LIGO, The Universe and Everything

Dr. Keith Thorne
LIGO Livingston Observatory

You might have heard the news…

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

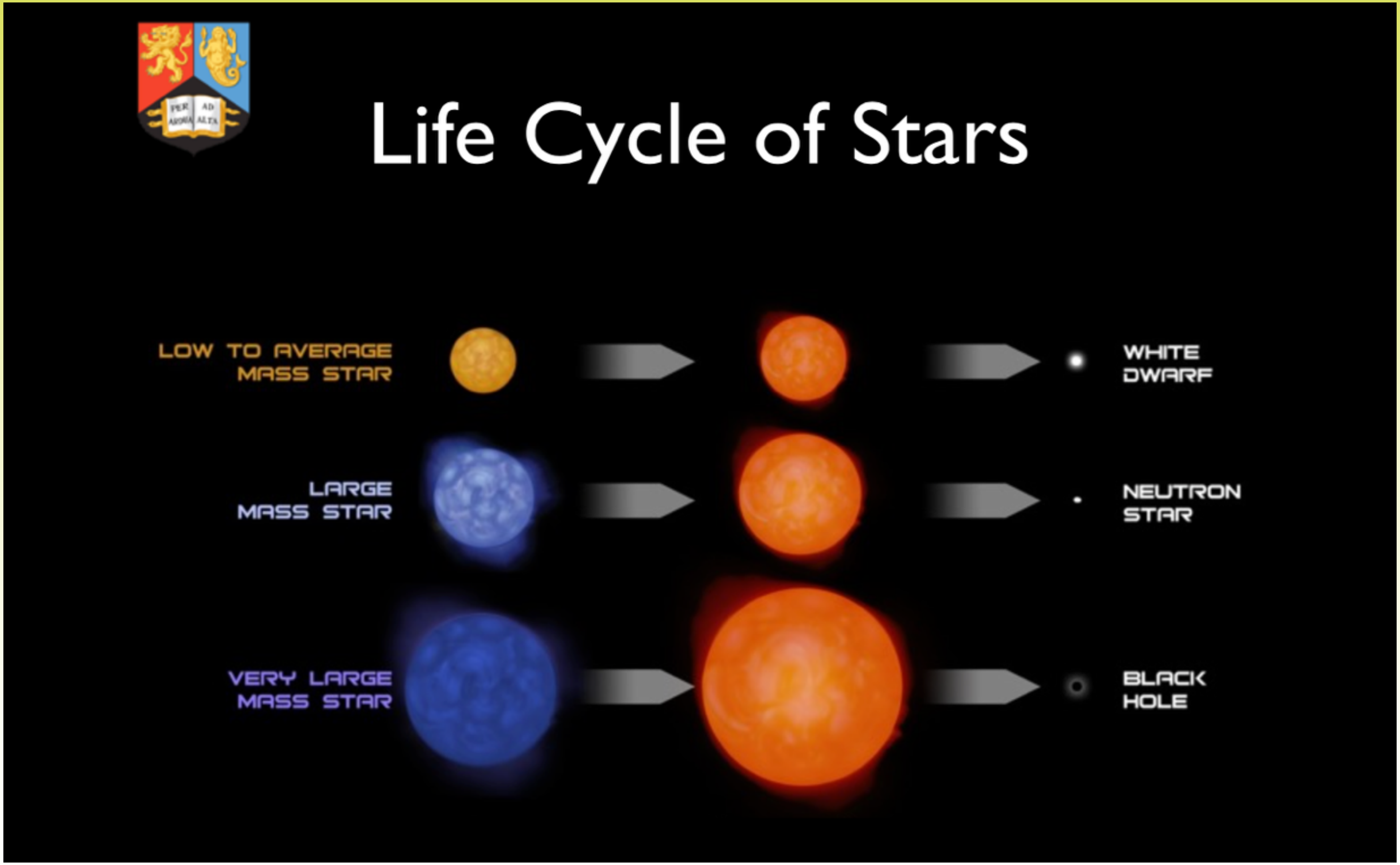
But they are finding that most matter is not visible to them

- 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 ?



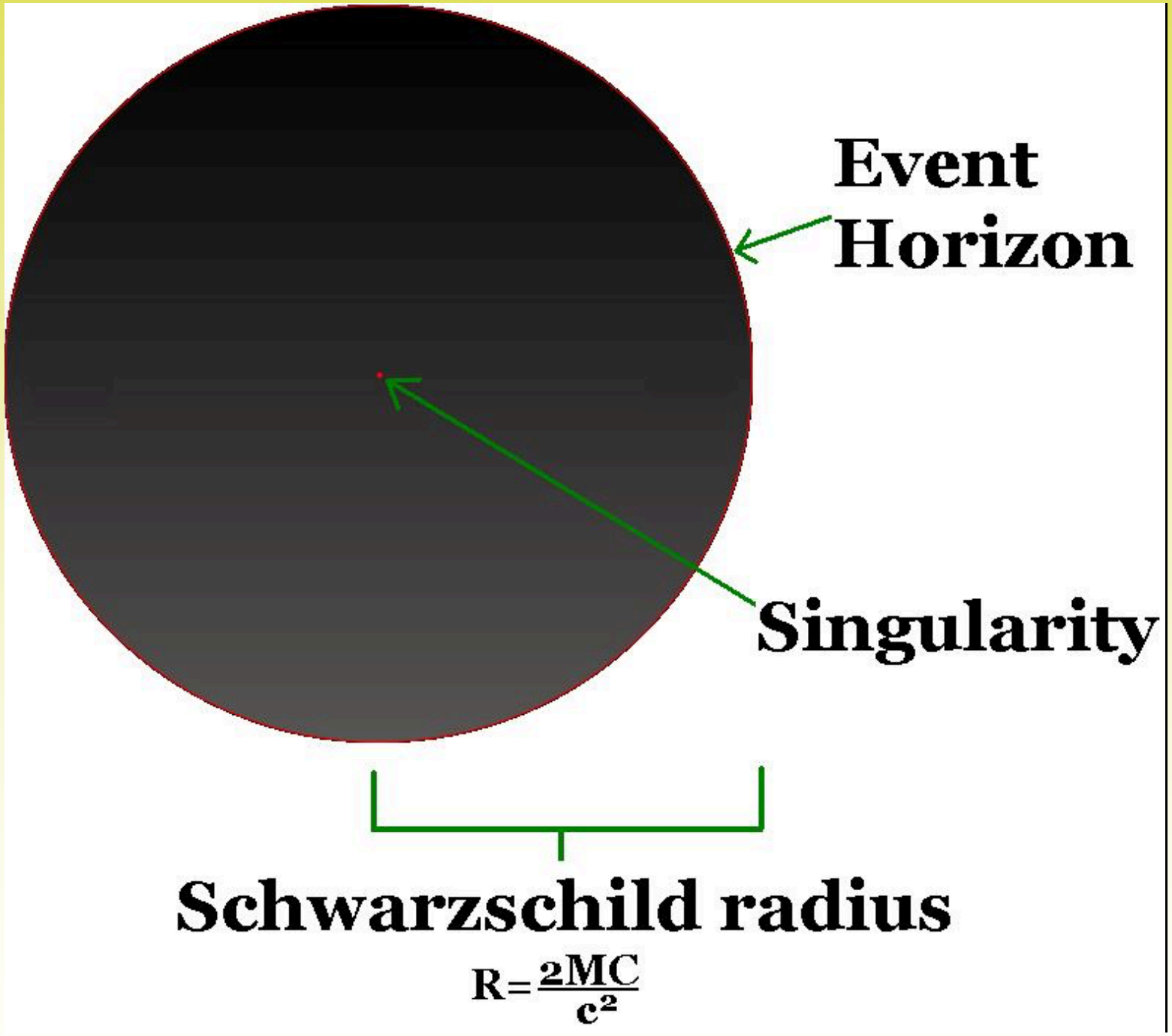
Courtesy Andreas Freise

Black Holes

Prediction of General Relativity

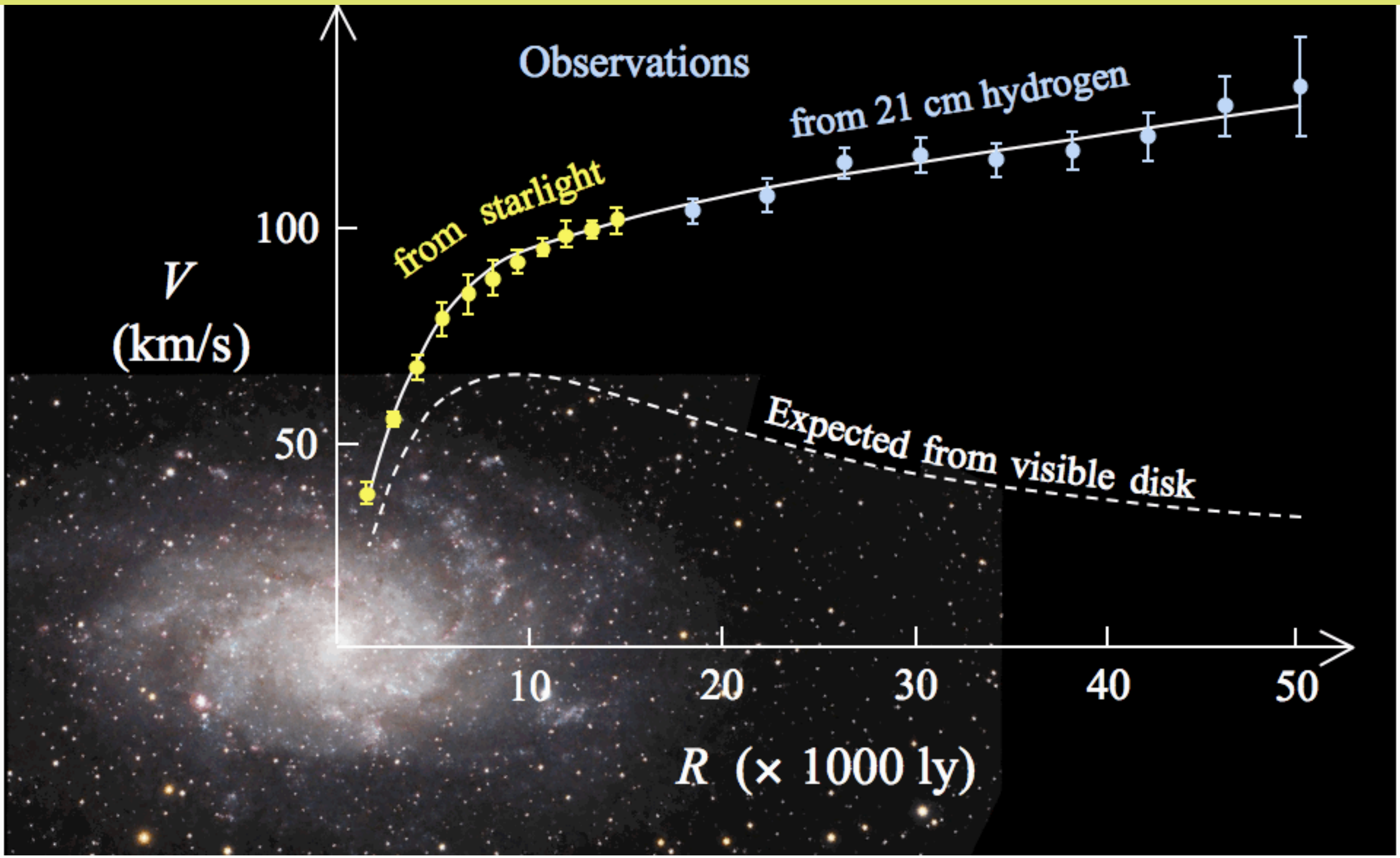
Gravitational collapse so extreme that even light never escapes the Event Horizon

