GRAVITATIONAL WAVES: FROM DETECTION TO NEW PHYSICS SEARCHES

Masha Baryakhtar

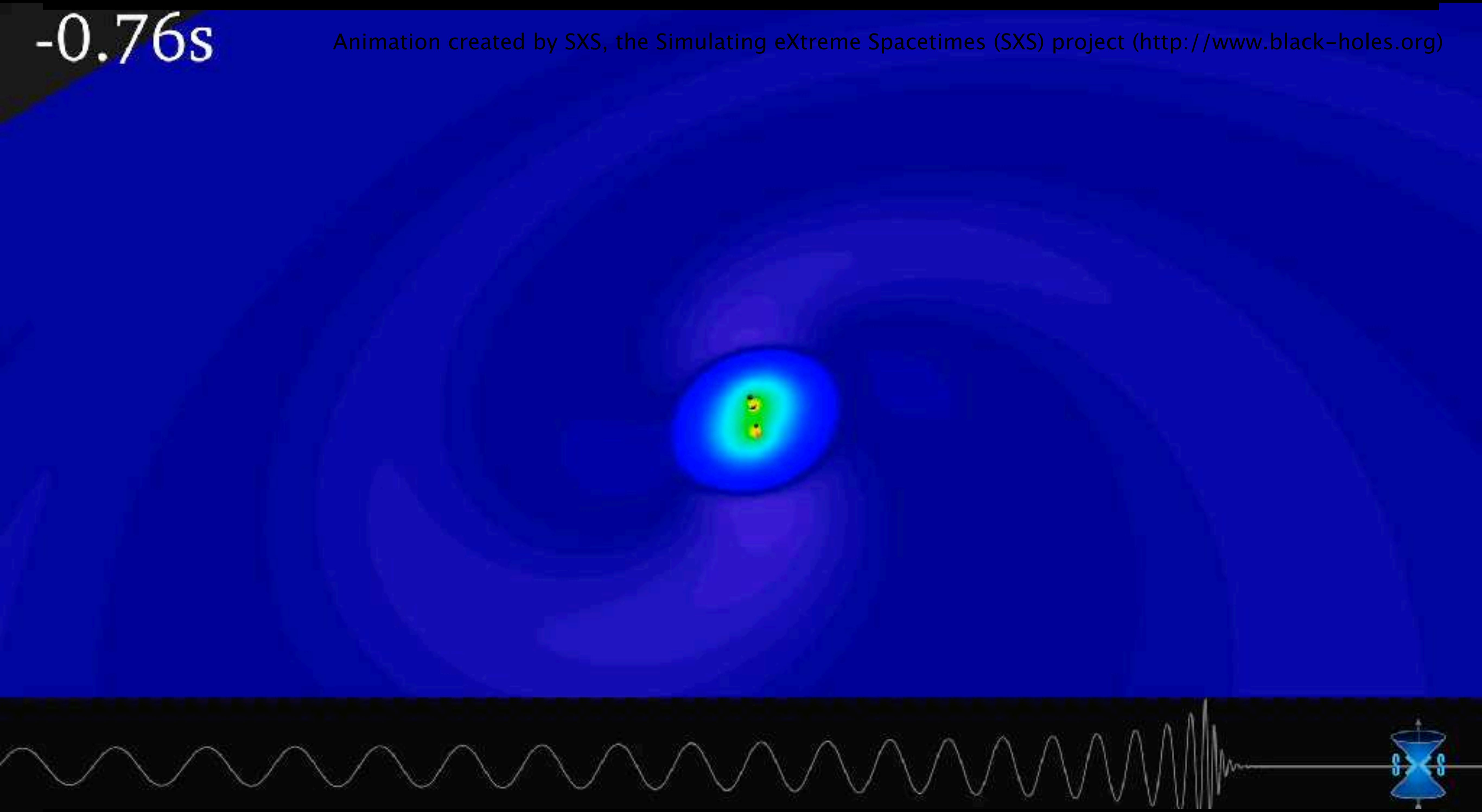
New York University

Lecture 1 June 29. 2020

1.3 Billion Years Ago

two ~30 solar mass black holes merged and produced a burst of gravitational wave radiation

1.3 Billion Years Ago

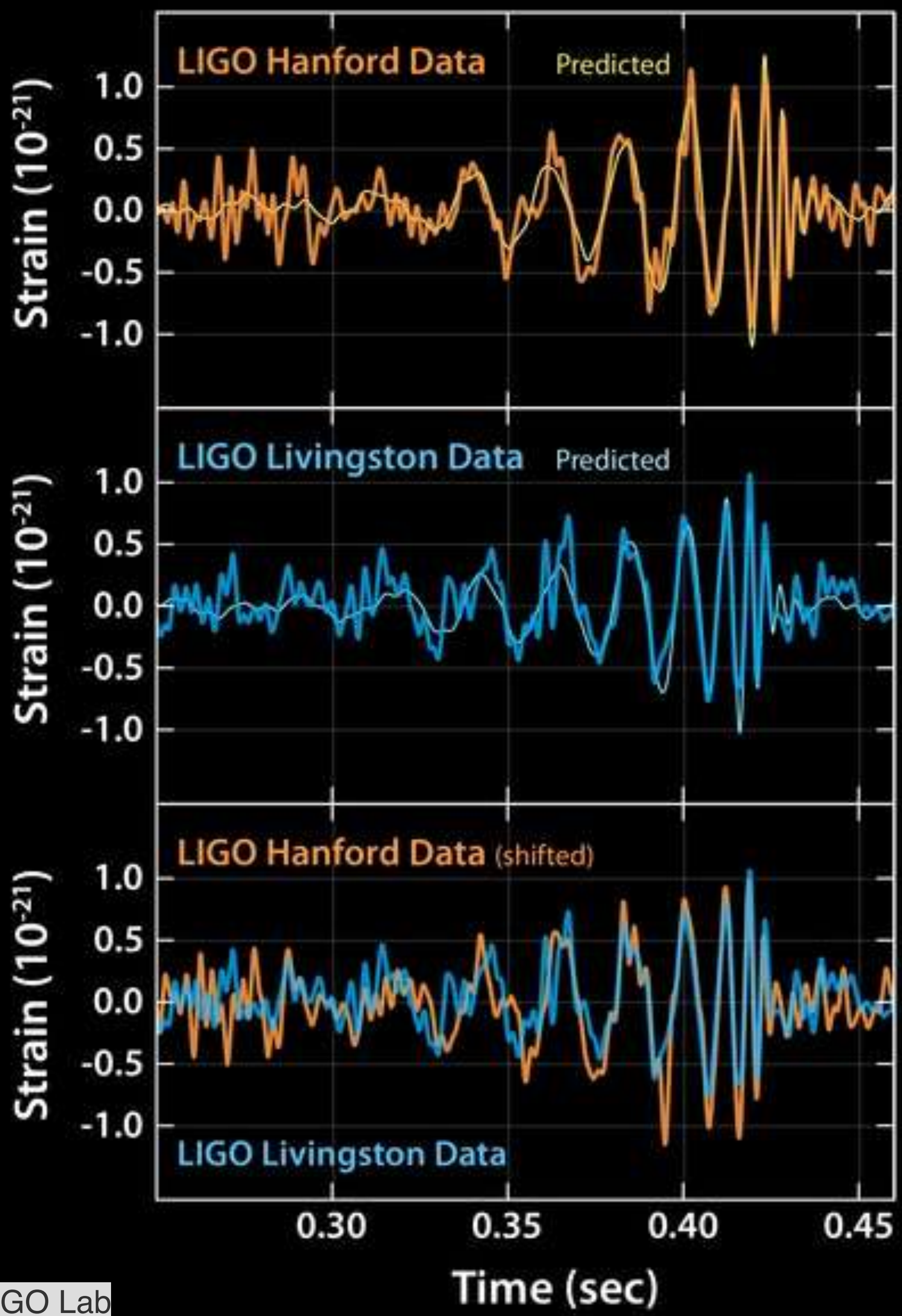


The colored surface is the space of our universe, as viewed from a hypothetical, flat, higher-dimensional universe, in which our own universe is embedded. Our universe looks like a warped two-dimensional sheet because one of its three space dimensions has been removed. Around each black hole, space bends downward in a funnel shape, a warping produced by the black hole's huge mass.

September 14, 2015

the LIGO detectors observe gravitational waves for the first time

September 14, 2015



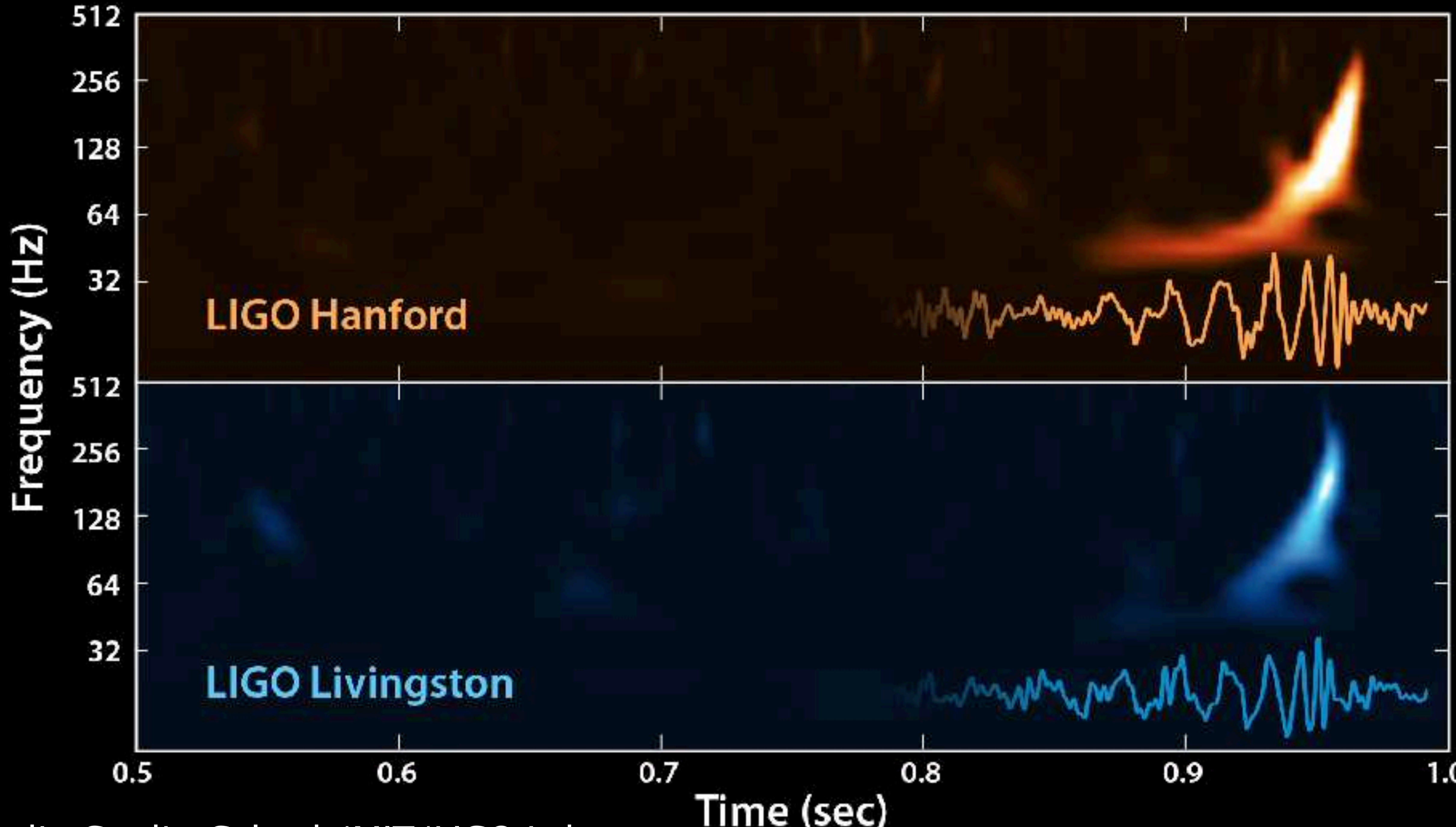
Caltech/MIT/LIGO Lab

On September 14, 2015, LIGO observed gravitational waves from the merger of two black holes, each about 30 times the mass of our sun. The incredibly powerful event, which released 50 times more energy than all the stars in the observable universe, lasted only fractions of a second.

