

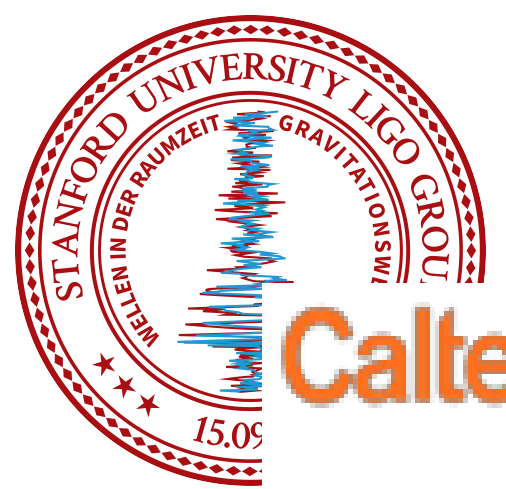


Realtime Control for LIGO, the Laser Interferometer Gravitational-wave Observatory - Lessons from seismic isolation and machine control

Presentation at LLRF26, Nova Gorica, Slovenia

Brian Lantz, for a large team in the LIGO Scientific Collaboration
LIGO-G2602216, 13 October 2026

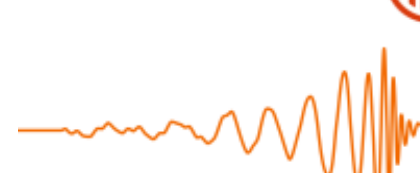
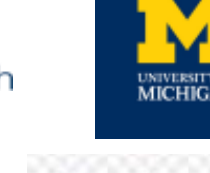
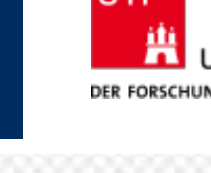
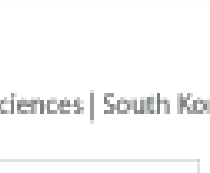


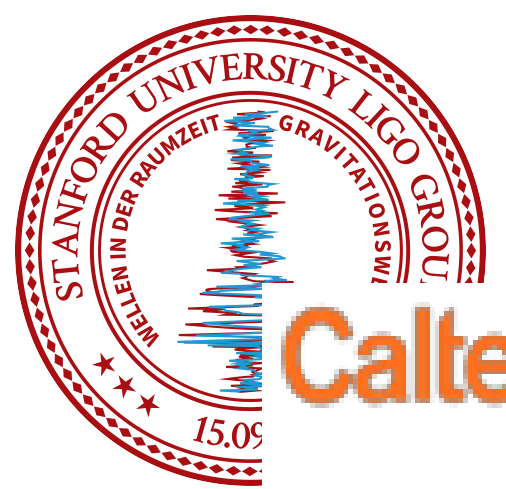


LIGO Scientific Collaboration



Caltech





LIGO Scientific Collaboration

LIGO Detectors are funded by the NSF



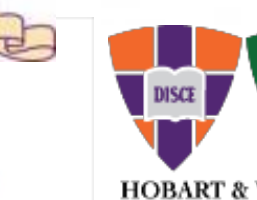






















































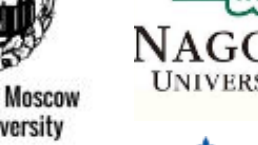


































































































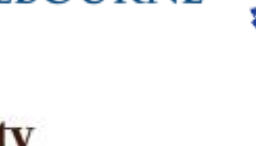




































































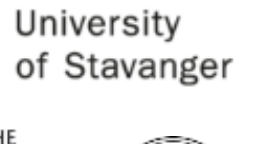


















































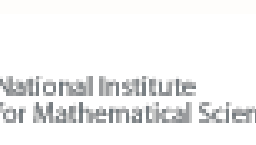










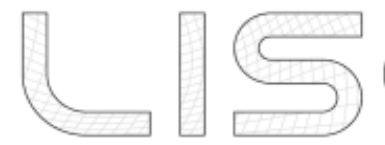
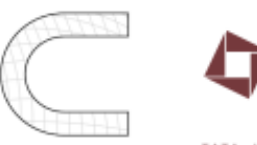





















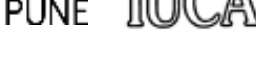














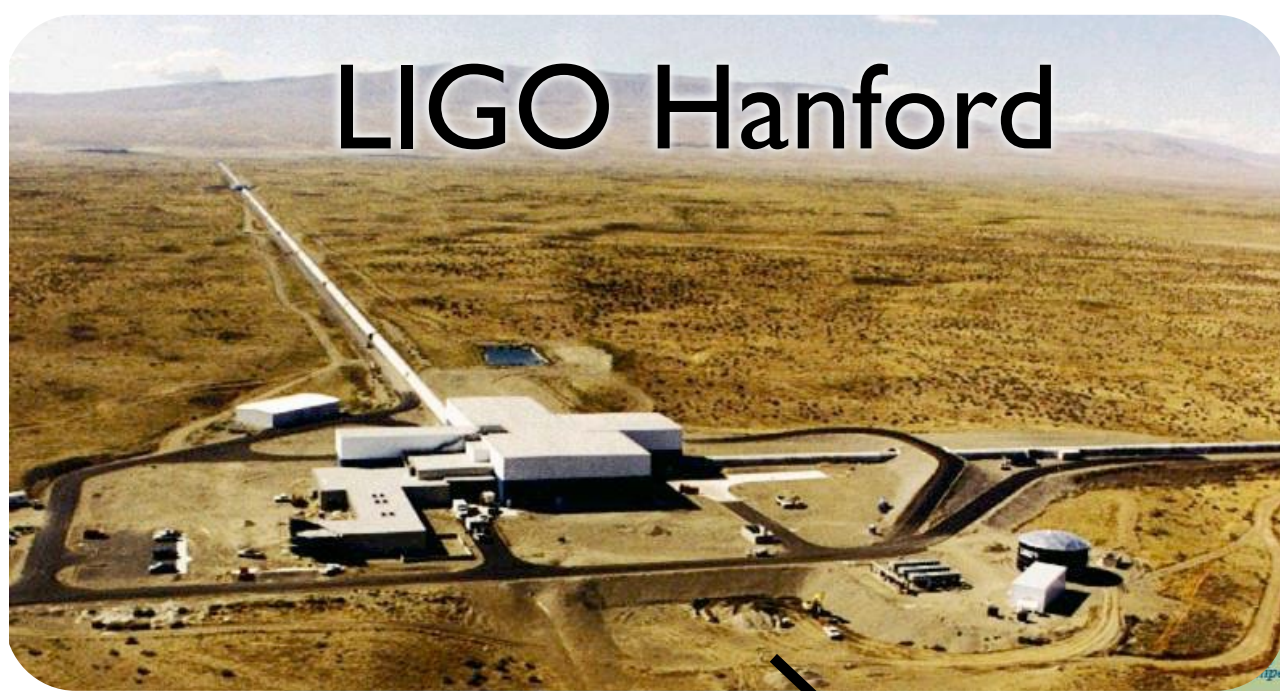








LIGO Hanford



International Network

KAGRA



LIGO Livingston



VIRGO

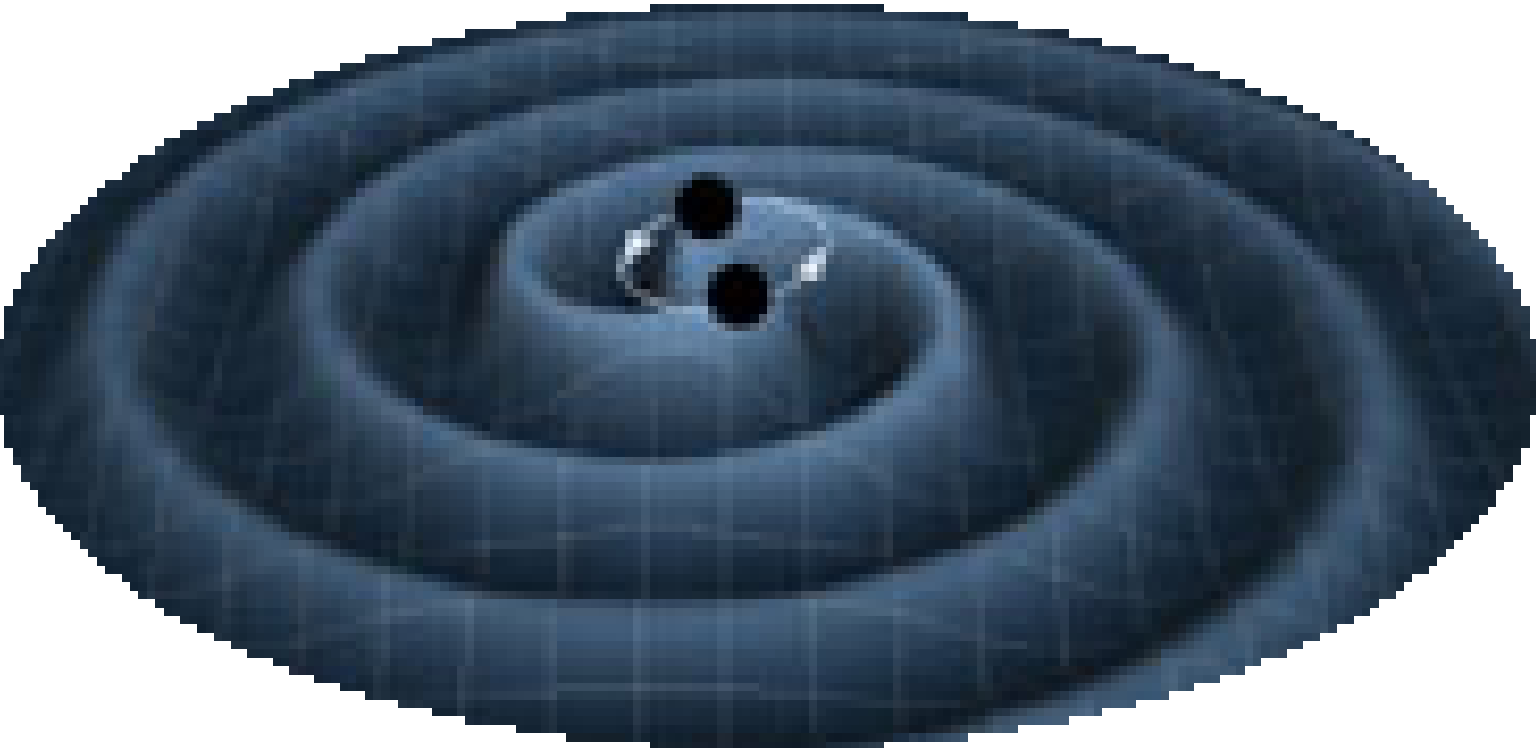


LIGO India



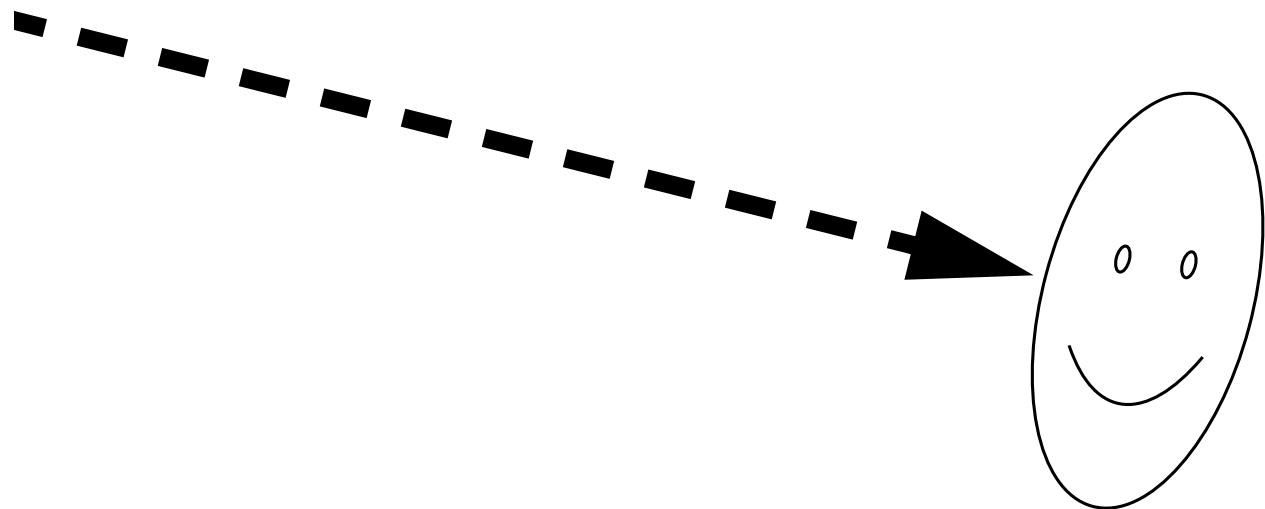
Aundha



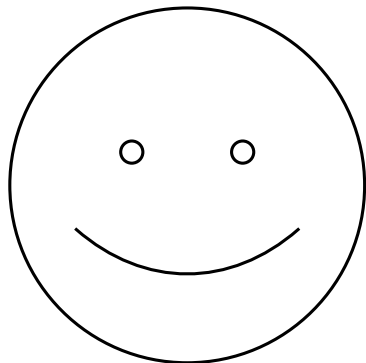


LIGO concept

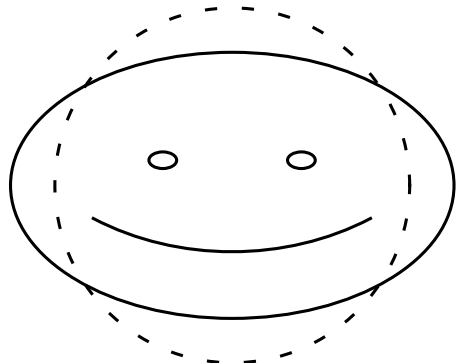
Use an interferometer to do astronomy



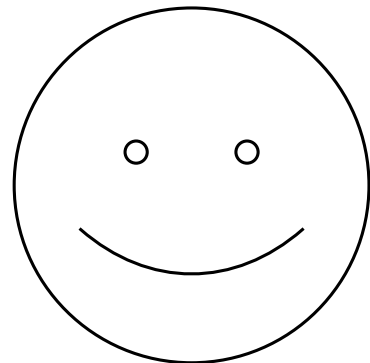
h_+



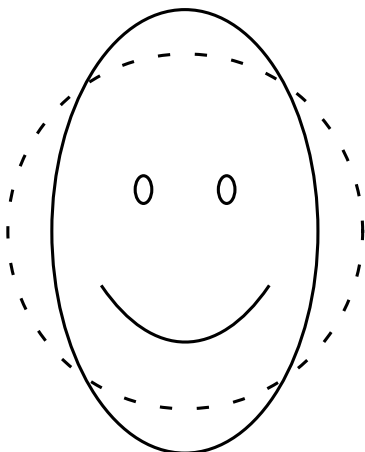
Time = 0



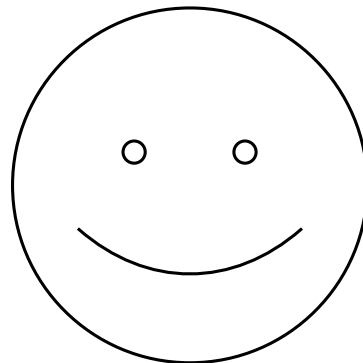
$T = \frac{P}{4}$



$T = \frac{P}{2}$

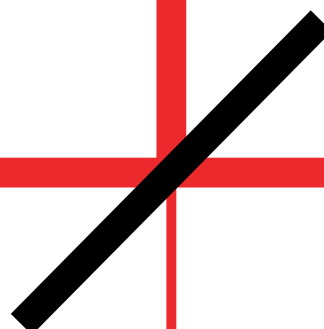


$T = \frac{3P}{4}$



$T = 1 \text{ Period}$

input light



4km arm cavity

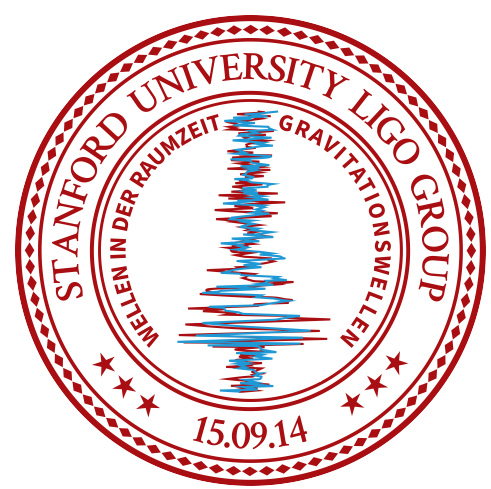


4km arm cavity



output light, containing
gravitational wave signal





First signal GW150914

Initial Masses: $29 (+4/-4) \& 36 (+5/-4) M_{\text{sun}}$

Final Mass: $62 (+4/-4) M_{\text{sun}}$

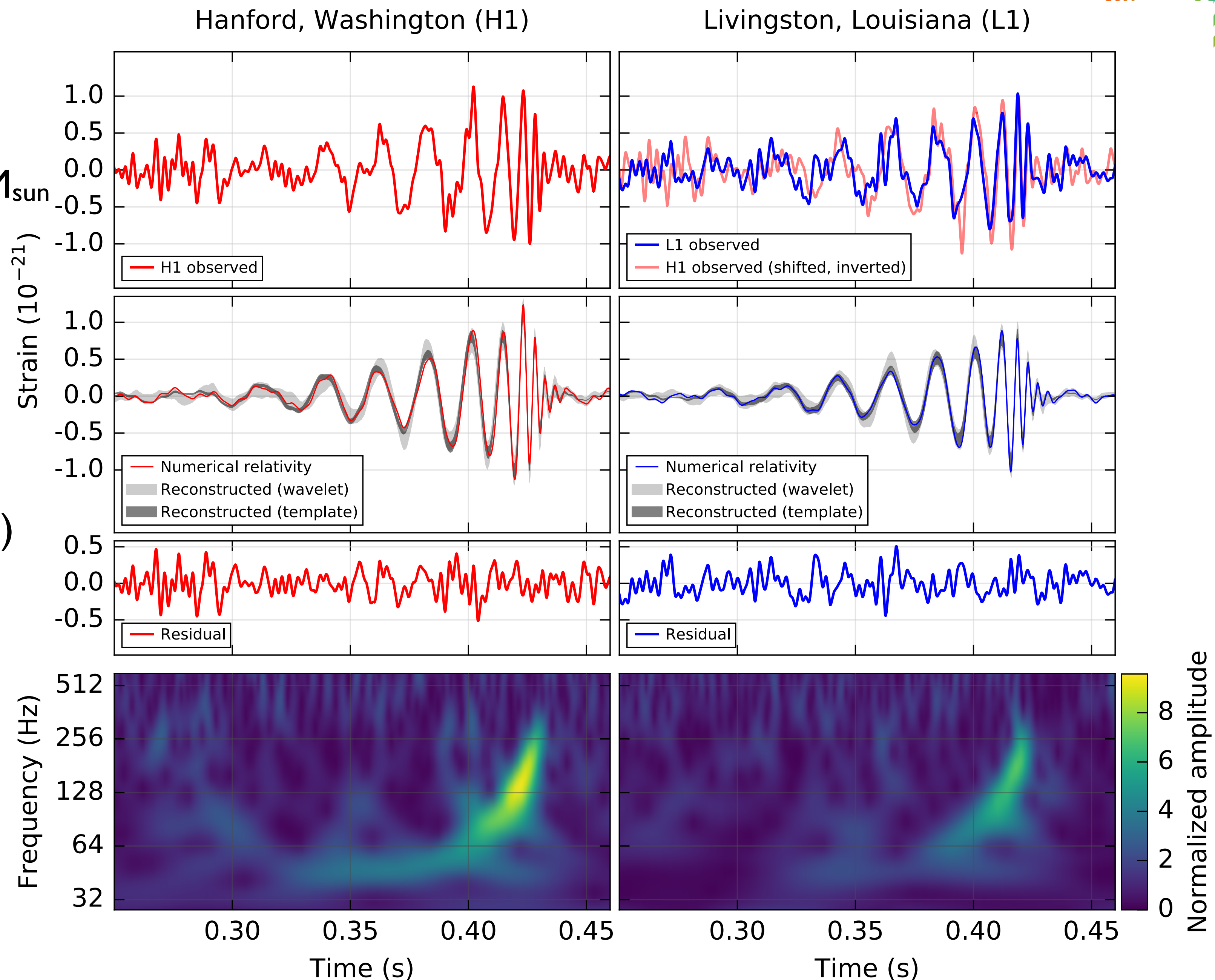
Energy radiated: $3 (+0.5/-0.5) M_{\text{sun}} c^2$

Distance $420 (+160/-180) \text{ MPc}$
(1.3 Billion light years)

Peak amplitude: $\sim 1 \text{e-}21$ strain ($4 \text{e-}18 \text{ m}$)

Freq: in band $\sim 40 \text{ Hz}$, merge $\sim 250 \text{ Hz}$

Arrived in the middle of the night after
commissioning team went home.

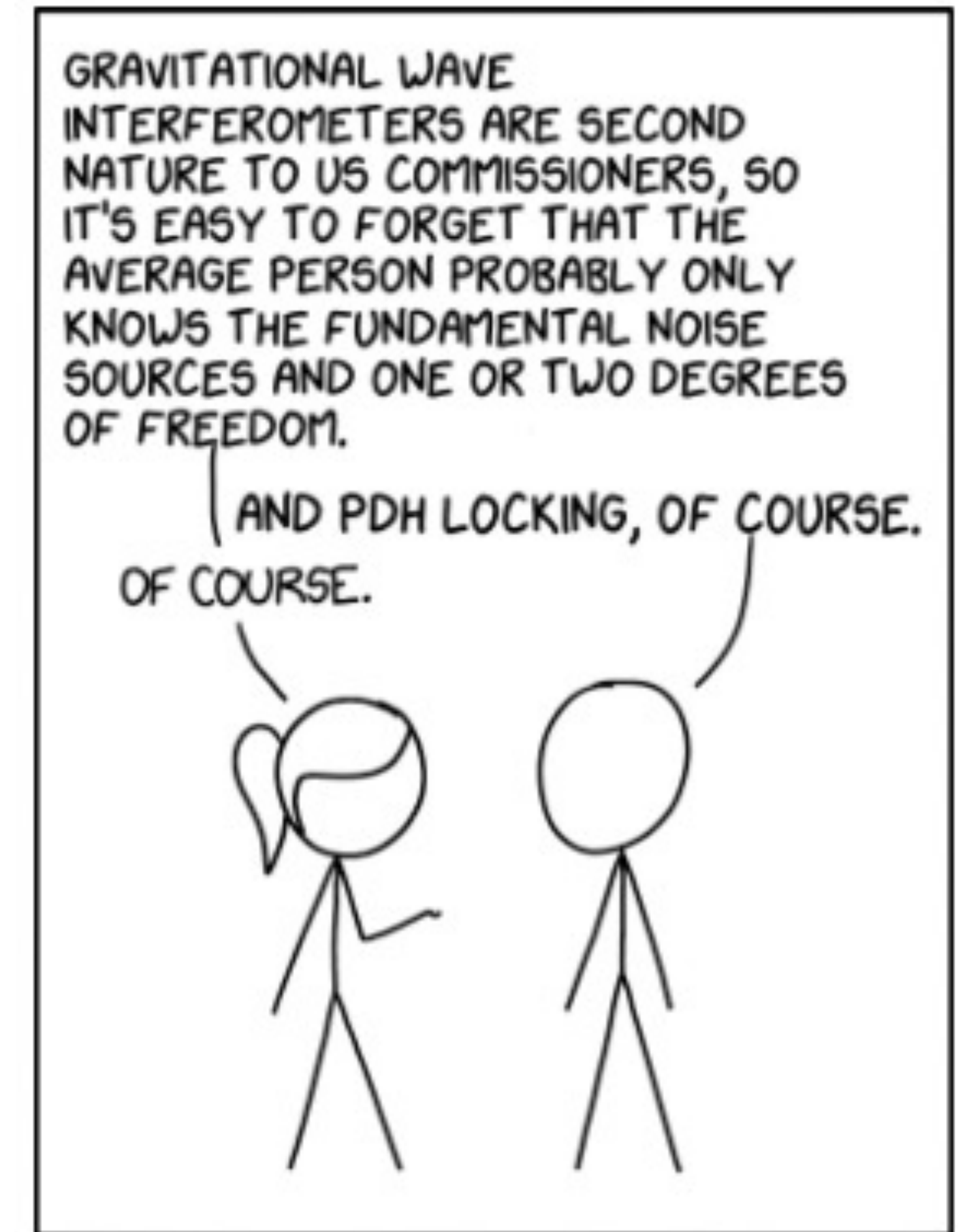




Outline



- LIGO controls talk
- Overview of how the detectors work & why we rely on realtime control
- Detector Improvements from Initial LIGO to now (25 years)
- Intro to the LIGO Control and Data System (CDS)
- Use of control in the Seismic Isolation subsystem
 - flexible
 - multiple sensors and degrees of freedom
 - EPICS/ Guardian for sequencing and automation



EVEN WHEN THEY'RE TRYING TO COMPENSATE FOR IT, EXPERTS IN ANYTHING WILDLY OVERESTIMATE THE AVERAGE PERSON'S FAMILIARITY WITH THEIR FIELD.



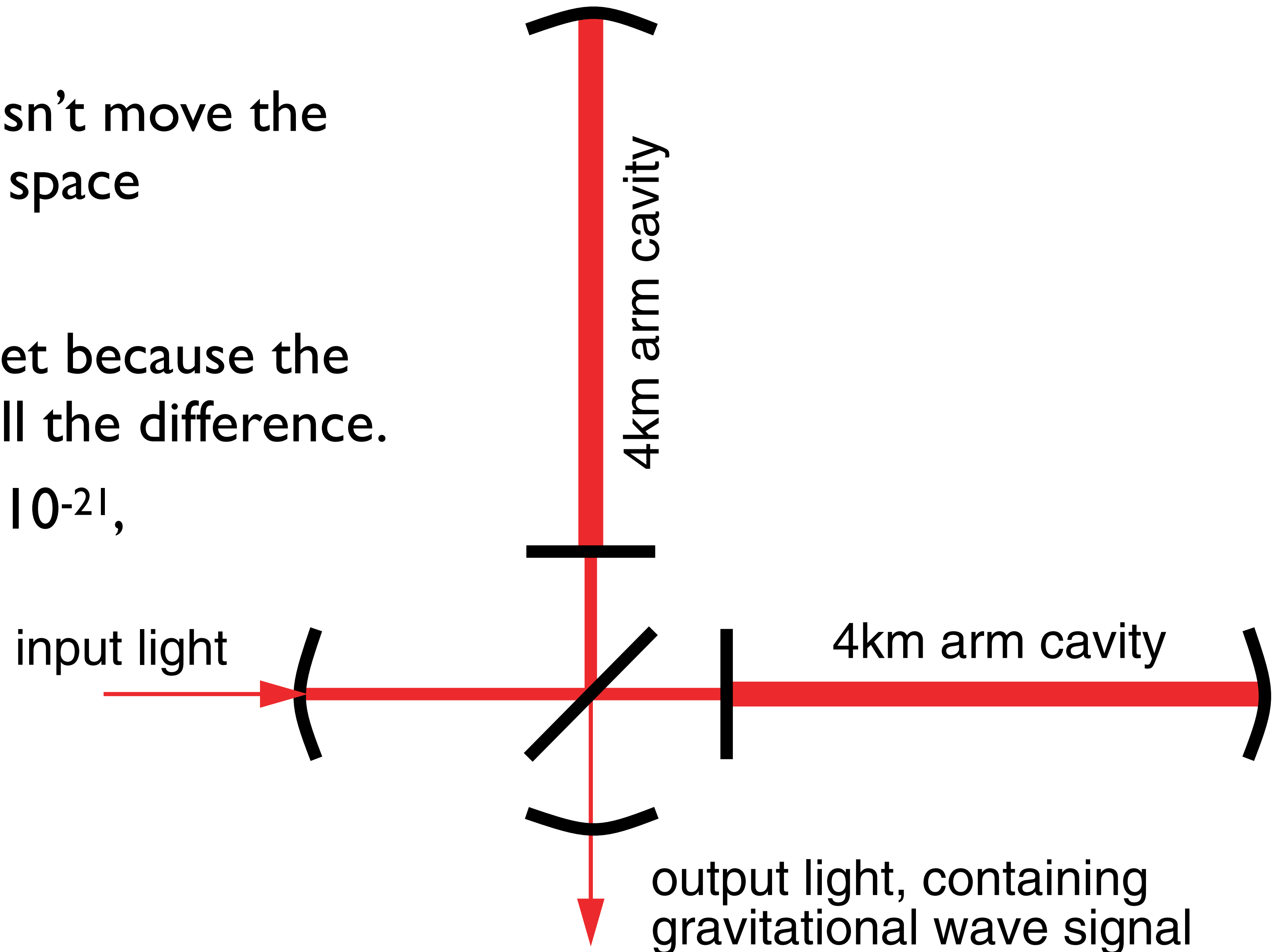
The interferometer needs control

Gravitational wave doesn't move the mirror, it stretches the space

- but -

Mirrors need to be quiet because the interferometer can't tell the difference.

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





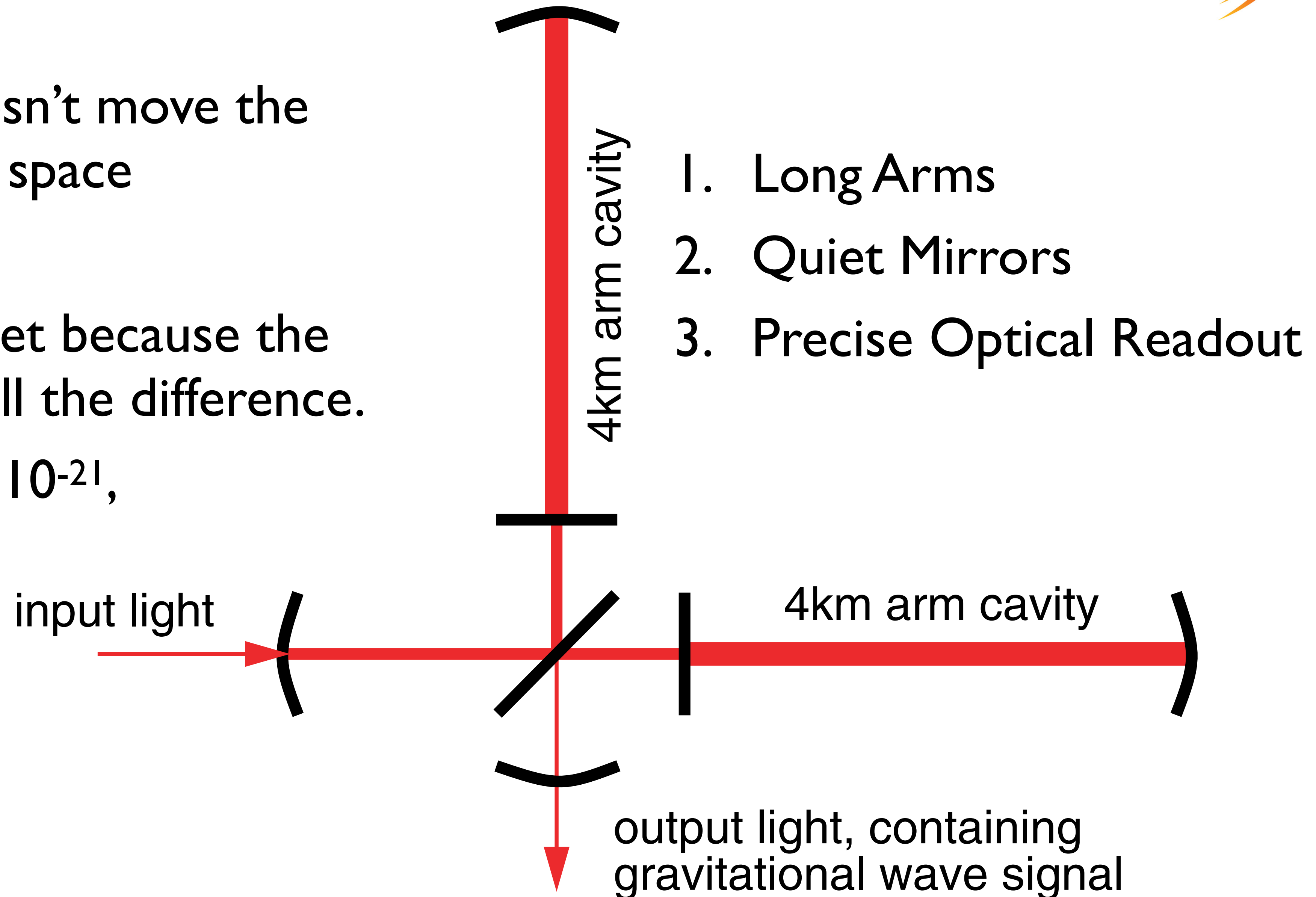
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1. Long Arms
2. Quiet Mirrors
3. Precise Optical Readout

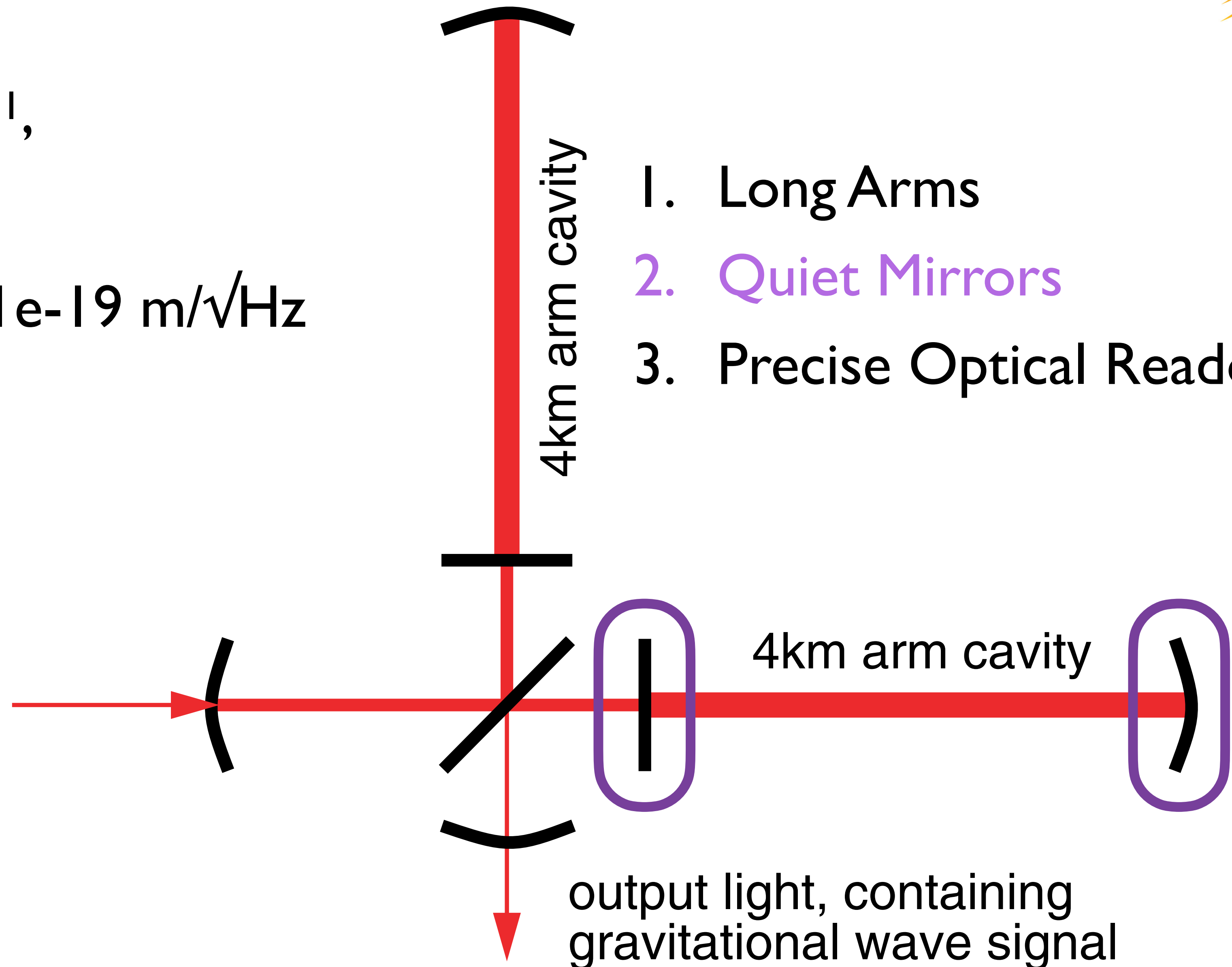


The interferometer needs control

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 $dL = 4 \times 10^{-18}$ meters

Mirror motion at 10 Hz $\sim 1 \text{e-}19 \text{ m}/\sqrt{\text{Hz}}$

1. Long Arms
2. Quiet Mirrors
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The interferometer needs control

Our signal strain (h) = 10^{-21} ,
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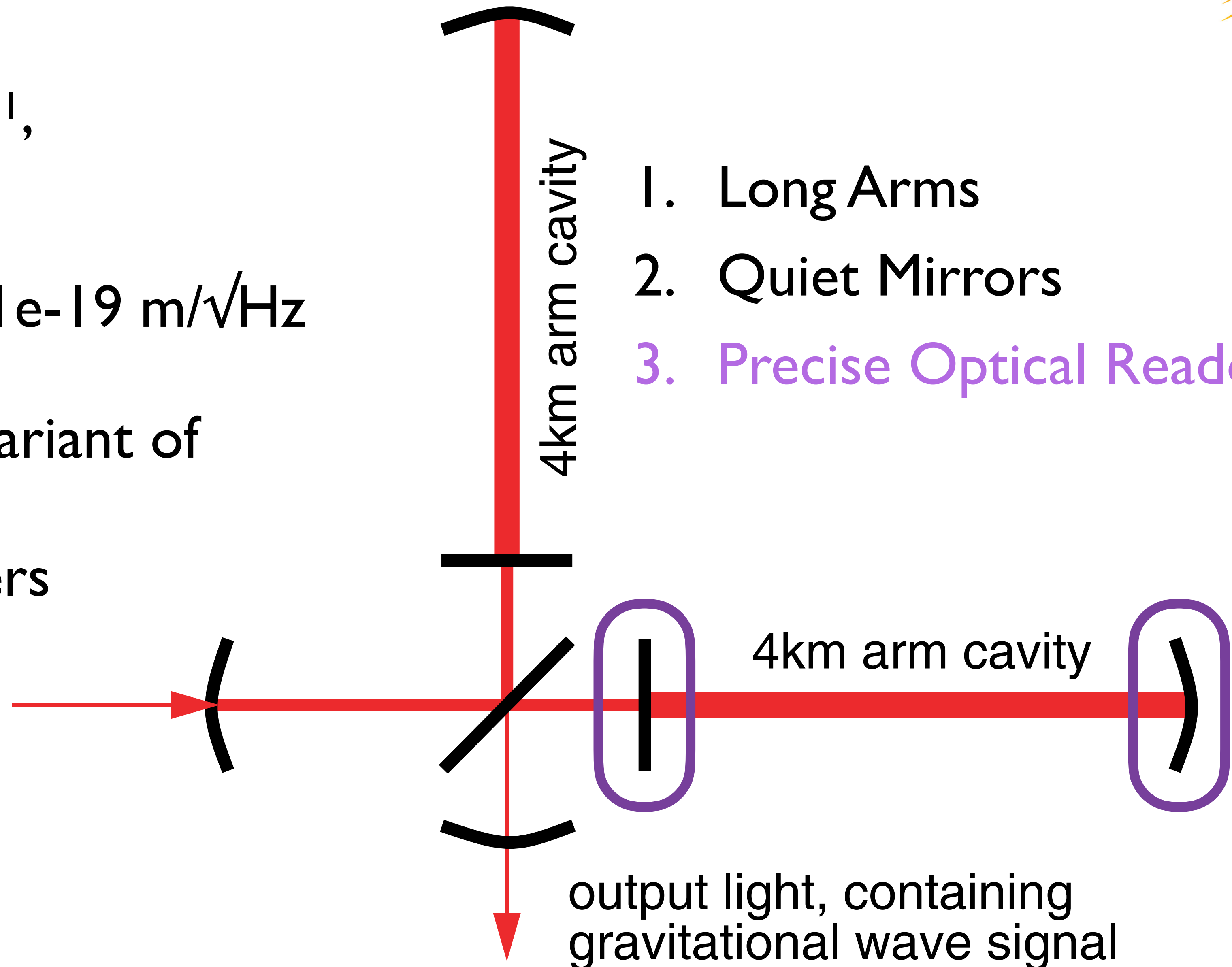
Mirror motion at 10 Hz $\sim 1e-19$ m/ $\sqrt{\text{Hz}}$

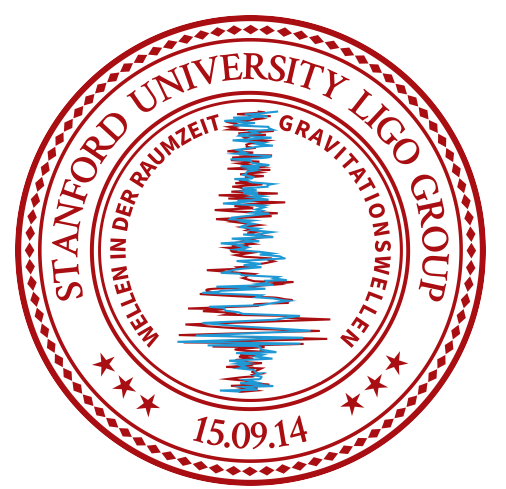
Arm cavity controlled by variant of
Pound-Drever-Hall locking

Length rms $< 1e-14$ meters

angle rms $< 1e-9$ radian

1. Long Arms
2. Quiet Mirrors
3. Precise Optical Readout





advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



R. Bork et. al. DOI: [10.1016/j.softx.2020.100619](https://doi.org/10.1016/j.softx.2020.100619)

- Developed in-house, runs on Linux
- More than 36 control computers running in parallel
- Over 120 “user models”
- Thousands of control loops
- Over 10,000 ‘fast channels’
- Over 300,000 monitors
- Data IO at 65,5366 samples/ sec
- Typically update rate for control is 16,384 cycles/ sec

advligorts: The Advanced LIGO Real-Time Digital Control and Data Acquisition System

Rolf Bork^a, Jonathan Hanks^{b,a}, David Barker^{b,a}, Joseph Betzwieser^{c,a}, Jameson Rollins^a, Keith Thorne^{c,a}, Erik von Reis^{b,a}

^aCalifornia Institute of Technology, Pasadena, CA 91125, USA
^bLIGO Hanford Observatory, Richland, WA 99352, USA
^cLIGO Livingston Observatory, Livingston, LA 70754, USA

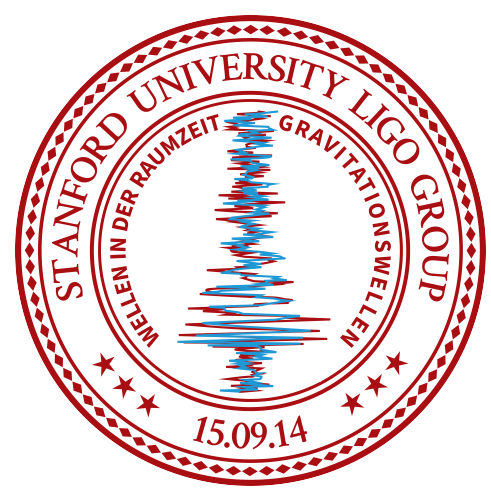
Abstract

The Advanced LIGO detectors are sophisticated opto-mechanical devices. At the core of their operation is feedback control. The Advanced LIGO project developed a custom digital control and data acquisition system to handle the unique needs of this new breed of astronomical detector. The **advligorts** is the software component of this system. This highly modular and extensible system has enabled the unprecedented performance of the LIGO instruments, and has been a vital component in the direct detection of gravitational waves.

