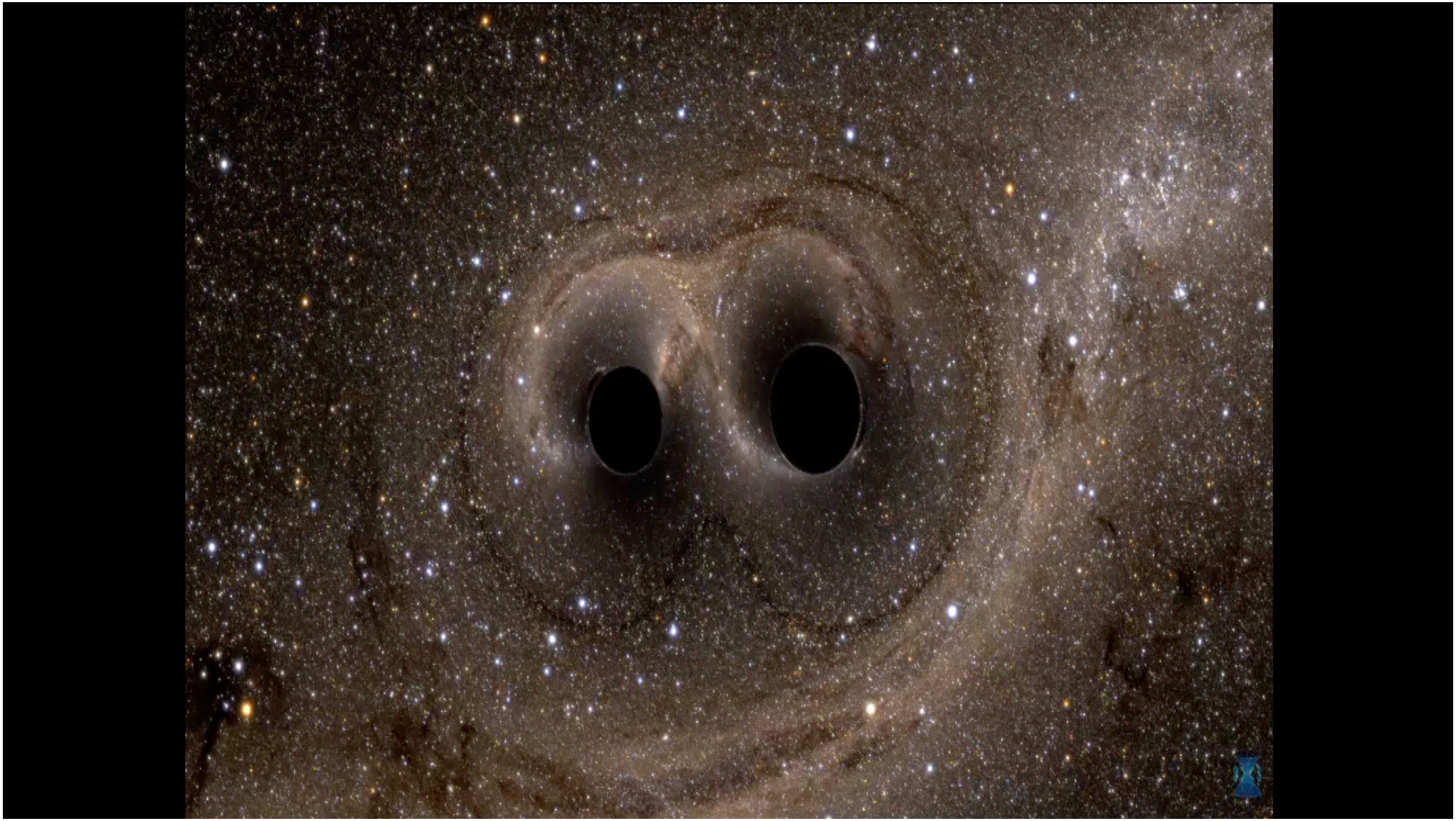
# Gravitational waves —
# The New Cosmic Messenger

Australian Institute of Physics
Perth 11 December 2018
G1802274

David Shoemaker
For the LIGO and Virgo Scientific Collaborations

Credits
Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); Phys. Rev. Lett. 119, 161101 (2017);
Phys. Rev. Lett. 119, 141101 (2017); Phys. Rev. Lett. 118, 221101 (2017);
Phys. Rev. Lett. 116, 241103 (2016)
Simulations: SXS Collaboration; LIGO Lab and Collaboration
Localization: S. Fairhurst arXiv:1205.6611v1
Photographs: LIGO Laboratory; MIT; Caltech
…And as noted on slides



# 1609: Galileo observes the heavens (and lands in jail)

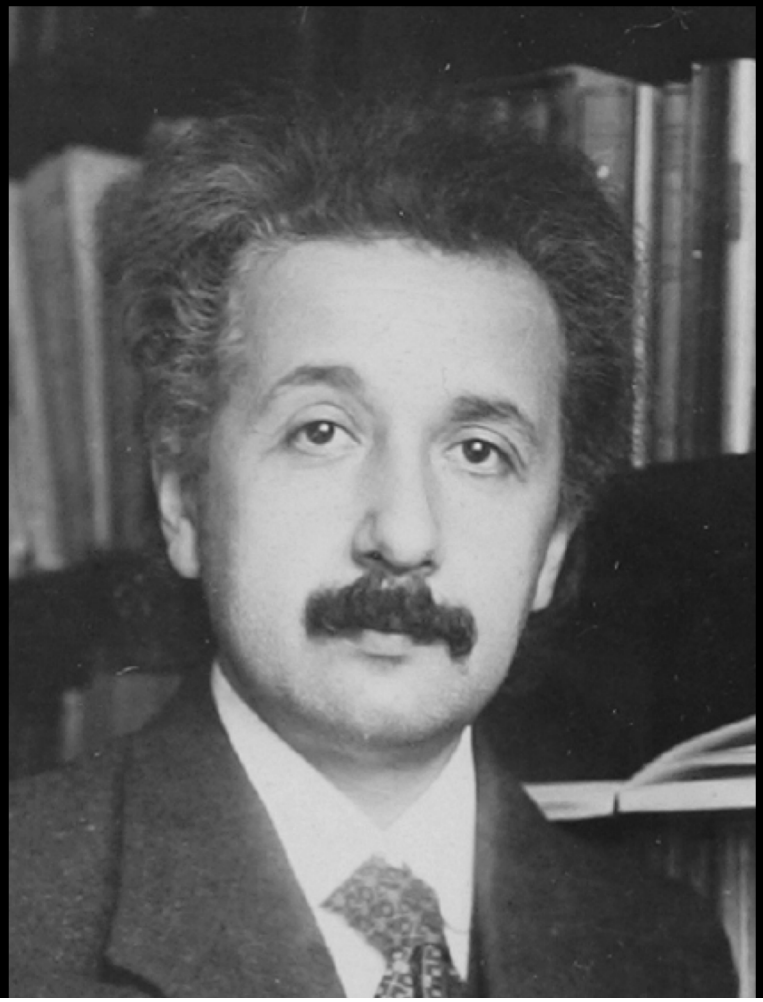
Hevelius, contemporary of Galileo

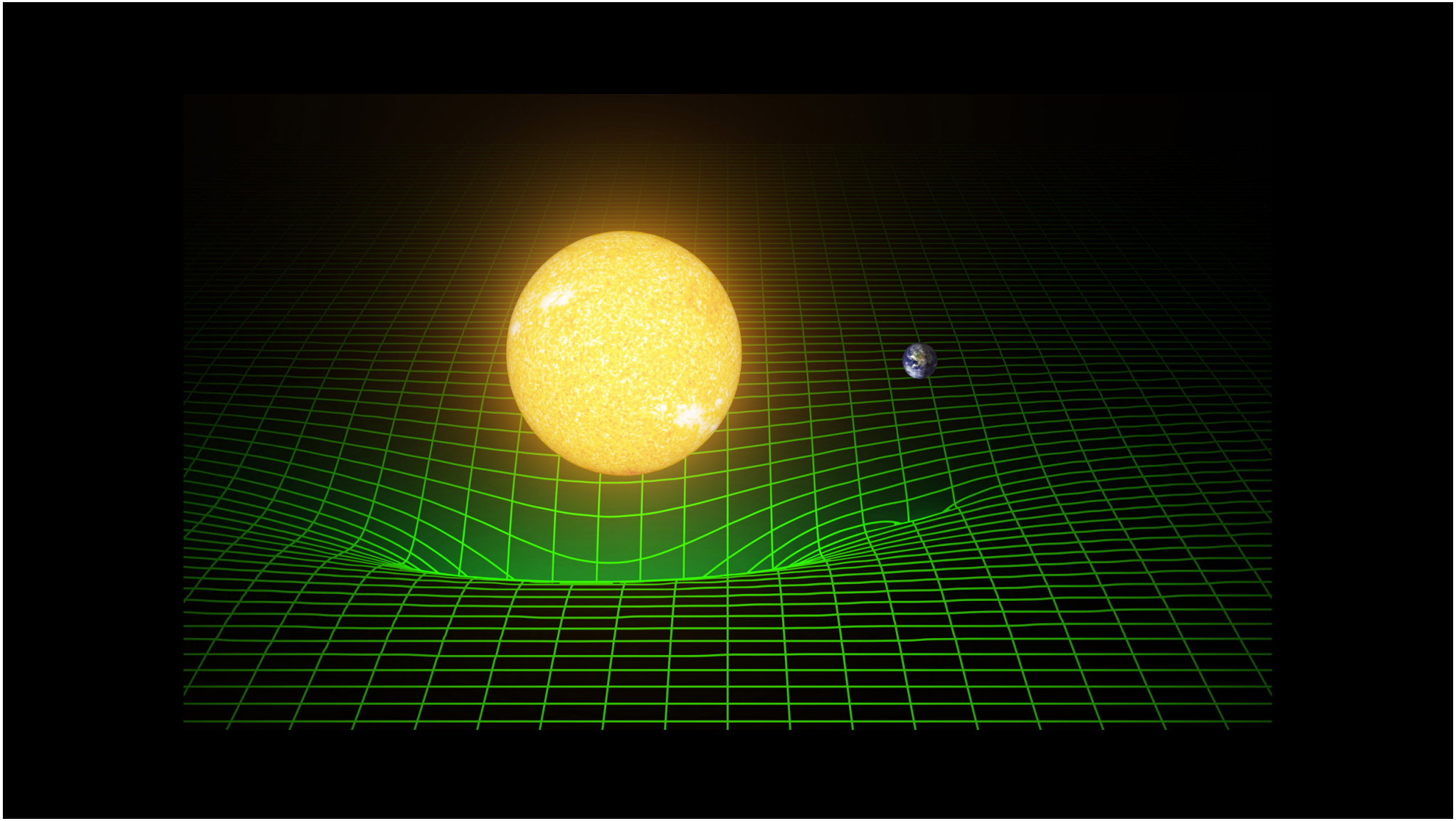
Isaac Newton, 1687:

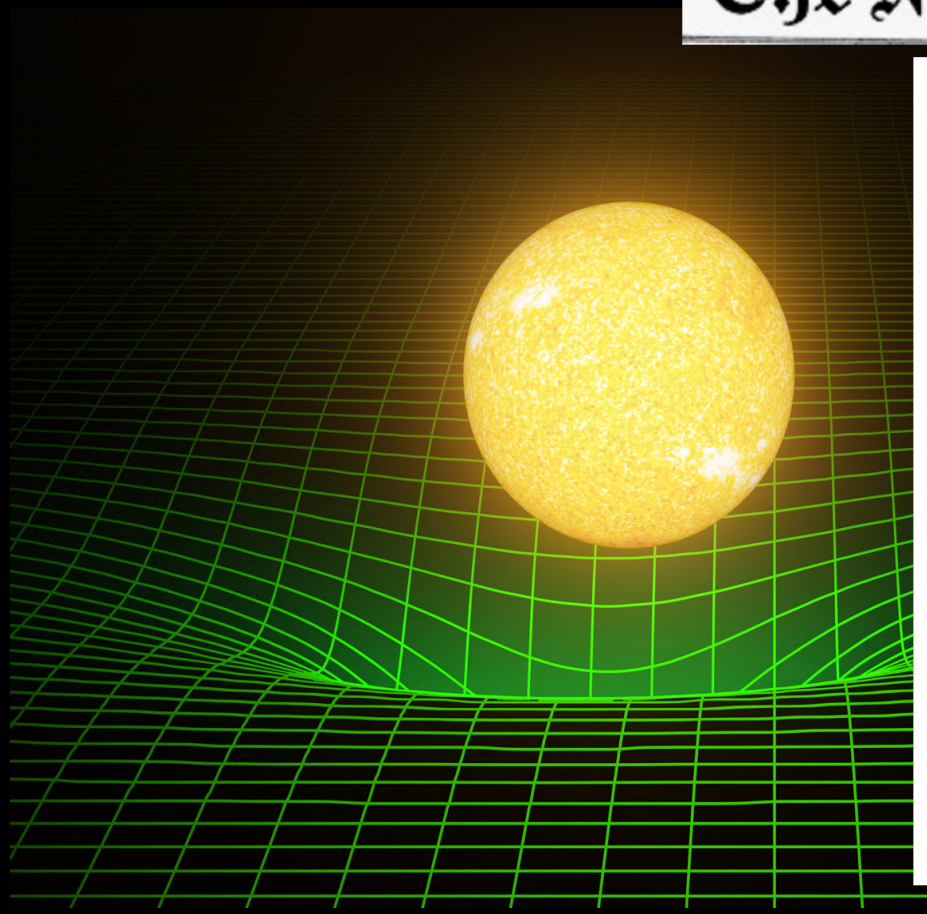
*Philosophiæ Naturalis Principia Mathematica*


aps.org

Albert Einstein
1915







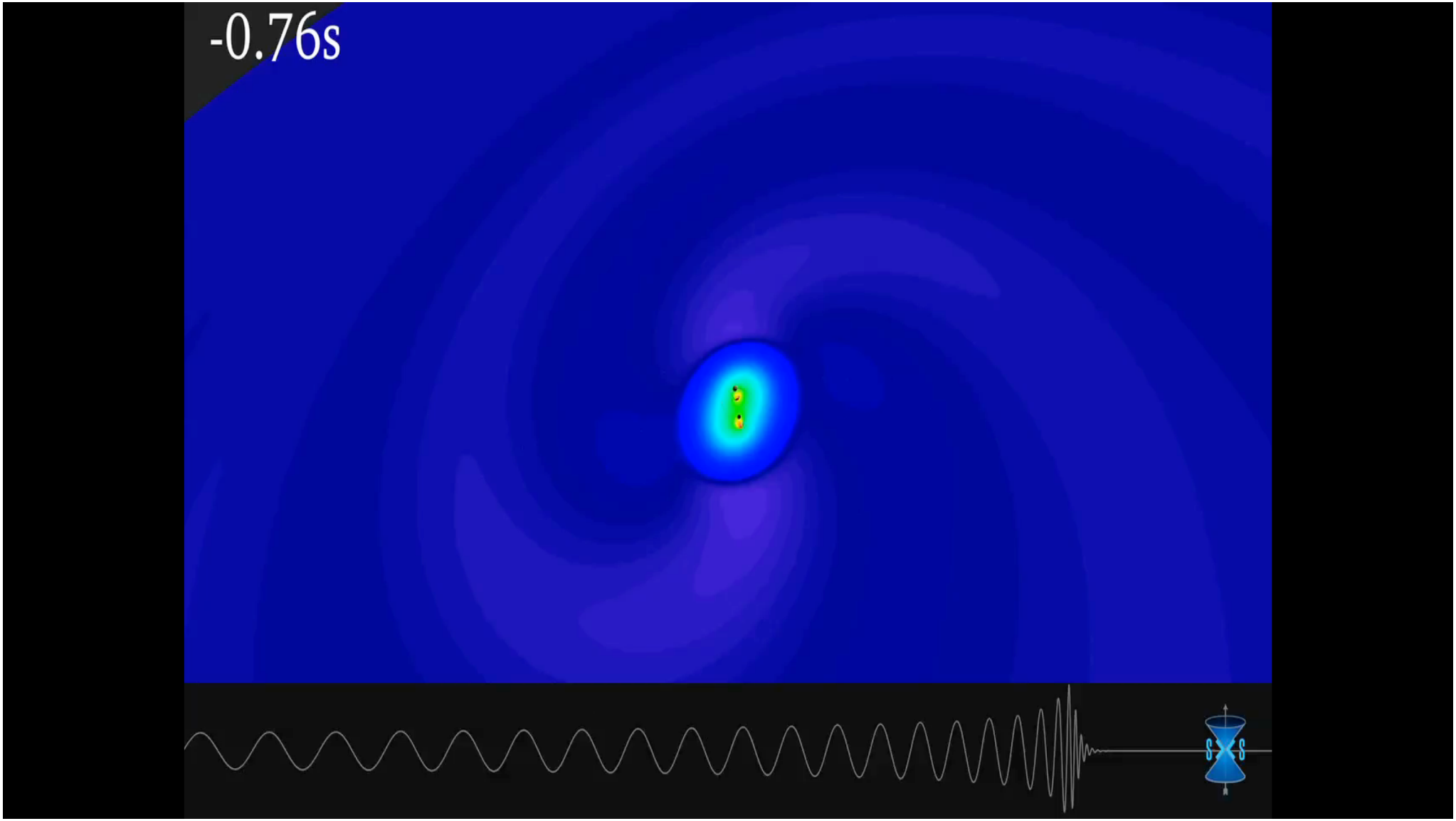
The New York Times.

