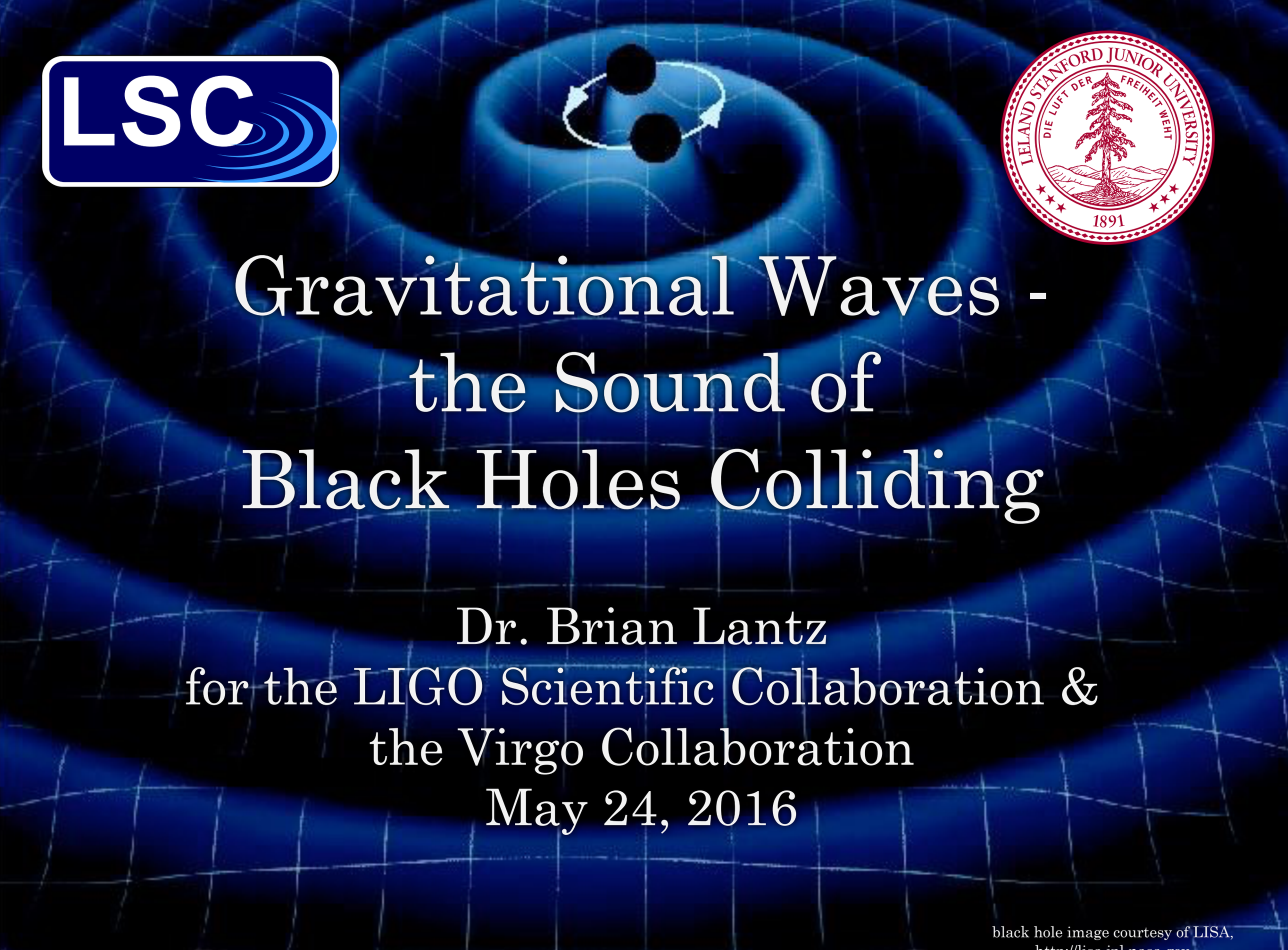
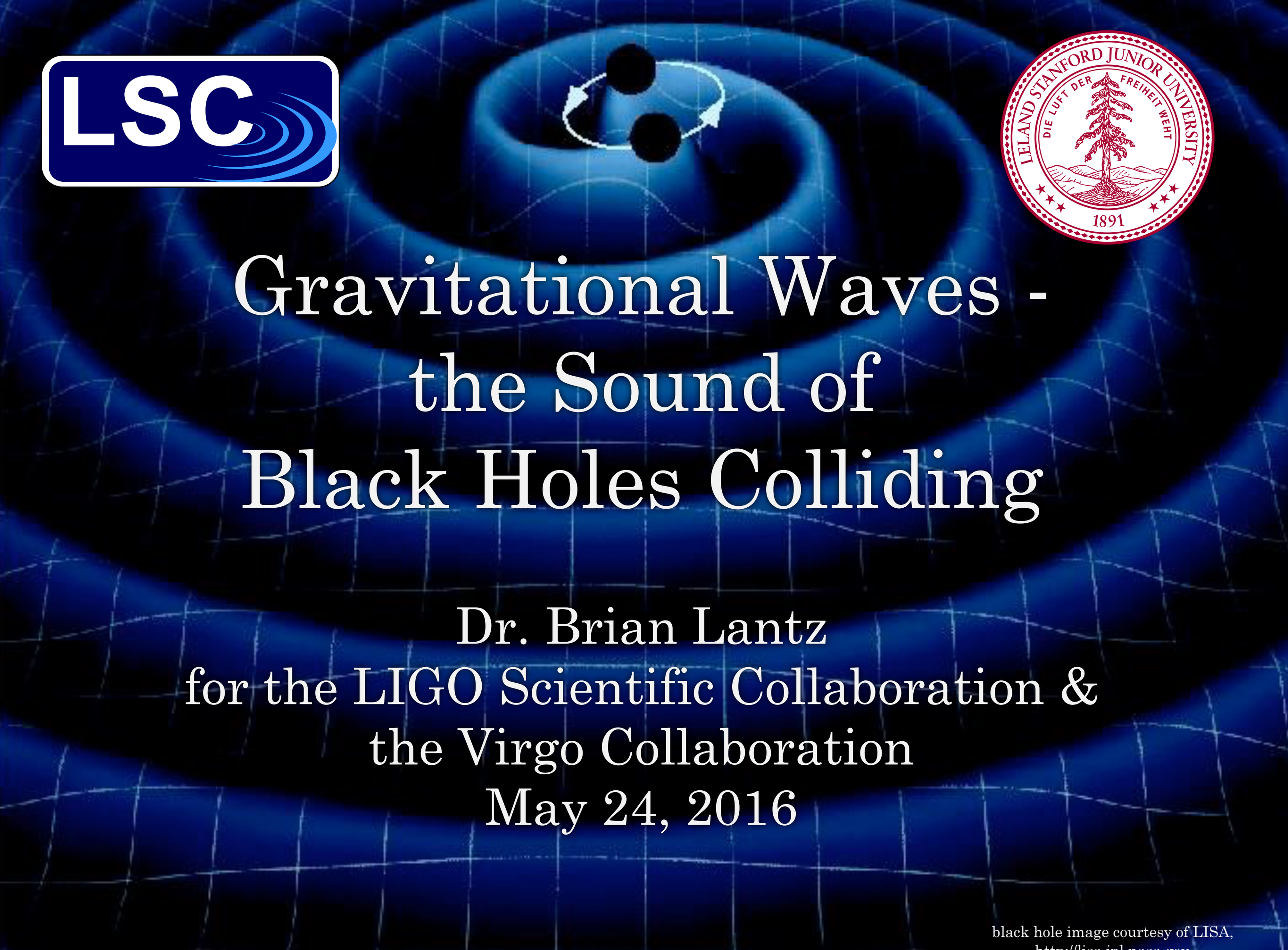


Gravitational Waves - the Sound of Black Holes Colliding

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

May 24, 2016

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



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LIGO Scientific Collaboration

LIGO

LSC

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UNIVERSITY OF MARYLAND

Andrews University

WASHINGTON STATE UNIVERSITY

CALIFORNIA STATE UNIVERSITY FULLERTON

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

SONOMA STATE UNIVERSITY

indigo

MONTCLAIR STATE UNIVERSITY

University of Glasgow

Australian National University

WHITMAN COLLEGE

AMERICAN UNIVERSITY WASHINGTON, DC

UNIVERSITY OF THE WEST of SCOTLAND UWS

TEXAS TECH UNIVERSITY

Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics ALBERT EINSTEIN INSTITUTE

UNIVERSITY OF STRATHCLYDE

MICHIGAN

Università degli Studi del Sannio

CITA | ICAT Canadian Institute for Theoretical Astrophysics / L'institut Canadien d'astrophysique theorique

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

NASA GODDARD SPACE FLIGHT CENTER

LELAND STANFORD JUNIOR UNIVERSITY 1891

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Caltech

UNIVERSITY OF MINNESOTA

UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF MELBOURNE

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UIB | Universitat de les Illes Balears

GEO 600

UNIVERSITY OF WASHINGTON

UTRGV

UNIVERSITY of WISCONSIN UWMILWAUKEE

SYRACUSE UNIVERSITY FOUNDED AD 1870

CARDIFF UNIVERSITY

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Korean Gravitational-Wave Group

LSU LOUISIANA STATE UNIVERSITY

ACIGA

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CHARLES STURT UNIVERSITY

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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

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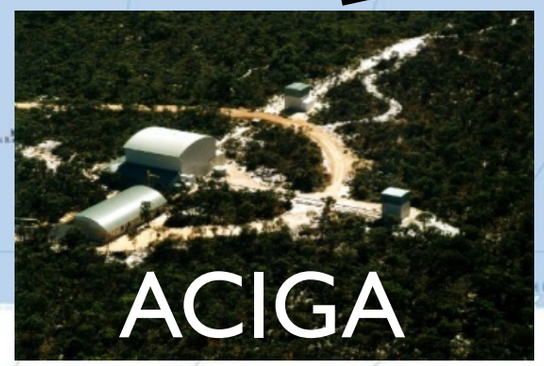

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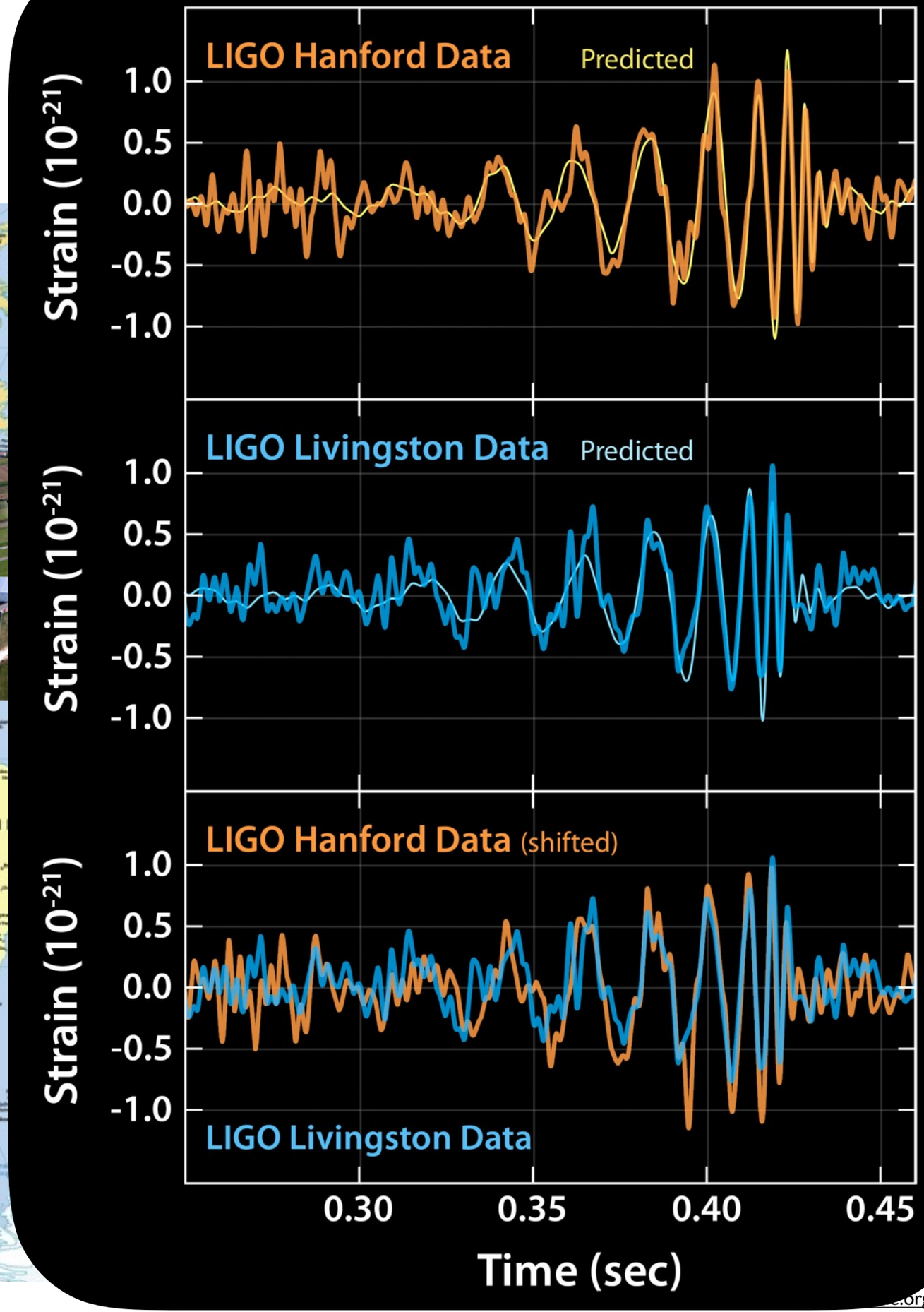

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two black holes merging

http://mediaassets.caltech.edu/gwave

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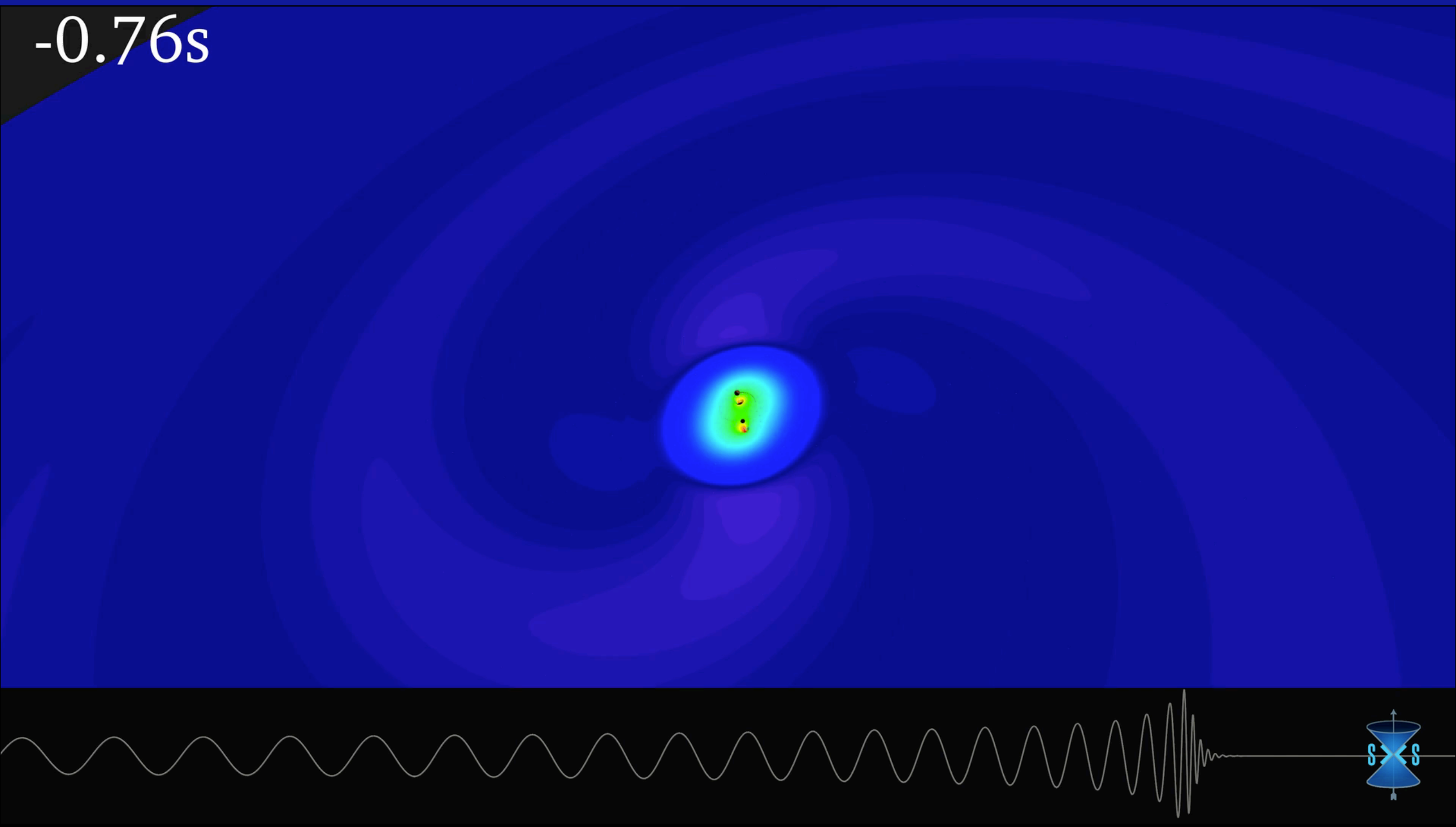
Simulation of the event



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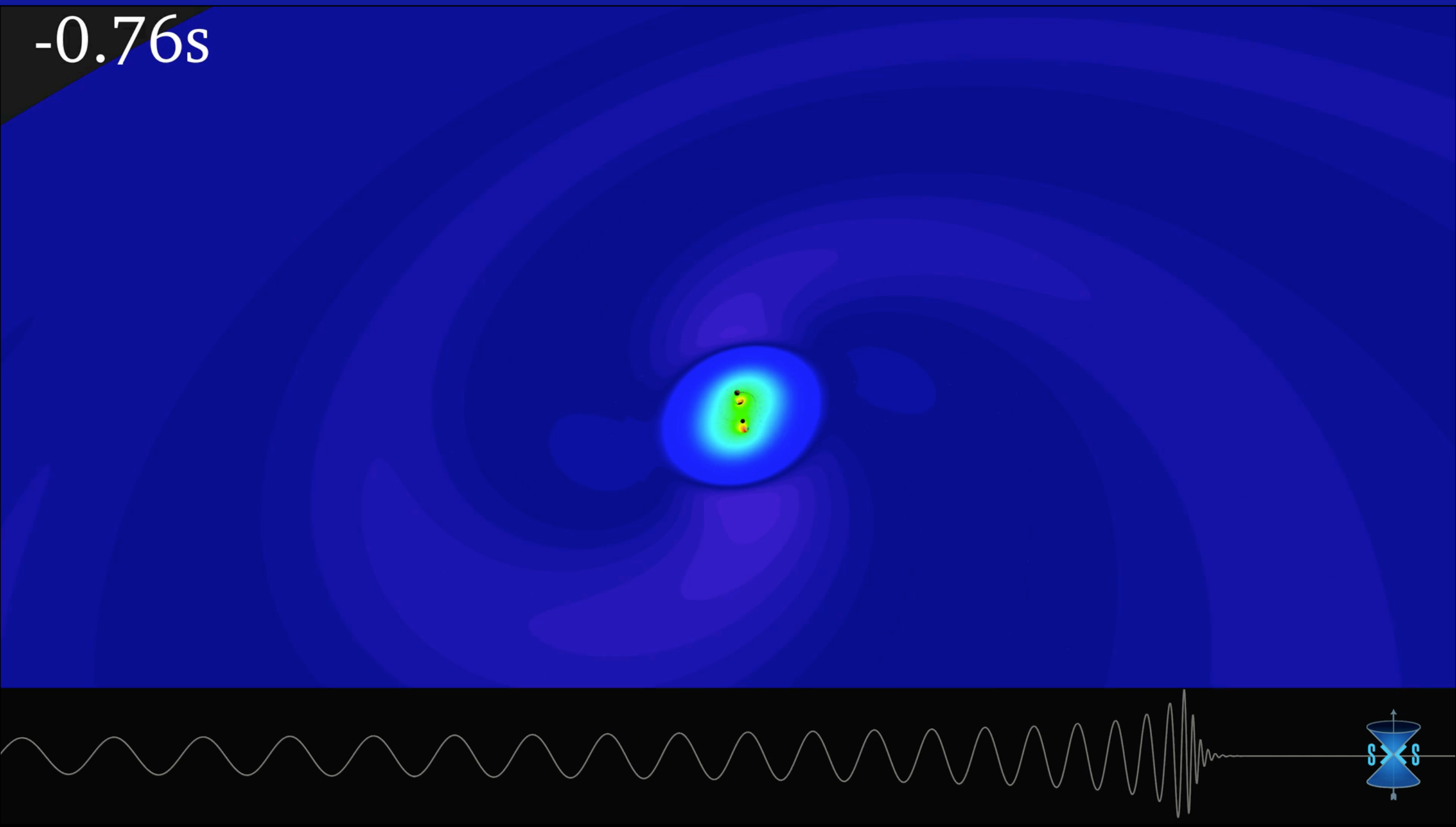

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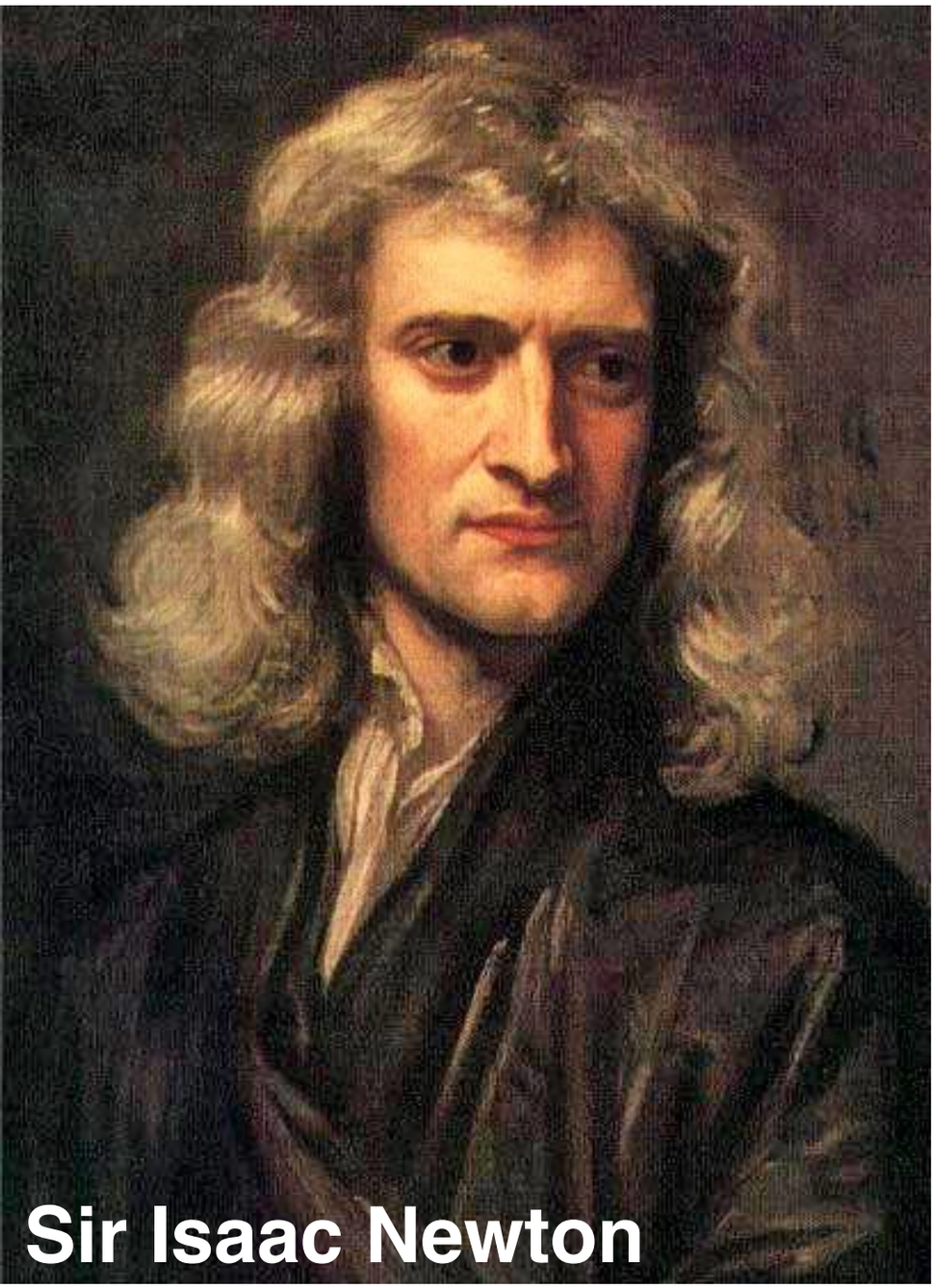
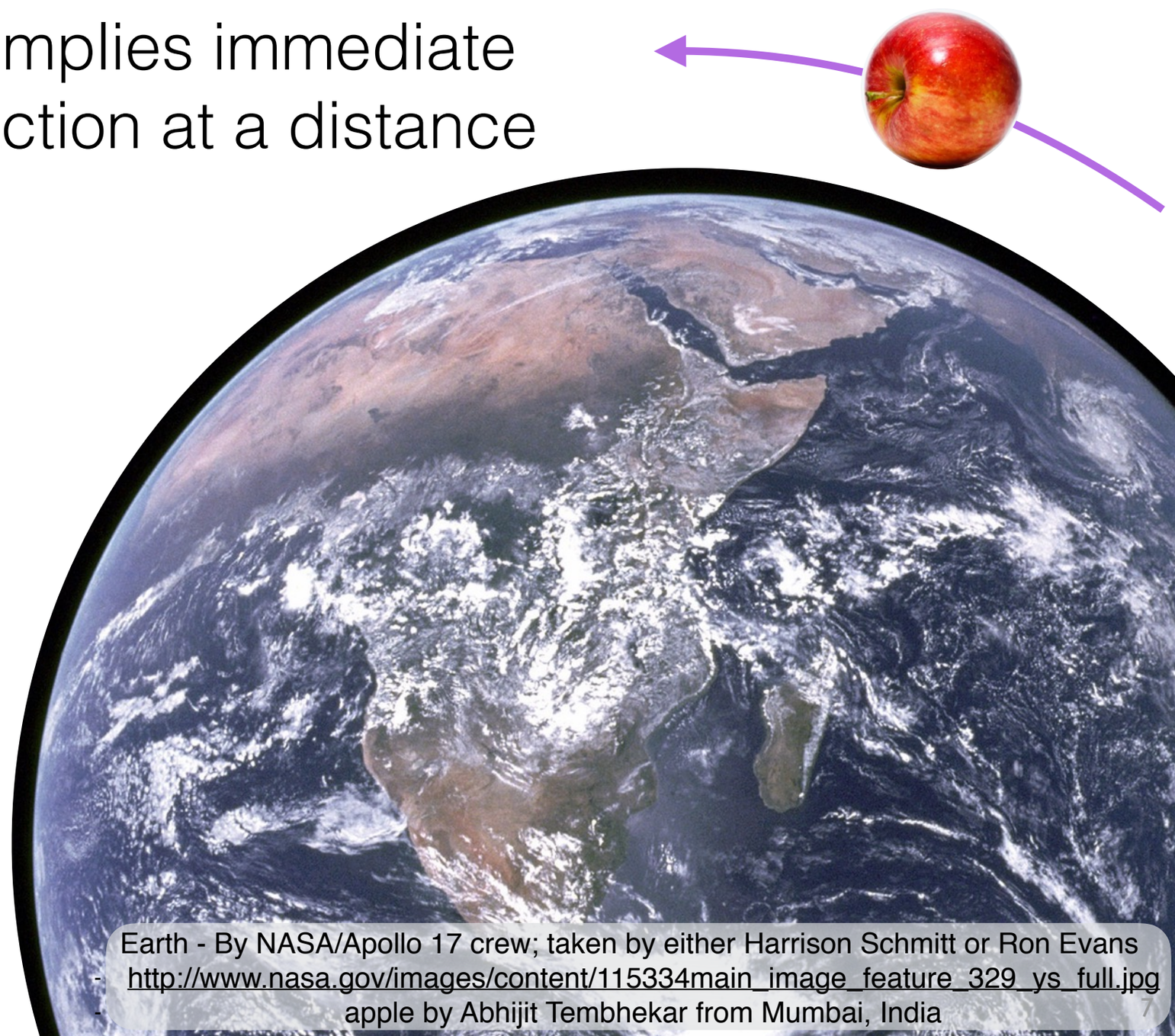
What is a Gravitational Wave?

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



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

Implies immediate
action at a distance



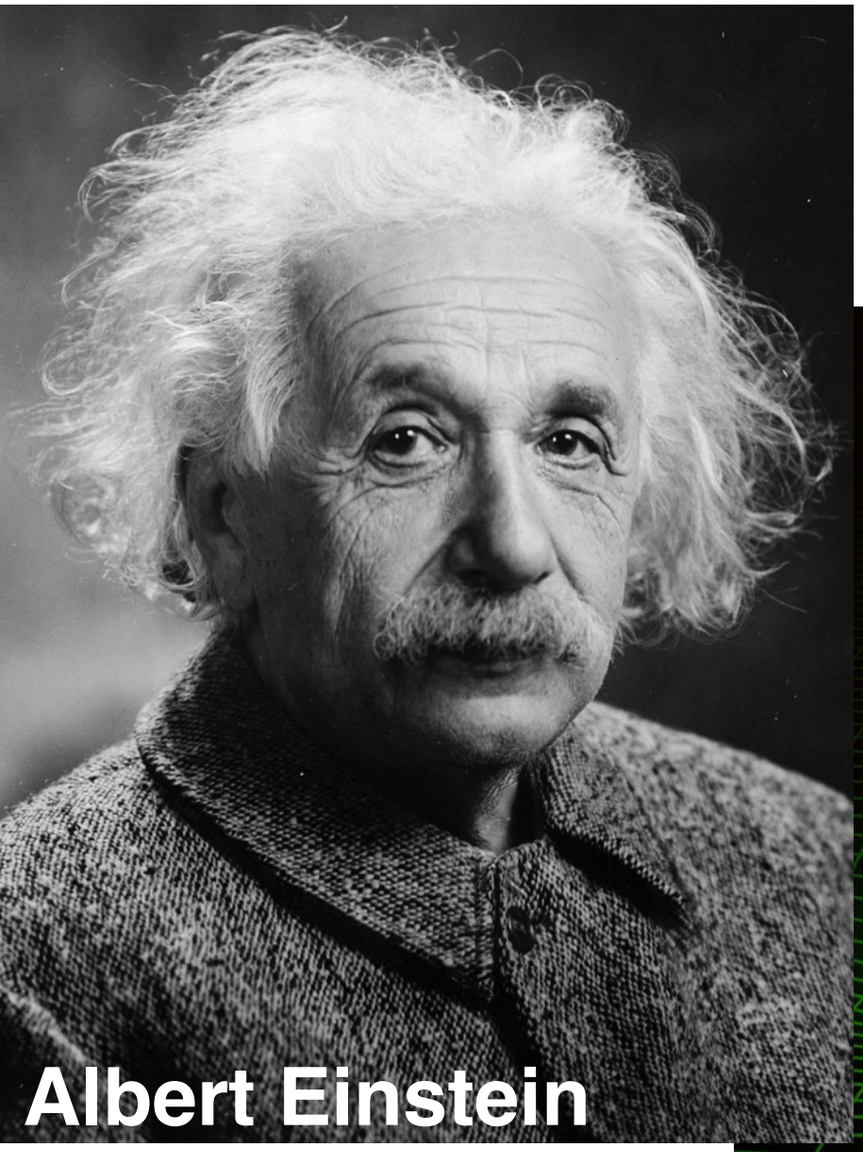
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

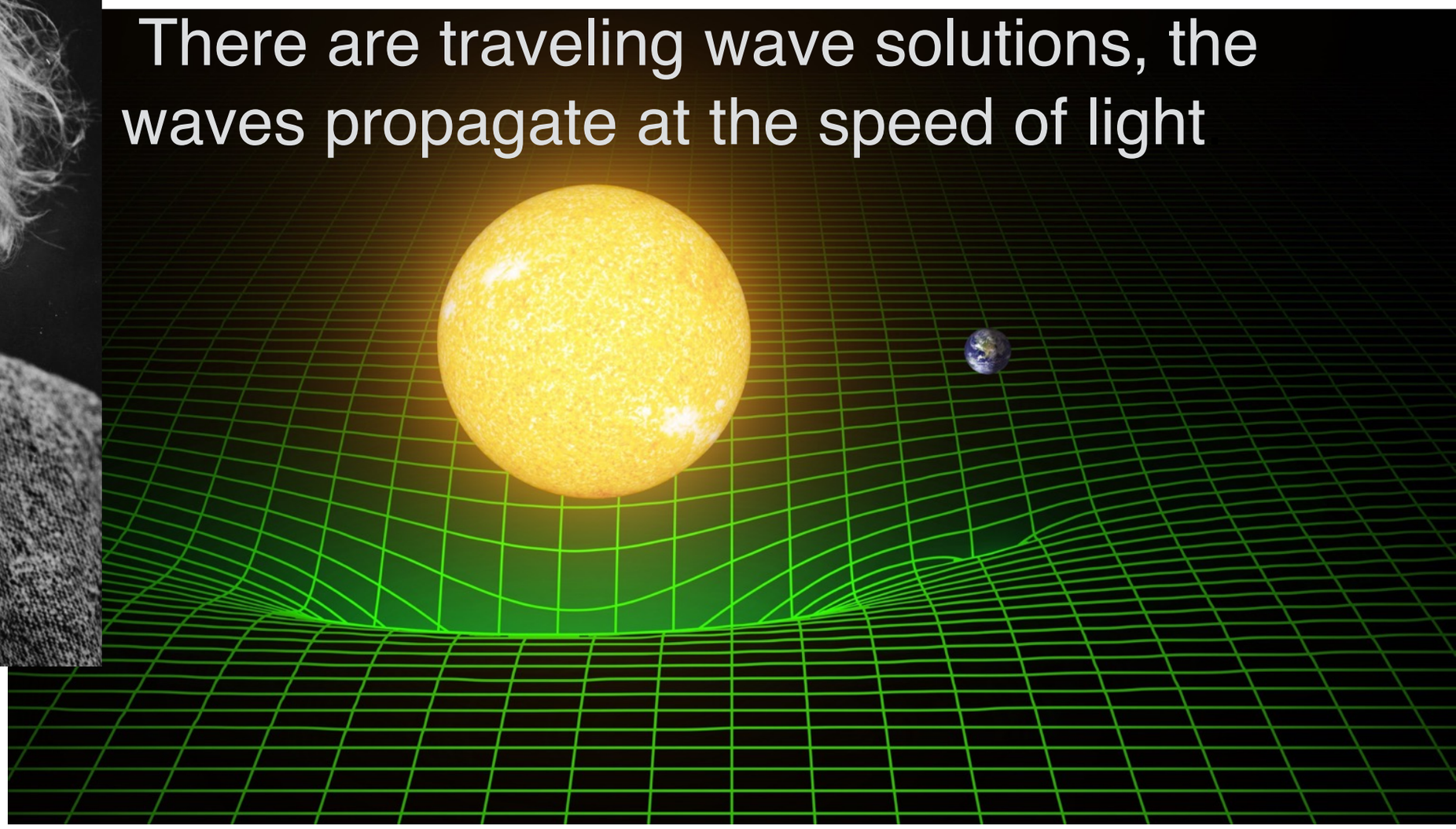
"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- 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.

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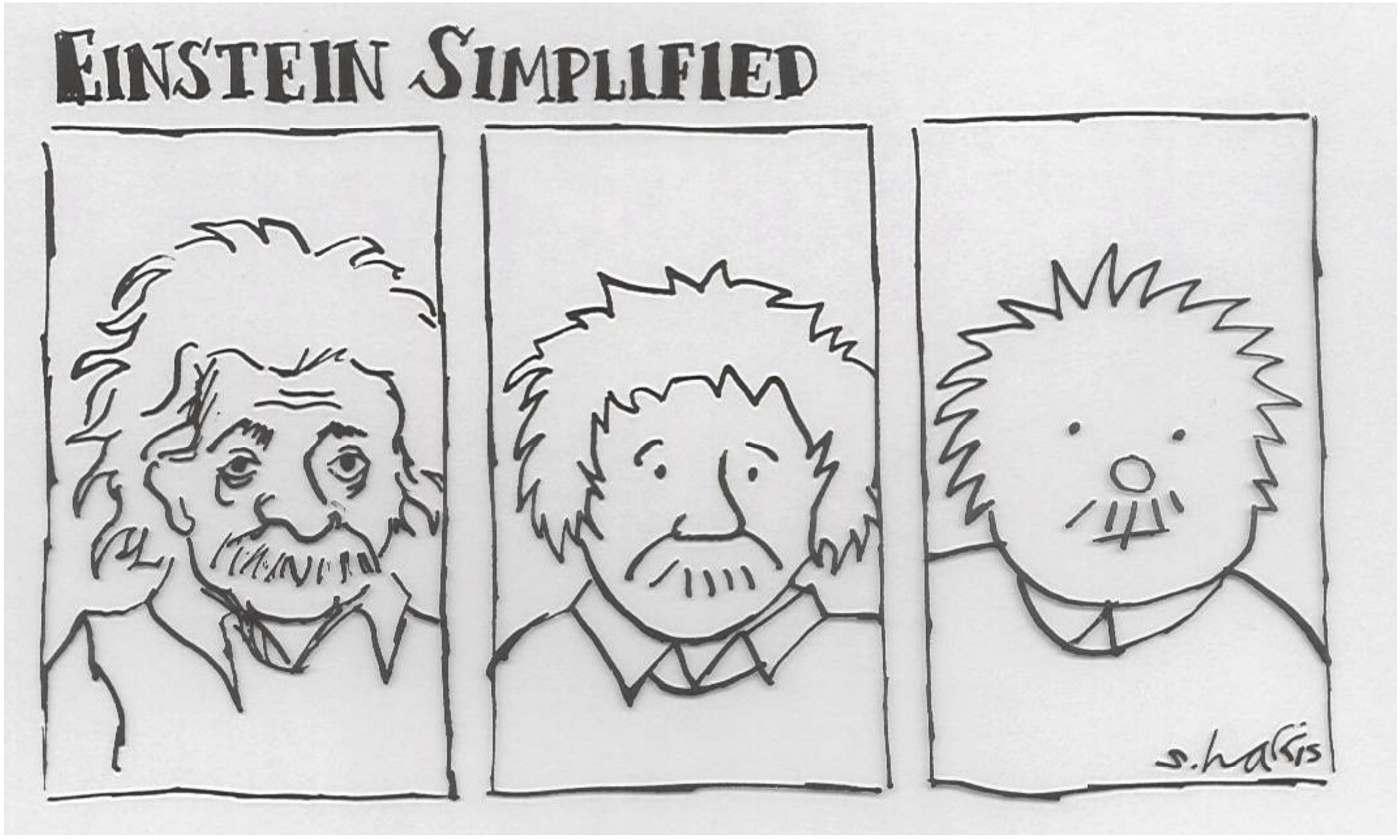

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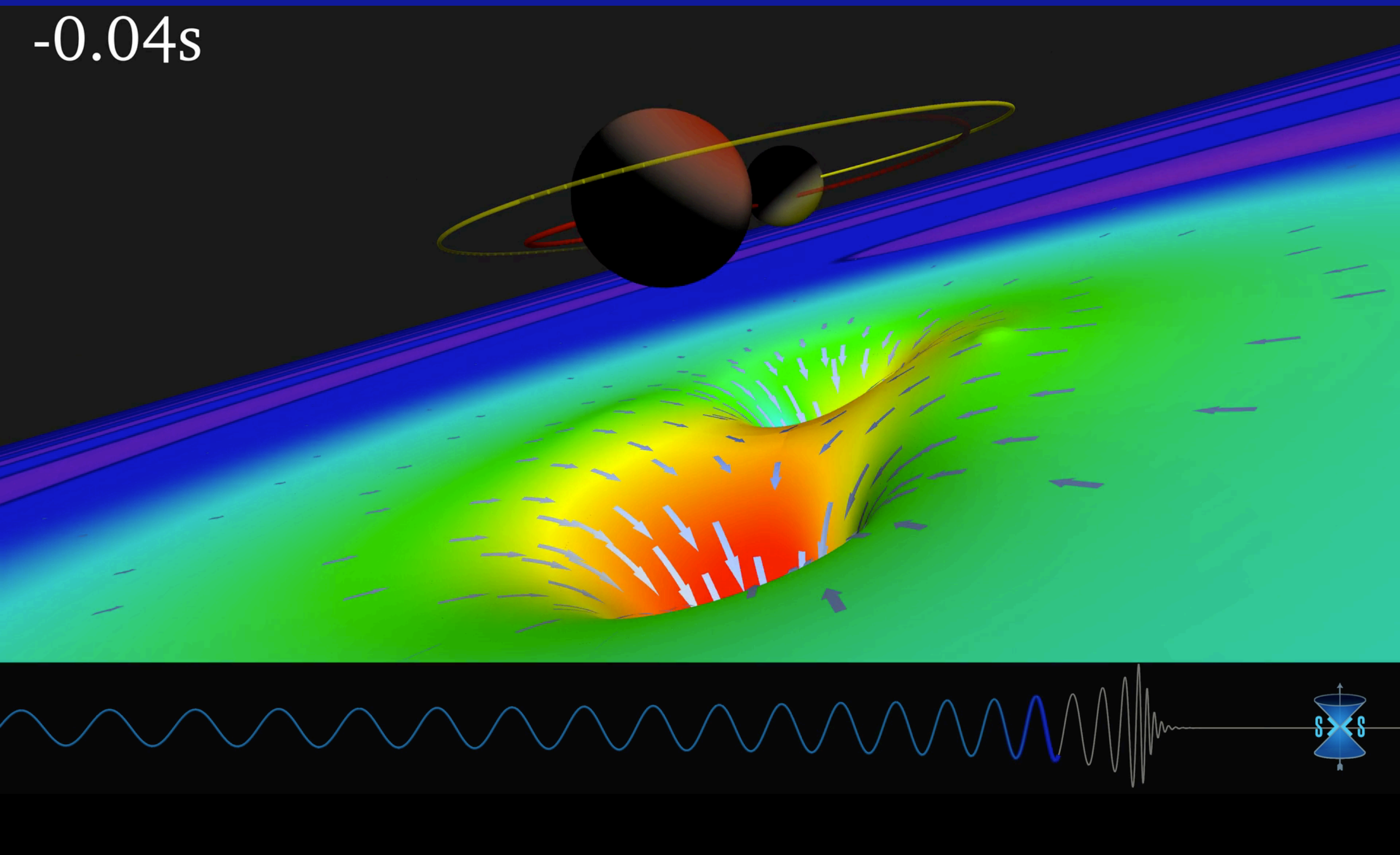