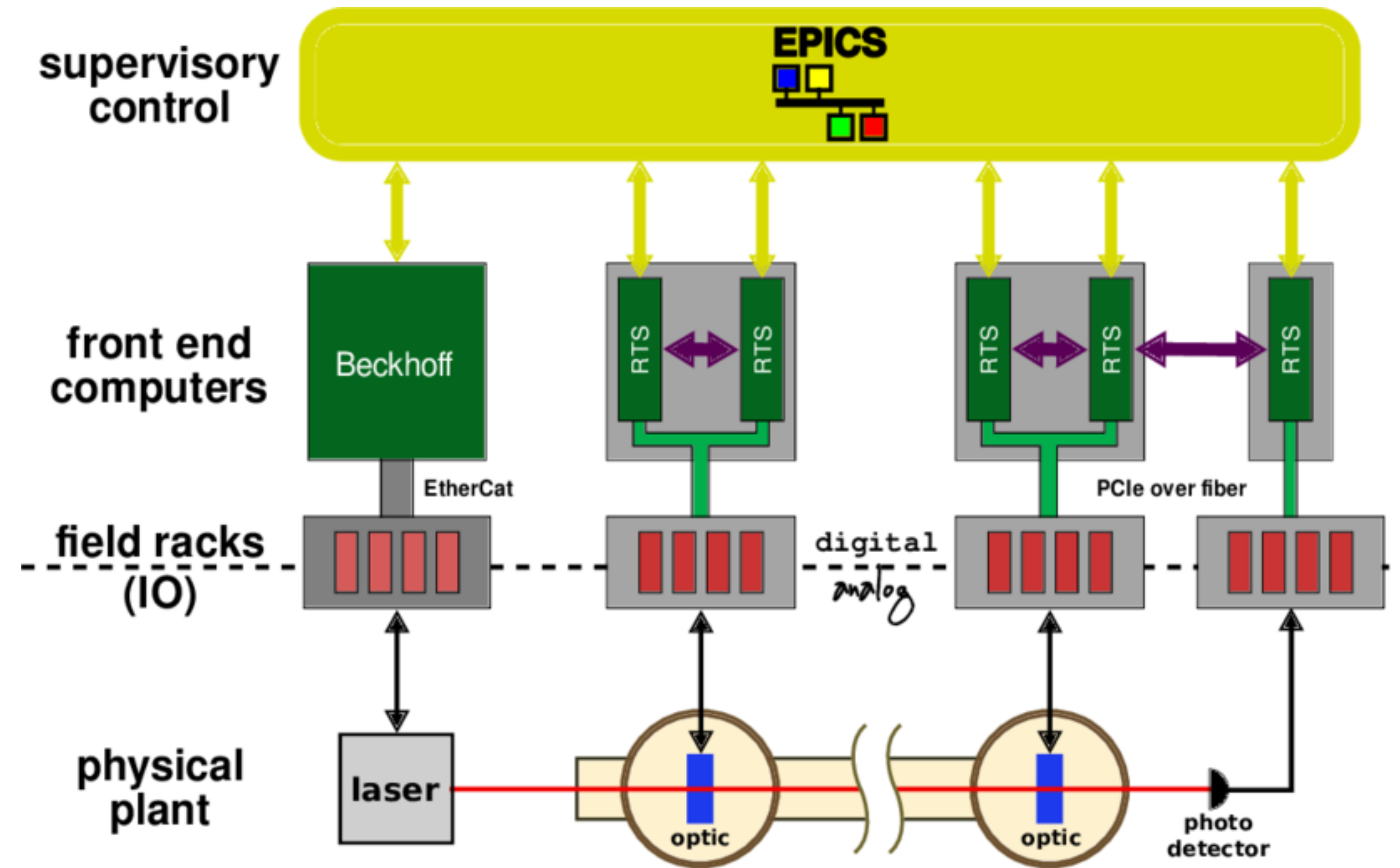
Keywords:
real-time processing, feedback control, hardware control, data acquisition

Nr.	Code metadata	
C1	Current code version	4.0~pre
C2	Permanent link to code/repository used for this code version	https://git.ligo.org/cds/advligorts
C3	Code Ocean compute capsule	n/a
C4	Legal Code License	GPLv3
C5	Code versioning system	git
C6	Software code languages, required tools and services	C/C++, Perl, Python
C7	Compilation requirements, operating environments	C99, Linux OS
C8	Developer documentation/manual	https://dcc.ligo.org/LIGO-E1200653
C9	Support email	jameson.rollins@ligo.org

Table 1: Code metadata

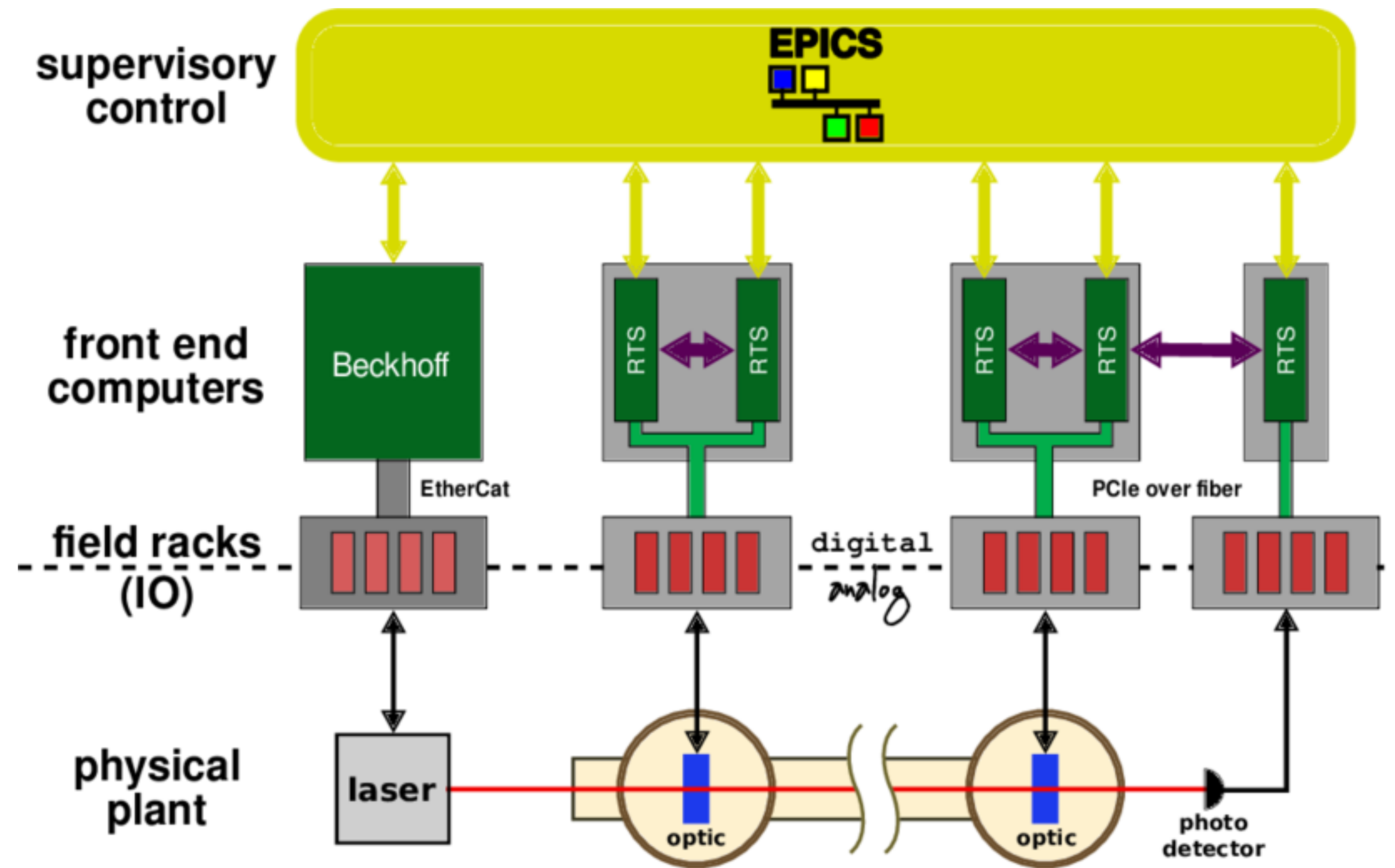


advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)





advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



Divide up the detector into pieces
(a mirror suspension, a seismic isolation
table, interferometer readouts)

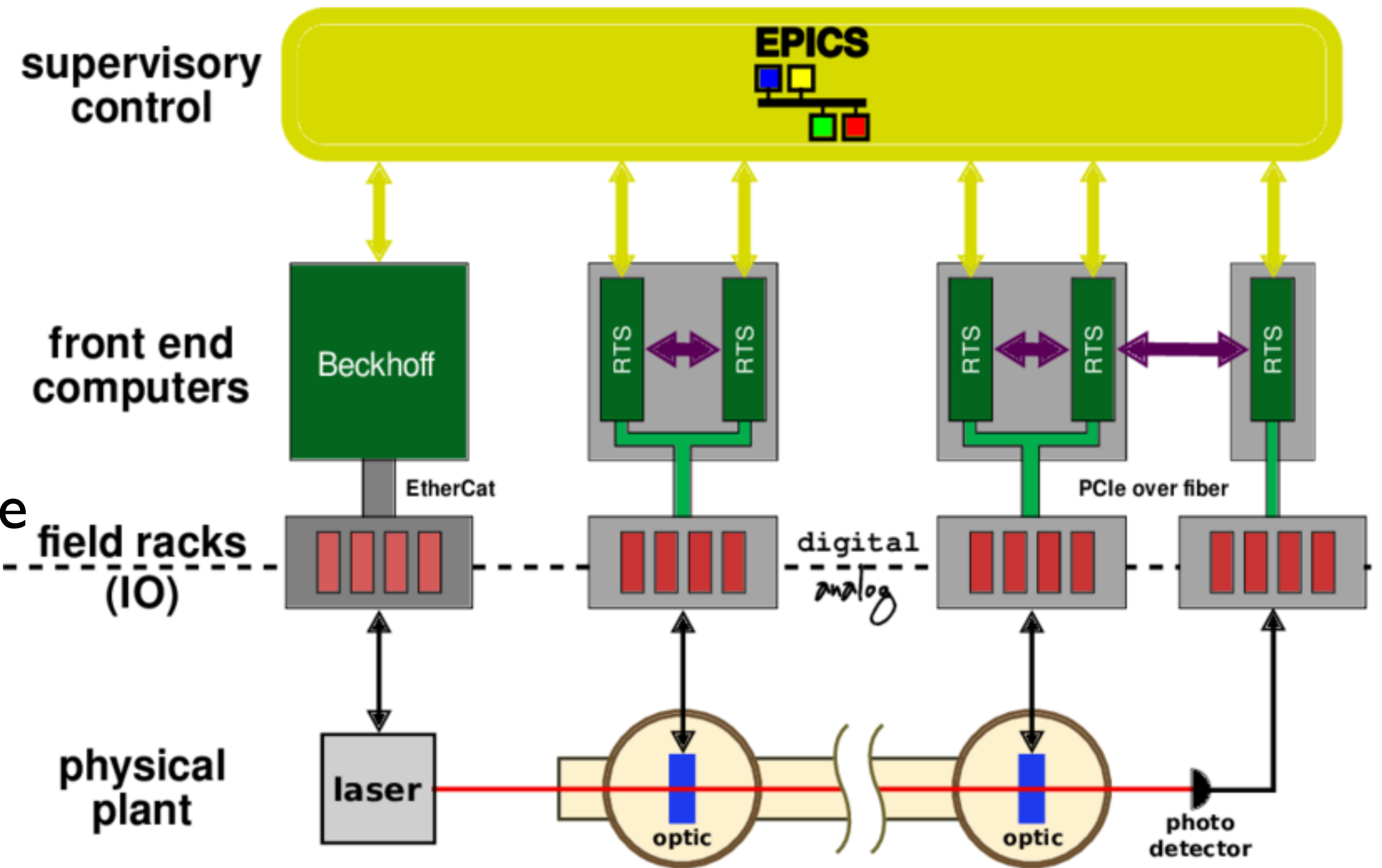


advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



Dedicate 1 core of linux computer as the Real Time System controlling that piece.
It runs a “control model”

Divide up the detector into pieces
(a mirror suspension, a seismic isolation table, interferometer readouts





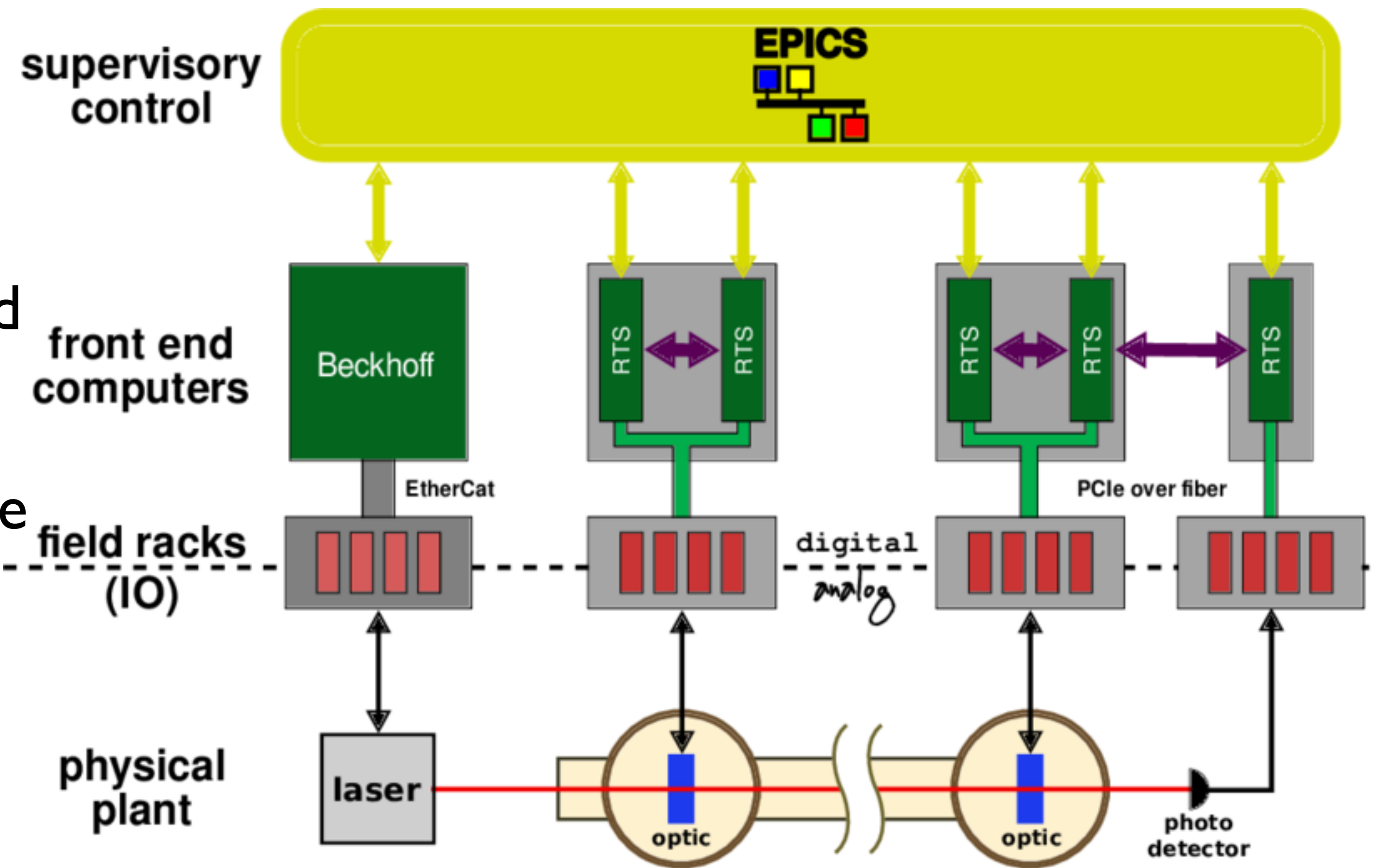
advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



RTS communicate with ADCs, DACs, and other RTS models at high speed

Dedicate 1 core of linux computer as the Real Time System controlling that piece.
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Divide up the detector into pieces
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advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)

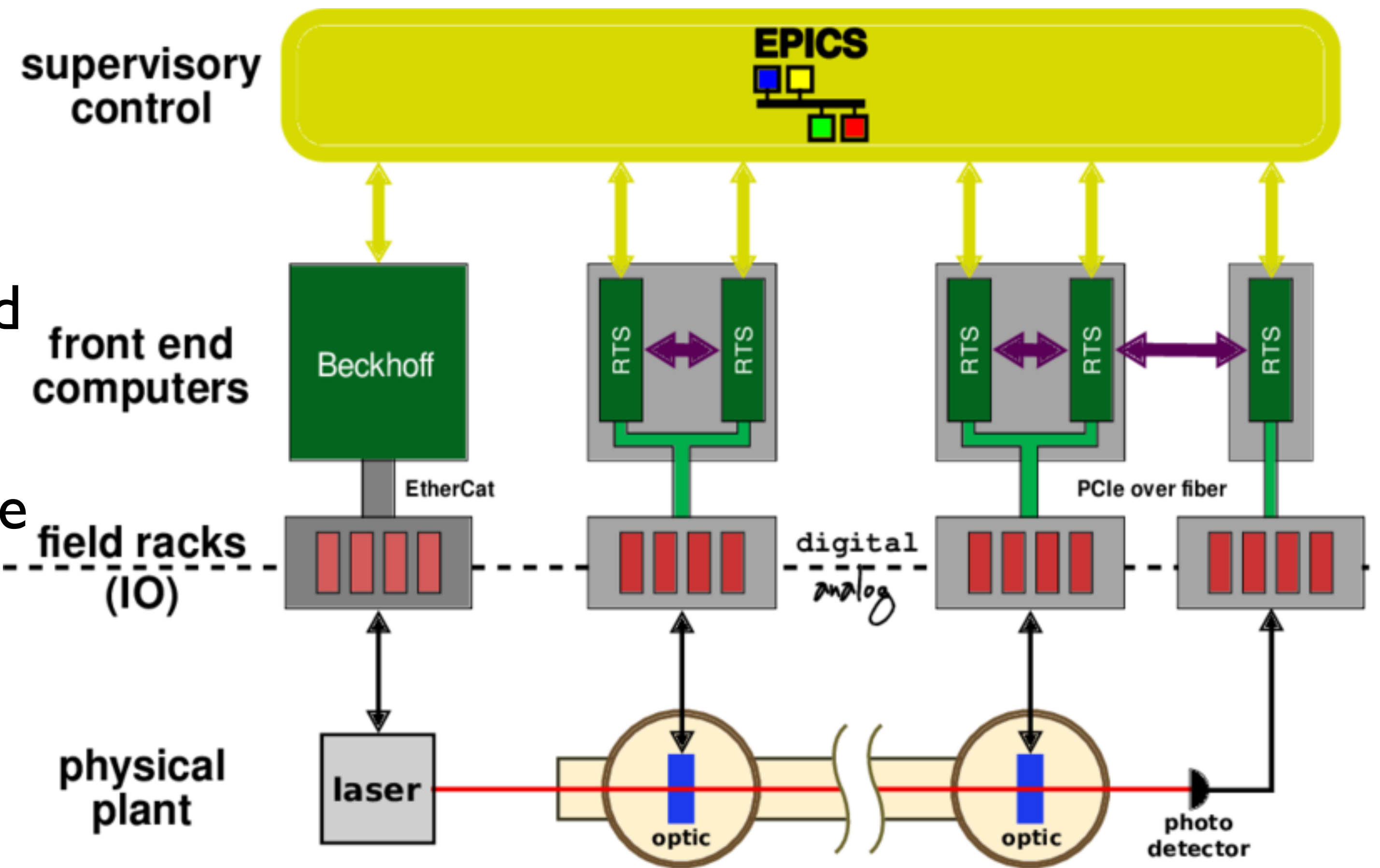


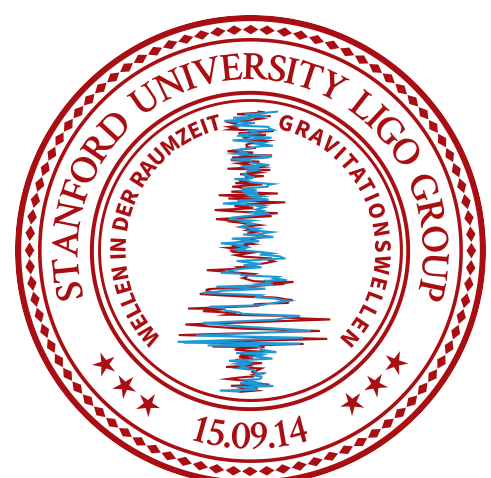
EPICS is used as the supervisory level

RTS communicate with ADCs, DACs, and other RTS models at high speed

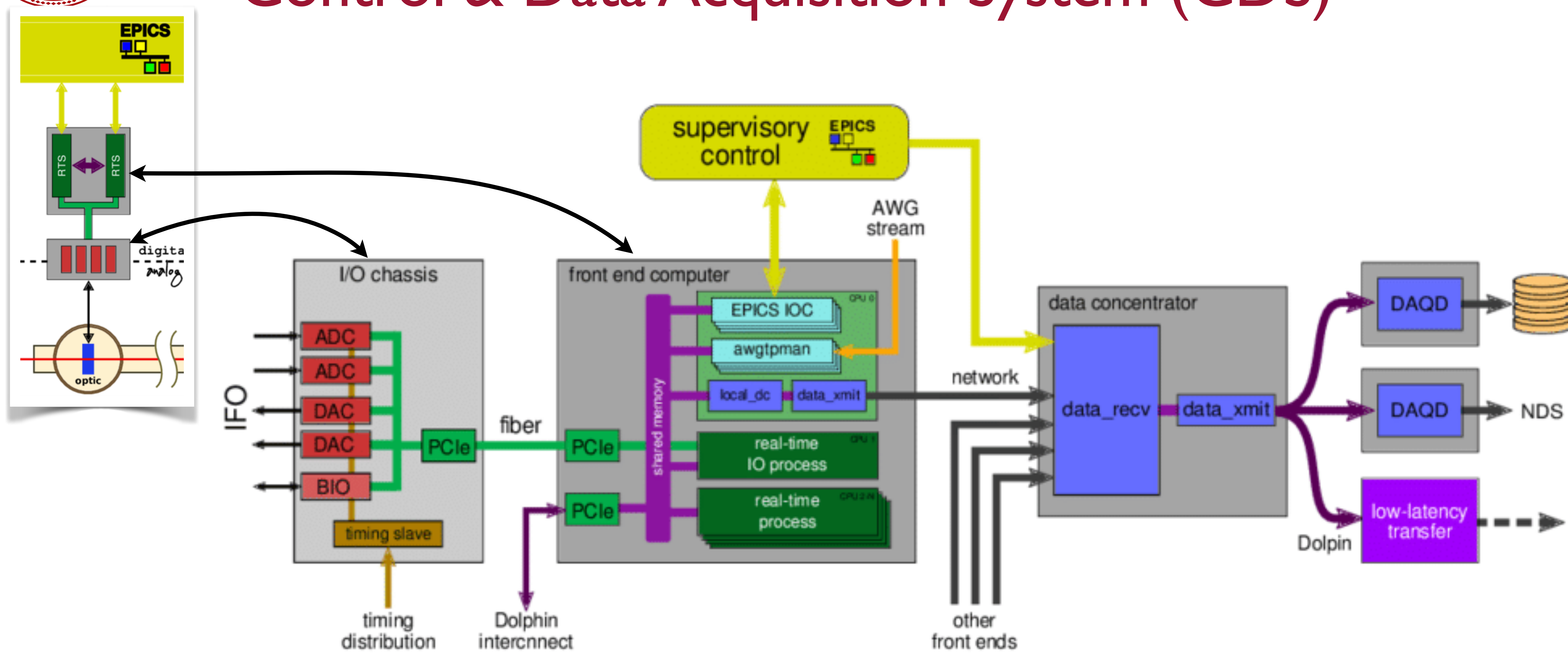
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Divide up the detector into pieces
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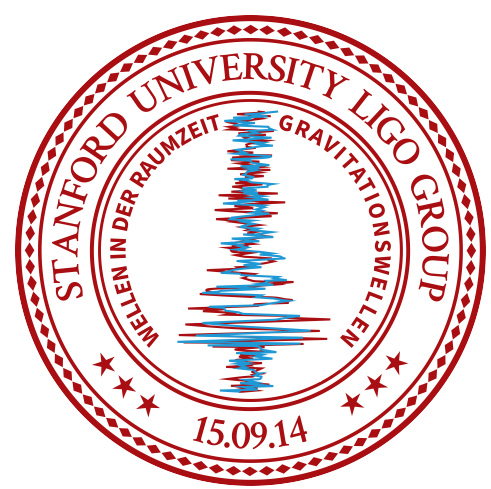


advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



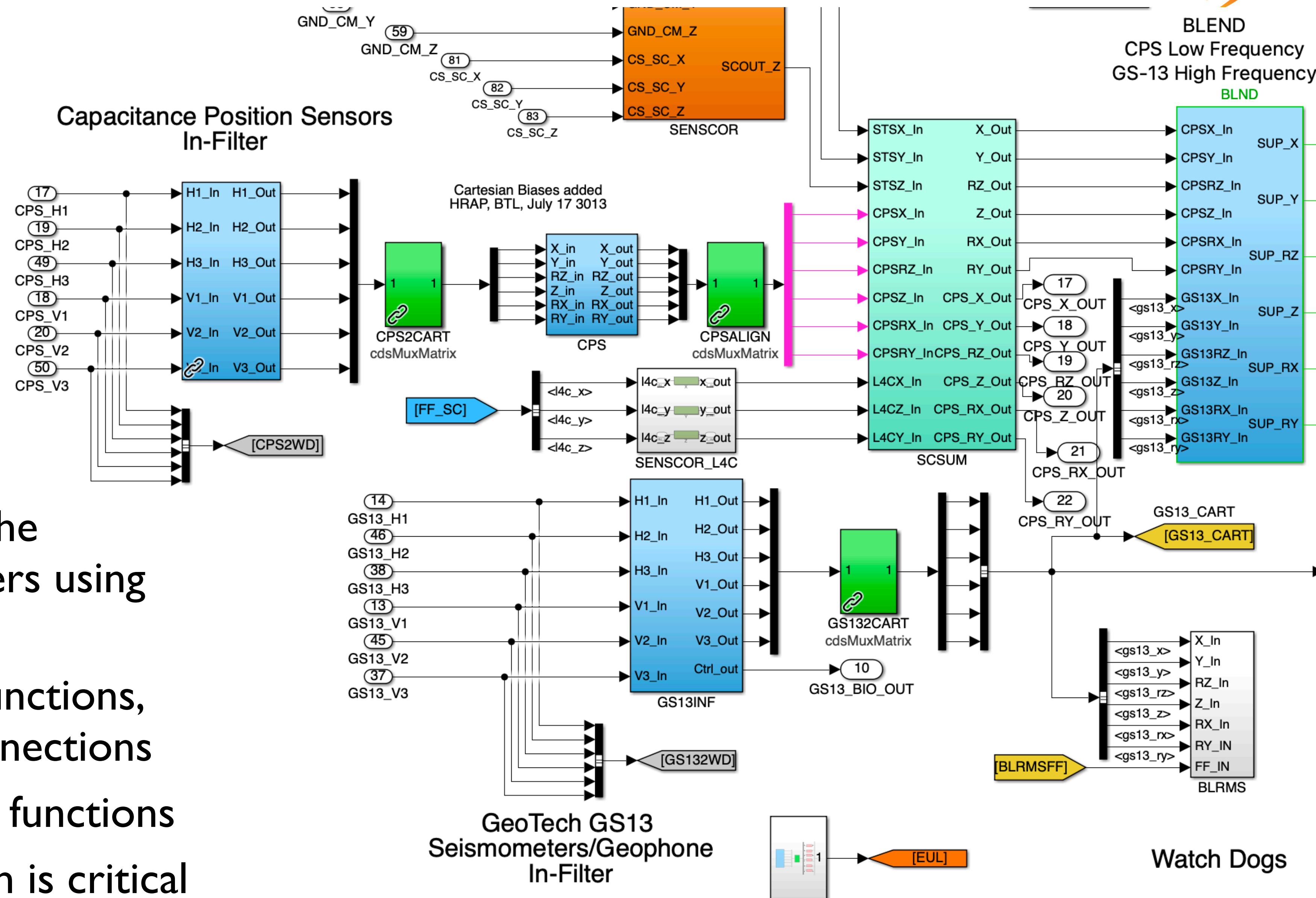
Single timing system

Data system combines all data streams



Control model

Excerpt of the HAM-ISI model



Control models developed by the operators & hardware developers using Simulink.

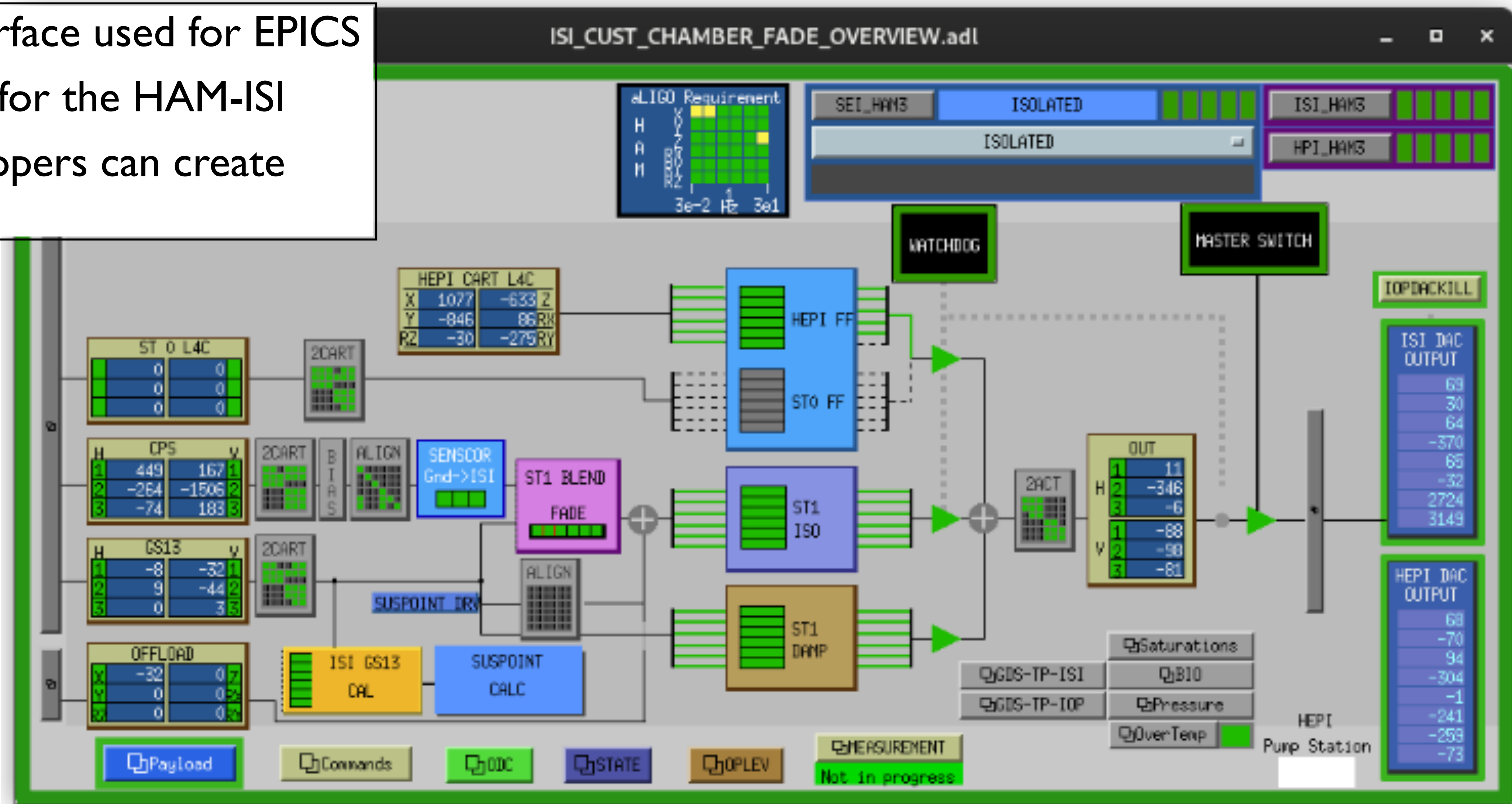
Lots of standard parts - math functions, filters, matrices, data ports/ connections

Custom C parts for new/ novel functions

Models can be big - visual design is critical

User Interface

MEDM is the interface used for EPICS
Overview screen for the HAM-ISI
Operators/ developers can create
interface screens

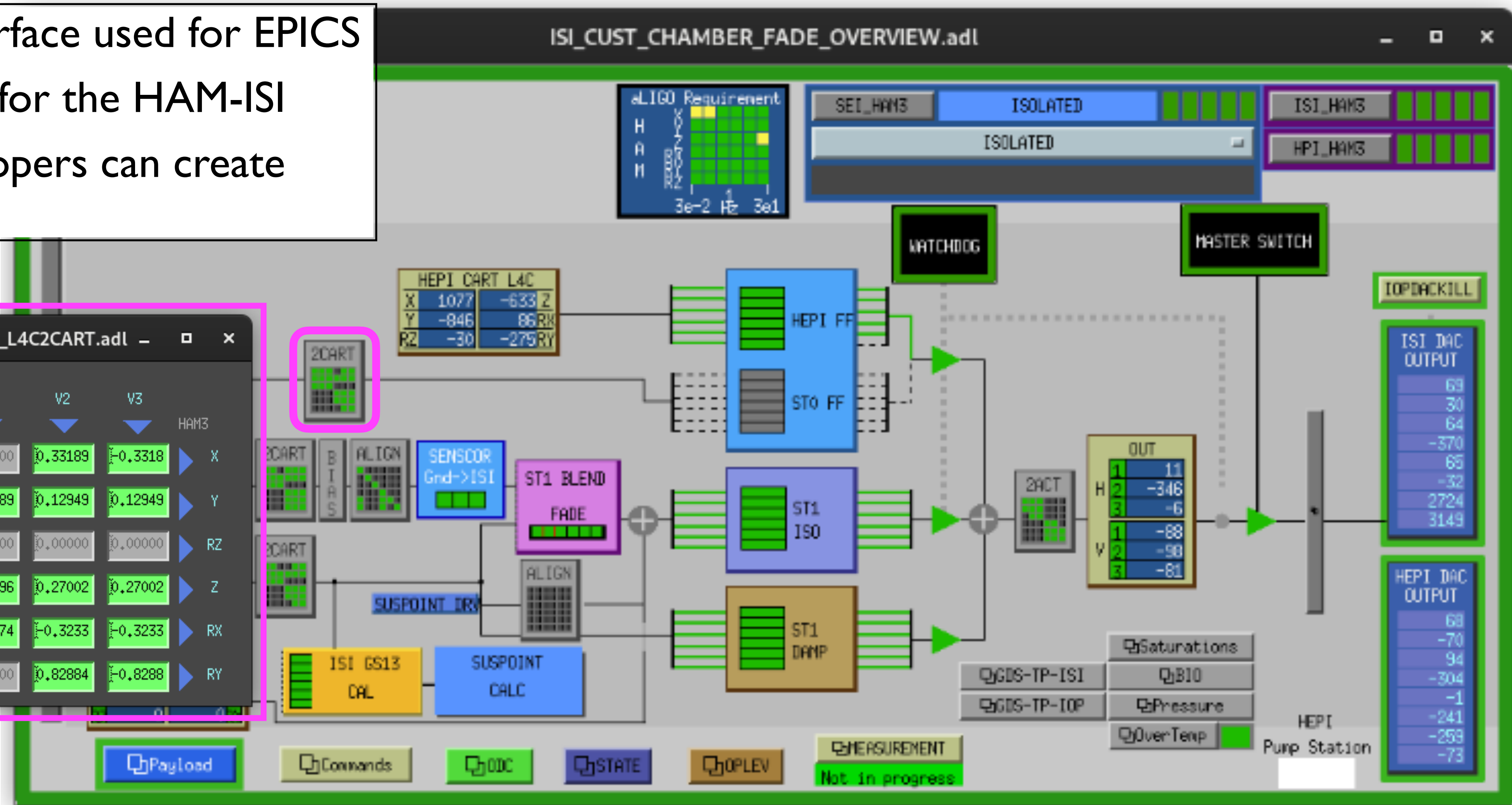


User Interface

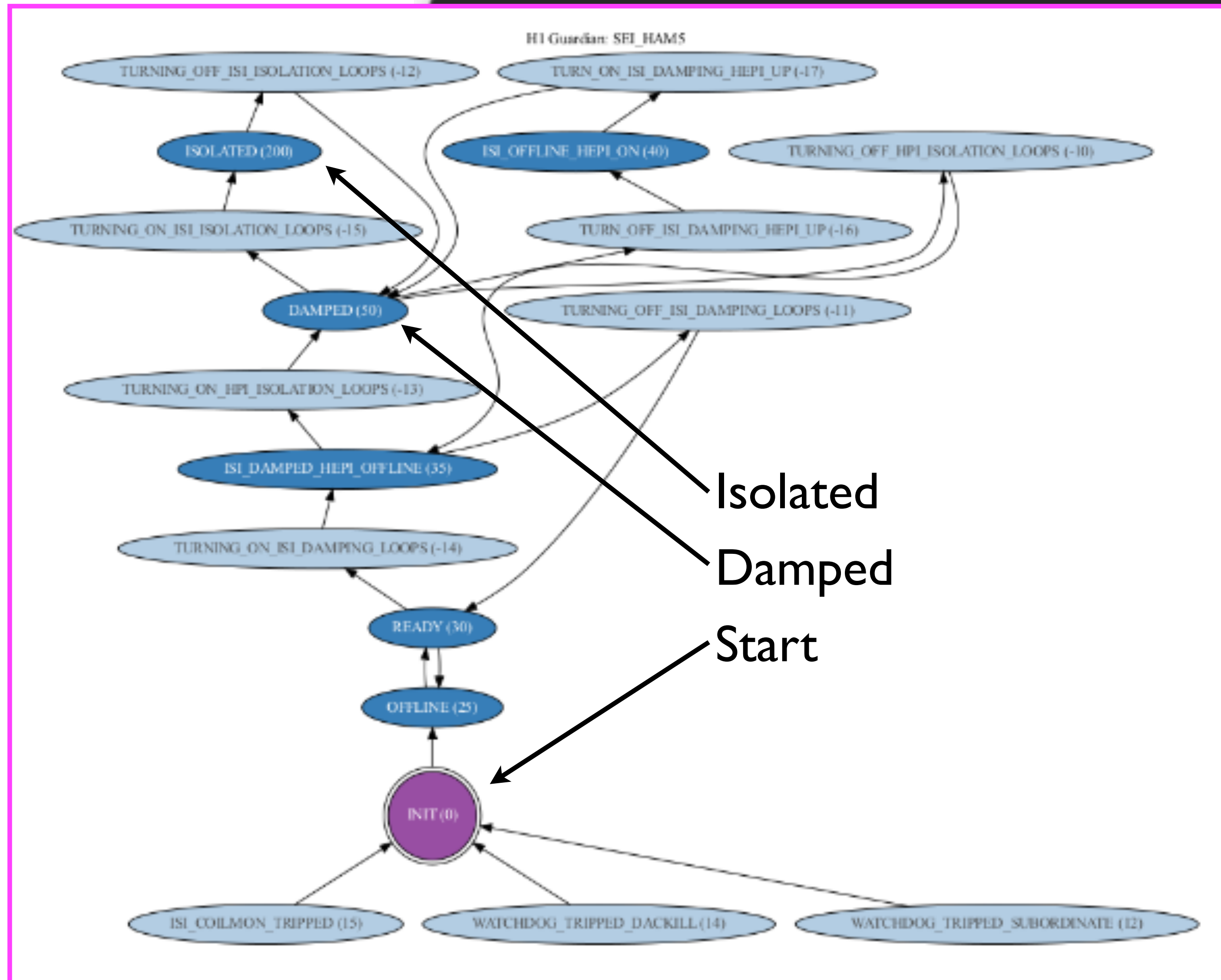
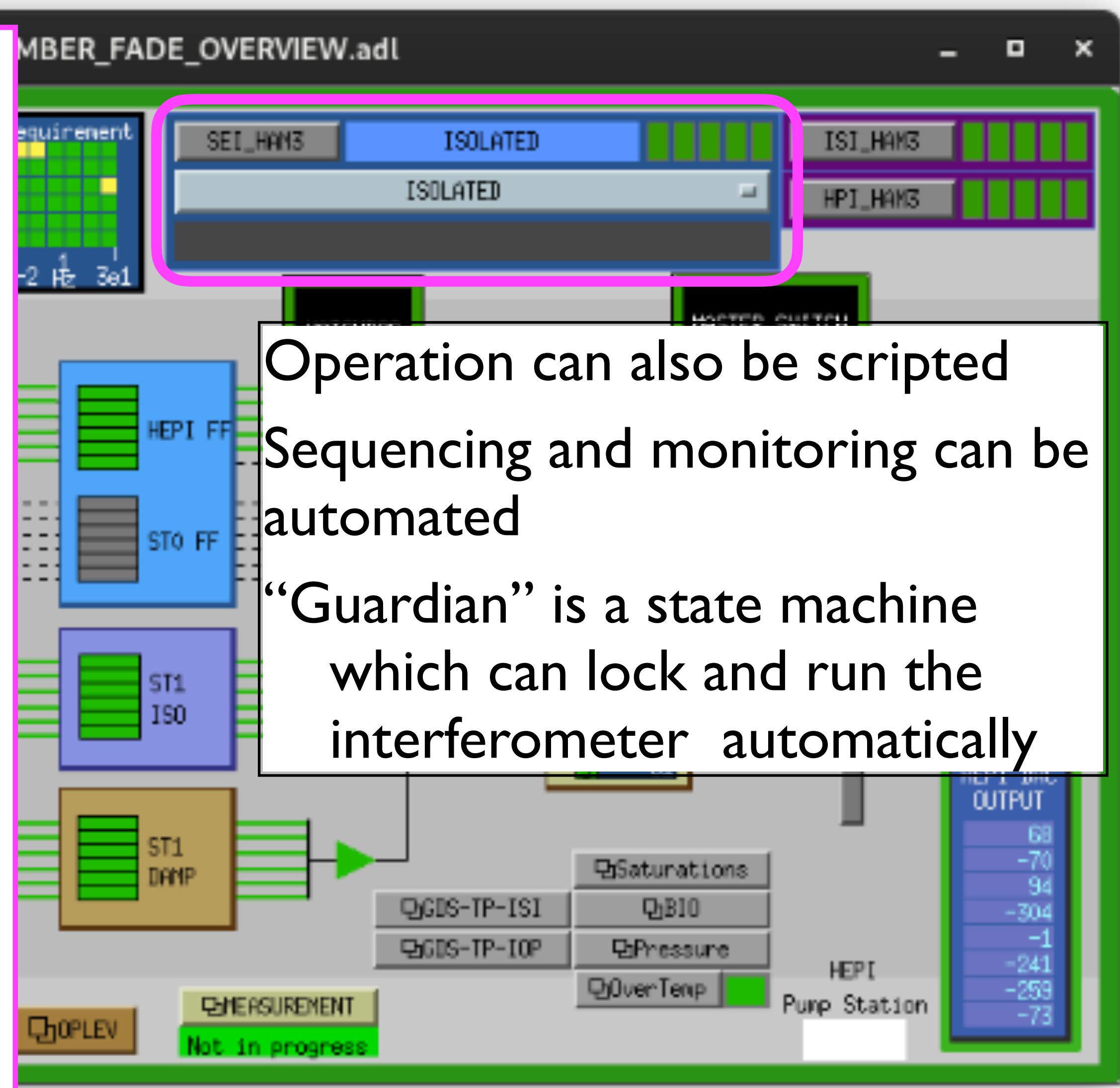
MEDM is the interface used for EPICS
Overview screen for the HAM-ISI
Operators/ developers can create
interface screens

ISI_CUST_CHAMBER_L4C2CART.adl

H1	H2	H3	V1	V2	V3		HAM3
0.63581	-0.4915	-0.1442	0.00000	0.33189	-0.3318	X	
0.20047	0.45039	-0.6508	-0.2589	0.12949	0.12949	Y	
-0.6561	-0.6561	-0.6561	0.00000	0.00000	0.00000	RZ	
0.00000	0.00000	0.00000	0.45996	0.27002	0.27002	Z	
0.00000	0.00000	0.00000	0.64674	-0.3233	-0.3233	RX	
0.00000	0.00000	0.00000	0.00000	0.82884	-0.8288	RY	



Guardian



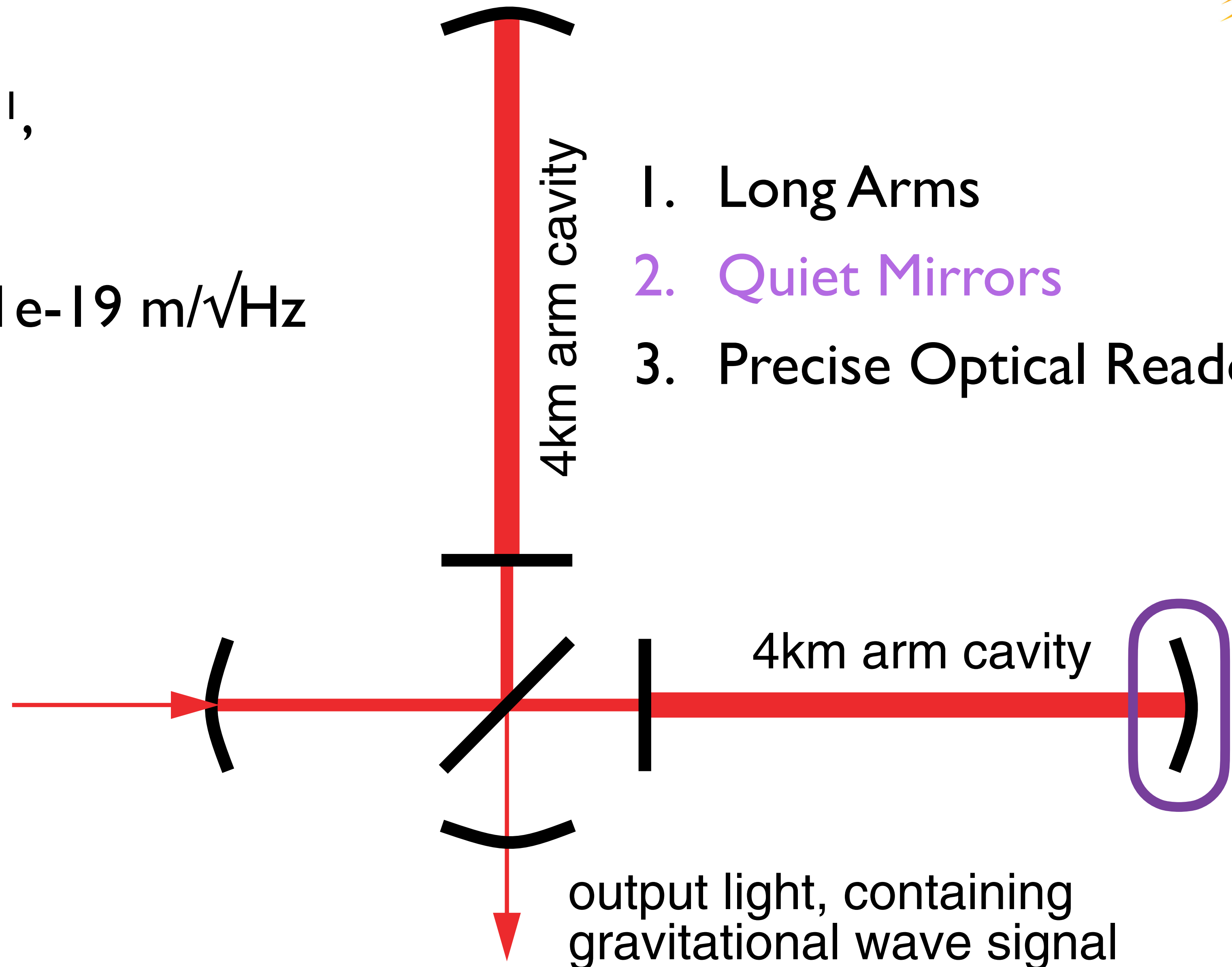


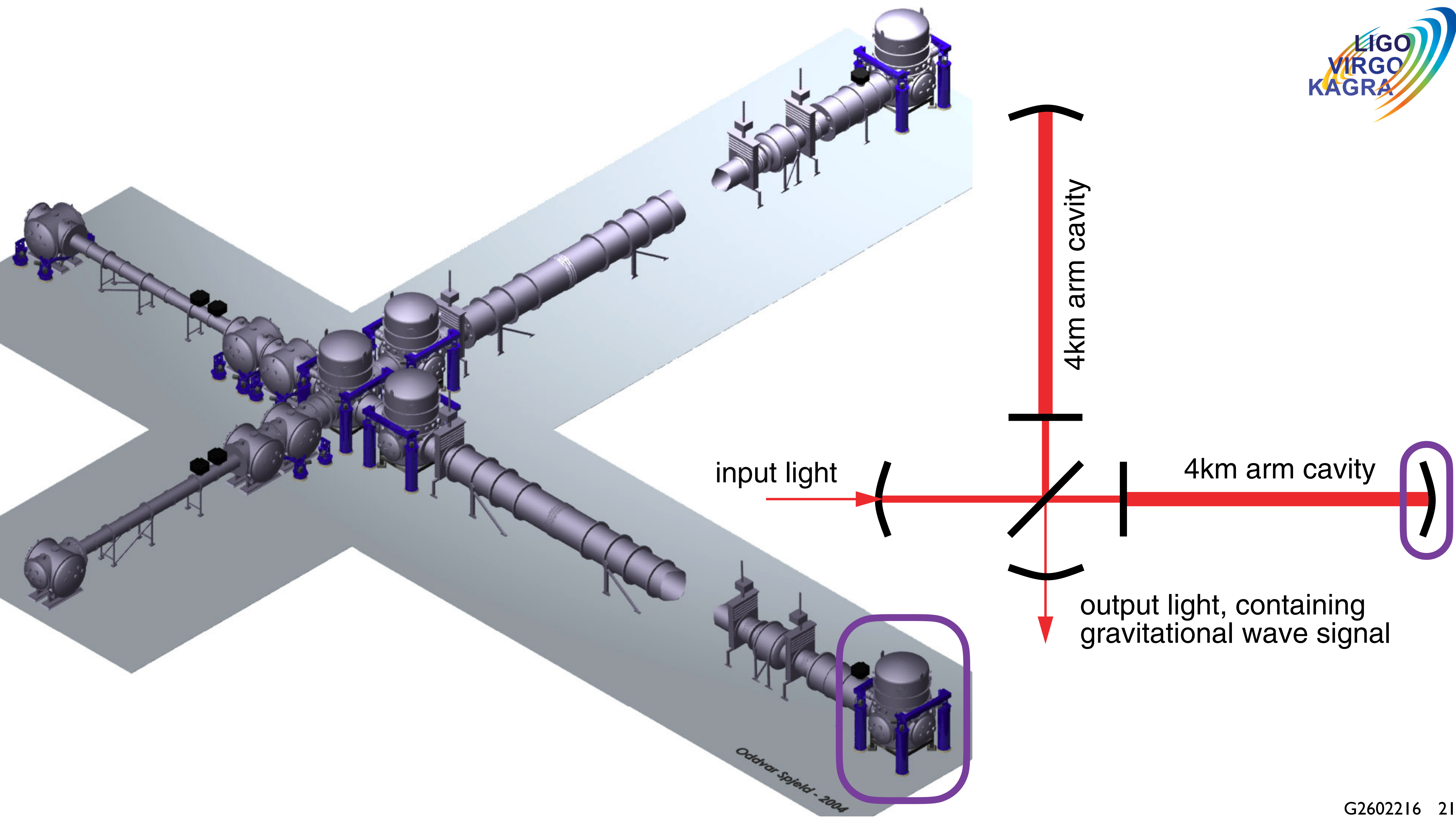
The interferometer needs control

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

Mirror motion at 10 Hz $\sim 1 \text{e-}19 \text{ m}/\sqrt{\text{Hz}}$

1. Long Arms
2. Quiet Mirrors
3. Precise Optical Readout





Mirrors are separated from the ground by 7 stages, each providing isolation and control.

