binary neutron star merger on August 17, 2017

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



Neutron stars are laboratories for extreme physics

Mass: from about 1.1 to about 2.2 solar mass

Density: up to several time nuclear density

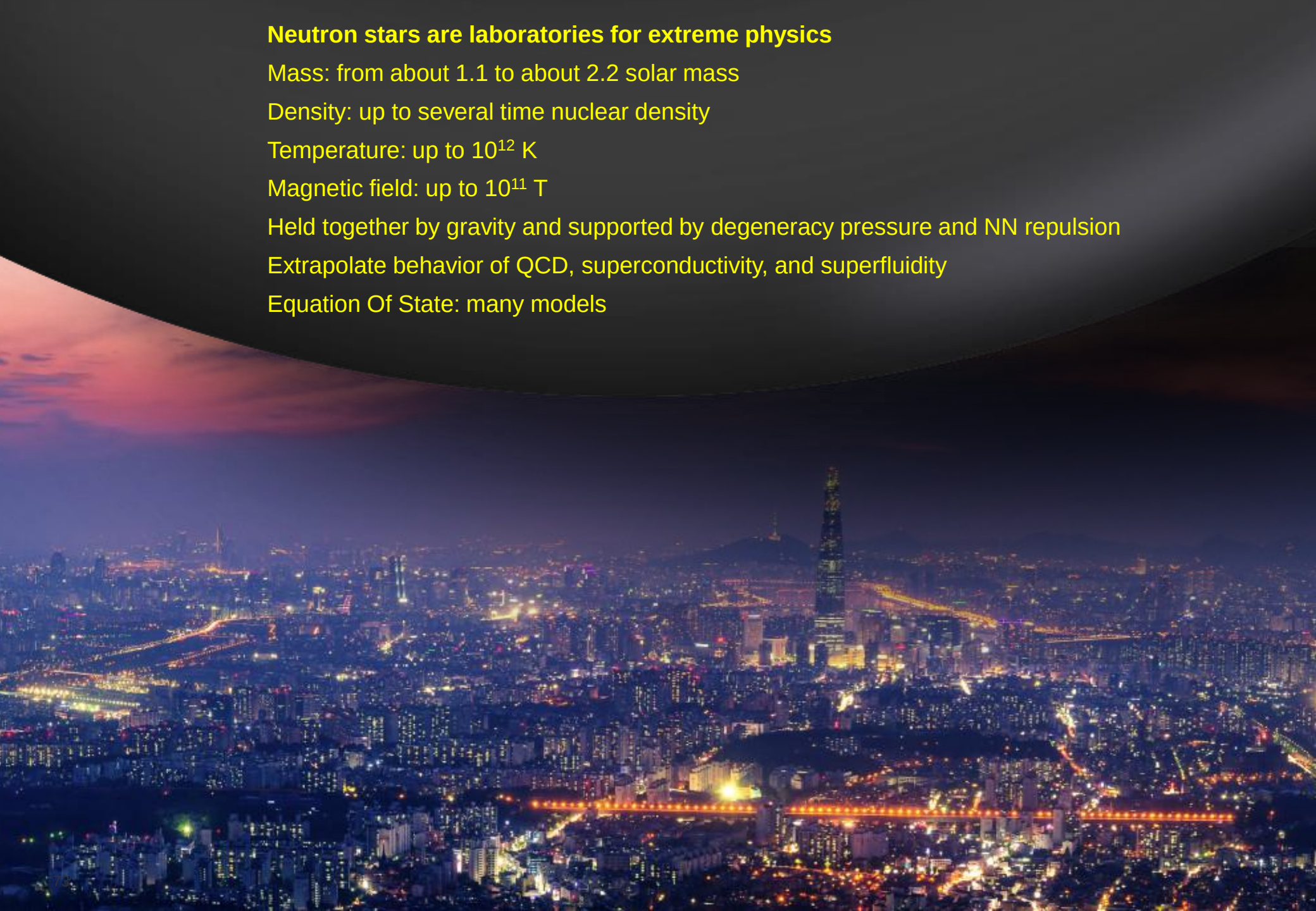
Temperature: up to 10^{12} K

Magnetic field: up to 10^{11} T

Held together by gravity and supported by degeneracy pressure and NN repulsion

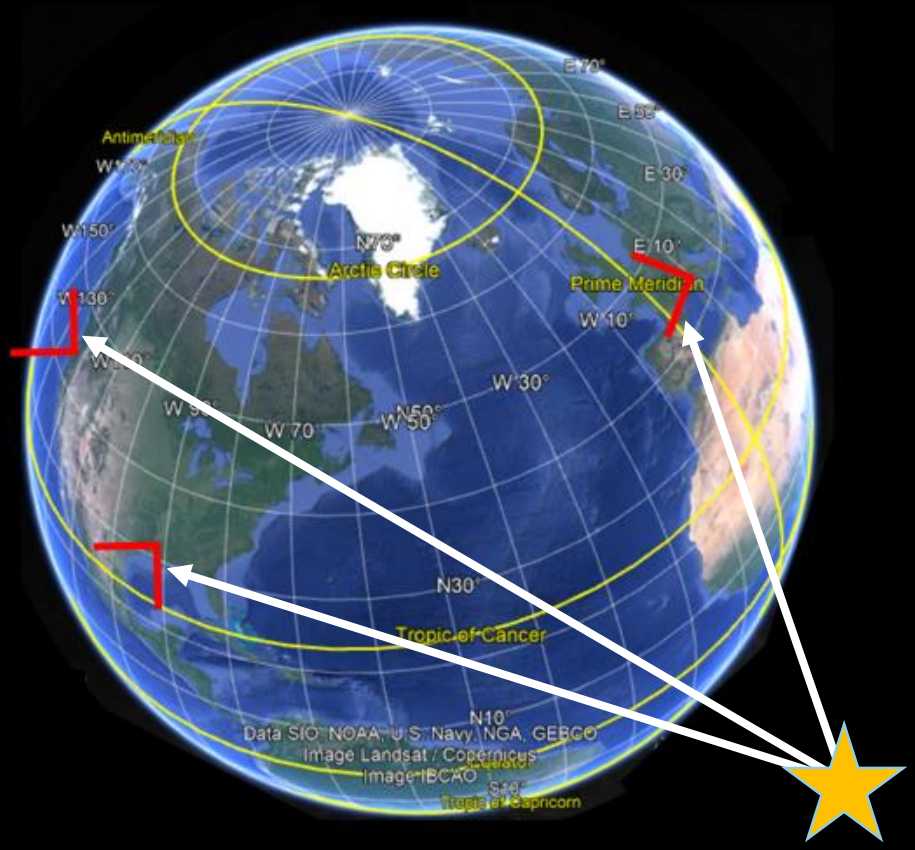
Extrapolate behavior of QCD, superconductivity, and superfluidity

Equation Of State: many models



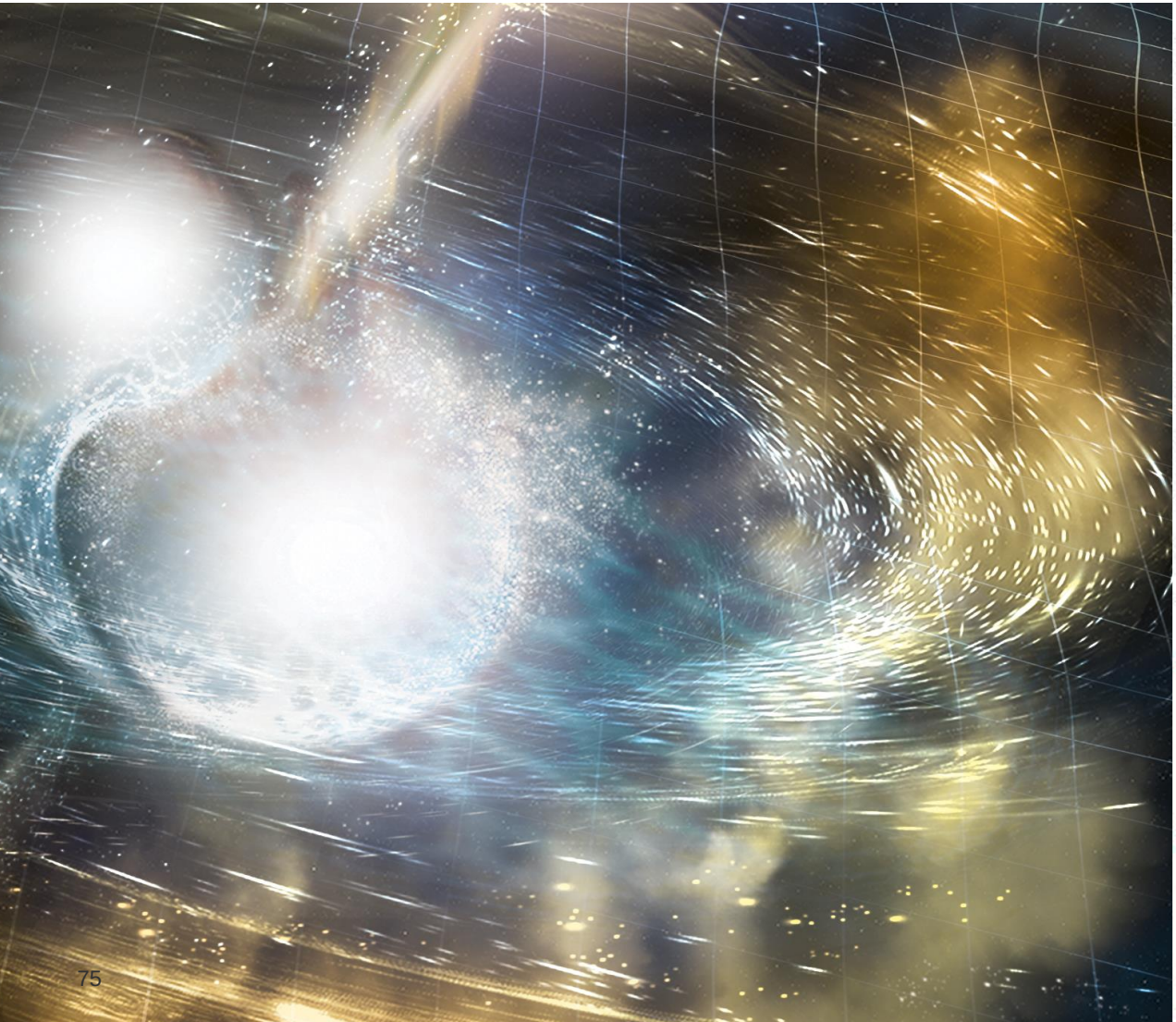
Source location via triangulation

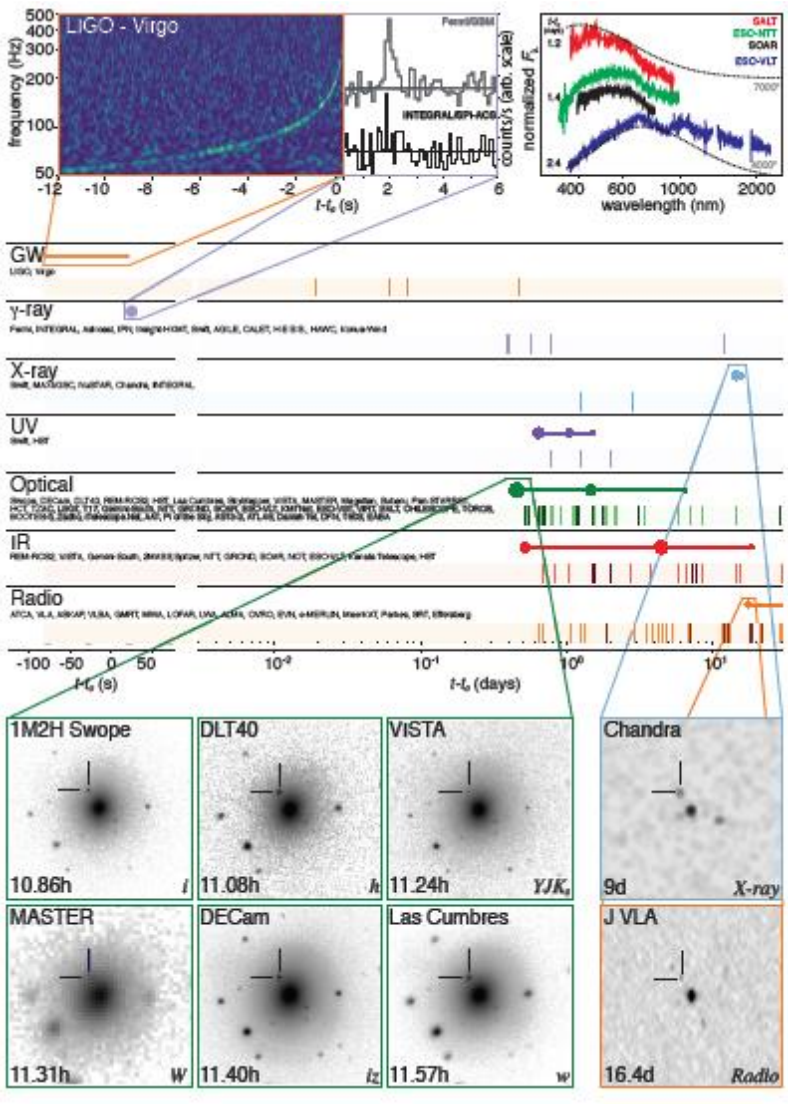
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it

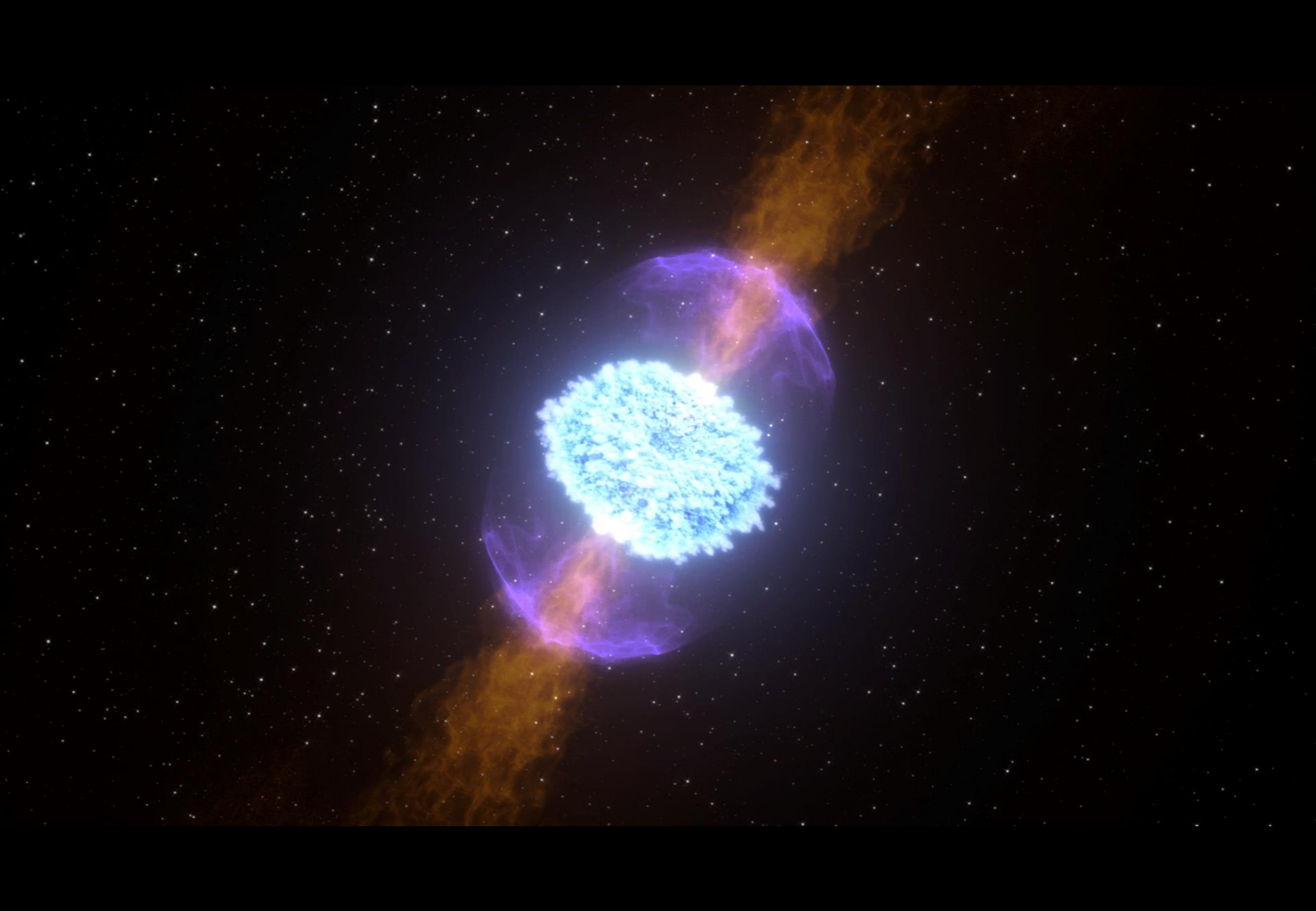


GW170817: start of multi-messenger astronomy with GW

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







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)

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

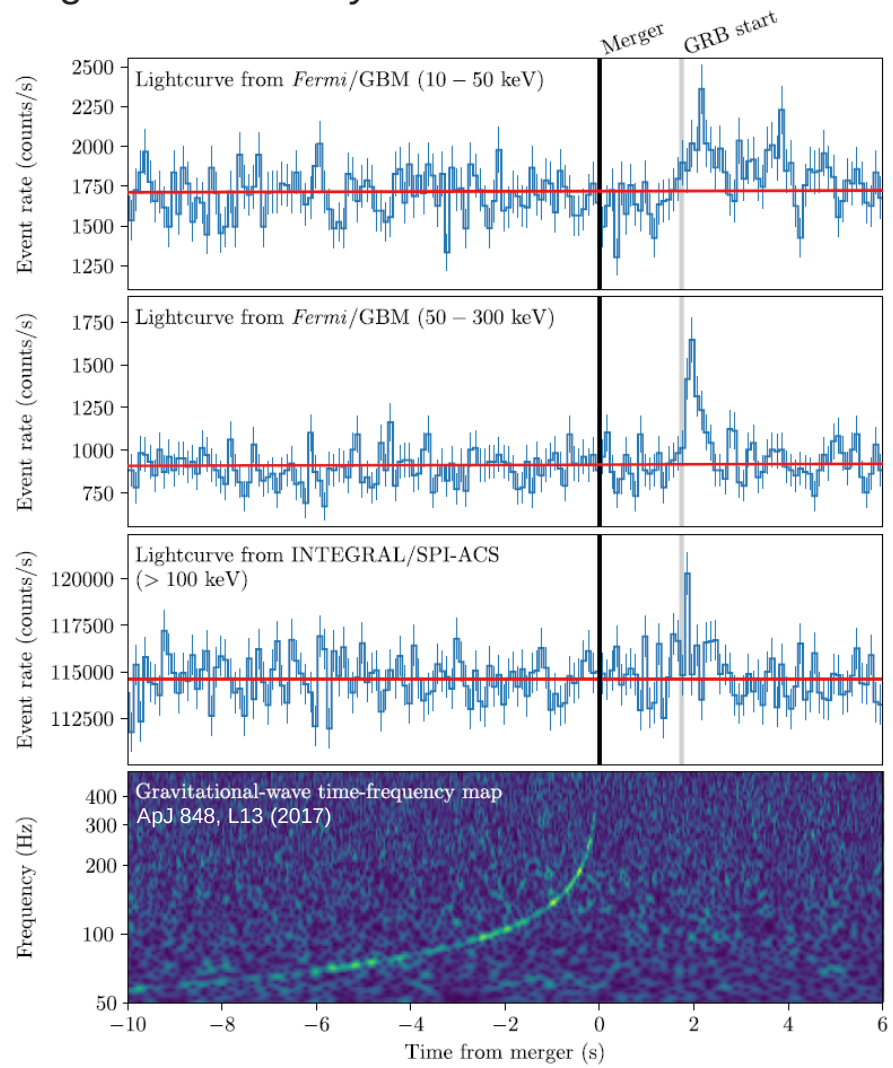
Test of Equivalence Principle

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 $-2.6 \times 10^{-7} \leq \gamma_{\text{GW}} - \gamma_{\text{EM}} \leq 1.2 \times 10^{-6}$

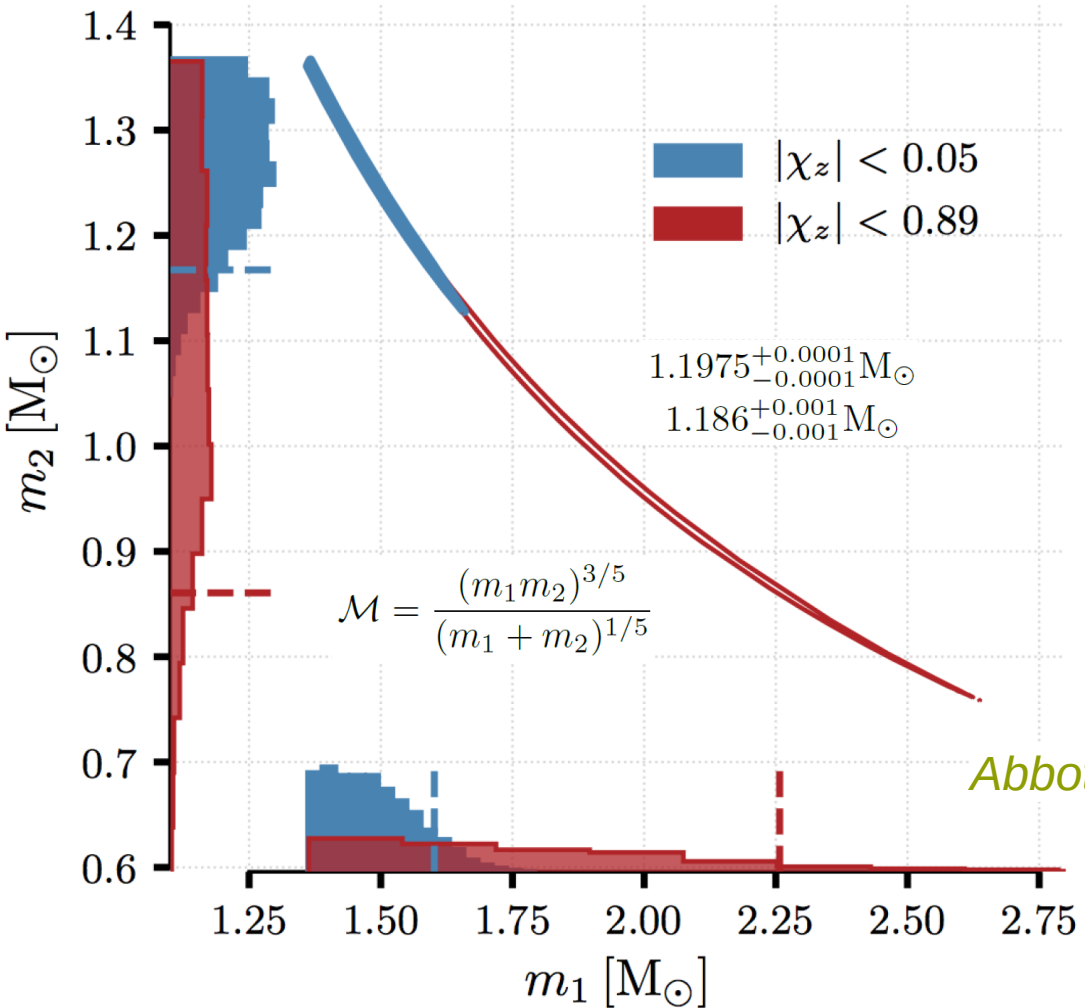
Including data on peculiar velocities to 50 Mpc we find $\Delta\gamma \leq 4 \times 10^{-9}$



Inferring neutron star properties: masses

Early estimates now improved using known source location, improved waveform modeling, and re-calibrated Virgo data. Chirp mass can be inferred to high precision. There is a degeneracy between masses and spins

Observation of **binary pulsars** in our galaxy indicates spins are **not larger than ~0.04**



To lowest approximation $\tilde{h}(f) \propto e^{i\Psi(f)}$

with $\Psi(f) = \frac{3}{4}\left(\frac{G\mathcal{M}}{c^3}8\pi f\right)^{-5/3} + \ldots$

Abbott et al. PRL 119 (2017) 161101

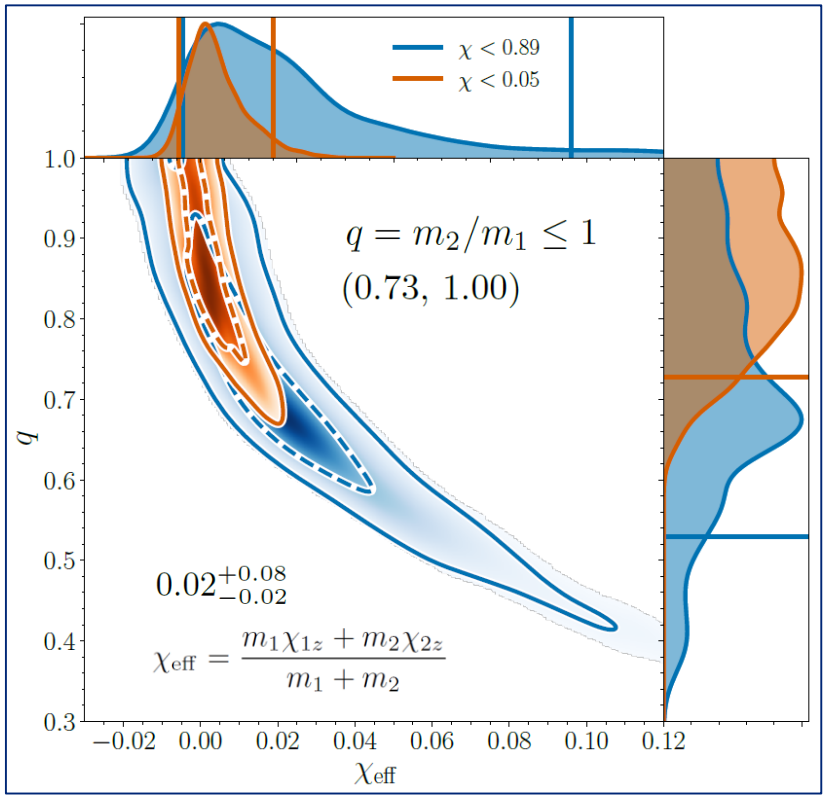
Inferring neutron star properties: spins

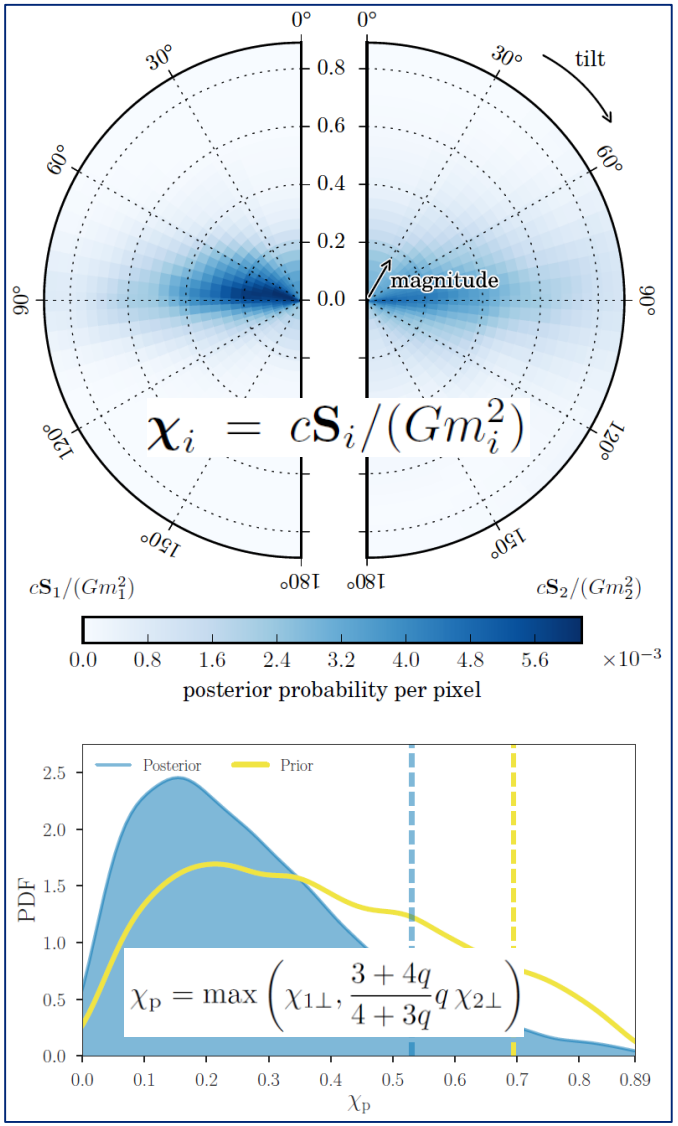
Constrains on mass ratio q, $\chi_{\rm i}$ dimensionless spin, $\chi_{\rm eff}$ effective spin, and $\chi_{\rm p}$ effective spin precession parameter. See https://arxiv.org/abs/1805.11579

No evidence for NS spin

$\chi_{\rm eff}$ contributes to GW phase at 1.5 PN, and degenerate with q

$\chi_{\rm p}$ starts contributing at 2 PN



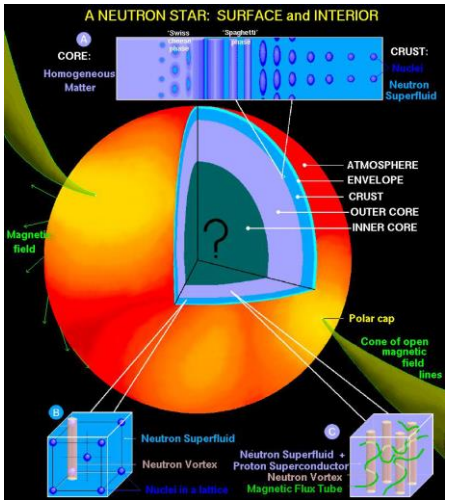


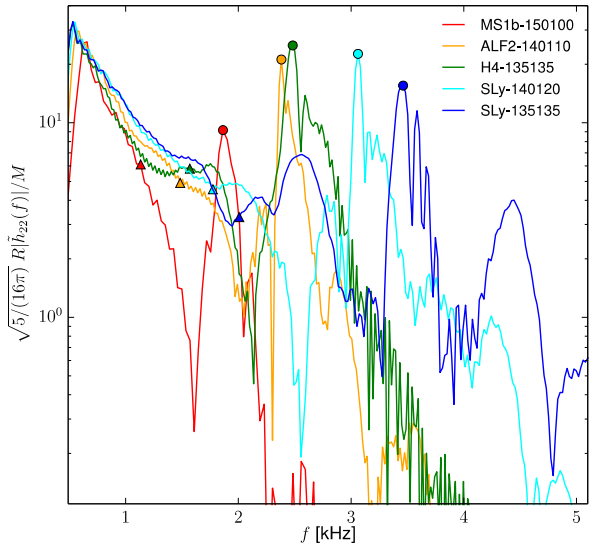
Solving an astrophysical conundrum

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?

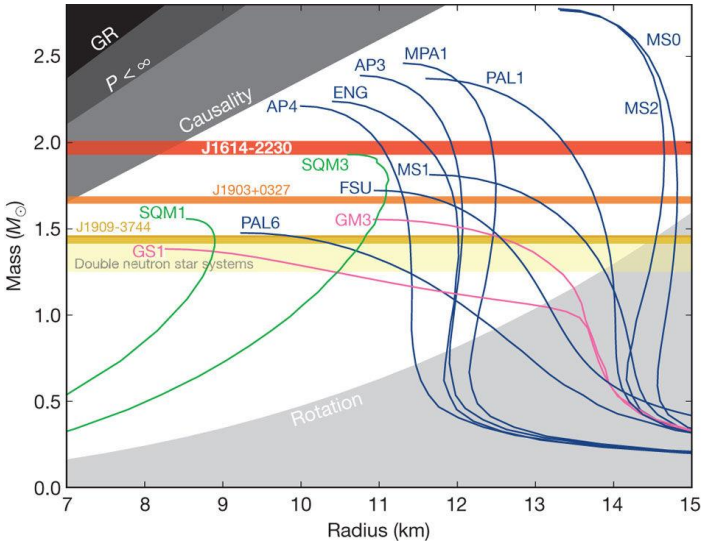
- Structure of the crust?
- Proton superconductivity
- Neutron superfluidity
- “Pinning” of fluid vortices to crust
- Origin of magnetic fields?
- More exotic objects?