the LIGO detectors observe gravitational waves for the first time

September 14, 2015

The Sound of Two Black Holes Colliding



Audio Credit: Caltech/MIT/LIGO Lab

the LIGO detectors observe gravitational waves for the first time

Today

watching the announcement of GW discovery at Perimeter Institute

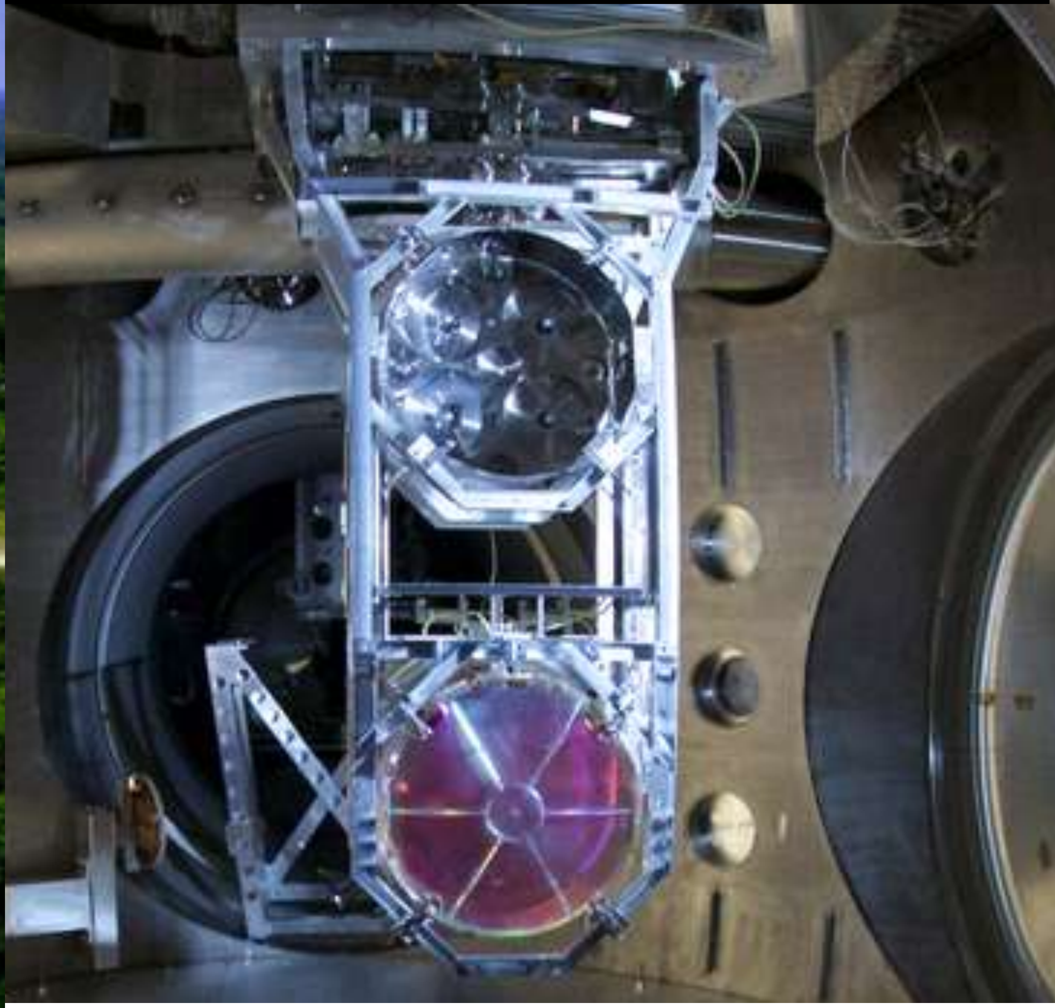
what have we learned and where do we go from here?

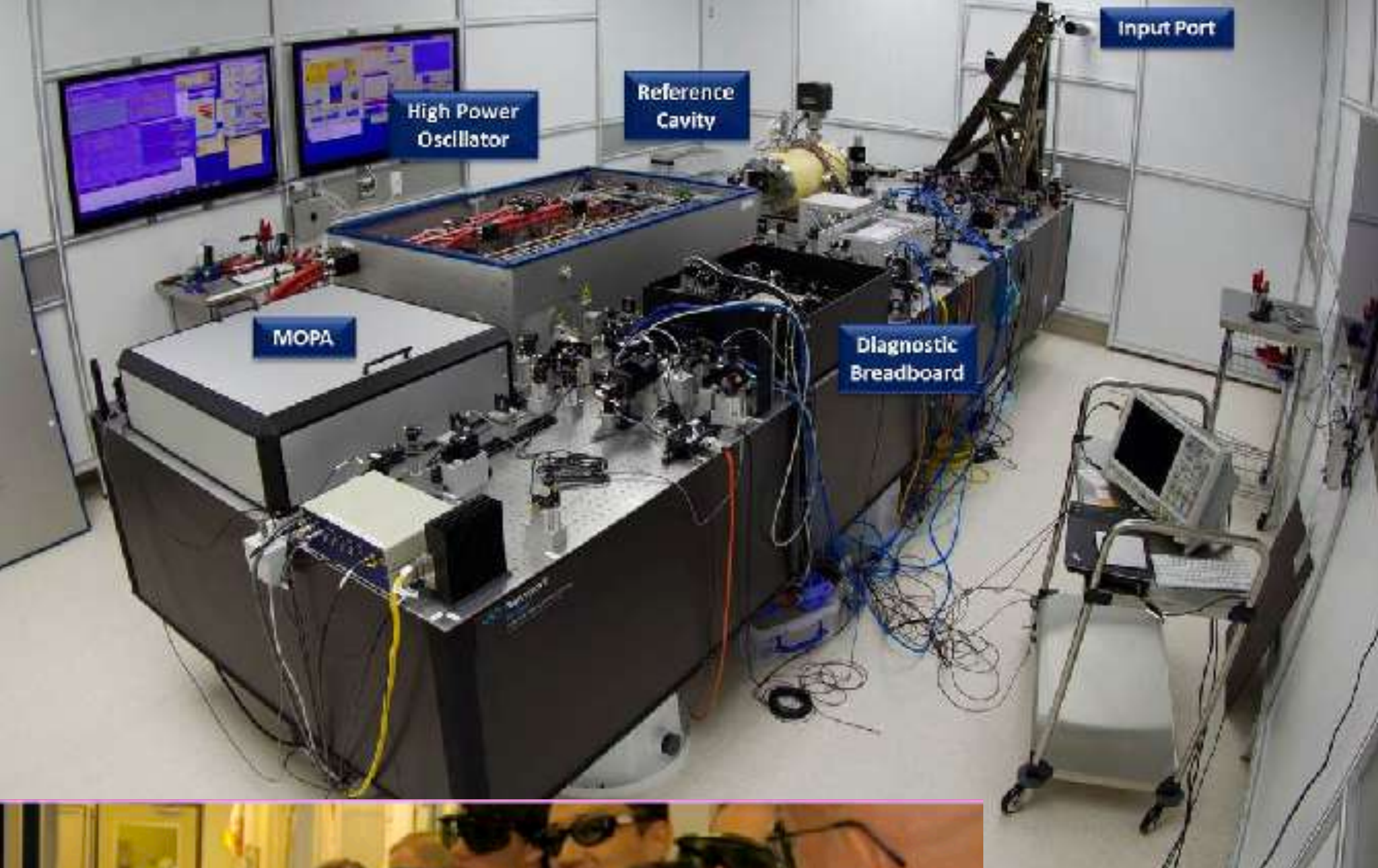
Observation of Gravitational Waves

- An amazing scientific and technological achievement
- Confirms what we predicted about strong gravity and are learning new things about the most extreme objects
- New window on the universe and a new tool for new physics searches

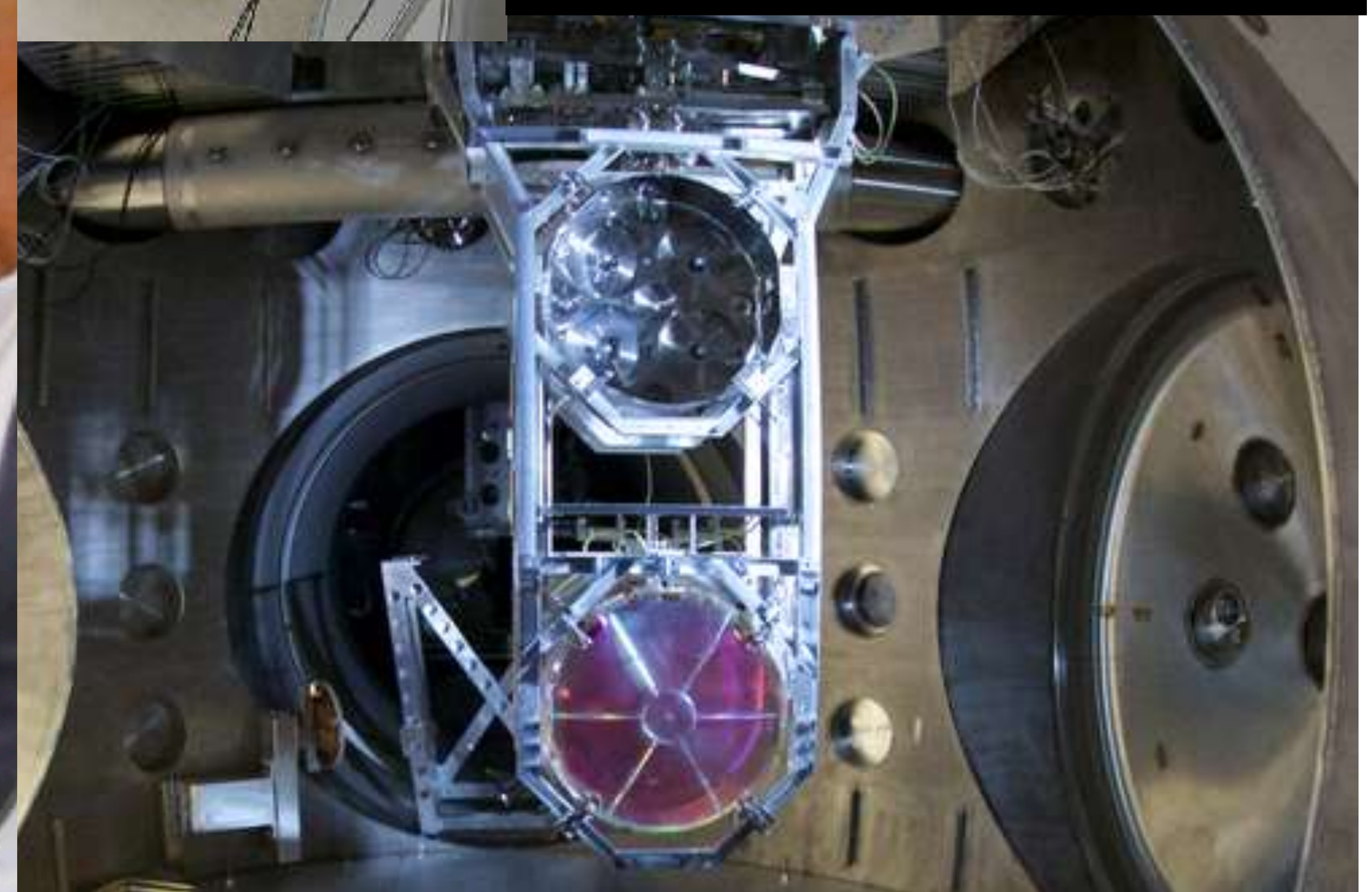
4 kilometer long Michelson interferometers, measuring displacements at better than one part in 10^21

An amazing scientific and technological achievement

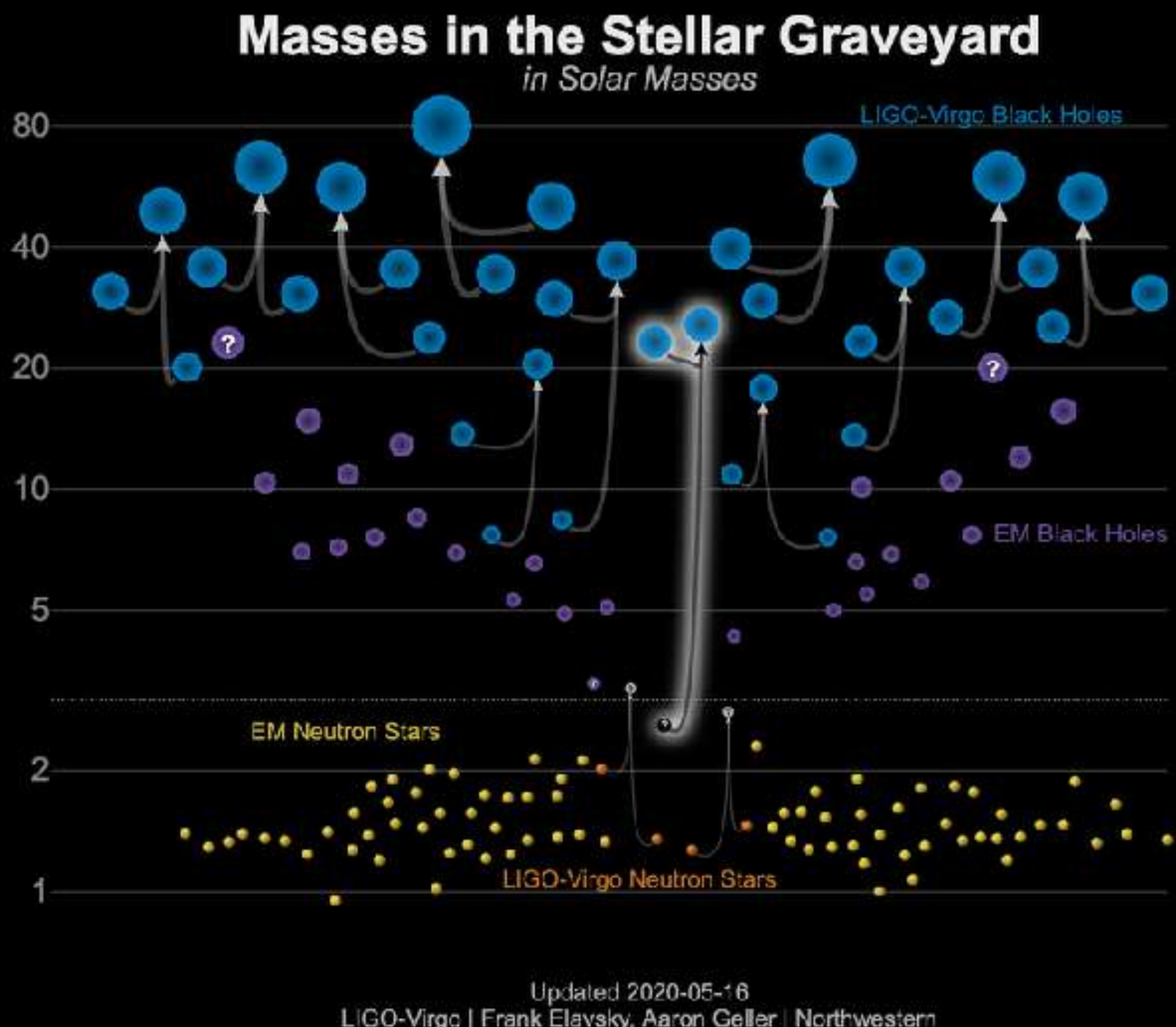




Powerful and complex laser, optics, and isolation systems and a team of over 1000 people