# LIGHTS ALL ASKEW IN THE HEAVENS

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

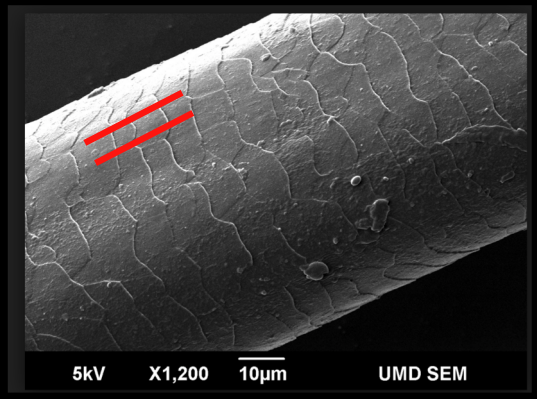
## EINSTEIN THEORY TRIUMPHS

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


-0.76s

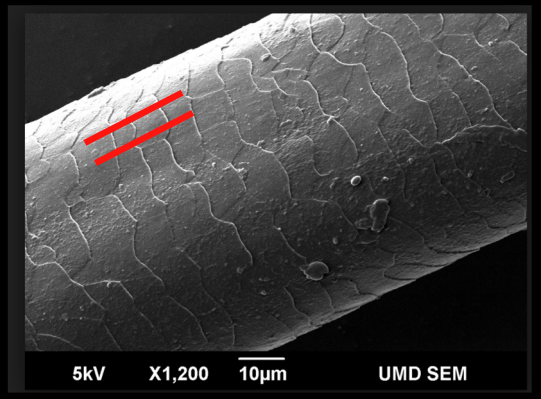
Effect on Earth: *tiny* change in length of Meter Stick

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




Then…

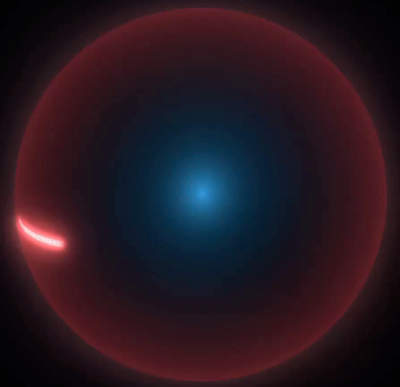
From a Meter to
1/10 human hair is
a factor of 1 million



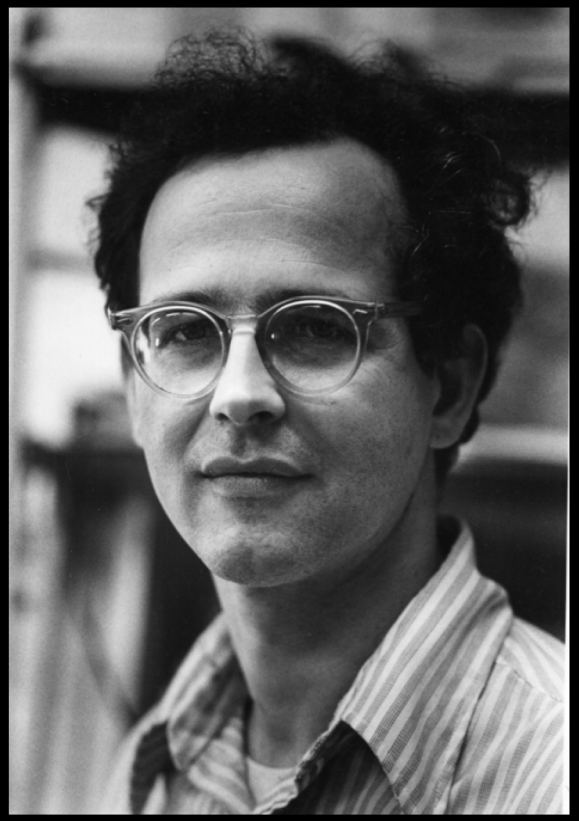

Divide that by a million

Divide that by a *billion*

**That's $10^{-21}$m**



# Rai Weiss, circa 1967



gravitational wave, and it is assumed that all components of this 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

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

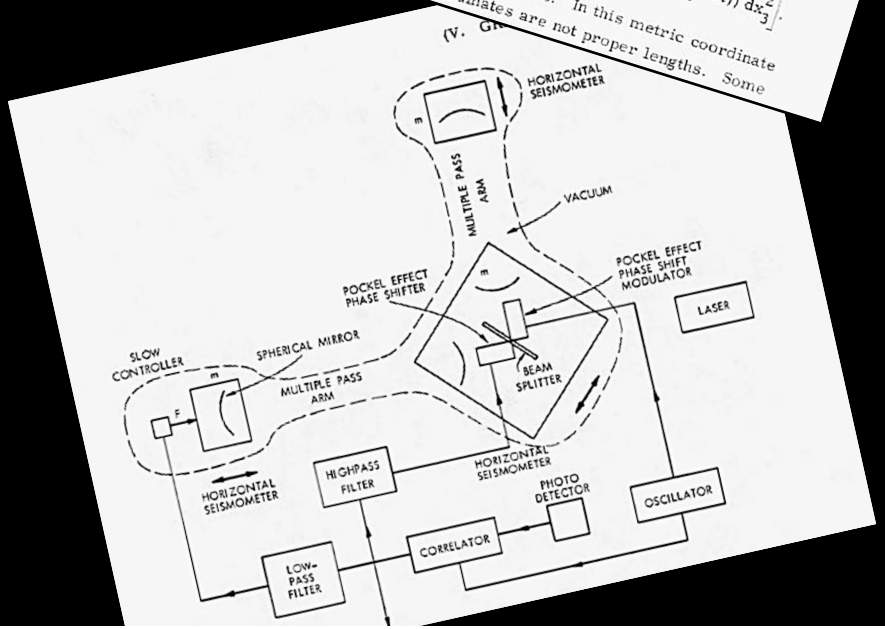
with $h_{22} = -h_{33}$, and $h_{23} = h_{32}$. The tensor components have the usual functional dependence $f(x_1 - ct)$.

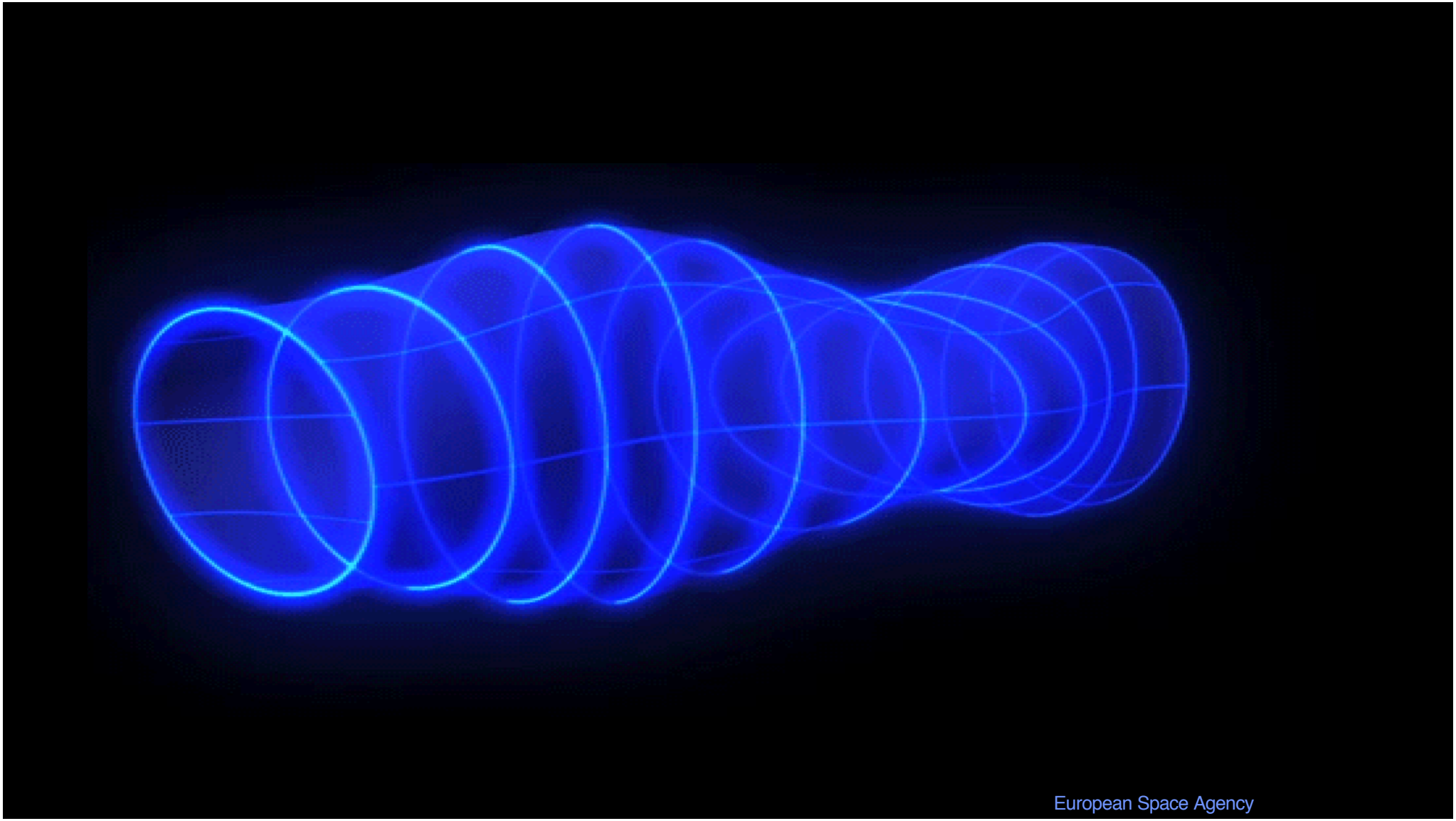
To gain some insight into the meaning of a plane gravitational wave, assume that the wave is in the single polarization state $h_{23} = h_{32} = 0$, and furthermore let $h_{22} = -h_{33} = h \sin(kx_1 - \omega t)$. The interval between two neighboring events is then given by

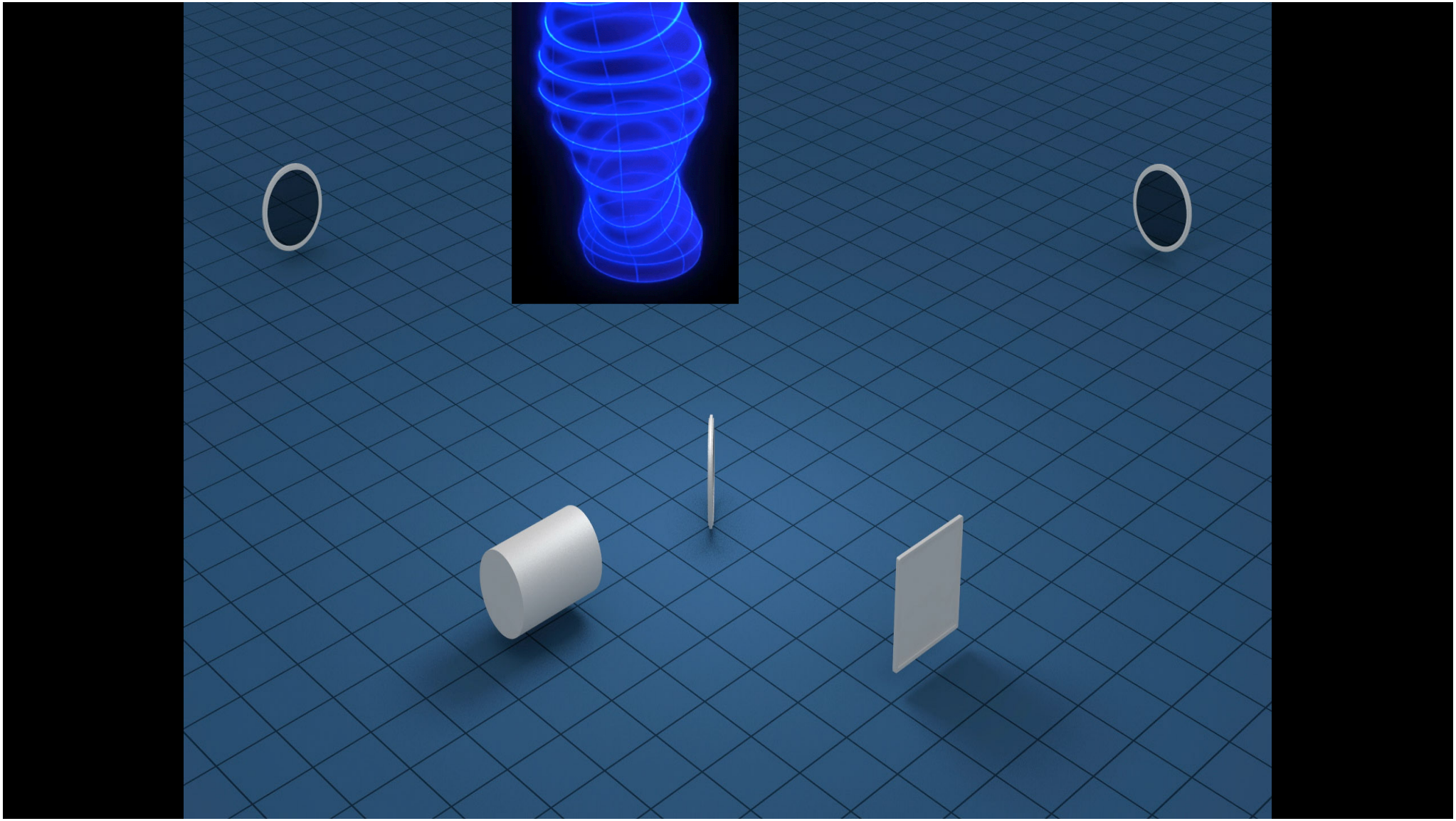
$$ds^2 = g_{ij}\,dx^i dx^j = c^2dt^2 - \left[dx_1^2 + (1 + h\sin(kx_1 - \omega t))\,dx_2^2 + (1 - h\sin(kx_1 - \omega t))\,dx_3^2\right].$$

