# Gravitational Wave Astronomy with Advanced LIGO


Brett Shapiro

For the LIGO Scientific Collaboration


Lawrence Berkeley National Laboratory – 23 June 2016



Image credit: NASA

# Gravitational Wave Astronomy with Advanced LIGO

## LIGO: Laser Interferometer Gravitational Wave Observatory

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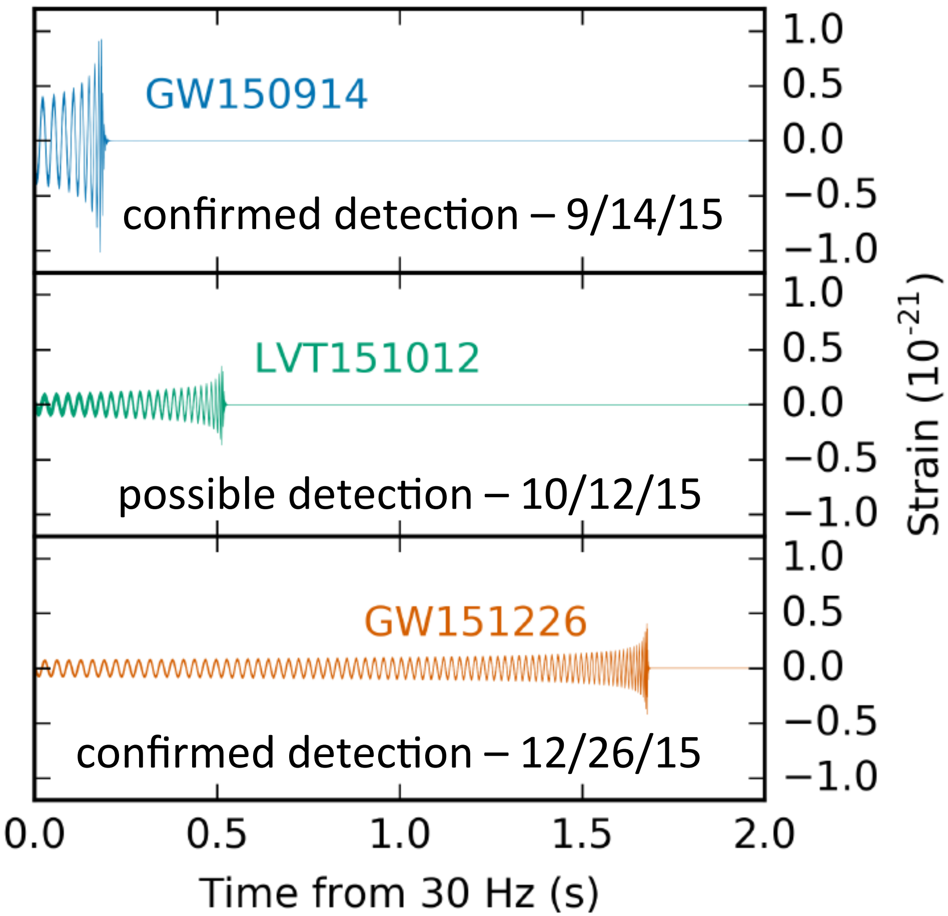
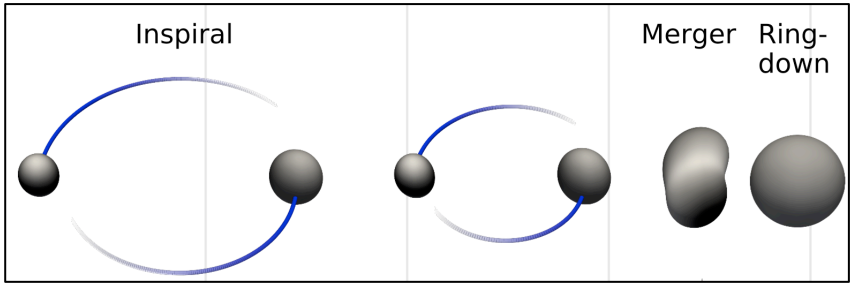
Image credit: NASA

# Advanced LIGO observations so far

Black hole observations made




Black hole merger evolution

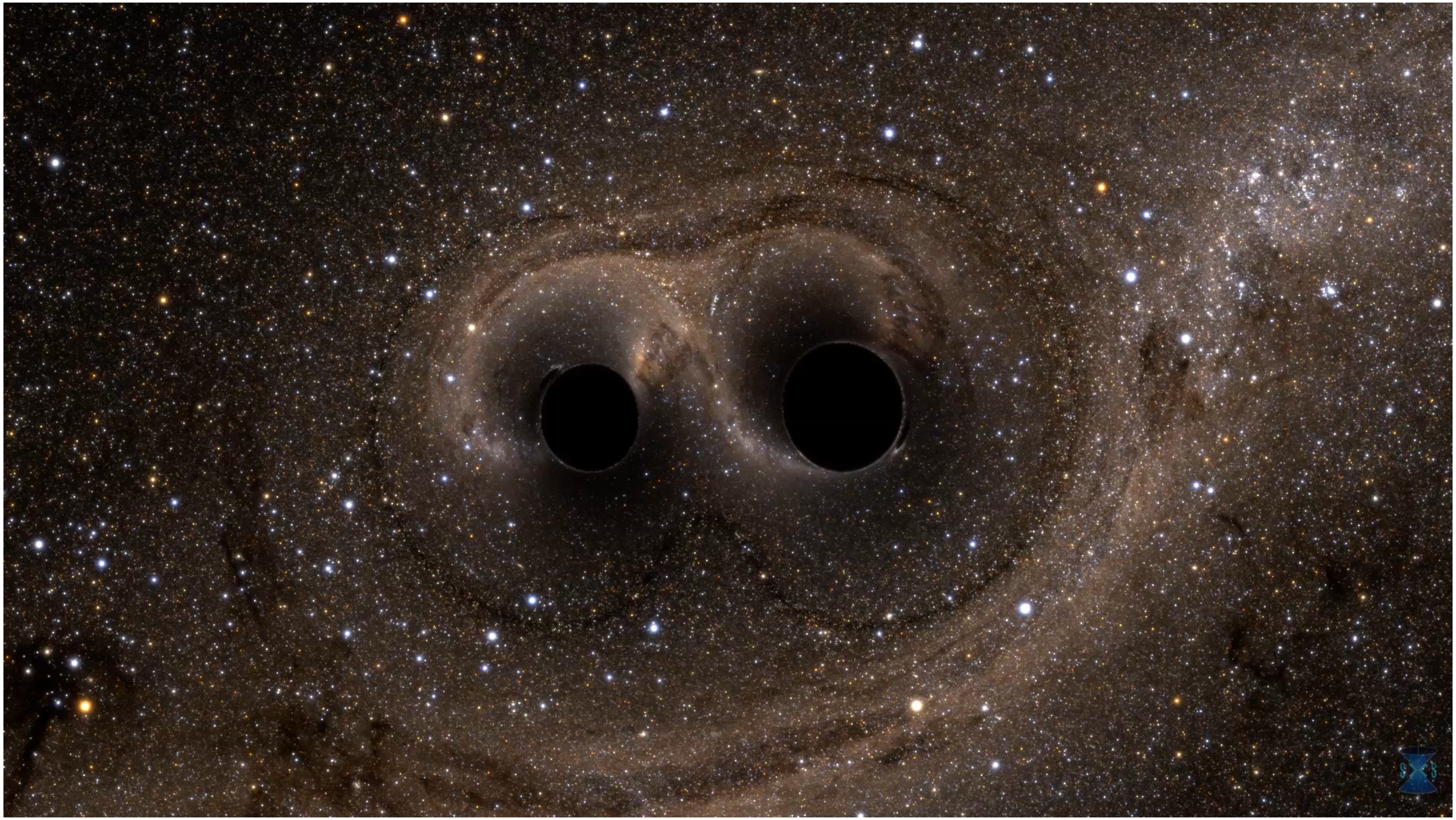



https://dcc.ligo.org/LIGO-P150914/public

https://dcc.ligo.org/LIGO-P1600088/public

# Simulation of Merging BHs

Observed 14 September 2016



Simulating Extreme Spacetimes Project: http://www.black-holes.org/

# My background

# Penn State Eng. Science B.S. 2005

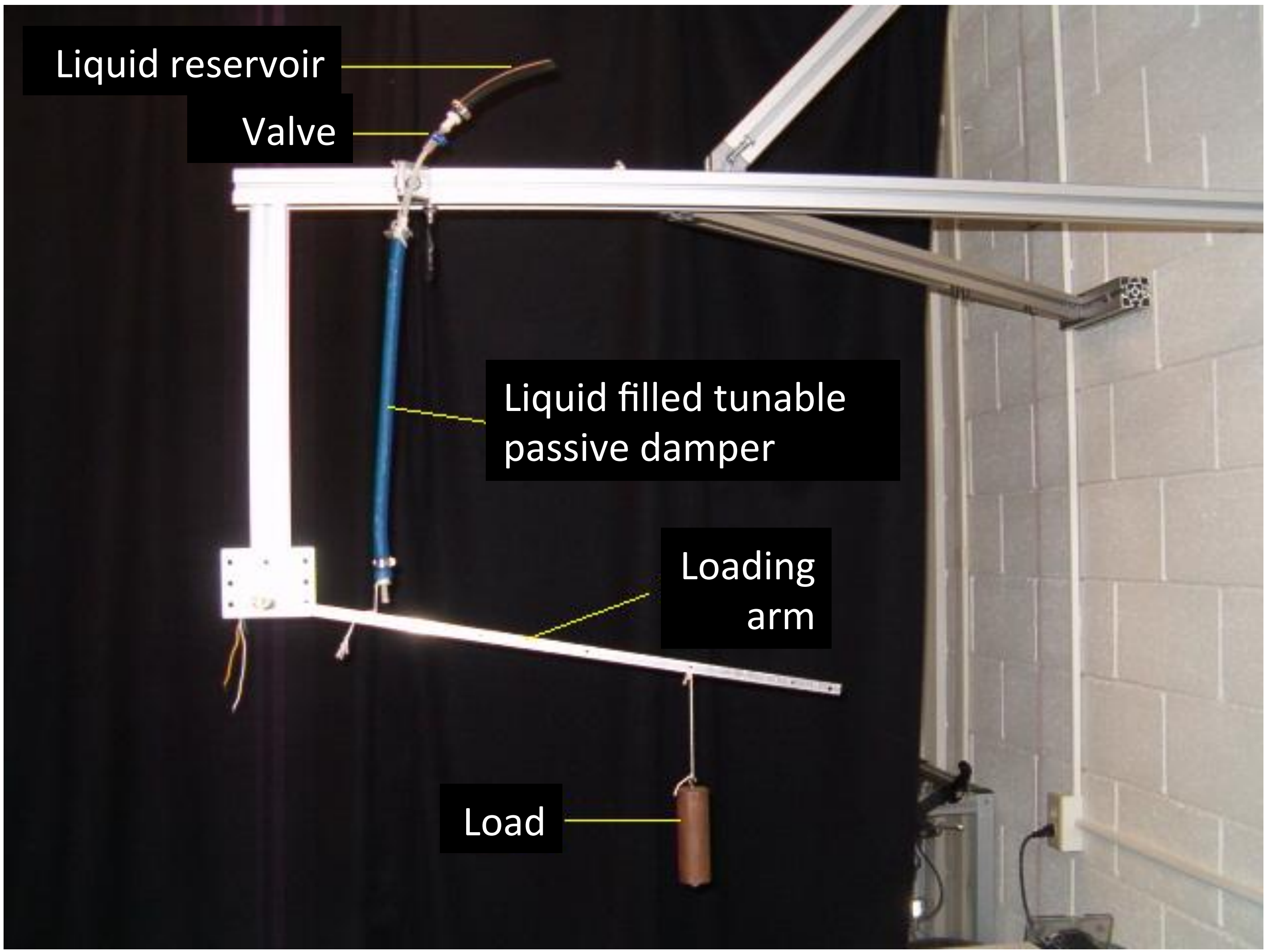
PENNSTATE
Engineering Science and Mechanics Department

Senior Thesis

# Semi-active Damping Using a Fiber Wound Elastic Tube

By Brett Shapiro
Advisor: Dr. Christopher Rahn
- Professor of Mechanical Engineering

# Semi Active Damping Experiment

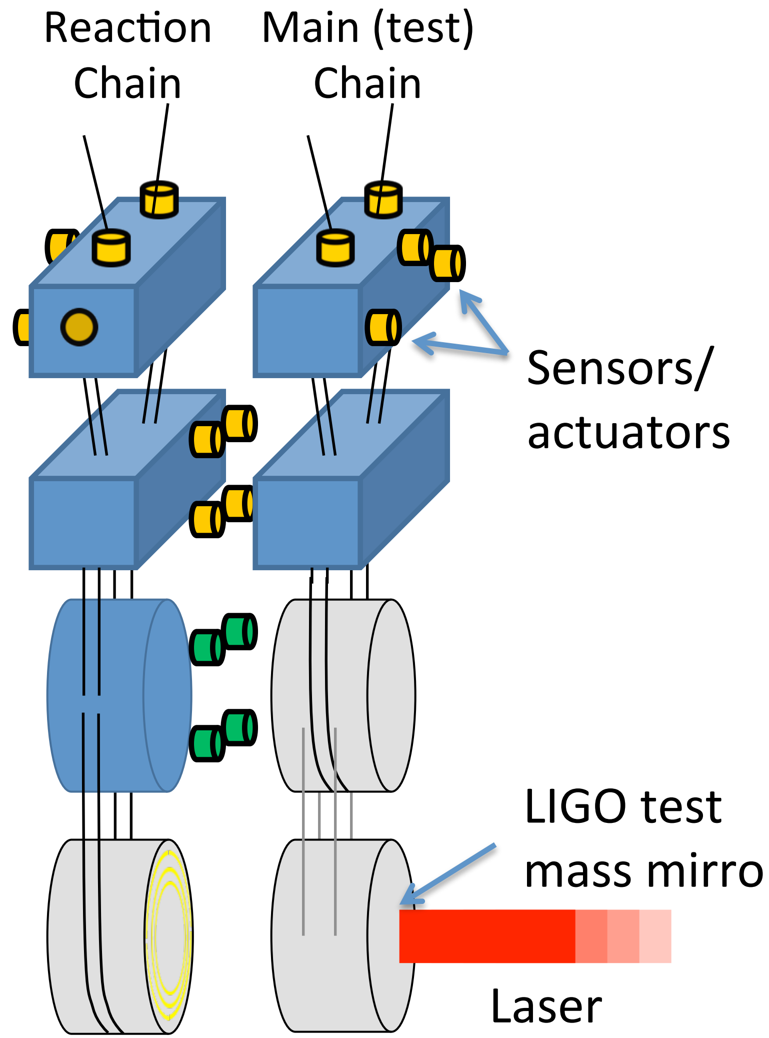


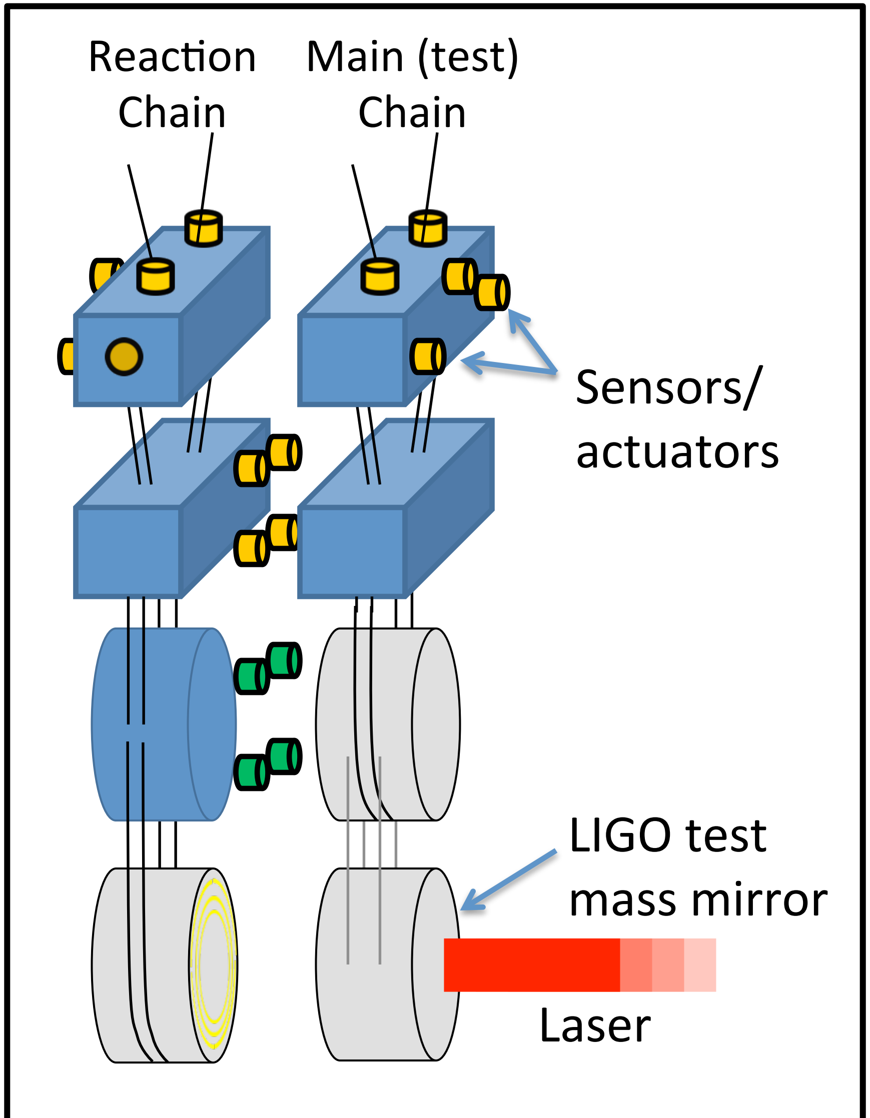
Massachusetts Institute of Technology

MITMECHE

# MIT Mechanical Engineering – Masters 2007, PhD 2012

Installing the Test Mass Suspension Prototype at MIT - 23 January 2009



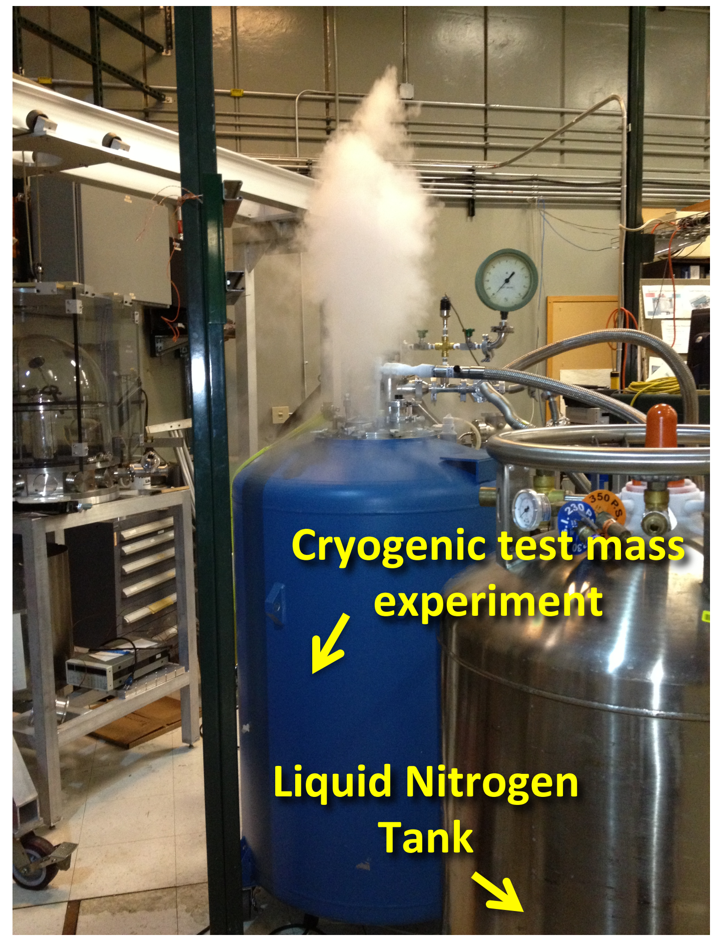



**PhD Thesis:**
Adaptive Modal Damping for Advanced LIGO Suspensions

**My PhD work involved:**
Mechanical modeling, assembly, vibration isolation, control theory; and testing of the Advanced LIGO prototype test mass vibration isolation system.

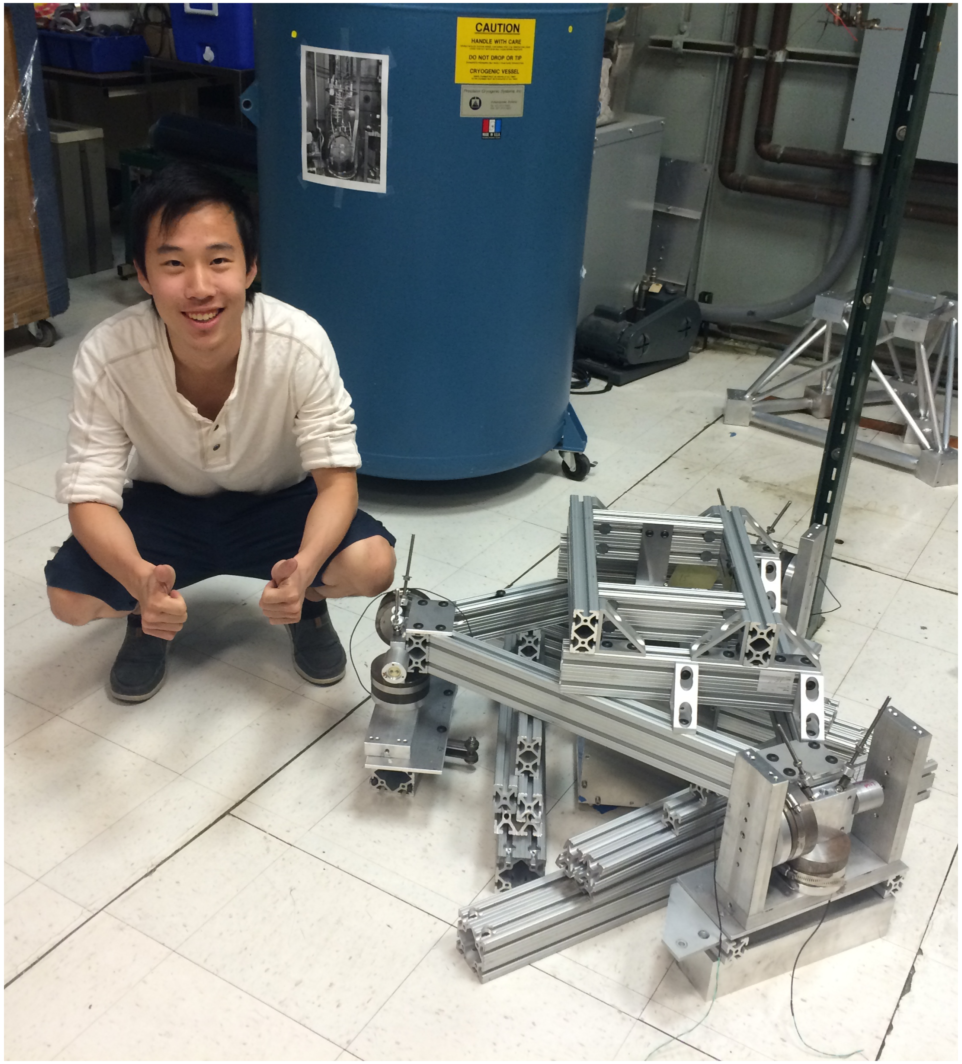
# Stanford University – Postdoc since 2012


Upgrading the test mass suspension with cryogenics to reduce thermally driven displacements.

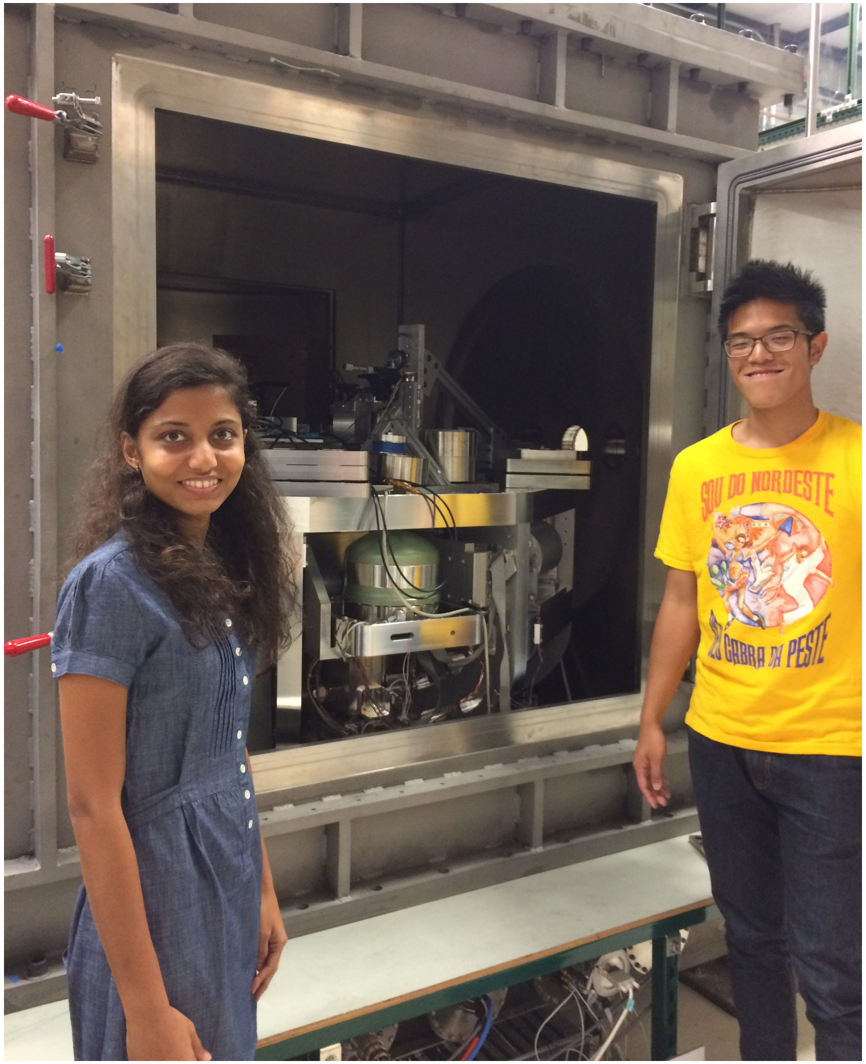



Stanford – September 2013

# Students in Lab



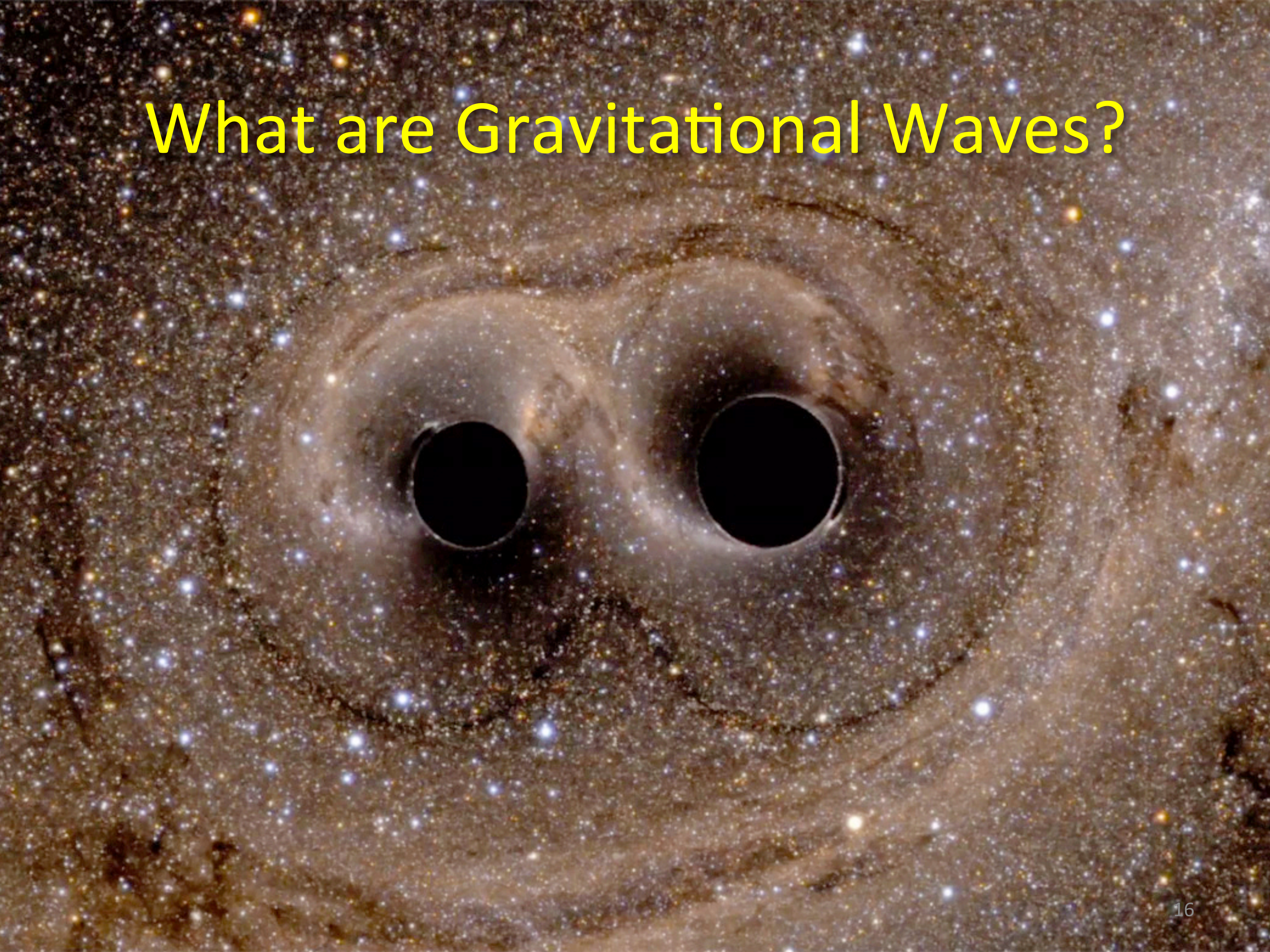

Dan: mechanical engineering undergraduate




Sanditi: mechanical engineering masters
Litawn: physics undergraduate

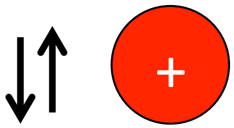
# Questions?