Widely differing theoretical predictions for different 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



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

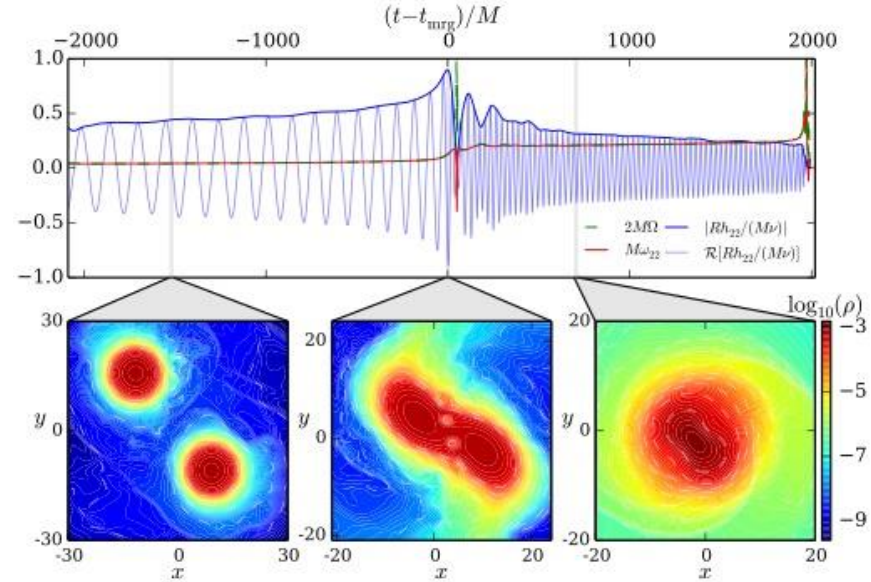
Bernuzzi *et al*., PRL 115, 091101 (2015)

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

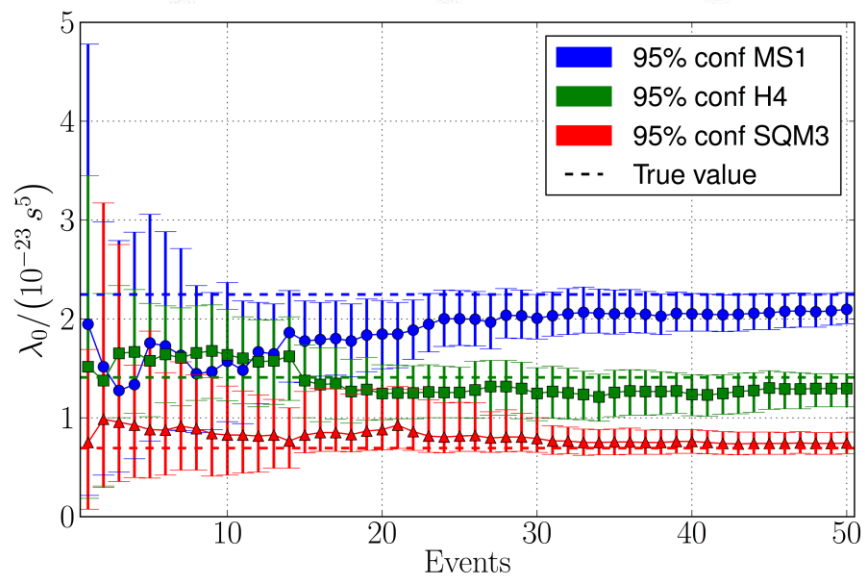
Gravitational waves from inspiraling binary neutron stars

- 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)

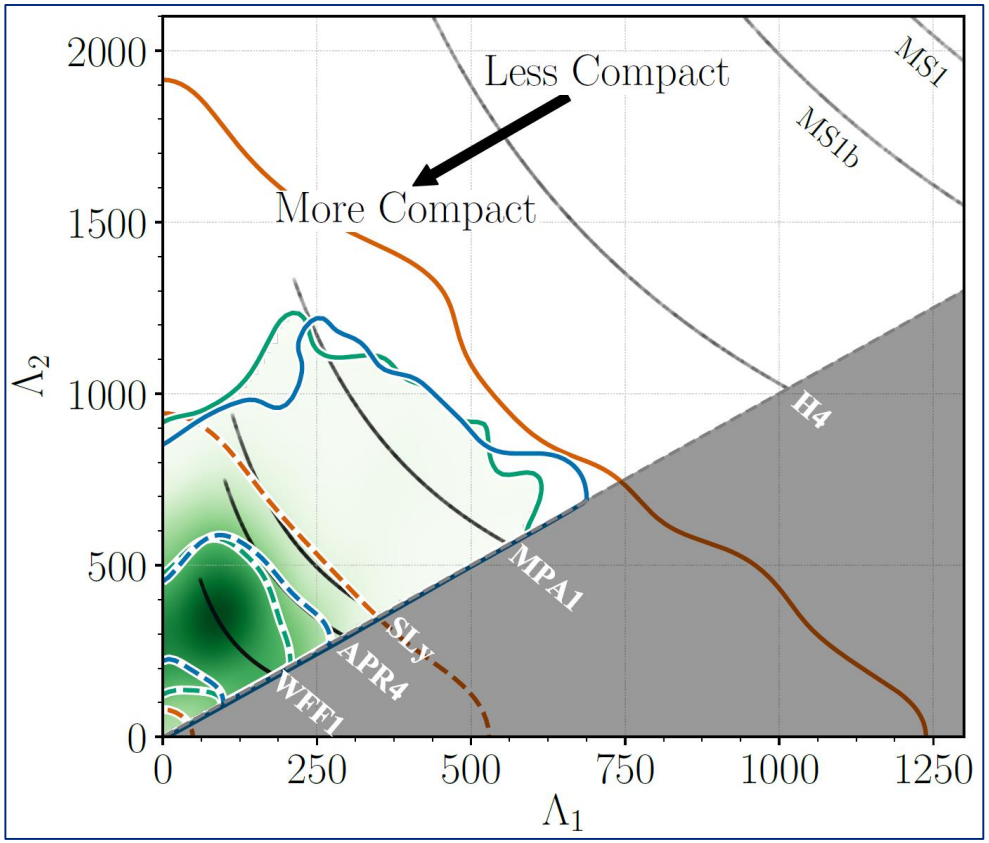
Bernuzzi, Nagar, Font, …

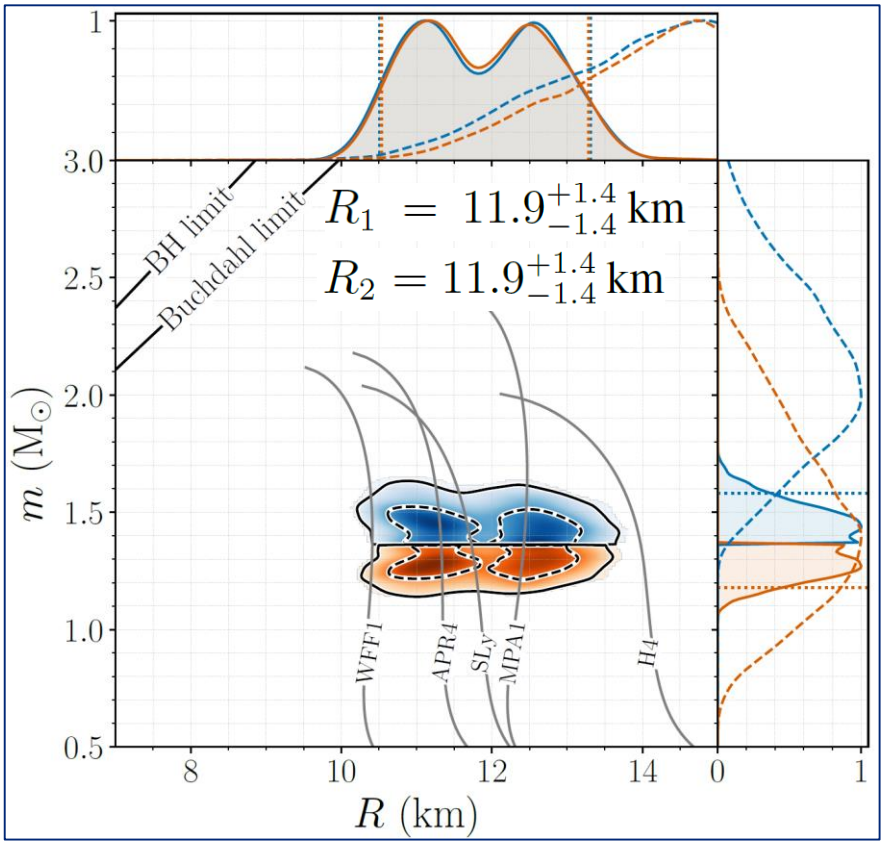
Event GW170817: tidal deformability, EOS, radii

Tidal deformability gives support for “soft” EOS, leading to more compact NS. Various models can now be excluded. We can place the additional constraint that the EOS must support a NS $1.97\,\mathrm{M}_\odot$

Leading tidal contribution to GW phase appears at 5 PN: $\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$

Employ common EOS for both NS (green shading), EOS insensitive relations (green), parametrized EOS (blue), independent EOSs (orange). See: LVC, https://arxiv.org/abs/1805.11581



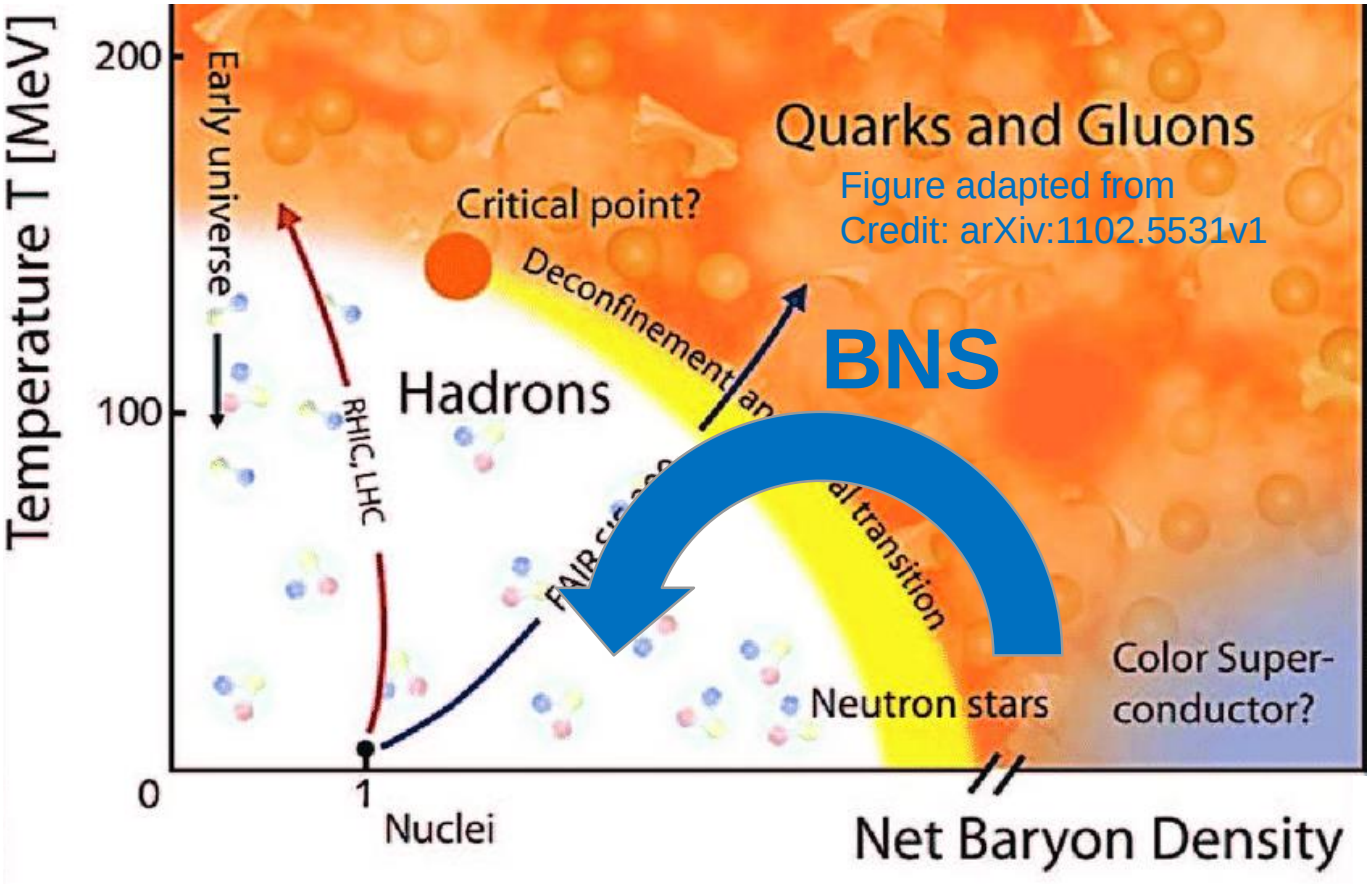


Schematic QCD phase diagram

Cores of neutron stars hold supranuclear-density matter in a cold neutron-rich equilibrium

Physics of binary neutron star mergers is relevant for high baryon density (up to $10n_0$) and temperatures from keV to 50 – 100 MeV

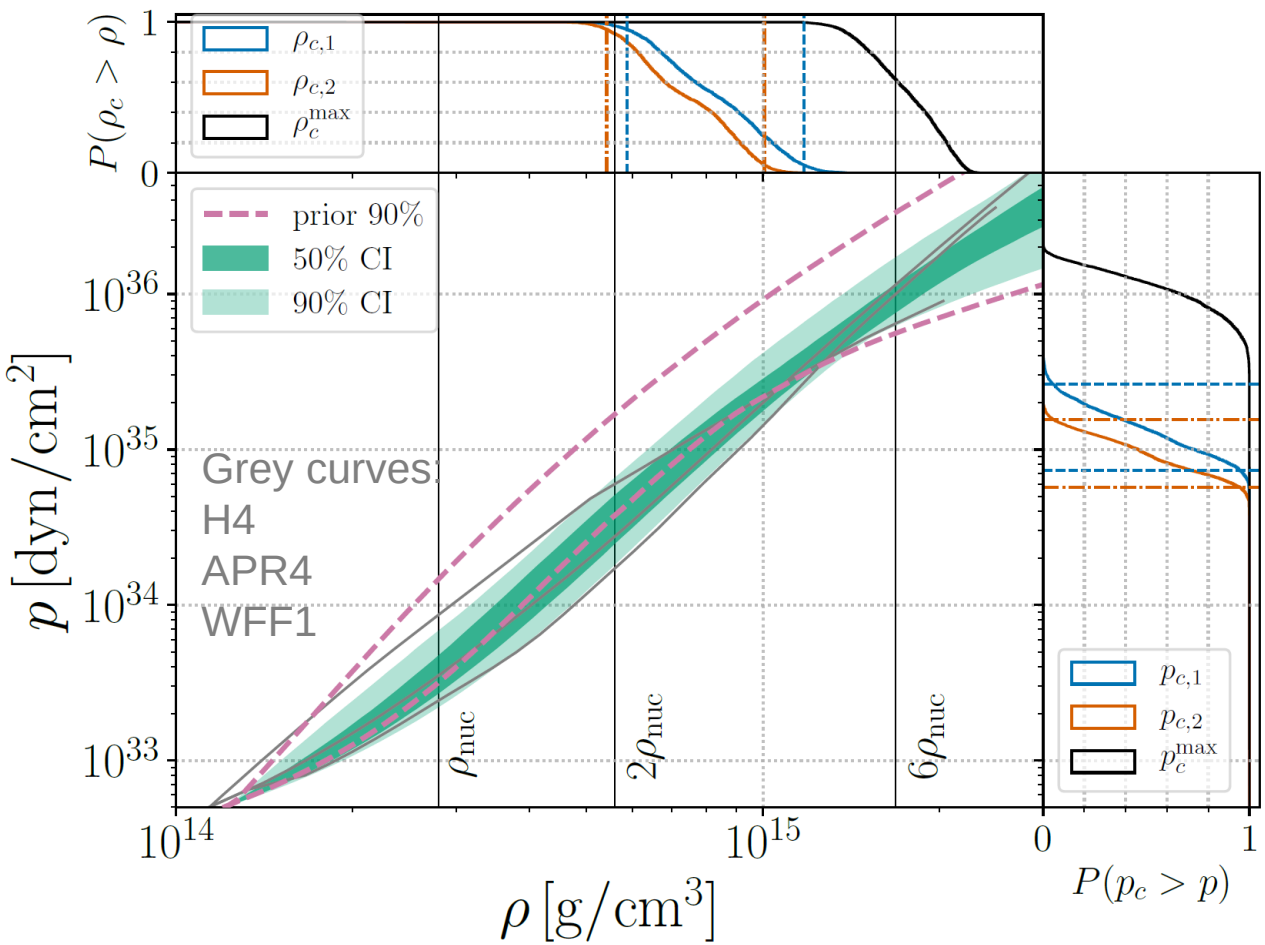
Study effective degrees of freedom and their interactions



Pressure versus rest-mass density of NS interior

Spectral EOS parametrization and imposing a lower limit on the maximum NS mass supported by the EOS of 1.97 M_solar

The pressure posterior is shifted from the 90% credible prior region (marked by the purple dashed lines) and towards the soft floor of the parametrized family of EOS



No experimental support for new degrees of freedom or phase transition around five times nuclear density

See: LVC, https://arxiv.org/abs/1805.11581

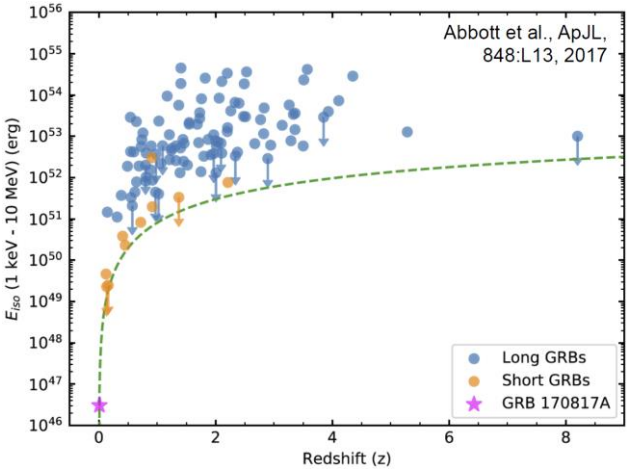
Looking into the heart of a dim nearby sGRB

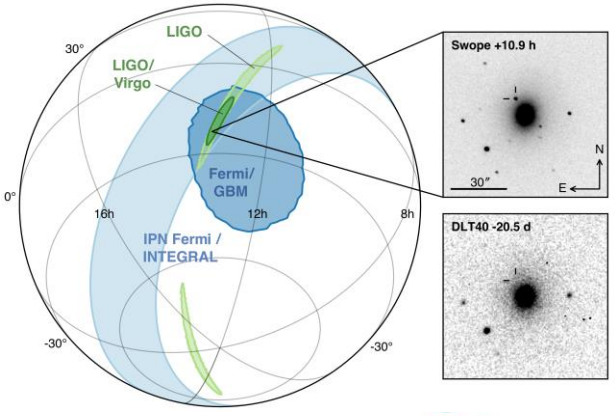
Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

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

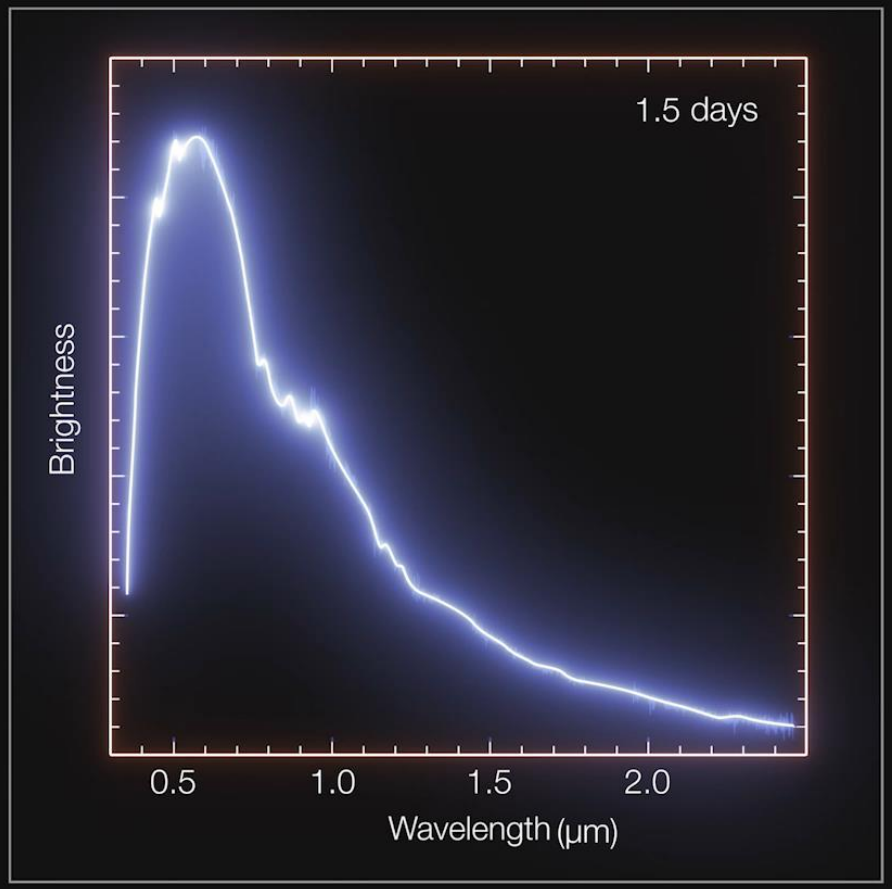


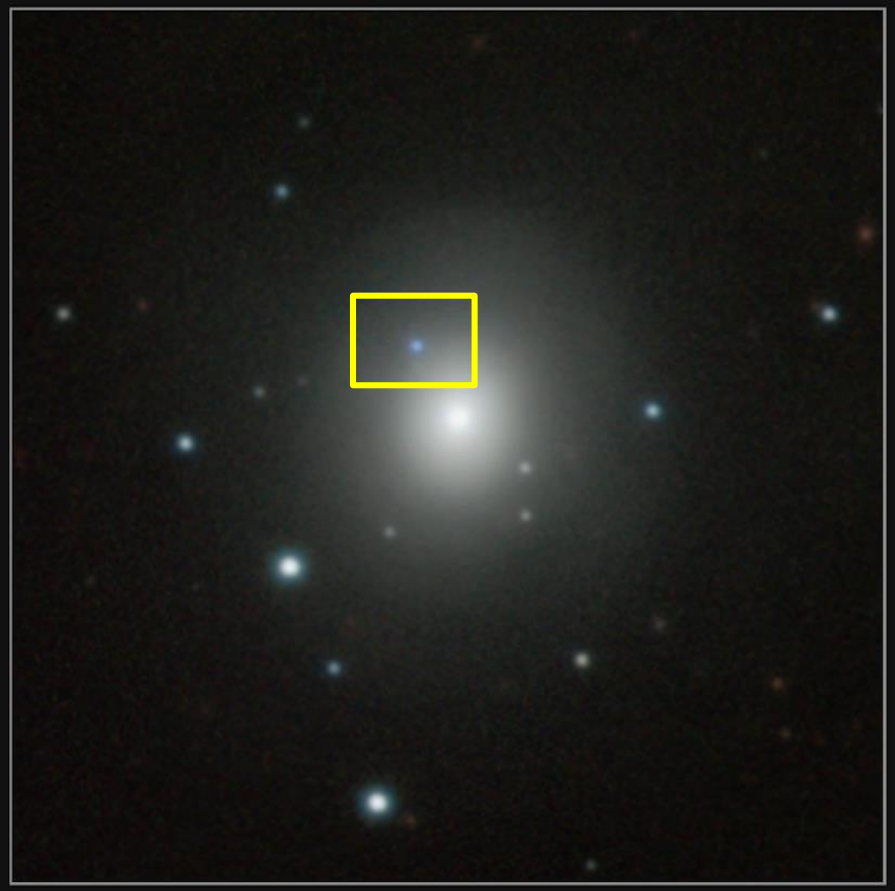


European Southern Observatory

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

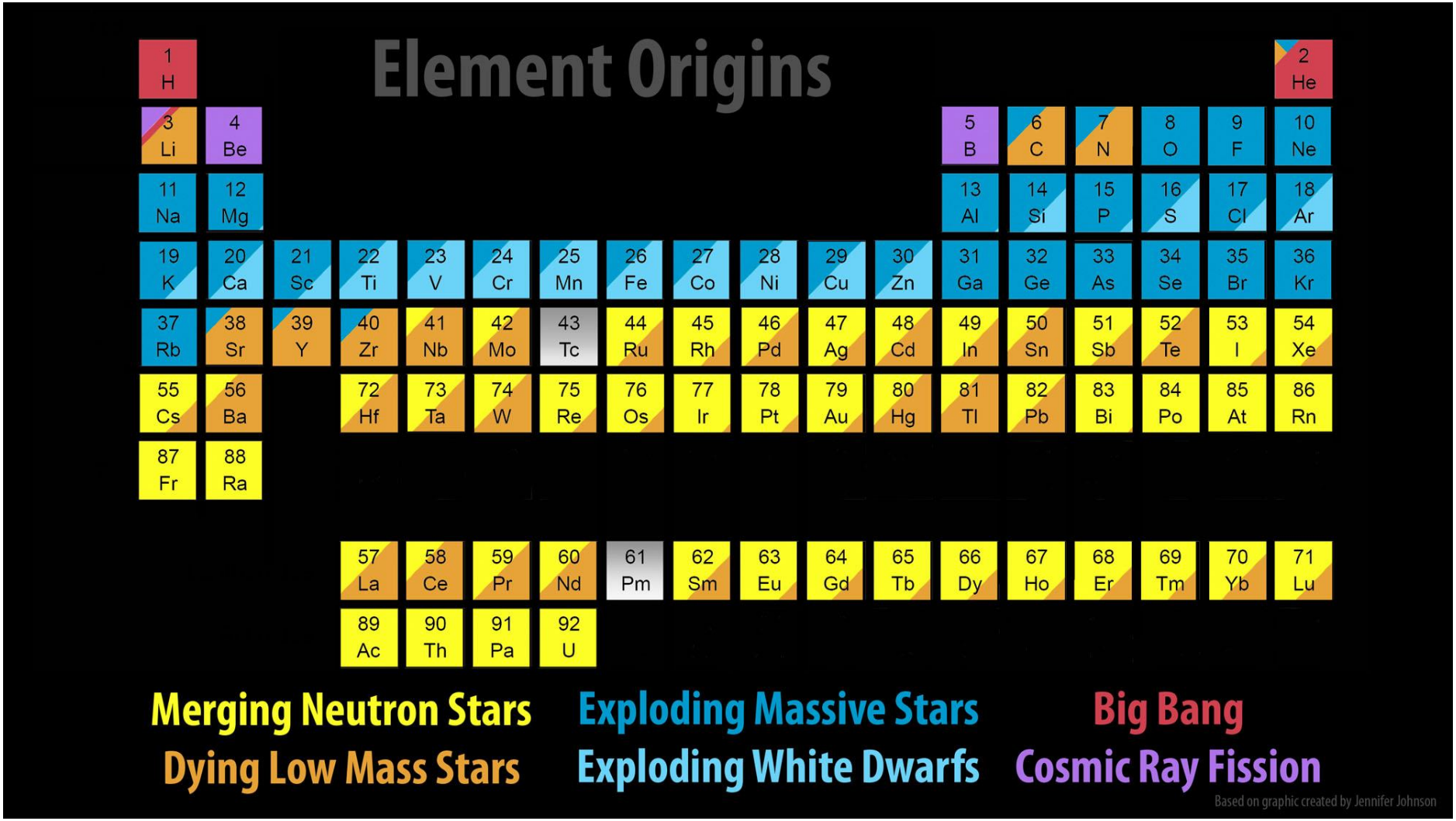
Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region





Many heavy elements were produced in such collisions

GW170817 does not allow identification of spectra of these individual elements



Identification of strontium in event GW170817

Identification of Strontium, an element that could only have been synthesised so quickly under an extreme neutron flux, provides the first direct spectroscopic evidence that neutron stars comprise neutron-rich matter

The kilonova essentially has a blackbody (blue dotted lines) with a temperature of 3,700 K

Assume solar r-process abundance ratios

Sr accounts for at least a few percent by mass of all r-process elements

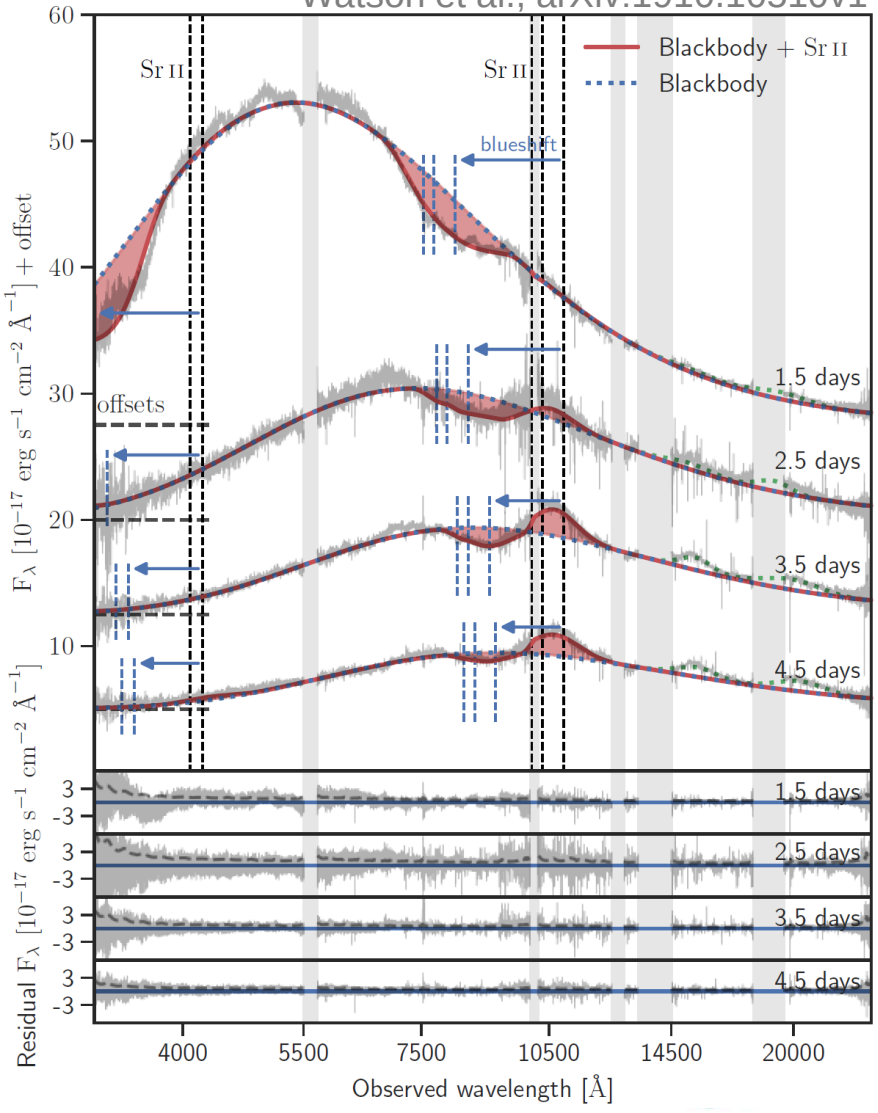
P Cygni profiles (red transparent fill) increasingly develop in time for the Sr lines

Lines are Doppler broadened by 0.2 c due to the high speed of the ejected material and blue-shifted by 0.23 c

Extreme-density stars composed of neutrons were proposed shortly after the discovery of the neutron, and identified with pulsars three decades later

GW170817 provides first spectroscopic evidence of neutron-rich matter in neutron stars

Watson et al., arXiv:1910.10510v1



Release of Open Public Alerts

LIGO and Virgo Collaborations release Open Public Alerts, with low latency, for all interesting signal triggers, and follow-up information sufficient for non-GW observers to find hosts. We also release data and data analysis software

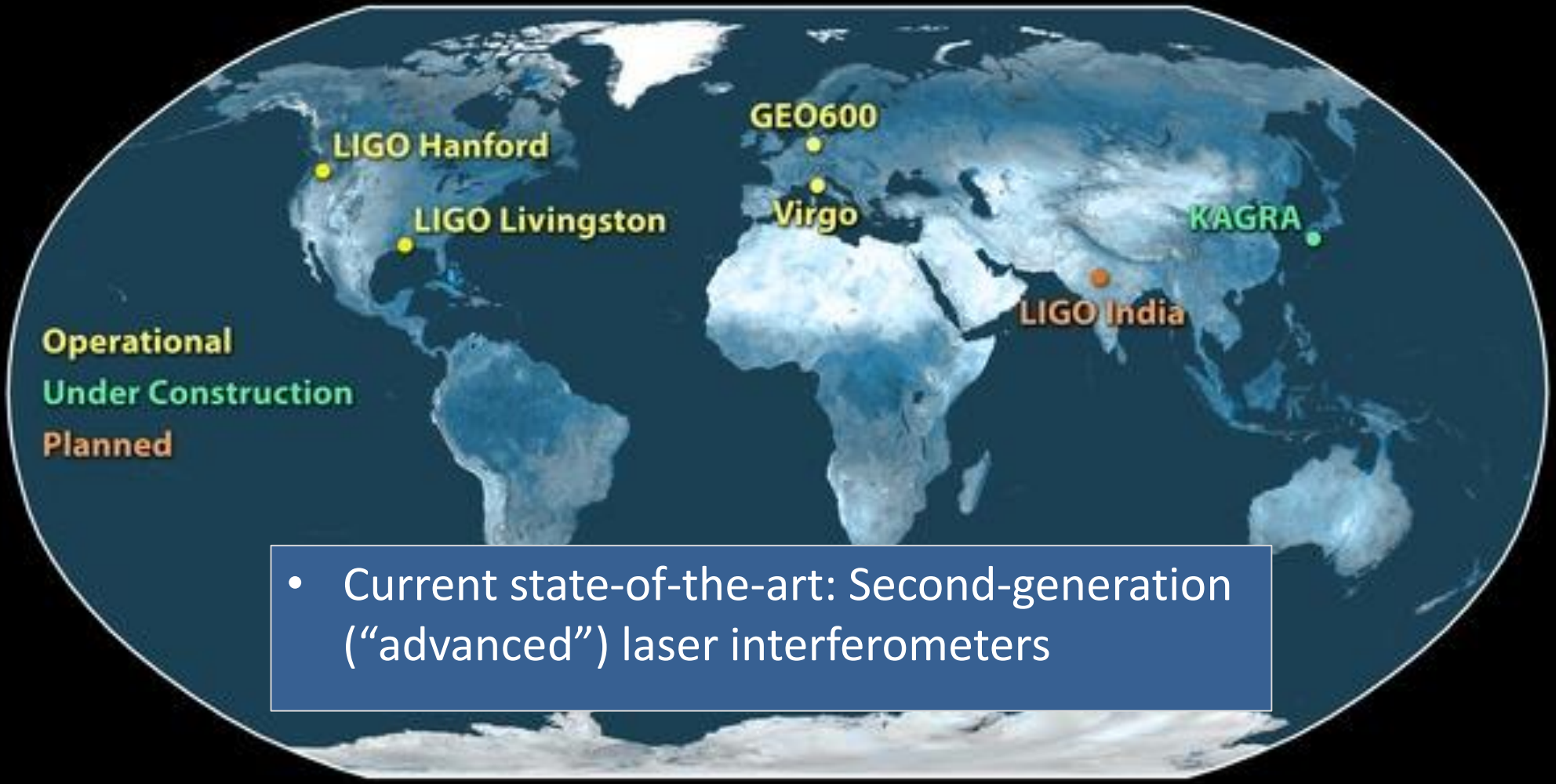
For a quick overview of all our new papers
See our Science Summaries available in multiple languages:
https://www.ligo.org/science/outreach.php

You can also find tutorials, GW data analysis software and other tools
at our Gravitational Wave Open Science Center:
https://www.gw-openscience.org/about/

If you'd like to receive alerts about new GW detections
Check out our LIGO/Virgo Public Alerts User Guide:
https://emfollow.docs.ligo.org/userguide/