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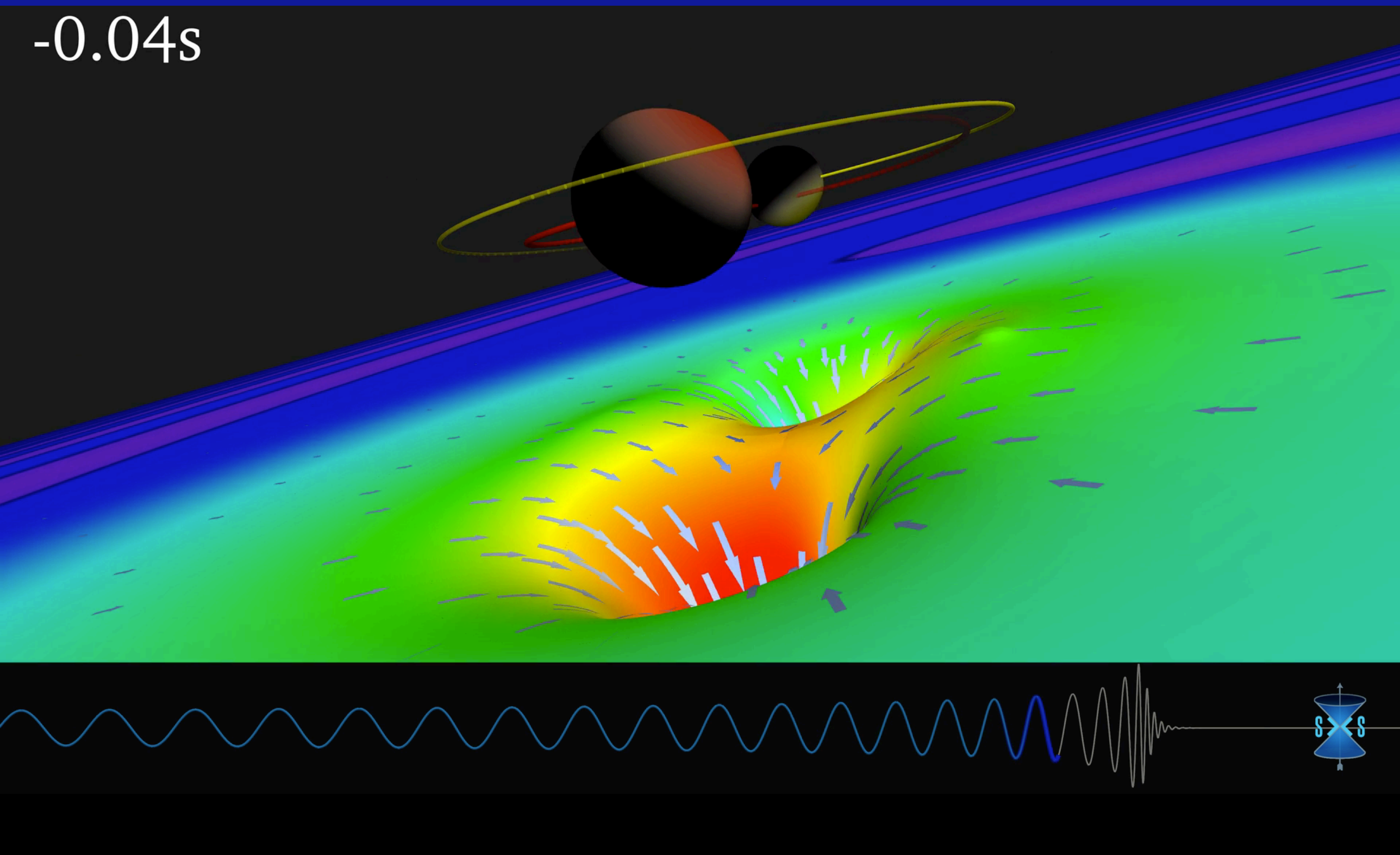
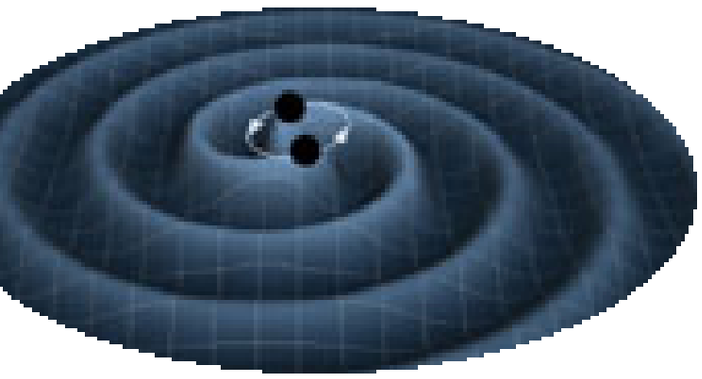
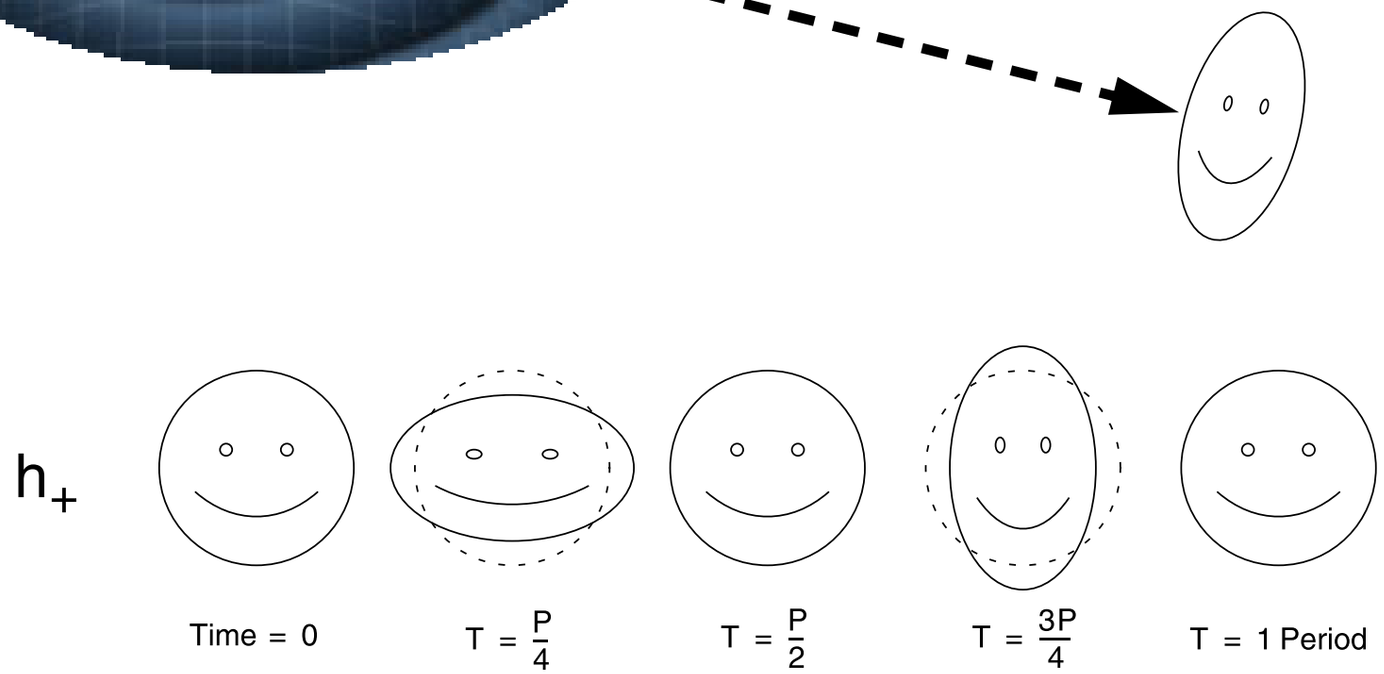
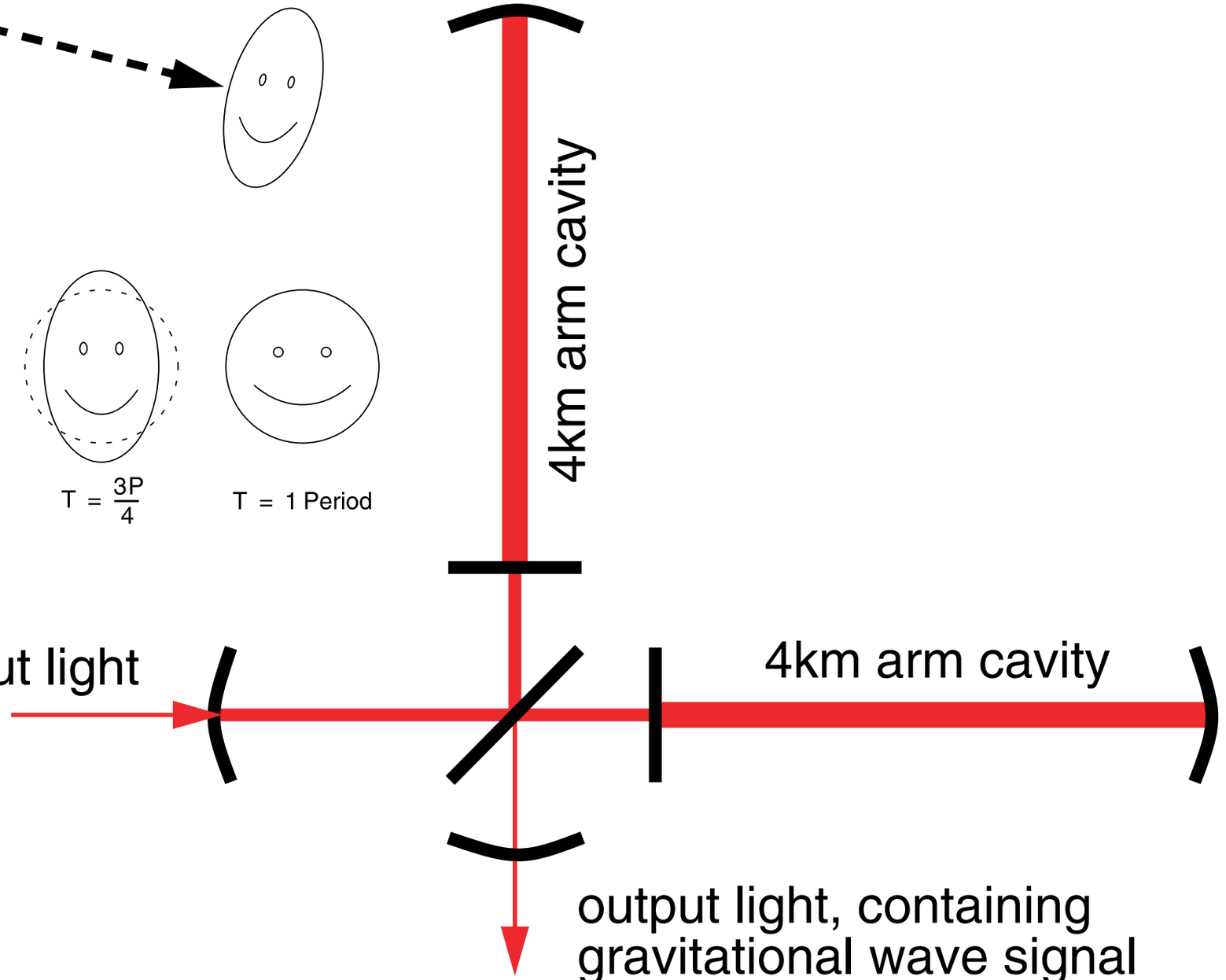


The LIGO concept



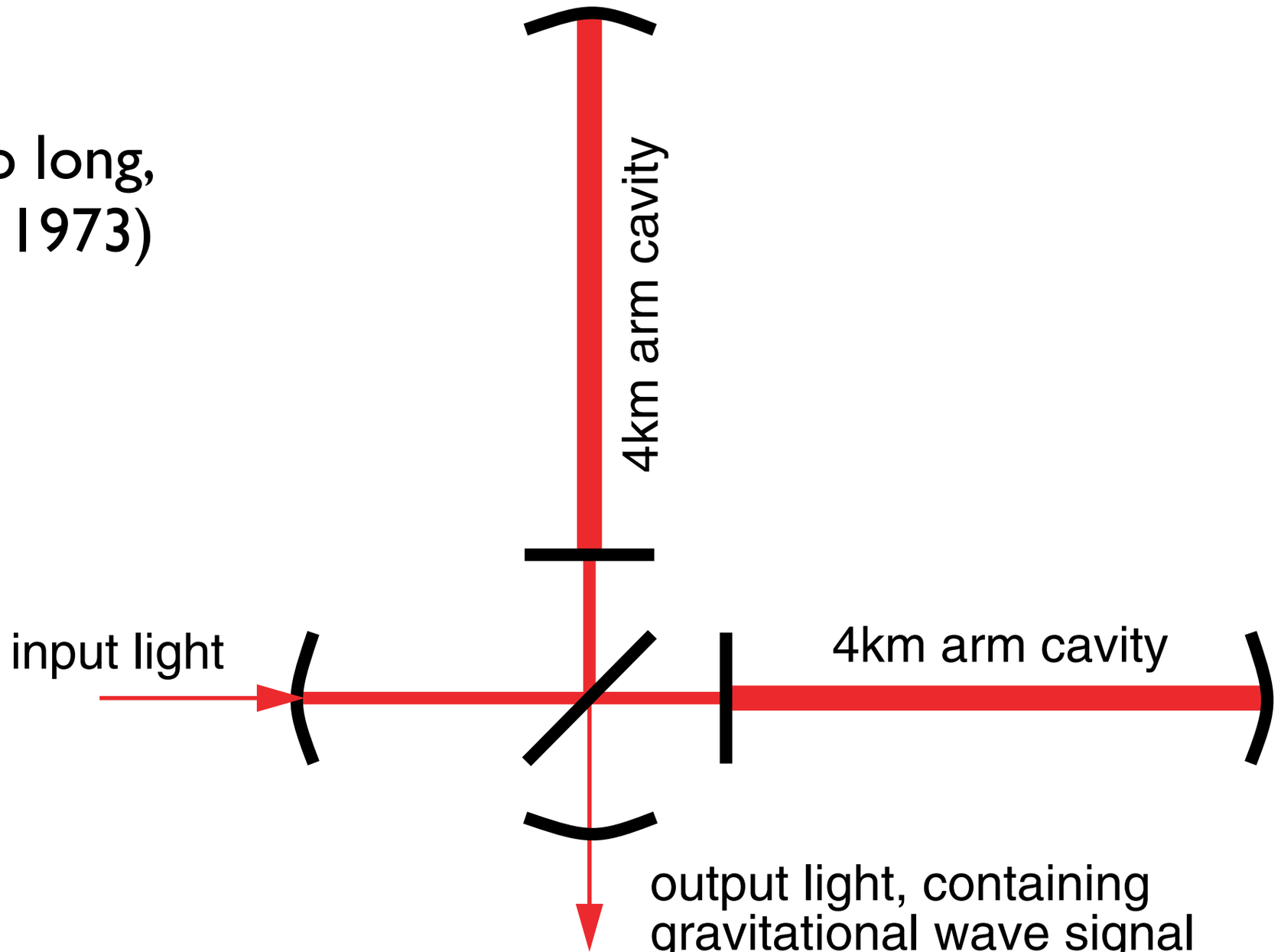


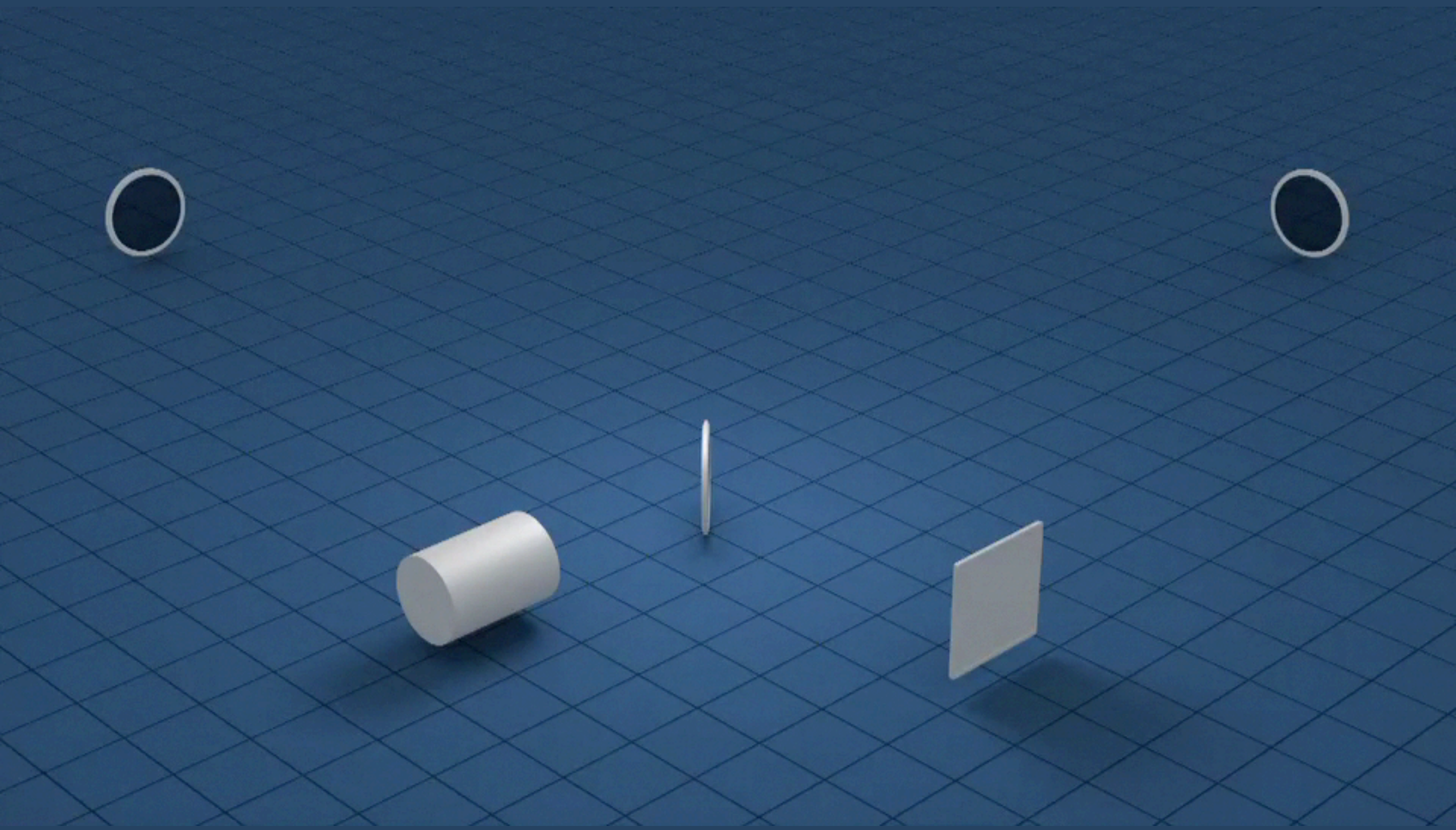


The LIGO concept
why it is nearly impossible

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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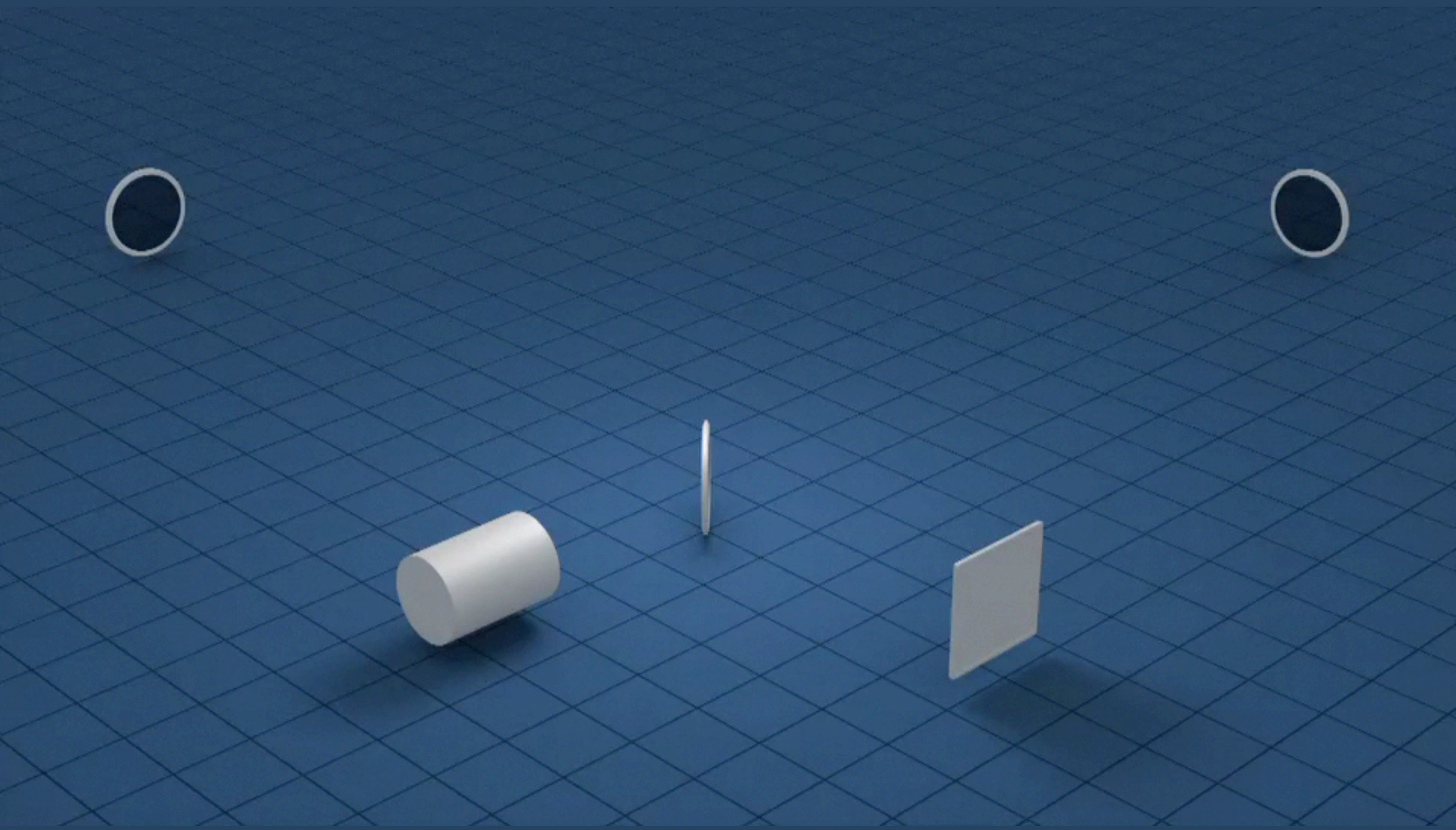

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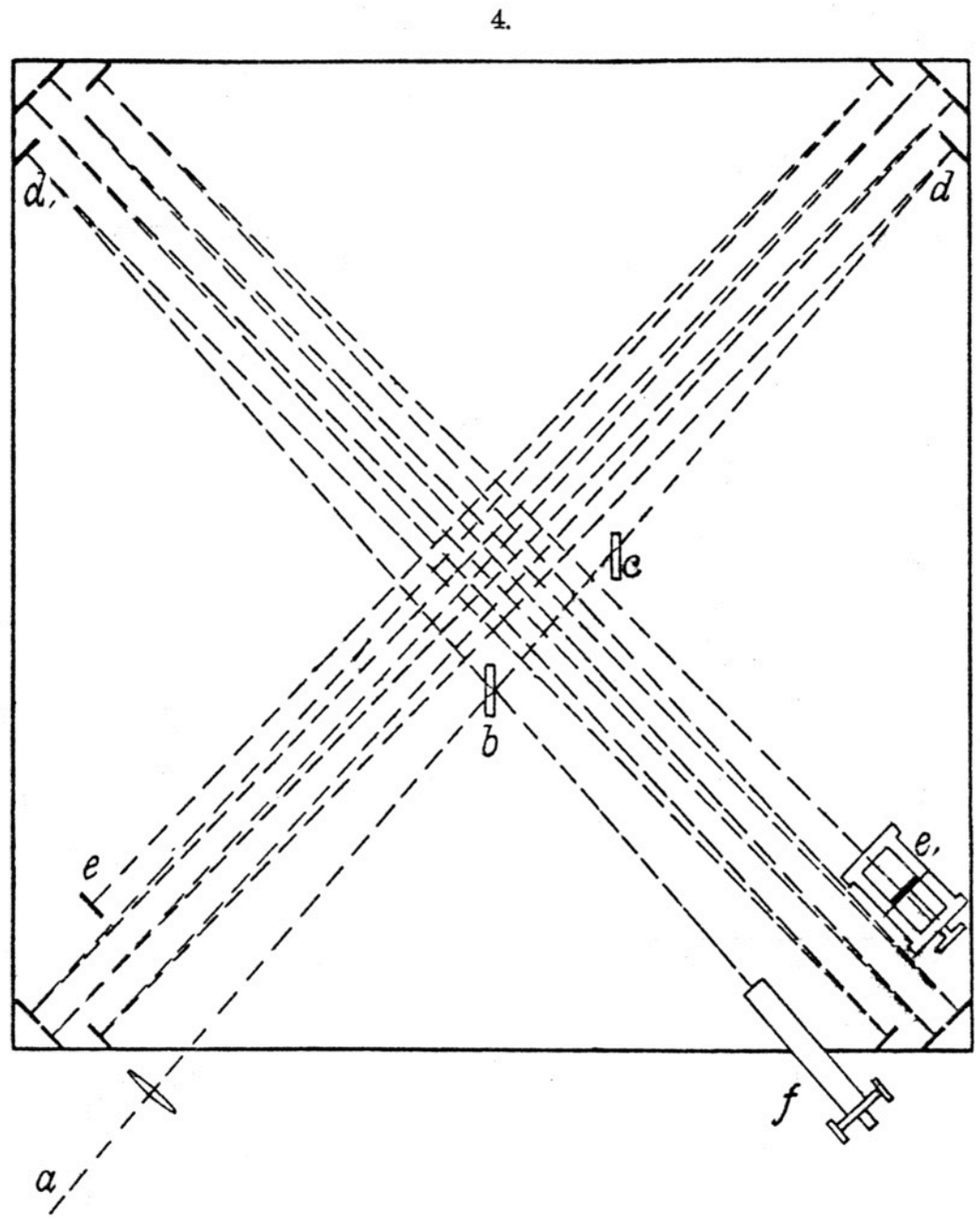
Michelson's Interferometer!

1887 experiment to measure
"luminiferous ether" with an interferometer



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

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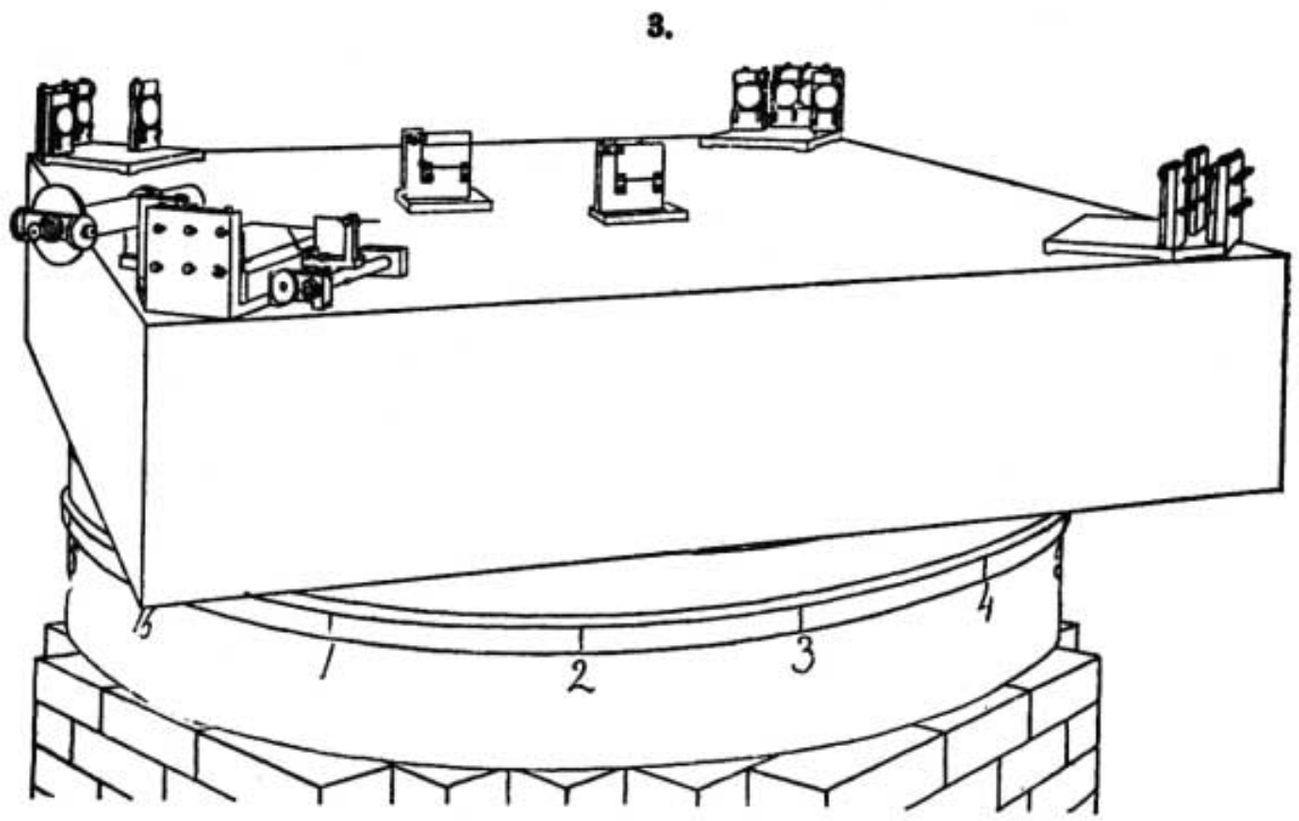

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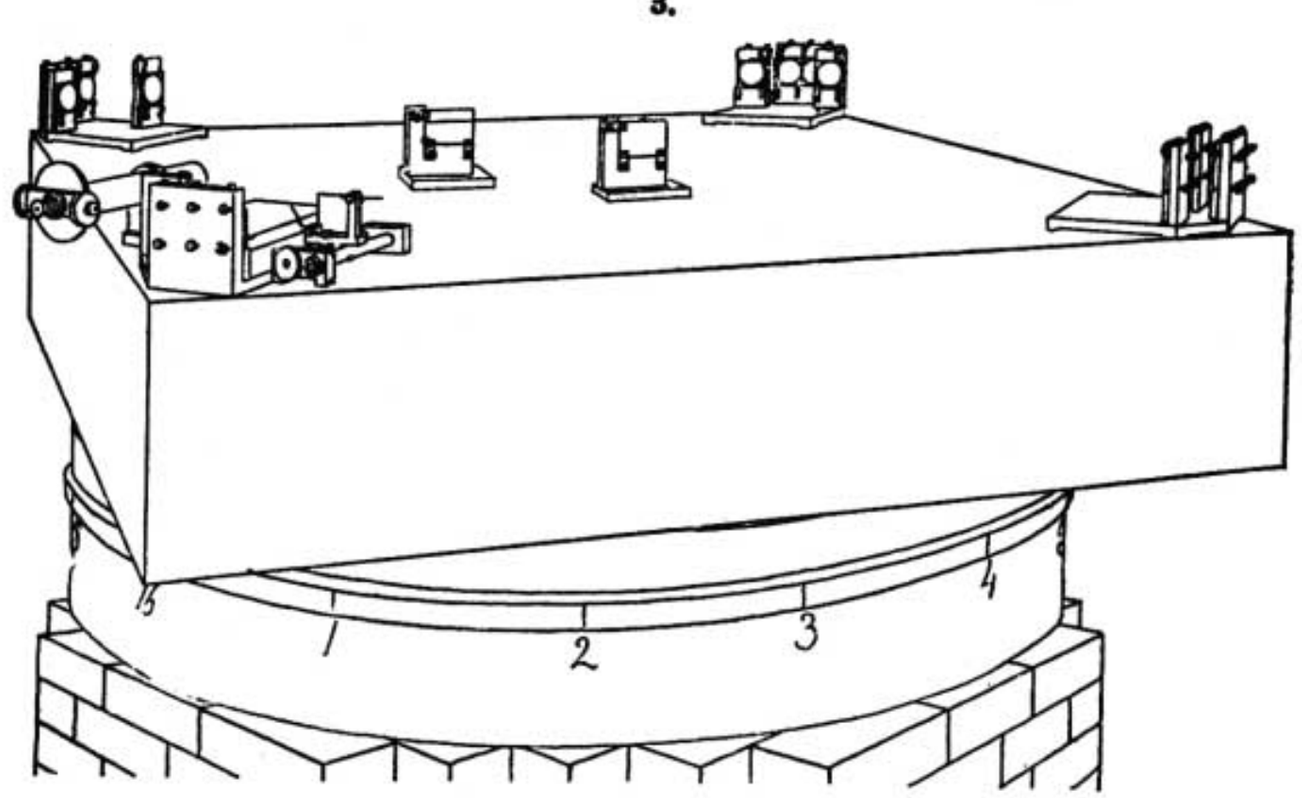
Michelson's Interferometer!

1887 experiment to measure "luminiferous ether" with an interferometer

In the first experiment one of the principal difficulties encountered was that of revolving the apparatus without producing distortion; and another was its extreme sensitiveness to vibration. This was so great that it was impossible to see the interference fringes except at brief intervals when working in the city, even at two o'clock in the morning.

3.



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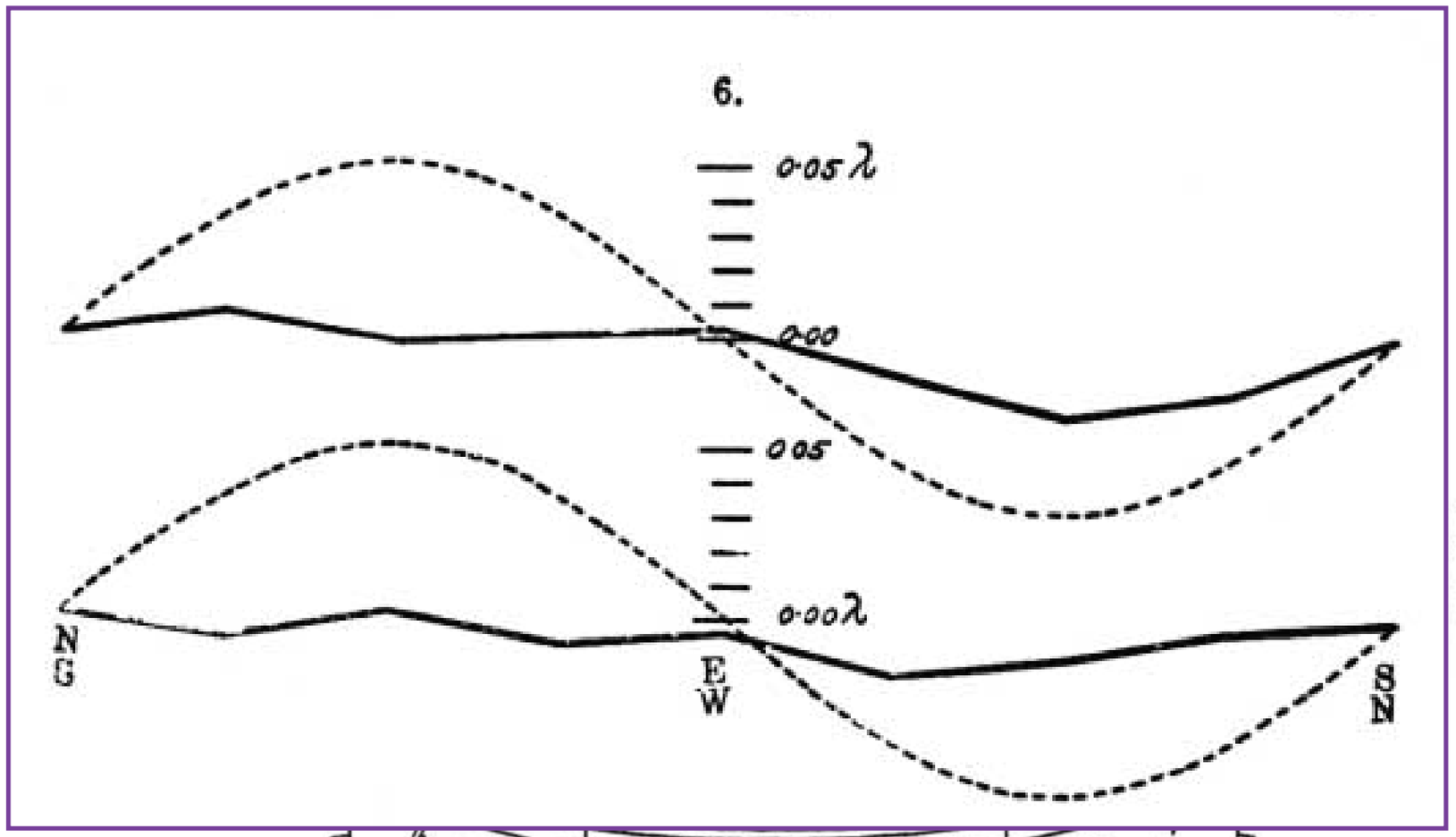

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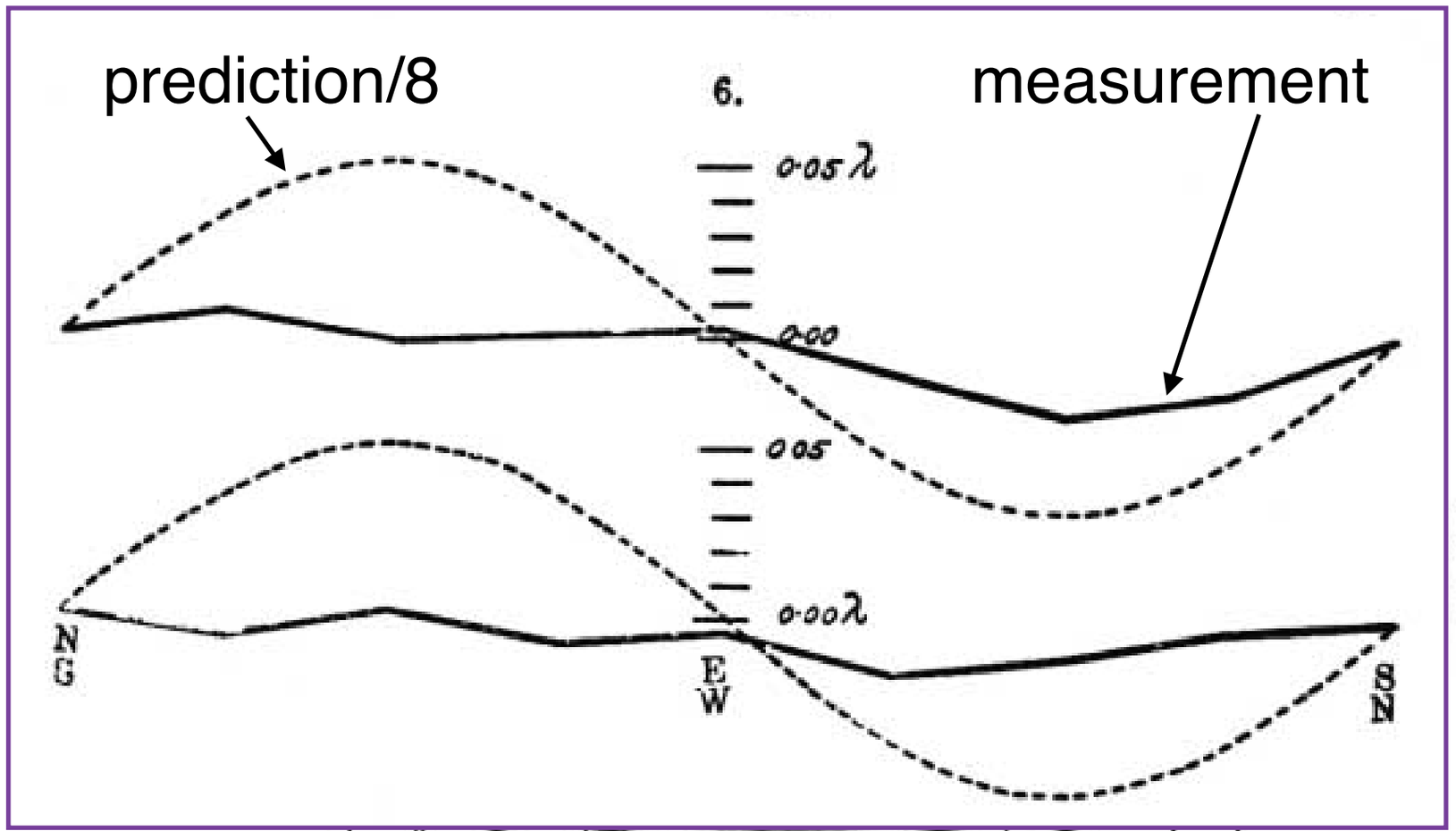

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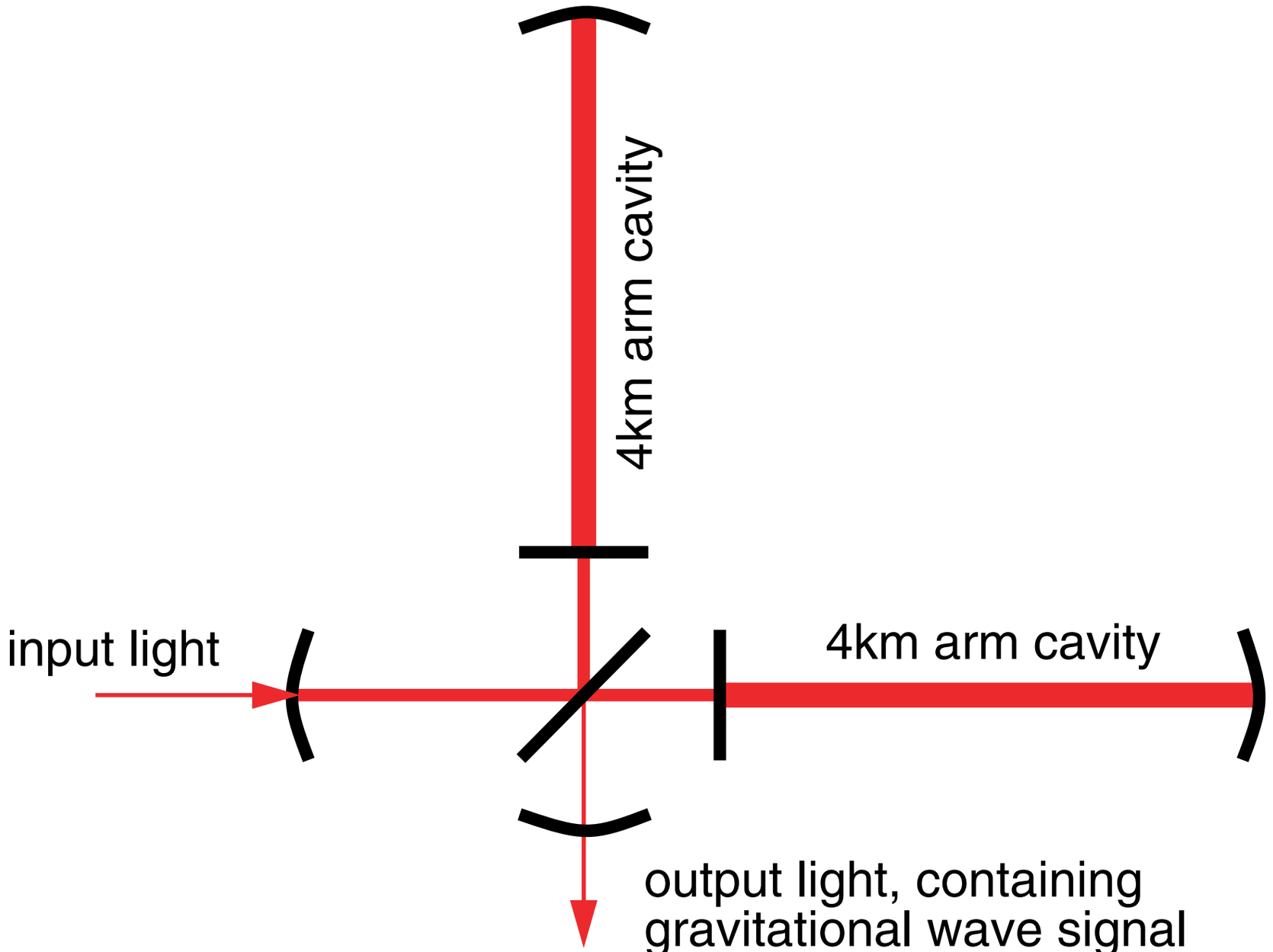

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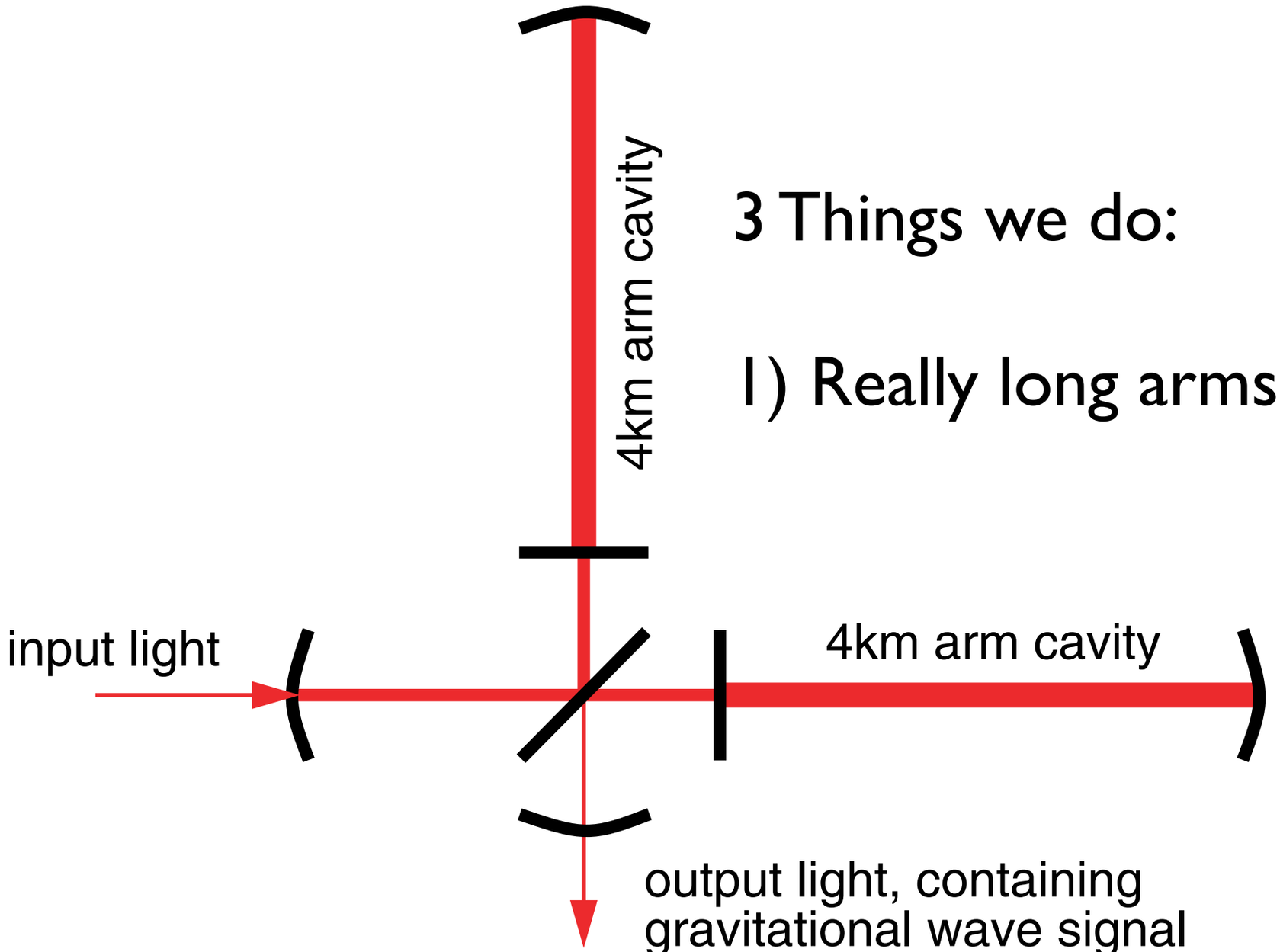
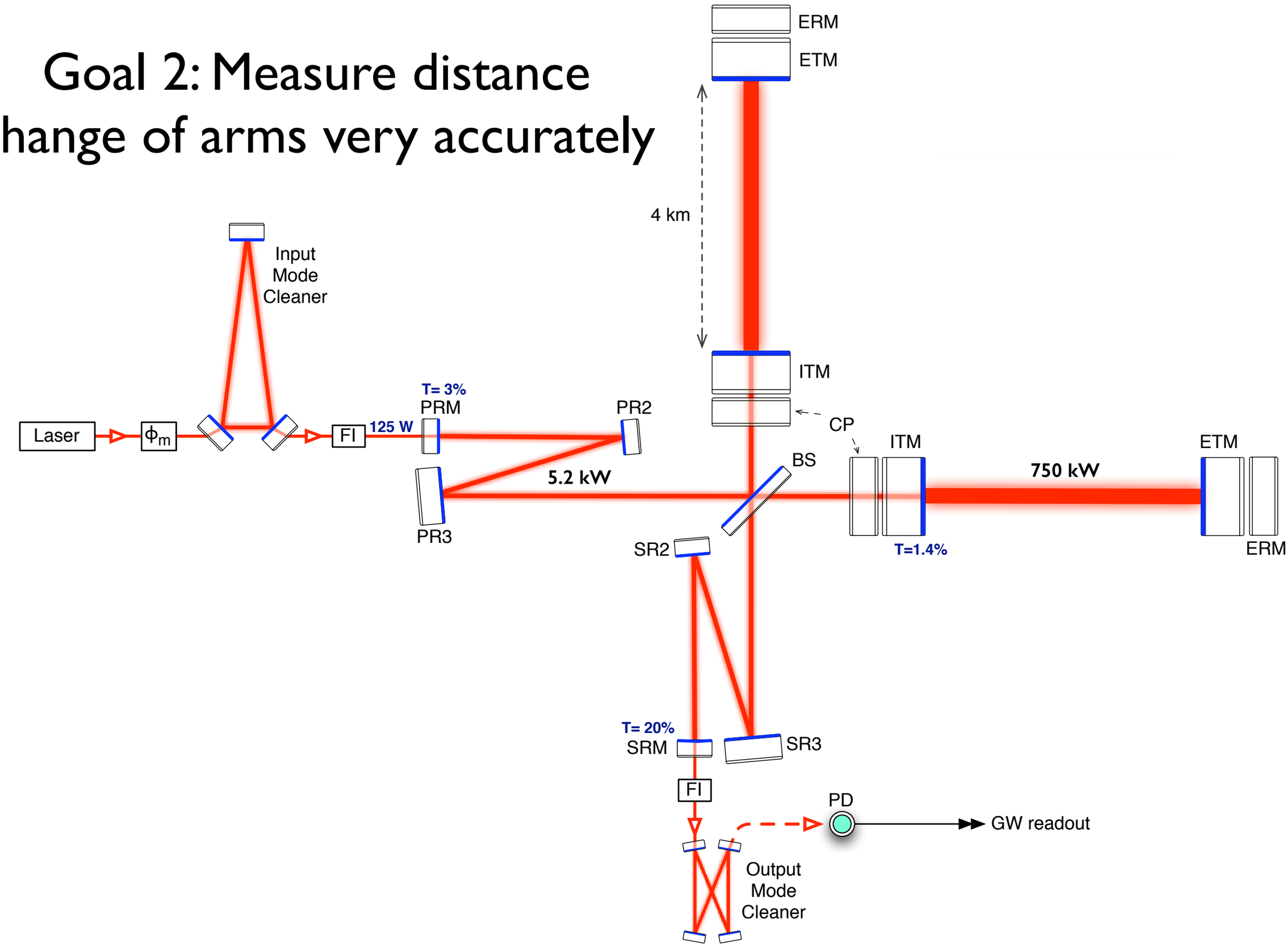


3 Things we do:

1) Really long arms.