# What are Gravitational Waves?



# What are Gravitational Waves?

EM detector



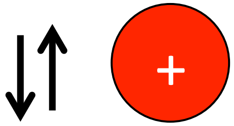

Charged particle

Stanford Dish
http://www.everytrail.com

# What are Gravitational Waves?

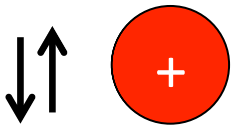
EM detector

Stanford Dish
http://www.everytrail.com

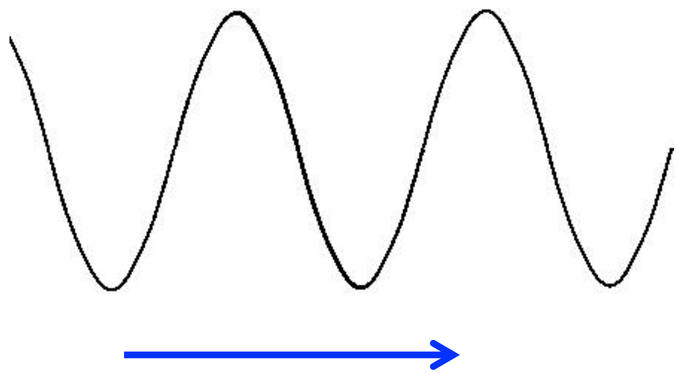



Charged particle

Information travels at speed of light




Charged particle



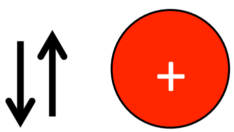
Information travels at speed of light

EM detector

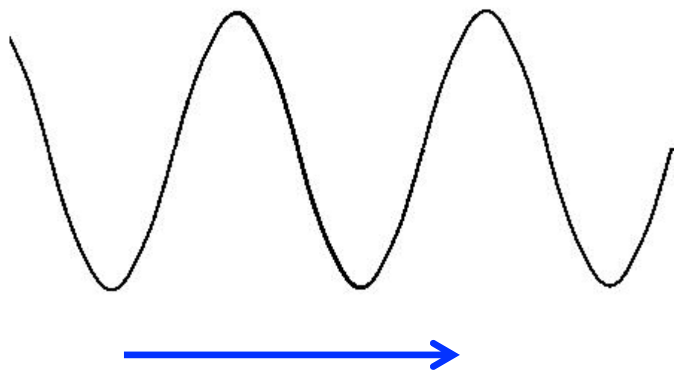
Stanford Dish

http://www.everytrail.com

# What are Gravitational Waves?



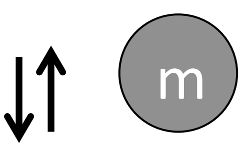

Charged particle



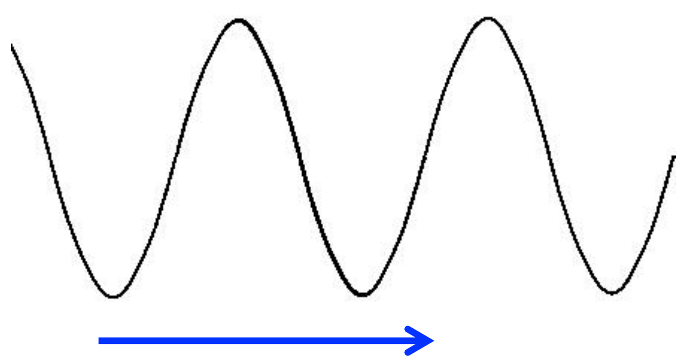
Information travels at speed of light

EM detector

Stanford Dish
http://www.everytrail.com




Massive particle



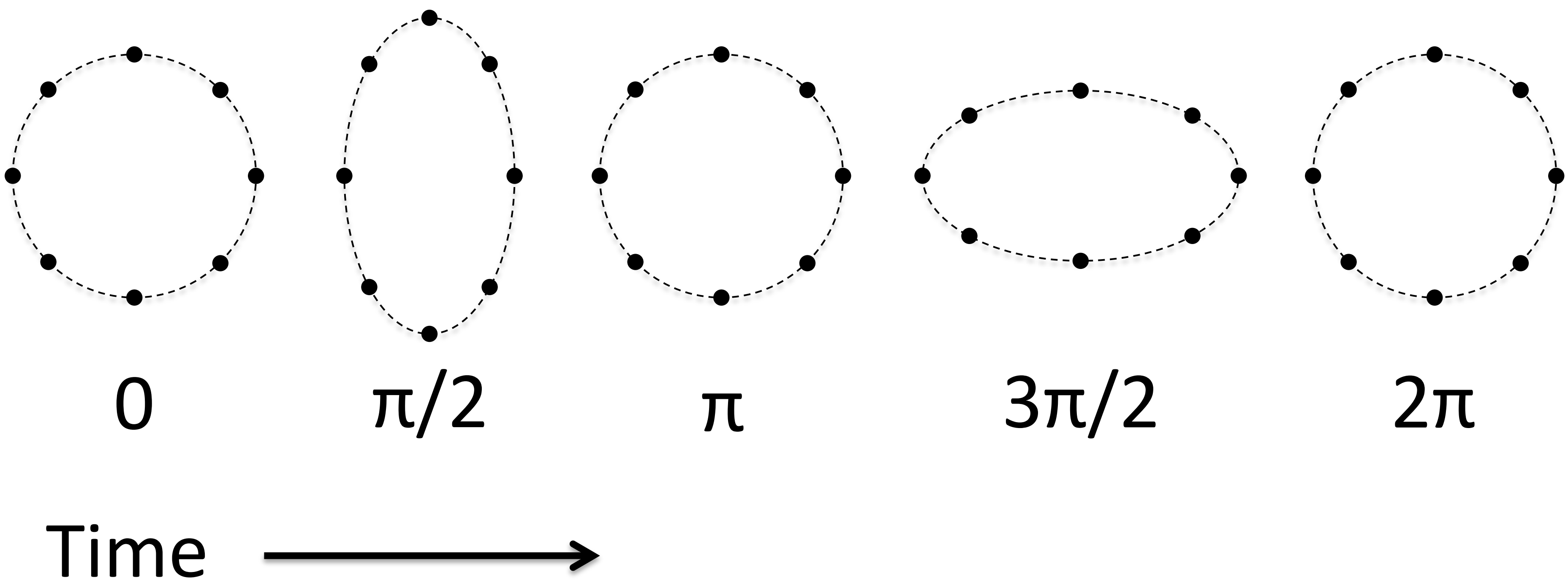
Information travels at speed of light

GW detector

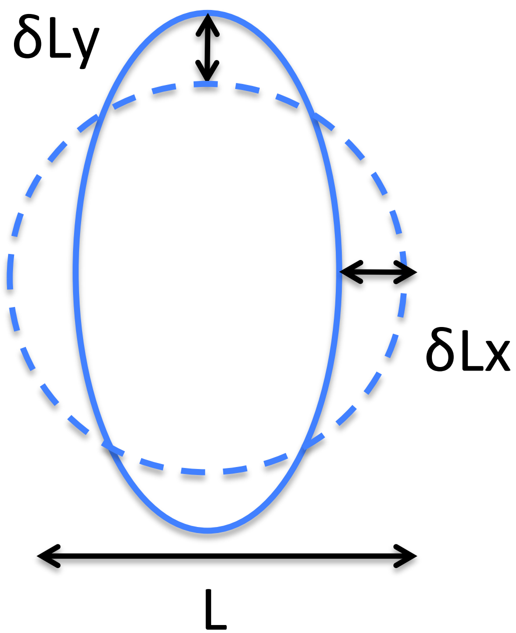
LIGO Livingston
Courtesy LIGO lab

# Waves stretch/compress space

Wave traveling through a circle of free falling test particles



# Waves stretch/compress space



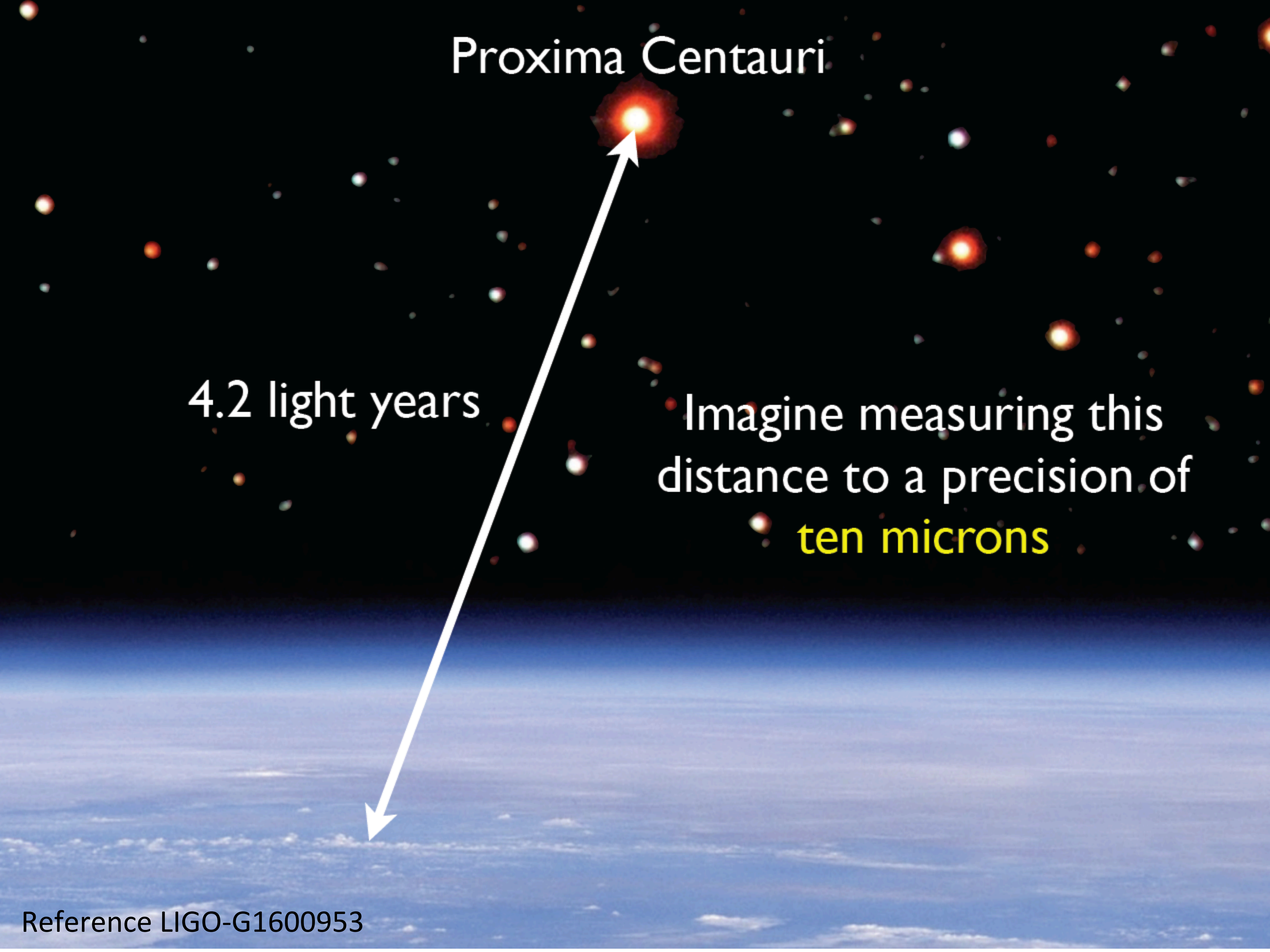

**Strain** over distance L

$$\frac{\Delta L}{L} = \frac{\delta L_x - \delta L_y}{L} = h$$

Peak amplitude of detected wave

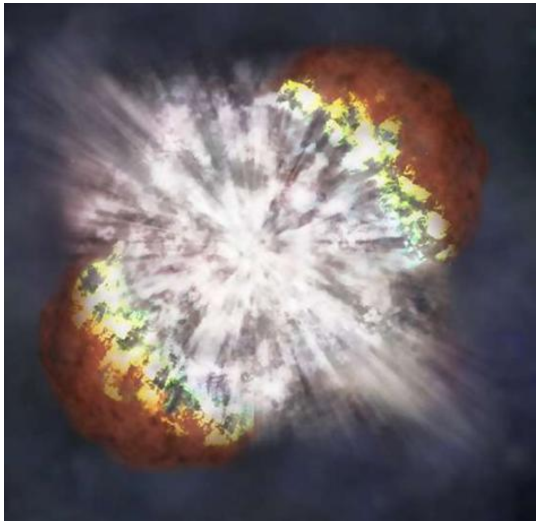
$$h \sim 10^{-21}$$

Reference LIGO-G1600340

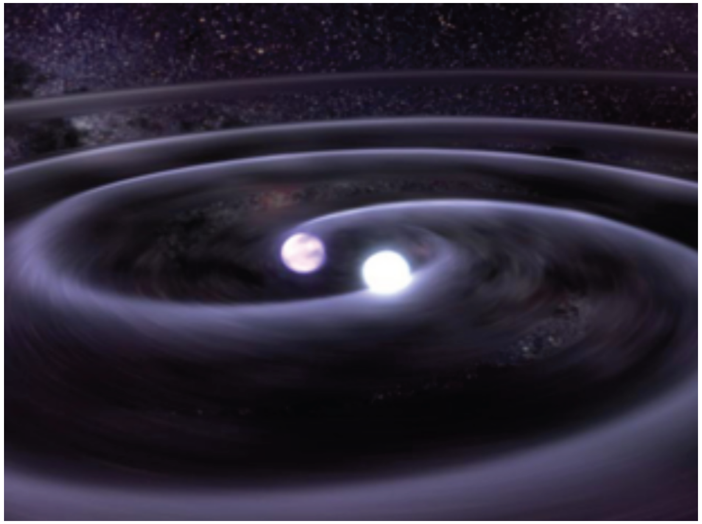


Reference LIGO-G1600953

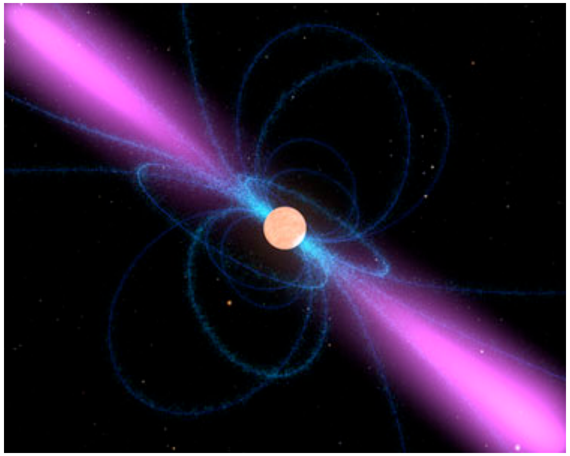
# Where do GWs Come From?



Supernovae



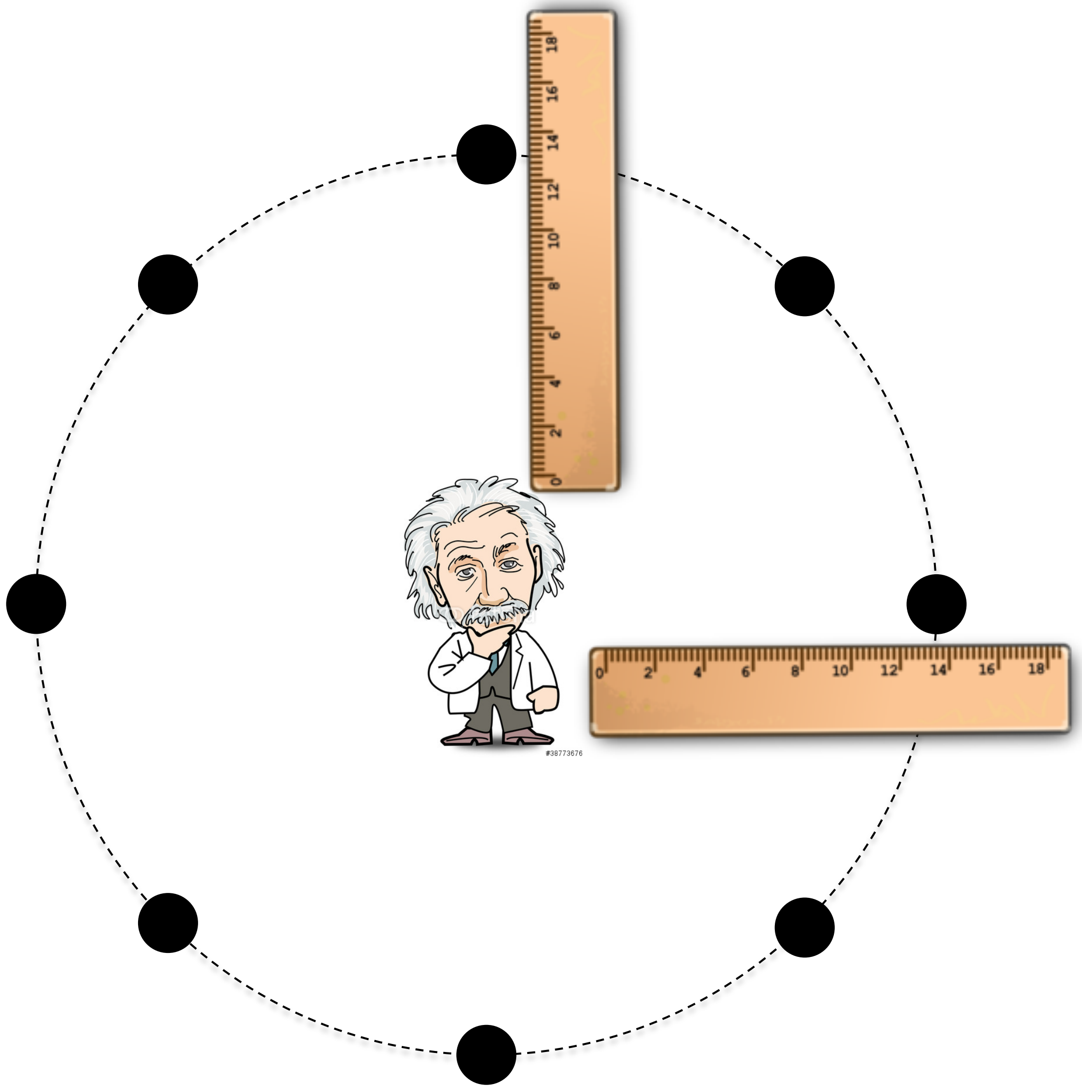
Merging Black Holes and/or Neutron Stars



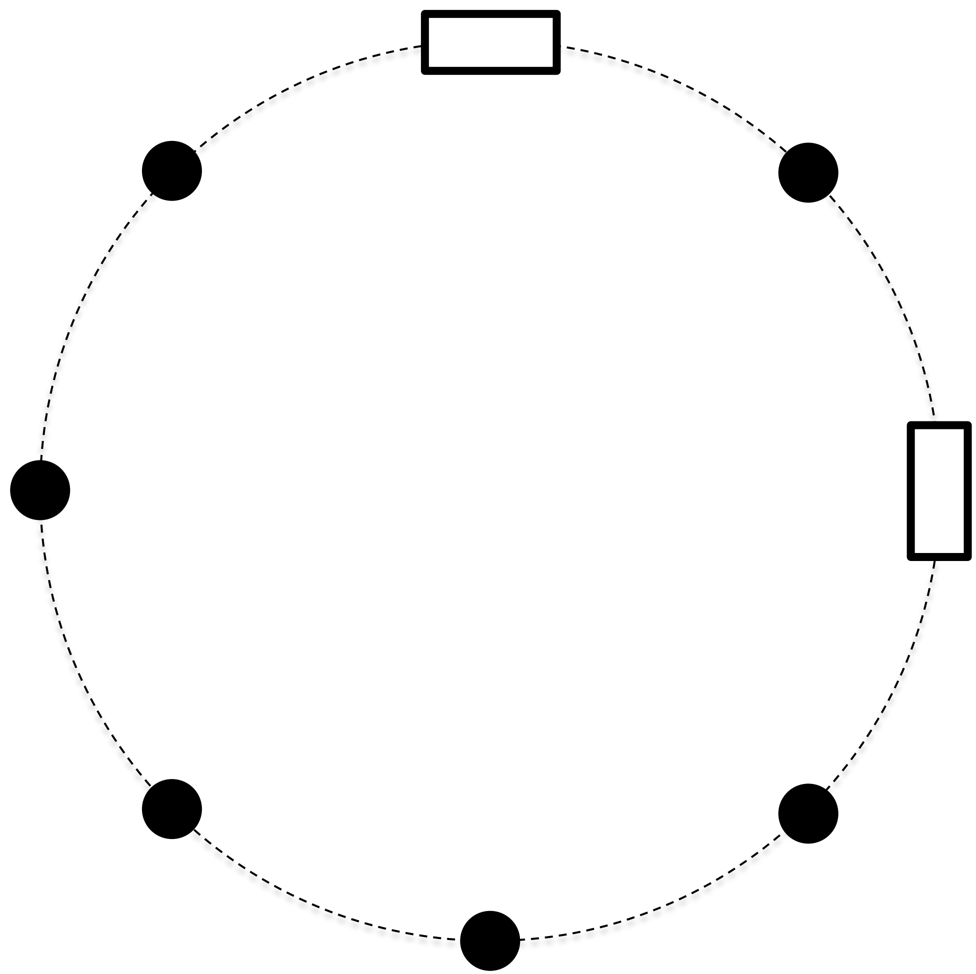
Pulsars

Image credits: NASA

# Measuring Gravitational Waves

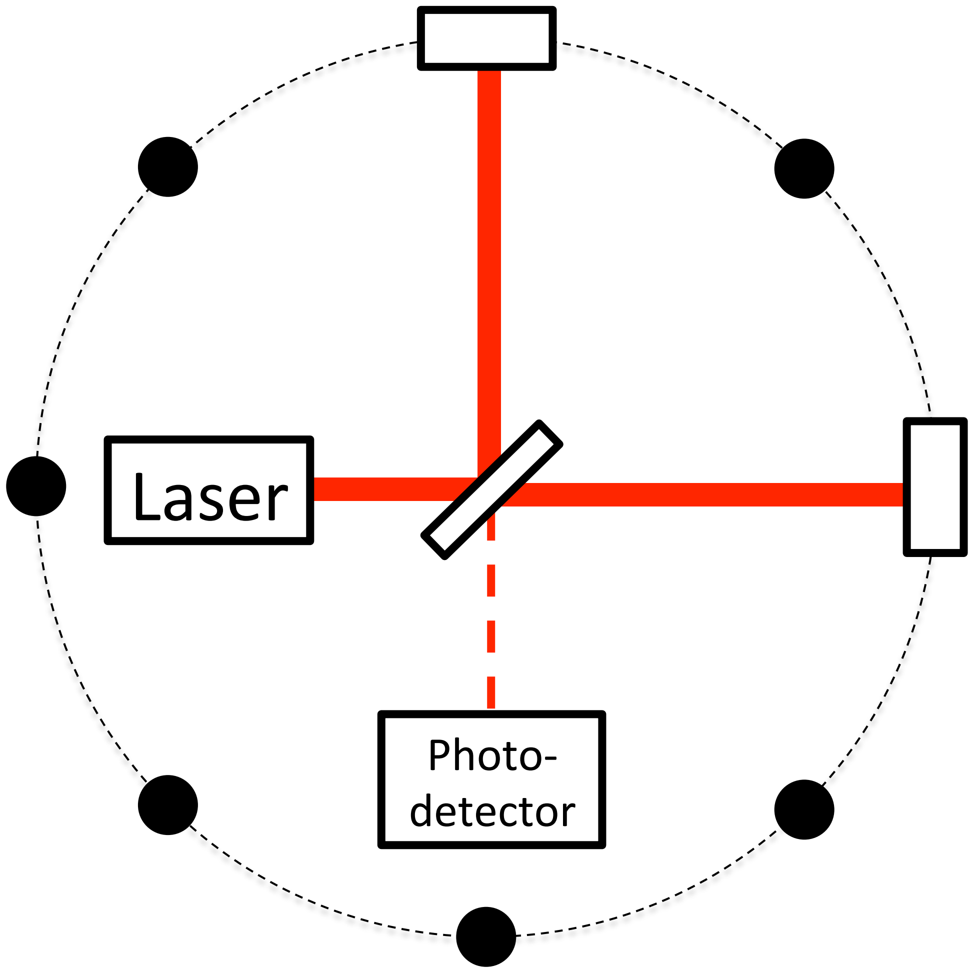


# Measuring Gravitational Waves

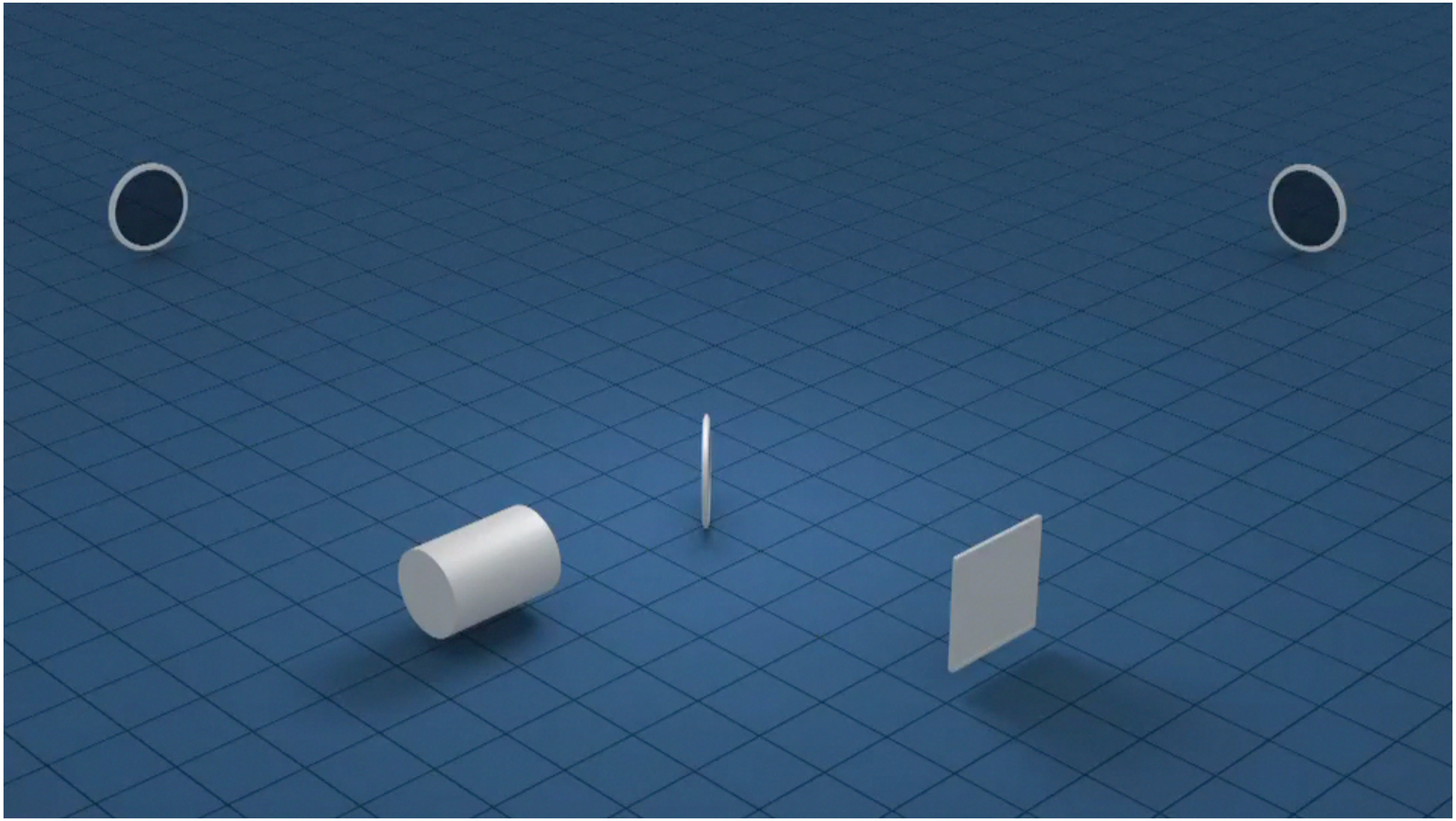


# Measuring Gravitational Waves

Michelson Interferometer



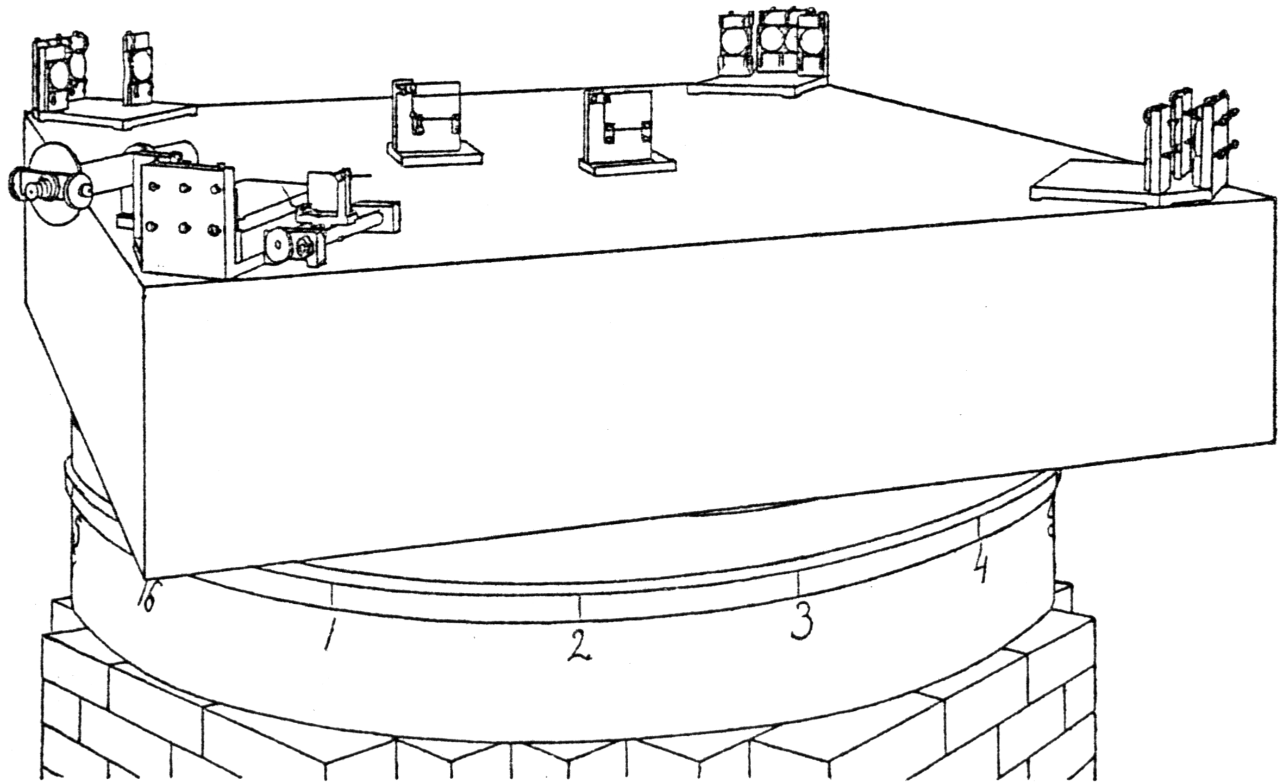
# How LIGO Works



Reference LIGO-G1600340

# Michelson–Morley experiment 1887






A. Michelson and W. Morley. On the Relative Motion of the Earth and the Luminiferous Ether. 1887



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

# Michelson–Morley experiment 1887



Attempted to measure the speed of light relative to the hypothetical stationary 'luminiferous aether'.

1) One of the earliest uses of a Michelson interferometer.

2) Aether not found. Observations consistent with the speed of light being independent of the observer's velocity. Relativity eventually replaces the aether theory.

A. Michelson and W. Morley. On the Relative Motion of the Earth and the Luminiferous Ether. 1887



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

# LIGO Hanford, Washington Observatory

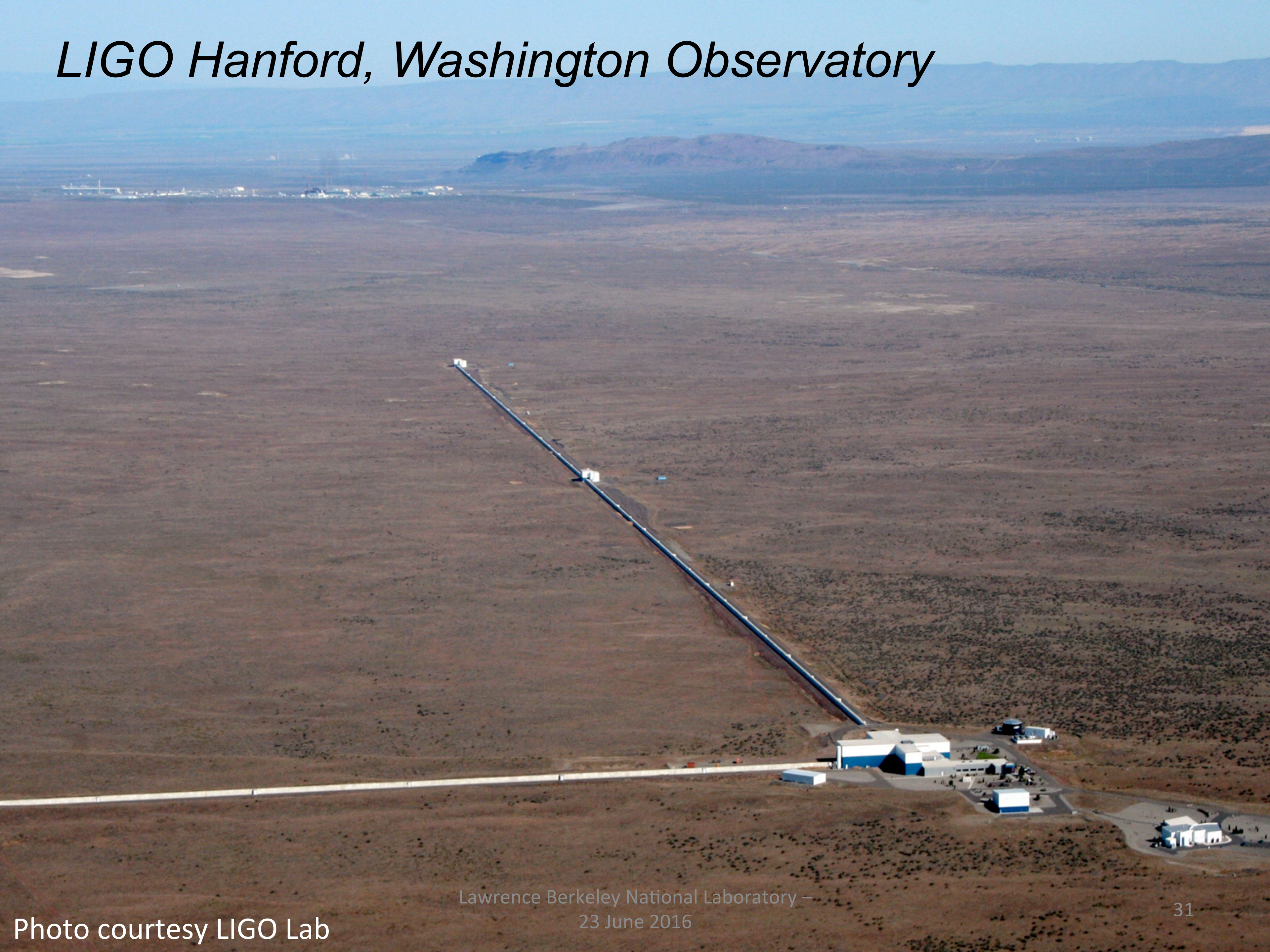


Photo courtesy LIGO Lab

# *LIGO Hanford, Washington Observatory*

- 4 km Michelson Interferometer
- Initial LIGO observations – 2002-2010
- Advanced LIGO observations began in 2015