Instrumentation

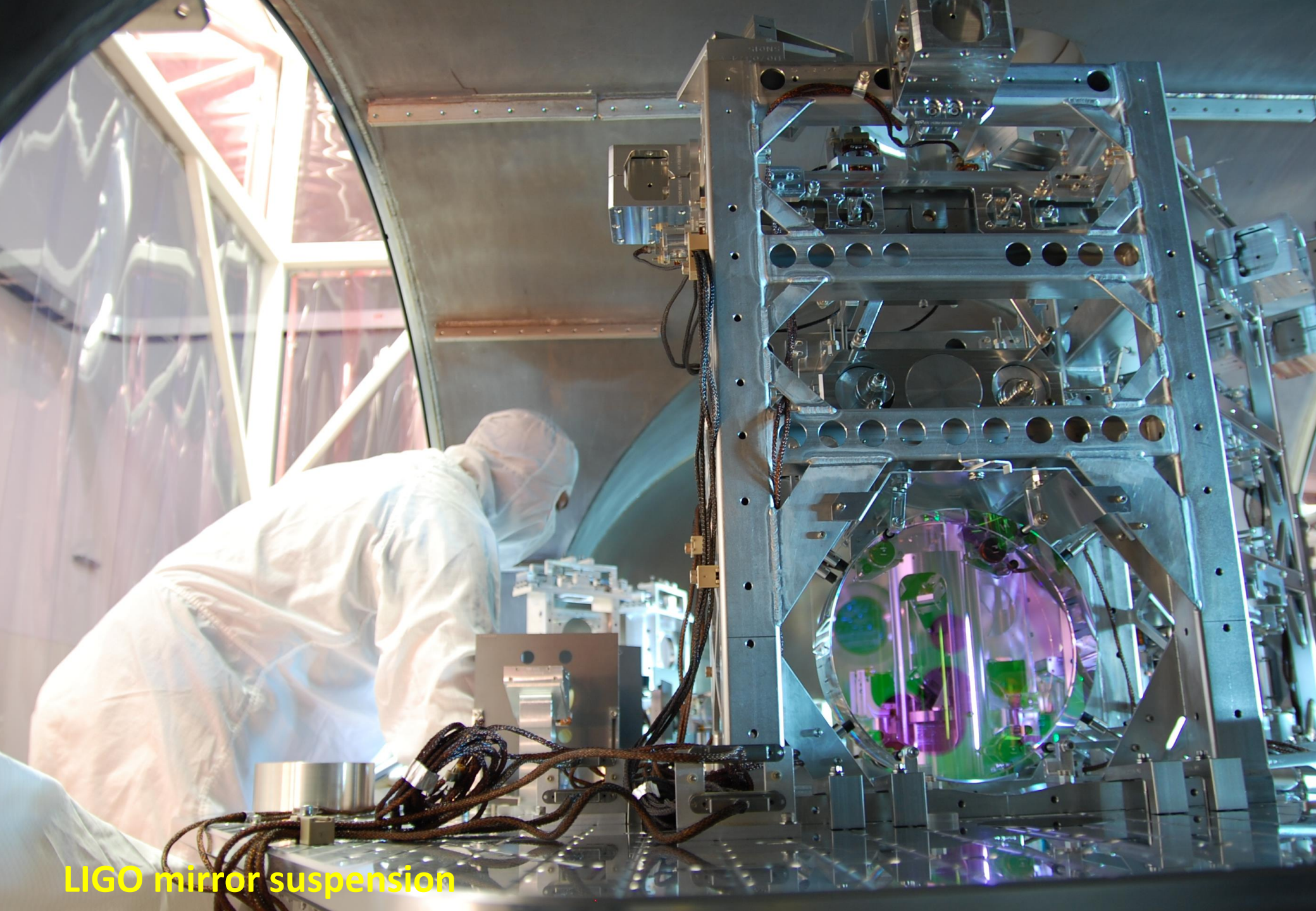
Global GW Detector Network



- Current state-of-the-art: Second-generation ("advanced") laser interferometers

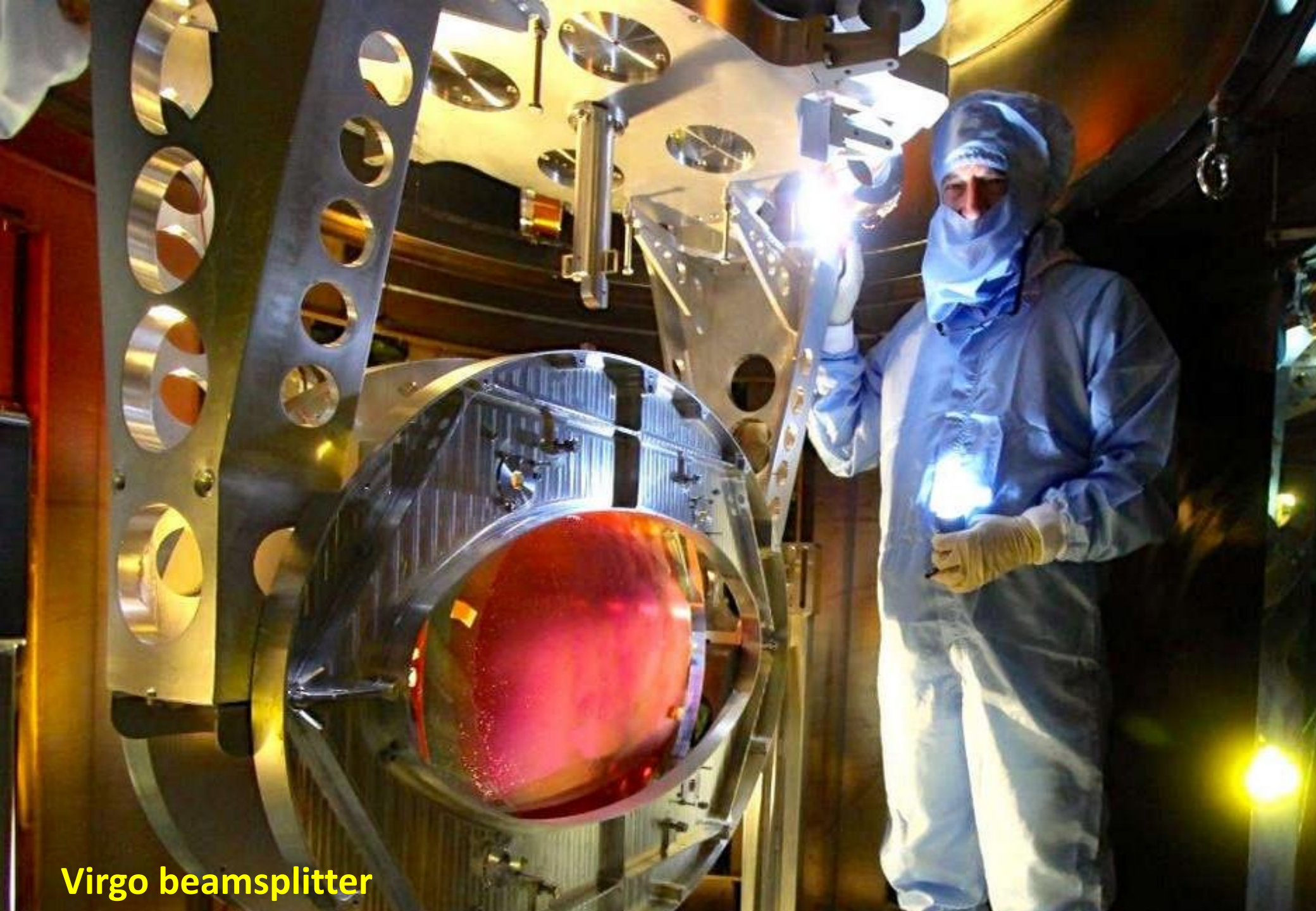
LIGO Livingston, Louisiana

LIGO mirror


LIGO mirror suspension

Virgo interferometer

Virgo interferometer



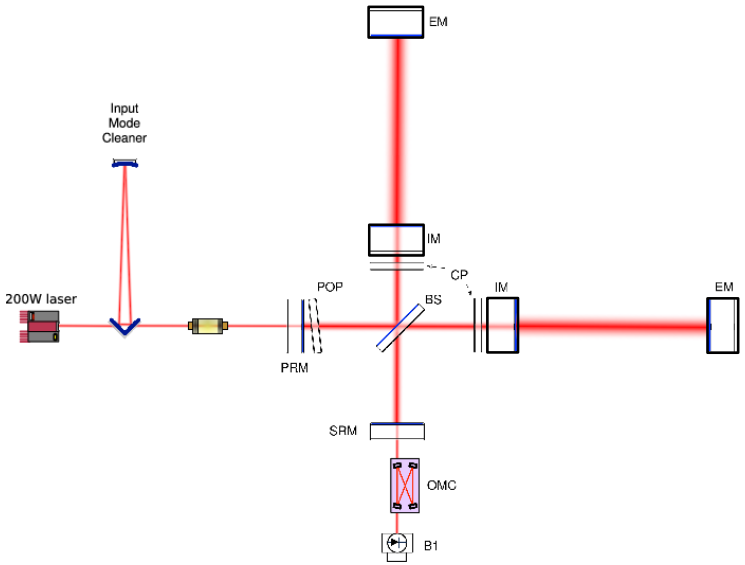
Virgo beamsplitter

Input mode cleaner cavity

Di-hedron: two-mirror system

Input mode cleaner

- 144 m long triangular ring cavity
- Finesse about 1100
- Di-hedron cavity mirror pair
- Filter unwanted modes
- First step in Virgo’s frequency stabilization
- Designed by Nikhef
- Fabricated in collaboration with Optronica

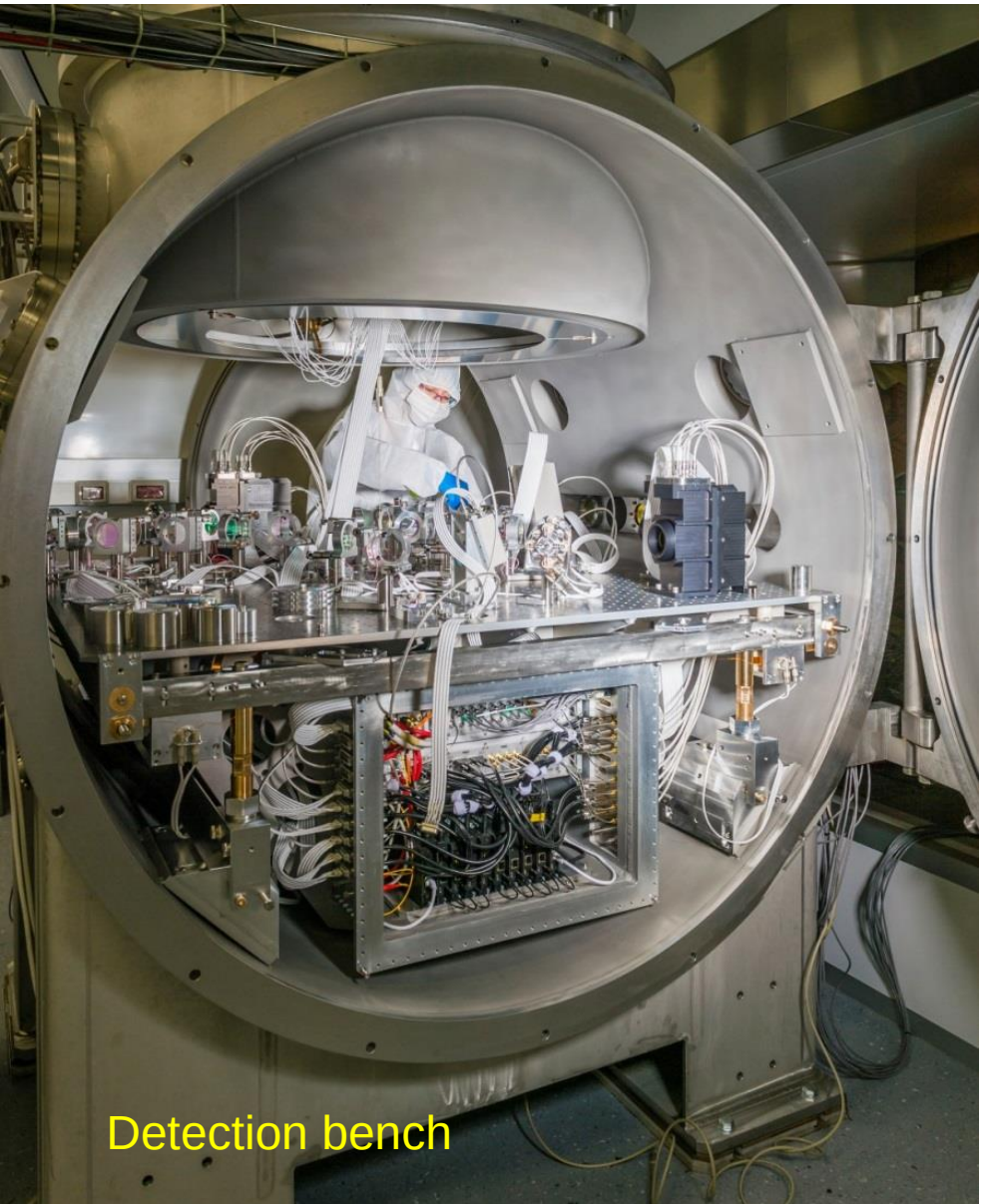


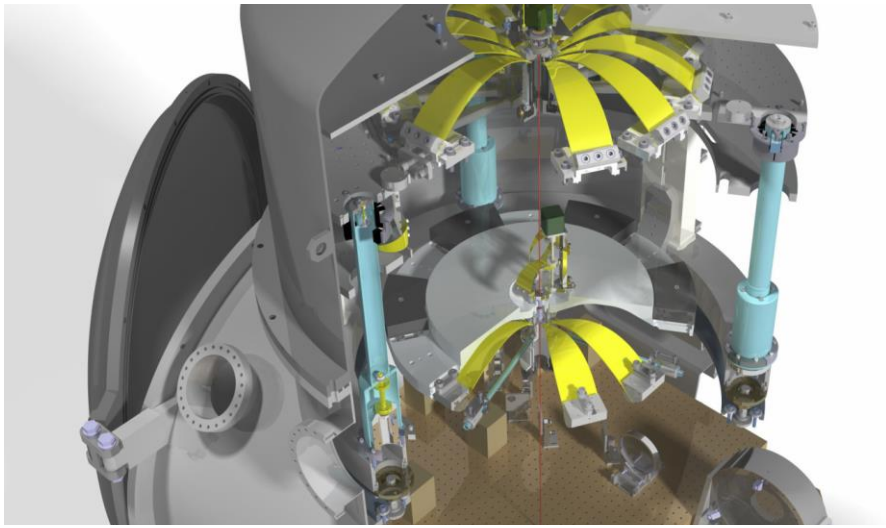
End mirror system of the input mode cleaner

End mirror including recoil mass and marionette. Installed and commissioned for Advanced Virgo

Vibration isolation systems

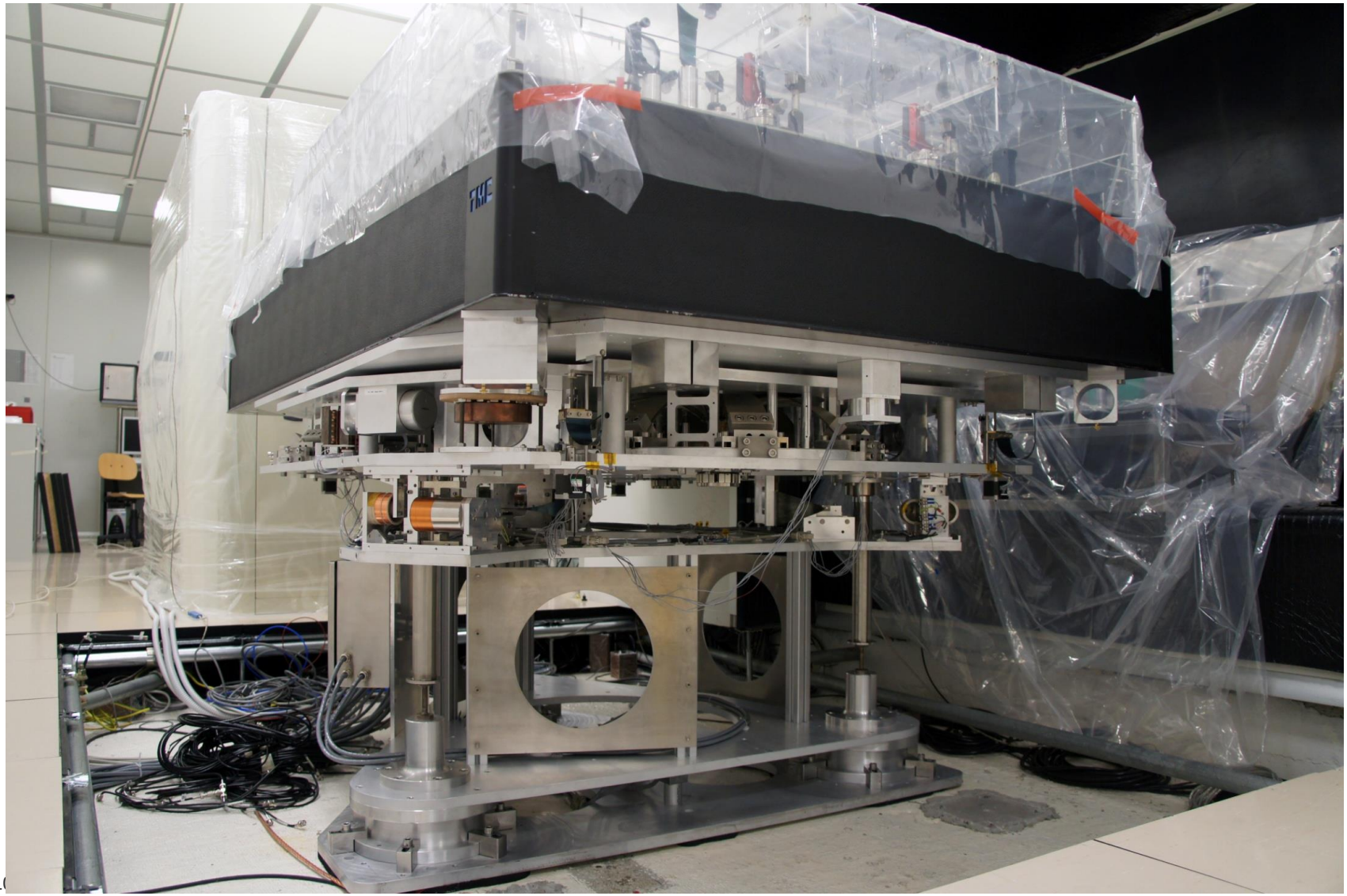
Optical systems for linear alignment, vibration isolation, IMC and phase camera's, etc.





External injection bench suspended

EIB is last laser bench before laser enters the vacuum. EIB-SAS provides vibration attenuation by about a factor 1000 in 6 DOFs



Phase camera

Spatial amplitude and phase distribution at high speed for carrier and side bands. Unique tool to identify distortions of circulating beams

Diagnostic tool for Virgo commissioning

- Mode purity of circulating light
- Clipping of HG08 mode? Stray light?

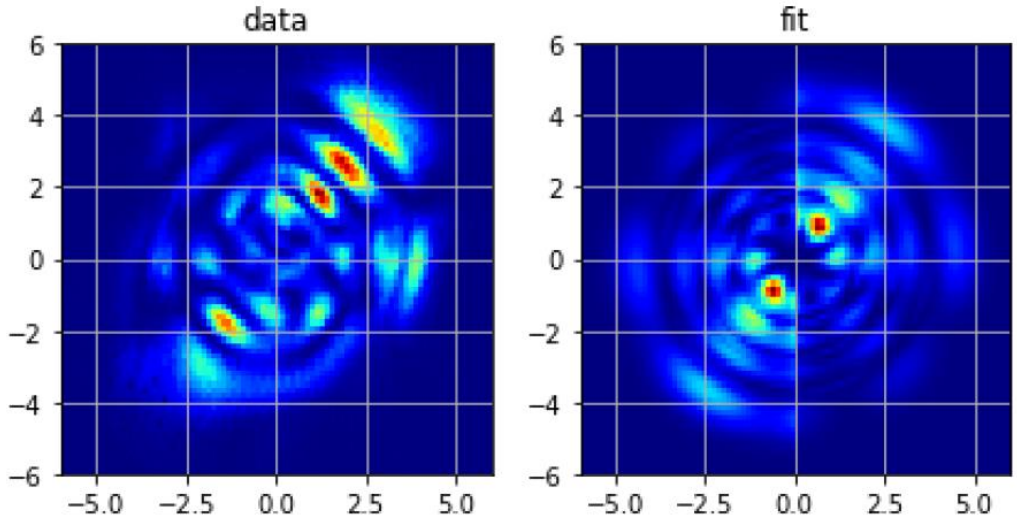
Crucial sensor for TCS

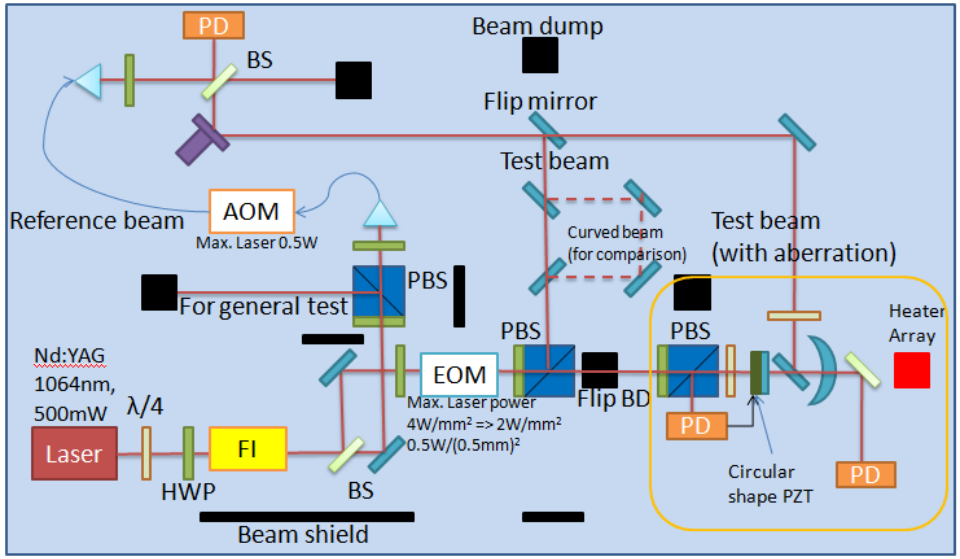
Increasingly important at higher powers (3G)

Interest from LIGO (UBirmingham)

Applications:

See http://www.liquidinstruments.com/

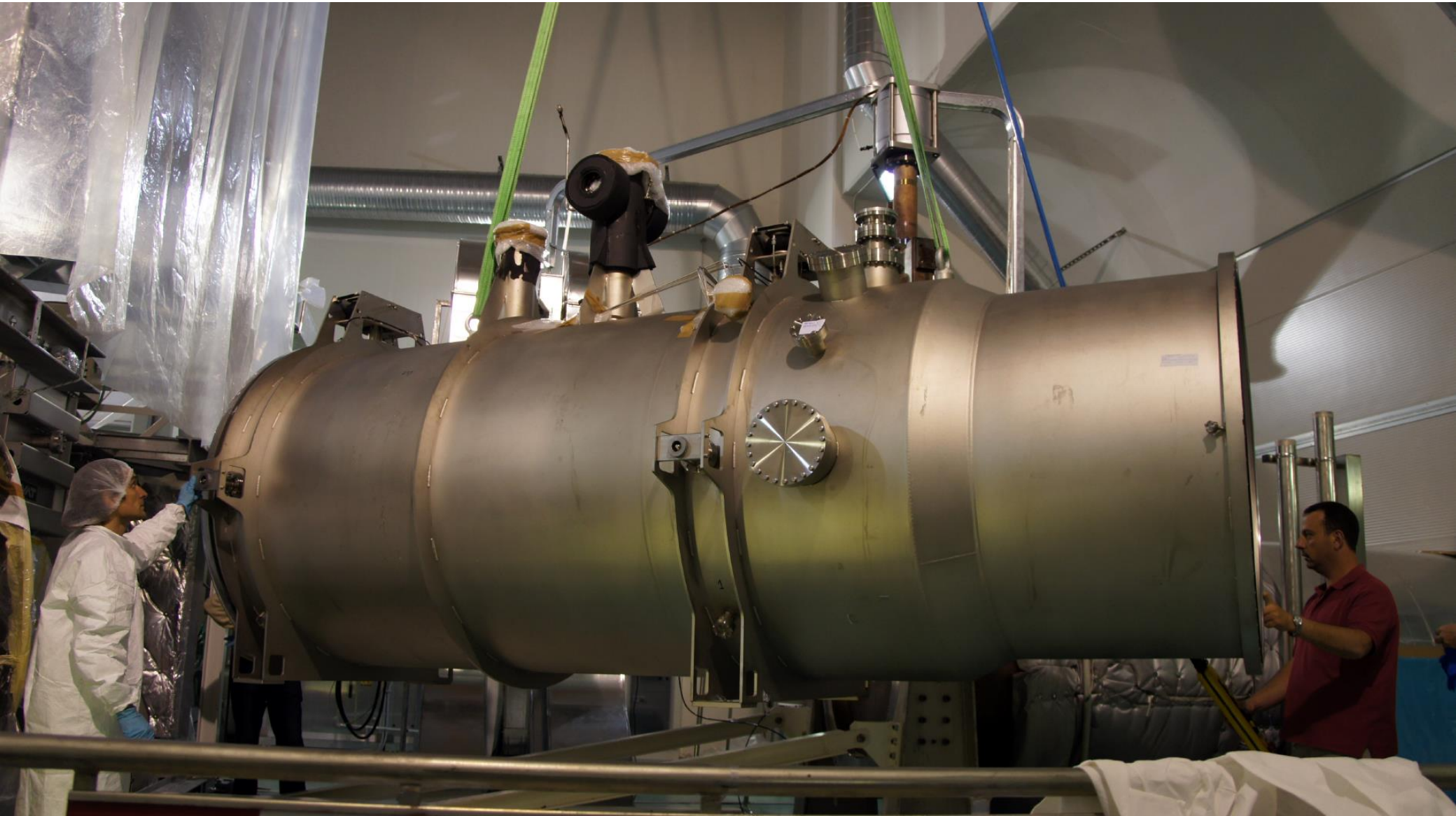




Virgo vacuum system

Cryolinks to achieve UHV in the ITF arms of Advanced Virgo

Four cryogenic links installed and commissioned. Advanced Virgo requires an ultra-high vacuum with pressures below 10^{-9} mbar



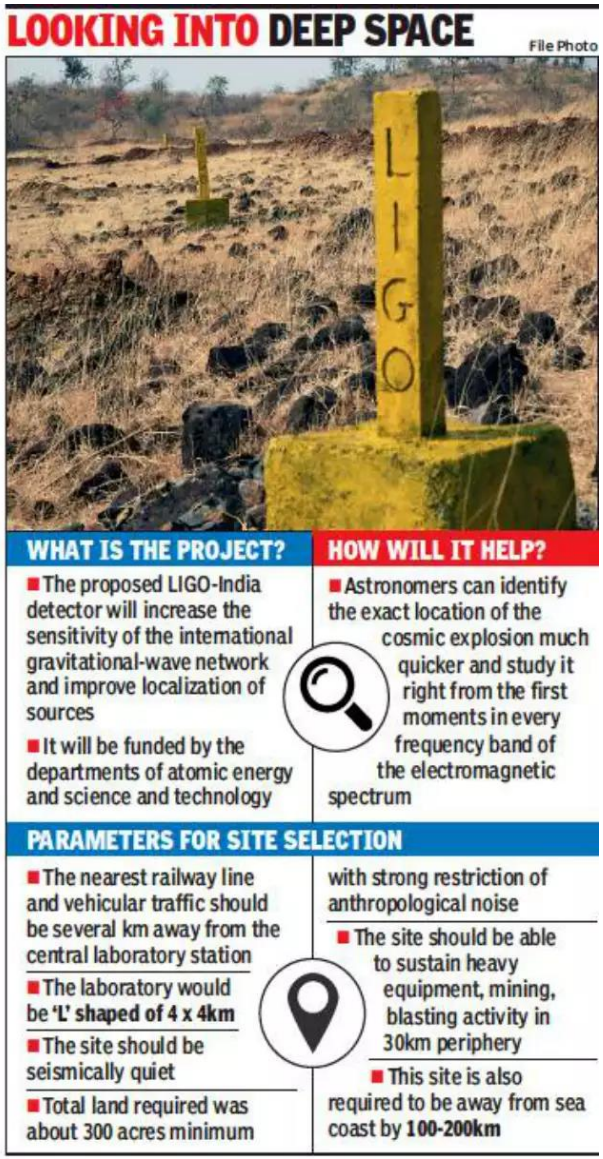
KAGRA inauguration

Signing of the MOA with LIGO and VIRGO
Toyama, October 4, 2019

KAGRA

LIGO-India: construction has started (online 2025?)

The 4 km interferometer will be sited at Hingoli in Maharashtra, about 450 km from Pune



LOOKING INTO DEEP SPACE

File Photo

WHAT IS THE PROJECT?

- The proposed LIGO-India detector will increase the sensitivity of the international gravitational-wave network and improve localization of sources
- It will be funded by the departments of atomic energy and science and technology

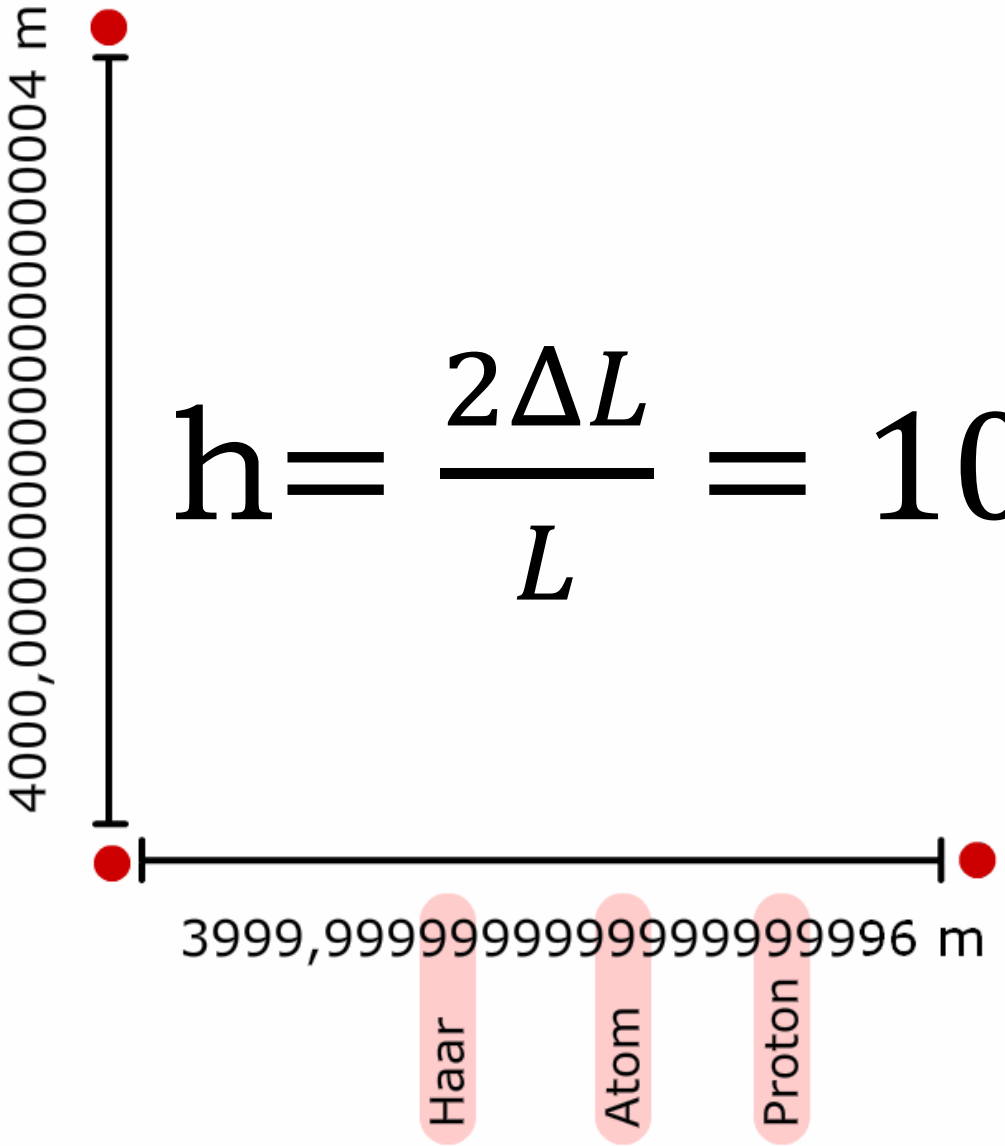
HOW WILL IT HELP?