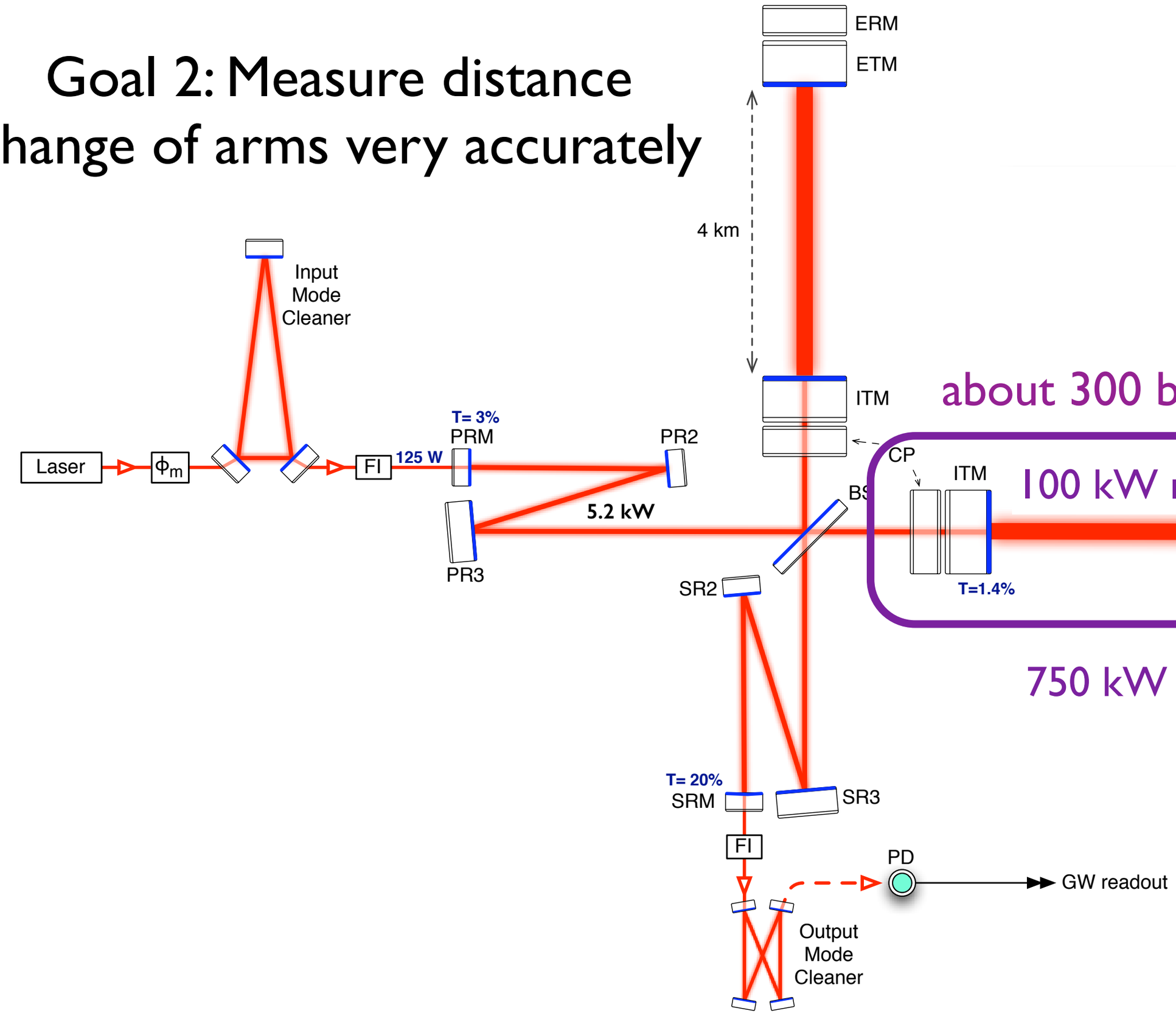
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately



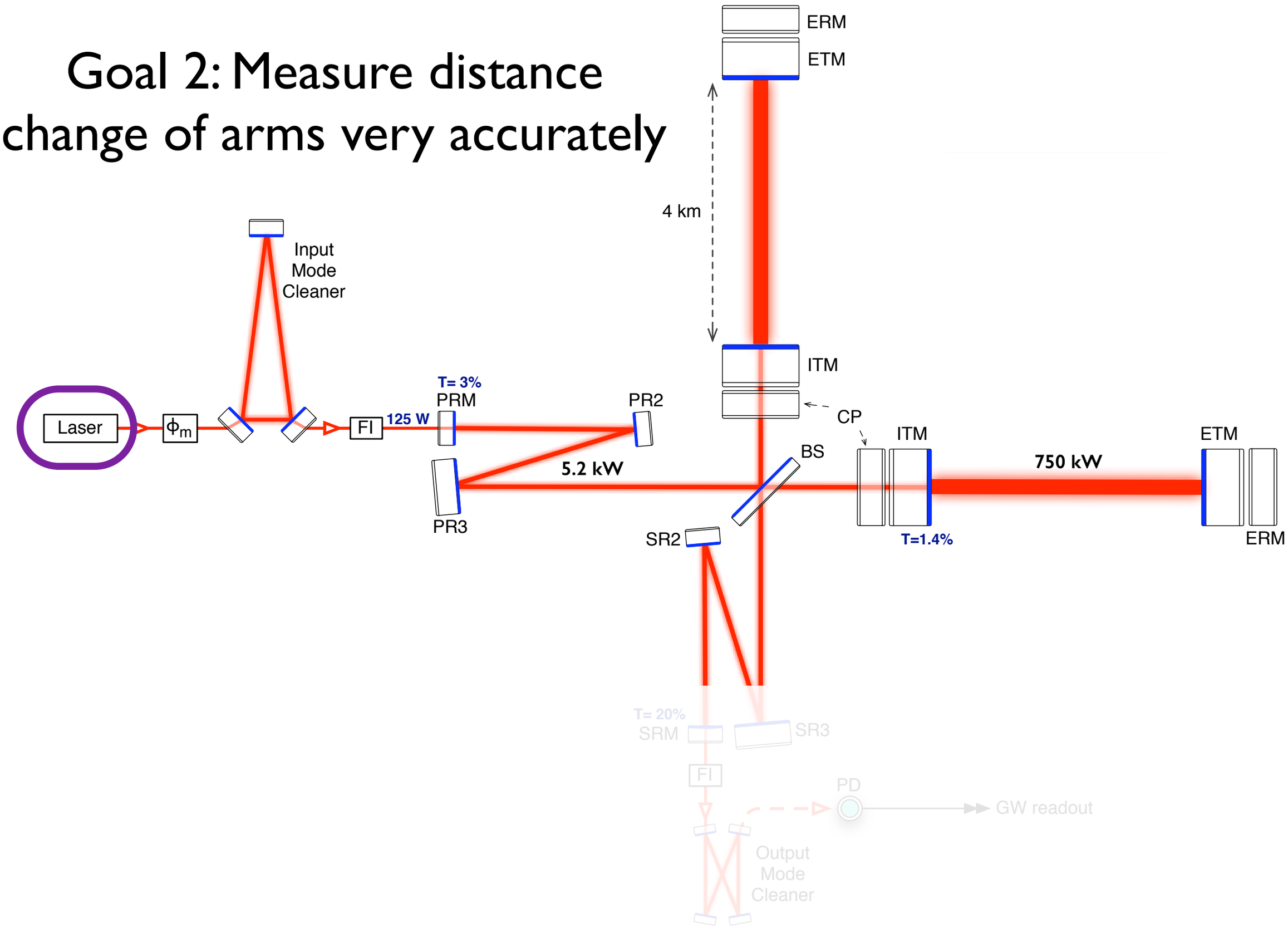
Fabry-Perot arms

Goal 2: Measure distance change of arms very accurately



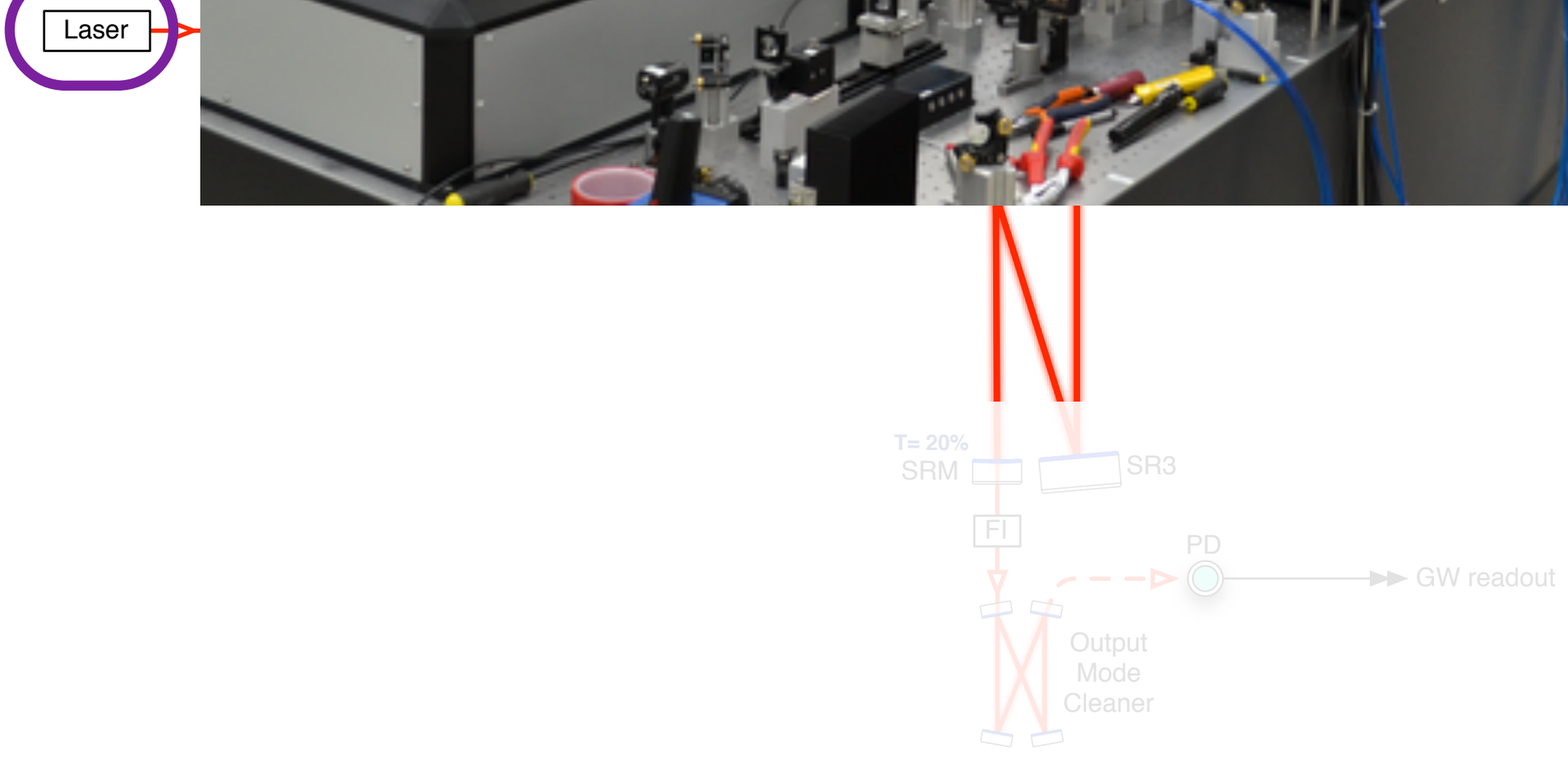
Power

Goal 2: Measure distance change of arms very accurately



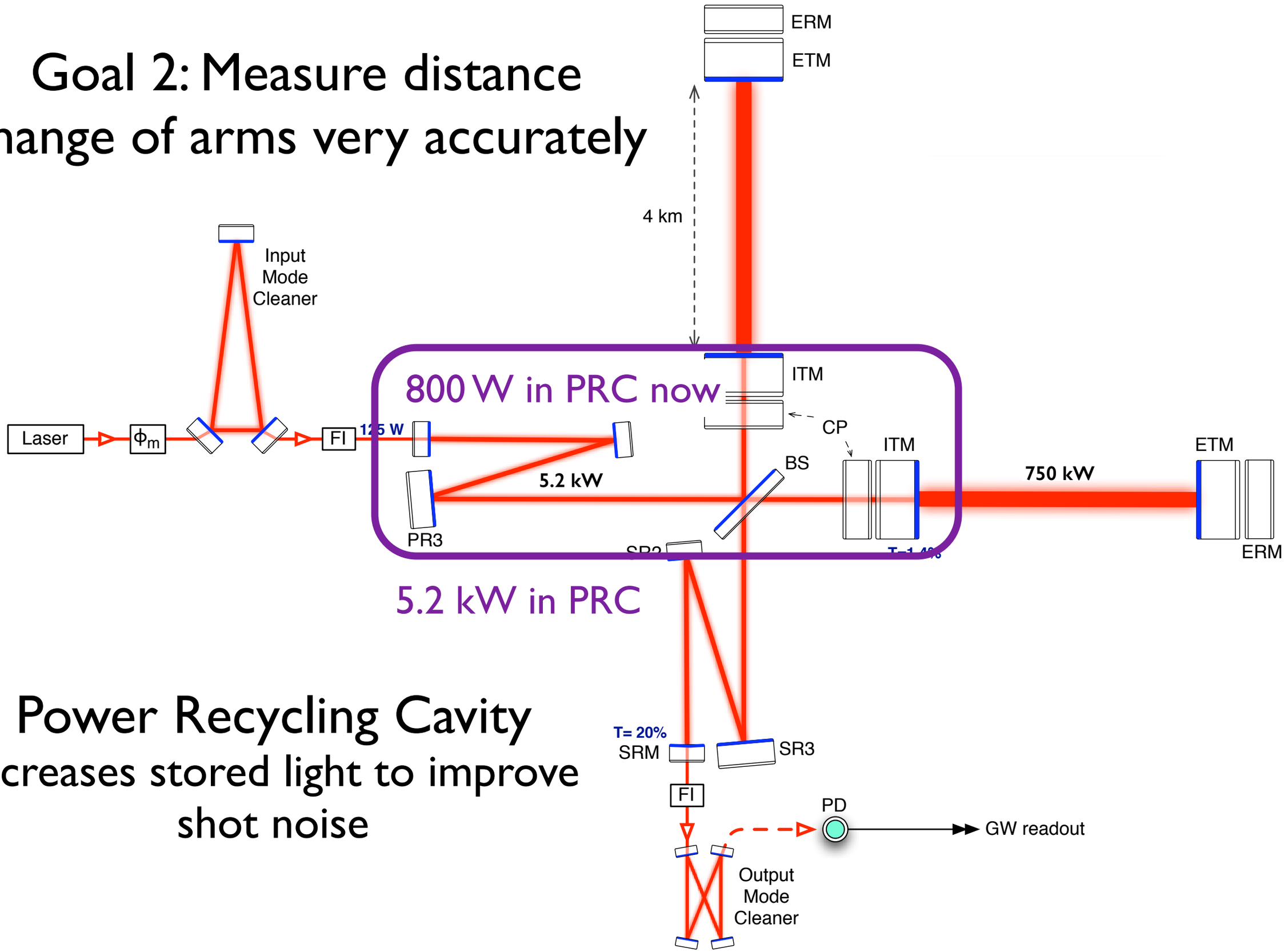
Power

Goa
change



Power recycling

Goal 2: Measure distance change of arms very accurately

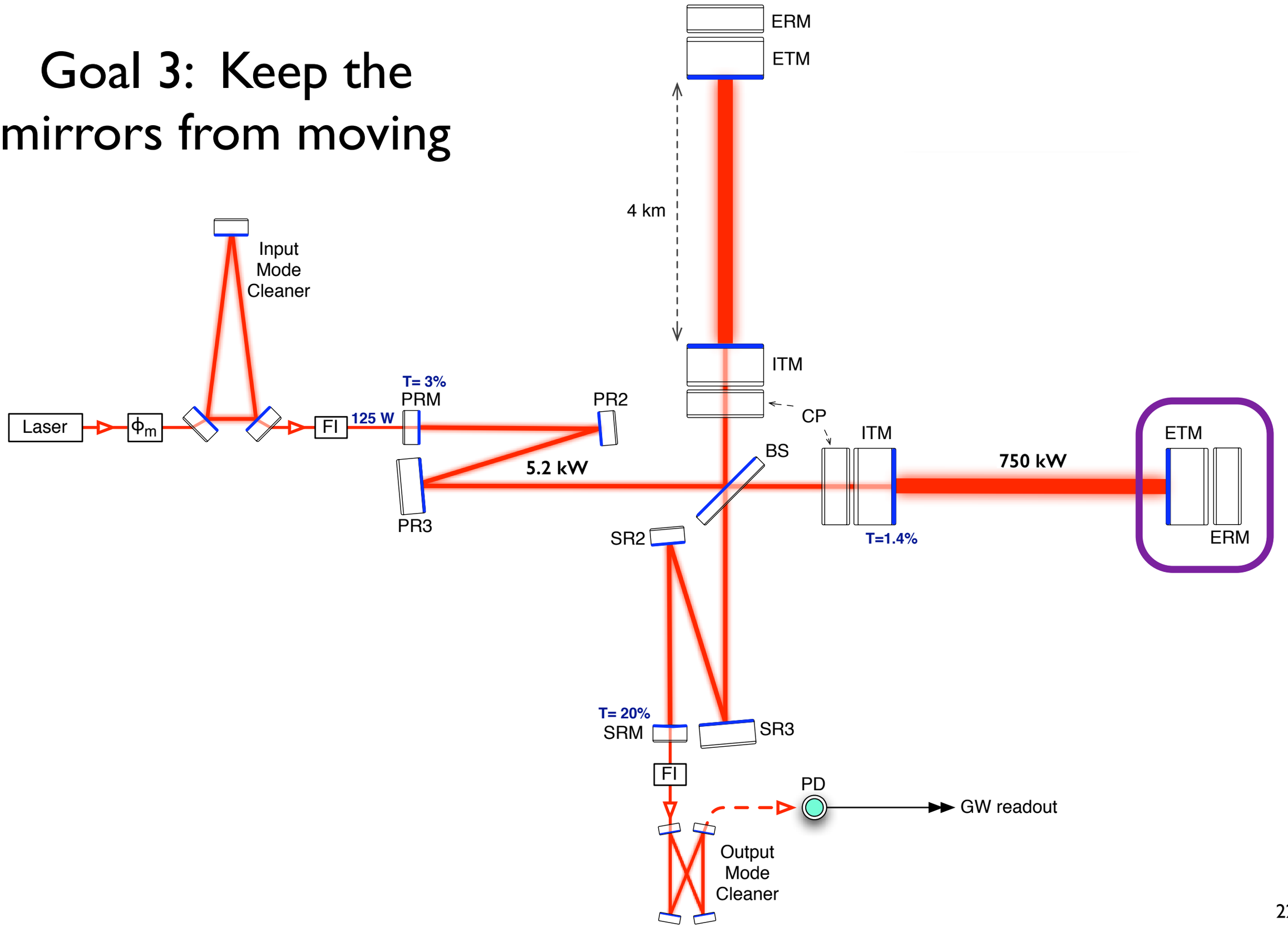


Power Recycling Cavity

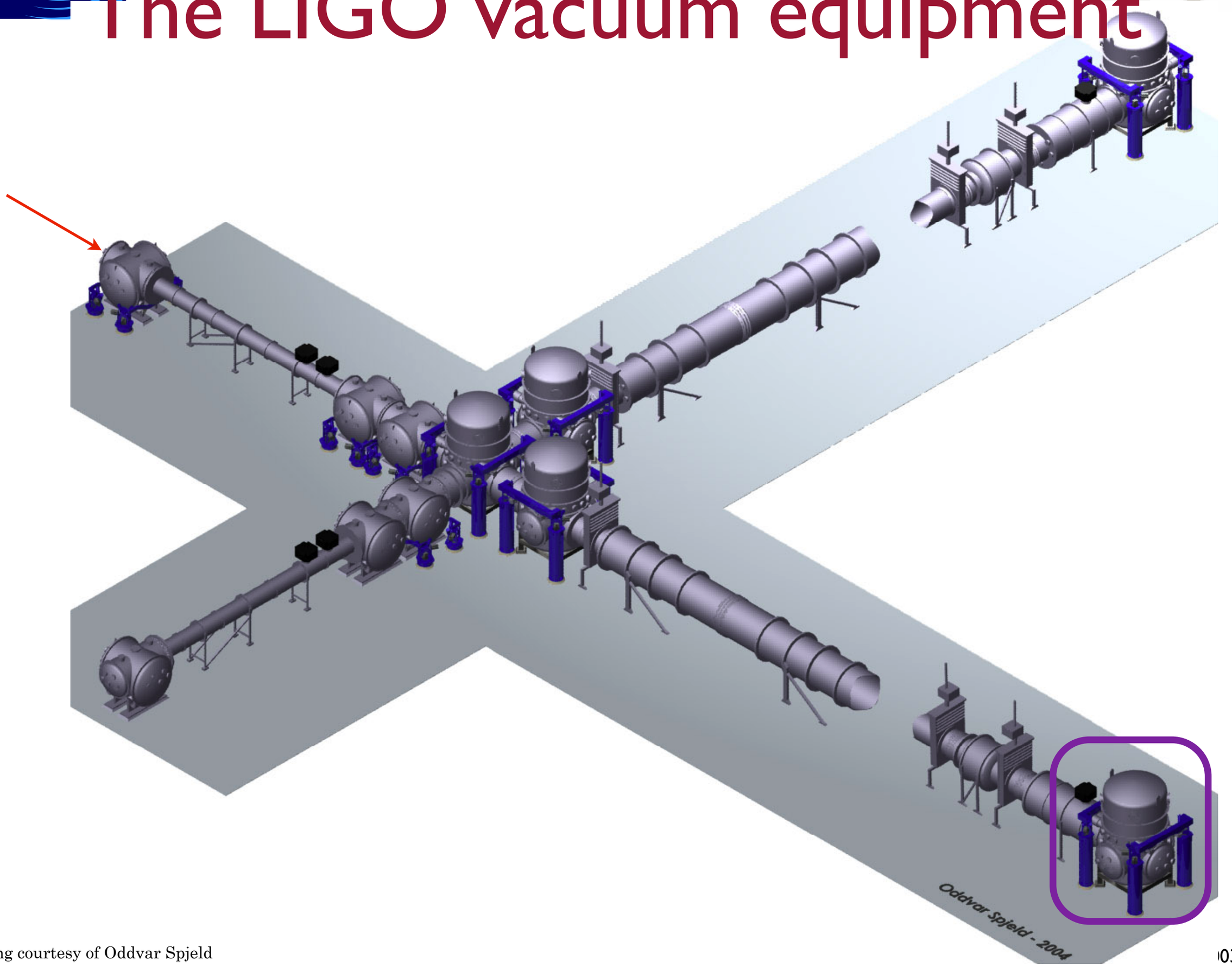
increases stored light to improve shot noise

Layout of the interferometer

Goal 3: Keep the mirrors from moving

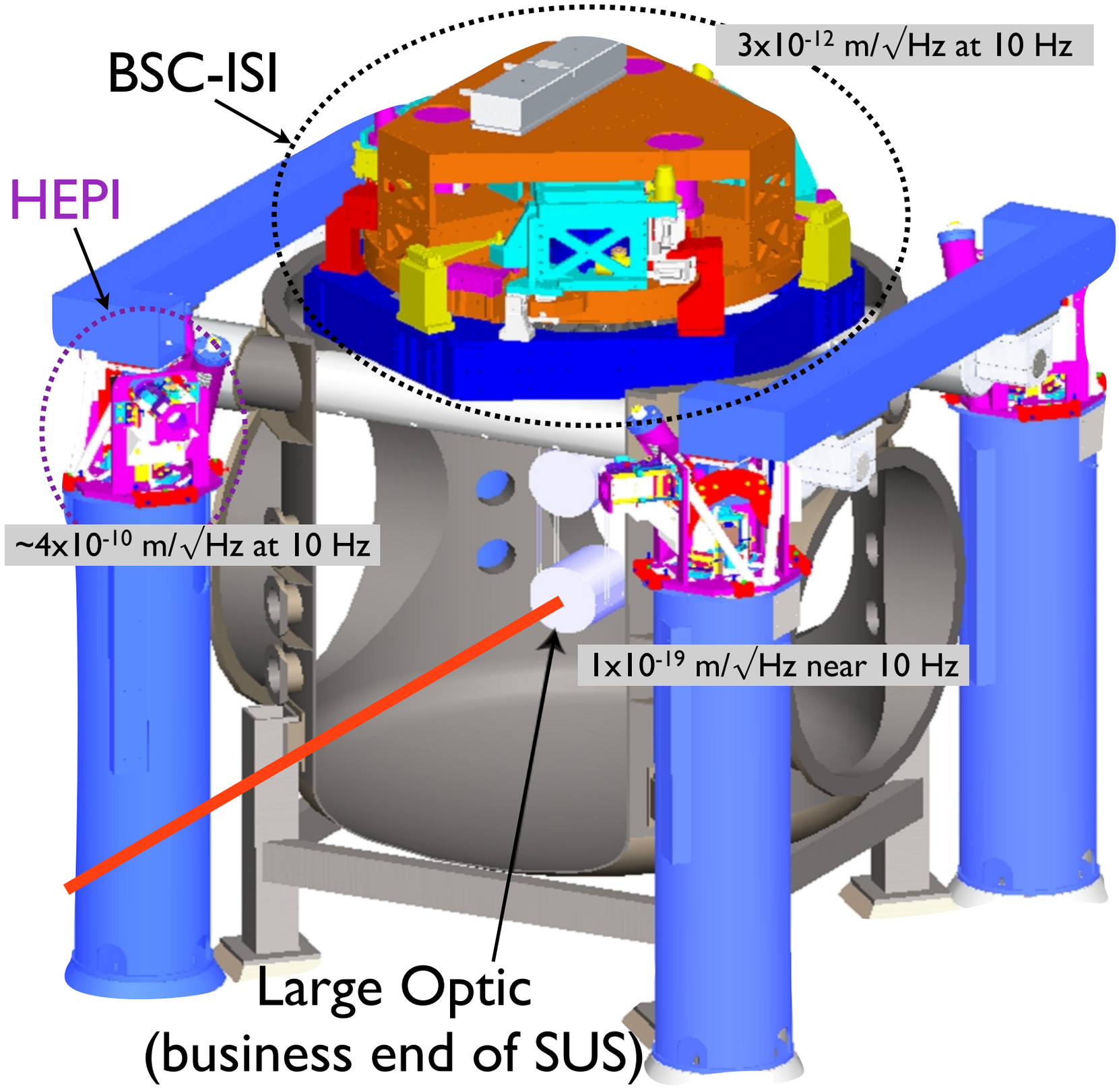


The LIGO vacuum equipment



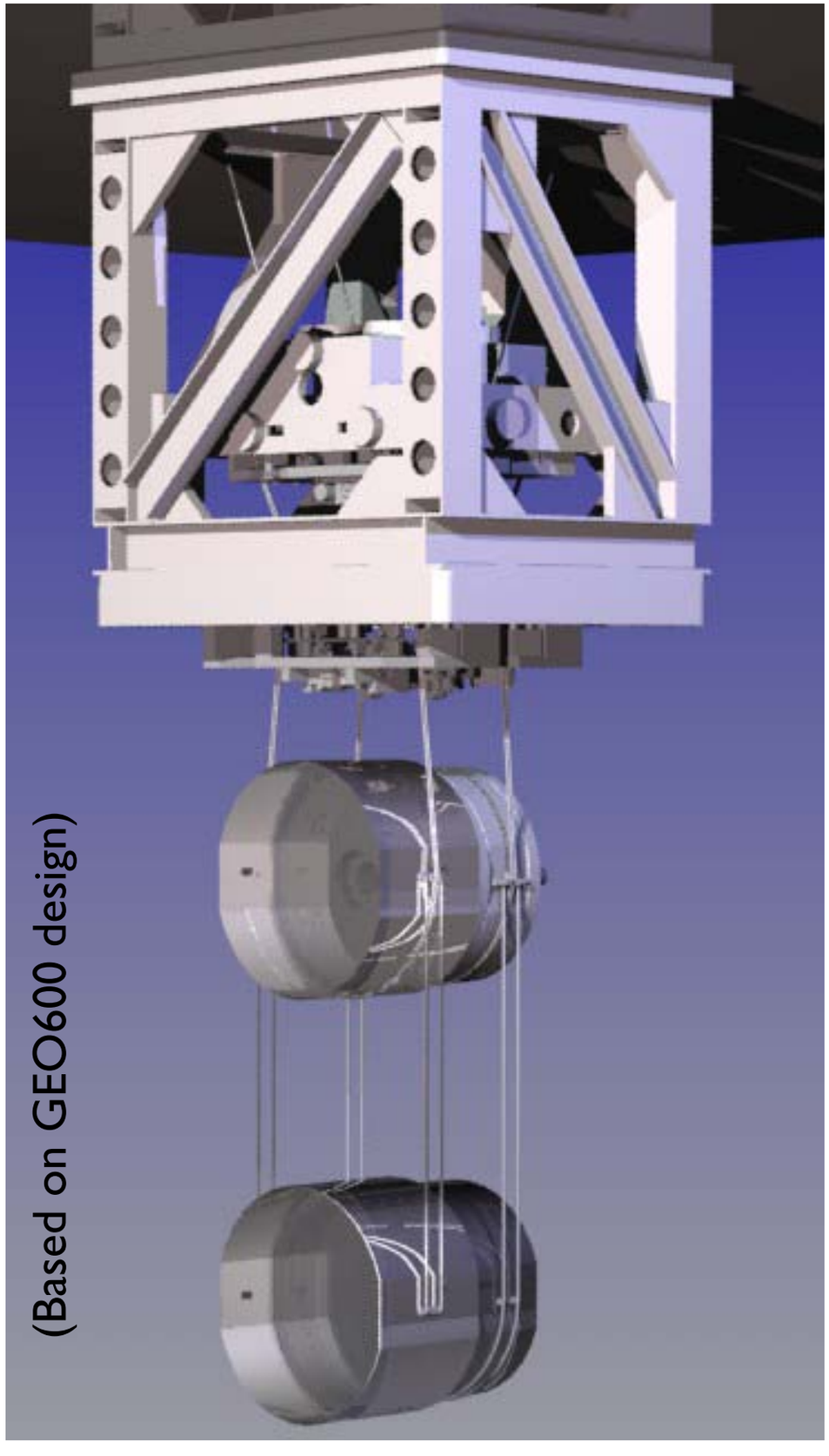
drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses



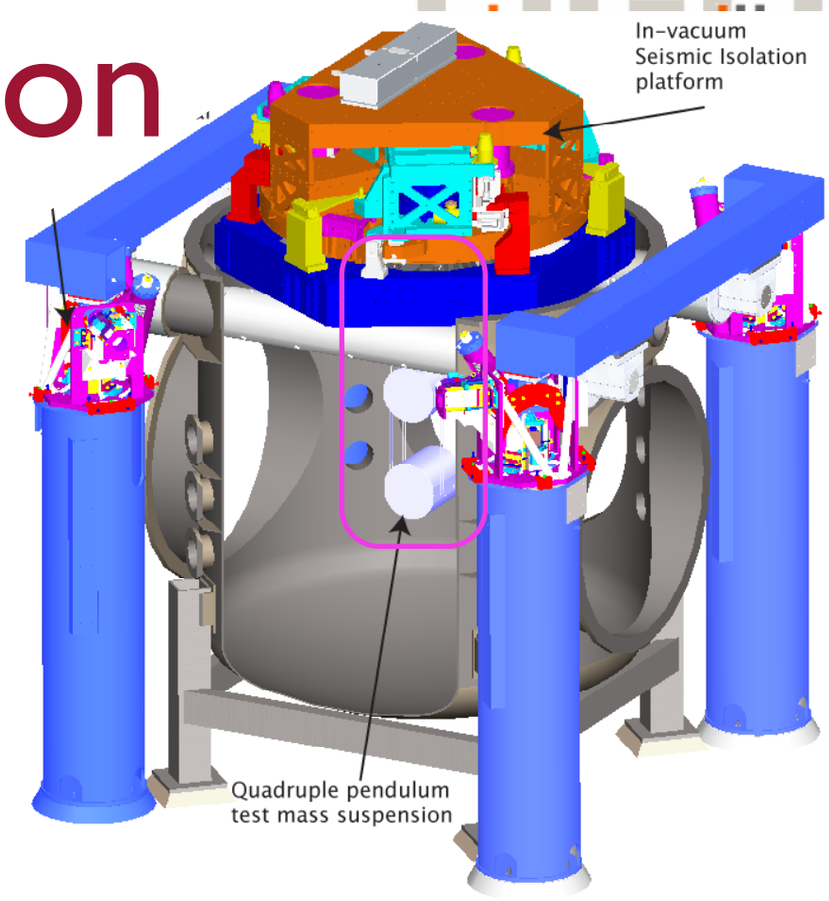
G1600349

Pendulum Suspension



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

Suspended as a
4 stage pendulum



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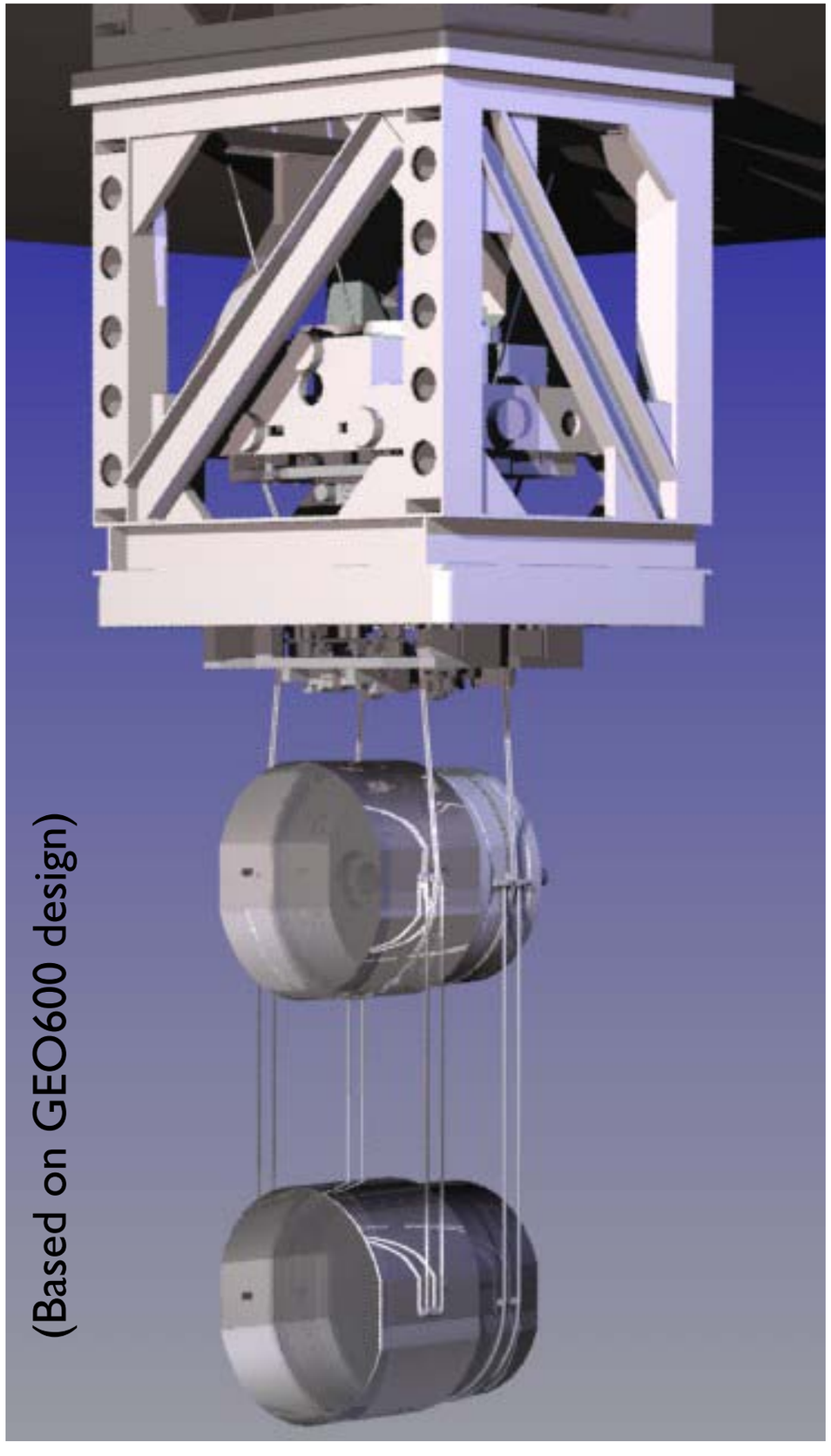

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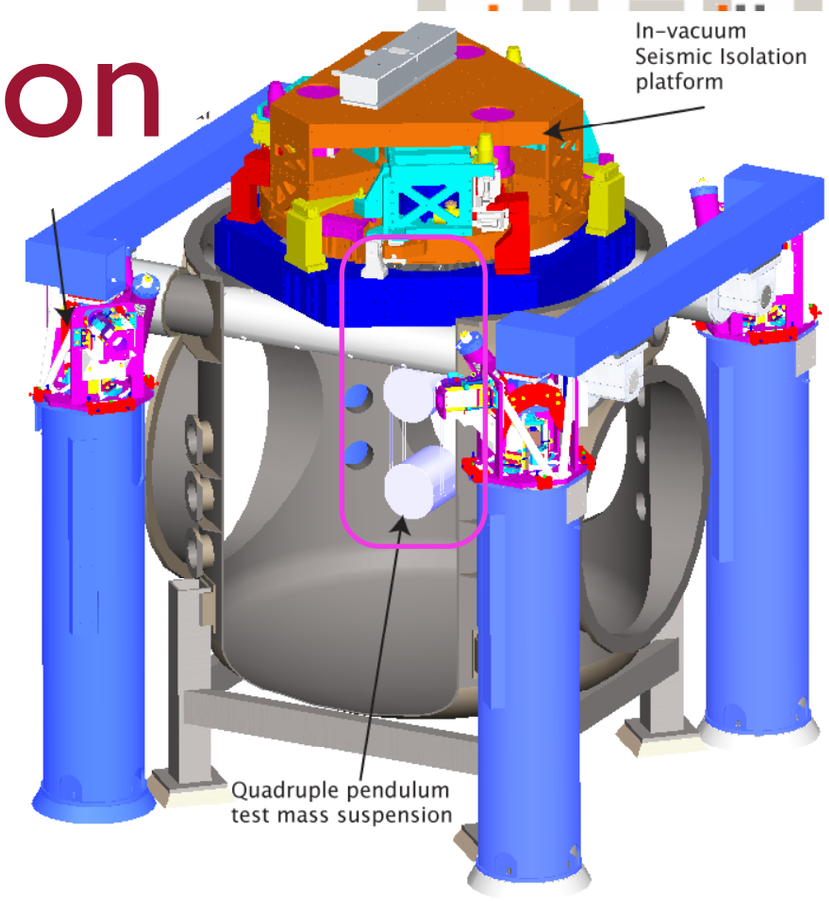
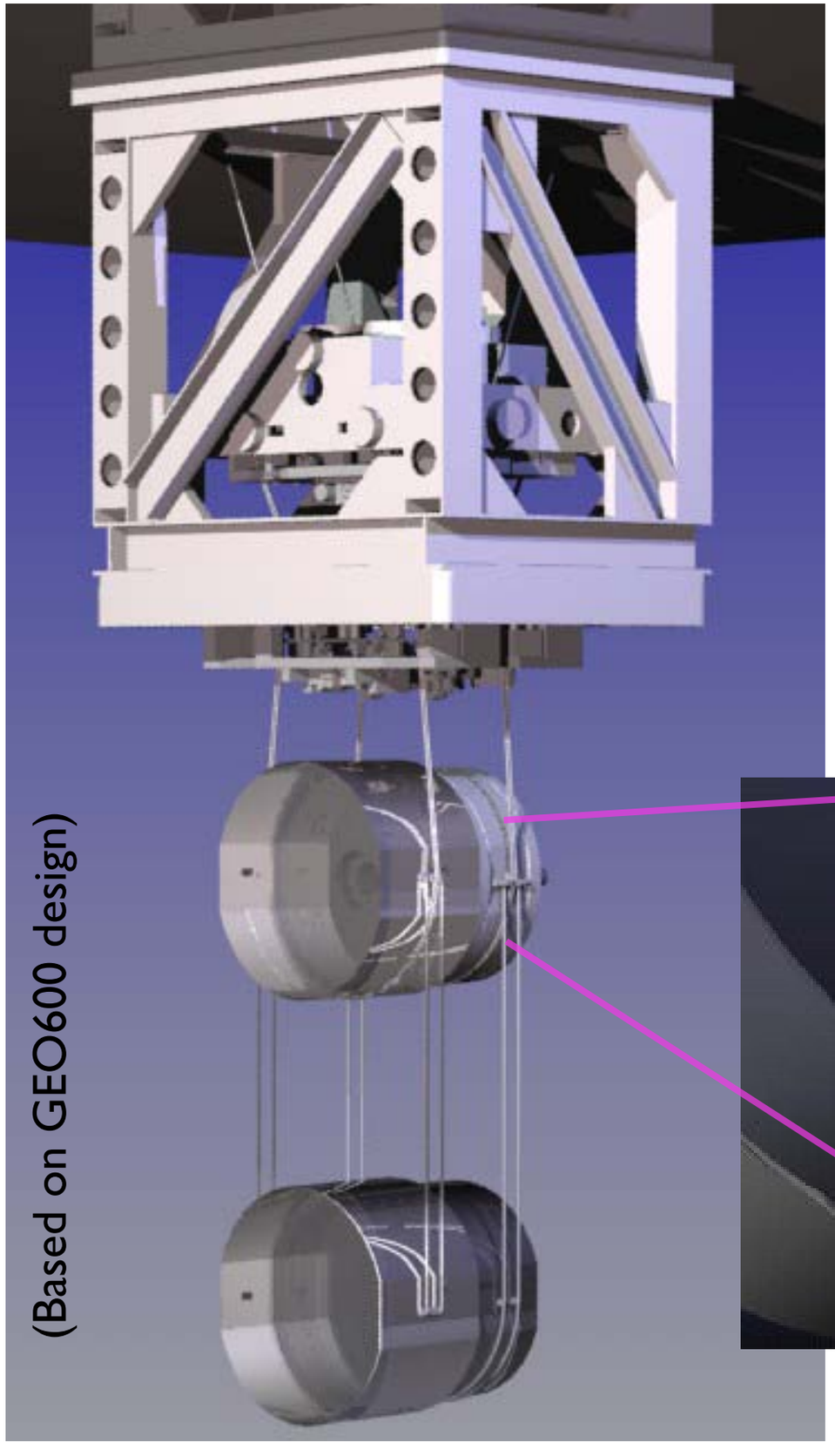


