

LIGO, The Universe and Everything

Dr. Keith Thorne
LIGO Livingston Observatory

You might have heard the news...

nature.com

11 February 2016



Einstein's gravitational waves found at last

LIGO 'hears' space-time ripples produced by black-hole collision.

Latest news

- ▶ The hundred-year quest for gravitational waves — in pictures
- ▶ LIGO live: Inside the hunt for gravitational waves

The New York Times

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

NEW YORK, FRIDAY, FEBRUARY 12, 2016

40 + © 2016 The New York Times \$2.50



WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

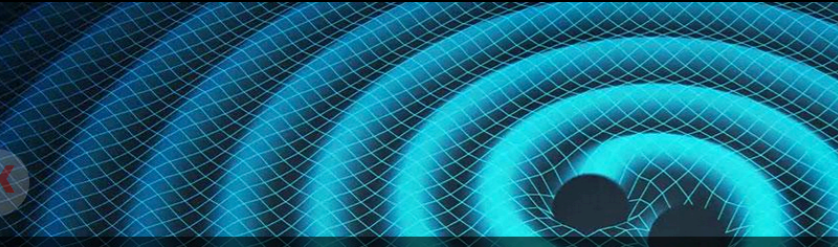
By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of

Science AAAS

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Gravitational waves, Einstein's ripples in spacetime, spotted for first time

Latest News | Feb. 11, 2016

Swinburne Astronomy Productions

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and trouncing it against Mr. Clinton.

A worker installed a baffle in 2010 to control light in the Laser I

President Obama @POTUS

Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.

3:43 PM - 11 Feb 2016

5,740 RETWEETS 12.1K LIKES

LIGO

Laser Interferometer Gravitational-Wave Observatory

- What is a Laser Interferometer ?
- What is a Gravitational Wave ?
- What does it observe ?

Astronomy (1970s)

Telescopes now cover the electromagnetic spectrum (light)

- X-rays, Gamma Rays, Visible Light, Infrared, Radio Waves

But they are finding that most matter is not visible to them

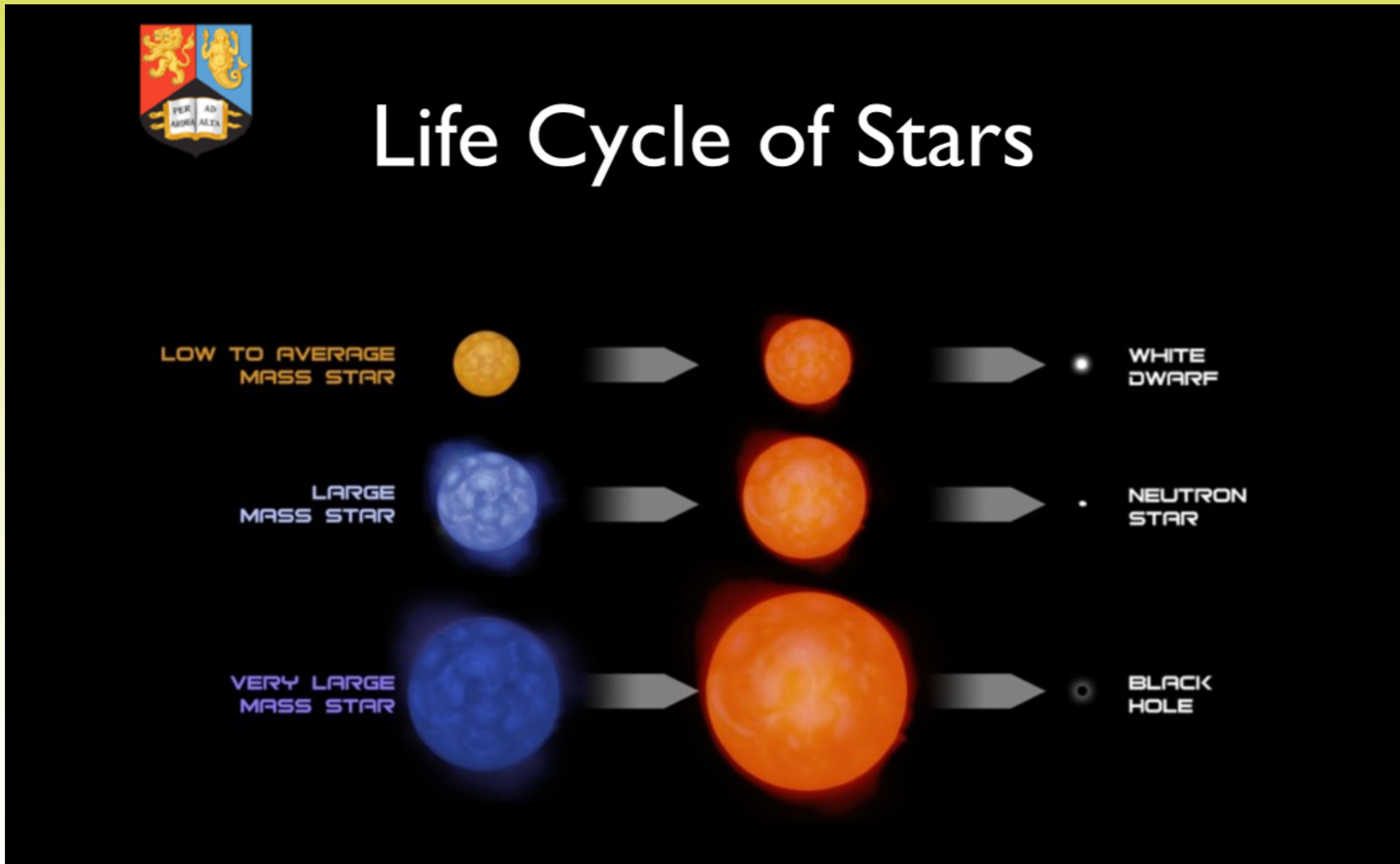
- Black Holes

- Dark Matter

Light-based telescopes could only see them indirectly

Stars

Star : balloon inflated by pressure of light from fusion in core
But what happens when fusion fuel is exhausted ?



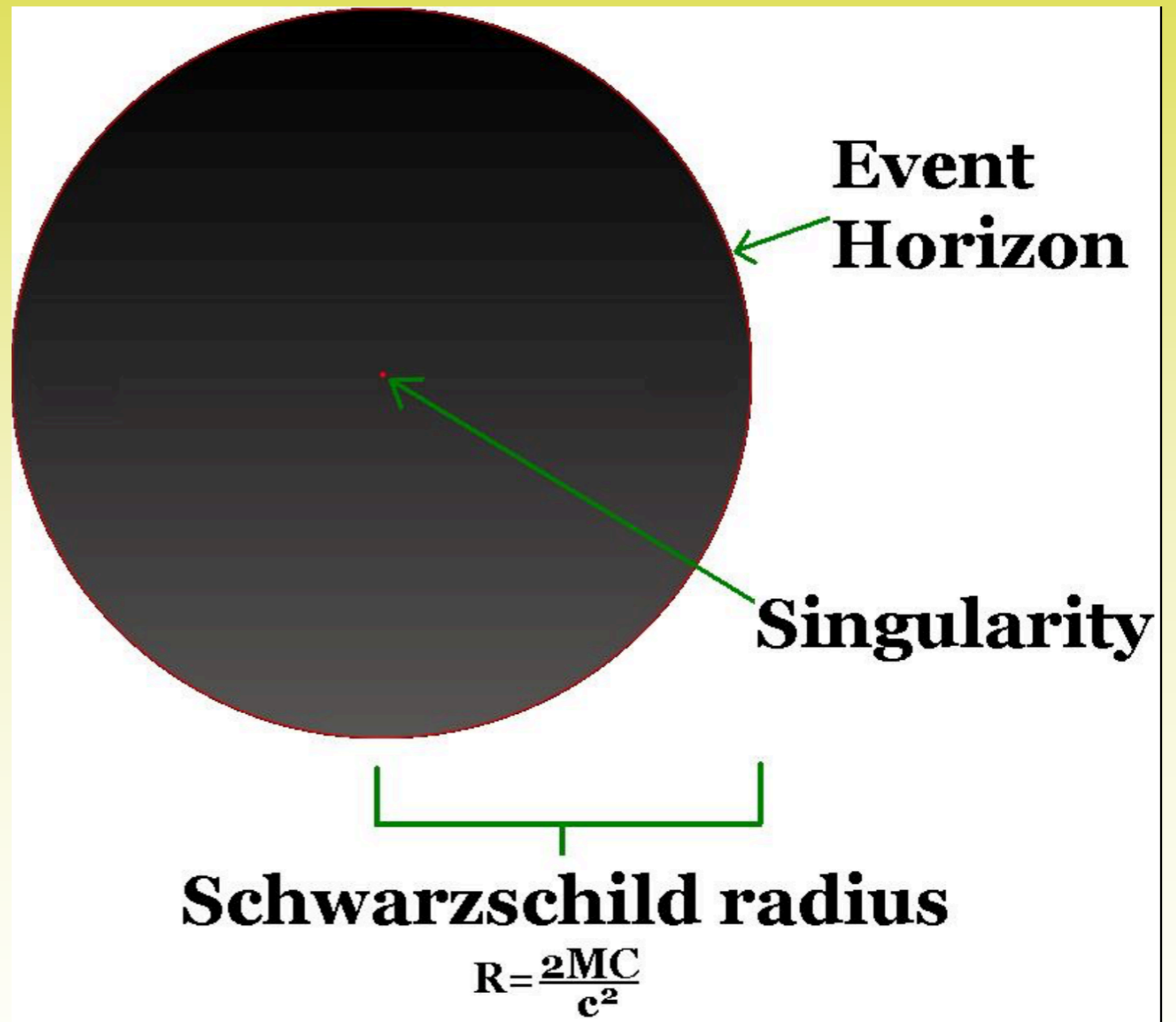
Courtesy Andreas Freise

Black Holes

Prediction of General Relativity

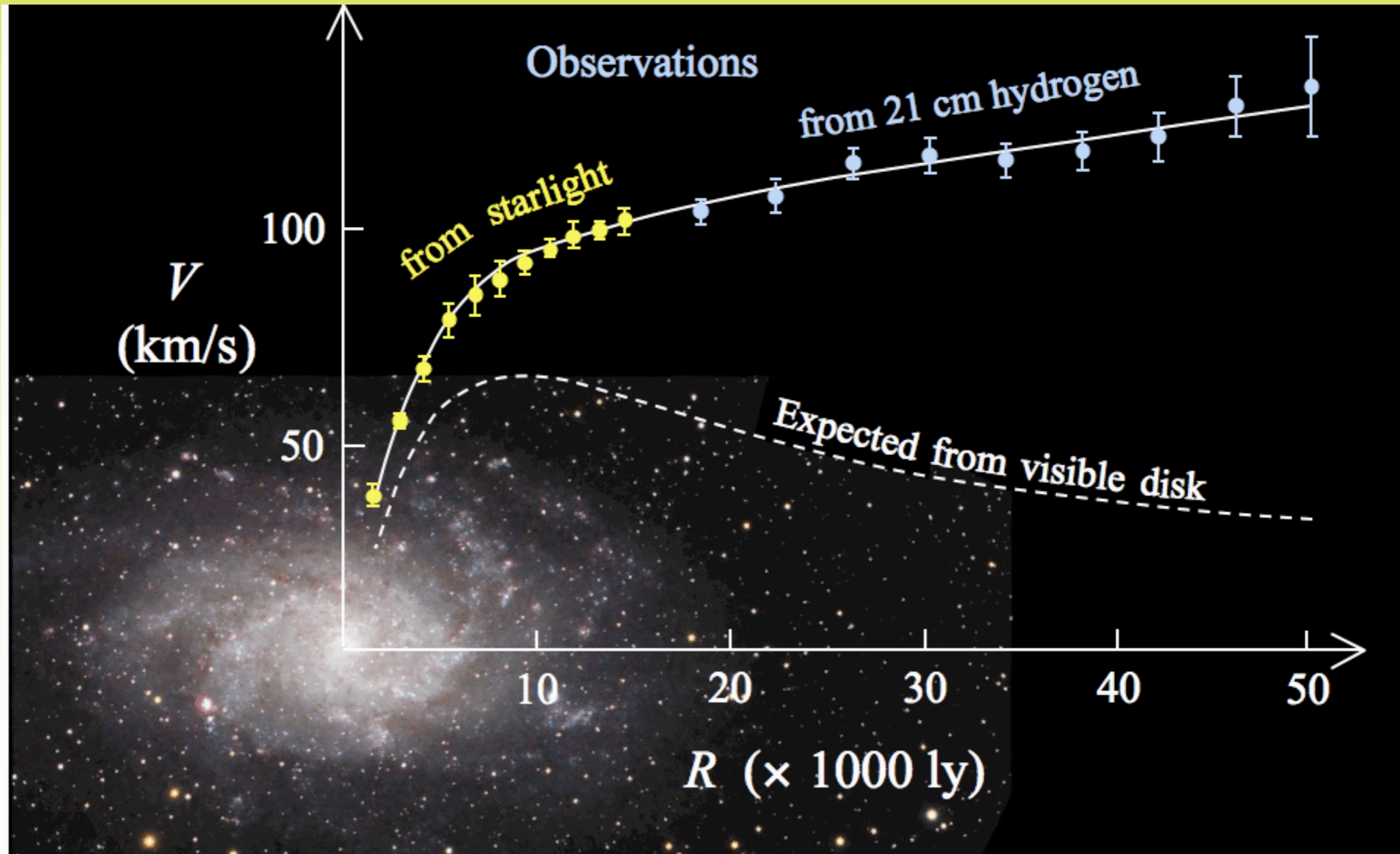
Gravitational collapse so extreme that even light never escapes the Event Horizon