- Astronomers can identify the exact location of the cosmic explosion much quicker and study it right from the first moments in every frequency band of the electromagnetic spectrum

PARAMETERS FOR SITE SELECTION

- The nearest railway line and vehicular traffic should be several km away from the central laboratory station
- The laboratory would be **'L' shaped of 4 x 4km**
- The site should be seismically quiet
- Total land required was about 300 acres minimum with strong restriction of anthropological noise
- The site should be able to sustain heavy equipment, mining, blasting activity in 30km periphery
- This site is also required to be away from sea coast by **100-200km**

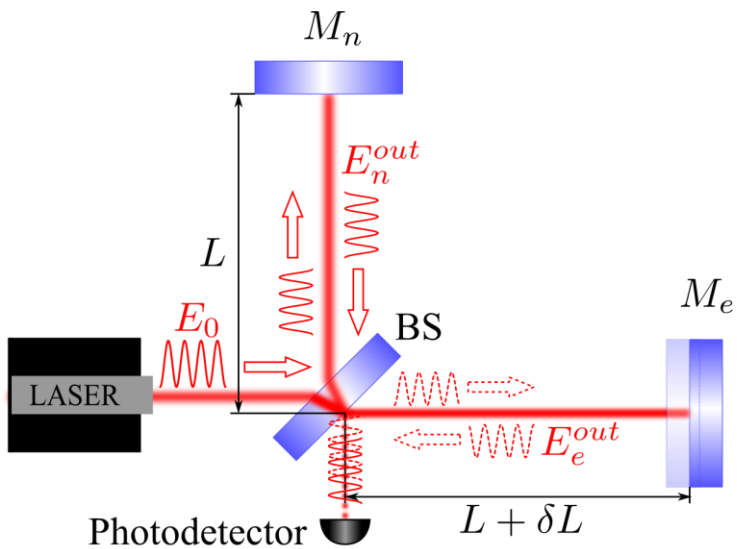
Effect of a strong gravitational wave on ITF arm



$$h = \frac{2\Delta L}{L} = 10^{-22}$$

Laser interferometer detectors

Michelson interferometer

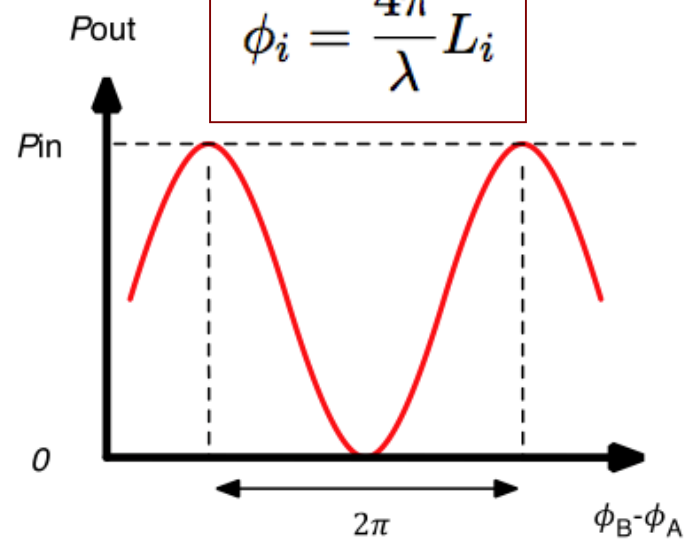


$$E_{out} = \frac{1}{2}\left(e^{-i\phi_A} - e^{-i\phi_B}\right)E_{in}$$

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

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

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



If we would use a single photon and only distinguish between bright and dark fringe, then such an ITF would not be sensitive:

$$h_{\text{crude}} \approx \frac{\lambda/2}{L_{\text{optical}}} = \frac{0.5 \times 10^{-6}\ \text{m}}{4000\ \text{m}} \approx 10^{-10}$$

Need to do 10^{12} times better. This would required 10^{24} photons in each 0.01 s interval

Power required $P_{in} = \frac{2\pi\hbar c}{\lambda}\bar{N} \approx 20\ \text{MW}$

Virgo uses 18 W of input power

Michelson (Nobel Prize in 1907) could read a fringe to $\lambda/20$, yielding h_{rms} of a few times 10^{-9}

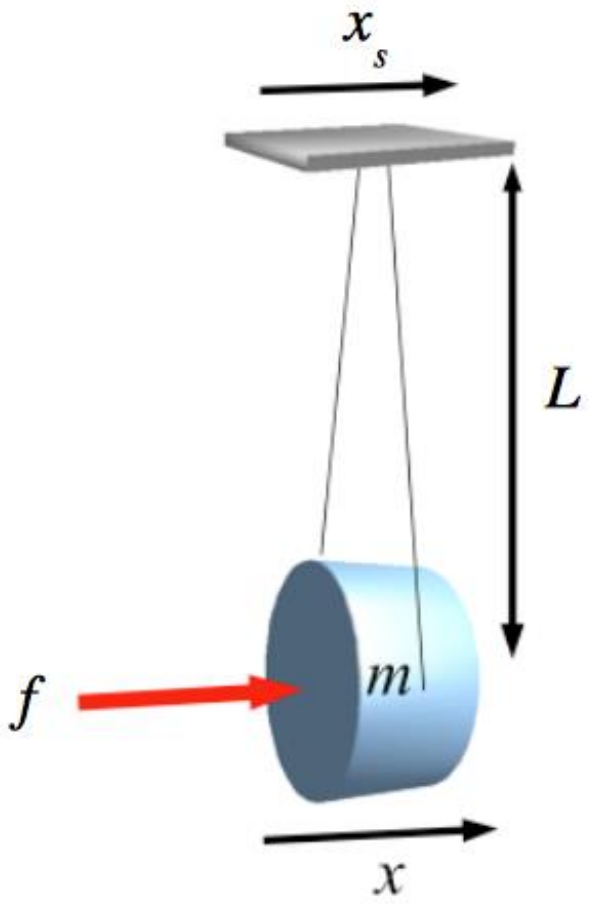
Laser interferometer detectors

Free-falling interferometers on Earth

Earth is not an inertial reference frame

nevertheless

It's always possible to make a test mass 'free falling' in a certain frequency range by 'suspending' it, i.e. by connecting it to the Earth as a pendulum



Laser interferometer detectors

Simple pendulum transfer function

The equation of motion is:

$$m\ddot{x} + b\dot{x} + \frac{mg}{L}(x - x_s) = f$$

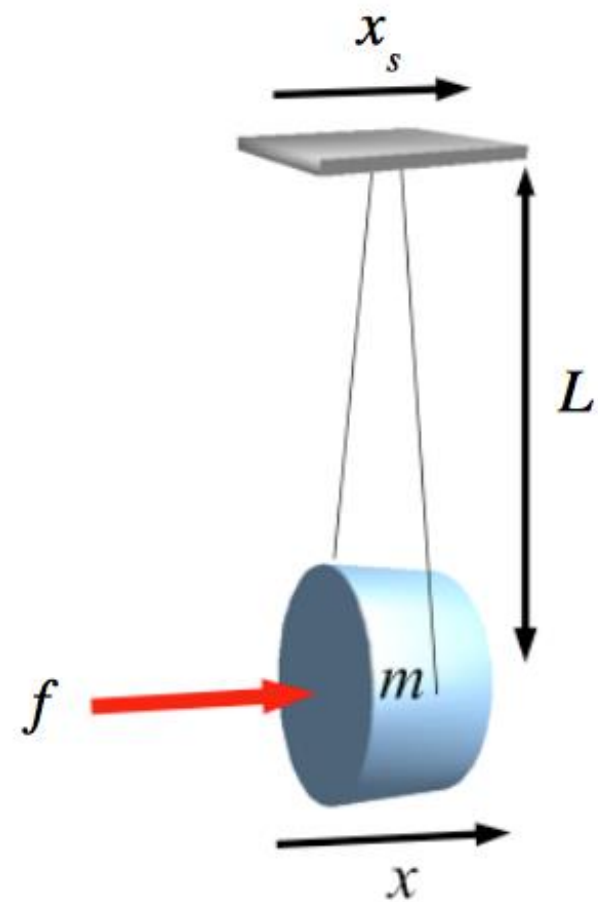
which is in the frequency domain is

$$-m\omega^2 X + i\omega X + \frac{mg}{L}(X - X_s) = F$$

by solving it we find

$$X = \frac{{\omega_0}^2}{\omega_0^2 - \omega^2 + i\frac{\omega\omega_0}{Q}} \cdot X_s + \frac{F/m}{{\omega_0}^2 - \omega^2 + i\frac{\omega\omega_0}{Q}}$$

where $\omega_0 = \sqrt{\frac{g}{L}}$ and $Q = \frac{m\omega_0}{b}$



Laser interferometer detectors

Simple pendulum transfer function

at low frequencies ($\omega \ll \omega_0$)

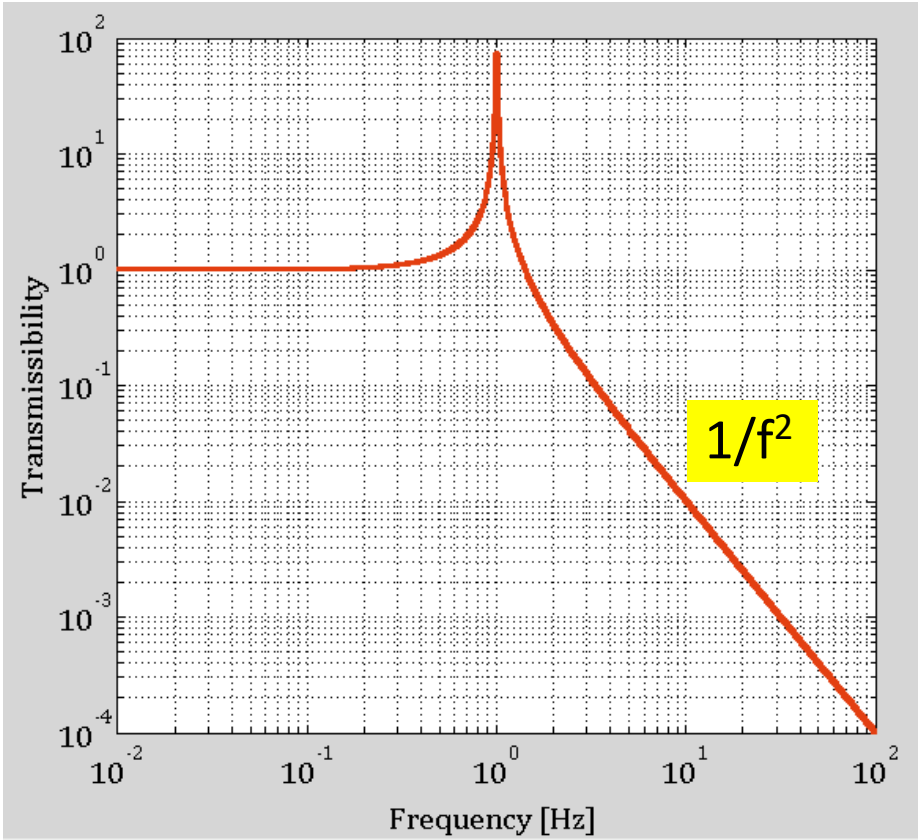
$$X \simeq X_s + F/m{\omega_0}^2$$

at the natural frequency ($\omega = \omega_0$)

$$X \simeq Q(X_s + F/m{\omega_0}^2)$$

while at high frequency ($\omega \gg \omega_0$)

$$X \simeq \frac{{\omega_0}^2}{\omega^2} X_s + F/m\omega^2$$

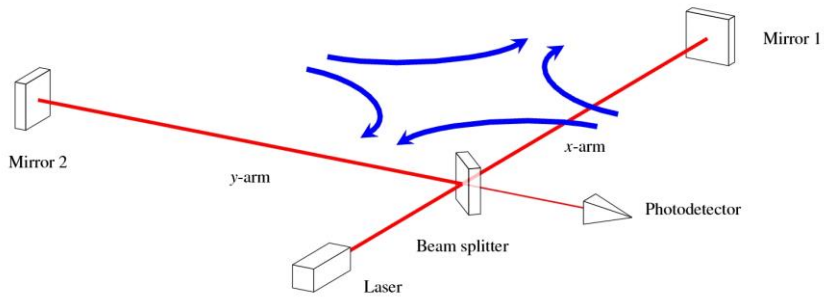


At high frequency the mirrors respond to external forces only with their inertia. They act as if the suspension is not there! In that sense they are “freely falling”

At low frequency we use feedback control to mimic rigidly mounting of our mirrors

Laser interferometer detectors

Michelson interferometer: response to a gravitational wave



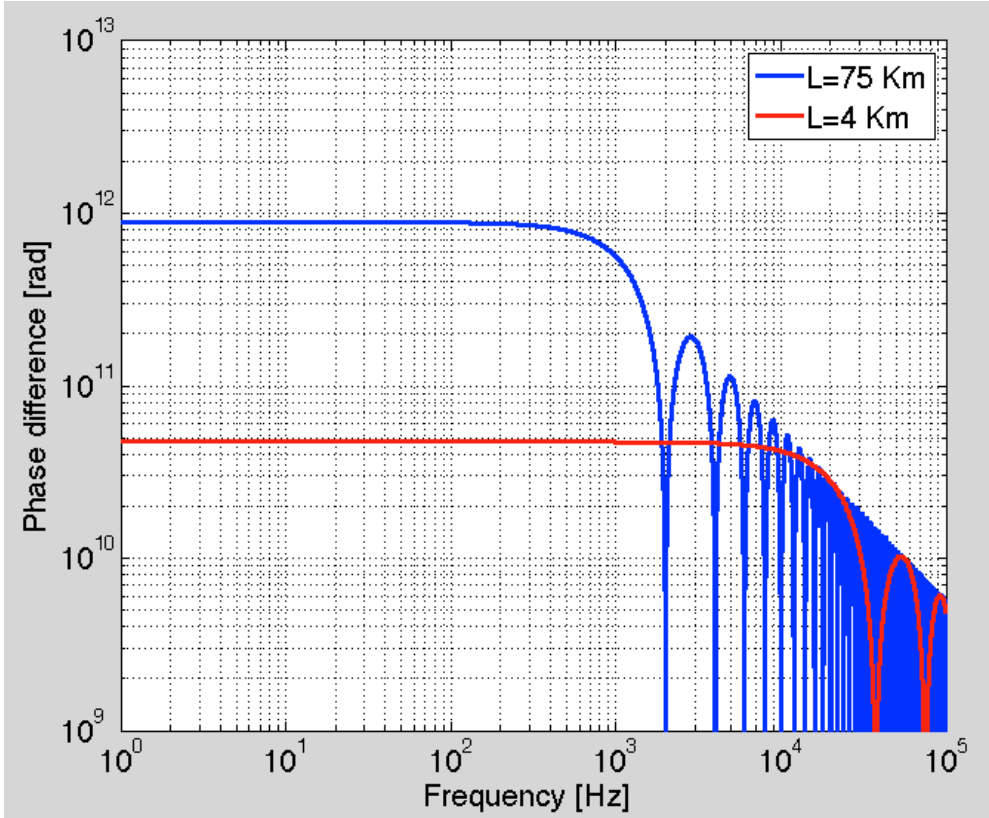
for $f_{gw} \ll c/2L$ the response is flat with

$$\phi_x - \phi_y = \frac{4\pi L}{\lambda} h$$

$$\phi_x - \phi_y = \Omega(\tau_x - \tau_y) = \Omega \int_0^{2L/c} h(\tau) d\tau$$

which for $h(t) = h_0 e^{i\omega t}$ is

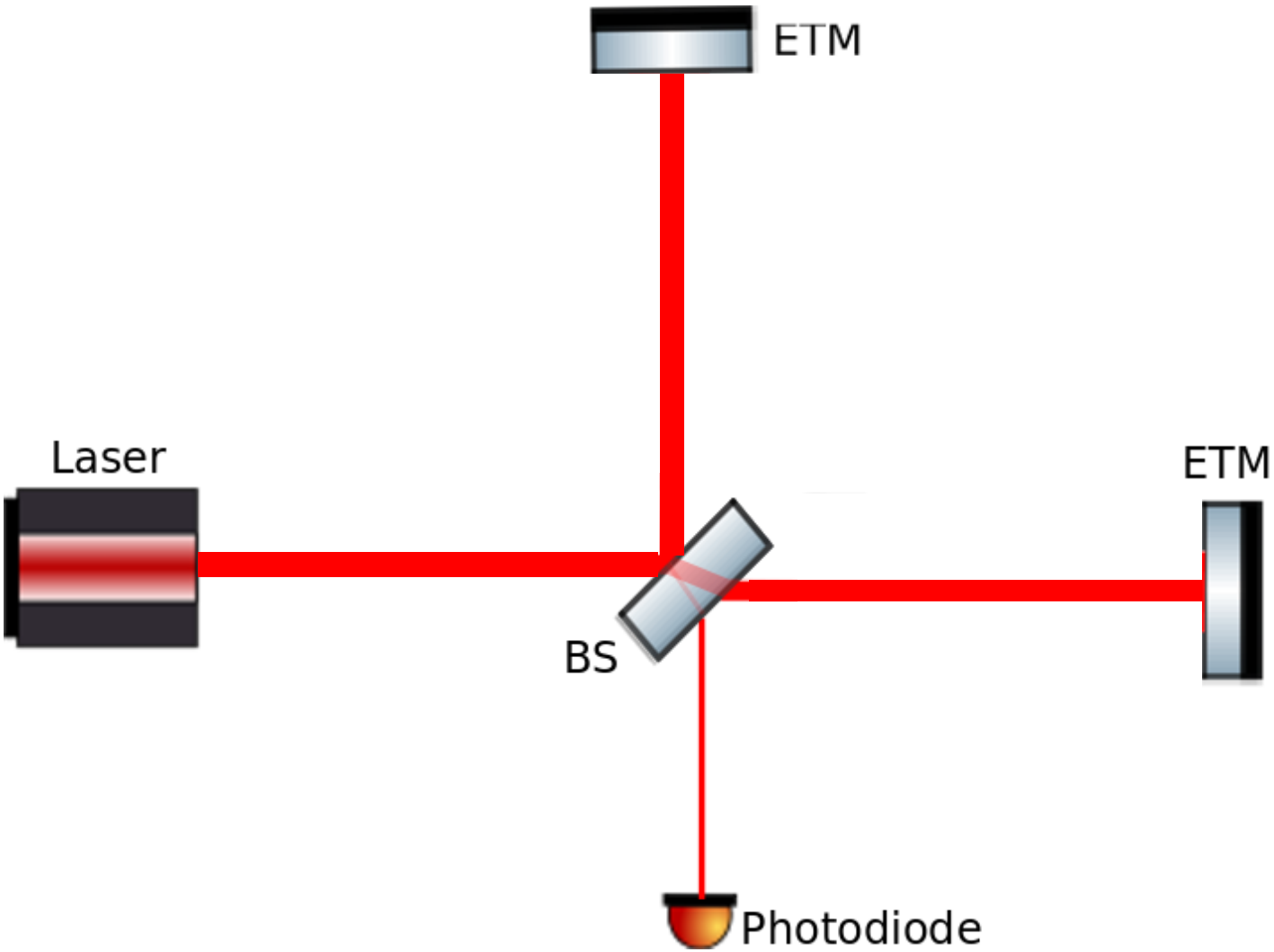
$$\phi_x - \phi_y = \frac{4\pi L}{\lambda} \left[\frac{\sin \omega L/c}{\omega L/c} e^{-i\omega L/c} \right] h_0 e^{i\omega t}$$



One would love to have *L = 75* km but ....

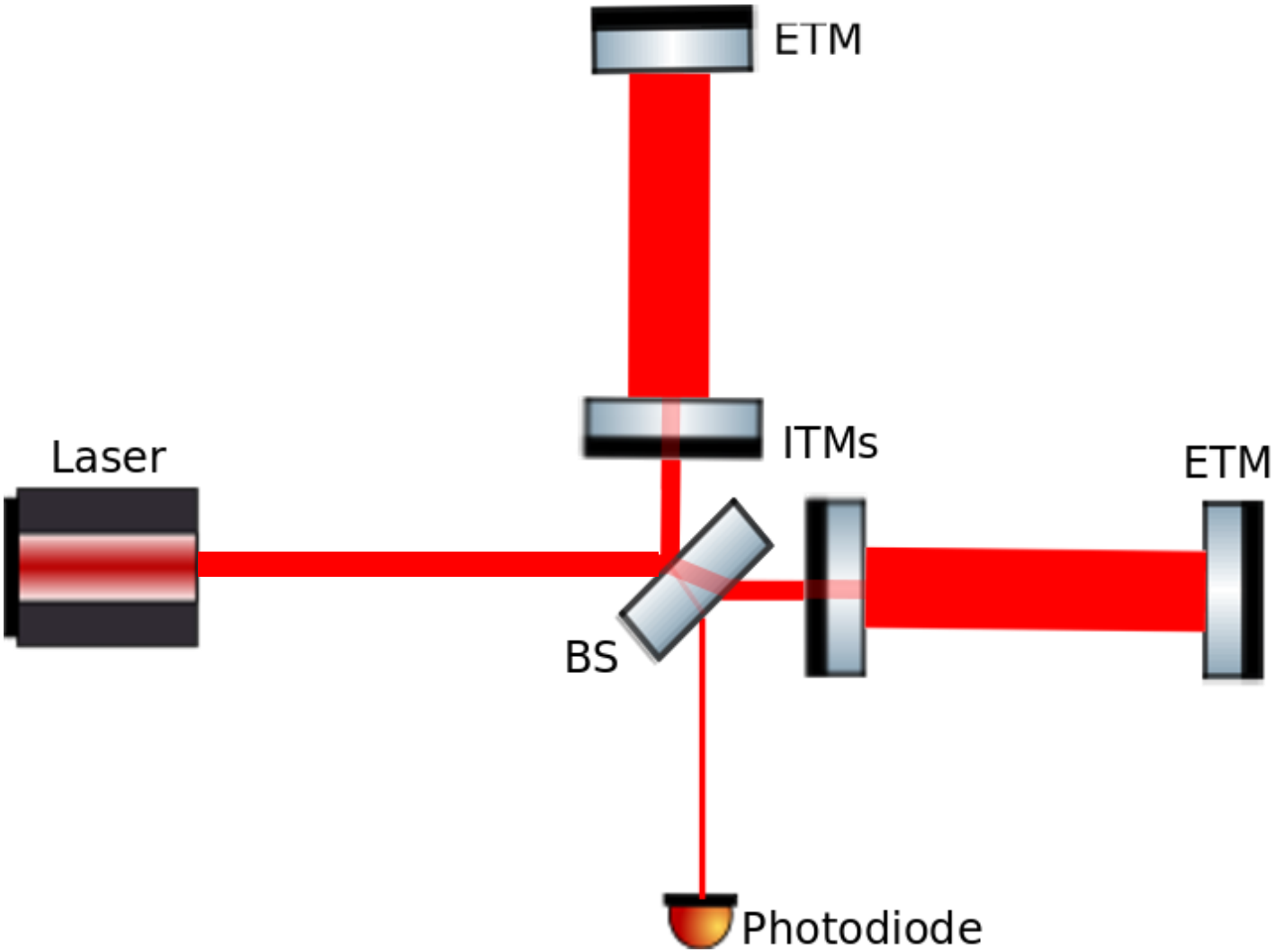
Laser interferometer detectors

Michelson interferometer



Laser interferometer detectors

Fabry-Perot cavities in the arms



Laser interferometer detectors

Fabry-Perot arm cavities *(idea from Ron Drever)*

$$E_{in}(t,x) = E_{in}^0 e^{i(\Omega t - \frac{2\pi}{\lambda}x)}$$

for the **circulating** field we find

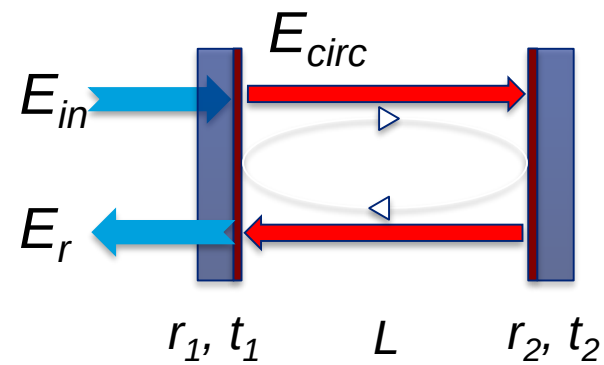
$$E_{circ} = t_1 E_{in} + r_1 r_2 E_{circ} e^{-i4\pi L/\lambda}$$

$$\boxed{\frac{E_{circ}}{E_{in}} = \frac{t_1}{1 - r_1 r_2 e^{-i4\pi L/\lambda}}}$$

while for the **reflected** field we find

$$E_r = -t_1 E_{in} + r_2 t_1 E_{circ} e^{-i4\pi L/\lambda}$$

$$\boxed{\frac{E_r}{E_{in}} = -r_1 + \frac{t_1^2 r_2 e^{-i4\pi L/\lambda}}{1 - r_1 r_2 e^{-i4\pi L/\lambda}}}$$



Circulating power builds up for $L=n\lambda/2$

Laser interferometer detectors

Fabry-Perot arm cavities

The ‘’sharpness’’ of the peaks is defined by the finesse

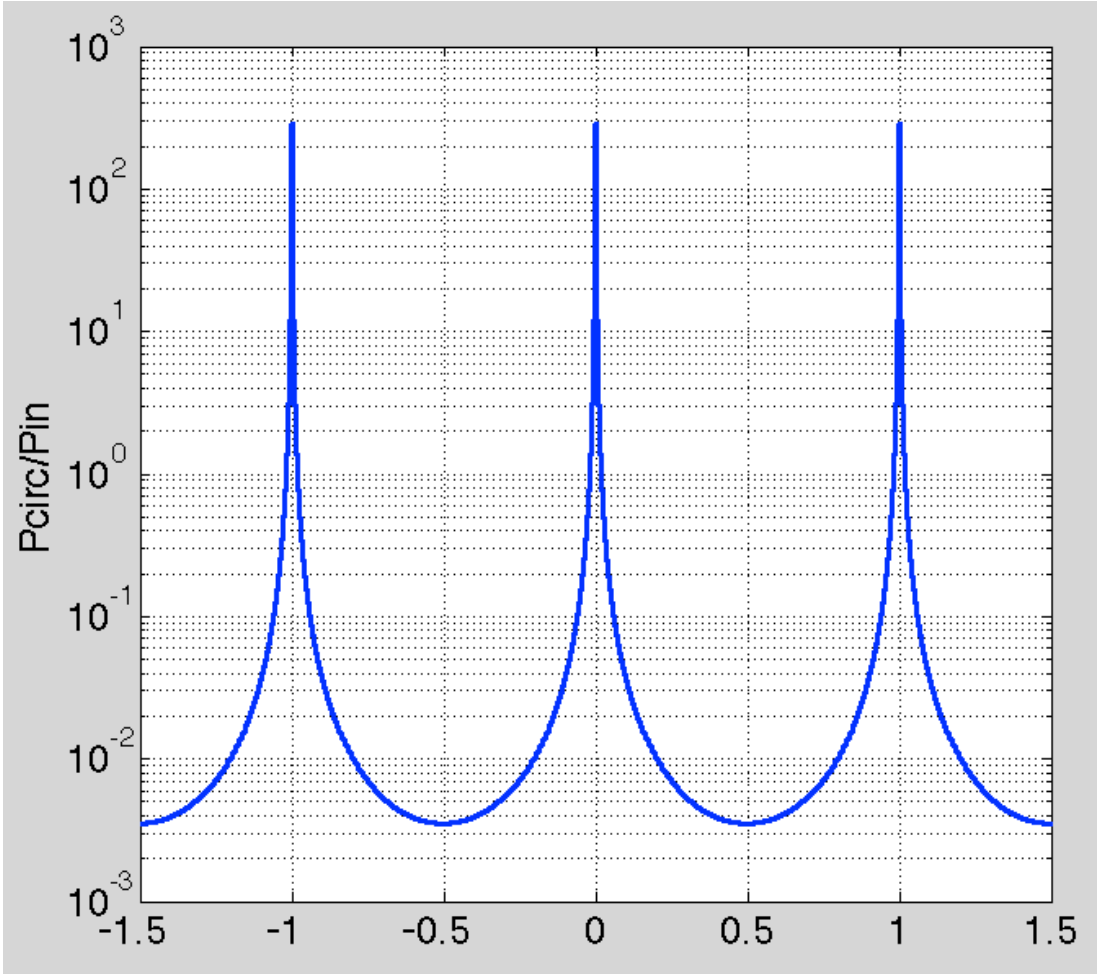
$$F = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

The finesse is related to the number of round trips the light makes inside the cavity

$$N = \frac{2F}{\pi}$$

For Advanced Virgo

$$T_1 = t_1^2 = 0.014$$
$$T_2 = t_2^2 = 10 \text{ ppm}$$
$$L = 3 \text{ km}$$
$$F = 440$$
$$P_{\text{circ}} = 650 \text{ kW}$$
$$N = 280$$



Laser interferometer detectors

Fabry-Perot arm cavities

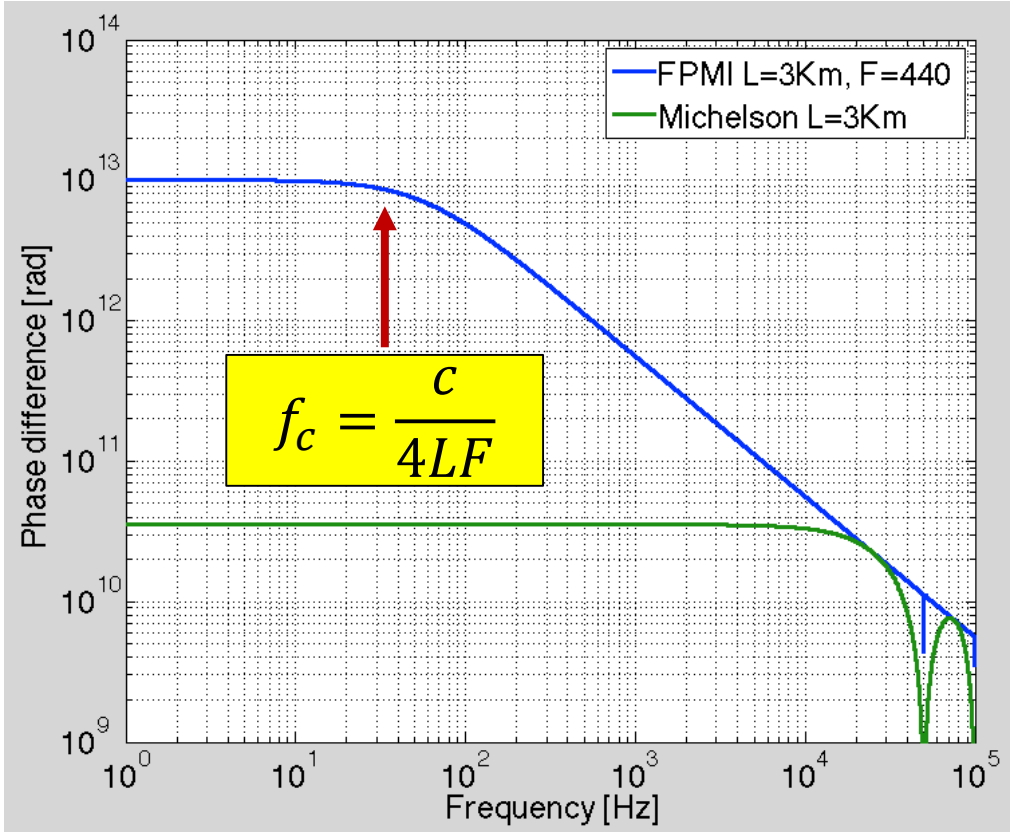
$$\phi_x - \phi_y = \frac{4\pi L}{\lambda}\left[\frac{\sin \omega L/c}{\omega L/c} e^{-i\omega L/c}\right]\left[\frac{t_1^2 r_2/(1-r_1 r_2)}{1 - r_1 r_2 e^{-i2L\omega/c}}\right] h_0 e^{i\omega t}$$

which, for $f_{gw} \ll c/2L$, is well approximated by

$$\phi_x - \phi_y = \frac{8LF}{\lambda} \cdot \frac{h_0 e^{i\omega t}}{1 + i\omega \frac{2LF}{\pi c}}$$

The ''effective'' arm length increases by a factor *N*

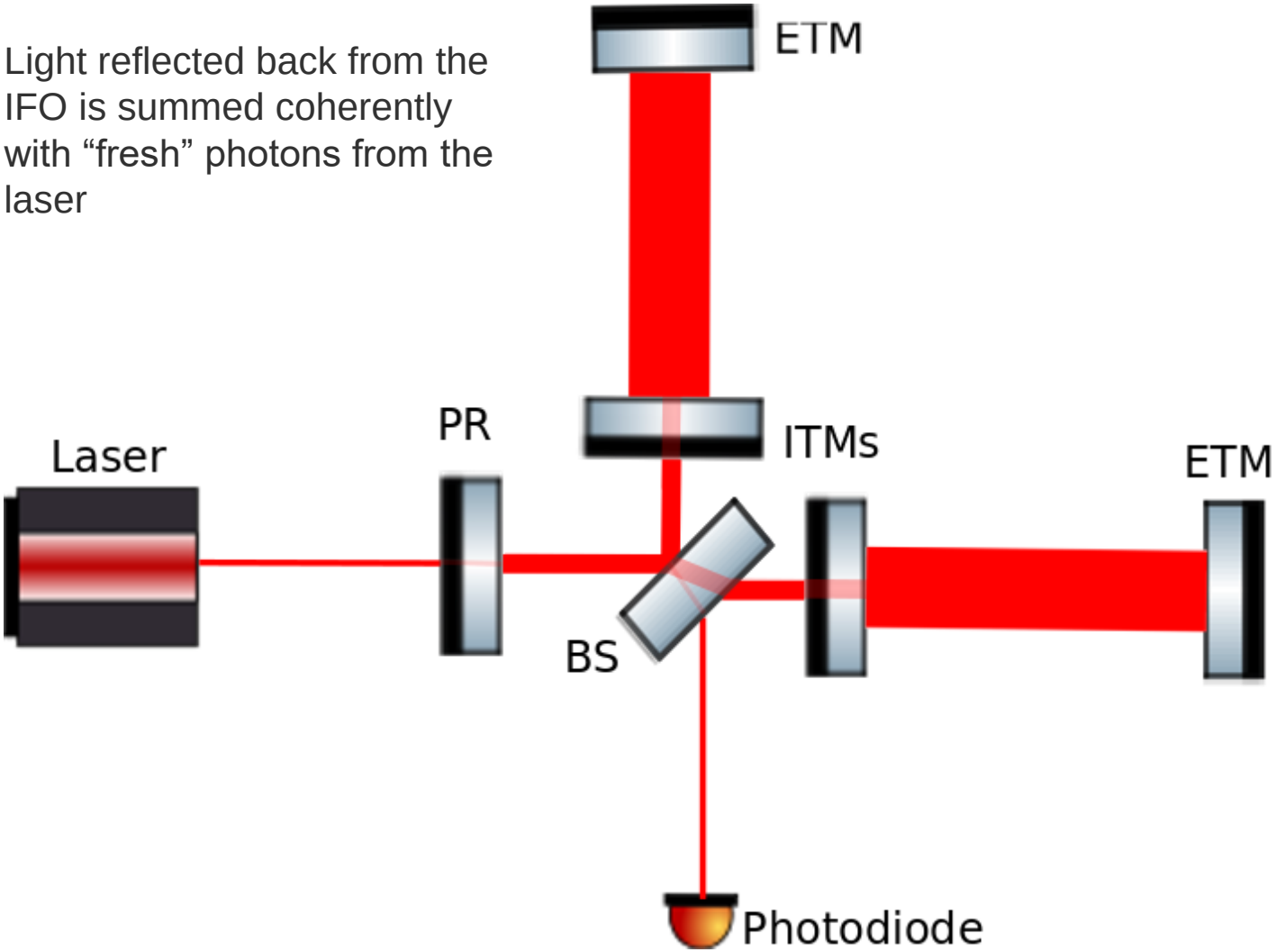
What else can we do to enhance the signal?



