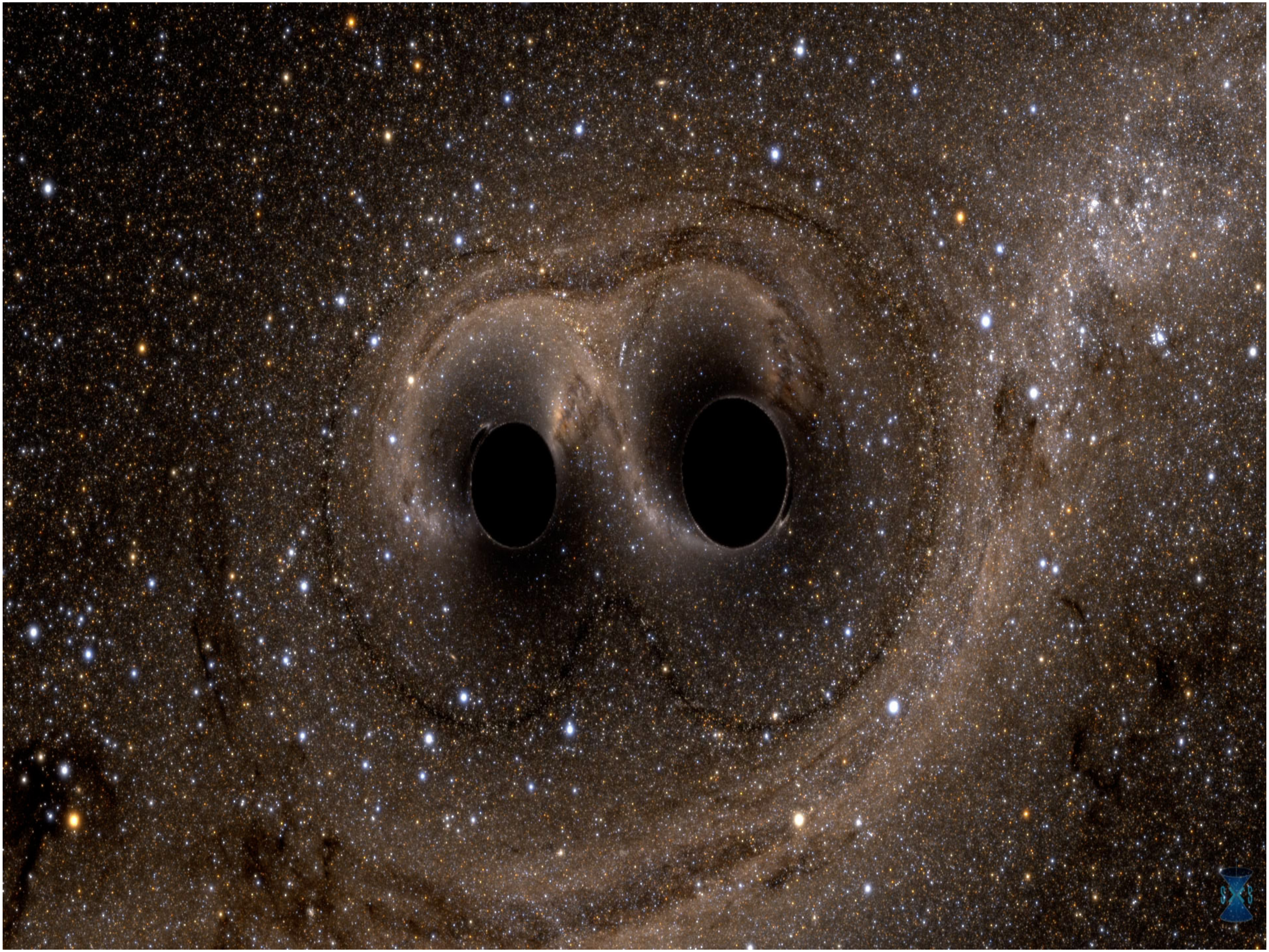
LIGO's discovery of gravitational waves and observation of black holes

NEAF

2016-04-09 2016

G1600842

David Shoemaker
For the LIGO and Virgo Scientific Collaborations



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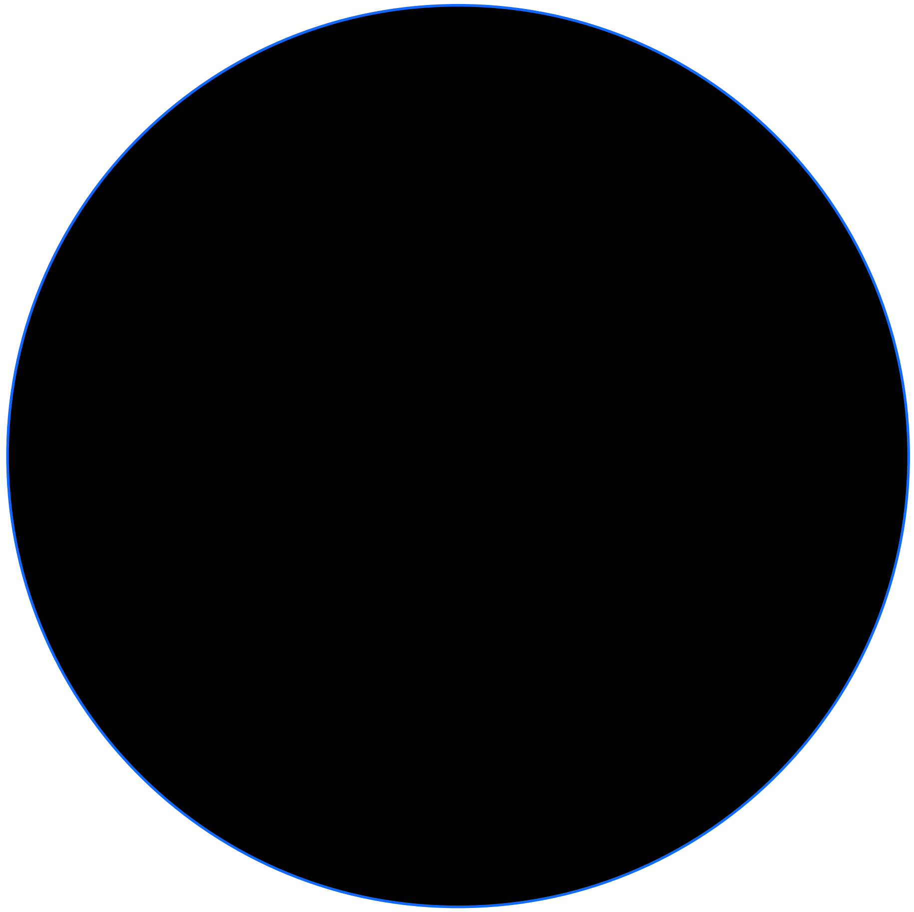
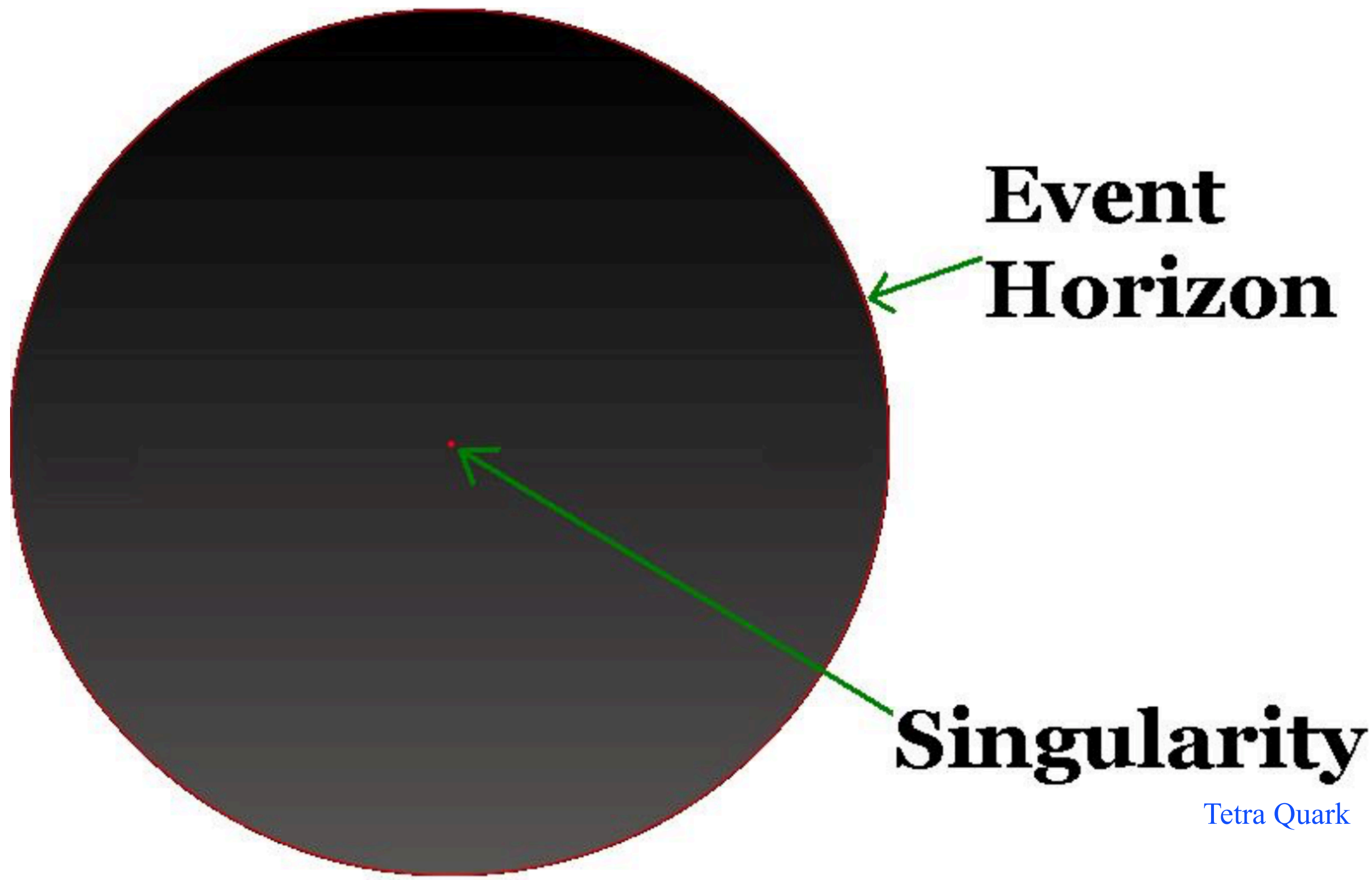
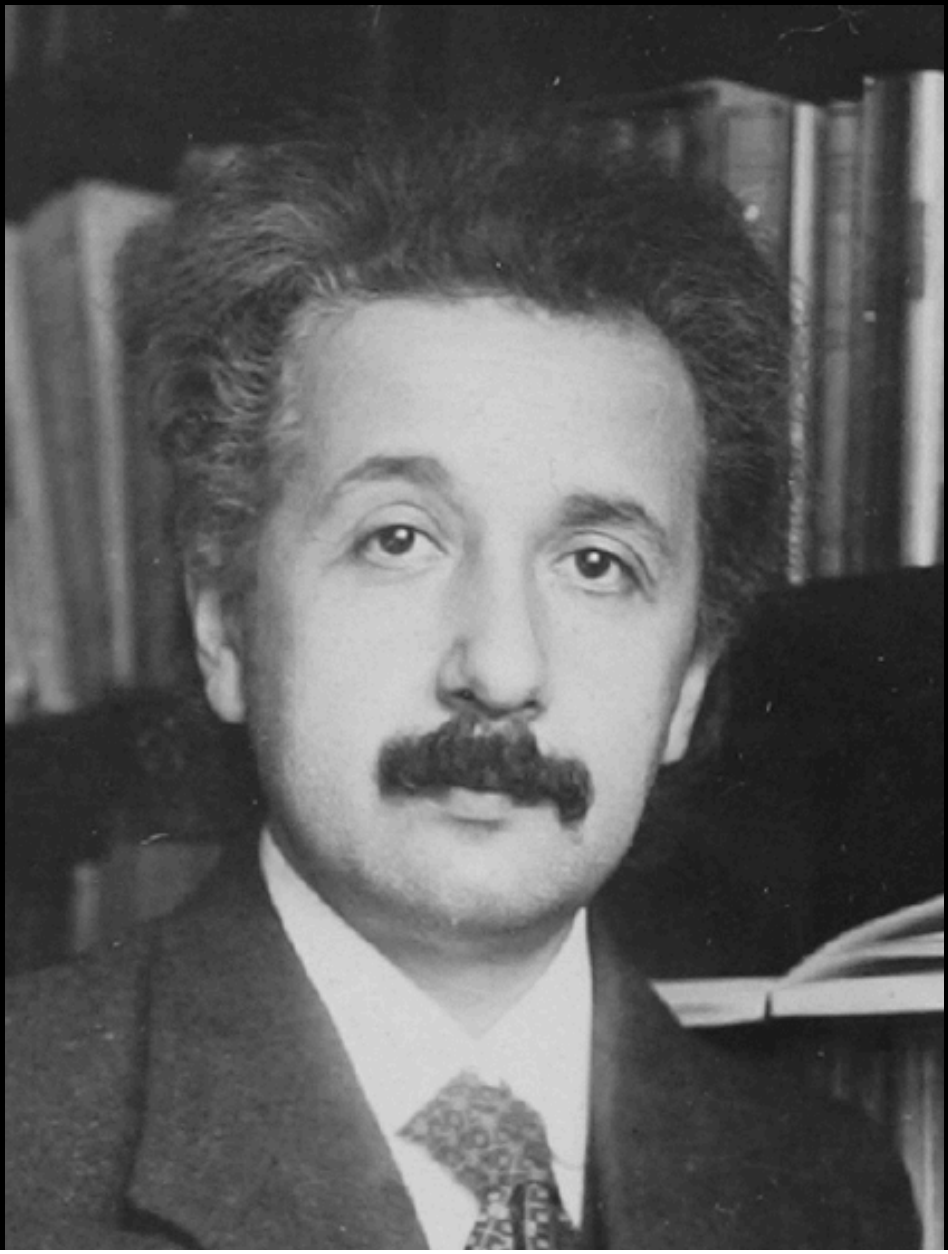



Event
Horizon
Singularity
Tetra Quark

Hevelius, contemporary of Galileo

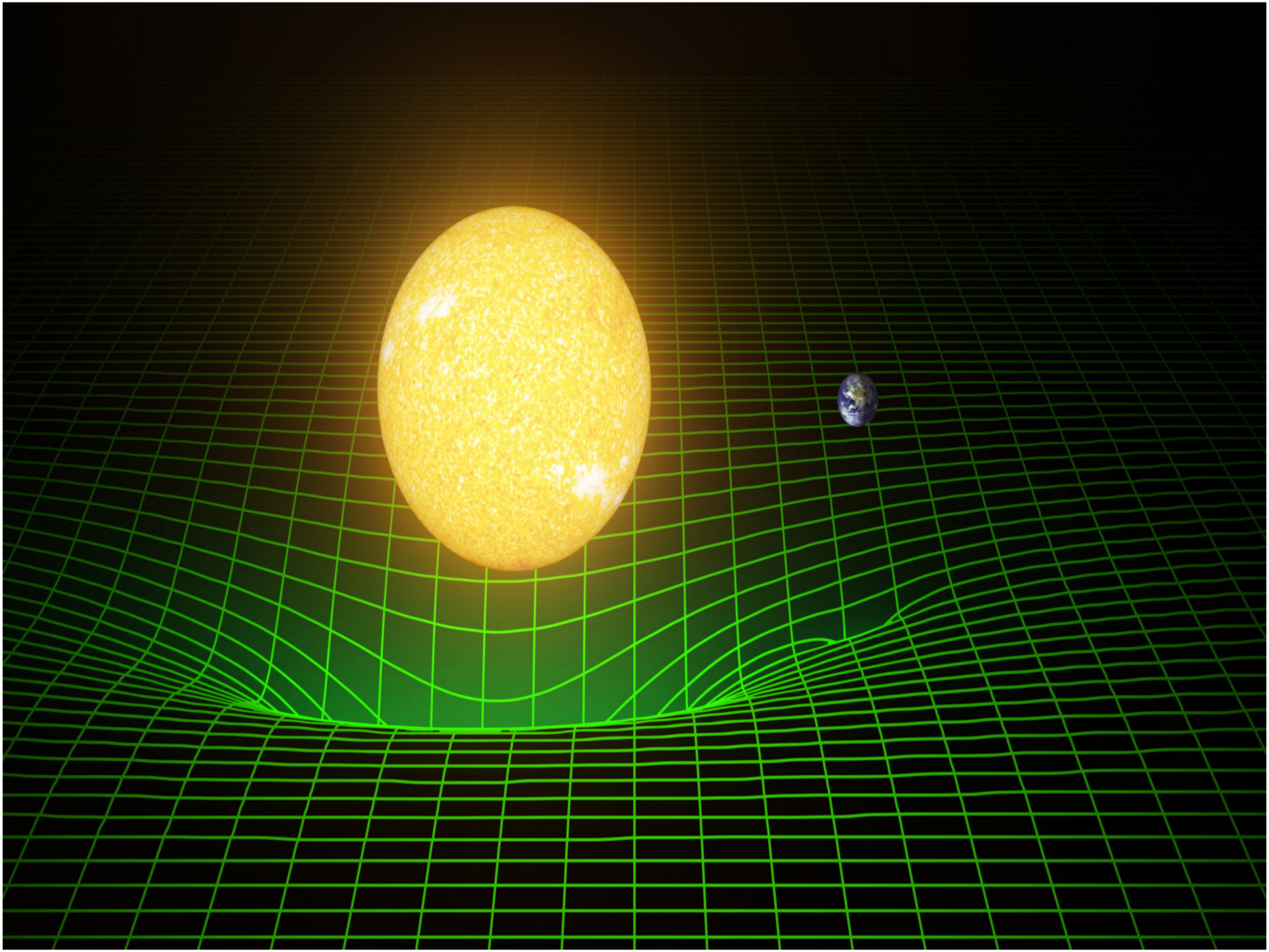
Albert Einstein

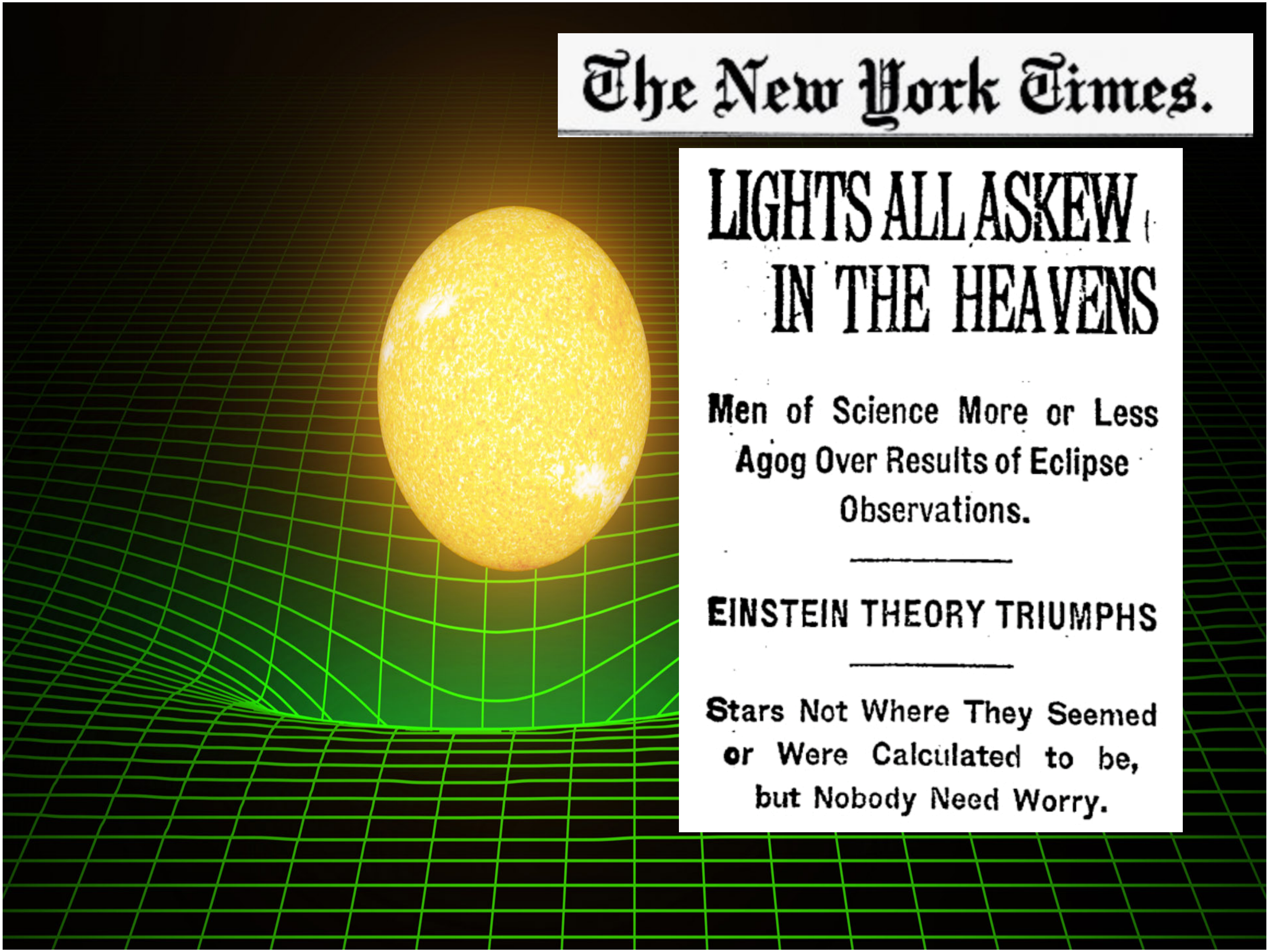


Isaac Newton, 1687:

Philosophiæ Naturalis Principia Mathematica

aps.org





The New York Times.

