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

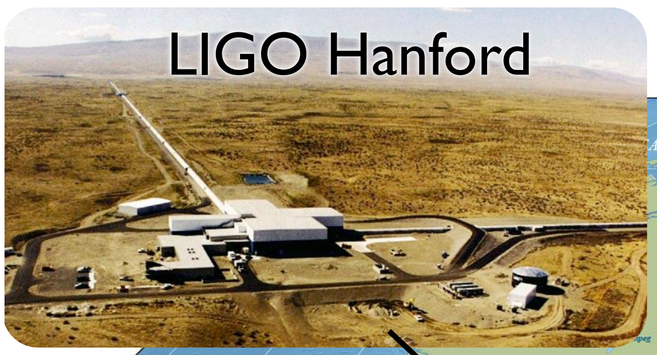


LIGO Scientific Collaboration

LIGO Detectors are funded by the NSF



International Network









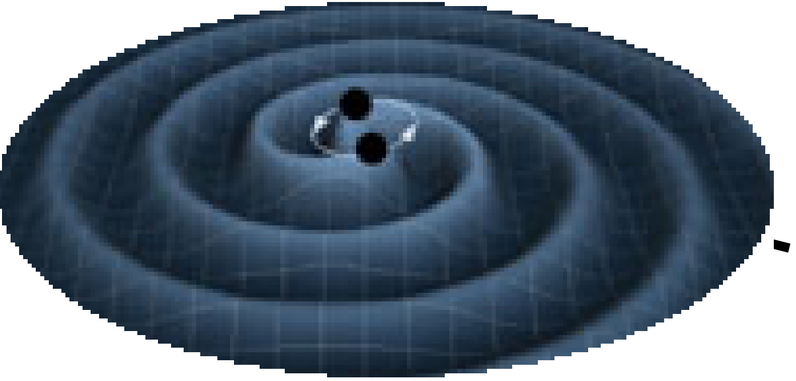


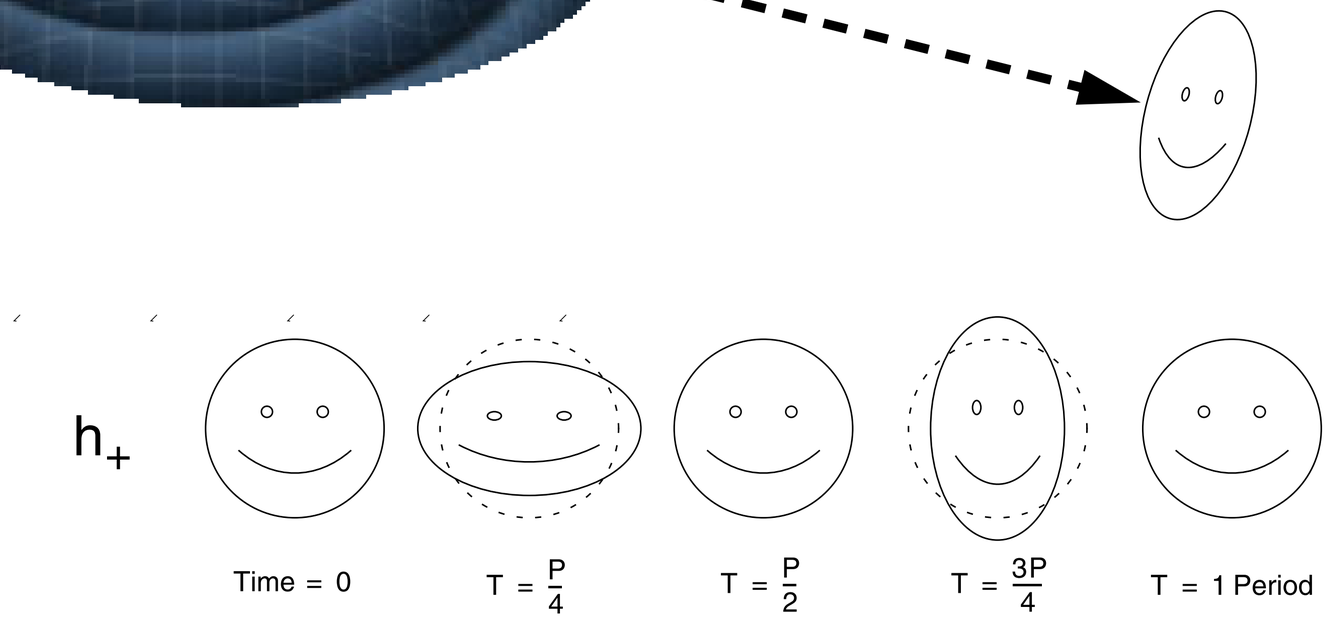
© Nations Online Project

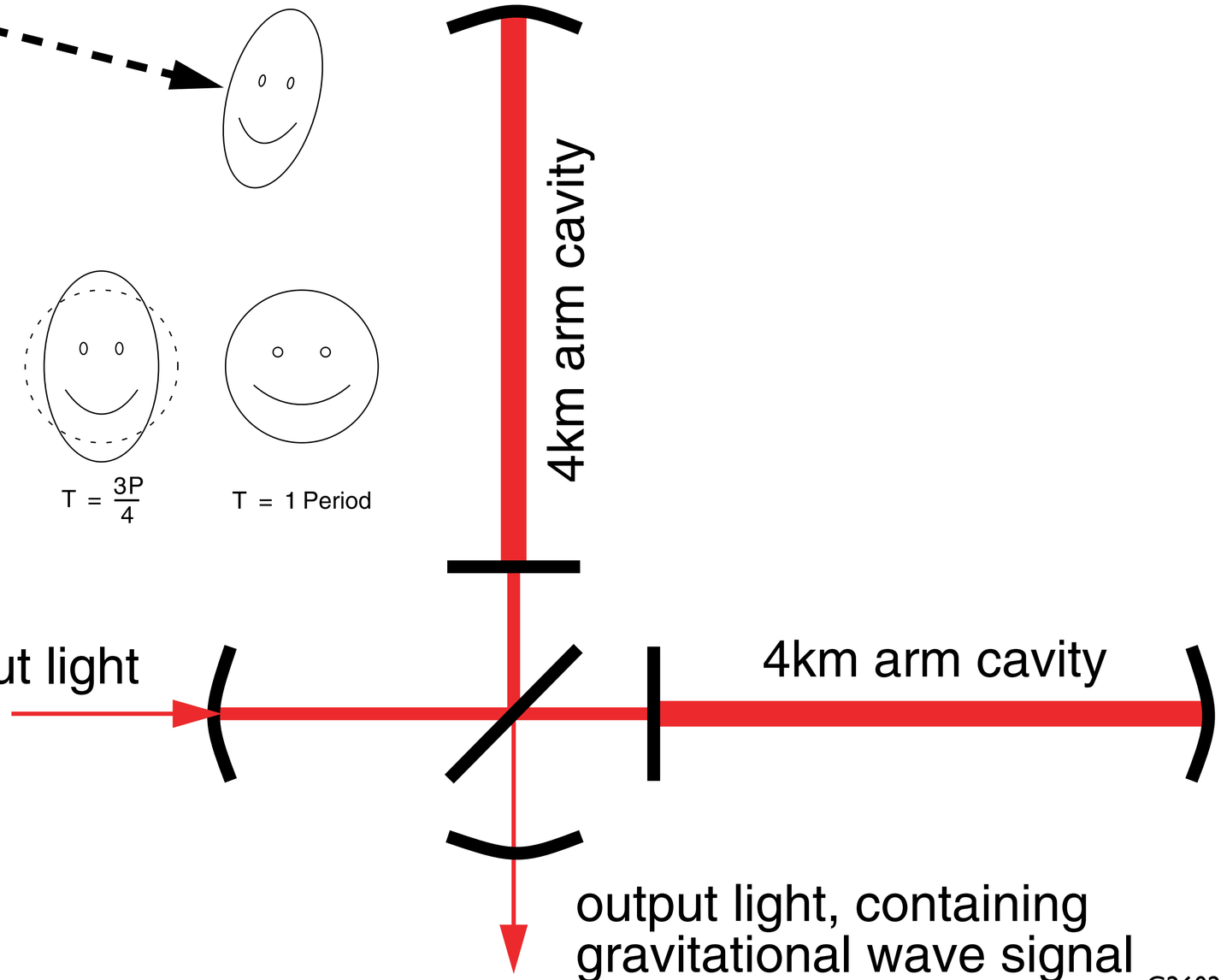
map from https://www.nationsonline.org/maps/Political-World-Map-3360.jpg

LIGO concept

Use an interferometer to do astronomy







First signal
GW150914

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

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

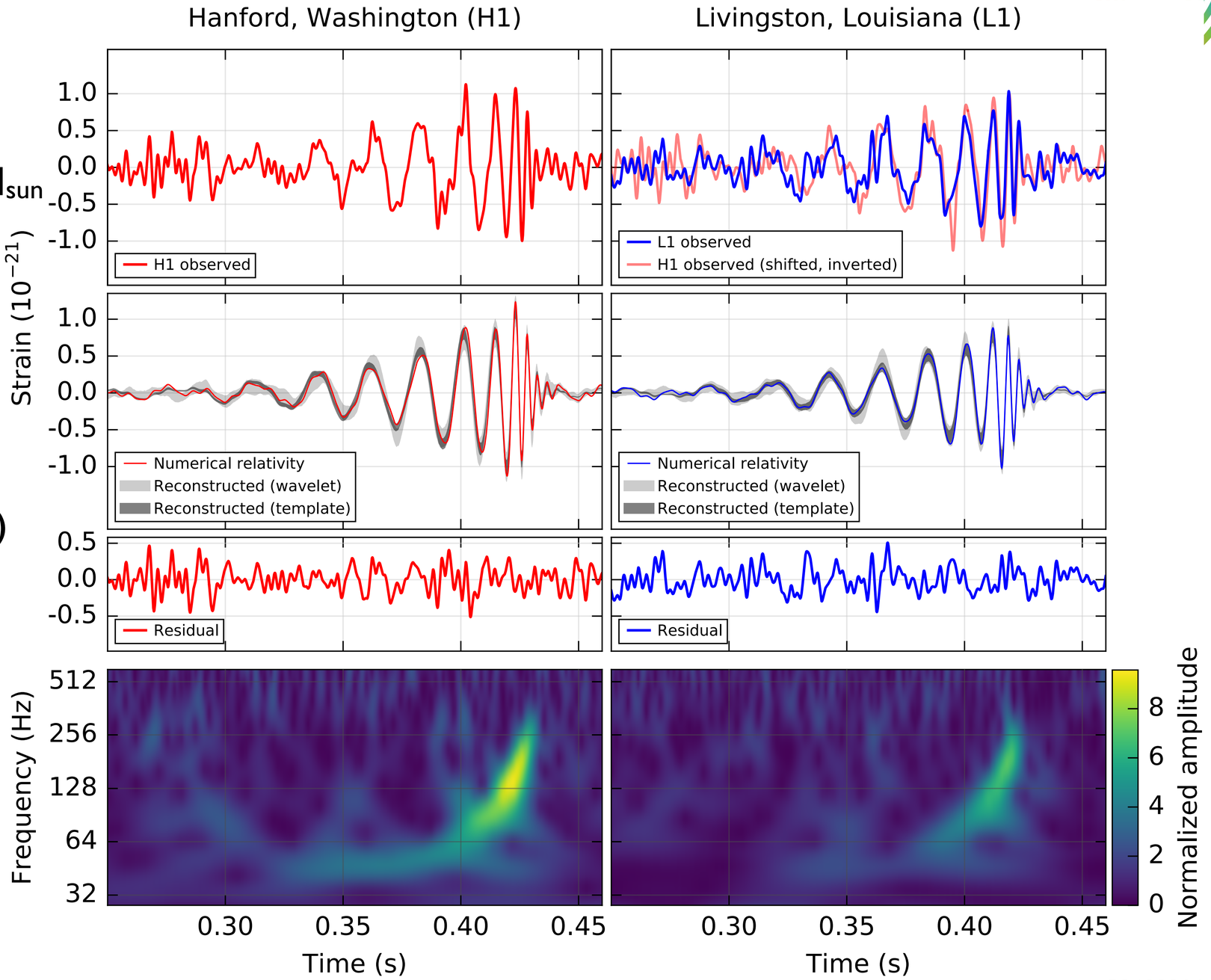
Energy radiated: 3 (+0.5/-0.5) $M_{sun}\ c^2$

Distance 420 (+160/-180) MPc
(1.3 Billion light years)

Peak amplitude: ~1e-21 strain (4e-18 m)

Freq: in band ~ 40 Hz, merge ~ 250 Hz

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

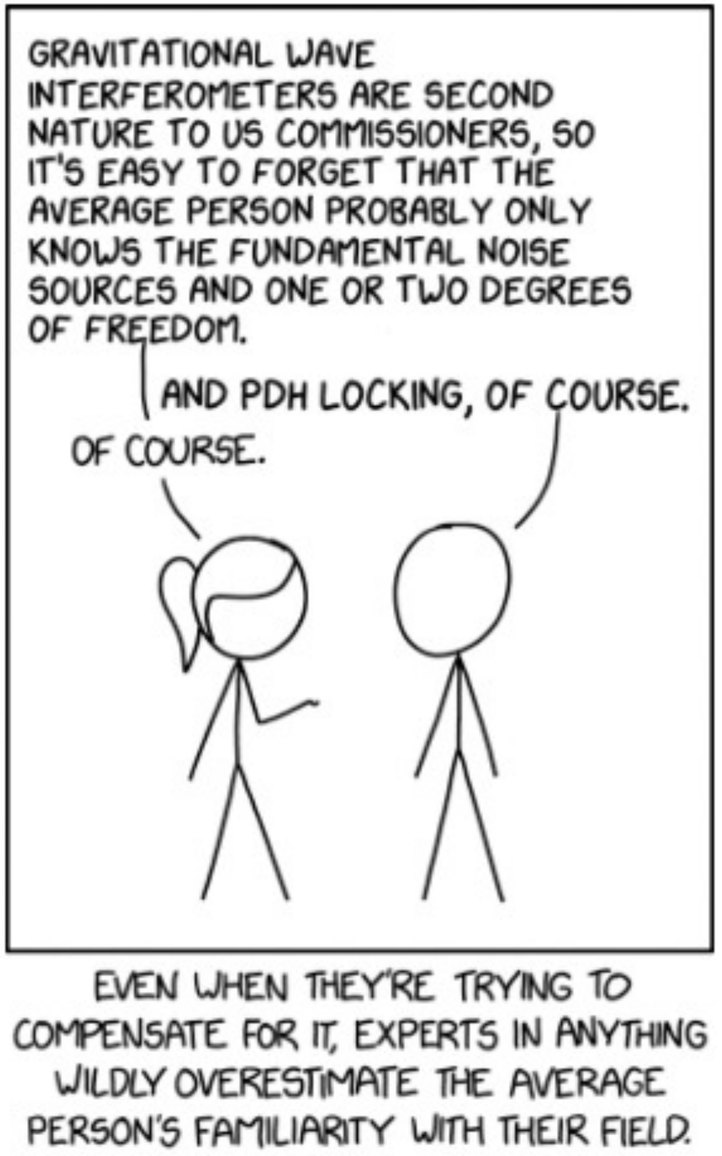


http://dx.doi.org/10.1103/PhysRevLett.116.061102

Outline

LIGO controls talk

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



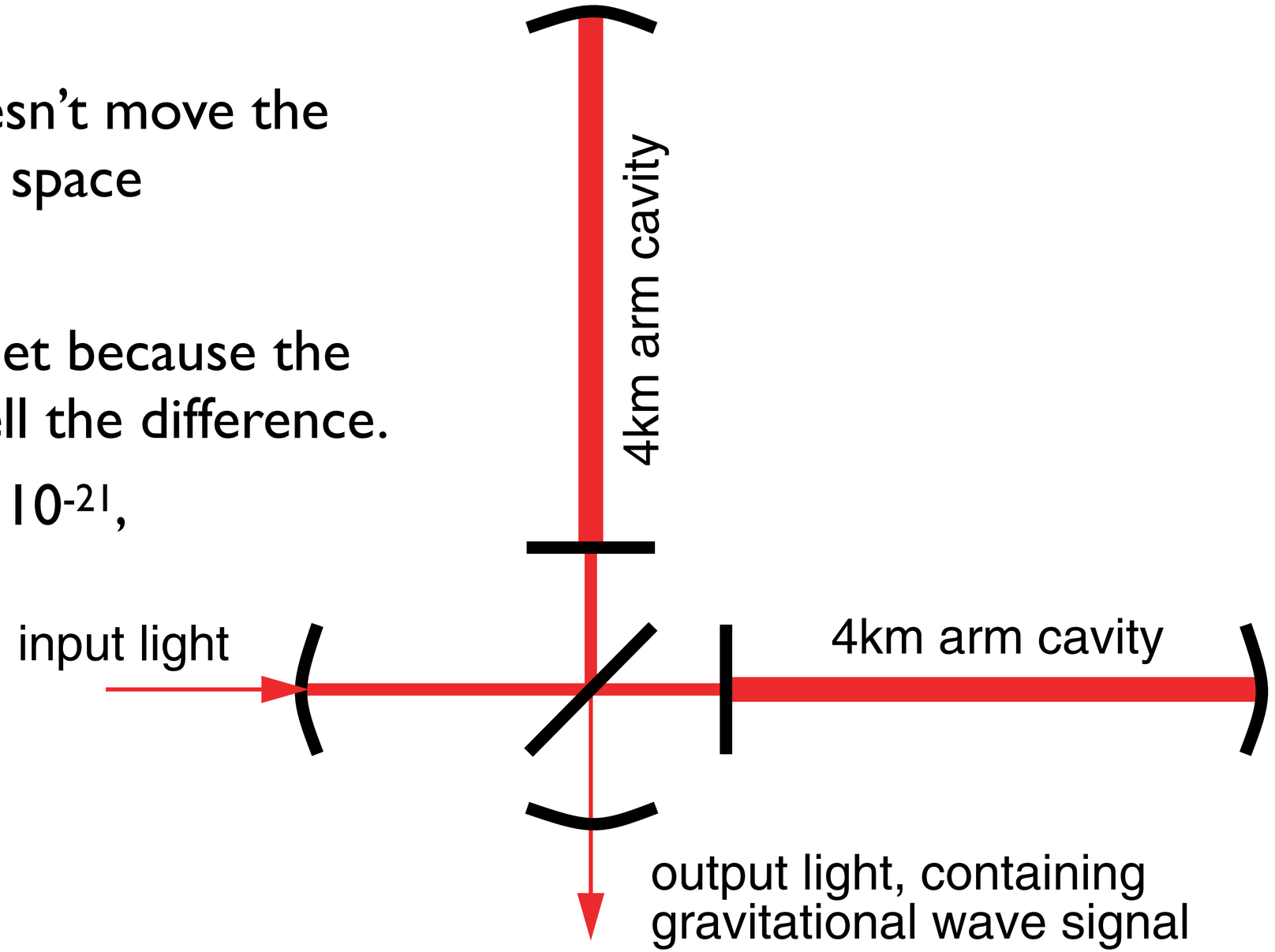
The interferometer needs control

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 = $4*10^{-18}$ meters



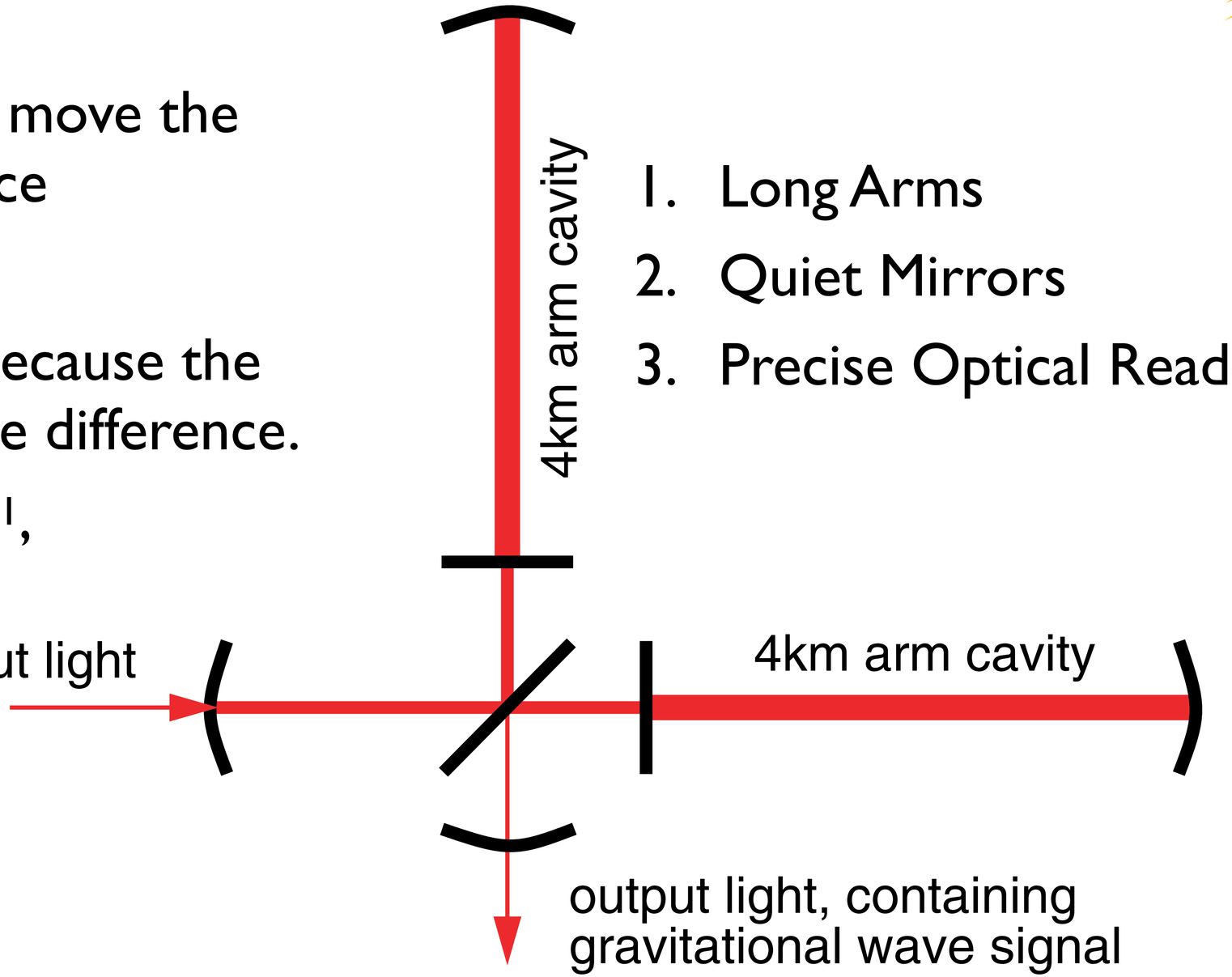
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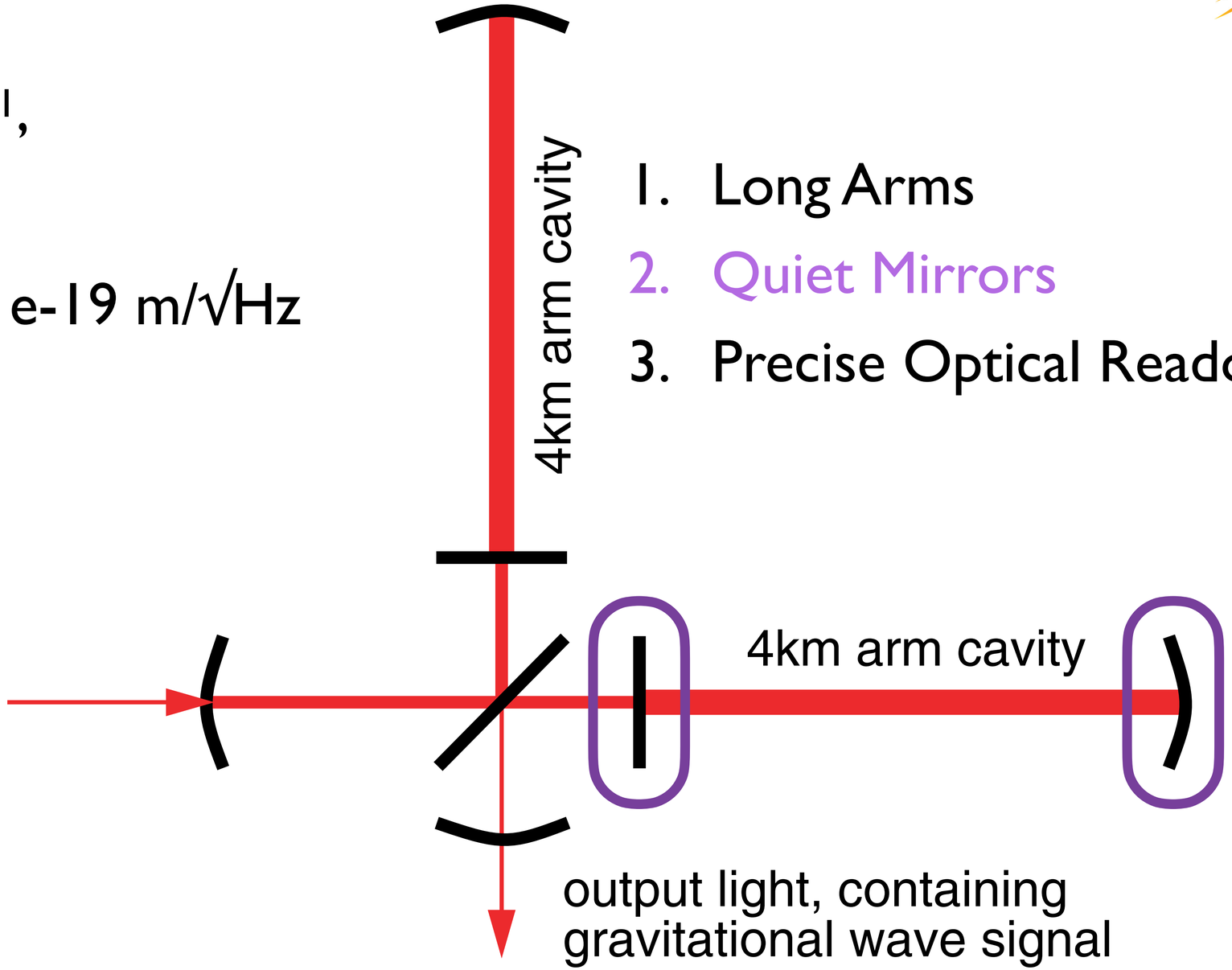


1. Long Arms
2. Quiet Mirrors
3. Precise Optical Readout

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Mirror motion at 10 Hz ~1e-19 m/√Hz



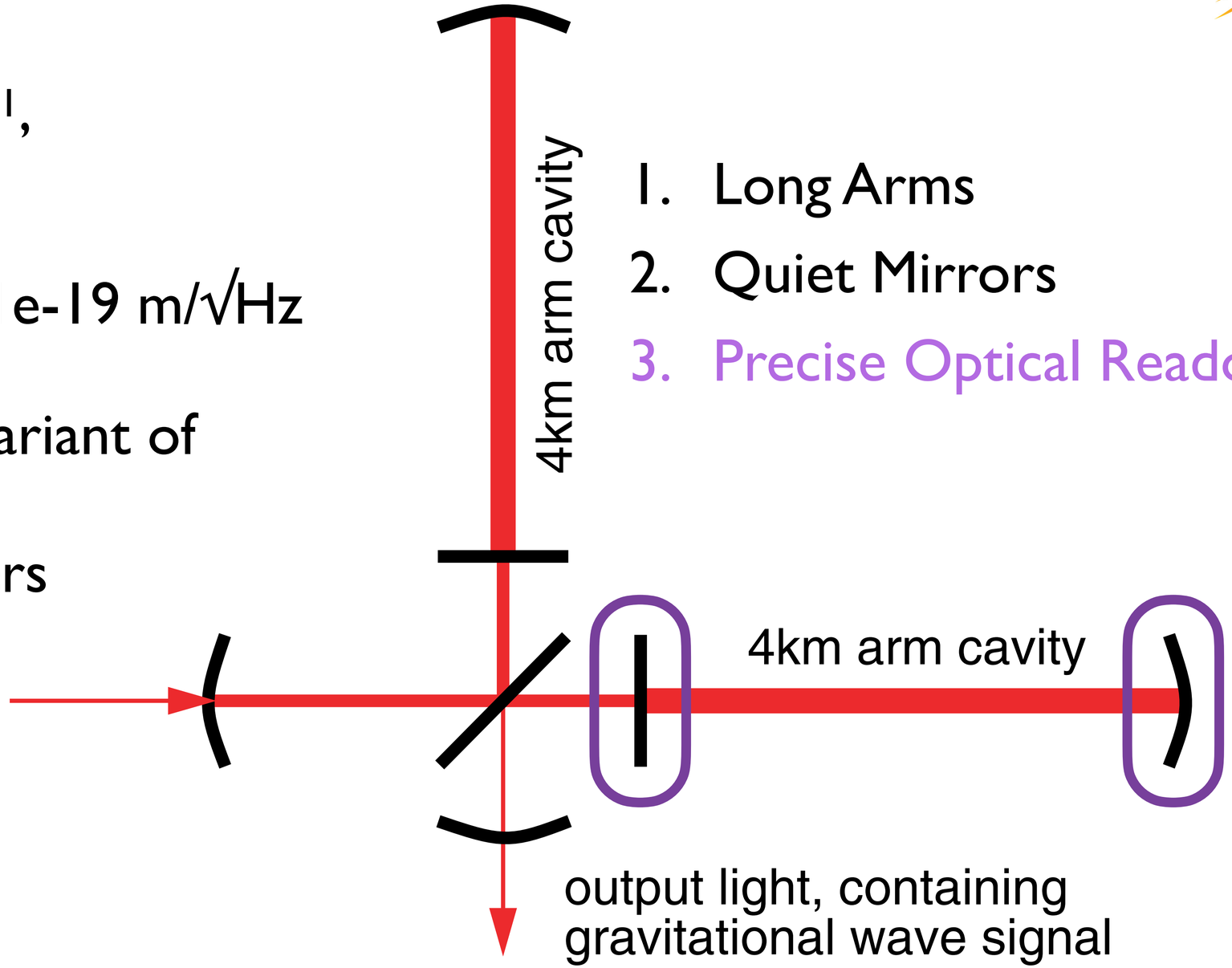
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Mirror motion at 10 Hz ~1e-19 m/√Hz

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

Developed in-house, runs on Linux

More than 36 control computers running in parallel

Data IO at 65,536 samples/ sec

Typically update rate for control is 16,384 cycles/ sec

Over 120 "user models"

Thousands of control loops

Over 10,000 'fast channels'

Over 300,000 monitors



`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]

[a] *California Institute of Technology, Pasadena, CA 91125, USA*
[b] *LIGO Hanford Observatory, Richland, WA 99352, USA*
[c] *LIGO 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.

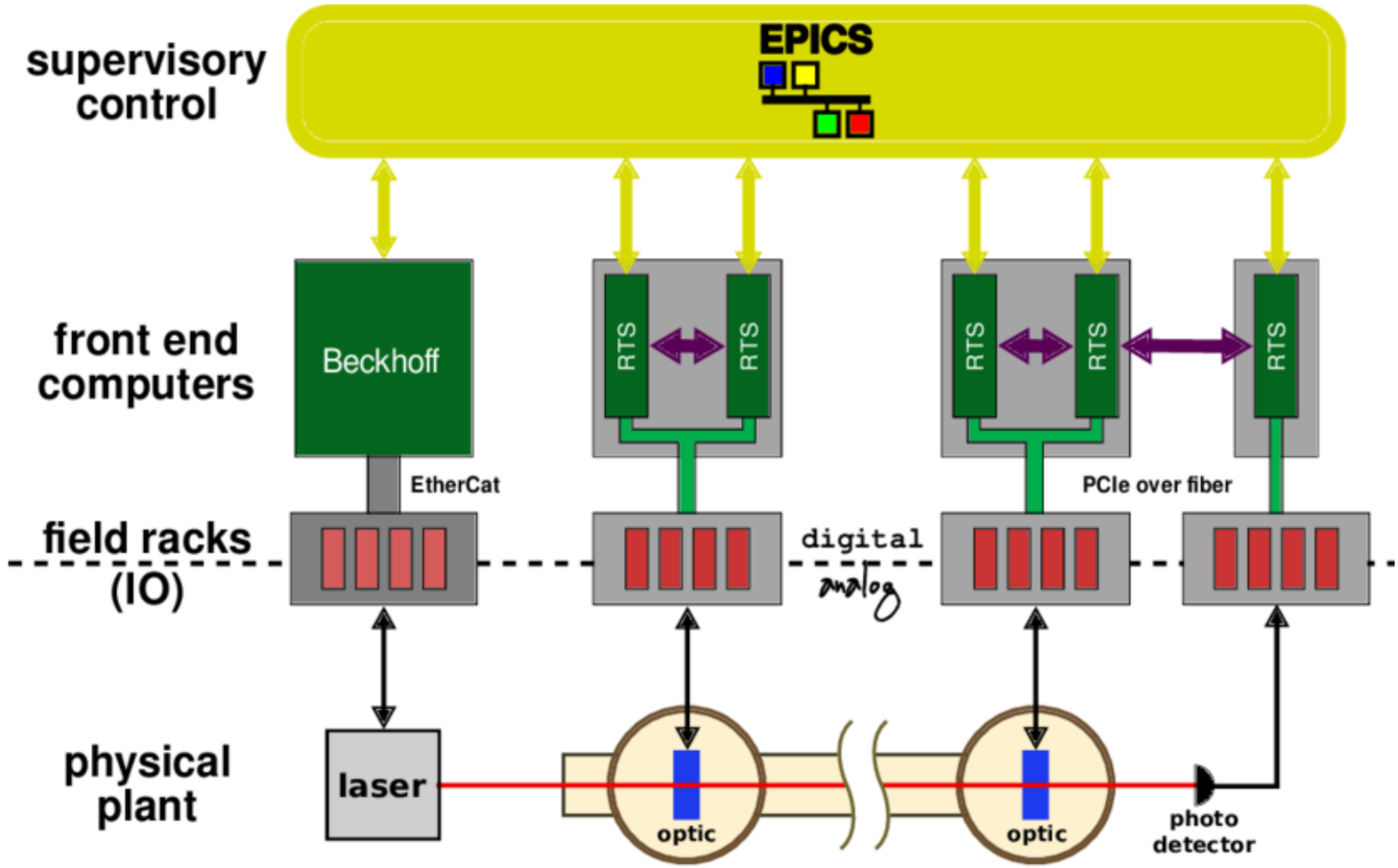
Keywords:
real-time processing, feedback control, hardware control, data acquisition

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

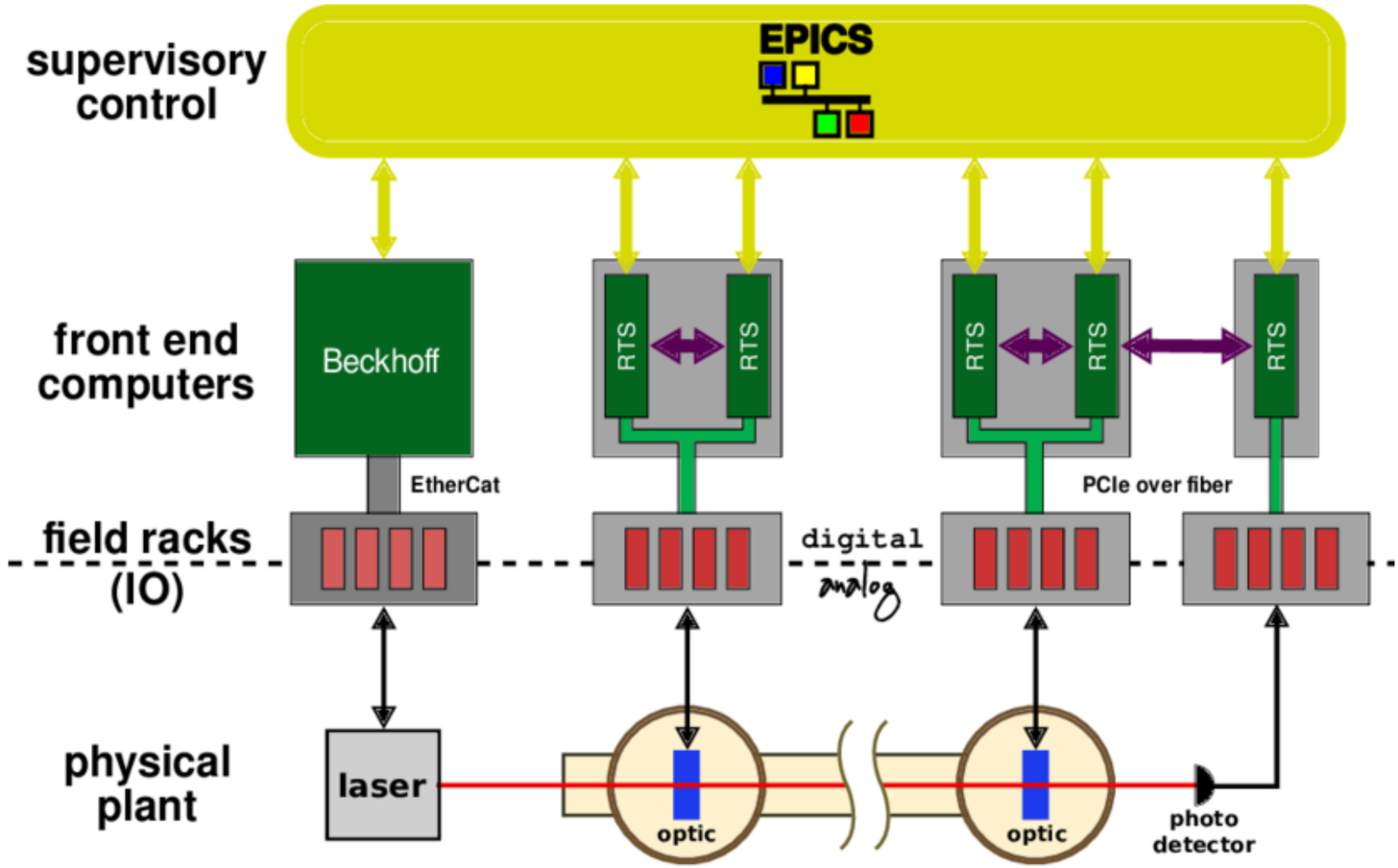
Preprint submitted to SoftwareX *May 6, 2020*