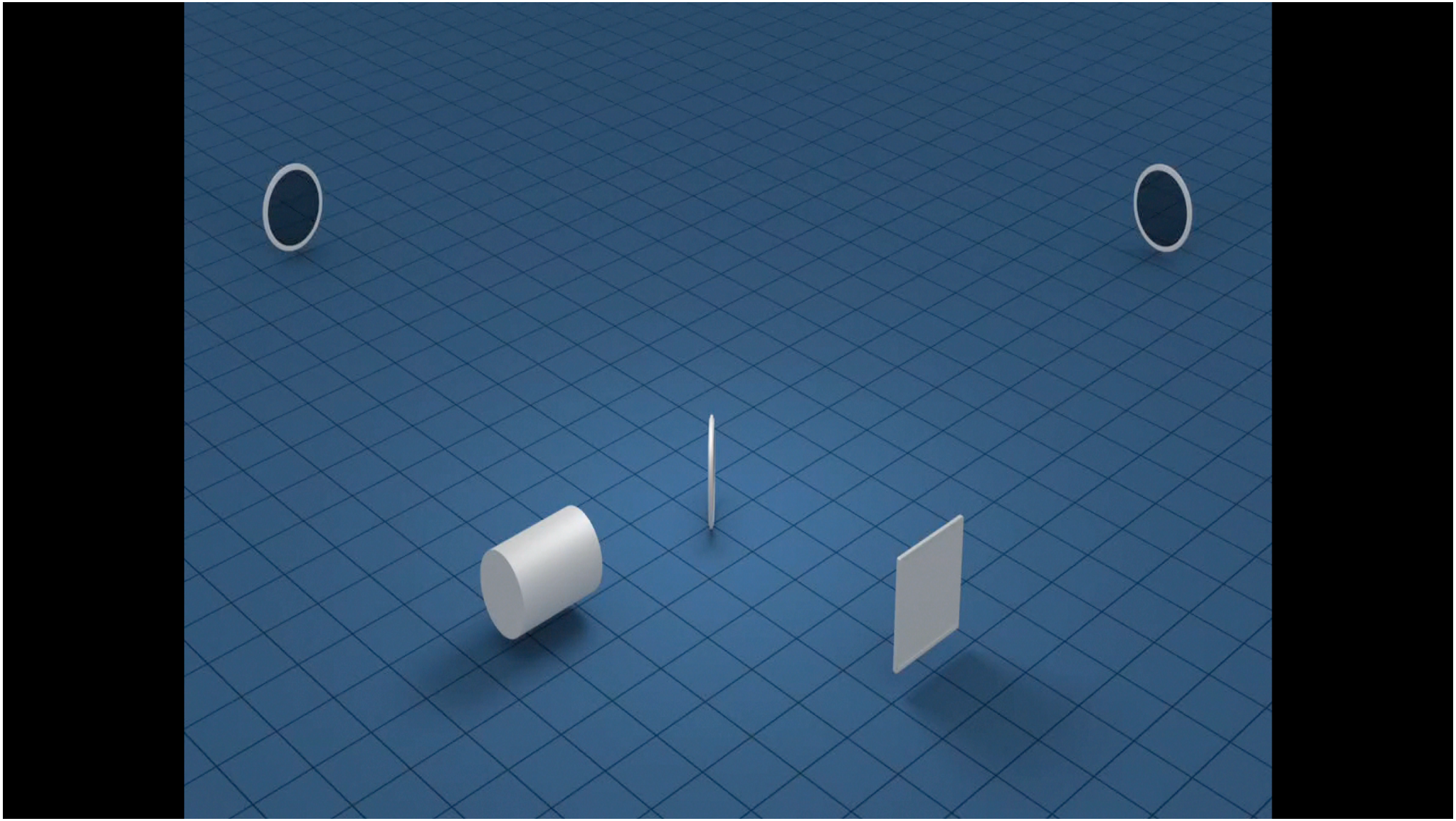
The metric relates coordinate distances to proper lengths. In this metric coordinate time is proper time; however, the spatial coordinates are not proper lengths. Some

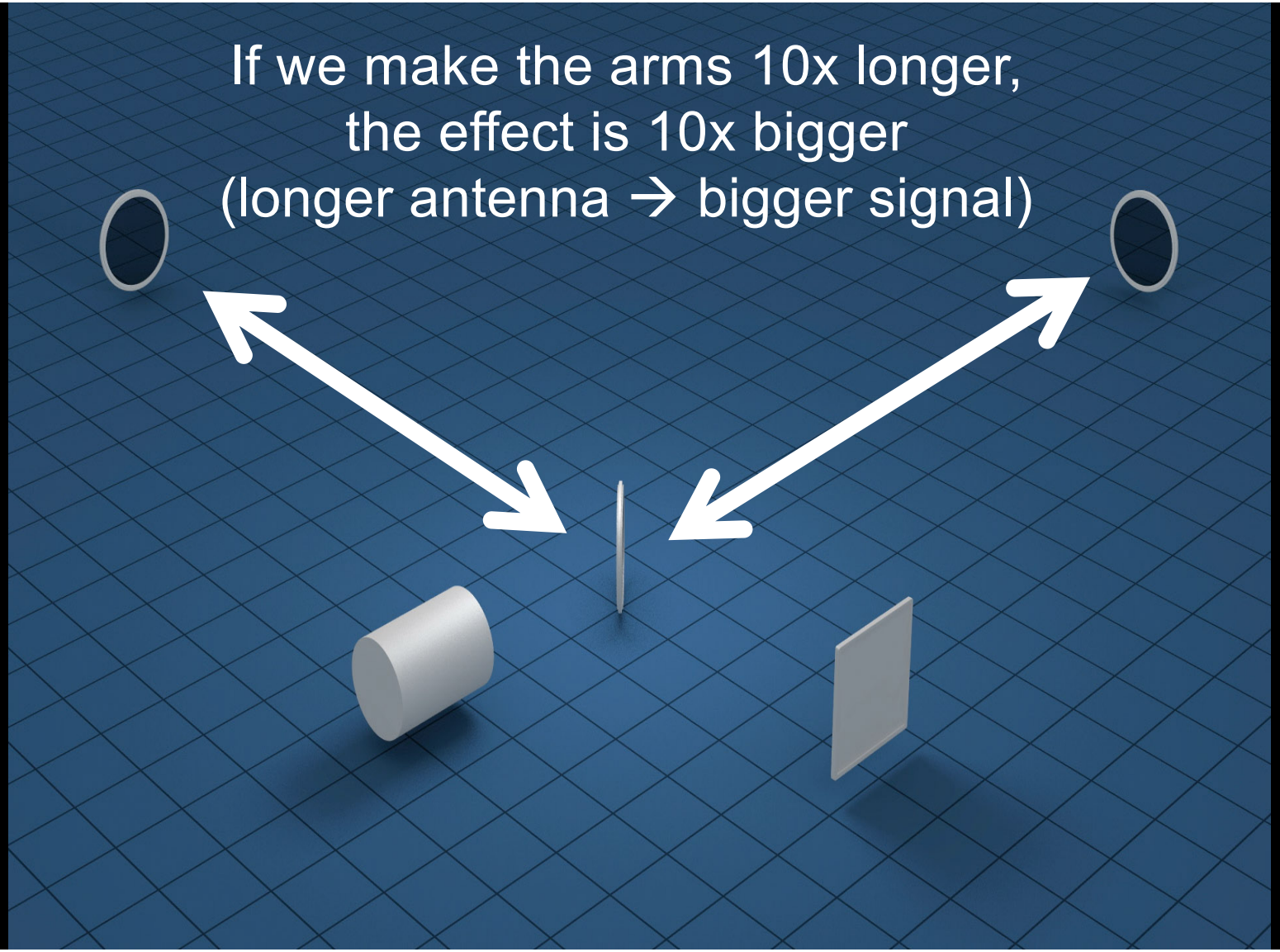
(V. G



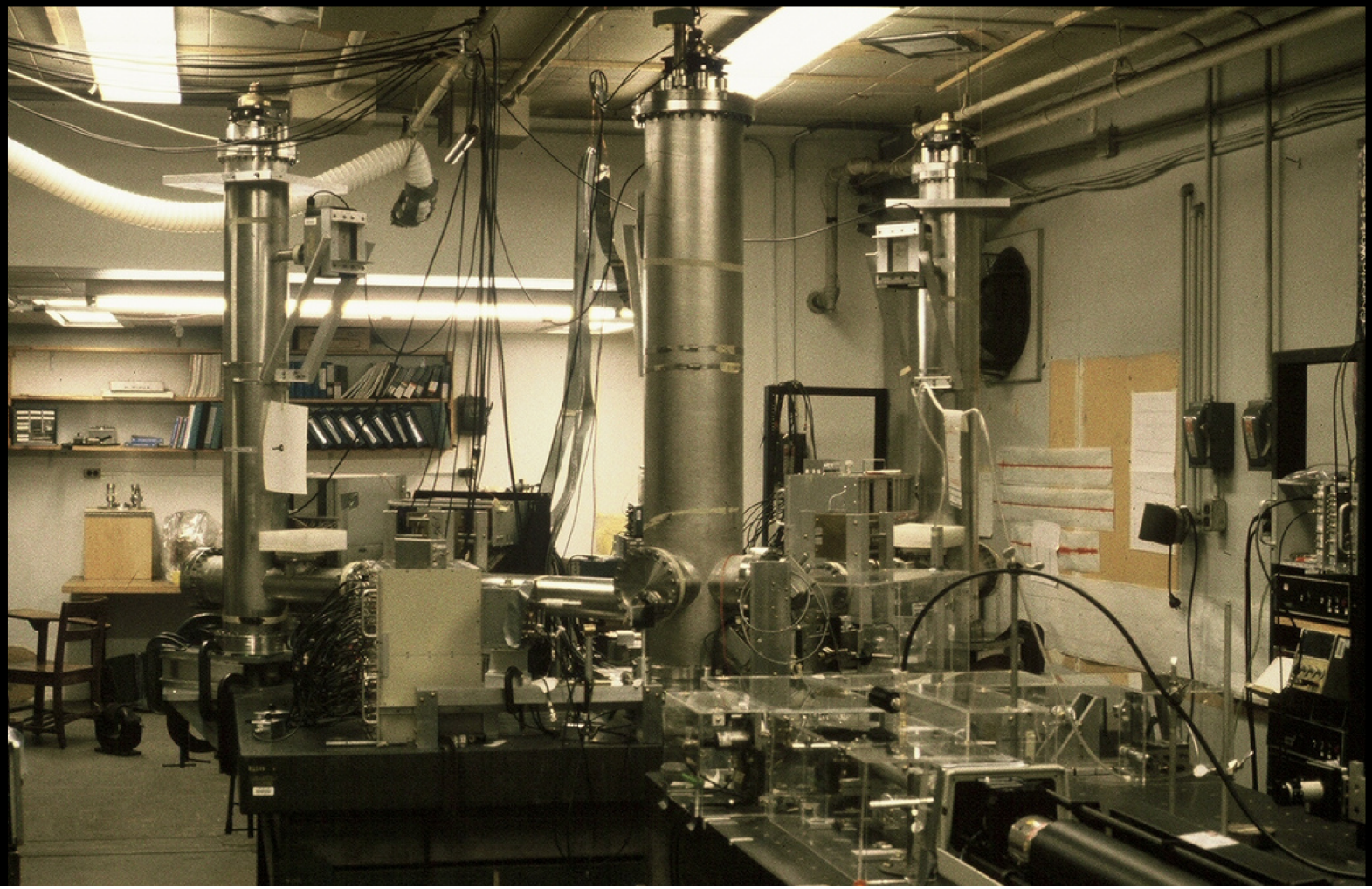

European Space Agency

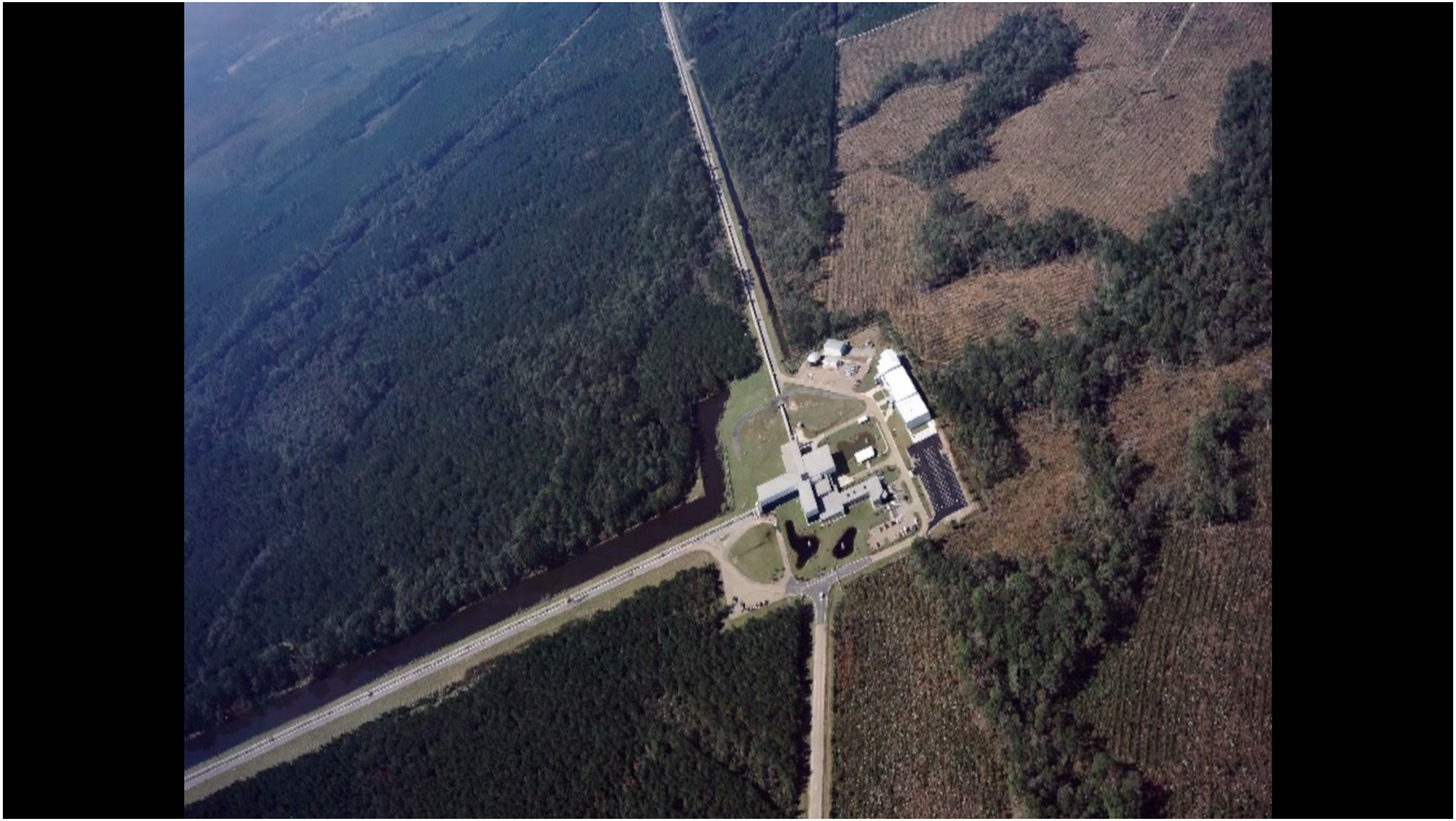


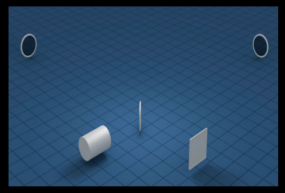



If we make the arms 10x longer,
the effect is 10x bigger
(longer antenna → bigger signal)

