



*Listening to Black
Holes with LIGO*

Prof. Brian Lantz

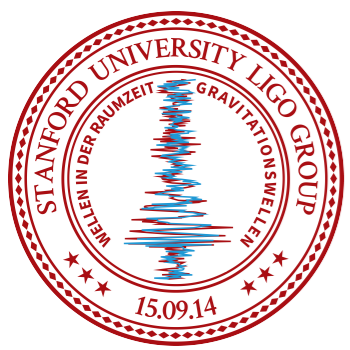
April 17, 2026
Oak Elementary
LIGO-G2600956



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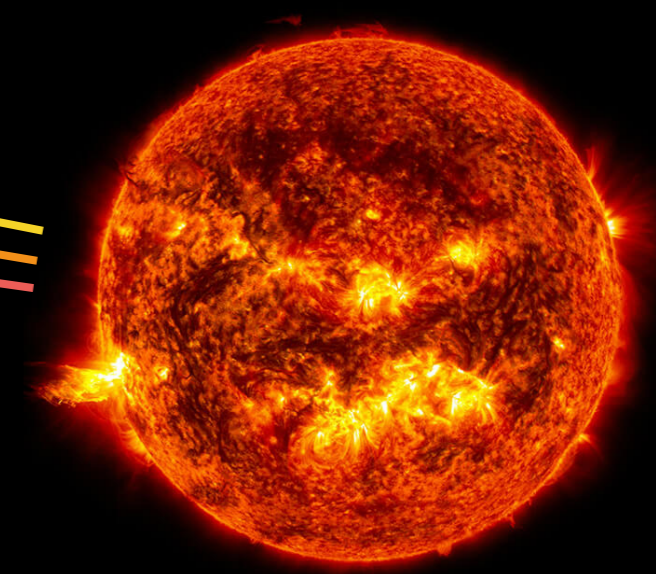
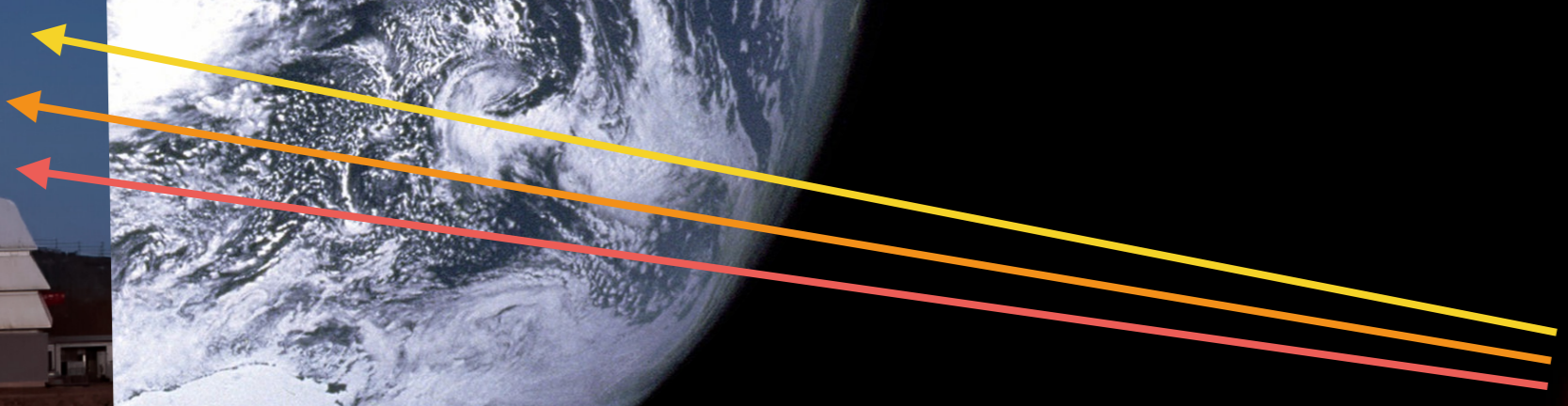
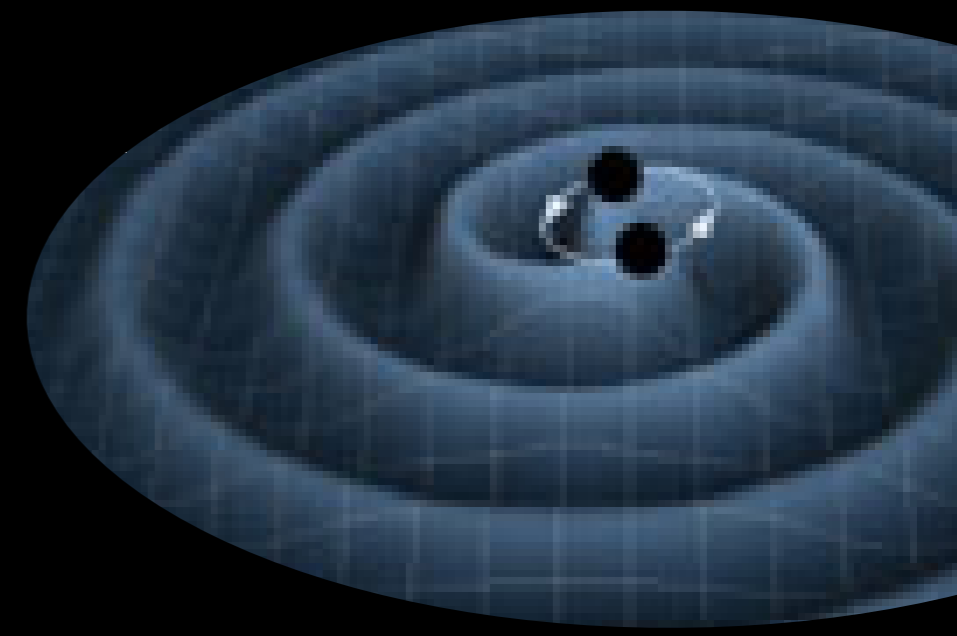
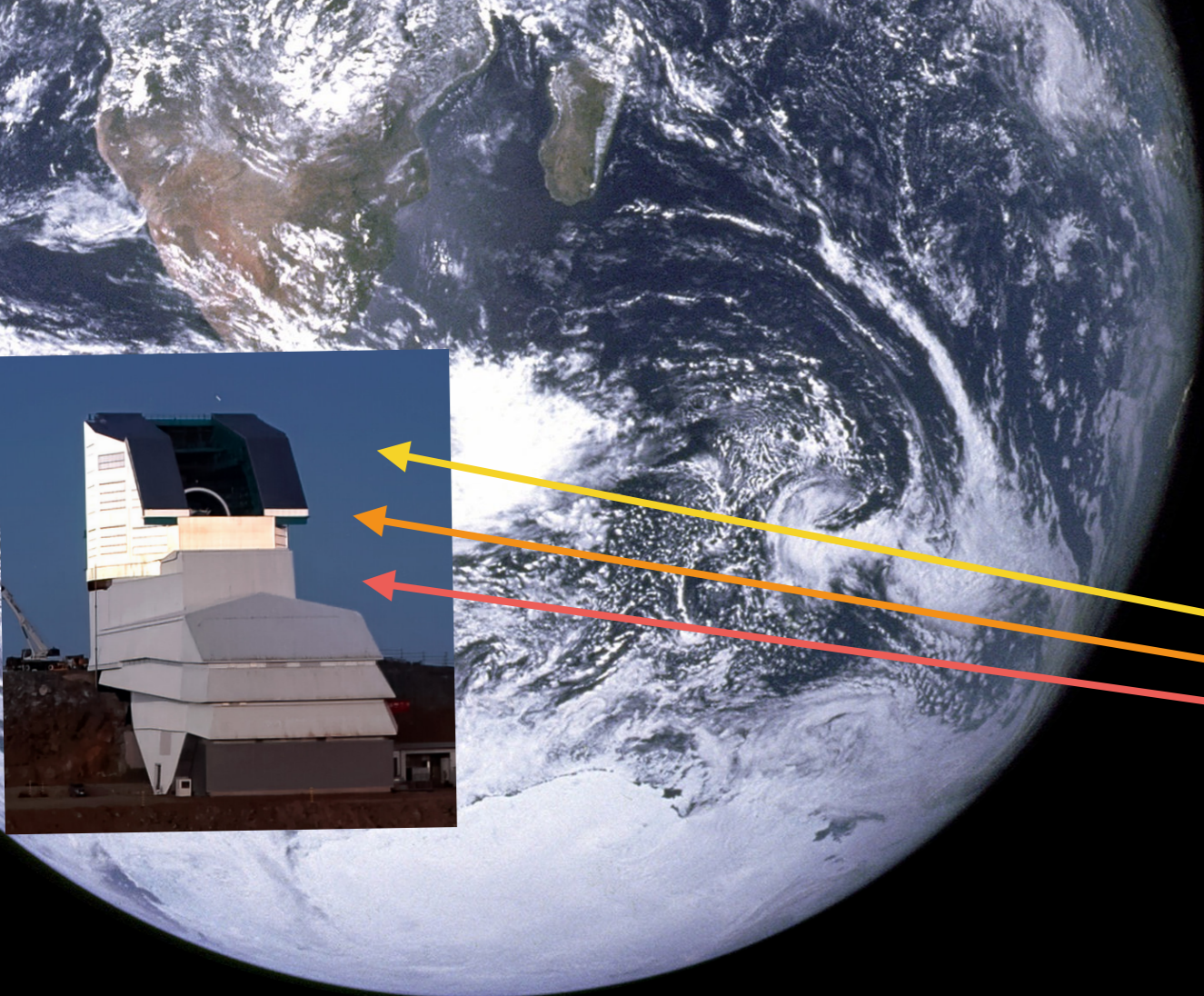
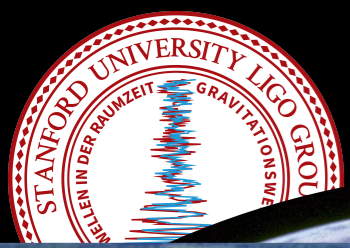


LIGO?

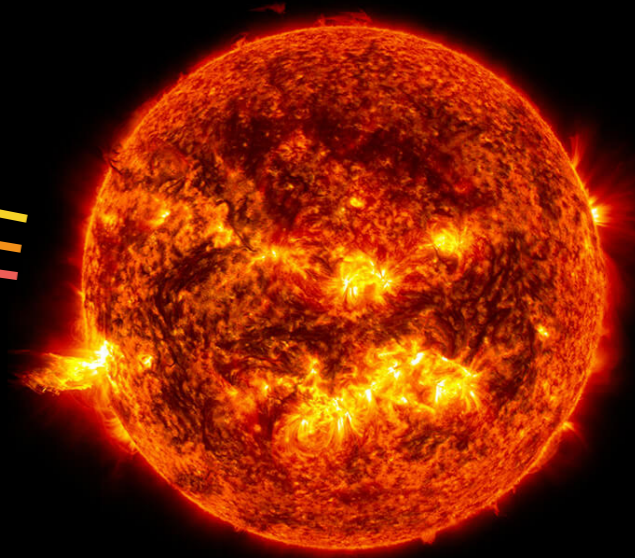
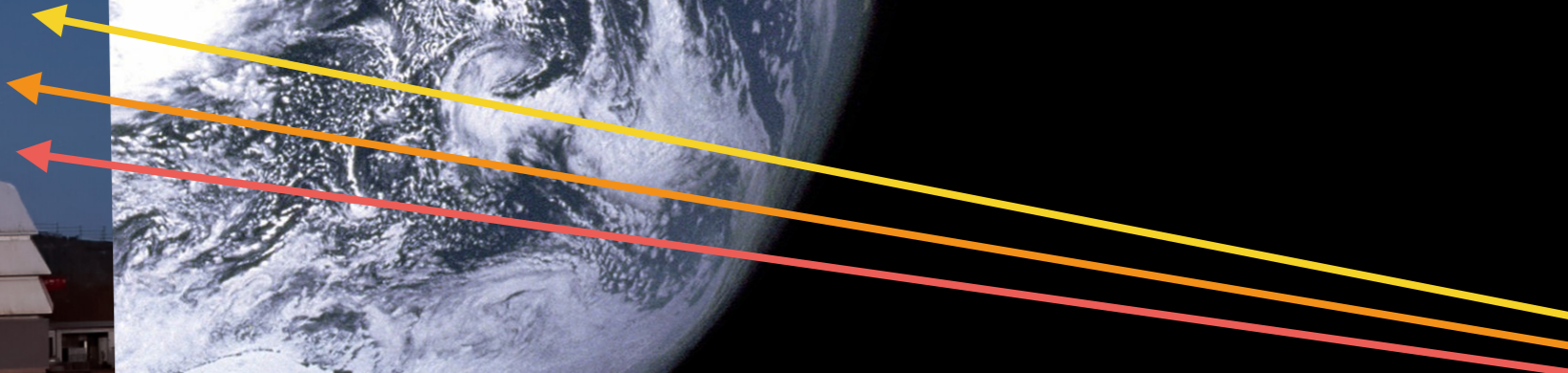
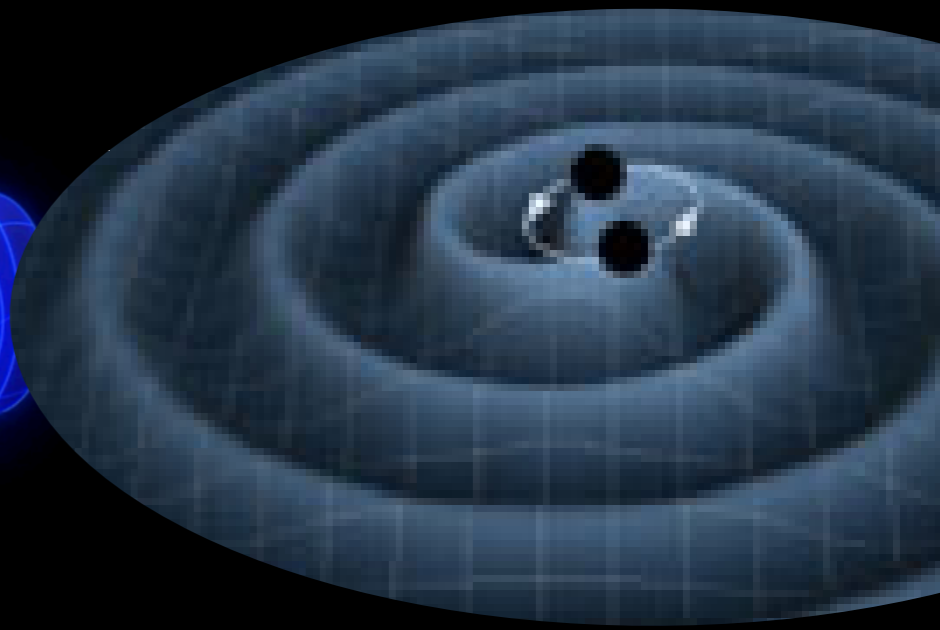
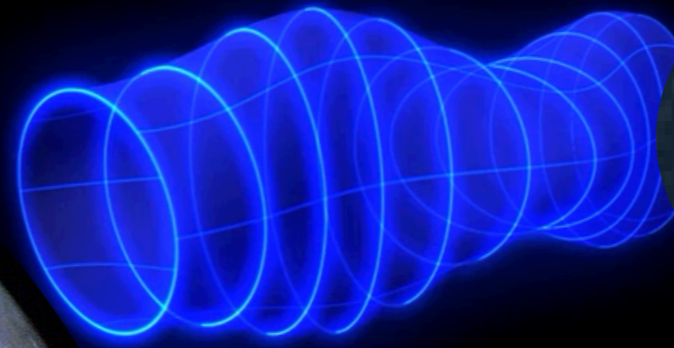
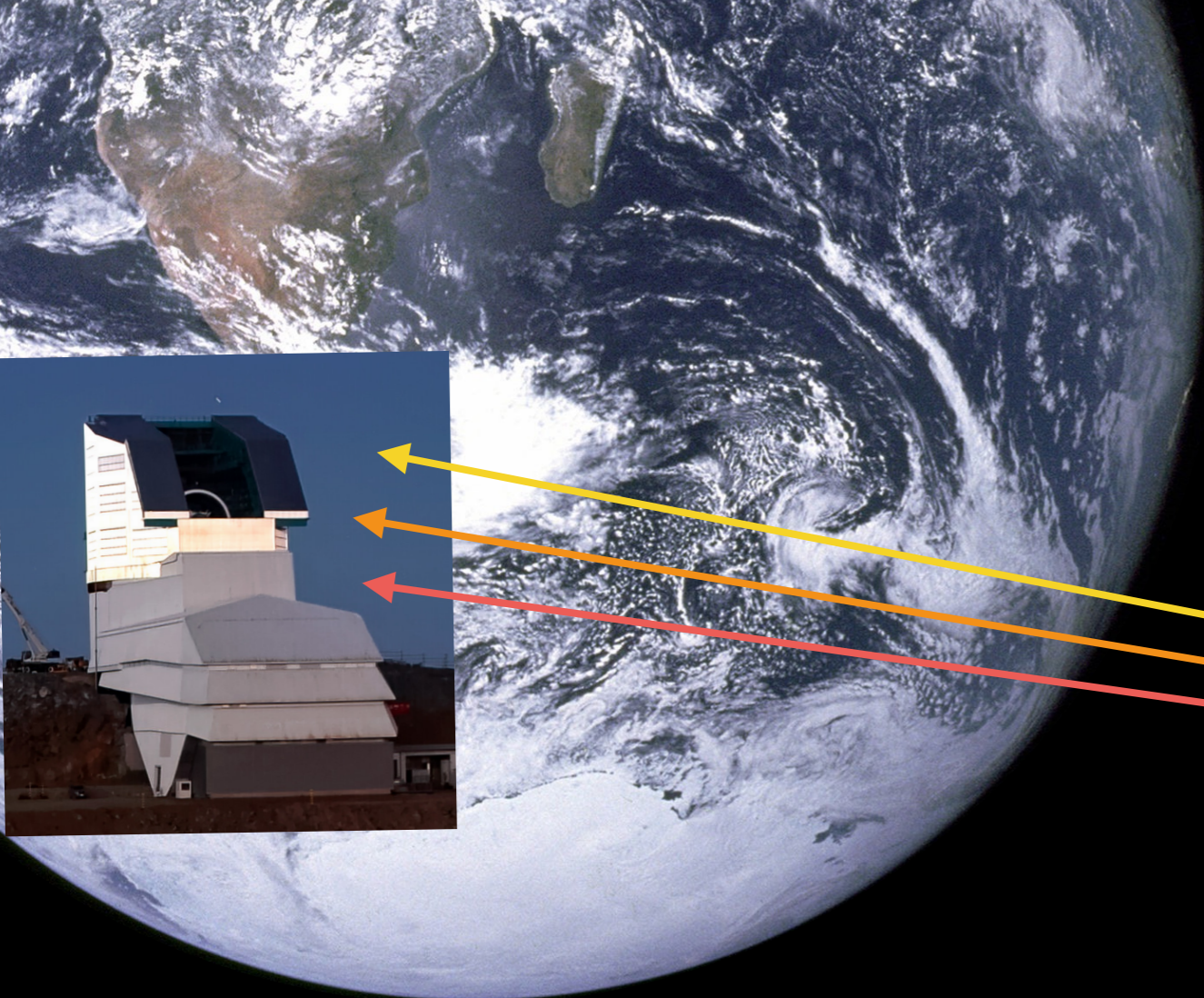
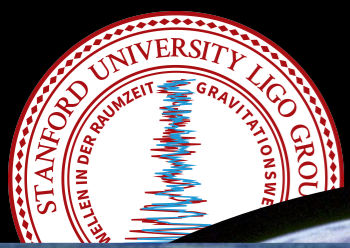


LIGO = Laser Interferometer Gravitational-wave Observatory

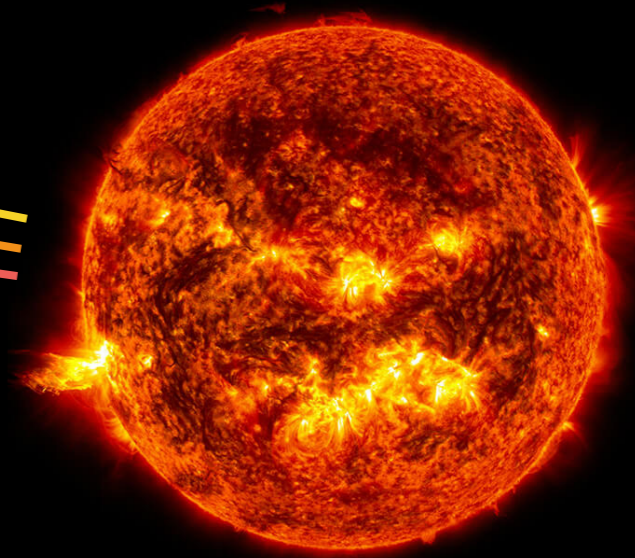
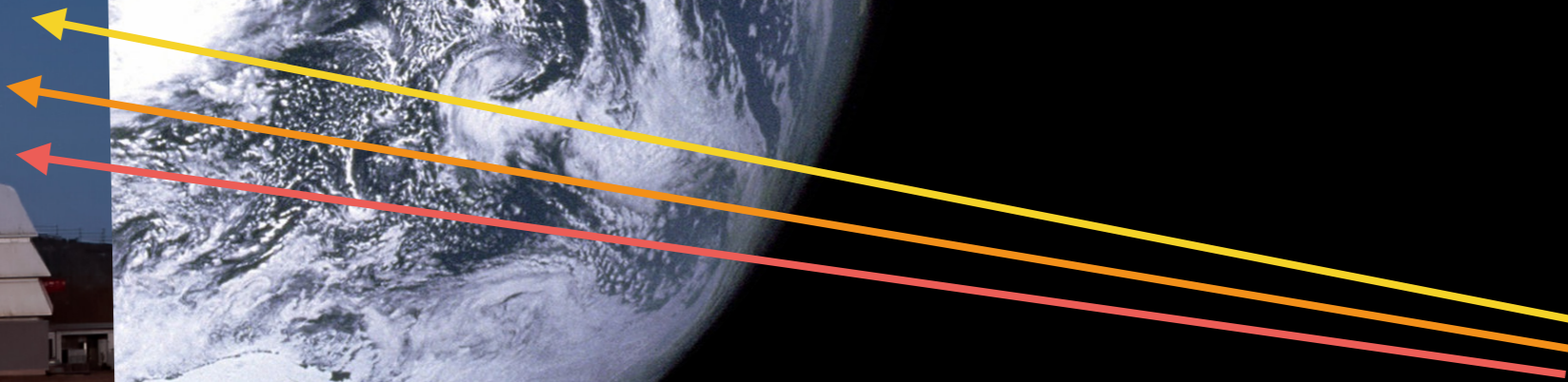
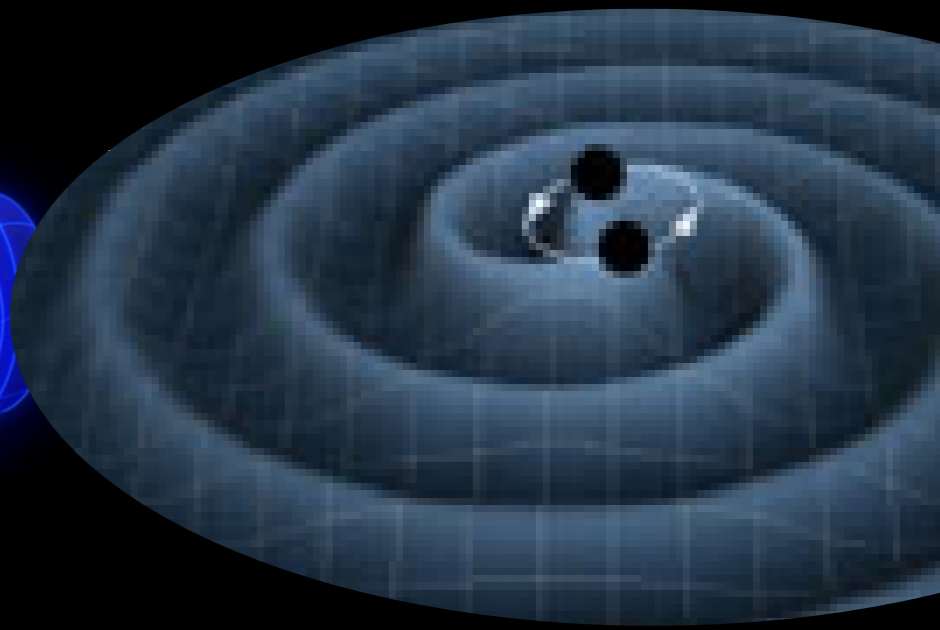
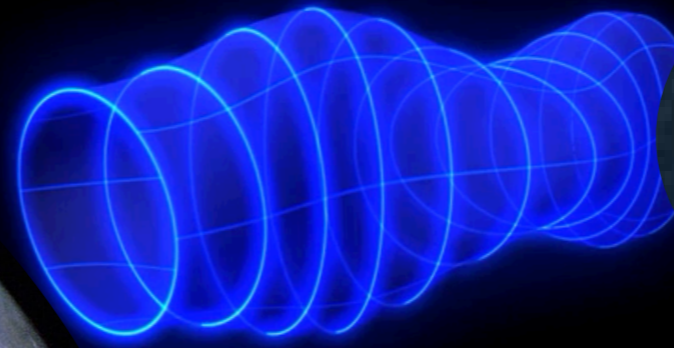
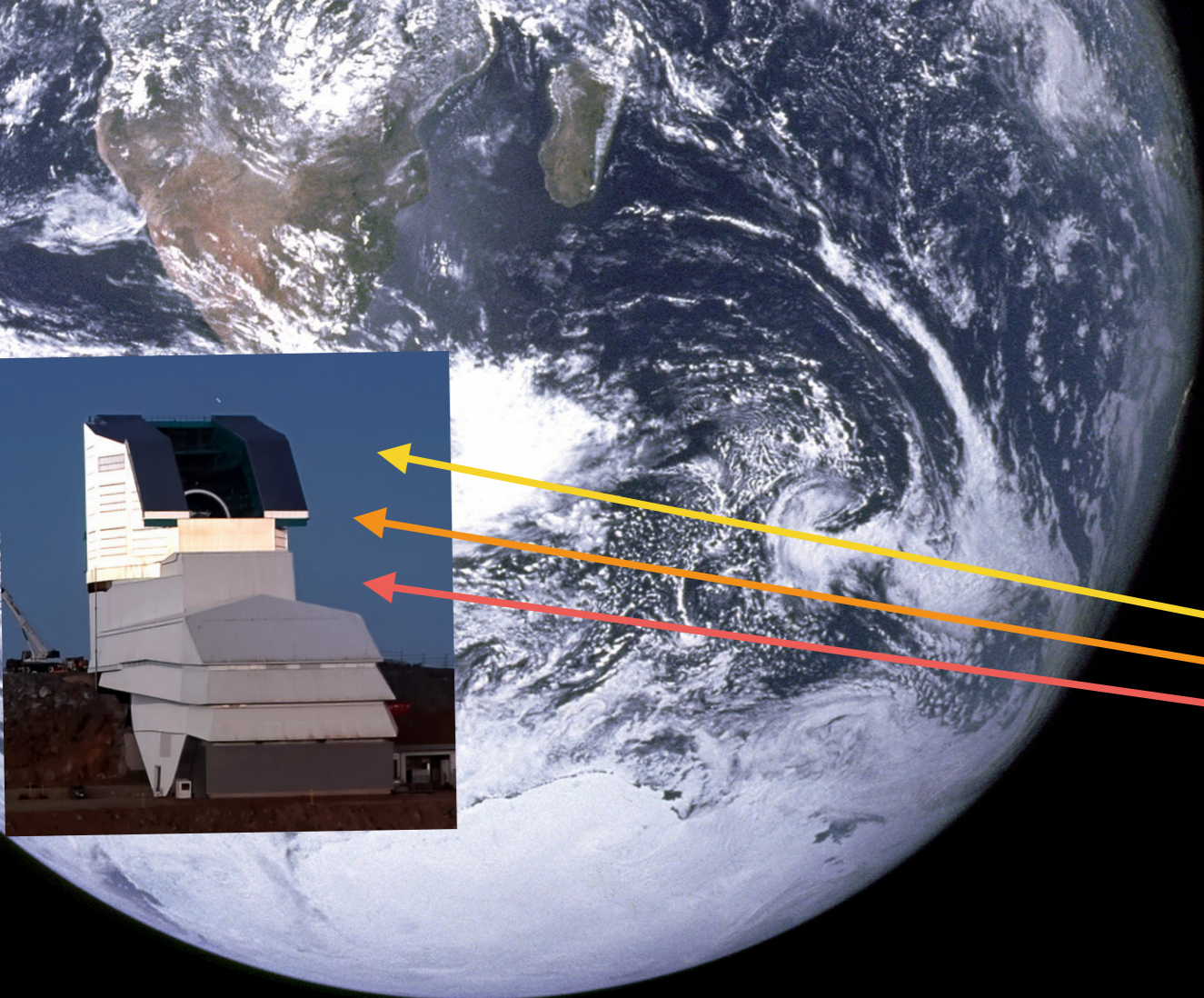
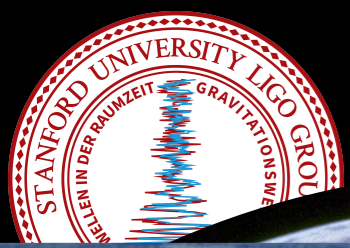




