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

LIGO

LSC

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

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

ICTP SAIFR

THE UNIVERSITY OF WESTERN AUSTRALIA

PAH

UNIVERSITY OF CAMBRIDGE

MONASH University

SOUTHERN UNIVERSITY Agricultural & Mechanical College

THE UNIVERSITY OF CHICAGO

MONTANA STATE UNIVERSITY

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

GEO 600

UNIVERSITY OF WASHINGTON

UTRGV

UNIVERSITY of WISCONSIN UWMILWAUKEE

SYRACUSE UNIVERSITY 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

Science & Technology Facilities Council Rutherford Appleton Laboratory

International Network

LIGO India

project approved

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

Sept. 14, 2015

LIGO Hanford

GEO 600

KAGRA

VIRGO

LIGO Livingston

LIGO India

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ACIGA

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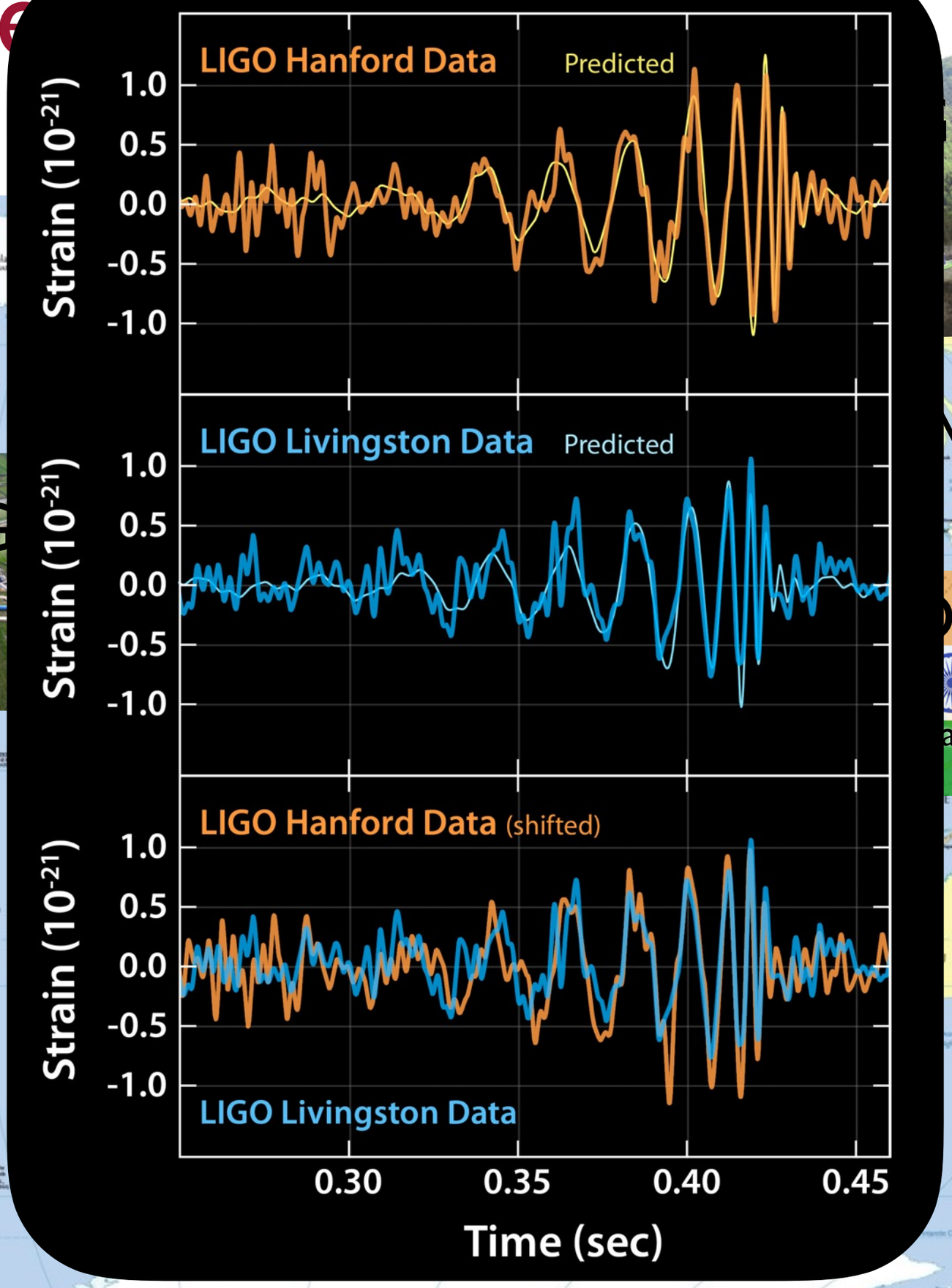
Se

LIGO Hanford

LIGO Livingston



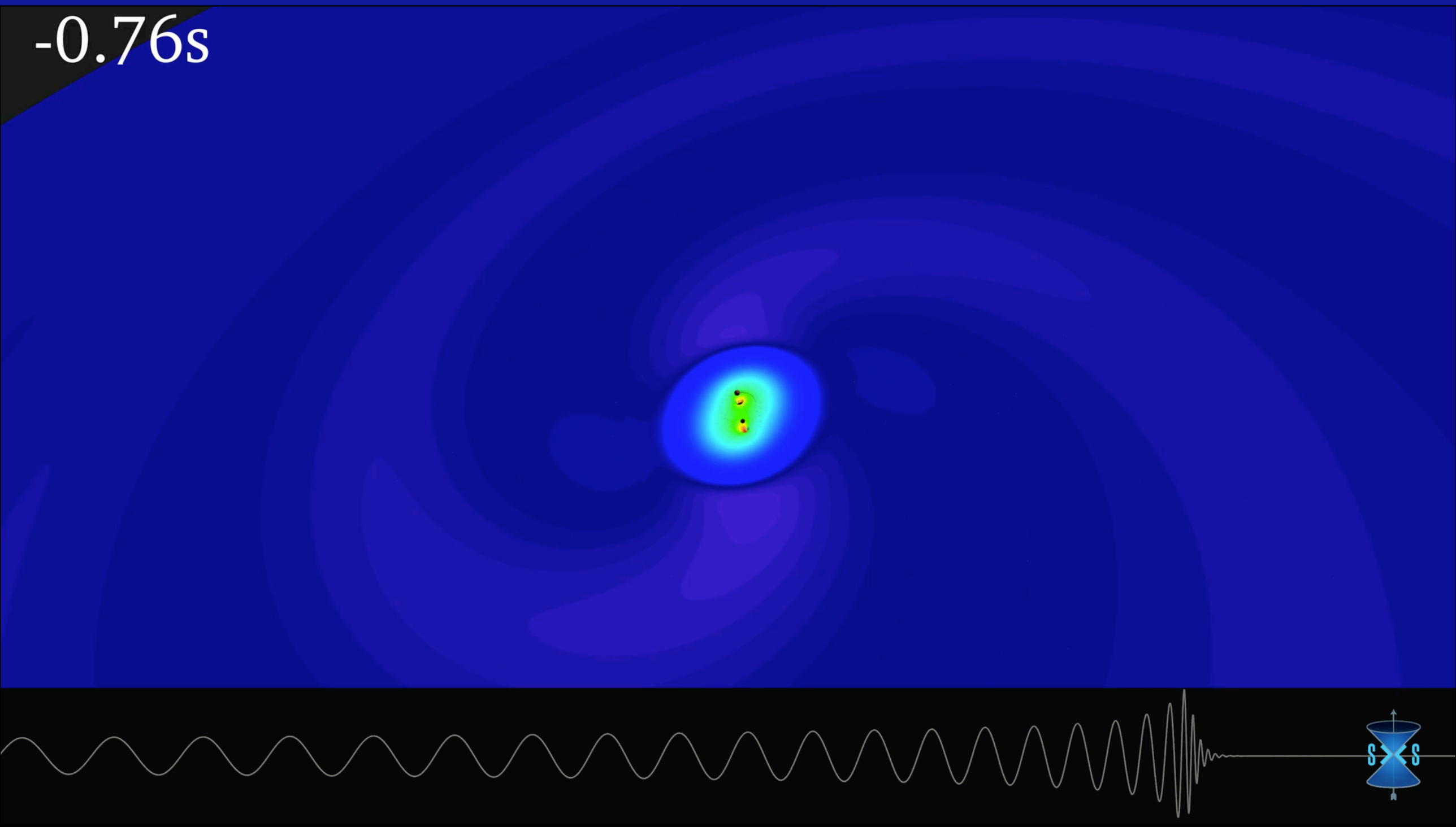
RA

India

approved

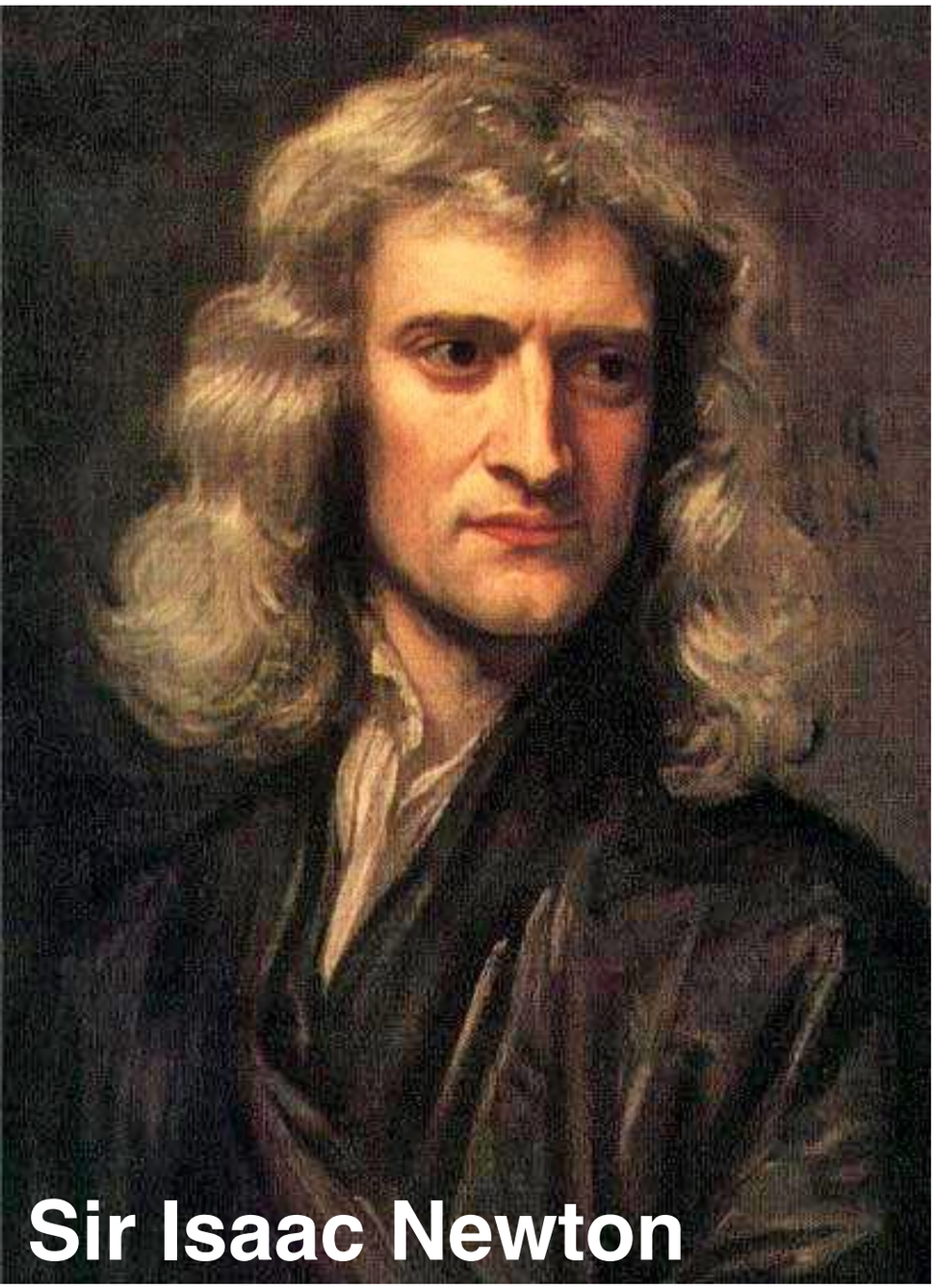
map from http://www.nationsonline.org/maps/political_world_map3000.jpg

Simulation of the event



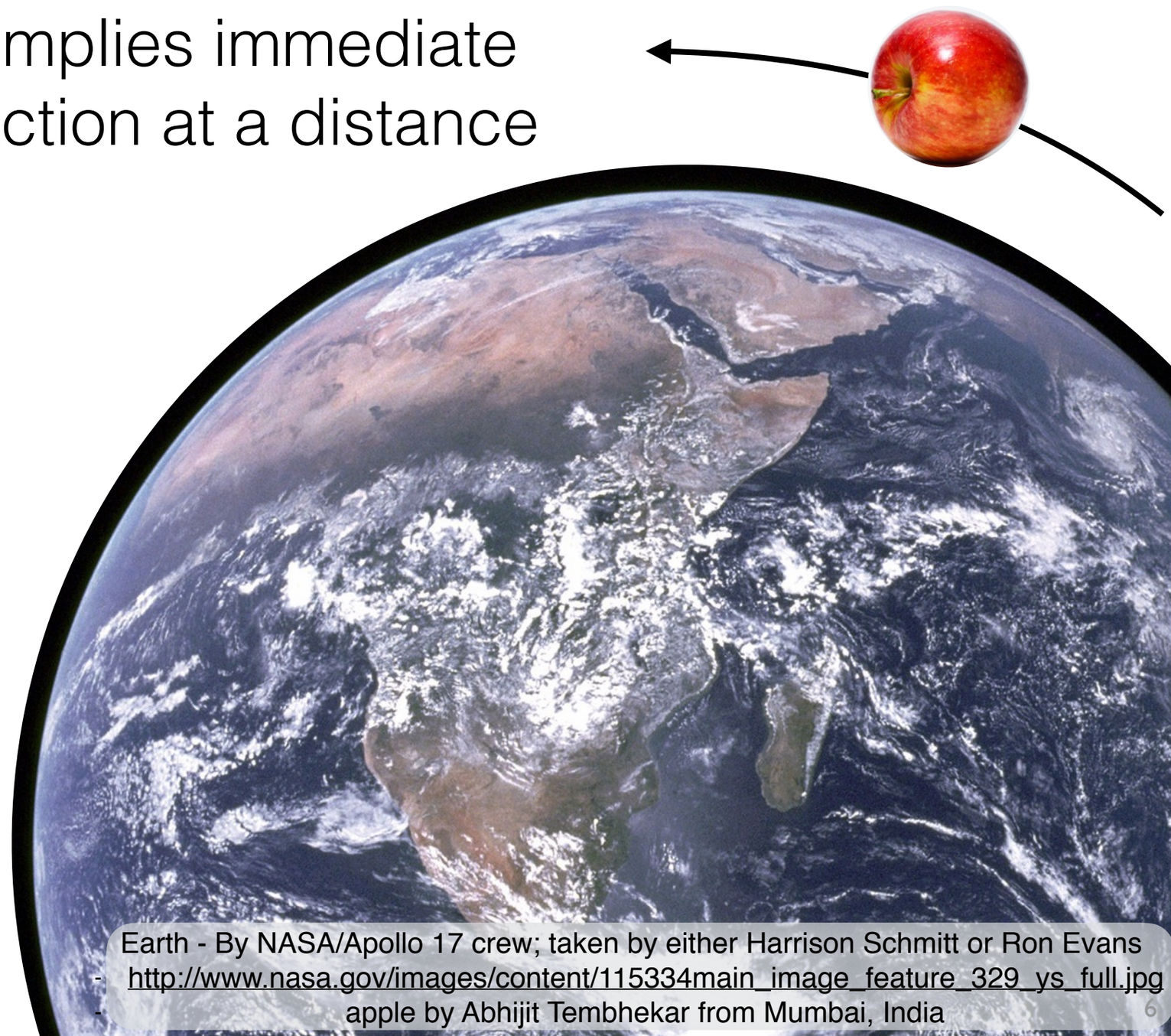
What is a Gravitational Wave?

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



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

Implies immediate action at a distance



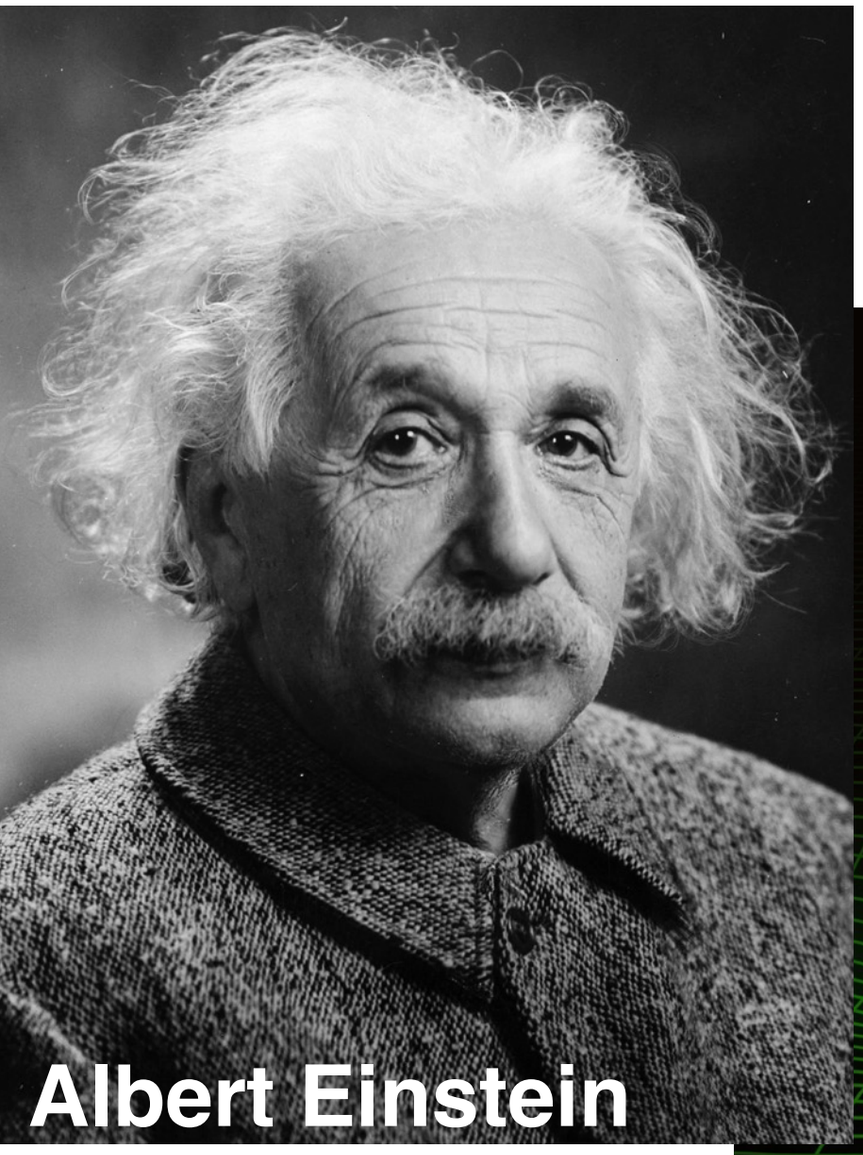
Earth - By NASA/Apollo 17 crew; taken by either Harrison Schmitt or Ron Evans
- http://www.nasa.gov/images/content/115334main_image_feature_329_ys_full.jpg
- apple by Abhijit Tembhekar from Mumbai, India

What is a Gravitational Wave?

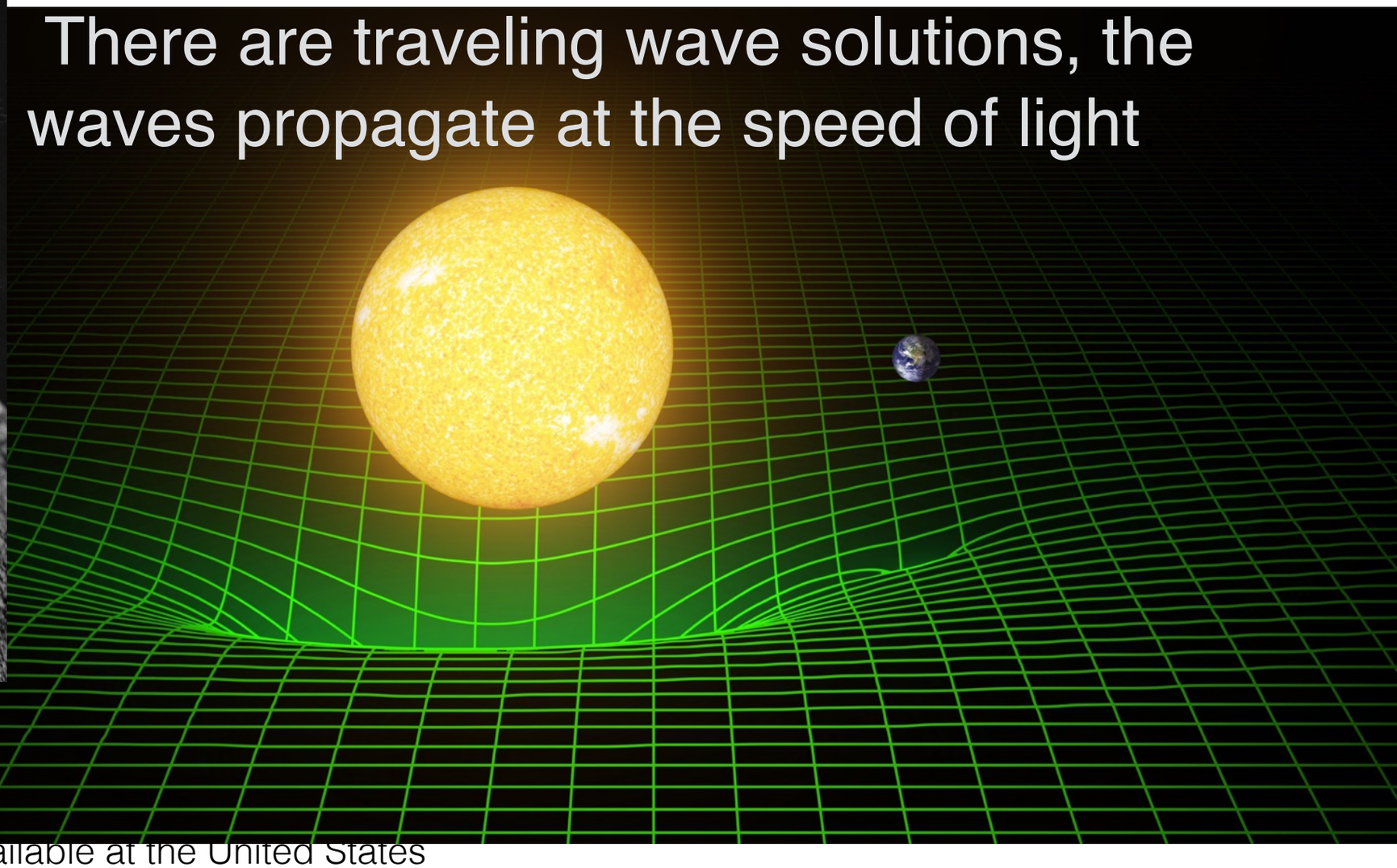
Predicted by Einstein in 1916 as part of GR.

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

- J. A. Wheeler

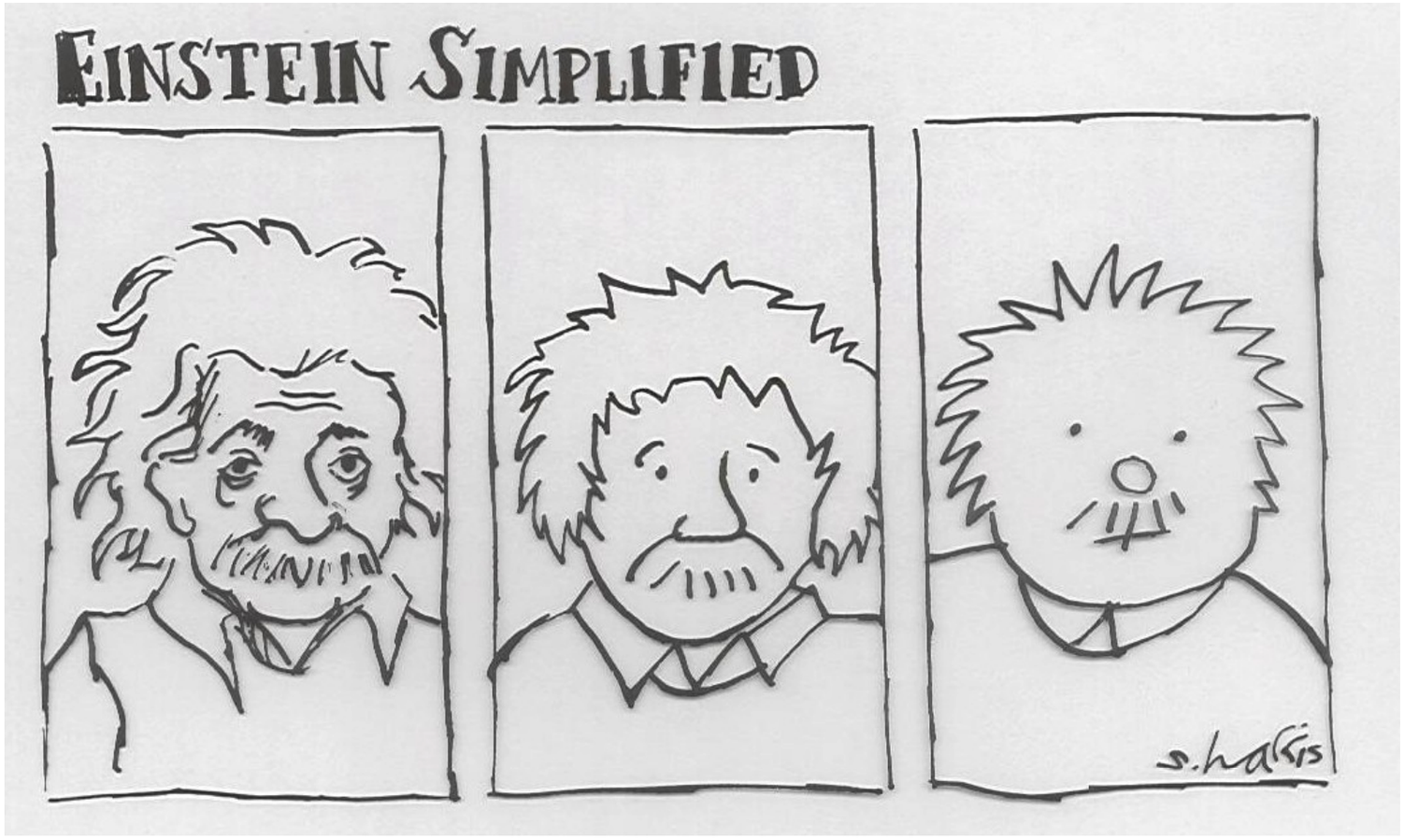


Albert Einstein



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

What is a Gravitational Wave?



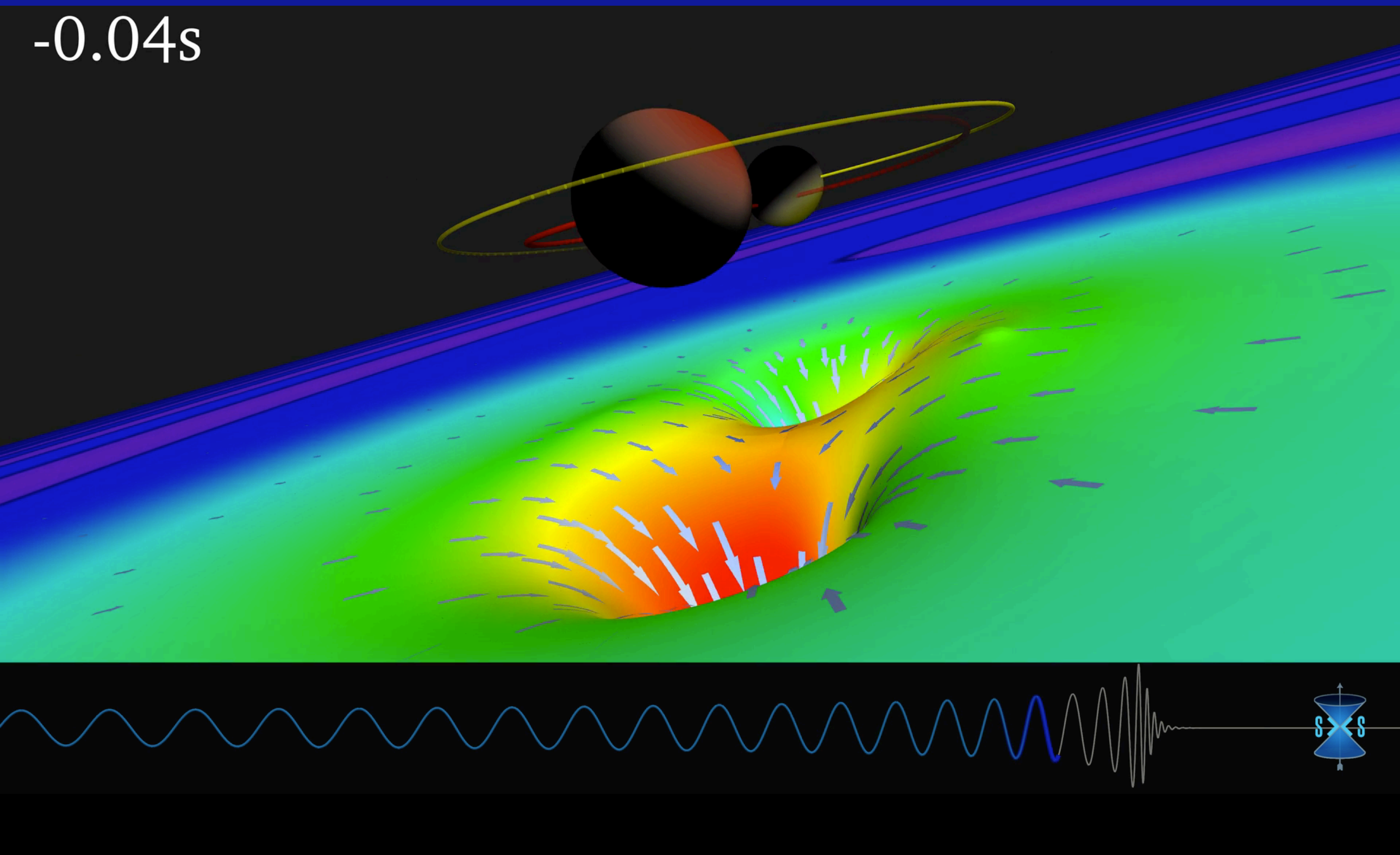
Assert an analogy:

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

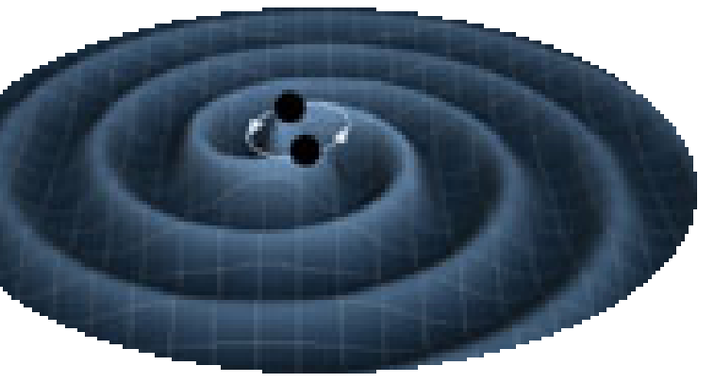
A stationary mass has a gravitational field, and accelerating the mass creates waves.

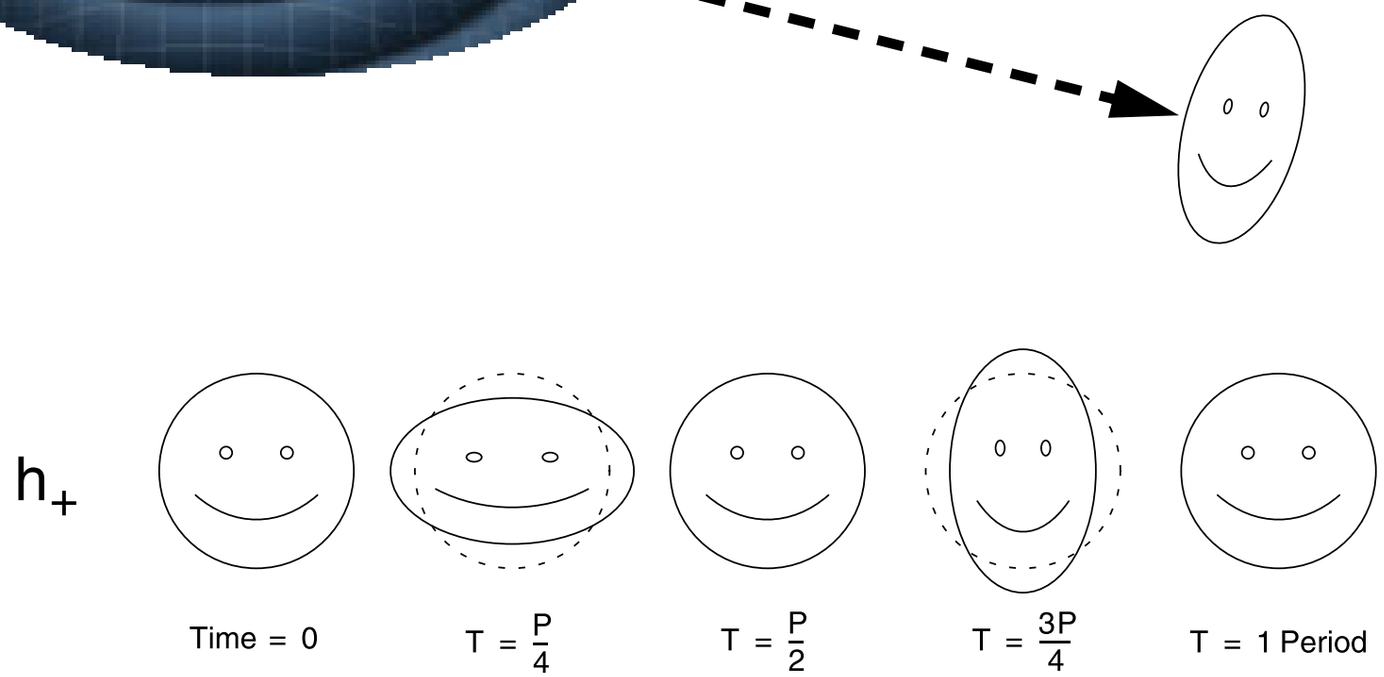
But, gravitational forces are relatively weak, or space is very stiff.