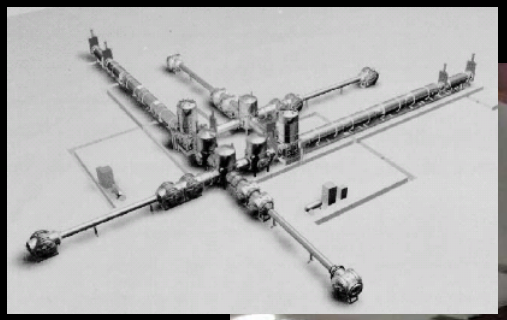
First prototype detectors in 70’s – 80’s

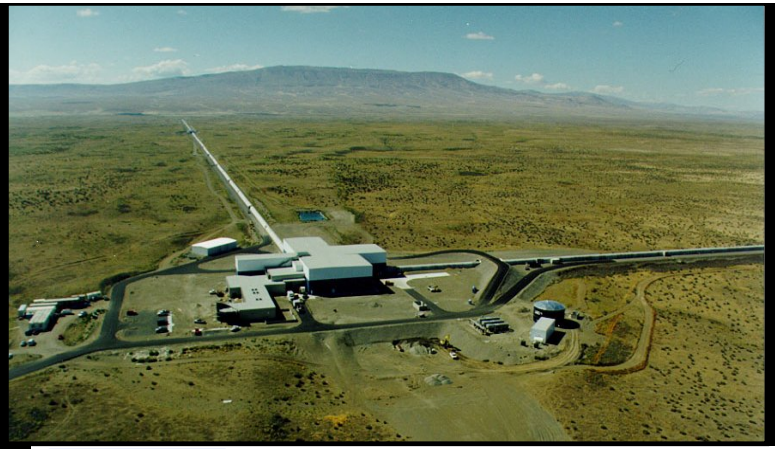




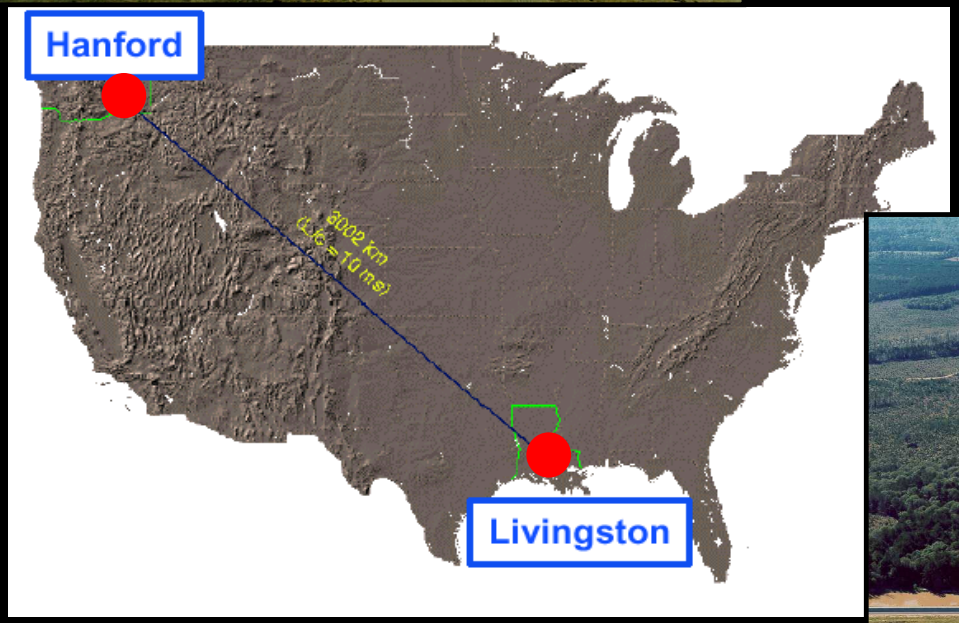


# Vacuum chambers to protect and isolate optics





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

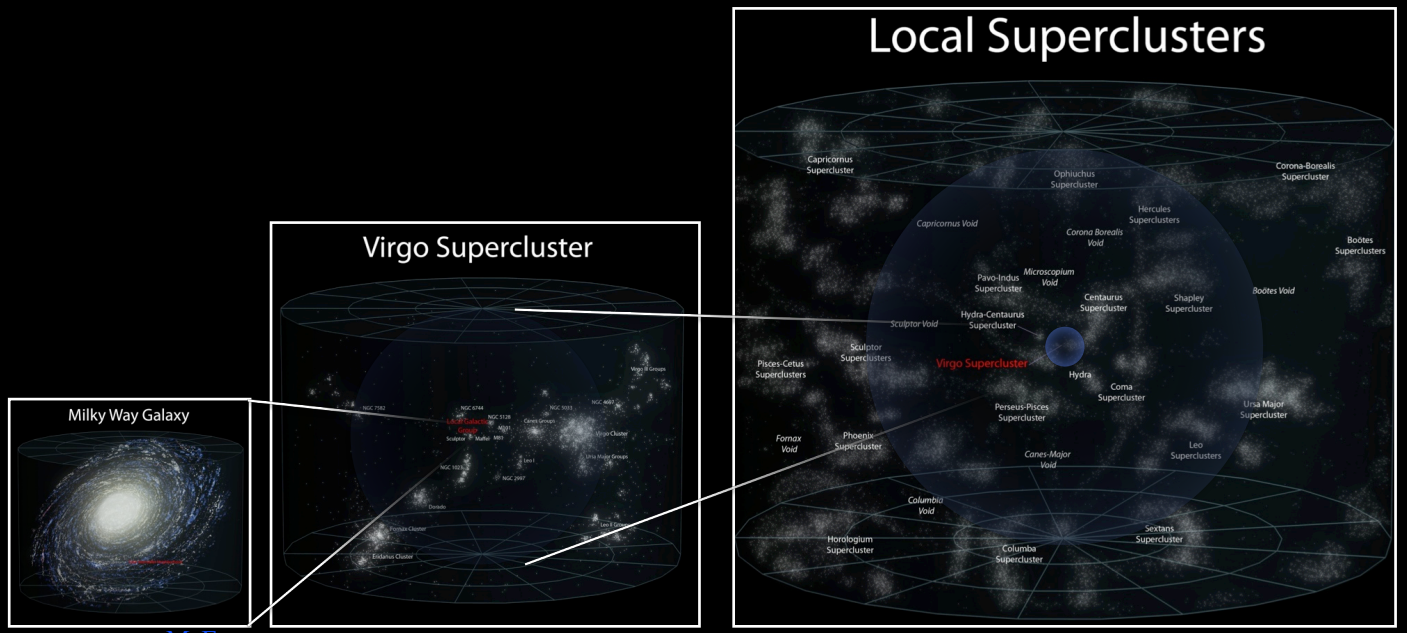
We learned how to analyze the data

We created new upper limits and significant ‘non-detections’

…but it was clear we needed more sensitive detectors.

# Initial LIGO to Advanced LIGO:

Volume of space grows as the *cube* of sensitivity…
factor of 10 improvement means *1000x* more stars in reach

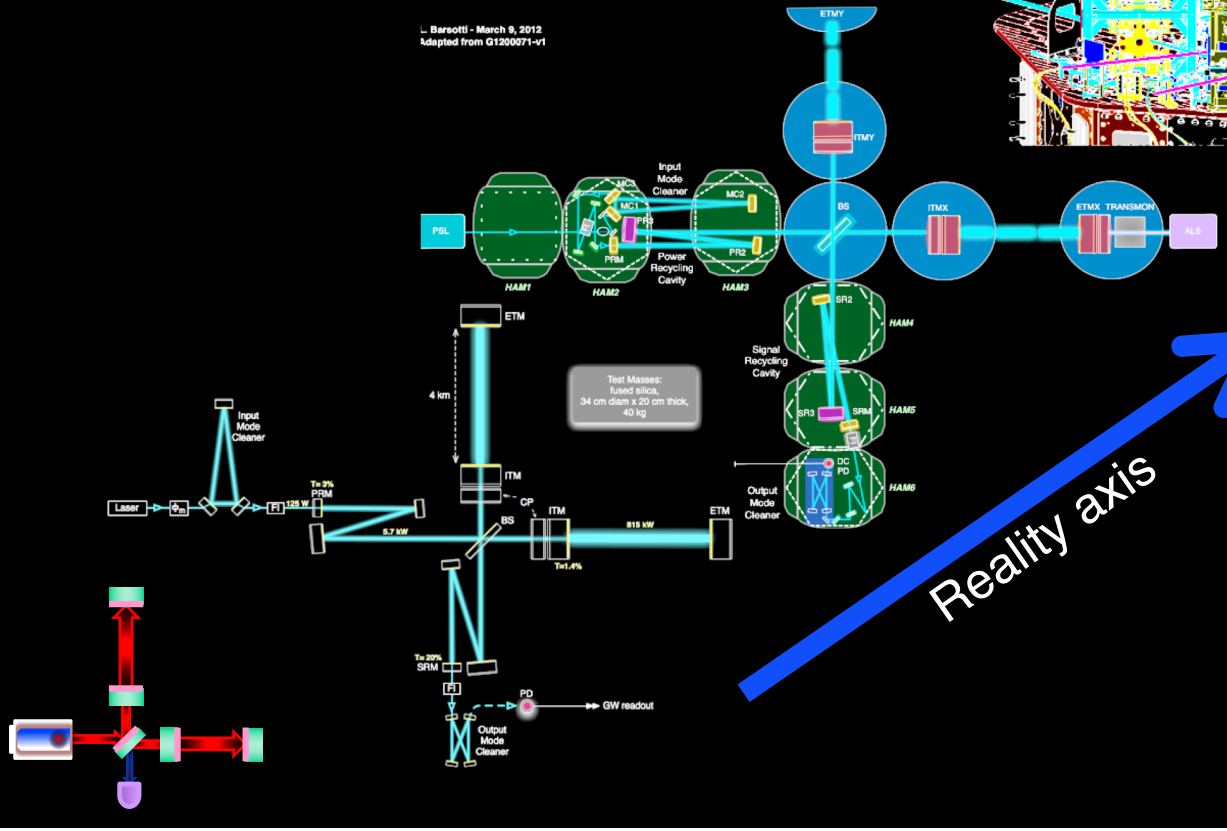



M. Evans

Initial Reach
If we had one
signal here…

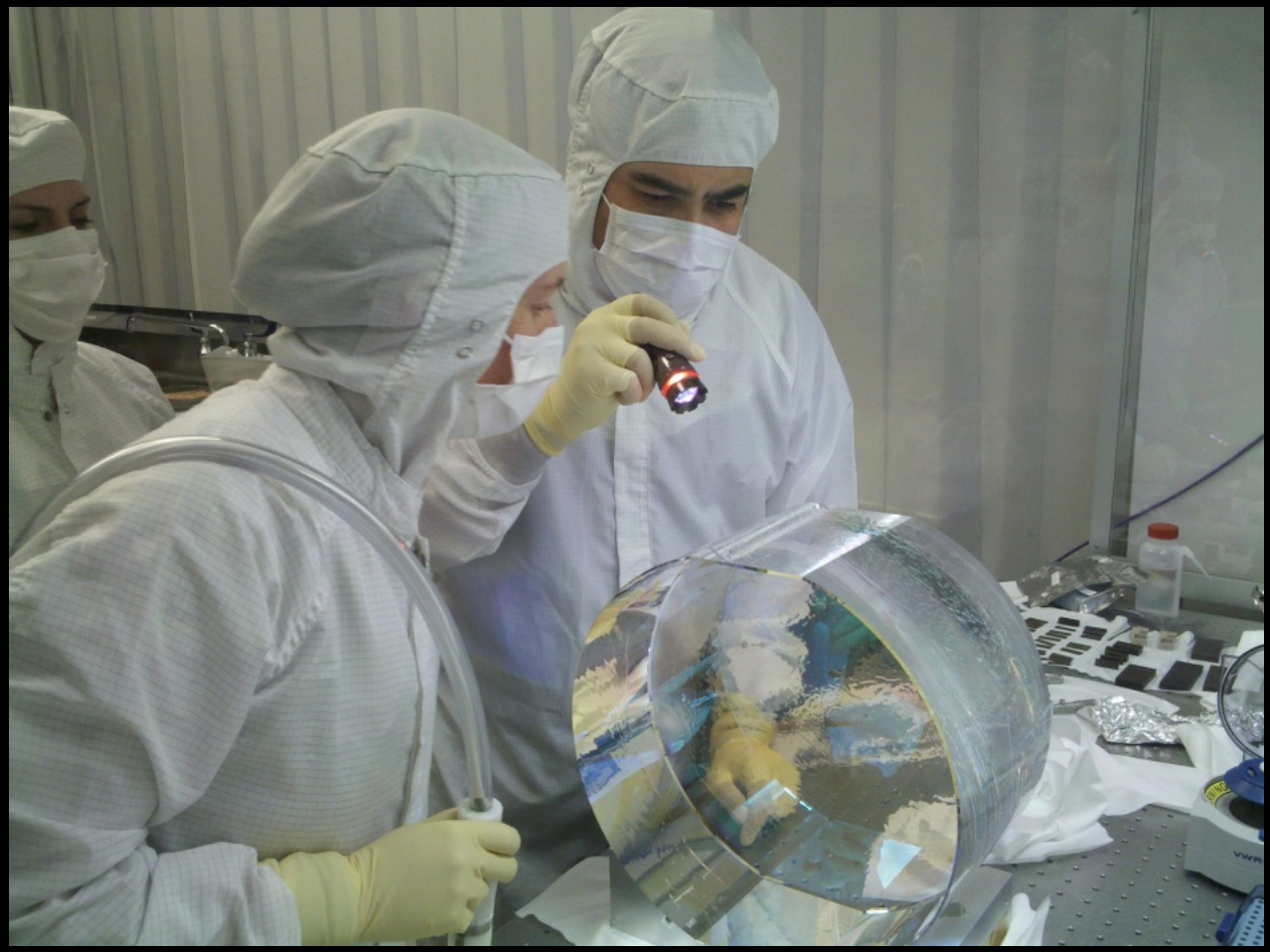
Advanced Reach
…we would have
1000 here!