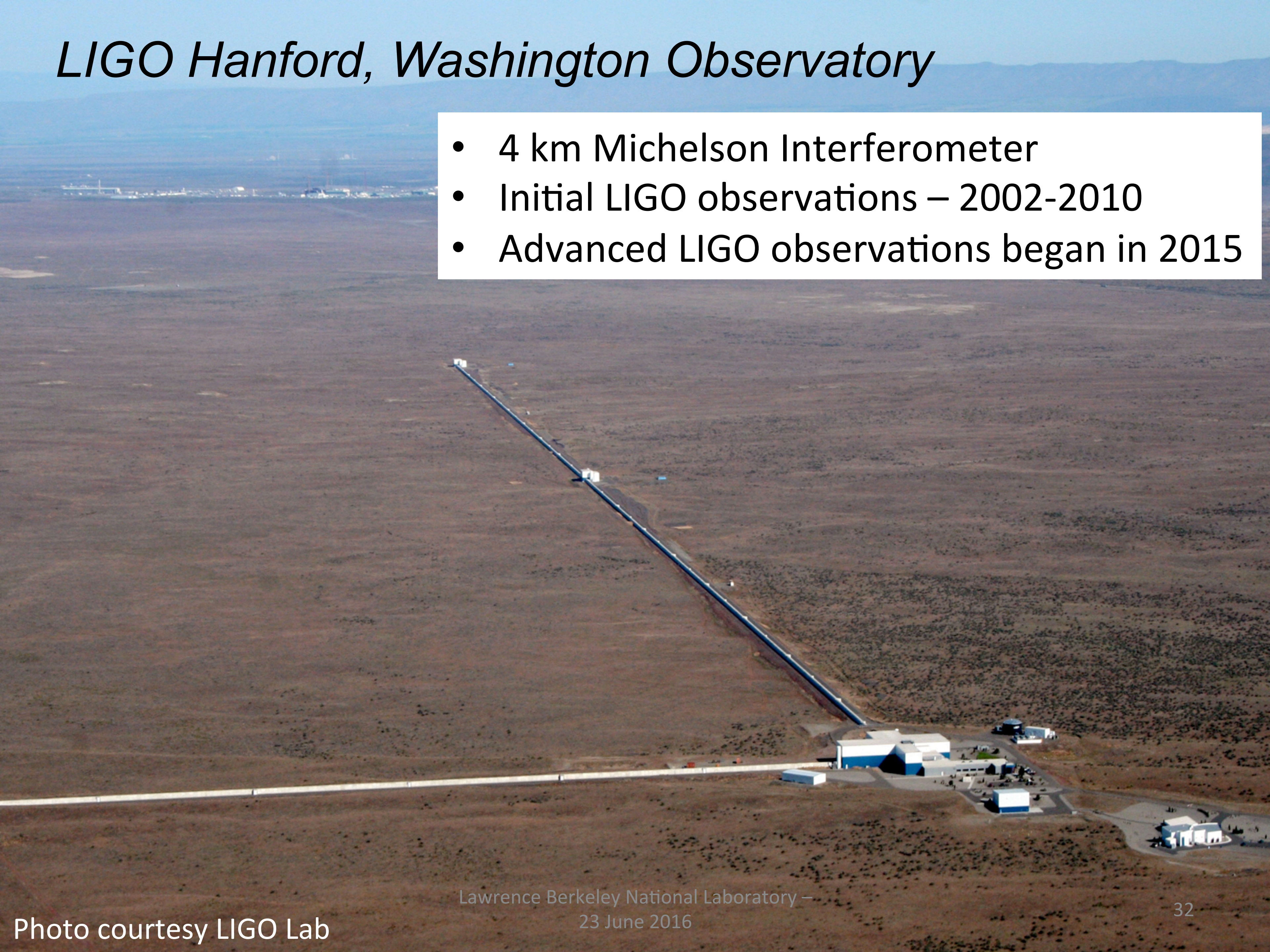


Photo courtesy LIGO Lab


LIGO Livingston, LA Observatory
Photo courtesy LIGO Lab

LIGO

LSC

# LIGO Scientific Collaboration

Trinity University
University of Maryland 1856
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
American University Washington, DC
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
R·I·T
Leland Stanford Junior University 1891
University of Strathclyde
Michigan
Max Planck Institute for Gravitational Physics
Albert Einstein Institute
The University of Western Australia
PAH
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique
Università degli Studi del Sannio
Massachusetts Institute of Technology
NASA Goddard Space Flight Center
University of Cambridge
ICTP SAIFR
The University of Chicago
Montana State University
ACU
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
The University of Mississippi
The University of Adelaide Australia
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
Universitat de les Illes Balears
University of Washington
GEO 600
UTRGV
University of Wisconsin Milwaukee
Syracuse University
Cardiff University Prifysgol Caerdydd
Northwestern
Universität Hamburg
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational-Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState 1855
Hobart and William Smith Colleges
Science & Technology Facilities Council
Rutherford Appleton Laboratory

# A Network of Interferometric Gravitational Wave Detectors

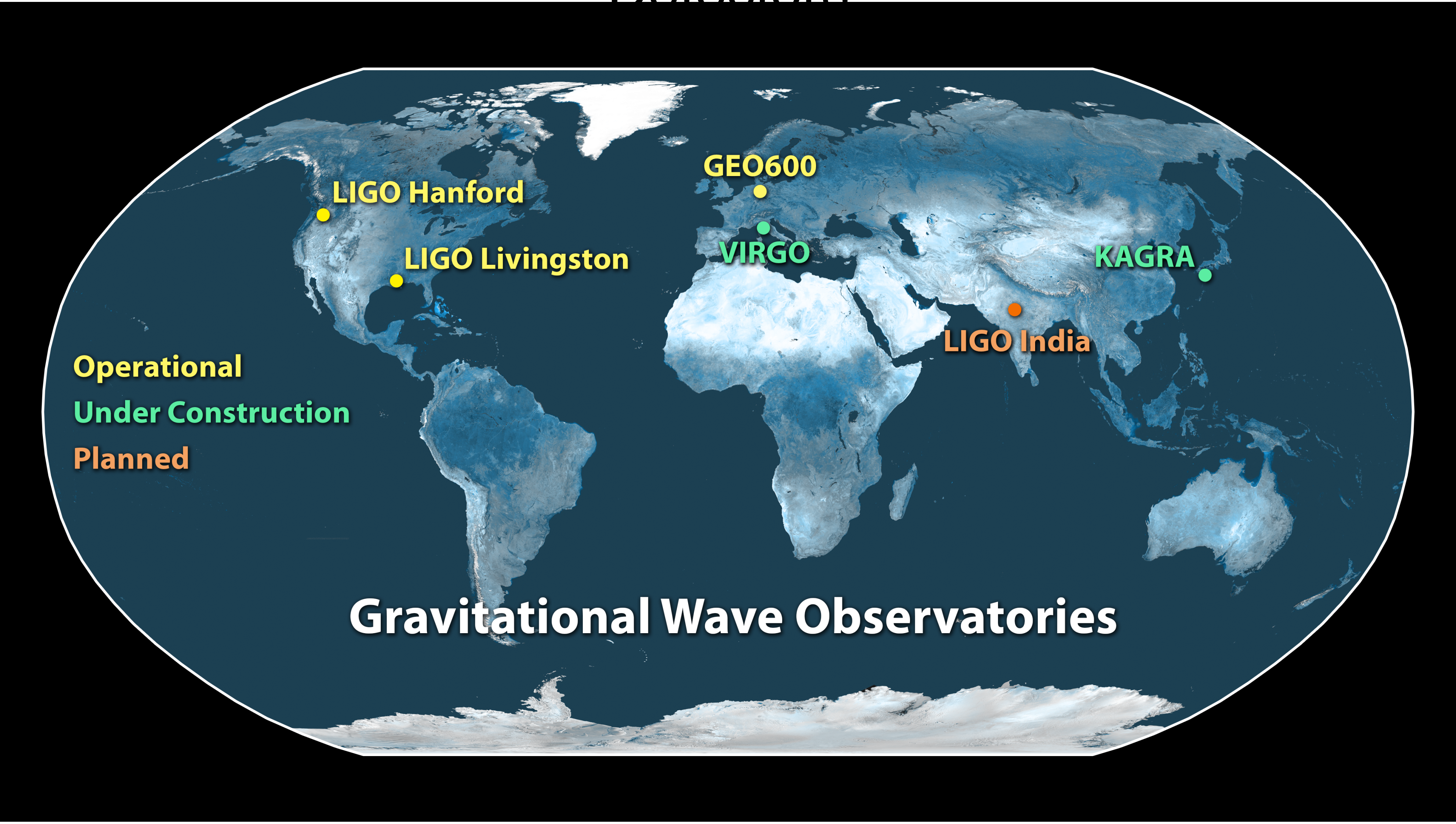


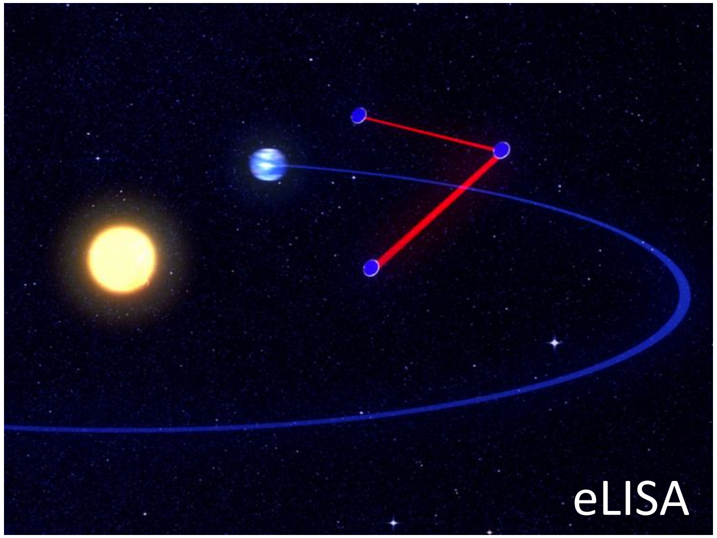

Image Credit: LIGO

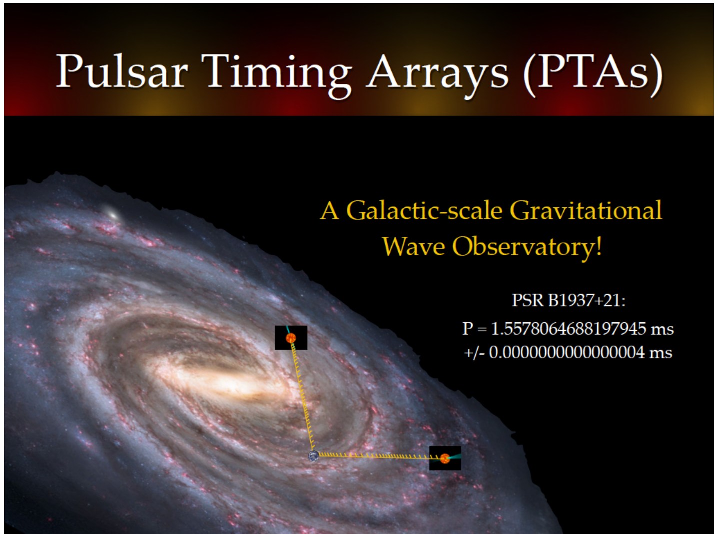
Reference LIGO-G1600275

# Other types of GW detectors

Resonant bar detectors

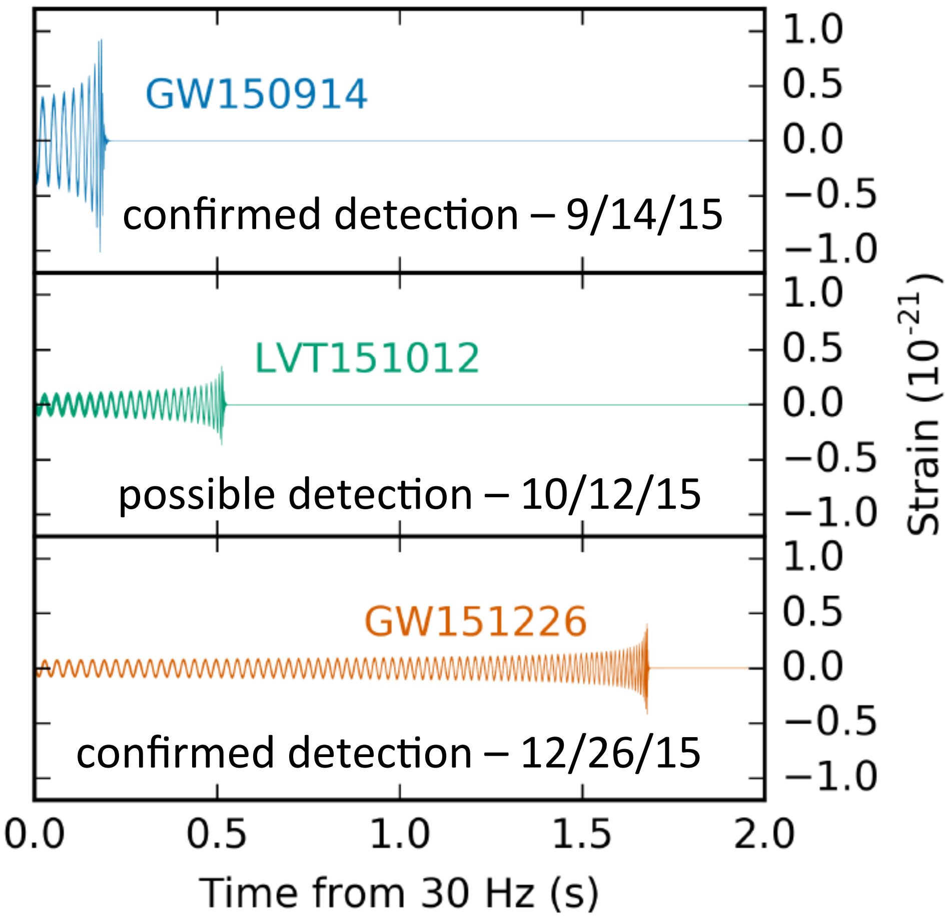
Space based  interferometers



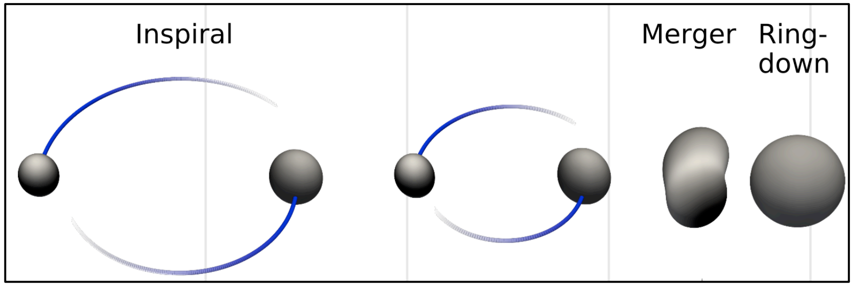
# Advanced LIGO observations so far

Black hole observations made



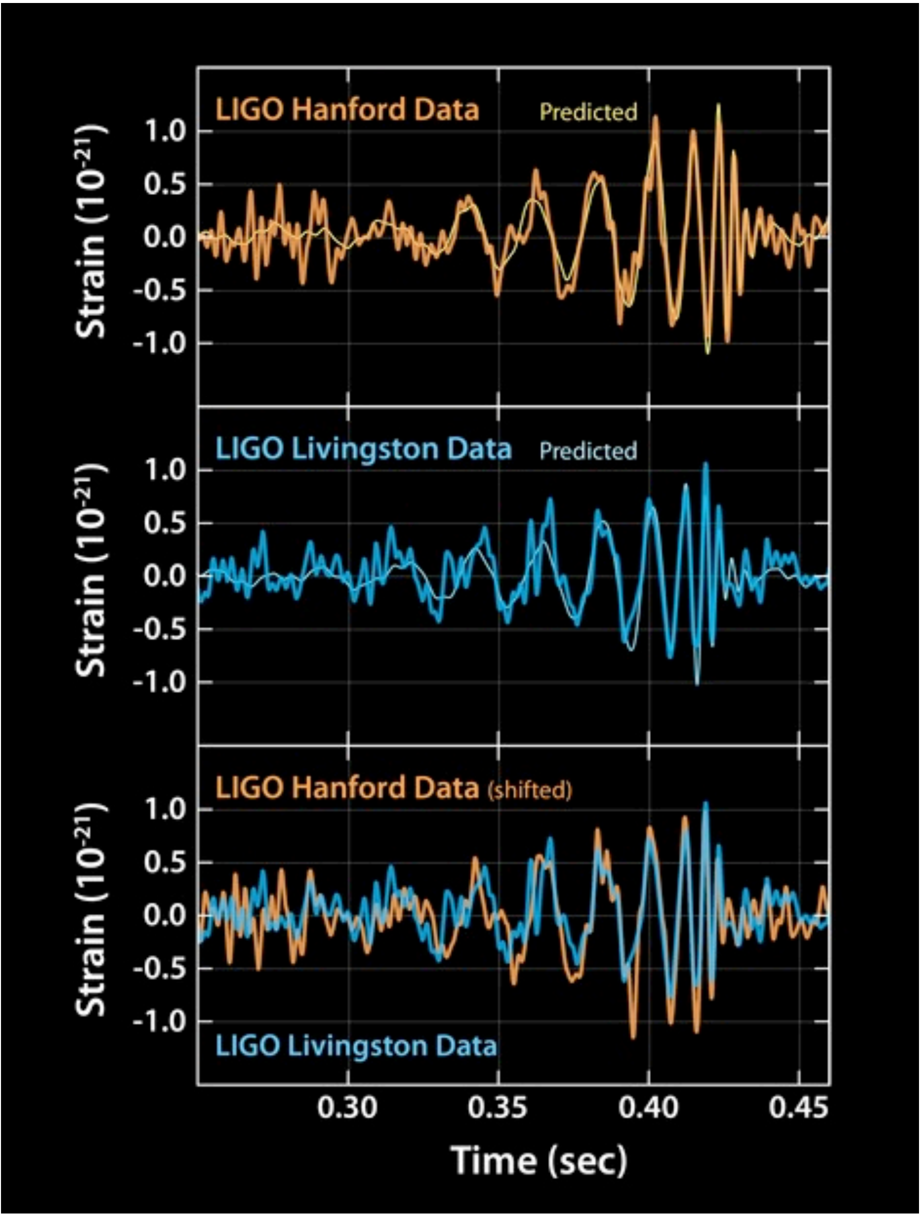

https://dcc.ligo.org/LIGO-P1600088/public

Black hole merger evolution

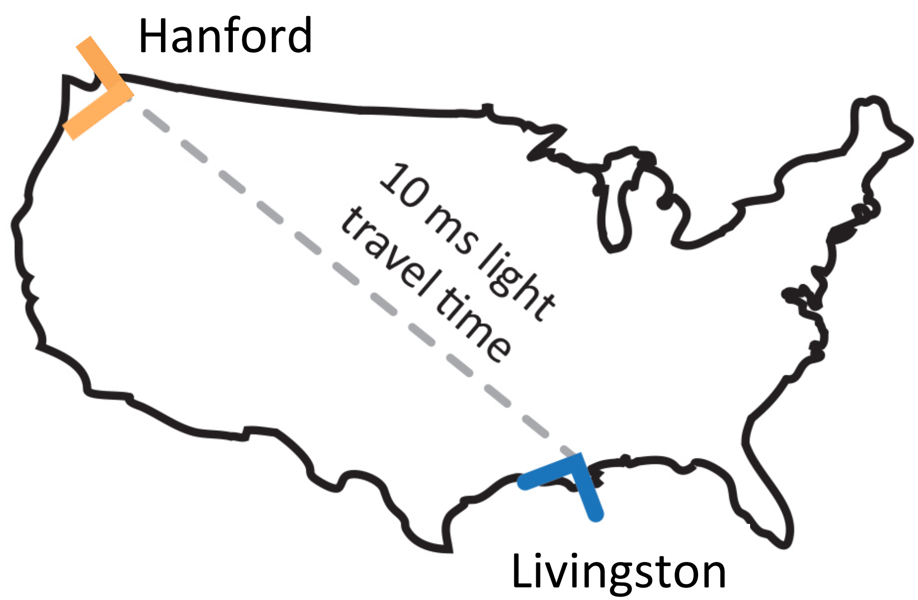



https://dcc.ligo.org/LIGO-P150914/public

# What LIGO detected on 14 Sept 2016

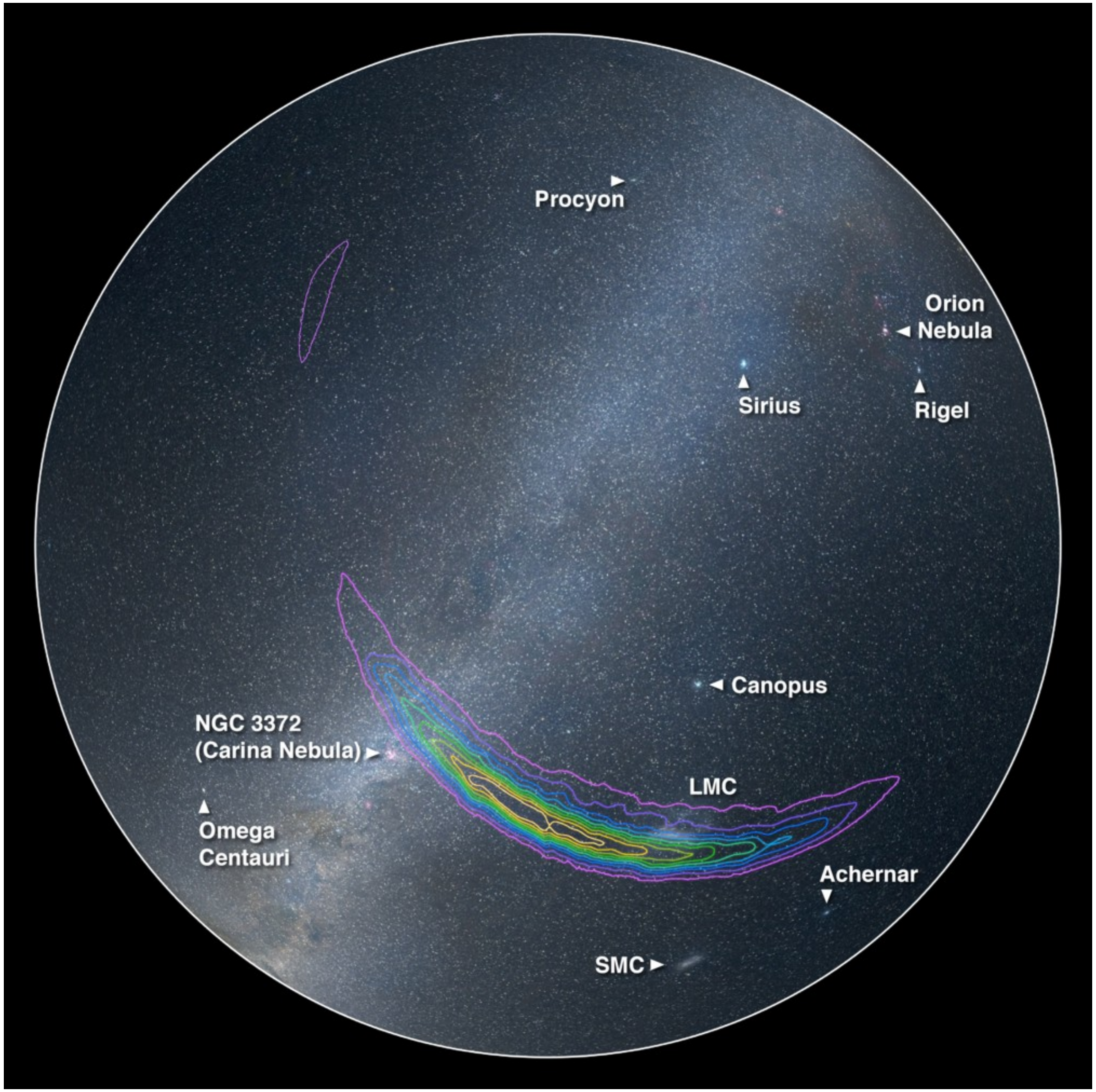



Orientation of the observatories

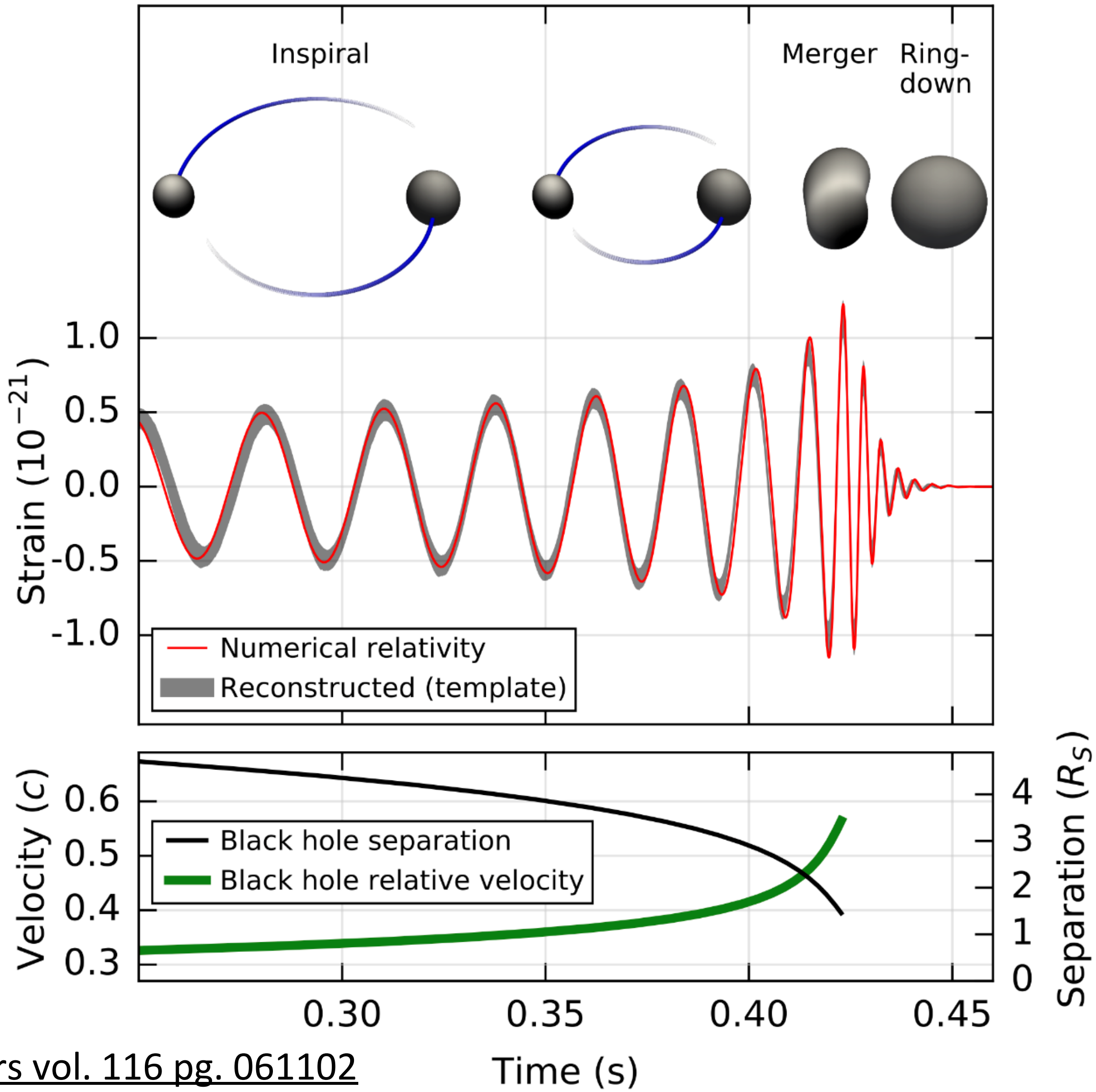



https://www.ligo.caltech.edu/image/ligo20160211a

# Sky localization of detected signal



# Source was a binary black hole merger

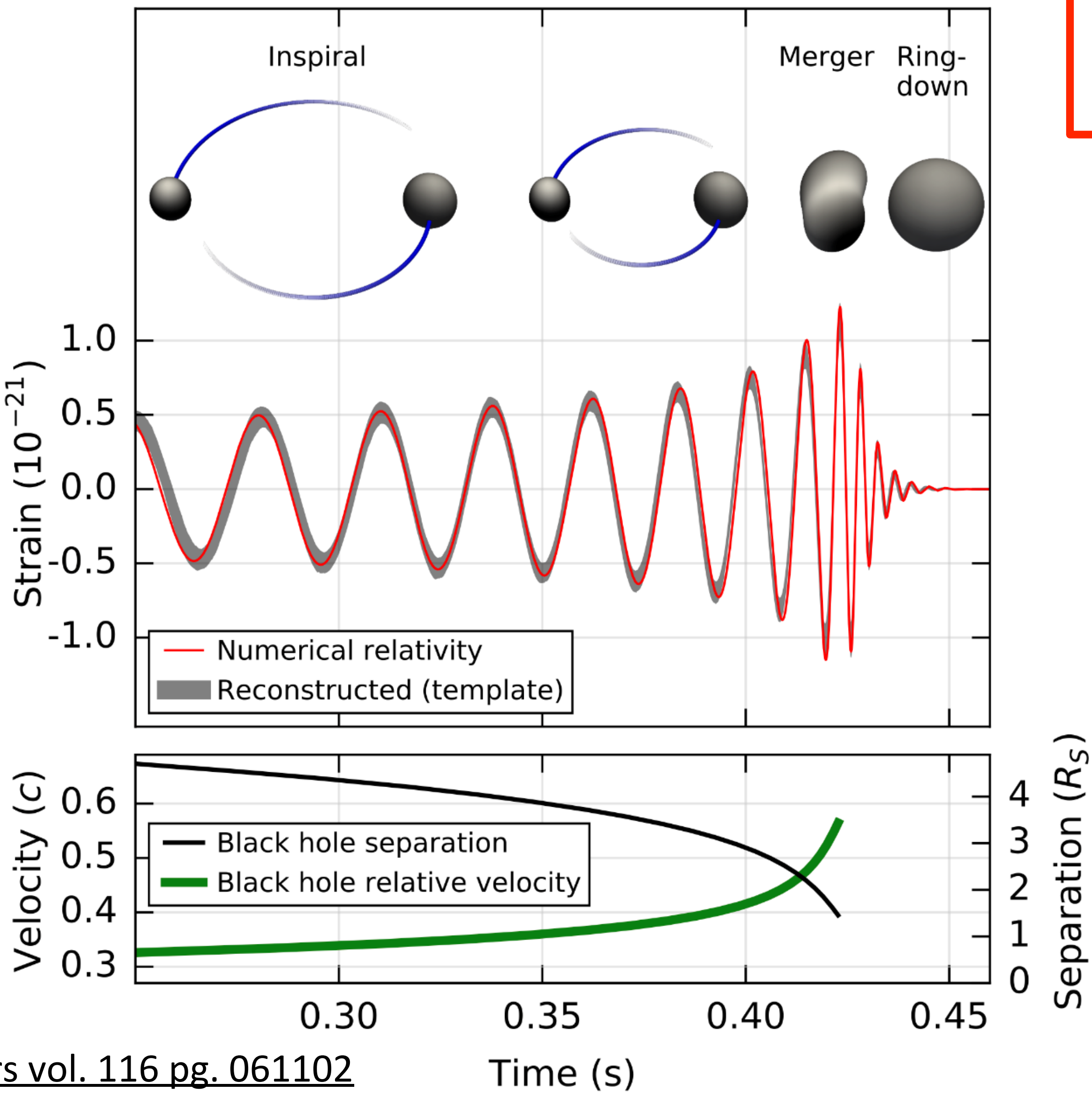



Phys Rev Letters vol. 116 pg. 061102

# Source was a binary black hole merger

Source distance

$1.3^{+0.52}_{-0.59} \times 10^{9}$ lys

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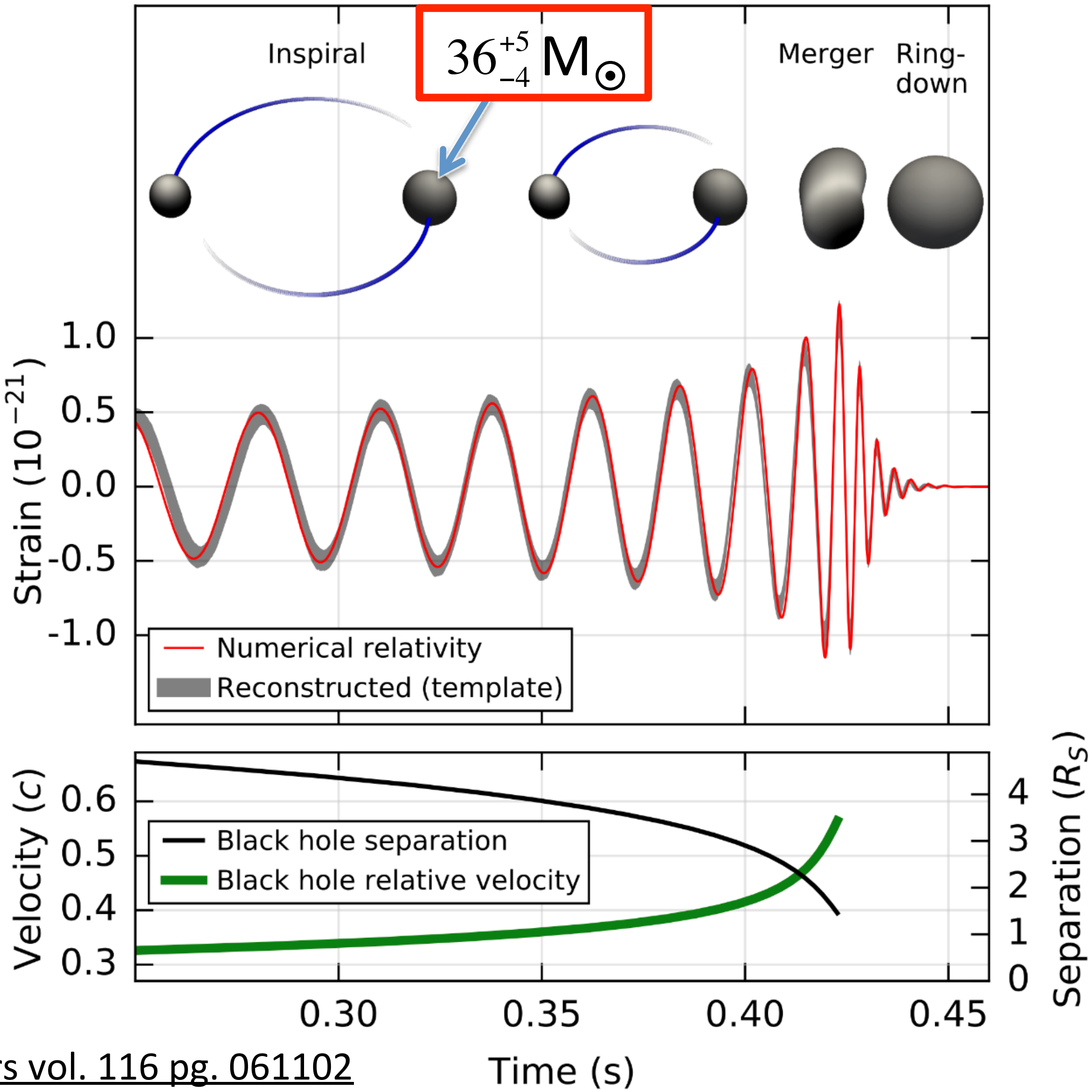