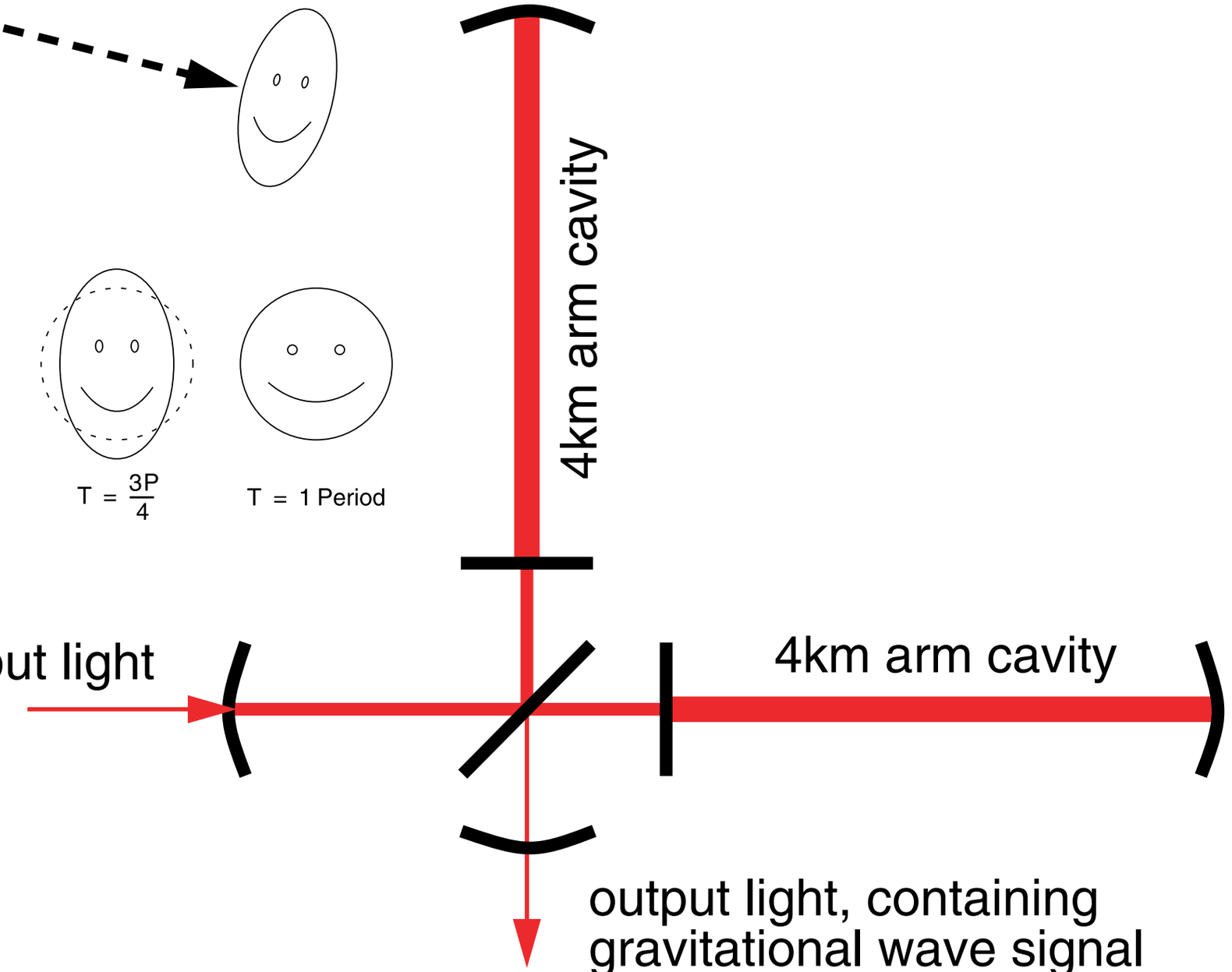
Simulation of the event



The LIGO concept





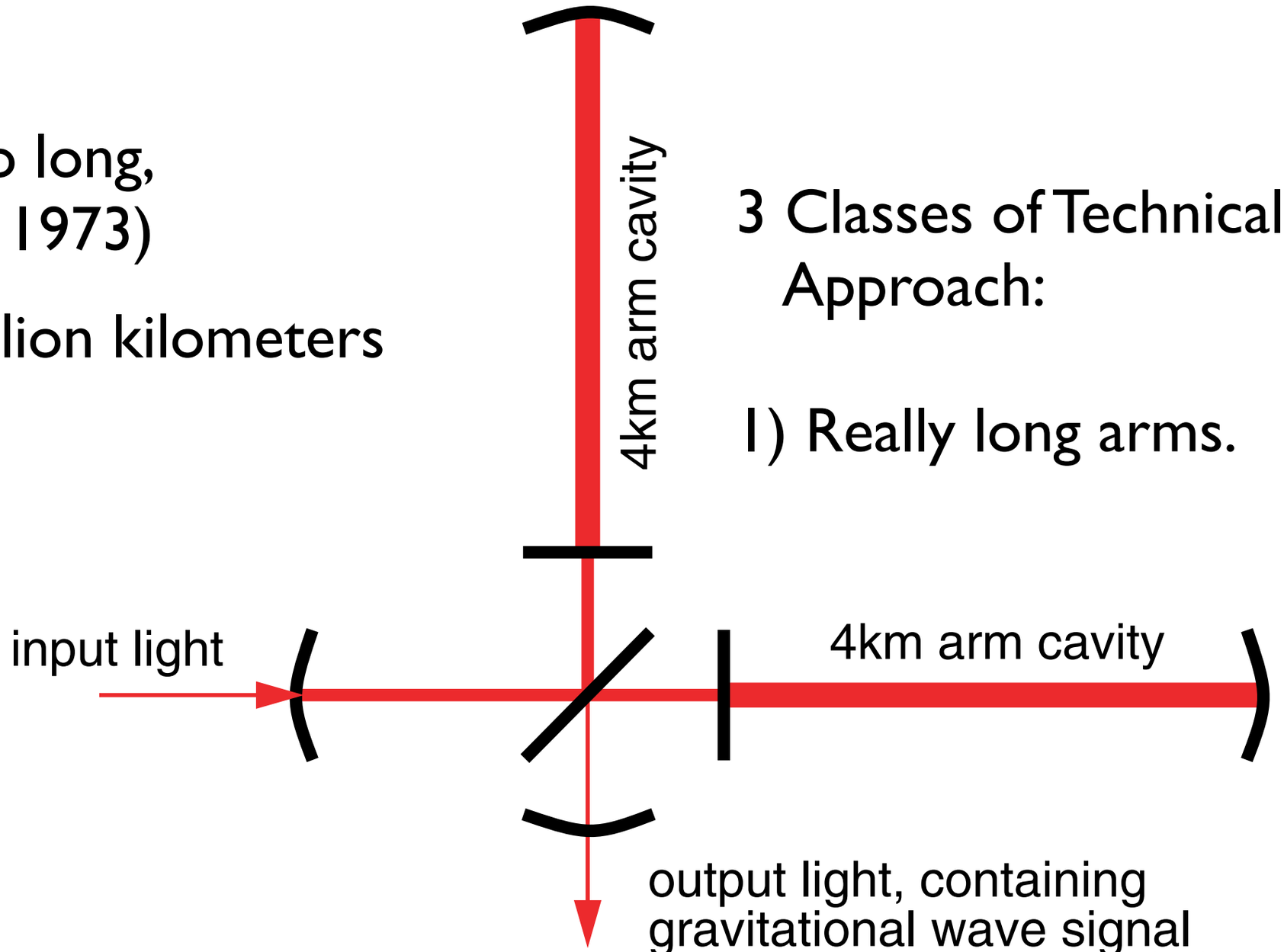


The LIGO concept
why it is nearly impossible

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

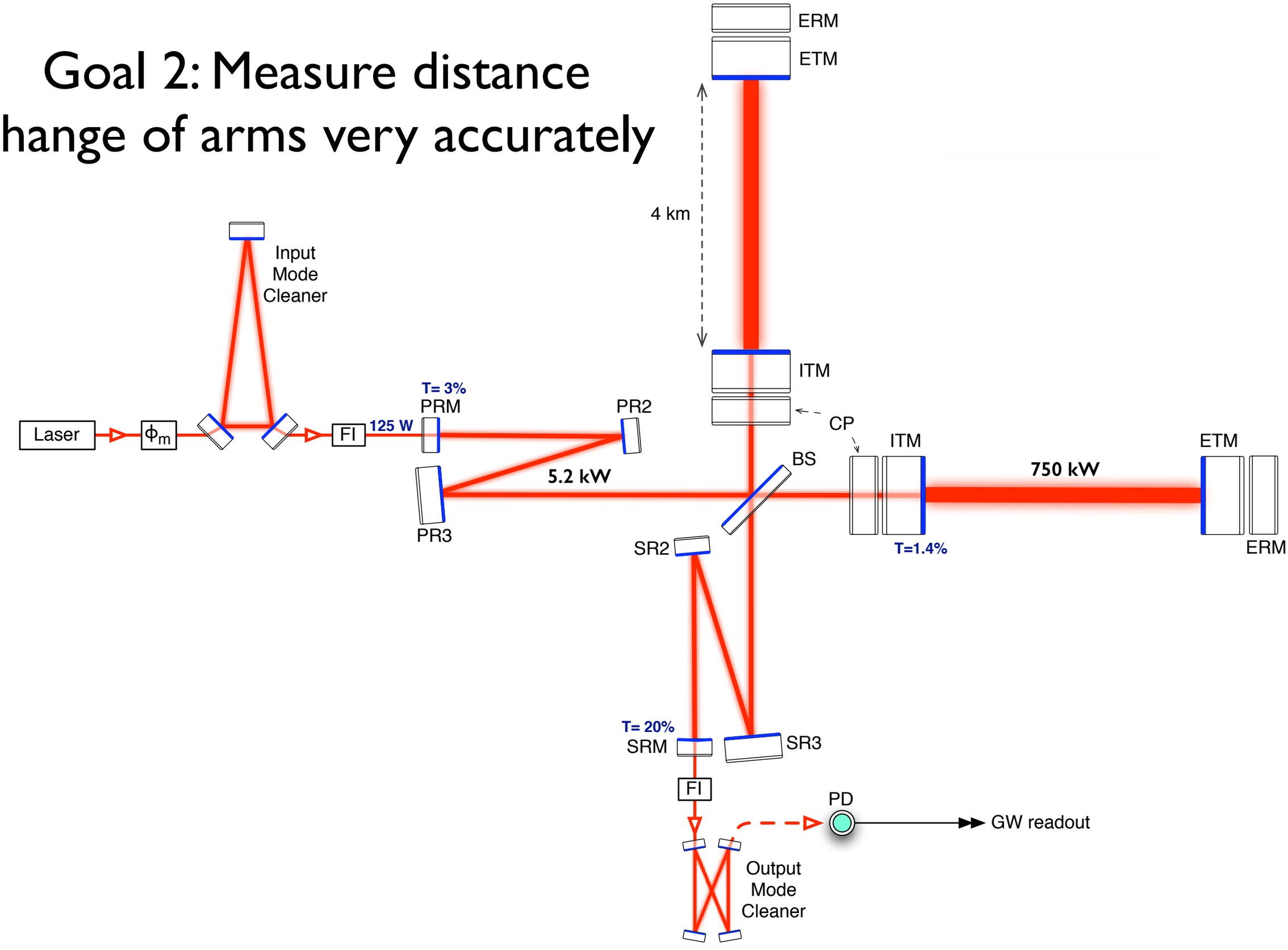


3 Classes of Technical Approach:

1) Really long arms.

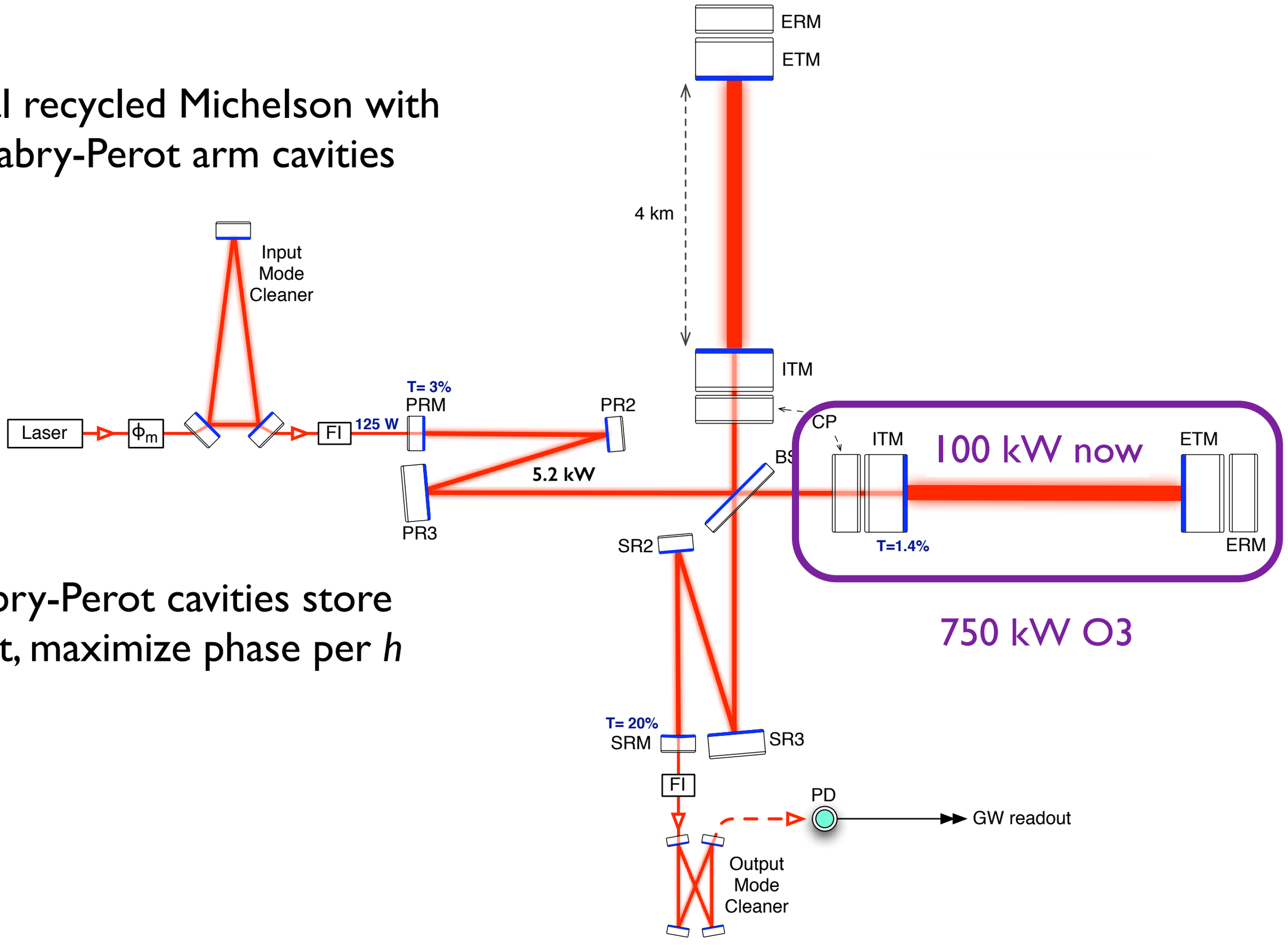
Layout of the interferometer

Goal 2: Measure distance change of arms very accurately



Fabry-Perot arms

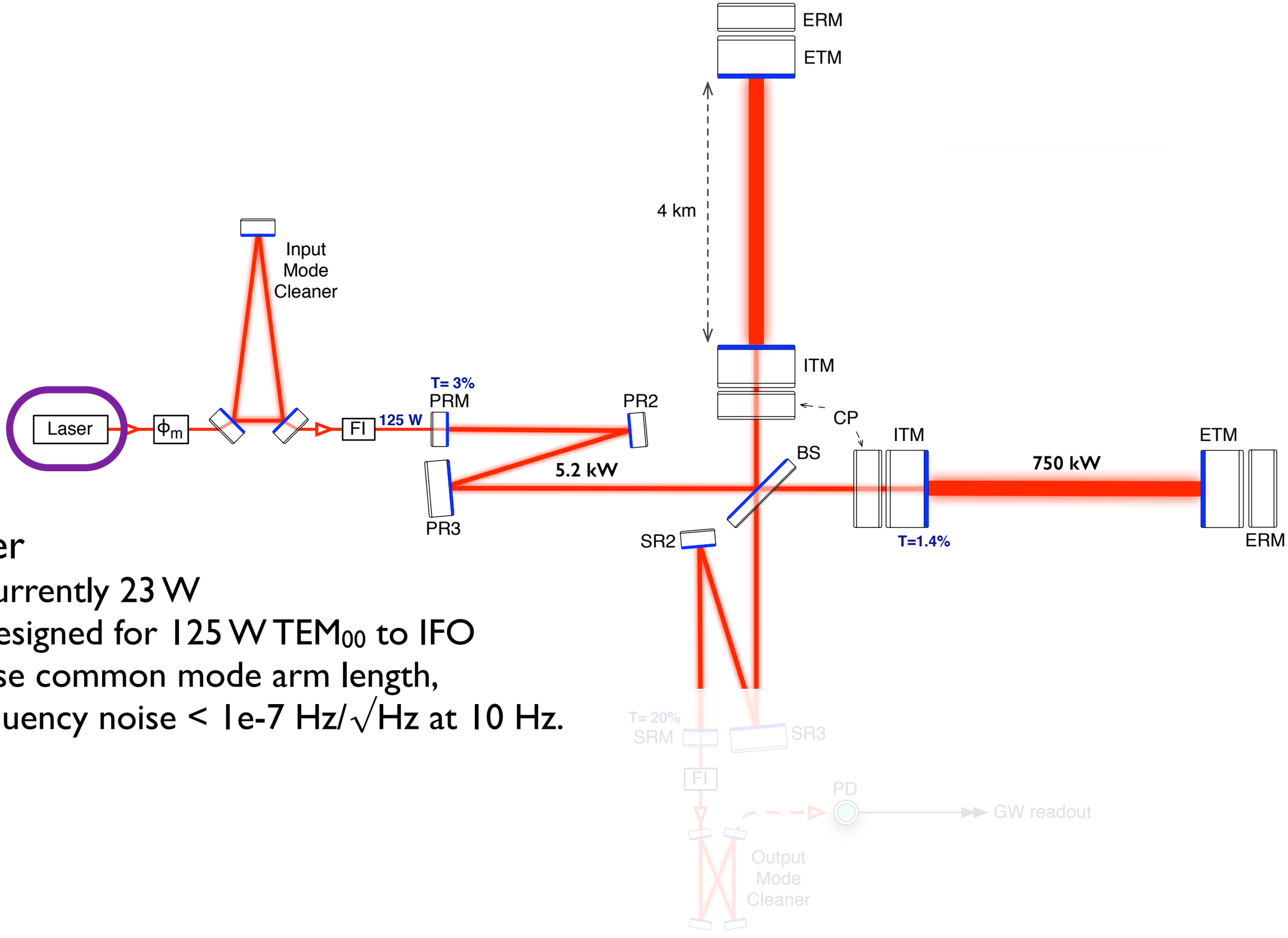
Dual recycled Michelson with Fabry-Perot arm cavities



750 kW O3

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/$\sqrt{}$Hz at 10 Hz.

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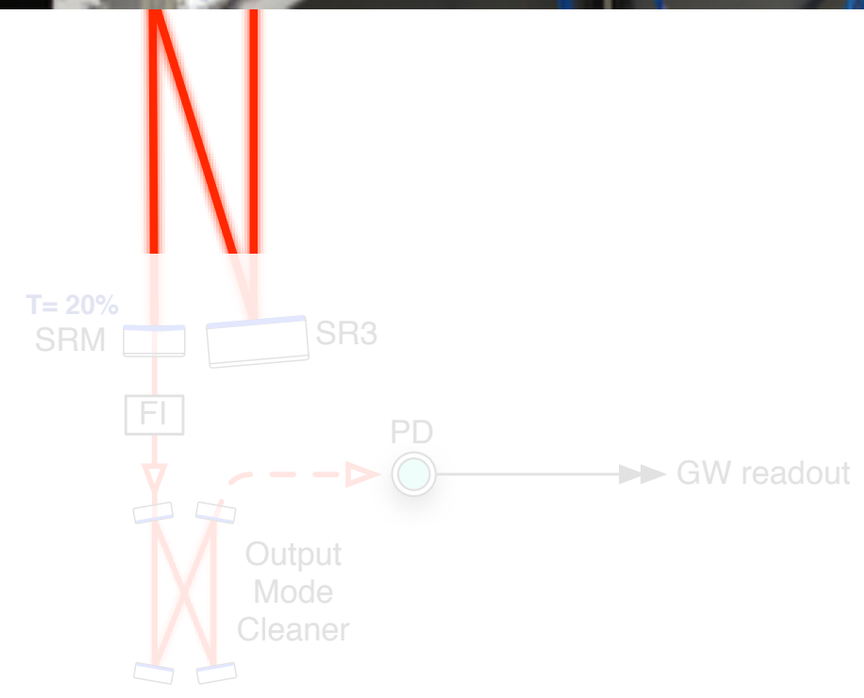
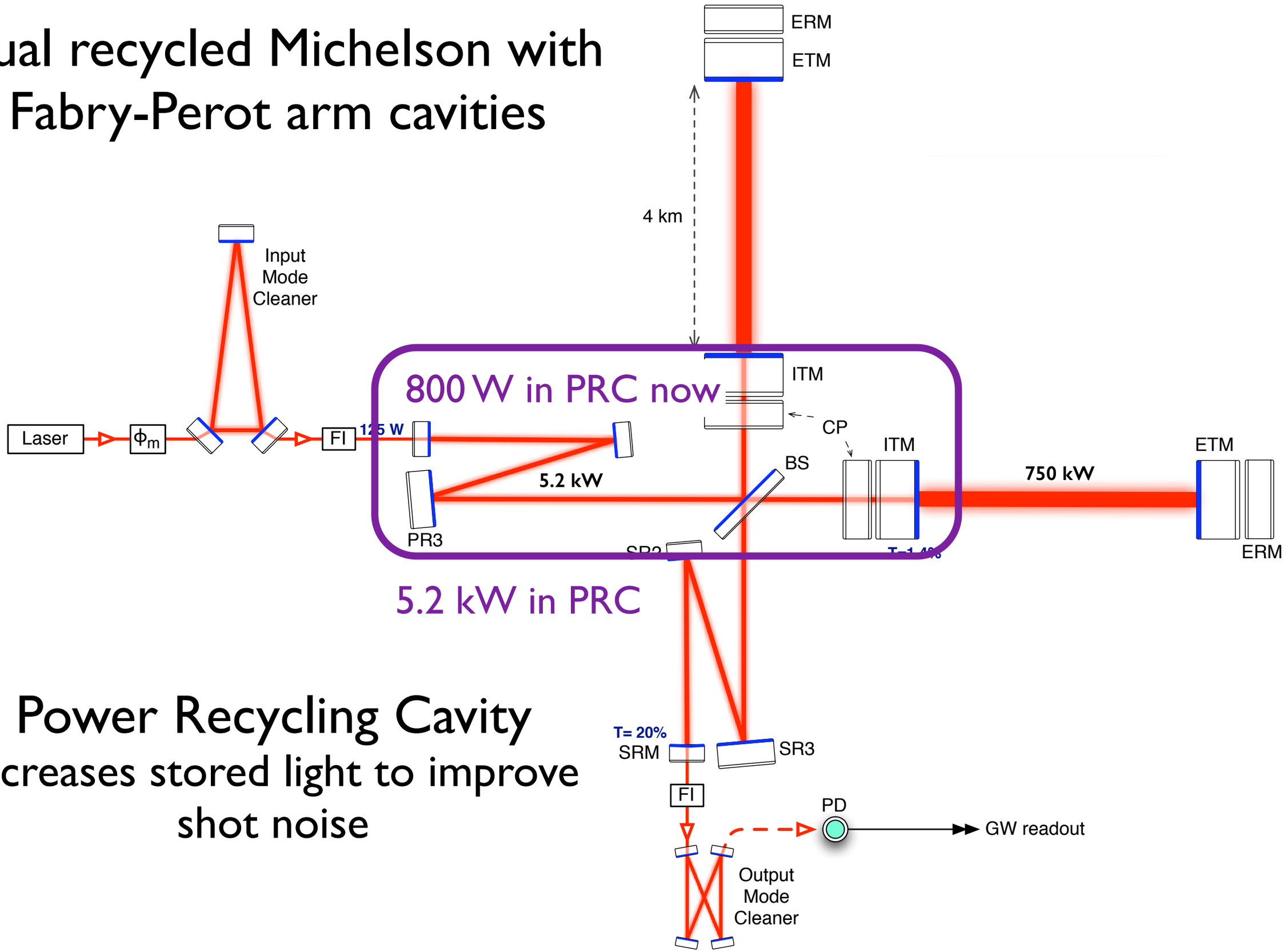


Power recycling

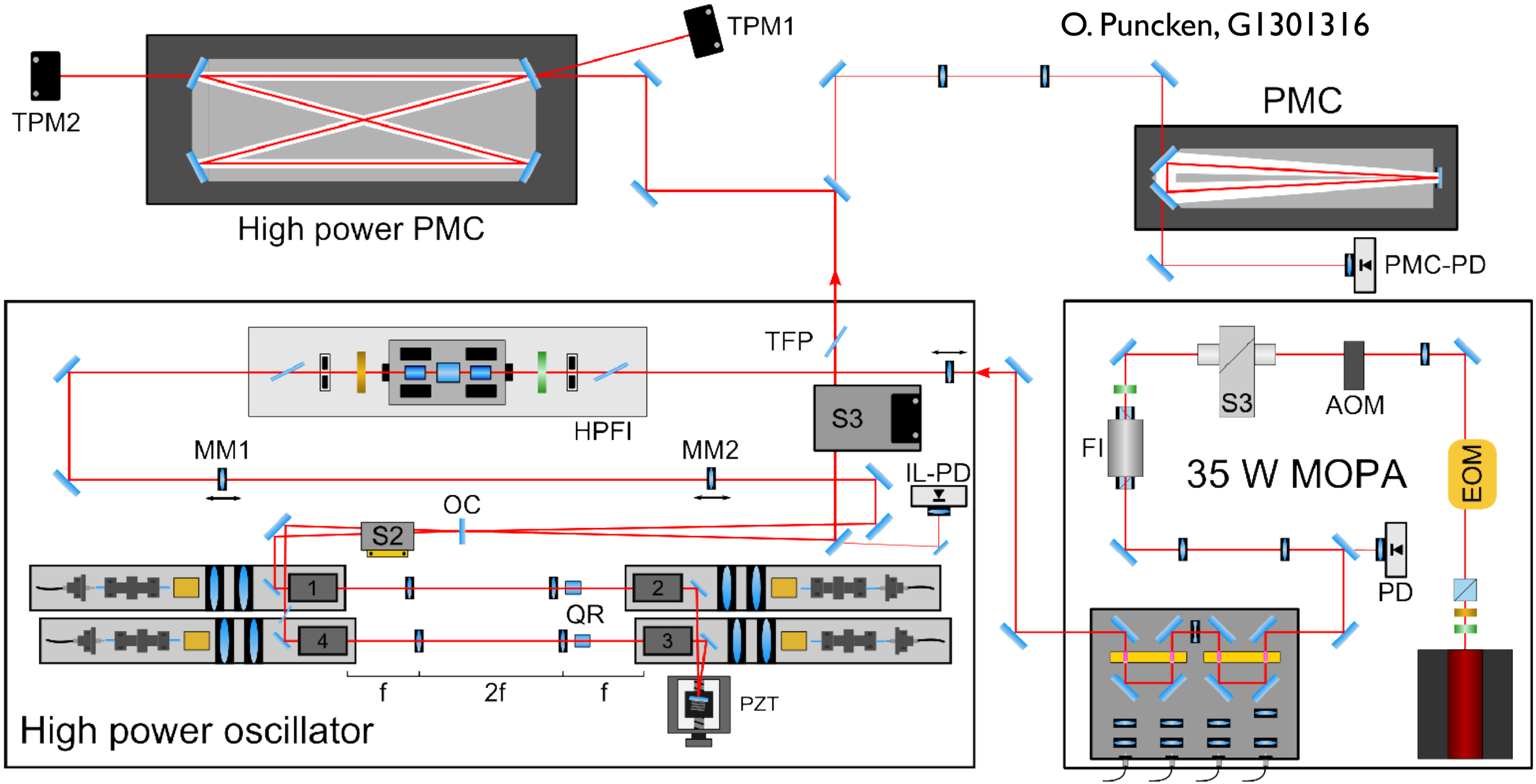
Dual recycled Michelson with Fabry-Perot arm cavities



Power Recycling Cavity

increases stored light to improve shot noise

aLIGO Laser (by L.Z.H.)



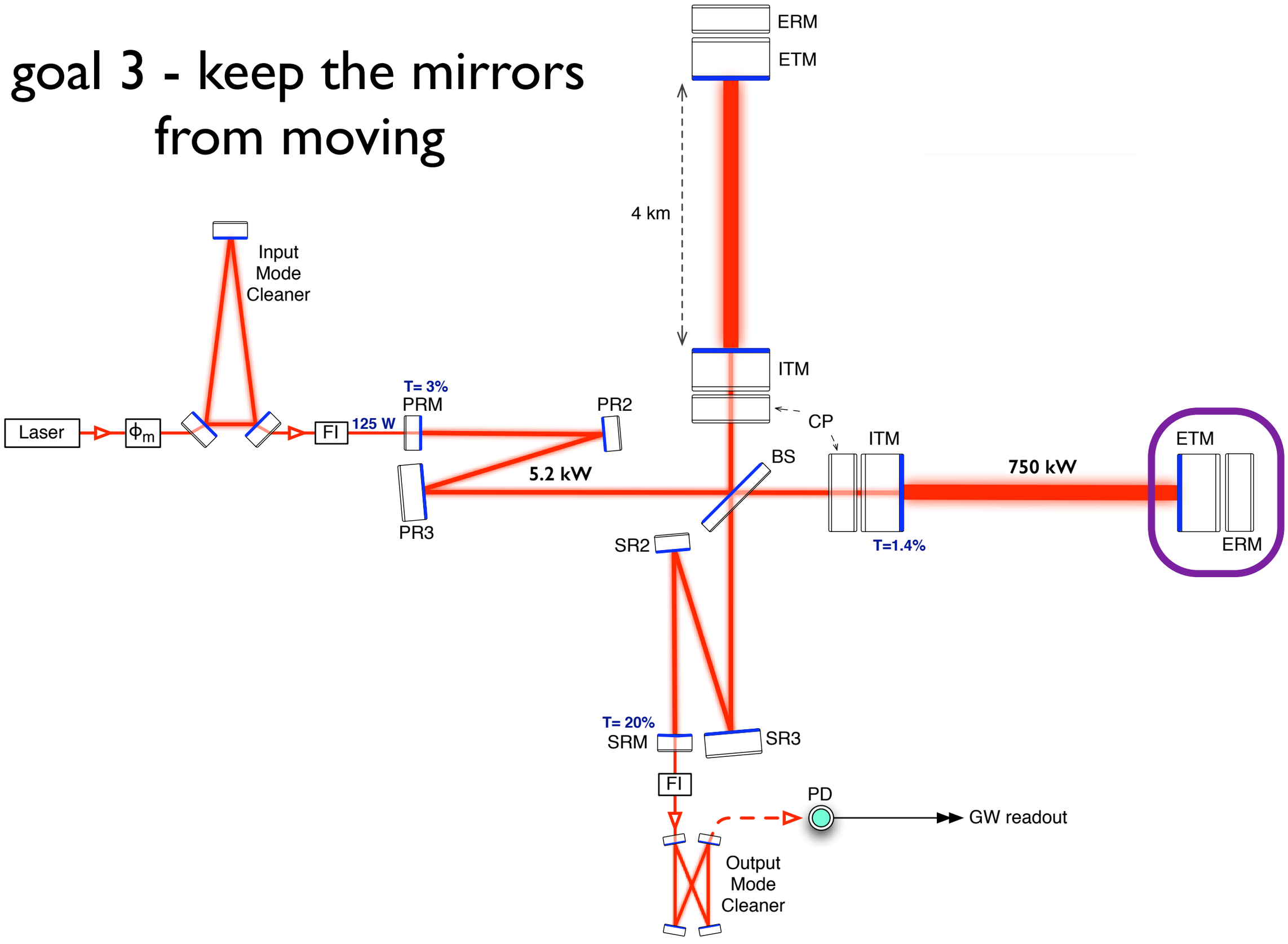
Commercial NPRO, 2 W, Nd:YAG crystal pumped by laser diodes at 808 nm

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

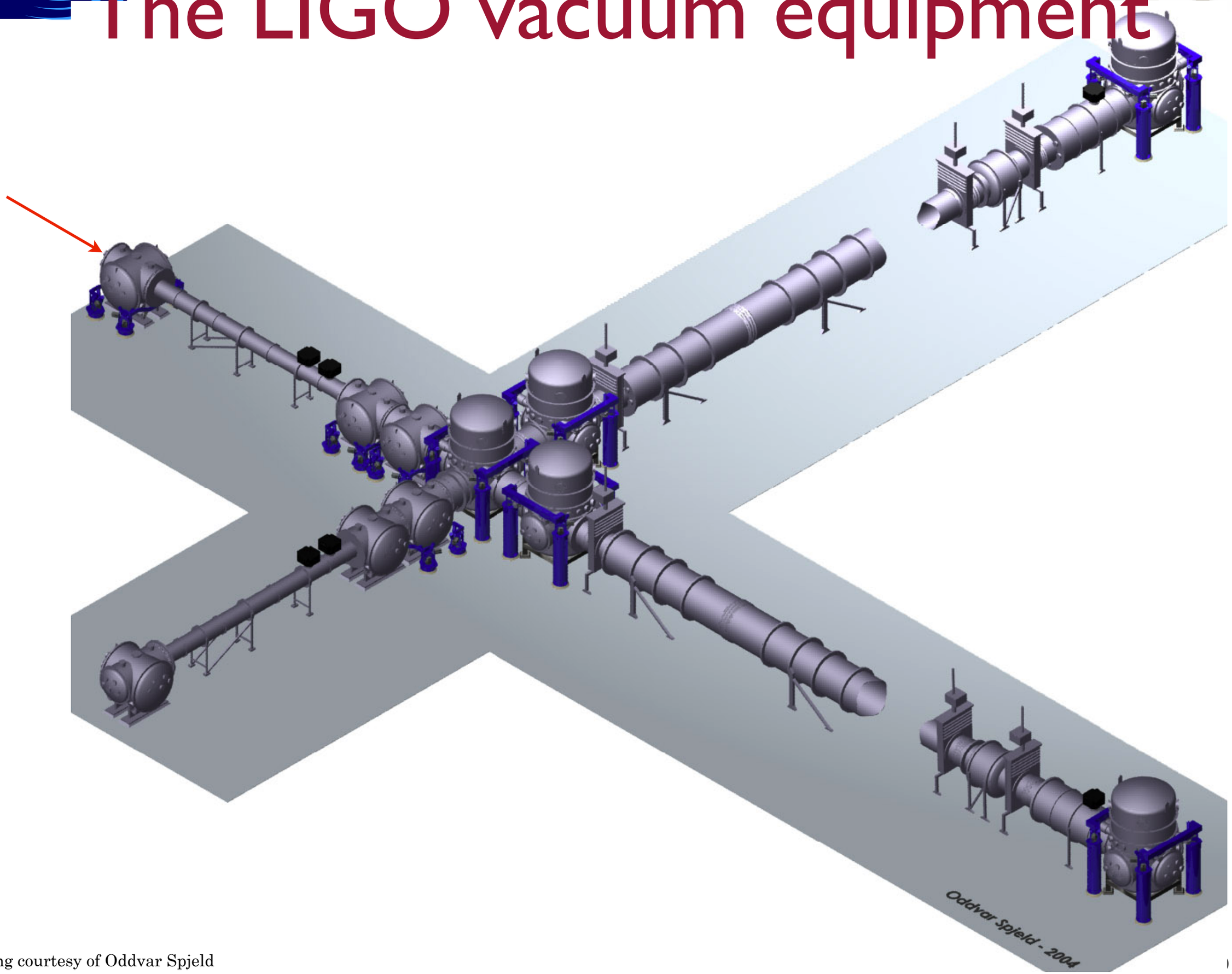
Ring oscillator, 220 W, 4 Nd:YAG crystals each pumped by 7 LD at 808 nm