# Incredibly complex design, and hardware, needed



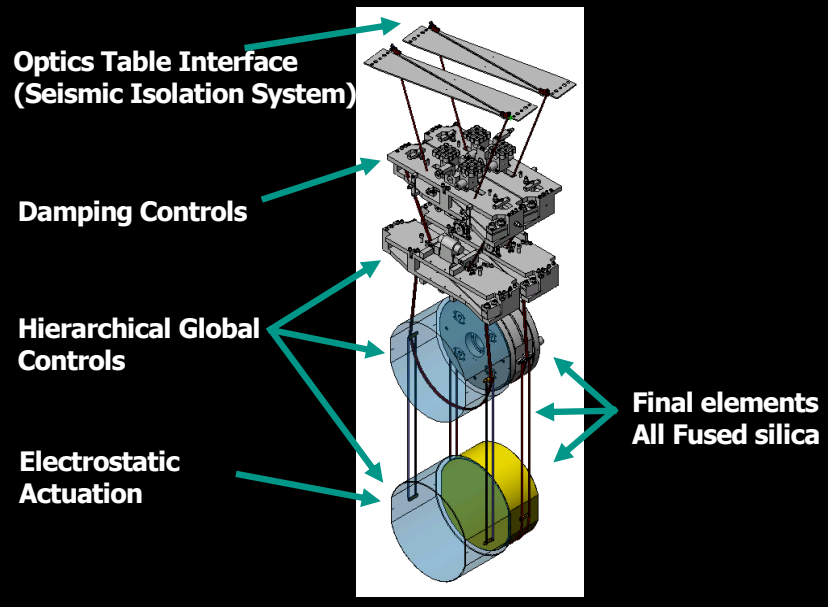

Reality axis

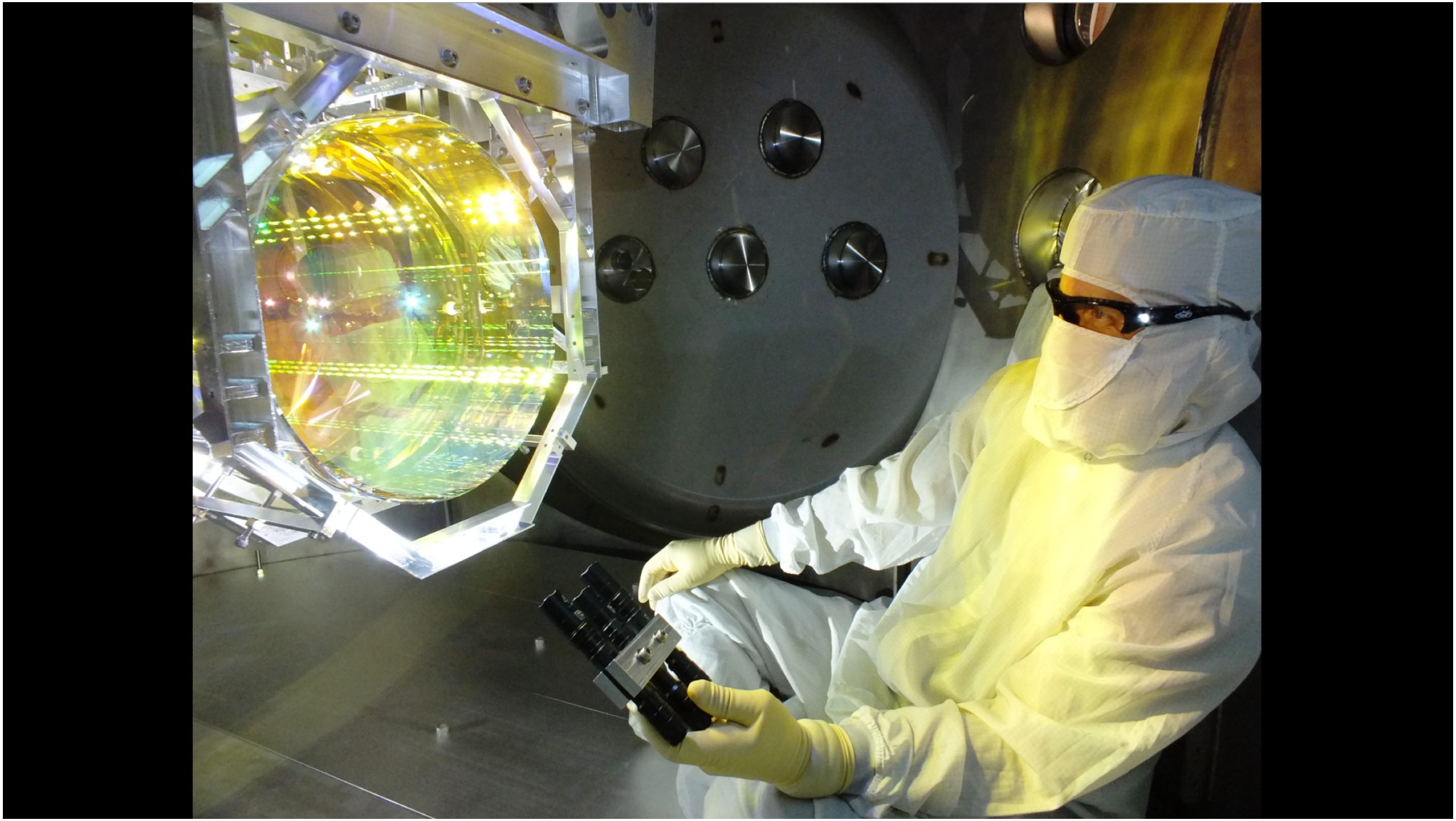
# Inspecting mirror during fabrication



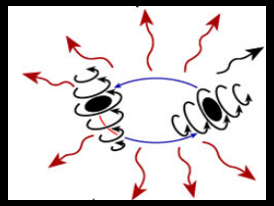
# Mirror Isolation from Seismic noise

Quadruple pendulums;
final stages built out of pristine glass

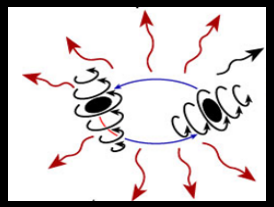


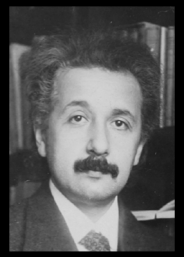




9:03
PACIFIC
11:03
CENTRAL
17:03
GMT



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





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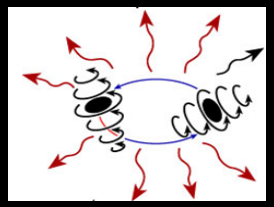
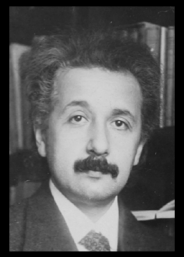
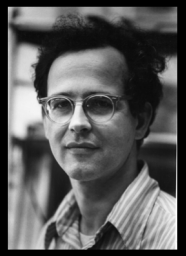
**100 years after Einstein predicted gravitational waves…**







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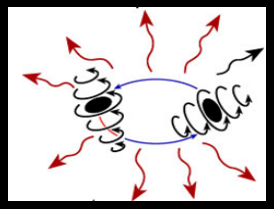
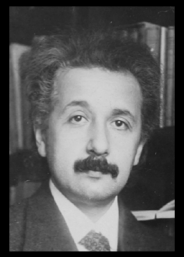
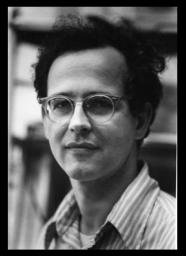


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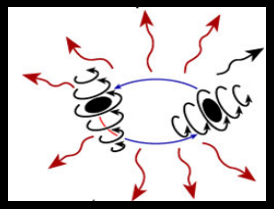
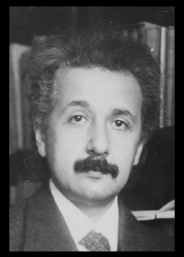
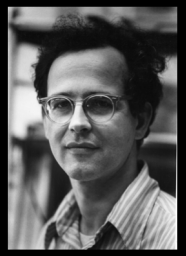

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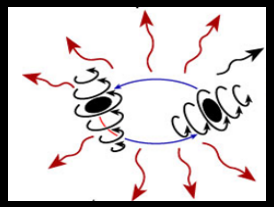
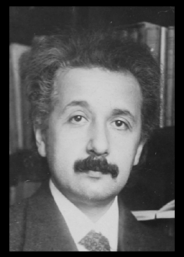
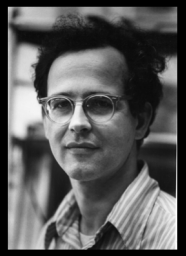


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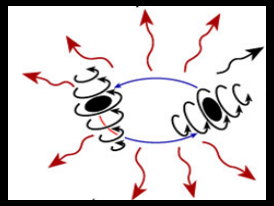
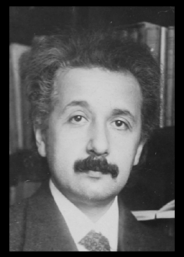
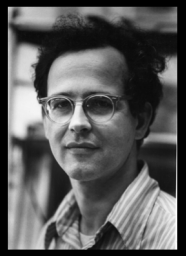
**6 months after starting detector tuning...**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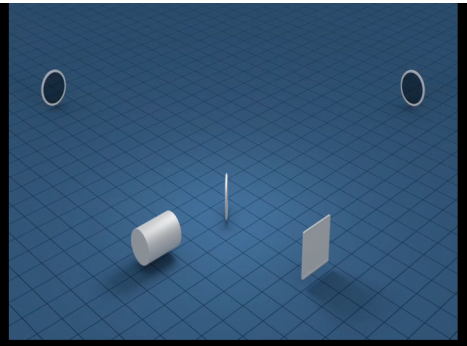
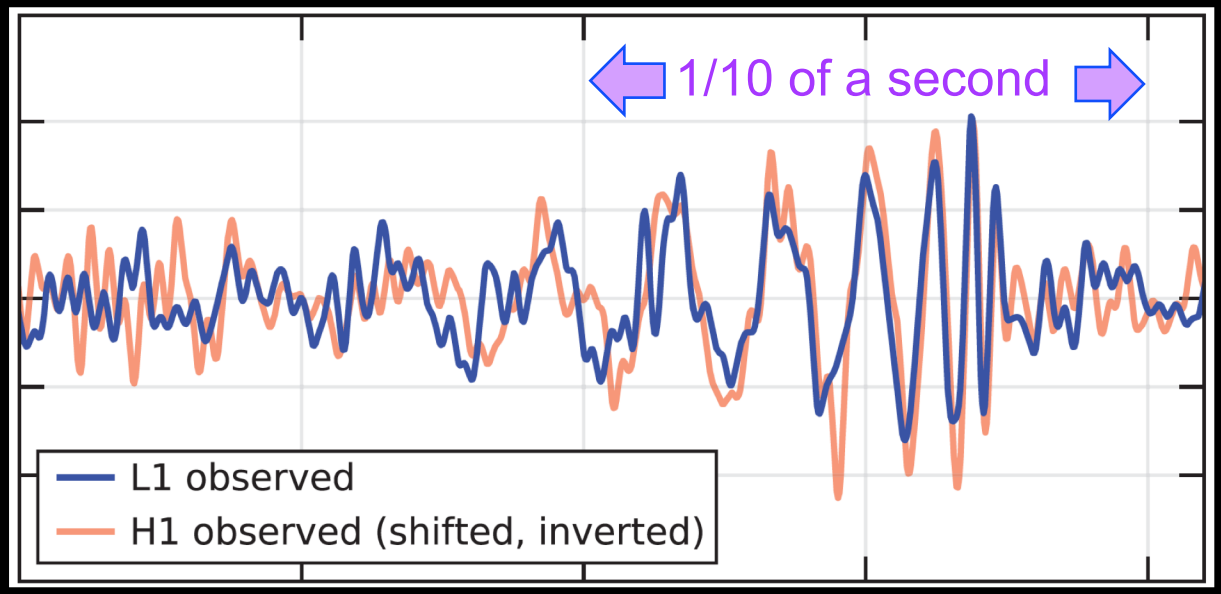
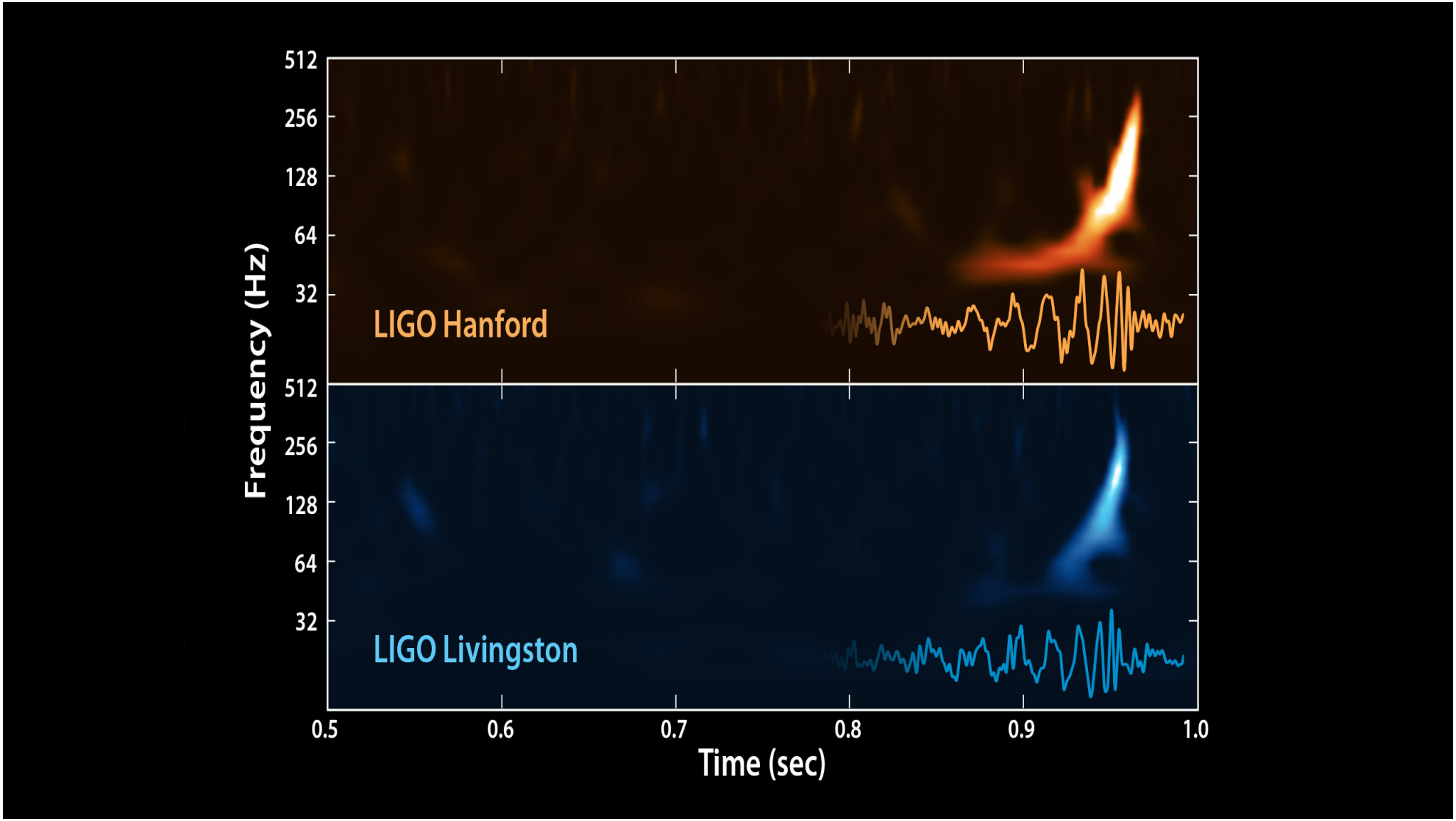
***Two days*** **after we started observing...**