A singularity of pure gravity



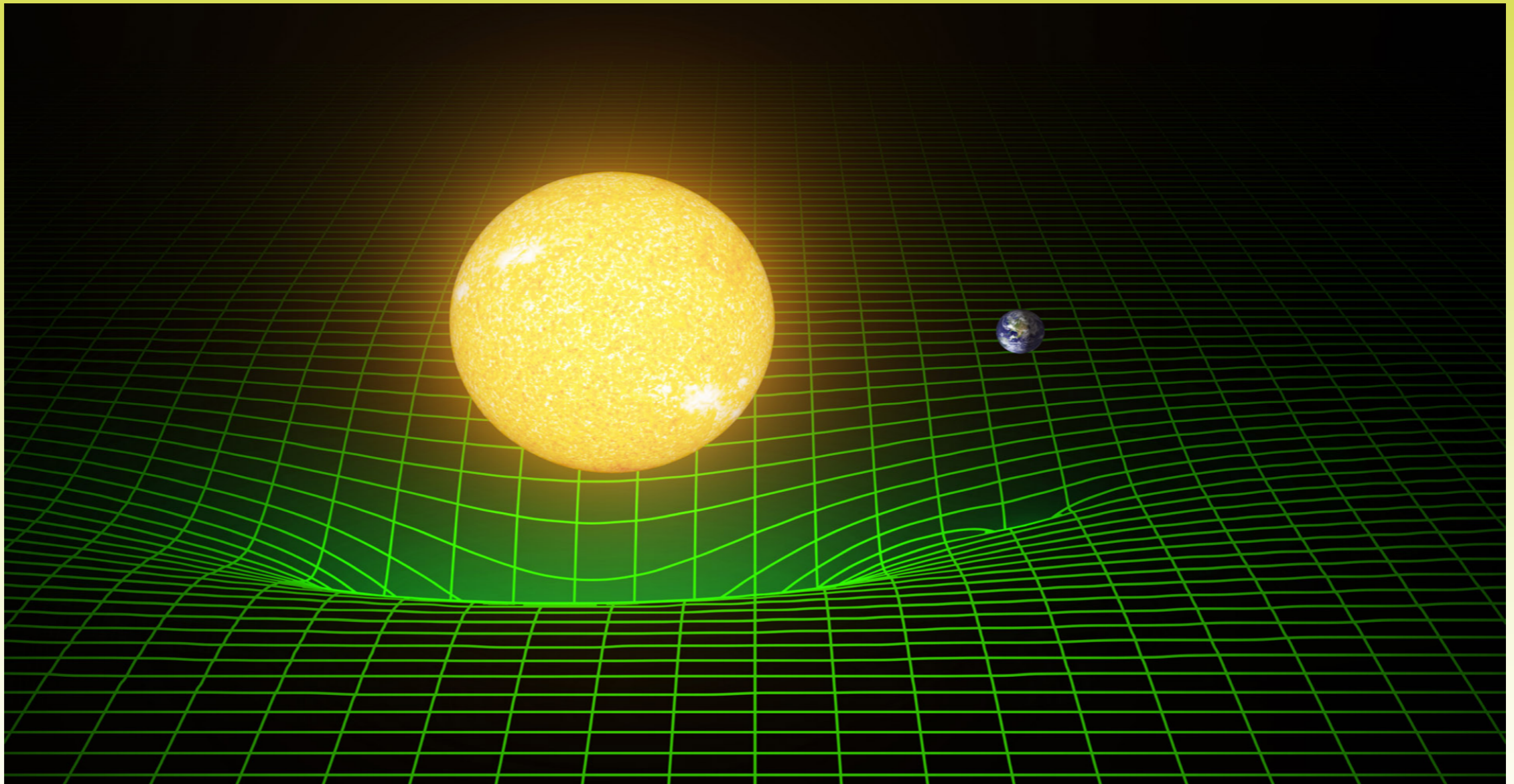
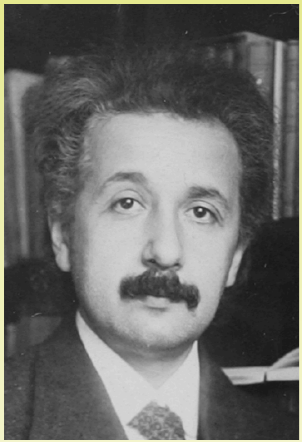
Dark Matter

- Outer stars orbit spiral galaxies too fast for mass of visible stars
- Some 80% of matter appears to only interact with stars by gravity alone



General Relativity

Einstein (1916): gravity = warping of space-time due to mass



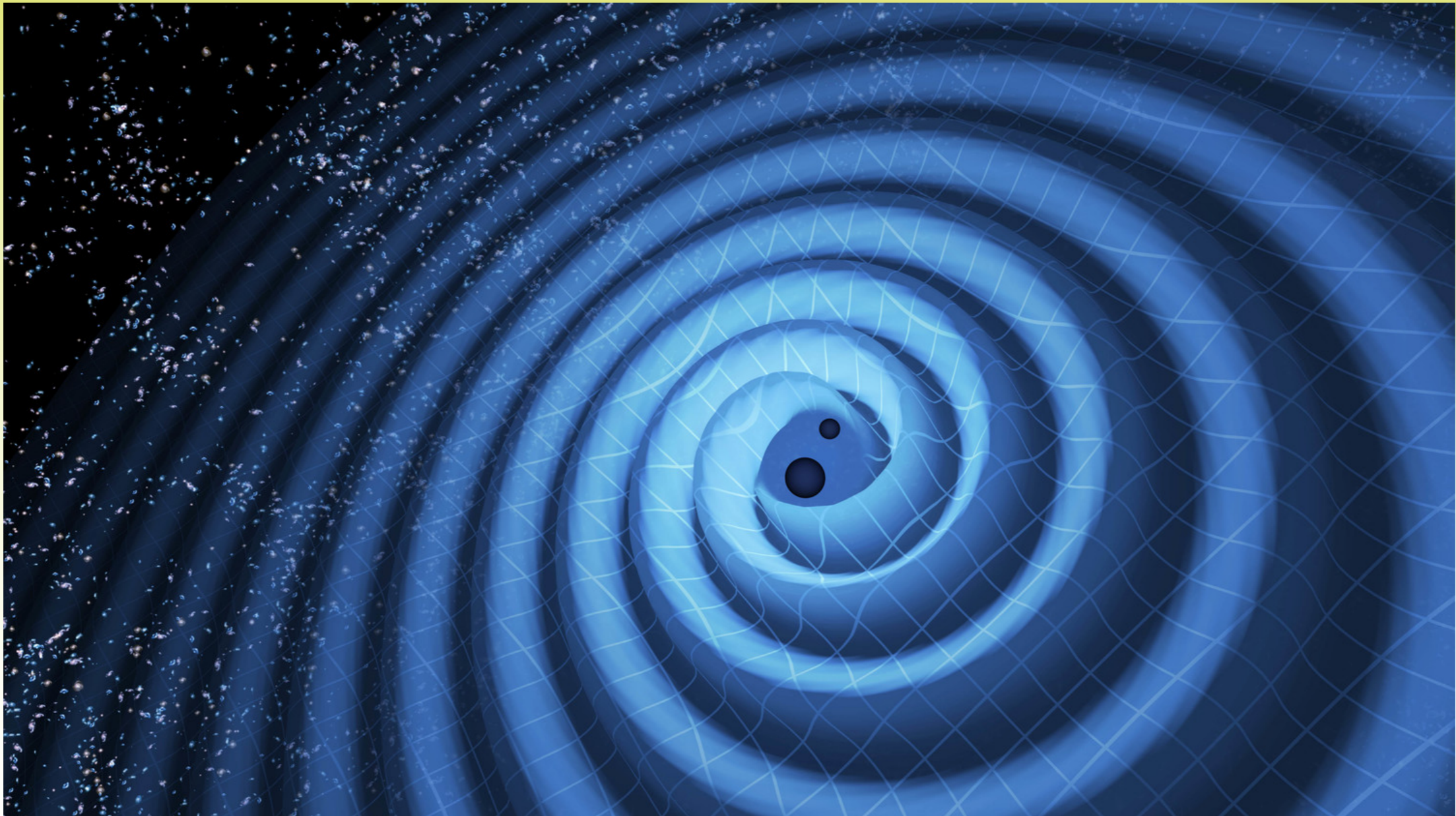
General Relativity has real-work effects:

- If we didn't correct for it, GPS would be miles off !

Gravitational Waves (GW)

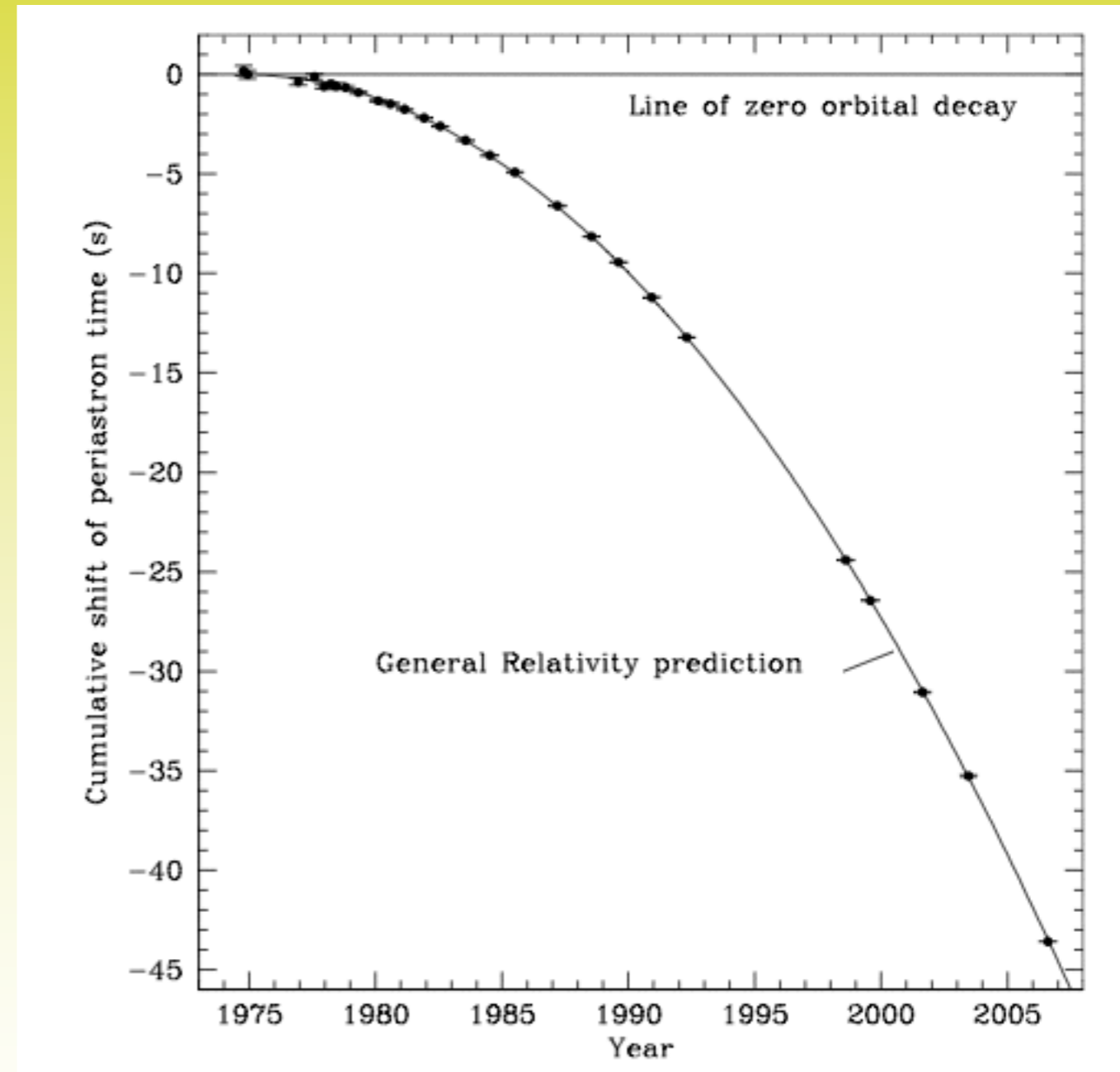
Einstein's general relativity also predicted

- If masses are accelerating, they should emit gravitational radiation in the form of 'waves'