Power recycling

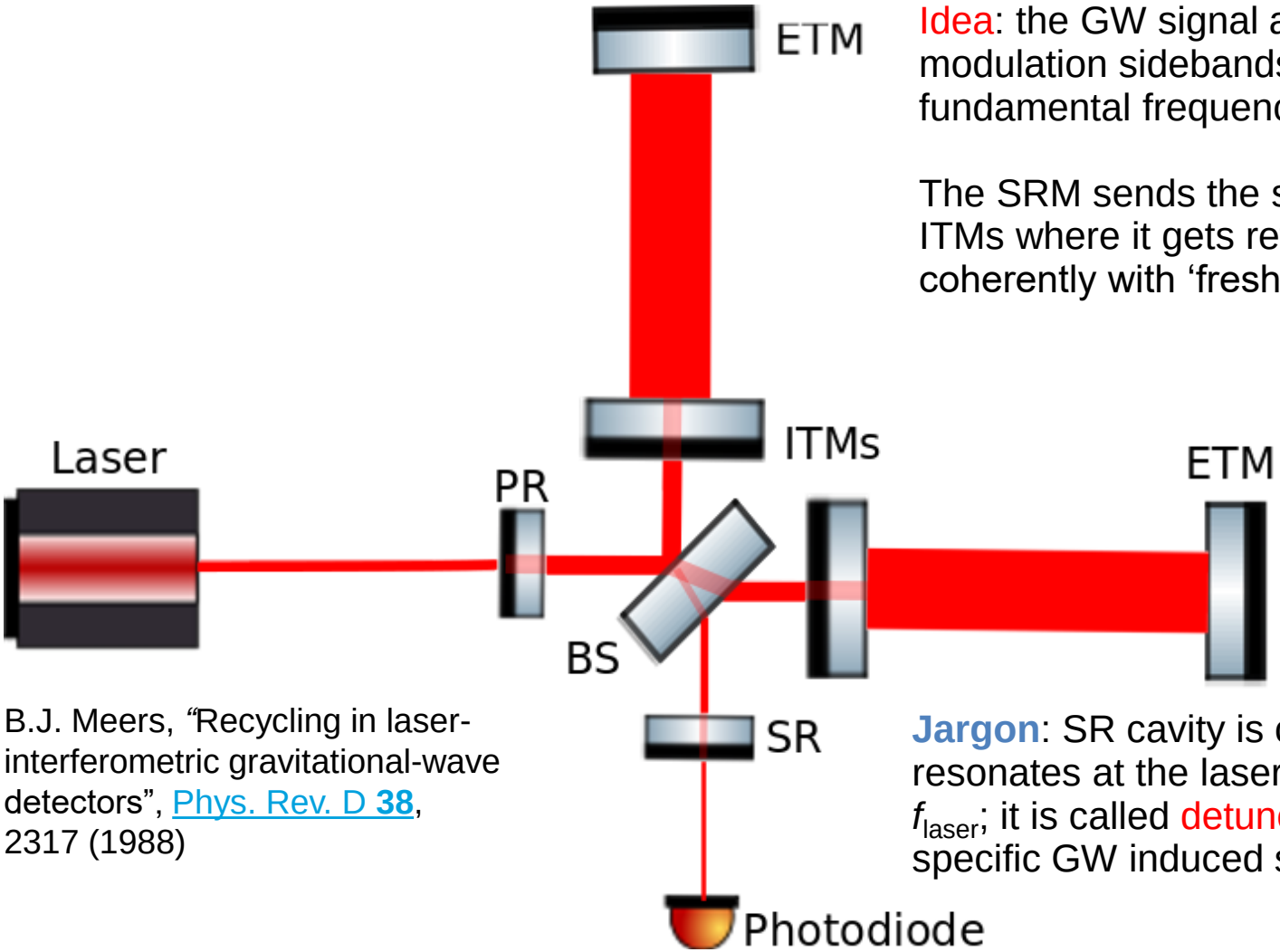
The interferometer is operated close to a dark fringe, and almost all the light is reflected back to the laser. Install partially transmitting mirror (PRM) between laser and beam splitter forming a three-mirror cavity with the ITMs

Light reflected back from the IFO is summed coherently with “fresh” photons from the laser



Signal recycling

By introducing a partially reflective mirror between BS and PD a three-mirror resonator is formed between the end mirrors and SRM



Idea: the GW signal appears as an amplitude modulation sidebands around the laser fundamental frequency

The SRM sends the signal back towards the ITMs where it gets reflected and summed coherently with 'fresh' signal from the arms

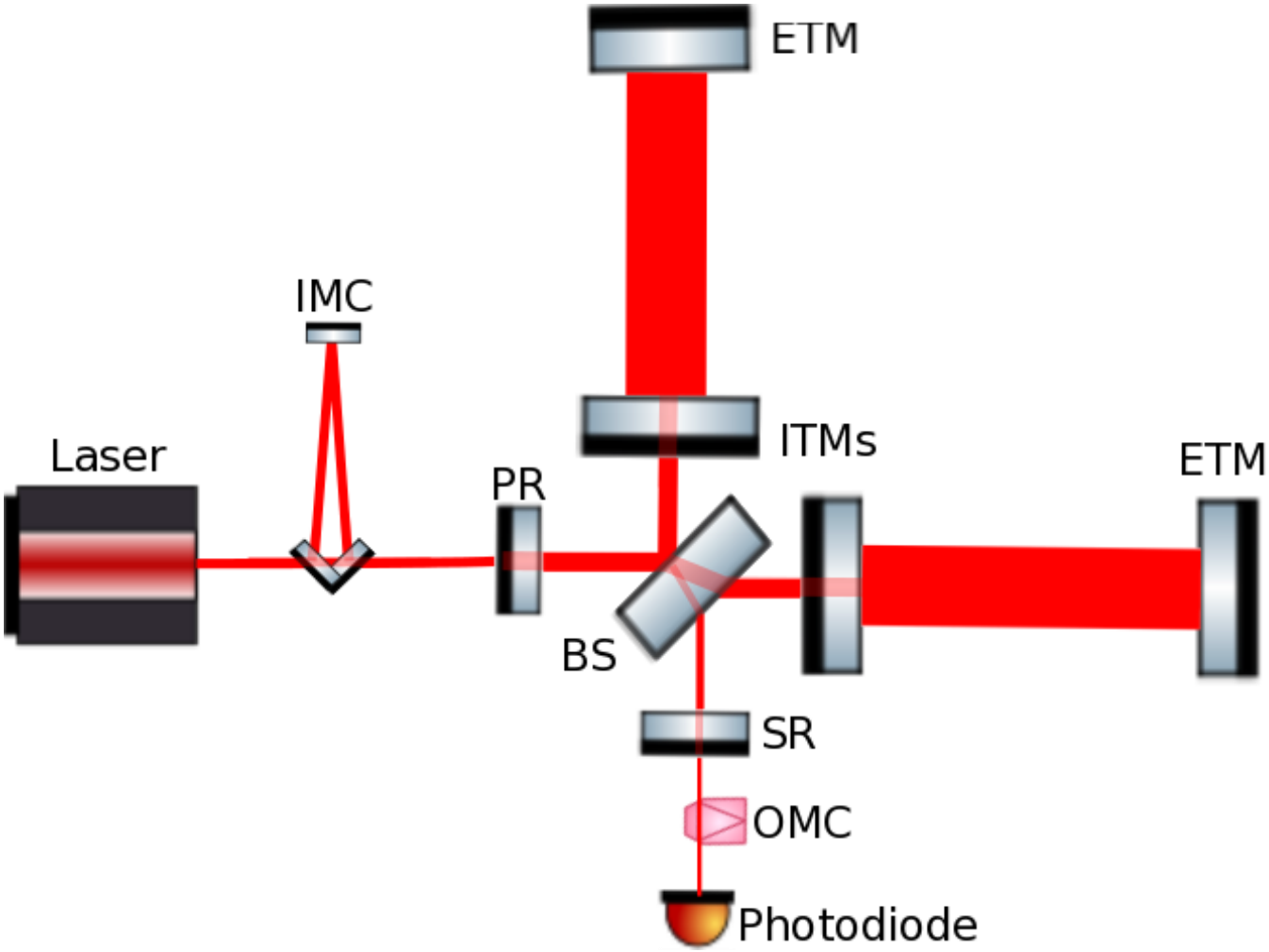
Advanced Virgo plans $T_{SRM} = 0.20$ and $F = 26$

B.J. Meers, "Recycling in laser-interferometric gravitational-wave detectors", Phys. Rev. D **38**, 2317 (1988)

Jargon: SR cavity is called tuned when it resonates at the laser fundamental frequency f_{laser}; it is called detuned when it resonates at a specific GW induced sideband $f_{laser}+f_{GW}$

Dual recycled Fabry-Perot interferometer

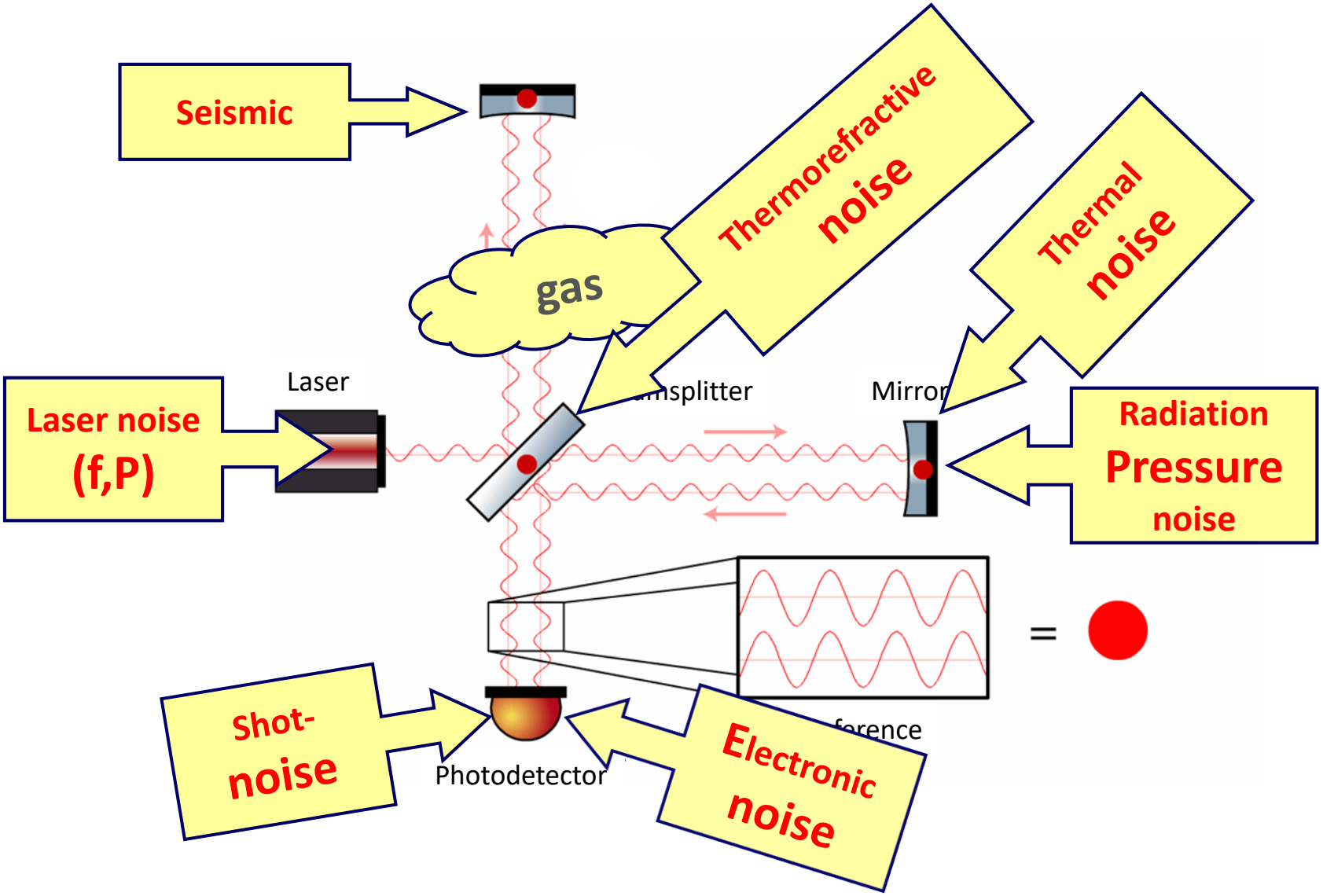
Dual recycled Fabry-Perot interferometer including input mode cleaner and output mode cleaner



Interferometer: noise sources

Interferometer: noise sources

Fundamental and technical noise sources limit the sensitivity of our instruments



Laser interferometer detectors

Fundamental limits: shot noise

A light beam consists of a stream of photons: a beam with power *P* has a photon flux (photons/sec)

$$\bar{N} = \frac{P}{h\nu}$$

We know that

- nothing guarantees that *N* photons will arrive every second; some seconds there will arrive more, and in other seconds fewer photons will arrive at the photodiode;
- experiments show that the behavior is regulated by a Poisson statistics;
- then, if we expect *N* independent events on average, the standard deviation is $\sigma = \sqrt{N}$
- then, the higher the power, the lower the relative fluctuation

In frequency domain the photon counting error appears as white noise with rms value

$$\Delta P_{shot} = \sqrt{2h\nu P \Delta f}$$

The corresponding minimum GW signal observable over 1 Hz bandwidth is (close to the dark fringe)

$$\boxed{h_{min}^{GW} = \frac{\lambda}{4\pi L_e}\sqrt{\frac{2h\nu}{P_{in}}} = 1 \cdot 10^{-24}}$$

ν = *300* THz
P_{in} = *3.9* kW
L_e = 840 Km

Laser interferometer detectors

Fundamental limits: radiation pressure

Photons carry momentum and exert a mechanical pressure on the mirrors (static and dynamic)

$$F_{static} = 2\bar{N}\frac{h\nu}{c}$$

$$F_{noise} = 2\frac{h\nu}{c}\sqrt{\bar{N}} = 2\frac{h\nu}{c}\sqrt{\frac{P}{h\nu}} = 2\sqrt{\frac{Ph}{\lambda c}}$$

$$x_{noise} = \frac{2}{m\omega^2}\sqrt{\frac{Ph}{\lambda c}}$$

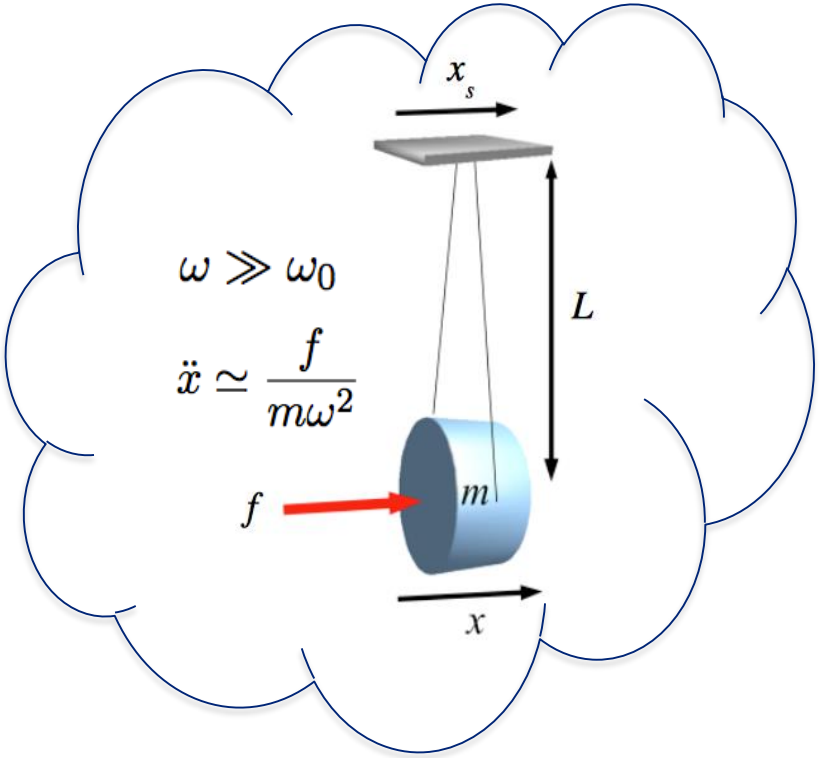
for a simple **Michelson** interferometer

$$h_{GW}^{rp} = \frac{2x_n}{L}$$

for a **FP Michelson** interferometer

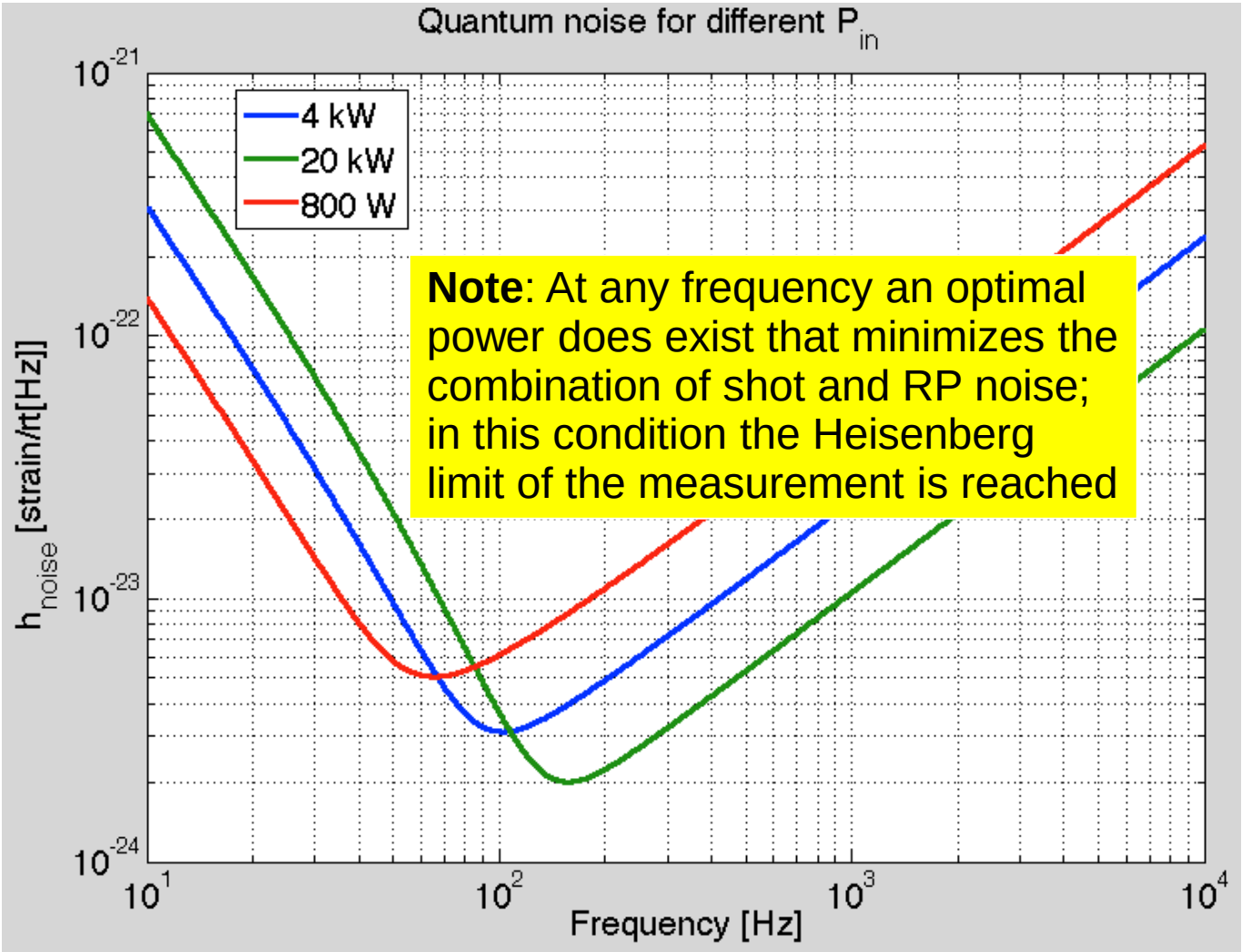
$$\boxed{h_{GW}^{rp} = 2\cdot\sqrt{2}\cdot\frac{2F}{\pi}\frac{x_n}{L} = \frac{8F}{\pi L m\omega^2}\sqrt{\frac{2P_{in}h}{\lambda c}}}$$

Reminder



Laser interferometer detectors

Fundamental limits: radiation pressure



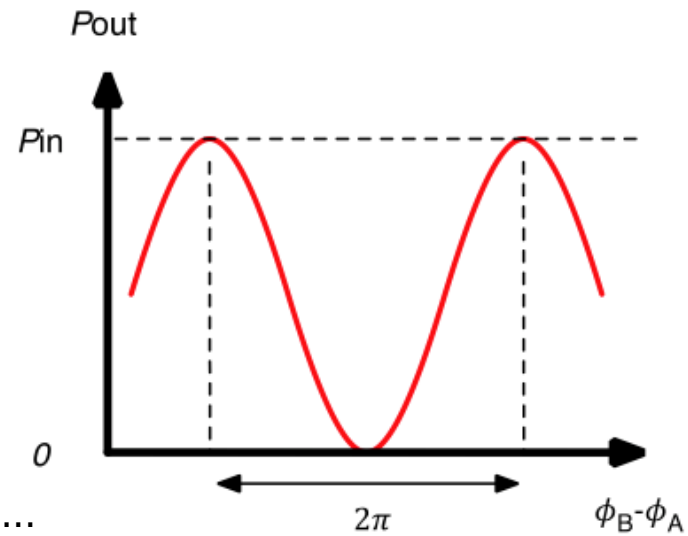
Note: At any frequency an optimal power does exist that minimizes the combination of shot and RP noise; in this condition the Heisenberg limit of the measurement is reached

Laser interferometer detectors

Working point (why the dark fringe?)

$$P_{out} = \frac{P_{in}}{2}\left[1 - \cos\left(\phi_0 + \frac{4\pi L_e}{\lambda}h\right)\right]$$

$$\boxed{\Delta P_{out} = \frac{2\pi L_e}{\lambda} P_{in} \sin\phi_0 h}$$



The max response to *h* is at $\pi/2$ but laser power fluctuations...
Even if the lasers used in GW detectors are the best ever made (dP/P < 10^{-8} at f > 10 Hz)

$$\Delta P_{out} = \frac{\Delta P_{in}}{2}(1 - \cos\phi_0) \Longrightarrow h_{min} = 10^{-8}\frac{\lambda}{4\pi L_e} = 8 \cdot 10^{-22}$$

not good enough !!

… better with a little offset from the dark fringe

$$\Delta P_{out} \simeq \frac{2\pi L_e}{\lambda} P_{in}\phi_0 h$$

$$h_{min} = 10^{-8}\phi_0\frac{\lambda}{4\pi L_e} = 8 \cdot 10^{-26}$$

Laser interferometer detectors

Seismic noise

Earth crust moves relentlessly in a wide frequency range from nHz to hundreds of Hz:

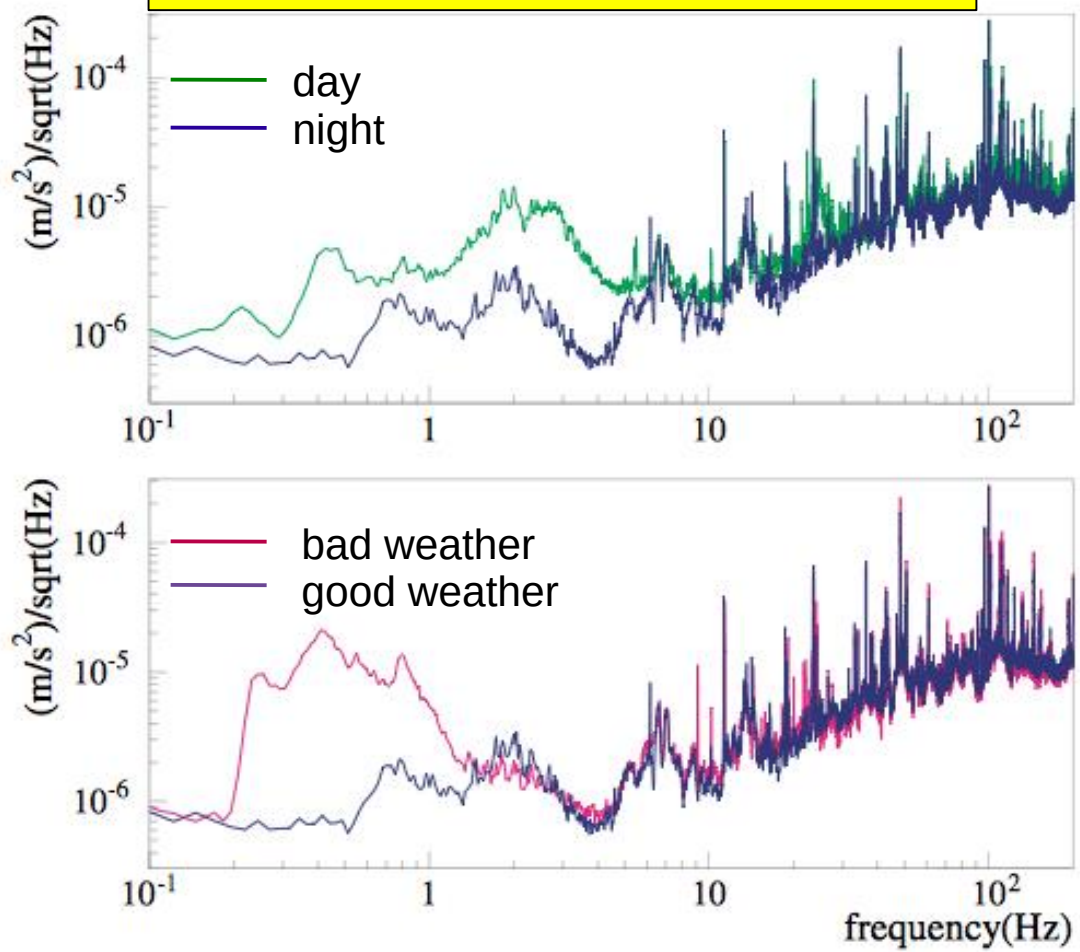
- Tectonic movements
- Lunar tides (few μHz)
- Microseismic peak from ocean waves (0.1-0.3 Hz)
- Anthropogenic and wind induced noise (f>1 Hz)

Amplitude exceeds by several orders of magnitude the test mass background motion aimed for GW detection ($<10^{-18}$m)

At the Virgo site:

at f > 10 Hz $$x_s \simeq \frac{10^{-7}}{f^2}\left[\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right]$$

Typical ground motion spectra at the Virgo site



Laser interferometer detectors

Simple pendulum transfer function

Reminder

at low frequencies ($\omega \ll \omega_0$)

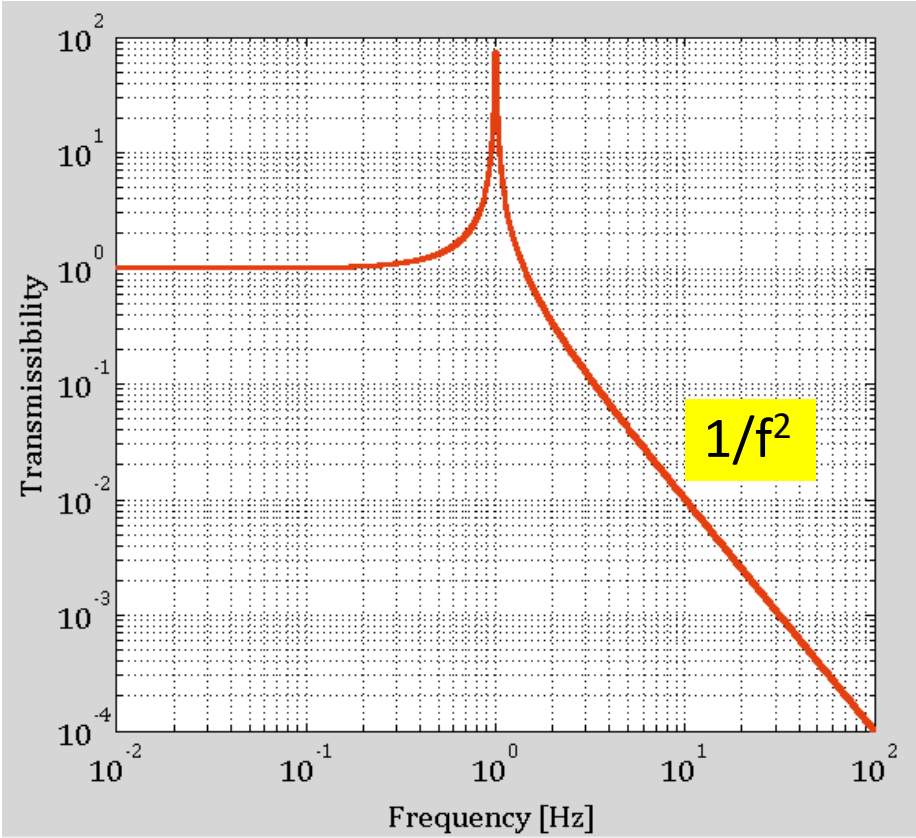
$$X \simeq X_s + F/m{\omega_0}^2$$

at the natural frequency ($\omega = \omega_0$)

$$X \simeq Q(X_s + F/m{\omega_0}^2)$$

while at high frequency ($\omega \gg \omega_0$)

$$X \simeq \frac{{\omega_0}^2}{\omega^2} X_s + F/m\omega^2$$



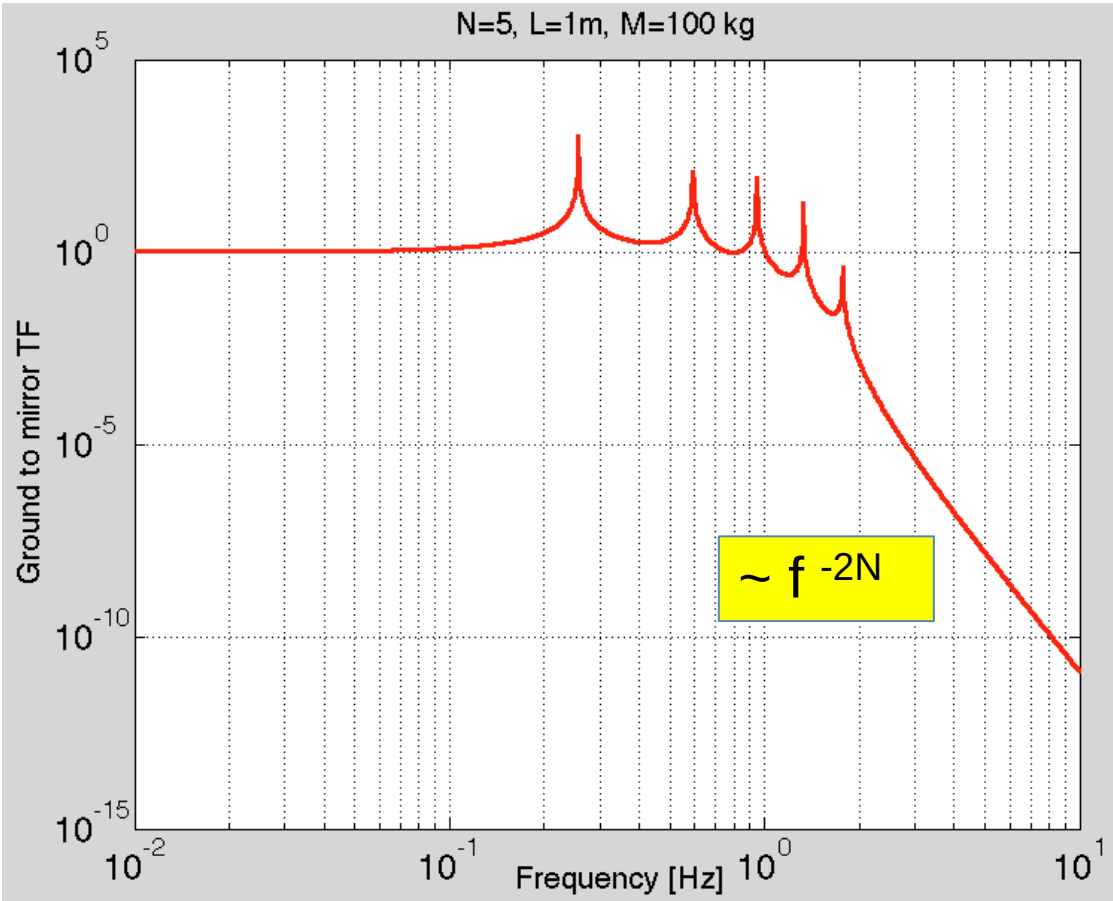
The suspension also provides attenuation of ground vibrations, ... but far from the 10^8-10^{10} seismic attenuation required in the GW detection band (10 Hz - 3 kHz)

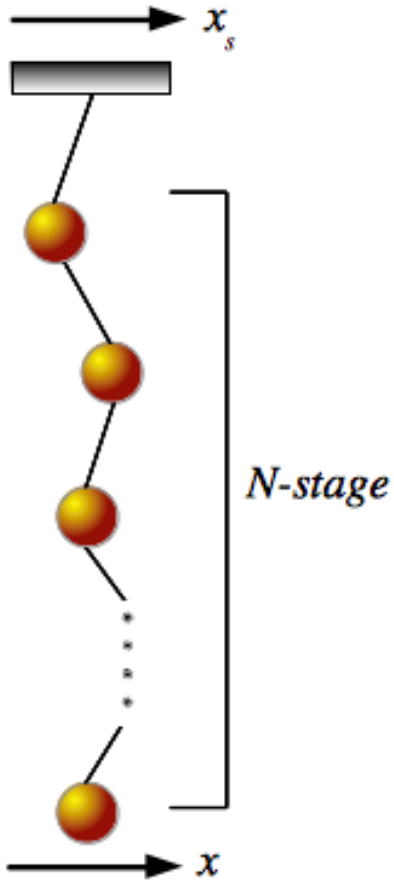
Laser interferometer detectors

Solution: cascading mechanical filters (*seismic filters*) with uncoupled natural frequencies sufficiently lower than 10 Hz

The Lagrangian of a chain of simple pendulums is:

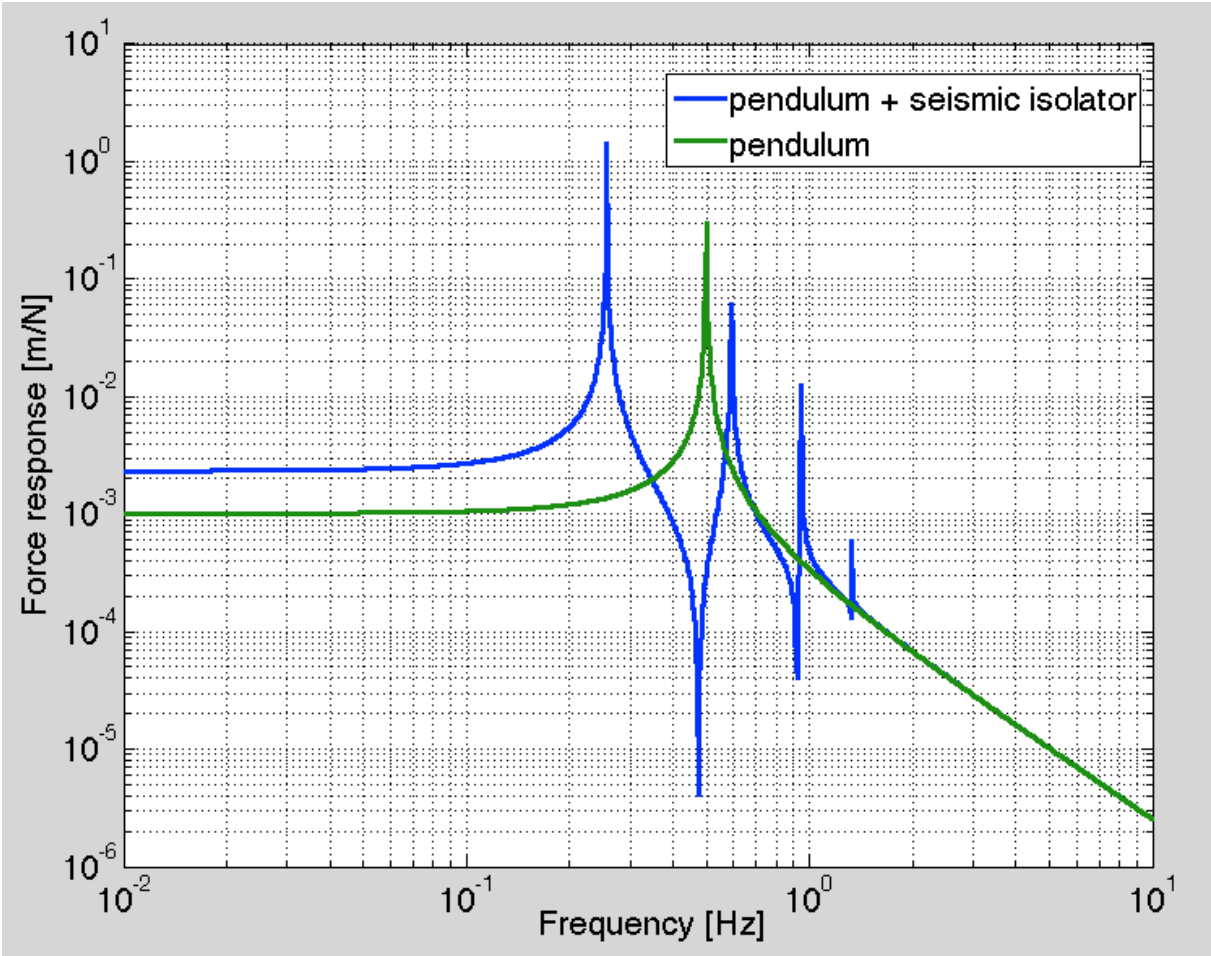
$$\mathcal{L} = T - V = \frac{1}{2}\sum_{i=1}^{N} m_i \dot{x}_i^2 - \frac{1}{2} g \sum_{i=1}^{N} \frac{\sum_{j=i}^{N} m_j}{L_i}(x_i - x_{i-1})^2$$