External Quiet Hydraulic stage for low frequency positioning

2 stage Internal Seismic Isolation (ISI) stage for isolation above about 100 mHz

4 stage mirror suspension to give excellent isolation at 10 Hz and quiet actuation for interferometer control

Goals:

1. reduce the motion by 30 billion at 10 Hz
2. Control the position of the optic below ~ 10 Hz
3. Staged isolation and action for low noise performance at the optic.

3×10^{-12} m/ $\sqrt{\text{Hz}}$ at 10 Hz

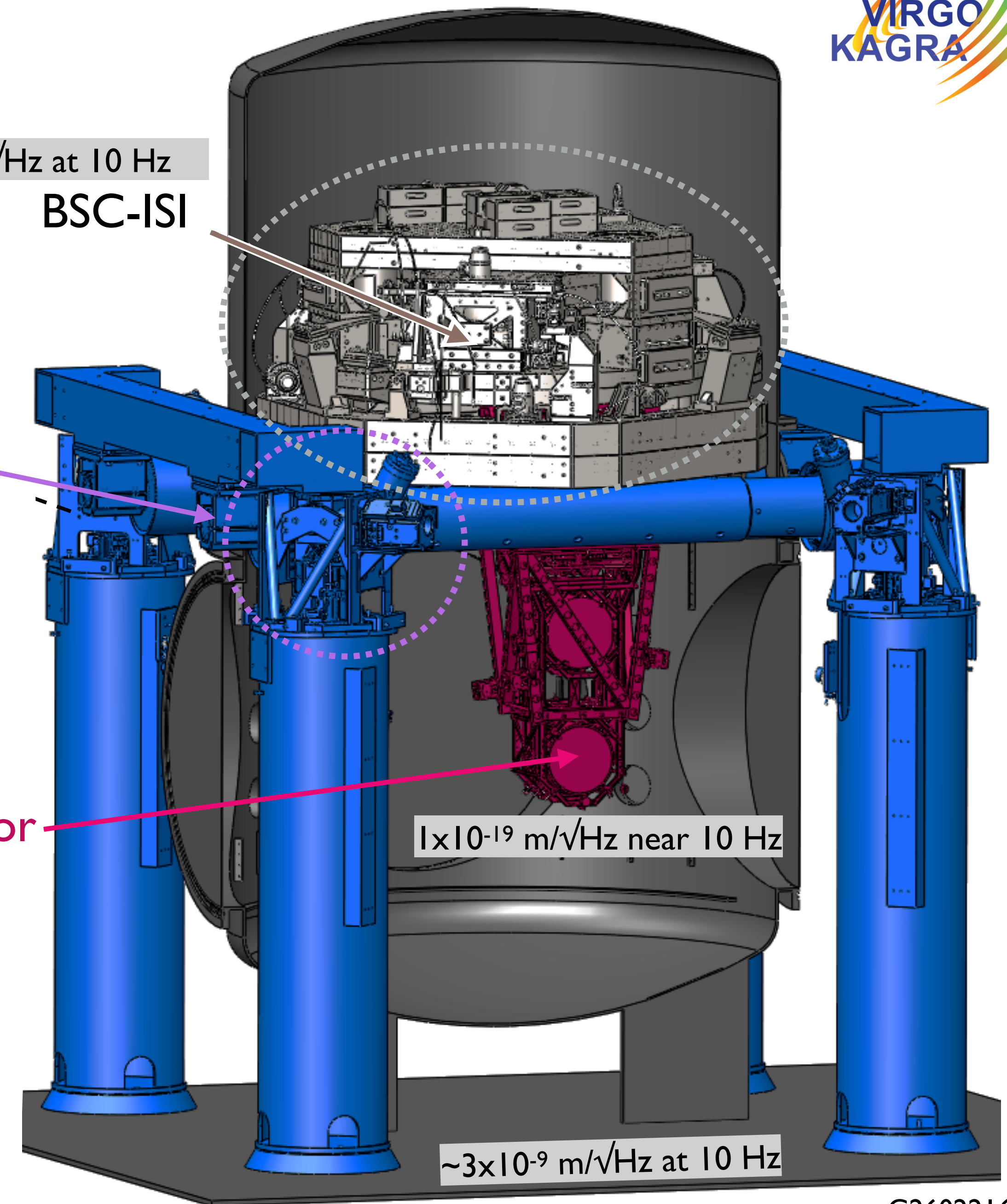
BSC-ISI

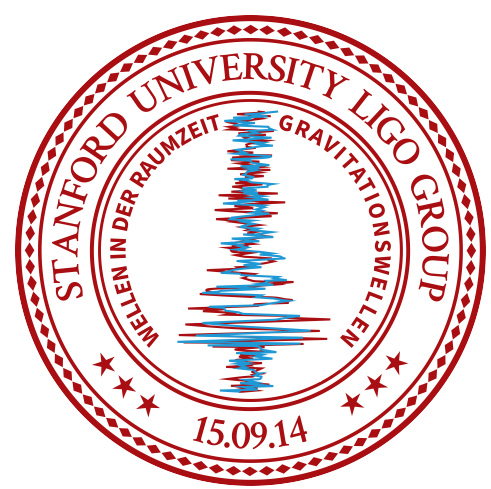
HEPI

Mirror

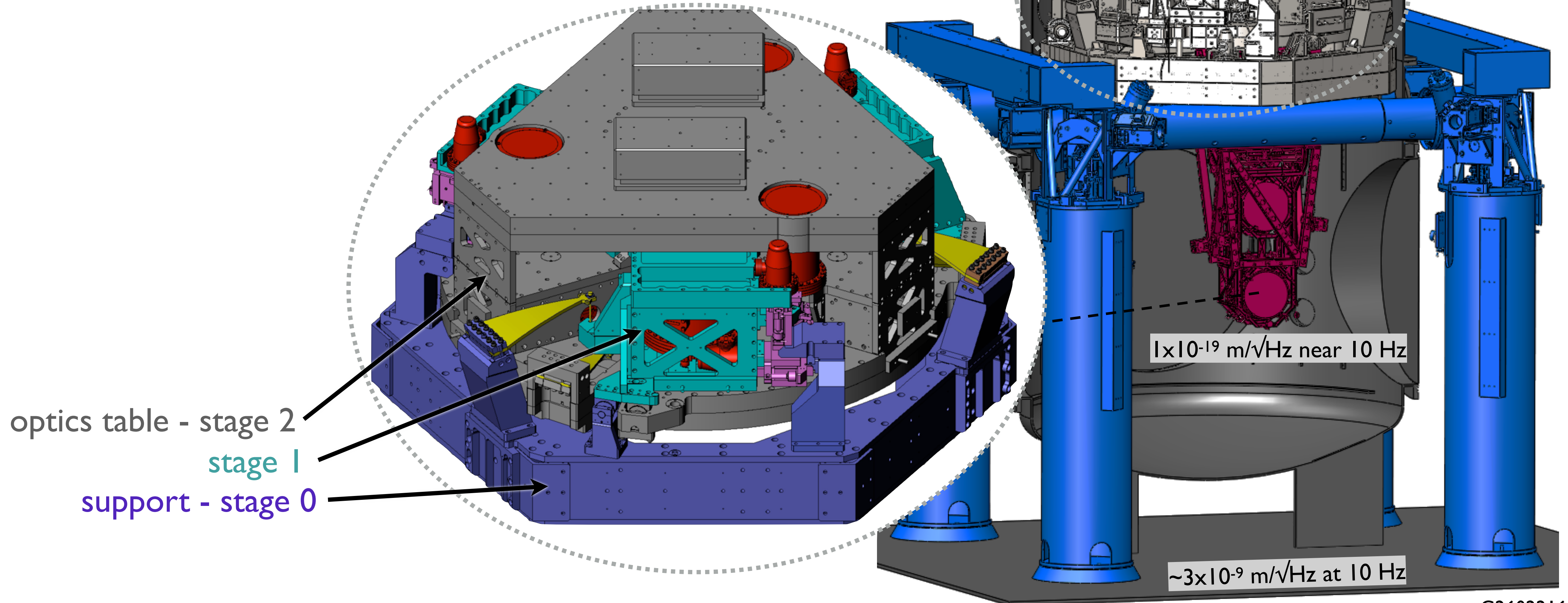
1×10^{-19} m/ $\sqrt{\text{Hz}}$ near 10 Hz

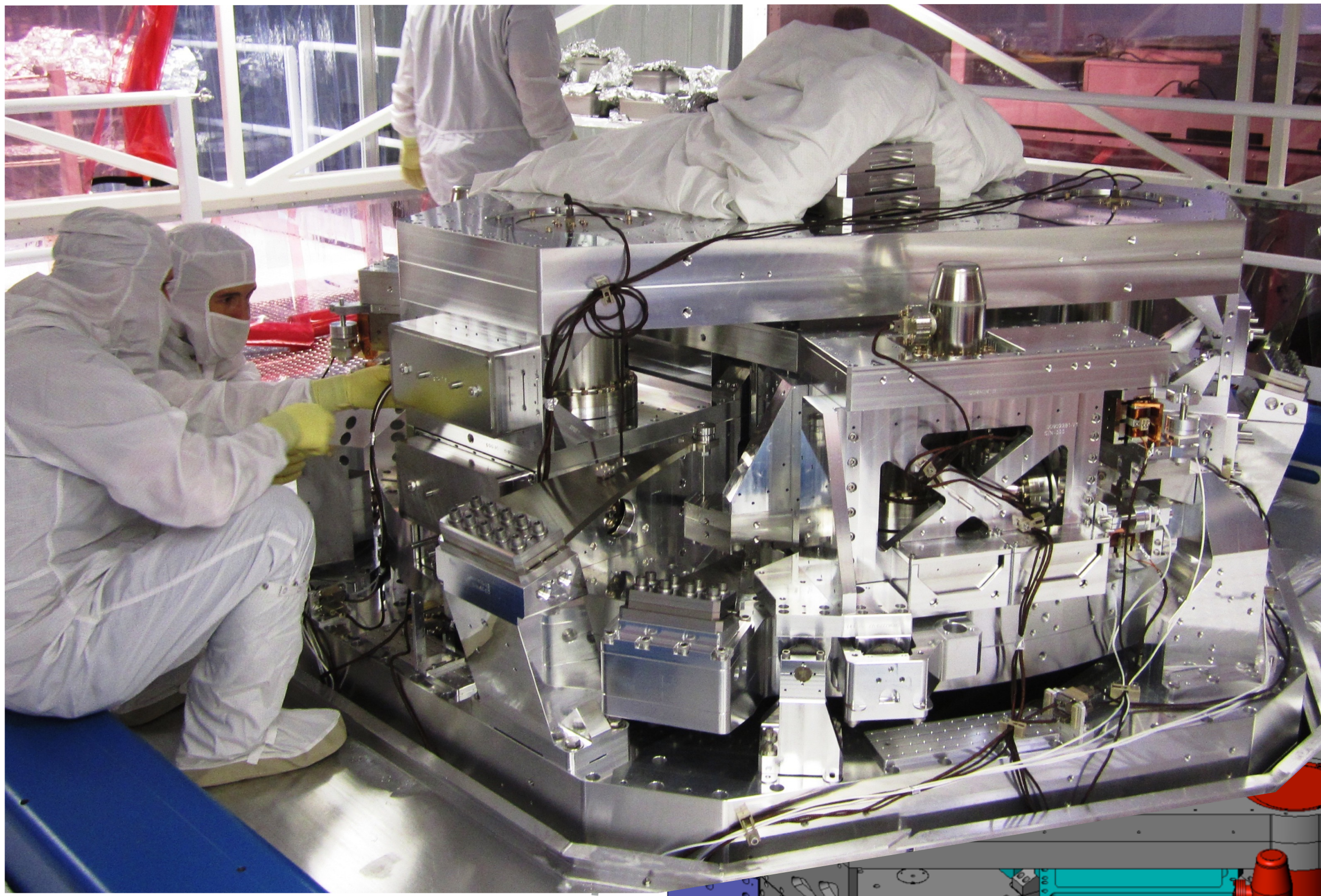
$\sim 3 \times 10^{-9}$ m/ $\sqrt{\text{Hz}}$ at 10 Hz



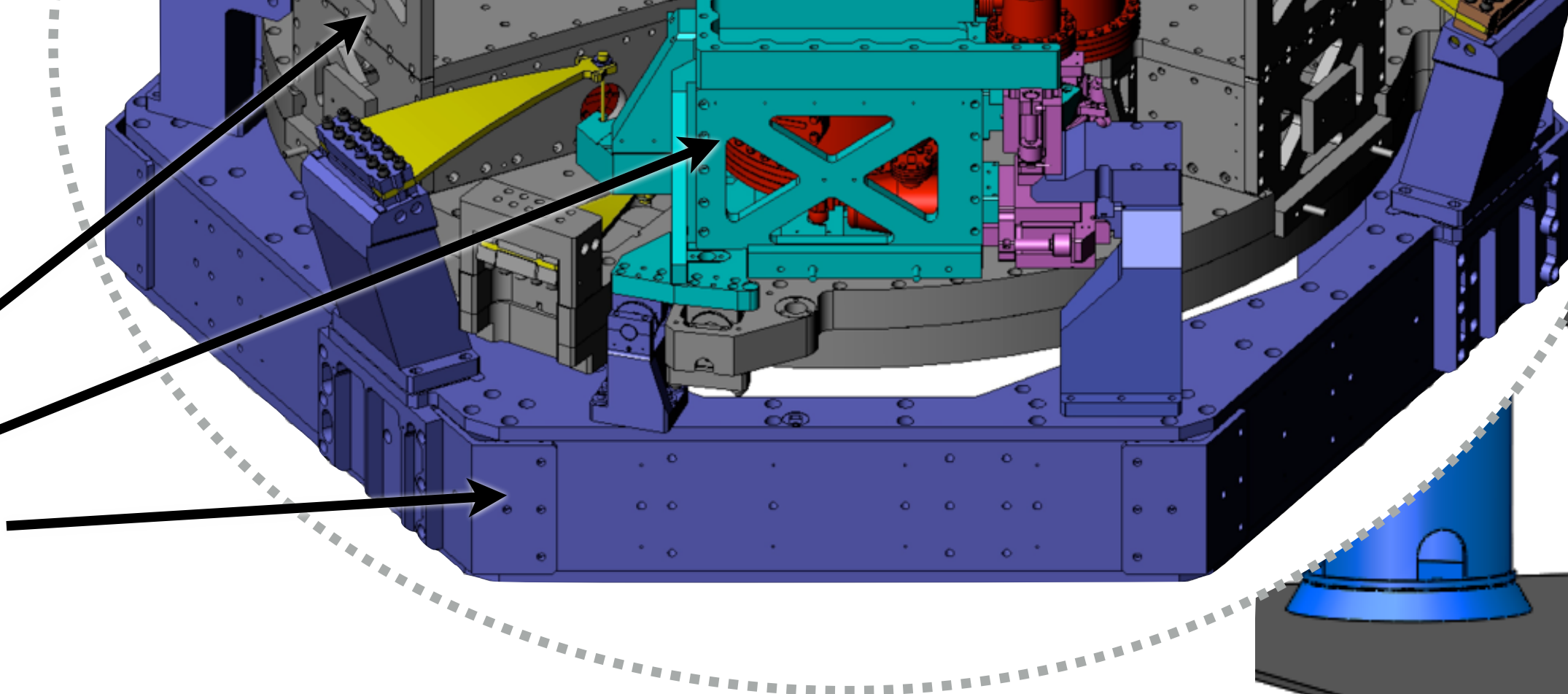
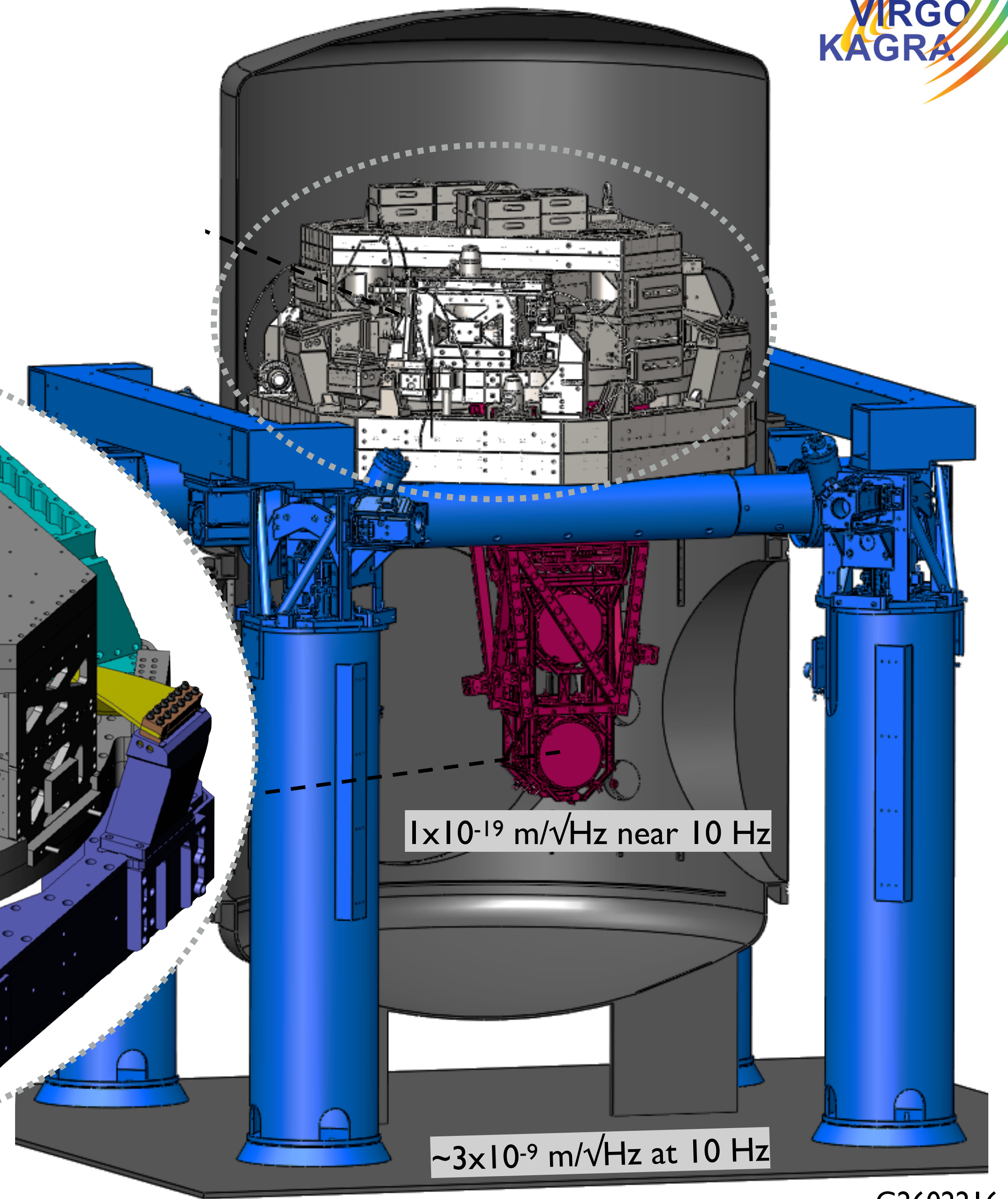


aLIGO Isolation





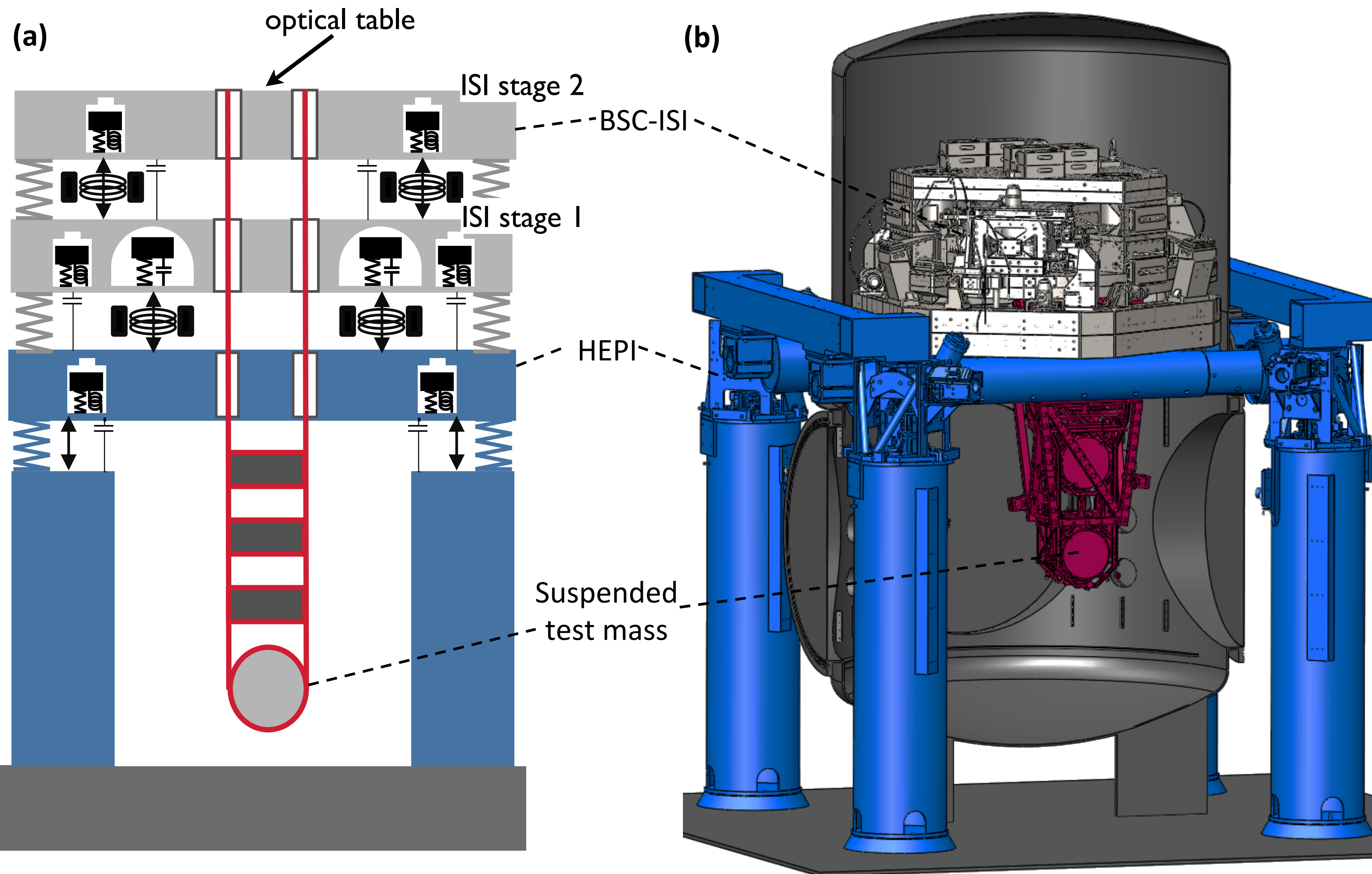
optics table - stage 2
stage 1
support - stage 0



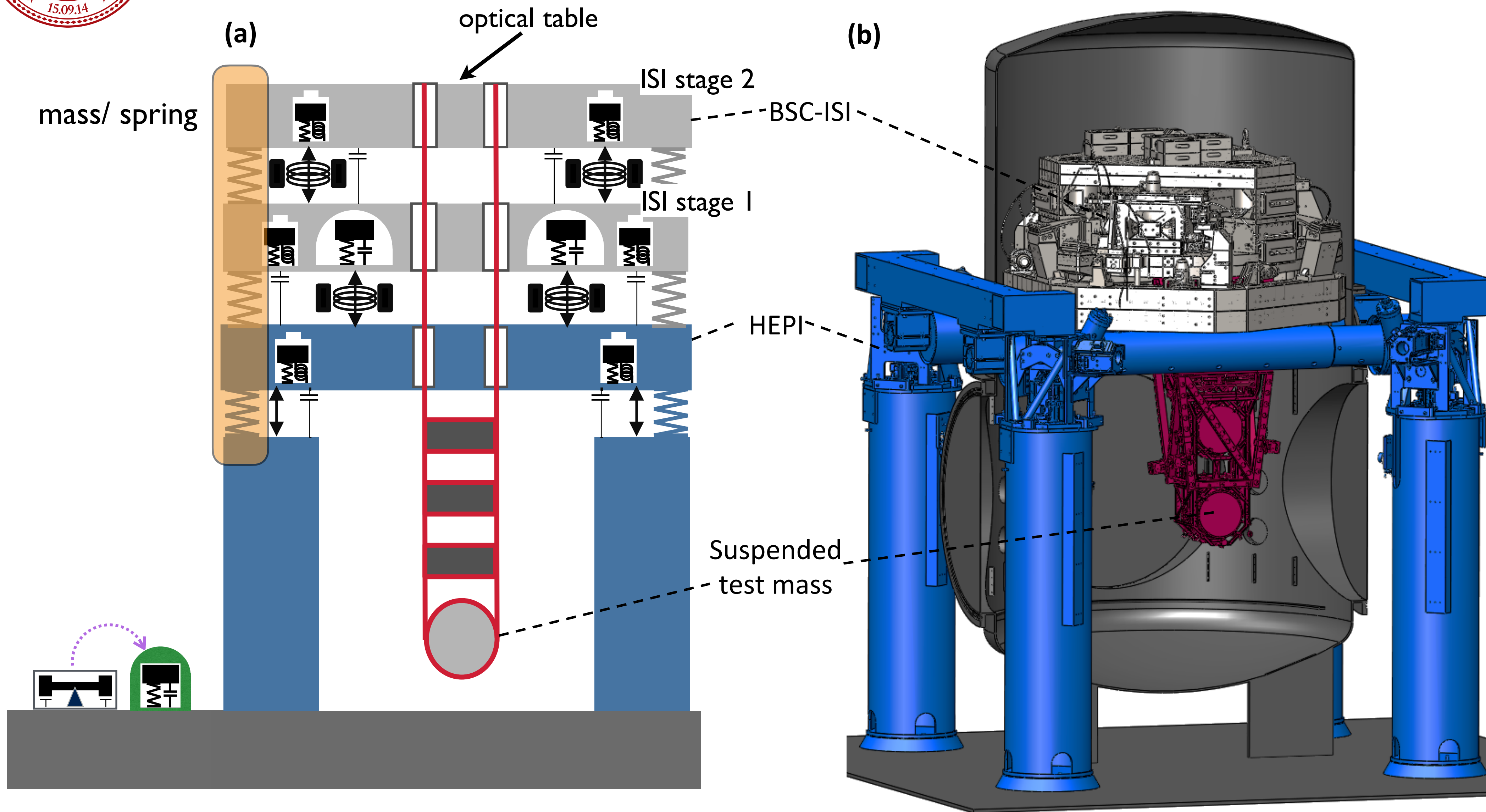
$1 \times 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ near 10 Hz

$\sim 3 \times 10^{-9} \text{ m}/\sqrt{\text{Hz}}$ at 10 Hz

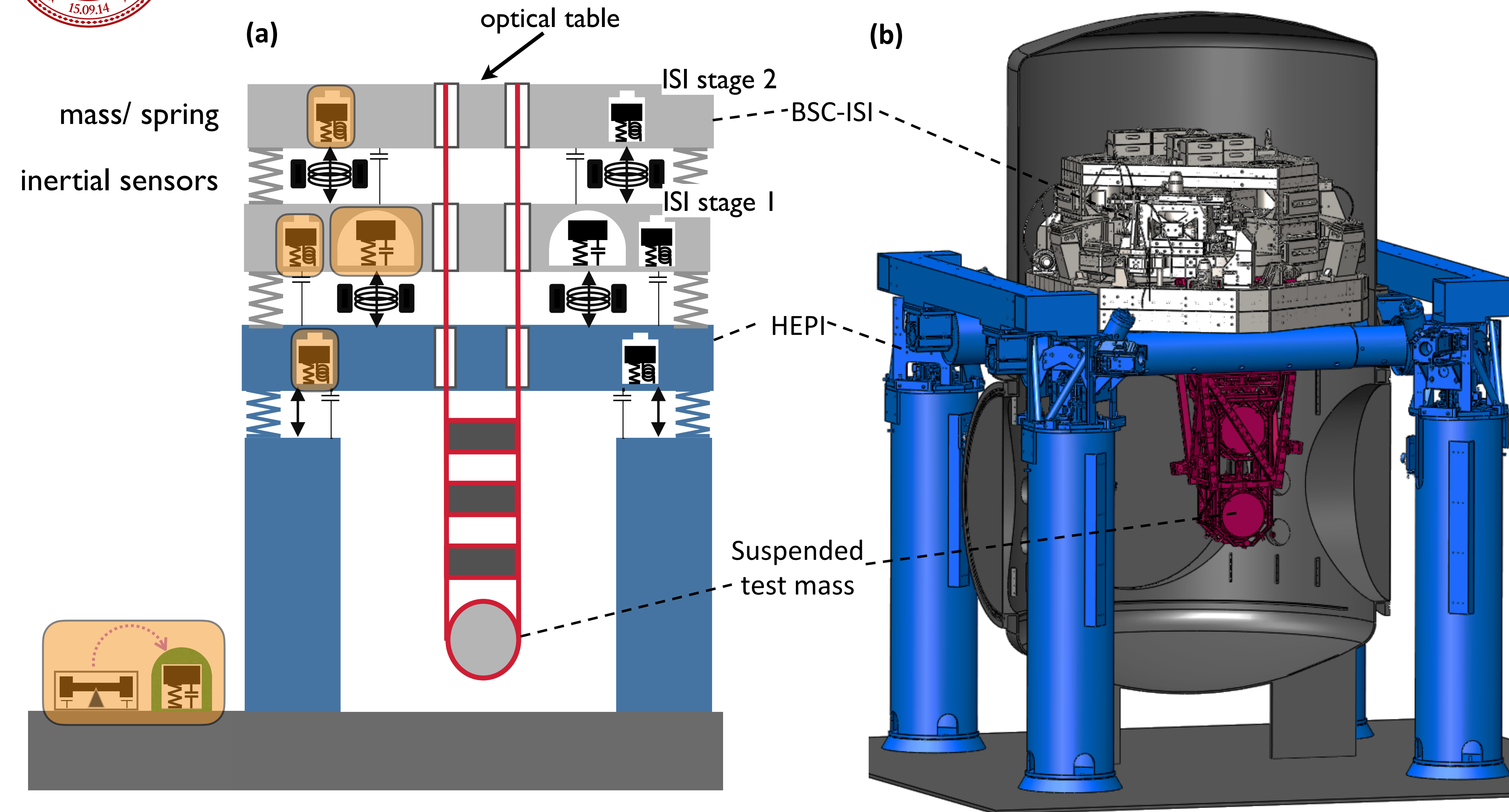
Isolation walkthrough



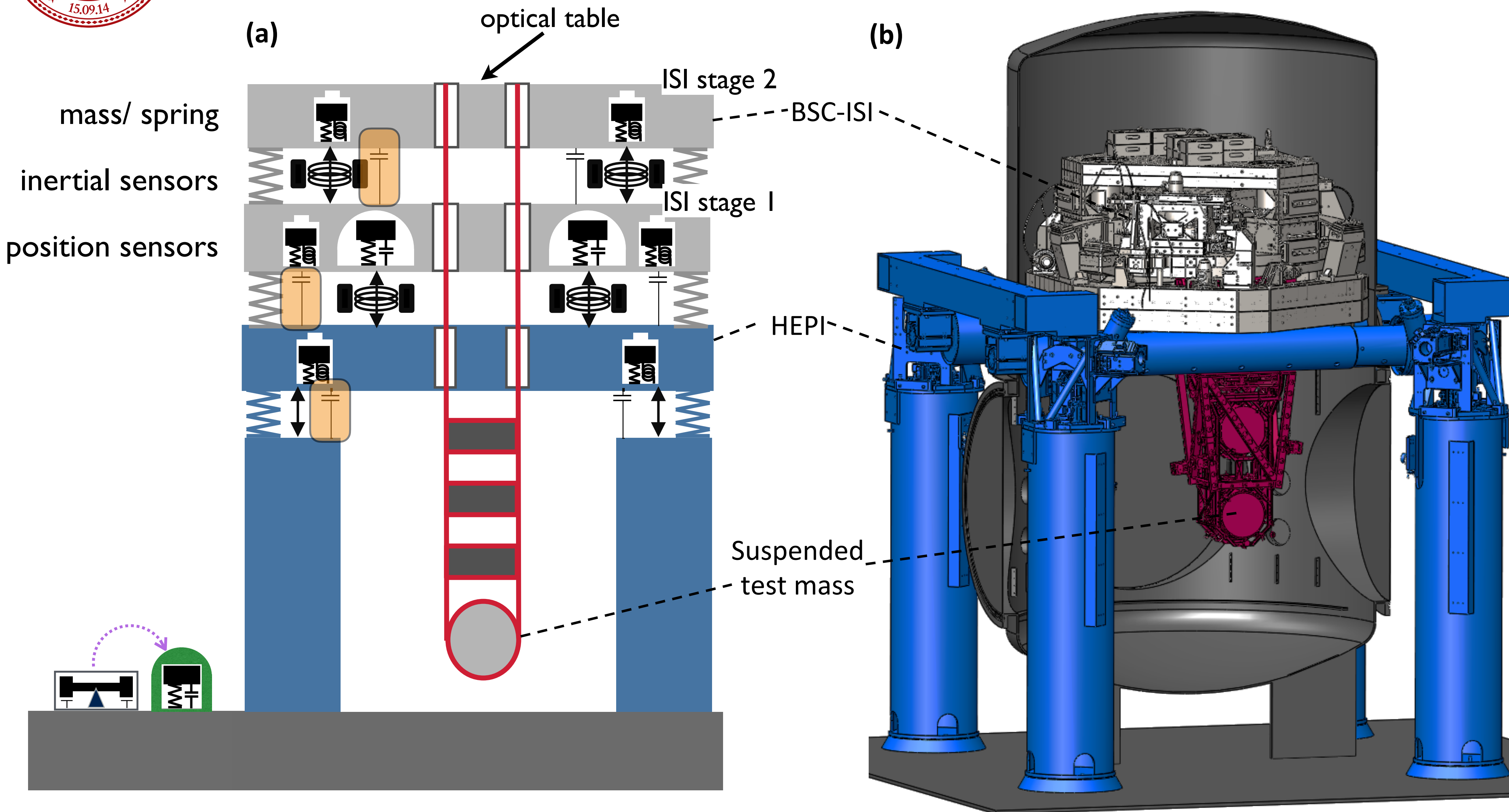
Isolation walkthrough

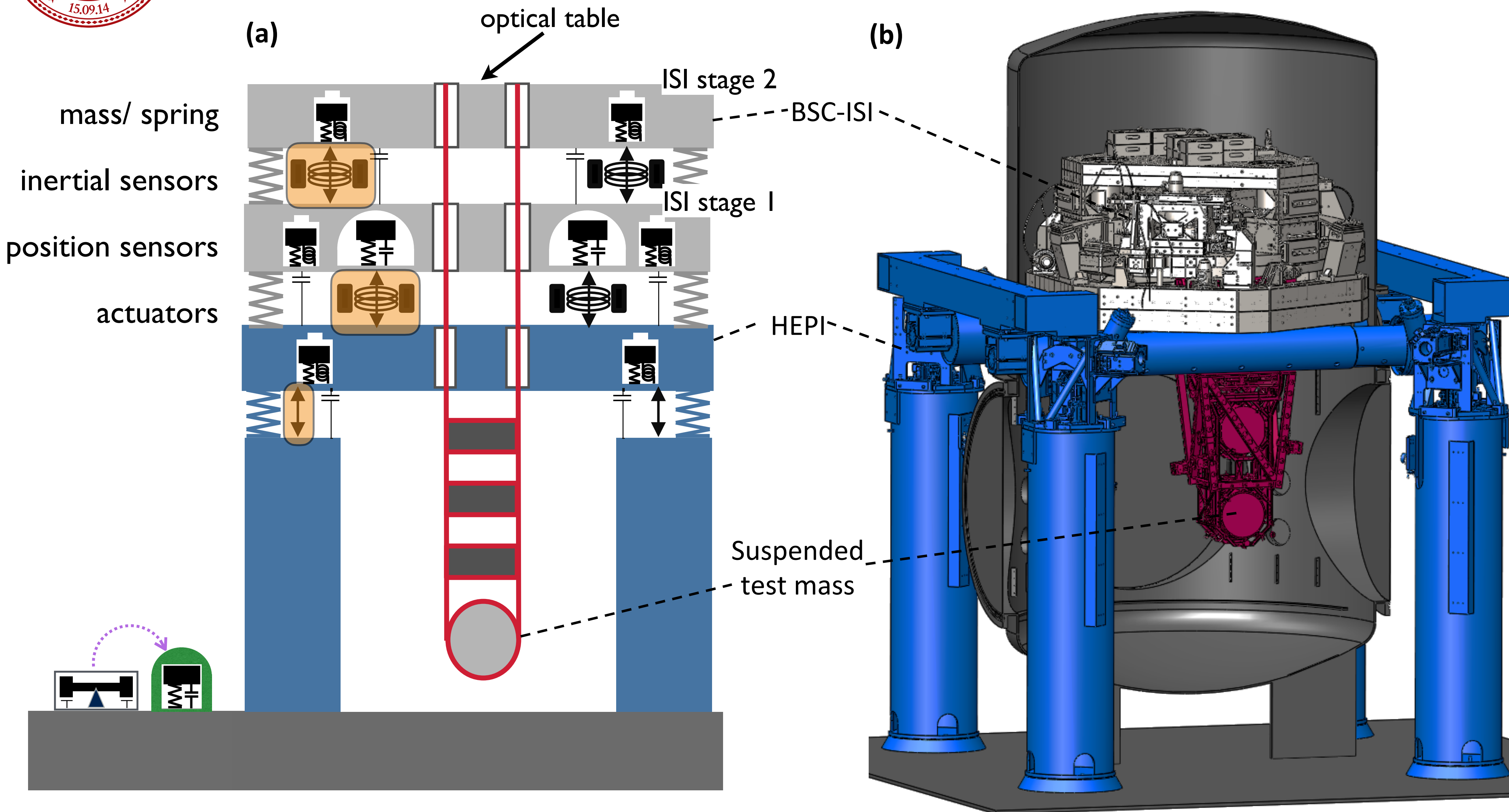


Isolation walkthrough

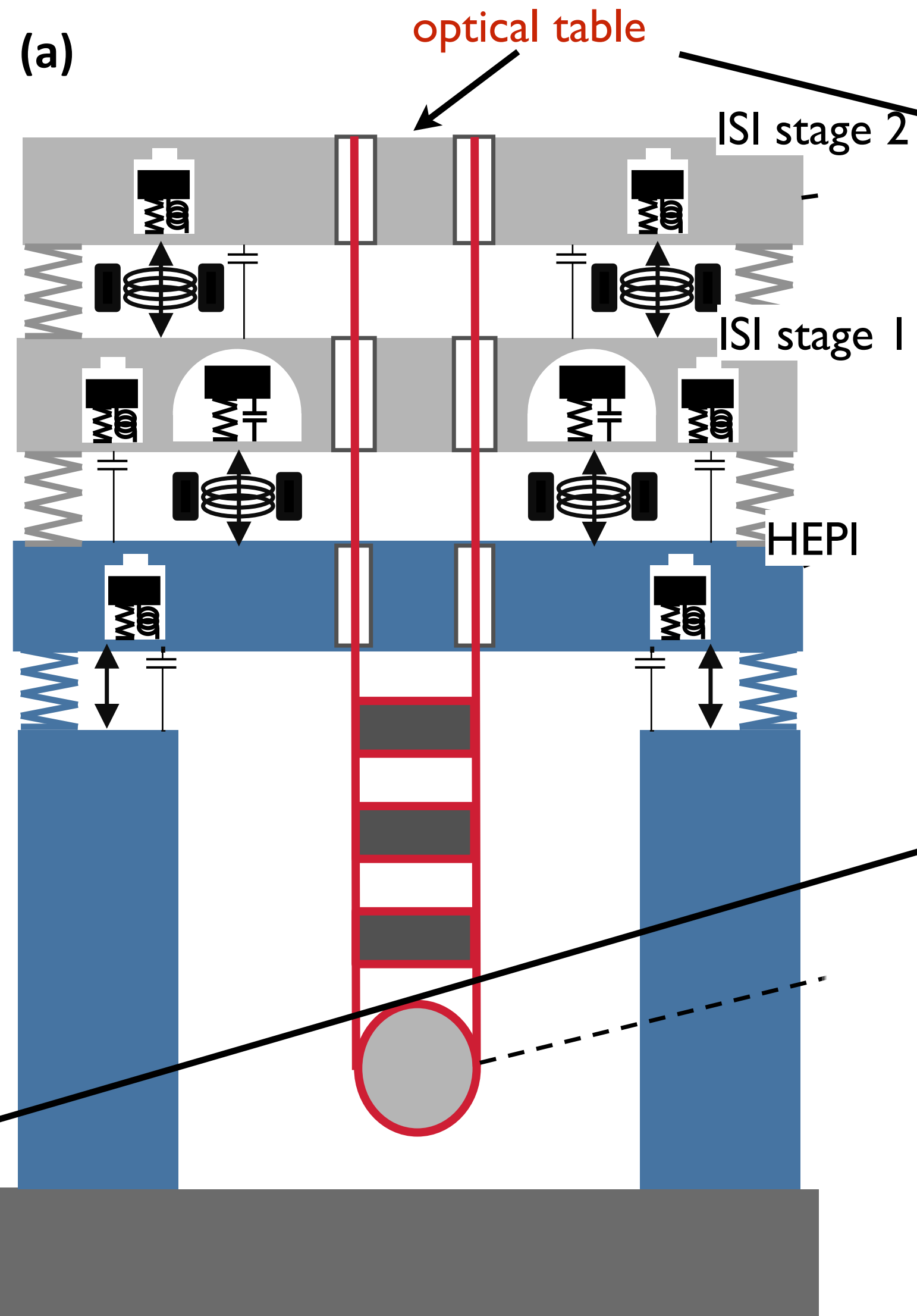
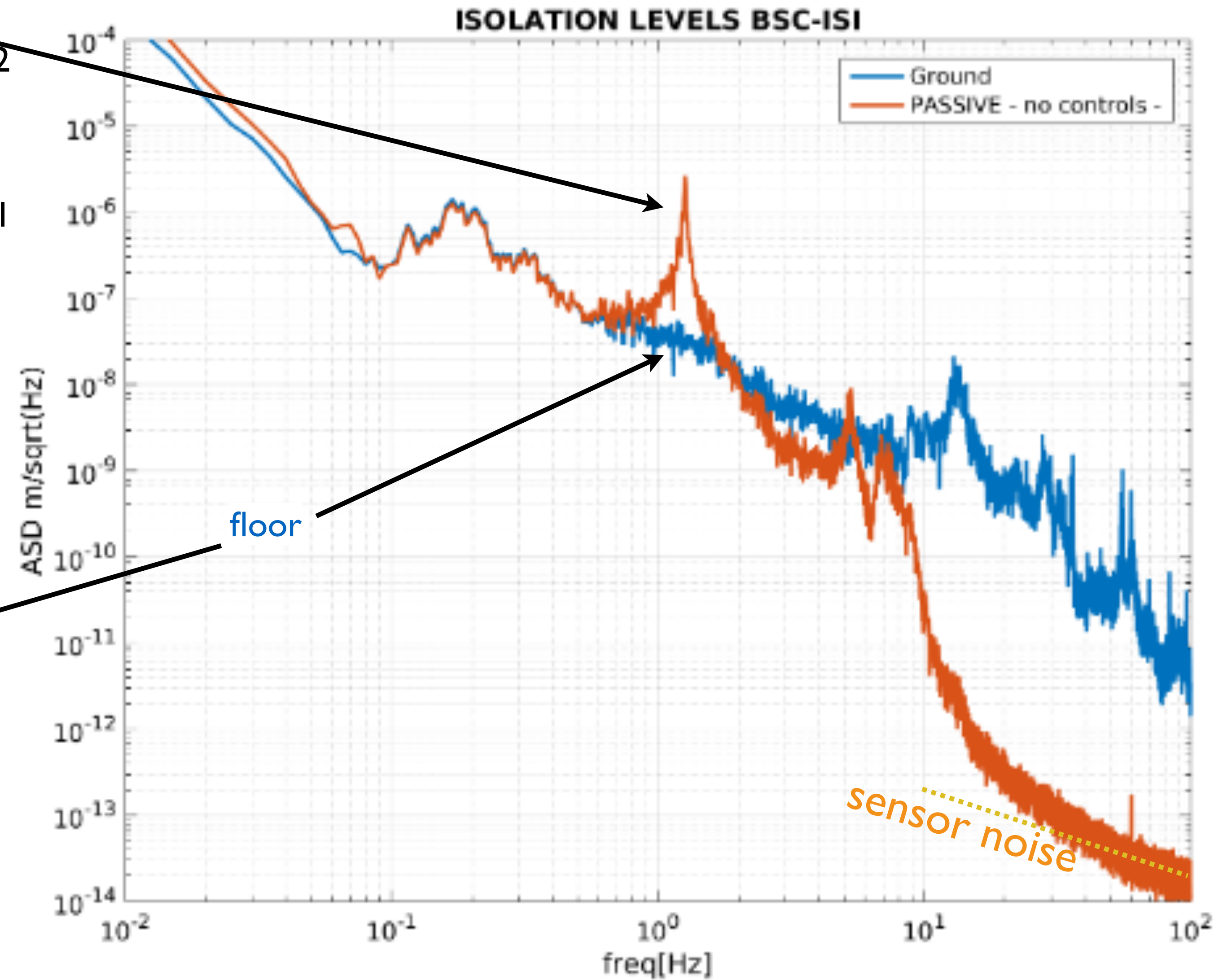