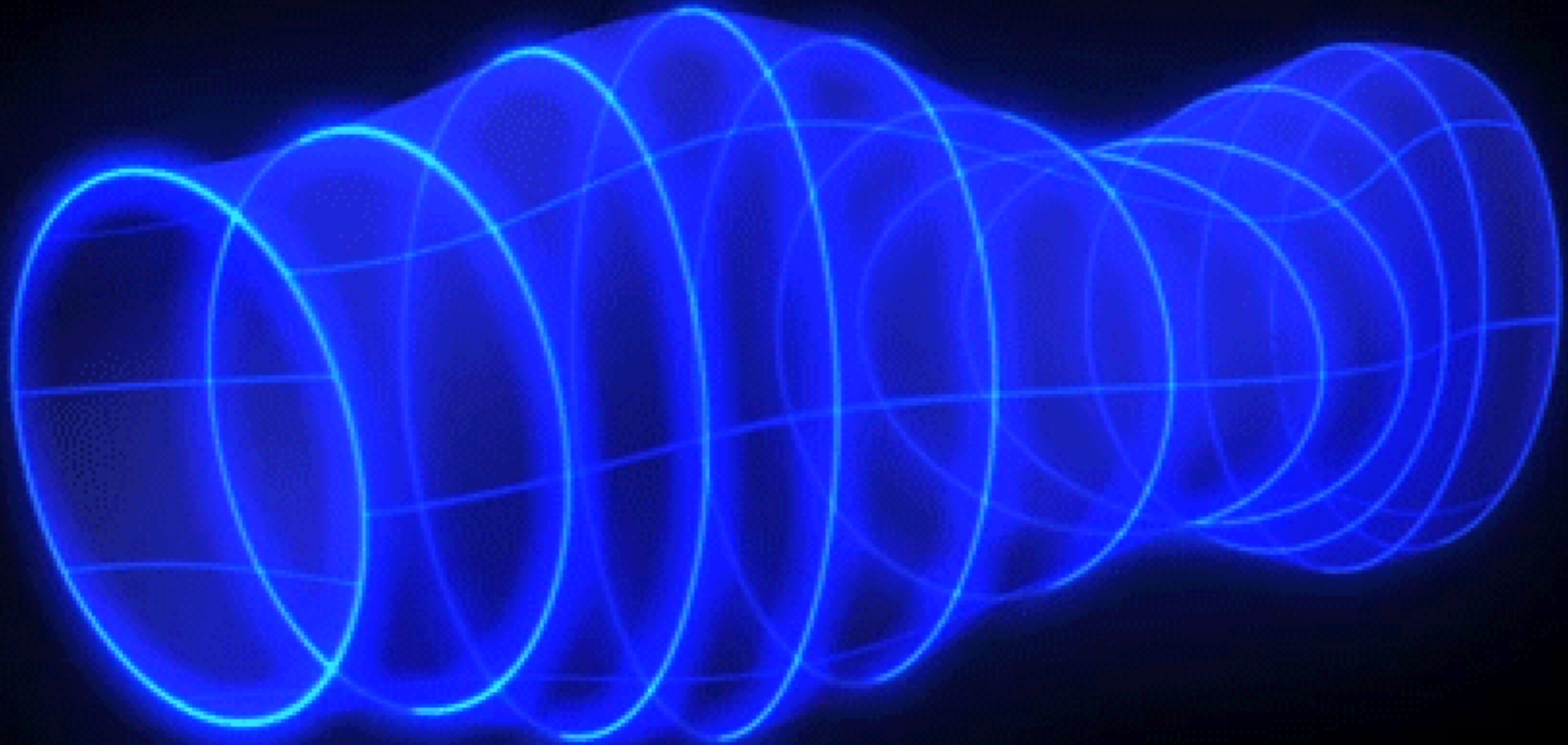


Any evidence for GW ?

- Until now, only indirectly
- Hulse-Taylor binary pulsar
- pair of neutron stars in tight orbit
- Lose energy consistent with gravitational waves



GW Propagation

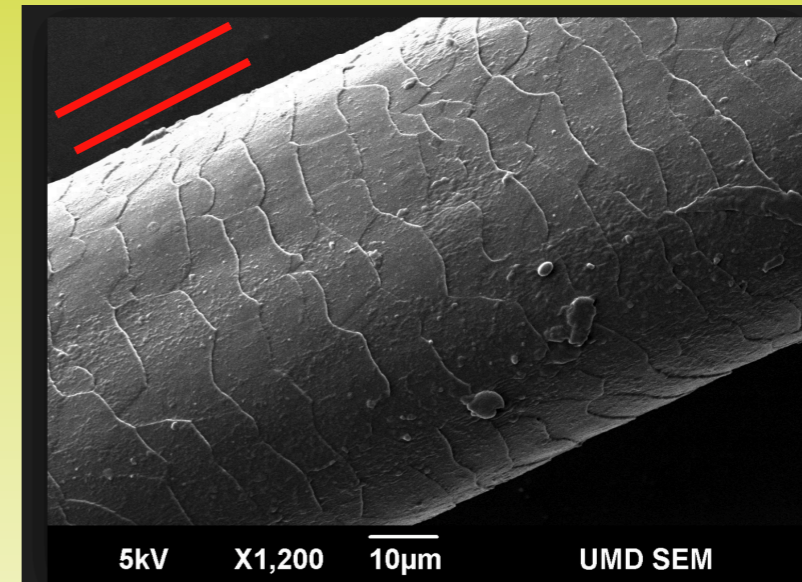


European Space Agency

GW radiation at the Earth

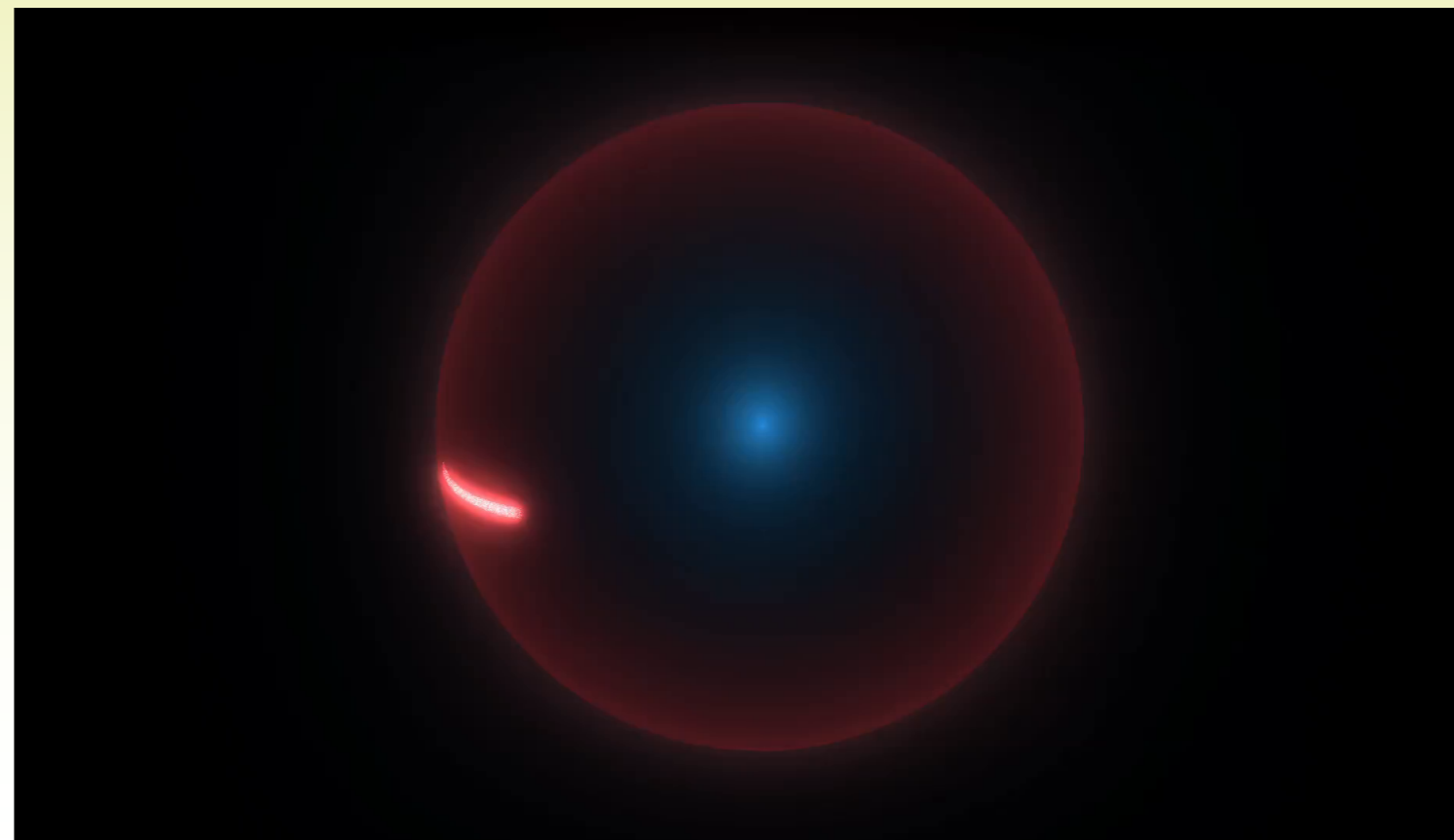


... is really small
From a Meter to
1/10 human hair is
a factor of 1 million



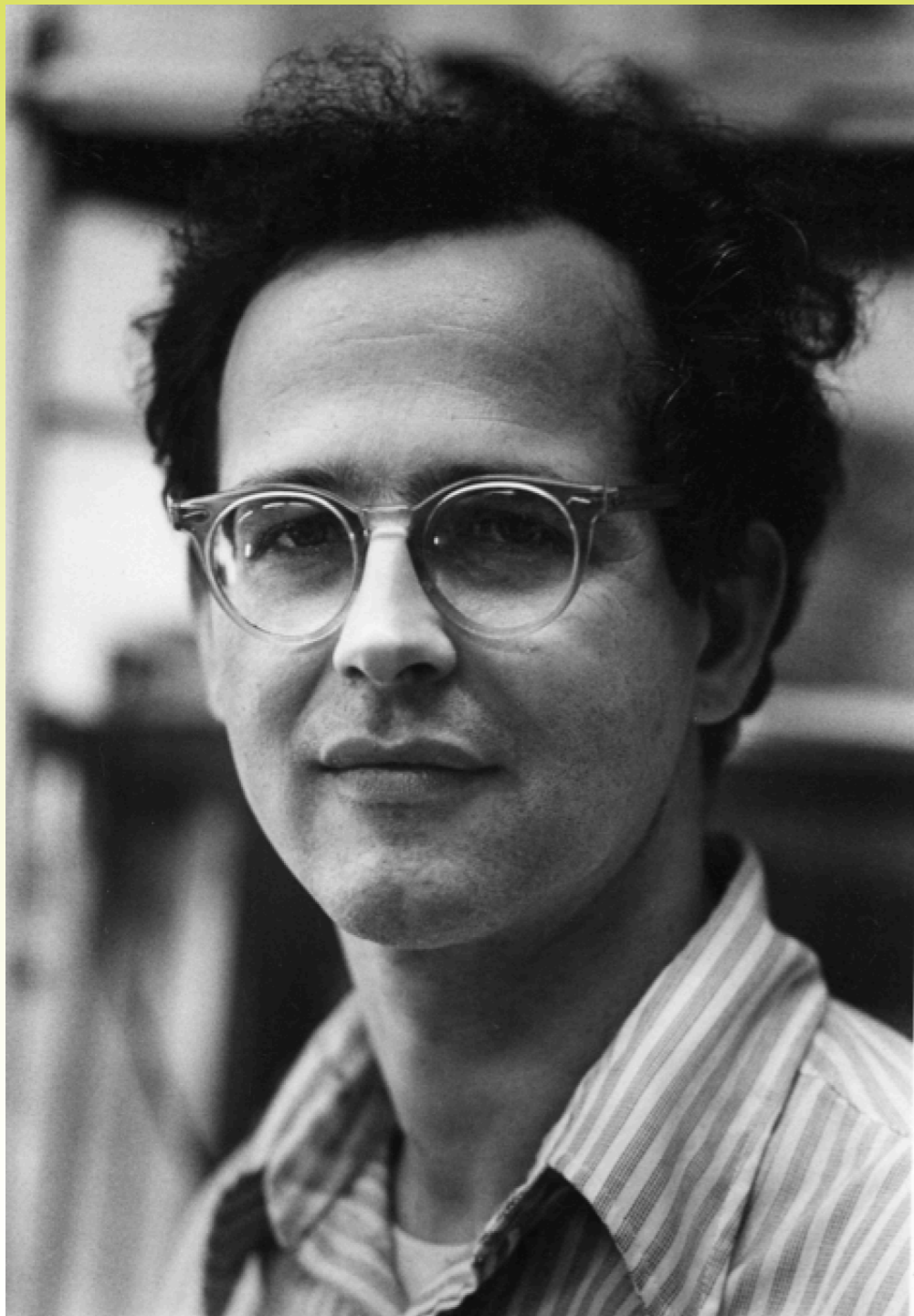
Divide that by a million

Divide that by a trillion
That's 10^{-21} m



LIGO Idea: Detect GW with Laser Interferometer

Rai Weiss,
circa 1967



resulting from the gravitational wave, and it is assumed that all components of this tensor are much smaller than 1. If the plane wave propagates in the x_1 direction, it is always possible to find a coordinate system in which h_{ij} takes the irreducible form

