Colliding black holes, Giant Laser Measurement Systems, and Ripples in the Fabric of Space and Time

Dr. Brian Lantz
for the LIGO Scientific Collaboration &
the Virgo Collaboration

May 31, 2016

black hole image courtesy of LISA,
http://lisa.jpl.nasa.gov

G1601228

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black hole image courtesy of LISA,
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Advanced LIGO Laser Interferometer Gravitational wave Observatory

LIGO Scientific Collaboration

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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International Network

LIGO India

project approved

map from http://www.nationsonline.org/maps/political_world_map3000.jpg

Sept. 14, 2015

LIGO Hanford

GEO 600

KAGRA

VIRGO

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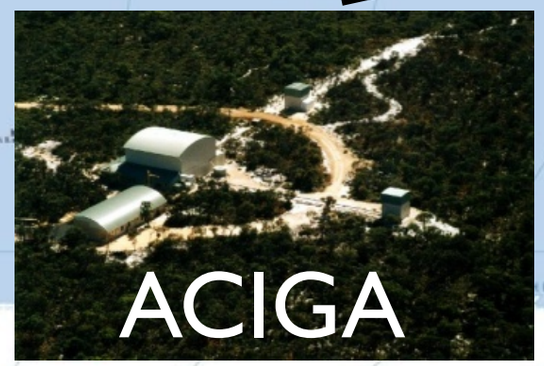
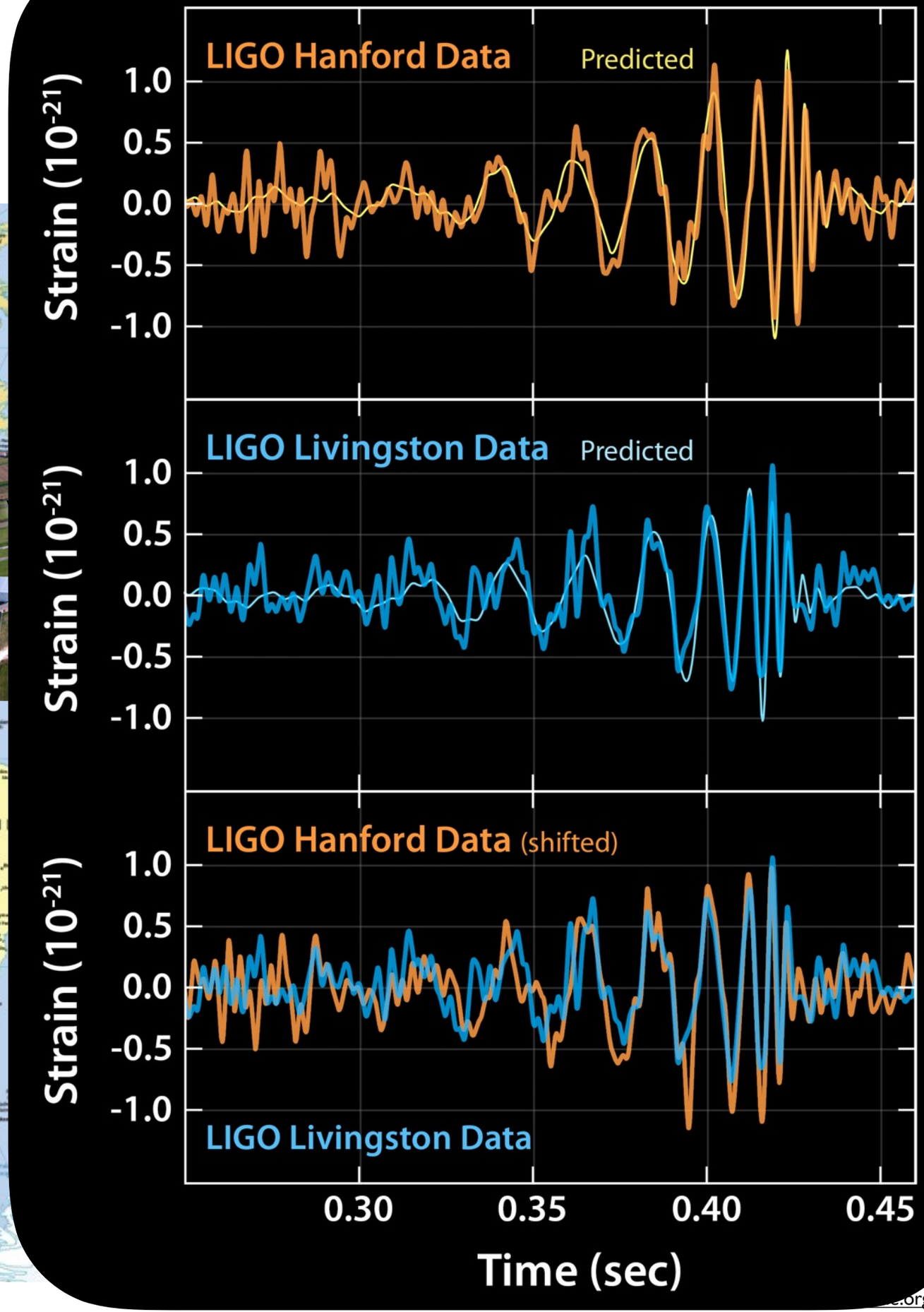


map from http://www.nationsonline.org/maps/political_world_map3000.jpg

LIGO Hanford

LIGO Livingston

VIRGO



AGRA

GO India

oject approved

.org/maps/political_world_map3000.jpg

two black holes merging

http://mediaassets.caltech.edu/gwave

two black holes merging

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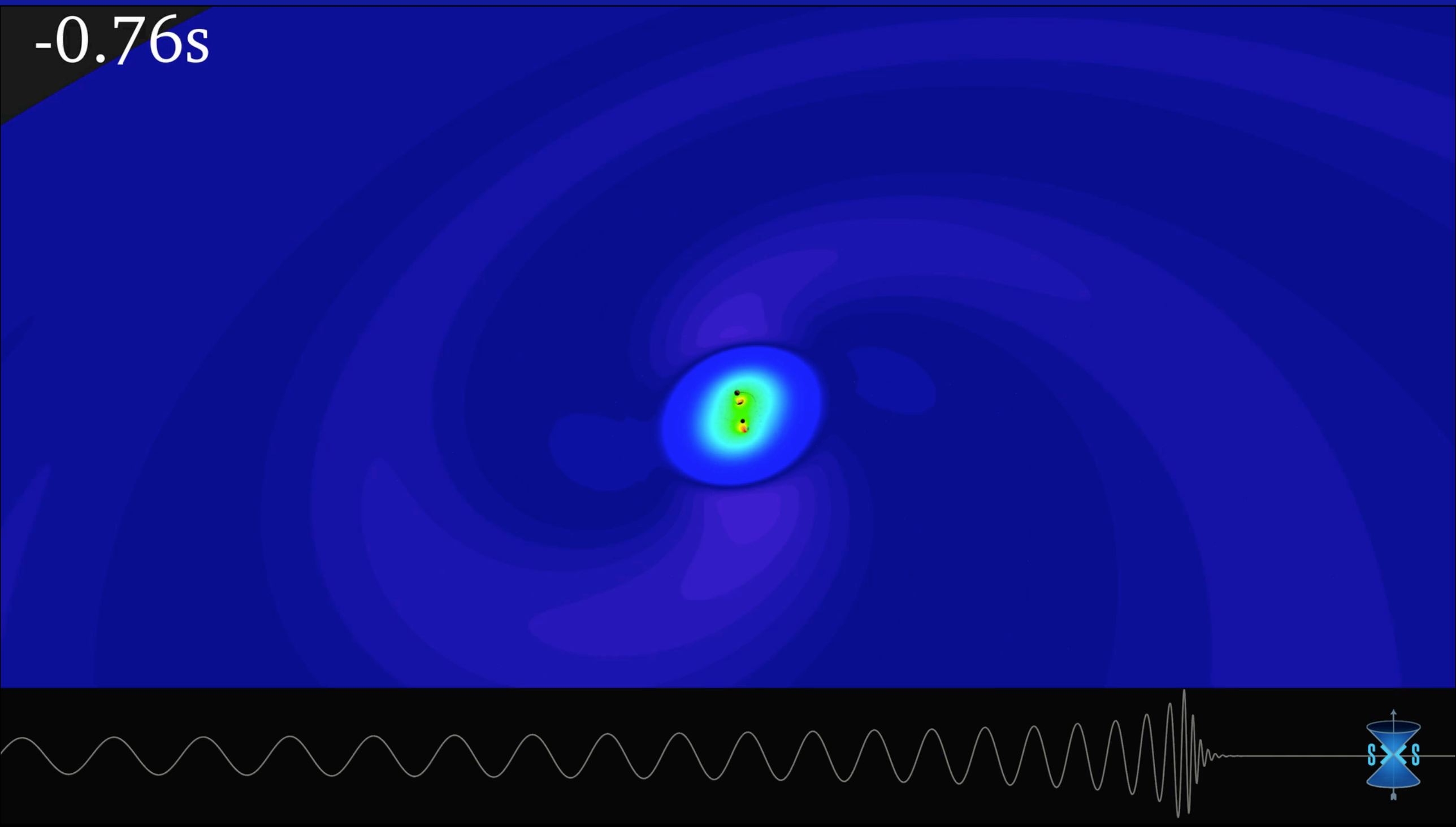
Simulation of the event



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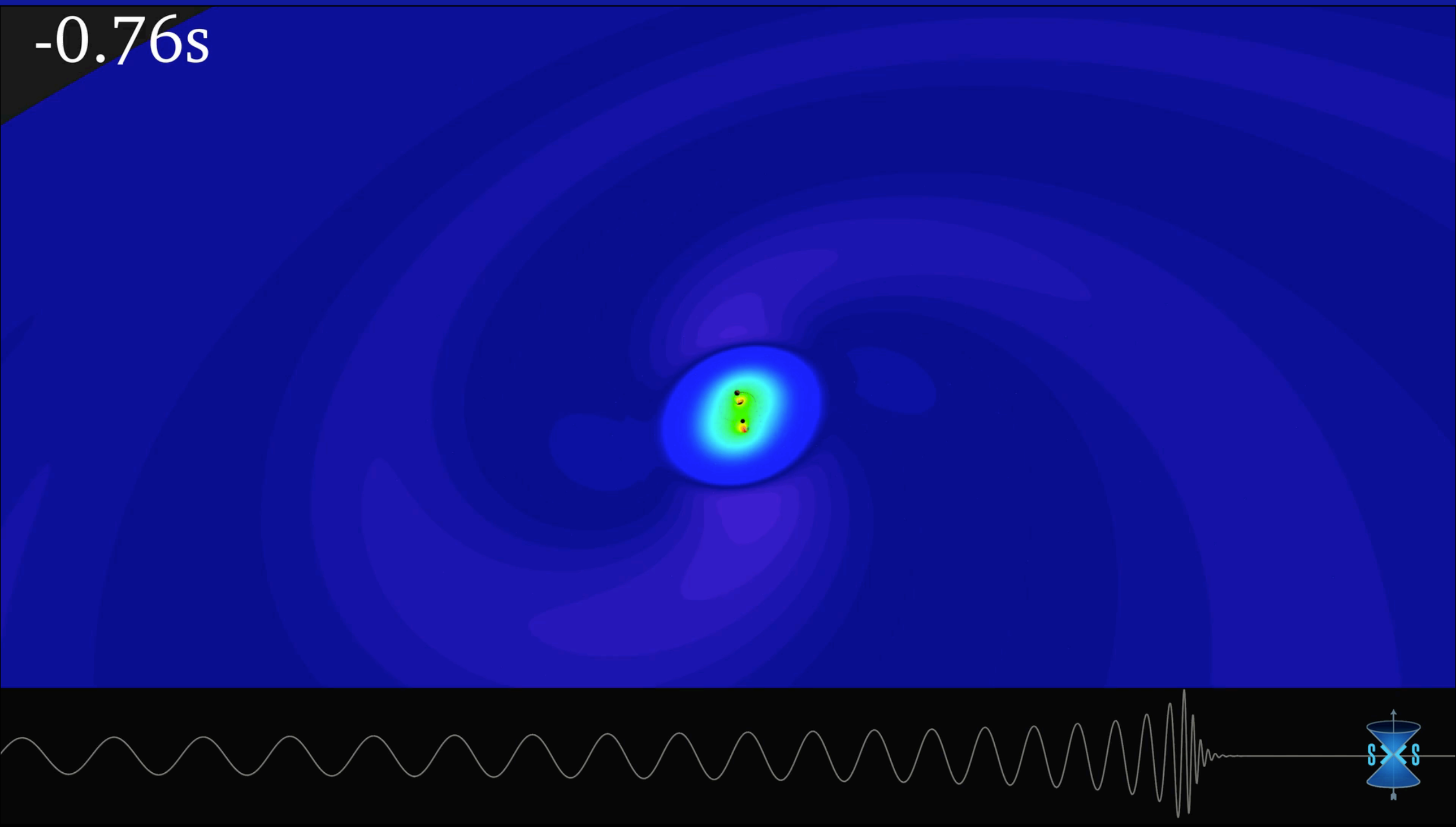

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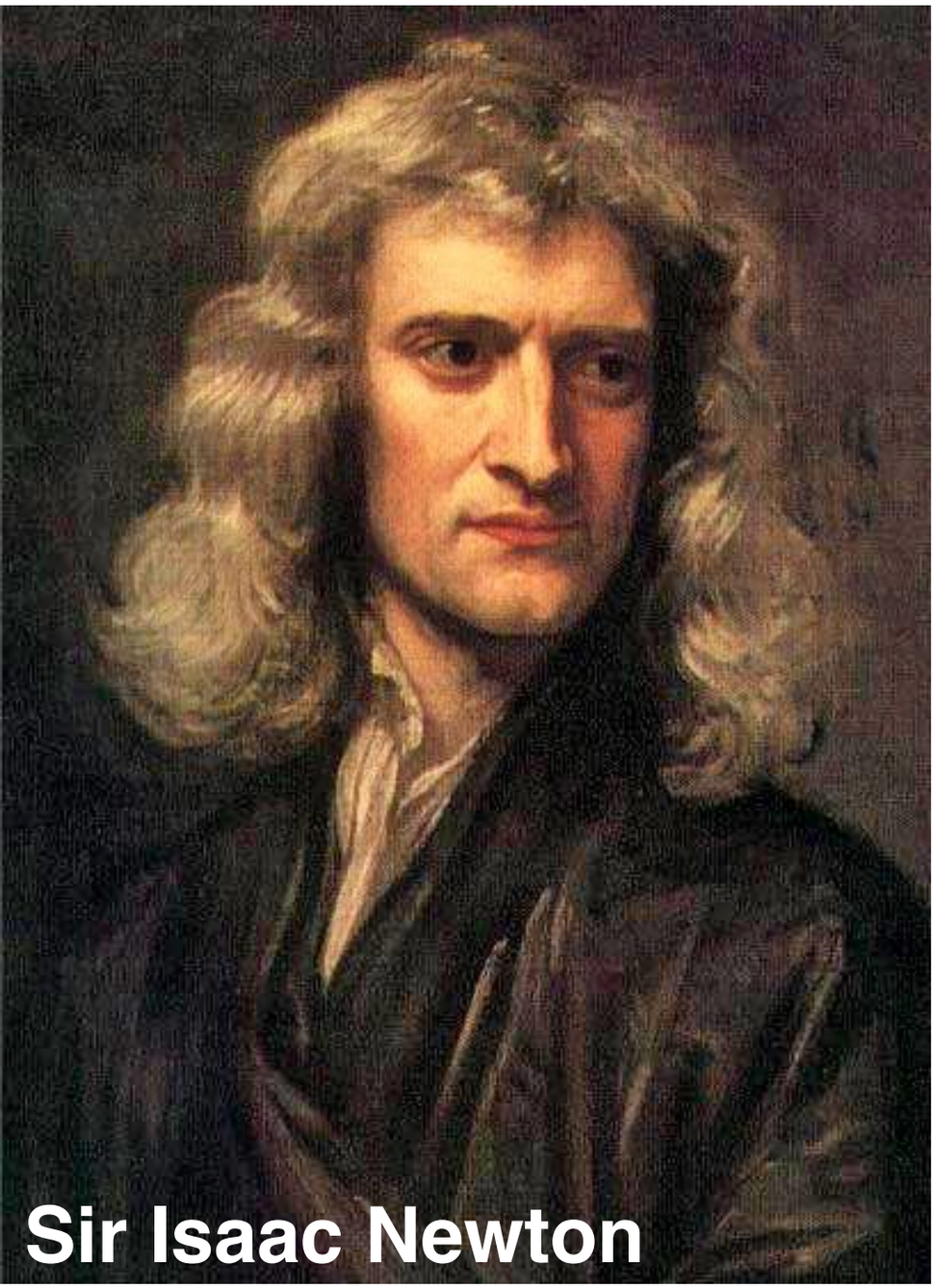
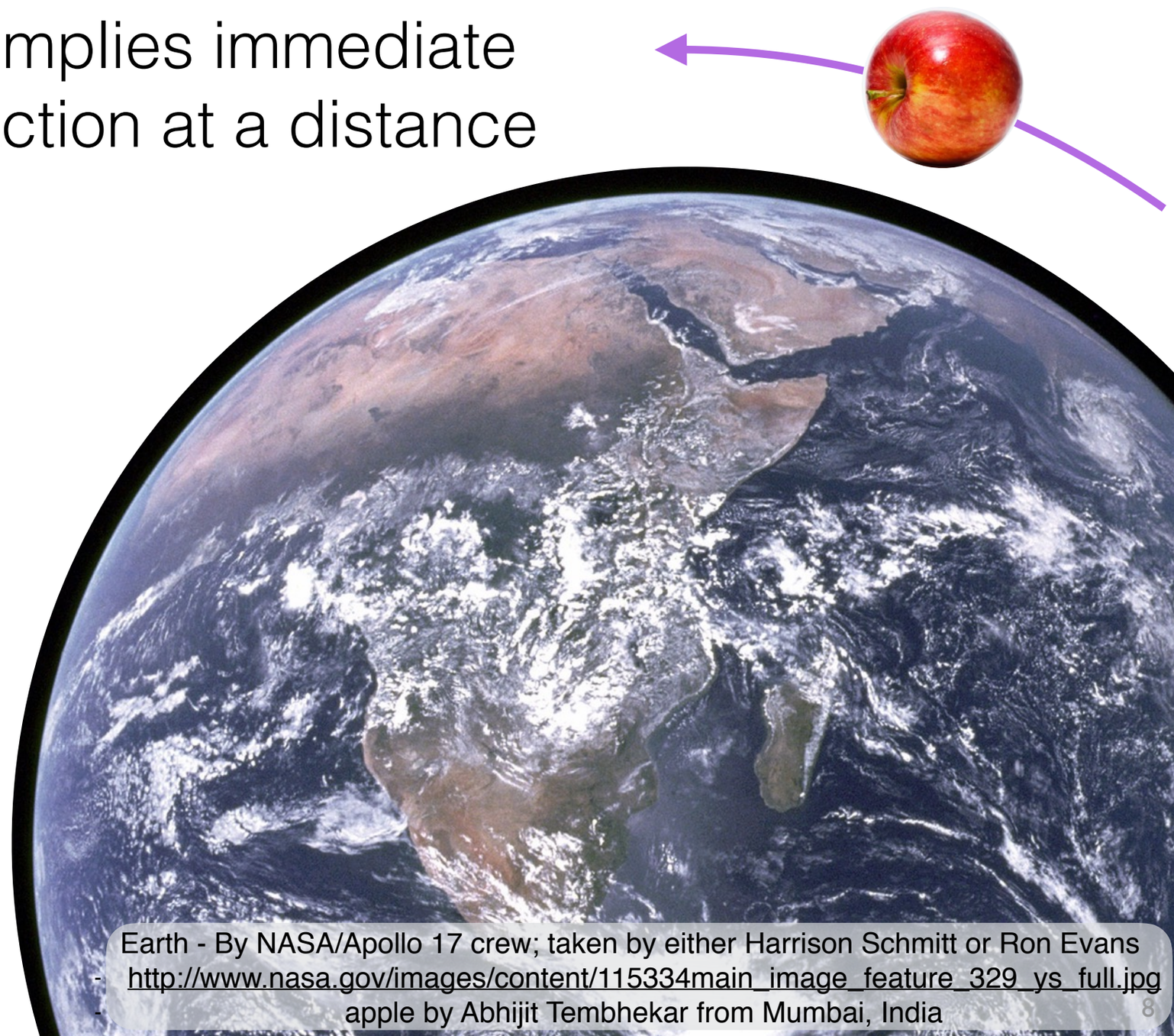
What is a Gravitational Wave?

$$F = \frac{G m_1 m_2}{r^2}$$



By Sir Godfrey Kneller
- http://www.newton.cam.ac.uk/art/portrait.html

Implies immediate action at a distance



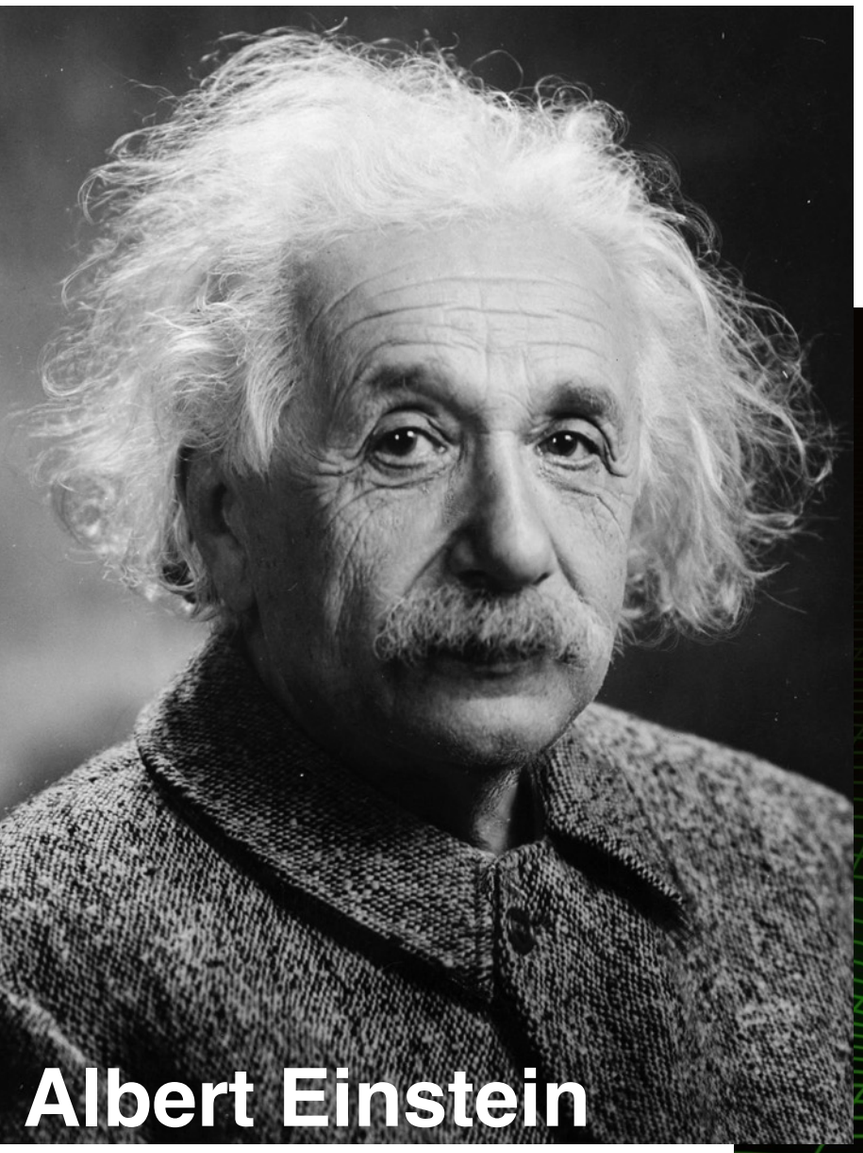
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

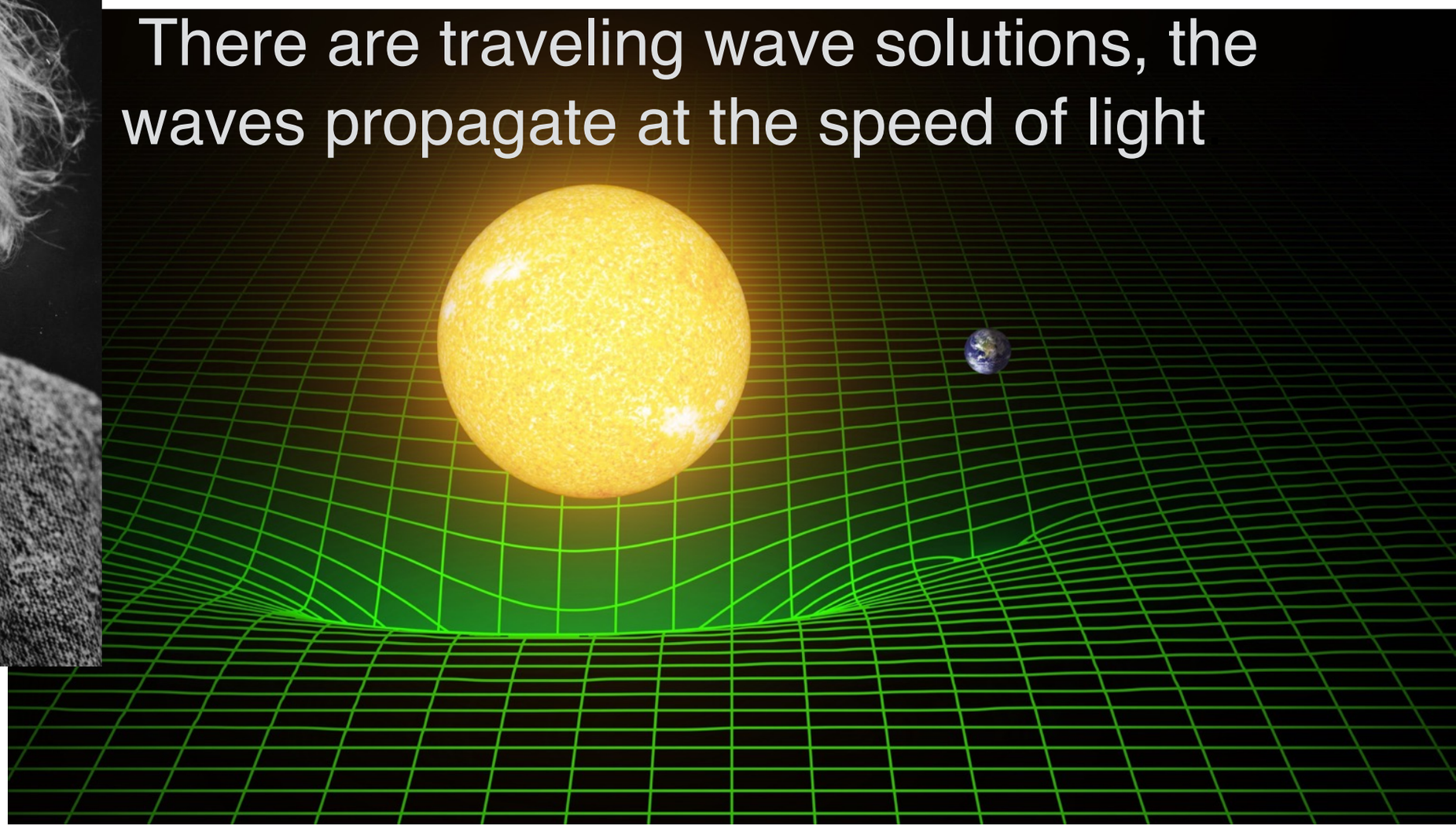
"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler



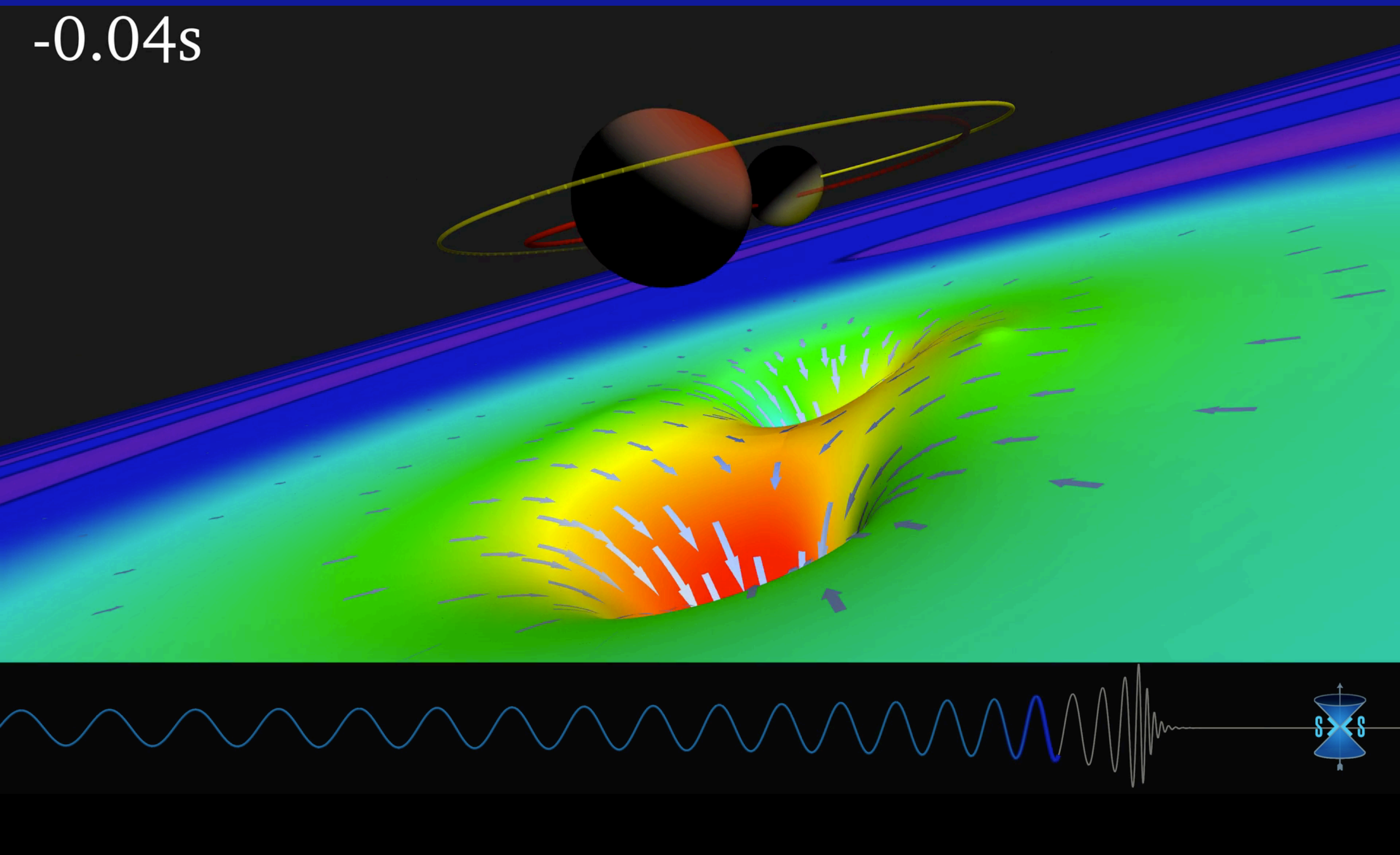
Albert Einstein

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



Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

Simulation of the event



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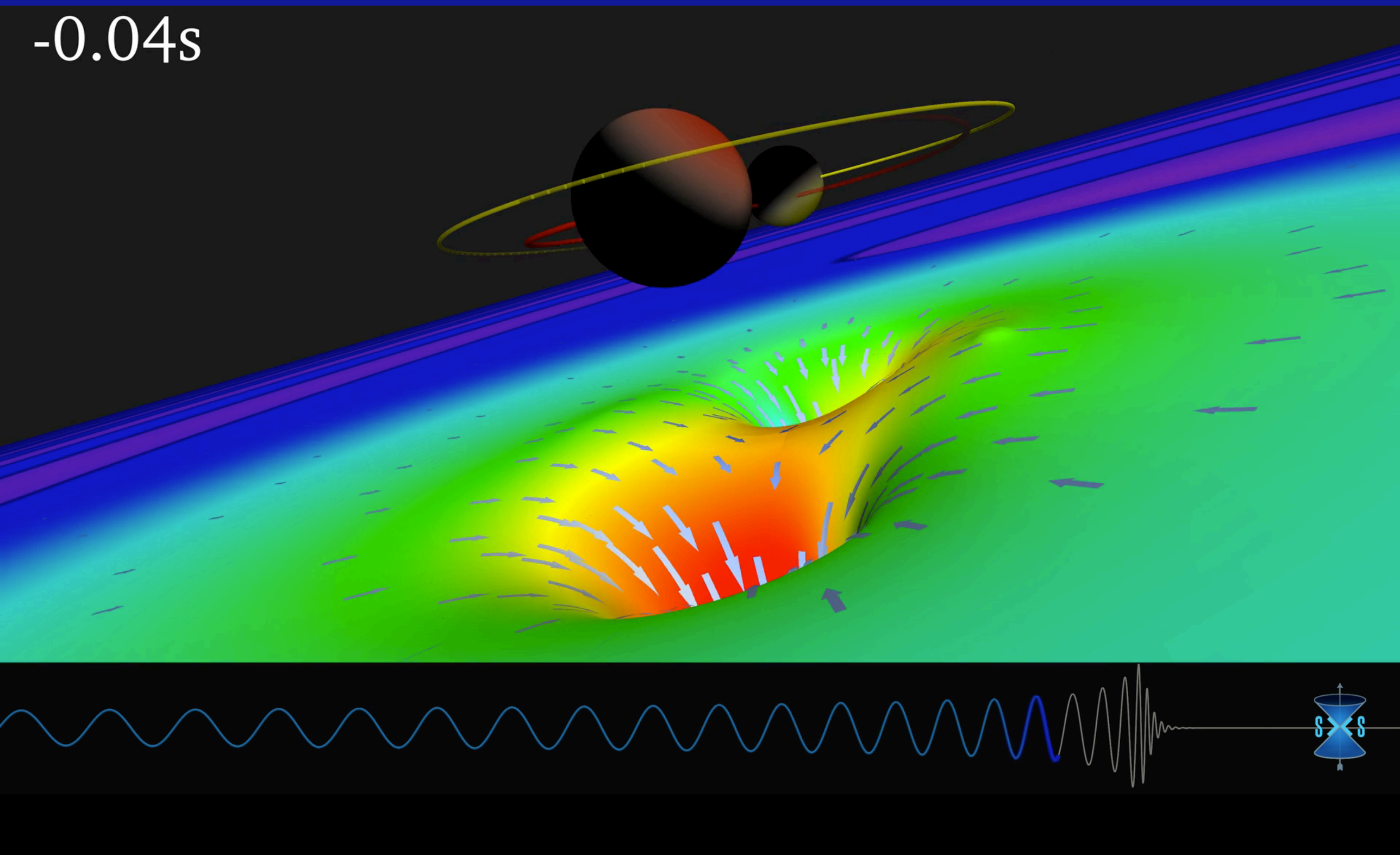
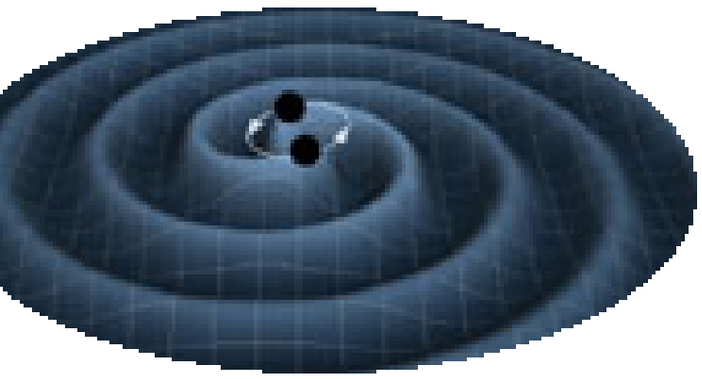
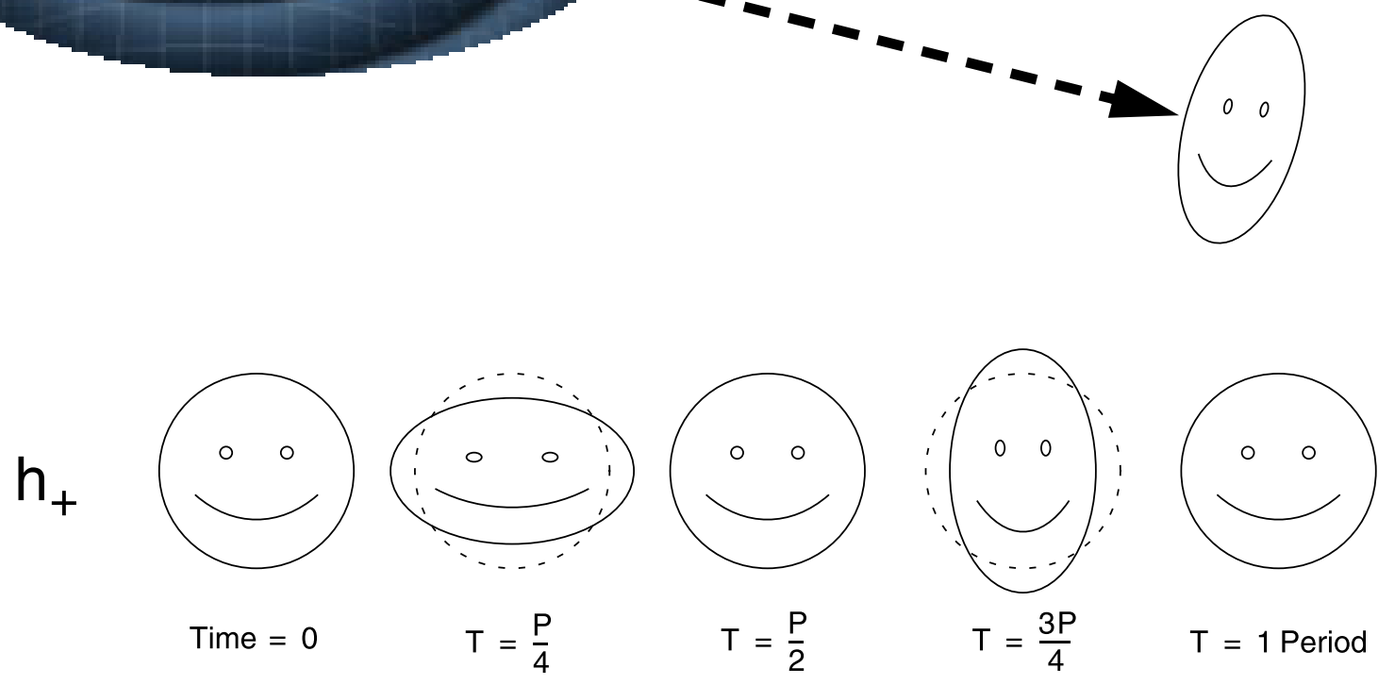
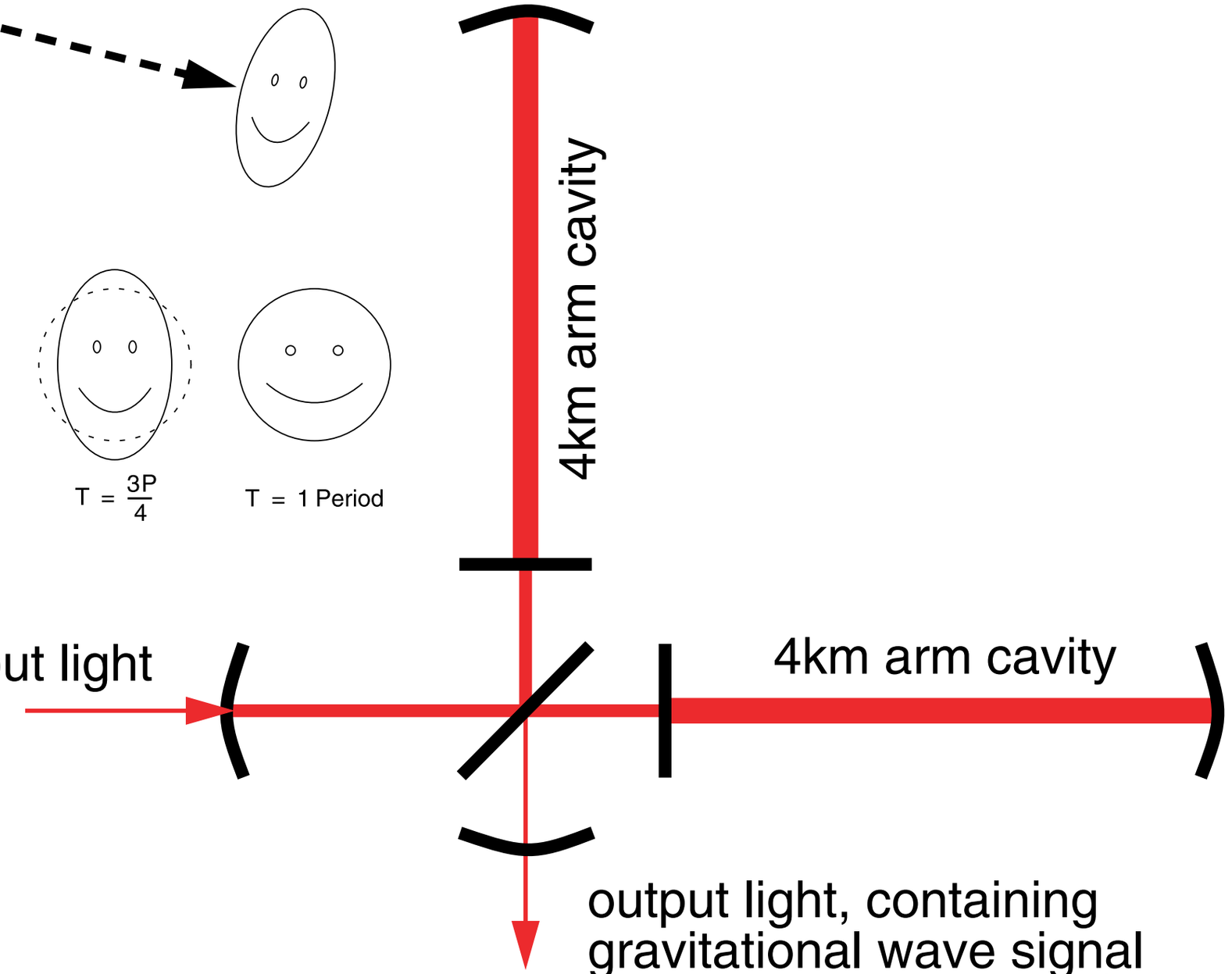