A singularity of pure gravity



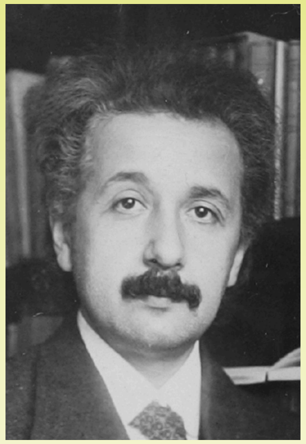
Dark Matter

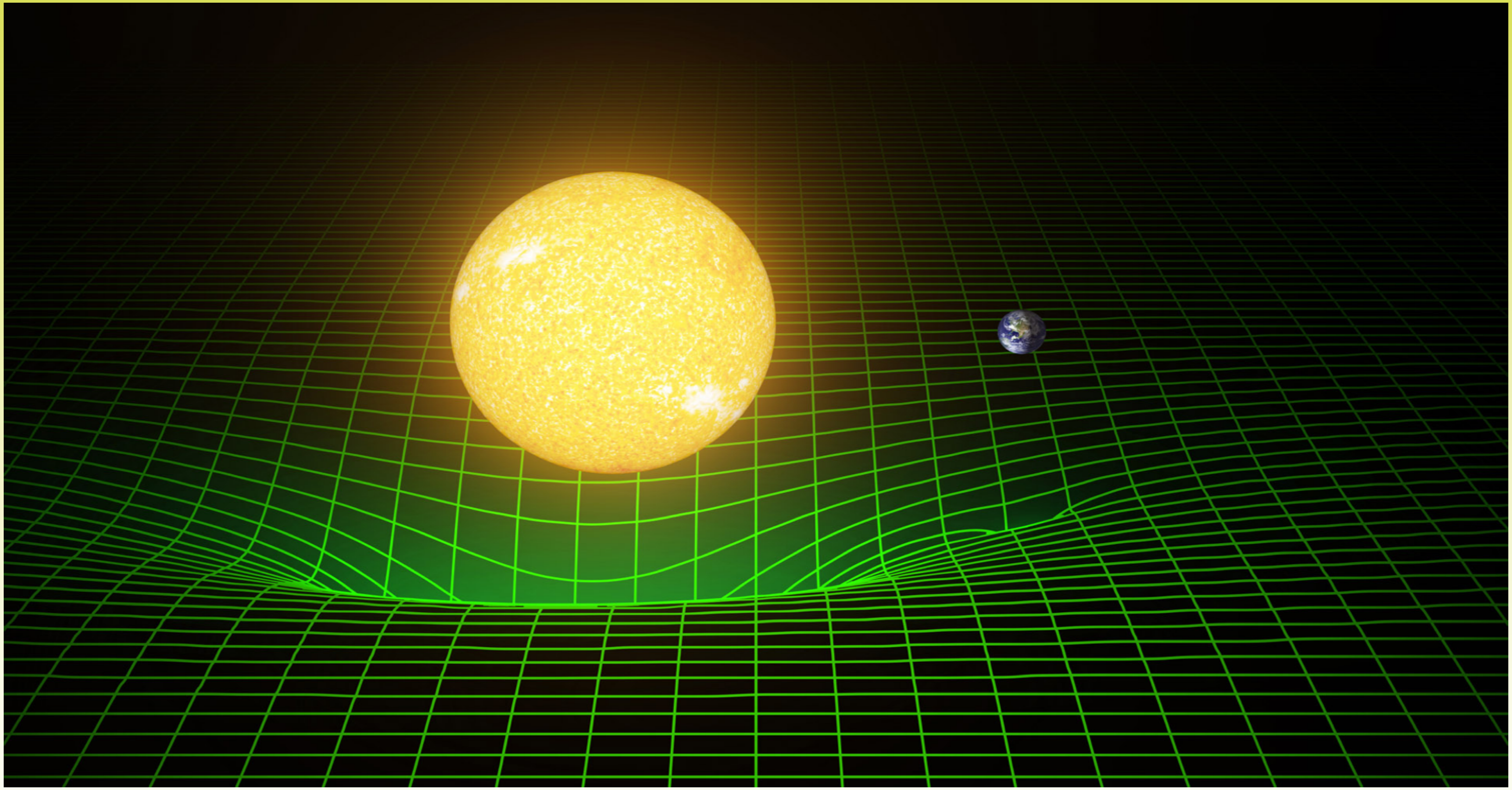
- Outer stars orbit spiral galaxies too fast for mass of visible stars
- Some 80% of matter appears to only interact with stars by gravity alone



General Relativity

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





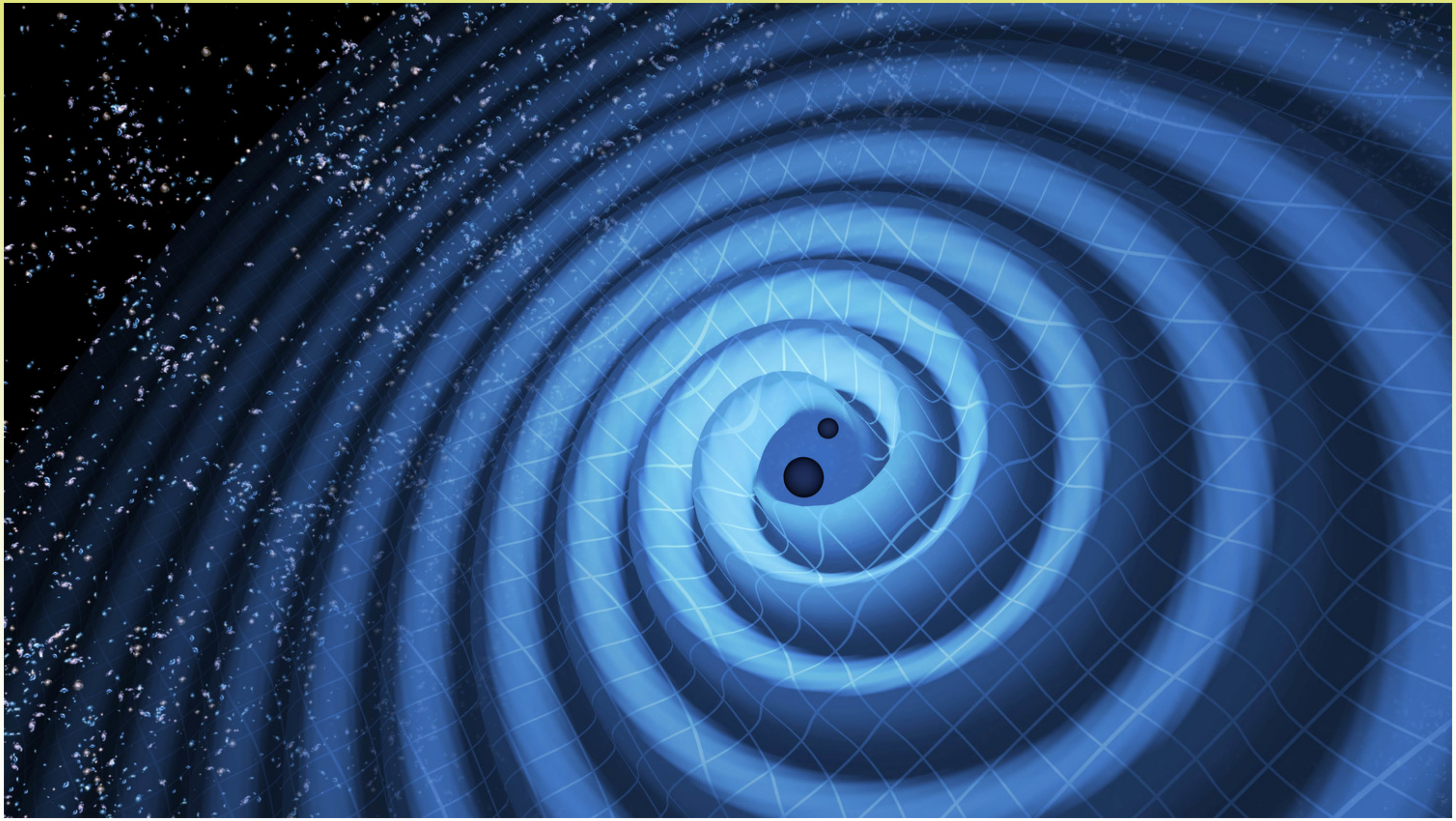
General Relativity has real-work effects:

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

Gravitational Waves (GW)

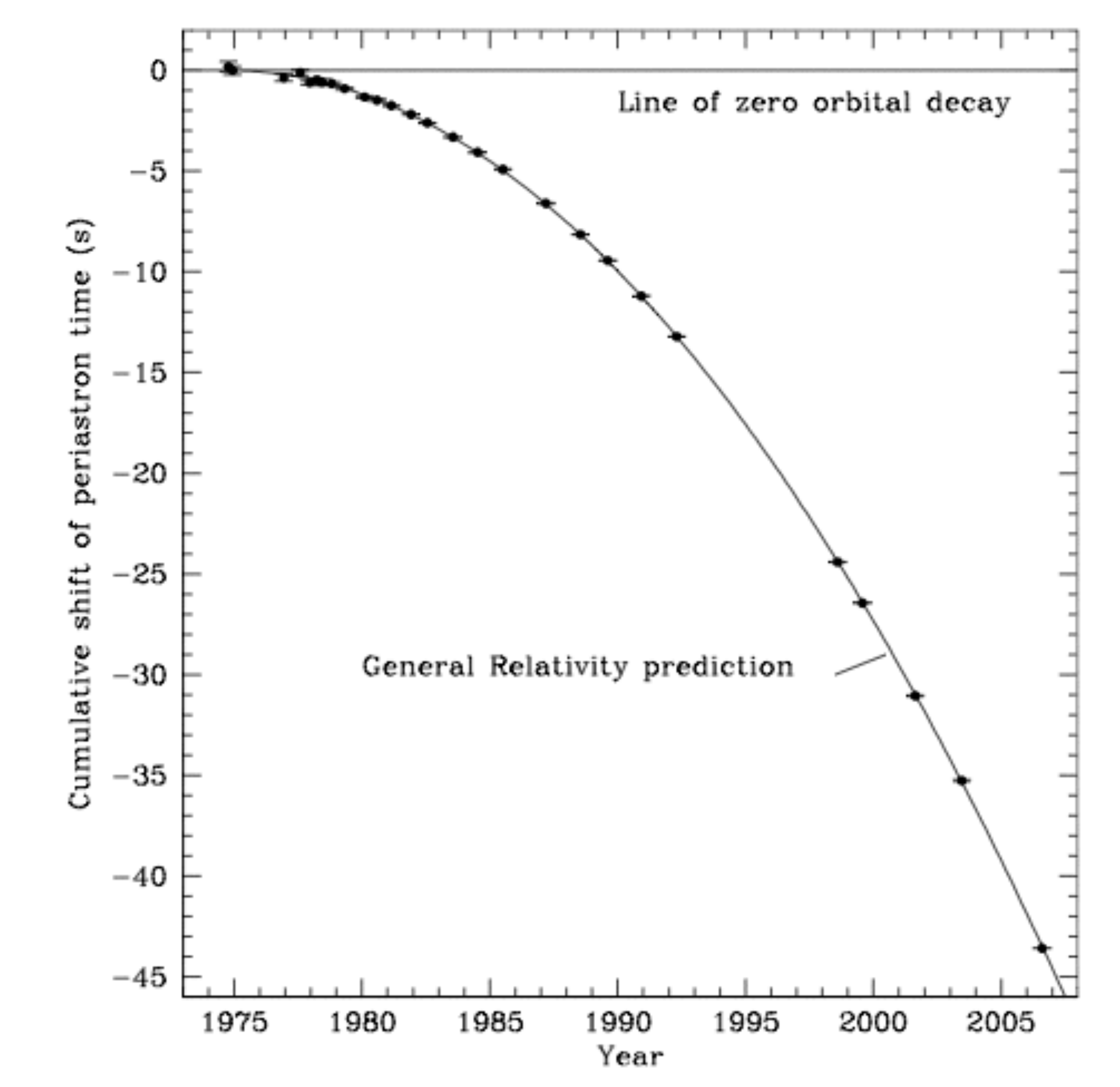
Einstein's general relativity also predicted

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

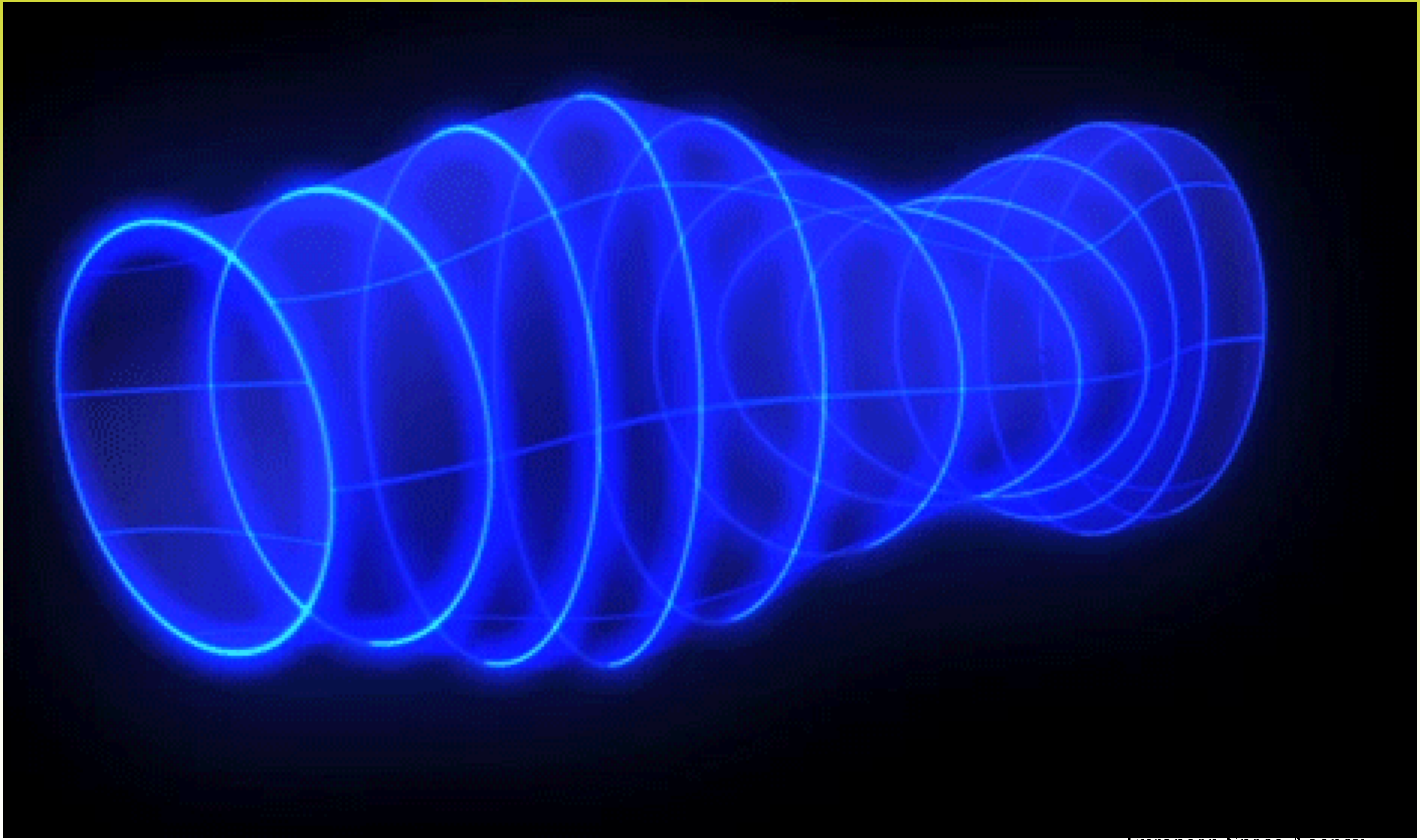


Any evidence for GW ?