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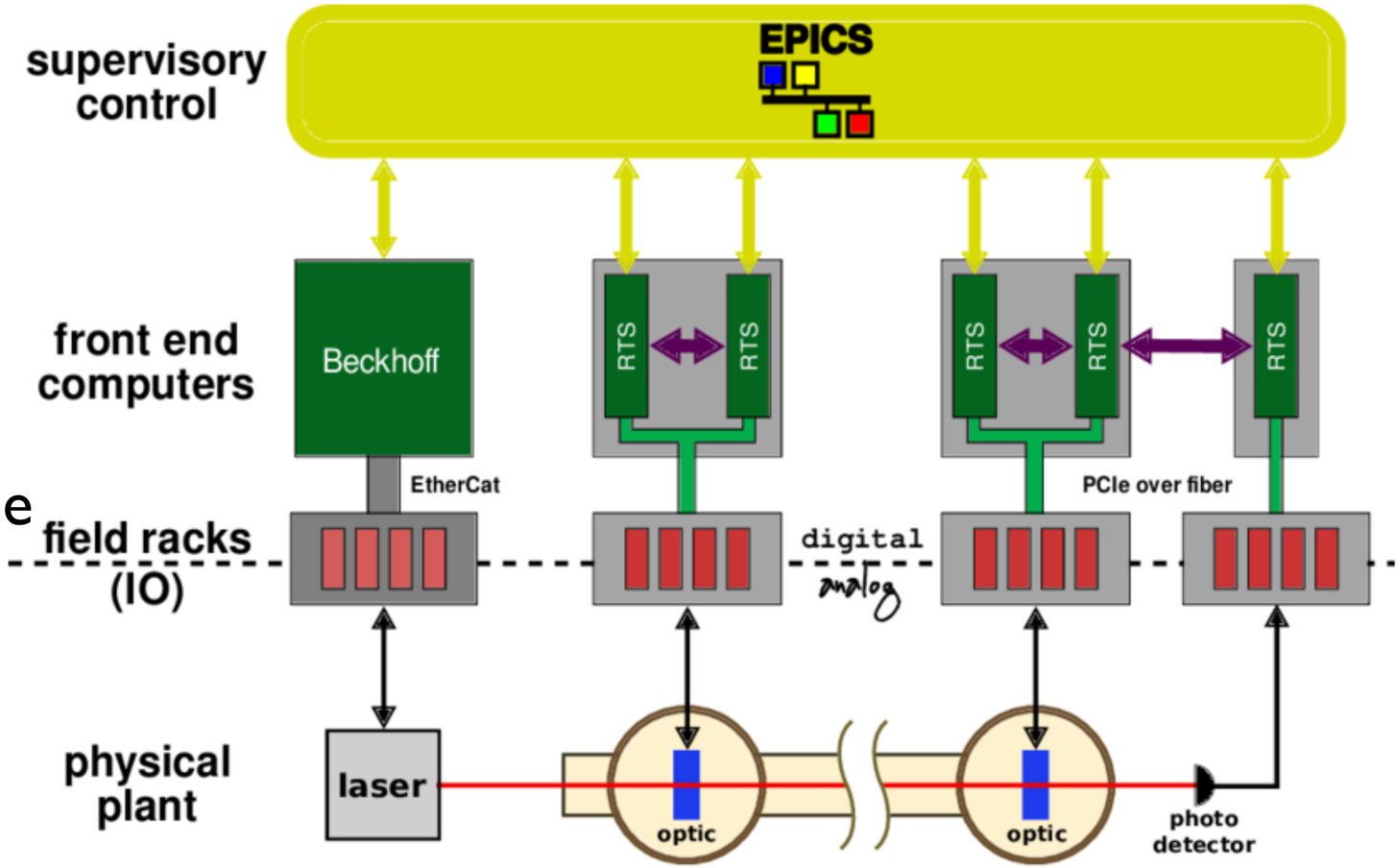
advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)



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

R. Bork et. al. DOI: 10.1016/j.softx.2020.100619

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

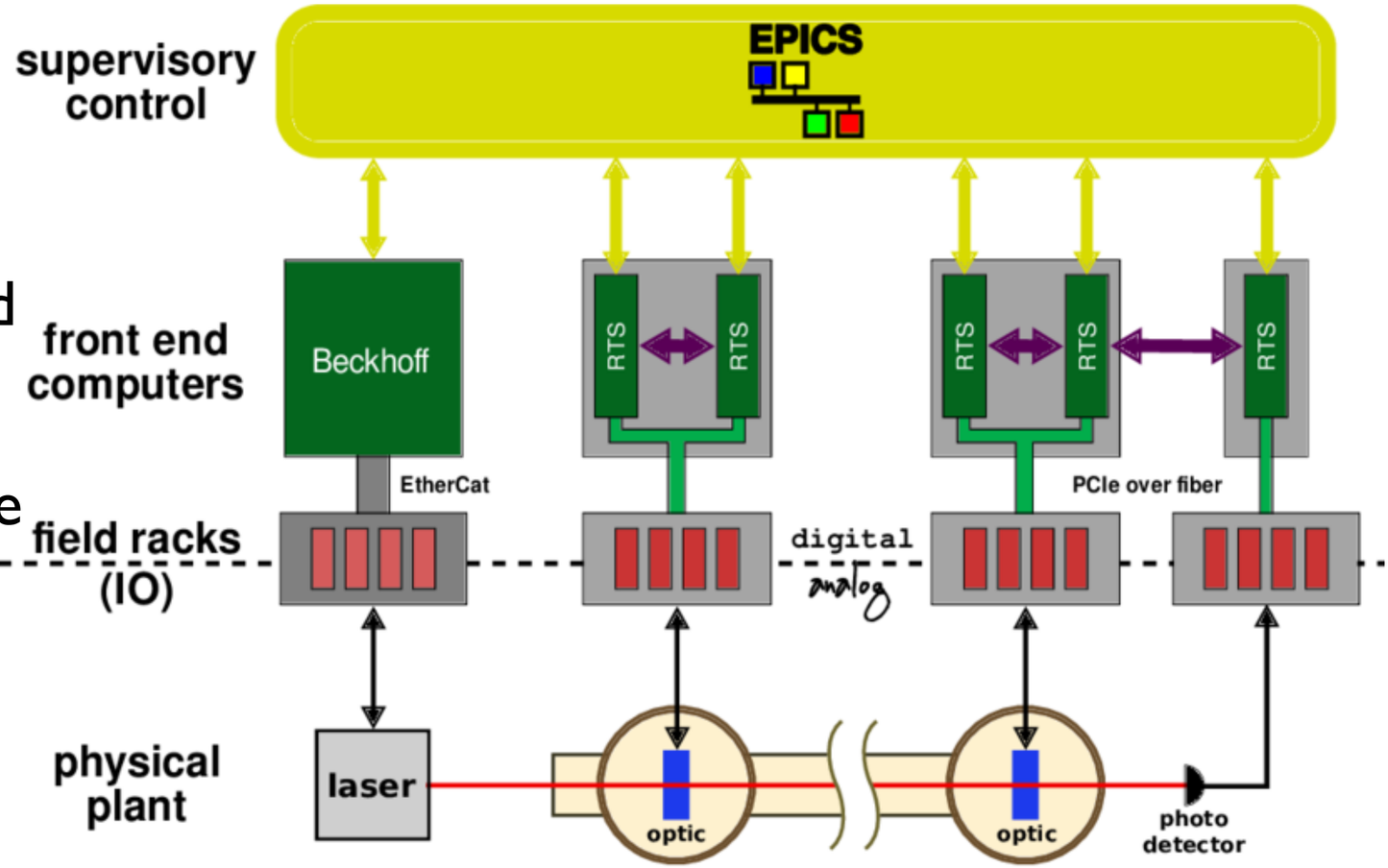
R. Bork et. al. DOI: 10.1016/j.softx.2020.100619

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

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

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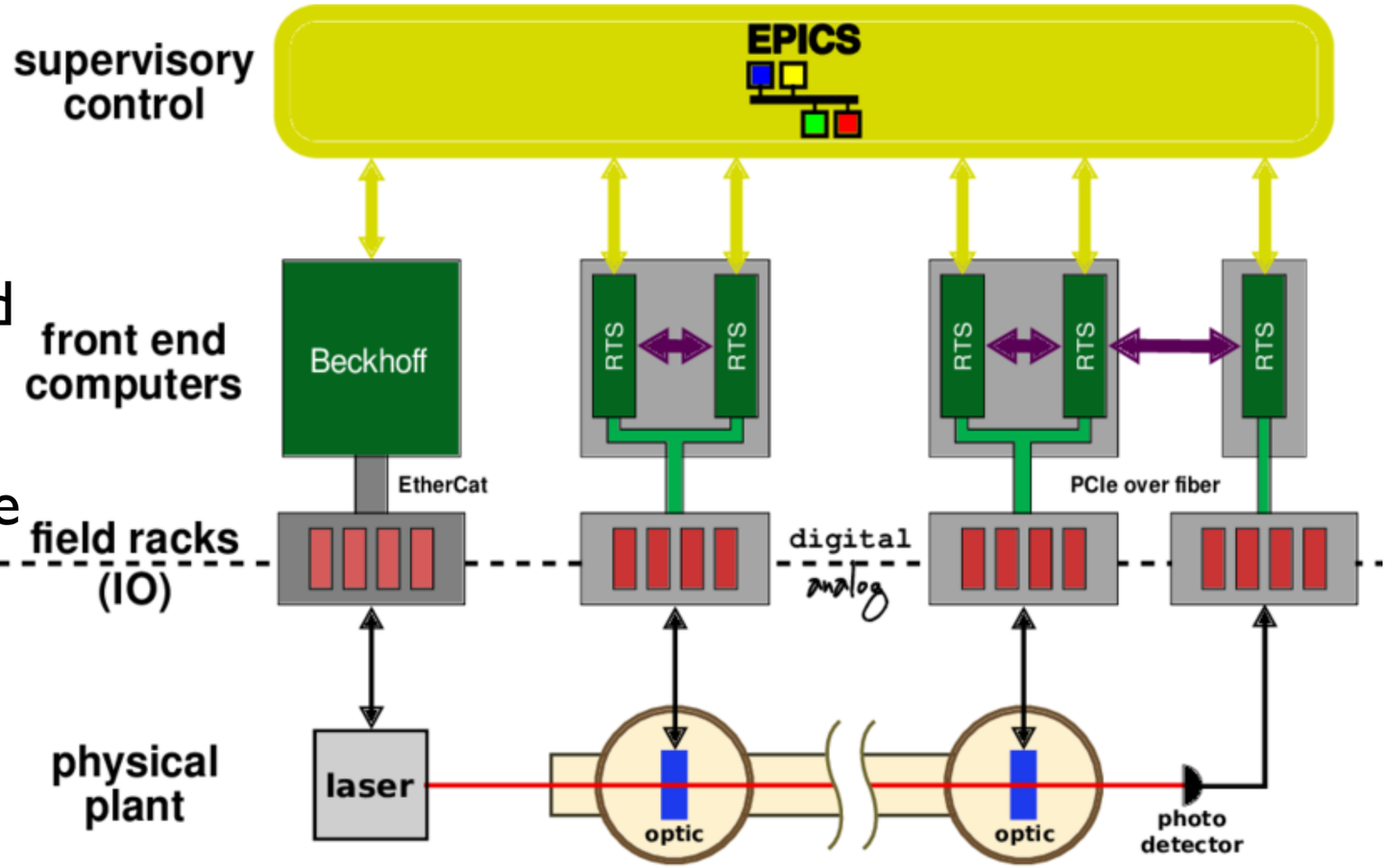
advligorts: The Advanced LIGO Real-Time Digital Control & Data Acquisition System (CDS)

EPICS is used as the supervisory level

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

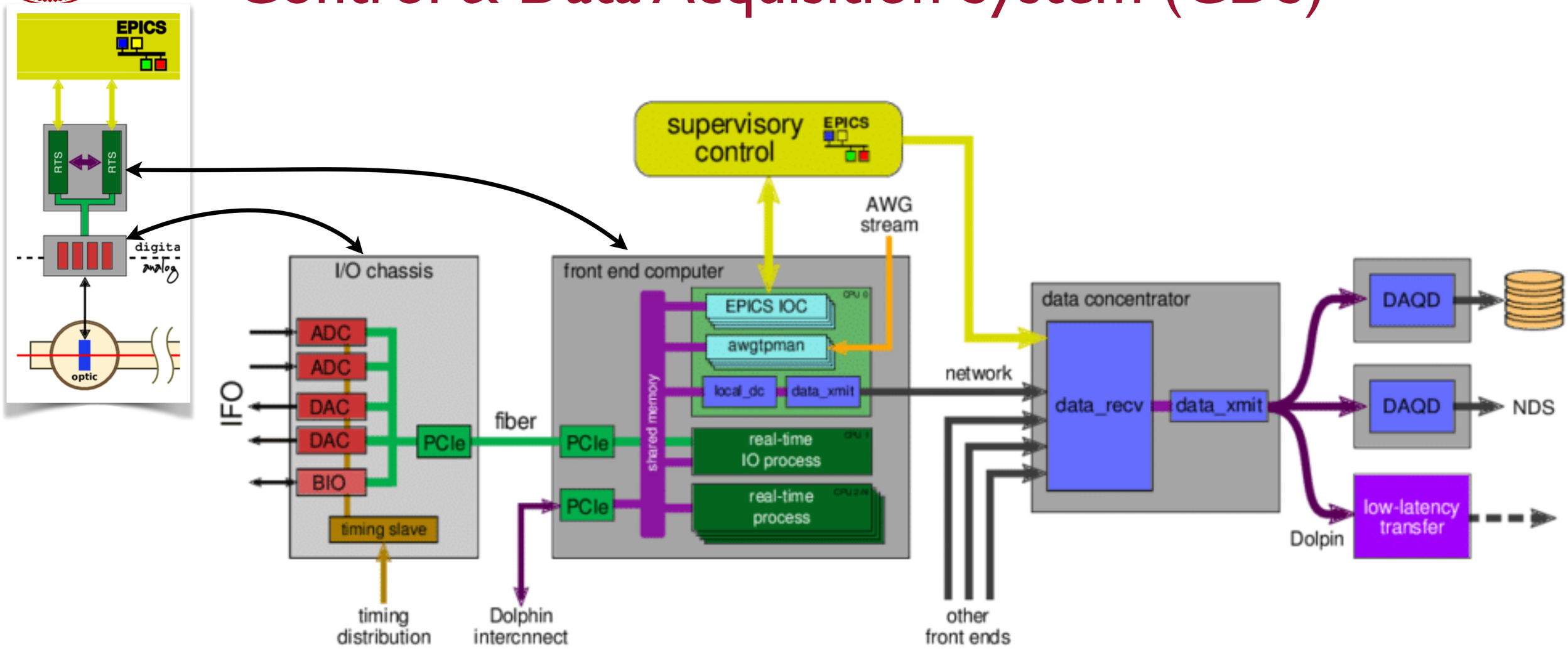
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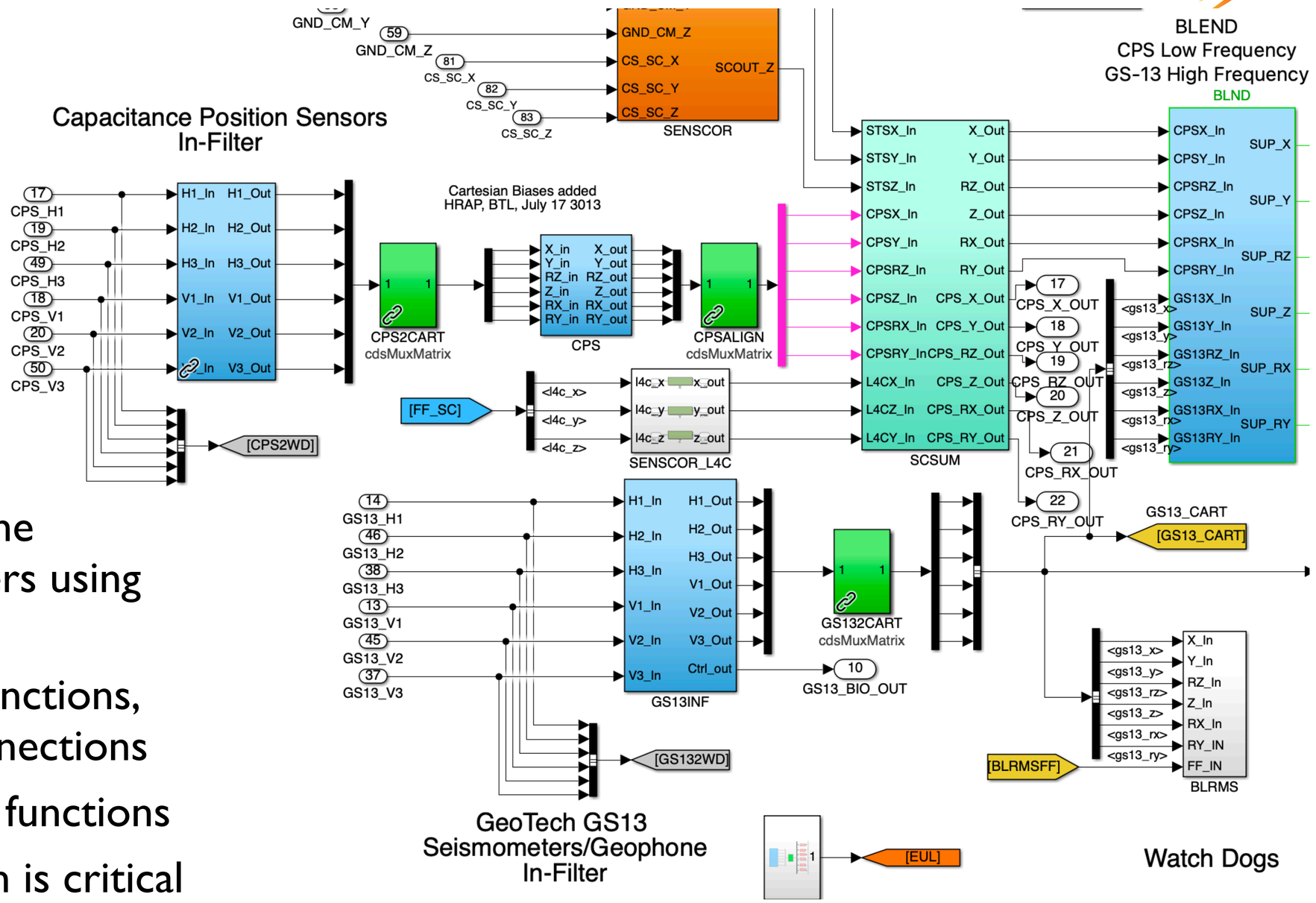
Single timing system

Data system combines all data streams

R. Bork et. al. DOI: 10.1016/j.softx.2020.100619

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

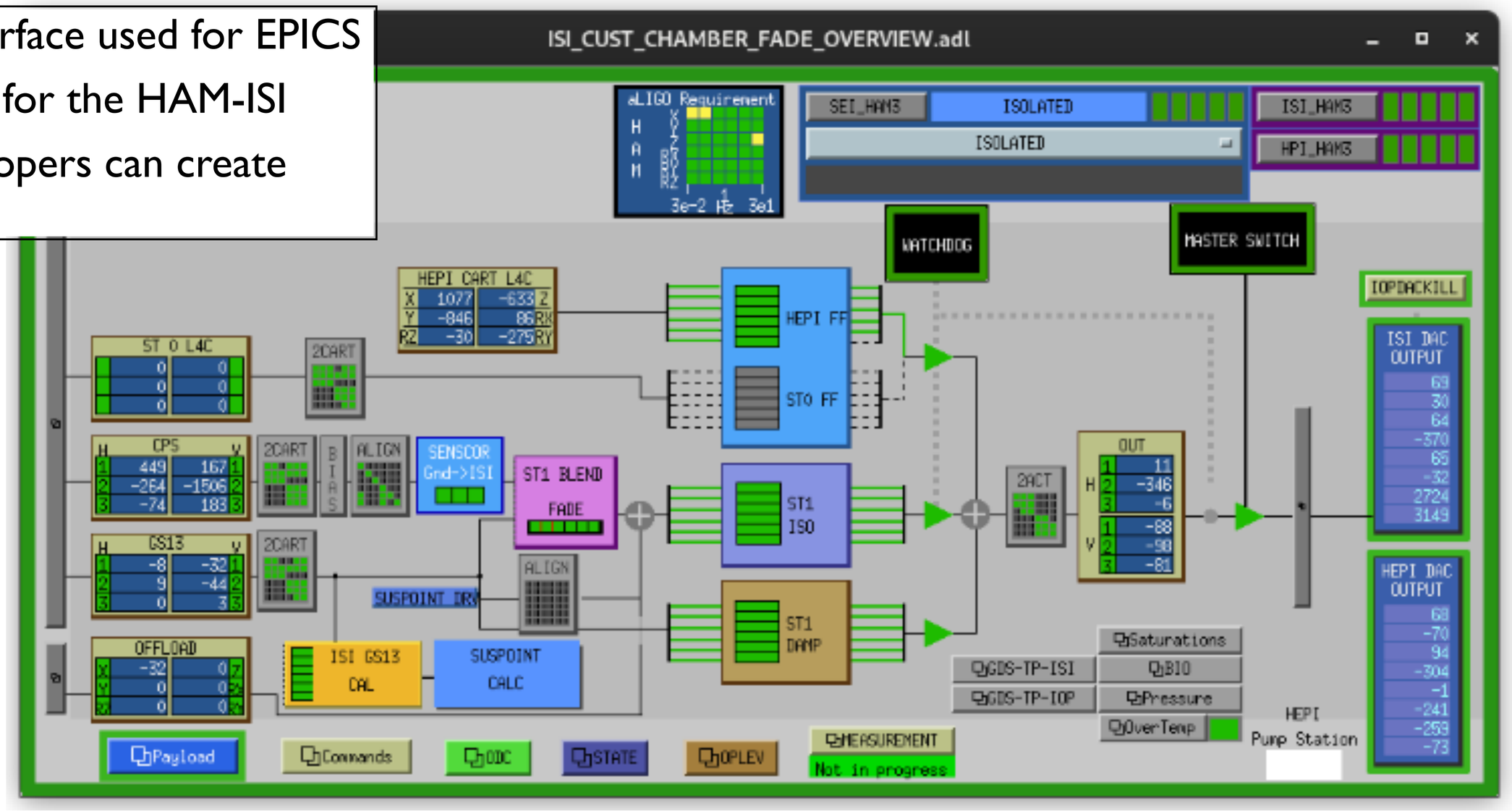
Models can be big - visual design is critical

User Interface

MEDM is the interface used for EPICS

Overview screen for the HAM-ISI

Operators/ developers can create interface screens

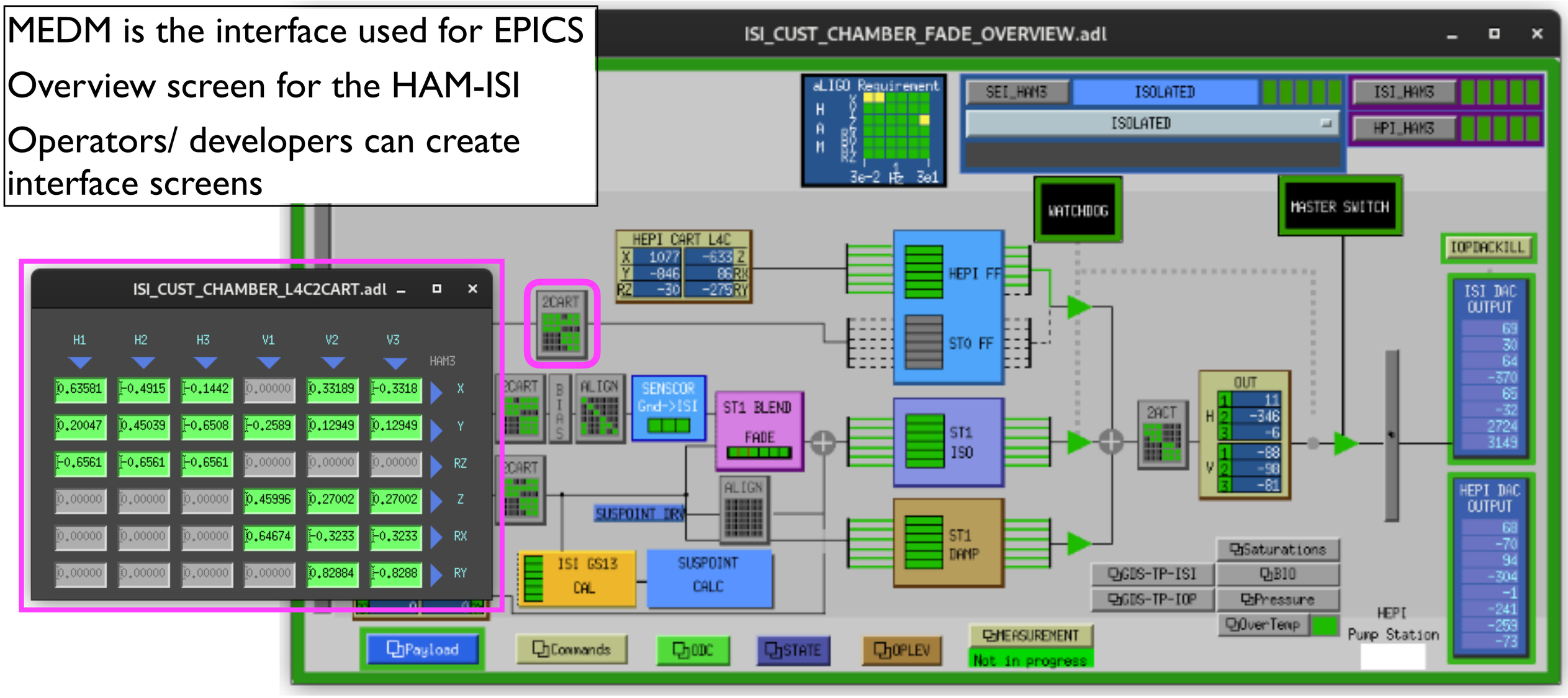


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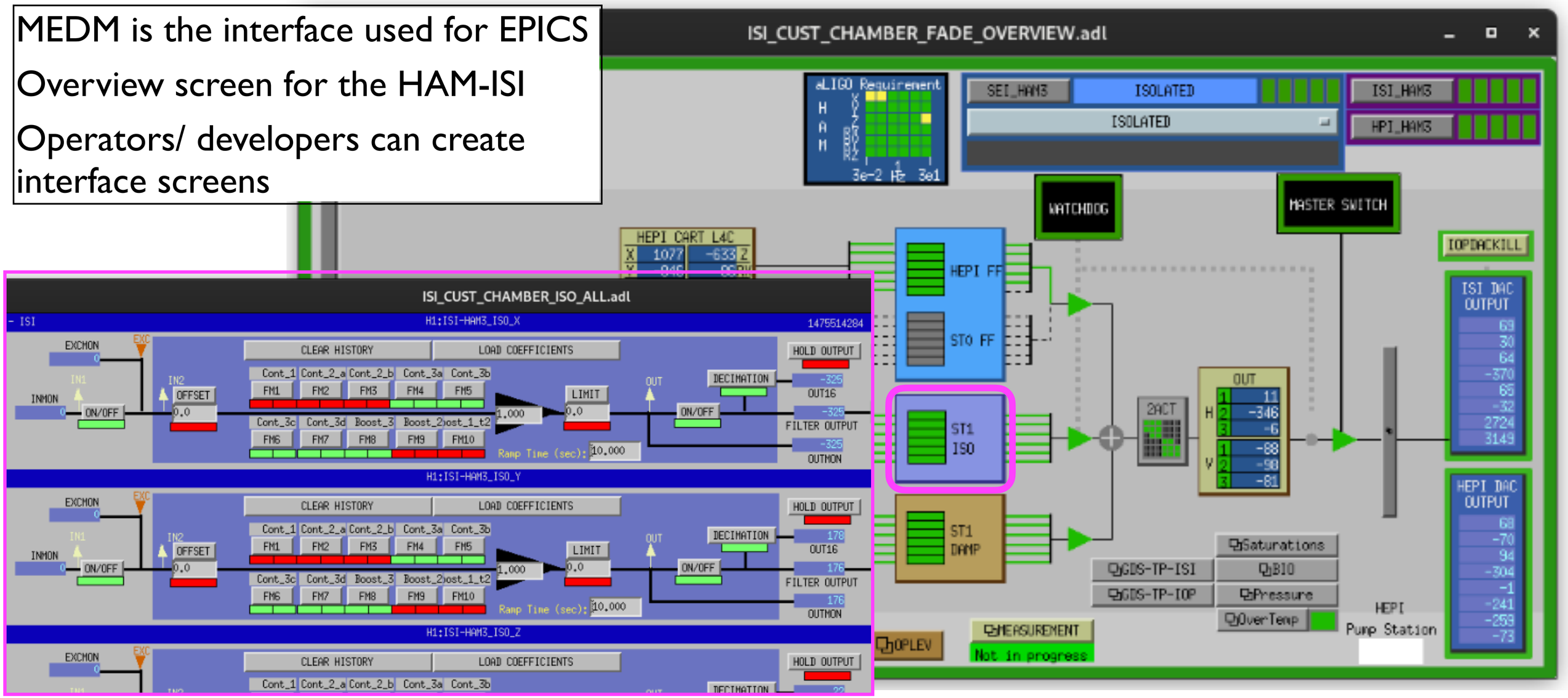


User Interface

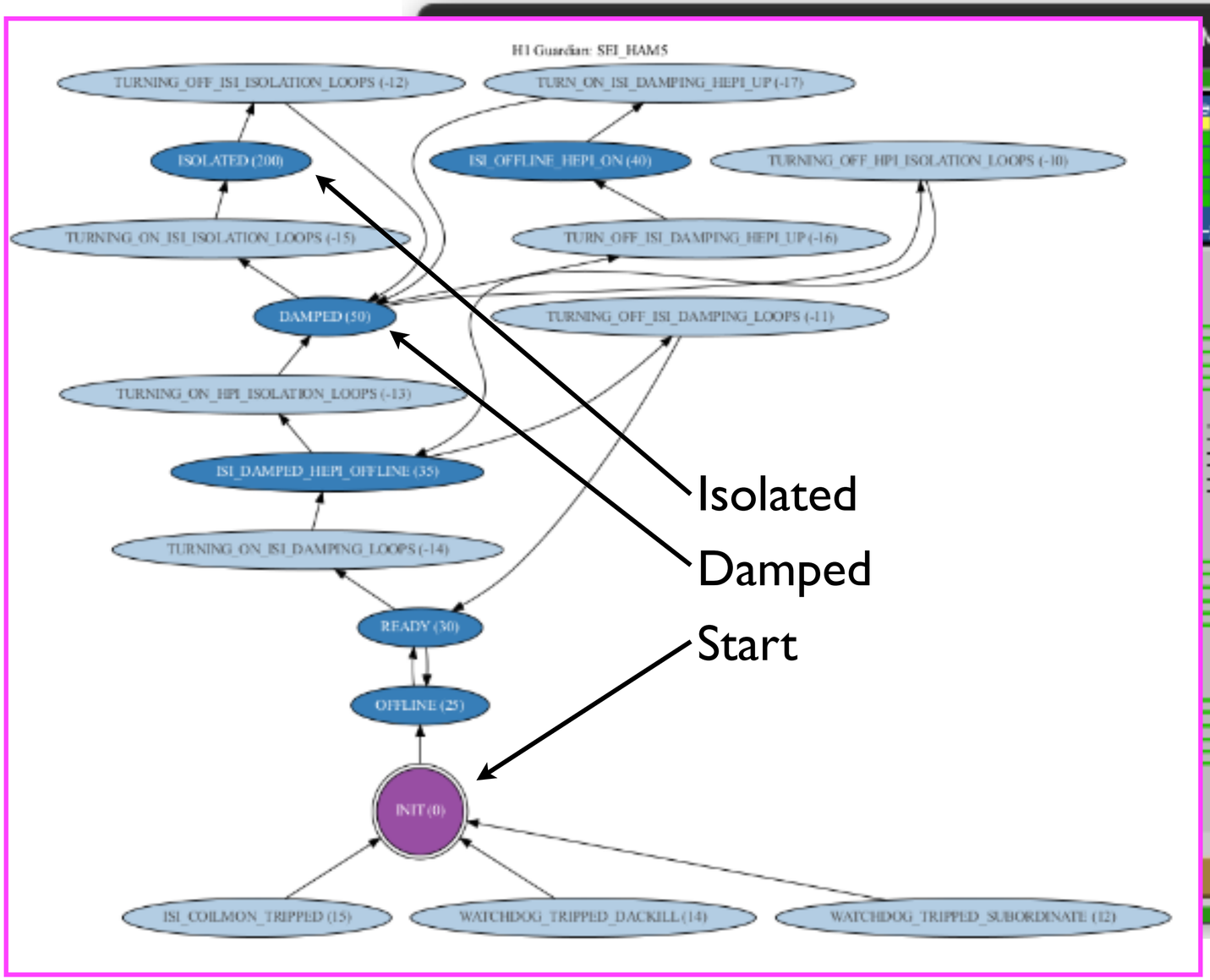
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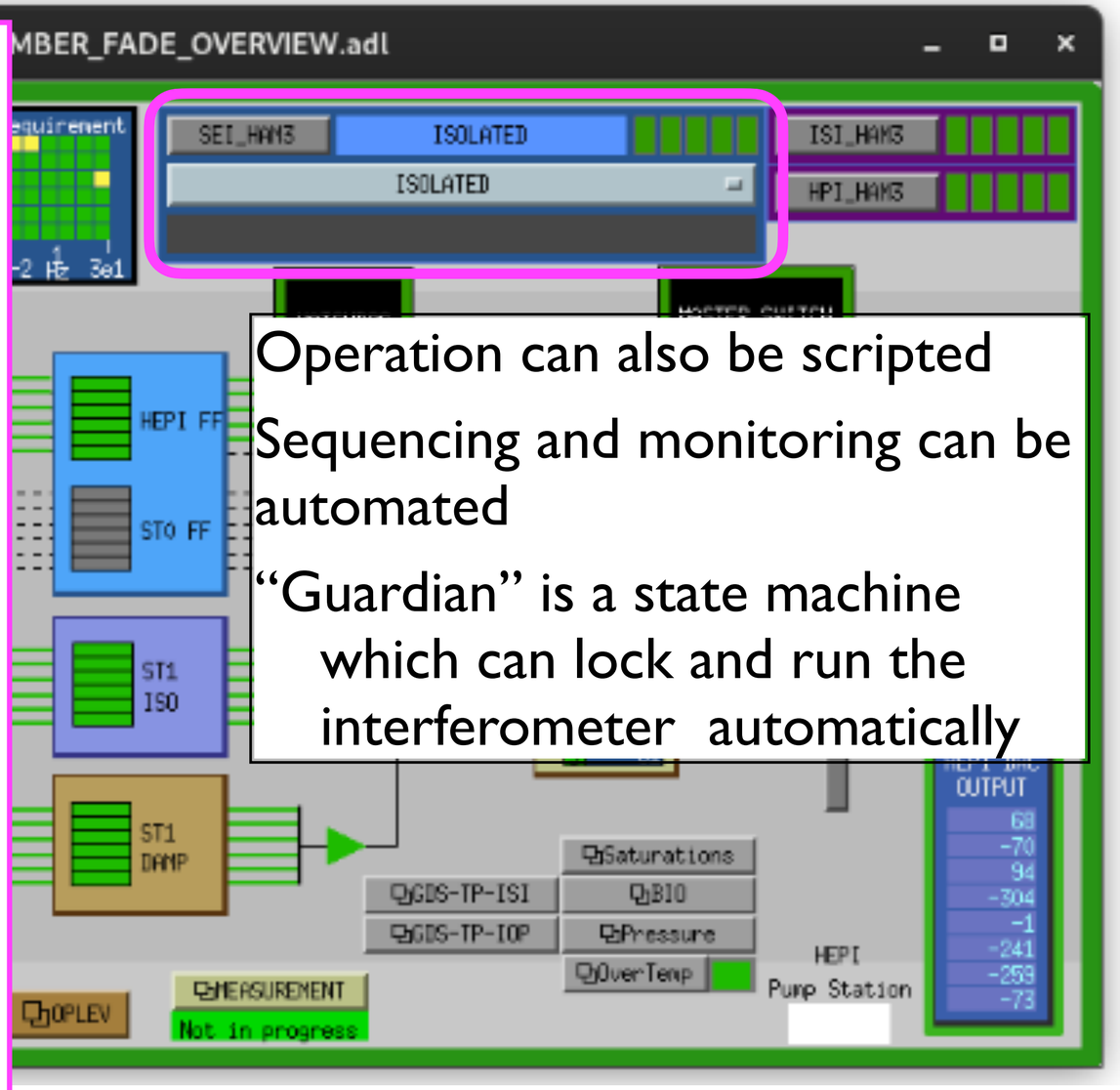
Overview screen for the HAM-ISI