New Types of BHs, Binaries, Sources of Elements



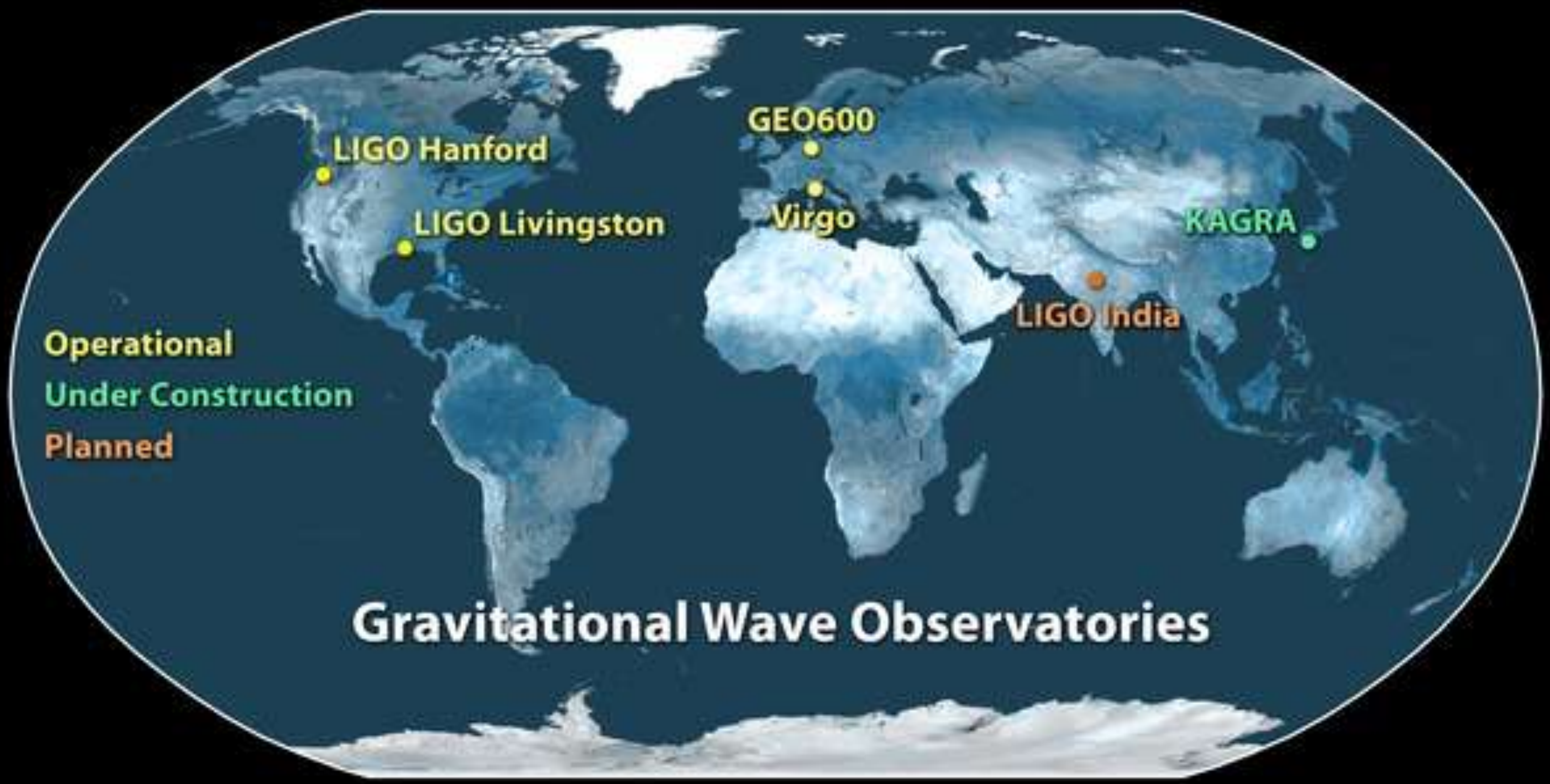
Since the first detection, >dozen BH BH mergers, two NS NS mergers, and a recent BH-? merger have been detected

New Types of BHs, Binaries, Sources of Elements

The first NSNS merger was followed up by many EM observations

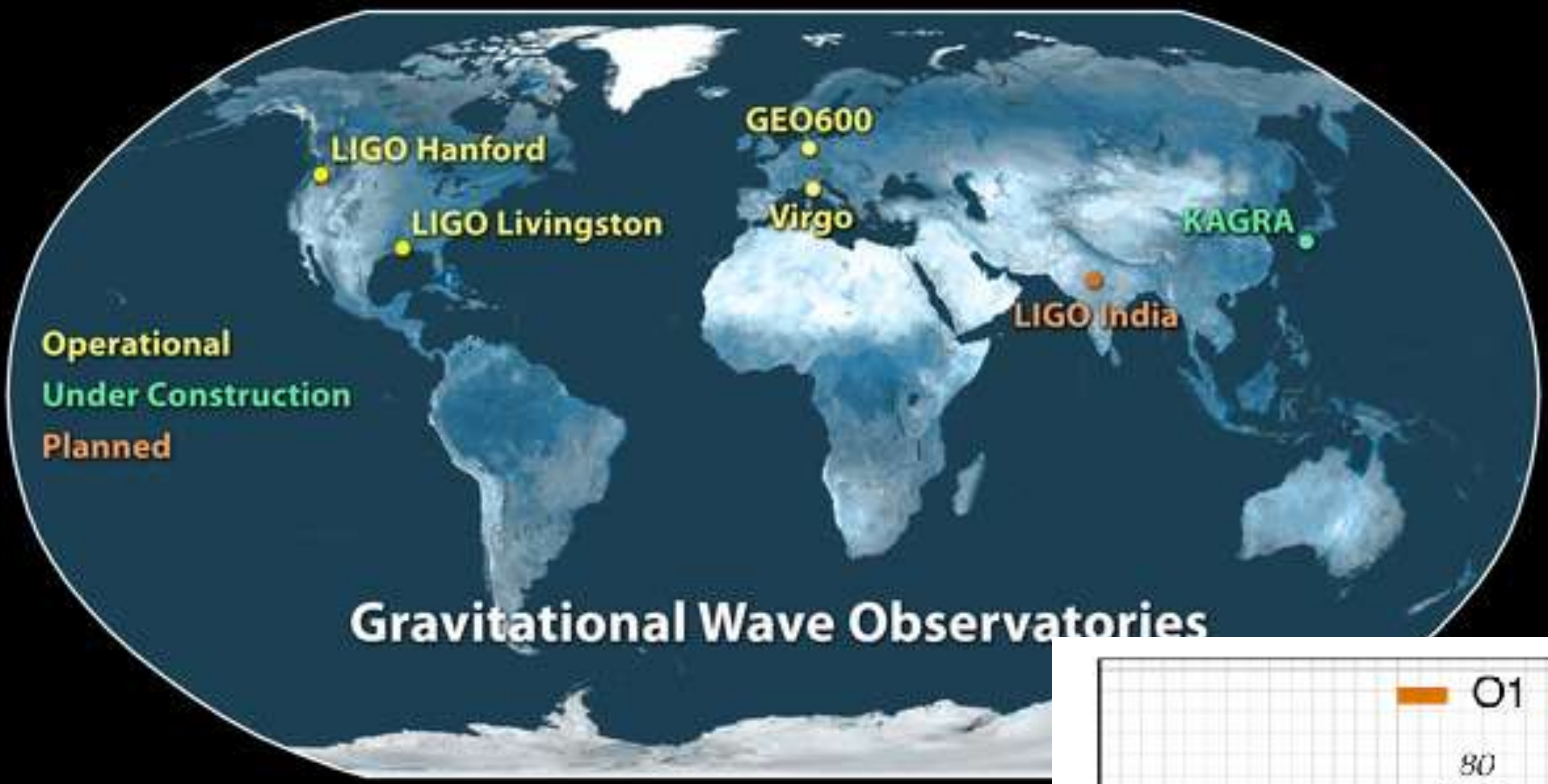
Learning about EoS of neutron stars and production of heavy element abundances

Just the beginning



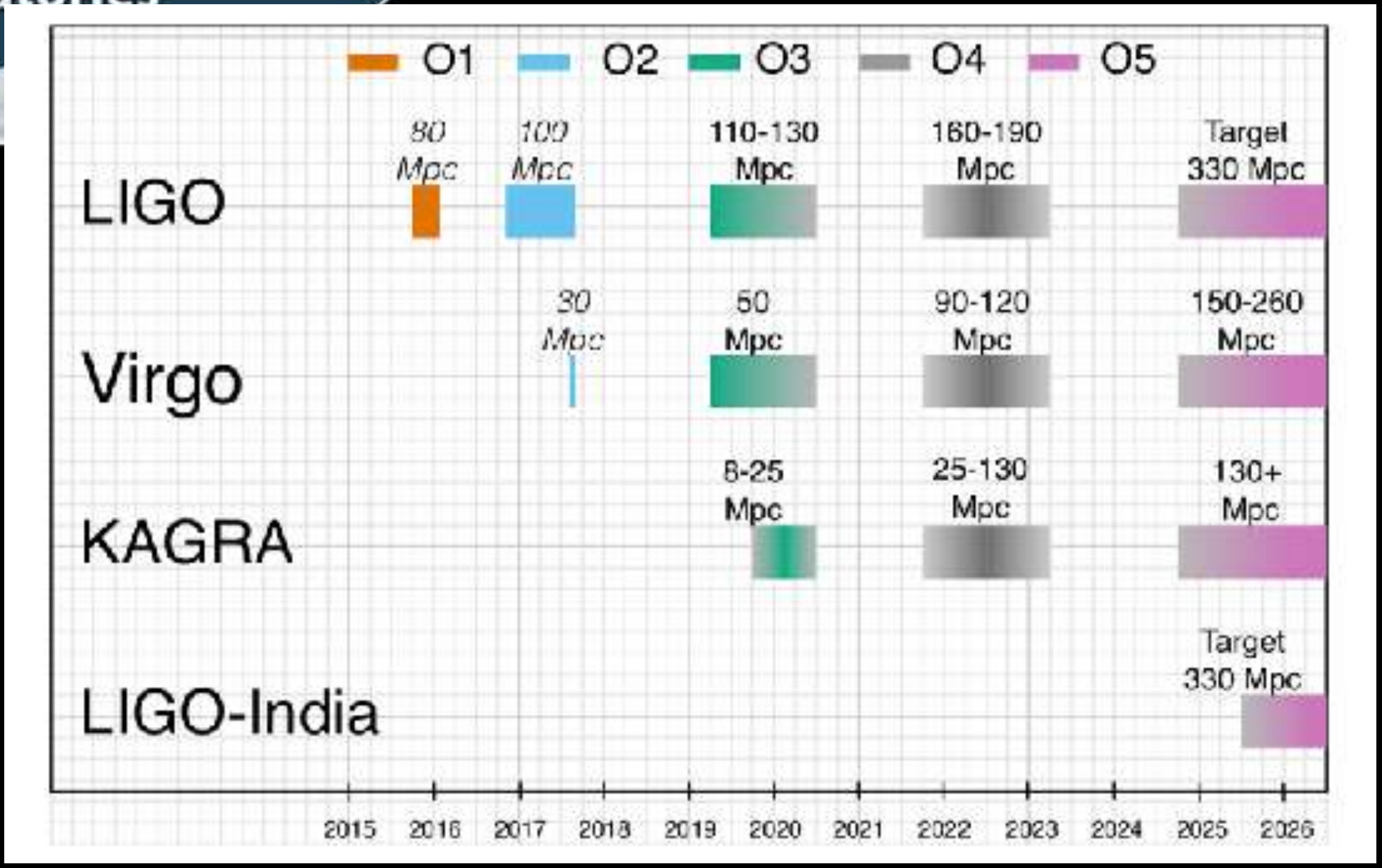
- Observatories around the world planned and under construction

Just the beginning



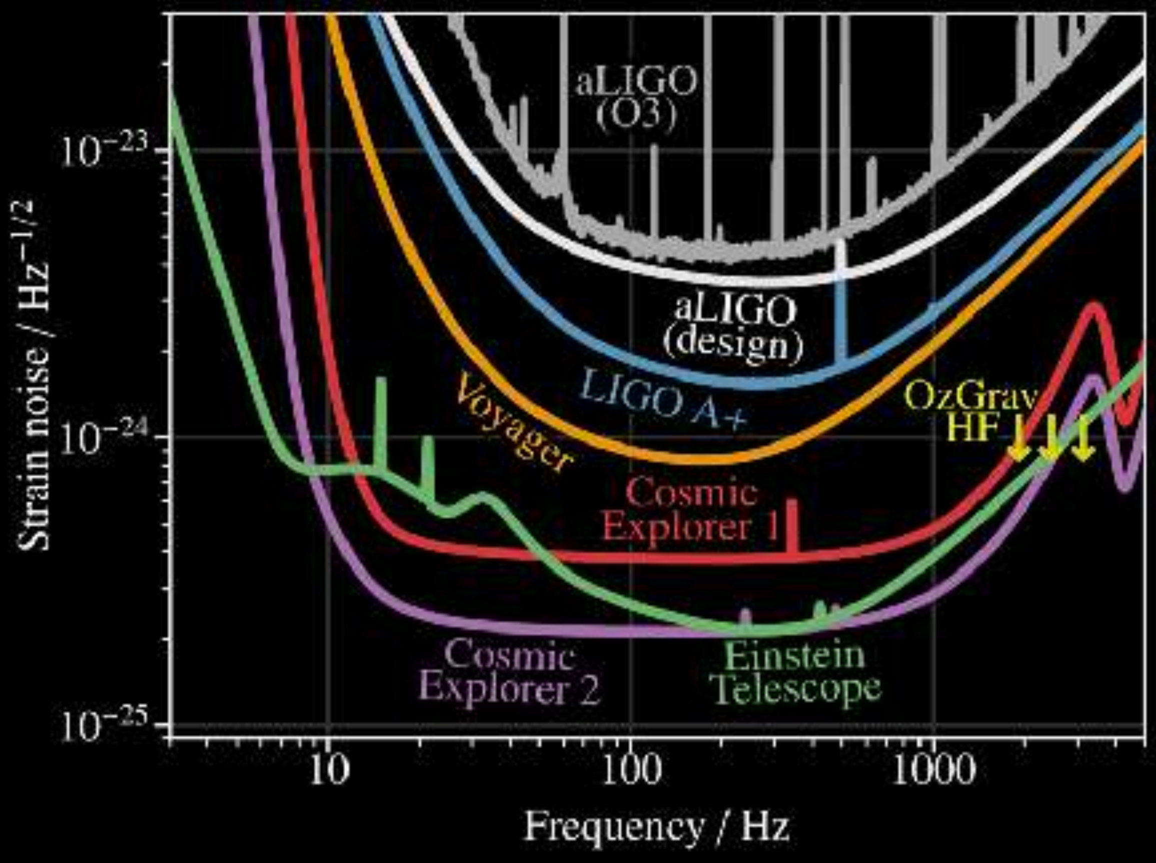
- Sensitivity improvements planned over the next decade