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



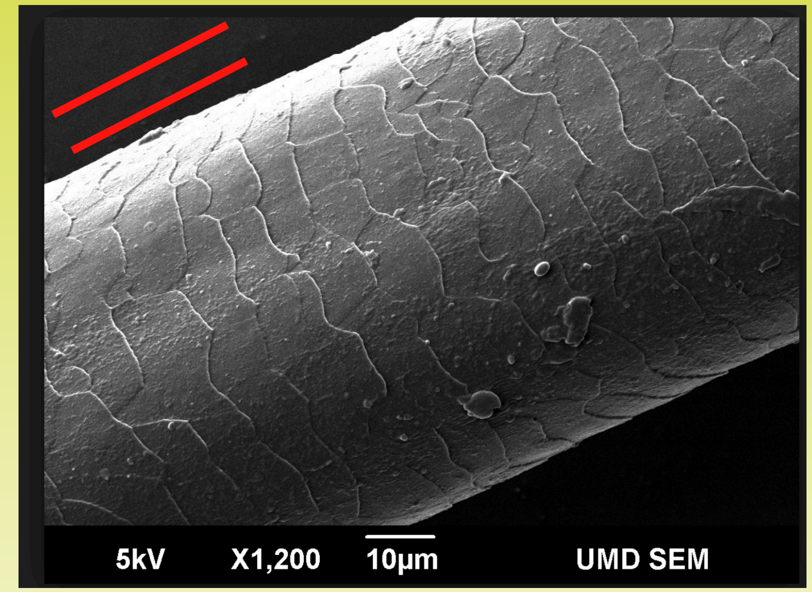
GW Propagation



European Space Agency

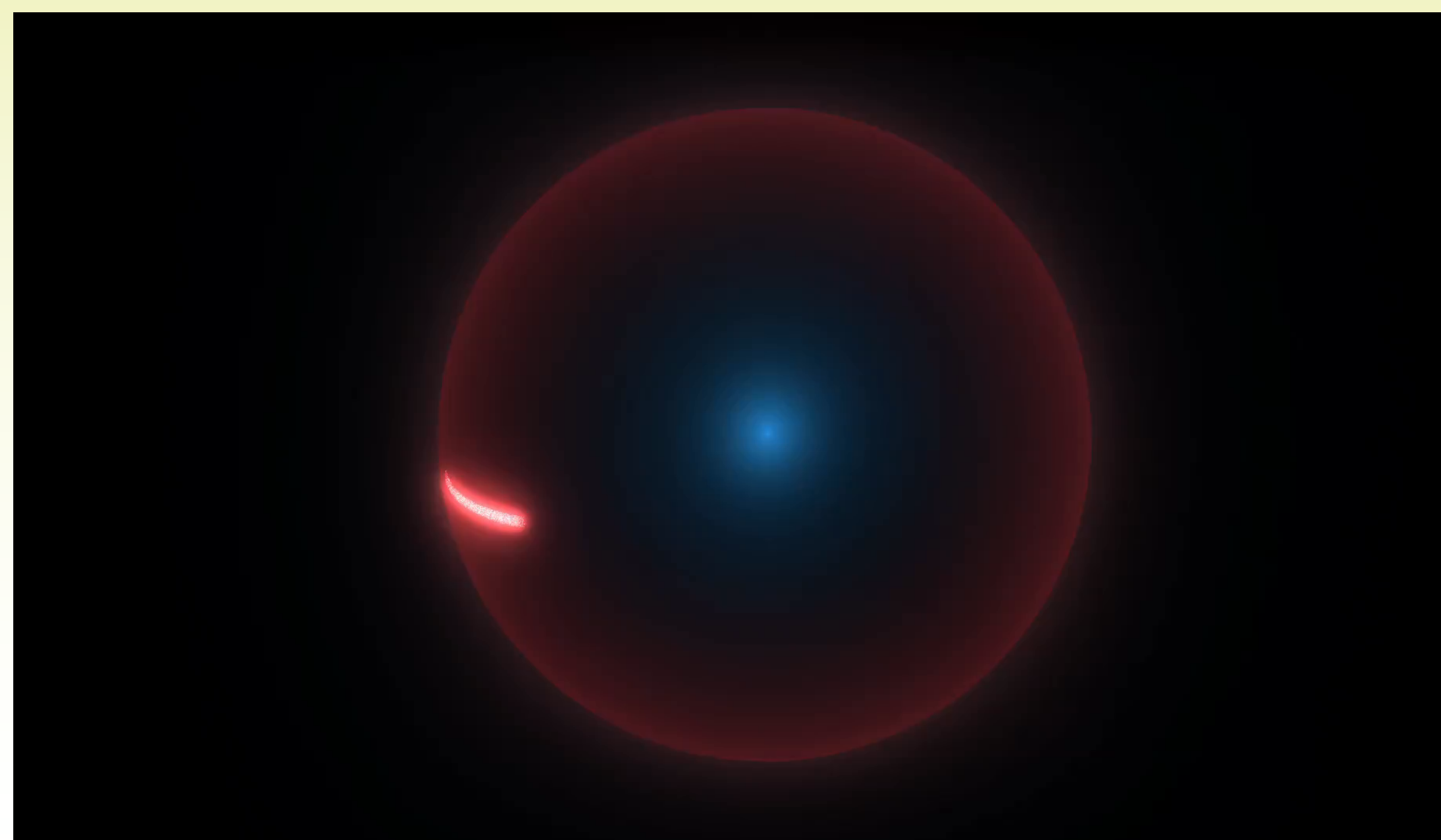
GW radiation at the Earth

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



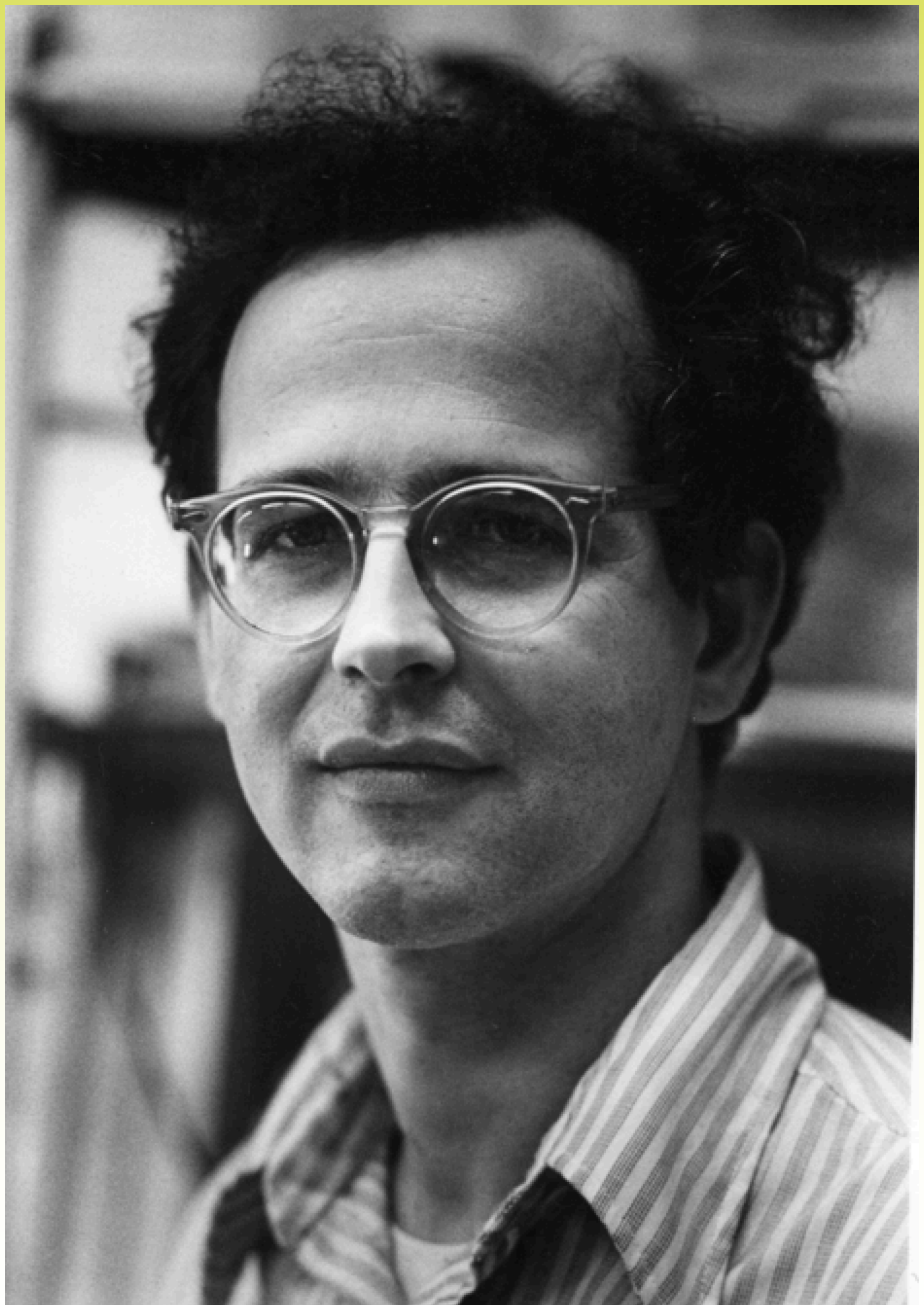
Divide that by a million

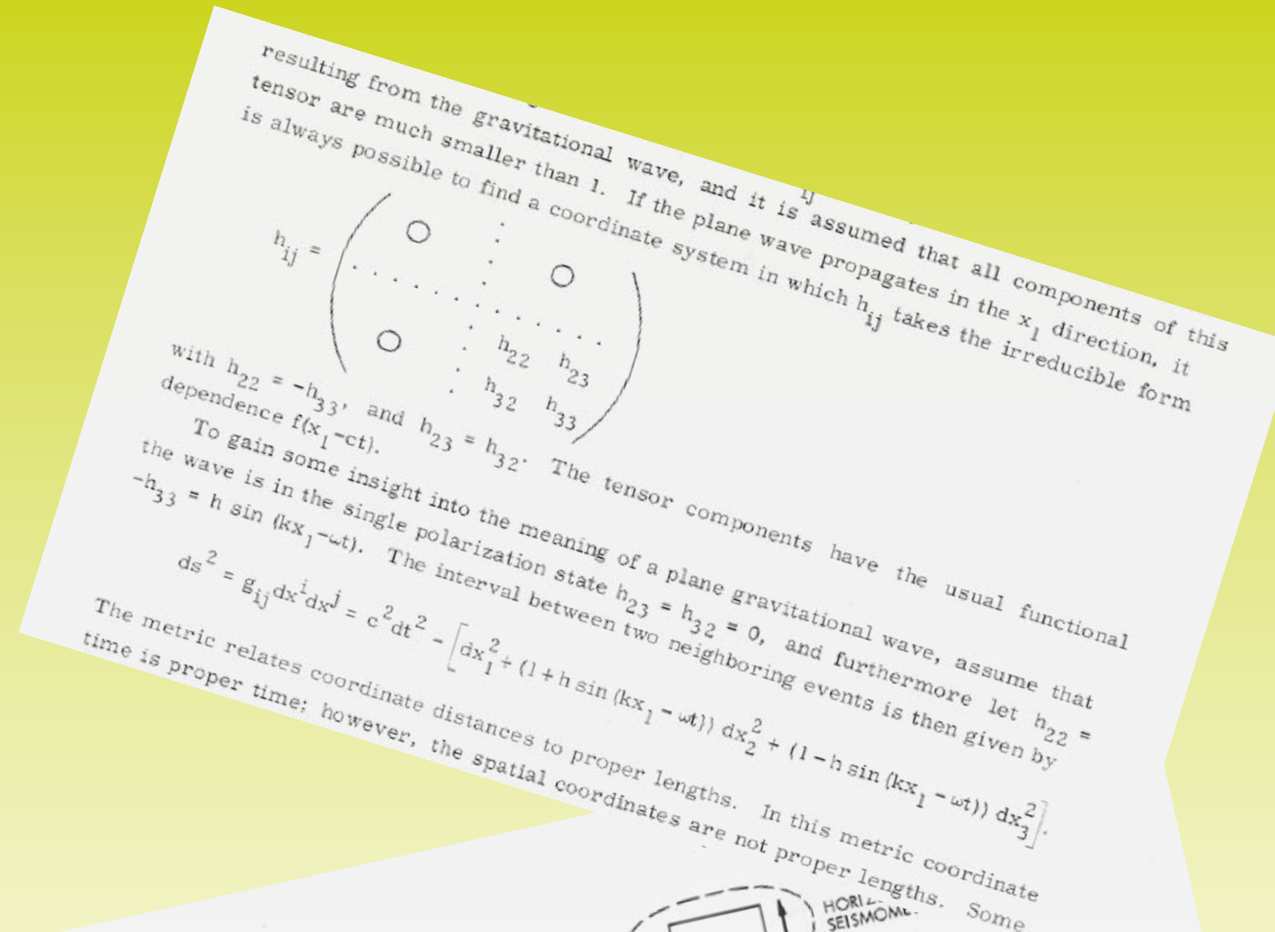
Divide that by a trillion
That's 10^{-21}m



