How to Detect a Gravitational Wave: A discussion about the Advanced LIGO Interferometers

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

May 18, 2016

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

LIGO Scientific Collaboration

Trinity University
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
Leland Stanford Junior University
University of Strathclyde
Michigan
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Università degli Studi del Sannio
CITA | ICAT Canadian Institute for Theoretical Astrophysics L'institut Canadien d'astrophysique theorique
Scientia Vincere Tenebras Universitas Bruxellensis
Massachusetts Institute of Technology
NASA Goddard Space Flight Center
ICTP SAIFR
PAH
The University of Western Australia
Monash University
Southern University and Agricultural & Mechanical College
University of Cambridge
The University of Chicago
Montana State University
ACU
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
Universitas Scientiarum Szegediensis Szegedi Tudományegyetem
UIB Universitat de les Illes Balears
University of Washington
GEO 600
Tsing Hua University
UTRGV
Sigill: Coll: Carleton Northfield, Minn. A.D. 1866
University of Budapest
University of Wisconsin UWMilwaukee
Universität Hamburg
Syracuse University Suos Cultores Scientia Coronat Founded AD 1870
Cardiff University Prifysgol Caerdydd
Northwestern
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
Hobart and William Smith Colleges
Science & Technology Facilities Council Rutherford Appleton Laboratory

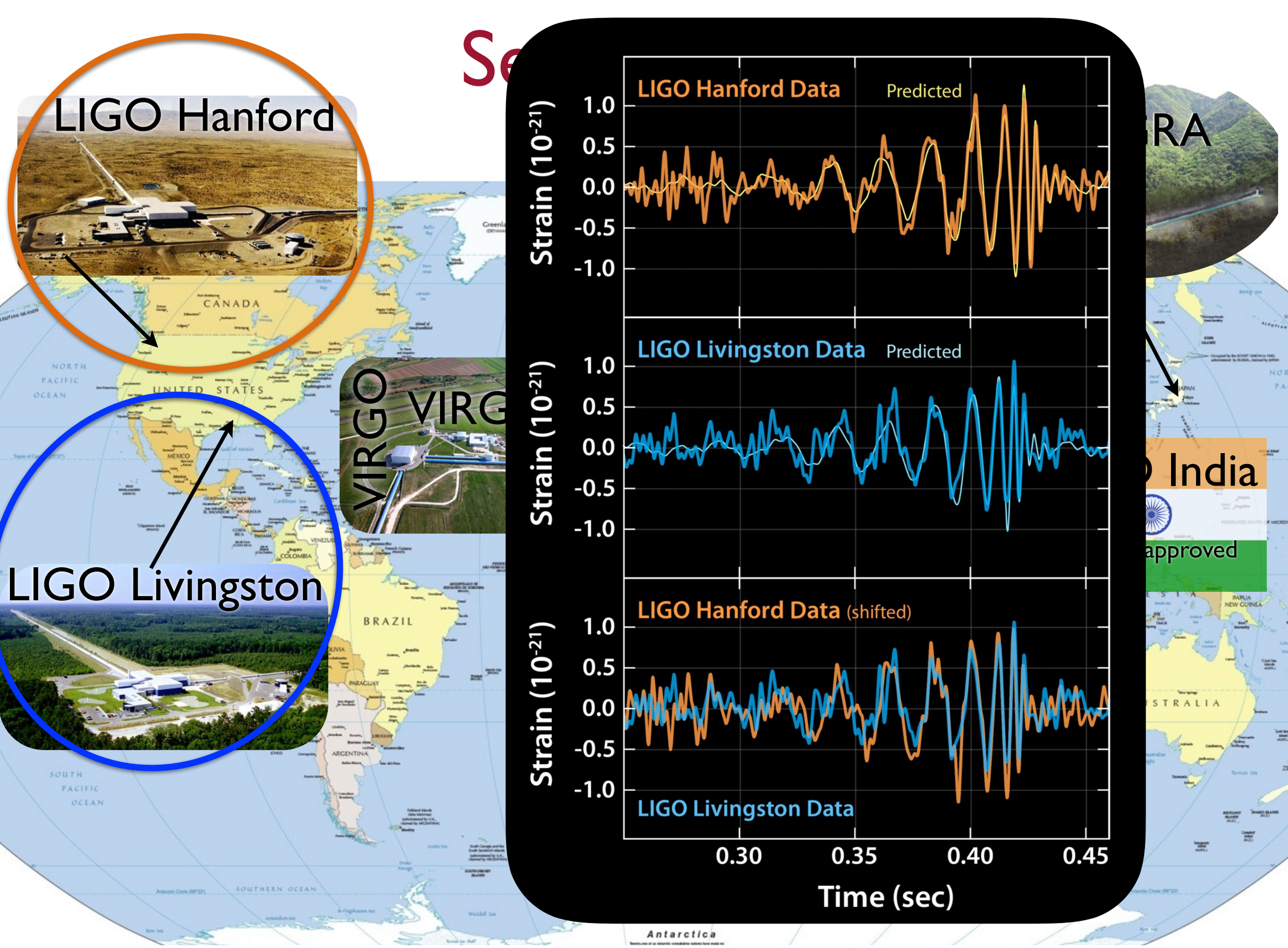
International Network

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

Sept. 14, 2015

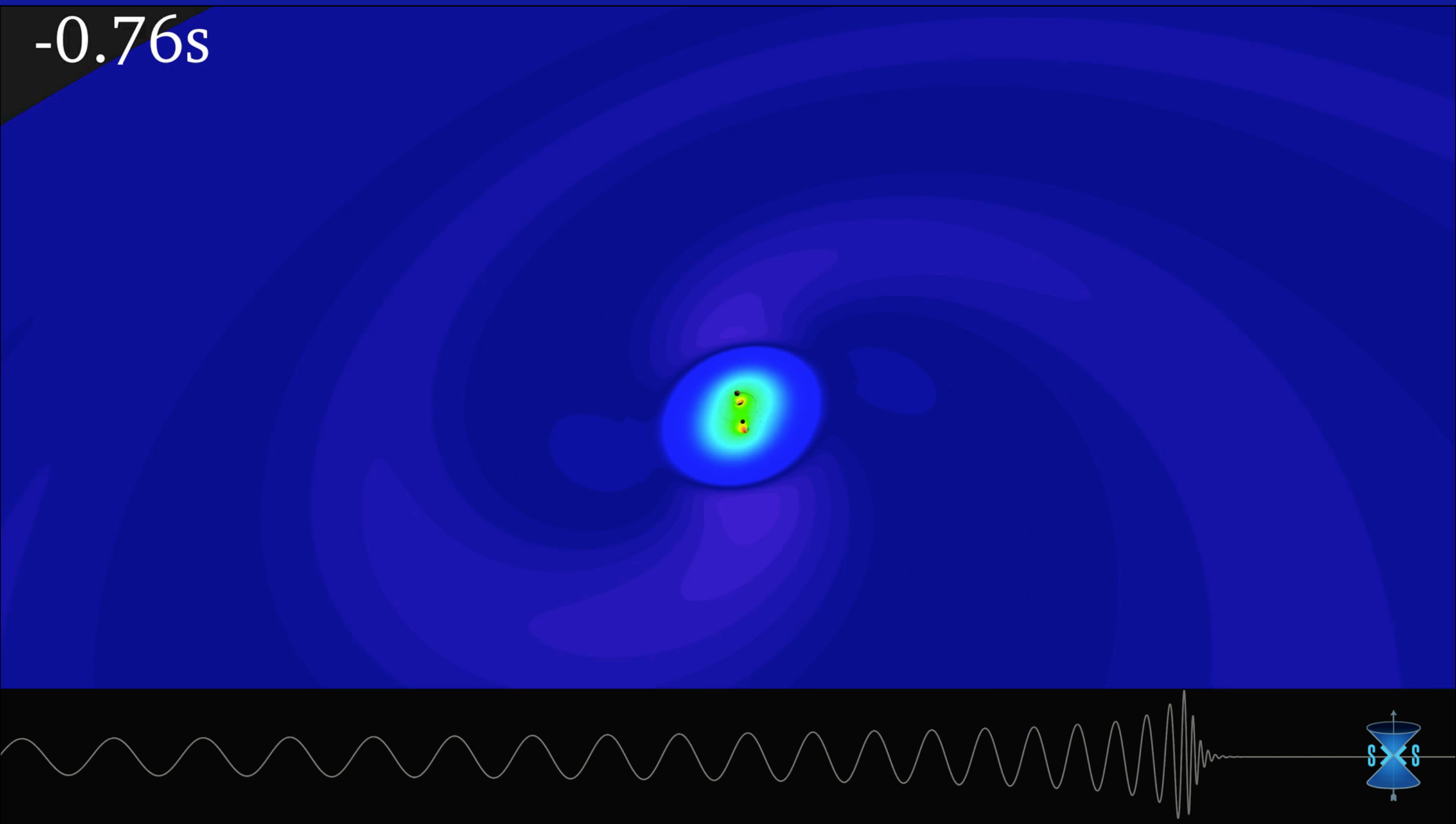
map from http://www.nationsonline.org/maps/political_world_map3000.jpg

Se

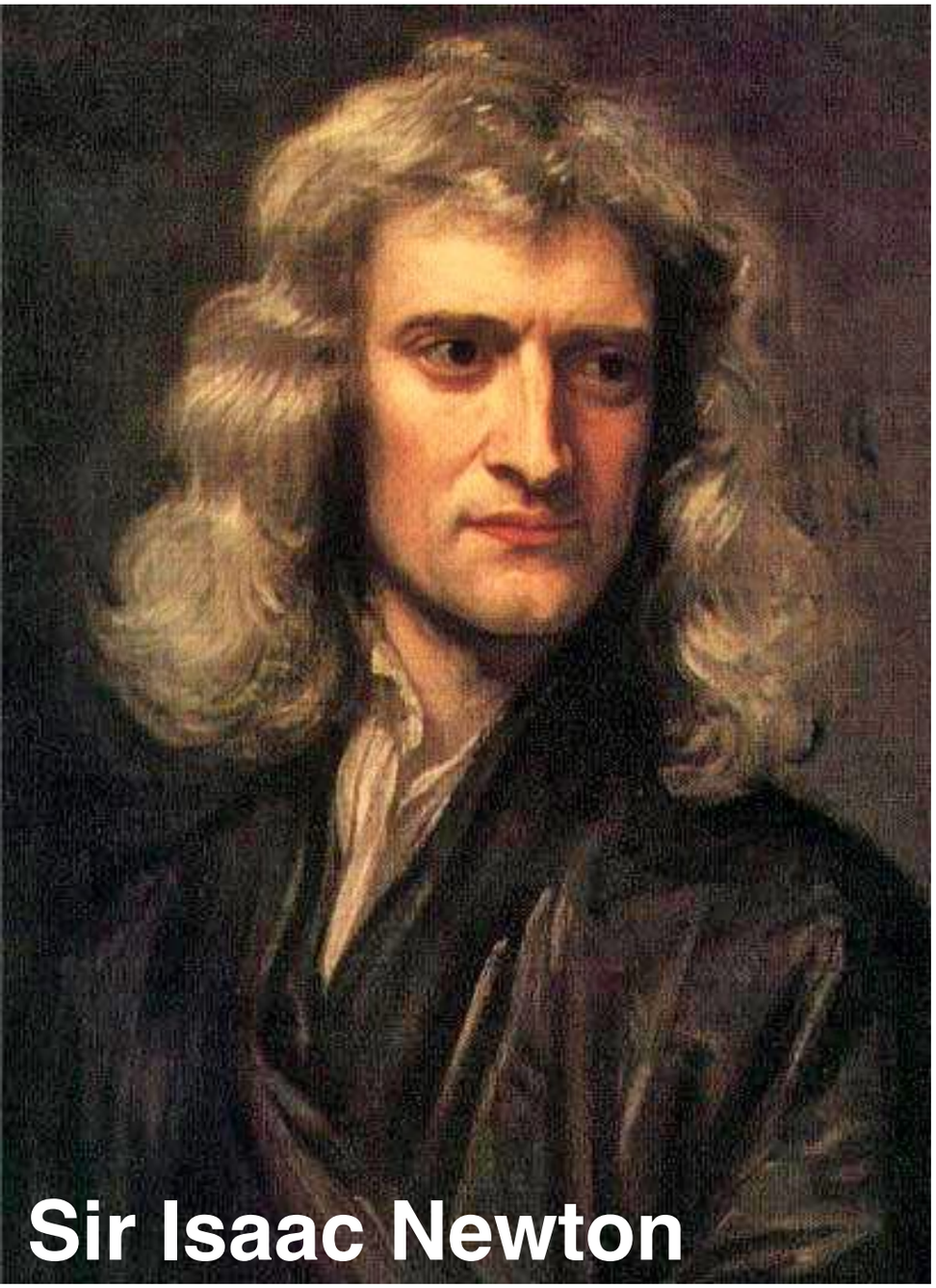


map from http://www.nationsonline.org/maps/political_world_map3000.jpg

Simulation of the event



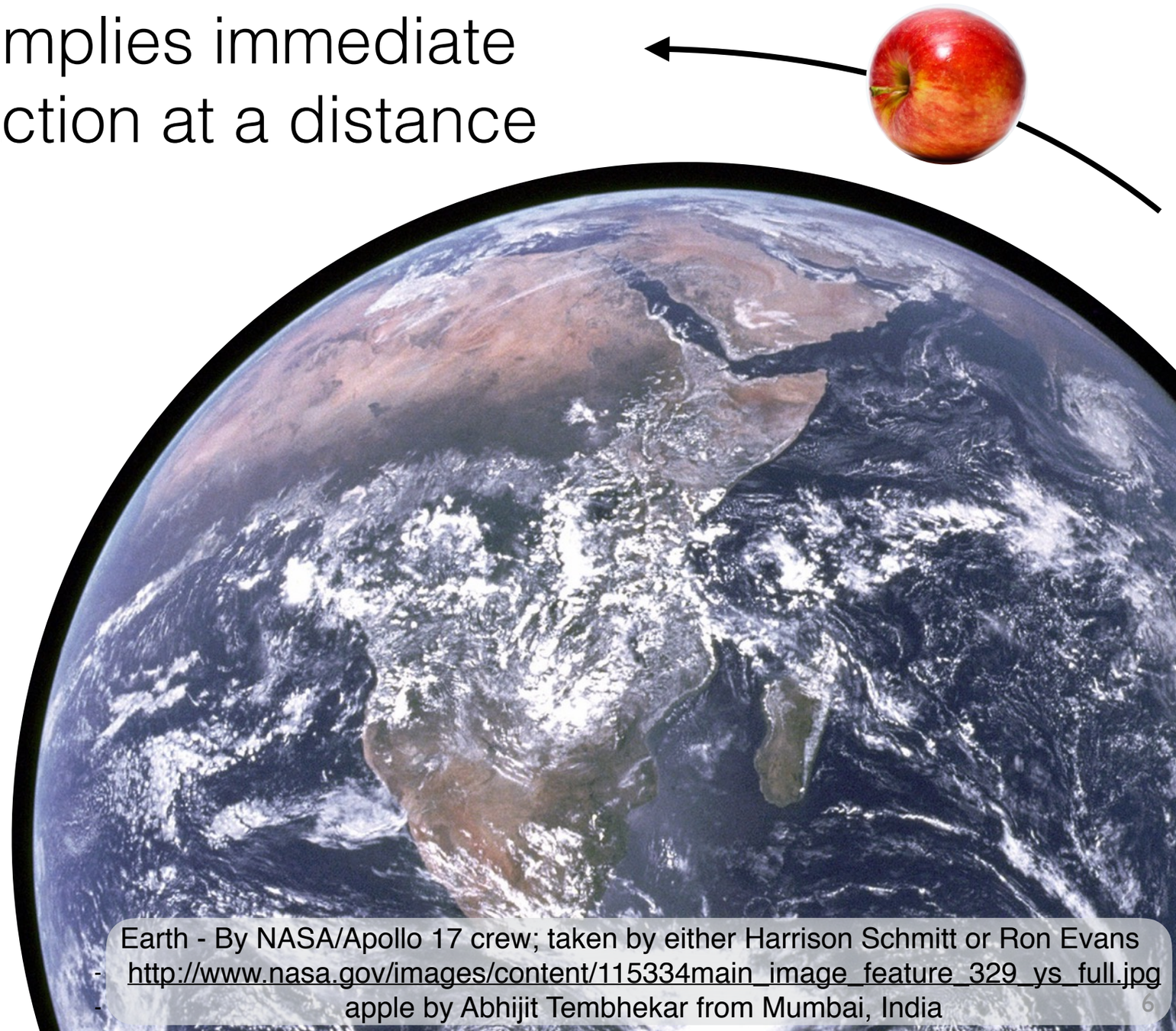
What is a Gravitational Wave?



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

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

Implies immediate action at a distance



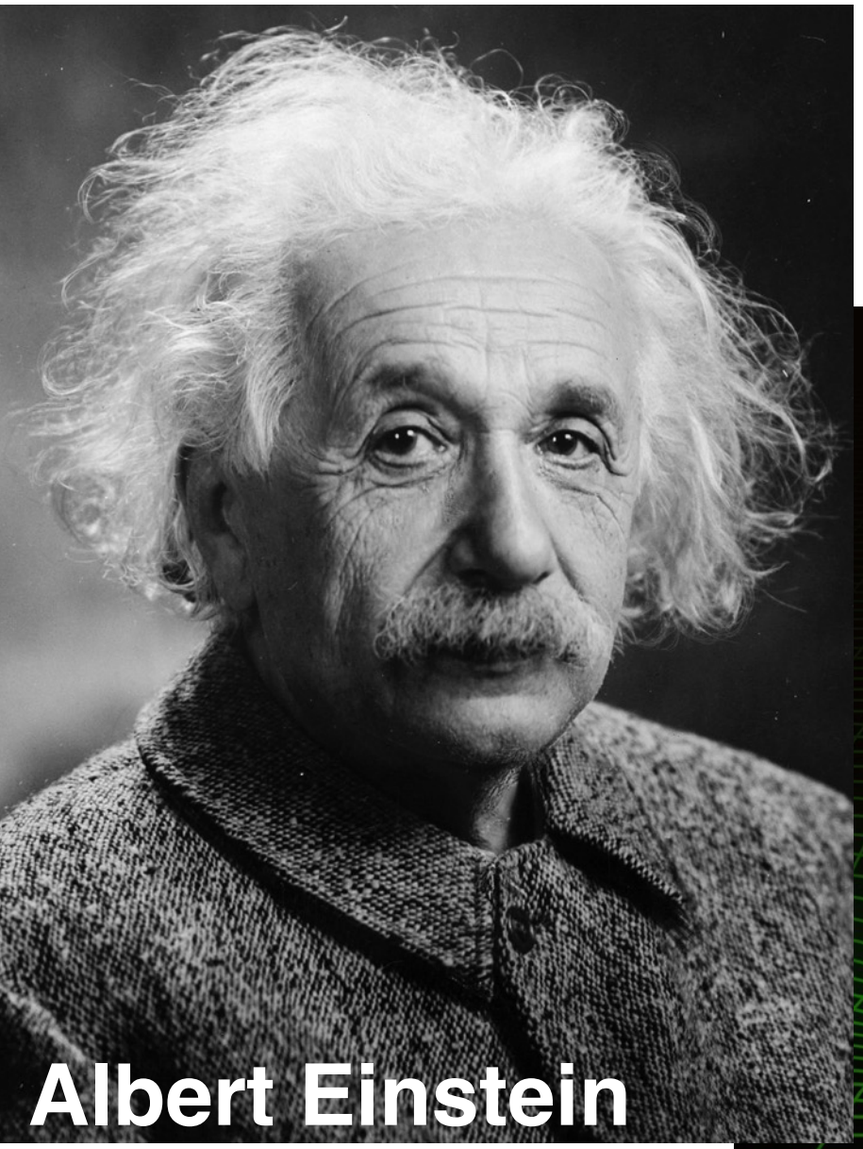
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

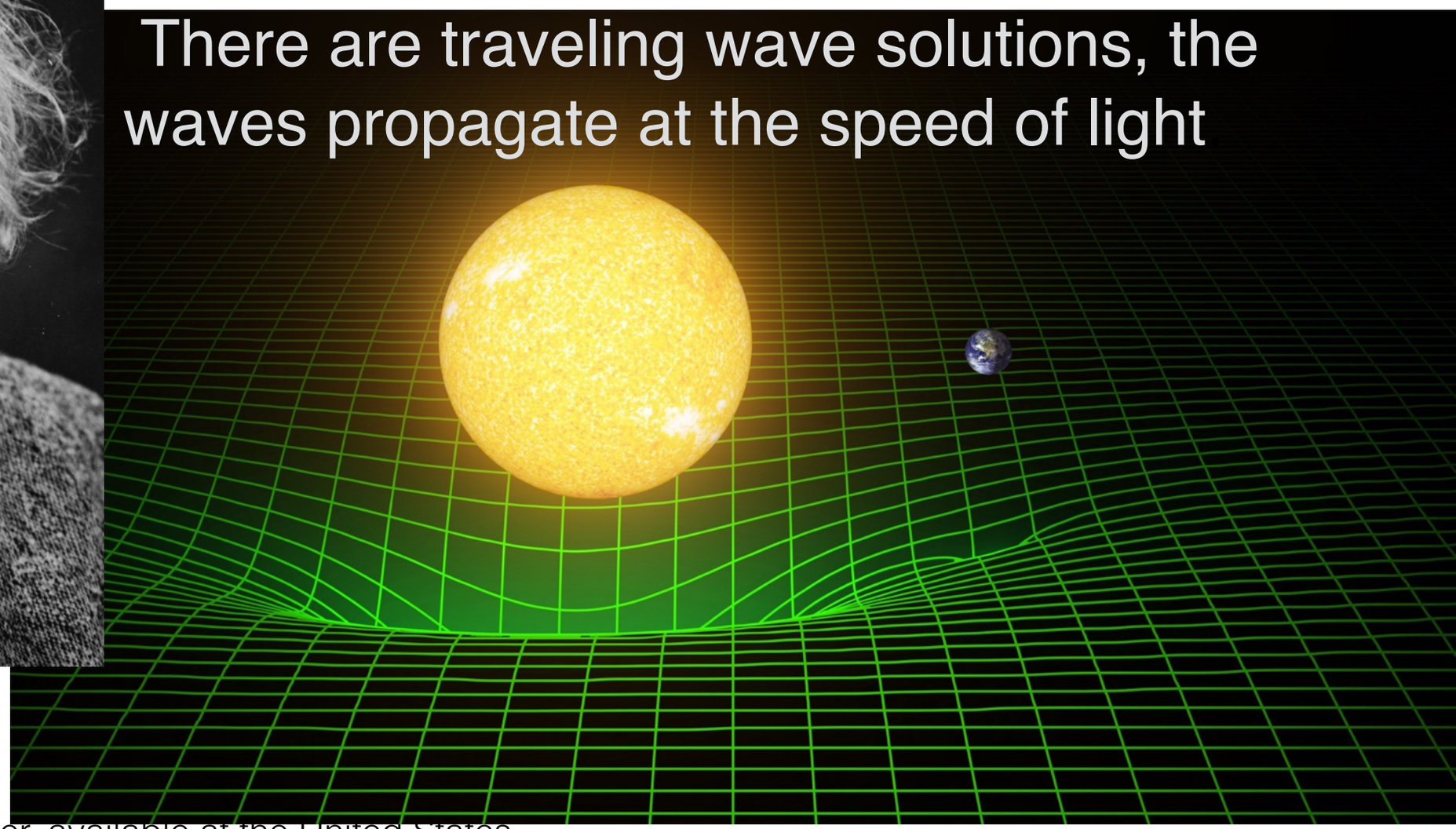
What is a Gravitational Wave?

Predicted by Einstein in 1916 as part of GR.

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

- J. A. Wheeler





Photograph by Orren Jack Turner, available at the United States Library of Congress's Prints and Photographs digital ID cph.3b46036.

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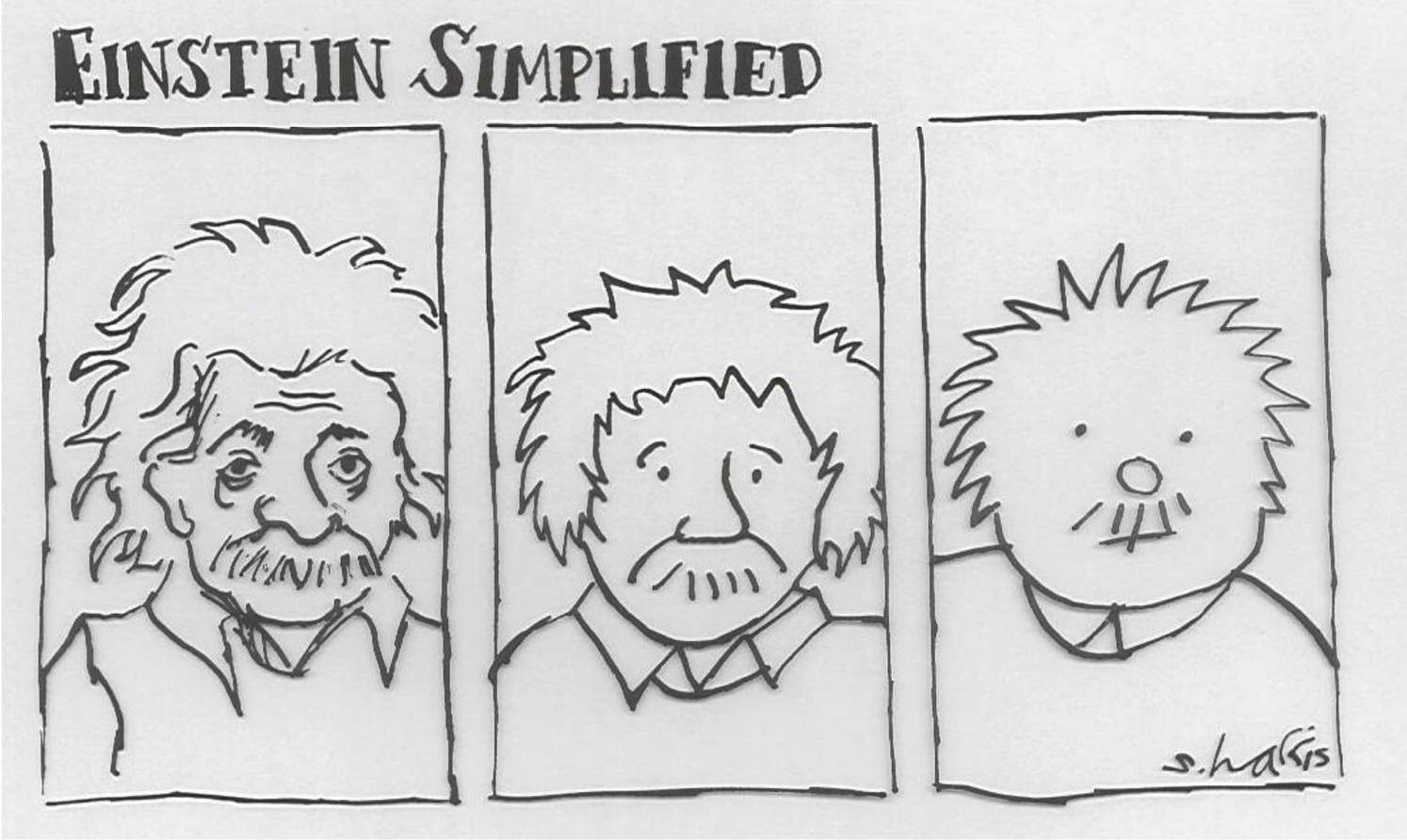


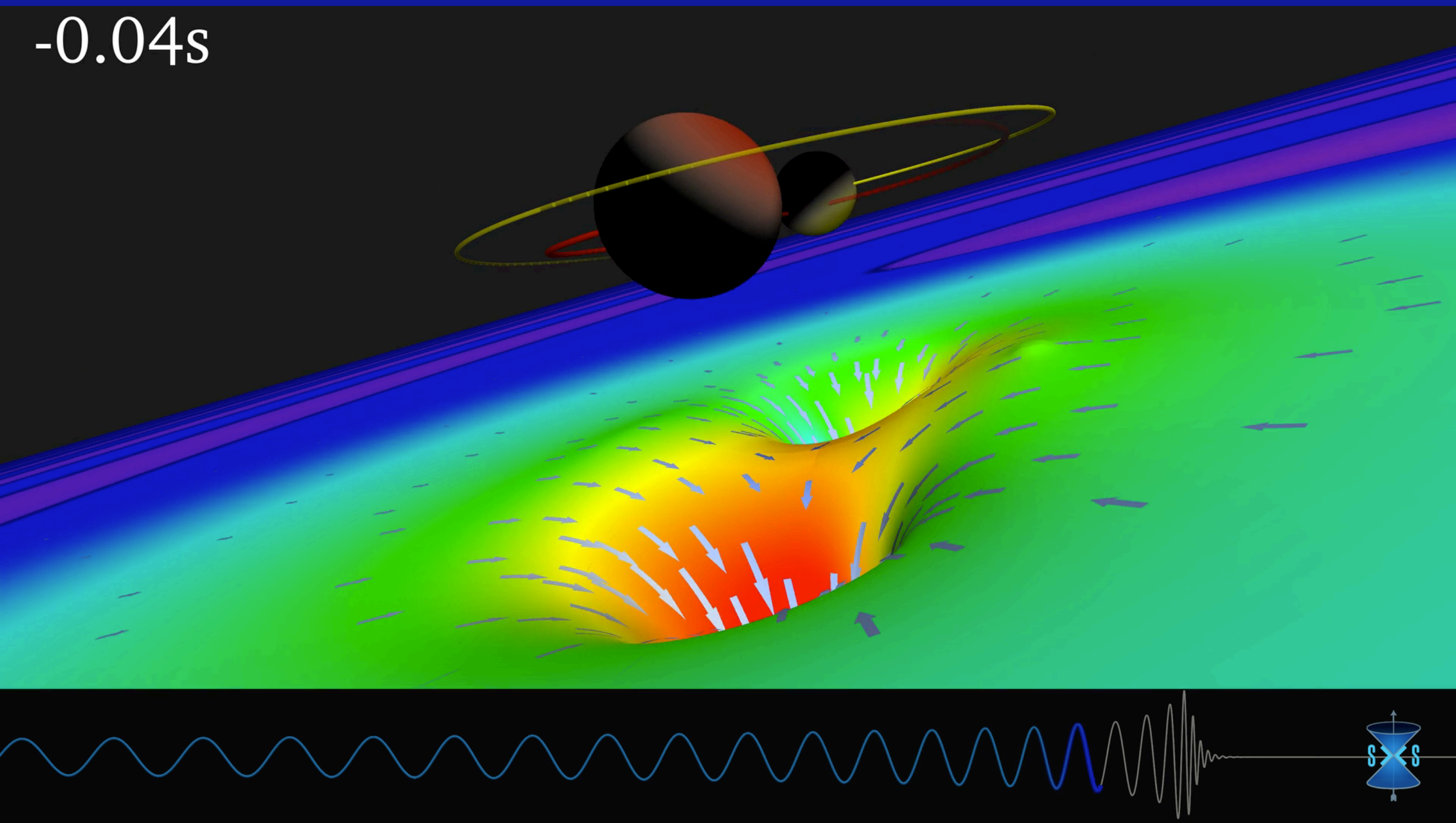
Assert an analogy:

A stationary electron has an electric field, and accelerating the electron creates waves.