- Observatories around the world planned and under construction



3rd Generation Detectors Planned to Improve Sensitivity

- 10 to 40 km long
- Quantum enhanced
- Novel mirrors

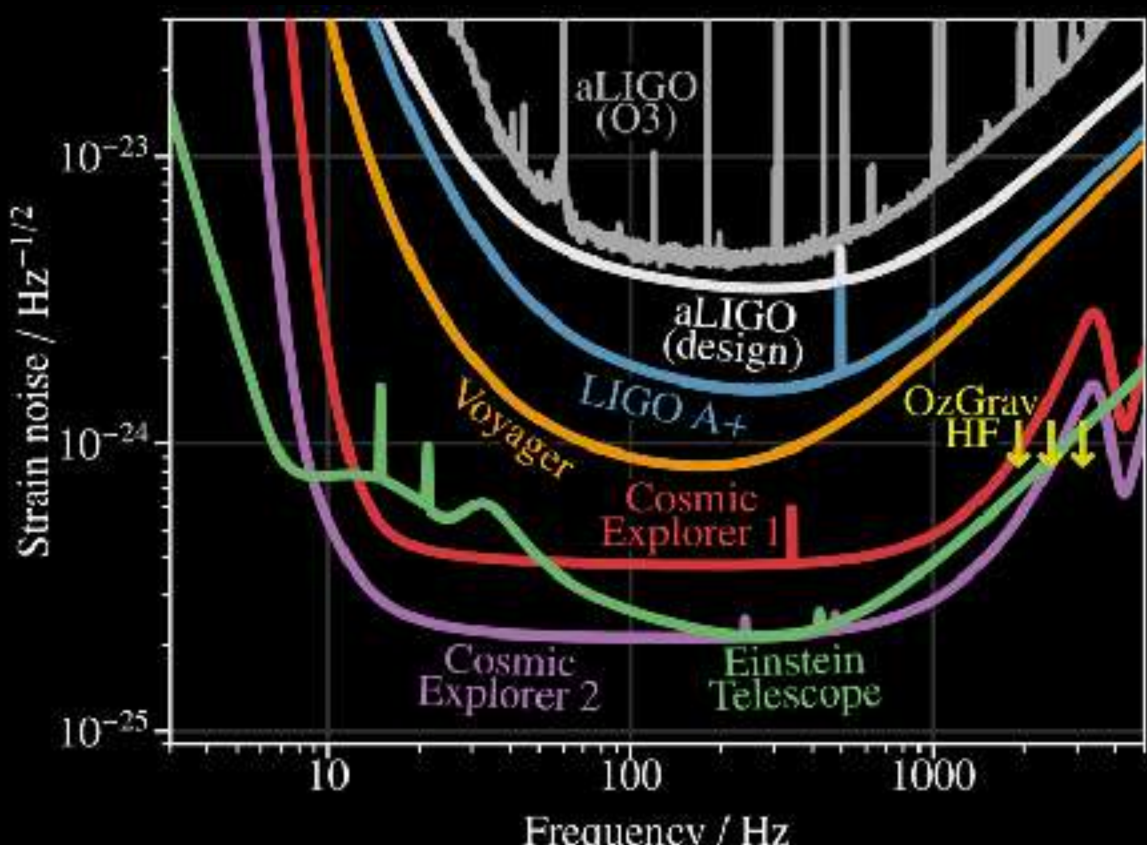


N. Mavalvala 2020

3rd Generation Detectors Planned to Improve Sensitivity

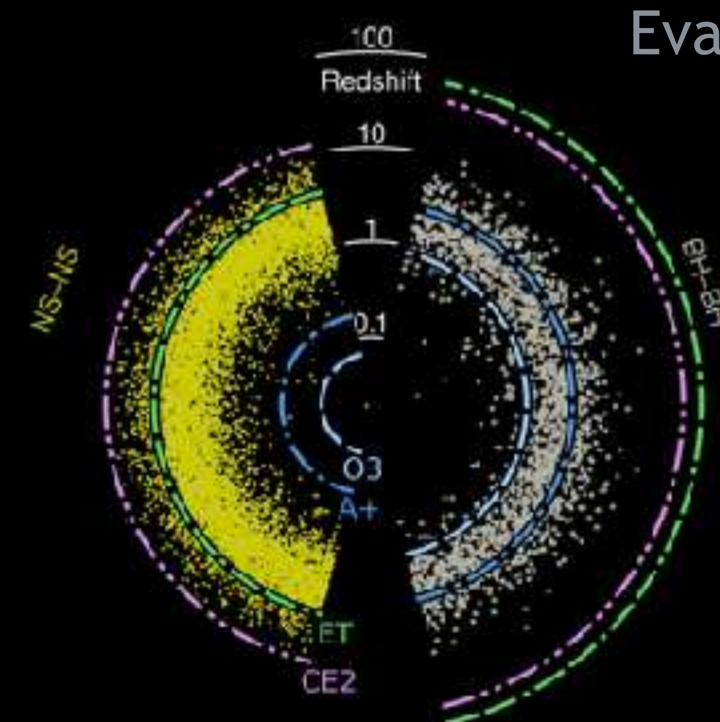
- 10 to 40 km long
- Quantum enhanced
- Novel mirrors

- Binary neutron stars out to z ≈ 6
- Binary black holes out to z ≈ 10



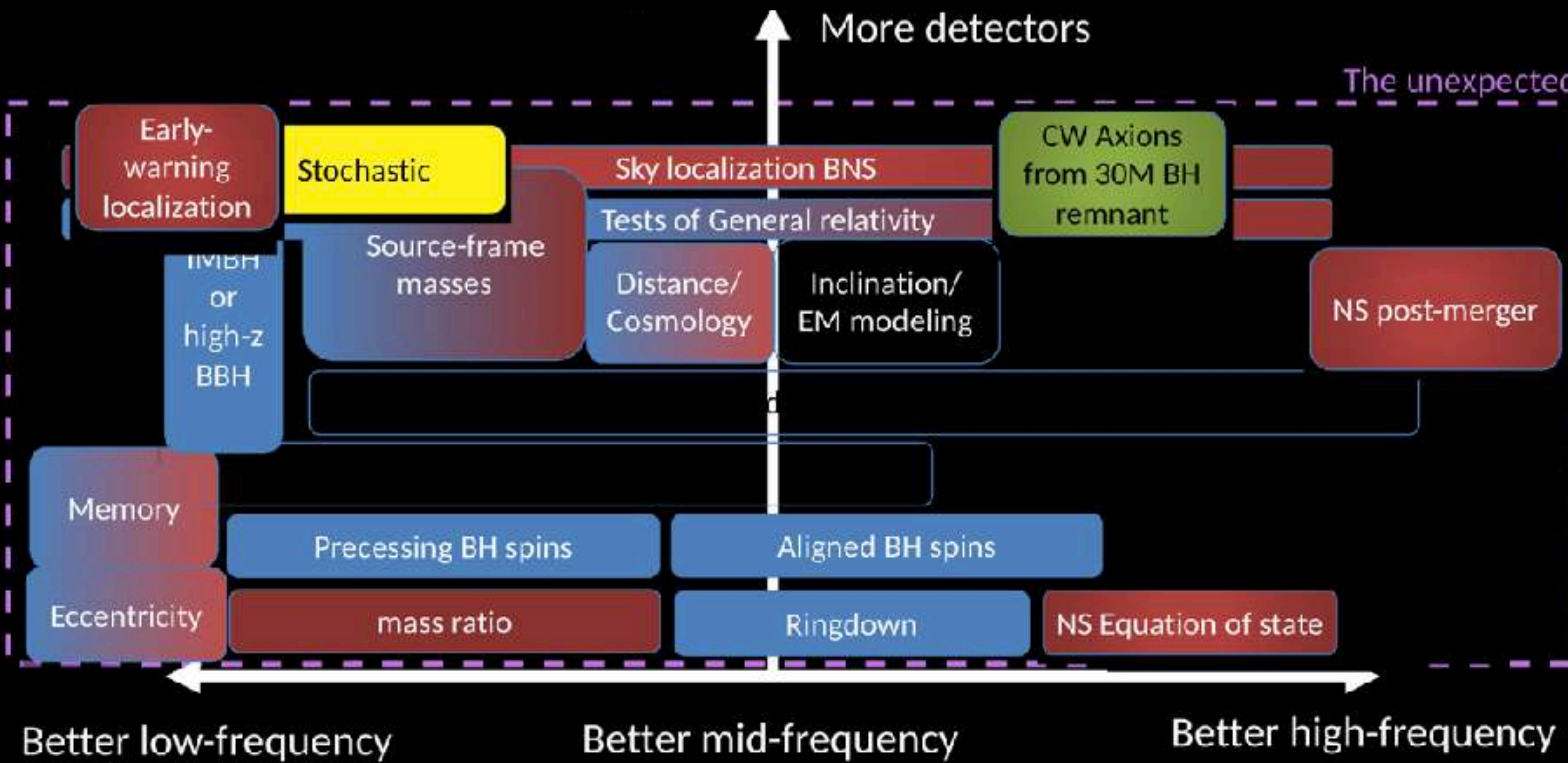
N. Mavalvala 2020

Evan Hall, 2019



will see ~all mergers in the observable Universe!