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

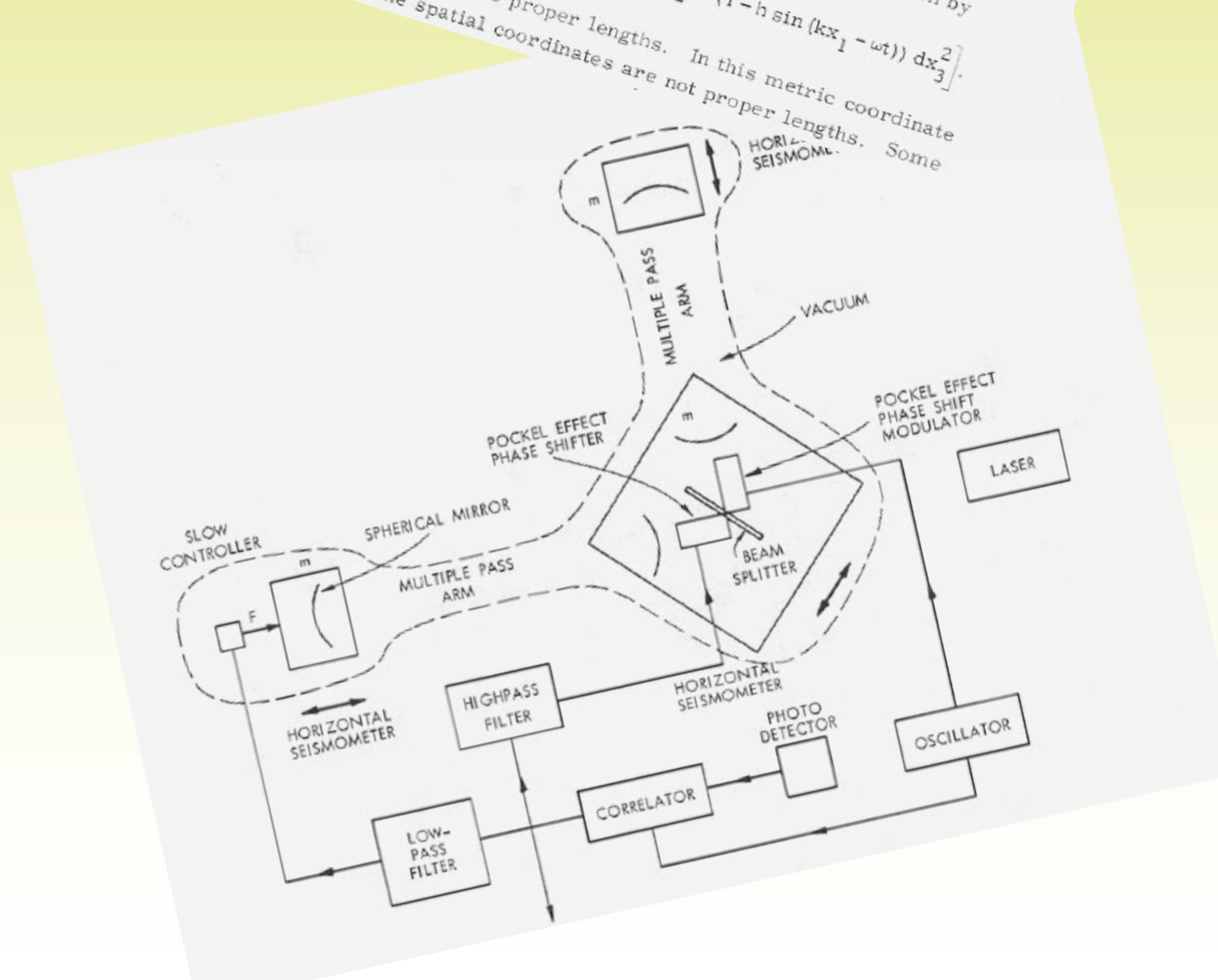
$$h_{ij} = \begin{pmatrix} 0 & \vdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \vdots & \begin{matrix} h_{22} & h_{23} \\ h_{32} & h_{33} \end{matrix} \end{pmatrix}$$

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

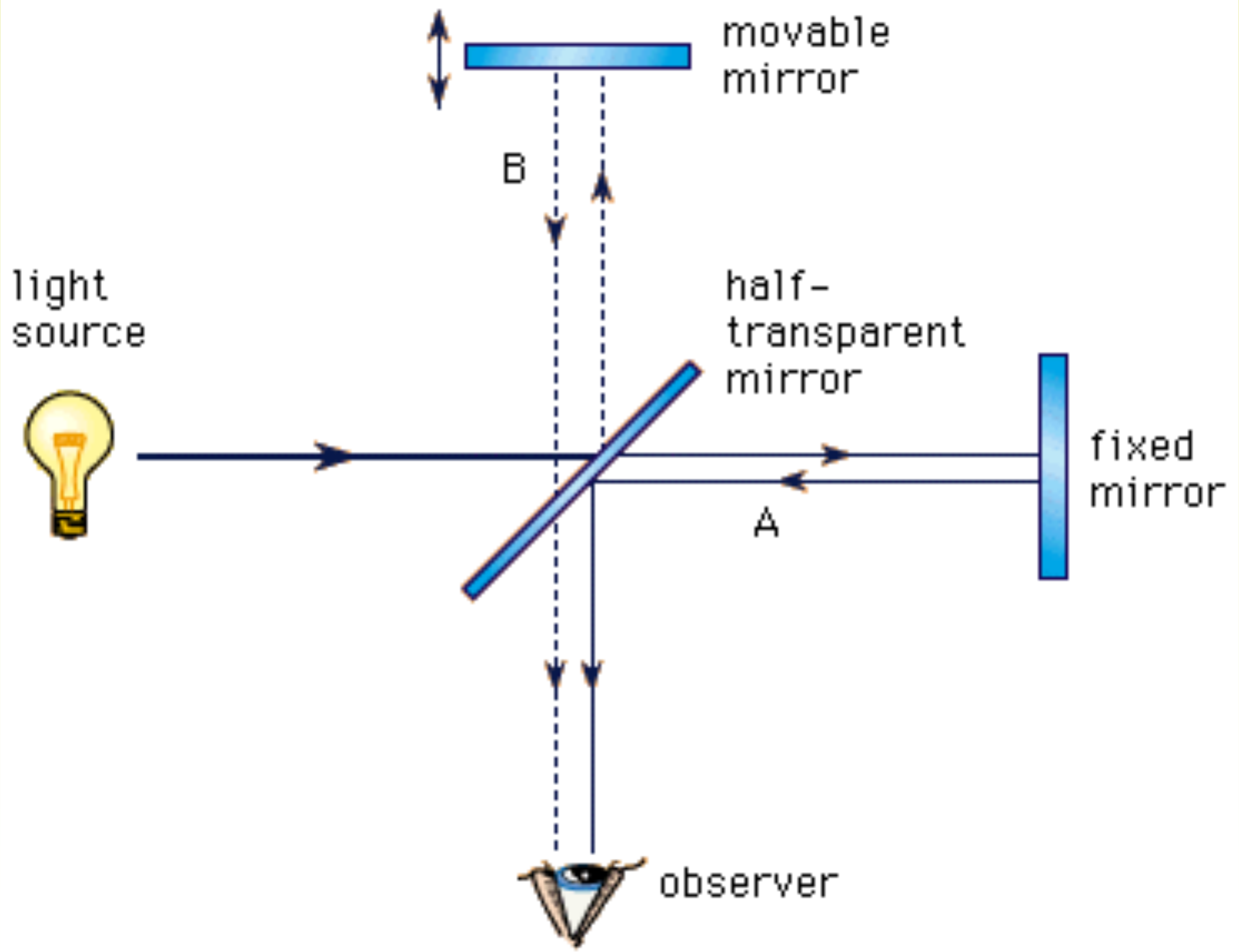
$$ds^2 = g_{ij} dx^i dx^j = c^2 dt^2 - \left[dx_1^2 + (1 + h \sin (kx_1 - \omega t))\, dx_2^2 + (1 - h \sin (kx_1 - \omega t))\, dx_3^2\right].$$

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 ~1/100 wavelength - 5 nm (10^{-9} m)



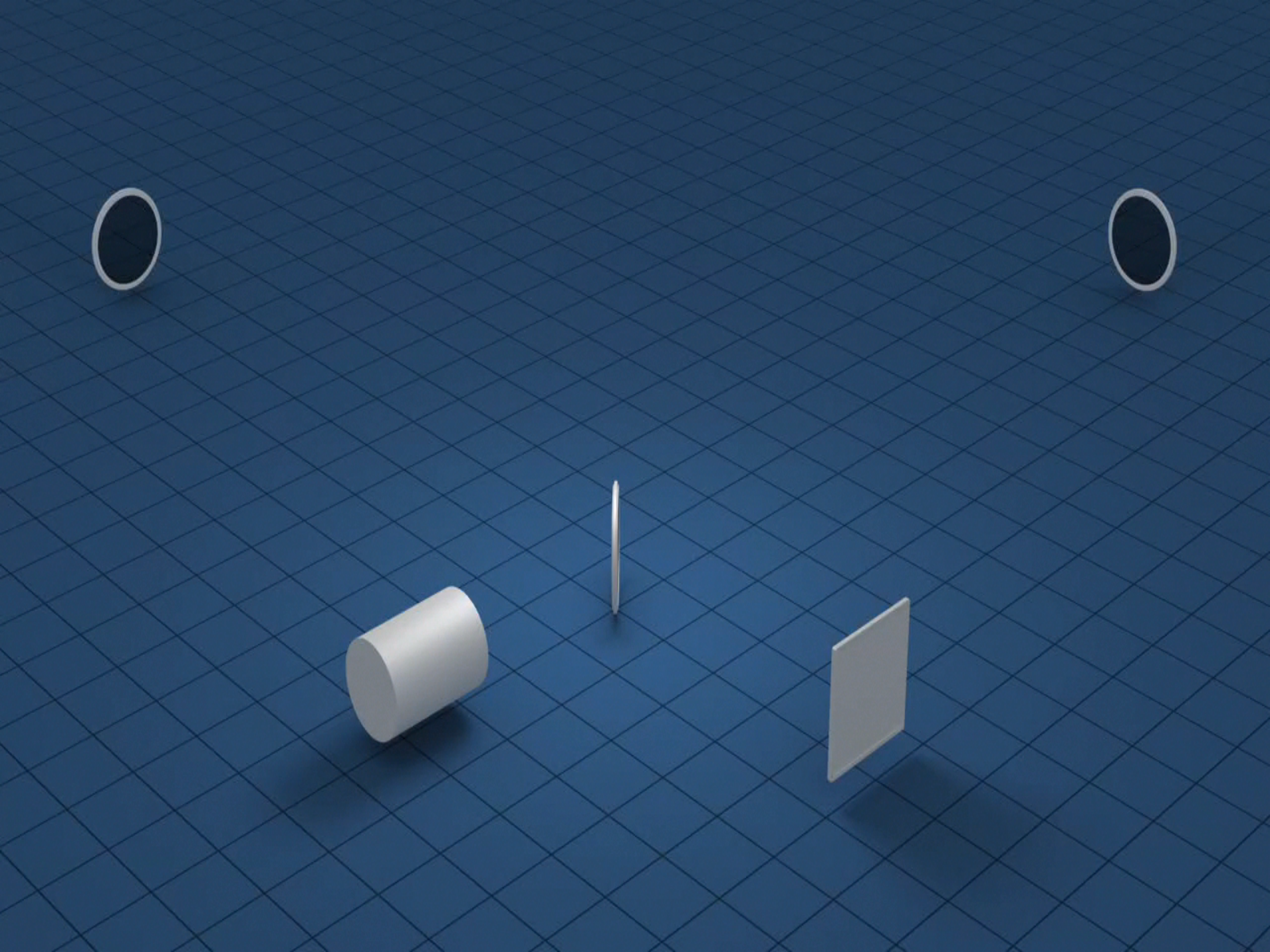
Laser Interferometer

- Properties of laser light
  - Single frequency
  - Same phase (coherent)