The LIGO concept



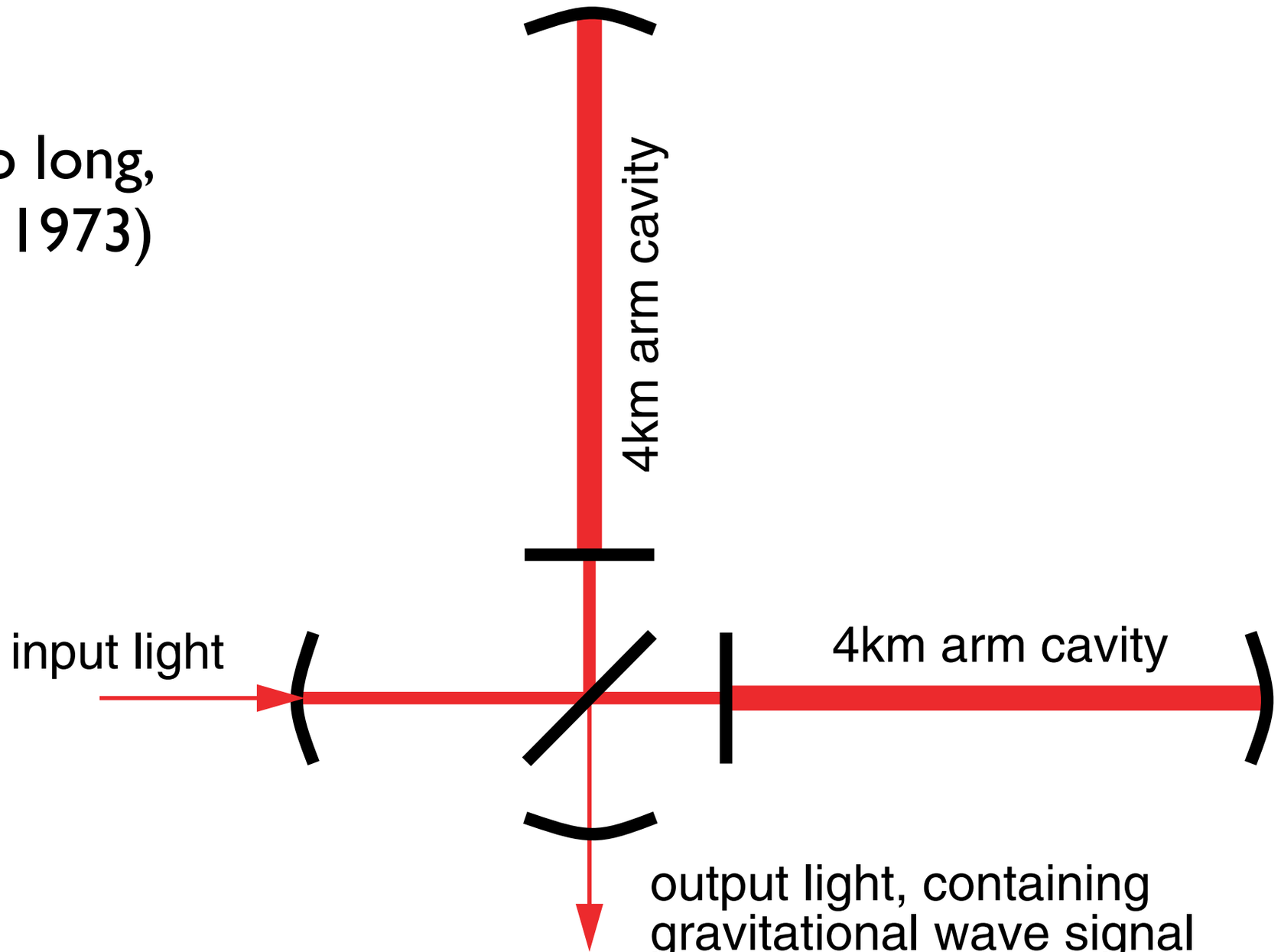


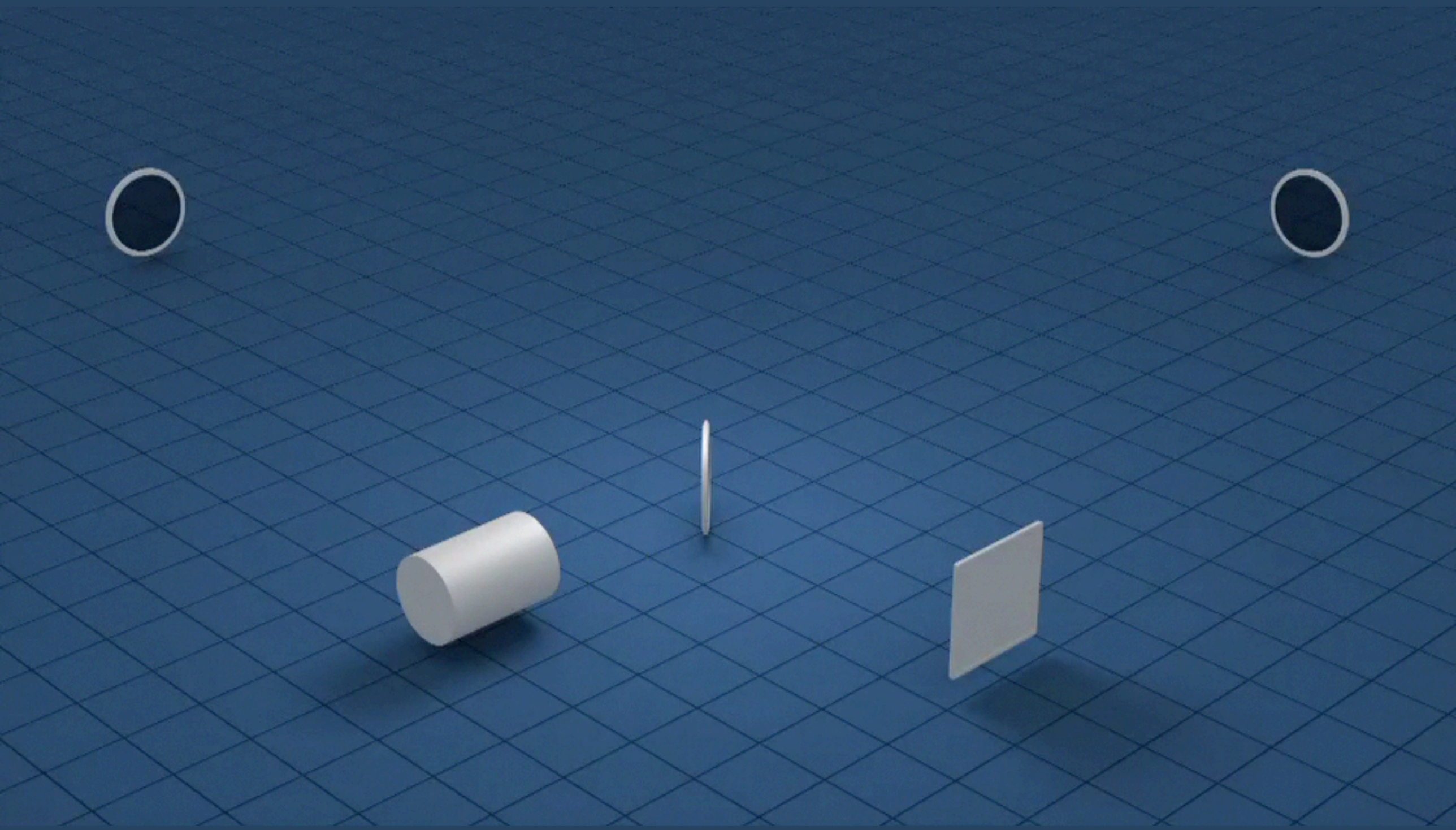


The LIGO concept
why it is nearly impossible

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

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





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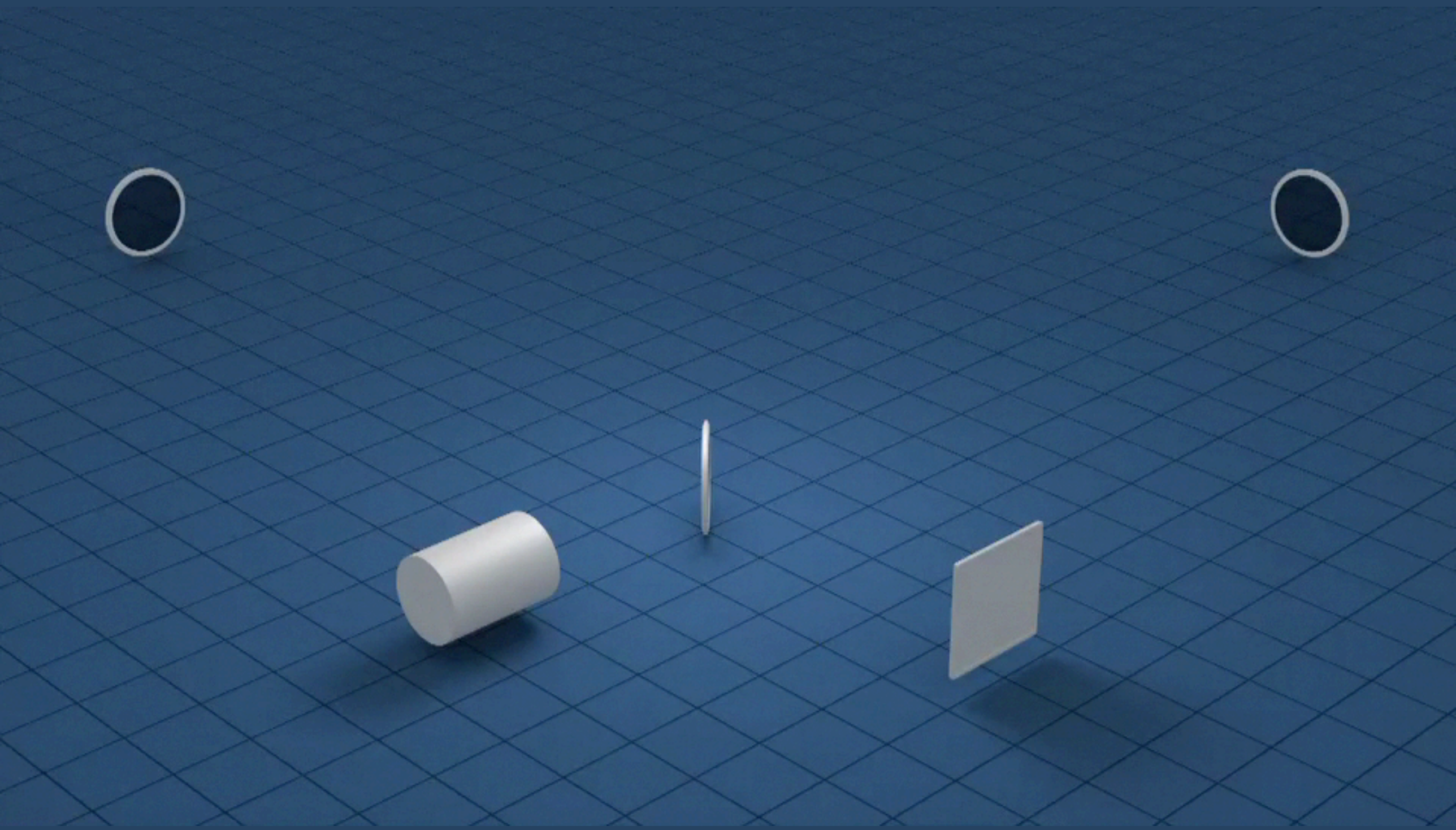

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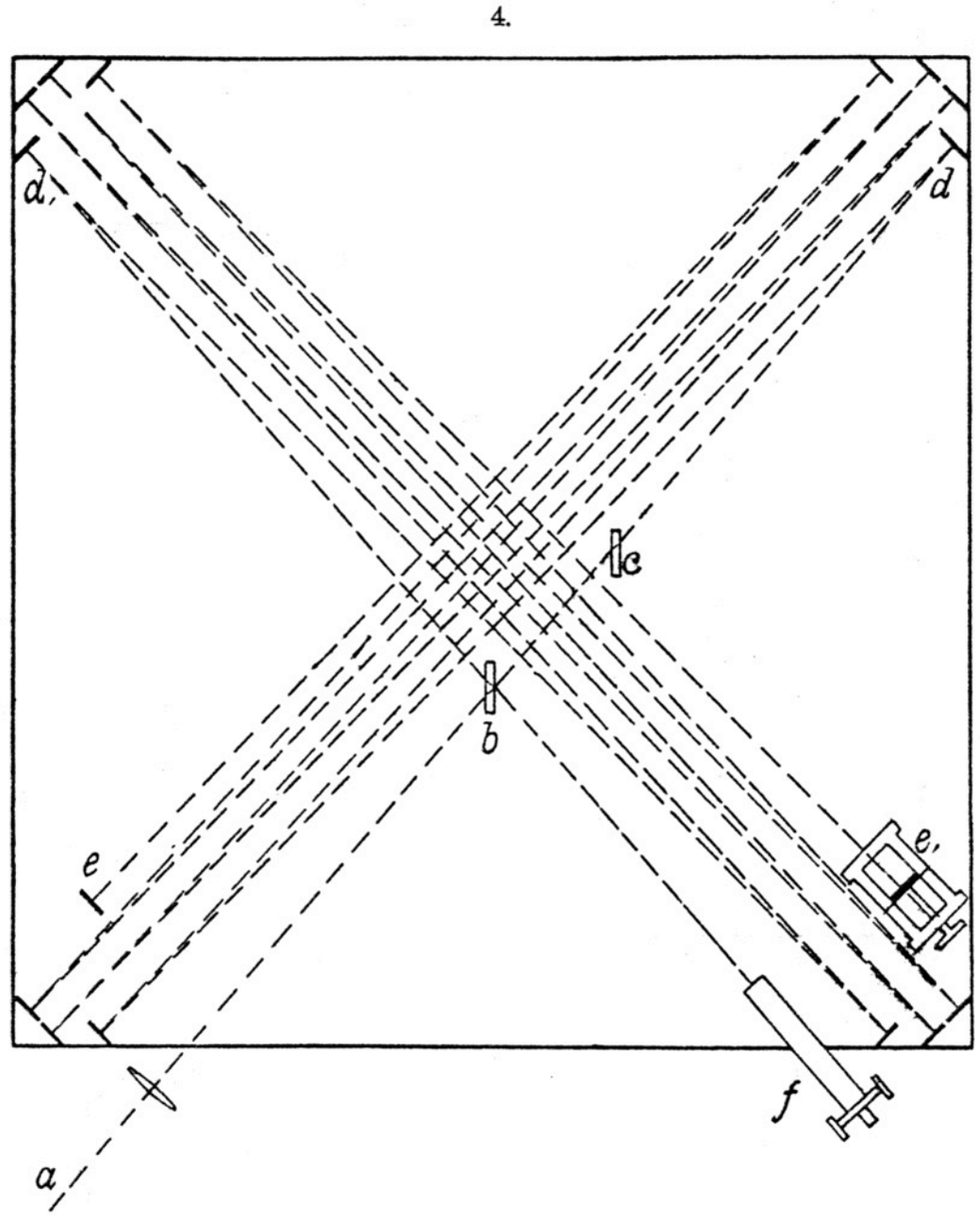
Michelson's Interferometer!

1887 experiment to measure
"luminiferous ether" with an interferometer



Am. Jour. Sci. - Third Series, Vol. 34, No. 203, Nov. 1887. pg 333-345

water waves

duck by Daderot, https://commons.wikimedia.org/w/index.php?curid=15477111

Ripple by Brocken Inaglory, https://commons.wikimedia.org/w/index.php?curid=2438314

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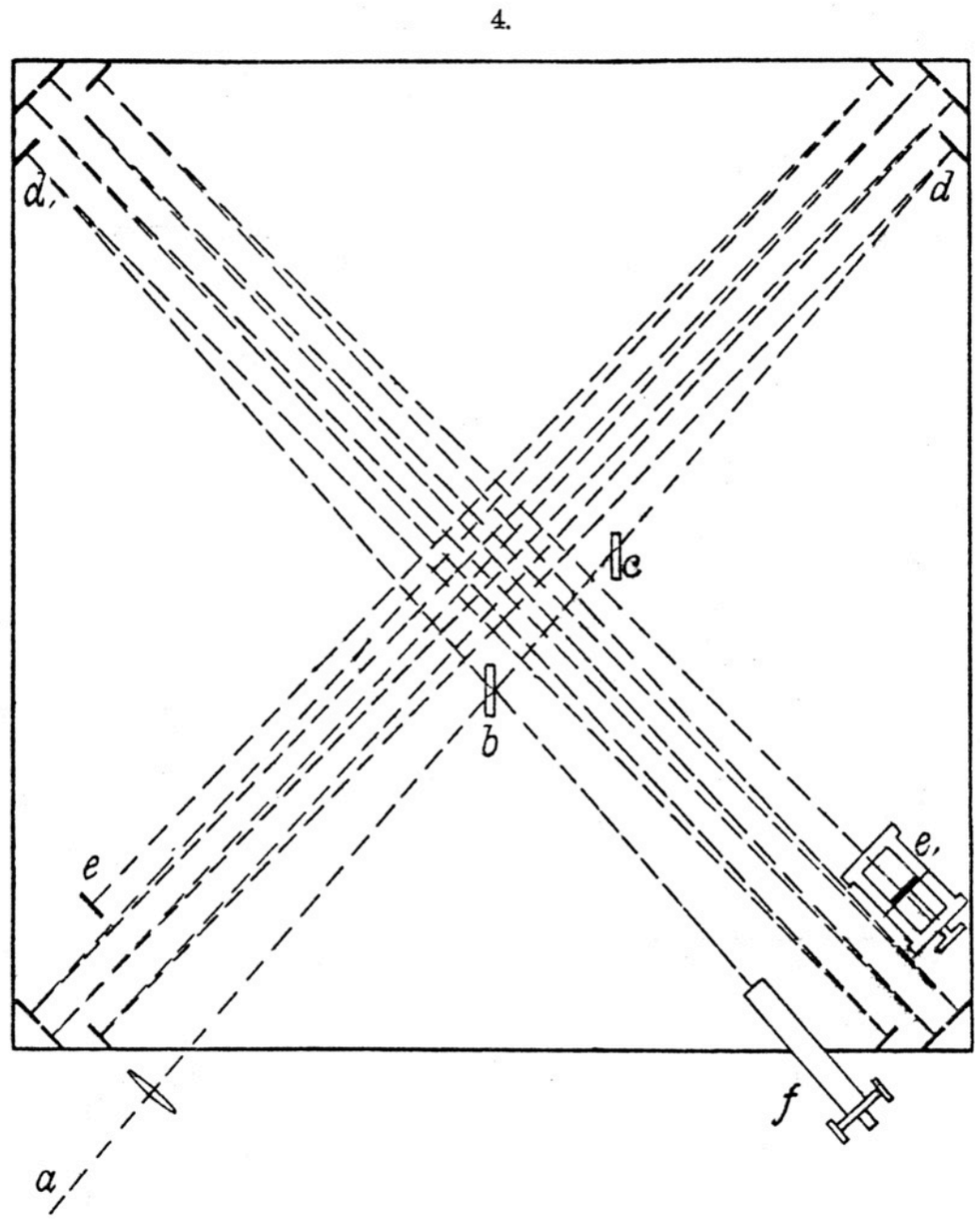

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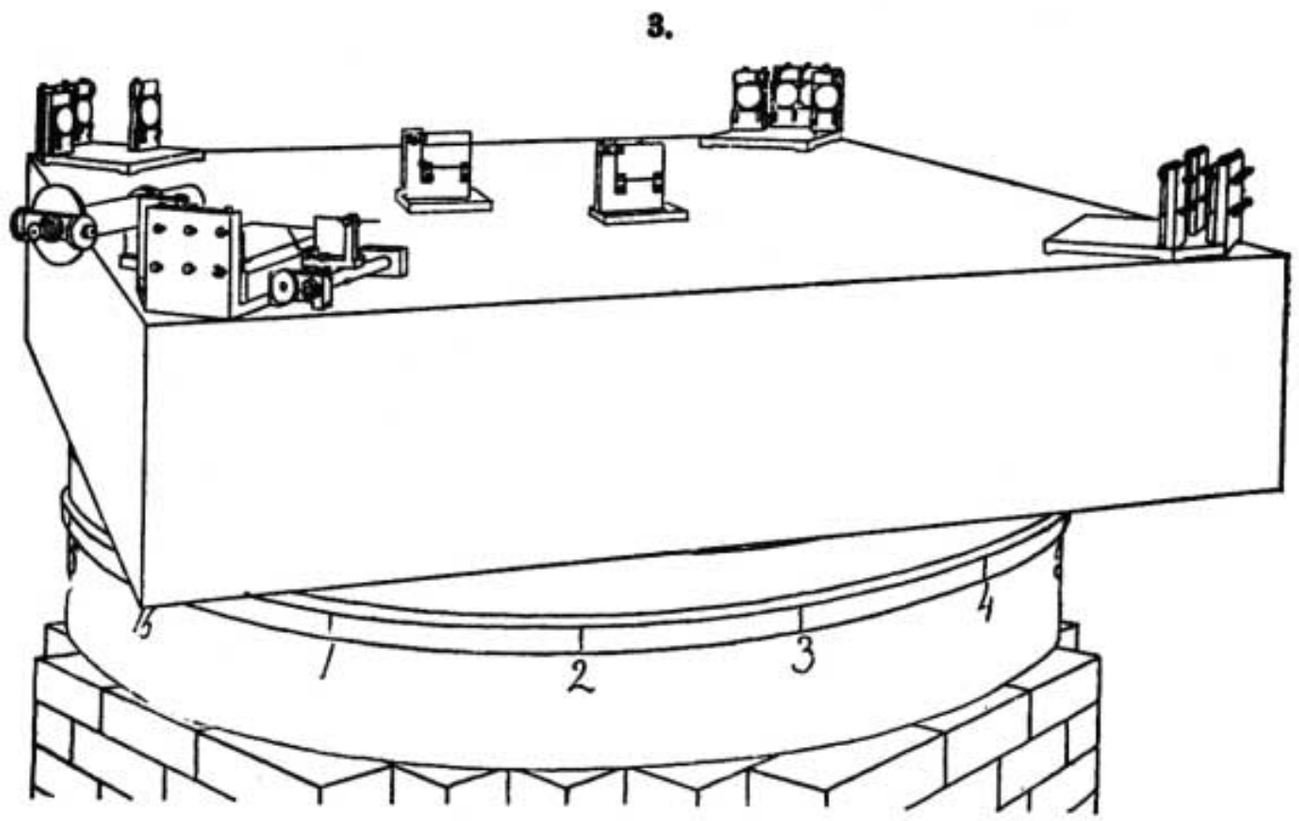

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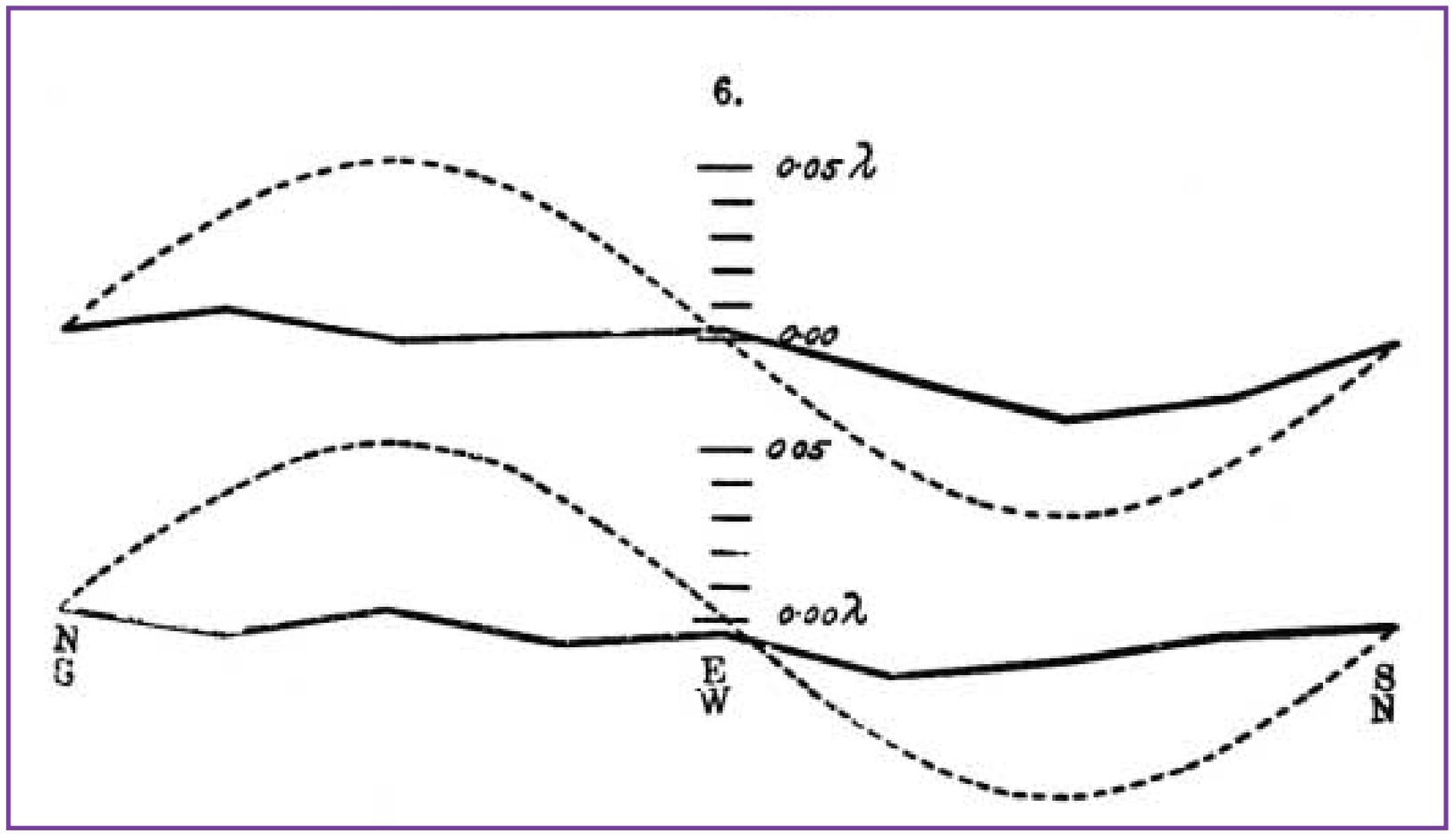

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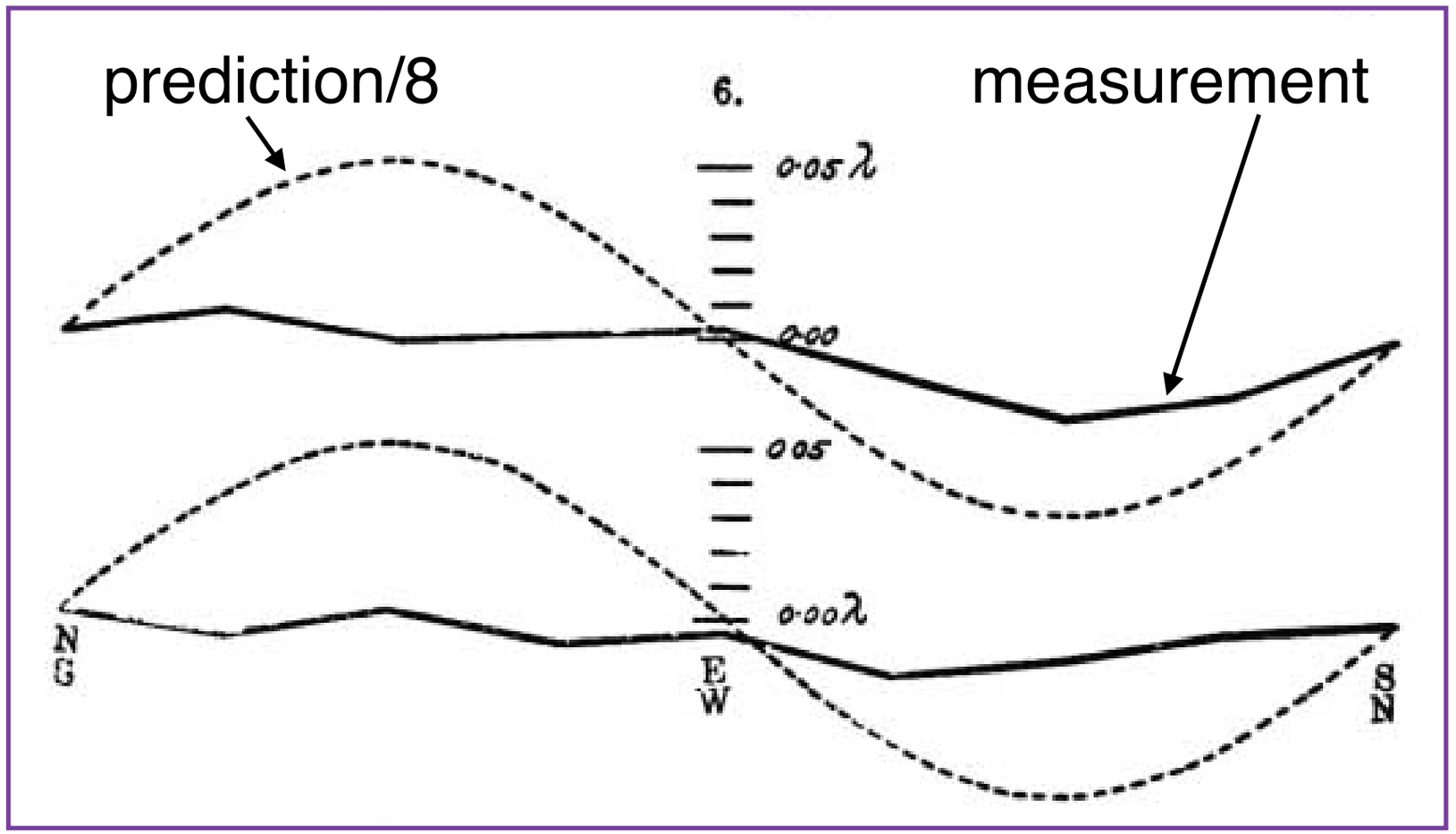

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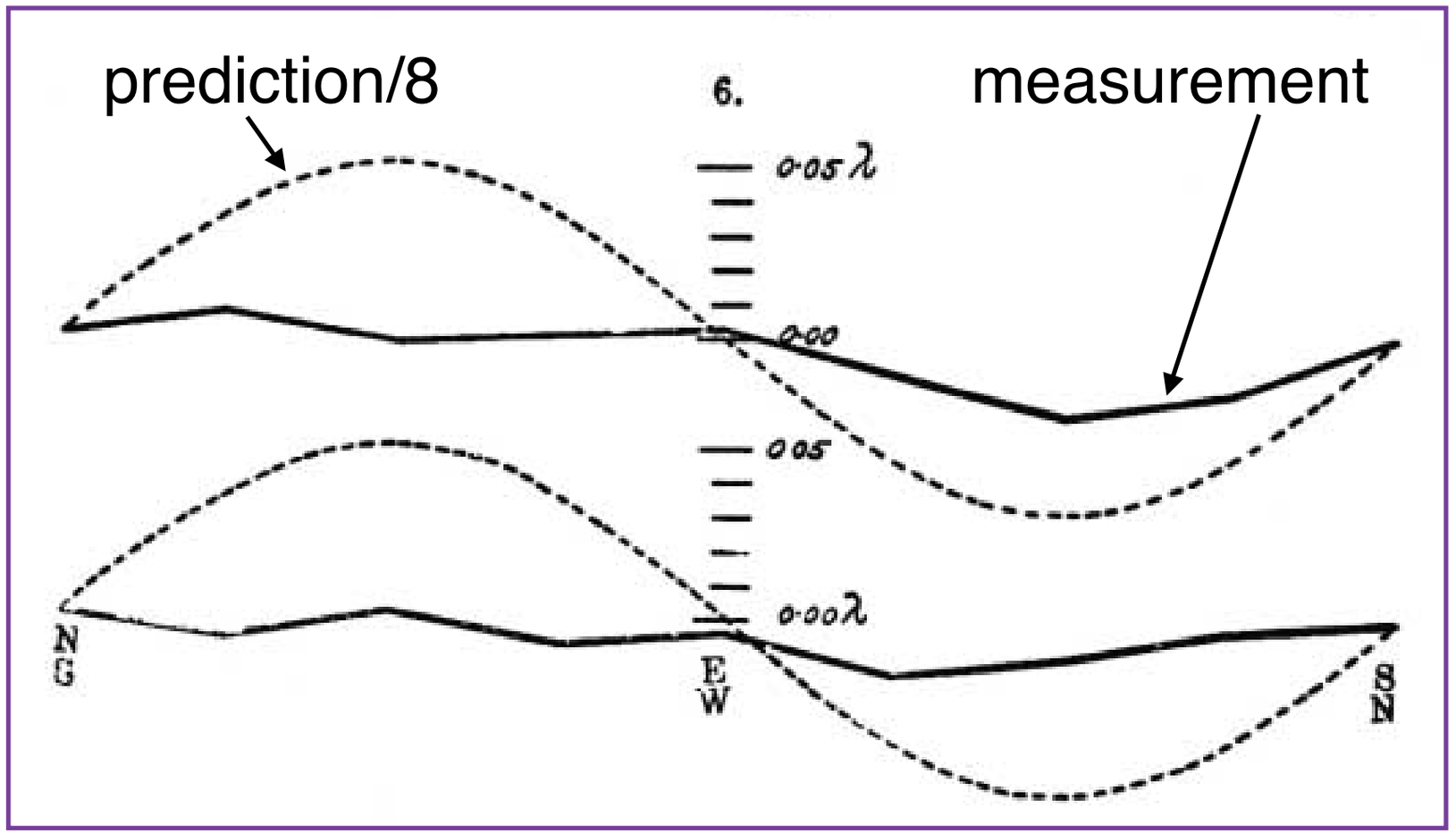

The speed of light doesn't change if you are moving!

Michelson's Interferometer!