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.

$$E = Mc^2$$

M=☺☺☺

3 suns converted to gravitational waves

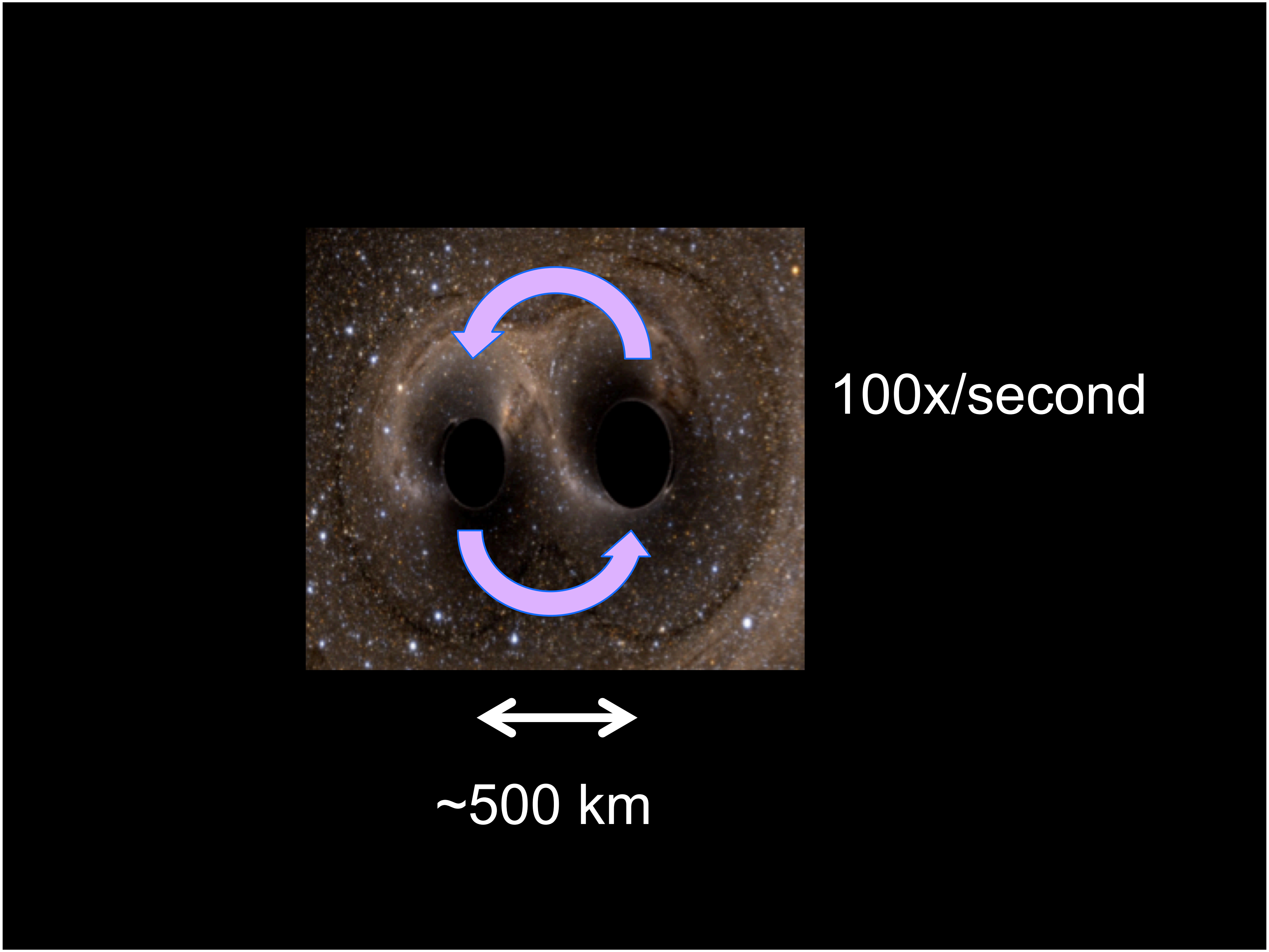
50 times the light of all the stars

or

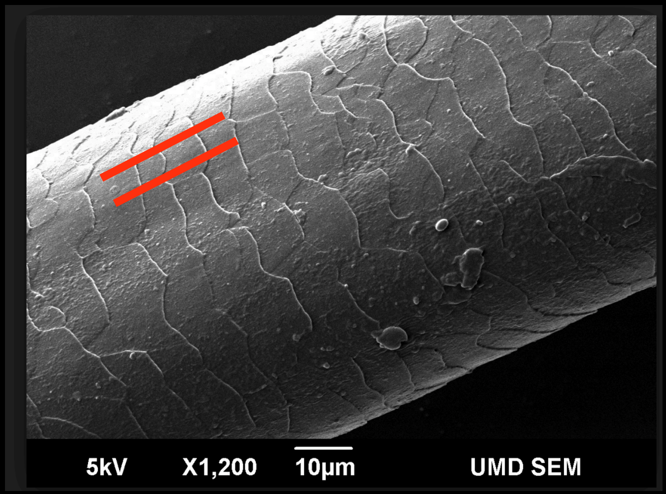
About a billion-billion-billion

years of energy consumption by humans

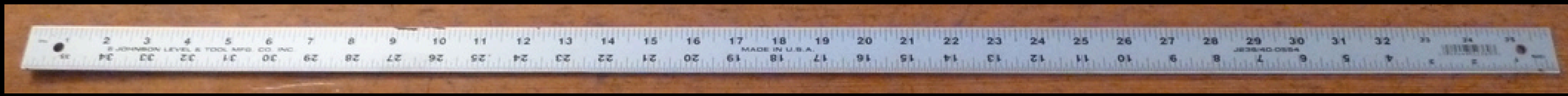
…in a few tenths of a second


100x/second
~500 km

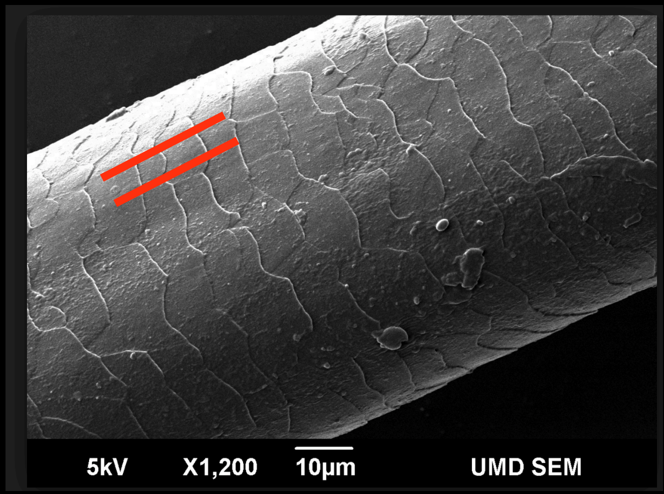
From a Meter to
1/10 human hair is
a factor of 1 million



Then…

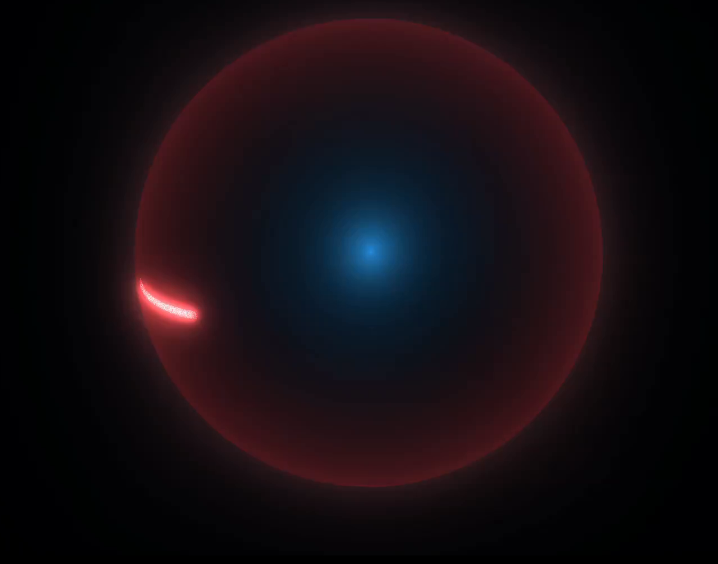


From a Meter to 1/10 human hair is a factor of 1 million



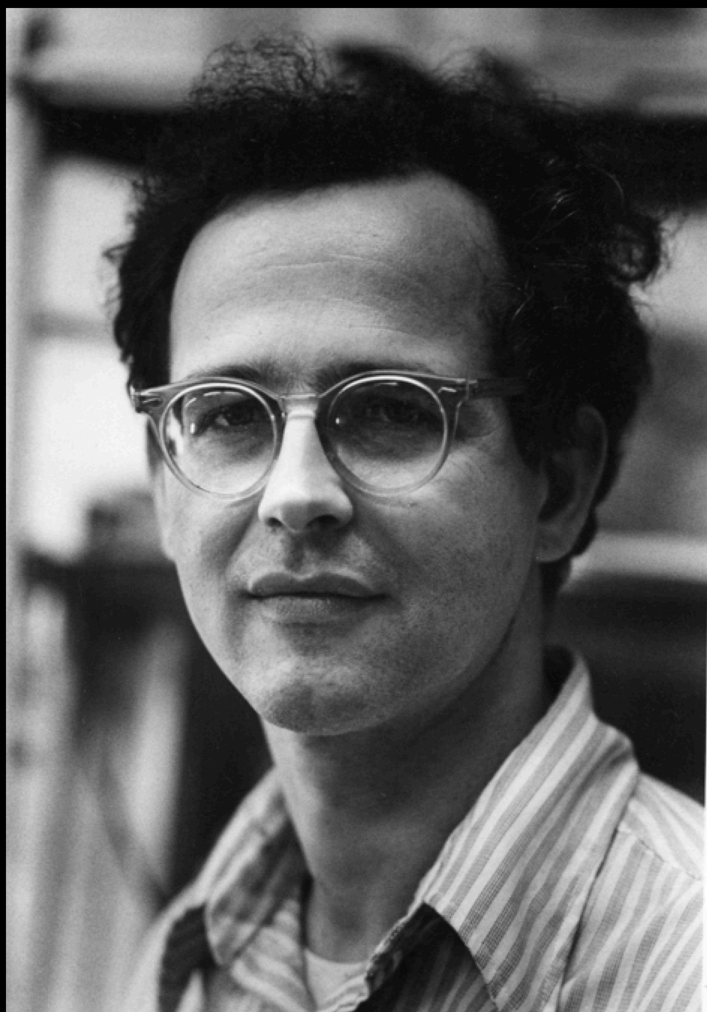
Divide that by a million

Divide that by a *billion*



That’s 10^{-21}m

Rai Weiss, circa 1967



... 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 fo...

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

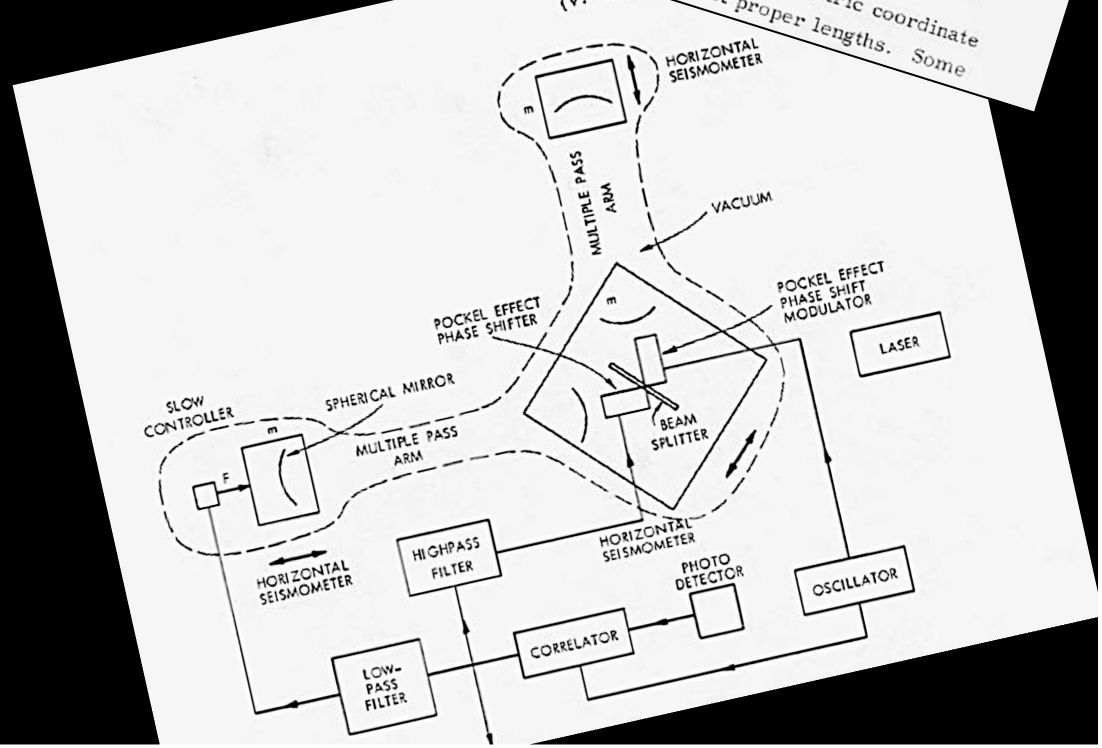
with $h_{22} = -h_{33}$, and $h_{23} = h_{32}$. The tensor components have the usual functional dependence $f(x_1 - ct)$.

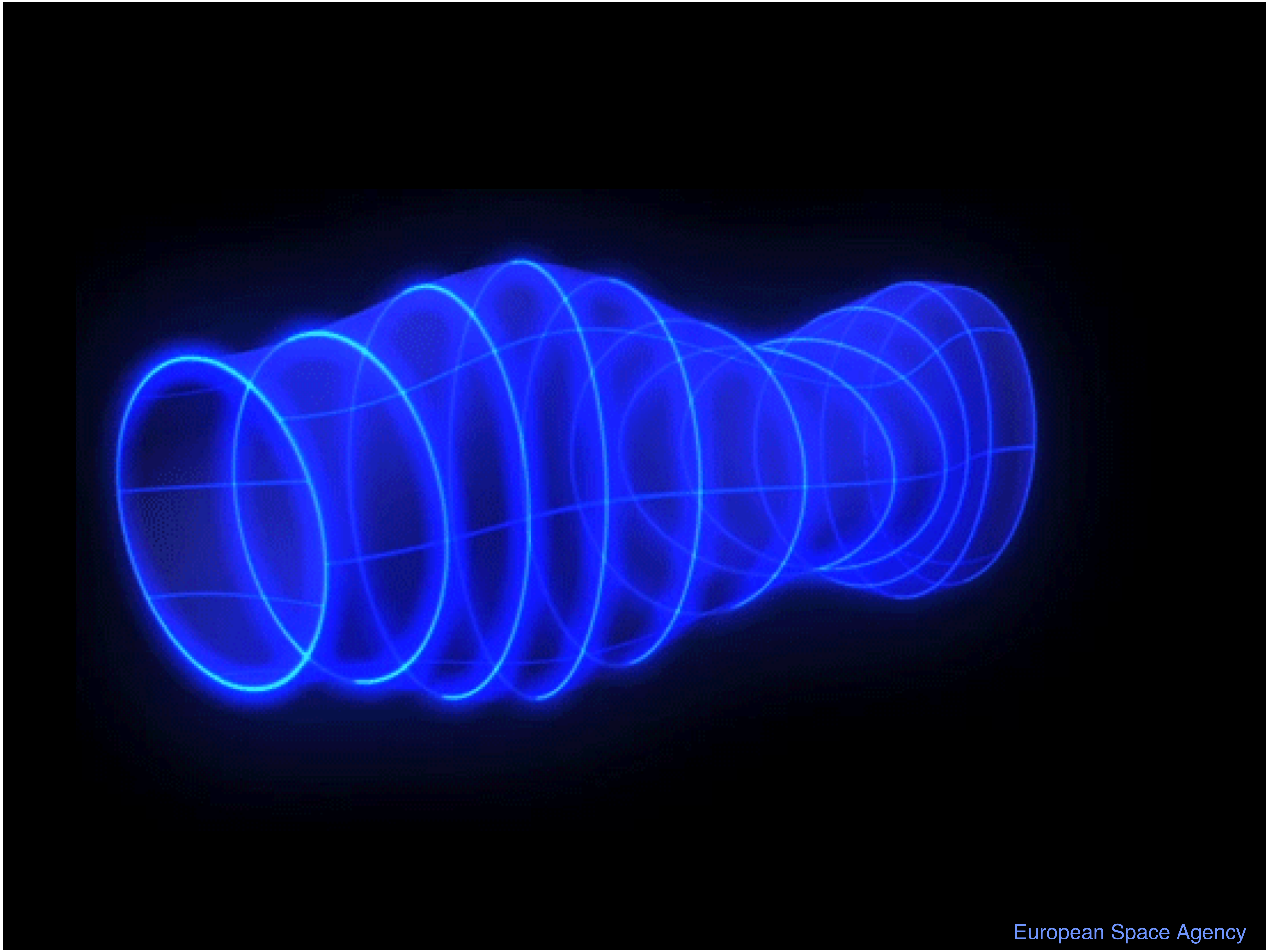
To gain some insight into the meaning of a plane gravitational wave, assume that the wave is in the single polarization state $h_{23} = h_{32} = 0$, and furthermore let $h_{22} = -h_{33} = h \sin(kx_1 - \omega t)$. The interval between two neighboring events is then given by

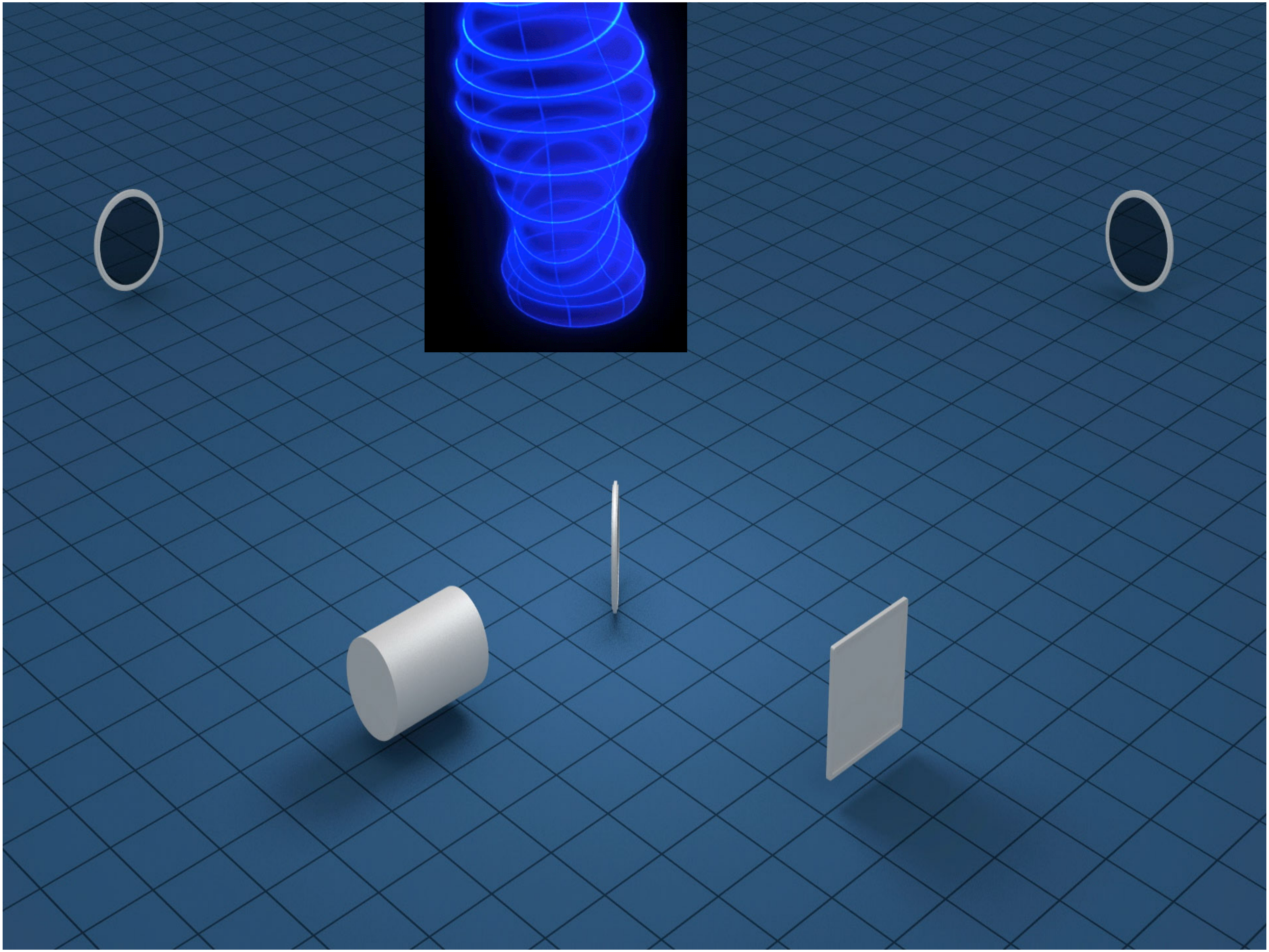
$$ds^2 = g_{ij}dx^i dx^j = c^2dt^2 - \left[dx_1^2 + (1 + h\sin(kx_1 - \omega t))\,dx_2^2 + (1 - h\sin(kx_1 - \omega t))\,dx_3^2\right].$$

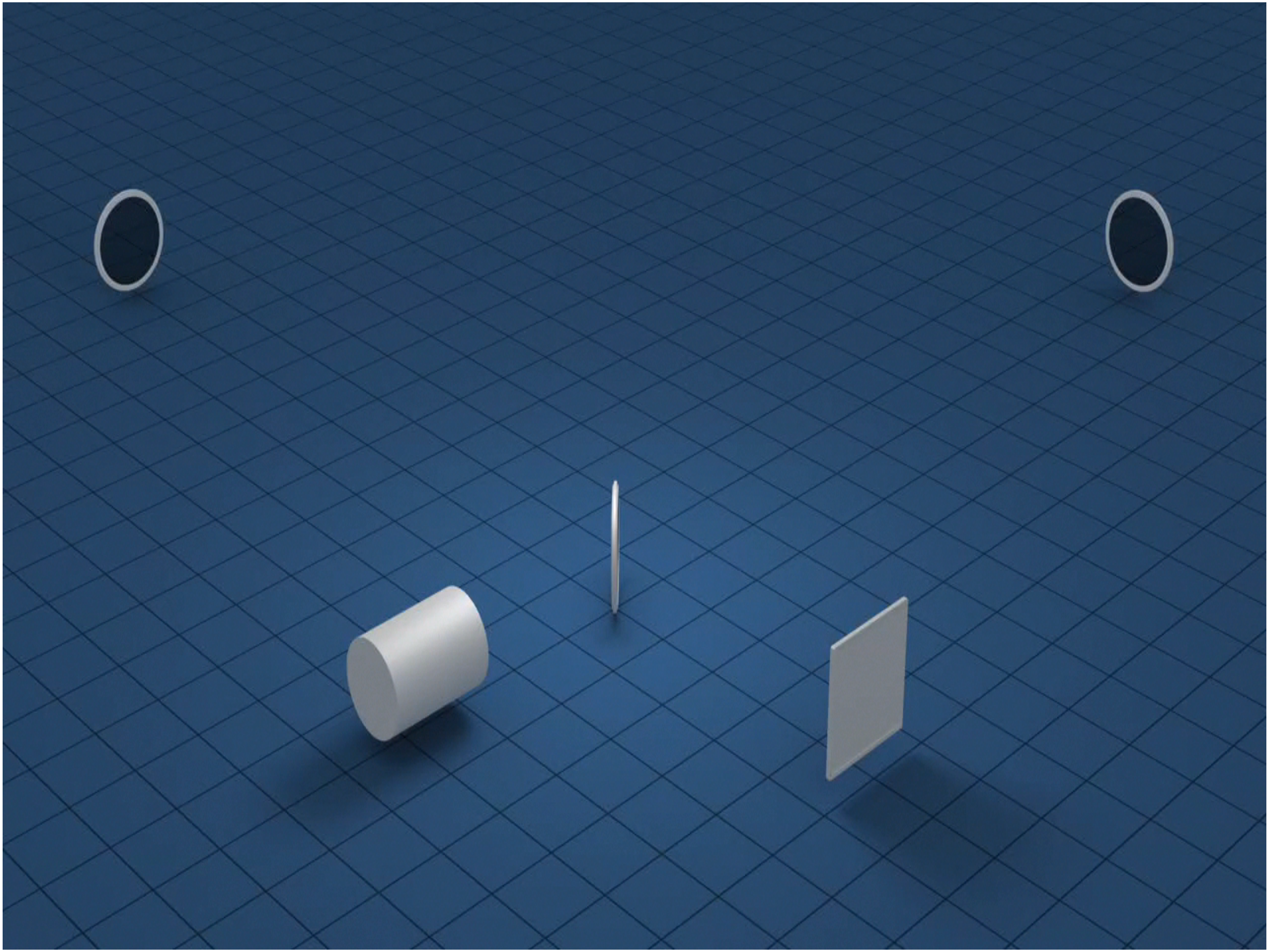
The metric relates coordinate distances to proper lengths. In this metric coordinate time is proper time; however, the spatial coordinates are not proper lengths. Some

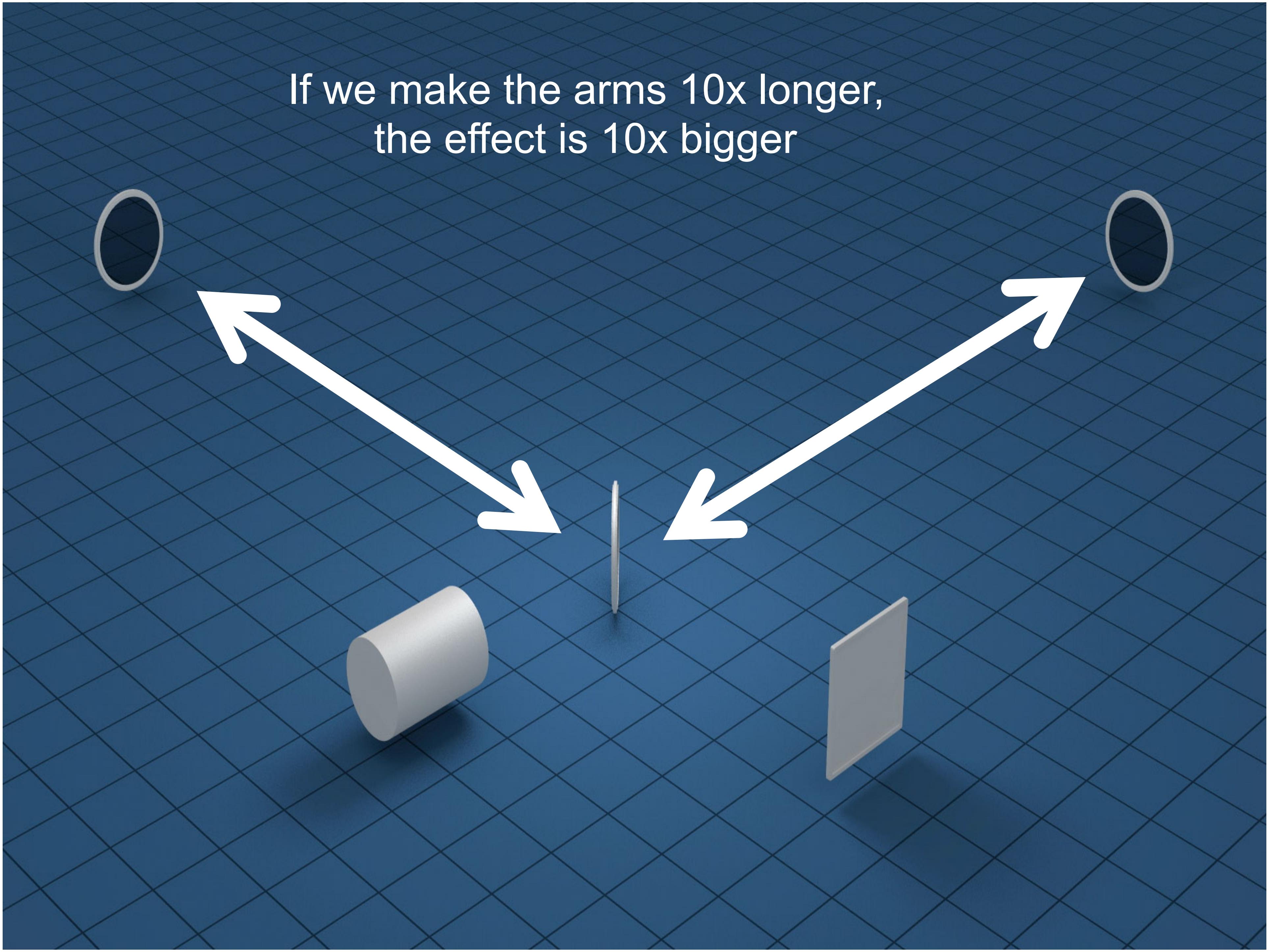
(V. GR...