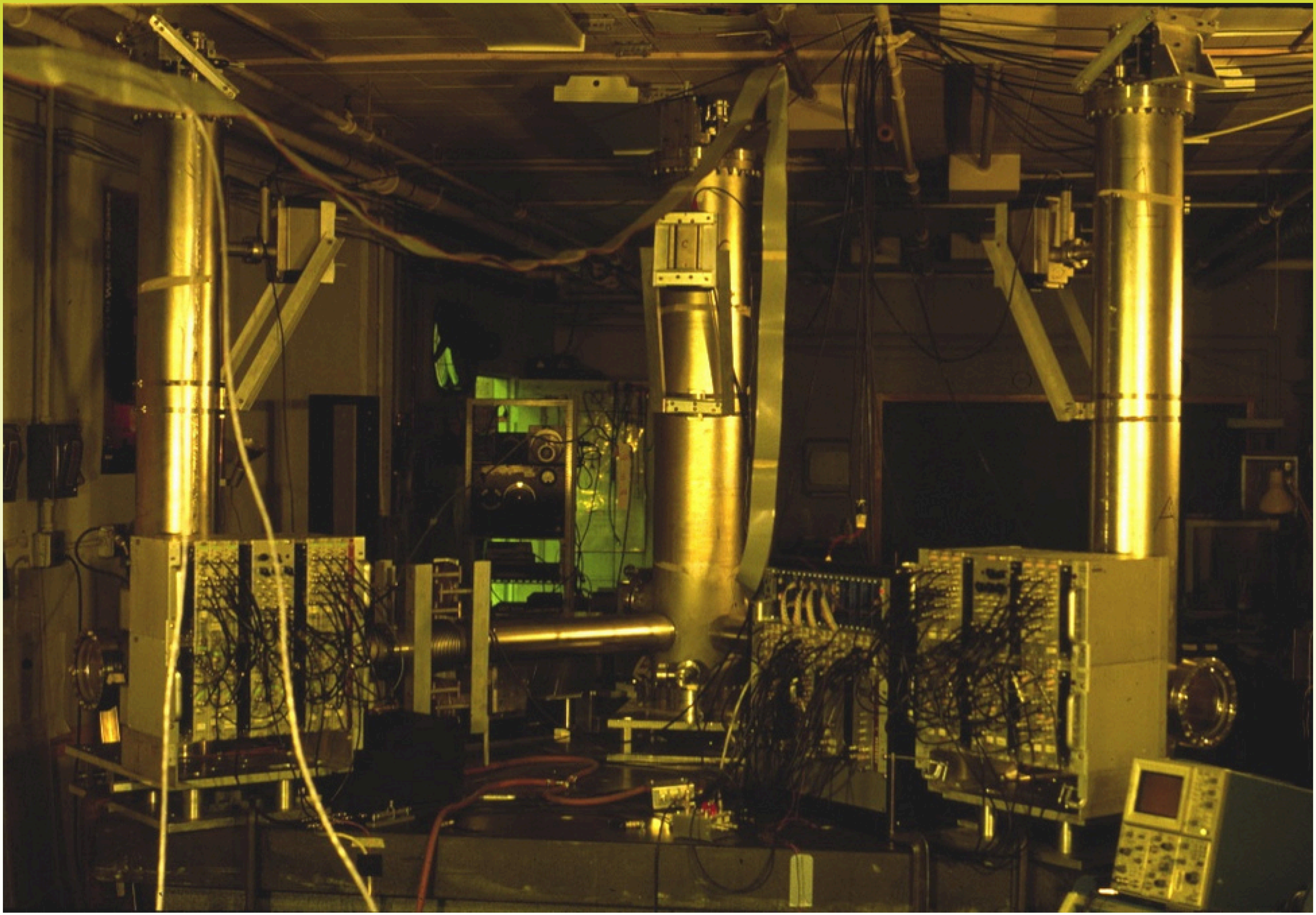
- With feedback, precisely control
  - Laser intensity (brightness)
  - Laser frequency

-> We can get nearly perfect interference

- Measure much smaller displacement



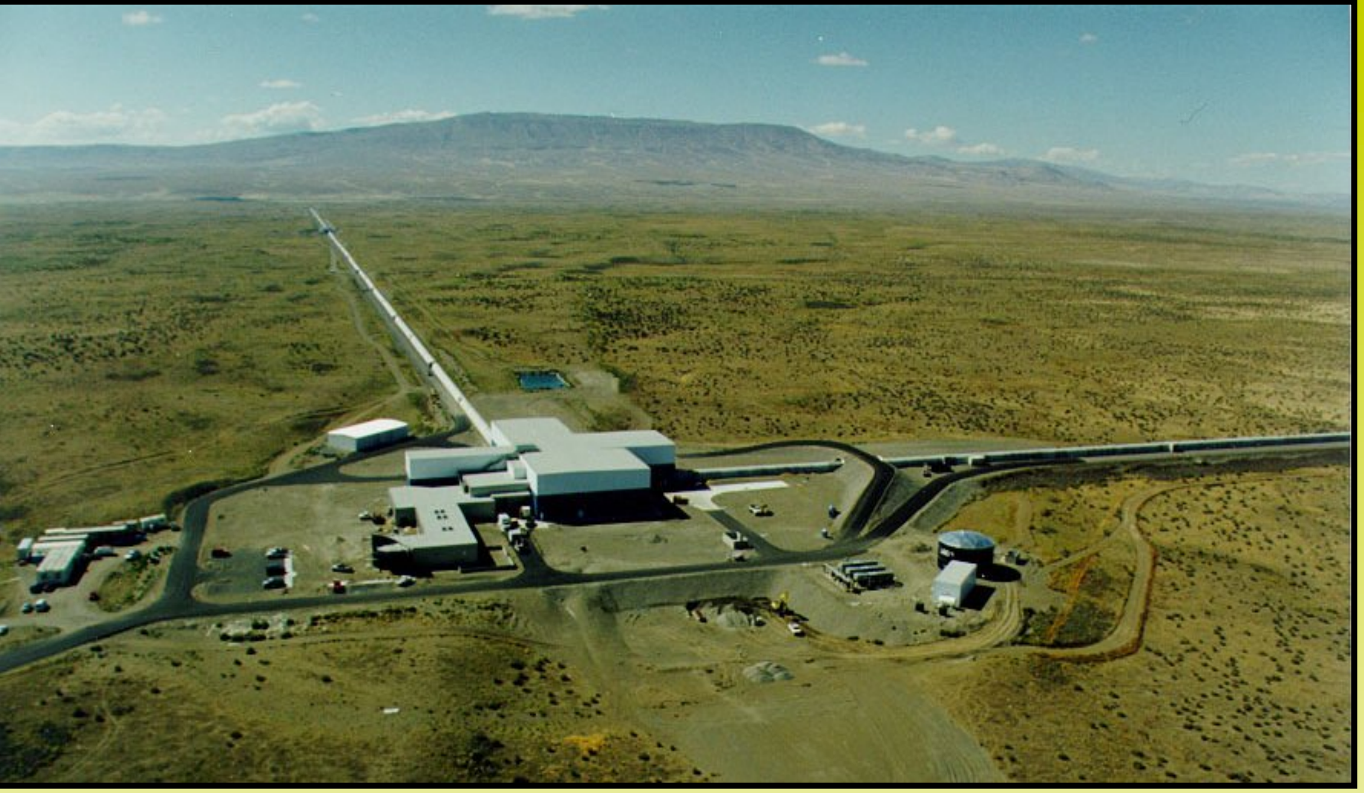
Desktop Laser Interferometer (MIT)