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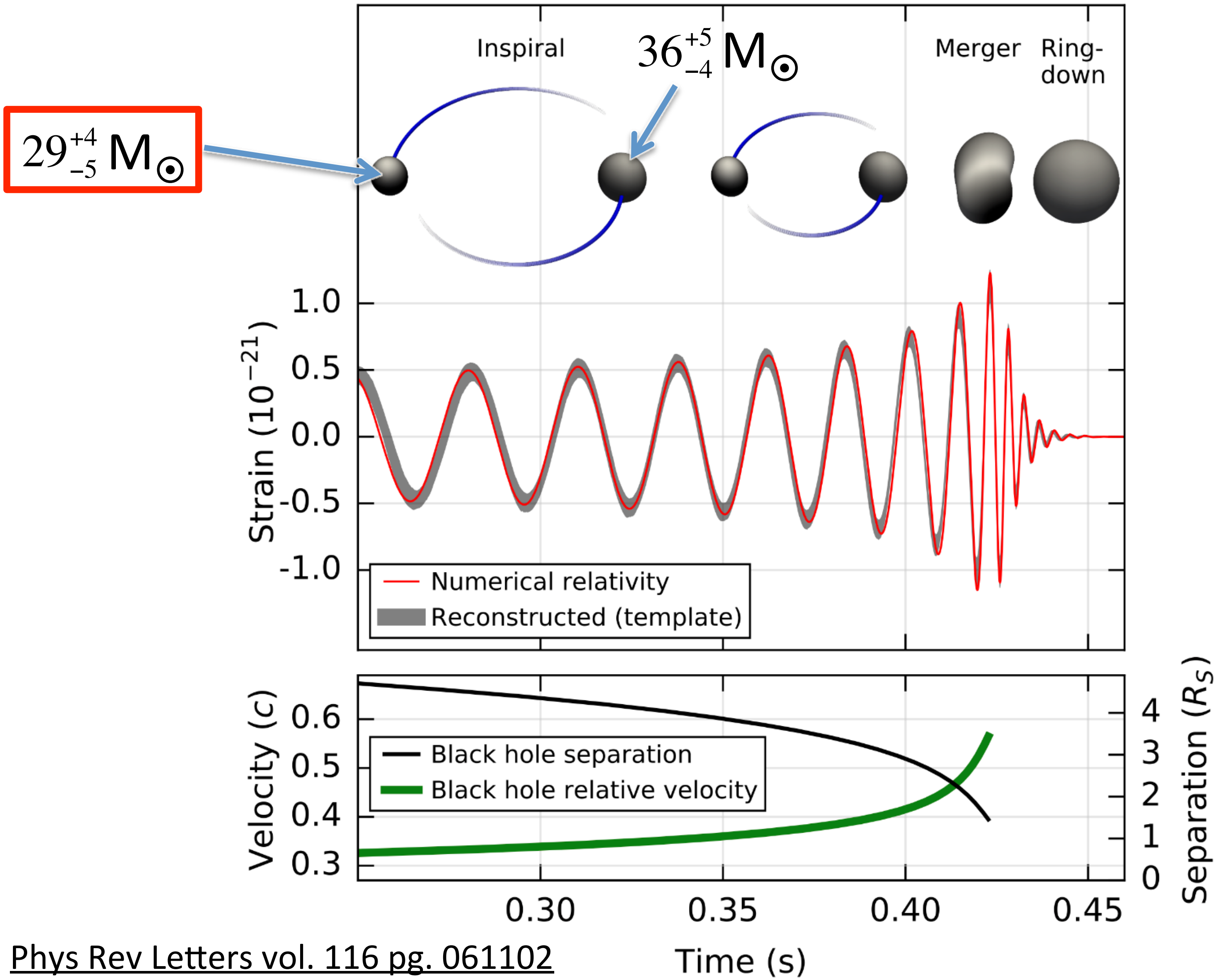
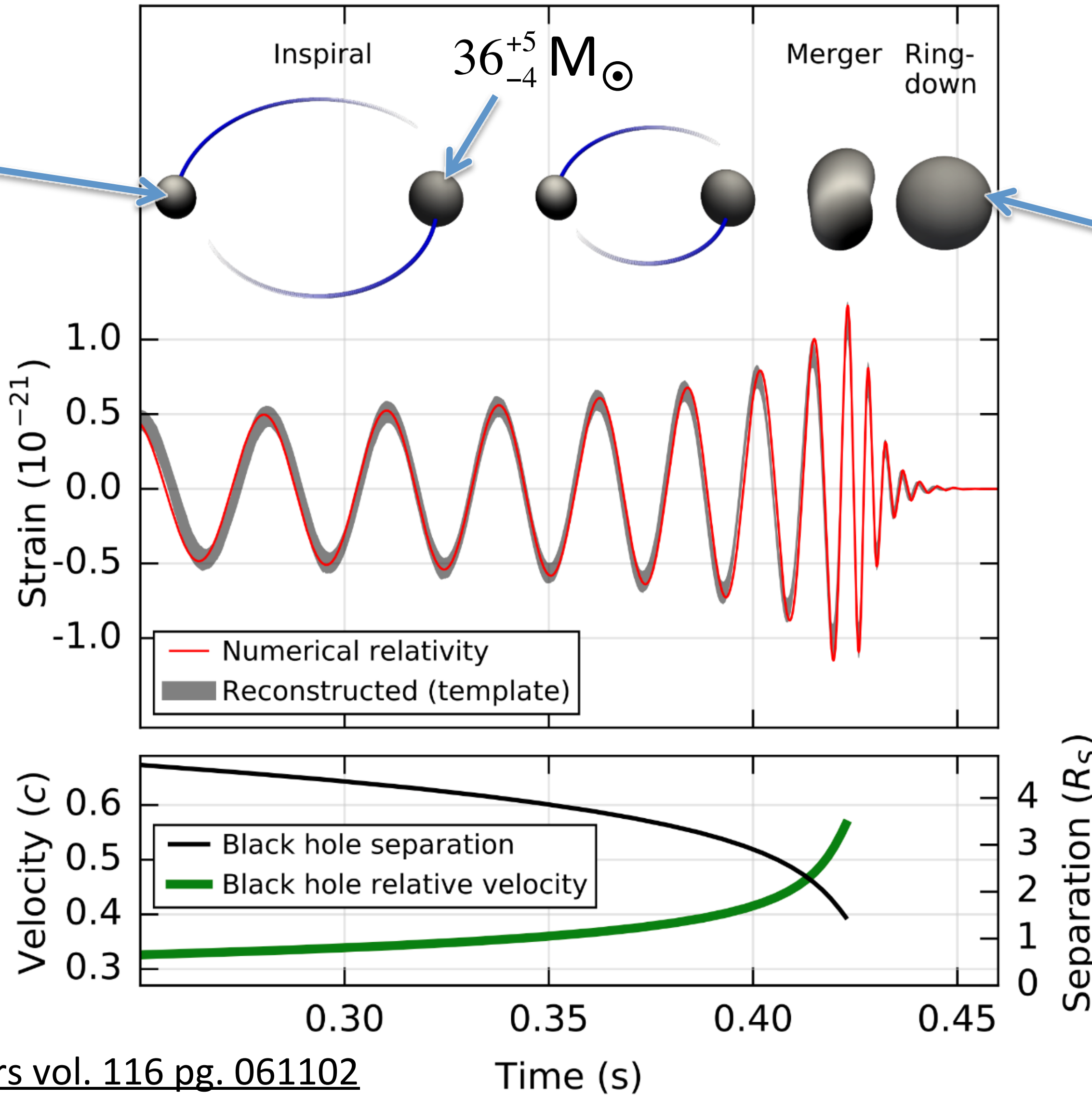



Phys Rev Letters vol. 116 pg. 061102

# Source was a binary black hole merger

$29^{+4}_{-5}\ M_\odot$

$36^{+5}_{-4}\ M_\odot$




Source distance

$1.3^{+0.52}_{-0.59} \times 10^9$ lys

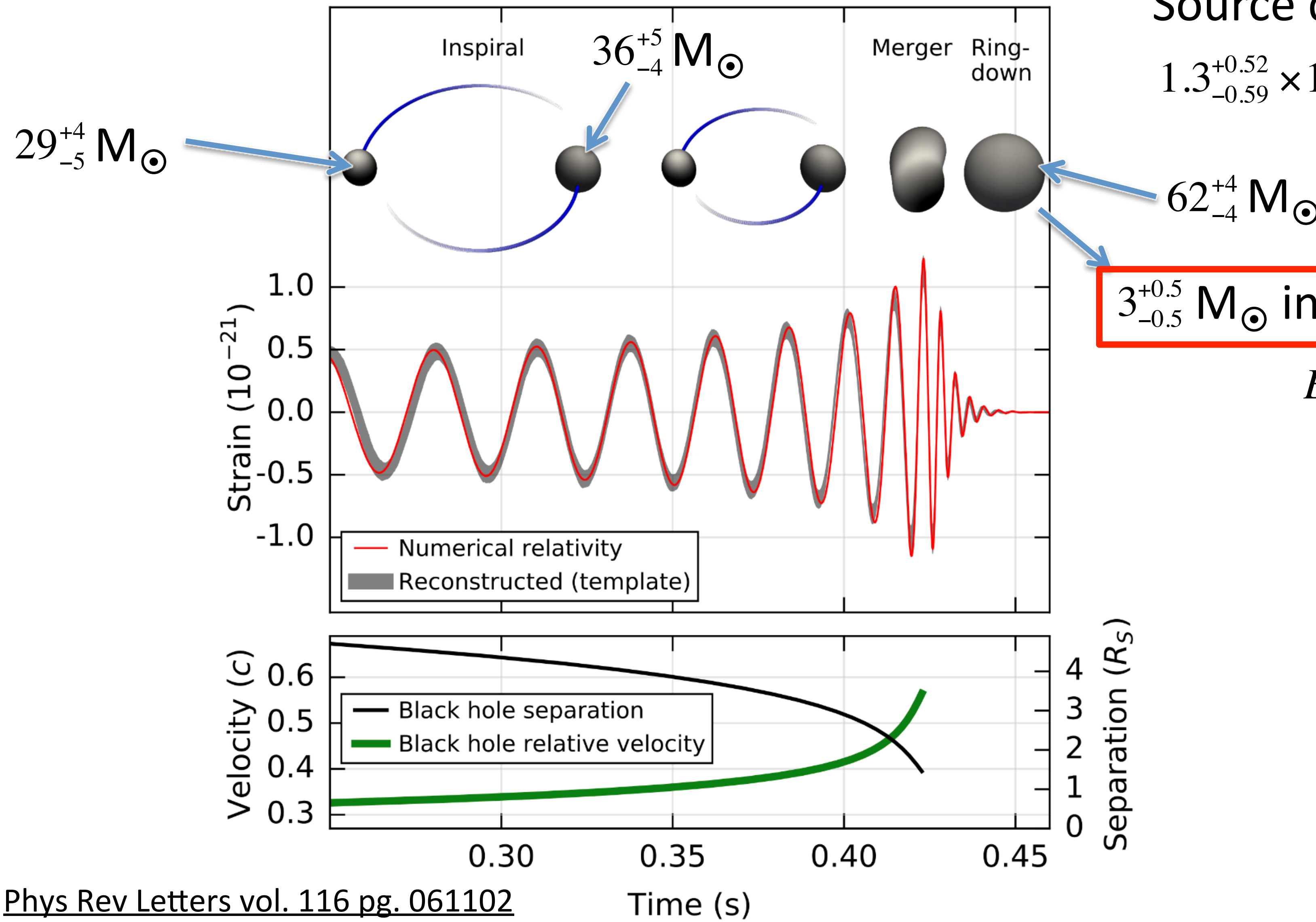
$62^{+4}_{-4}\ M_\odot$

Phys Rev Letters vol. 116 pg. 061102

# Source was a binary black hole merger

Source distance

$1.3^{+0.52}_{-0.59} \times 10^9$ lys



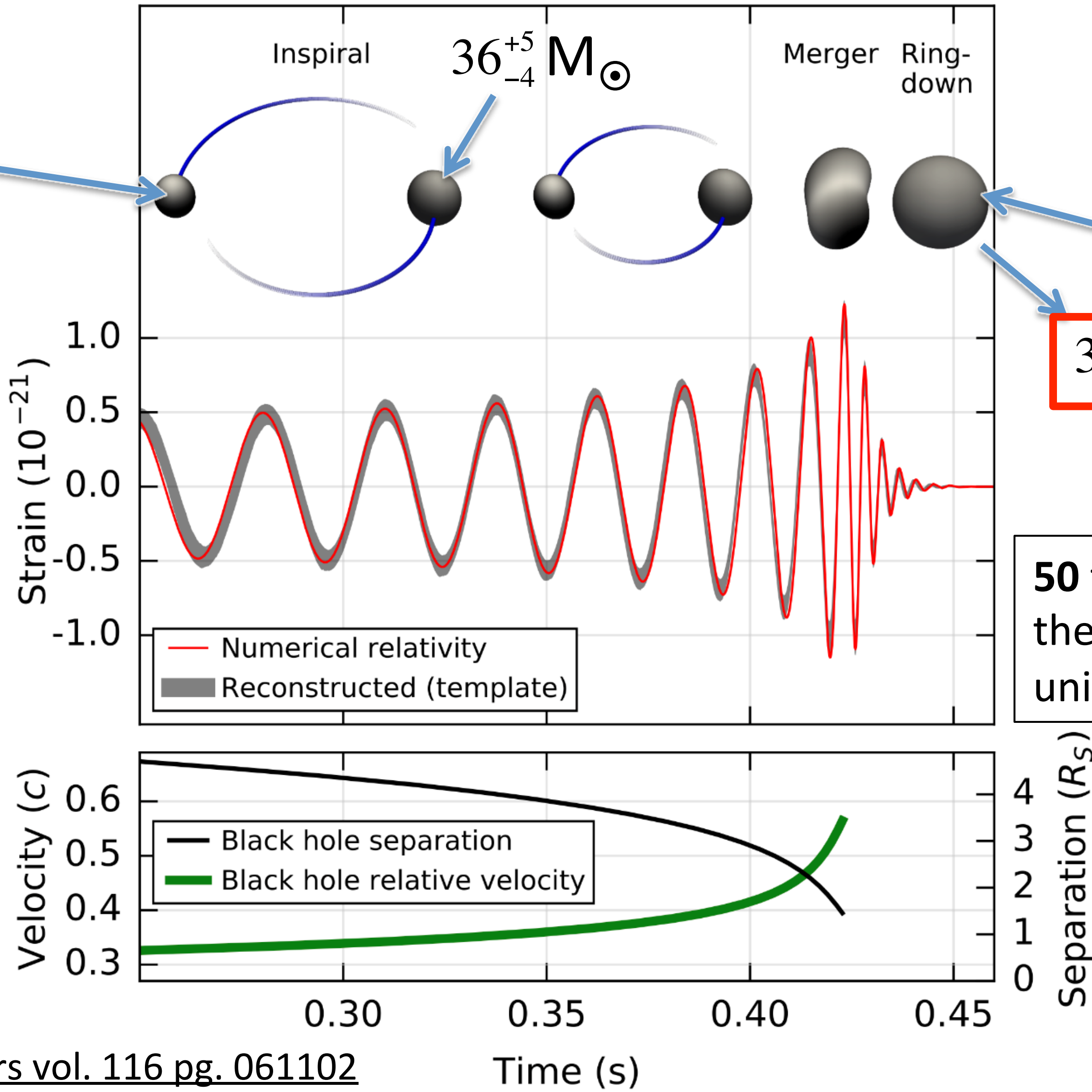

$3^{+0.5}_{-0.5}$ $M_\odot$ in GWs!

$E = mc^2$

Phys Rev Letters vol. 116 pg. 061102

# Source was a binary black hole merger

$29^{+4}_{-5}\, M_\odot$




Source distance

$1.3^{+0.52}_{-0.59} \times 10^9$ lys

$62^{+4}_{-4}\, M_\odot$

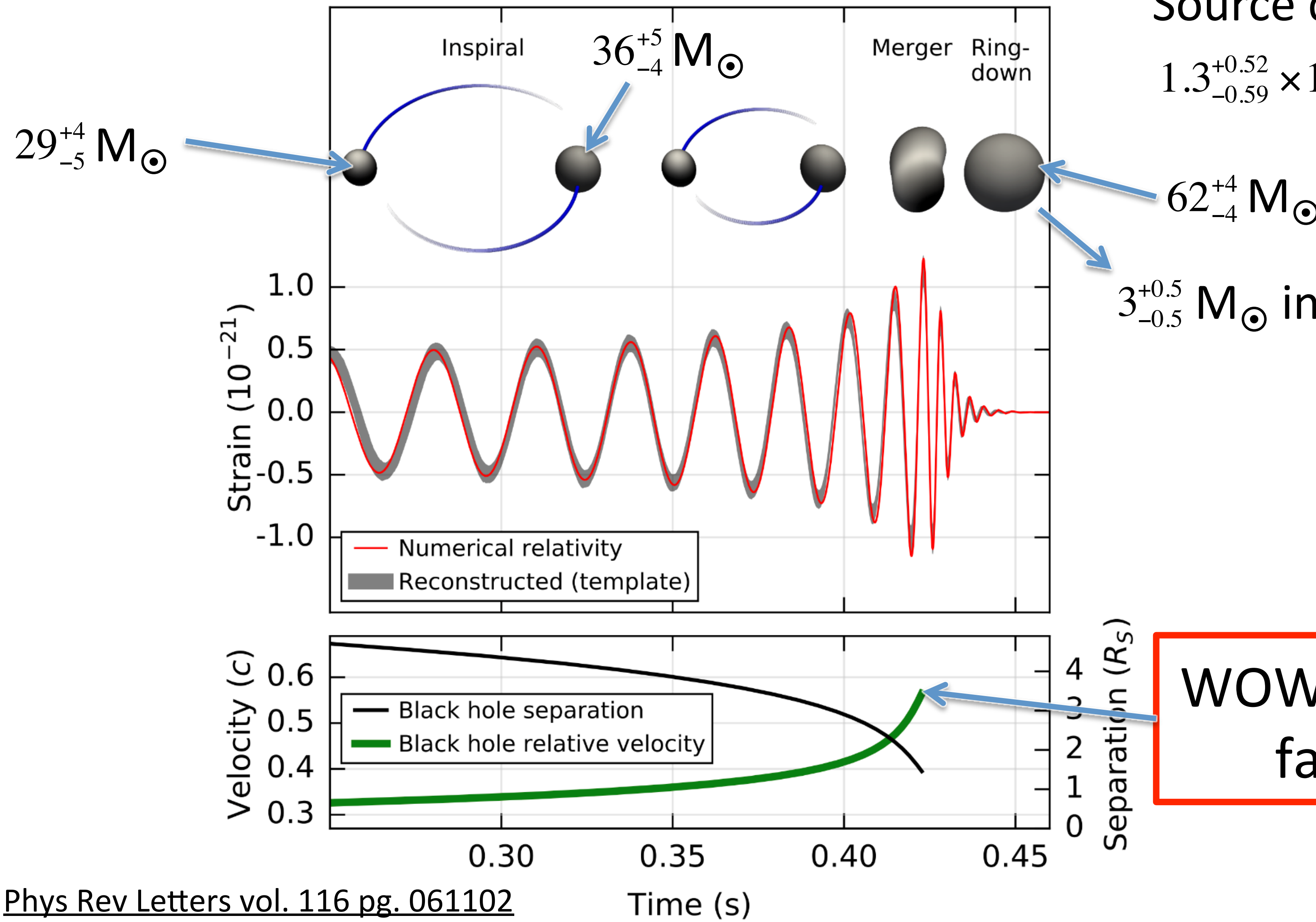
$3^{+0.5}_{-0.5}\, M_\odot$ in GWs!

$E = mc^2$

**50** times 'brighter' than all the stars in the known universe

Phys Rev Letters vol. 116 pg. 061102

# Source was a binary black hole merger



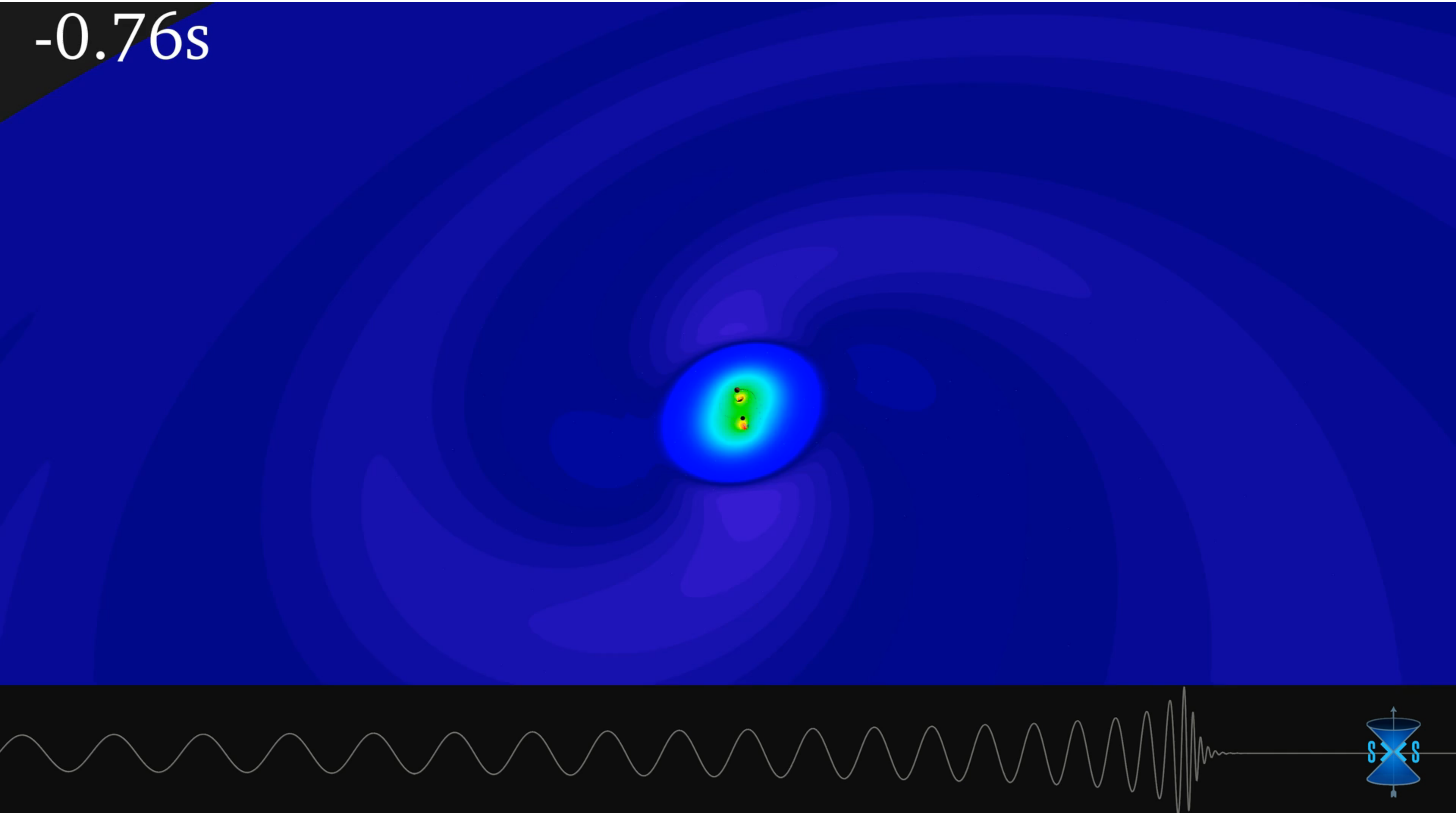

Source distance

$1.3^{+0.52}_{-0.59} \times 10^9$ lys

WOW that's fast!

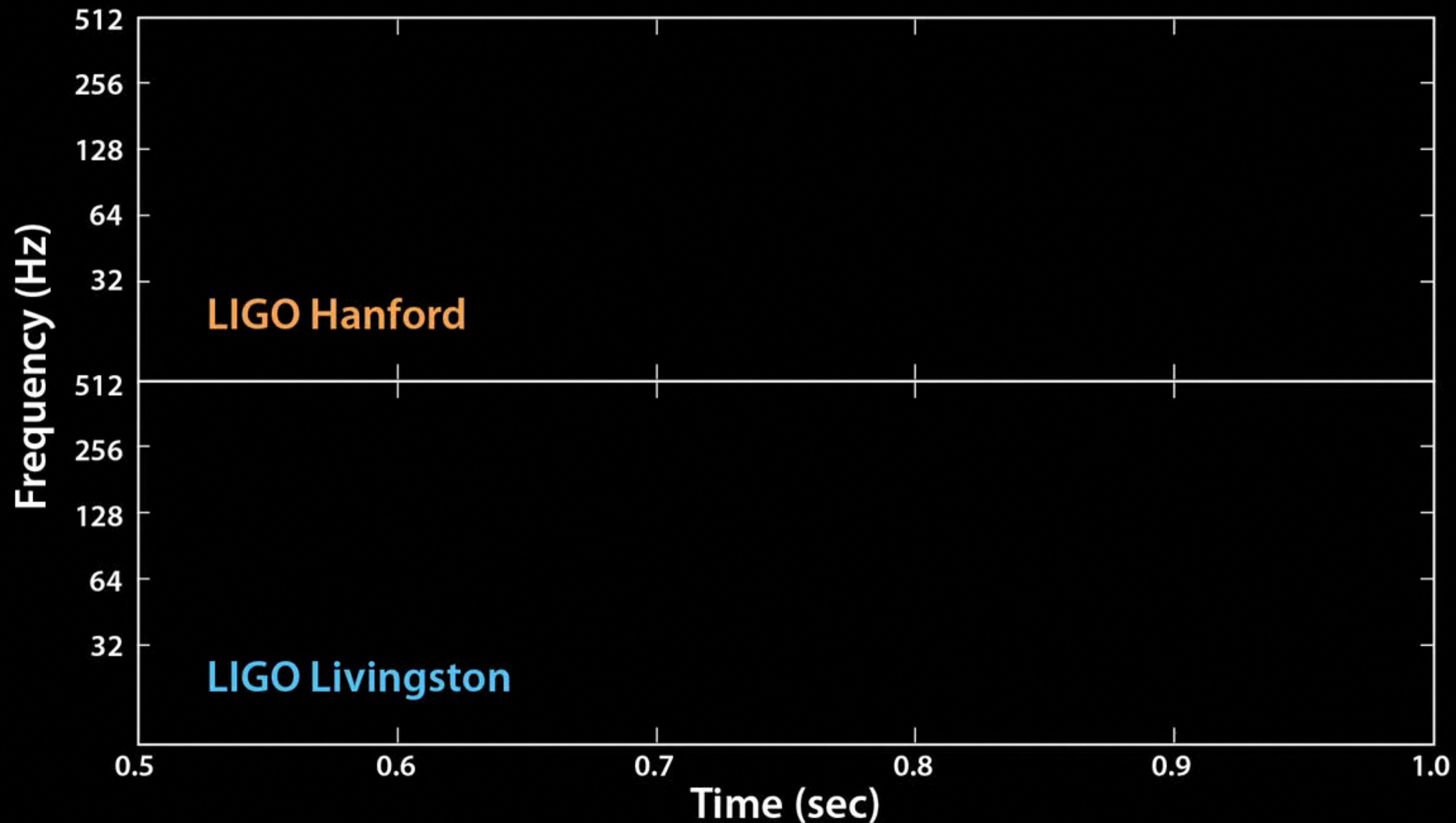
Phys Rev Letters vol. 116 pg. 061102

# The warping of spacetime




Simulating Extreme Spacetimes Project: http://www.black-holes.org/

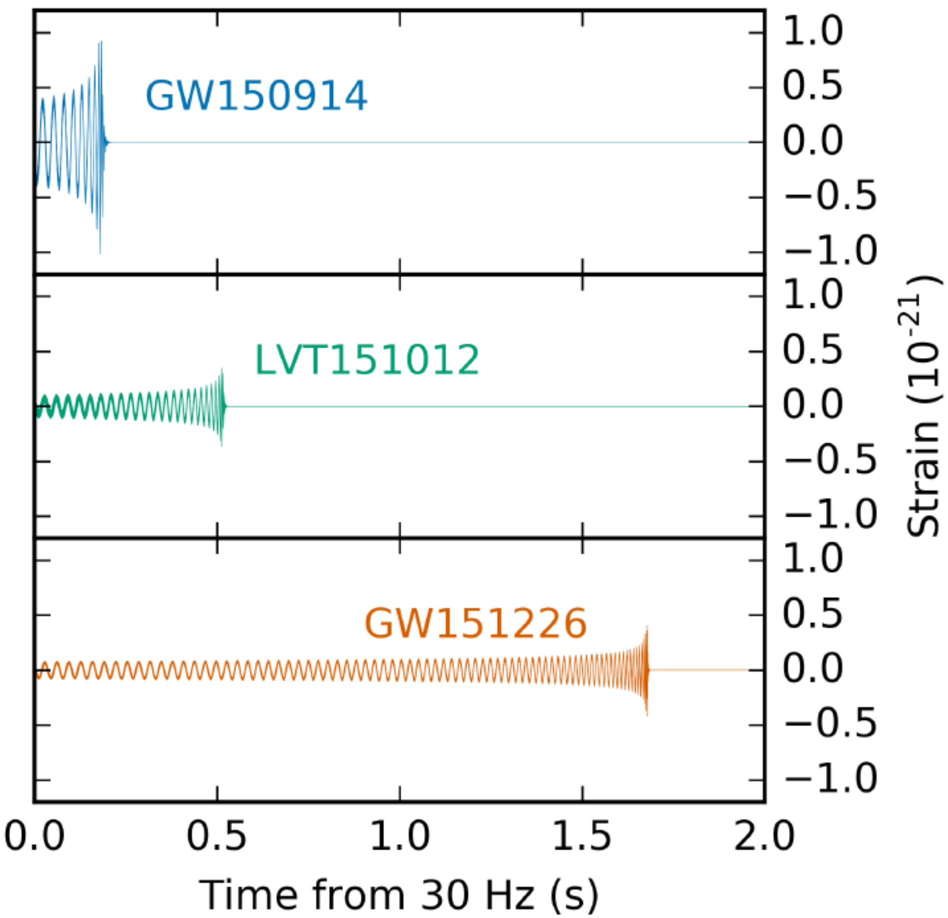
# The Music of the Spheres




Movie Credit: LIGO

# Advanced LIGO observations so far

Best fit of observed signals




Size of black holes in solar masses ($M_\odot$)

| Primary | Secondary |
|---|---|
| $36^{+5}_{-4}\,M_\odot$ | $29^{+4}_{-5}\,M_\odot$ |
| $23^{+18}_{-6}\,M_\odot$ | $13^{+4}_{-5}\,M_\odot$ |
| $14^{+8}_{-4}\,M_\odot$ | $7.5^{+2}_{-2}\,M_\odot$ |



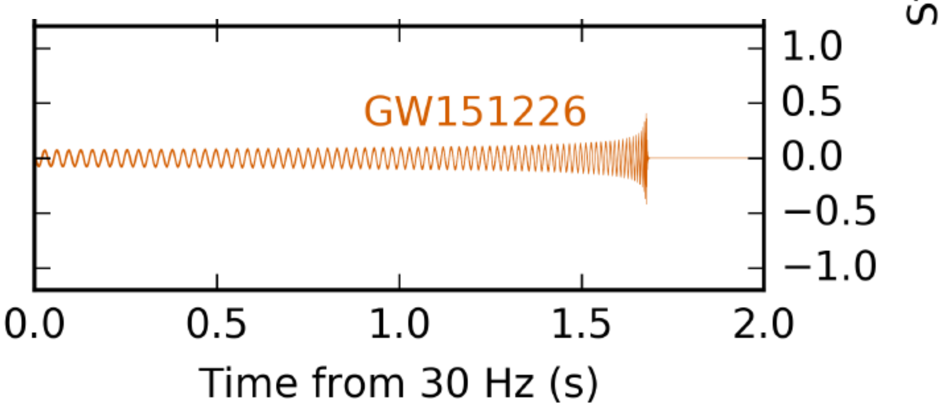
Reference https://dcc.ligo.org/LIGO-P1600088/public

# Advanced LIGO observations so far

The sounds of the of
12/26/15 event

Pure waveform

Frequency shifted waveform

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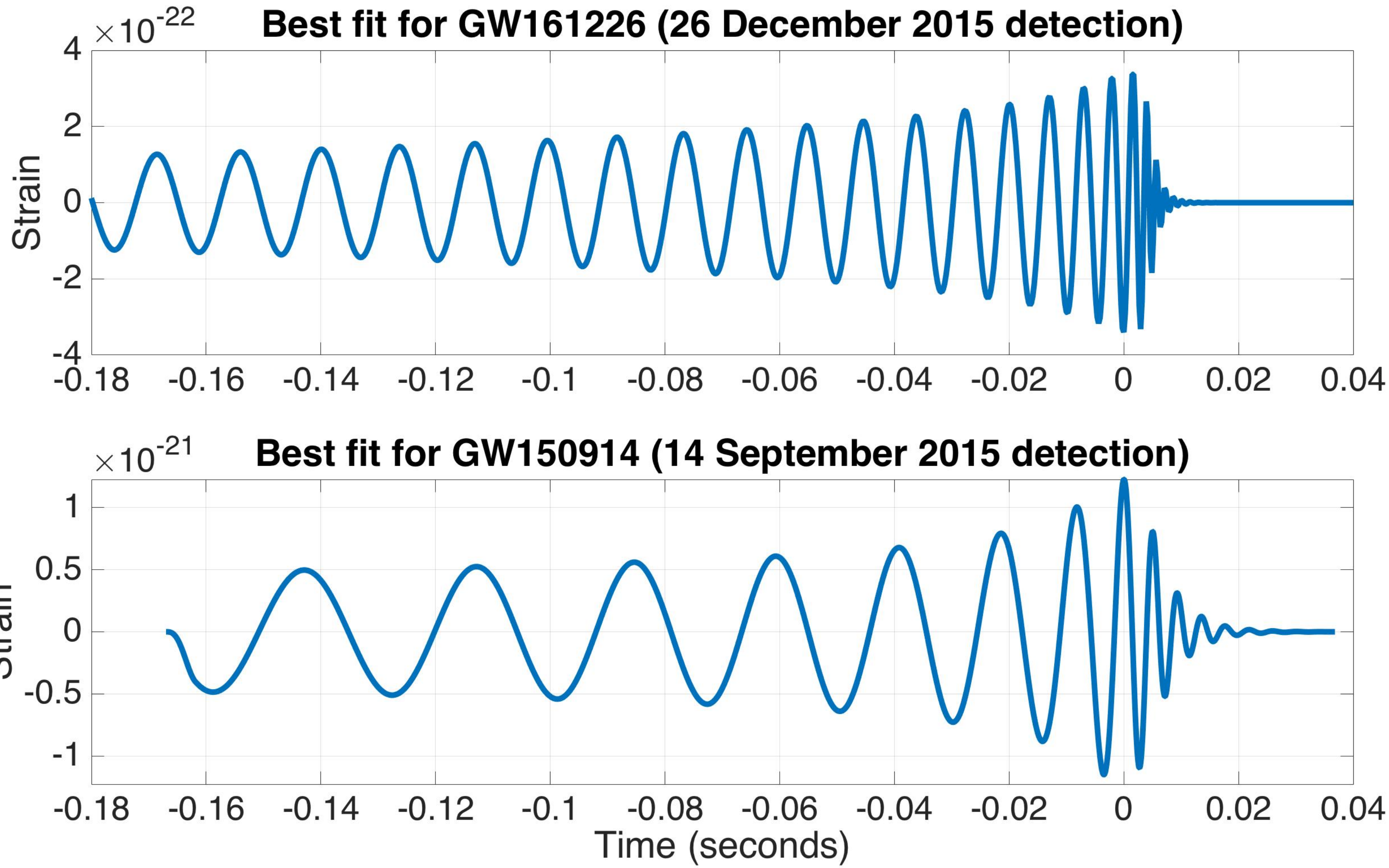
| $14^{+8}_{-4}\,M_\odot$ | $7.5^{+2}_{-2}\,M_\odot$ |