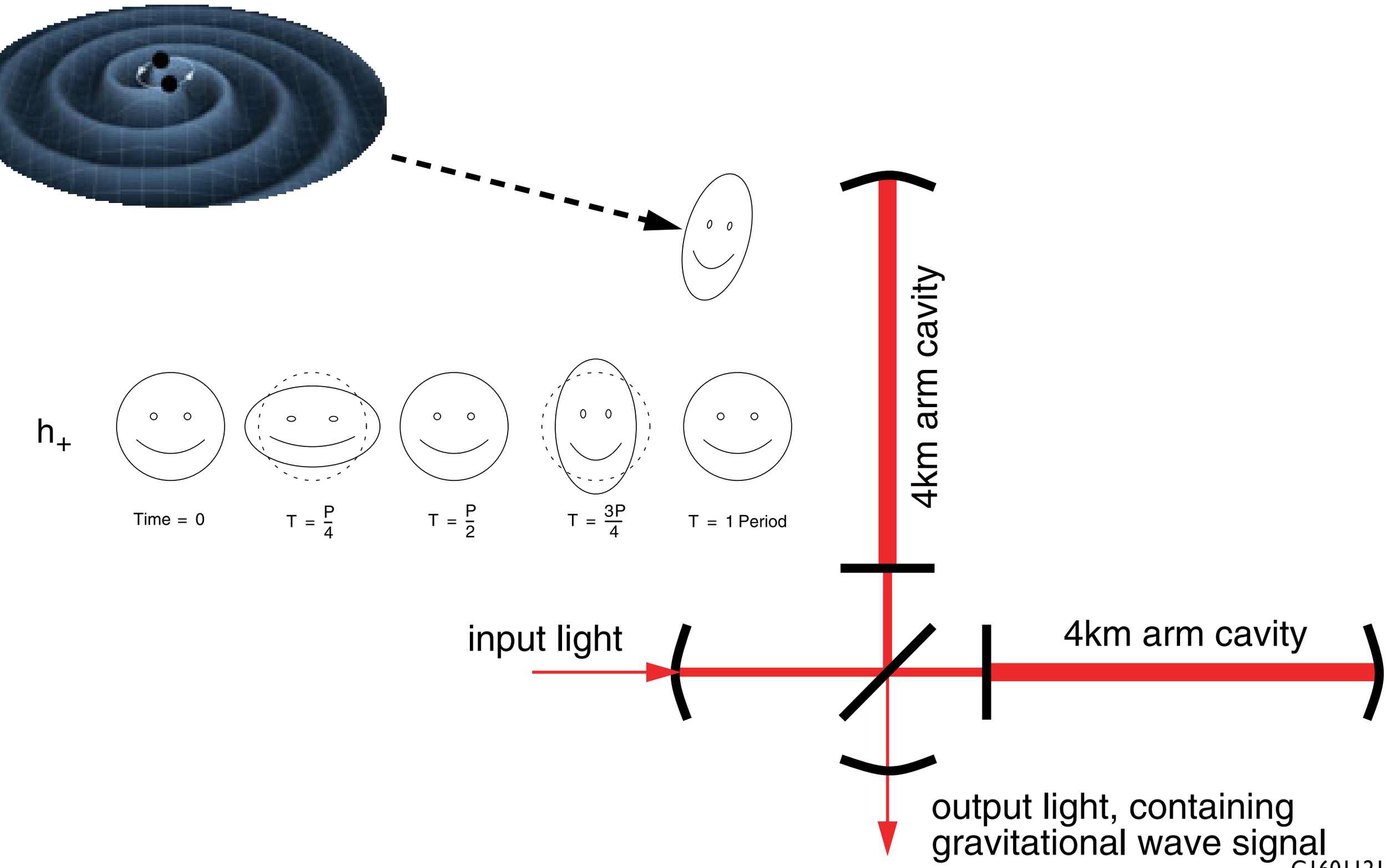
A stationary mass has a gravitational field, and accelerating the mass creates waves.

But, gravitational forces are relatively weak, or space is very stiff.

Simulation of the event



The LIGO concept

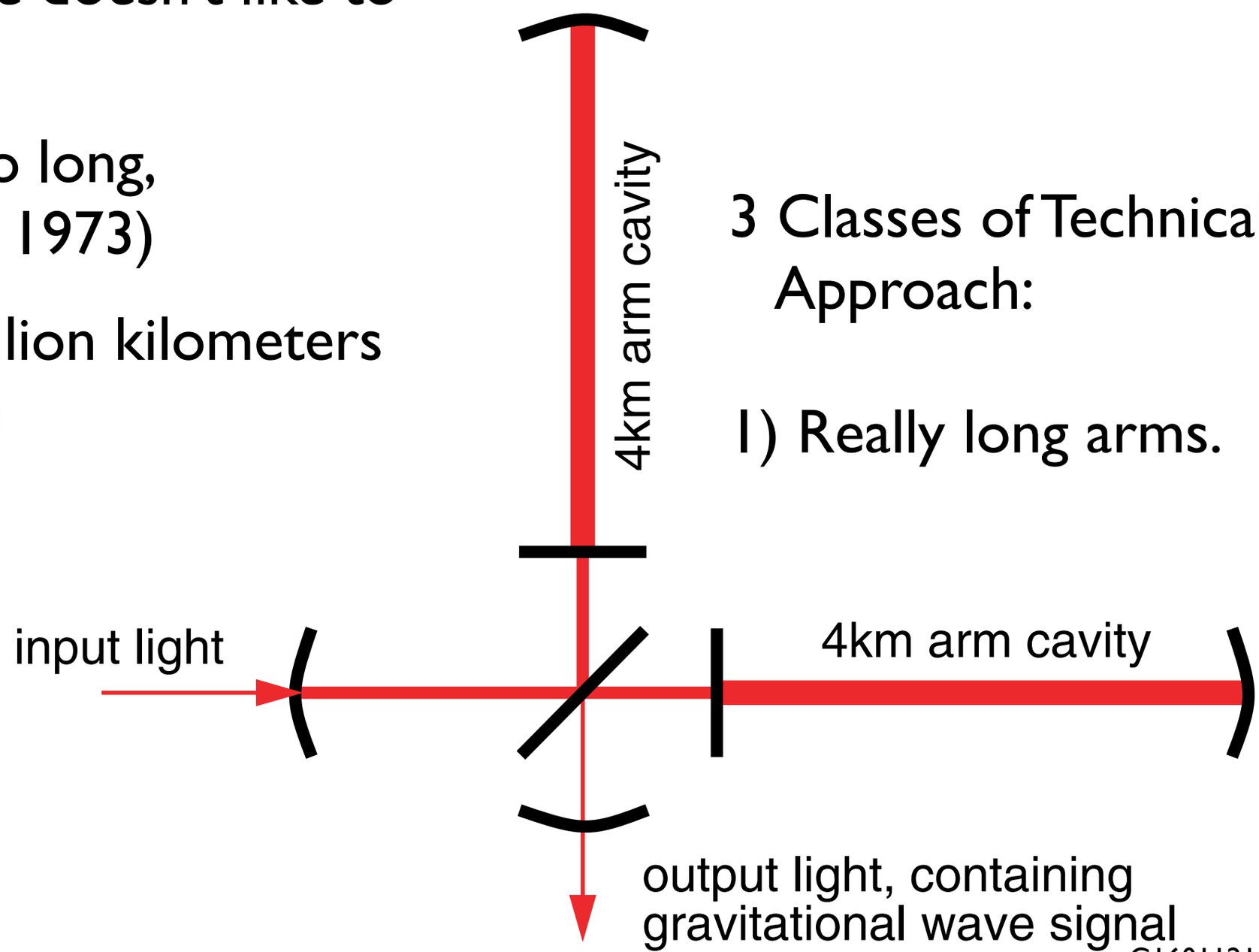


The LIGO concept why it is nearly impossible

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)

Earth-to-Sun ~ 150 million kilometers
1.5e11 m * 1e-21strain
= 1.5e-10 meters

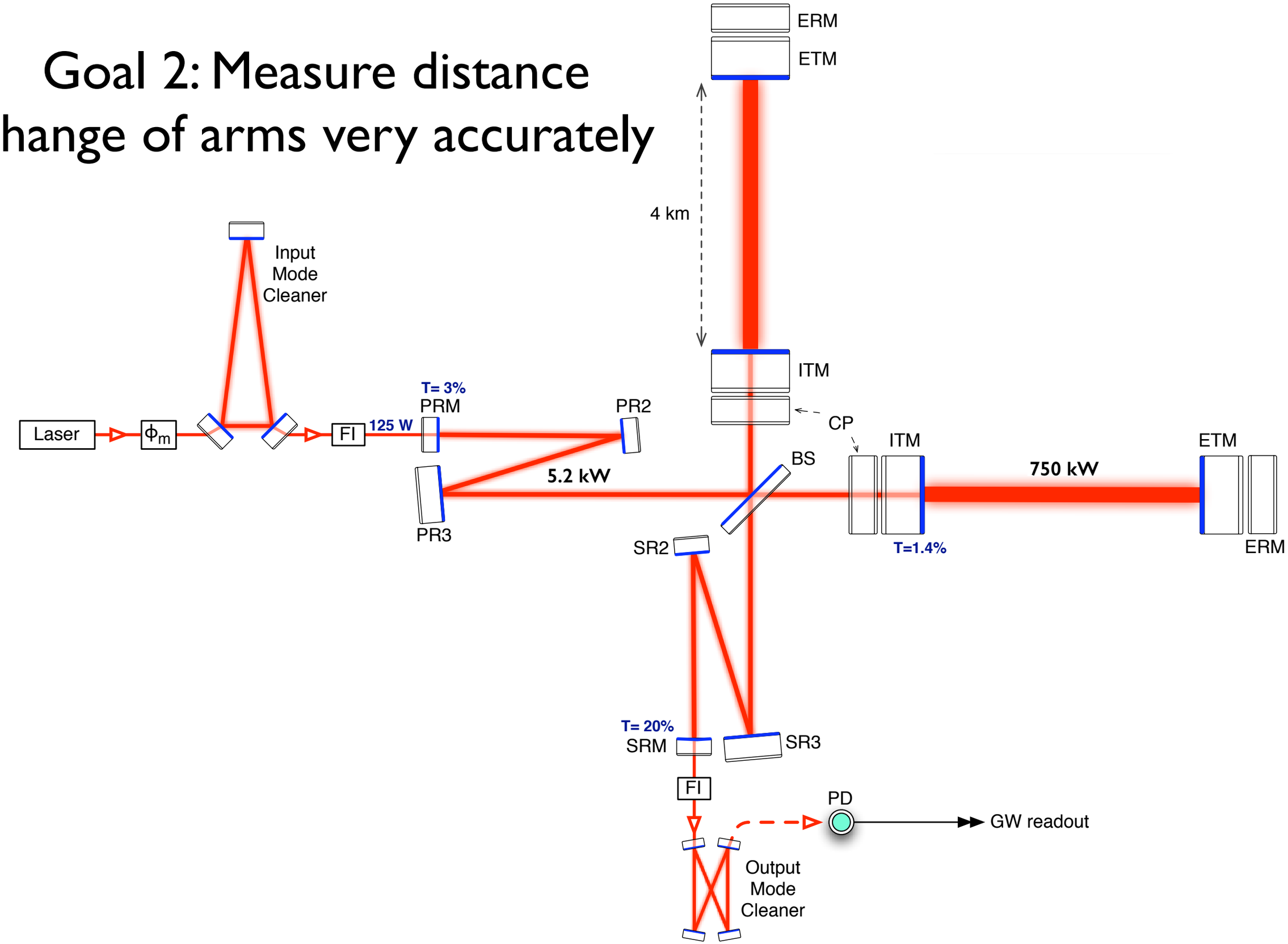


3 Classes of Technical Approach:

1) Really long arms.

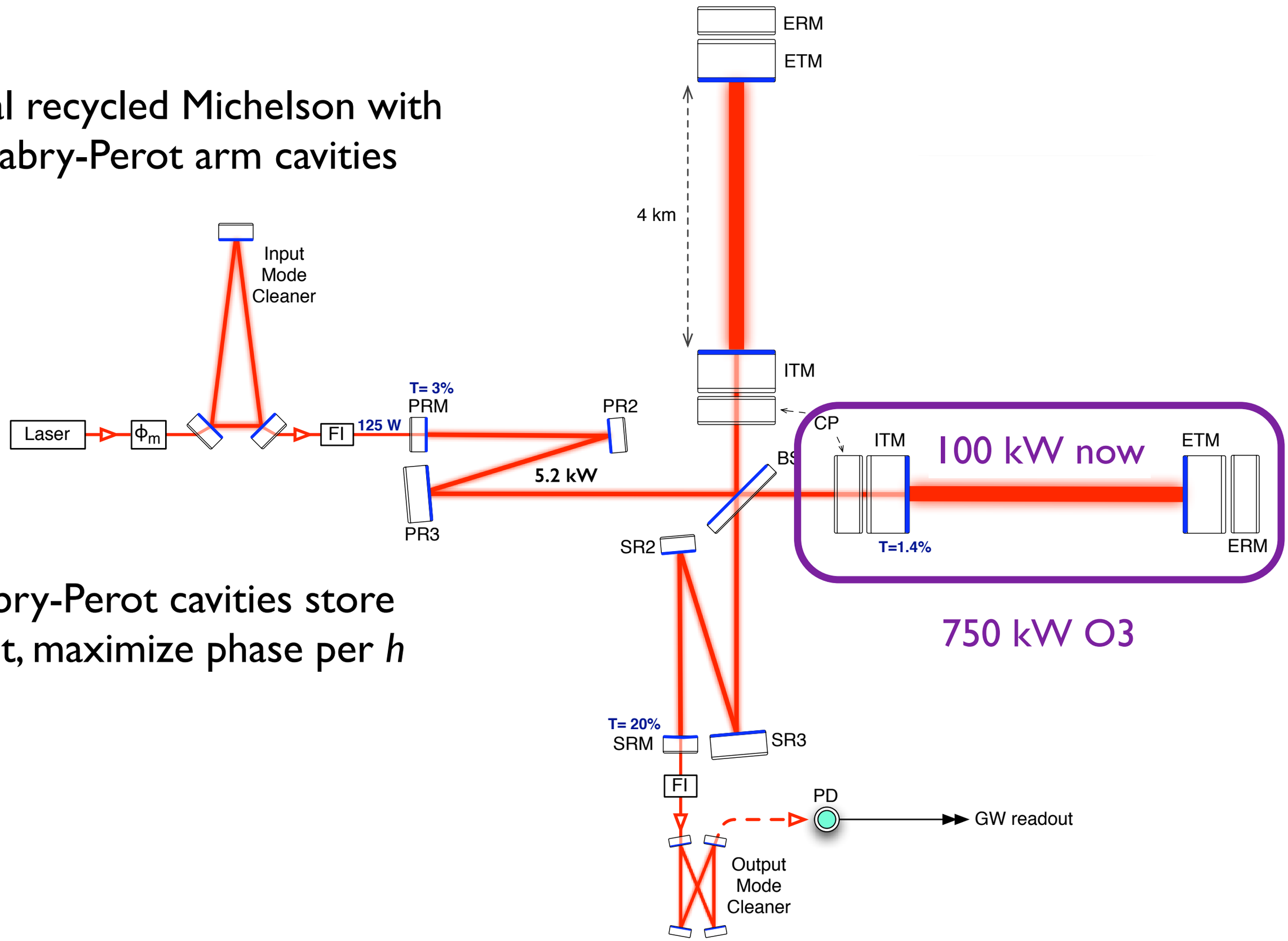
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately



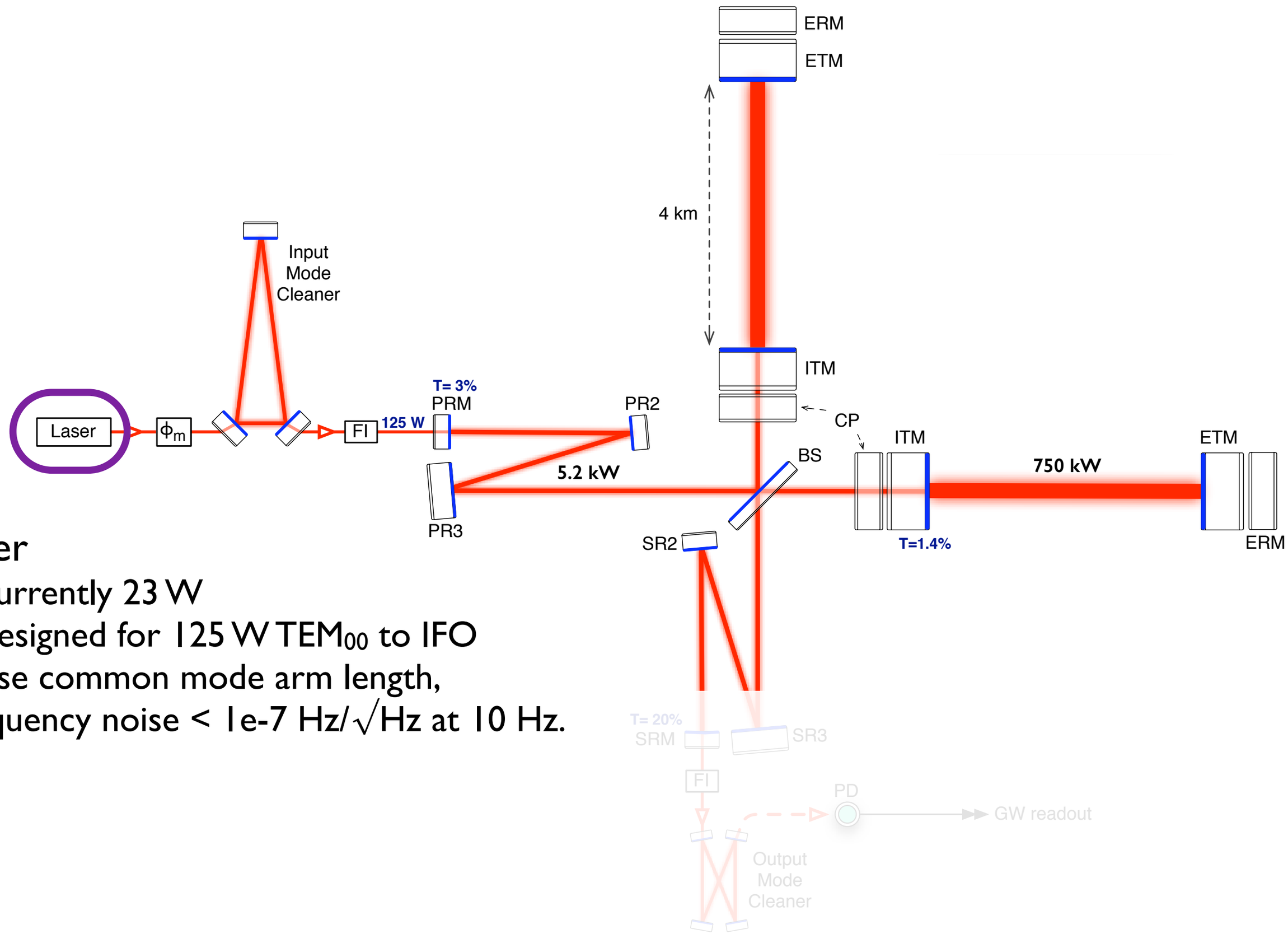
Fabry-Perot arms

Dual recycled Michelson with Fabry-Perot arm cavities



Fabry-Perot cavities store light, maximize phase per *h*

Power



Laser

- currently 23 W
- designed for 125 W TEM_{00} to IFO
- use common mode arm length,

frequency noise < 1e-7 Hz/$\sqrt{\text{Hz}}$ at 10 Hz.

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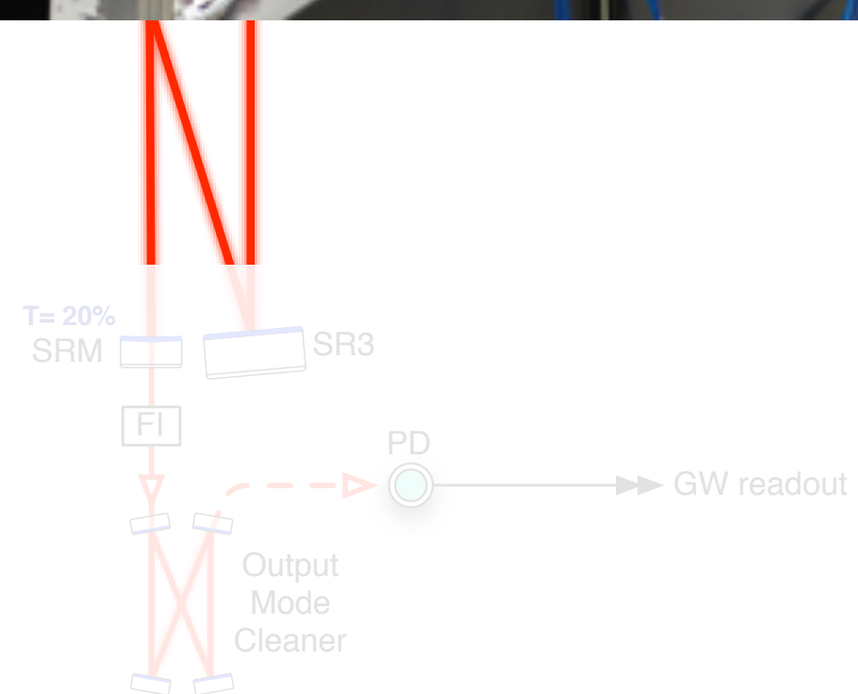
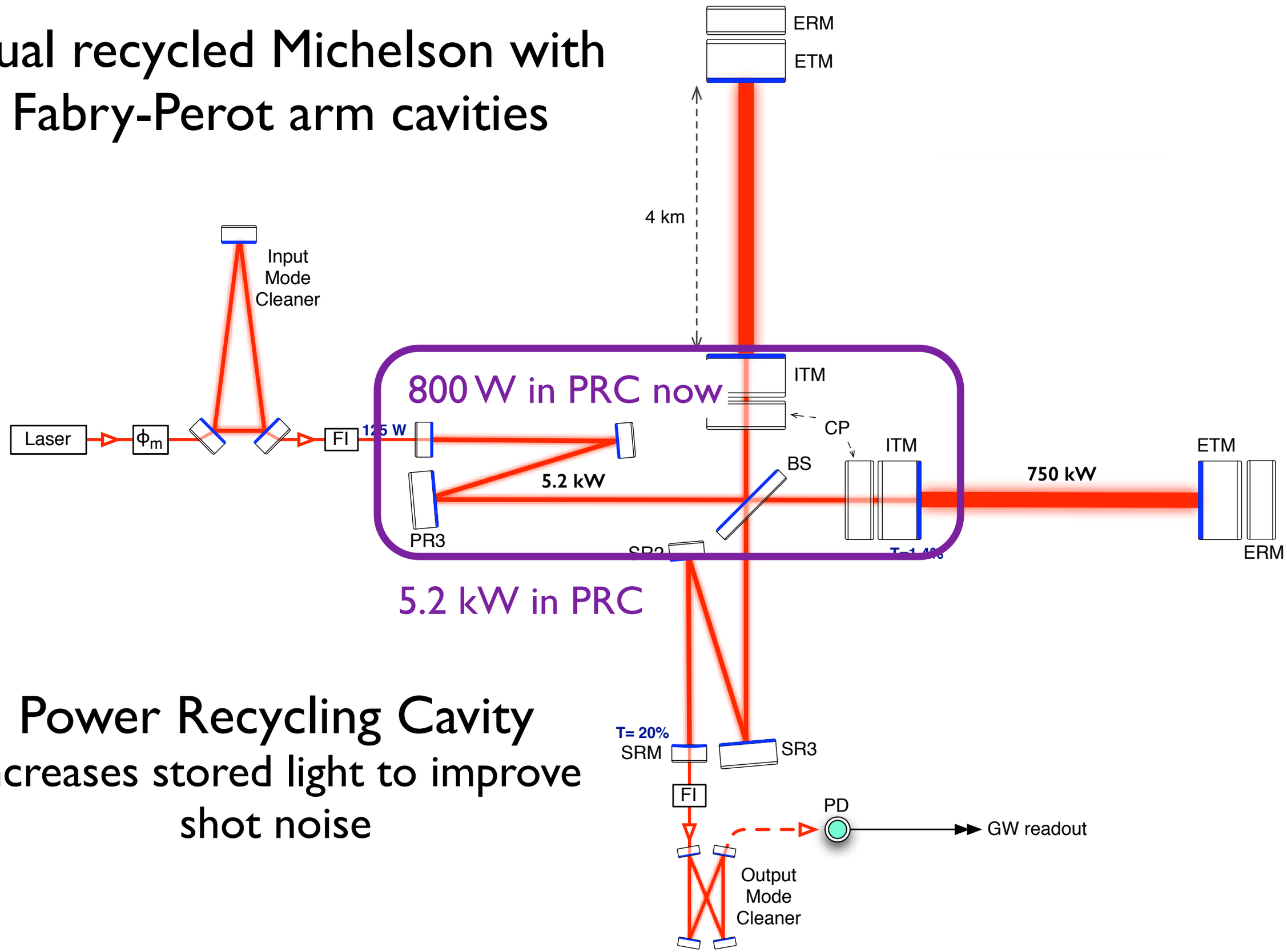


Power recycling

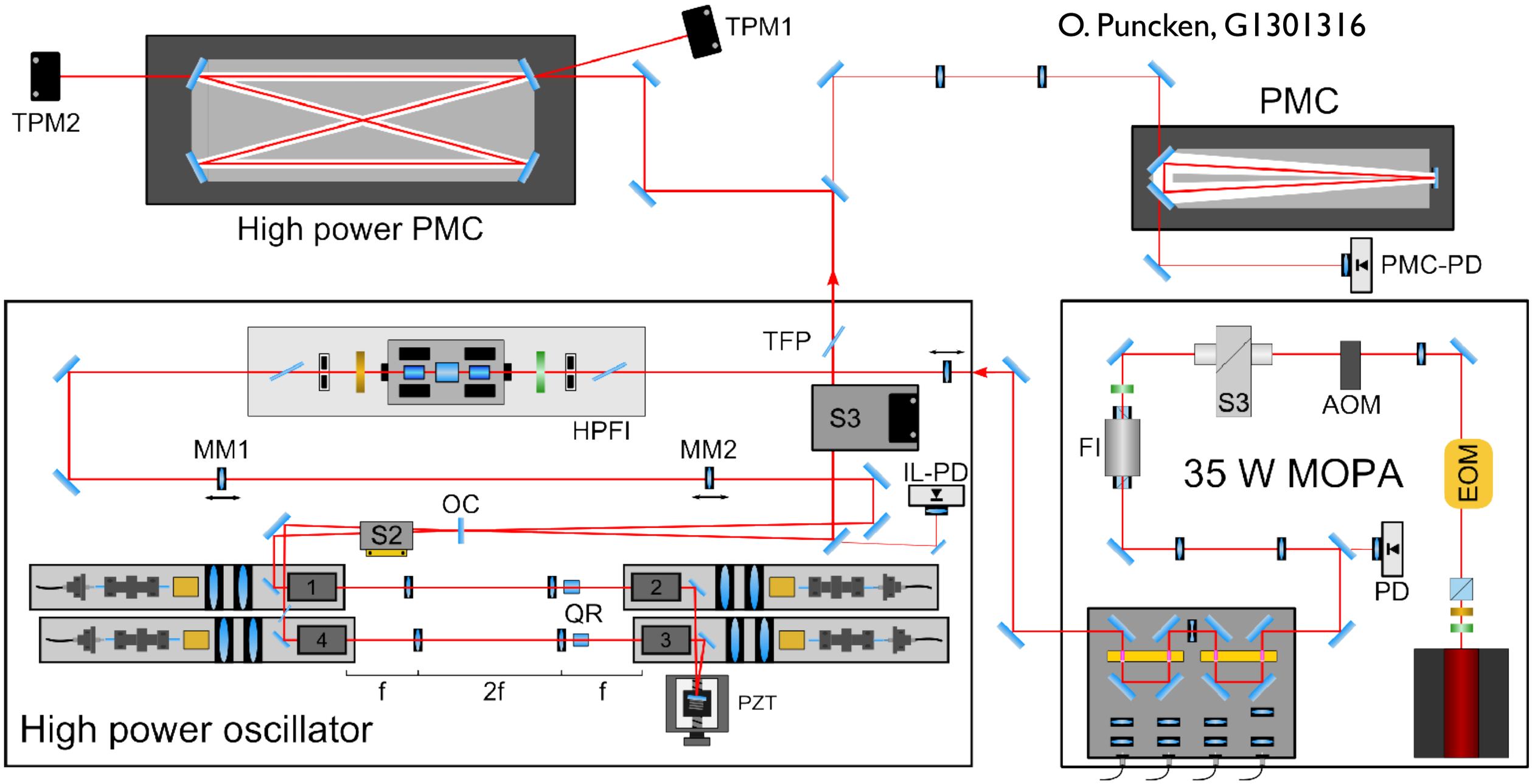
Dual recycled Michelson with Fabry-Perot arm cavities



Power Recycling Cavity
increases stored light to improve shot noise

aLIGO Laser (by L.Z.H.)

O. Puncken, G1301316



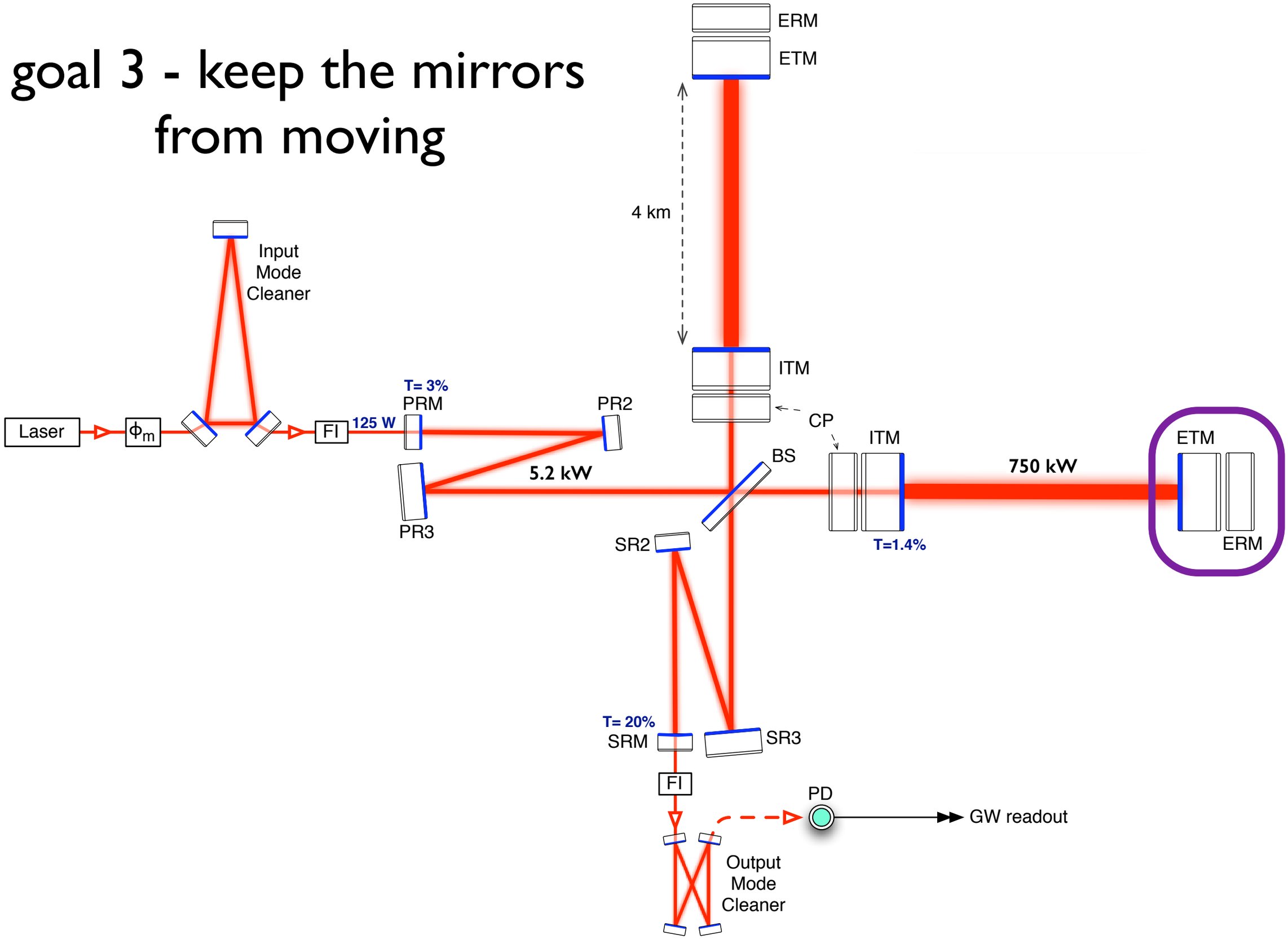
Commercial NPRO, 2 W, Nd:YAG crystal pumped by laser diodes at 808 nm