Layout of the interferometer

goal 3 - keep the mirrors from moving

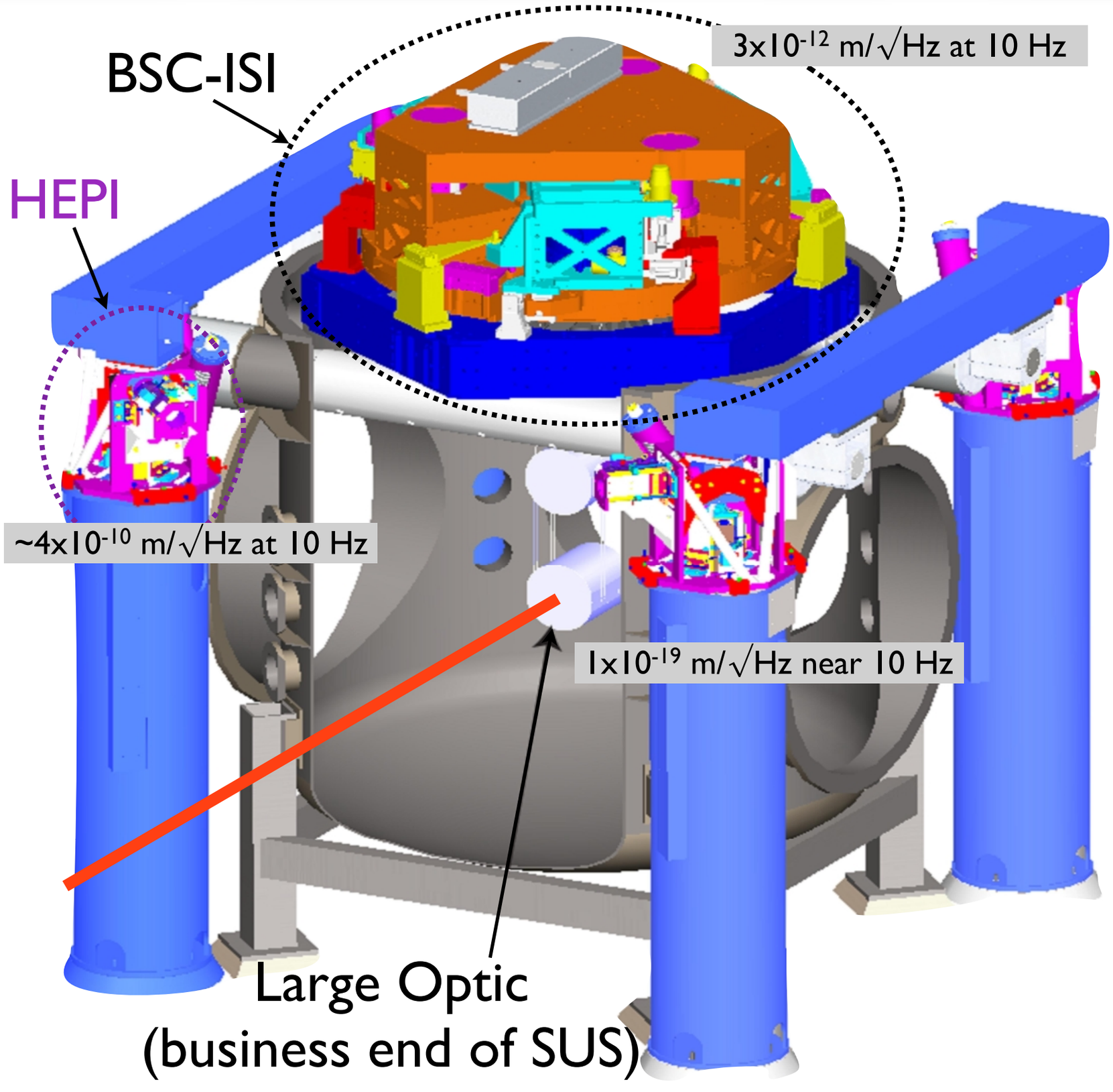


The LIGO vacuum equipment



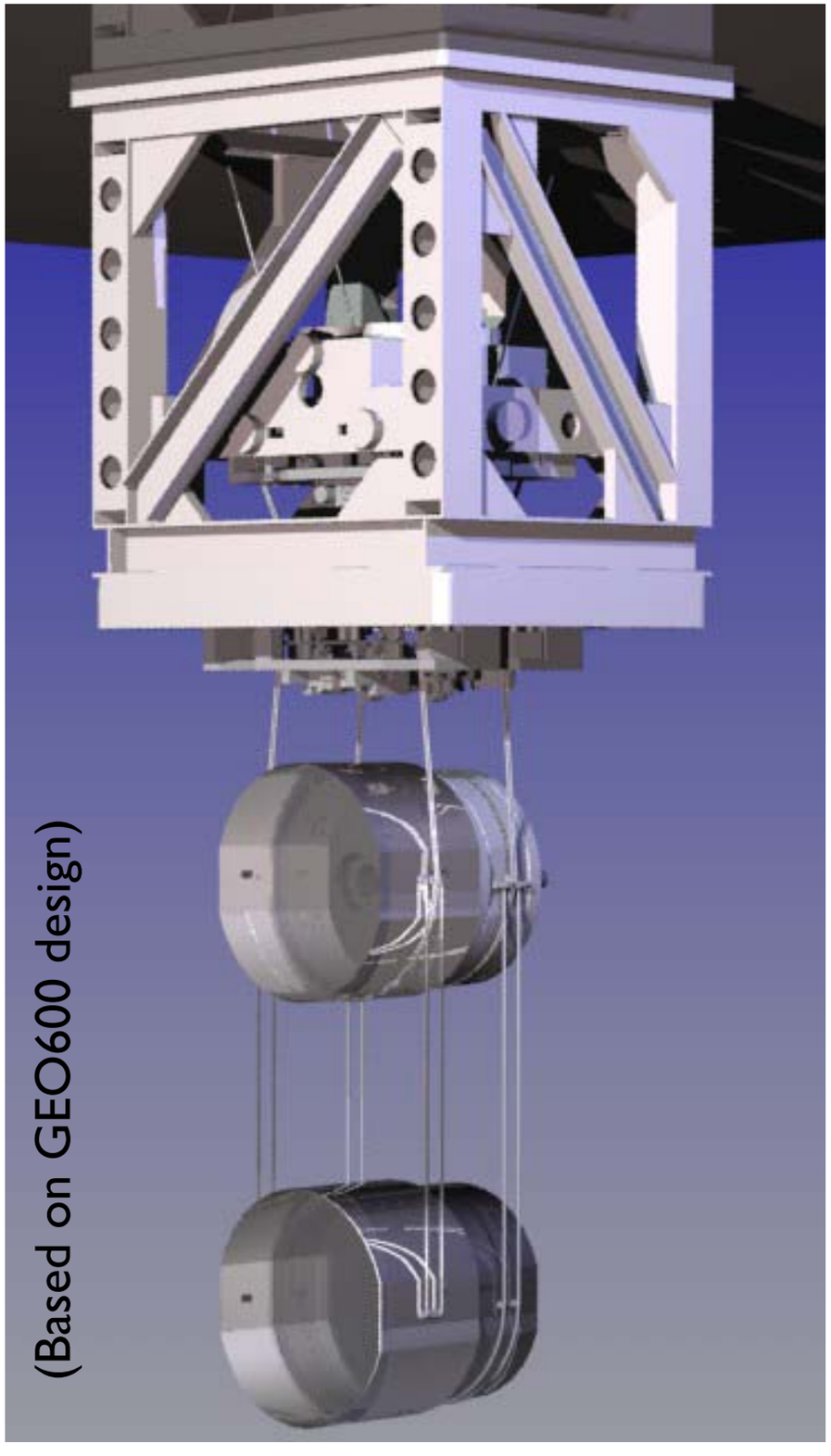
drawing courtesy of Oddvar Spjeld

Overall Isolation of Test Masses



Pendulum Suspension

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

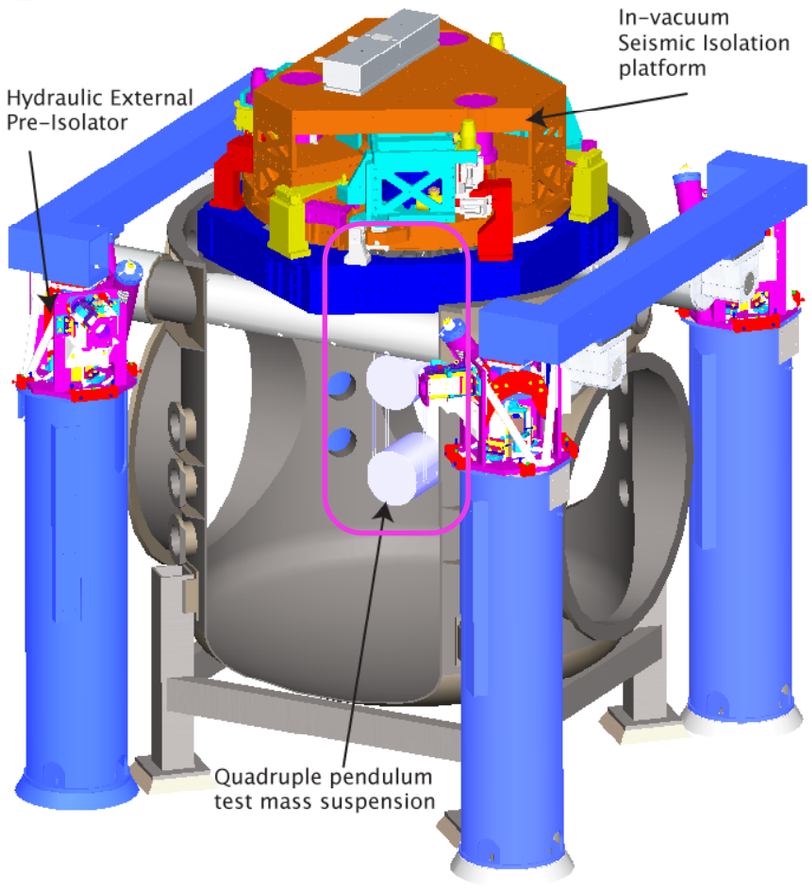


Drawings courtesy of Calum Torrie and GEO600

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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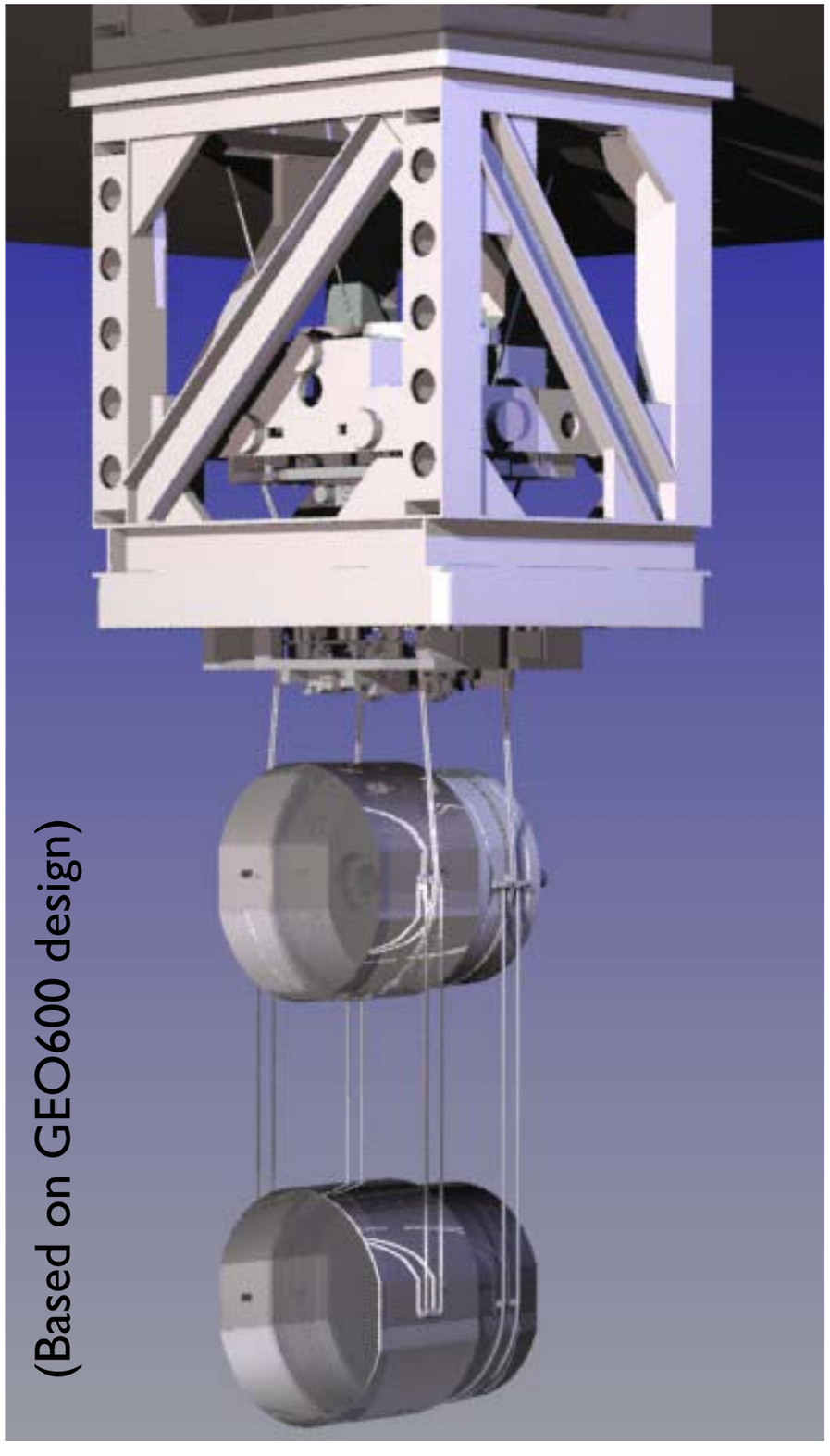

Drawings courtesy of Calum Torrie and GEO600

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Each stage gives ~$1/f^2$
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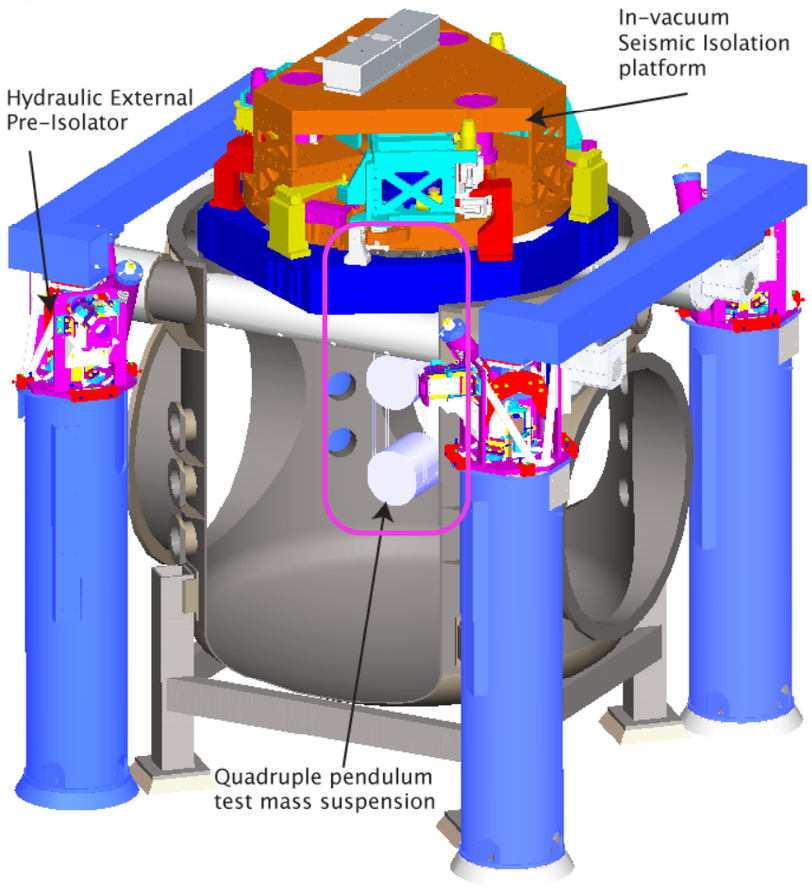
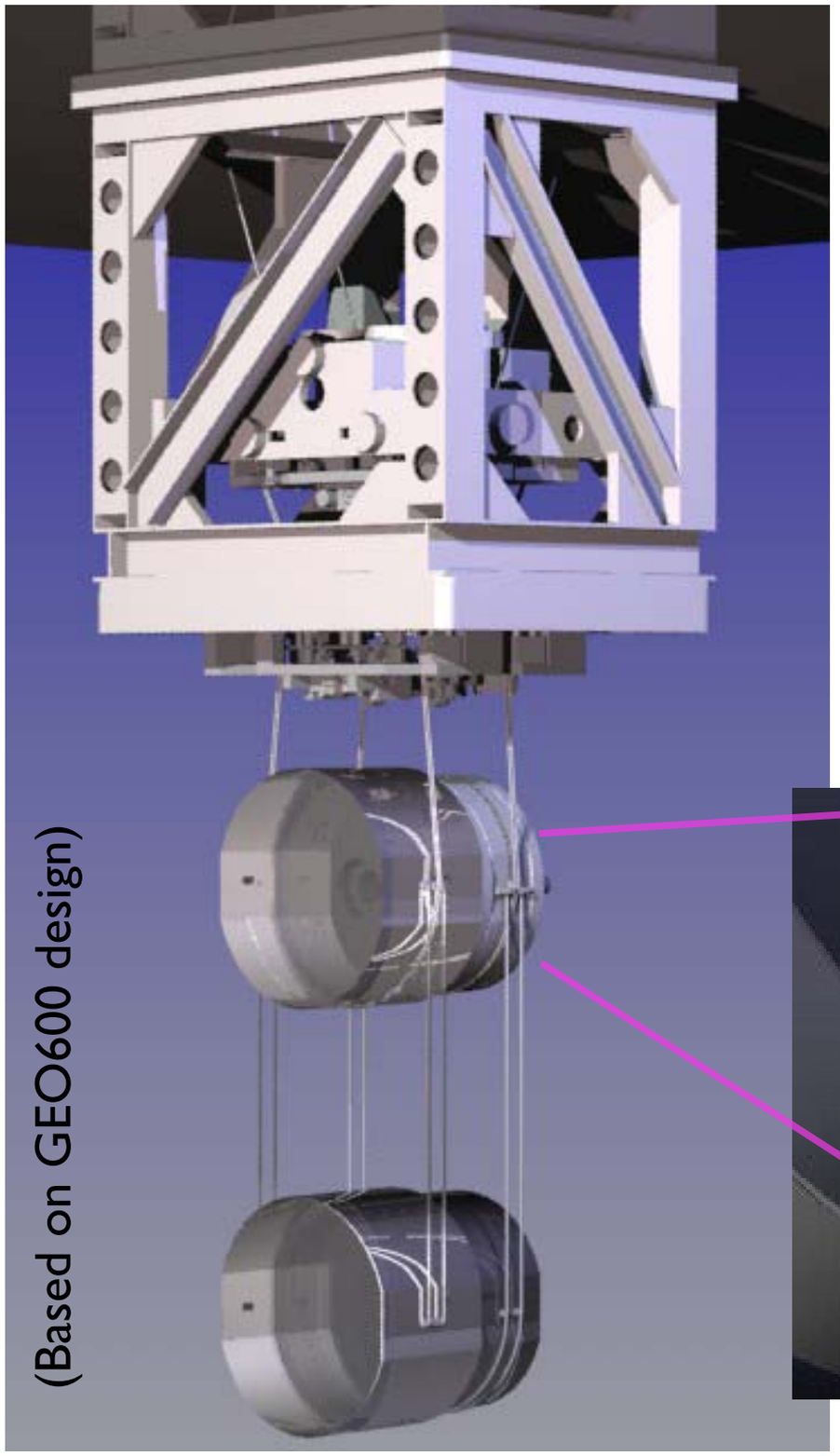


Test masses:
Synthetic fused silica,
40 kg, 34 cm dia.
» Q ≥ 1e7
» low optical absorption

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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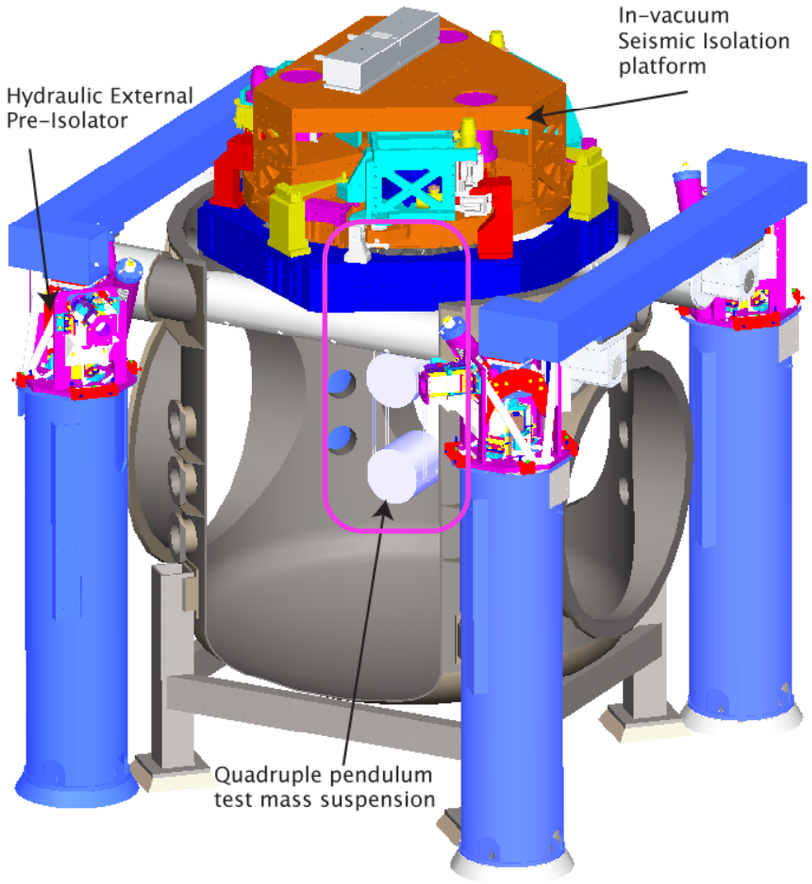
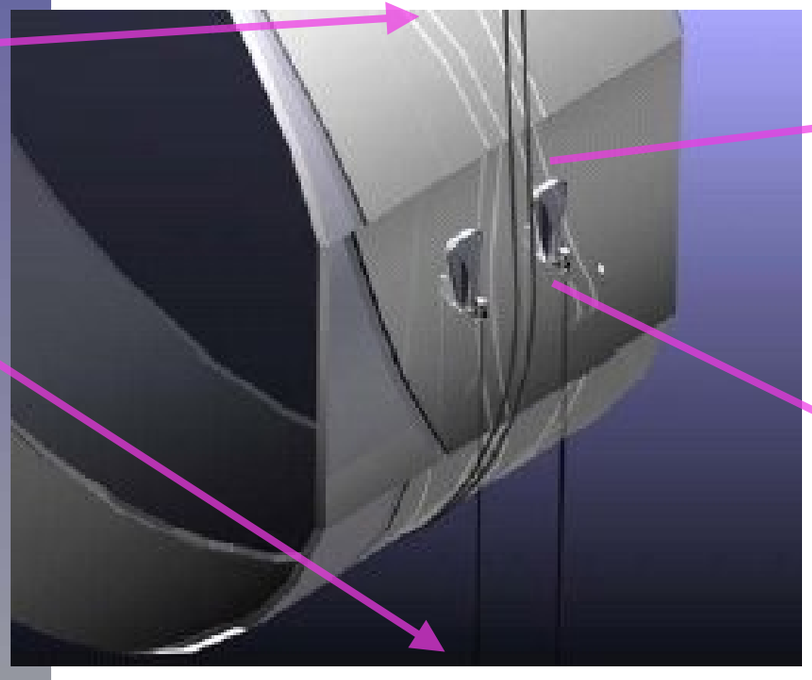
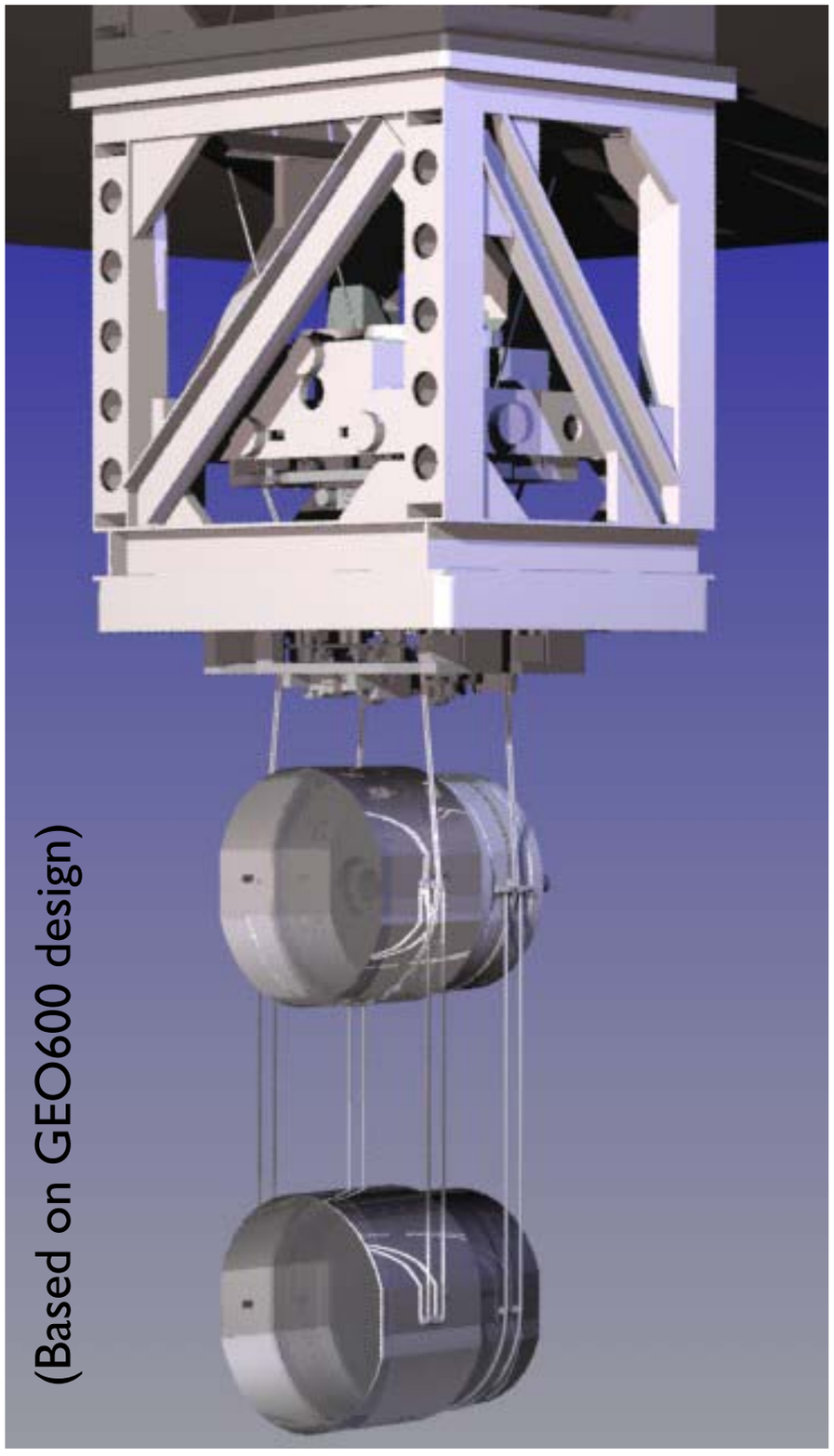