Reference https://dcc.ligo.org/LIGO-P1600088/public

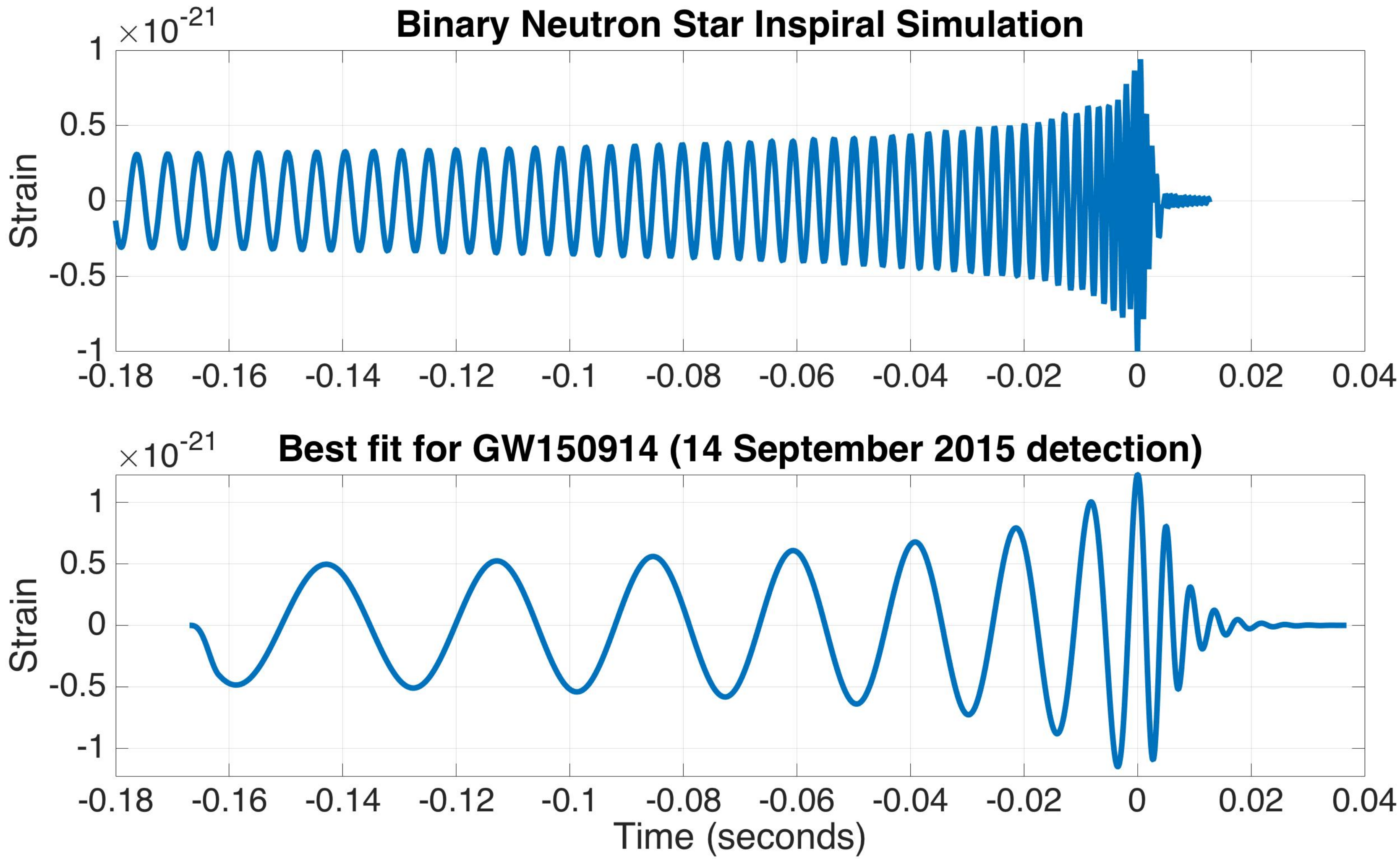
# How we know what we saw (heard)






LIGO Open Science Center: https://losc.ligo.org/about/

# How we know we saw black holes

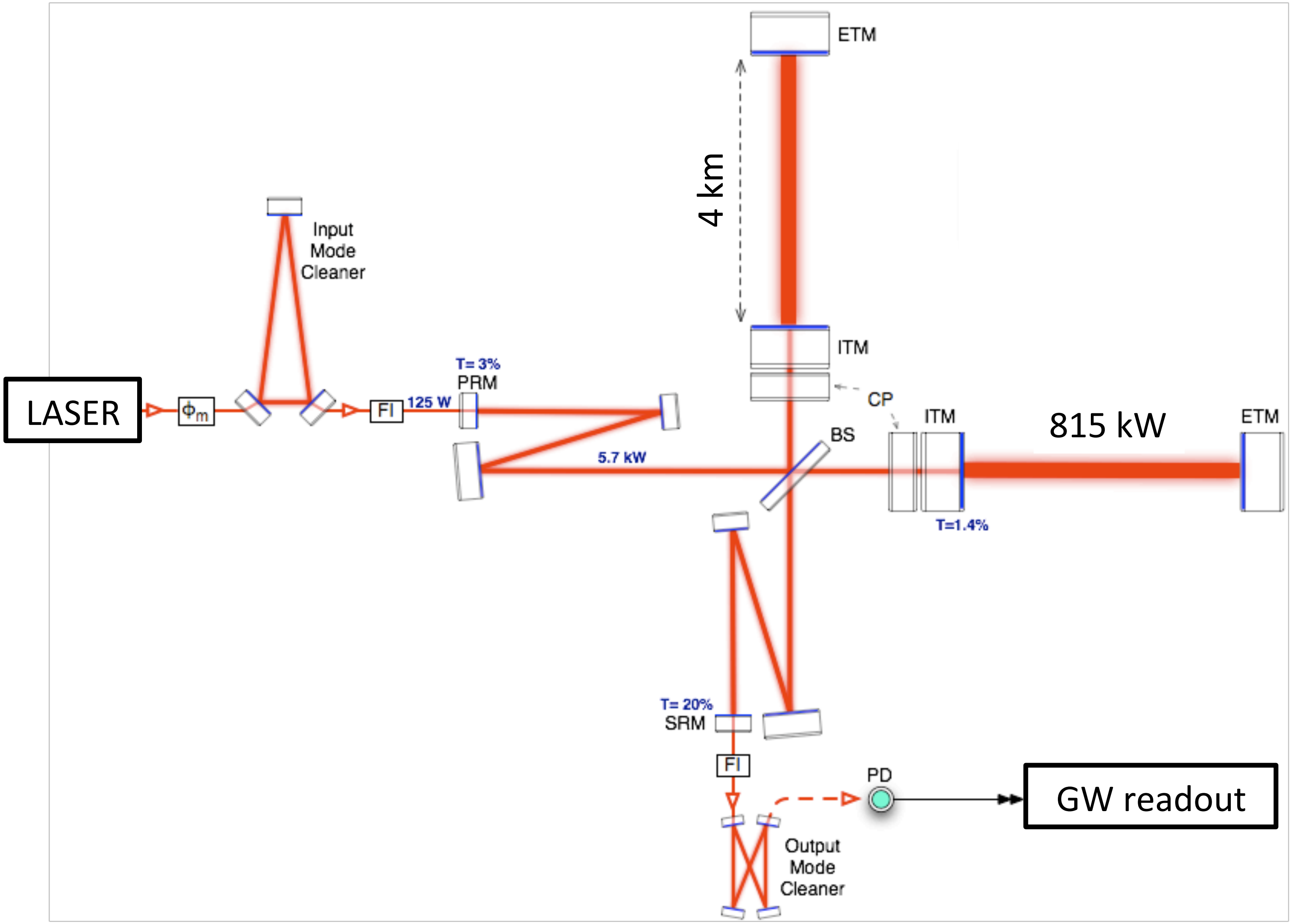



LIGO Open Science Center: https://losc.ligo.org/about/
Professor Scott Hughes: http://gmunu.mit.edu/sounds/sounds.html

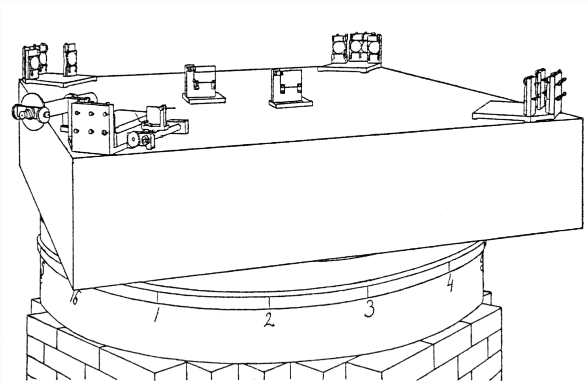
# How does Advanced LIGO Achieve the required sensitivity?

Photo courtesy LIGO Lab

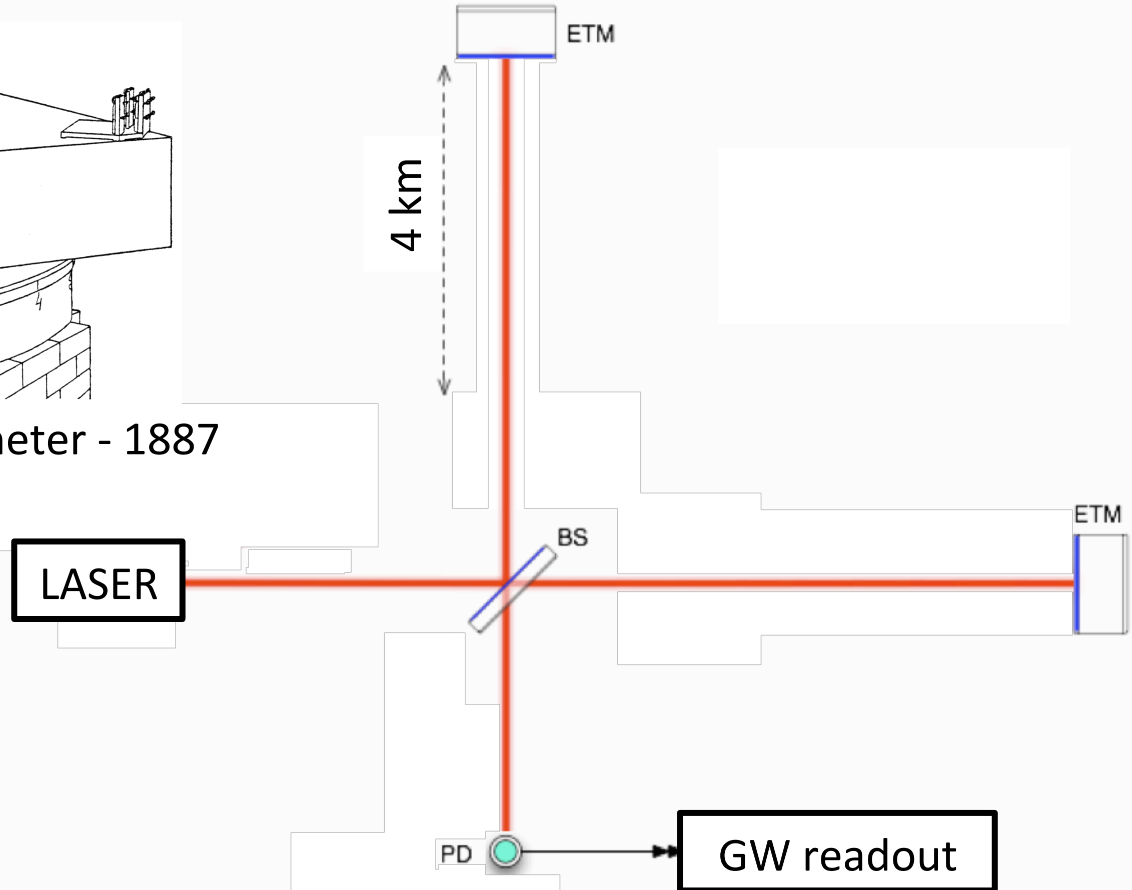
# Advanced LIGO Optical Layout



# Advanced LIGO Optical Layout

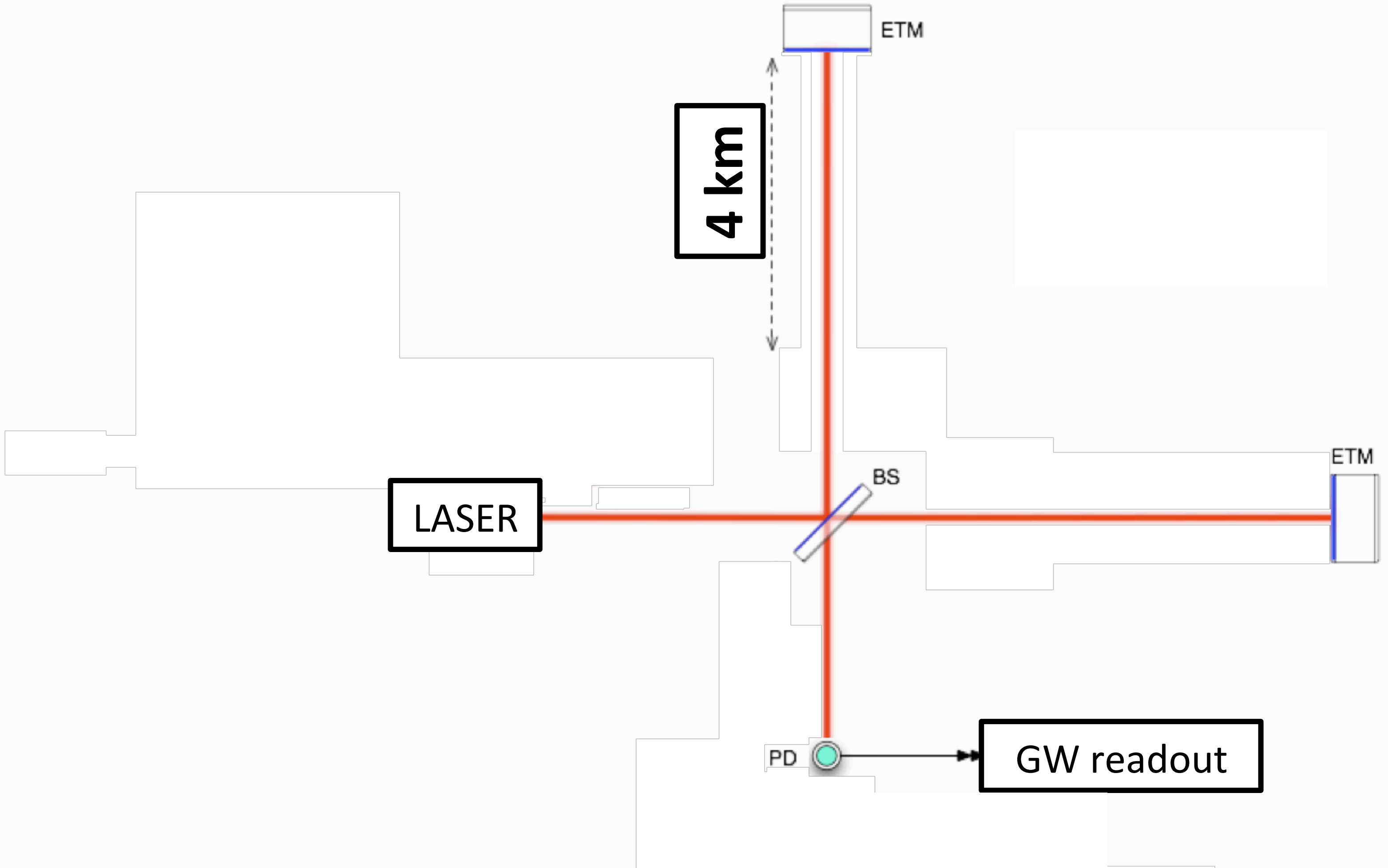


Michelson's interferometer - 1887




LIGO is essentially a Michelson Interferometer

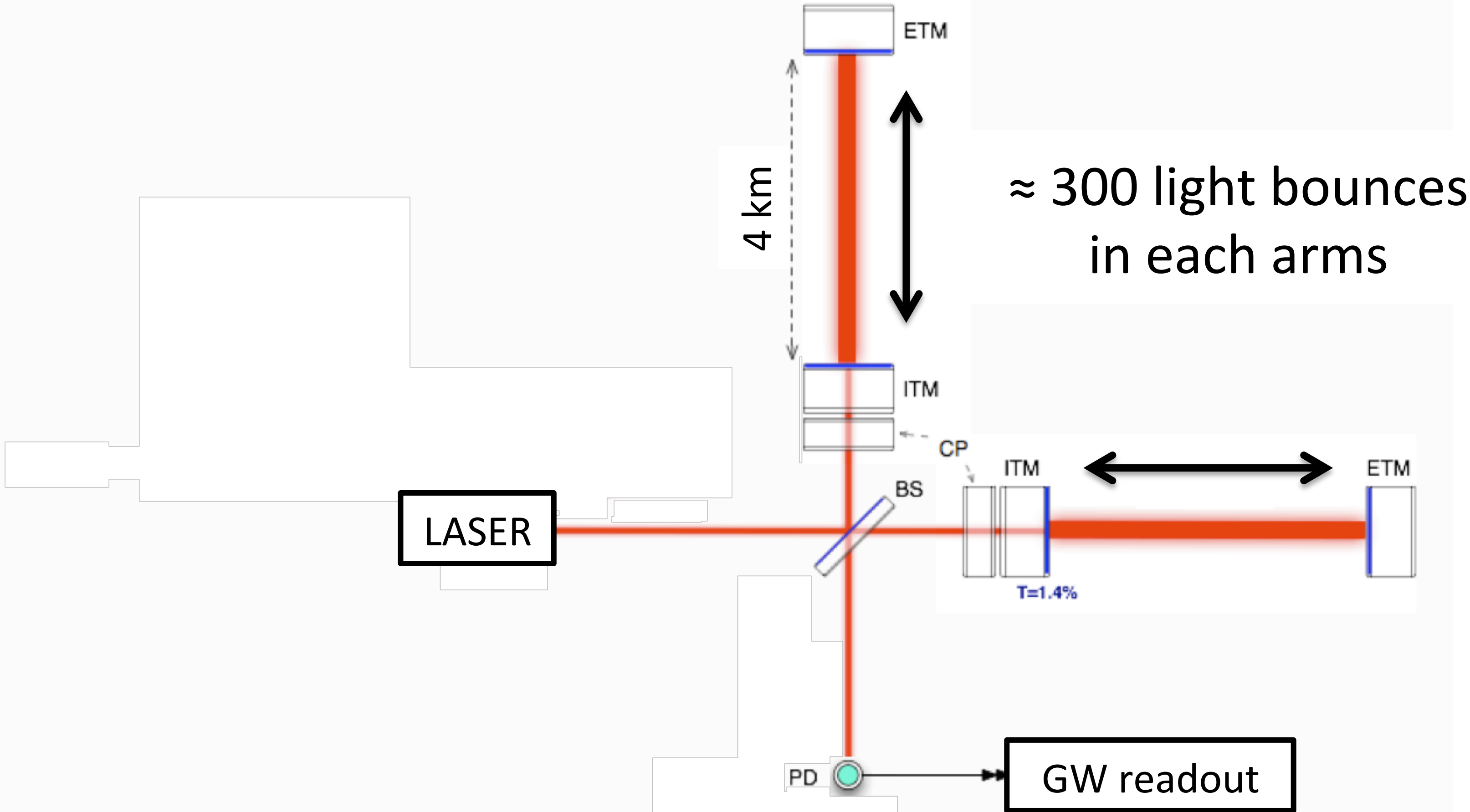
# Advanced LIGO Optical Layout




1. Use really long arms to amplify the strain in space

   $(10^{-21}$ strain) * (4000 m long arms) = $4*10^{-18}$ m

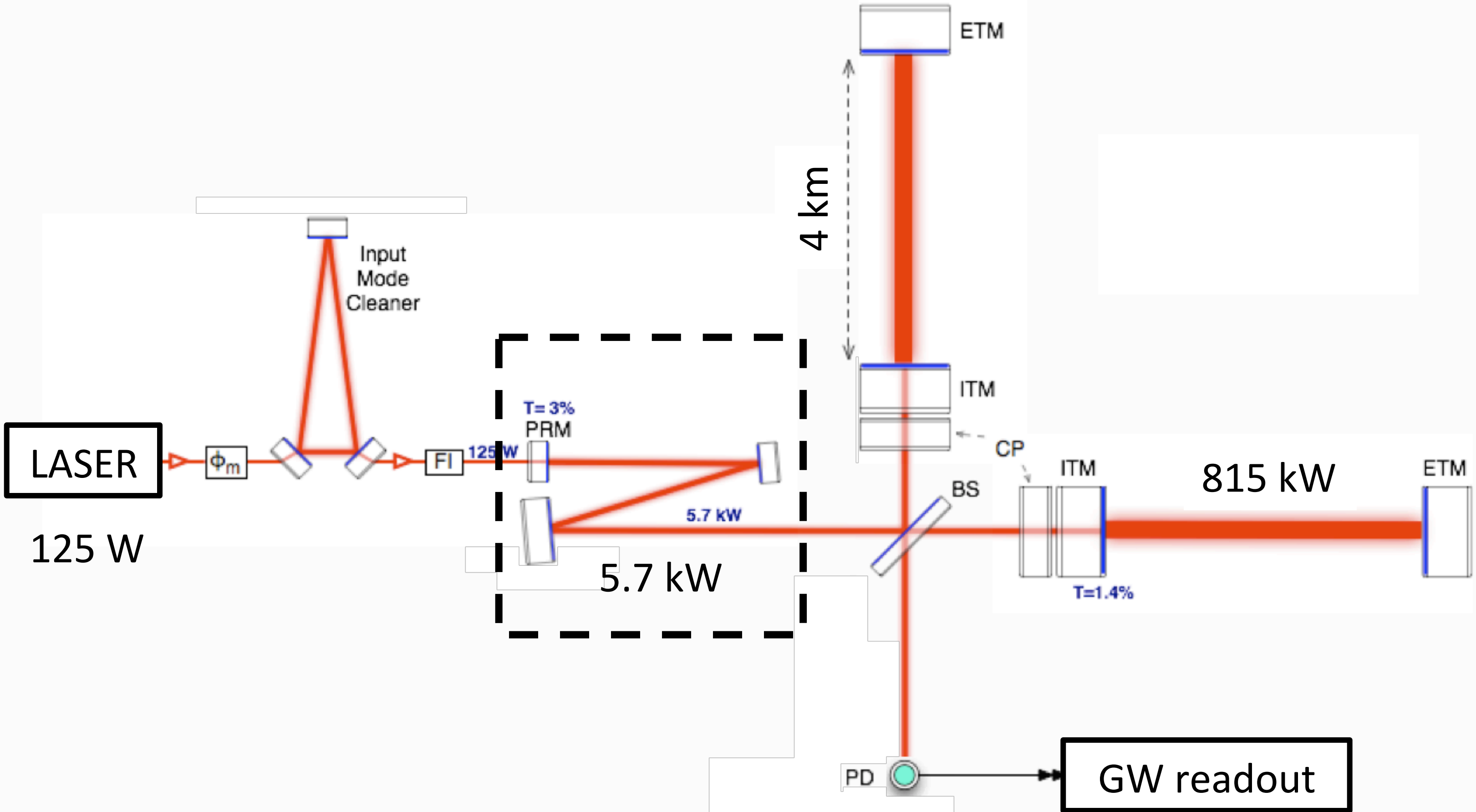
# Advanced LIGO Optical Layout




2. Fold the arms to make them effectively longer

(4000 m long arms) * (300 bounces) = 1,200,000 m

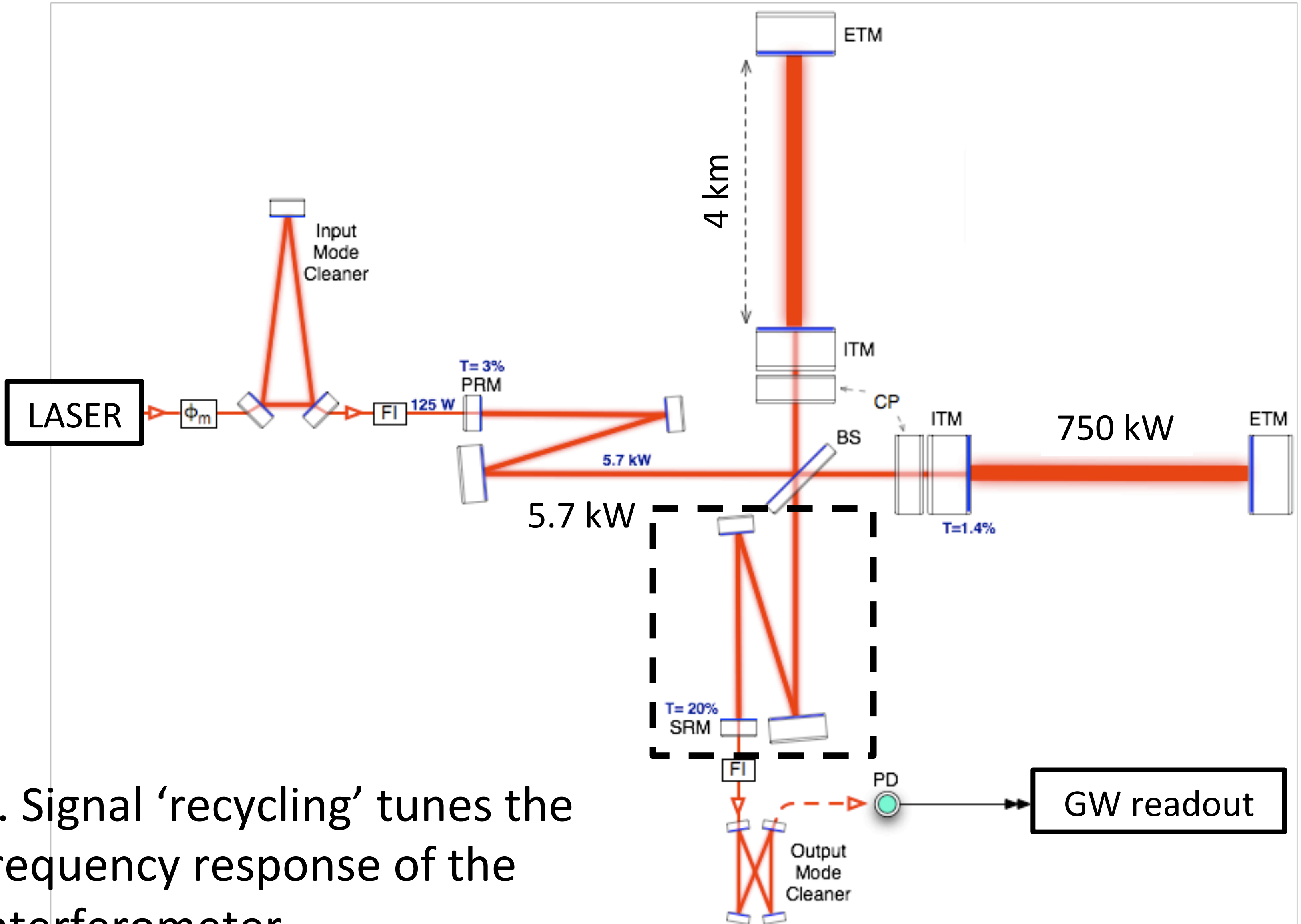
# Advanced LIGO Optical Layout




3. Most light is reflected back to the laser, so use another mirror to push it back into the Michelson.

More photons = more signal

# Advanced LIGO Optical Layout

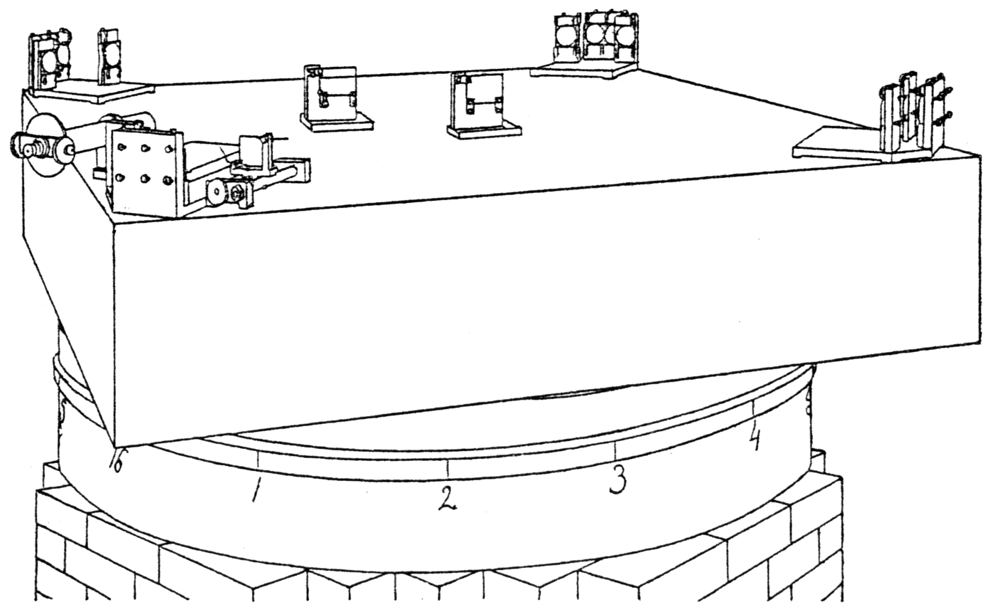



4. Signal 'recycling' tunes the frequency response of the interferometer.

# Michelson–Morley experiment 1887



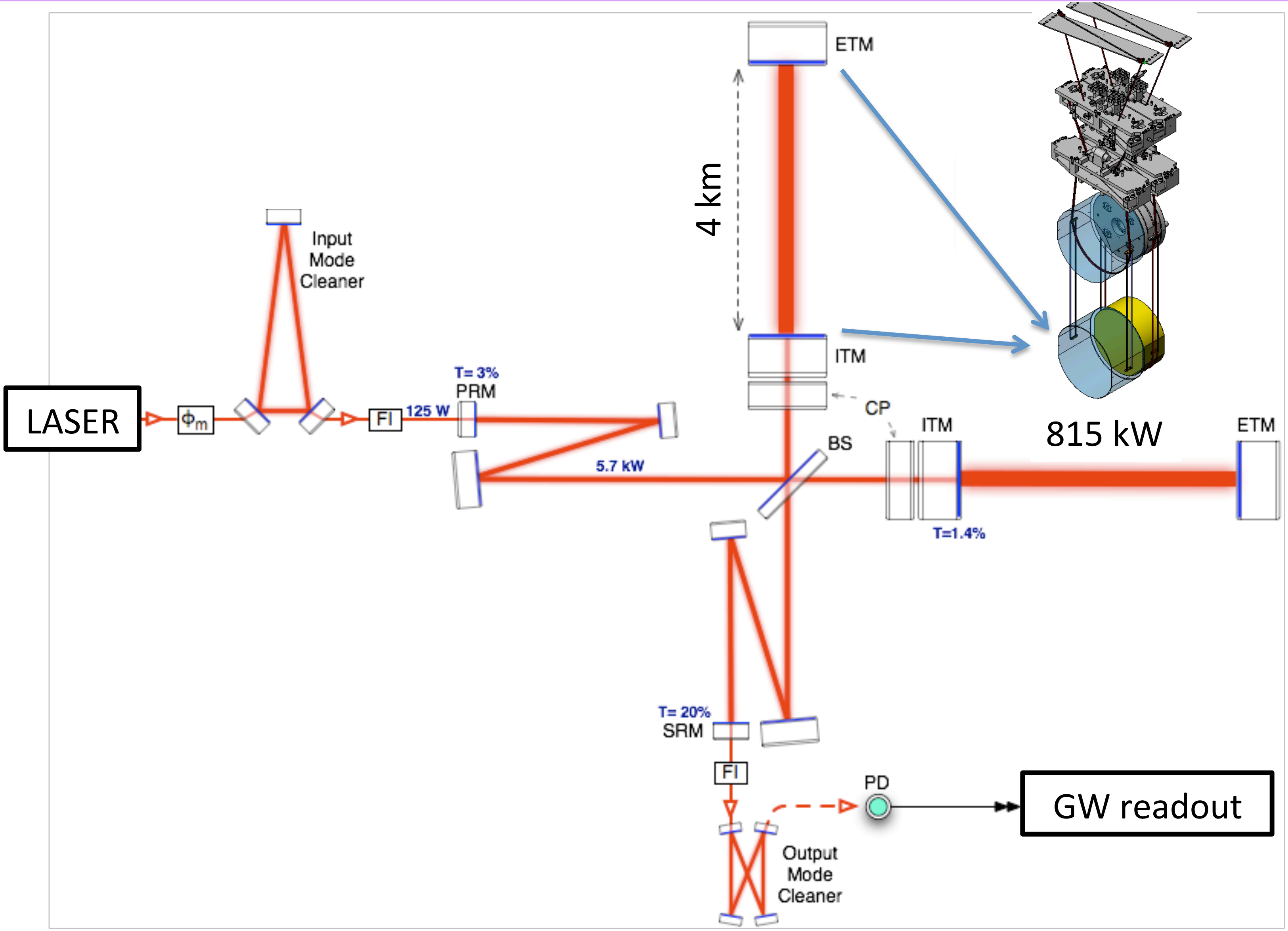
In the first experiment one of the principal difficulties encountered was that of revolving the apparatus without producing distortion; and another was its extreme sensitiveness to vibration. This was so great that it was impossible to see the interference fringes except at brief intervals when working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



