Listening to the Songs of the Universe

How Vibration Control for LIGO Allows us to Measure Ripples in the Fabric of Space.

Brian Lantz, May 2019
for the LSC, Virgo, &
~2500 astronomers!

A few questions…

What is LIGO?

Laser Interferometer Gravitational-wave Observatory,
a new kind of astronomy!

Why is there a LIGO guy at an ASA meeting?

We also care a lot about vibrations

Are there 2 LIGO talks?

I'm going to tell you why we care about vibrations,
and Arnaud is going to tell you what we do about them

National Science Foundation + International partners

LIGO

LIGO Scientific Collaboration

LSC

Caltech

Andrews University

Washington State University

California State University Fullerton

PennState

Southern University and Agricultural & Mechanical College

Massachusetts Institute of Technology

Leland Stanford Junior University

American University

The University Of Sheffield.

University of Maryland

indigo

Texas Tech University

West Virginia University

Hillsdale College

Montclair State University

Tsinghua University

Université de Montréal

Universitat de les Illes Balears

International Institute of Physics

Cal State LA

Bellevue College

Montana State University

University of Cambridge

Monash University

NCSA

Polytechnique Montréal

The University of Adelaide

Australia

University of Wisconsin Milwaukee

University of Southampton

Bothell

Michigan

ACU

University of the West of Scotland

UWS

University of Glasgow

Australian National University

Trinity University

Syracuse University

University of Strathclyde

Columbia University in the City of New York

OzGrav

Cardiff University

Prifysgol Caerdydd

The University of Western Australia

R·I·T

Lomonosov Moscow State University

Sonoma State University

NASA

The University of Chicago

University of Minnesota

Carleton College

RRCAT

Cornell University

University of Washington

Università degli Studi del Sannio

LSU

Louisiana State University

Colorado State University

Charles Sturt University

Marshall Space Flight Center

cmi Chennai Mathematical Institute

ICTS International Centre for Theoretical Sciences

Tata Institute of Fundamental Research

東京大学 The University of Tokyo

ACIGA

University of Birmingham

Georgia Institute of Technology

Korean Gravitational Wave Group

The University of Melbourne

Embry-Riddle Aeronautical University

Universitas Szegediensis

Universitas Villanovana

Whitman College

Northwestern

UF University of Florida

Universität Hamburg

Der Forschung | Der Lehre | Der Bildung

tifr

IUCAA

UTRGV

University and Institute of Advanced Research

The Puri Foundation for Education in India

Swinburne University of Technology

The University of Mississippi

INPE

University of Southern California

Indian Institute of Technology Madras

GEO 600

Max Planck Institute for Gravitational Physics Albert Einstein Institute

Leibniz Universität Hannover

University of Zurich

IISER Thiruvananthapuram

CITA | ICAT

King's College London

IISER Kolkata

NASA Goddard Space Flight Center

International Network

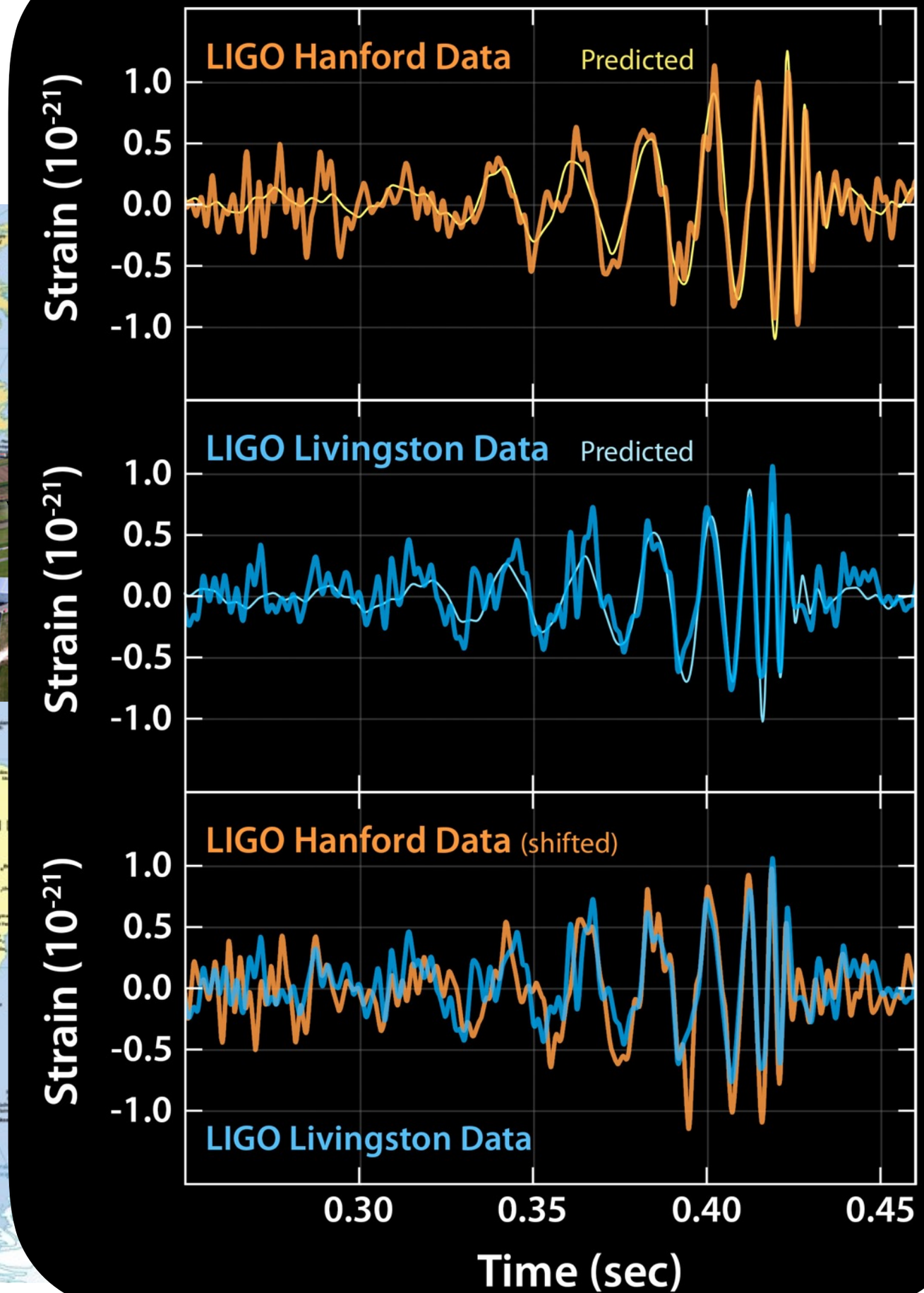
LIGO India

project approved

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

LIGO Hanford

LIGO Livingston



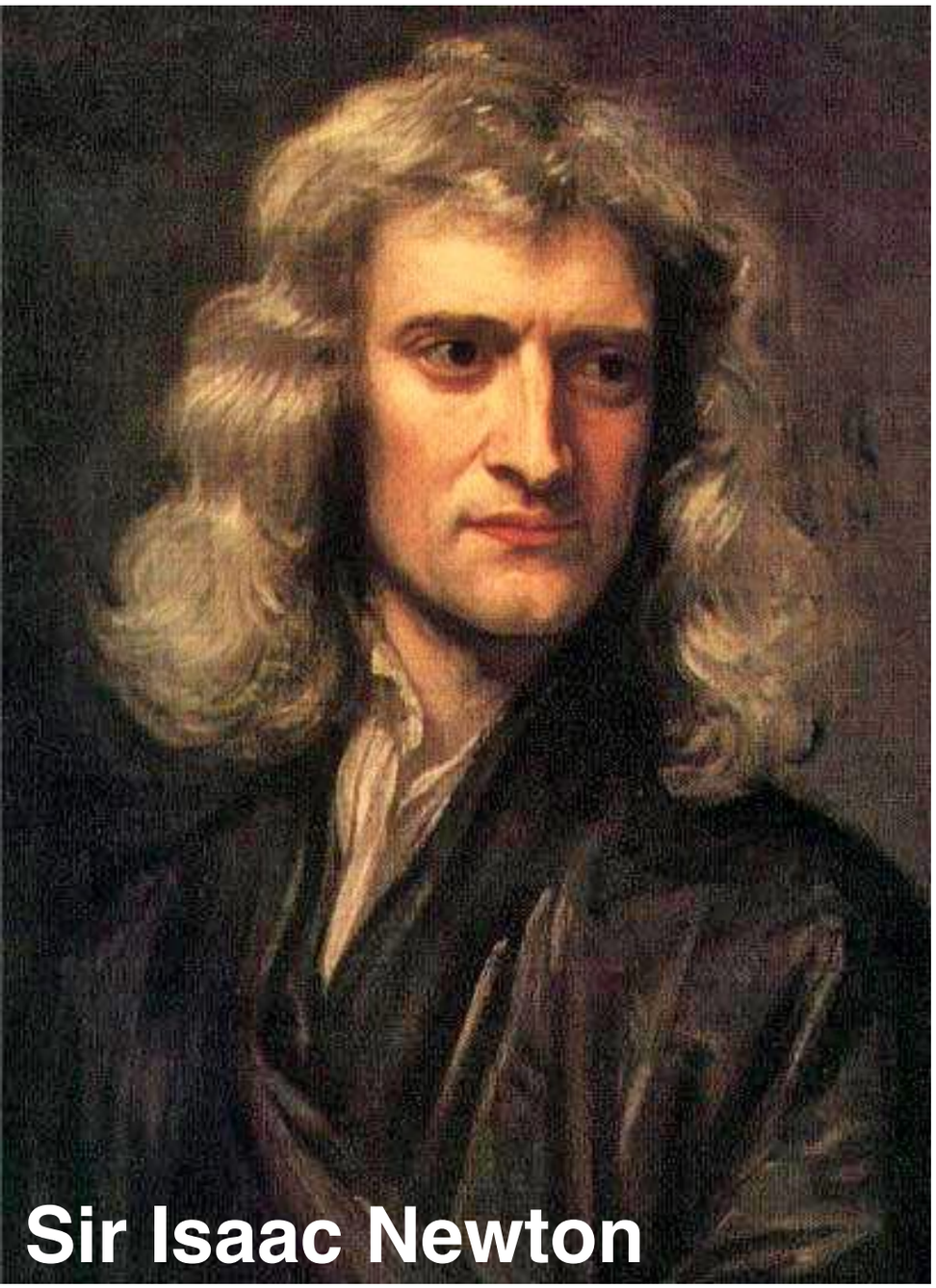
AGRA

GO India

oject approved

.org/maps/political_world_map3000.jpg

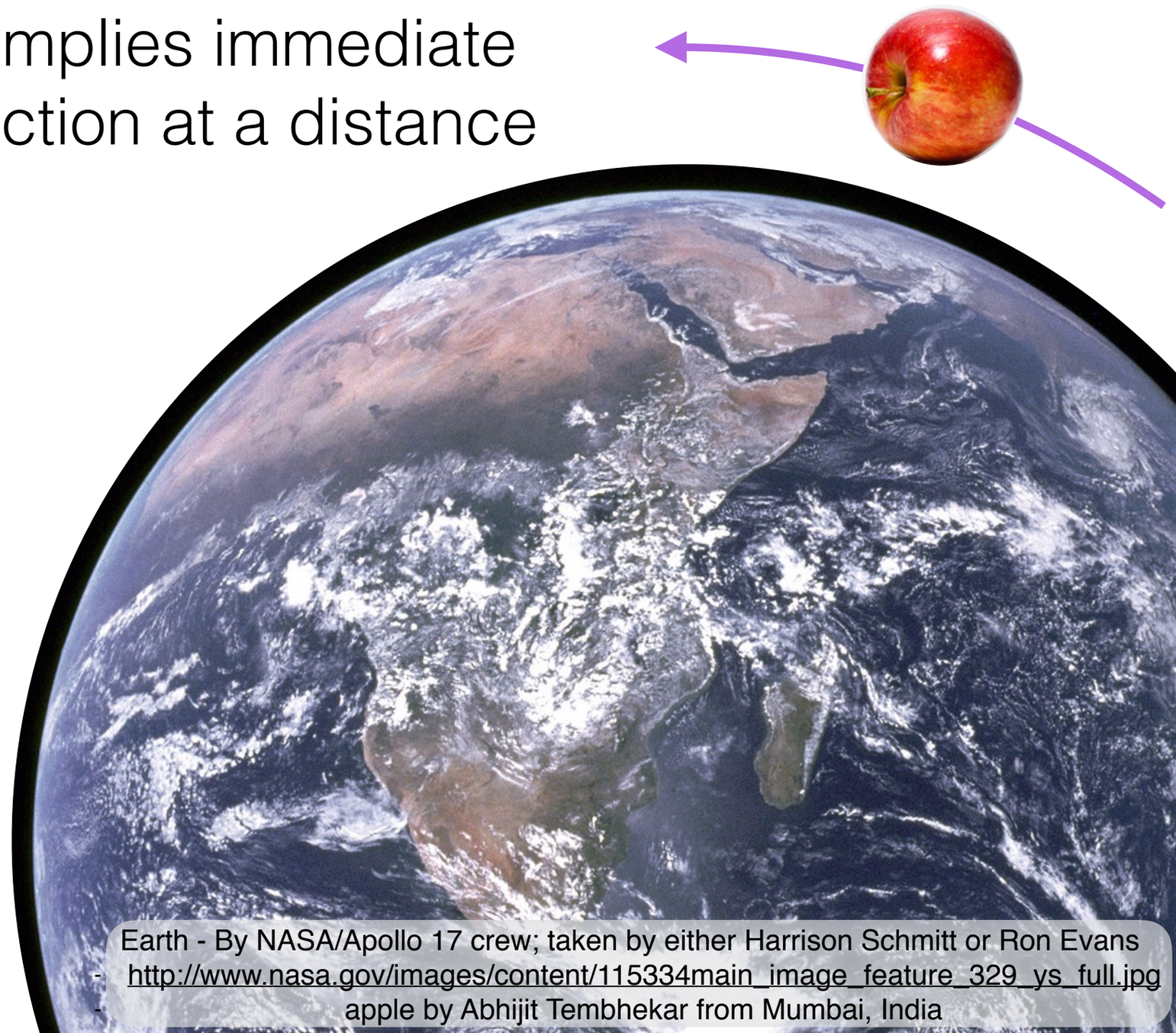
What is a Gravitational Wave?