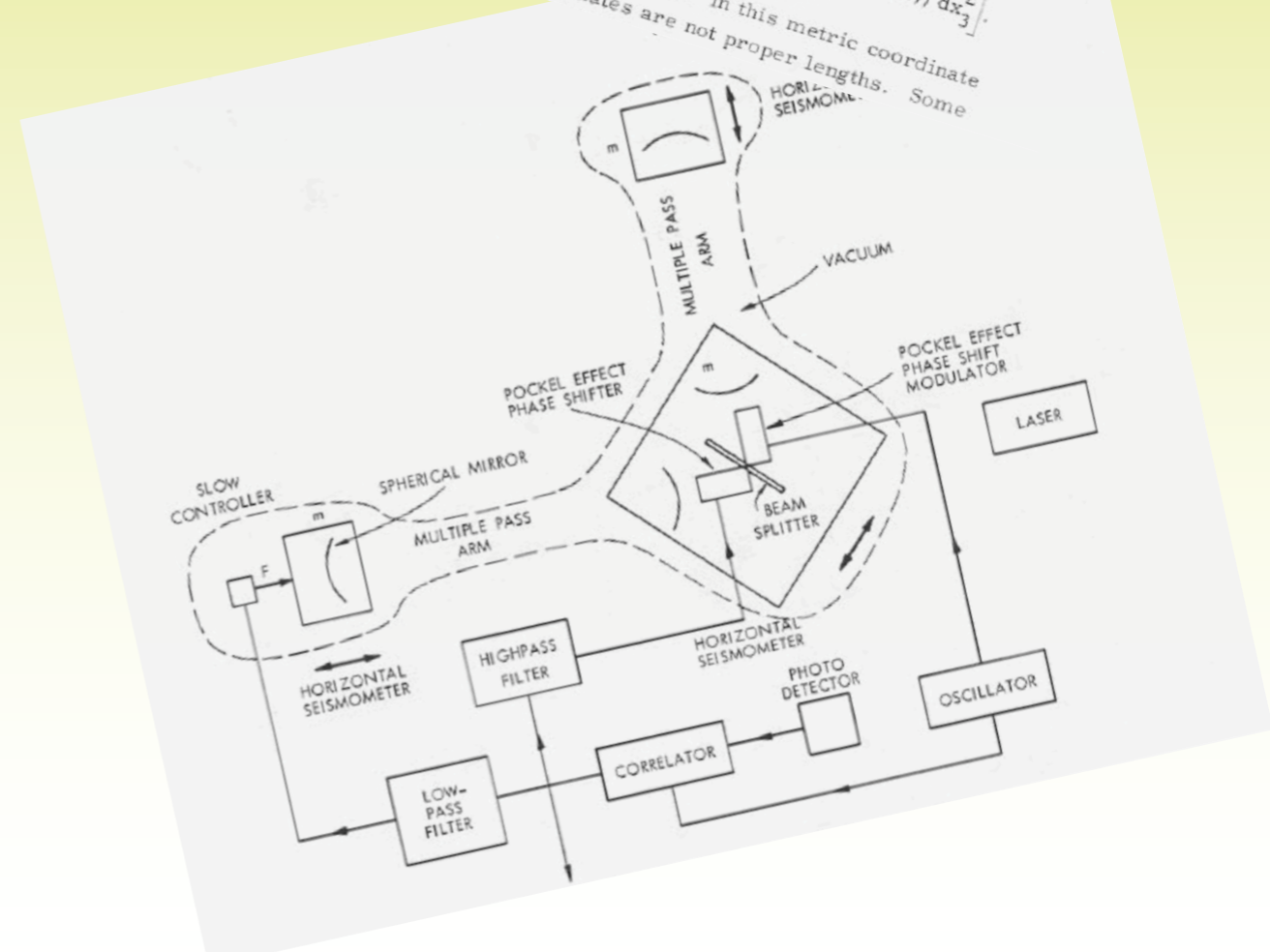
$$h_{ij} = \begin{pmatrix} 0 & & & & & \\ & \circ & & & & \\ & & \ddots & & & \\ & & & \circ & & \\ & & & & h_{22} & h_{23} \\ & & & & h_{32} & h_{33} \end{pmatrix}$$

with $h_{22} = -h_{33}$, and $h_{23} = h_{32}$. The tensor components have the usual functional dependence $f(x_1 - ct)$.

To gain some insight into the meaning of a plane gravitational wave, assume that the wave is in the single polarization state $h_{23} = h_{32} = 0$, and furthermore let $h_{22} = -h_{33} = h \sin(kx_1 - \omega t)$. The interval between two neighboring events is then given by

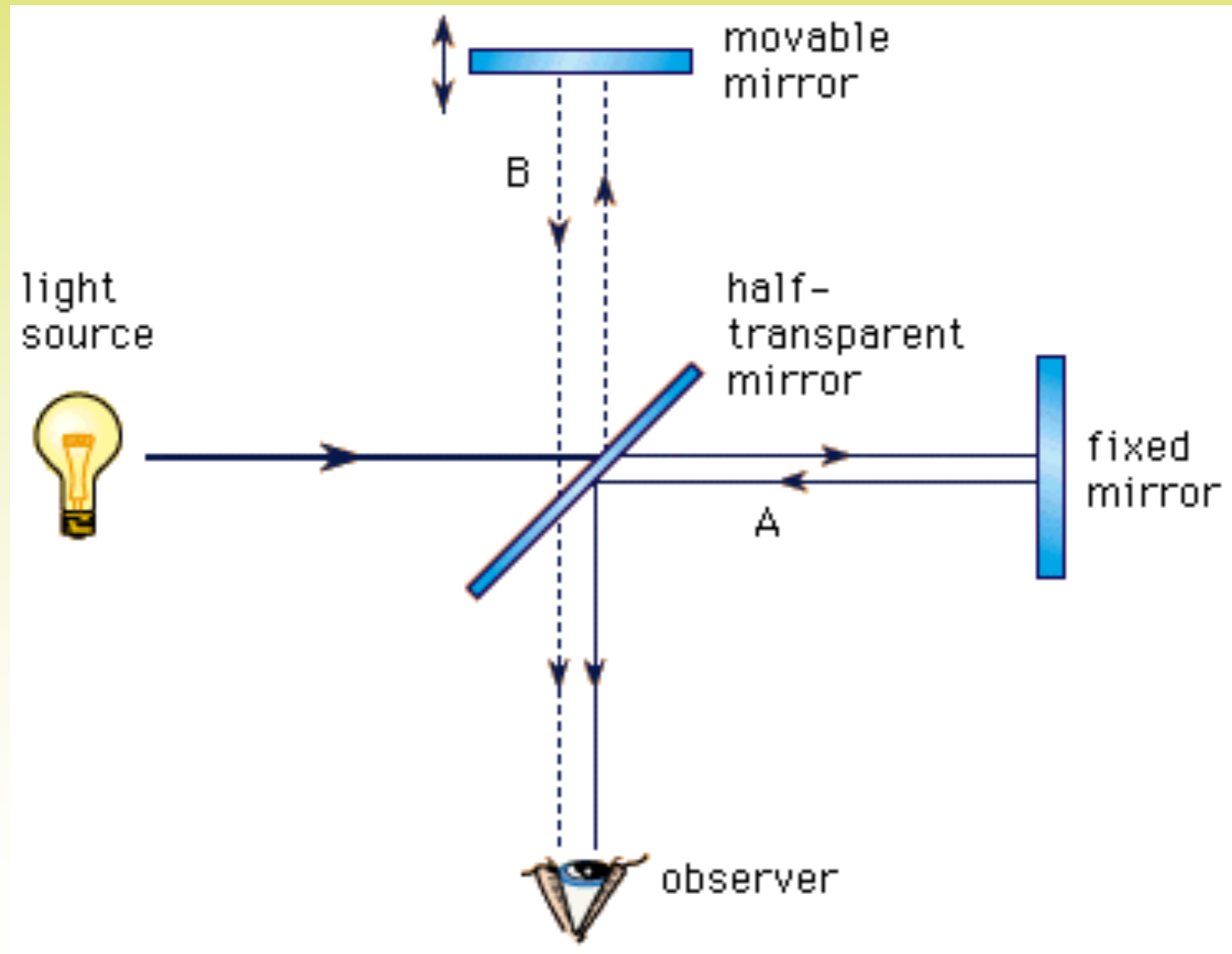
$$ds^2 = g_{ij} dx^i dx^j = c^2 dt^2 - [dx_1^2 + (1 + h \sin(kx_1 - \omega t)) dx_2^2 + (1 - h \sin(kx_1 - \omega t)) dx_3^2].$$

The metric relates coordinate distances to proper lengths. In this metric coordinate time is proper time; however, the spatial coordinates are not proper lengths. Some



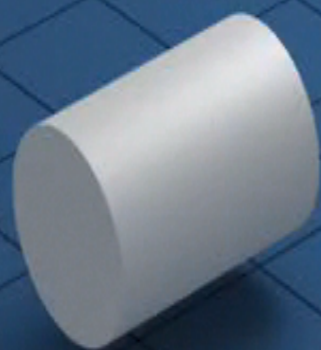
Interferometry 101

- Interference between one light wave and another
- Measures length difference of two arms
- White light $\sim 1/100$ wavelength - 5 nm (10^{-9} m)

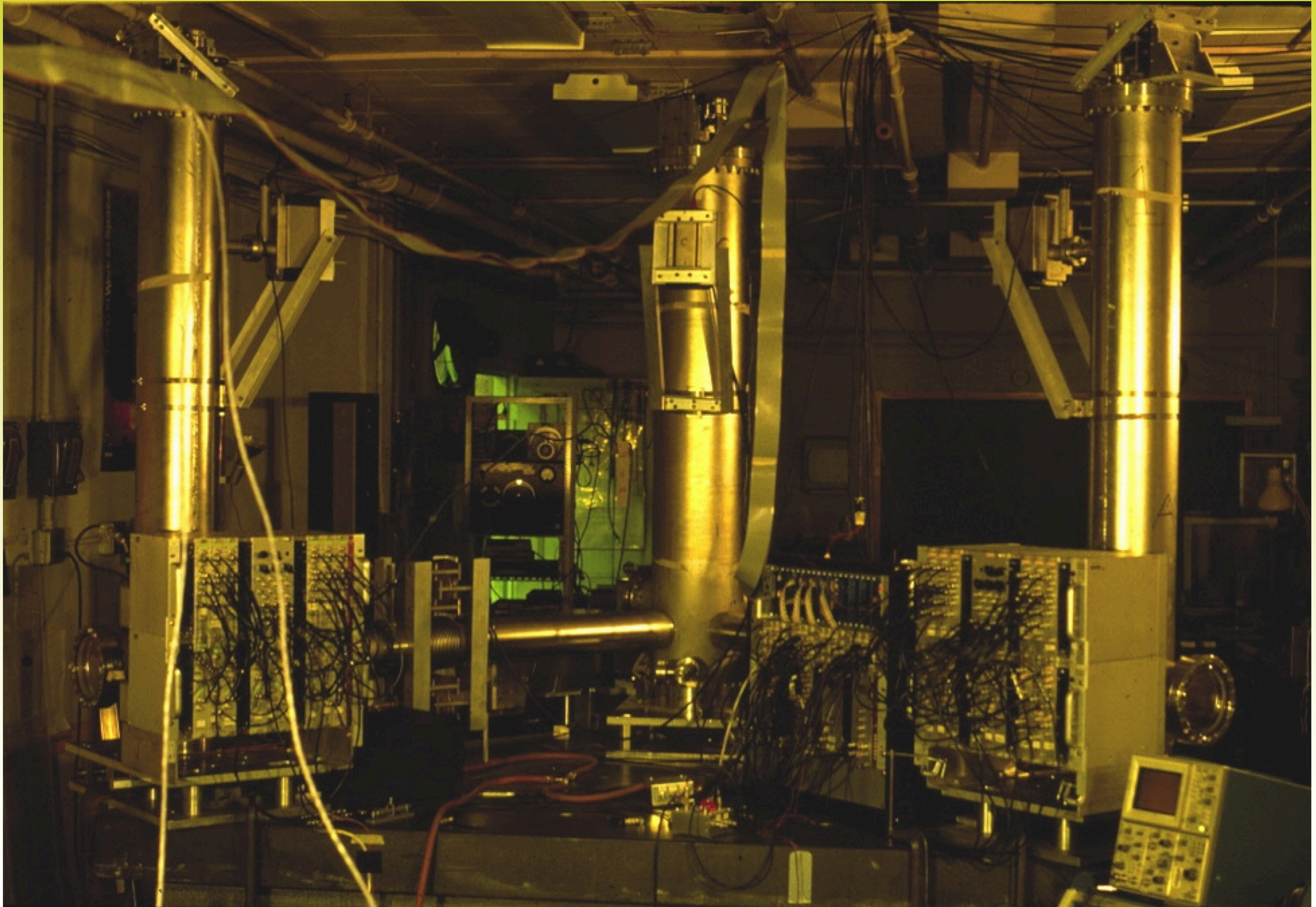


Laser Interferometer

- Properties of laser light
 - Single frequency
 - Same phase (coherent)
 - With feedback, precisely control
 - Laser intensity (brightness)
 - Laser frequency
- > We can get nearly perfect interference
- Measure much smaller displacement