Medium power amp, 35 W, 4 Nd:YVO_4 crystals pumped fiber-coupled LD at 808 nm

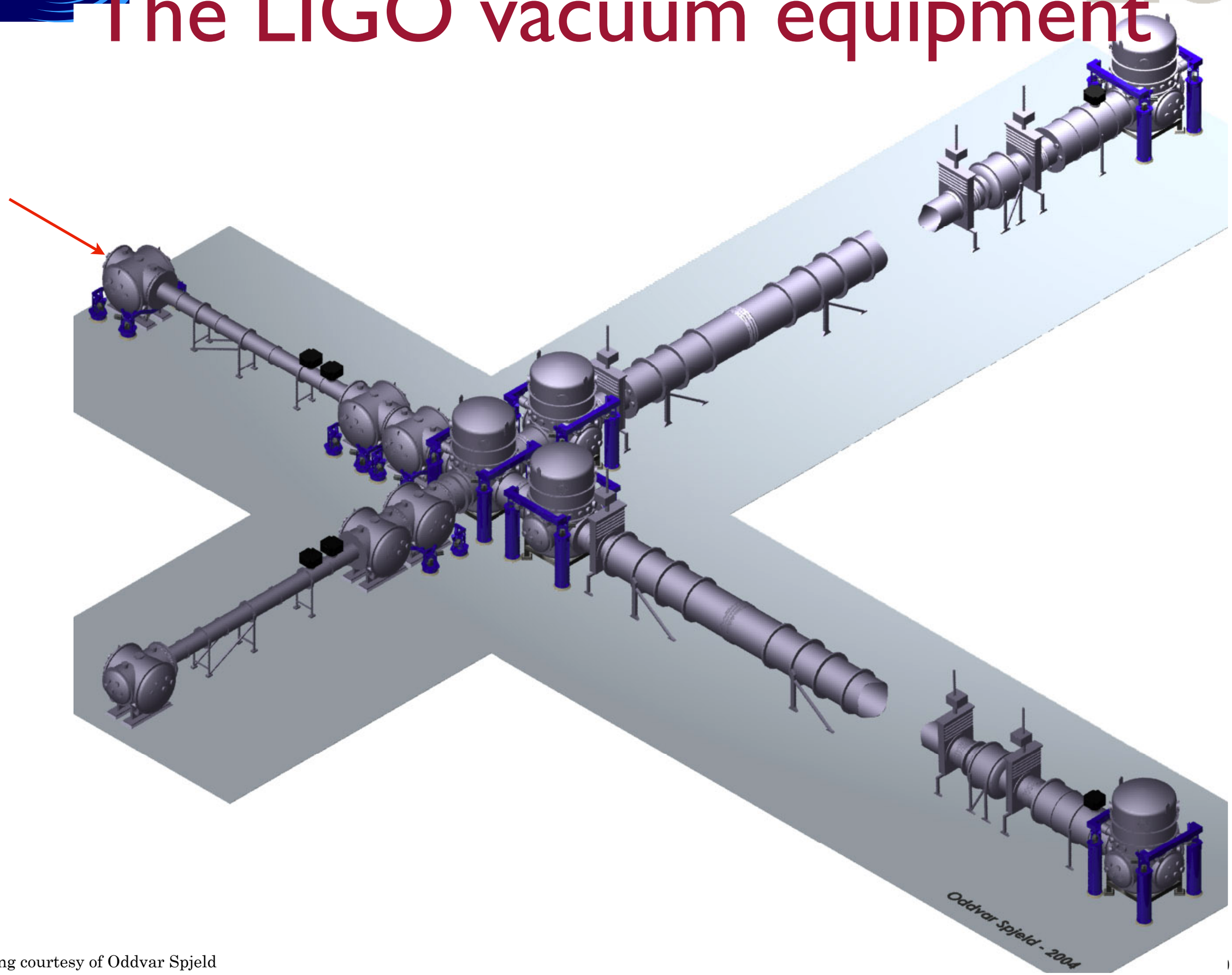
Ring oscillator, 220 W, 4 Nd:YAG crystals each pumped by 7 LD at 808 nm

Layout of the interferometer

goal 3 - keep the mirrors from moving

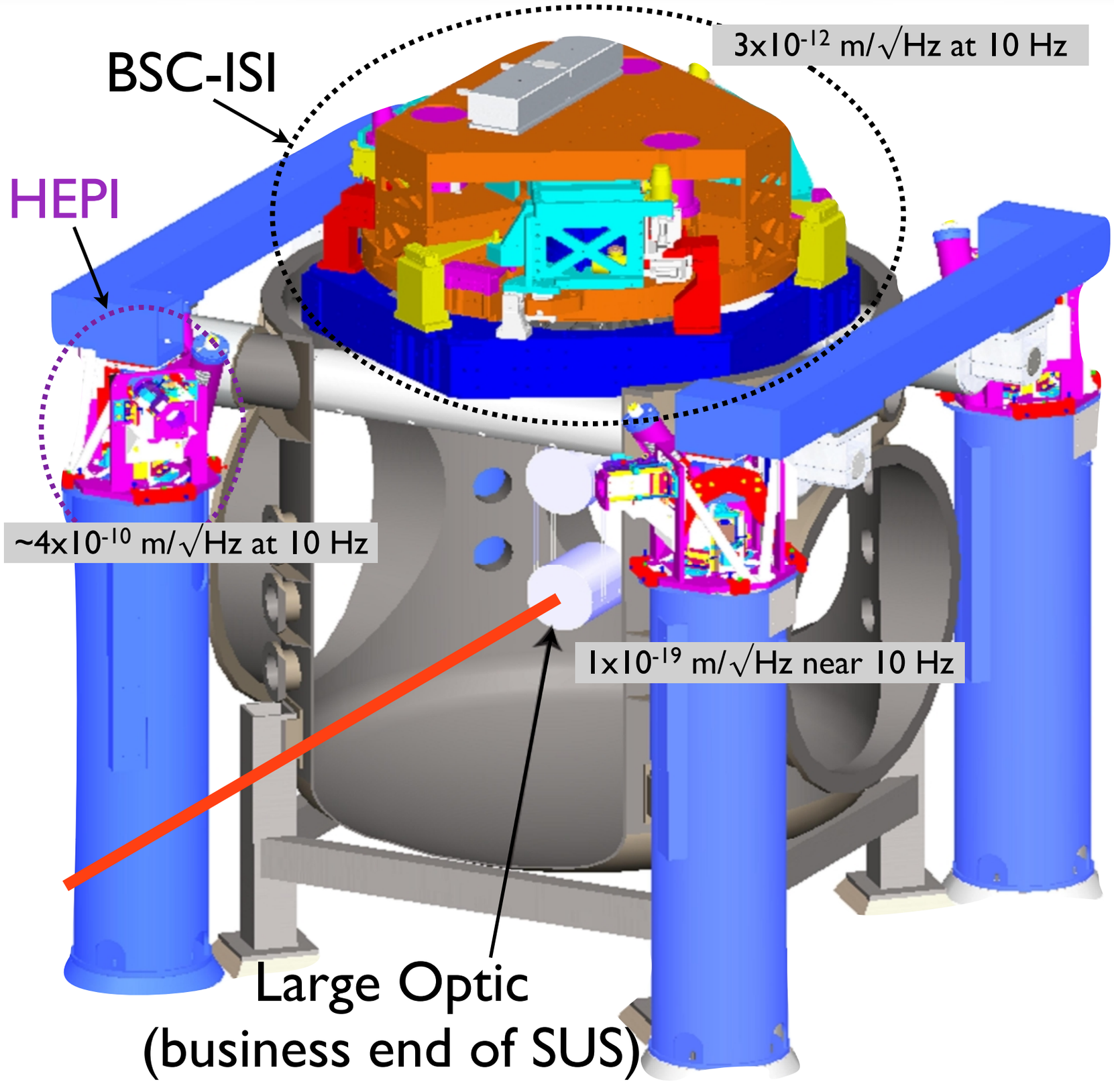


The LIGO vacuum equipment



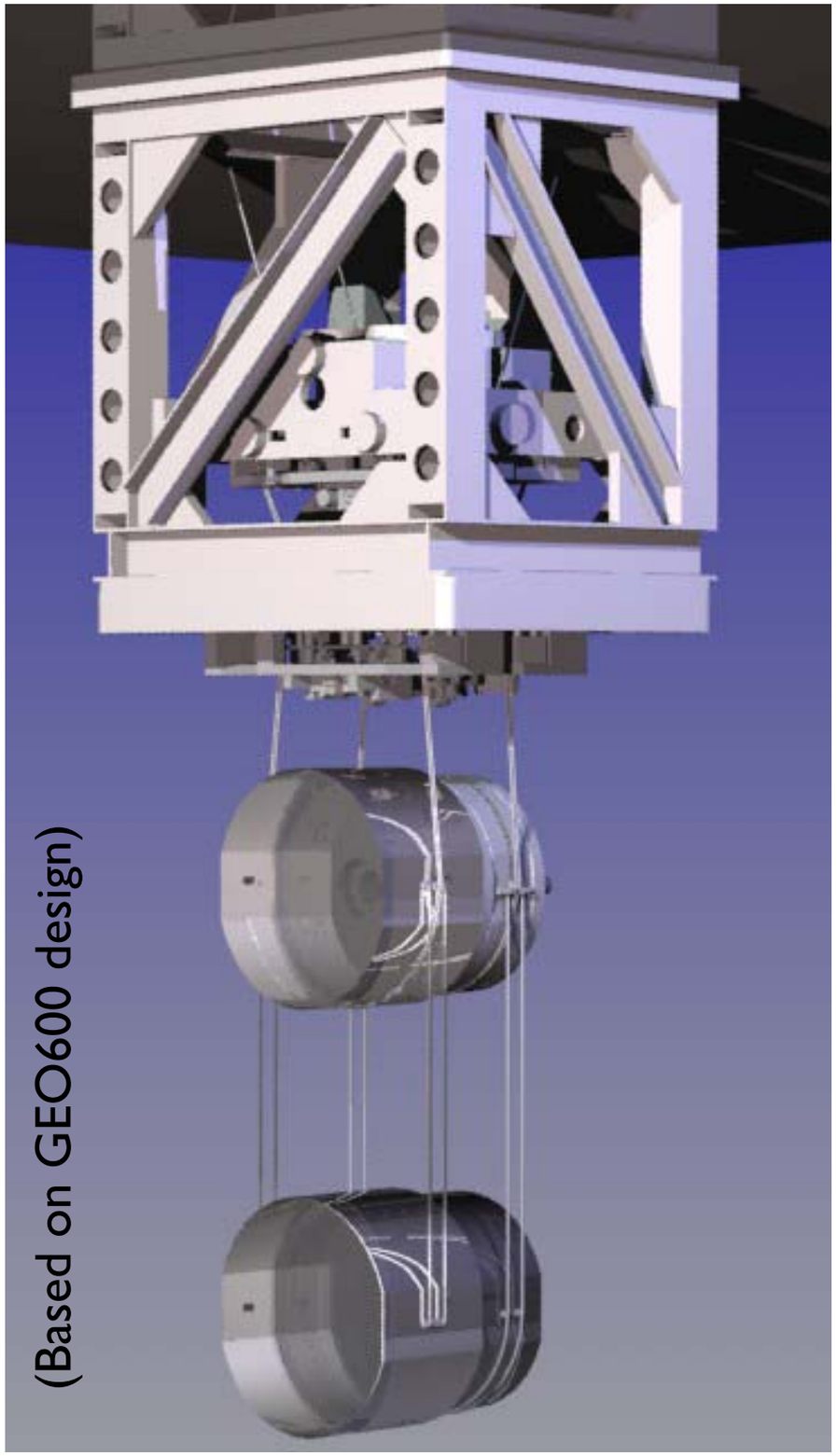
drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses



Pendulum Suspension

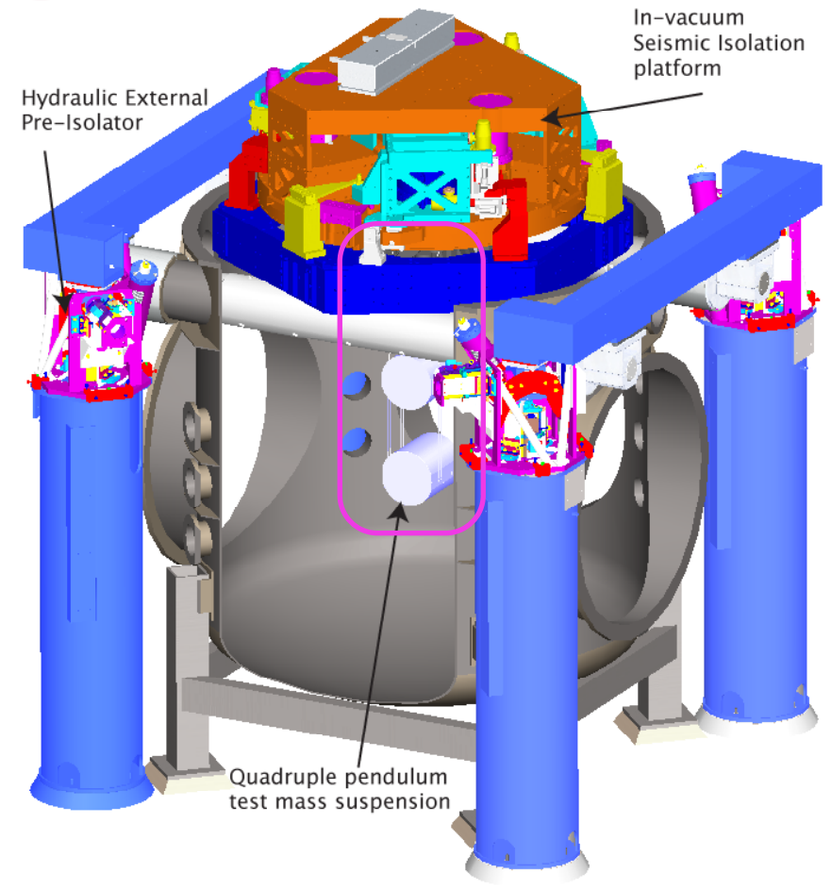
Suspensions material from N. Robertson, GEO600, and the SUS team



Drawings courtesy of Calum Torrie and GEO600

Multiple-pendulums for control flexibility & seismic attenuation

Each stage gives ~$1/f^2$ isolation above the natural frequency.
More that 1e6 at 10 Hz.



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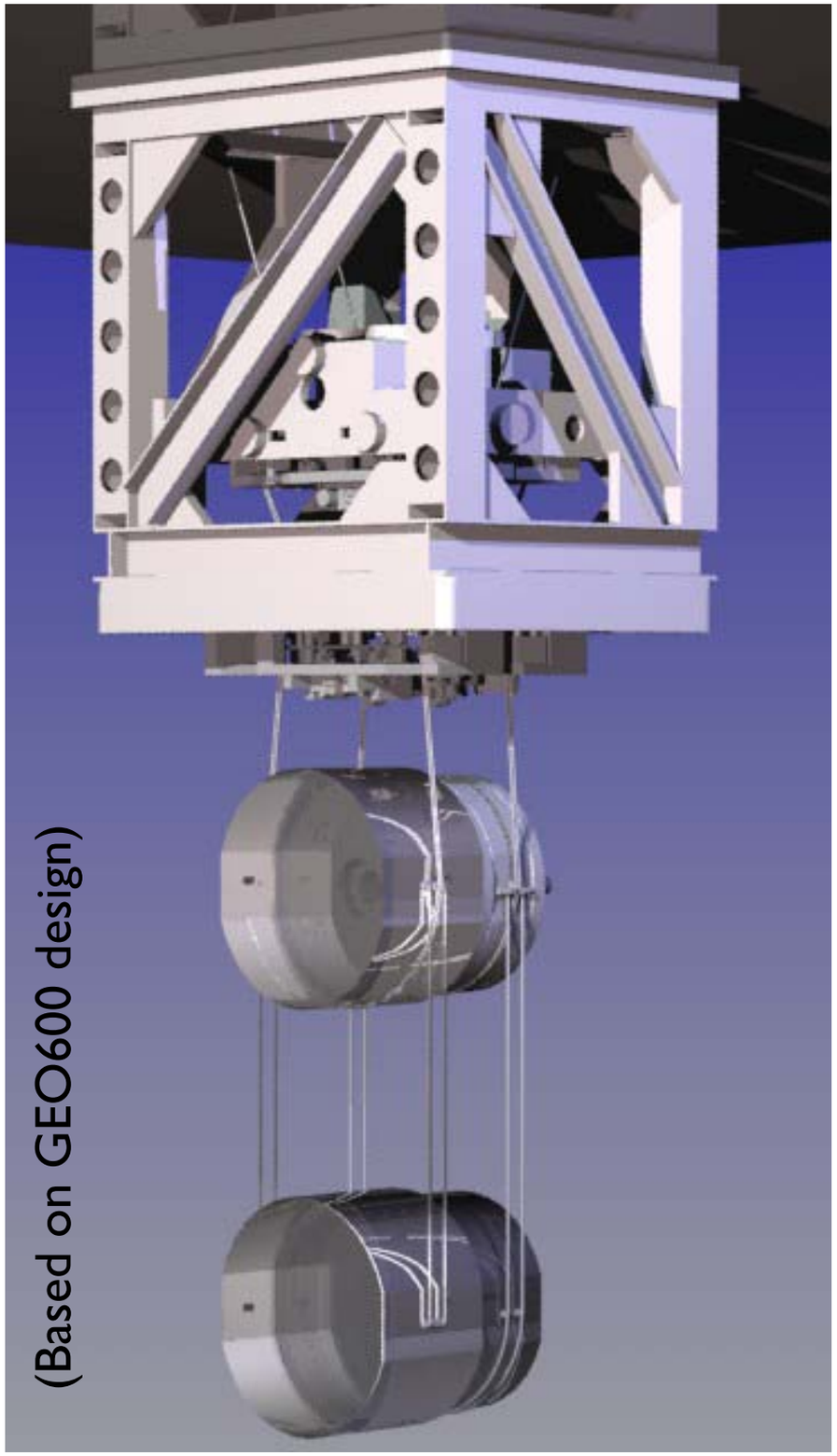

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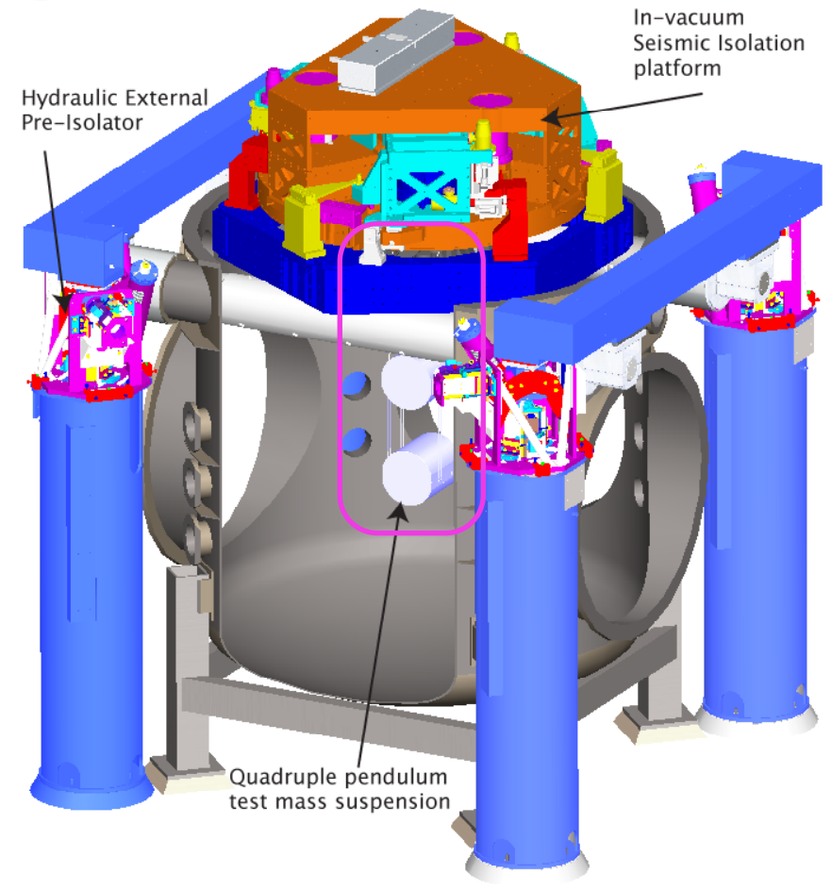
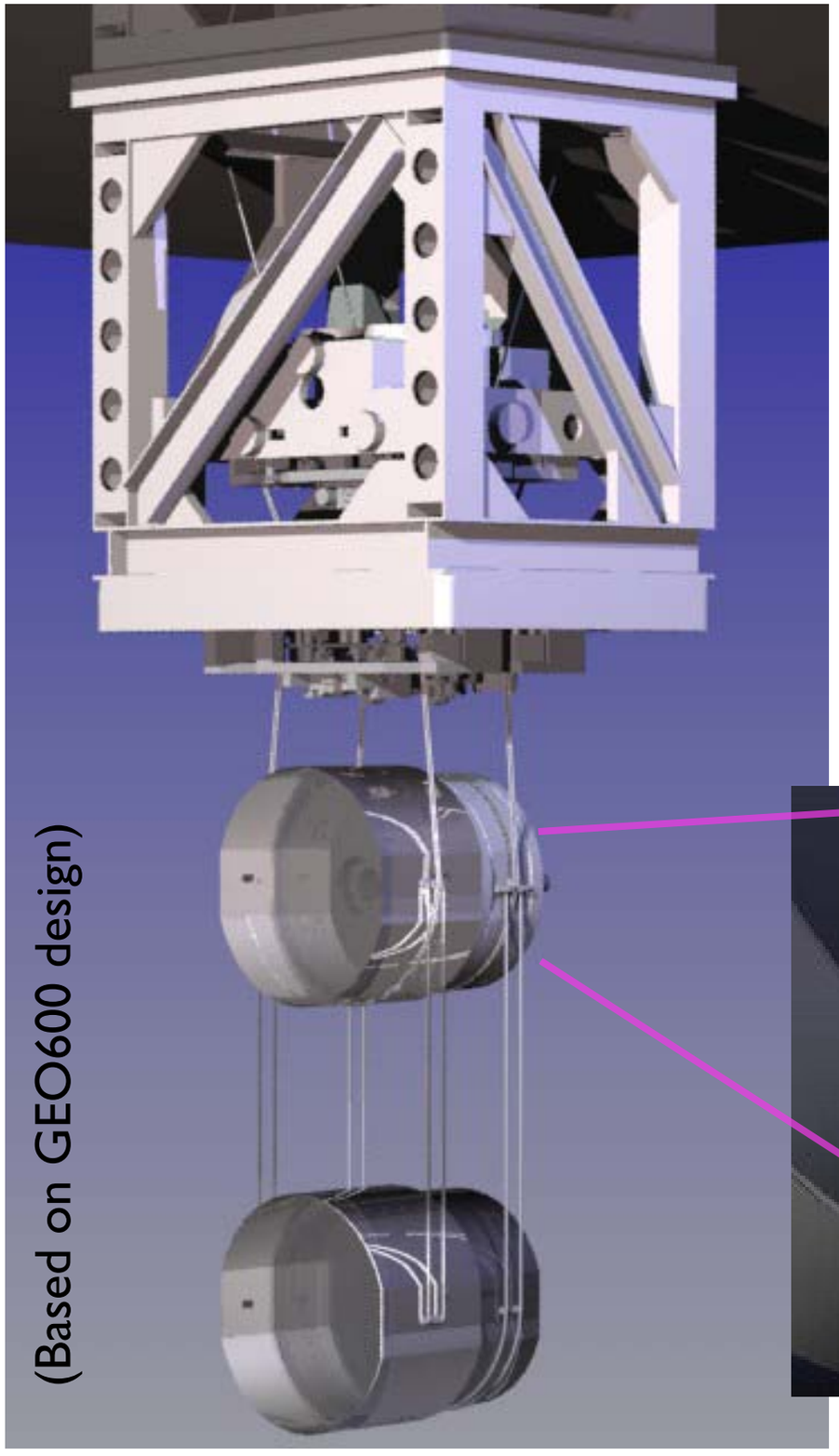


Test masses:
Synthetic fused silica,
40 kg, 34 cm dia.
» Q ≥ 1e7
» low optical absorption

Final suspensions are fused silica, joined to form monolithic final stages.

Thermal vibrations at the optical surface set the performance limit of the suspension.

Pendulum Suspension



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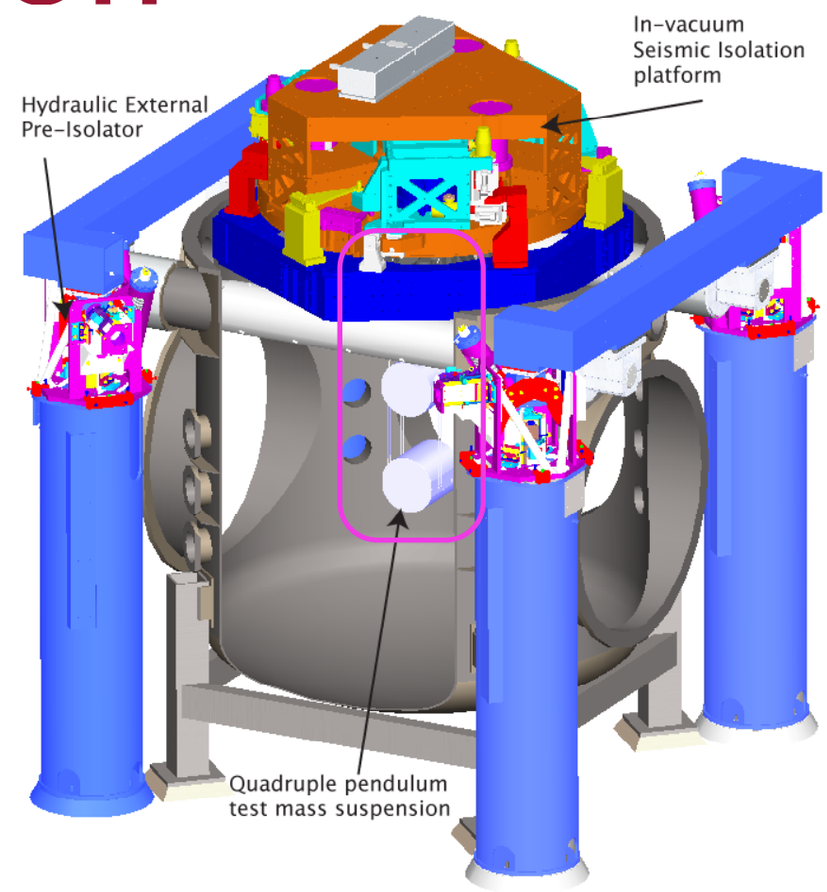
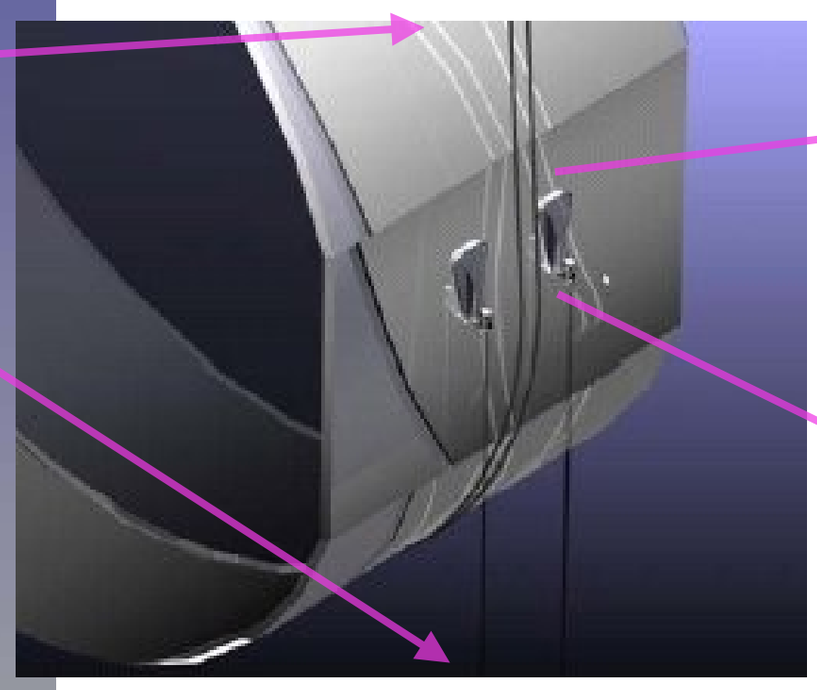
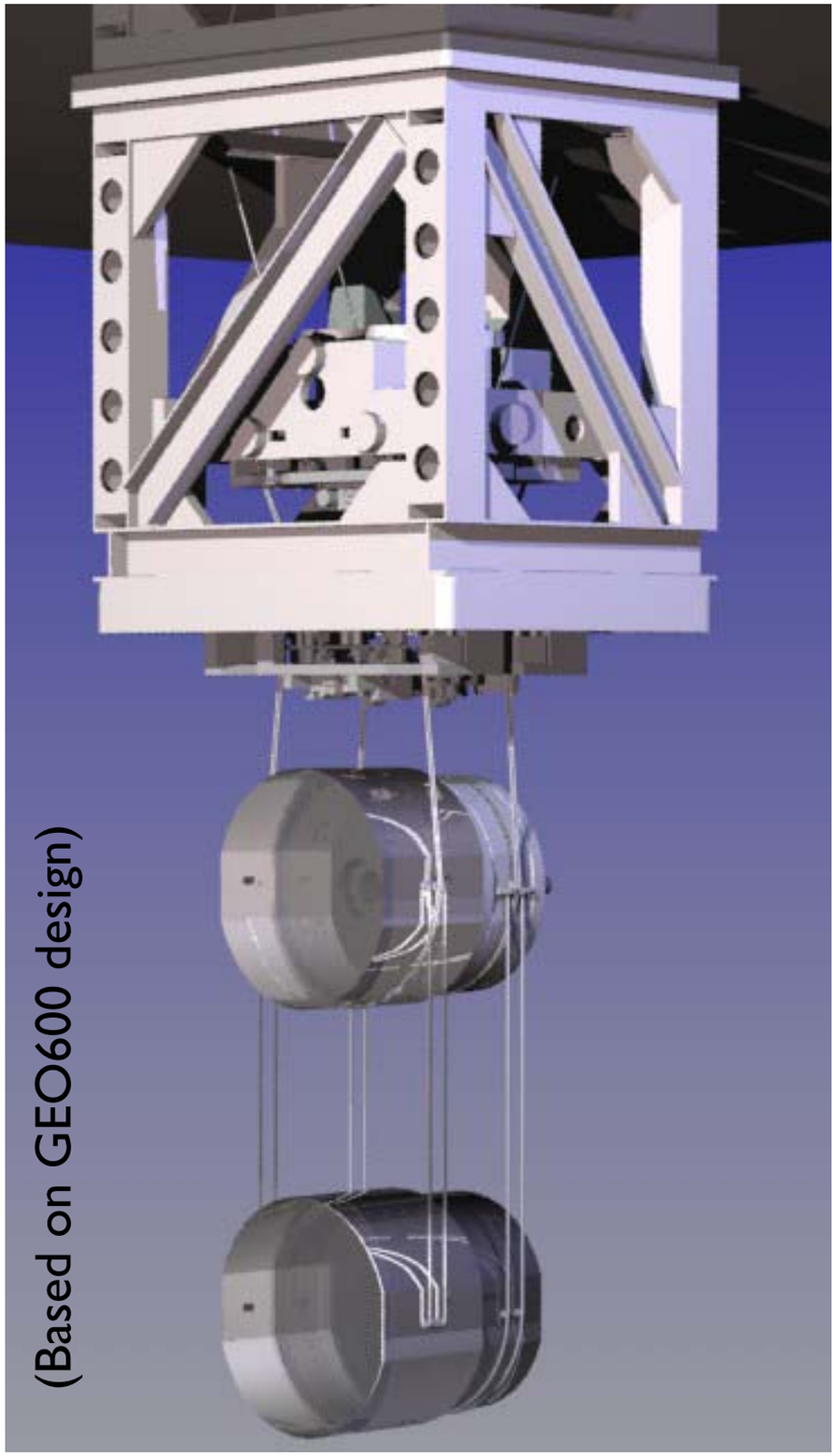