silicate bonding creates a monolithic final stage

Drawings courtesy of Calum Torrie and GEO600

Pendulum



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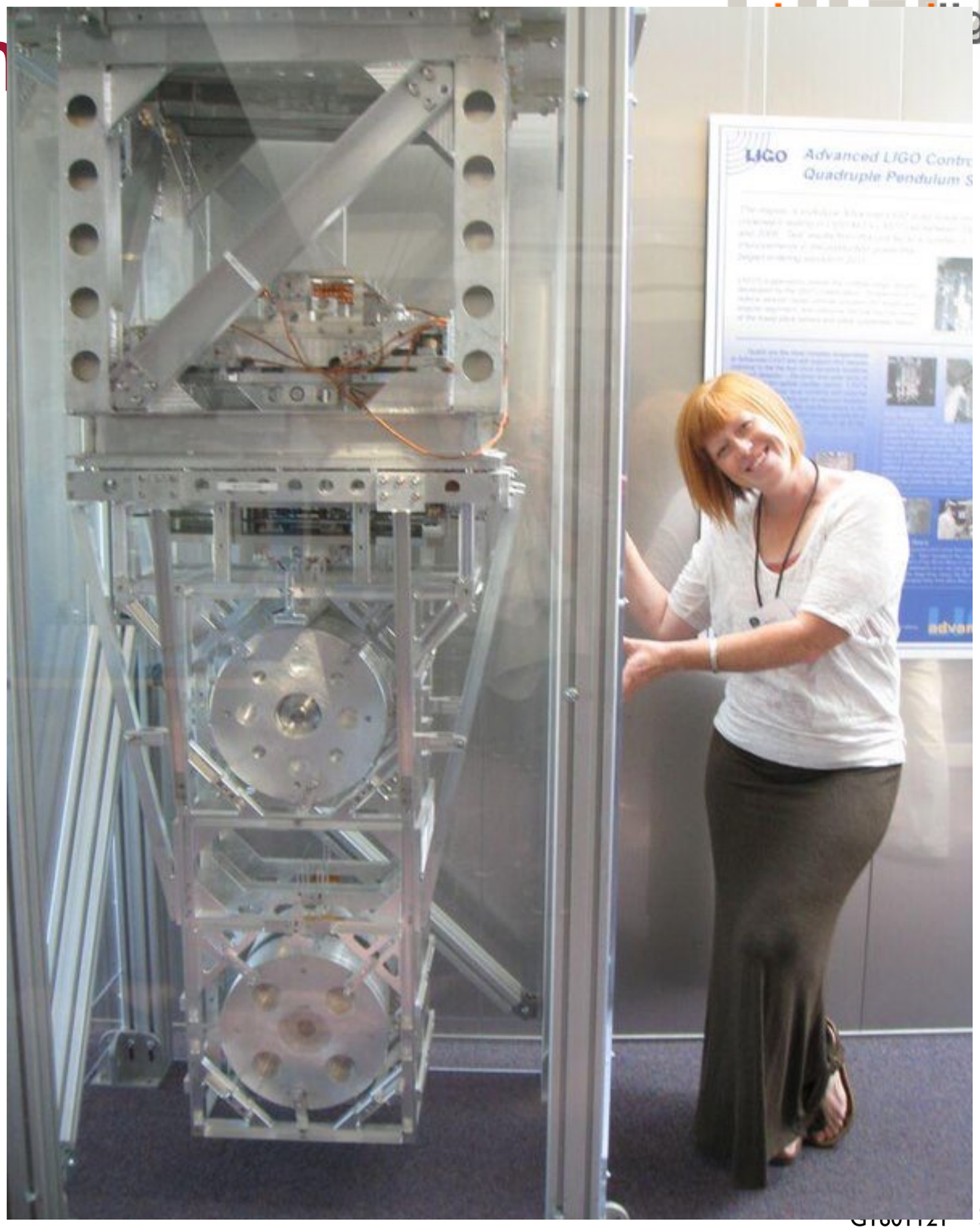
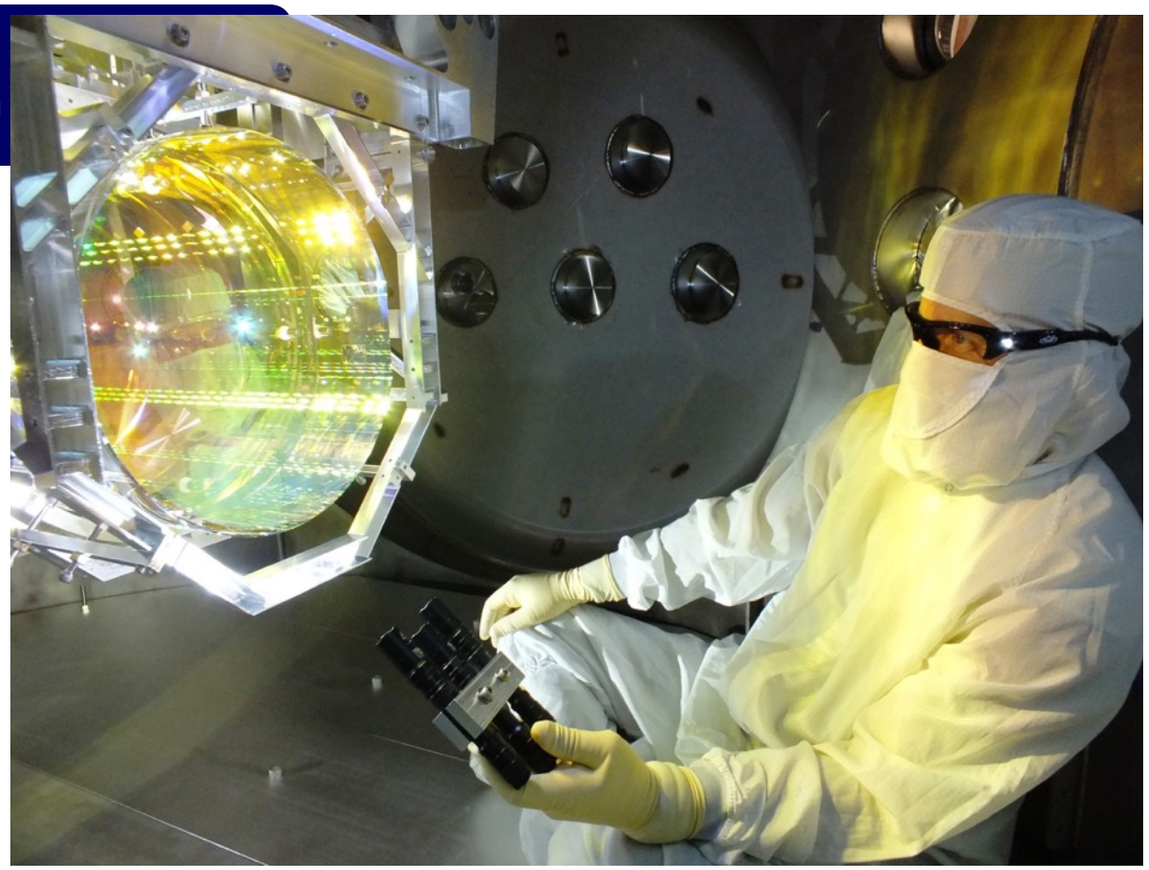
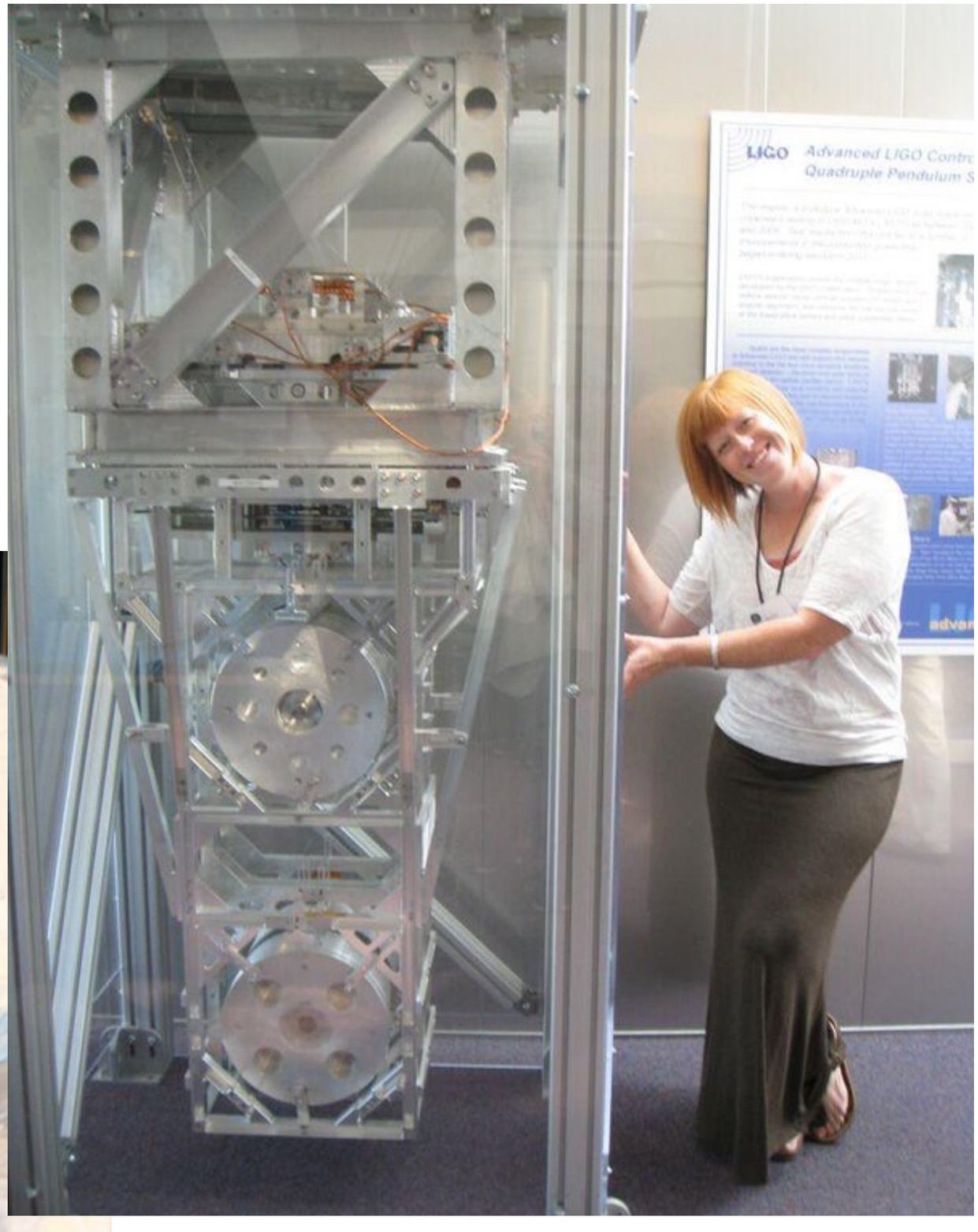
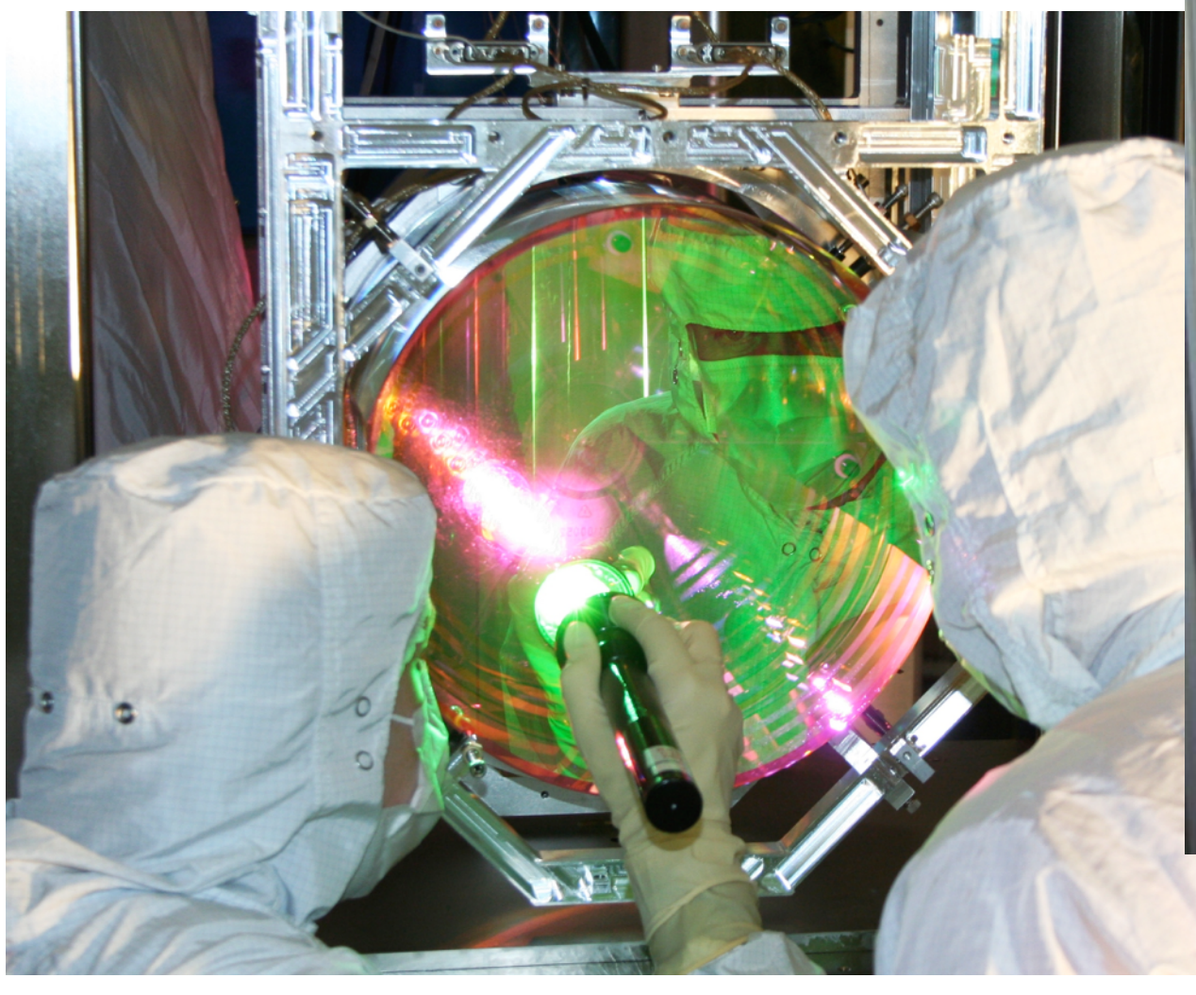
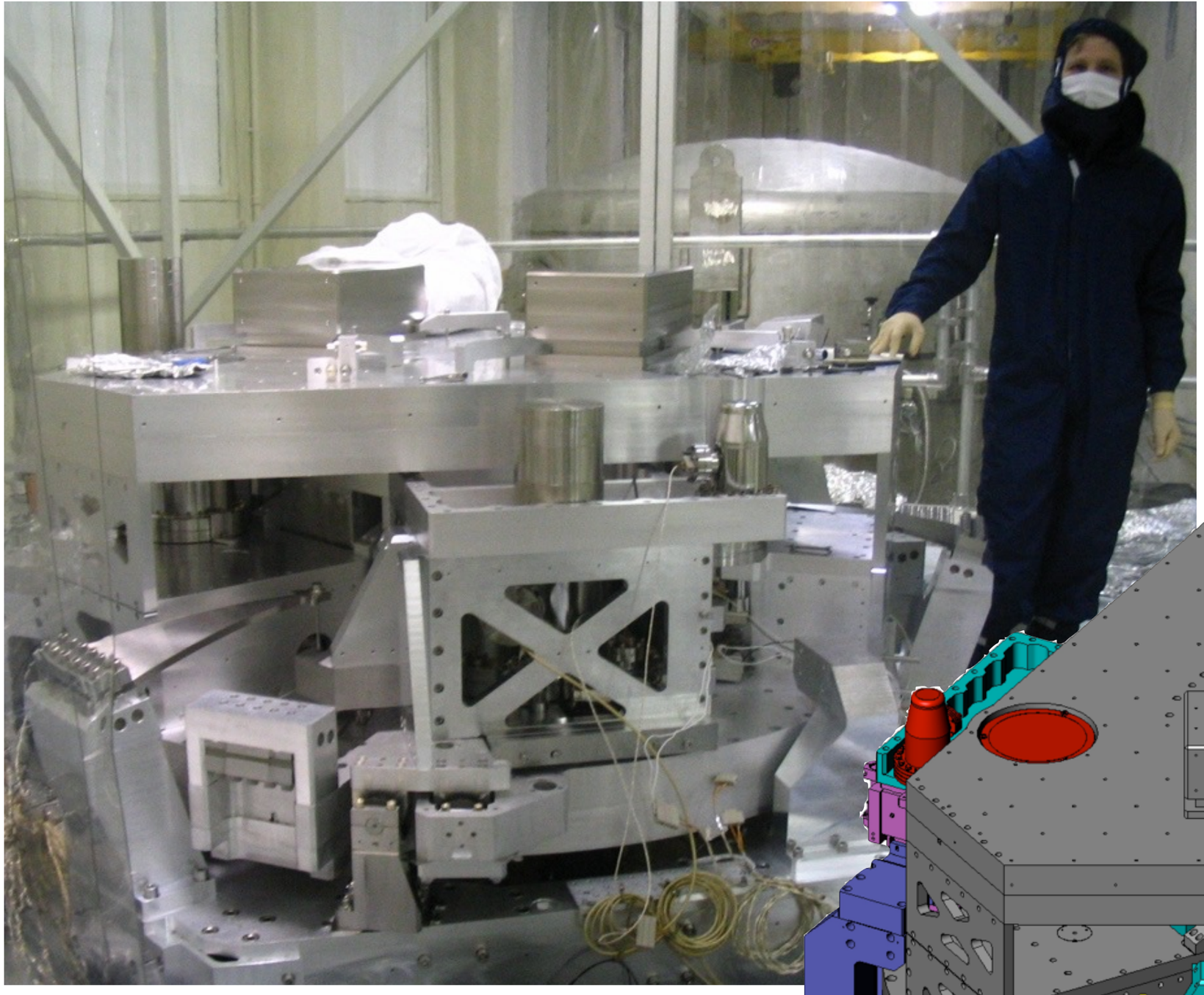


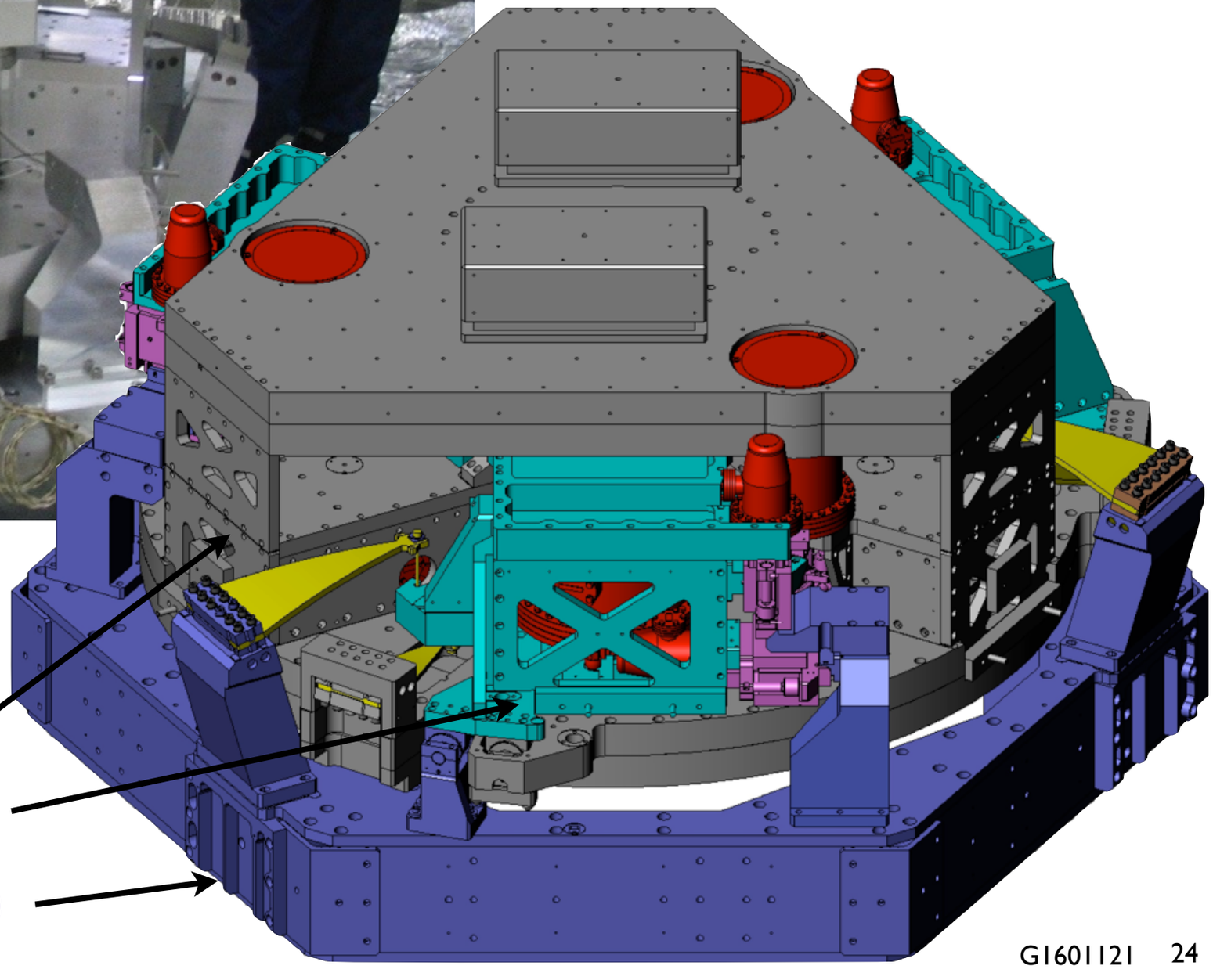



LIGO
Advanced LIGO Contr
Quadruple Pendulum S



BSC-ISI



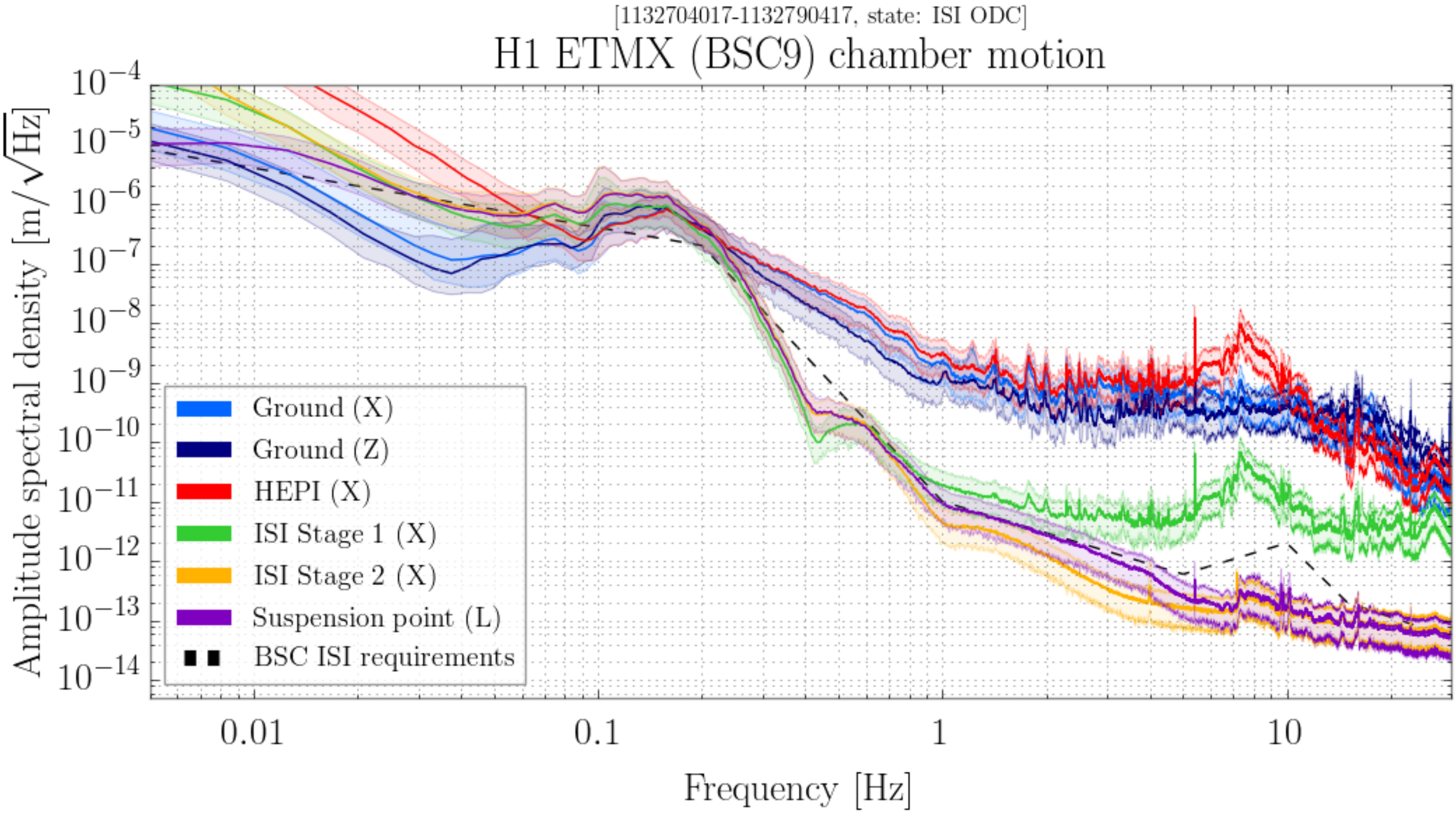


optics table - stage 2

stage 1

support - stage 0

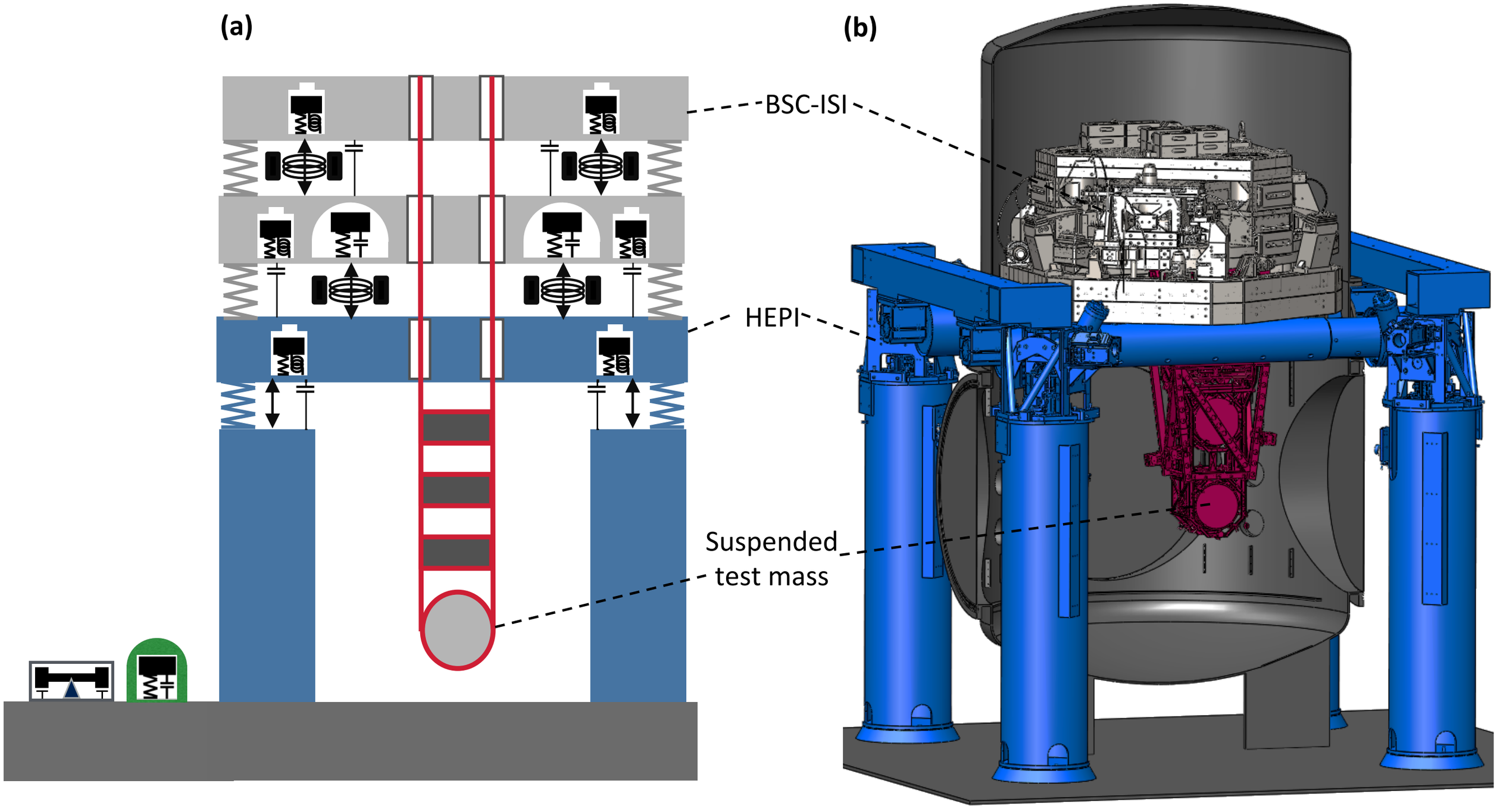
‘Typical’ performance



Nov 28th (Sat. after Thanksgiving)

Signals for processing

Use active and passive techniques
to get good performance



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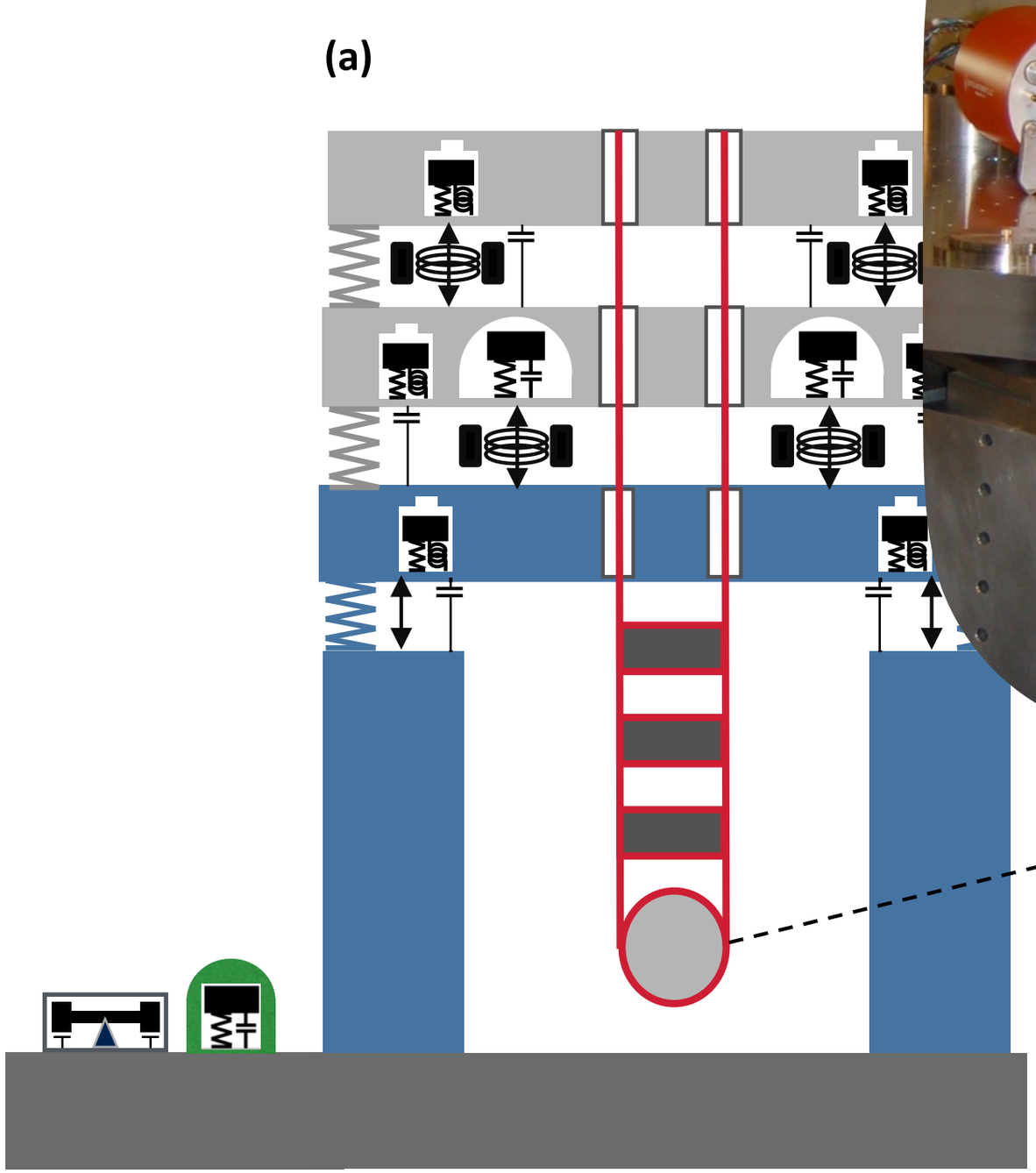

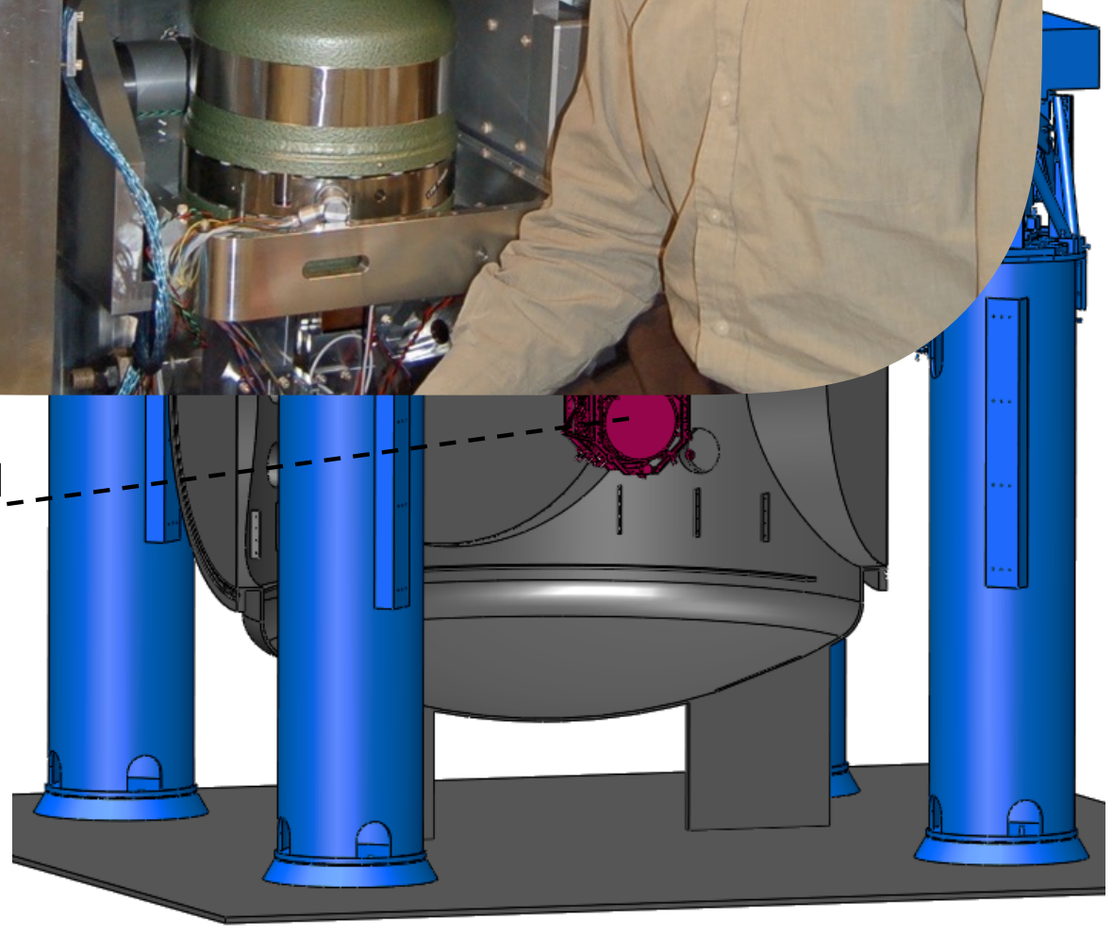

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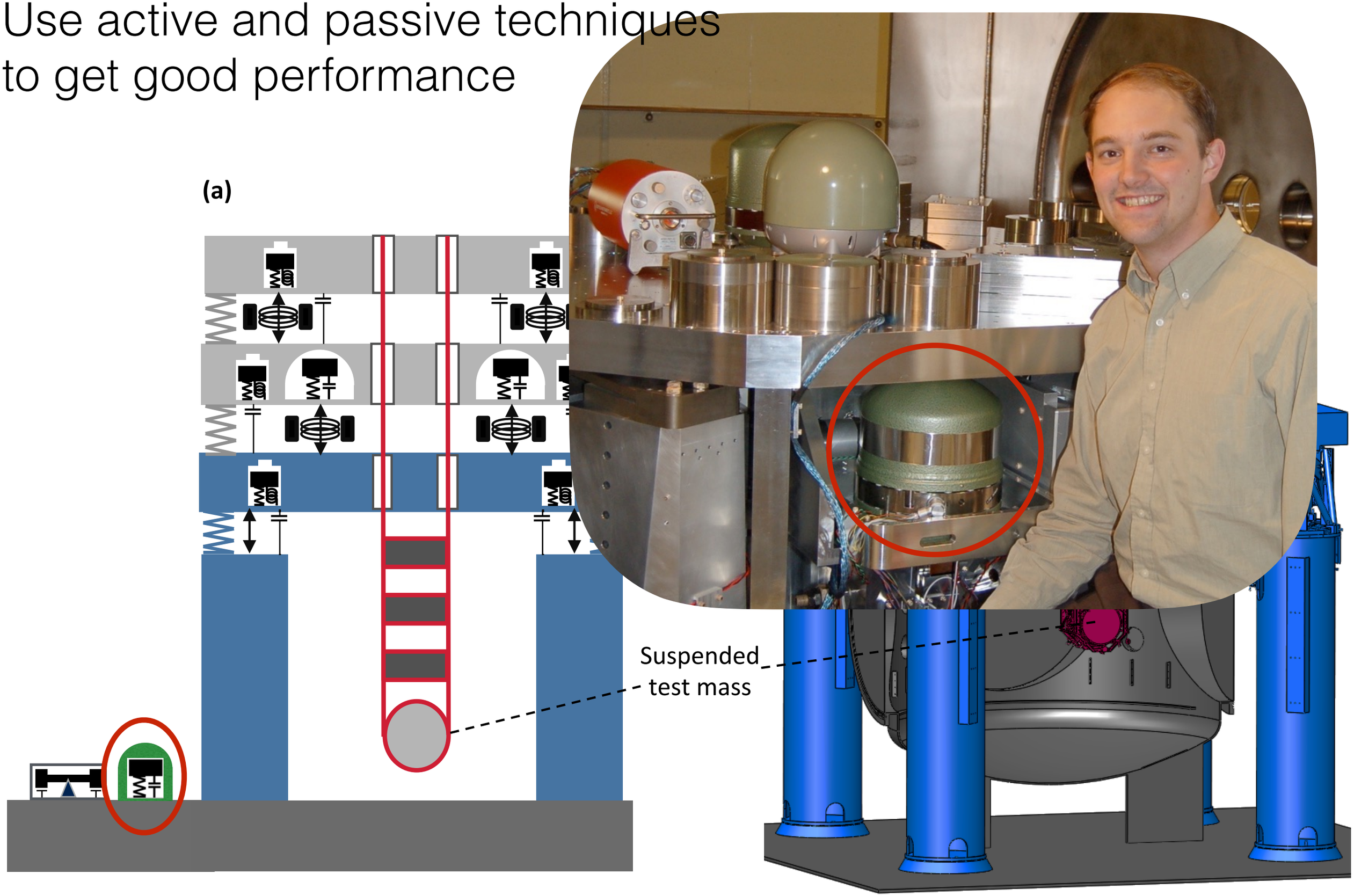