Desktop Laser Interferometer (MIT)



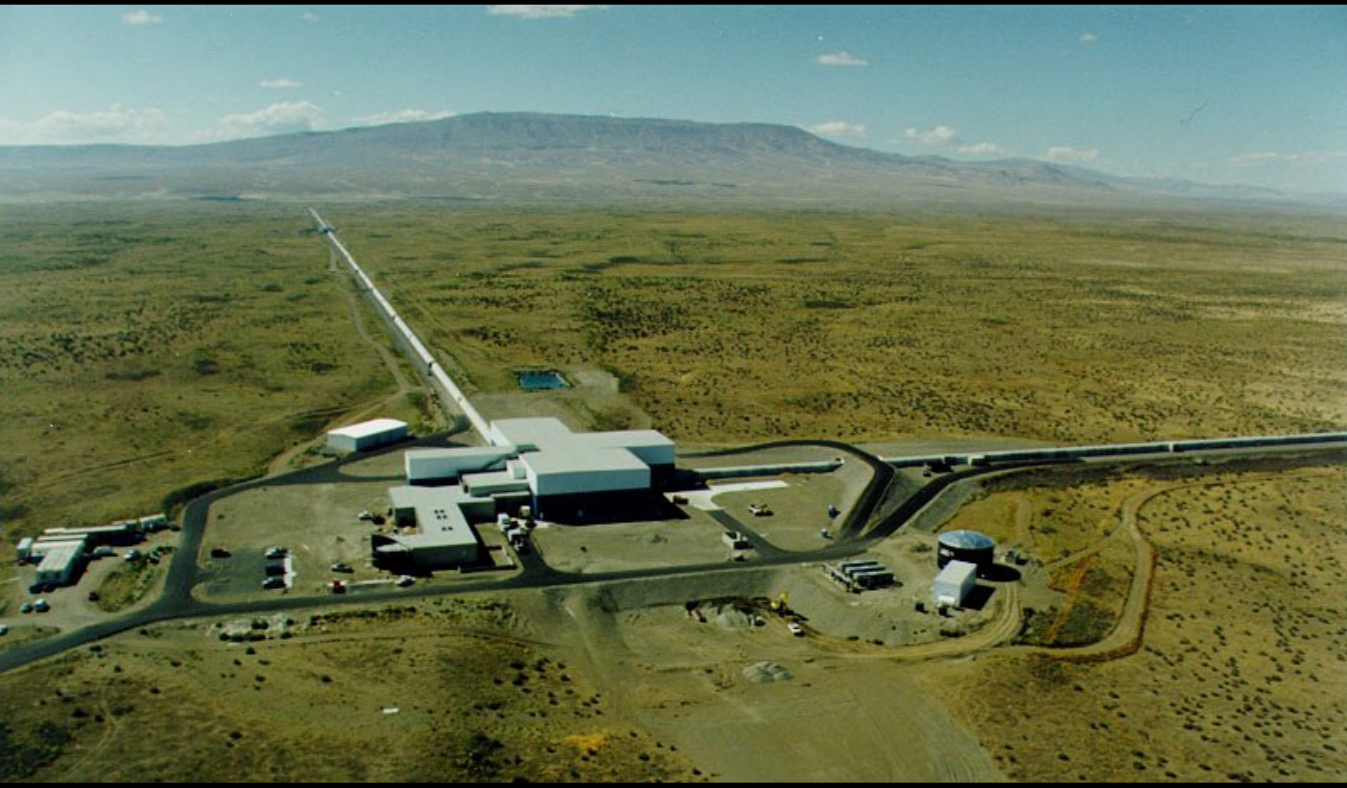
LIGO Livingston



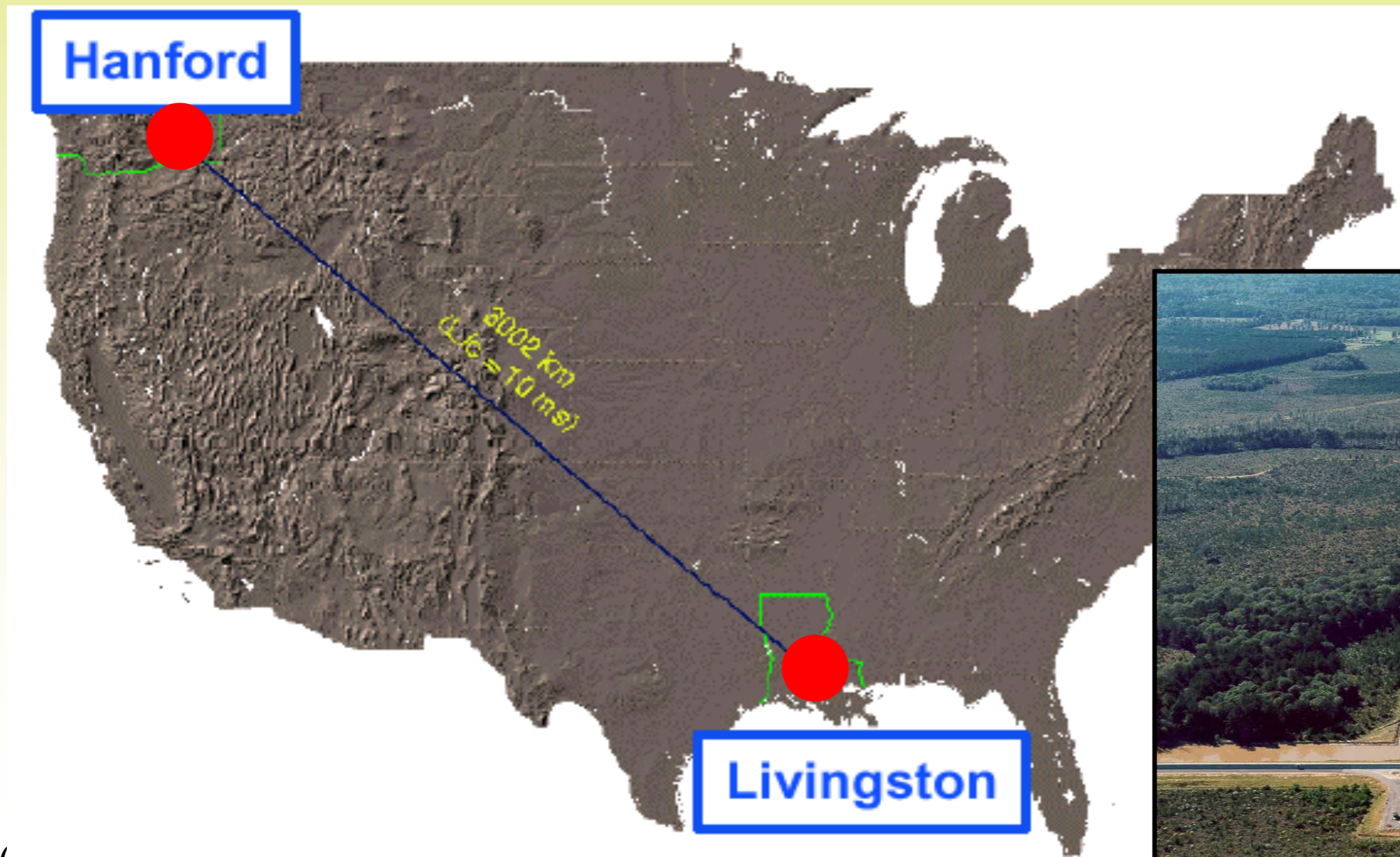


4 km long beam tubes – Vacuum 10^{-9} Torr

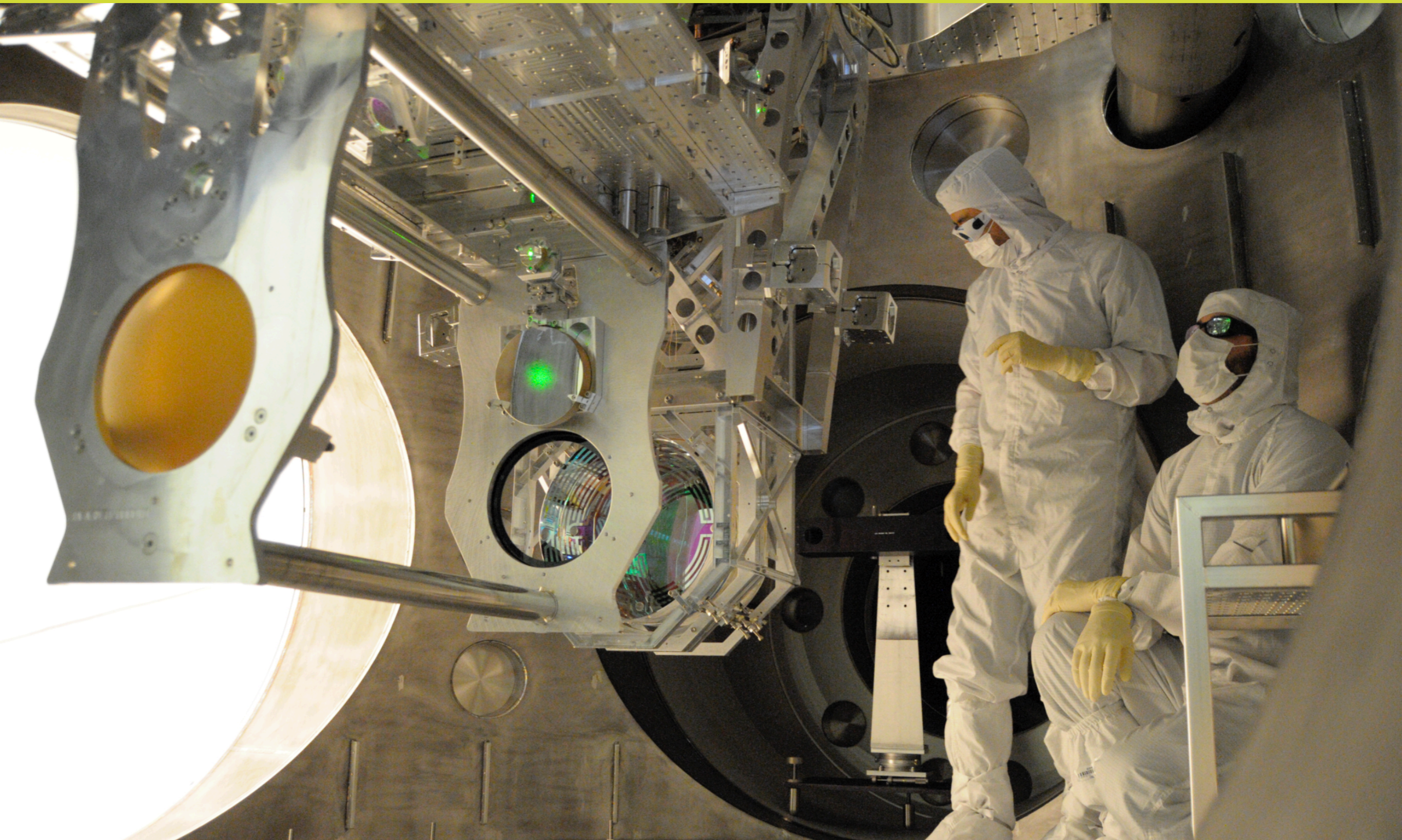


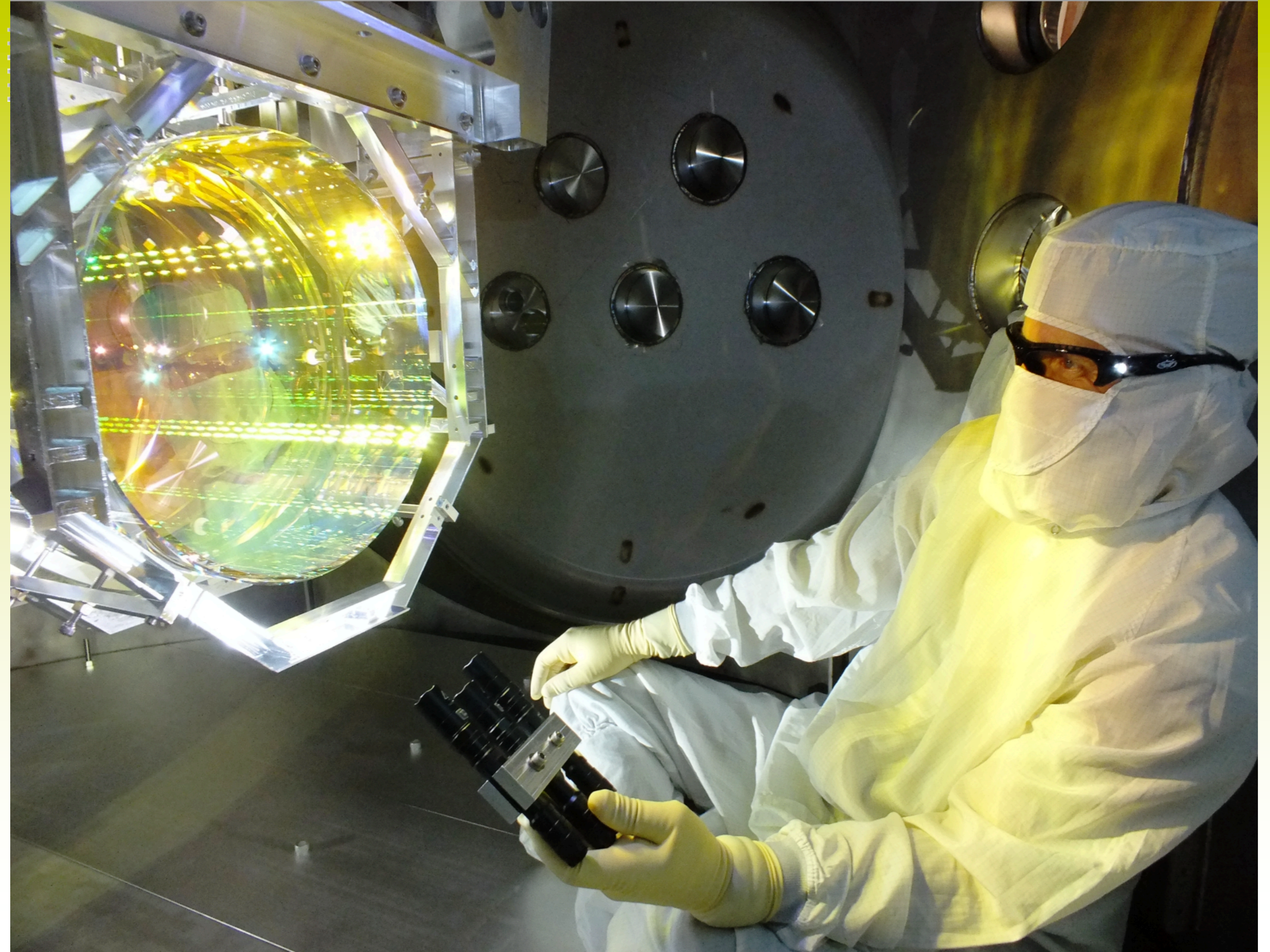


LIGO Laboratory Observatories; Operated by Caltech, MIT for NSF



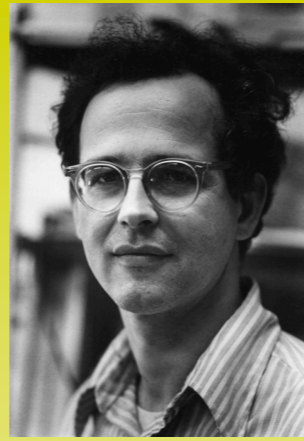
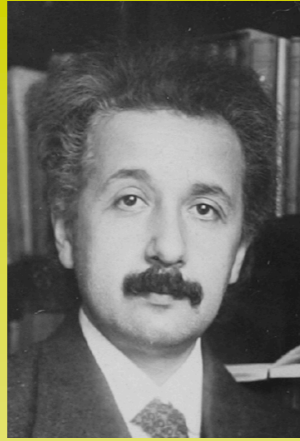
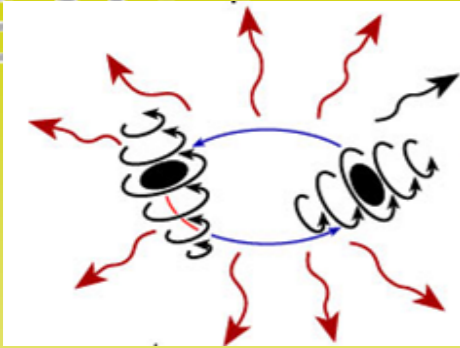