Operators/ developers can create interface screens



Guardian





Operation can also be scripted

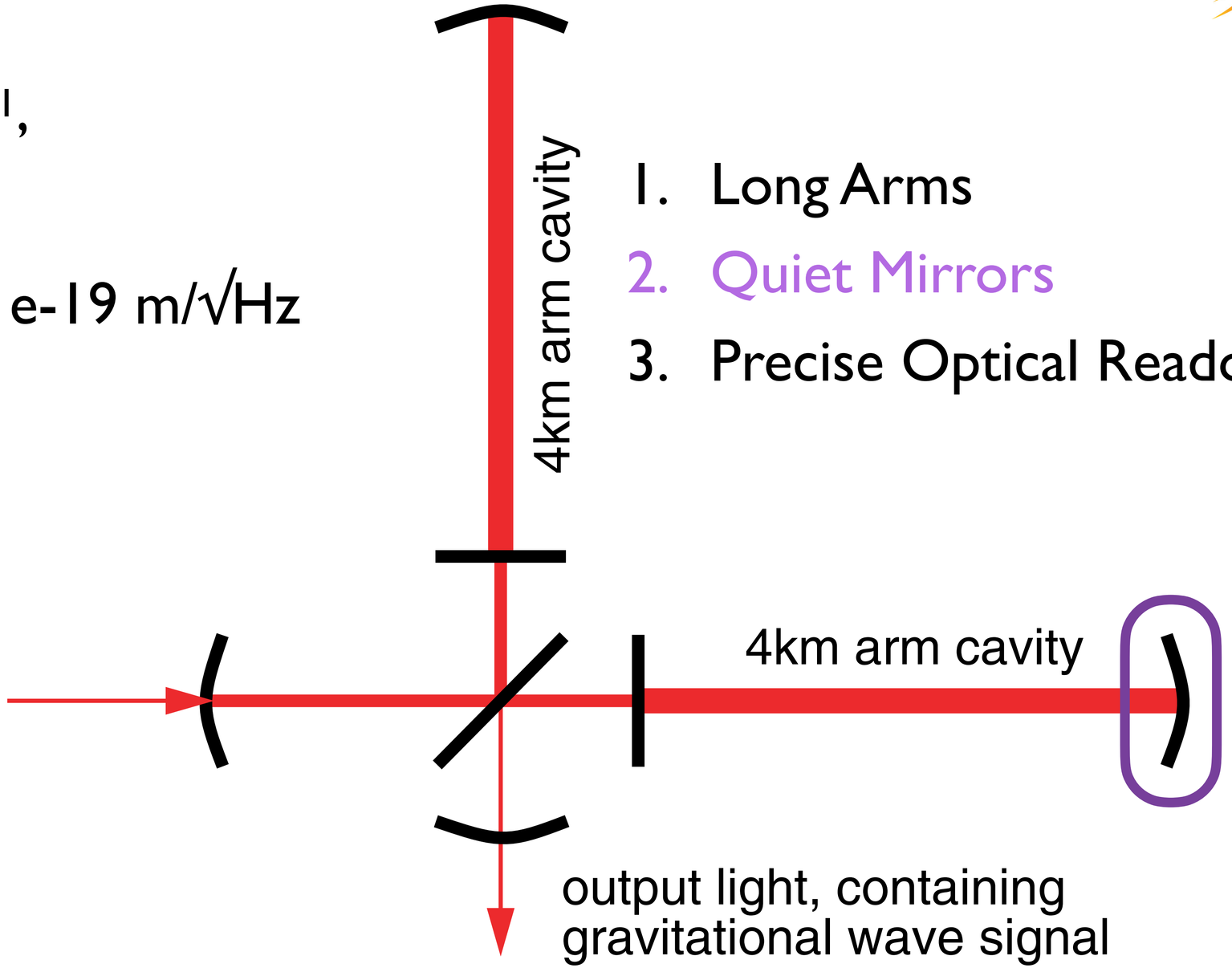
Sequencing and monitoring can be automated

"Guardian" is a state machine which can lock and run the interferometer automatically

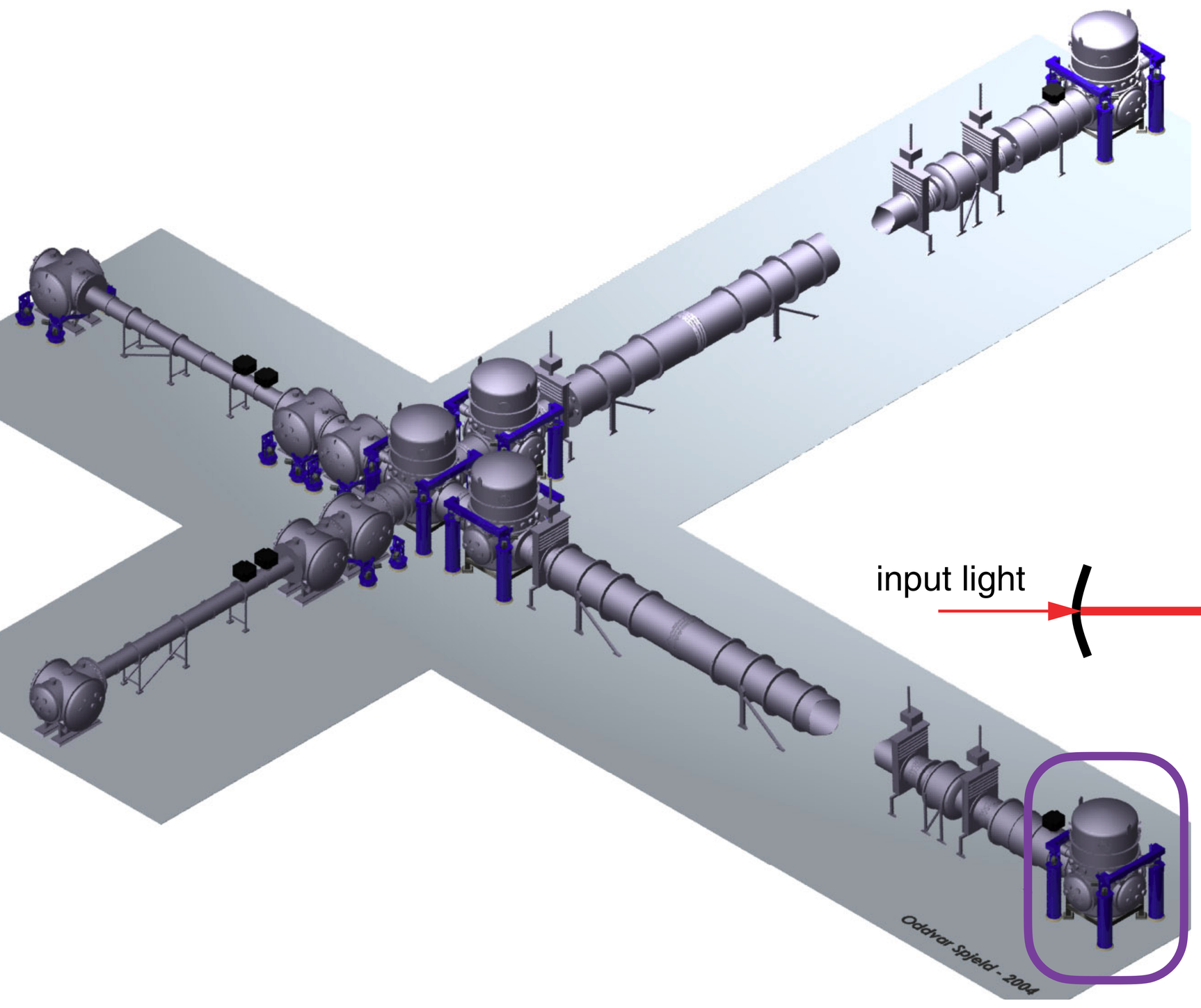
The interferometer needs control

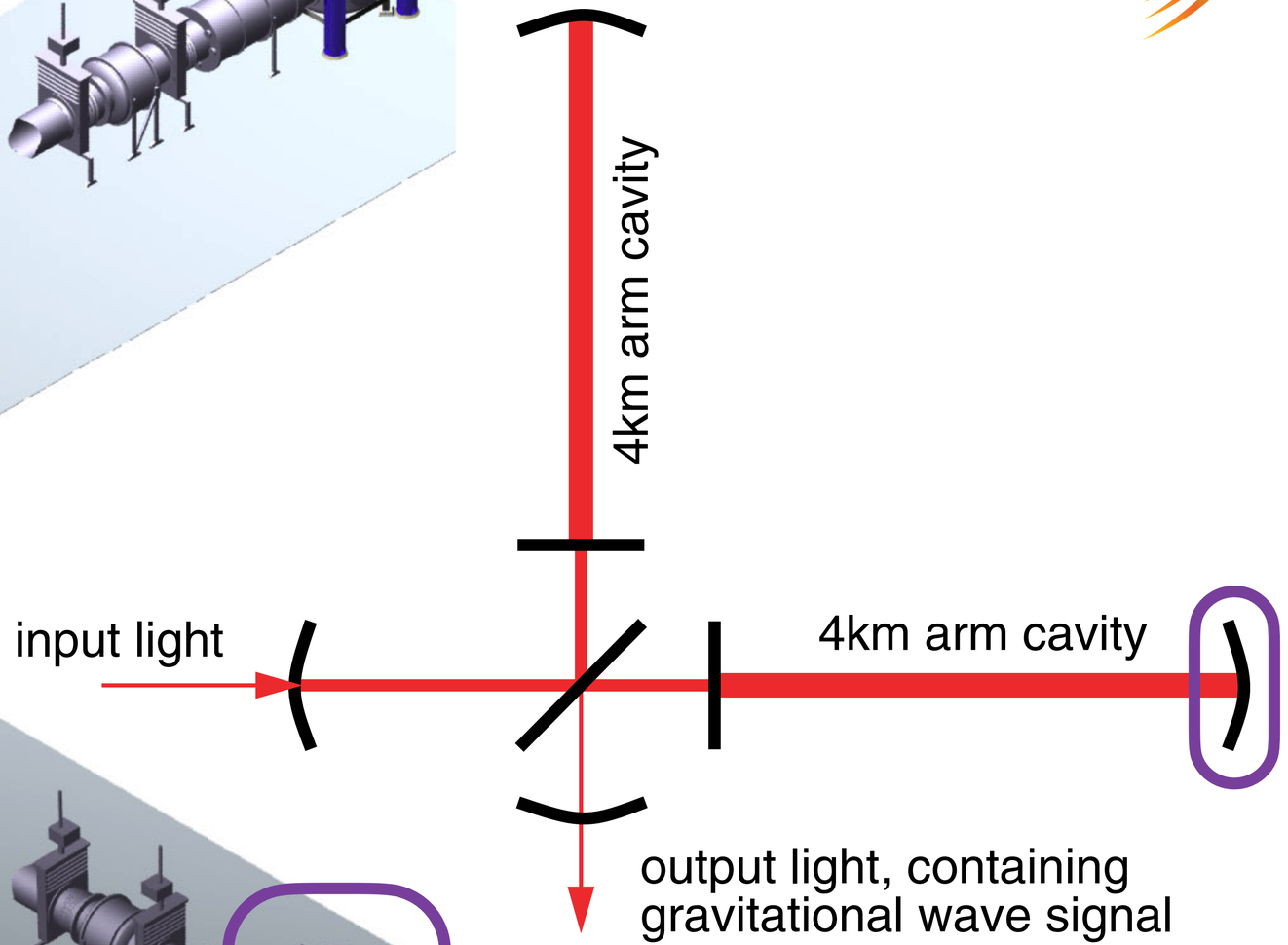
Our signal strain (h) = 10^{-21},
dL = $4*10^{-18}$ meters

Mirror motion at 10 Hz ~1e-19 m/√Hz



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


Oddvar Spjeld - 2004


4km arm cavity
input light
4km arm cavity
output light, containing
gravitational wave signal

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

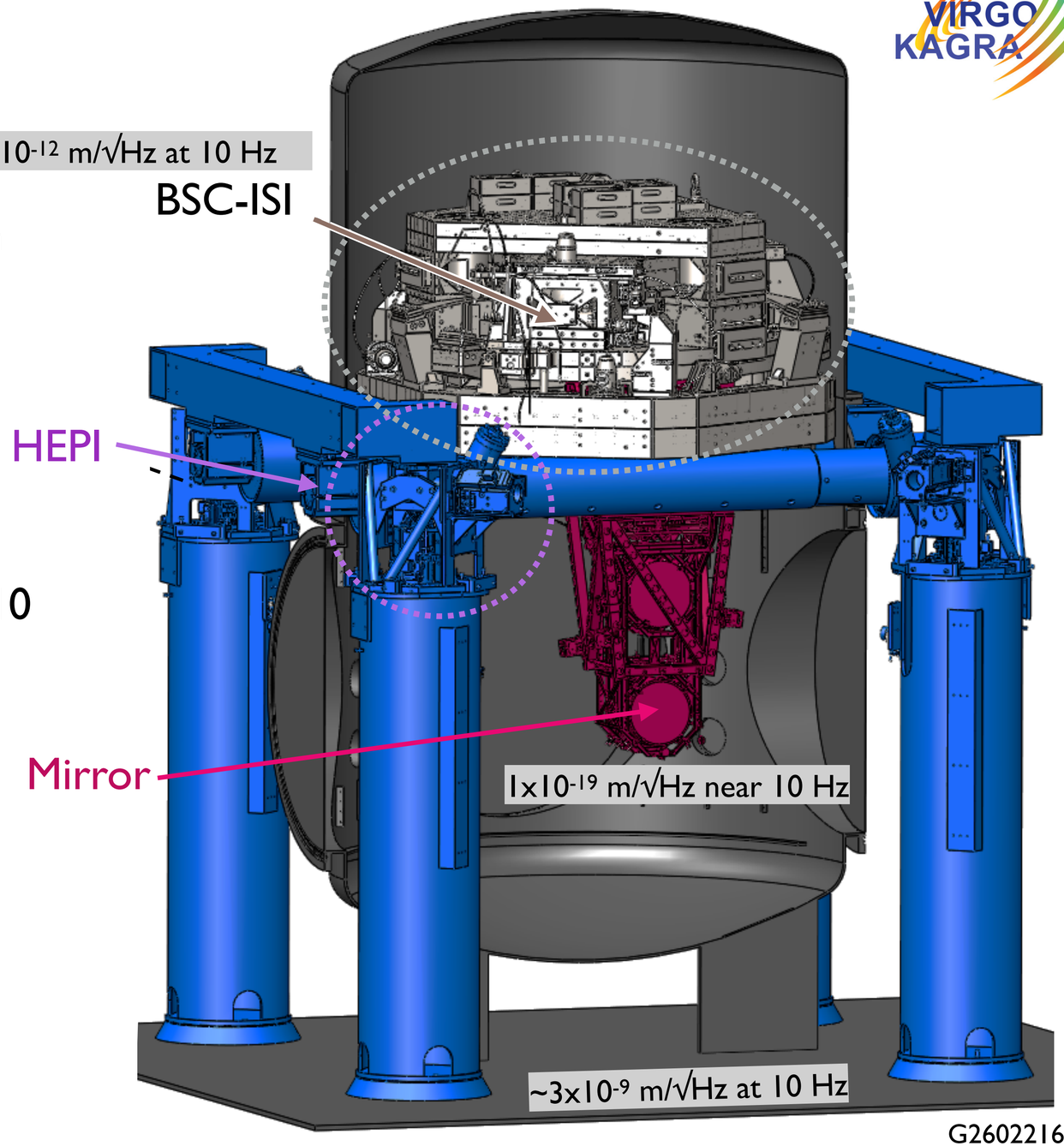
External Quiet Hydraulic stage for low frequency positioning

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

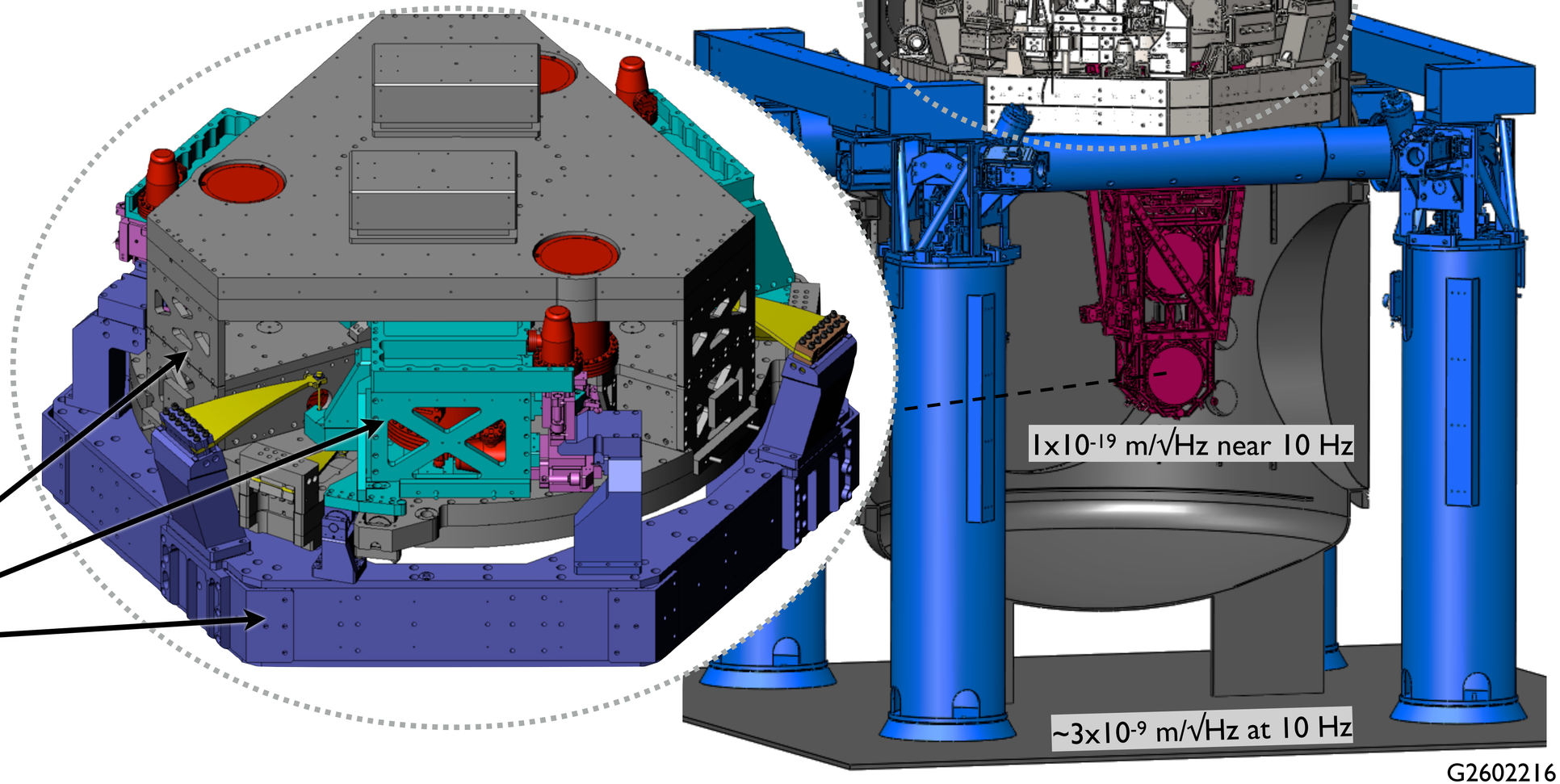
4 stage mirror suspension to give excellent isolation at 10 Hz and quiet actuation for interferometer control

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.



aLIGO Isolation





optics table - stage 2

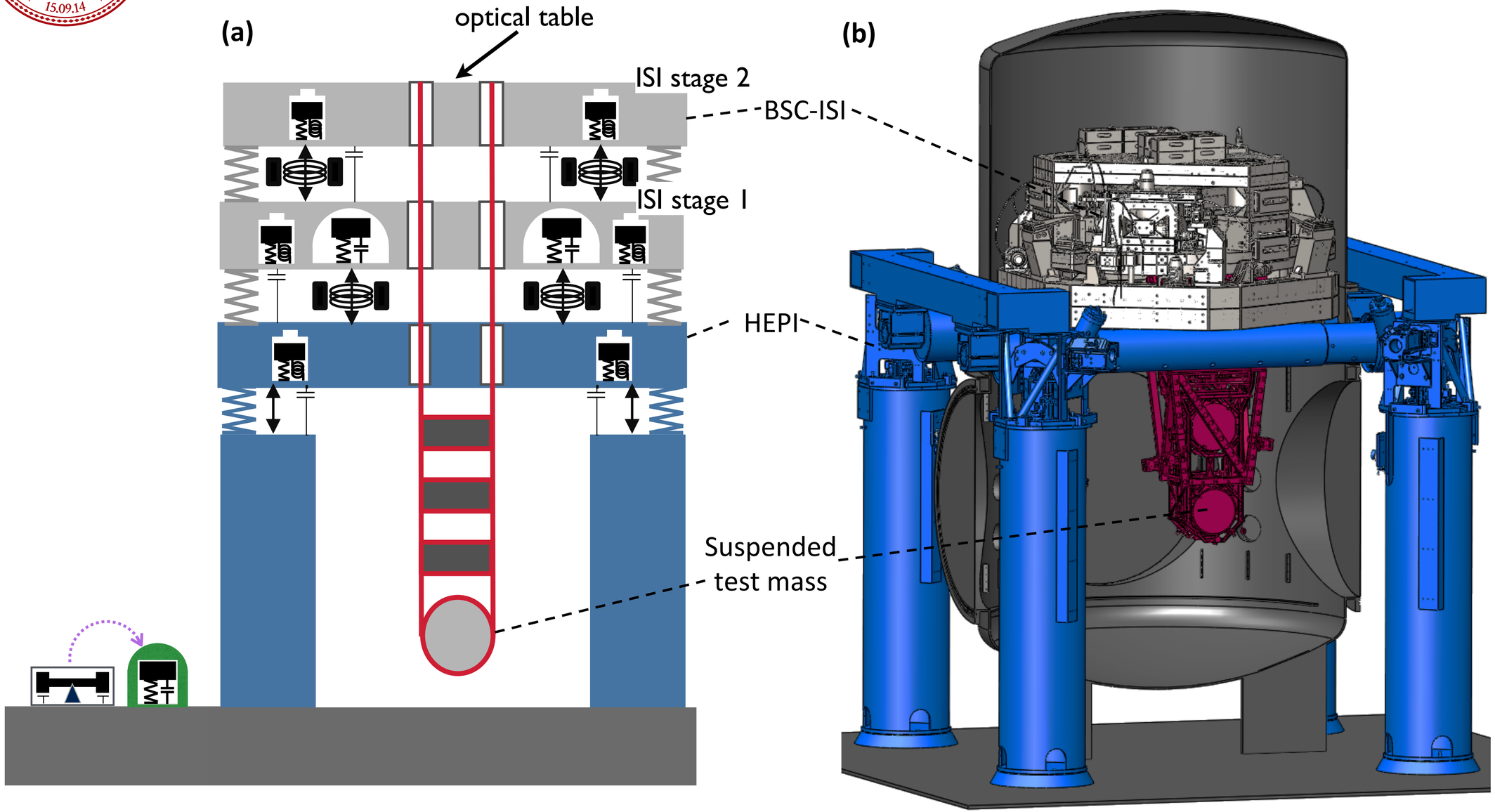
stage 1

support - stage 0

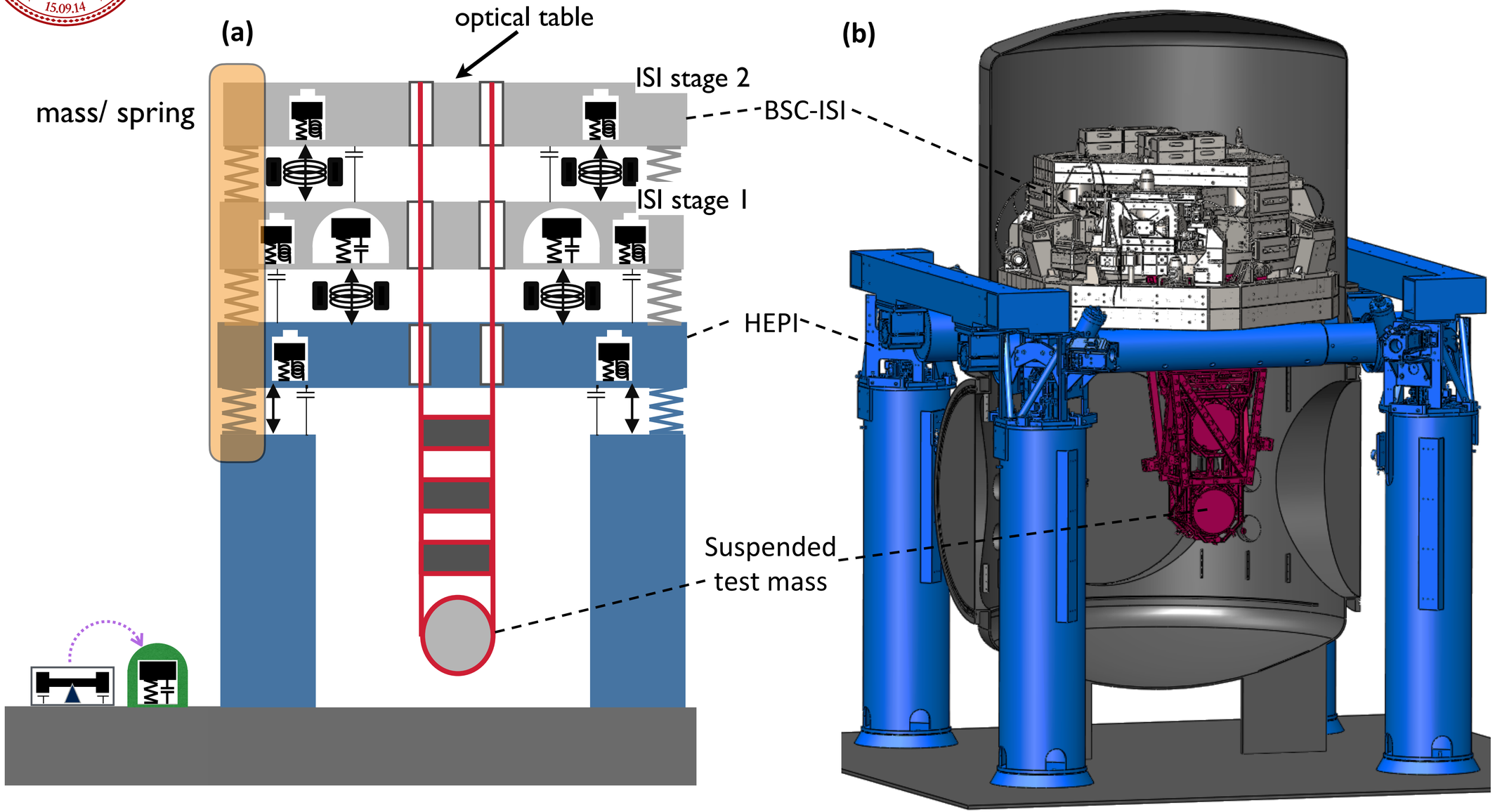
1x10^{-19} m/√Hz near 10 Hz

~3x10^{-9} m/√Hz at 10 Hz

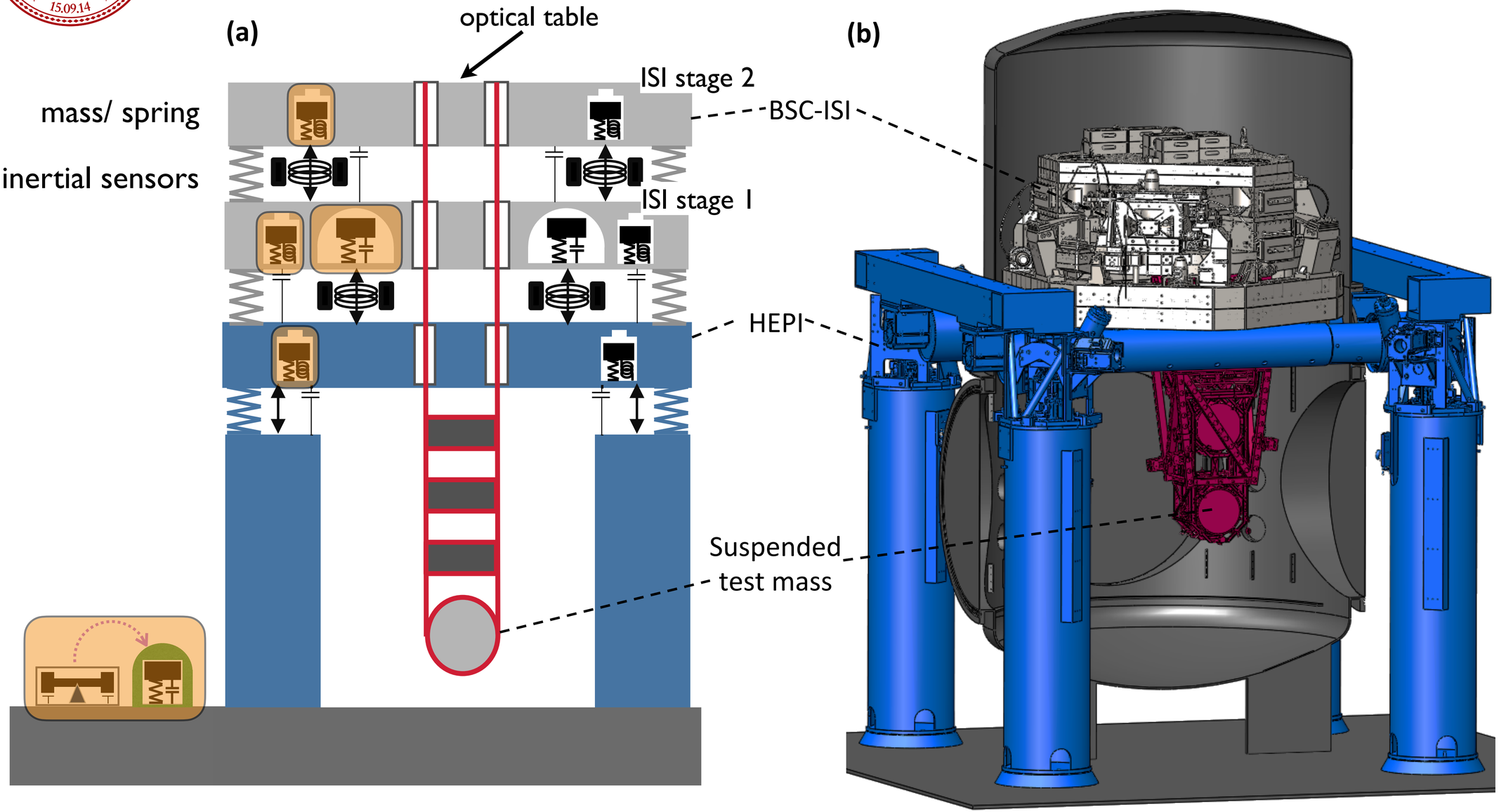
Isolation walkthrough



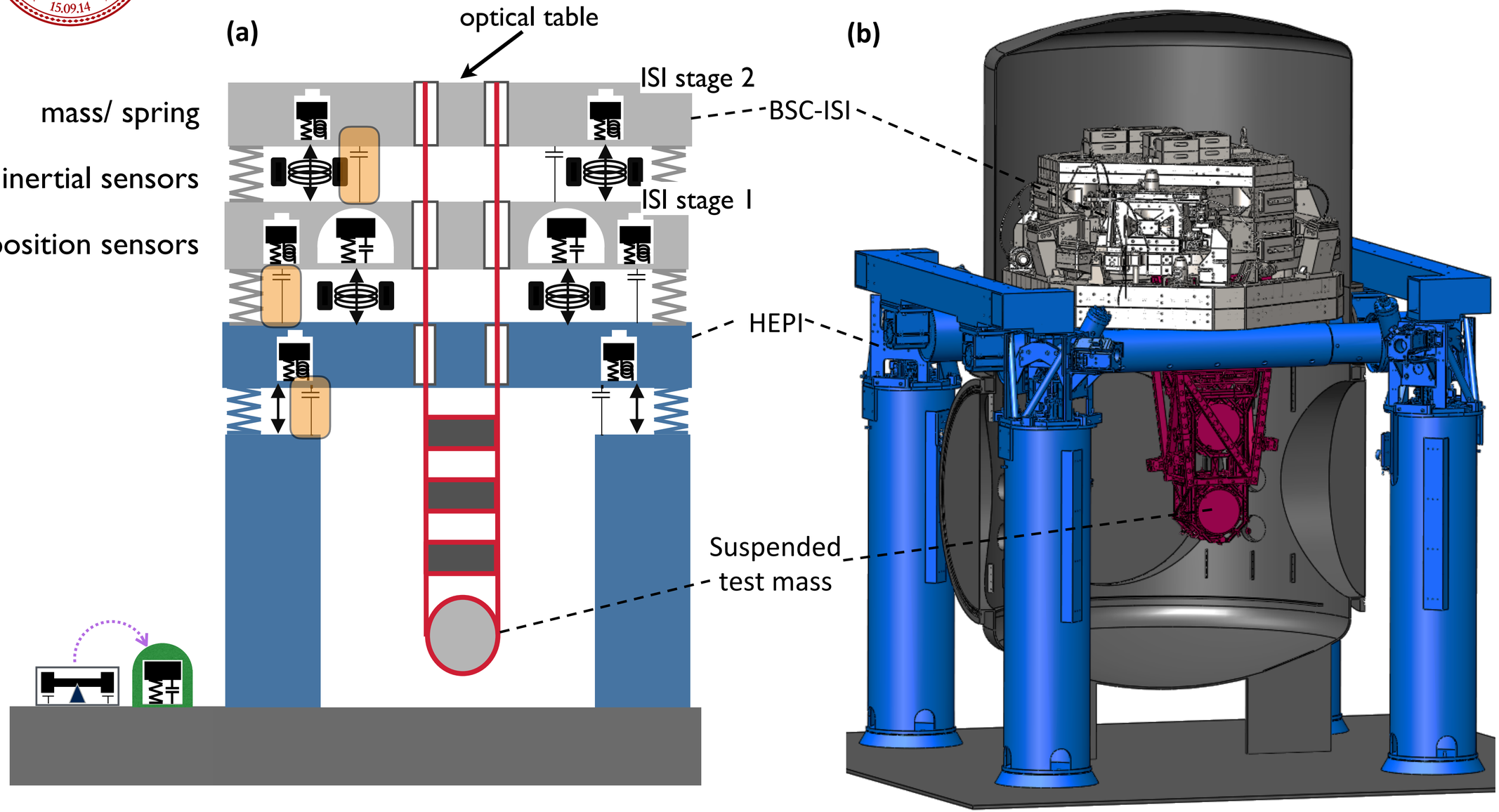
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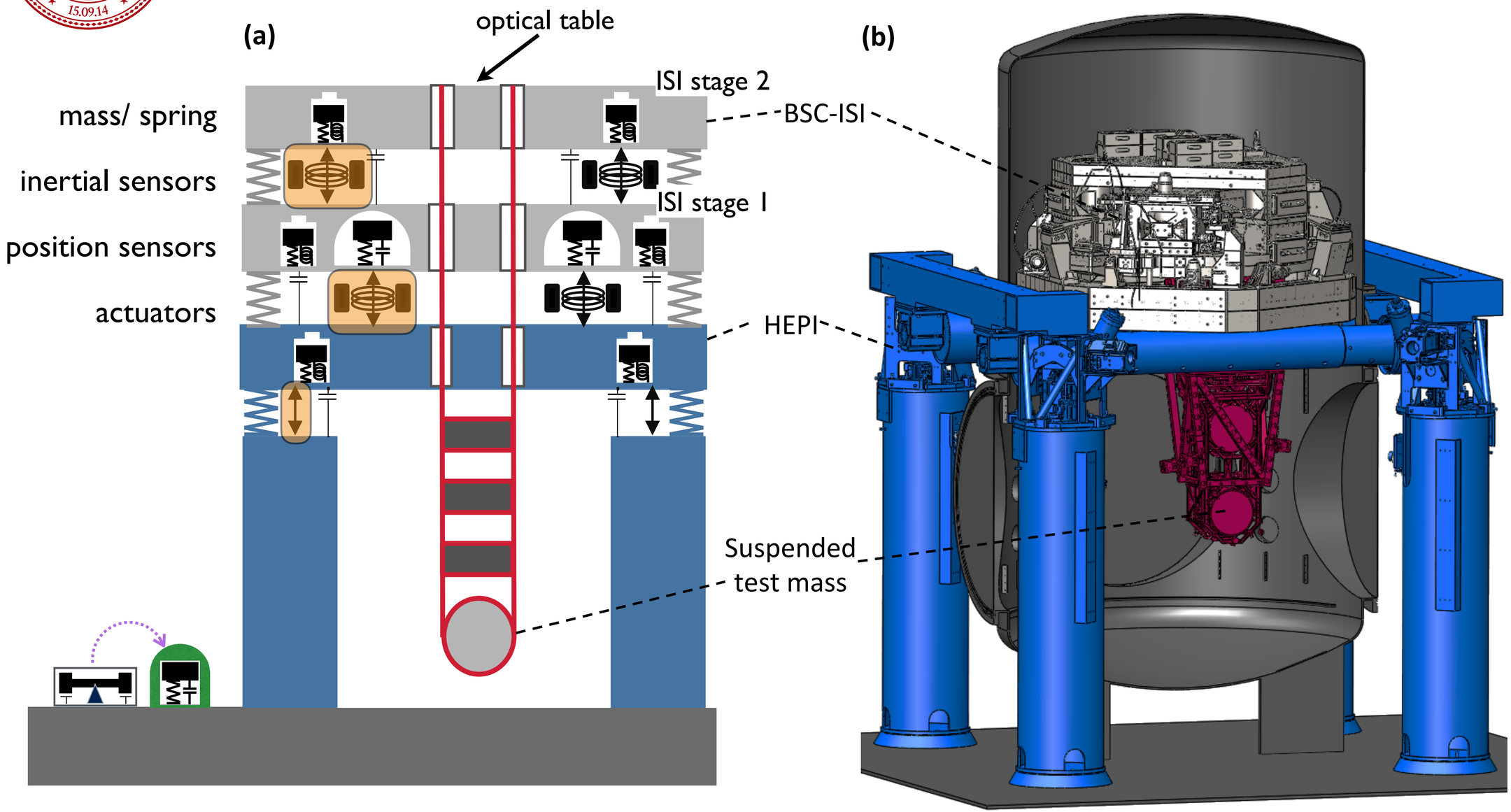