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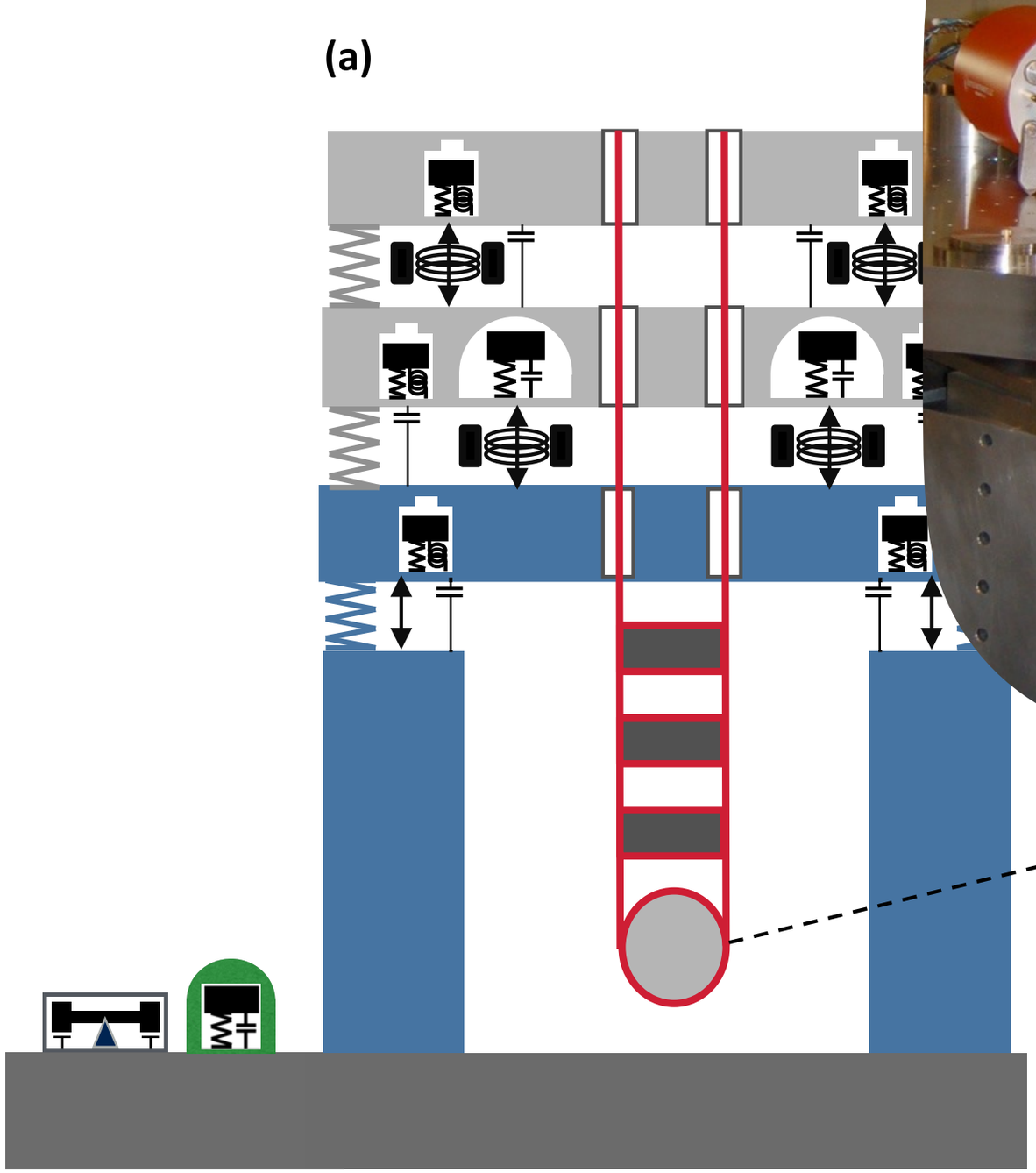

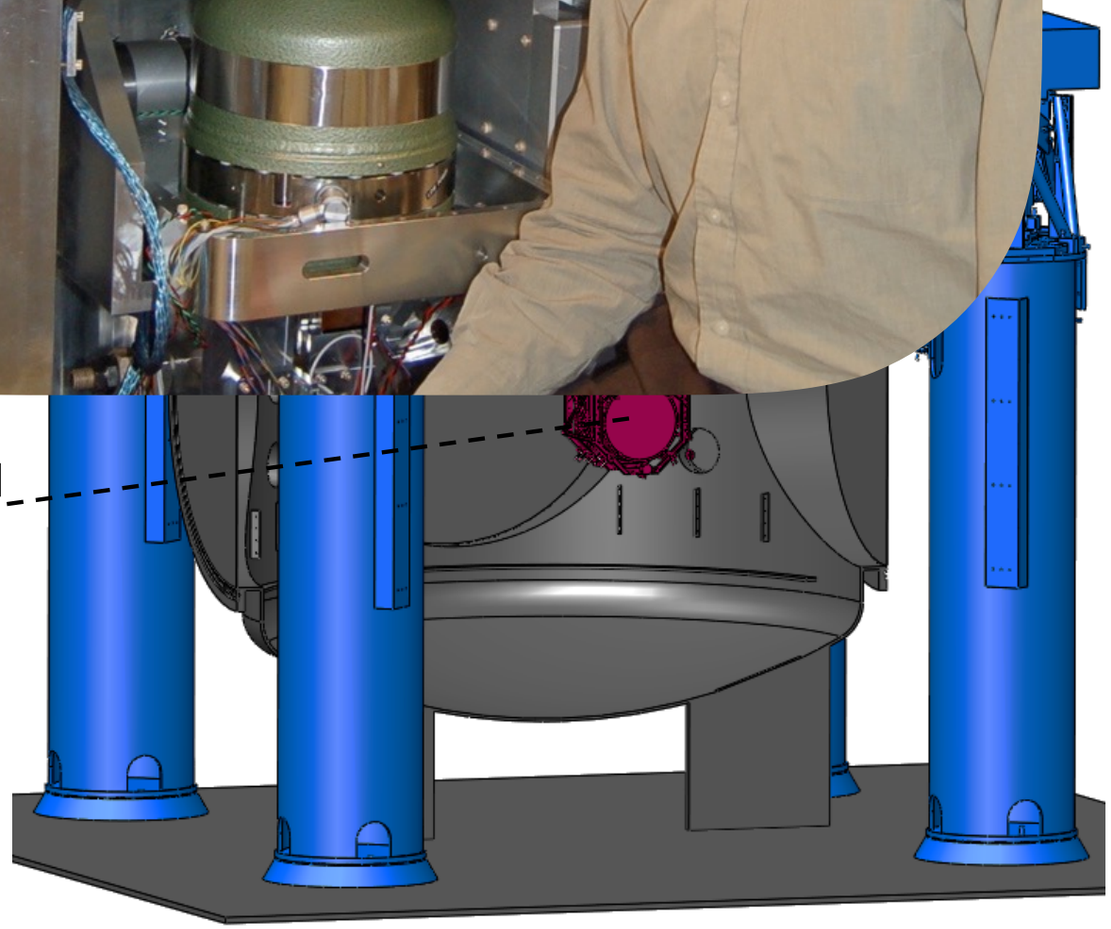

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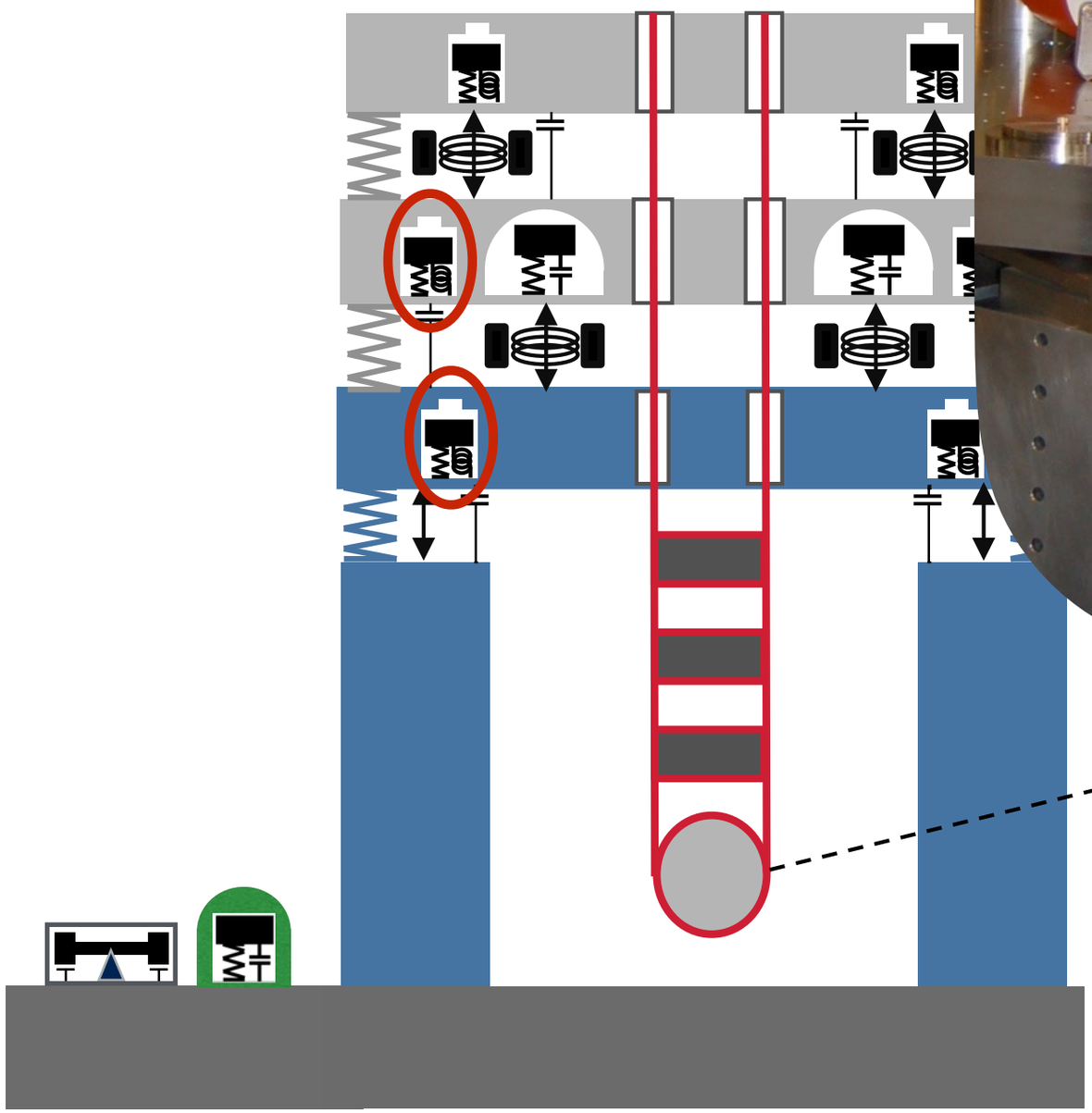

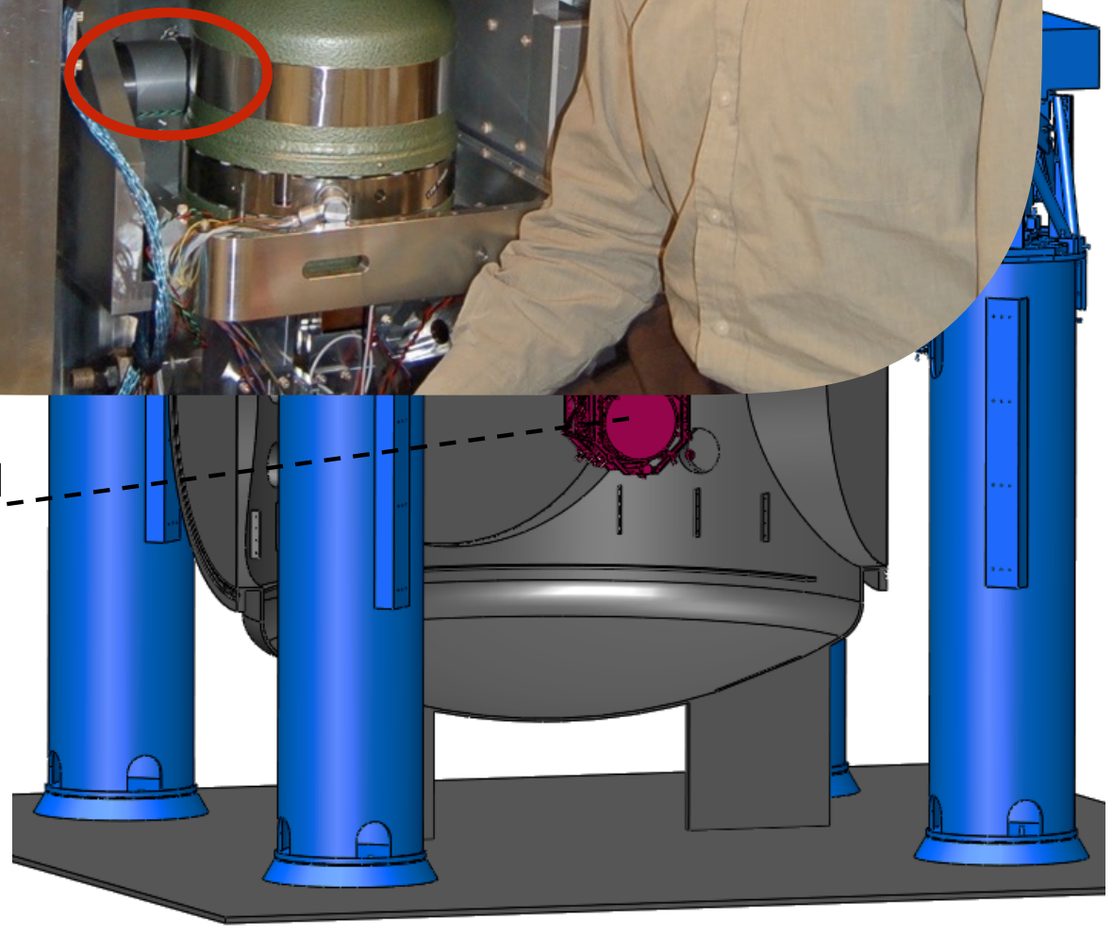

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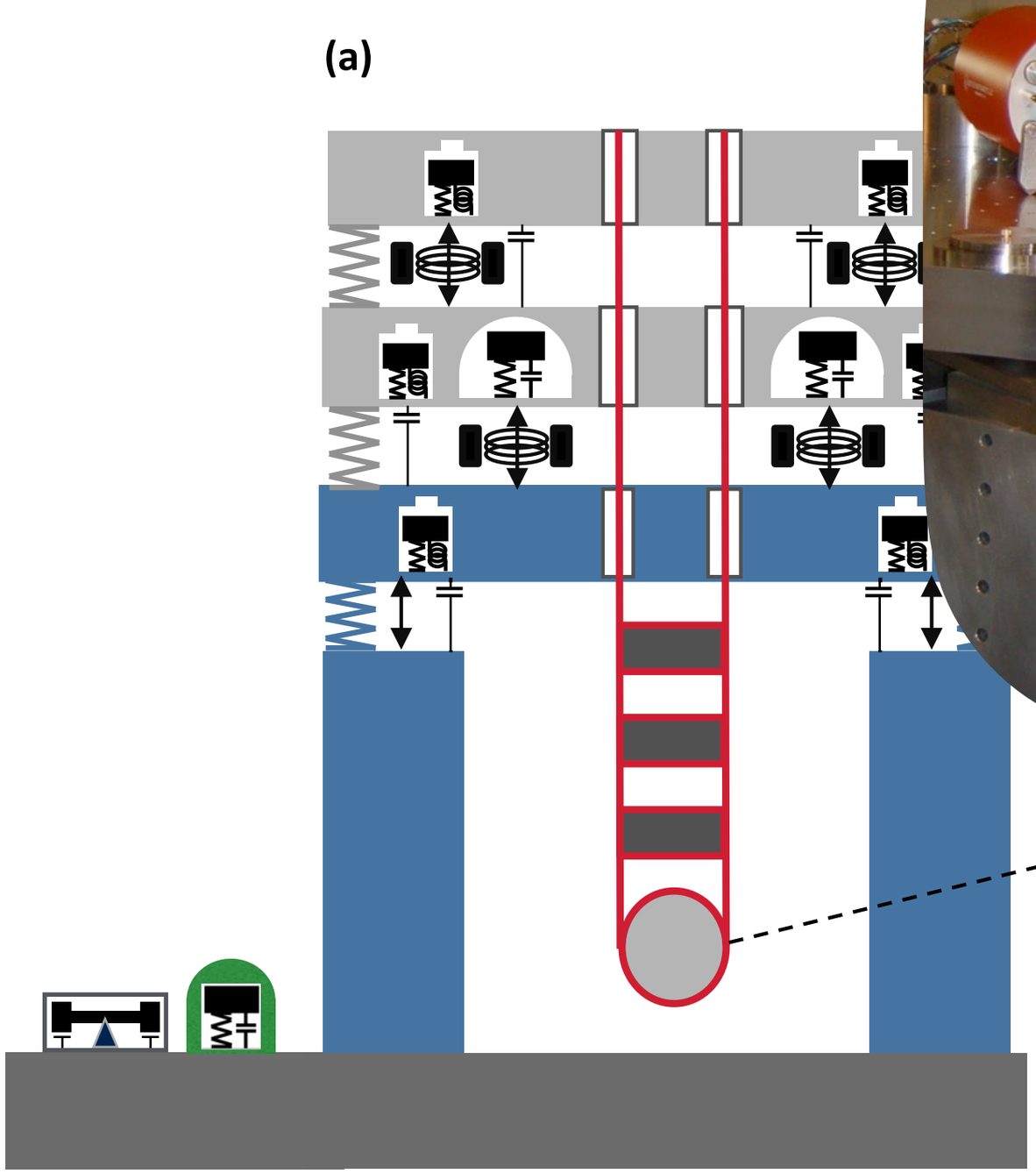
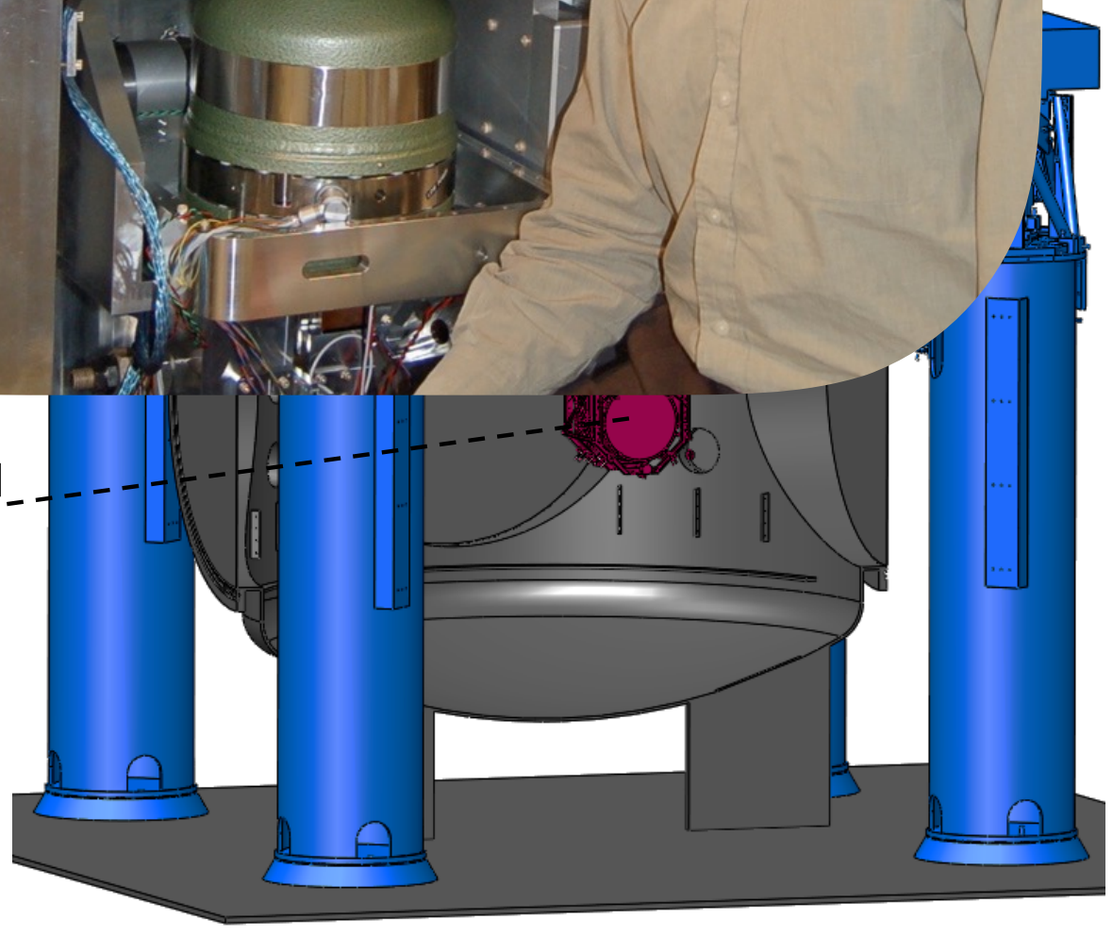
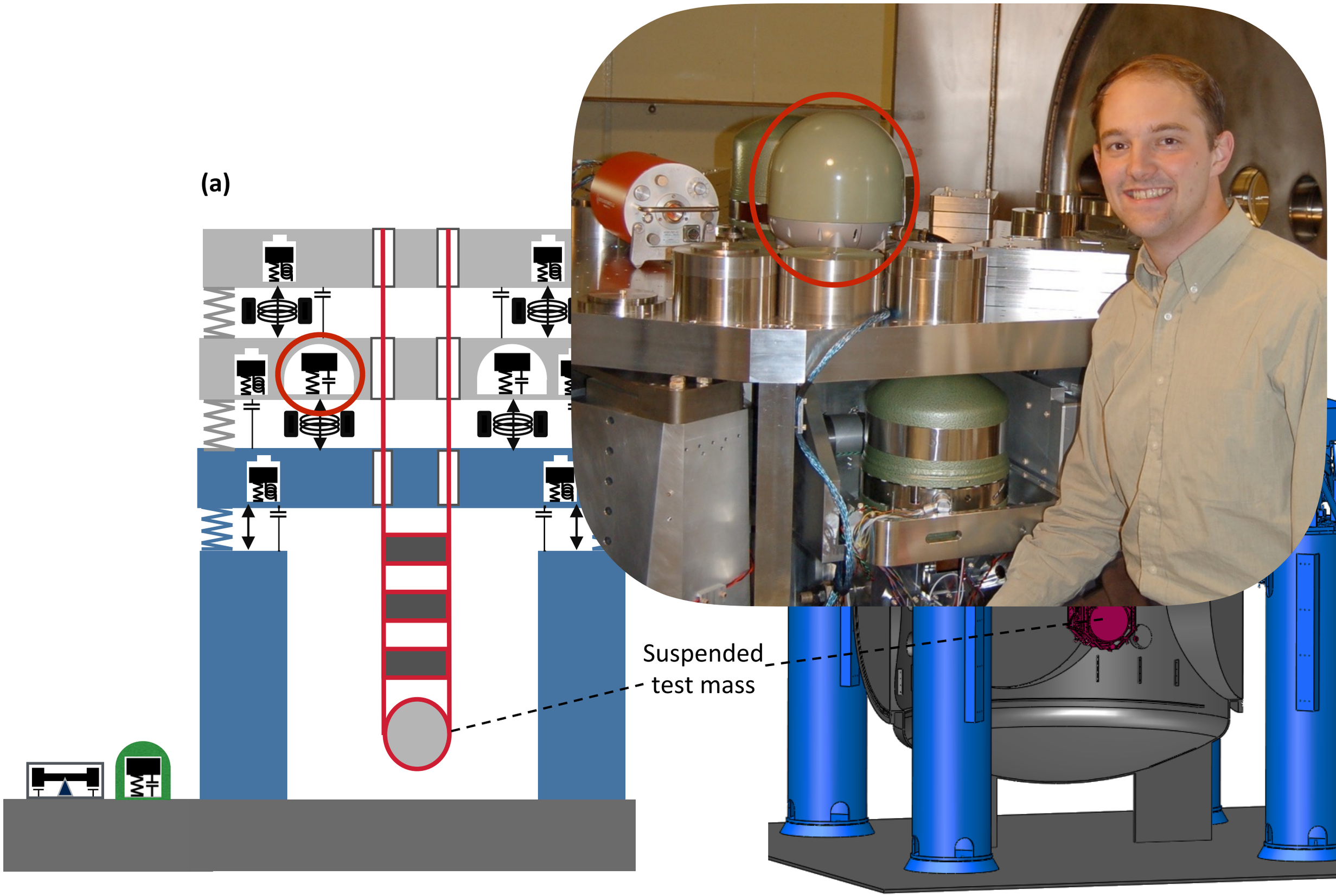
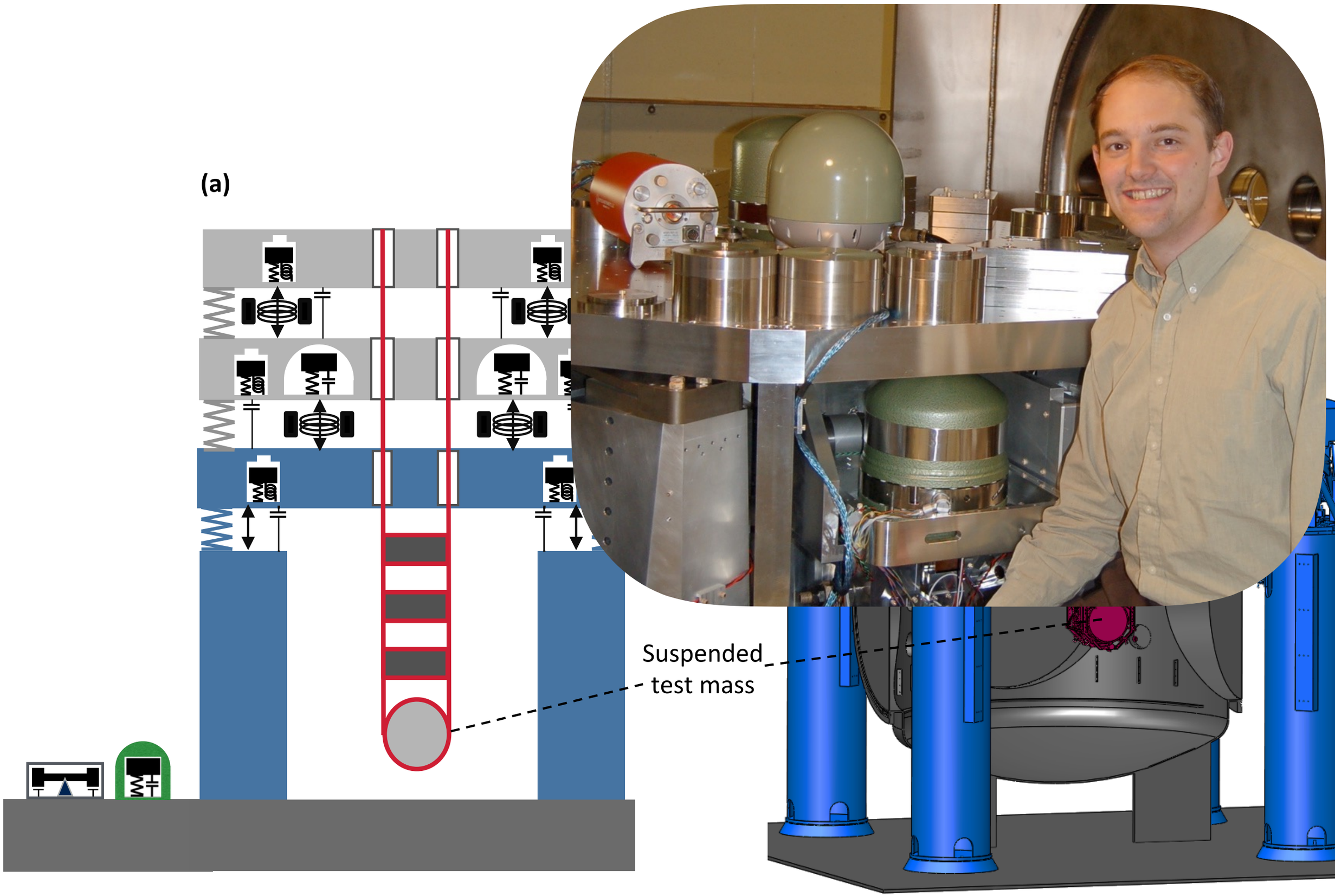