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

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

Implies immediate action at a distance



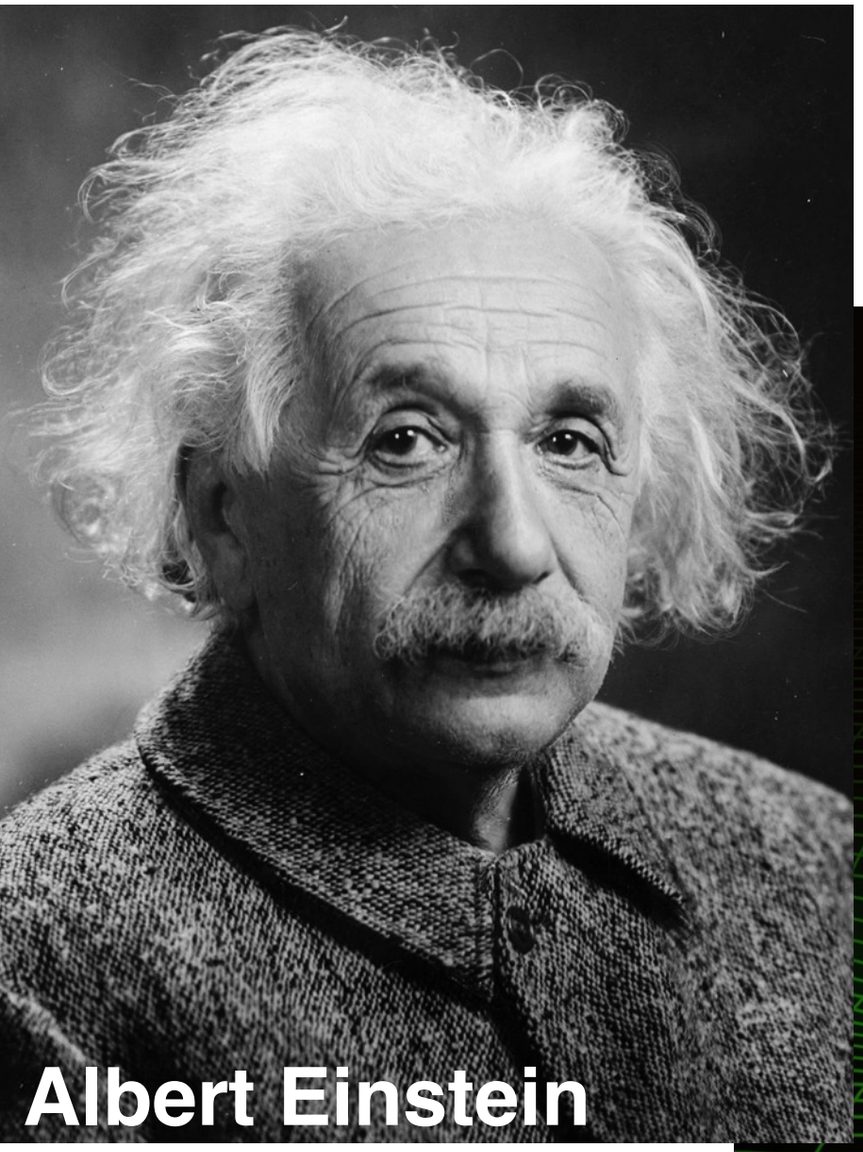
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans - http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

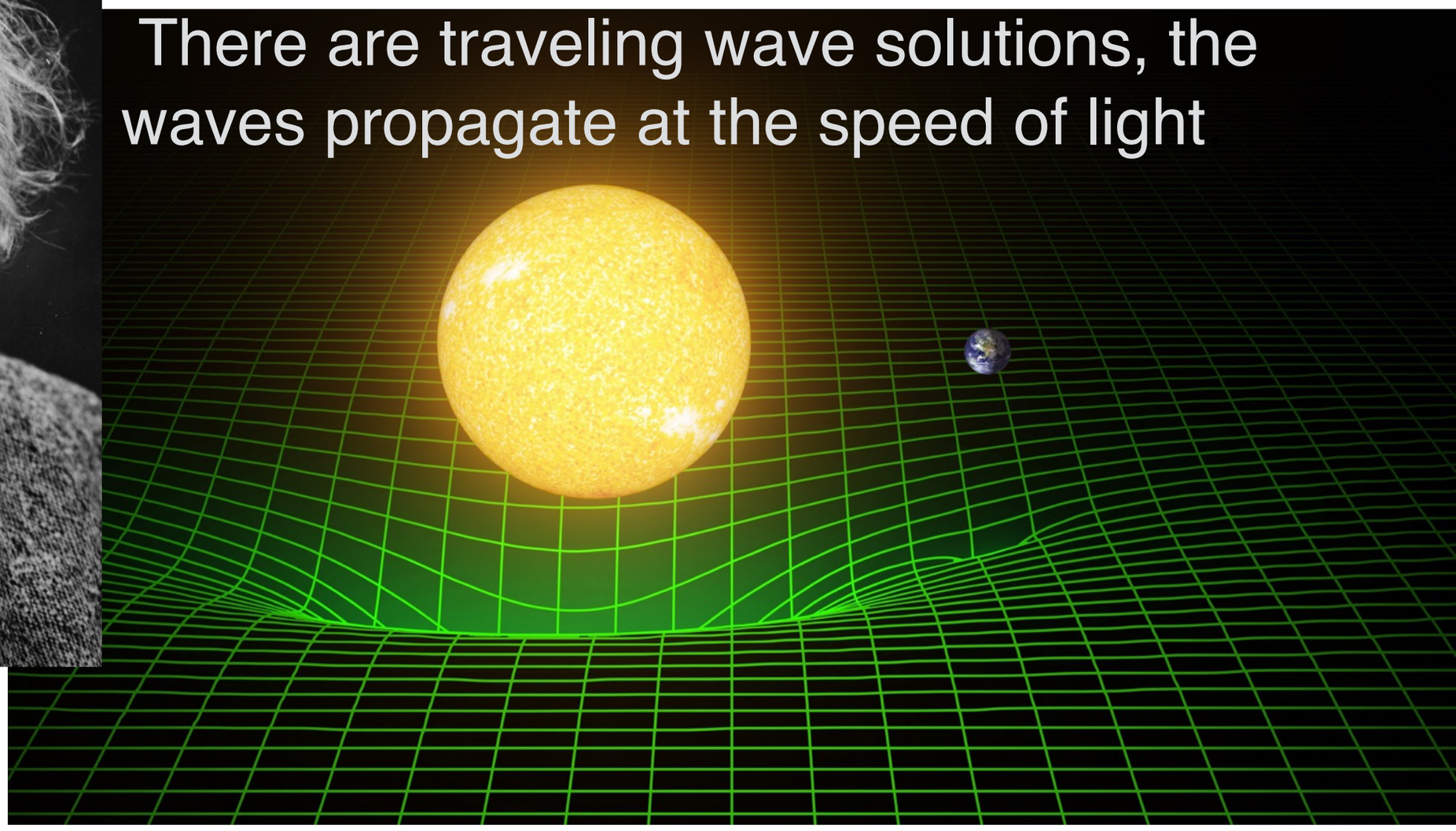
"Spacetime tells matter how to move,
matter tells spacetime how to curve"

- J. A. Wheeler



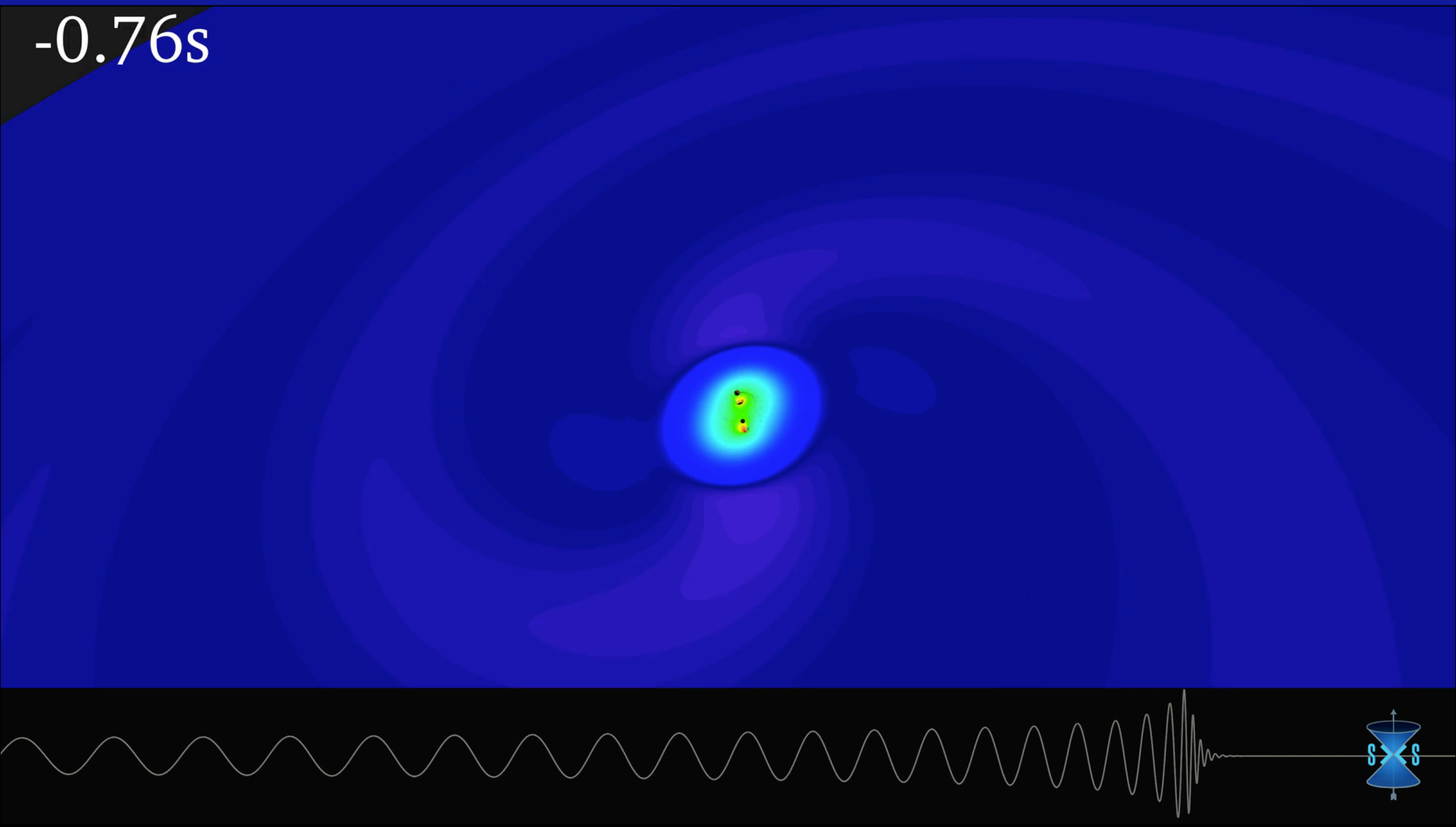
Albert Einstein

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



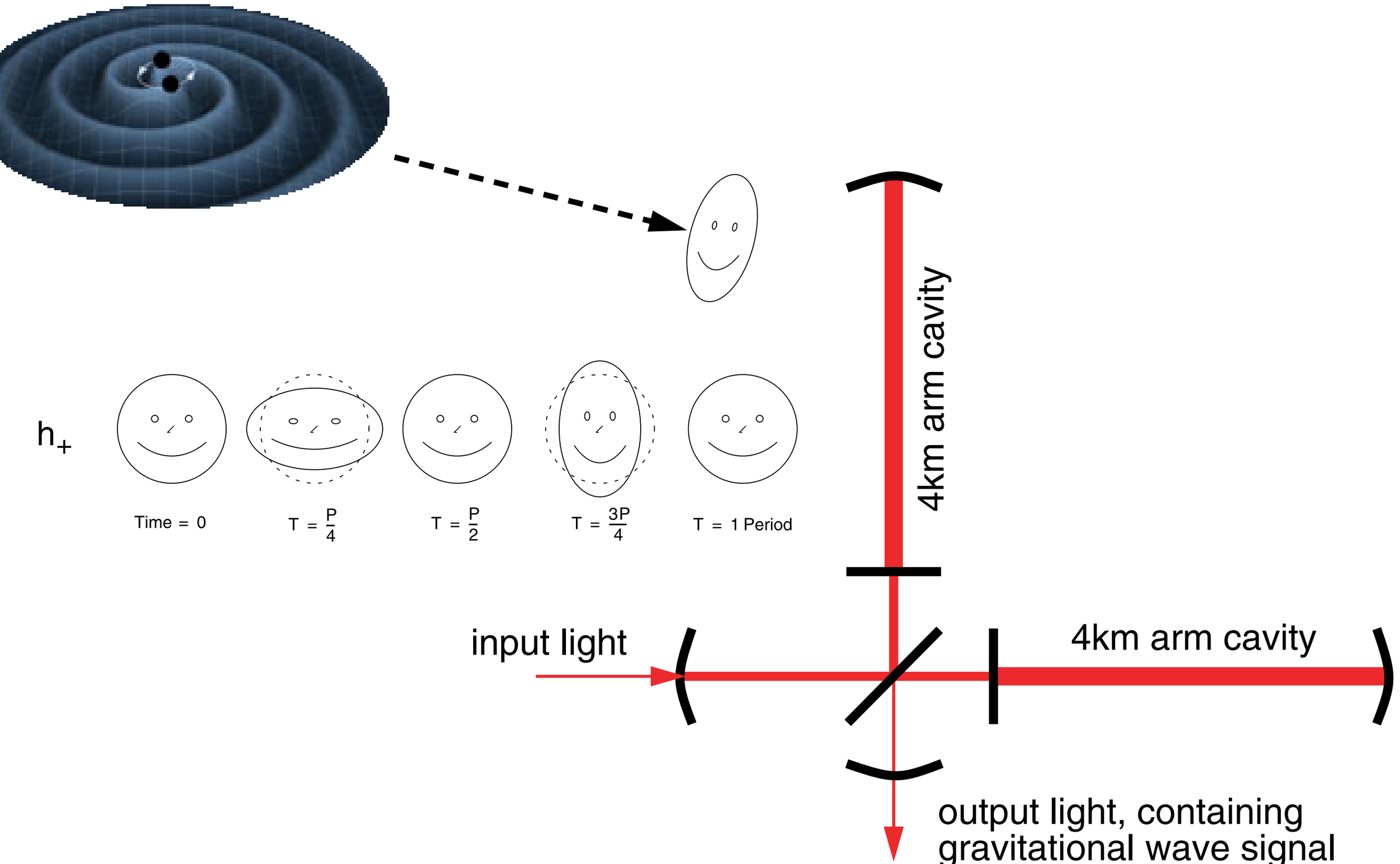
Photograph by Orren Jack Turner,
Library of Congress digital ID cph.3b46036.