Isolation walkthrough



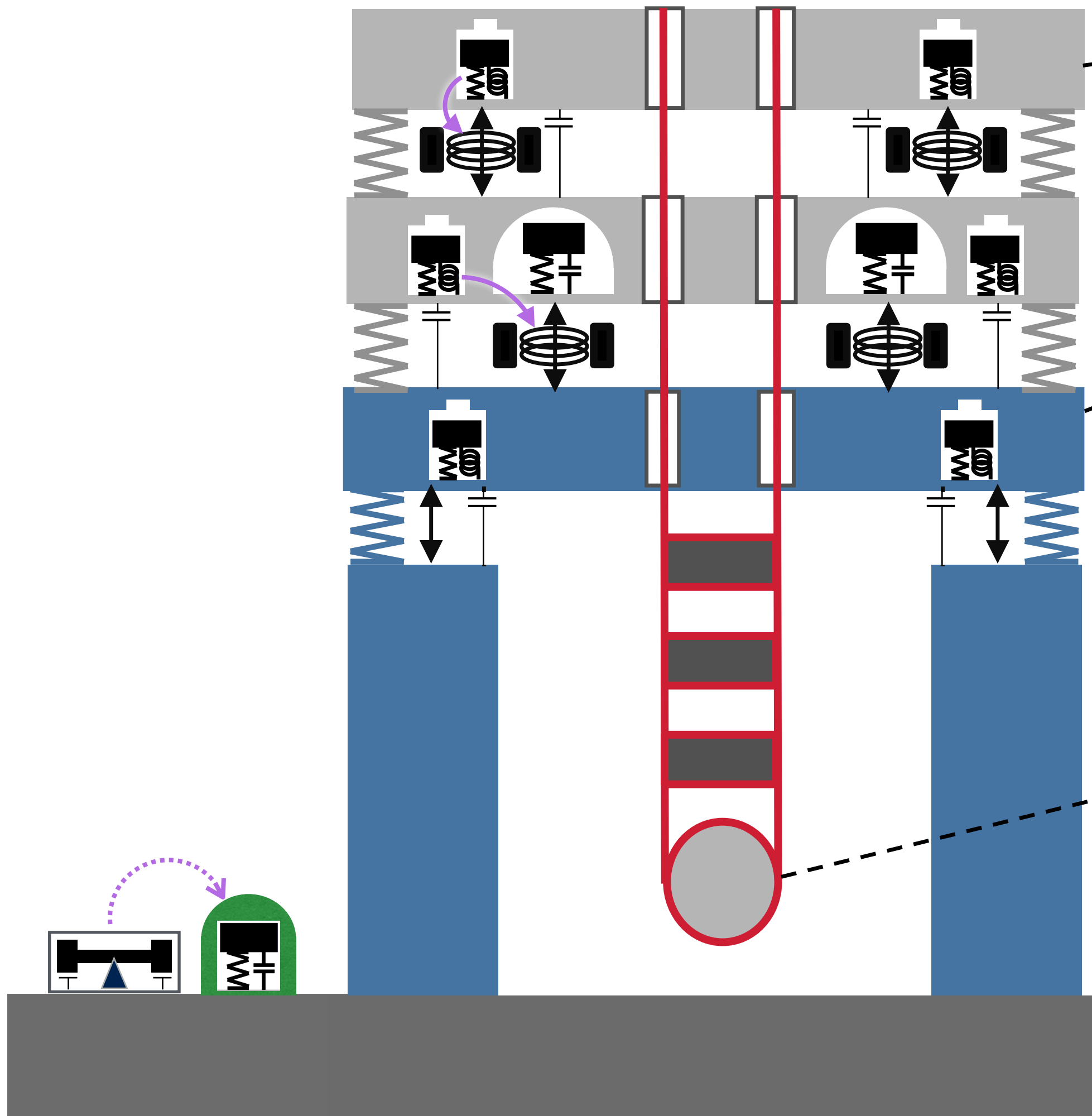
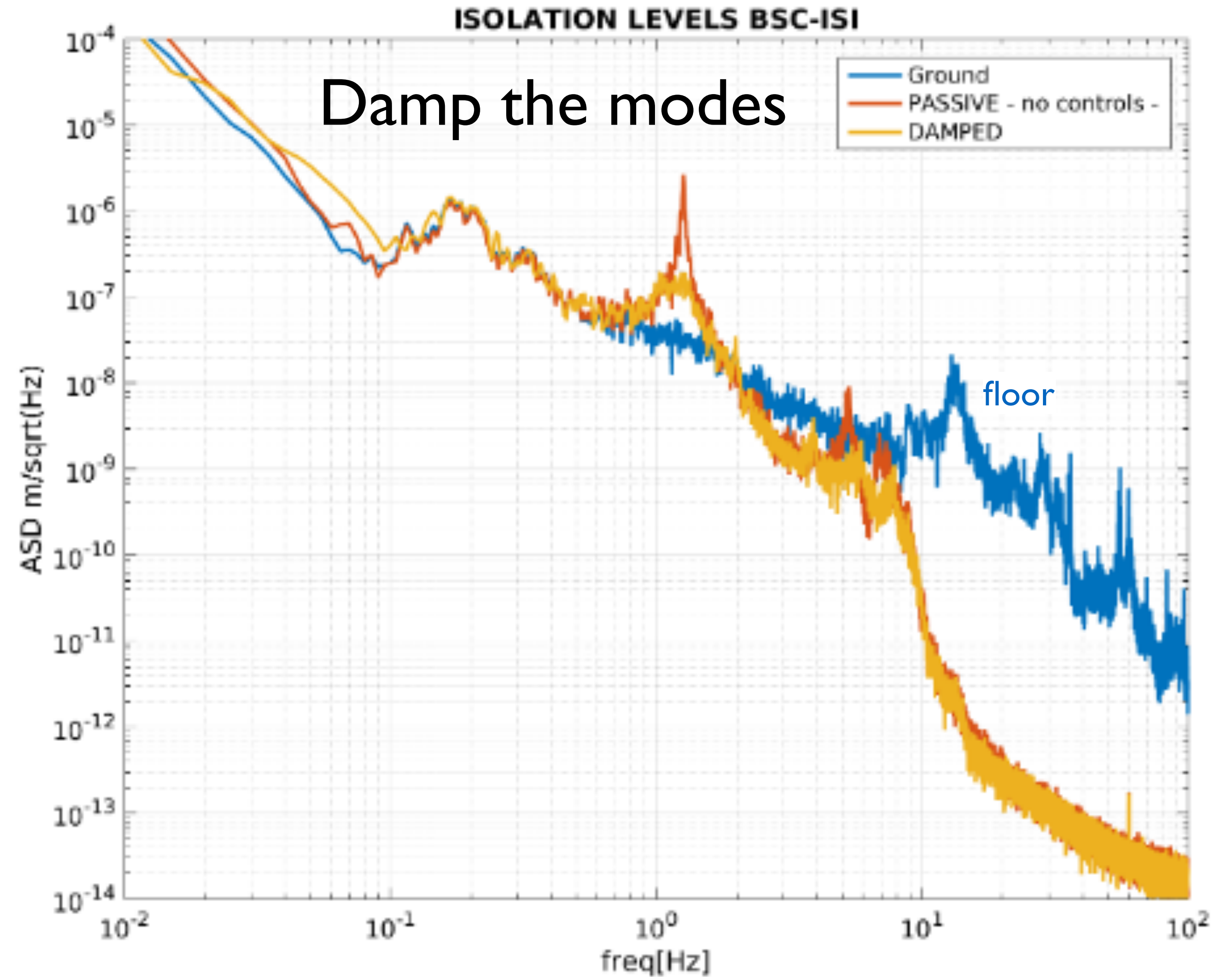


Isolation walkthrough



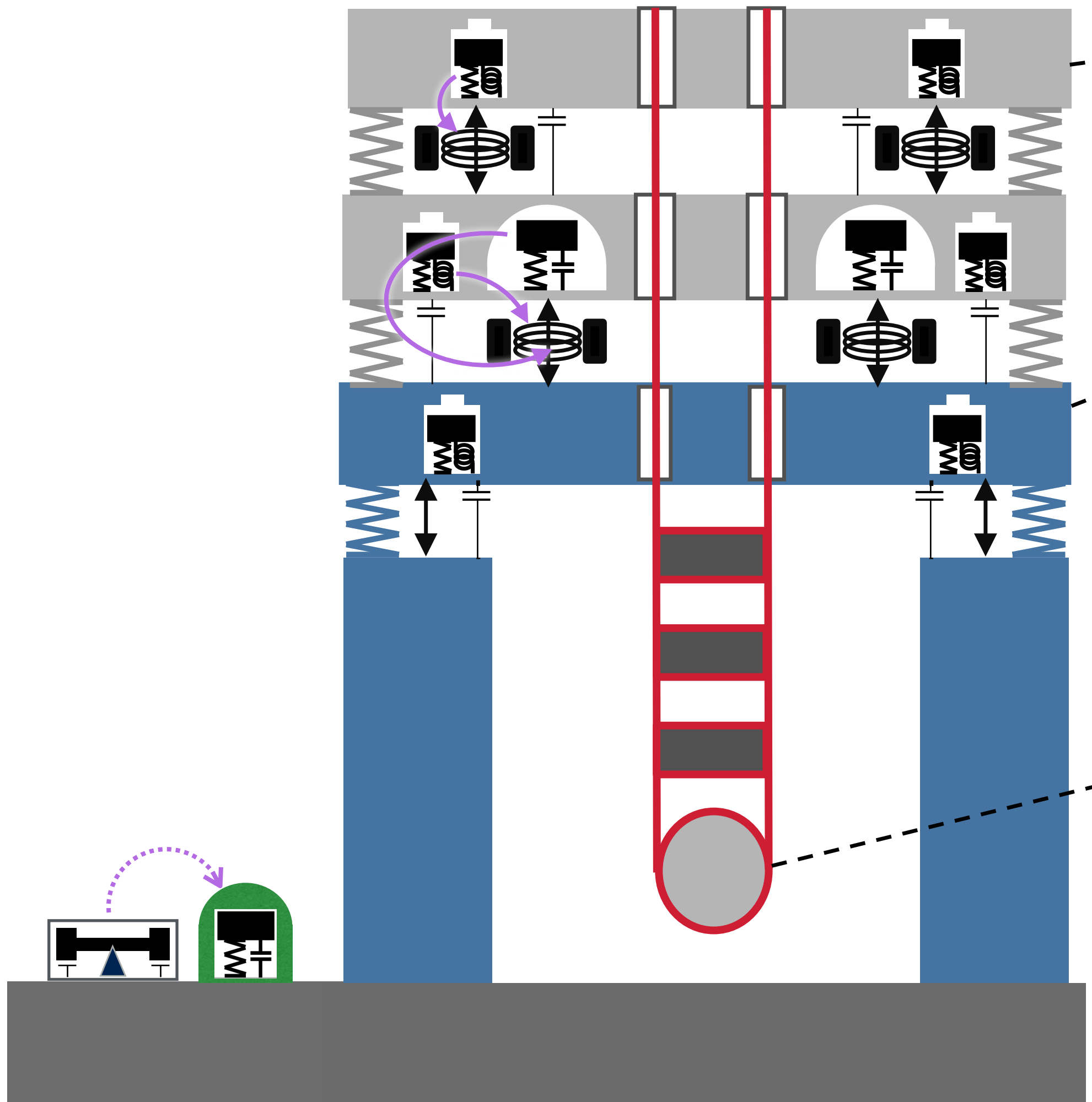
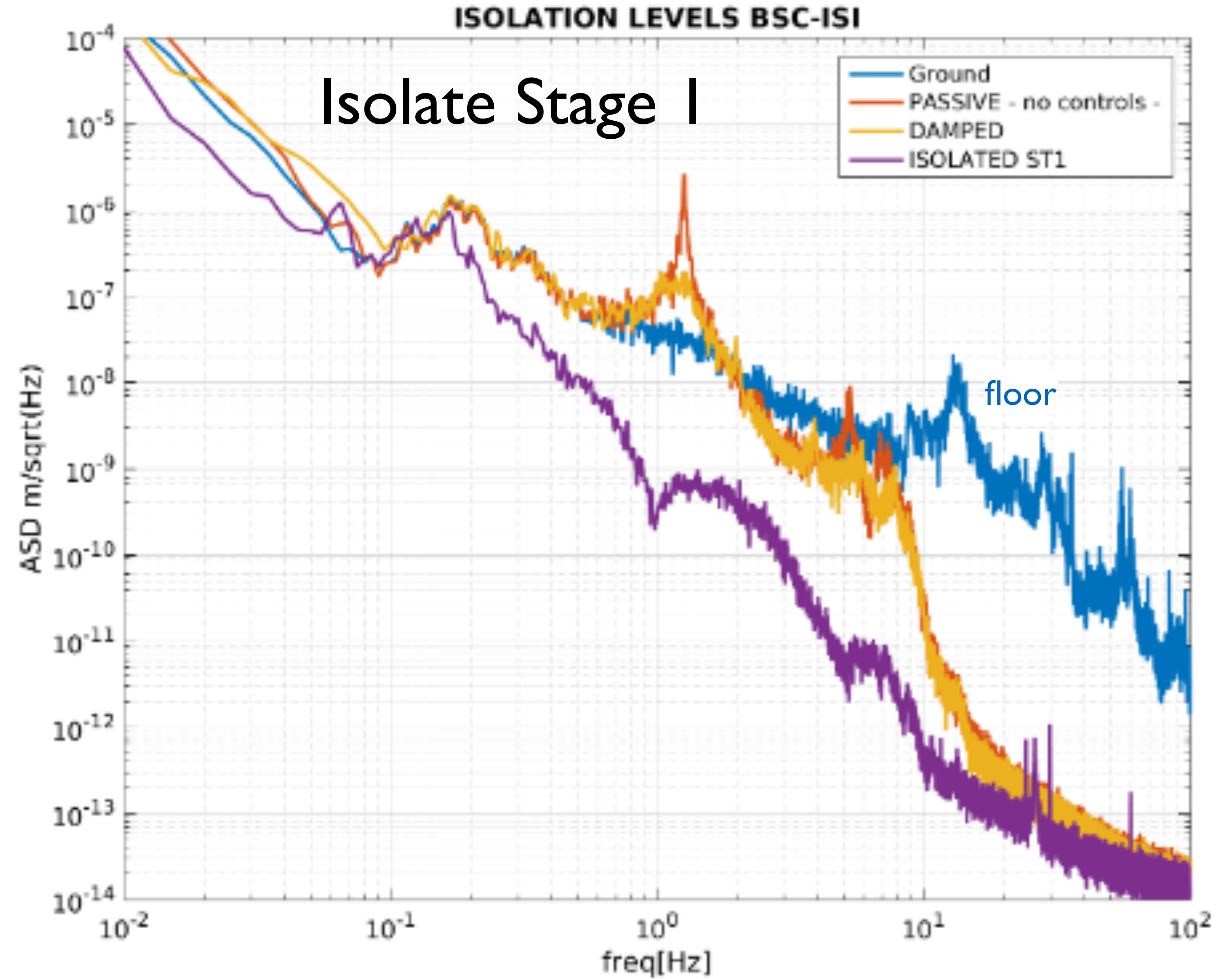
Isolation walkthrough

(a)



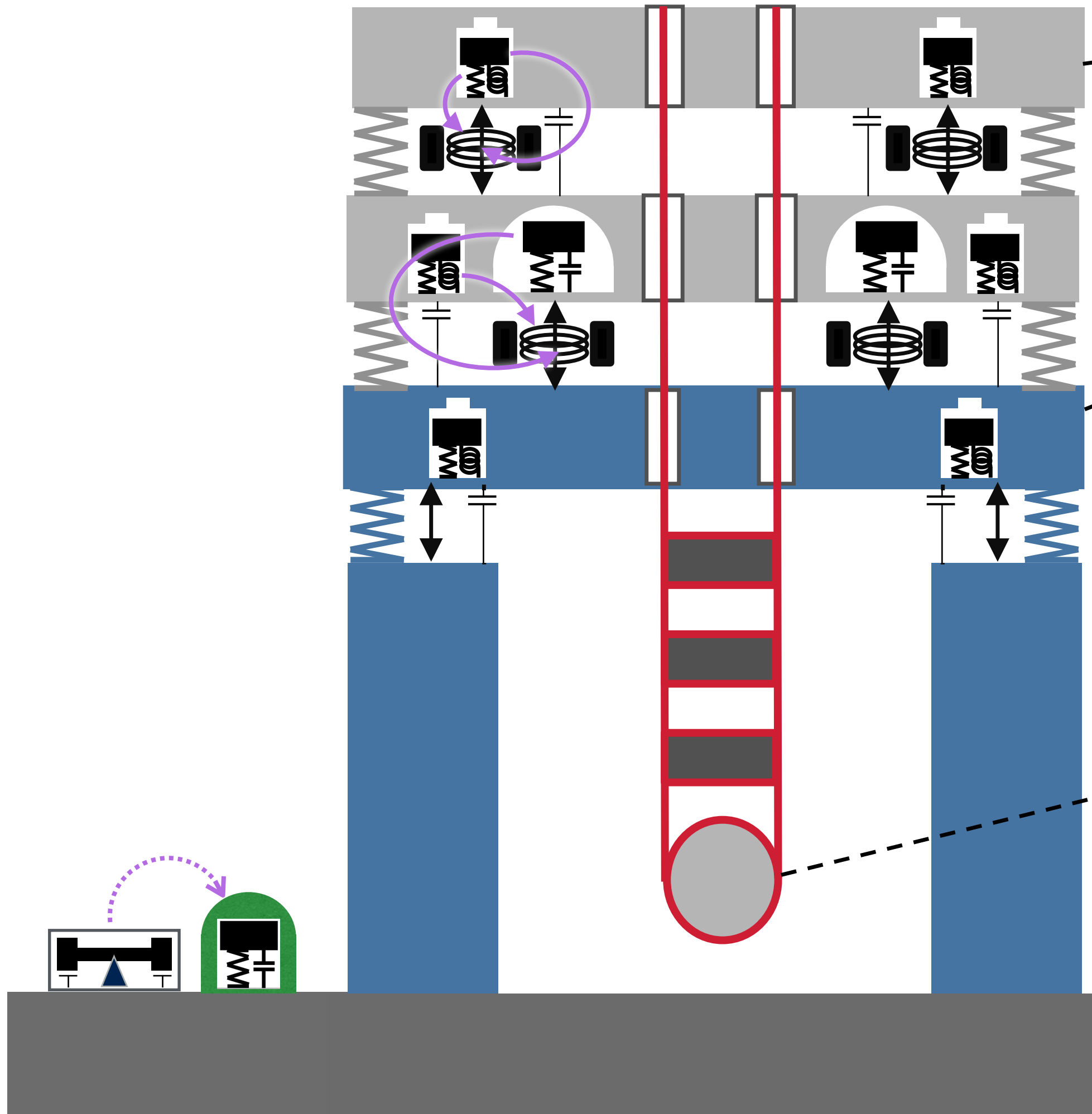
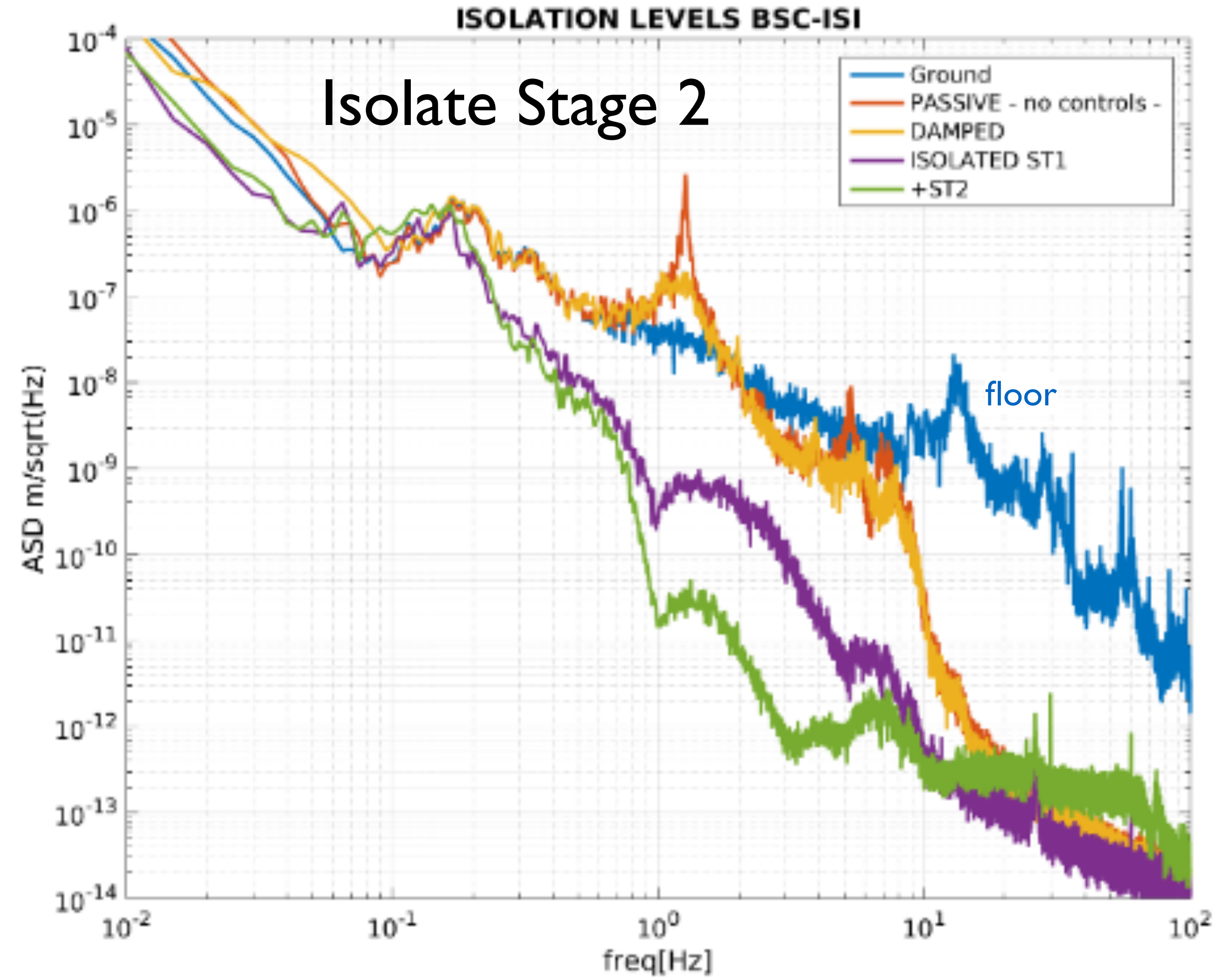
Isolation walkthrough

(a)



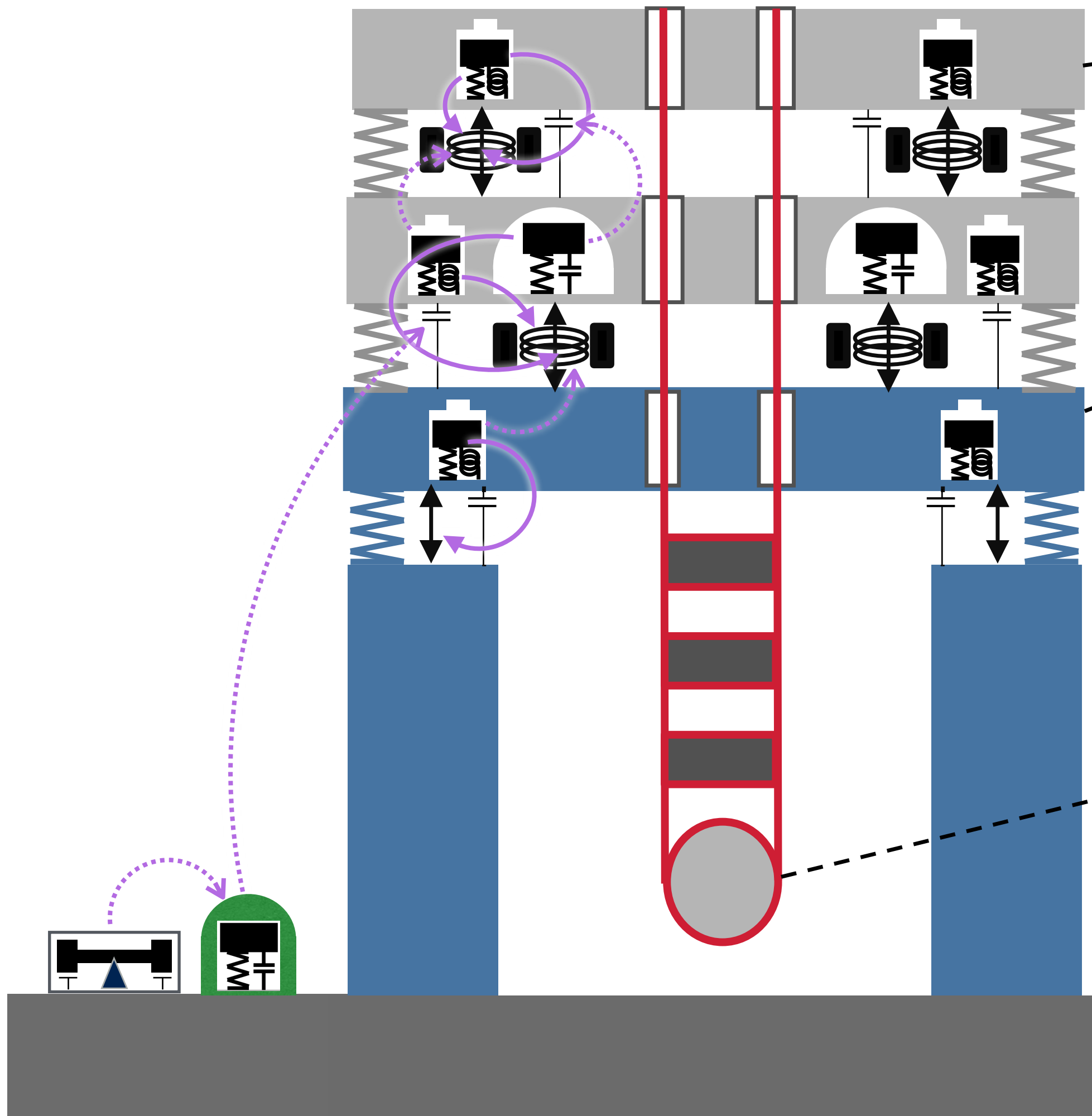
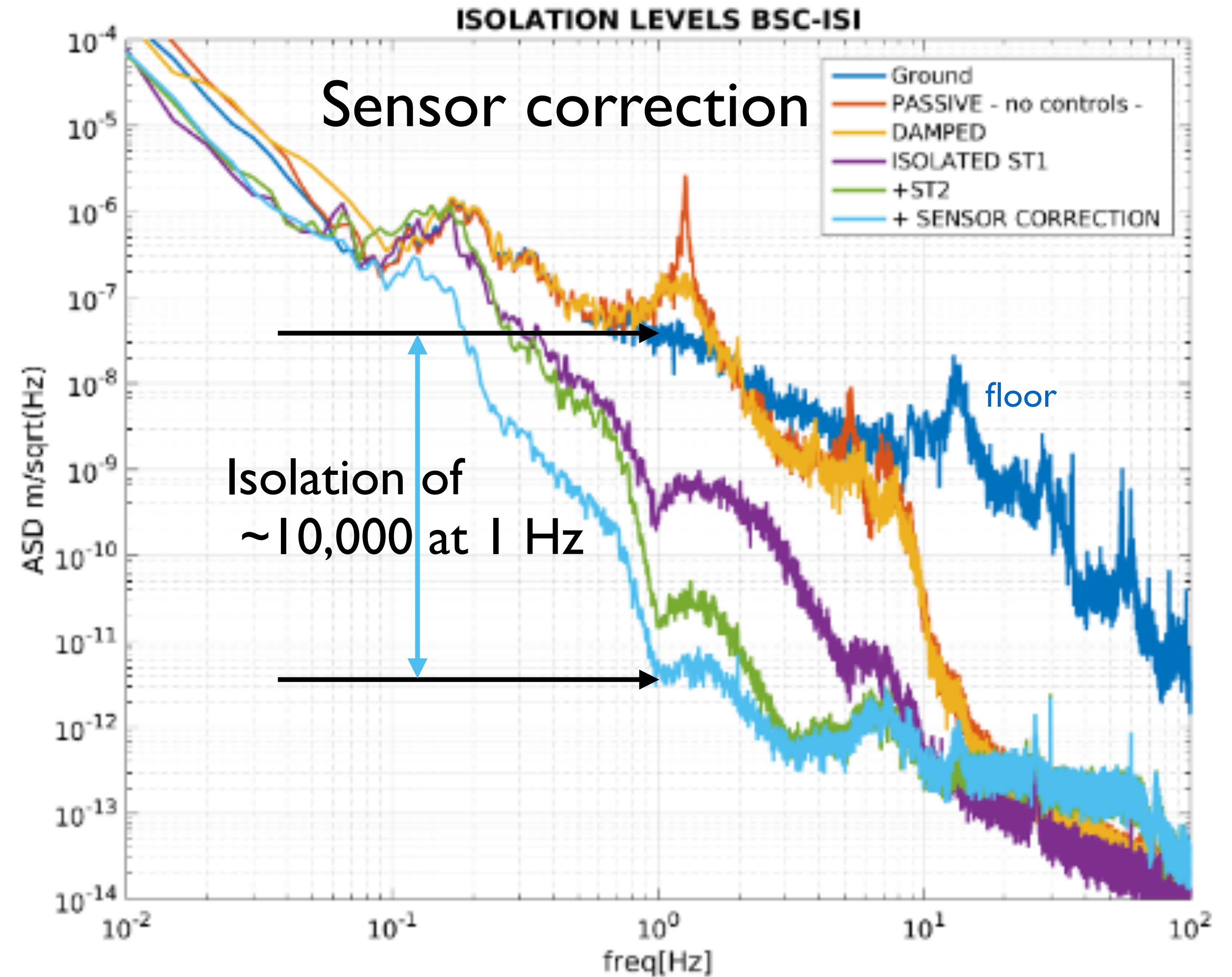
Isolation walkthrough

(a)



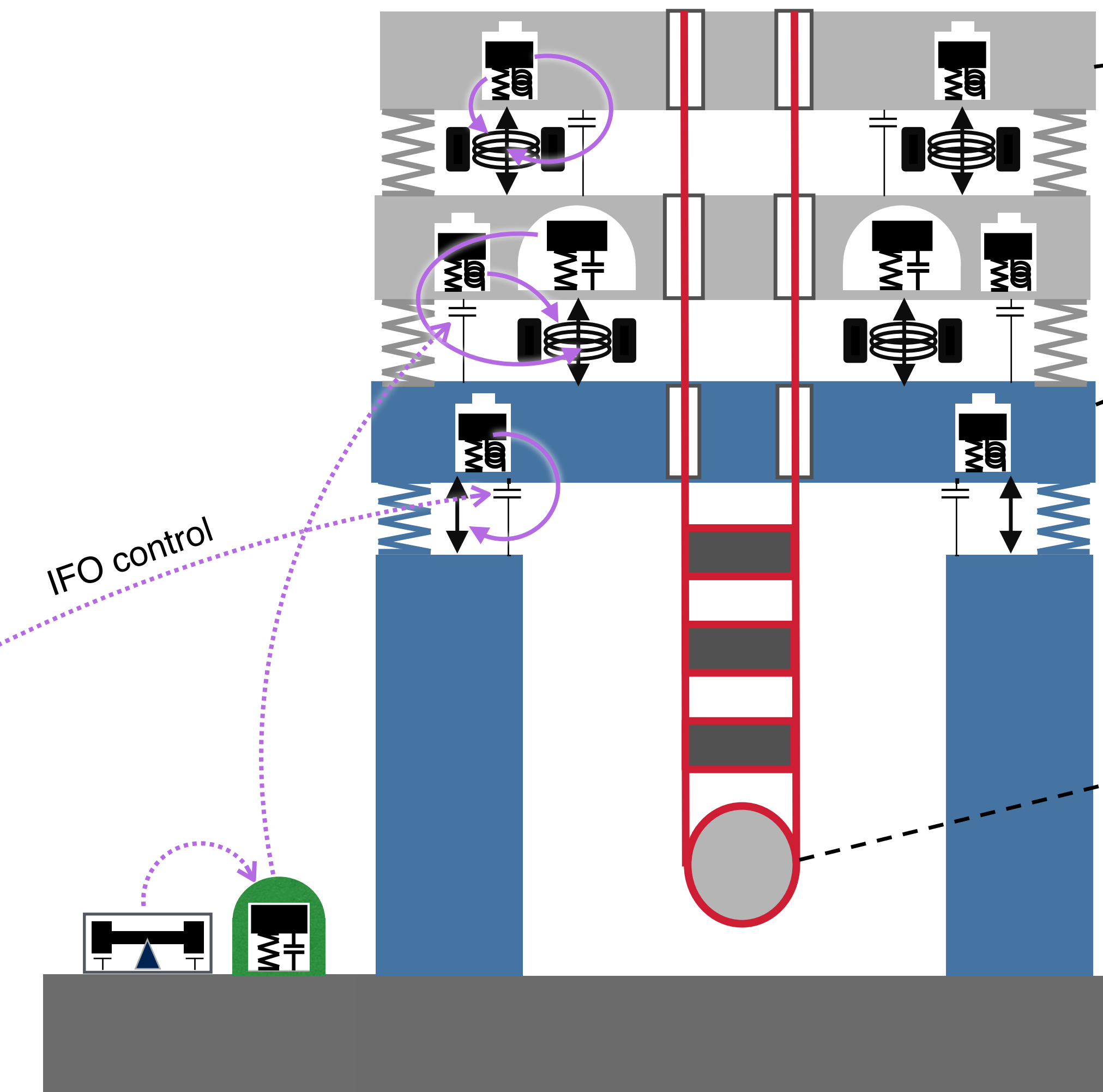
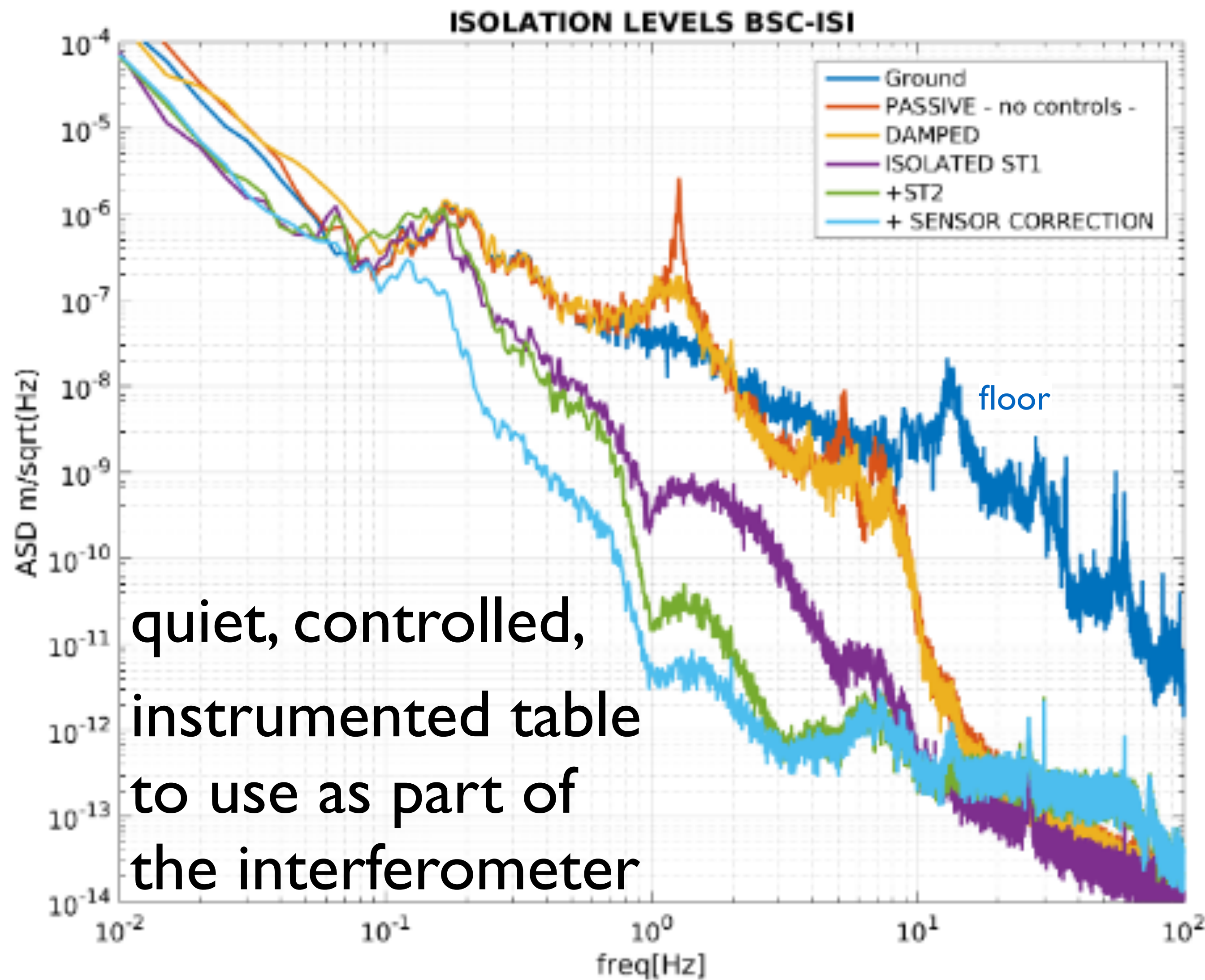
Isolation walkthrough

(a)



Isolation walkthrough

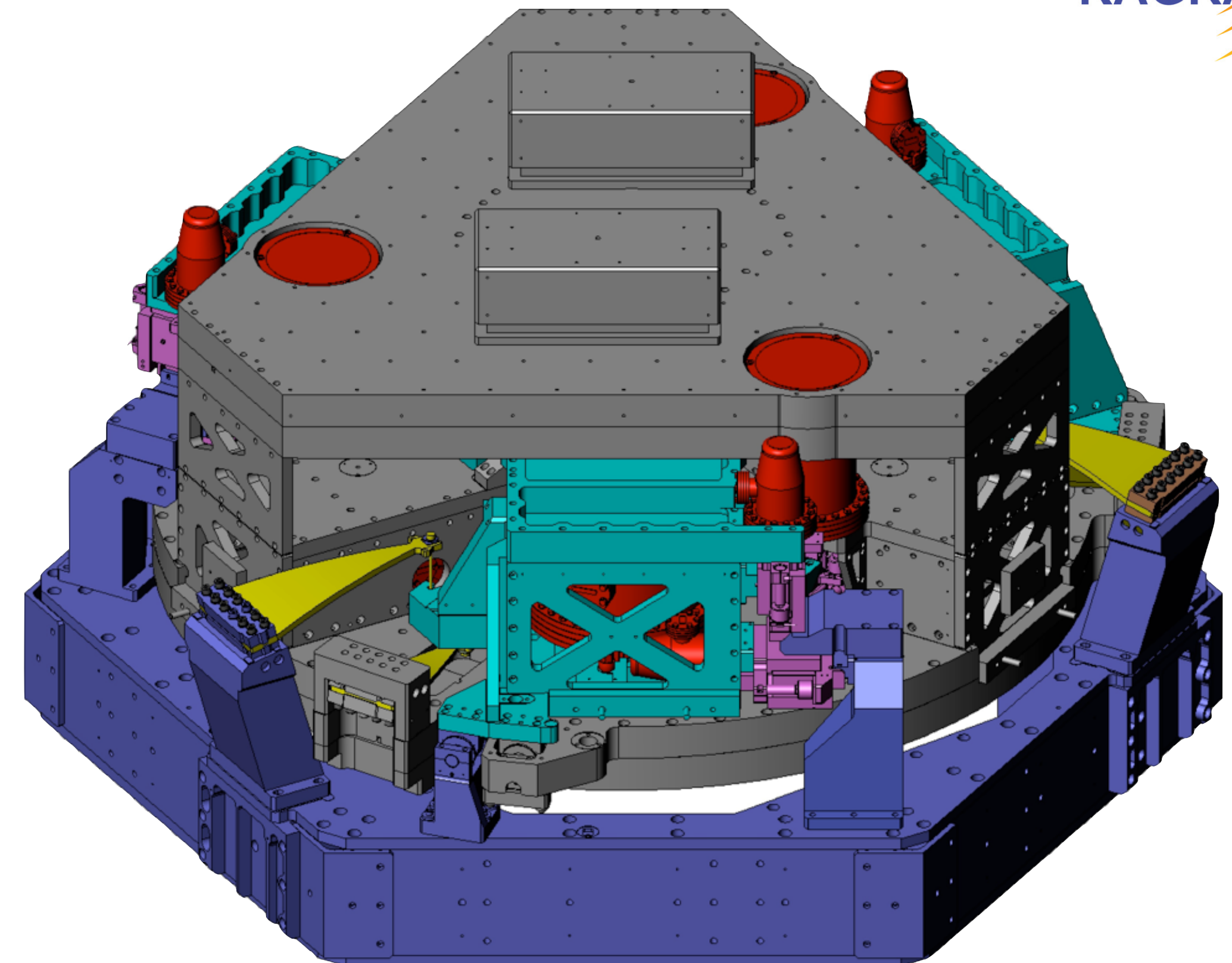
(a)