<https://spaceplace.nasa.gov/gallery-sun/en/>
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[https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/\(lang\)](https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/(lang))
https://storage.noirlab.edu/media/archives/images/large/rubin-MorningTwilight_Feb2023-CC.jpg



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International Network



LIGO India



project approved



International Network

LIGO Hanford



GEO 600



KAGRA



VIRGO



LIGO India



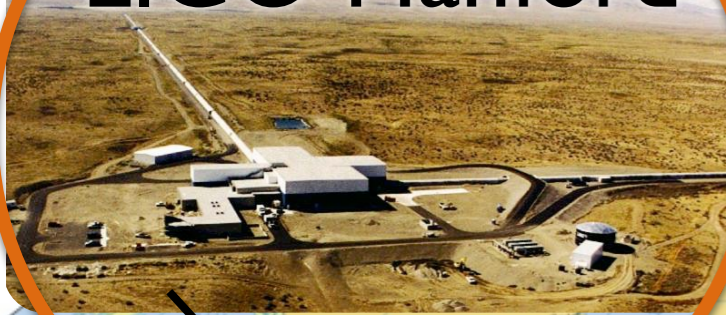
project approved

LIGO Livingston



Inter

LIGO Hanford



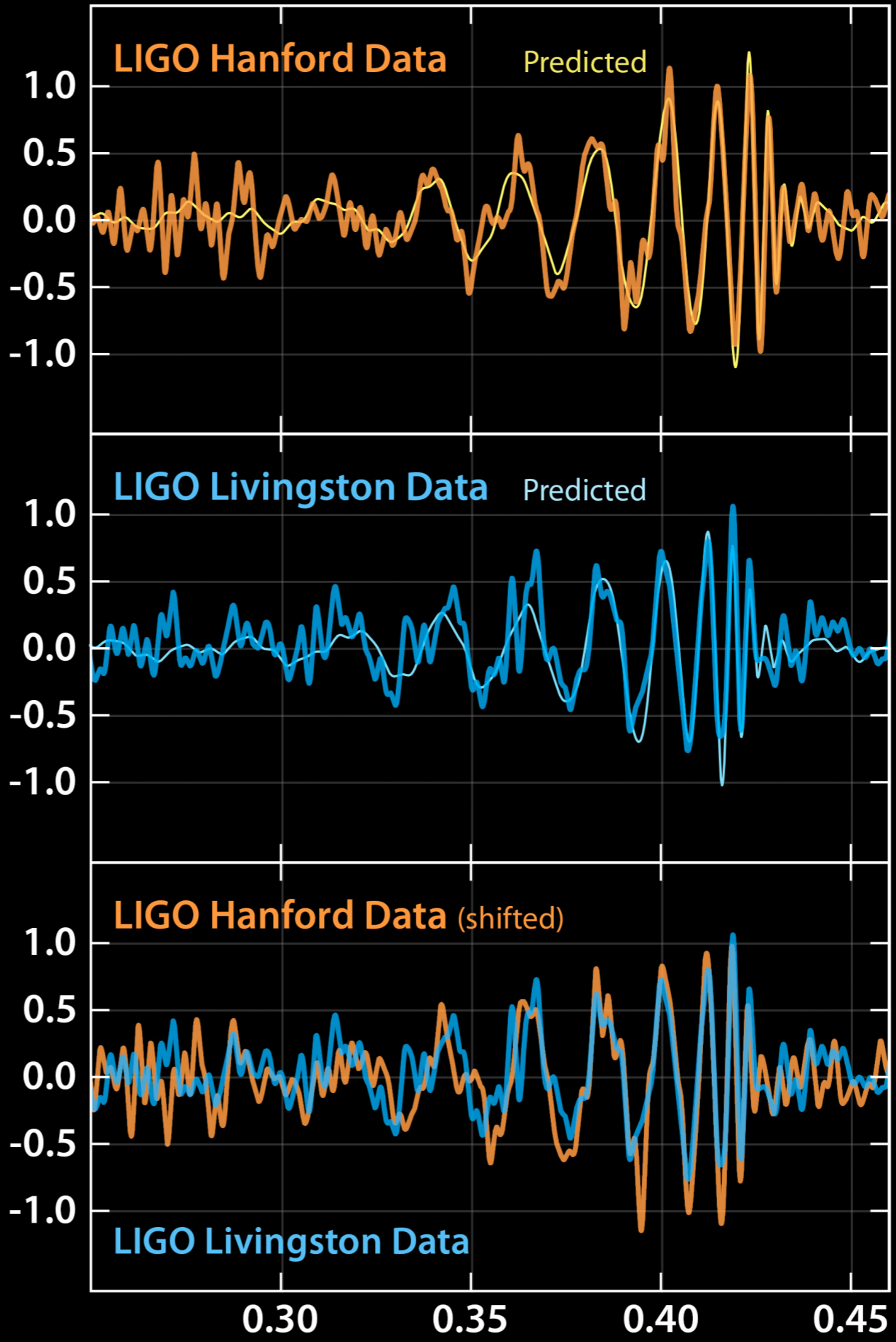
LIGO Livingston



Strain (10^{-21})

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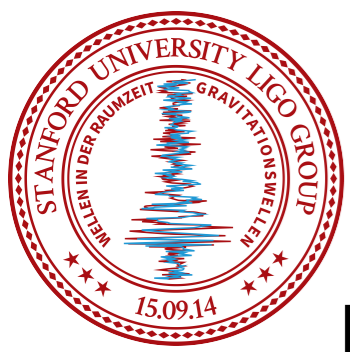


AGRA



LIGO India



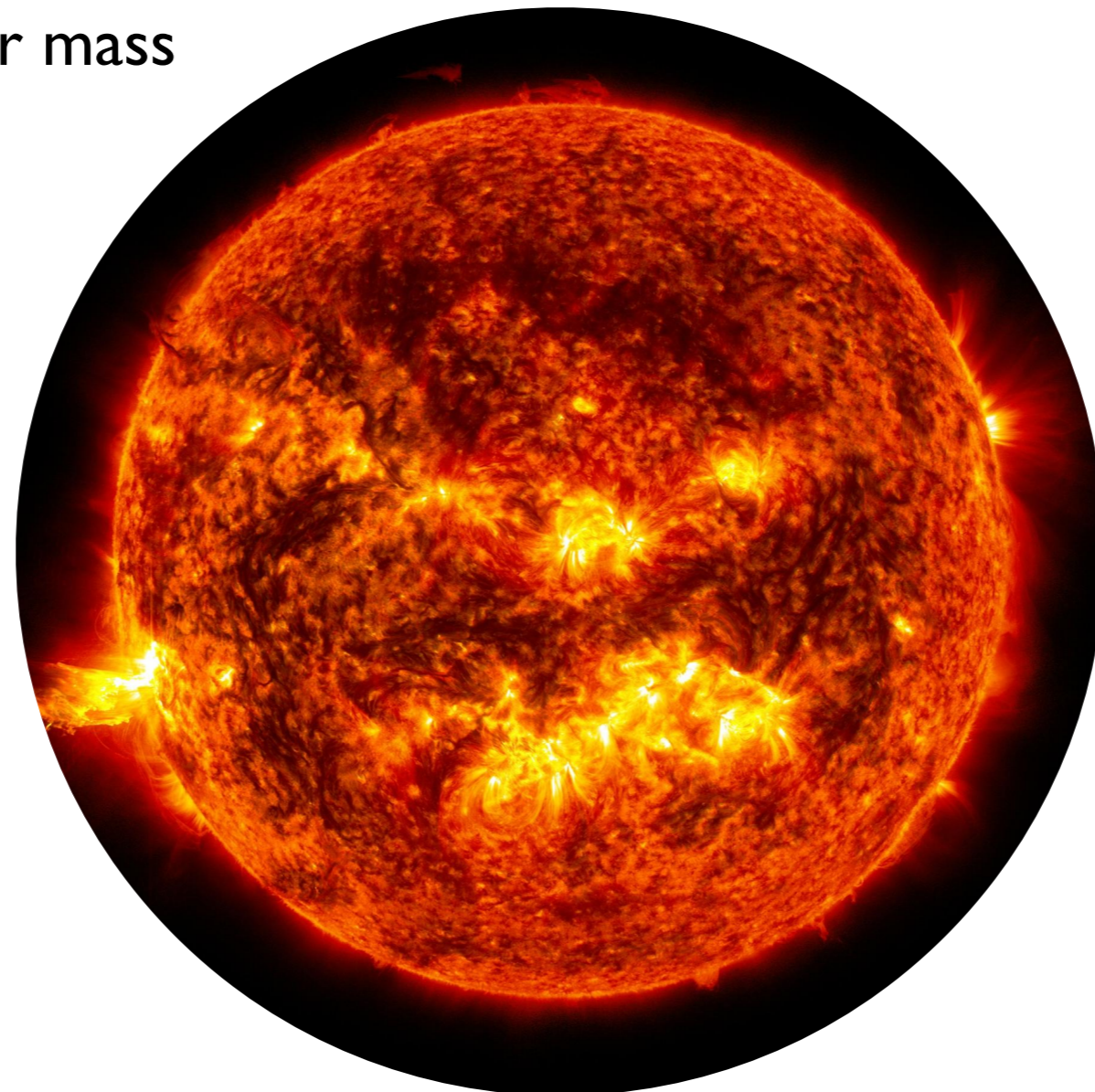


Black Holes

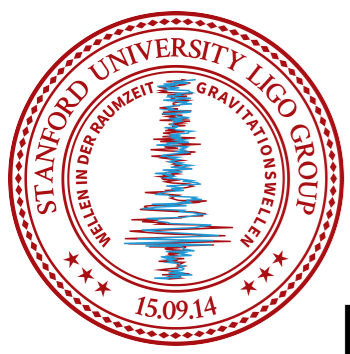


Black Hole - small and massive, gravitational pull is so strong that not even light can get out

Brian's favorite star
1 solar mass



865,000 miles



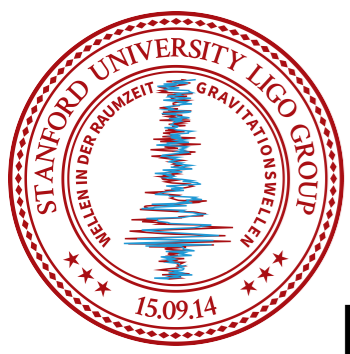
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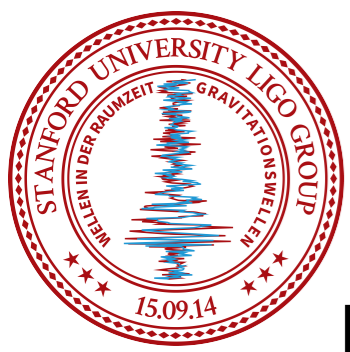
Black Holes



Black Hole - small and massive, gravitational pull is so strong that not even light can get out

- 3.7 miles
1 solar mass
(not going to happen)

865,000 miles



Black Holes



Black Hole - small and massive, gravitational pull is so strong that not even light can get out

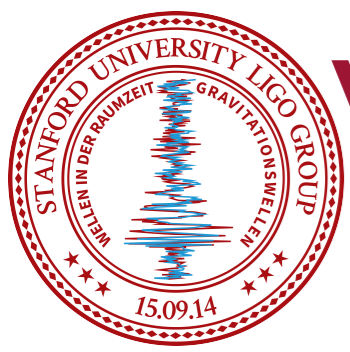
First LIGO detection:

- ~30 solar mass
110 miles in diameter

- 3.7 miles
1 solar mass
(not going to happen)

865,000 miles



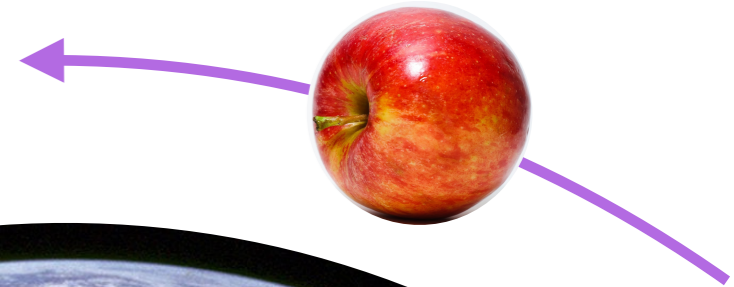


What is a Gravitational Wave?



$$F = \frac{Gm_1m_2}{r^2}$$

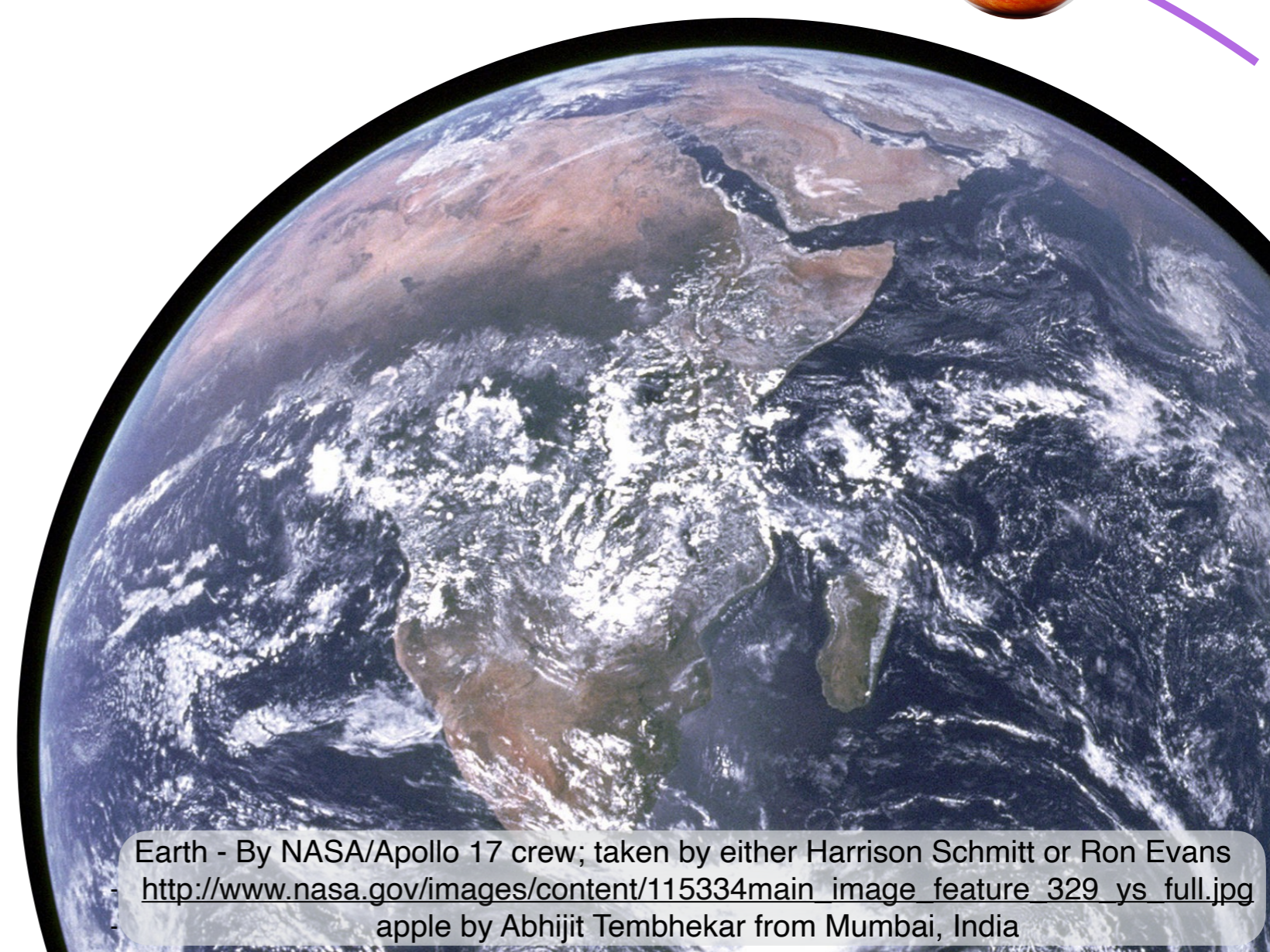
Implies immediate action at a distance



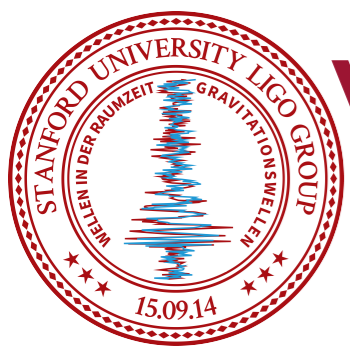
Sir Isaac Newton

By Sir Godfrey Kneller

- <http://www.newton.cam.ac.uk/art/portrait.html>



Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India



What is a Gravitational Wave?

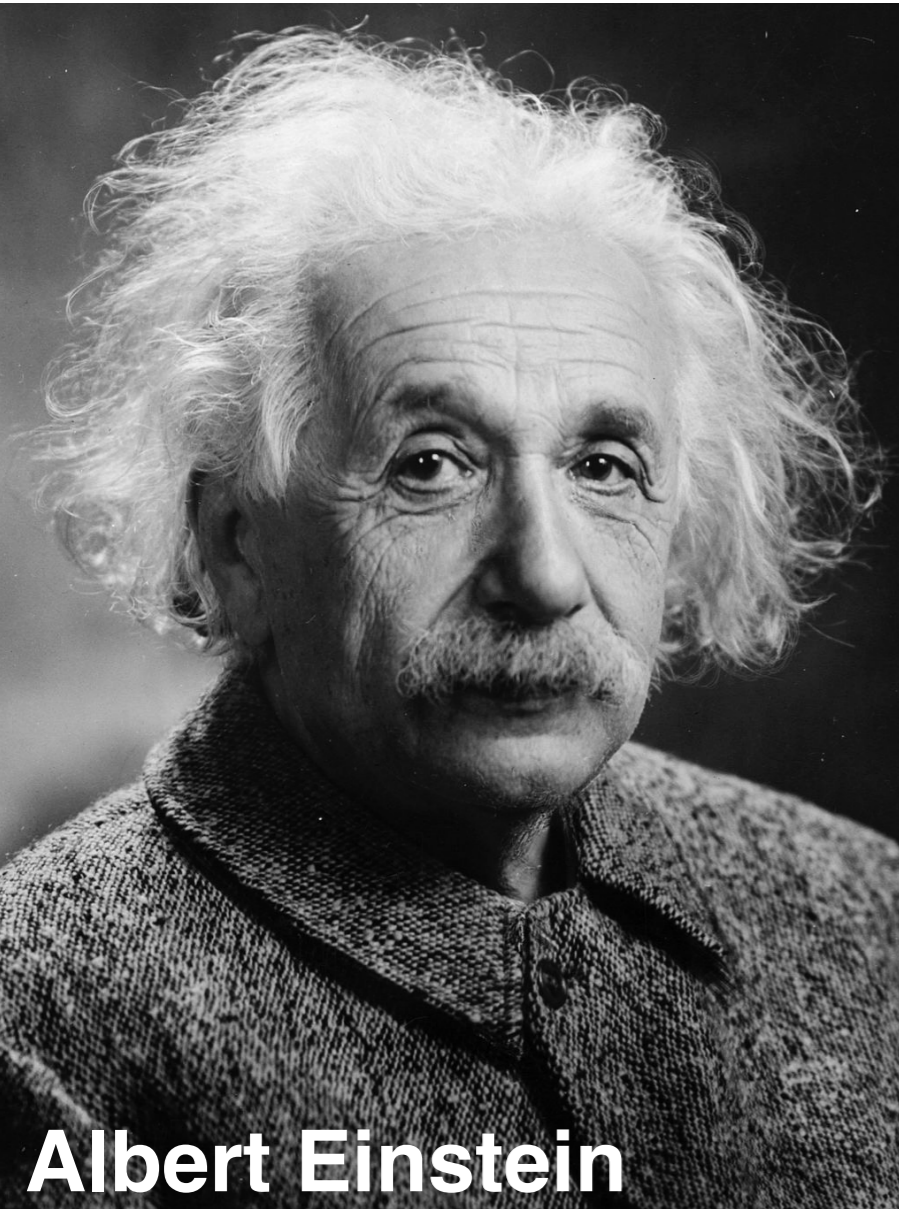


Predicted by Einstein in 1916 as part of GR.

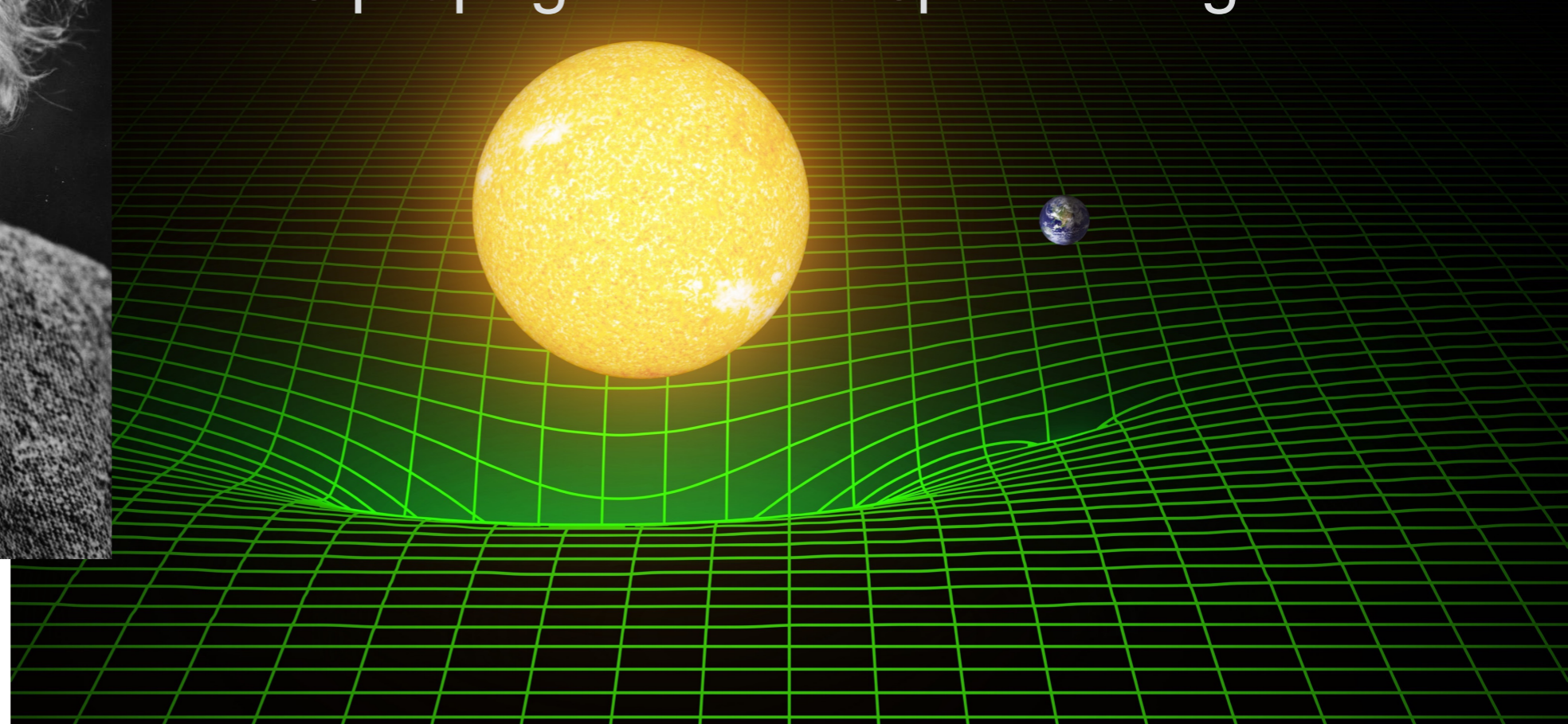
“Spacetime tells matter how to move,
matter tells spacetime how to curve”