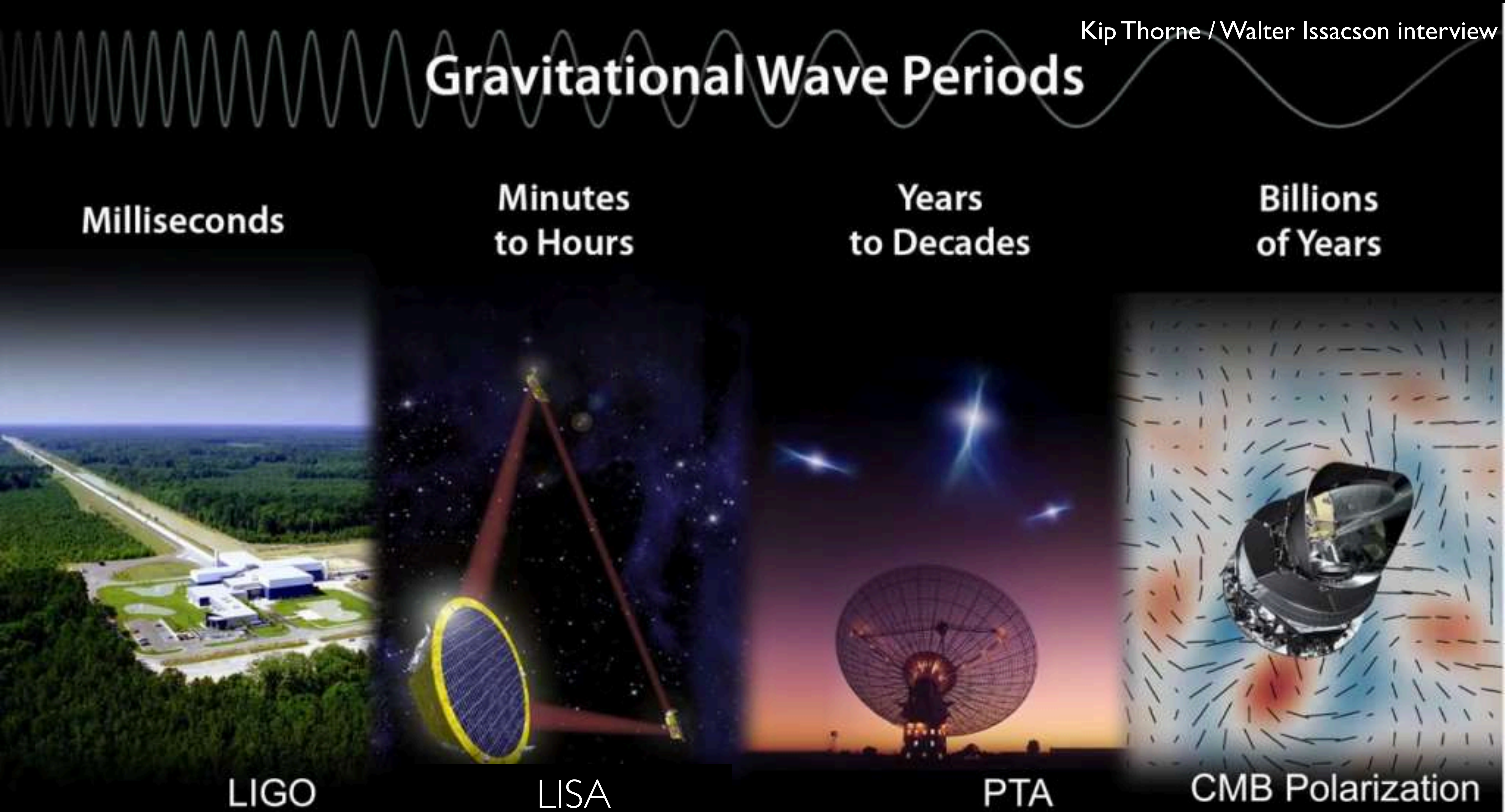
A huge range of science opportunities



S. Vitale, 2019

N. Mavalvala 2020

A wide spectrum of frequencies to explore

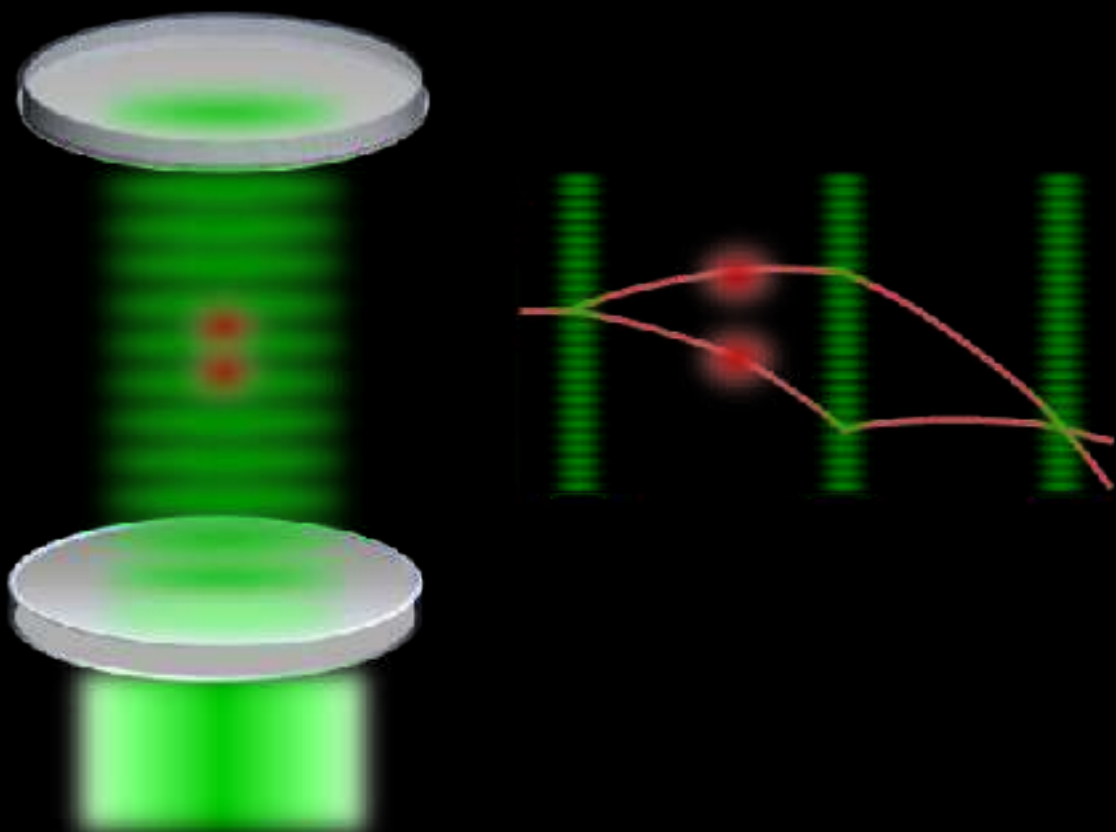


Observation of Gravitational Waves

- An amazing scientific and technological achievement
- Confirms what we predicted about strong gravity and are learning new things about the most extreme objects
- New window on the universe and a new tool for new physics searches

Using Tools of Gravitational Wave Astronomy To Look for Dark Matter (Tomorrow)

Atom interferometry



Paul Hamilton UCBerkeley

Pulsar Timing Array, artists conception

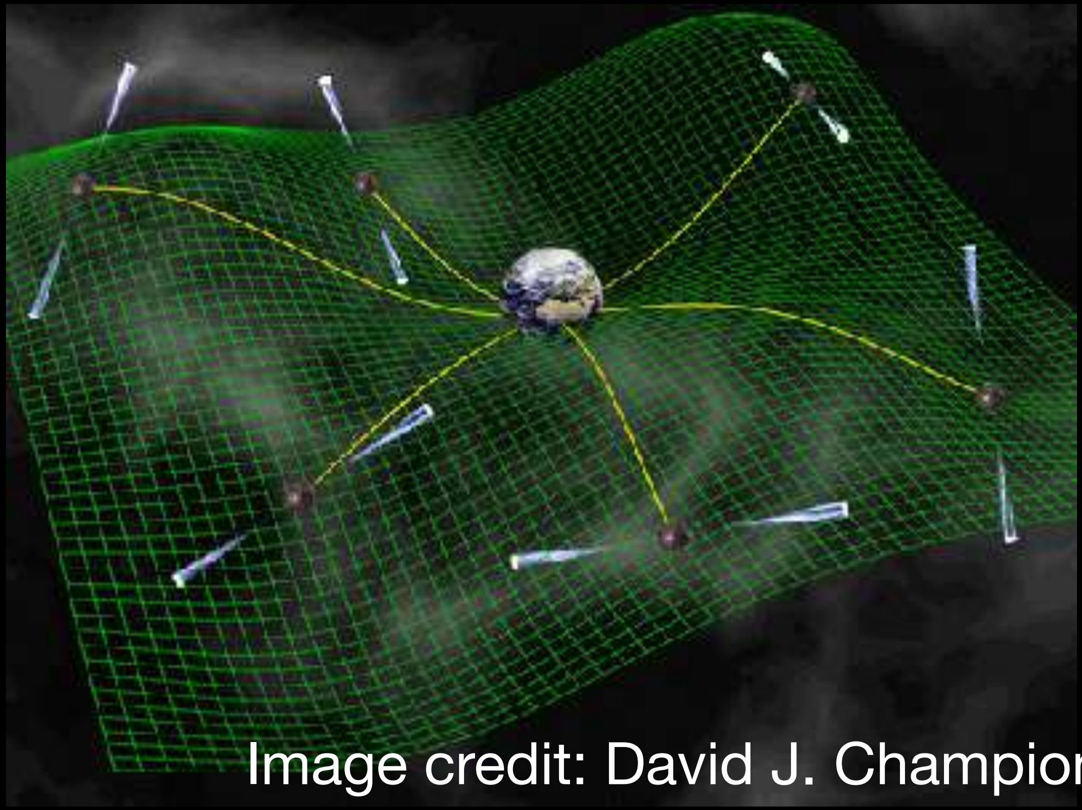
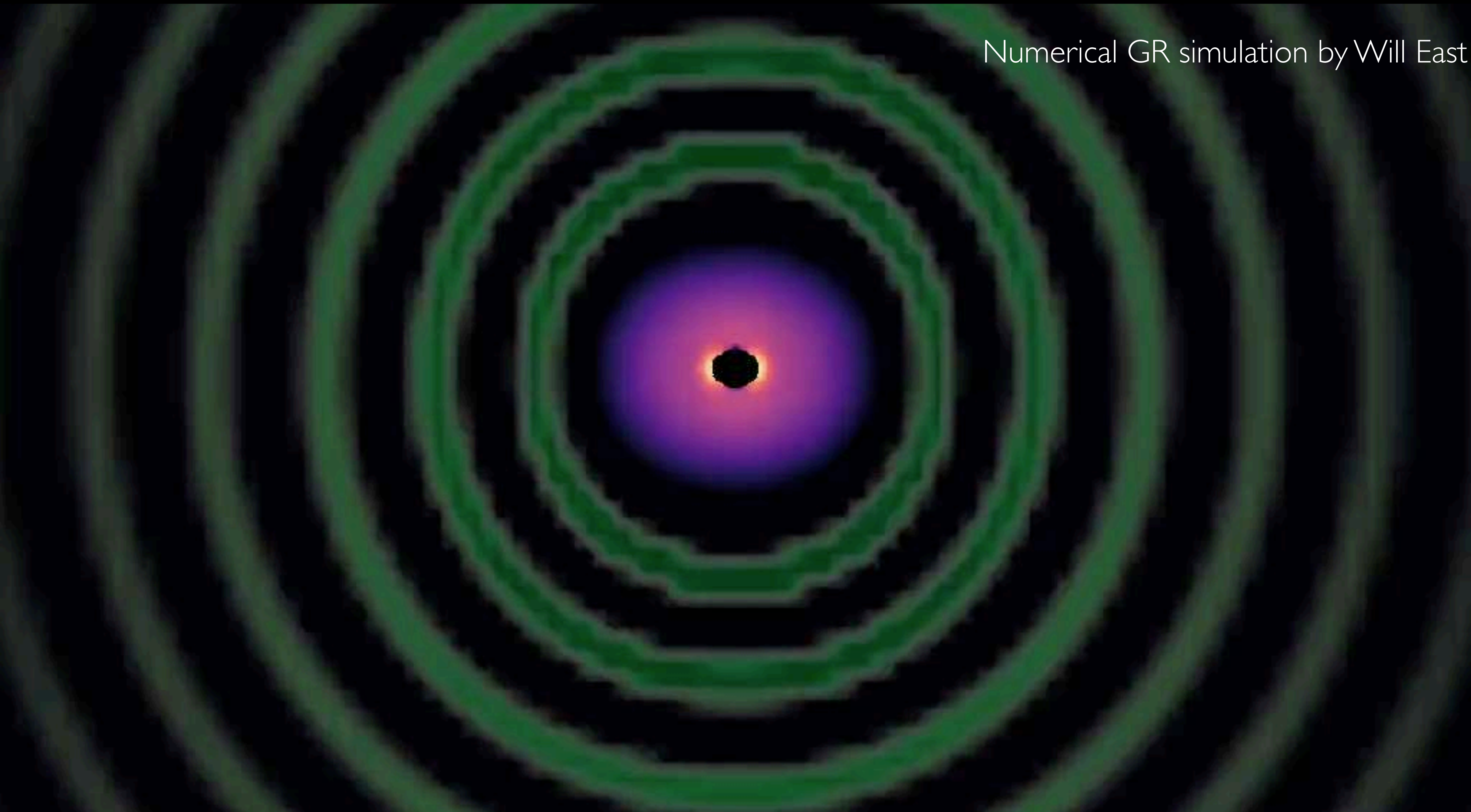


Image credit: David J. Champion

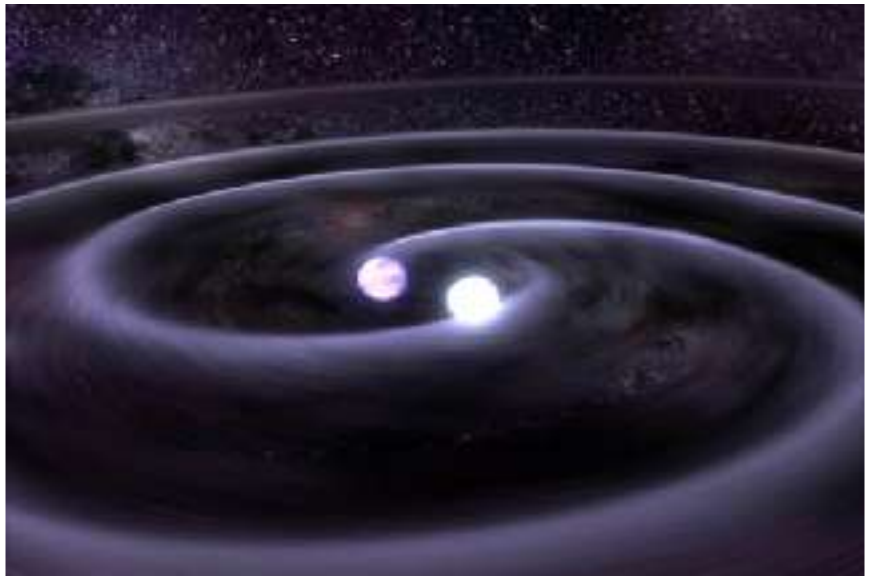
Gravitational Wave Signals from Axions and Dark Photons (Thursday)



Numerical GR simulation by Will East

LIGO is searching for signs of new particles around rotating black holes

Gravitational Waves from the Local Universe

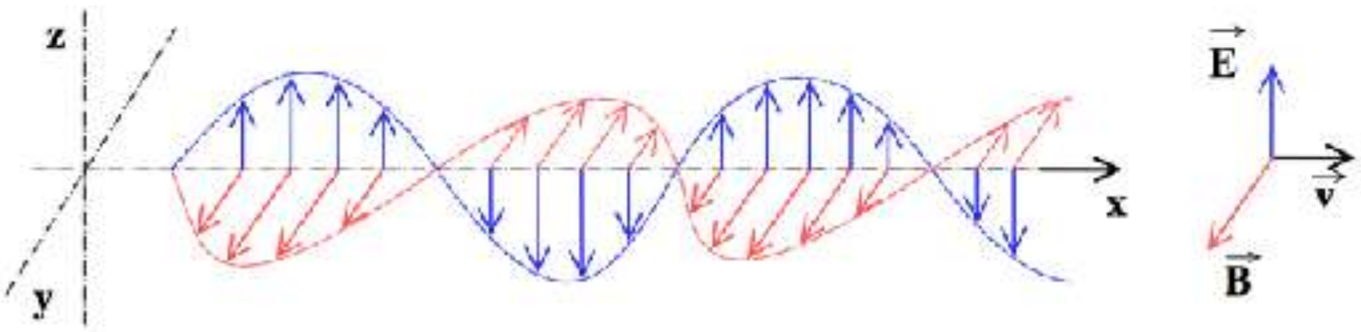


- A brief history from doubt to detection

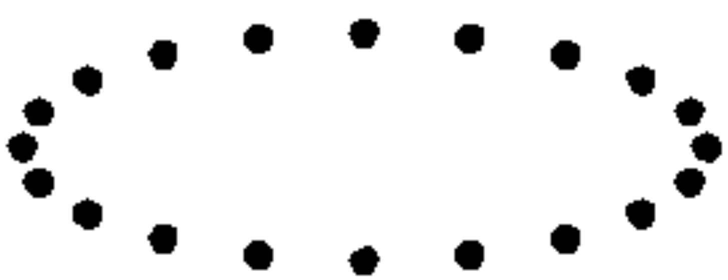
- How to produce and detect a gravitational wave

- Signals and noise — why is detection so difficult?