Isolation walkthrough

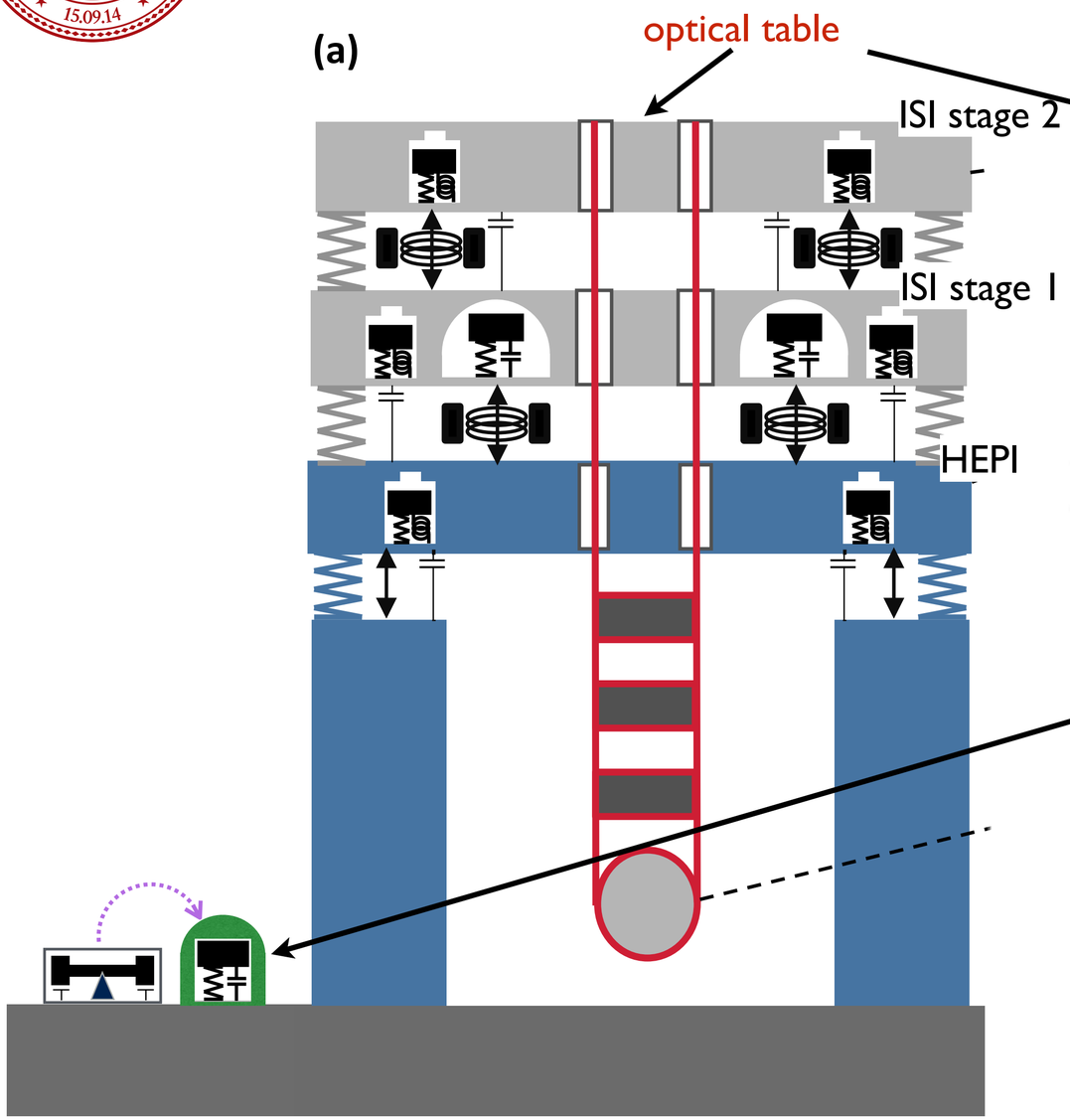


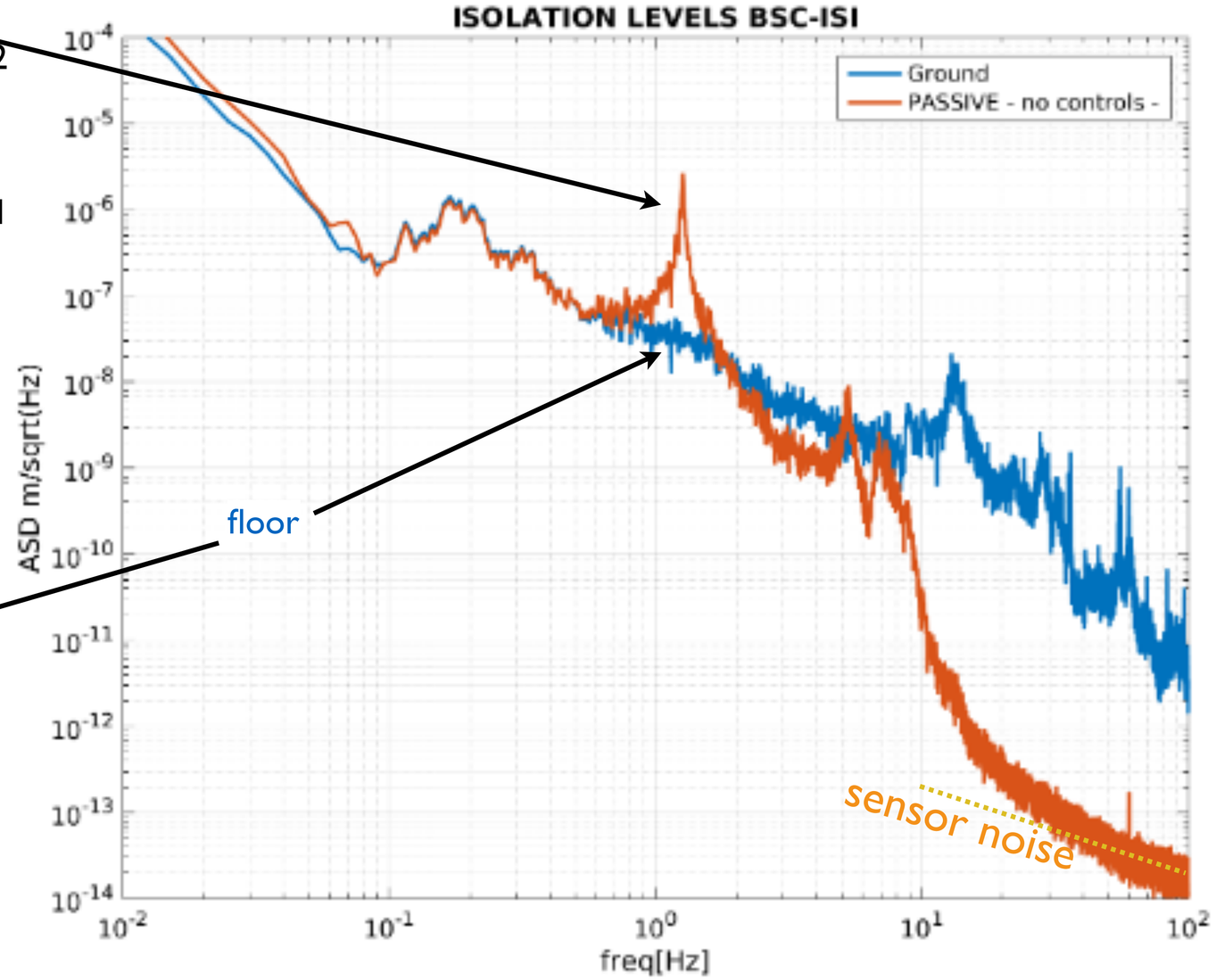
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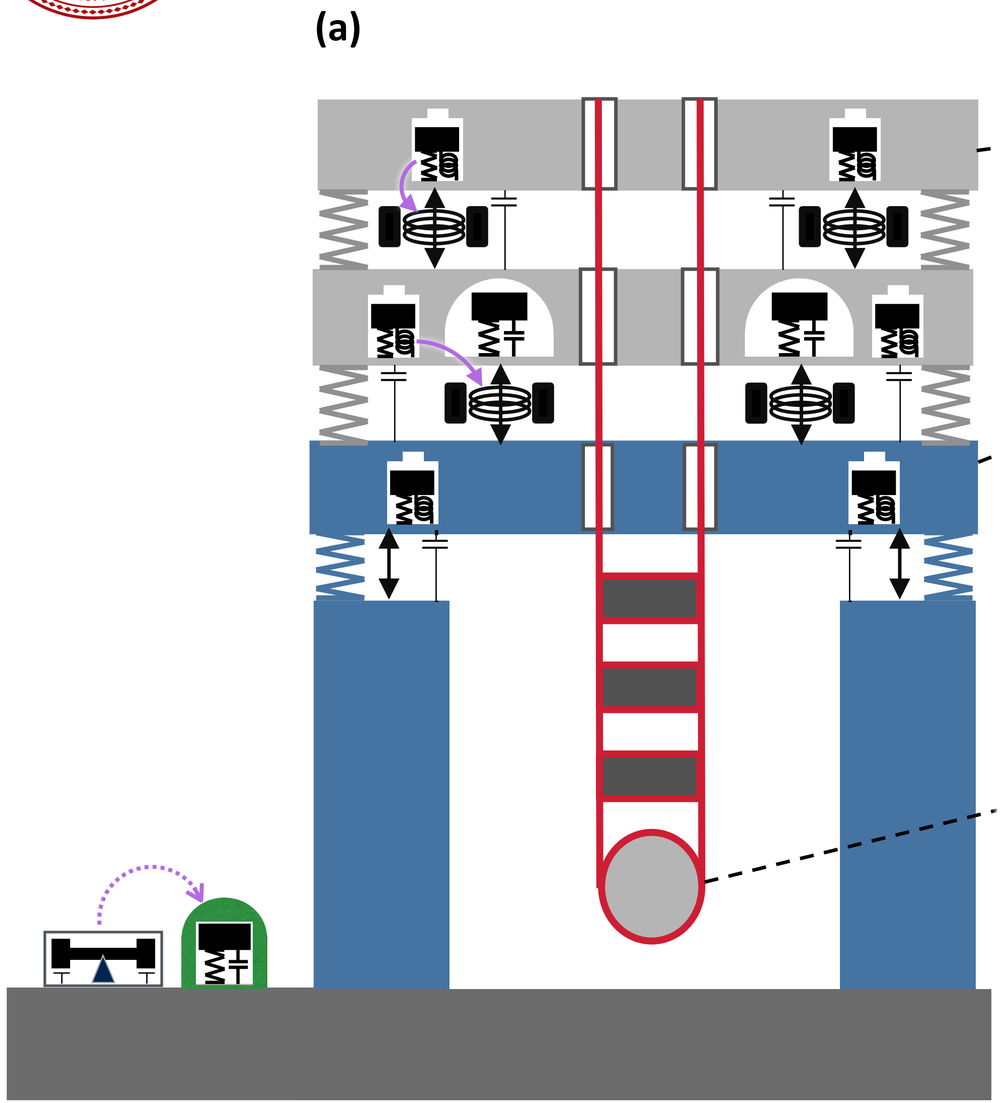

(a)
optical table
ISI stage 2
mass/ spring
inertial sensors
position sensors
actuators
ISI stage 1
(b)
BSC-ISI
HEPI
Suspended
test mass

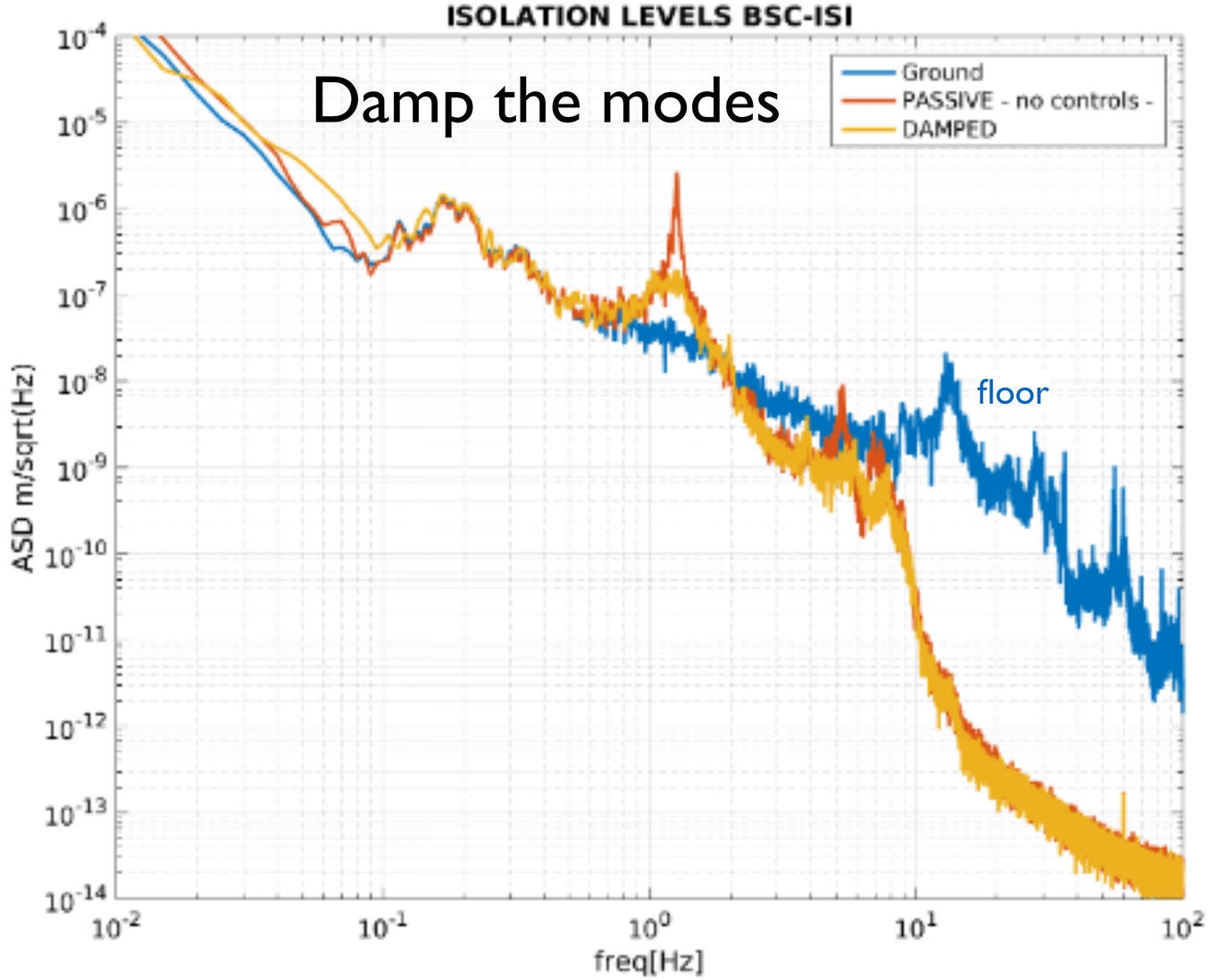
Isolation walkthrough



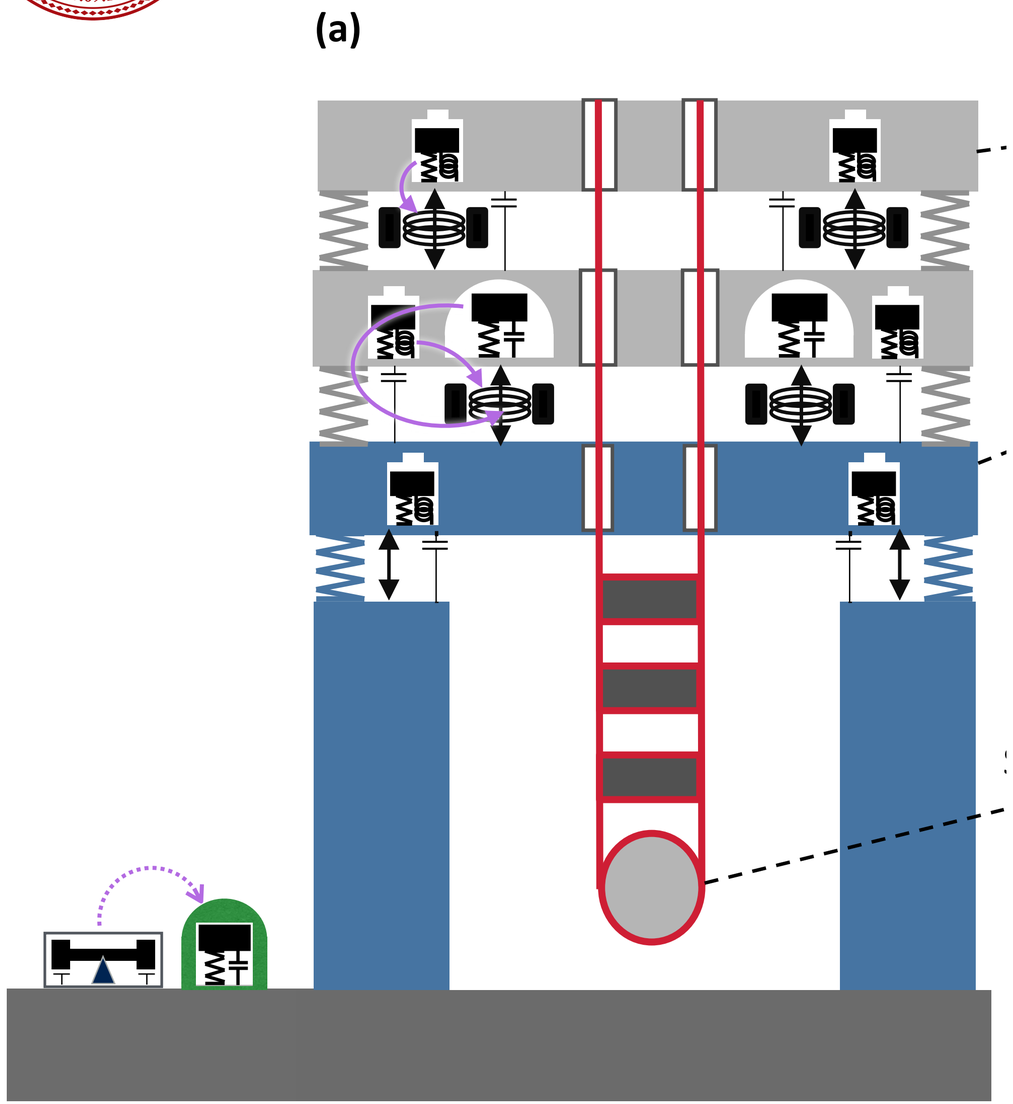


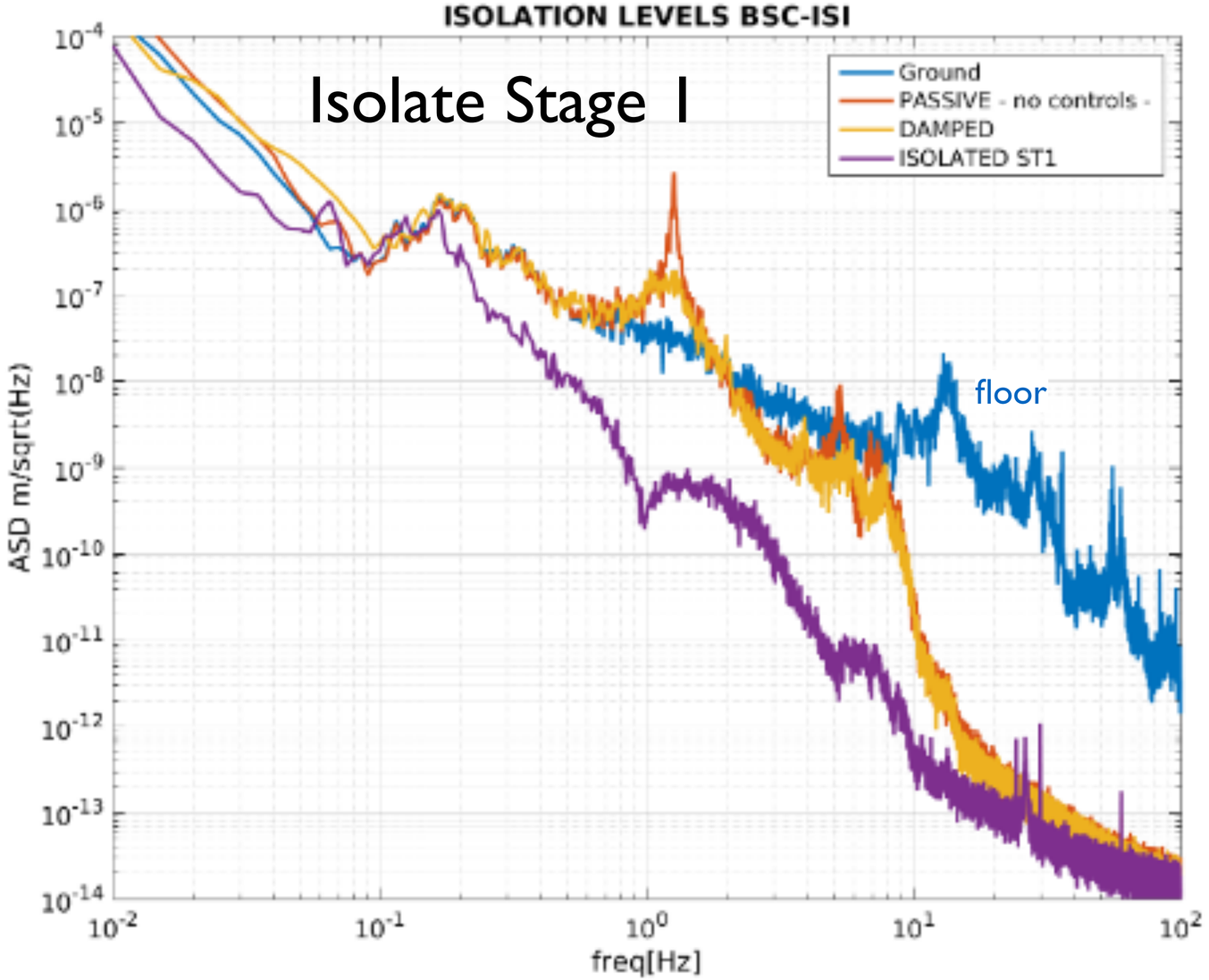
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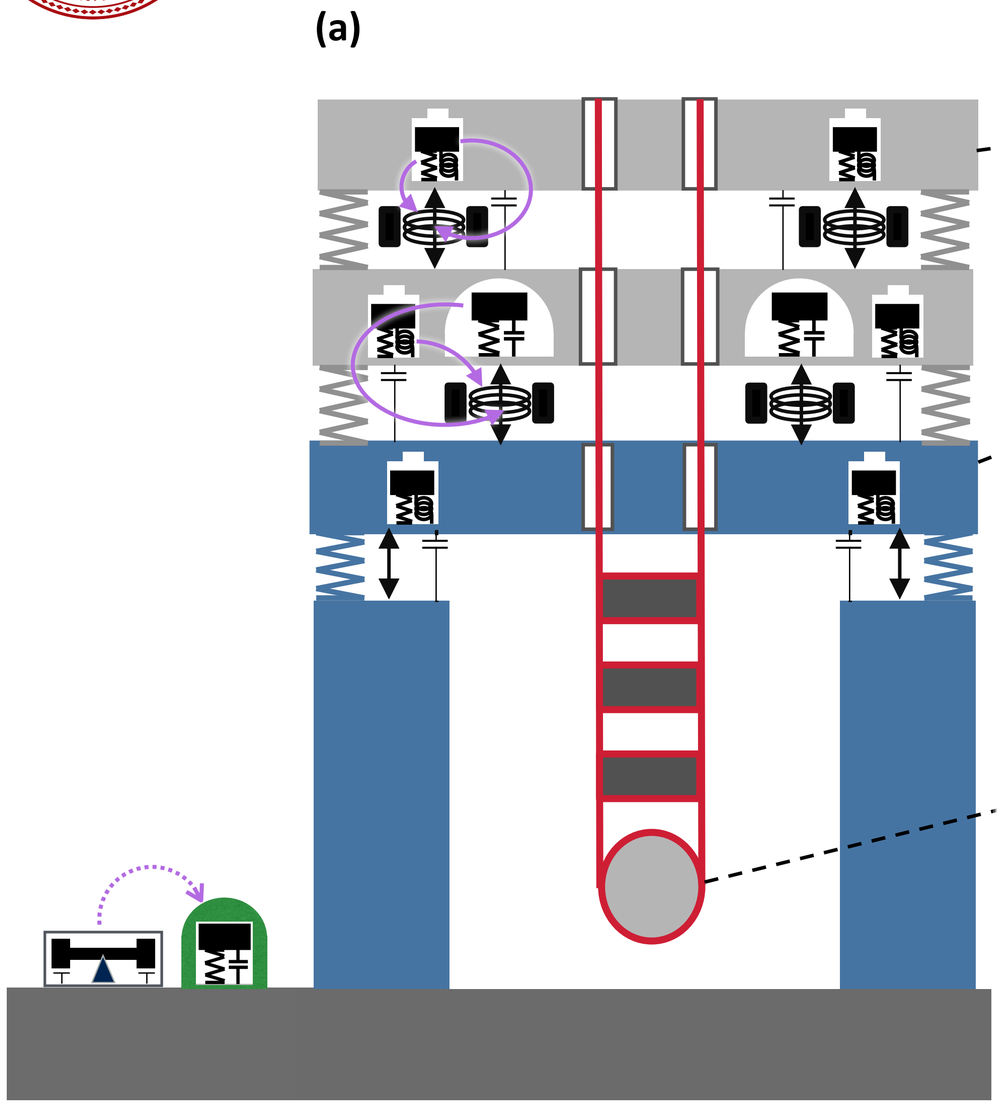


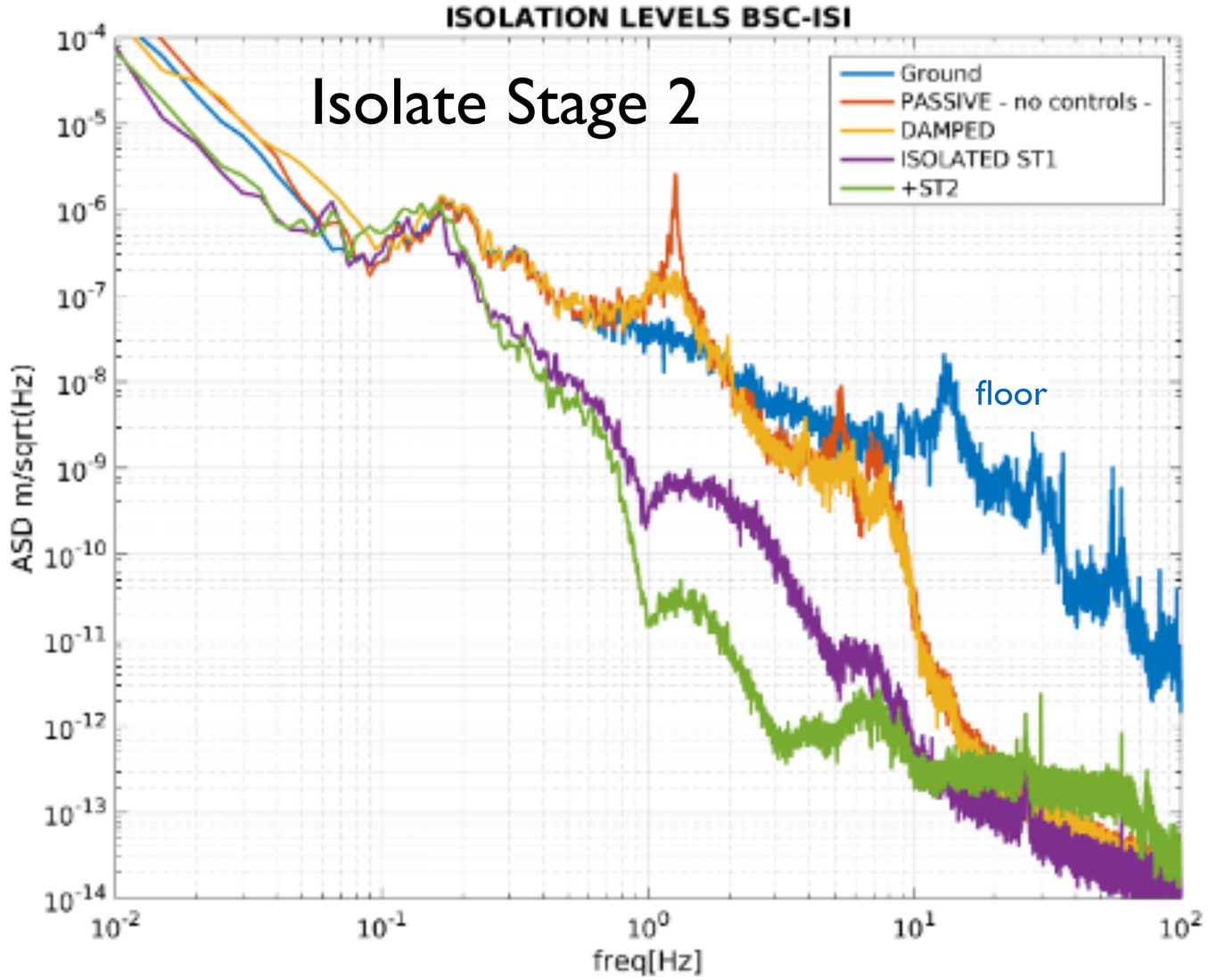
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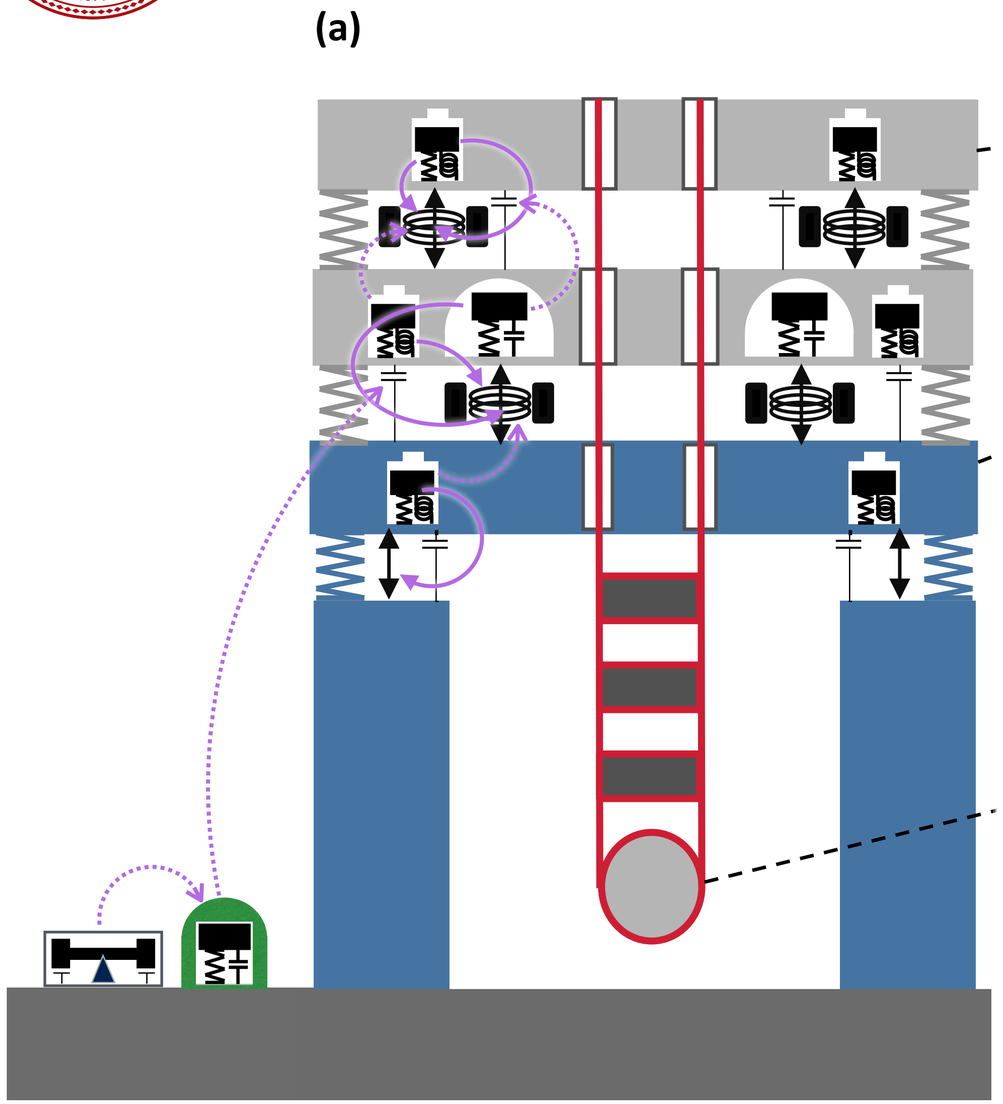