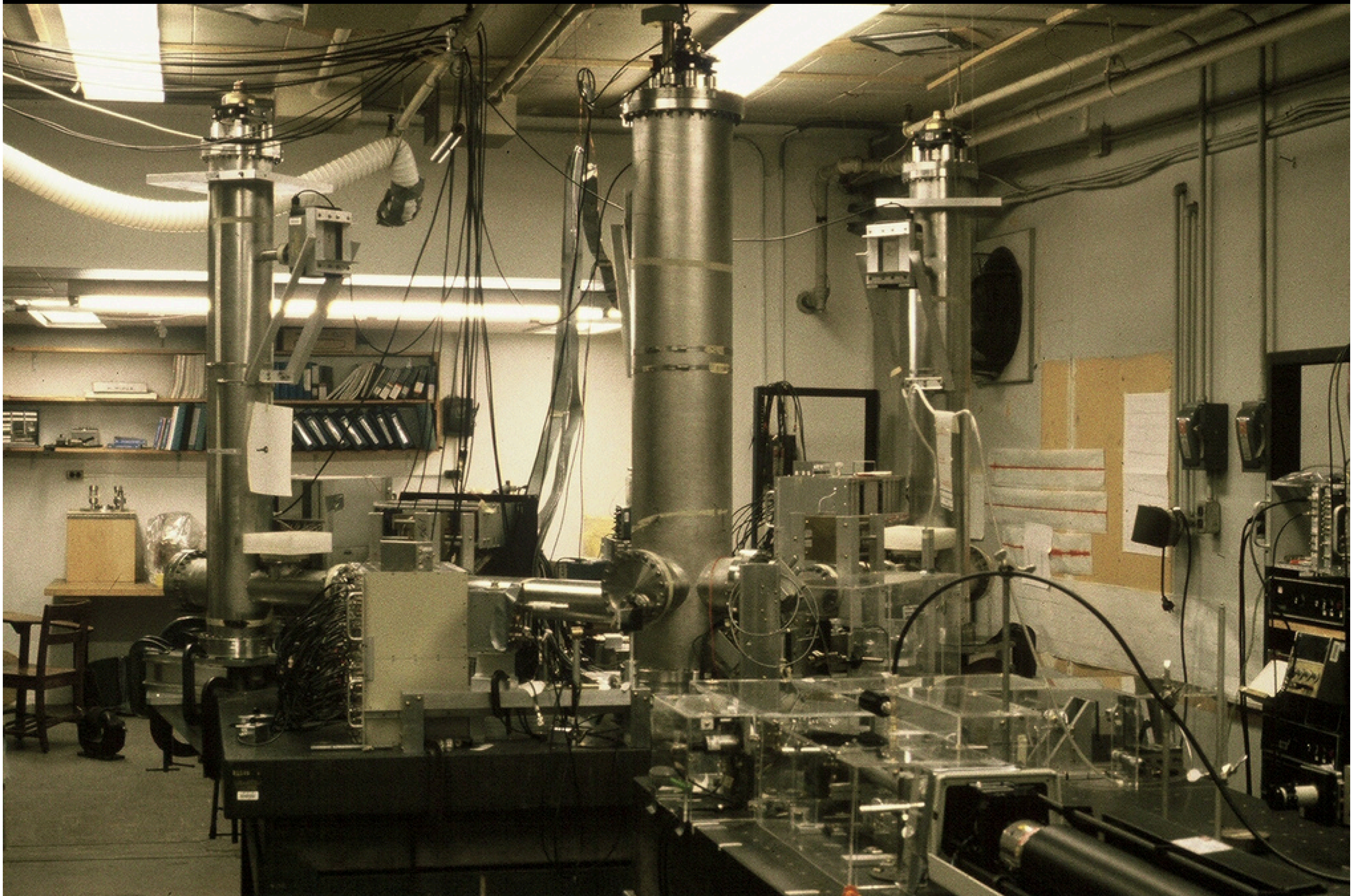



European Space Agency



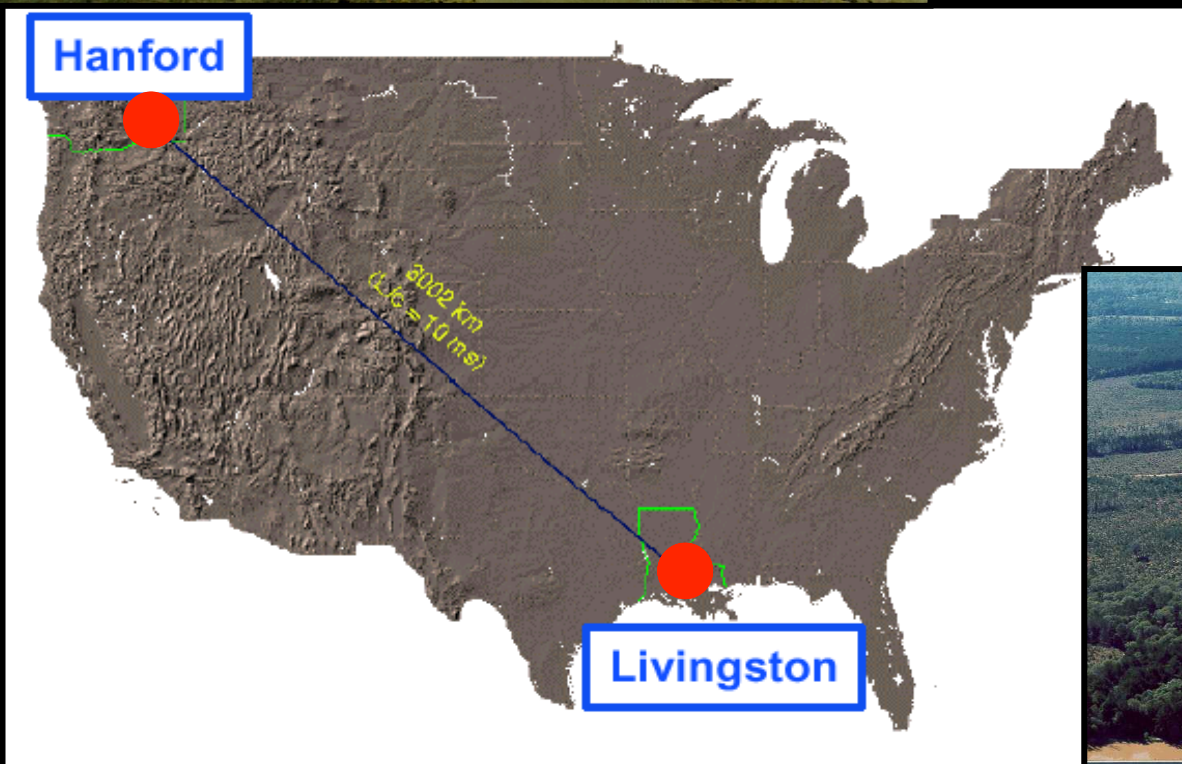



If we make the arms 10x longer,
the effect is 10x bigger



LIGO Laboratory
– Caltech, MIT –
built observatories
in '90s, and…

…Observed with
the initial detectors
2005-2011,
and saw…



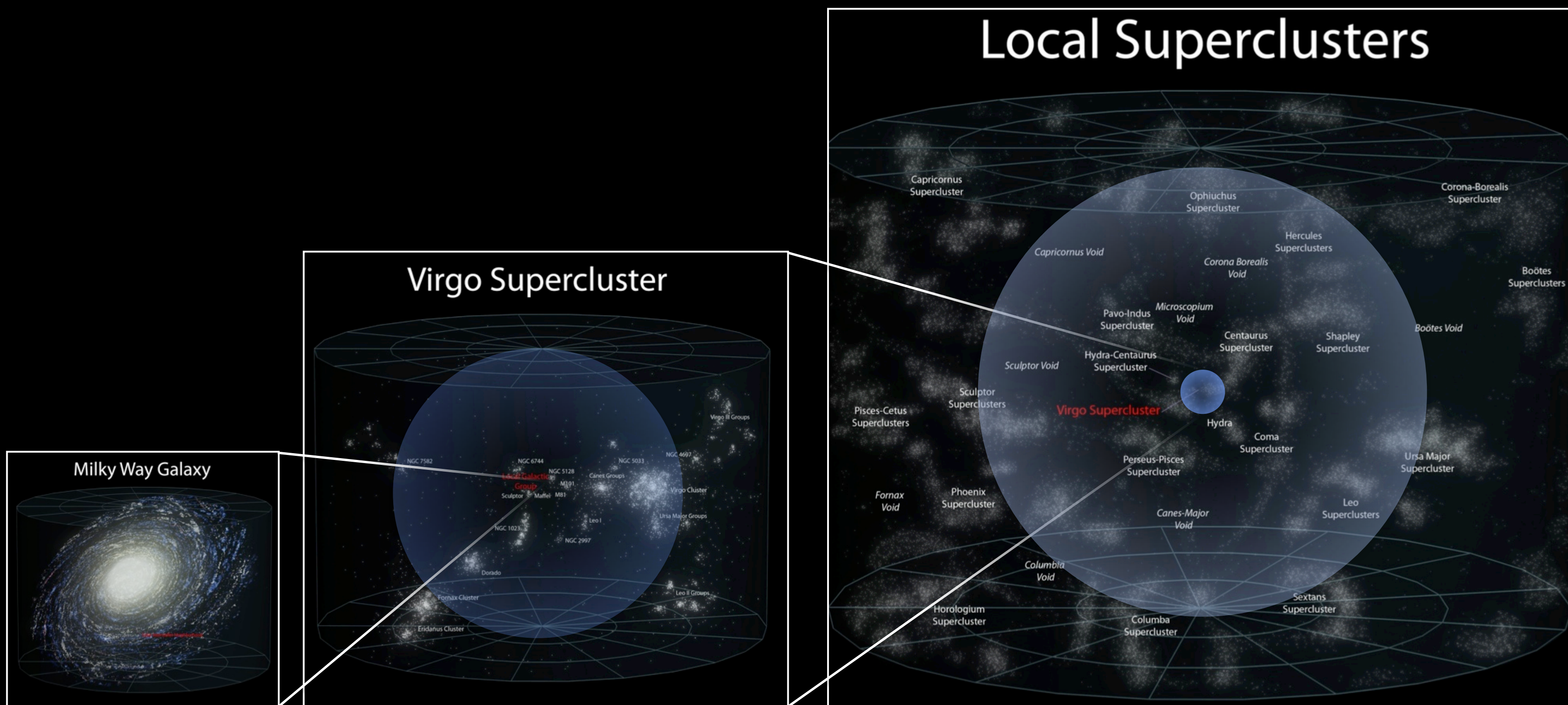
nothing

Initial Detectors

- That is to say, we saw no gravitational-wave signals.
  - We learned how to build and commission detectors
  - We learned how to analyze the data
  - We created new upper limits and significant ‘non-detections’

…but it was clear we needed more sensitive detectors.

Initial LIGO to Advanced LIGO



M. Evans

Initial Reach
If we had one
signal here…

Advanced Reach
…we would have
1000 here!

Advanced LIGO

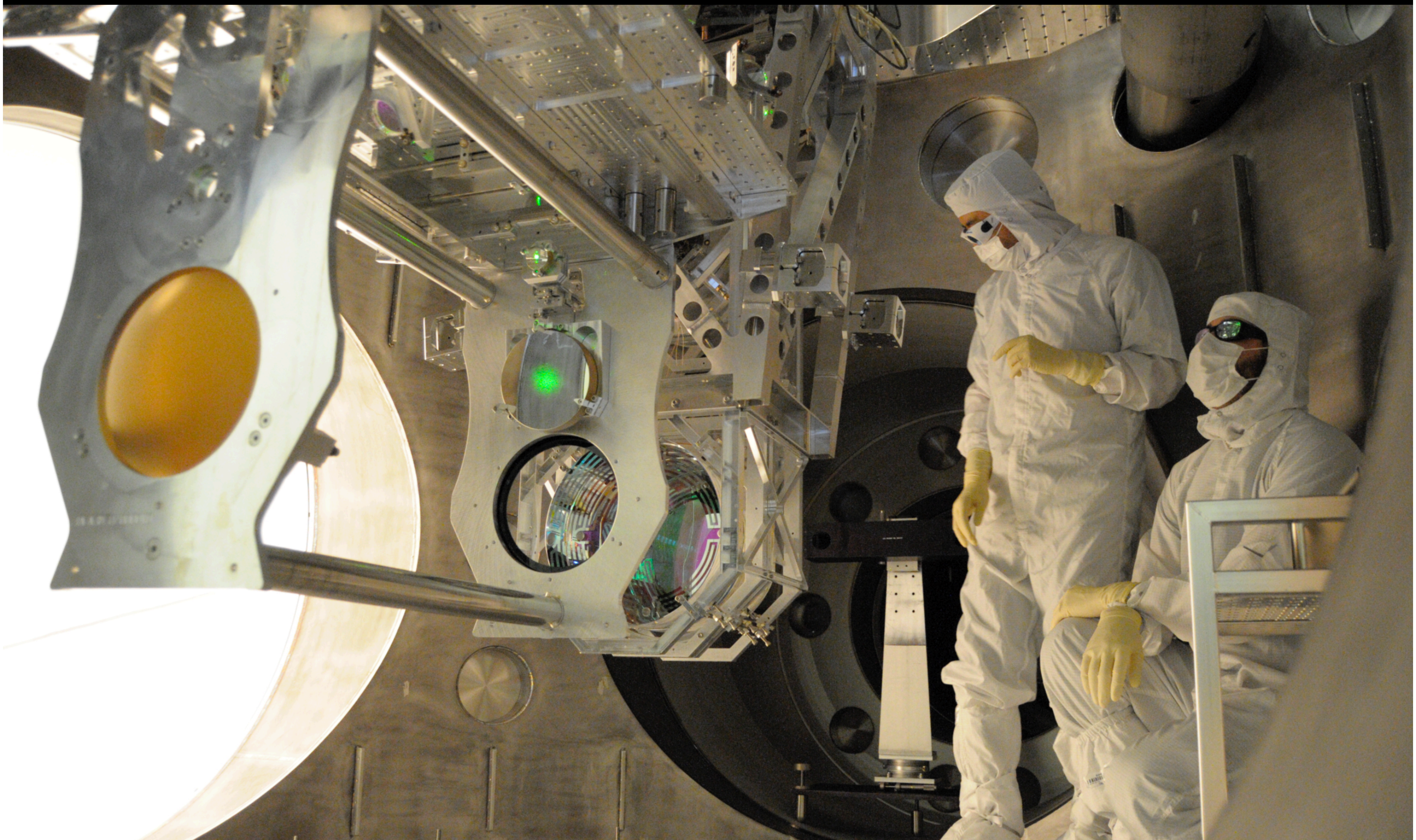
- Better basic science ideas for the detector
- Better technology to realize those ideas
- The experience of building initial LIGO
- Really good systems engineering and QA
- 15 years of the scientific life of 100 or so of the best instrument builders on the planet
- Incredible courage,

  vision,

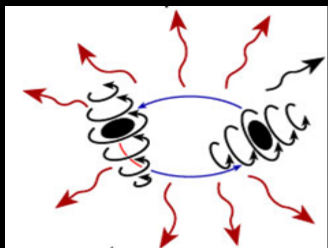
  patience

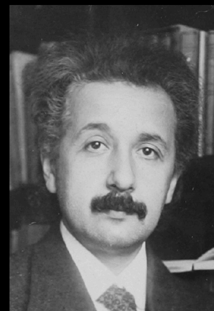
  on the part of the NSF

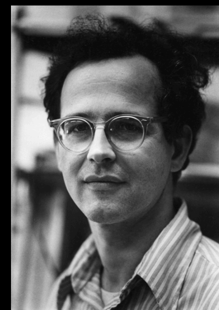
(and your generous support)

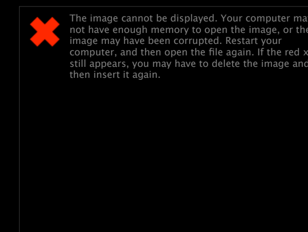


9:03
PACIFIC
11:03
CENTRAL
17:03
GMT
DARM NOISE
ALS / ISC
AS / IMC









1.3 Billion years after the Black Holes merged..
(and multicellular life started on earth…)

100 years after Einstein predicted gravitational waves…

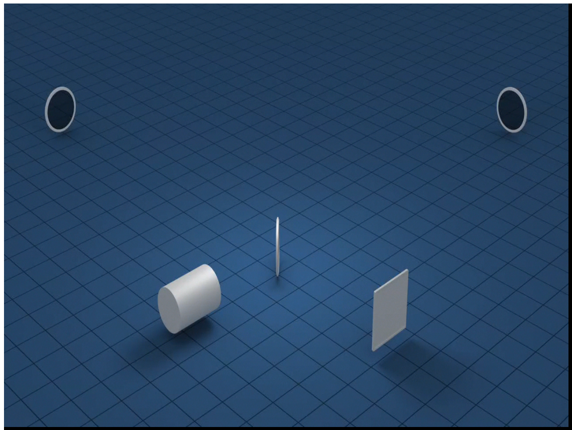
50 years after Rai Weiss invented the detectors...

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

10 years after Advanced LIGO got the ok...

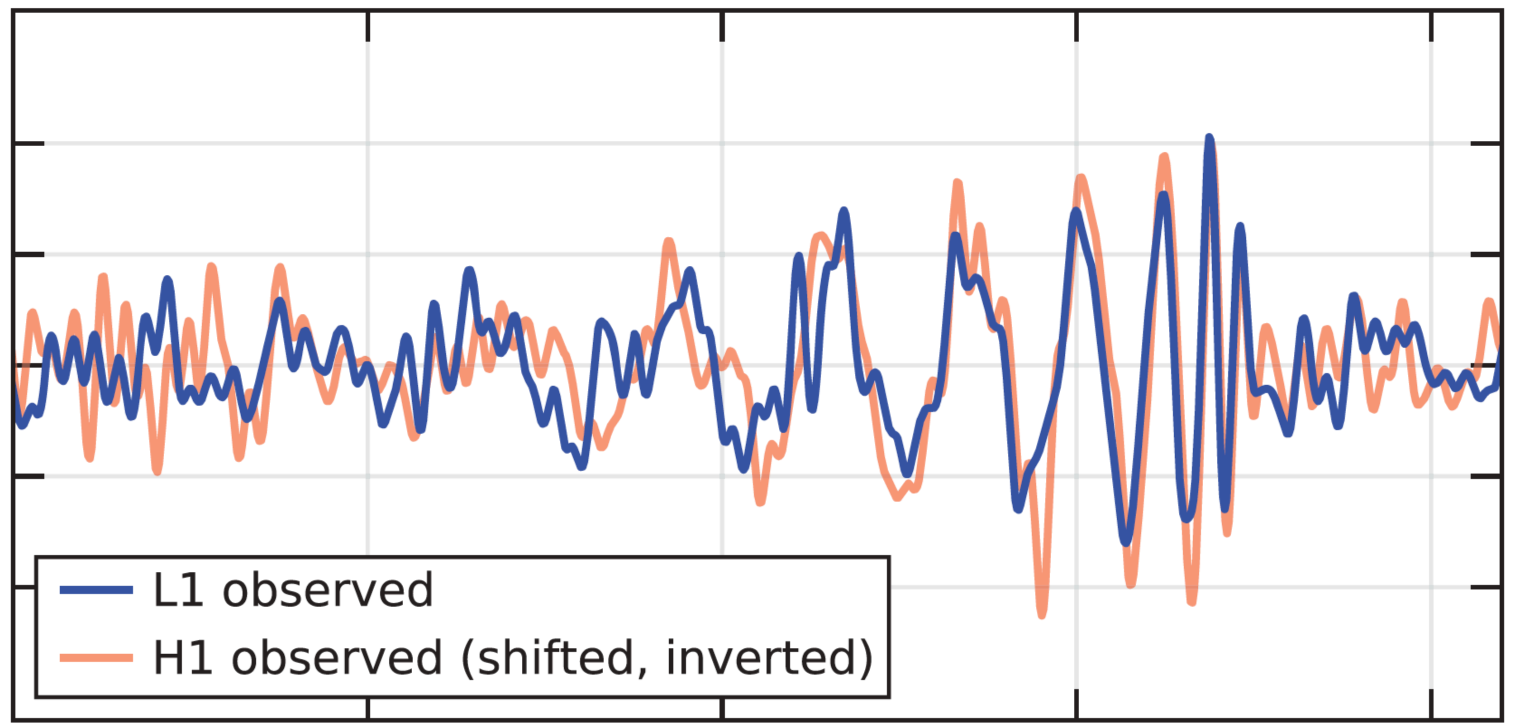
6 months after starting detector tuning...