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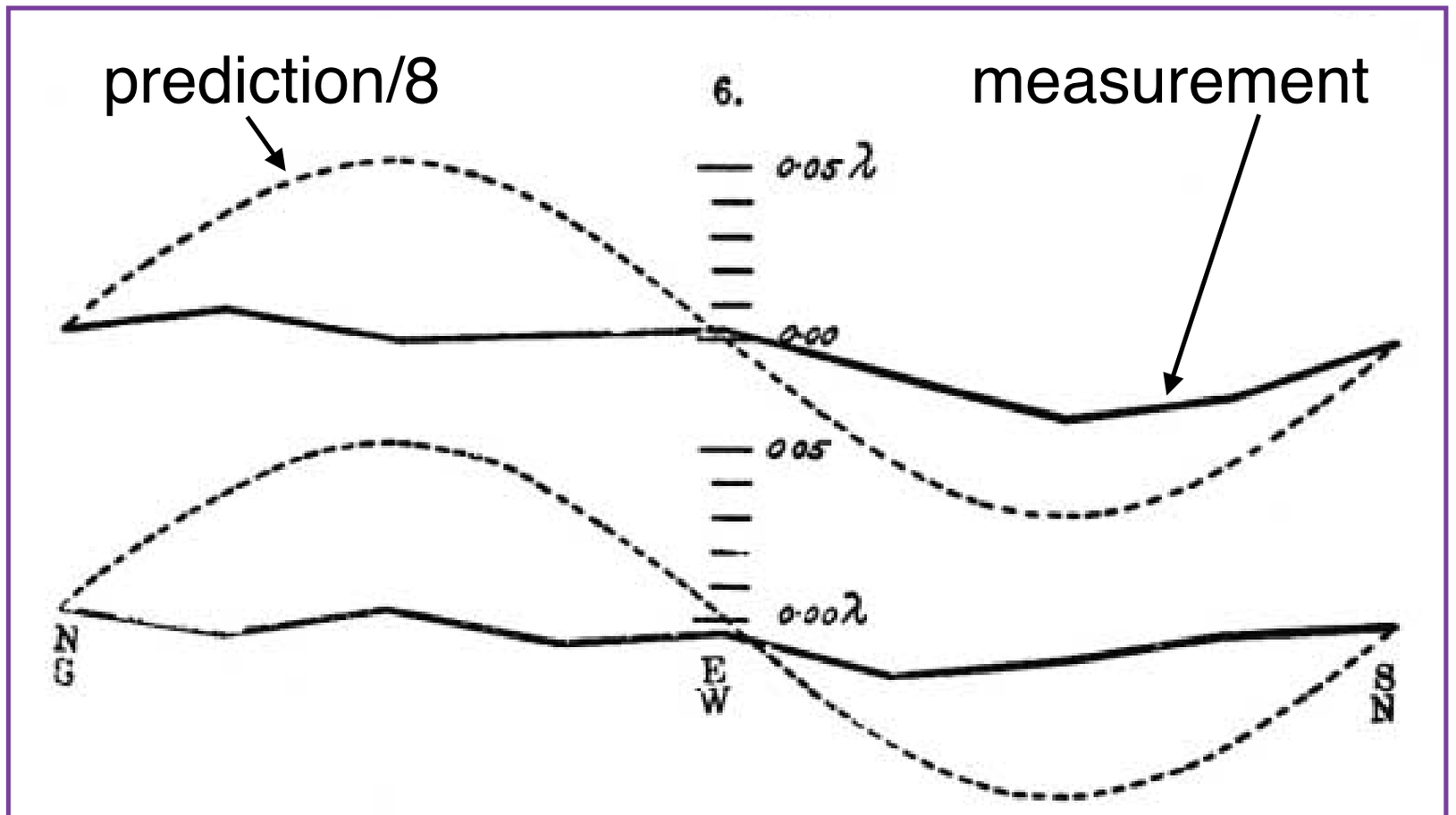

The speed of light doesn't change if you are moving!
Your perception of time and space are RELATIVE

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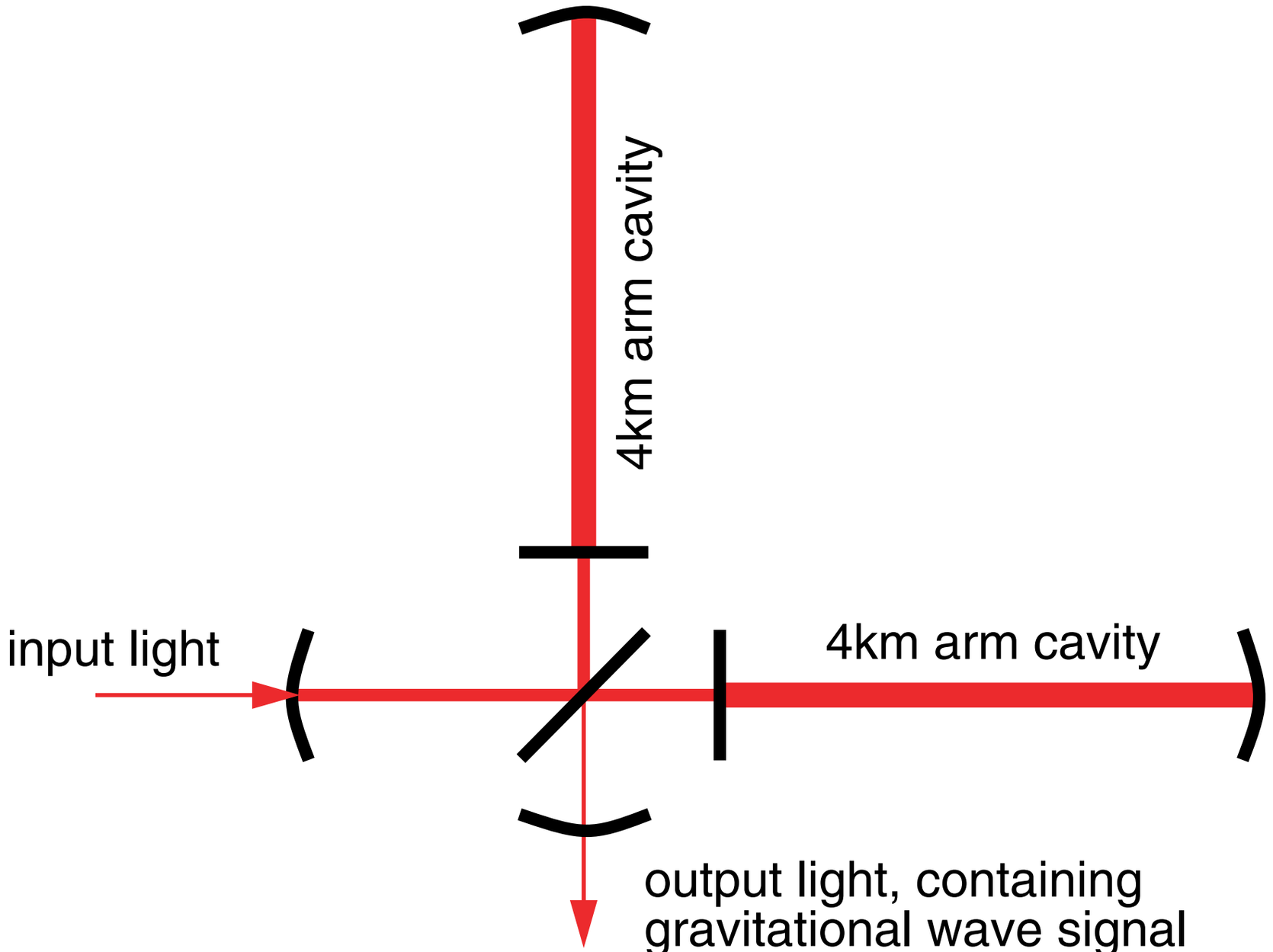
The LIGO concept
why it is nearly impossible

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



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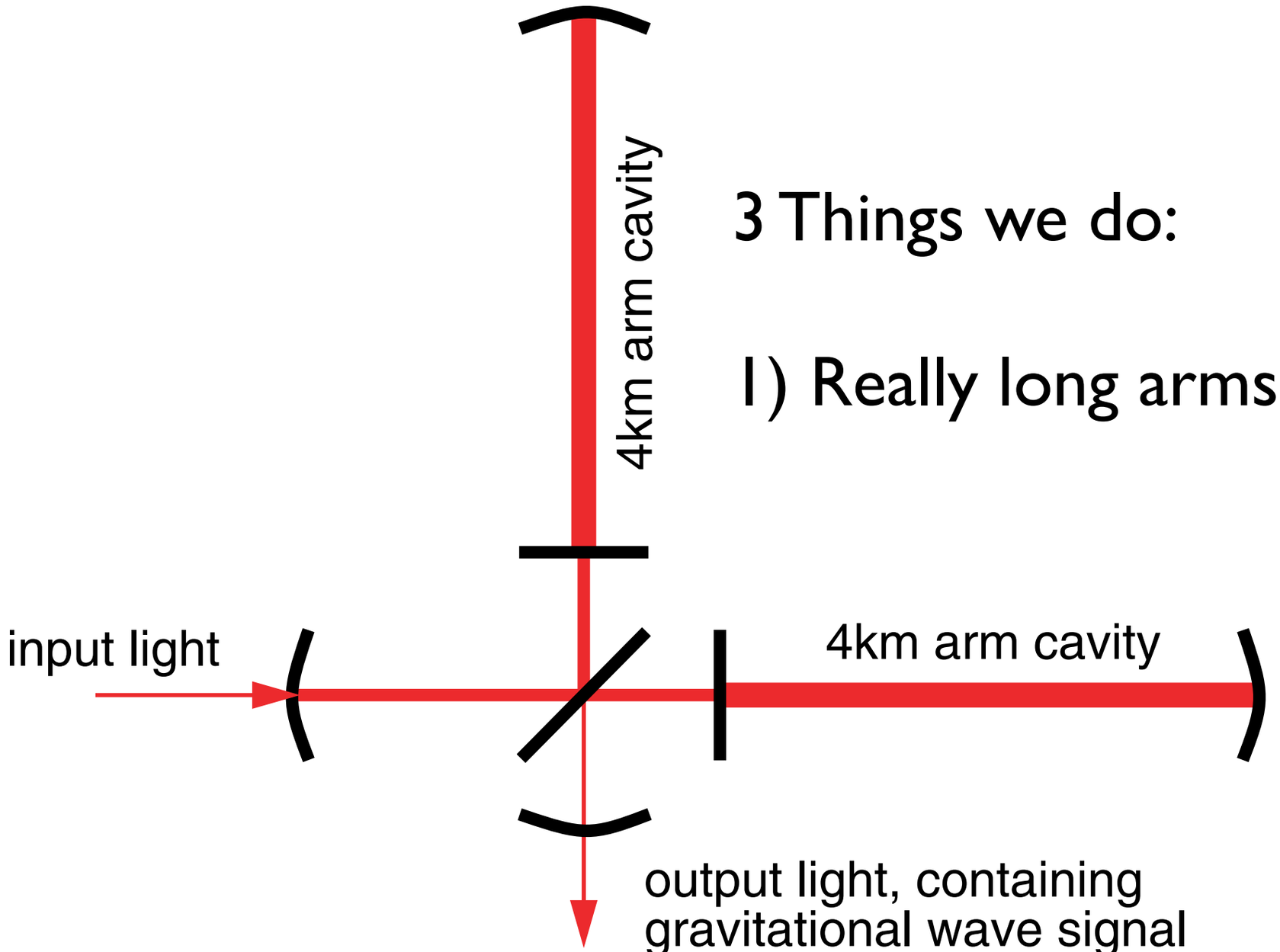
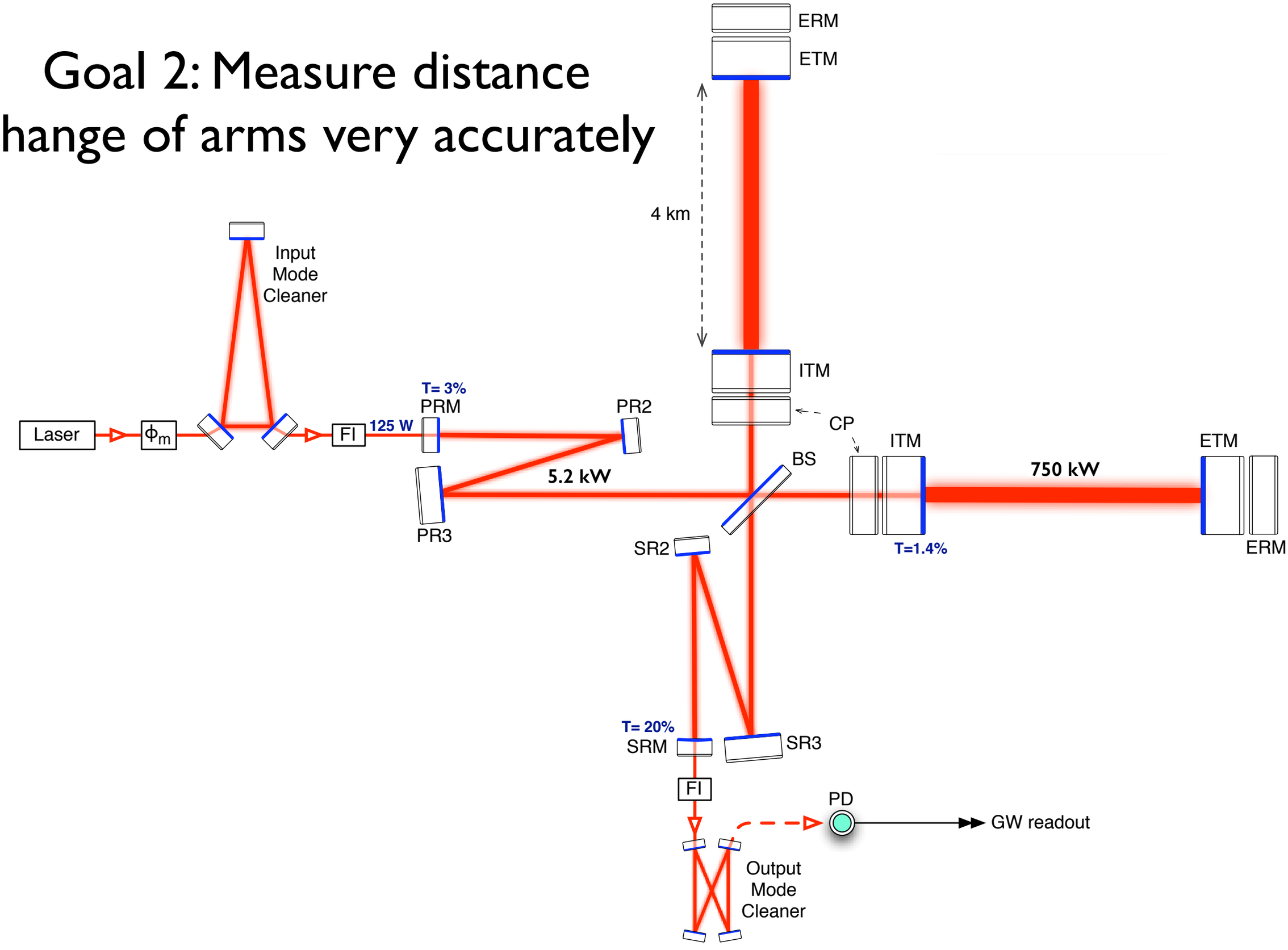


3 Things we do:

1) Really long arms.

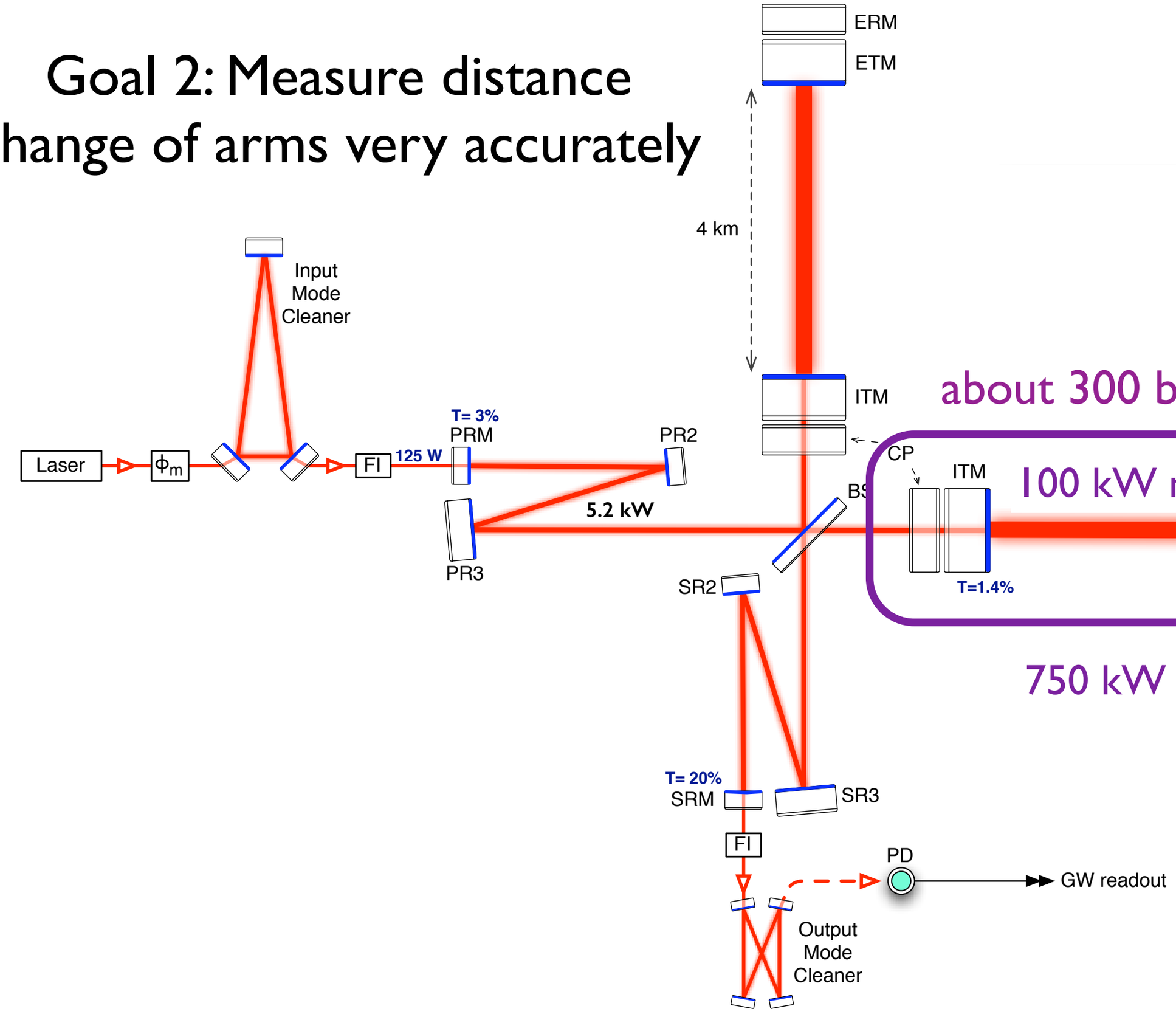
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately



Fabry-Perot arms

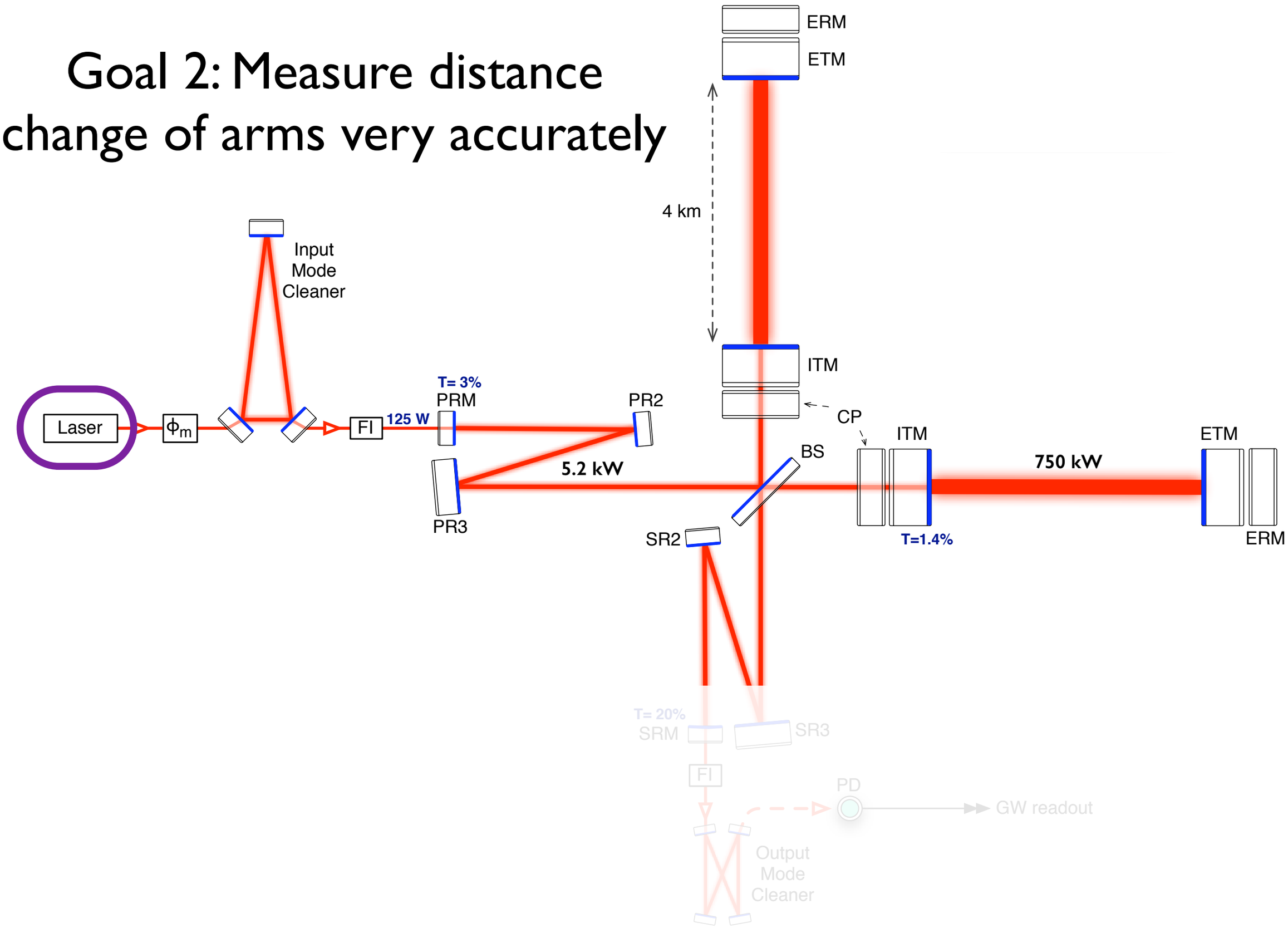
Goal 2: Measure distance change of arms very accurately



750 kW O3

Power

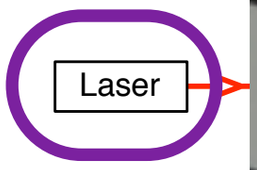
Goal 2: Measure distance change of arms very accurately

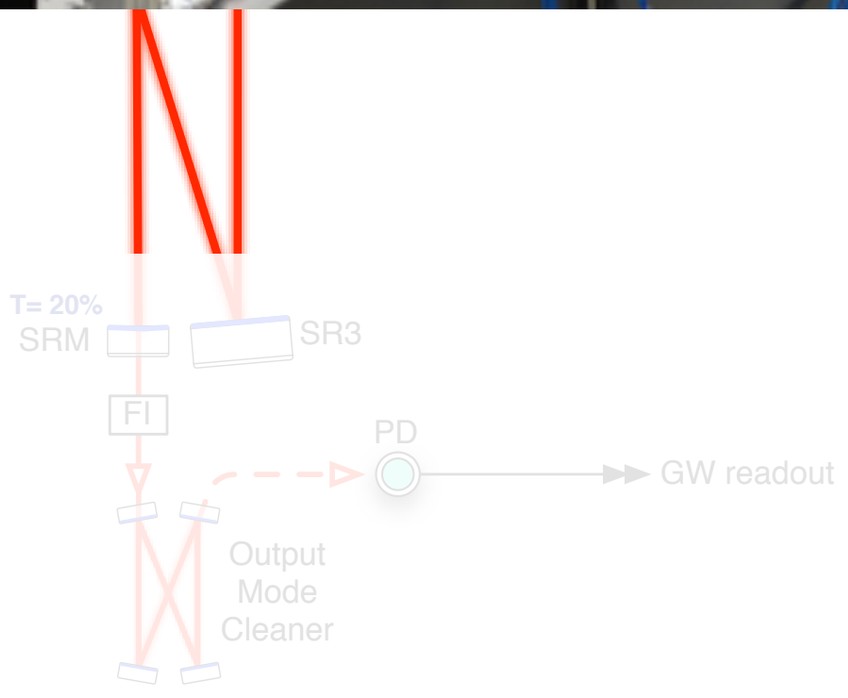


Power

Goa
change

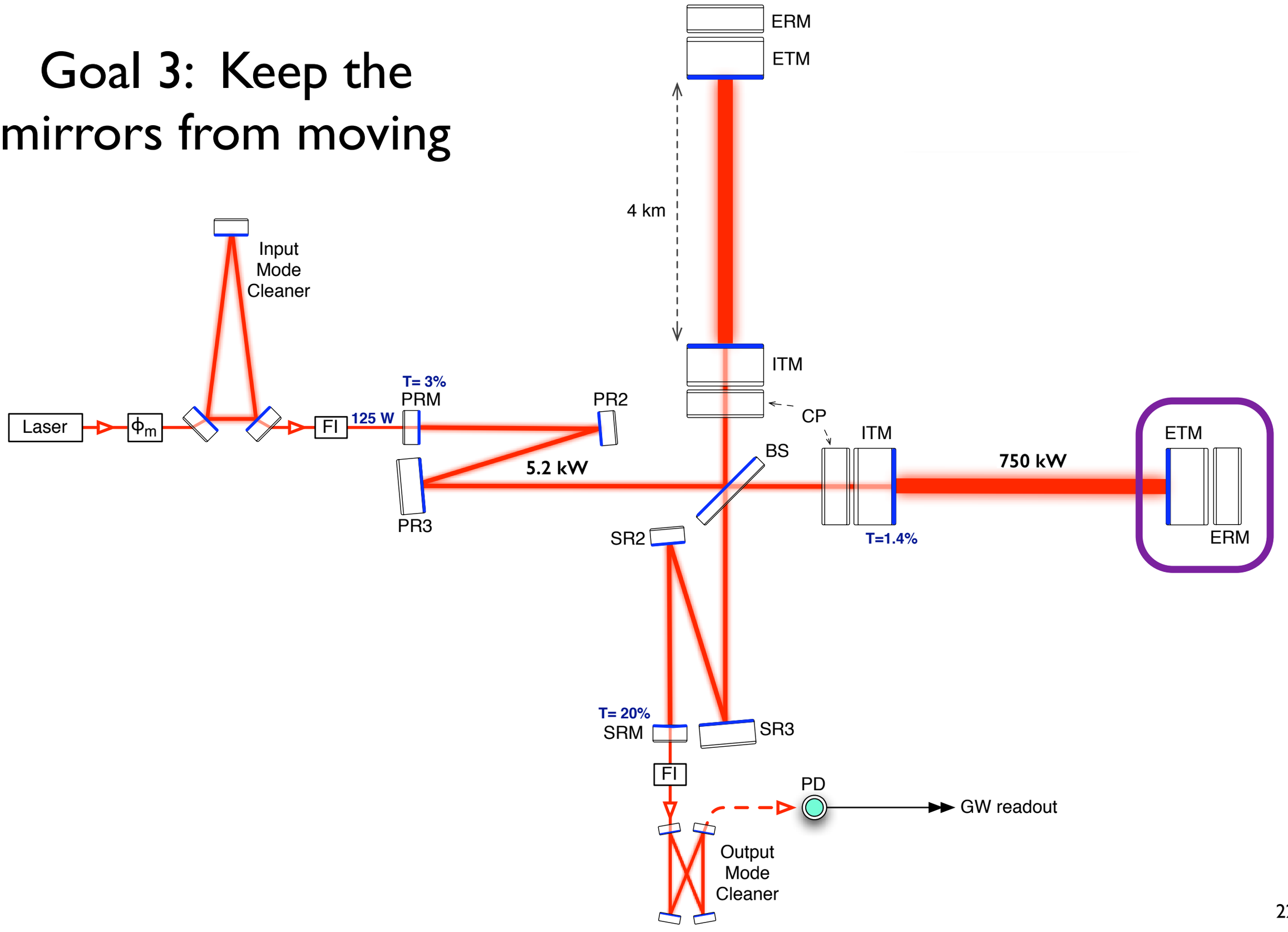
Big Scary Laser!



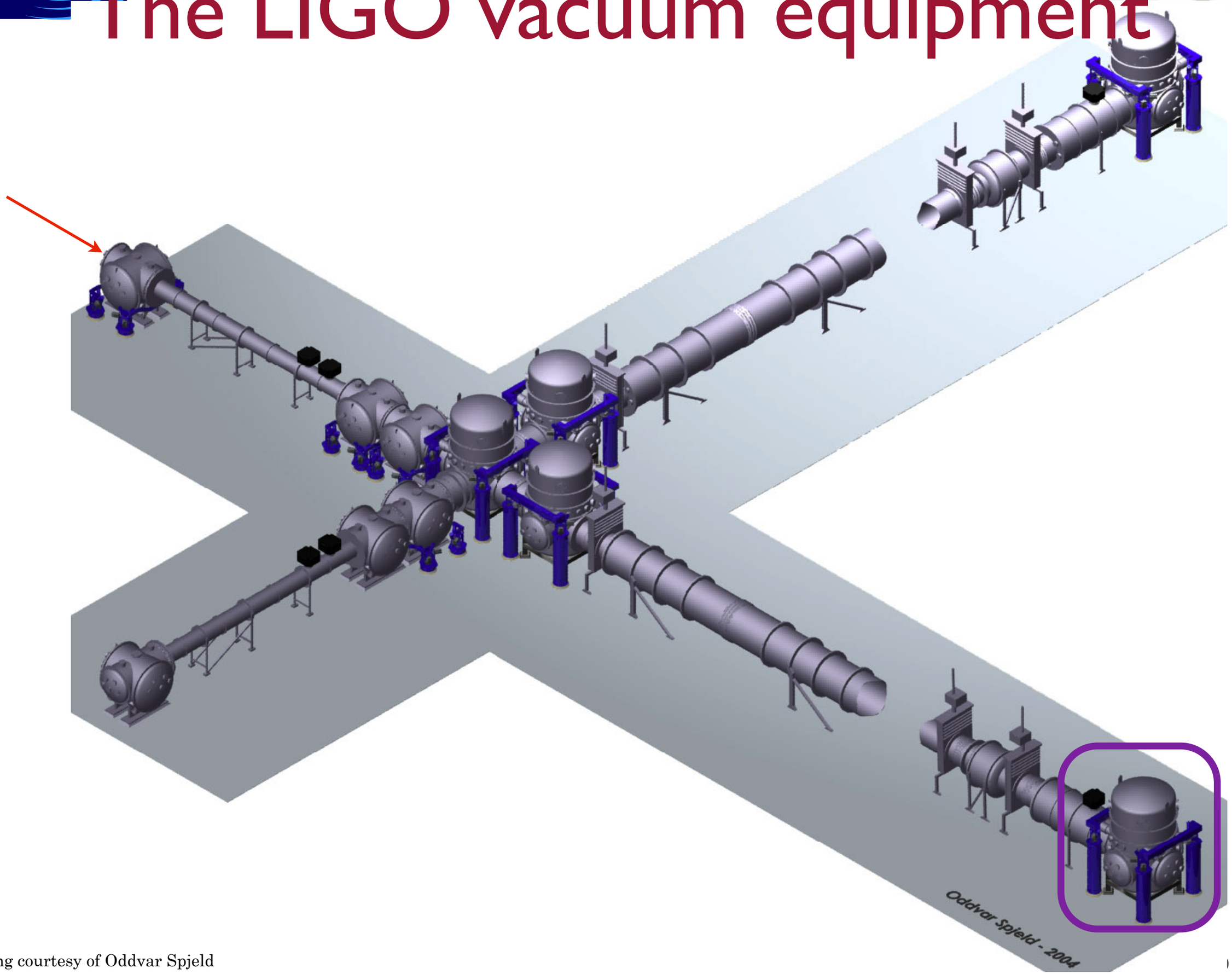


Layout of the interferometer

Goal 3: Keep the mirrors from moving

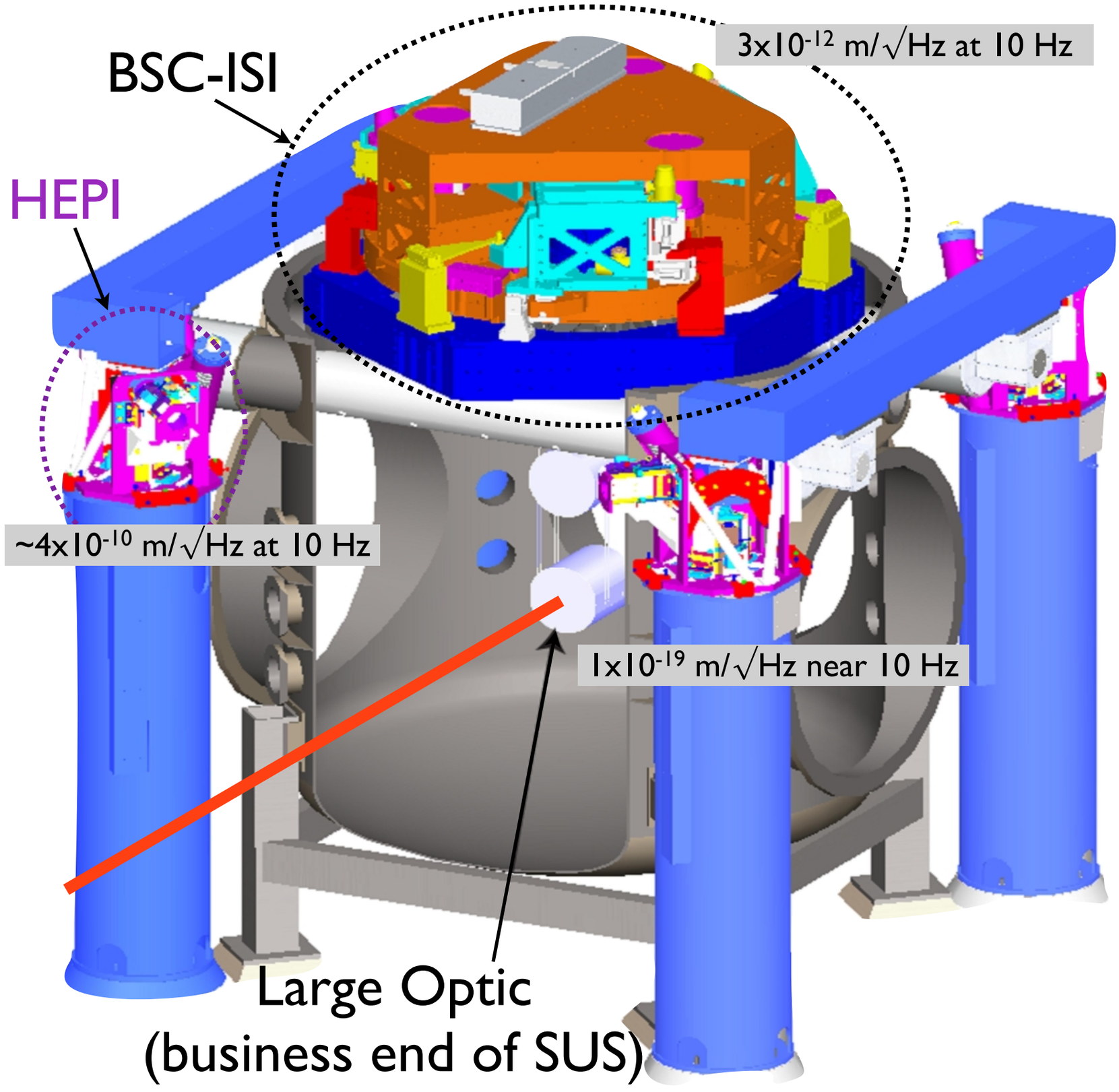


The LIGO vacuum equipment



drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses



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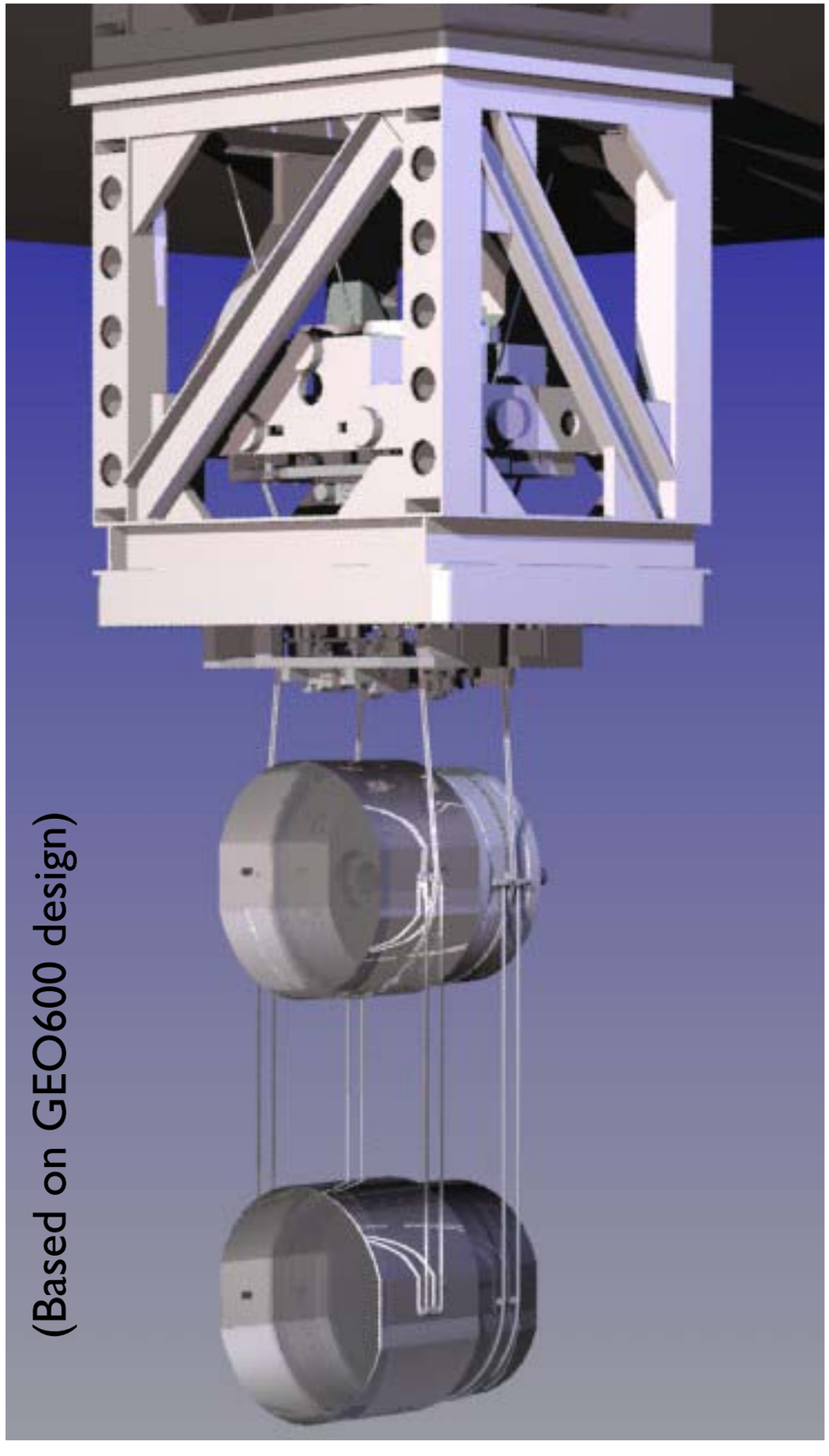
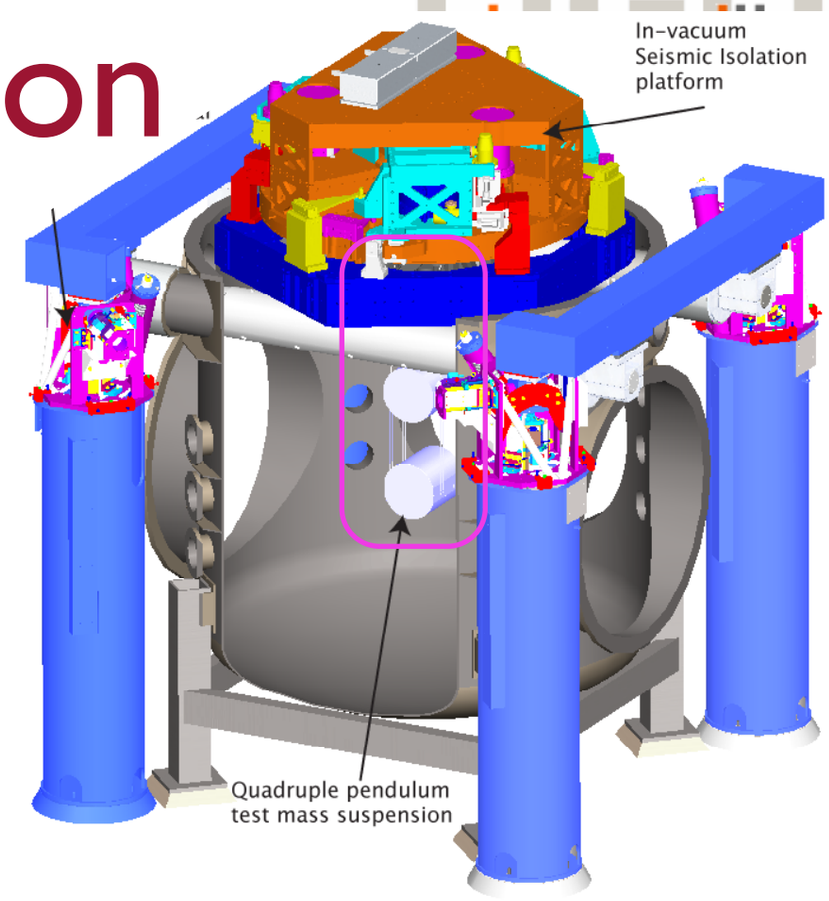
Pendulum Suspension