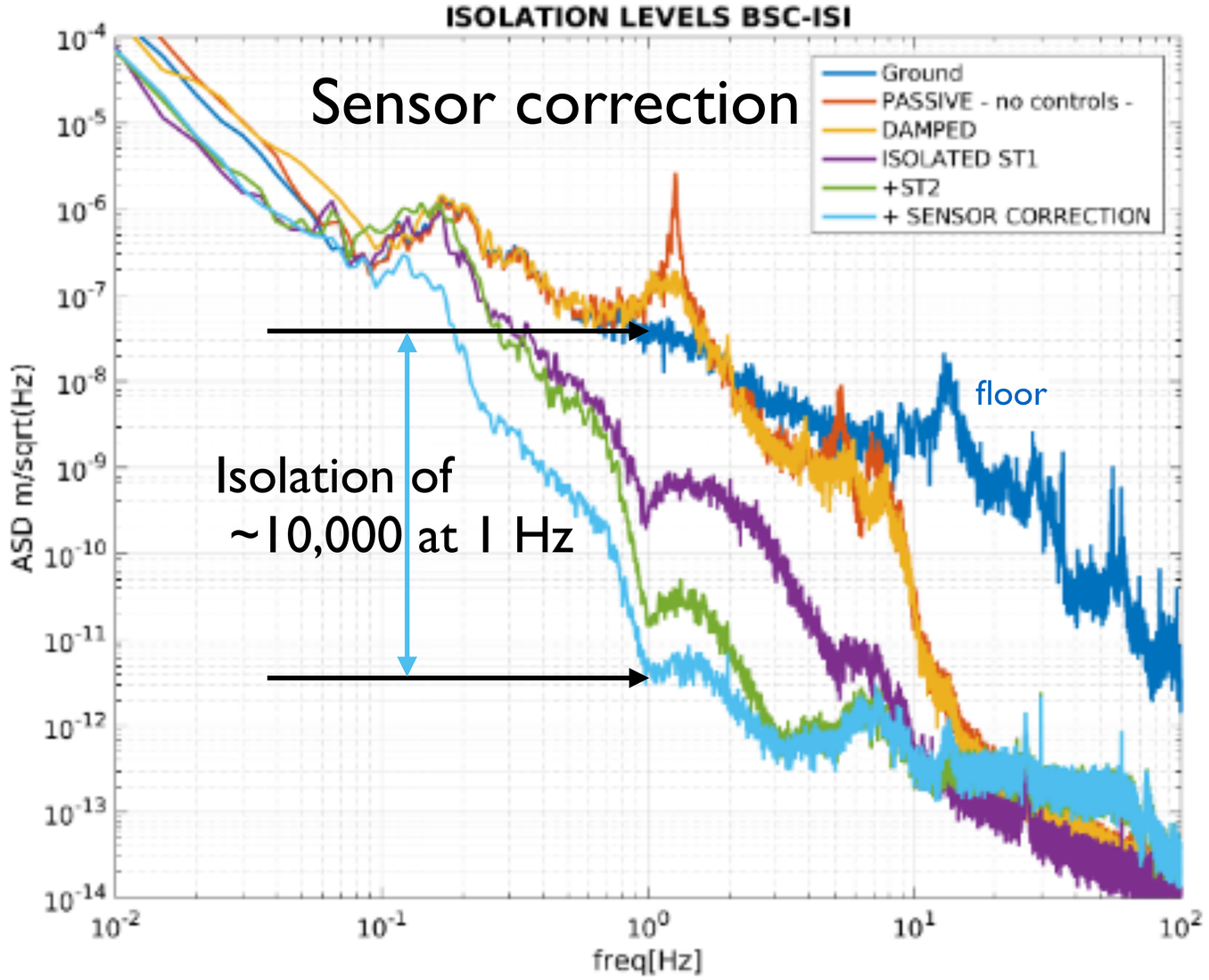
Isolation walkthrough



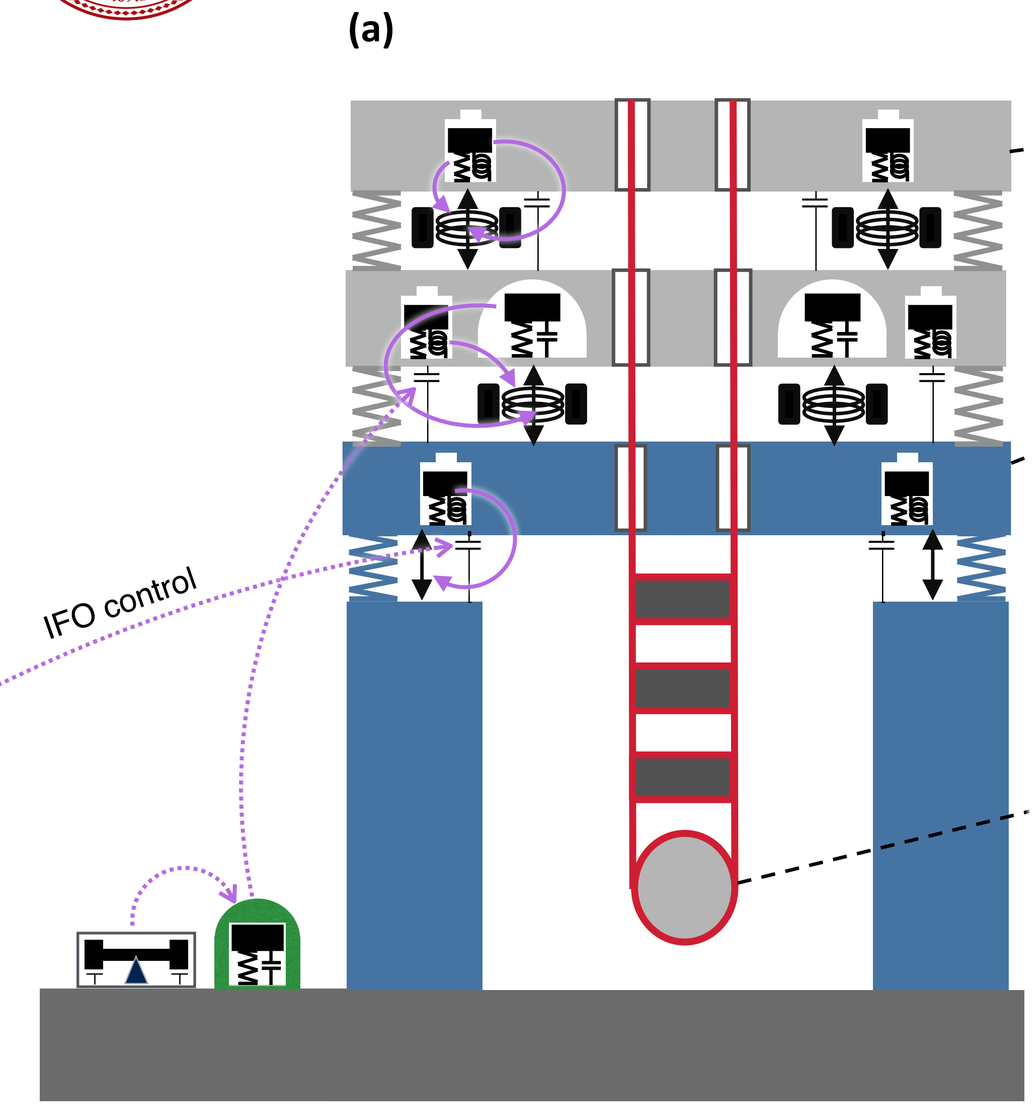


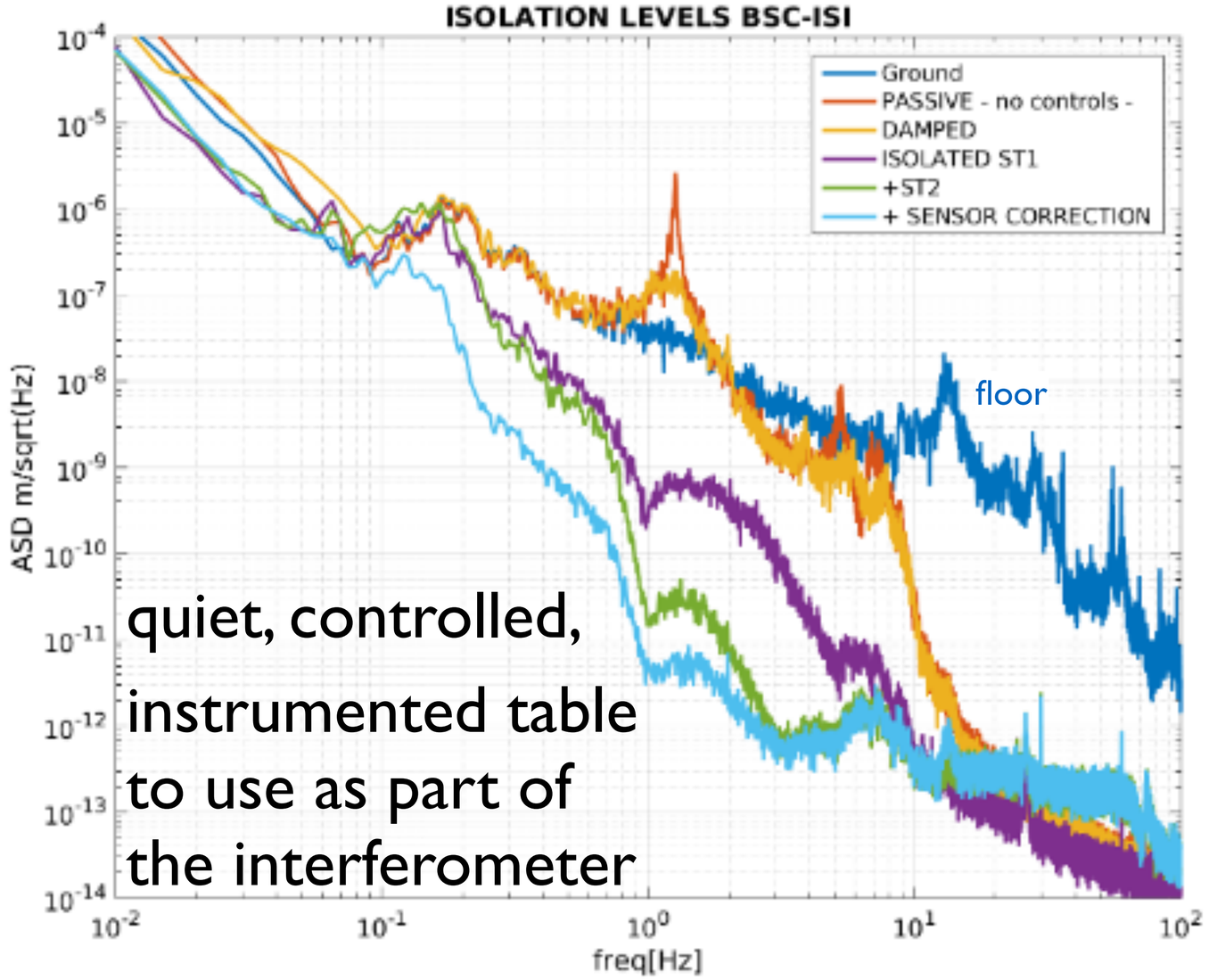
Isolation walkthrough



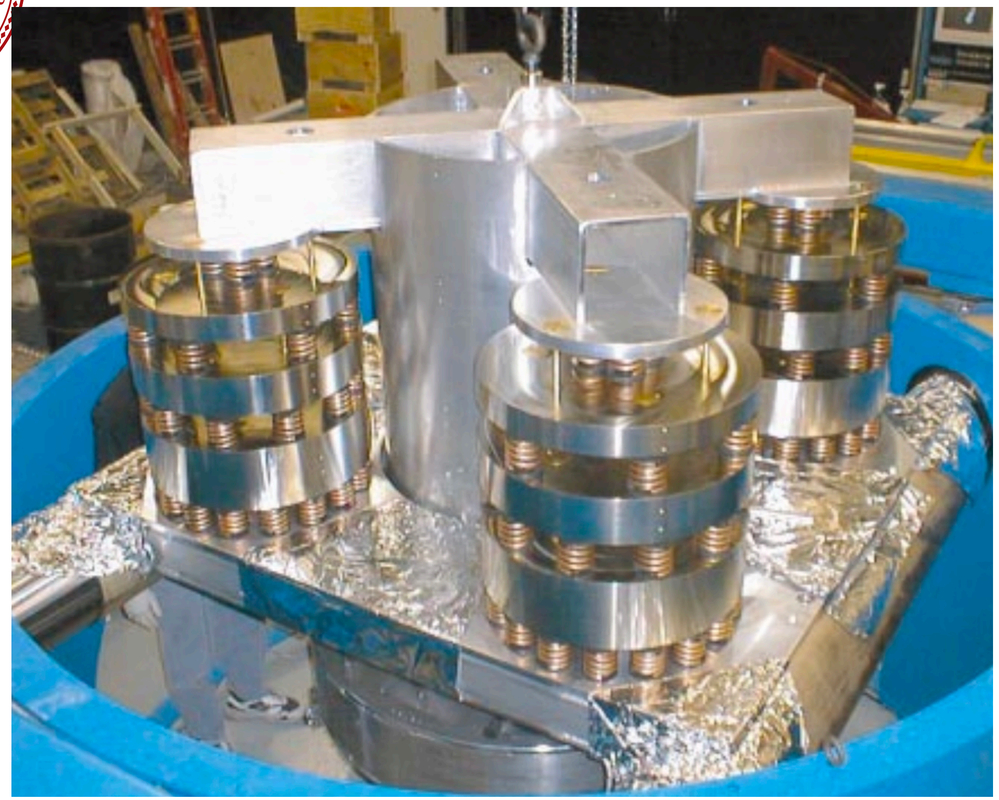


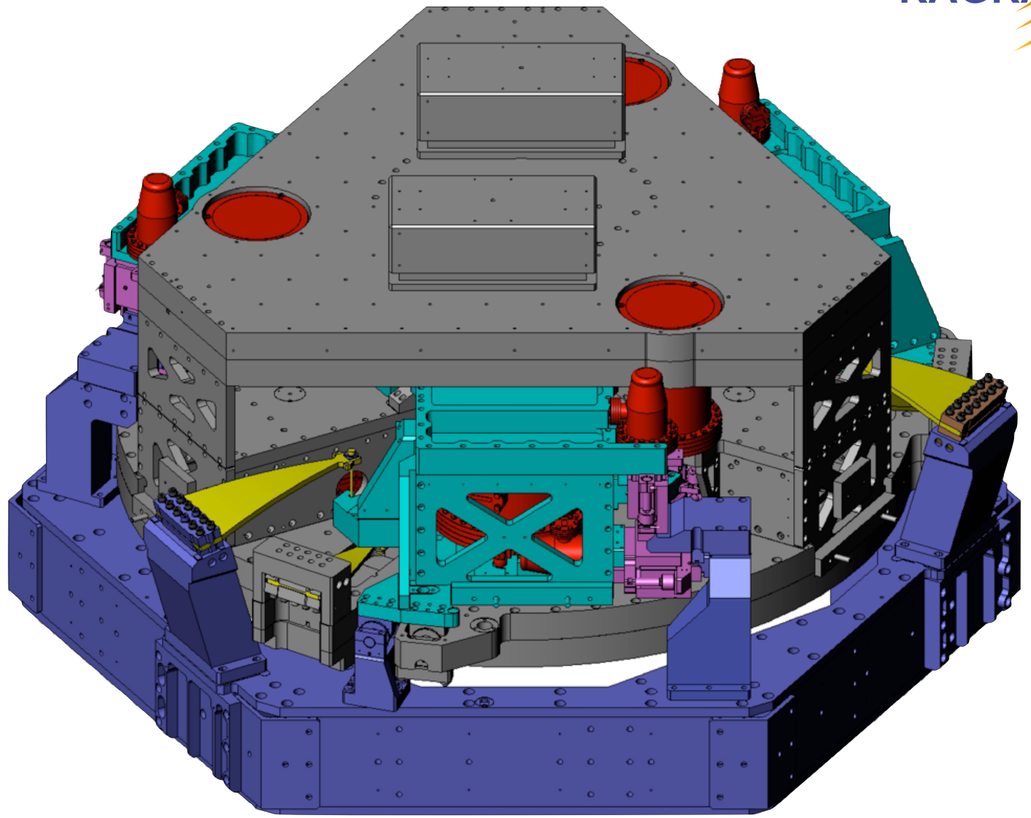
Isolation walkthrough





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

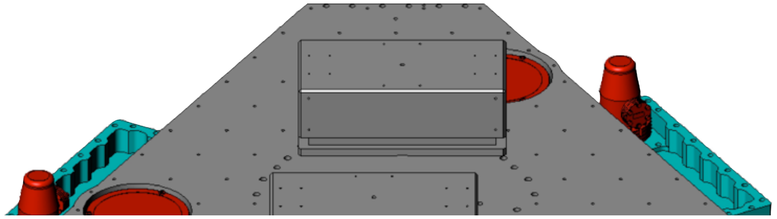
Passive/ Active Hybrid, 2 stages

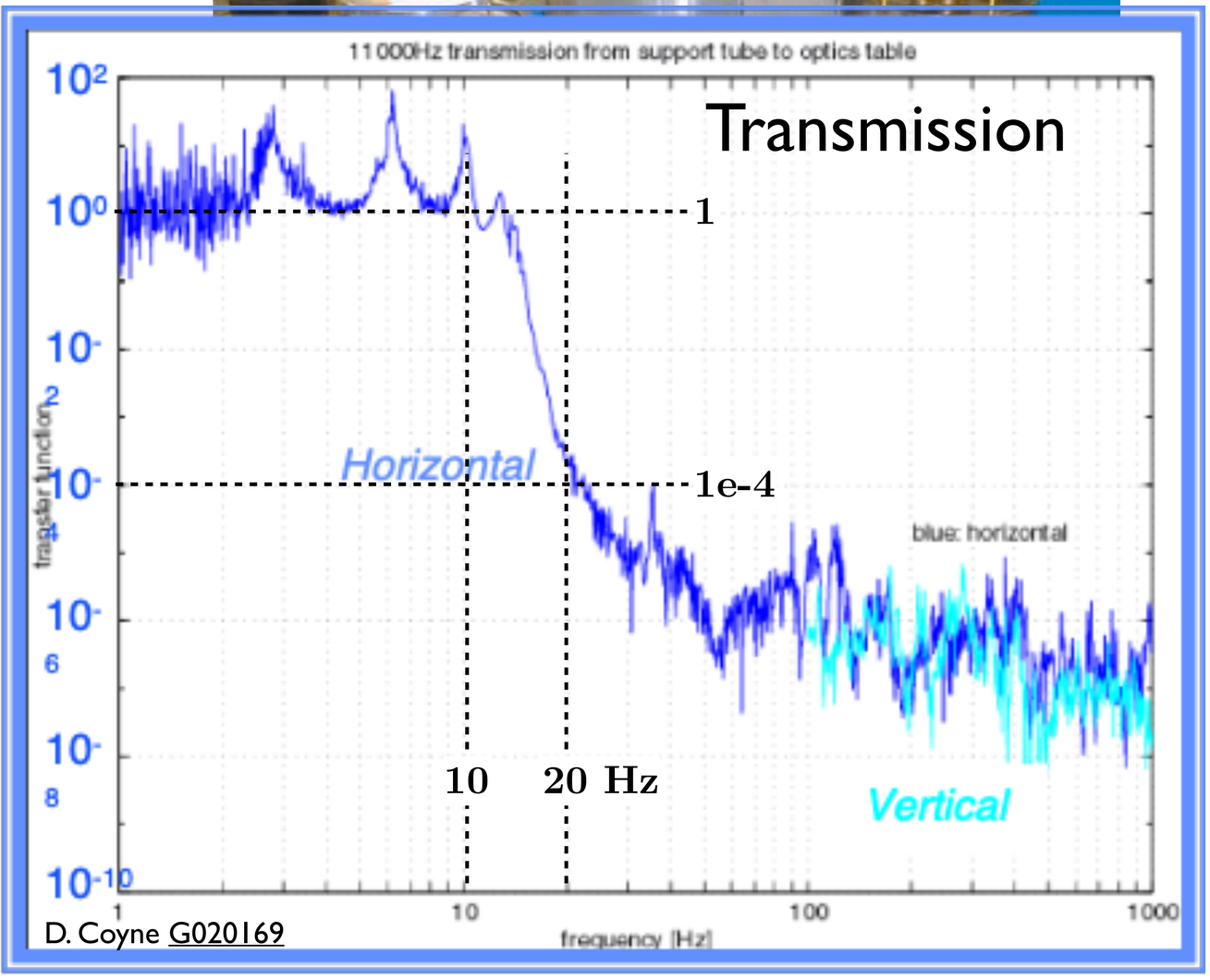
Excellent diagnostics

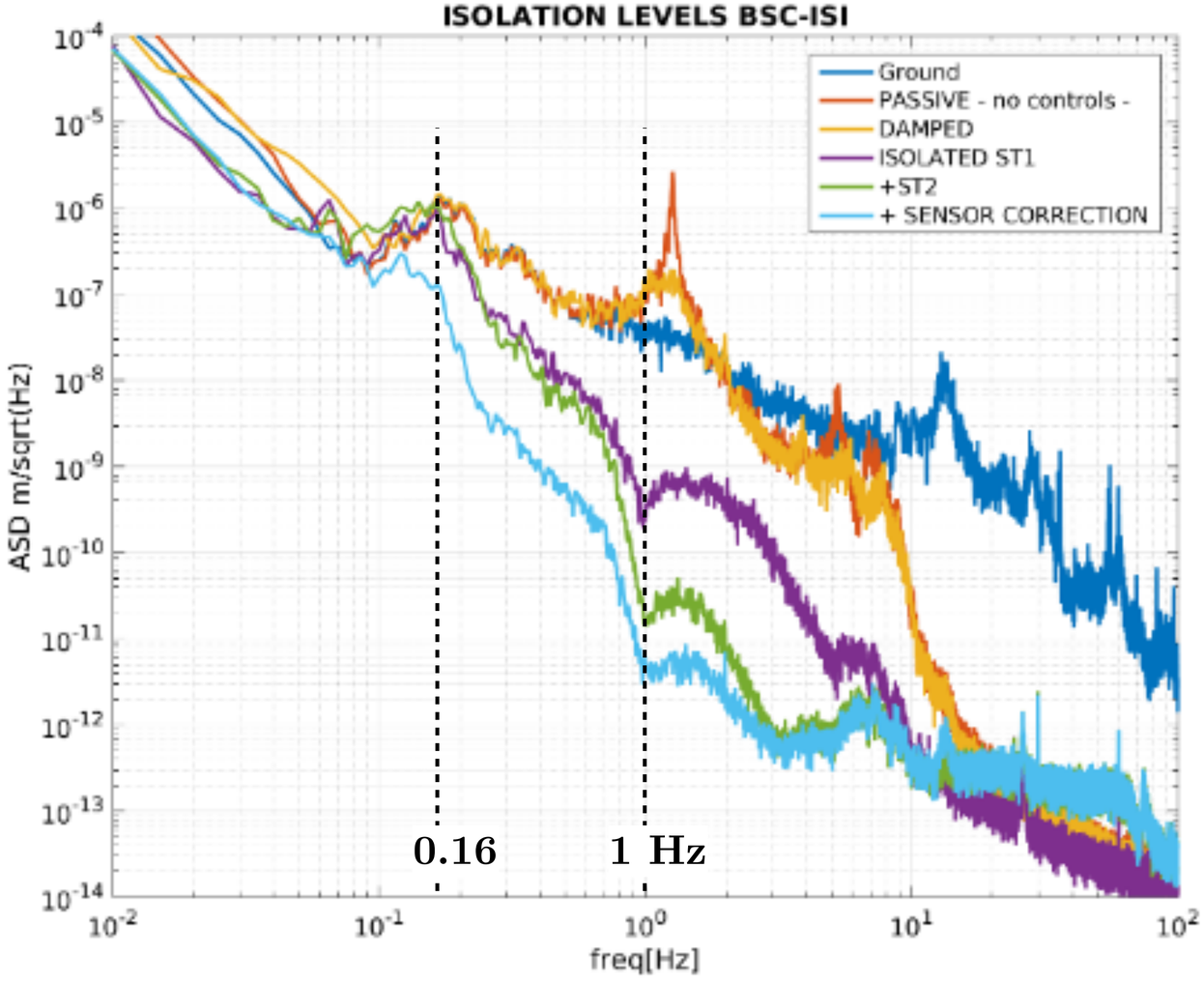
supports a 4-stage suspension

Initial to Advanced

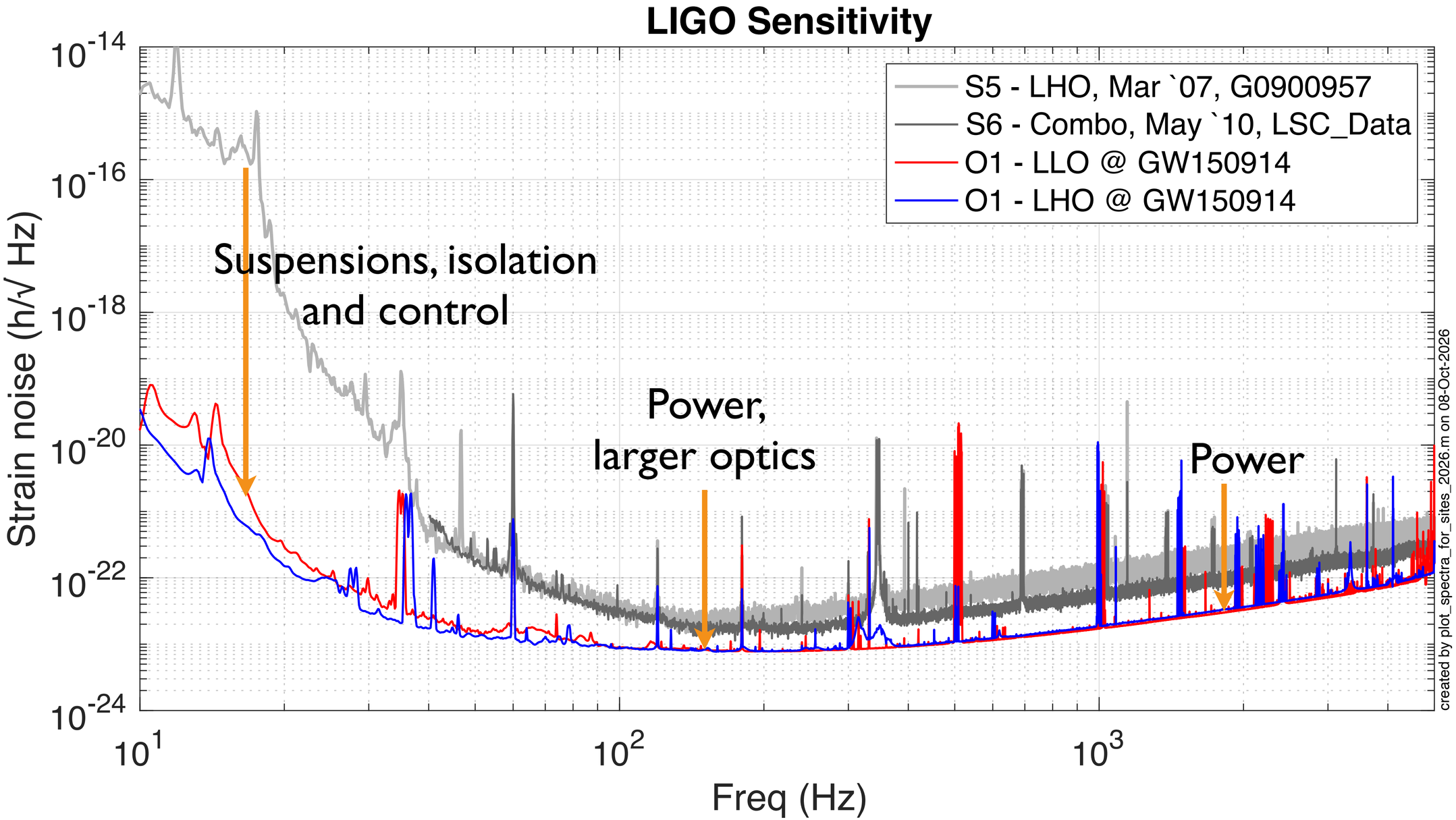




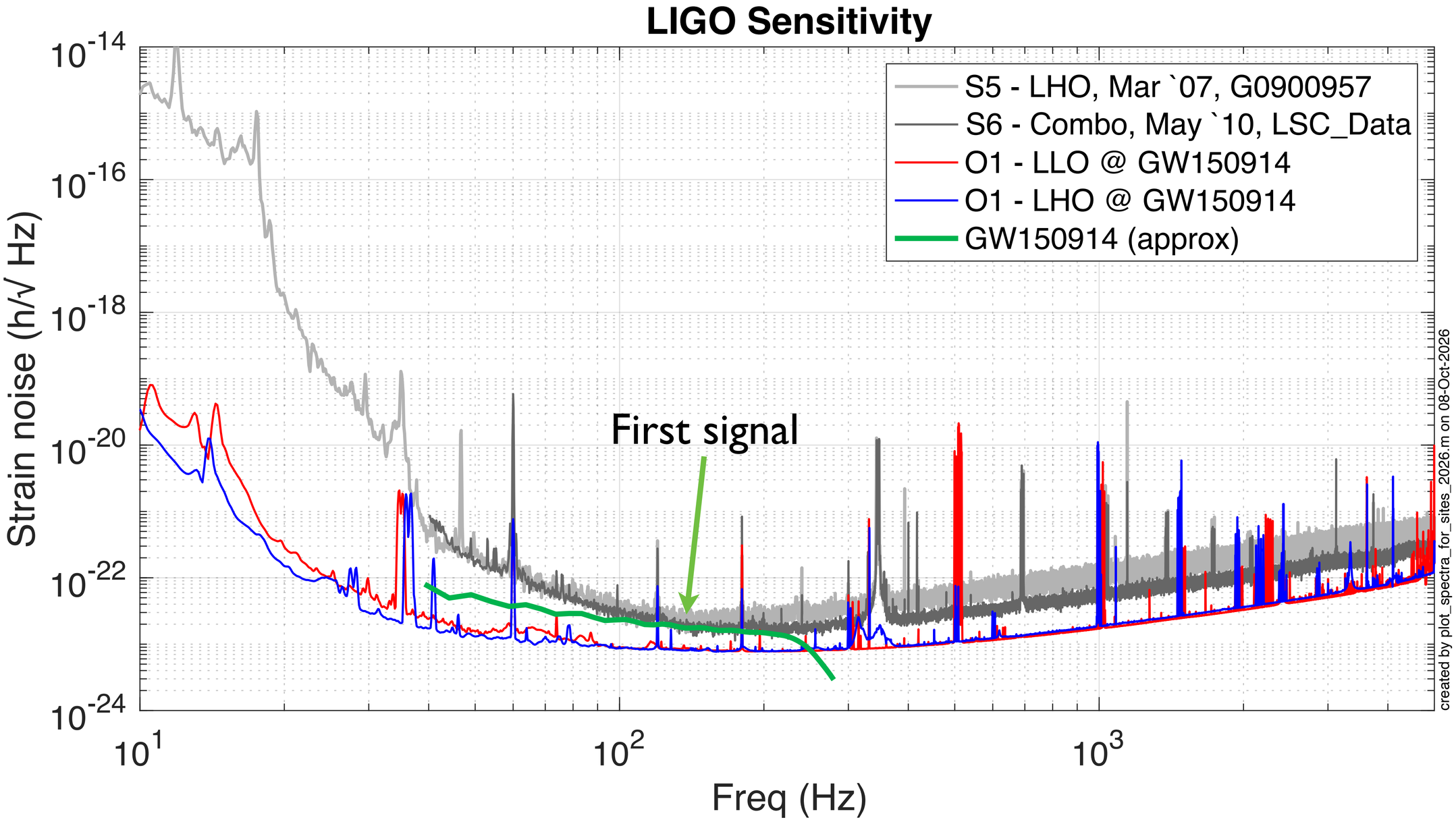




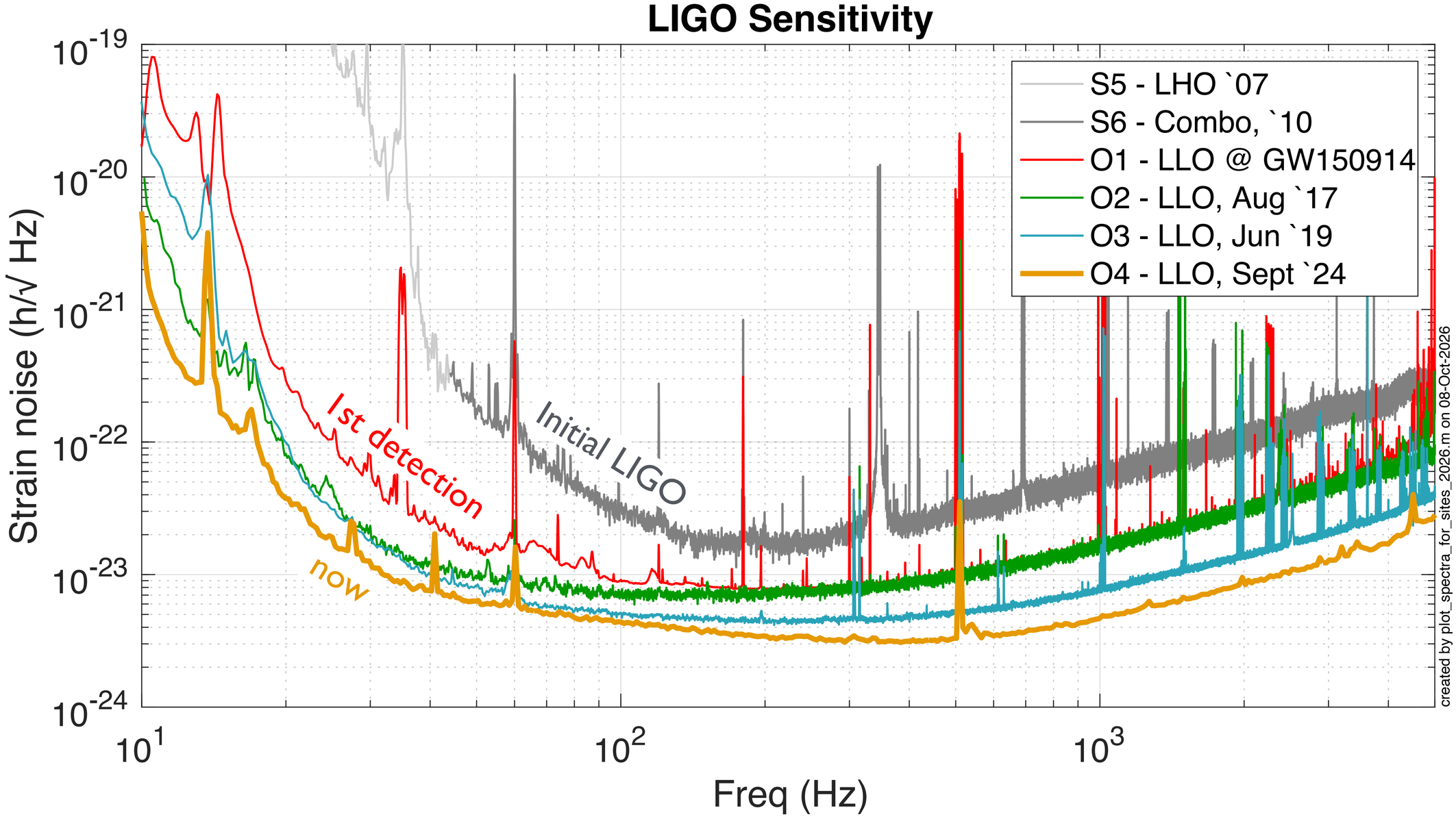
Detector Performance



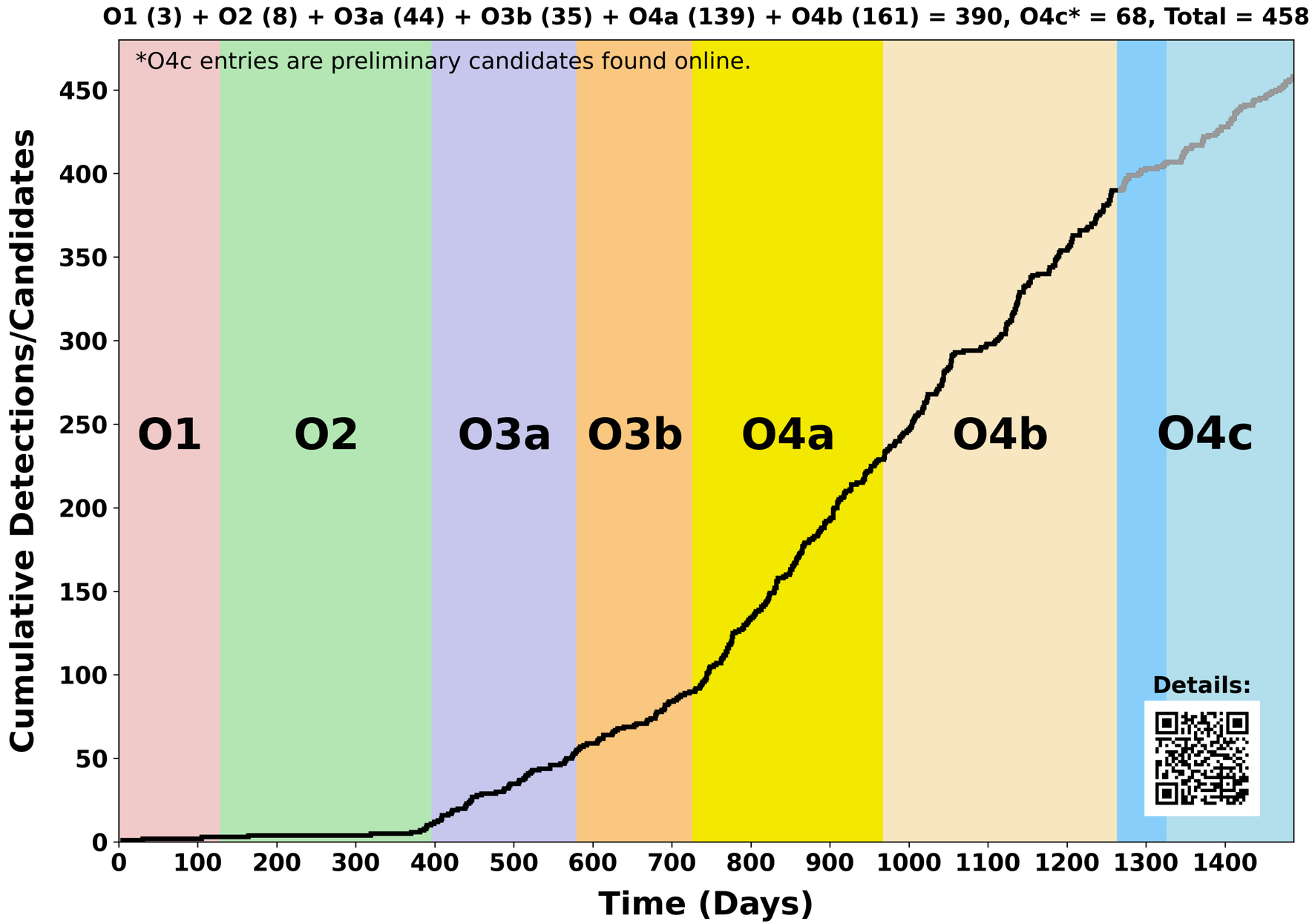
Detector Performance



Detector Performance



Cumulative Detections



LIGO-G2302098 (f244d4f6), updated on 25 May, 2026

Credit: LIGO-Virgo-KAGRA Collaboration

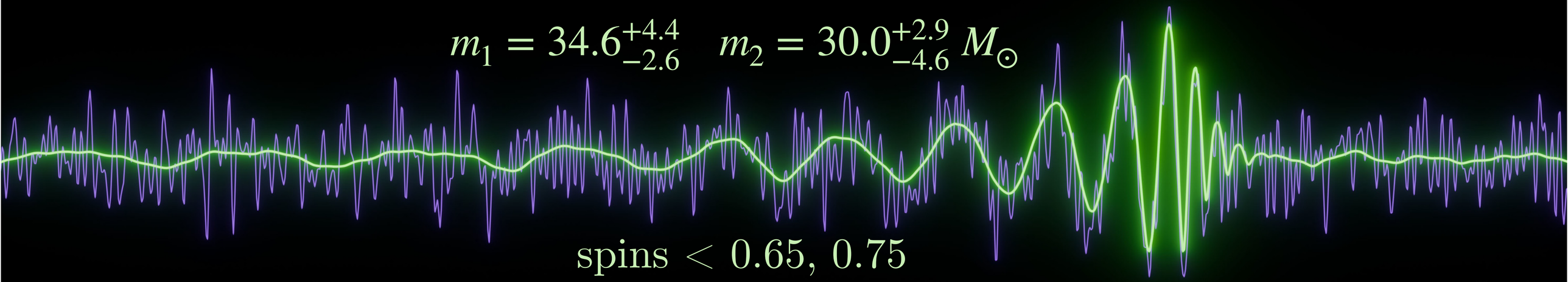
10 Years Later: LIGO Hears Loud and Clear

spins of GW150914: arXiv:1606.01210

masses of GW150914: arXiv:2108.01045

GW250114: arXiv:2509.08099

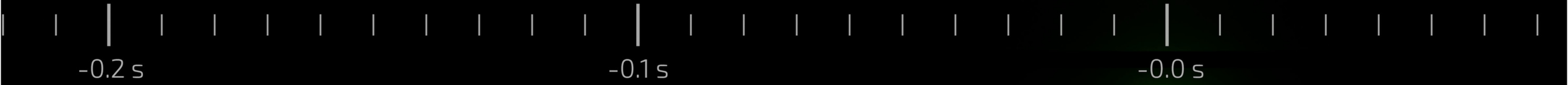
$m_1 = 34.6^{+4.4}_{-2.6} \quad m_2 = 30.0^{+2.9}_{-4.6}\ M_\odot$