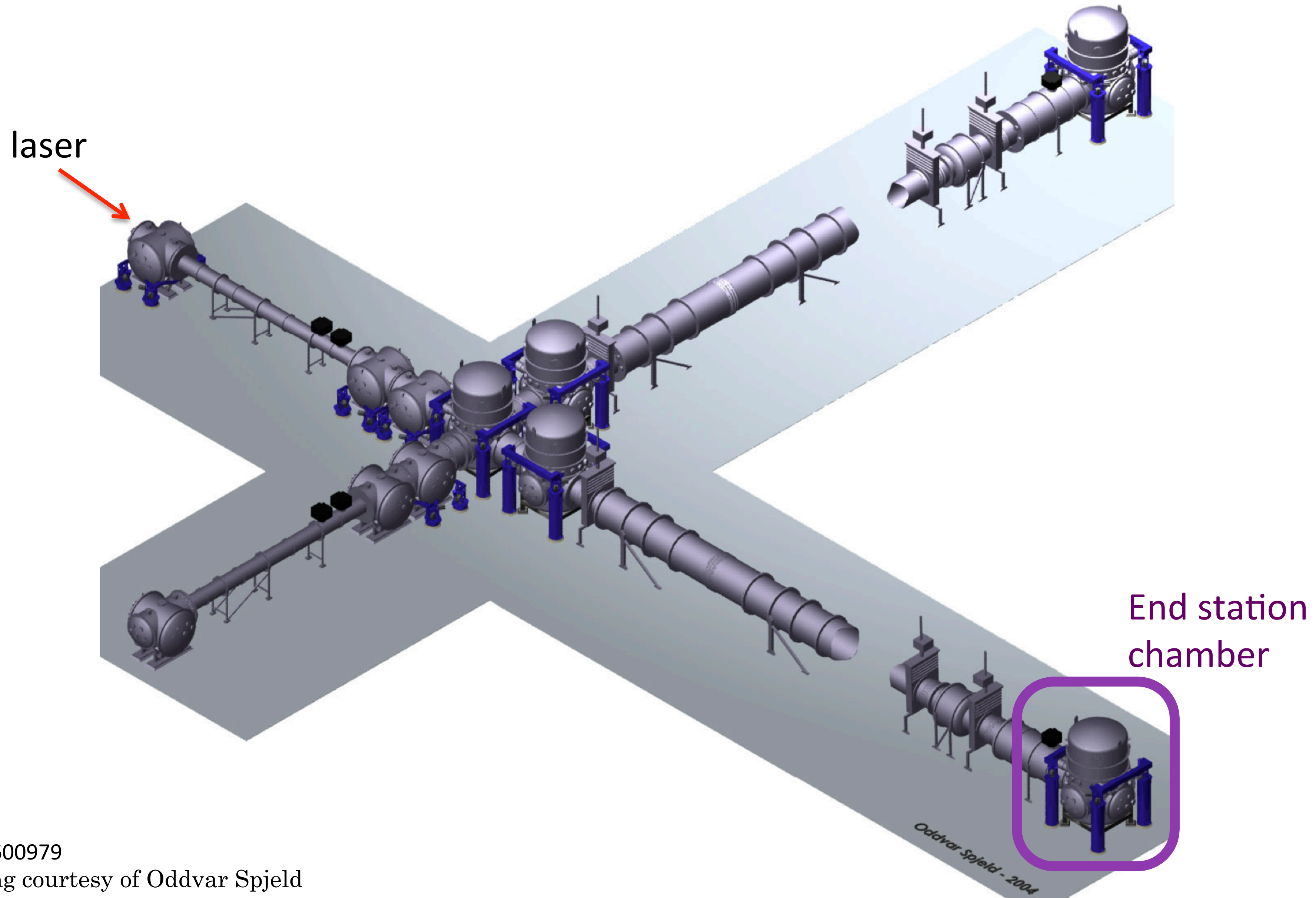

A. Michelson and W. Morley. On the Relative Motion of the Earth and the Luminiferous Ether. 1887

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

# Advanced LIGO Optical Layout

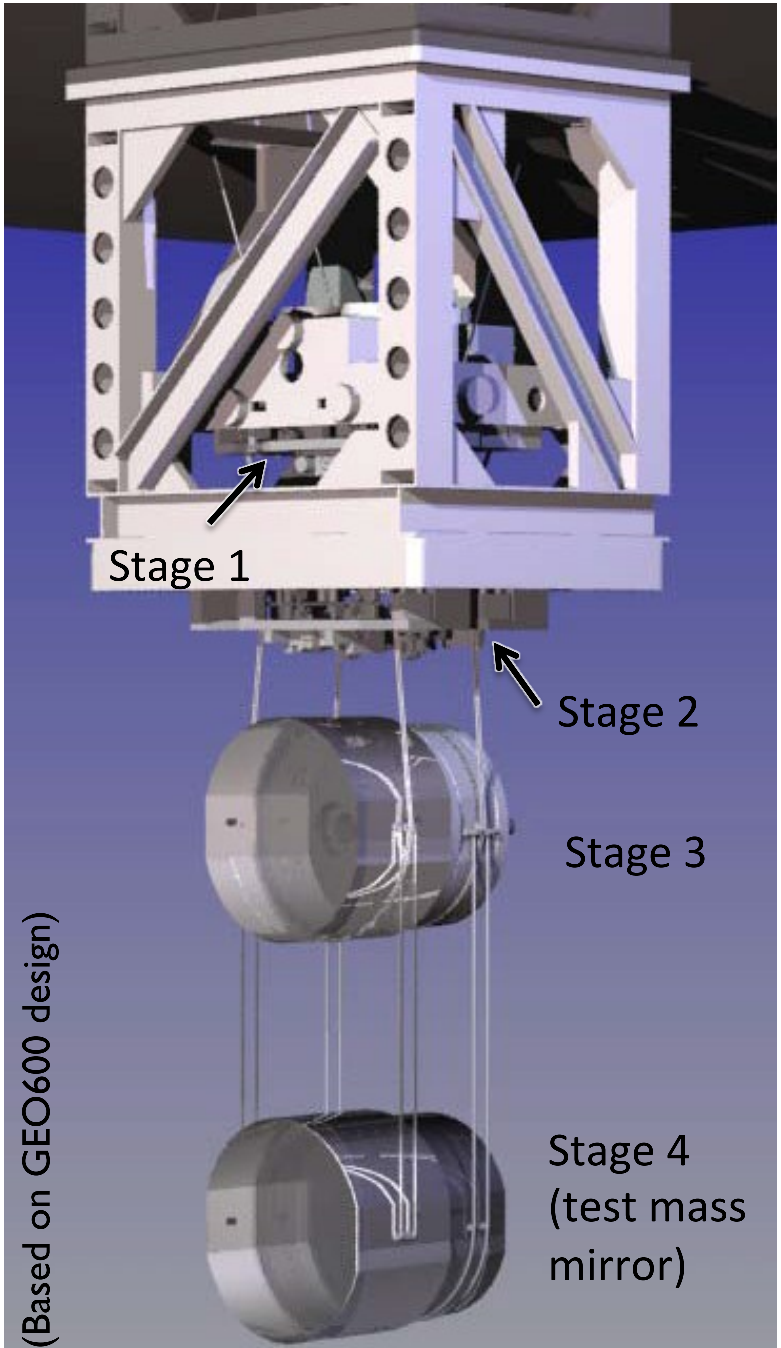


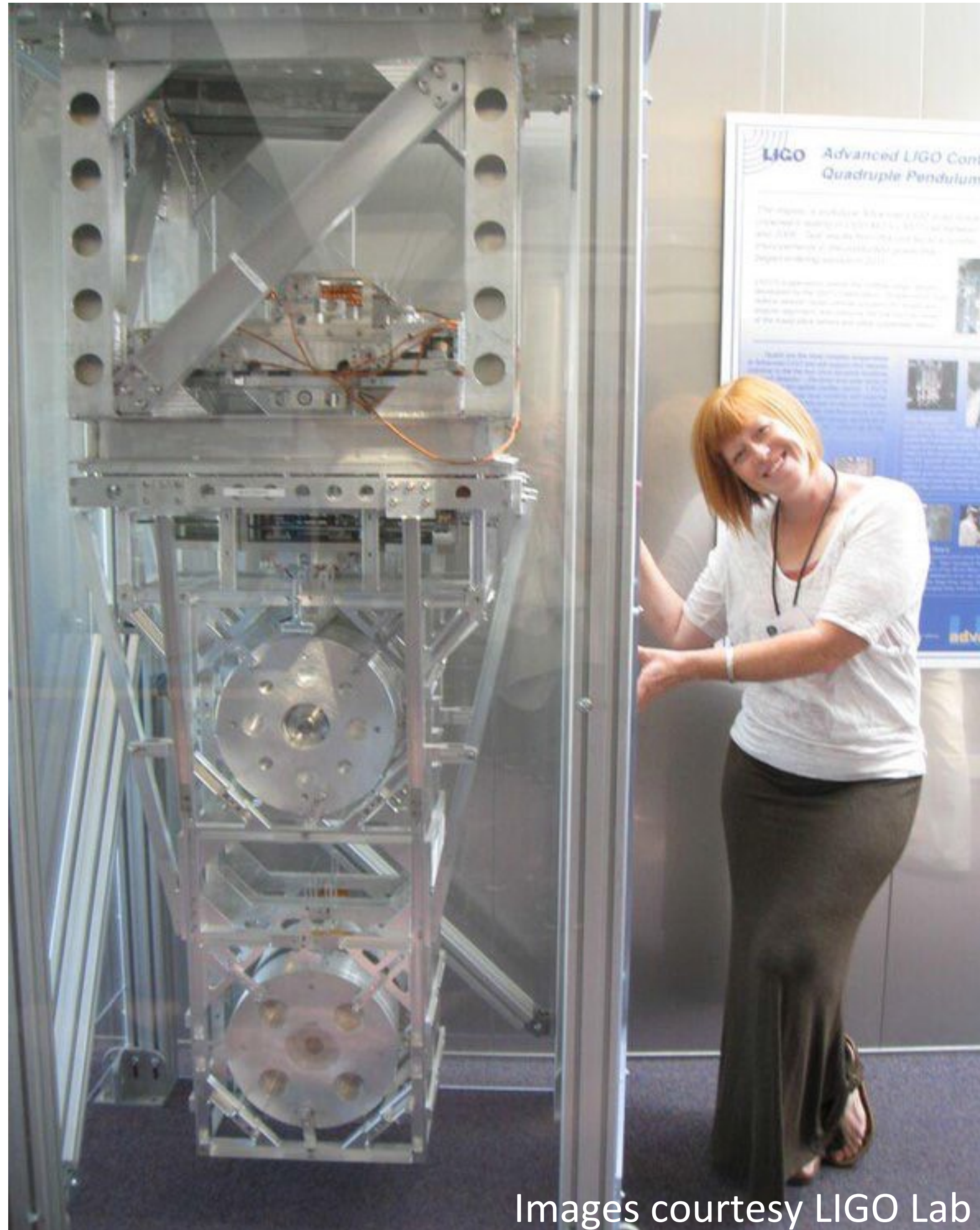
# The LIGO vacuum system

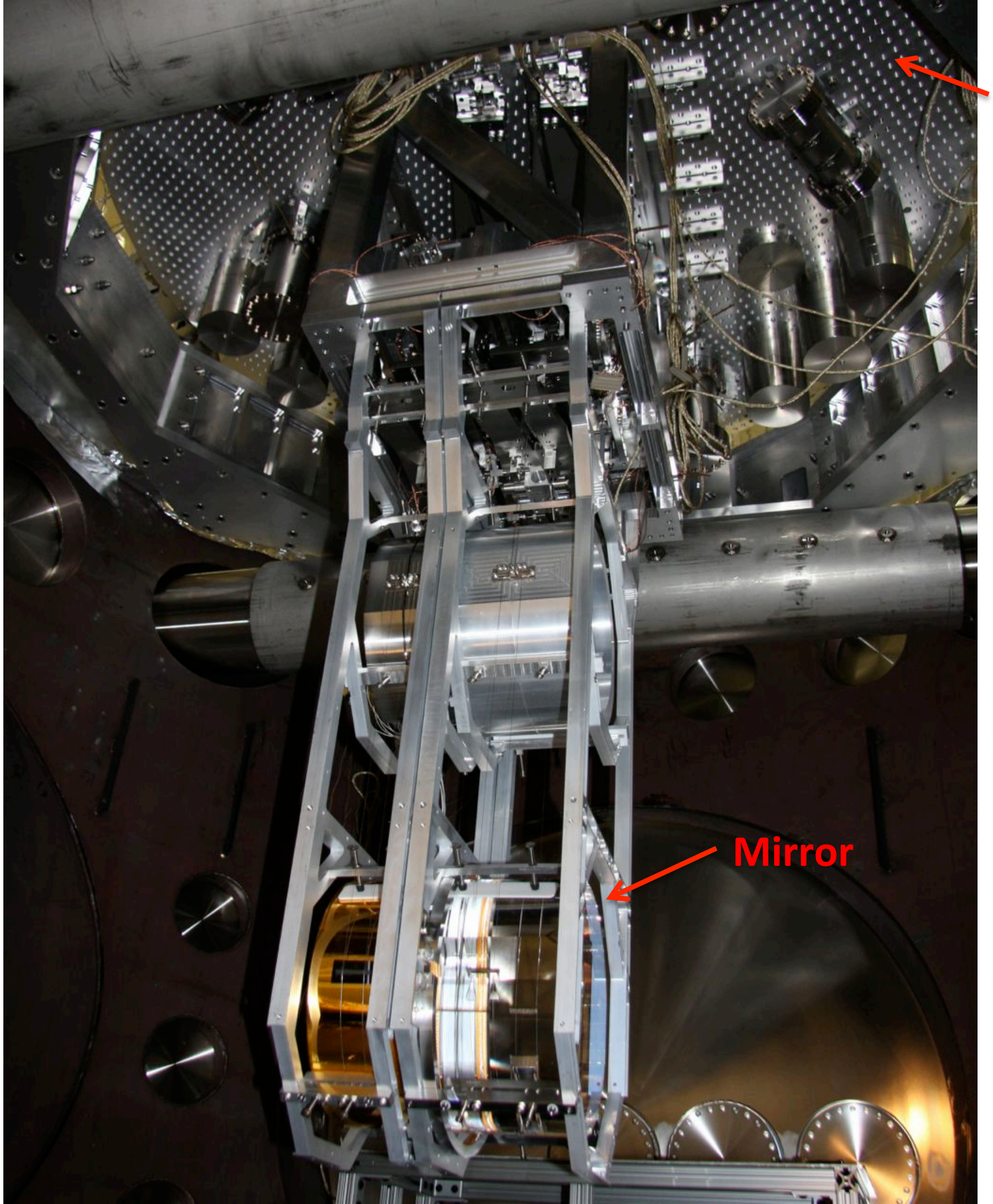



Ref G1600979
drawing courtesy of Oddvar Spjeld

H1 ITMX – 30 July 2014 - LHO alog 13044

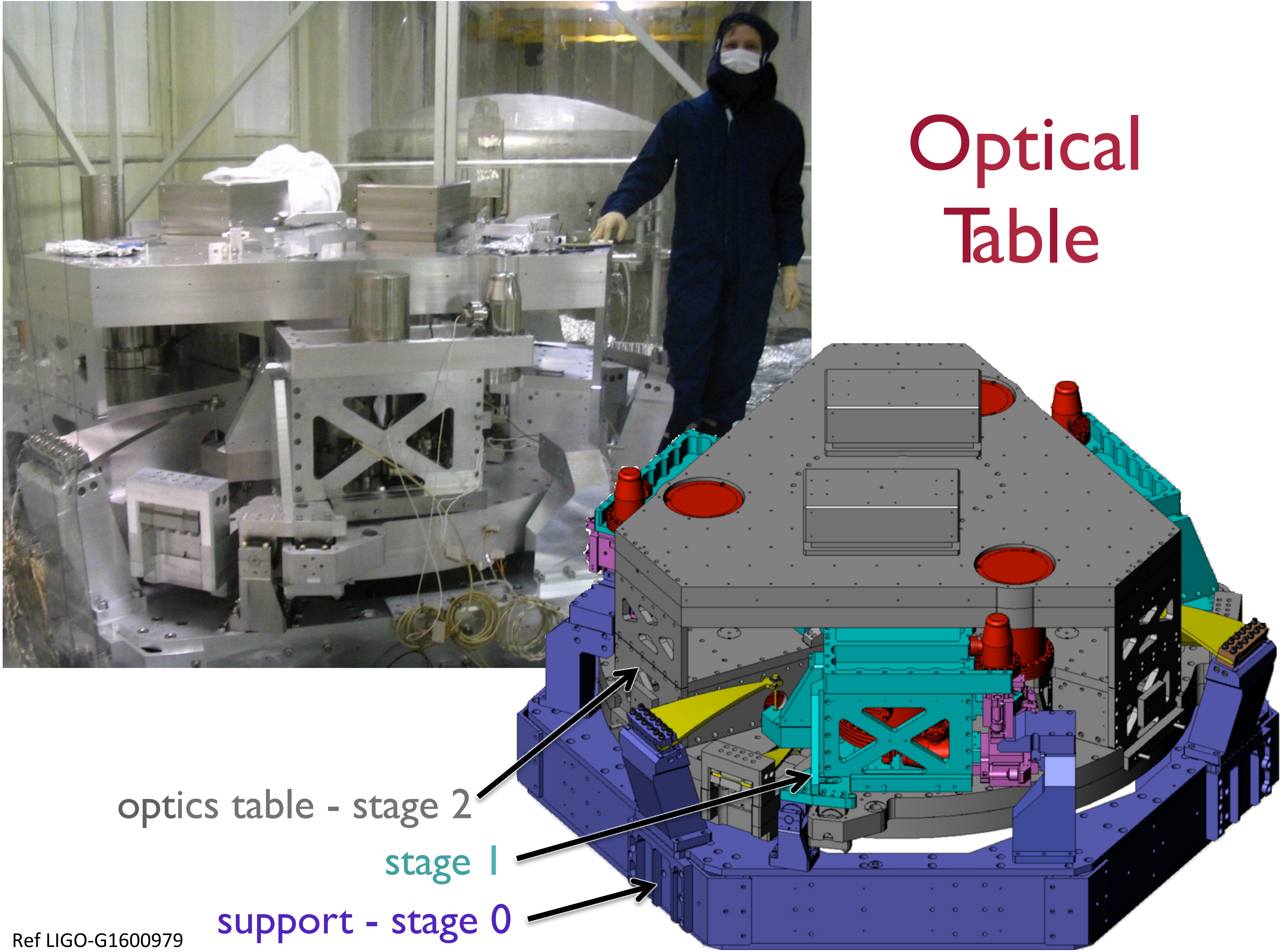

Stage 1
Stage 2
Stage 3
Stage 4
(test mass
mirror)
(Based on GEO600 design)


LIGO
Images courtesy LIGO Lab




prototype quad pendulum installation Jan 2009 at MIT

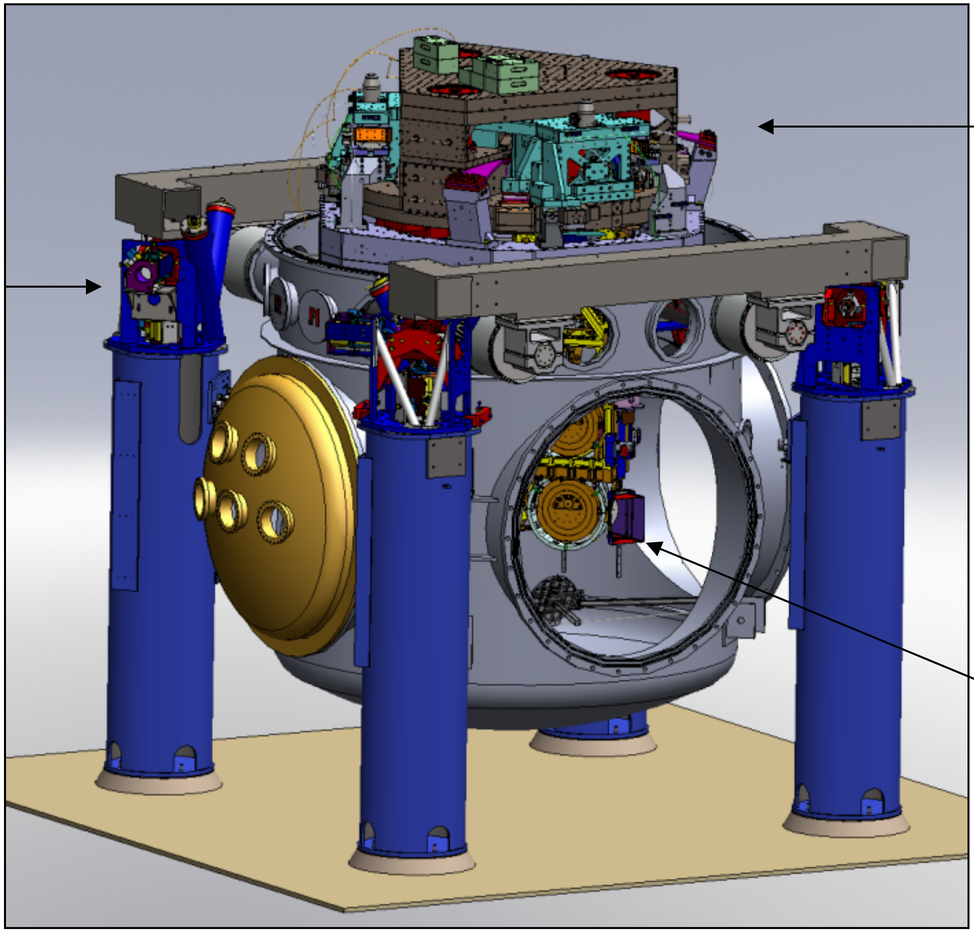
# Optical Table




Ref LIGO-G1600979

# Suspensions and Seismic Isolation

Advanced LIGO test mass isolation

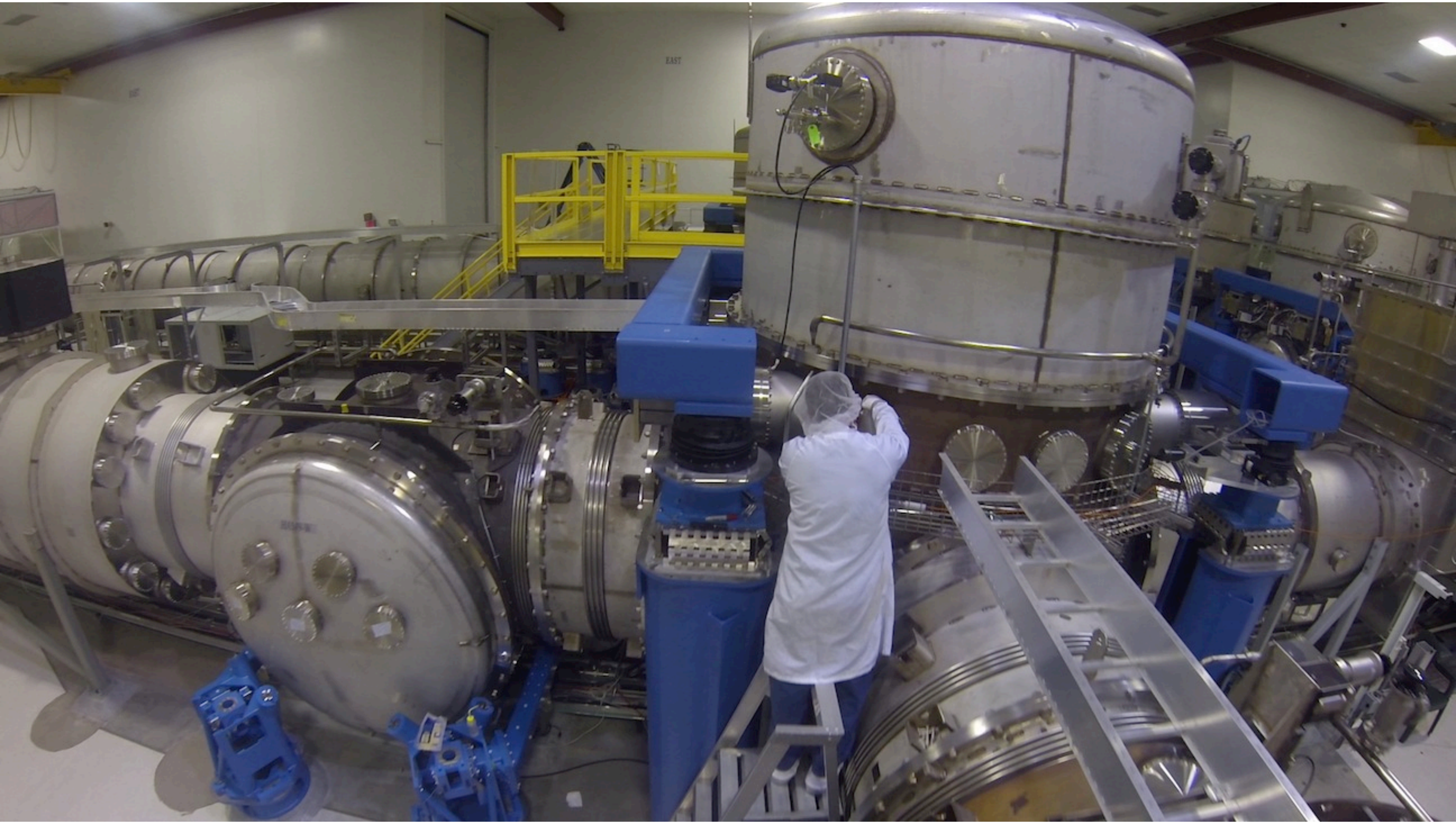


active isolation platform (2 stages of isolation)

hydraulic external pre-isolator (HEPI) (one stage of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

Ref: LIGO-G1000469-v1; Kissel PhD thesis

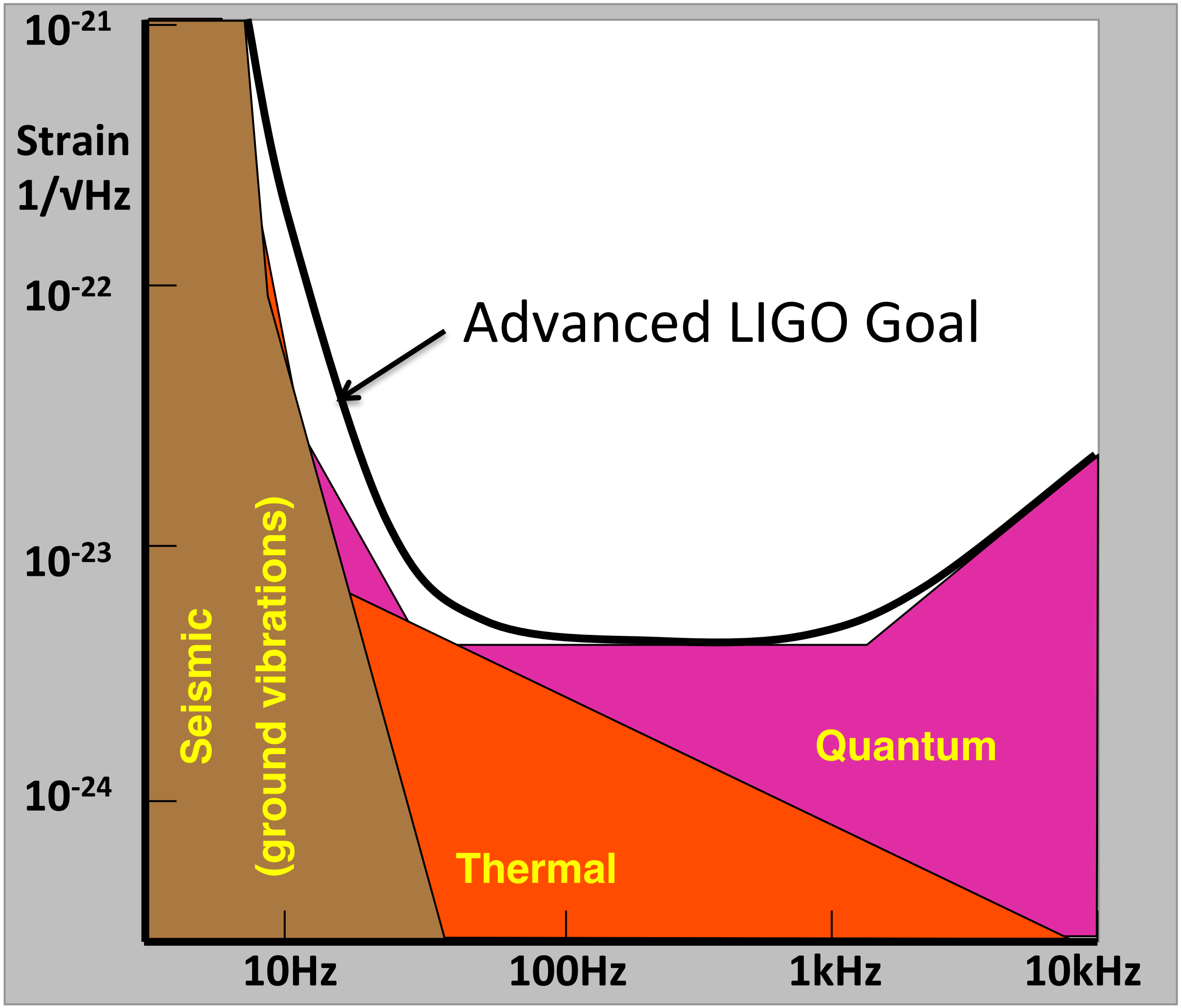


Credit Kai Staats

**Livingston corner station**

Image courtesy LIGO Lab

# Dominant Noise Contributions




Reference LIGO-G1600953

# Minimizing mirror thermal noise

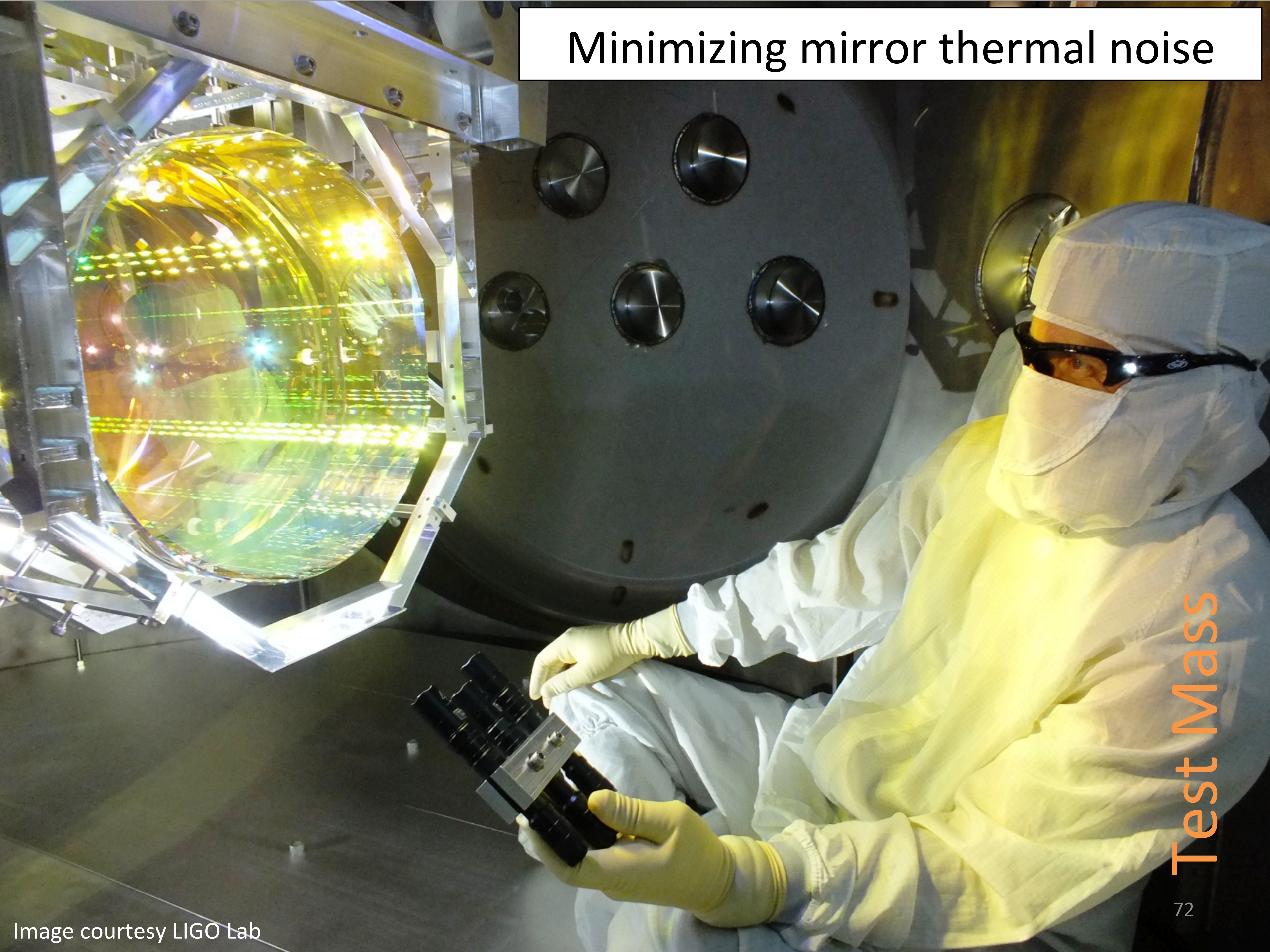
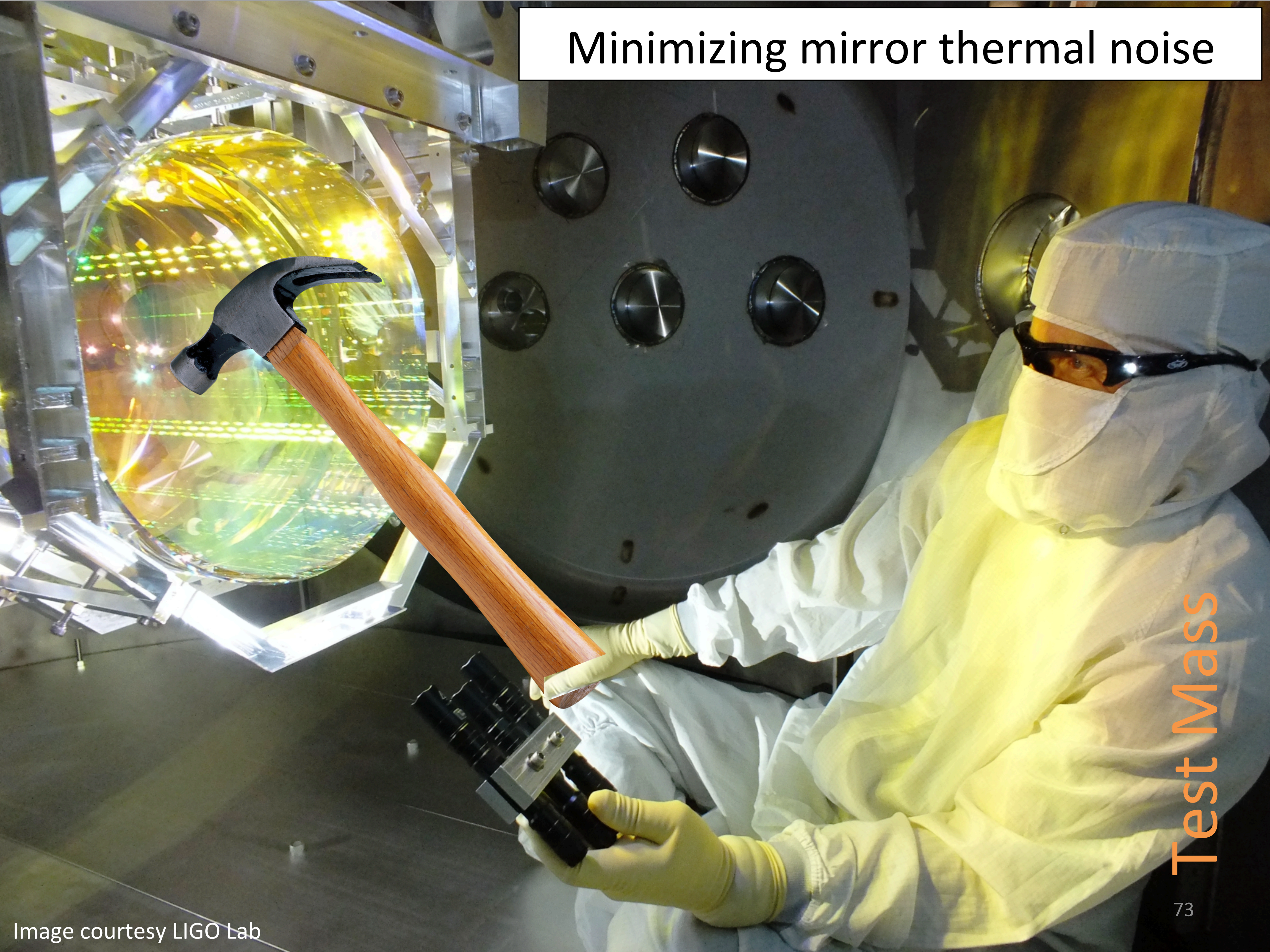