- J. A. Wheeler

There are traveling wave solutions, the
waves propagate at the speed of light

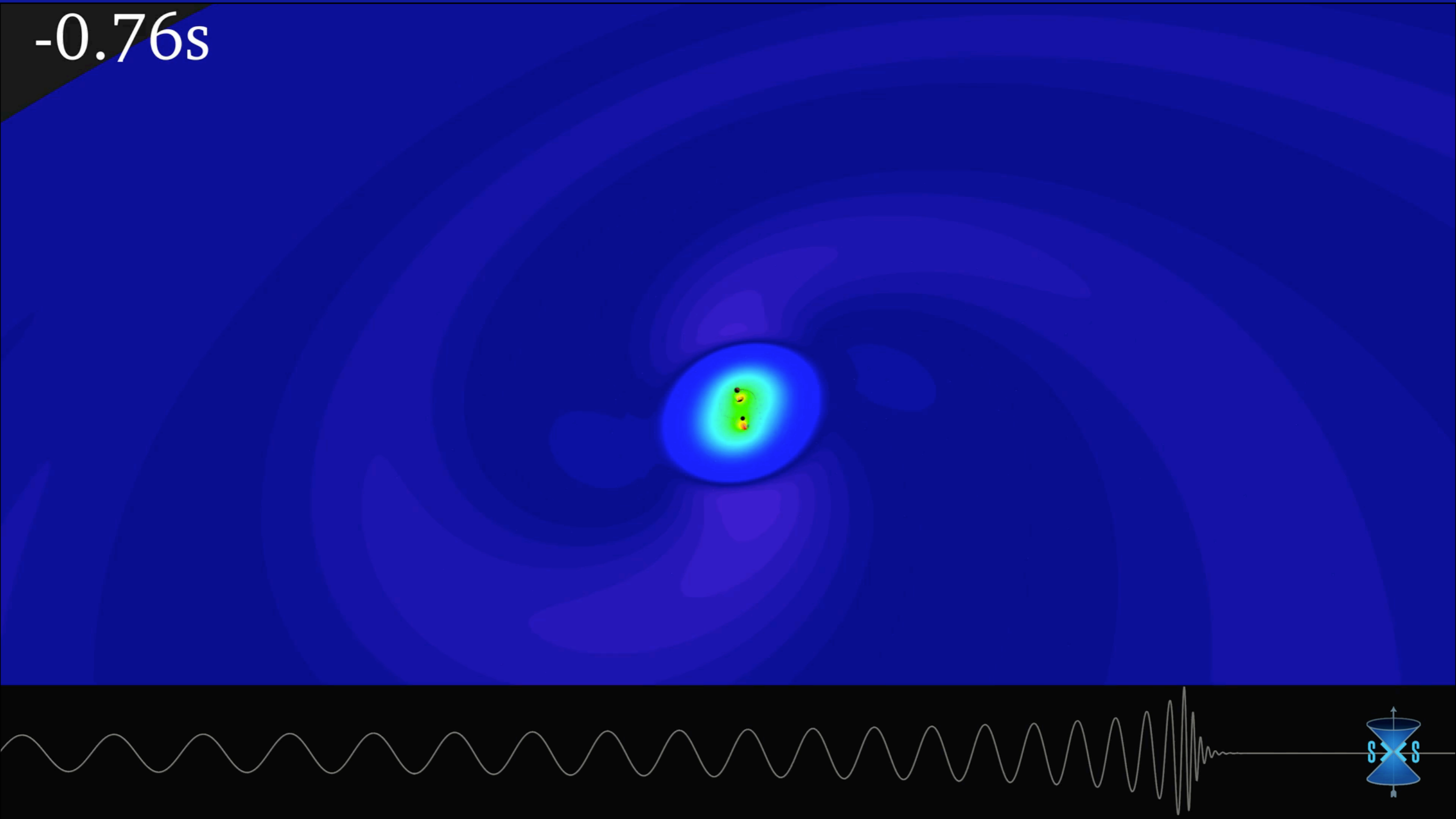


Albert Einstein



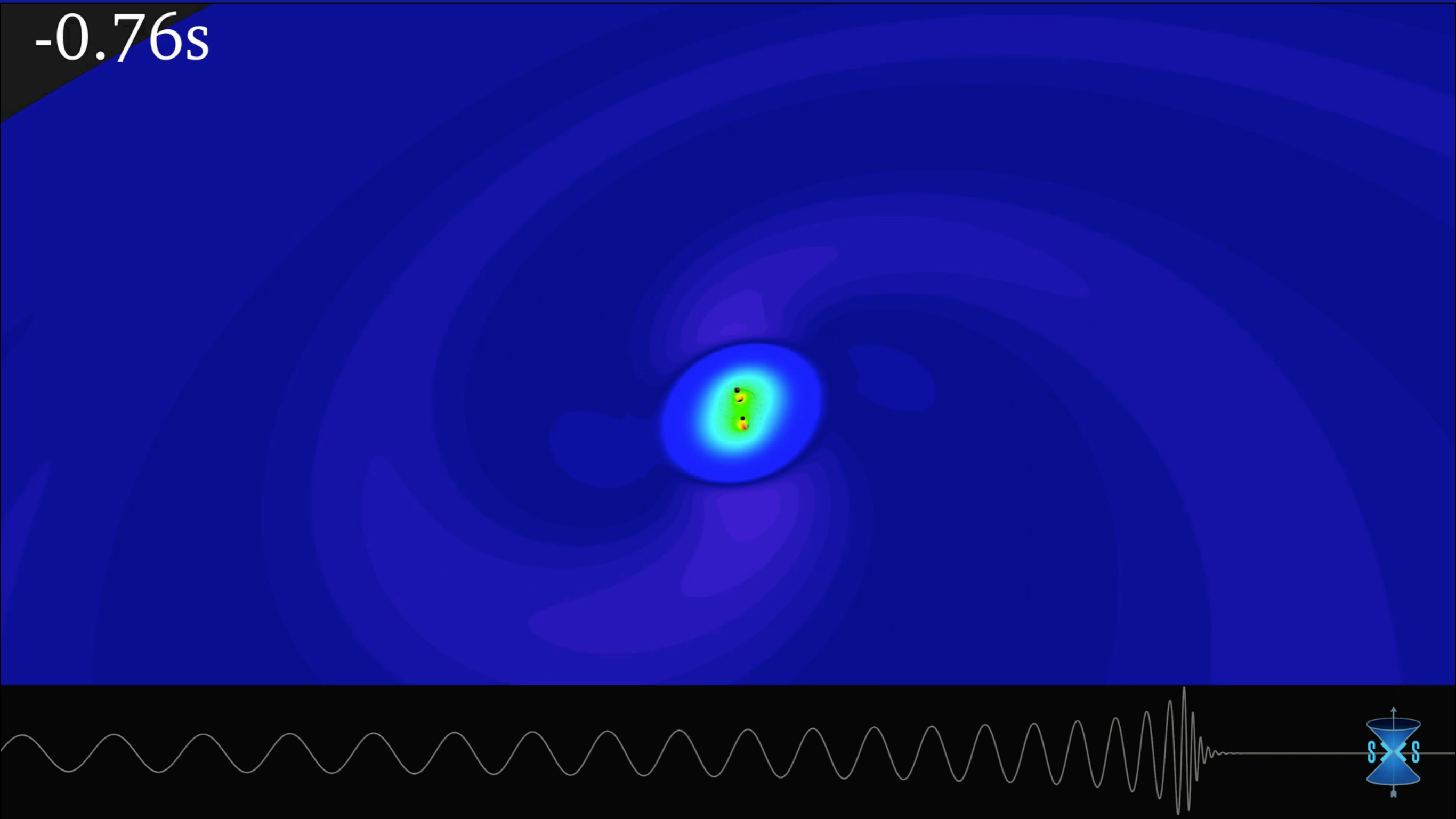
Simulation of the event

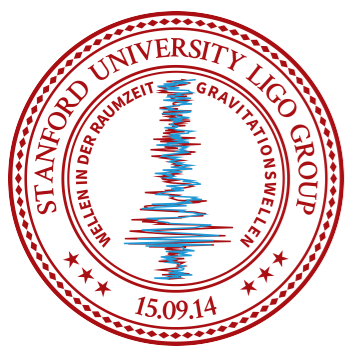
-0.76s



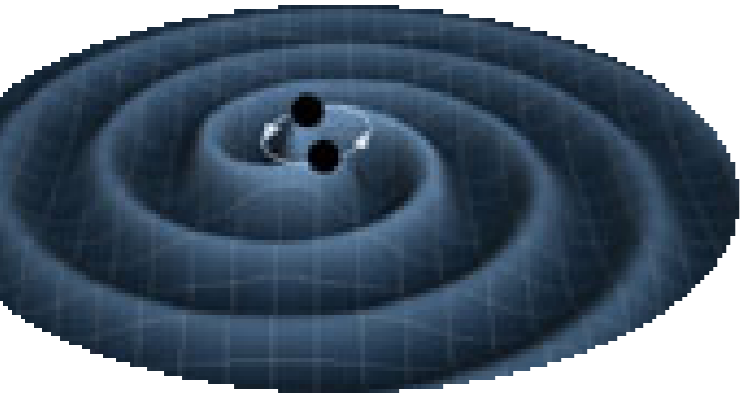
Simulation of the event

-0.76s

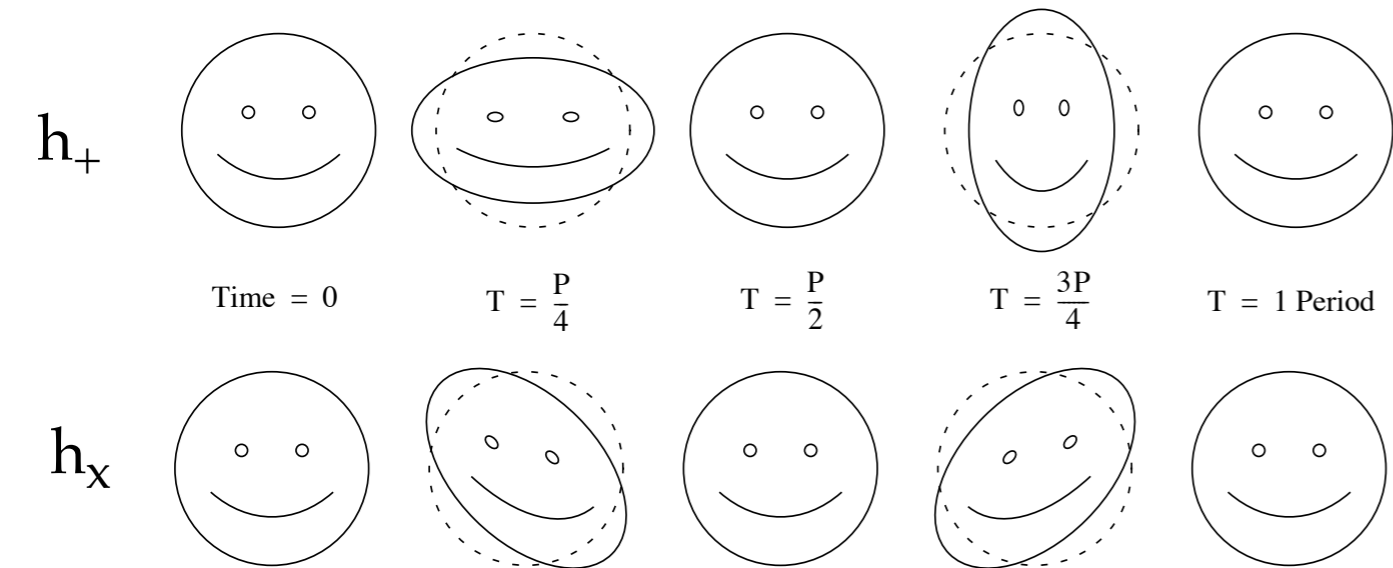




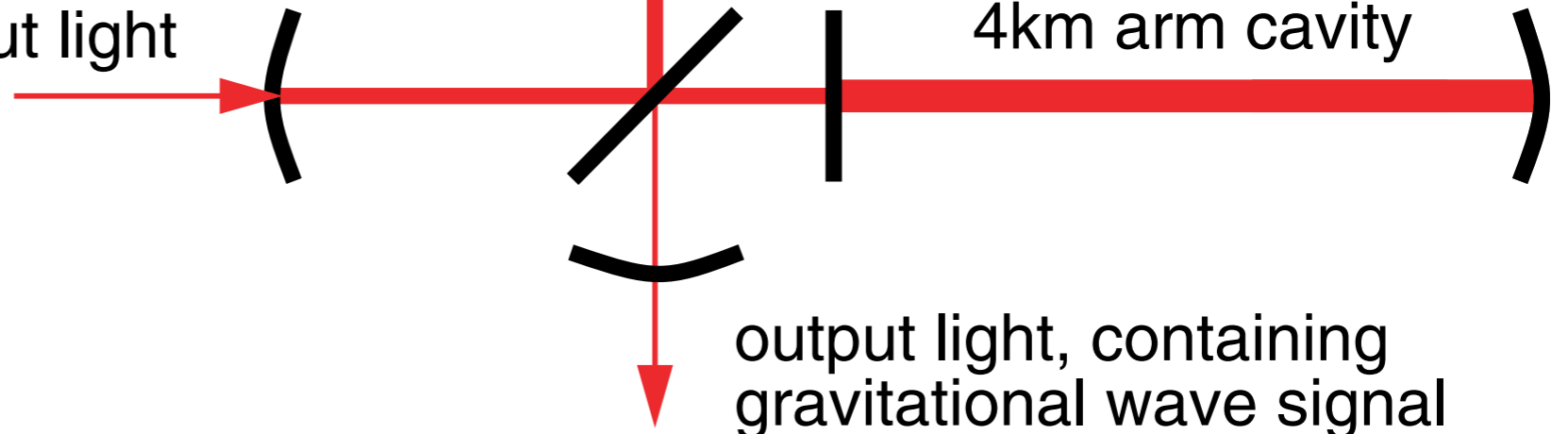
The LIGO concept



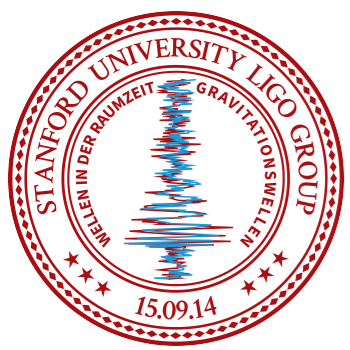
It's sort of like this,



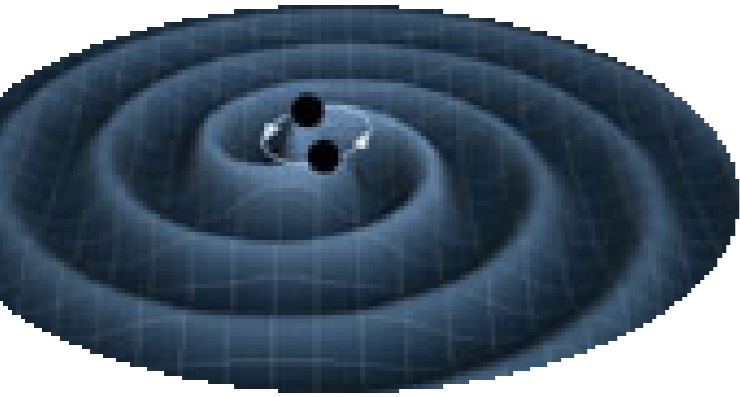
input light



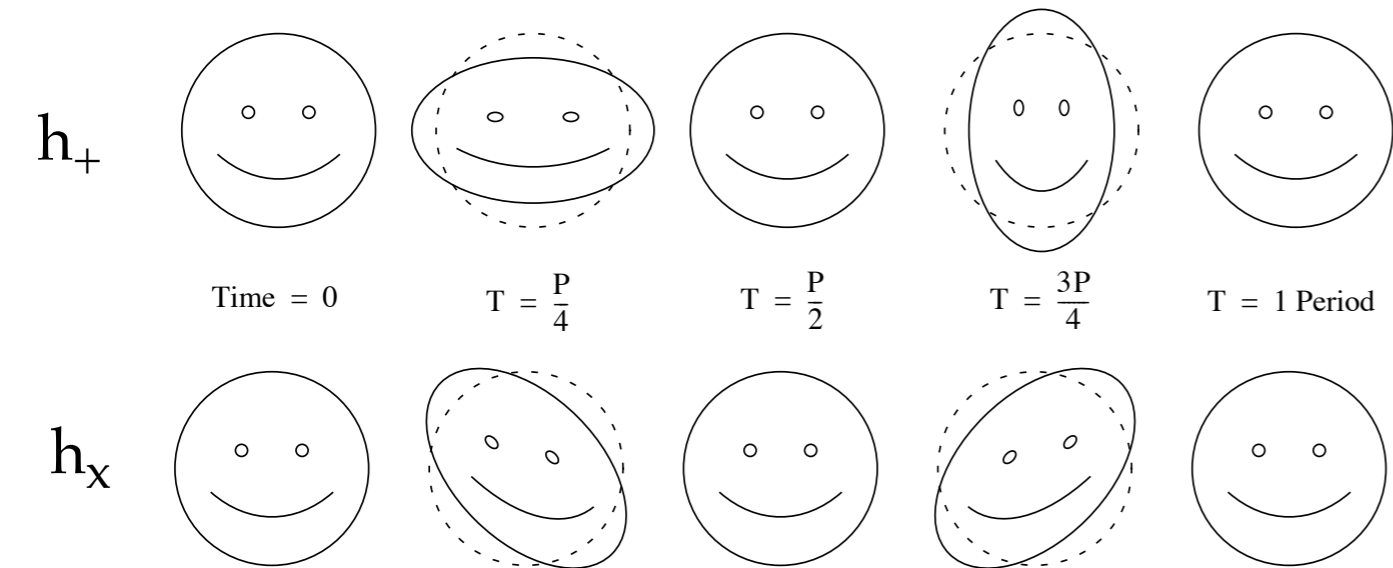
output light, containing gravitational wave signal



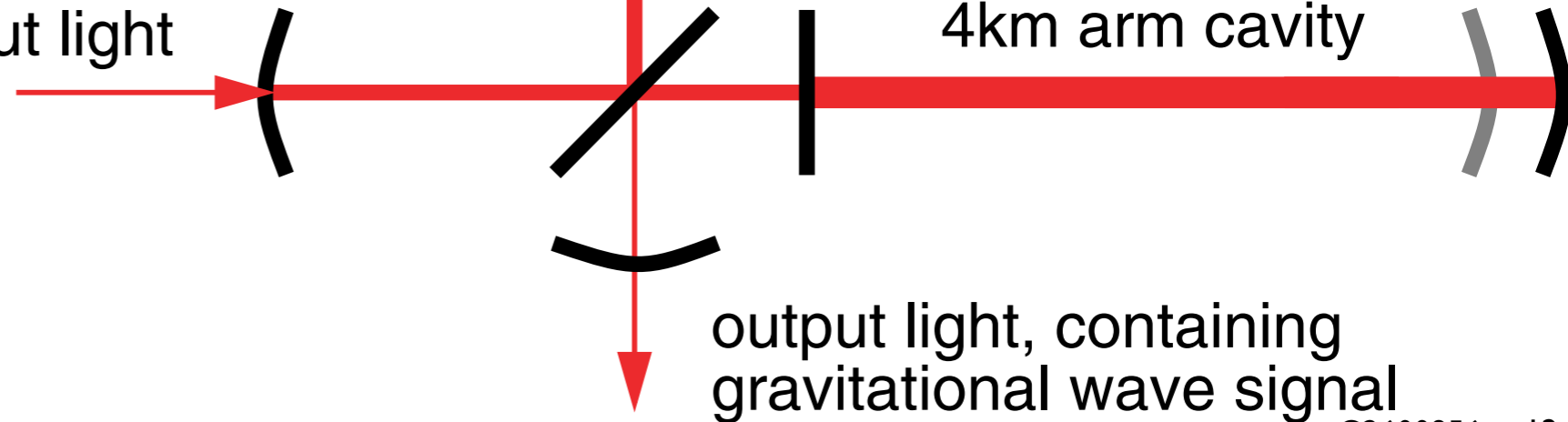
The LIGO concept



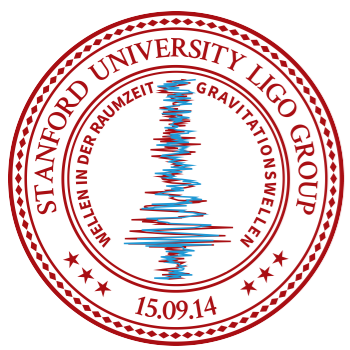
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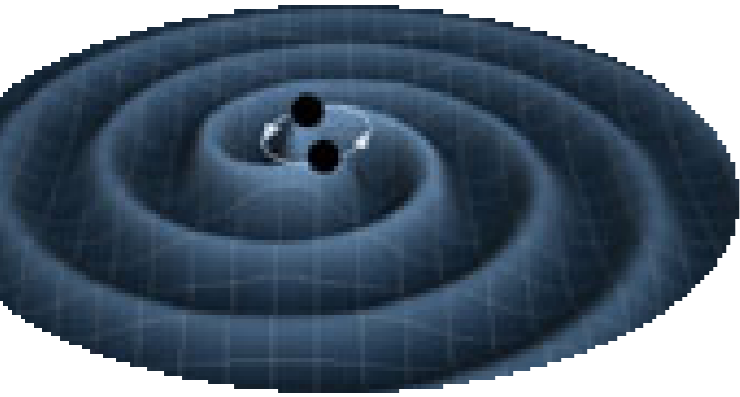
input light



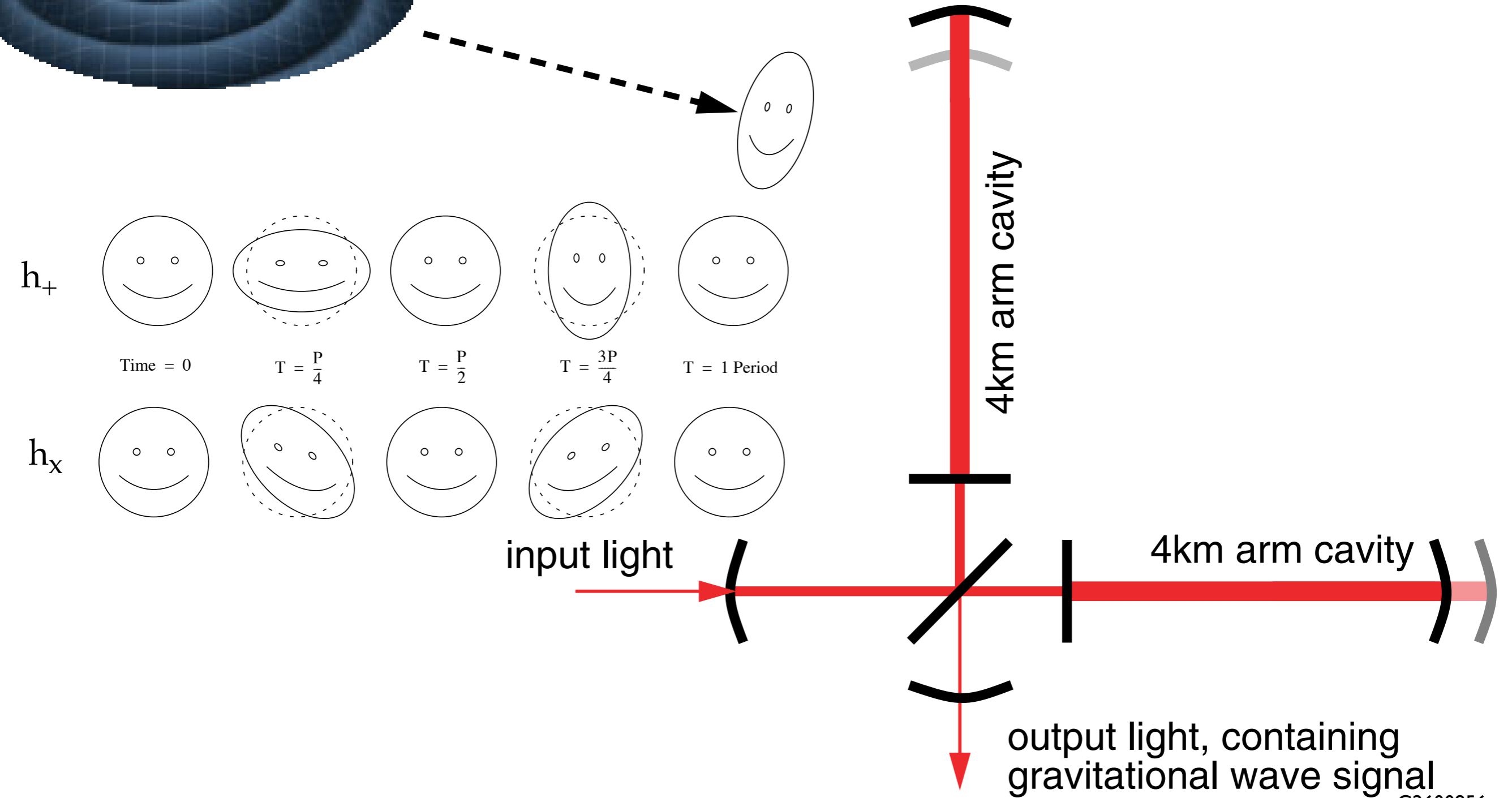
output light, containing gravitational wave signal



The LIGO concept

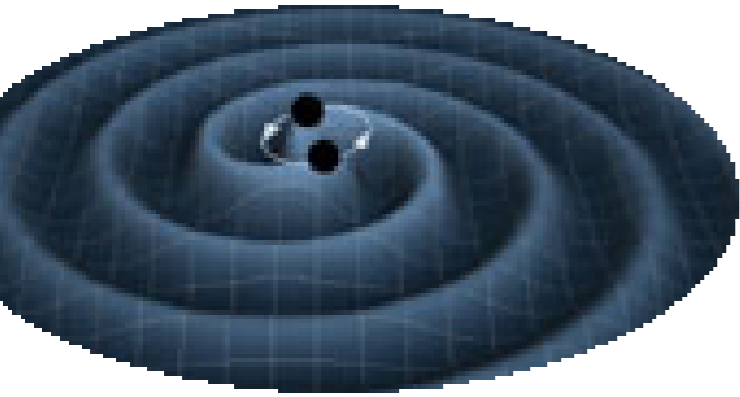


It's sort of like this,

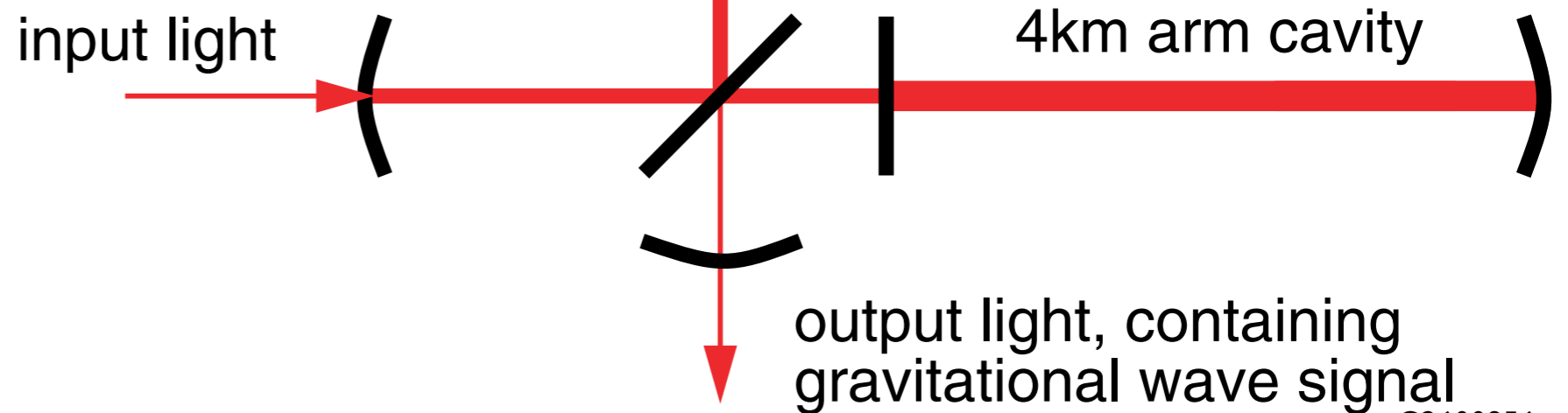
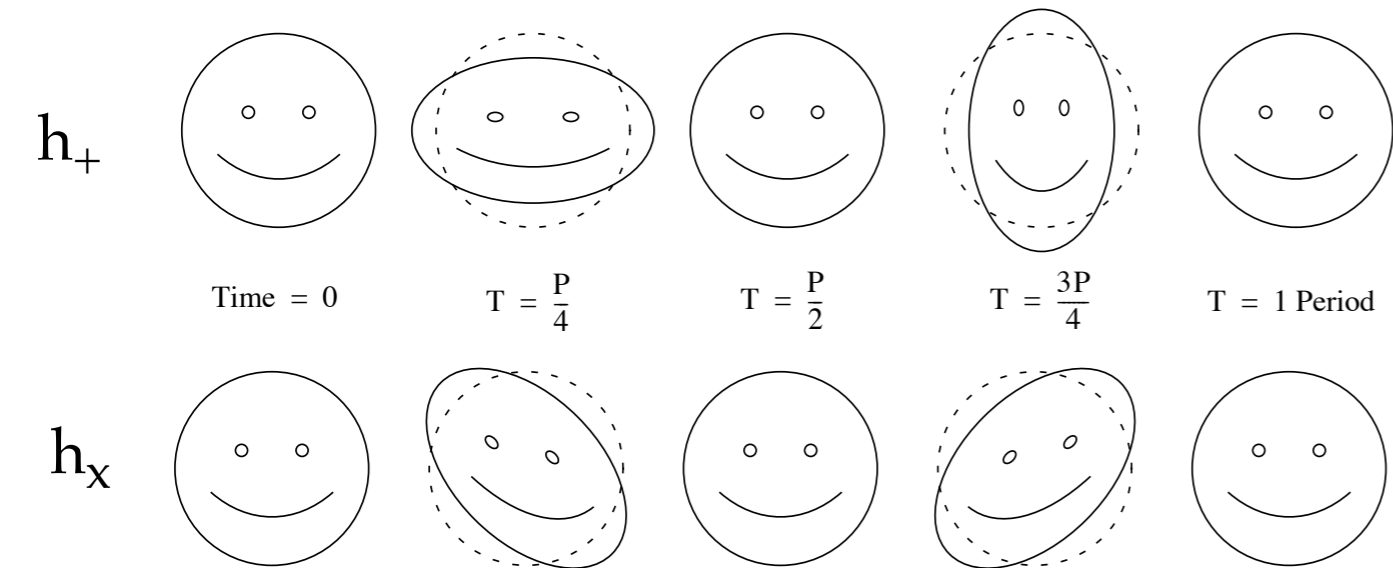


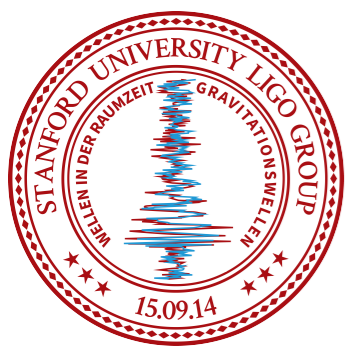


The LIGO concept



It's sort of like this, except spacetime is stretching, and the mirrors don't move.





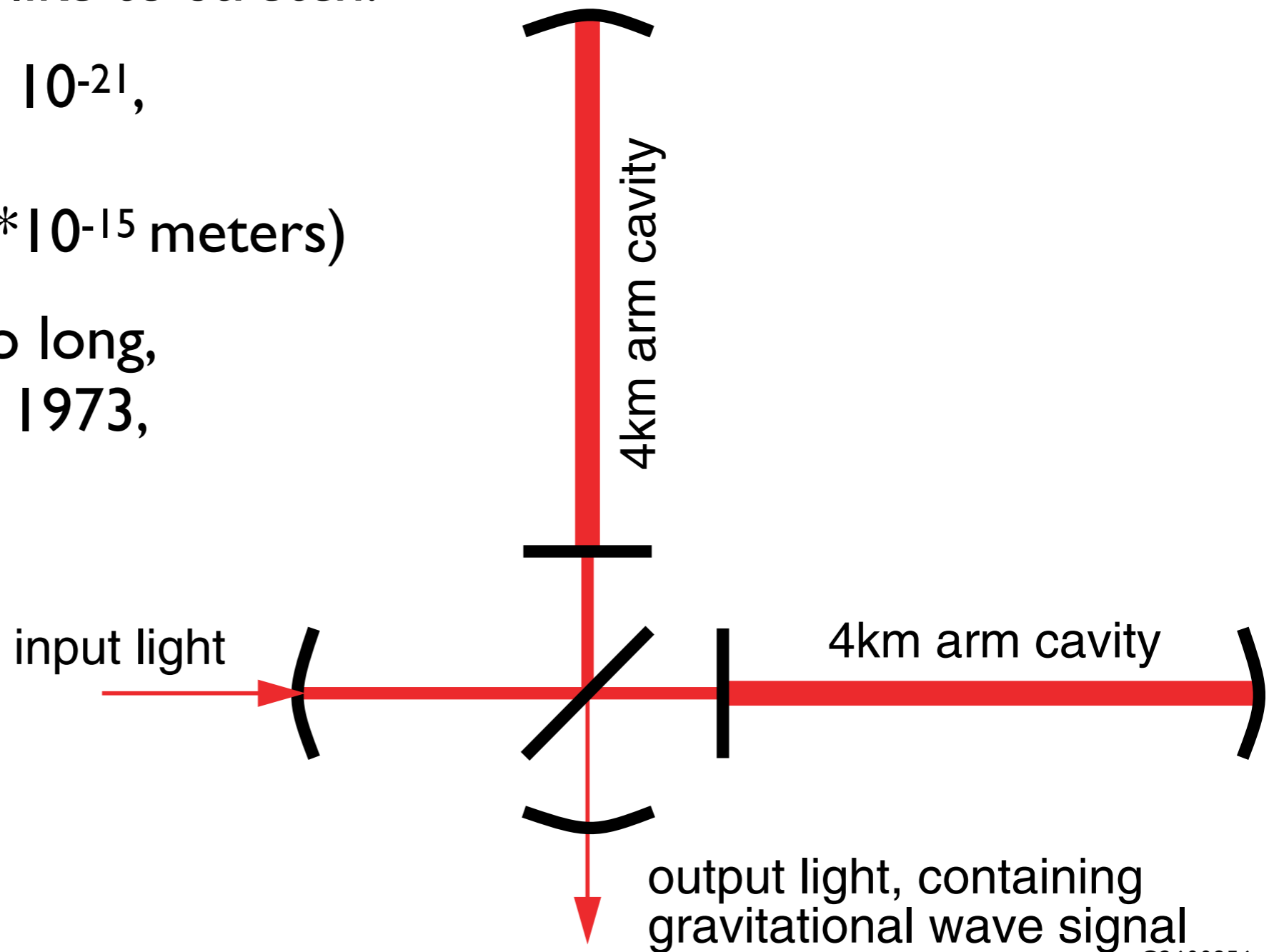
The LIGO concept

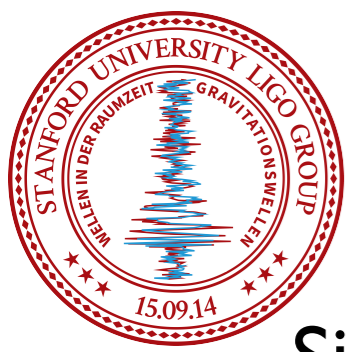


Gravitational waves are hard to measure because space doesn't like to stretch.