Two days **after we started observing...**

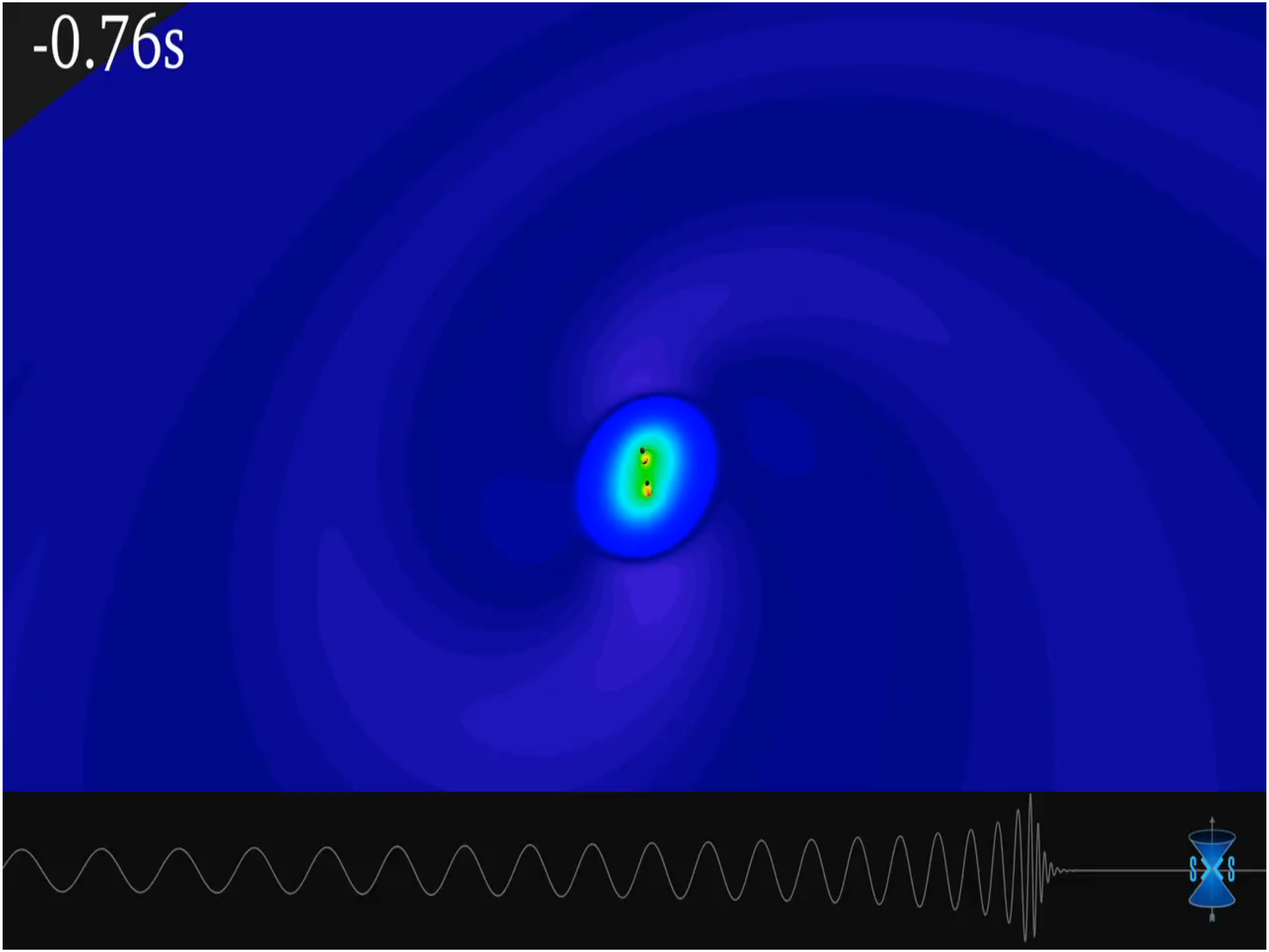


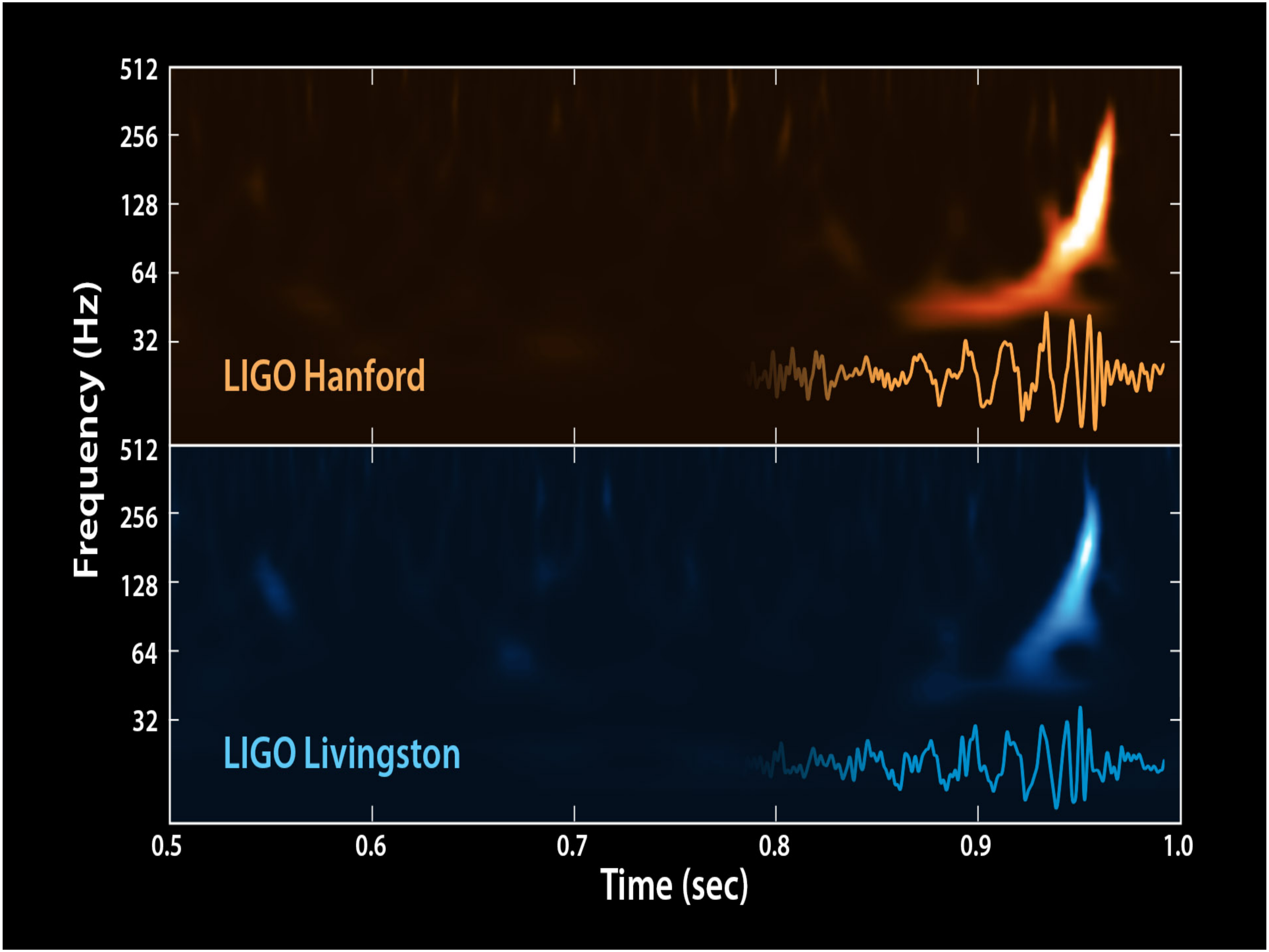
September 14, 2015 at 05:51 EDT:

Cosmic Rendezvous

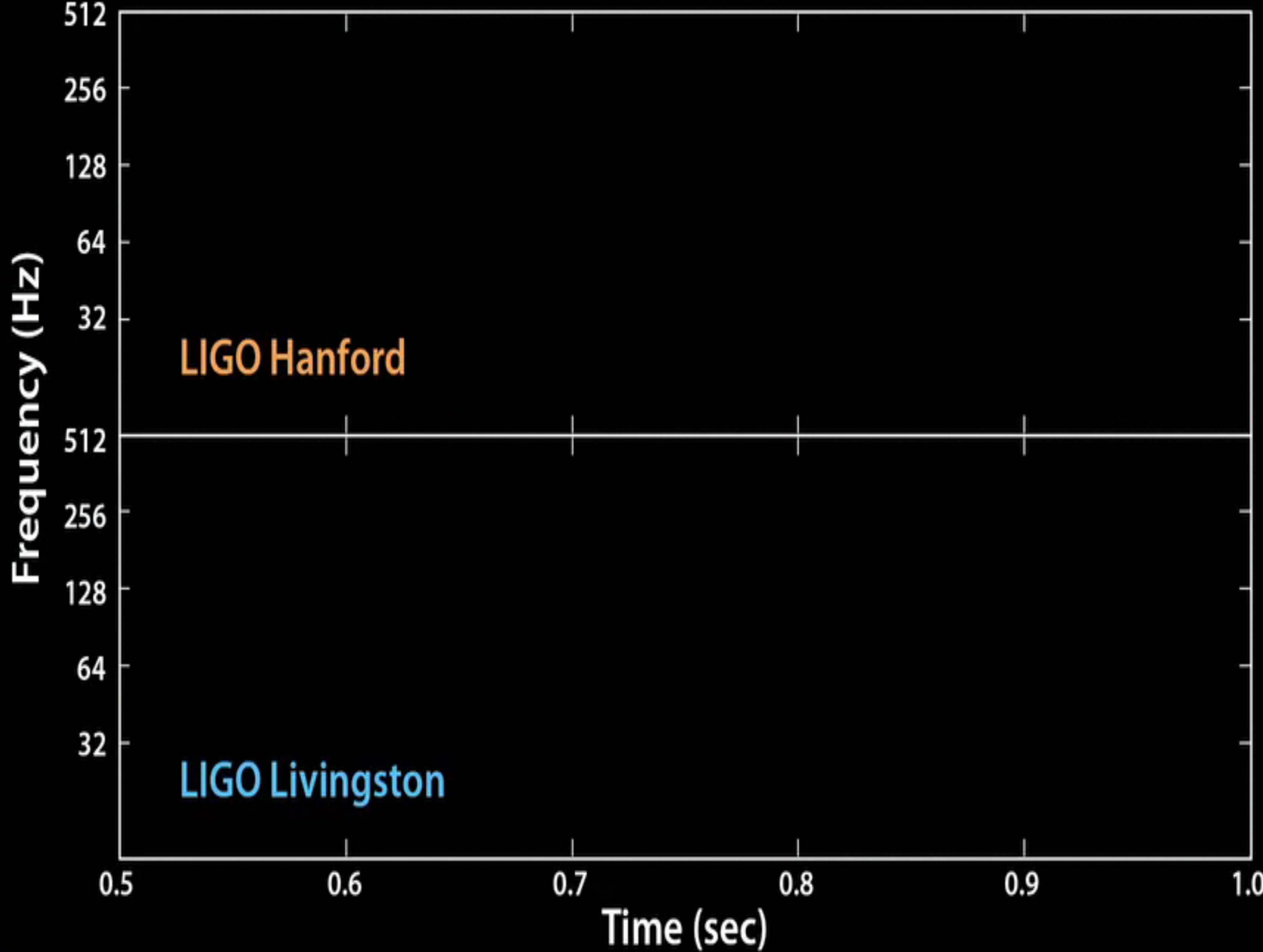


1/10 of a second


-0.76s
SXS



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)



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512
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LIGO Hanford
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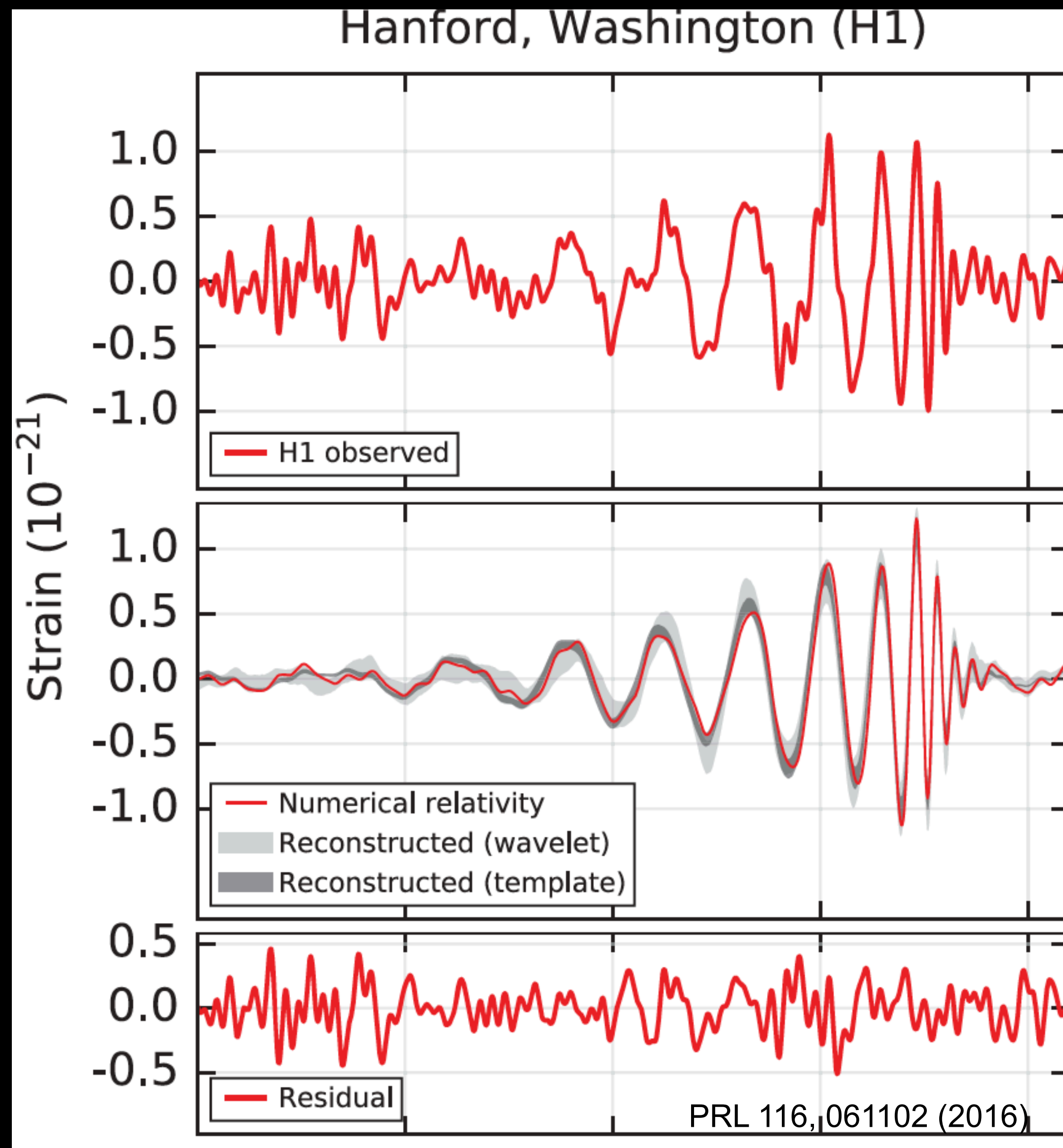
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

This measured signal…

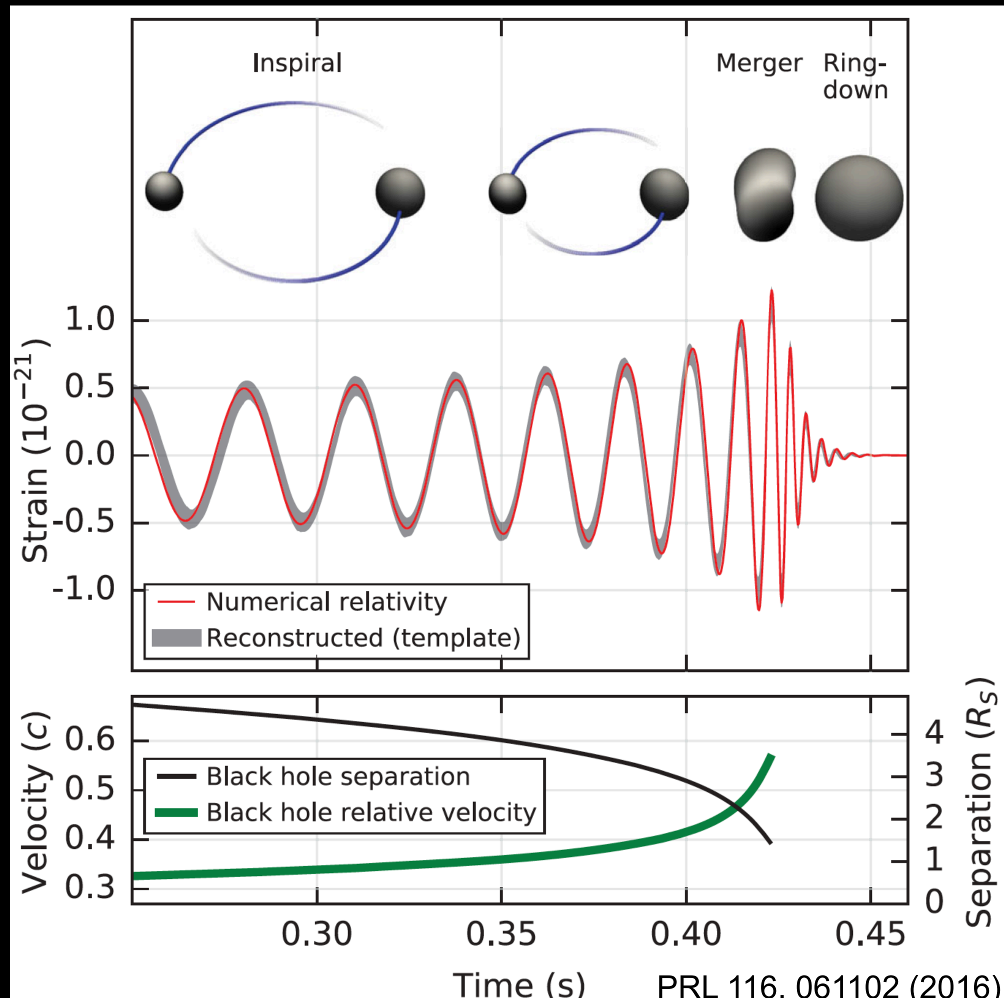
…minus Einstein's prediction…

…equals noise



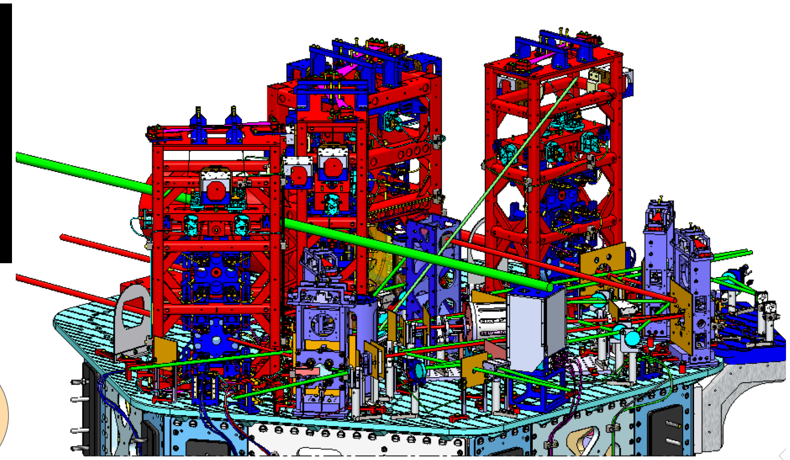
LIGO measures *h(t)* –
think 'strip chart recorder'

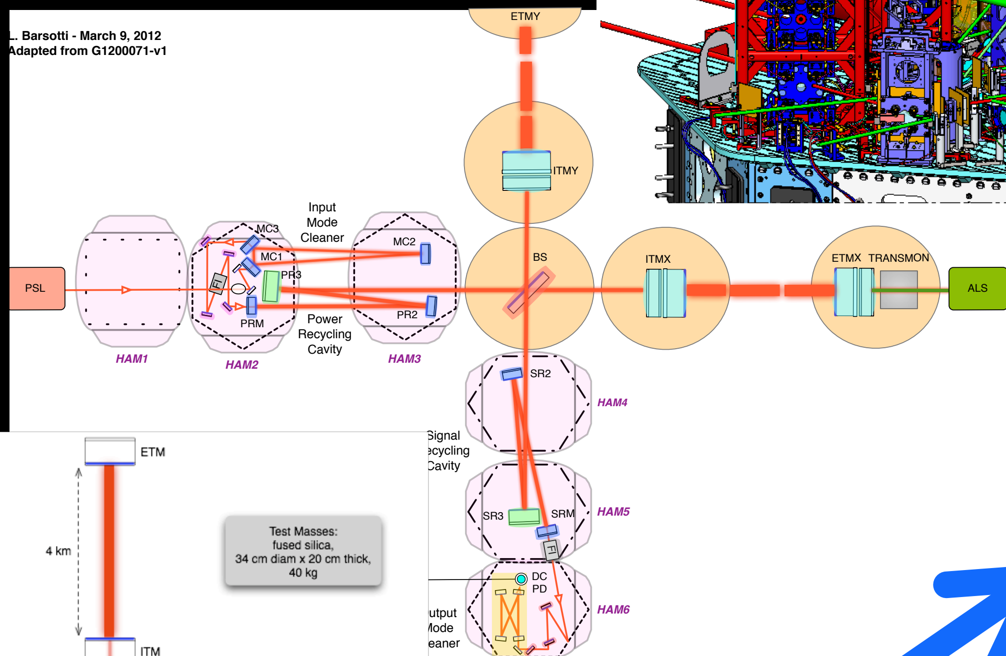
- The output of the detector is the (signed) strain as a function of time
- LIGO can actually measure the change in distance between our optics, due to a passing space-time ripple
- An astonishingly tangible connection between the most cataclysmic conditions of space and time, and stuff we make with our own hands

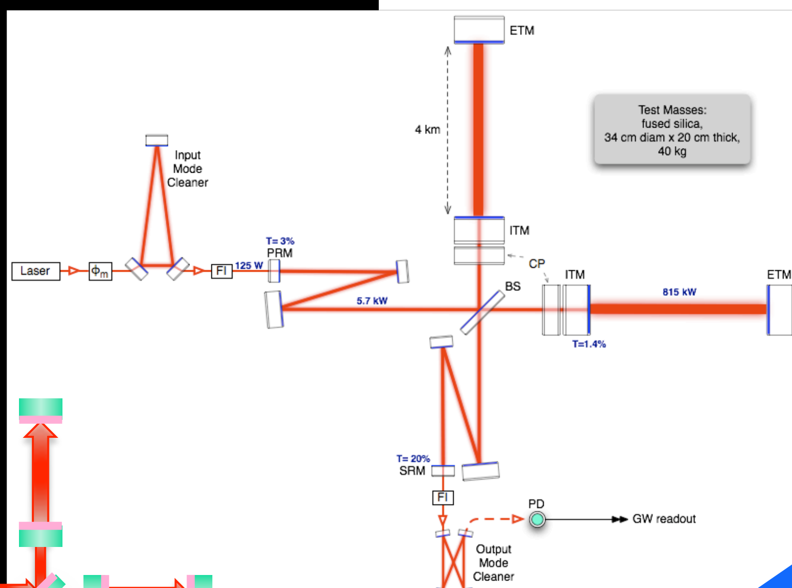


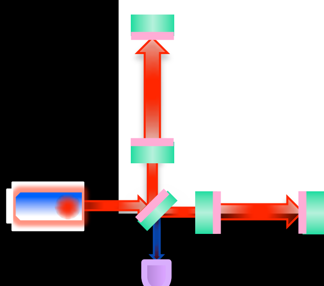
PRL 116, 061102 (2016)

Time for some Hardware!









photodiode

Reality axis

Telescope Tubes…in construction

- The ‘Before’ picture….