Image courtesy LIGO Lab

# Minimizing mirror thermal noise

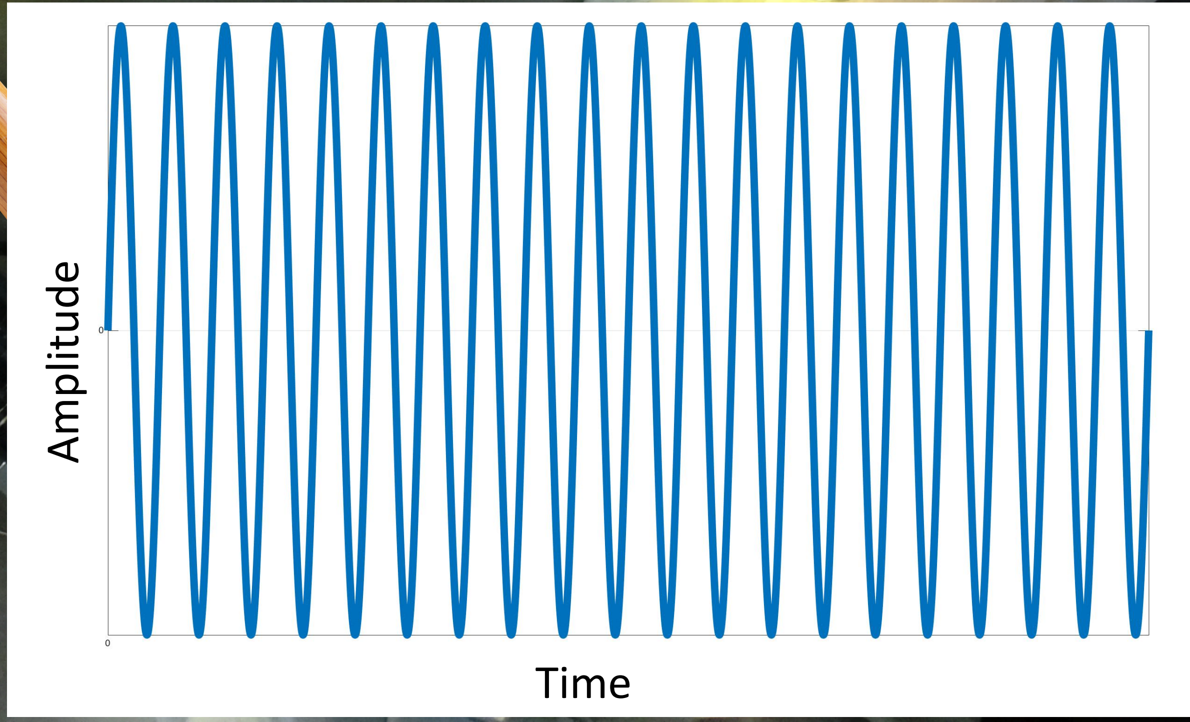


Test Mass

Image courtesy LIGO Lab

# Minimizing mirror thermal noise

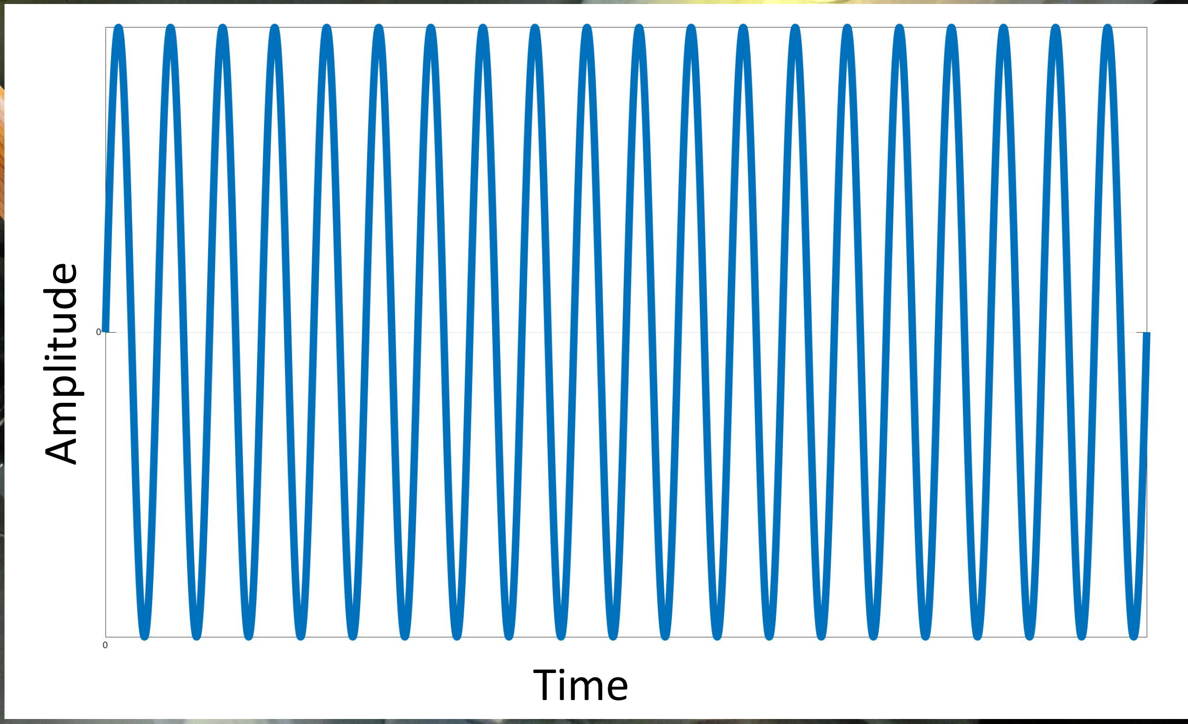
Image courtesy LIGO Lab



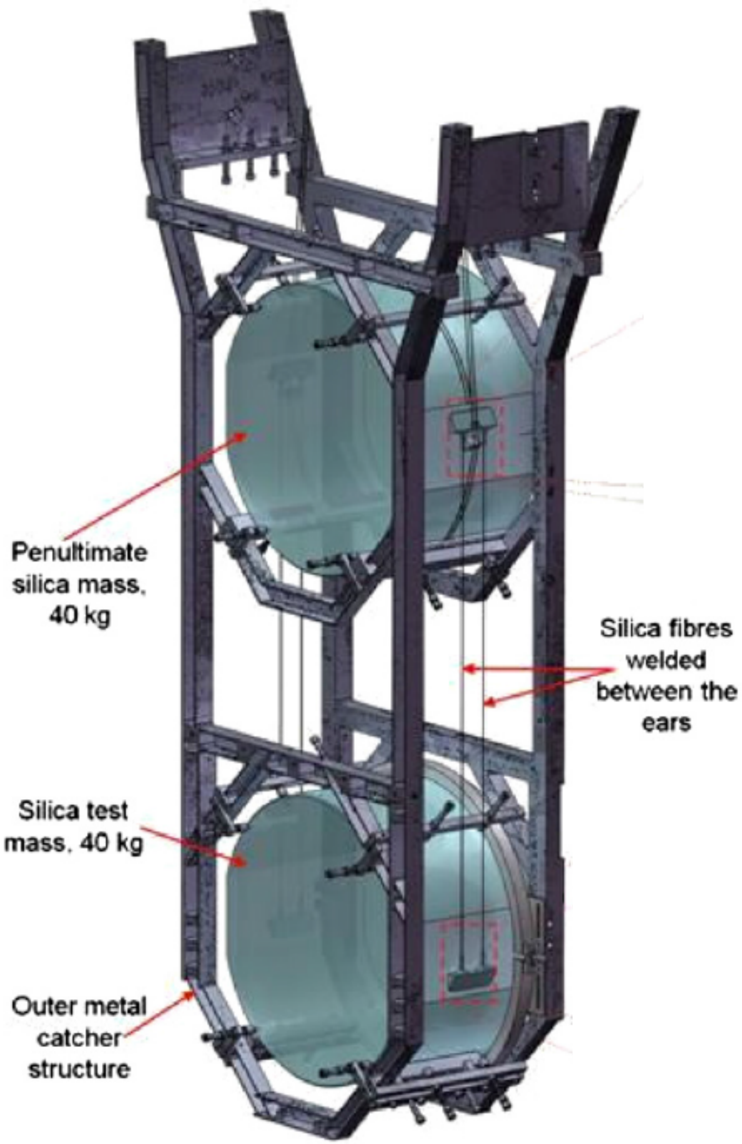
# Minimizing mirror thermal noise

- The mirror has a finite amount of thermal energy, which becomes ‘thermal noise’
- This energy is concentrated at the resonant frequencies
- The smaller the damping, the less energy there is outside these frequencies

Image courtesy LIGO Lab

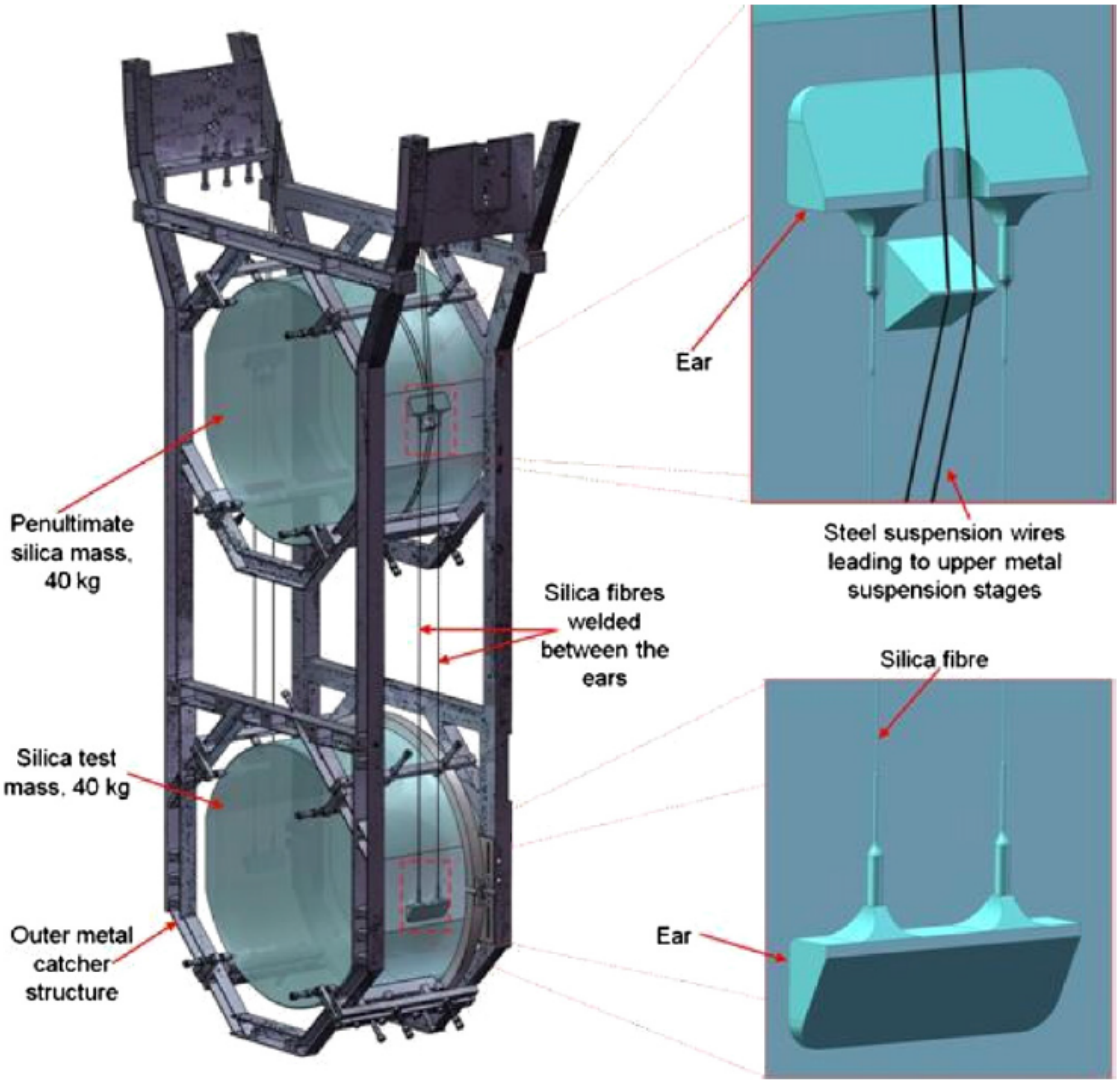


# Mirror hangs from glass fibers to mitigate thermal noise



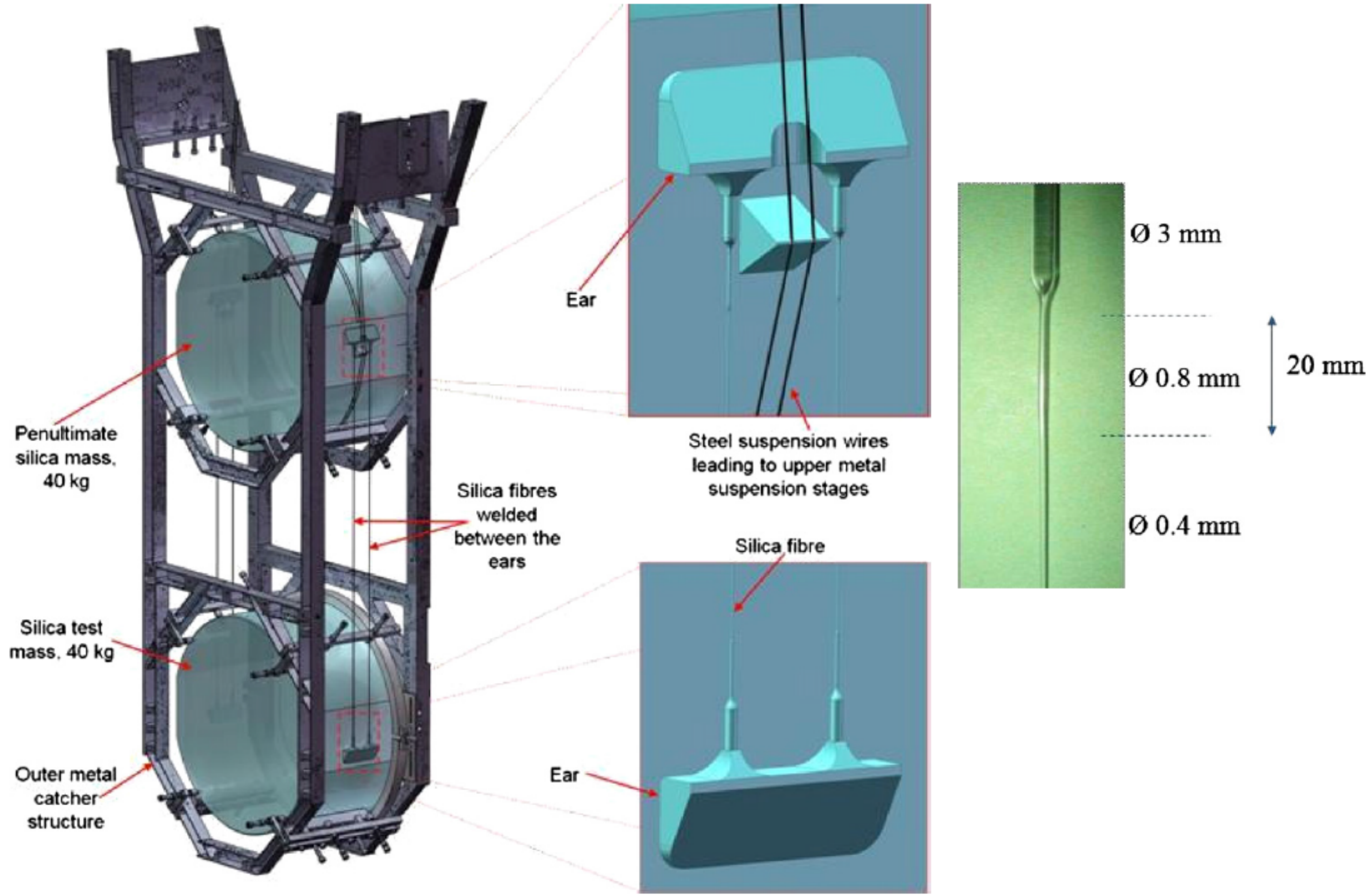

Class. Quantum Grav. 29 (2012) 235004

# Mirror hangs from glass fibers to mitigate thermal noise



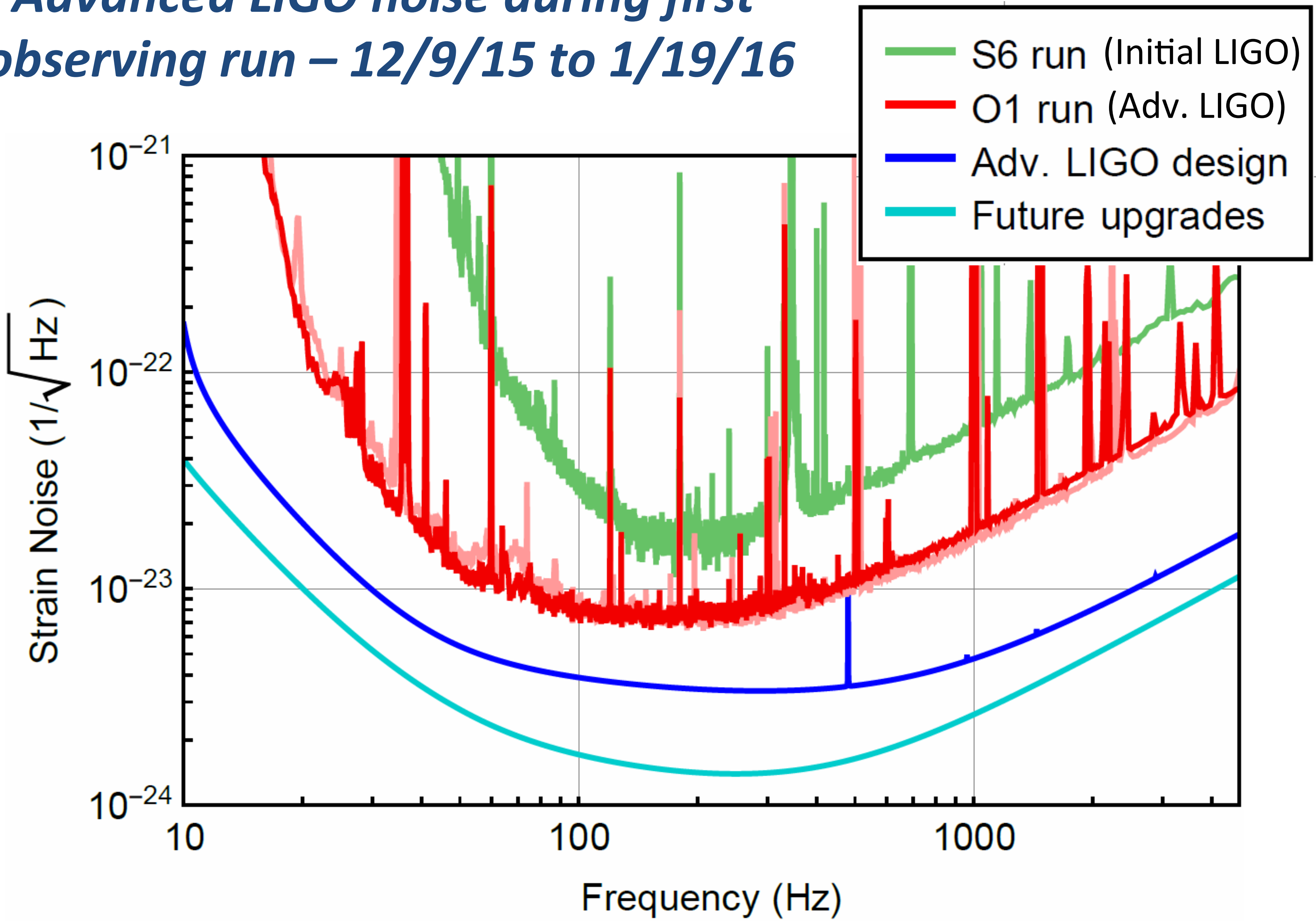

Class. Quantum Grav. 29 (2012) 235004

# Mirror hangs from glass fibers to mitigate thermal noise

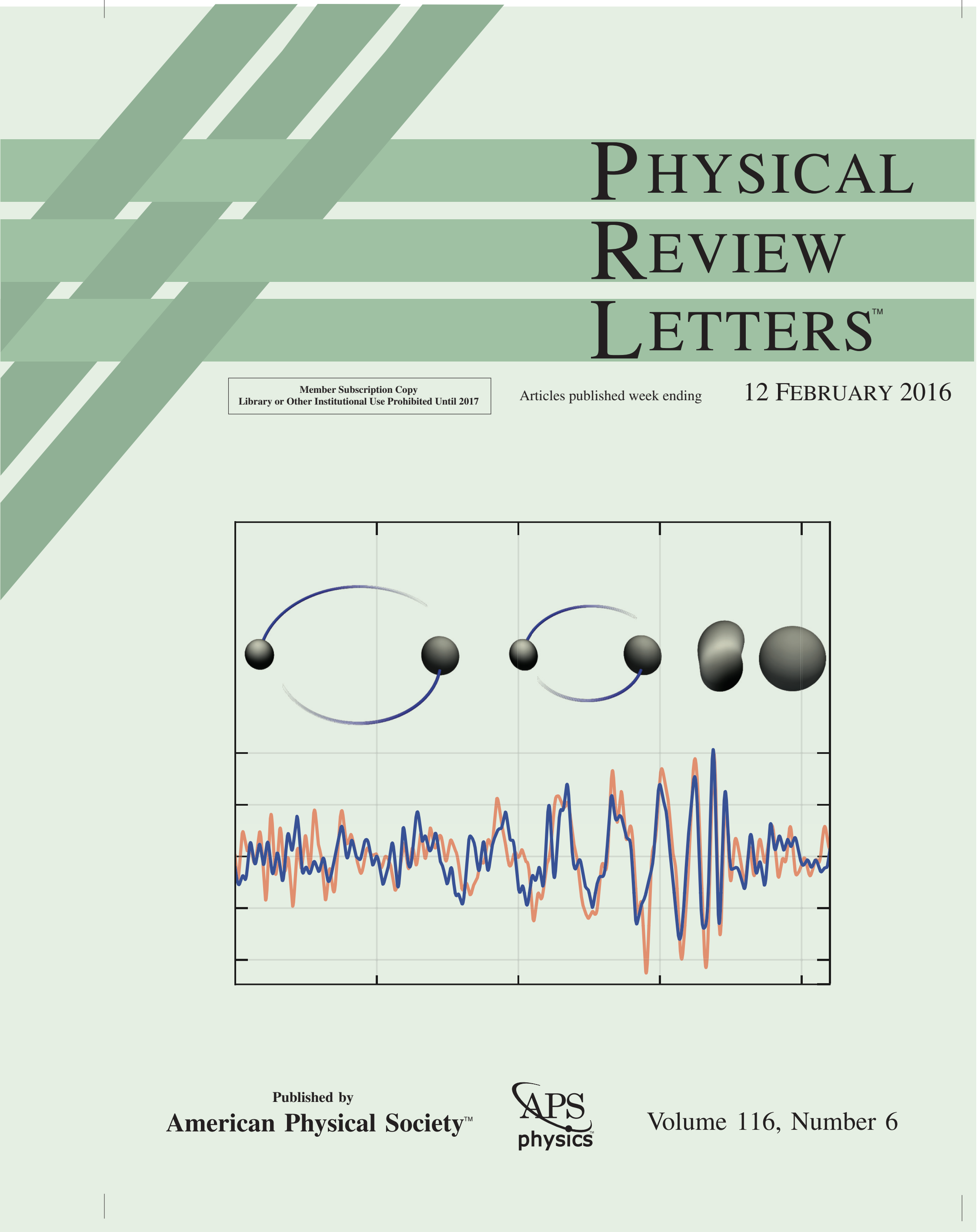



Class. Quantum Grav. 29 (2012) 235004

# *Advanced LIGO noise during first observing run – 12/9/15 to 1/19/16*




Reference LIGO-G1600745



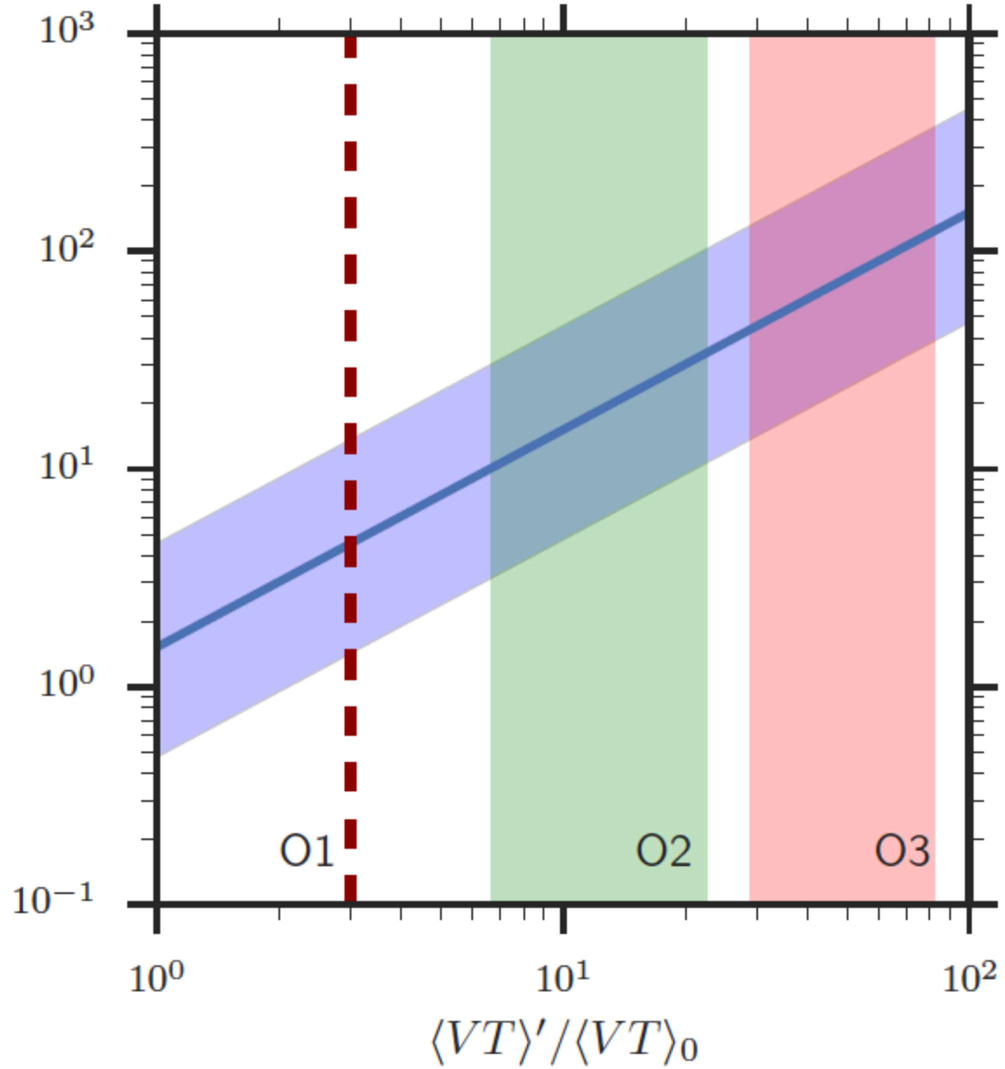

# Questions?

For papers associated with the detection go to **https://papers.ligo.org**

Acknowledgement:
LIGO is supported by the NSF

National Science Foundation
WHERE DISCOVERIES BEGIN

# More astronomy is coming!

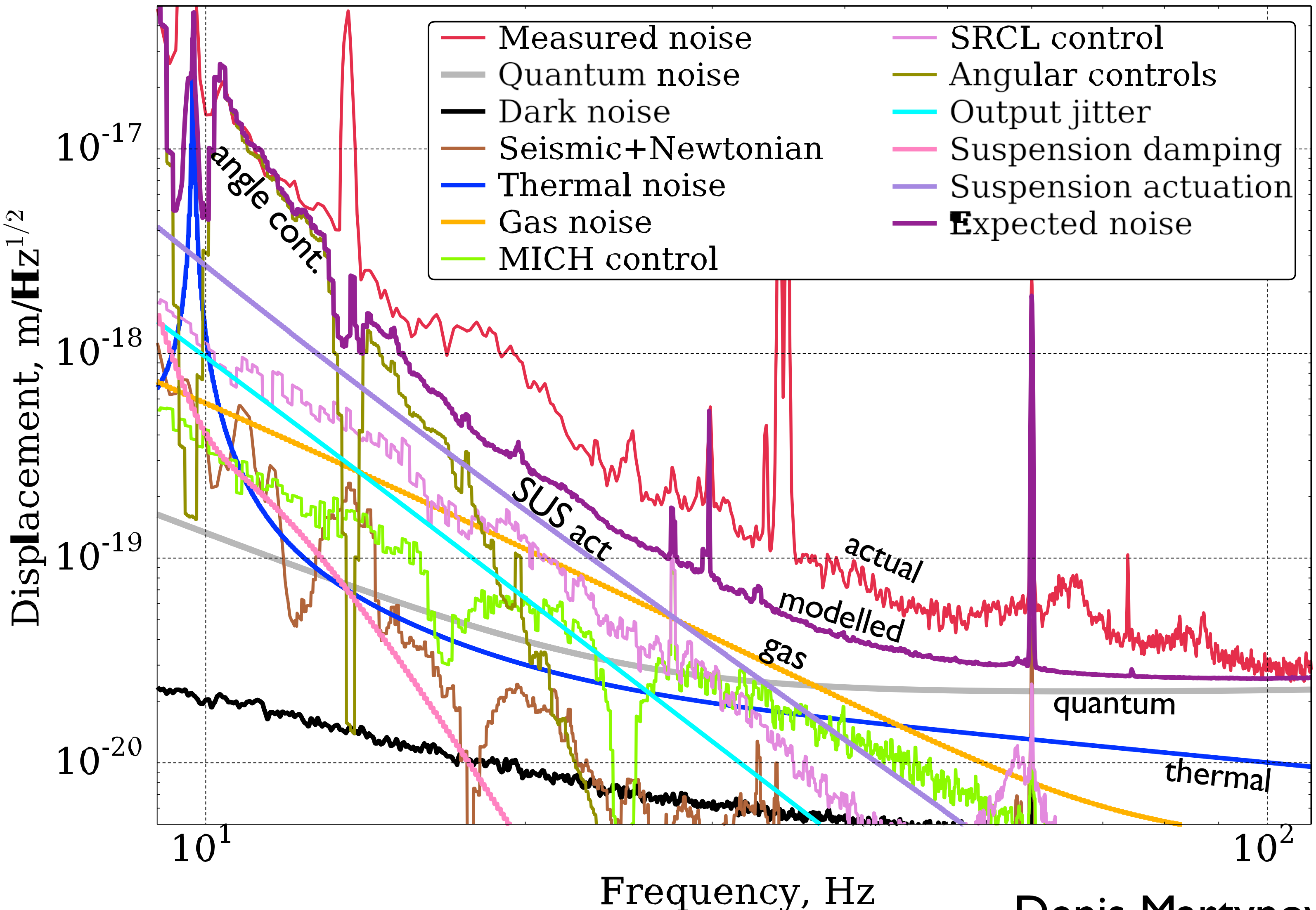



Estimated Number of observed binary black hole mergers

Observable volume of space * observation time

https://dcc.ligo.org/public/0122/P1500217/014/LIGO-P1500217_GW150914_Rates.pdf

# Noise at 10-100 Hz

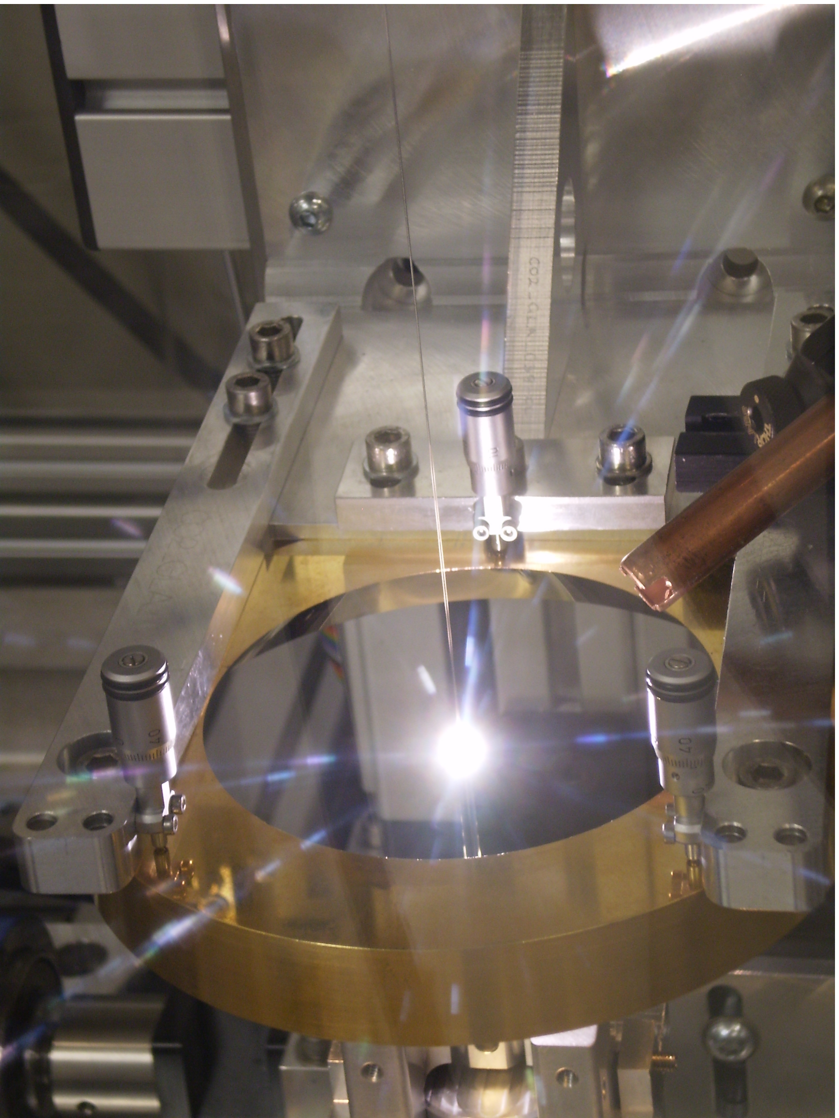


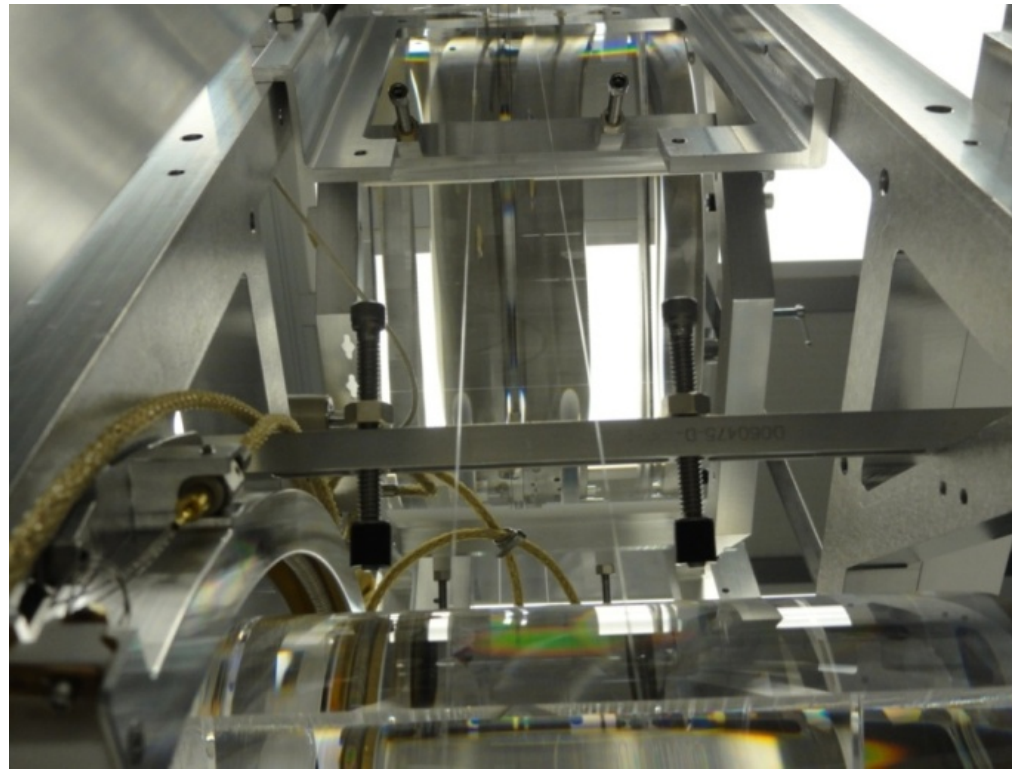

Denis Martynov, et. al.