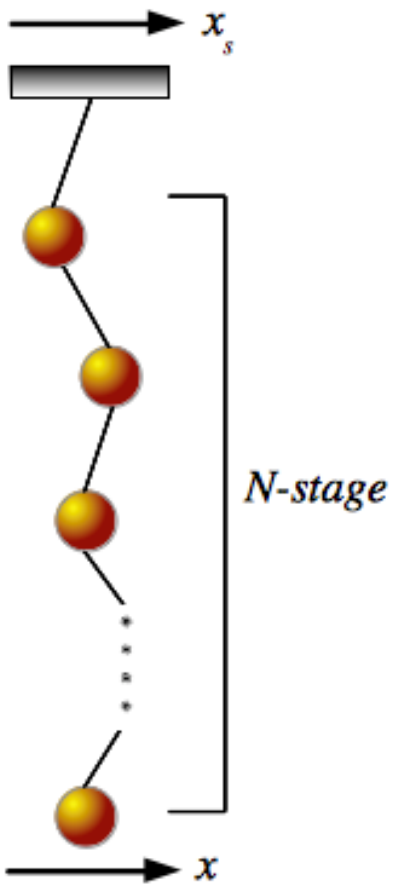




Laser interferometer detectors

Applying a force to the test-mass





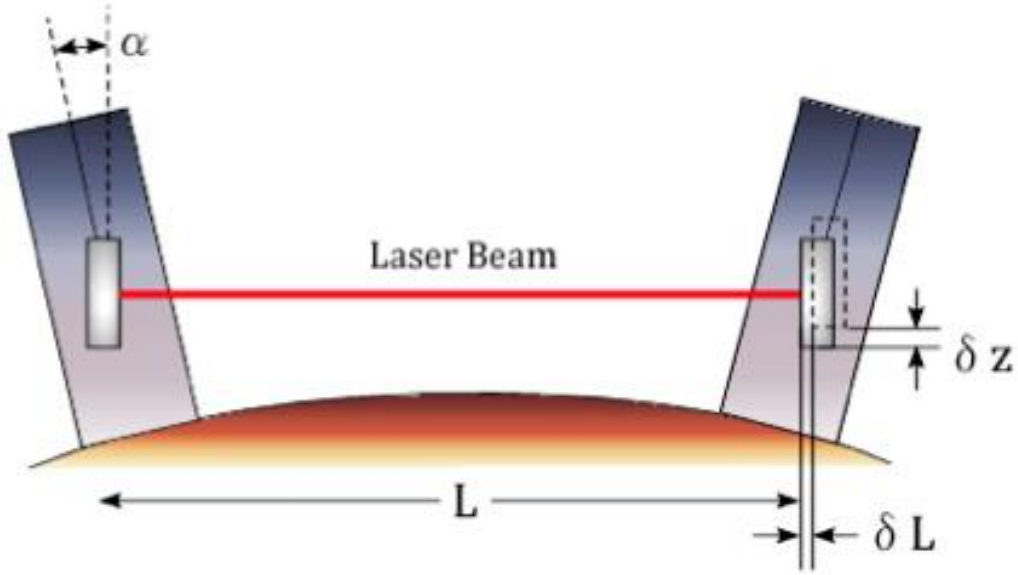
Above the seismic isolator cut-off the mirror responds as a single simple pendulum

Laser interferometer detectors

… but life is hard …

Horizontal seismic filtering is not sufficient because:

1. Non-parallelism of verticality between objects a few km apart channels vertical seismic noise along the GW sensing axis ($2*10^{-4}$ coupling over 3 km)

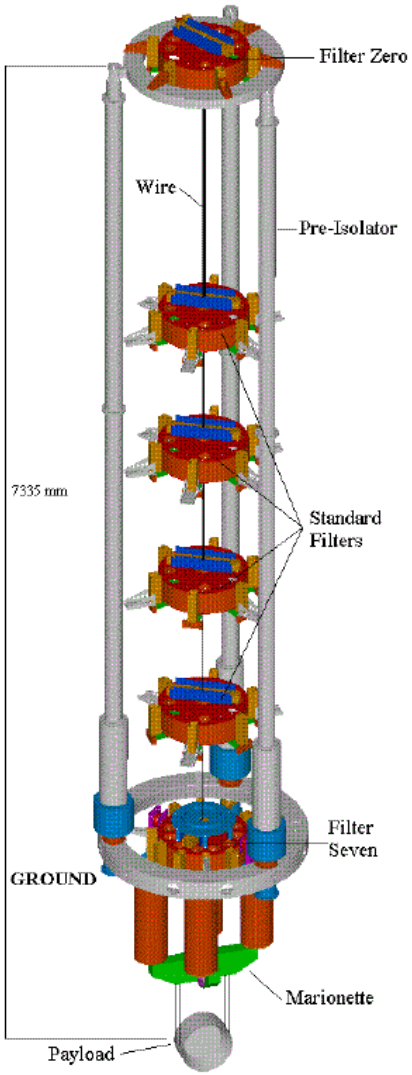


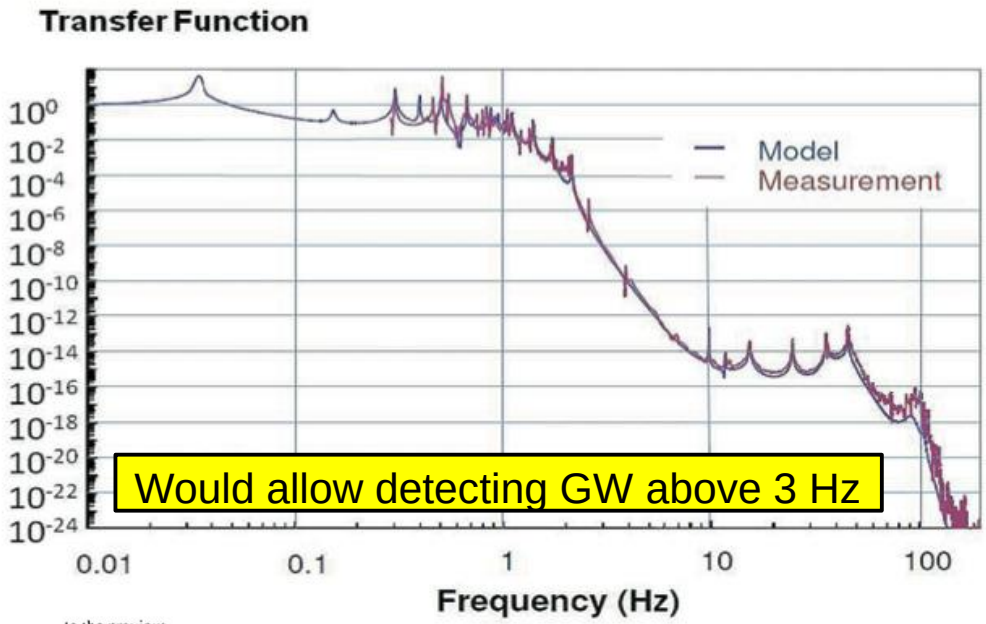
2. Imperfections in the mechanical assembly may cause even larger couplings (up to 1%)

Vertical seismic isolation is necessary !!

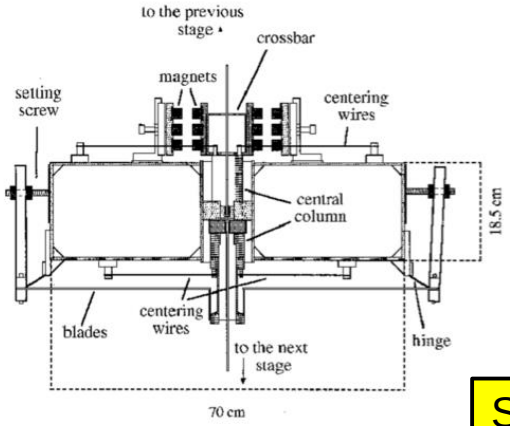
Laser interferometer detectors

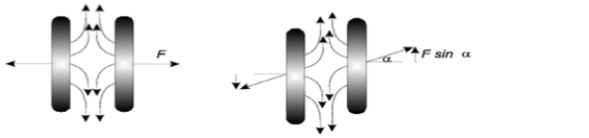
The Virgo superattenuator





Would allow detecting GW above 3 Hz





working principle of the magnetic anti-spring system. When the magnets are displaced in the vertical direction (right side) a vertical component of the repulsive force appears.

SA Magnetic anti-spring vertical filters

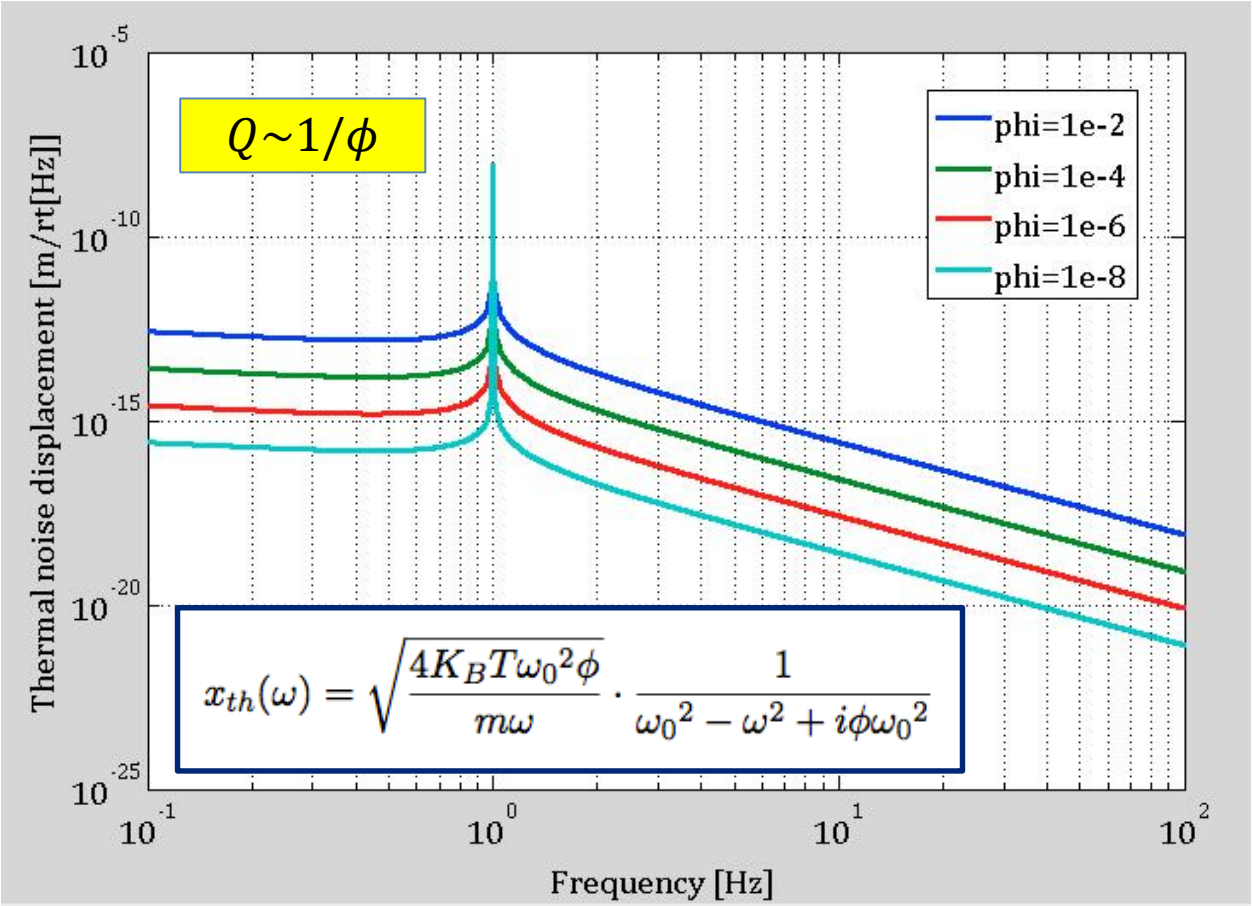
Laser interferometer detectors

Brownian motion

- Internal friction in the material of the suspension wires causes the mirrors to move
- The effect dominates over filtered seismic at f > 3 Hz

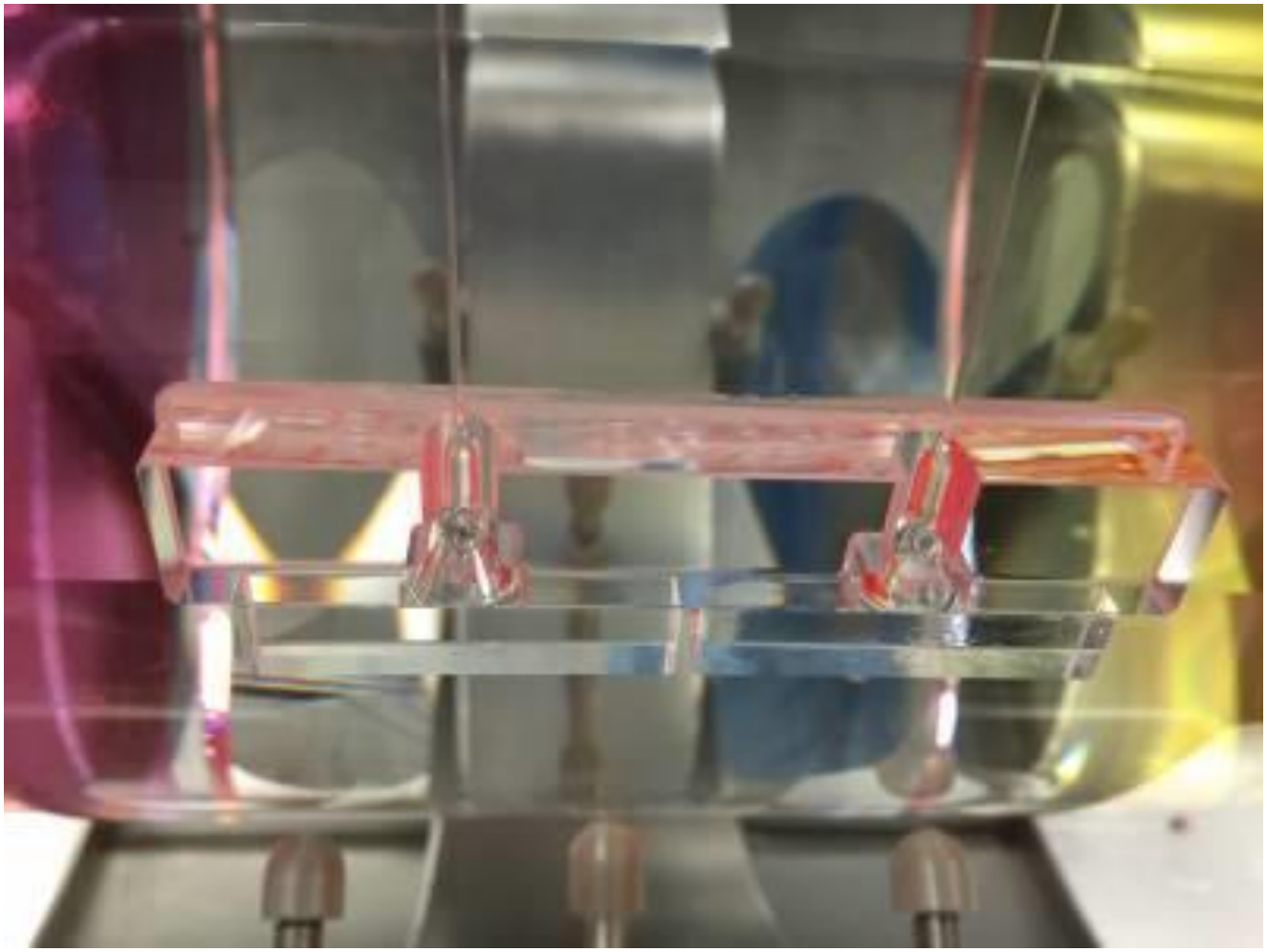
Two possible choices for the wire material:

- ❑ a ‘perfect’ crystal
- ❑ a ‘perfect’ glass



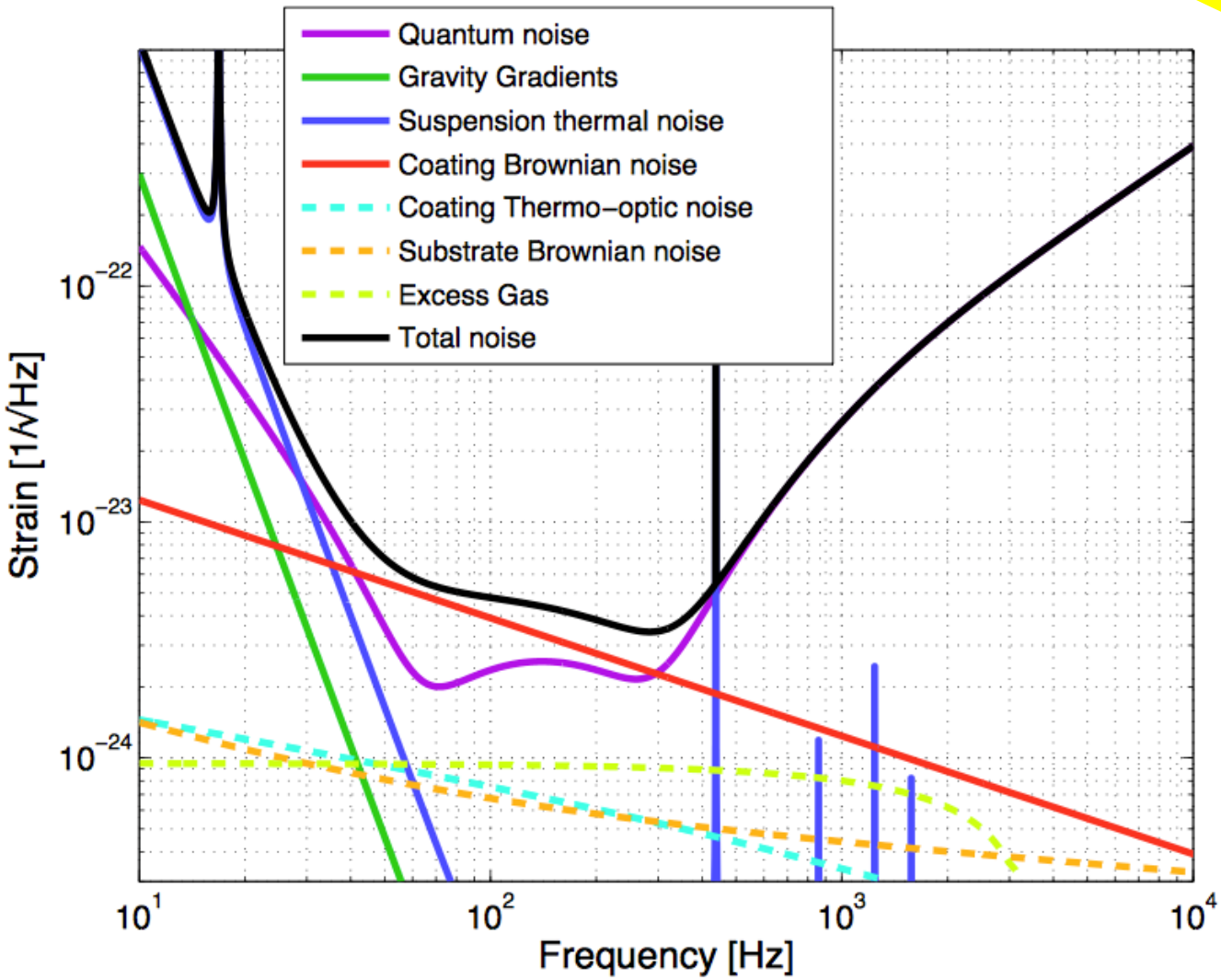
Thermal noise

Monolithic suspensions. High Q-values, but now sensitive to parametric instabilities



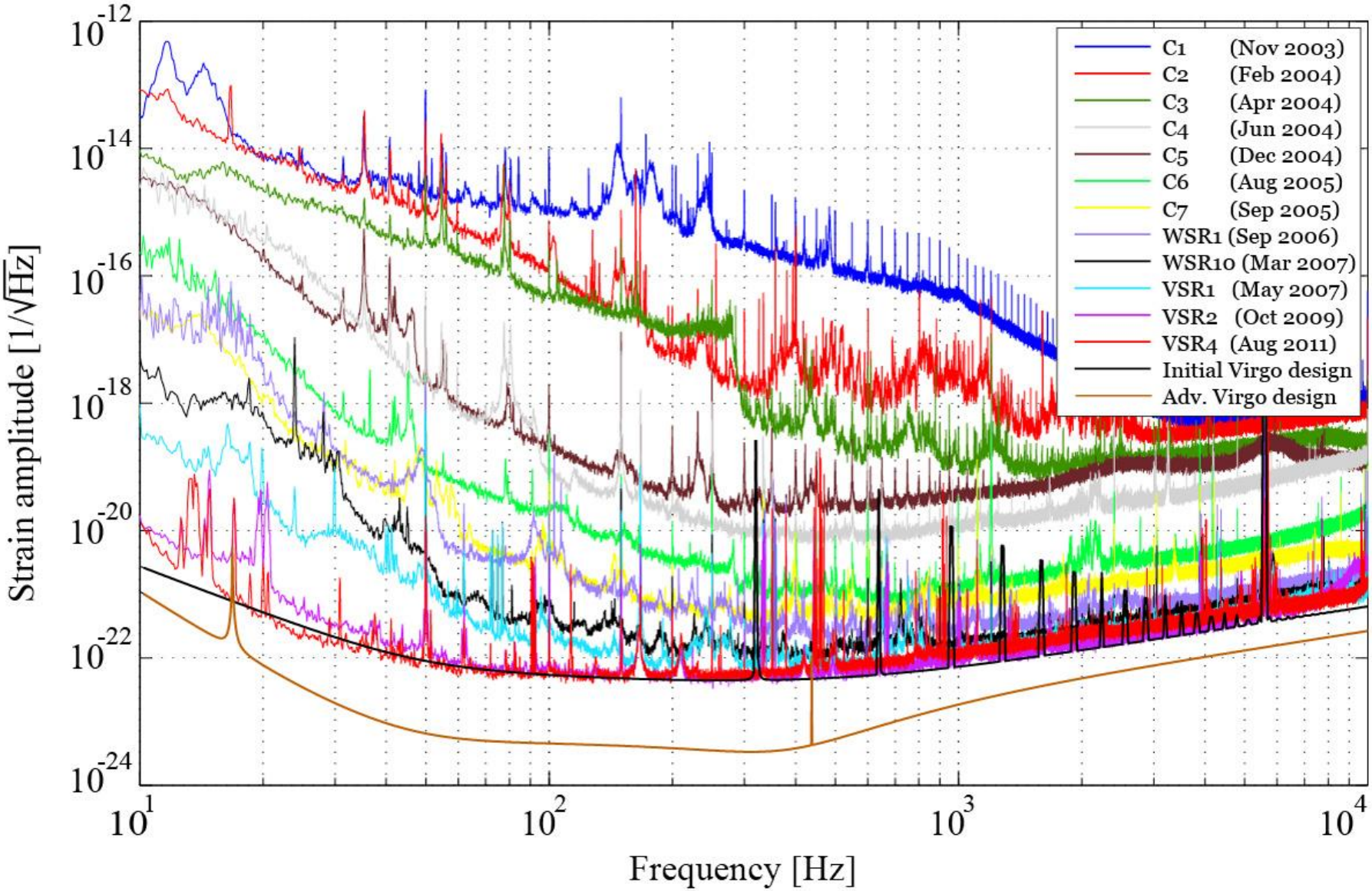
Laser interferometer detectors

Advanced Virgo sensitivity curve



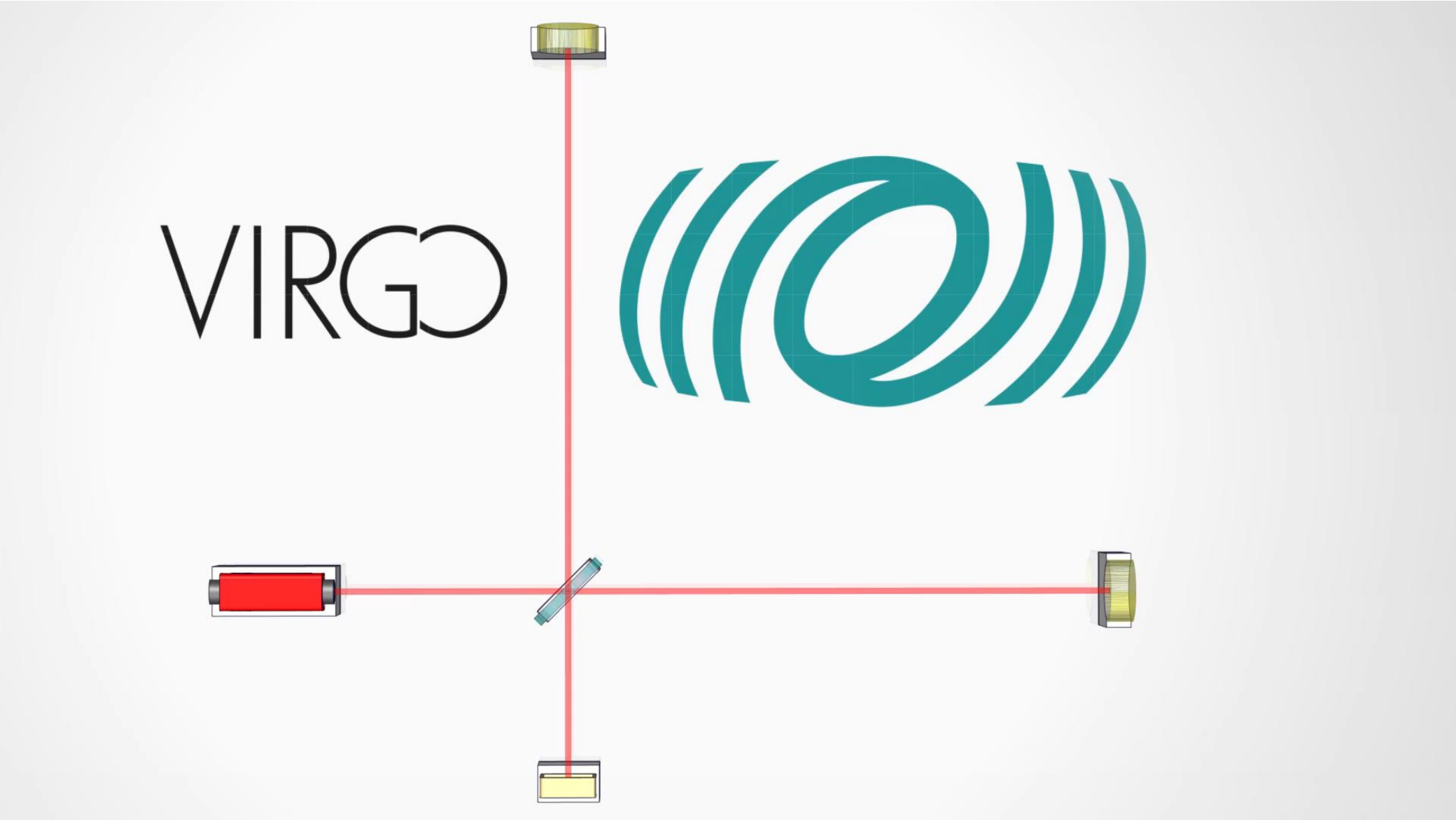
… now working hard to reach it ….

Virgo: sensitivity evolution



Detecting gravitational waves with an interferometer

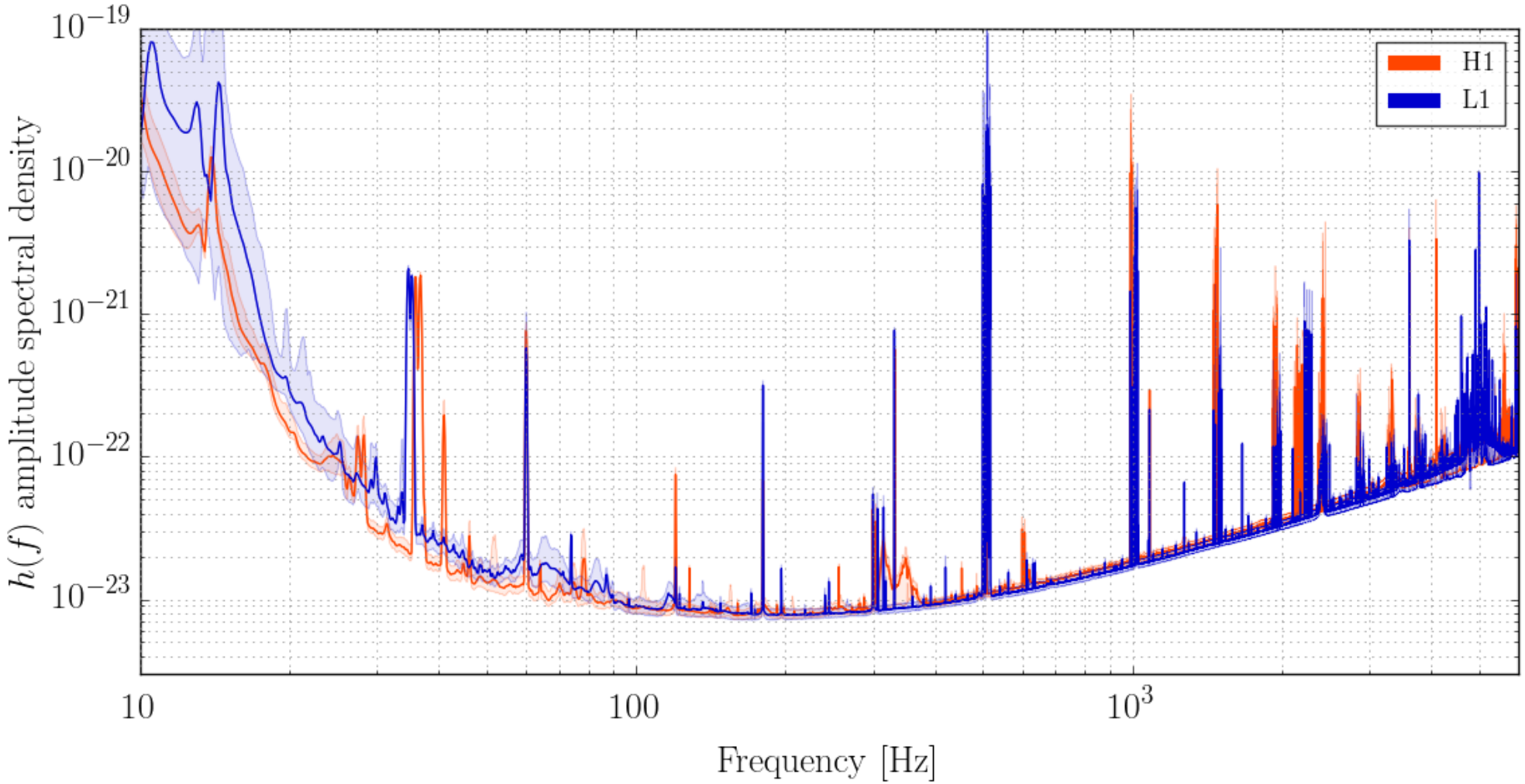
During our detection of GW150914 the mirrors moved by about 10^{-18} m



Detecting gravitational waves with an interferometer

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

Sensitivity of the LIGO instruments during O1



Detecting gravitational waves with an interferometer

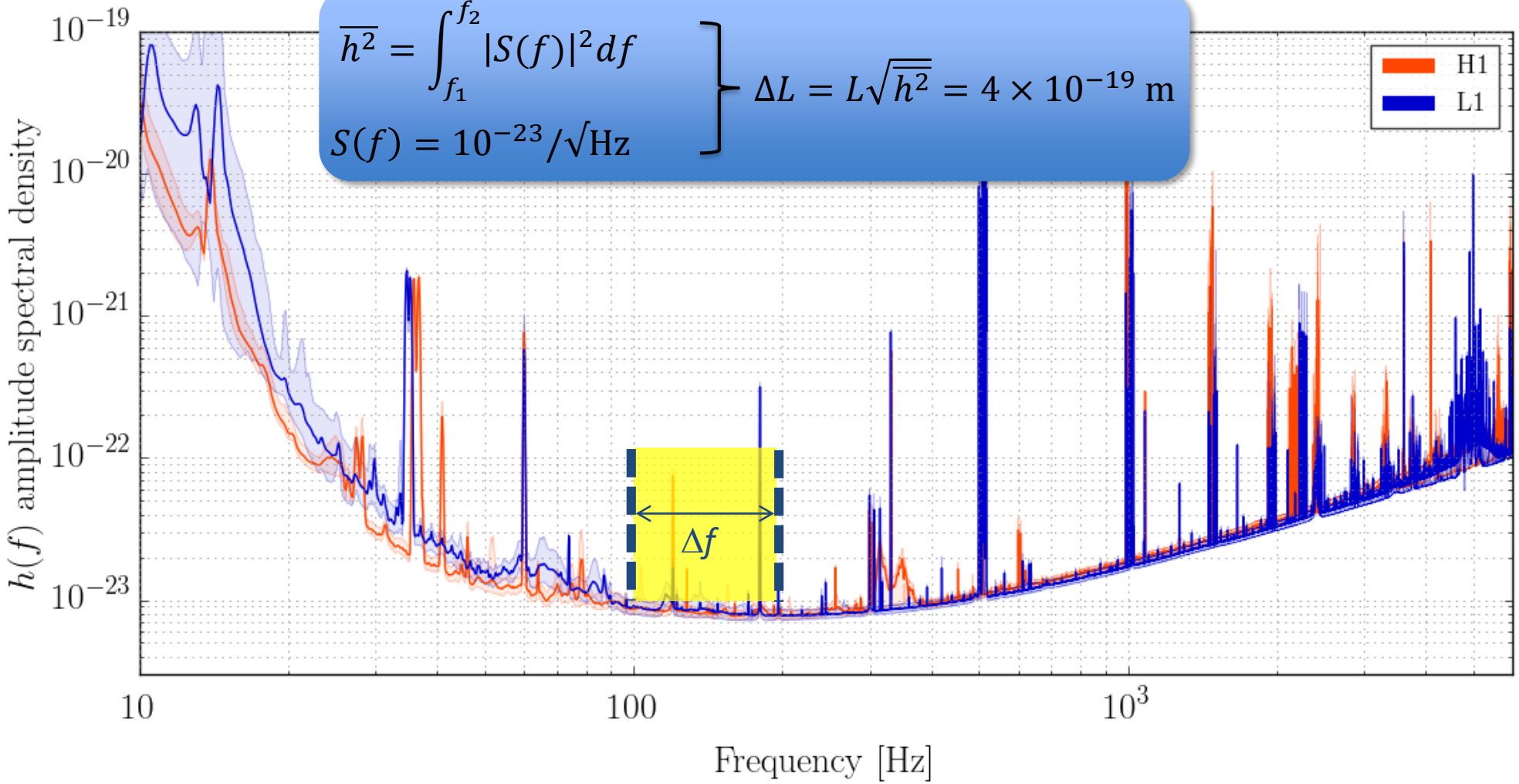
During the measurement of GW150914 our mirrors moved by about 10^{-18} m