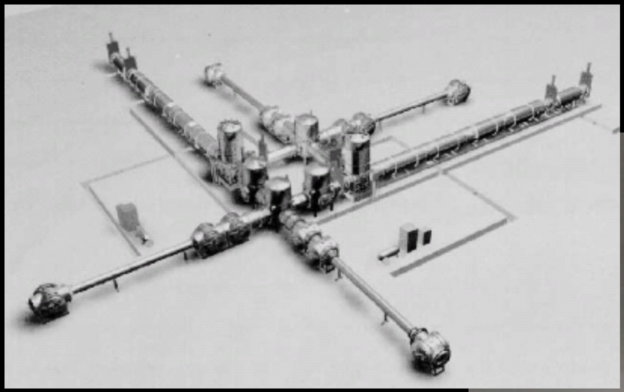
Telescope tube: Separates primary and secondary mirrors

- …and after: Hale 200” telescope

LIGO Tubes:
Separates end mirrors from beamsplitter

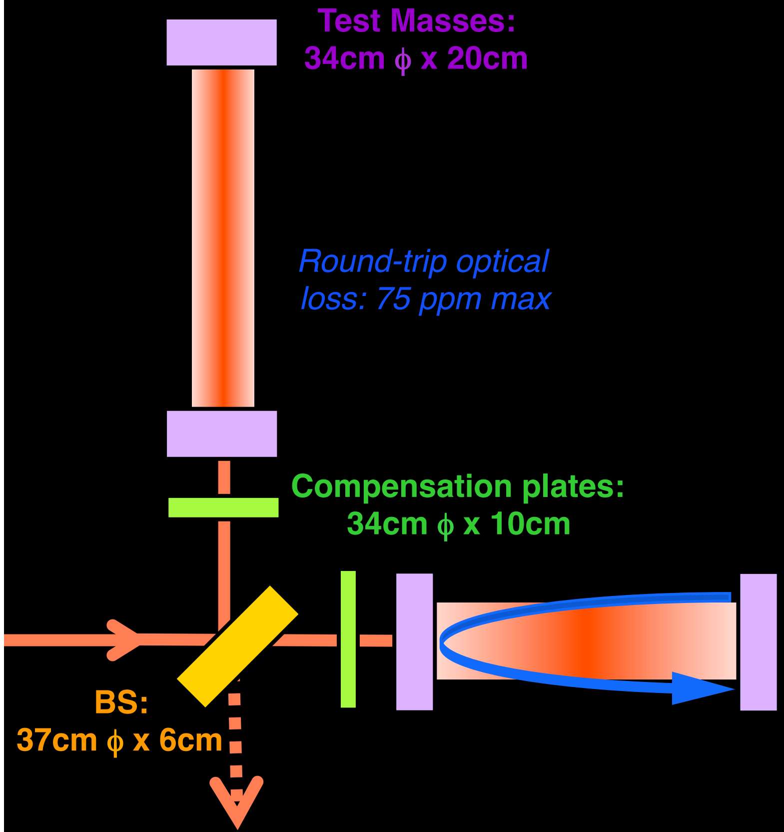
- Two arms, each one 4km – 2.5 miles long
- Here is one arm at our Hanford, Washington Observatory

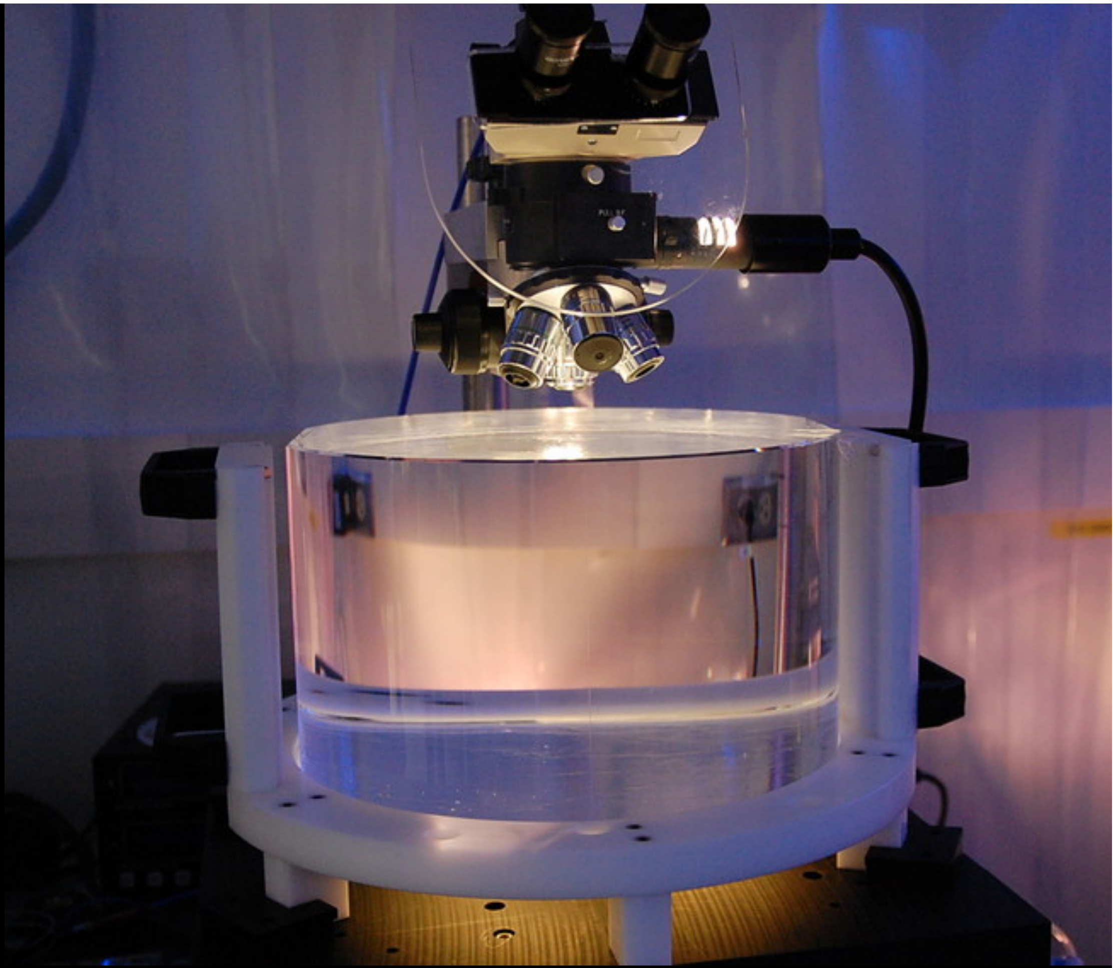
LIGO Vacuum Equipment –
designed for several generations of instruments



Mirrors

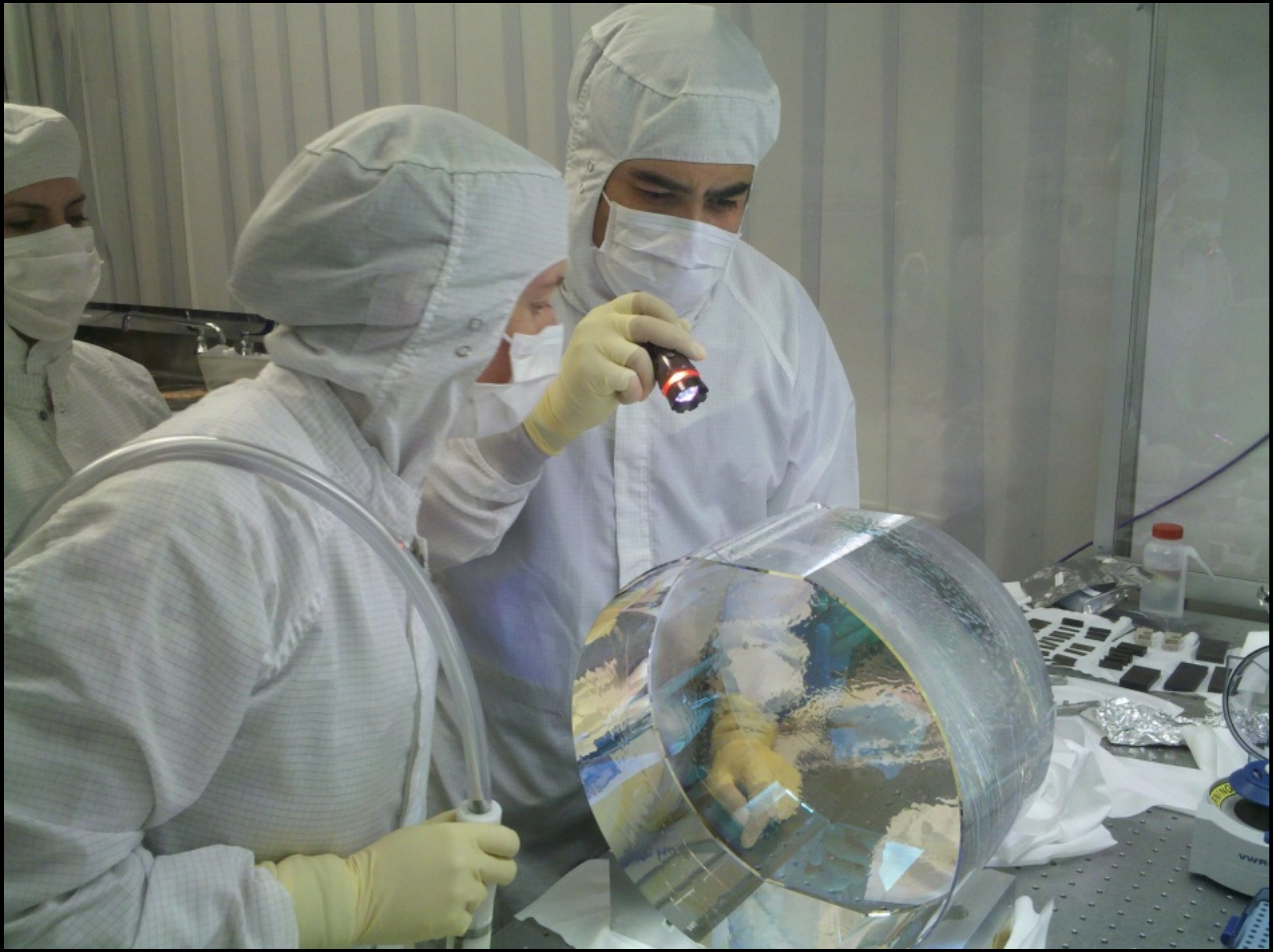
- Requires the state of the art in substrates, mirror figuring, and the reflective coating





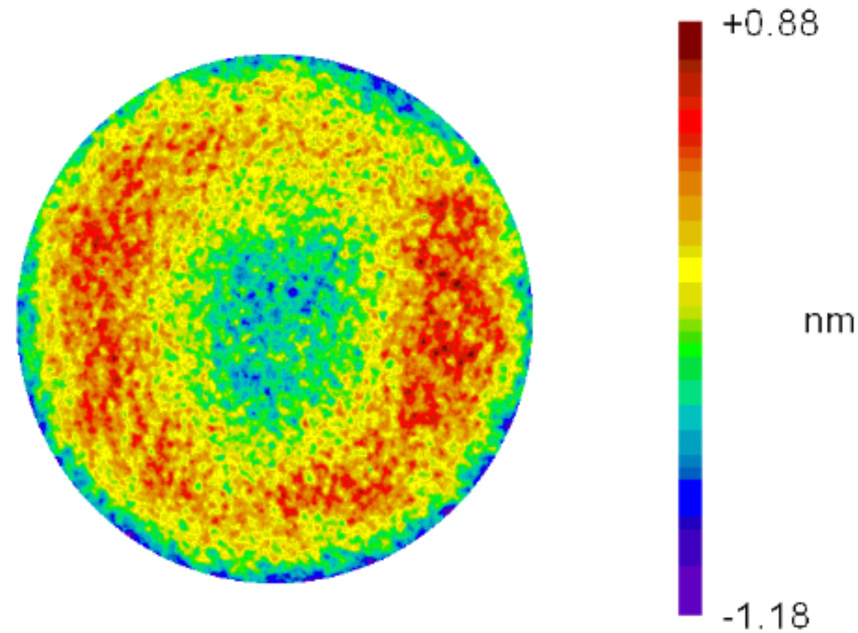
- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Inspecting mirror during fabrication



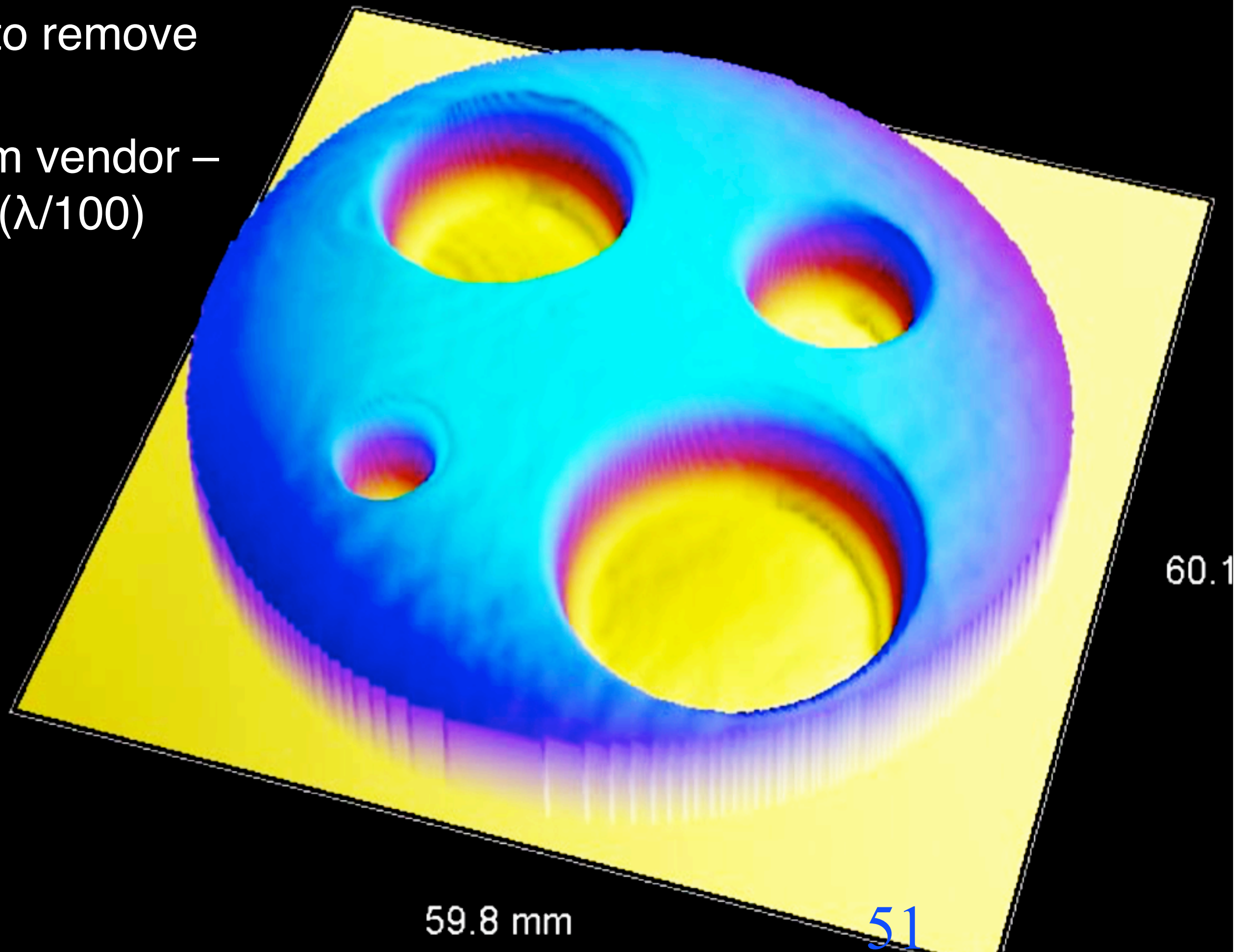
Test Mass Polishing, Coating, measuring

- Good telescope mirrors have average ripple RMS of λ/30 and a Strehl Ratio of .96
  - For ROC of say 48”, saggita of 0.08” – a penny.
- LIGO’s λ/10000 mirrors gives a Strehl Ratio of .99999964.
  - ROC of 2245 m – 2.2 km! – and sagitta of ~1 micron – 1/10 of a human hair



Ion Beam Milling for final figuring

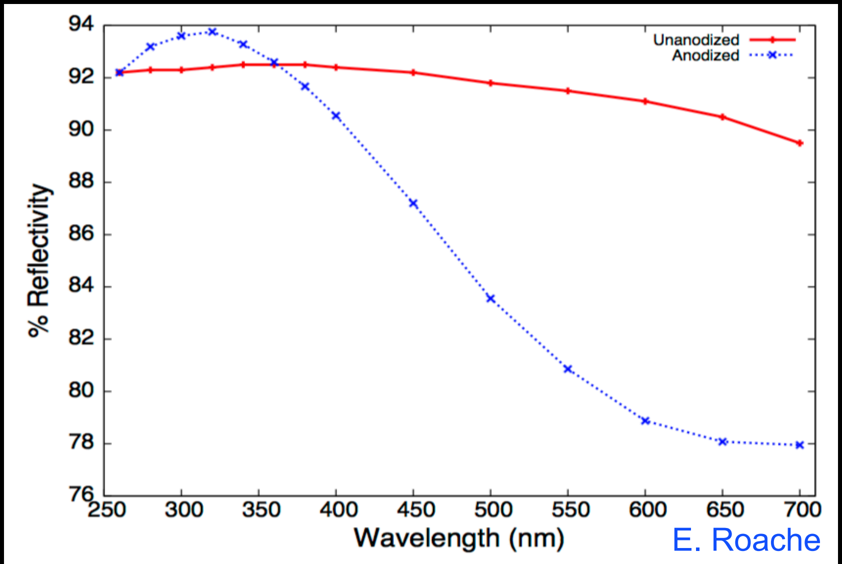
- The surface is compared with a reference flat, and places where a few atoms need to be removed are found
- Ion-beam milling is used to remove the high spots
- Demonstration image from vendor – holes are a few nm deep (λ/100)



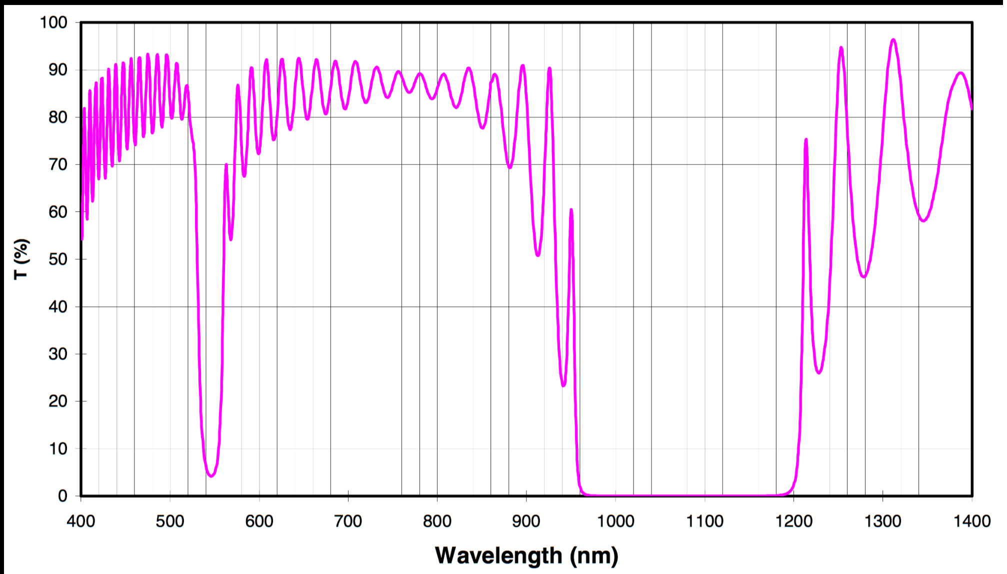
Mirror reflective coating

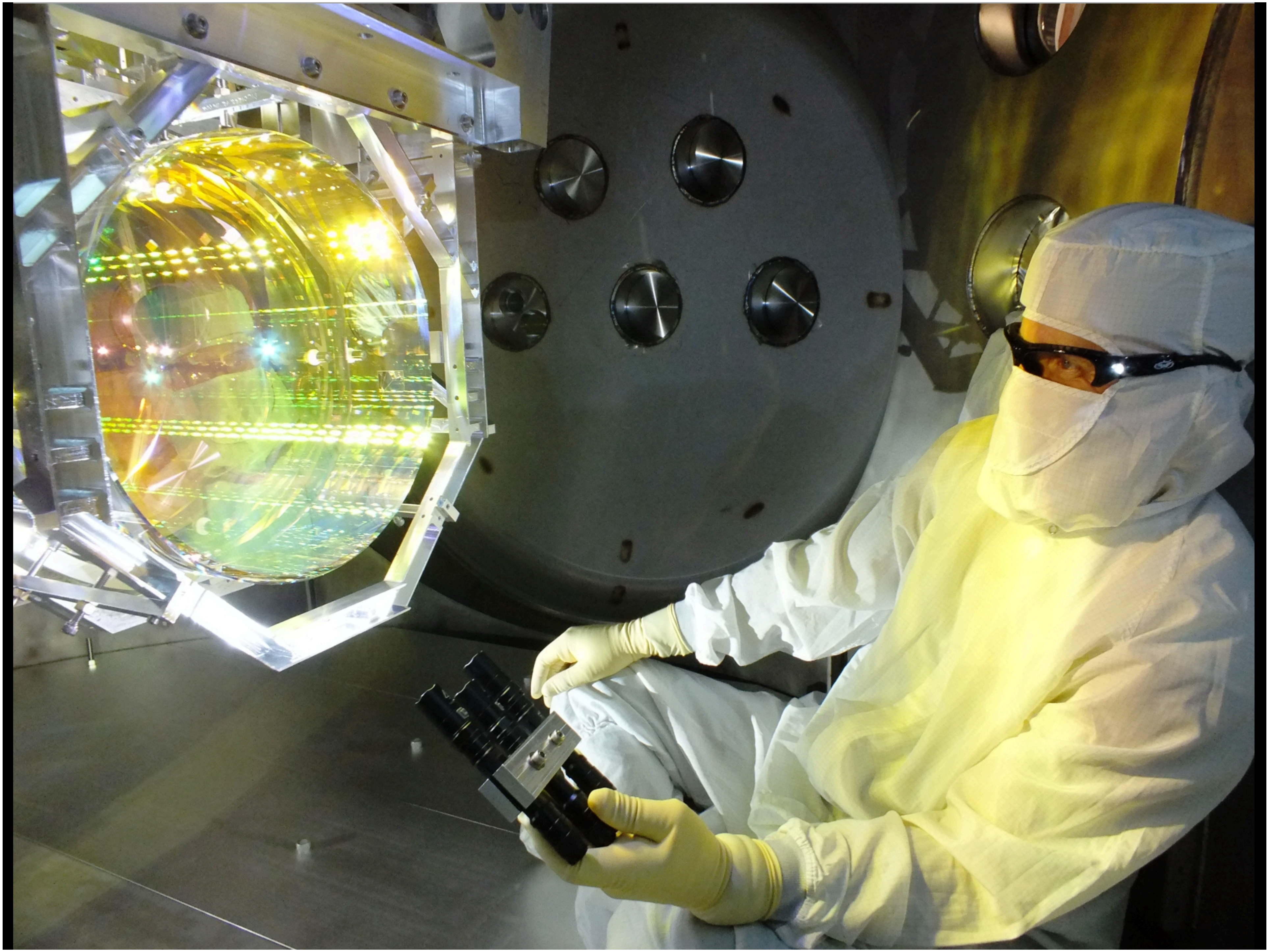
- Telescopes typically use Aluminum mirror coatings – up to ~98% over broad range of wavelengths
- LIGO uses multi-layer coatings, alternating optical indices
  - Reflectivity .99999 or so (transmission 10 parts per million)
  - Absorption 0.1 parts per million (turns laser light into heat)
  - Scatter ~10 parts per million (need baffles in our tube to catch this)

Auminum Coating



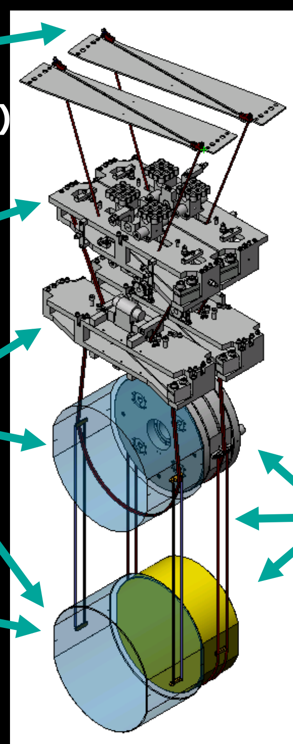
LIGO Coating





Mirror suspension

- Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet pushing platform
- Fused silica fibers to suspend 40 kg test mass
  - VERY Low thermal noise!