Best coatings available

Motion at 10 Hz set by
thermal driven vibration

silicate bonding creates a monolithic final stage

Pendulum Suspension



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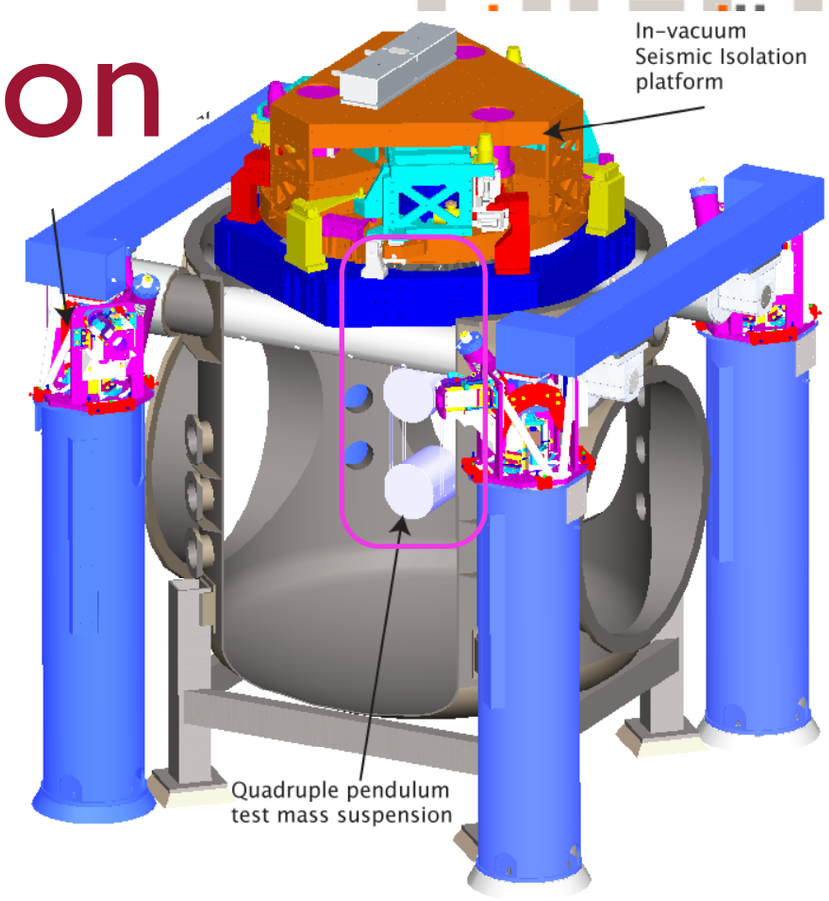
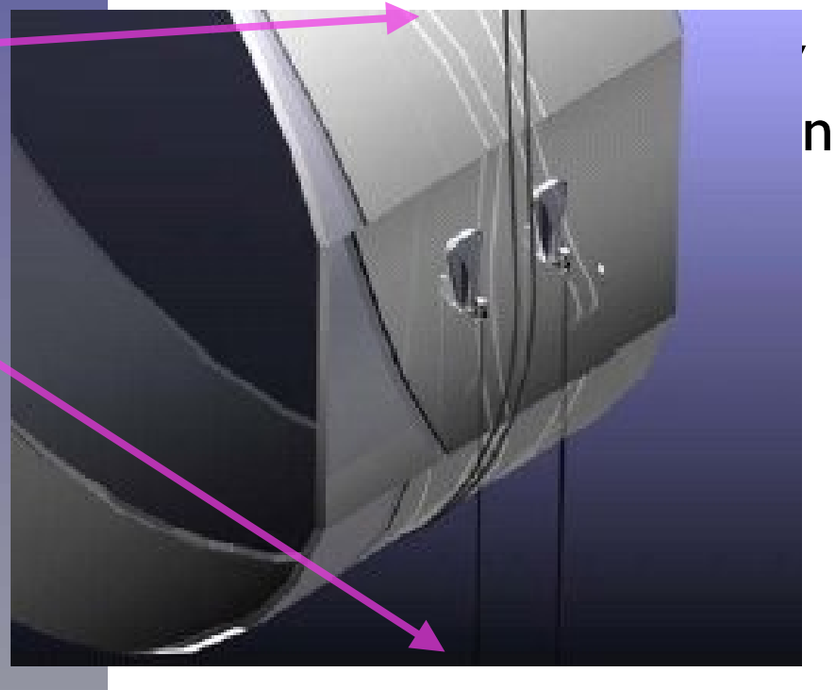


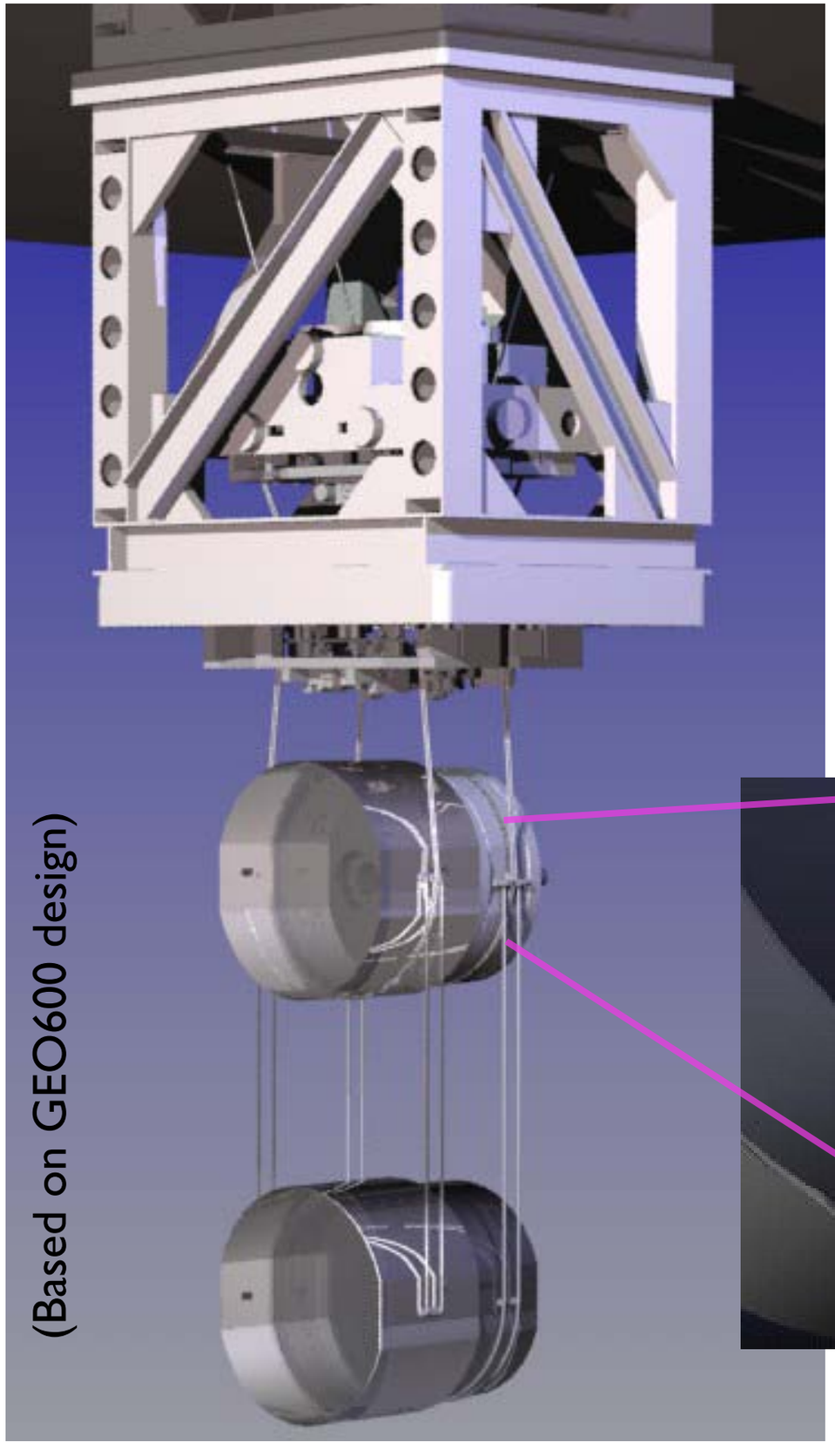
Best coatings available



n

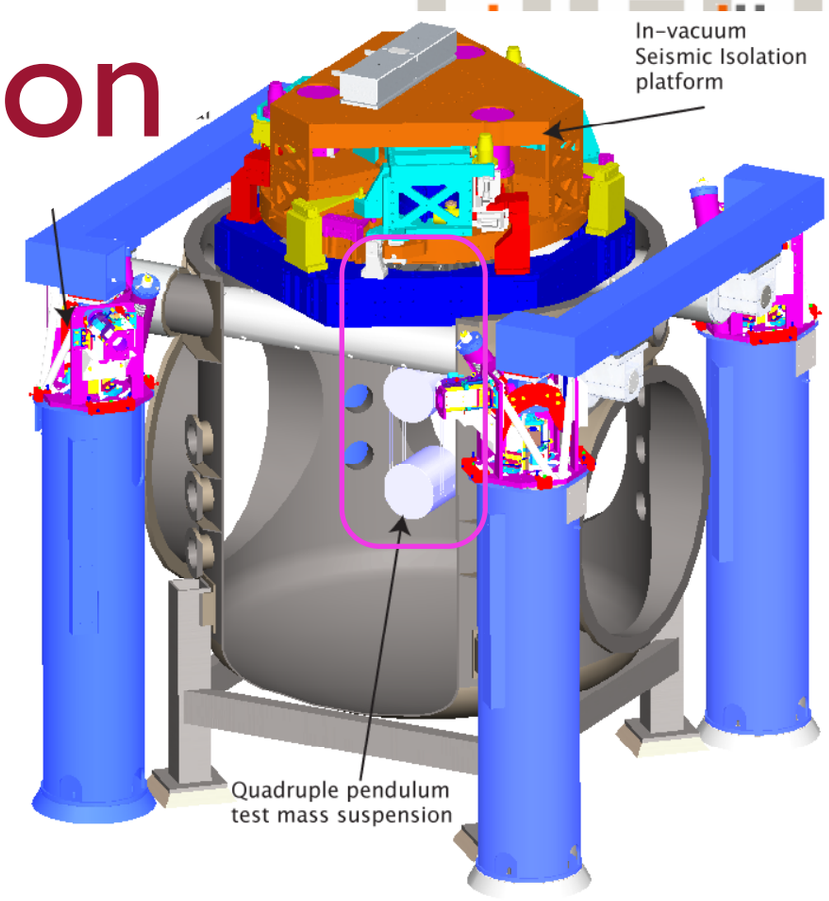
silicate bonding creates a monolithic final stage

Pendulum Suspension

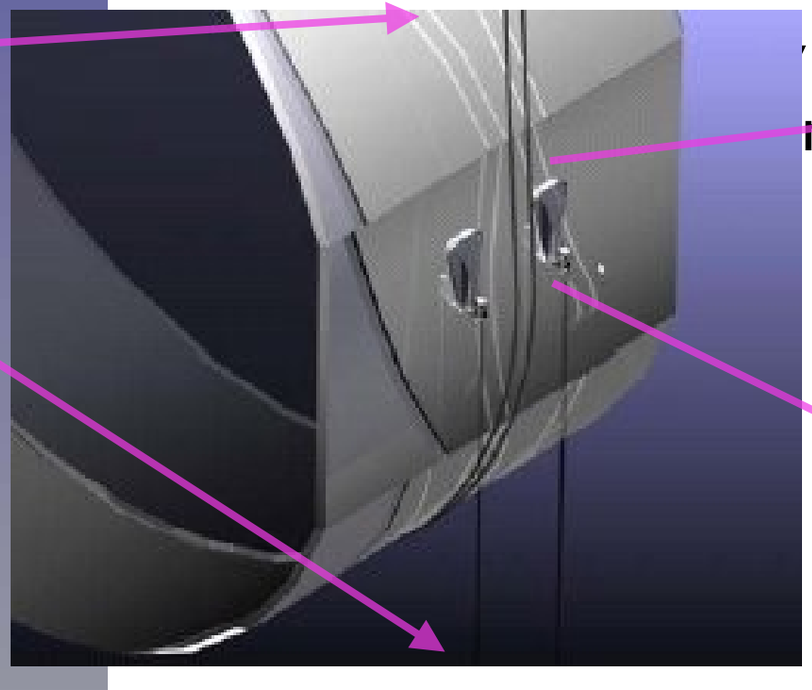


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum



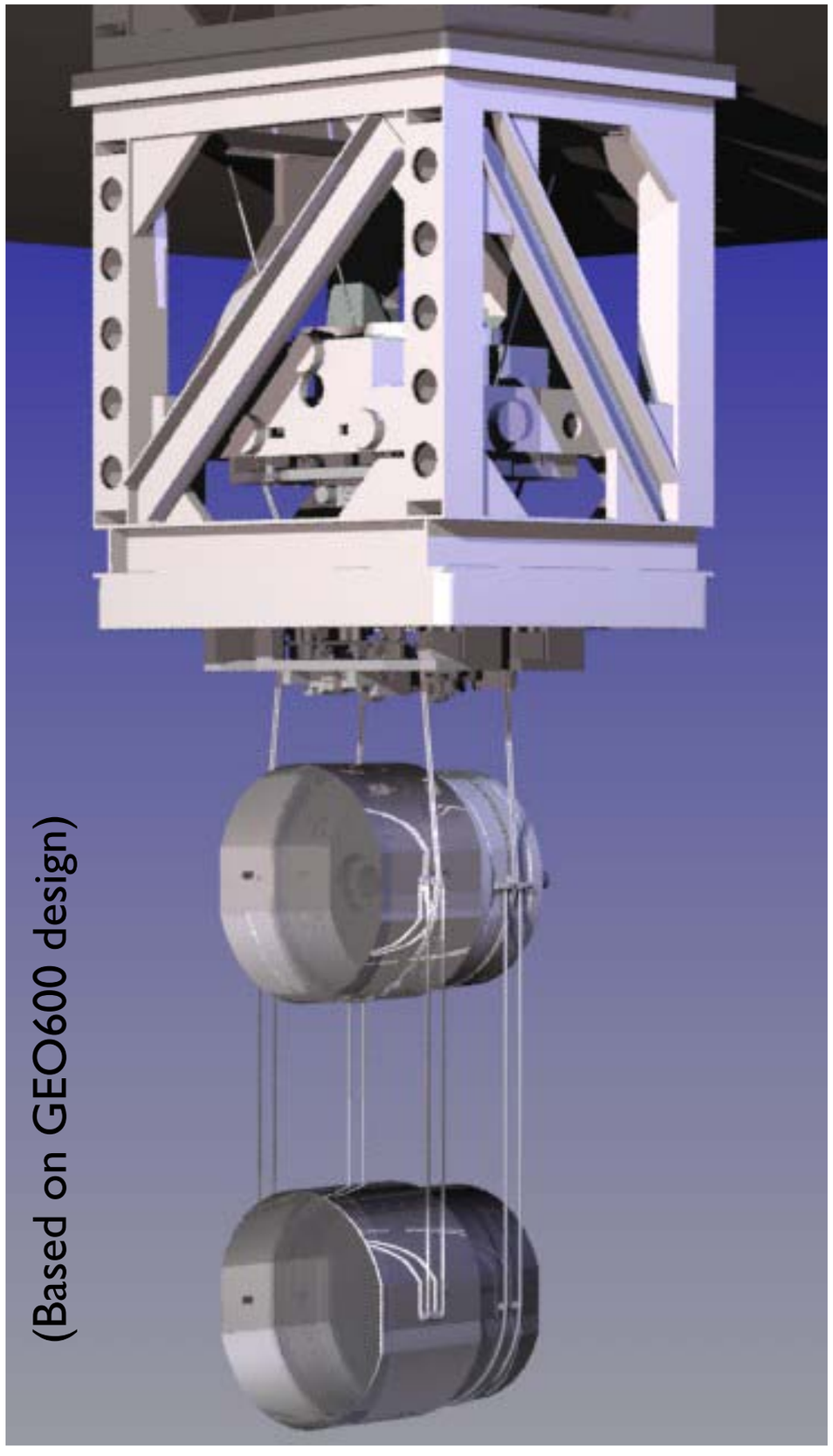
Best coatings available

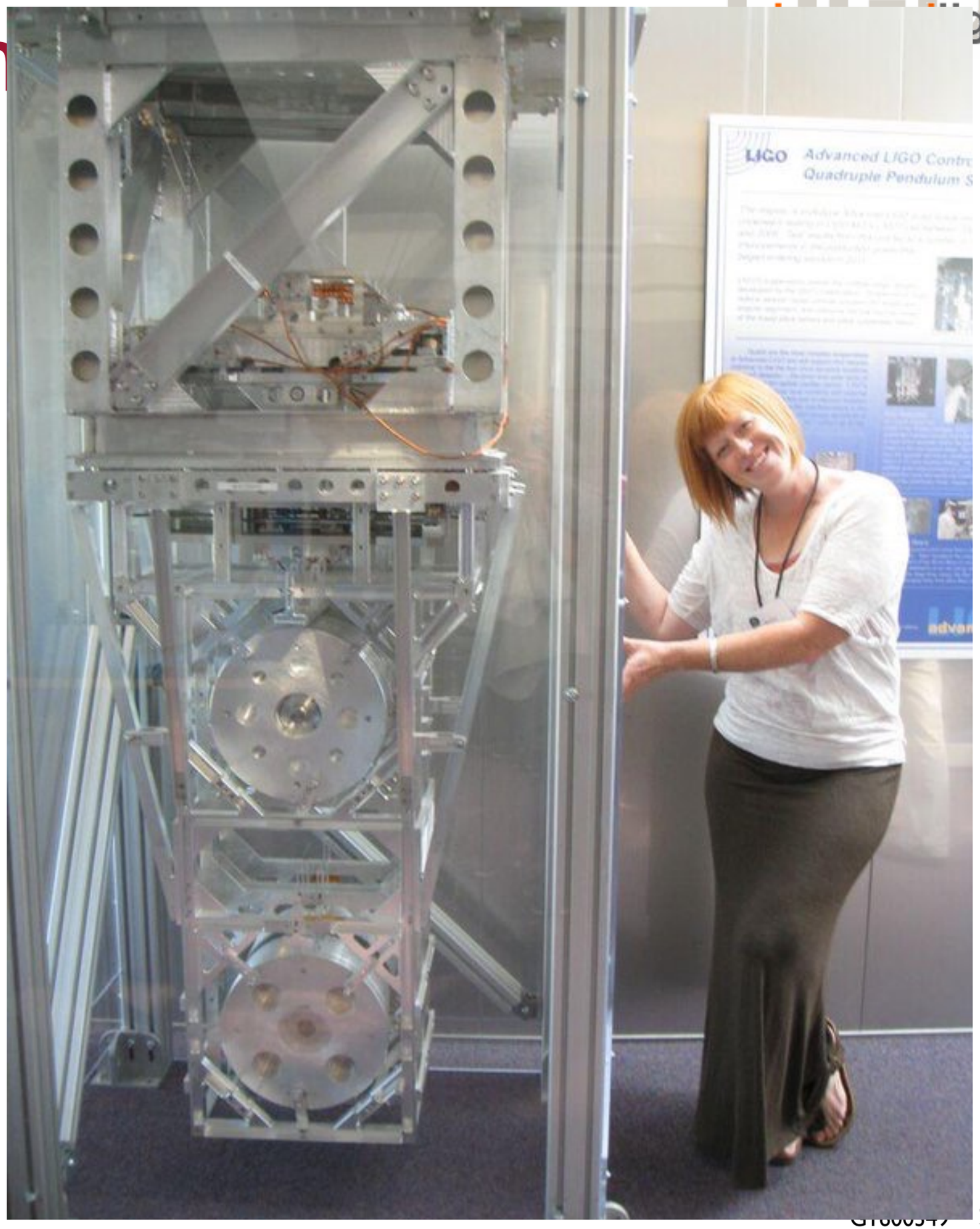


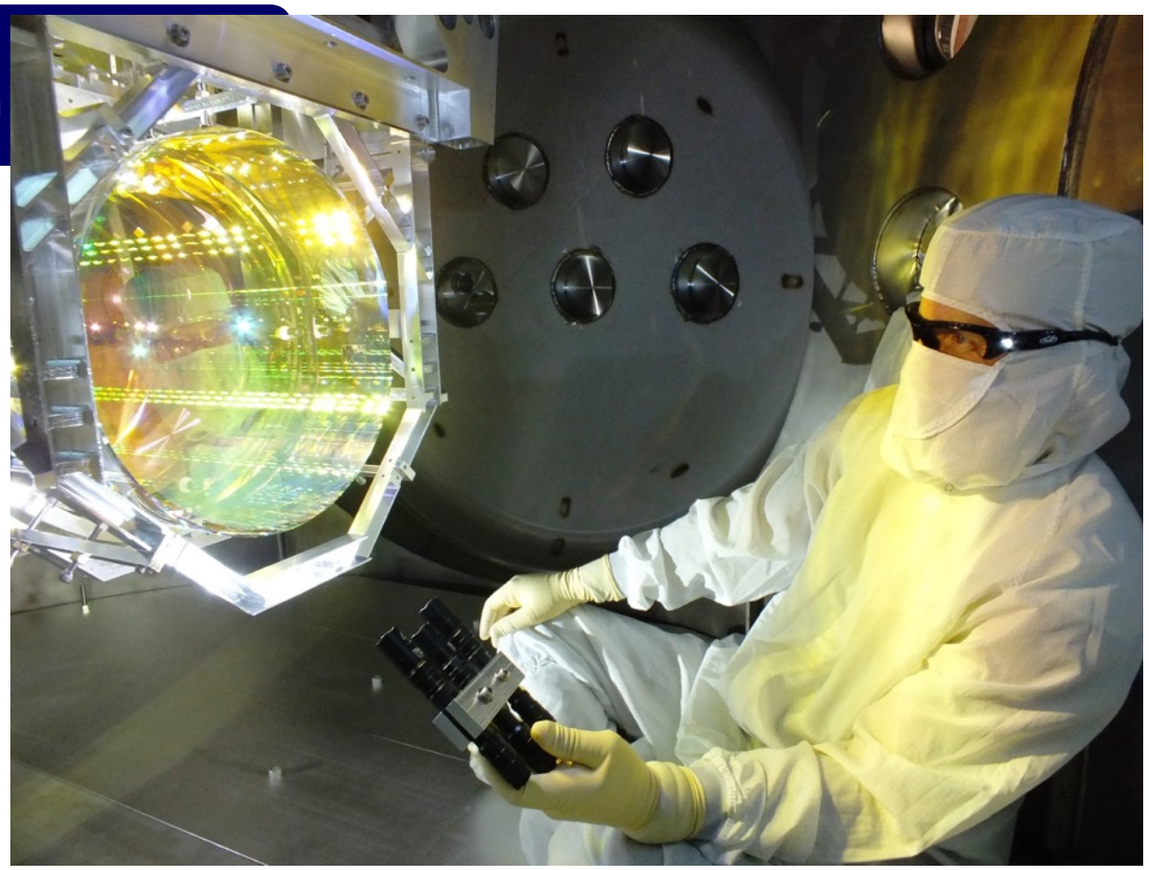
n

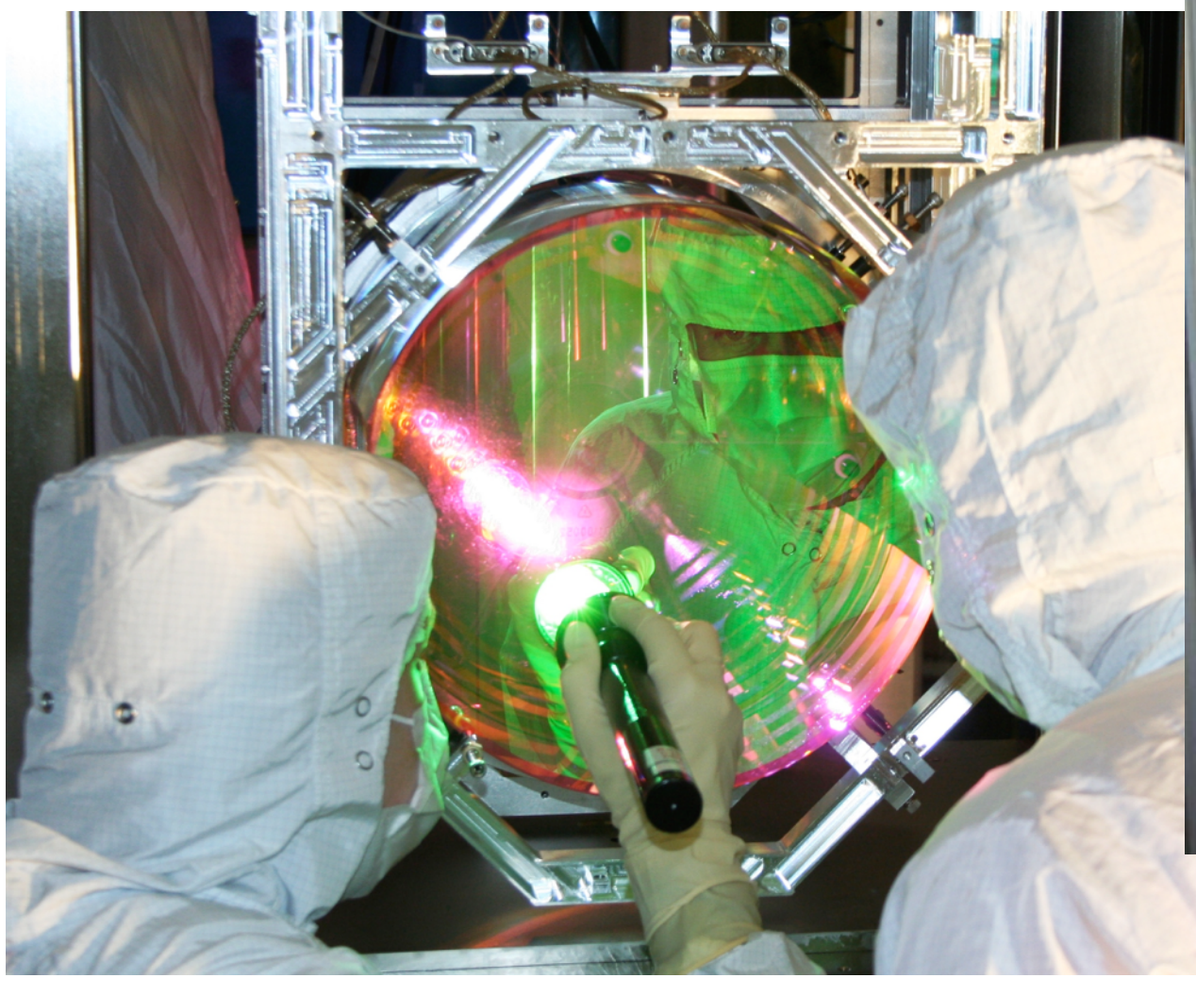
silicate bonding creates a monolithic final stage

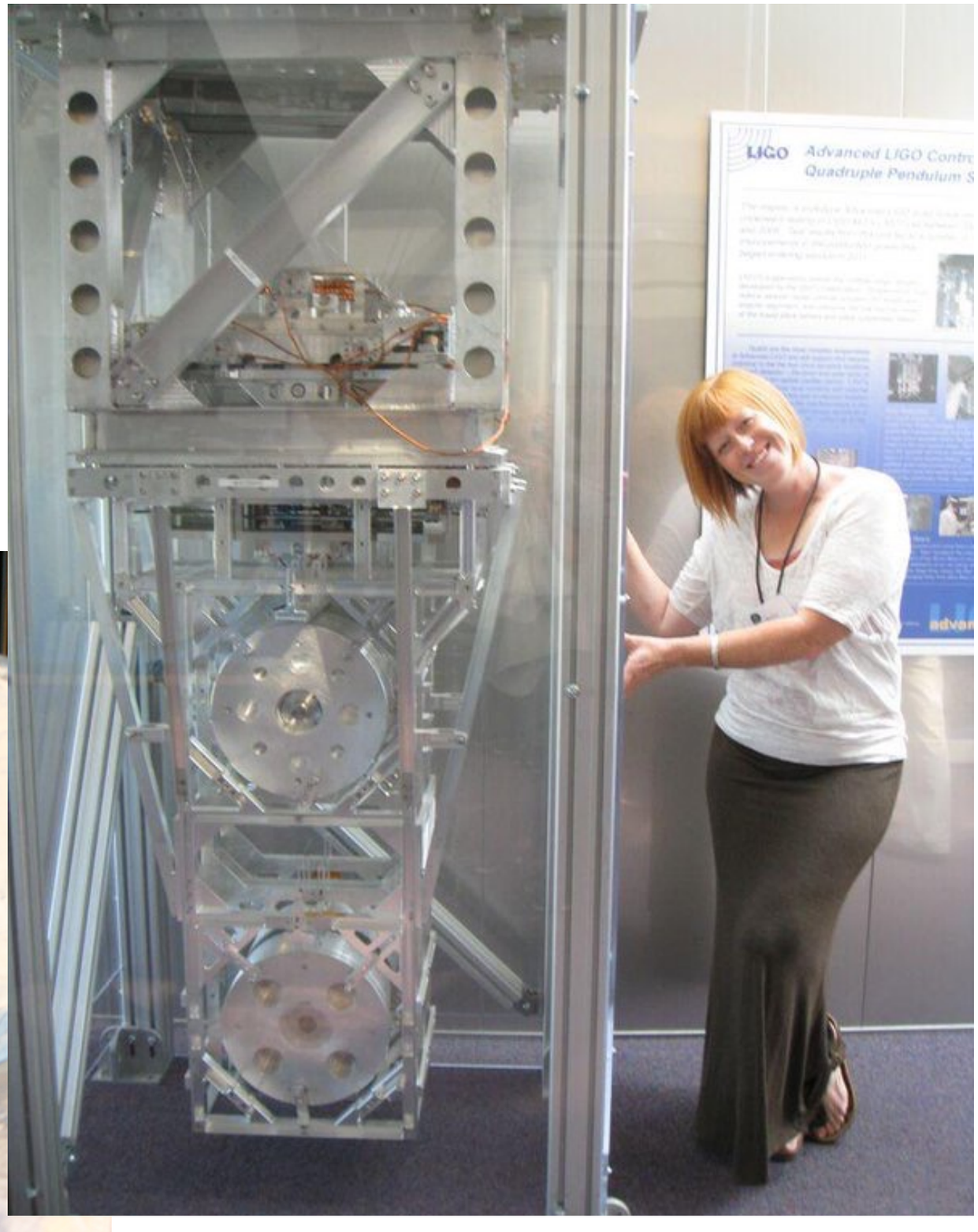
Pendulum


(Based on GEO600 design)