NSF Photo







LIGO



1.3 Billion years after the Black Holes merged..

100 years after Einstein predicted gravitational waves...

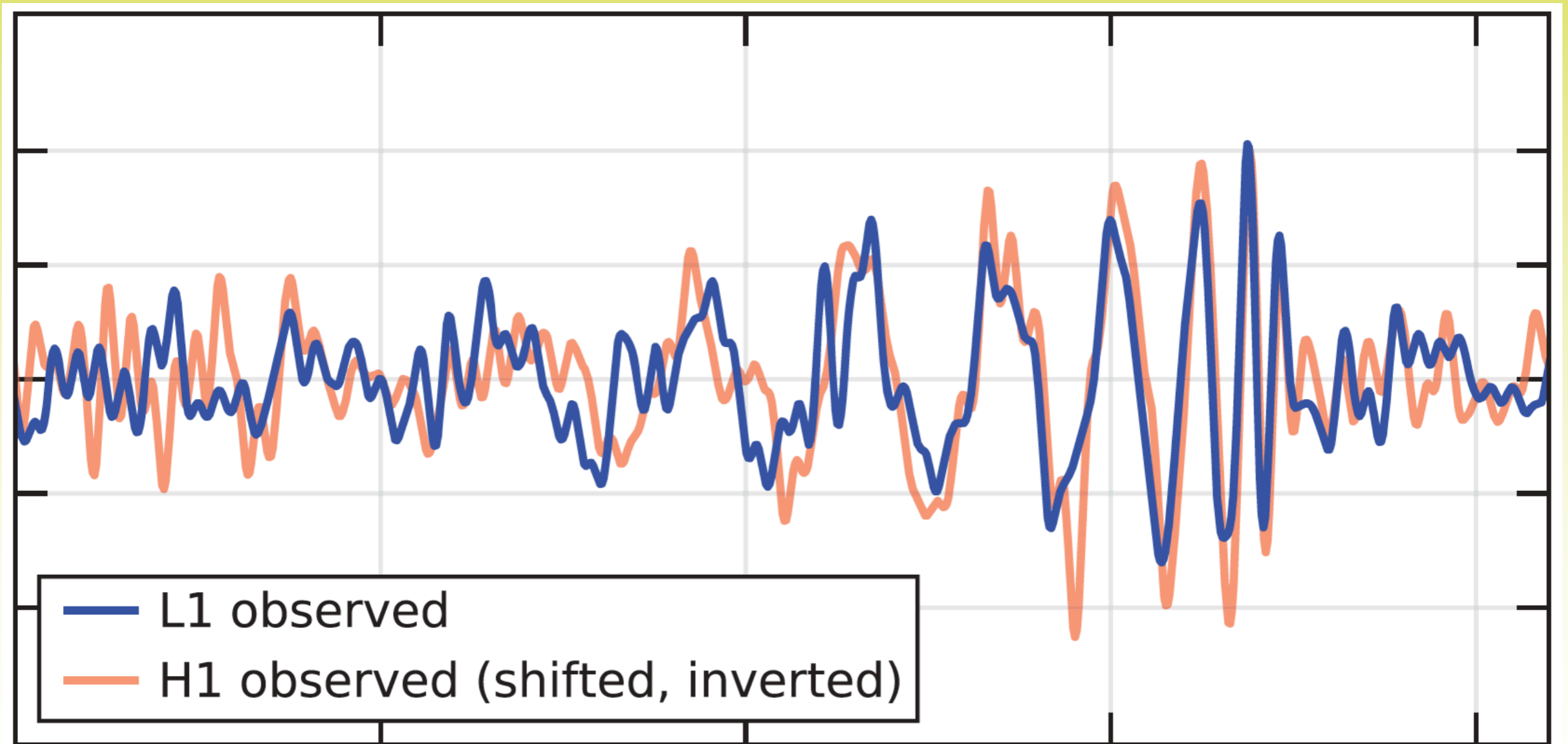
50 years after Rai Weiss invented the detectors...

20 years after the NSF, MIT, and Caltech Founded LIGO...

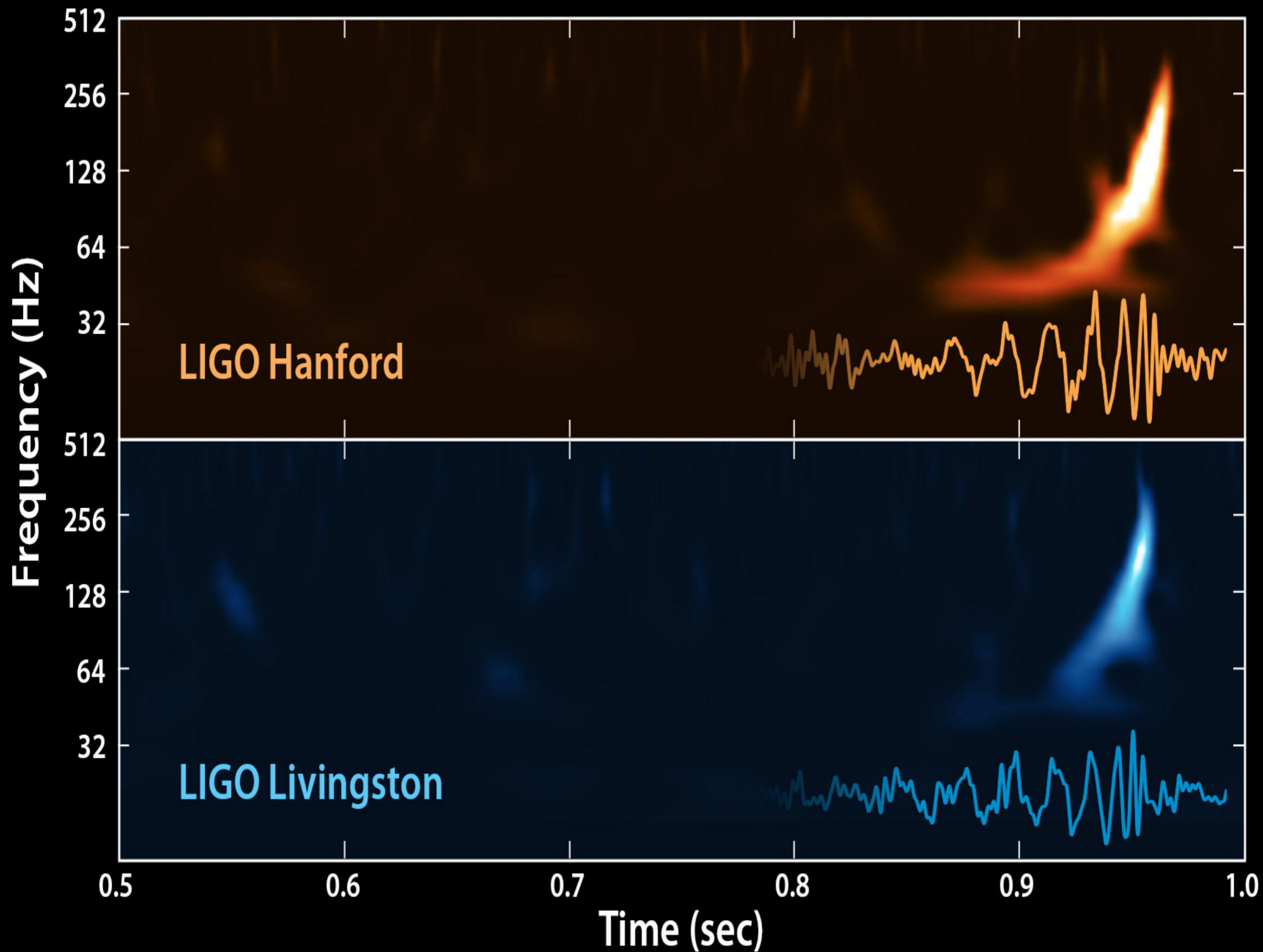
10 years after Advanced LIGO got the ok...

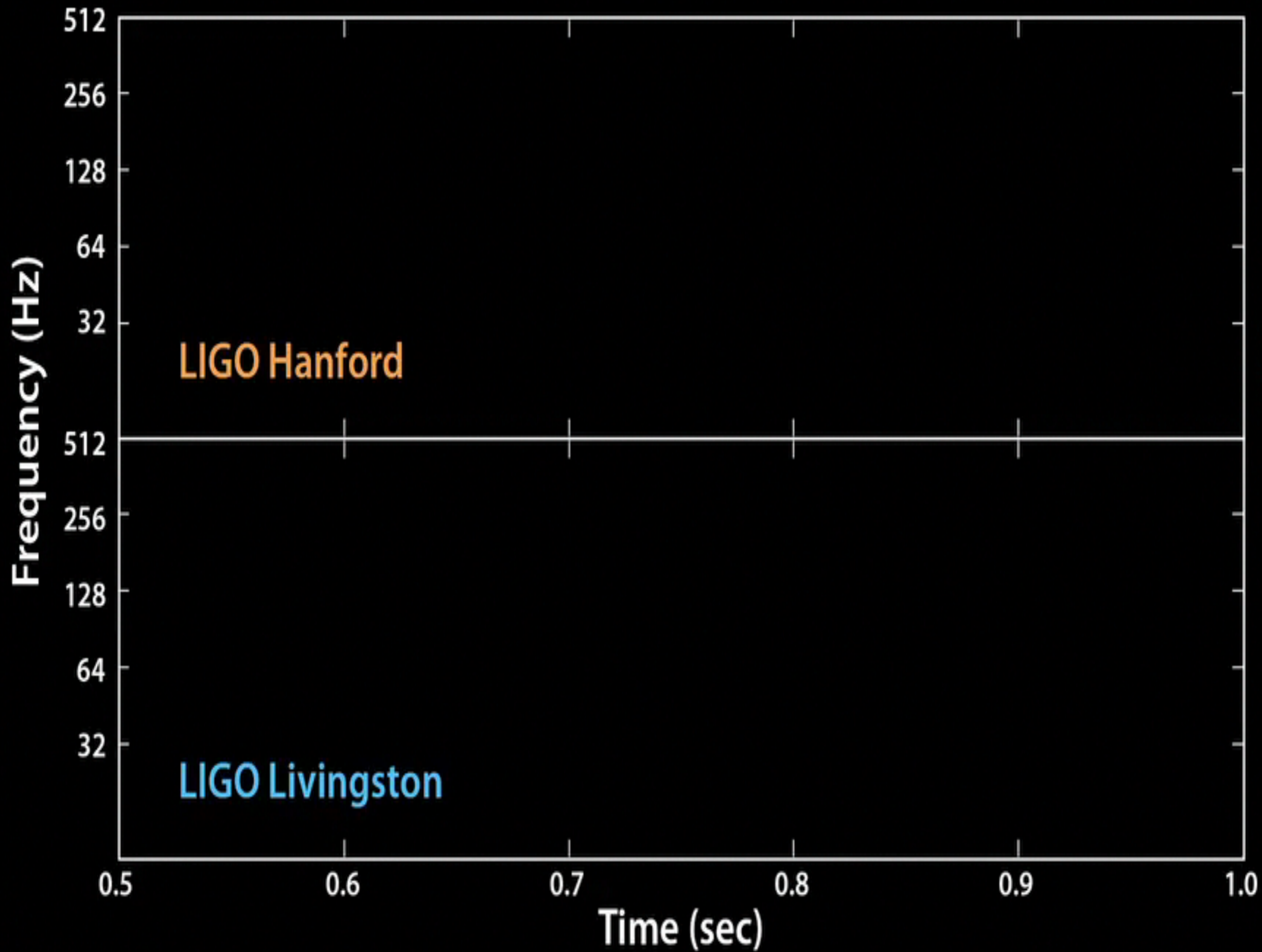
6 months after starting detector tuning...