Hubble focus compensation

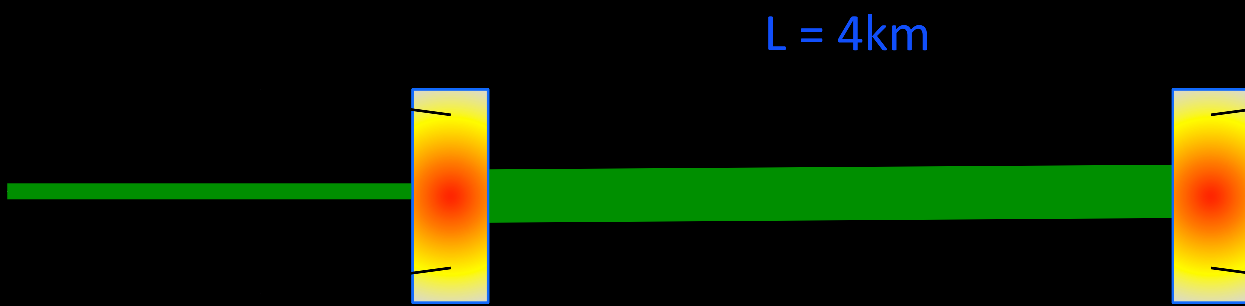
- Recall the problem of the figuring of the Hubble mirror (2.4m dia)
- Too flat by about 2,200 nanometers (2.2 microns).
- Repaired by a space walk and installation of a compensation plate

Before

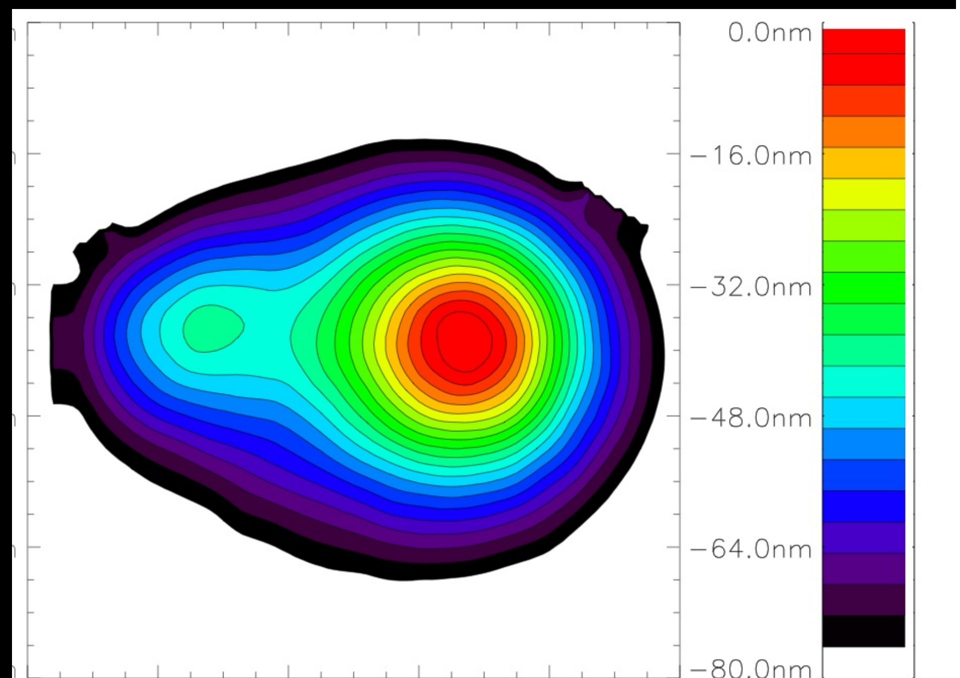
After

NASA

LIGO's focus challenge: Thermal deformation



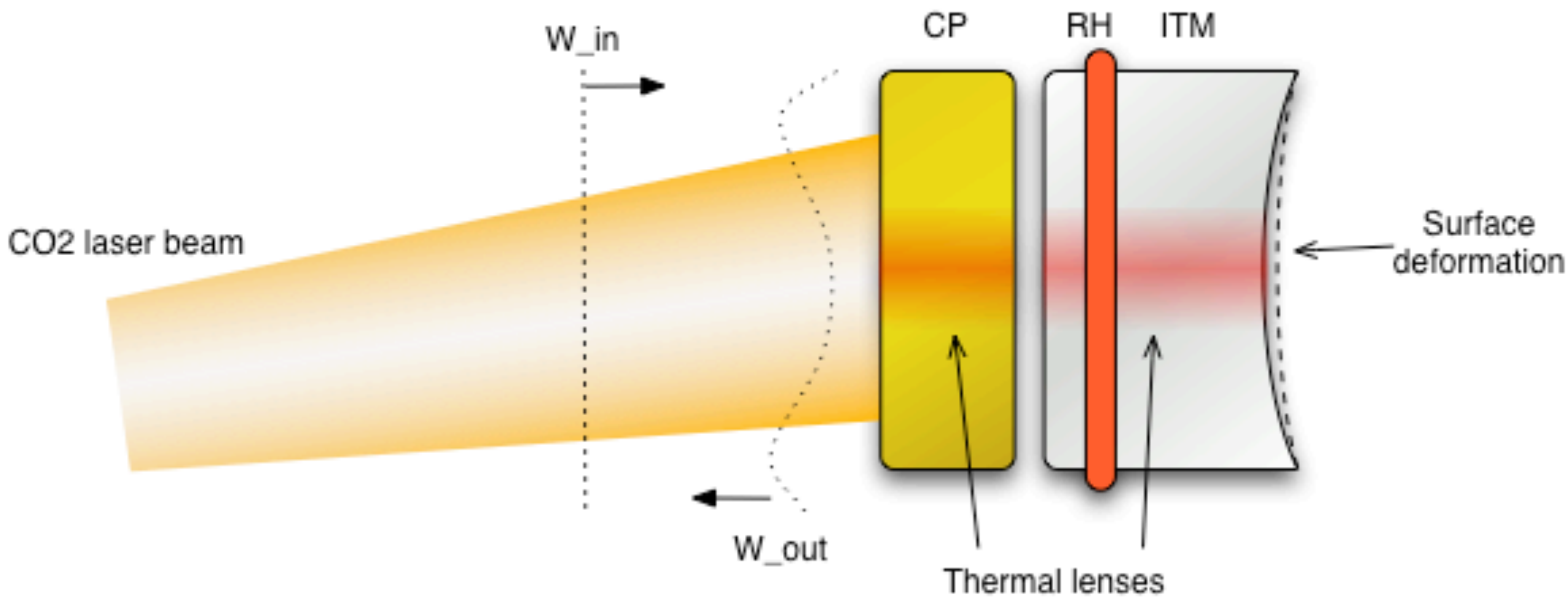
Example mirror thermal lens



- We use a high-power laser to achieve a high precision in measuring mass positions
- But the mirrors absorb laser light, heating, and deforming

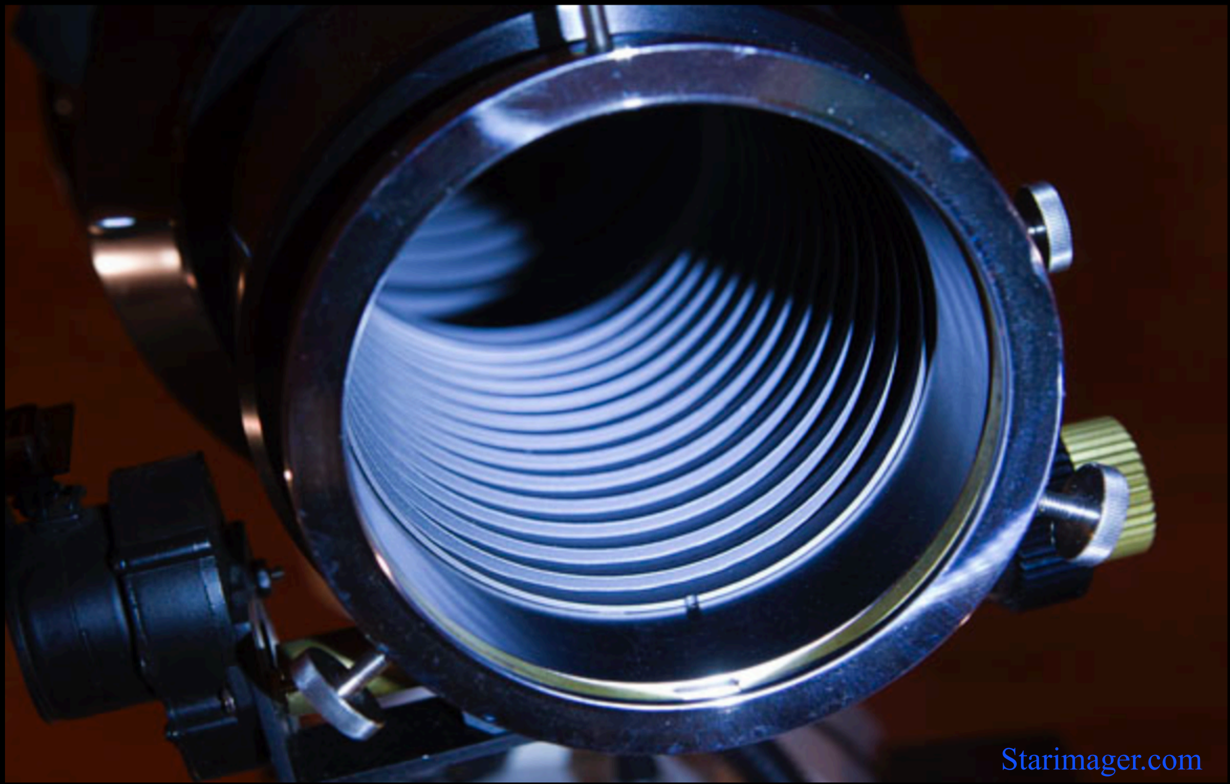
LIGO's focus solution

- Hartmann Wavefront Sensor to measure deformation
- Ring Heater (RH) to make cylindrical corrections
- CO2 Laser Projector to allow more irregular compensation



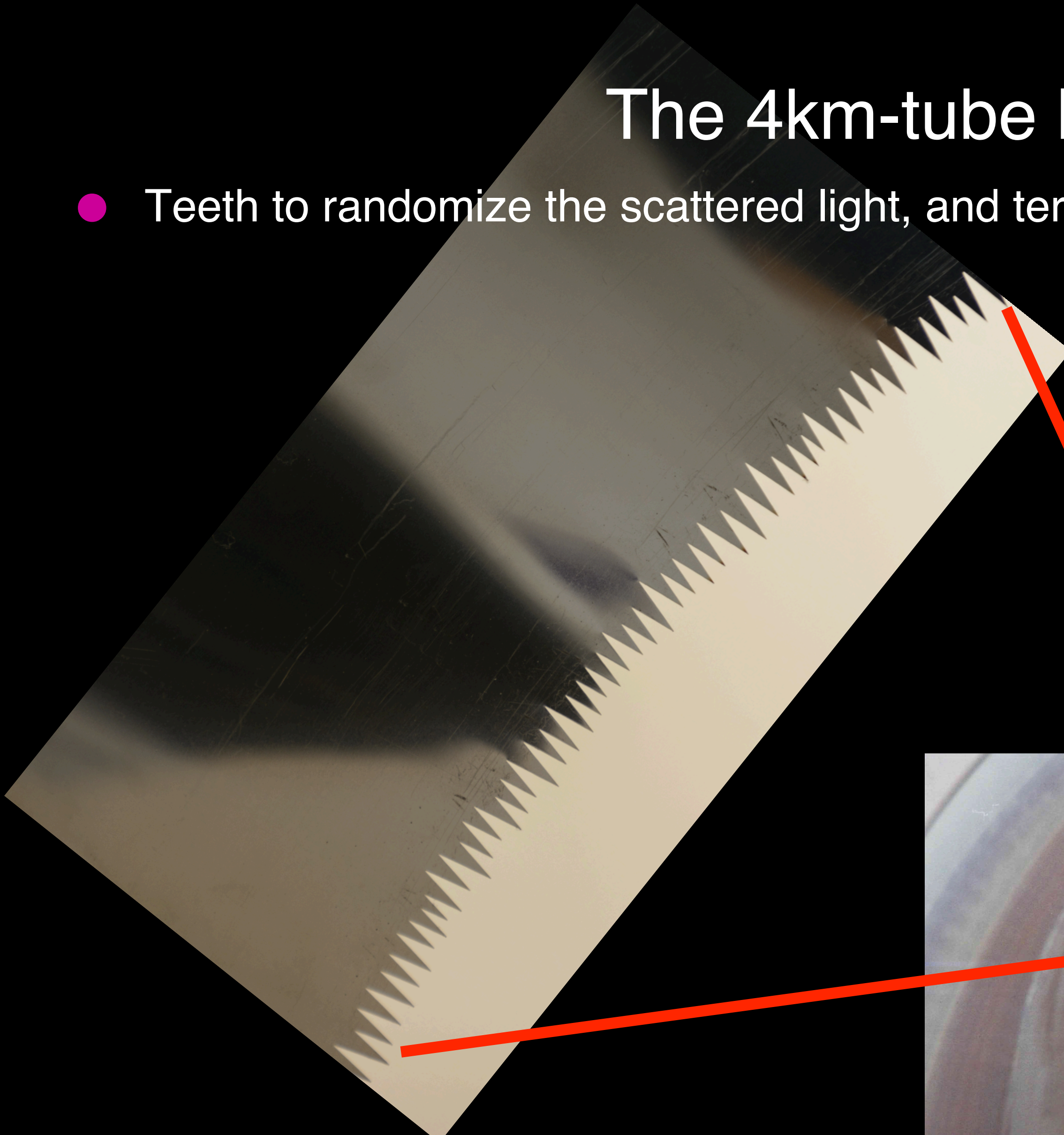
Telescope baffles

- To keep off-axis light from reaching the mirrors



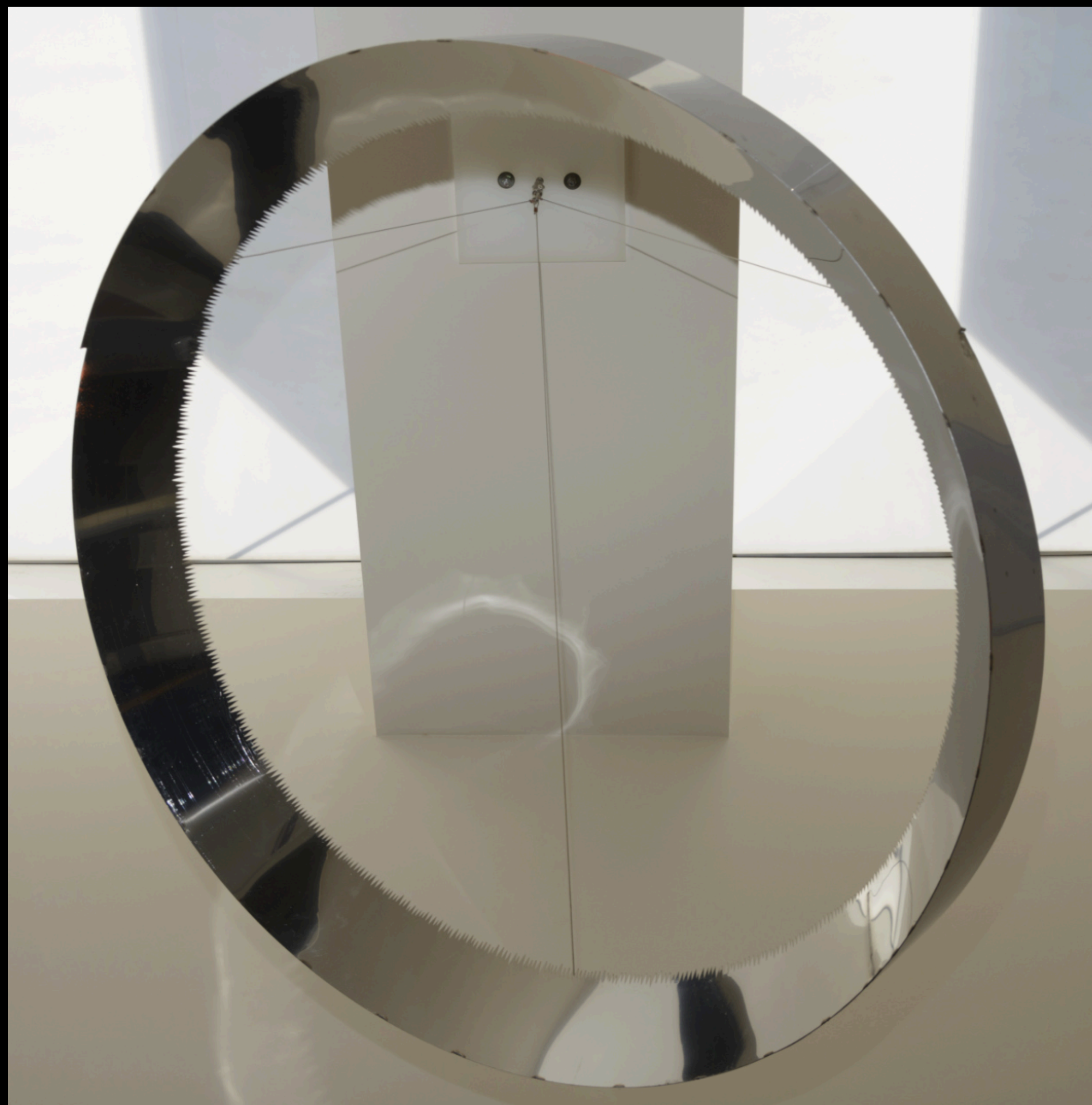
The 4km-tube baffles

- Teeth to randomize the scattered light, and terrorize the installers



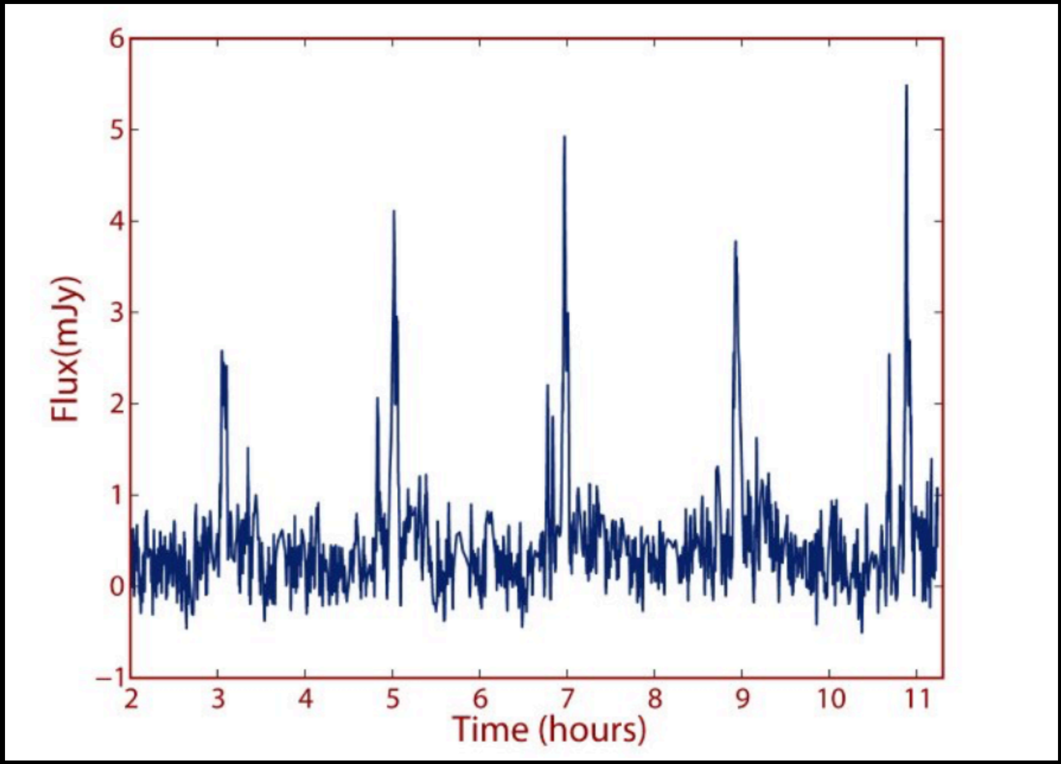
- Those installers, somewhere along 4km of tubing….

A baffle in a less forbidding space



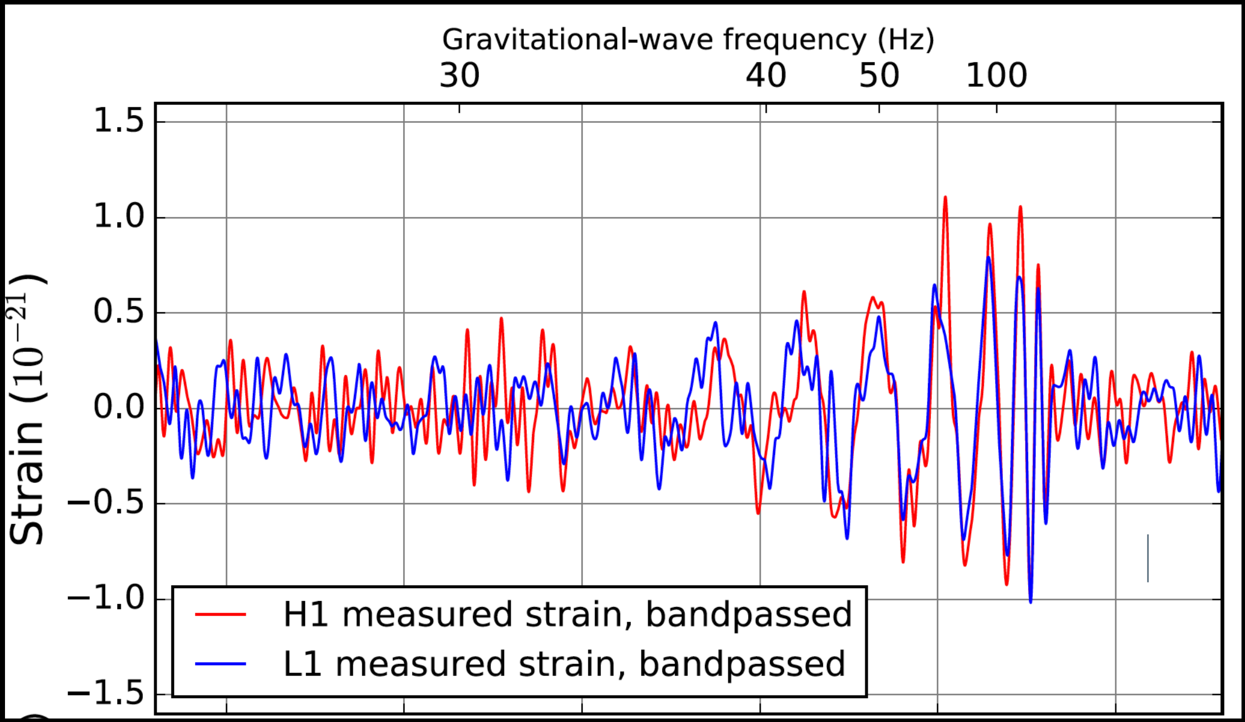
Time series from a Radio Telescope

- Radio emission from a rotating dwarf star
  - » A periodic pulse is detected when beams of radiation sweep across the Earth
- Measuring *power* – all values are positive (modulo noise!)



NUI Galway
OÉ Gaillimh

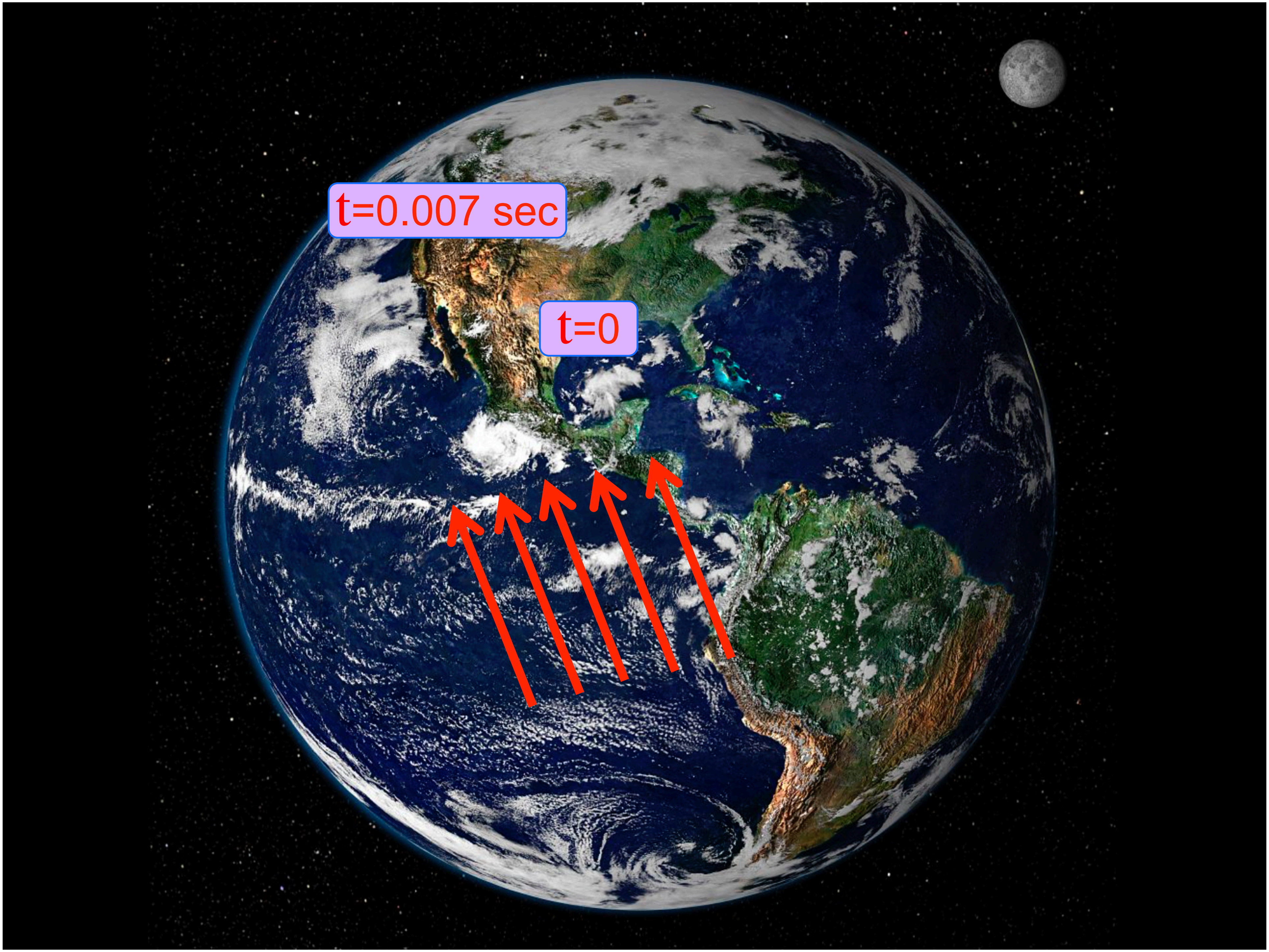
LIGO Time Series
Measuring *amplitude* – squeeze and stretch
Positive and negative values