Gravitational Waves:



Electromagnetic waves: displacement of charged particles



Gravitational waves: displacement of all matter

- Maxwell's1865 "The Dynamical Theory of the Electromagnetic Field" (where he deduced that electromagnetic waves travel at light speed): "After tracing to the action of the surrounding medium both the magnetic and the electric attractions and repulsions [oscillations]…we are naturally led to inquire whether the attraction of gravitation, which follows the same law of the distance, is not also traceable to the action of a surrounding medium."

Gravitational Waves: Einstein's untestable prediction

- Einstein completes theory of general relativity in 1915 and predicts gravitational waves in 1916, but does not think they can ever be observed. In 1918, he computes the energy lost to gravitational waves in a system.

Gravitational Waves: Einstein's untestable prediction

- Einstein completes theory of general relativity in 1915 and predicts gravitational waves in 1916, but does not think they can ever be observed. In 1918, he computes the energy lost to gravitational waves in a system.

- Twenty years later, he is still not sure whether gravitational waves are physical or a coordinate artifact; in 1936 he writes to Max Born:

> Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now.

Gravitational Waves: Einstein's untestable prediction

- Einstein completes theory of general relativity in 1915 and predicts gravitational waves in 1916, but does not think they can ever be observed. In 1918, he computes the energy lost to gravitational waves in a system.

- Twenty years later, he is still not sure whether gravitational waves are physical or a coordinate artifact; in 1936 he writes to Max Born:

> Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now.

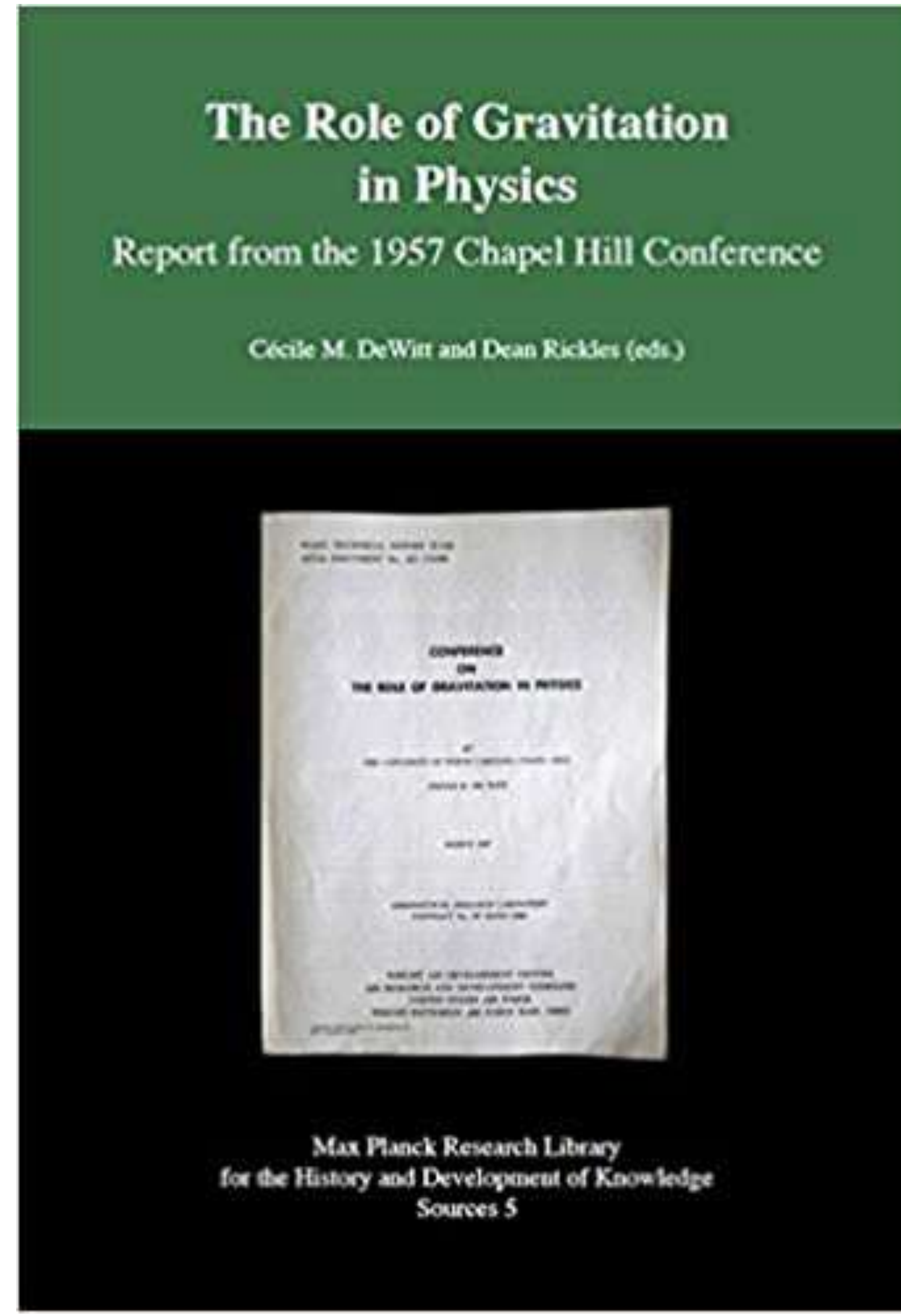
- The Physical Review received Einstein's submission on 1 June 1936 and had referree comments which did not suit Einstein.

> Dear Sir,
>
> We (Mr. Rosen and I) had sent you our manuscript for publication and had not authorized you to show it to specialists before it is printed. I see no reason to address the—in any case erroneous—comments of your anonymous expert. On the basis of this incident I prefer to publish the paper elsewhere
>
> P.S. Mr. Rosen, who has left for the Soviet Union, has authorized me to represent him in this matter.

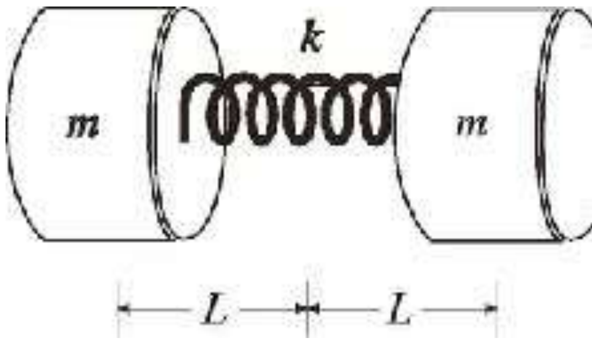
physicstoday.scitation.org/doi/10.1063/1.2117822

Gravitational Waves: finally physical

- At 1957 Chapel Hill Conference, Felix Pirani presented a calculation of the relative acceleration of initially mutually static test particles that encounter a sinusoidal gravitational plane wave.
- During the questions with his advisor Bondi they came up with the idea of connecting the two nearby masses with a dashpot or a spring thus absorbing energy from the wave.
- Bondi publishes the 'sticky bead argument' in Nature. Weber and Wheeler publish 'Reality of cylindrical waves of Einstein and Rosen' where they state 'the disturbance in question is real and not removable by any change of coordinate system', citing original argument

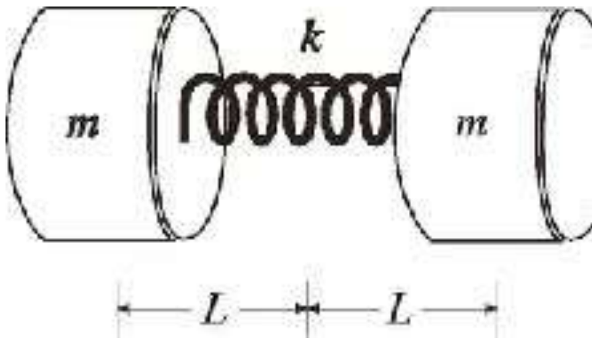


Gravitational Waves: first experimental efforts



- Joe Weber is at Pirani's talk and decides that since the gravitational waves are physical, he can detect them, publishing several papers with Wheeler on the topic
- In analogy to the masses connected by a spring, Weber designs the resonant aluminum bar

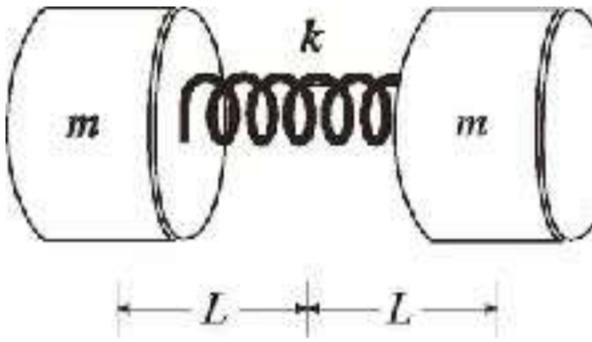
Gravitational Waves: first experimental efforts



- Joe Weber is at Pirani's talk and decides that since the gravitational waves are physical, he can detect them, publishing several papers with Wheeler on the topic
- In analogy to the masses connected by a spring, Weber designs the resonant aluminum bar
- Starting in 1969, Weber announces coincident detections of GWs. Follow-up experiments failed to confirm the detections.
- Weber bars are still used search for broadband gravitational waves at high frequencies (~kHz). Major limitation is a narrow frequency range.

AIP Emilio Segrè Visual Archives

Gravitational Waves: first experimental efforts



- Joe Weber is at Pirani's talk and decides that since the gravitational waves are physical, he can detect them, publishing several papers with Wheeler on the topic
- In analogy to the masses connected by a spring, Weber designs the resonant aluminum bar
- Starting in 1969, Weber announces coincident detections of GWs. Follow-up experiments failed to confirm the detections.
- Weber bars are still used search for broadband gravitational waves at high frequencies (~kHz). Major limitation is a narrow frequency range.
- One of the most recently built spherical detectors is the Mario Schenberg gravitational-wave detector, which is now at the National Institute for Space Research (INPE) in Brazil. The sphere is around 65 centimeters in diameter and weighs around 1150 kilograms.

AIP Emilio Segrè Visual Archives

Gravitational Waves: a new direction

- Laser interferometers first proposed in 1962 by Gertsenshtein and Pustovoit published in Russian (Zh. Eksp. Teor. Fiz., vol. 43, p. 605, 1962) and in English translation (Sov. Phys. JETP, vol. 16, p. 433, 1963), describing how instruments called interferometers could be used to detect gravitational waves

- Rainer Weiss proposes laser interferometer to detect GWs, 'Electromagnetically Coupled Broadband Gravitational Antenna' (MIT report). Includes detailed analysis of detector and noise sources
    - "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." -Pirani