LIGO
Advanced LIGO Contr
Quadruple Pendulum S

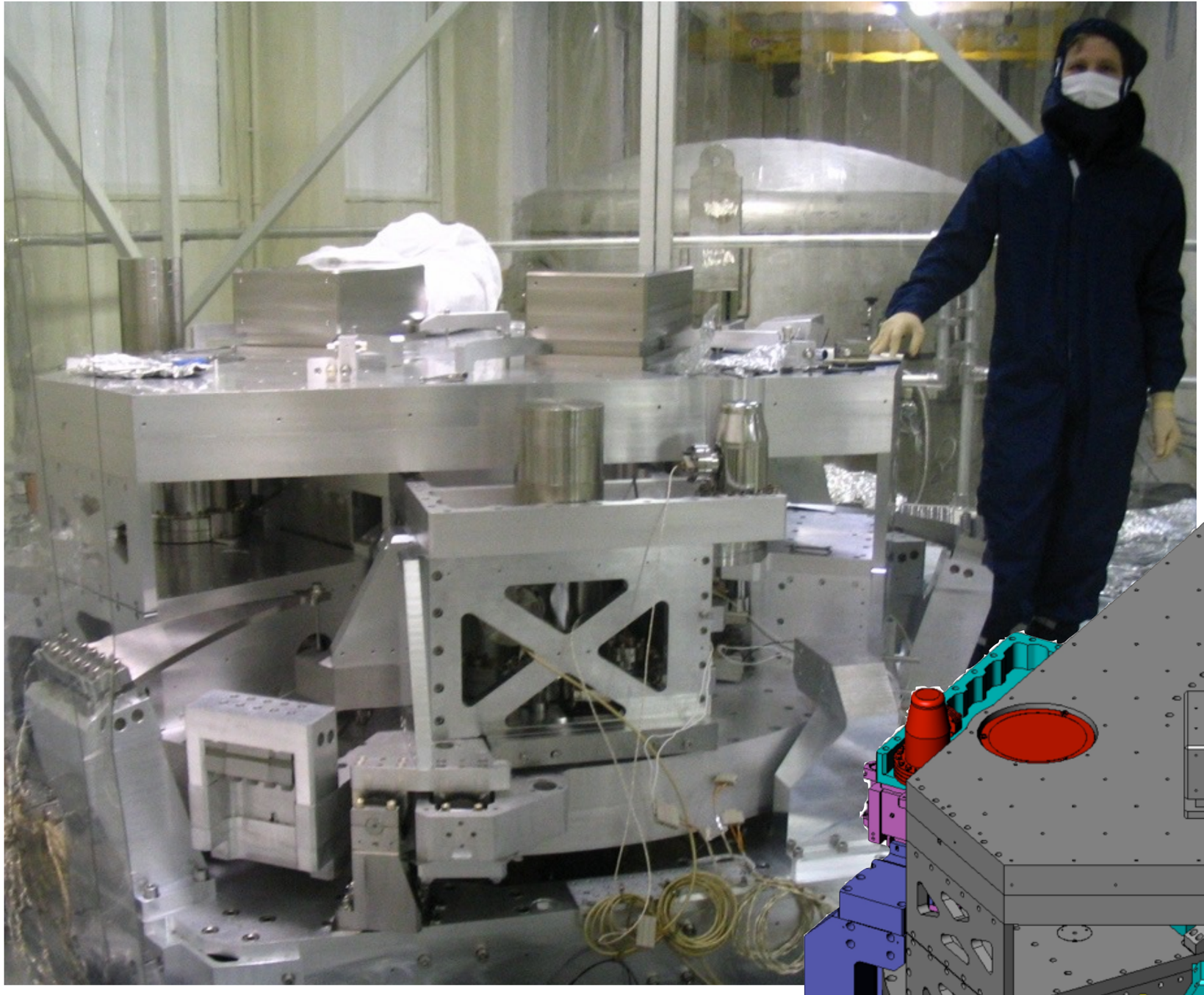


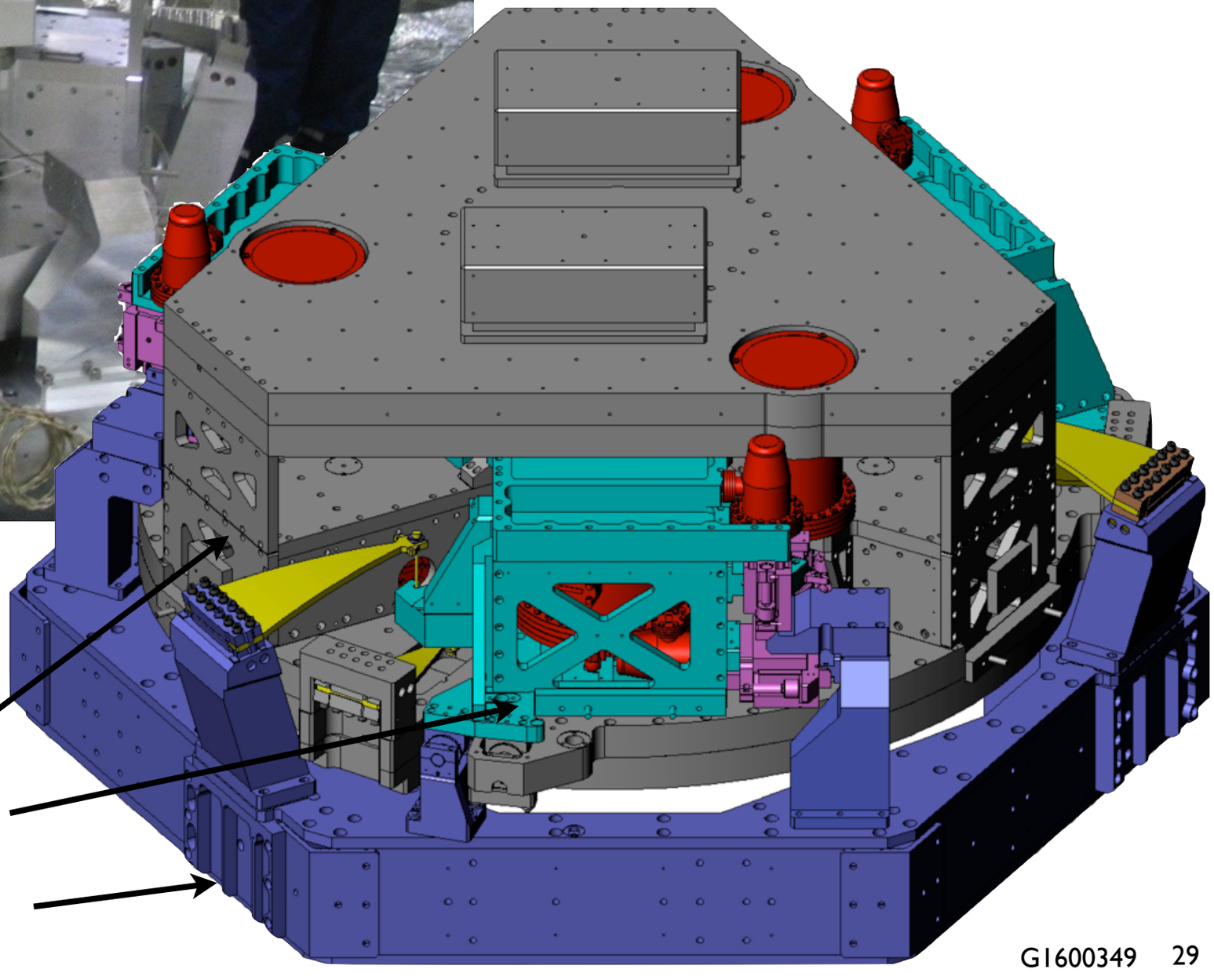



LIGO
Advanced LIGO Contr
Quadruple Pendulum S

advancedligo

Optical Table

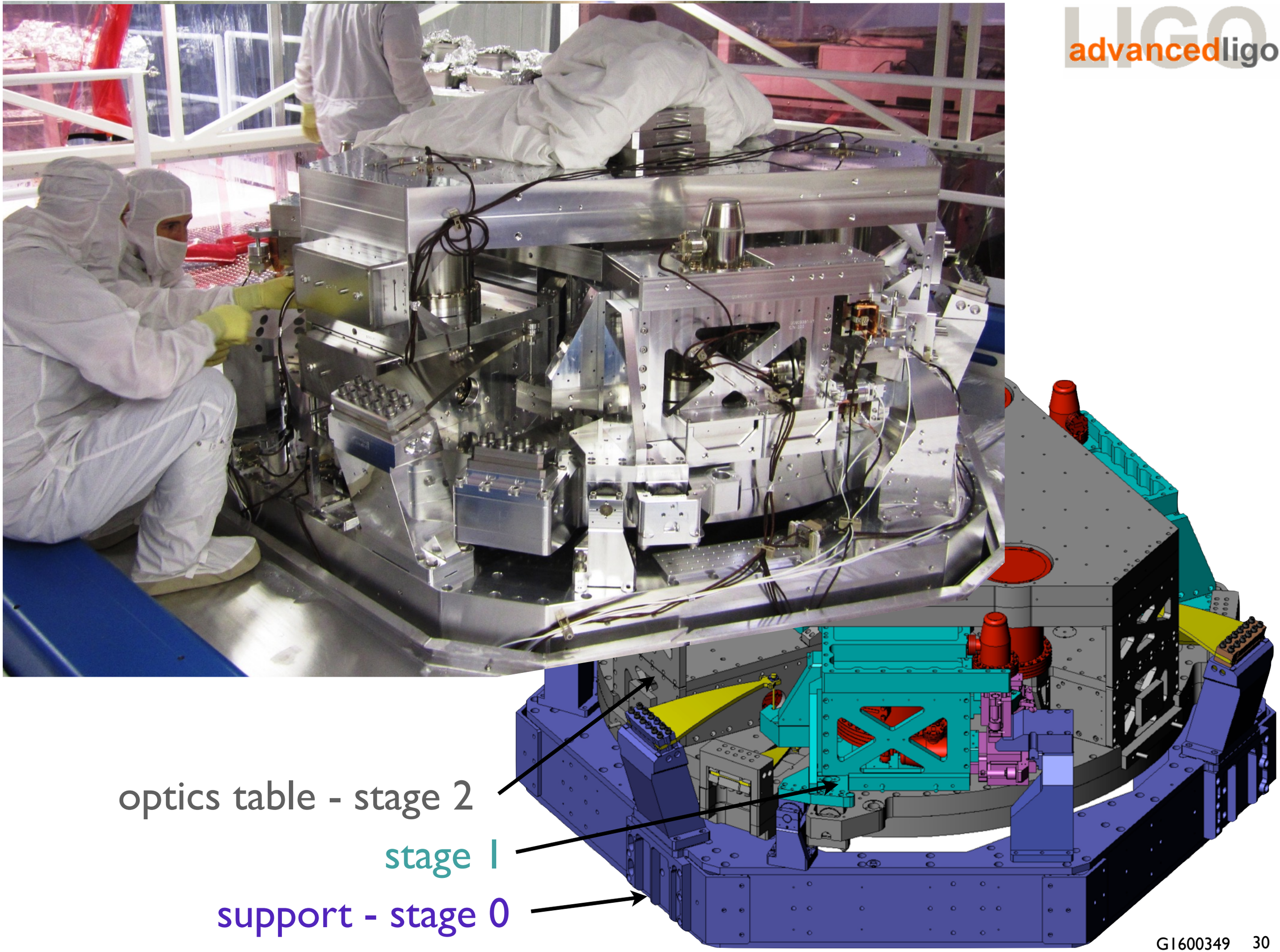




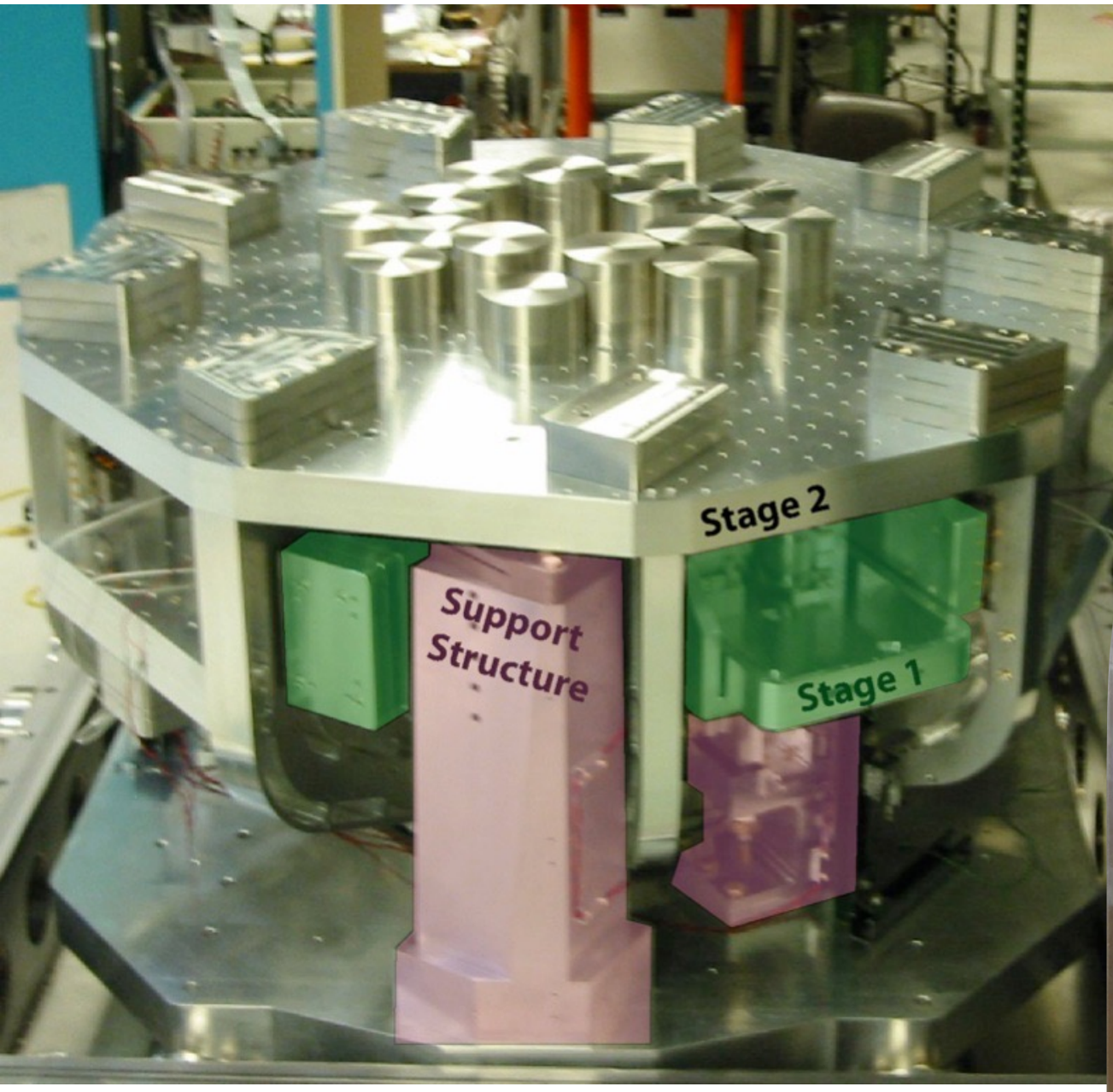
optics table - stage 2

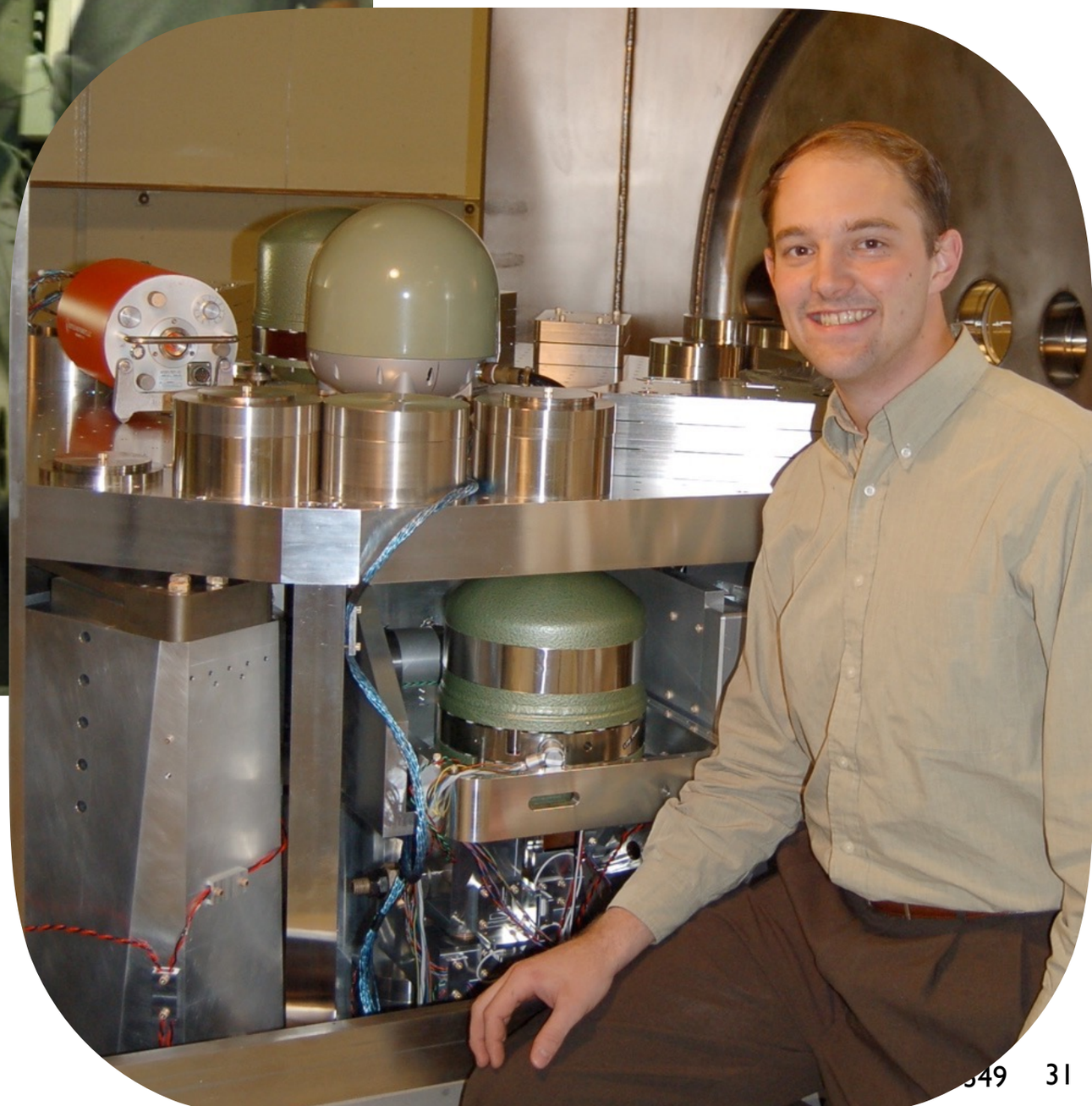
stage 1

support - stage 0


optics table - stage 2
stage 1
support - stage 0

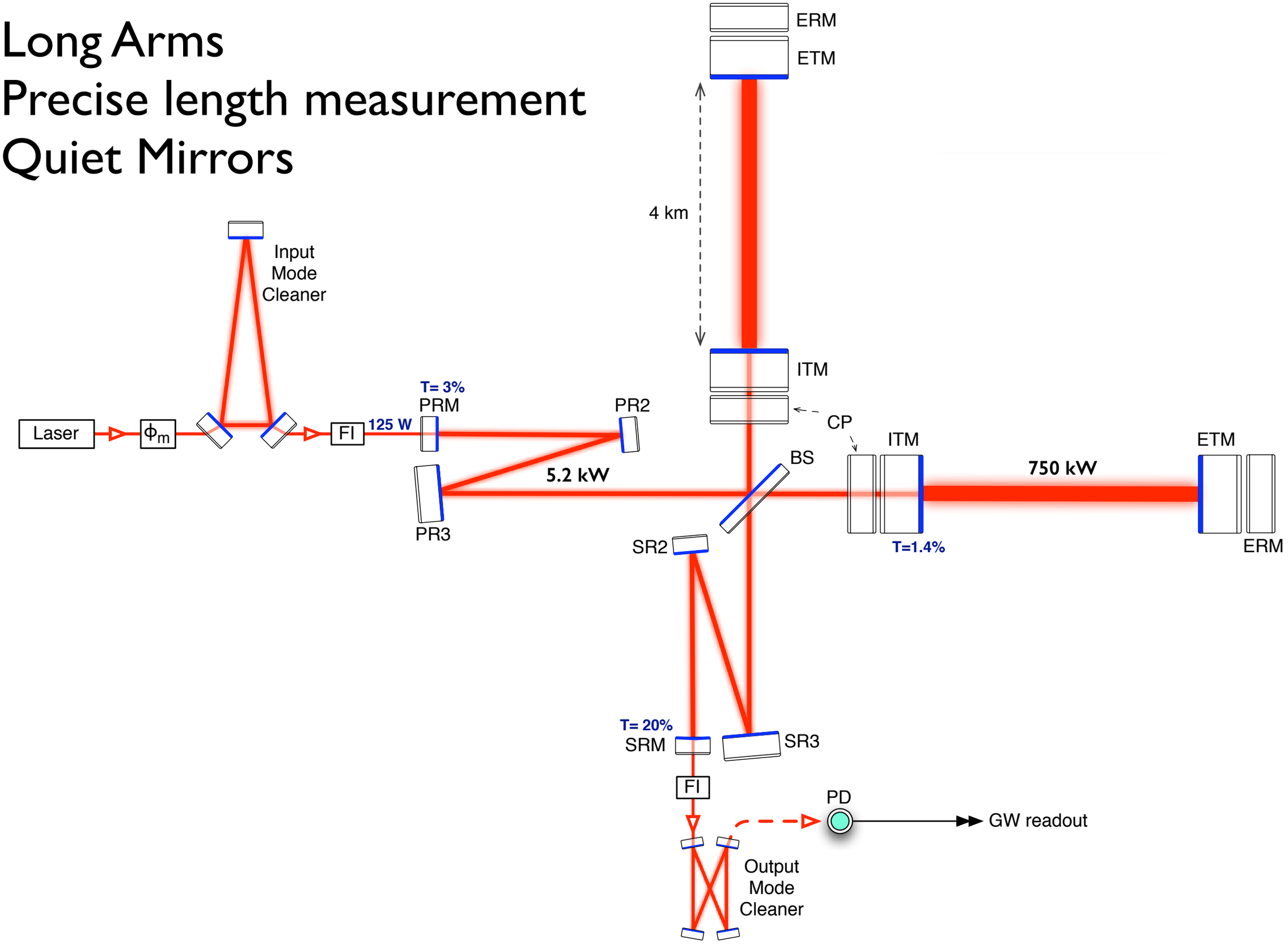
Stanford Prototype



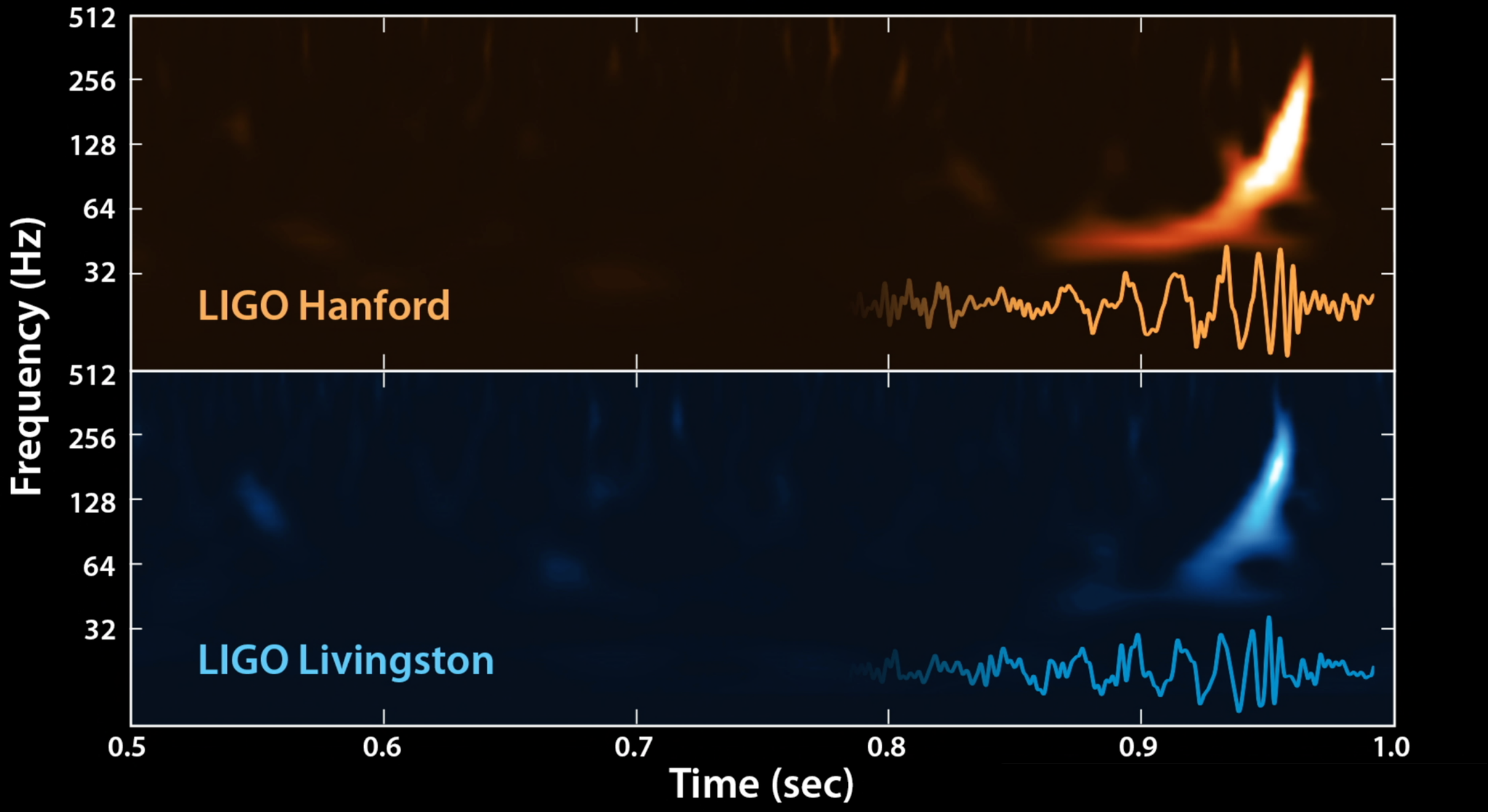


Now we are ready…

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

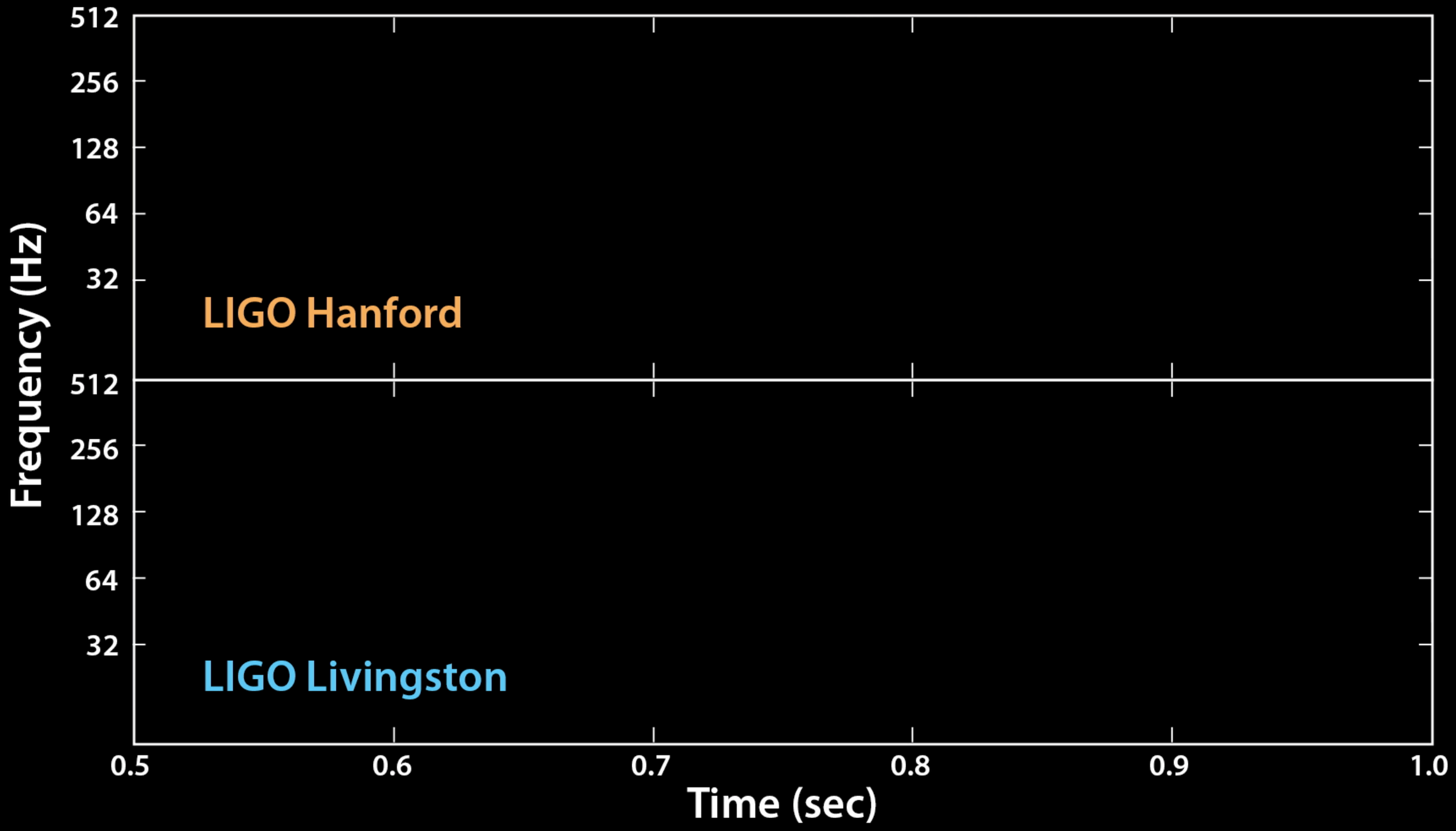


The sound of black holes colliding

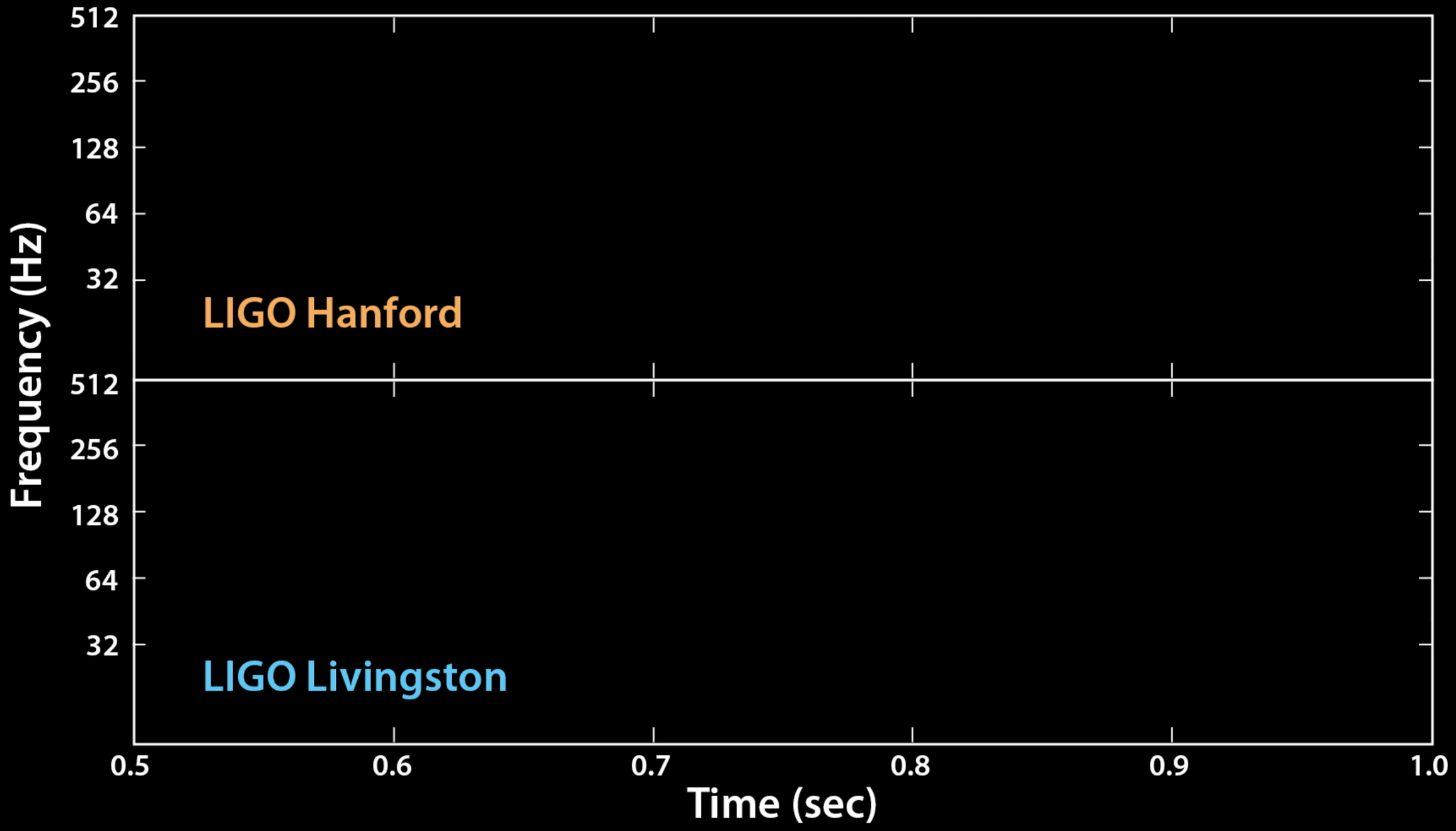


http://mediaassets.caltech.edu/gwave

The sound of black holes colliding



The sound of black holes colliding



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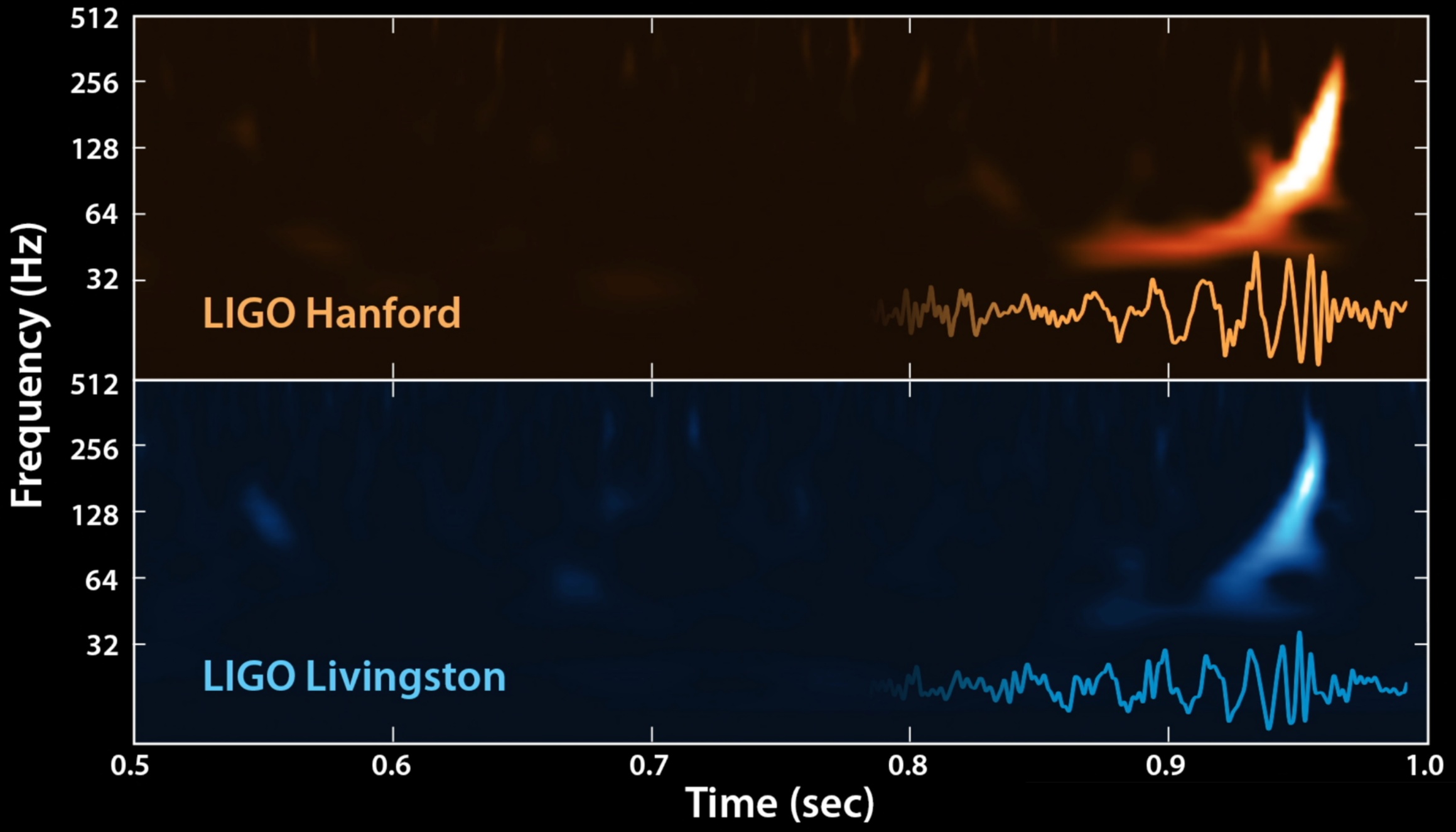

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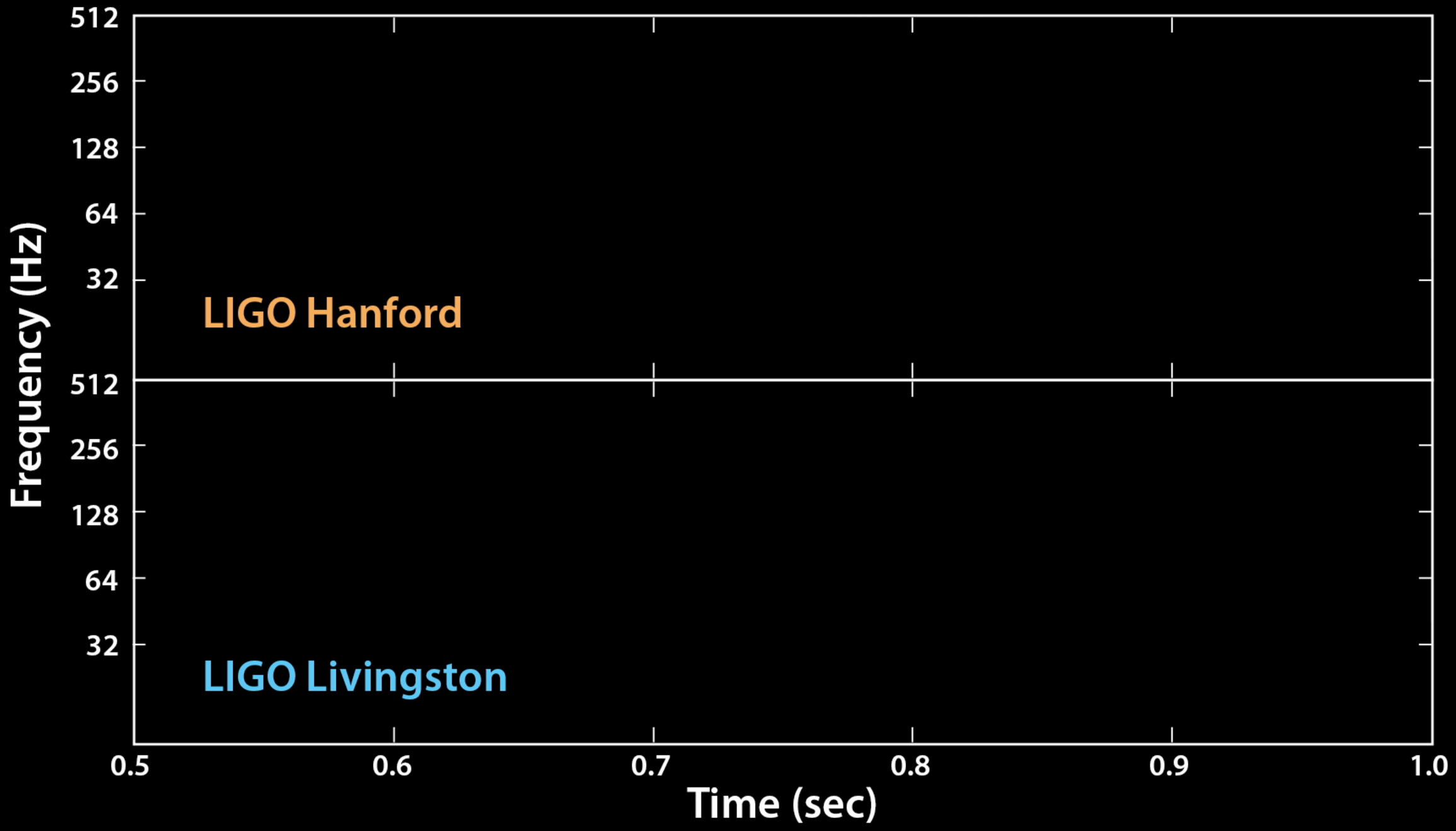

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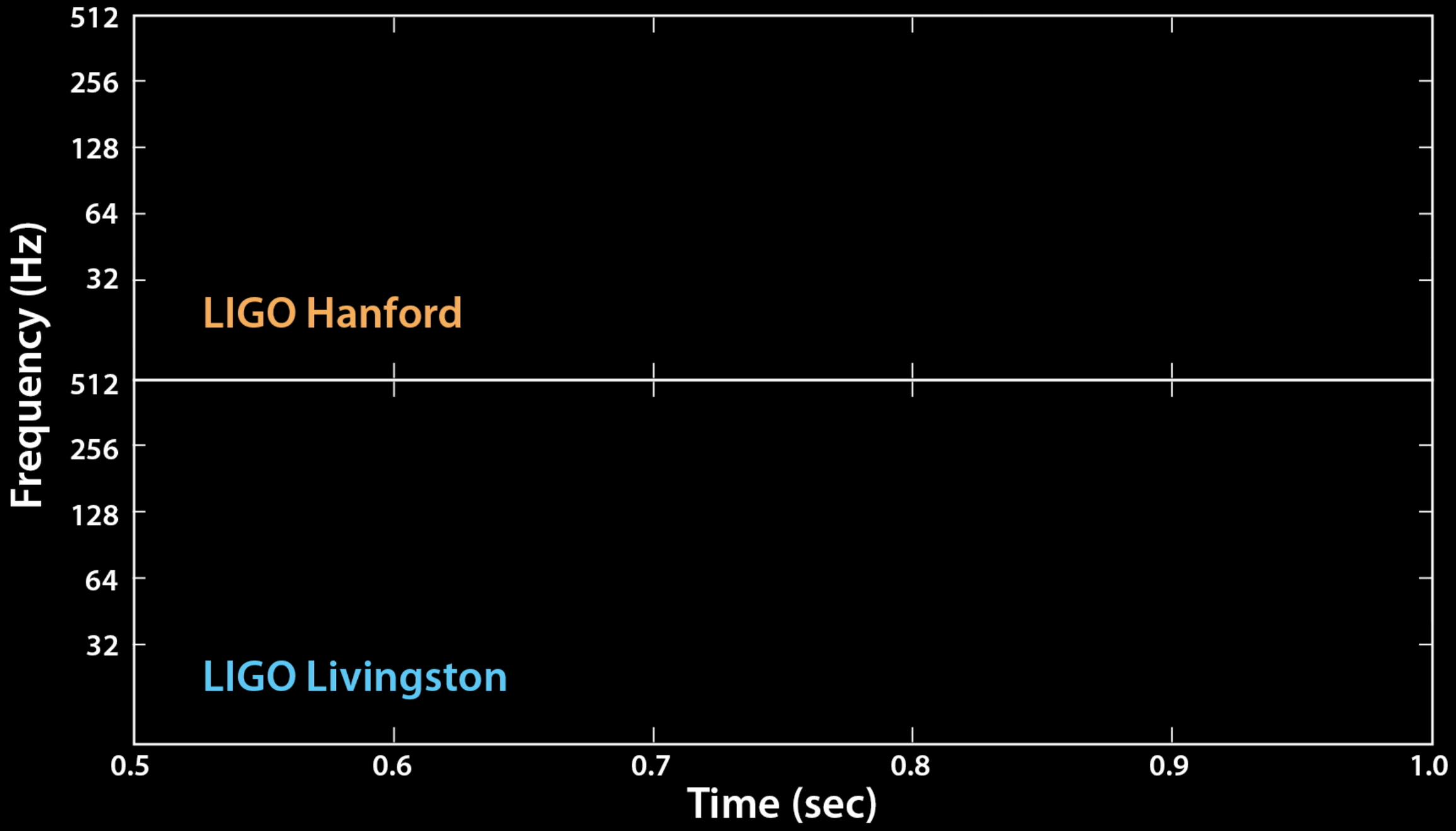
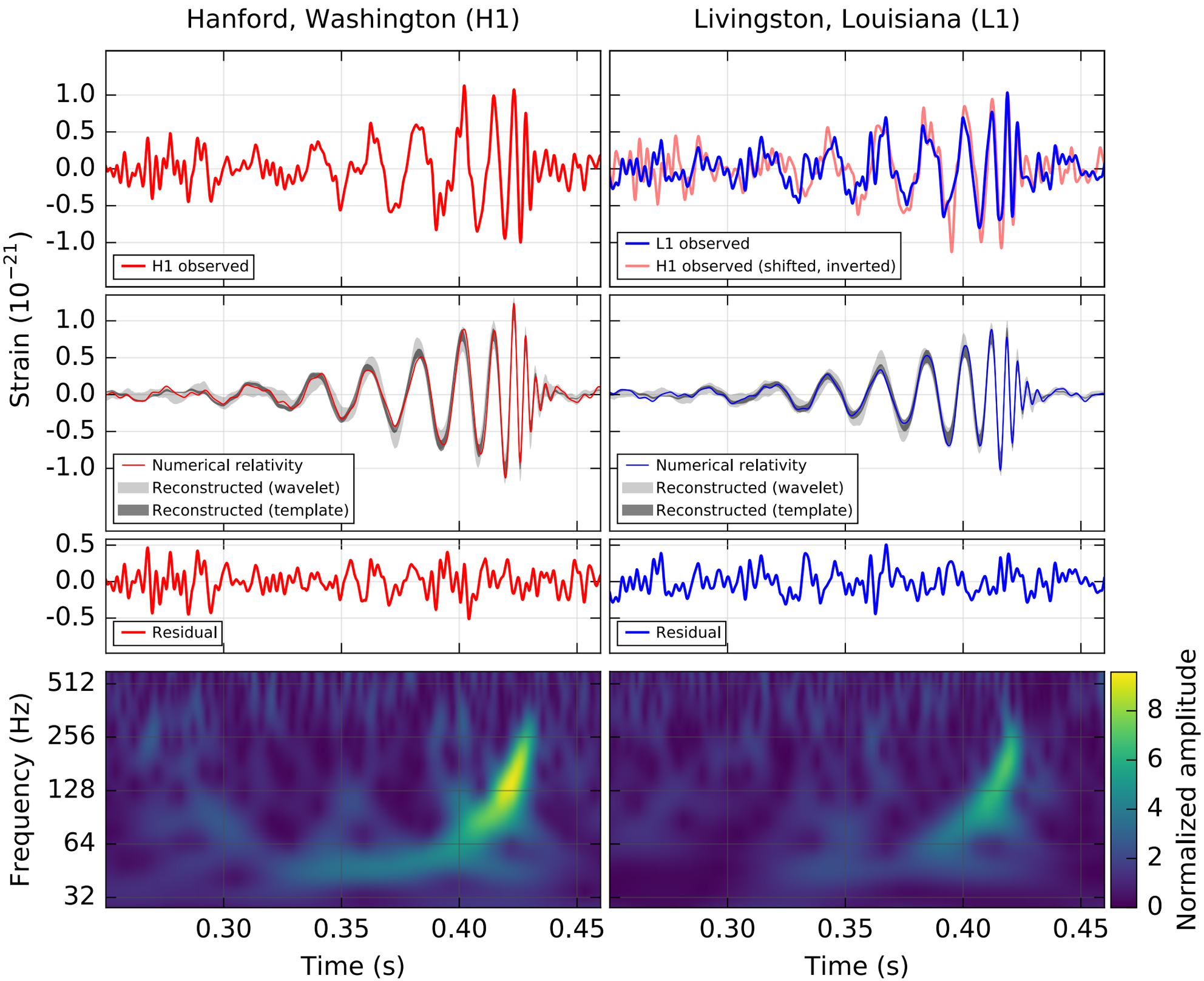


First signal - Sept 14, 2015



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

Best fit with Numerical Relativity

Initial Masses:

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

Final Mass:

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

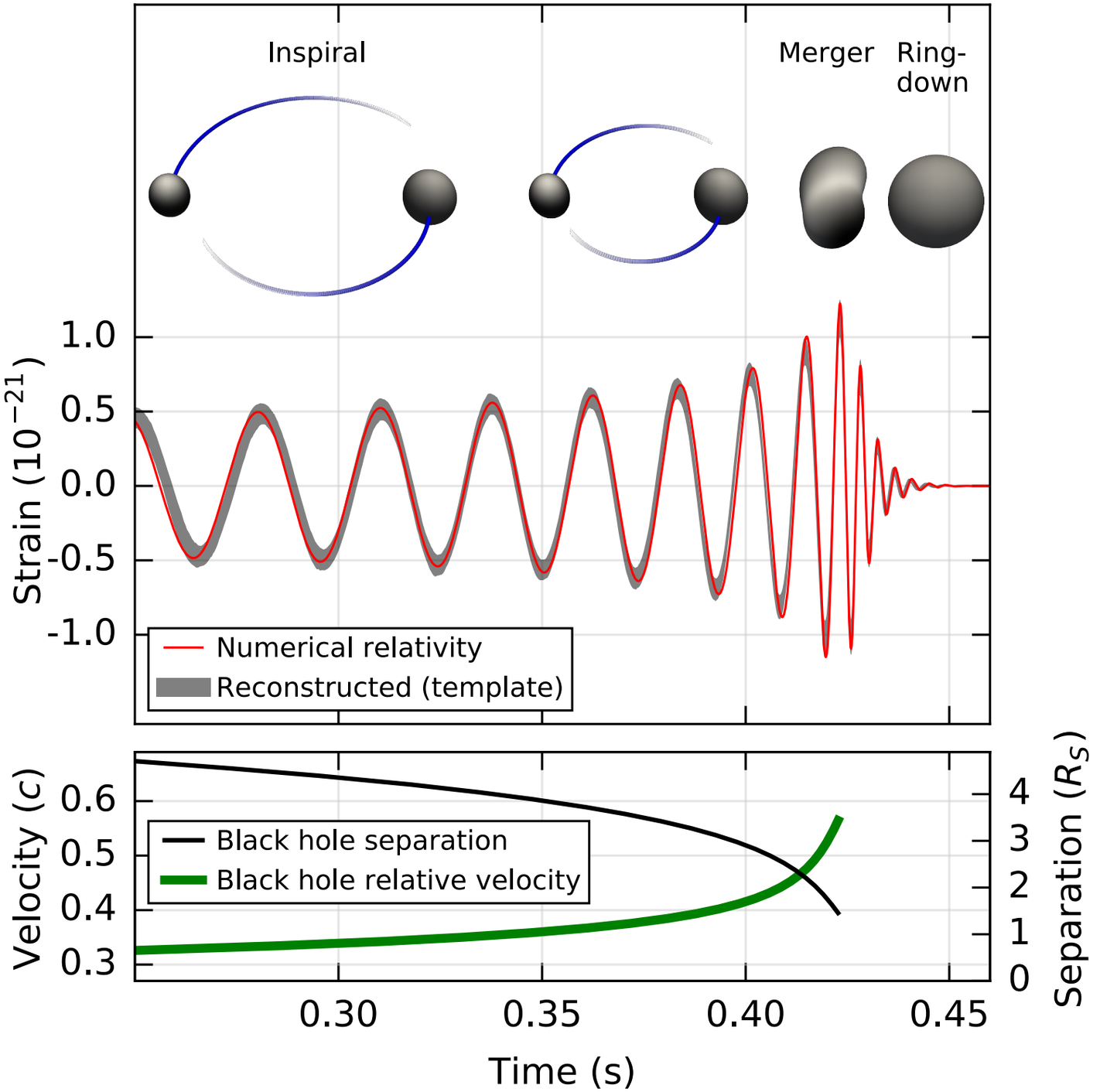
Energy radiated

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

Distance

410 (+160/-180) MPc

(1.3 Billion light years)



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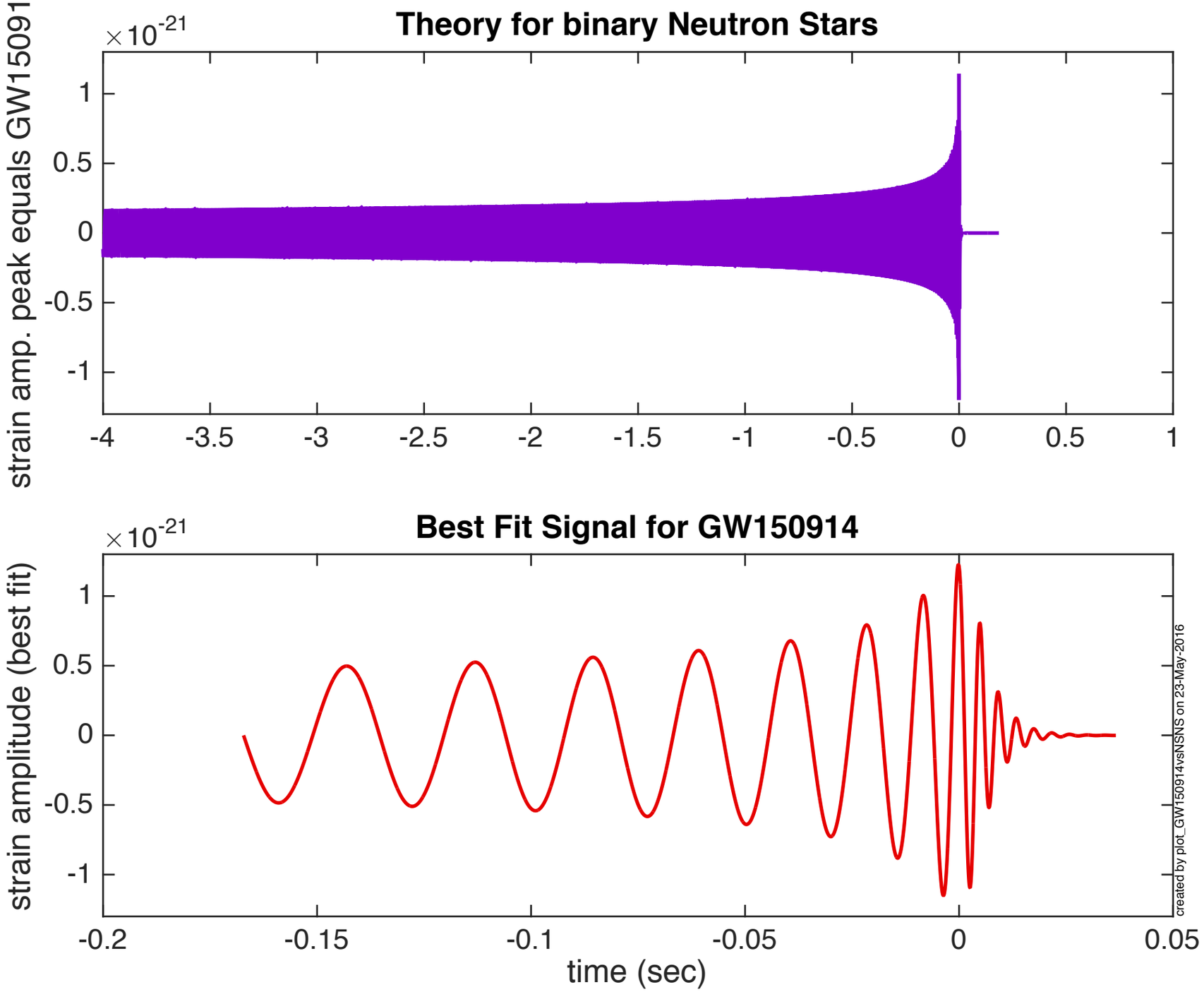

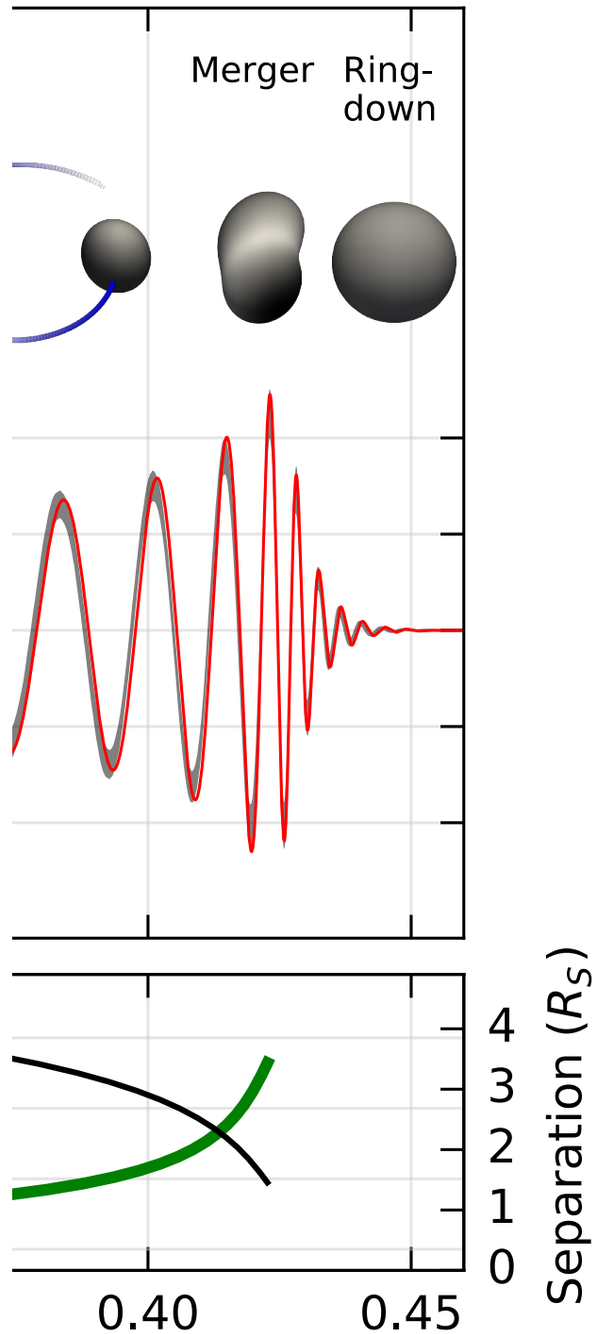

NS/NS waveform from http://web.mit.edu/sahughes/www/sounds.html

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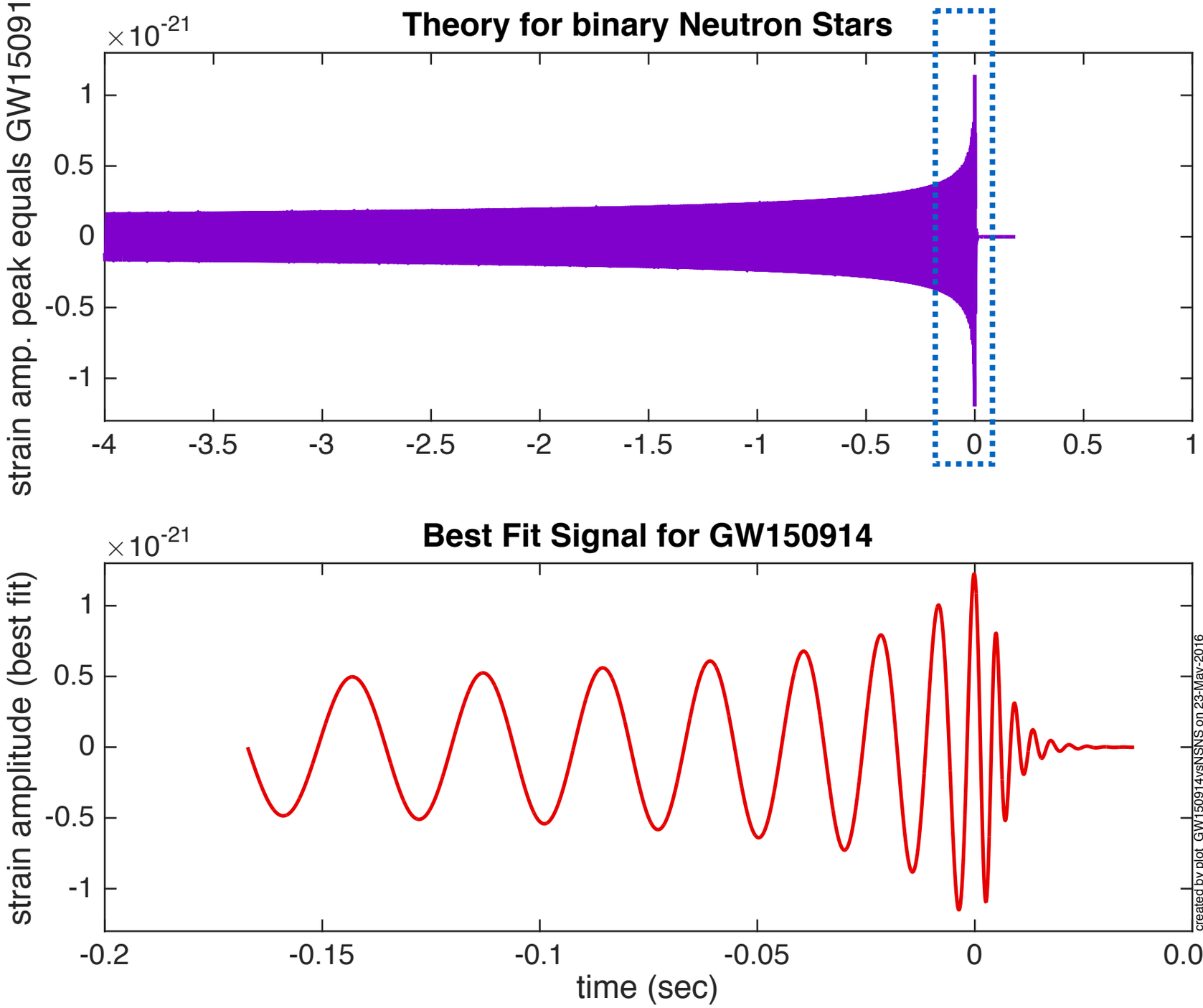