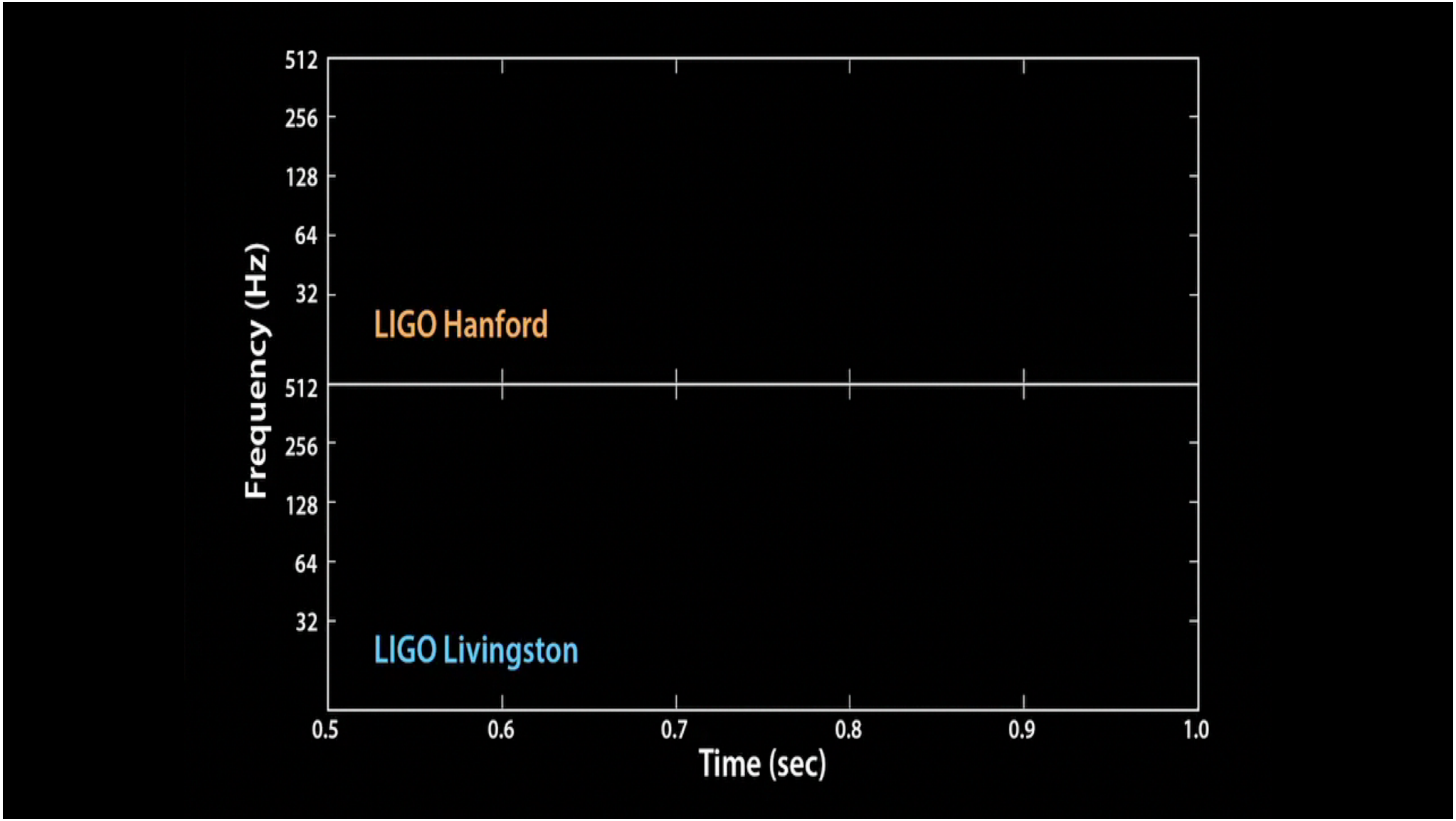


September 14, 2015 at 05:51 EDT:

# Cosmic Rendezvous



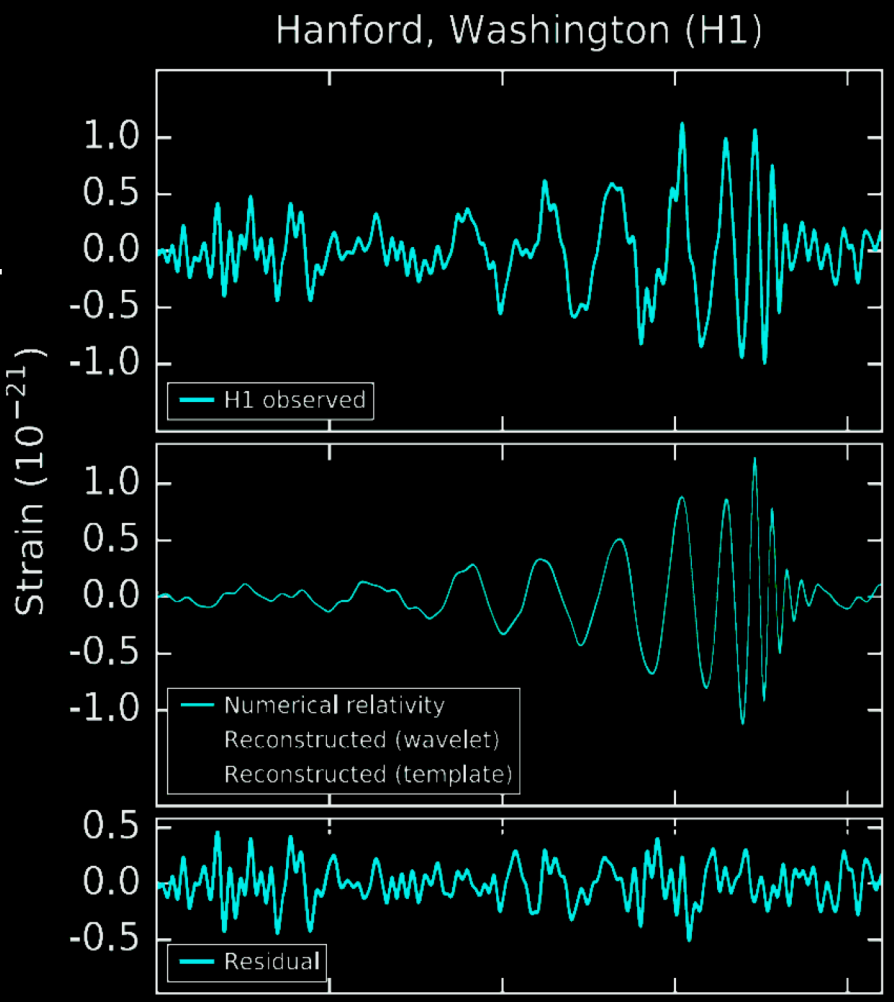

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


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)

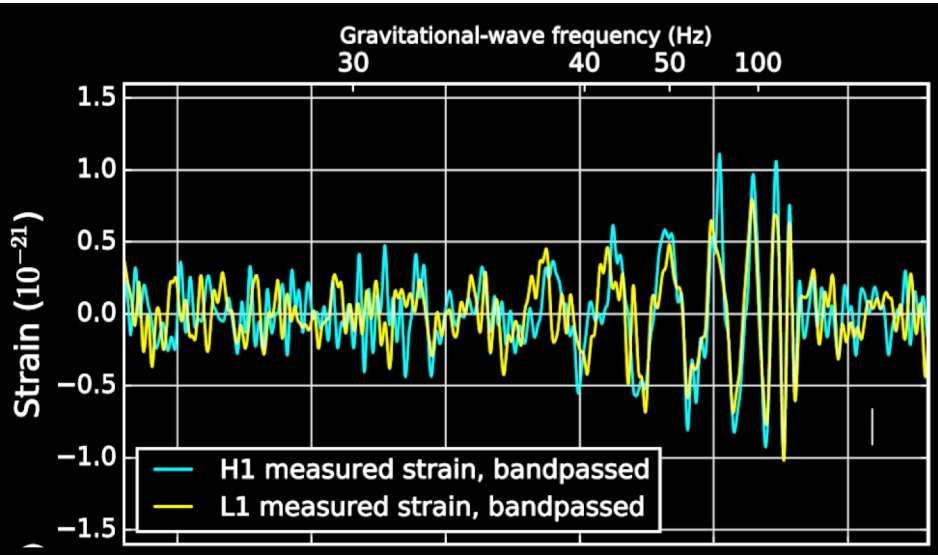
This measured signal…

…minus Einstein's prediction…

…equals noise



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

The New York Times



NEW YORK, FRIDAY, FEBRUARY 12, 2016

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

# WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

## A RIPPLE IN SPACE-TIME

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

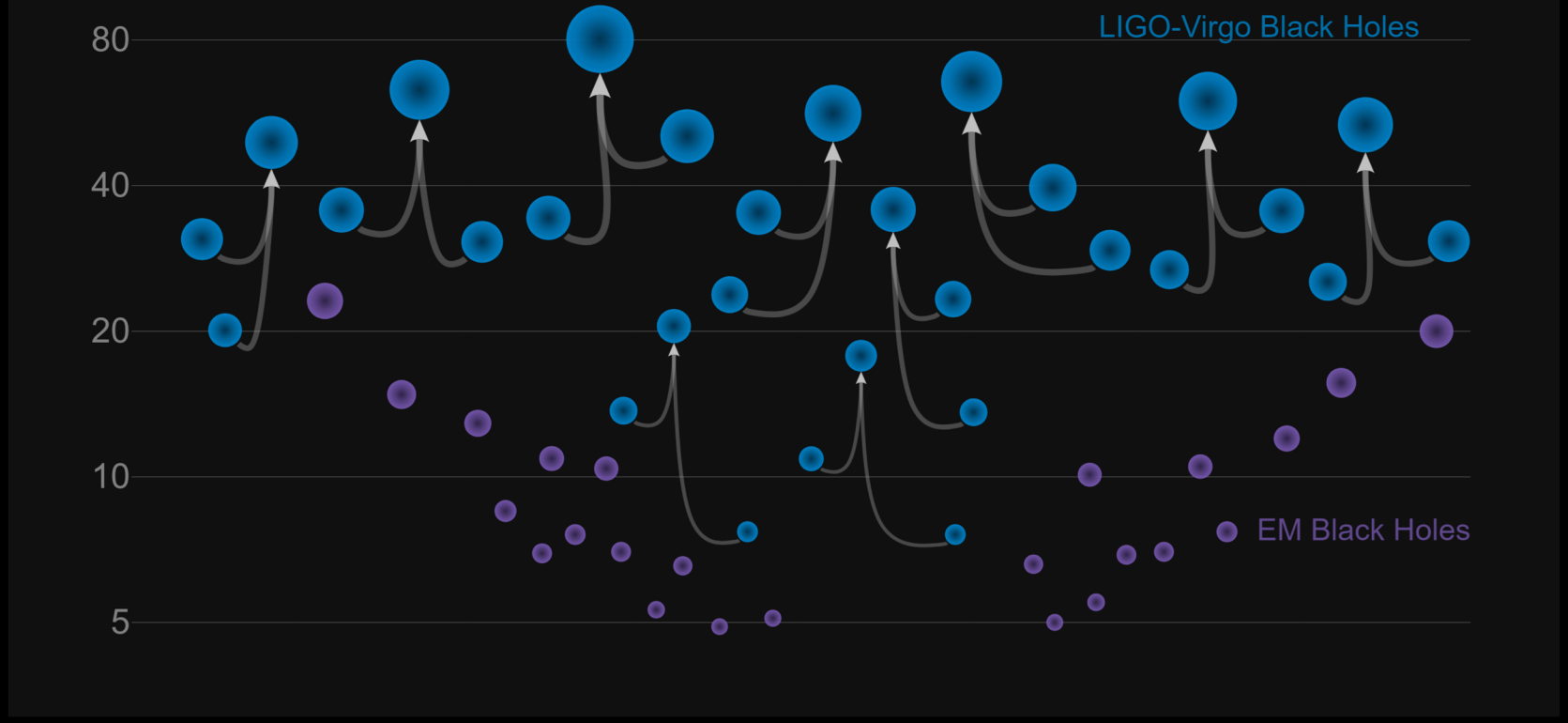
By DENNIS OVERBYE

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 Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle.

Was it a fluke? A one-time miracle?
…was it just a 1-in-100,000-years chance?