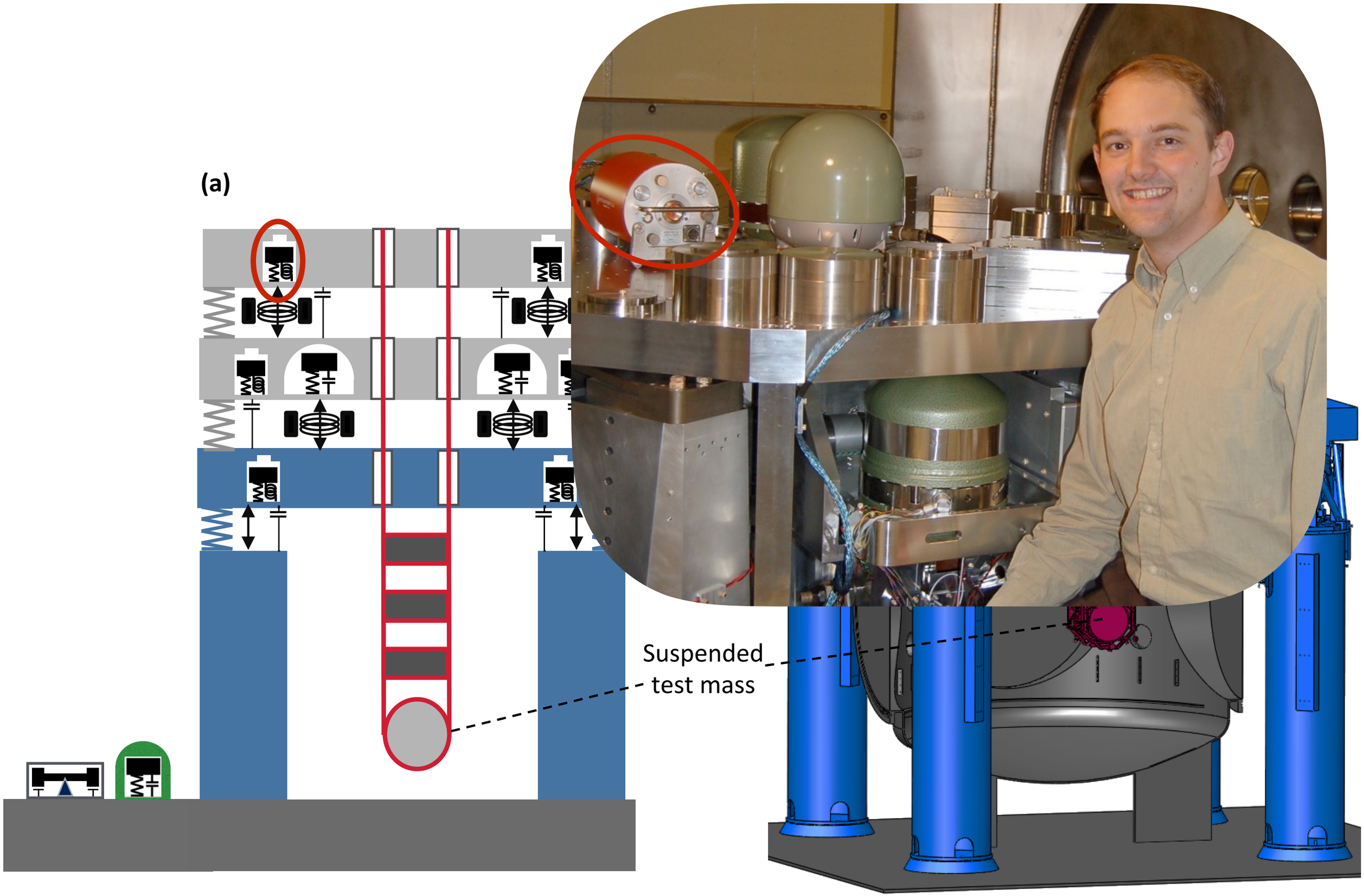
Signals for processing



Signals for processing

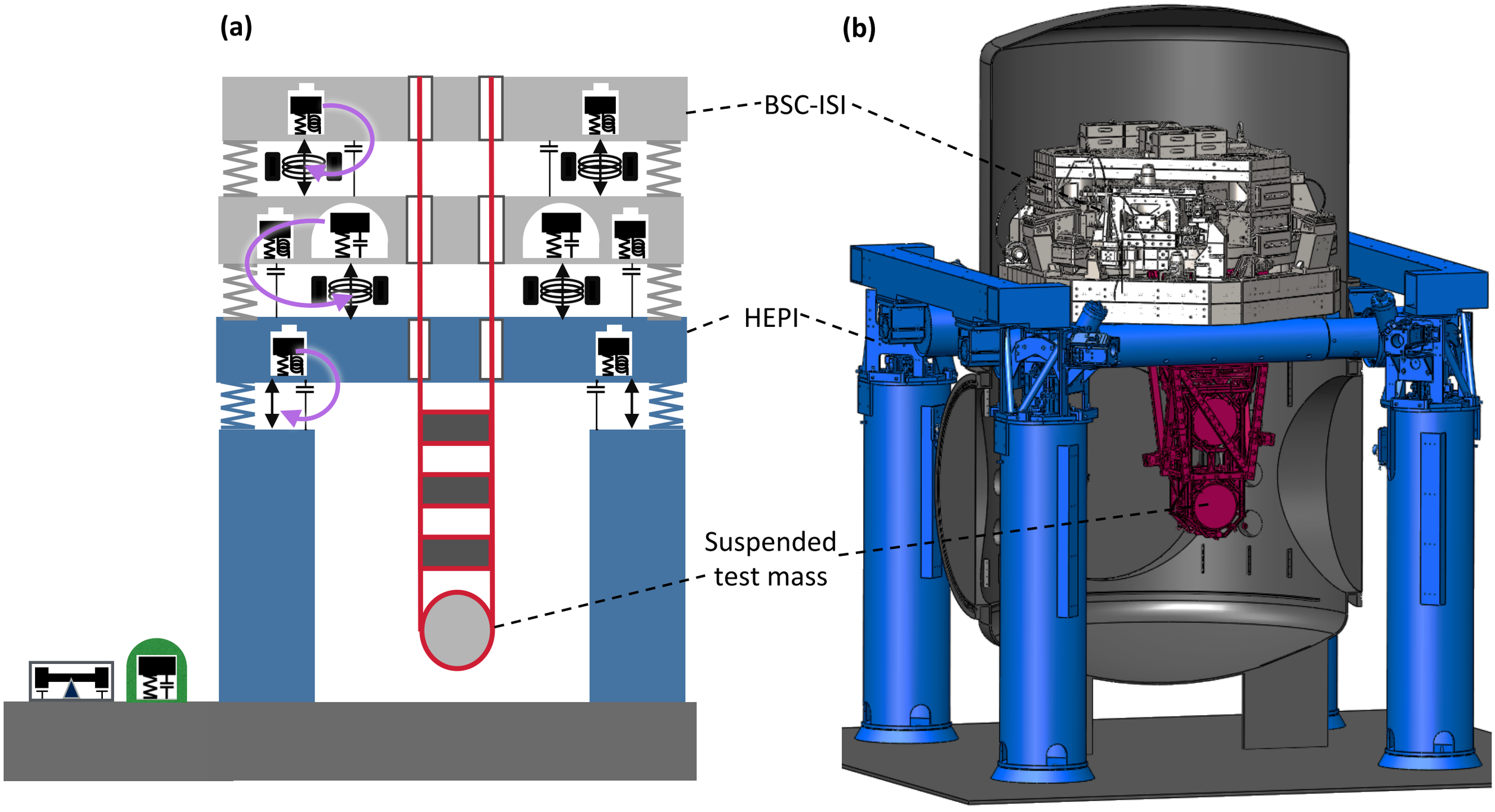


Signals for processing



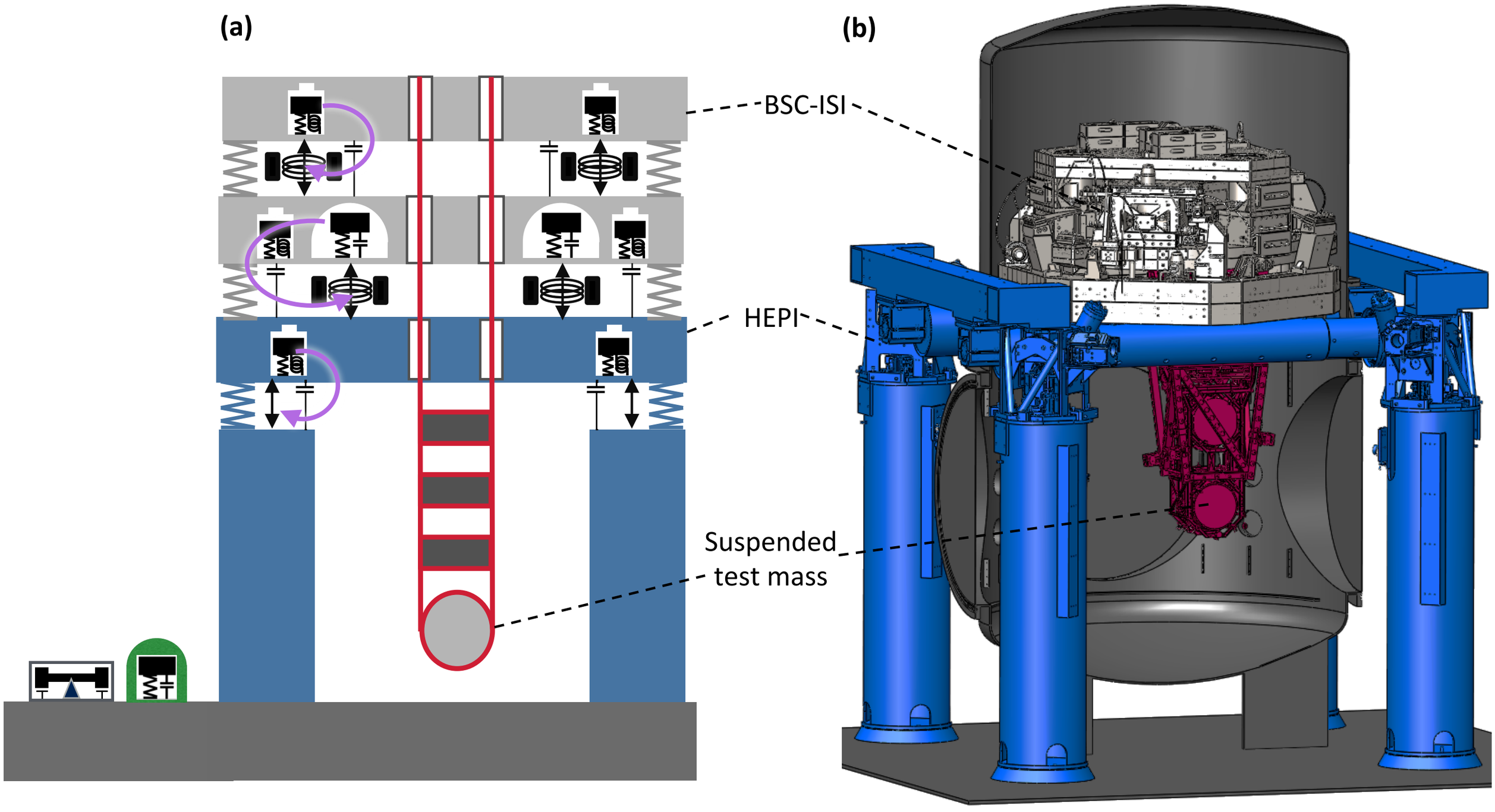
Signals for processing

Blended Feedback



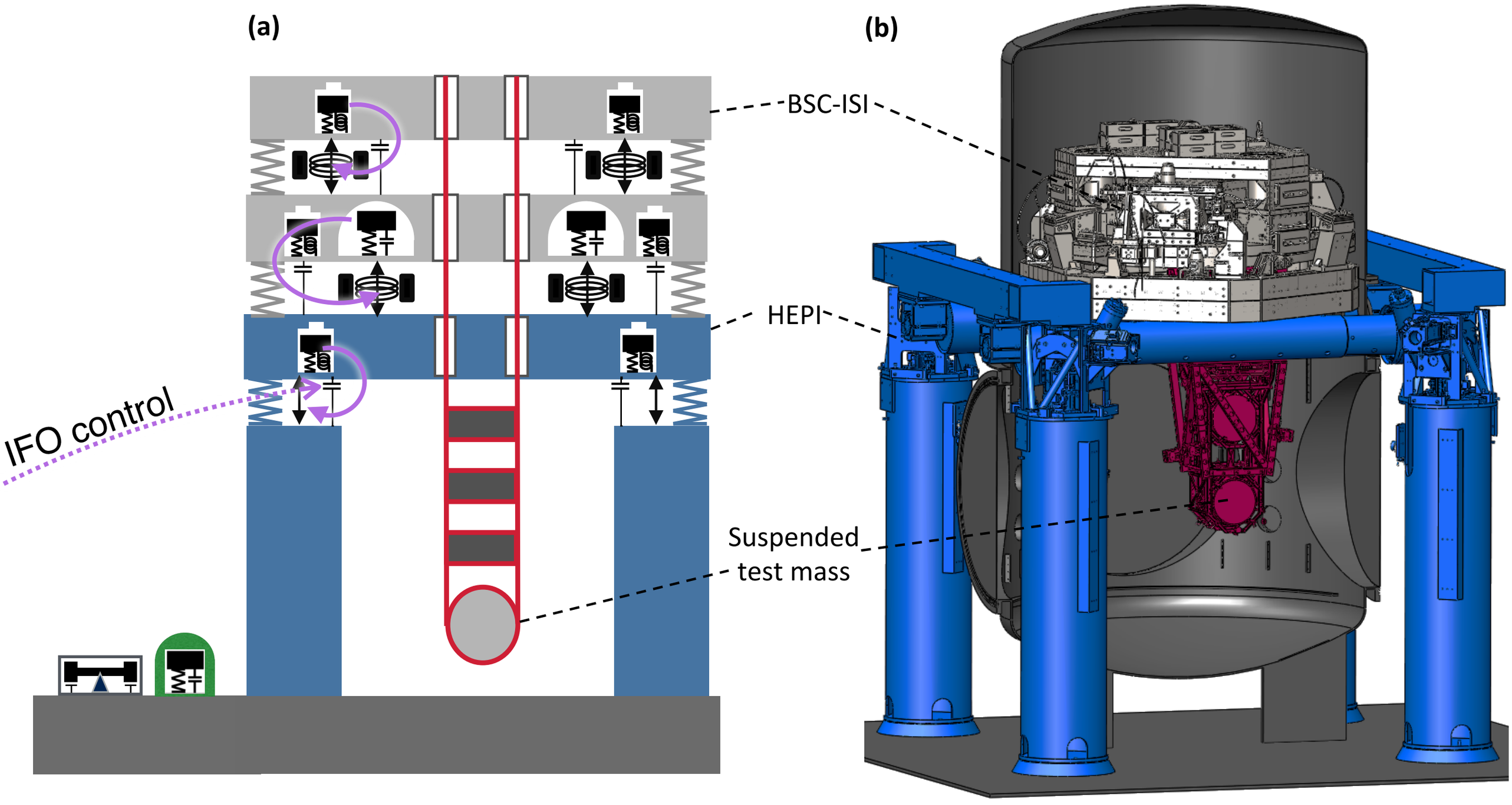
Signals for processing

Blended Feedback



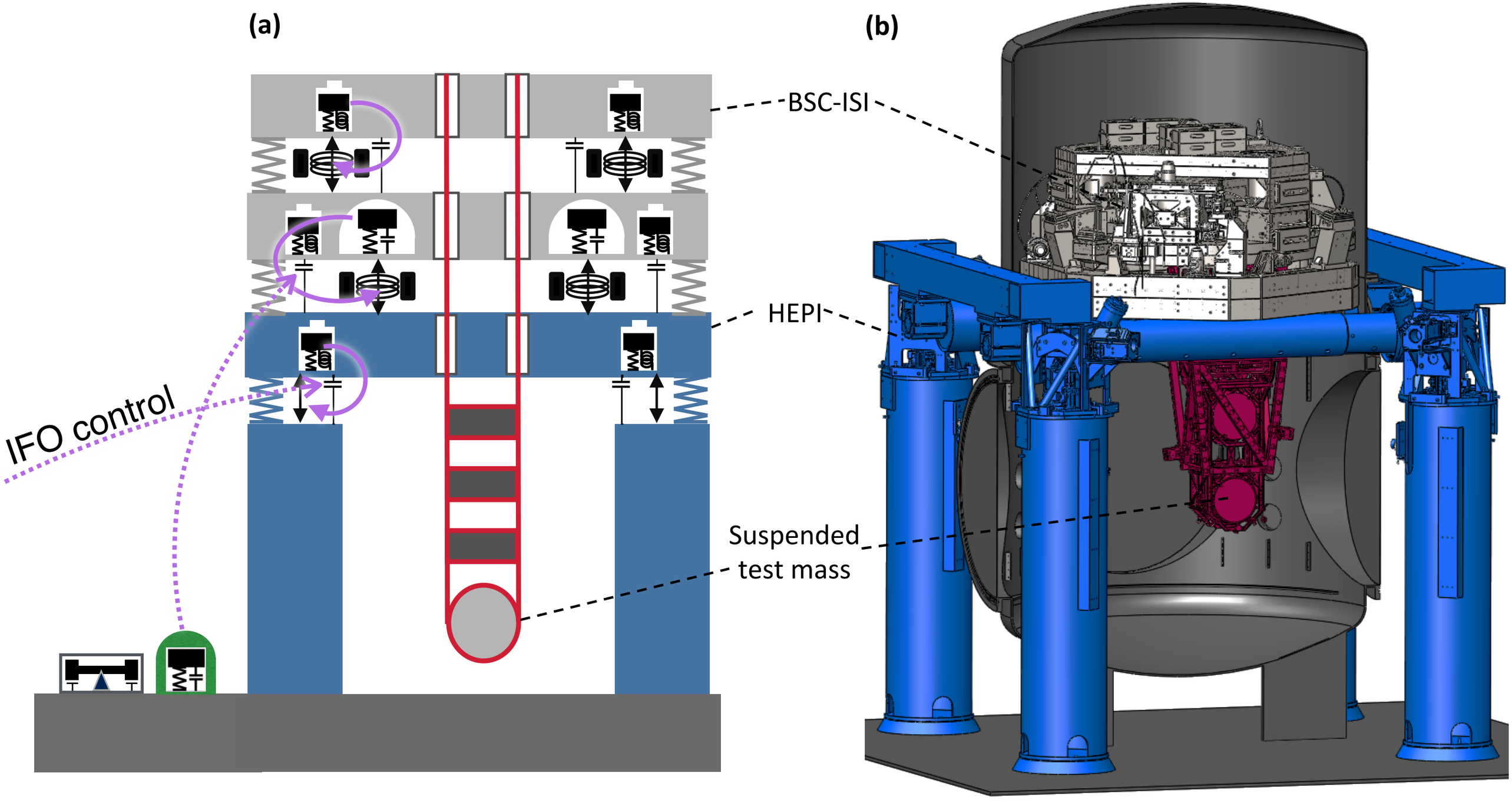
Signals for processing

Blended Feedback
Global commands



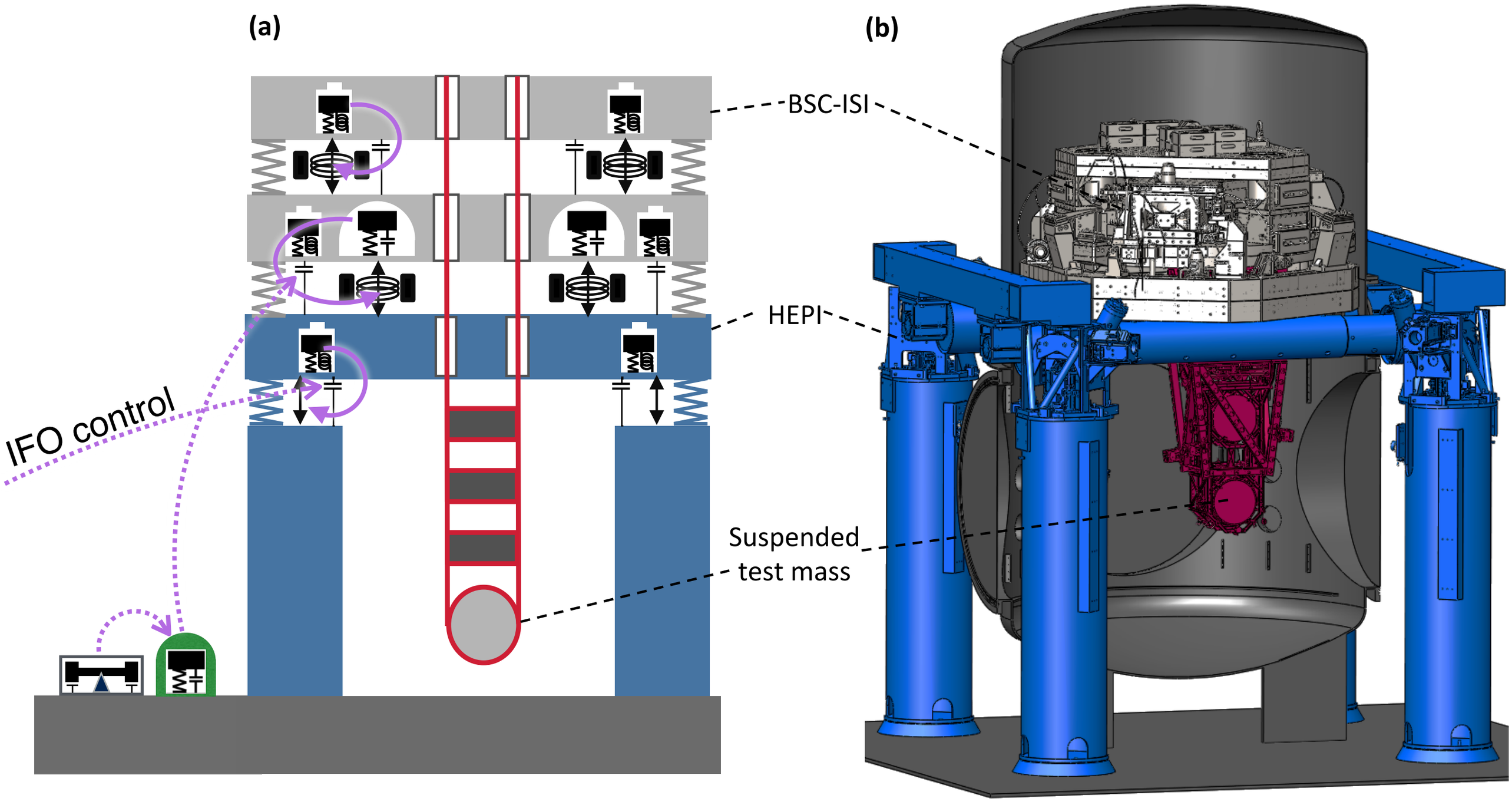
Signals for processing

Blended Feedback
Global commands
Sensor correction



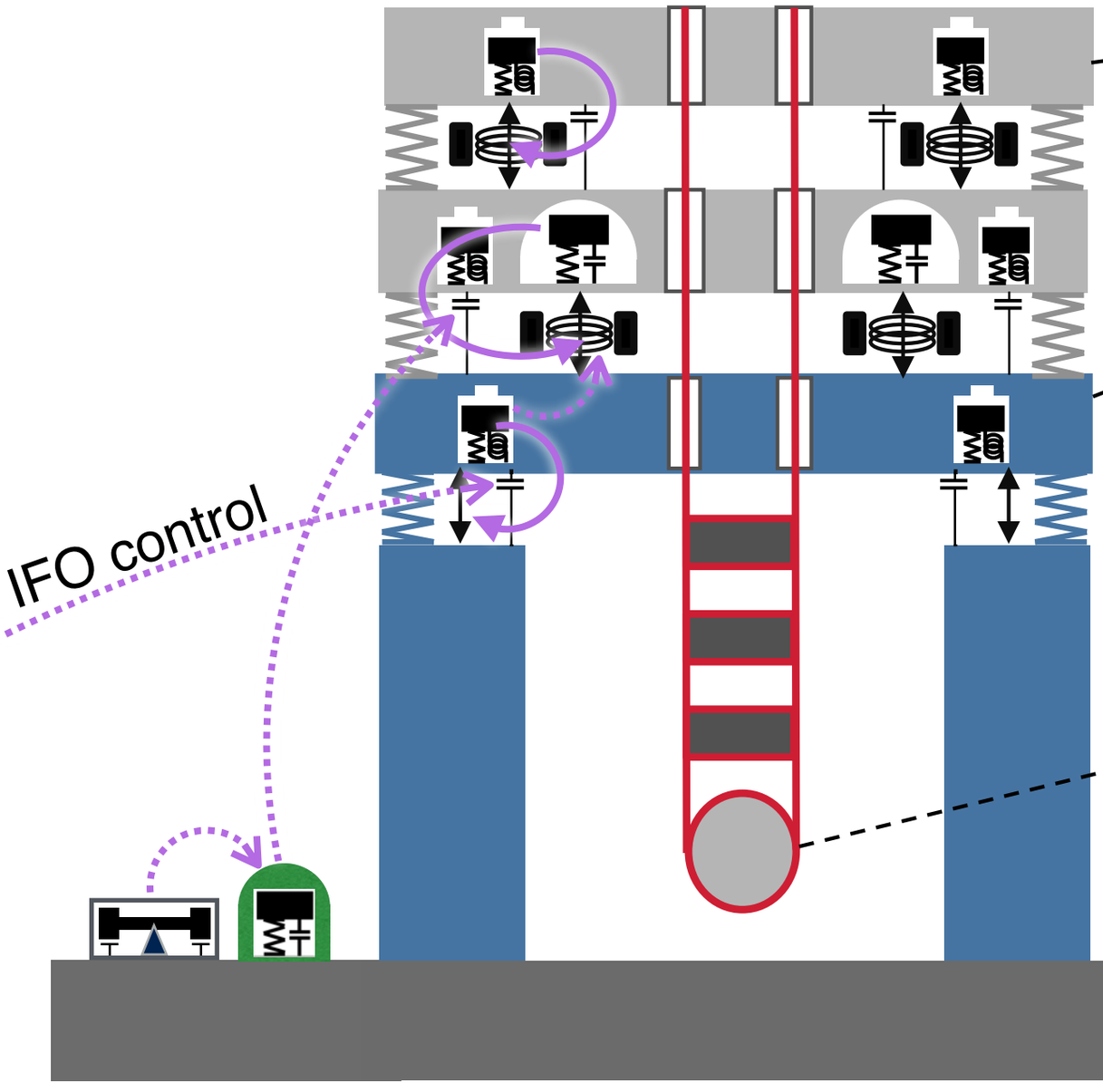
Signals for processing

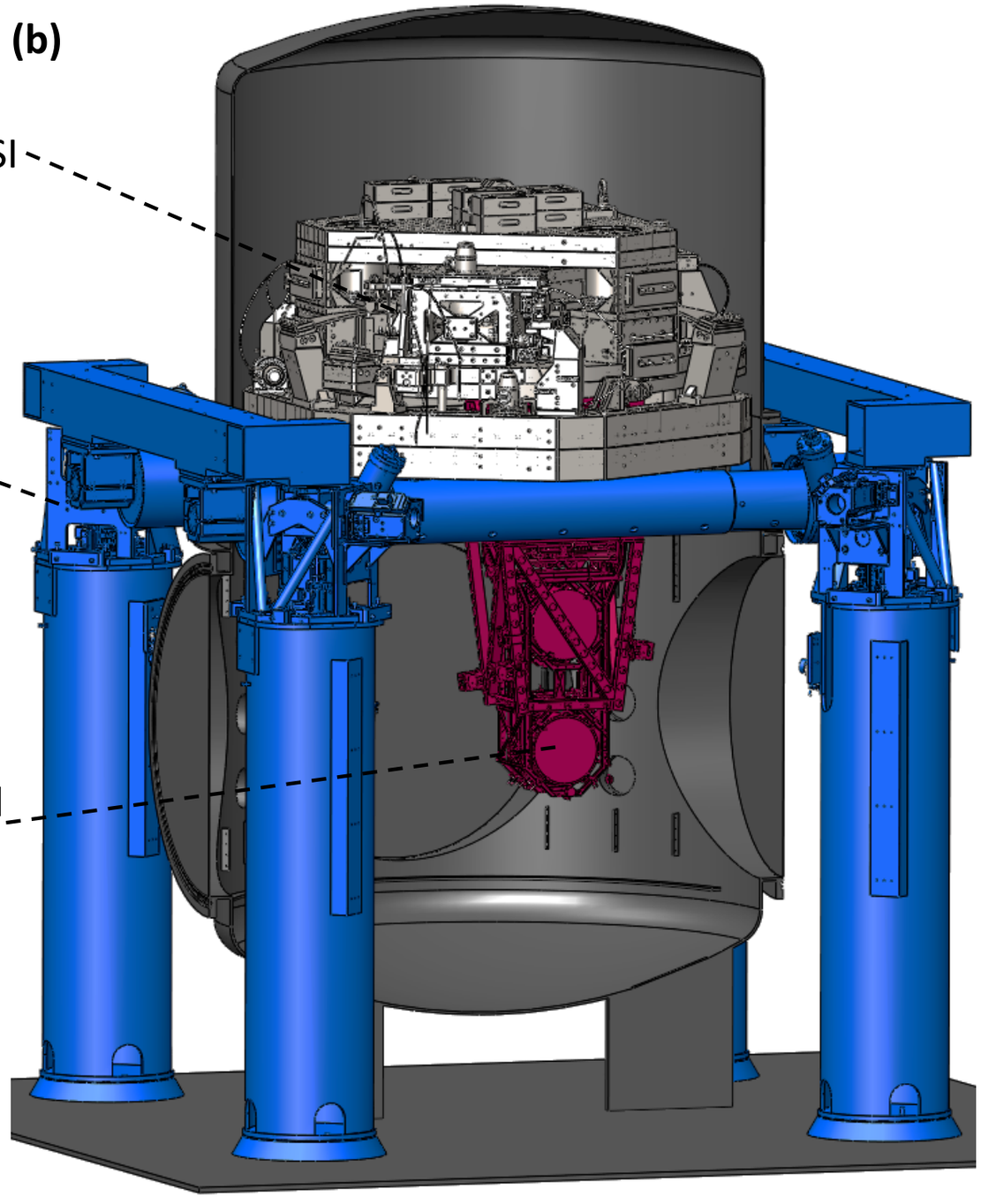
Blended Feedback
Global commands
Sensor correction



Signals for processing

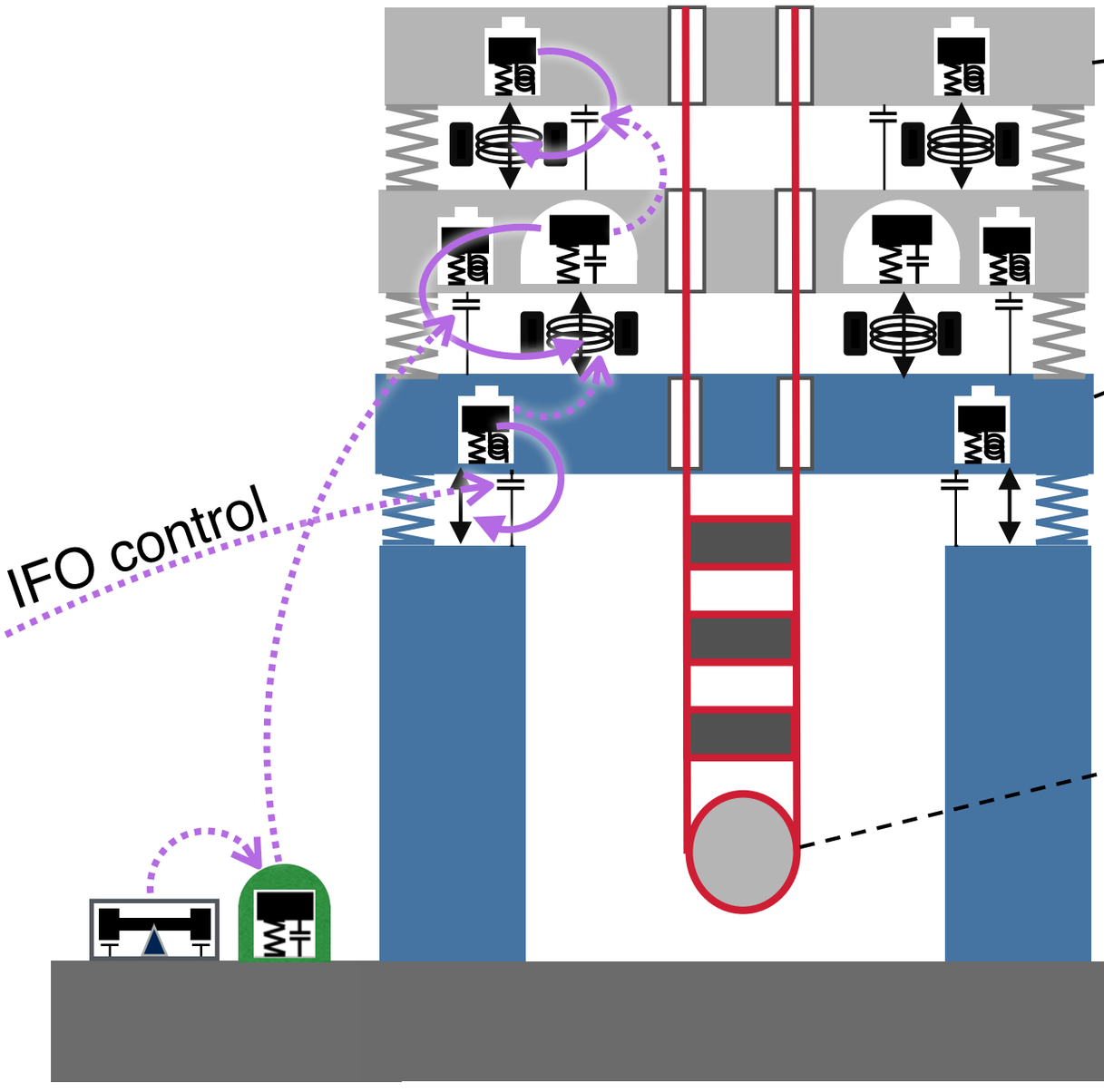
Blended Feedback
Global commands
Sensor correction
Feedforward

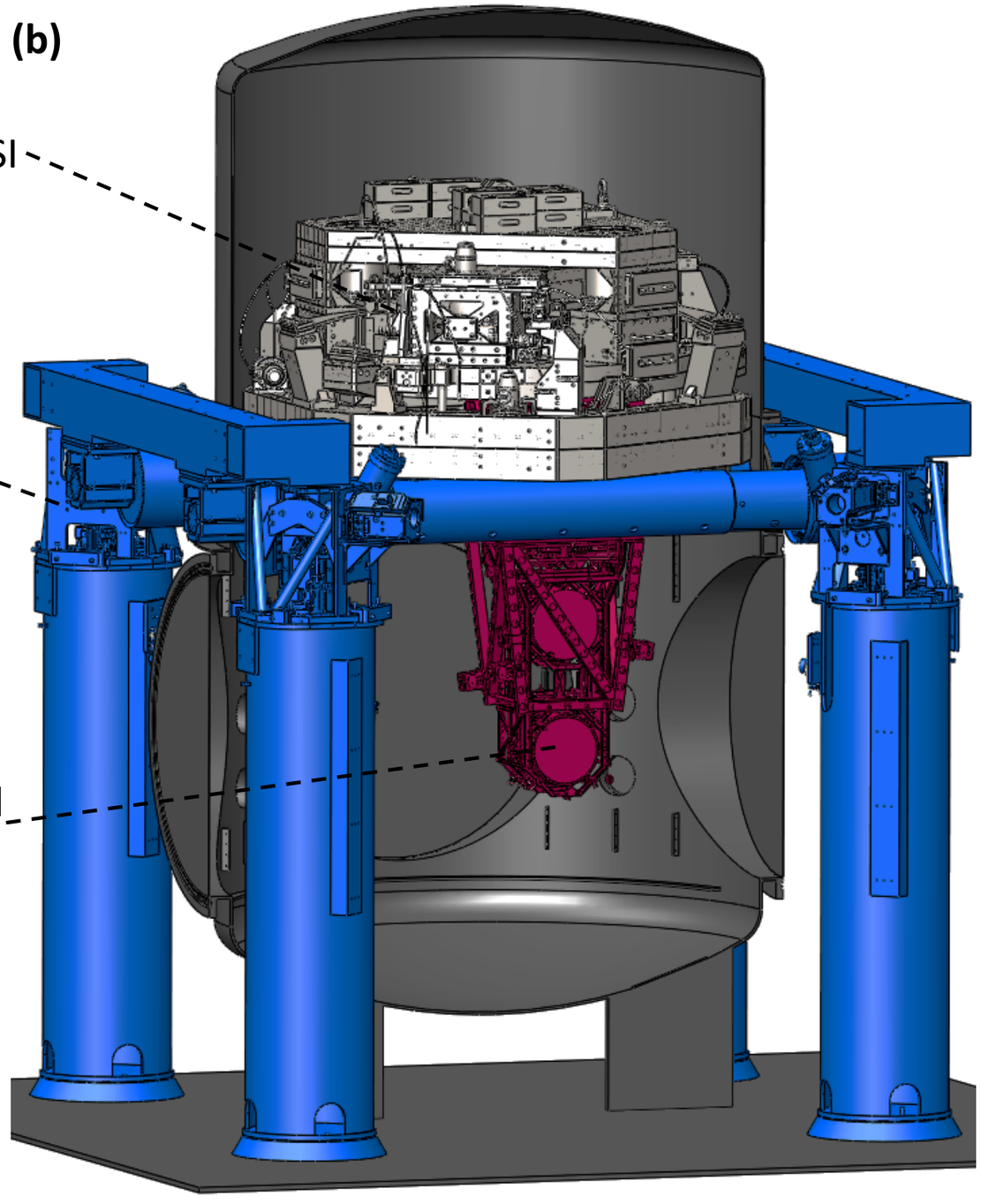




Signals for processing

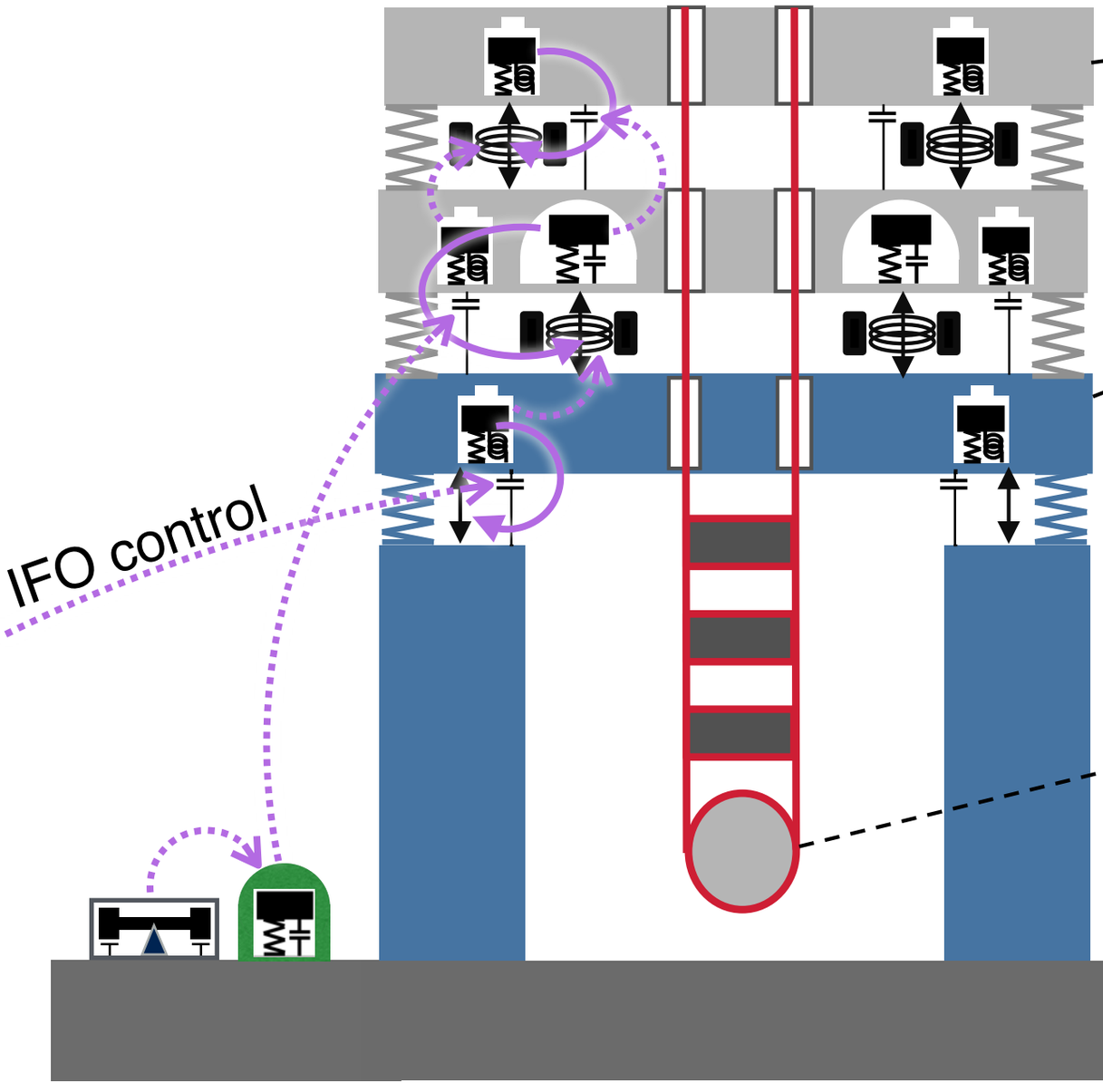
Blended Feedback
Global commands
Sensor correction
Feedforward