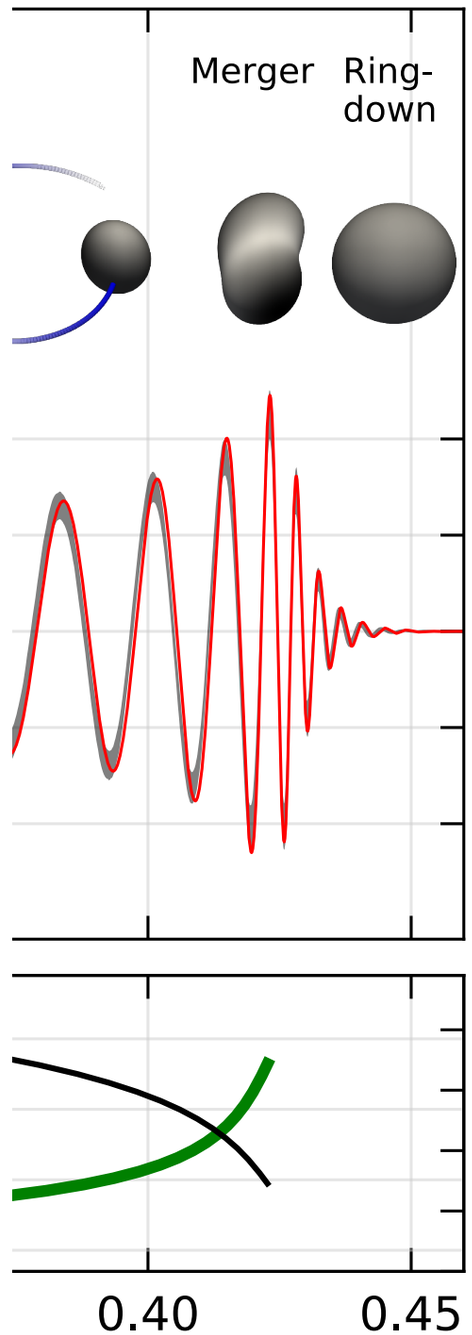

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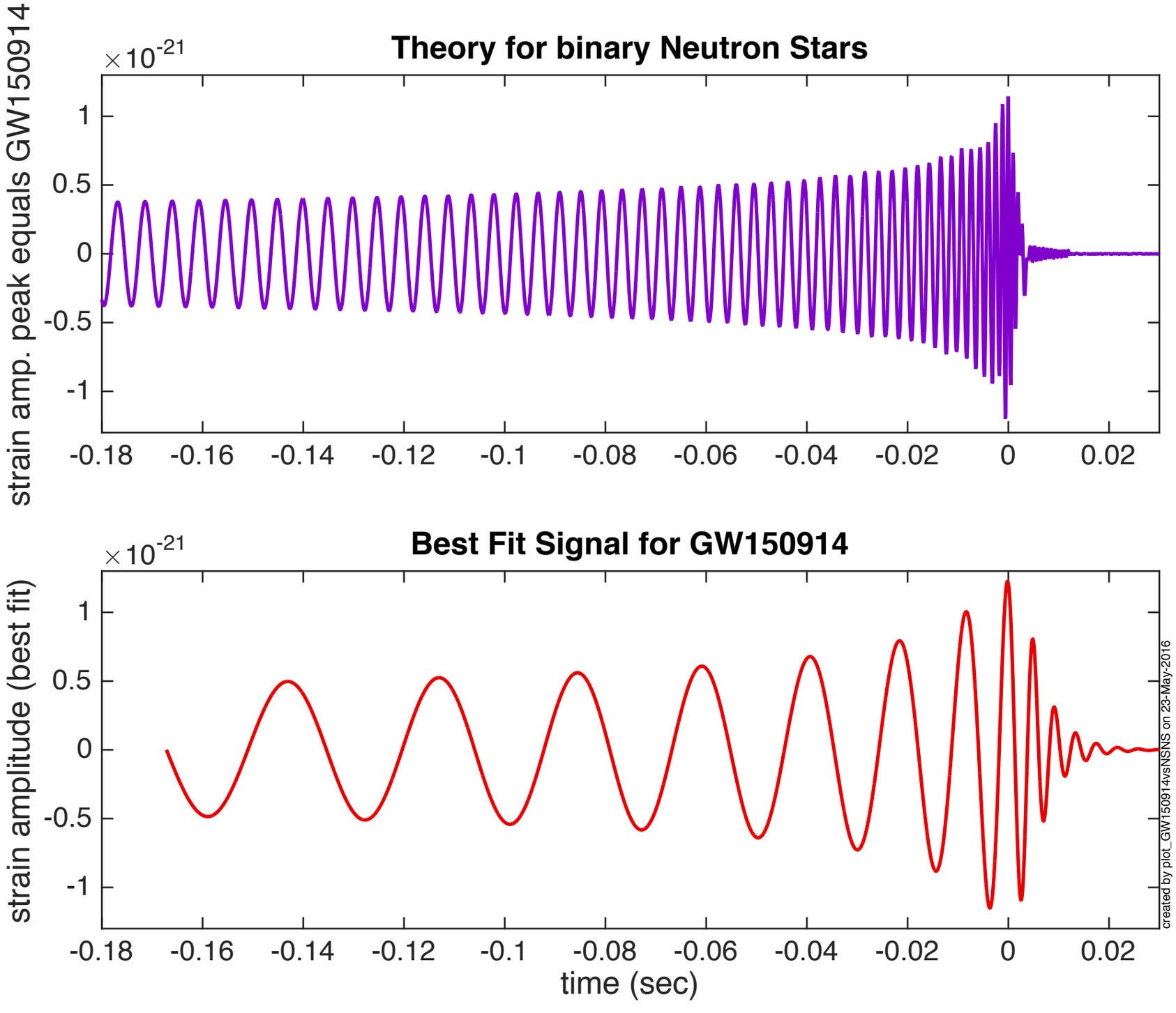

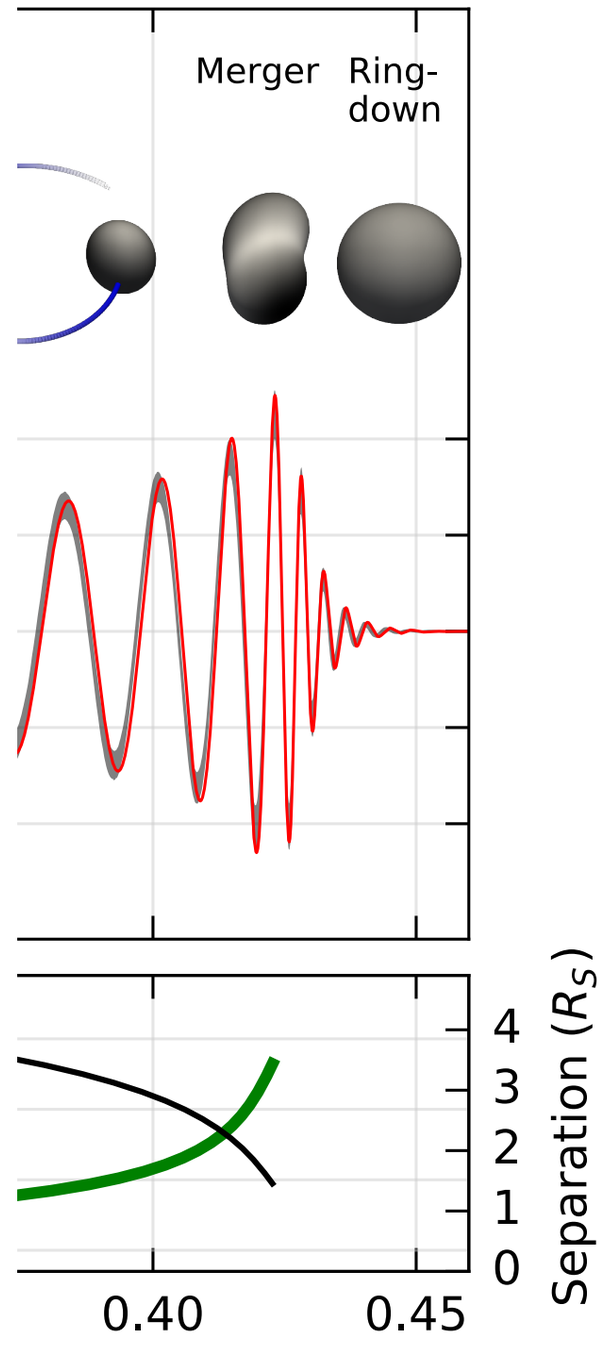

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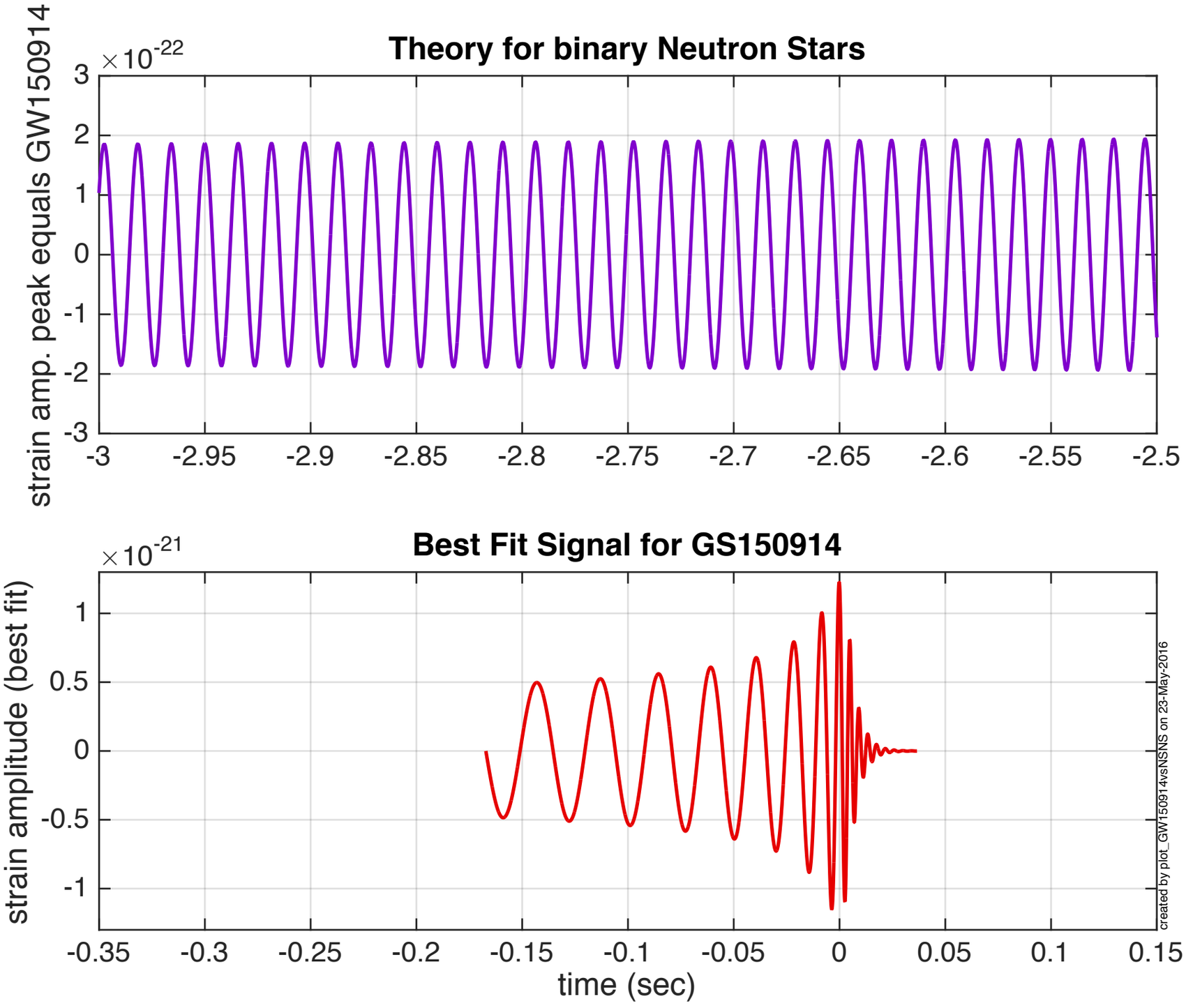

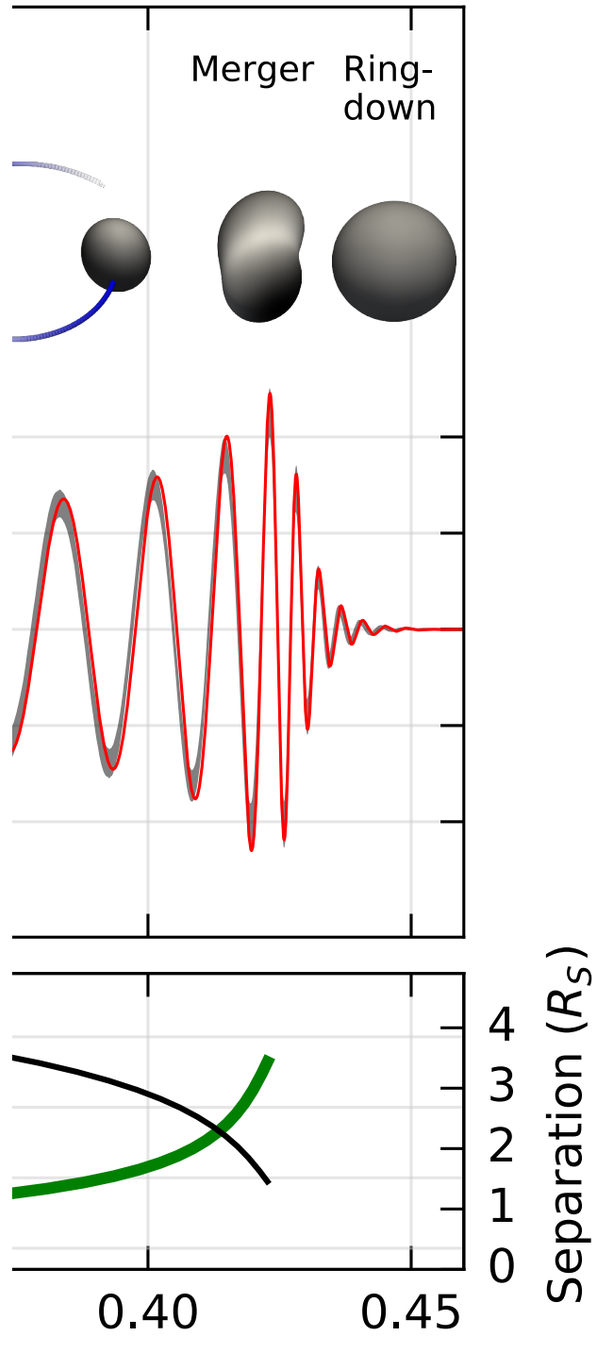

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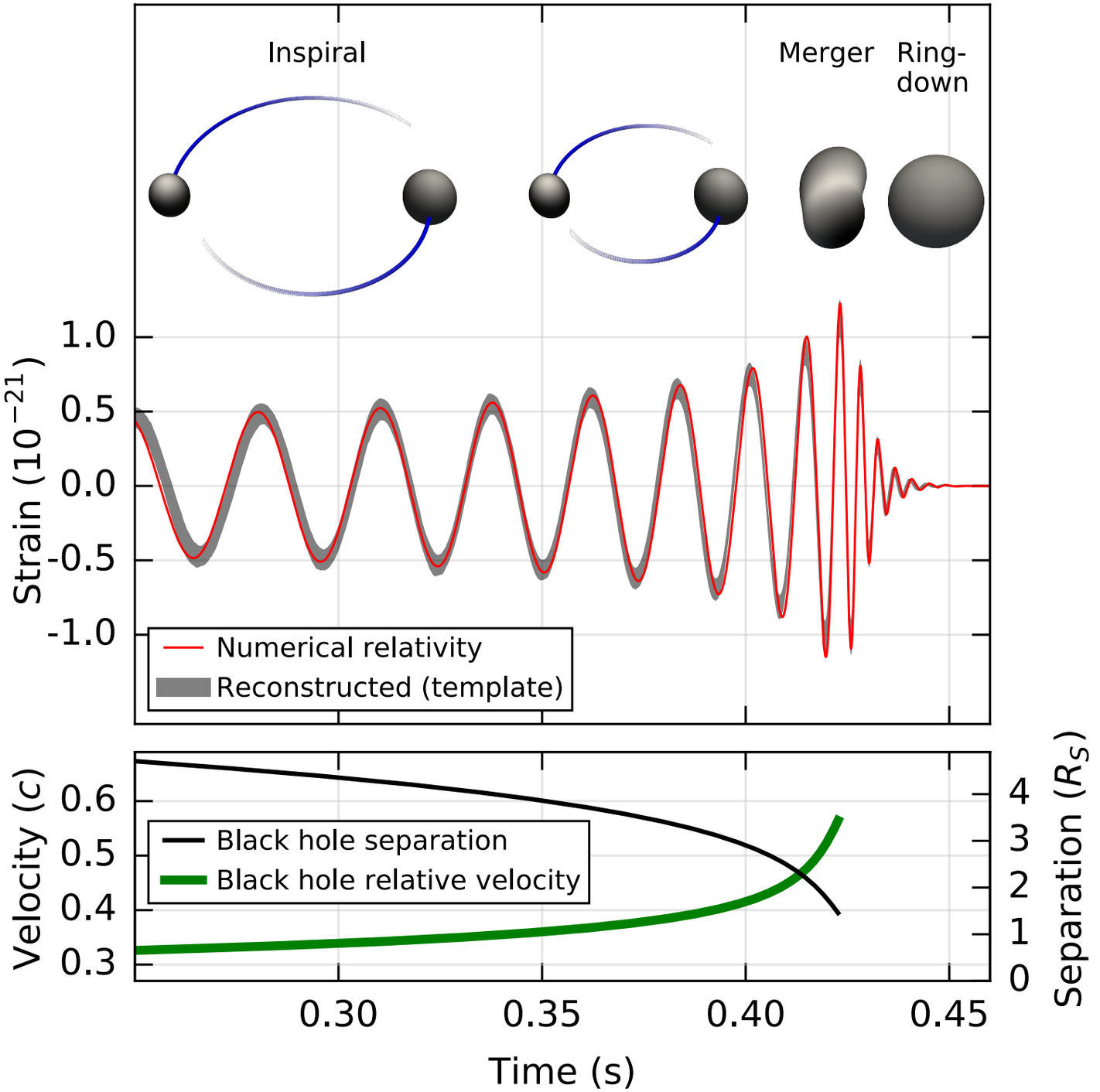
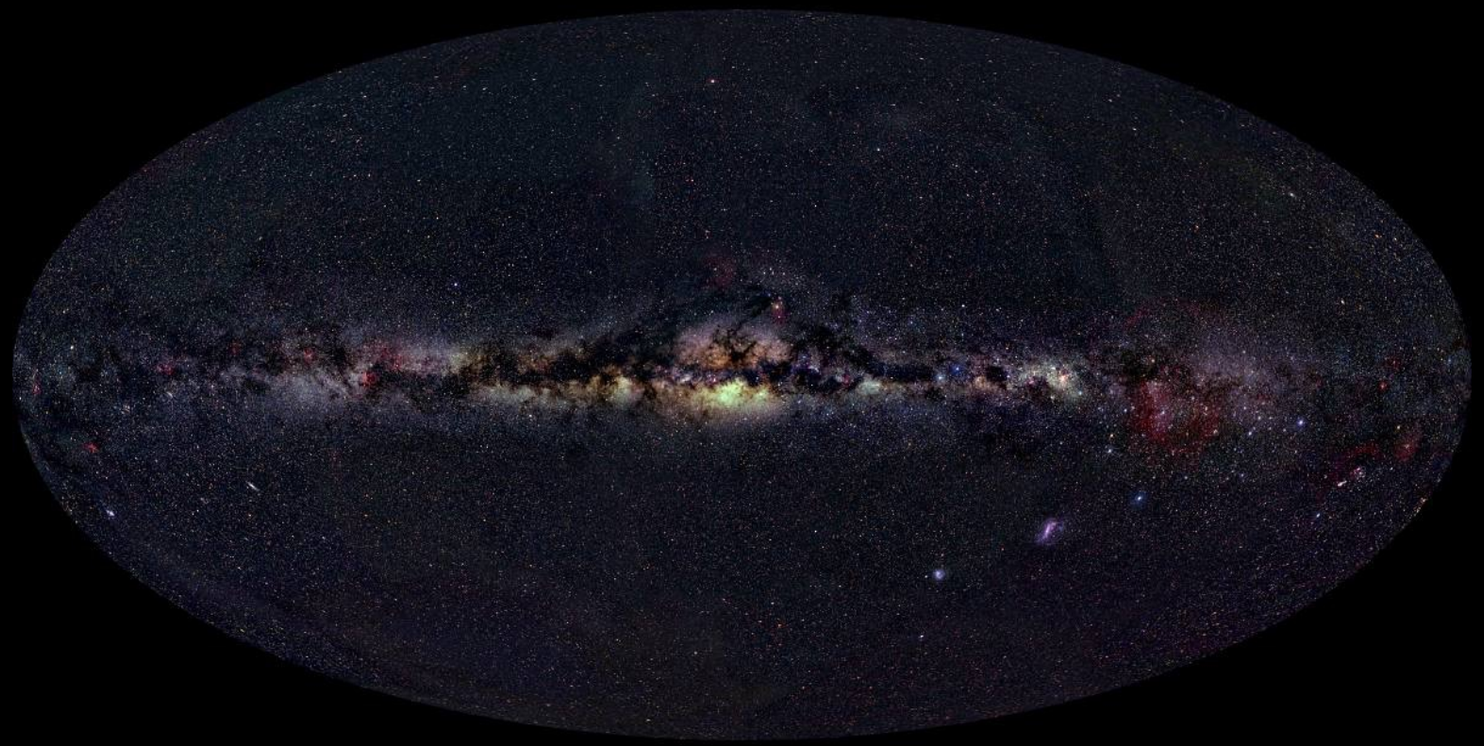
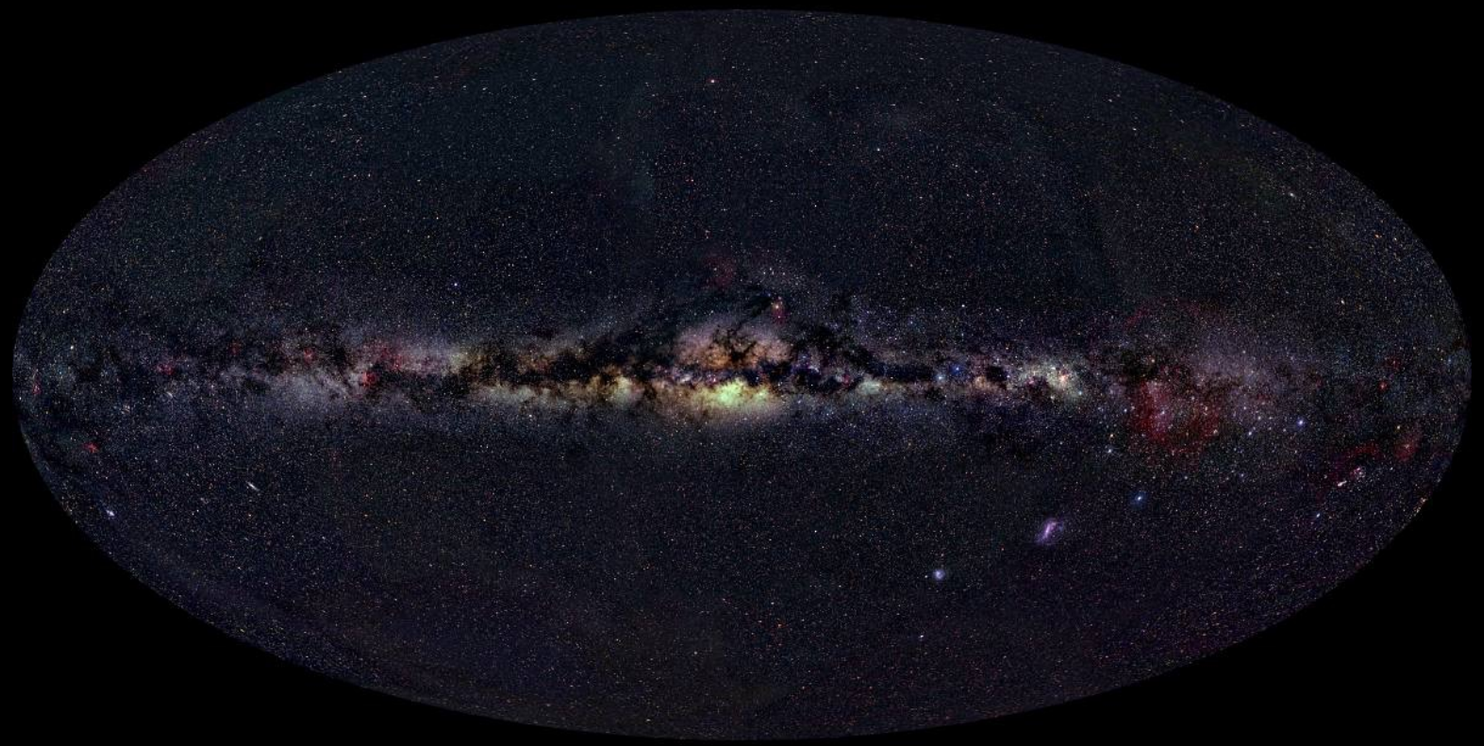