Simulation of the event

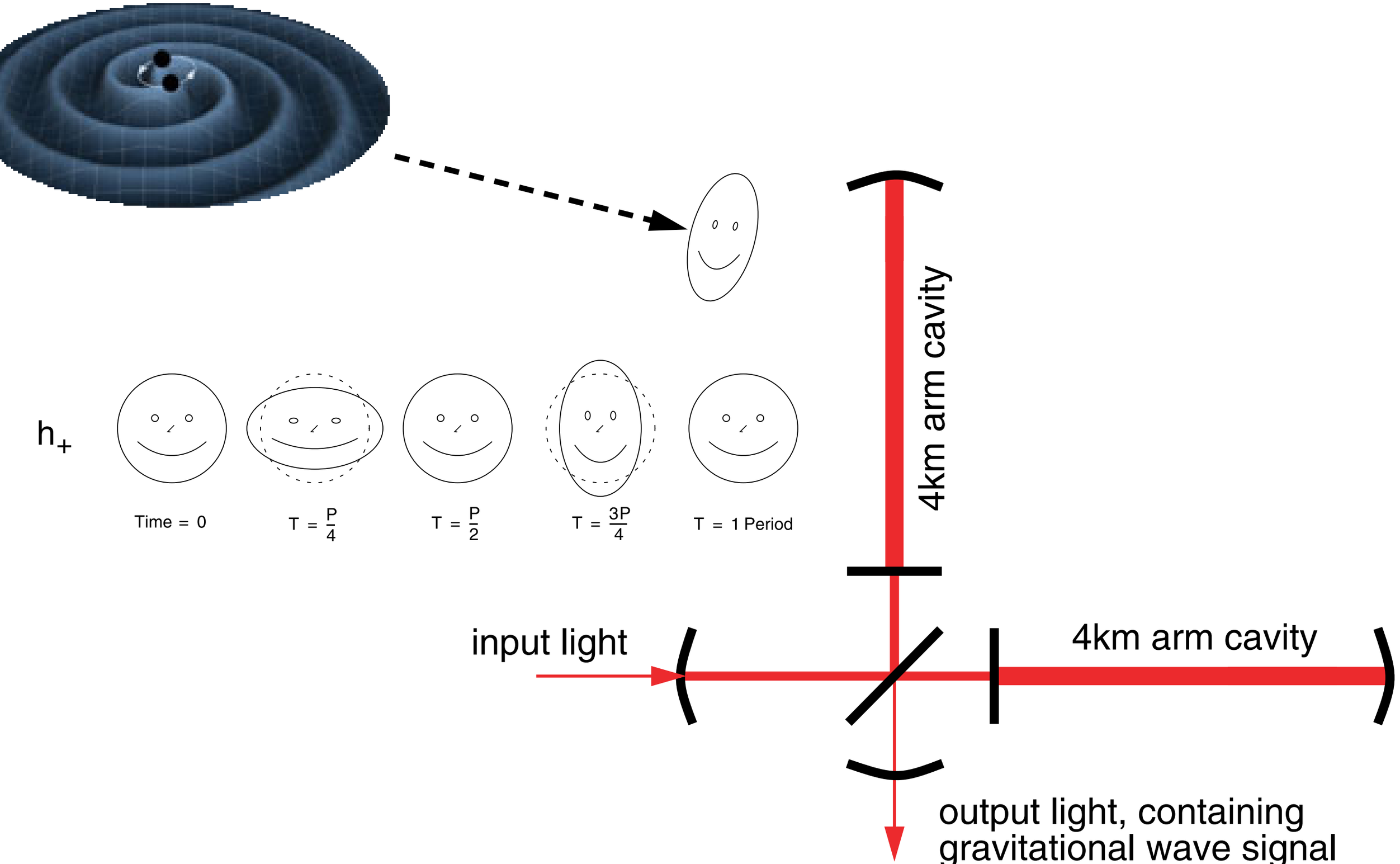


http://mediaassets.caltech.edu/gwave

The LIGO concept



The LIGO concept

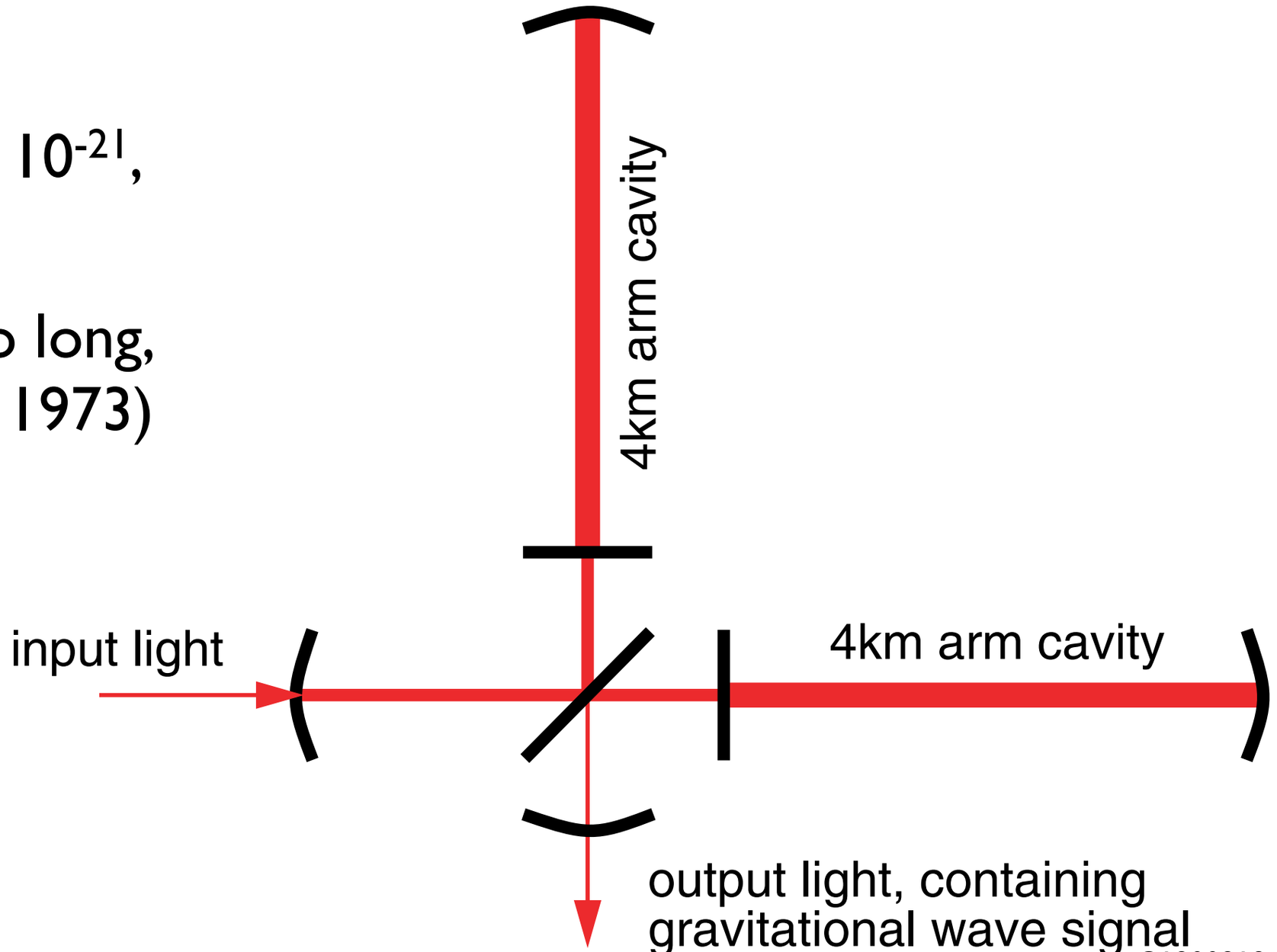


The LIGO concept

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

Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

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



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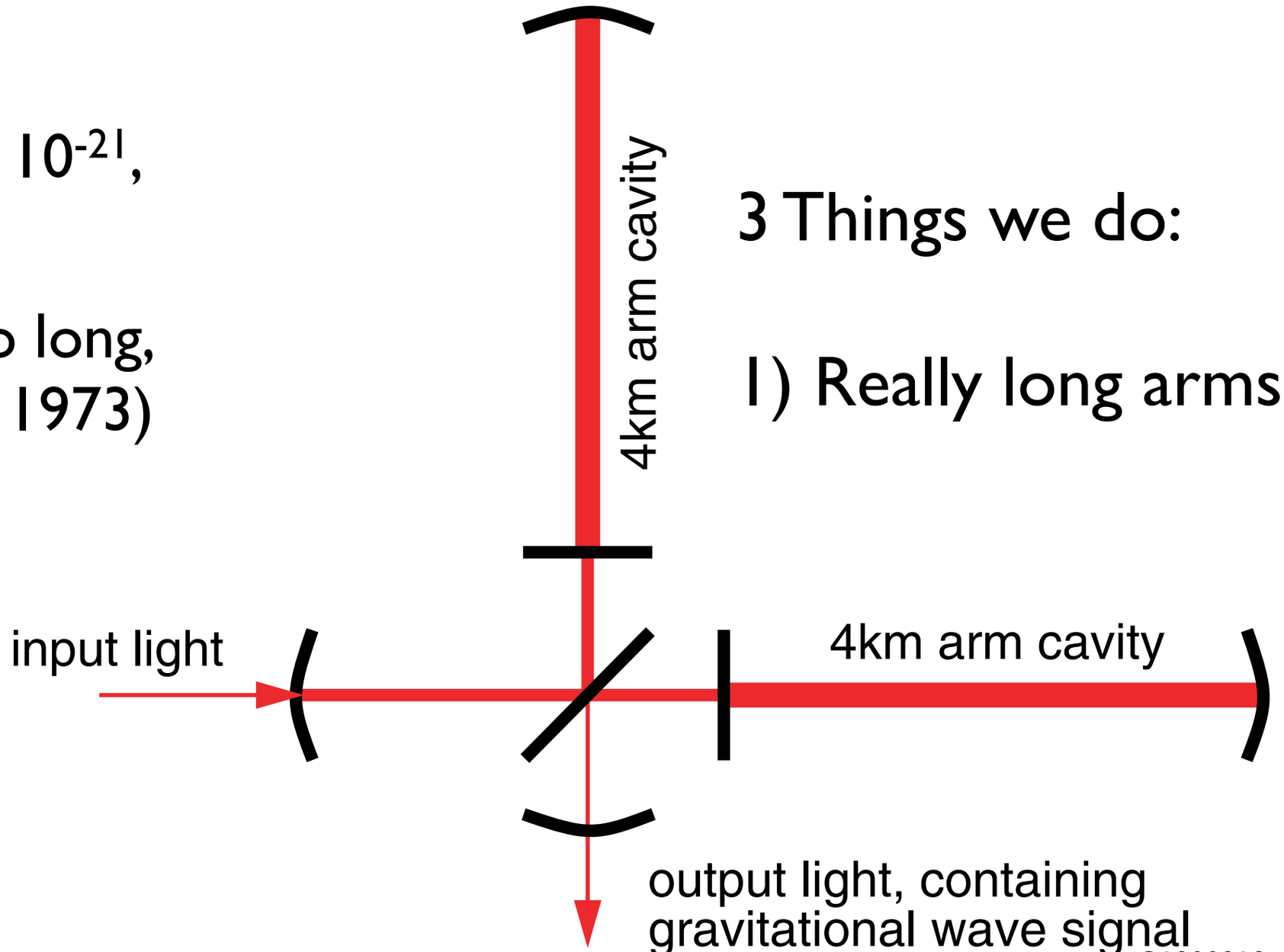
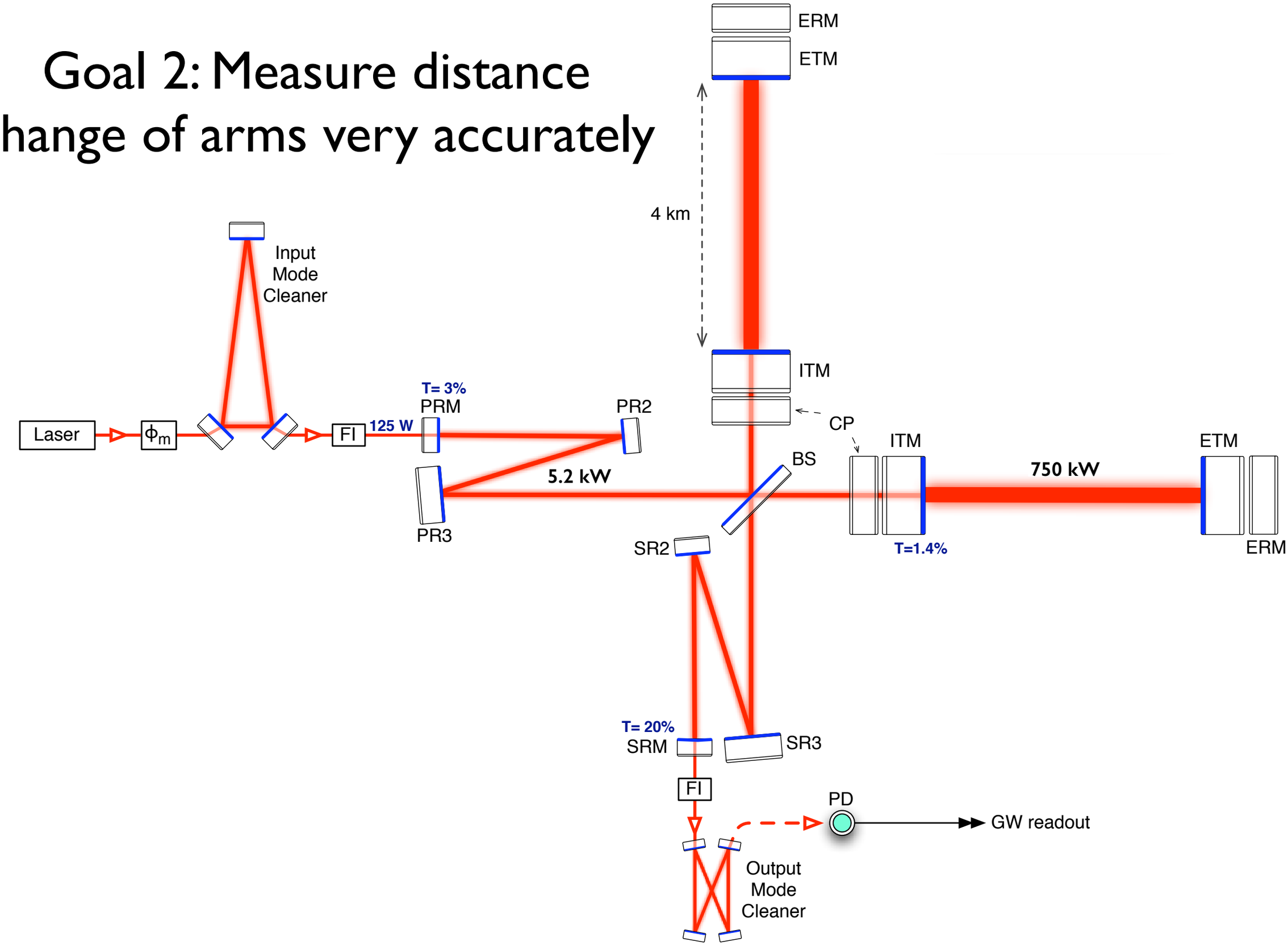


3 Things we do:

1) Really long arms.

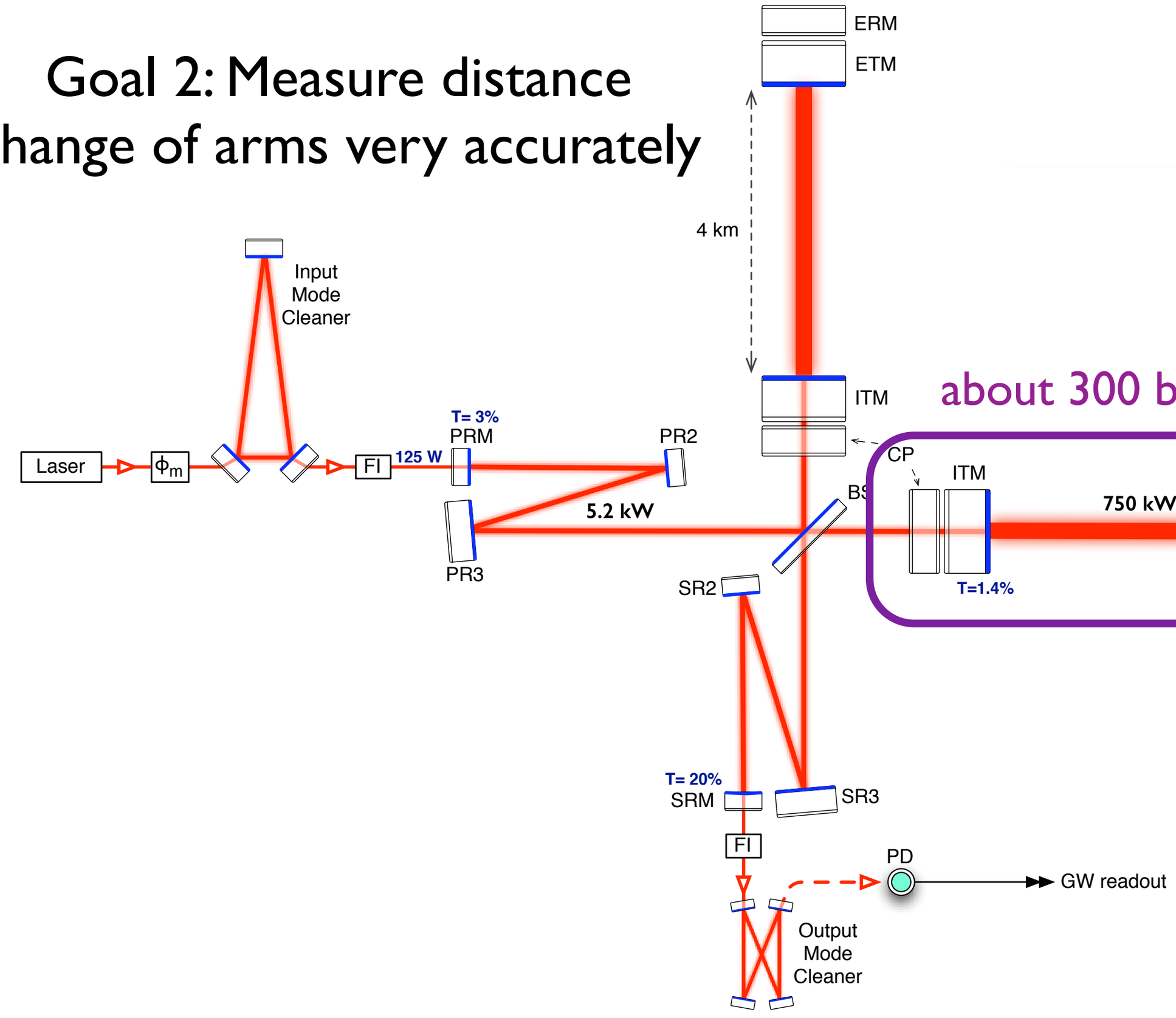
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately



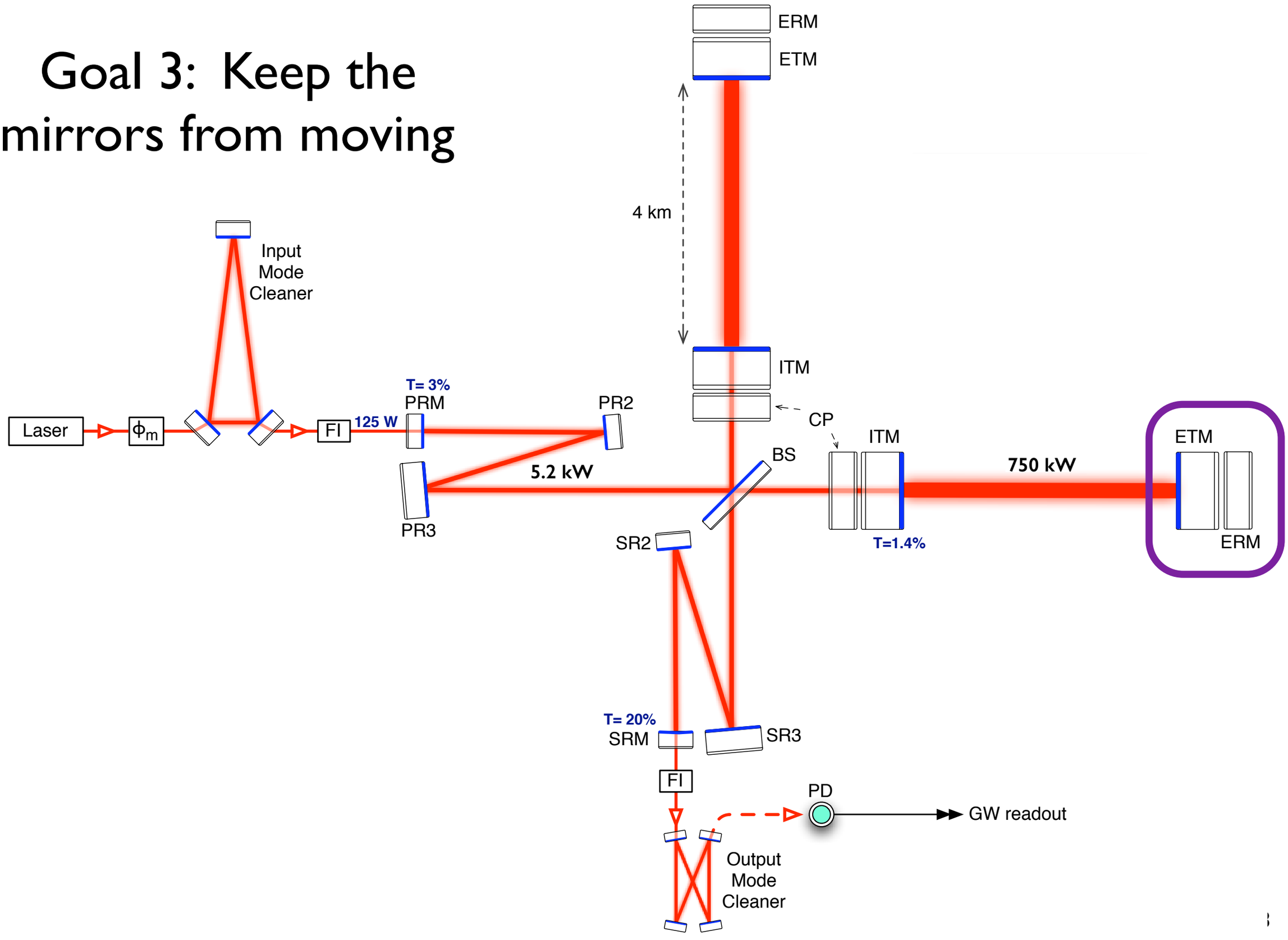
Fabry-Perot arms

Goal 2: Measure distance change of arms very accurately

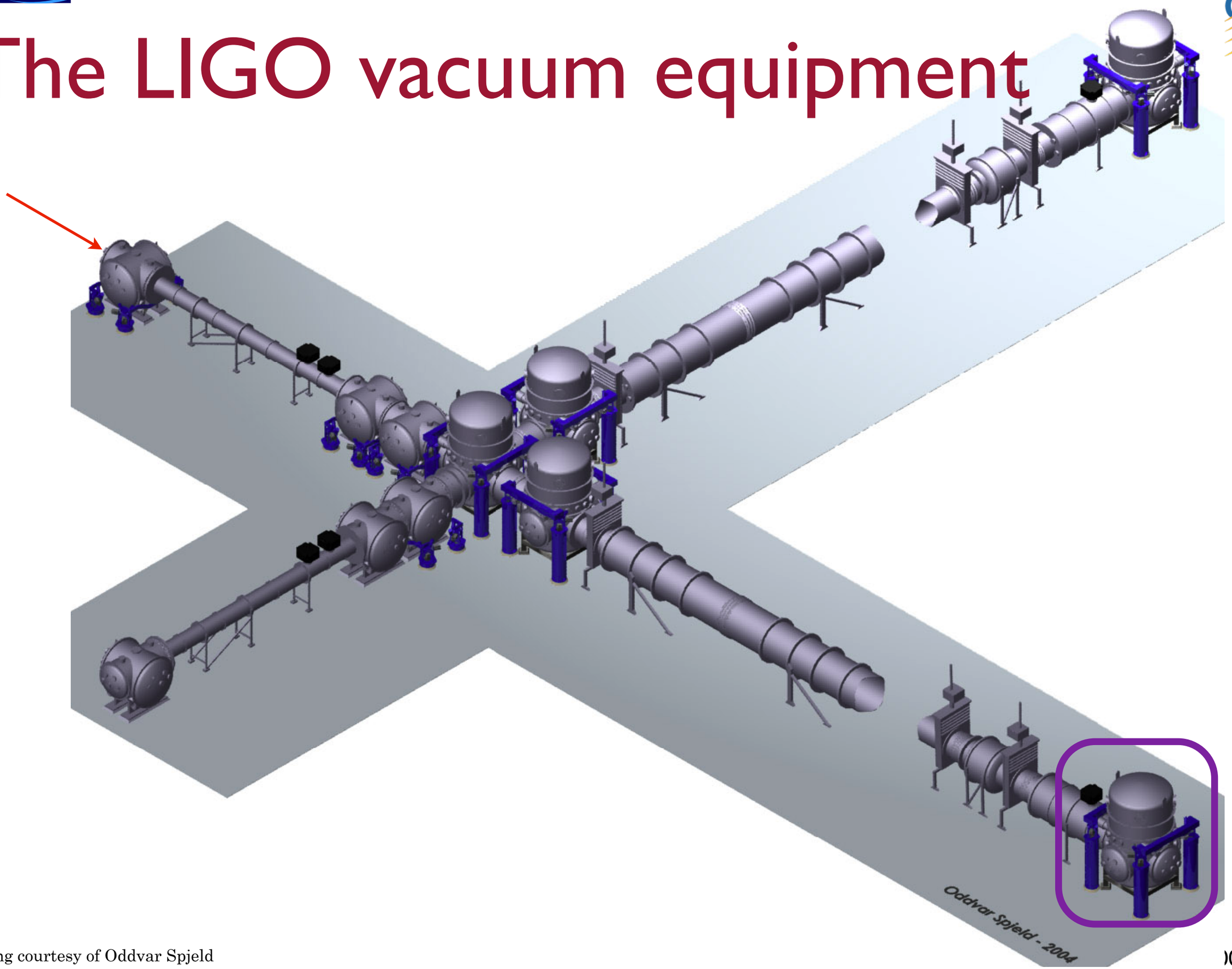


Layout of the interferometer

Goal 3: Keep the mirrors from moving

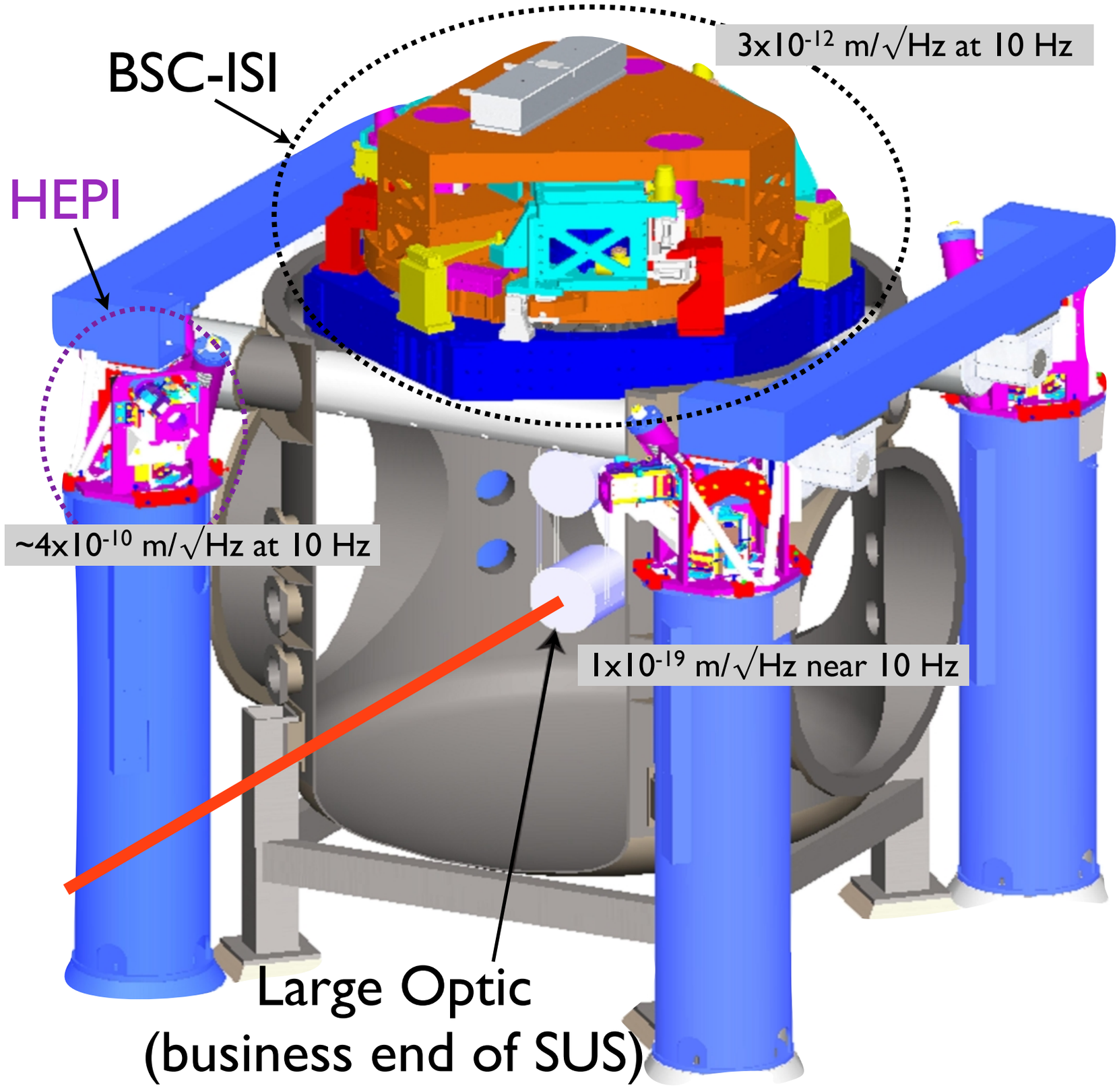


The LIGO vacuum equipment

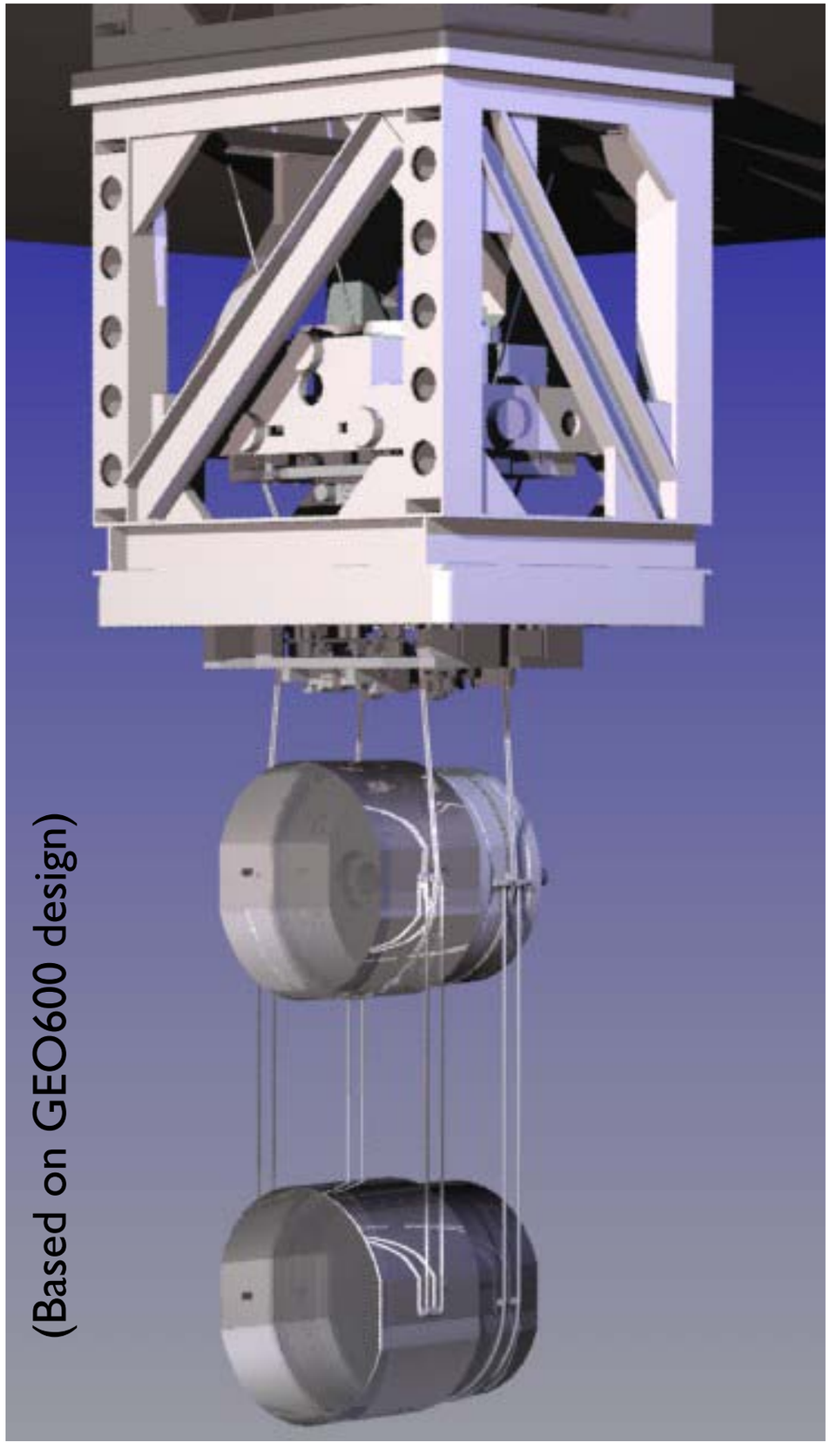


drawing courtesy of Oddvar Spjeld

Isolation of the Mirrors