Sensitivity of the LIGO instruments during O1

$$\overline{h^2} = \int_{f_1}^{f_2} |S(f)|^2 df$$

$$S(f) = 10^{-23}/\sqrt{\mathrm{Hz}}$$

$$\Delta L = L\sqrt{\overline{h^2}} = 4 \times 10^{-19}\ \mathrm{m}$$



Detecting gravitational waves with an interferometer

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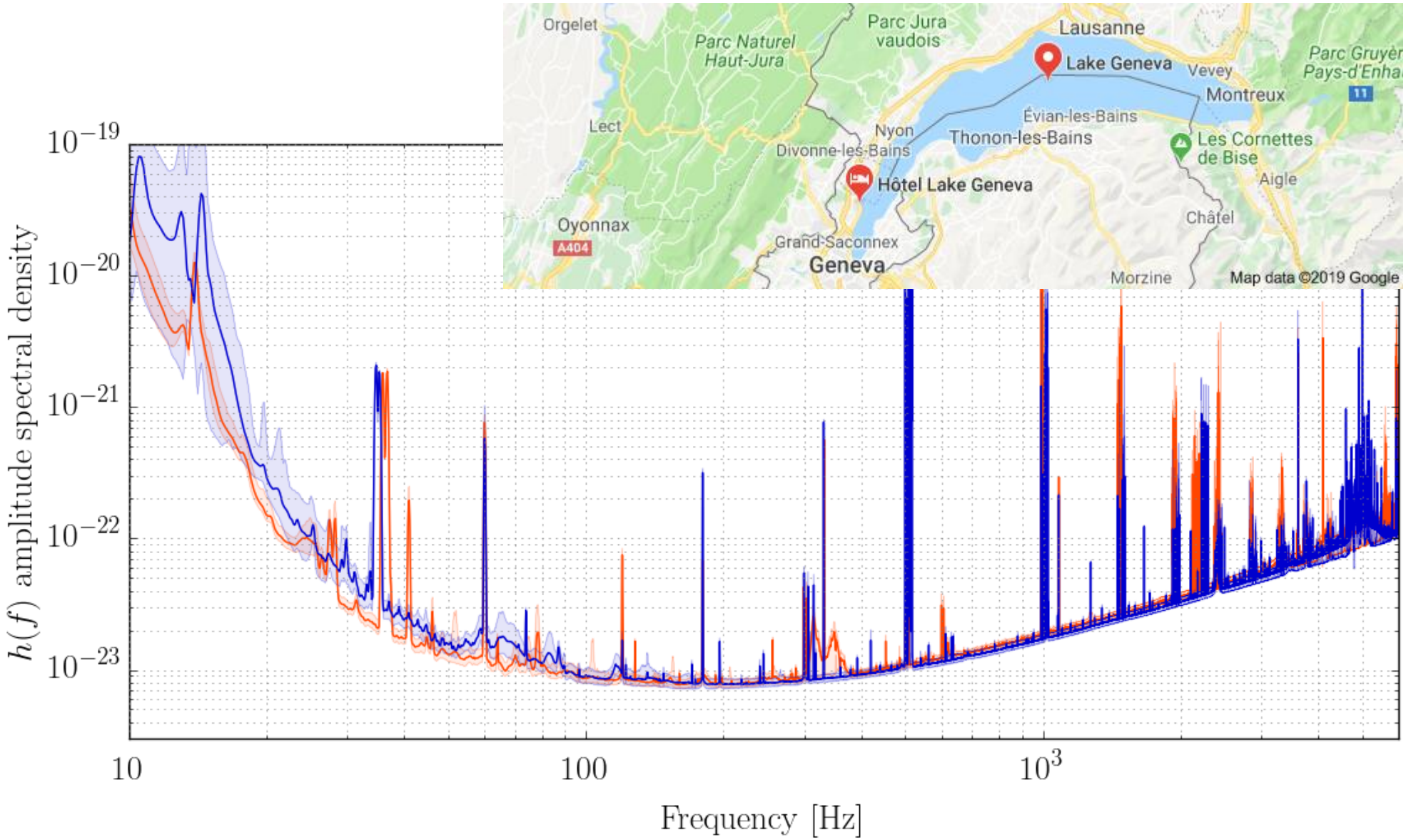
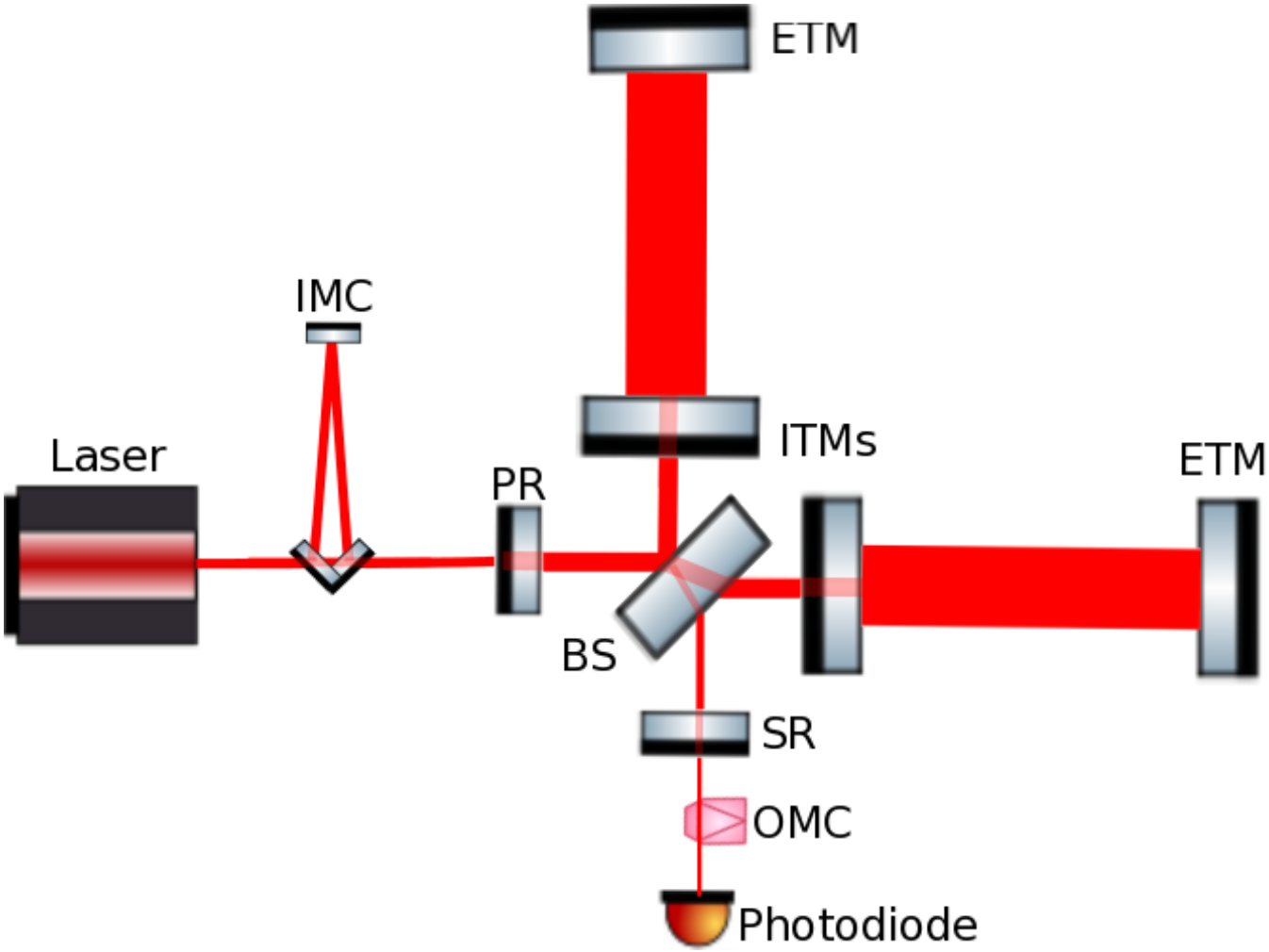


Outlook

Virgo interferometer

Dual recycled Fabry-Perot interferometer

LIGO and Virgo will use dual recycled Fabry-Perot interferometers including input mode cleaner and output mode cleaner



AdV+ as the next step forward in Virgo sensitivity

AdV+ will maximize Virgo's sensitivity within the constrains of the EGO site. It has the potential to increase Virgo's detection rate by up to an order of magnitude

AdV+ features

Maximize science and secure Virgo's scientific relevance

Safeguard investments by scientists and funding agencies

Implement new innovative technologies

De-risk technologies needed for third generation observatories

Attractive for groups wanting to enter the field

Upgrade activities: we now need to discuss Phase 2

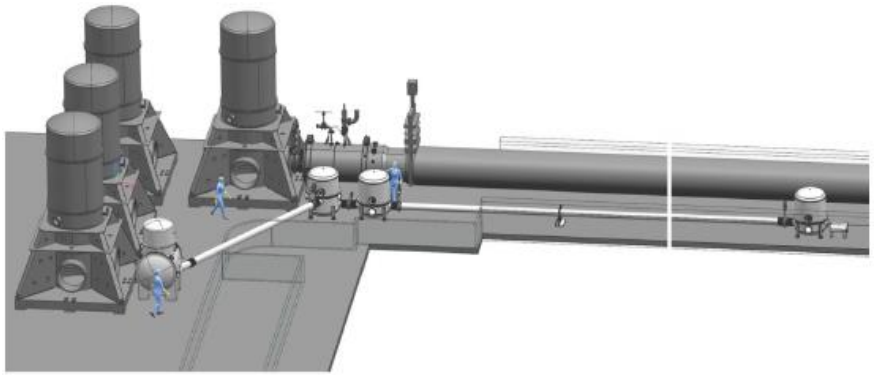
Tuned signal recycling and HPL: 120 Mpc

Frequency dependent squeezing: 150 Mpc

Newtonian noise cancellation: 160 Mpc

Larger mirrors (105 kg): 200-230 Mpc

Improved coatings: 260-300 Mpc



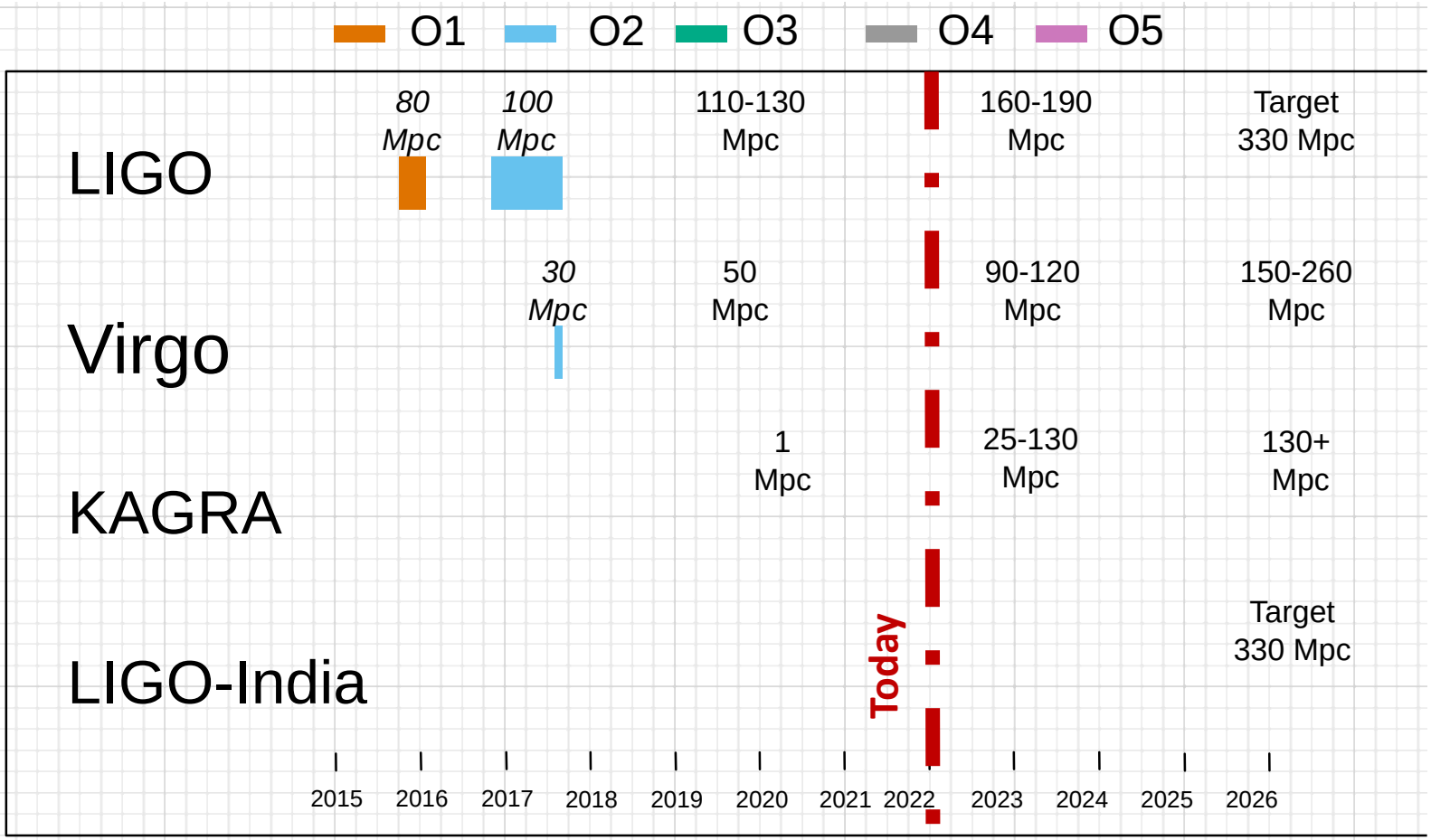
Phase 2 timeline

Stringent time constrains due to international context: LIGO, Indigo, KAGRA

Timeline for past and future science runs

AdV+ and A+ will be carried out in two steps
This allows installation and commissioning in between O4 and O4

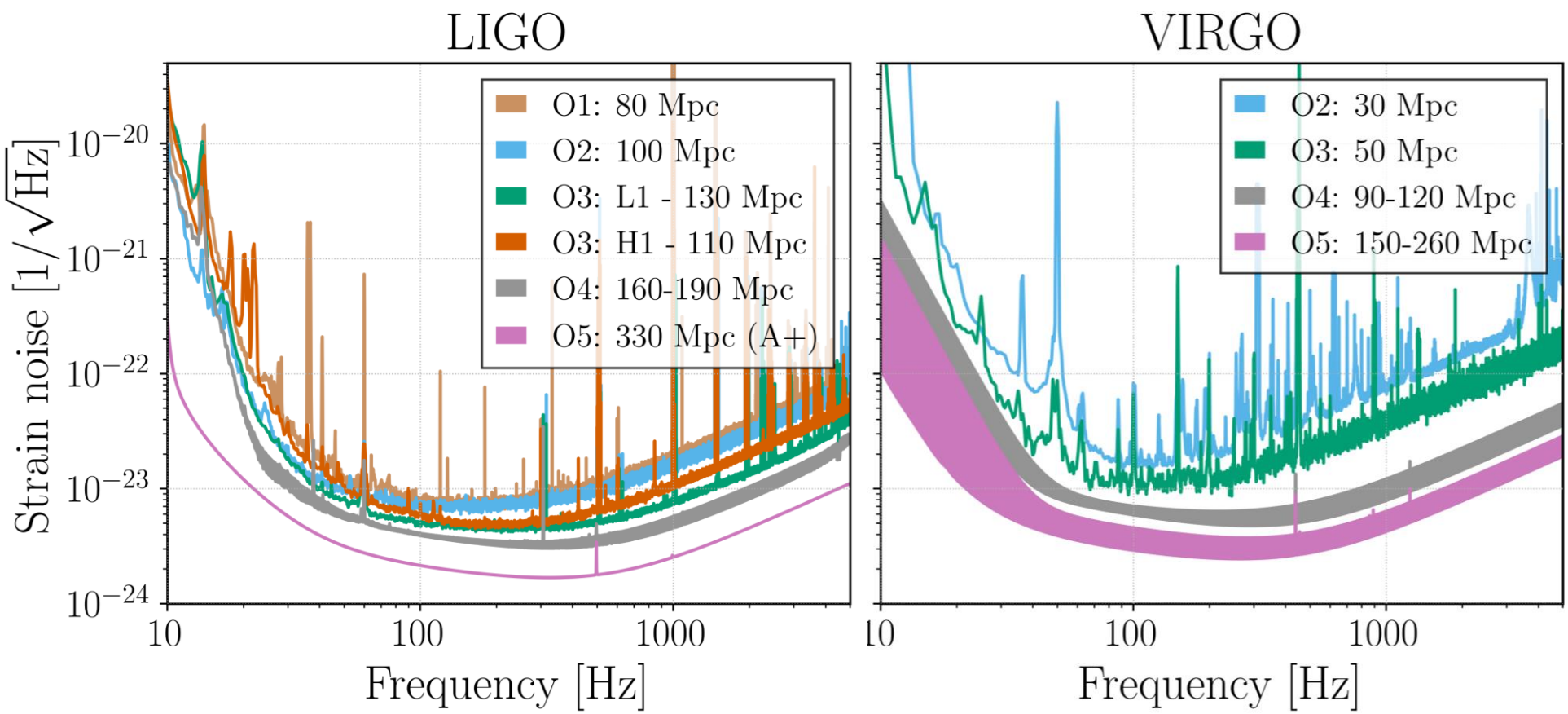
O4 is scheduled to start in March 2023



LIGO-G2002127-v4

Sensitivity targets for LIGO's A+ and Virgo's AdV+

Detector noise expressed as equivalent GW strain



AdV+ phase 1

Signal recycling will be implemented after O3, higher laser power, and improved squeezing

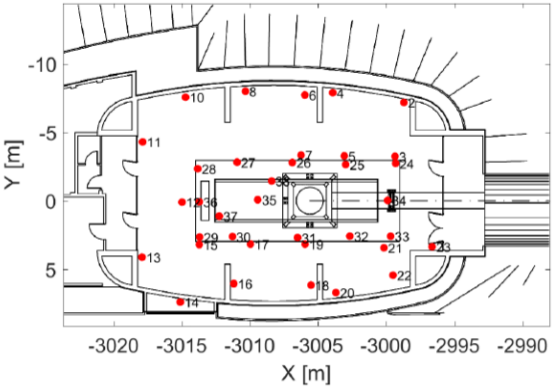
Frequency dependent squeezing

Filter cavity construction progressing

Newtonian noise cancellation

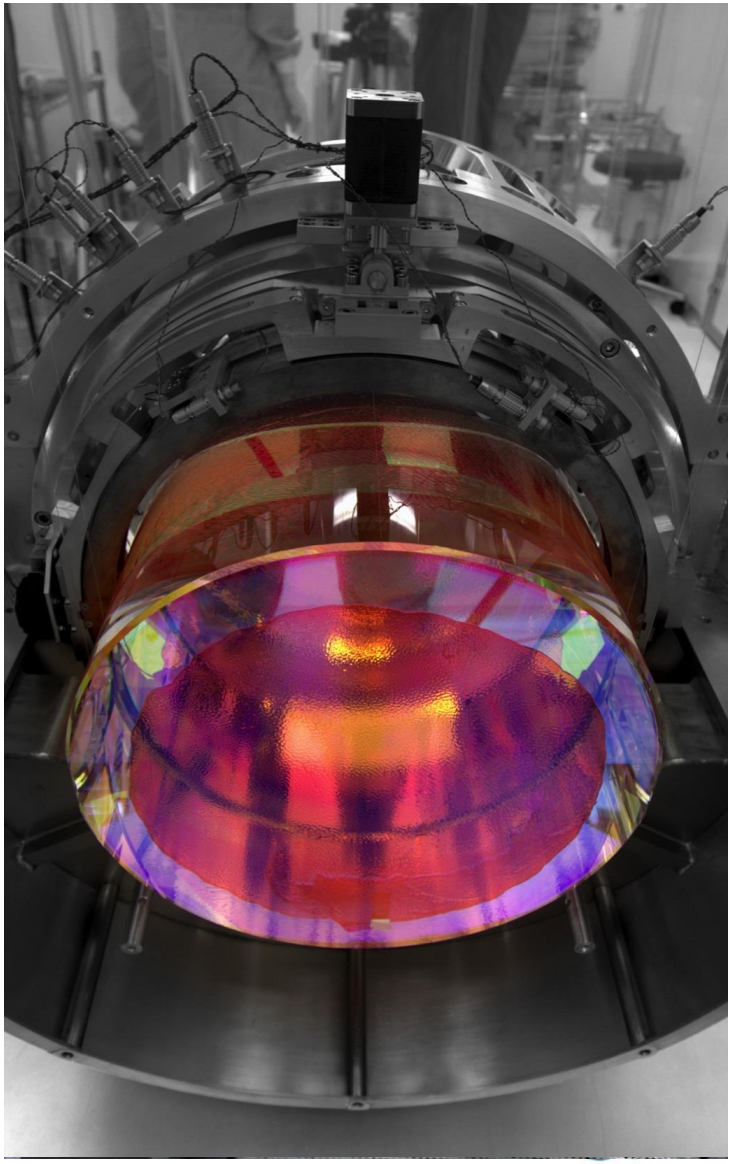
Smart sensor network (140 sensors) to monitor displacement field

Subtraction algorithms are under development



AdV+ phase 2 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

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

International context

Gravitational wave international committee

GWIC mission: facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational wave detection facilities world-wide. See https://gwic.ligo.org

GWIC member projects and collaborations

Project	Focus	Project	Focus
DECIGO	Space-based	LIGO	Ground-based
Einstein Telescope	Ground-based (nextgen)	LISA community	Space-based
Cosmic Explorer	Ground-based (nextgen)	NANOGrav	Pulsar timing
European Pulsar Timing Array EPTA	Pulsar timing	OzGrav/PPTA	Ground-based/Pulsar timing
GEO 600	Ground-based	Virgo	Ground-based
KAGRA	Ground-based	GW Theory Community	All

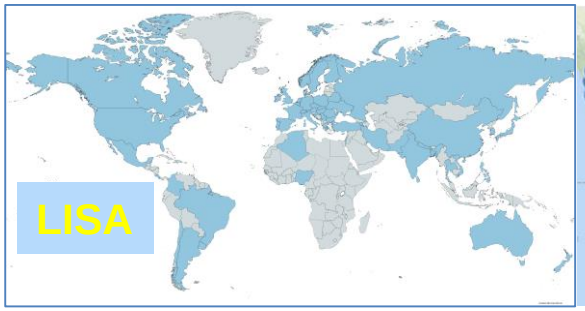
Statistics about GWIC member projects

- LISA about 1,550 members from 60 countries, IPTA about 200 members
- LIGO SC, Virgo and KAGRA about 2,000 members
- Cosmic Explorer and Einstein Telescope about 1,000 members

Slides represent the opinion of GWIC members

Affiliated members

- GWIC is Working Group 11 of IUPAP
- International Society of General Relativity and Gravitation – ISGRG is an Affiliated Commission (AC2) of IUPAP
- IAU Commission D1



Global PTAs and Telescopes

PTAs are rapidly growing in sensitivity

Various collaborations

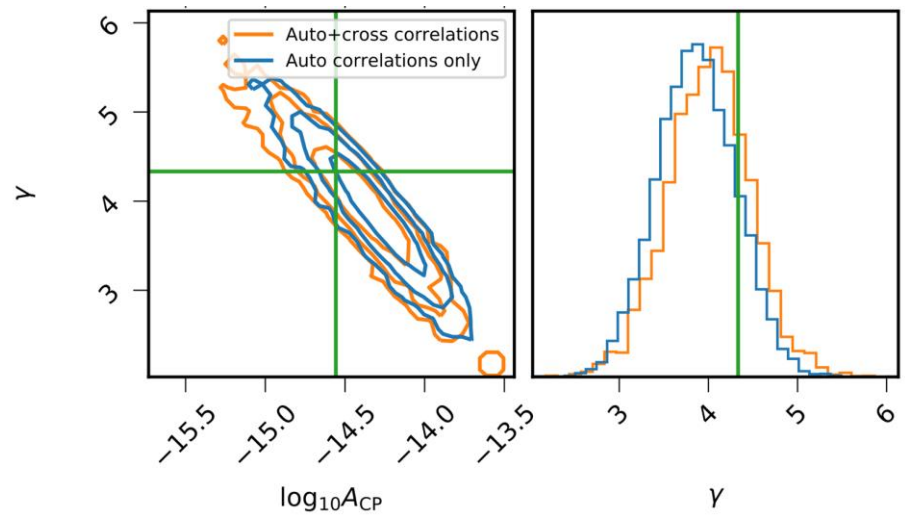
- EPTA
- NANOGrav
- PPTA
- InPTA
- IPTA
- + new ones coming up

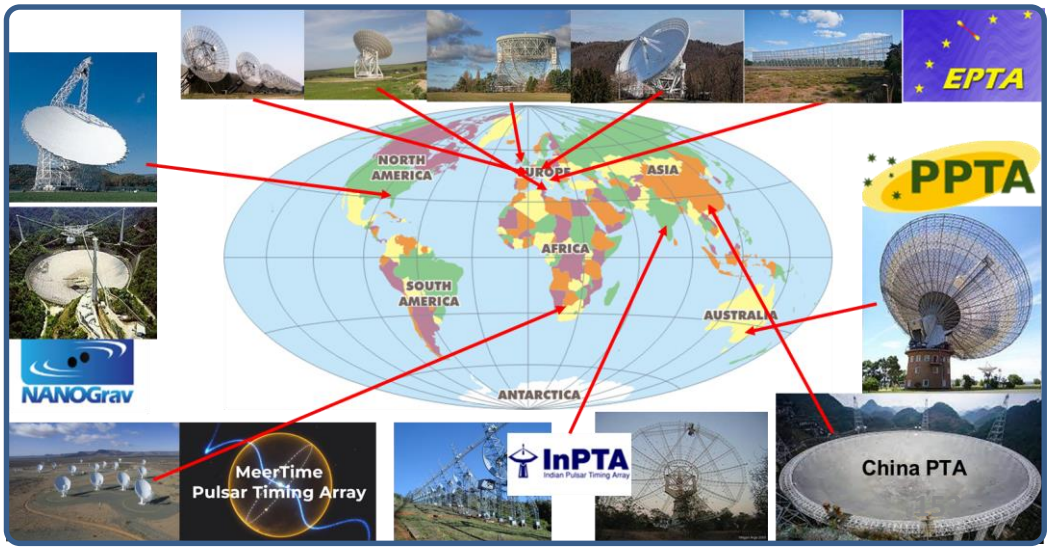
Progress

- IPTA “DR2” result published Jan 2022. Common process detected, consistent with expectations of supermassive black hole binary background.
- Spatial correlations not yet detected

The International Pulsar Timing Array second data release: “Search for an isotropic Gravitational Wave Background”

- See arXiv:2201.03980





OzGrav

OzGrav contributes to a range of activities from PPTA to LIGO to 3G. See https://www.ozgrav.org/

OzGrav R&D

- On 2G++ and 3G detectors, PTAs, and data analysis
- Carrying out a conceptual design and cost estimate for a 3G Pathfinder facility in Australia - NEMO

NEMO – Neutron Star Extreme Mater Observatory

- 4 km long, kHz band GW detector
- Science case: revolves around merger and ring-down phase of NS/NS mergers
- Neutron star Equation of State EOS studies => New information on nuclear matter plus other properties of neutron stars at two temperature extremes
- Cosmology once EOS known, independently measure redshift and luminosity distance
- International partnerships will be sought

Establish an Australian site for a future 3G detector

The LISA mission

LISA will explore the GW frequency range from 0.1 mHz to 100 mHz. See https://sci.esa.int/web/lisa

Science

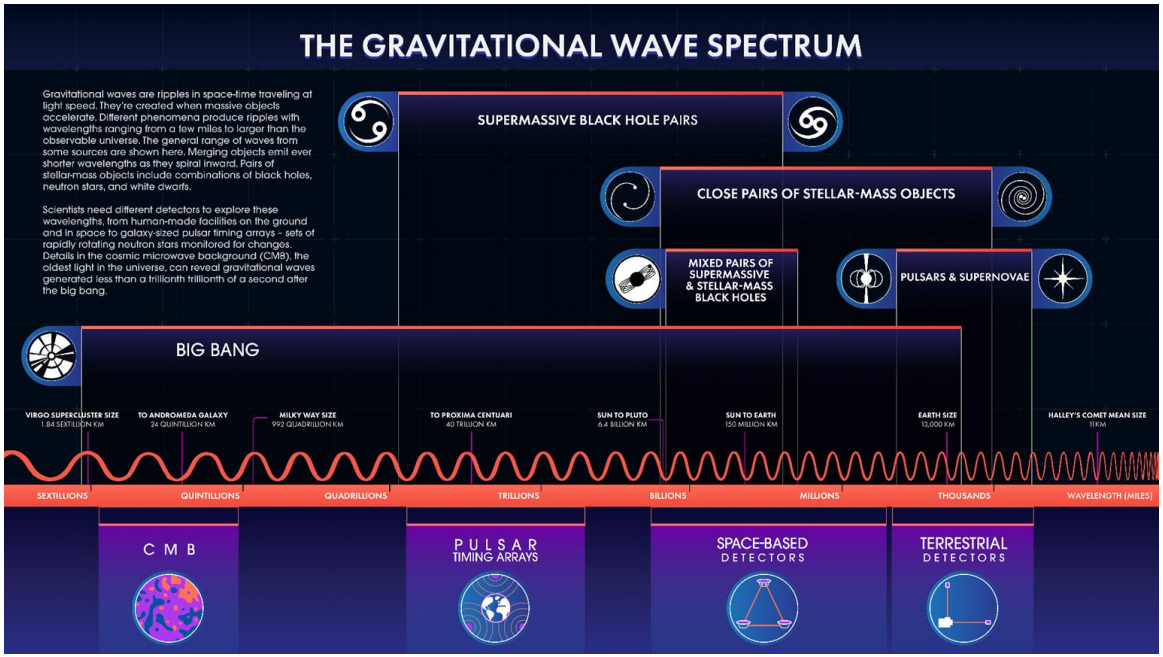
Targeting the origin and evolution of massive BHs, precision tests of GR, a census of galactic compact binaries, and potential new discoveries in the millihertz GW universe

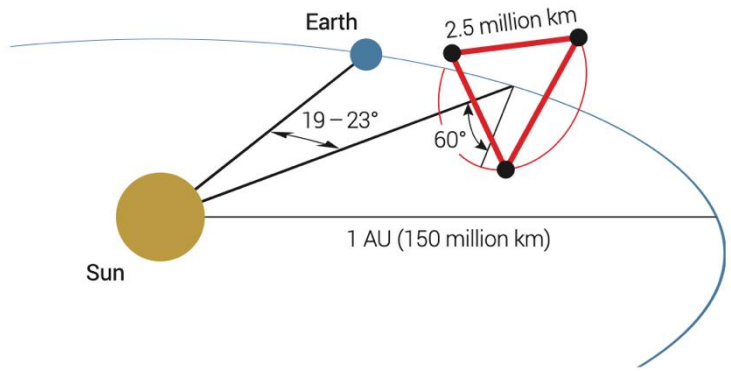
Detector

3 drag-free Spacecraft with 2.5 Gm laser transponder links

Mission

ESA large class mission with contributions from NASA and European Member States



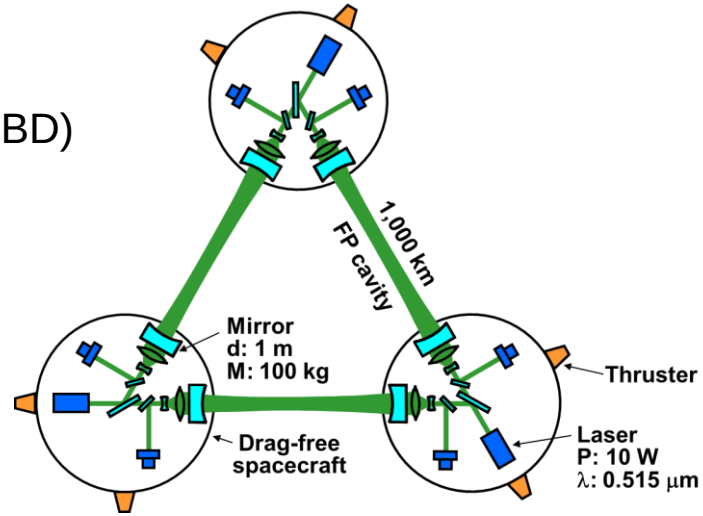


DECIGO: a Japanese 2nd-generation space detector

Deci-hertz Interferometer Gravitational Wave Observatory. See https://decigo.jp/index_E.html

DECIGO

- Frequency band: 0.1 Hz - 10 Hz
- Bridges the gap between LISA and ground-based detectors (GBD)
- Follow-up for LISA and predictor for GBD

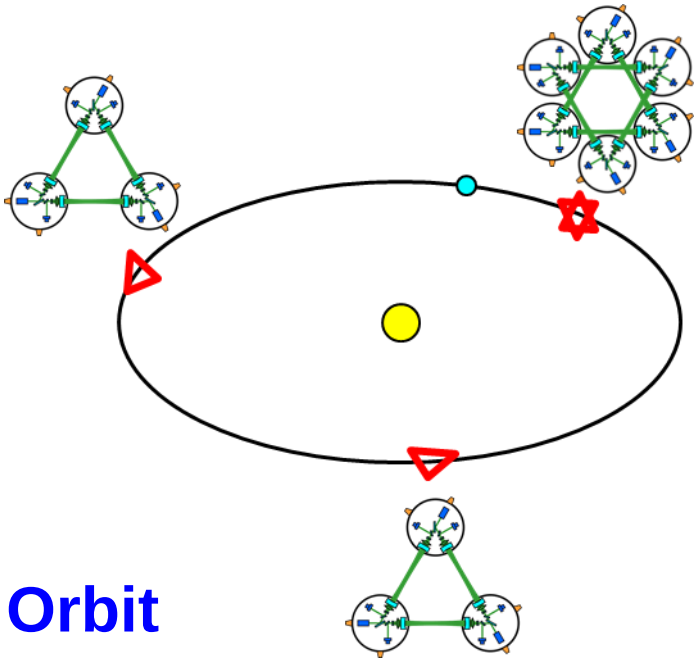


Pre-conceptual design

B-DECIGO

Pathfinder science mission for DECIGO

©NEC



Orbit

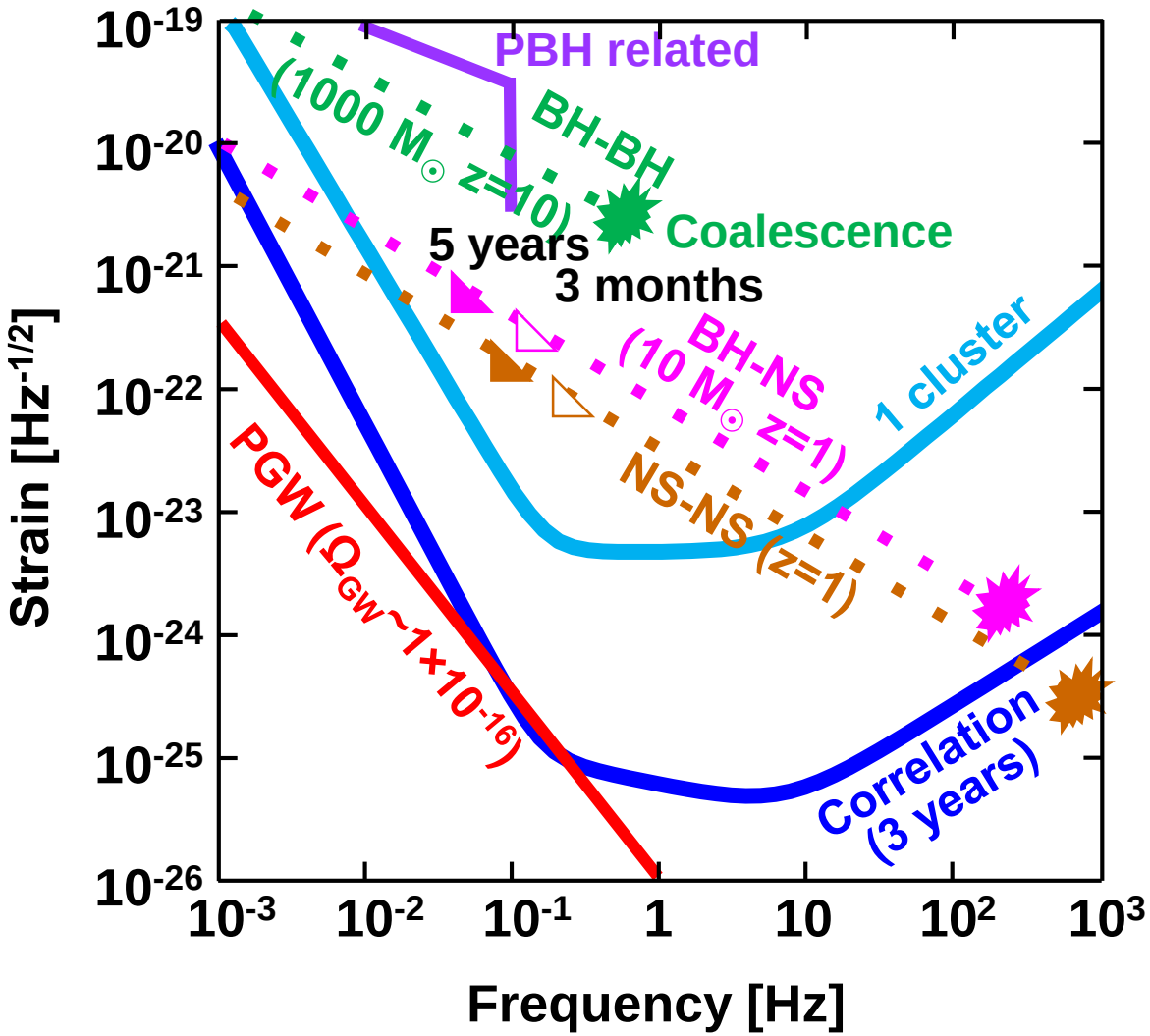
DECIGO: target sensitivity and aimed science