http://dx.doi.org/10.1103/PhysRevLett.116.061102

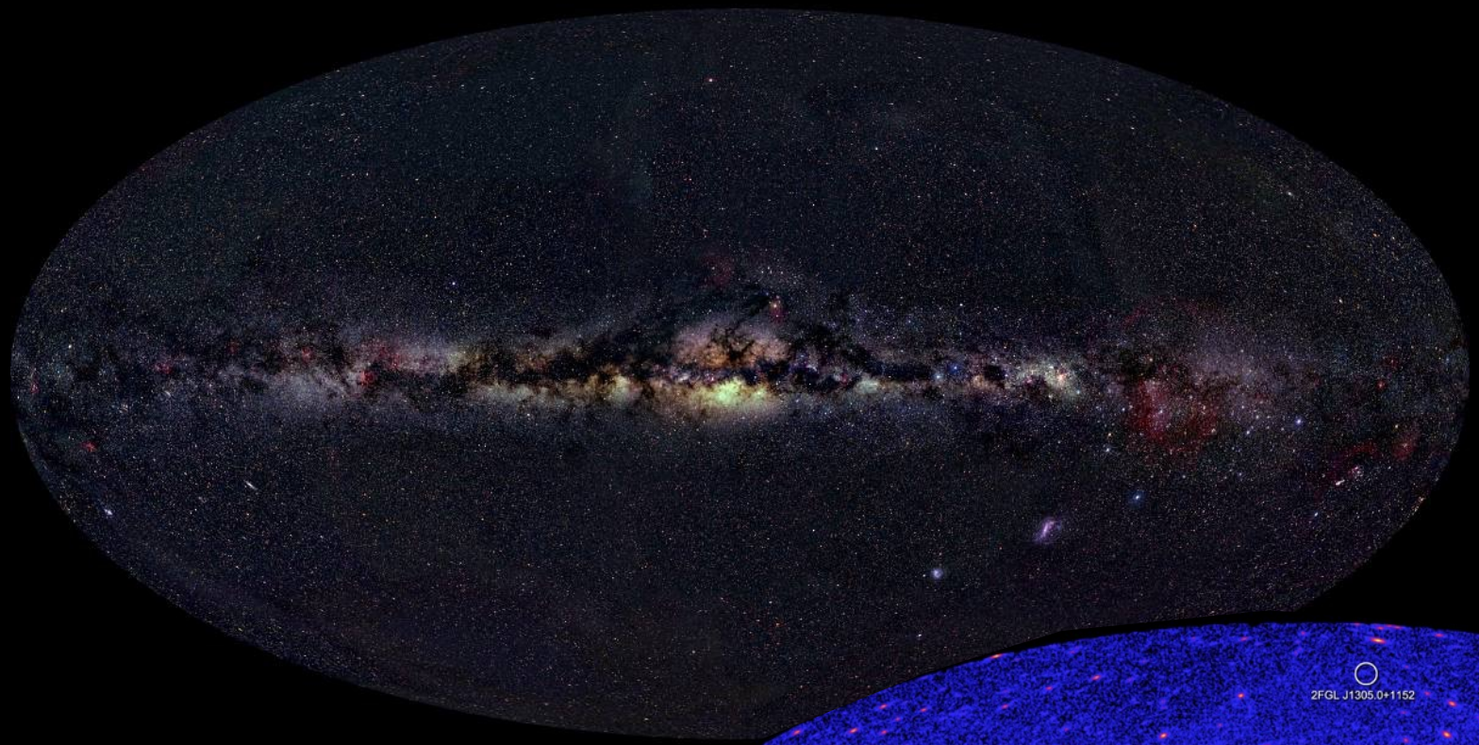
new ways to see the sky

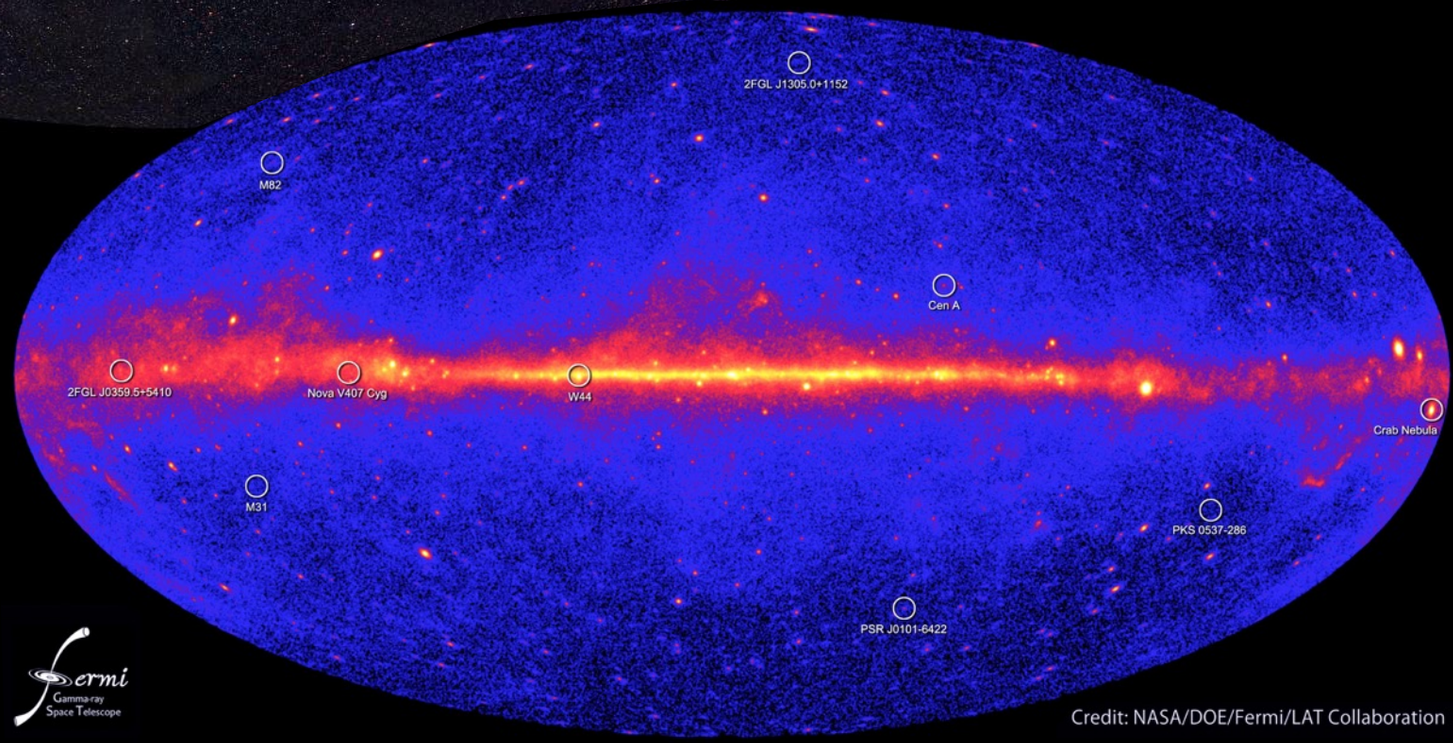


new ways to see the sky



new ways to see the sky

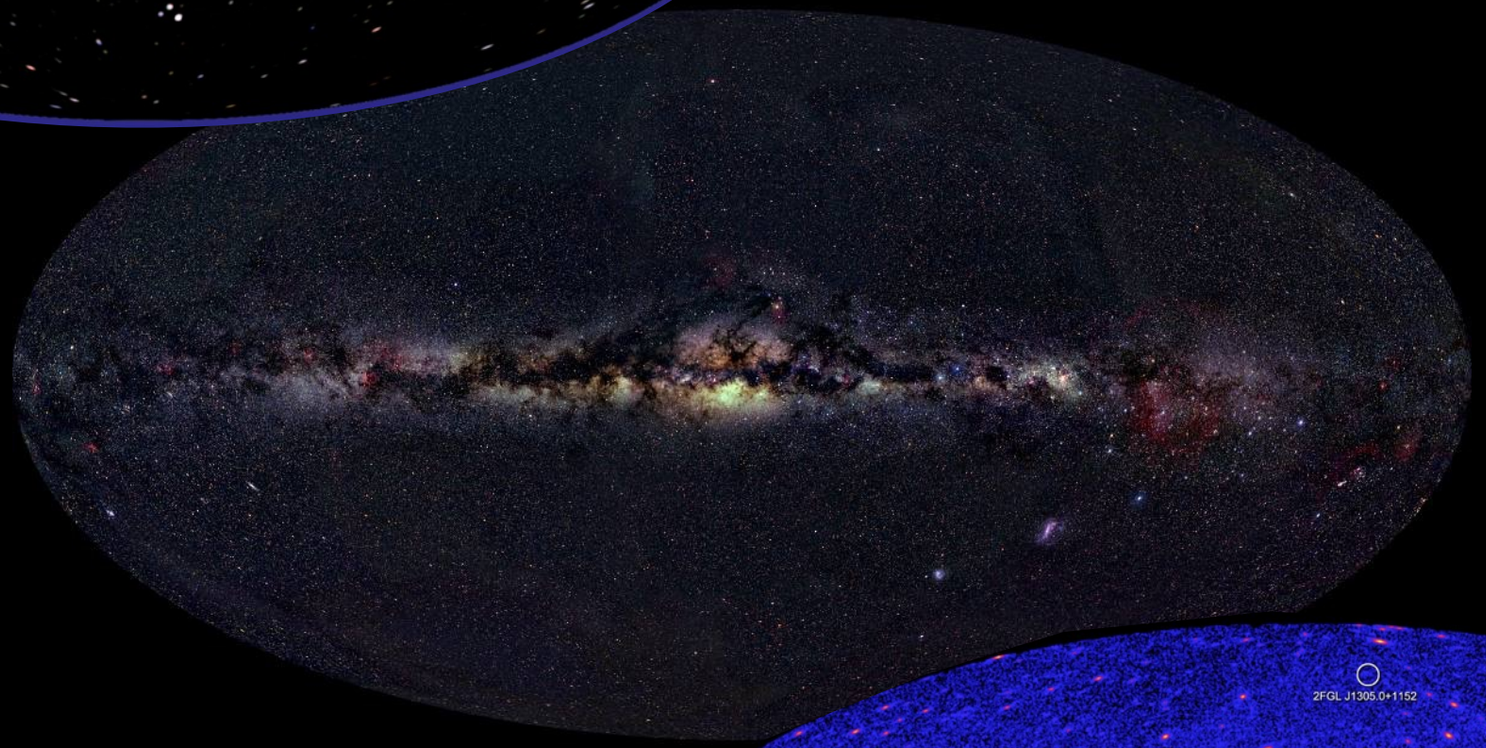


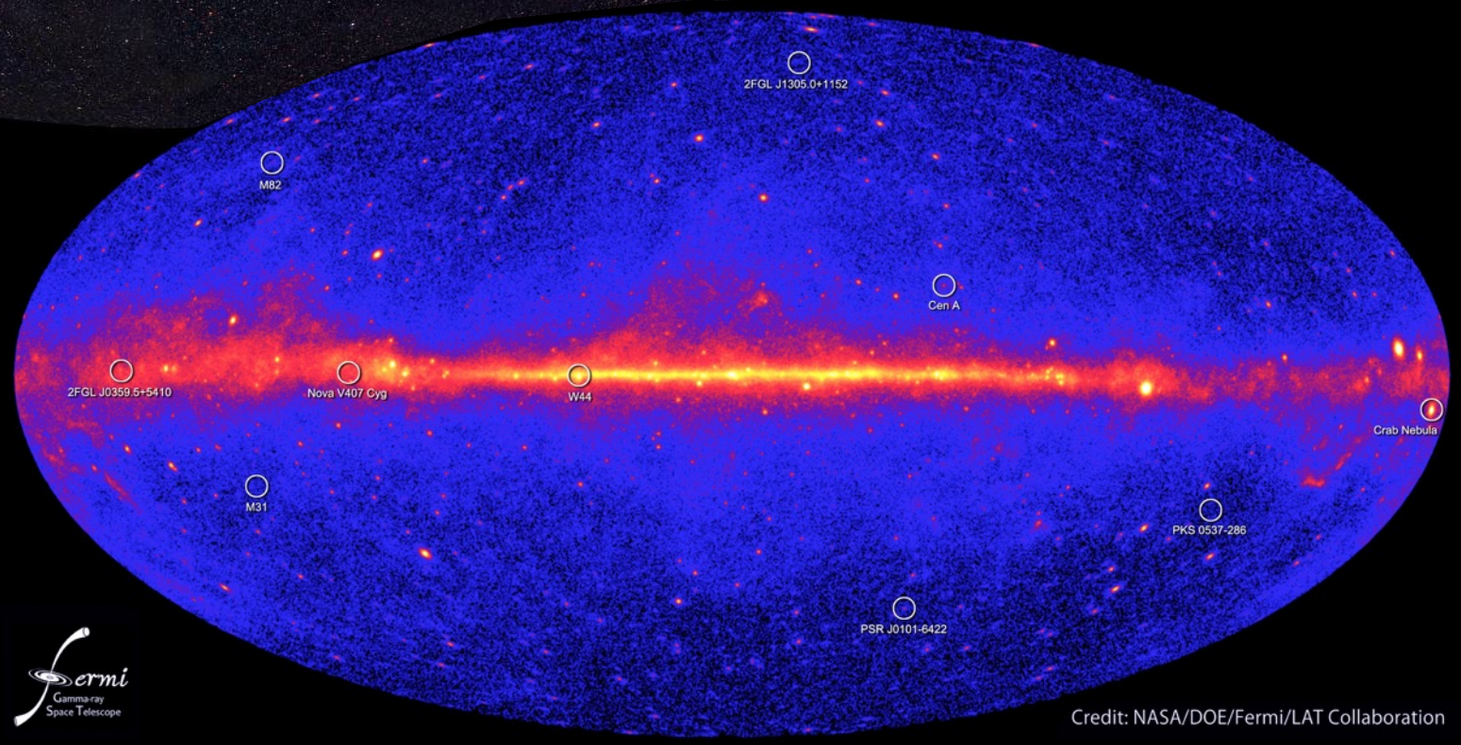


Credit: NASA/DOE/Fermi/LAT Collaboration

see the sky

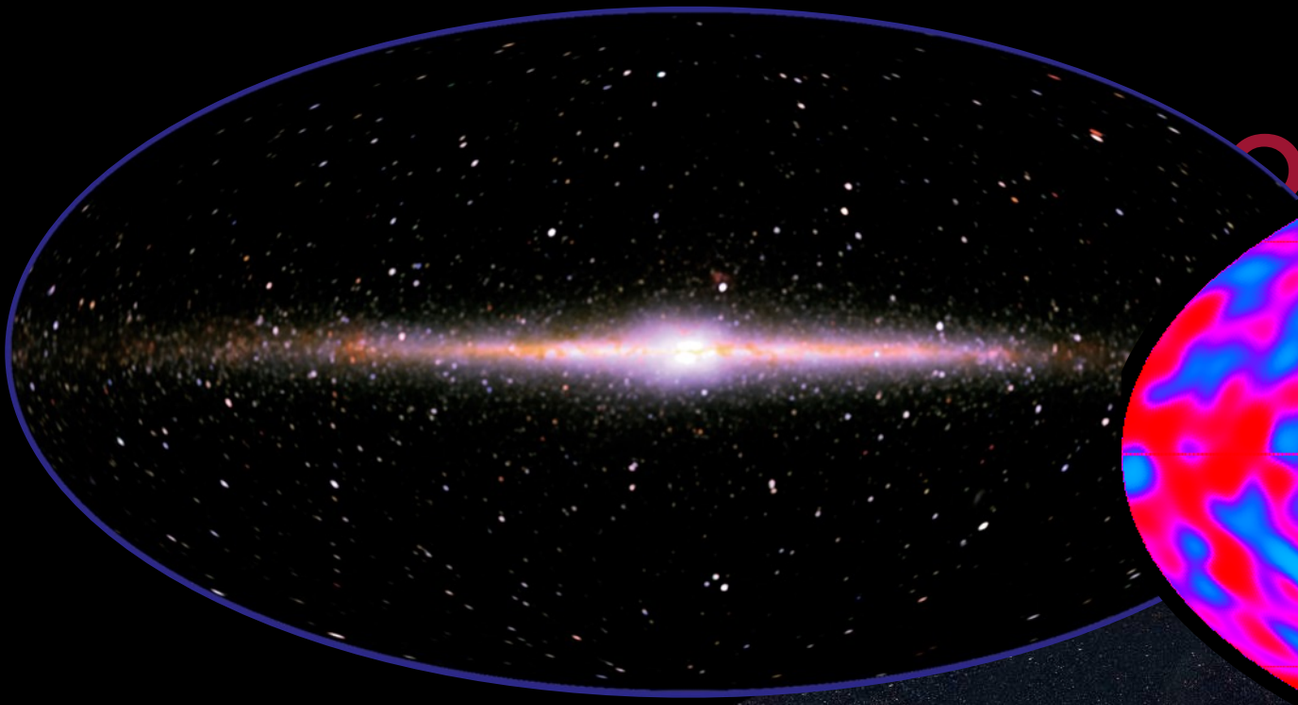
ep Sky

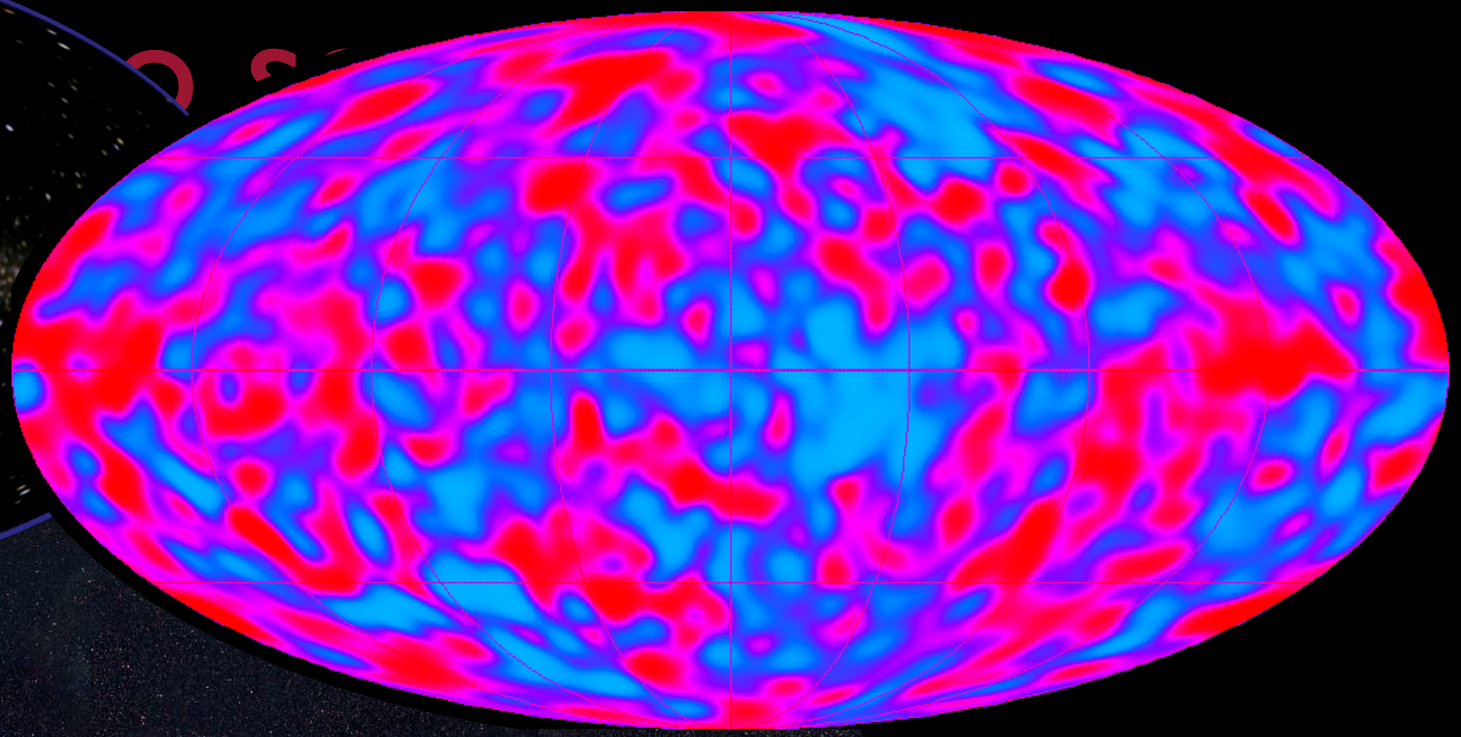


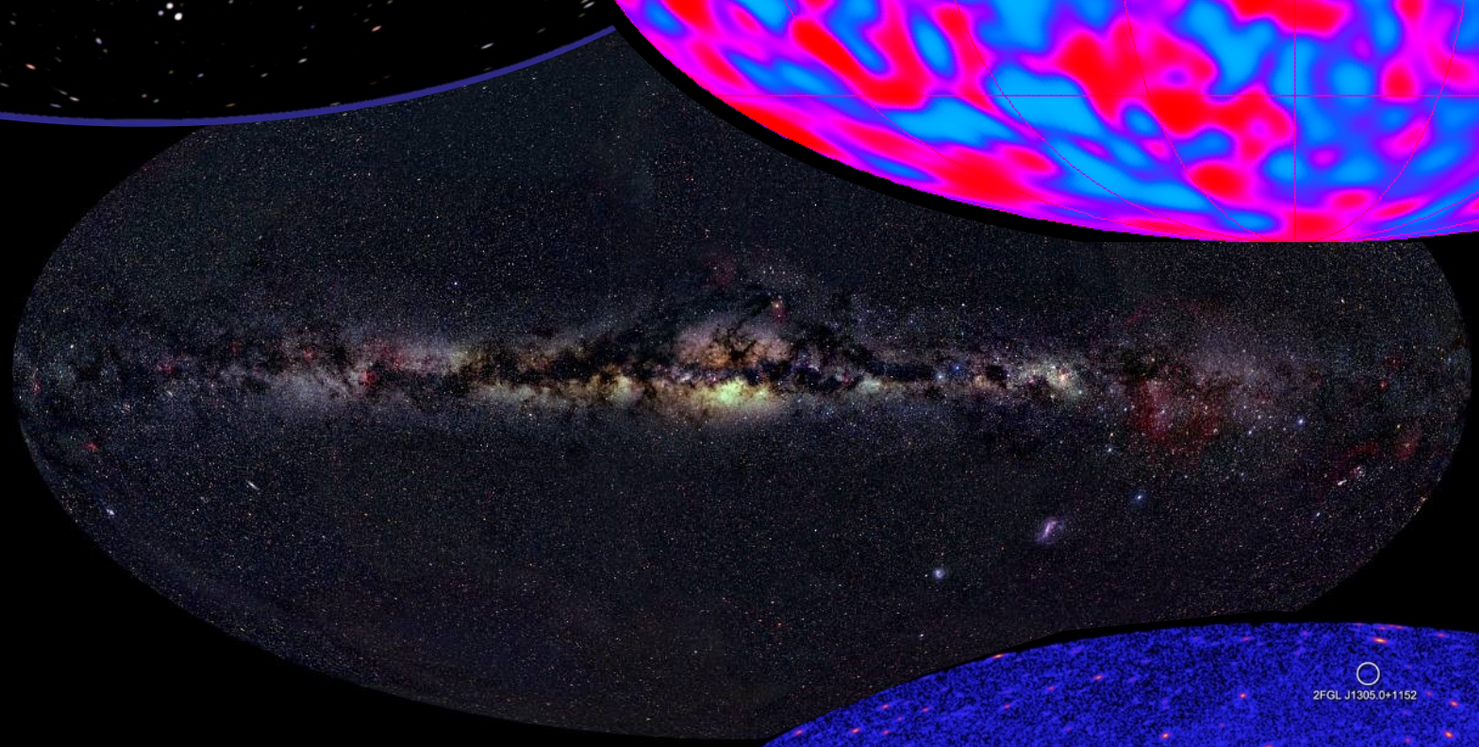


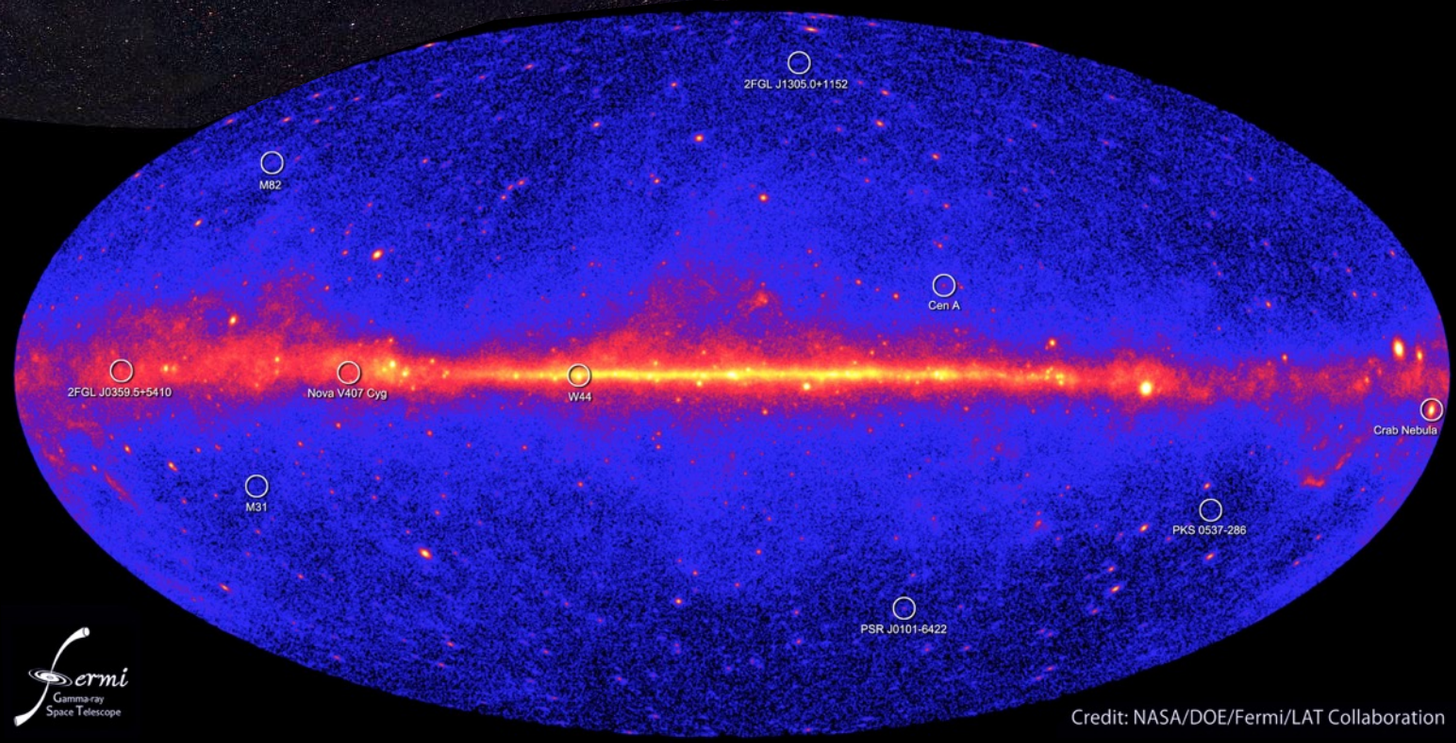
Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration





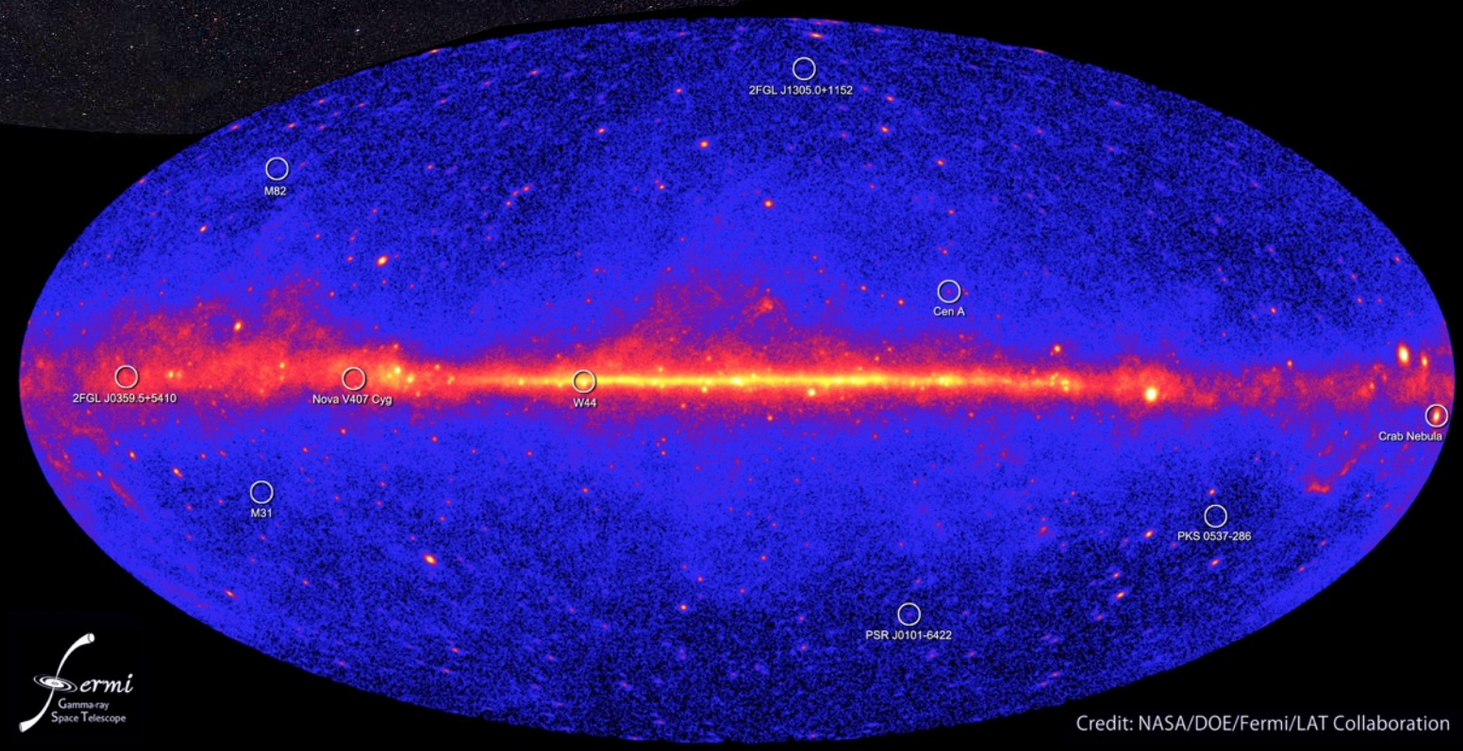




Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

And Now…



Fermi Gamma-ray Space Telescope

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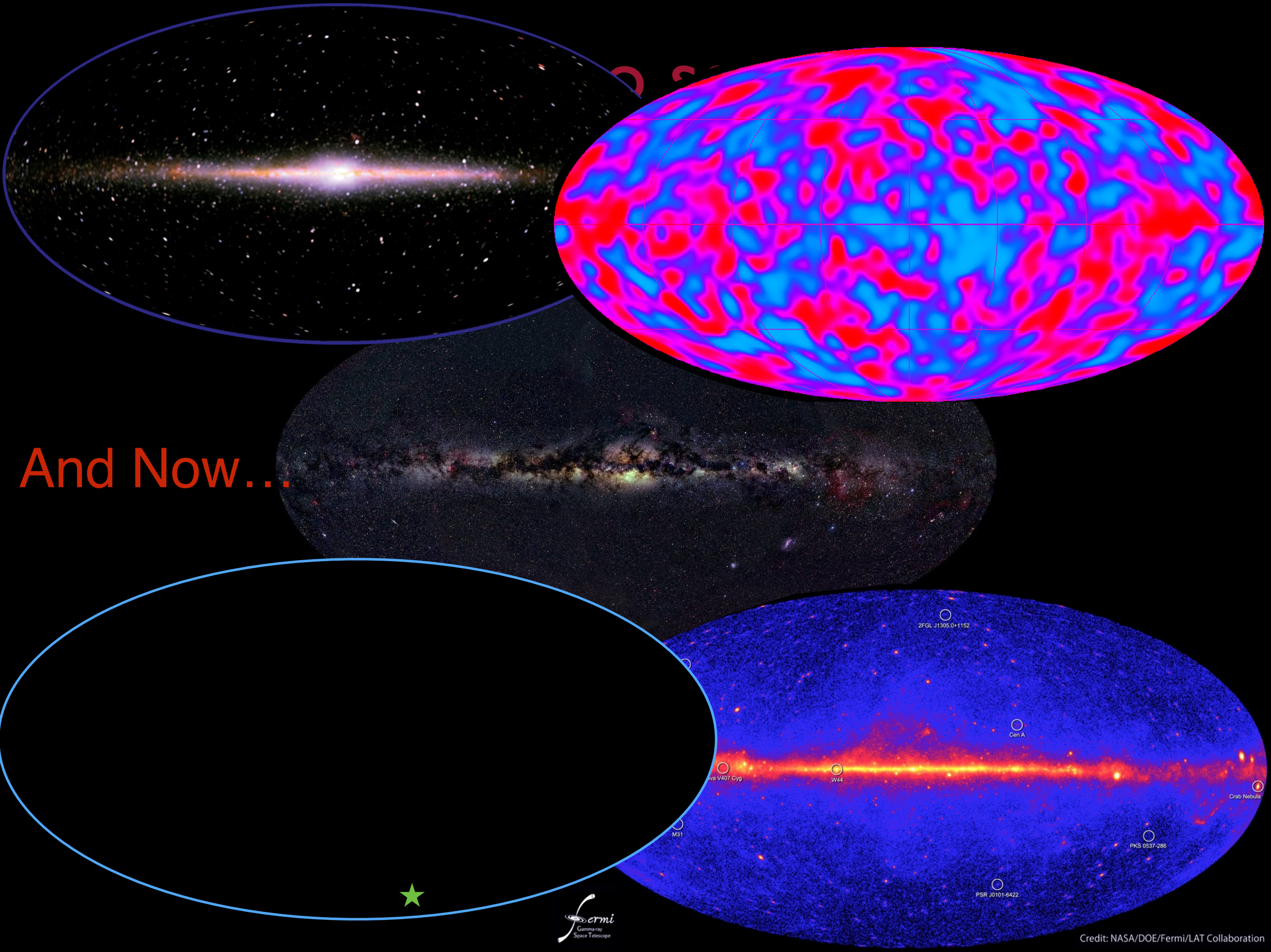
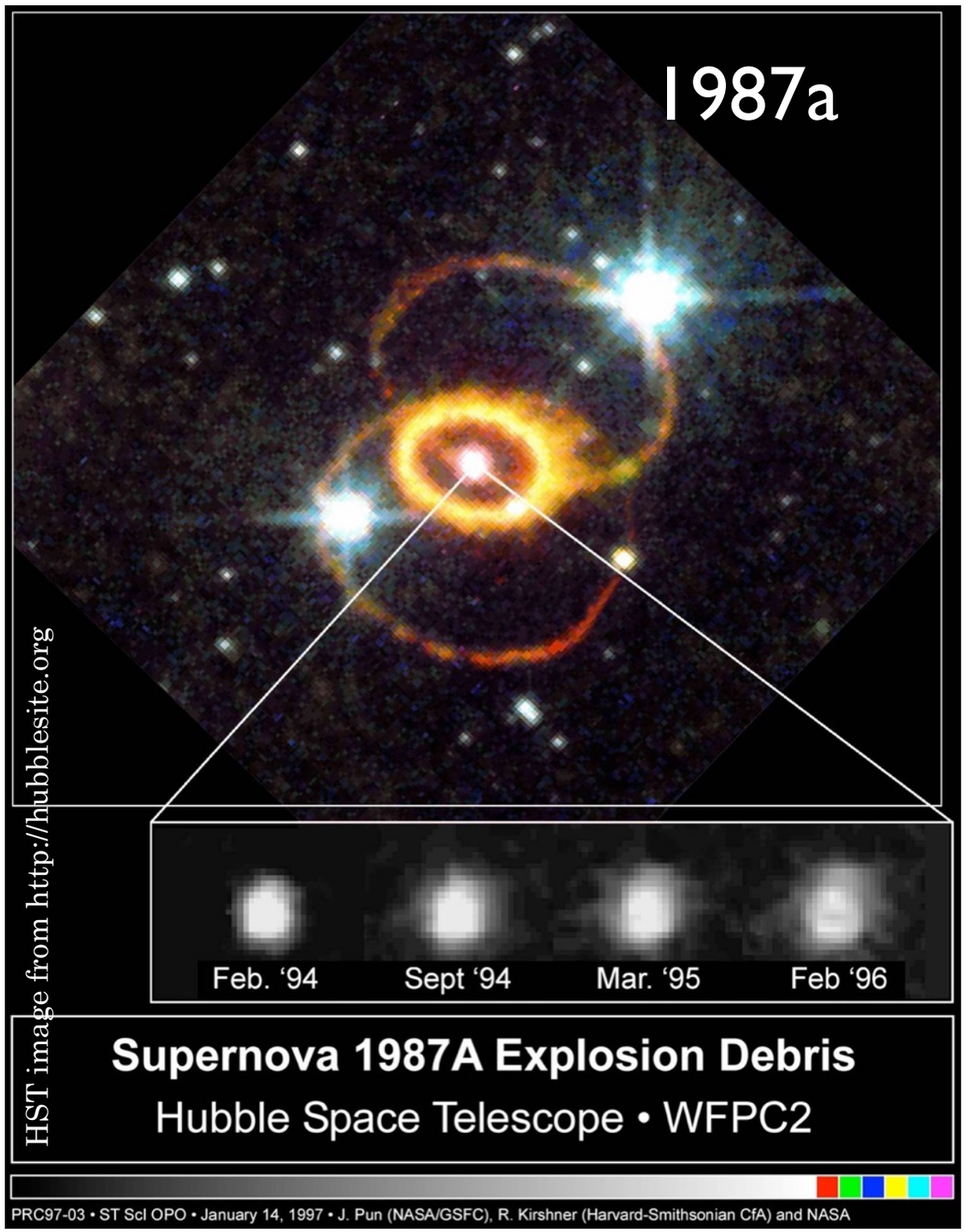
And Now…

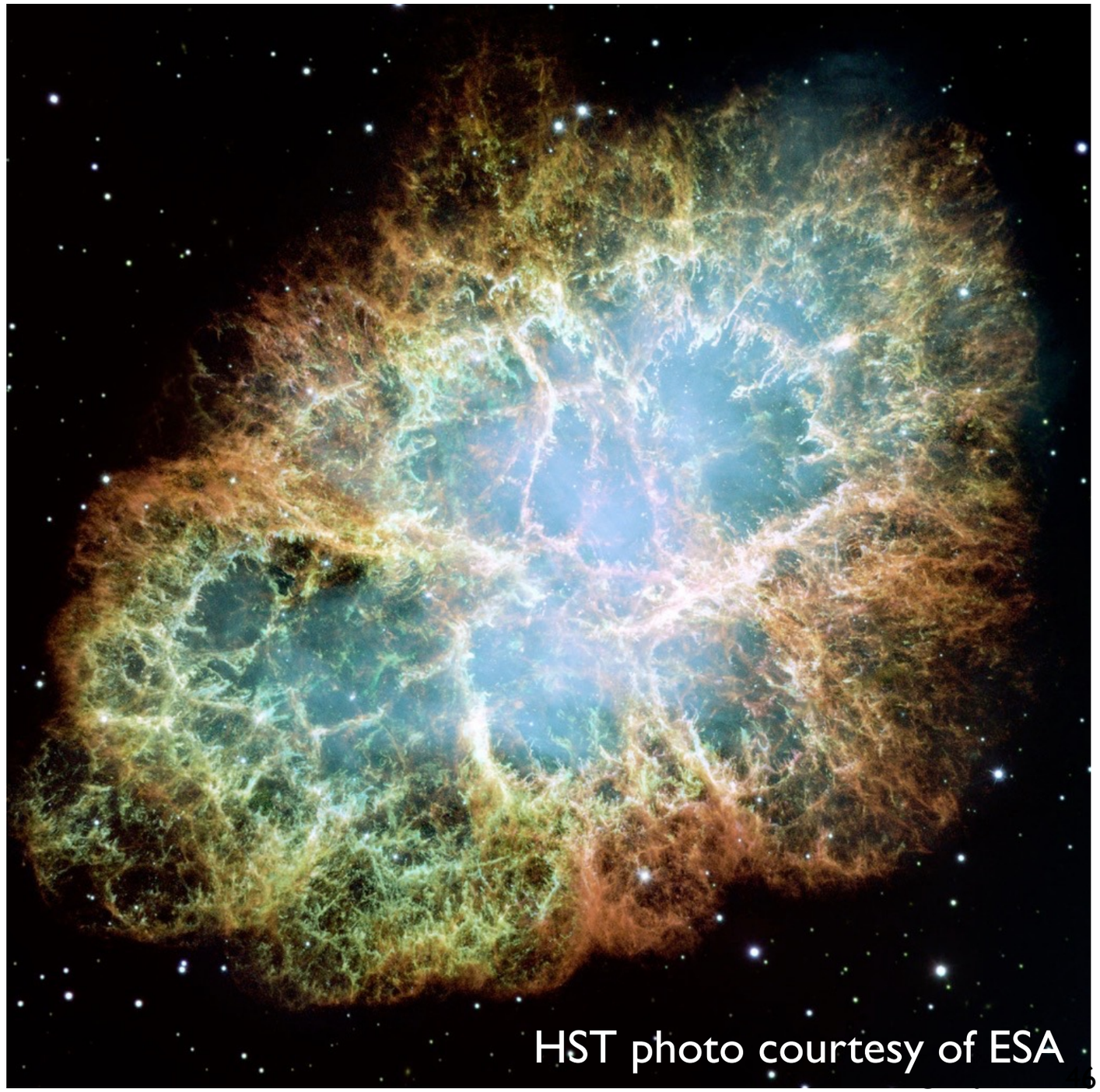


Credit: NASA/DOE/Fermi/LAT Collaboration

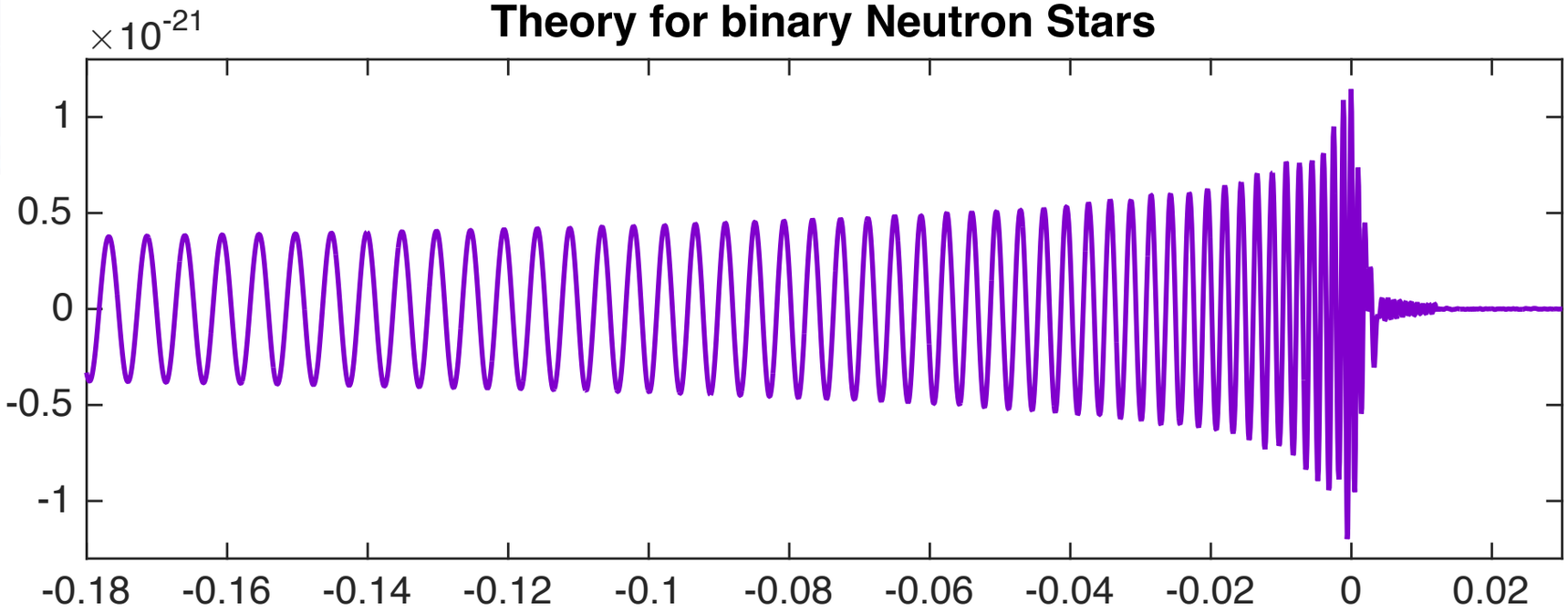
Supernovas and remnants



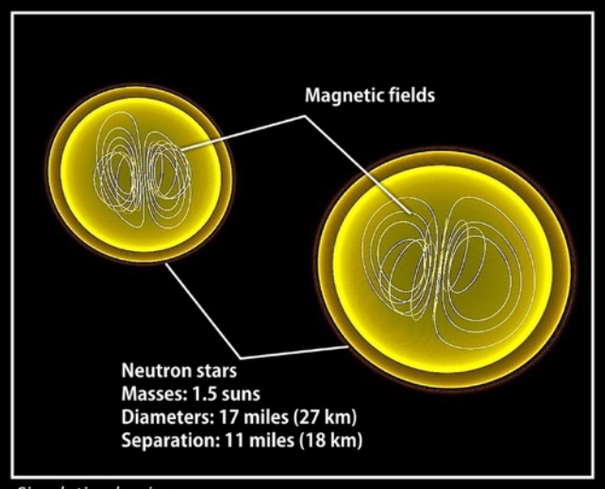
Crab Nebula, supernova in 1054, now a spinning neutron star



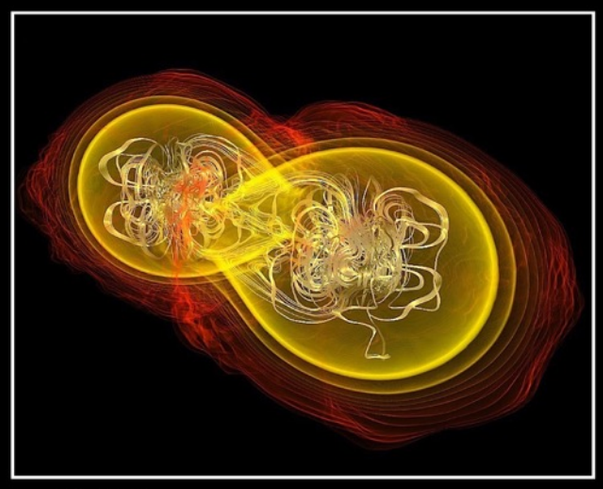
Theory for binary Neutron Stars



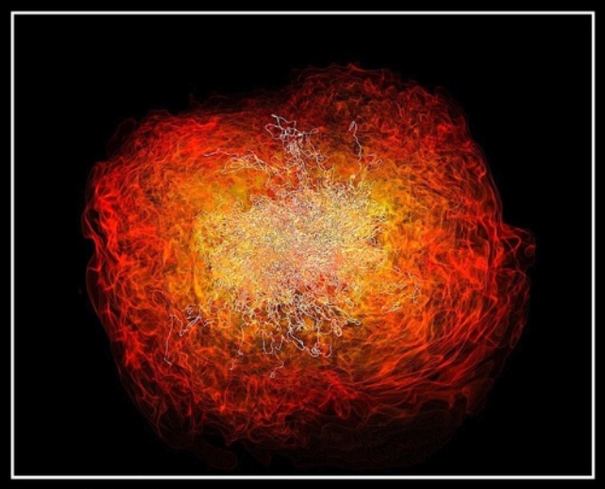
Crashing neutron stars can make gamma-ray burst jets



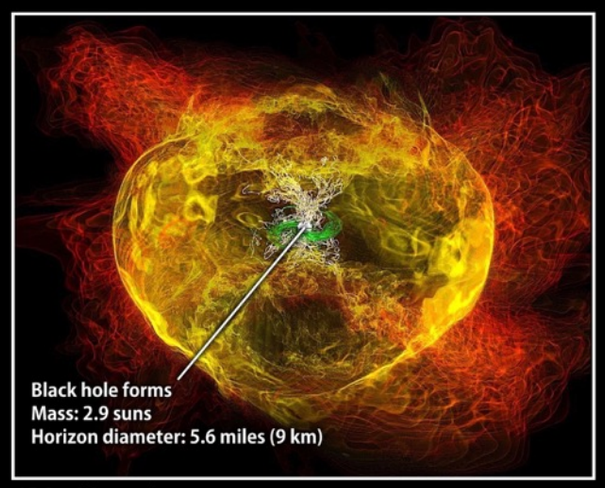
Simulation begins



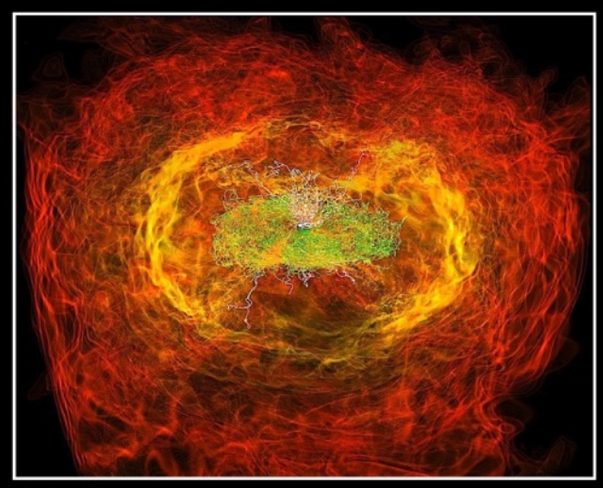
7.4 milliseconds



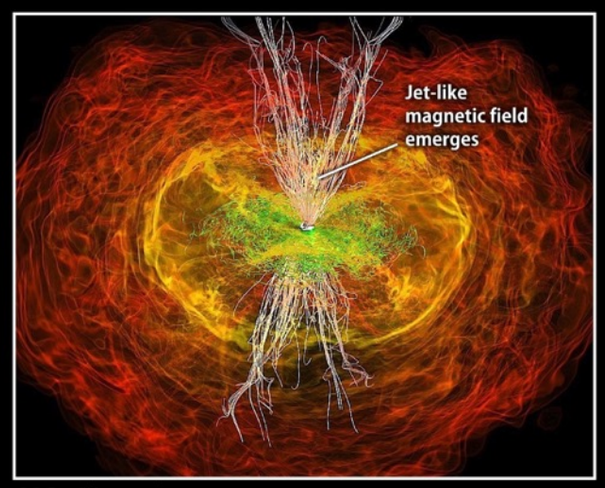
13.8 milliseconds



15.3 milliseconds



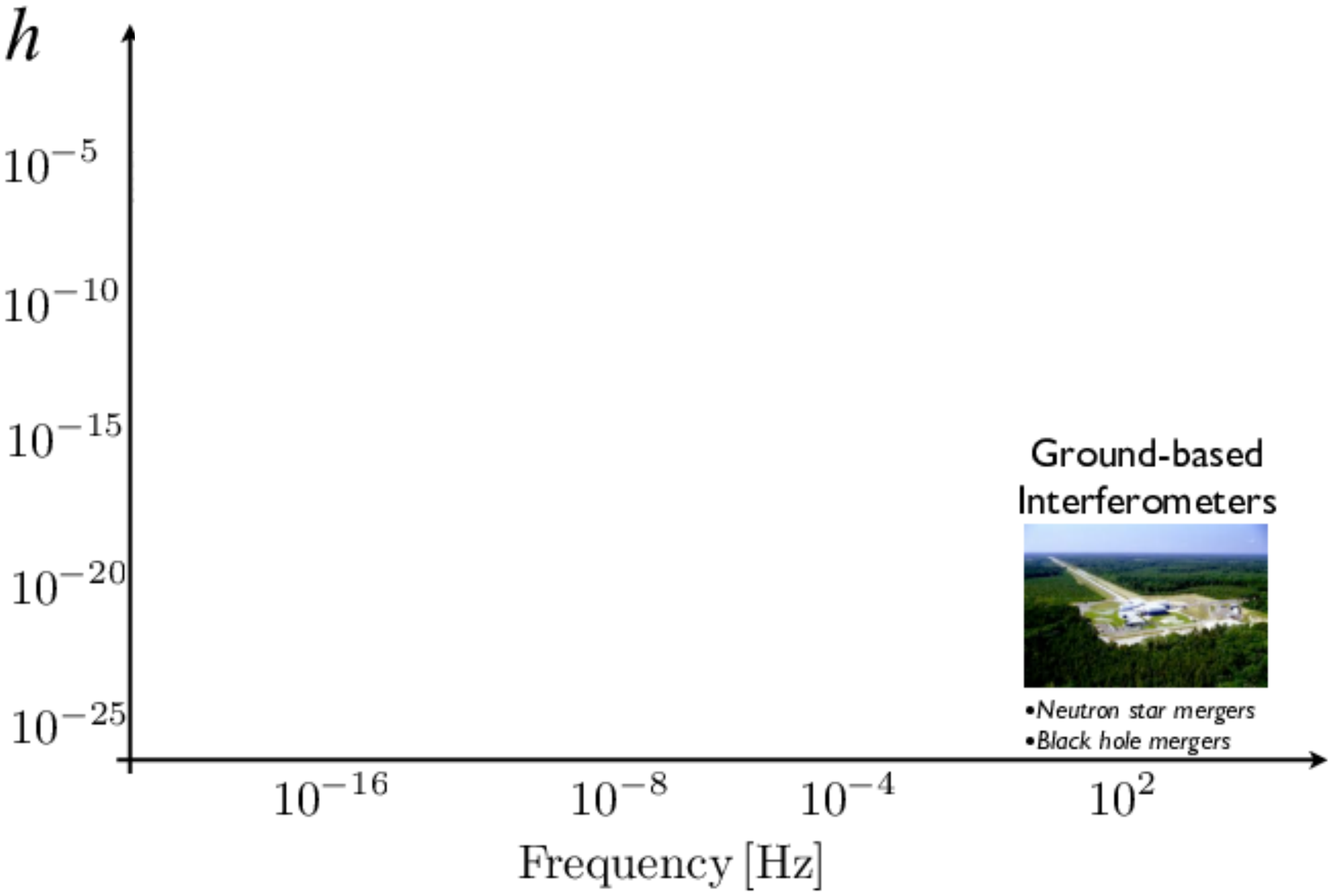
21.2 milliseconds



26.5 milliseconds

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

The spectrum of gravitational wave astronomy



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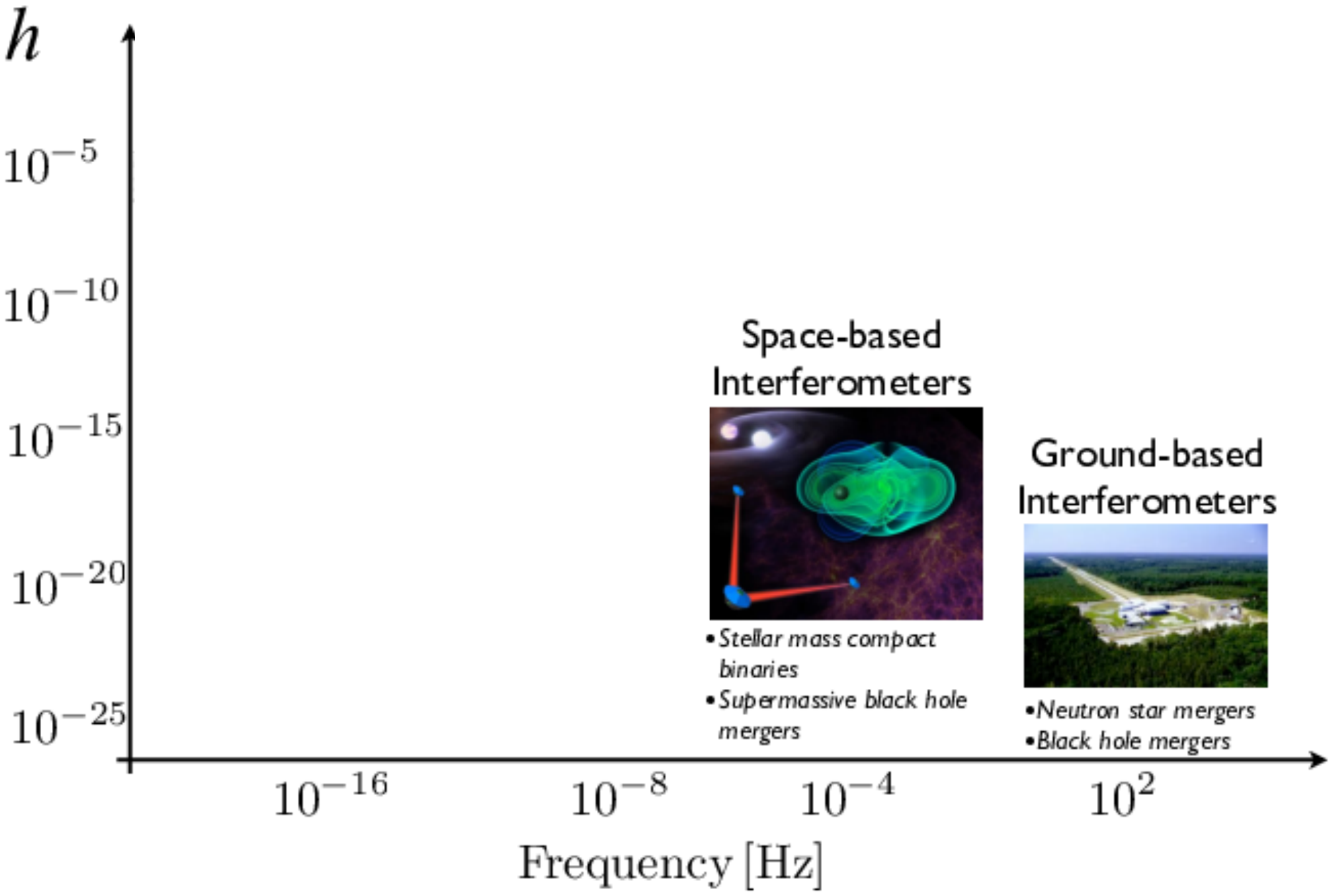
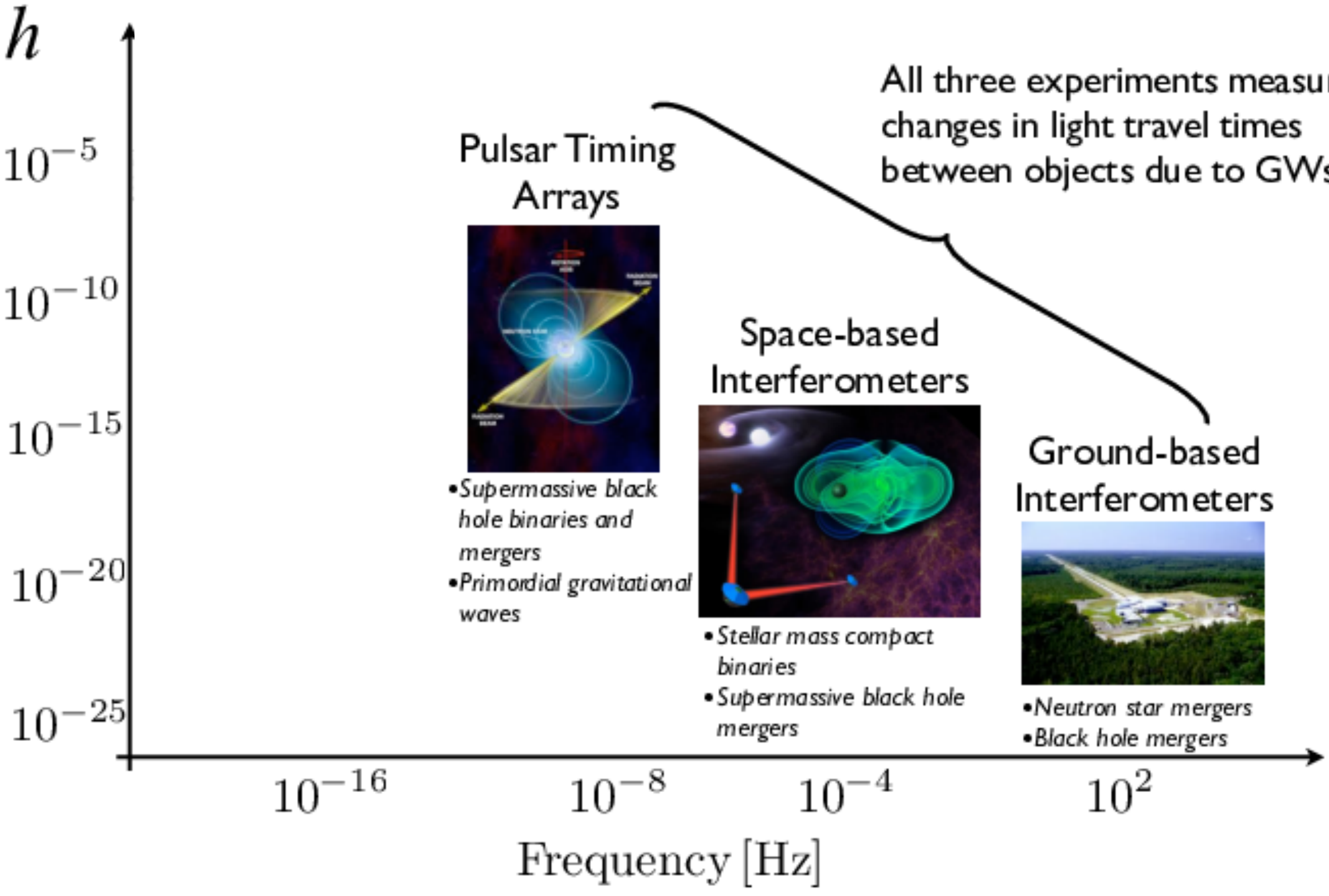
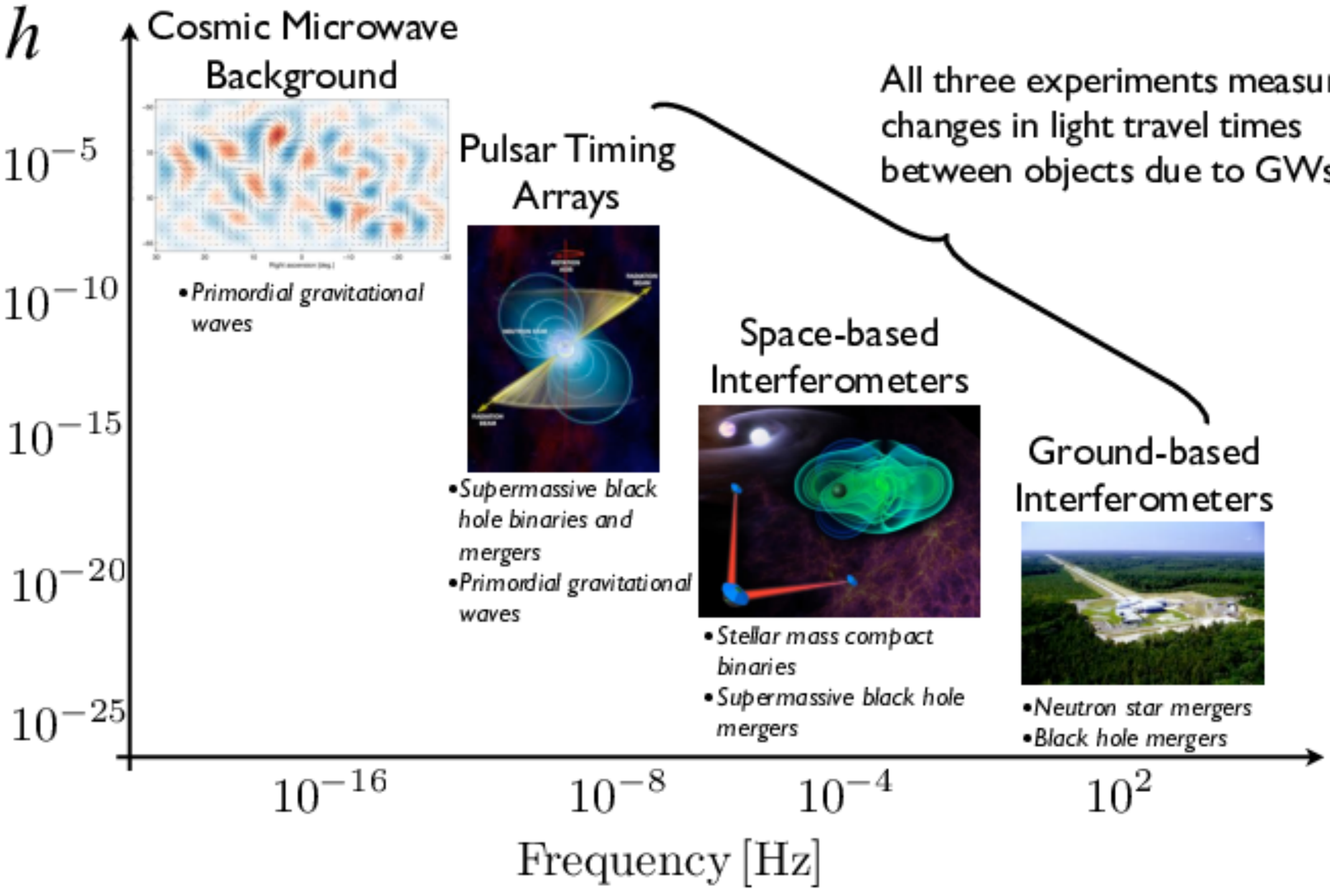