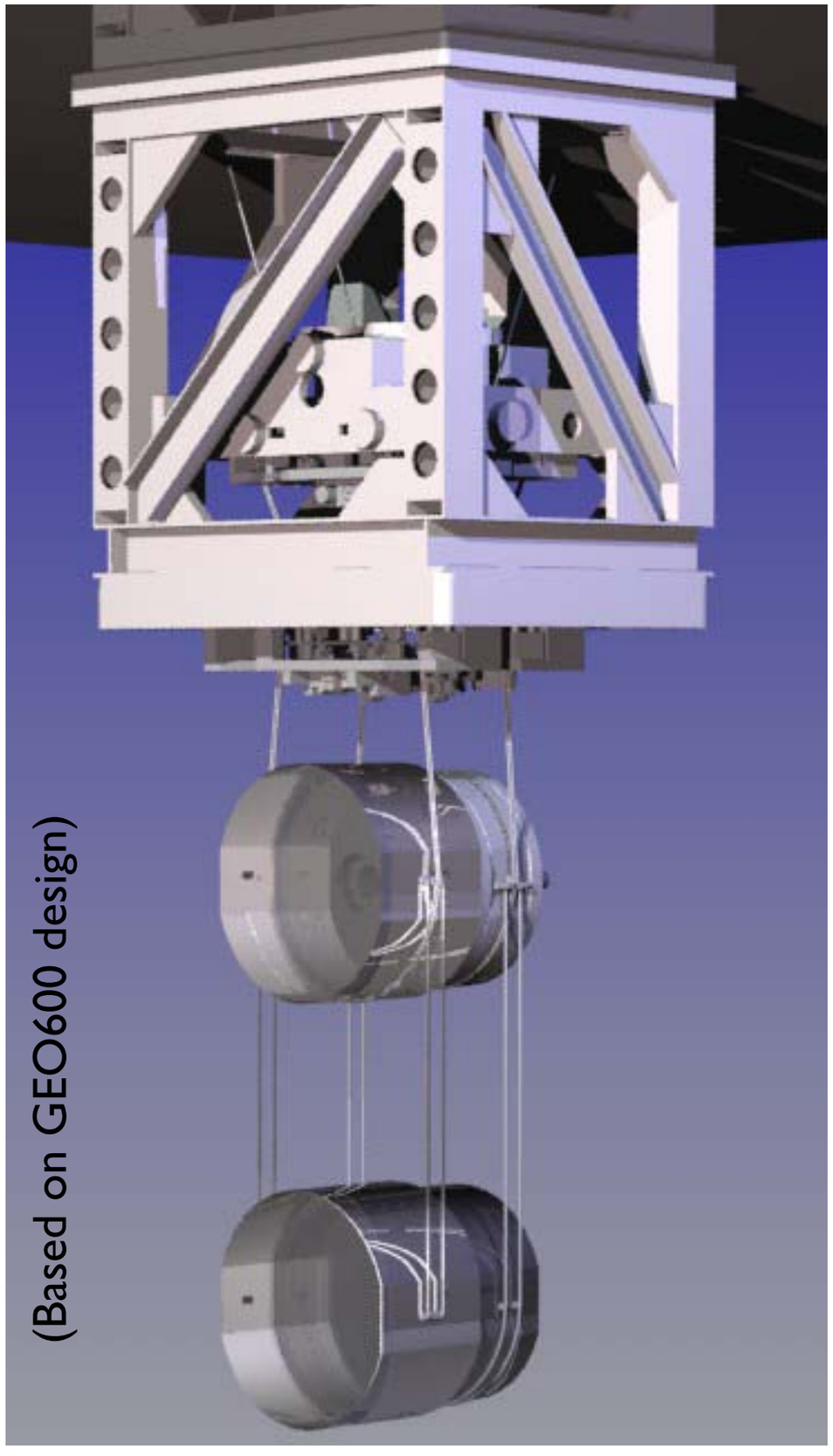


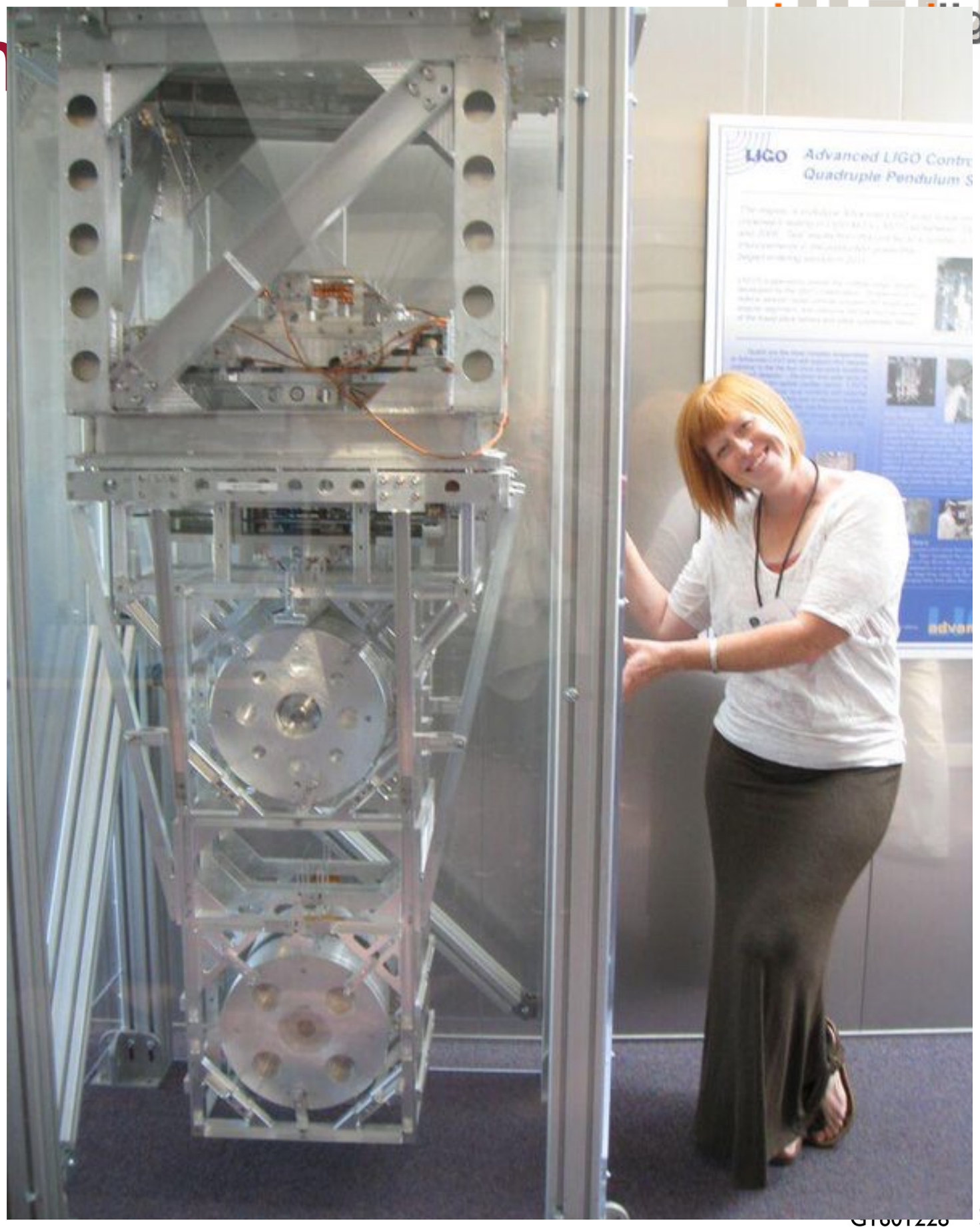
LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

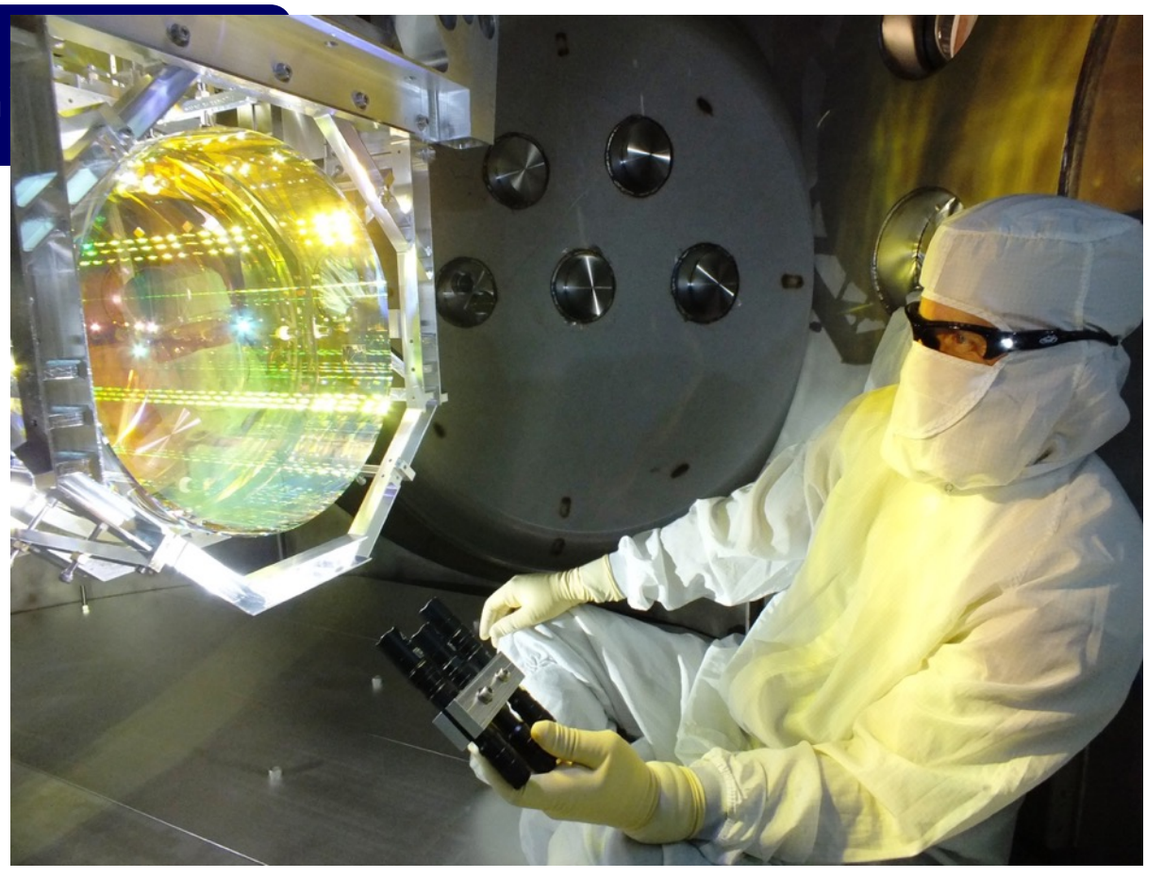
Suspended as a
4 stage pendulum

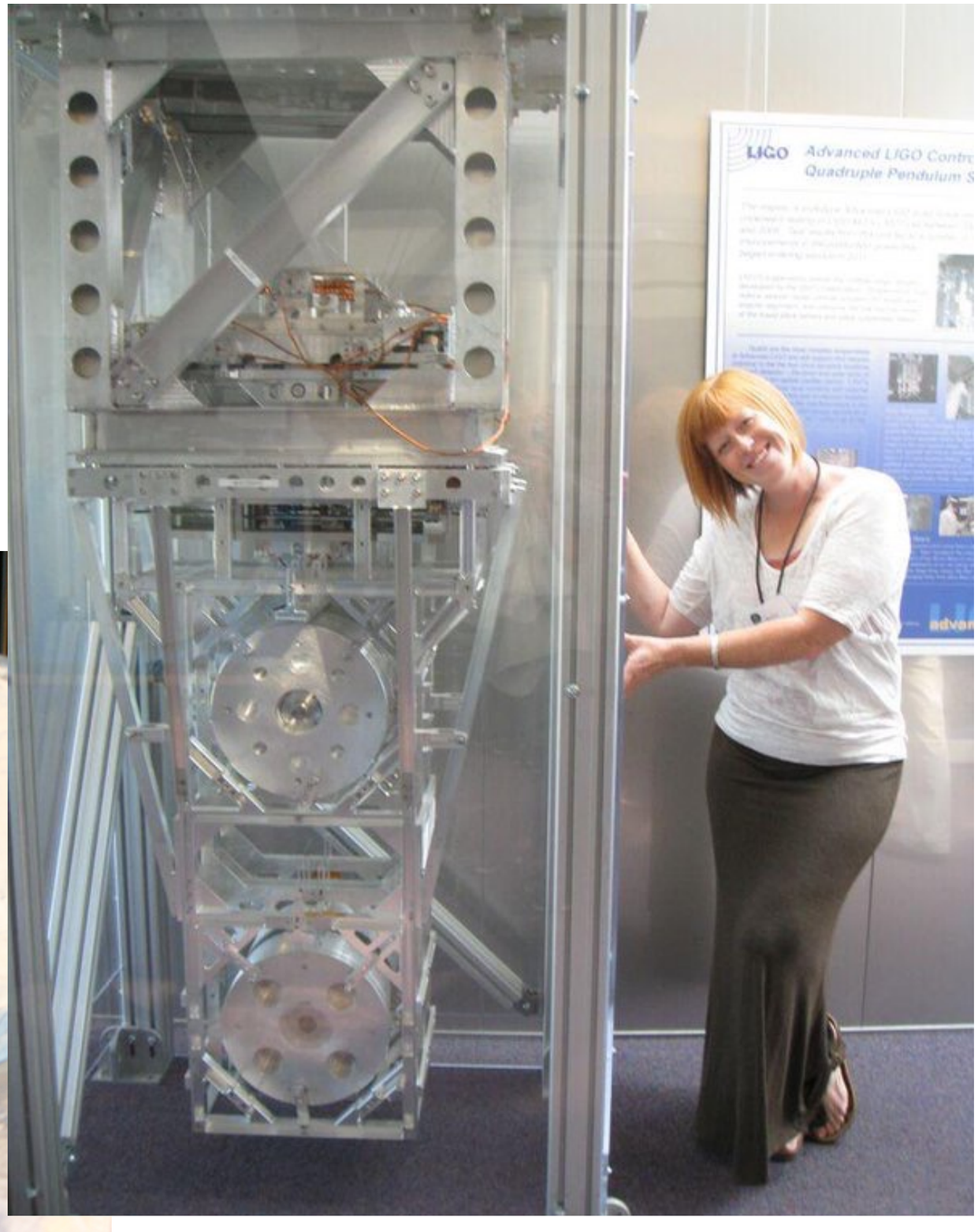


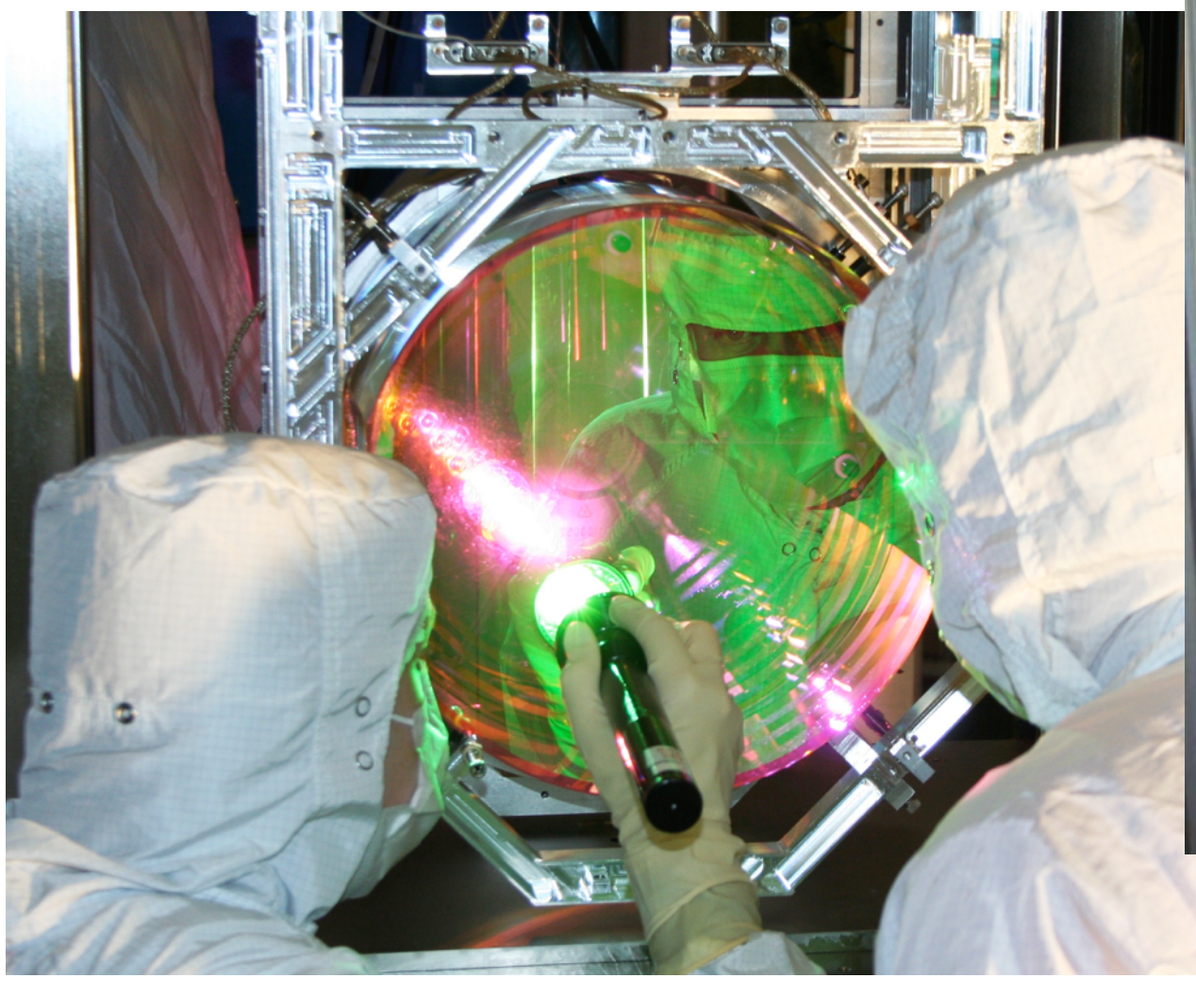
Pendulum


(Based on GEO600 design)

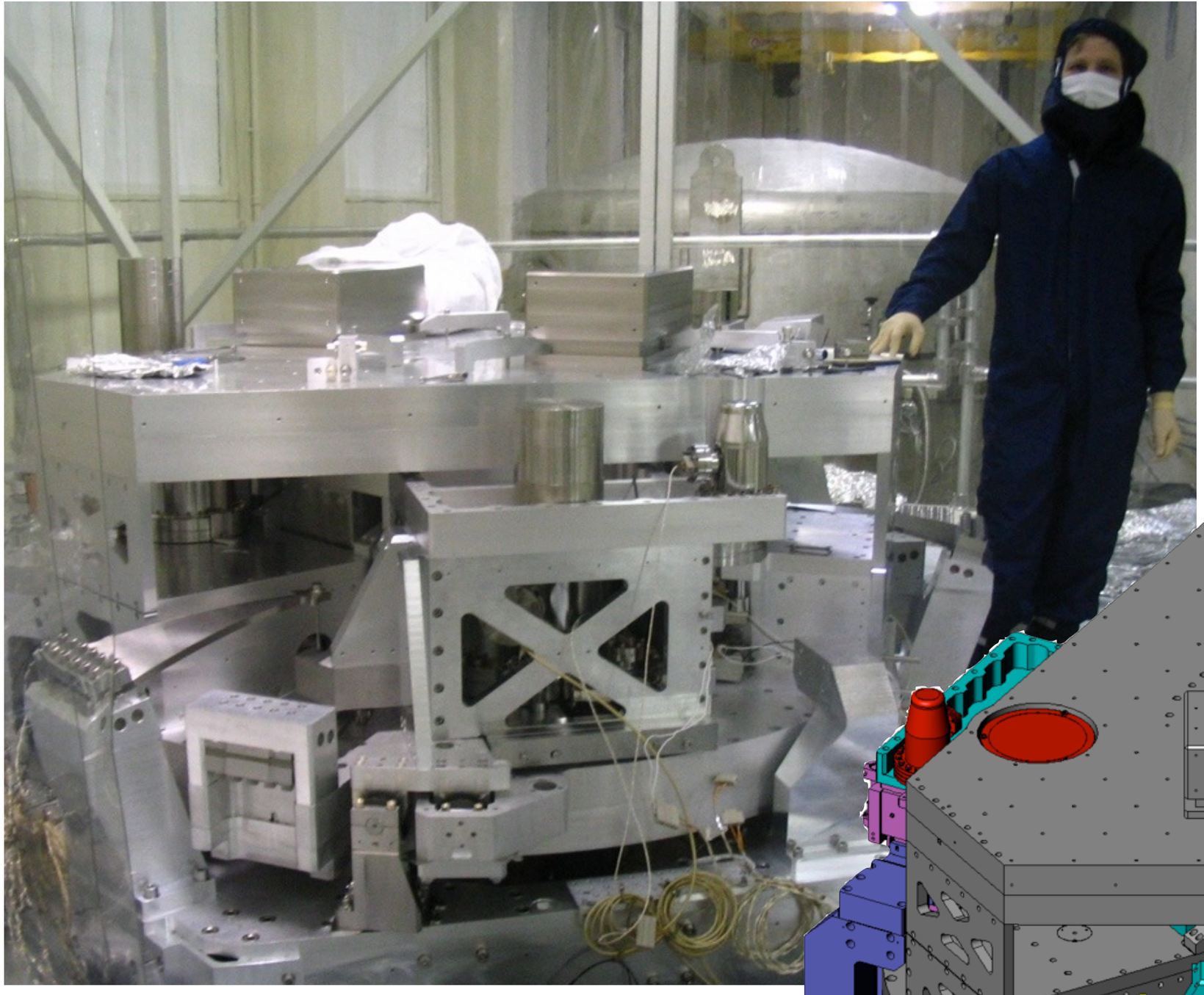

LIGO
Advanced LIGO Contr
Quadruple Pendulum S

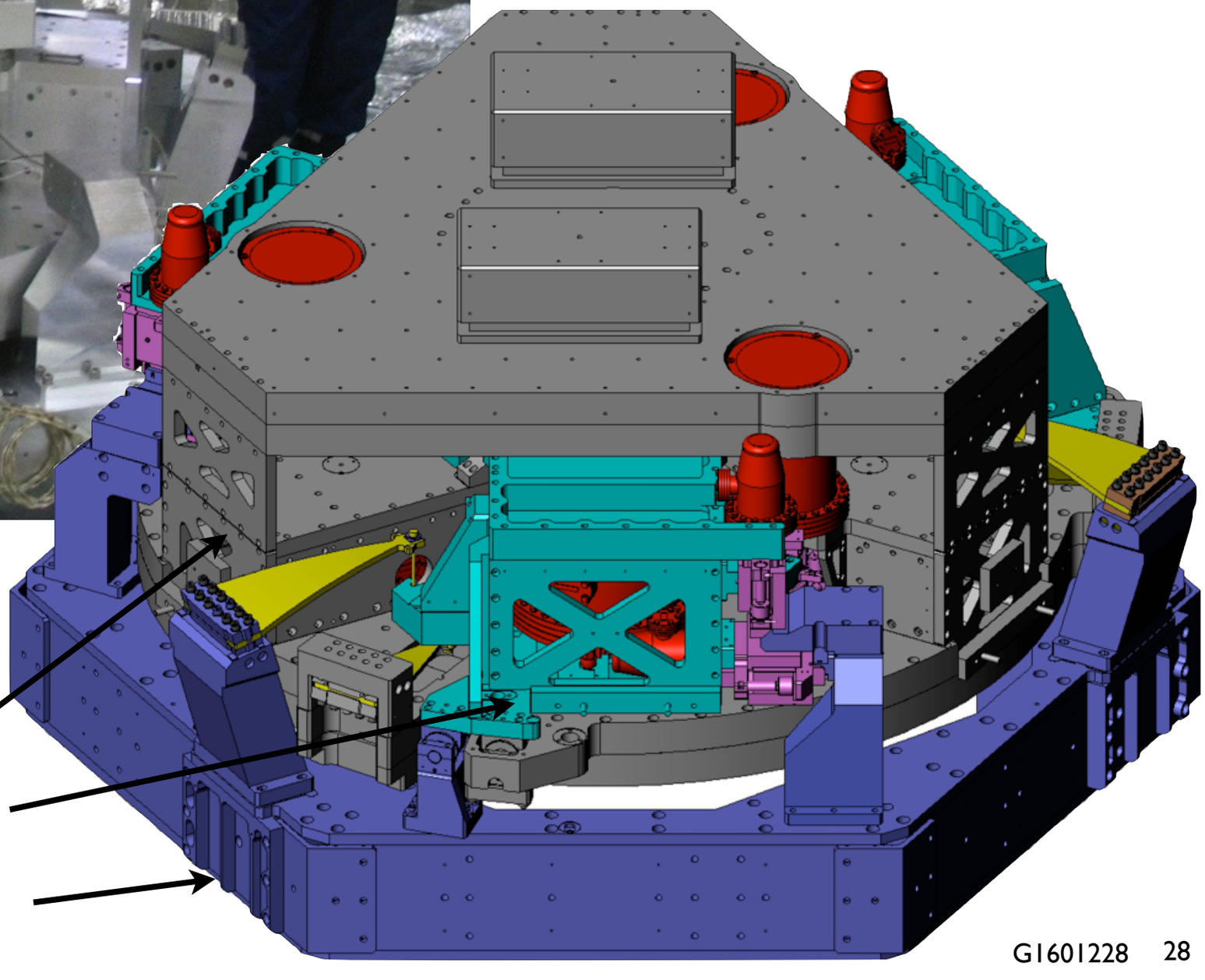



LIGO
Advanced LIGO Contr
Quadruple Pendulum S



Optical Table

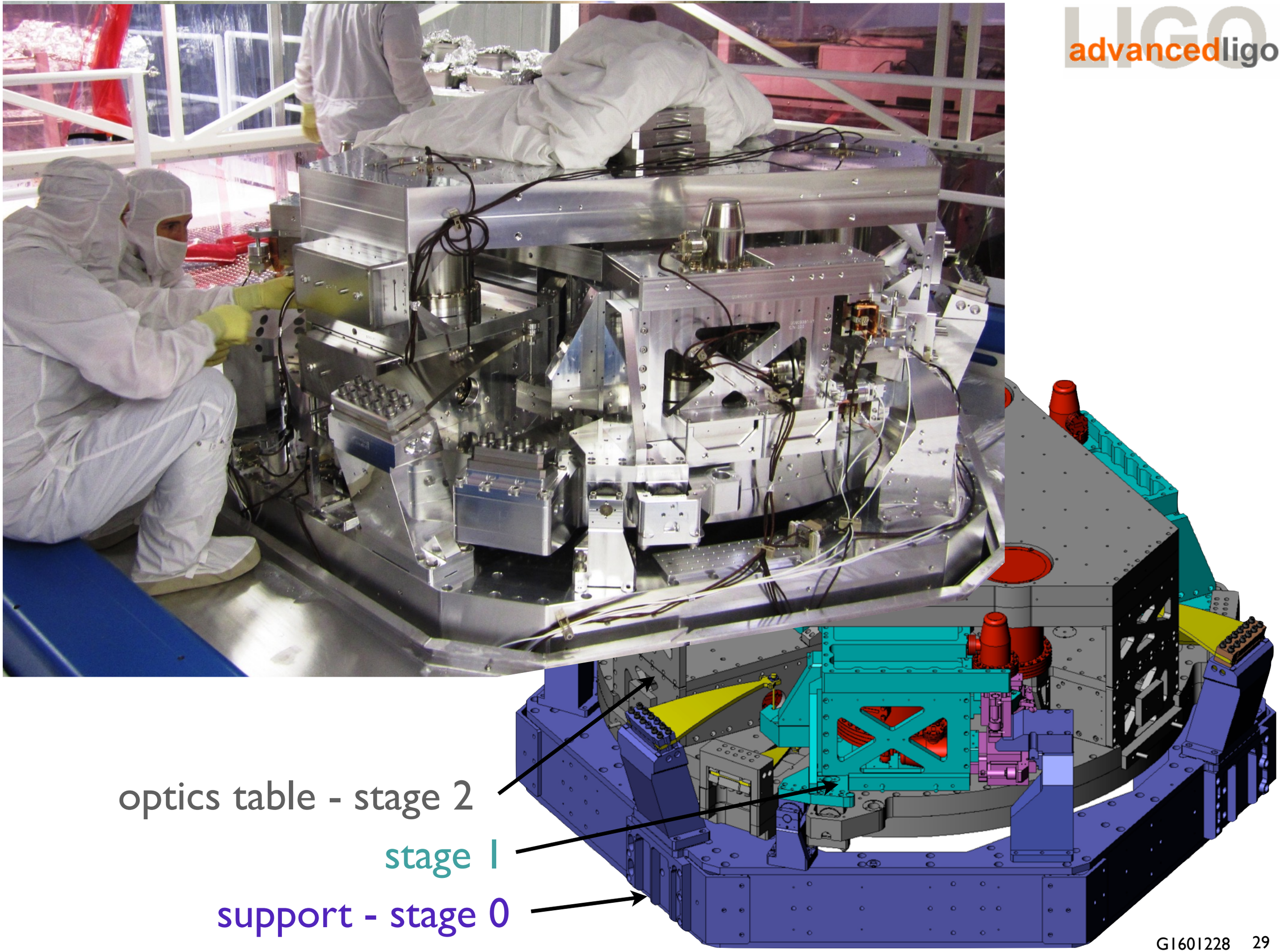




optics table - stage 2

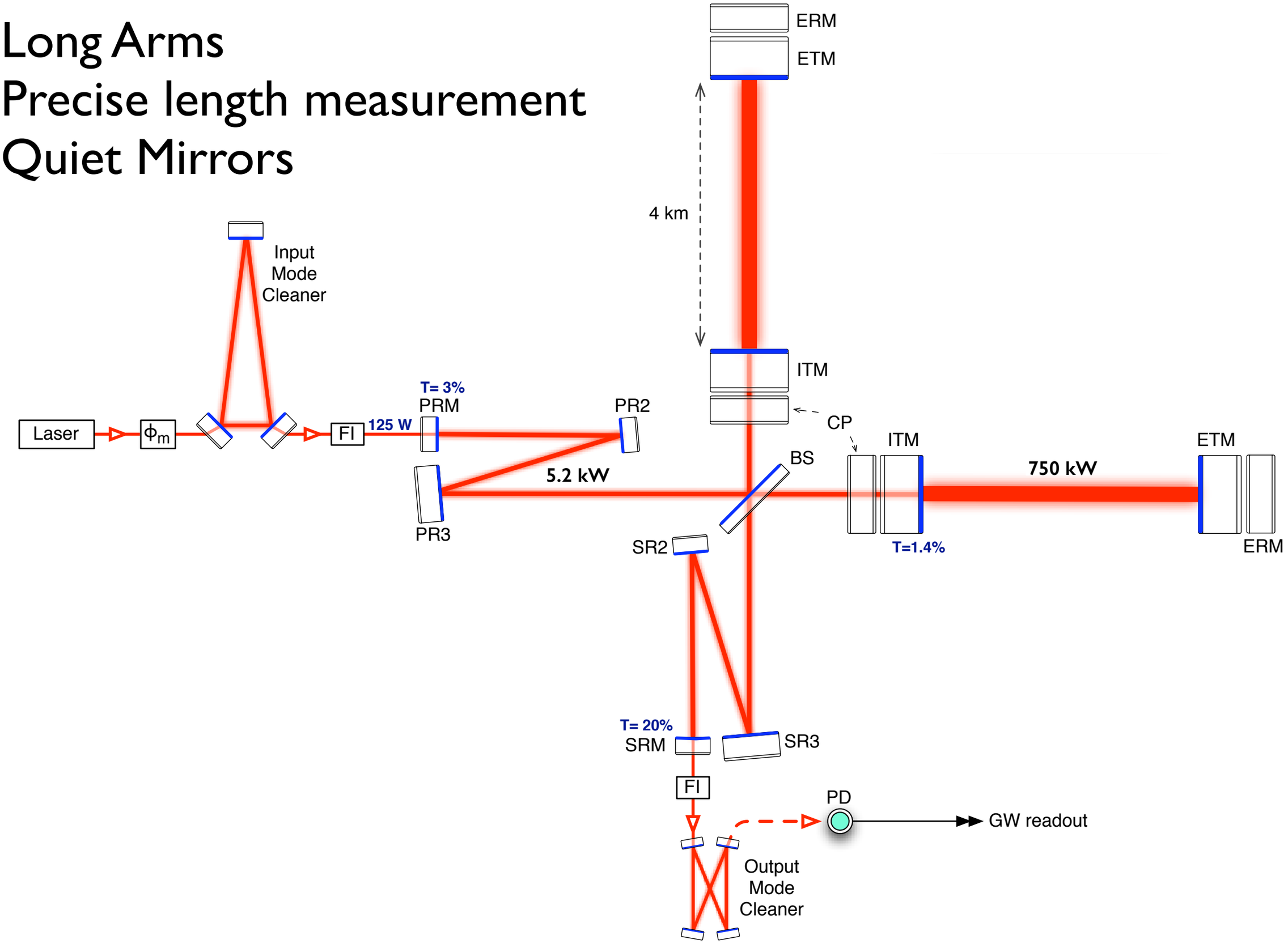
stage 1

support - stage 0

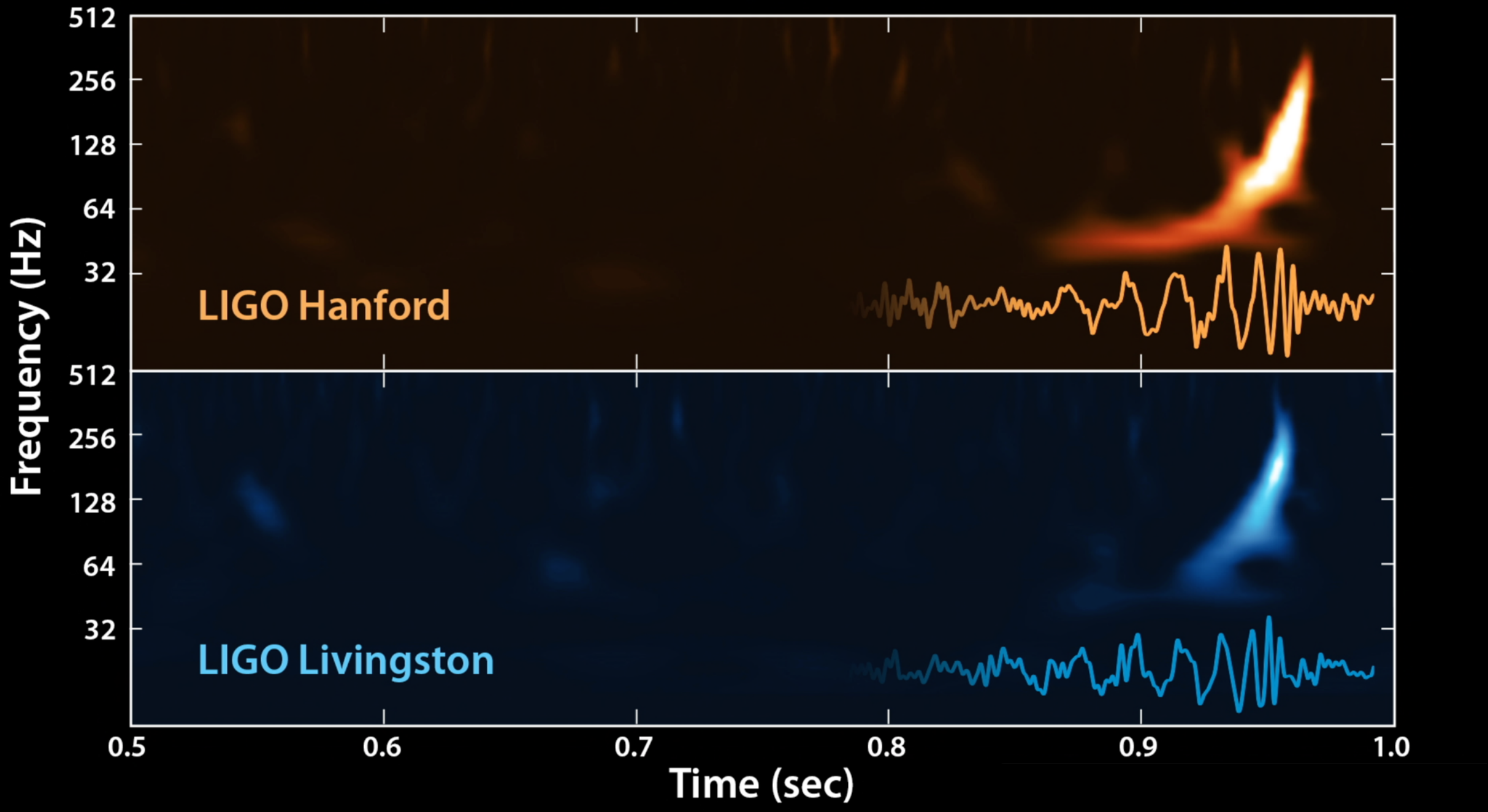

optics table - stage 2
stage 1
support - stage 0

Now we are ready…

1) Long Arms
2) Precise length measurement
3) Quiet Mirrors

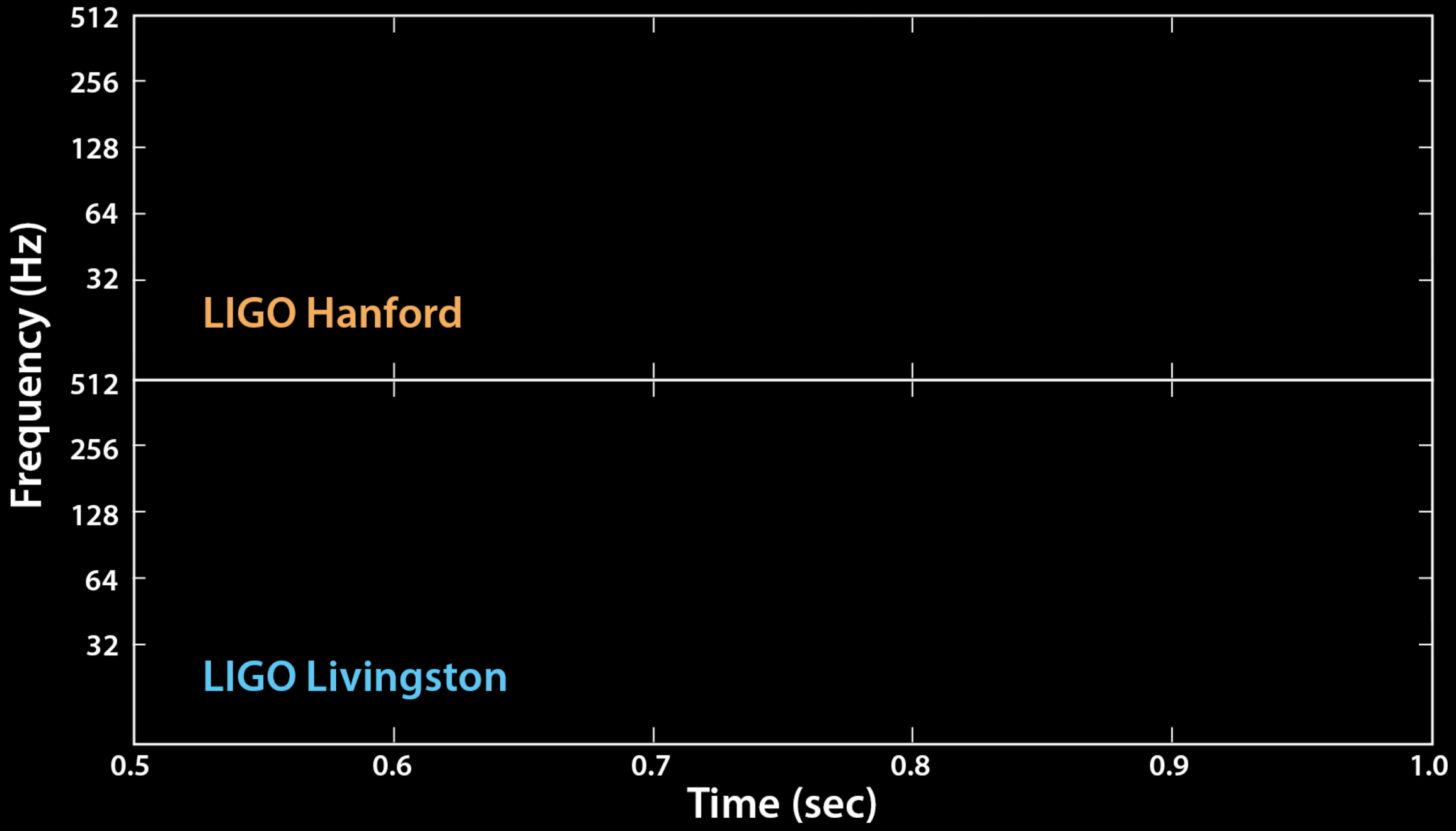


The sound of black holes colliding



http://mediaassets.caltech.edu/gwave

The sound of black holes colliding



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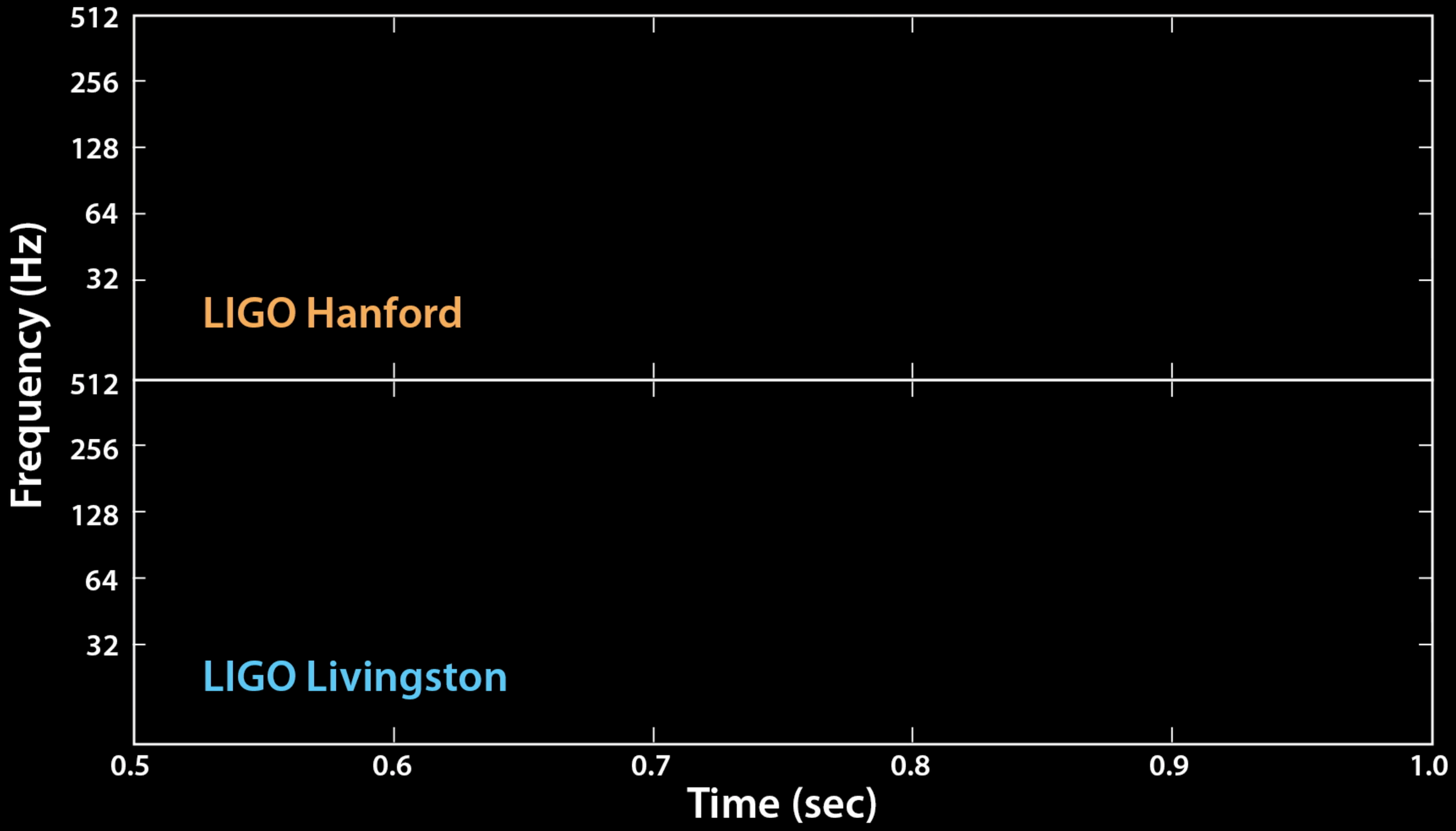