Drawings courtesy of Calum Torrie and GEO600

silicate bonding creates a monolithic final stage

Pendulum



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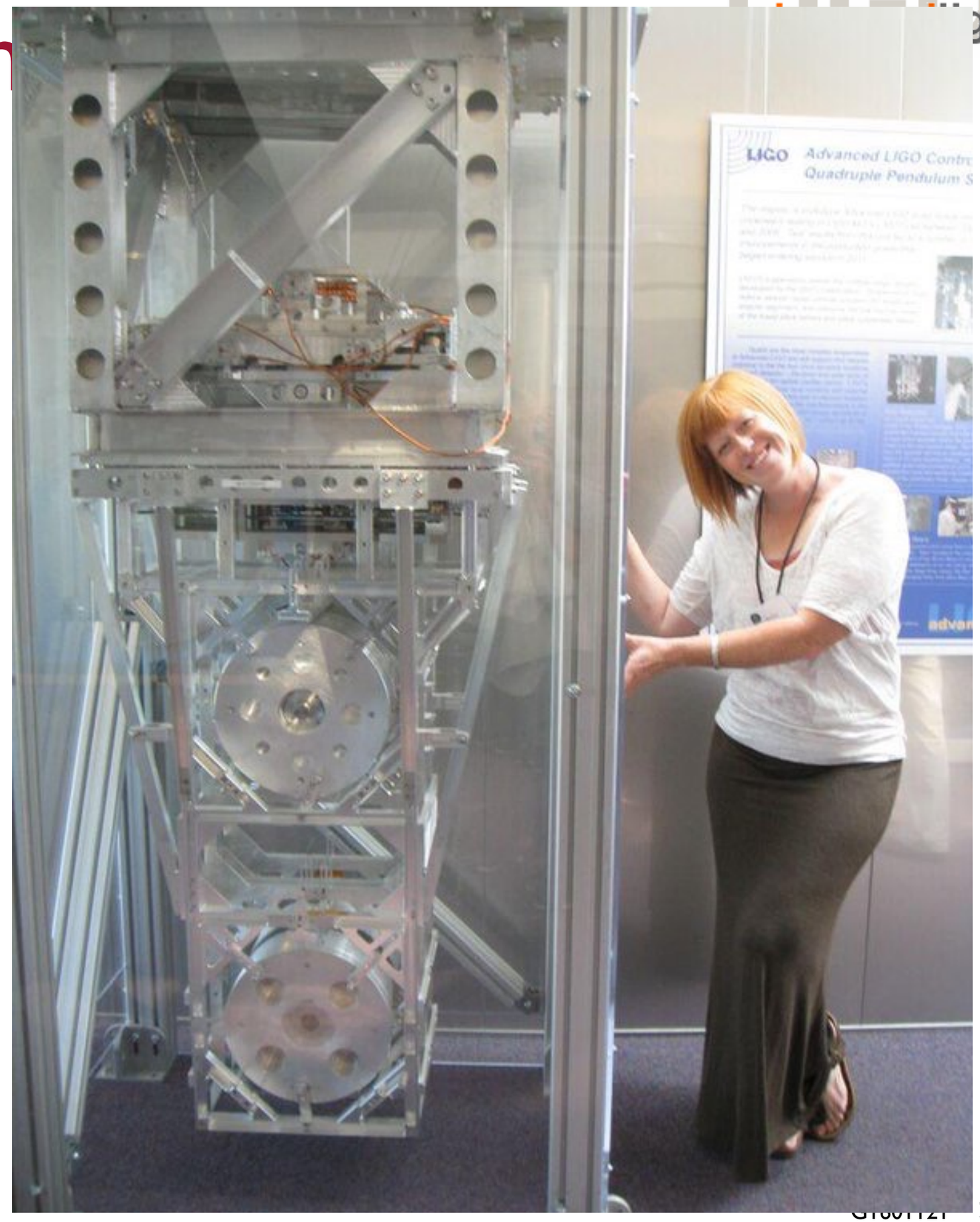
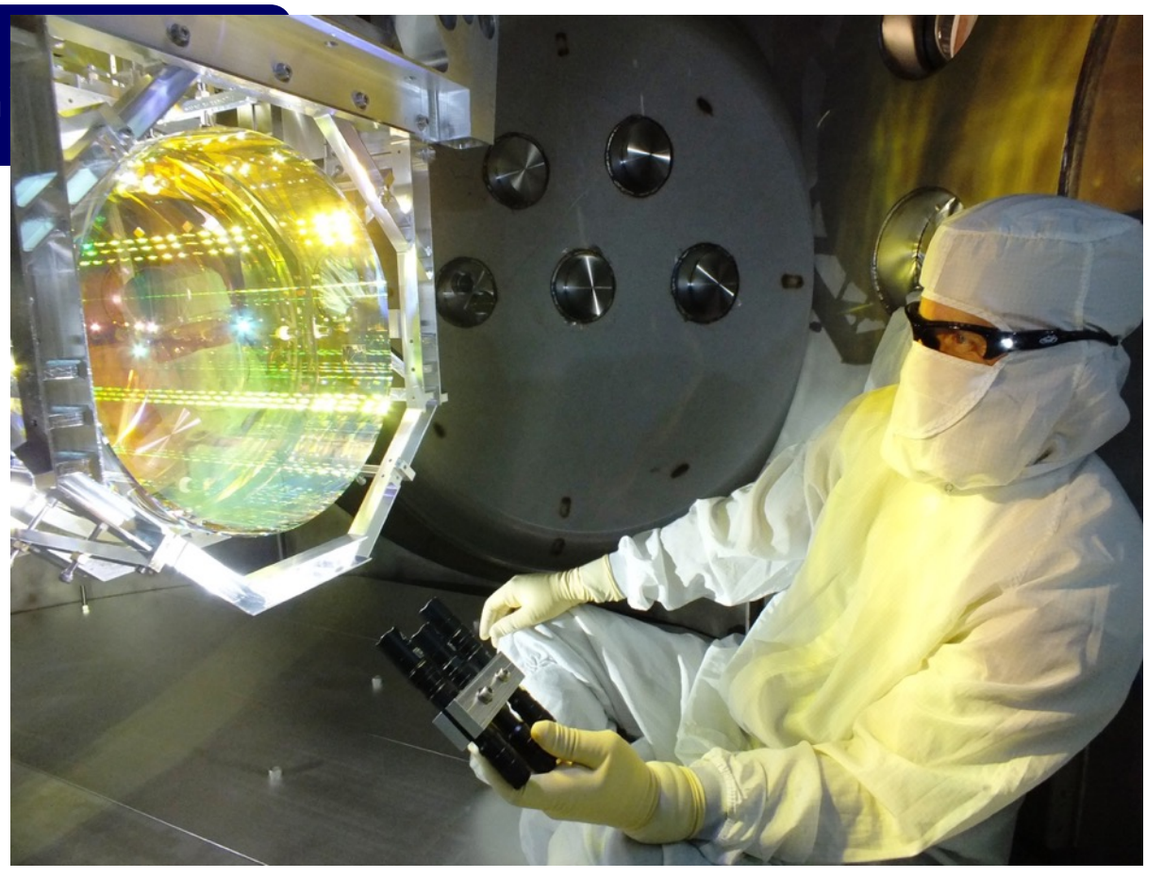
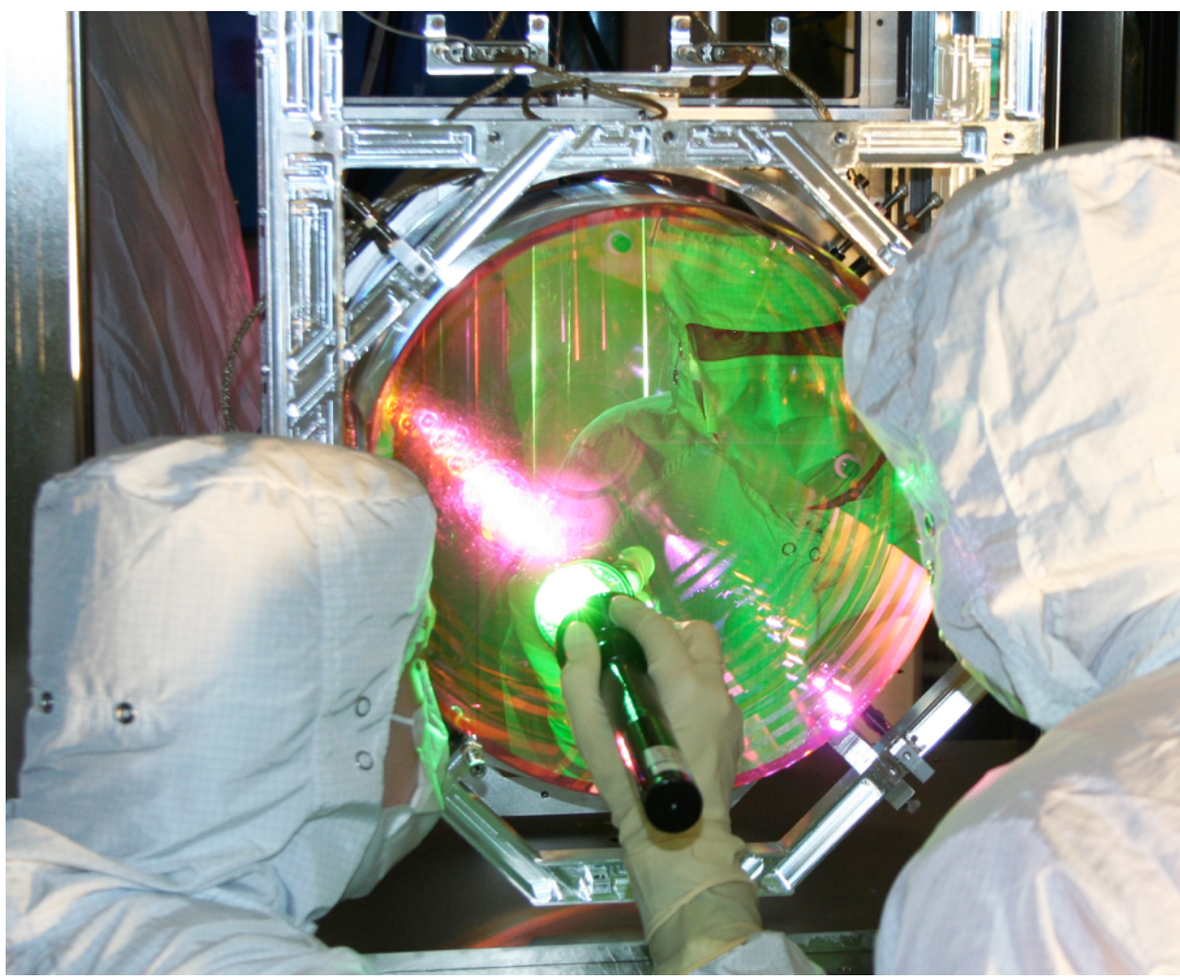
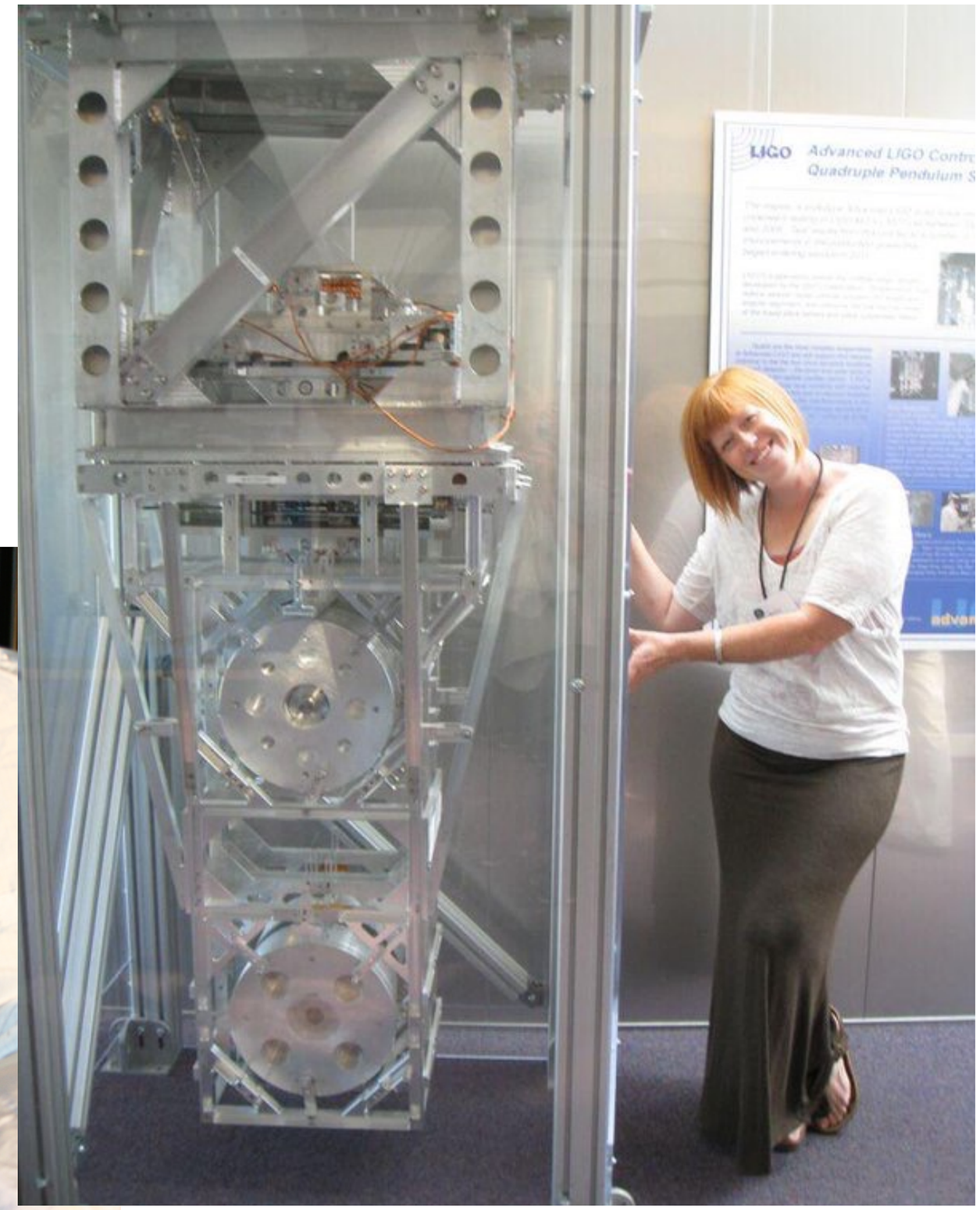
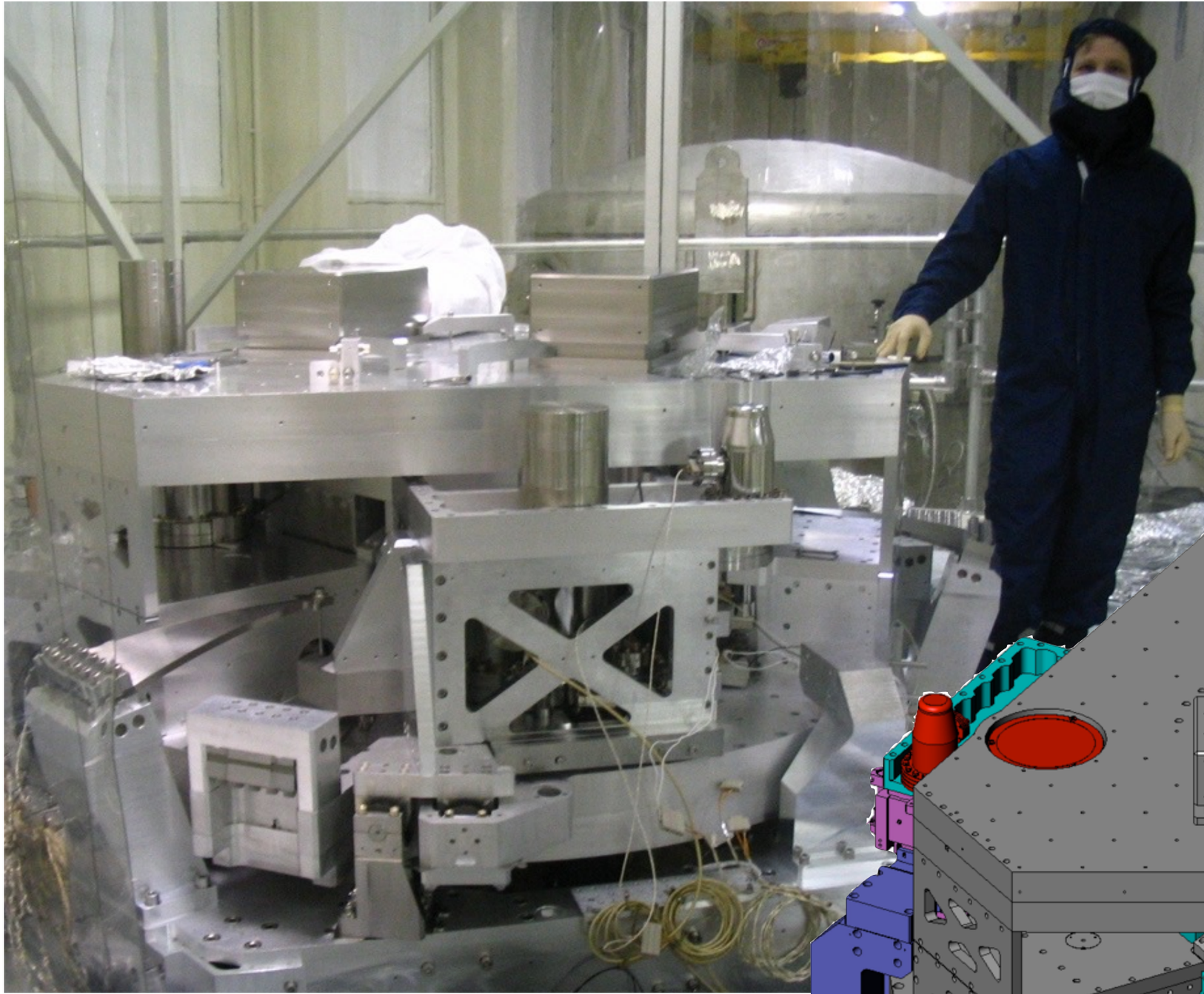


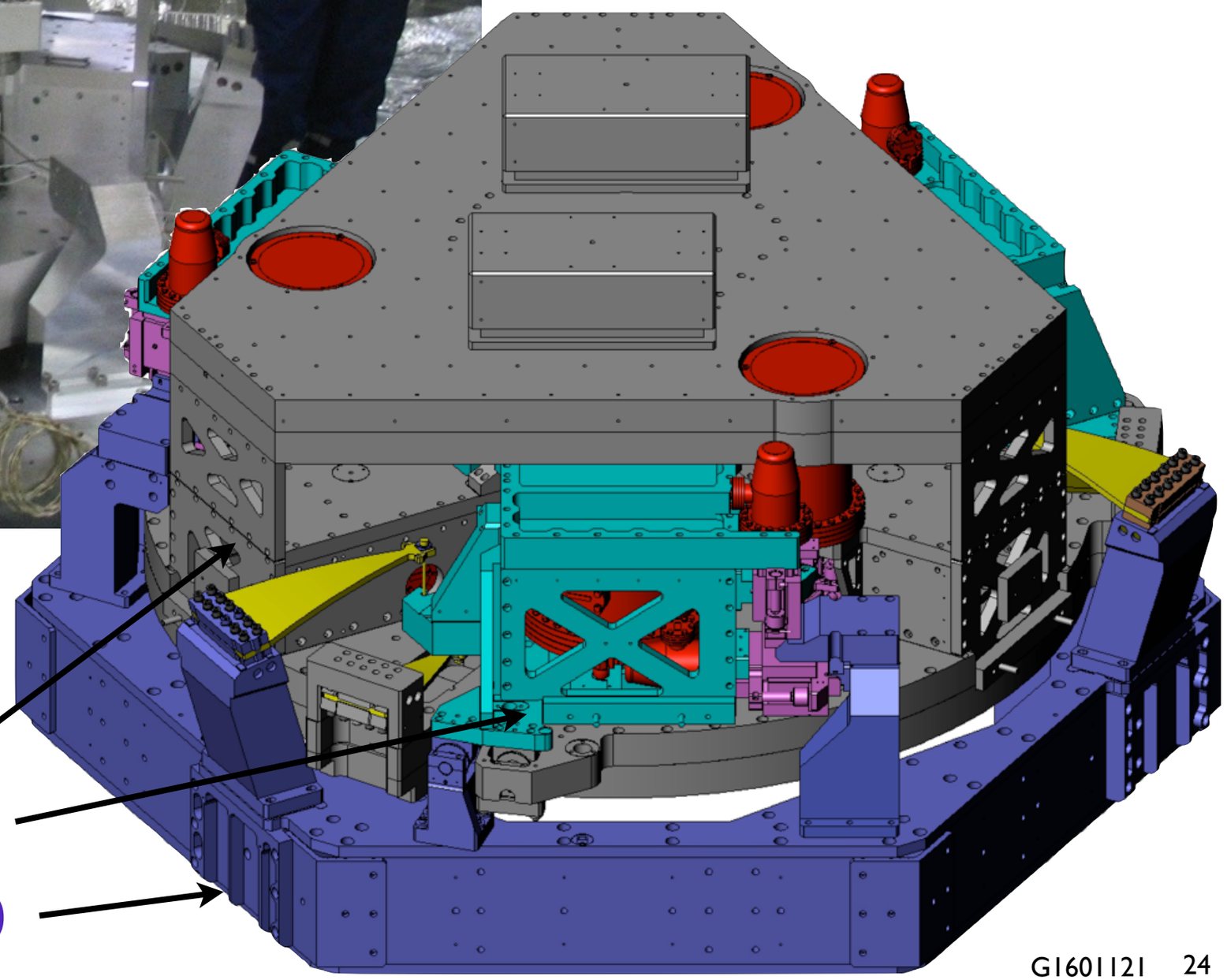





LIGO
Advanced LIGO Contr
Quadruple Pendulum S

BSC-ISI



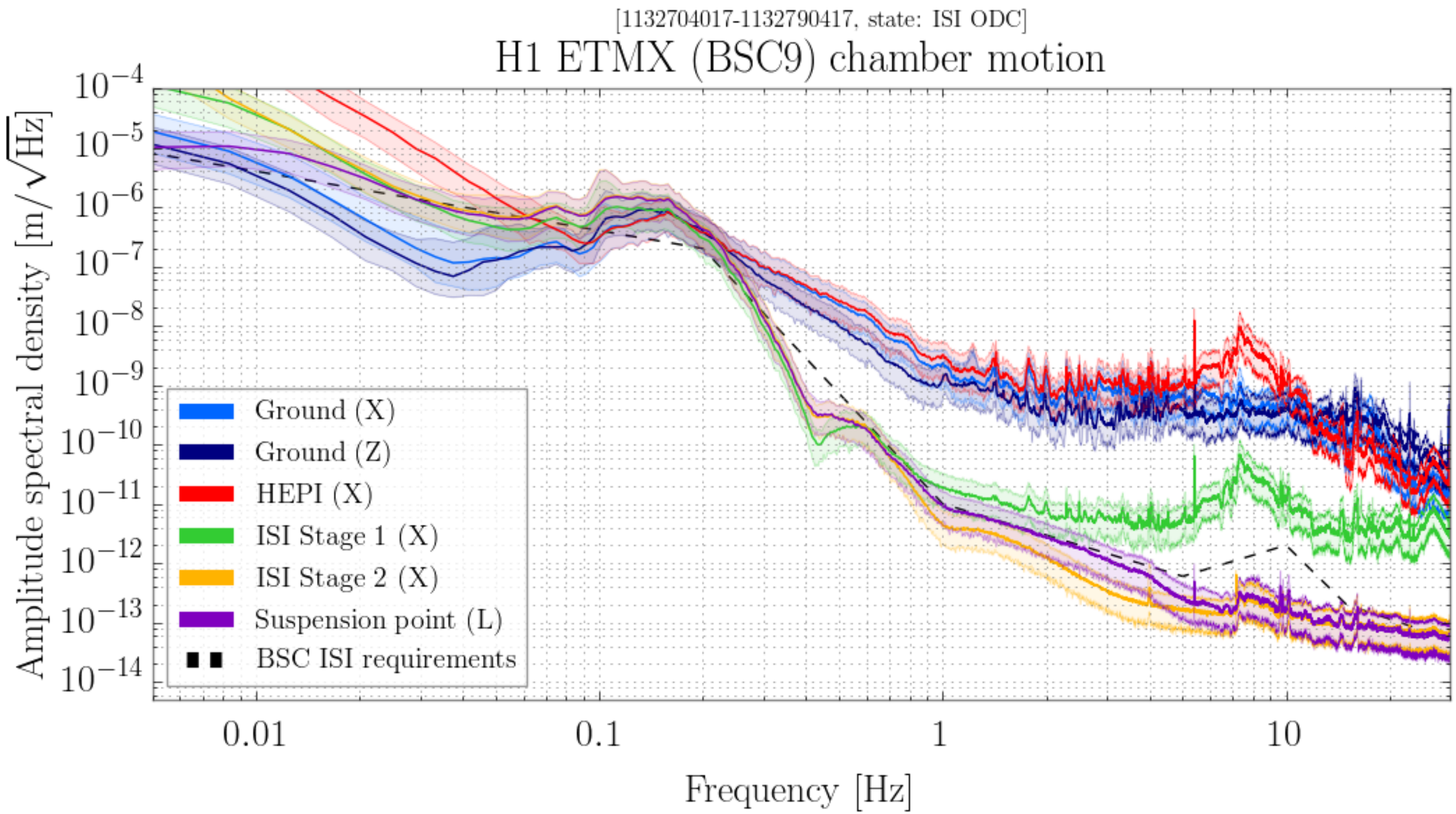


optics table - stage 2

stage 1

support - stage 0

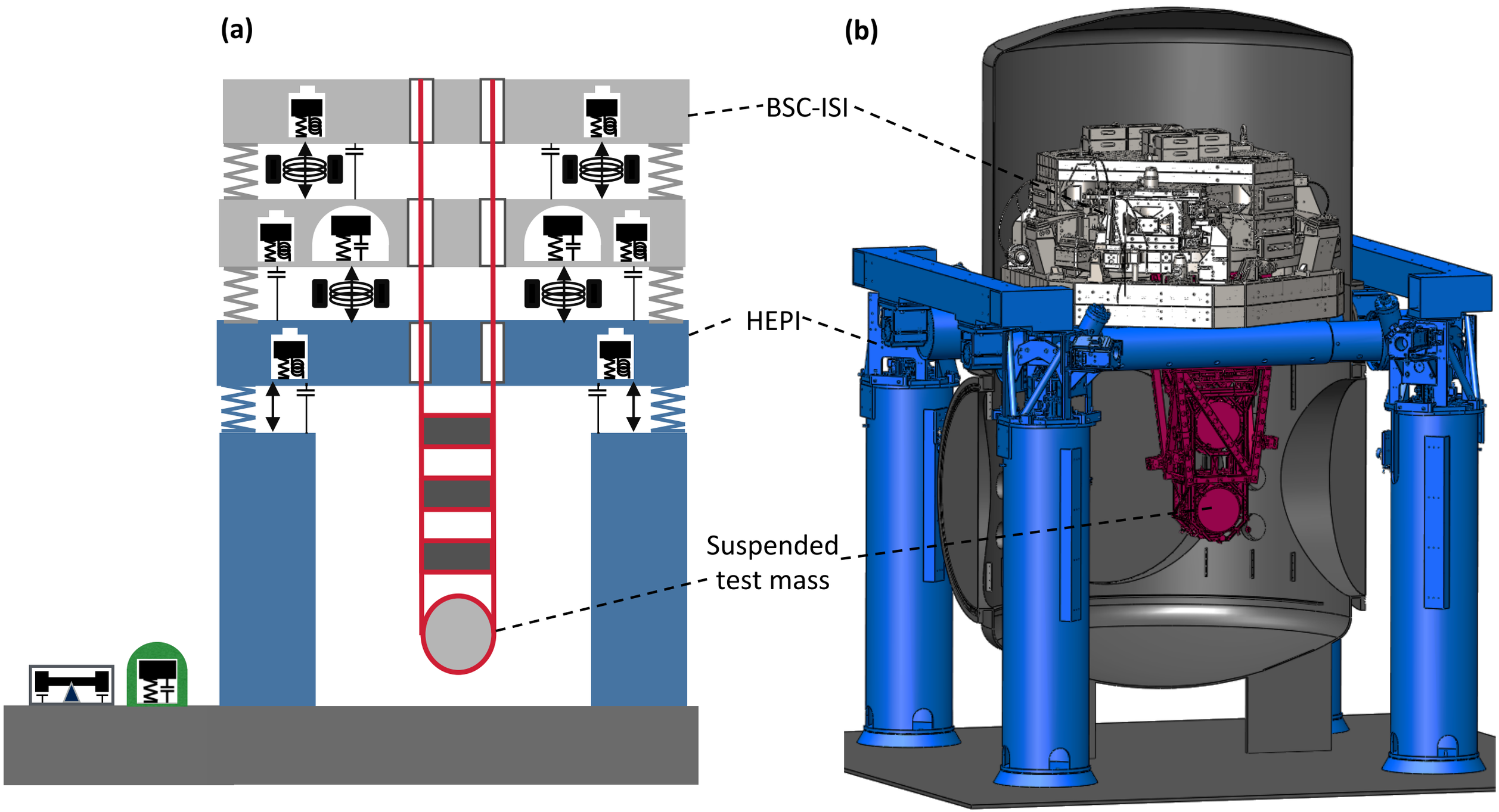
‘Typical’ performance



Nov 28th (Sat. after Thanksgiving)

Signals for processing

Use active and passive techniques
to get good performance



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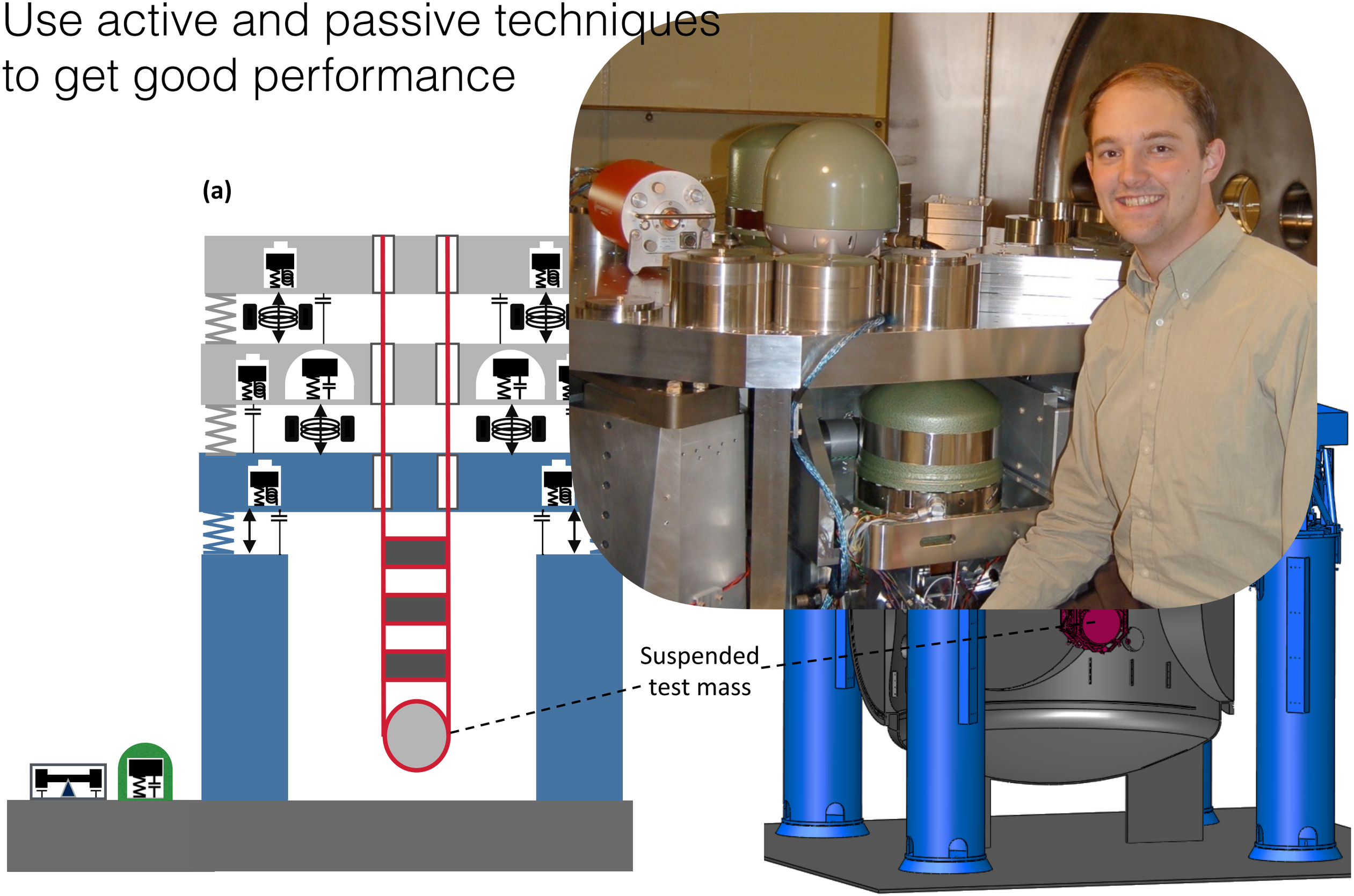