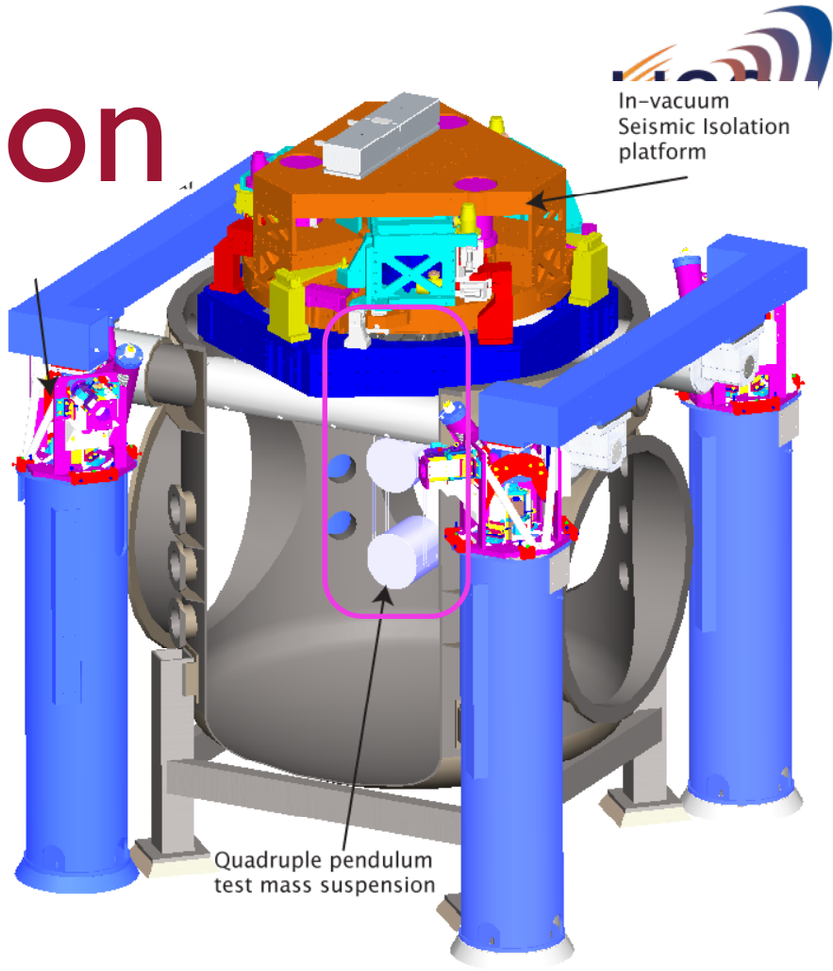


Pendulum Suspension

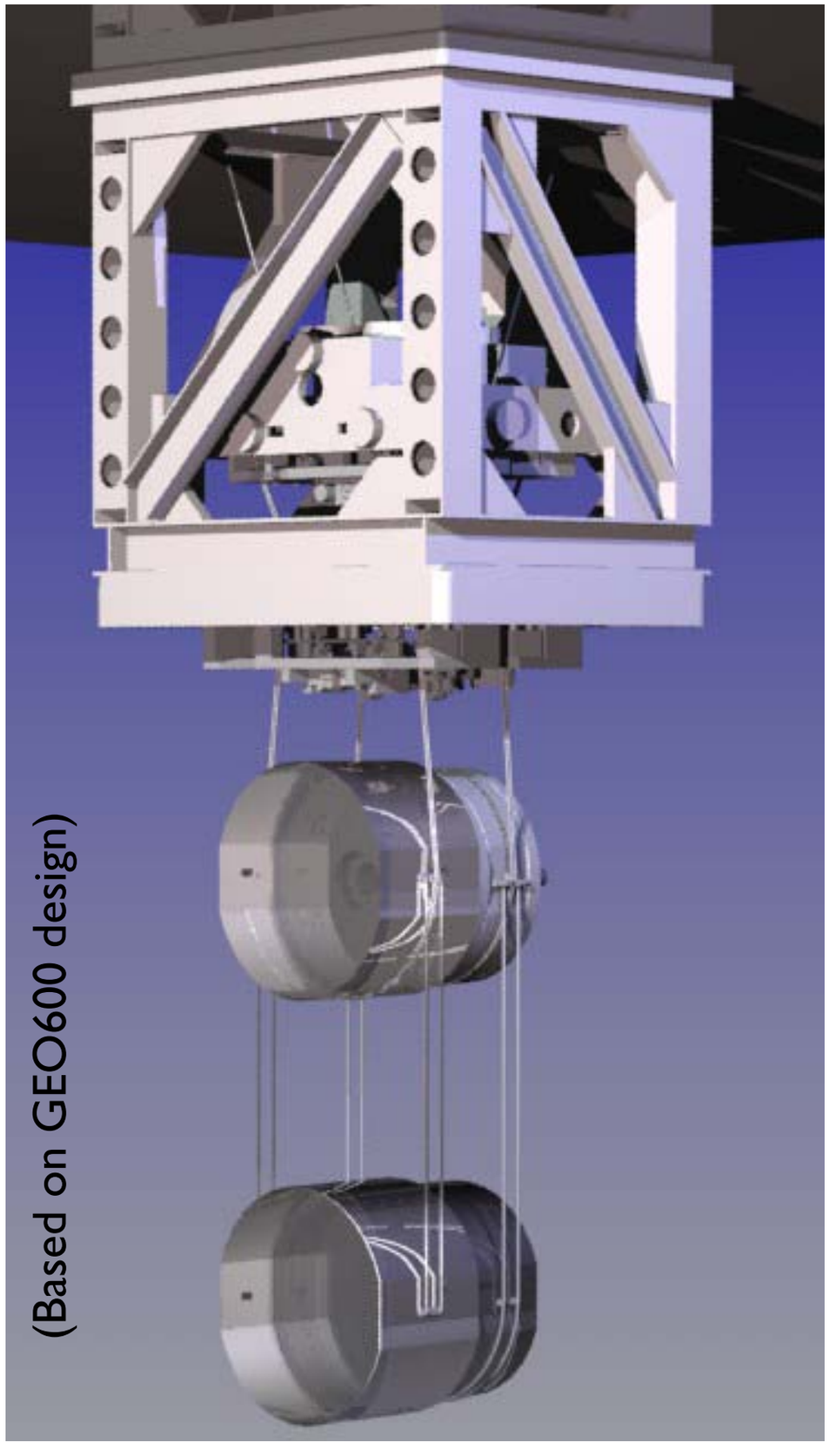


LIGO Mirrors:
Synthetic fused silica,
40 kg mass
34 cm diameter
20 cm thick

Suspended as a
4 stage pendulum



Pendulum Suspension



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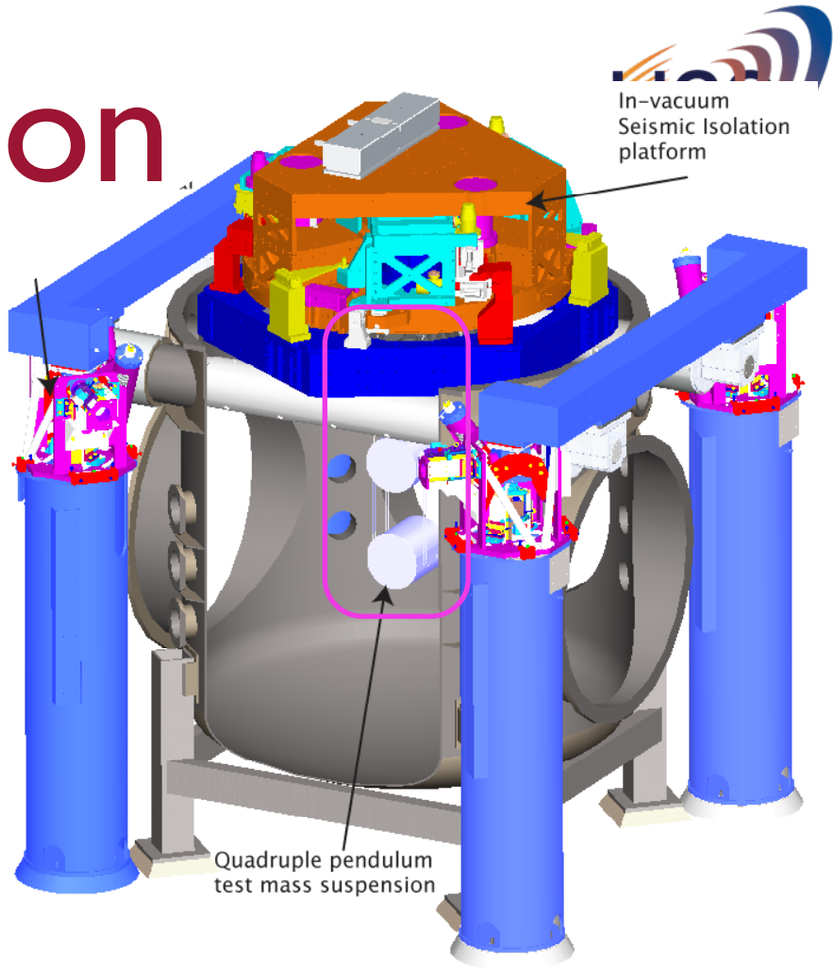
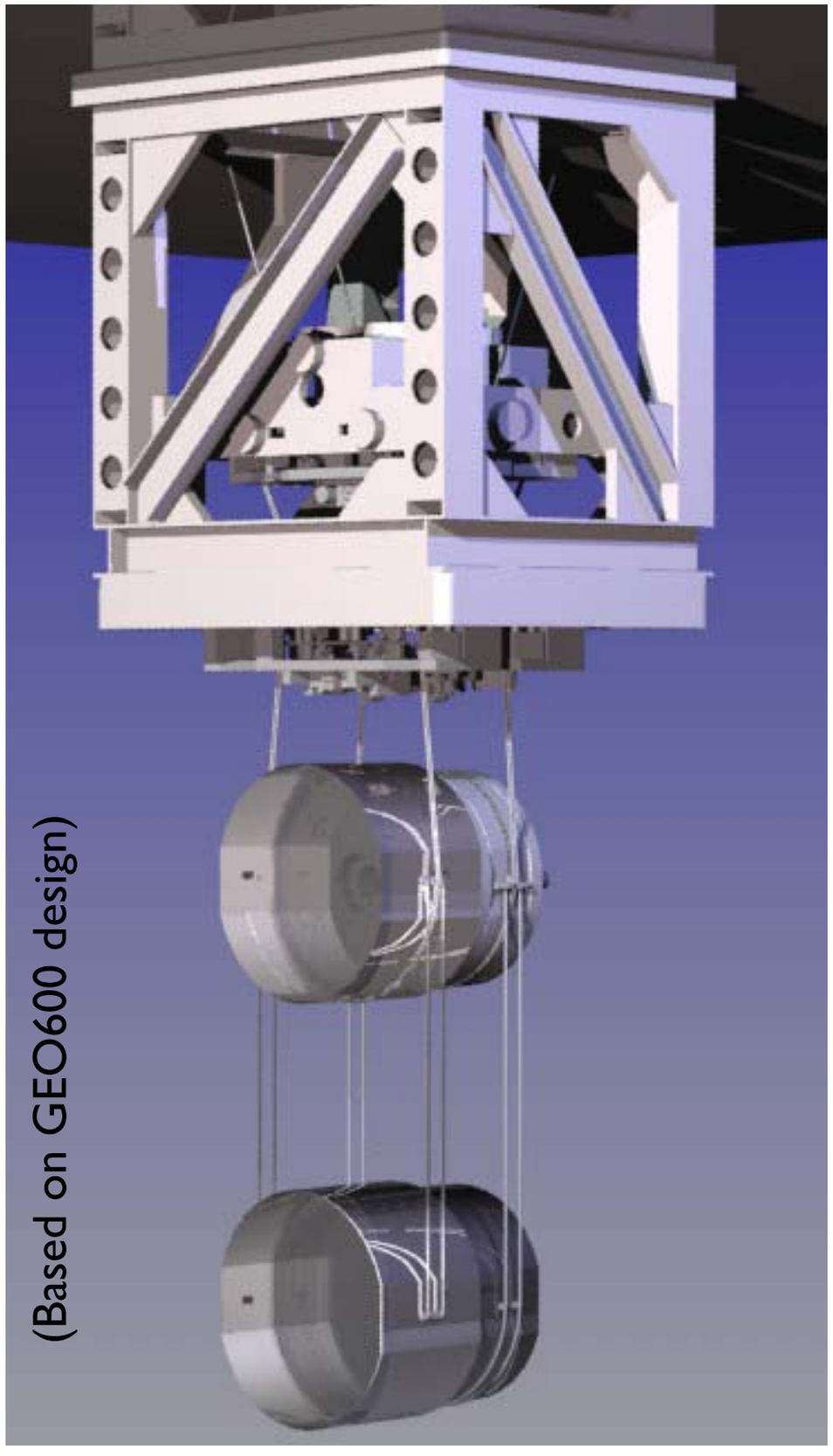