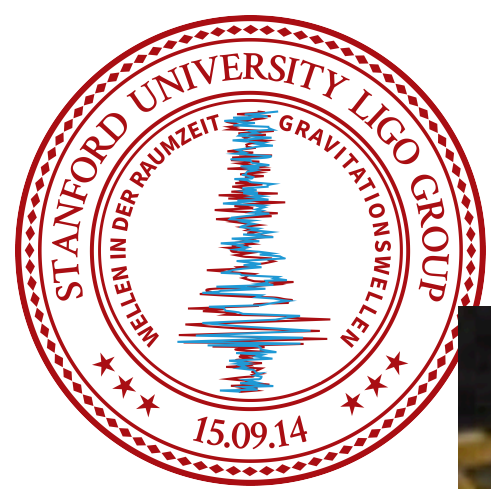
Initial to Advanced



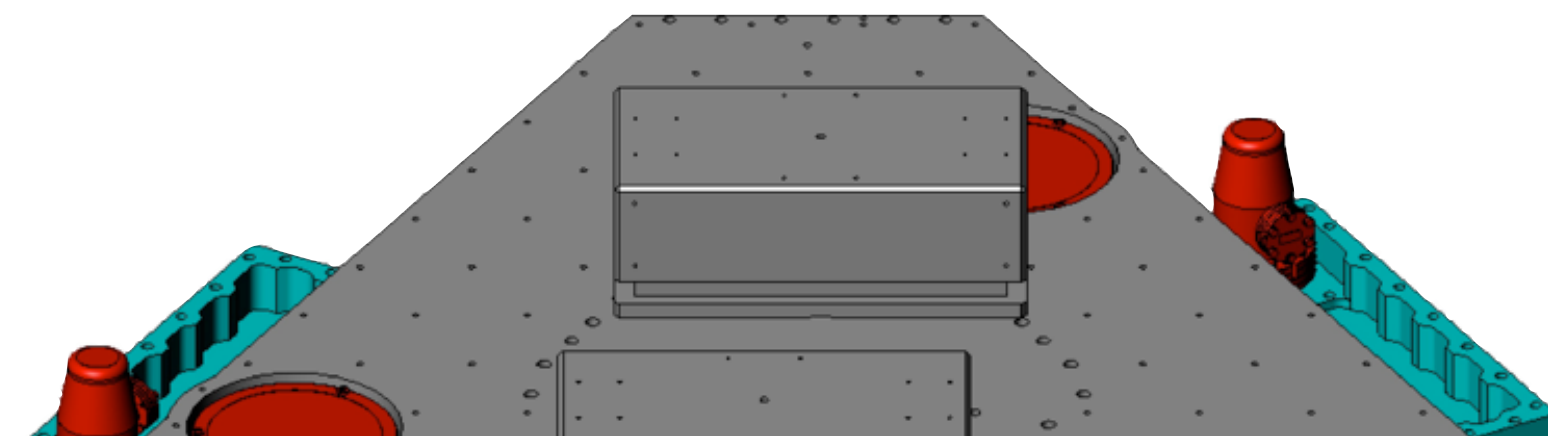
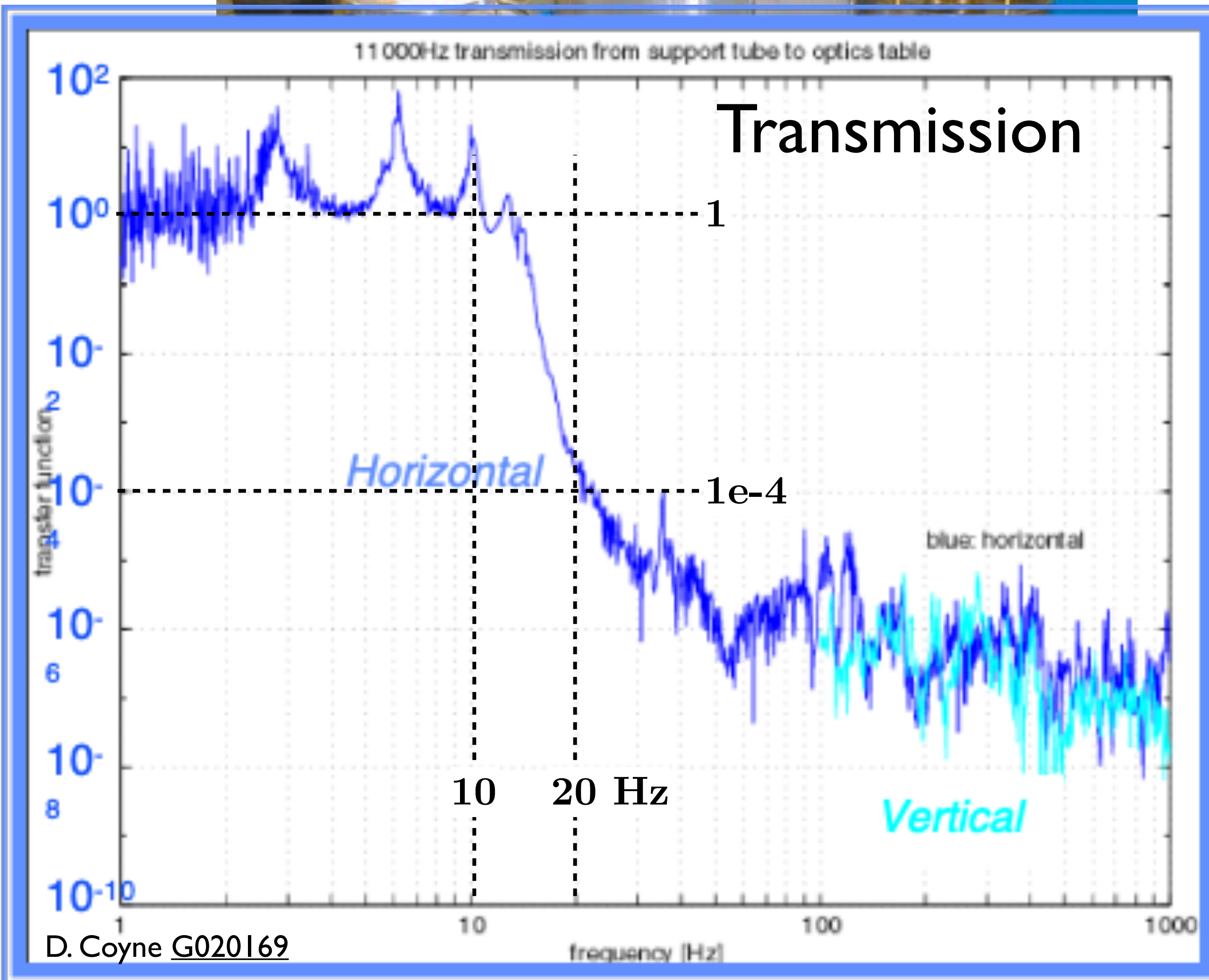
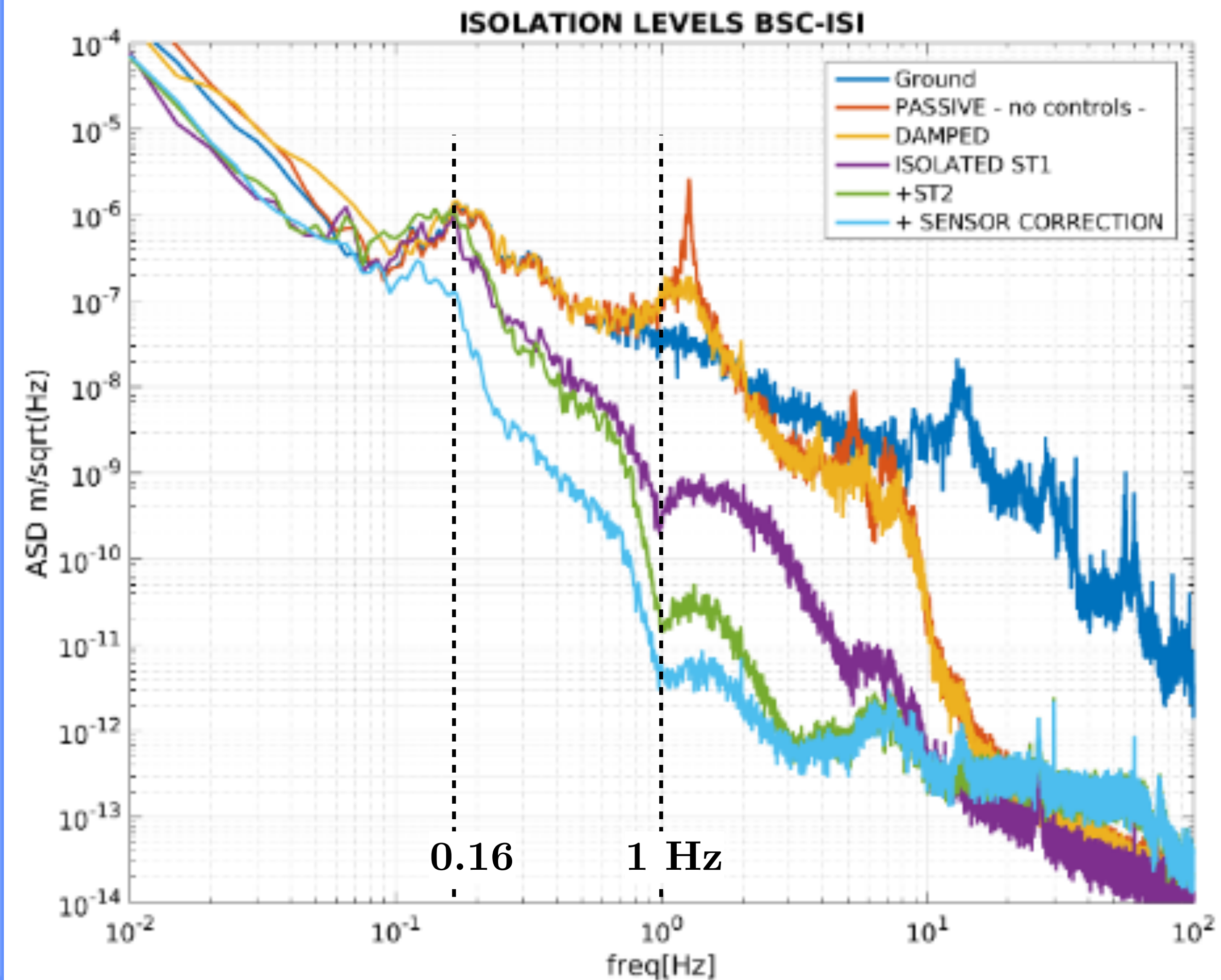
Initial LIGO (first article for testing)
All Passive, 4 layers of masses and springs
Almost no diagnostics
supports a single stage suspension

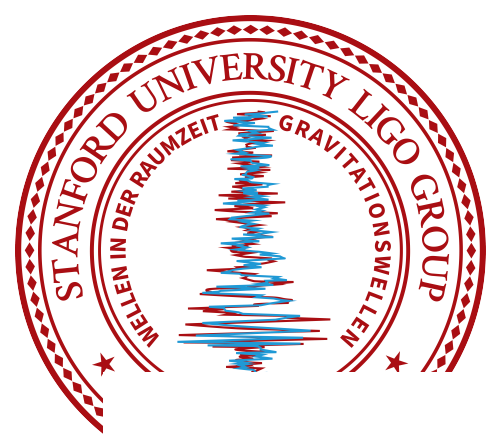


Advanced LIGO
Passive/ Active Hybrid, 2 stages
Excellent diagnostics
supports a 4-stage suspension



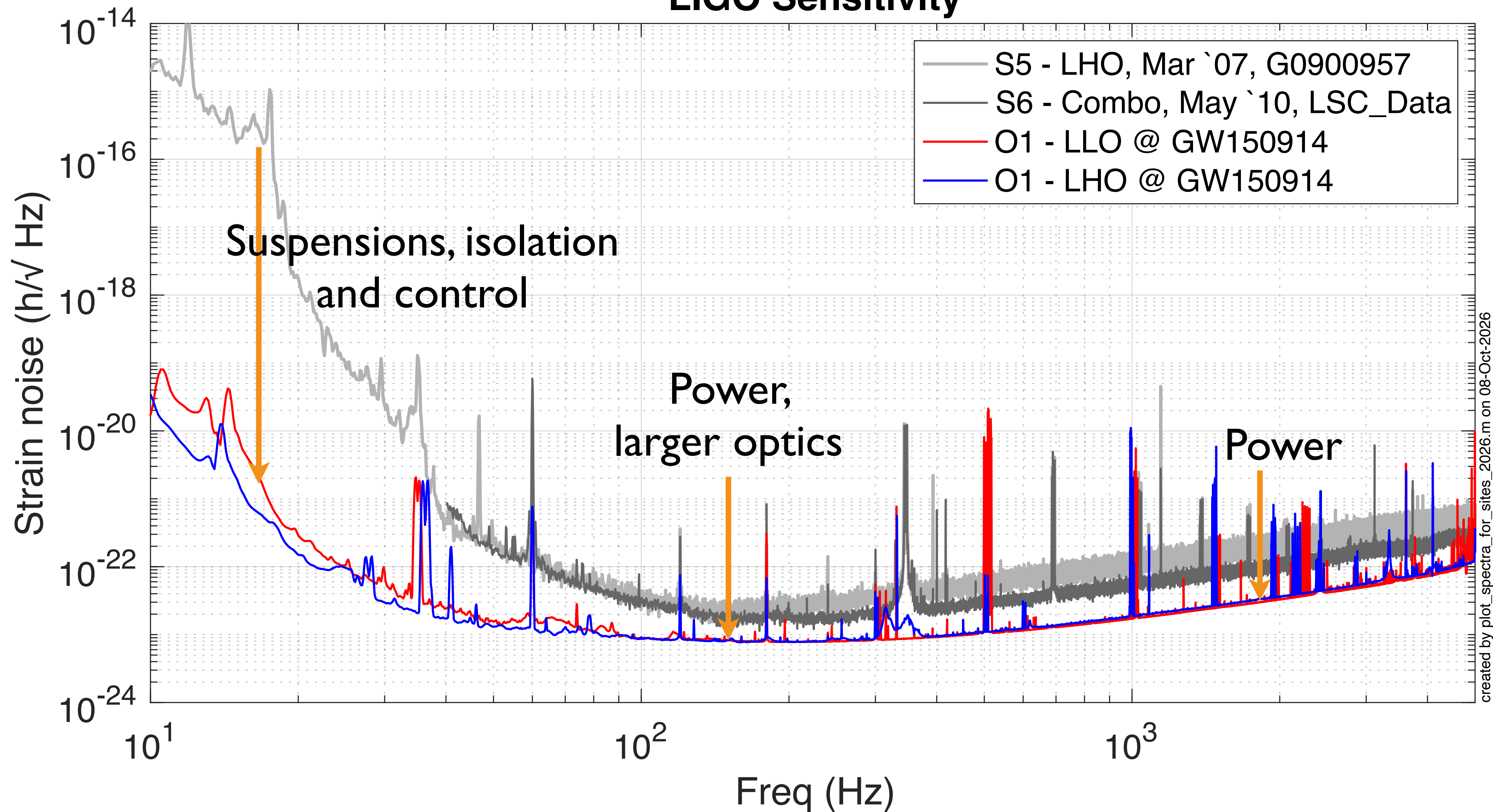
Initial to Advanced

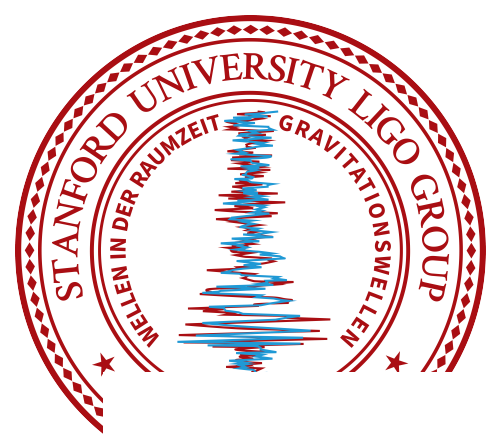




Detector Performance

LIGO Sensitivity

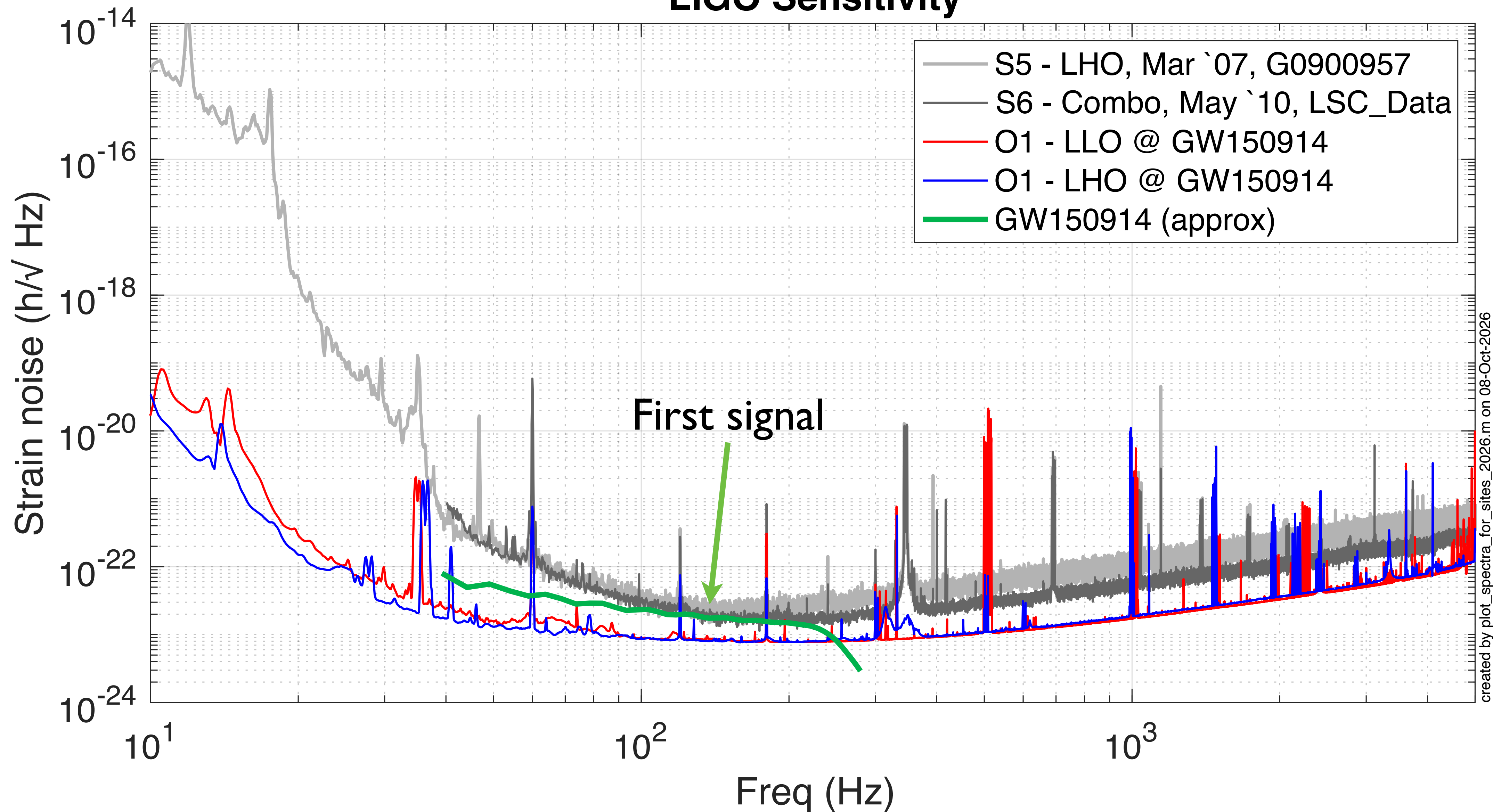


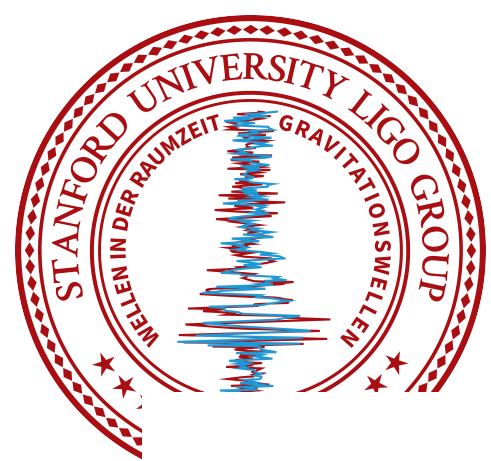


Detector Performance



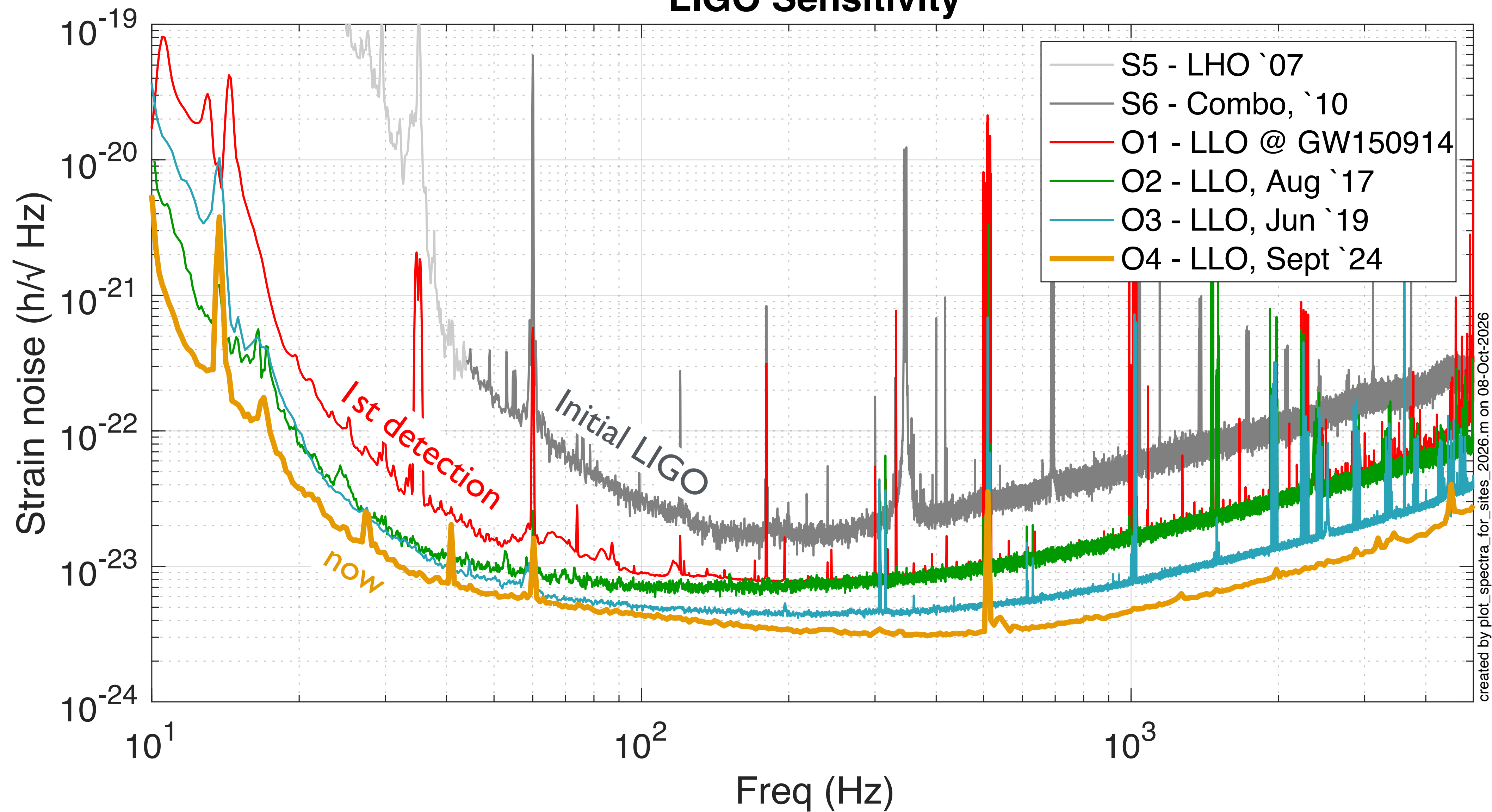
LIGO Sensitivity

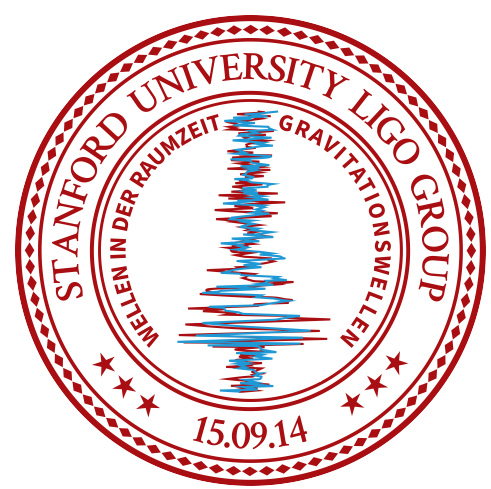




Detector Performance

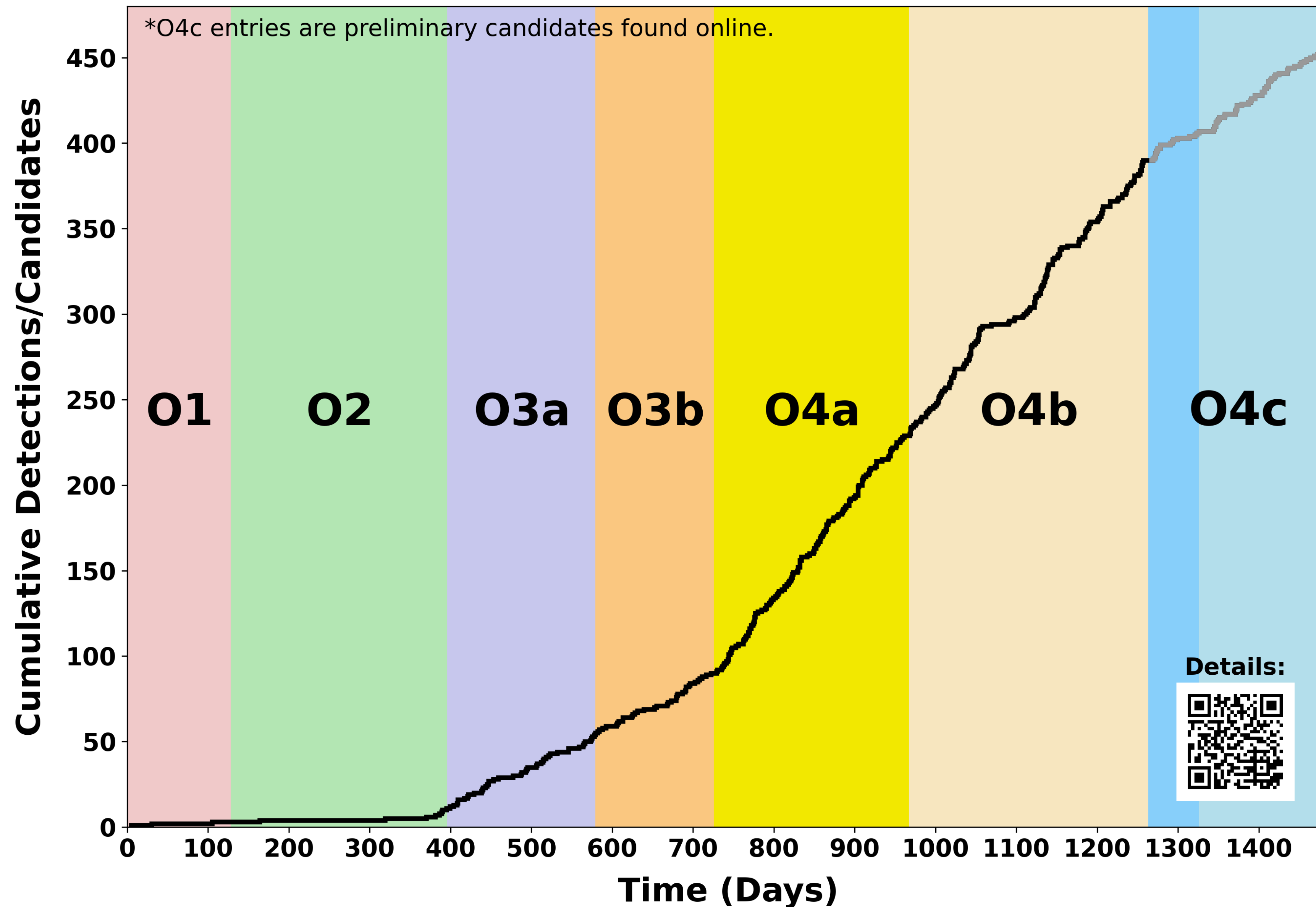
LIGO Sensitivity





Cumulative Detections

O1 (3) + O2 (8) + O3a (44) + O3b (35) + O4a (139) + O4b (161) = 390, O4c* = 68, Total = 458

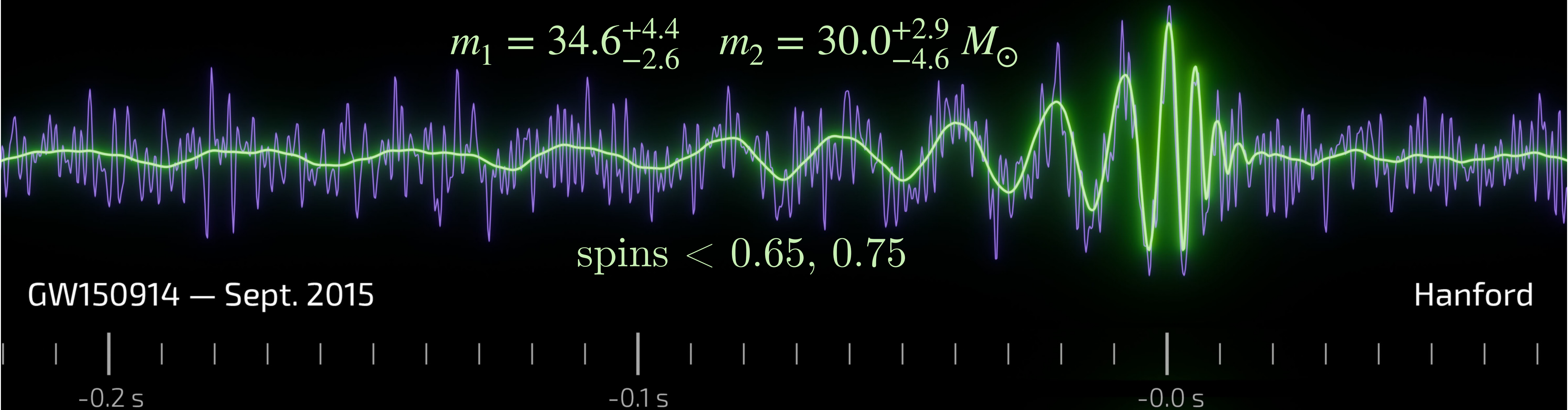
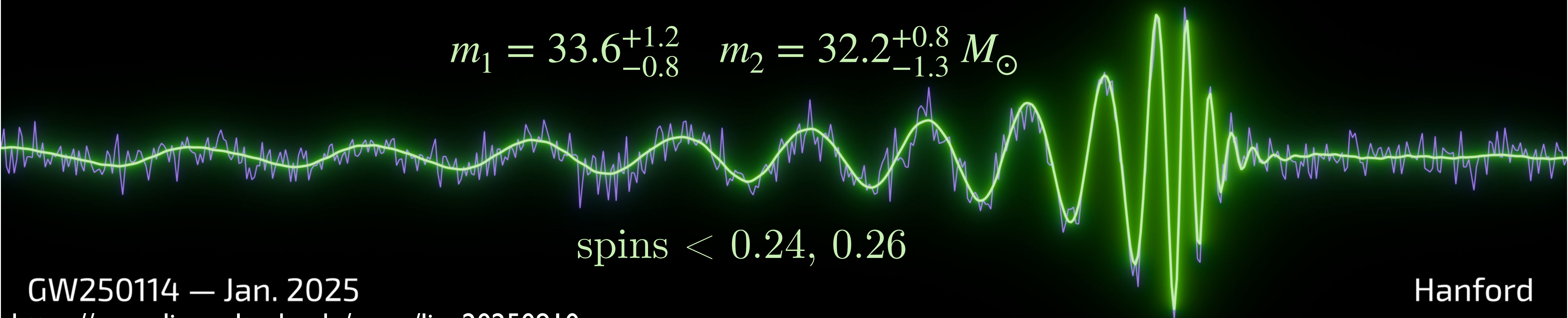


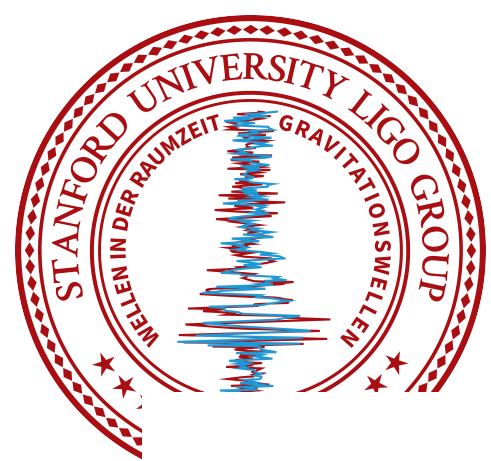
10 Years Later: LIGO Hears Loud and Clear

spins of GW150914: [arXiv:1606.01210](#)

masses of GW150914: [arXiv:2108.01045](#)

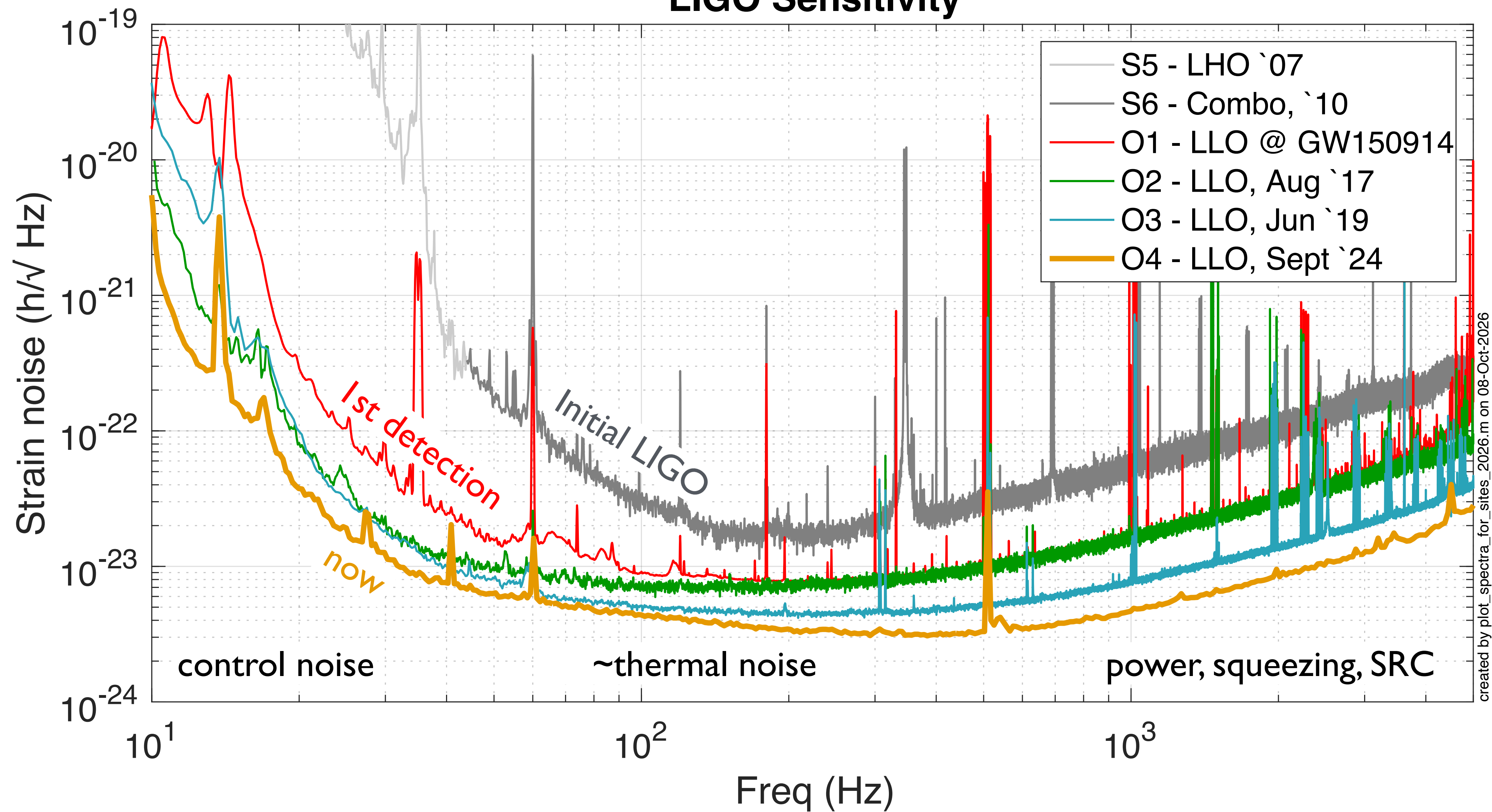
GW250114: [arXiv:2509.08099](#)





Detector Performance

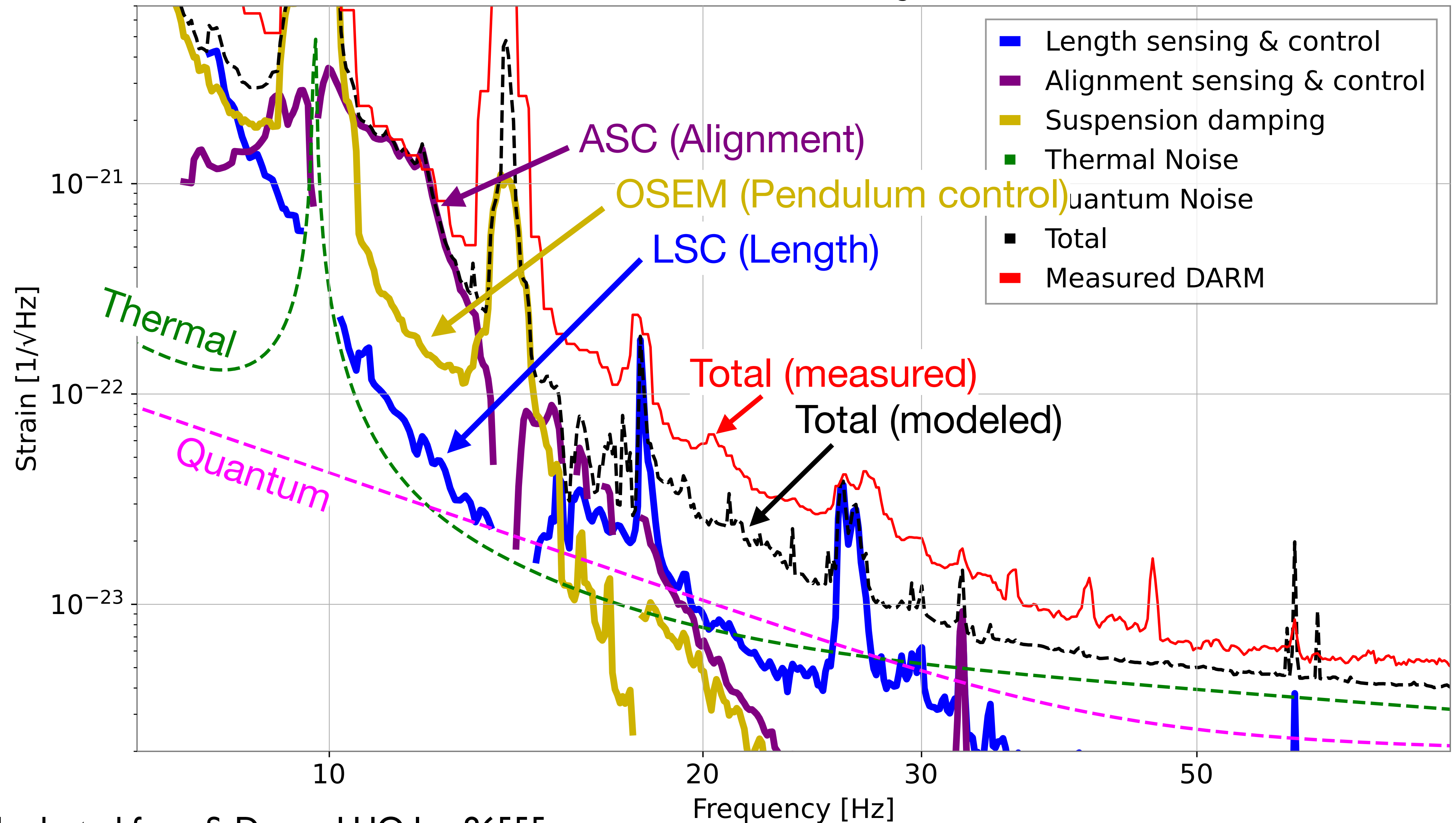
LIGO Sensitivity





Actual Detector Noise

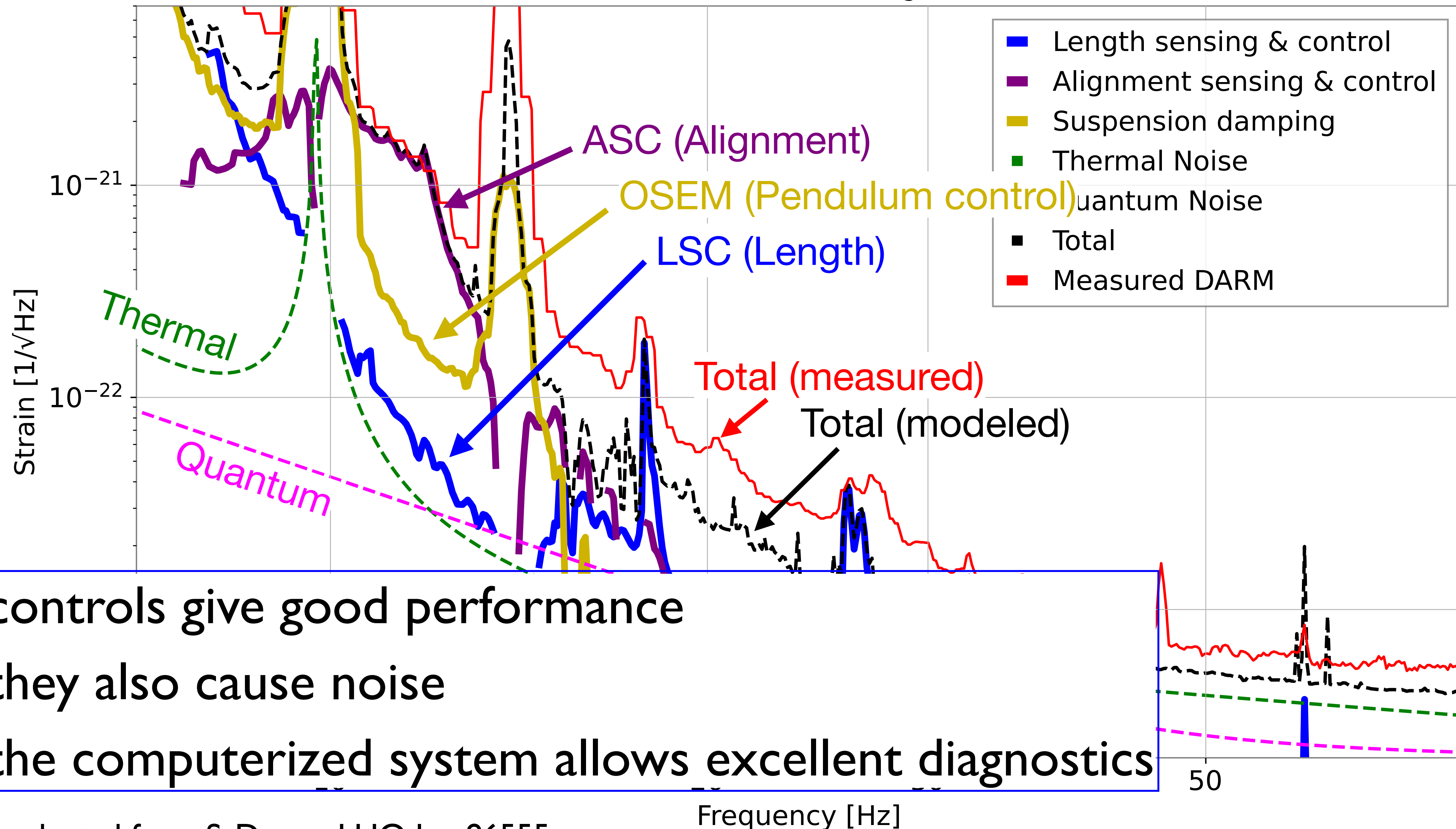
LIGO Hanford Noise Budget



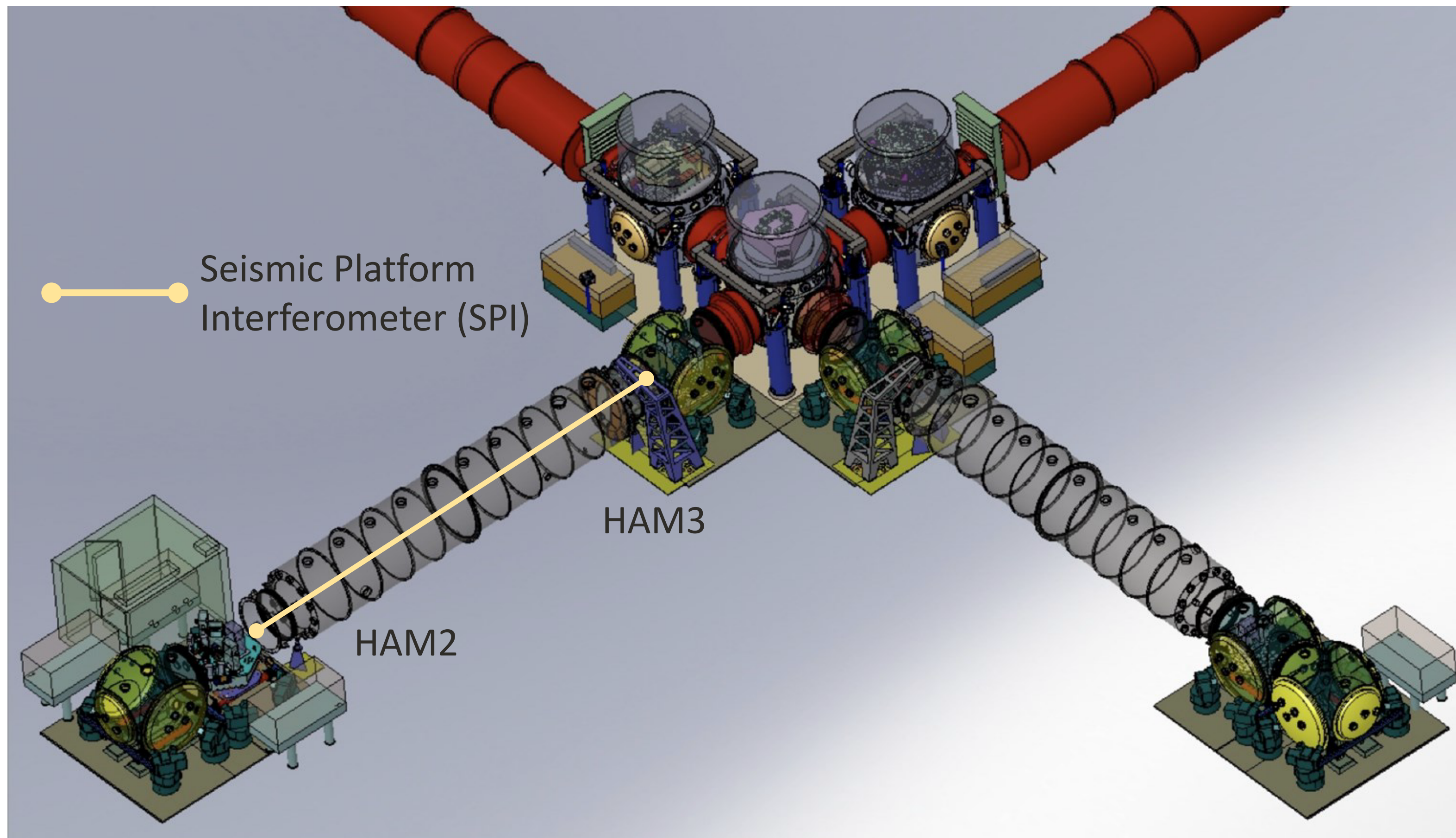


Actual Detector Noise

LIGO Hanford Noise Budget



Stabilizing the interferometer with more interferometers

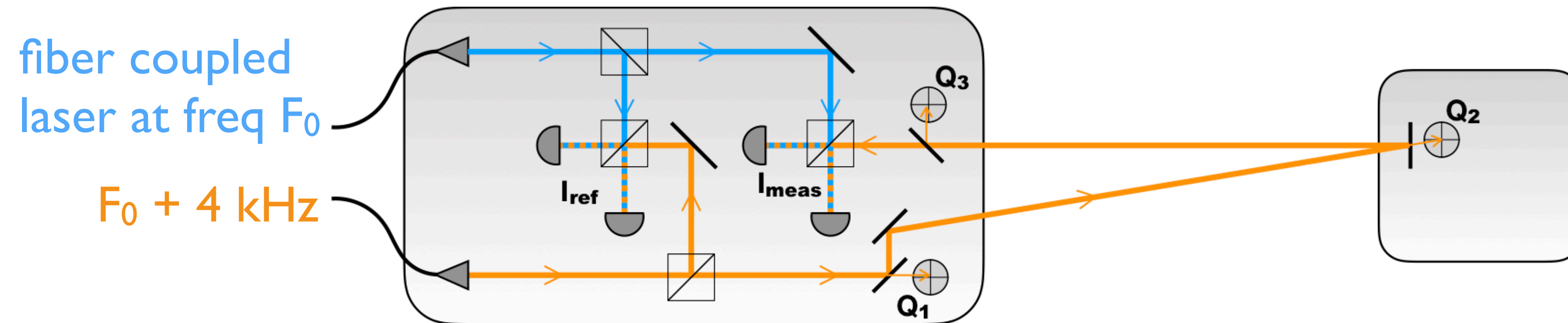


- Measure tilt and differential displacement between Internal Seismic Isolation (ISI) systems
- Explorative pathfinder between vacuum chambers HAM2 and HAM3 at LHO
- Host to input mode cleaner and power recycling mirrors
- Installation after O4!