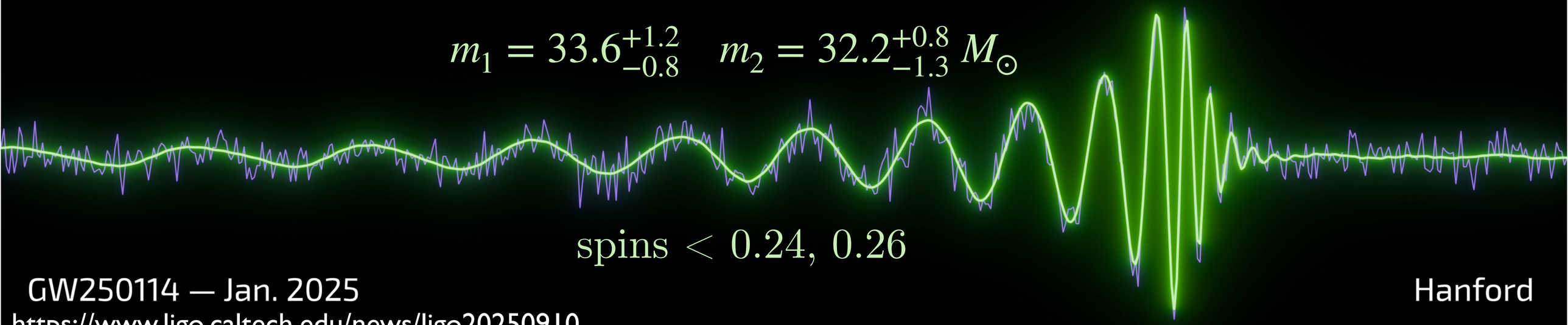
$\text{spins} < 0.65,\ 0.75$

GW150914 — Sept. 2015

Hanford



$m_1 = 33.6^{+1.2}_{-0.8} \quad m_2 = 32.2^{+0.8}_{-1.3}\ M_\odot$



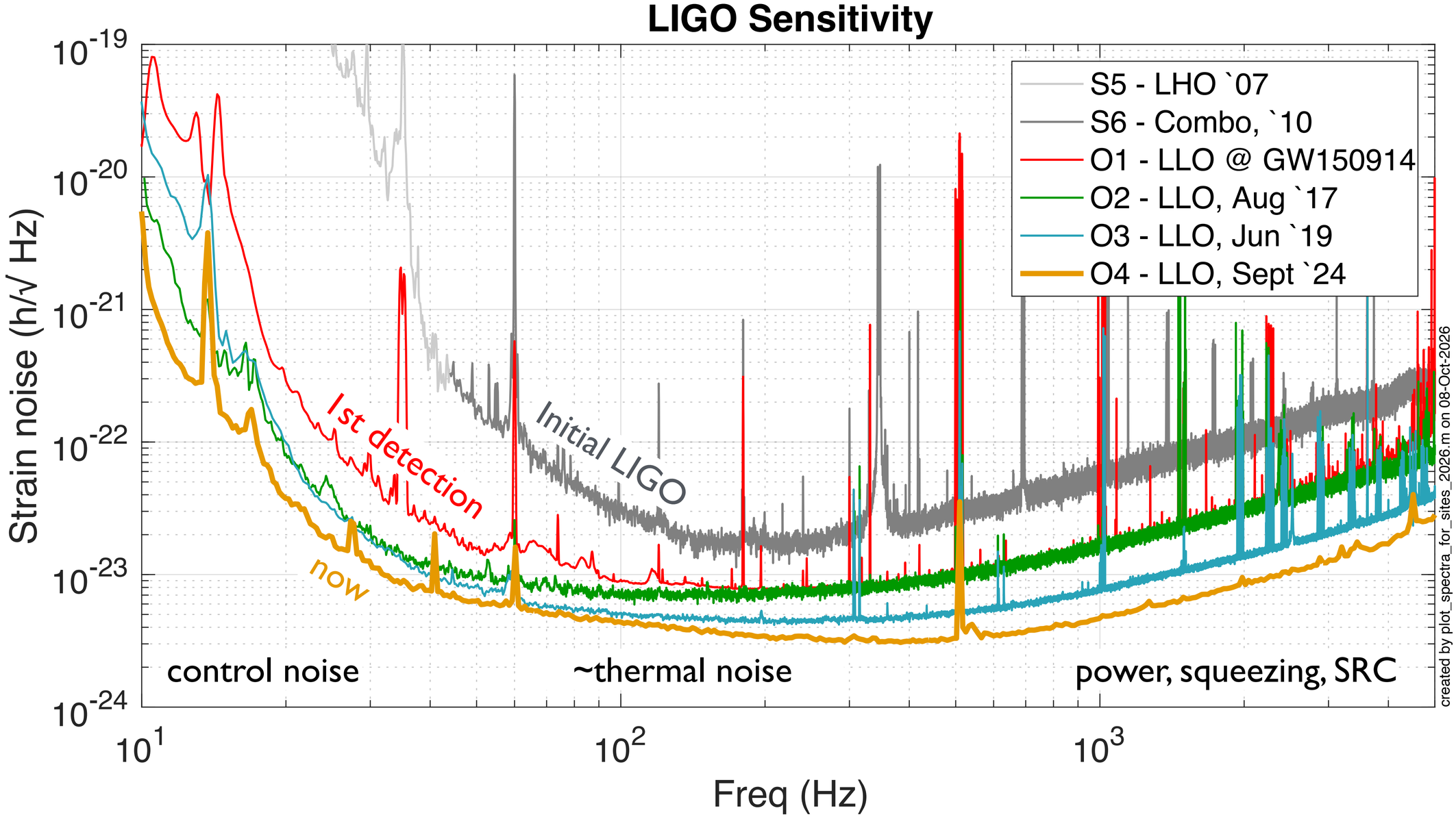
$\text{spins} < 0.24,\ 0.26$

GW250114 — Jan. 2025

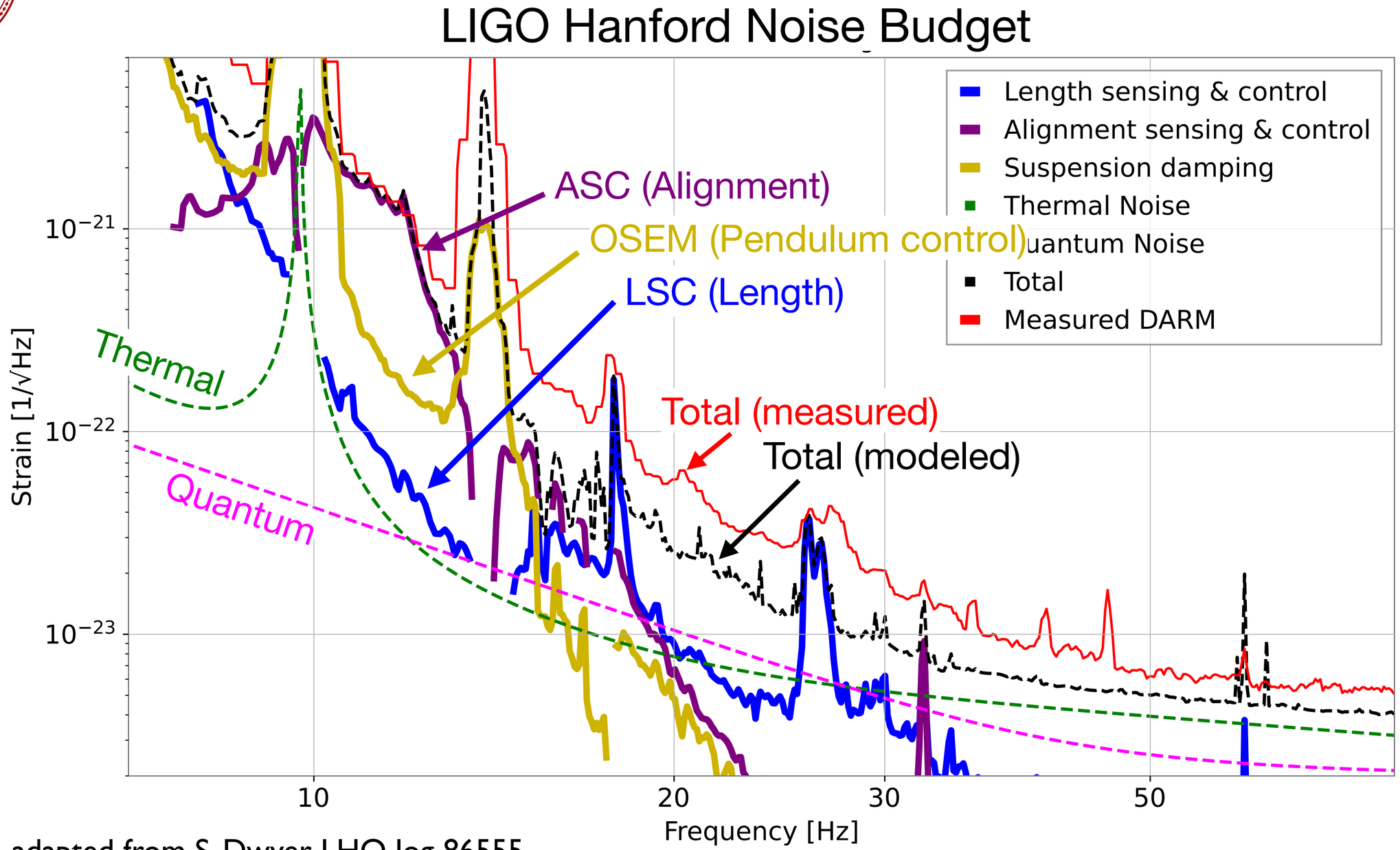
Hanford

https://www.ligo.caltech.edu/news/ligo20250910

Detector Performance

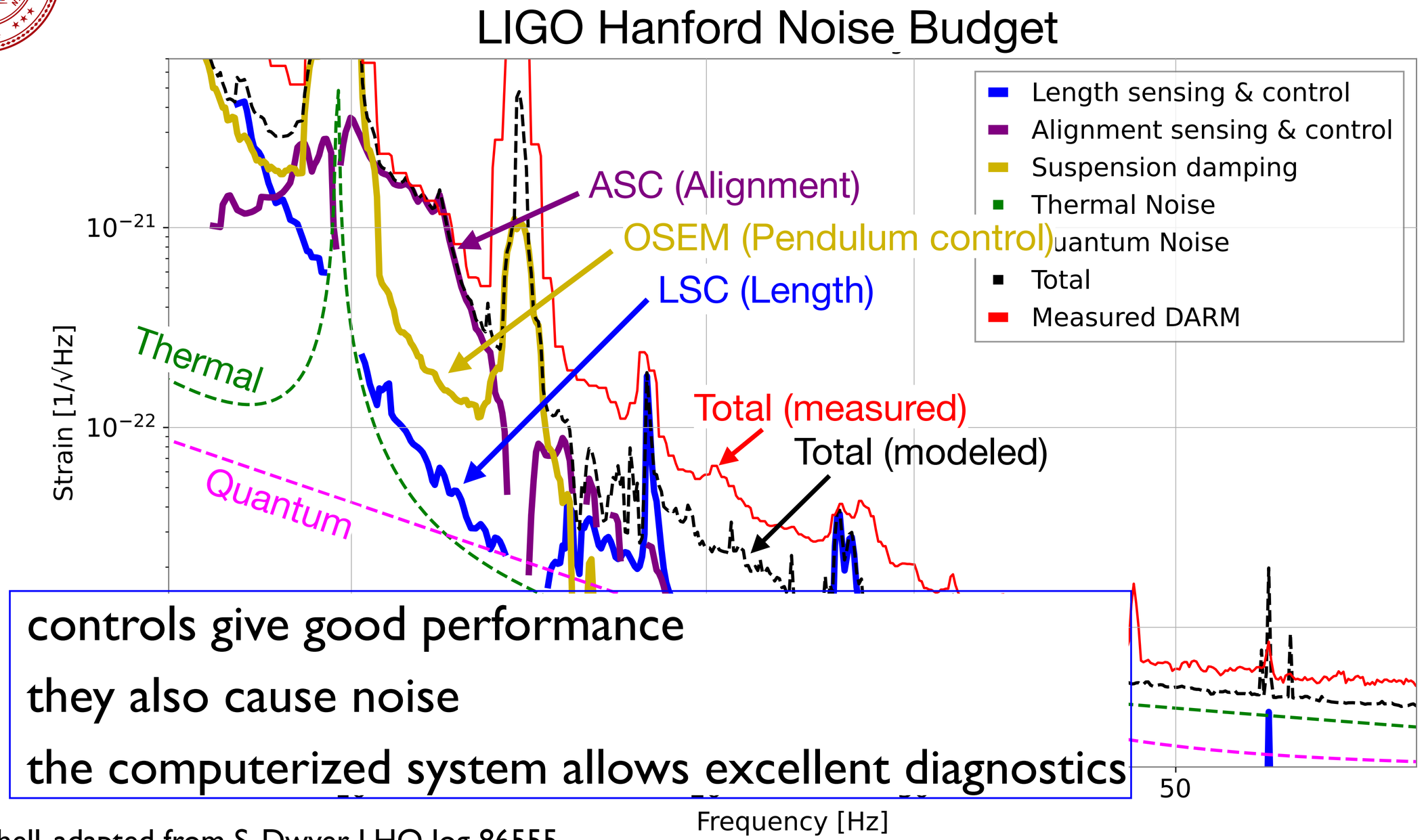


Actual Detector Noise



A. Mitchell, adapted from S. Dwyer LHO log 86555

Actual Detector Noise



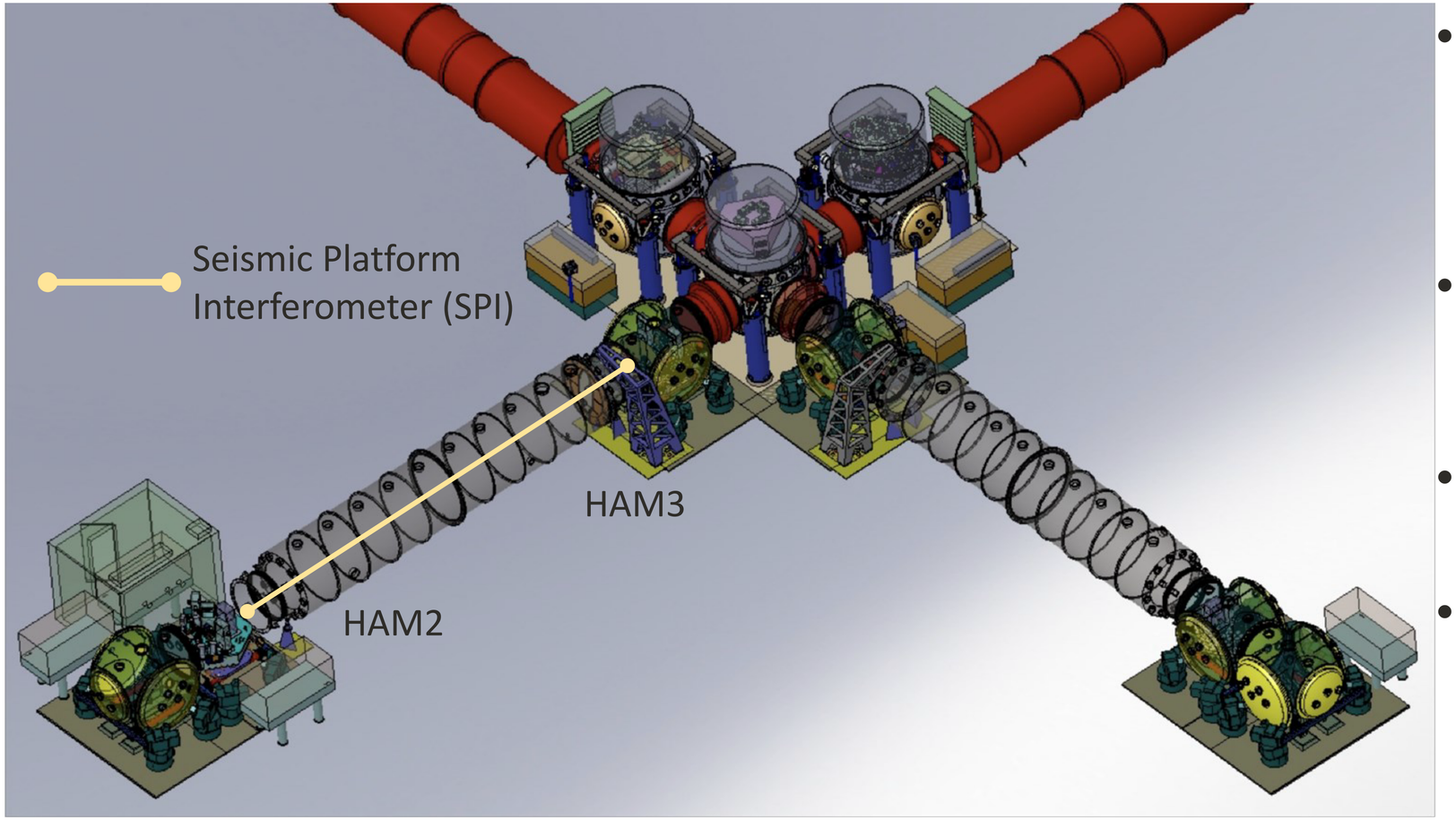
controls give good performance

they also cause noise

the computerized system allows excellent diagnostics

A. Mitchell, adapted from S. Dwyer LHO log 86555

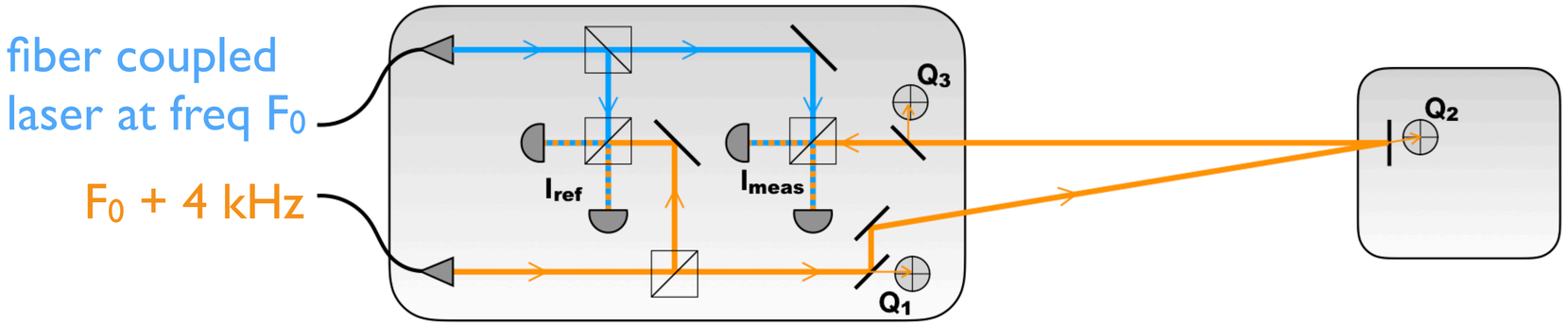
Stabilizing the interferometer with more interferometers



- 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

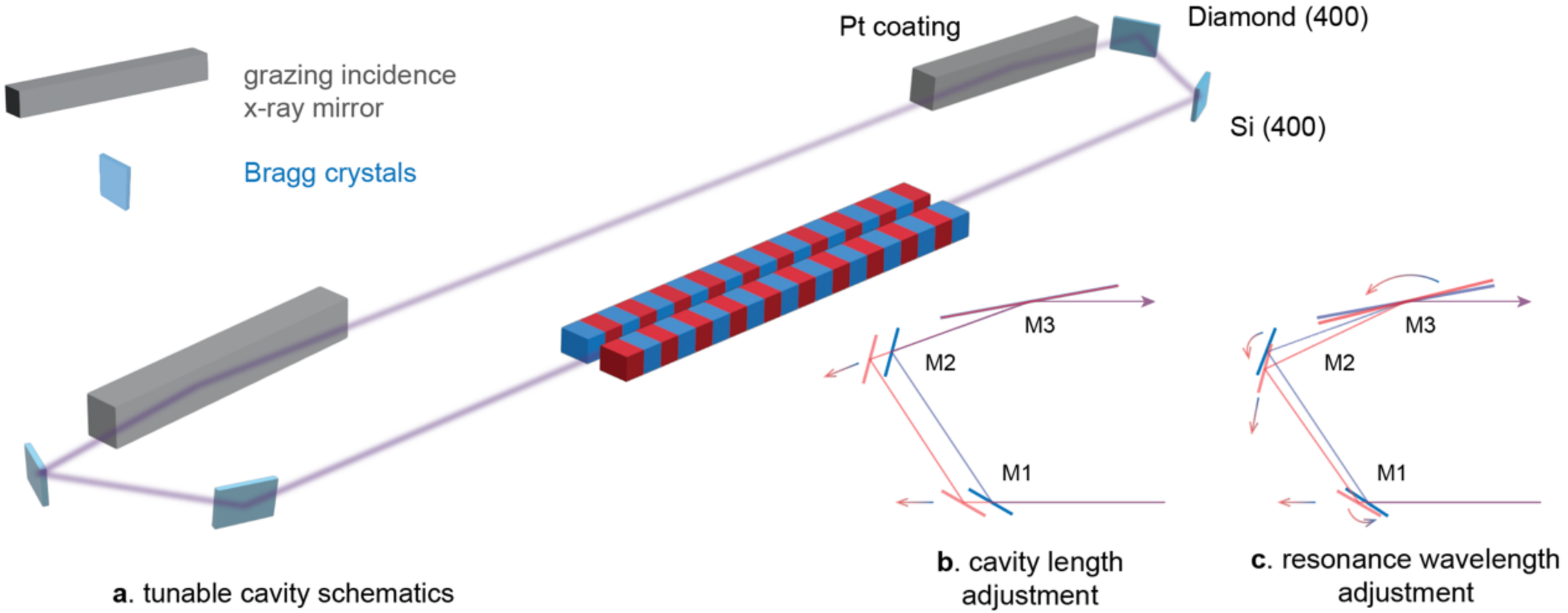
- Phase tracking heterodyne interferometer
- Phase of the beat note tracks the length change
  position of beam on quad diodes measures angle change
- based on the LISA phase-meter



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



a. tunable cavity schematics

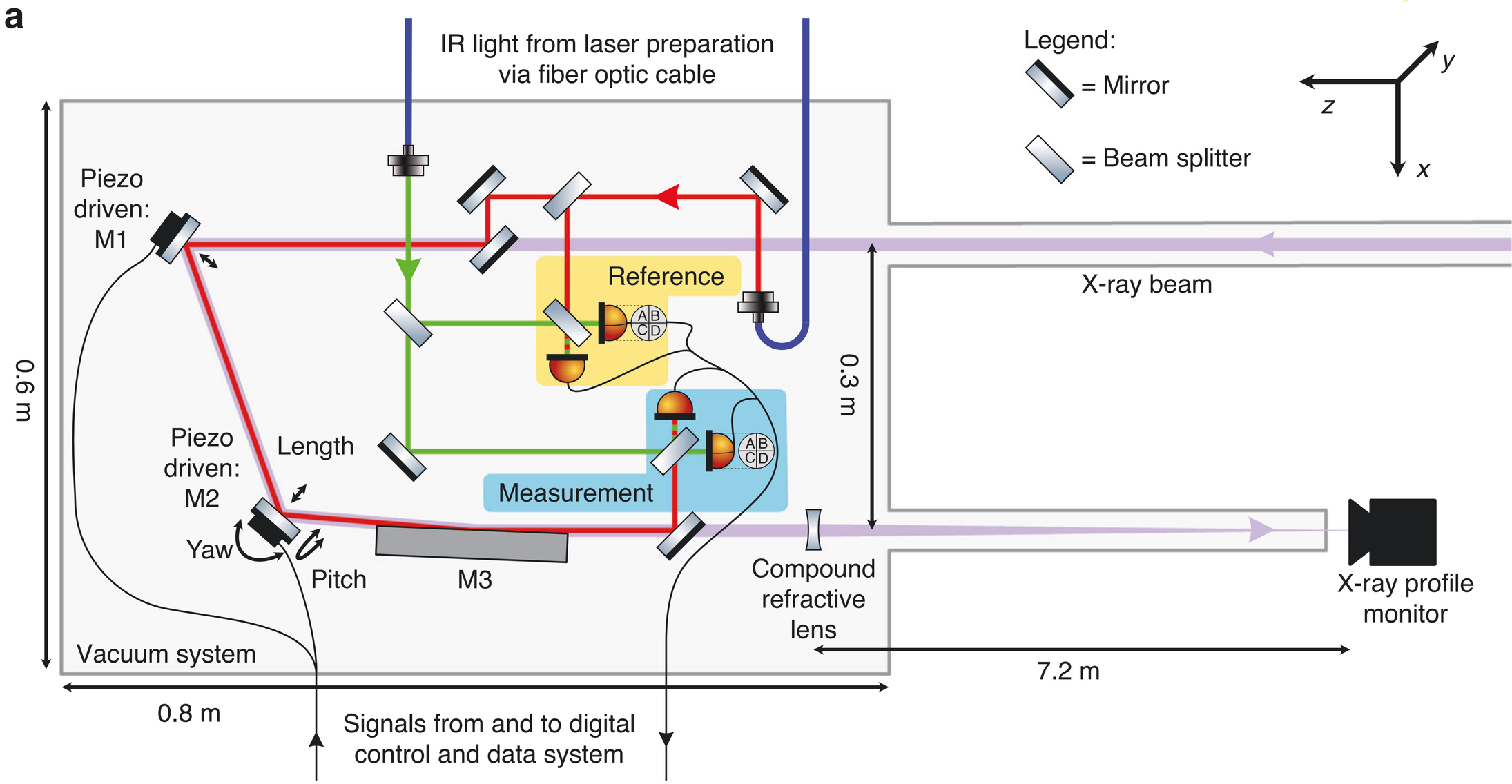
b. cavity length adjustment

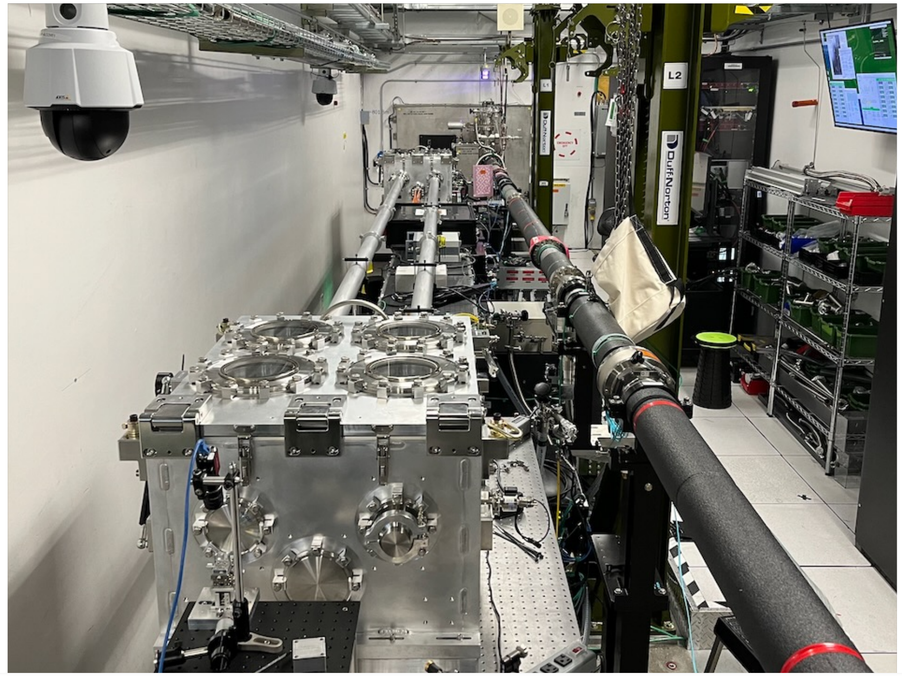
c. resonance wavelength adjustment

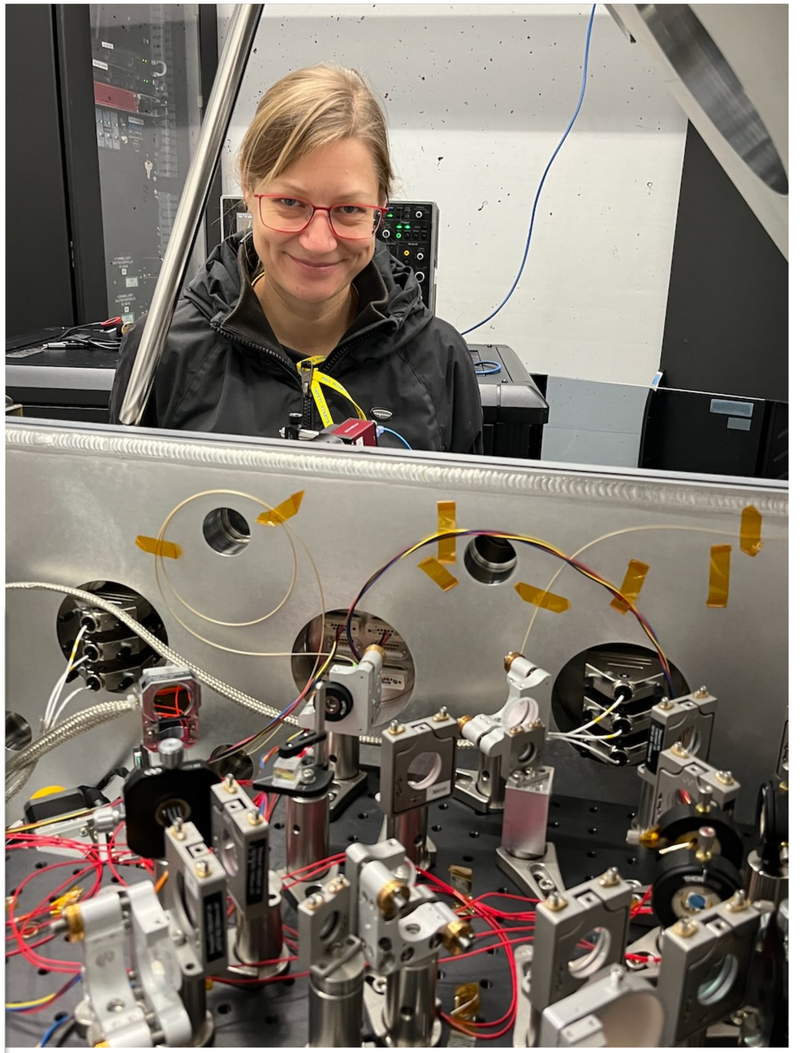
Sina Koehlenbeck w. Zhirong Huang, Diling Zhu, Jerry Hastings and others

DOI: 10.1038/s41377-025-01774-5

SPI at SLAC


a
IR light from laser preparation
via fiber optic cable
Legend:
= Mirror
= Beam splitter
y
z
x
Piezo
driven:
M1
Reference
A B
C D
X-ray beam
0.6 m
0.3 m
Piezo
driven:
M2
Length
Measurement
Yaw
Pitch
M3
Compound
refractive
lens
X-ray profile
monitor
Vacuum system
7.2 m
0.8 m
Signals from and to digital
control and data system


L2
DuffNorton

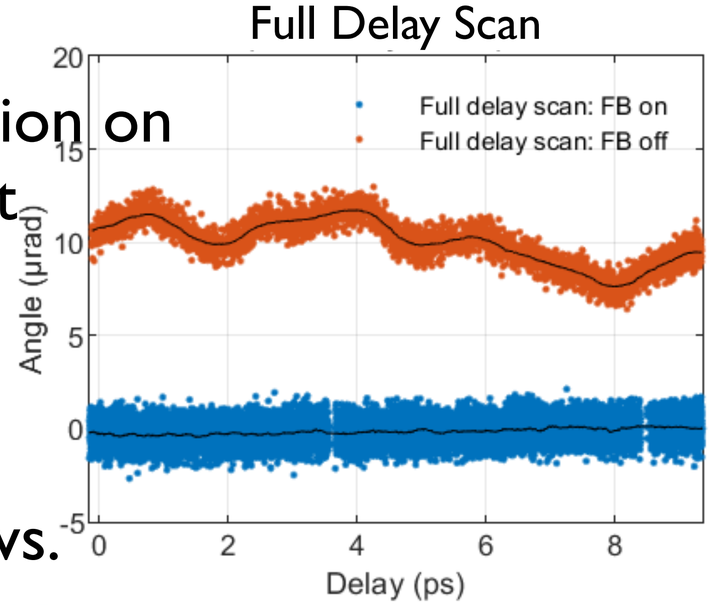


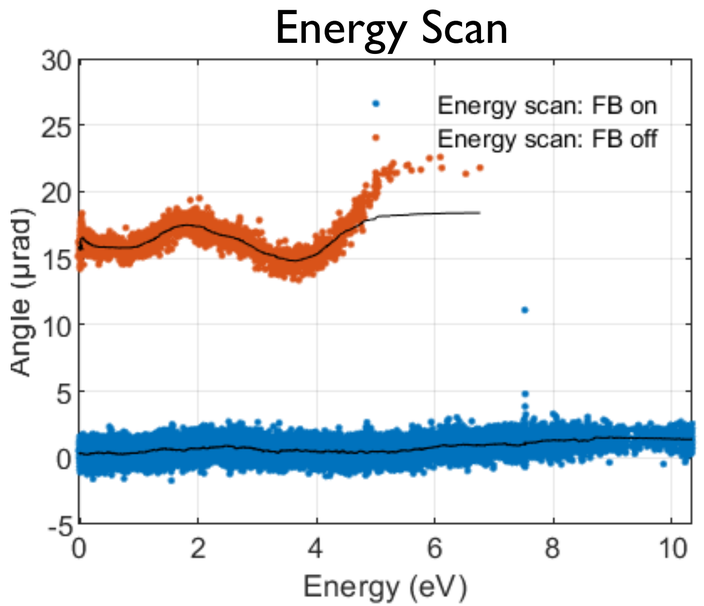

DuffNorton

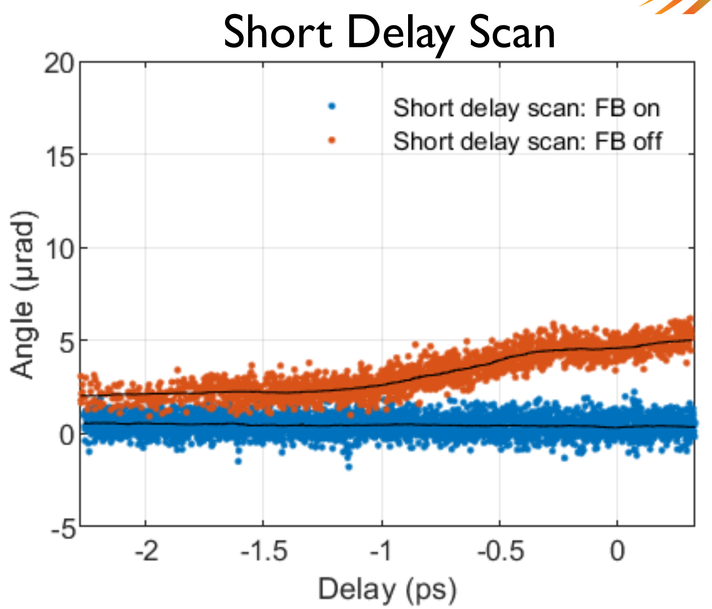
Active control makes it better

beam position on x-ray target

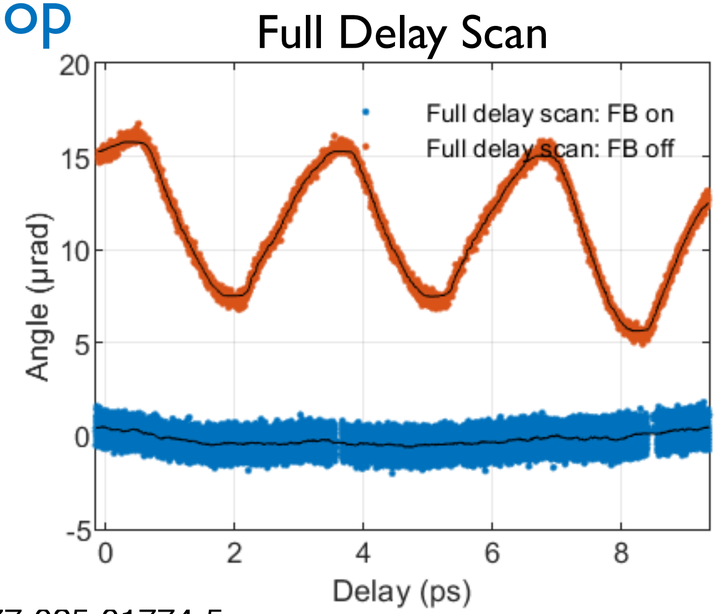
open loop vs. closed loop

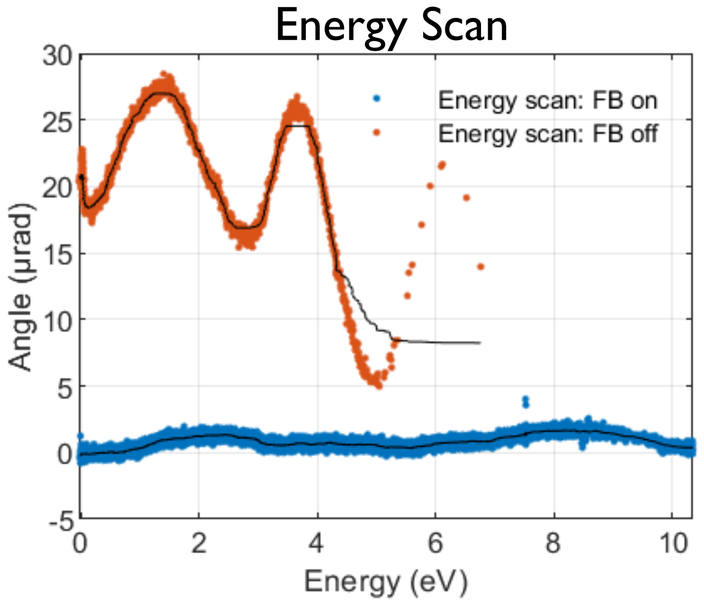


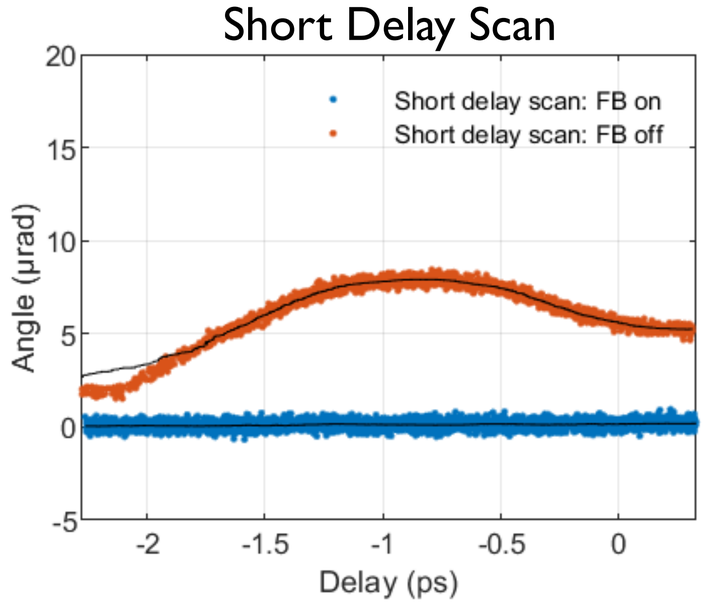




Pitch





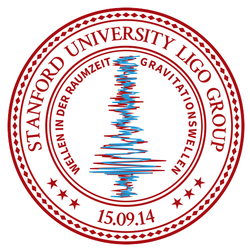


Yaw

DOI: 10.1038/s41377-025-01774-5

Summary

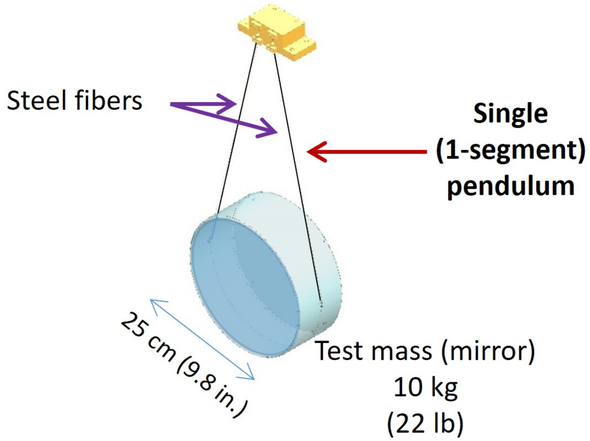
- Advanced LIGO is an example of an instrument designed with control in mind
- (almost) everything is monitored and controlled
- We get excellent performance
- We get excellent diagnostics
- Helps guide improvements
- Hopefully, some of the things we do have more general application