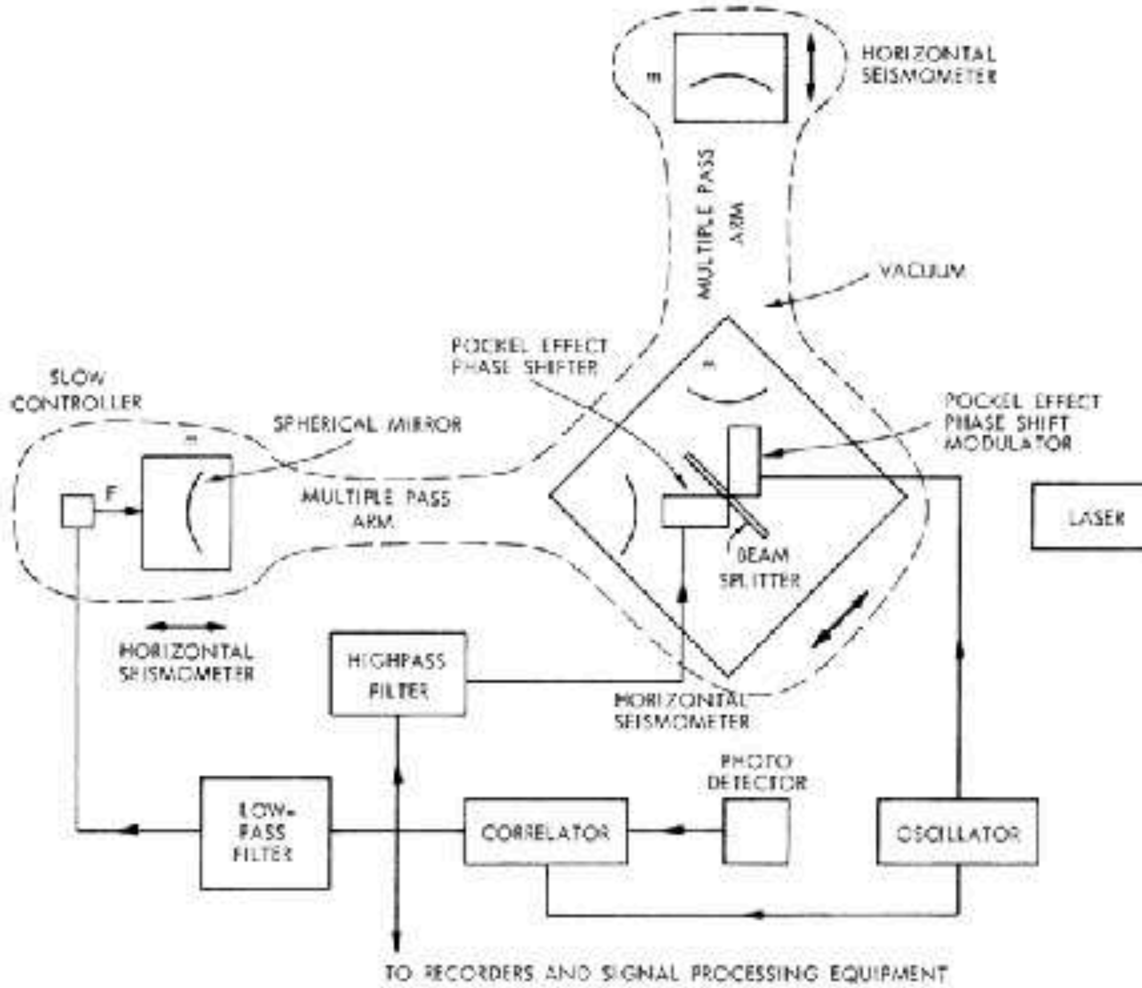
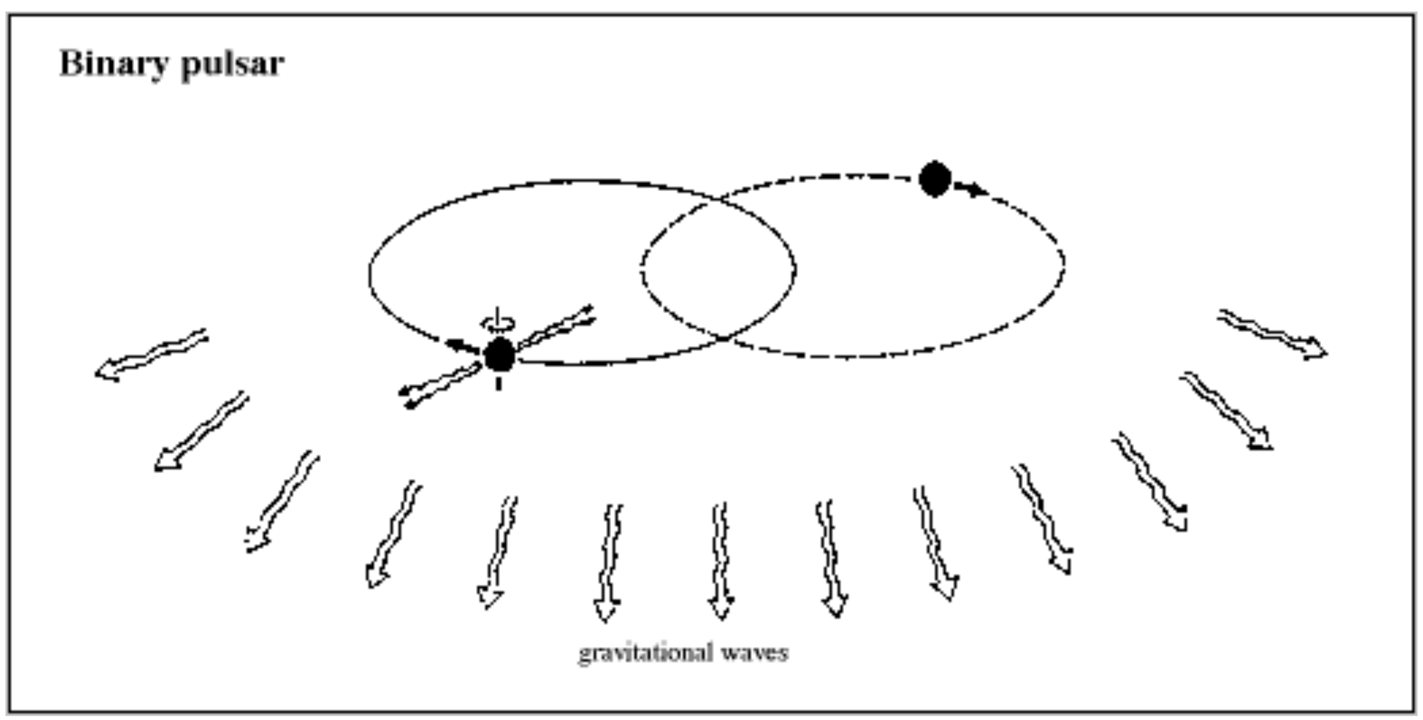


Fig. V-20. Proposed antenna.

Gravitational Waves: indirect observation

In the meantime…

- Hulse and Taylor discovery the first pulsar in a neutron star binary system, 1975
- Orbital decay of the Hulse and Taylor pulsar matches GR prediction, 1980



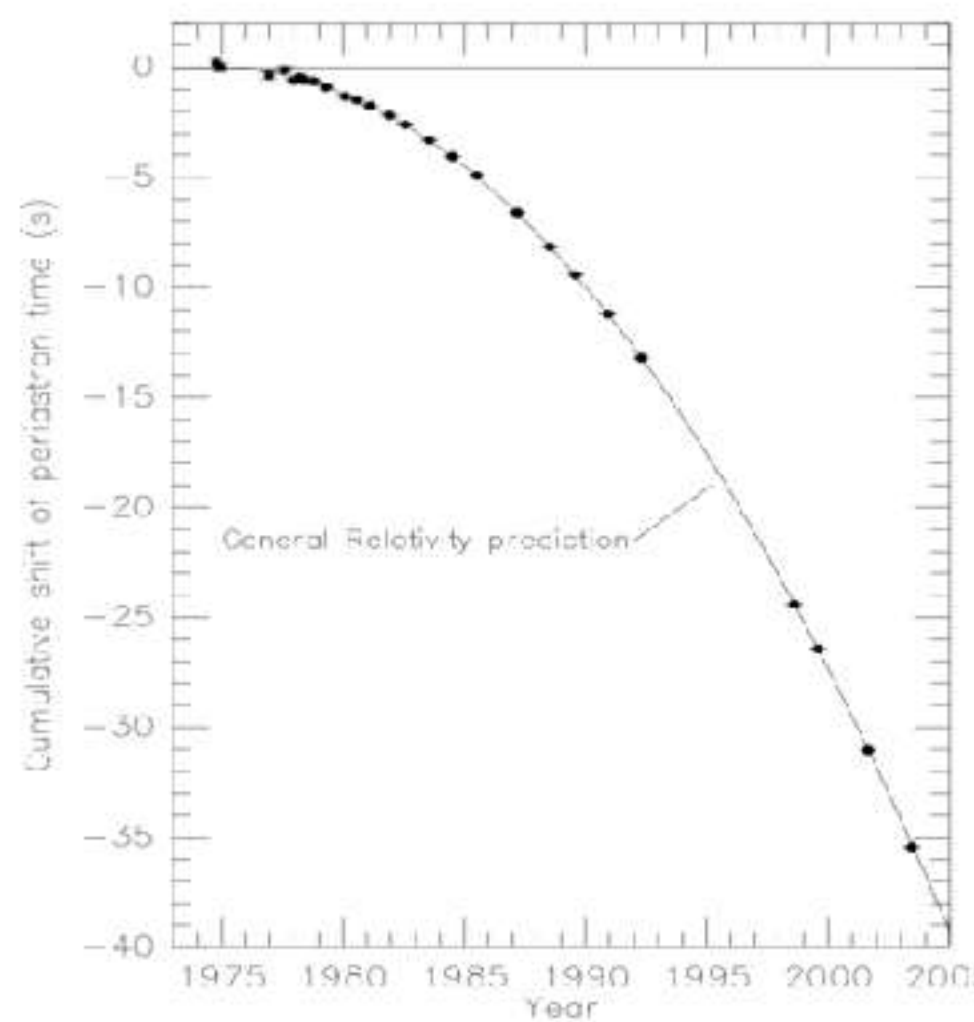


Figure 1. Orbital decay of PSR B1913+16. The data points indicate the observed change in the epoch of periastron with date while the parabola illustrates the theoretically expected change in epoch for a system emitting gravitational radiation, according to general relativity.

Gravitational Waves: a new direction

- Late 70s: Munich group starts (1975) construction of 3m laser interferometer prototype. Drever, in Glasgow, starts similar research (1977).
- 1992: Weiss, Drever and Thorne found LIGO (Laser Interferometer Gravitational Wave Observatory) as a National Science Foundation projec

- 1999-2010 Initial LIGO in operation, reaching design sensitivity in 2006, Virgo joins collaboration
- 2011 - 2014 Advanced LIGO installation and testing
- Sept 14, 2015 Advanced LIGO detects gravitational waves from collision of two black holes

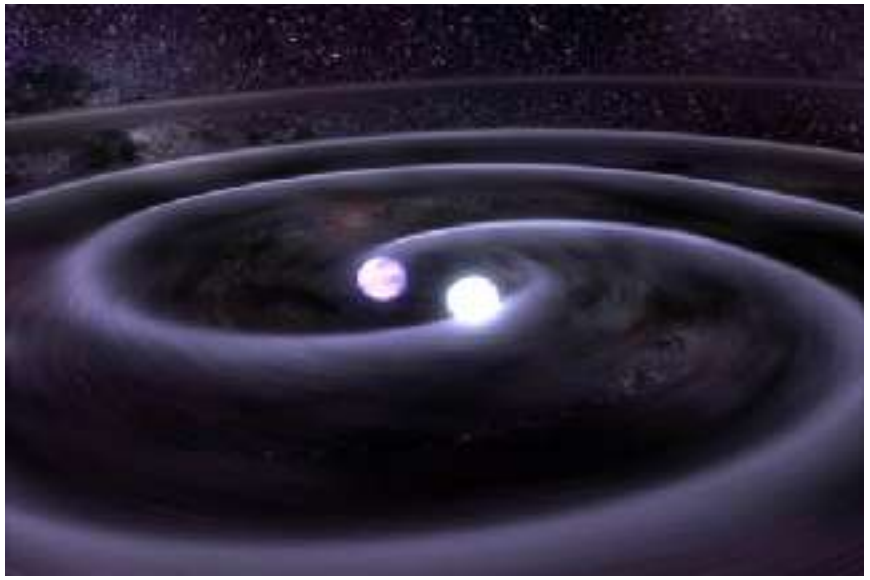
Gravitational Waves: a new direction

- Late 70s: Munich group starts (1975) construction of 3m laser interferometer prototype. Drever, in Glasgow, starts similar research (1977).
- 1992: Weiss, Drever and Thorne found LIGO (Laser Interferometer Gravitational Wave Observatory) as a National Science Foundation projec

one hundred years after GR formulated and nearly fifty years after first experiments!

- 1999-2010 Initial LIGO in operation, reaching design sensitivity in 2006, Virgo joins collaboration
- 2011 - 2014 Advanced LIGO installation and testing
- Sept 14, 2015 Advanced LIGO detects gravitational waves from collision of two black holes

Outline



- A brief history from doubt to detection
- Generation and signals
- Signals and noise — why is detection so hard?

Gravitational Wave Definition

From this morning (Daniel Figueroa)

(TT gauge: 6 - 4 = 2 d.o.f.)

1st approach to GWs

$$h^{0\mu} = 0\,, \qquad h^i_i = 0\,, \qquad \partial_j h_{ij} = 0$$

Outside Source

$$\partial_\mu \partial^\mu h_{ij} = 0$$

Wave Eq. → Gravitational Waves !

can GW be 'gauged away' ? No !

---

2 *dof* = 2 polarizations

$$h_{ab}(t, \mathbf{x}) = \int_{-\infty}^{\infty} df \int d\hat{n}\, h_{ab}(f, \hat{n}) e^{-2\pi i f (t - \hat{n}\mathbf{x})}$$

transverse plane

(plane wave)

$$h_{ab}(f, \hat{n}) = \sum_{A=+,\mathrm{x}} h_A(f, \hat{n}) \epsilon^{(A)}_{ab}(\hat{n}) = \begin{pmatrix} h_+ & h_x & 0 \\ h_x & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Transverse-Traceless (2 dof)

Gravitational Wave Definition

From this morning (Daniel Figueroa)

(TT gauge: 6 - 4 = 2 d.o.f.)

1st approach to GWs

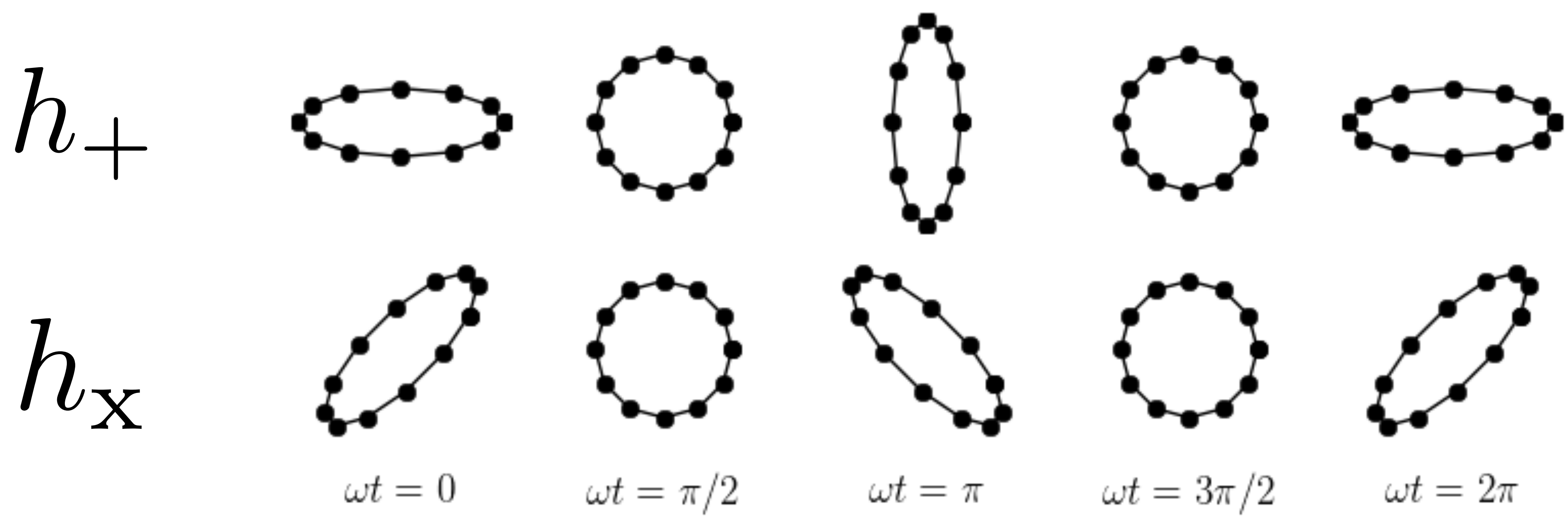
$$h^{0\mu} = 0\,, \quad h^i_i = 0\,, \quad \partial_j h_{ij} = 0$$

Outside Source

$$\partial_\mu \partial^\mu h_{ij} = 0$$

Wave Eq. → Gravitational Waves !

can GW be 'gauged away' ? No !



https://www.youtube.com/watch?v=U_hLM1WPDqM

https://www.youtube.com/watch?v=EtL9UyRx_Us

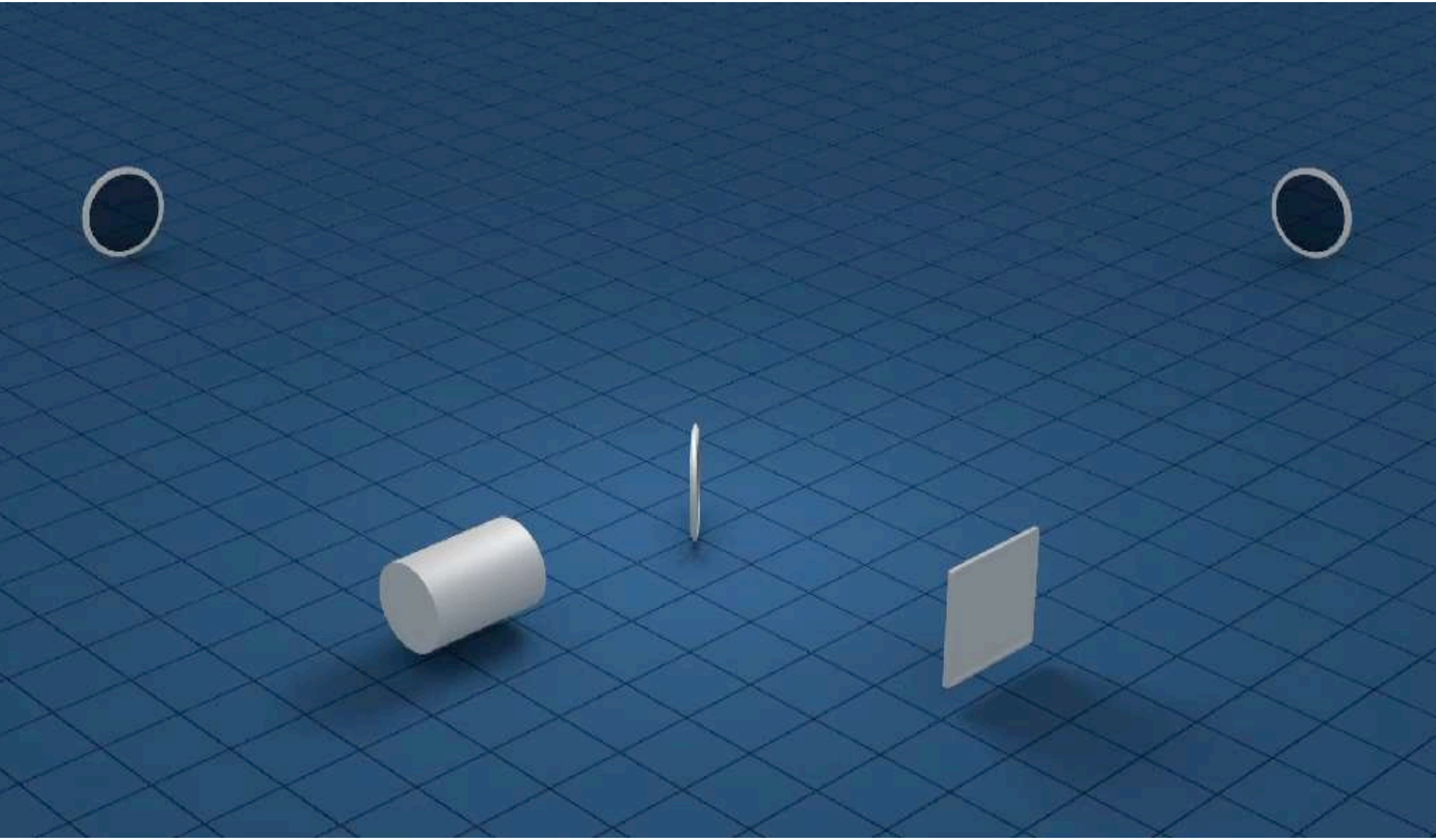
Gravitational wave emission and detection

- What is the typical amplitude of these GWs?

- How do you detect one? What is the physical effect?

- (see blackboard)

Michelson Interferometer



Animation created by T. Pyle, Caltech/MIT/LIGO Lab

Outline

- A brief history from doubt to detection

- Generation and signals

- Signals and noise — why is detection so hard?

Noise in Gravitational Wave Detectors

Gravitational wave strain $h = \left(\frac{4G_N P}{r^2\omega^2}\right)^{1/2} \sim \frac{\Delta L}{L}$

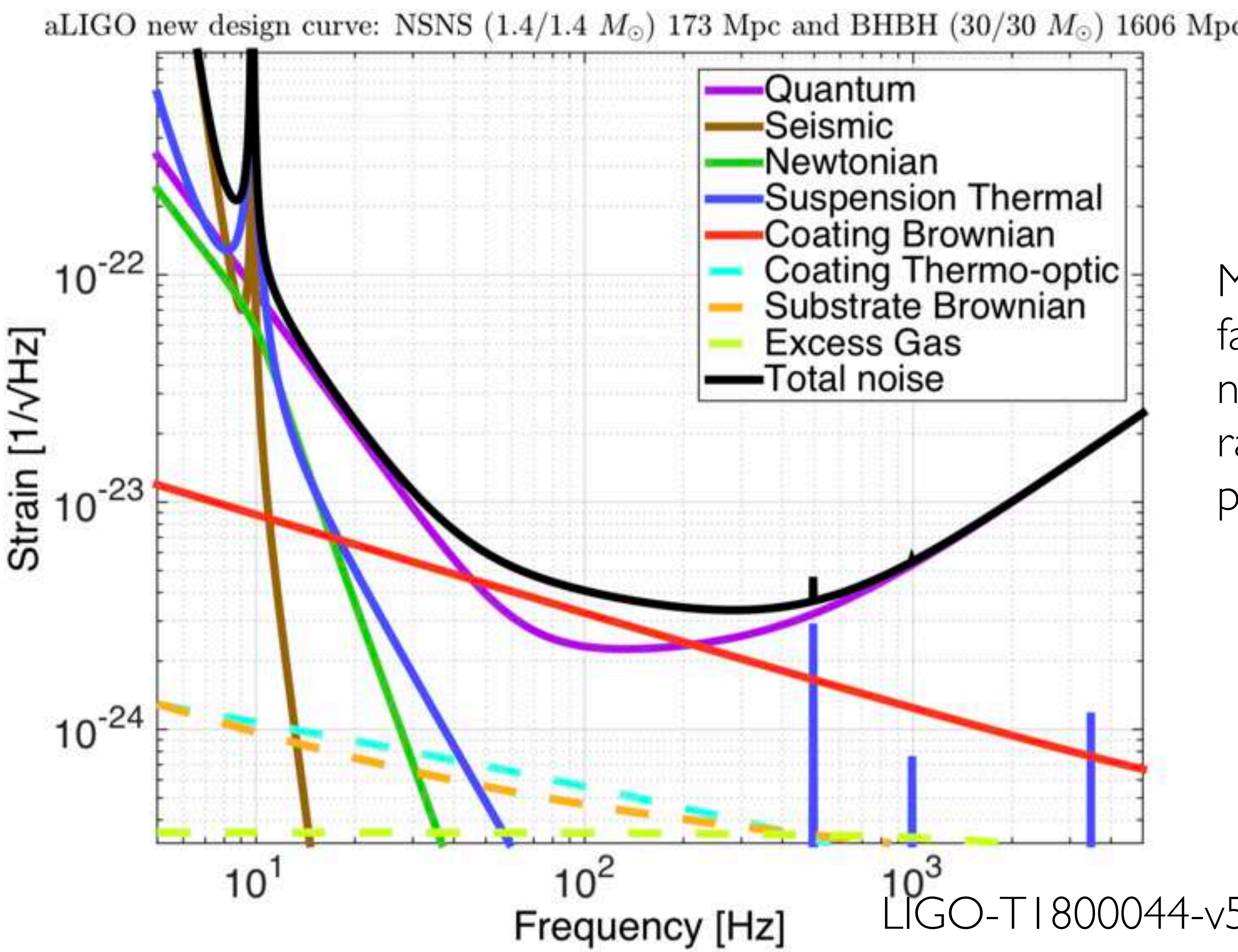
Advanced LIGO

Advanced VIRGO

Advanced LIGO and VIRGO already made several discoveries

Goal to reach target sensitivity in the next years

Noise in Gravitational Wave Detectors



LIGO-T1800044-v5

Figure 1: Updated estimate of the Advanced LIGO design curve.

Main limiting factors: shot noise and radiation pressure

Noise in Gravitational Wave Detectors

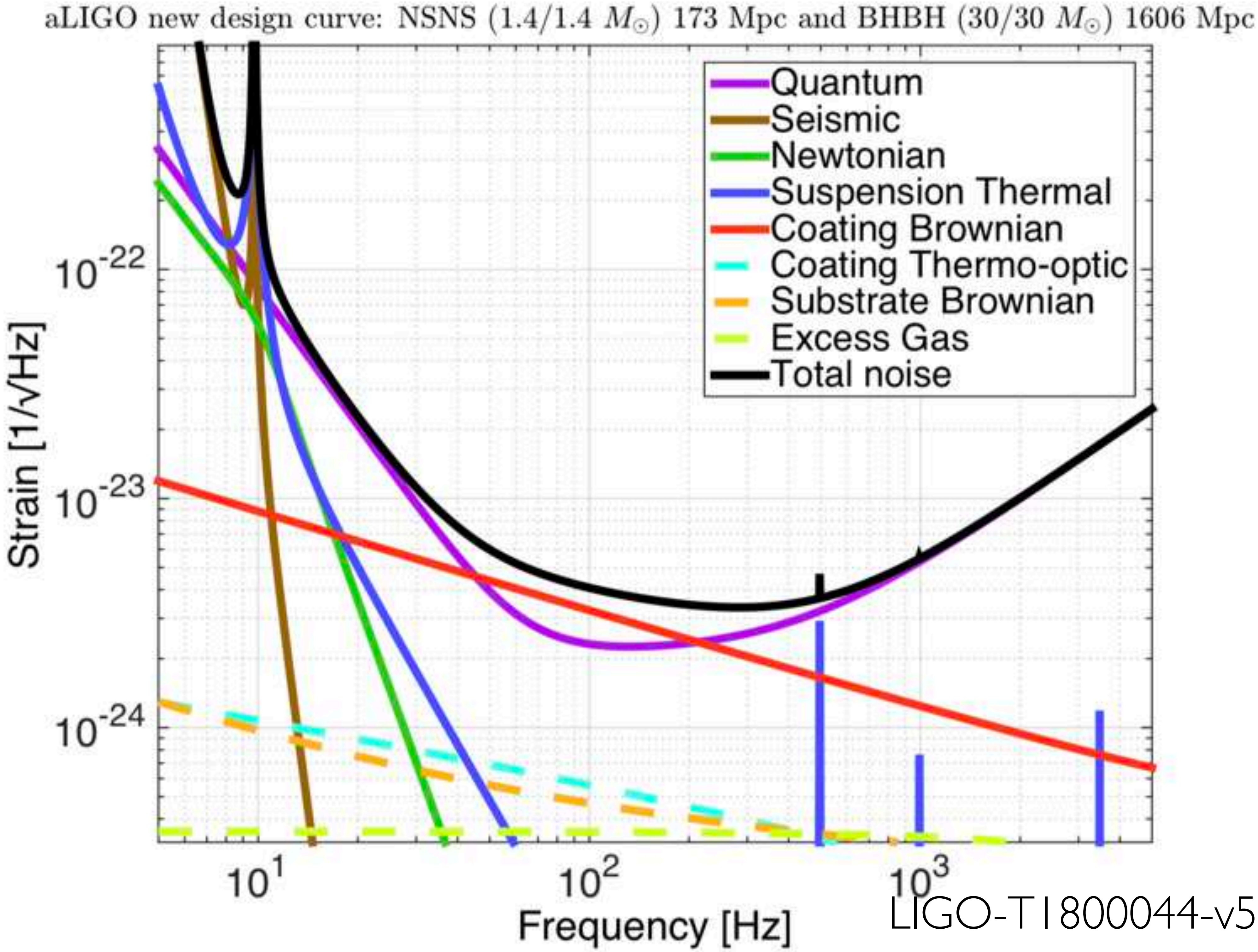
- What are the limiting noise sources?

- Seismic noise, requires passive and active isolation

- Quantum nature of light: shot noise and radiation pressure

  - See blackboard

Noise in Gravitational Wave Detectors



LIGO-T1800044-v5

Figure 1: Updated estimate of the Advanced LIGO design curve.