Seismic Platform Interferometer

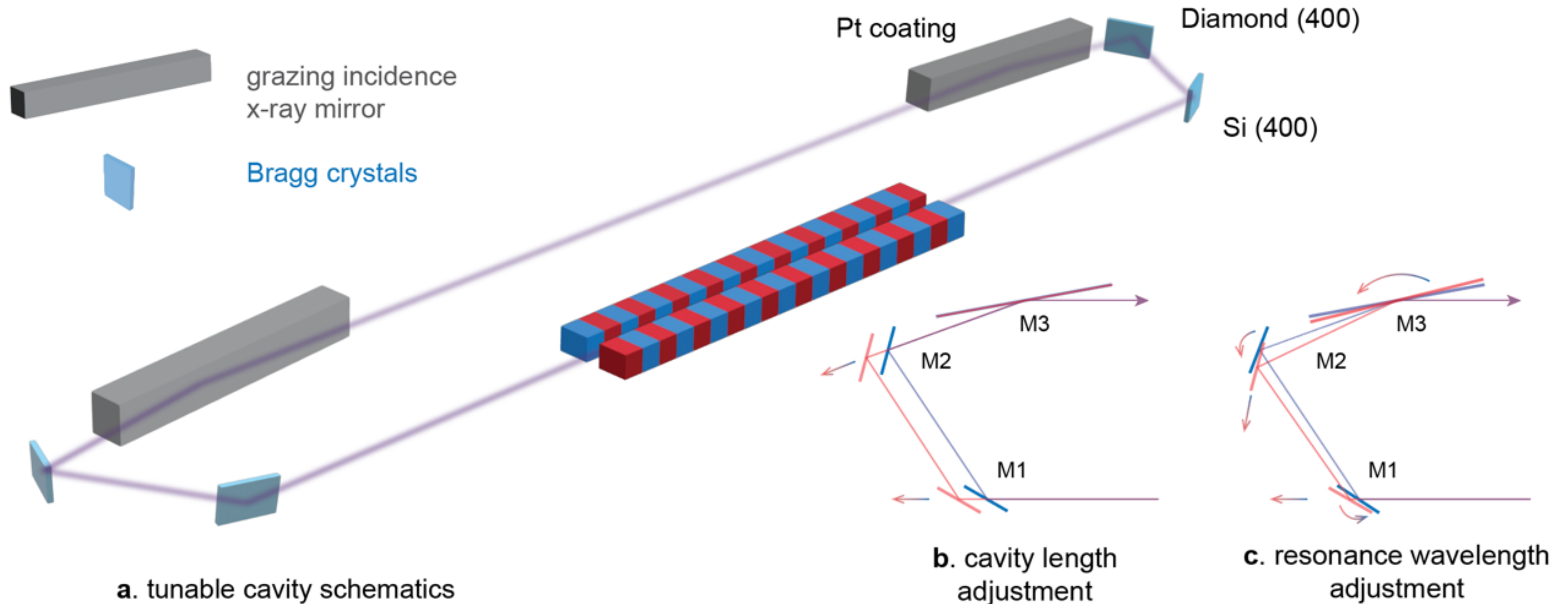
- Phase tracking heterodyne interferometer
- Phase of the beat note tracks the length change
position of beam on quad diodes measures angle change
- based on the LISA phase-meter



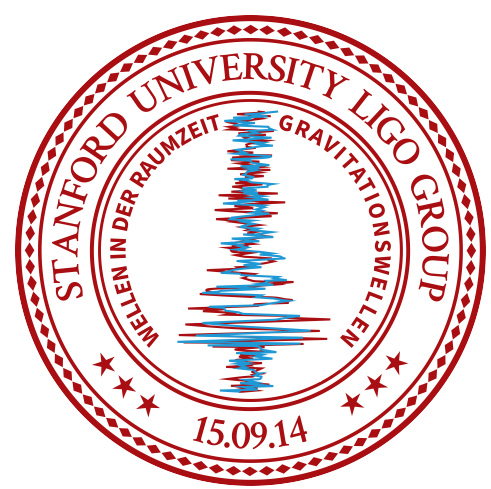
Recently adapted to an XFEL experiment at SLAC

SPI at SLAC

Stabilize the x-ray beam
co-propagate (nearly) an optical beam to measure the path
use realtime servos to stabilize the path



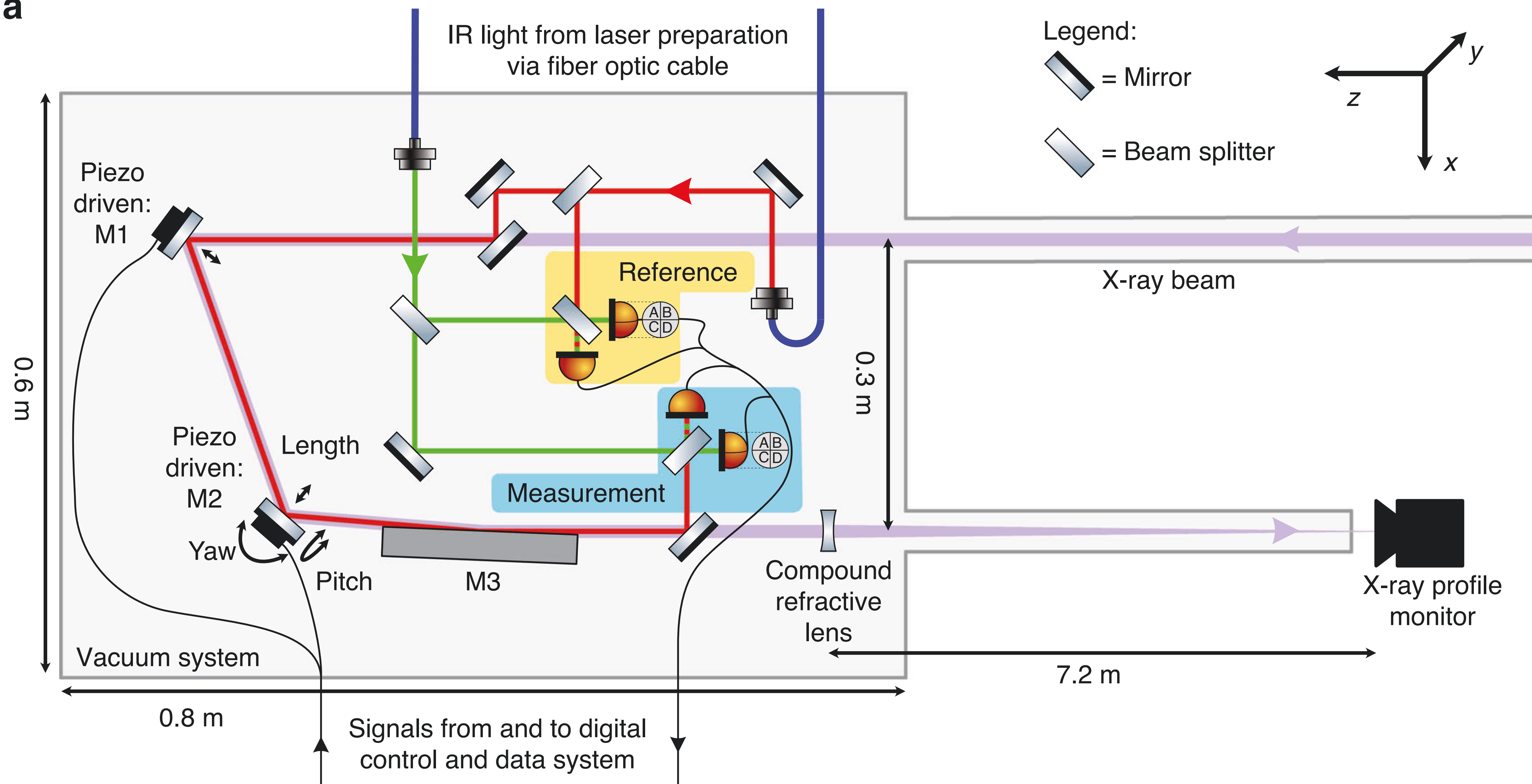
Sina Koehlenbeck w. Zhirong Huang, Diling Zhu, Jerry Hastings and others

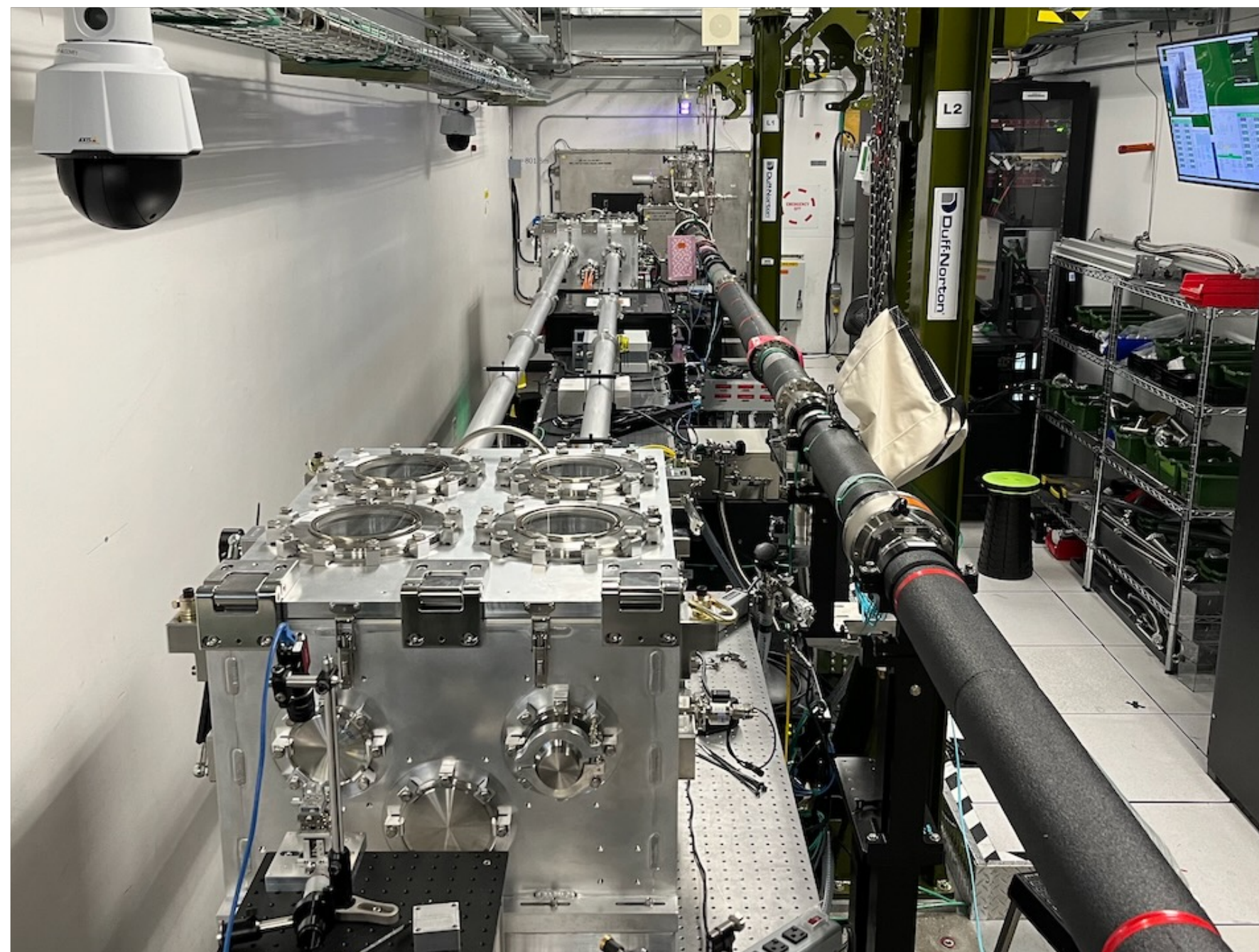
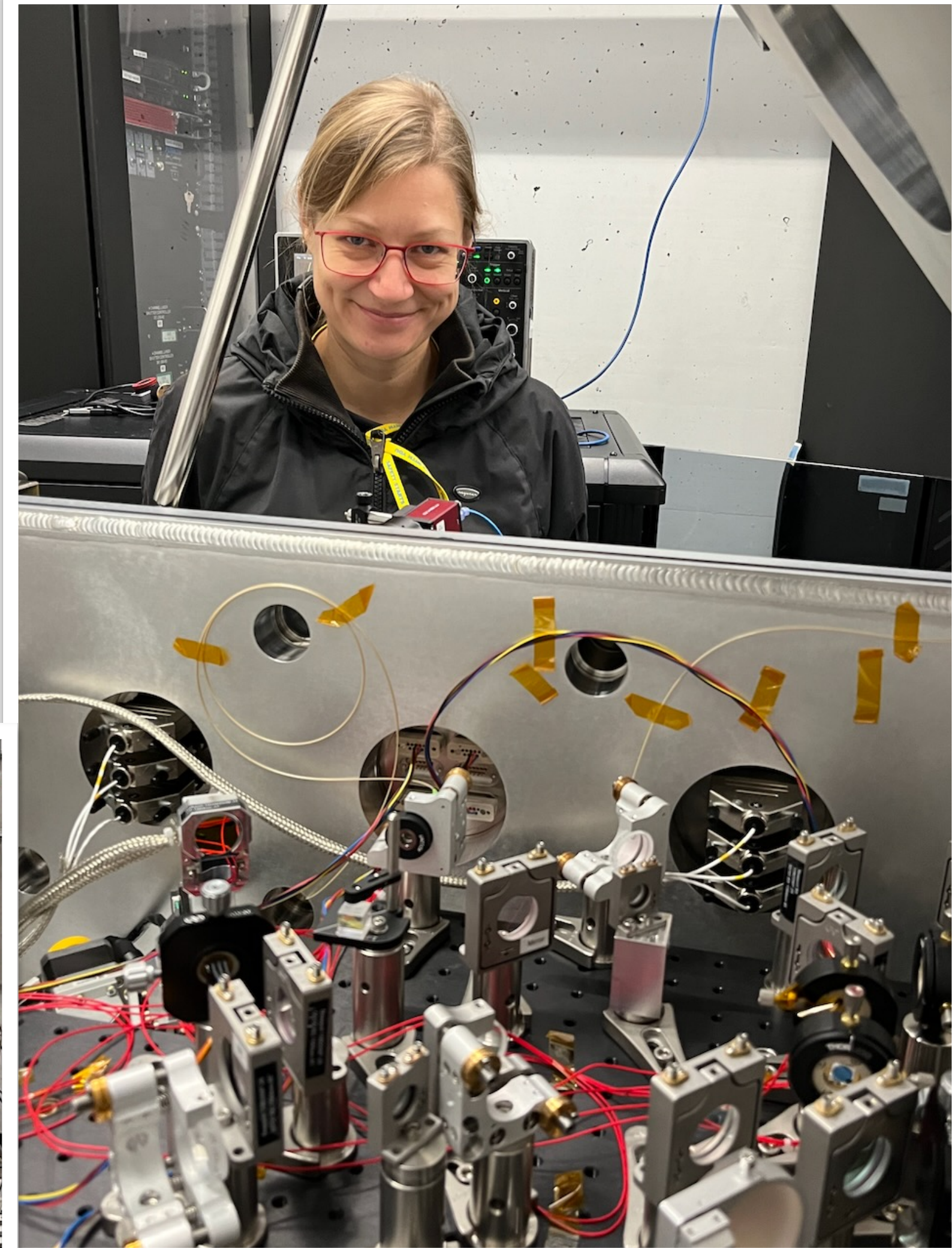
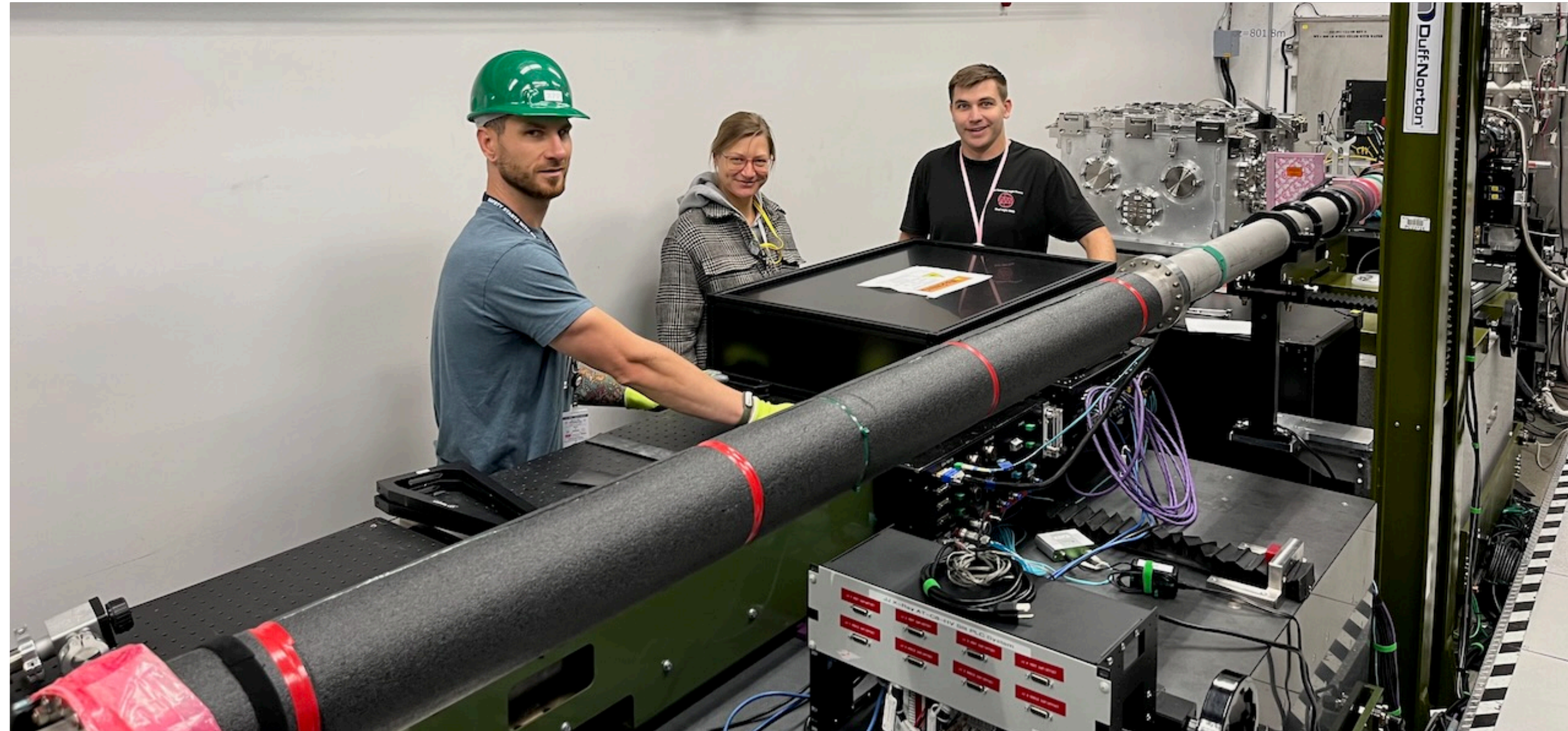


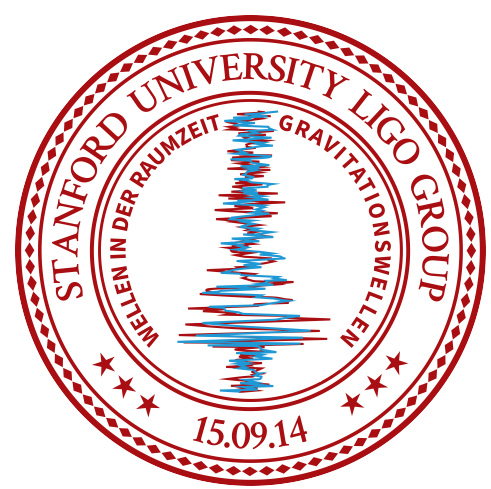
SPI at SLAC



a







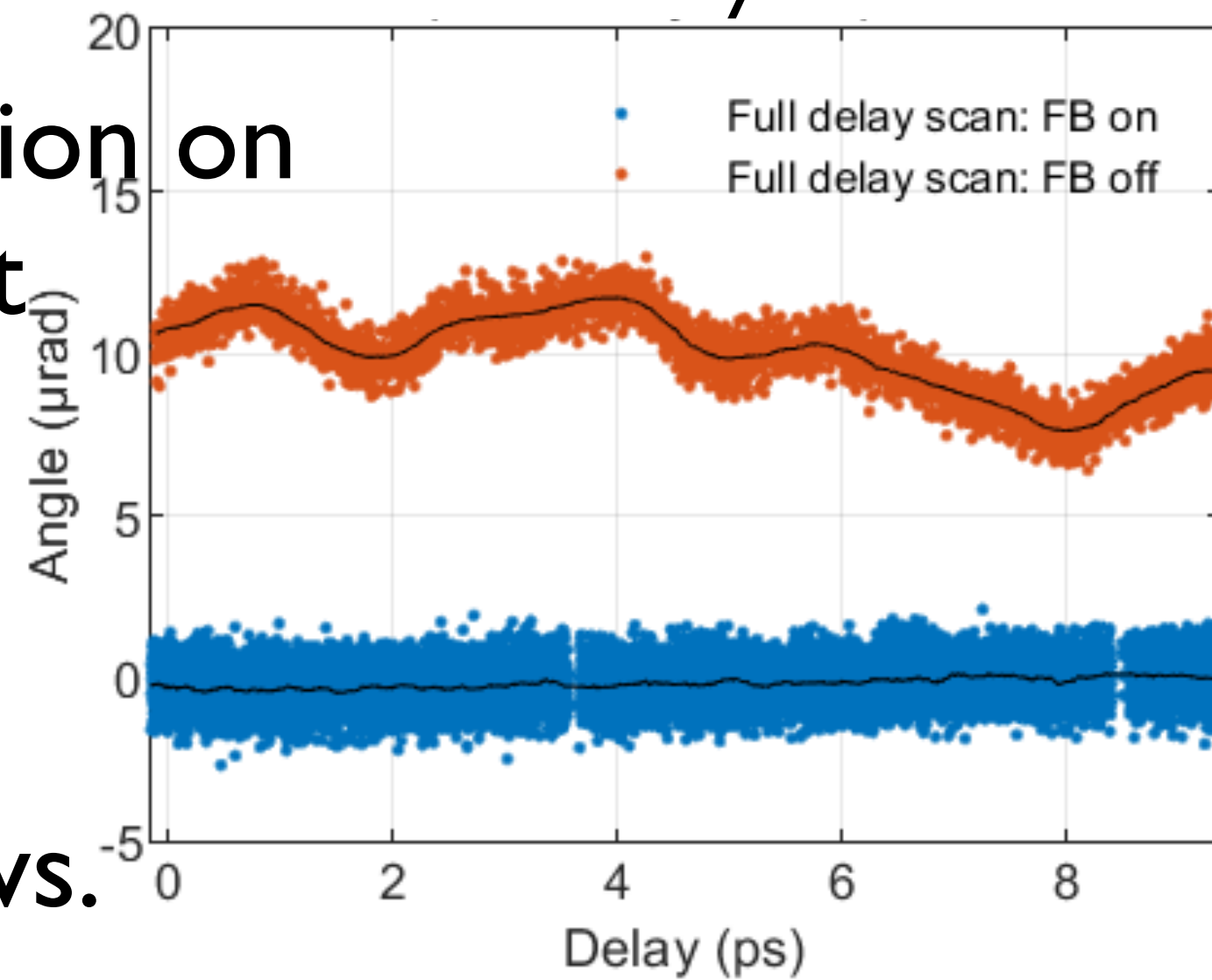
Active control makes it better



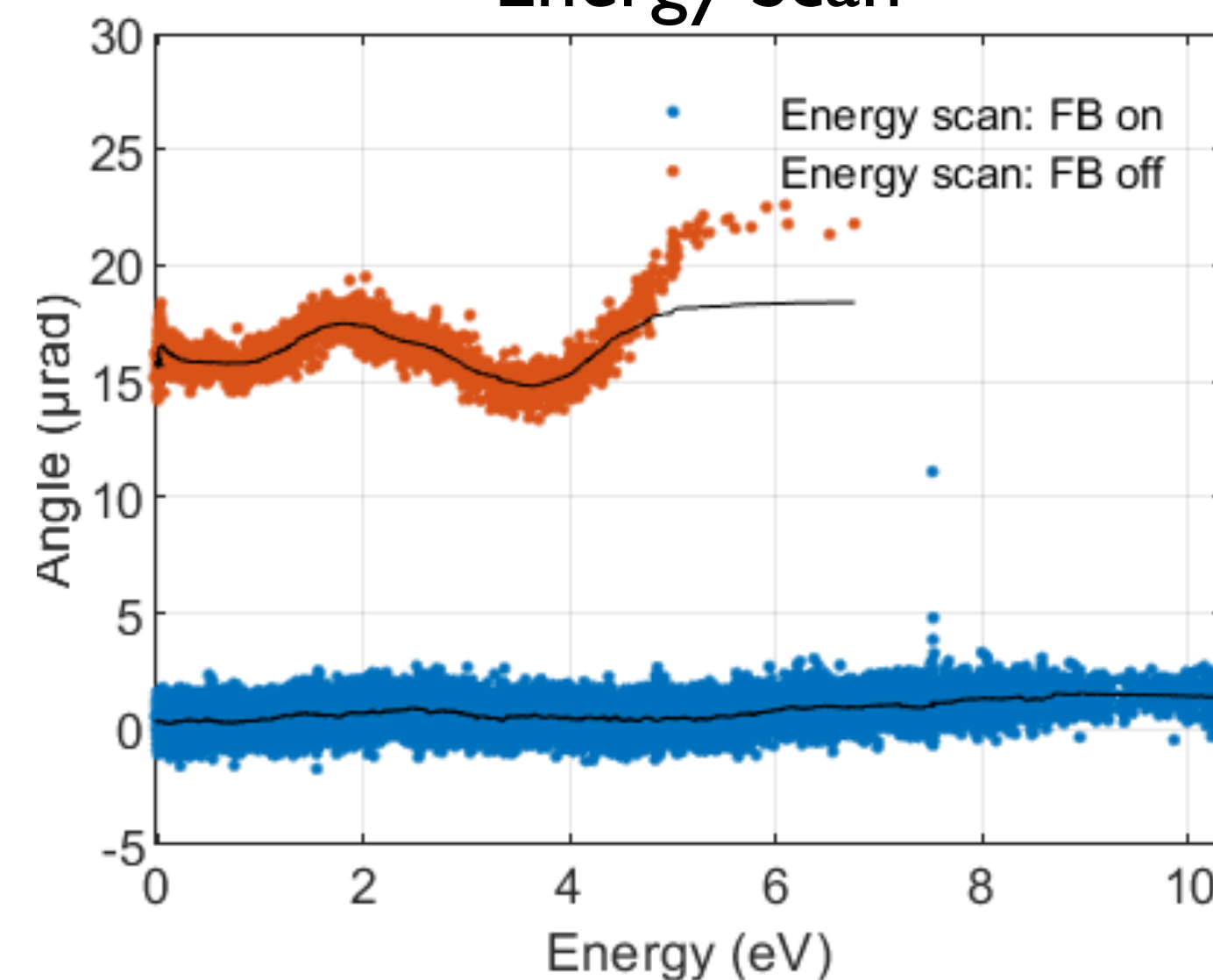
beam position on
x-ray target

open loop vs.
closed loop

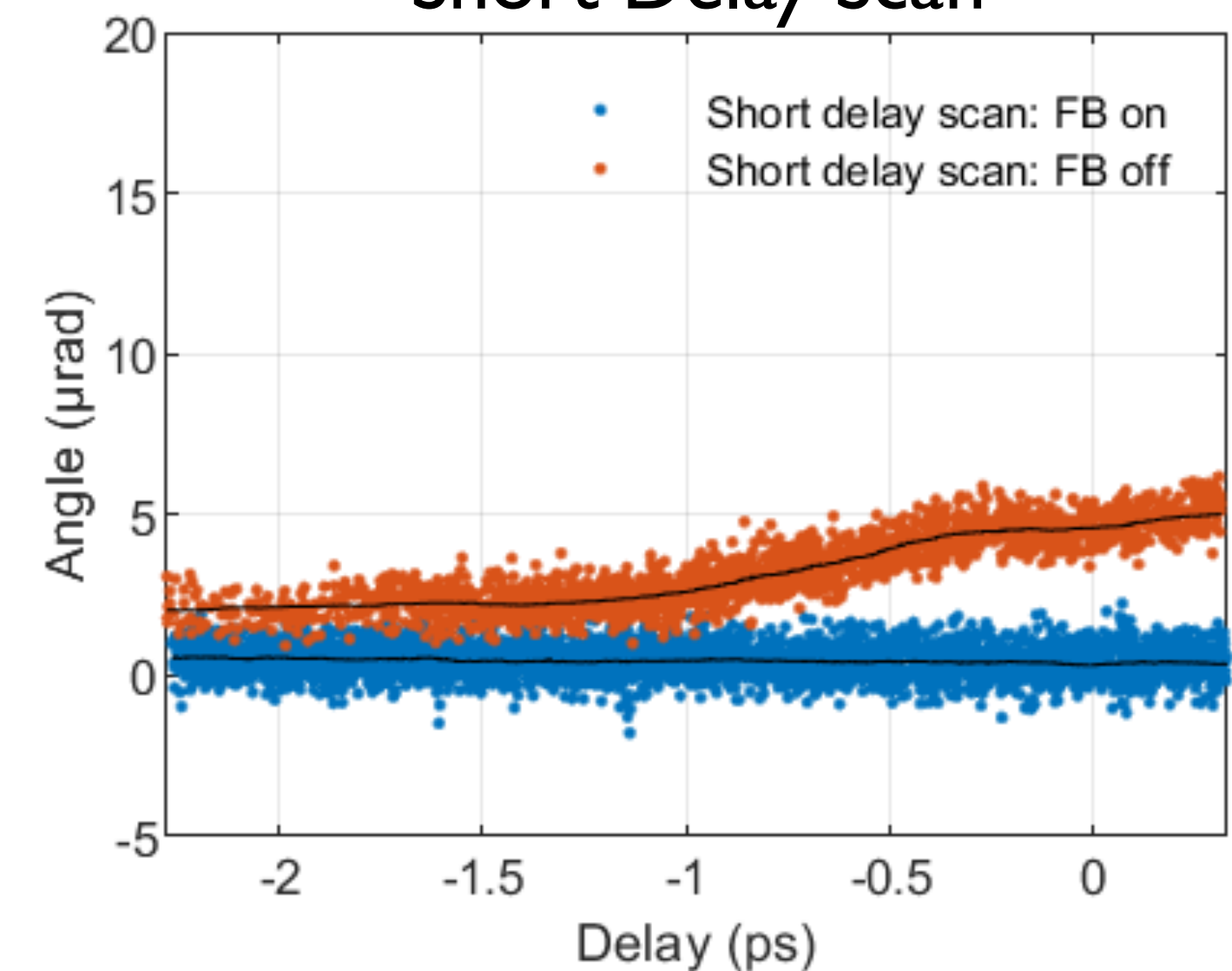
Full Delay Scan



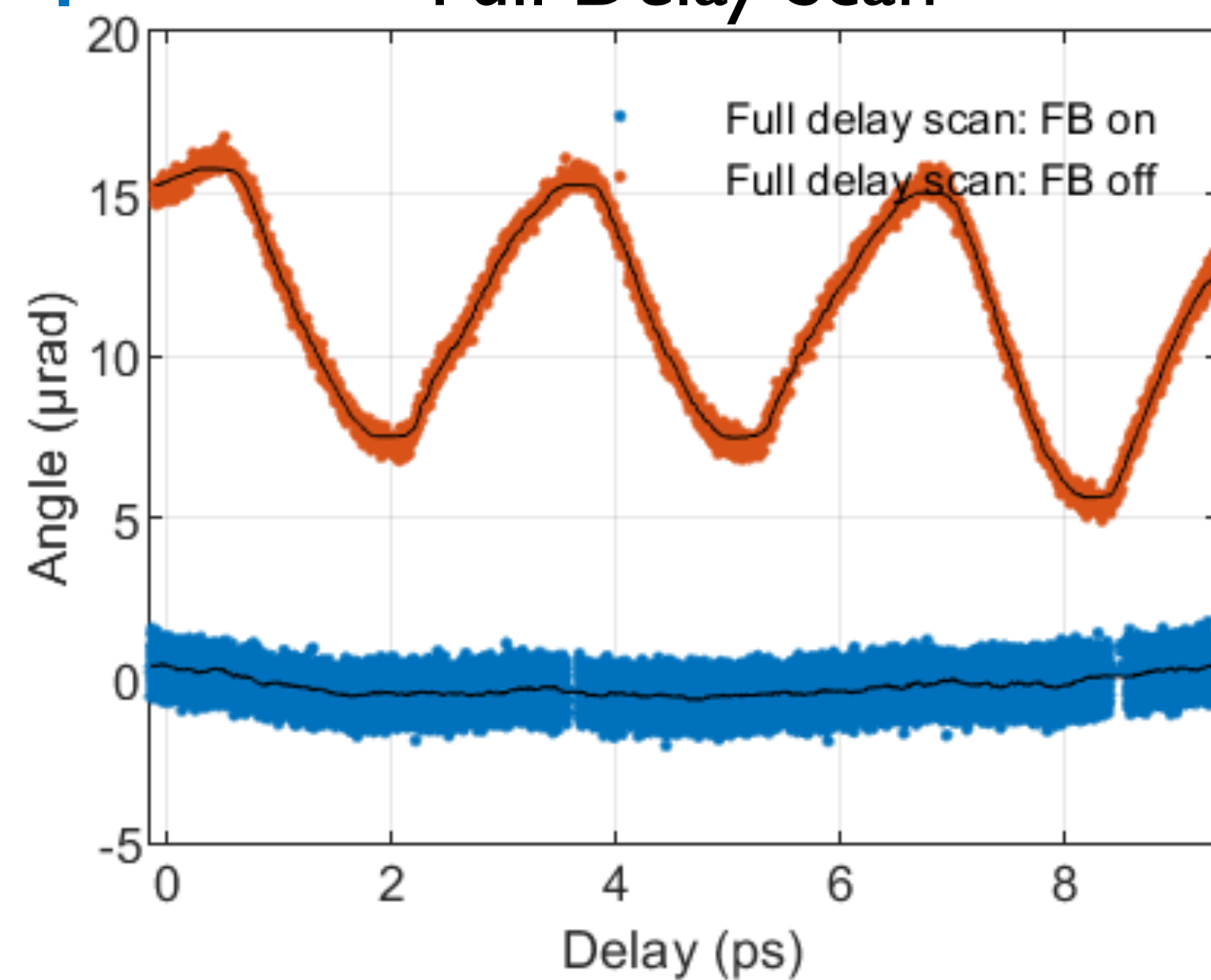
Energy Scan



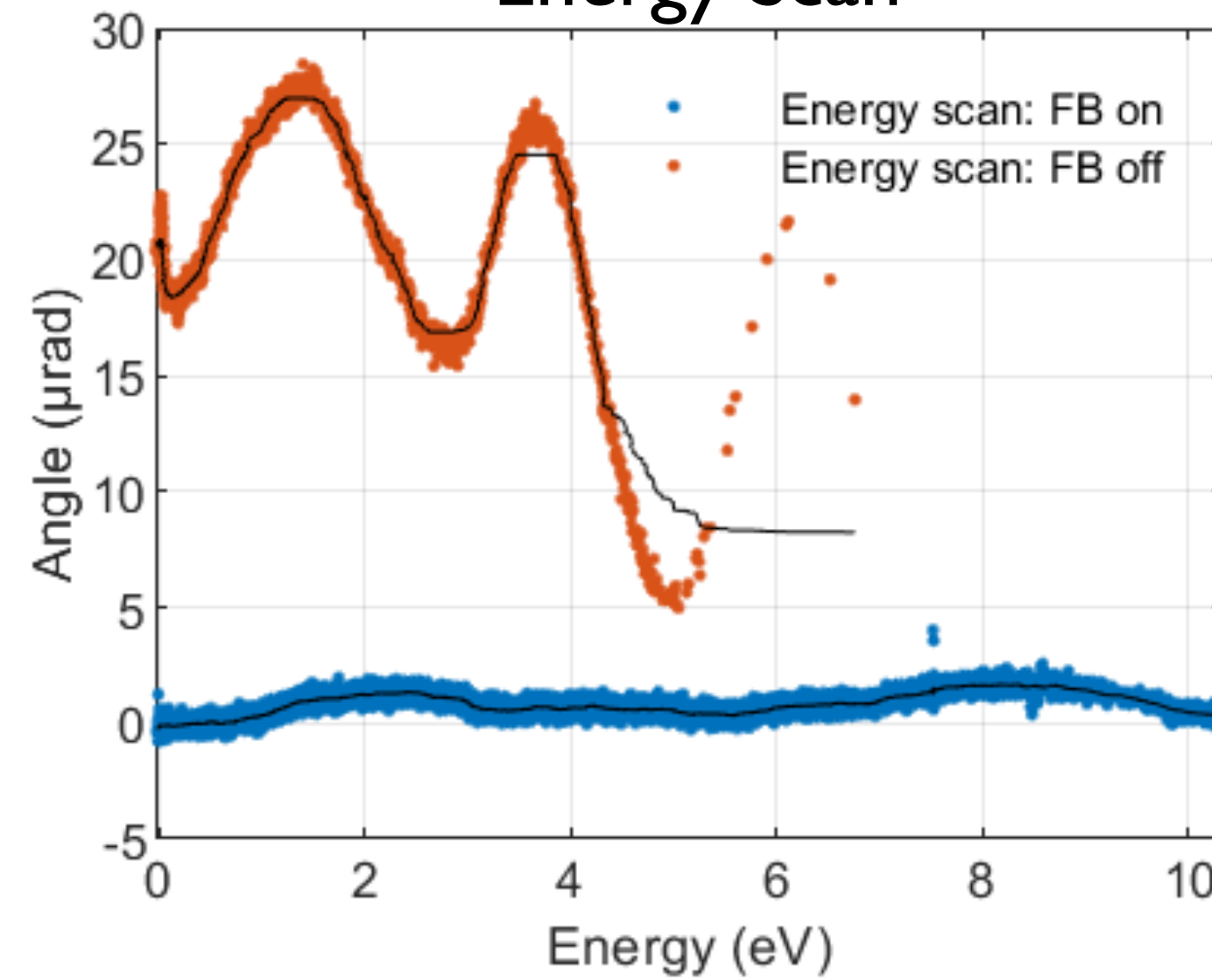
Short Delay Scan



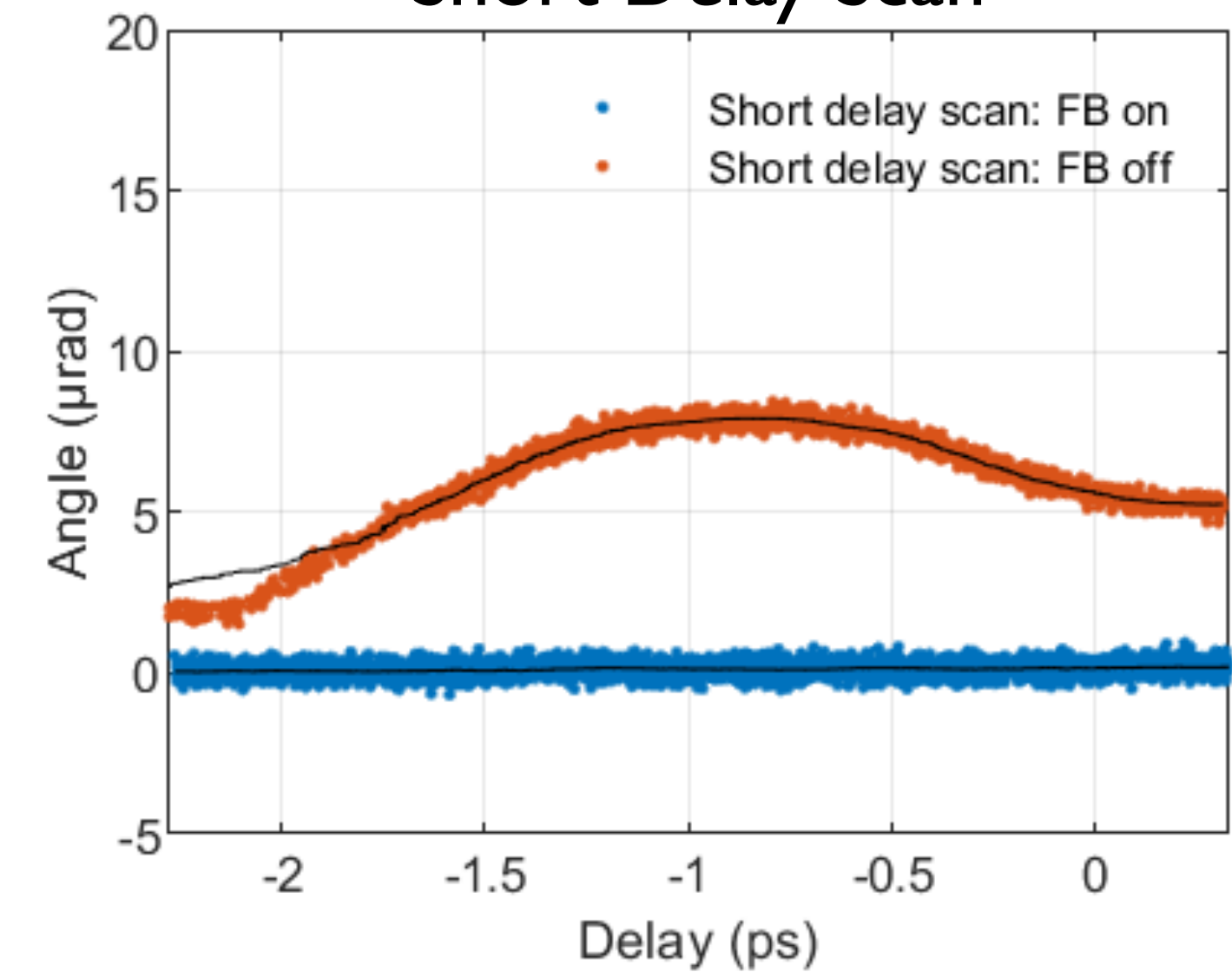
Full Delay Scan

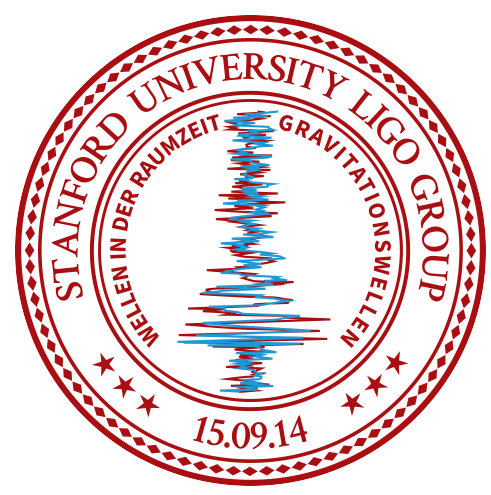


Energy Scan



Short Delay Scan

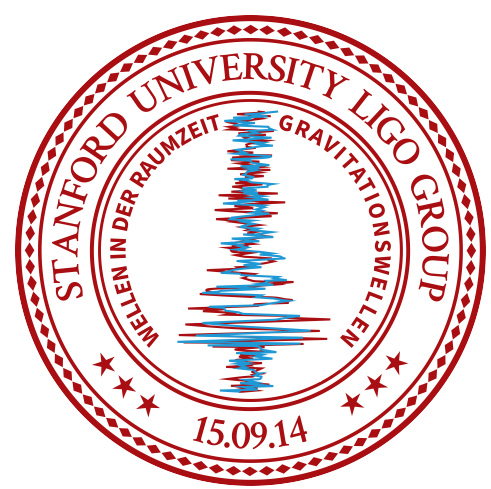




Summary



- Advanced LIGO is an example of an instrument designed with control in mind
- (almost) everything is monitored and controlled
- We get excellent performance
- We get excellent diagnostics
- Helps guide improvements
- Hopefully, some of the things we do have more general application