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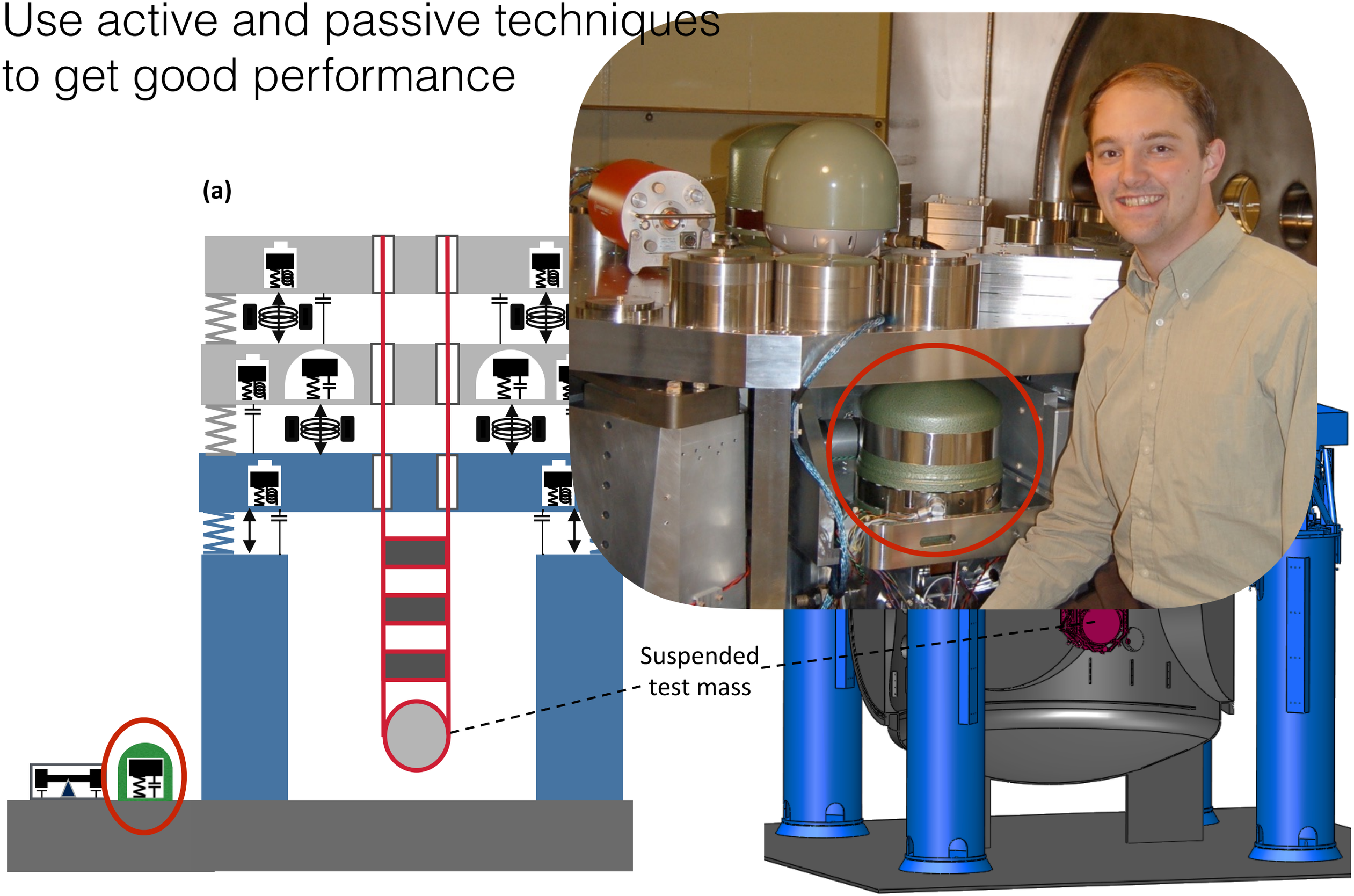

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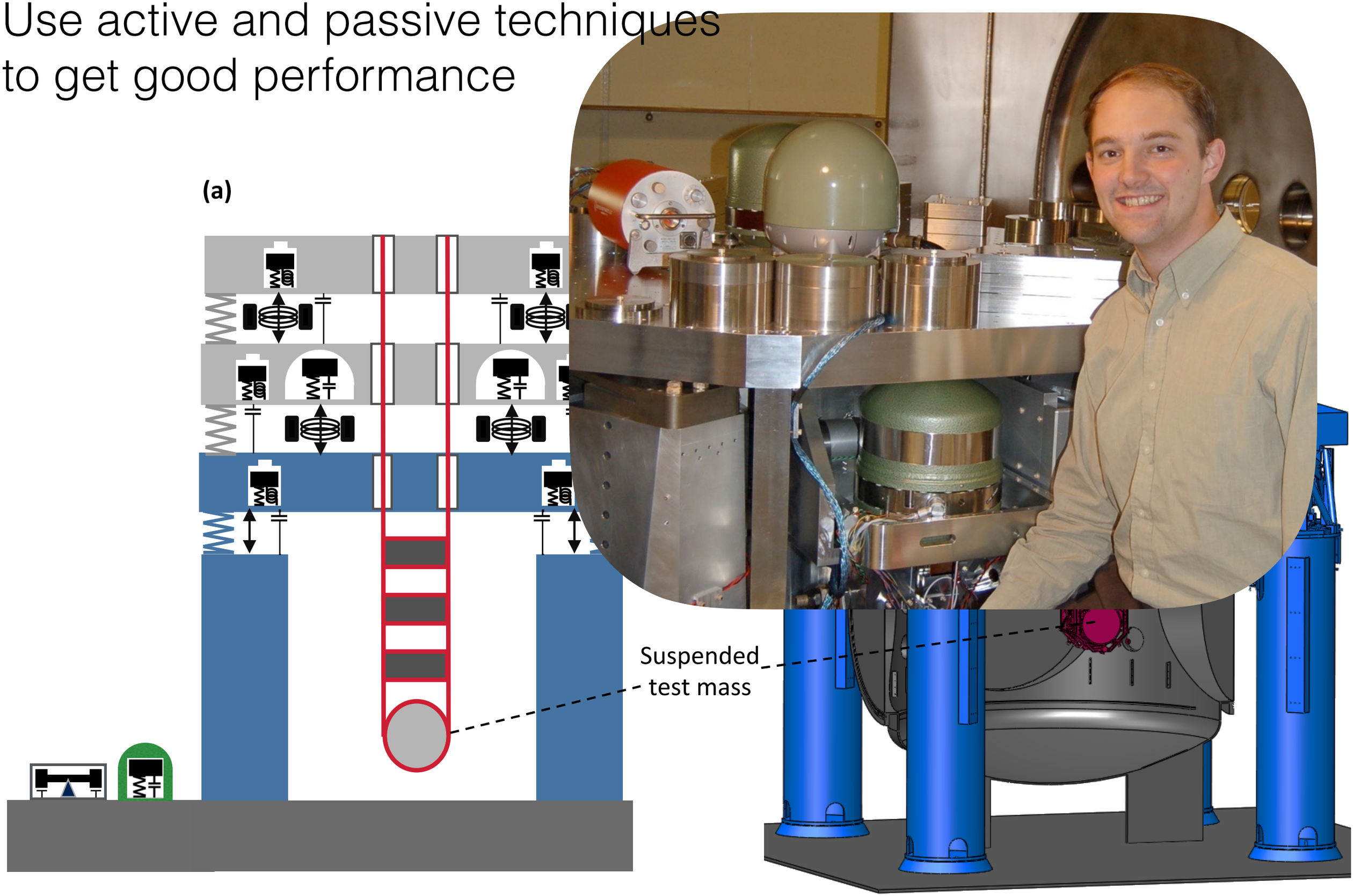

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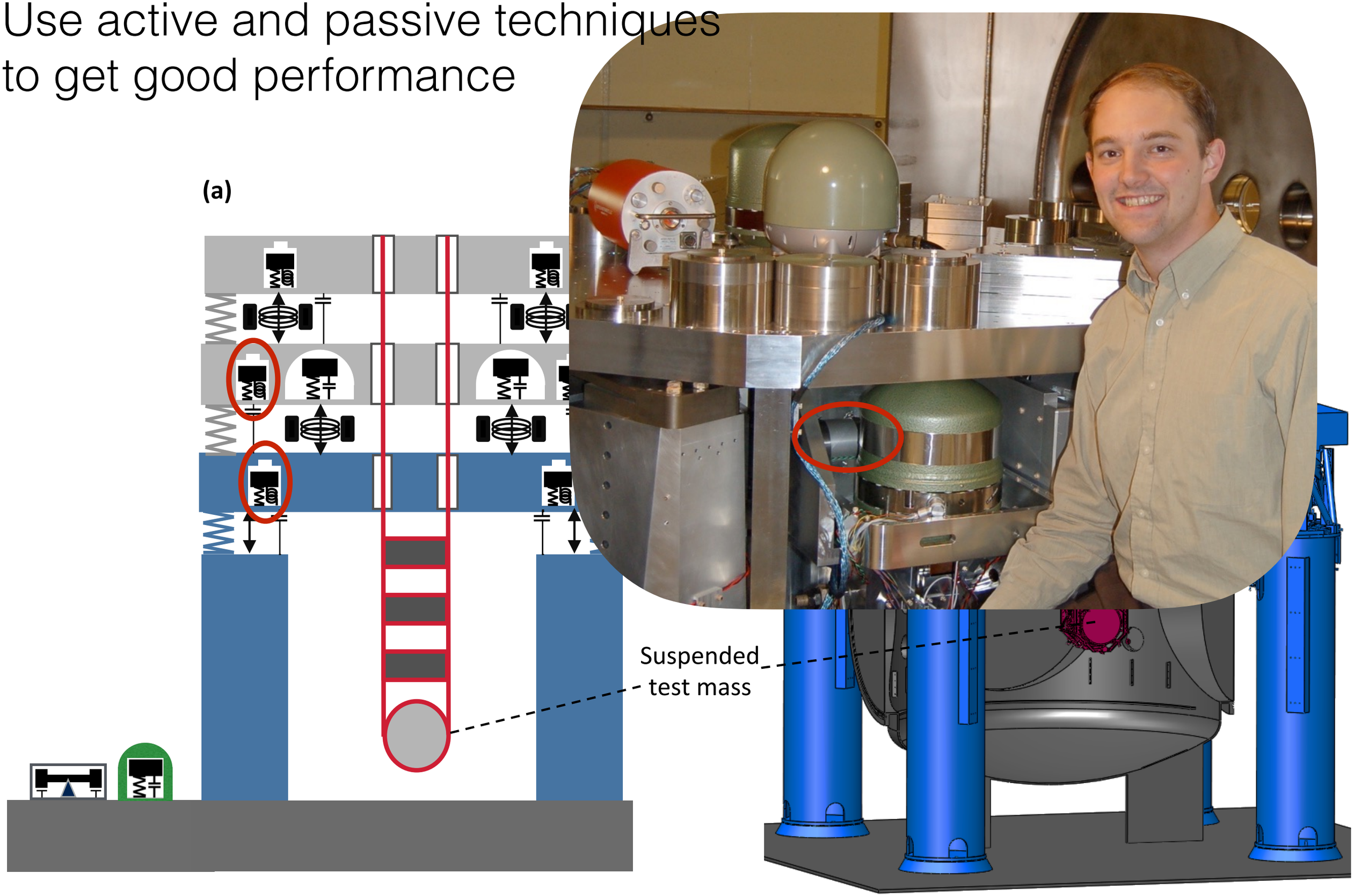

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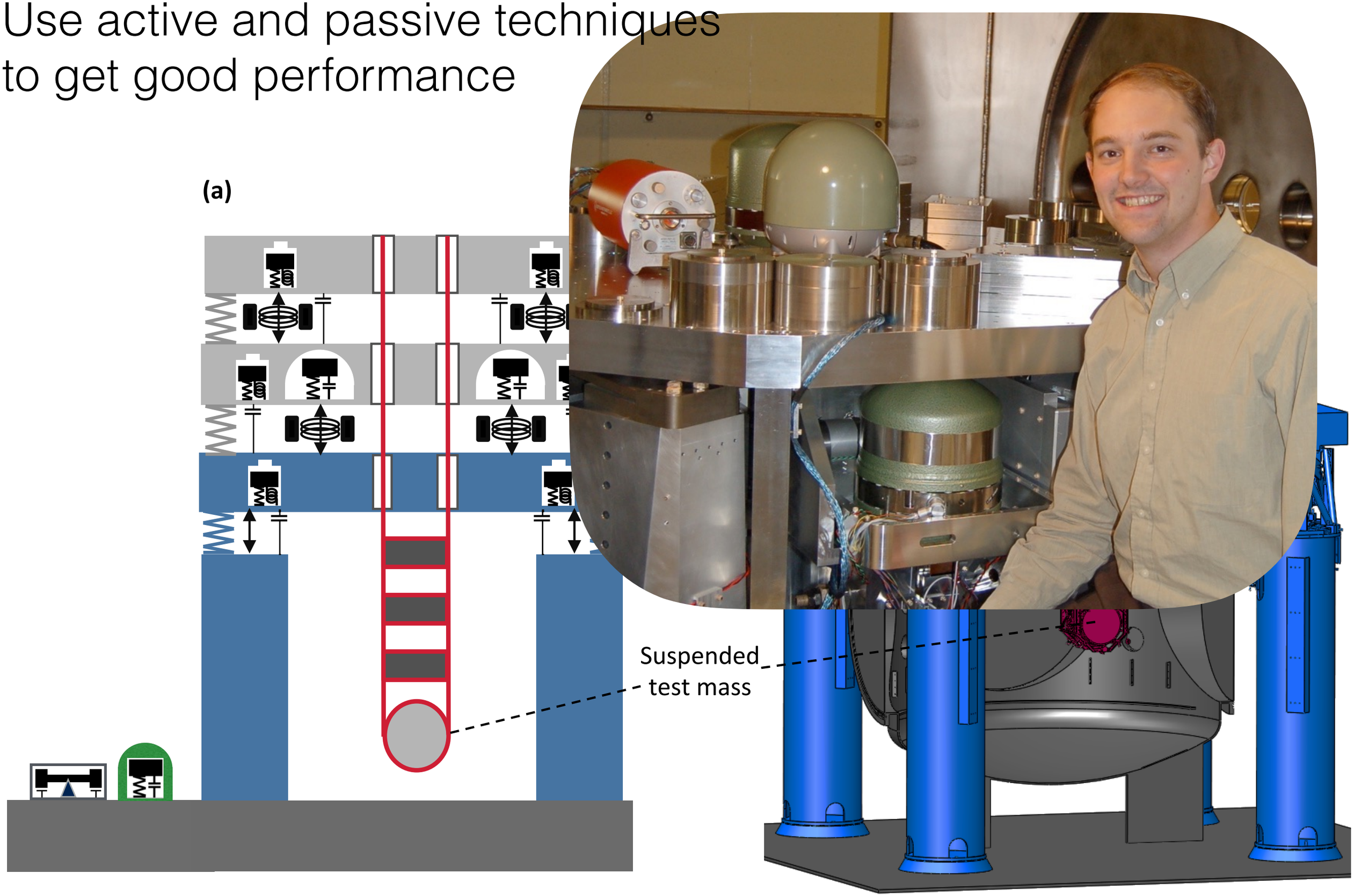

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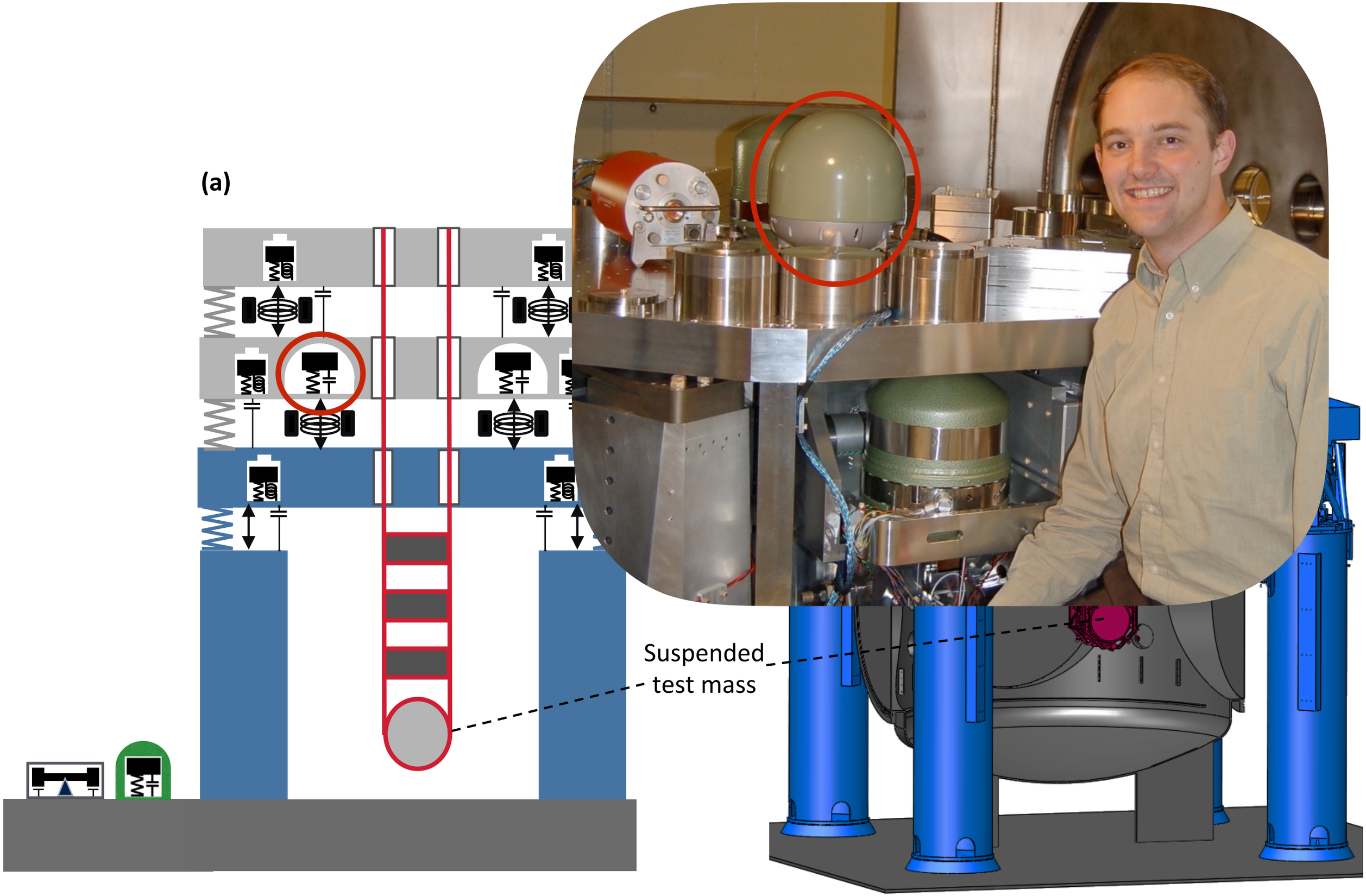

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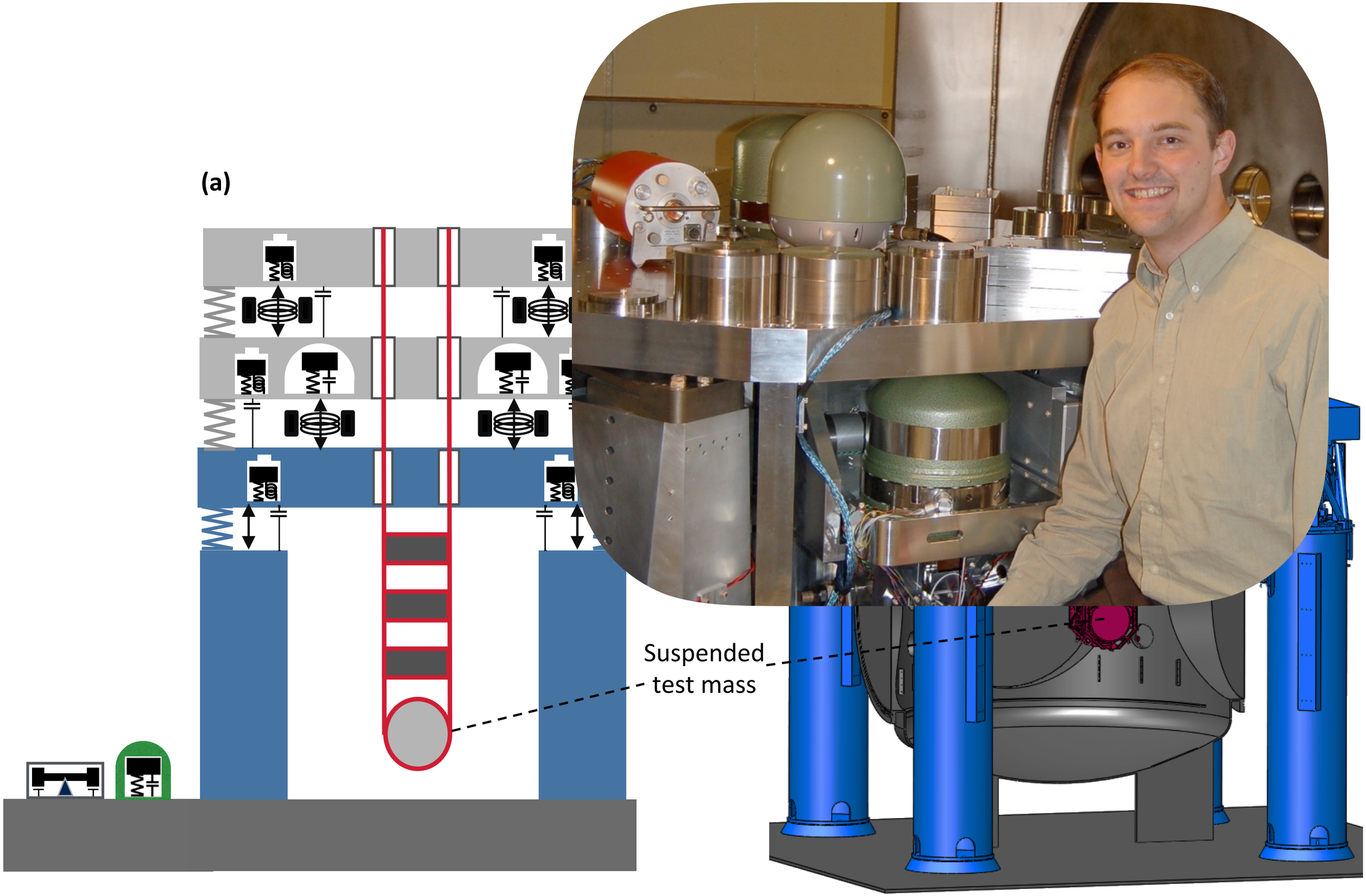

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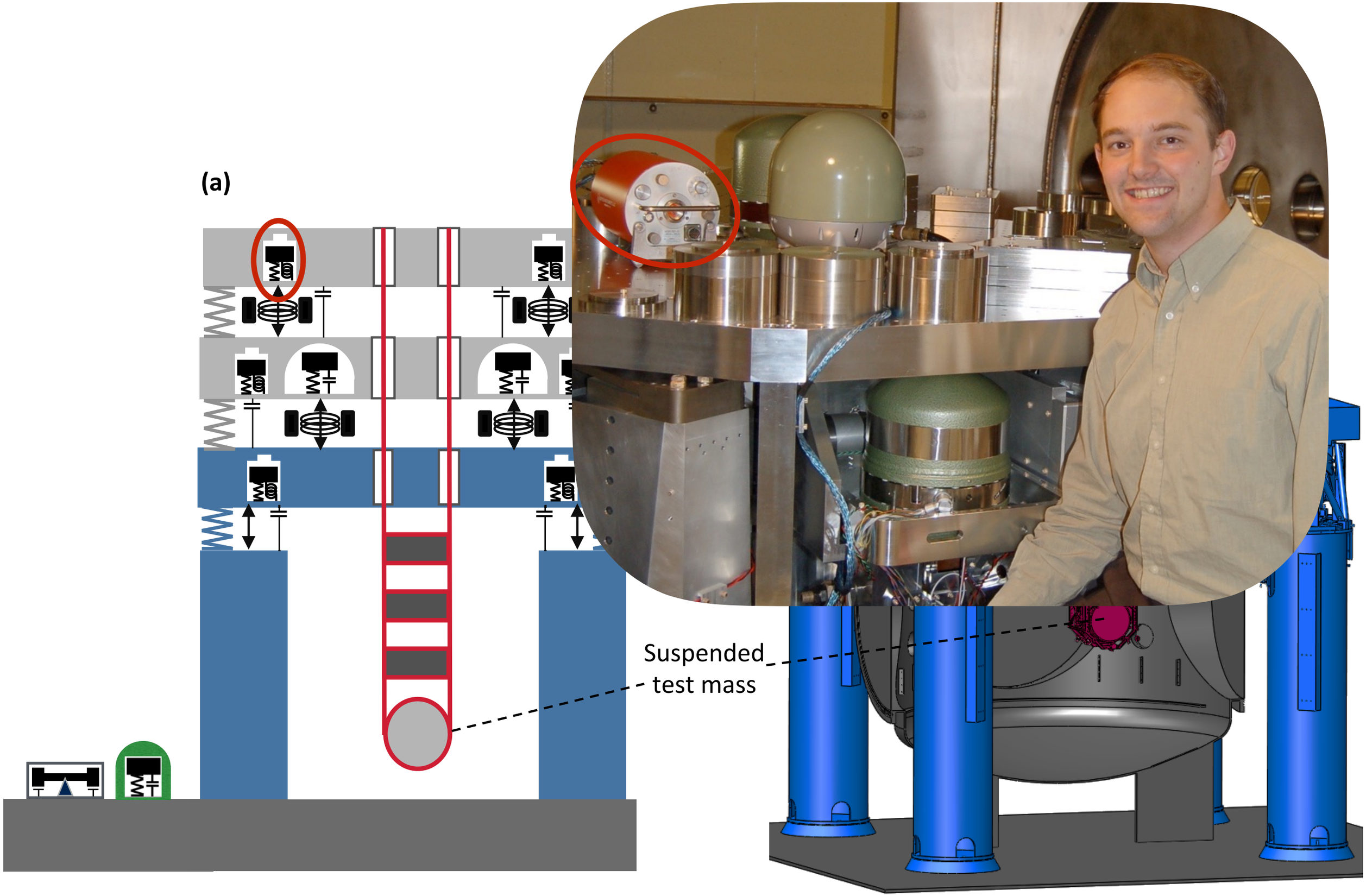
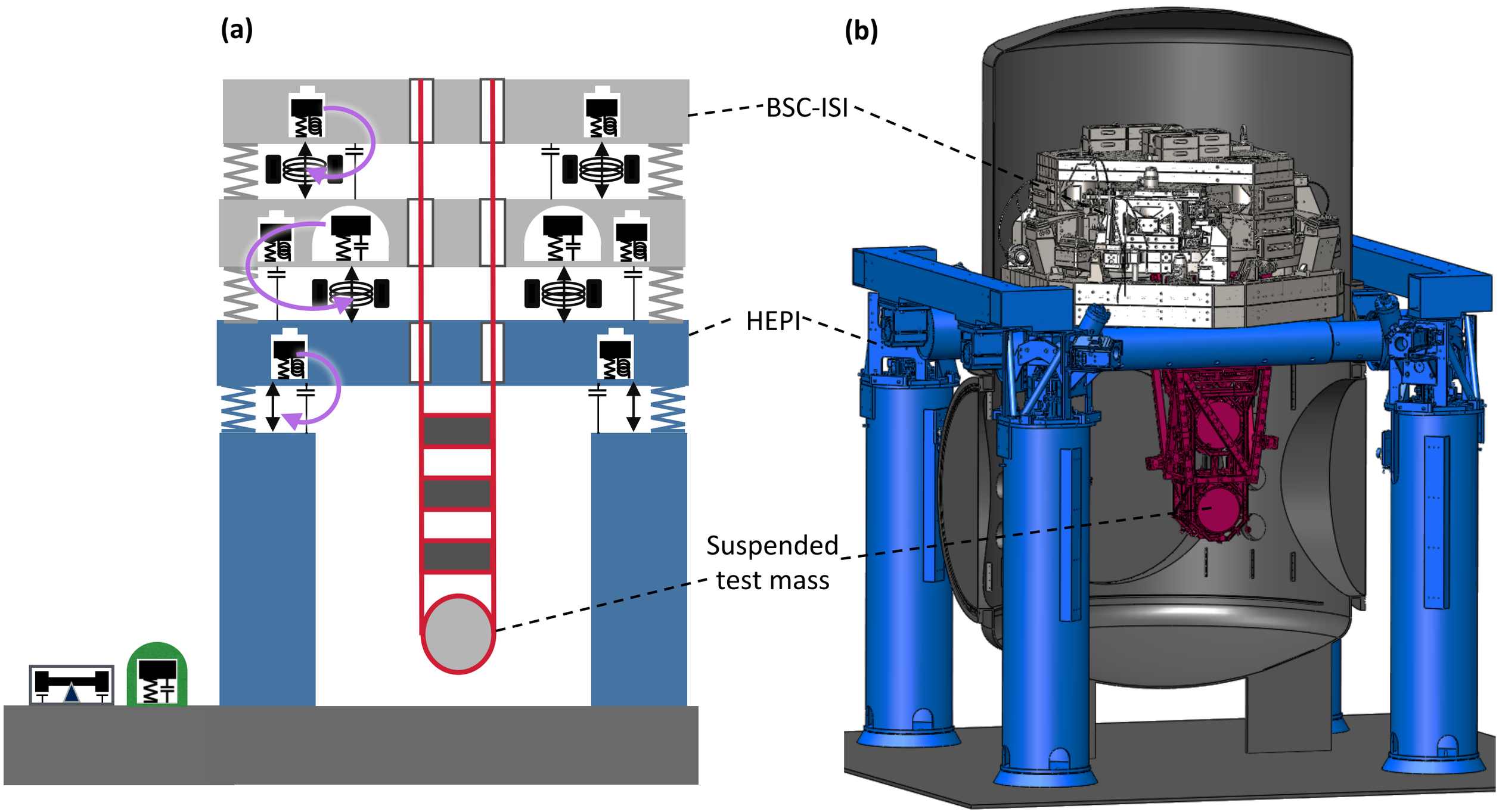


Signals for processing

Blended Feedback



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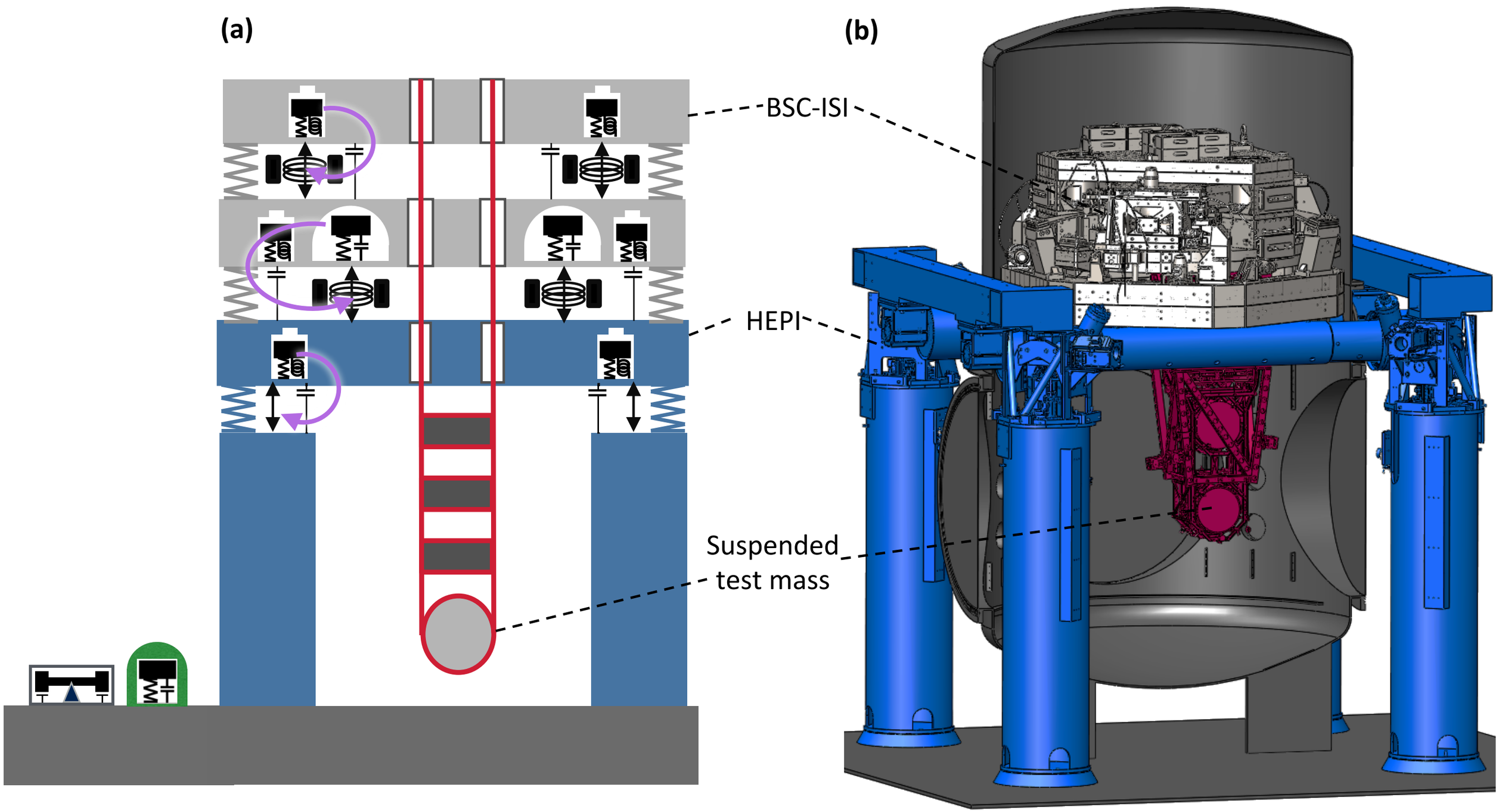
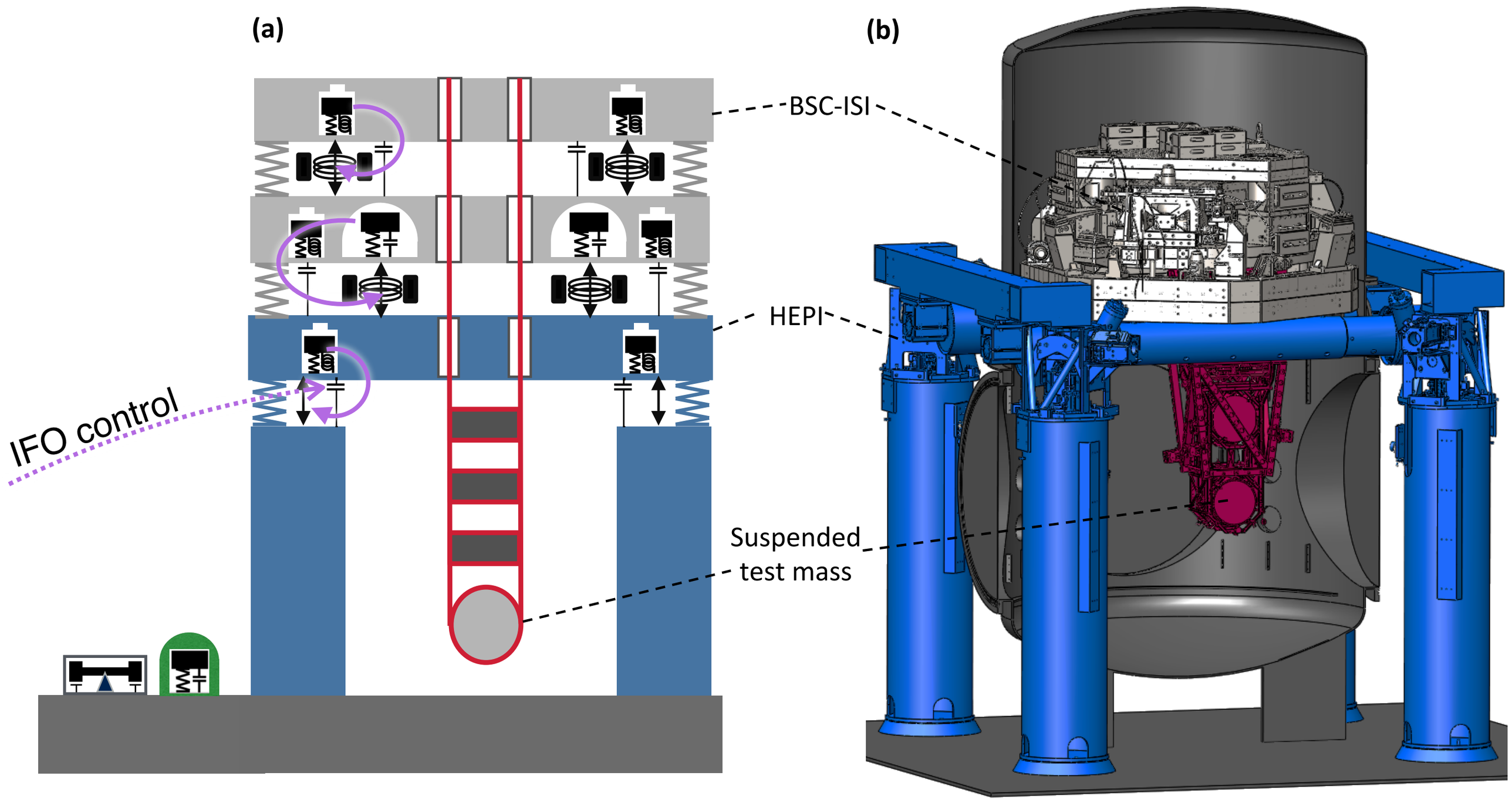