# Currently 10 Black-hole binaries discovered

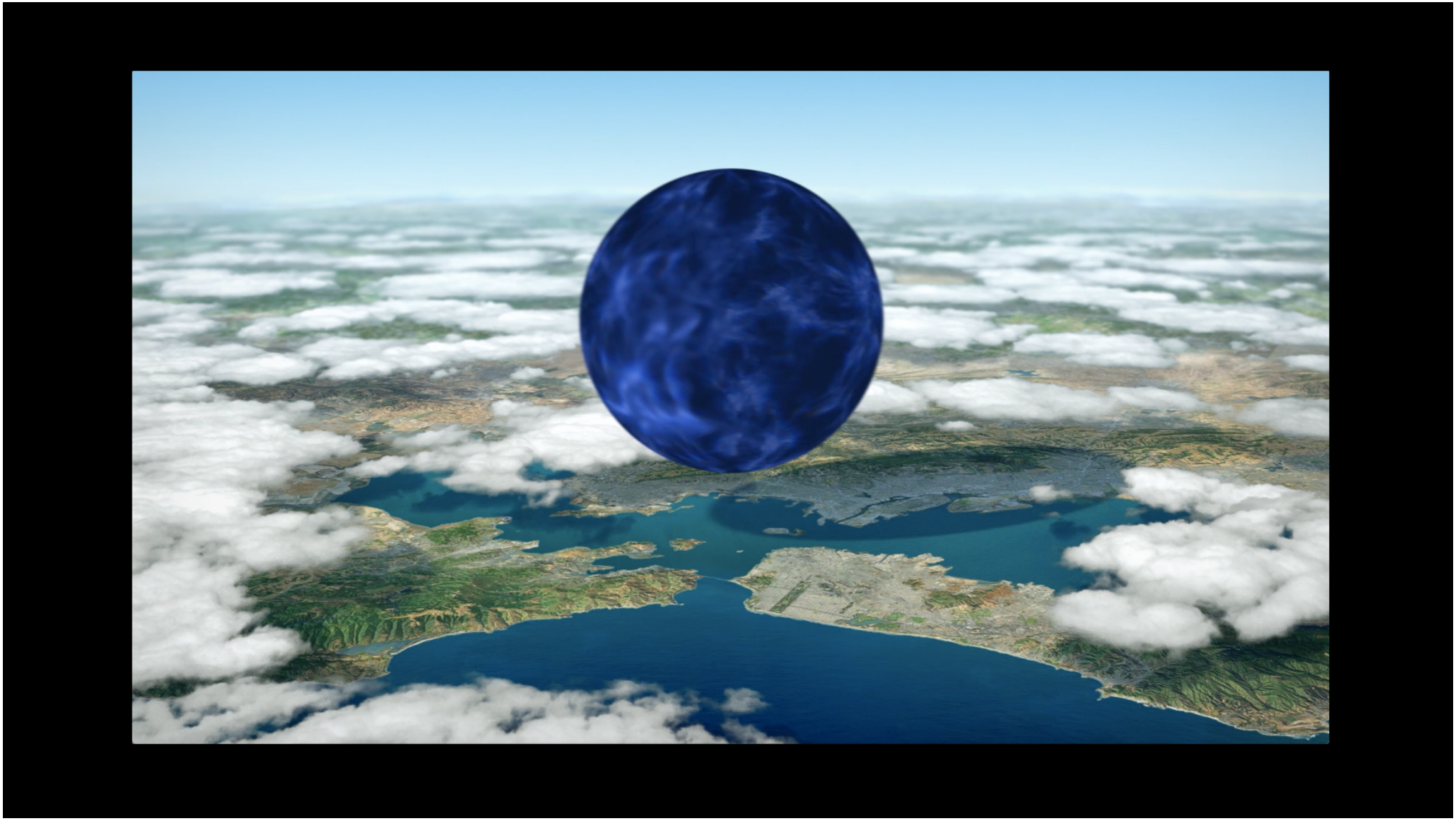



LIGO-Virgo | Frank Elavsky | Northwestern

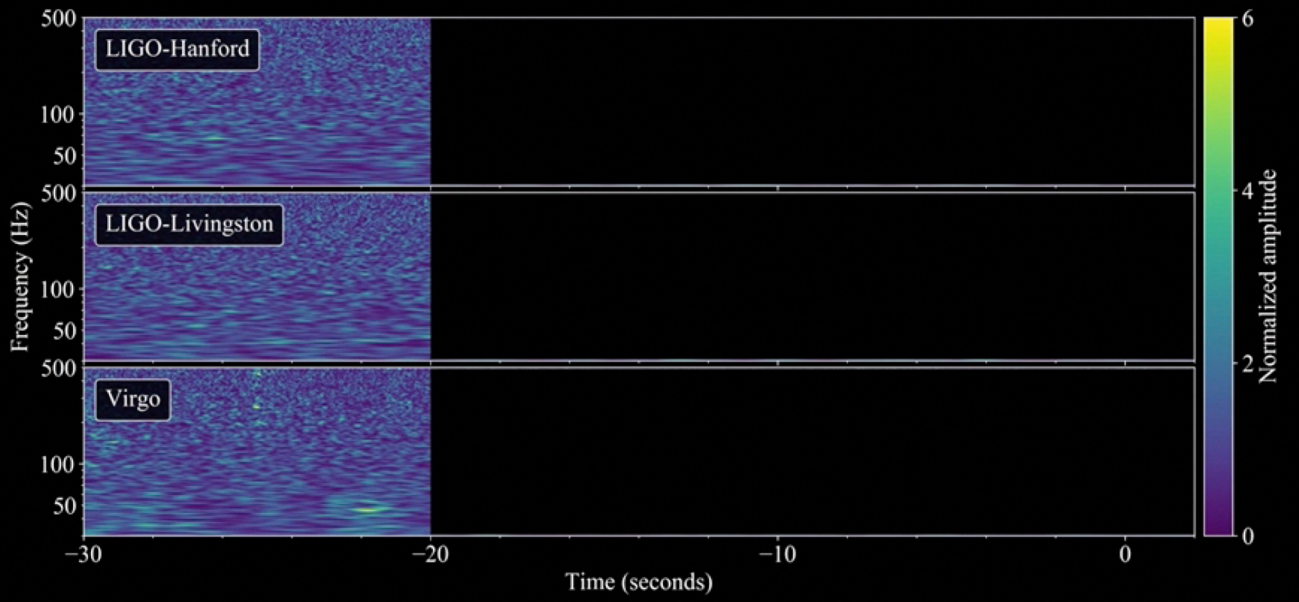
And that’s not all!

On 17 August 2017, LIGO and Virgo
saw something new:
Two Neutron Stars coalescing

t = 6.7 ms



# LIGO/Virgo have observed gravitational waves from a binary neutron star inspiral!

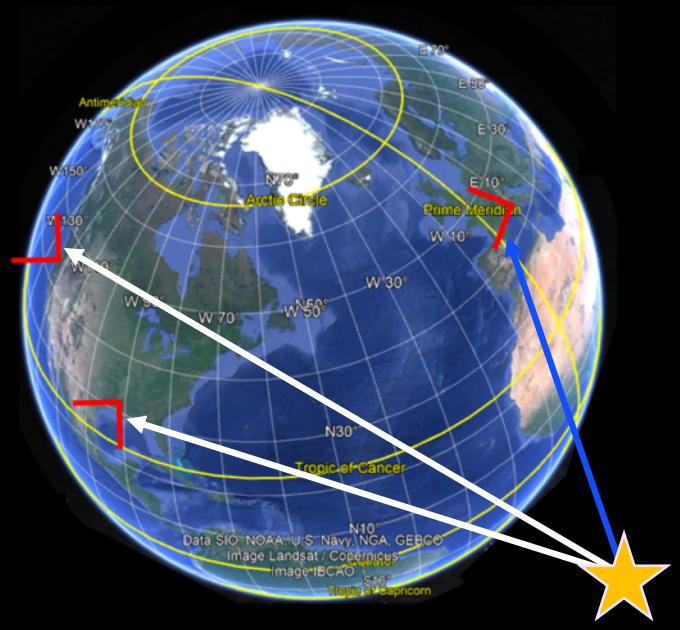



LIGO-Virgo/Geoffrey Lovelace, Duncan Brown, Duncan Macleod, Jessica McIver, Alex Nitz