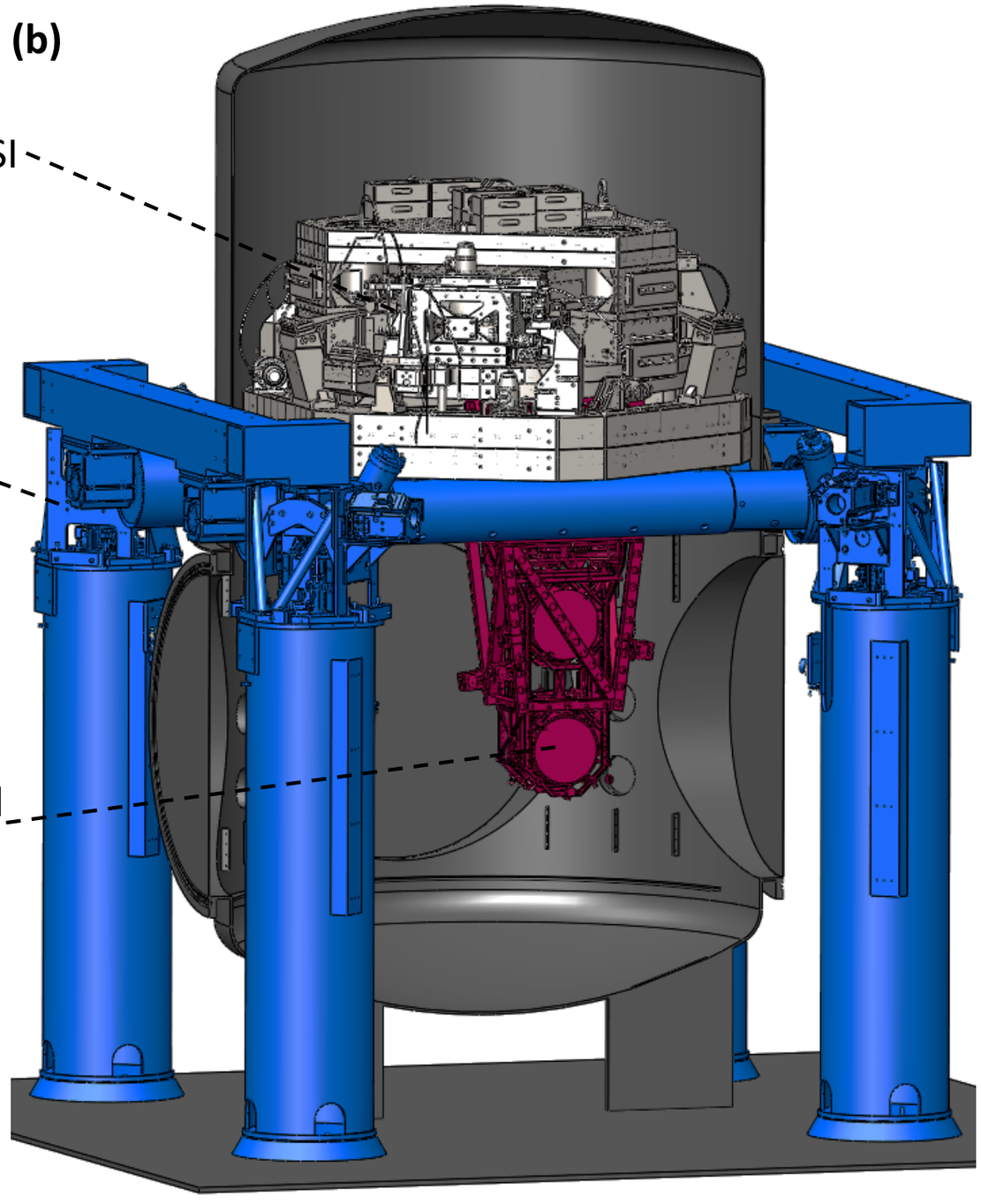




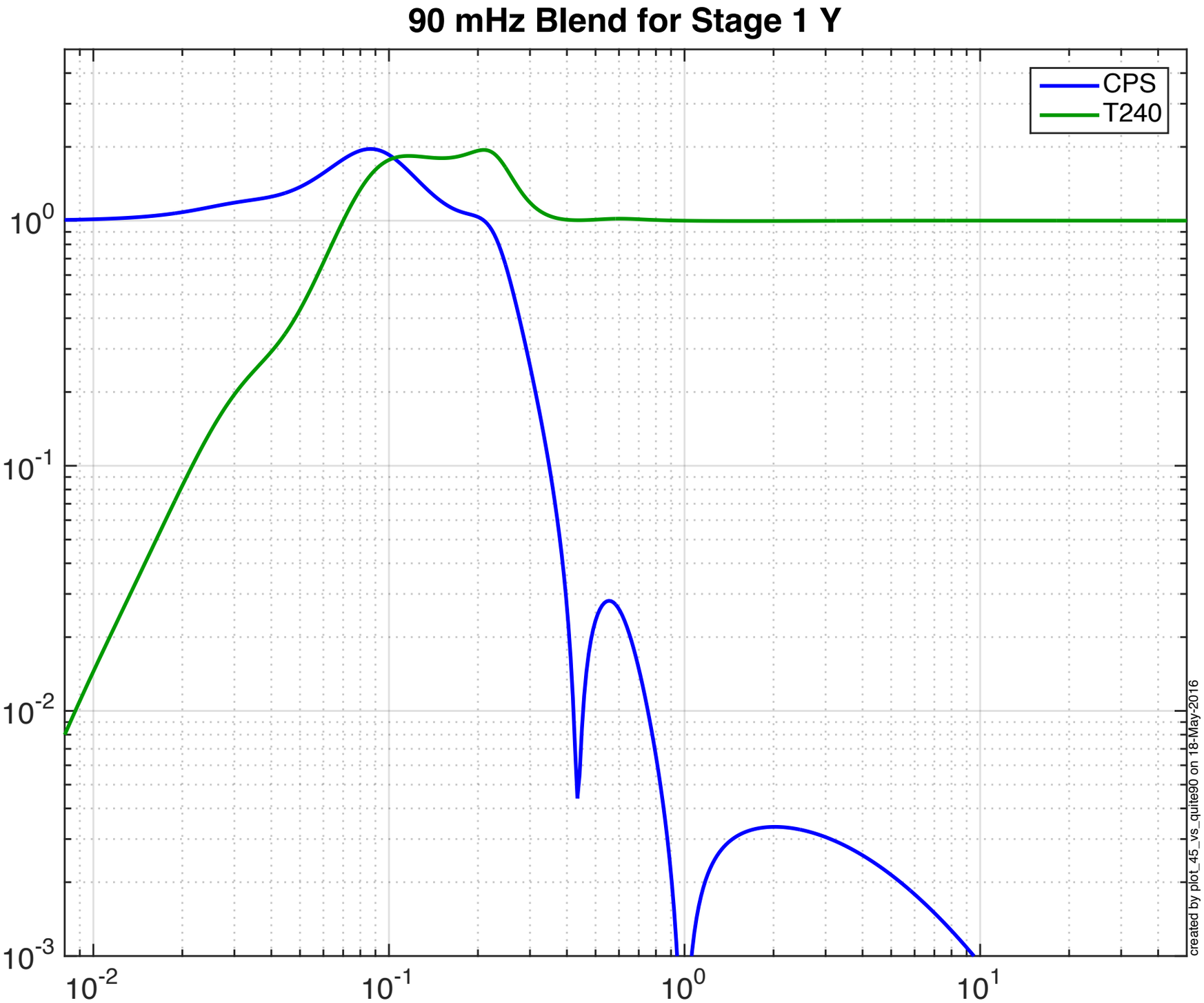
Signals for processing

Blended Feedback
Global commands
Sensor correction
Feedforward

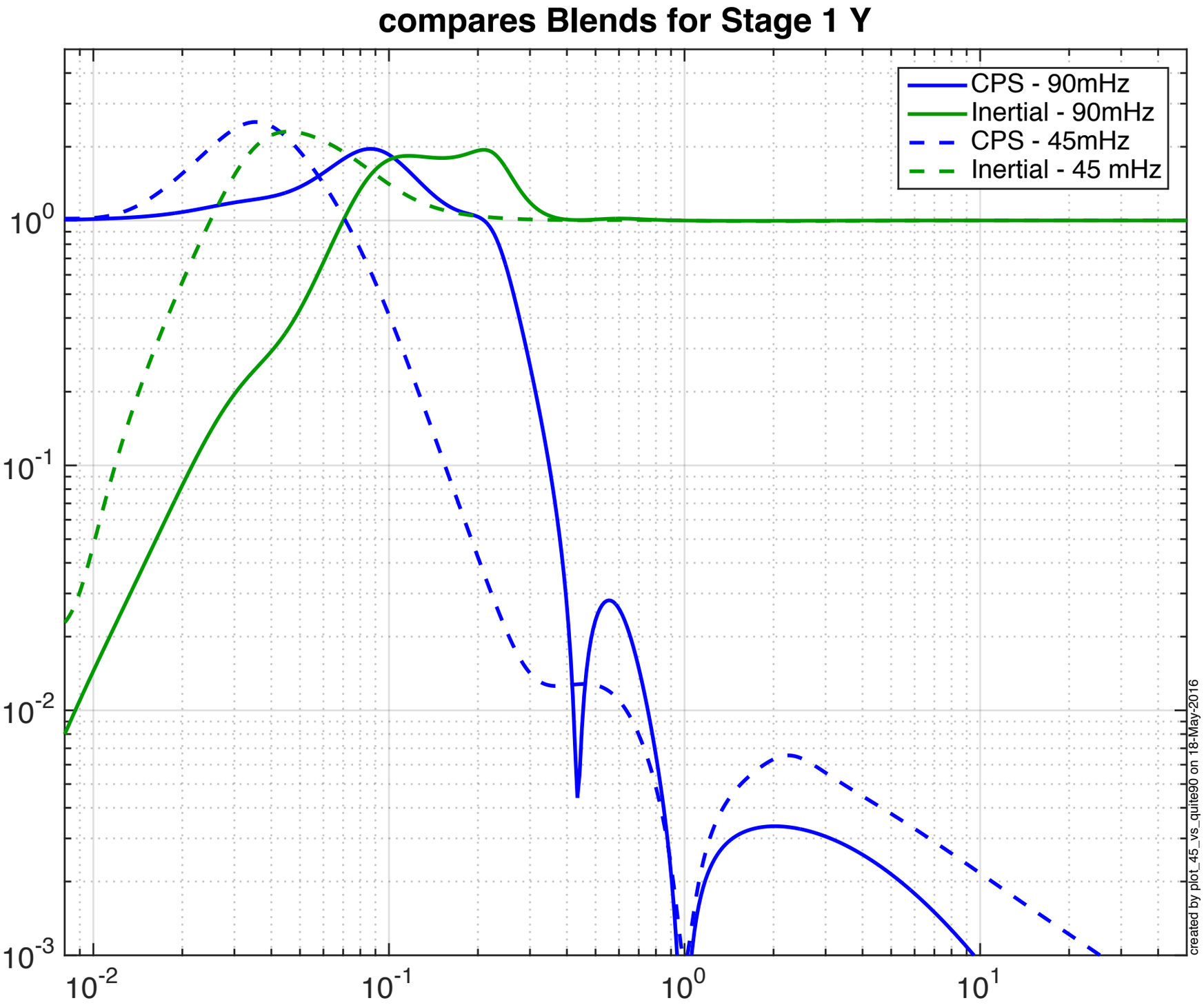




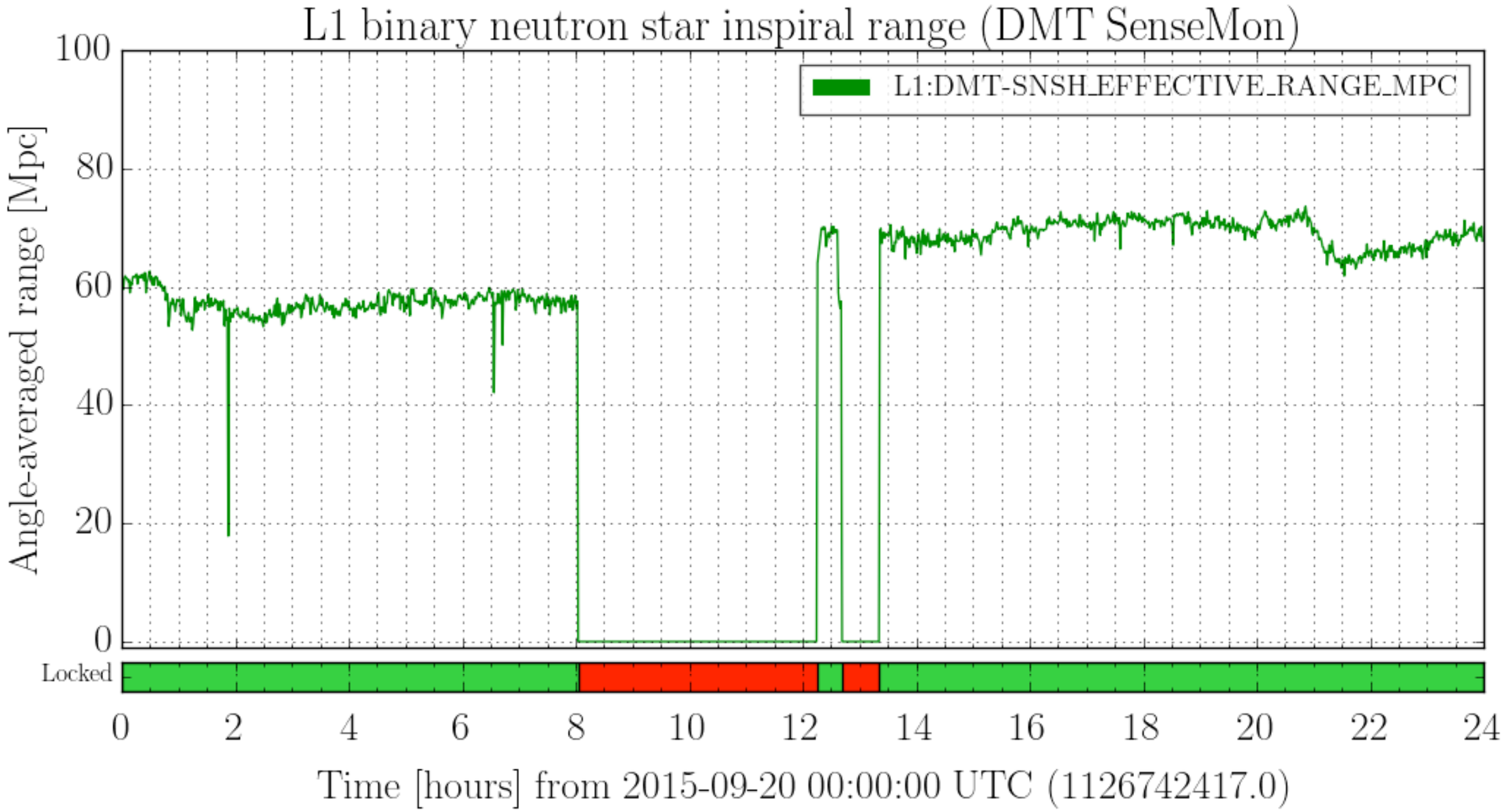
Blending sensors



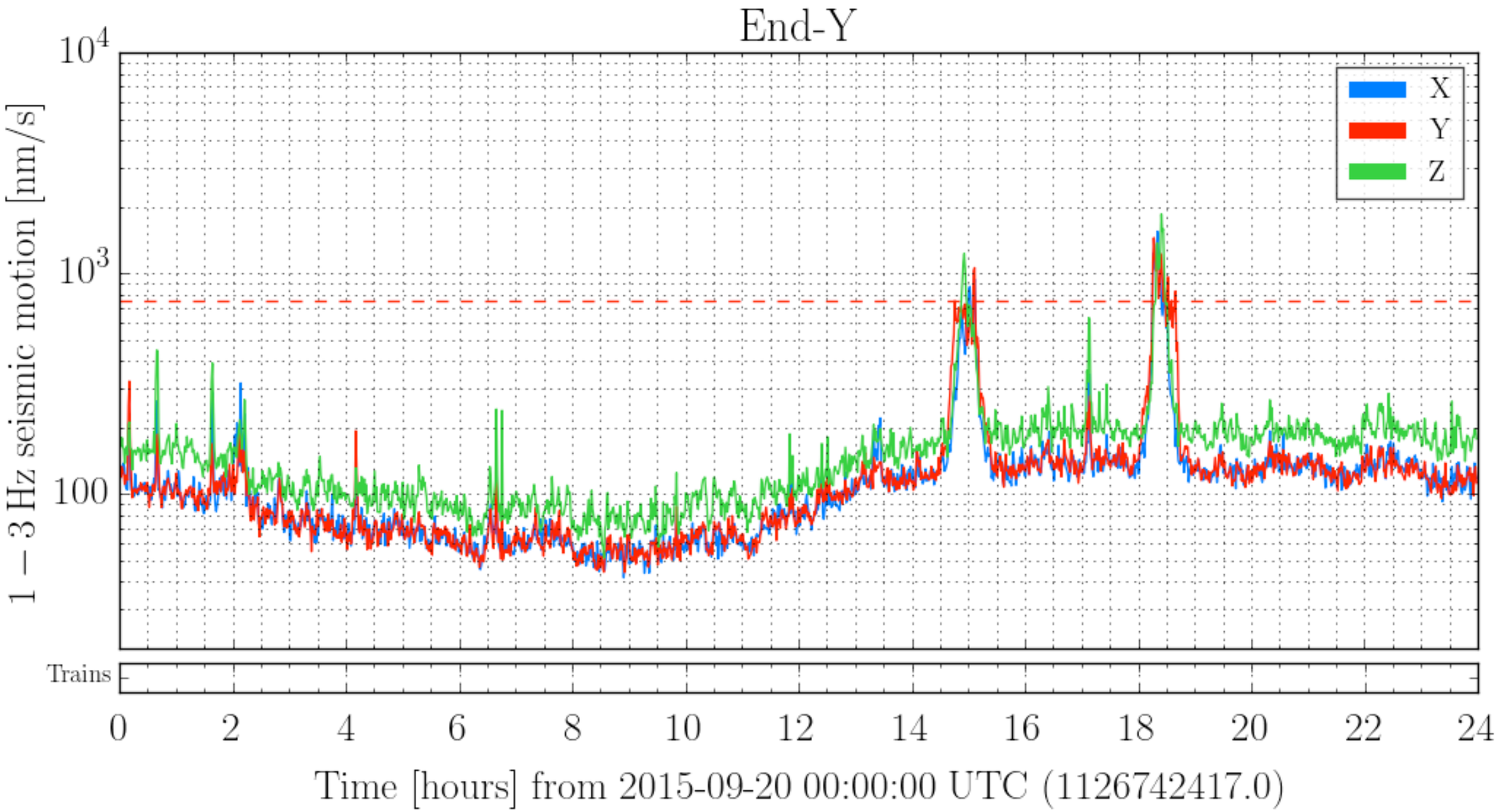
Blending sensors



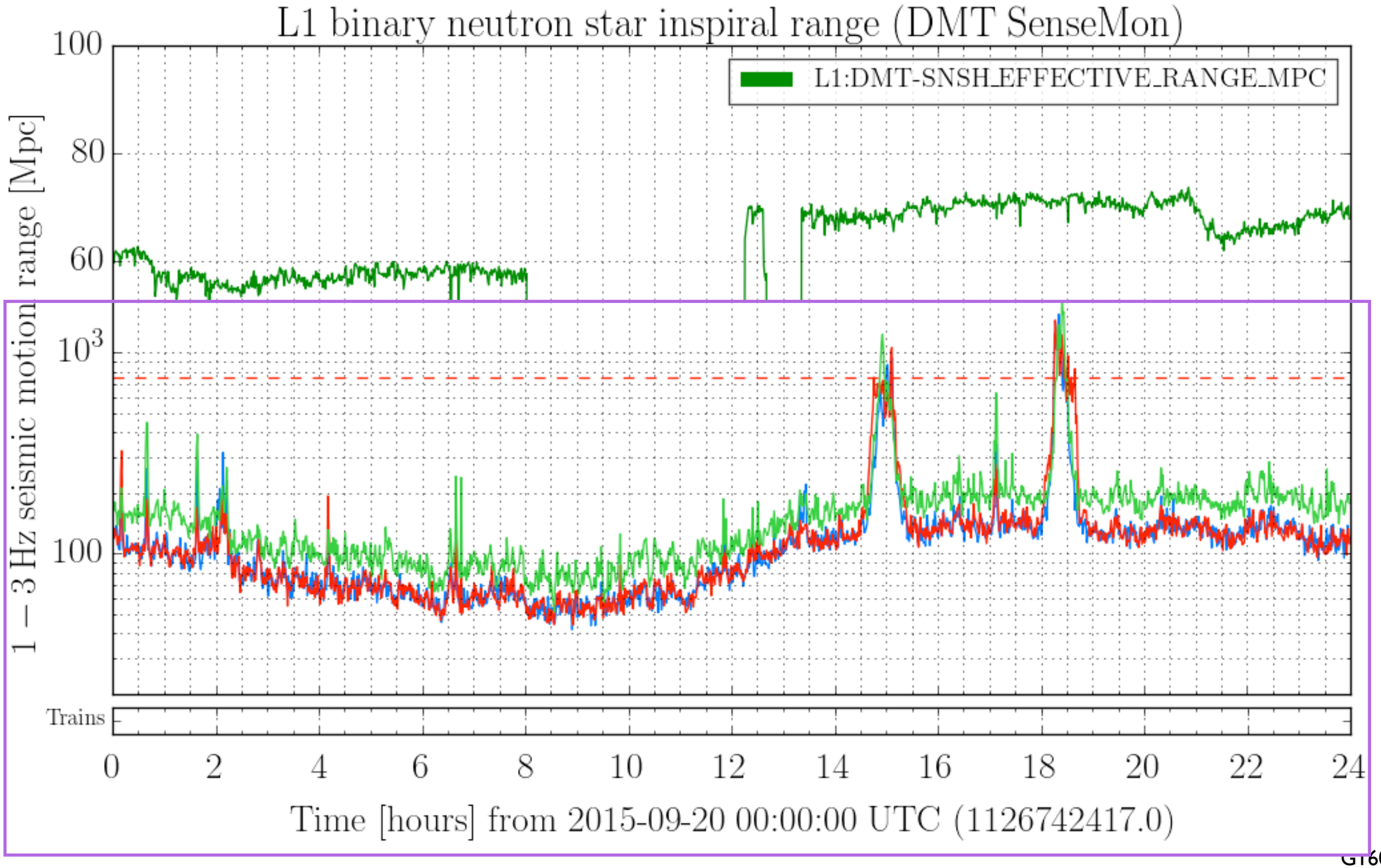
Real impact of isolation, alignment & control



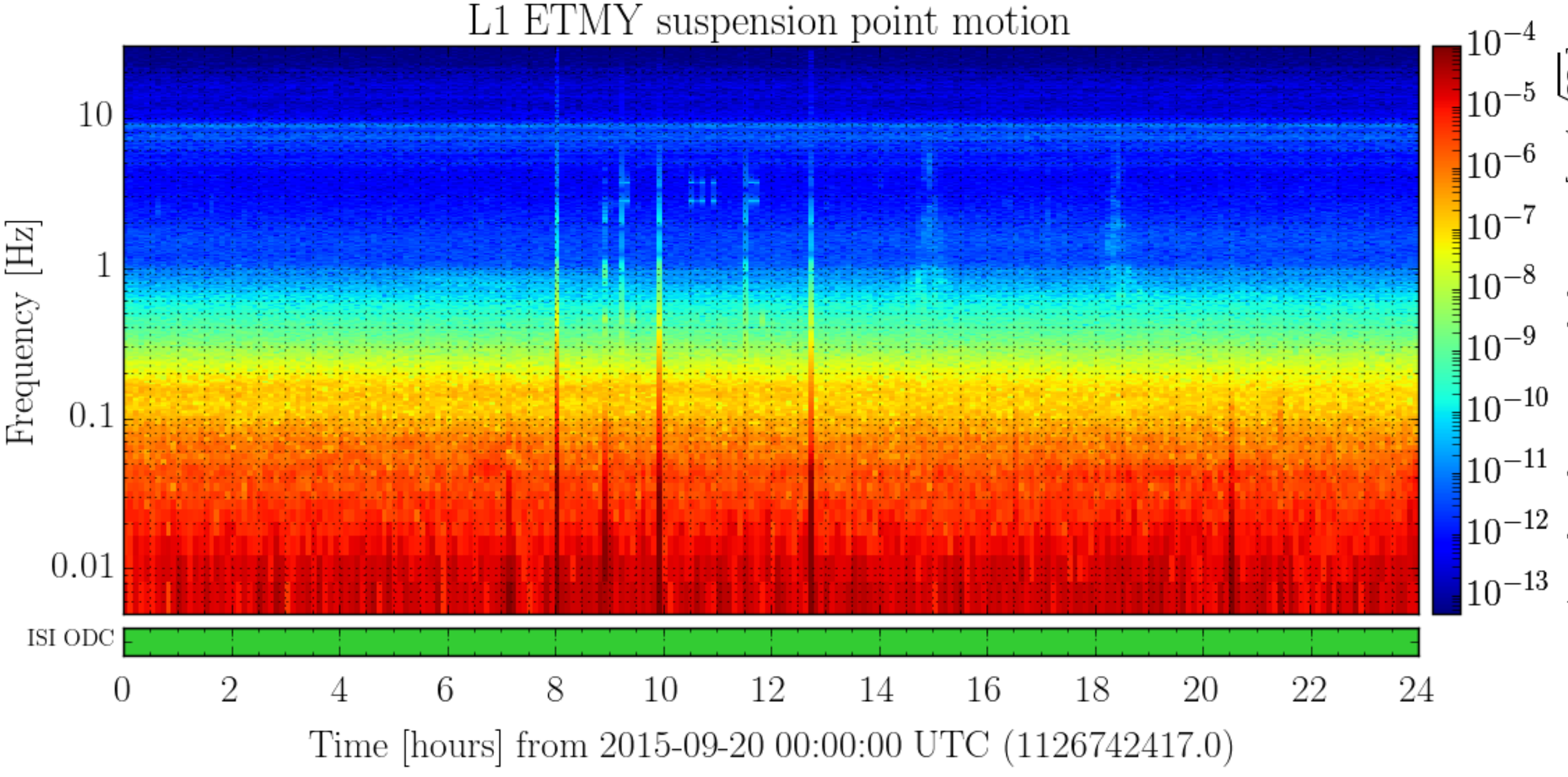
but there was a train…



Real impact of isolation, alignment & control

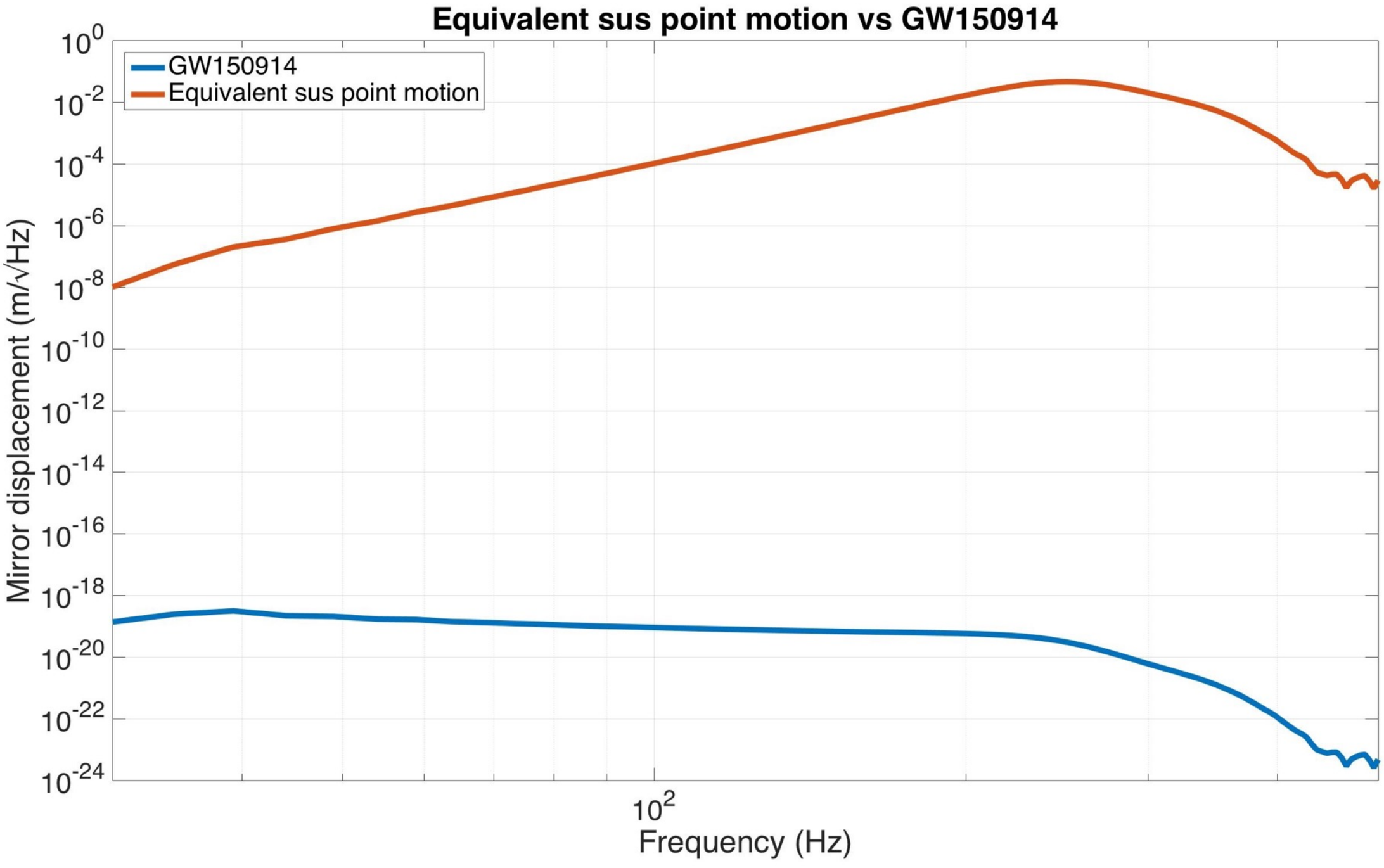


‘Environmental’ sensors

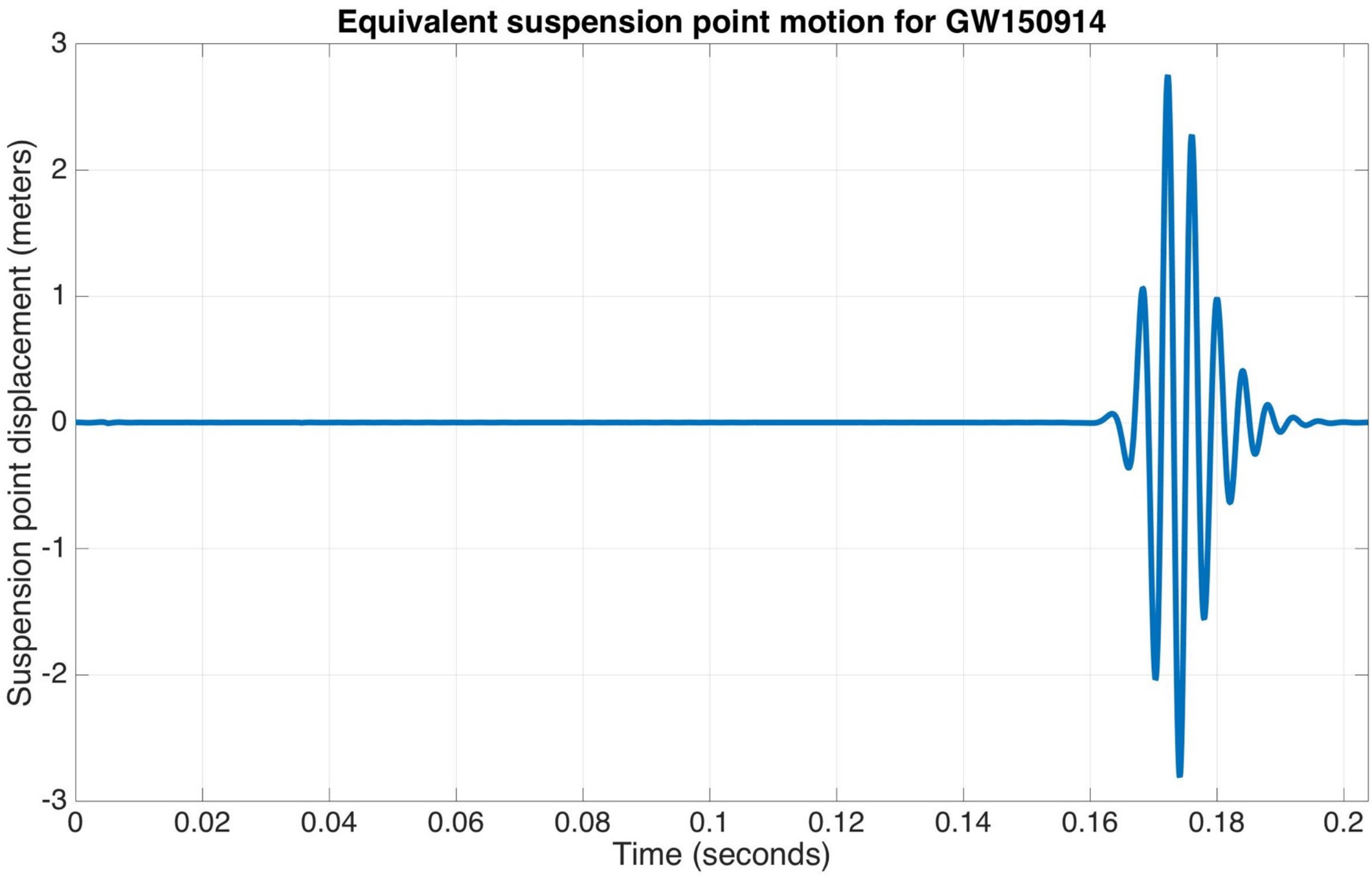


Power of the monitors

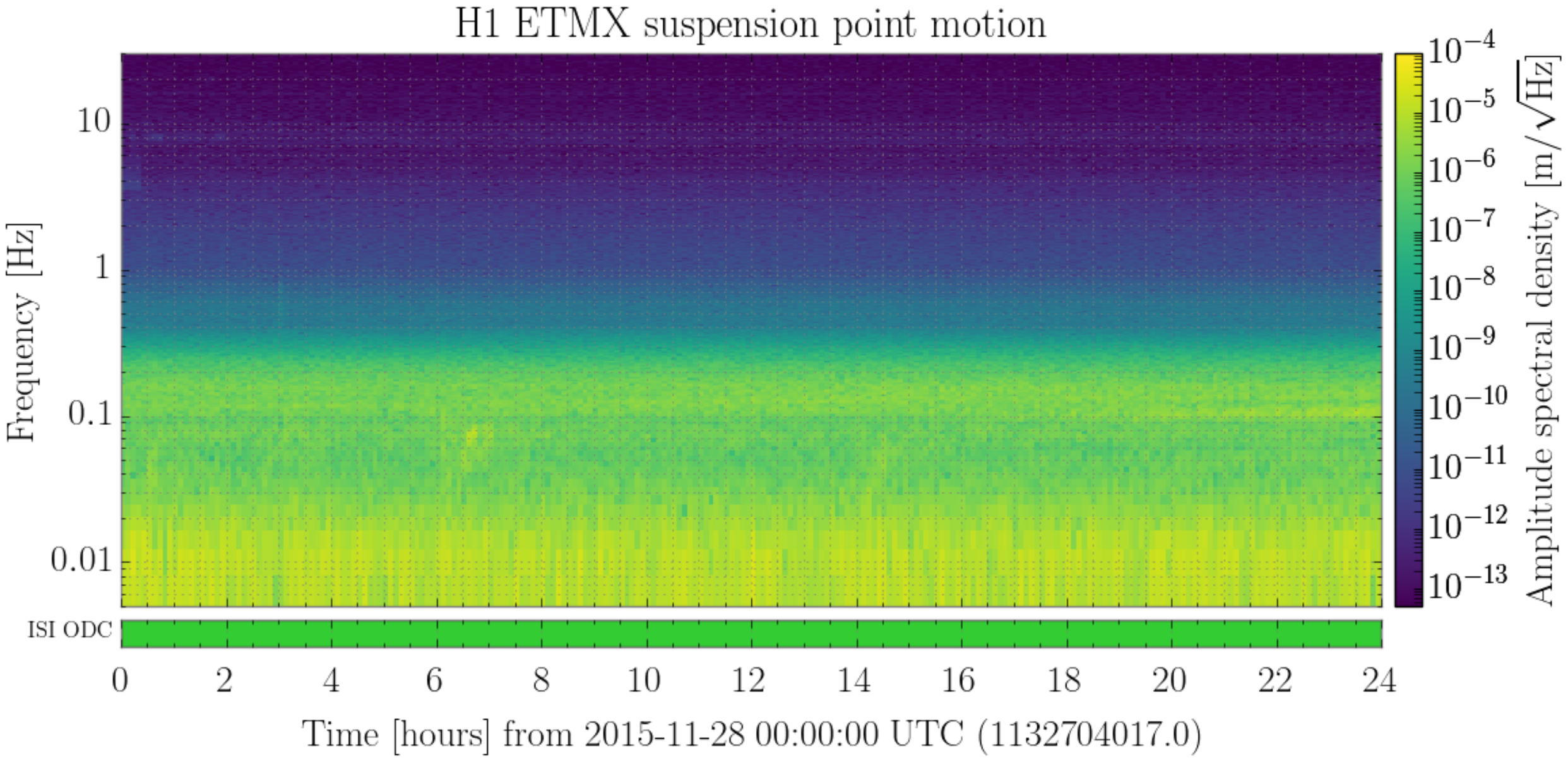
If GS150914 was linearly coupled seismic motion