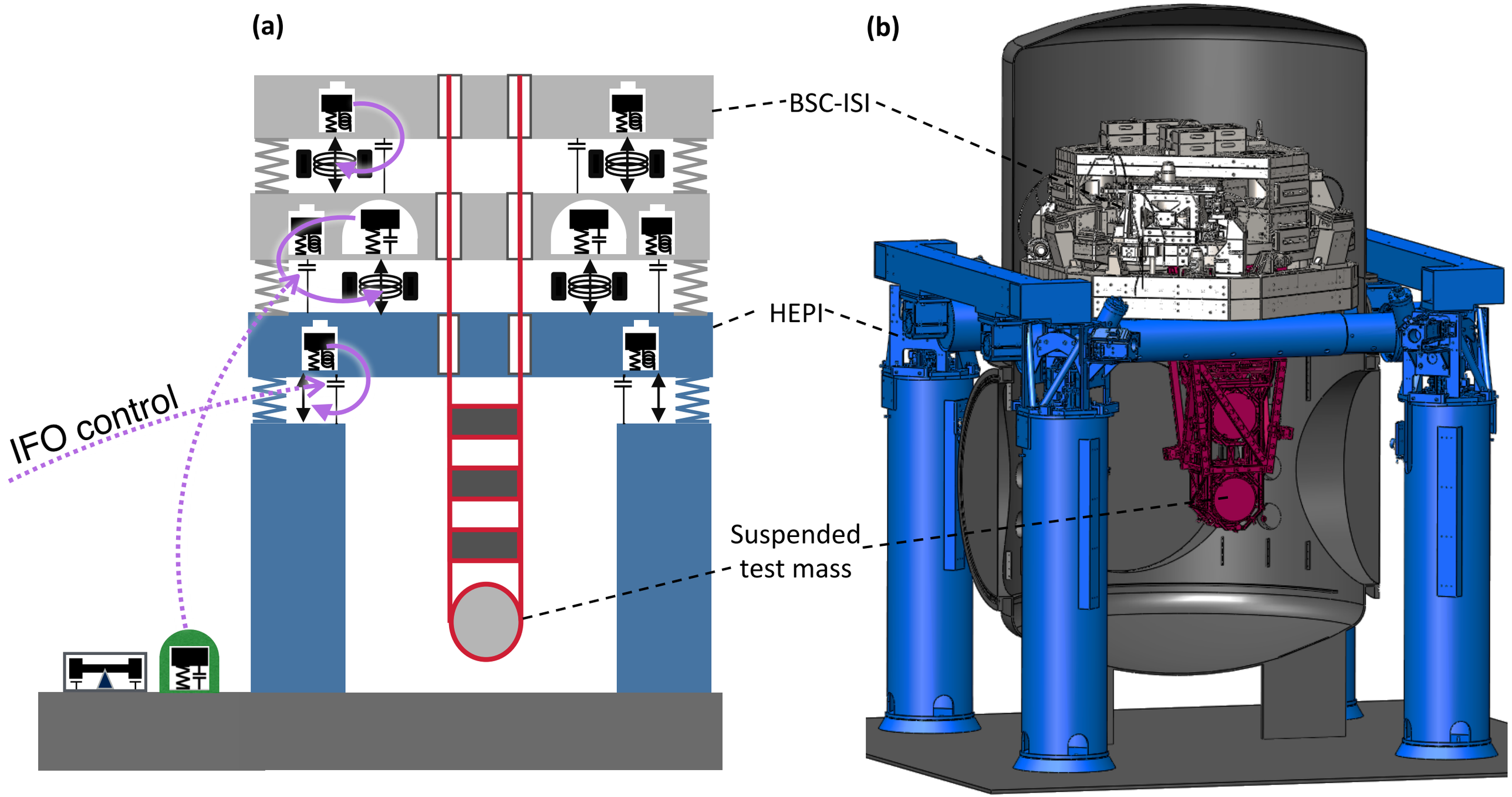
Signals for processing

Blended Feedback
Global commands



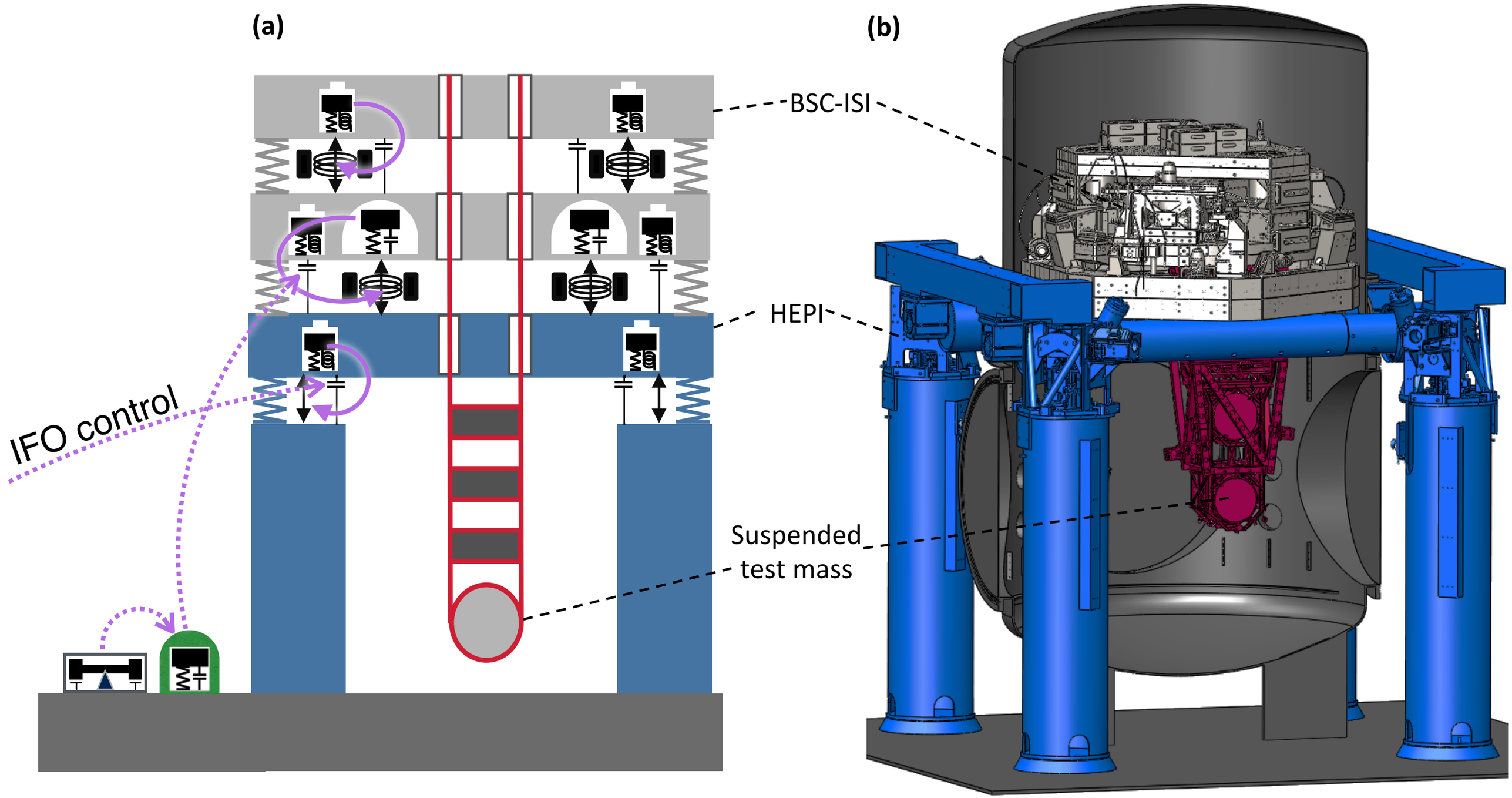
Signals for processing

Blended Feedback
Global commands
Sensor correction



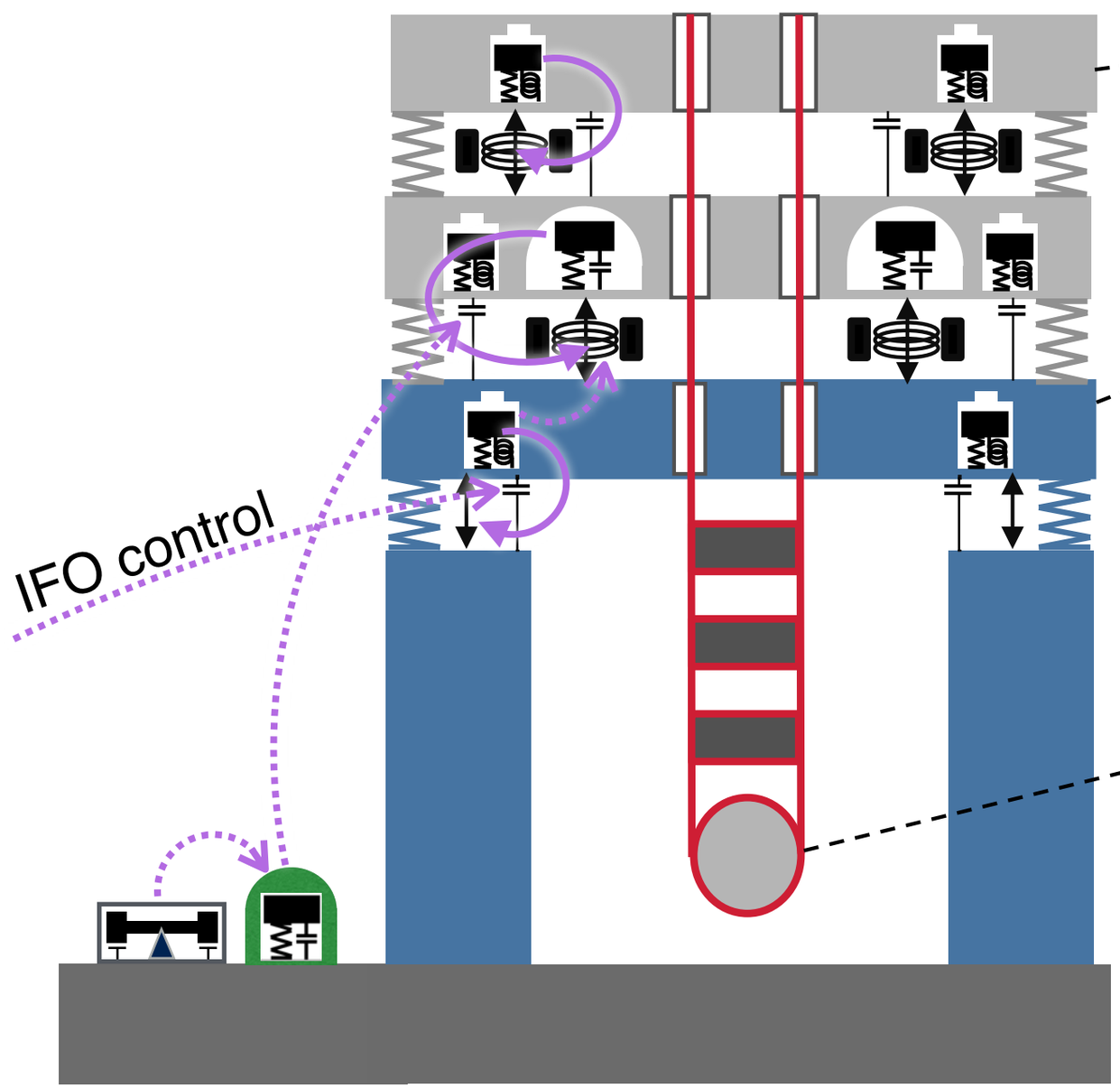
Signals for processing

Blended Feedback
Global commands
Sensor correction

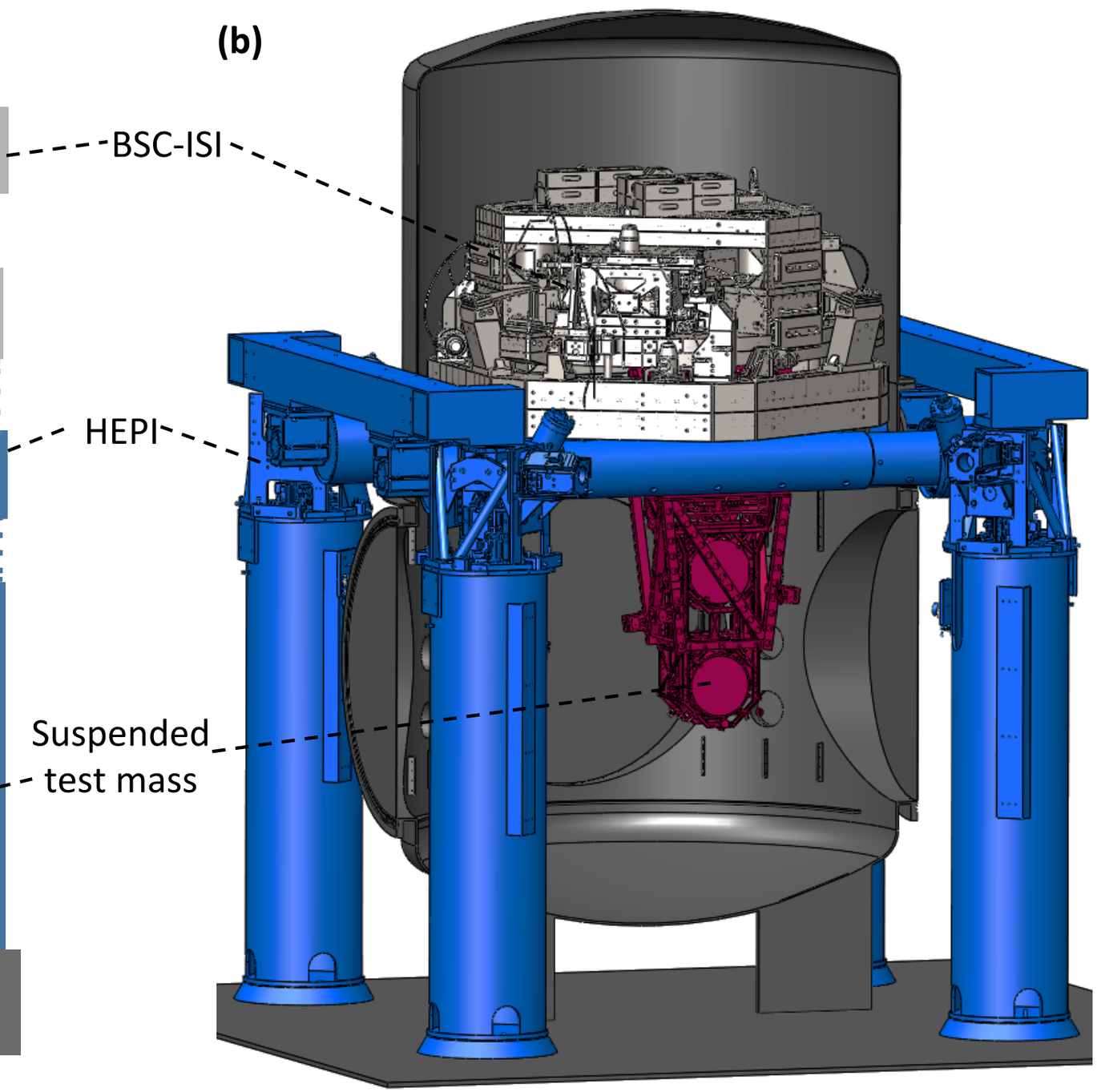


Signals for processing

Blended Feedback
Global commands
Sensor correction
Feedforward

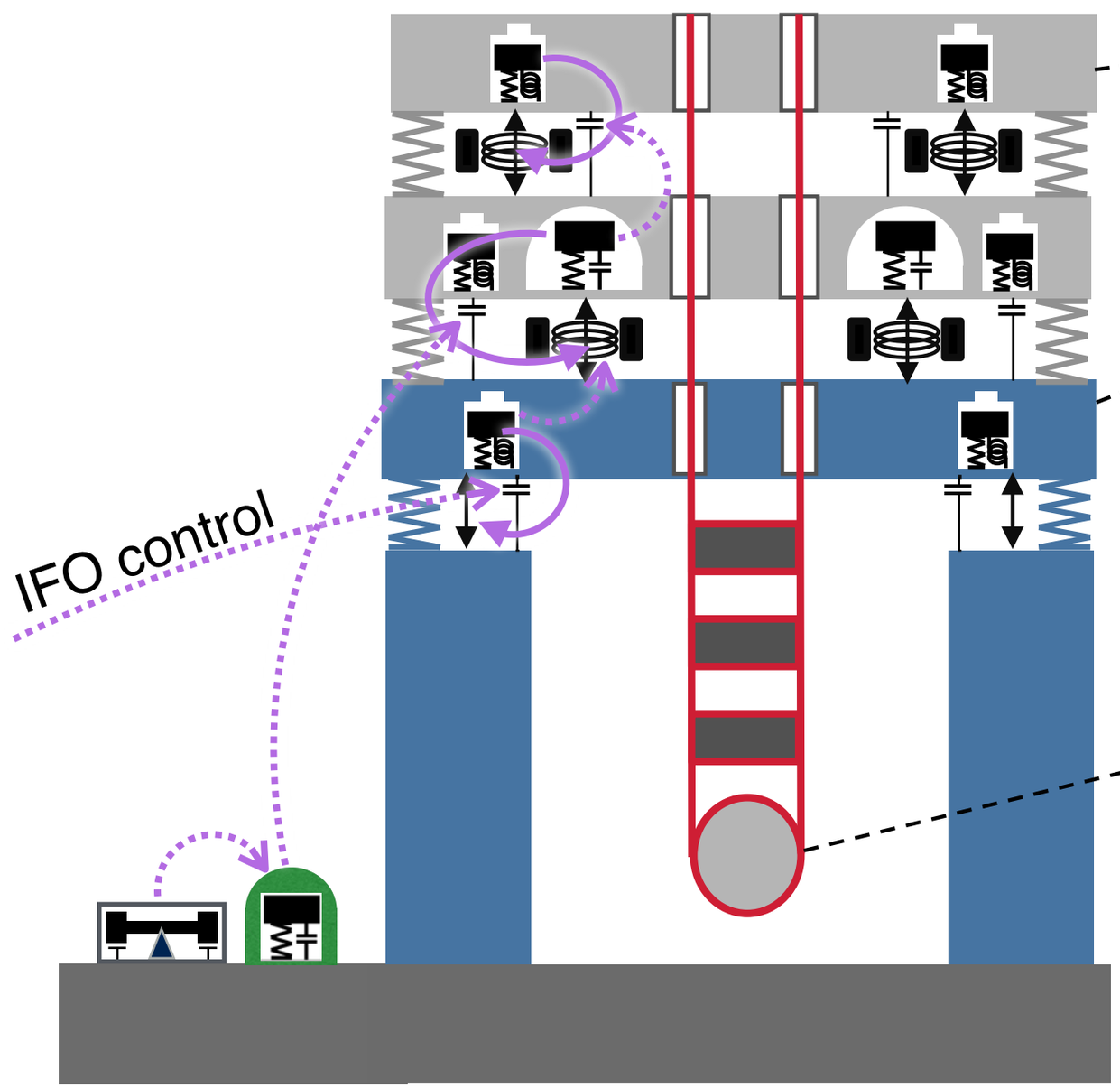


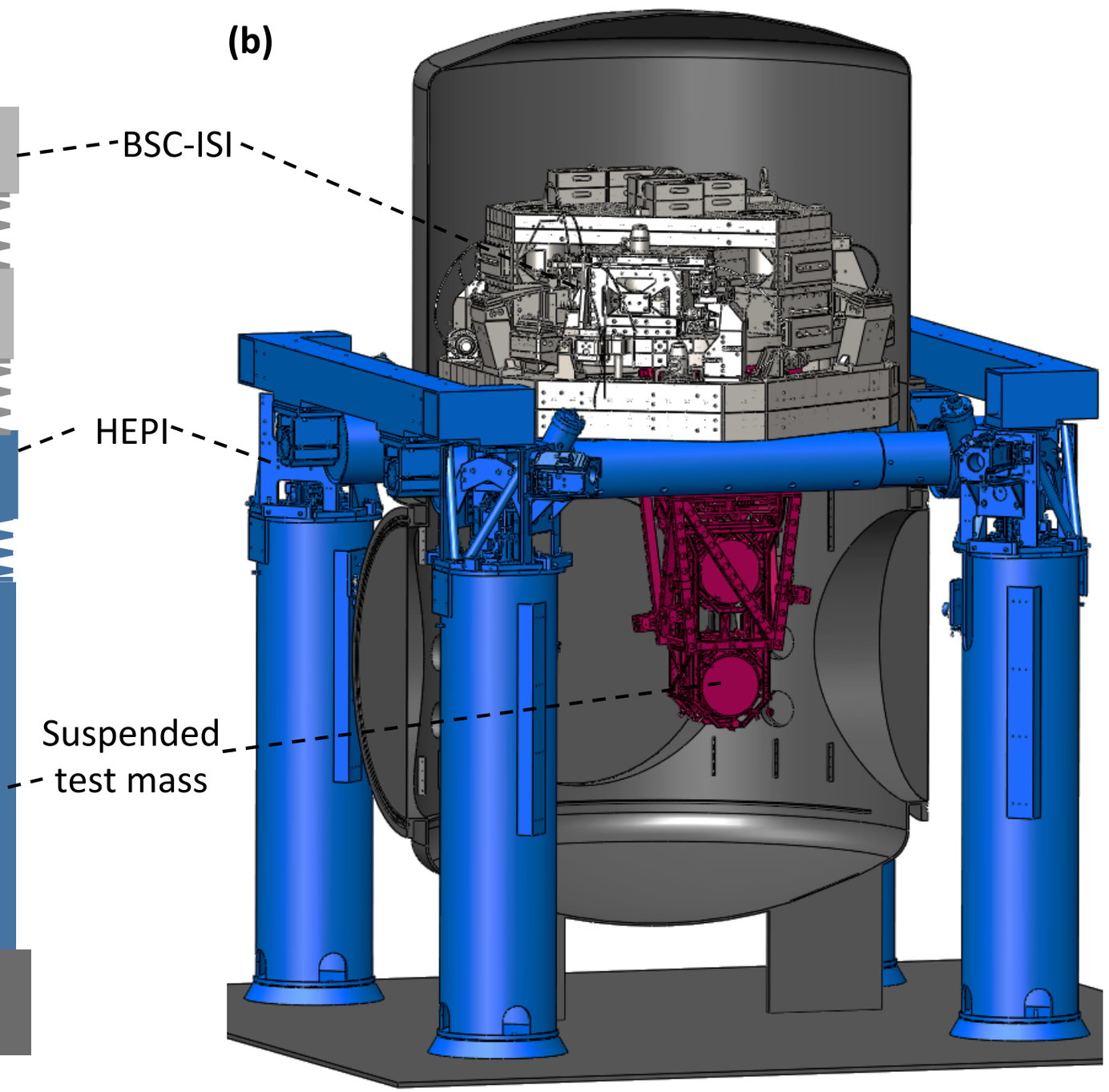
(b)



Signals for processing

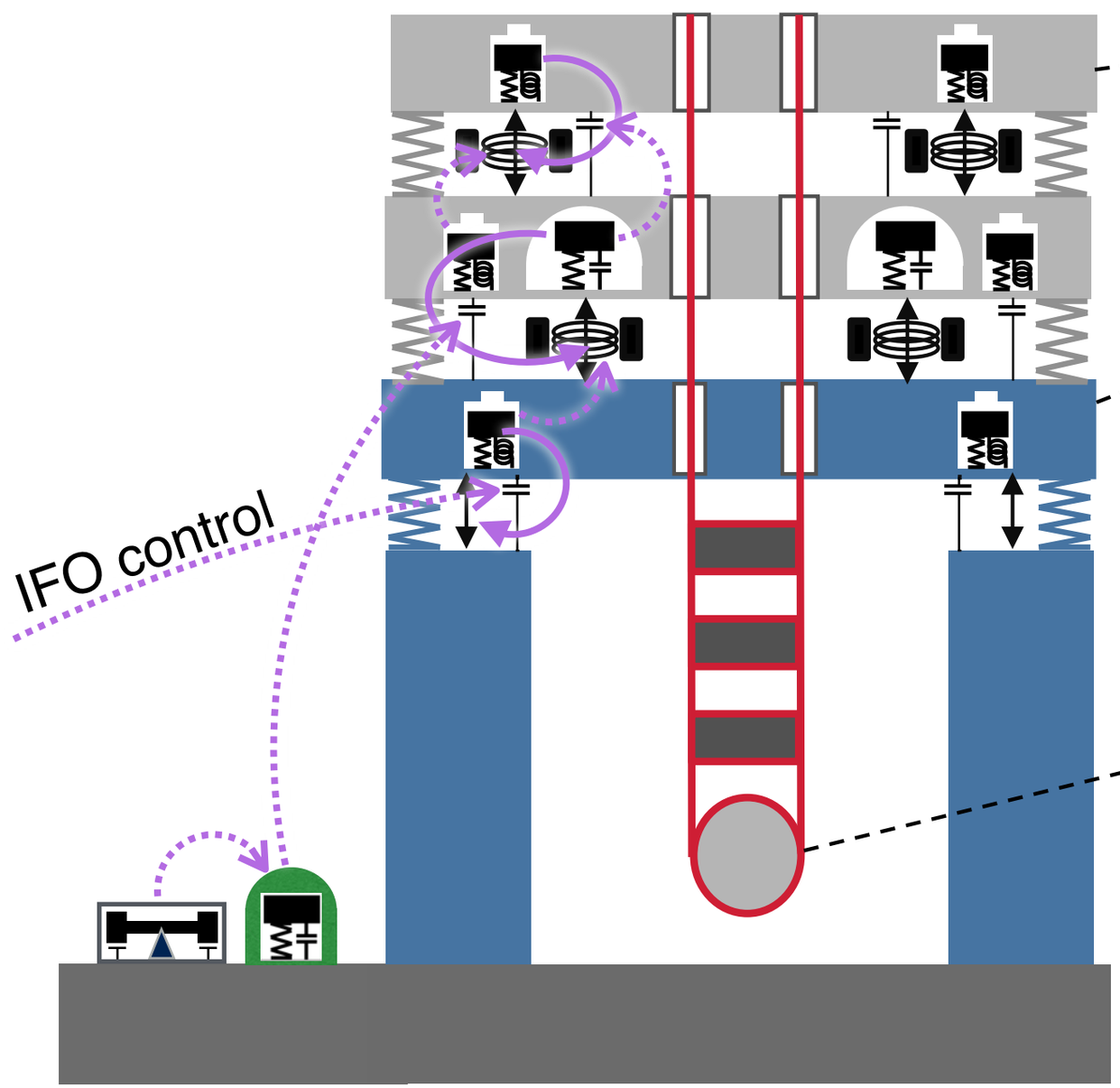
Blended Feedback
Global commands
Sensor correction
Feedforward