Our signal strain (h) = 10^{-21} ,
 $dL = 4 \times 10^{-18}$ meters
(proton is about 1.7×10^{-15} meters)

(that's why it's taken so long,
Einstein 1916, Weiss 1973,
first signal 2015)

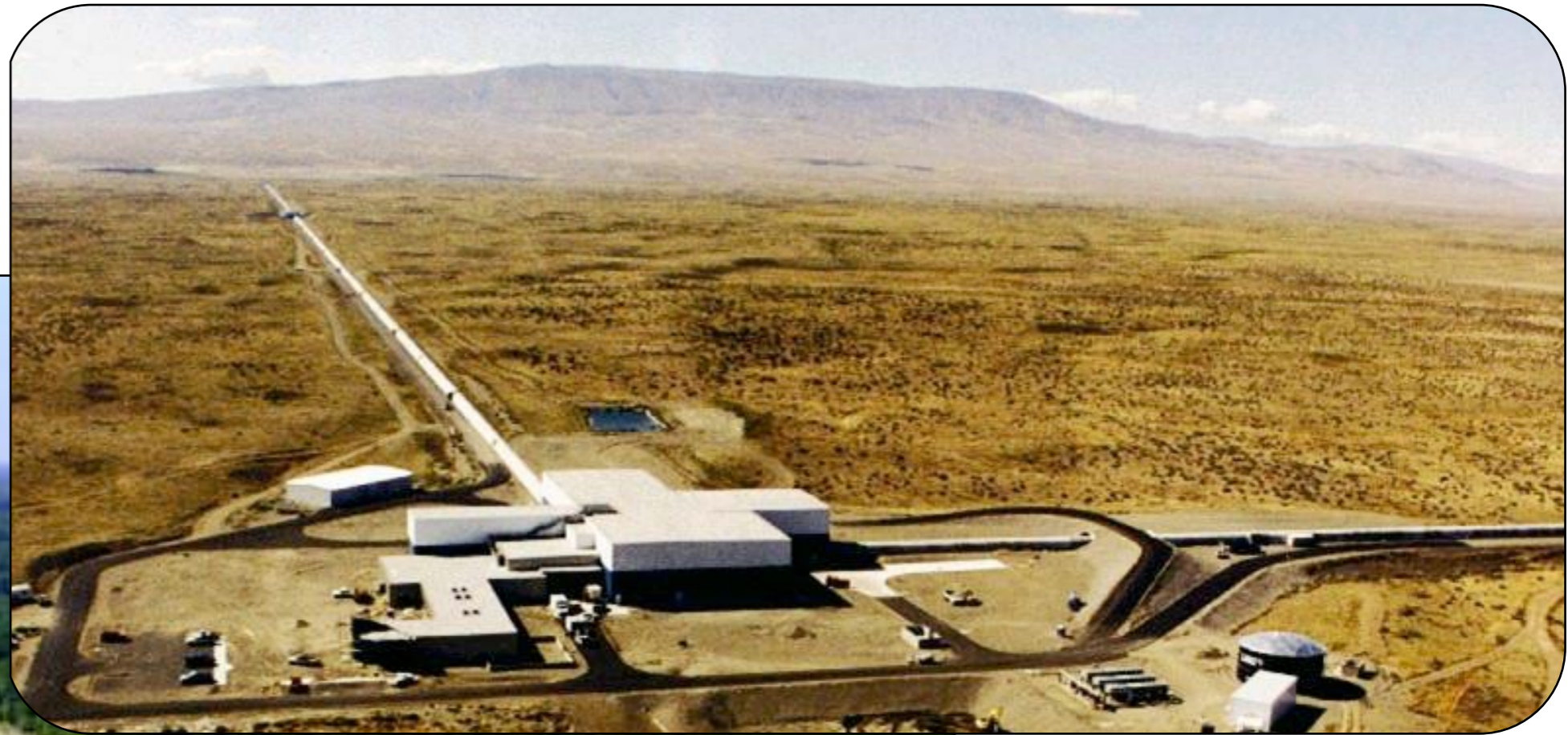


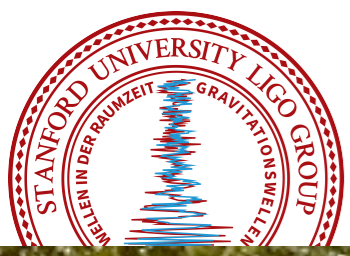


Long arms



Since $h = dL/L$ (or $dL = h * L$) more L gives you more dL of signal,
World's 3rd largest ultra-clean vacuum system
- each arm is 4 km long, 4 ft. diameter





LIGO Beamtube



LIGO Beamtube

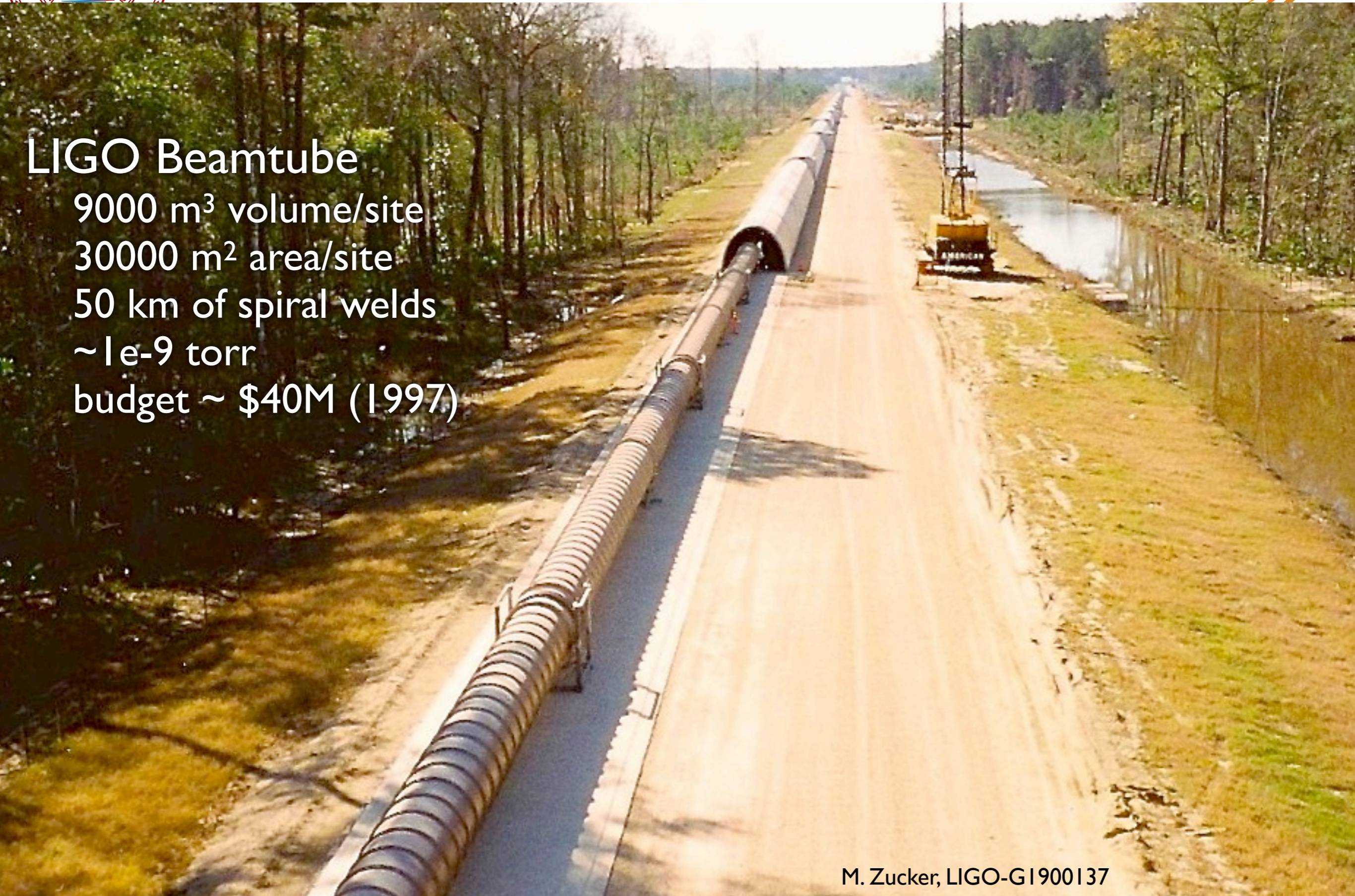
9000 m³ volume/site

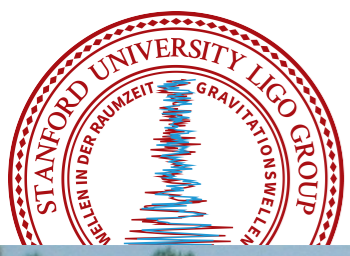
30000 m² area/site

50 km of spiral welds

~1e-9 torr

budget ~ \$40M (1997)





LIGO Beamtube



LIGO Beamtube

9000 m³ volume/site

30000 m² area/site

50 km of spiral welds

~1 e-9 torr

budget ~ \$40M (1997)

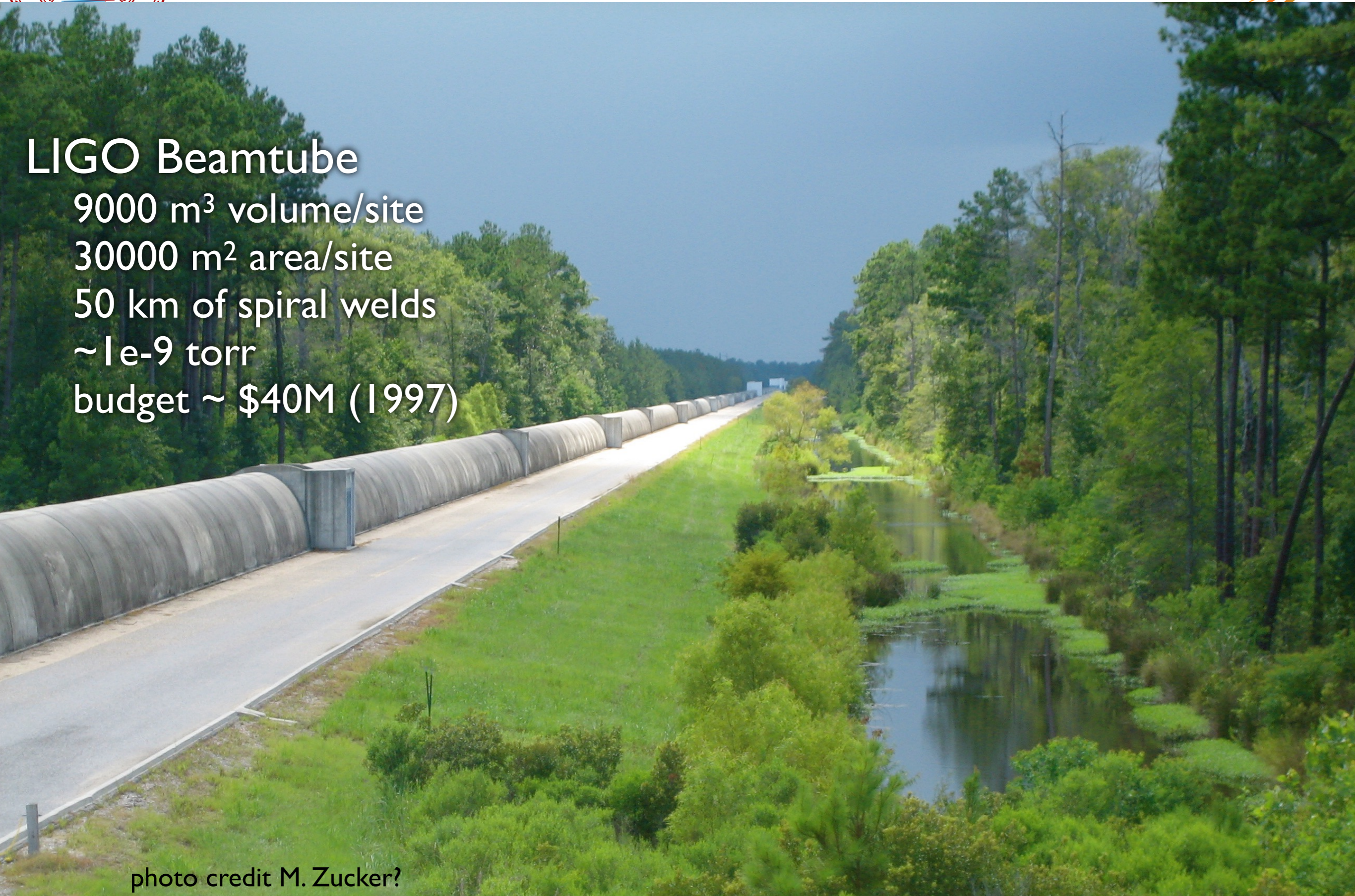
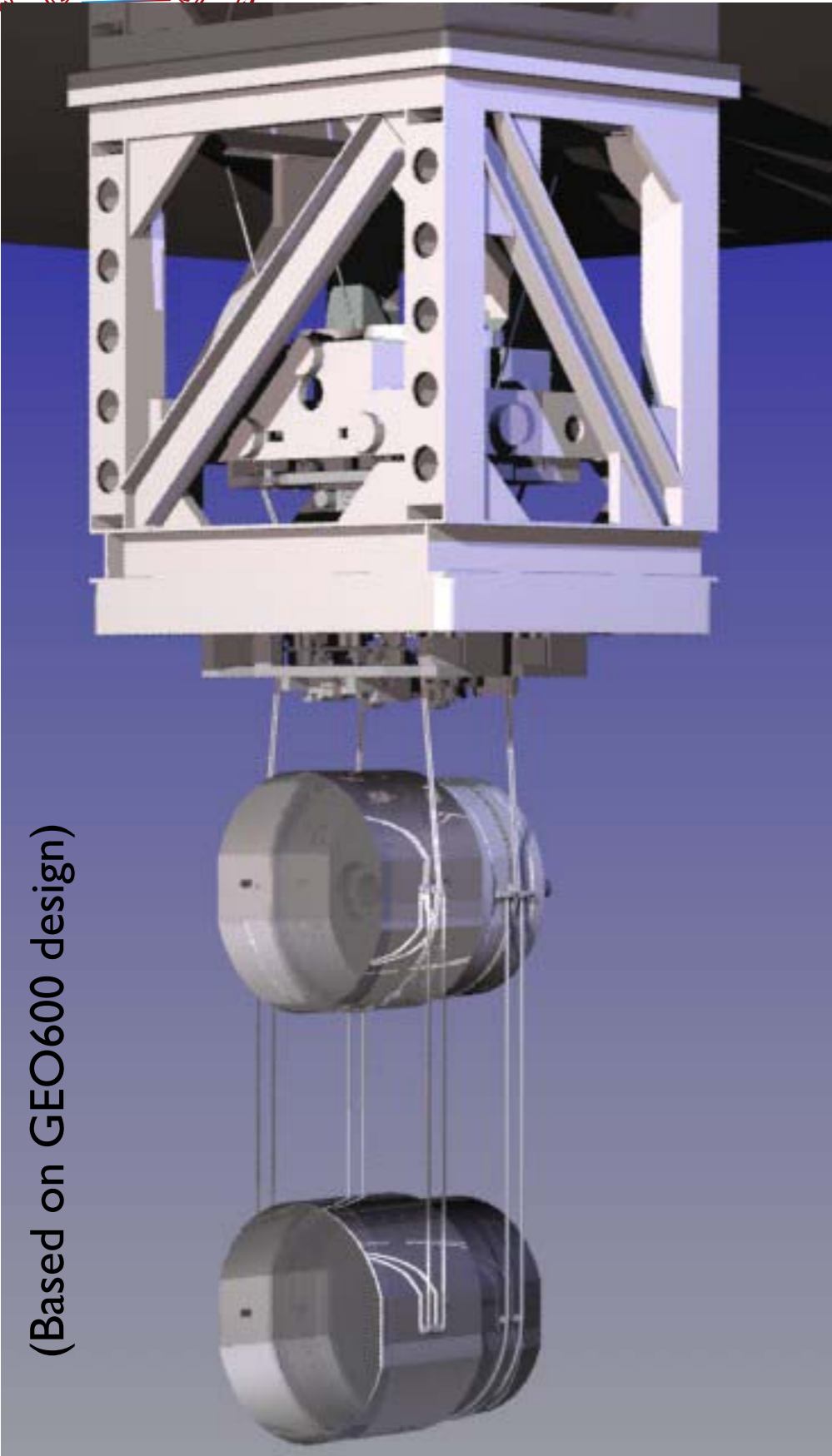


photo credit M. Zucker?

Pendulum Suspension



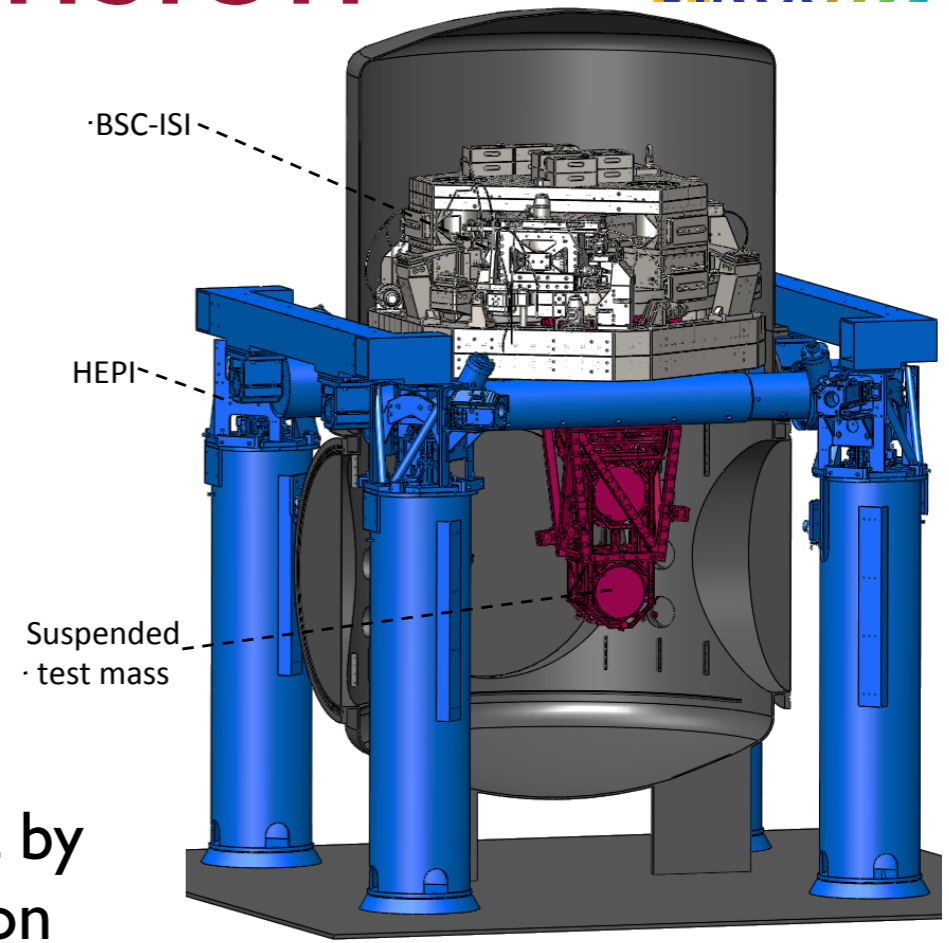
(Based on GEO600 design)

LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

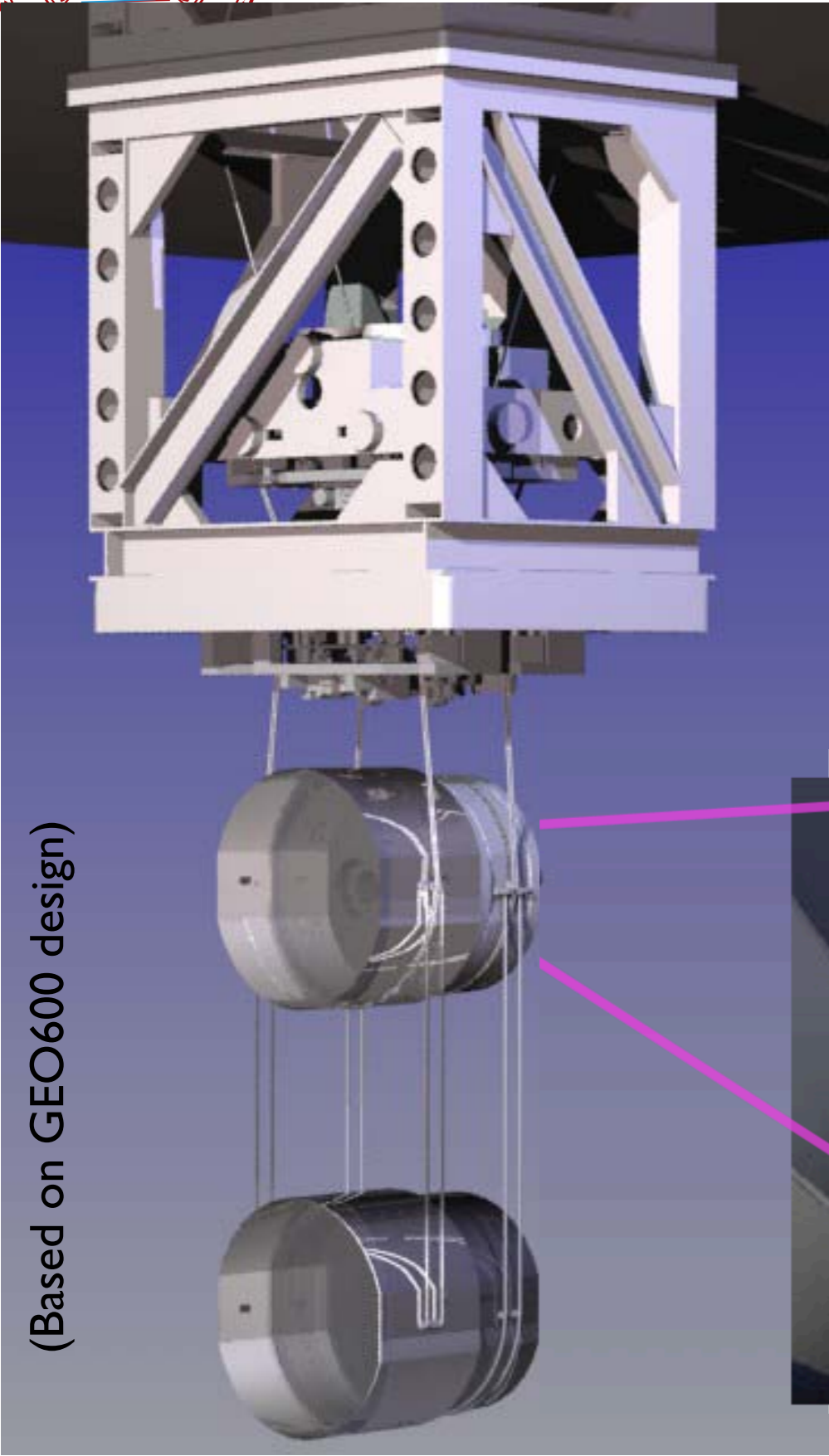
Suspended as a
4 stage pendulum

Best coatings available

Motion at 10 Hz is set by
thermal driven vibration



Pendulum Suspension

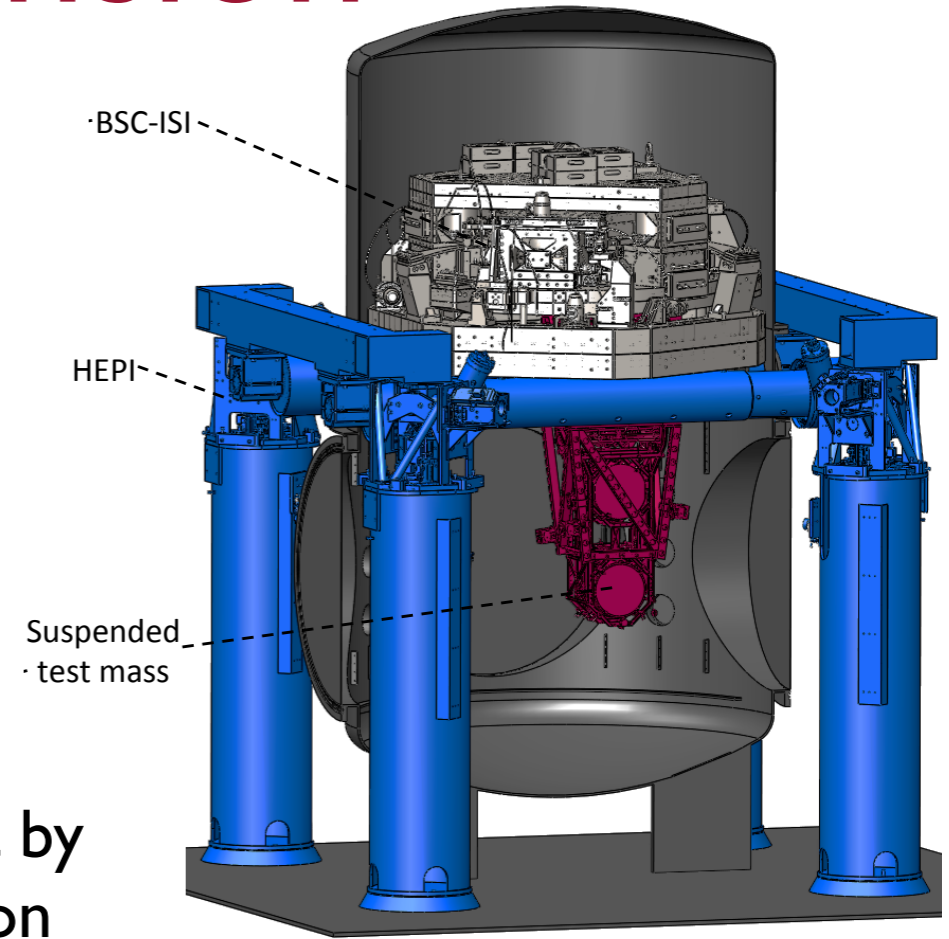


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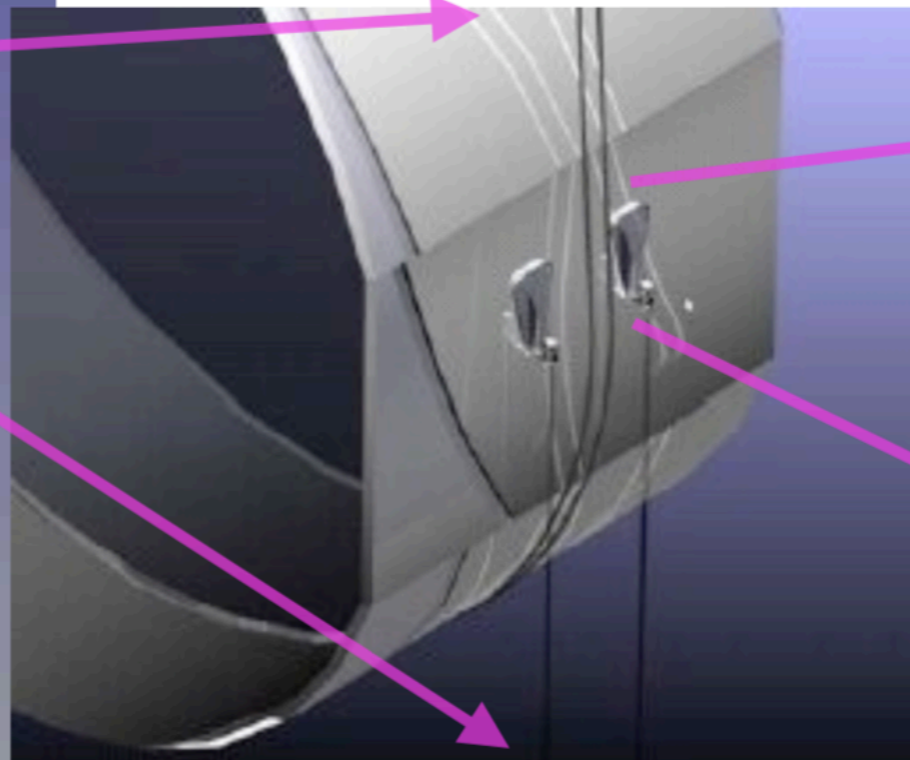
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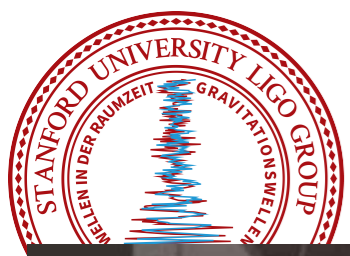
Motion at 10 Hz is set by
 thermal driven vibration