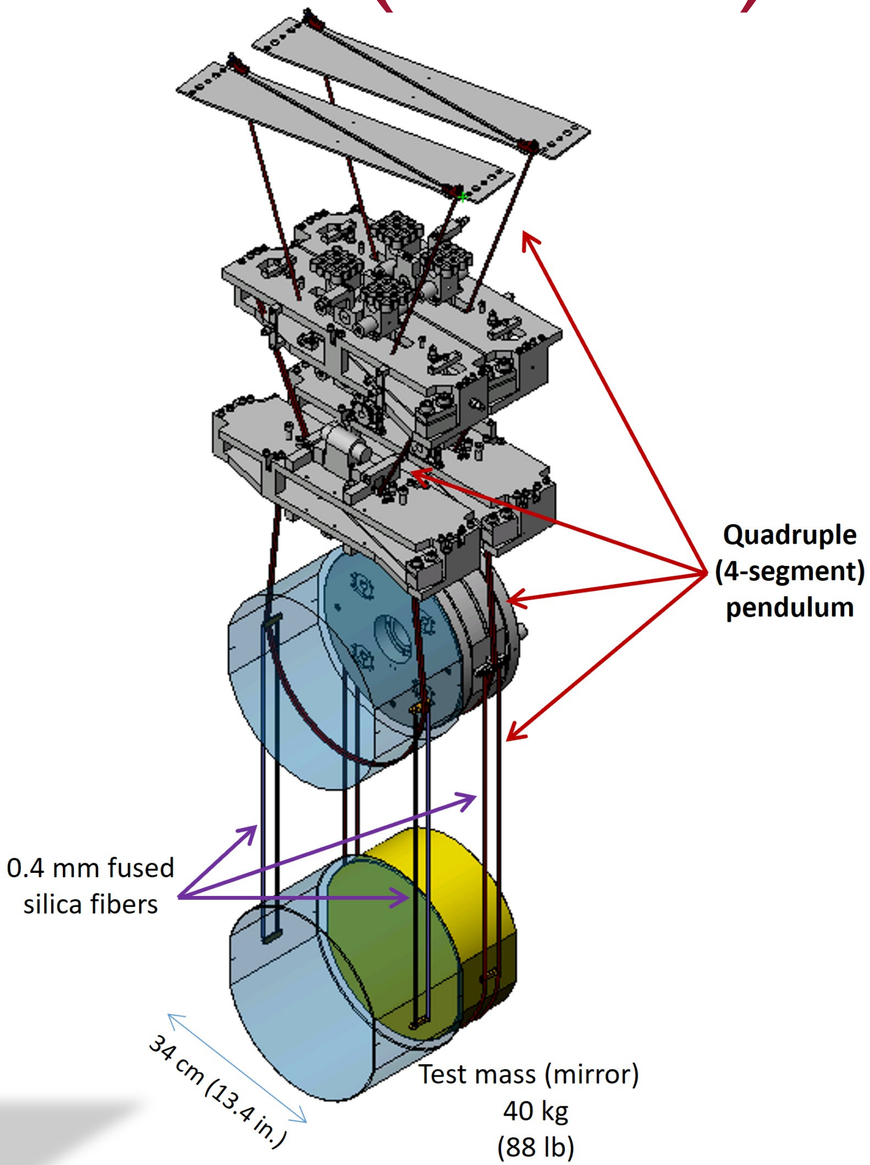
extra slides



aLIGO Suspension (UK led)



Initial LIGO Suspension



Advanced LIGO Suspension

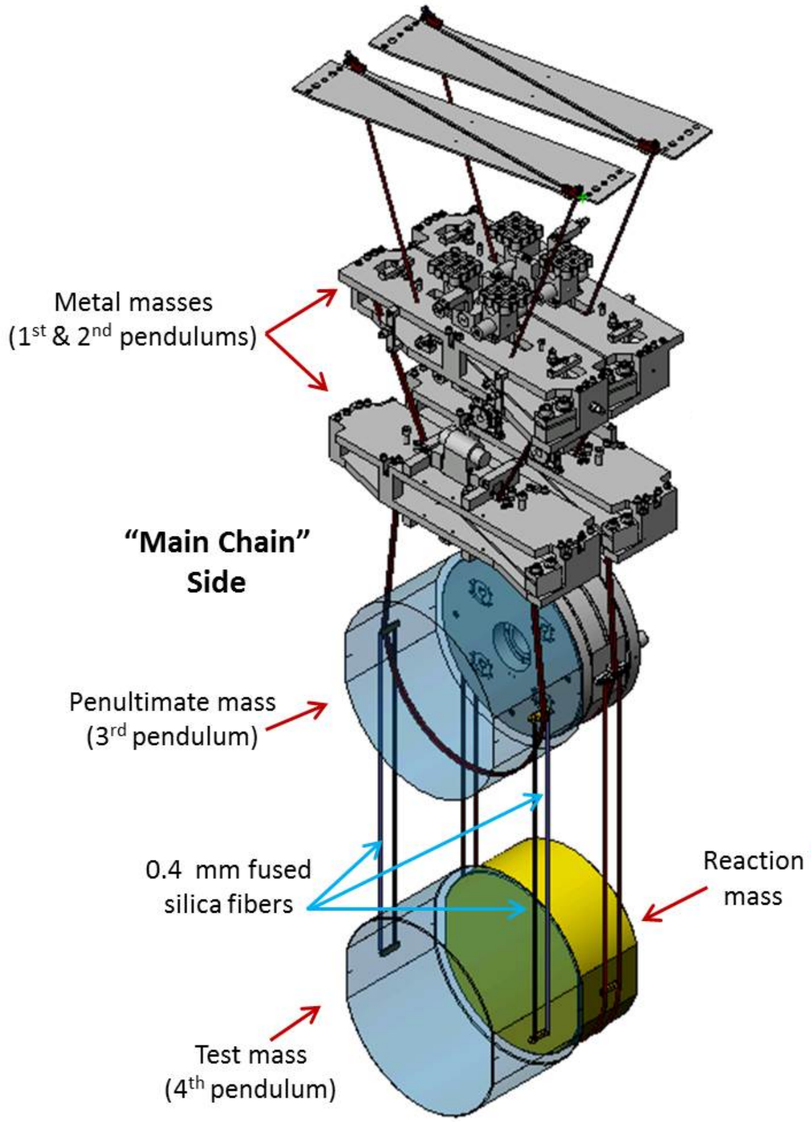
iLIGO vs aLIGO suspension systems

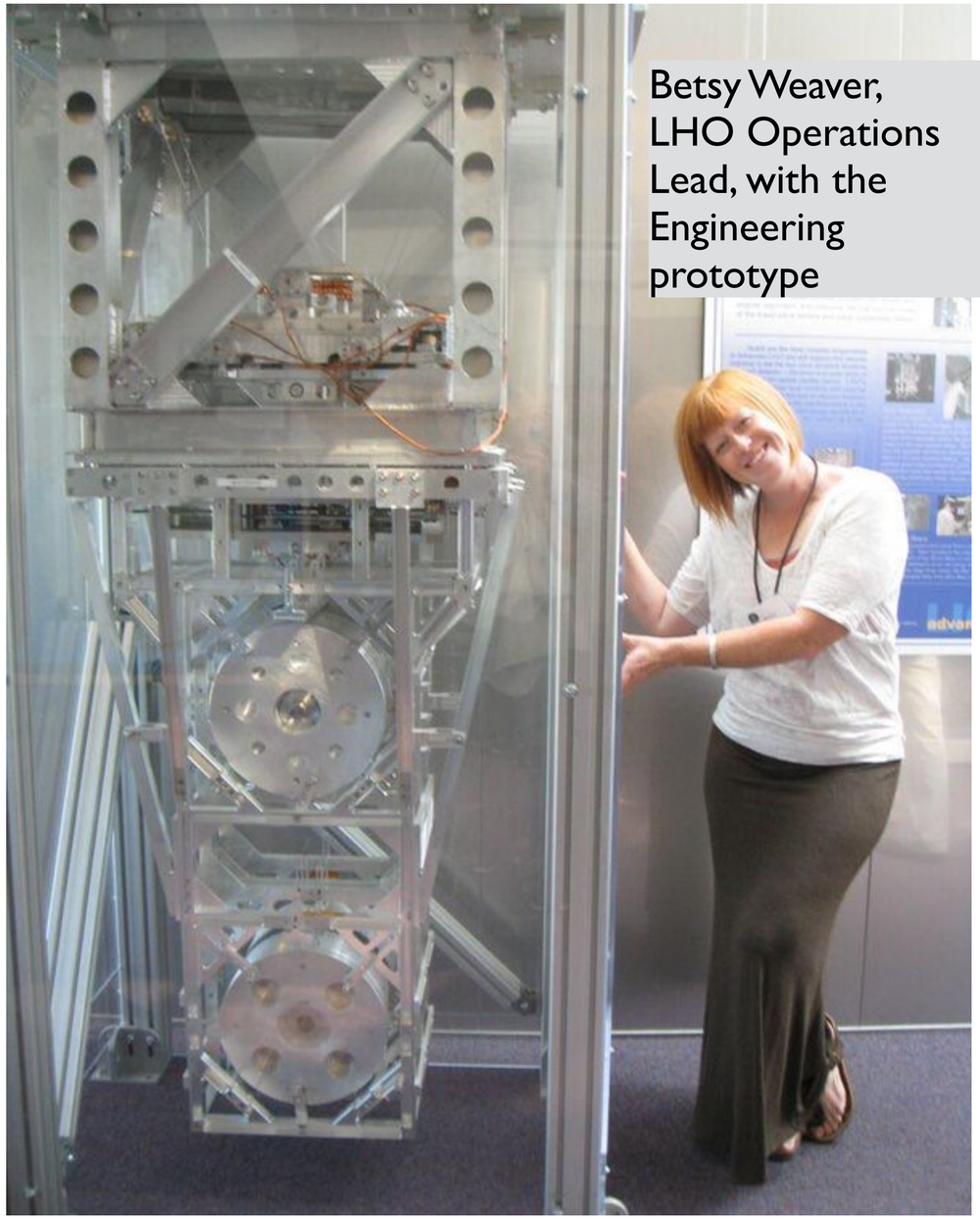
These engineering drawings illustrate the striking differences between Initial and Advanced LIGO's suspensions. The suspensions are shown to scale.

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 heftier quadruple ("quad") pendulum with a 40 kg (88 lb) test mass hung by fused silica fibers.

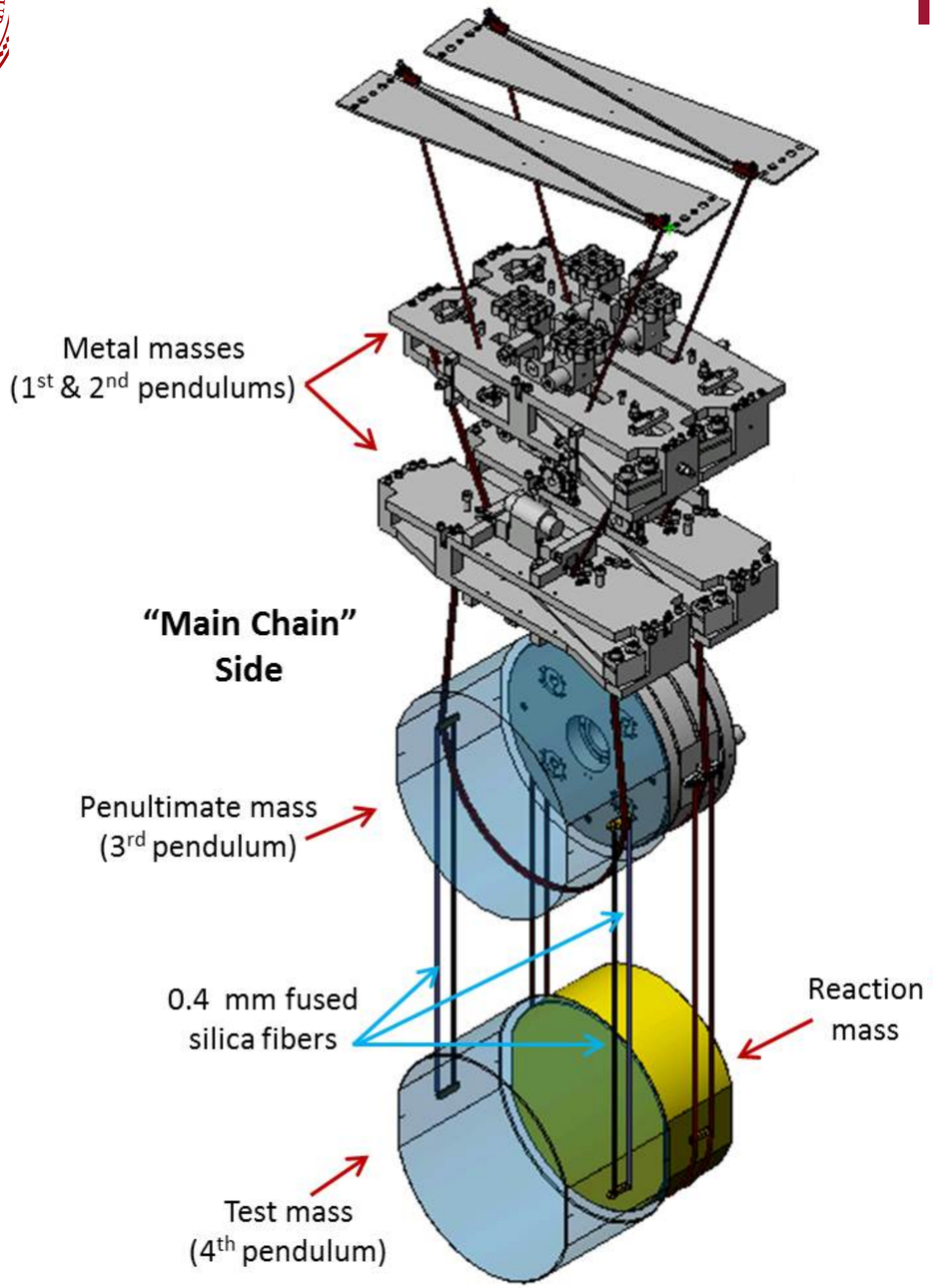
aLIGO Suspension (UK led)

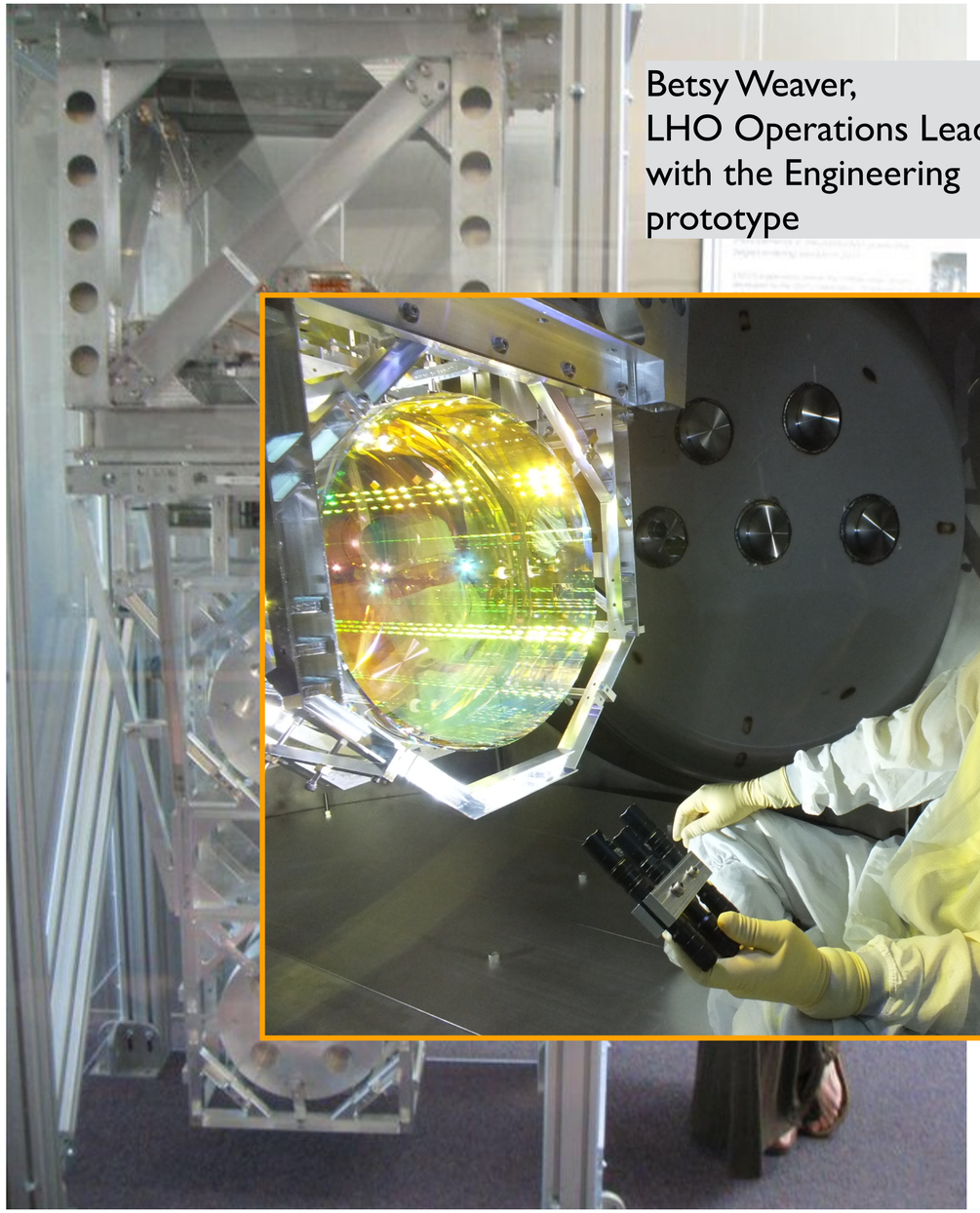




Betsy Weaver, LHO Operations Lead, with the Engineering prototype

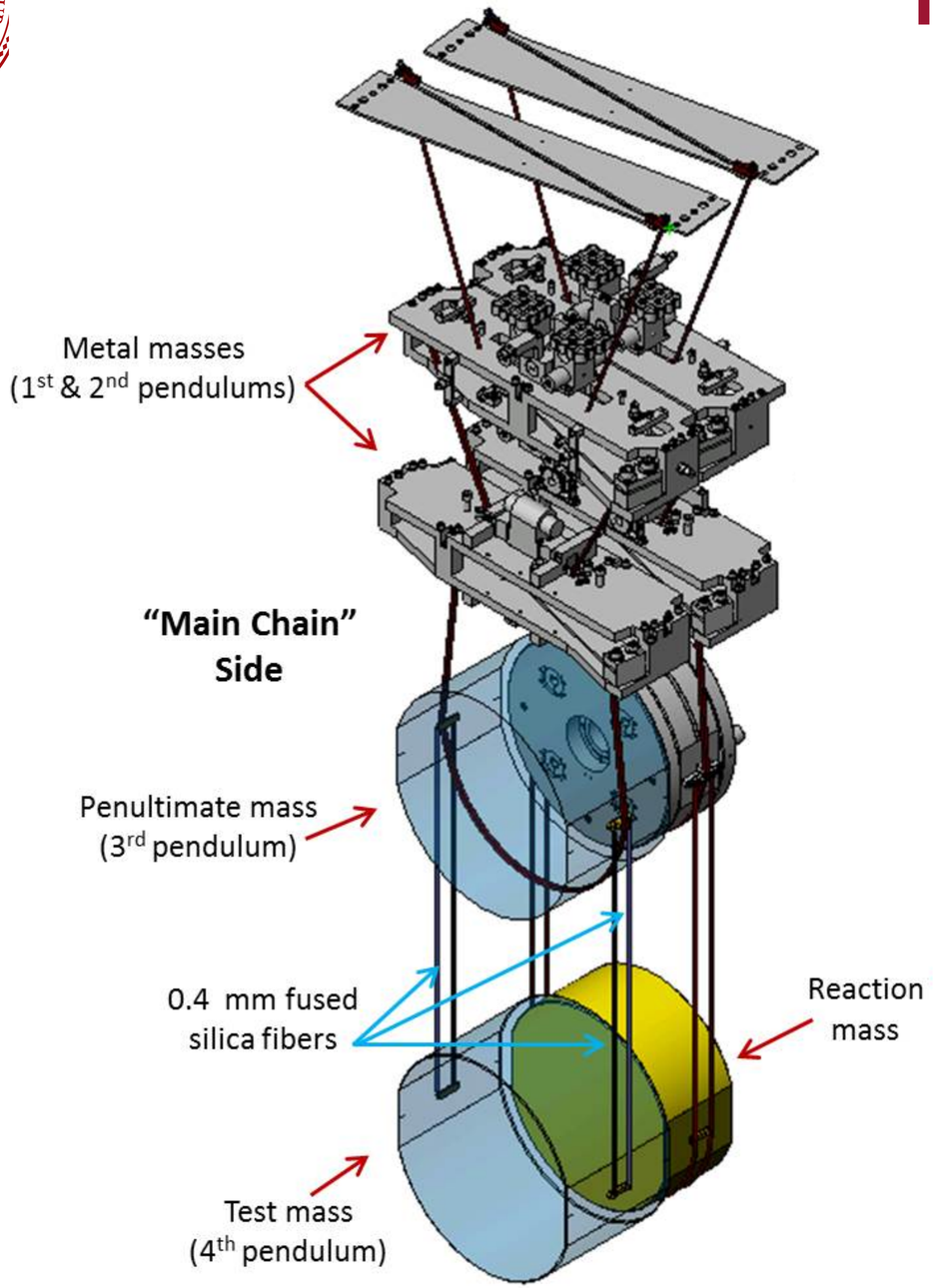
aLIGO Suspension (UK led)

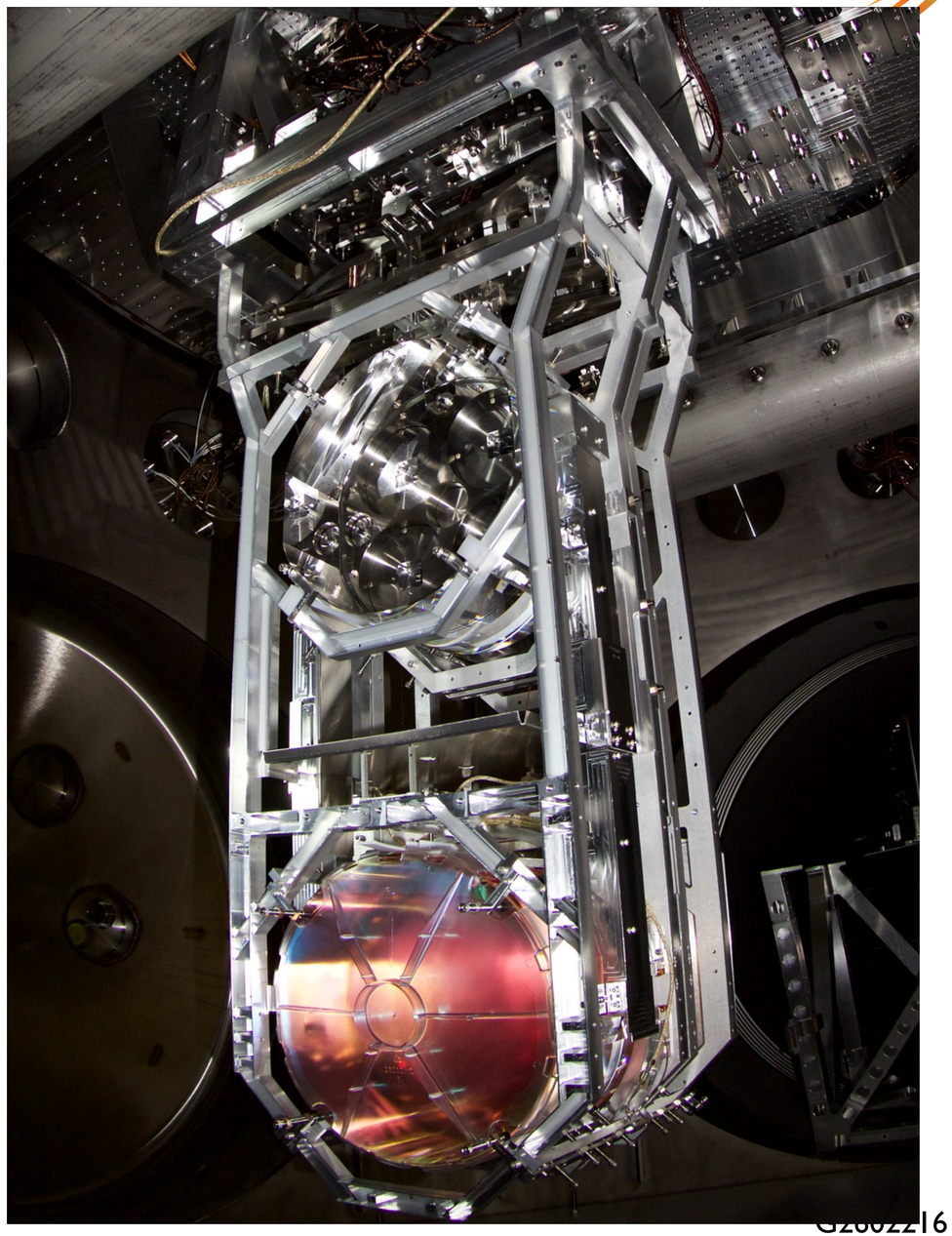


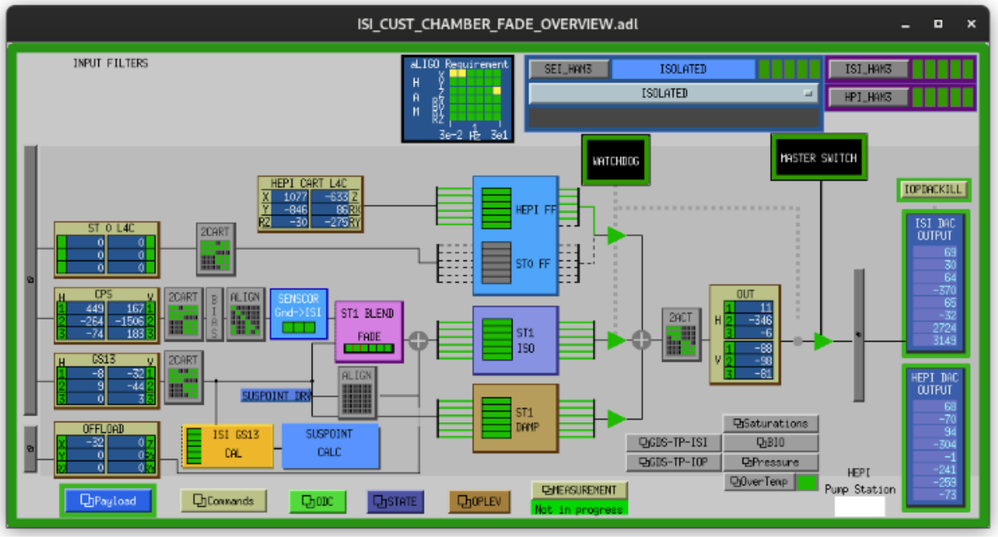


Betsy Weaver,
LHO Operations Lead,
with the Engineering
prototype

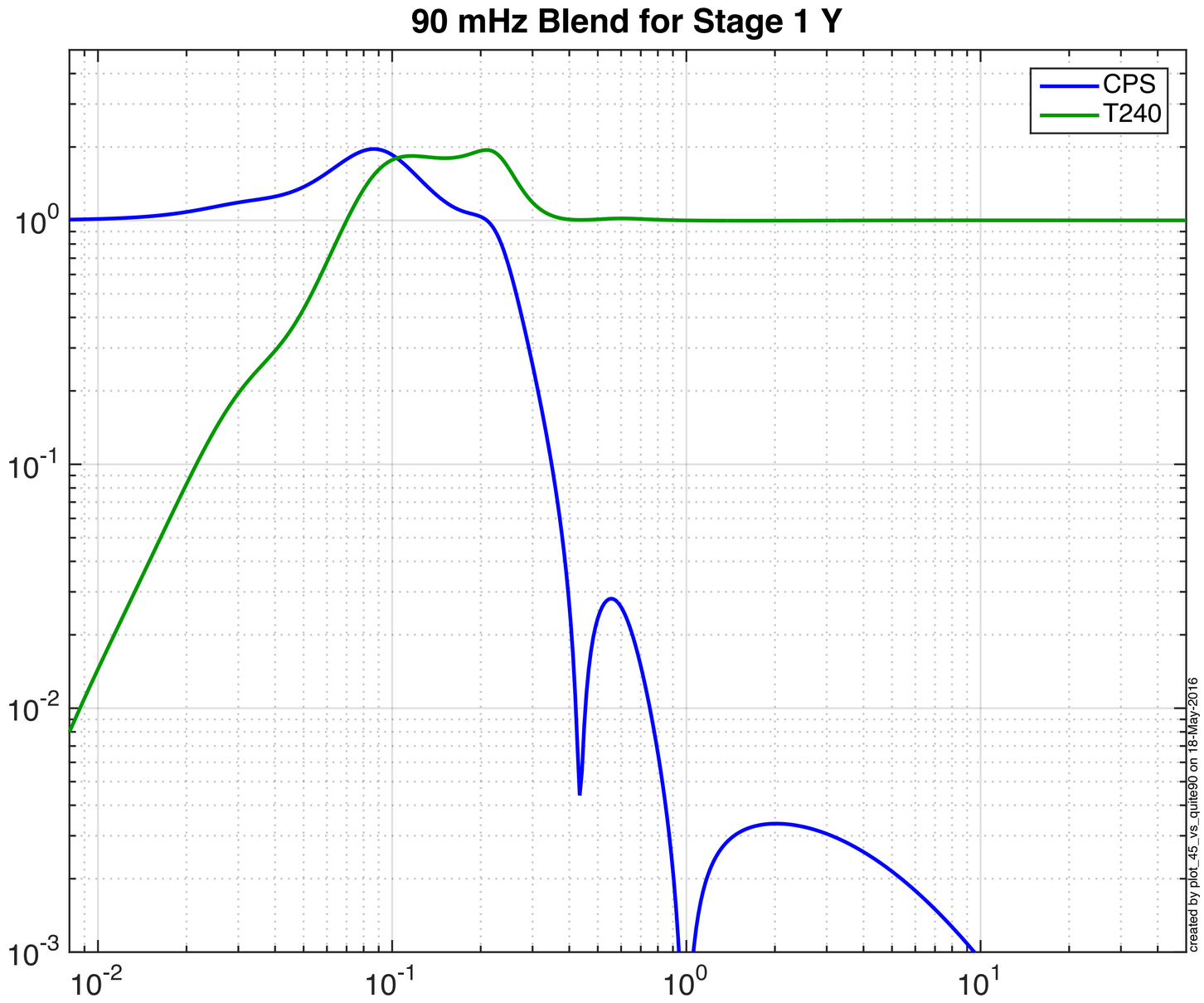
aLIGO Suspension (UK led)



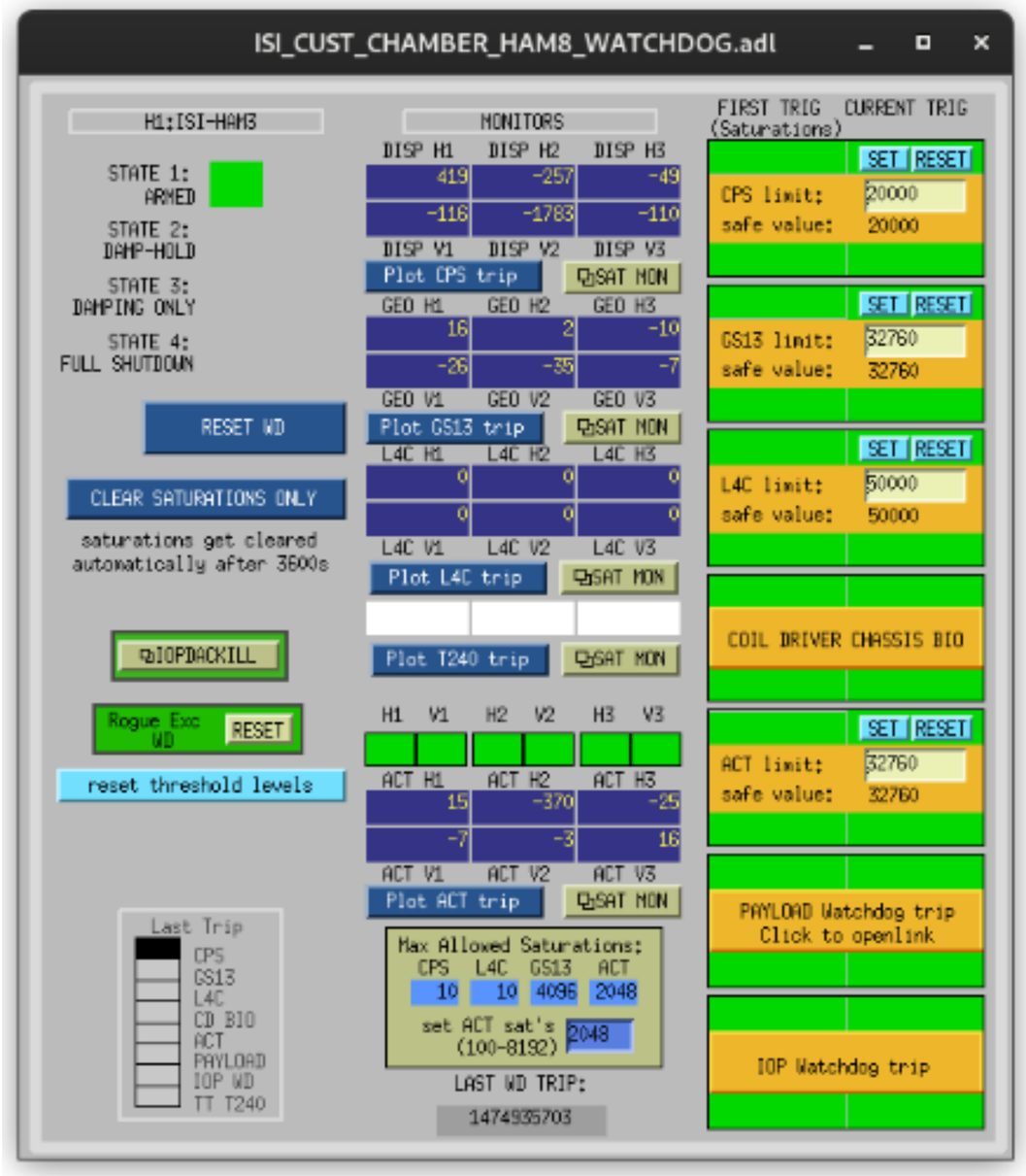



ISI_CUST_CHAMBER_FADE_OVERVIEW.adl
INPUT FILTERS
aLIGO Requirement
SEI_HAM3
ISOLATED
ISOLATED
ISI_HAM3
HPI_HAM3
WATCHDOG
MASTER SWITCH
IOPBACKILL
HEPI CART L4C
HEPI FF
ST0 FF
ST0 L4C
2CART
CPS
ALIGN
SENSCOR Gnd->ISI
ST1 BLEND
FADE
ST1 ISO
ST1 DAMP
2ACT
OUT
ISI DAC OUTPUT
HEPI DAC OUTPUT
GS13
SUSPOINT ISI
OFFLOAD
ISI GS13 CAL
SUSPOINT CALC
Saturations
GDS-TP-ISI
BIO
GDS-TP-IOP
Pressure
OverTemp
HEPI Pump Station
Payload
Commands
ODC
STATE
OPLEV
MEASUREMENT
Not in progress