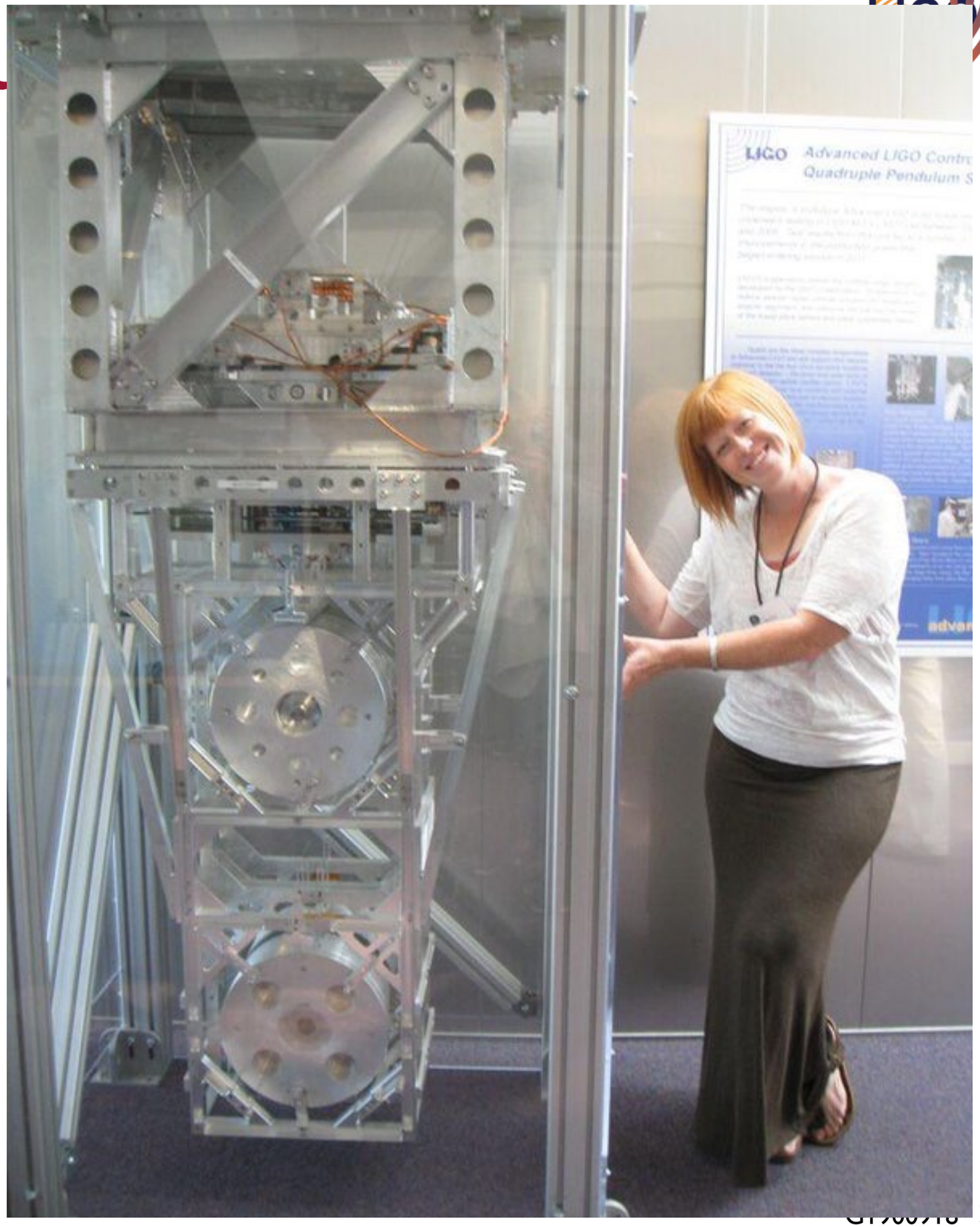
Best coatings available

Motion at 10 Hz set by
thermal driven vibration

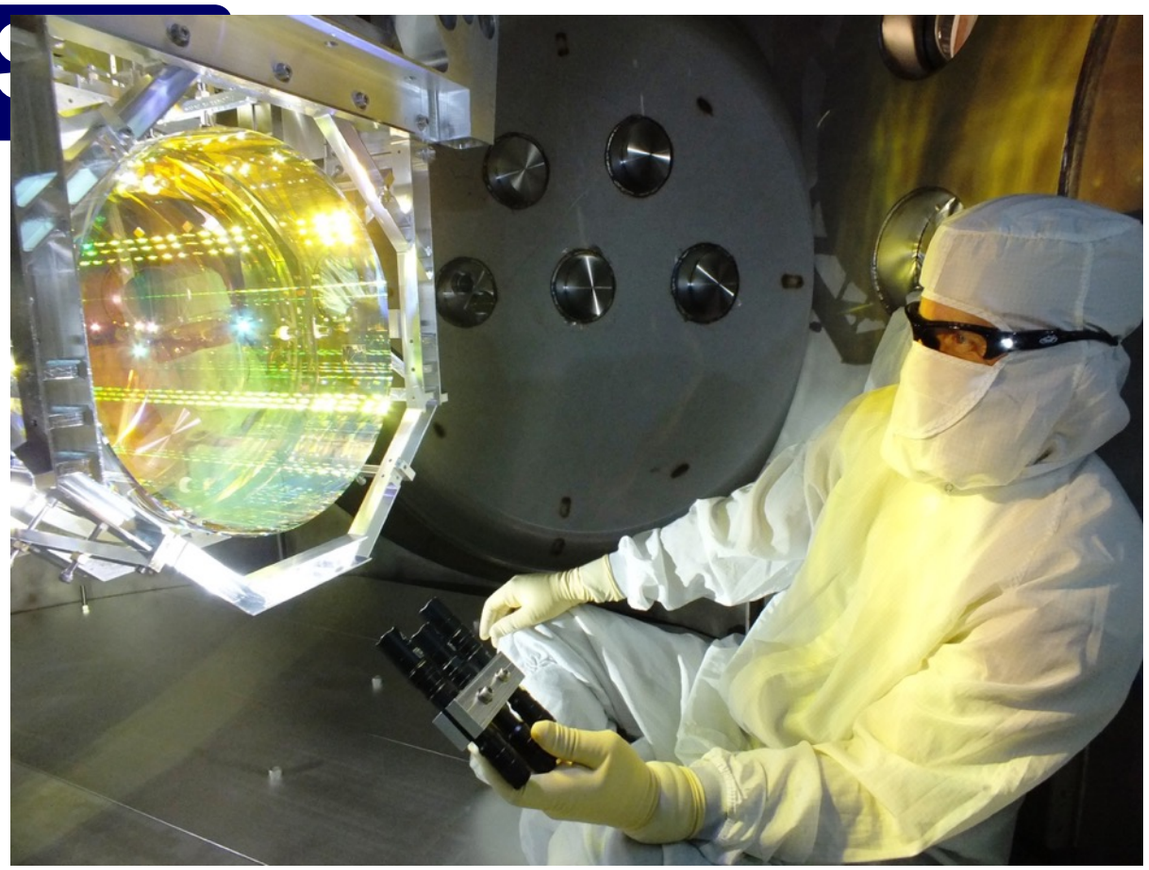
silicate bonding creates a monolithic final stage

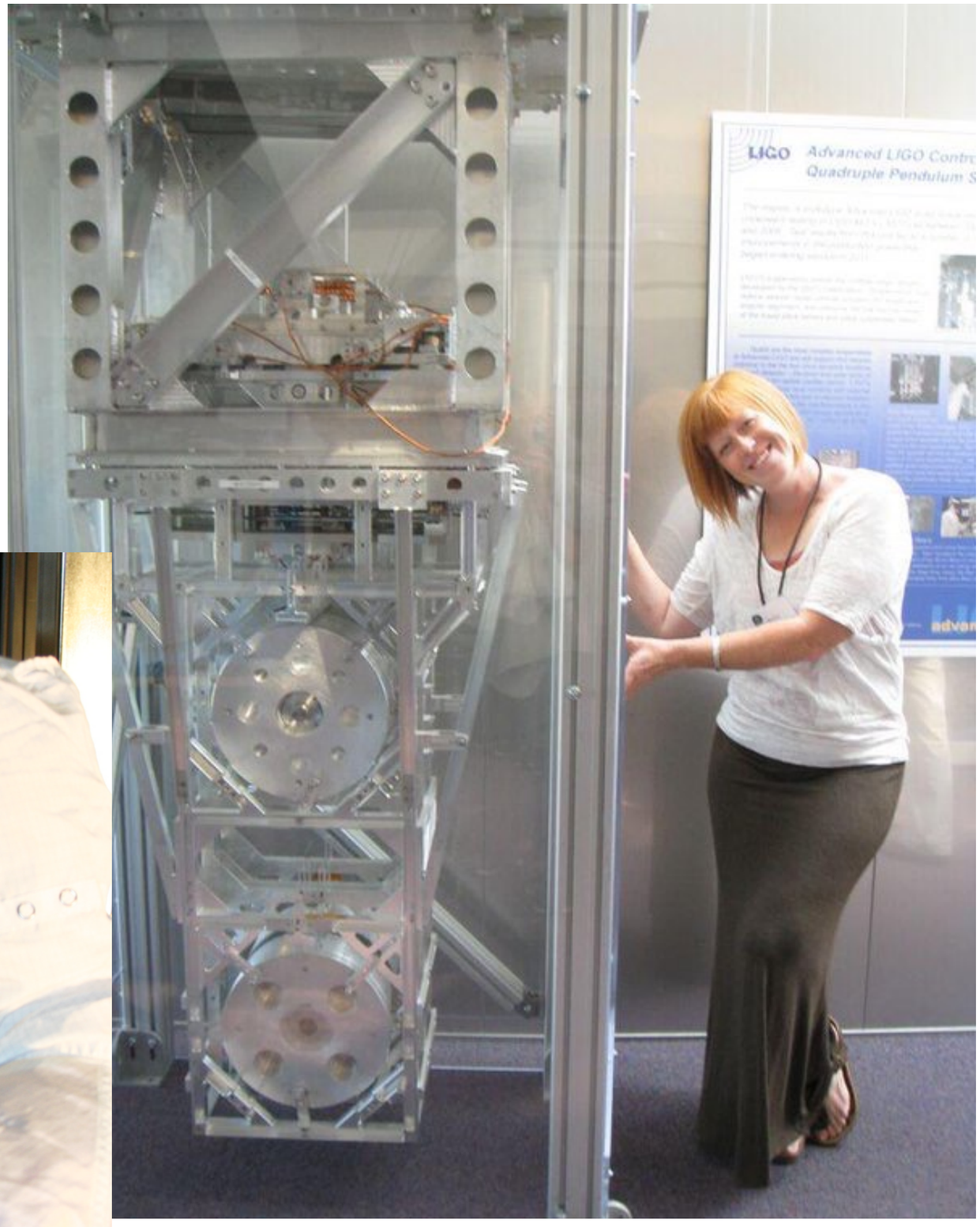
Pendulu

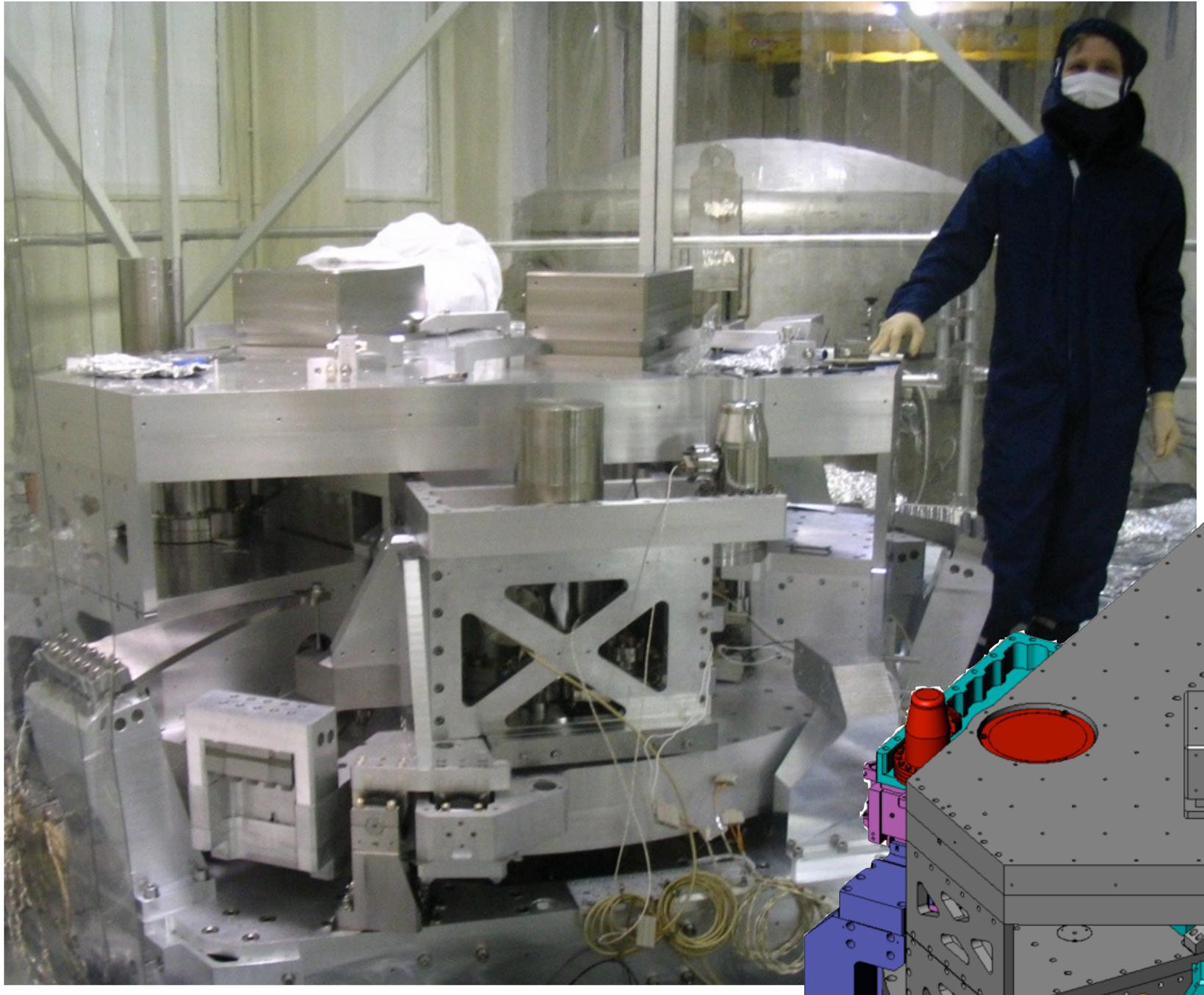

(Based on GEO600 design)