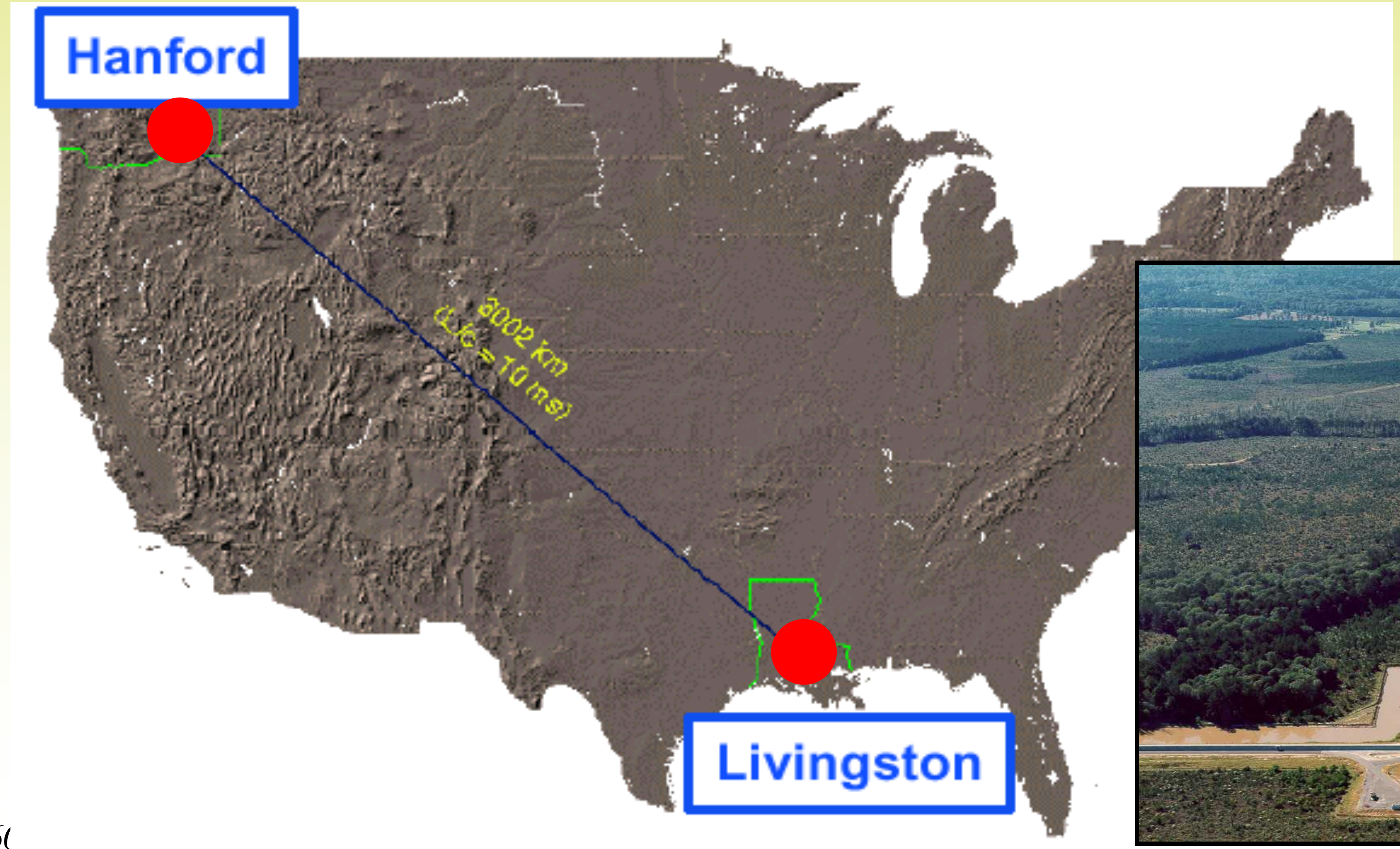


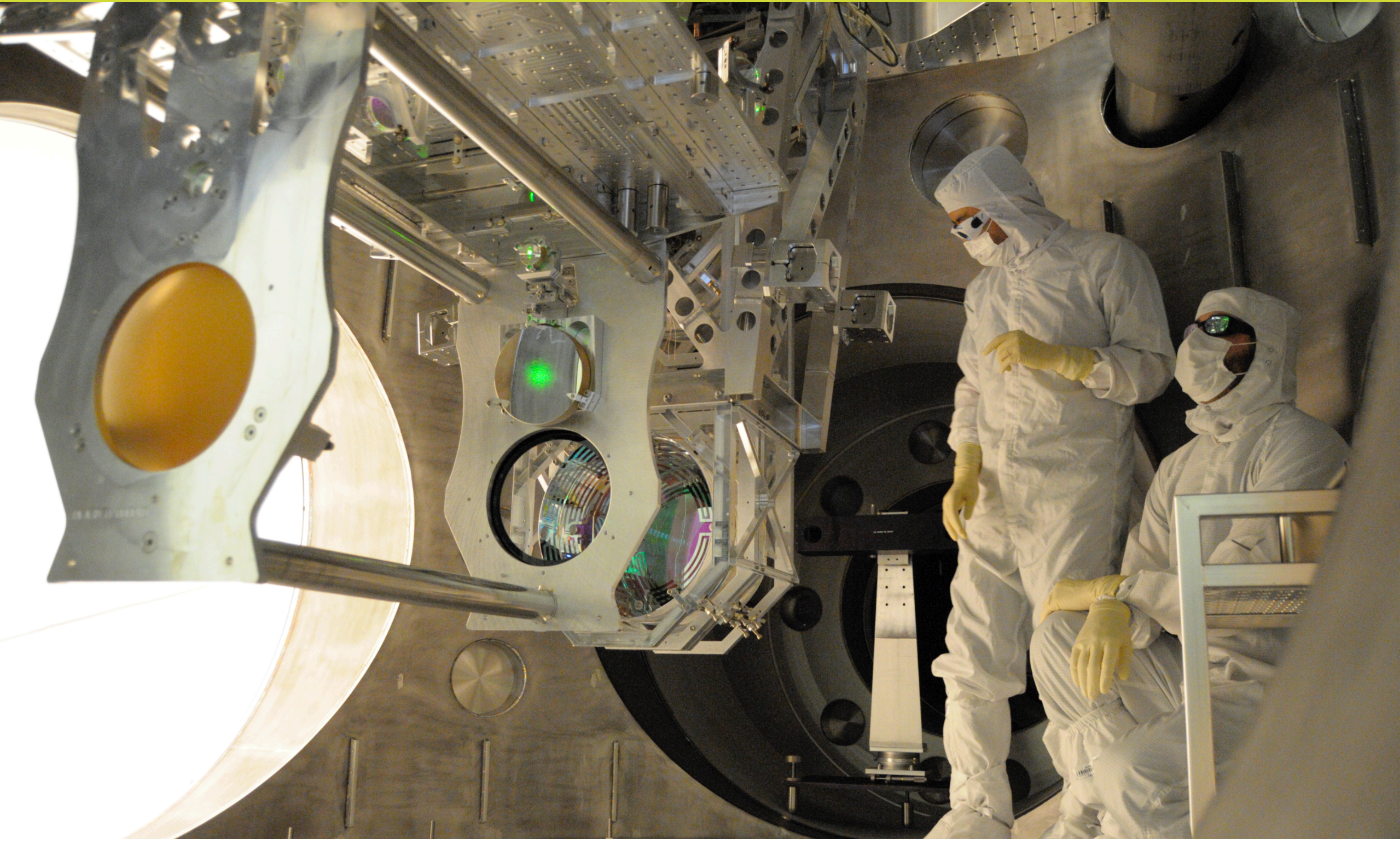

LIGO Livingston

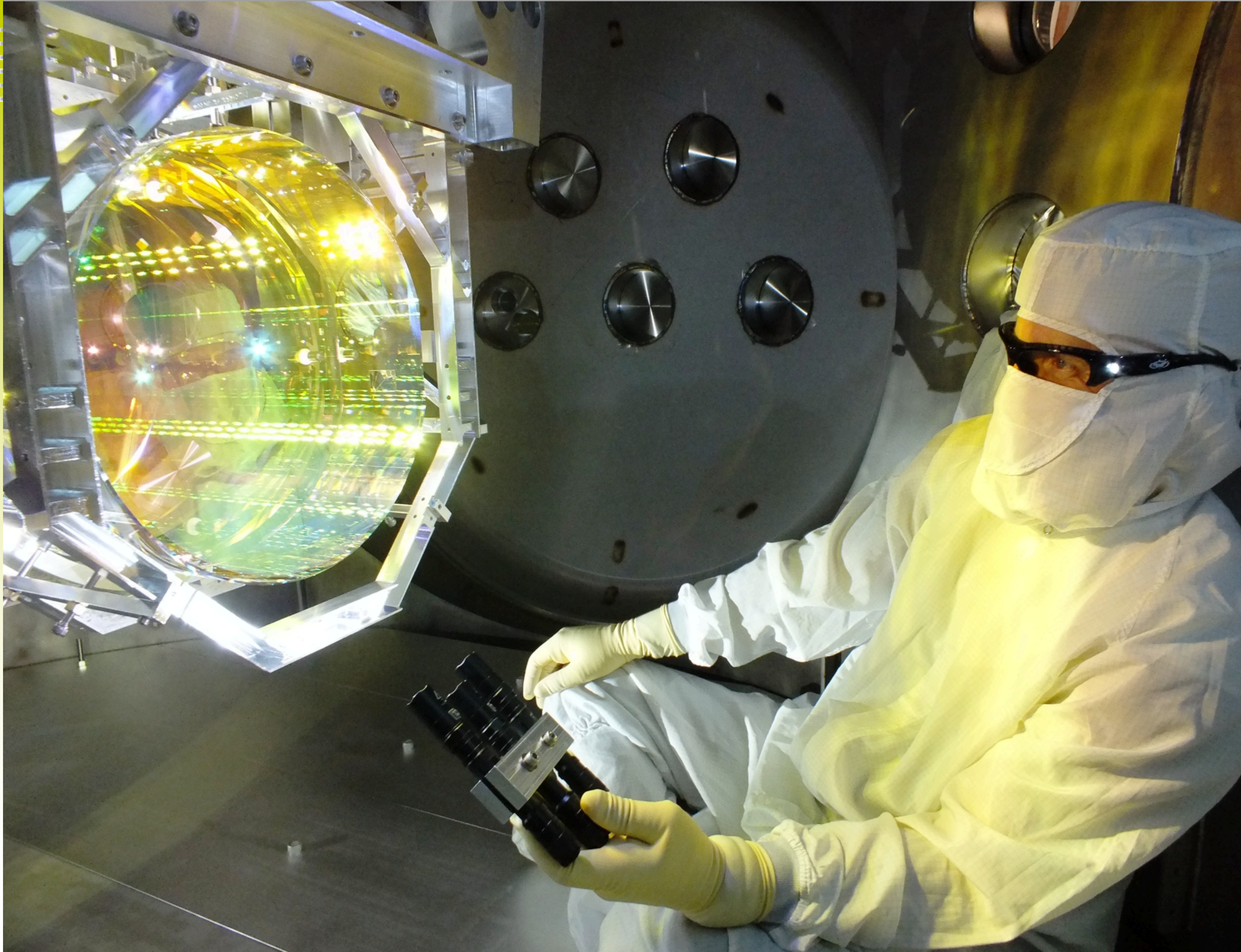
4 km long beam tubes – Vacuum 10^{-9} Torr

LIGO Laboratory Observatories; Operated by Caltech, MIT for NSF

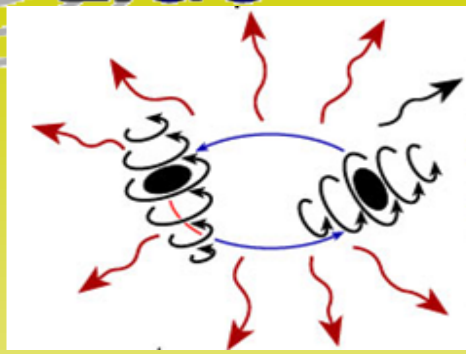
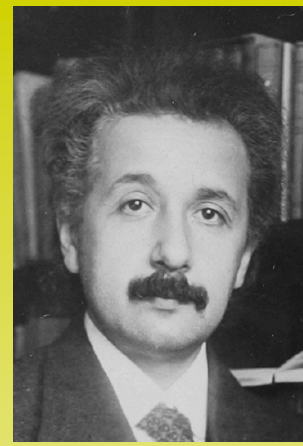
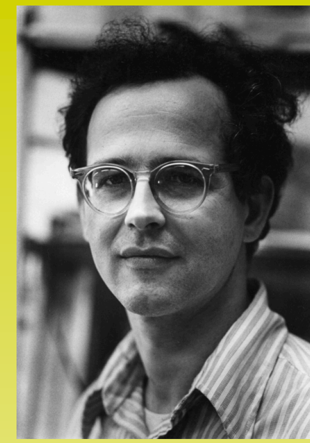









9:03
PACIFIC
11:03
CENTRAL
17:03
GMT
DARM NOISE
ISC
OMC NOISE
ALS / ISC
AS / IMC
PRC / IMC
MICH / PRC
ITMX
PSL BEAMS


1.3 Billion years after the Black Holes merged..

100 years after Einstein predicted gravitational waves…

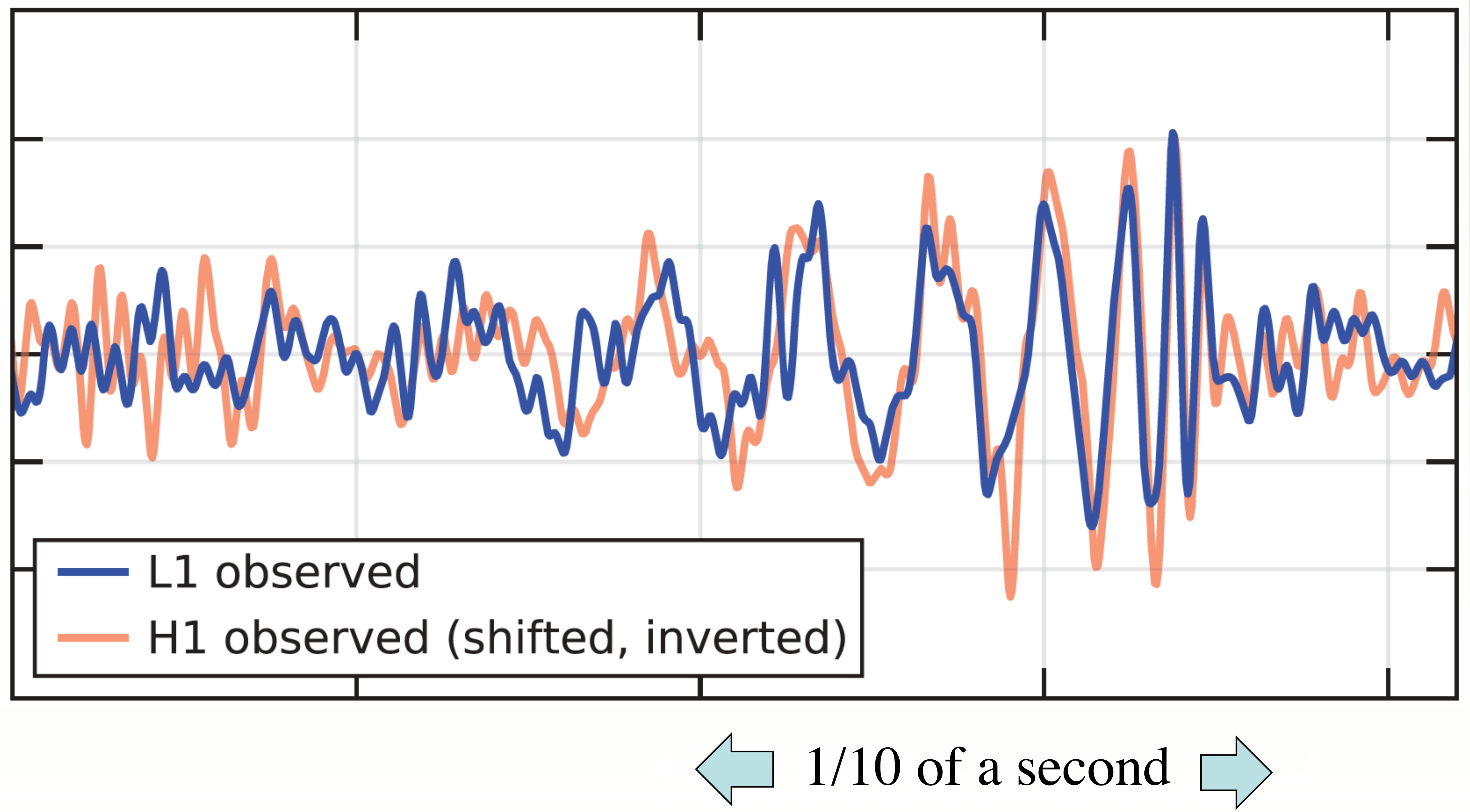
50 years after Rai Weiss invented the detectors...

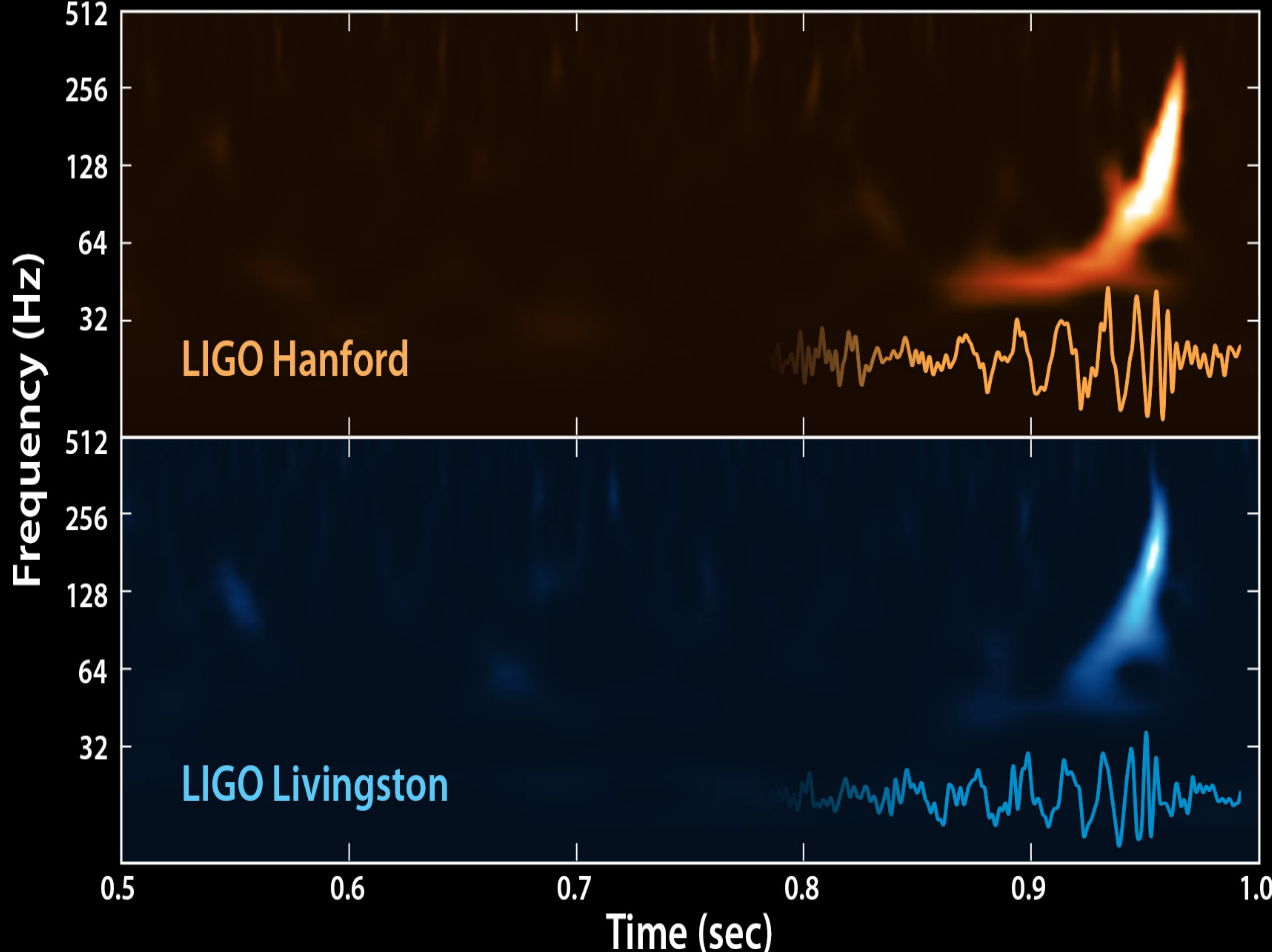
20 years after the NSF, MIT, and Caltech Founded LIGO...