(Based on GEO600 design)

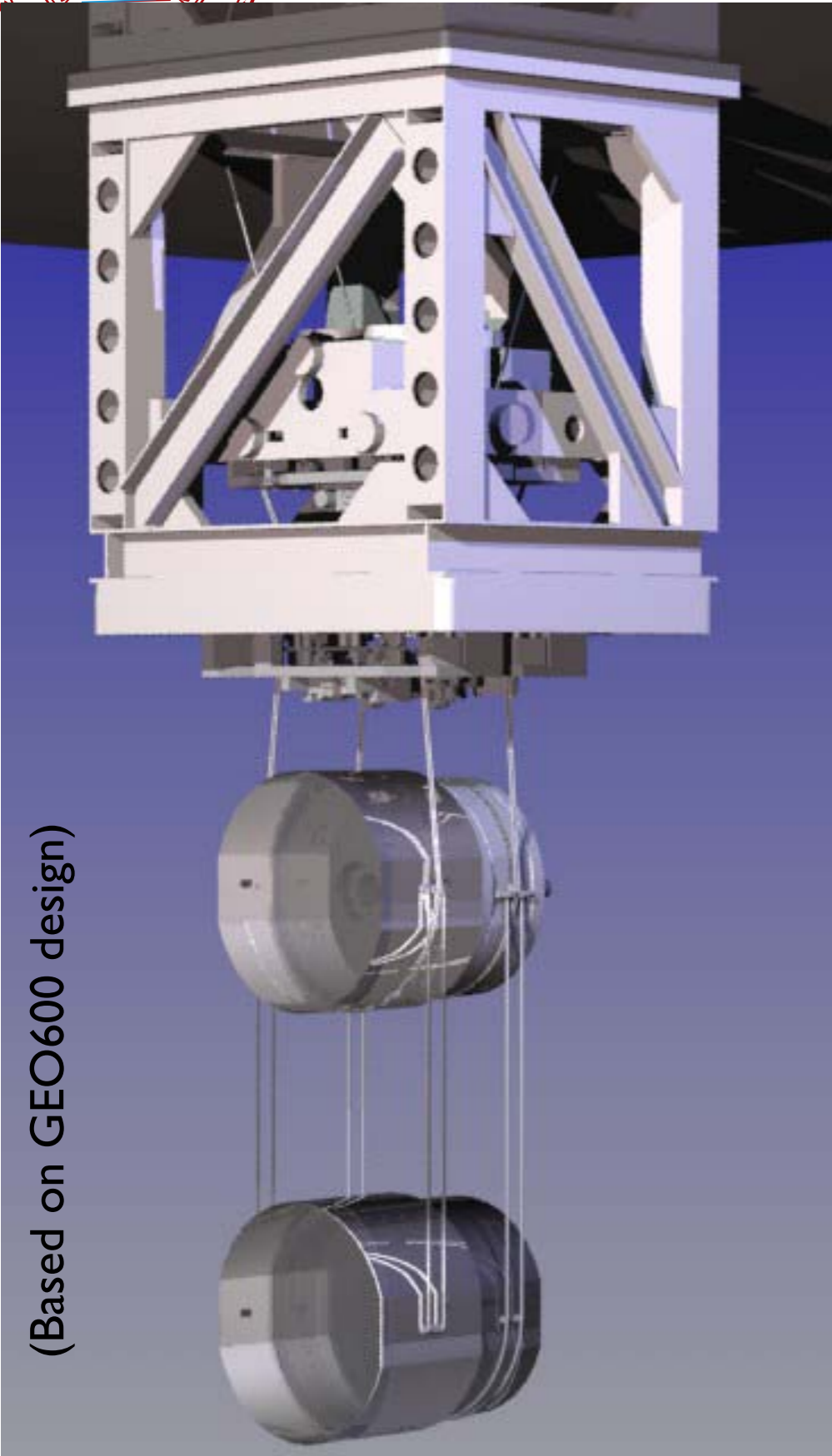


silicate bonding creates a monolithic final stage

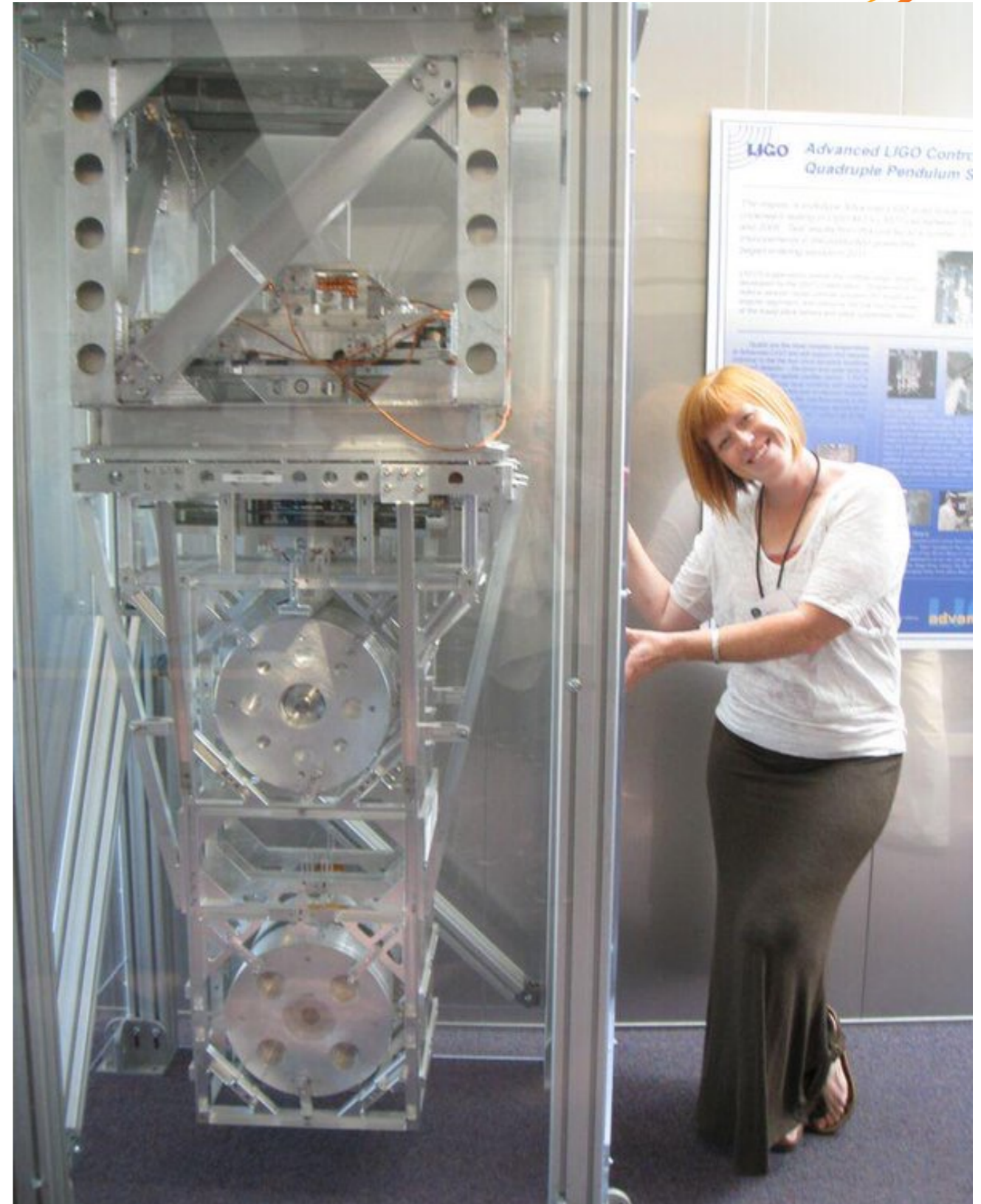


Pendulum

LHO suspension expert, Betsy Weaver with the Engineering prototype

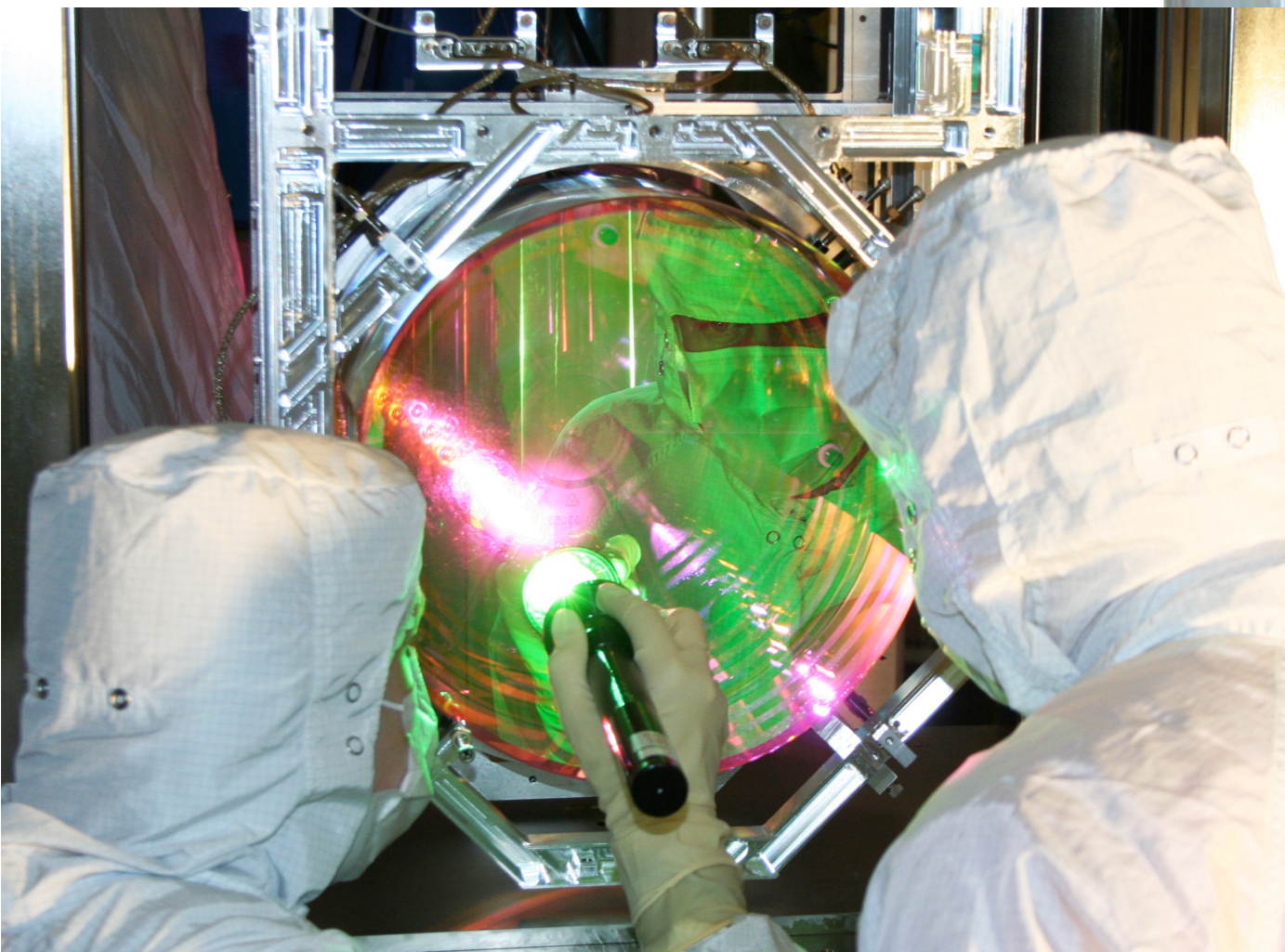
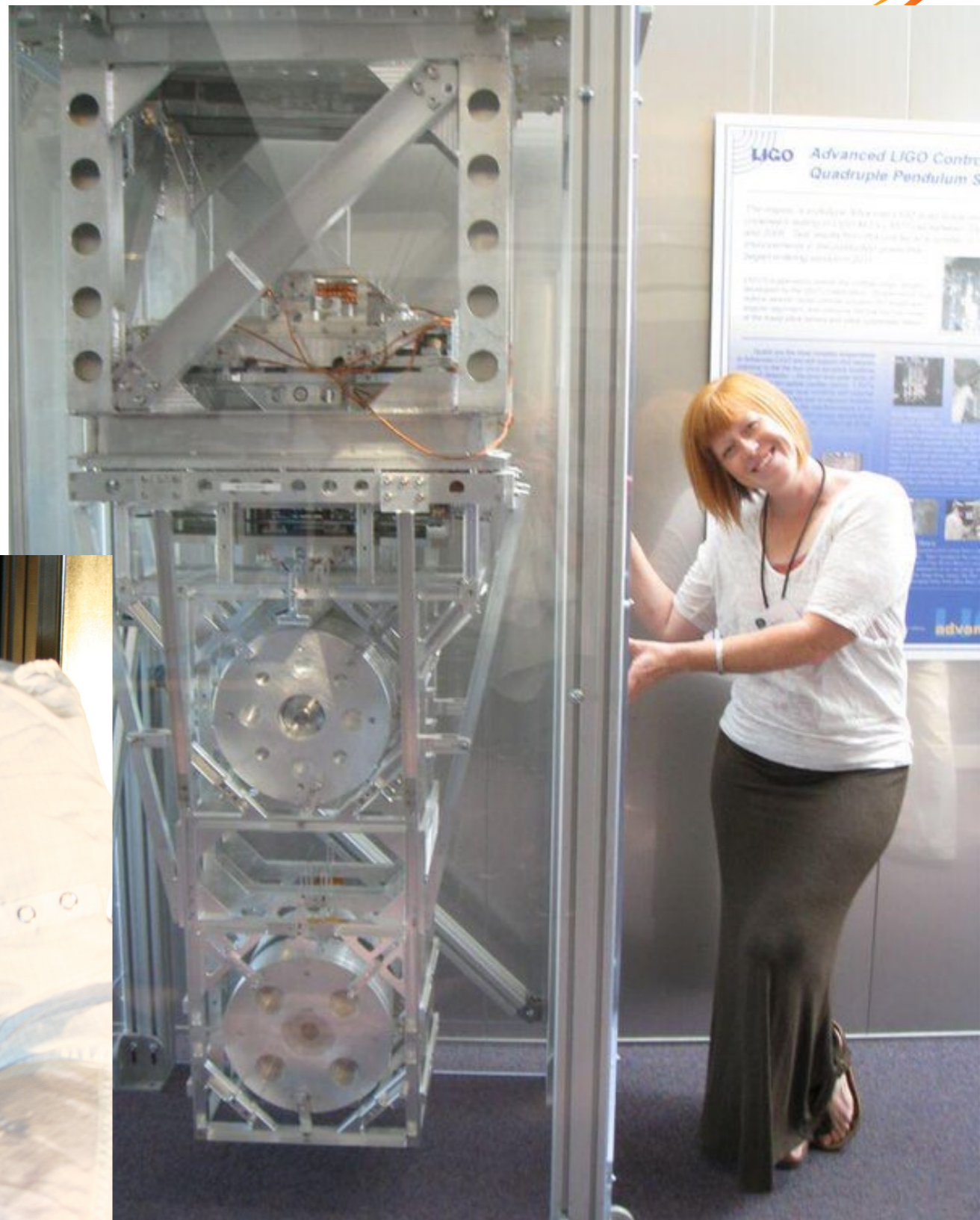
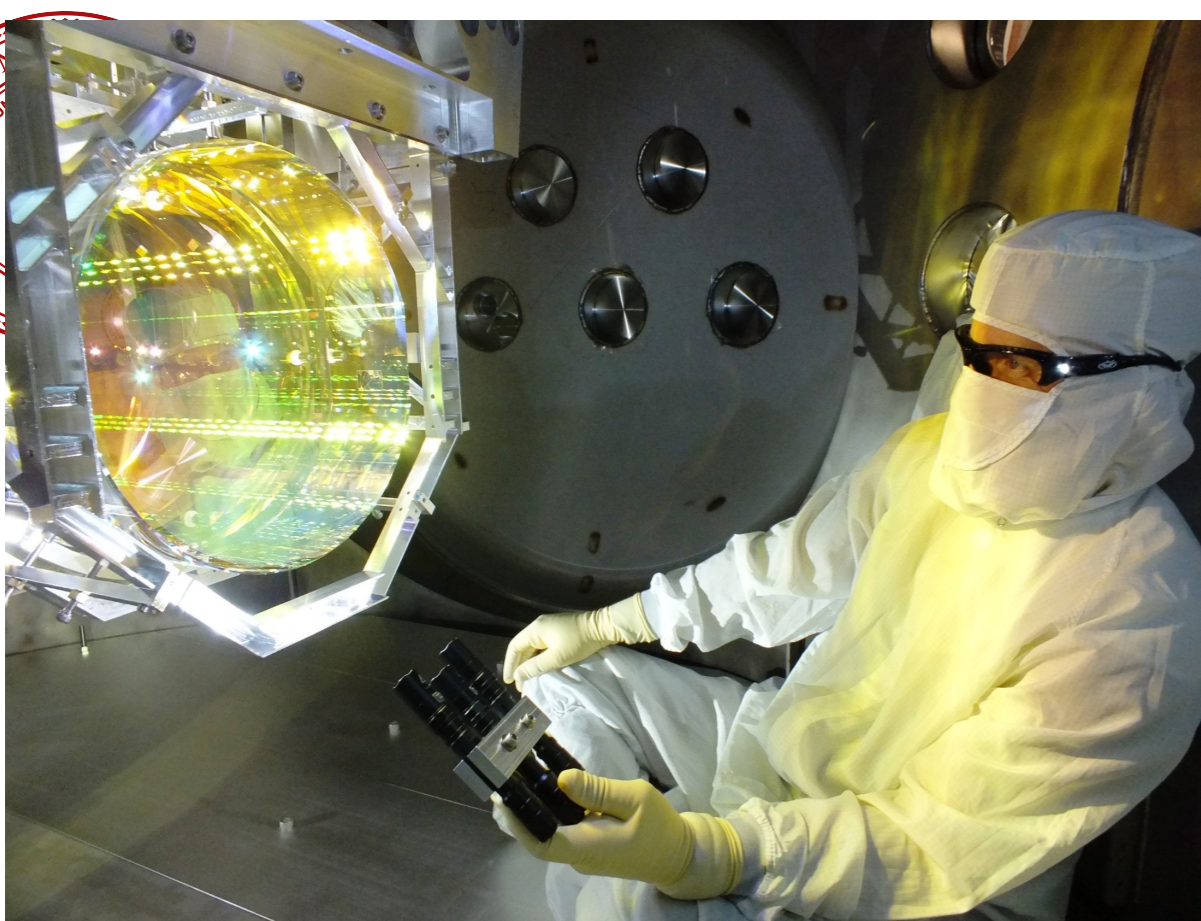


(Based on GEO600 design)



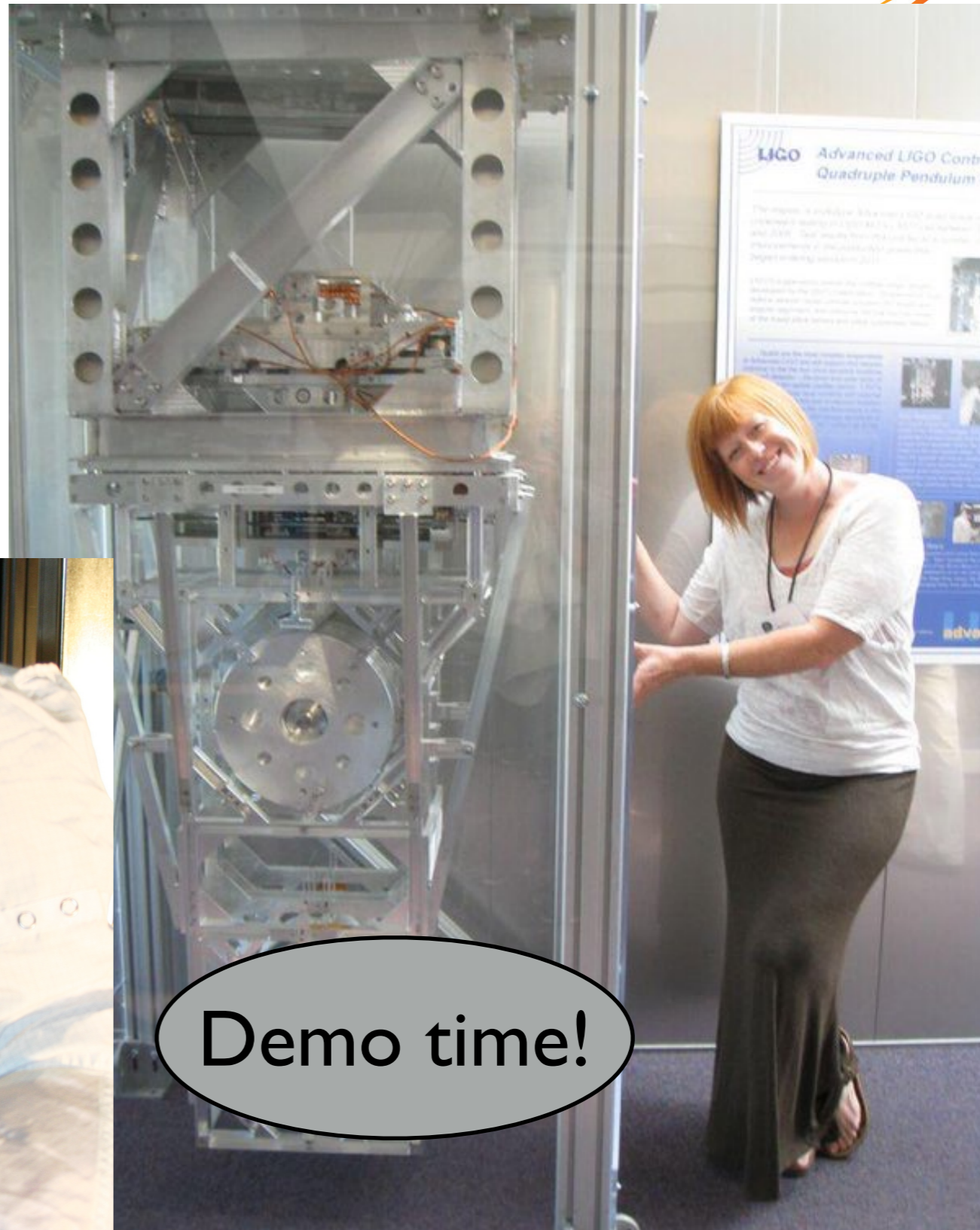
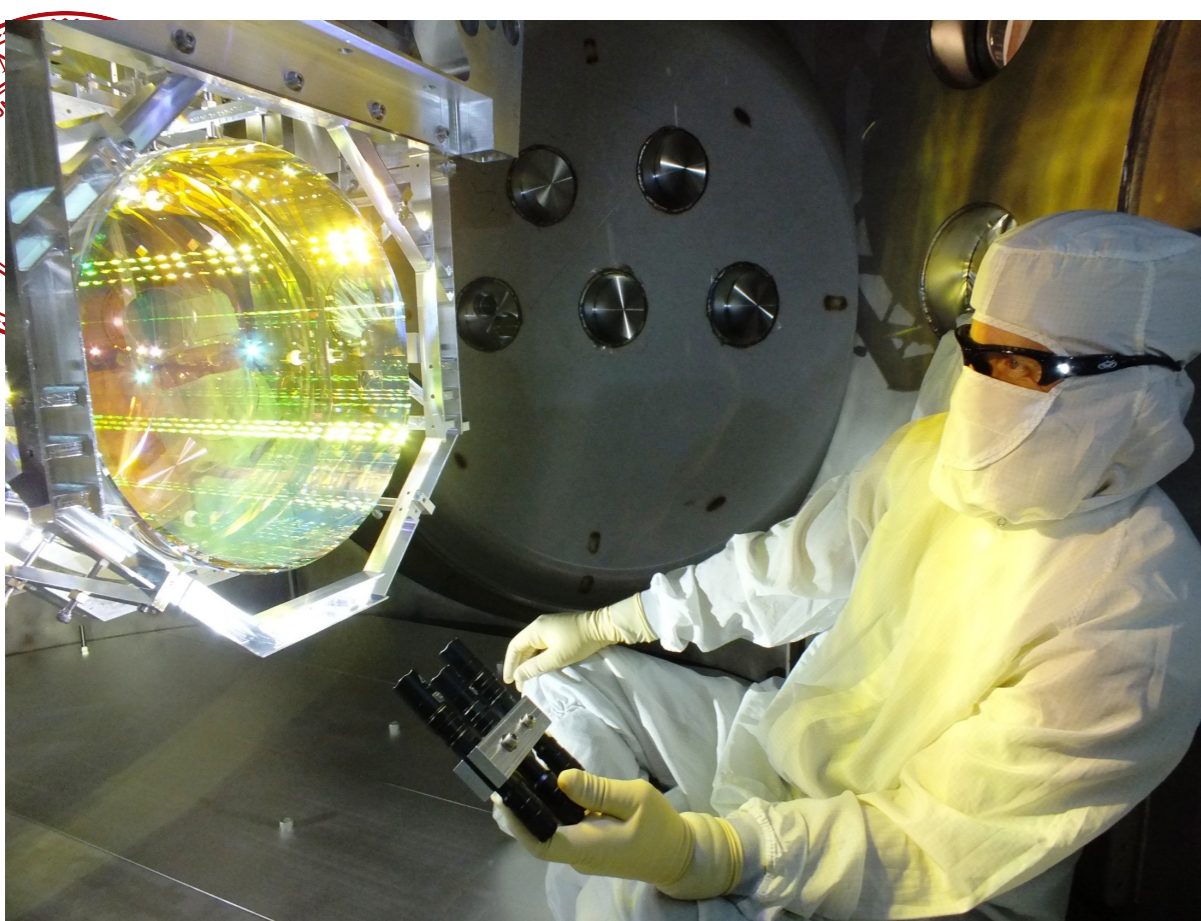


or picts

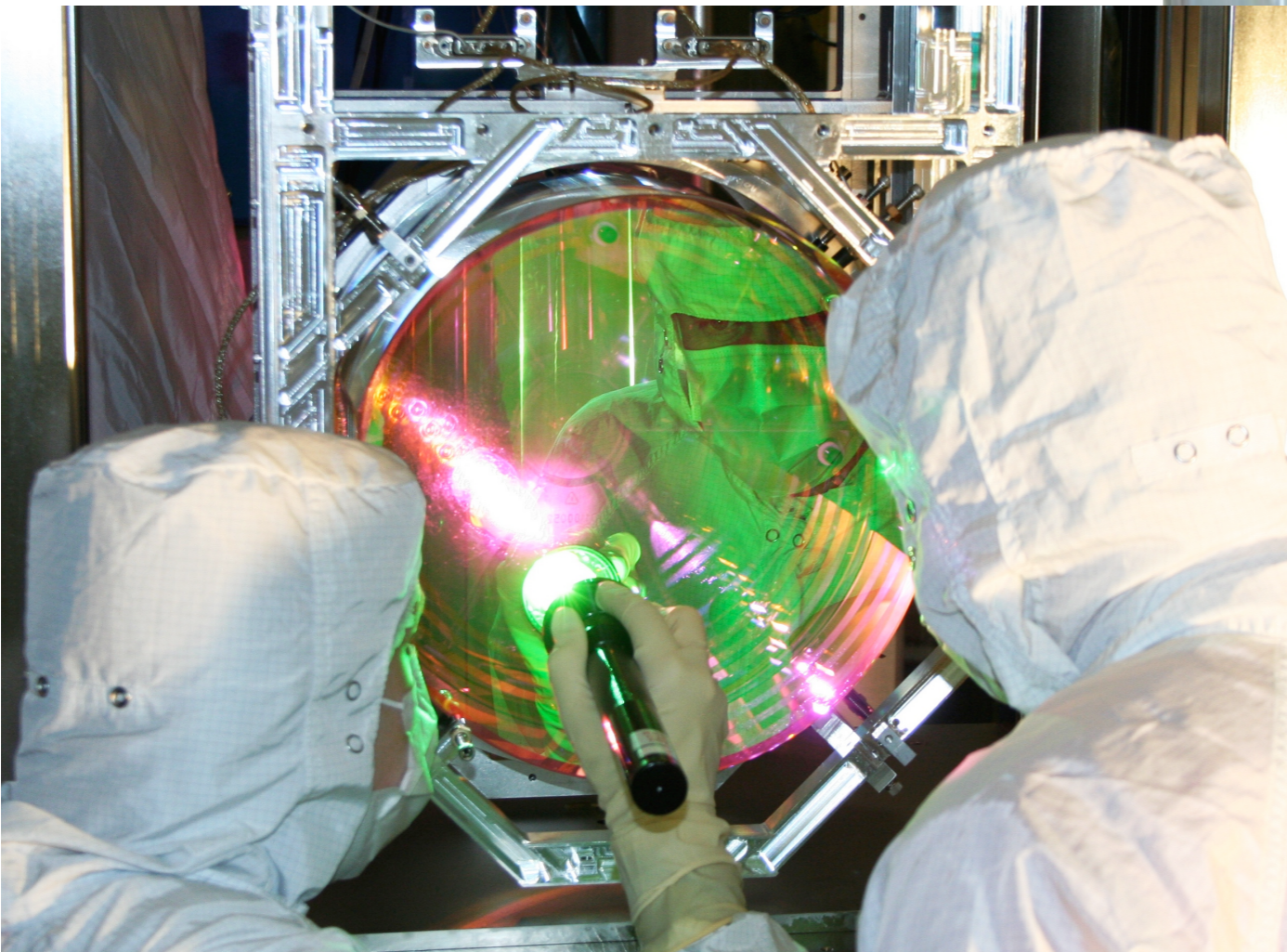




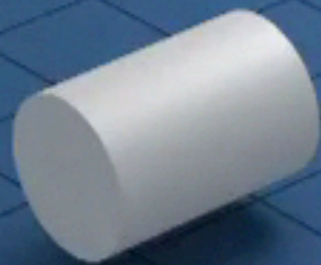
or picts



Demo time!