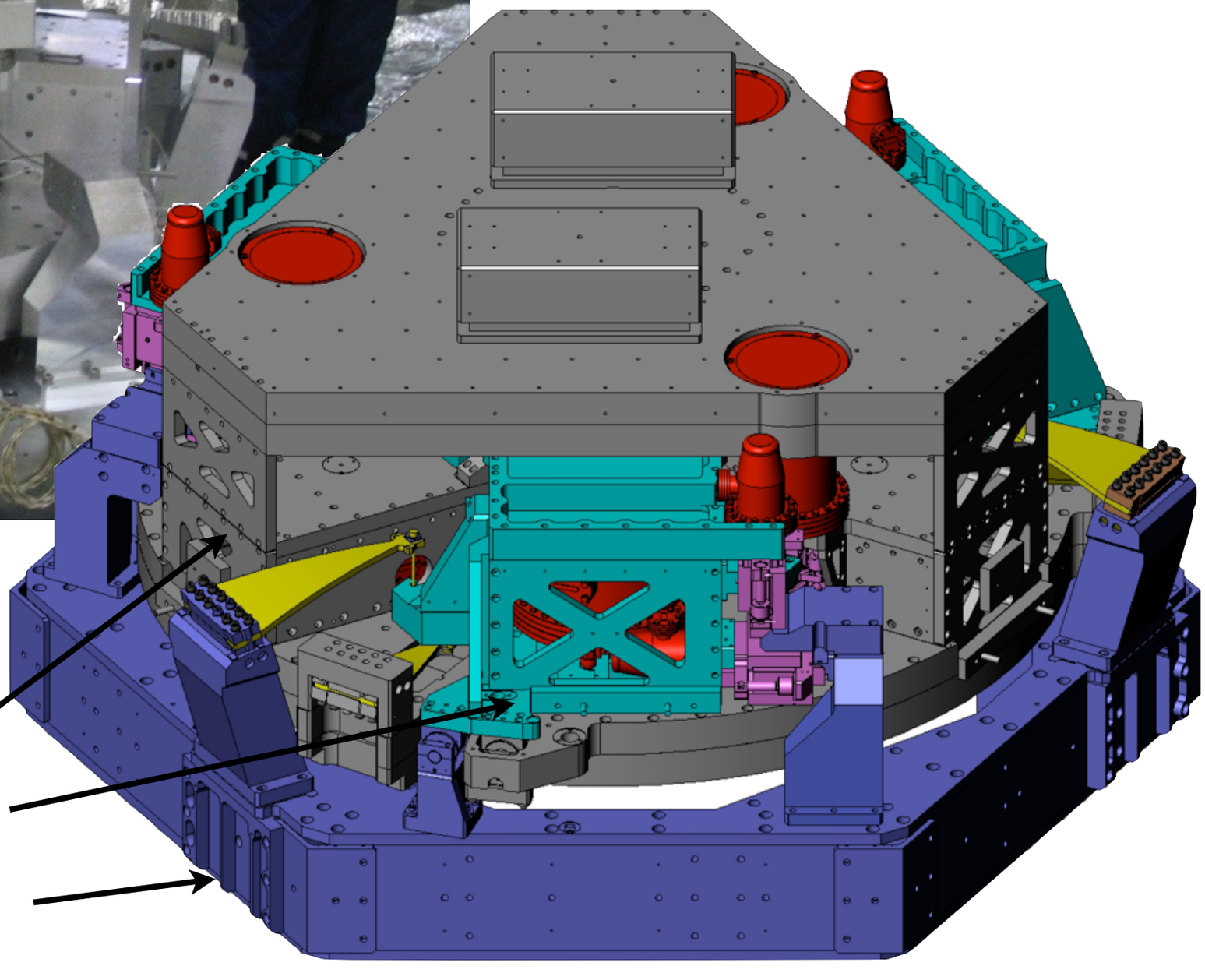

LIGO
Advanced LIGO Contr
Quadruple Pendulum S

Mirror picts









optics table - stage 2

stage 1

support - stage 0

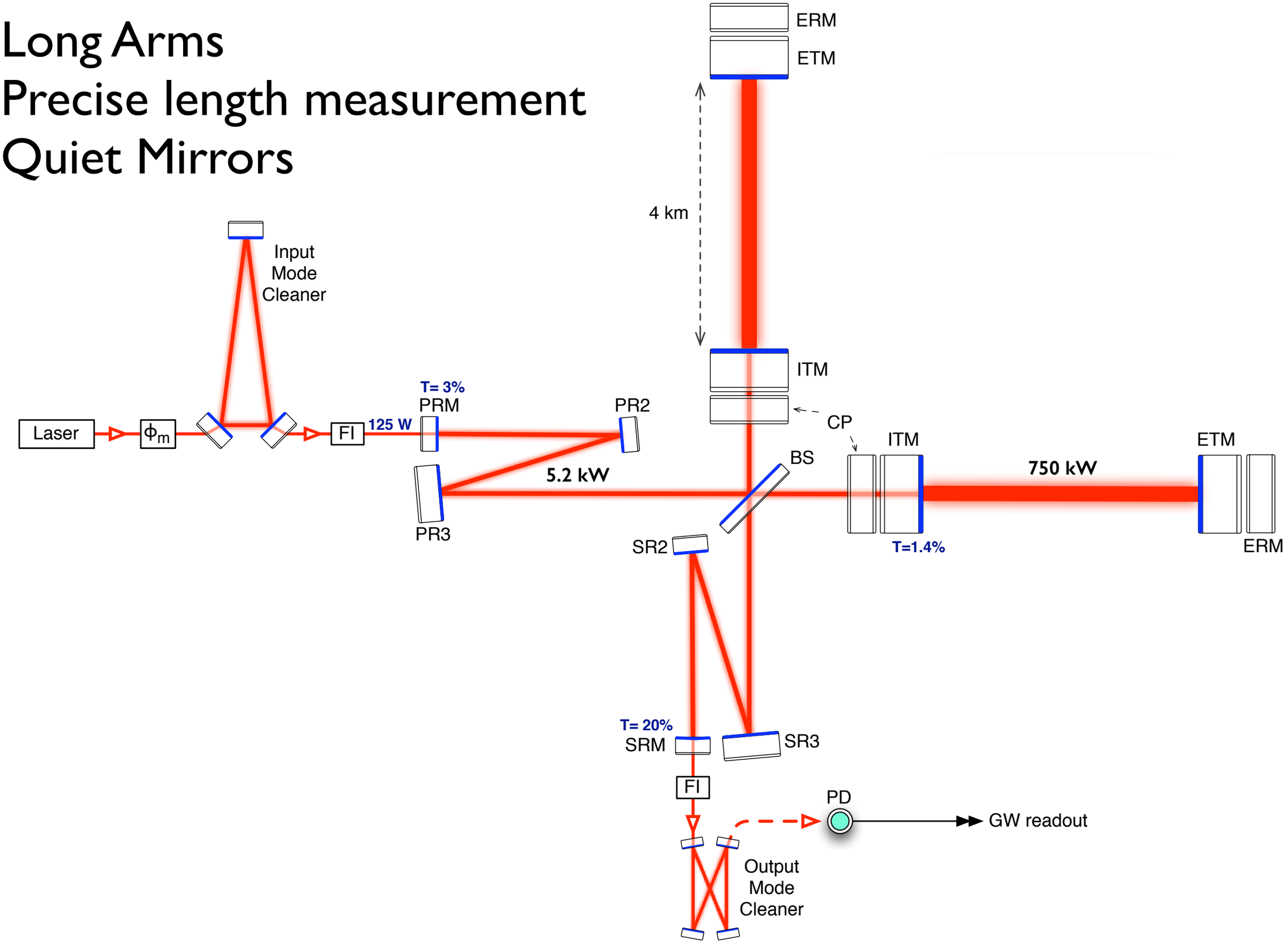
optics table - stage 2

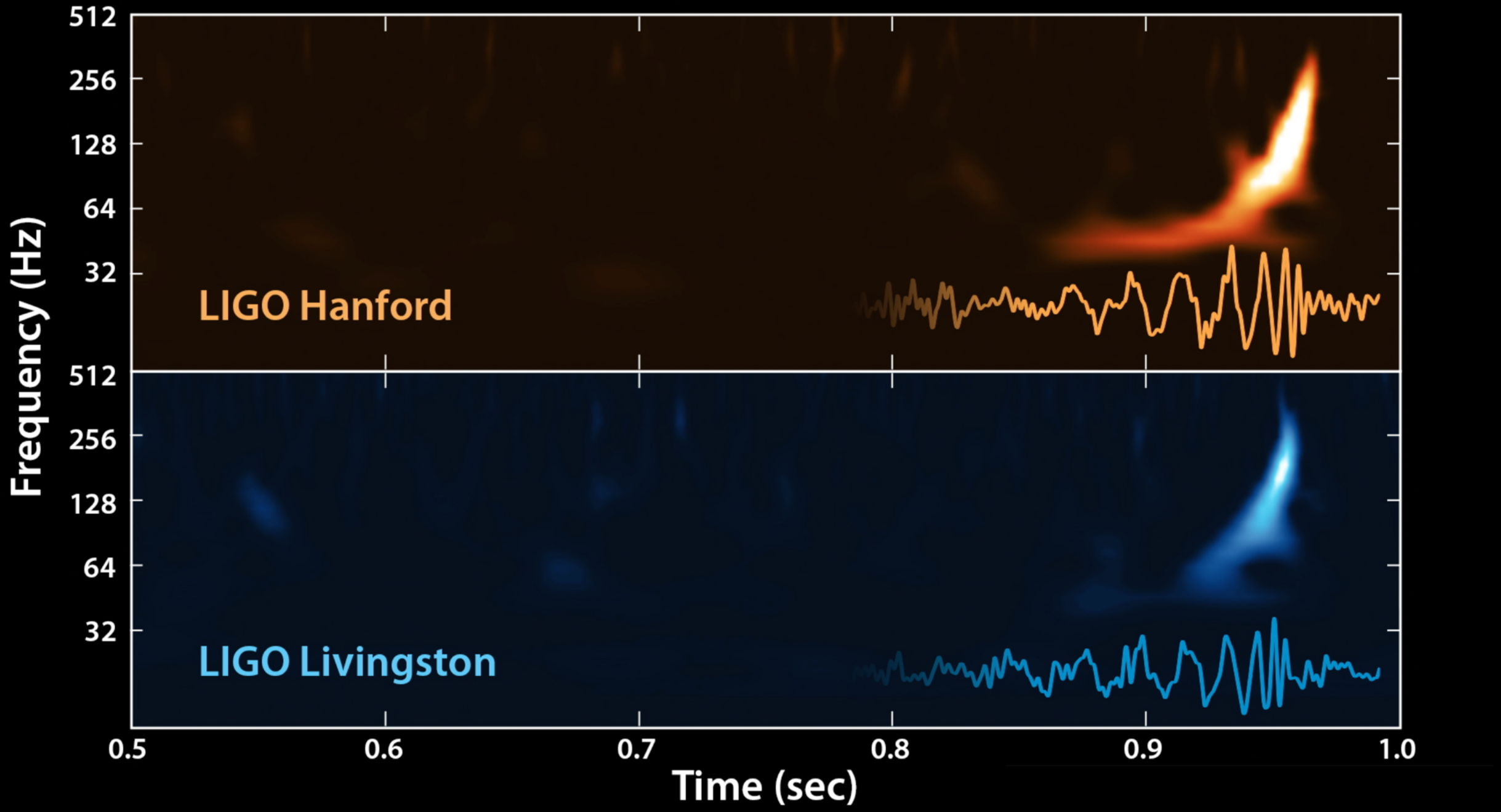
stage 1

support - stage 0

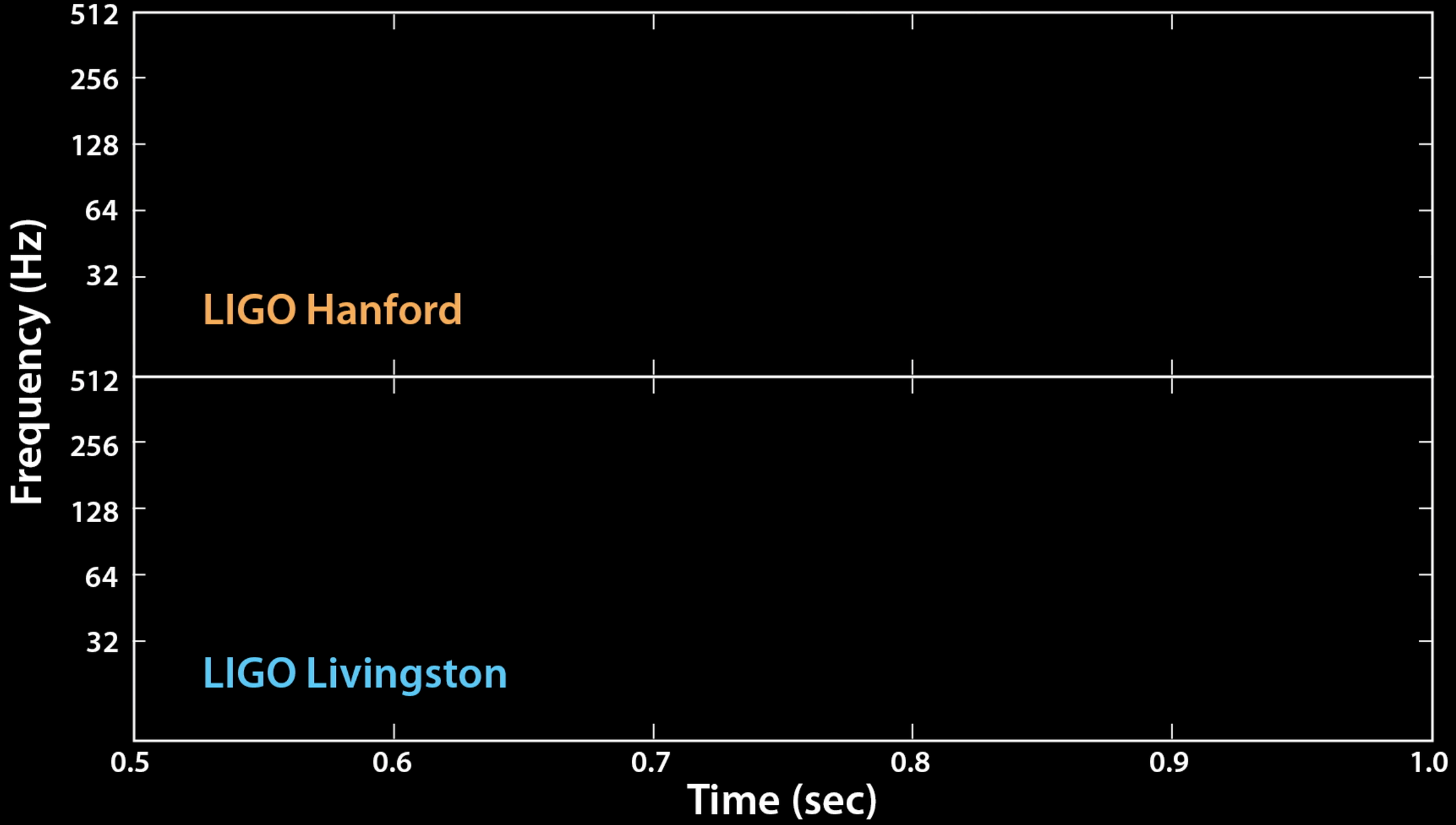
Now we are ready…

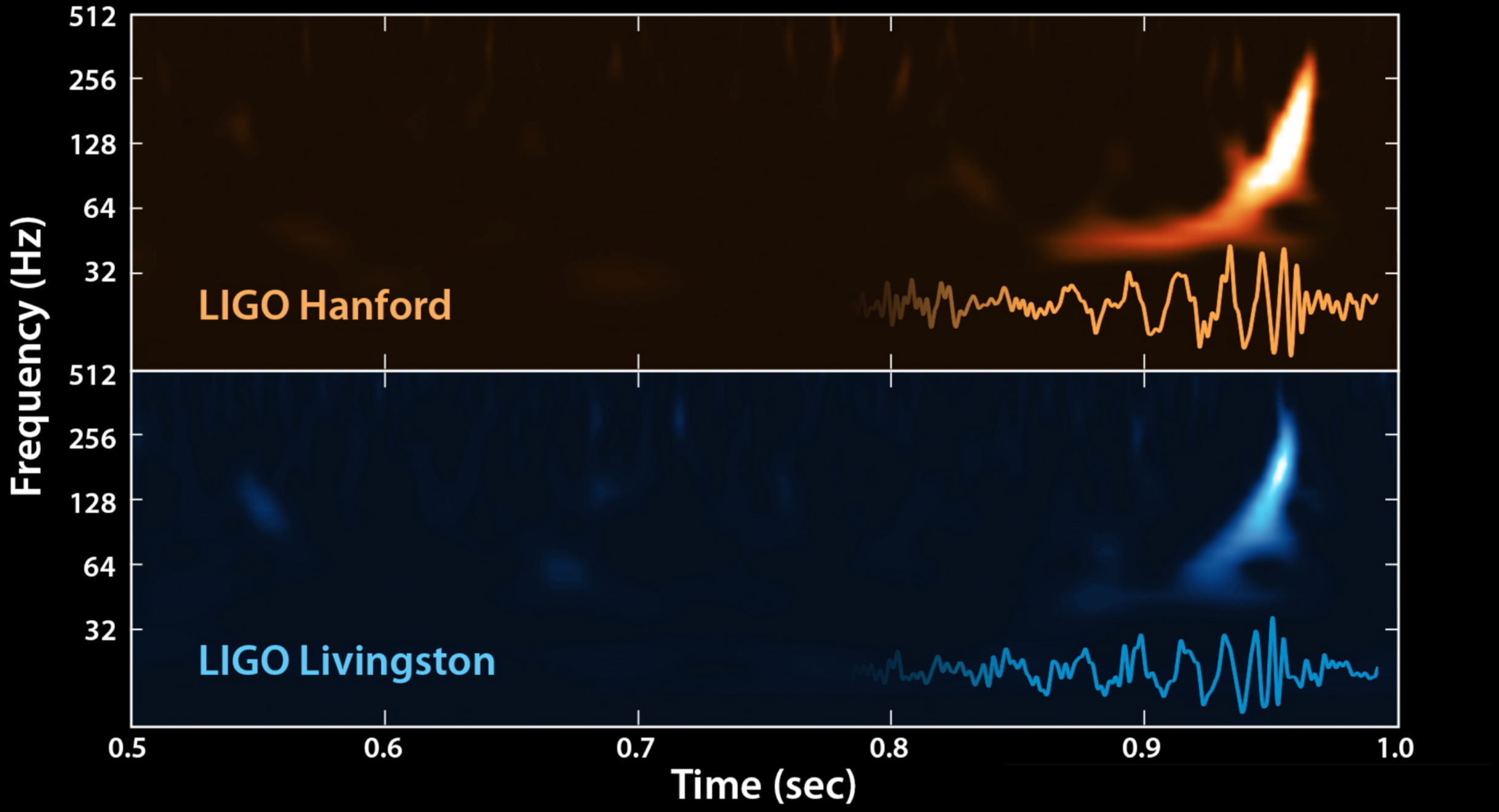
1) Long Arms
2) Precise length measurement
3) Quiet Mirrors