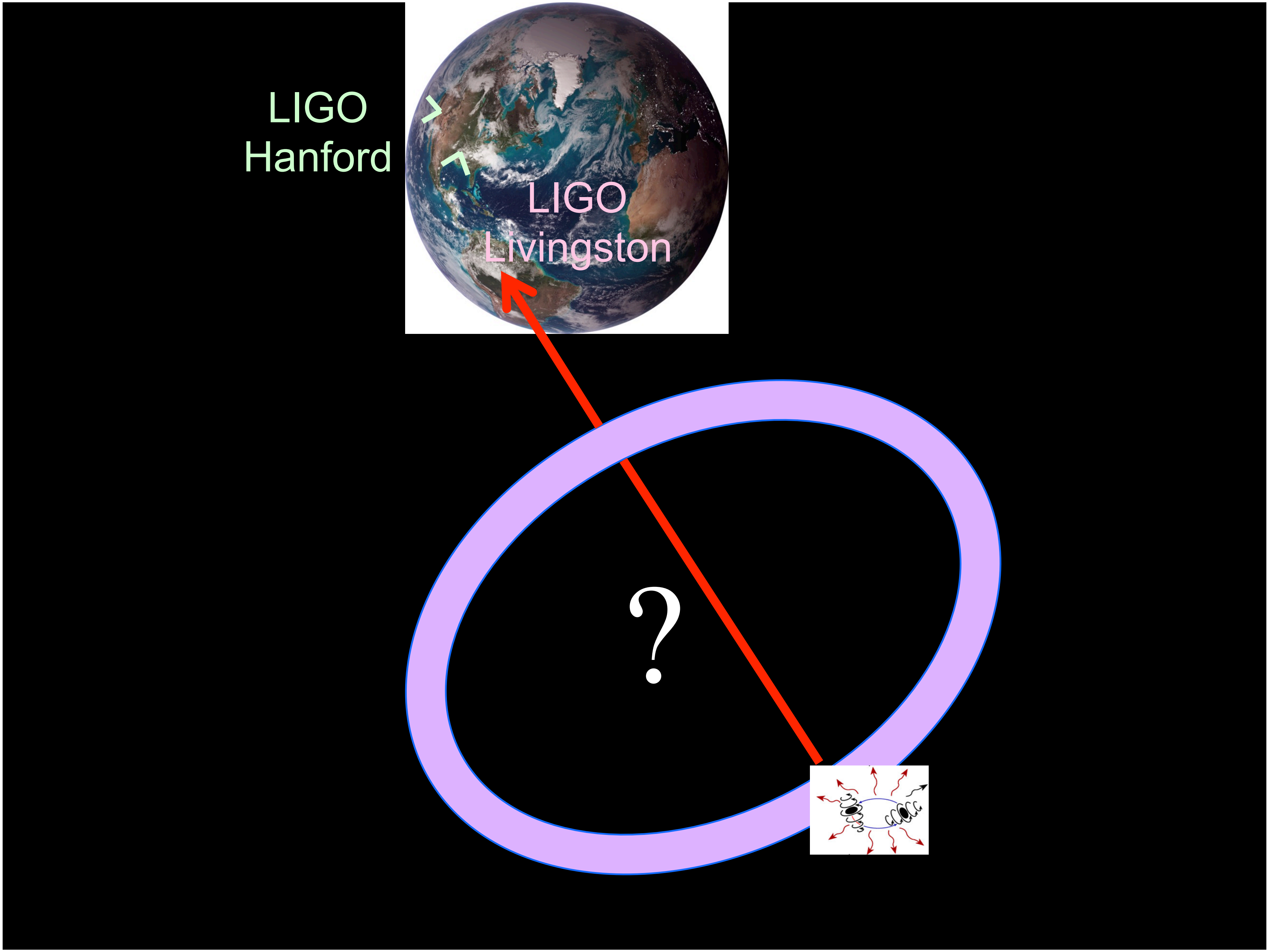


Contrast of Electromagnetic vs. Gravitational Waves

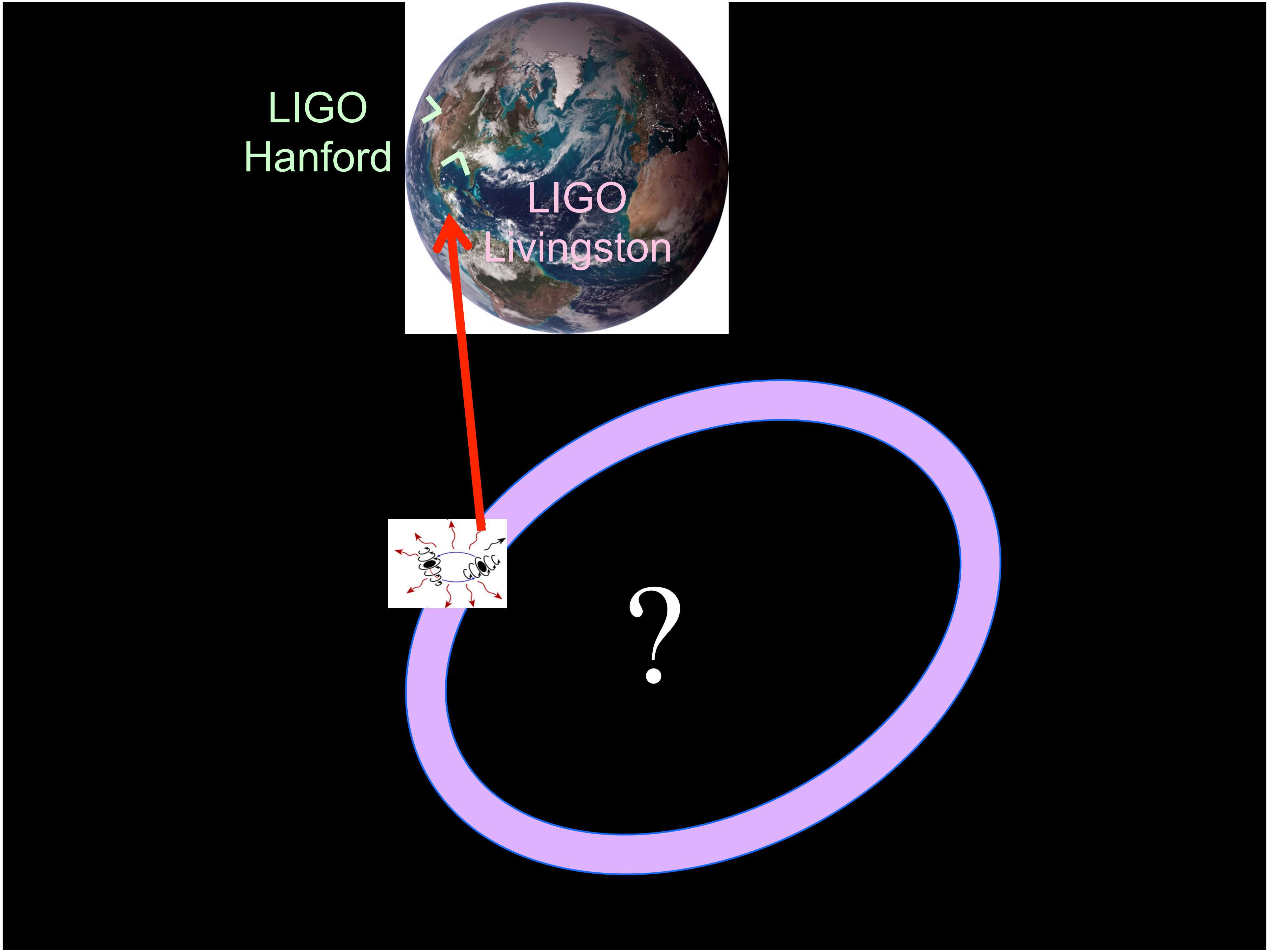
- **Visible, IR, Xray**
  - High spatial resolution
  - Relatively small masses radiating (atoms!)
  - Exterior surface of astronomical objects
  - Masked by intervening matter, $1/r^2$ fall-off
  - Scattered by intervening matter

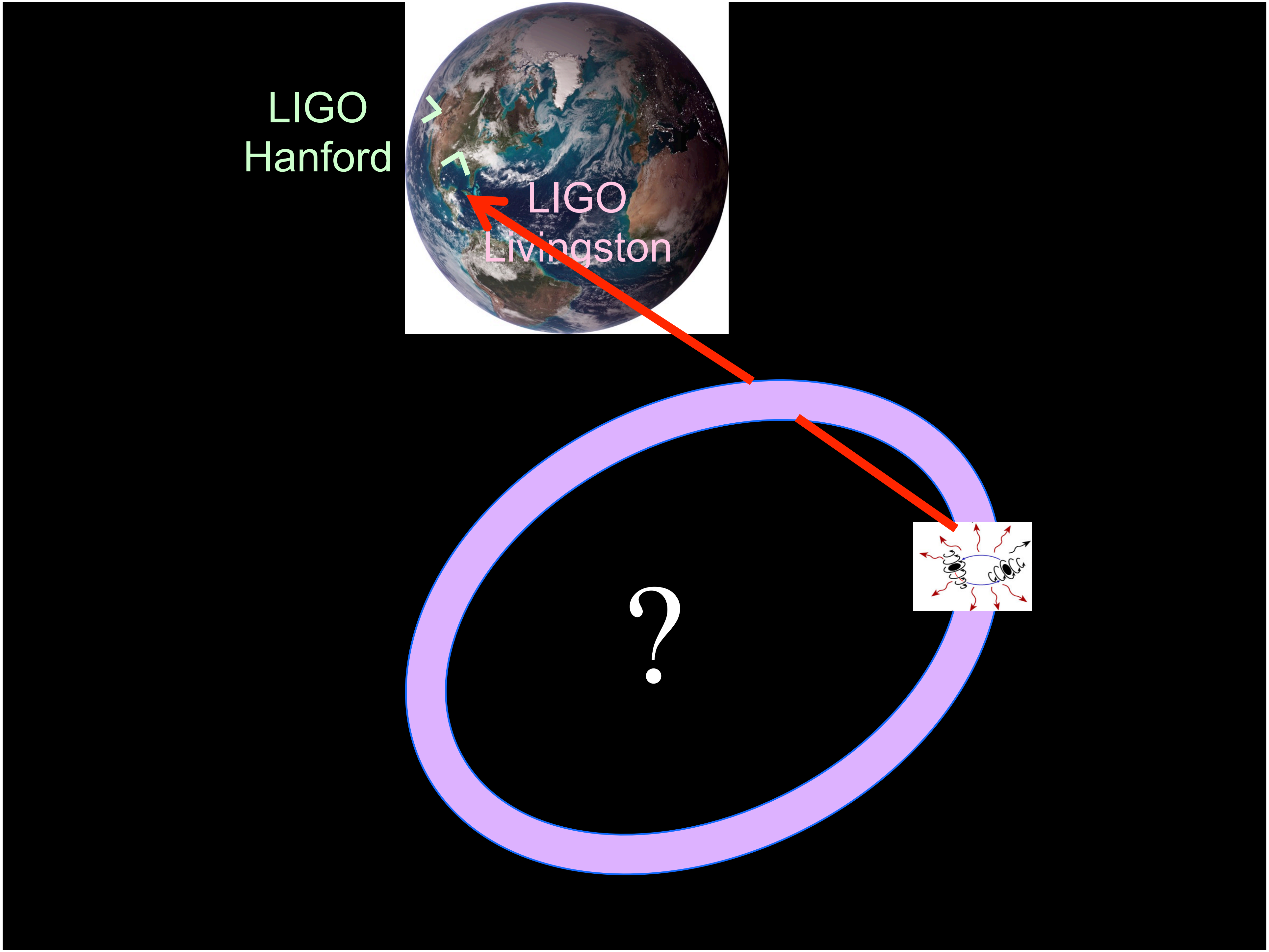
- **Gravitational waves:**
  - Low spatial resolution
  - Coherent motion of Huge masses
  - Deep interior of objects – where the mass is
  - No masking, $1/r$ fall-off
  - No scattering


t=0.007 sec
t=0

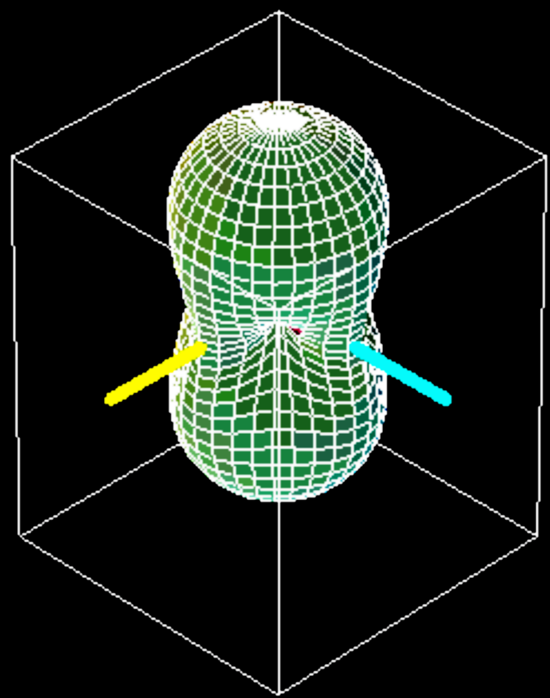


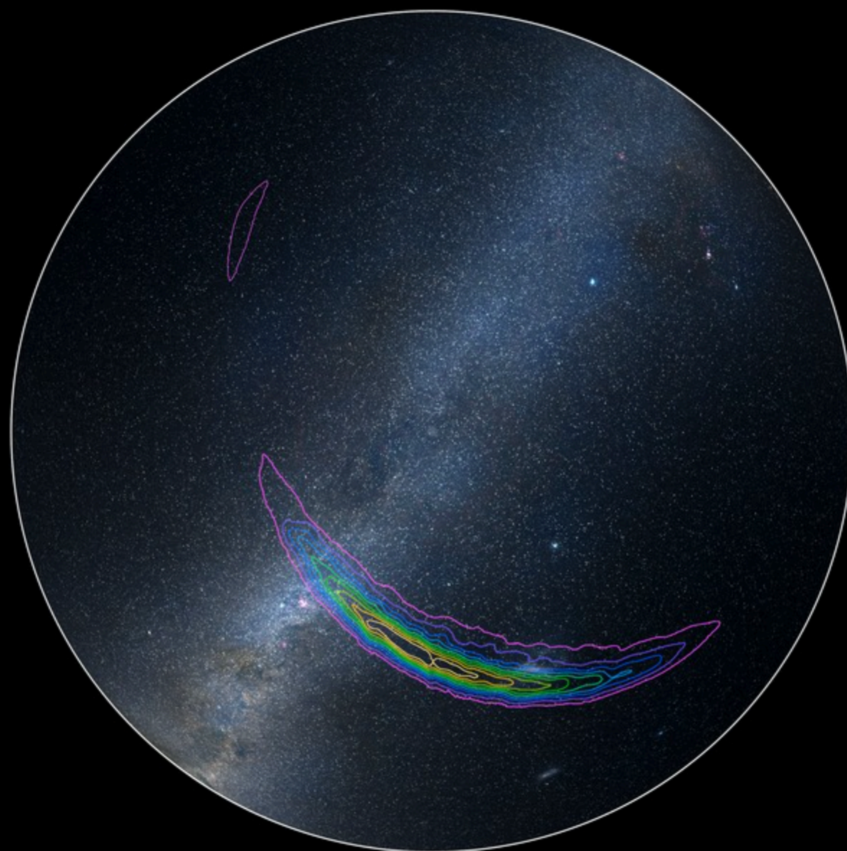
LIGO
Hanford
LIGO
Livingston
?


LIGO
Hanford
LIGO
Livingston
?


LIGO
Hanford
LIGO
Livingston
?

Source direction – a bit better defined than the complete annulus





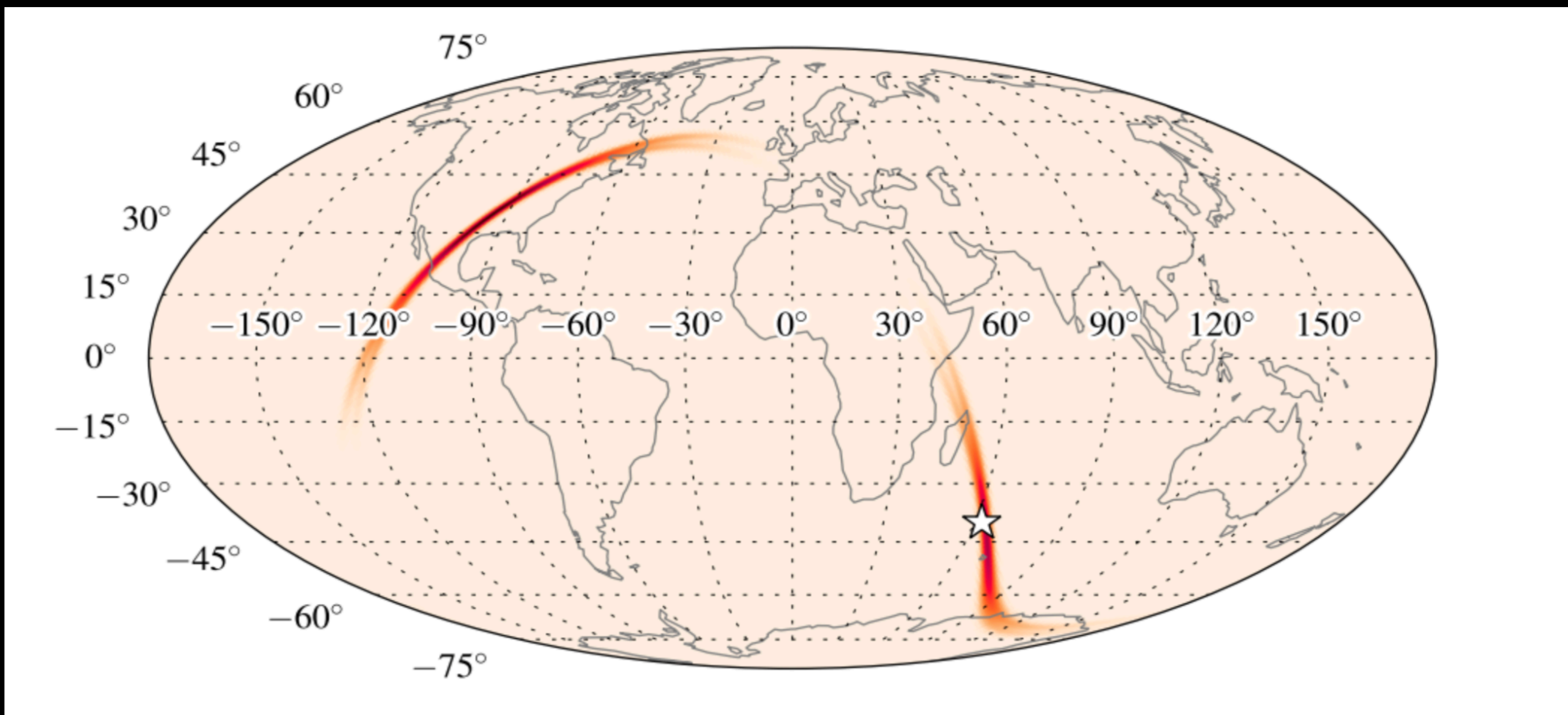
- Only weak angular sensitivity from a single detector
- With two detectors, signal time-of-arrival can be used to identify an annulus in the sky of possible source positions; better than nothing

How can we do better in localizing
the source?

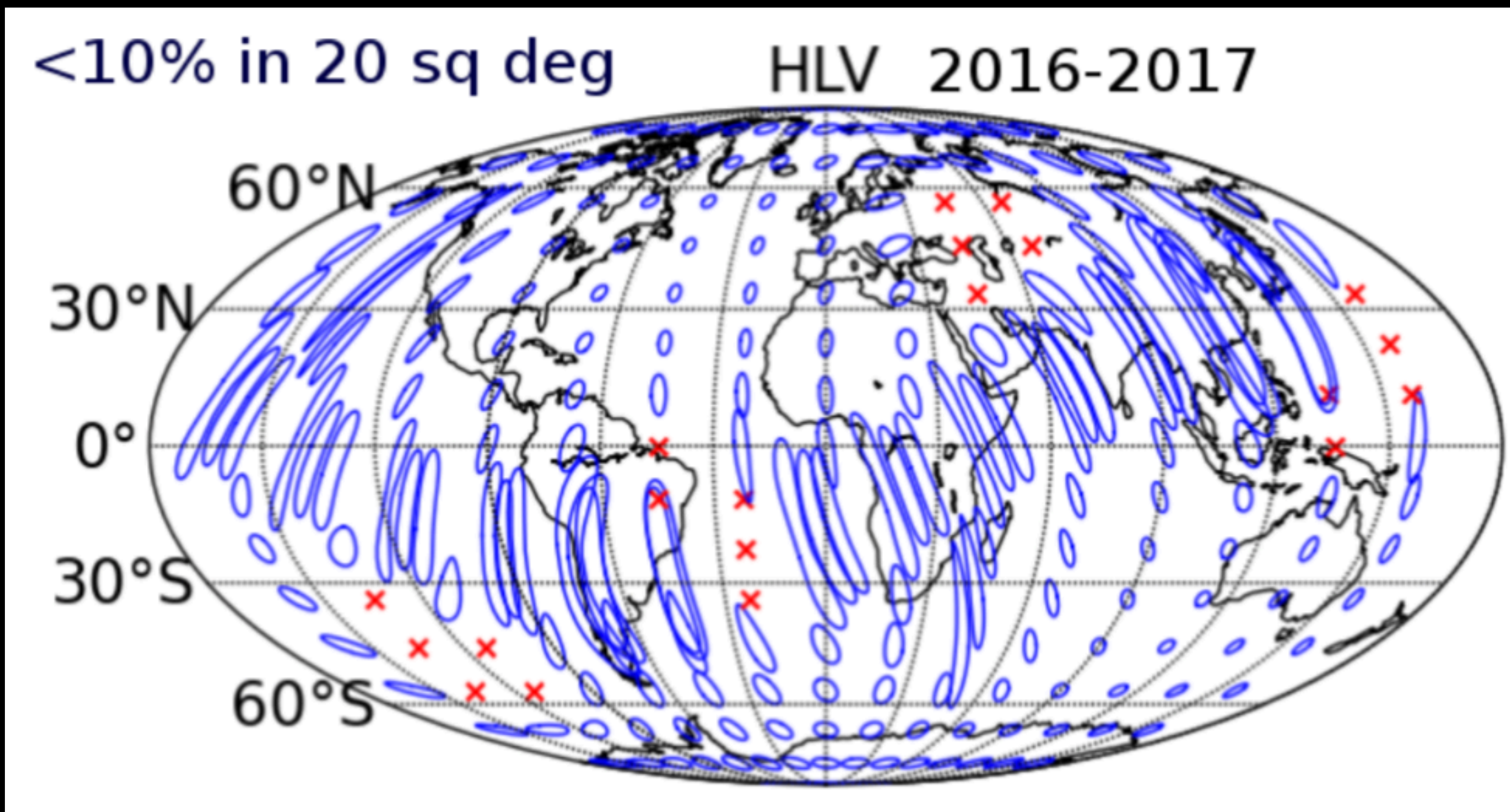
How will the instruments evolve?

What other sorts of sources
might we see?