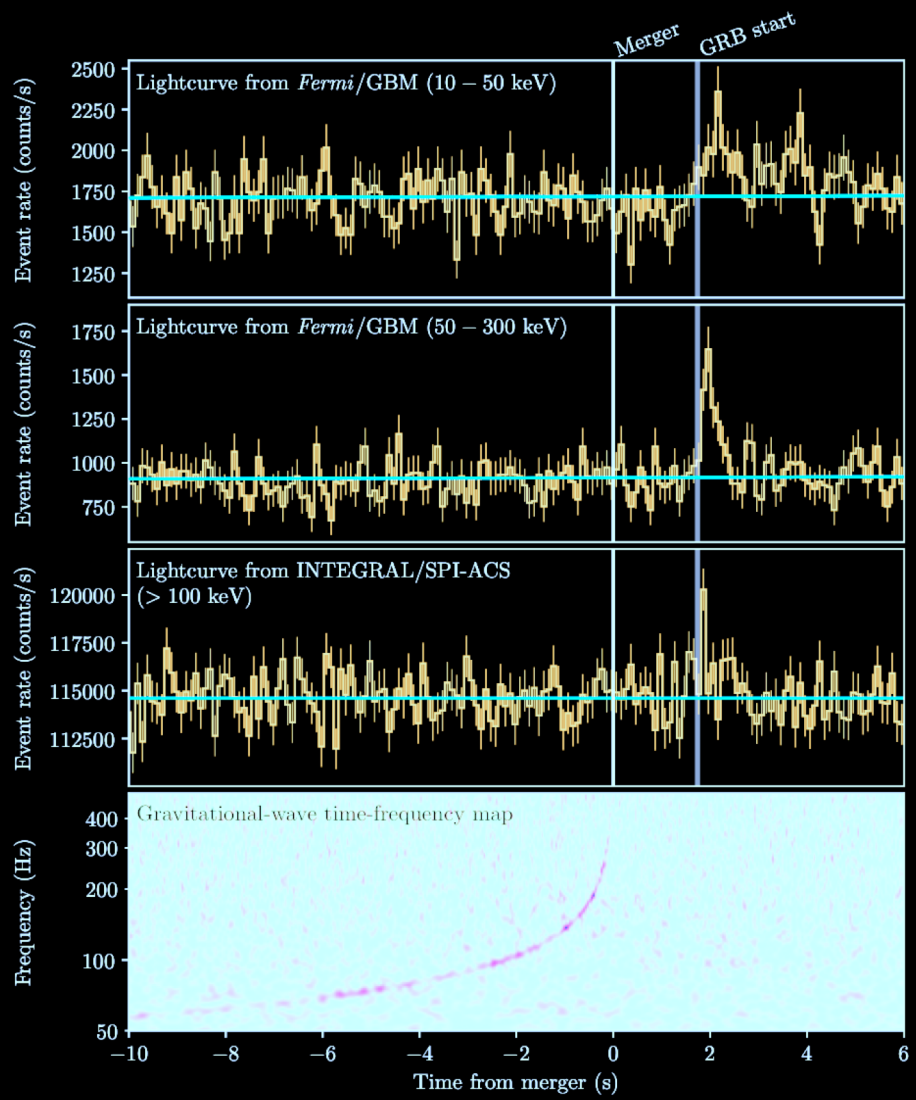
Virgo, Cascina, Italy

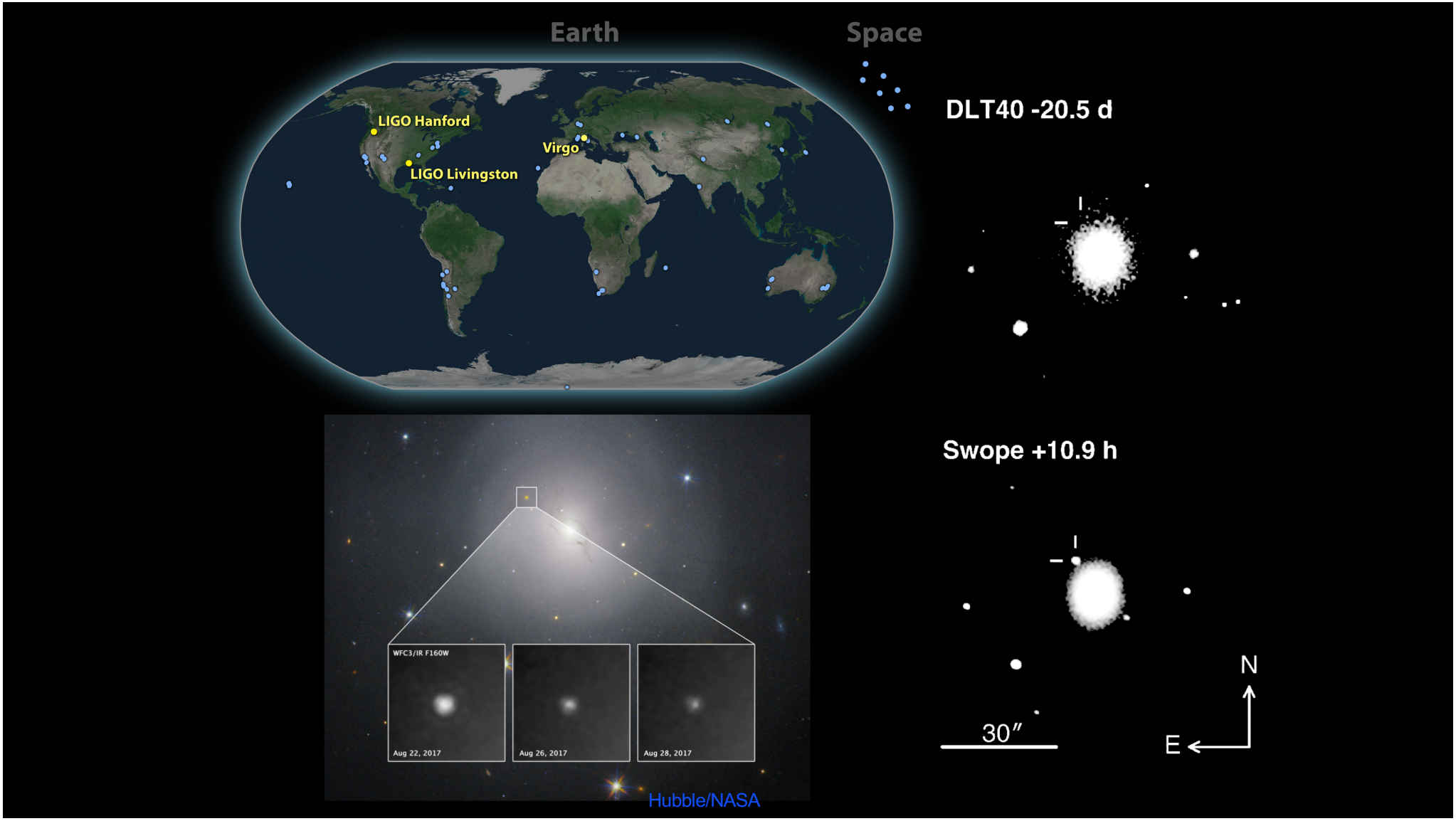
LIGO, Livingston, LA

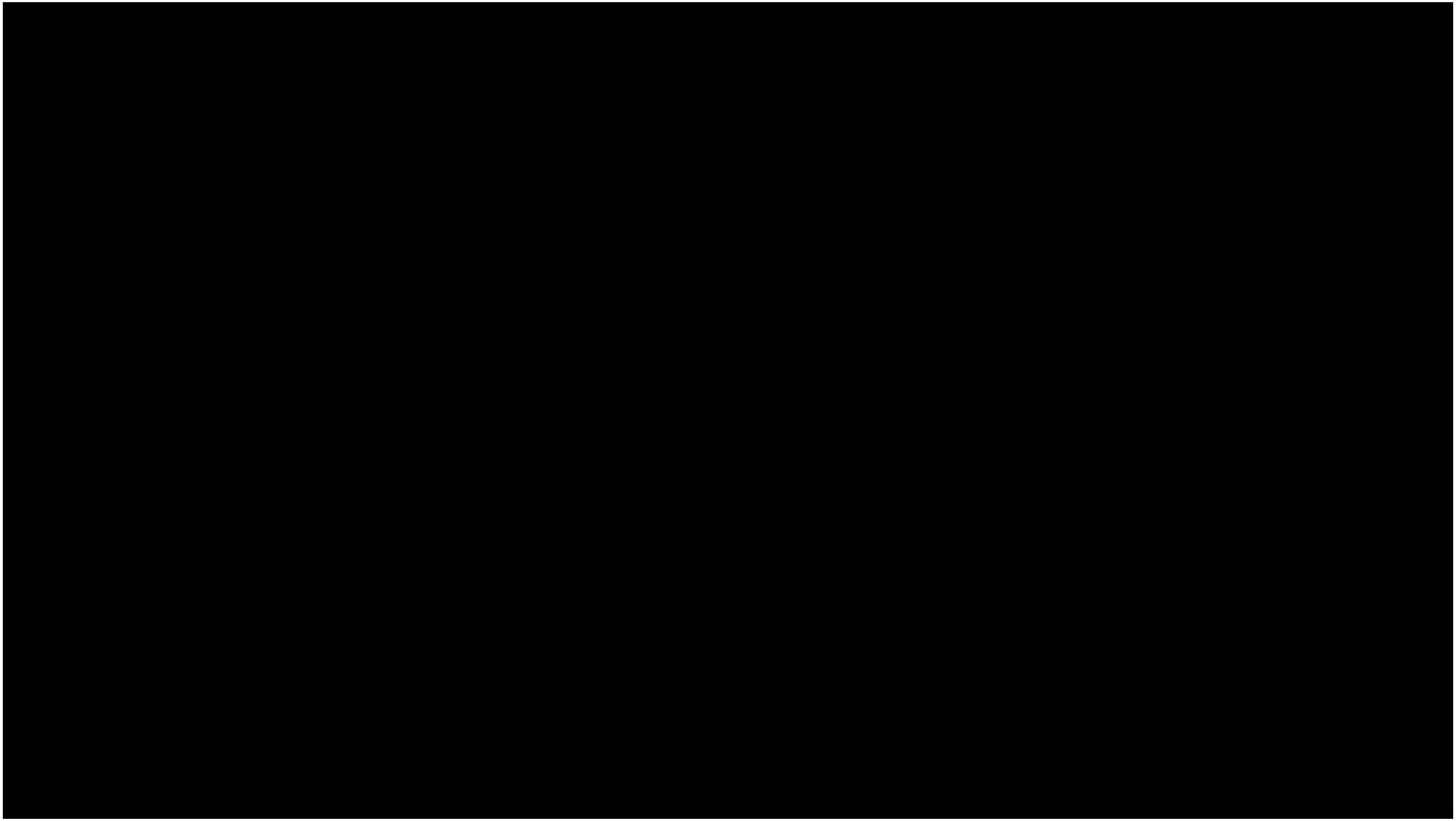
LIGO, Hanford, WA

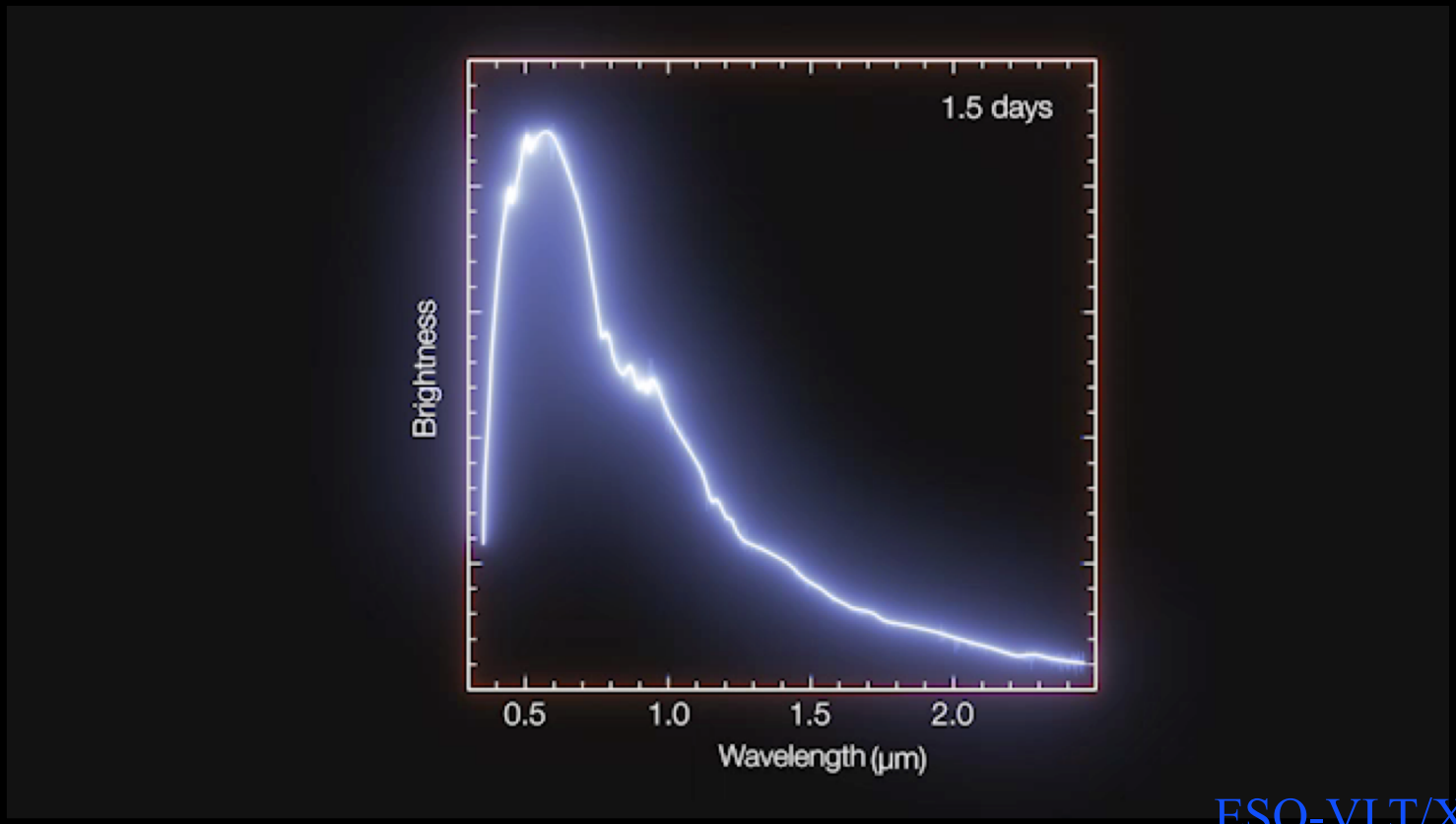


But not only gravitational waves…


Merger
GRB start
Lightcurve from *Fermi*/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from *Fermi*/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)


Earth
Space
LIGO Hanford
Virgo
LIGO Livingston
DLT40 -20.5 d
Swope +10.9 h
WFC3/IR F160W
Aug 22, 2017
Aug 26, 2017
Aug 28, 2017
Hubble/NASA
30″
N
E






ESO-VLT/X-Shooter

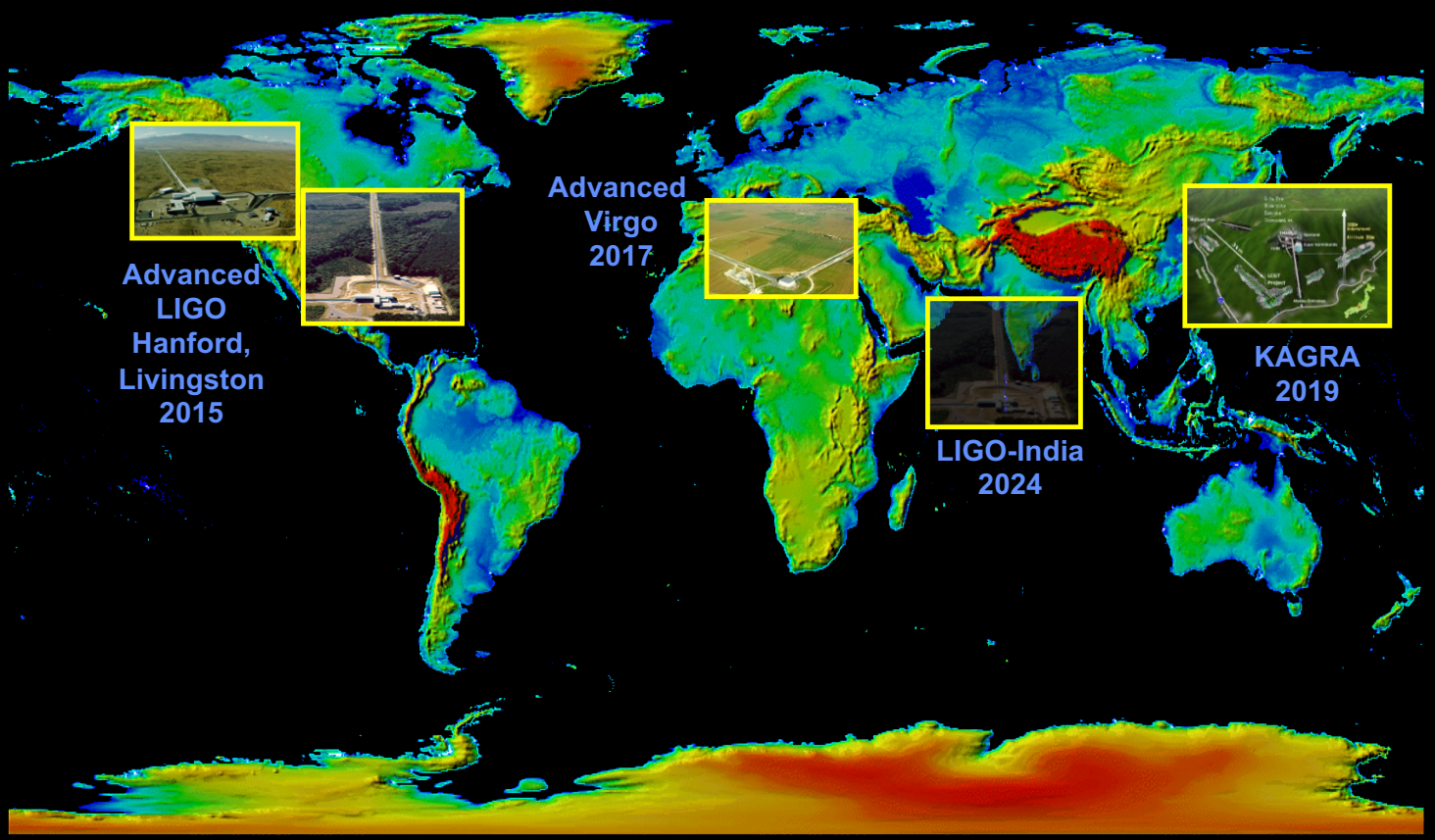
# Periodic Table of the Elements

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H | | | | | | | | | | | | | | | | | 2 He |
| 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 55 Cs | 56 Ba | | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 87 Fr | 88 Ra | | | | | | | | | | | | | | | | |
| | | | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| | | | 89 Ac | 90 Th | 91 Pa | 92 U | | | | | | | | | | | |

**Yellow: Formed by Merging Neutron Stars**

What’s next for LIGO?

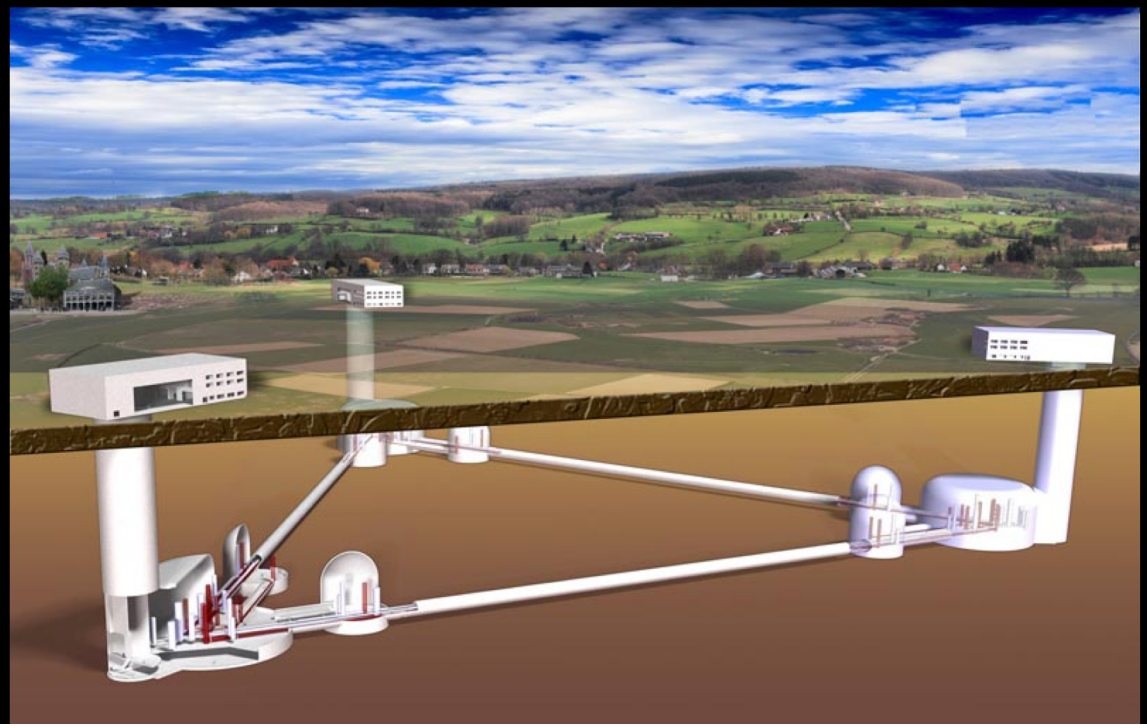
# The advanced GW detector network



# Future Improvements: Reaching even further

- Want to fully exploit the observatories we have
- Ultimately will want more sensitive instruments – longer arms, quieter places

On earth….



# And in Space: LISA, a joint European-US mission planned for the 2030's

AEI Max Planck

# LIGO Scientific Collaboration

"All the News That's Fit to Print"

# The New York Times

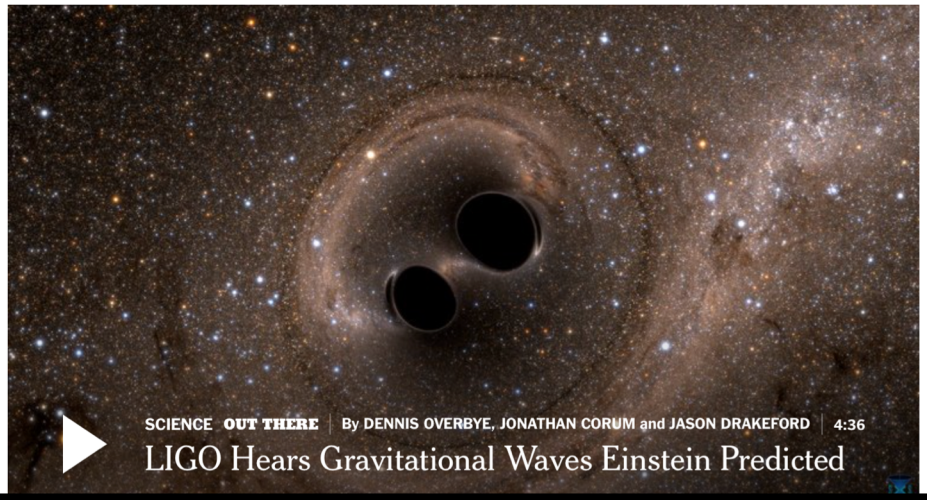
Late Edition
**Today,** abundant sunshine, seasonably warm, high 72. **Tonight,** clear and moonlit, warmer than usual, low 58. **Tomorrow,** mostly sunny, high 77. Weather map appears on Page B10.

VOL. CLXVII ... No. 57,739 +  NEW YORK, TUESDAY, OCTOBER 3, 2017 $2.50

SCIENCE

## *2017 Nobel Prize in Physics Awarded to LIGO Black Hole Researchers*

By **DENNIS OVERBYE** OCT. 3, 2017




**RELATED COVERAGE**

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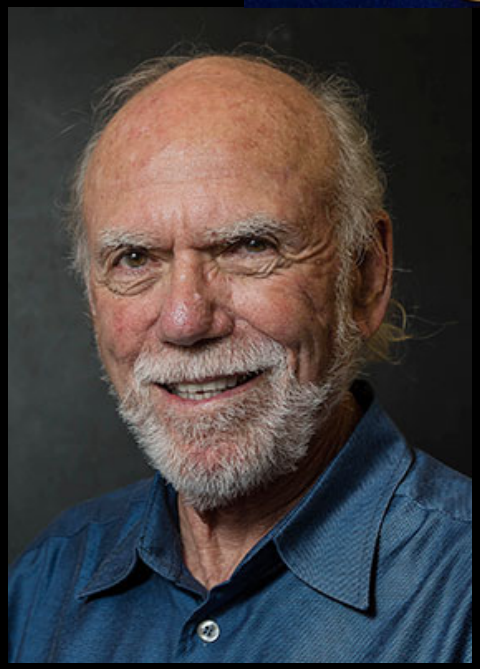
# The 2017 Nobel Prize


Rai Weiss



Barry Barish

Kip Thorne

# The 2017 Nobel Prize