http://mediaassets.caltech.edu/gwave


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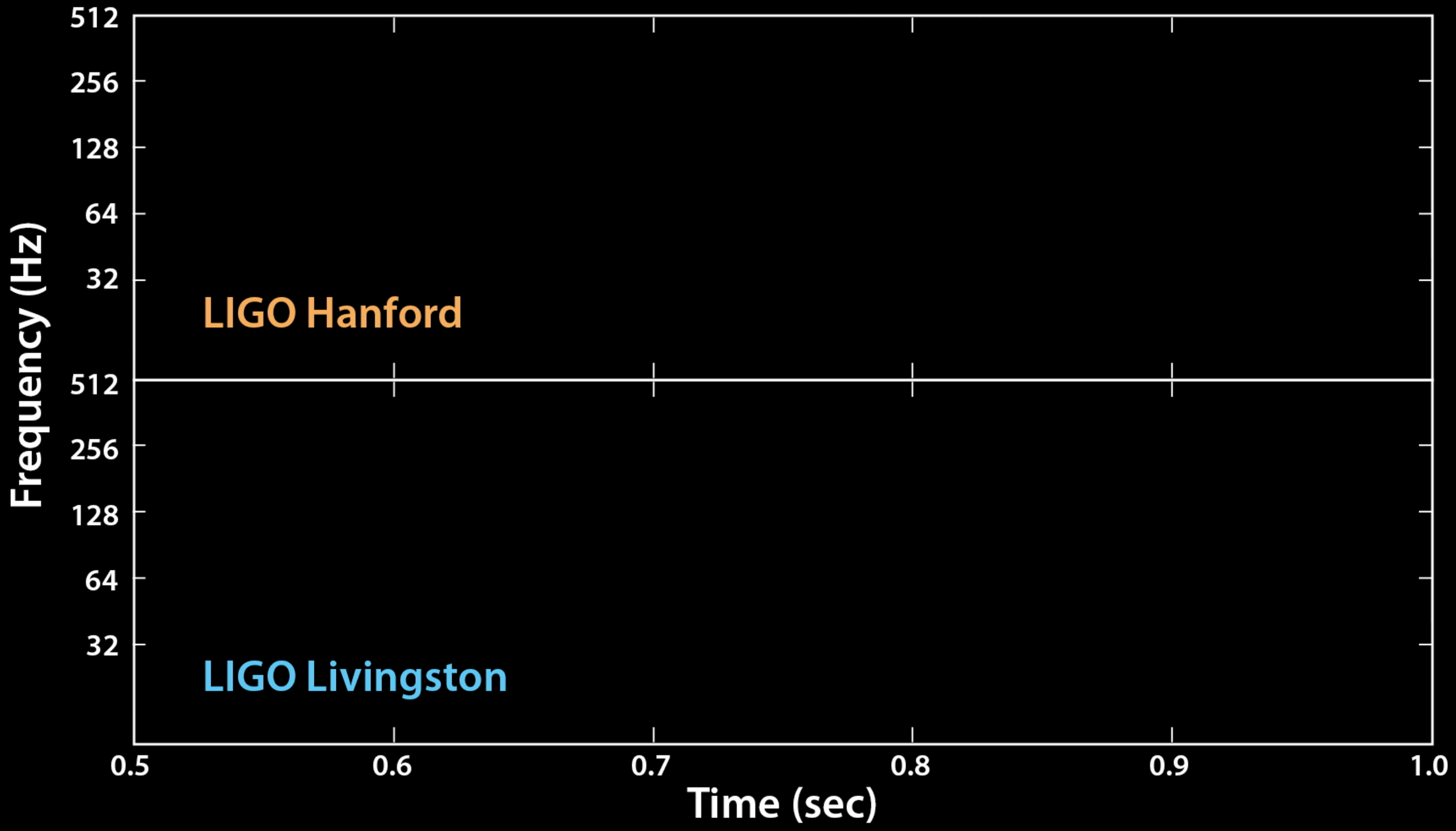
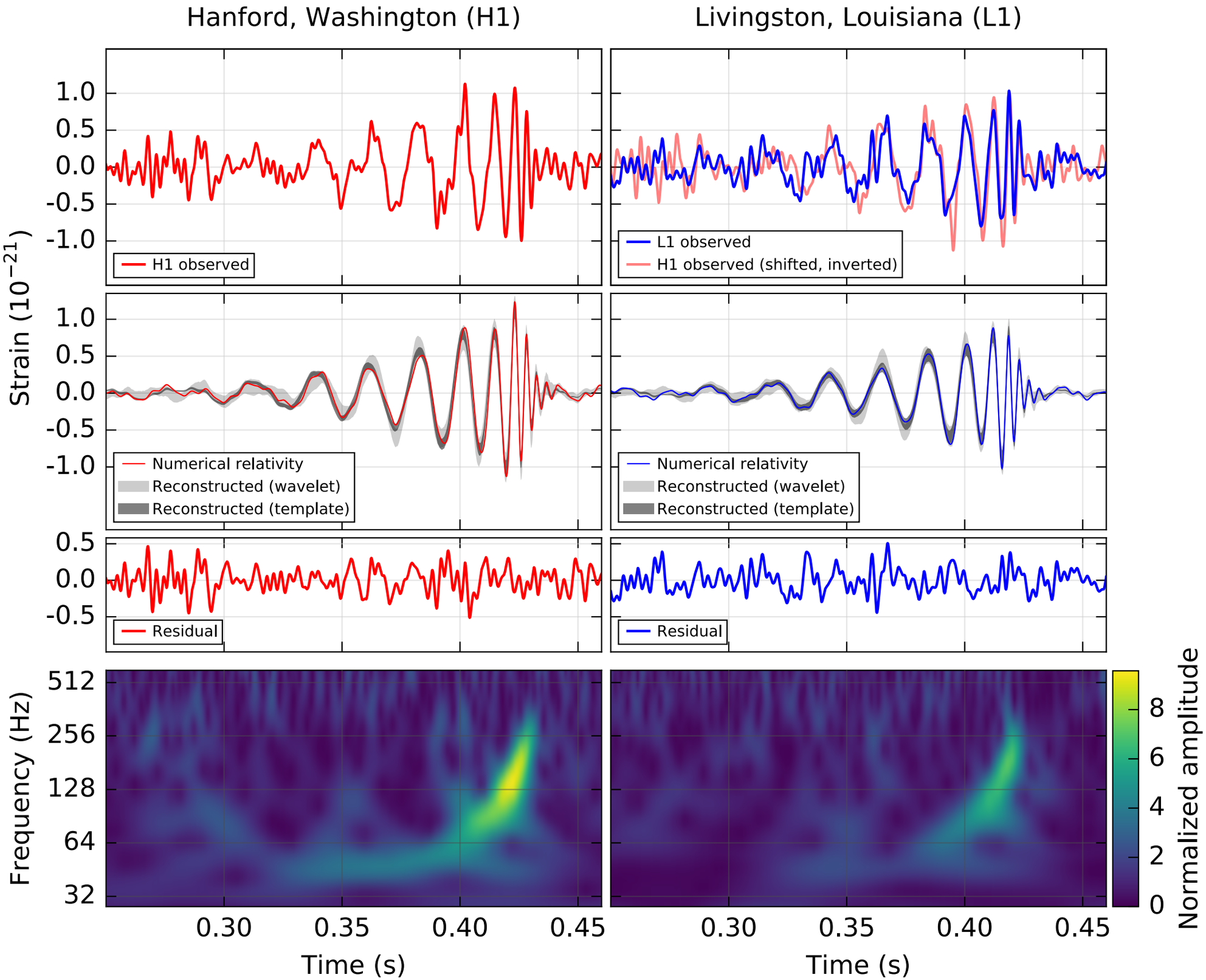
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

The sound of black holes colliding



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}

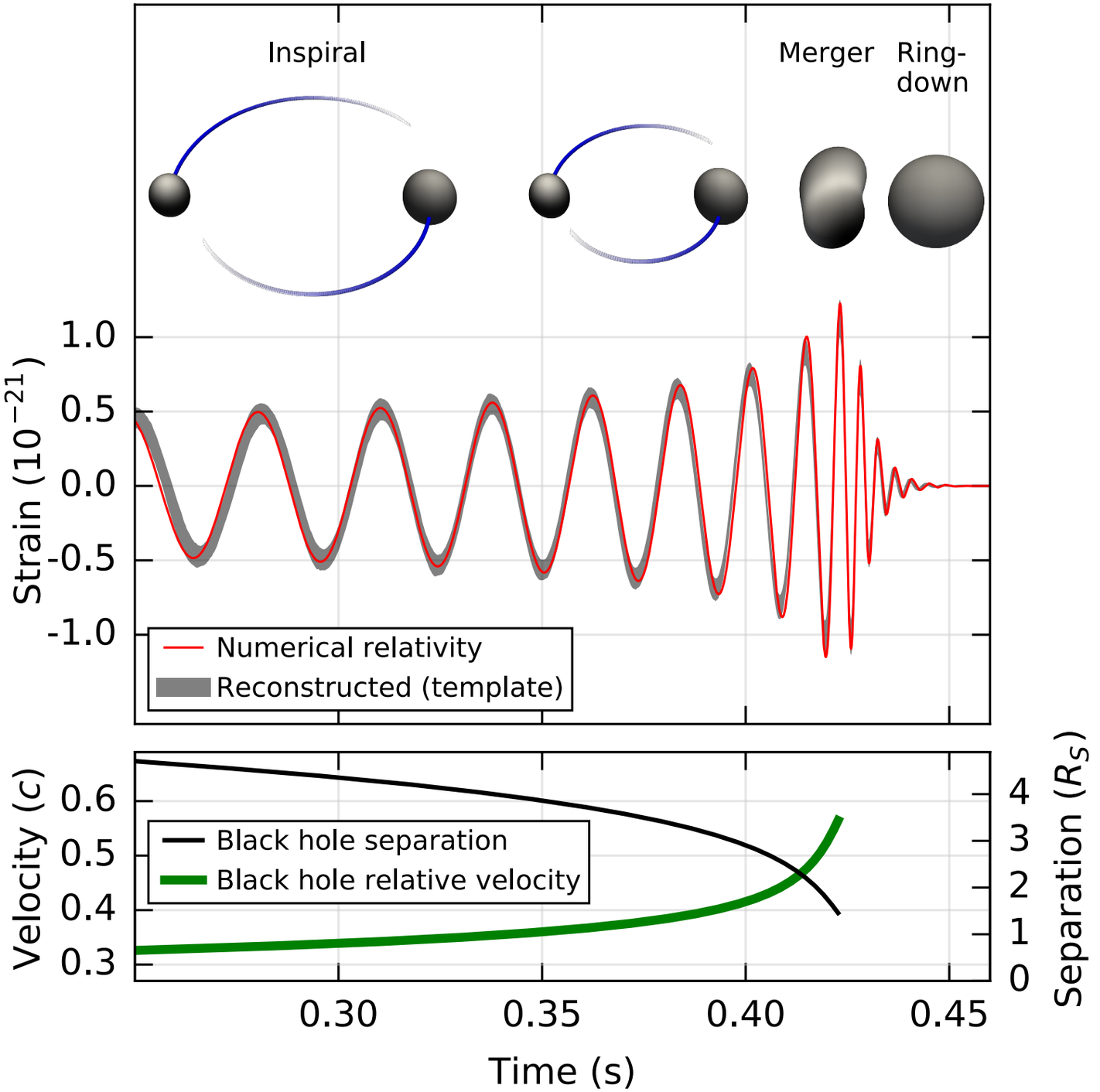
Final Mass:

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

Distance

420 (+160/-180) MPc

(1.3 Billion light years)



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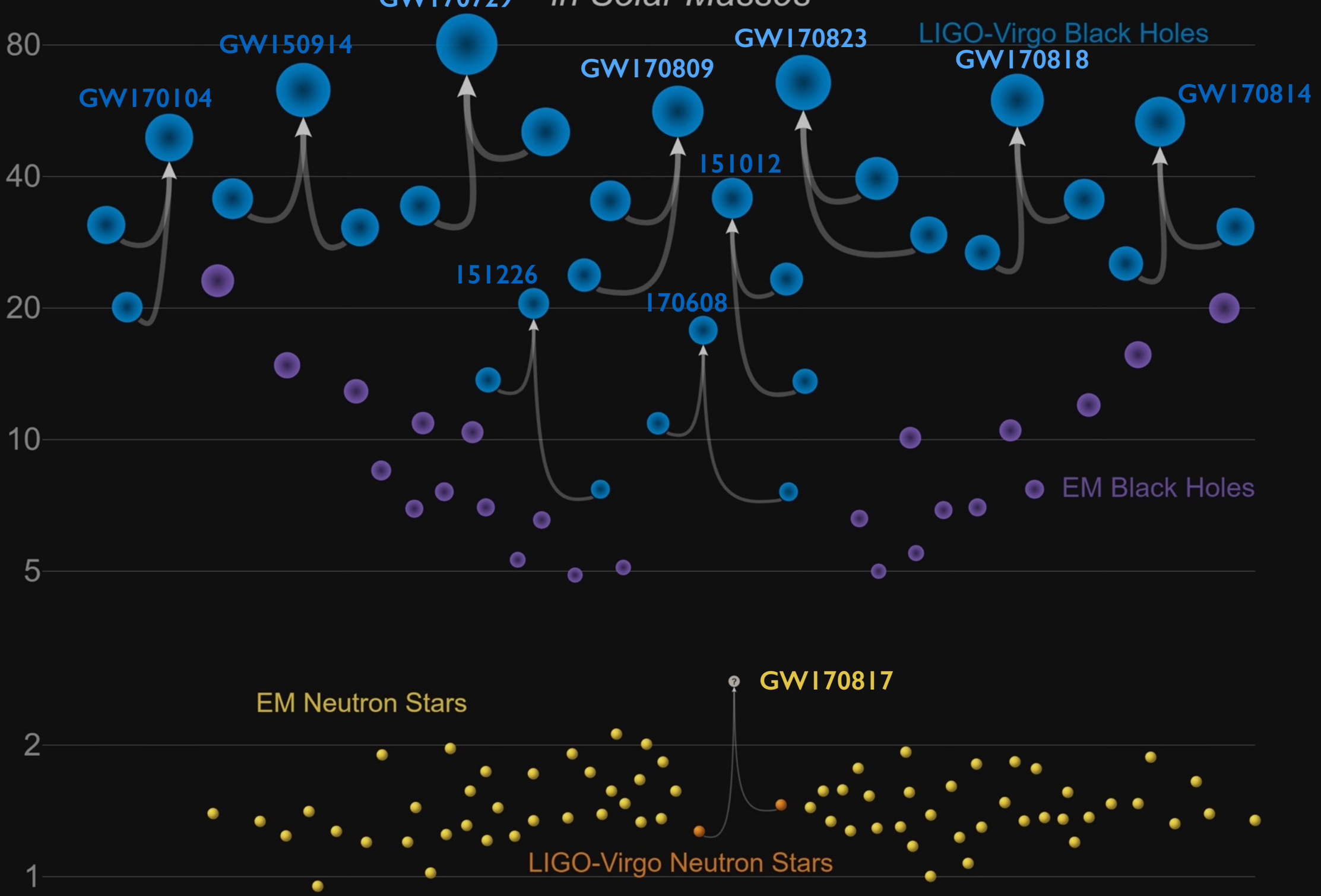
Masses in the Stellar Graveyard

in Solar Masses

Lots of astrophysics

But no light…



https://media.ligo.northwestern.edu/gallery/mass-plot

LIGO-Virgo | Frank Elavsky | Northwestern

Masses in the Stellar Graveyard

in Solar Masses

Lots of astrophysics

But no light…

80
40
20
10
5
2

GW170729
GW150914
GW170104
GW170809
GW170823
LIGO-Virgo Black Holes
GW170818
GW170814
151012
151226
170608
EM Black Holes
EM Neutron Stars
GW170817

and in the last six weeks, we've seen:
5 more binary black-hole mergers,
1 more binary Neutron star merger, and
1 more faint signal which might be a BNS, or may be a BH + NS

Neutron star slide

summary & conclusions