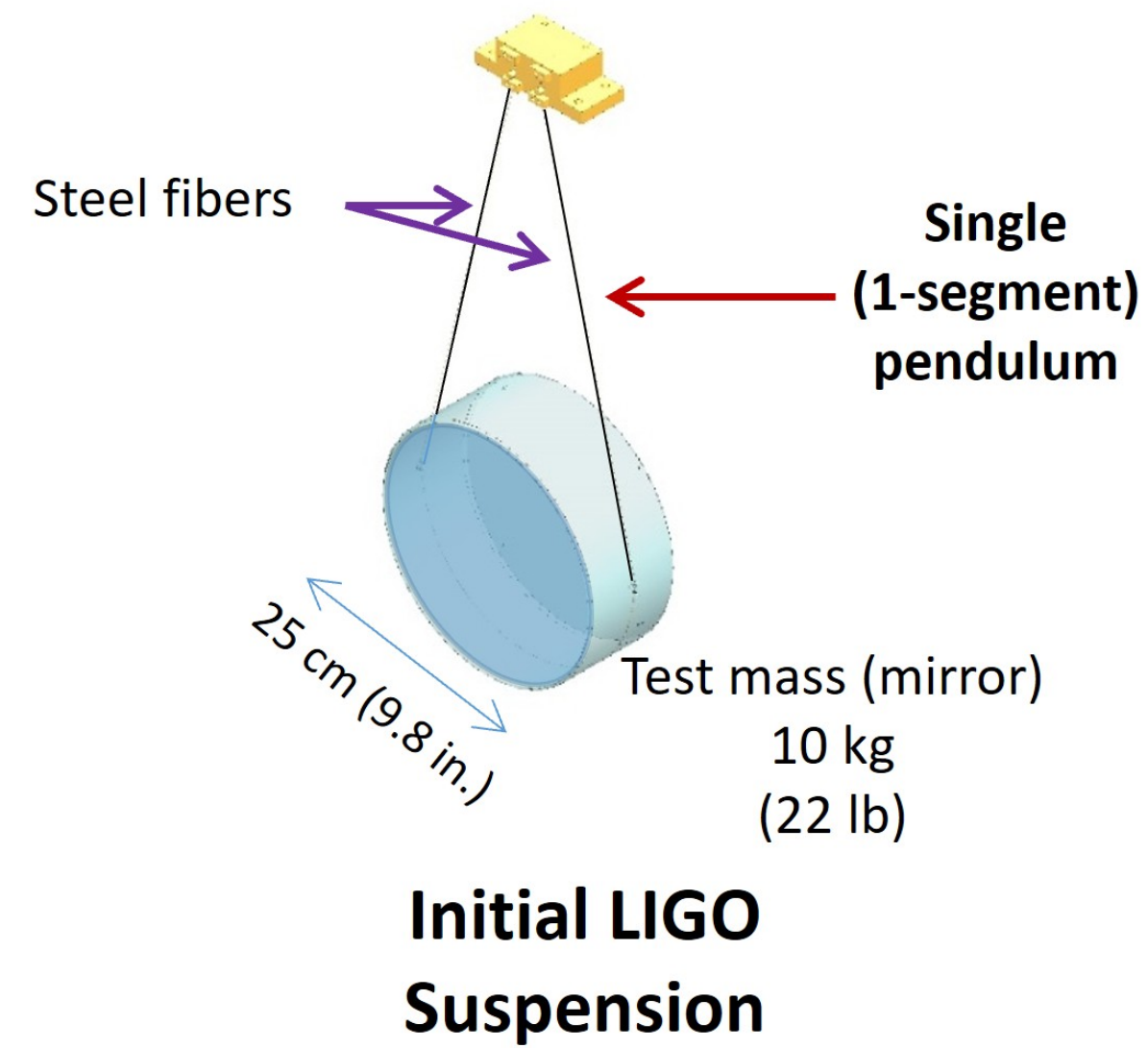


extra slides





aLIGO Suspension (UK led)



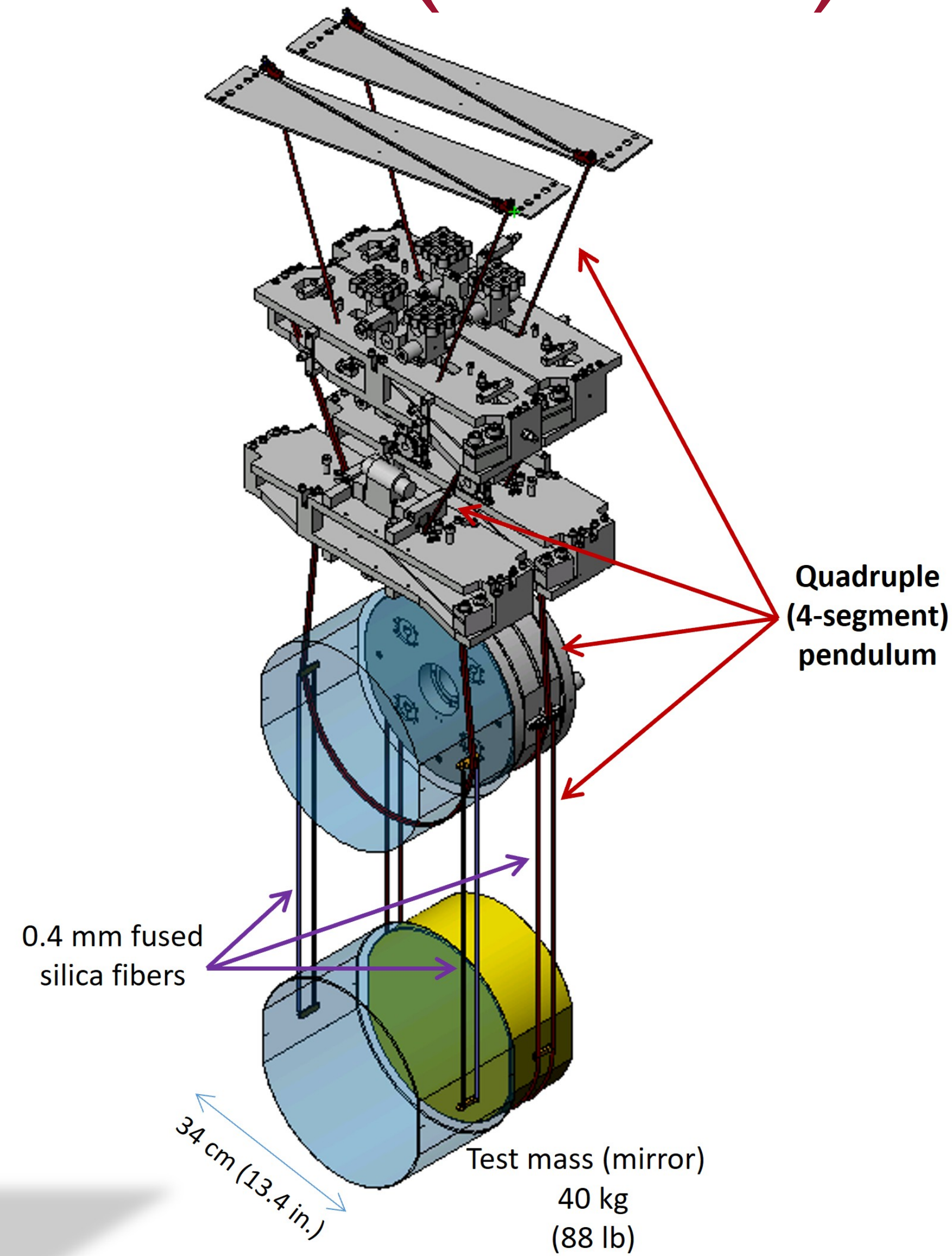
**Initial LIGO
Suspension**

iLIGO vs aLIGO suspension systems

These engineering drawings illustrate the striking differences between Initial and Advanced LIGO's suspensions. The suspensions are shown to scale.

Initial LIGO's suspension was a single pendulum design with a 10 kg (22 lb) 'test mass' (mirror) hung by steel fibers.

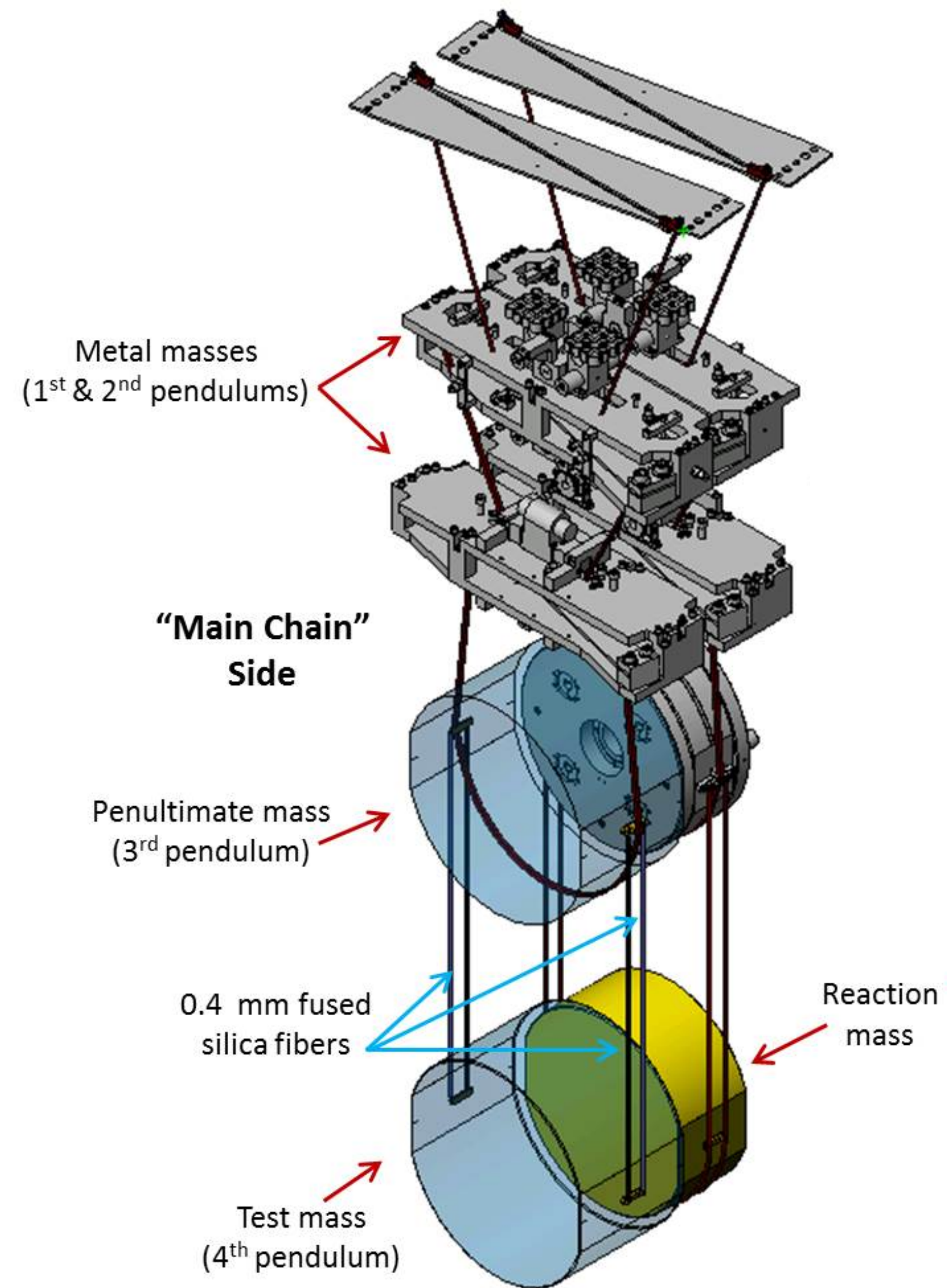
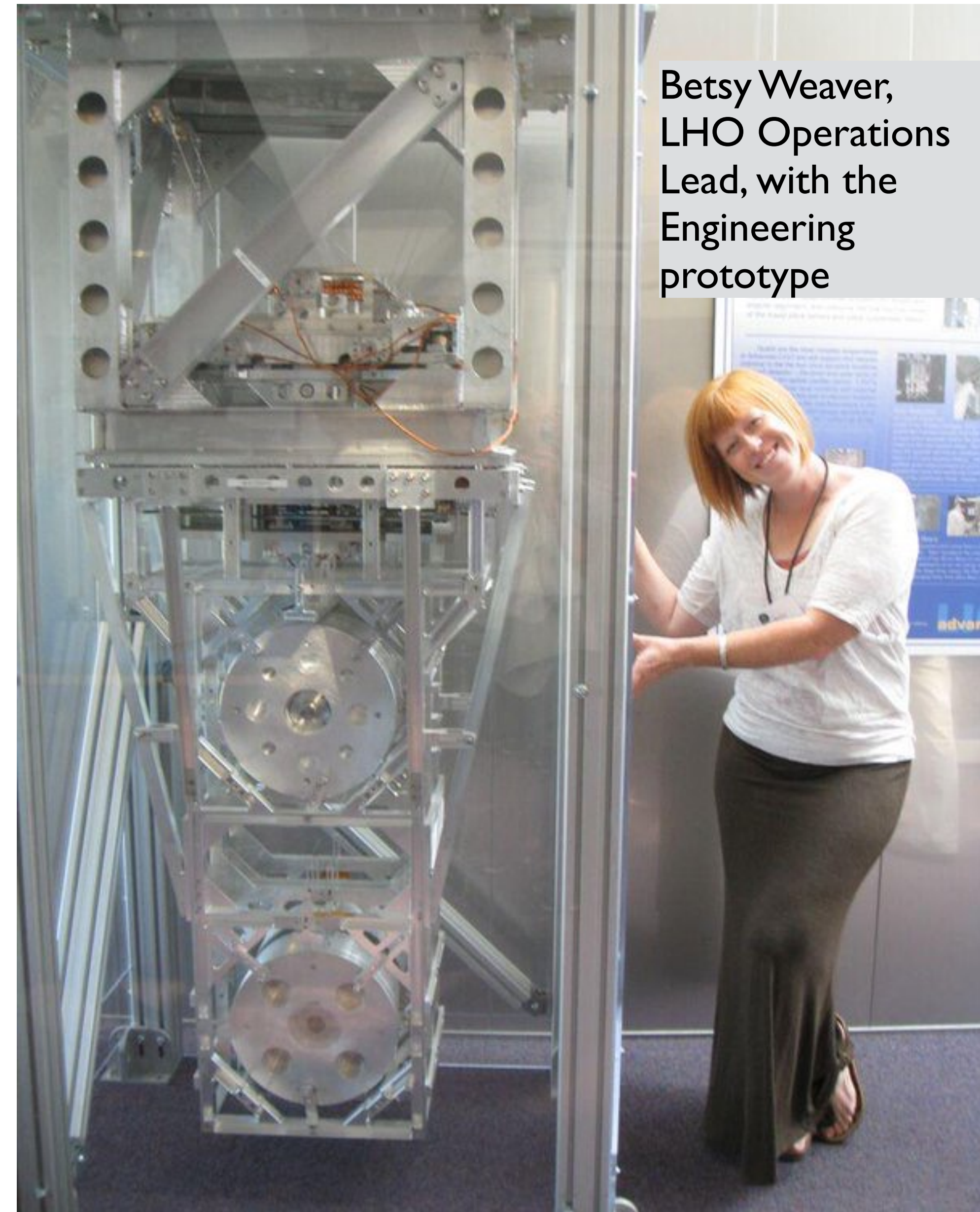
Advanced LIGO's suspension system is a much heavier quadruple ("quad") pendulum with a 40 kg (88 lb) test mass hung by fused silica fibers.



**Advanced LIGO
Suspension**

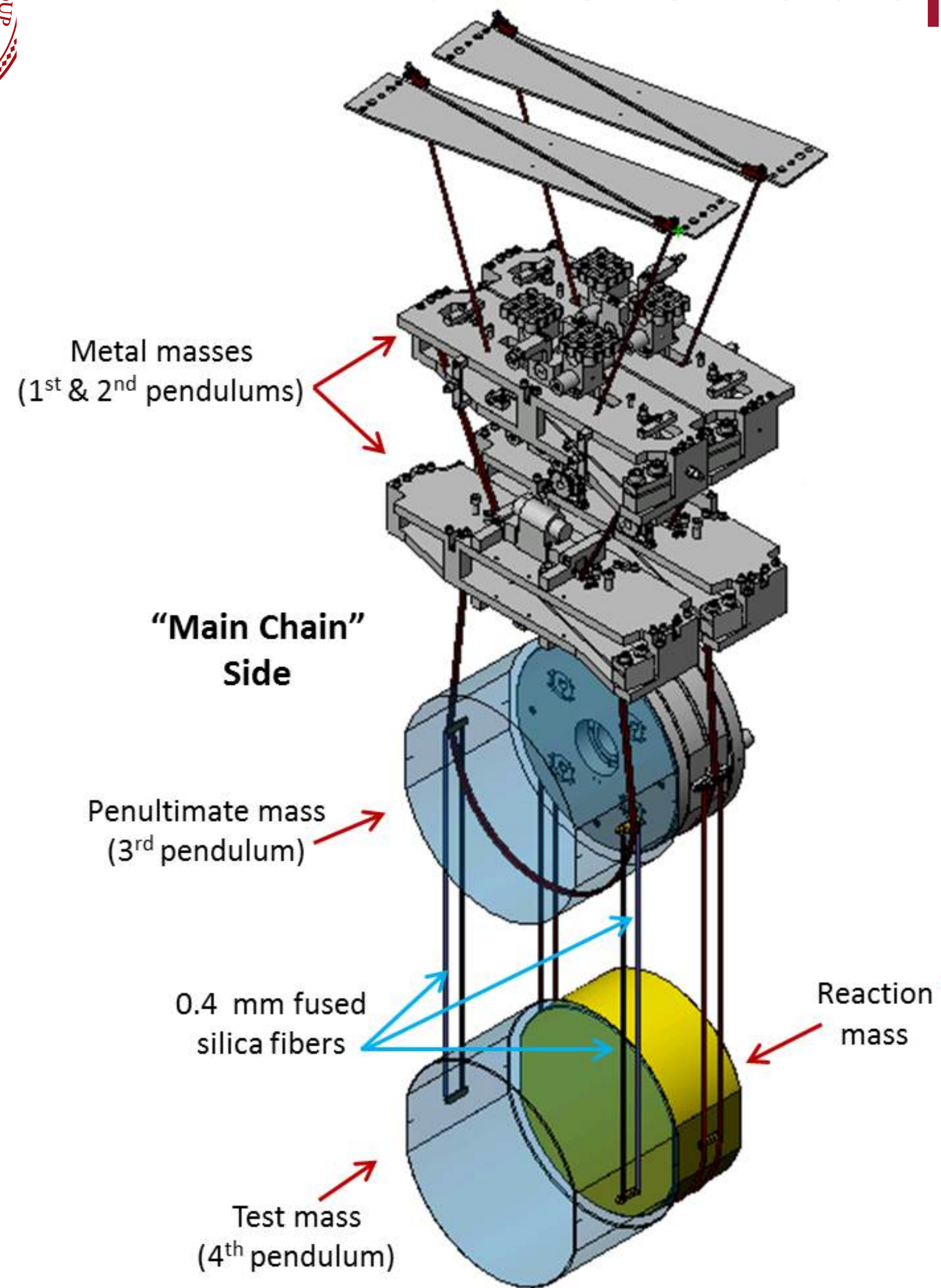
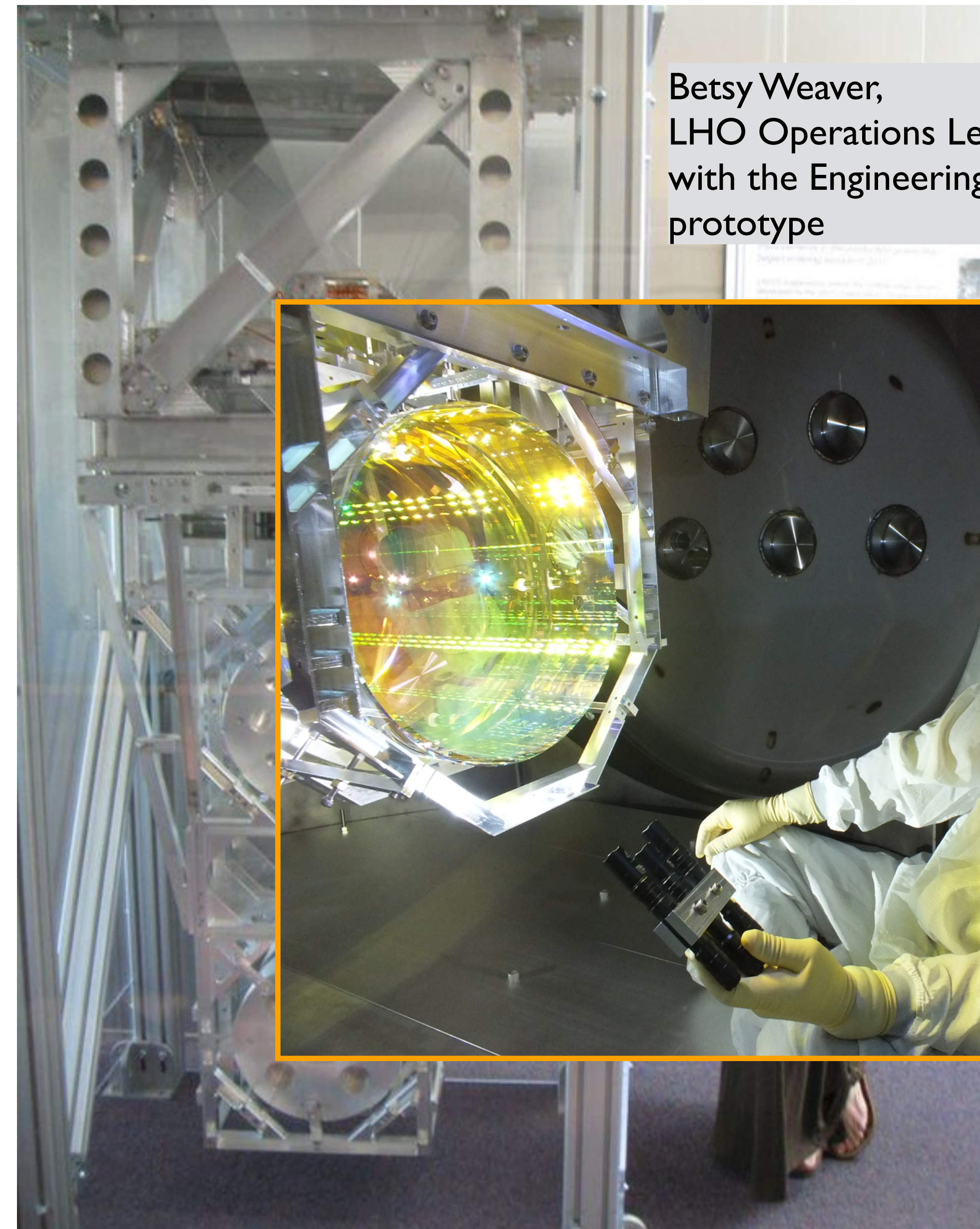


aLIGO Suspension (UK led)



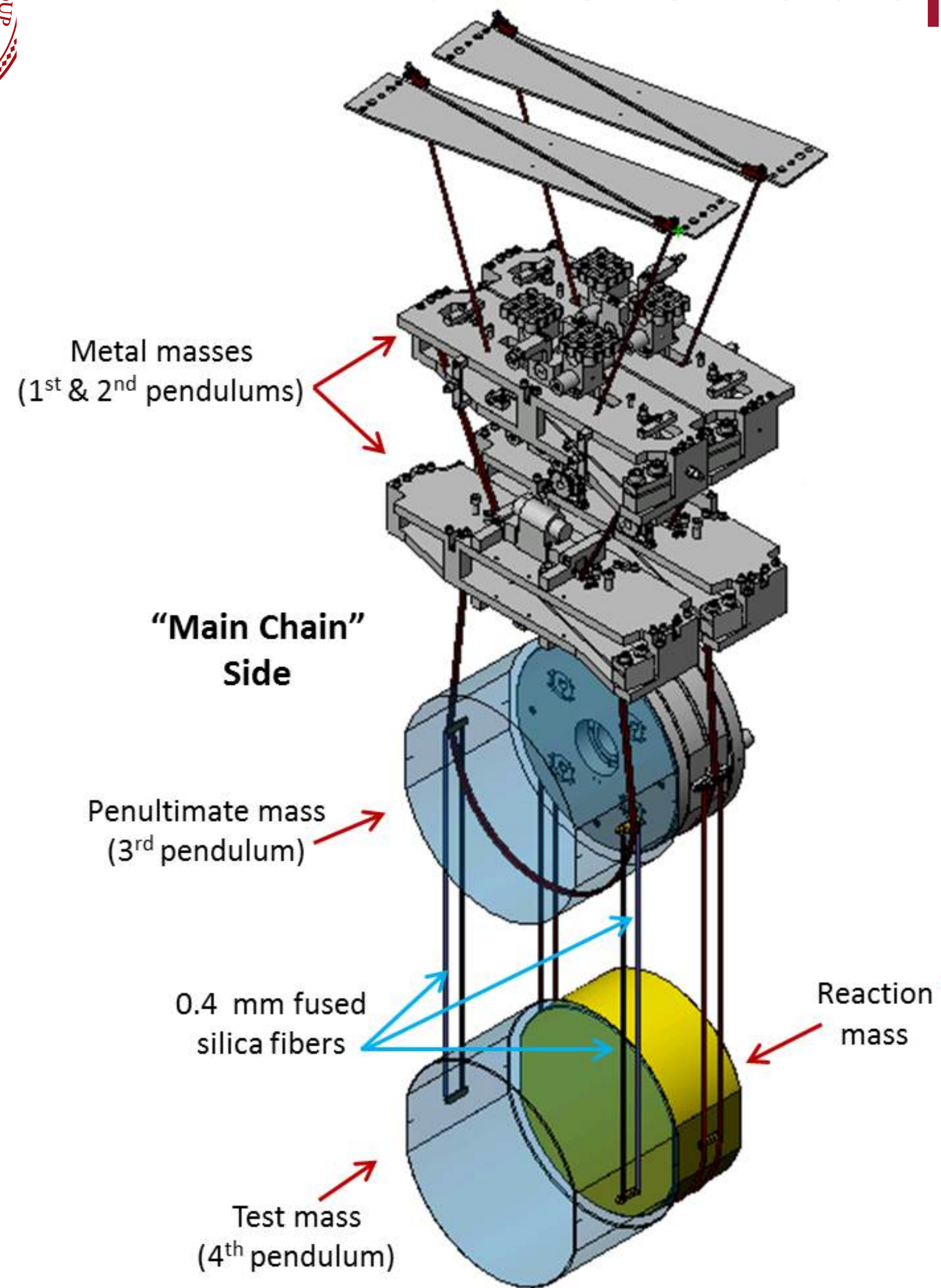
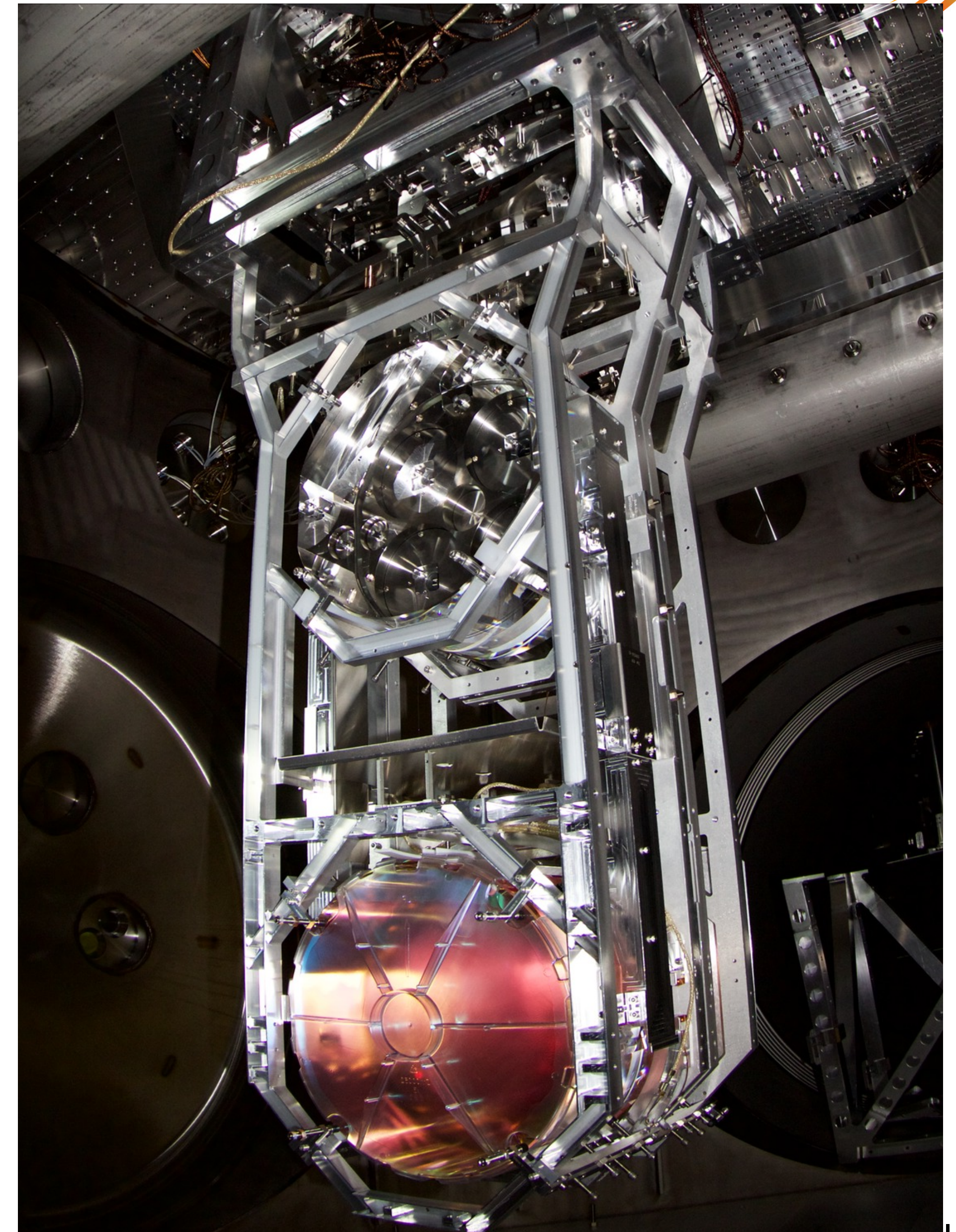
Betsy Weaver,
LHO Operations
Lead, with the
Engineering
prototype

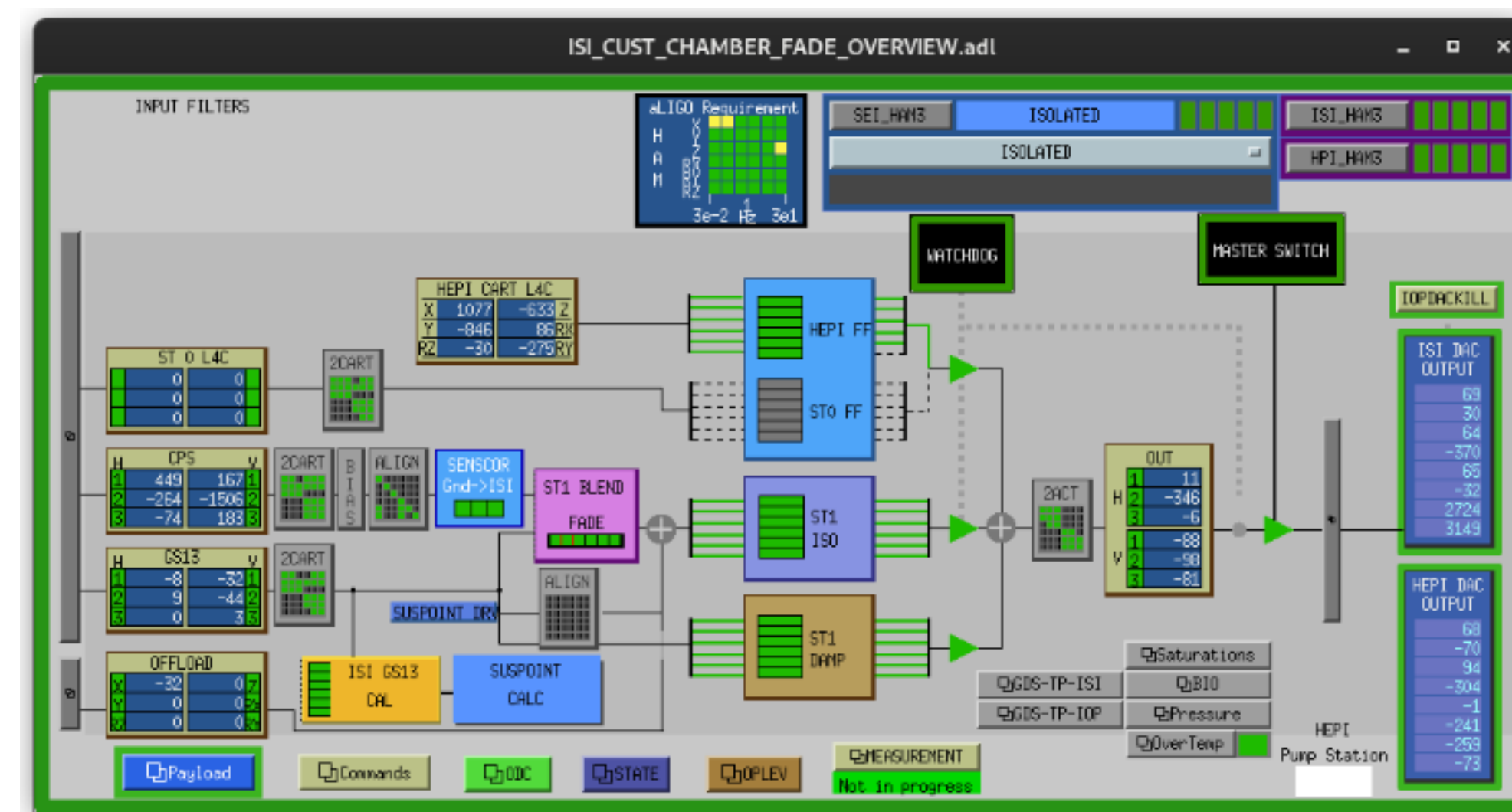
aLIGO Suspension (UK led)

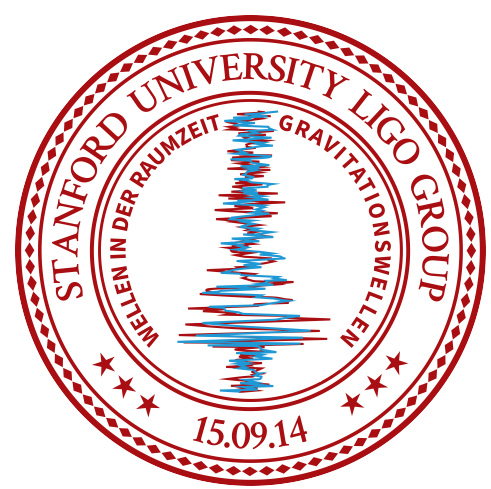


Betsy Weaver,
LHO Operations Lead,
with the Engineering
prototype

aLIGO Suspension (UK led)