LIGO Livingston Observatory

ref G1600349

# Test mass fibers for low thermal noise

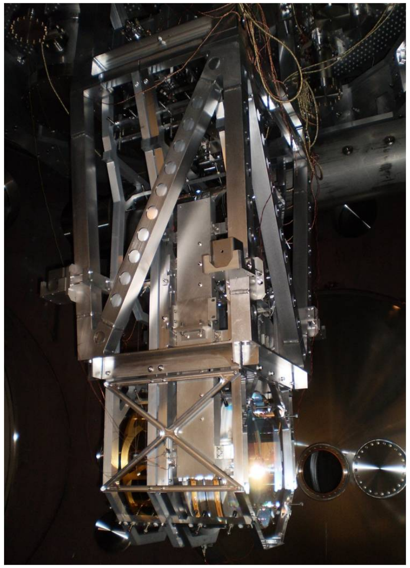


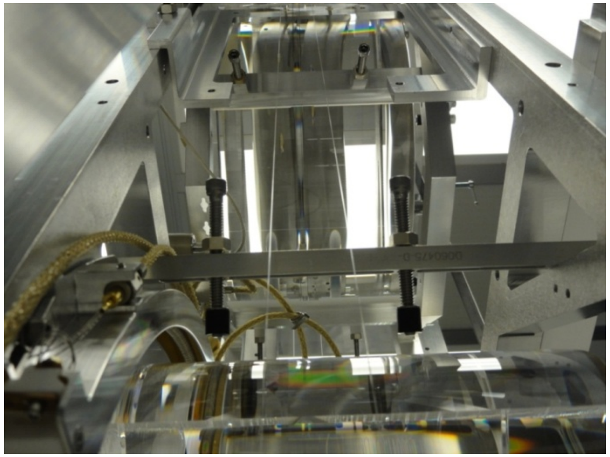


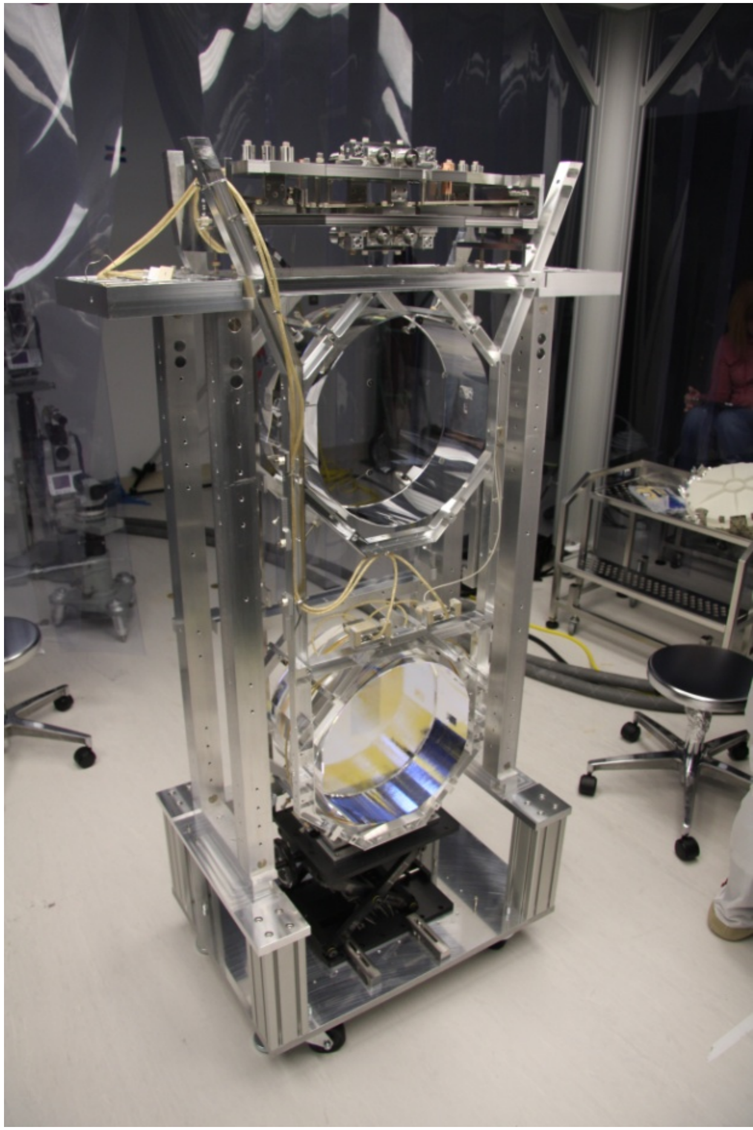
Left – a fused silica glass fiber being heated with an infrared laser and pulled

Top – 2 visible fibers welded between the test mass and the stage above

# aLIGO Suspensions

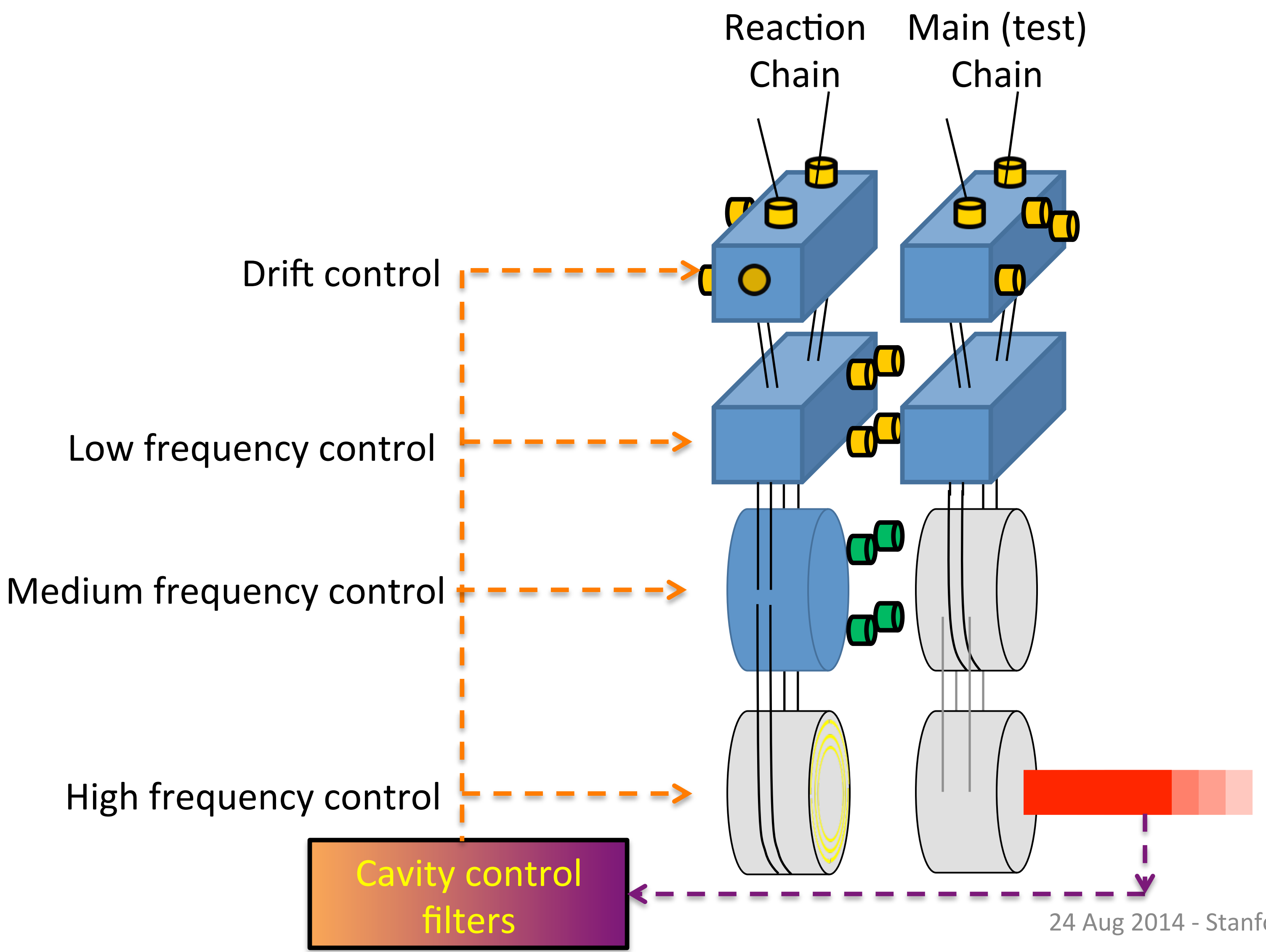






Ref G1401227 – courtesy Giles Hammond

# Suspension cavity control

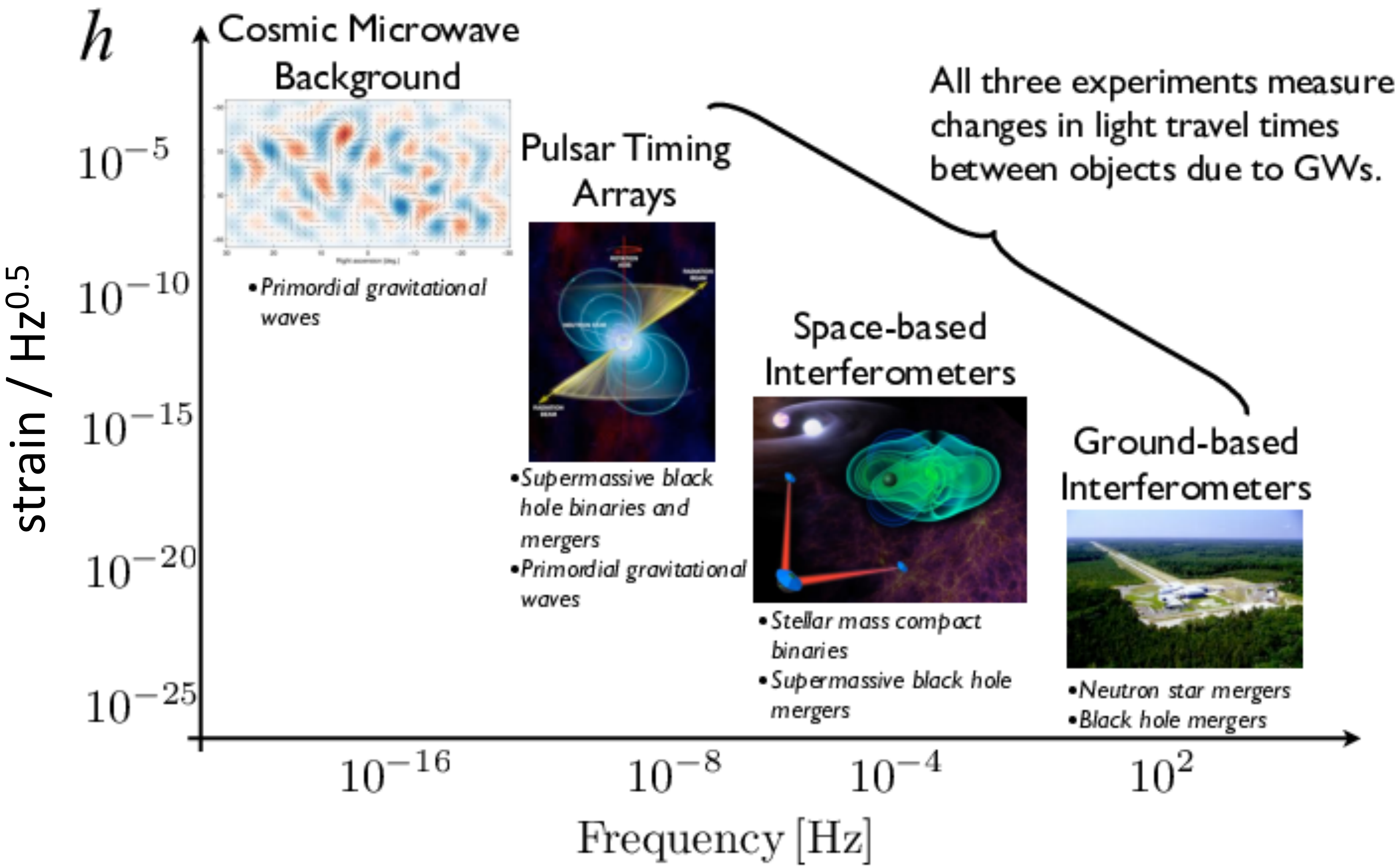


# Hardware Upgrades

| Component | Initial LIGO | Advanced LIGO |
|---|---|---|
| Laser | 10 W | 200 W |
| Test masses | 11 kg, 25 cm diameter | 40 kg, 34 cm diameter |
| Test mass suspensions | Steel wire slings, single stage | Fused silica fibers, four stages |
| GW Readout Method | RF heterodyne | DC homodyne |
| Seismic isolation | Cutoff frequency 40 Hz | Active servos reduce seismic cutoff frequency to 10 Hz |
| Optimal Strain Sensitivity | $3 \times 10^{-23}$ / rHz | Tunable, better than $5 \times 10^{-24}$ / rHz in broadband |

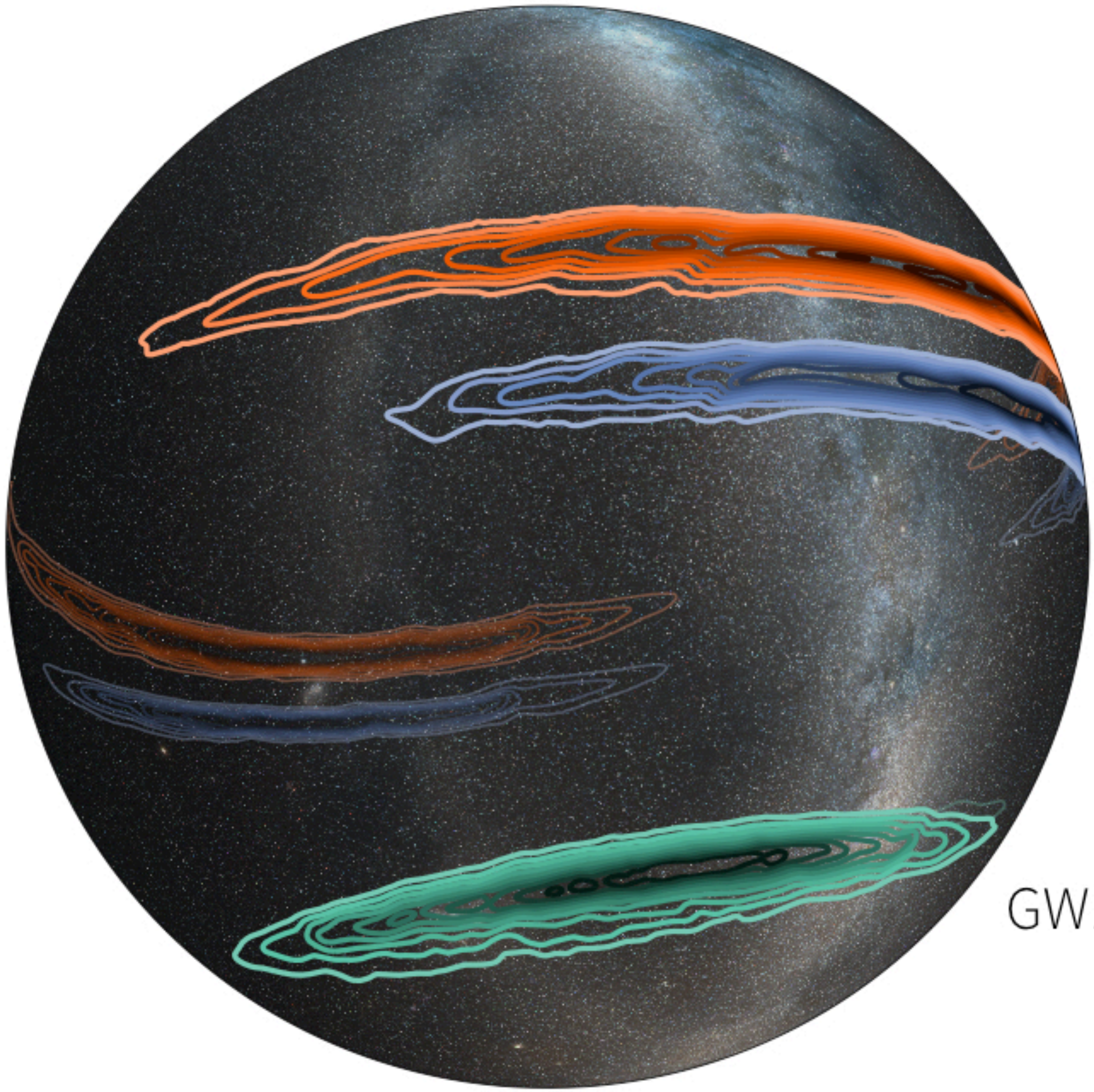
Reference LIGO-G1600340

# The spectrum of gravitational wave astronomy



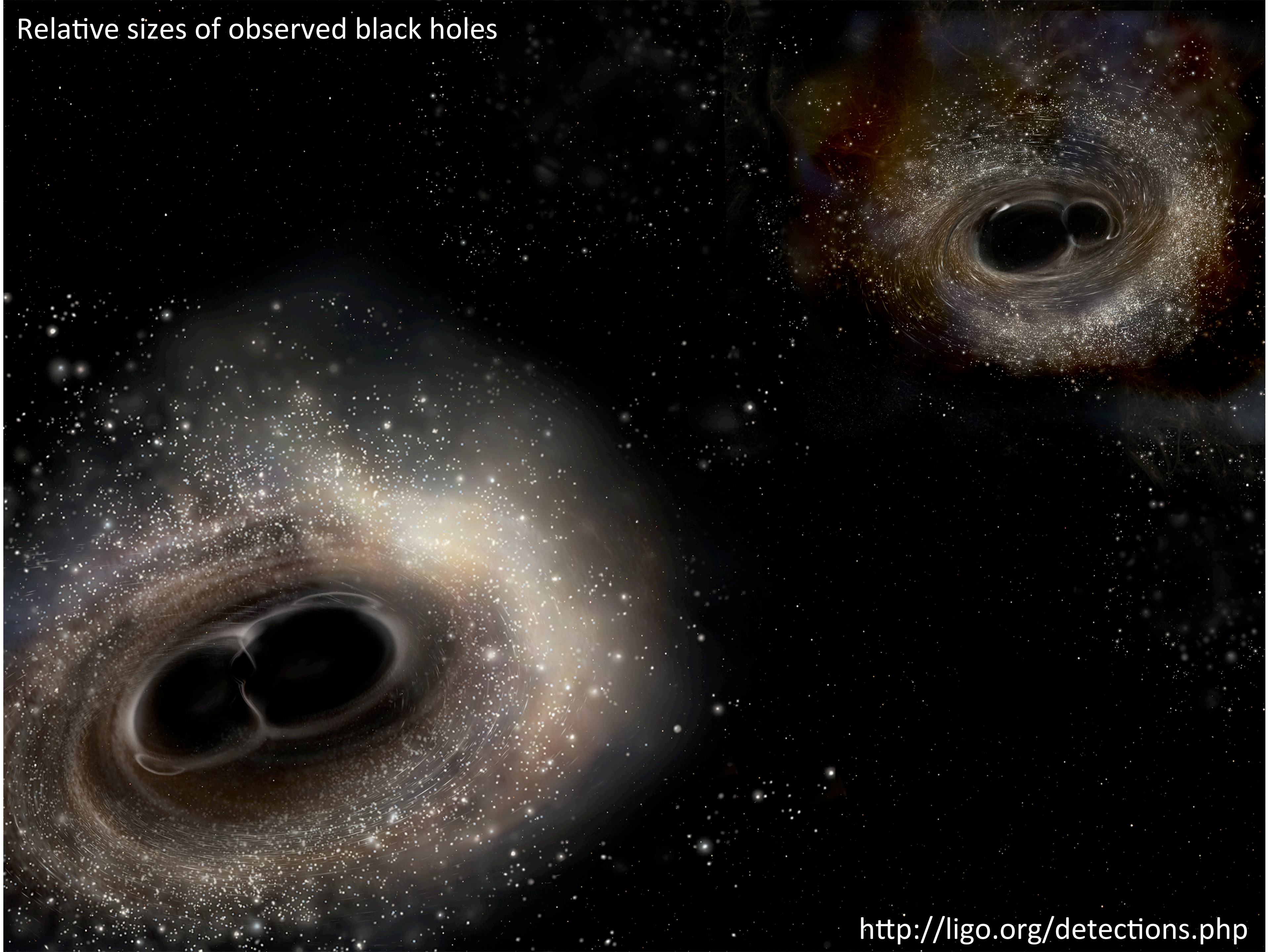

http://nanograv.org/press/

Detection sky localizations



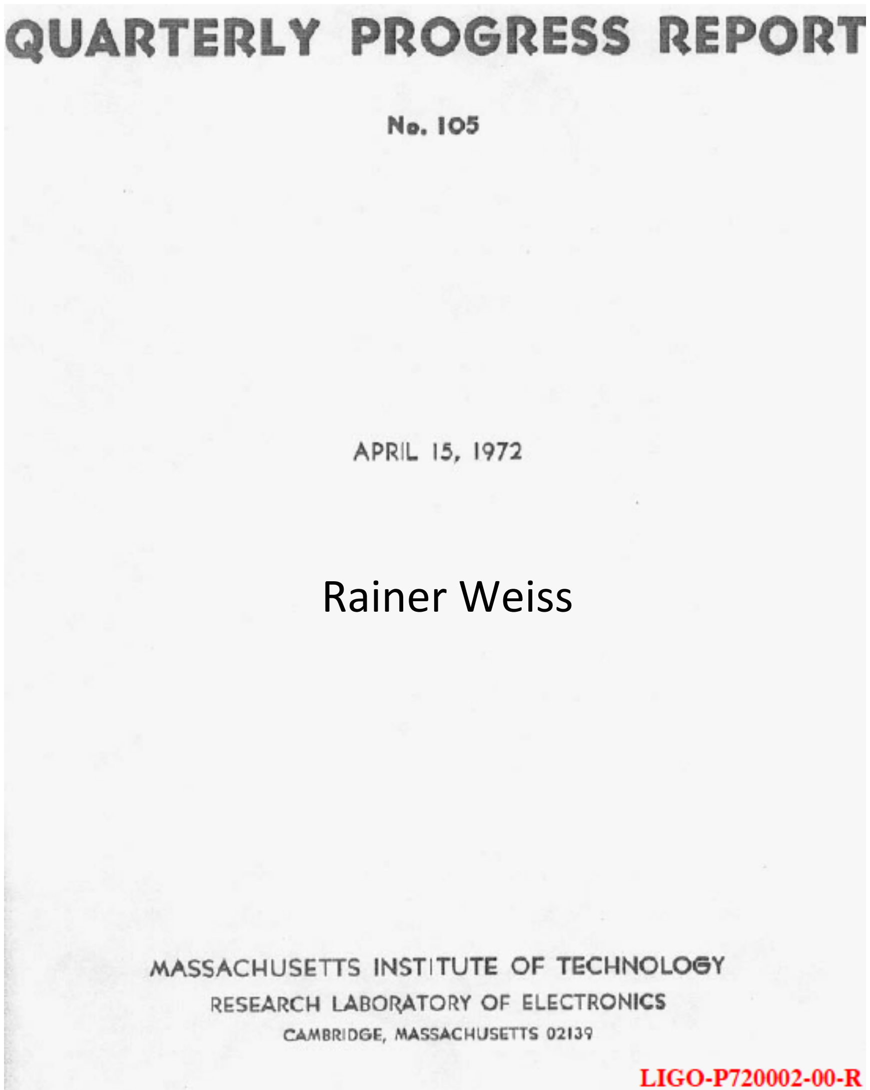

http://ligo.org/detections.php

Relative sizes of observed black holes



http://ligo.org/detections.php

# LIGO's Origins


QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

LIGO-P720002-00-R

Rainer Weiss

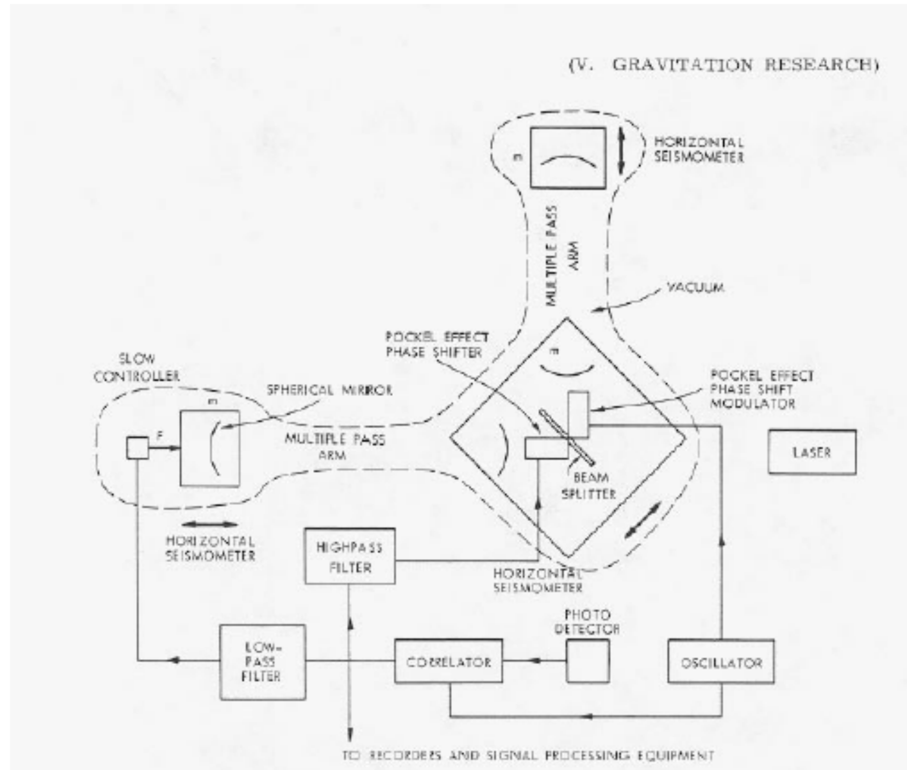


Fig. V-20. Proposed antenna.

Professor Weiss's original sketch of an interferometric GW detected

# From Laurie Kerrigan Cosmology Workshop Coordinator

- There will be about 40 high school students & 11 high school Physics teachers. All the students have had chemistry & many have had physics. They have all had 3 years of college prep math & some are now taking Calculus.

- Usually the talks are for 1-1 ½ hours. The first part is introducing your story, your education, how you got to your position, what you do now, and the basic concepts upon which your research depends. Then we have a brief question period. The last part of the talk goes in depth on your topic & research with a question period at the end. We are hoping not only the students learn the Physics, but also appreciate all the various interests & career paths.

- You can split the parts as you feel fits best. Also, feel free to split it into 3 parts if that works better.

Bring speakers for audio, Laurie says they don't have audio accept through the microphone.
From email on 31 May 2016.

# From Alex Kim, May 24

- The most important things are the actual event, a bit about how from the event we can infer that it was a BH-BH merger, and then the technological amazingness of LIGO.

- Laurie said on May 31 the presentation is on Auditorium 50.
- Alex Kim said he sent a parking permit on 2 June 2016. There is another email with a link to follow.

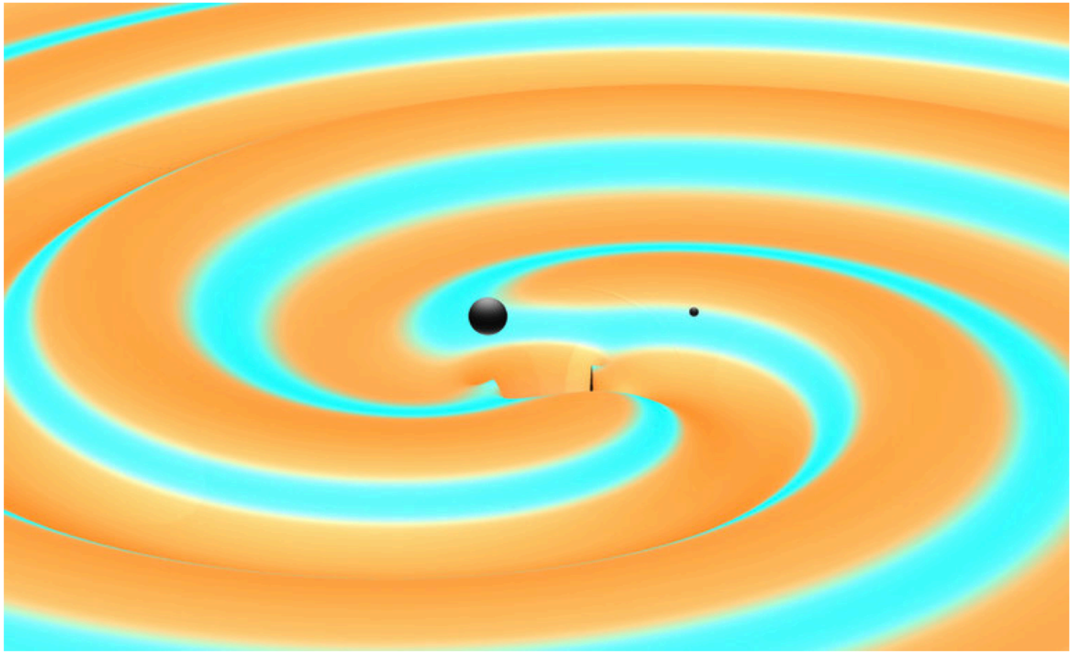
- Who came up with a big ifo
  - Rai's paper
- How you tackle all the major noise sources
  - Got seismic and shot noise, add thermal
- Backup: Where's this going in the future

# Notes

- Say how this is a new kind of astronomy

# *Scientists Hear a Second Chirp From Colliding Black Holes*

By **DENNIS OVERBYE** JUNE 15, 2016



New York Times