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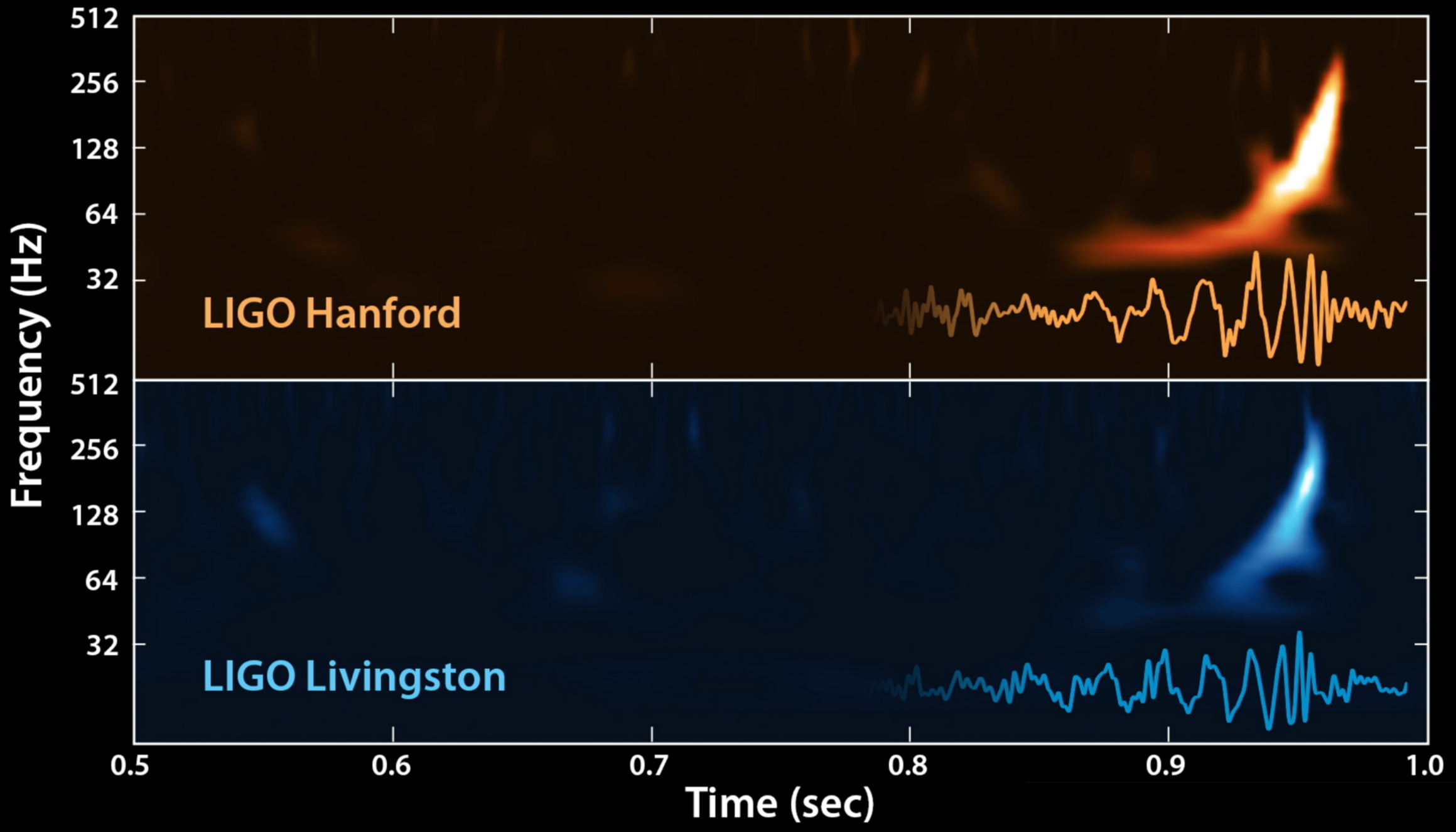
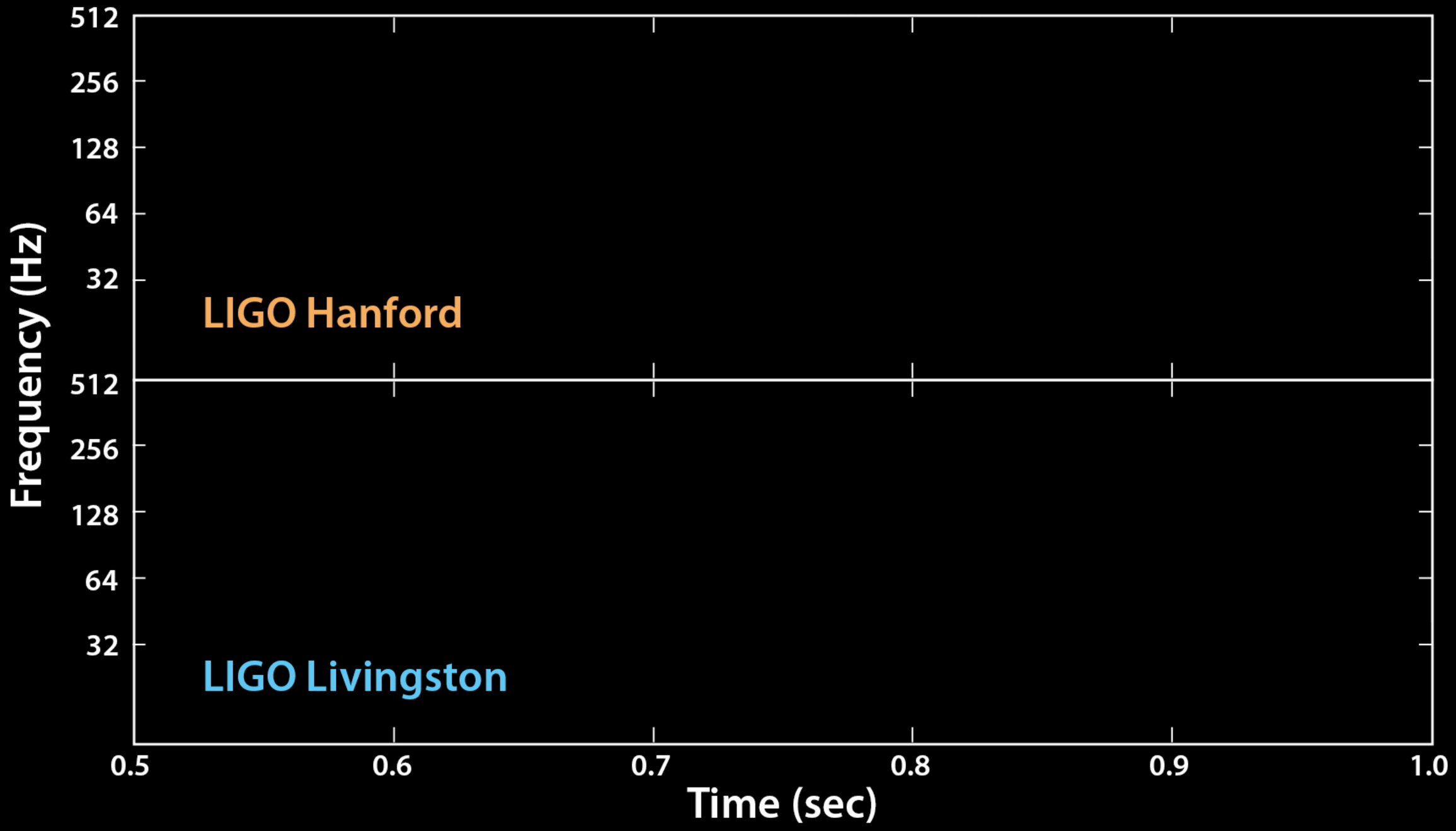


The sound of black holes colliding



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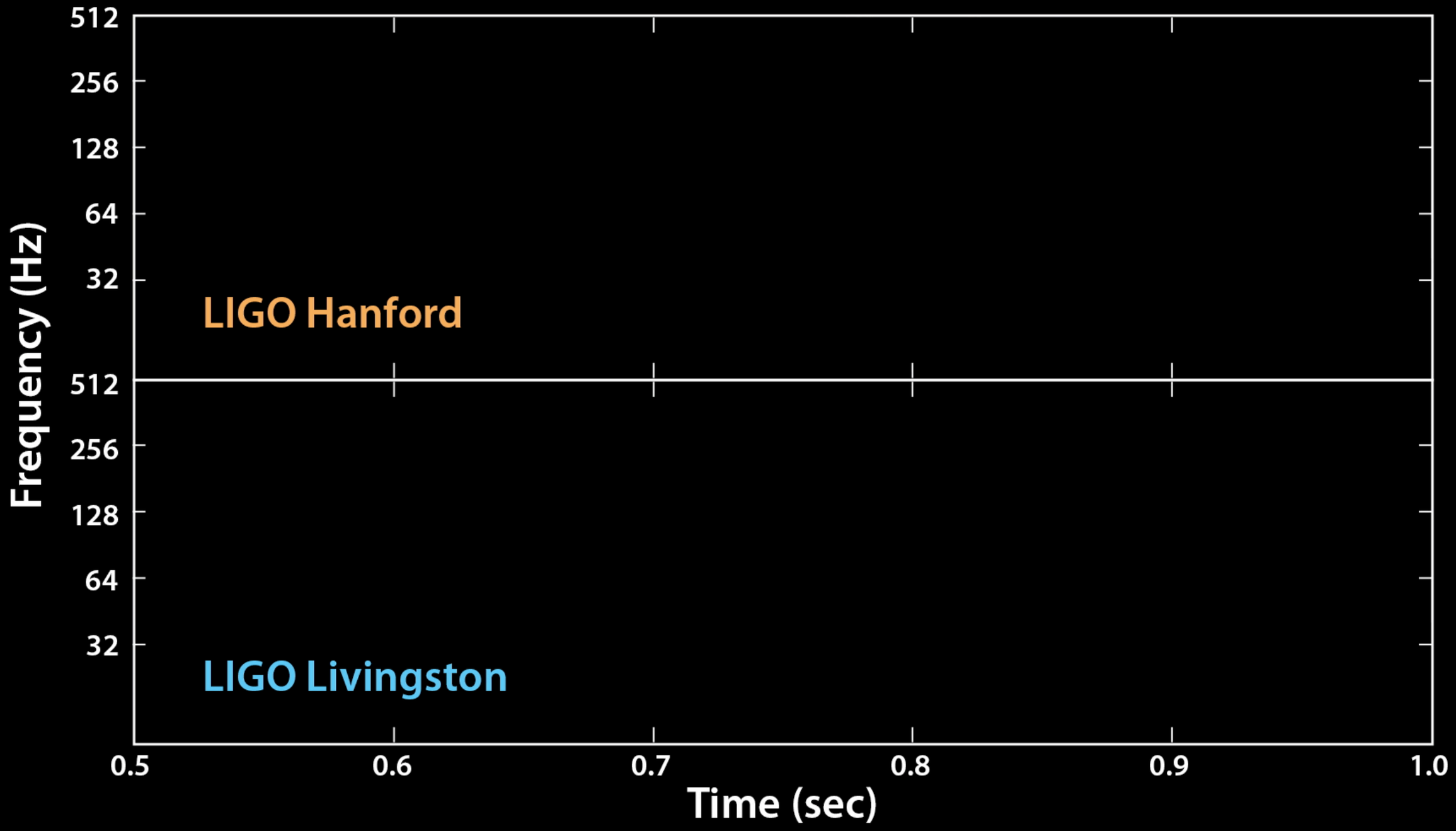


Best fit with Numerical Relativity

Initial Masses:

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

Final Mass:

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

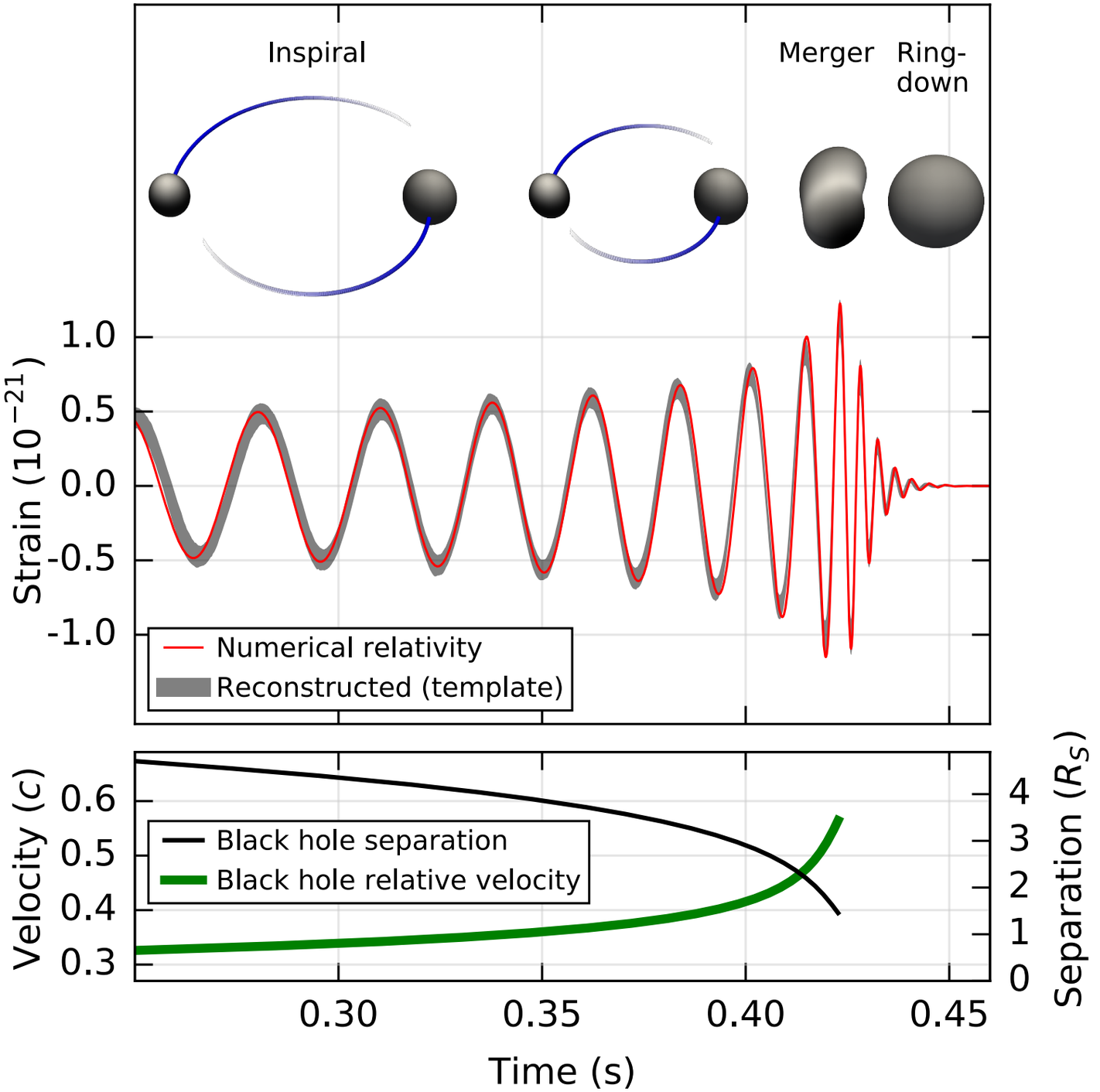
Energy radiated

3 (+0.5/-0.5) M_{sun} c^2

Distance

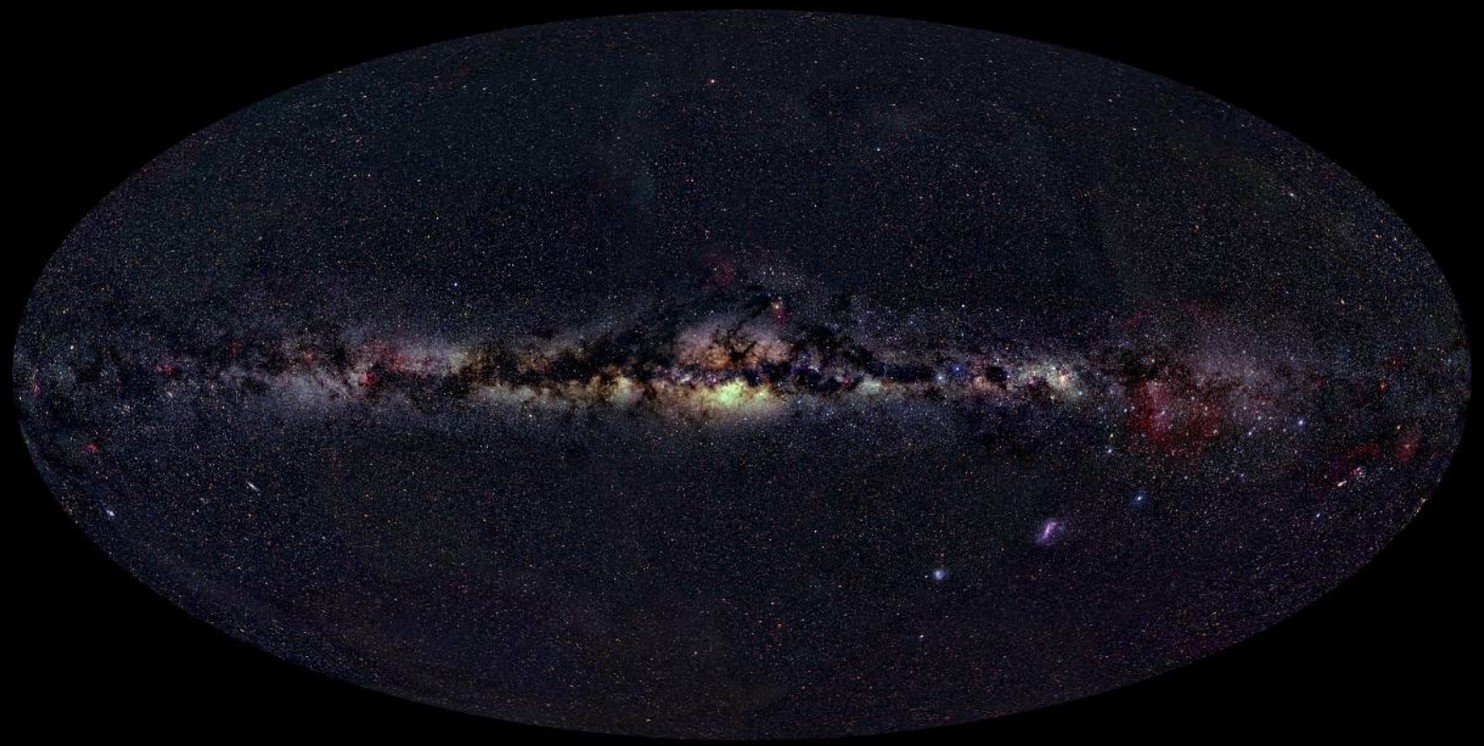
410 (+160/-180) MPc

(1.3 Billion light years)

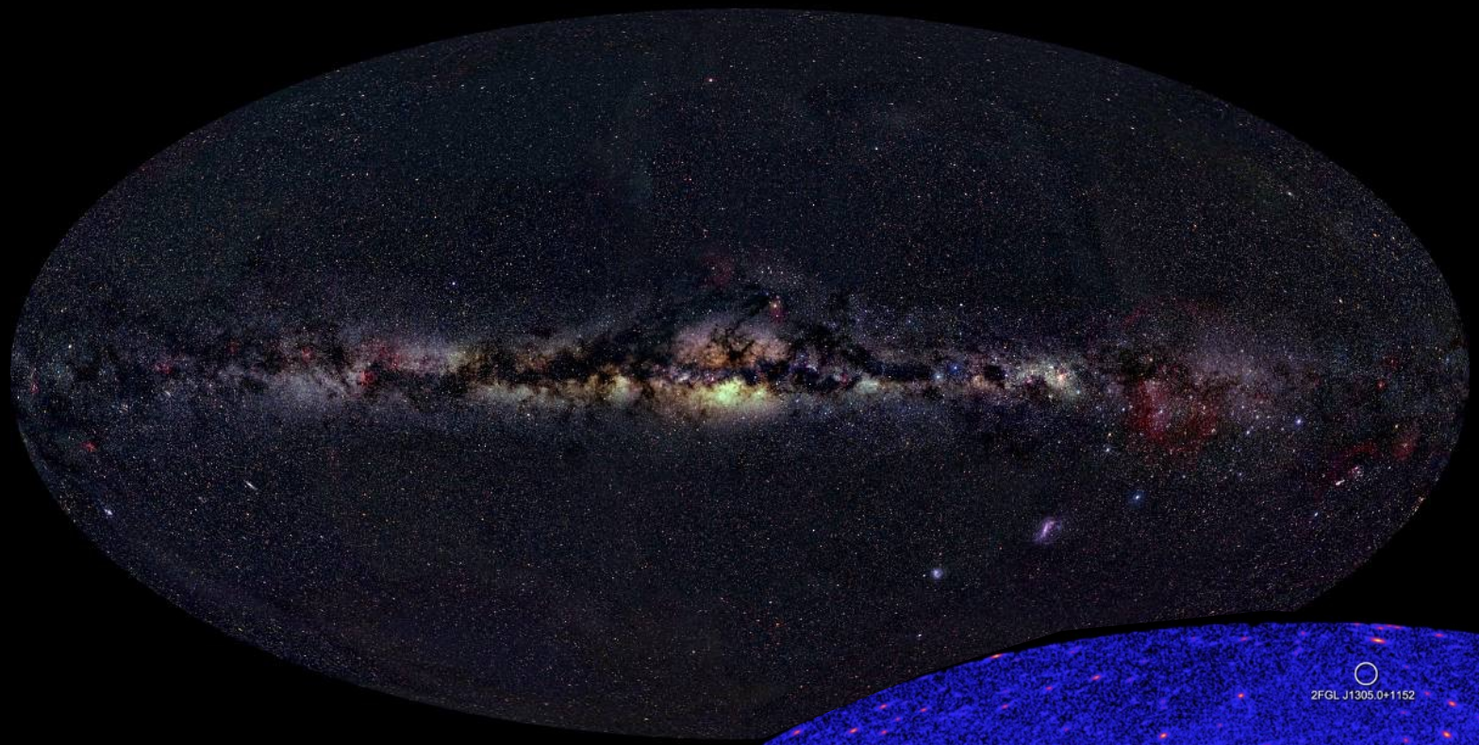


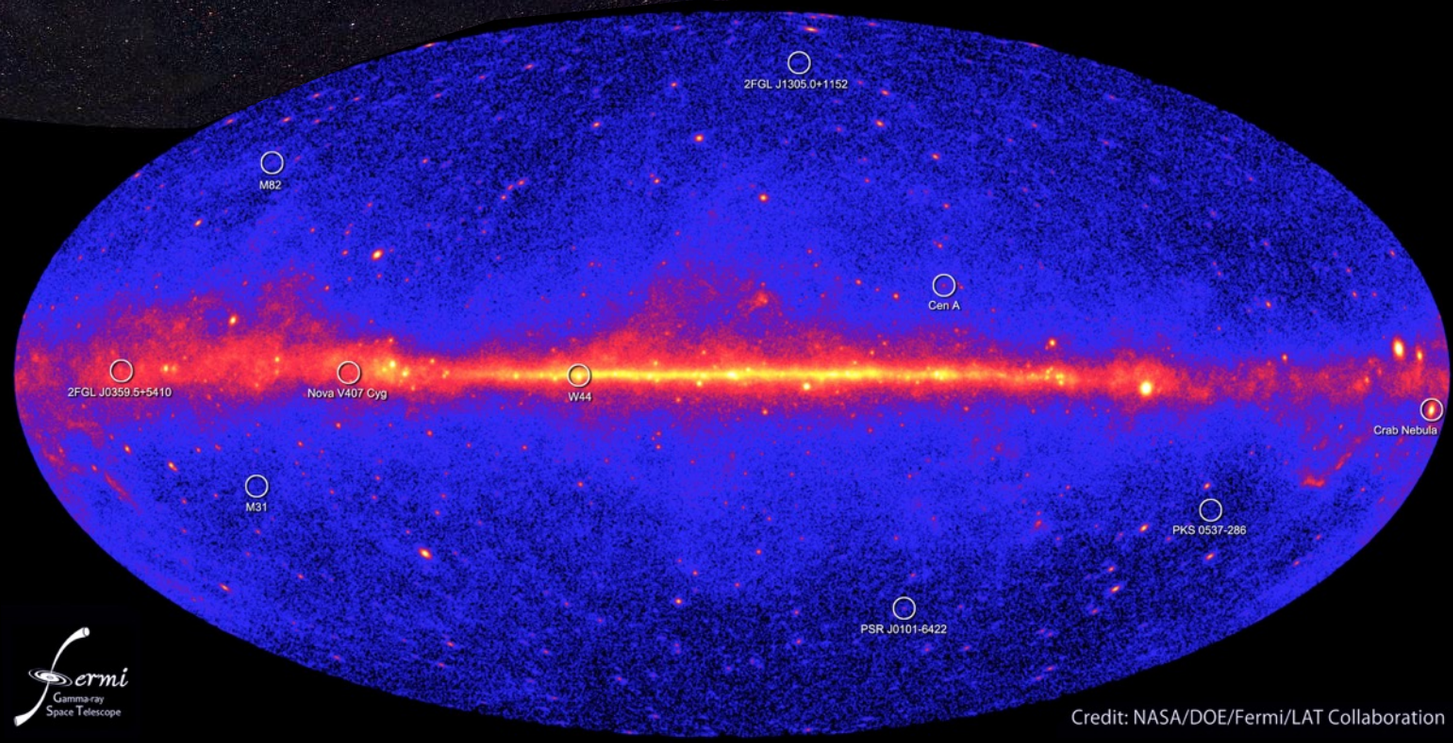
http://dx.doi.org/10.1103/PhysRevLett.116.061102