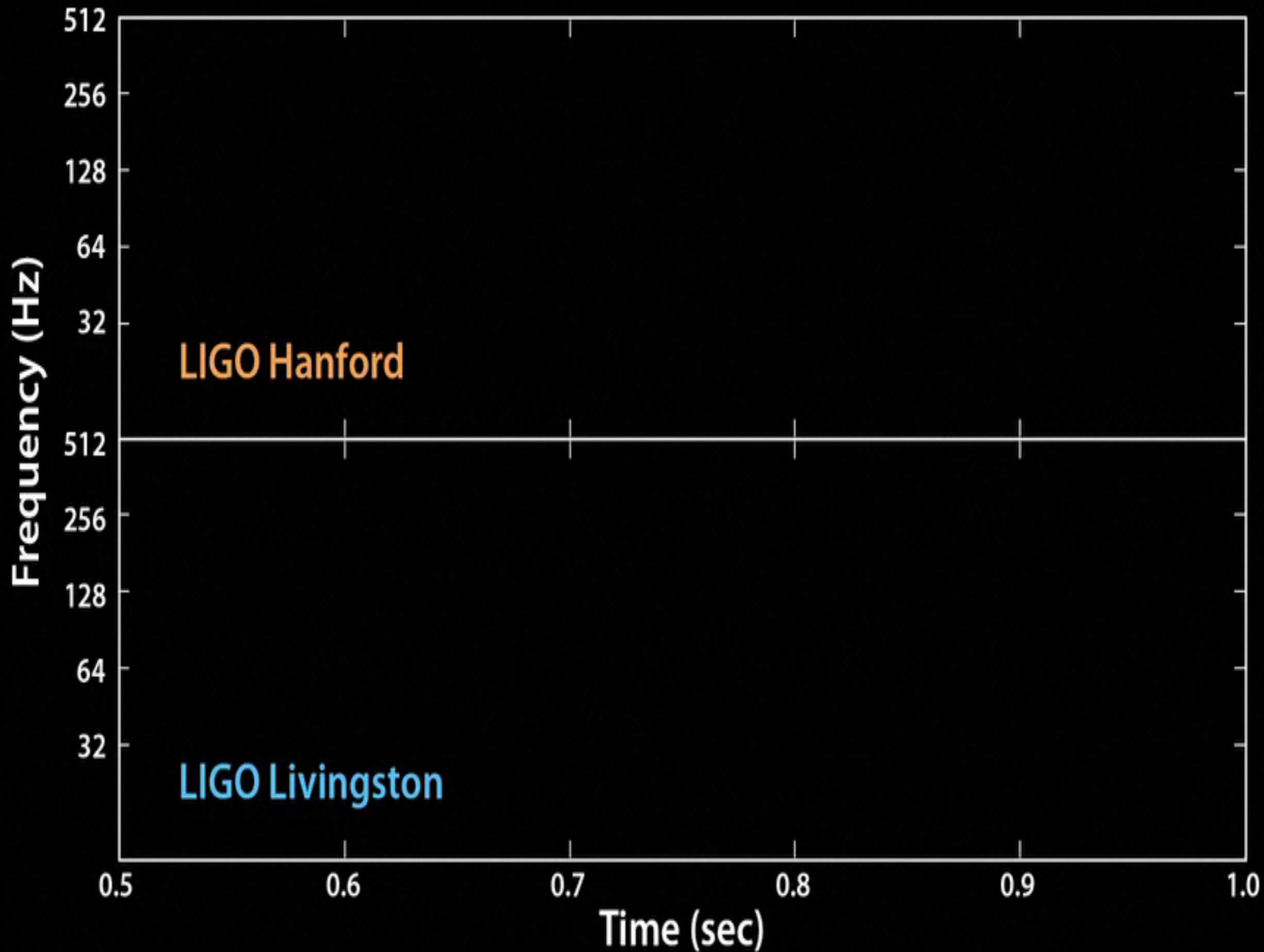
September 14, 2015 at 05:51 EDT: Cosmic Rendezvous



← 1/10 of a second →







Confirmation of General Relativity

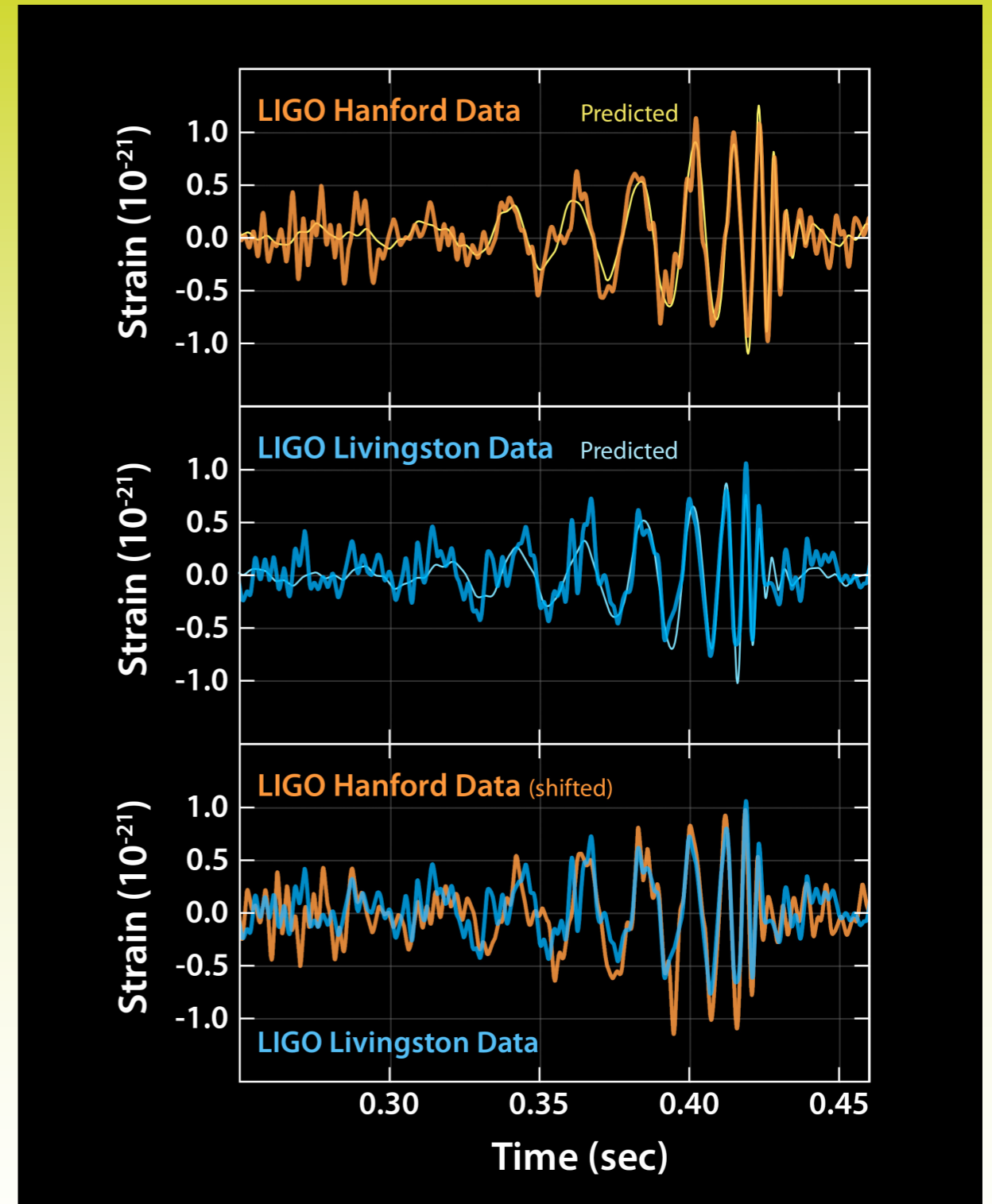
1.3 Billion Years Ago:

Two Massive Black Holes

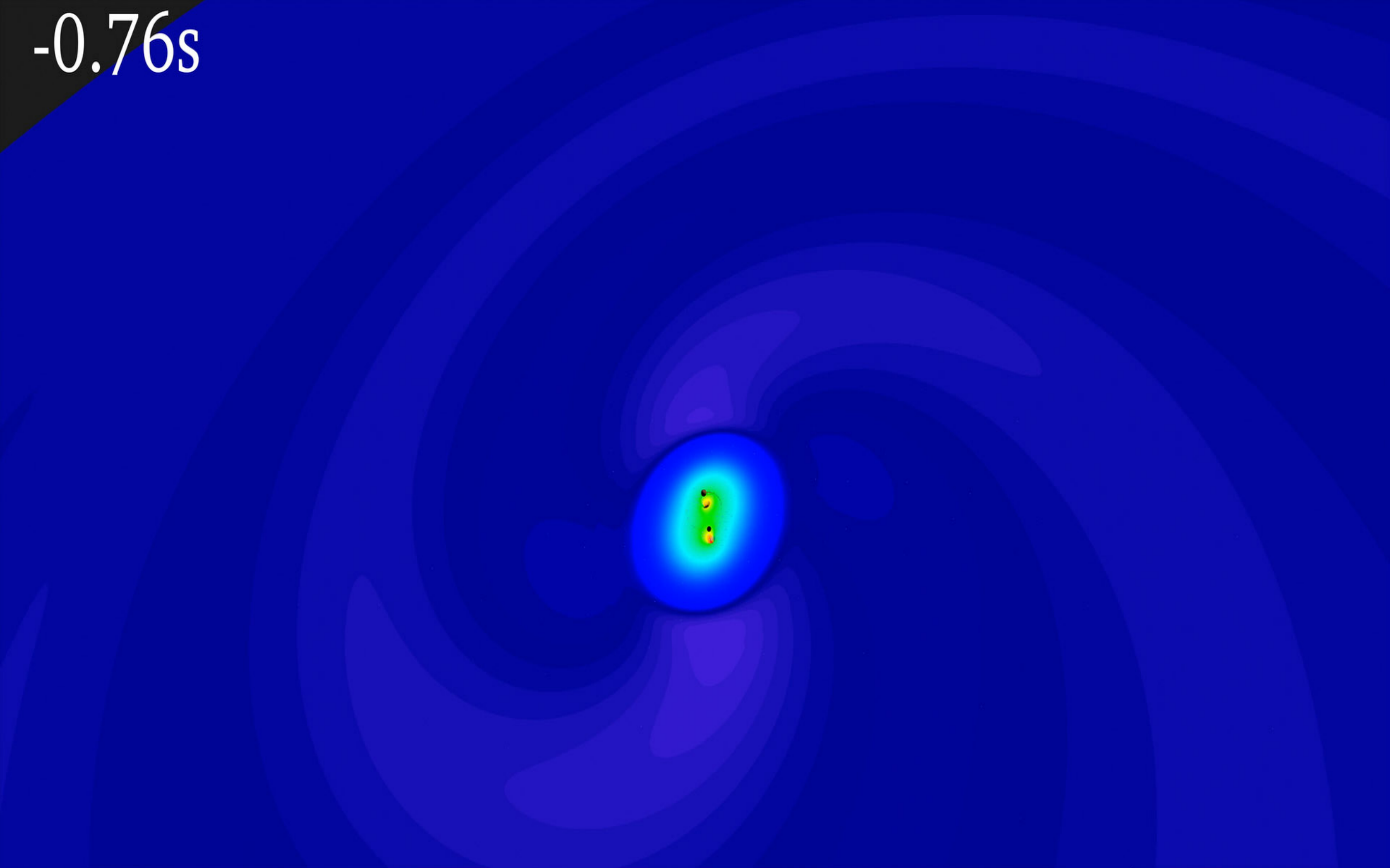
$29 M_{\text{sun}}$ x $35 M_{\text{sun}}$