Animated Interferometer

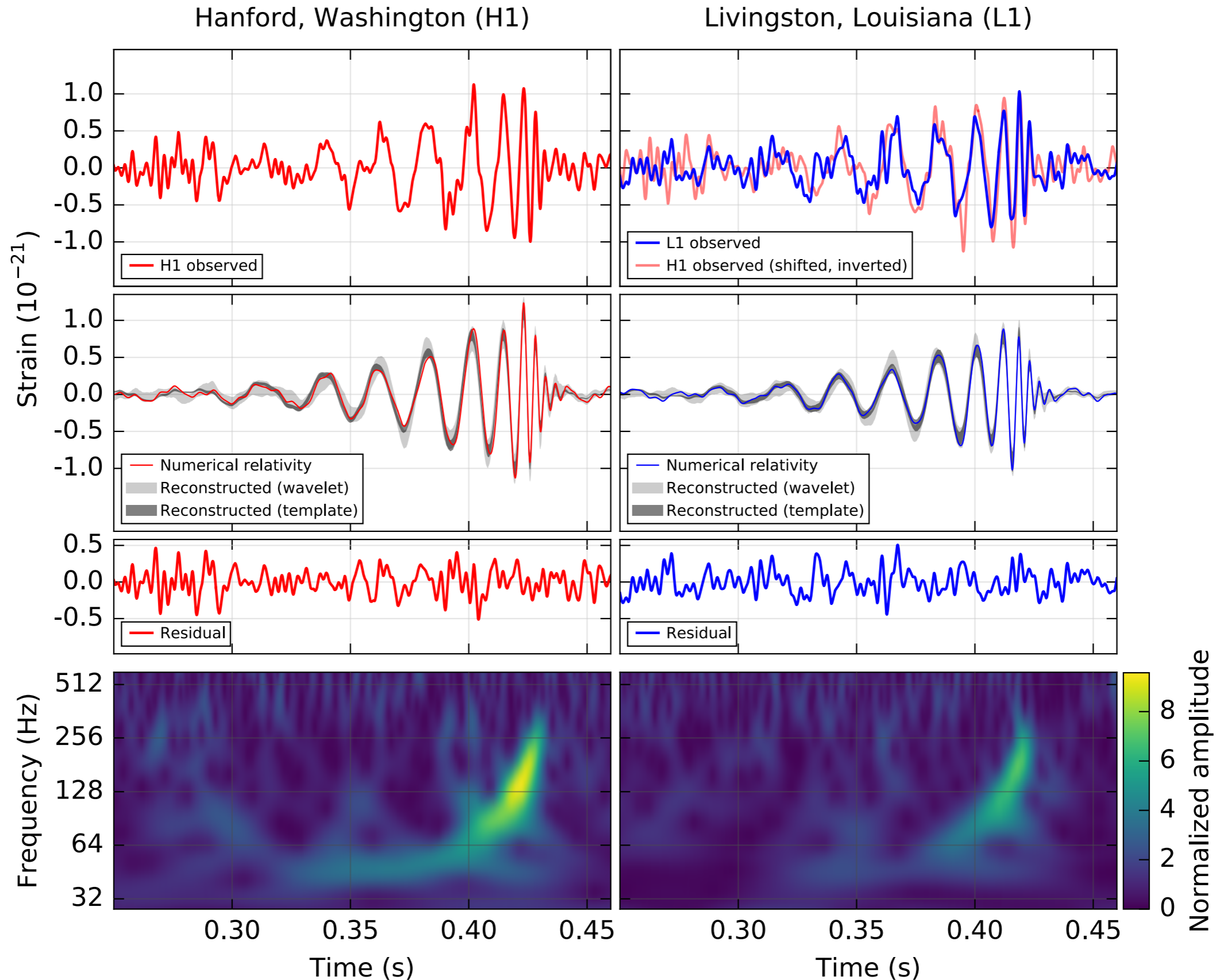


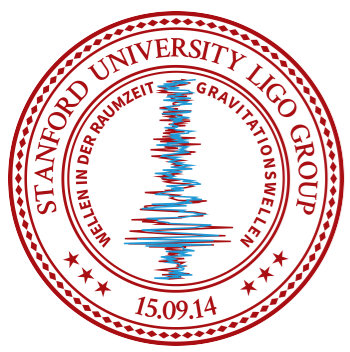
Animated Interferometer





First signal - Sept 14, 2015





Best fit with



Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

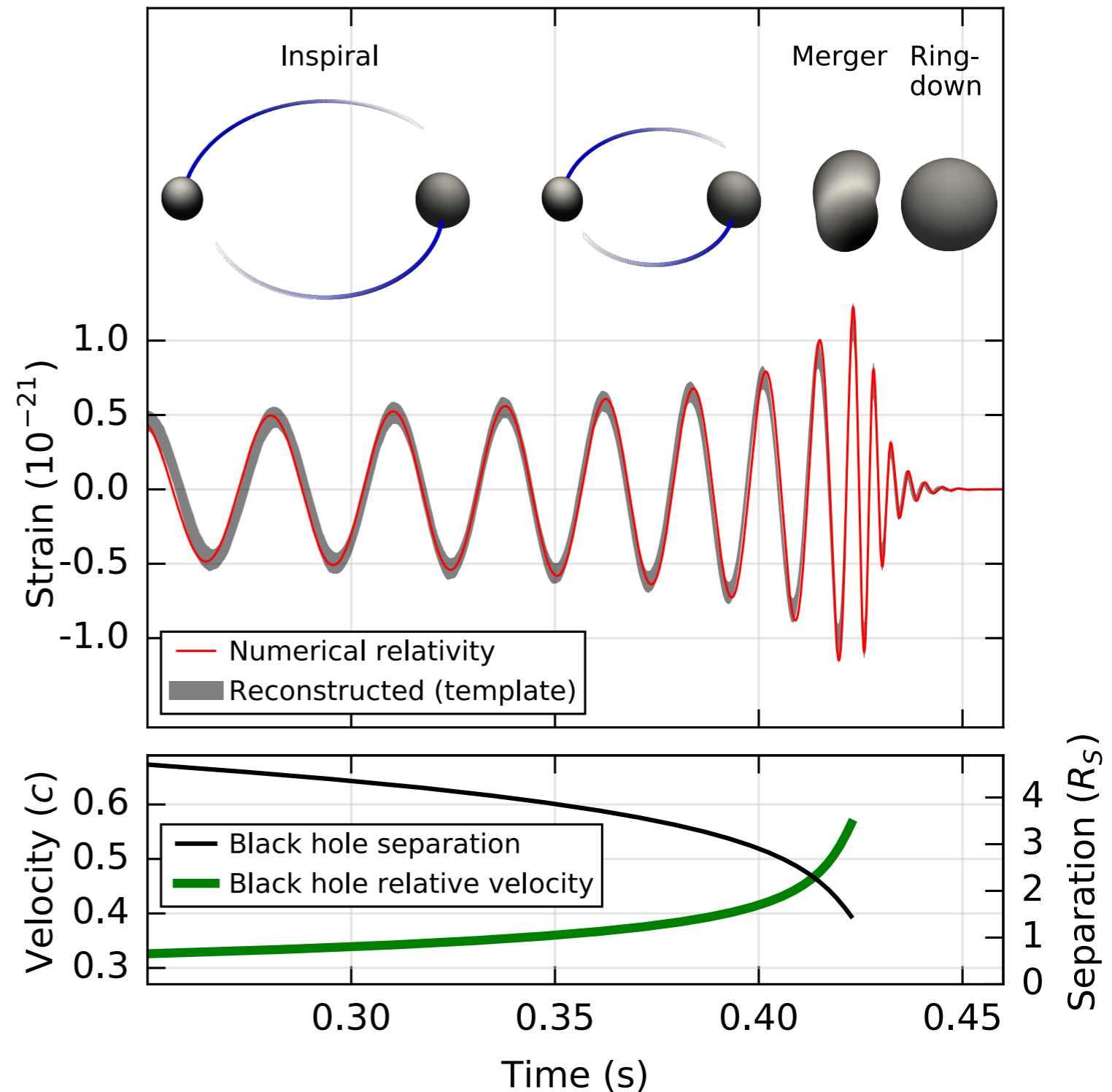
Final Mass:

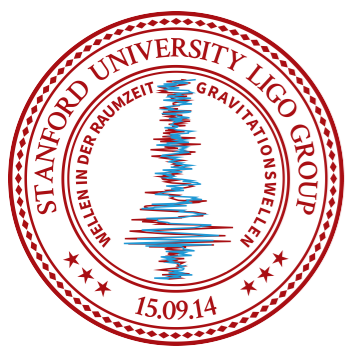
62 (+4/-4) M_{sun}

Distance

420 (+160/-180) MPc

(1.3 Billion light years)





Best fit with



Initial Masses:

29 (+4/-4) & 36 (+5/-4) M_{sun}

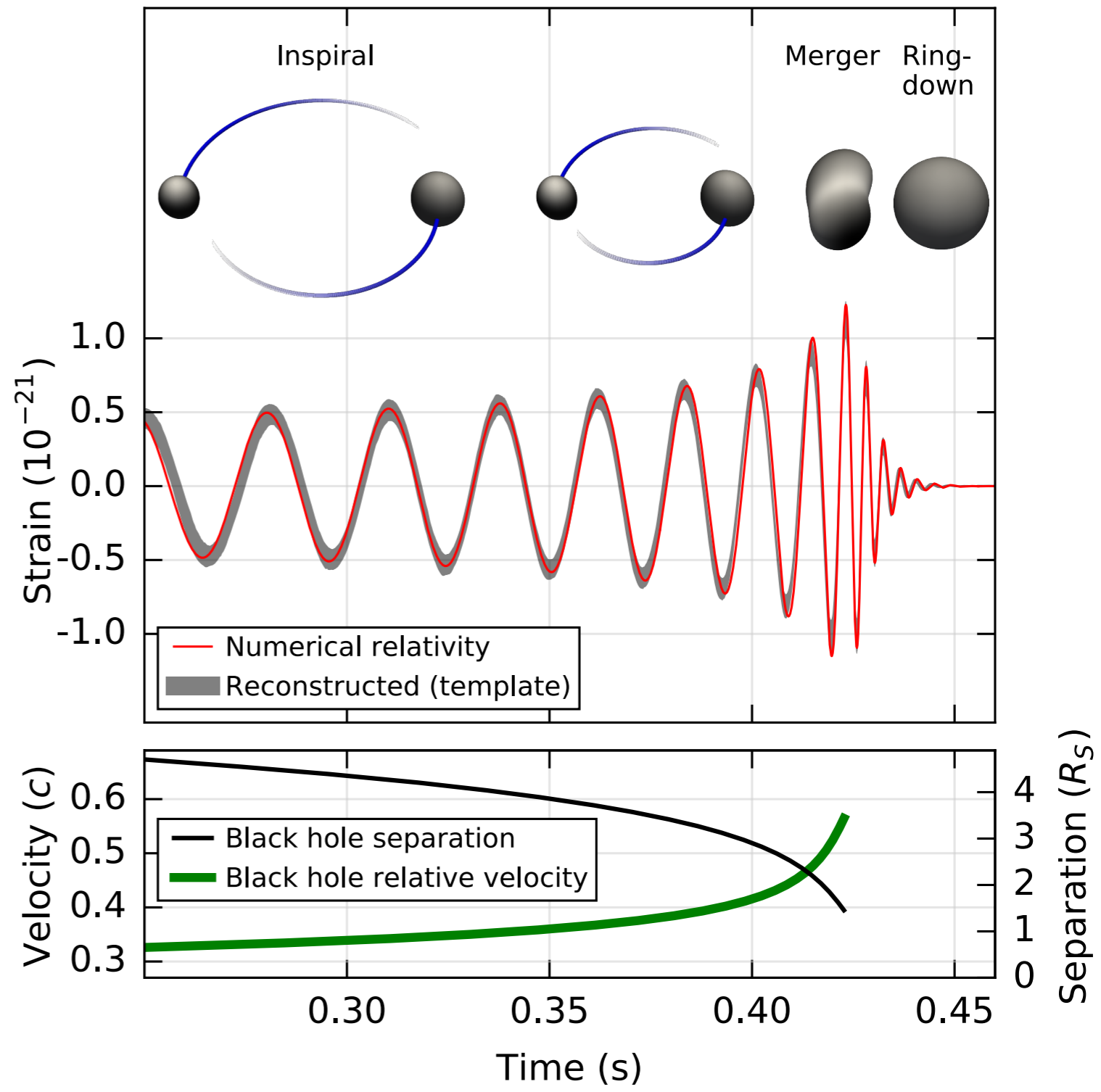
Final Mass:

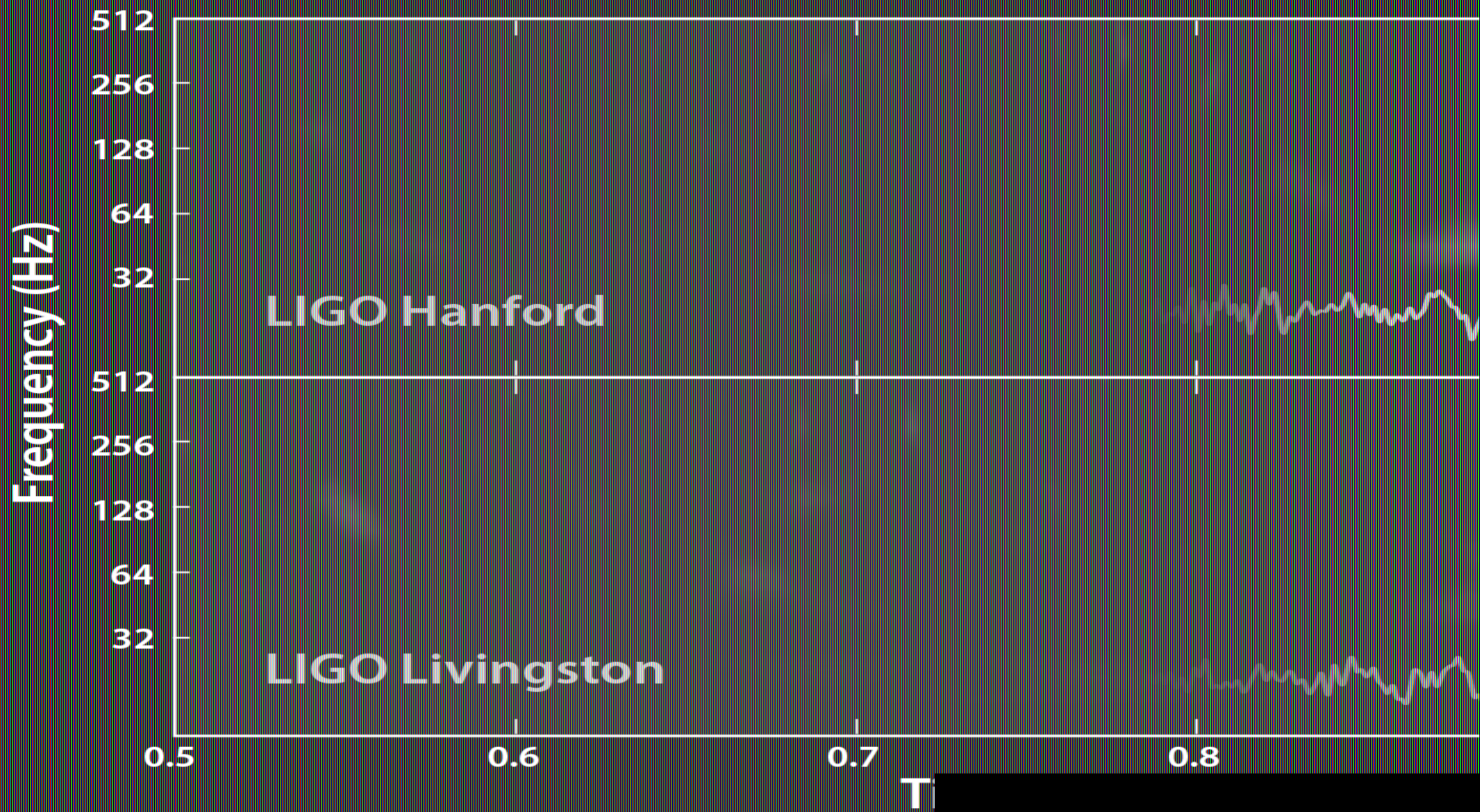
62 (+4/-4) M_{sun}

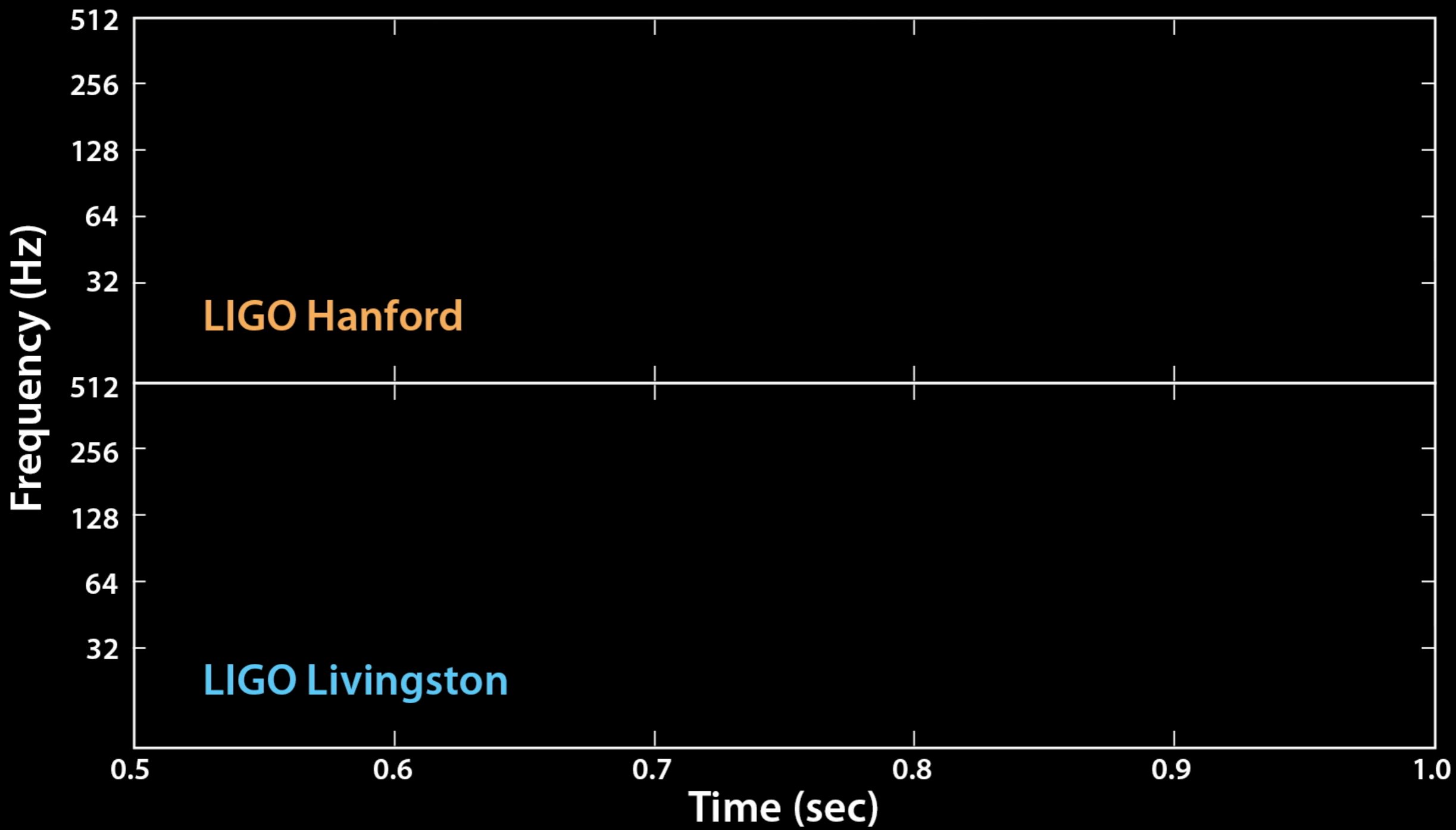
3 solar masses were radiated as GWs

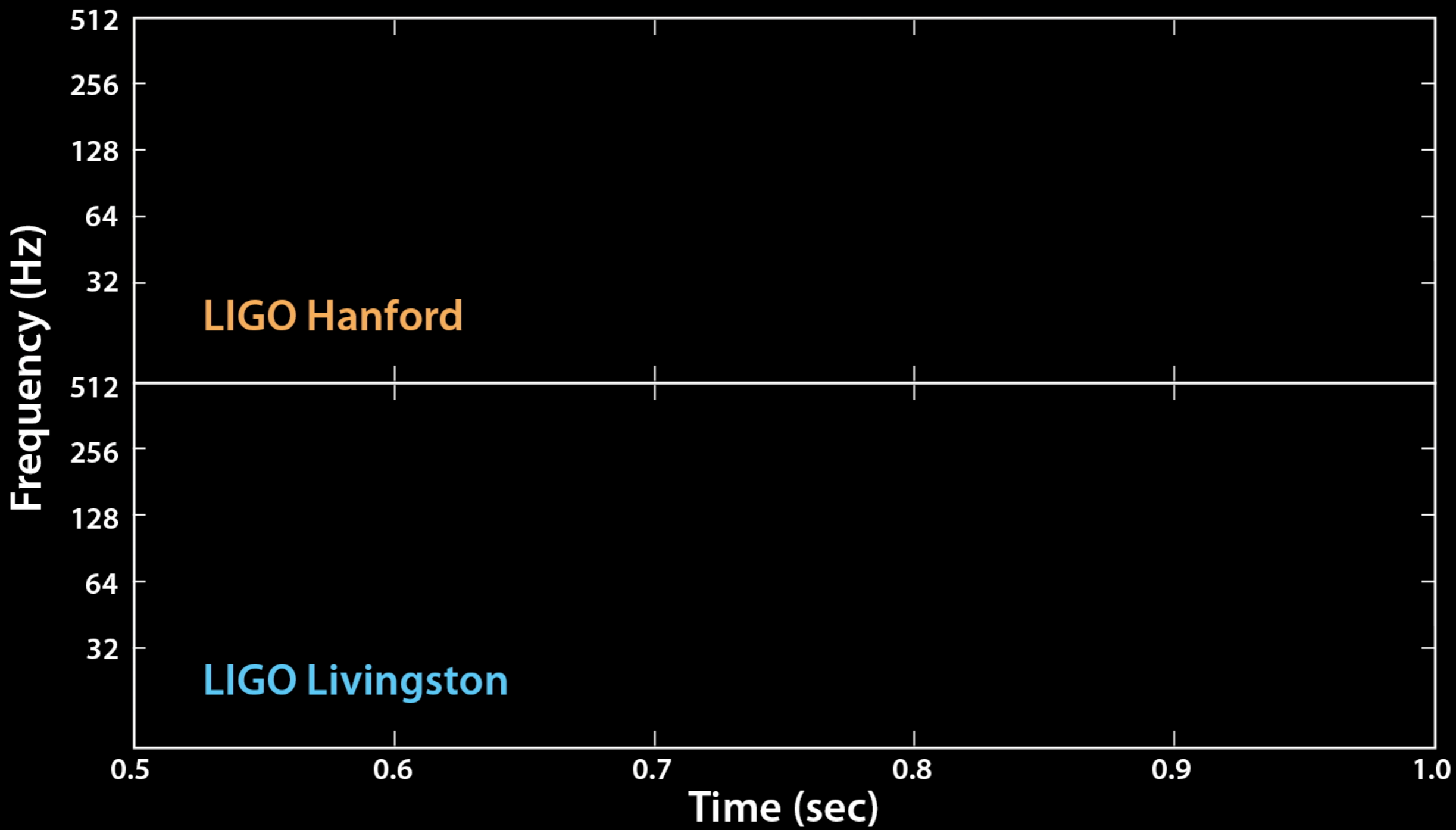
Distance

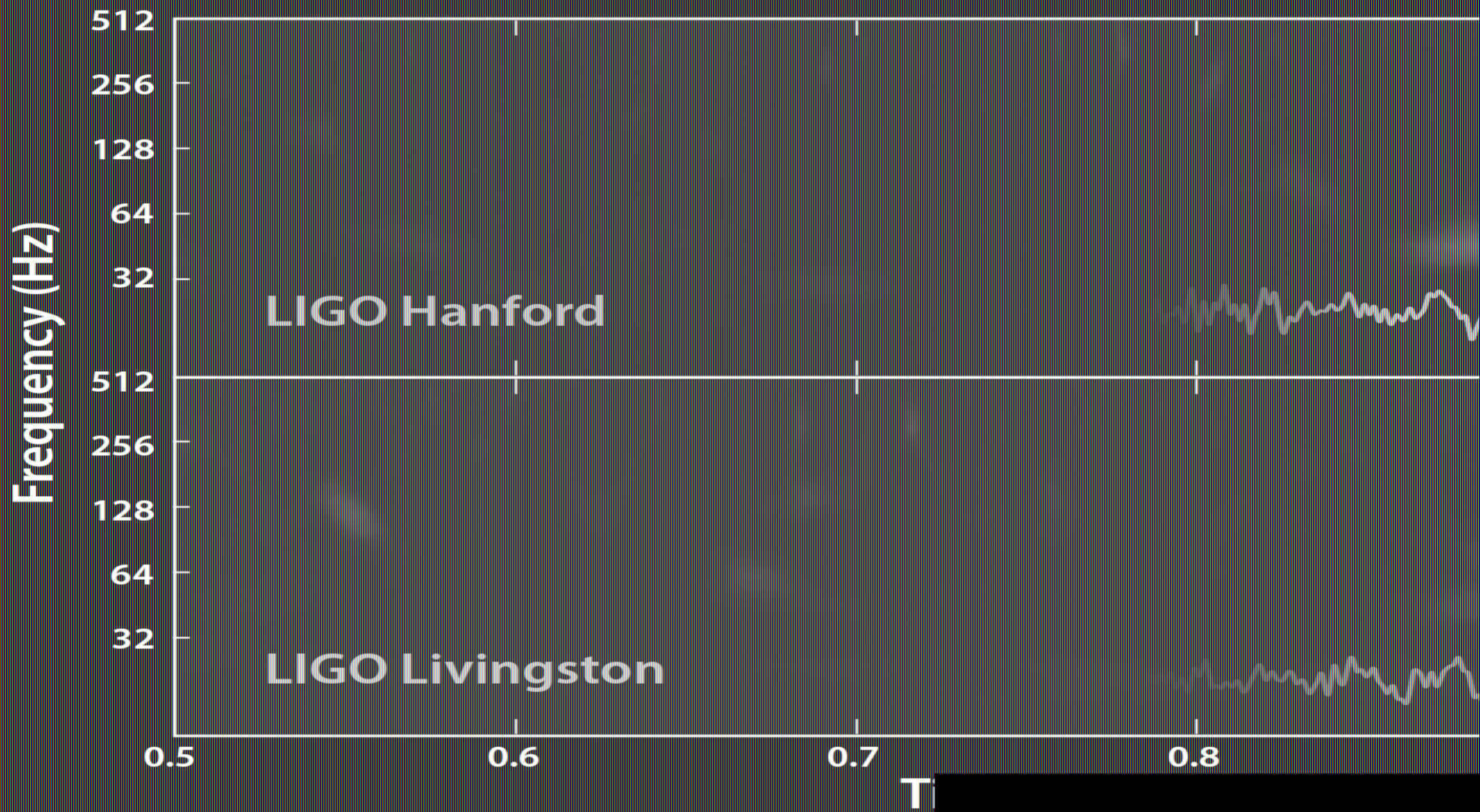
420 (+160/-180) MPc
(1.3 Billion light years)