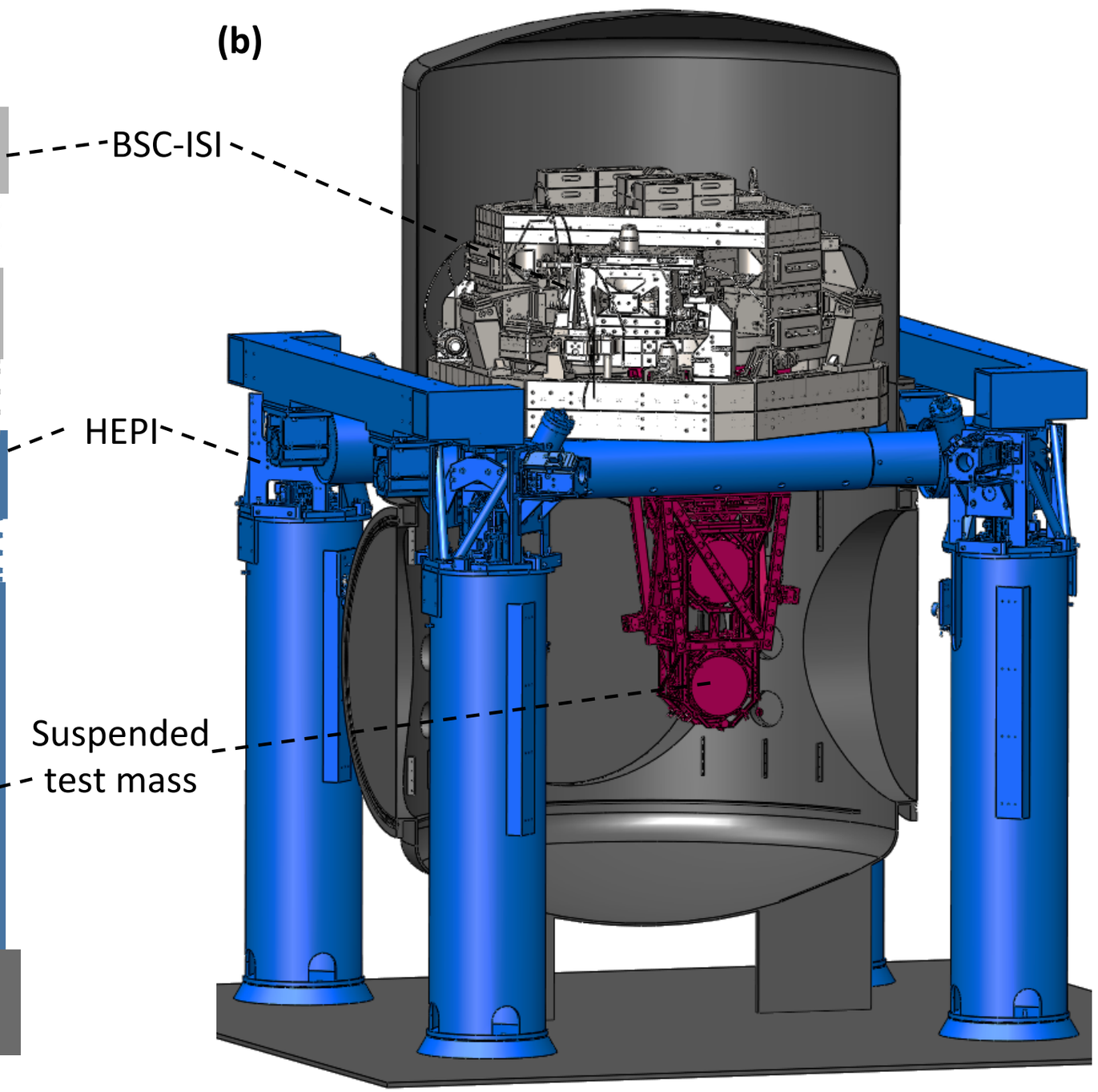




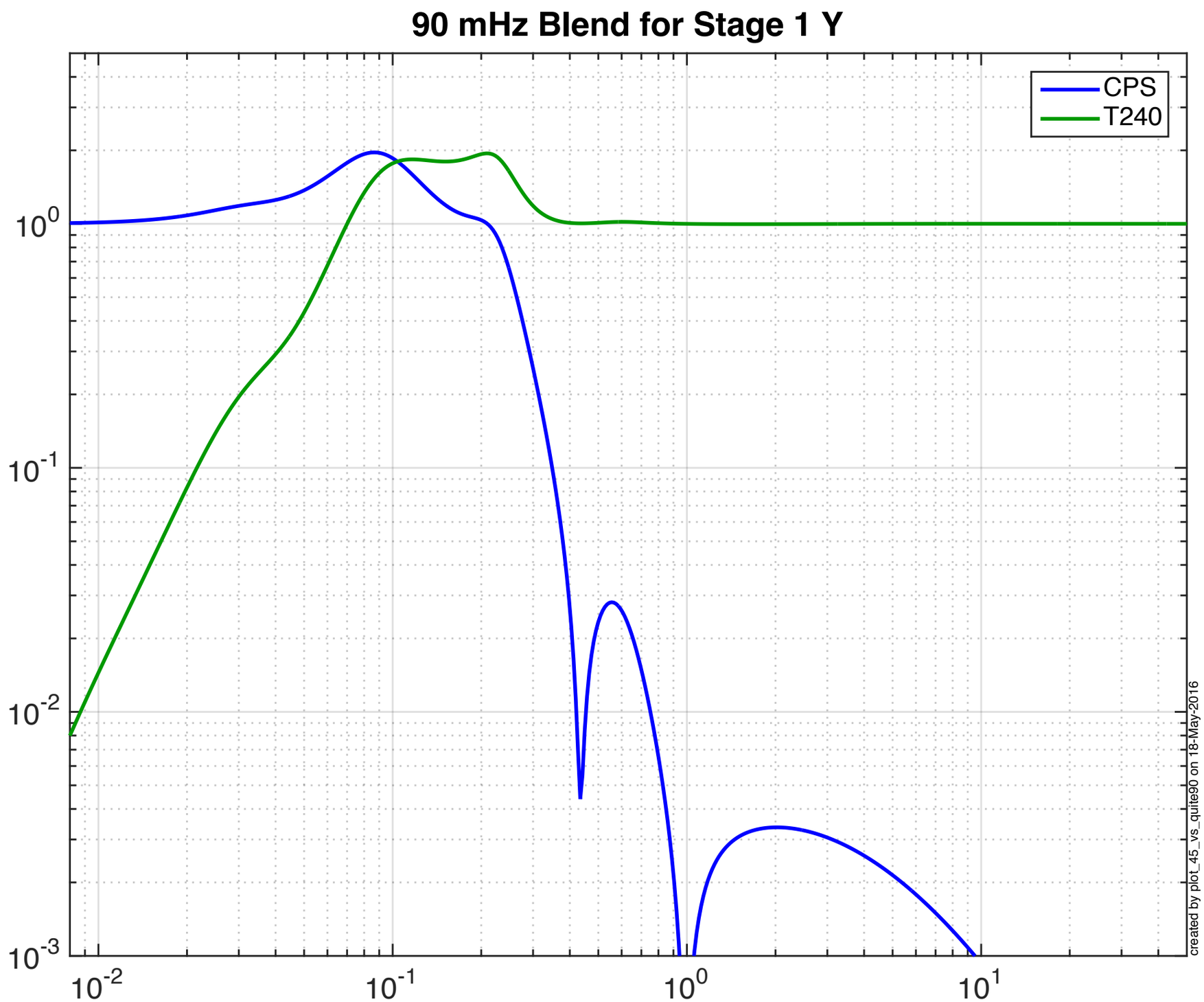
Signals for processing

Blended Feedback
Global commands
Sensor correction
Feedforward

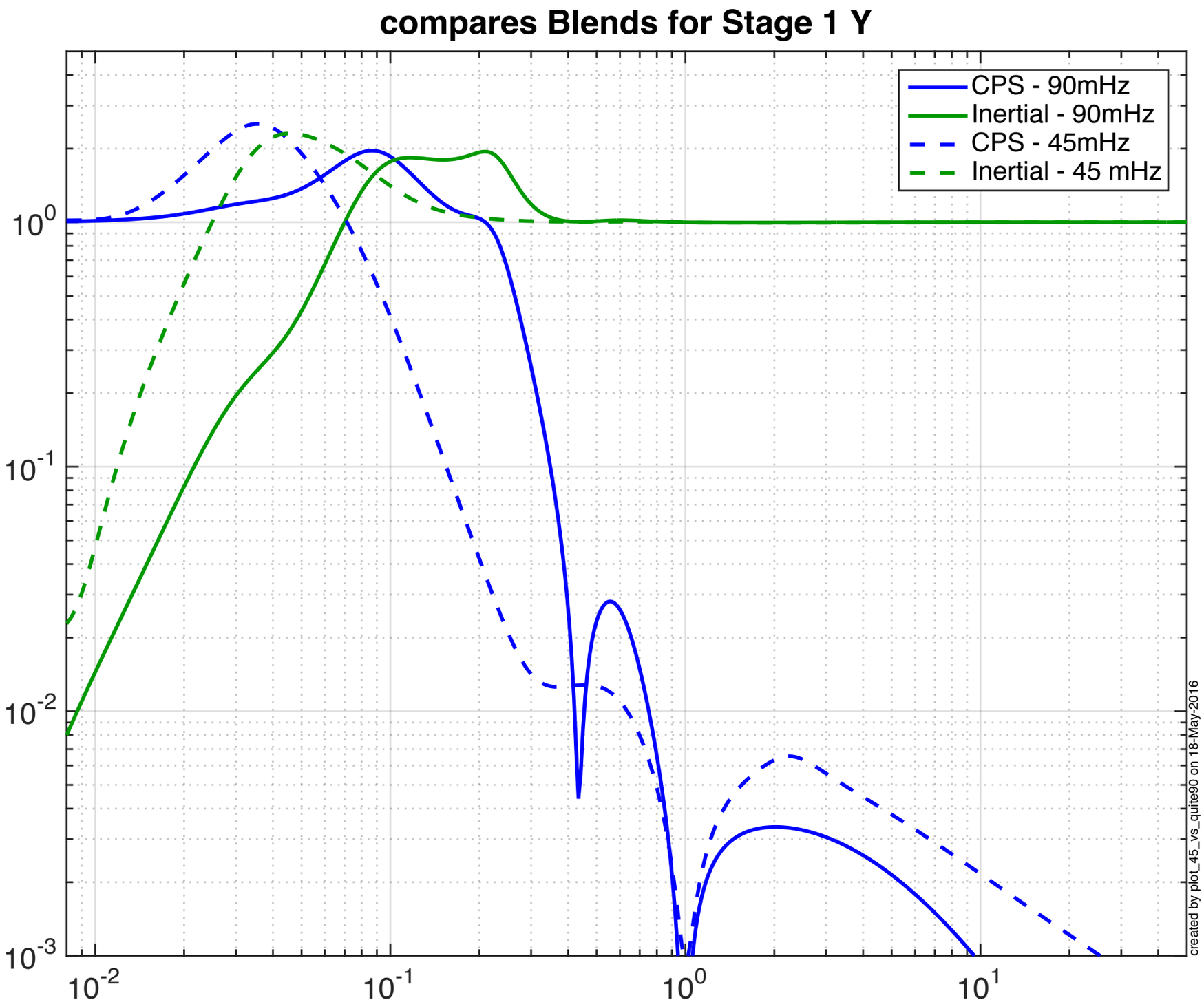




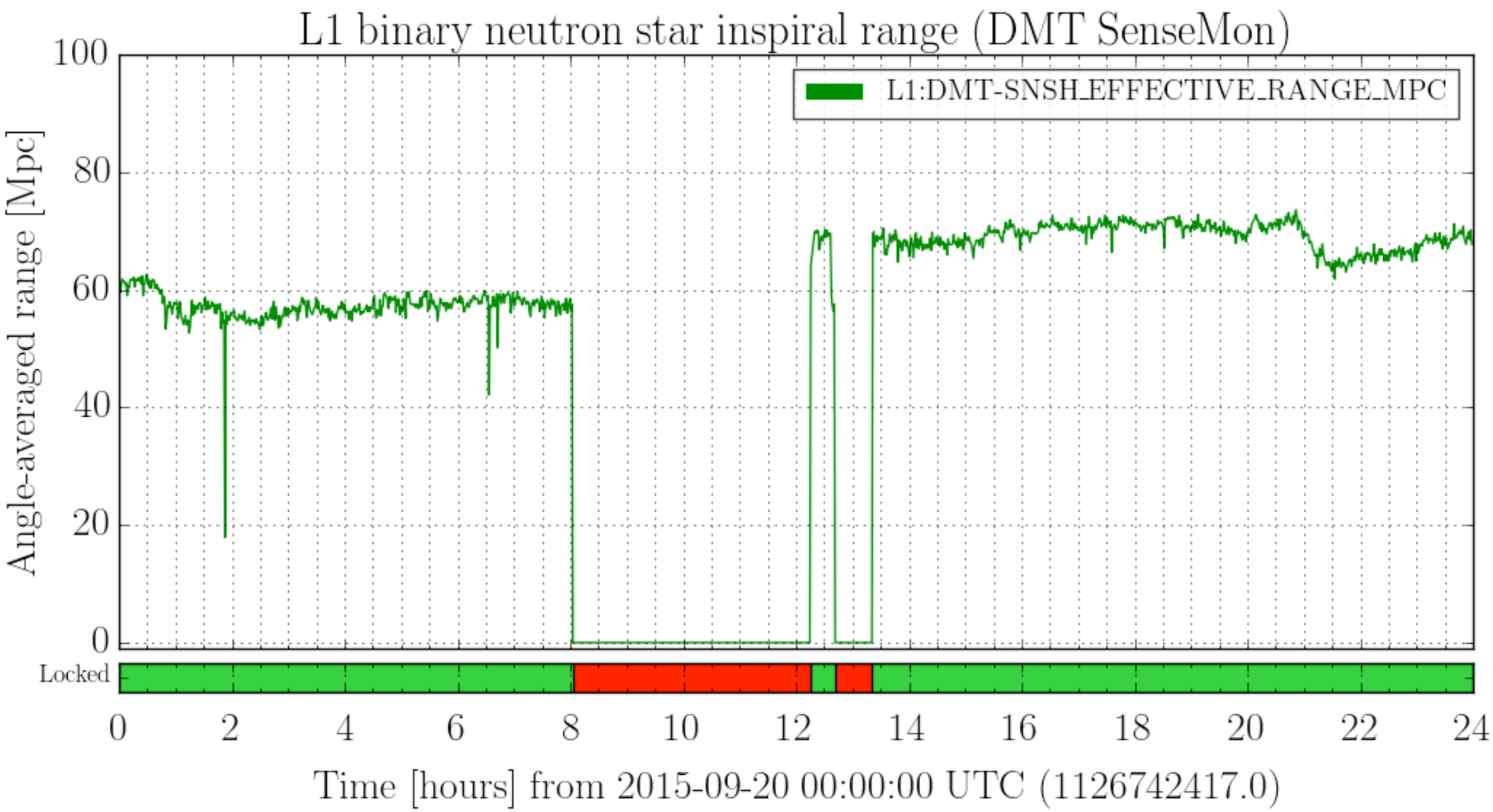
Blending sensors



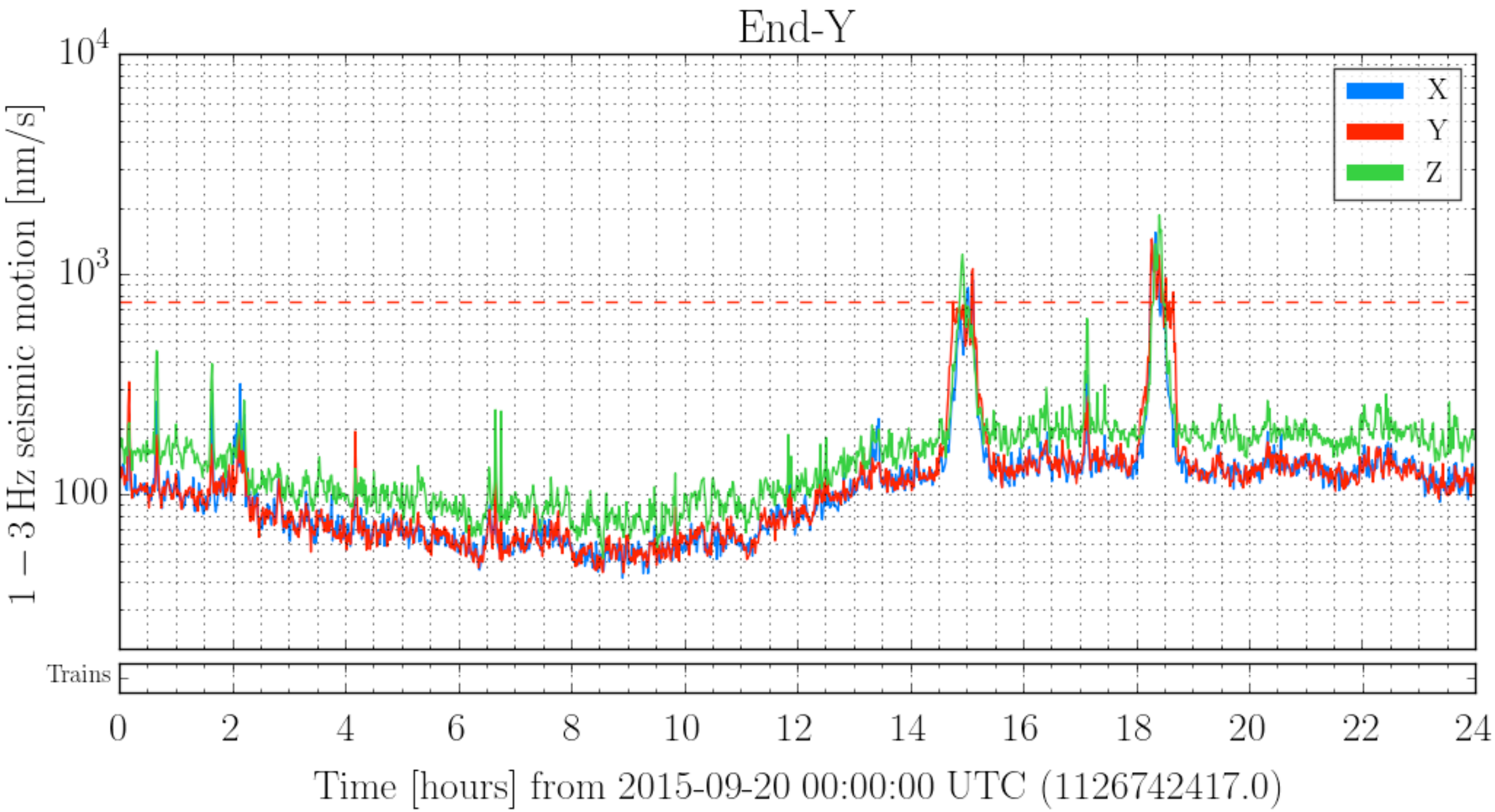
Blending sensors



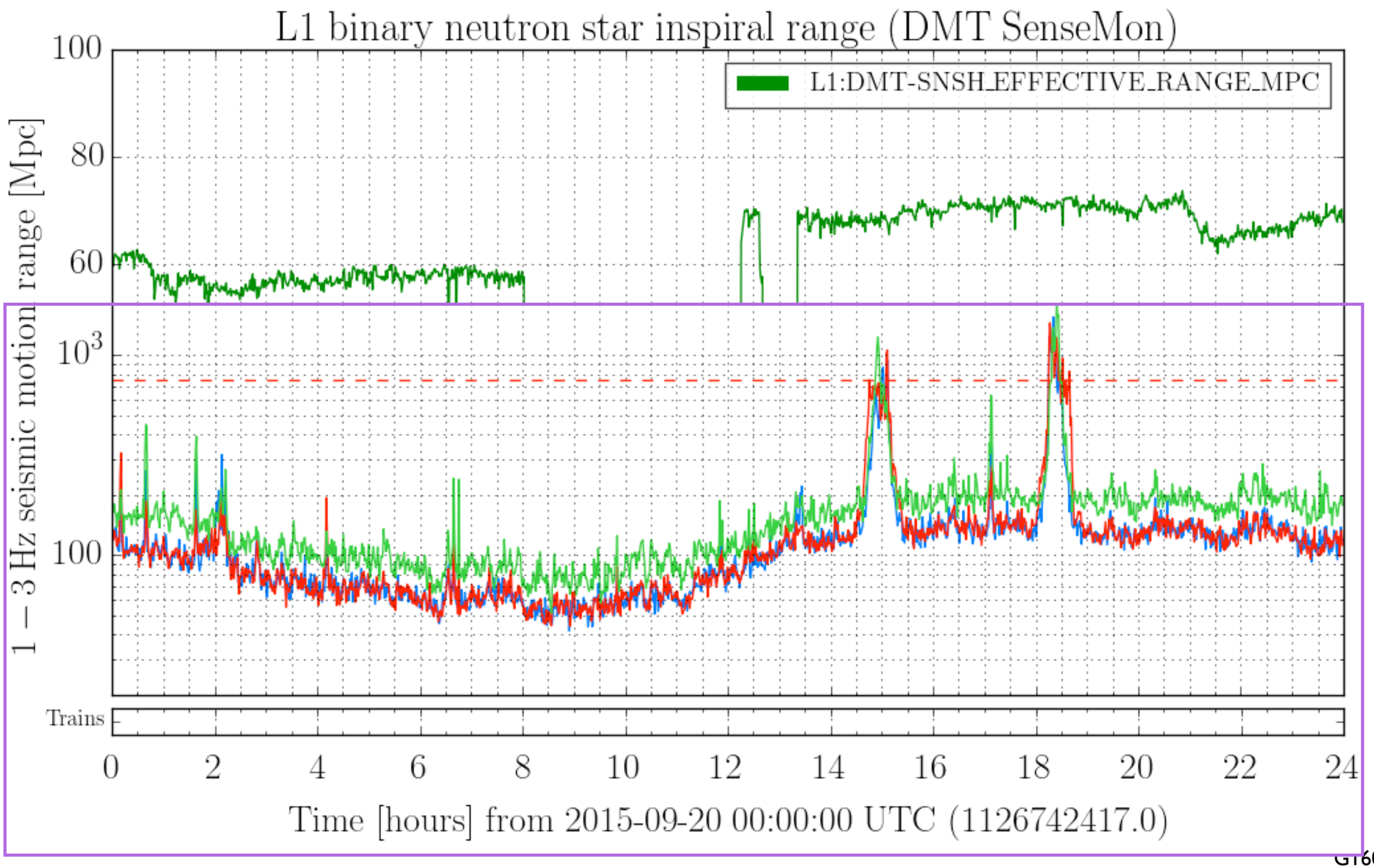
Real impact of isolation, alignment & control



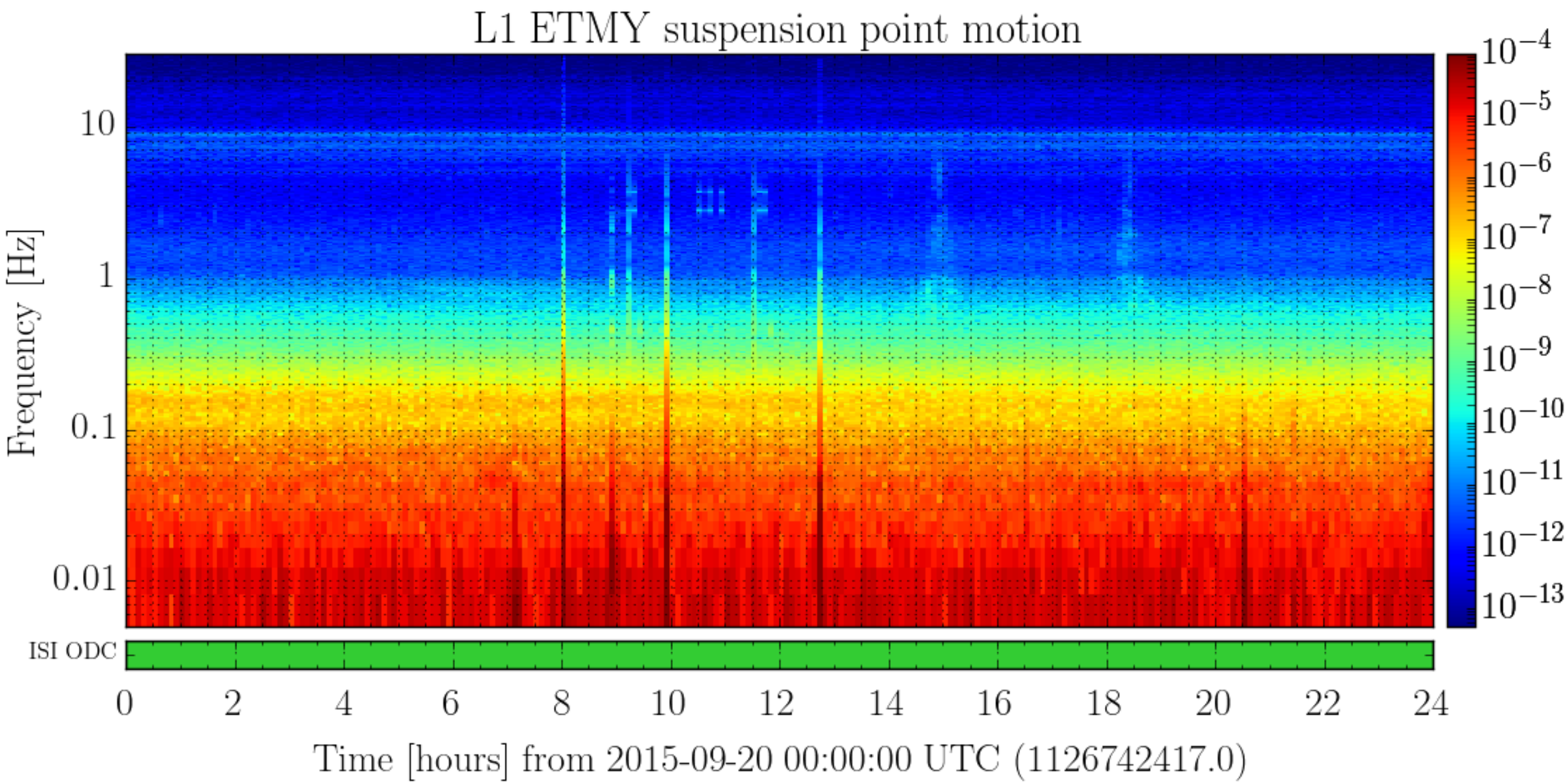
but there was a train…



Real impact of isolation, alignment & control

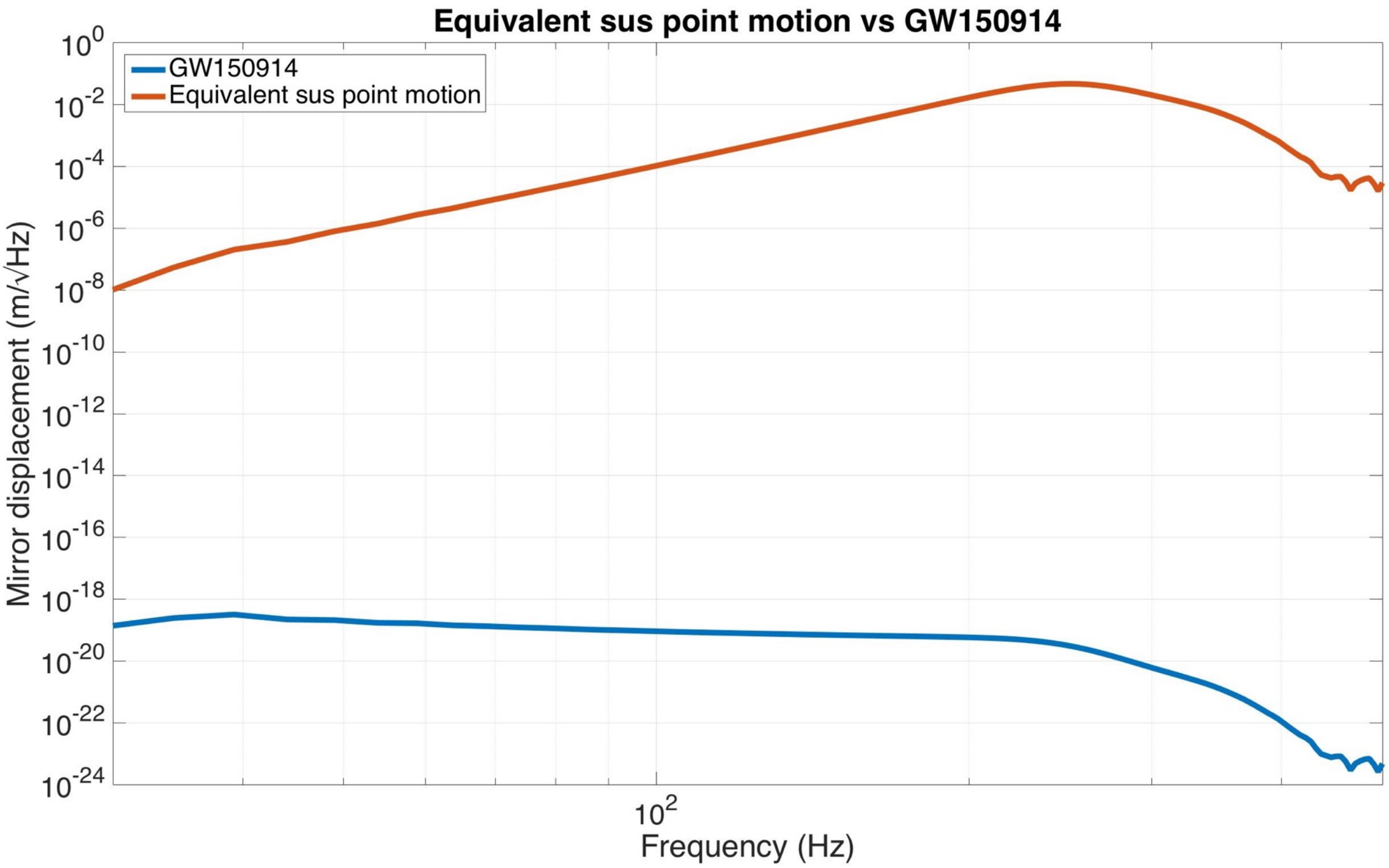


‘Environmental’ sensors

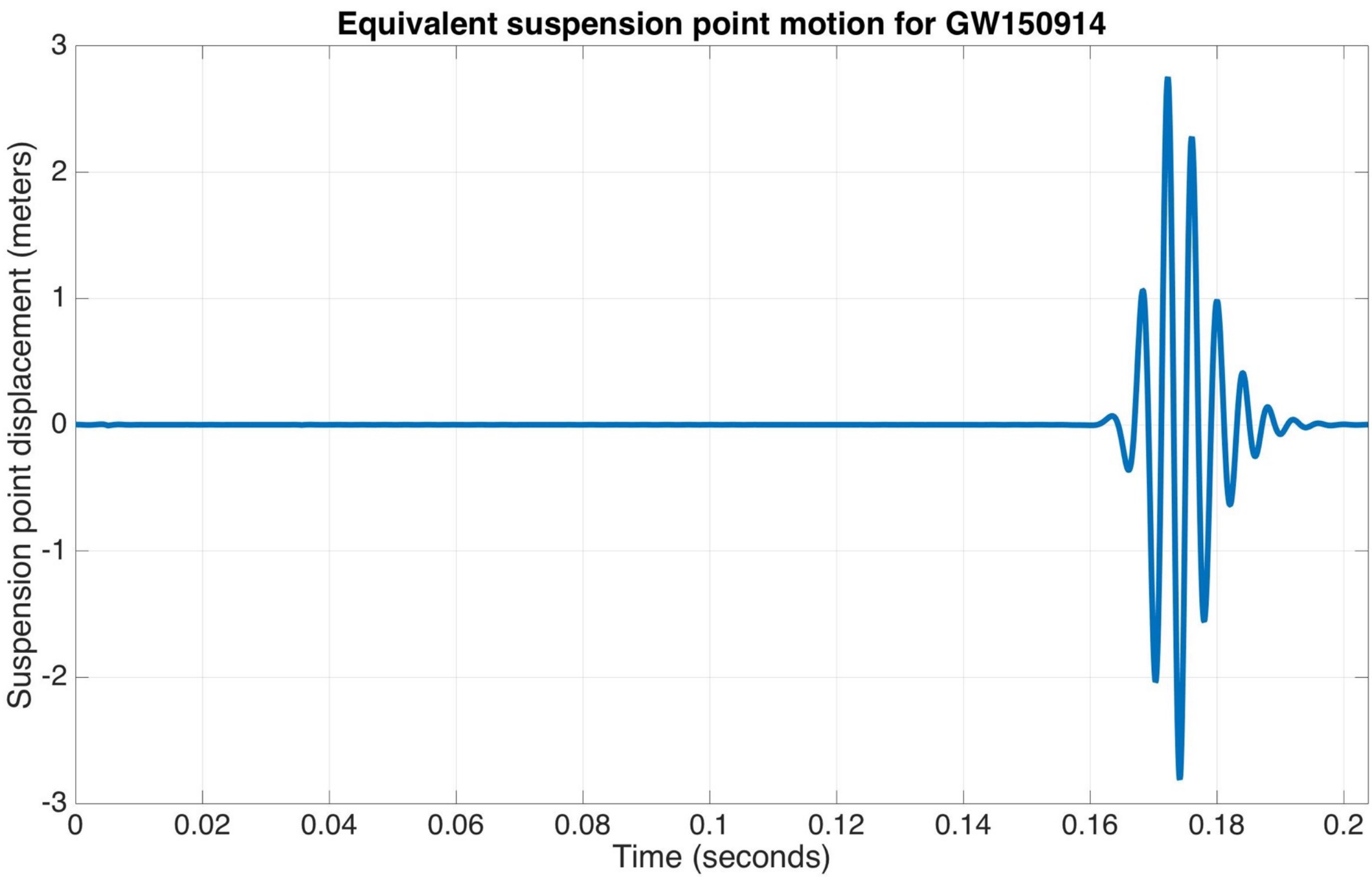


Power of the monitors

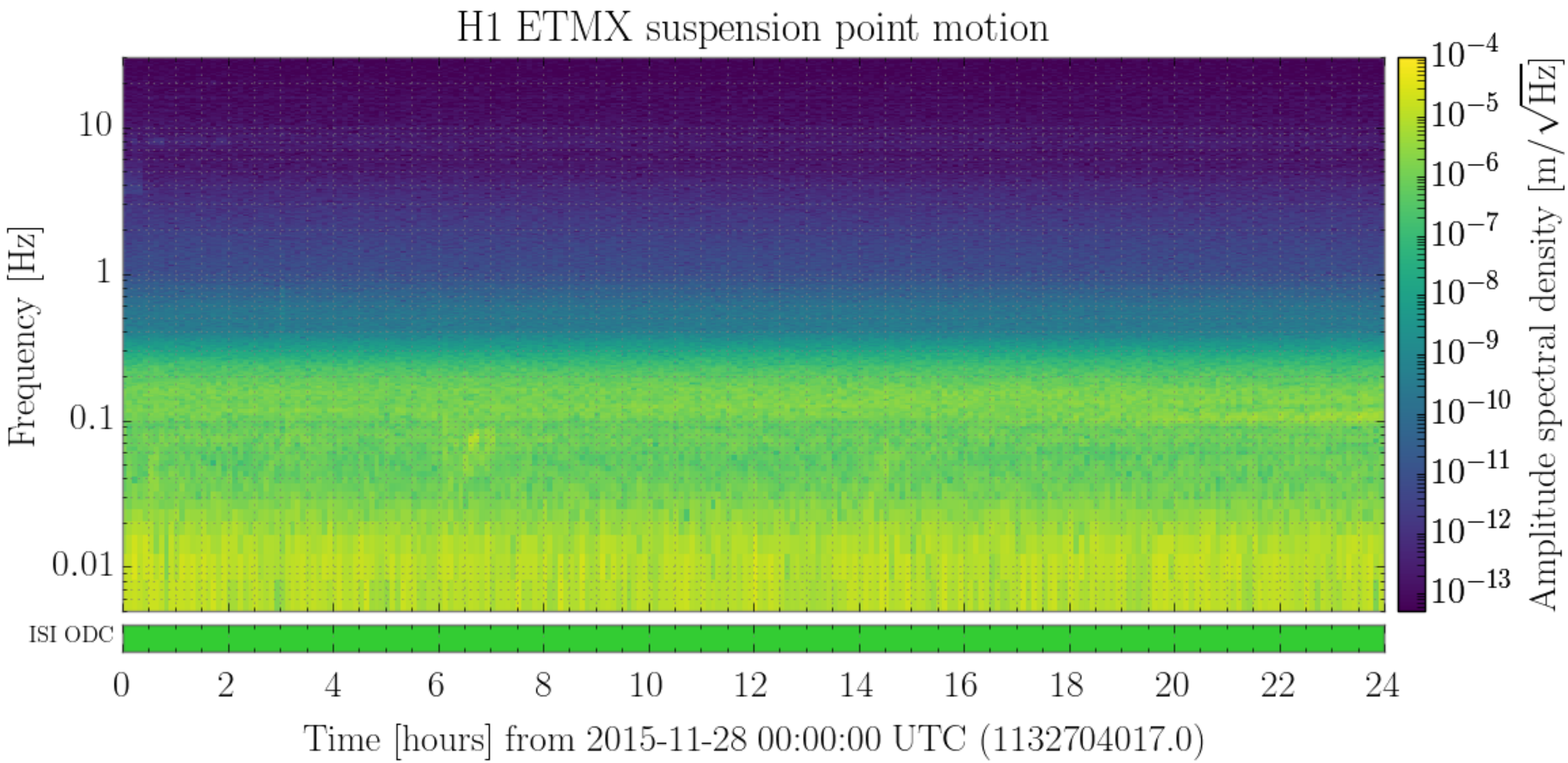
If GS150914 was linearly coupled seismic motion