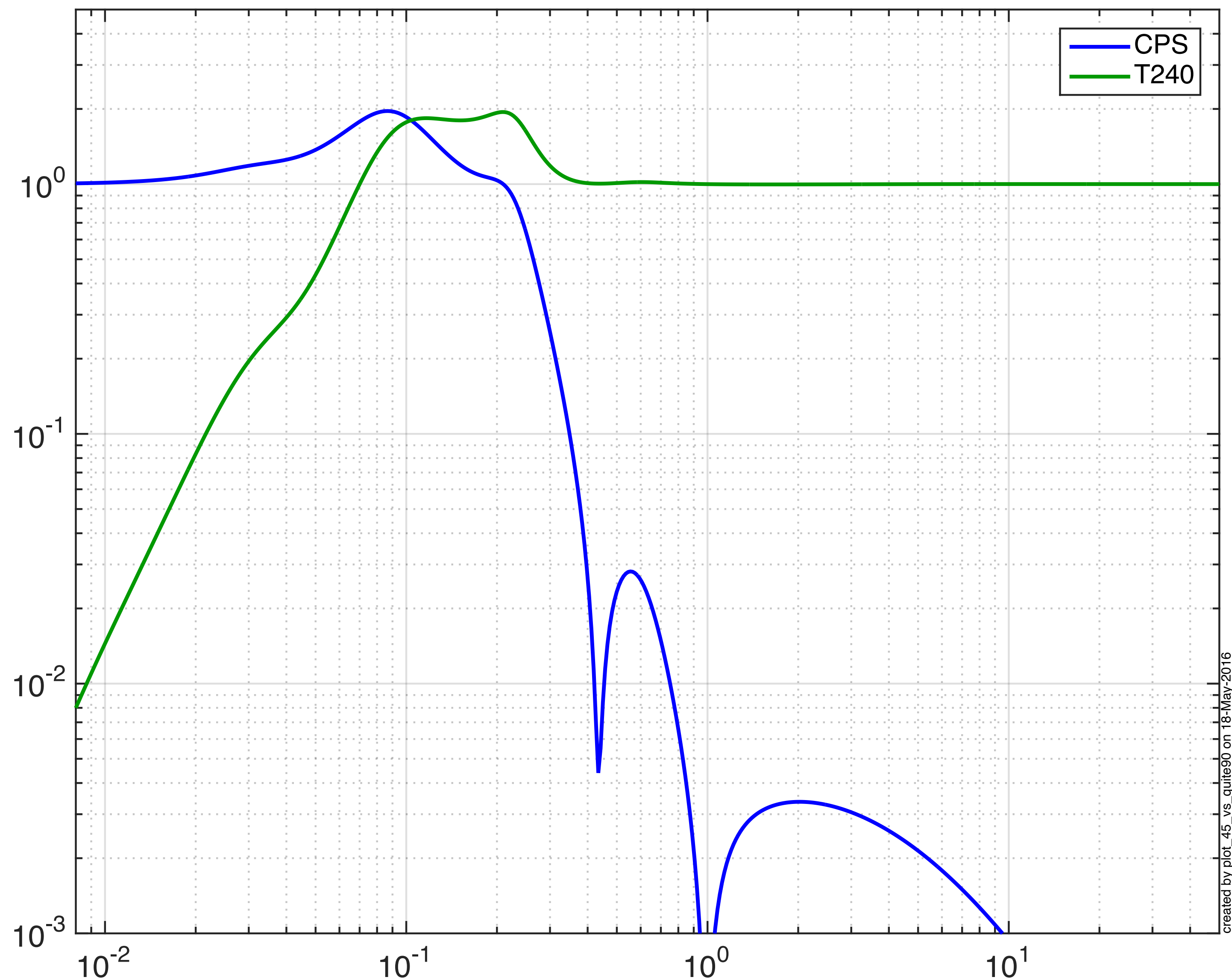






Blend filter example

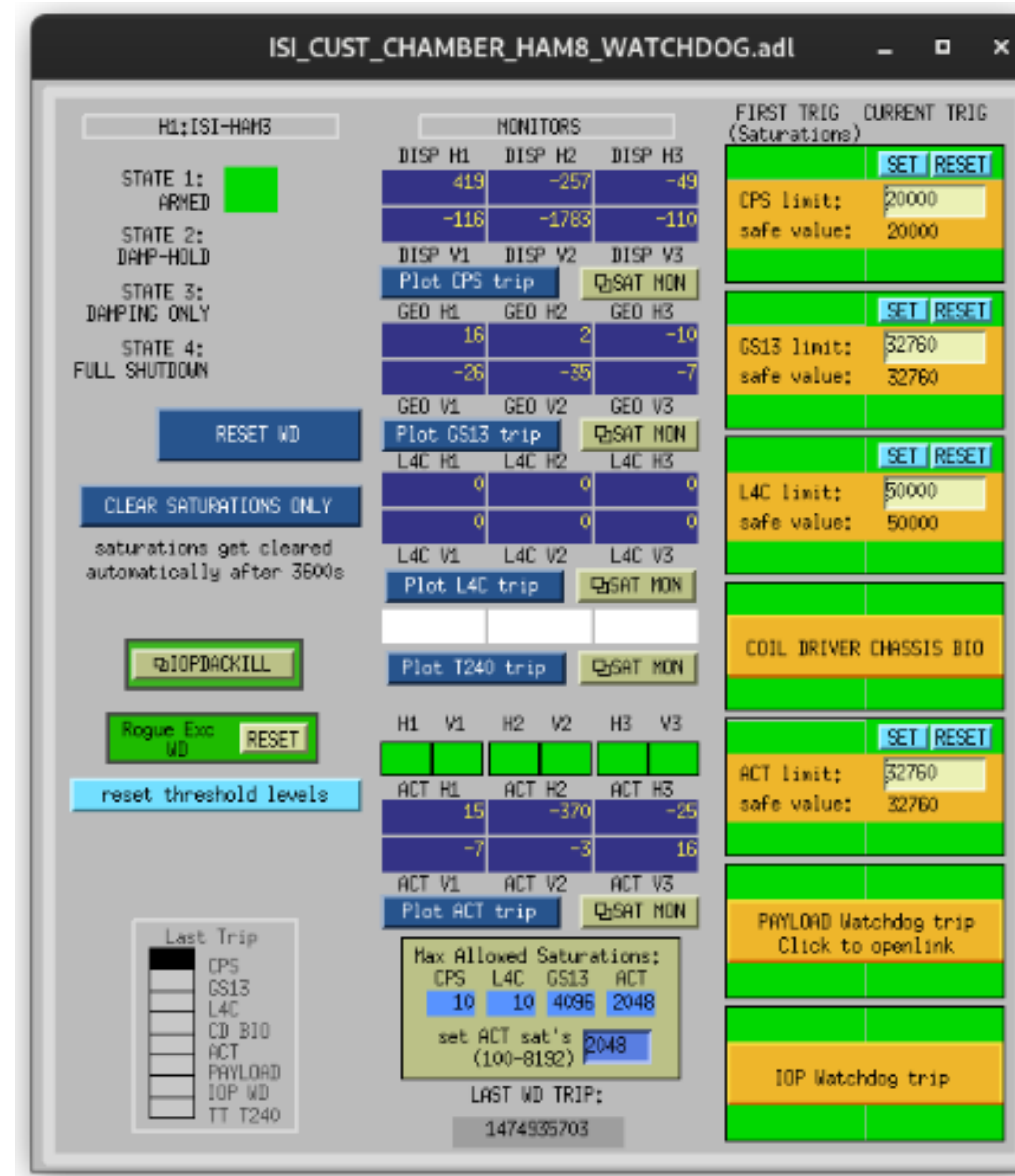
90 mHz Blend for Stage 1 Y



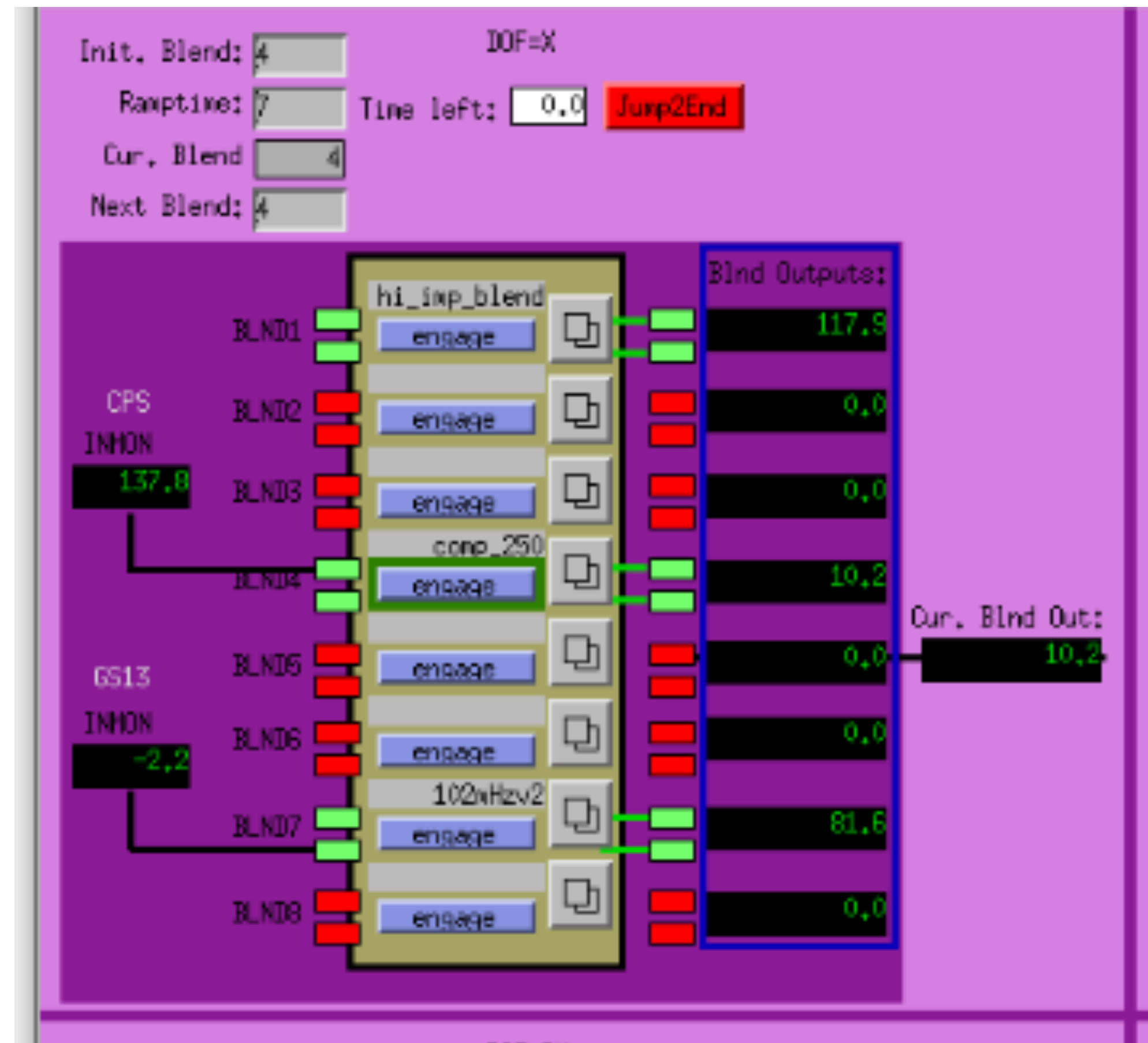
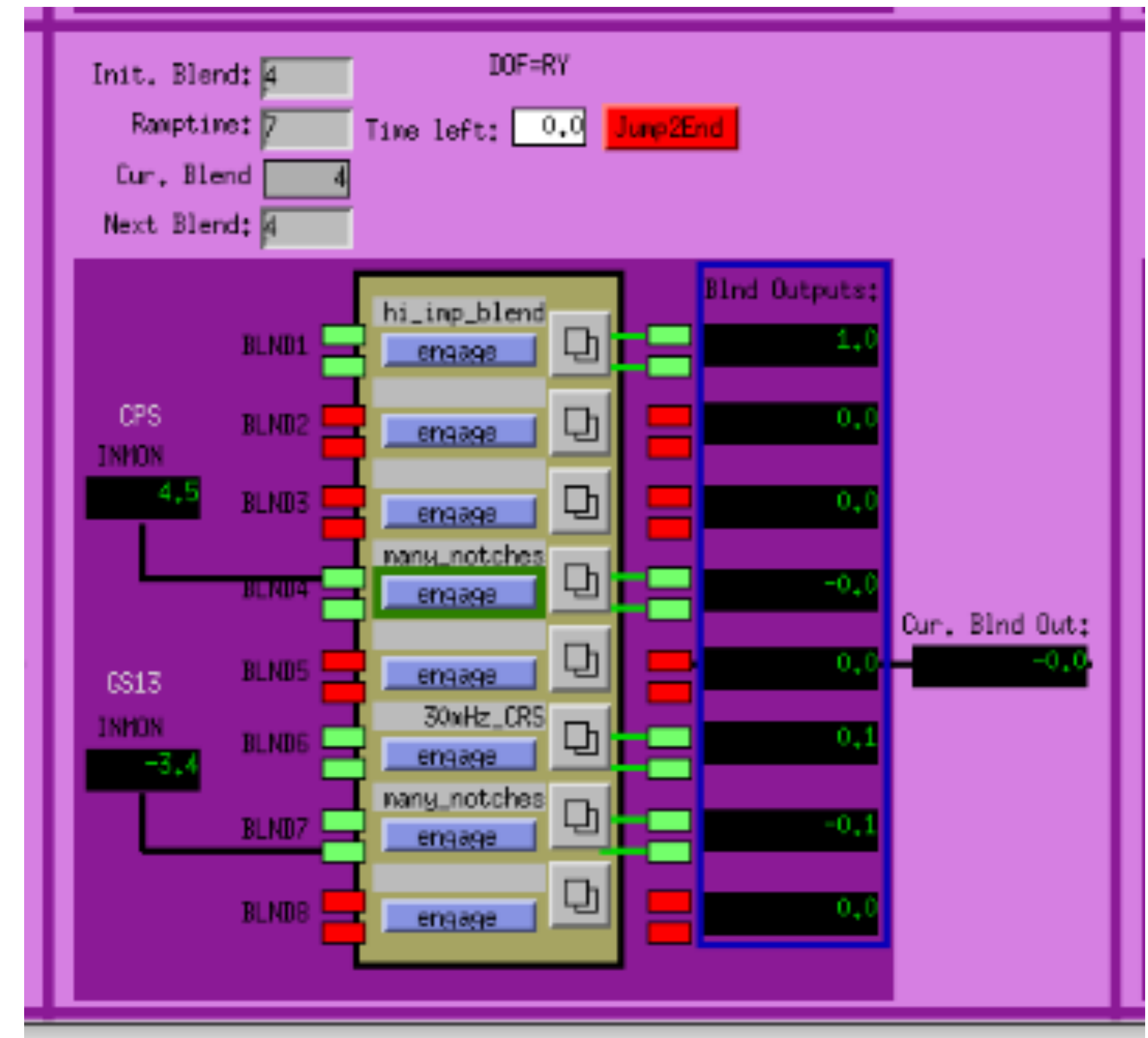
created by plot_45_vs_quite90 on 18-May-2016



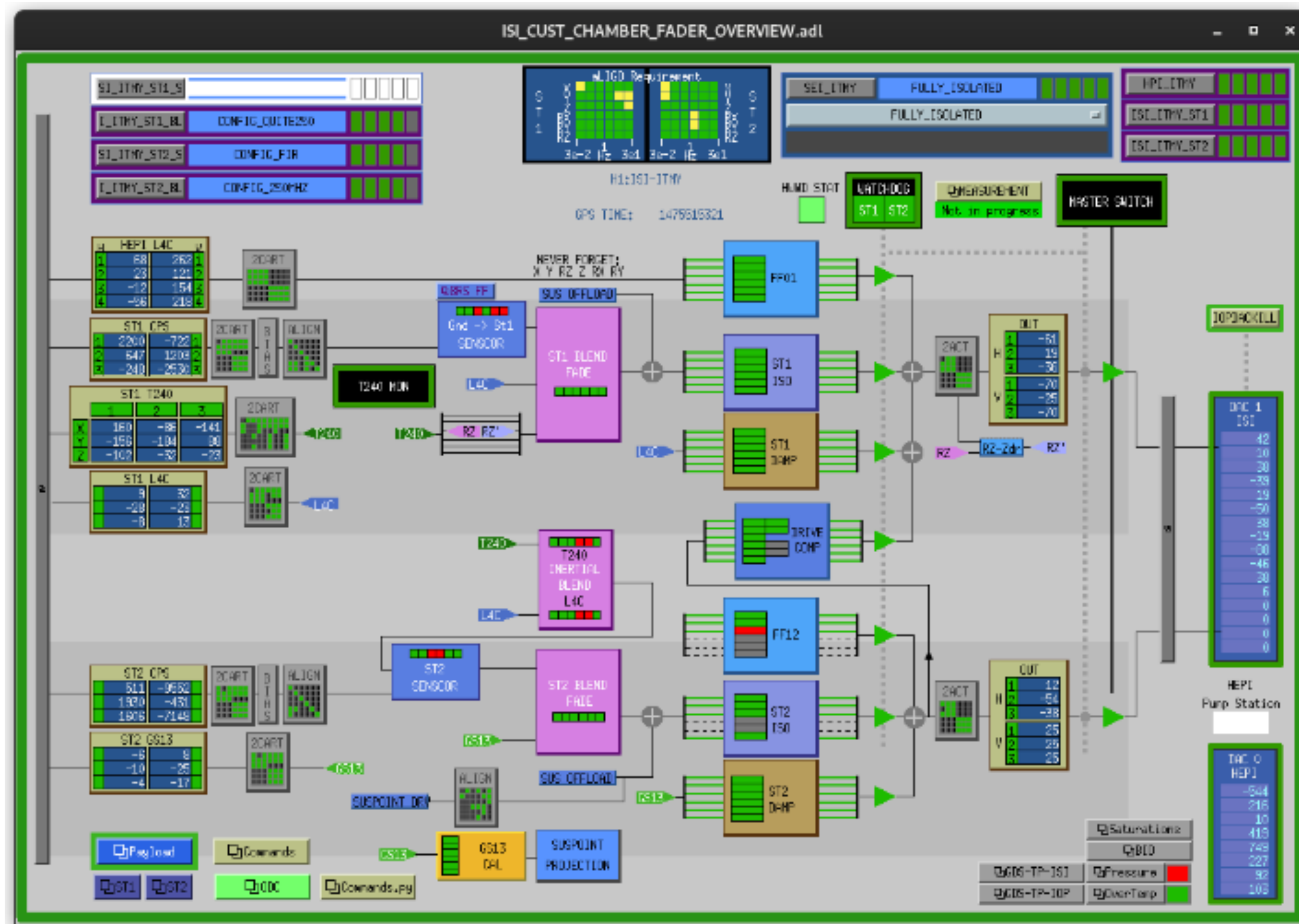
Watchdog screen



Blend switching



Overview screen for BSC-ISI





Guardian control

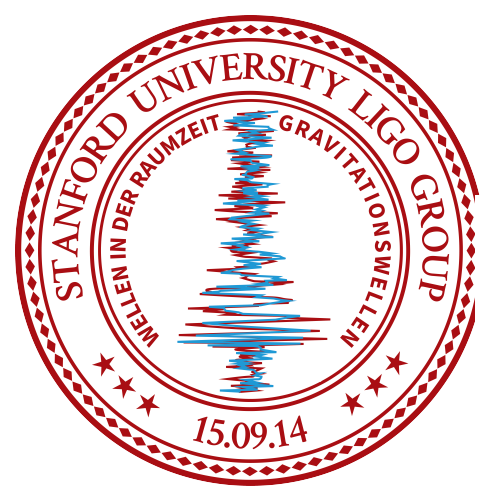


H1:GRD-SEI_HAM5.MAIN.2spqagar.adl

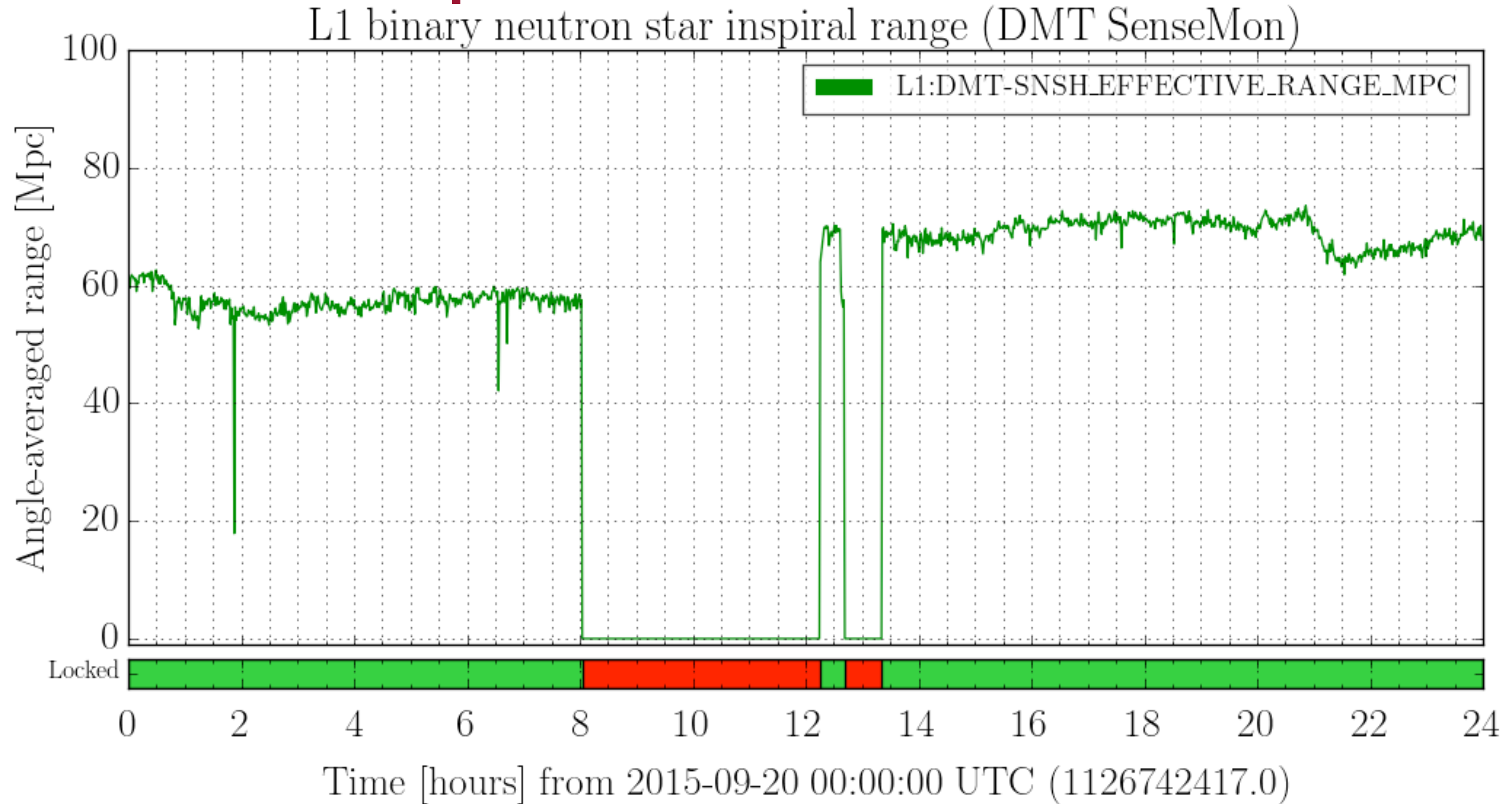
version: 1.5.3 GUARDIAN: SEI_HAM5 archive id: 64760577

STATE	ISOLATED	200	log graph edit code history				
TARGET	ISOLATED	200					
REQUEST	ISOLATED	200					
	ISOLATED	all					
NOMINAL	ISOLATED	200	+OP+MODE+STATUS=OK				
USERMSG	all						
OP	EXEC	LOAD	LOG	INFO	DONE	0.000	0.002
GRDMSG	executing state: ISOLATED (200)						
MODE	AUTO						
PVs	27	SET	6	DIFFs	0	SPM DIFFs	MONITORING





Real Impact of seismic isolation

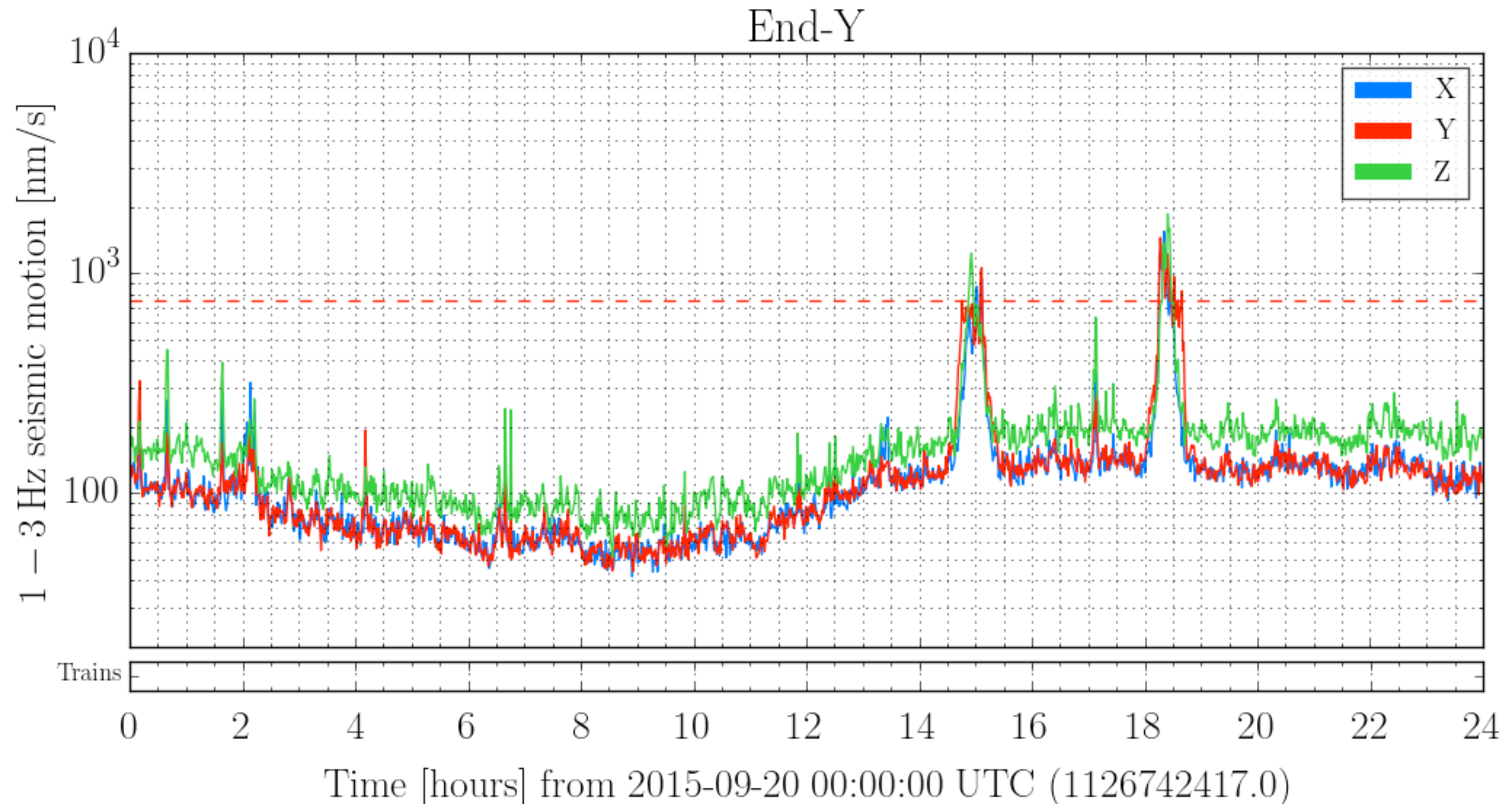


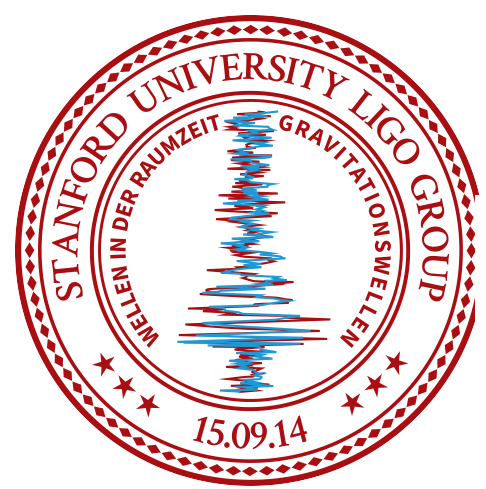
range monitor over 24 hours



Real Impact of seismic isolation

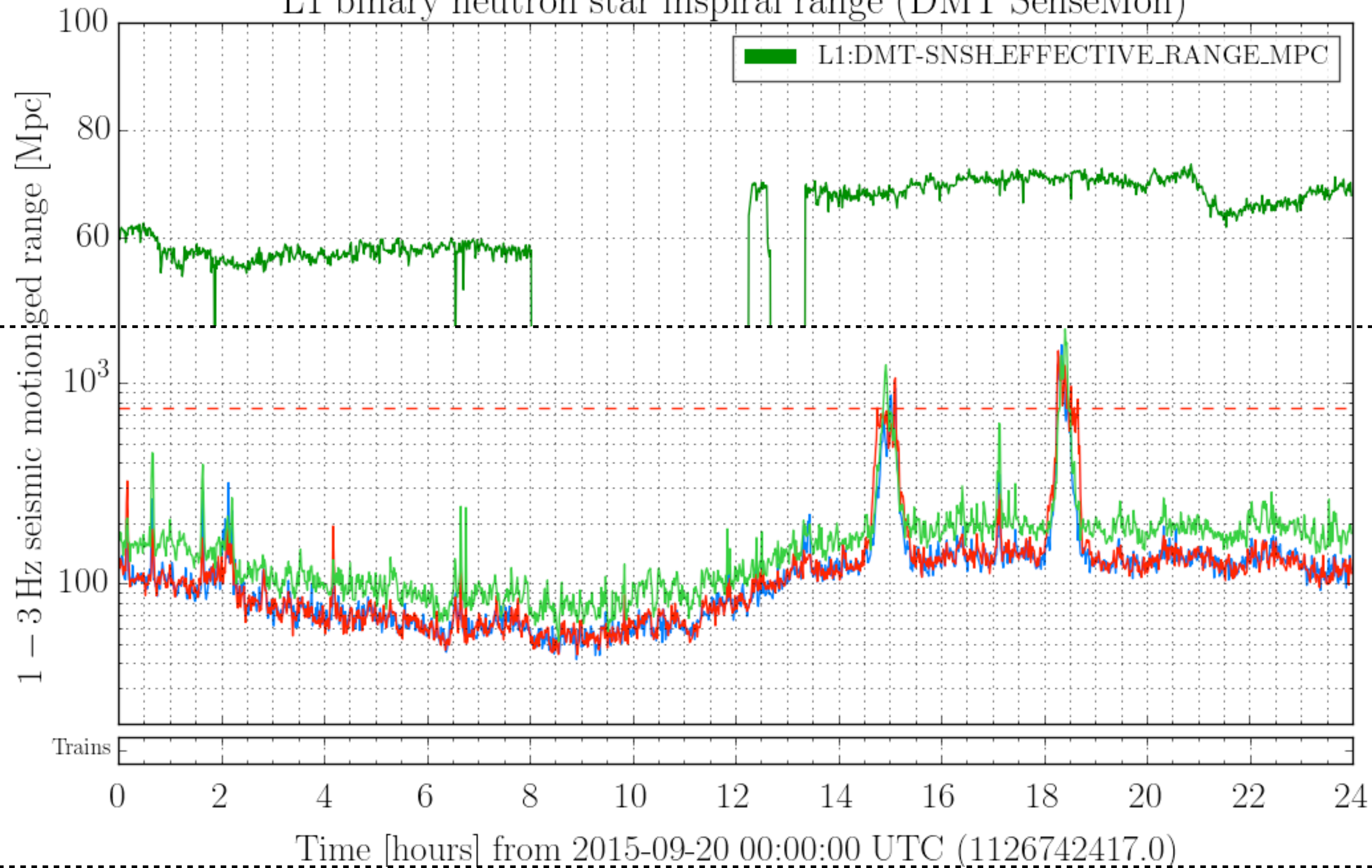
but there was a train



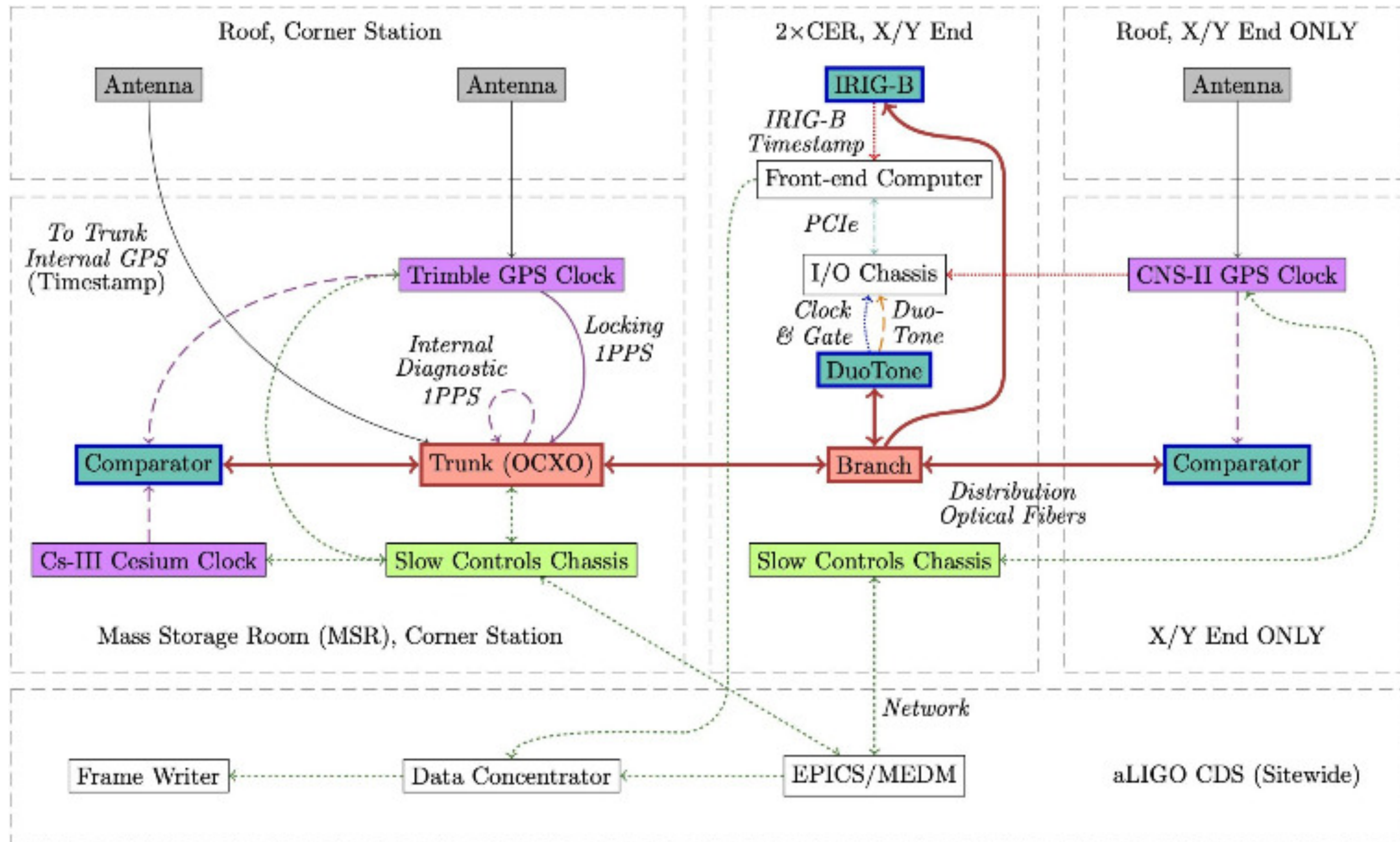


Real Impact of seismic isolation

L1 binary neutron star inspiral range (DMT SenseMon)



Timing System





Timing system performance

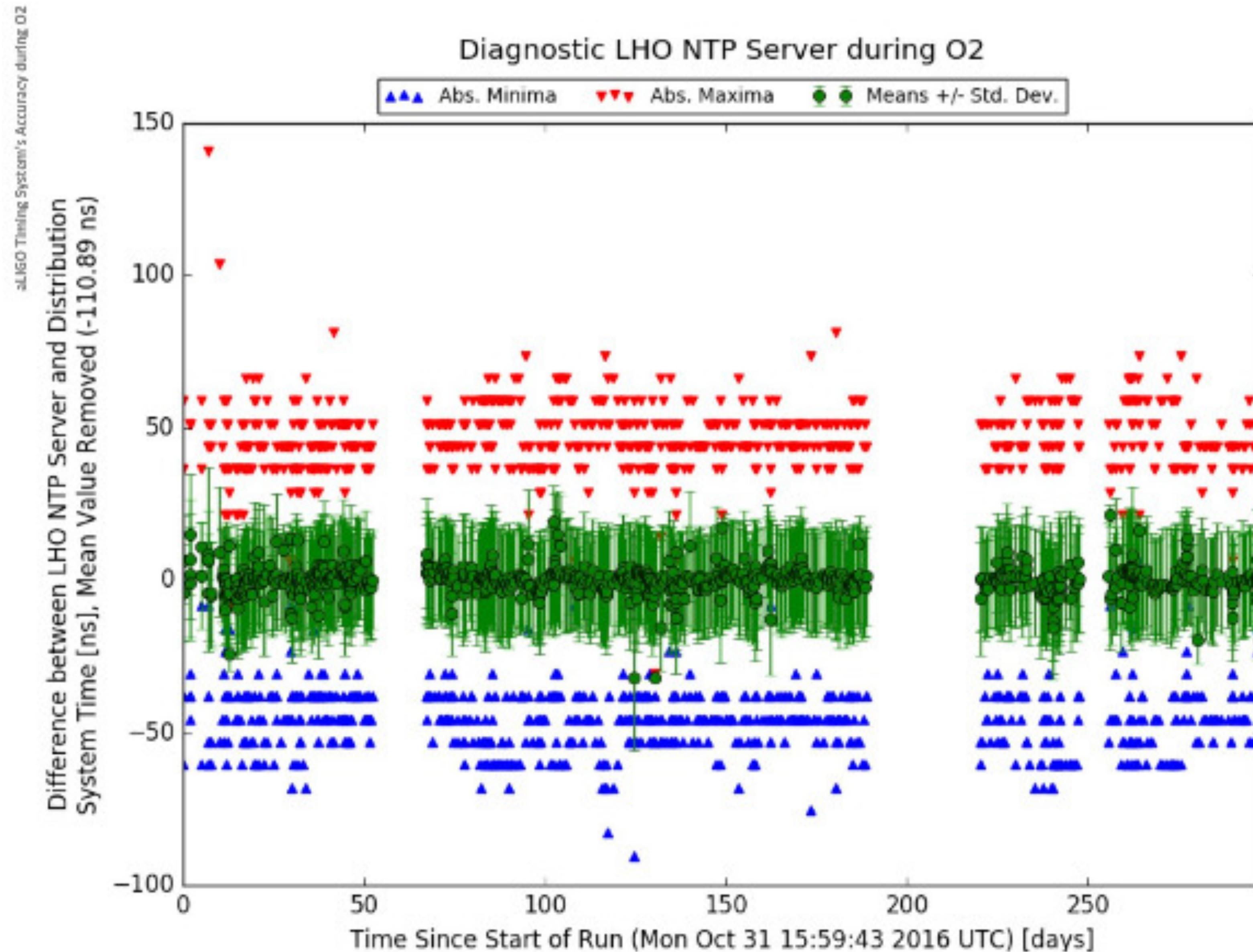
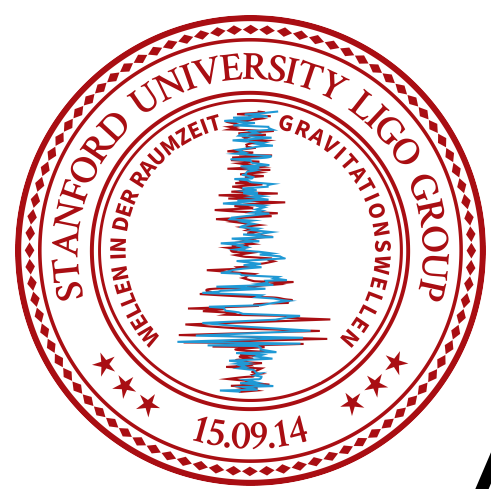


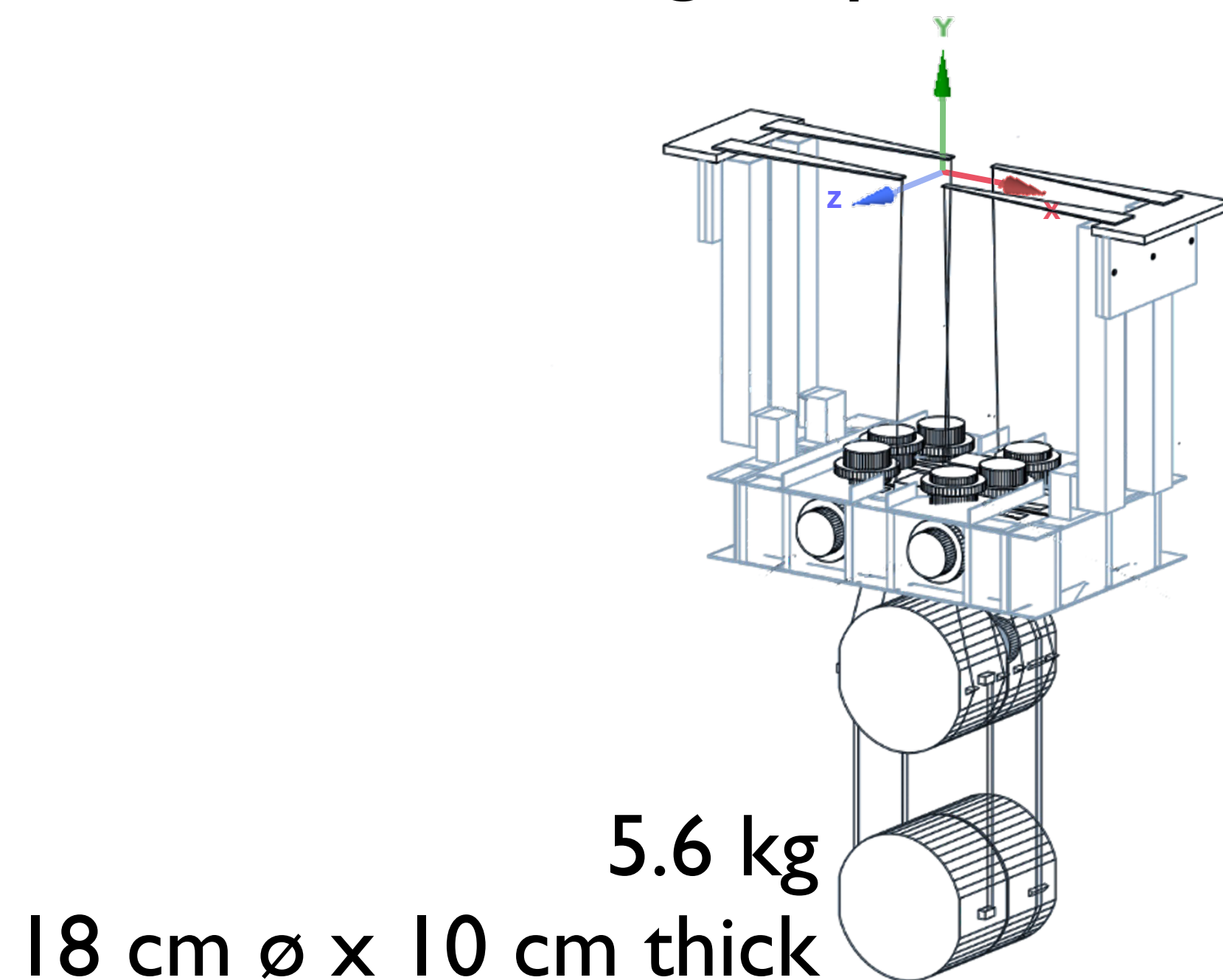
Figure 1: Timing Difference between the NTP Server and the Timing System's Internal 1PPS signal at LHO during O2. (EPICS channel name: H1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_3; DQ Flag: H1:DMT-ANALYSIS_READY:1)



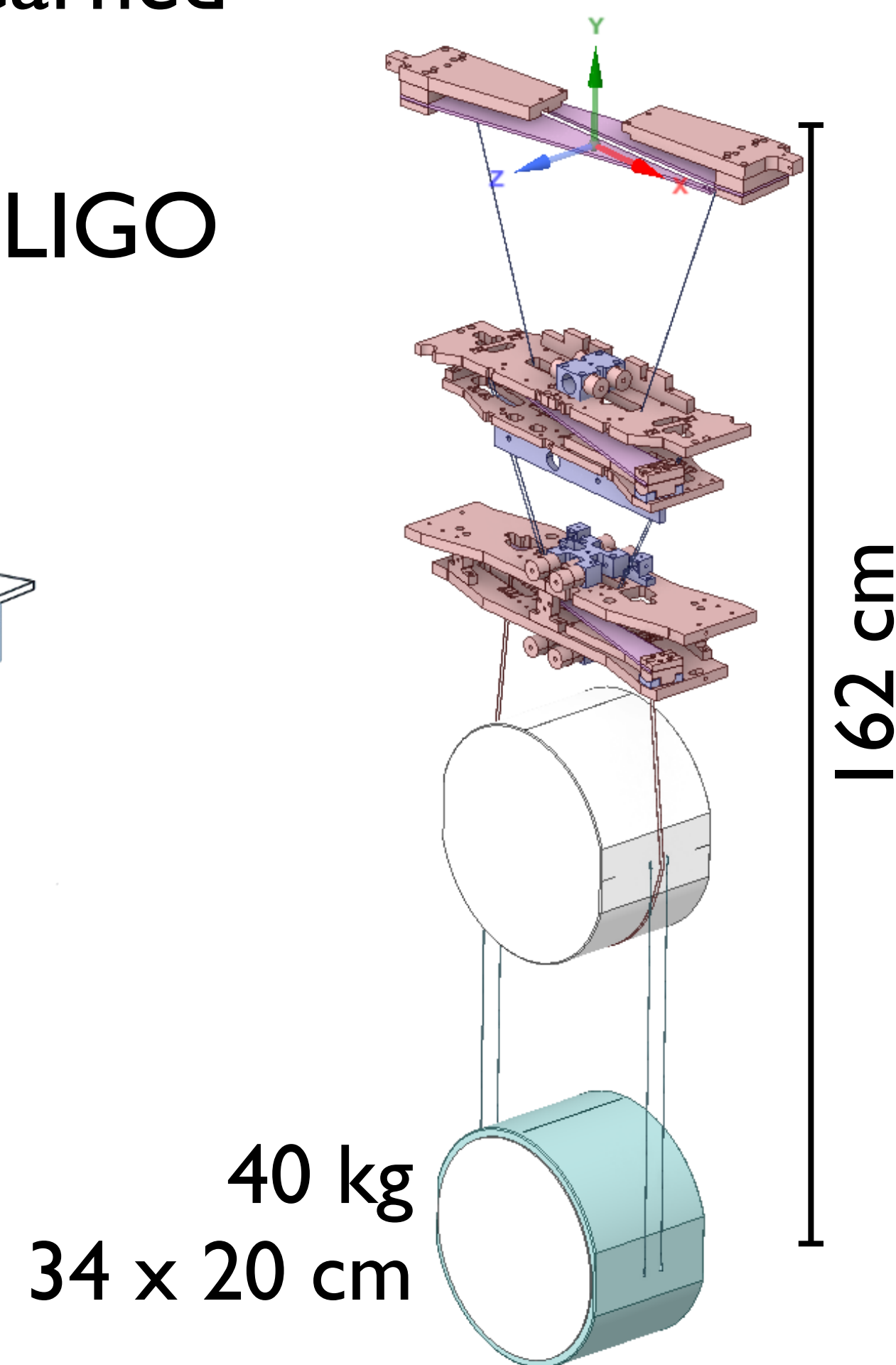
A# suspension

A# suspension is an upgrade the current suspension design with lessons learned from Advanced LIGO operation

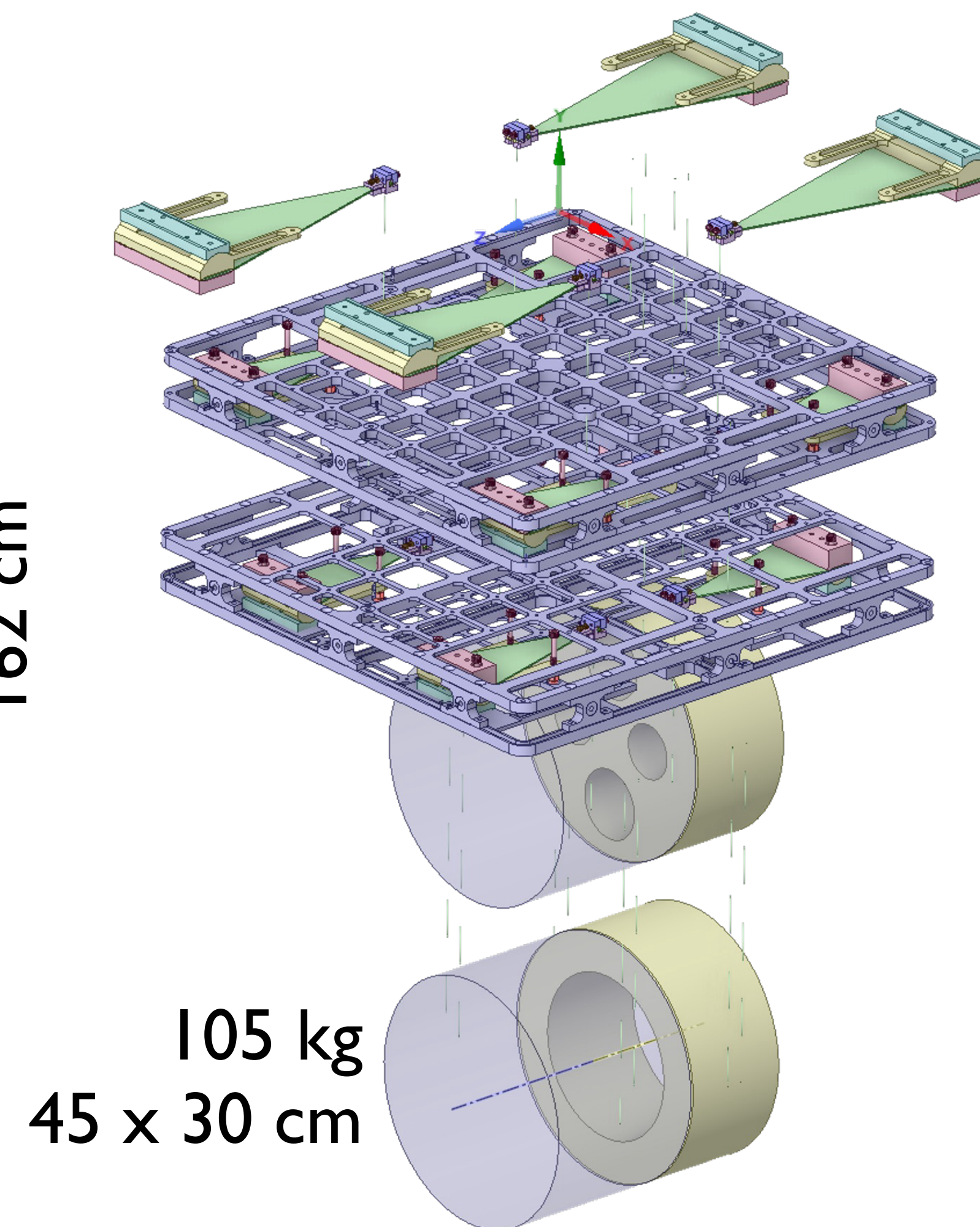
Joint effort of Glasgow, Stanford, LIGO Lab and other LSC groups



GEO600



**Advanced
LIGO**



**LIGO
A#**