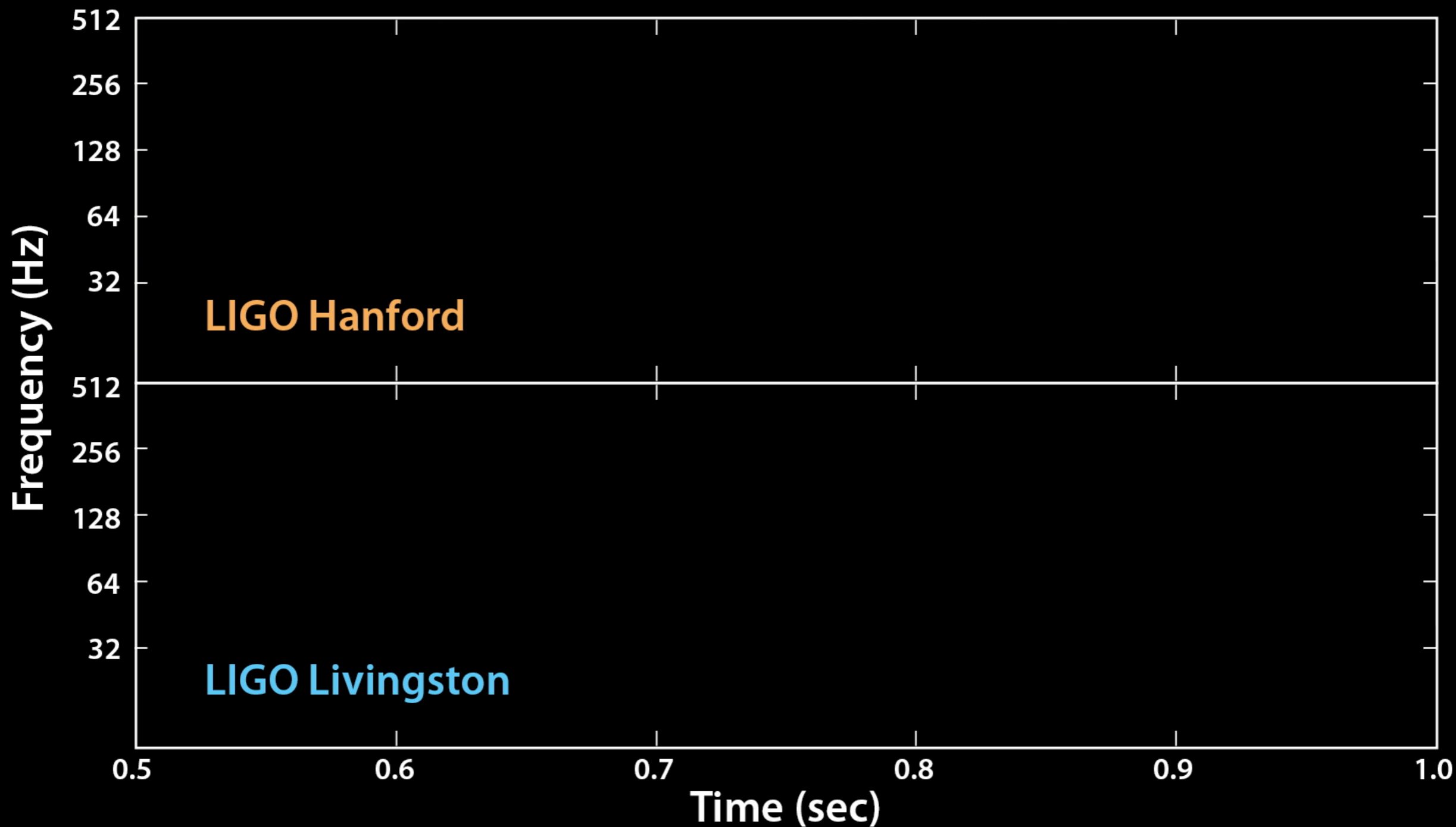




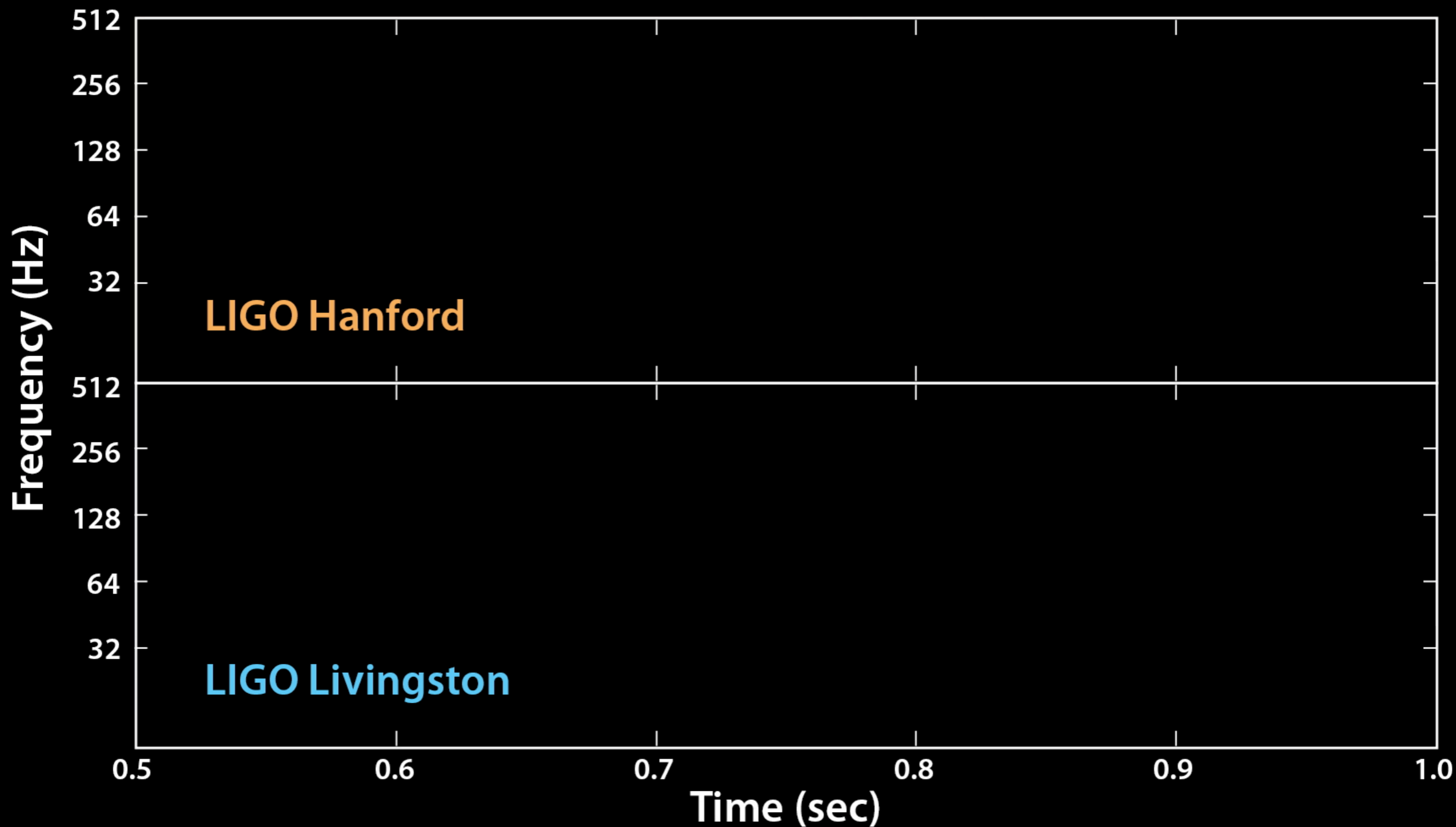




The sound of black holes colliding

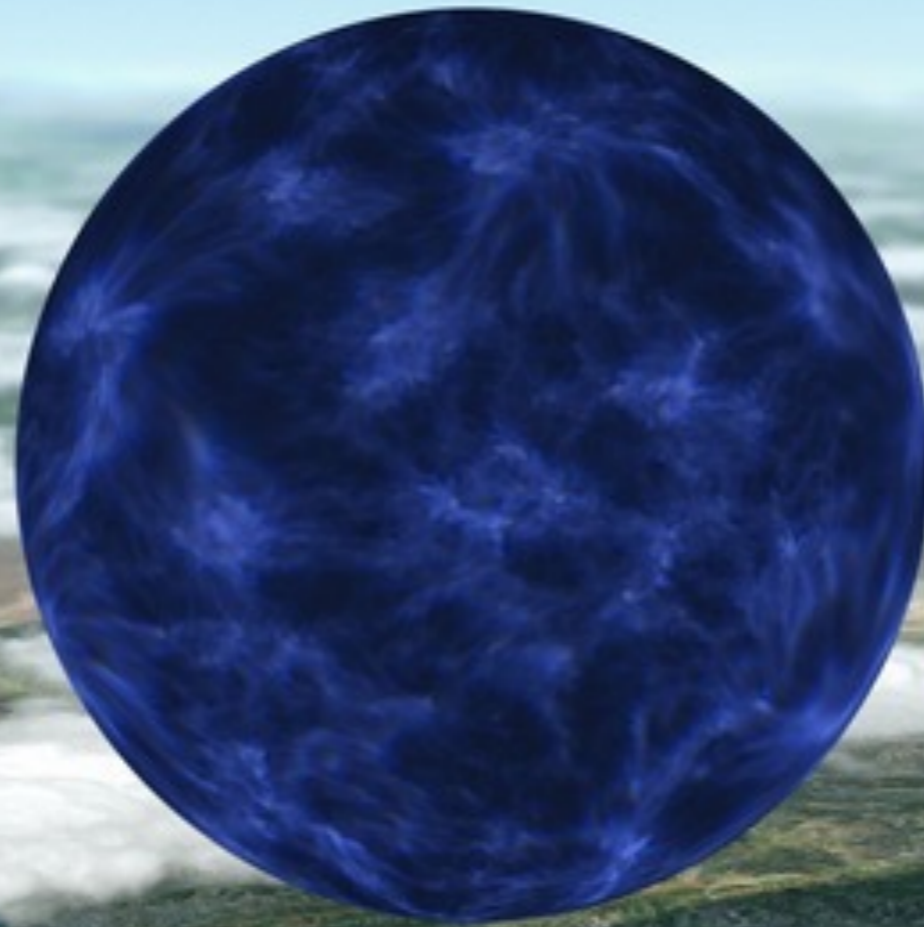


The sound of black holes colliding



Neutron star & San Francisco
Supernova remnant
~1.4 solar masses

composed of dense neutrons
hot topic in astronomy
pulsars, Hulse-Taylor
kilonovas...

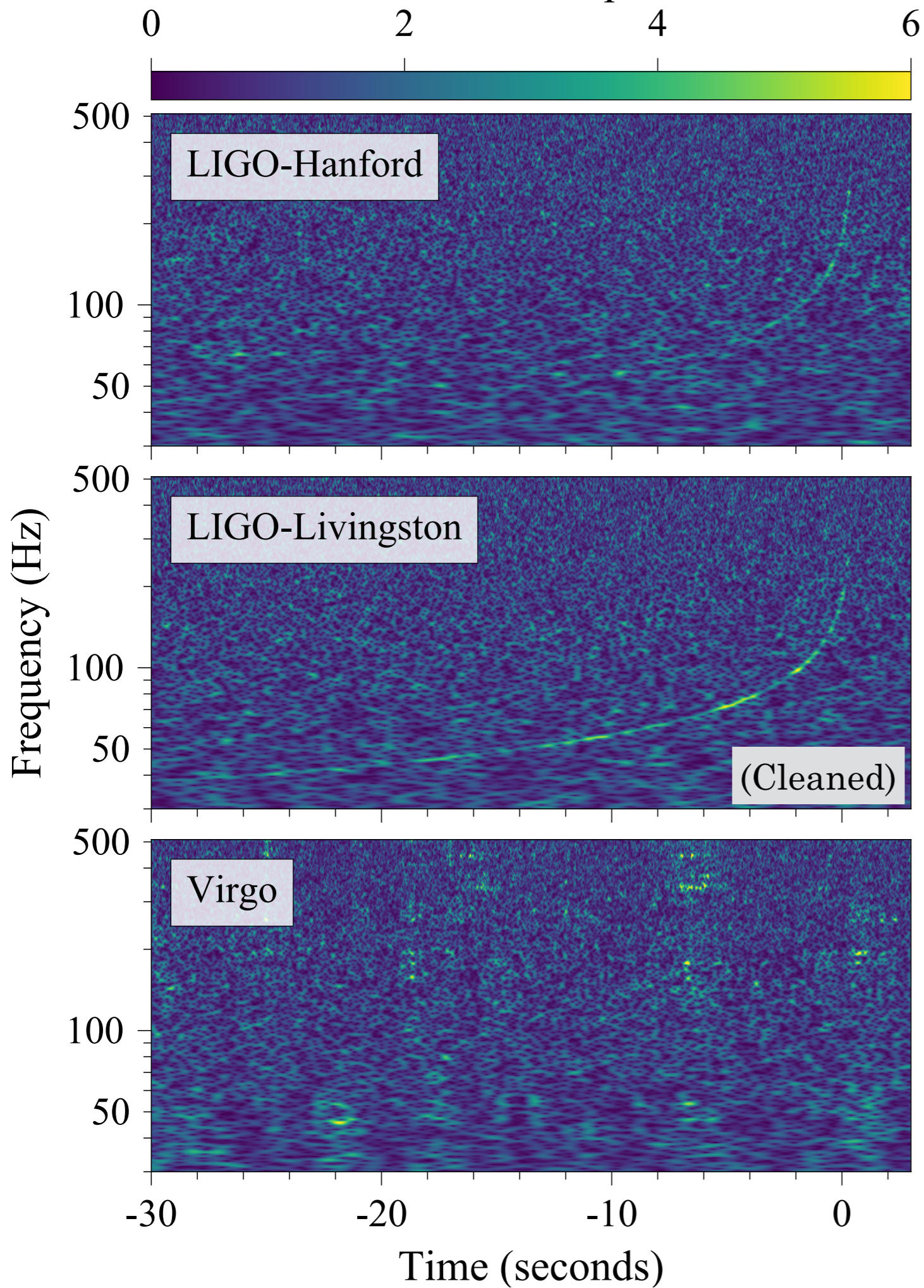


Neutron star & San Francisco
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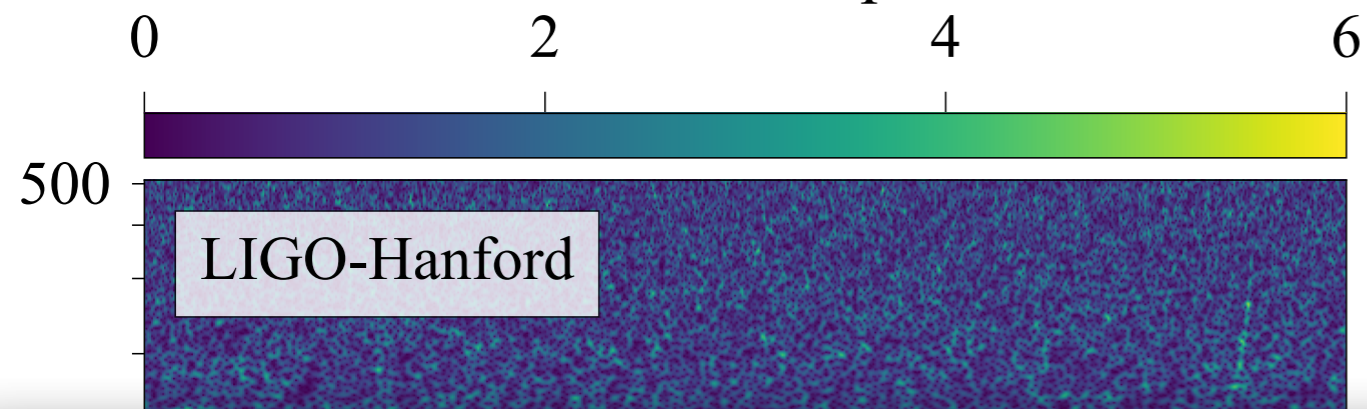
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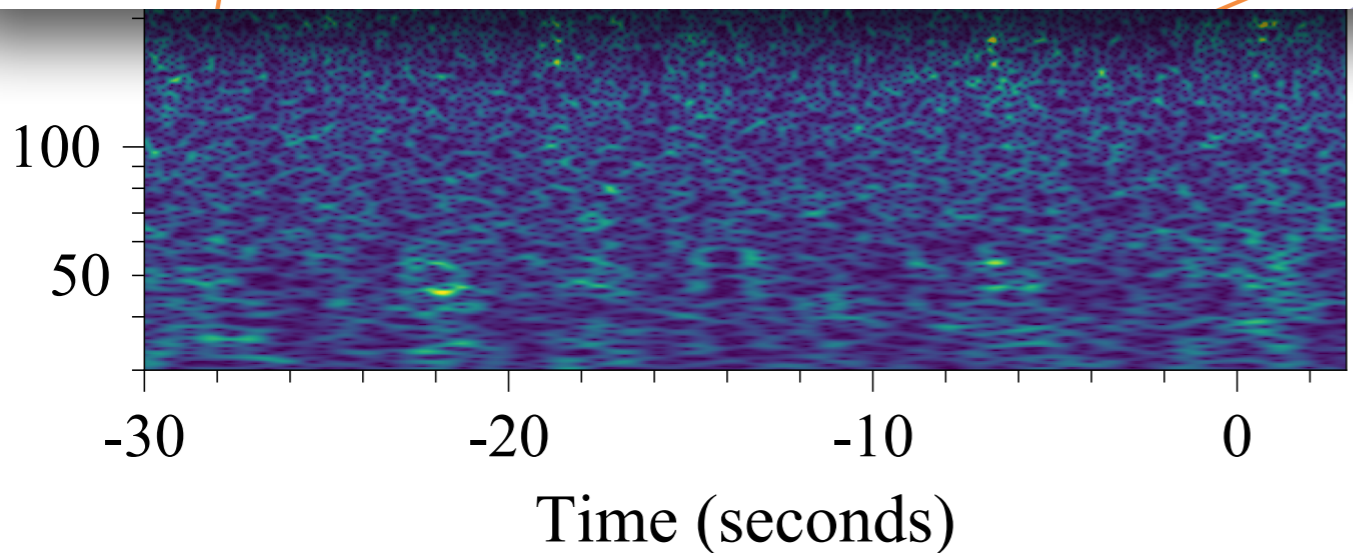
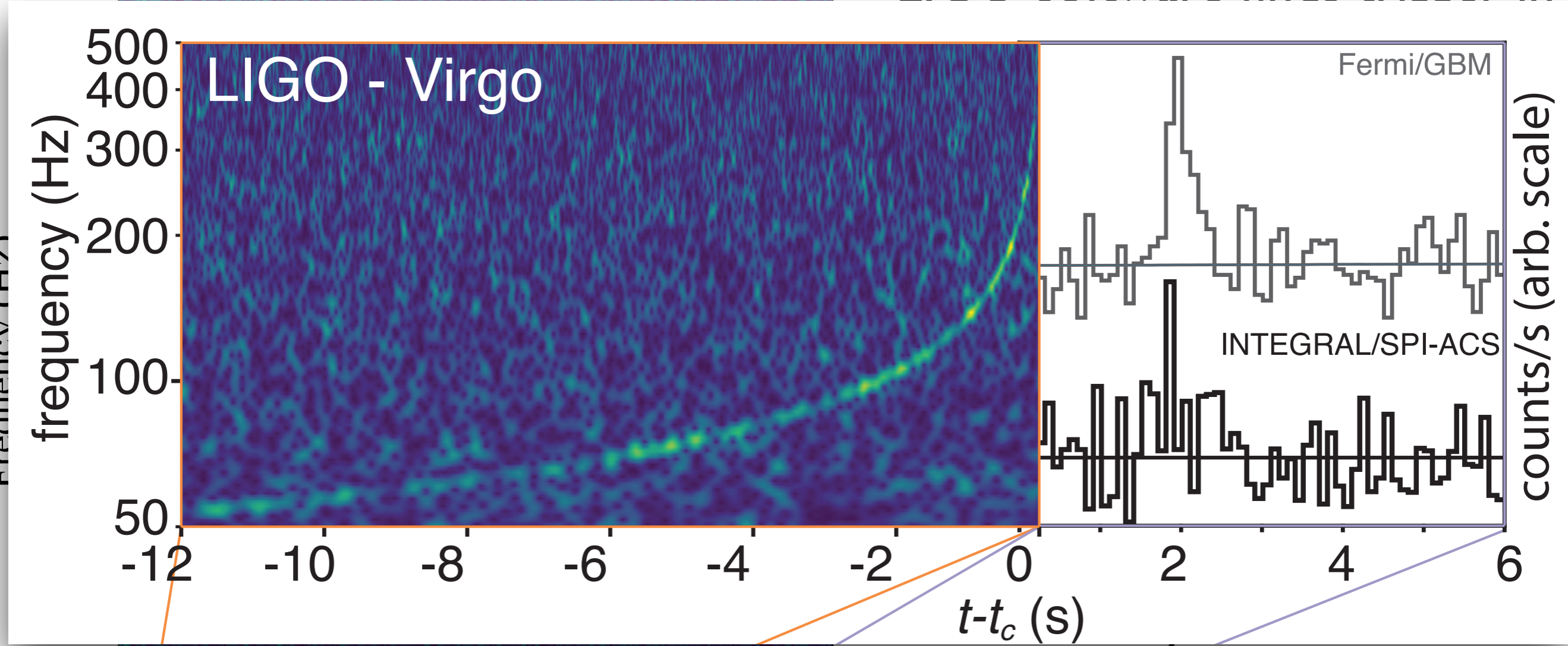
GW170817



- LIGO software finds trigger in LHO data - 5:41:04 am Pacific time, August 17.
- LIGO realizes that Fermi GBM has triggered on event 1.7 seconds after GW merger.
- Thus, BNS mergers cause short gamma-ray bursts.
- Finally solving a mystery uncovered by Vela-4 in 1967. (as predicted by many).
- Forcing a best match to Virgo (~in the blind spot, so SNR is only 2!)

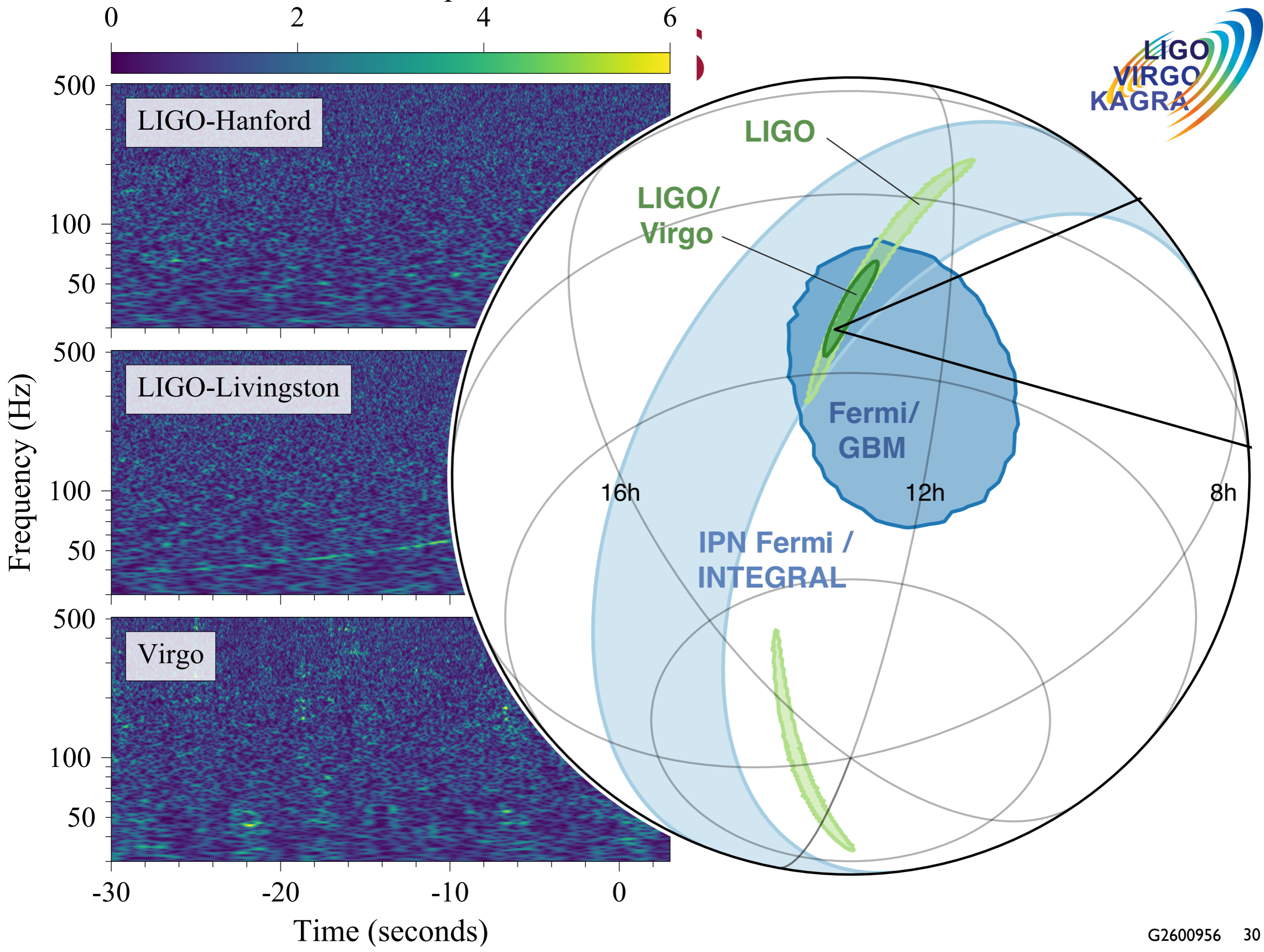


• LIGO software finds trigger in

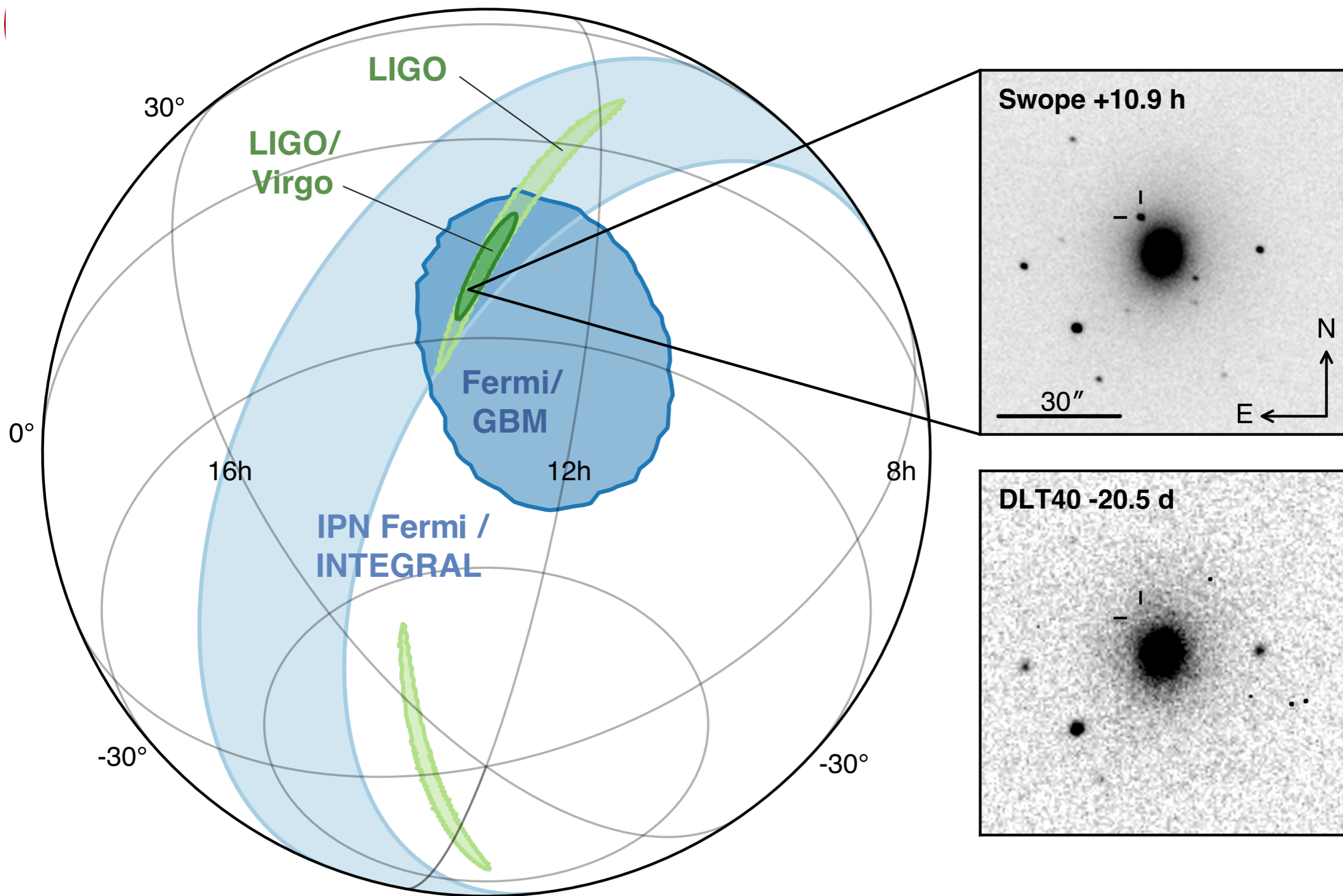


(as predicted by many).

- Forcing a best match to Virgo (~in the blind spot, so SNR is only 2!)