new ways to see the sky



new ways to see the sky

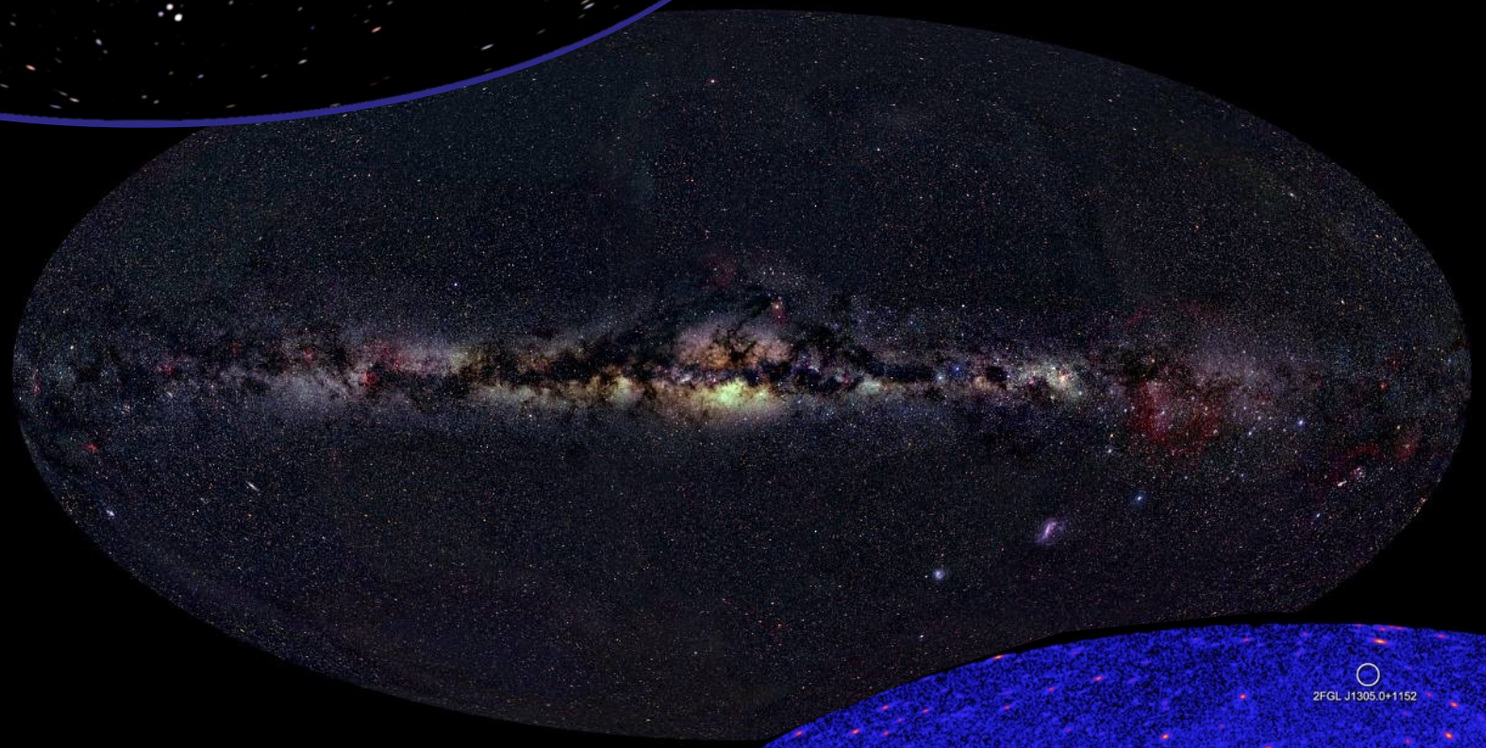


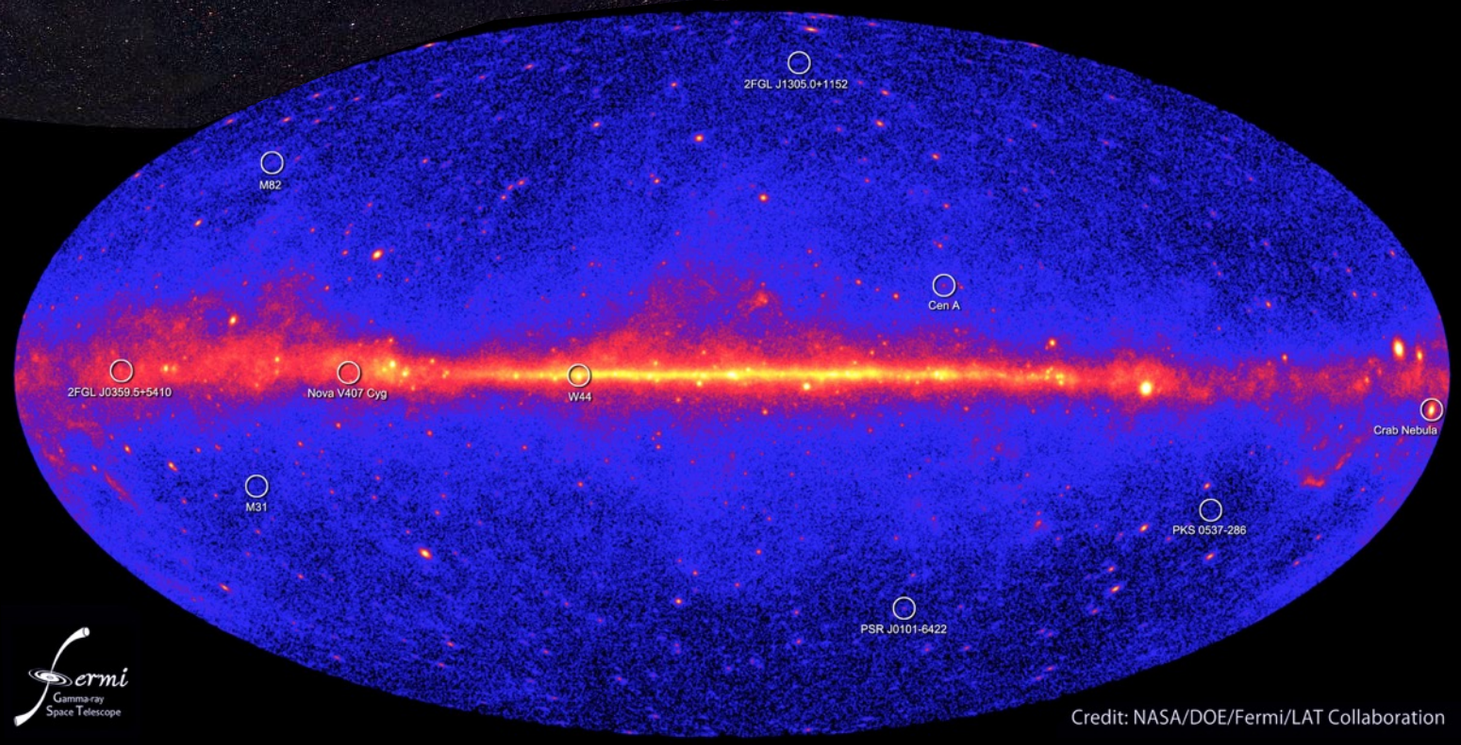


Credit: NASA/DOE/Fermi/LAT Collaboration

see the sky

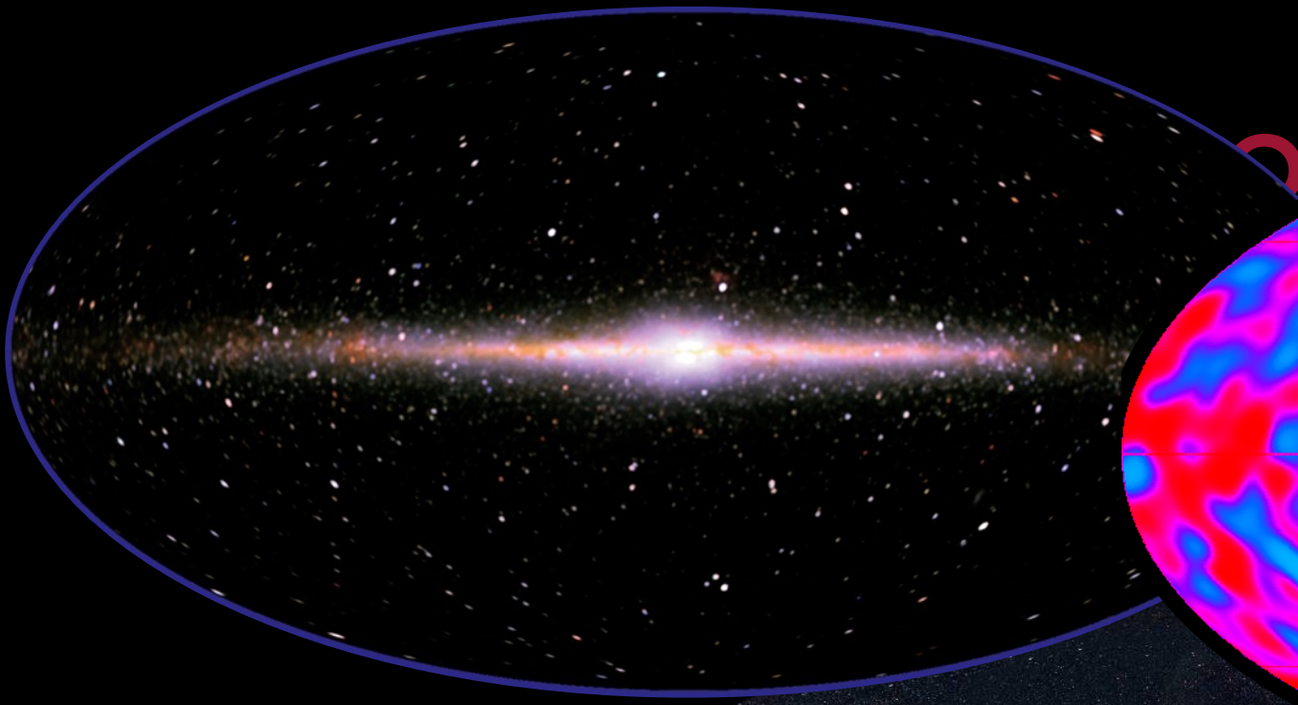
ep Sky

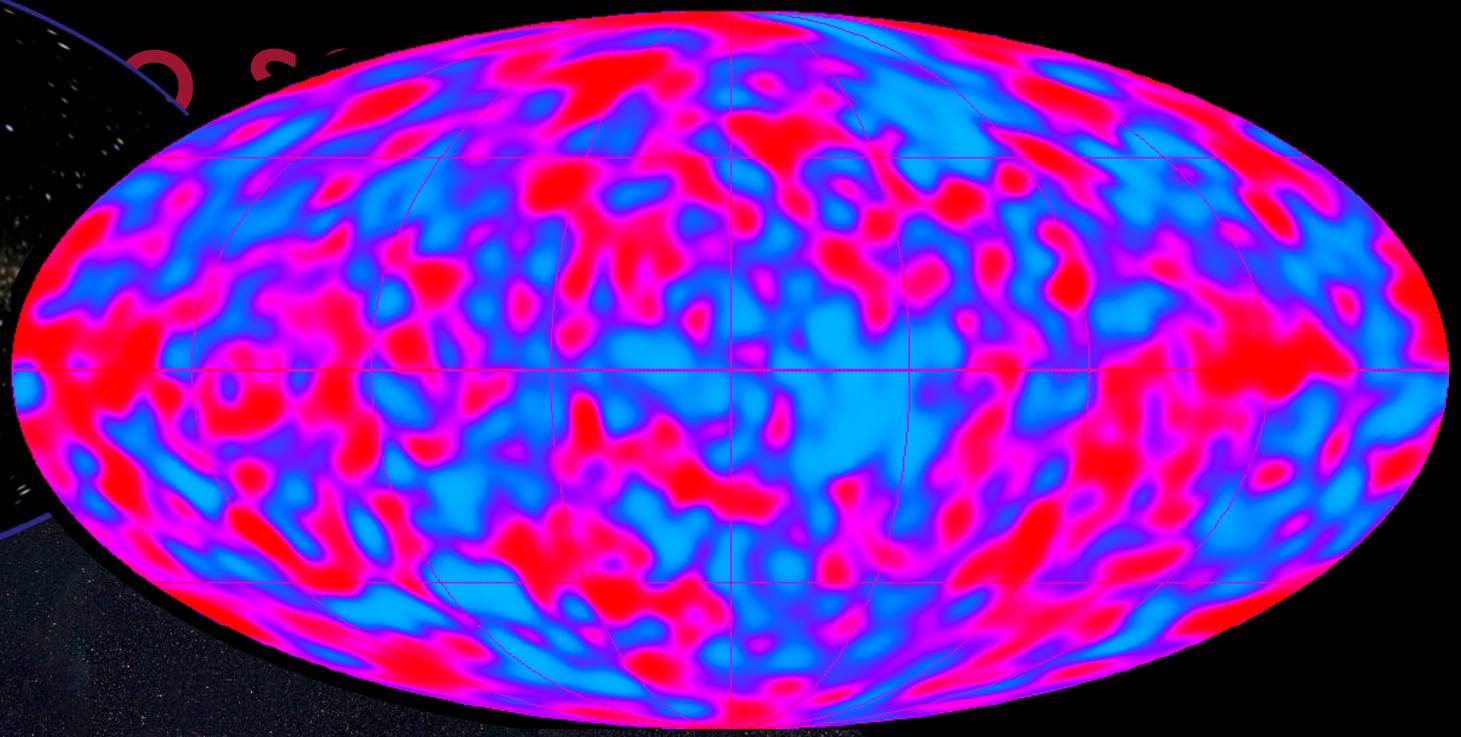


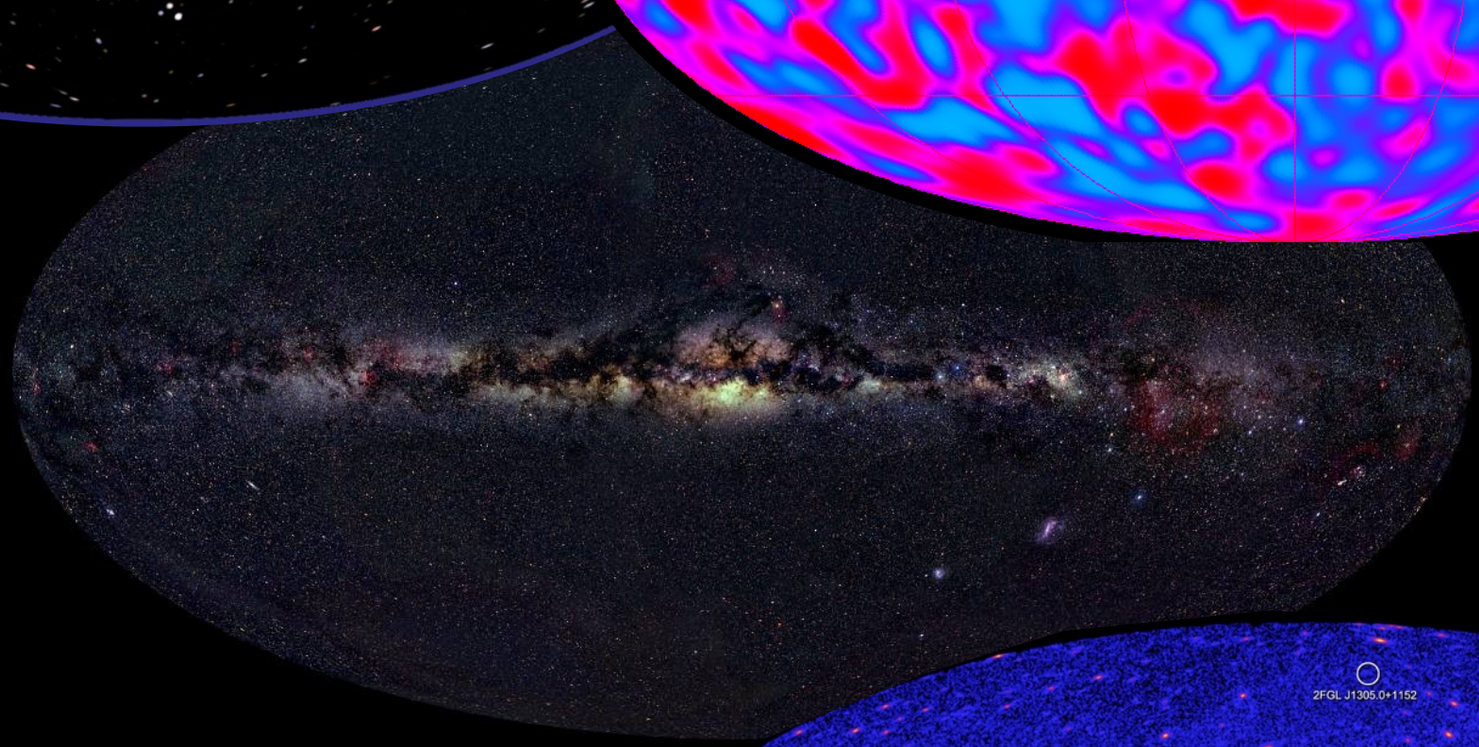


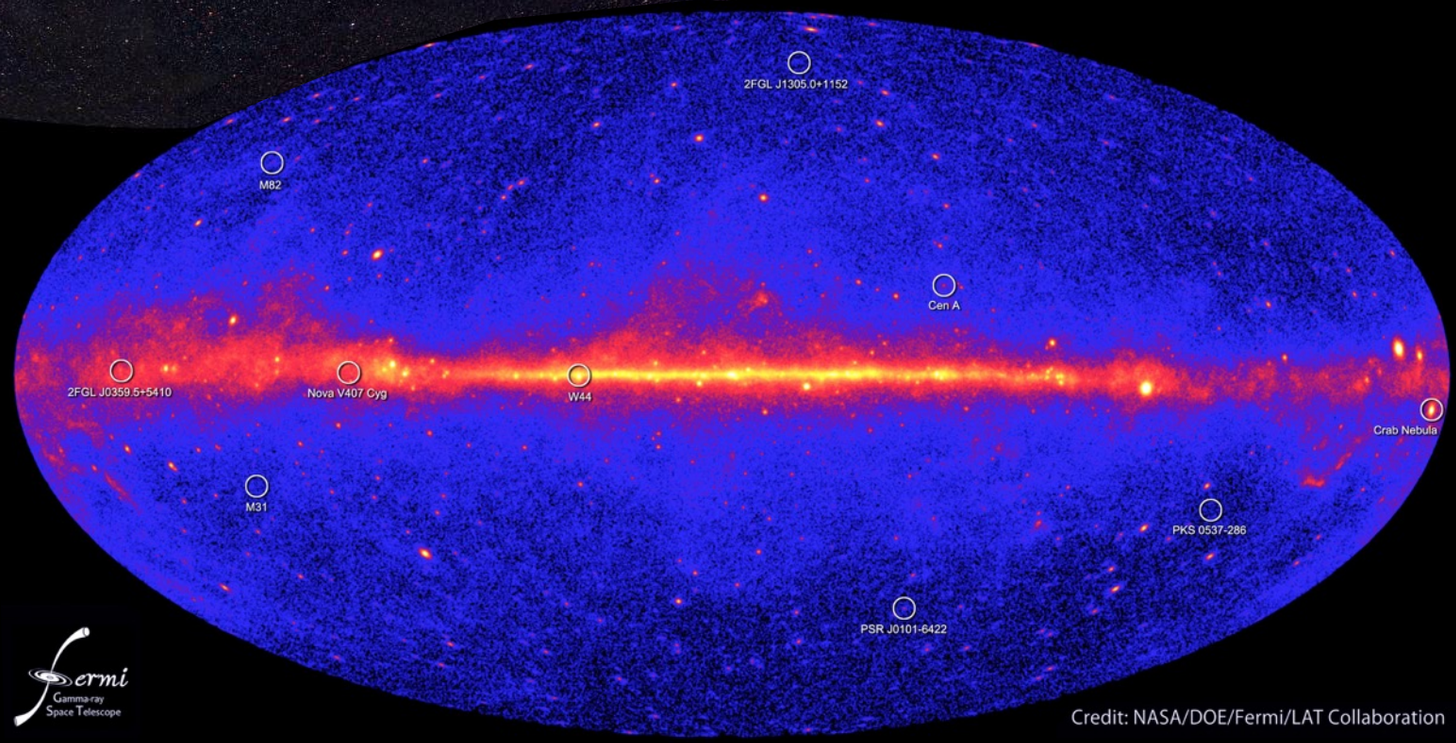
Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration





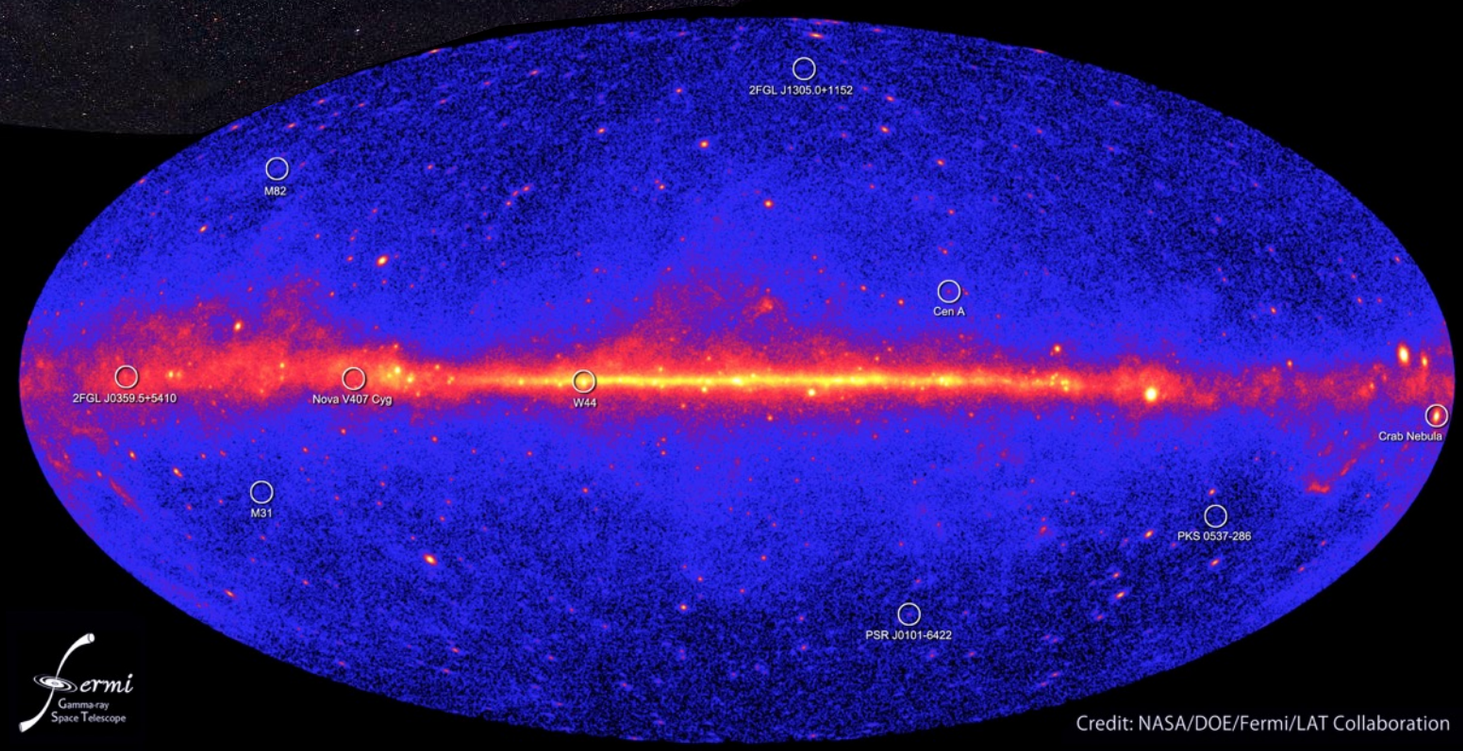




Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

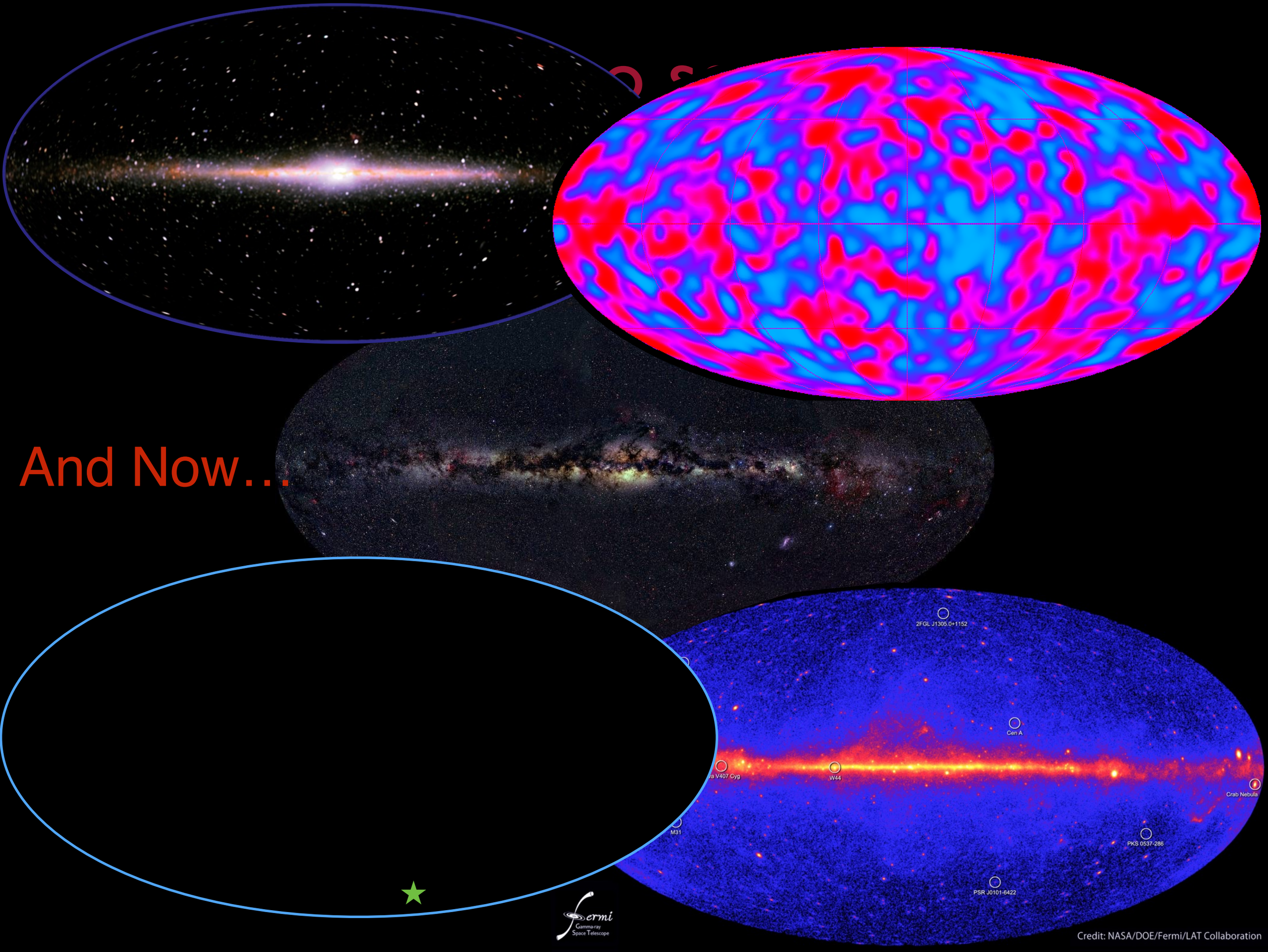
And Now…



Fermi Gamma-ray Space Telescope

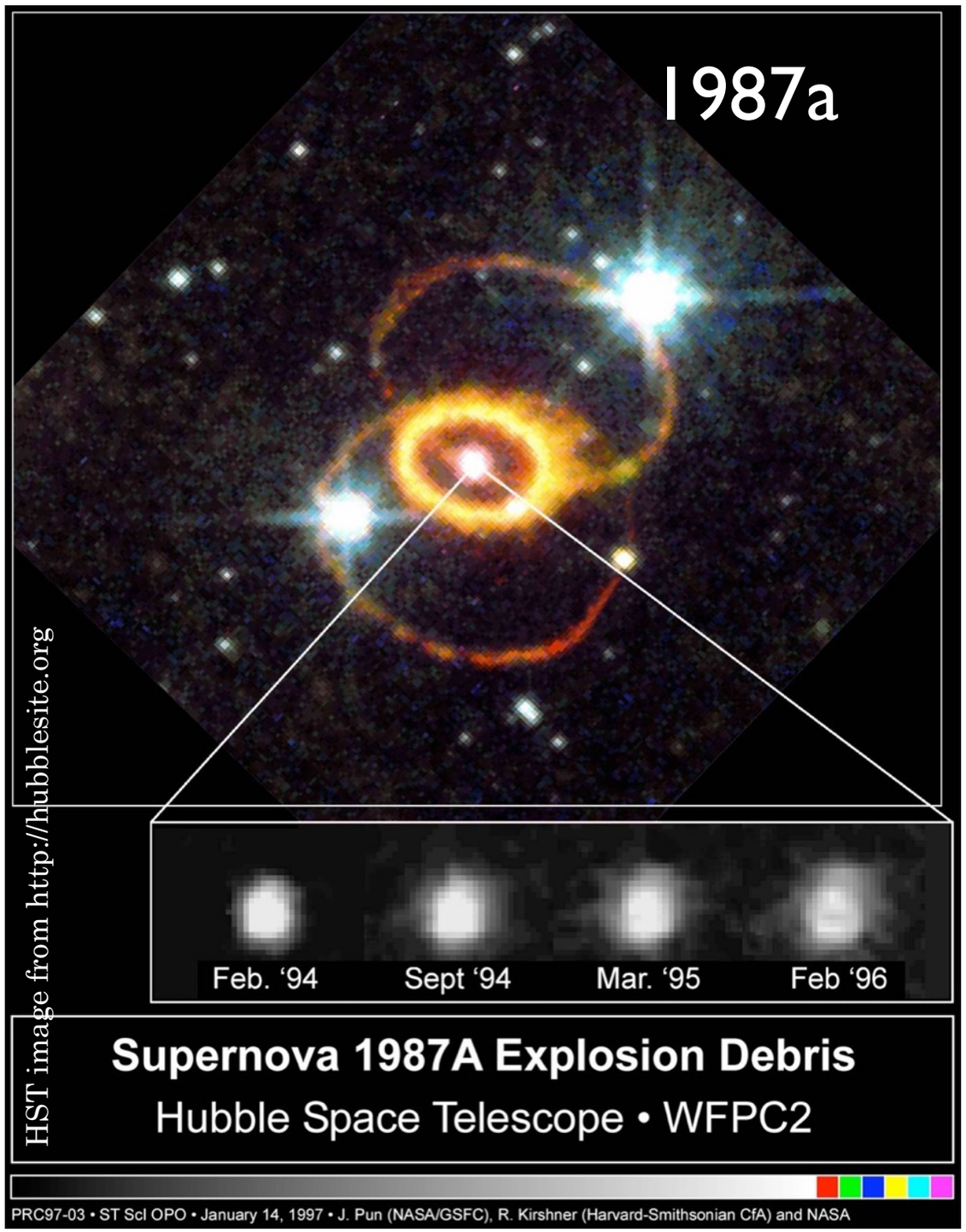
Credit: NASA/DOE/Fermi/LAT Collaboration

And Now…

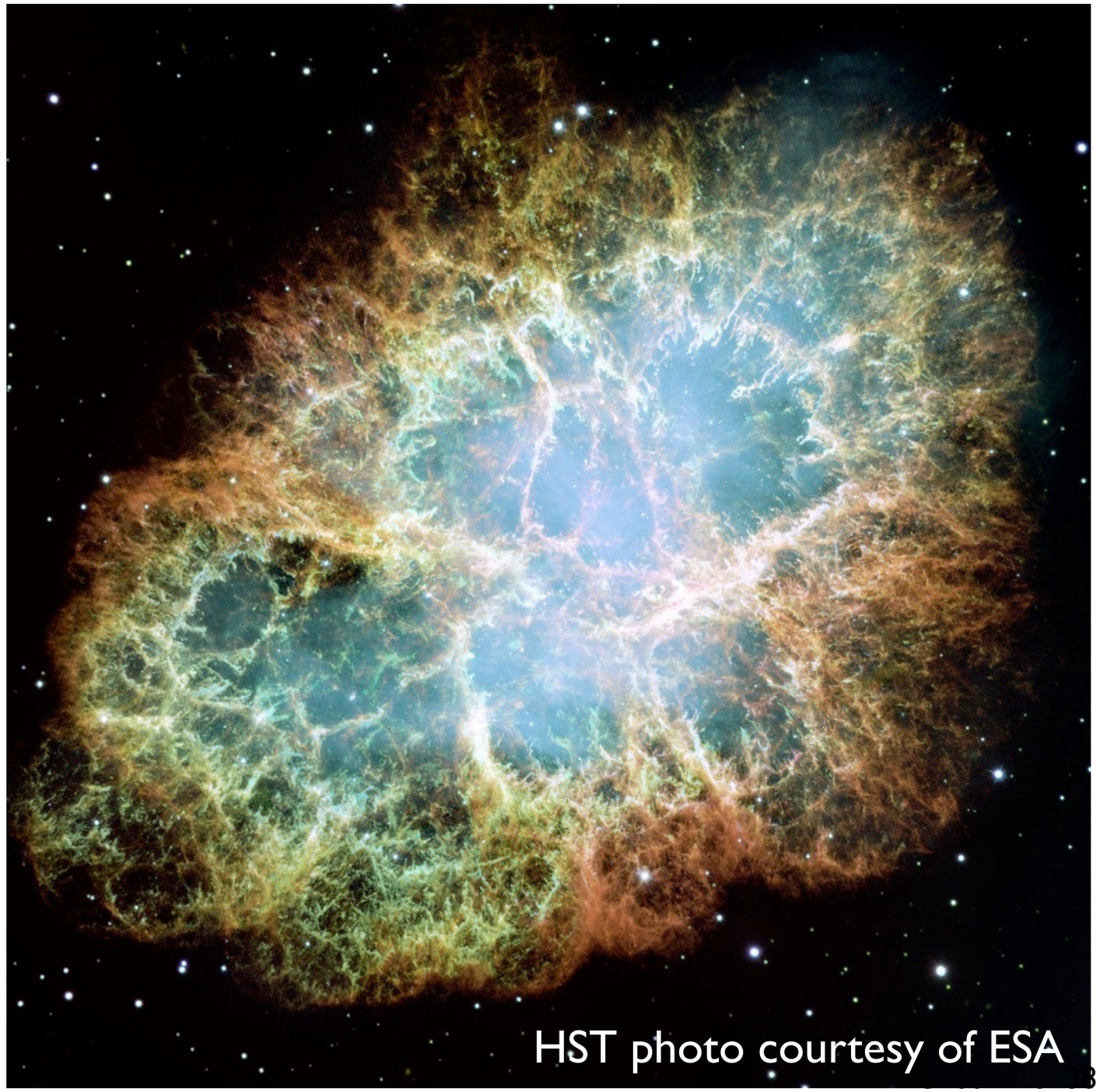


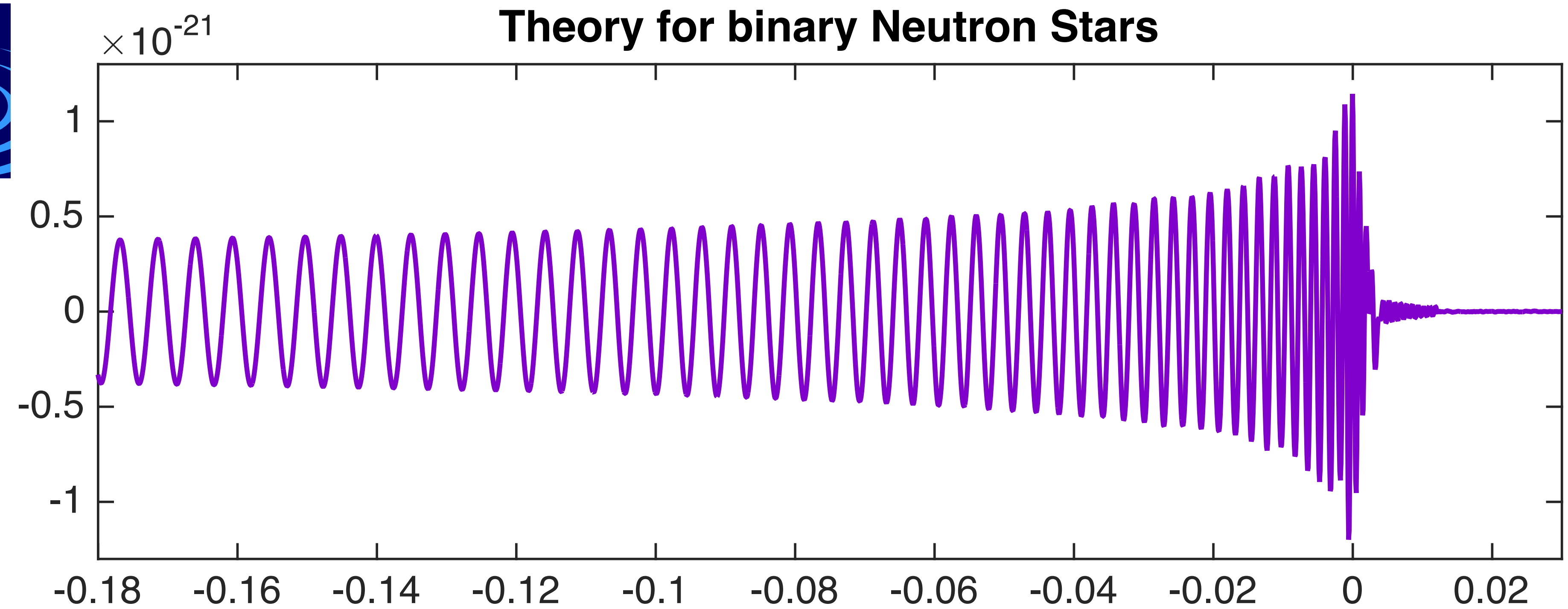
Credit: NASA/DOE/Fermi/LAT Collaboration

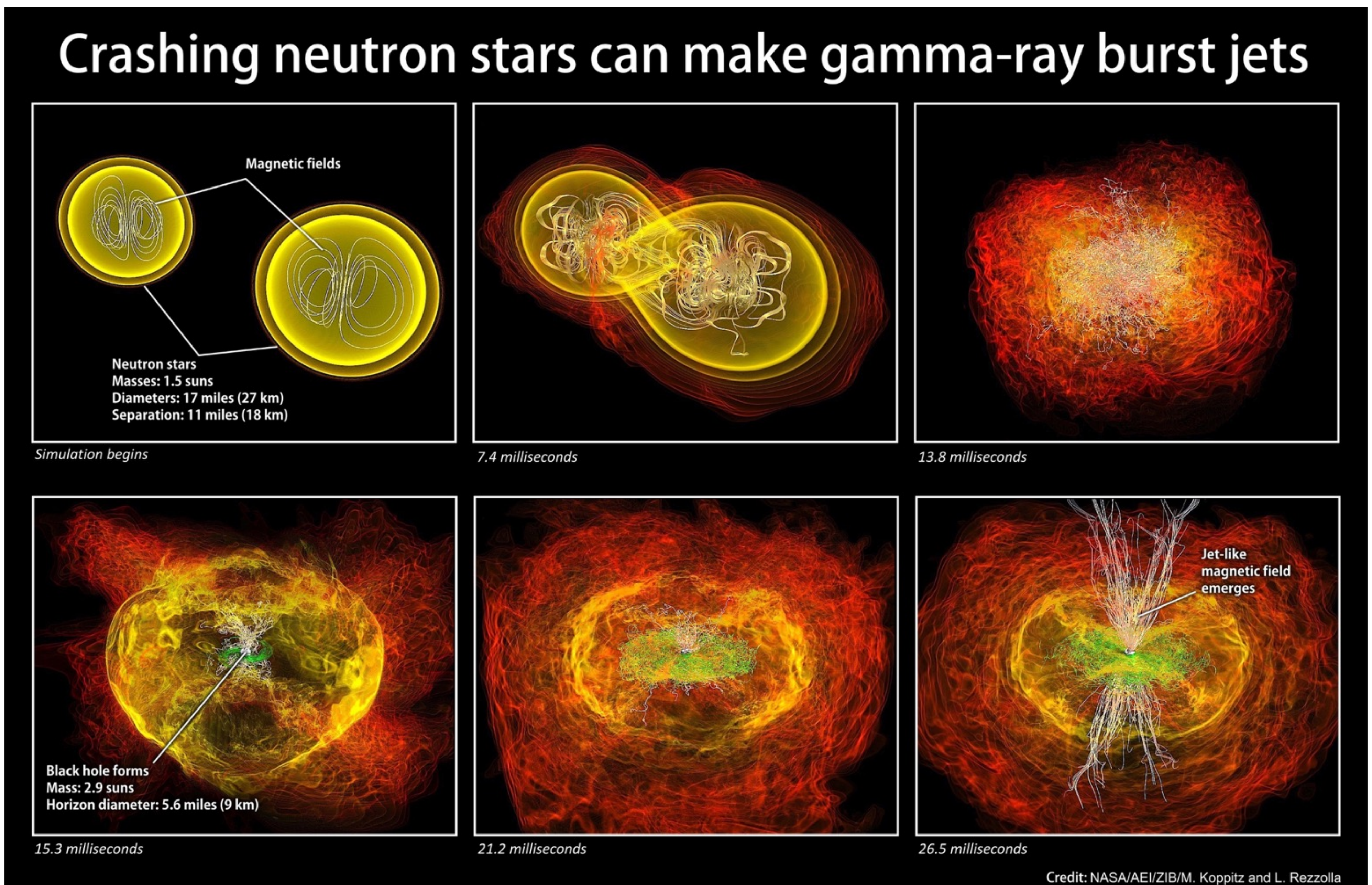
Supernovas and remnants



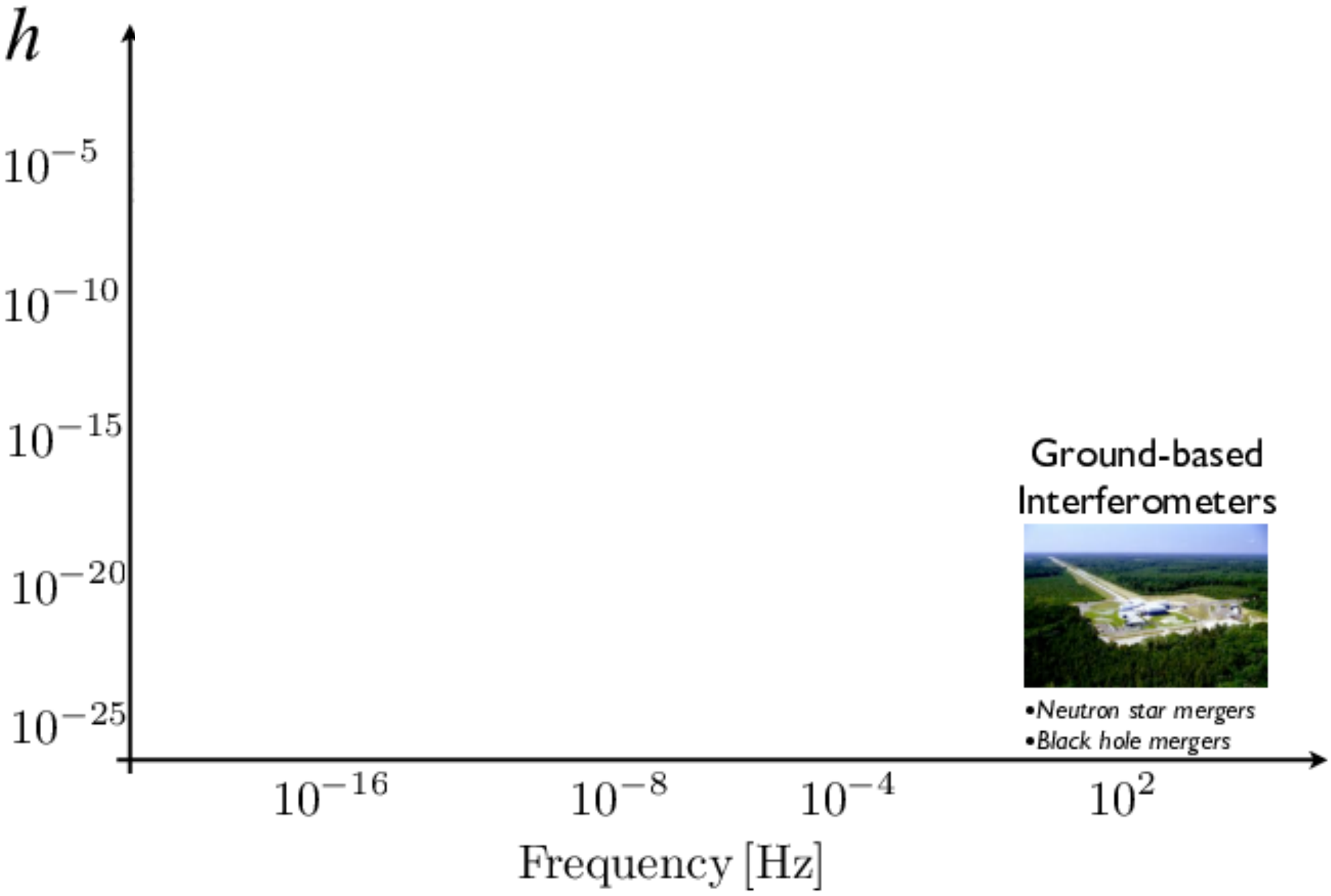
Crab Nebula, supernova in 1054, now a spinning neutron star



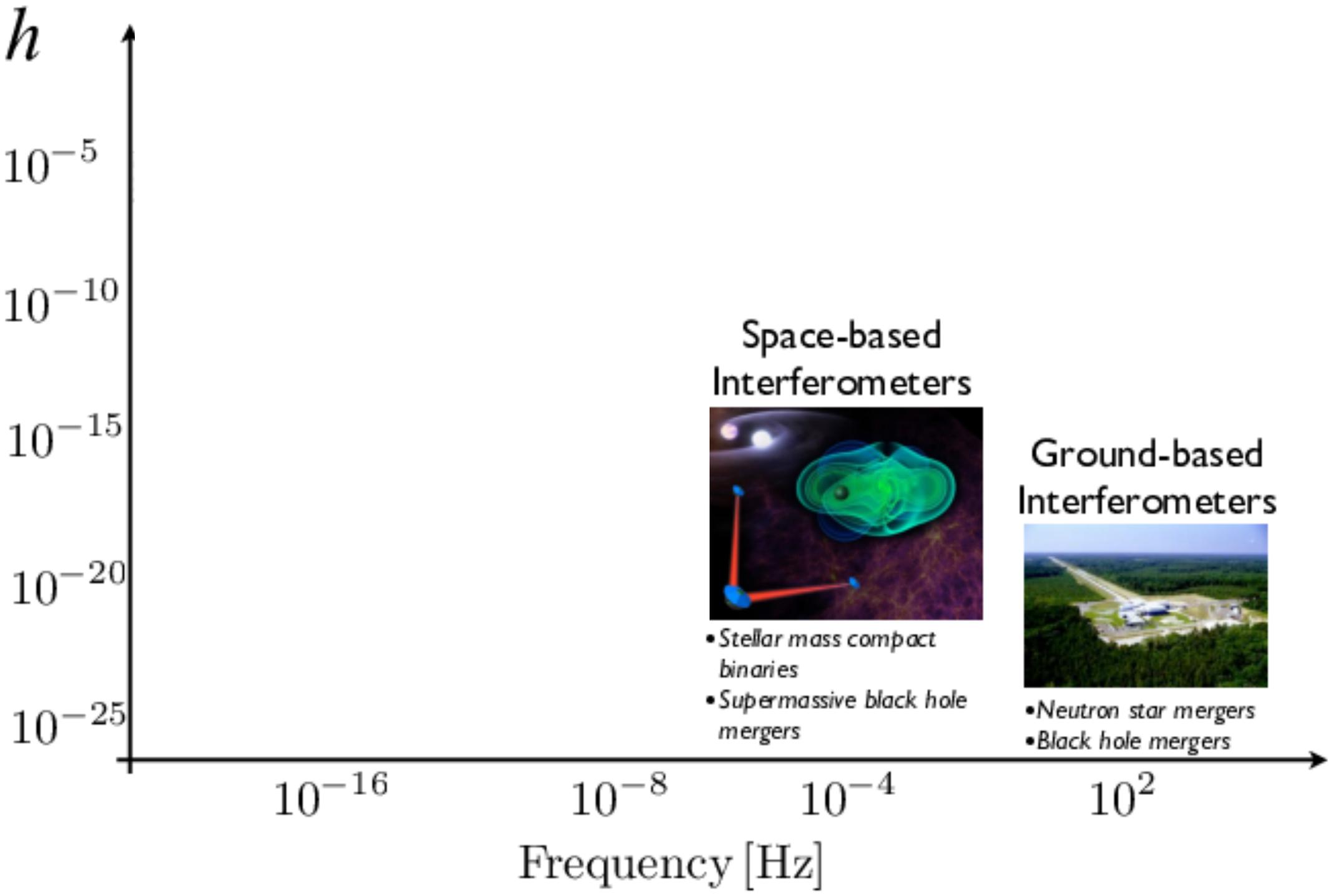

Theory for binary Neutron Stars
×10^-21
1
0.5
0
-0.5
-1
-0.18
-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02


Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like
magnetic field
emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