Merged $62 M_{\text{sun}}$ Black Hole

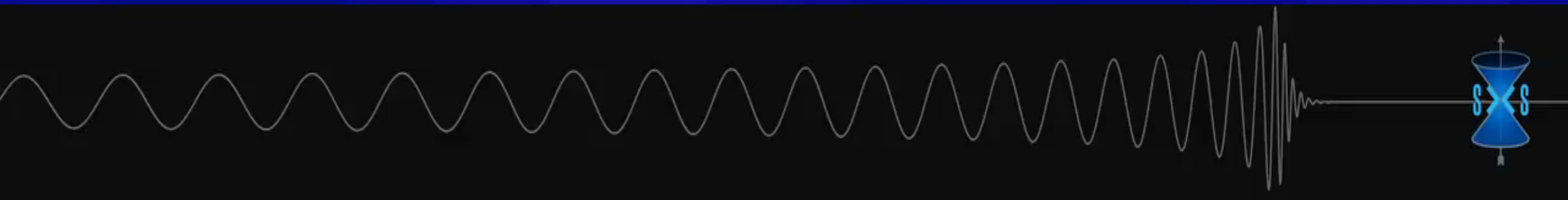
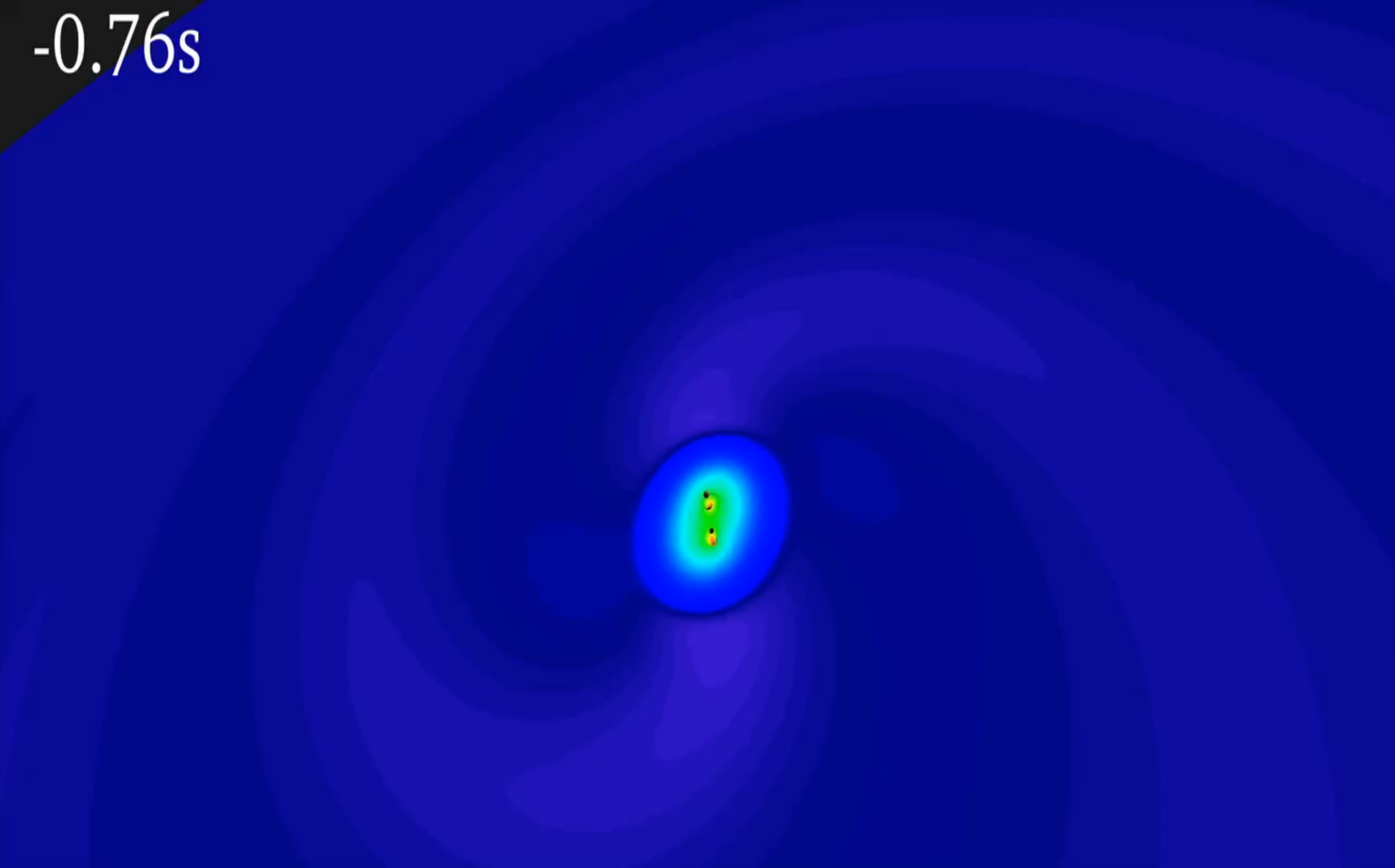
-> $3 M_{\text{sun}}$ converted to GWs !



-0.76s

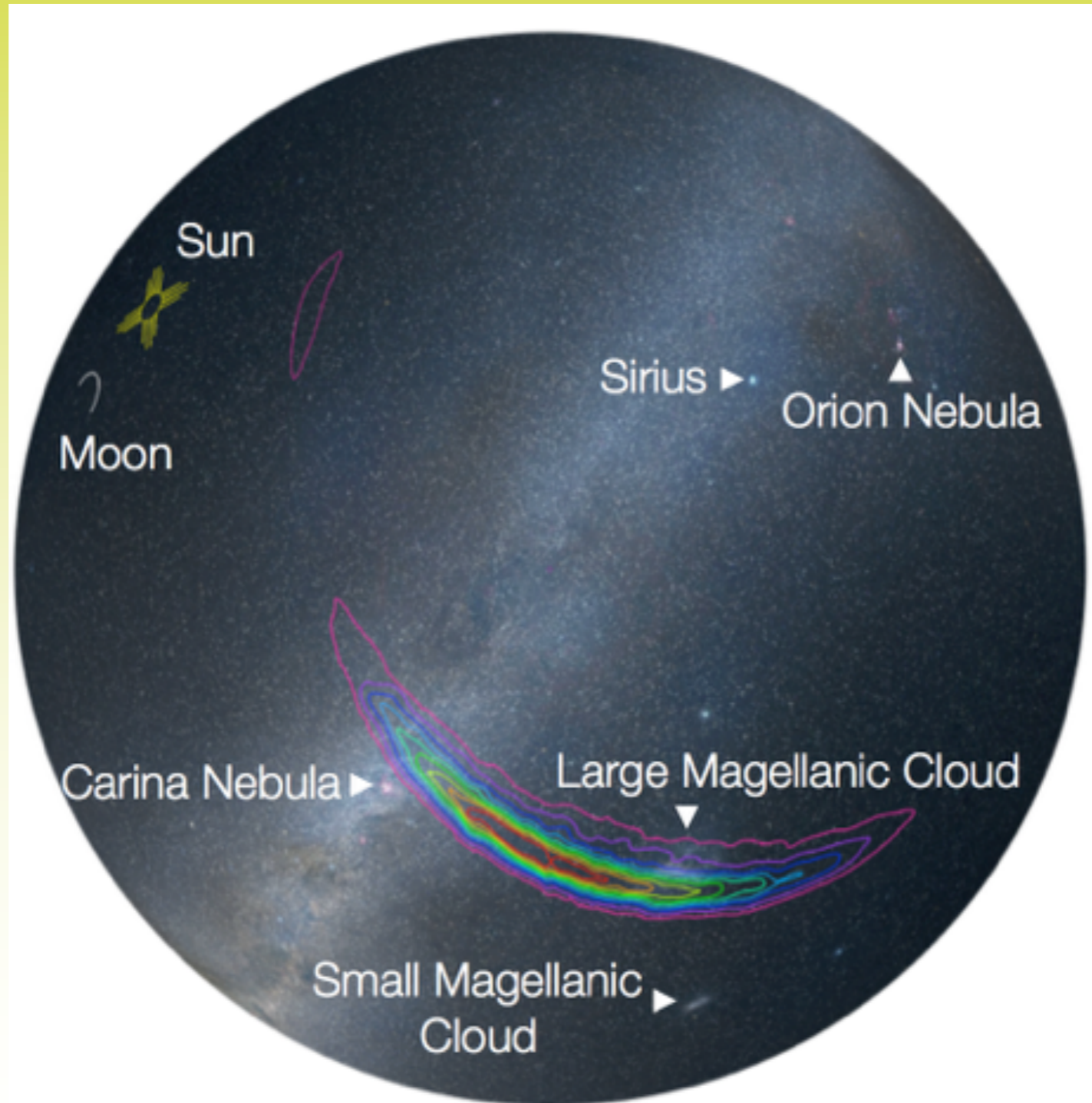


-0.76s



GW150914 Localization

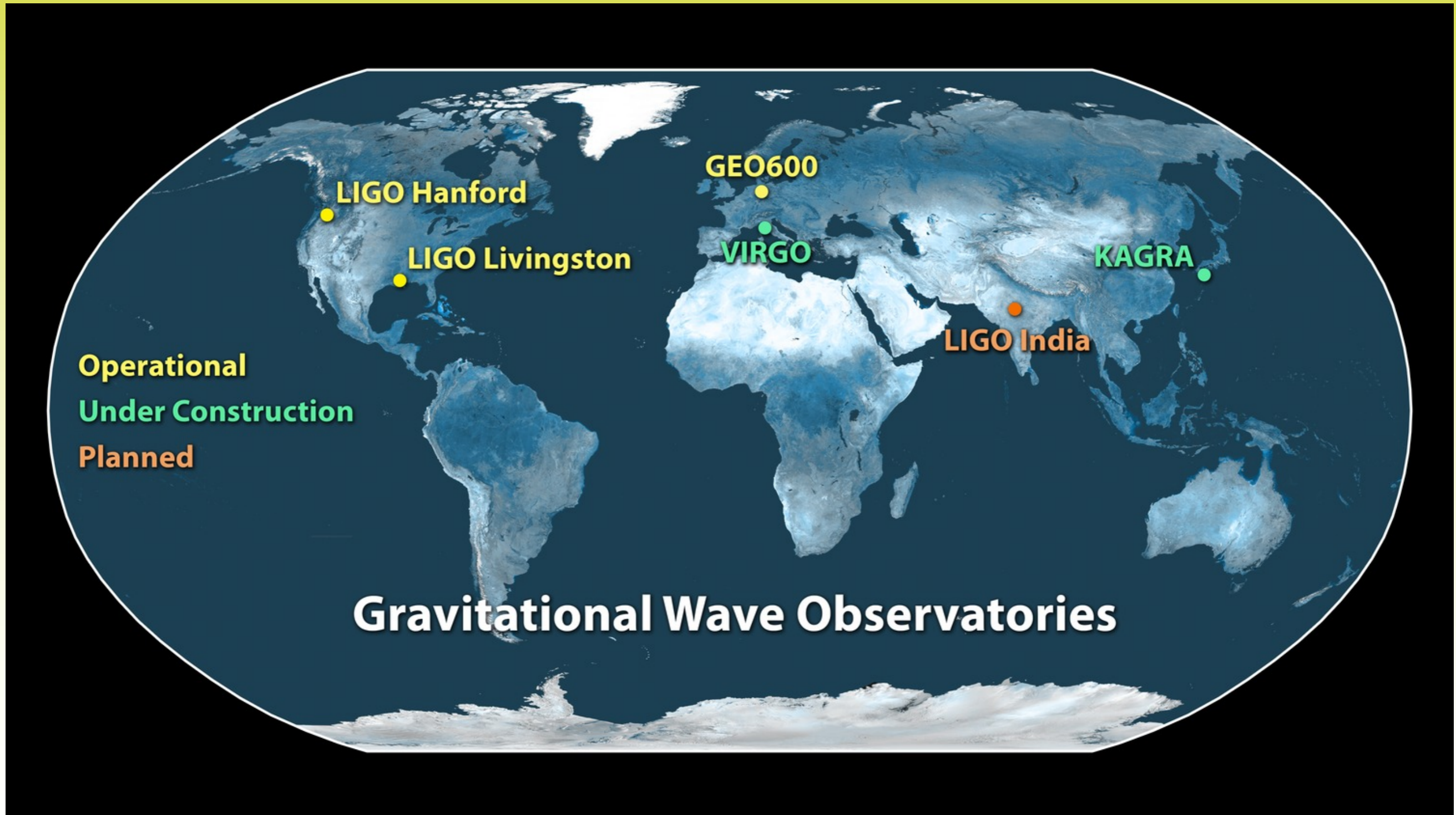
With only two instruments, location is imprecise





GW Observatory Network

Can't focus GWs, need many 'ears' to triangulate



GW in Space: LISA