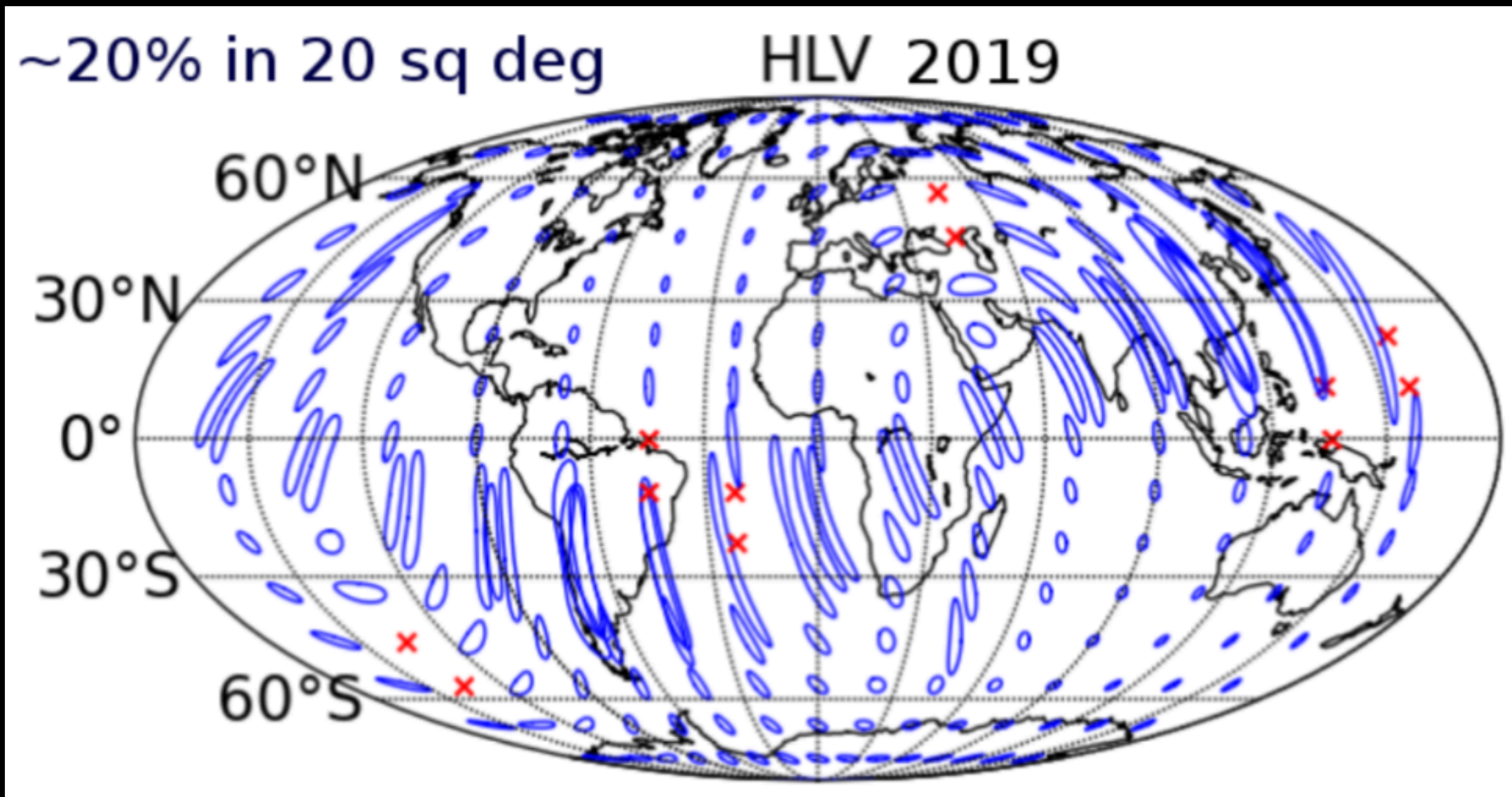
Present Sensitivity/configuration:
2 detectors, 1/3 goal sensitivity
1 signal in 1 month of observation



2016-17 Sensitivity/configuration:
3 detectors (add Virgo), ~1/2 goal sensitivity
~2-3 signals per month of observation



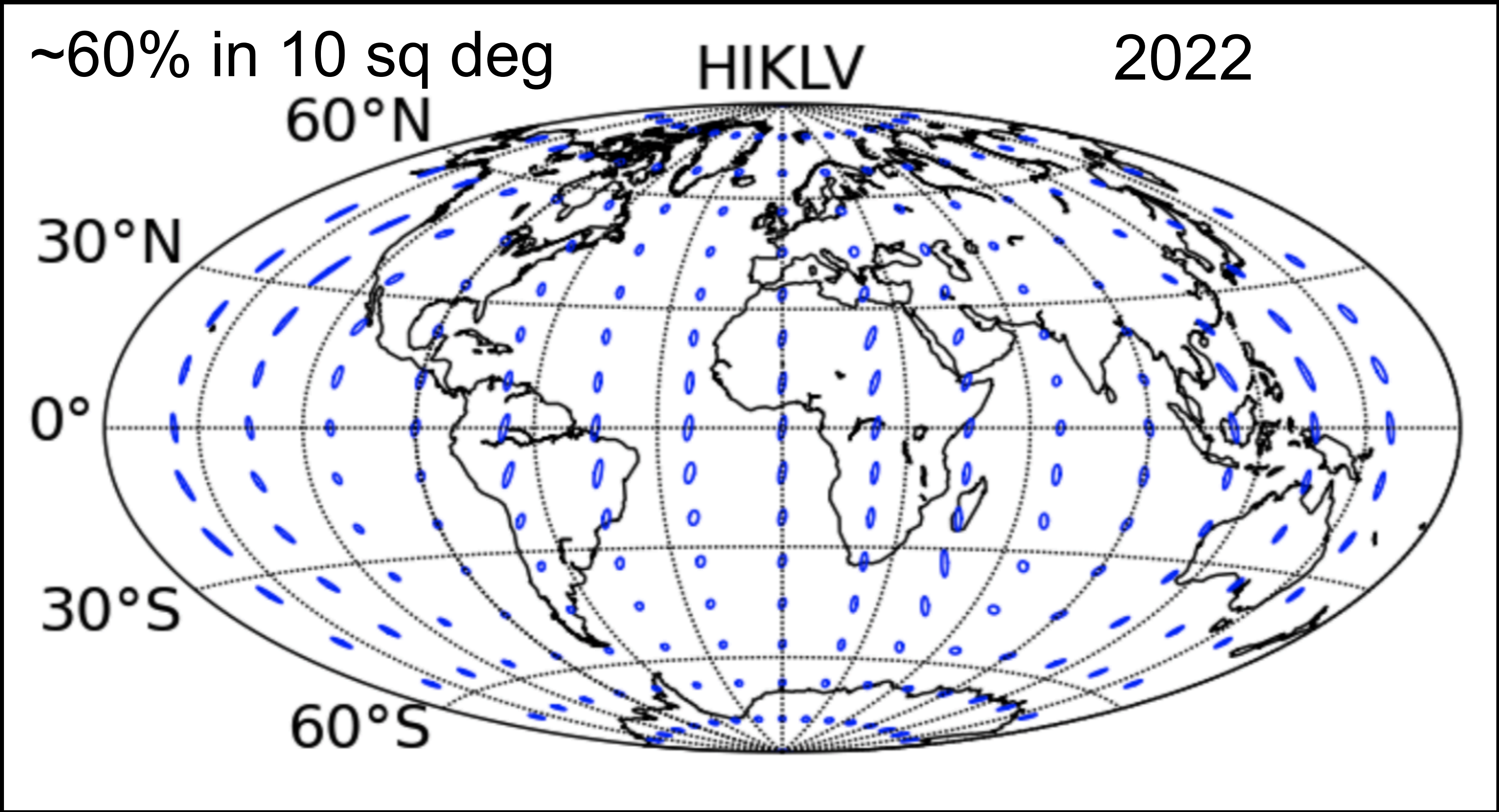
2018-19 Sensitivity/configuration:
3 detectors, full goal sensitivity
~1 signal *per day*



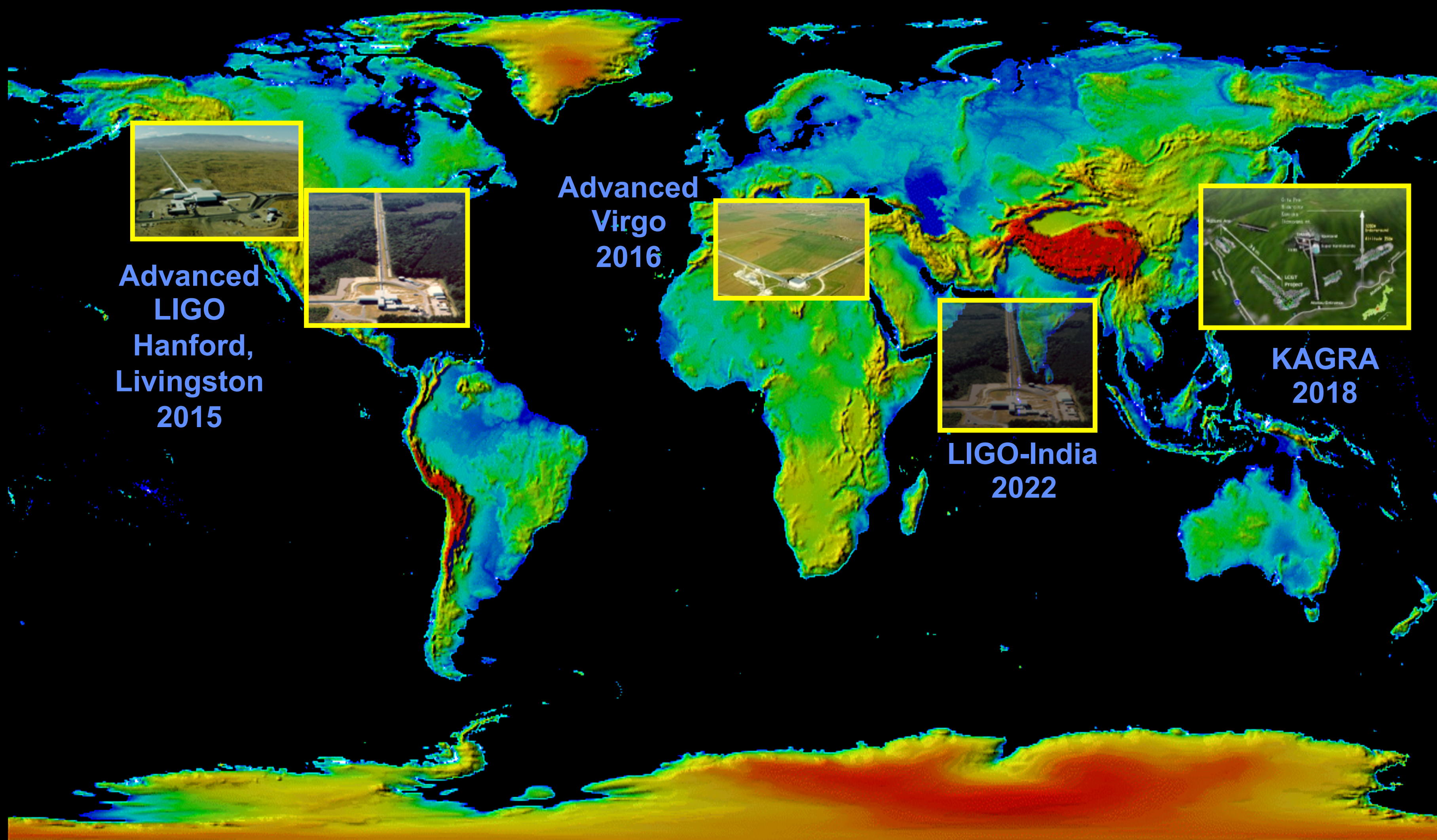
2022 Sensitivity/configuration:

5 detectors (add India and Japan)

far improved source localization



The advanced GW detector network



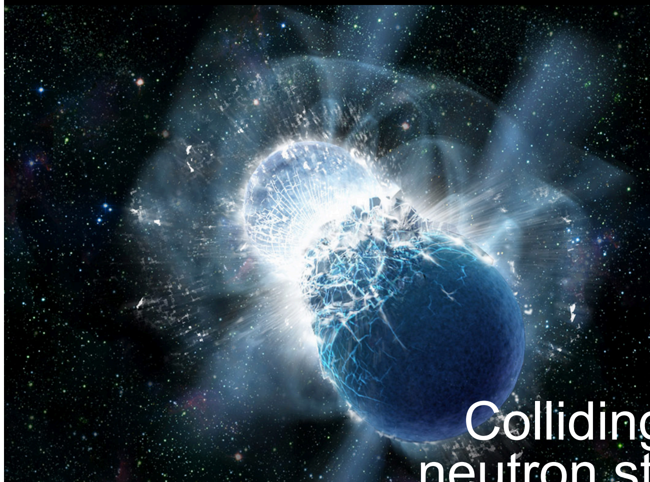
LIGO Scientific Collaboration

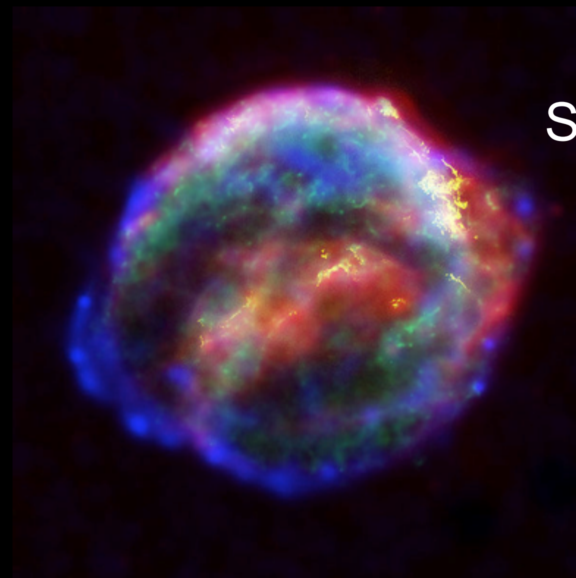
www.ligo.org 1000+ members, 90 institutions, 16 countries

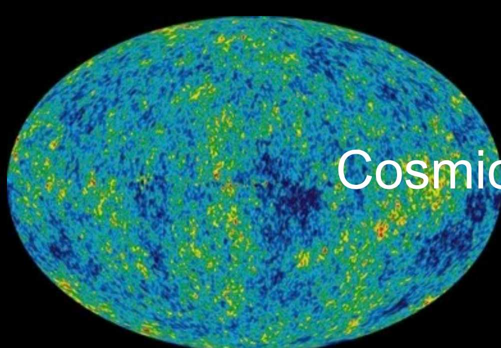
Slide: Gabriela González


22:55:58
15:55:58
H1:DARM_ERR

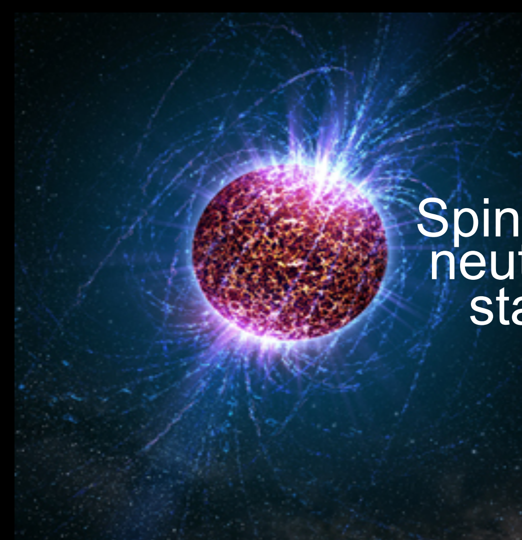
Possible future sources for signals



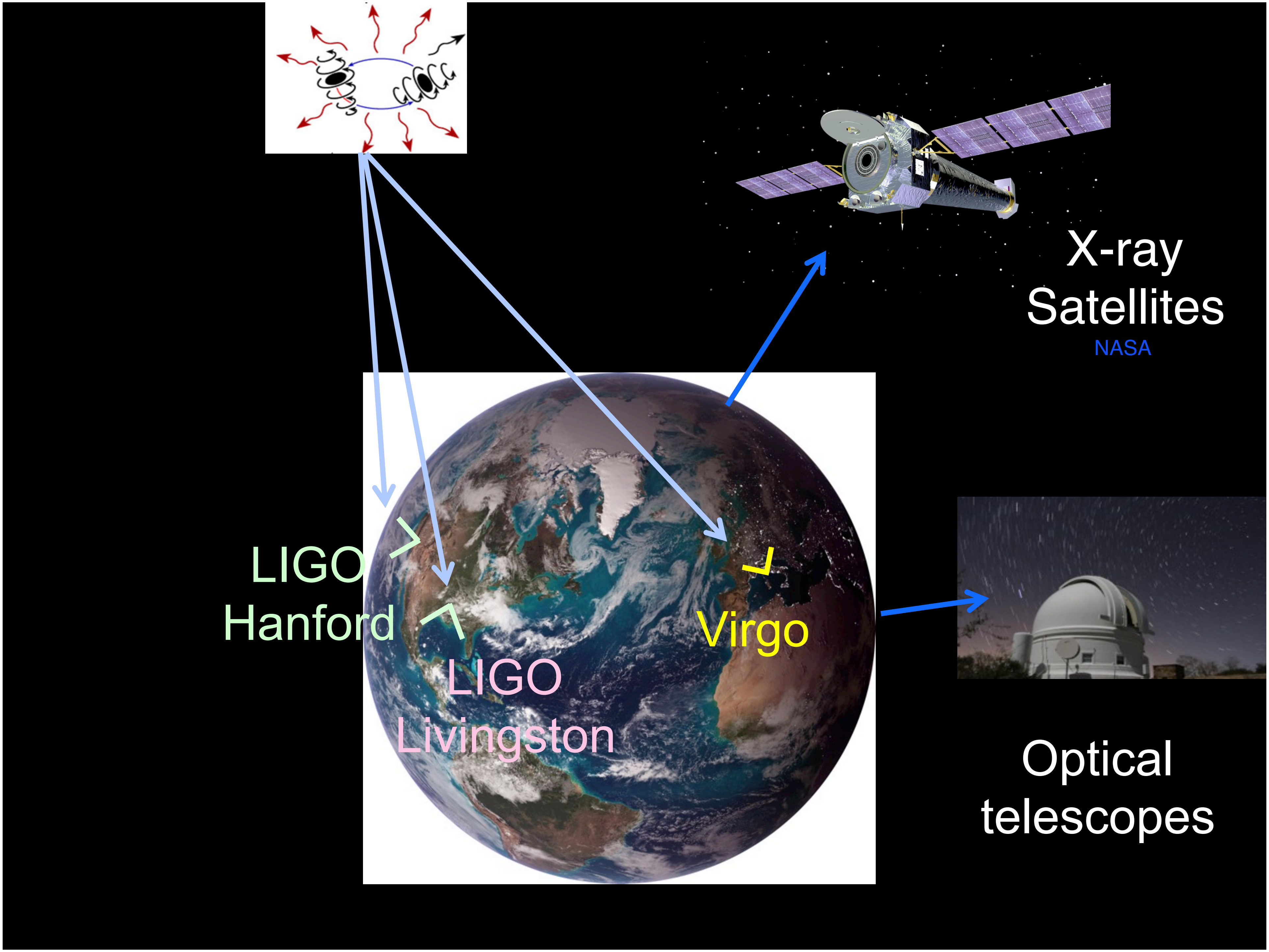




NASA/WMAP Science Team

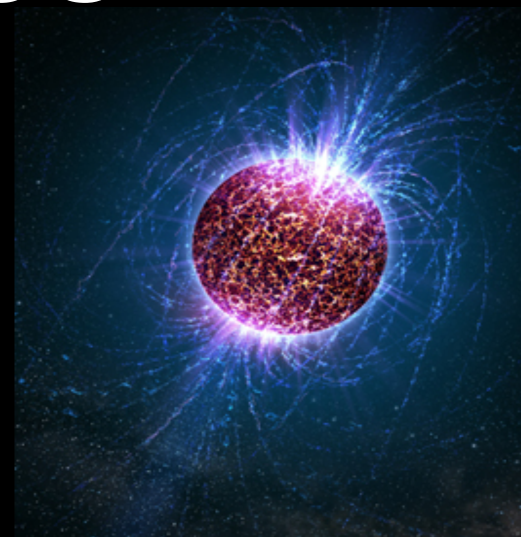


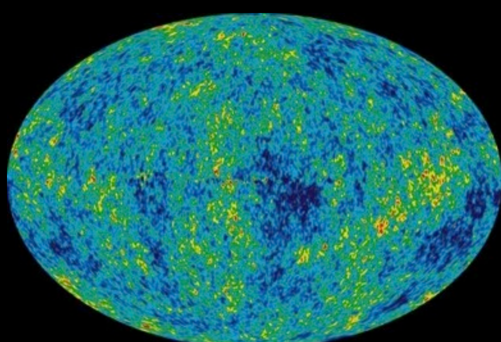
Reed, Penn State



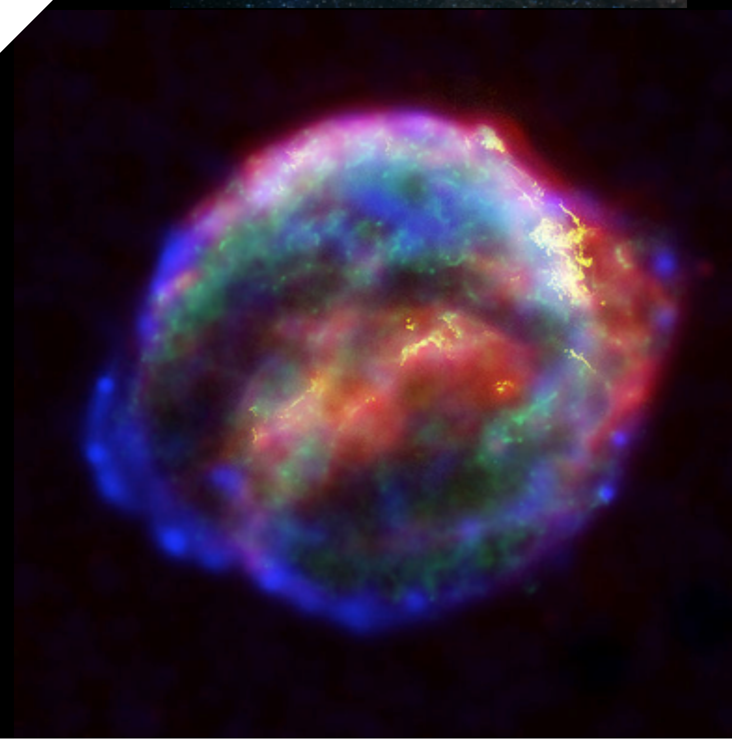
X-ray
Satellites
NASA
LIGO
Hanford
LIGO
Livingston
Virgo
Optical
telescopes

Surprises





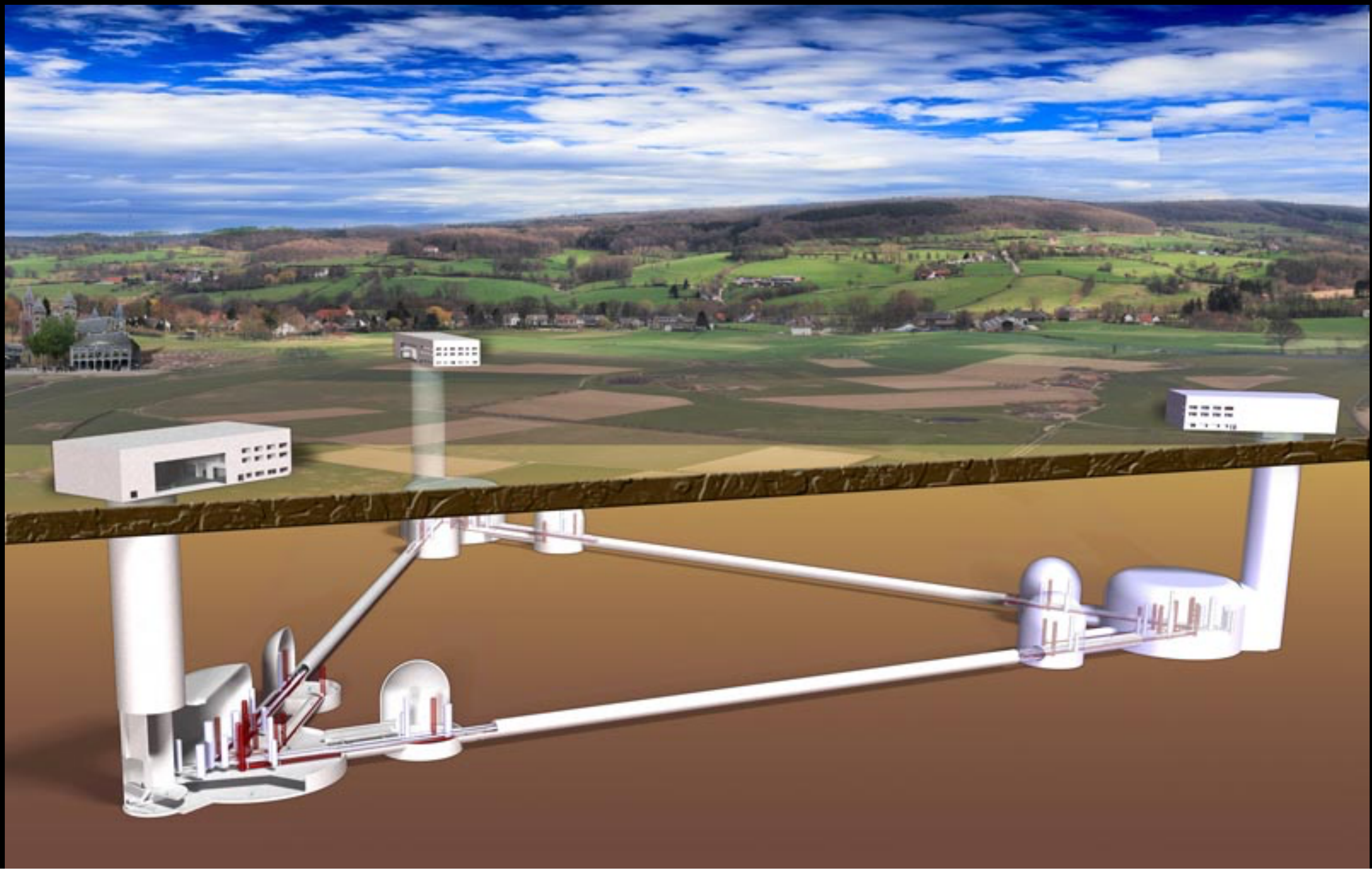
NASA/WMAP Science Team



?

Future Improvements: Reaching even further

- Want to fully exploit the instrument we designed
- Ultimately will want more sensitive instruments – longer arms, quieter places
- On earth….



…and in Space: LISA

- Once you are there, vacuum is inexpensive – make *very* long arms
  - Very high signal-to-noise – precision tests of gravitation
- Can observe much larger masses – Galaxies with black holes of a billion solar masses coalescing
- Analogous to adding Radio Astronomy to Optical

AEI Max Planck