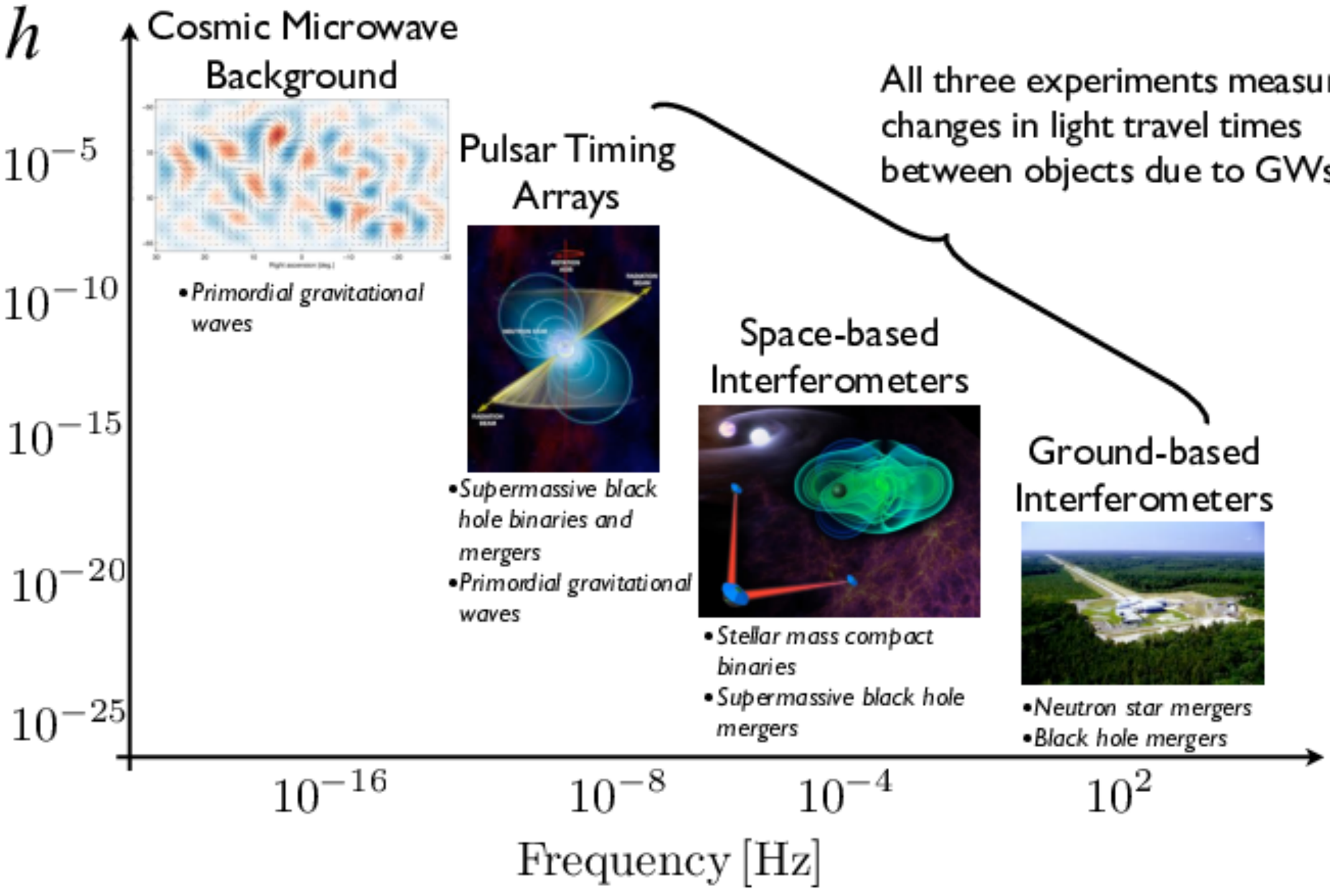
The spectrum of gravitational wave astronomy

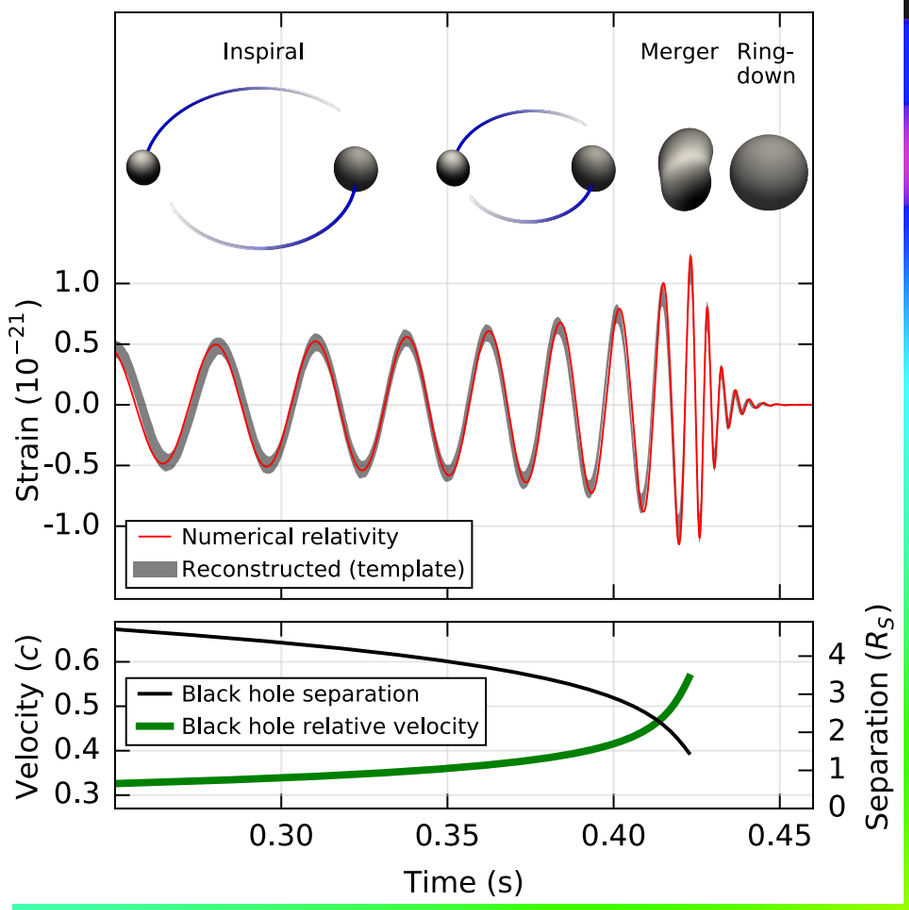


The spectrum of gravitational wave astronomy

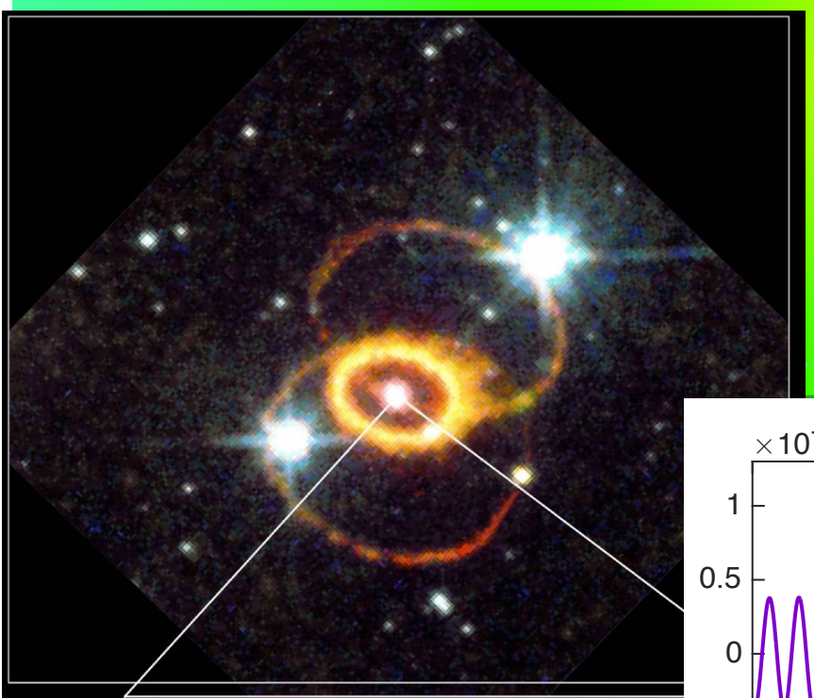


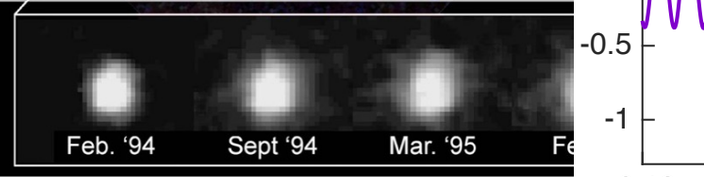
The spectrum of gravitational wave astronomy



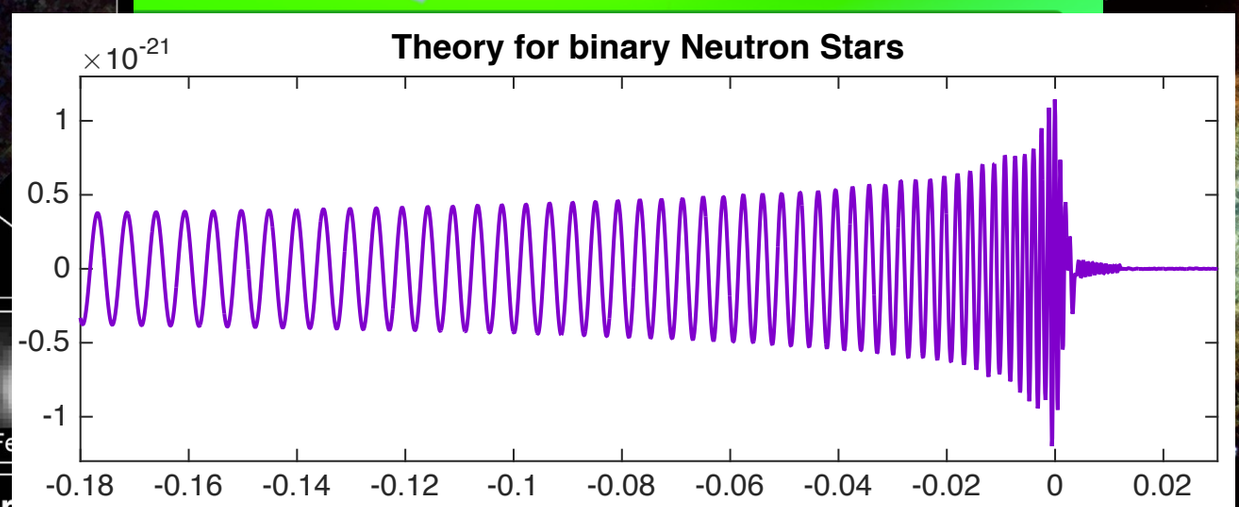


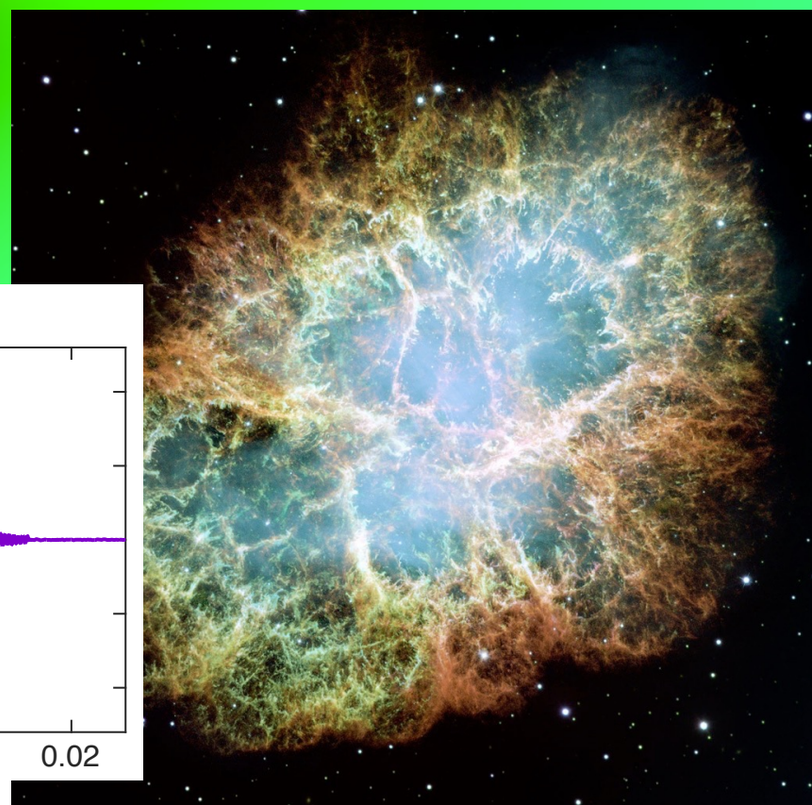
http://papers.ligo.org





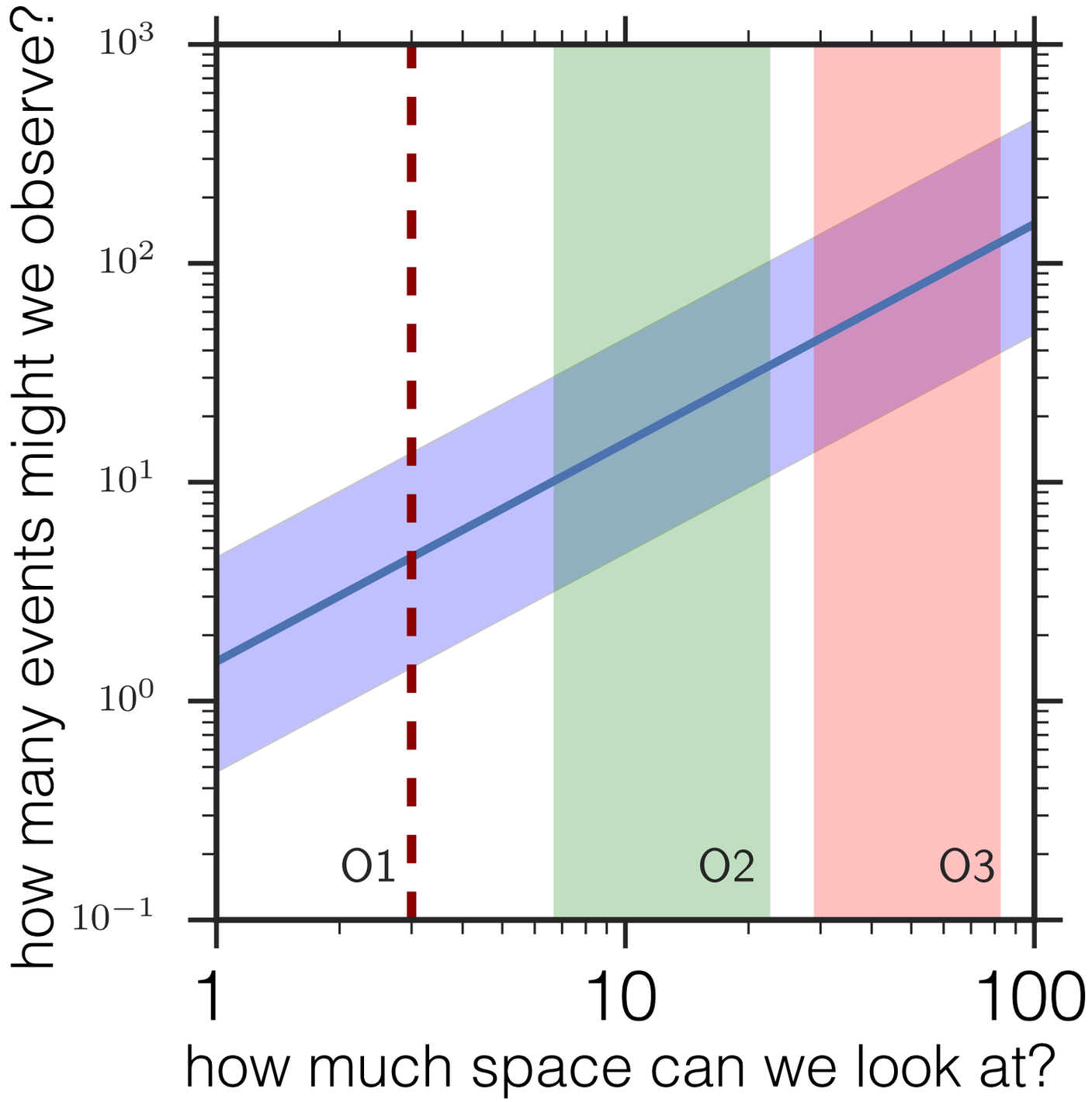
Supernova 1987A Explosion Debris



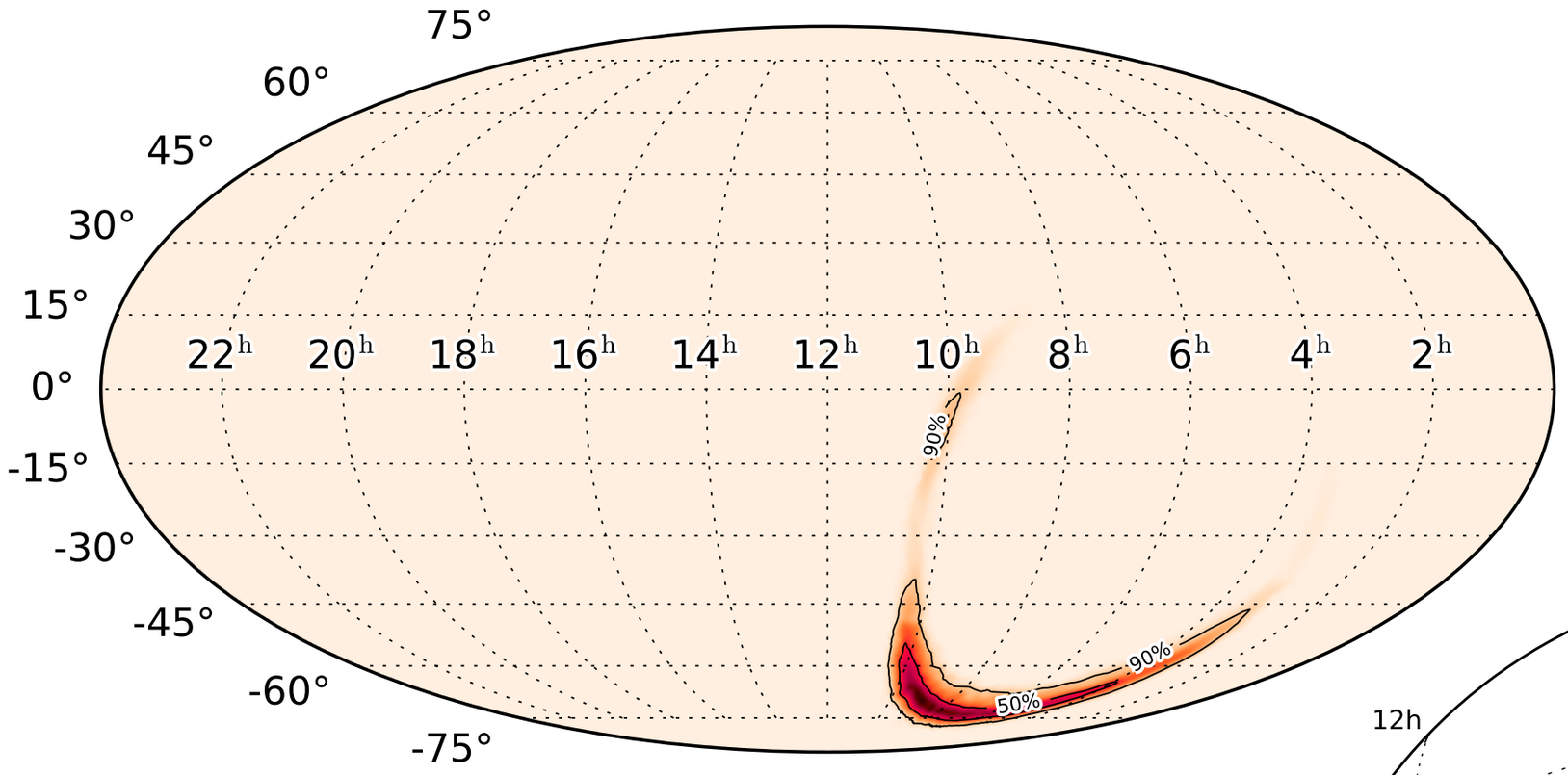


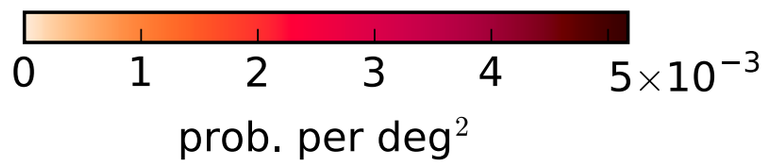
The End/ The Beginning…

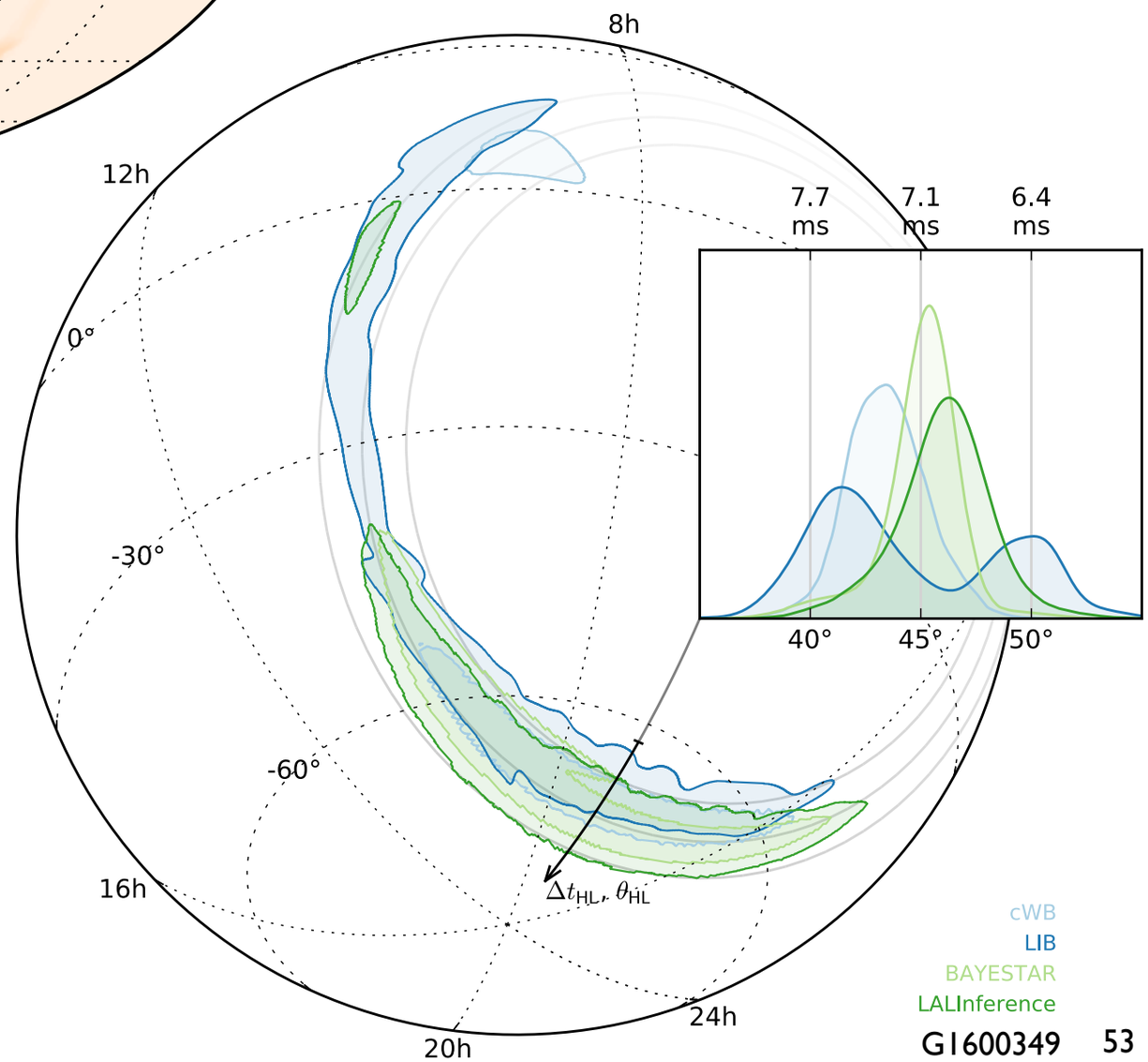
How many black hole collisions can we see?



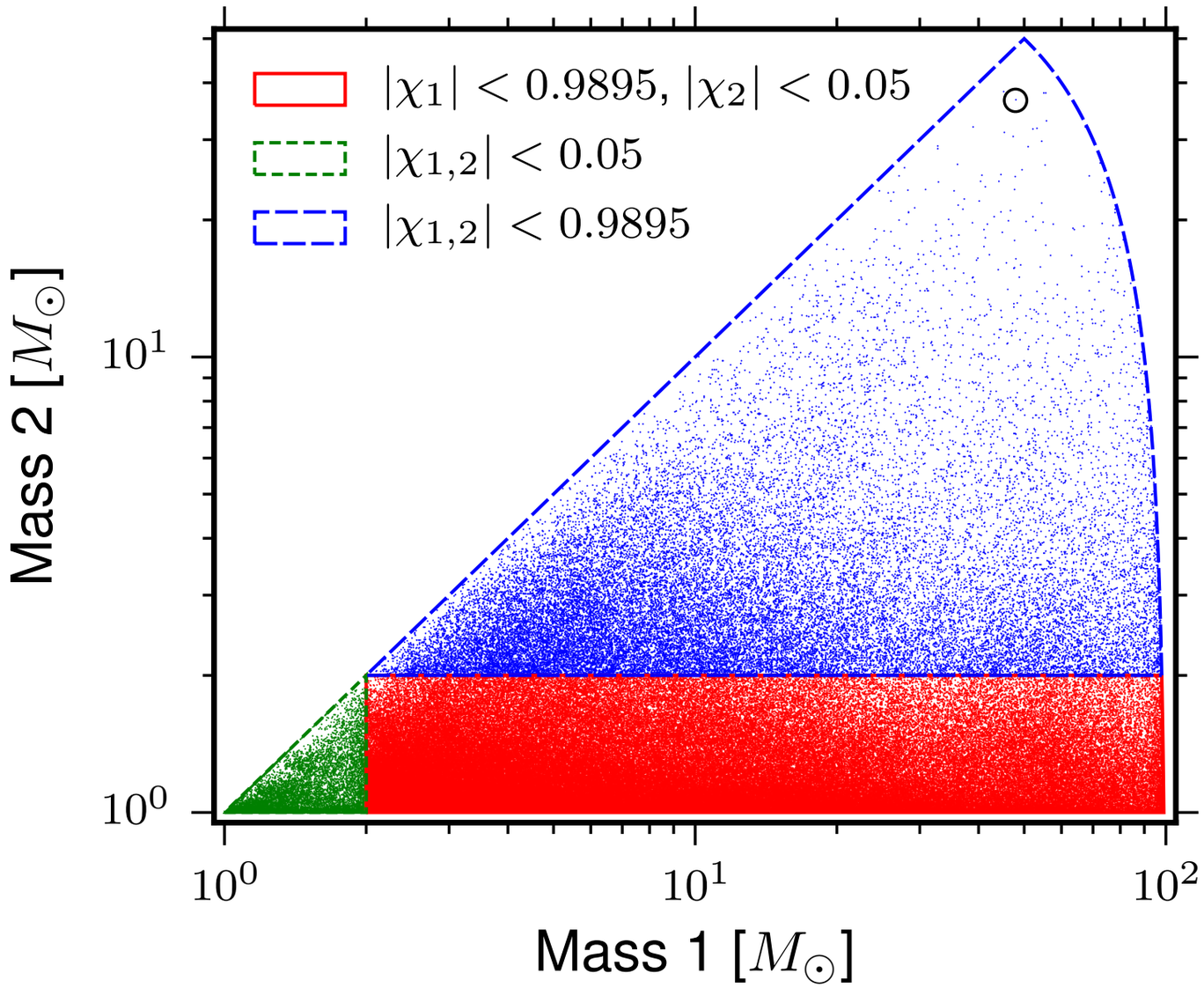
Where was it?


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 deg^2


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

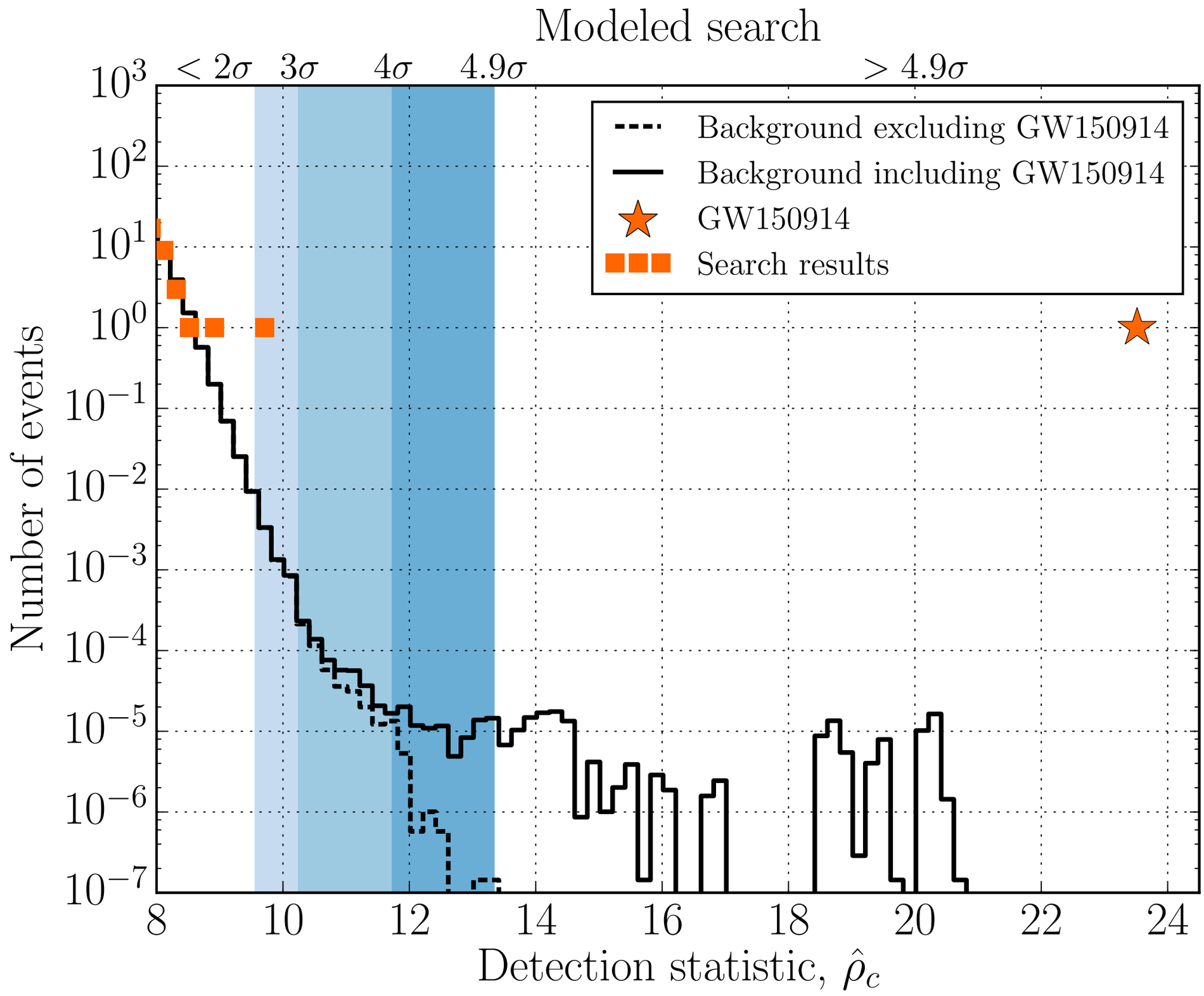
CBC template bank

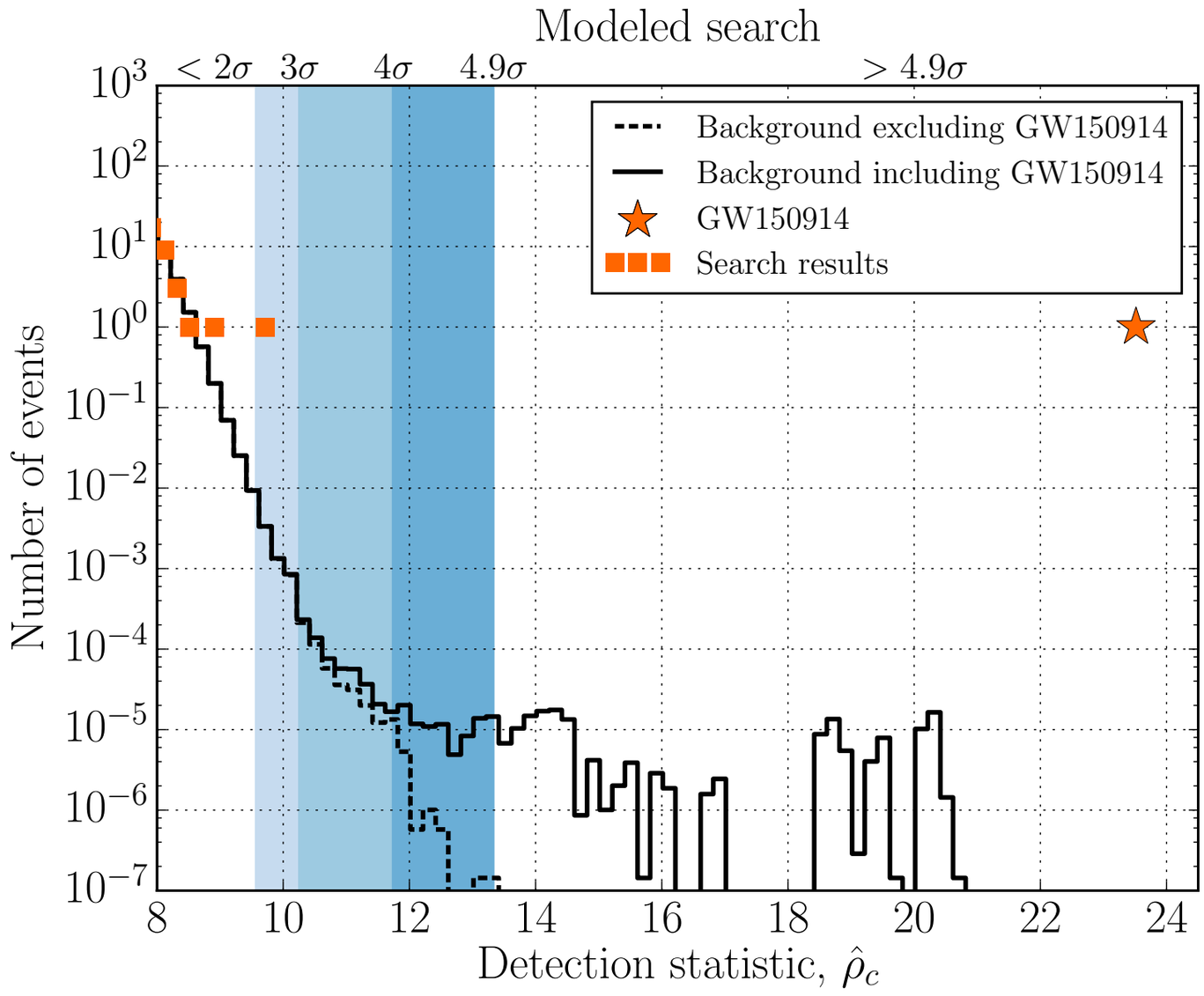


(just at the edge…)

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

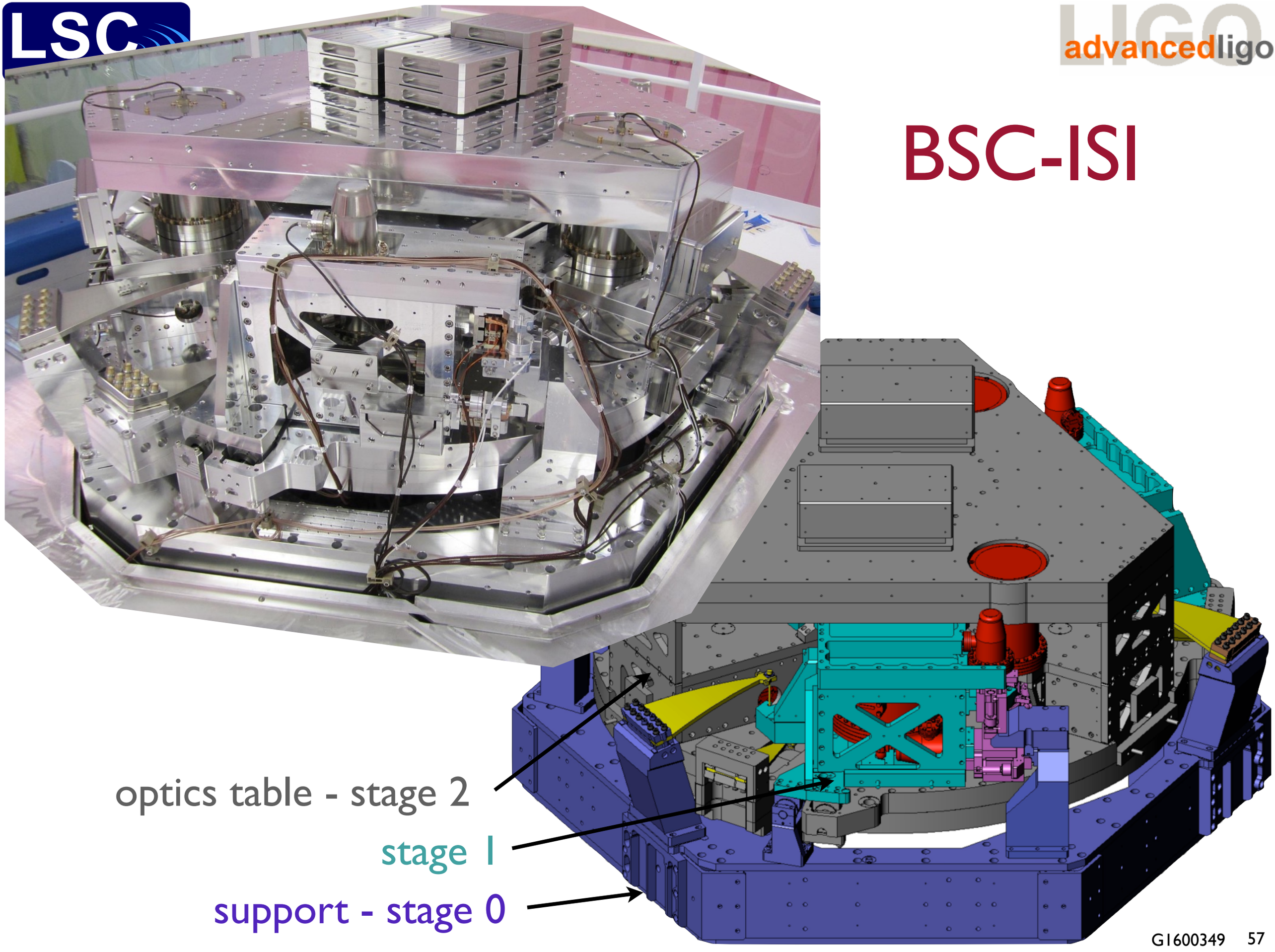
Detection statistic





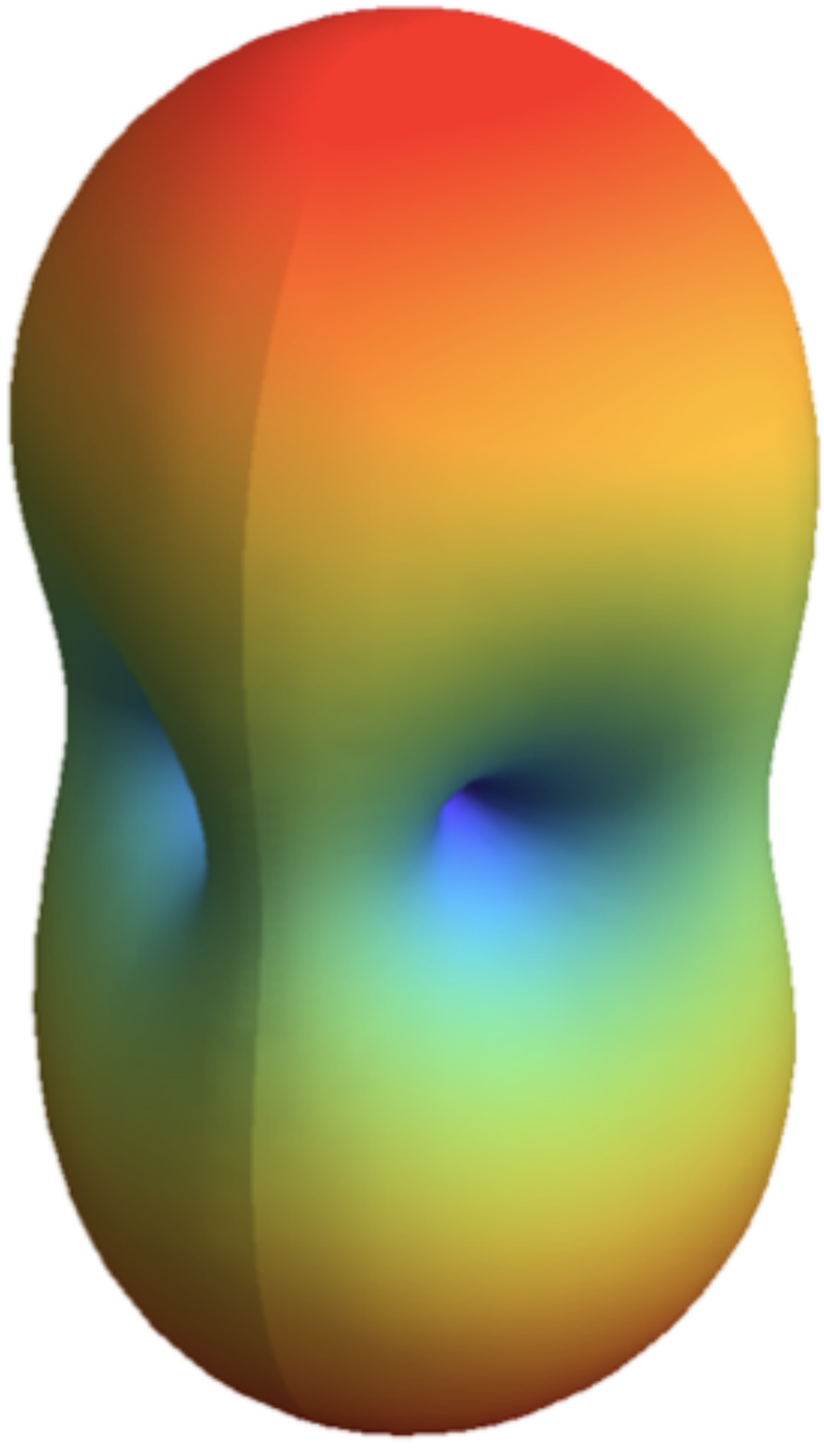
Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ ($\mathrm{M}_\odot$)	m_1 ($\mathrm{M}_\odot$)	m_2 ($\mathrm{M}_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	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



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.