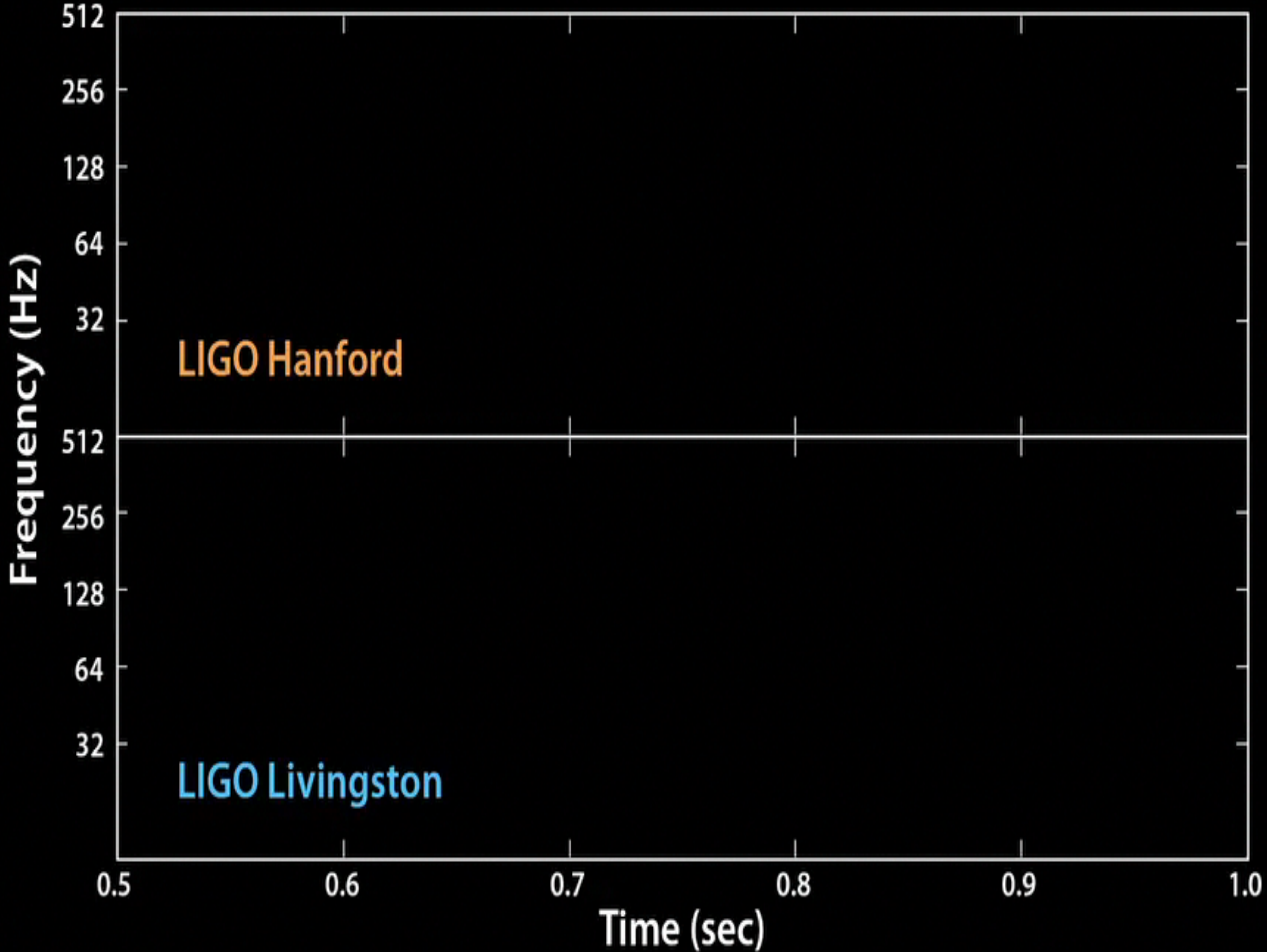
10 years after Advanced LIGO got the ok...

6 months after starting detector tuning...

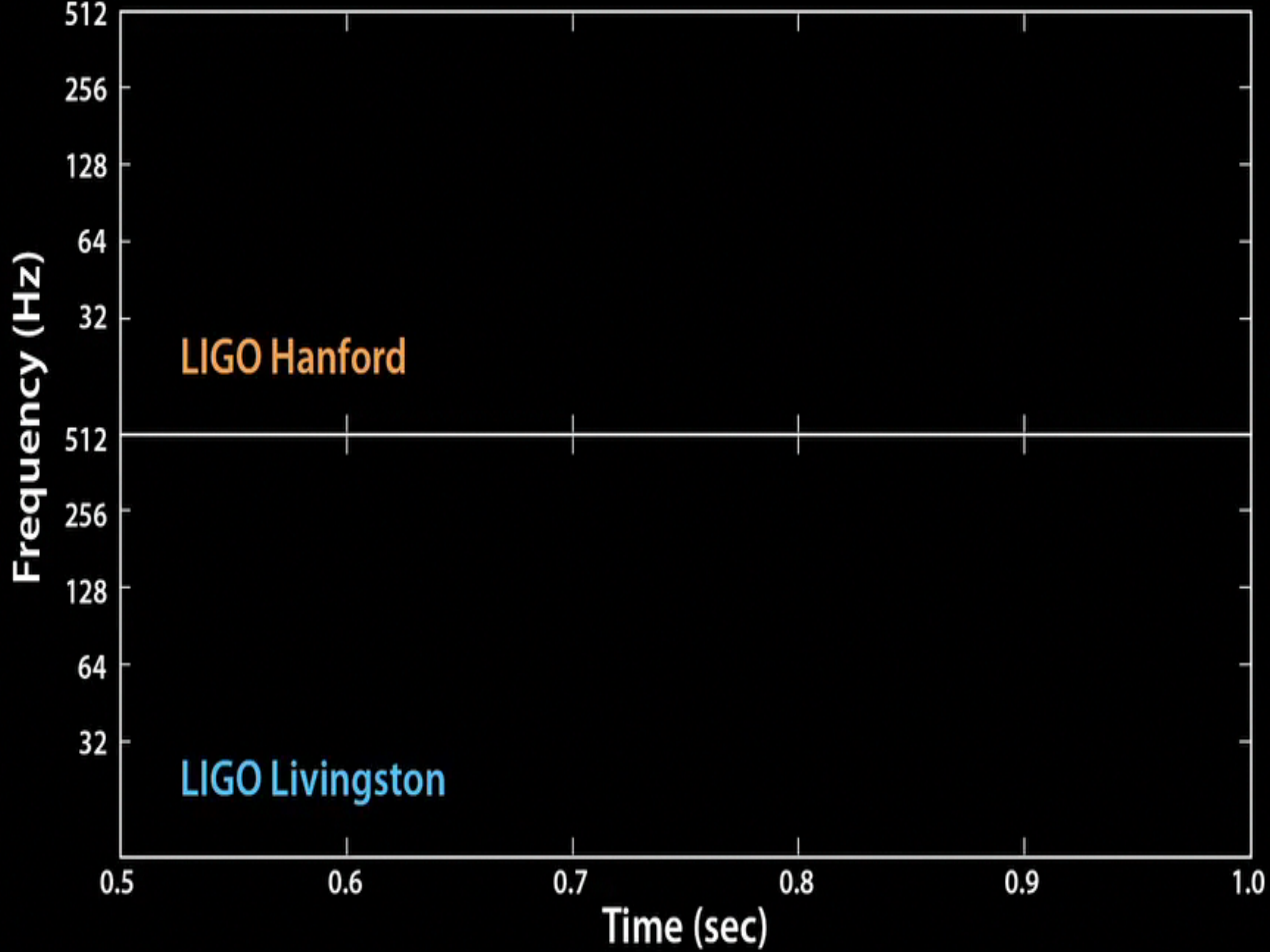
September 14, 2015 at 05:51 EDT: Cosmic Rendezvous




512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

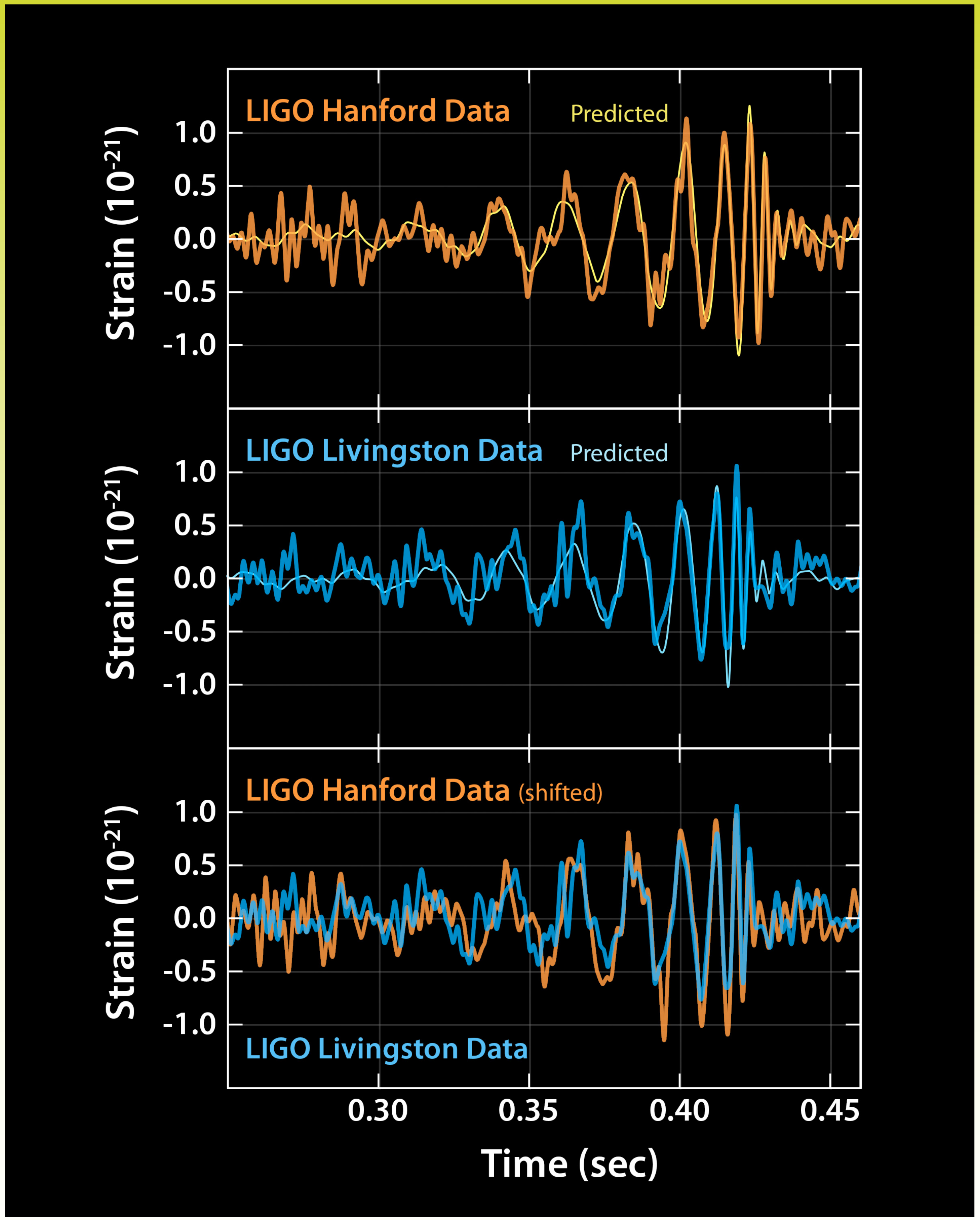
Confirmation of General Relativity

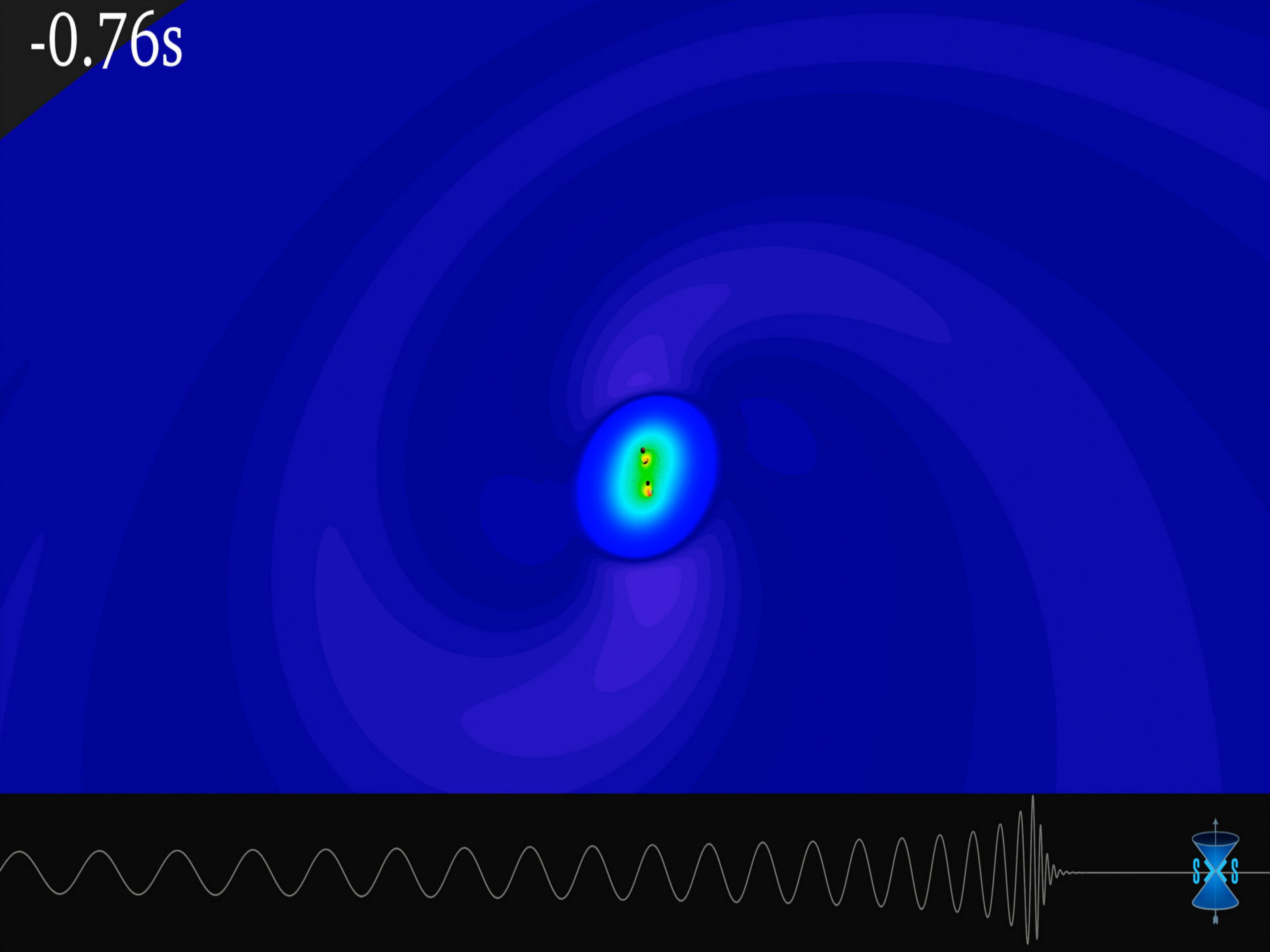
1.3 Billion Years Ago:

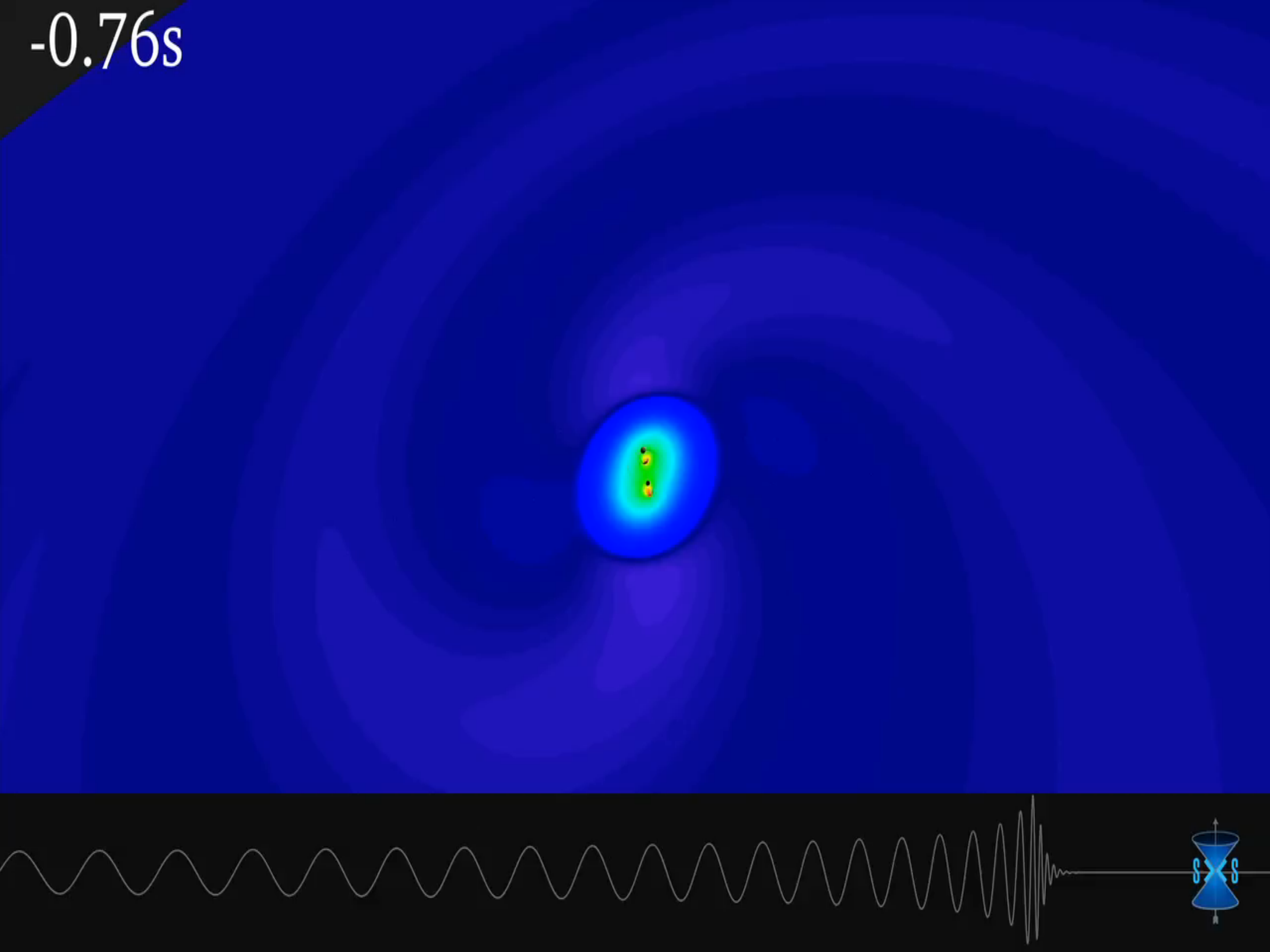
Two Massive Black Holes
29 M_{sun} x 35 M_{sun}

Merged 62 M_{sun} Black Hole

-> 3 M_{sun} converted to GWs !

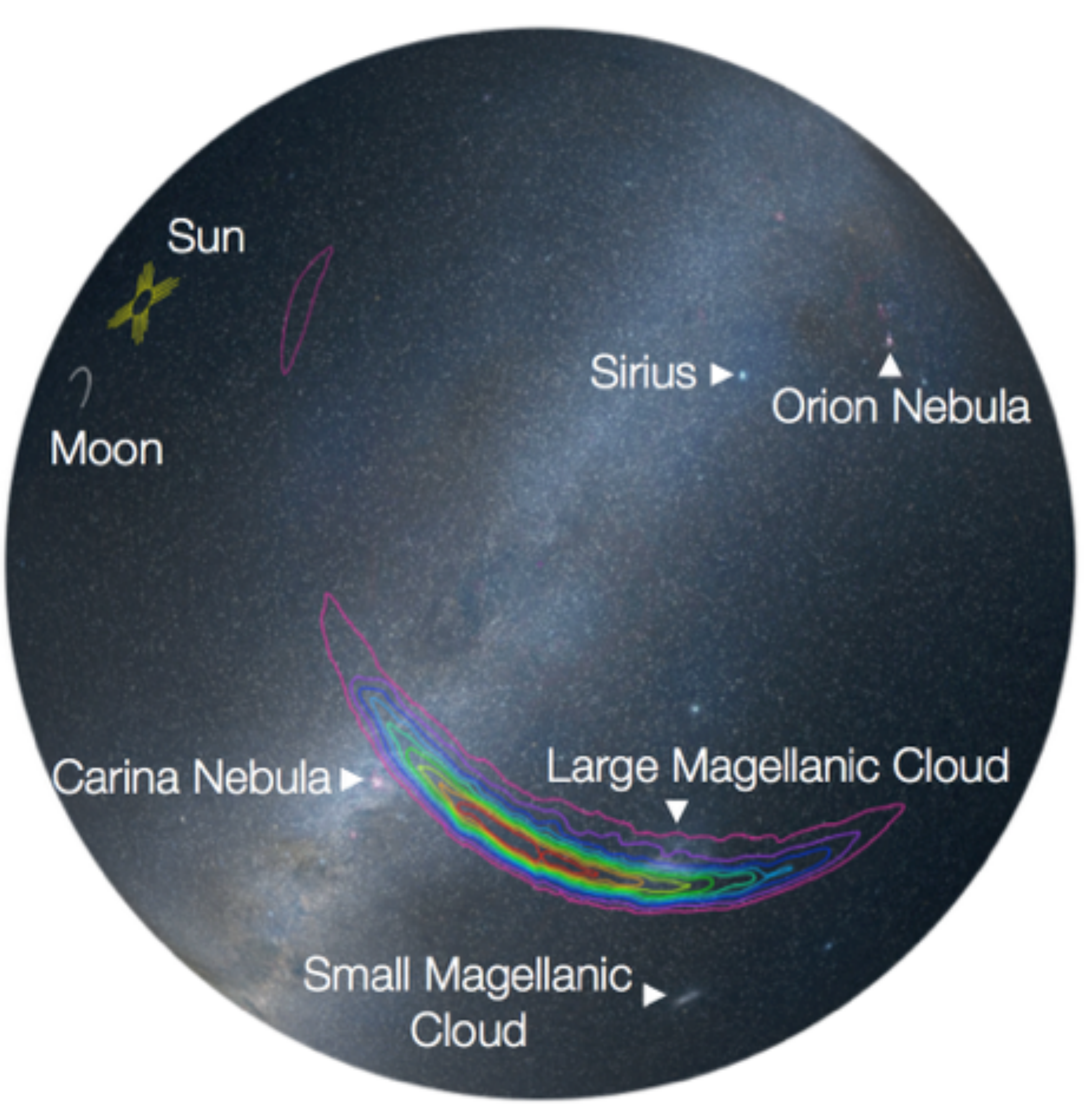



-0.76s


-0.76s

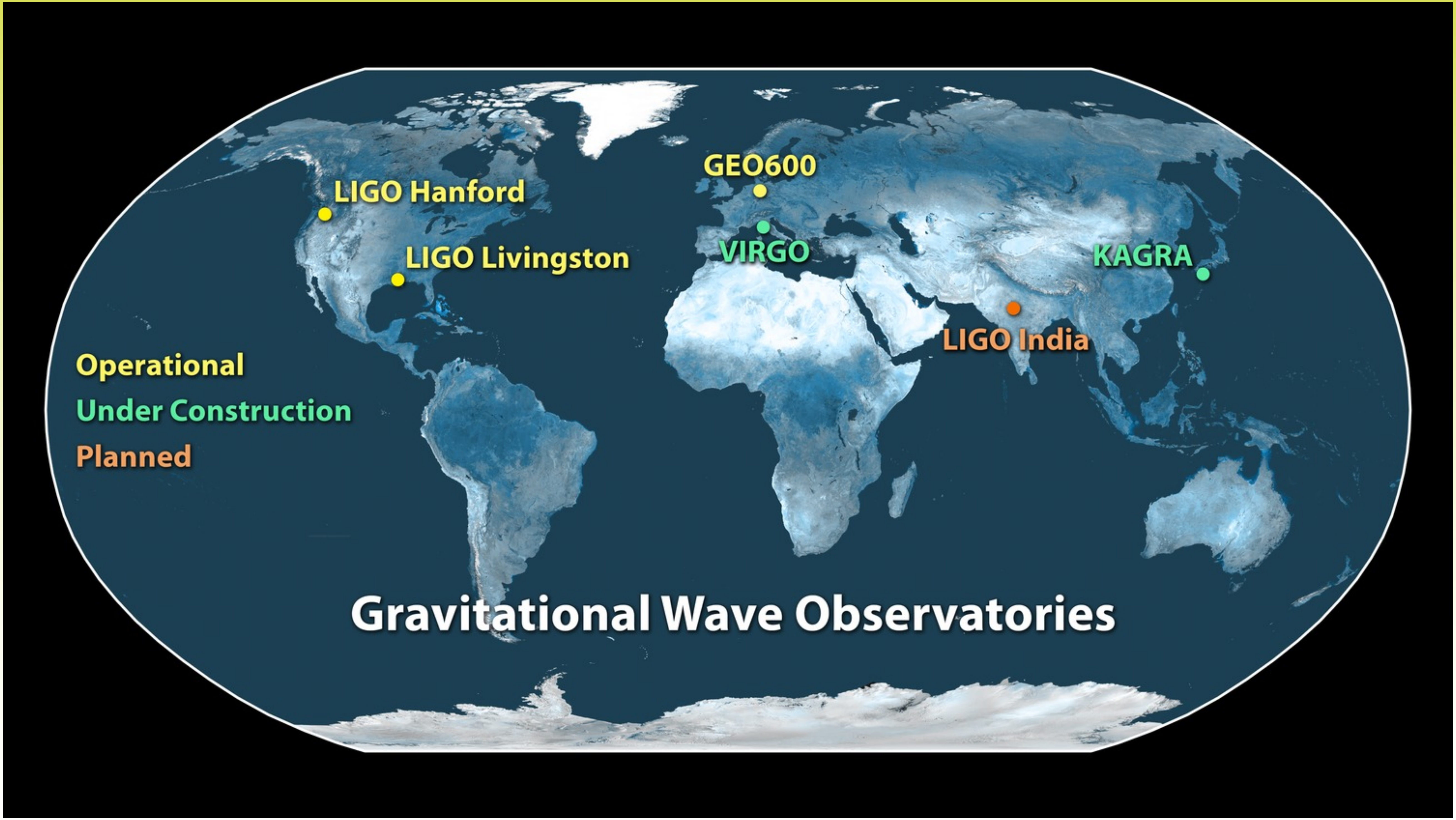
GW150914 Localization

With only two instruments, location is imprecise



GW Observatory Network

Can’t focus GWs, need many ‘ears’ to triangulate



GW in Space: LISA