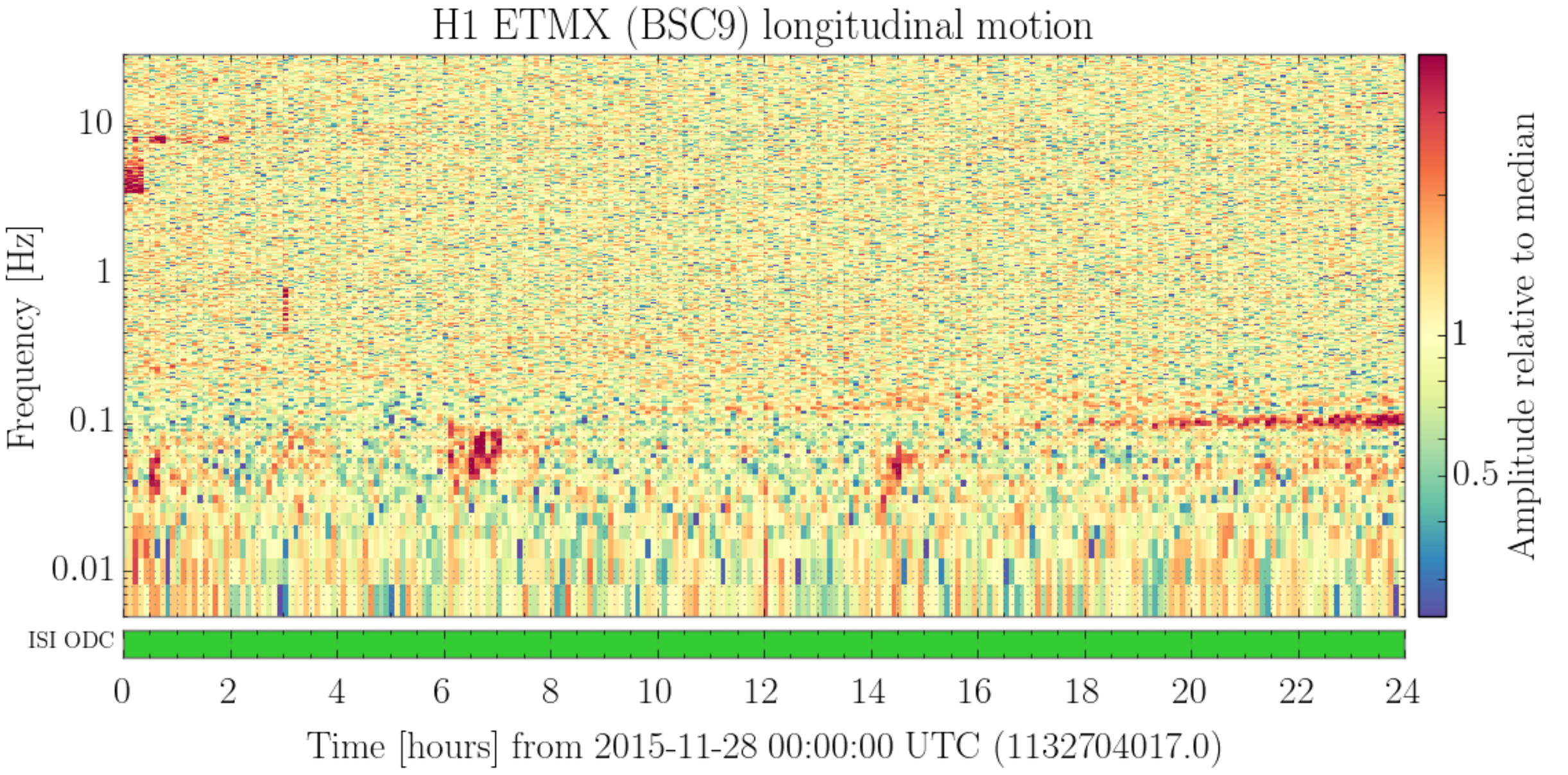


If GS150914 was

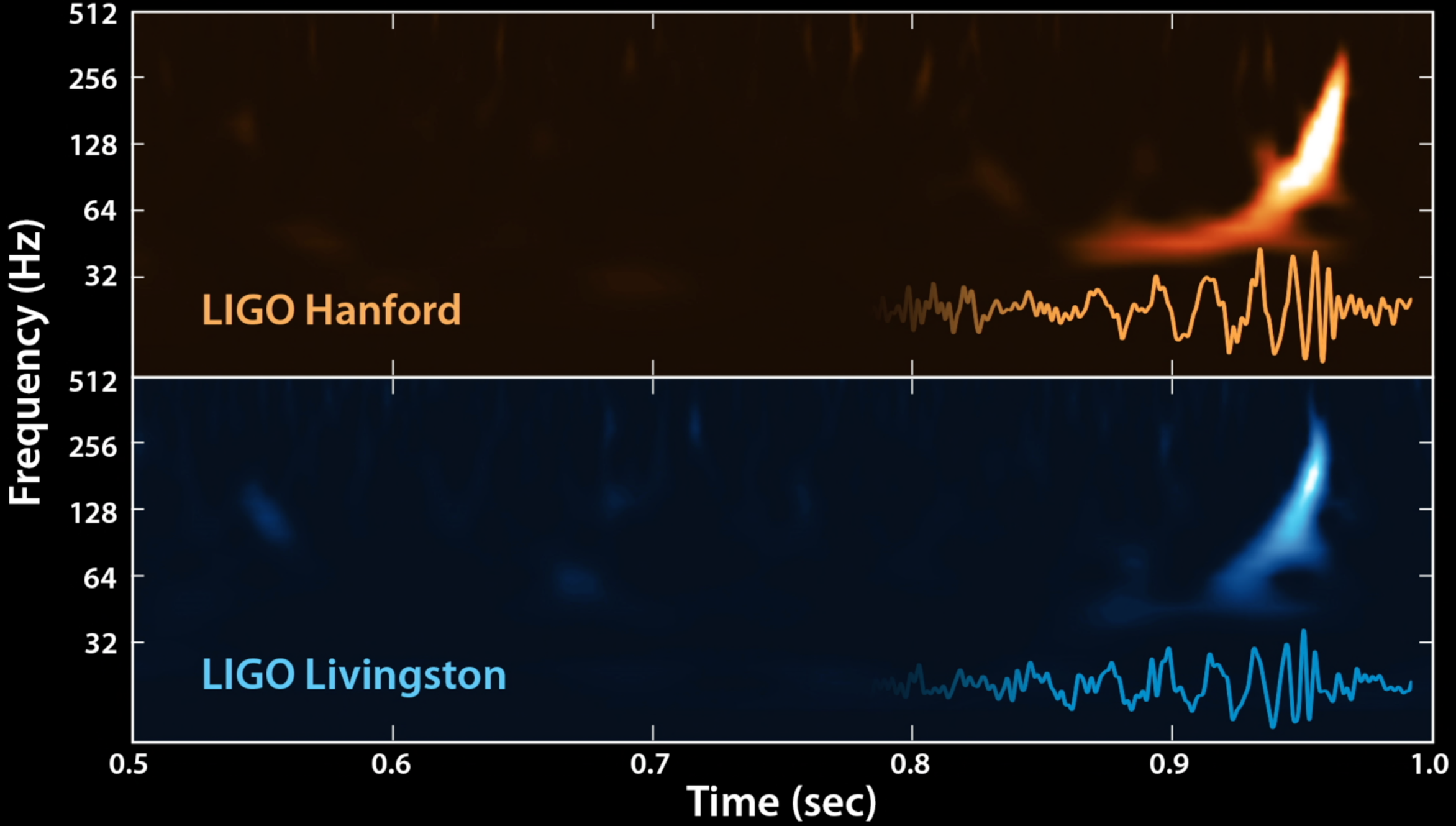


This is what we strive for

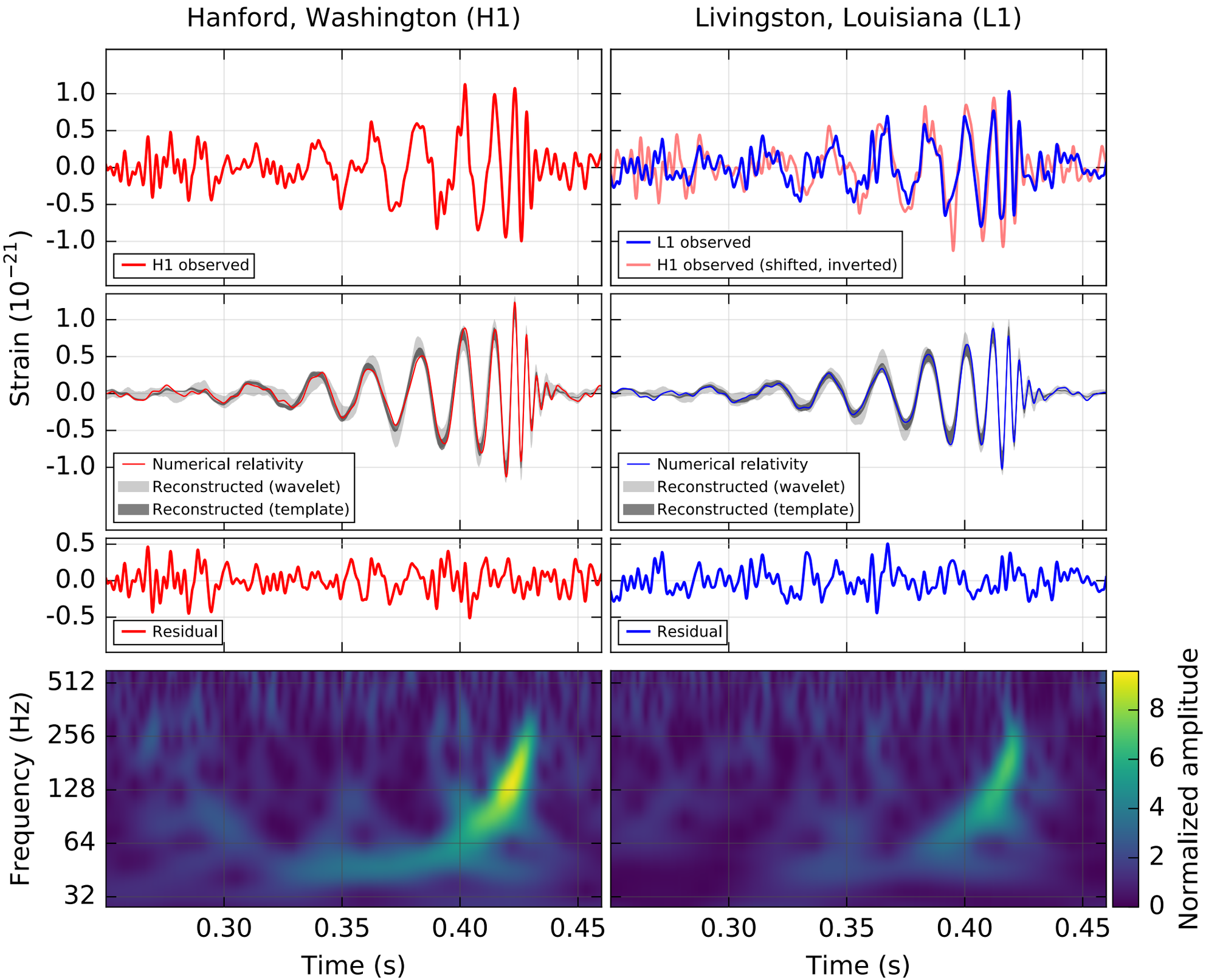



H1 ETMX (BSC9) longitudinal motion
Frequency [Hz]
10
1
0.1
0.01
ISI ODC
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2015-11-28 00:00:00 UTC (1132704017.0)
1
0.5
Amplitude relative to median

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:

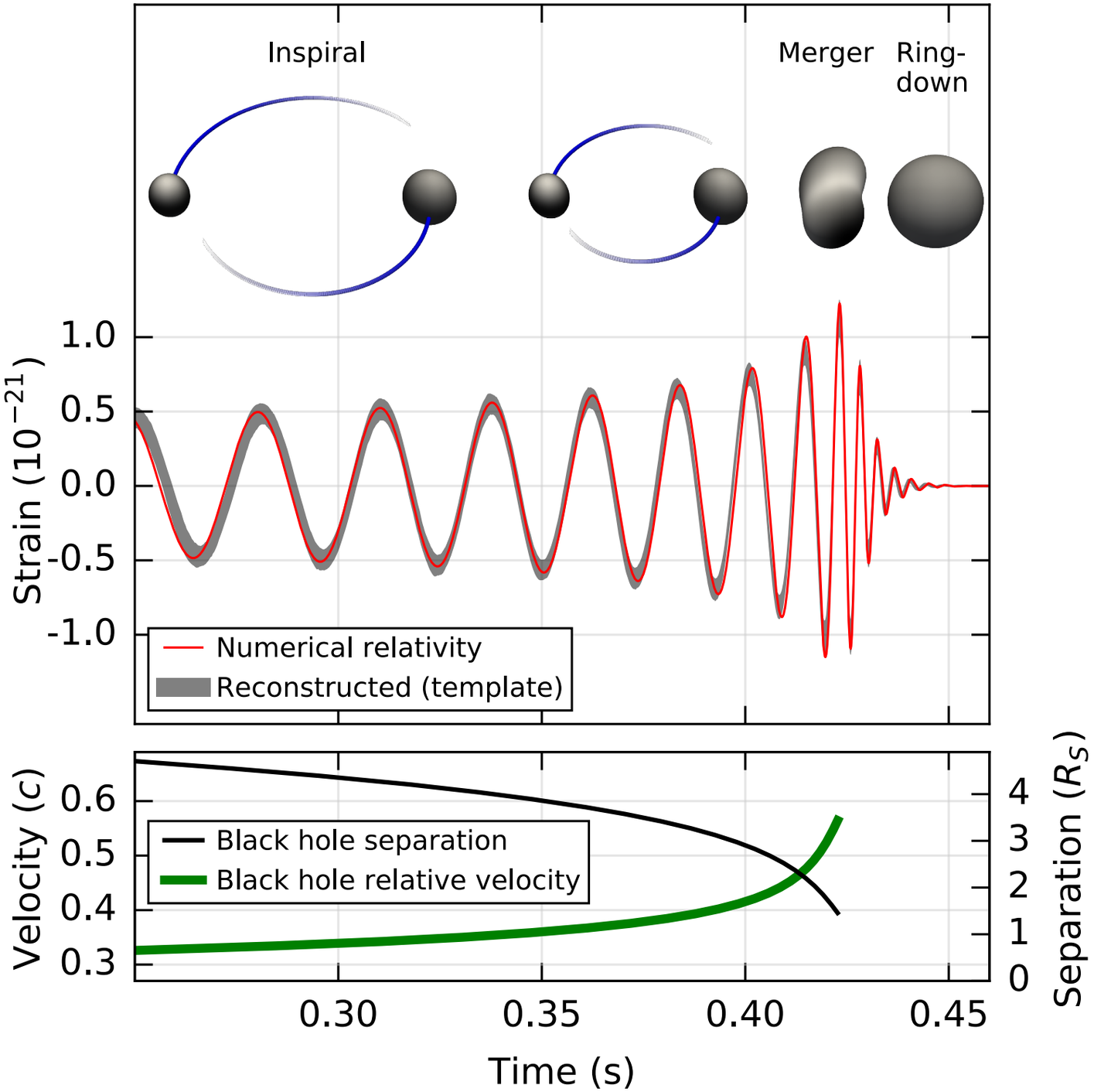
62 (+4/-4) M_{sun}

Energy radiated

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

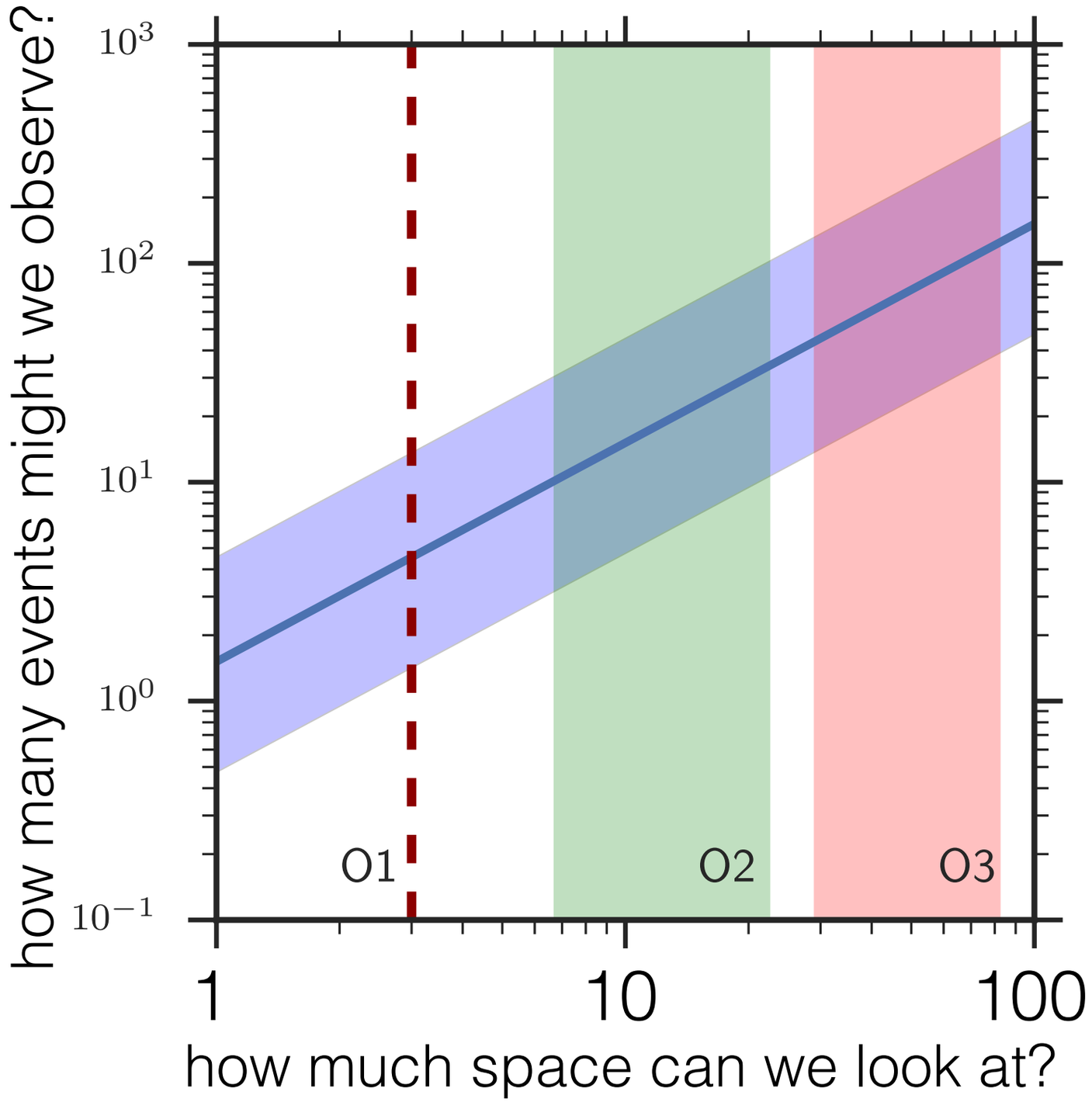
Distance

410 (+160/-180) MPc

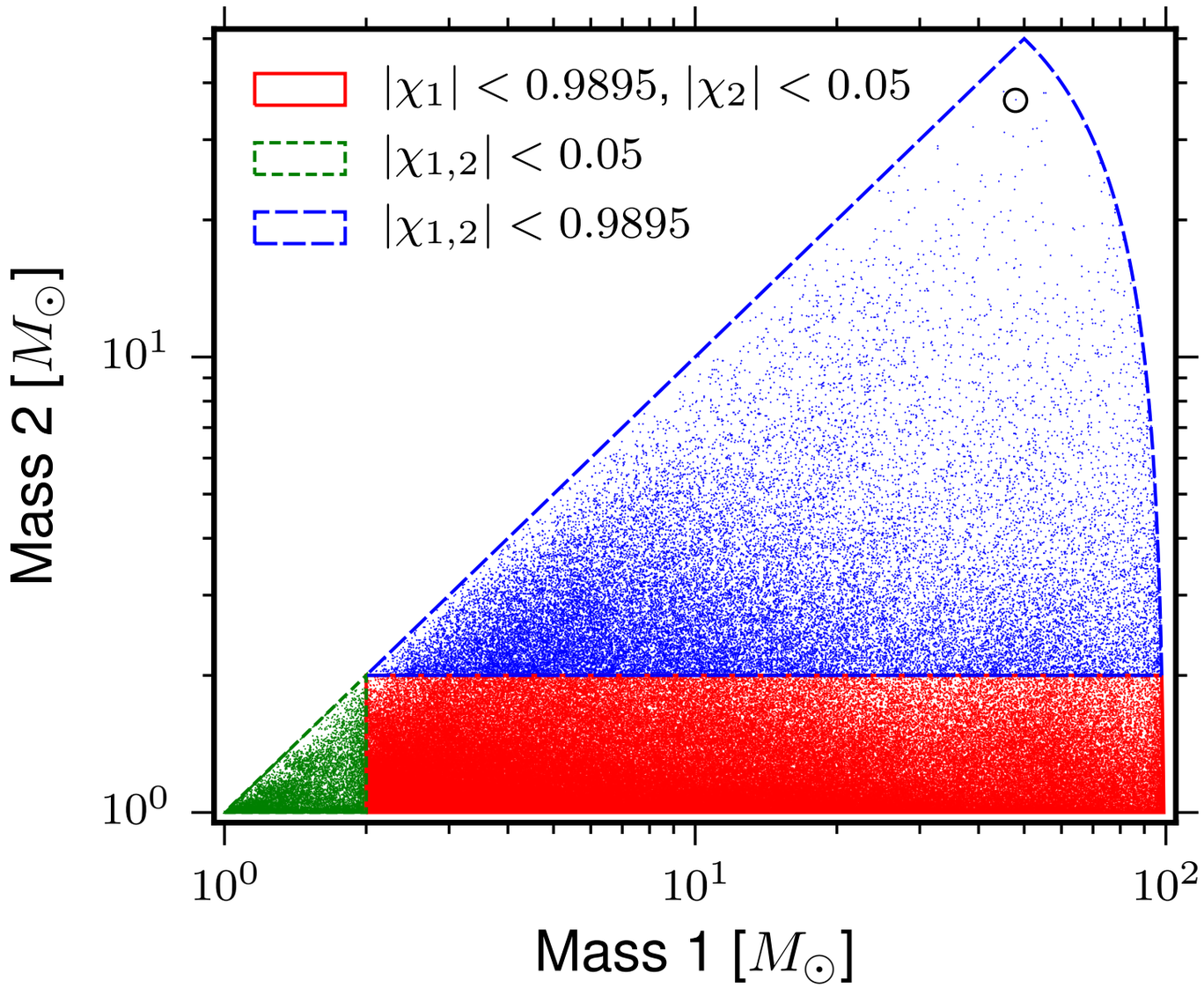


The End/ The Beginning…

How many black hole collisions can we see?



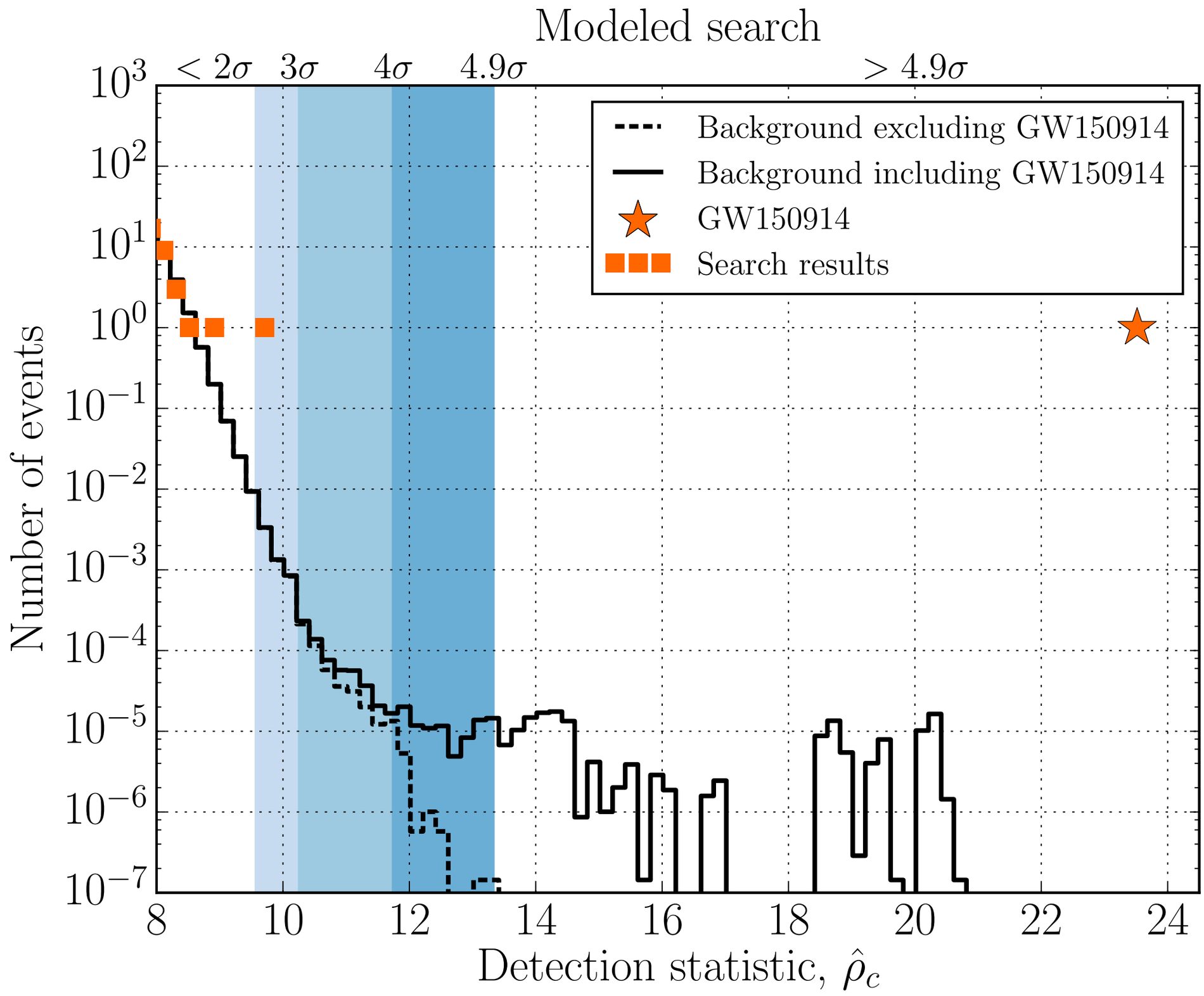
CBC template bank

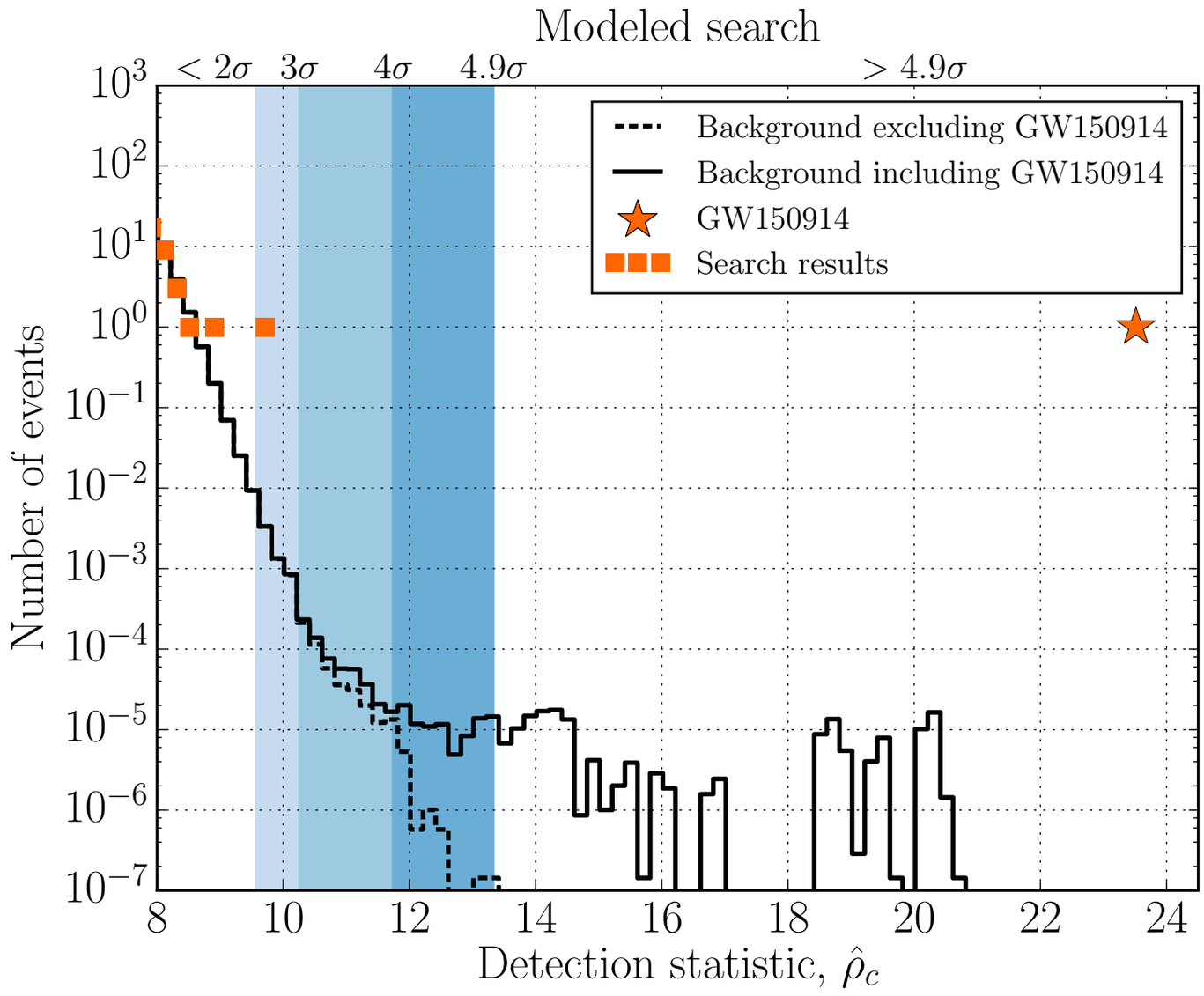


(just at the edge…)

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}