Deci-hertz Interferometer Gravitational Wave Observatory. See https://decigo.jp/index_E.html

Science goals

- Detect primordial gravitational waves (PGW)
- Prediction of NS-NS coalescences
- Measure acceleration of expansion of Universe
- Reveal formation of intermediate-mass BH
- Detect Primordial-BH related GWs
- Improve accuracy of general relativity

Design parameters: under optimization for PGW

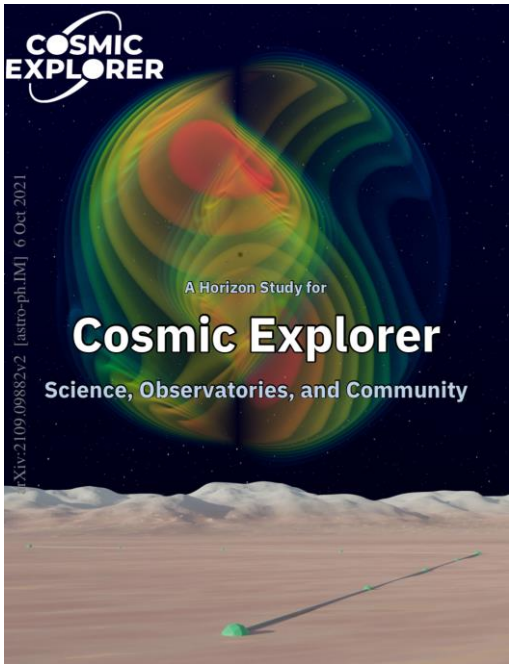


Cosmic Explorer

CE is the planned U.S. contribution to the global third-generation ground-based gravitational-wave detector network. See https://cosmicexplorer.org/

Quick reminder

- US concept for next-generation GW detectors
- Two ‘L’ sites, one 40 km, one 20 km, on the Earth’s surface
- Using incrementally-improved LIGO detector designs for the first detectors
- Plan to match Einstein Telescope’s planned schedule with joint observing in the 2030’s

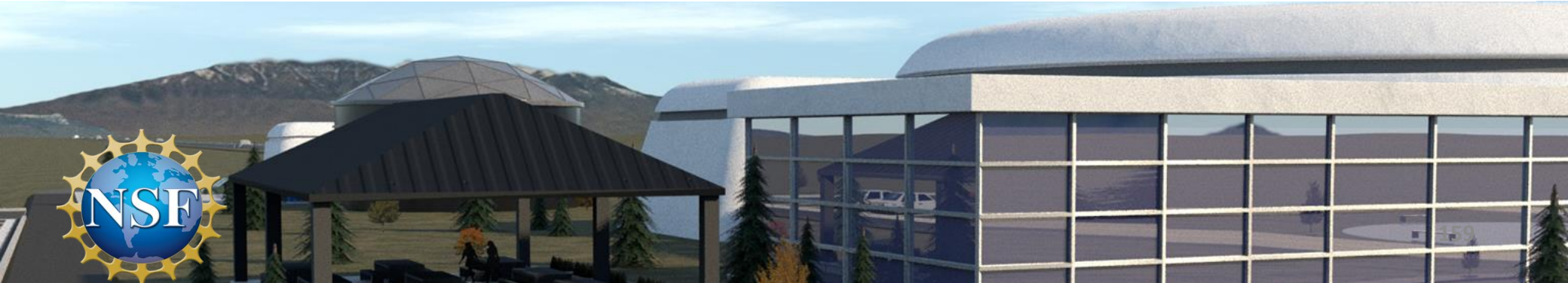


Cosmic Explorer: key steps forward in the last year

Significant progress in organization of the Cosmic Explorer Project and in community building

Key steps forward

- The Cosmic Explorer Horizon Study https://cosmicexplorer.org/ submitted to NSF
- The Dawn VI community meeting focused on CE, the Horizon study, and connections to the broader MMA community
  - Consensus that Cosmic Explorer is a valid path forward
  - Dawn VI Report: https://gwic-documents.s3.us-west-2.amazonaws.com/dawn/Dawn-VI-report.pdf
- Astro Decadal report strongly supportive of GWs, MMA, and CE
  - Astro Decadal Report: https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020
- White papers on science and detectors from the community as input
- Formation of a Project organization with both Project and Technical meetings
- First draft of a proposal for the Conceptual Design; first meeting of the CE Project Advisory Committee and review of the draft proposal



Einstein Telescope

Einstein Telescope appeared on the ESFRI Roadmap June 30, 2021. See http://www.et-gw.eu/

ESFRI proposal

- Submitted by: Italy, Belgium, Netherlands, Poland and Spain

Project and collaboration also include agencies and institutions belonging to

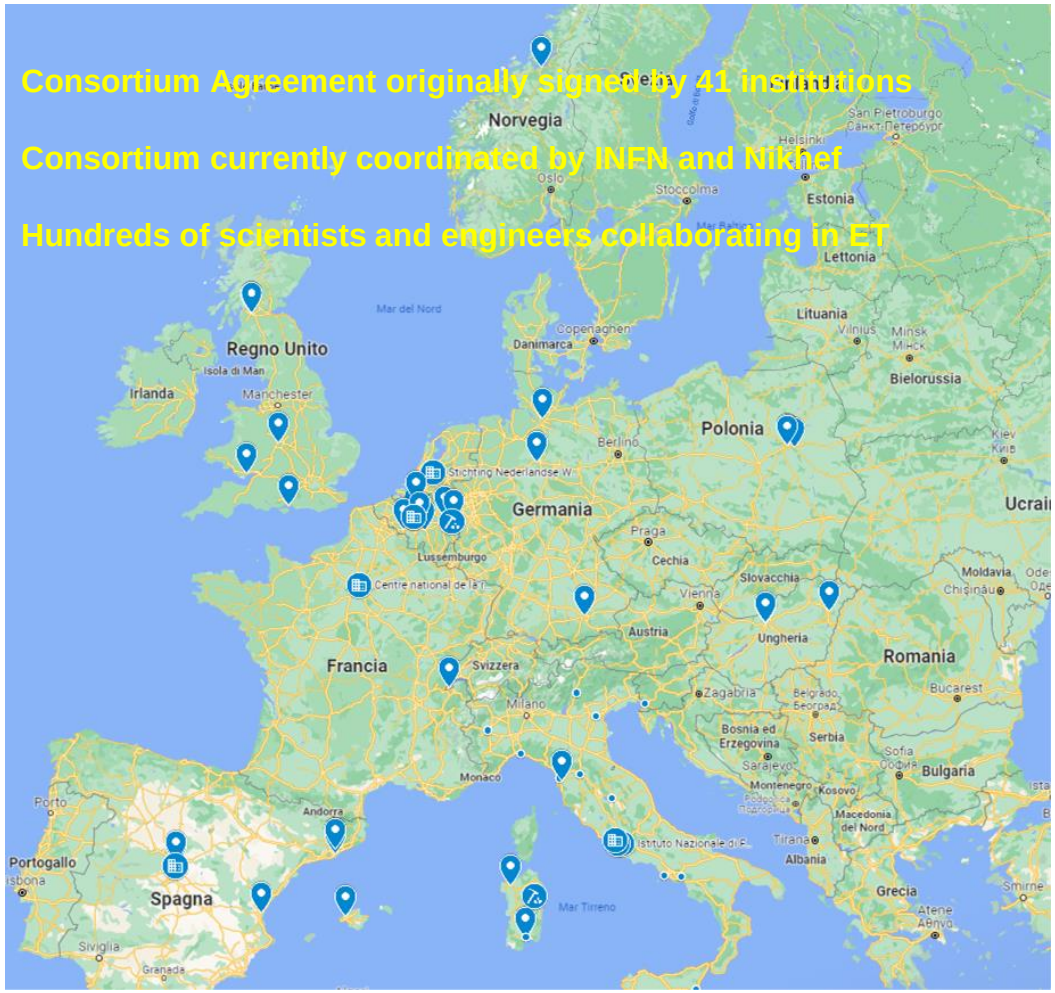
- Austria, France, Germany, Hungary, Switzerland and UK

Funds

- Preparatory funds available in some countries (IT, NL, …)
- EU INFRA-DEV proposal approved
- EU INFRA-TECH proposal just submitted

Site candidates

- Studies ongoing in Sardinia in Italy, B-G-NL border region, and Saxony in Germany



ESFRI ROADMAP 2021

European Strategy Forum on Research Infrastructures

ET EINSTEIN TELESCOPE

ETIC – Einstein Telescope Infrastructure Consortium

Next Generation EU investment approved of 50 M€ focused on ET enabling technology and Sardinian site candidature support

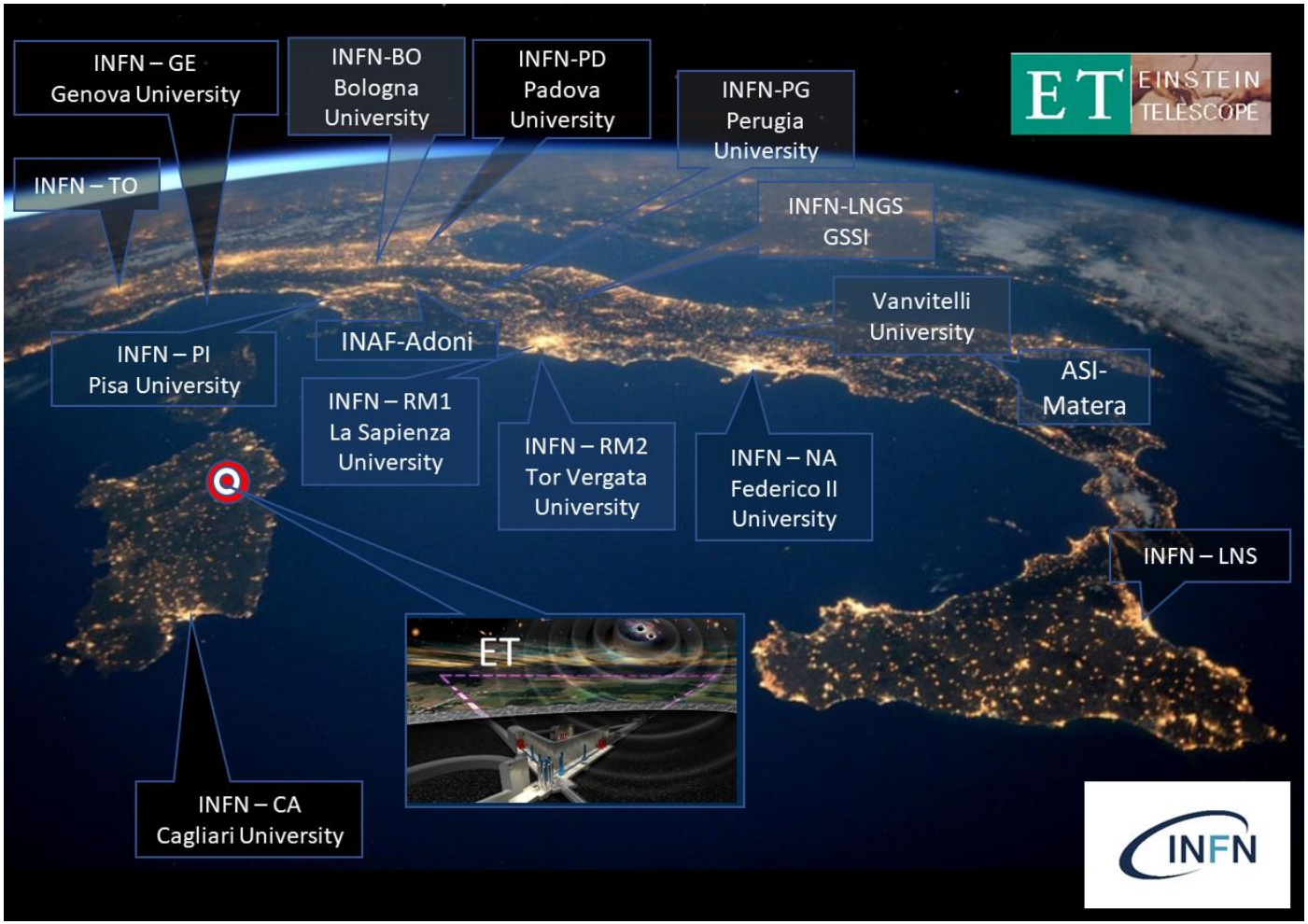
Support for

- 8% Human resources
- 30% Scientific apparatuses
- 12% Distributed infrastructures
- 28% ET design
- 12% Training

Additional 5 M€ funding on the same framework for the site characterization

Feedback expected soon

Discussion ongoing on an Italian share toward ET realization



Einstein Telescope in Germanny

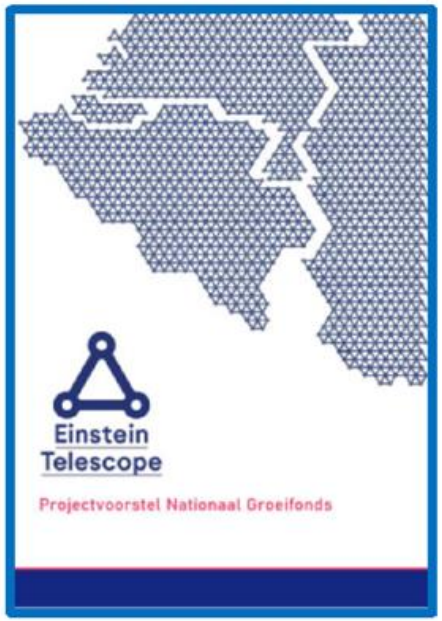
BMBF in Germany decides to create an astrophysics institute in Saxony with an annual of budget of 180 M€ with as pillars Einstein Telescope and SKA

Einstein Telescope in Euregio Meuse-Rhine (EMR)

Einstein Telescope approved by Dutch National Growth Fund on April 14, 2022. Development funds of M€ 42 available to prepare bid book, while M€ 870 will be available in case EMR region hosts ET

Connected institutions in:
Belgium,
Germany &
the Netherlands

Nationaal Groeifonds (the Netherlands)



Emphasis on potential socio-economic Impact

Submitted by OCW Ministry
(EZK Ministry support)

Supported by ~70 Dutch Industries/institutions

In October 2021 the Netherlands submitted large funding proposal within context of the '*Nationaal Groeifonds*'. Decision in April 2022.

Includes 42 M€ for geology, R&D & organization
as well as possible Dutch share towards ET realization

Formal birth of the Einstein Telescope Collaboration

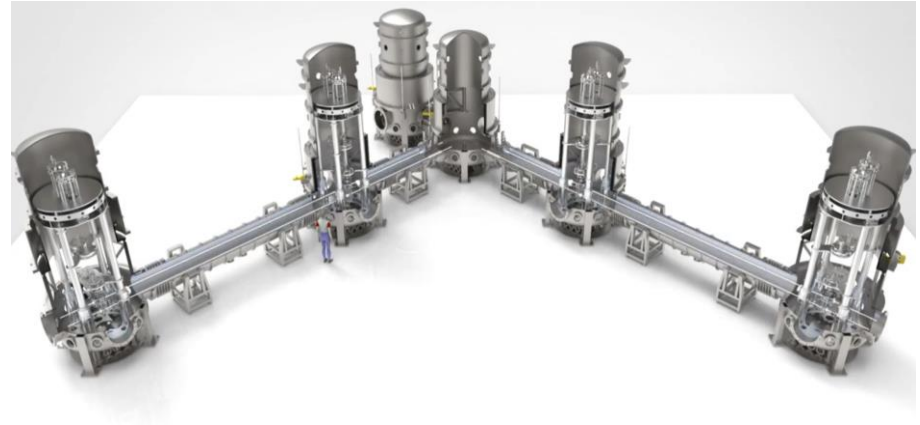
XII Einstein Telescope Symposium, Budapest June 7-8, 2022

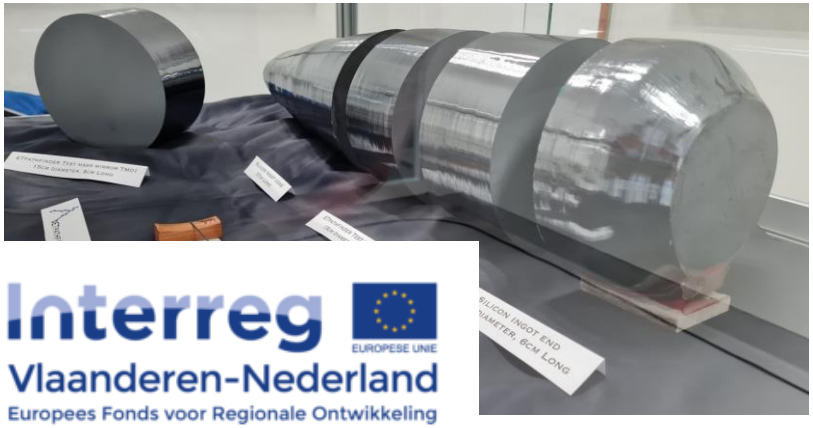
See https://indico.ego-gw.it/event/411/

ETpathfinder

ETpathfinder is a new R&D infrastructure for testing innovative concepts and technologies for future gravitational wave observatories. Open for everyone interested to join. See https://www.etpathfinder.eu

- New facility for testing ET technology in a low-noise, full-interferometer setup
- Key aspects: silicon mirrors (3 to 100+ kg), cryogenics (cryogenic liquids and sorption coolers, water/ice management), “new” wavelengths (1,550 and 2,090nm), new coatings
- Start with 2 FPMI: at 120 K and at 15 K (2022+)
- 20 partners from NL/B/G/FR/SP/UK
- Initial capital funding of 14.5 M€
- Detailed Design Report available at https://apps.et-gw.eu/tds/?content=3&r=17177





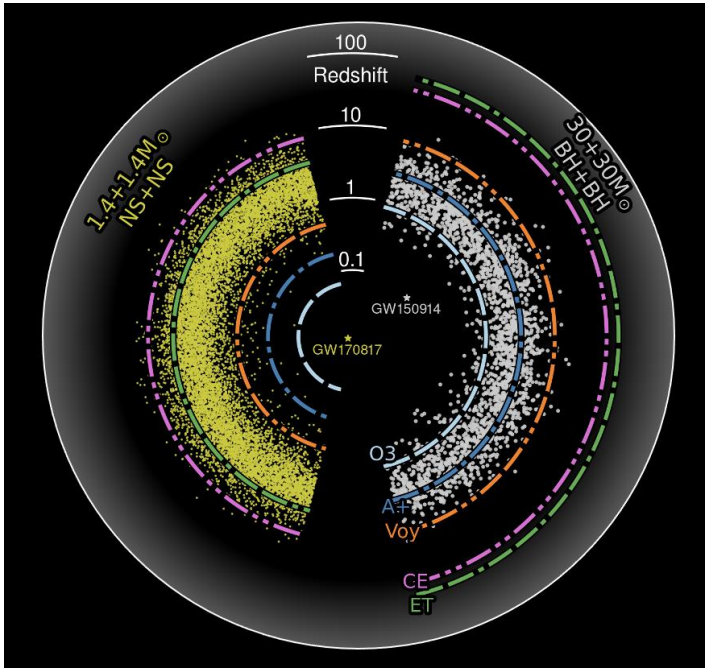
Interreg
EUROPESE UNIE
Vlaanderen-Nederland
Europees Fonds voor Regionale Ontwikkeling

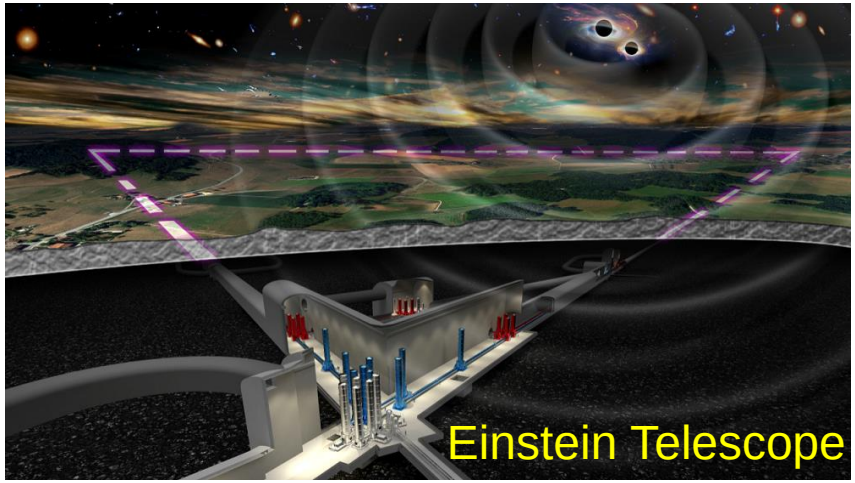
Building a Global Next-Generation Observatory Network

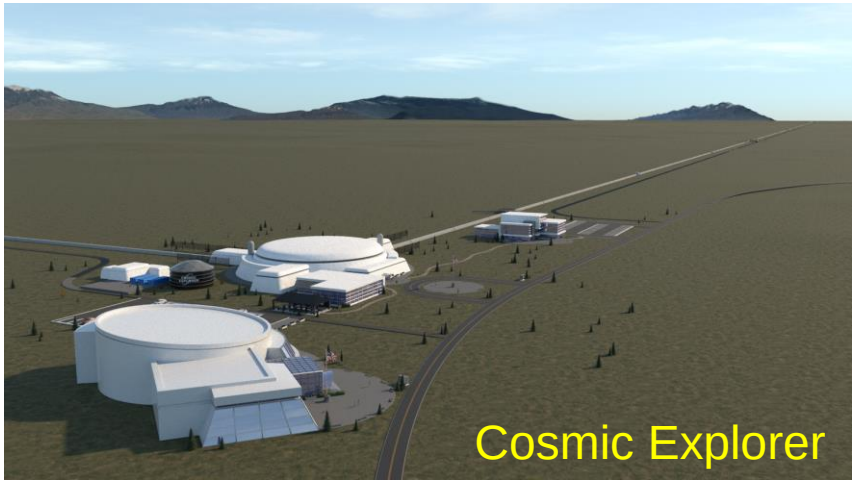
Realization of 3G observatories will profit from collaboration and a coordinated effort

Points of attention

- The most science and best use of infrastructures will come from a fully coordinated effort
- There are initial differences in project maturity, funding status
- Wish to take advantage of a coherent effort world-wide
  - Shared observational science basis
  - Shared R&D for detector and infrastructure
  - …networked observing

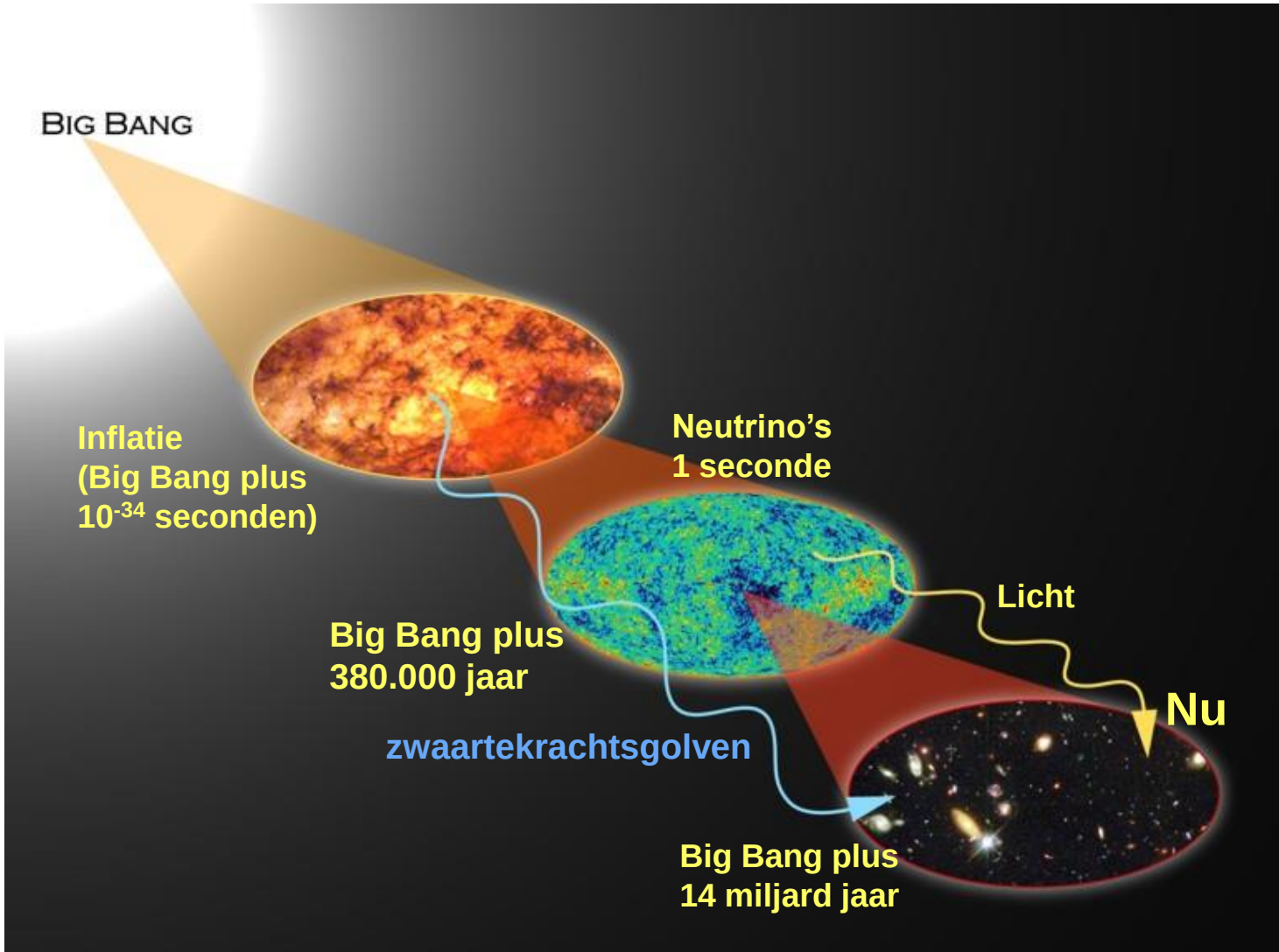






Early Universe

What is powering the Big Bang?
Gravitational waves can escape from the earliest moment of the Big Bang

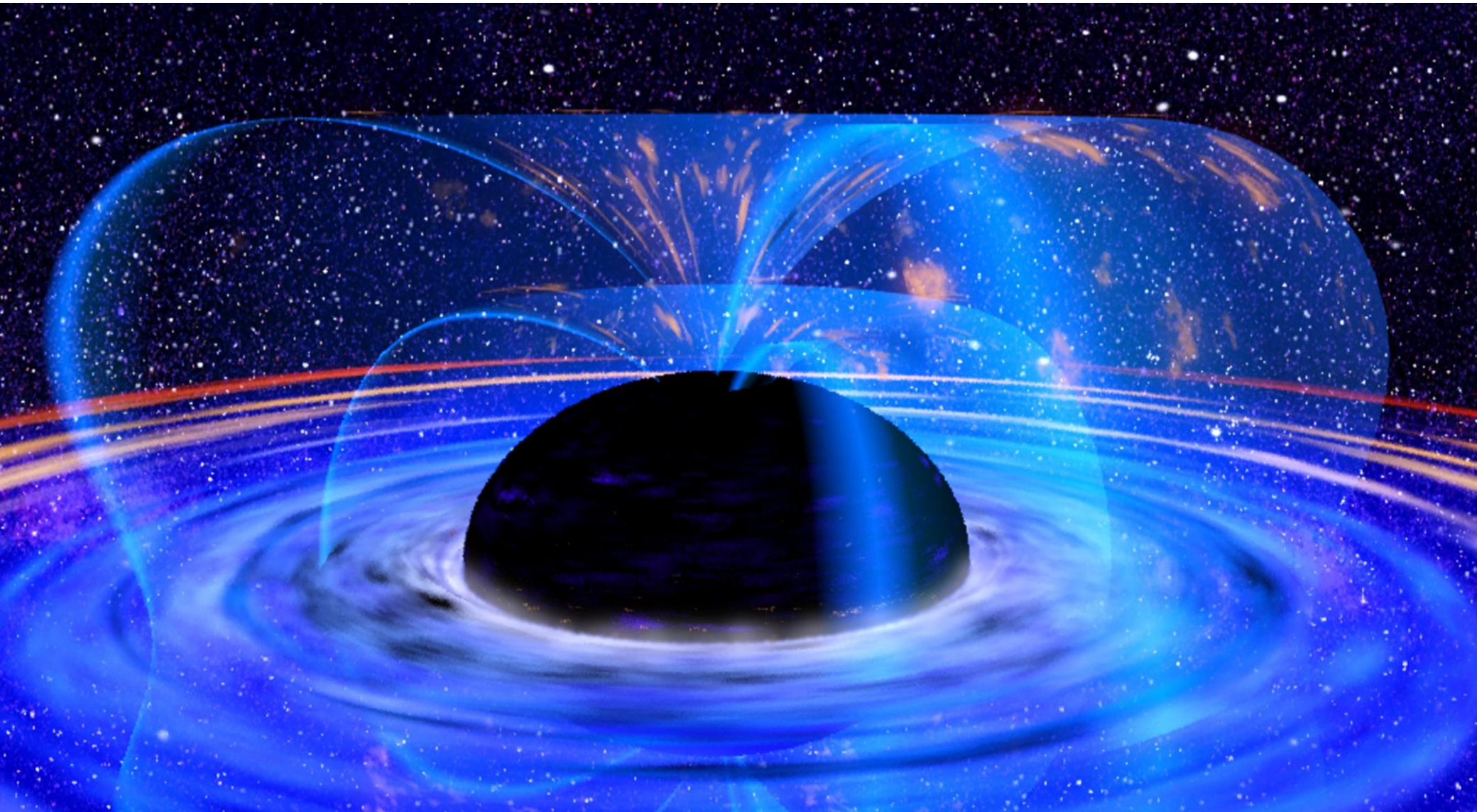


Cosmography

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

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?

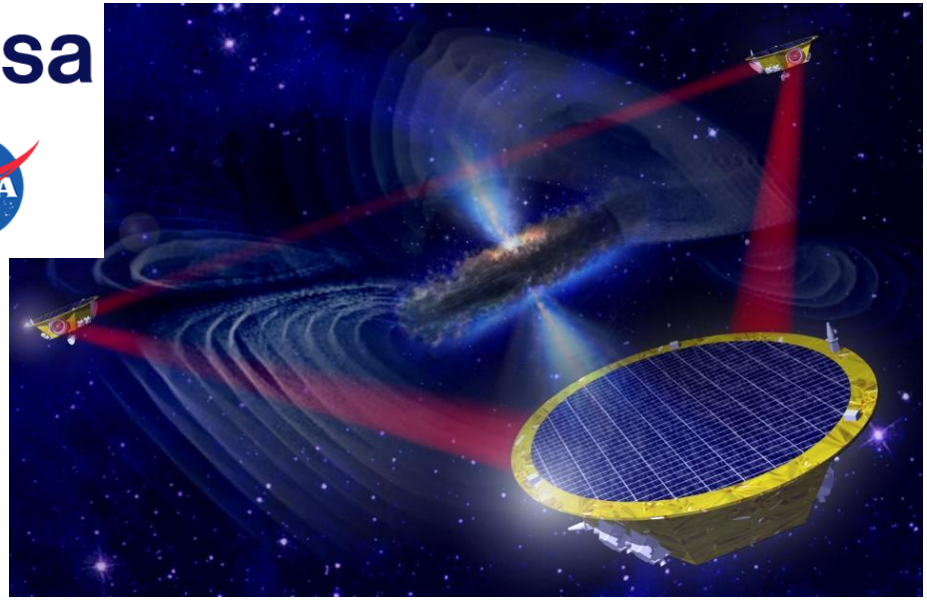


Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan joined in 2020, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope and CE CDRs financed. Strong support by APPEC

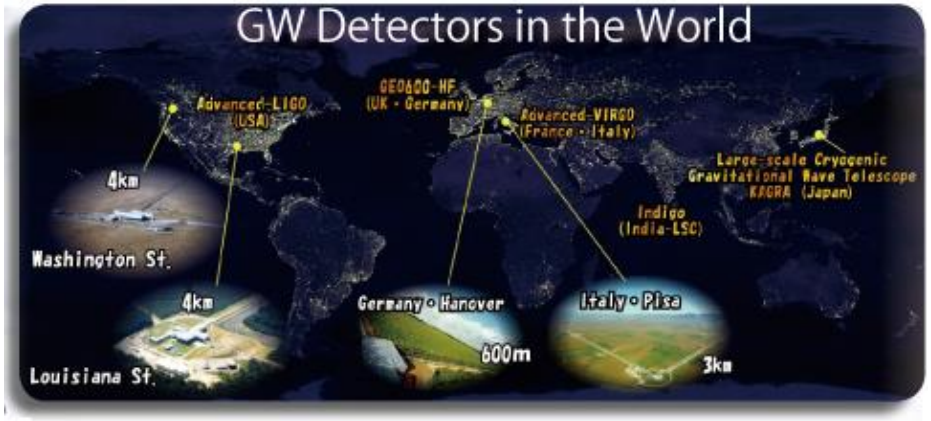
Gravitational wave research

- LIGO and Virgo operational
- KAGRA joined in 2020
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation



Einstein Telescope and Cosmic Explorer

- ET on ESFRI Roadmap in 2021, CE by NSF
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET



Next steps for 3G

- Organize the community and prepare a credible plan for EU funding agencies
- Support 3G: http://www.et-gw.eu/index.php/letter-of-intent

Thank you for your attention!