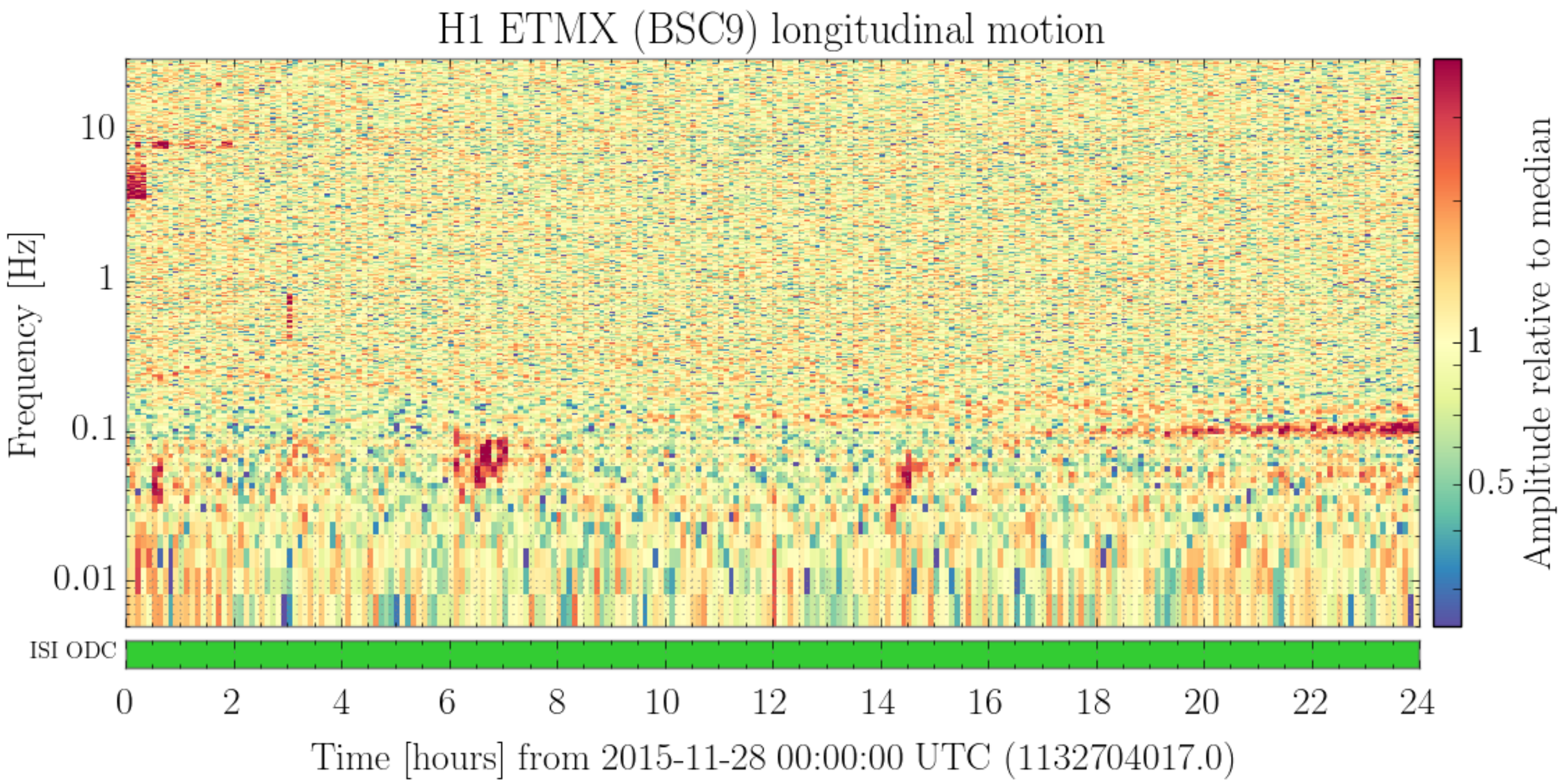


If GS150914 was

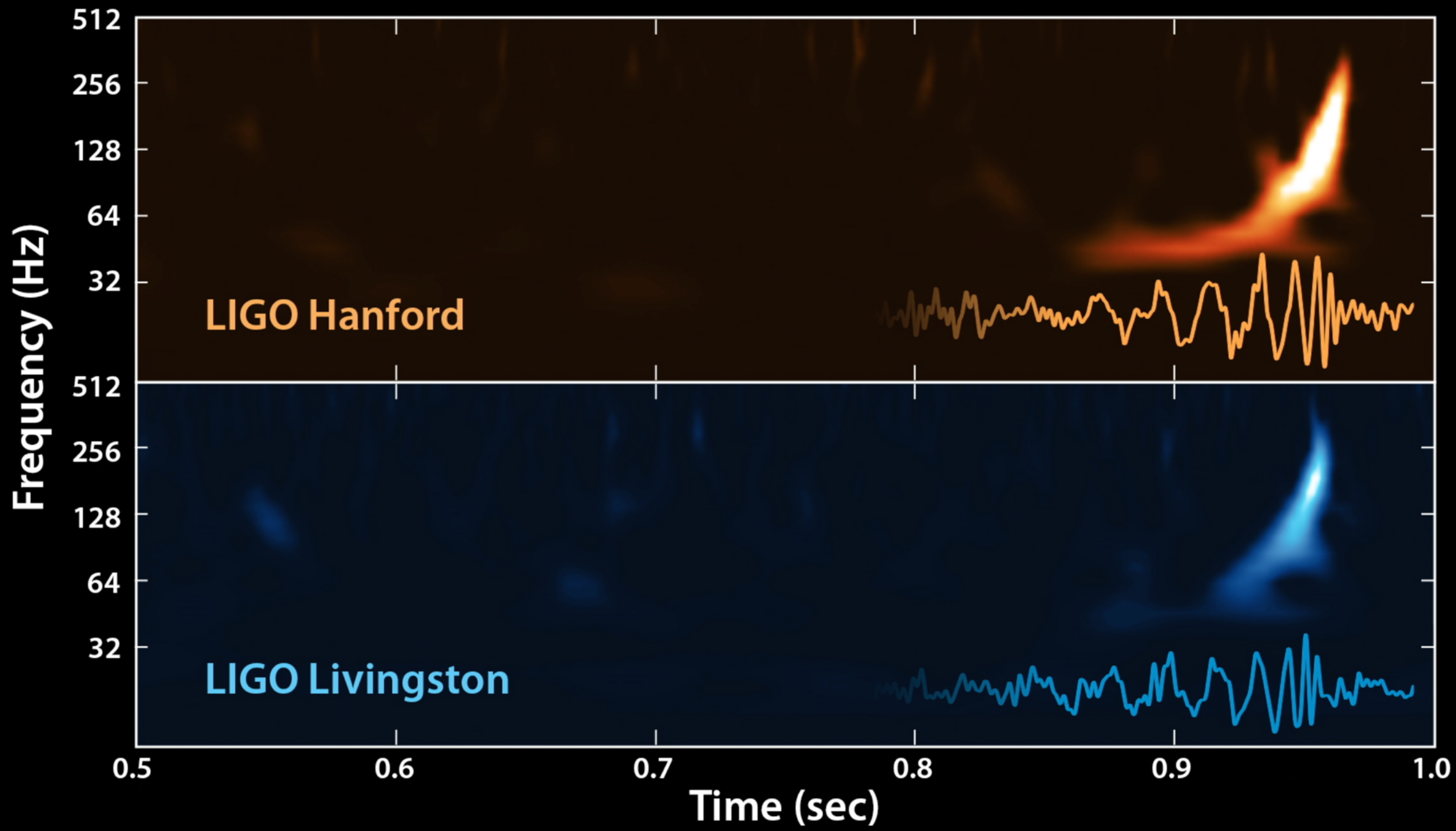


This is what we strive for

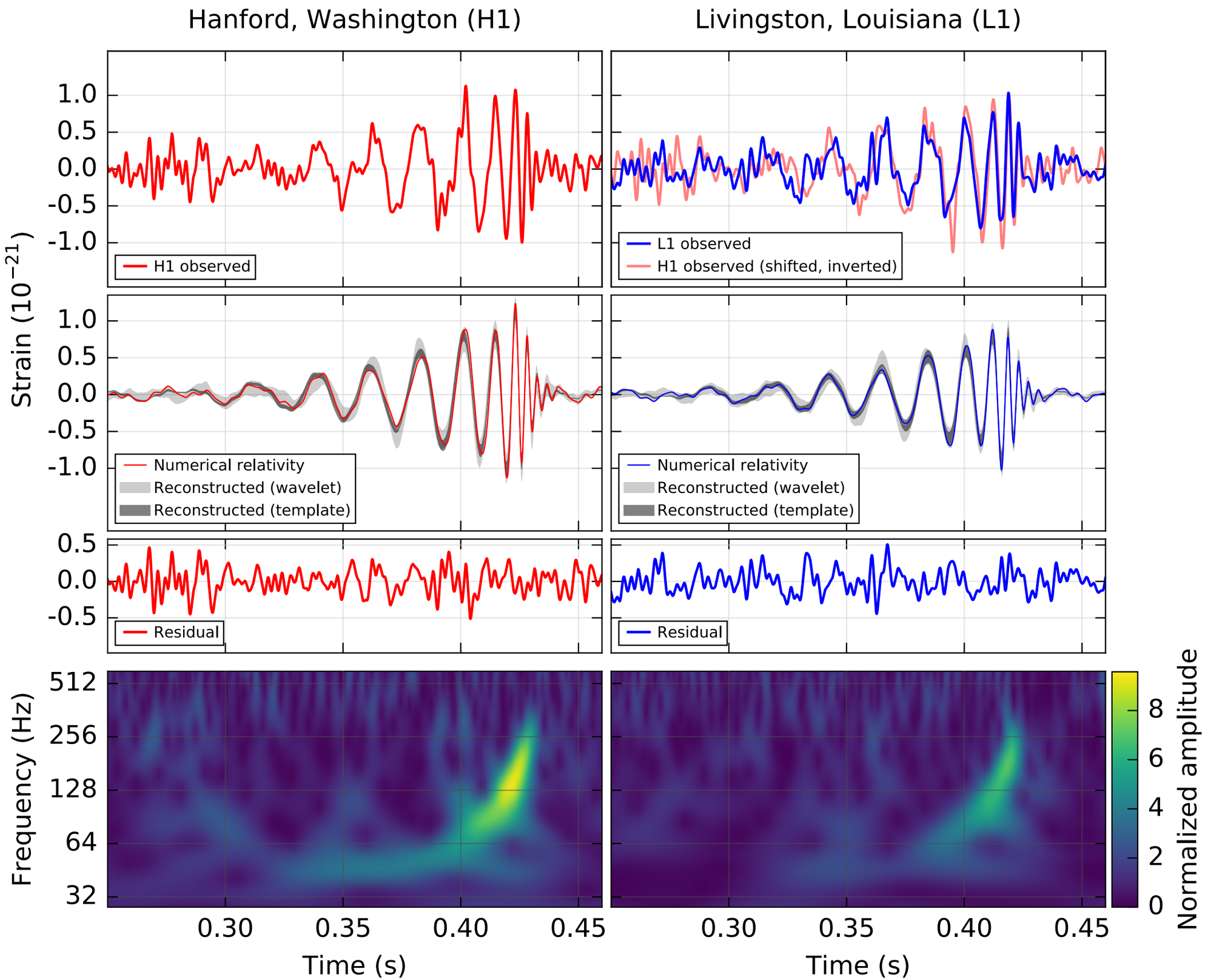



H1 ETMX (BSC9) longitudinal motion
Frequency [Hz]
10
1
0.1
0.01
ISI ODC
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2015-11-28 00:00:00 UTC (1132704017.0)
Amplitude relative to median
1
0.5

The sound of black holes colliding



First signal - Sept 14, 2015



Best fit with numerical Relativity

Initial Masses:

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

Final Mass:

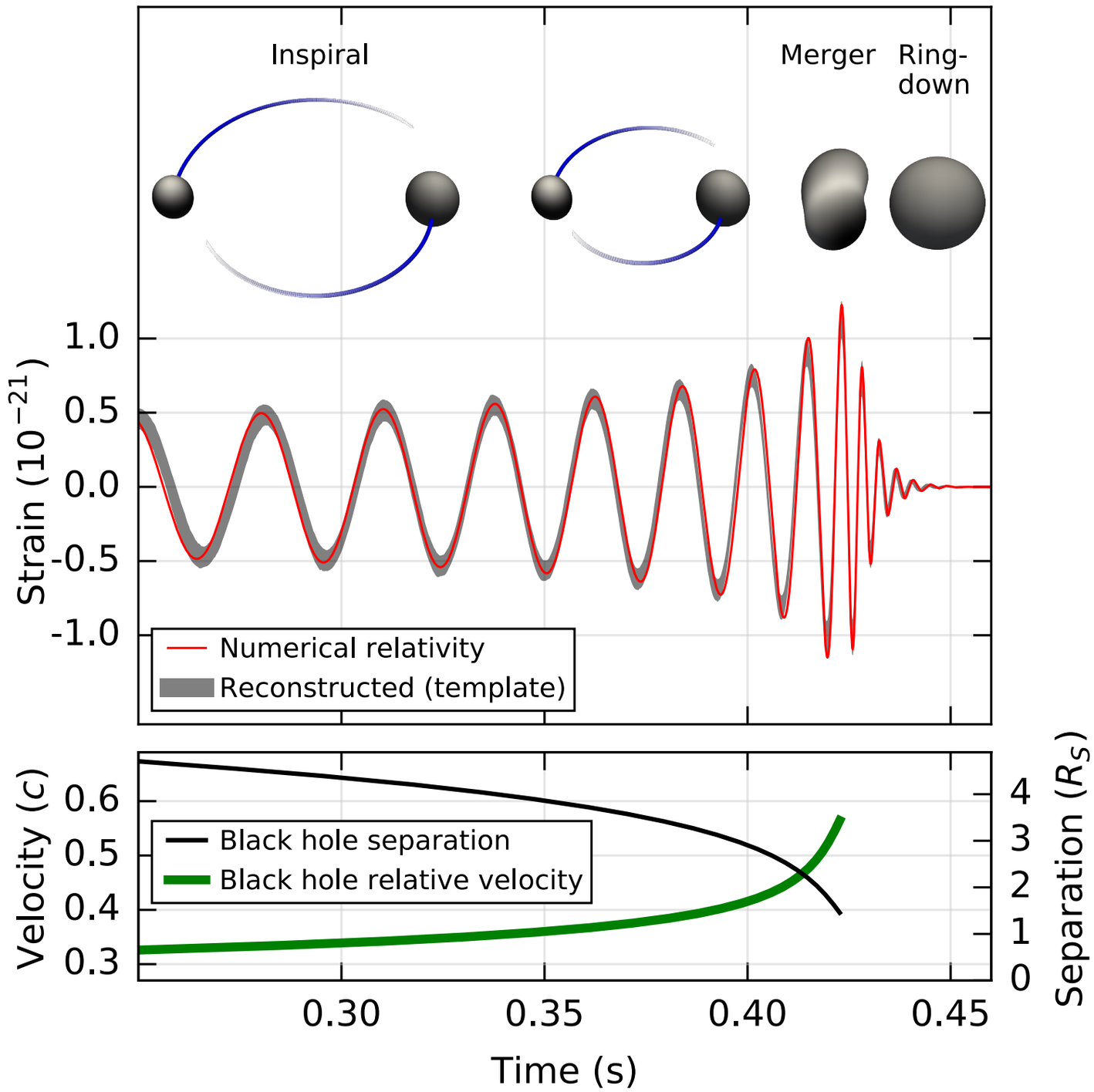
62 (+4/-4) M_{sun}

Energy radiated

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

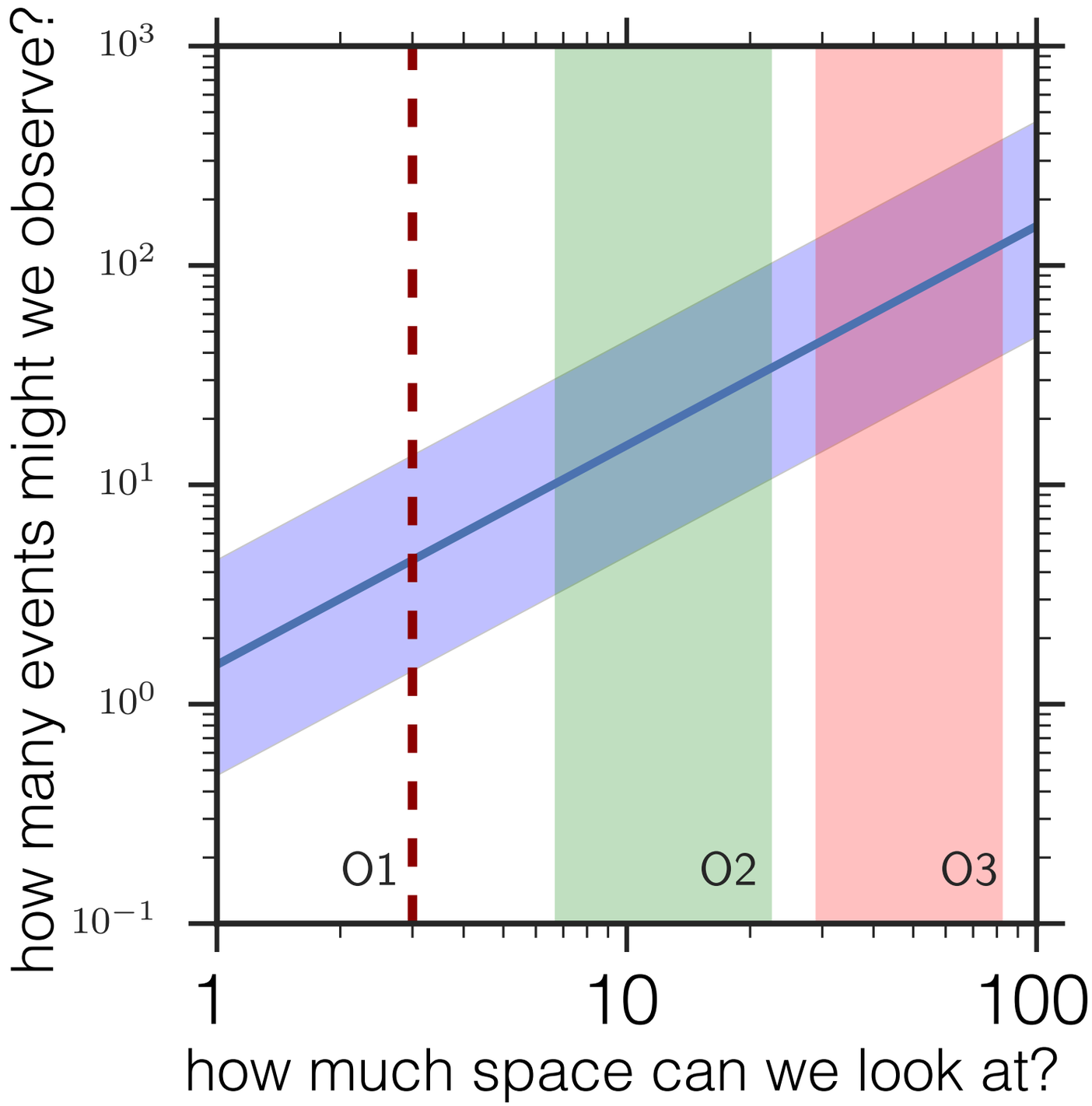
Distance

410 (+160/-180) MPc

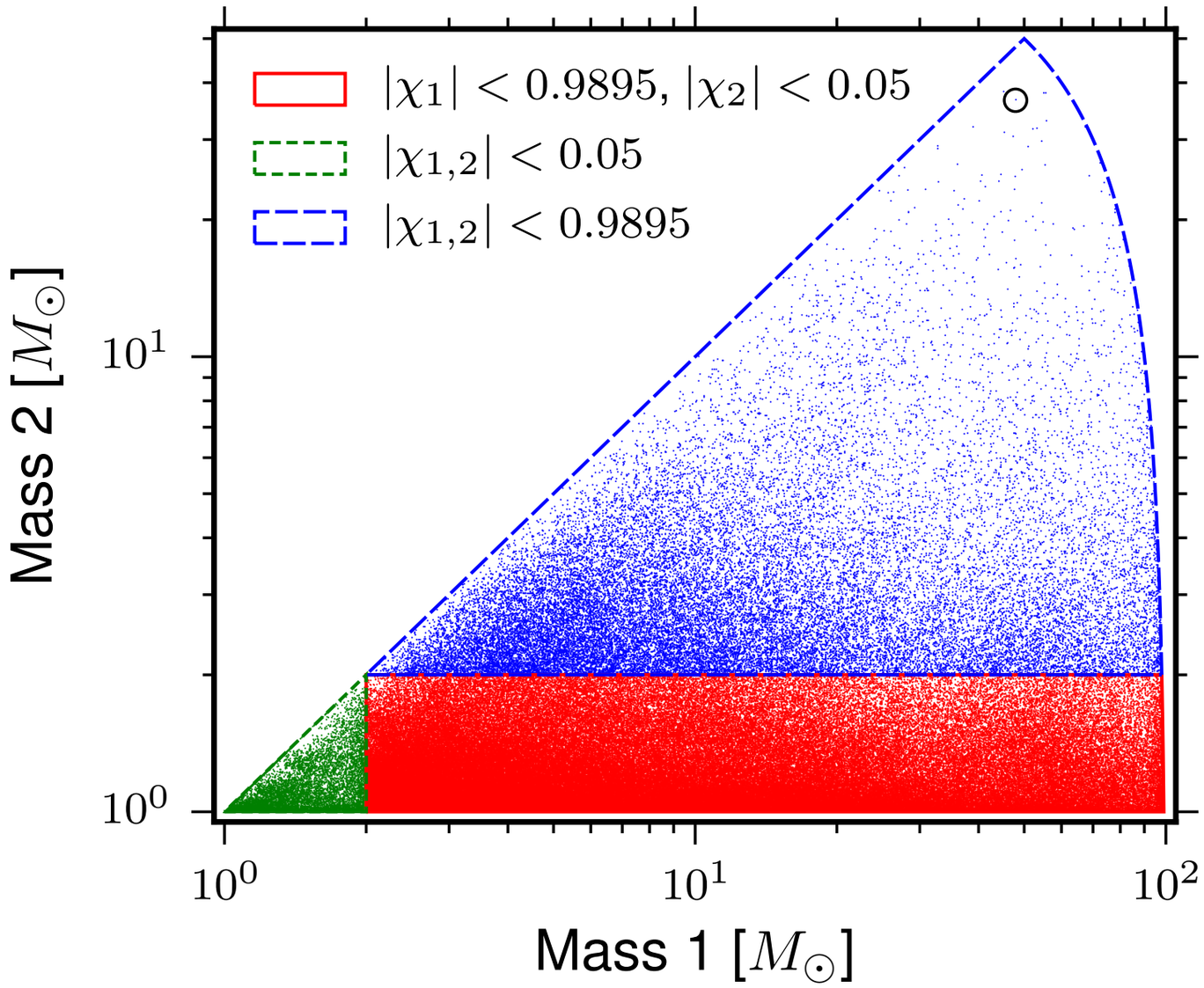


The End/ The Beginning…

How many black hole collisions can we see?



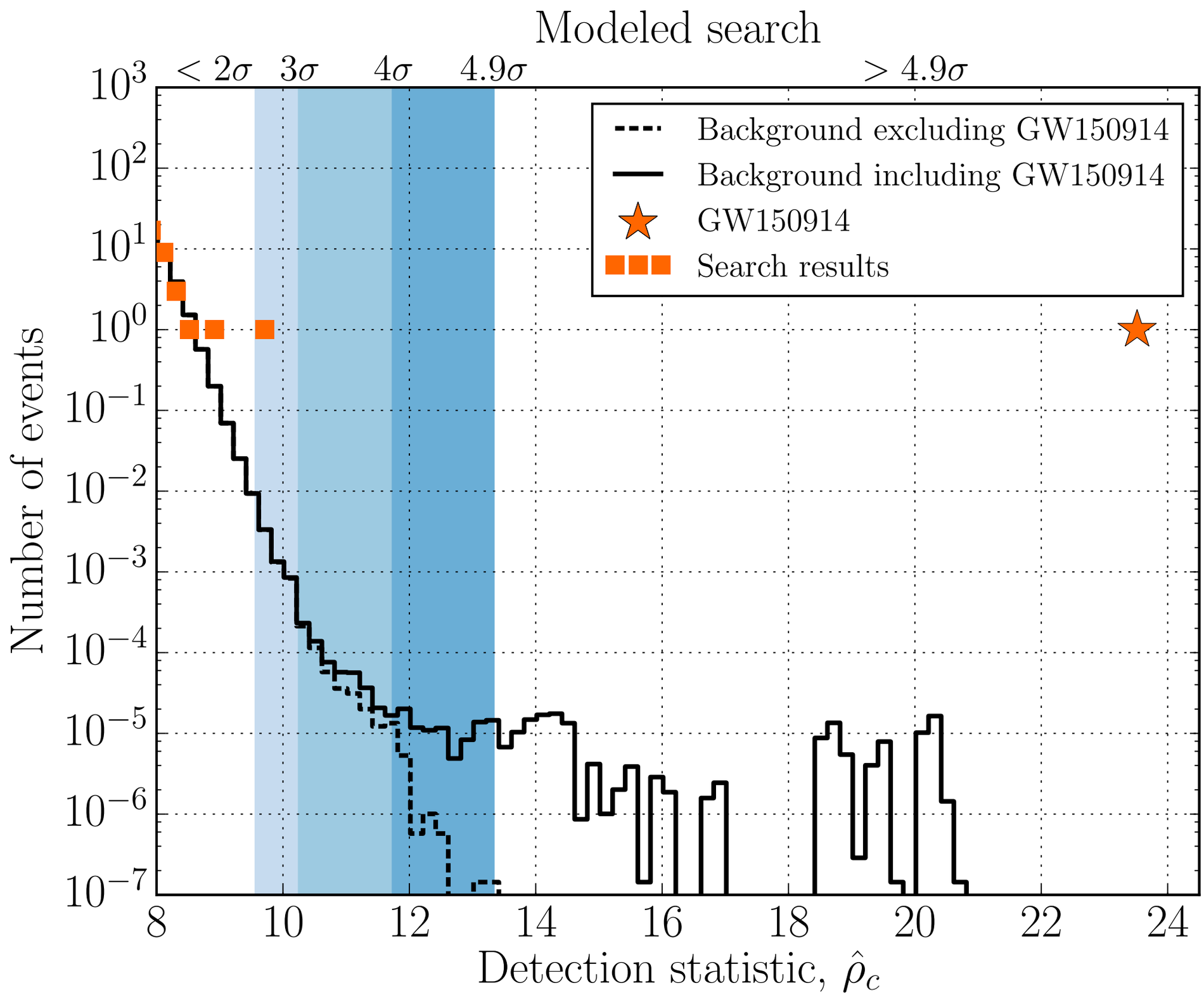
CBC template bank

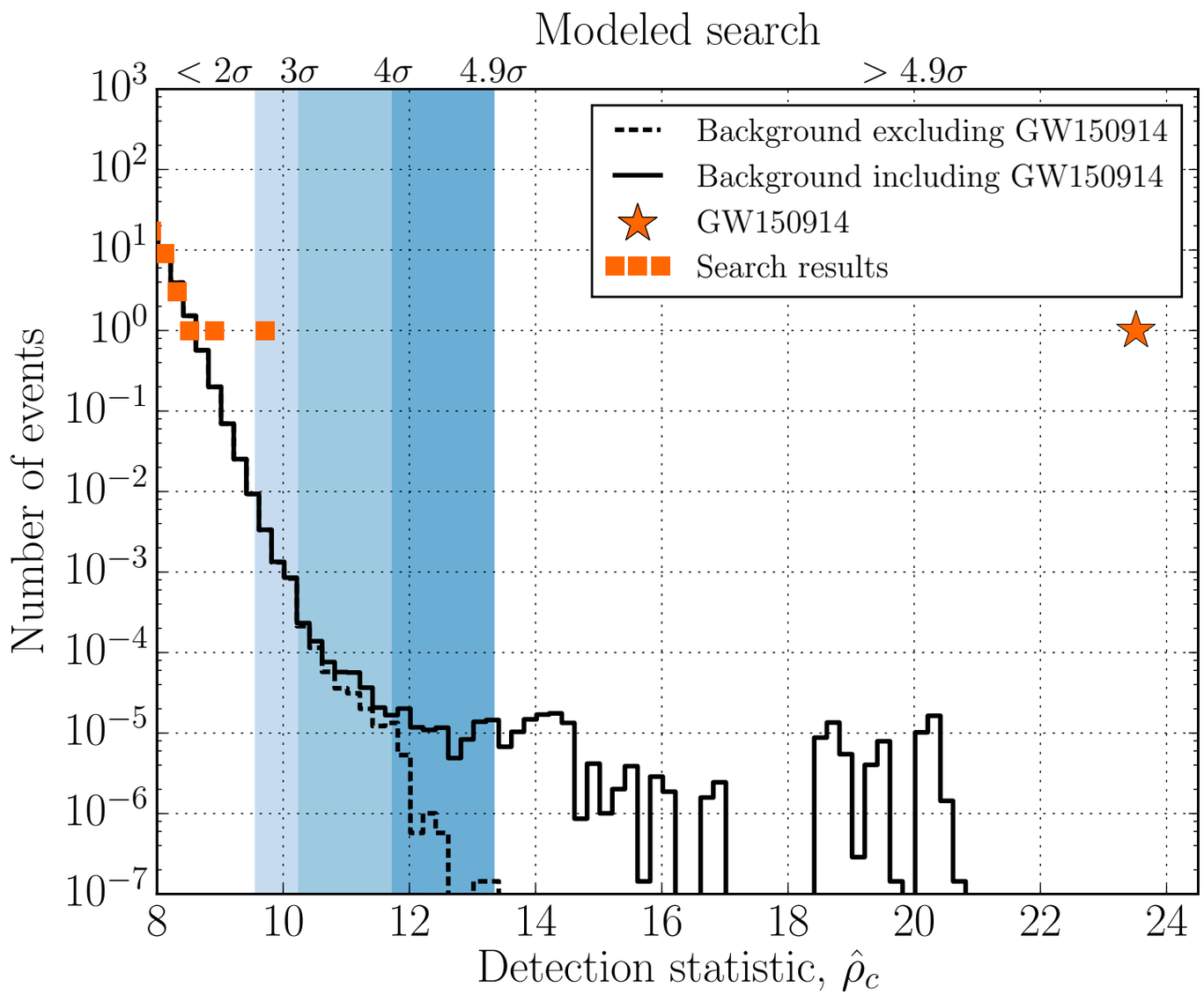


(just at the edge…)

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}