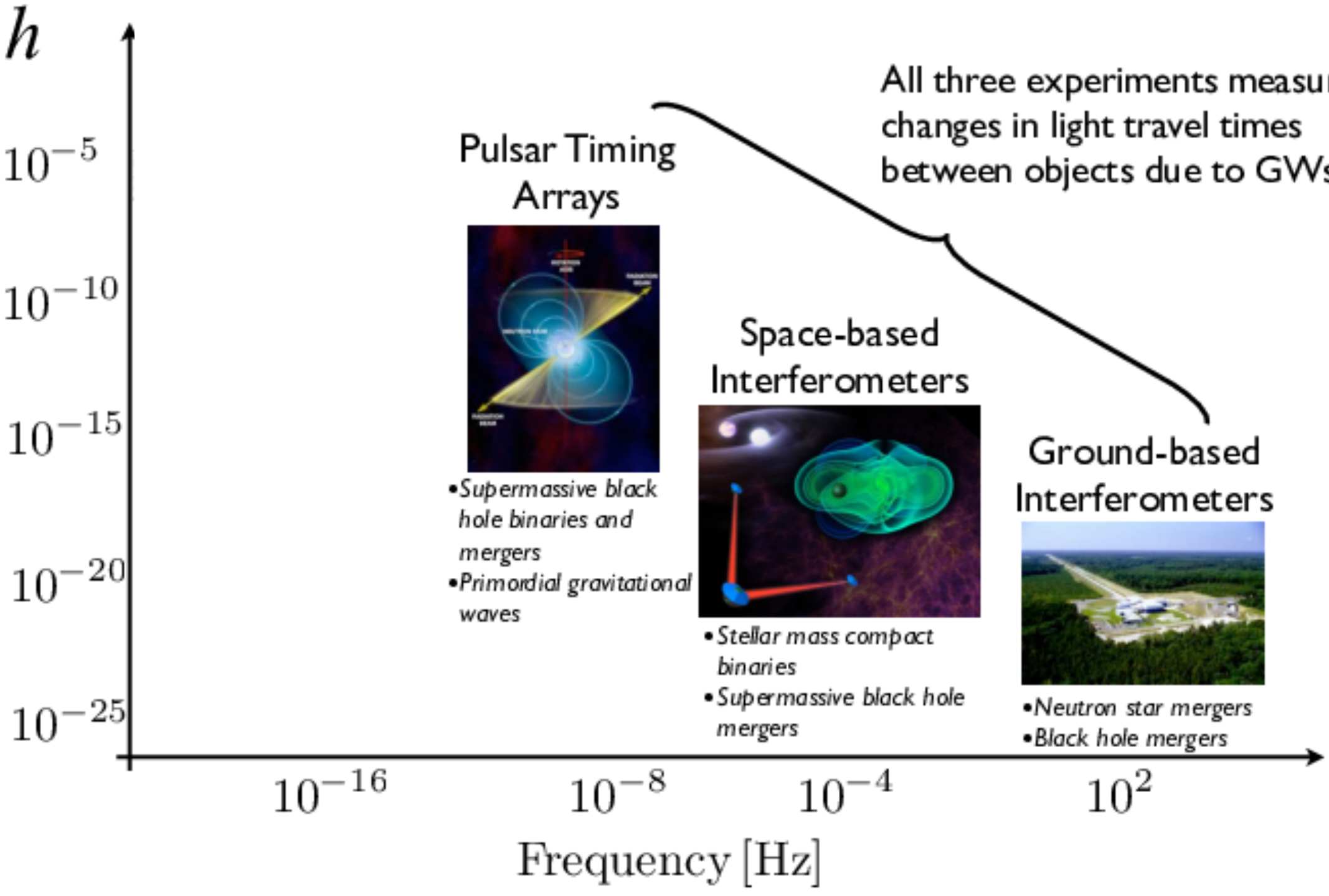
The spectrum of gravitational wave astronomy



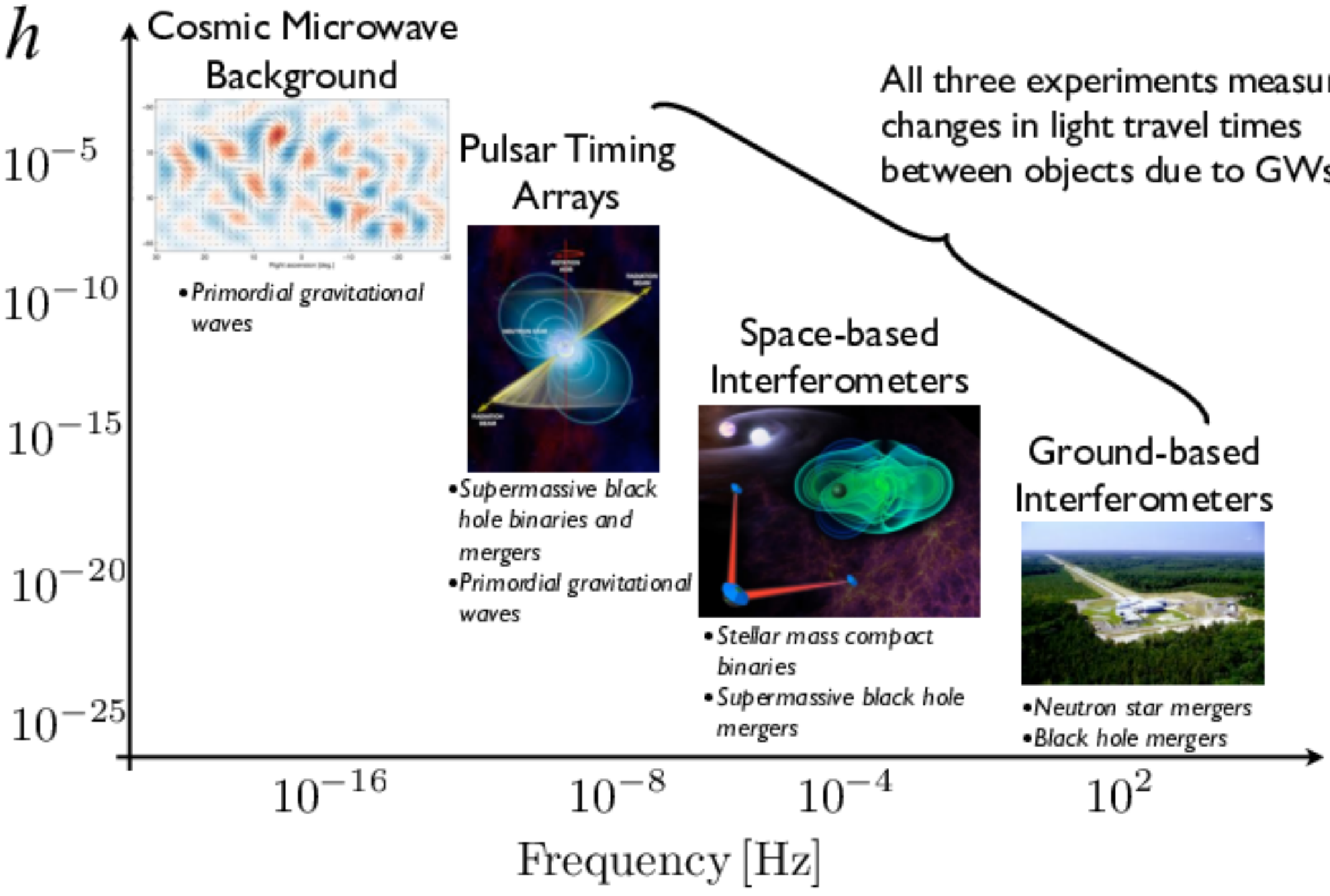
The spectrum of gravitational wave astronomy



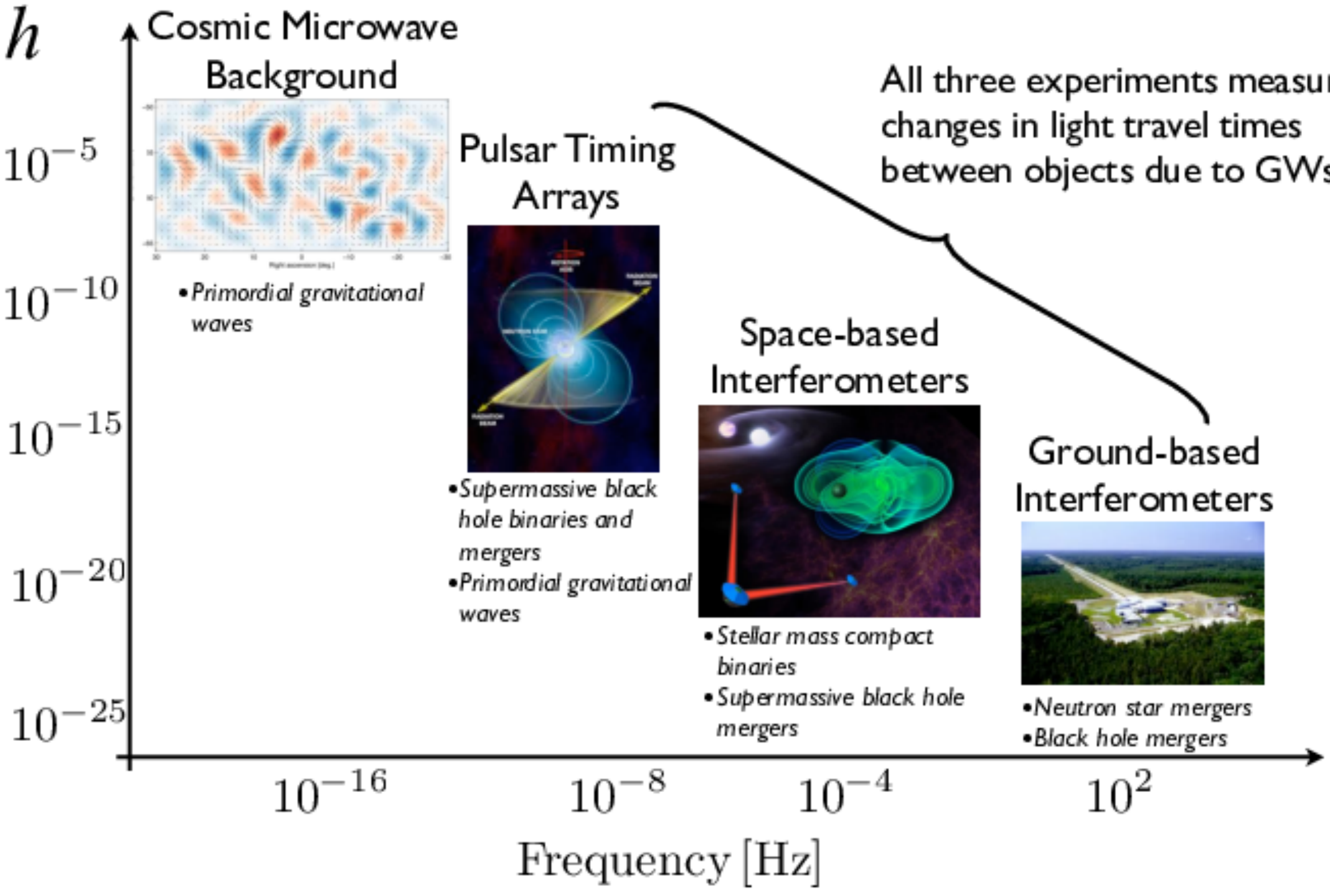
The spectrum of gravitational wave astronomy

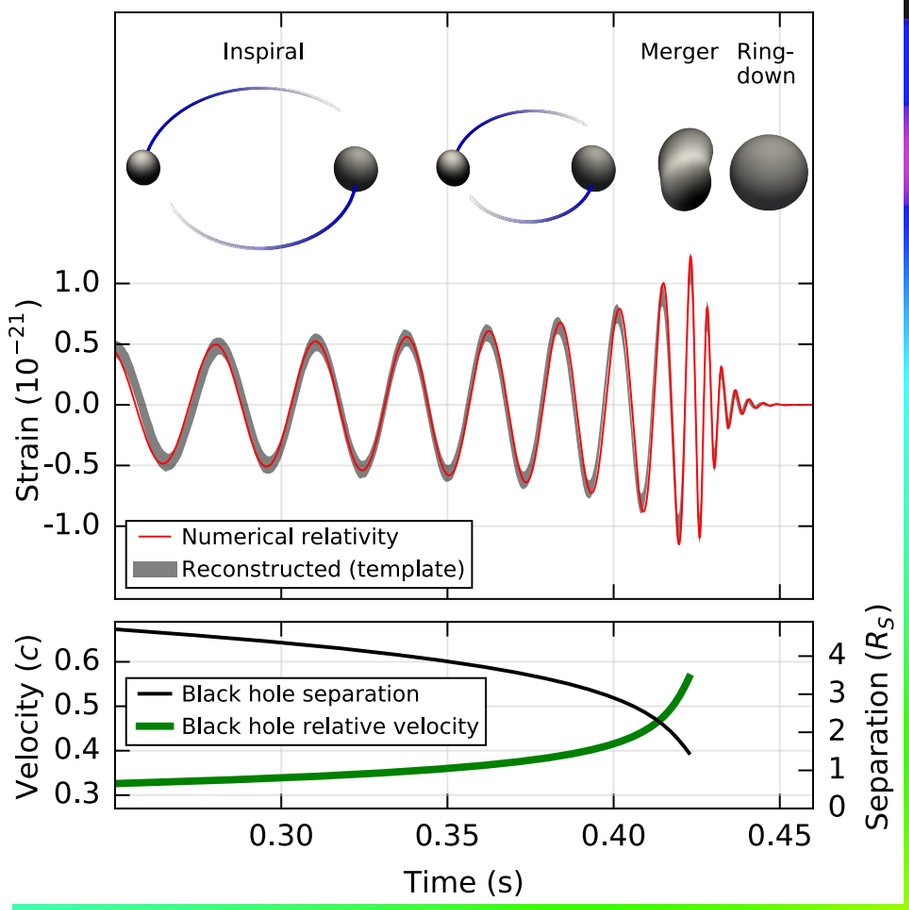


The spectrum of gravitational wave astronomy

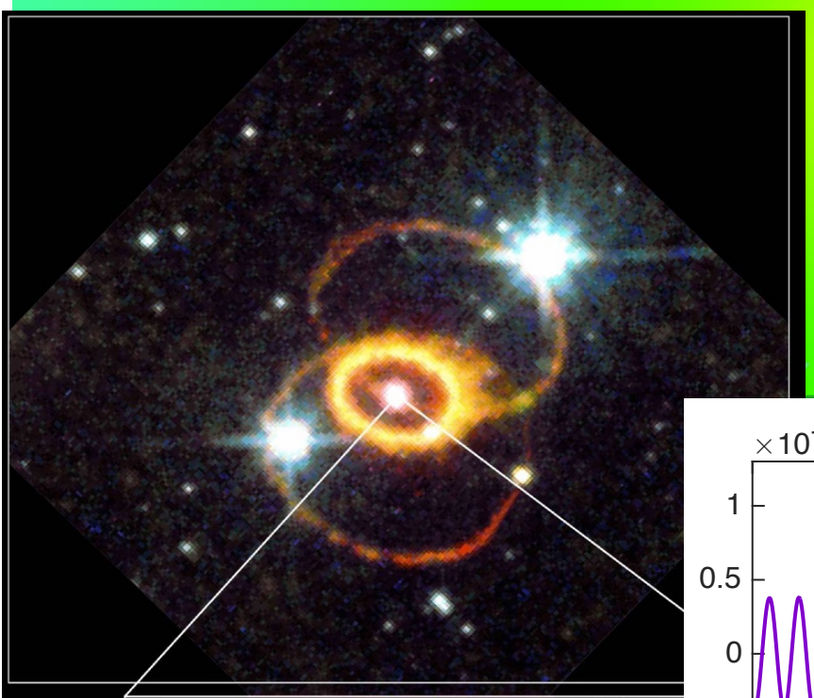


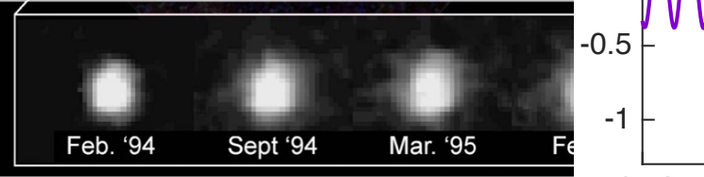
The spectrum of gravitational wave astronomy



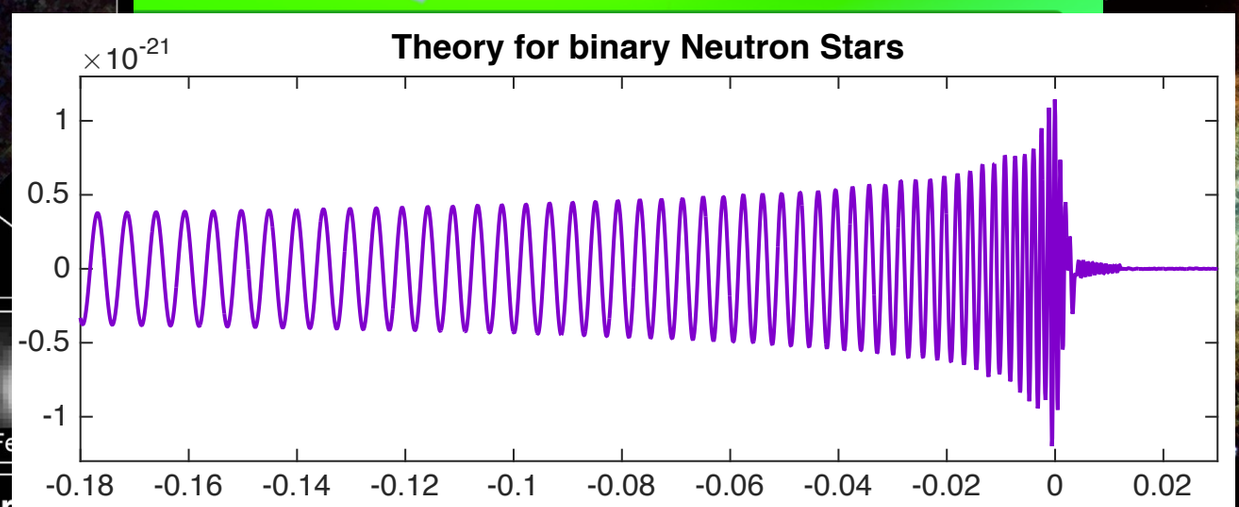


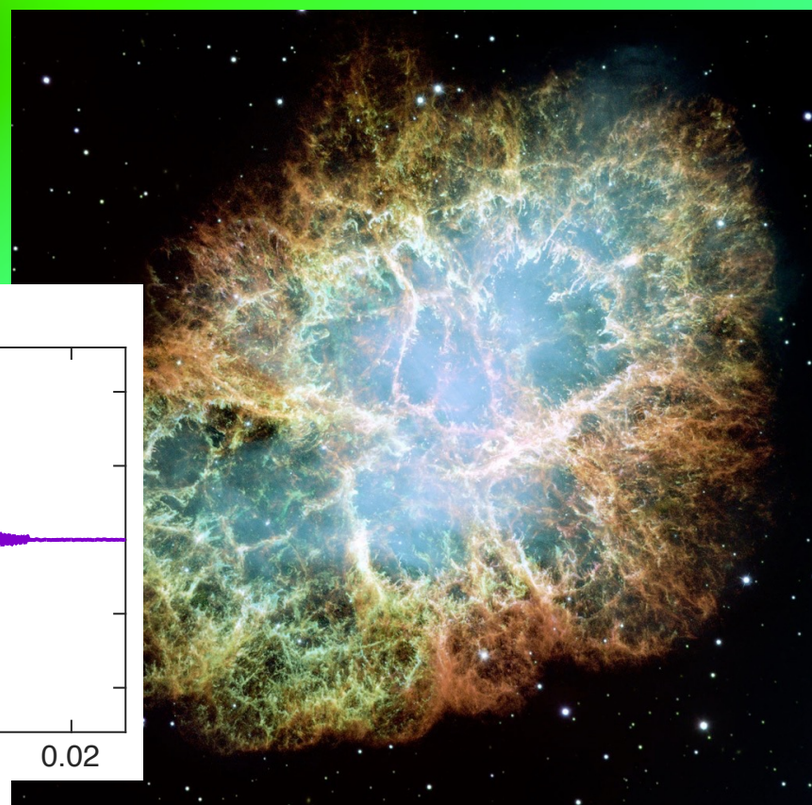
http://papers.ligo.org



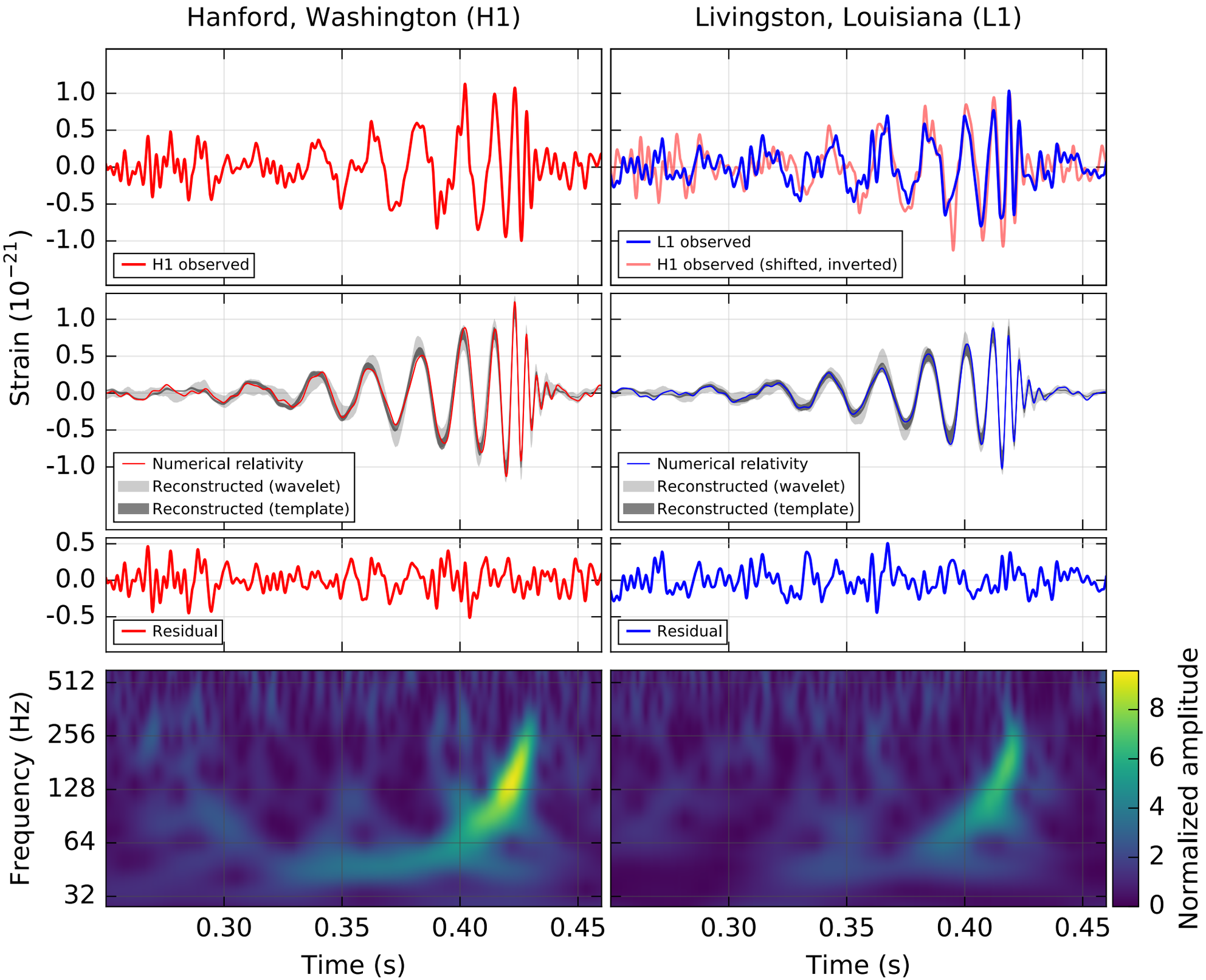


Supernova 1987A Explosion Debris



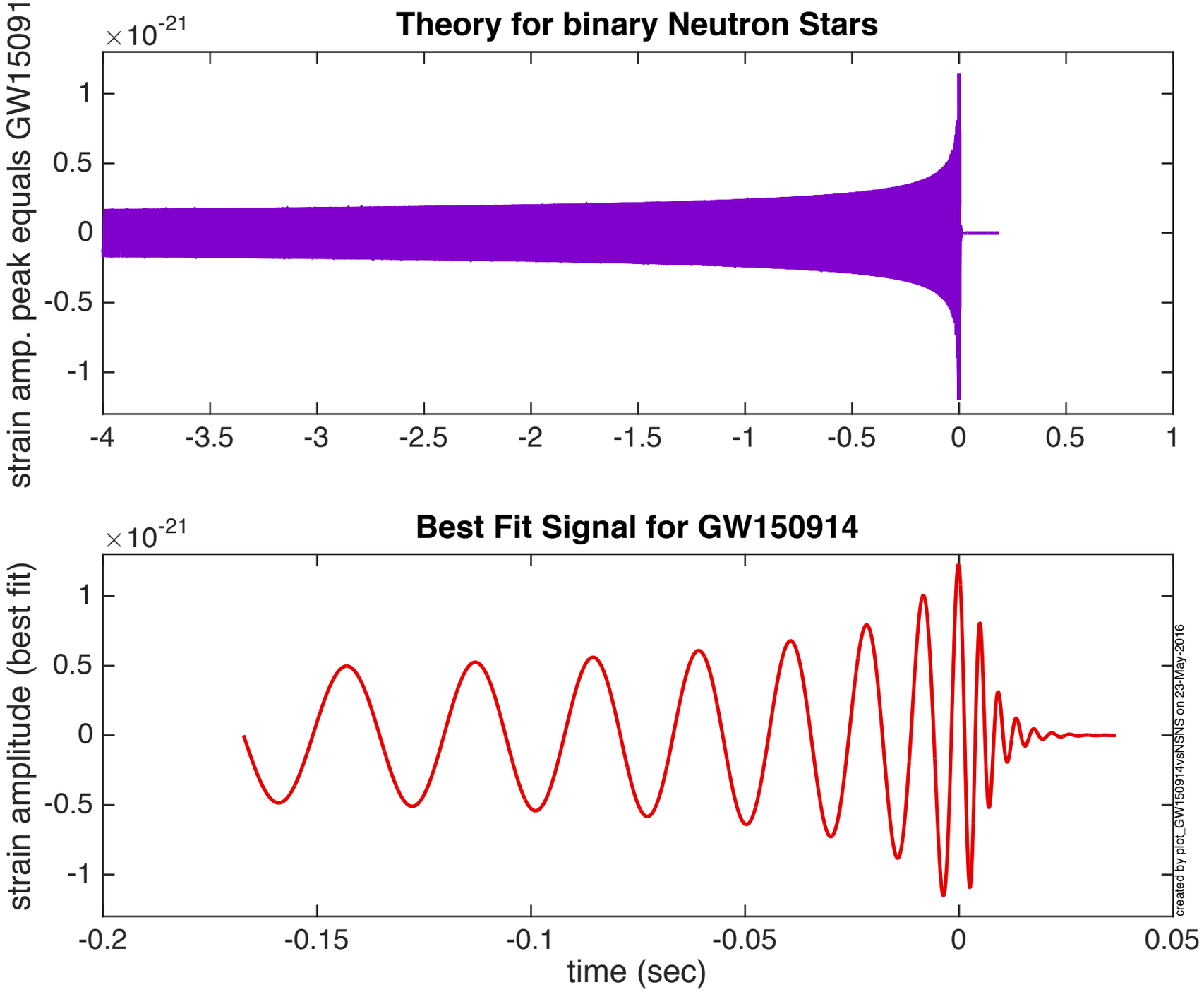


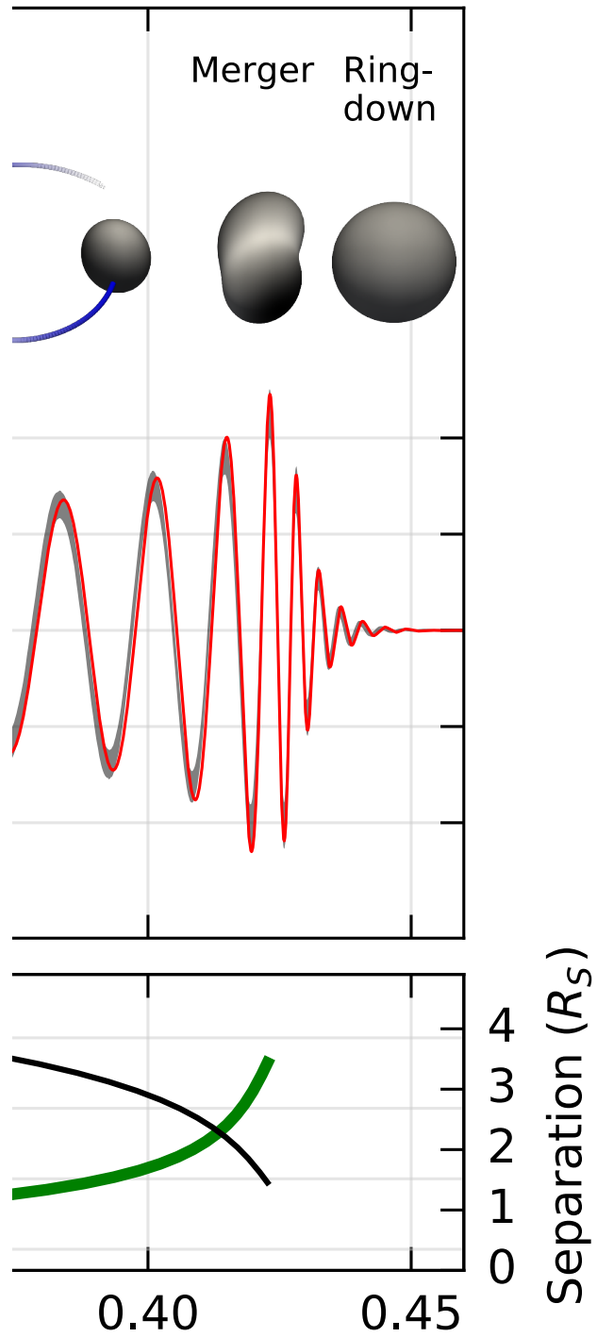
First signal - Sept 14, 2015



http://dx.doi.org/10.1103/PhysRevLett.116.061102

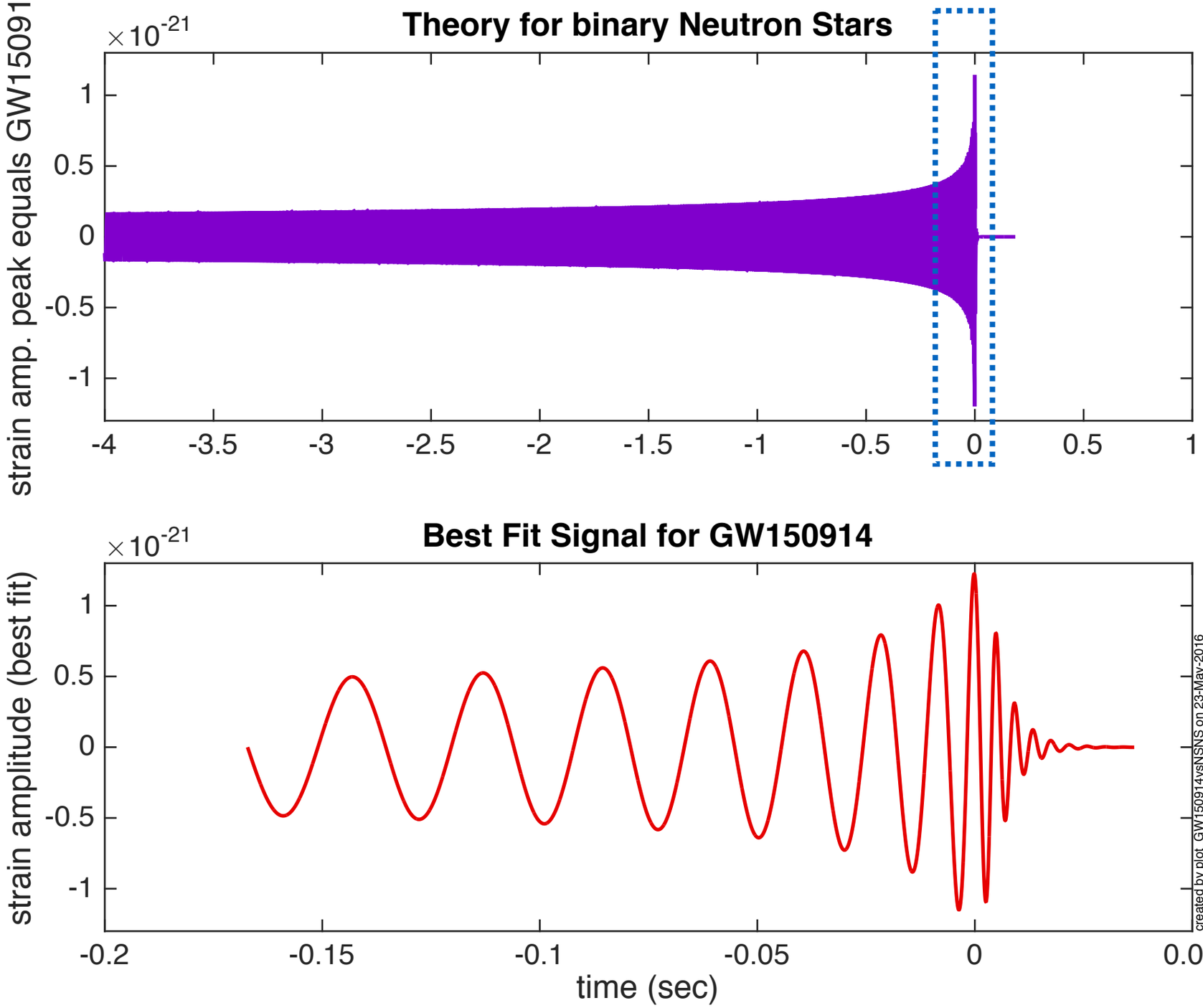
Best fit with Numerical Relativity

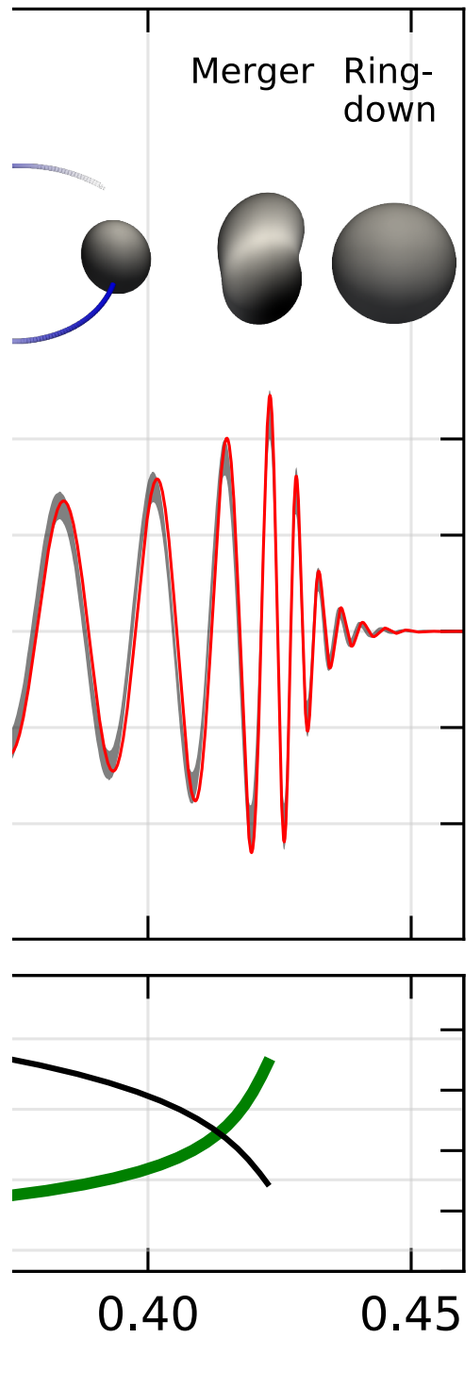




NS/NS waveform from http://web.mit.edu/sahughes/www/sounds.html

Best fit with Numerical Relativity





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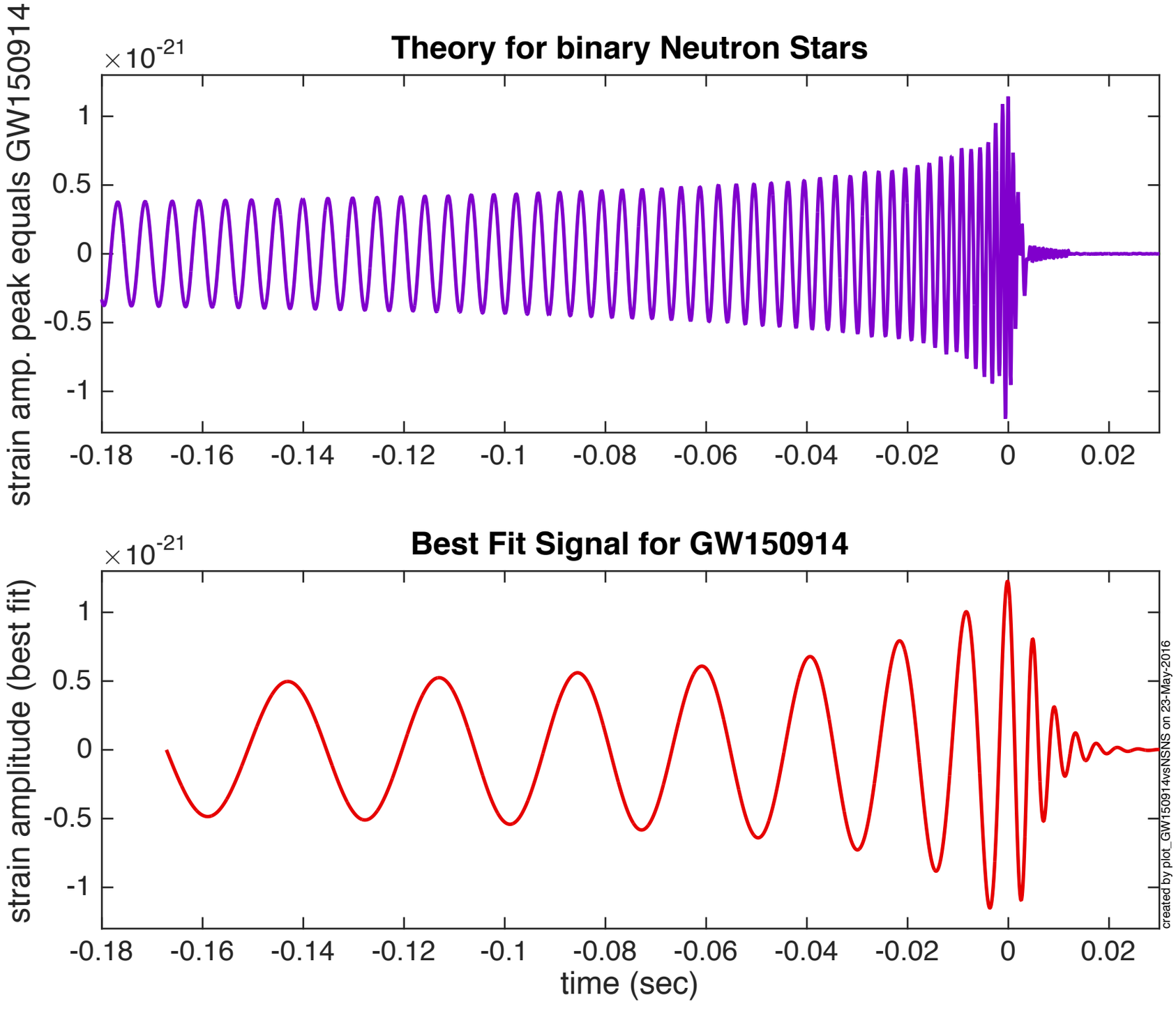

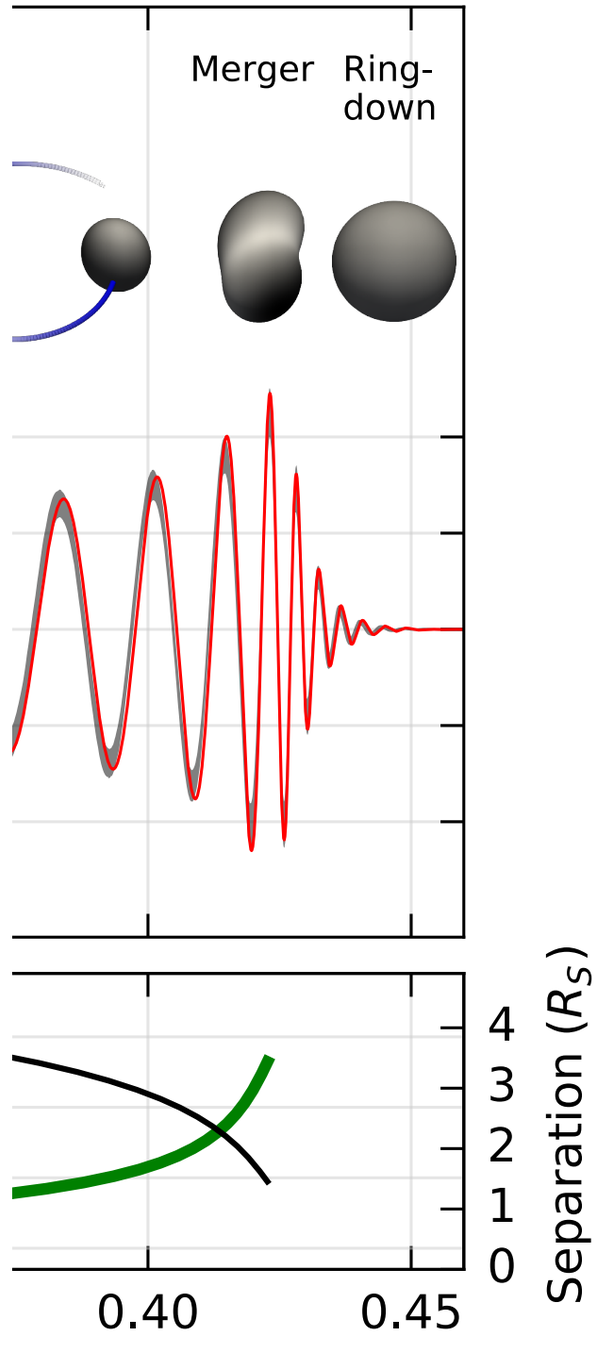

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Final Mass:

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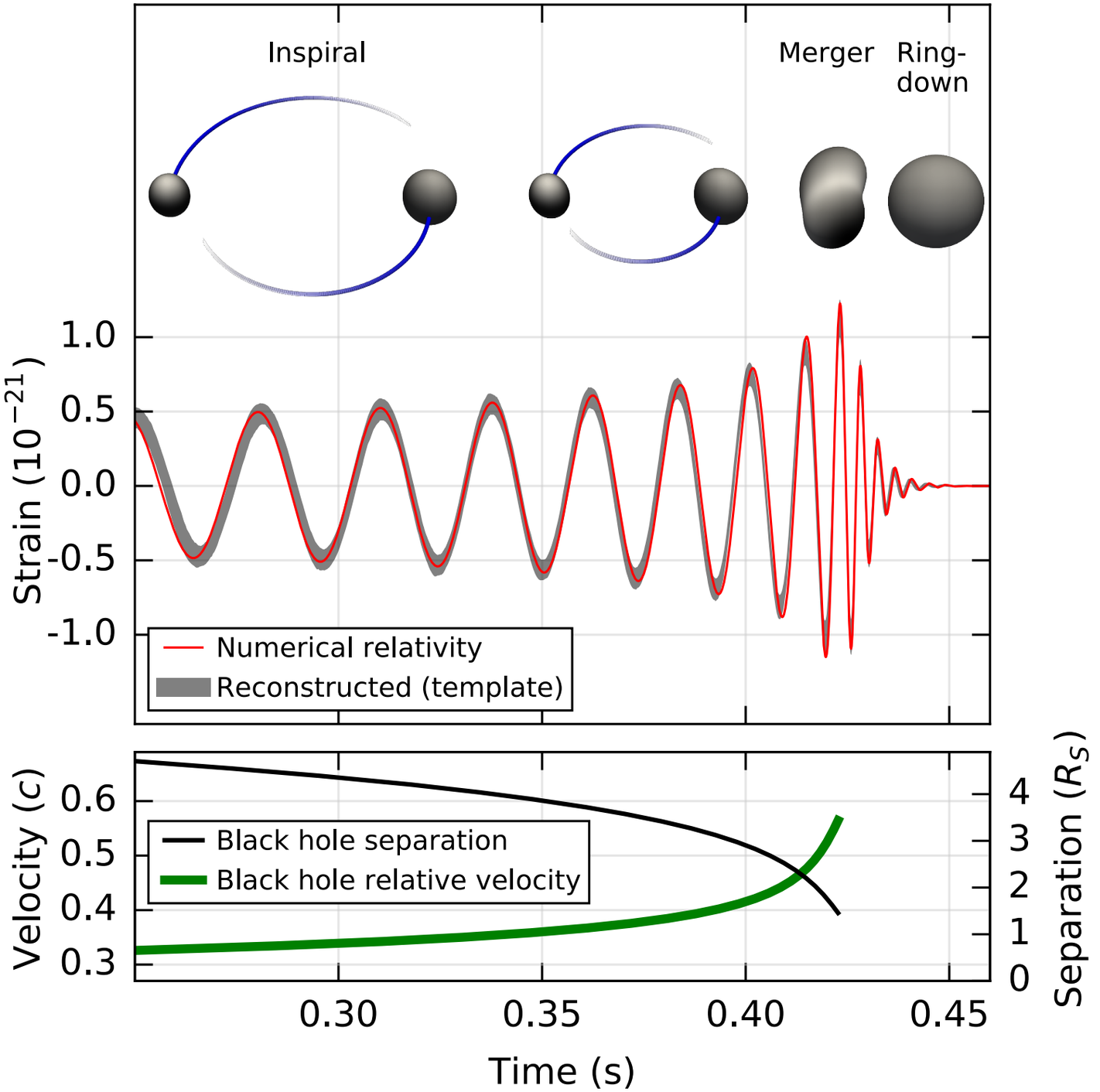
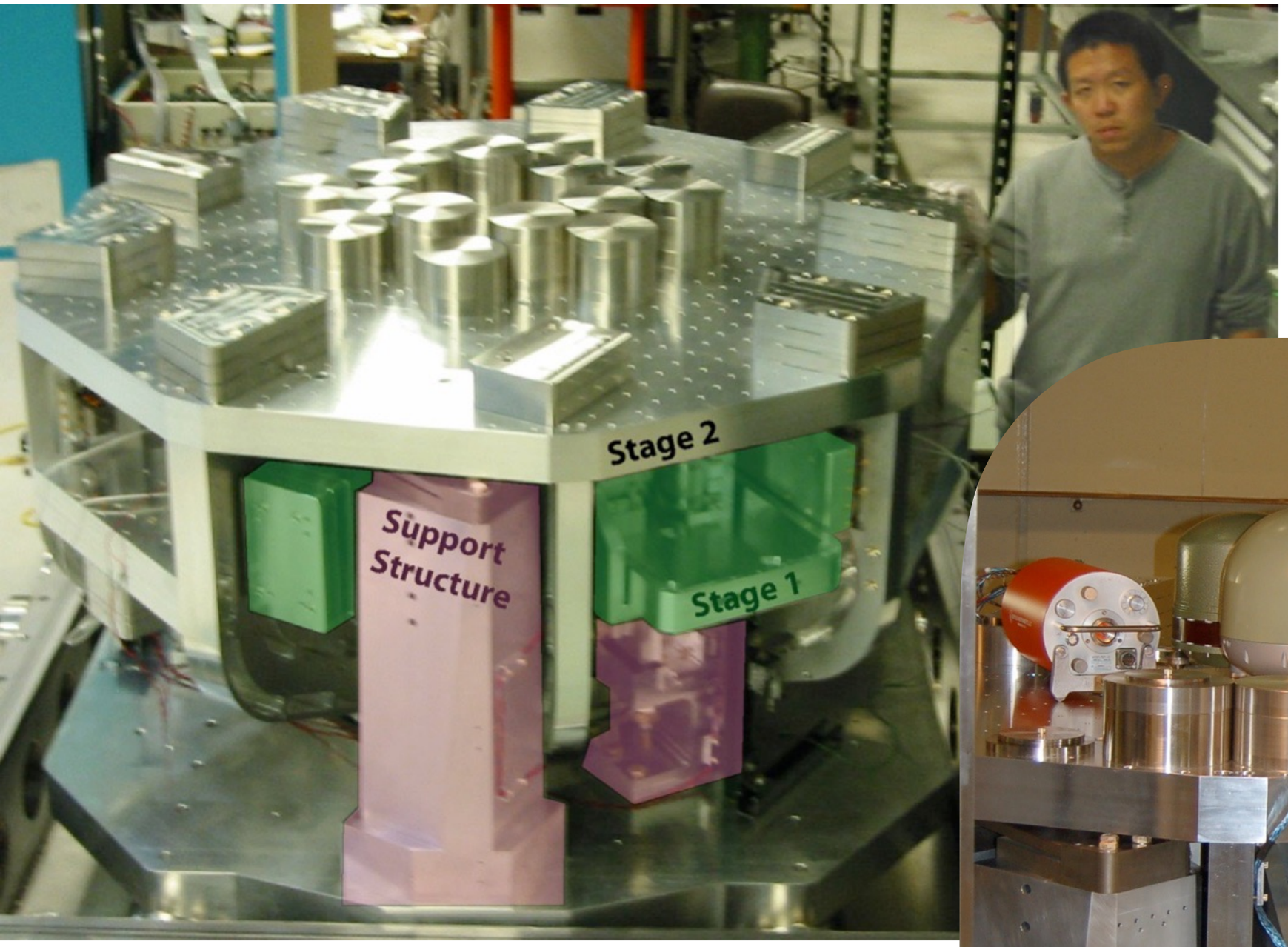
1.3 Billion light years

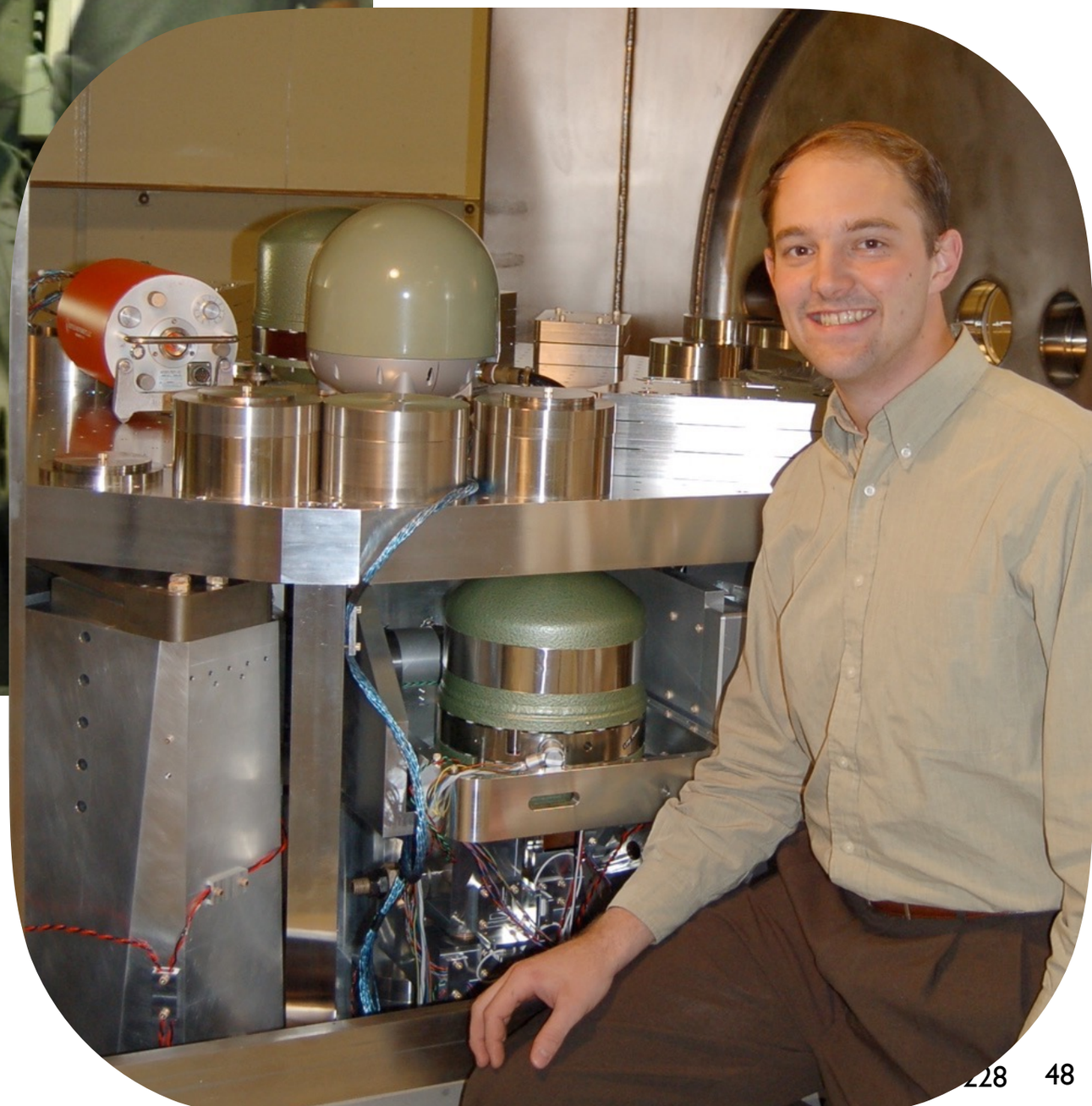
(410 (+160/-180) MPc)



http://dx.doi.org/10.1103/PhysRevLett.116.061102

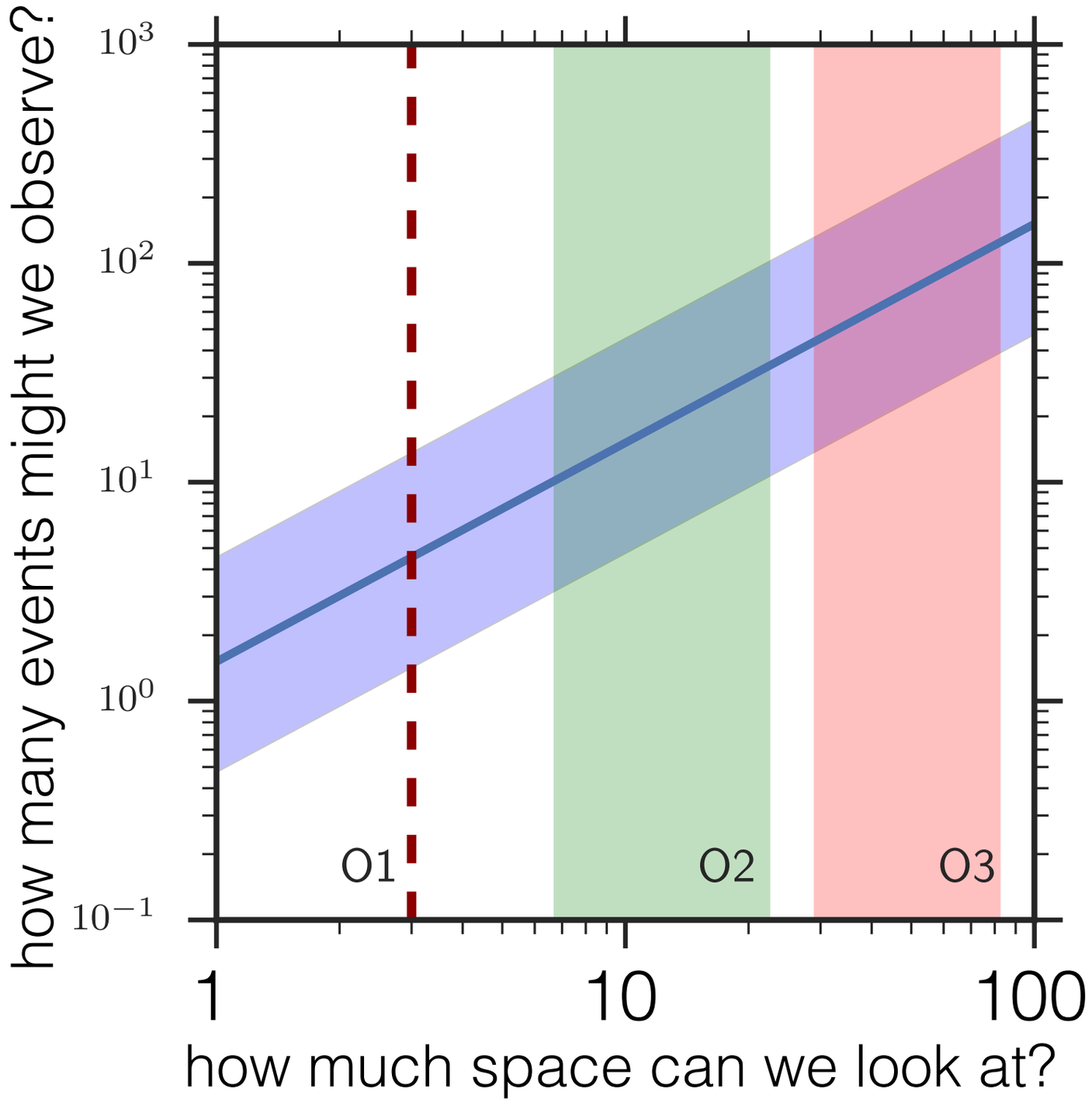
Stanford Prototype



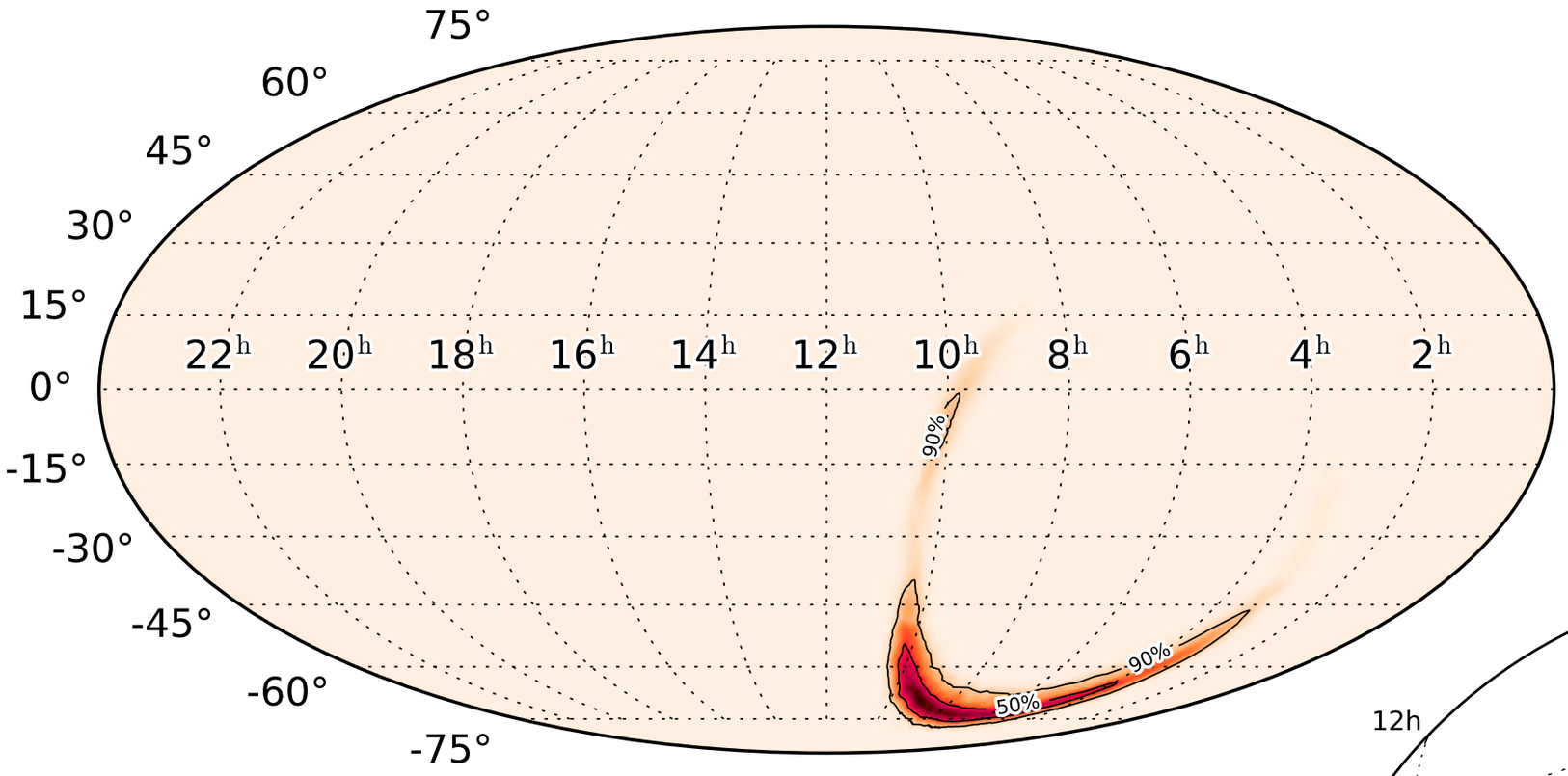


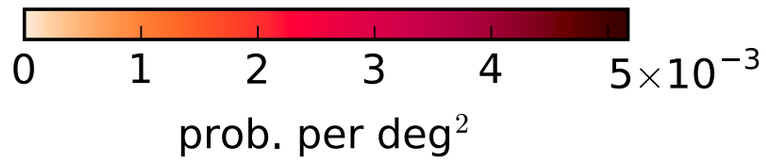
The End/ The Beginning…

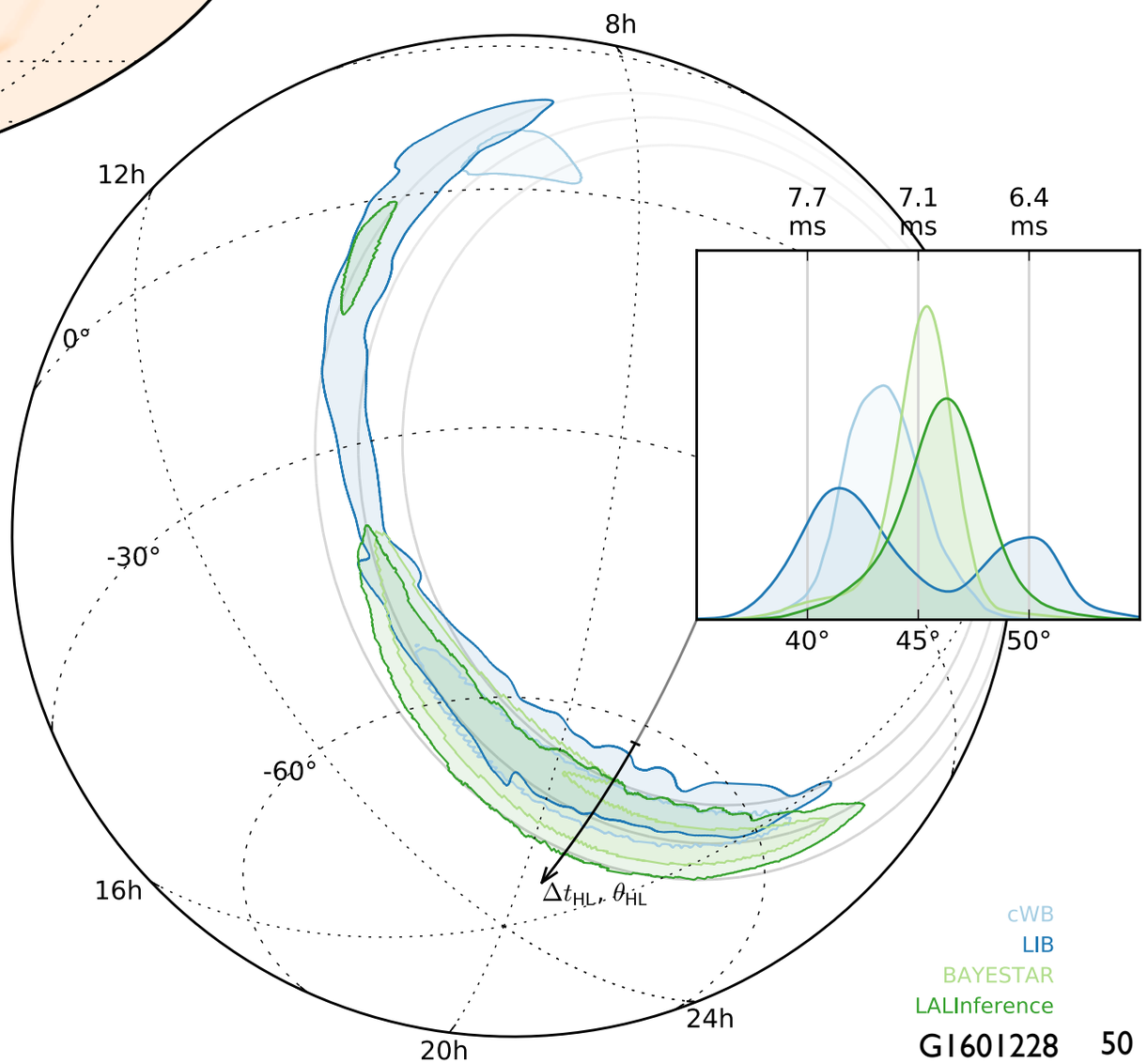
How many black hole collisions can we see?



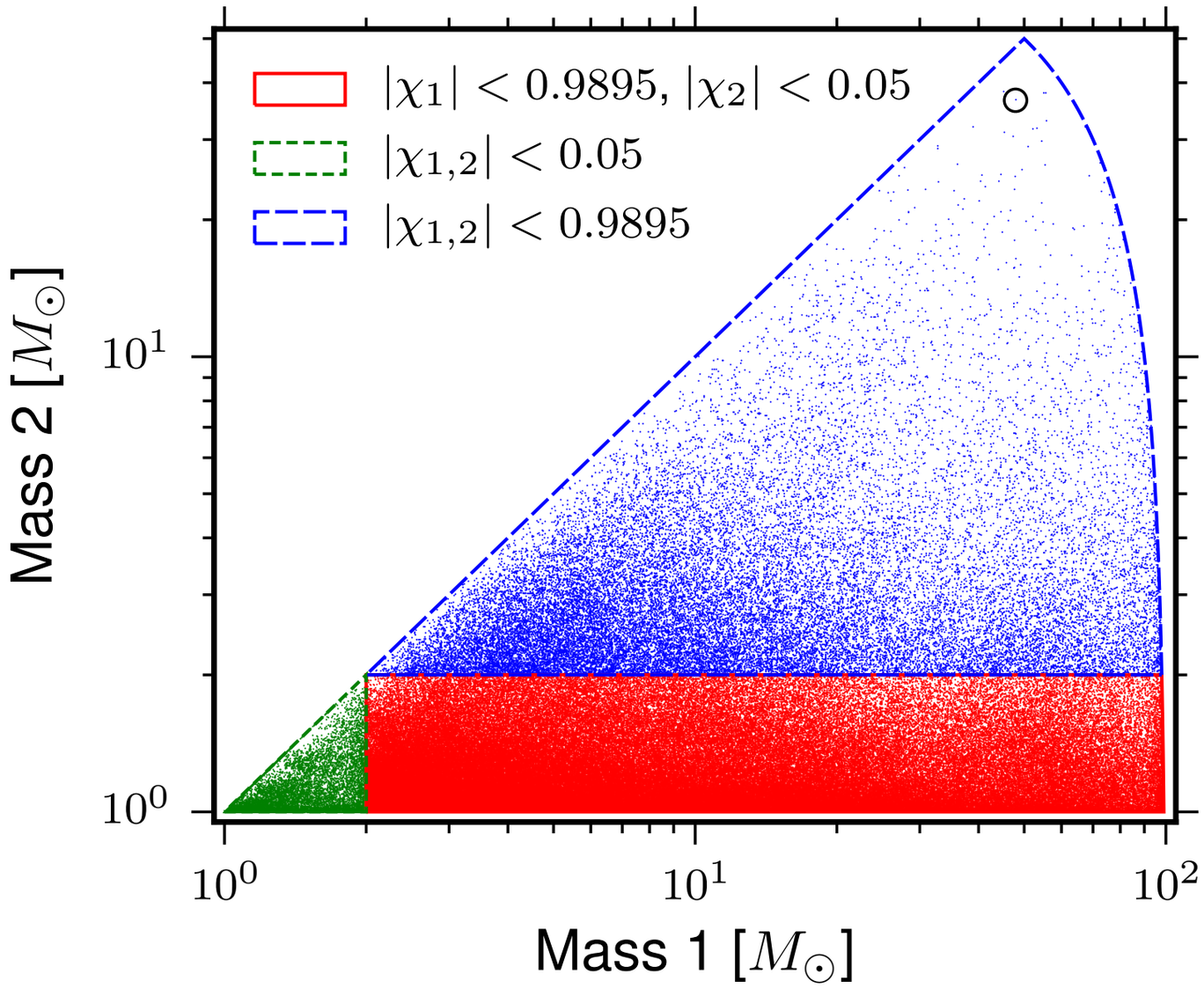
Where was it?


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
22h
20h
18h
16h
14h
12h
10h
8h
6h
4h
2h
90%
50%
90%


0
1
2
3
4
5×10−3
prob. per deg2


8h
12h
16h
20h
24h
0°
-30°
-60°
7.7 ms
7.1 ms
6.4 ms
40°
45°
50°
$\Delta t_{HL}, \theta_{HL}$
cWB
LIB
BAYESTAR
LALInference

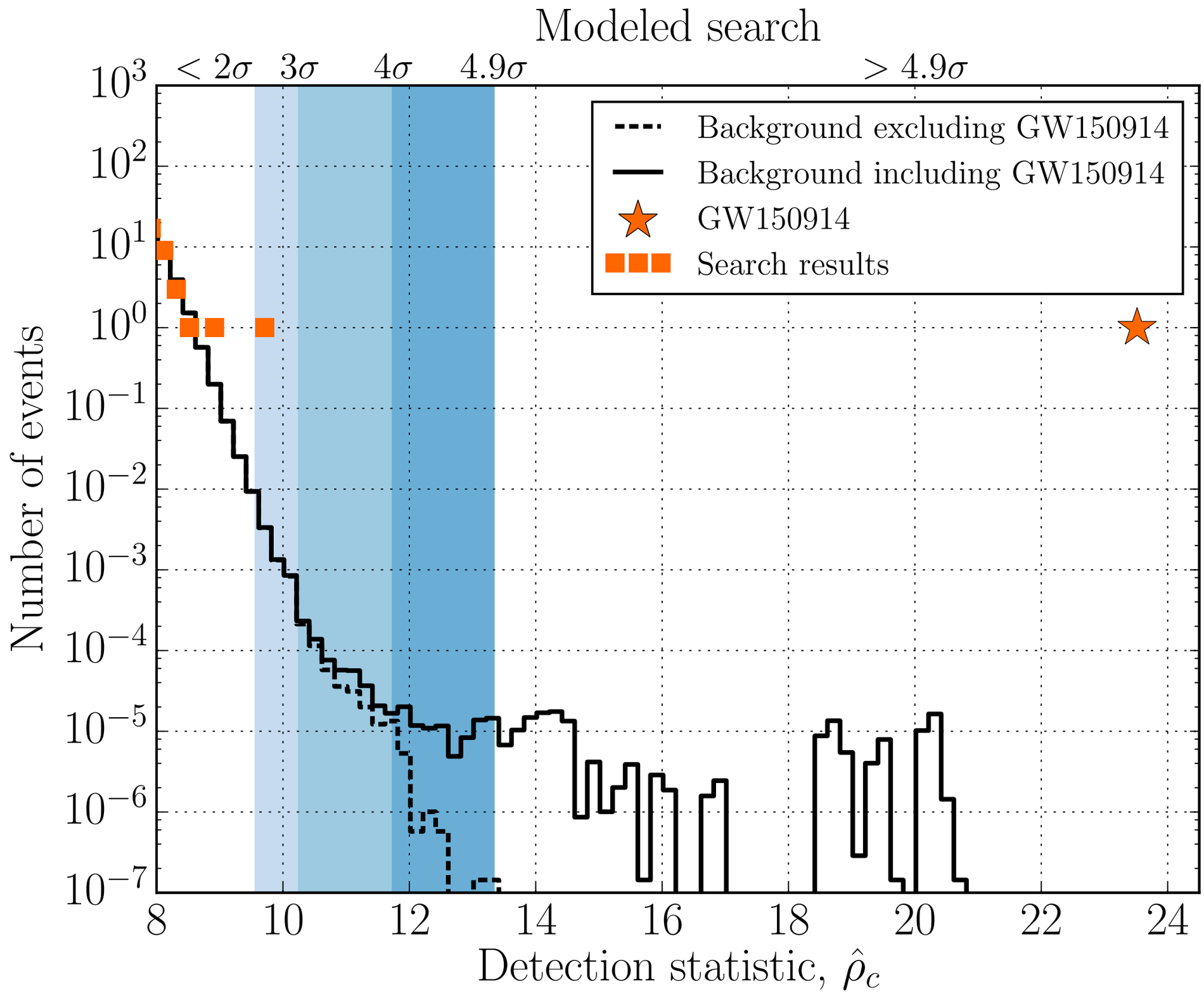
CBC template bank

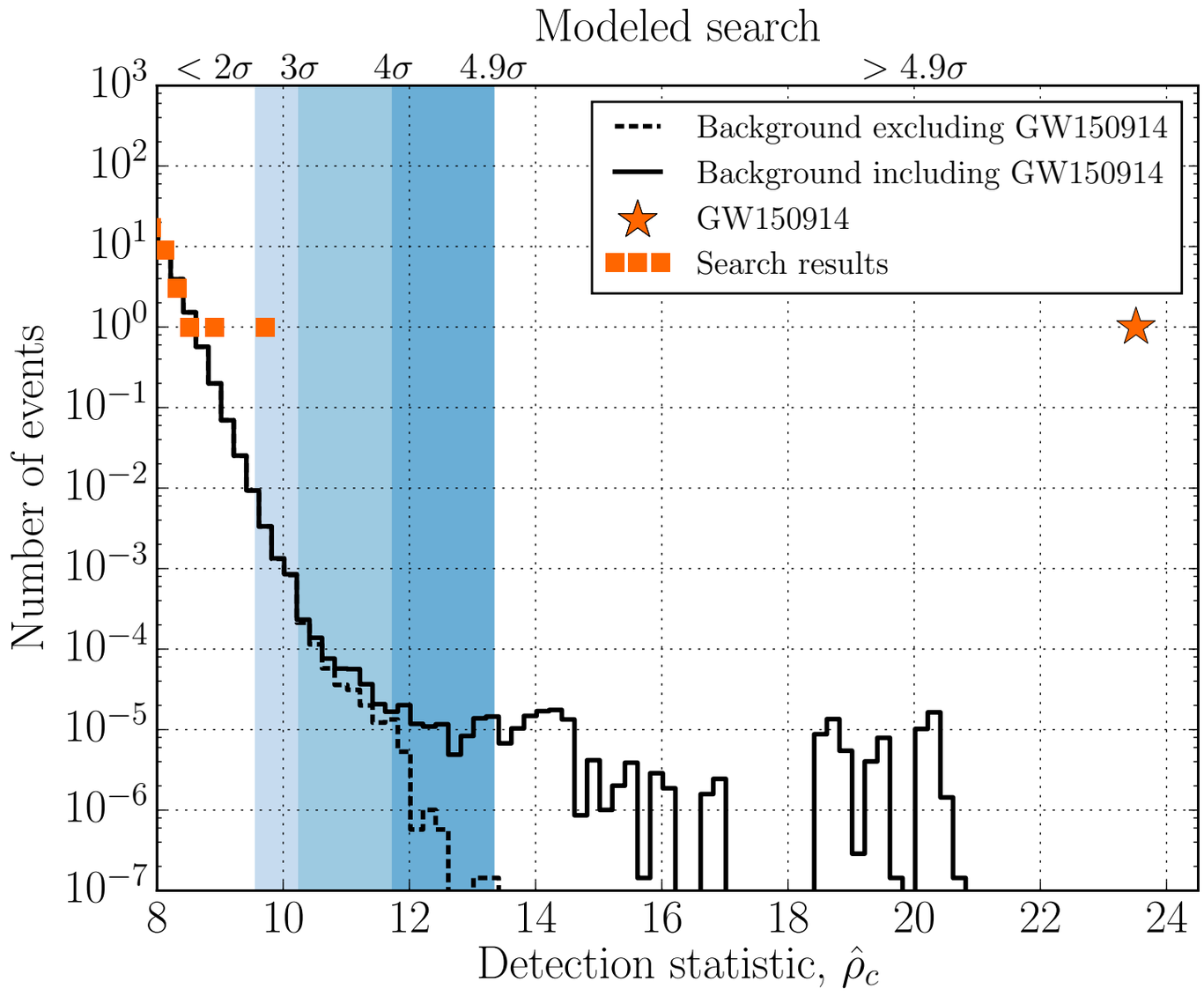


(just at the edge…)

FIG. 1. The four-dimensional search parameter space covered by the template bank shown projected into the component-mass plane, using the convention $m_1 > m_2$. The lines bound mass regions with different limits on the dimensionless aligned-spin parameters χ_1 and χ_2. Each point indicates the position of a template in the bank. The circle highlights the template that best matches GW150914. This

Detection statistic





Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

BSC-ISI

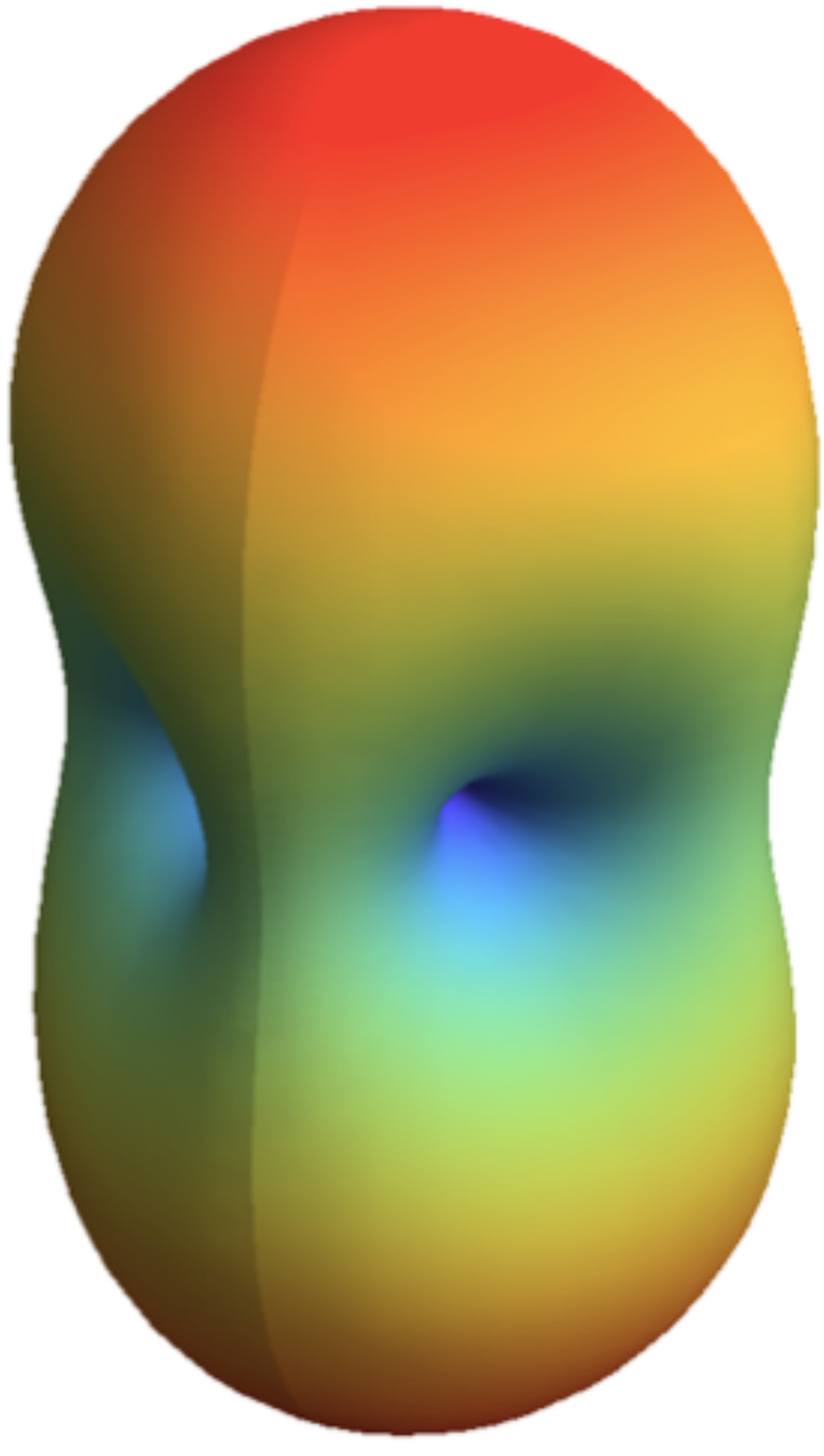
optics table - stage 2

stage 1

support - stage 0

Interferometer's Antenna Pattern
LIGO is not an Imaging Detector

- Antenna pattern for aLIGO, for an optimally polarized wave.
- LIGO is more like a microphone than a telescope.
- i.e. We measure the amplitude of a wave coming from pretty much any direction.
- Good for first detections, but not so good for finding the source.



From R. Adhikari, P1200121.