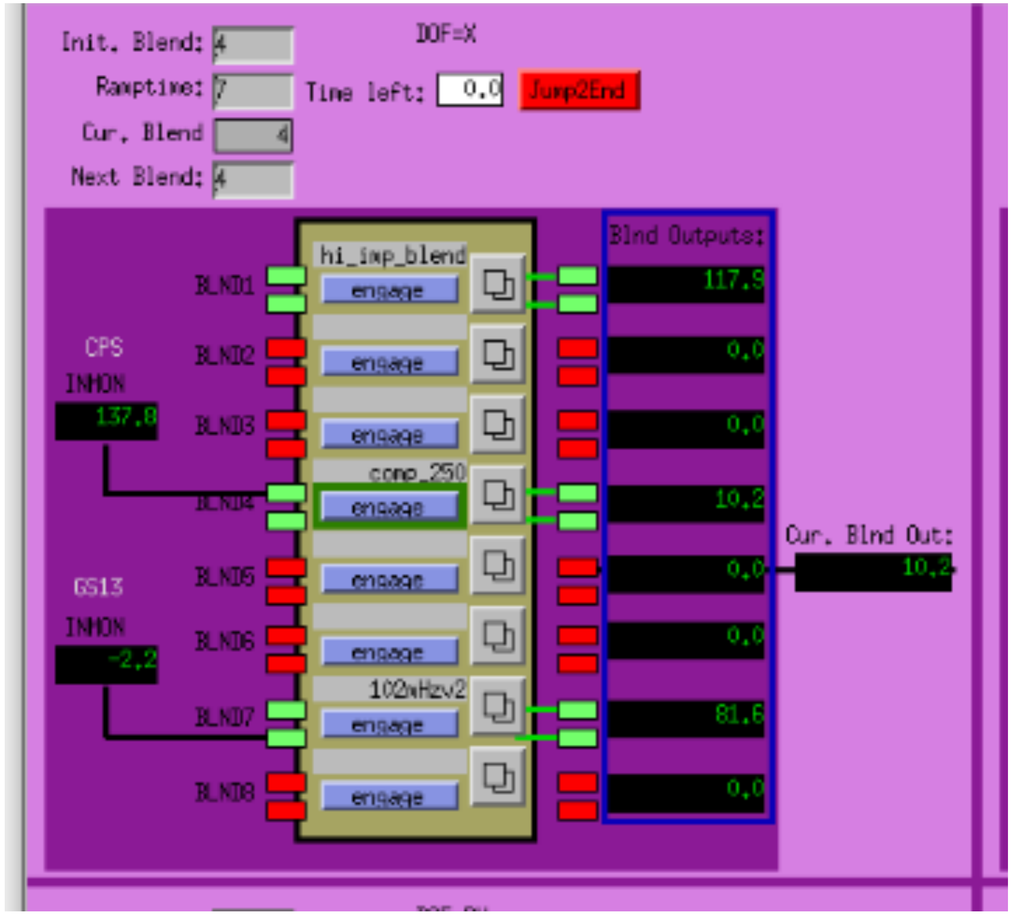
Blend filter example

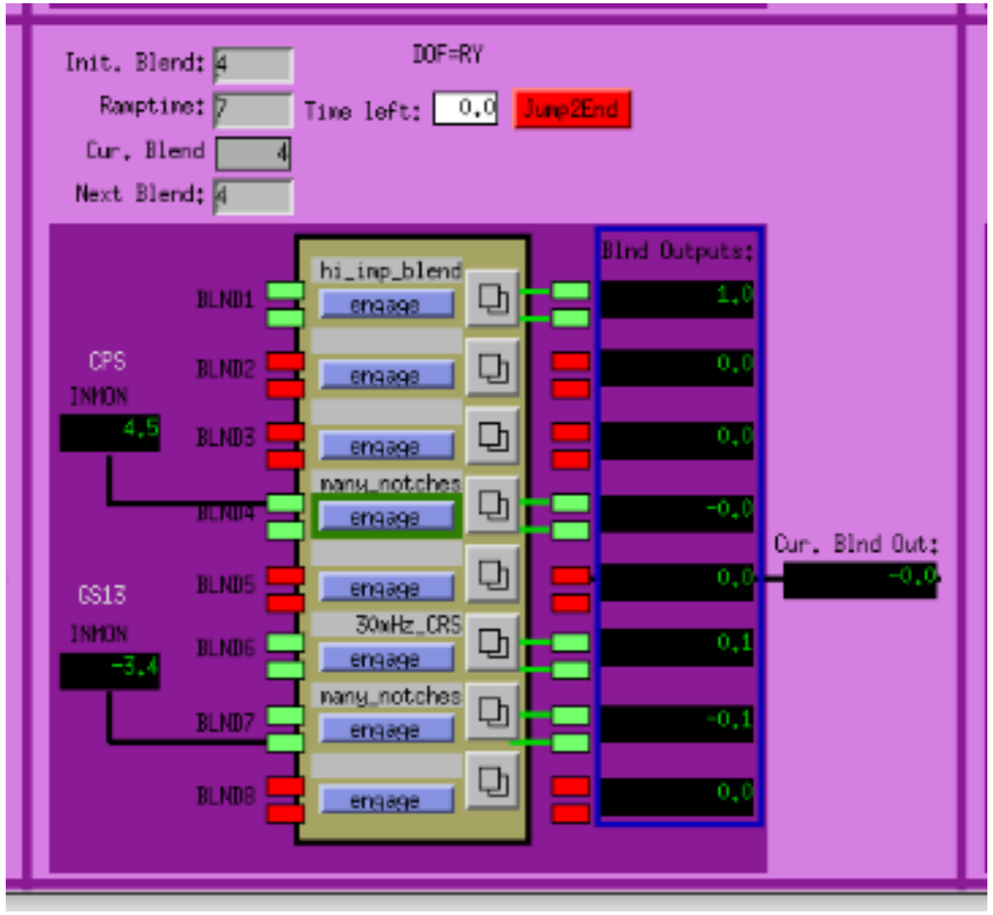


Watchdog screen

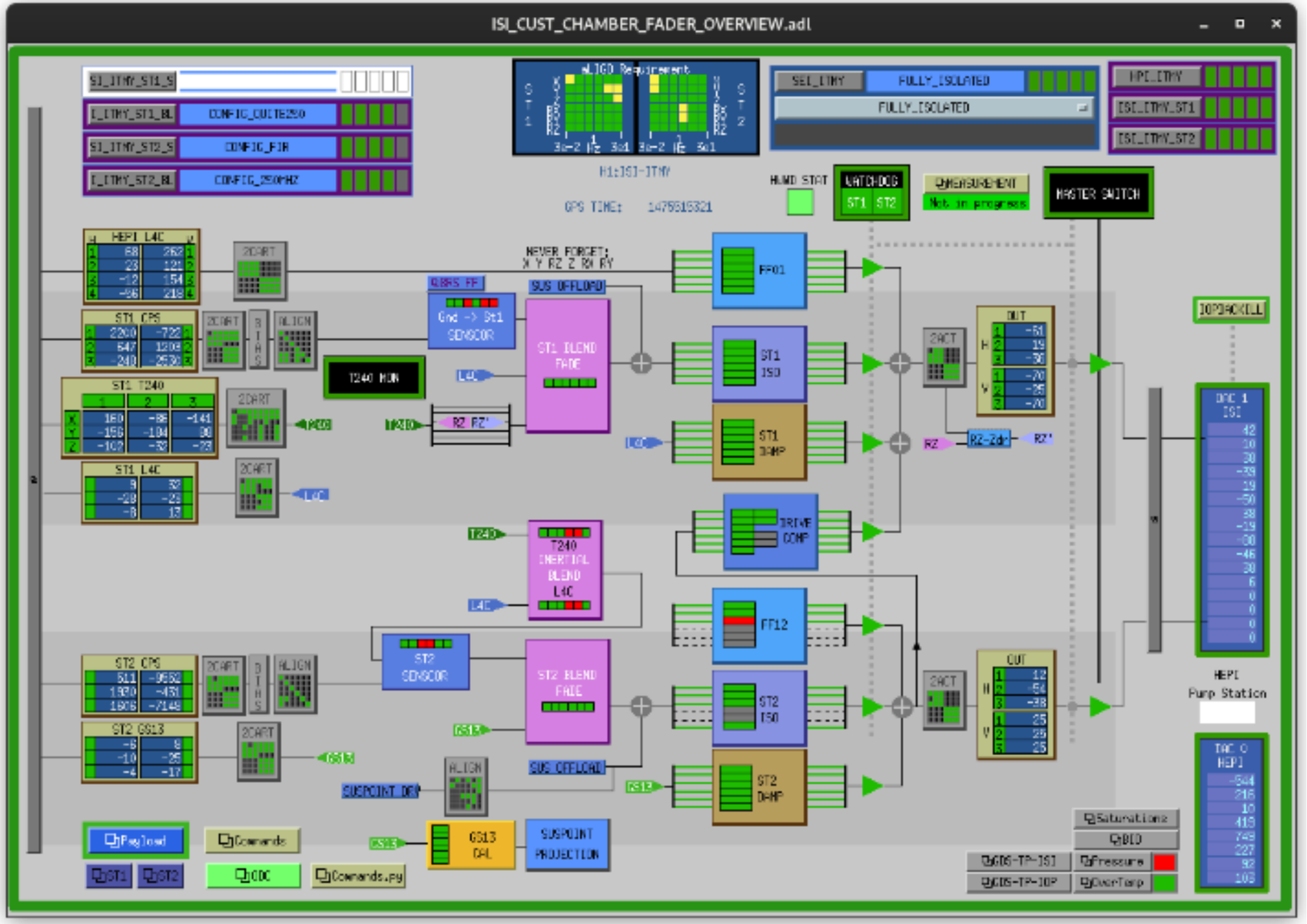


Blend switching

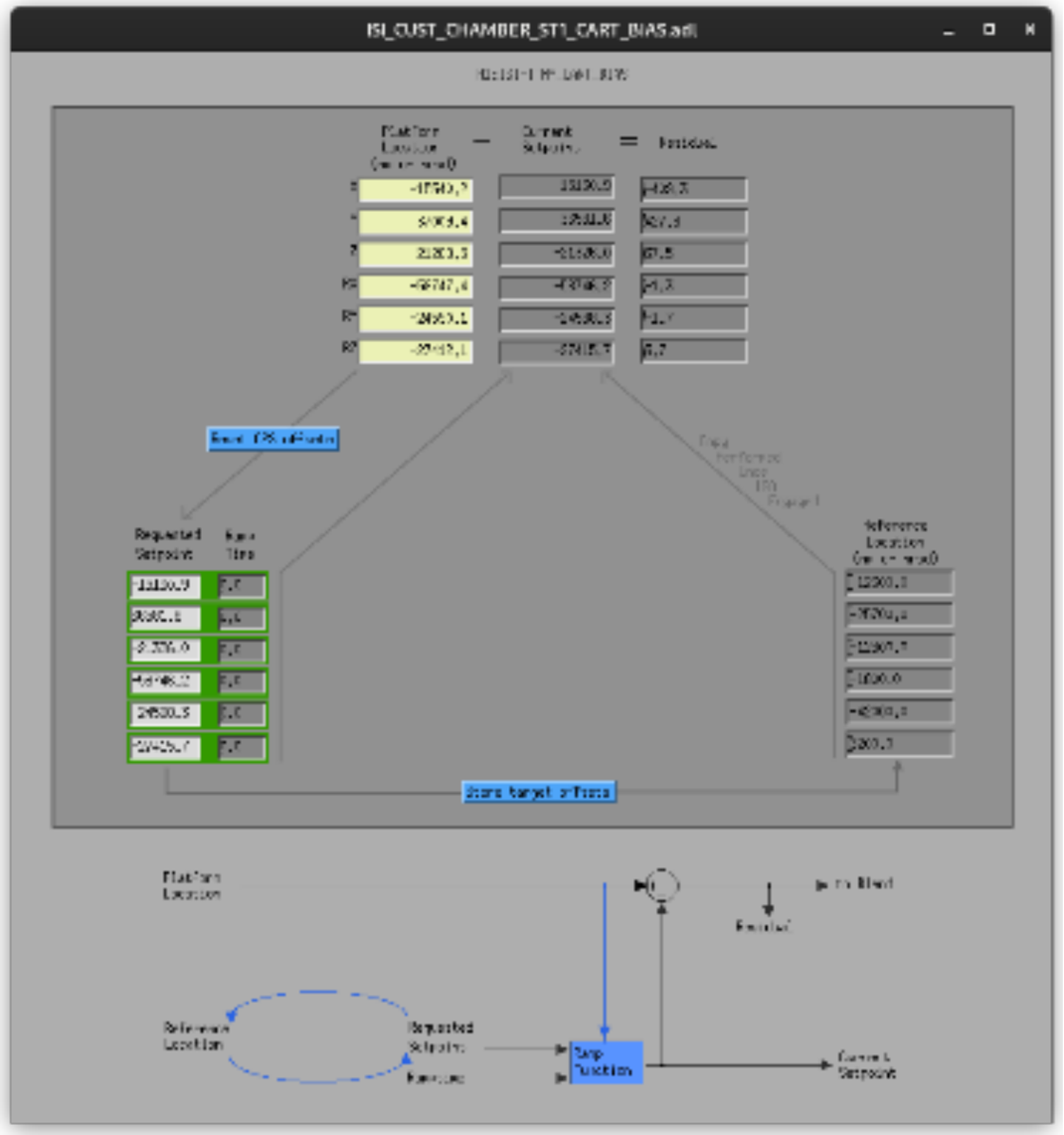




Overview screen for BSC-ISI



Bias controls

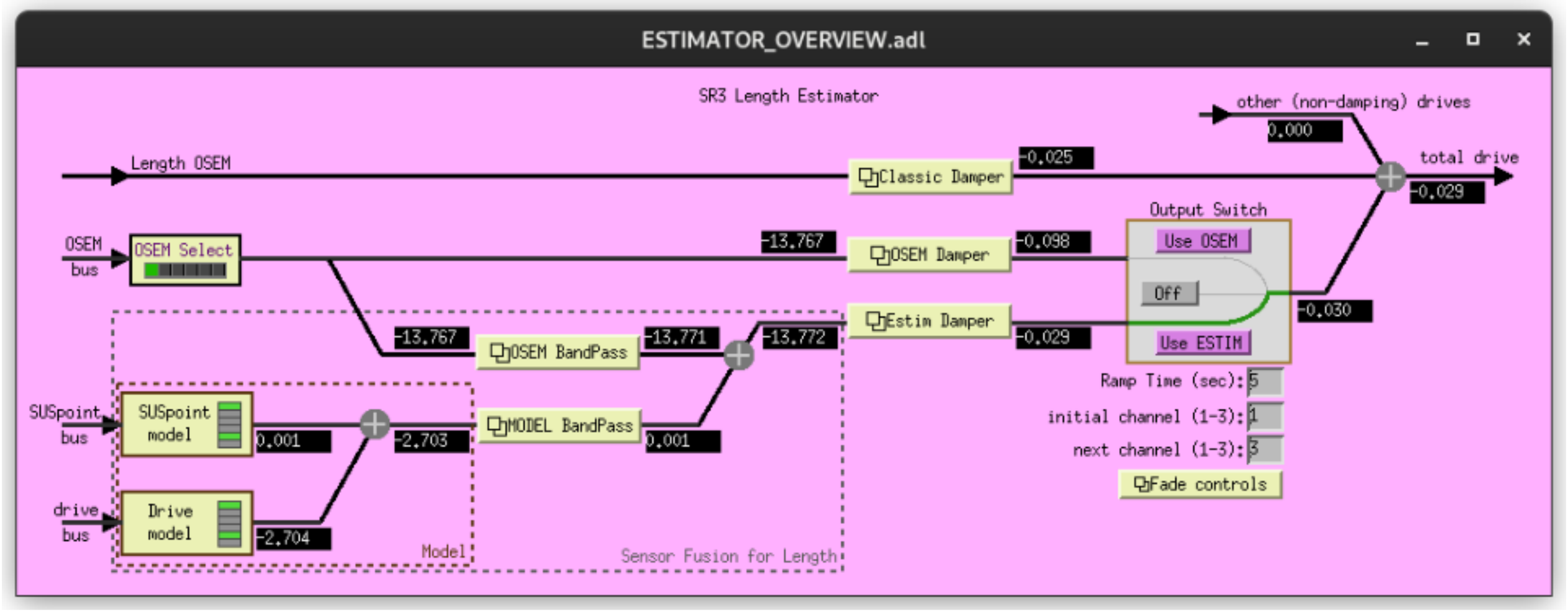


Guardian control

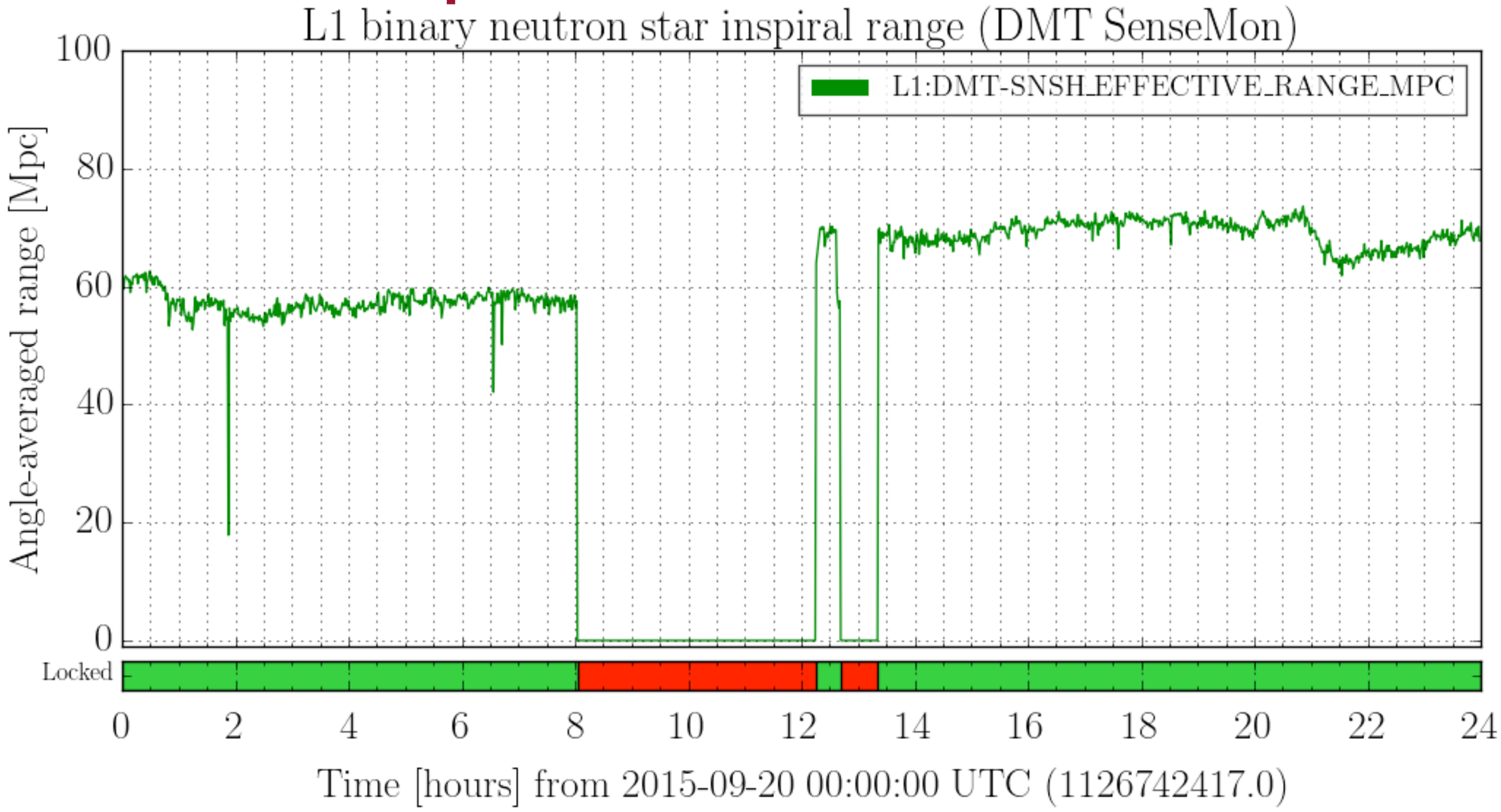


OSEM estimator

sophisticated control



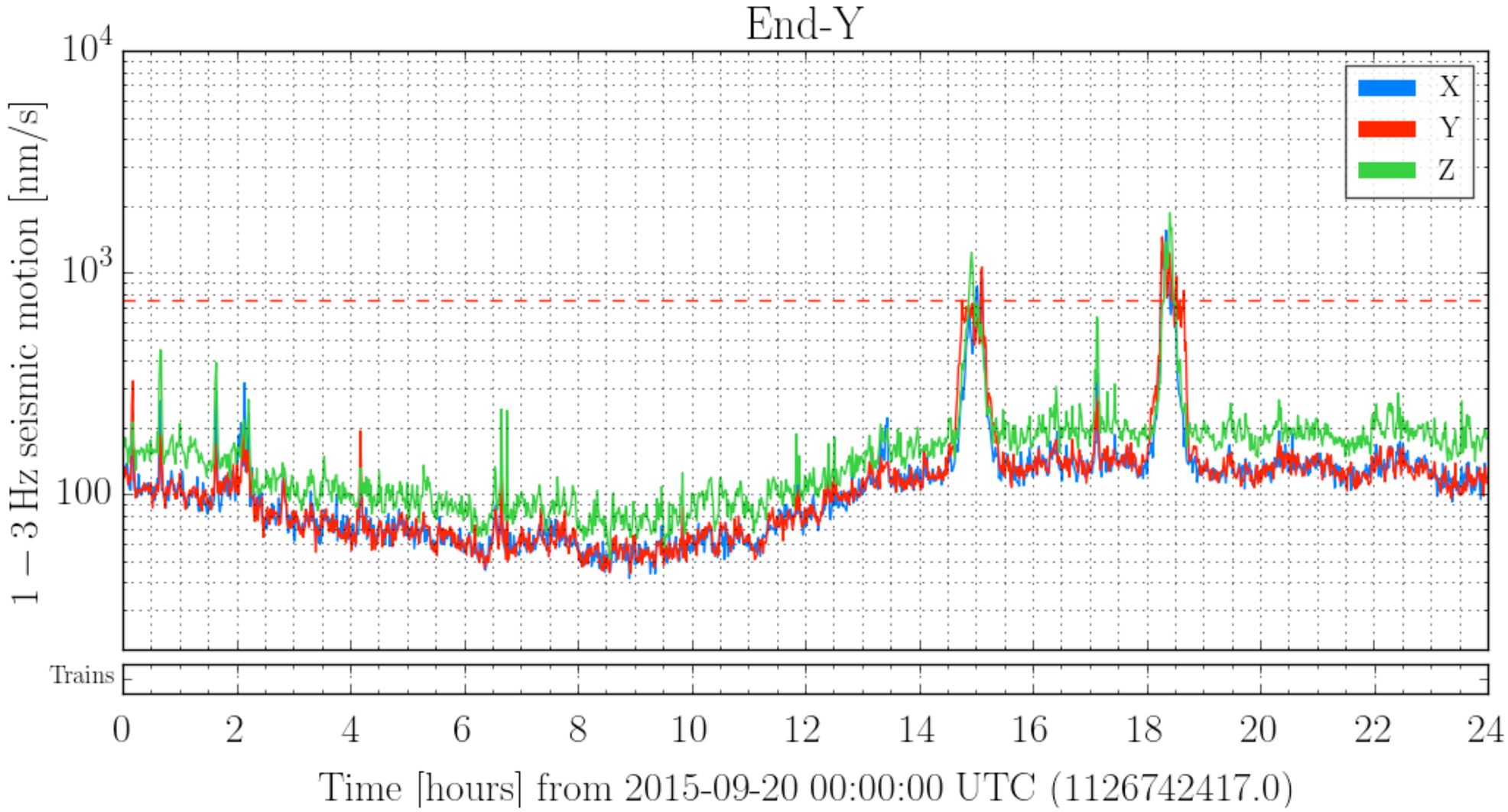
Real Impact of seismic isolation



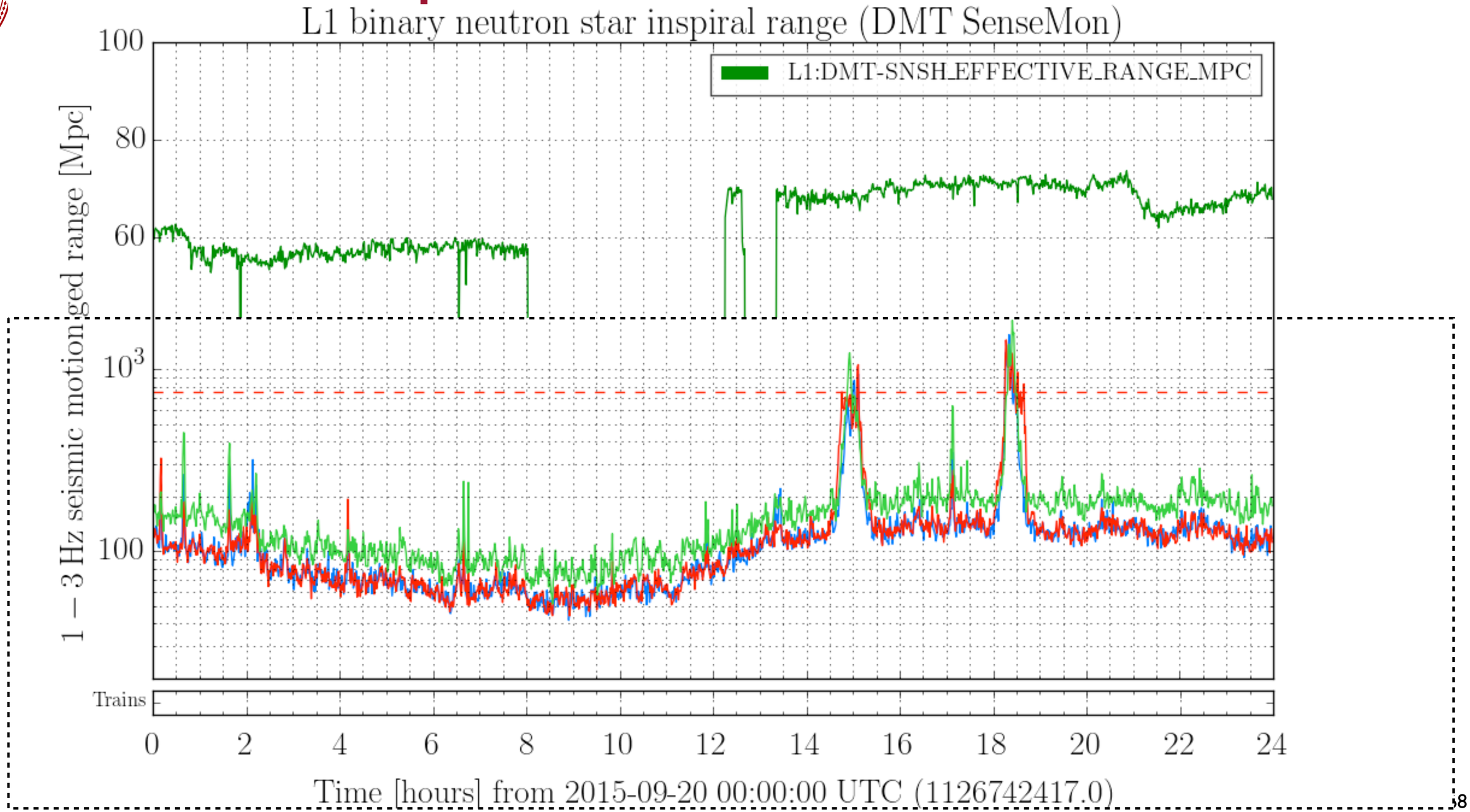
range monitor over 24 hours

Real Impact of seismic isolation

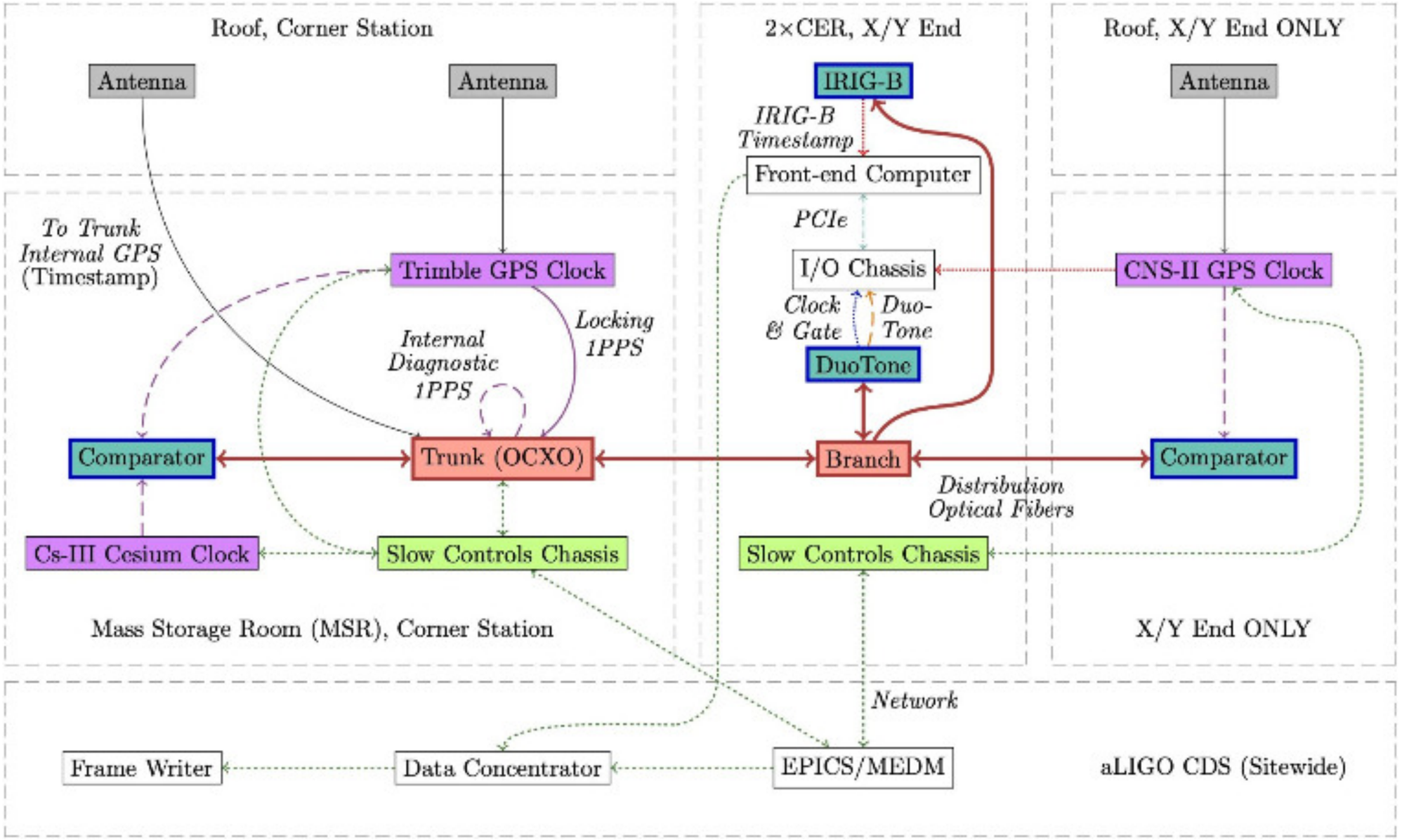
but there was a train



Real Impact of seismic isolation



Timing System



S Countryman D2200137

Timing system performance

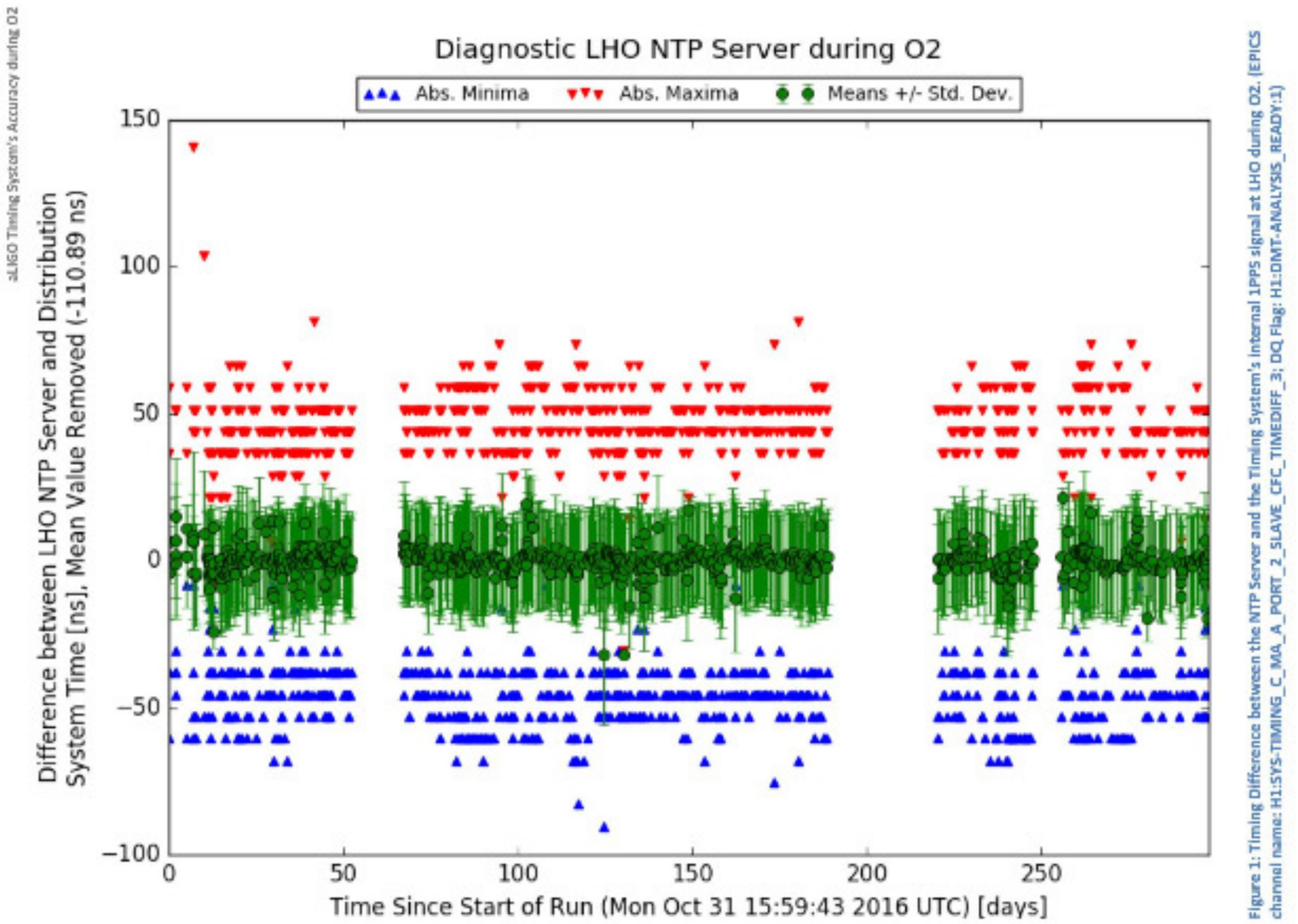
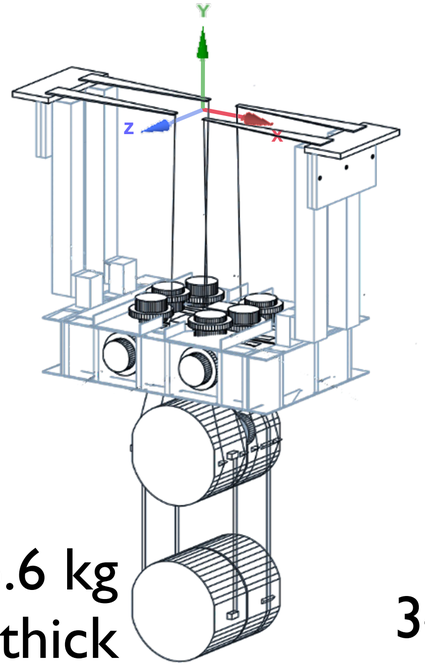


Figure 1: Timing Difference between the NTP Server and the Timing System's Internal 1PPS signal at LHO during O2. (EPICS channel name: H1:SYS-TIMING_C_MA_A_PORT_2_SLAVE_CFC_TIMEDIFF_3; DQ Flag: H1:DMT-ANALYSIS_READY:1)

A# suspension

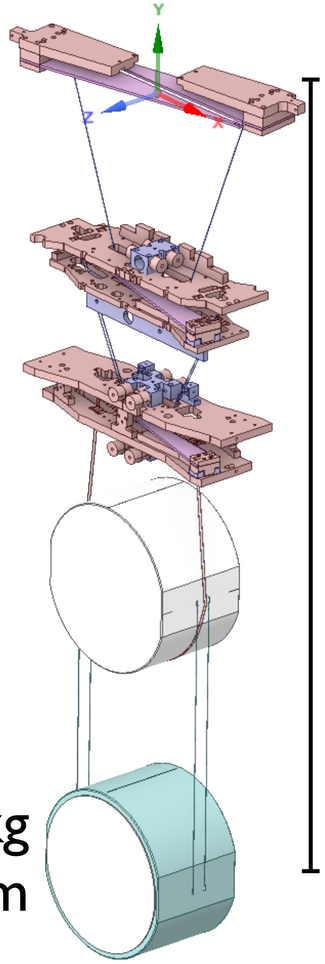
A# suspension is an upgrade the current suspension design with lessons learned from Advanced LIGO operation

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



5.6 kg
18 cm ø x 10 cm thick

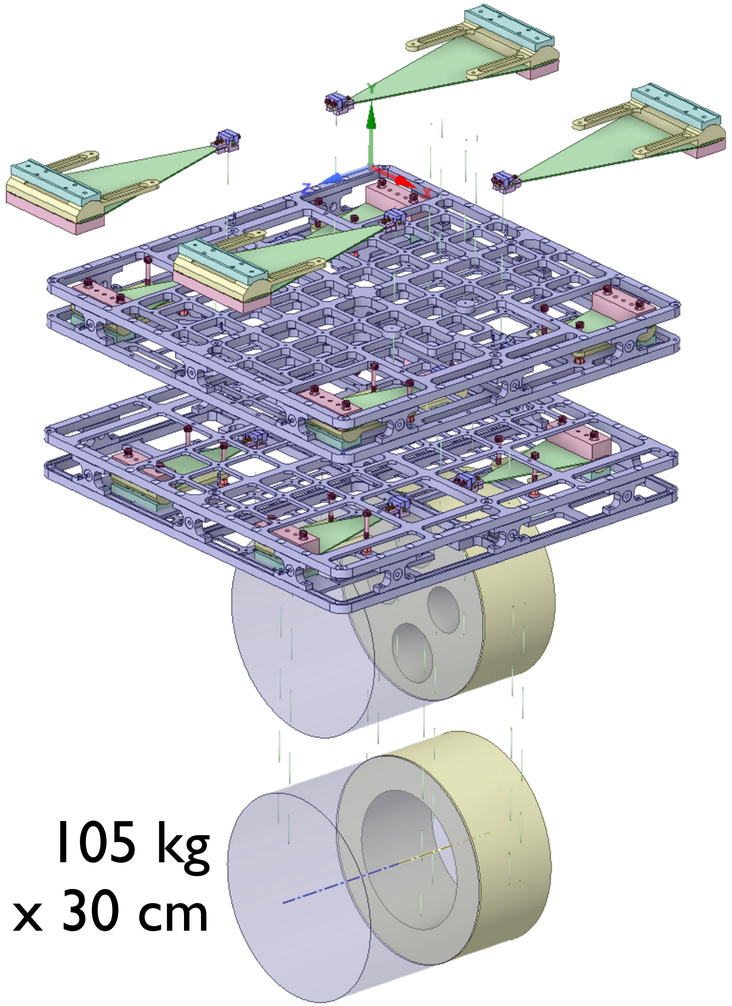
GEO600



162 cm

40 kg
34 x 20 cm

Advanced LIGO



105 kg
45 x 30 cm

LIGO A#