GW + GRB + Kilonova

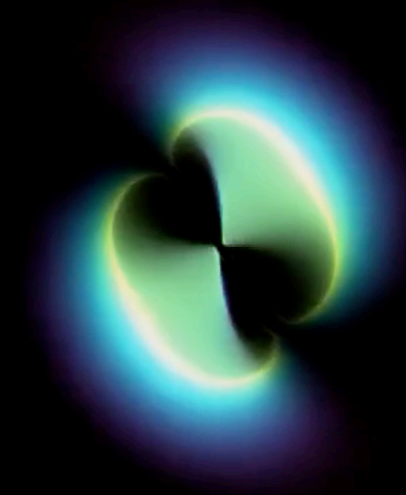


There is matter, and we can watch it

What are they looking for?

We suspect that $\sim 1/2$ of all heavy elements are created in kilonovas.
Energetic explosion in a neutron rich environment \rightarrow nuclei in ejecta

GW170817: The Merger of Two Neutron Stars



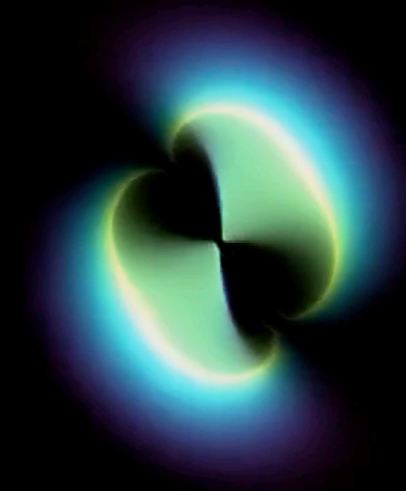
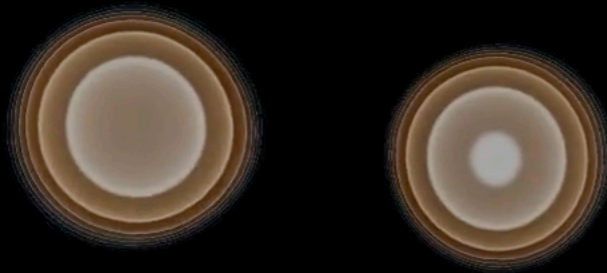
Matter Density

Gravitational Waves

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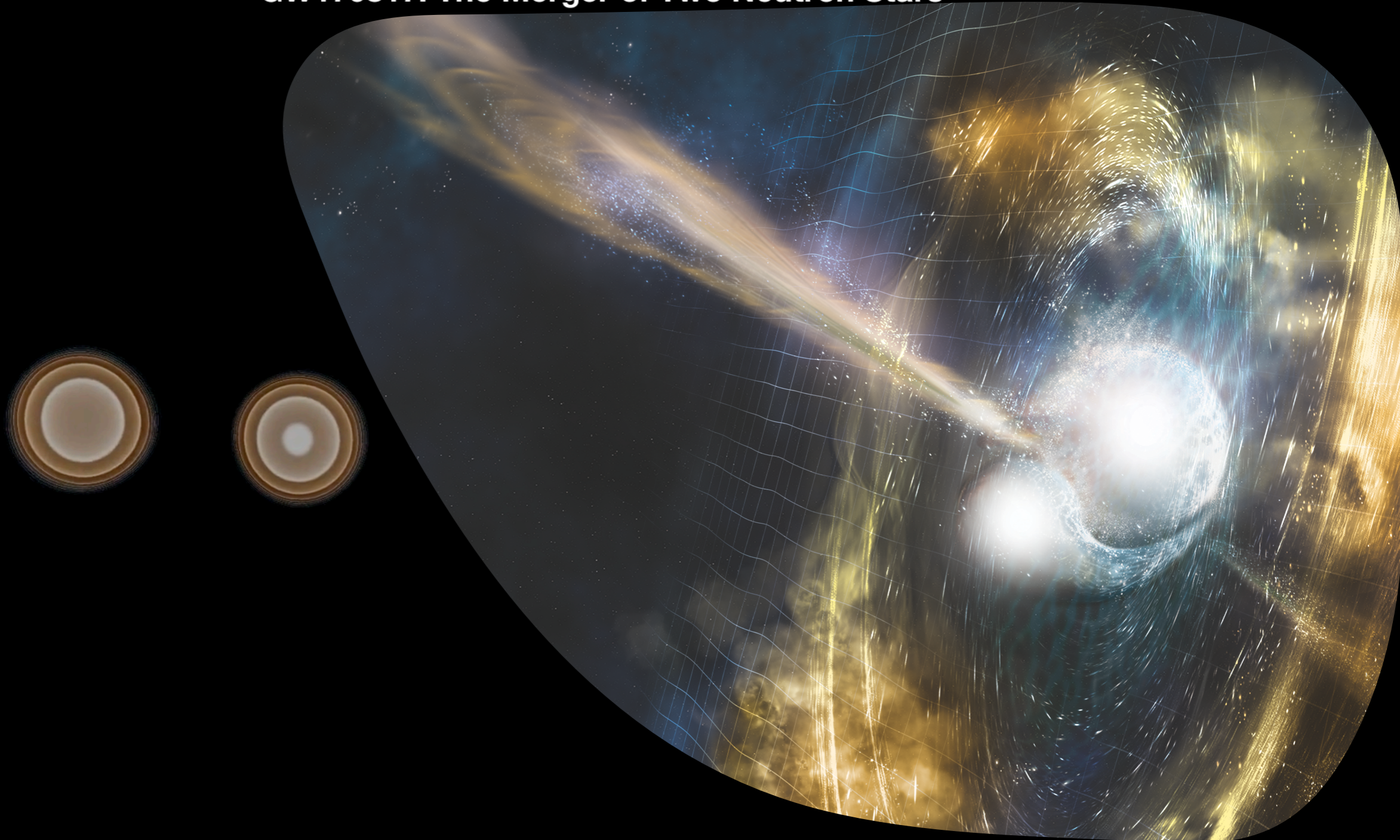
Matter Density

Gravitational Waves

What are they looking for?

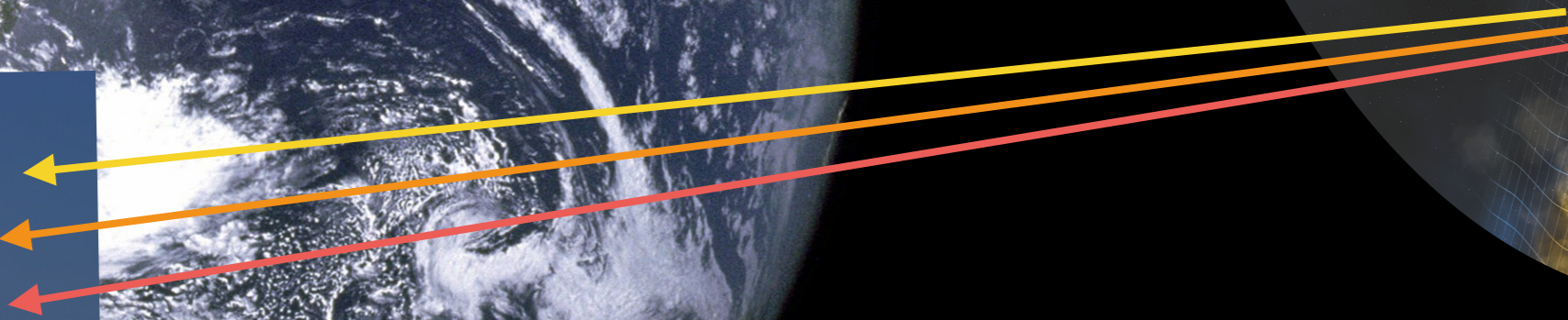
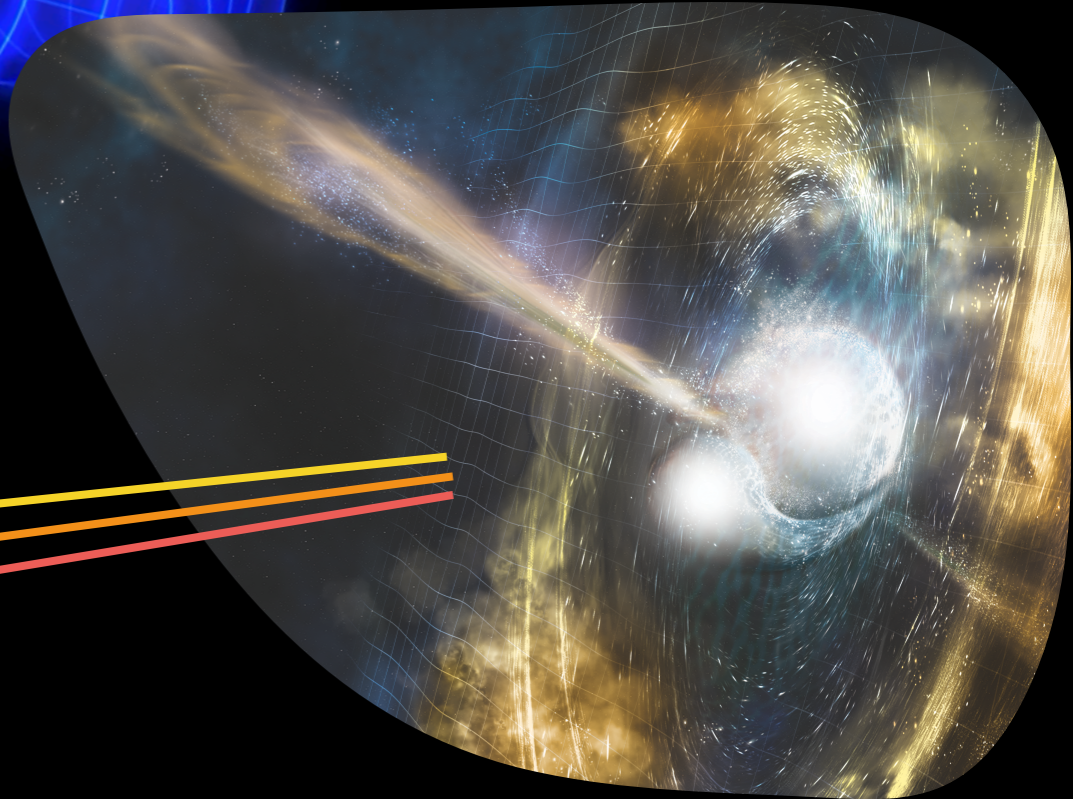
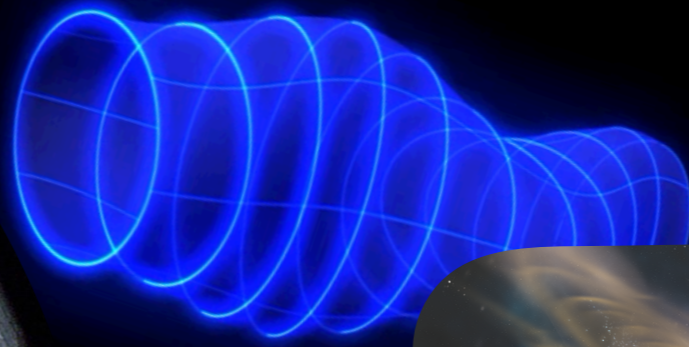
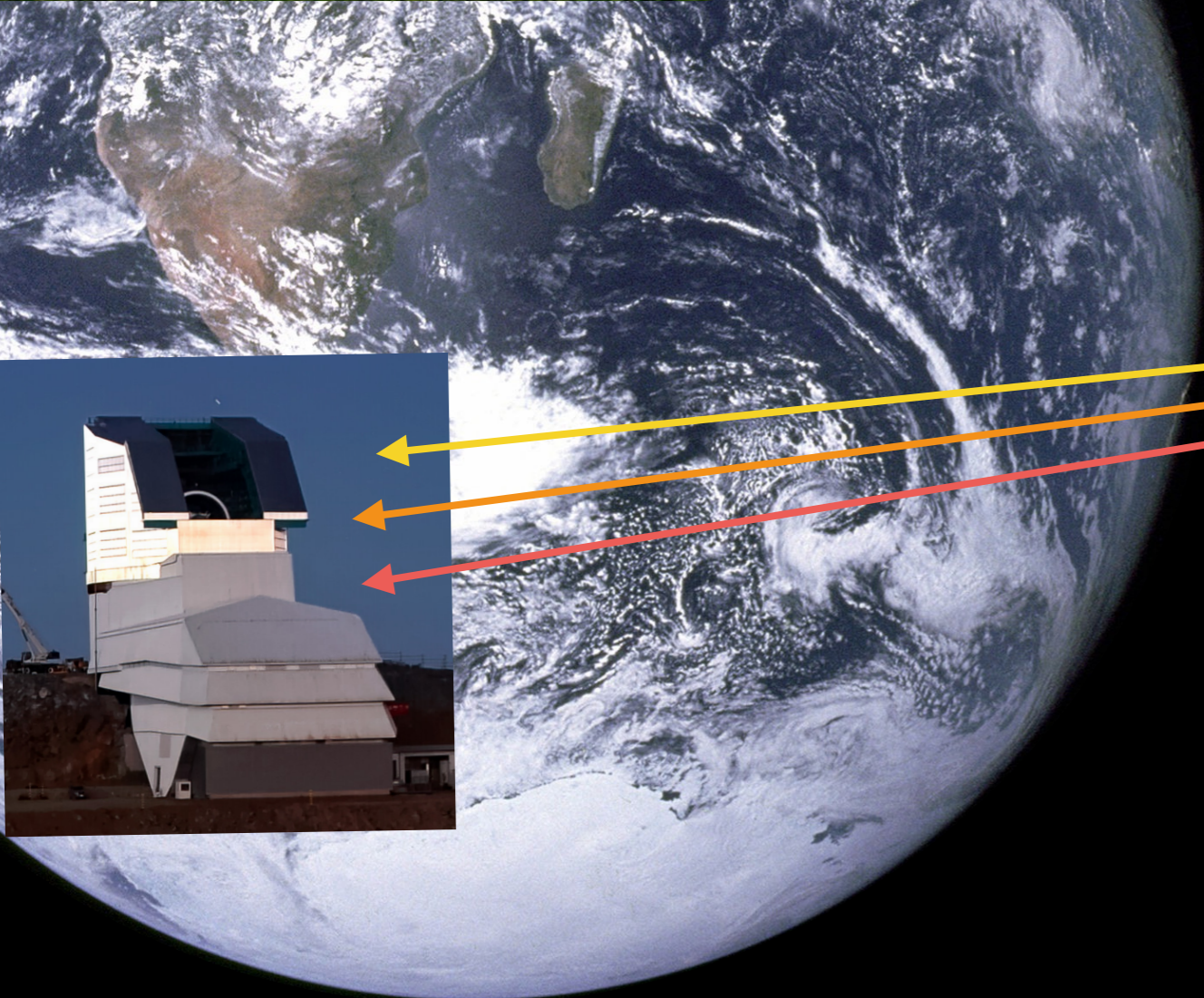
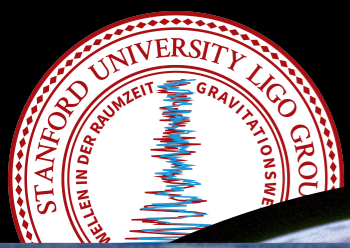
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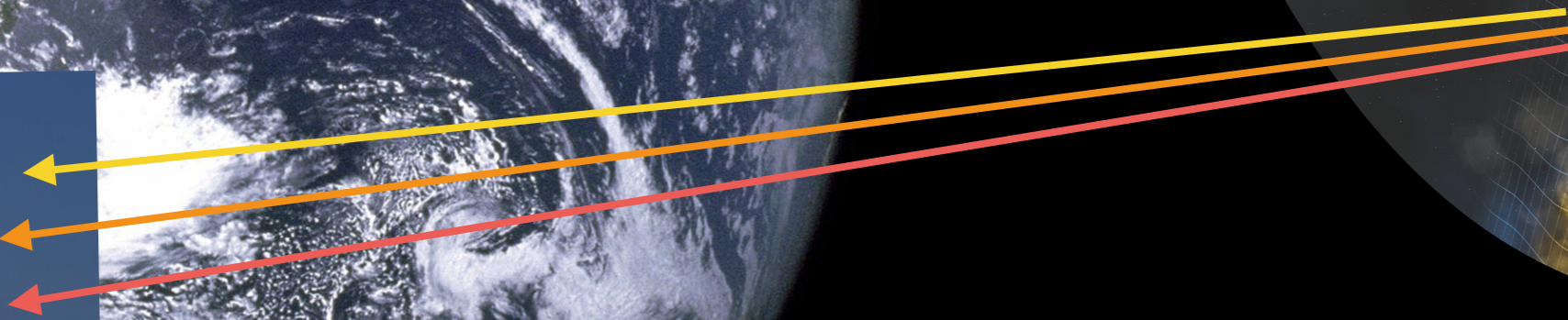
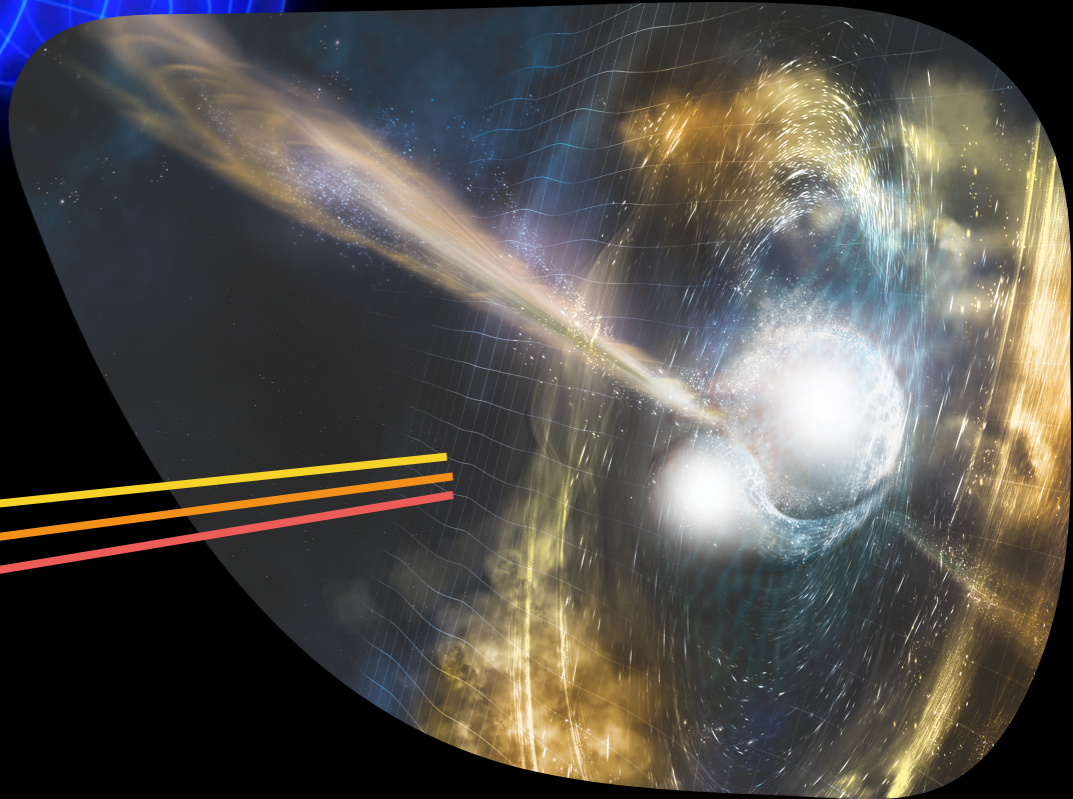
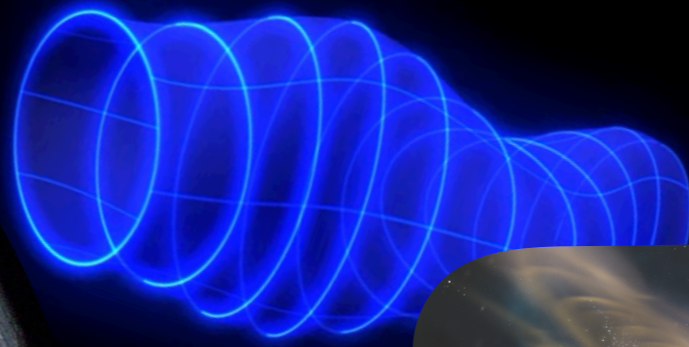
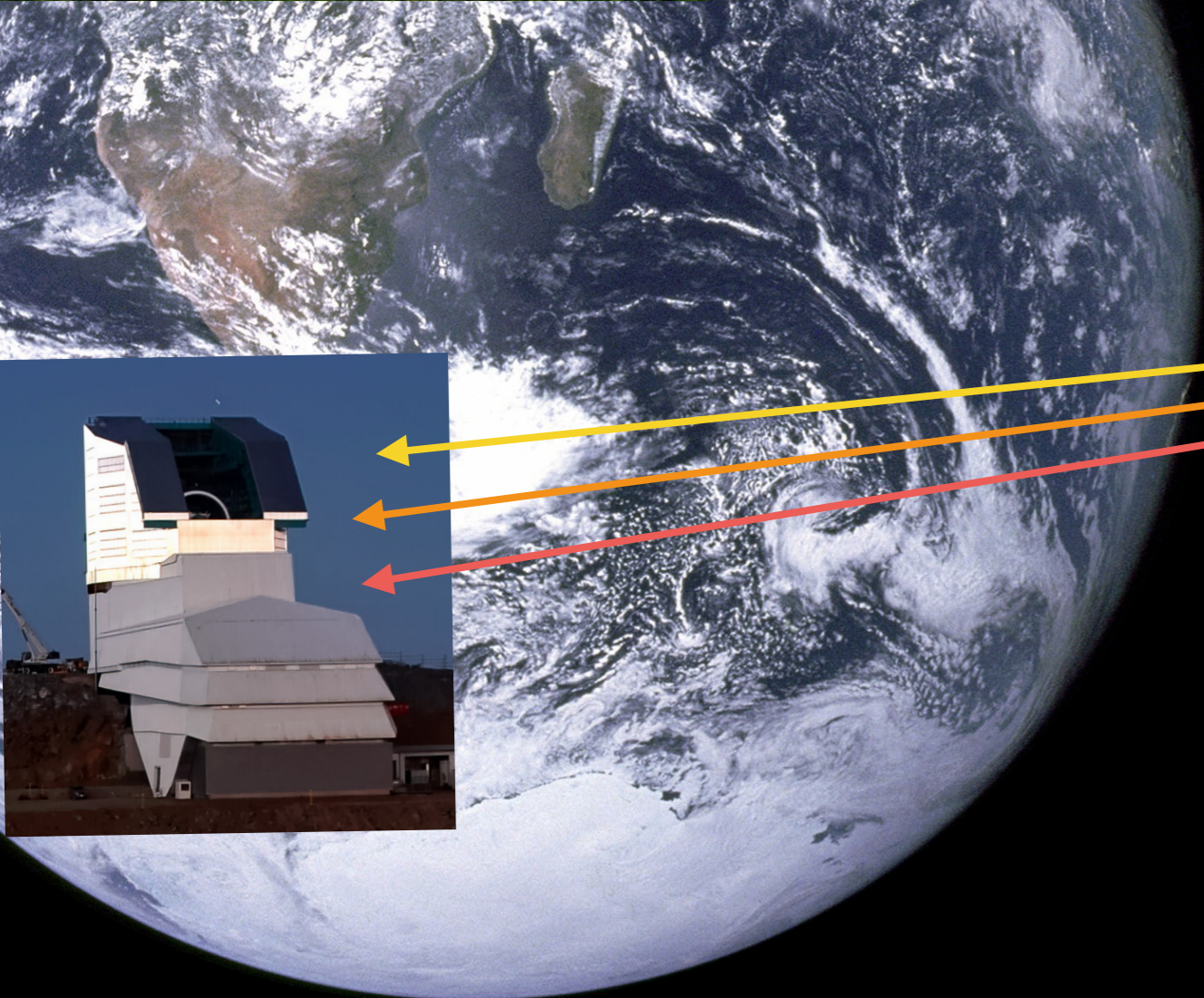
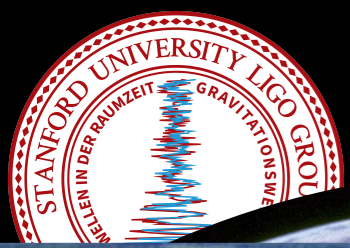


Matter Density

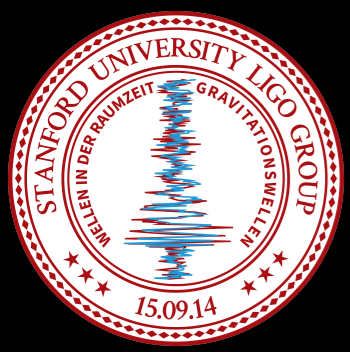
Gravitational Waves



<https://spaceplace.nasa.gov/gallery-sun/en/>
http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
[https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/\(lang\)](https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/(lang))
https://storage.noirlab.edu/media/archives/images/large/rubin-MorningTwilight_Feb2023-CC.jpg



<https://spaceplace.nasa.gov/gallery-sun/en/>
http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
[https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/\(lang\)](https://www.esa.int/ESA_Multimedia/Videos/2015/09/Gravitational_waves/(lang))
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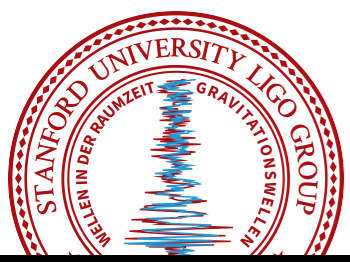
Finally...

LIGO = New Astronomy,
Laser Interferometer to Observe Gravitational waves

Big numbers & Small numbers

Interferometers are cool

Universe is wild, and it's filled with crazy stuff

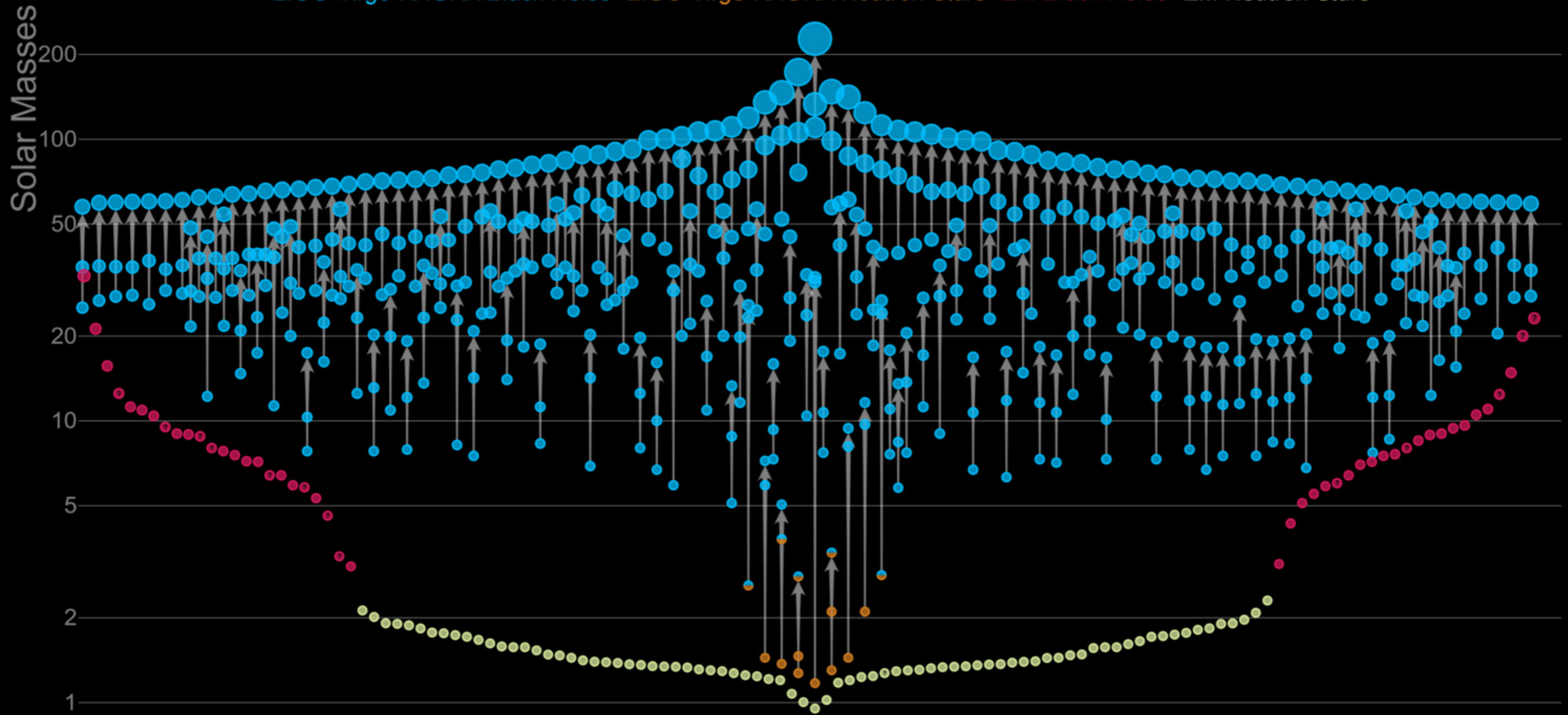


Lots of Events!



Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern