Seismic Isolation and Positioning for Advanced LIGO

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LIGO-India: The Road Ahead

Dr. Brian Lantz

for the SEI team & LIGO Scientific Collaboration

August 16, 2016

G1601604

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

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Overview

Part 1 - What is the the system?
- Role of the Seismic Isolation and Positioning subsystem
- Parts of the subsystem
- Key design features

Part 2 - How well does it work?
- Commissioning process
- Performance

Part 3 - Challenges
- Tilt-horizontal coupling
- Wind
- Earthquakes
- Structure bending

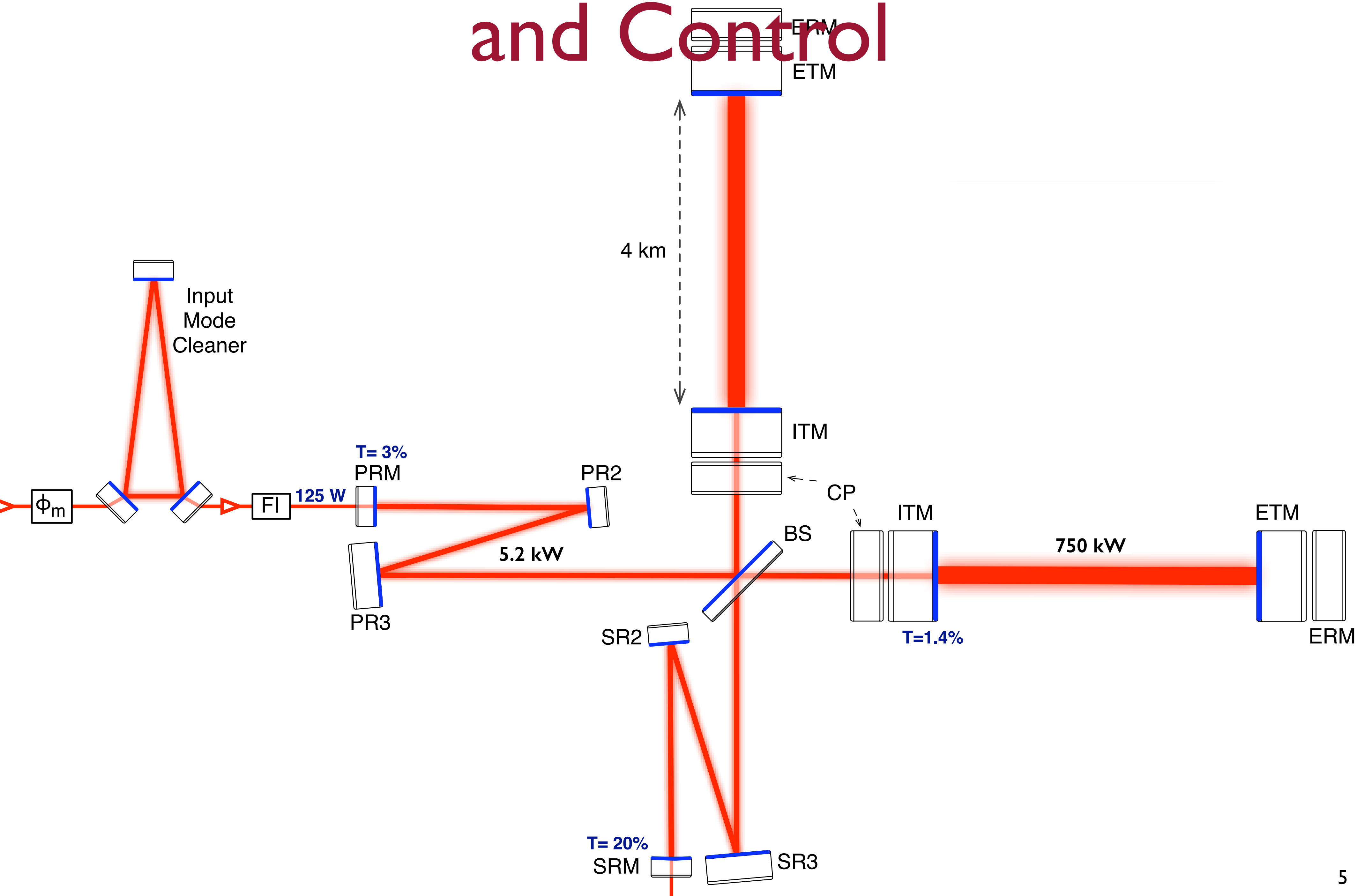
Role of Seismic Isolation and Control

- Provides good performance at 10 Hz.
- It is more than "isolation for the mirrors"
- Need to isolate, position, and monitor the mirrors
  - Stable positioning below ~0.1 Hz
  - Isolation from the microseism (~0.15 Hz) to 10 Hz.
- Need to mount many optical components
- Seismic and Suspensions are
  one system split into a few parts.

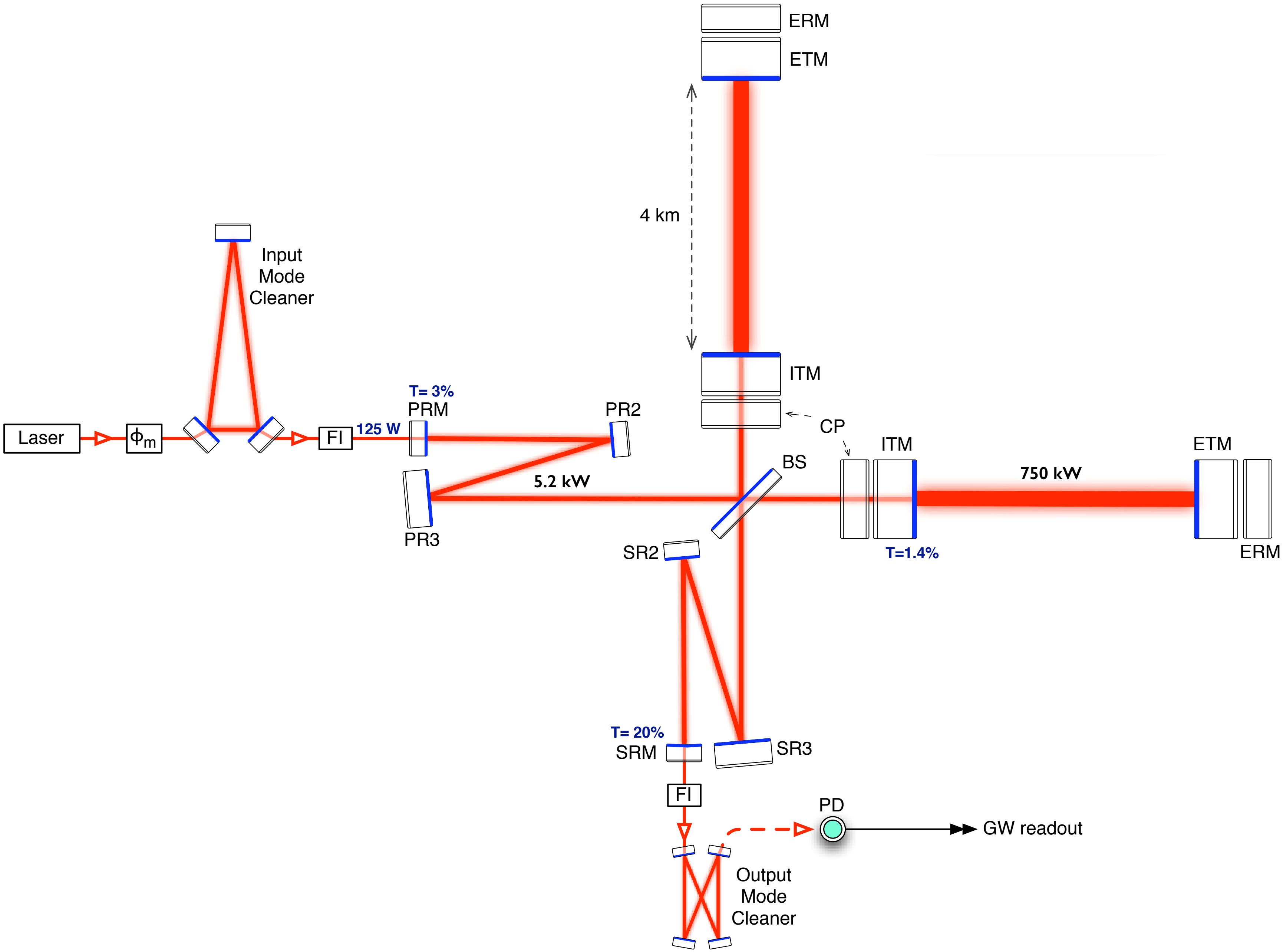
Role of Seismic Isolation and Control

- Good active and passive isolation at 10 Hz
  passive above a few hertz, active isolation from 0.1 to 30 Hz
- Provides good isolation in the "Control Band",
  work to minimize velocity below 0.1 Hz
- Can monitor the table motion from DC to 2 kHz.
- Big tables mount many components, payloads are flexible.
- Seismic and Suspensions are
  one system split into a few parts.

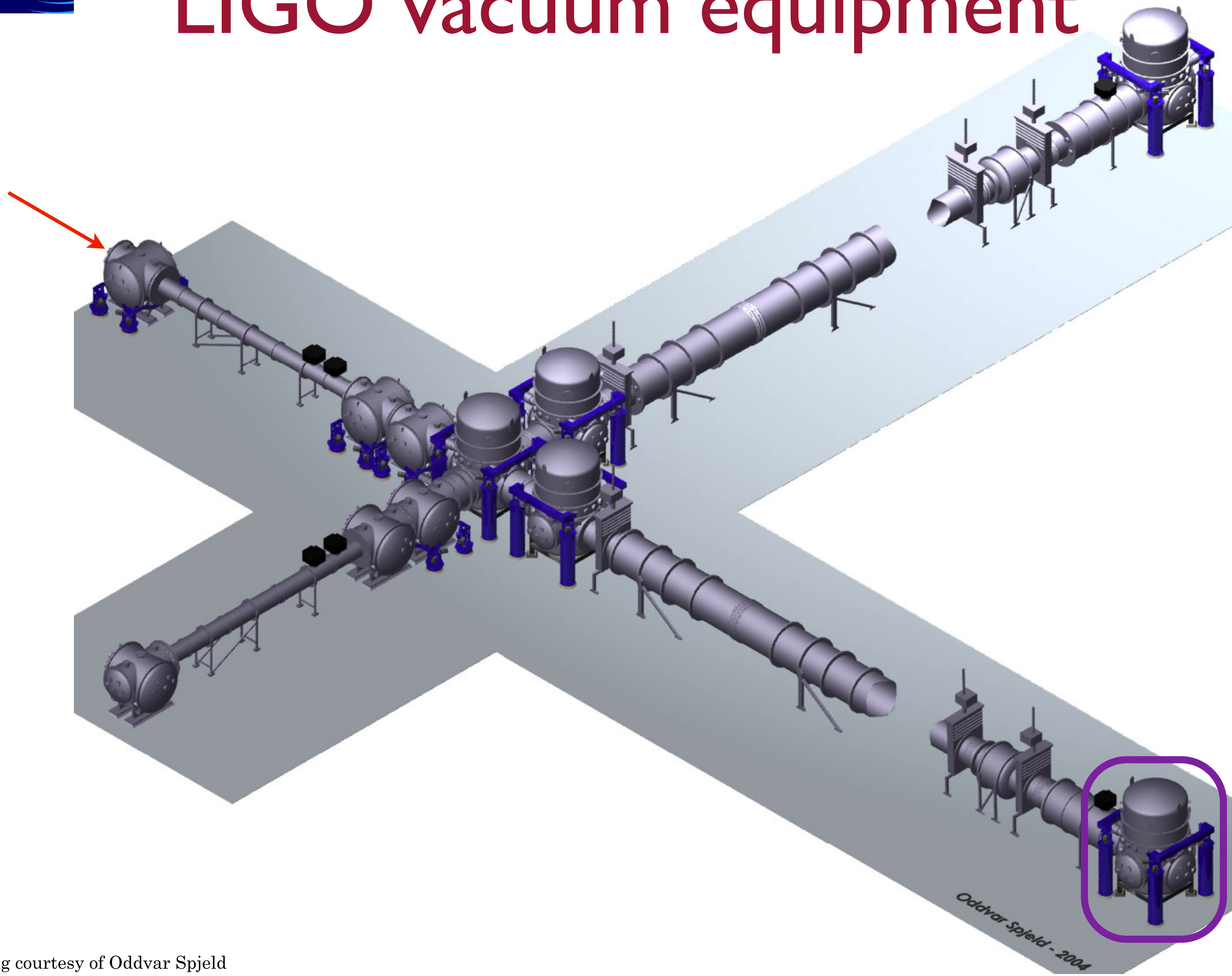
Role of Seismic Isolation and Control



Role of Seismic Isolation and Control



LIGO vacuum equipment



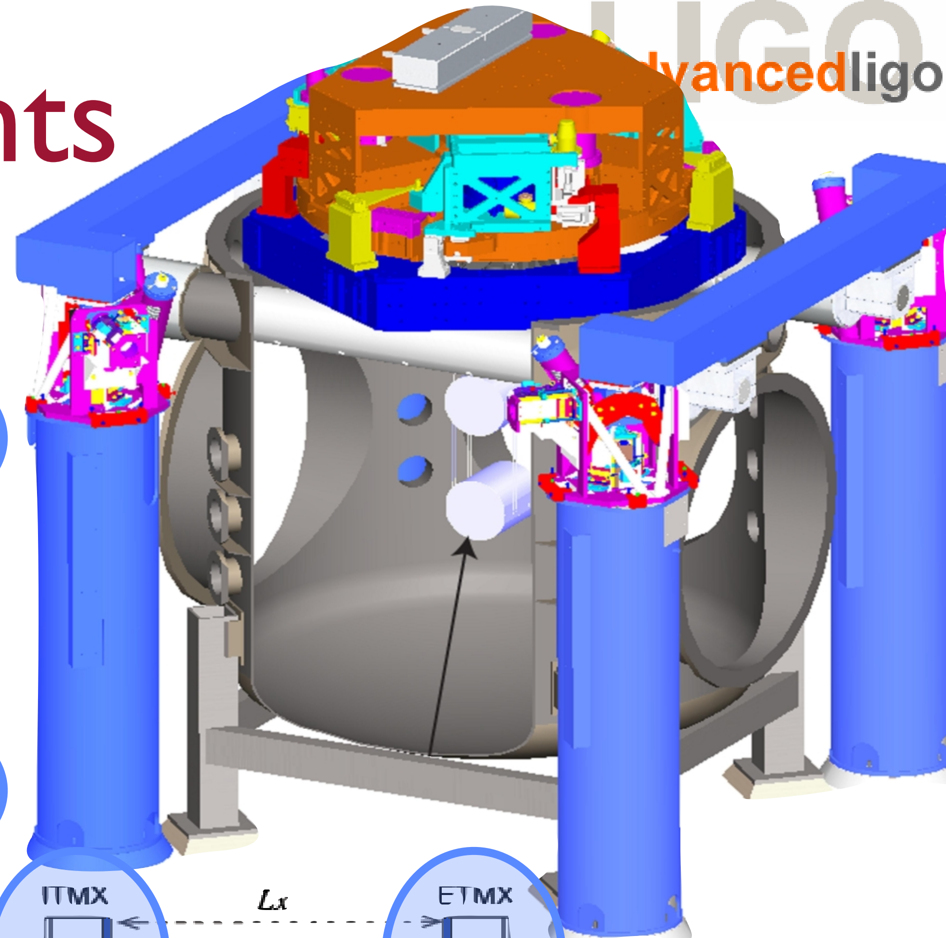
drawing courtesy of Oddvar Spjeld

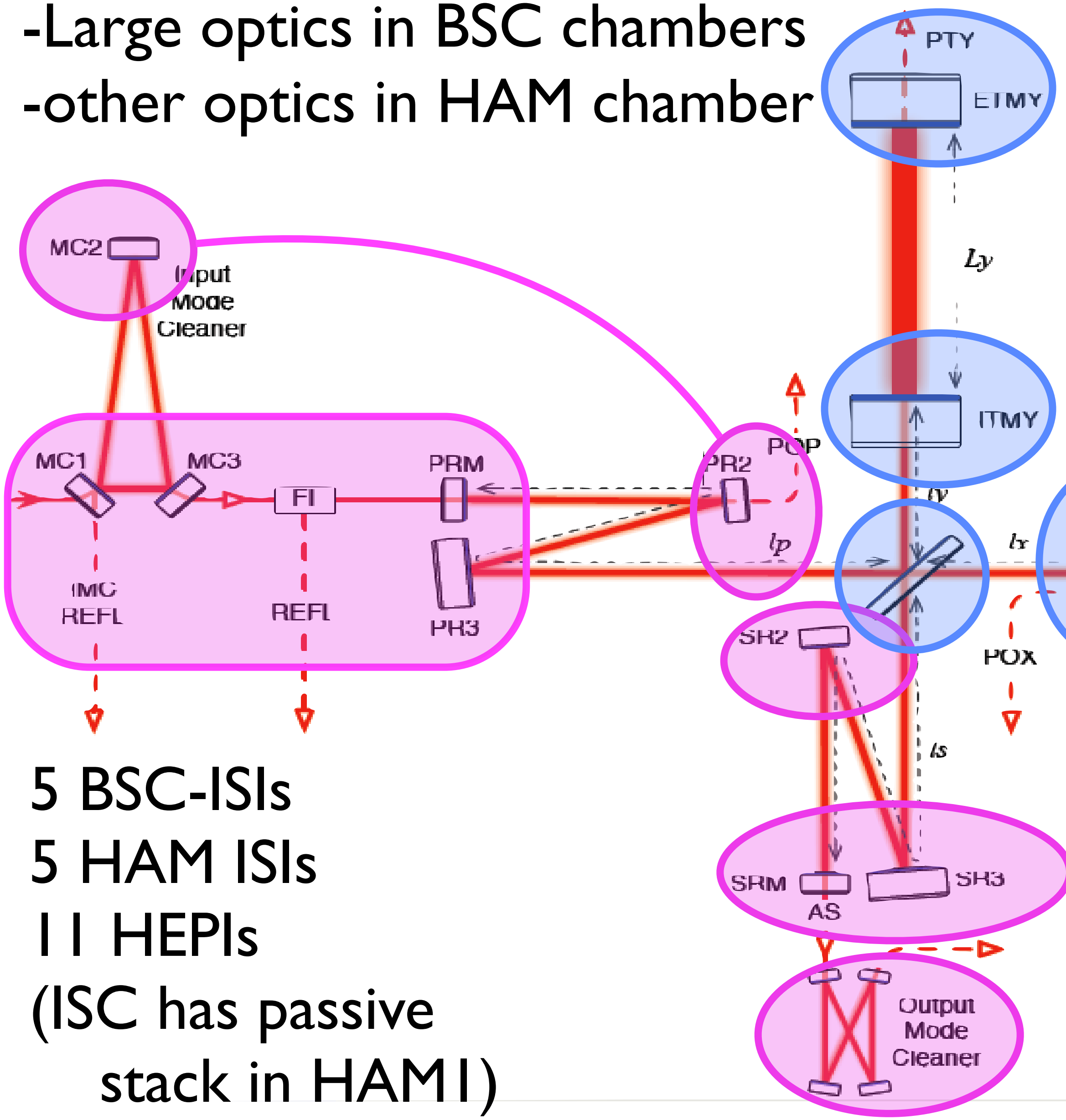
Requirements

Support all the in-vacuum IFO optics

-Large optics in BSC chambers

-other optics in HAM chamber



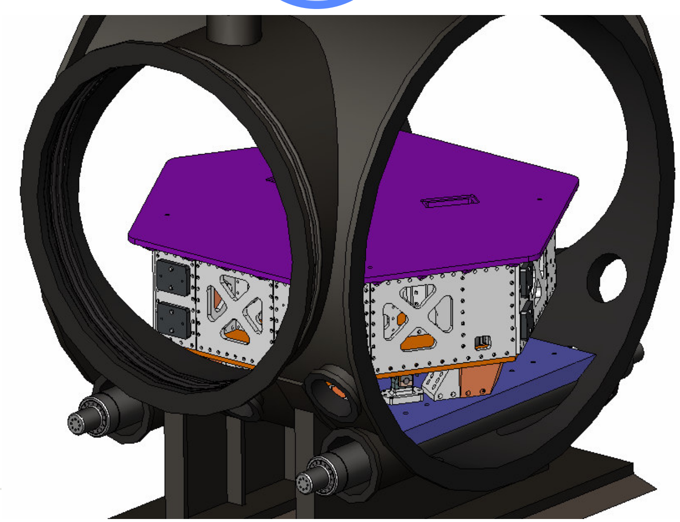


5 BSC-ISIs

5 HAM ISIs

11 HEPIs

(ISC has passive stack in HAM1)



Overall Isolation of Test Masses

Bolted Aluminum structure

2 active stages,

each supported by 3 blade springs and flexures.

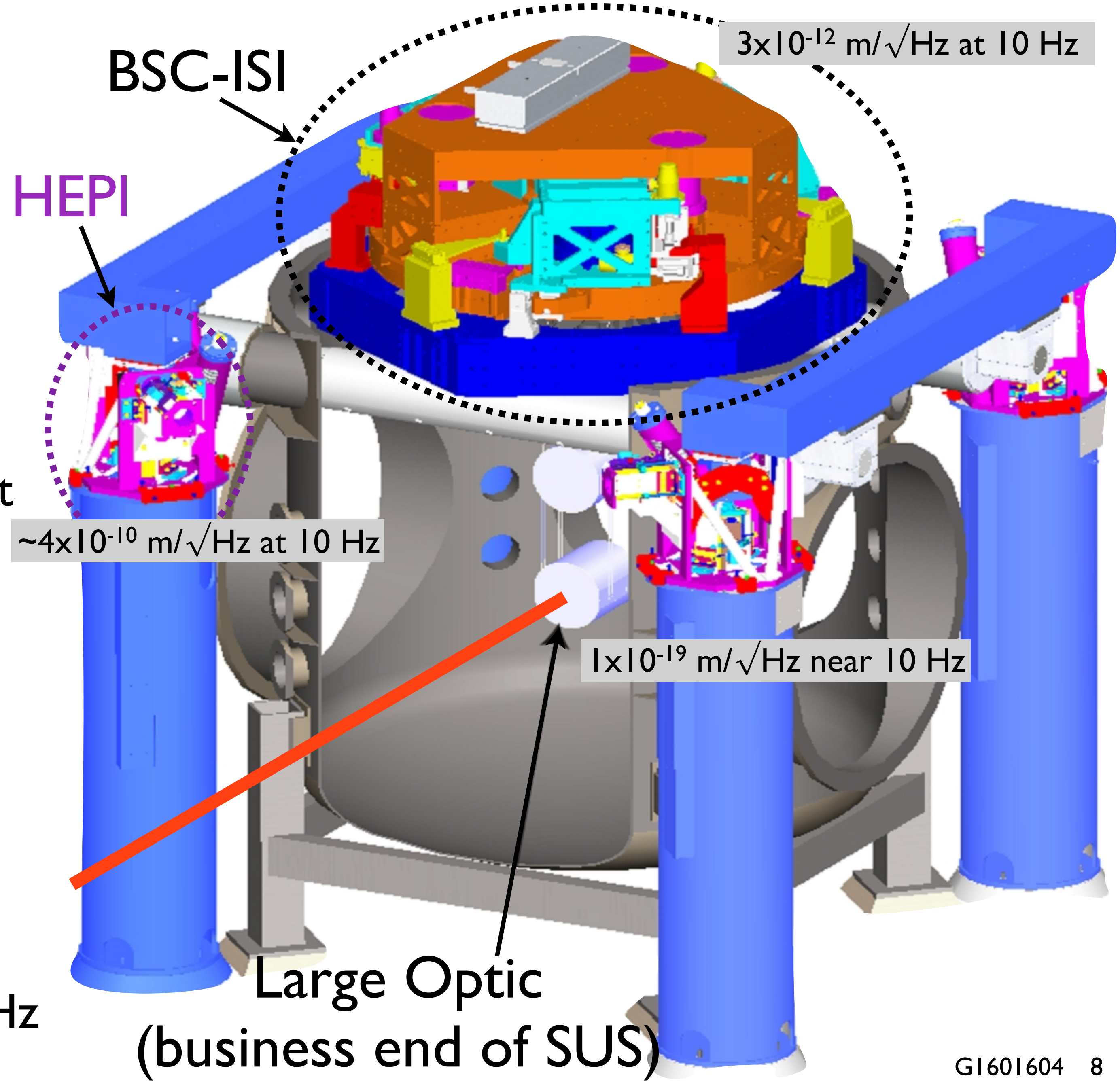
all 6 DOFs controlled for each stage.

6 actuators, 6 displacement sensors, 6 DOF inertial sensing for each stage.

Passive freq's 1.3-7 Hz

Optics hang down from table, supports 1100 kg of total load.

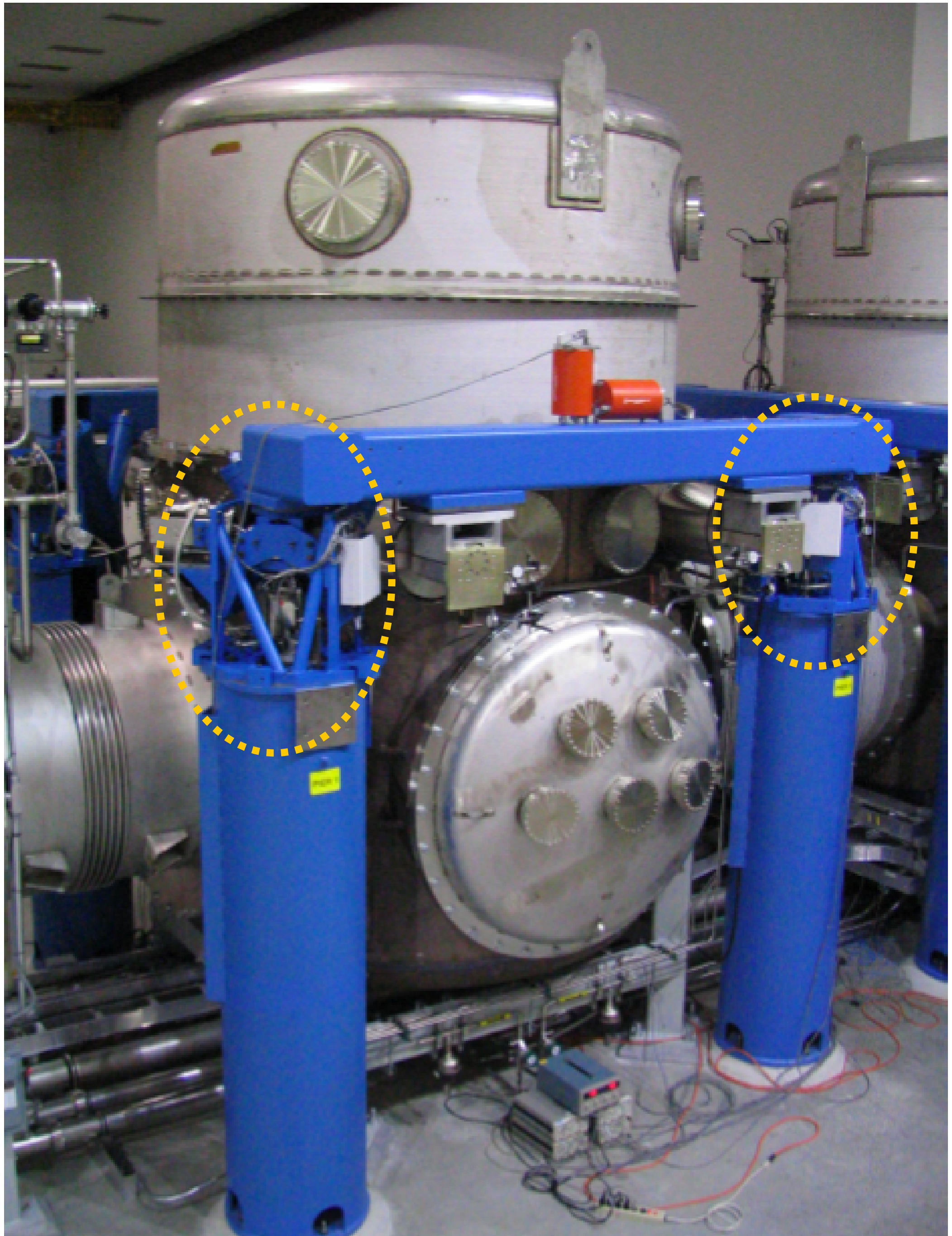
Unity gain freq's around 30 Hz

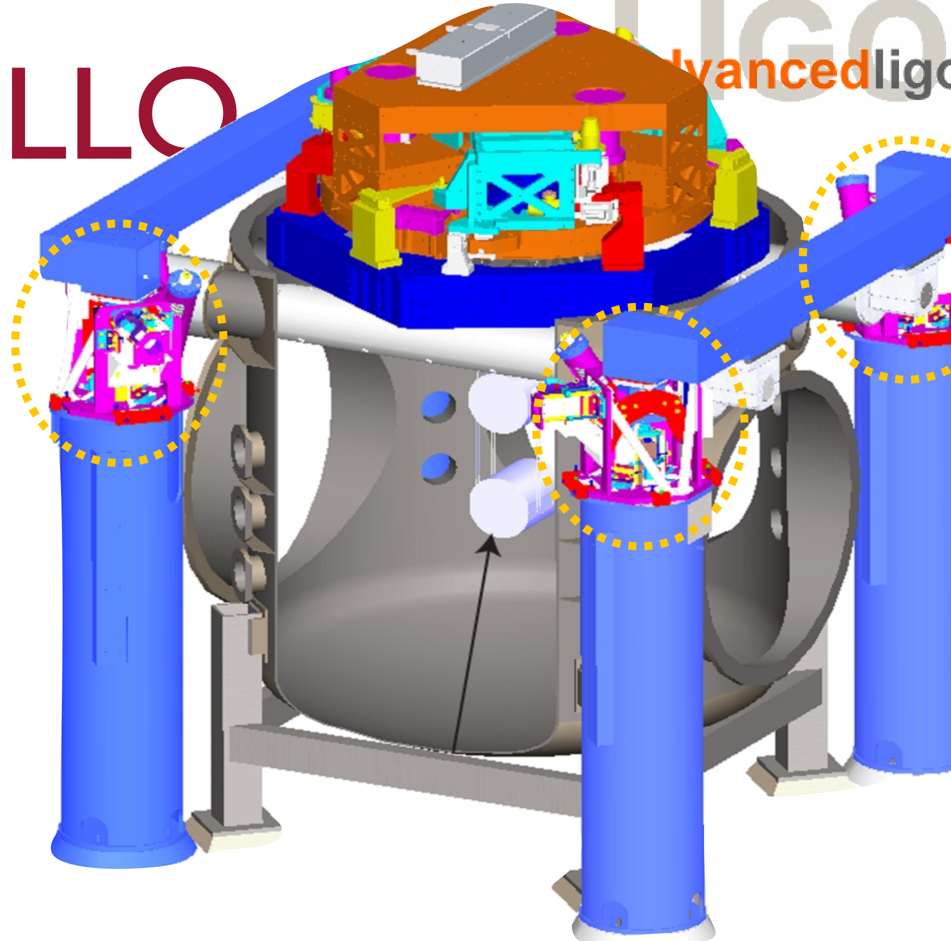


Parts of the Subsystem

- Plant
  - The mechanical thing we are controlling
  - designed to be controlled
  - it's a really good mechanical system, but not perfect
- Sensors - Really good sensors
  - We sense all 6 DOF,
  - Displacement sensors for platform location at Low Freq
  - Inertial sensor for platform vibration when possible.
  - plagued by tilt-horizontal coupling at low frequency
- Actuators - Hydraulic actuators for HEPI, voice coils for ISI
- Controls - all DOFs controlled,
  - each control is simple.
  - there are many of them.

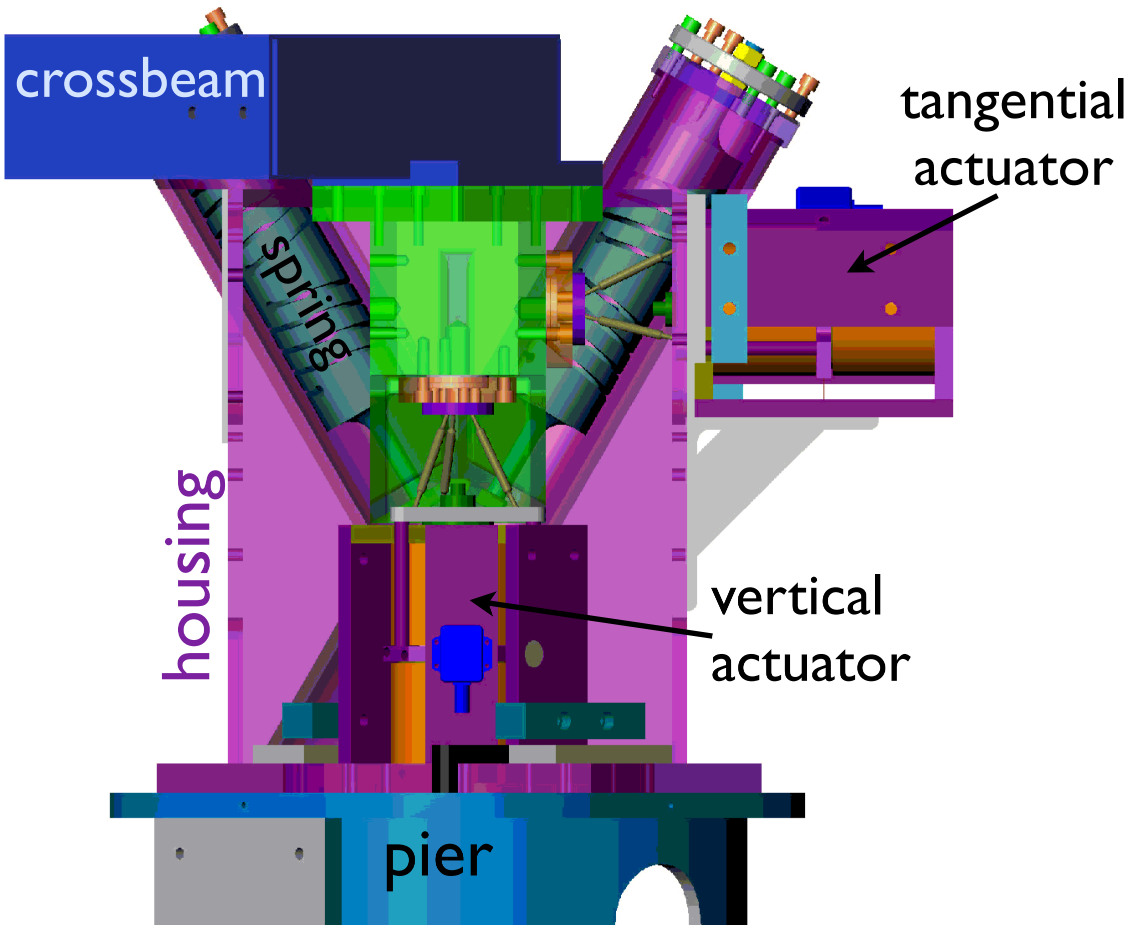
HEPI at LLO

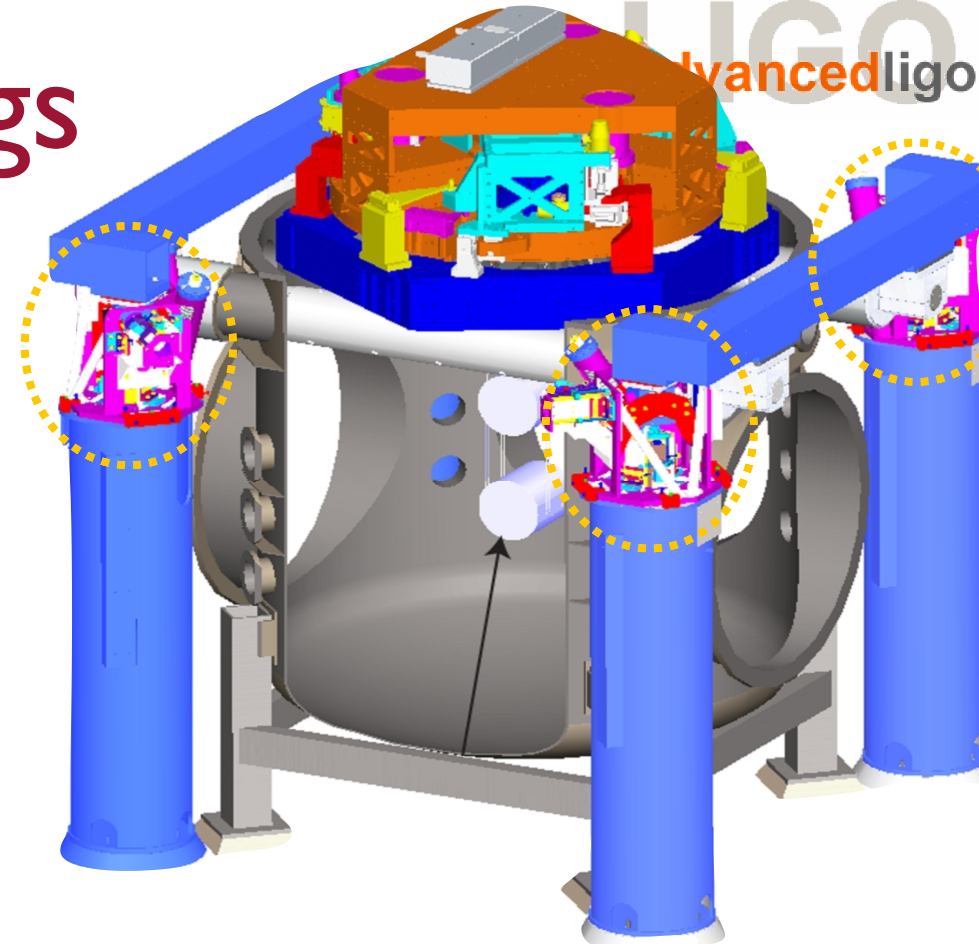




Hydraulic
External
Pre-
Isolator

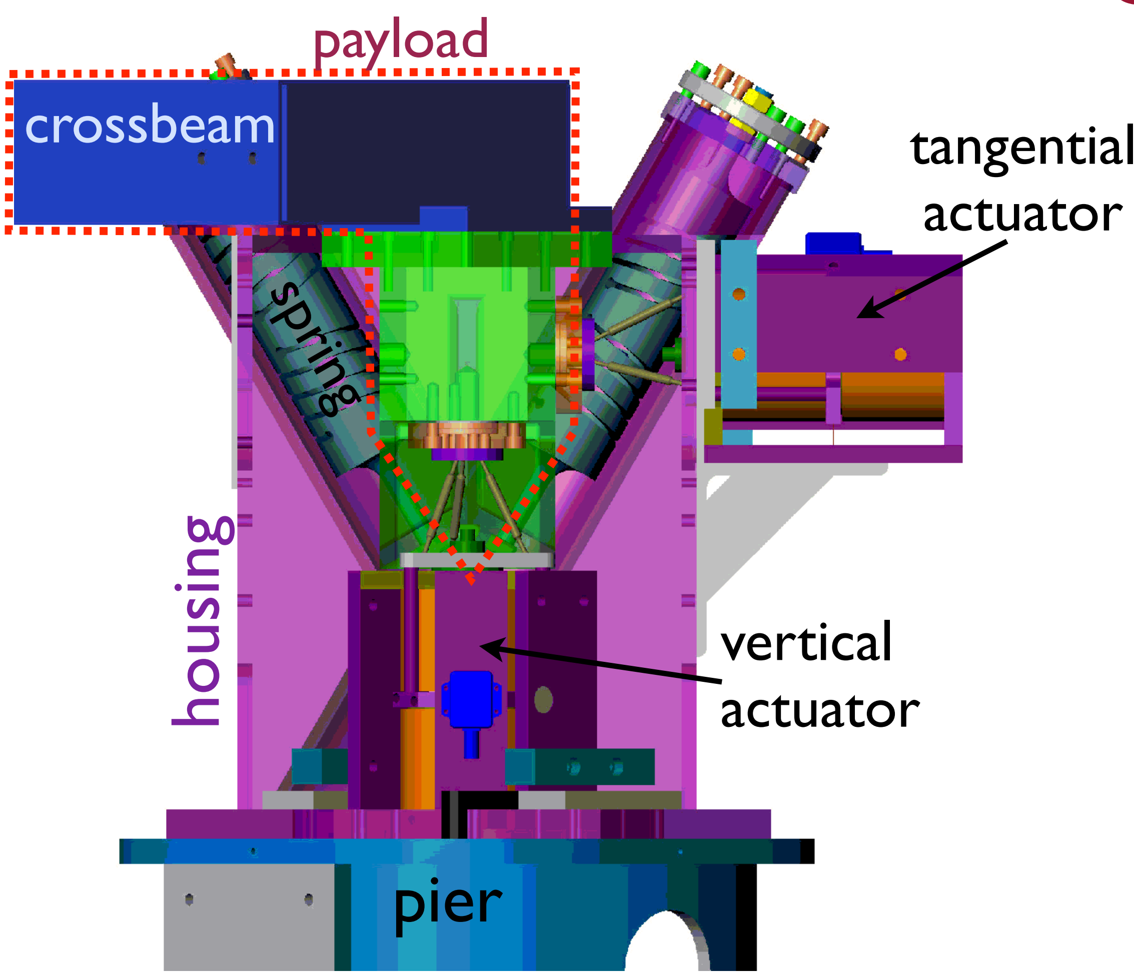
HEPI housings

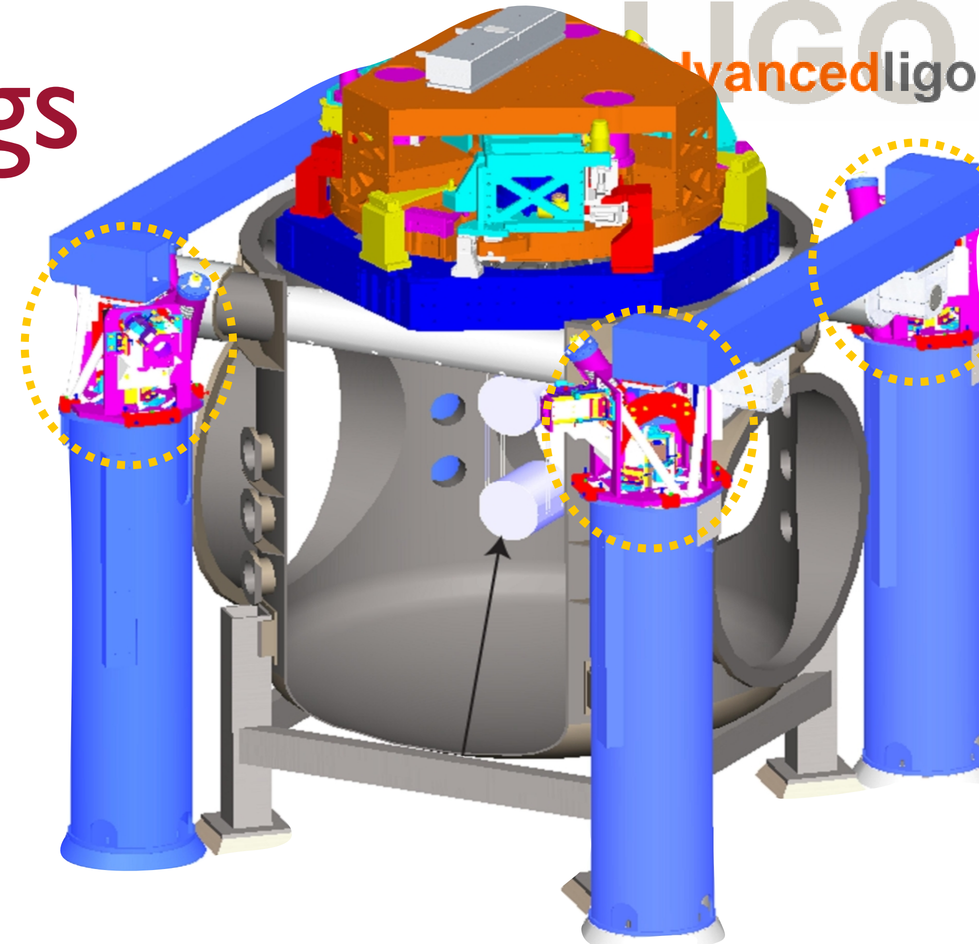




HEPI housing on pier top holds:
- Actuators and sensors for
  vertical and tangential directions
- Offload springs & payload adjustment
- Caging, stops, alignment features...

HEPI housings





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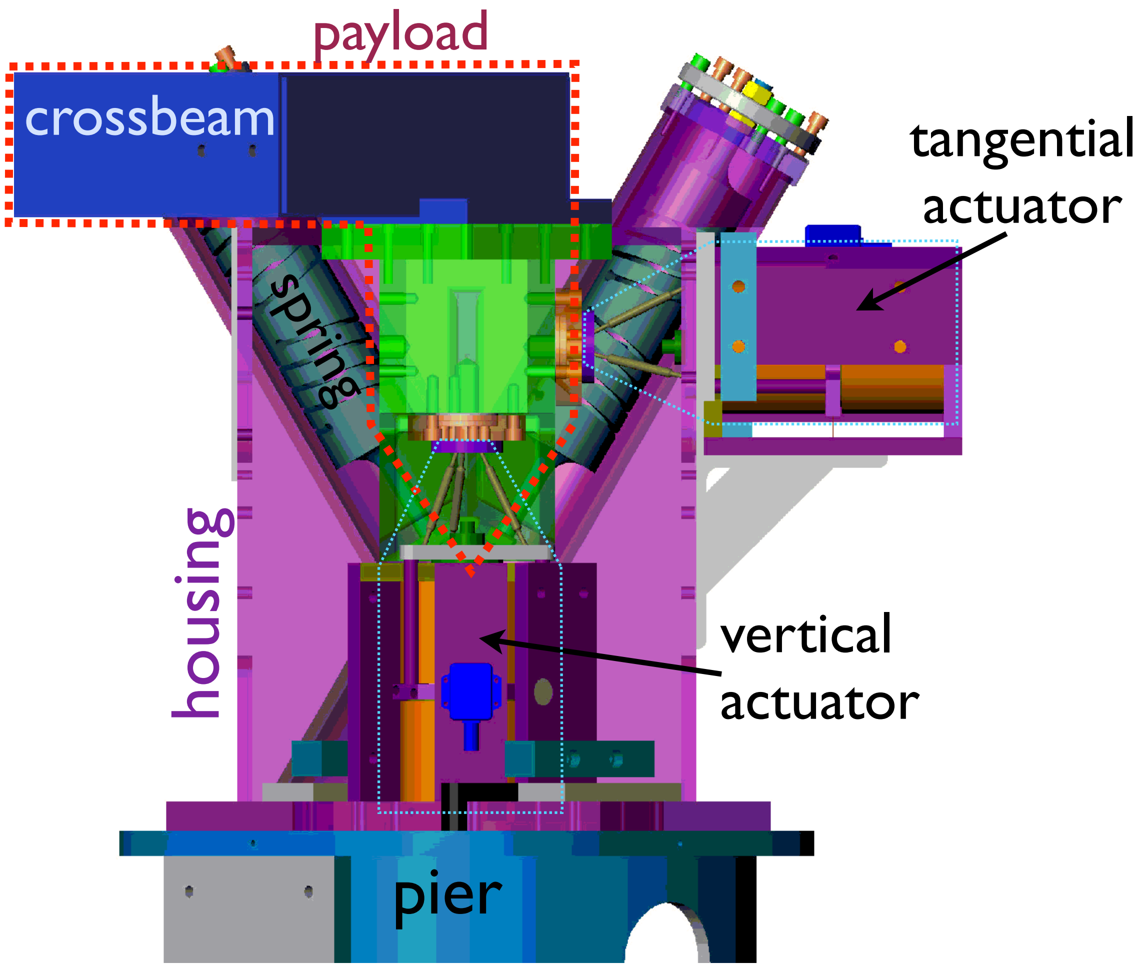

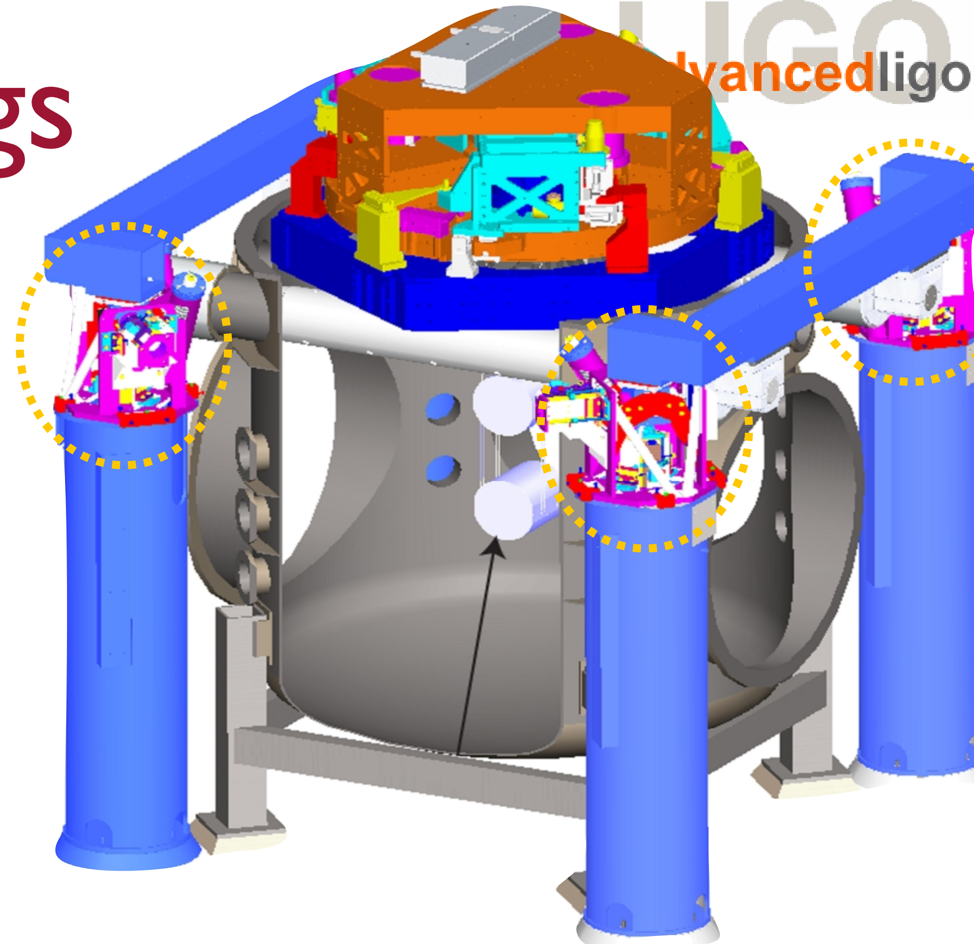

HEPI housing on pier top holds:

- Actuators and sensors for
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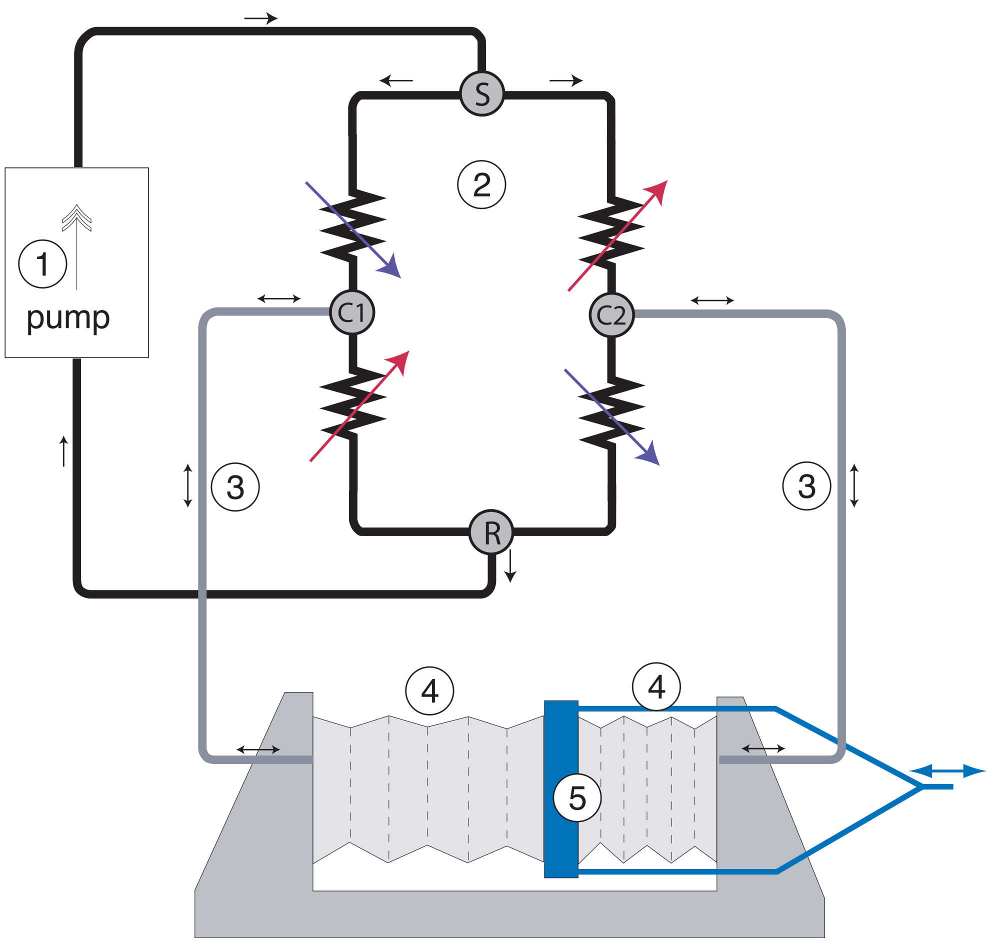
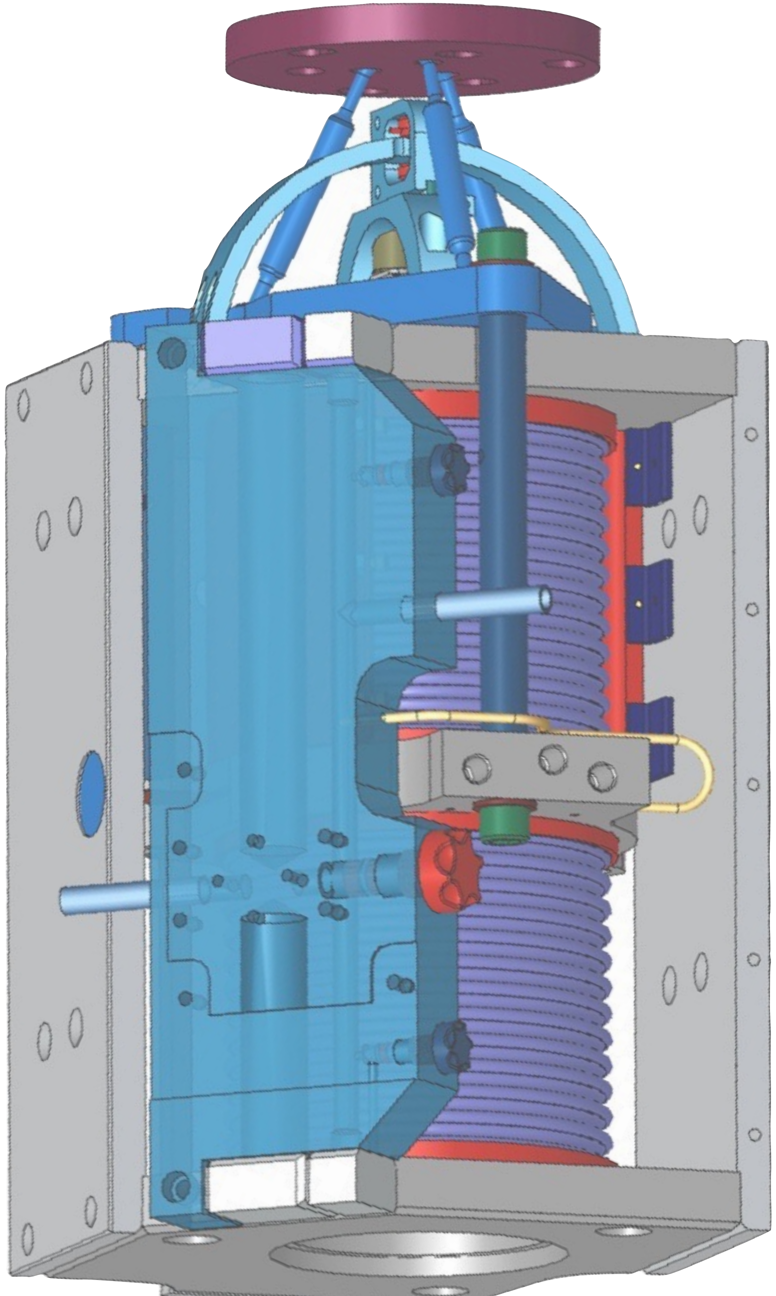
- Offload springs & payload adjustment
- Caging, stops, alignment features...

HEPI Actuator

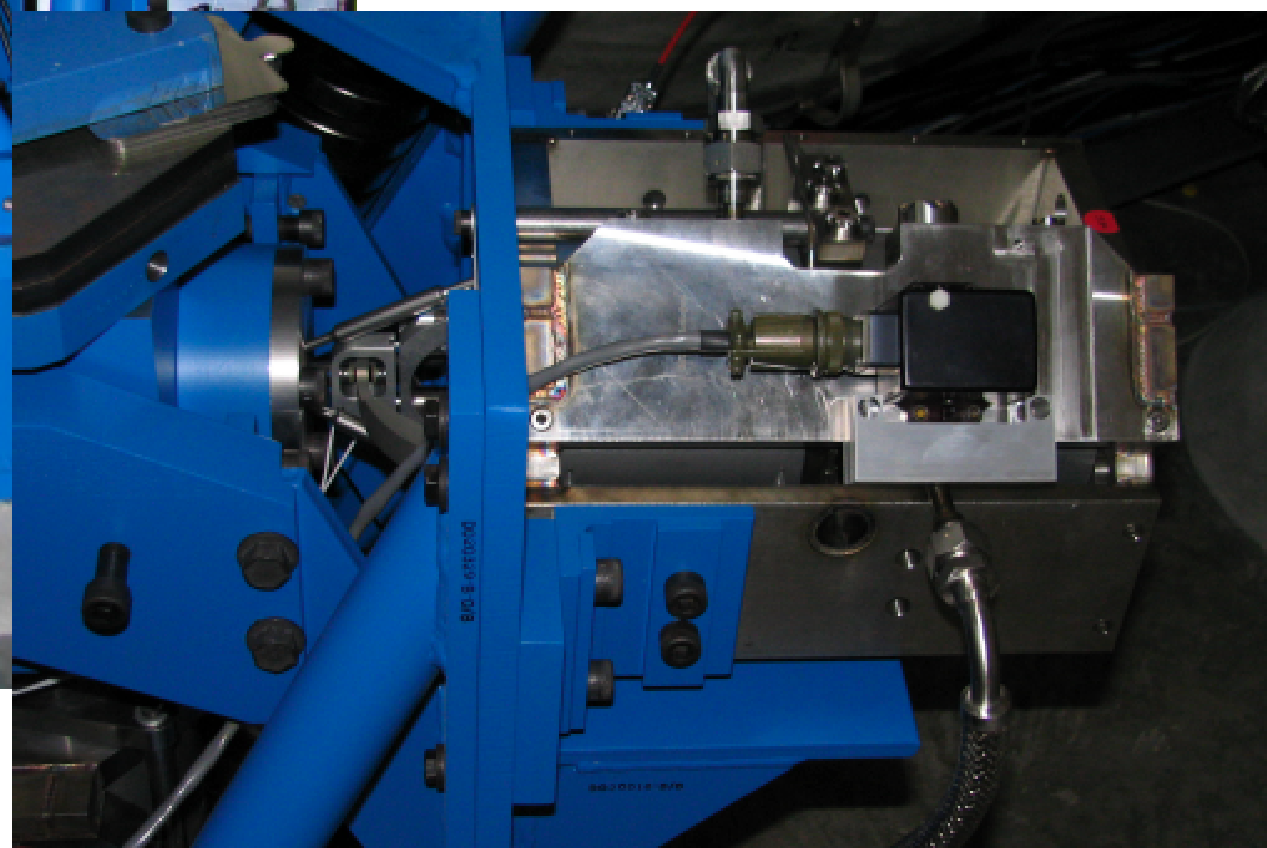
> More range than PZTs (+/- 1 mm)
> More force than voice coils
    (~400 lbs, static offset)
> Quiet (<1 nm/√Hz at 1 Hz)



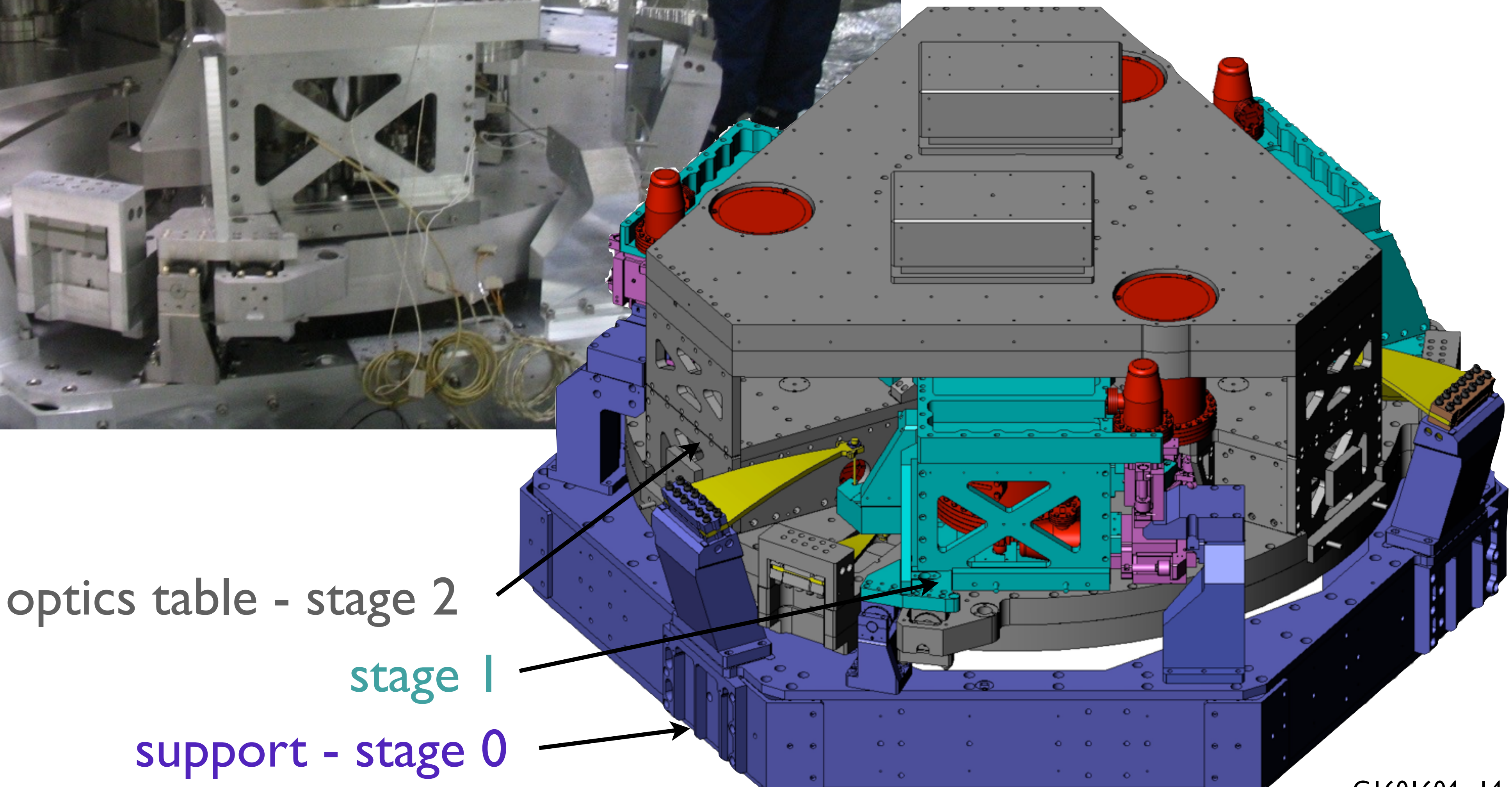


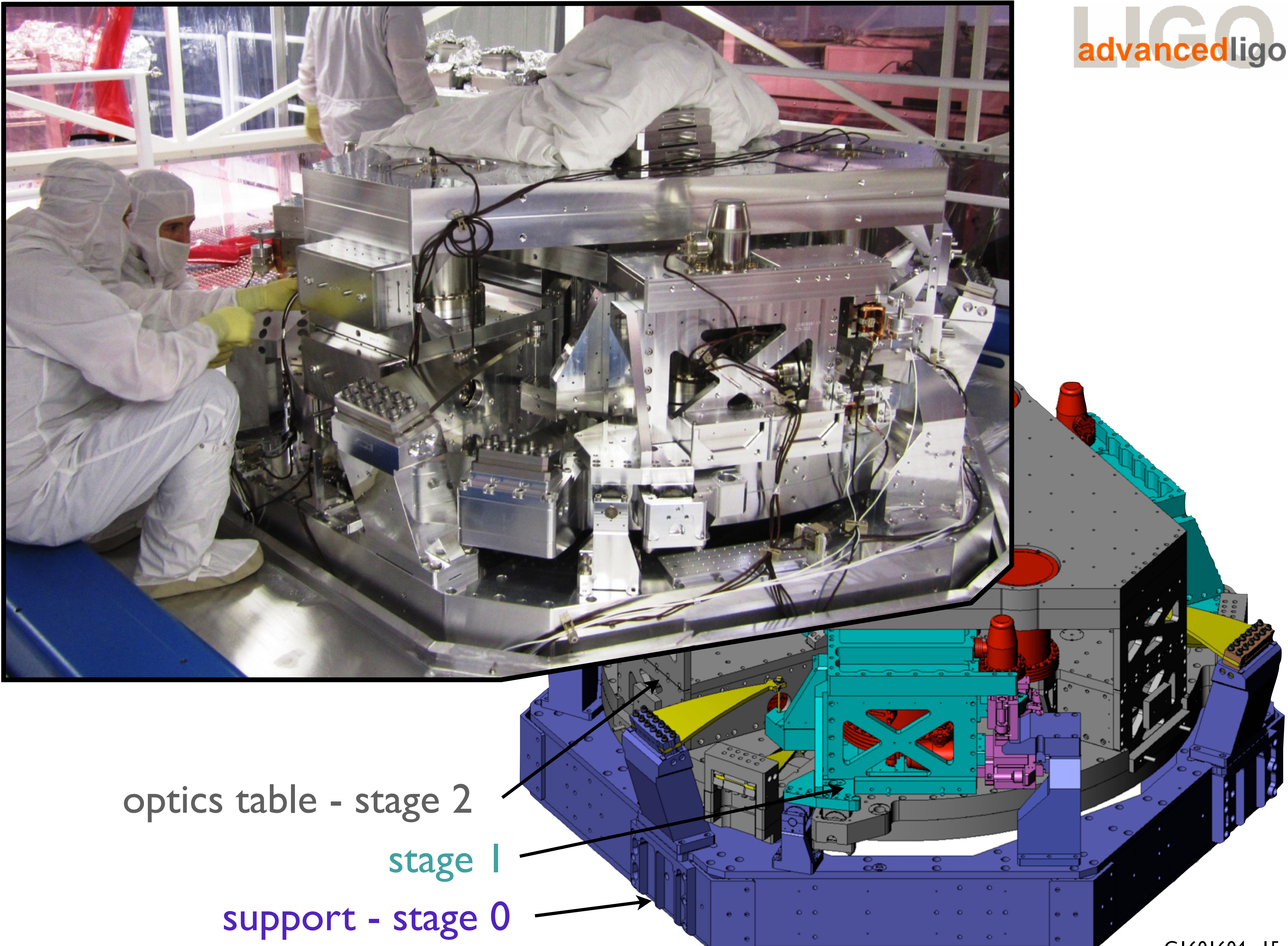
HEPI installation

em



BSC-ISI Optical Table





optics table - stage 2
stage 1
support - stage 0

HAM Design

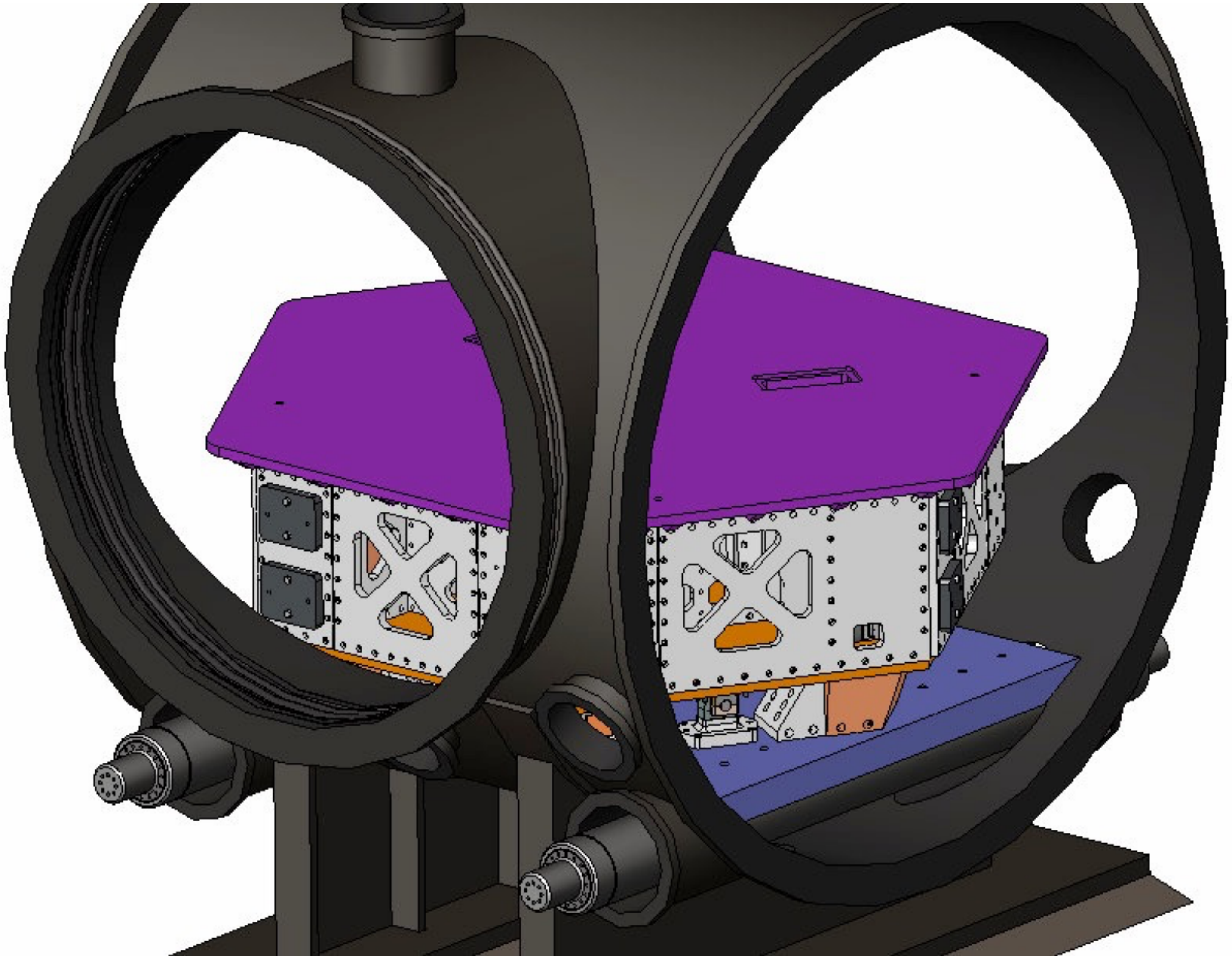
- Bolted aluminum structure
  Suspended by 3 blade
  springs & "wires"

- mass:
  stage 1 ~ 1500 kg
  plus 510 kg of payload

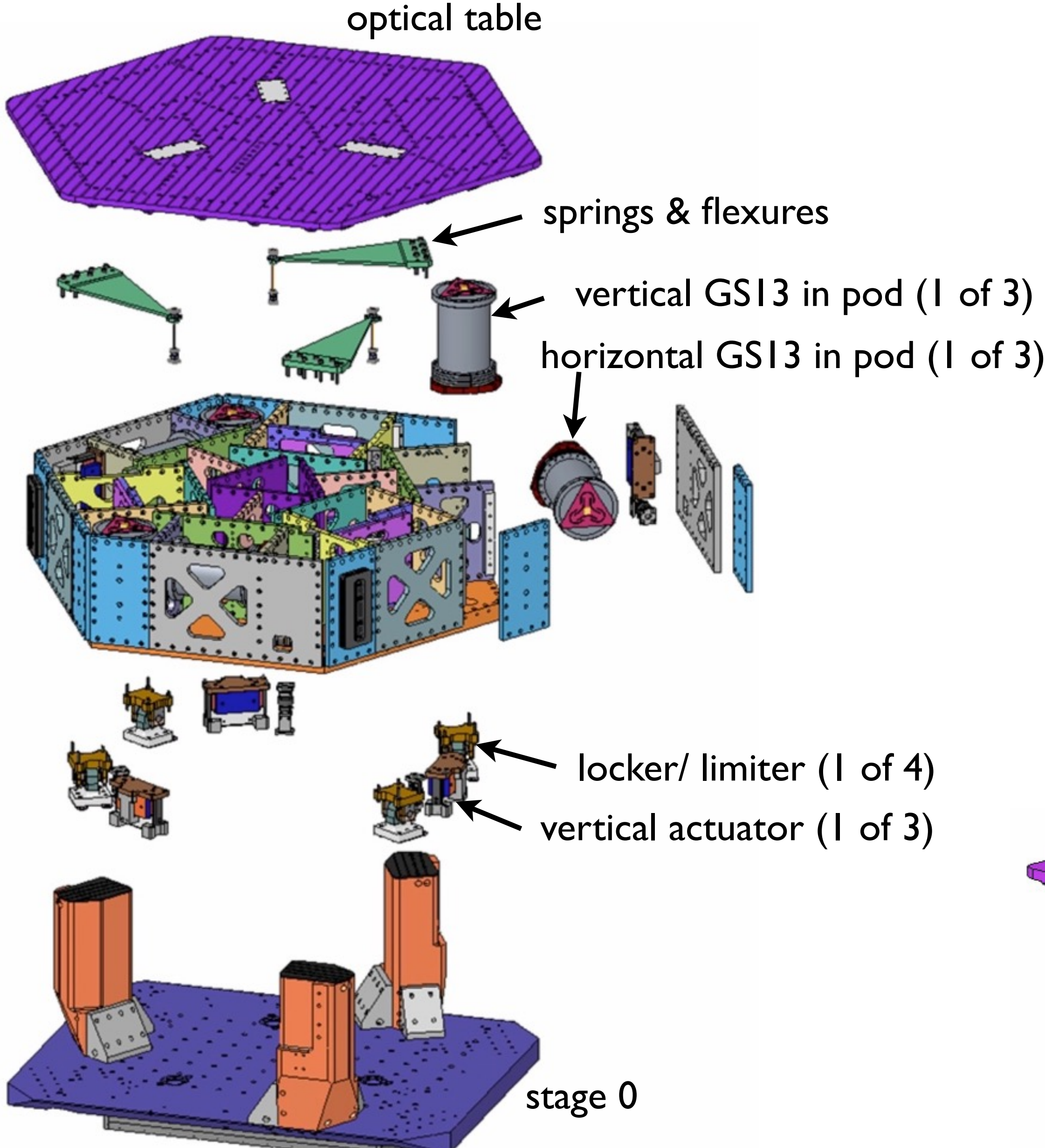
- Natural freq's
  x & y: 1.35 Hz
  z: 1.8 Hz
  tip/tilt: 1.07 Hz
  yaw: 0.9 Hz

- first bending mode:
  > 250 Hz

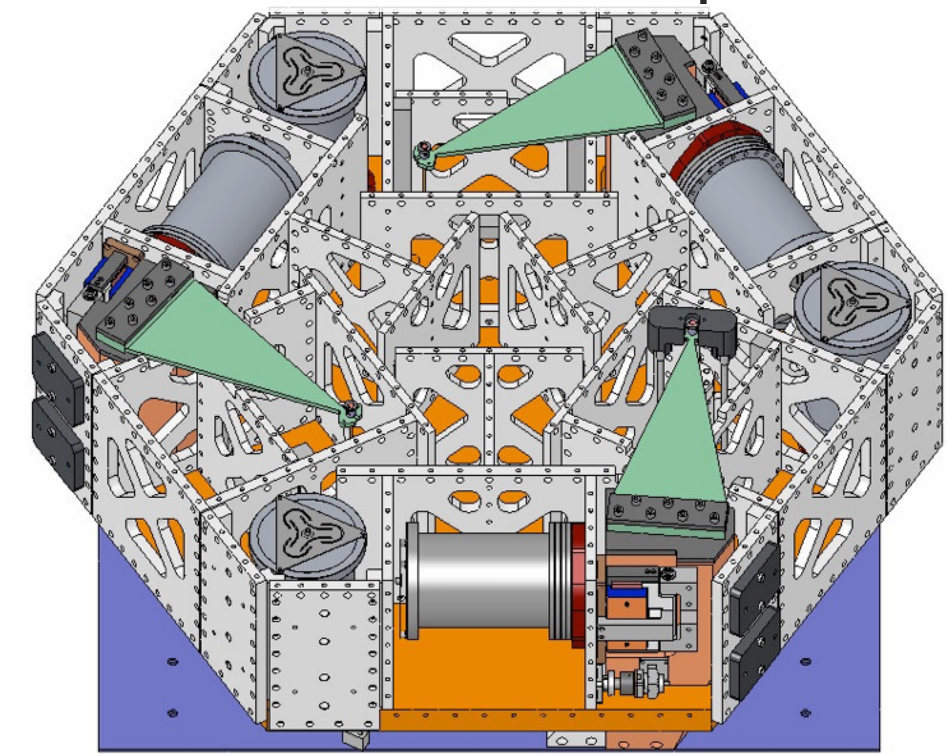
- Servos with
  unity gain around 25 Hz



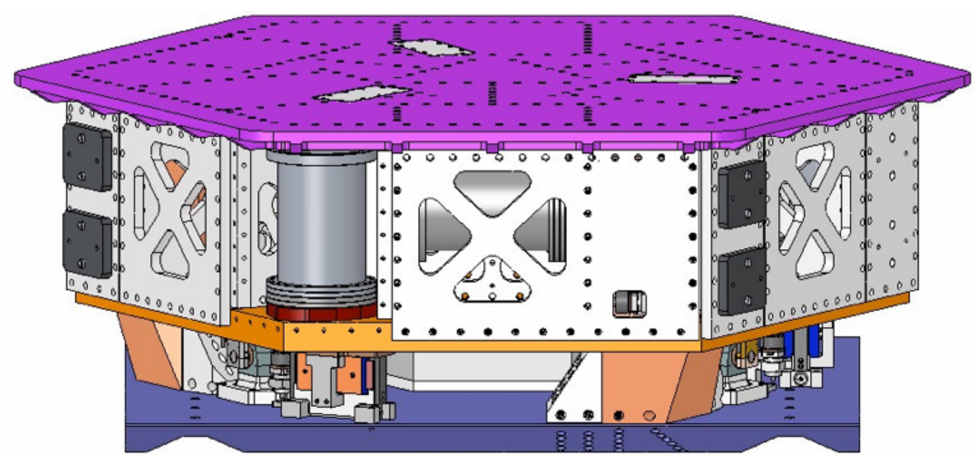
HAM Design



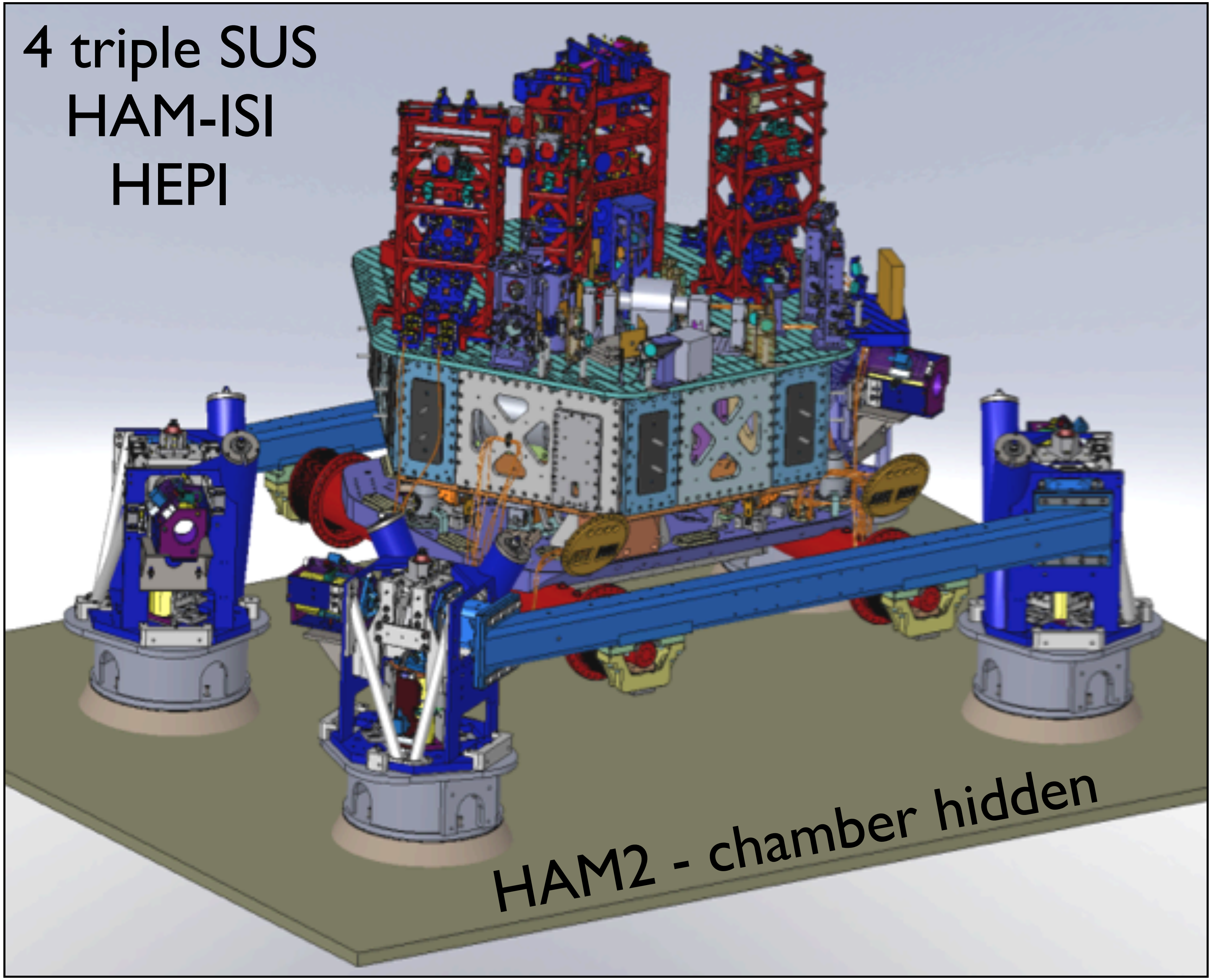
springs and sensors under the table top

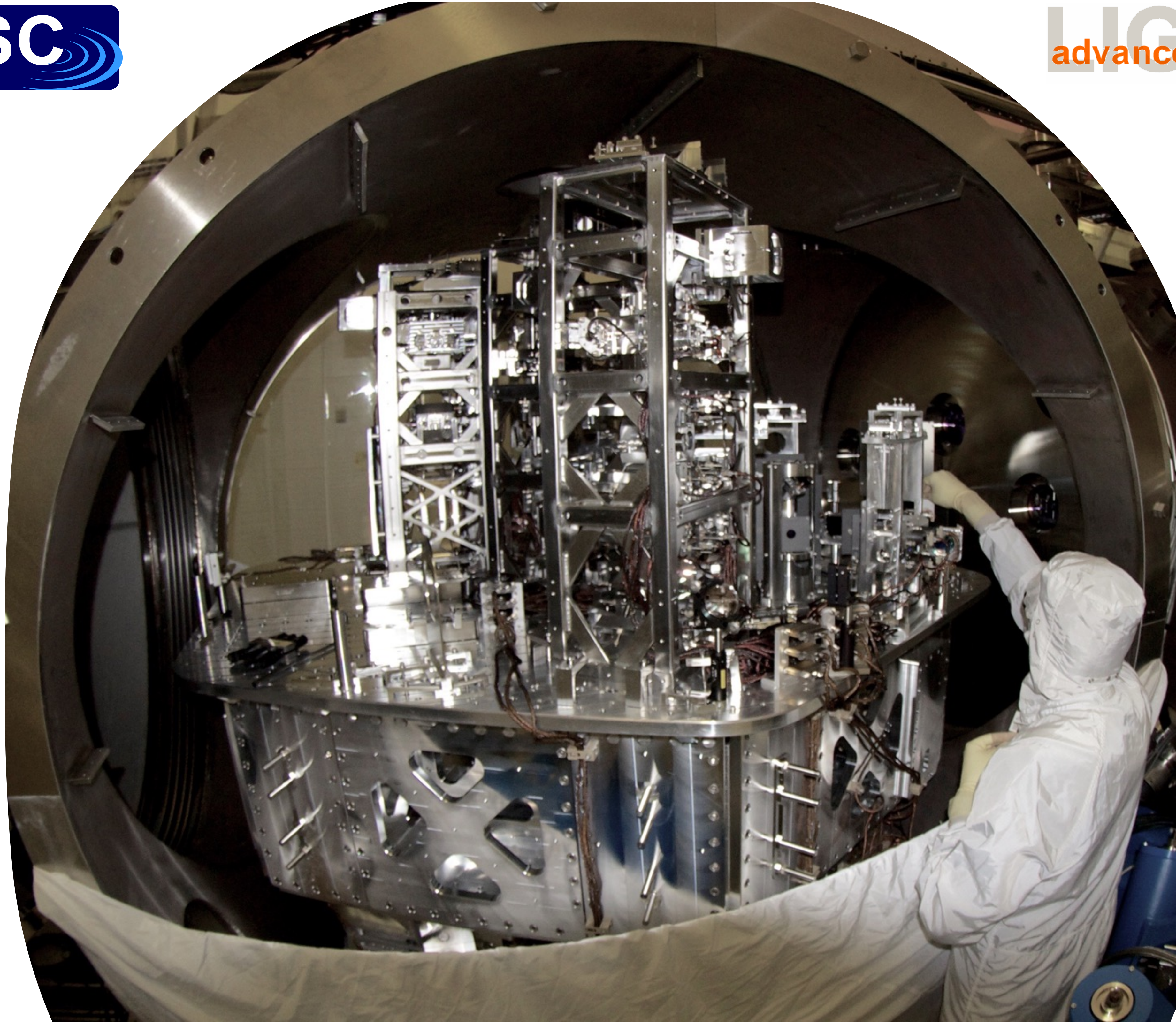


access to a vertical sensor

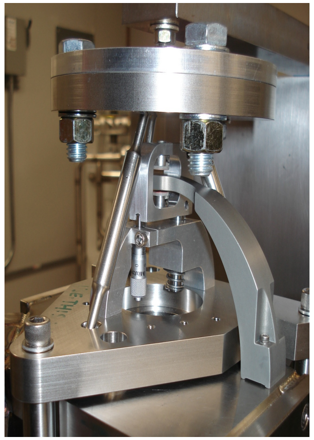


Overall Isolation of triples





SEI sensors and their noise



IPS

Kaman's Inductive Position Sensors

Used On: HEPIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Reasonable Noise, Long Range

DC

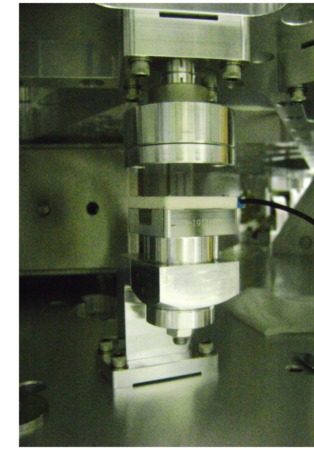
CPS

MicroSense's Capacitive Displacement Sensors

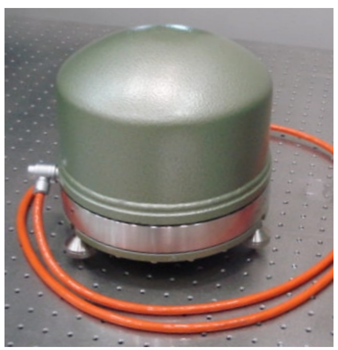
Used On: HAM-ISIs and BSC-ISIs

Used For: ≤ 0.5 Hz Control, Static Alignment

Used 'cause: Good Noise, UHV compatible



10 mHz



STS2

Strekheisen's STS-2

Used On: HEPIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Best in the 'Biz below 1 Hz, Triaxial

T240

Nanometric's Trillium 240

Used On: BSC-ISIs

Used For: 0.01 ≤ f ≤ 1Hz Control

Used 'cause: Like STS-2s, Triaxial, no locking mechasim -> podded

1 Hz

GS13

GeoTech's GS-13

Used On: HAM-ISIs and BSC-ISIs

Used For: ≥ 0.5 Hz Control

Used 'cause: awesome noise above 1Hz,

no locking mechanism -> podded

L4C

Sercel's L4-C

Used On: All Systems

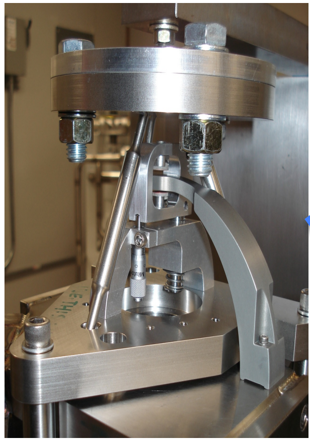
Used For: ≥ 0.5 Hz Control

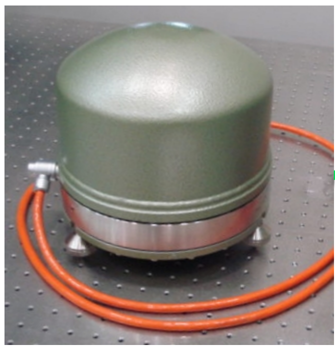
Used 'cause: Good Noise, Cheap, no locking mechanism -> podded

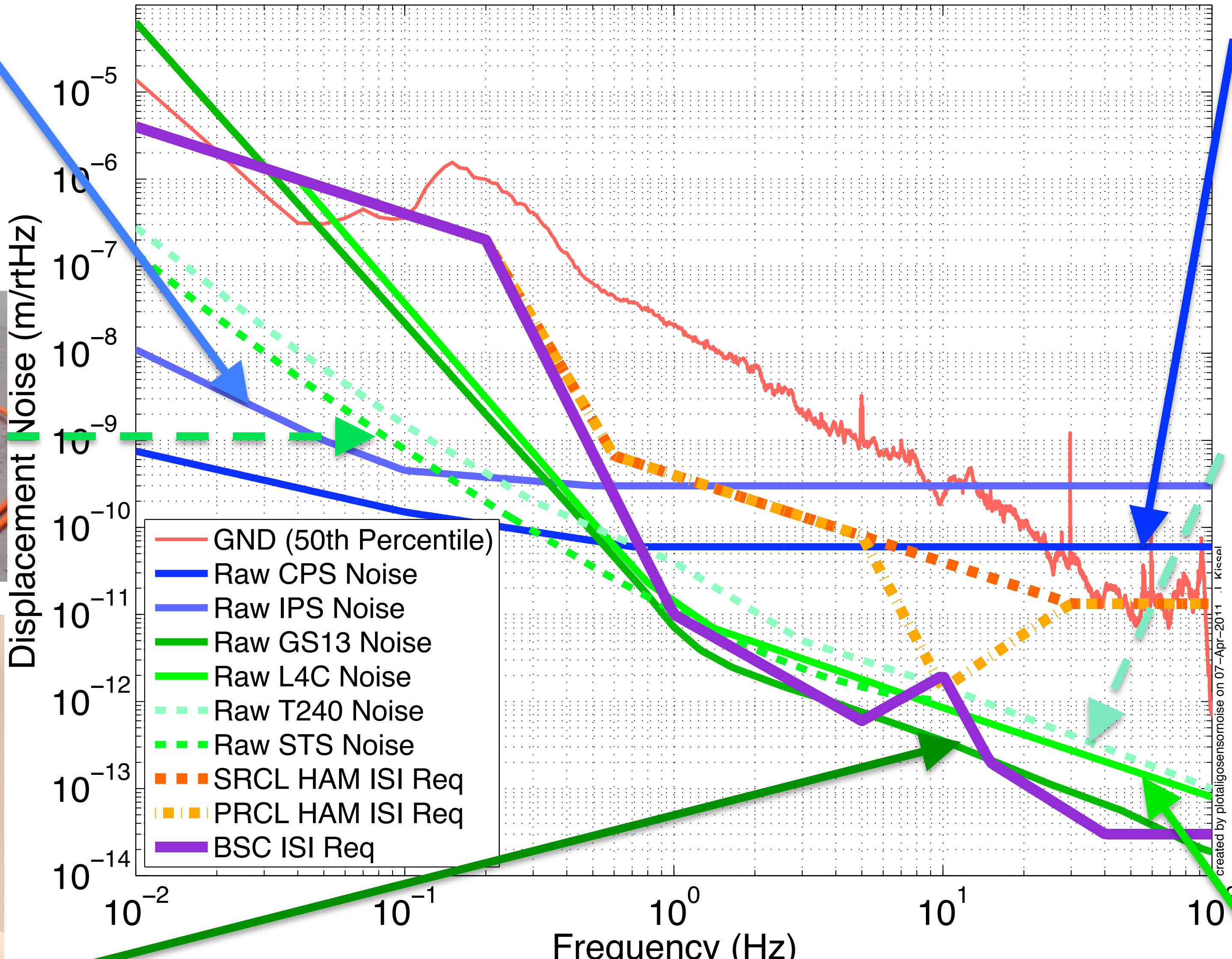
800 Hz

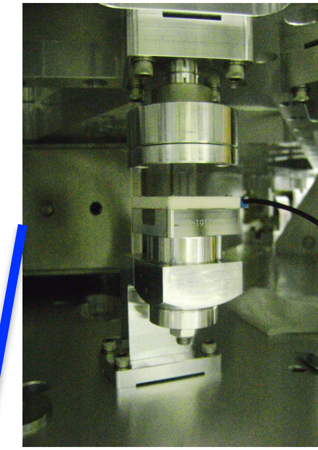
"High" Frequency

SEI sensors and their noise







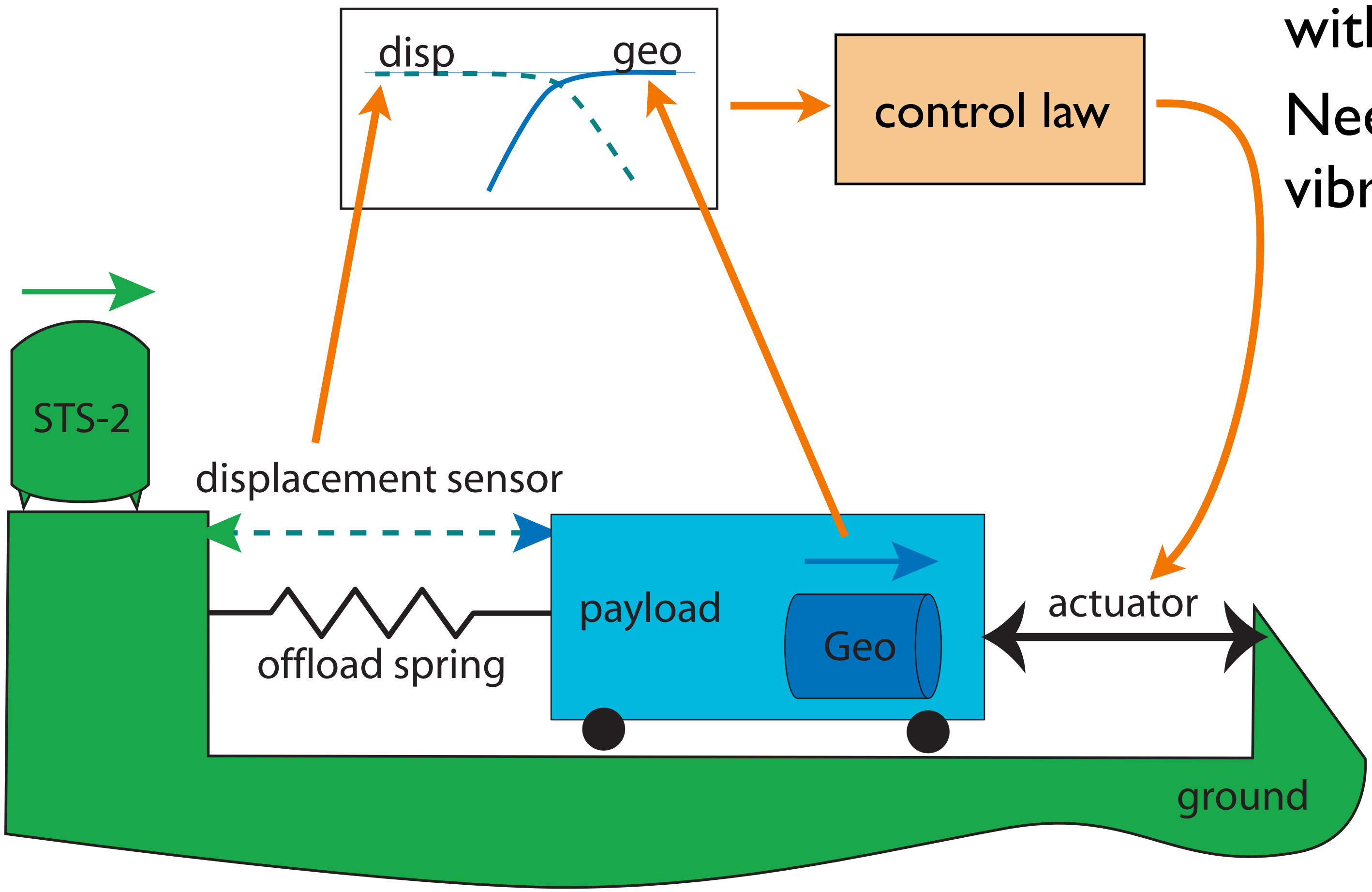


J. Kissel G1100431

Controls

- All DOFs are controlled
  - Choose X, Y, Z, rX, rY, and rZ as basis
  - Aligned with gravity (tilt)
  - Aligned with IFO basis
- Each DOF is pretty simple
  - Blended loops control position at low-frequency isolation at high frequencies, unity gain freq of ~ 30-40 Hz
  - Use feed-forward, feedback, sensor correction
  - note that much 10 Hz performance is passive
- Worst thing at low frequencies is tilt-horizontal coupling
- Biggest complexity is the number of controls
- Biggest lure for the young is to reinvent the control scheme

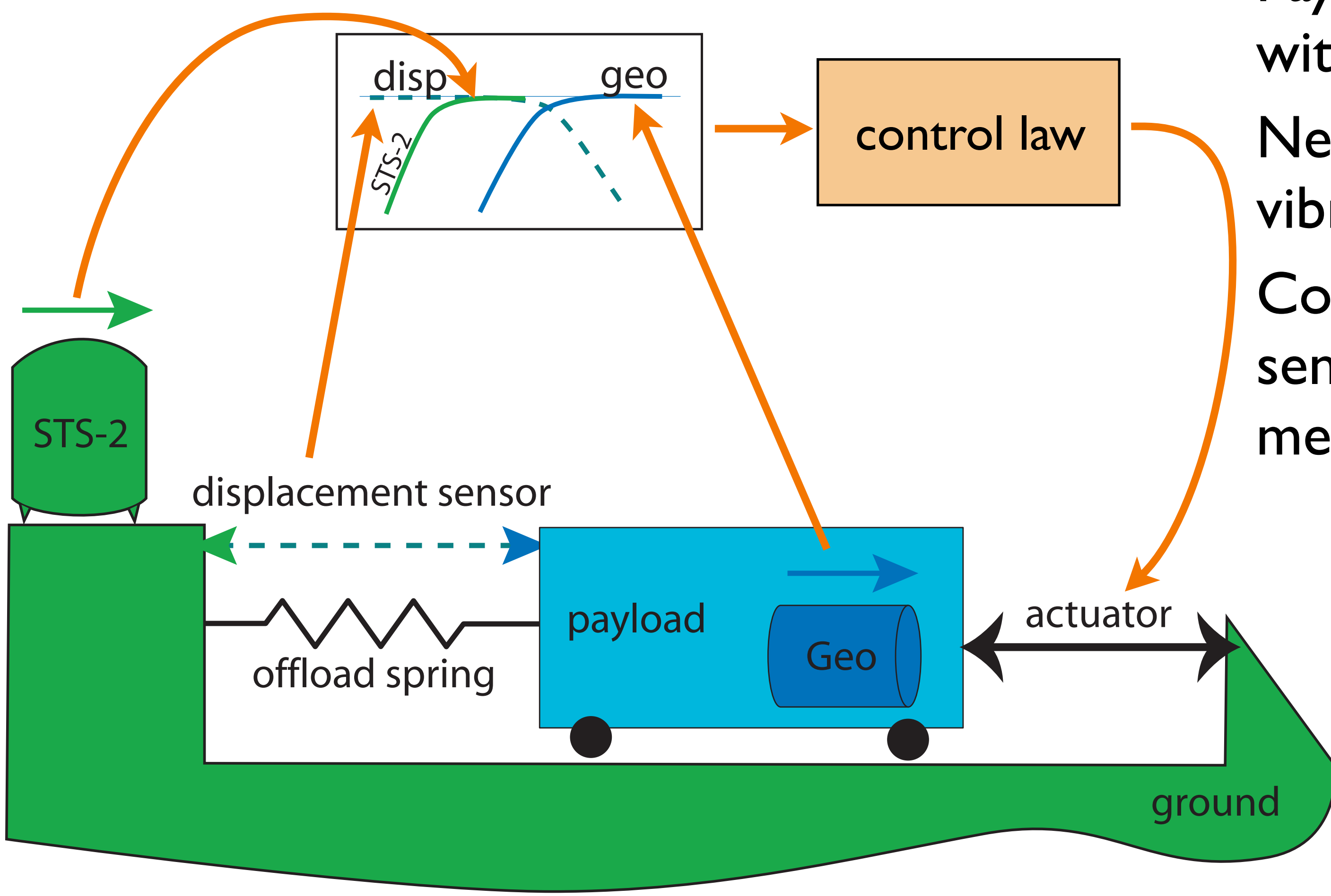
Control philosophy



Payload attached to ground with compliance (1-2 Hz)

Need both alignment and vibration control.

Control philosophy

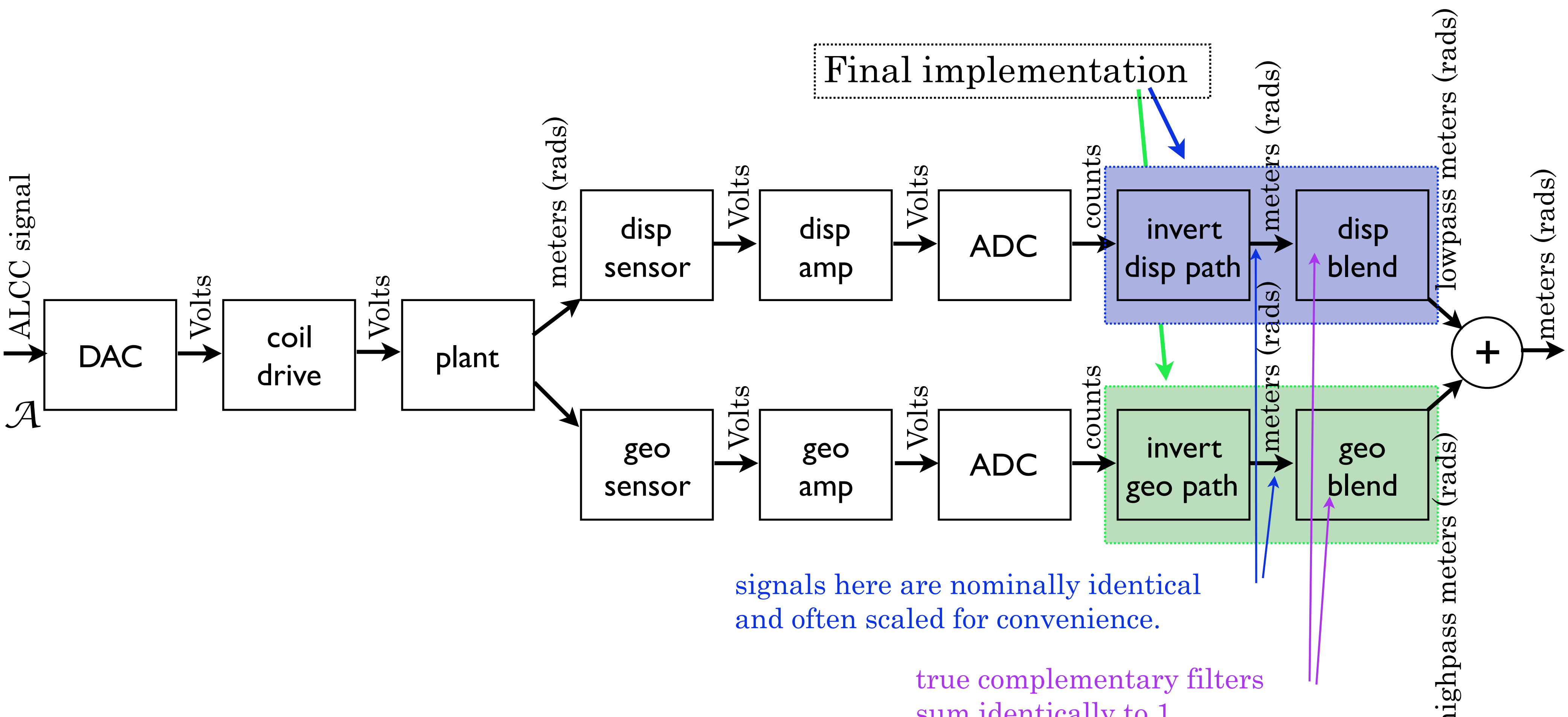


Payload attached to ground with compliance (1-2 Hz)

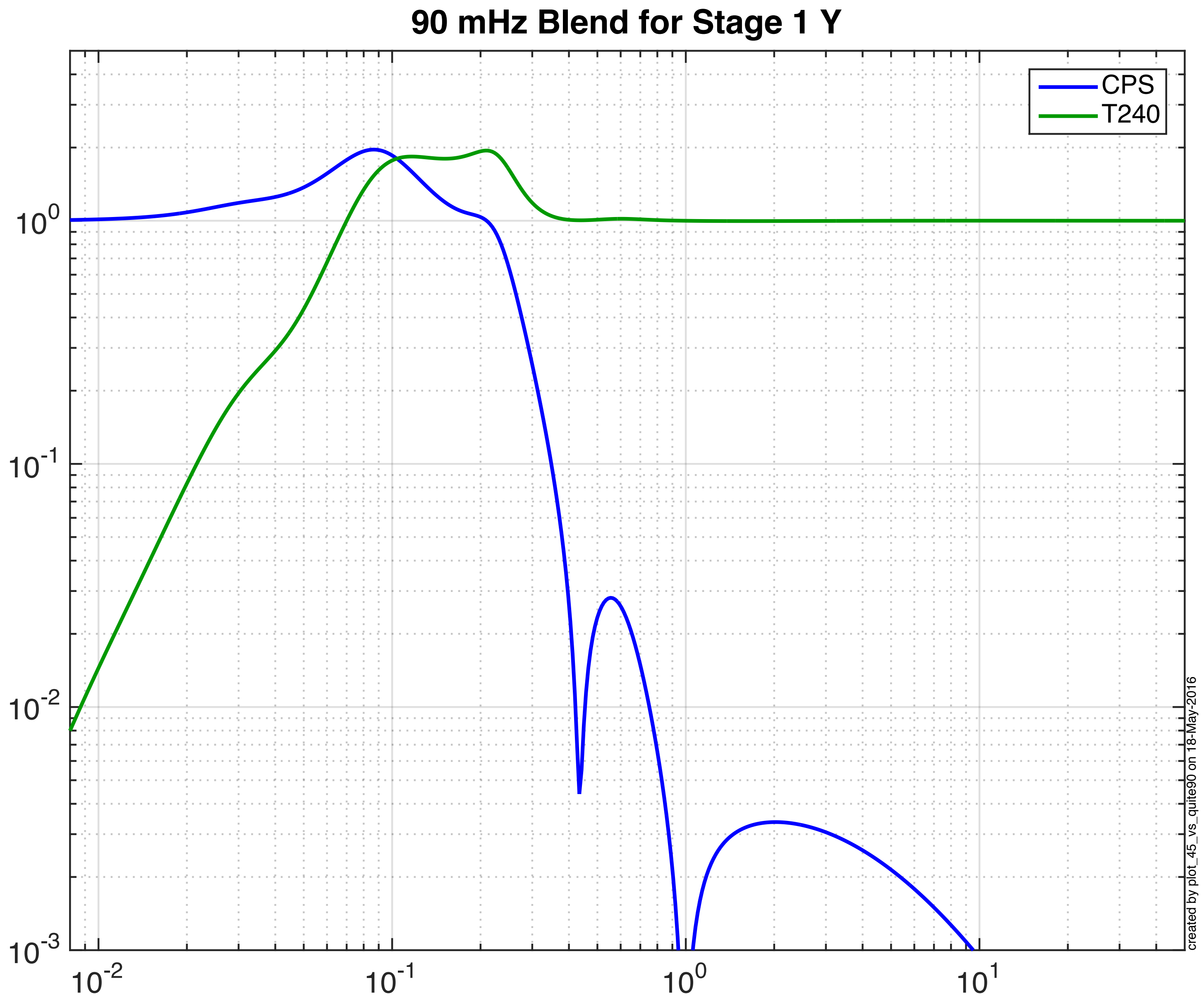
Need both alignment and vibration control.

Correct displacement sensor with ground motion measurements.

Sensor Blending

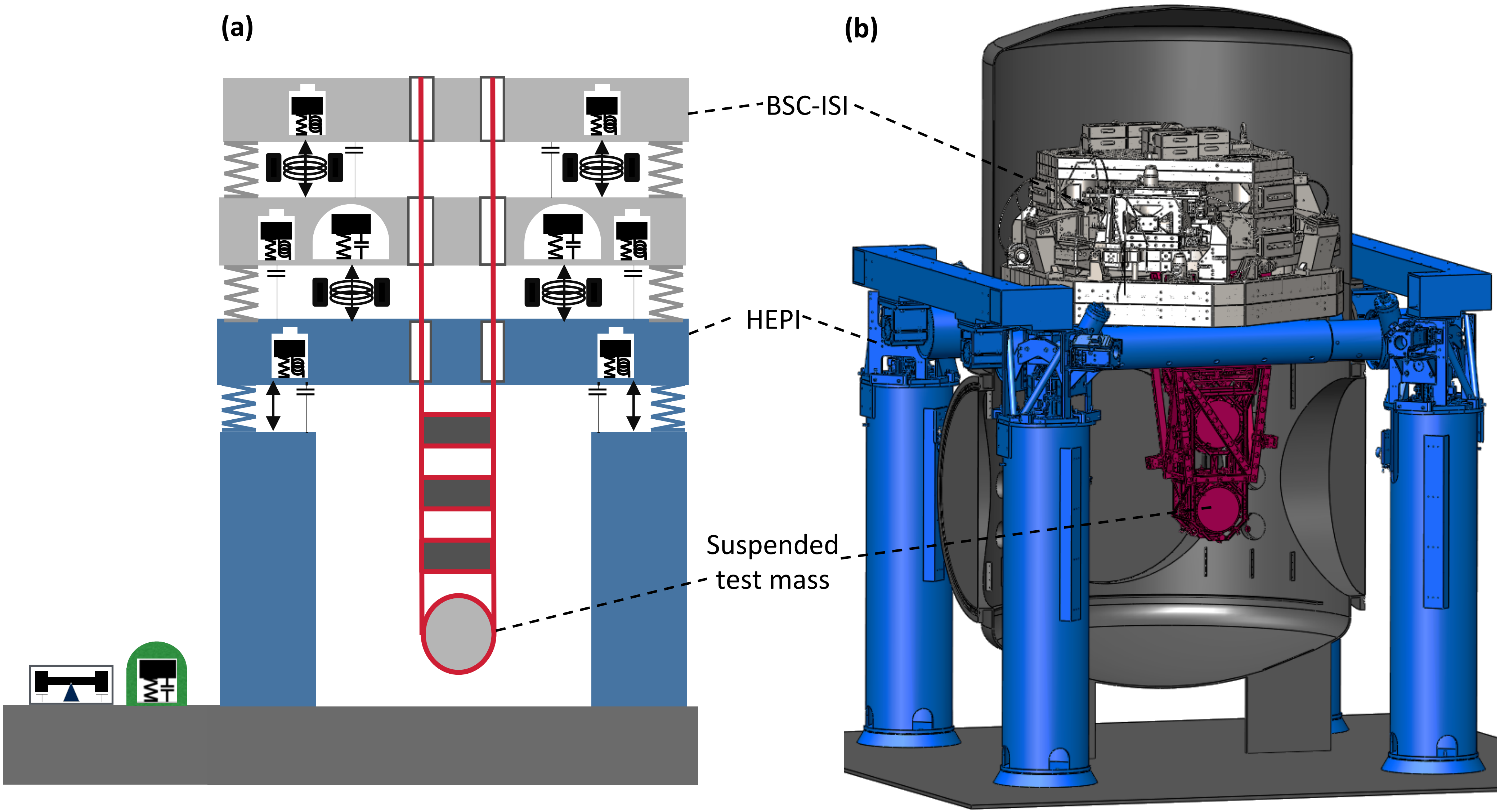


Blending sensors



Sensors for Control

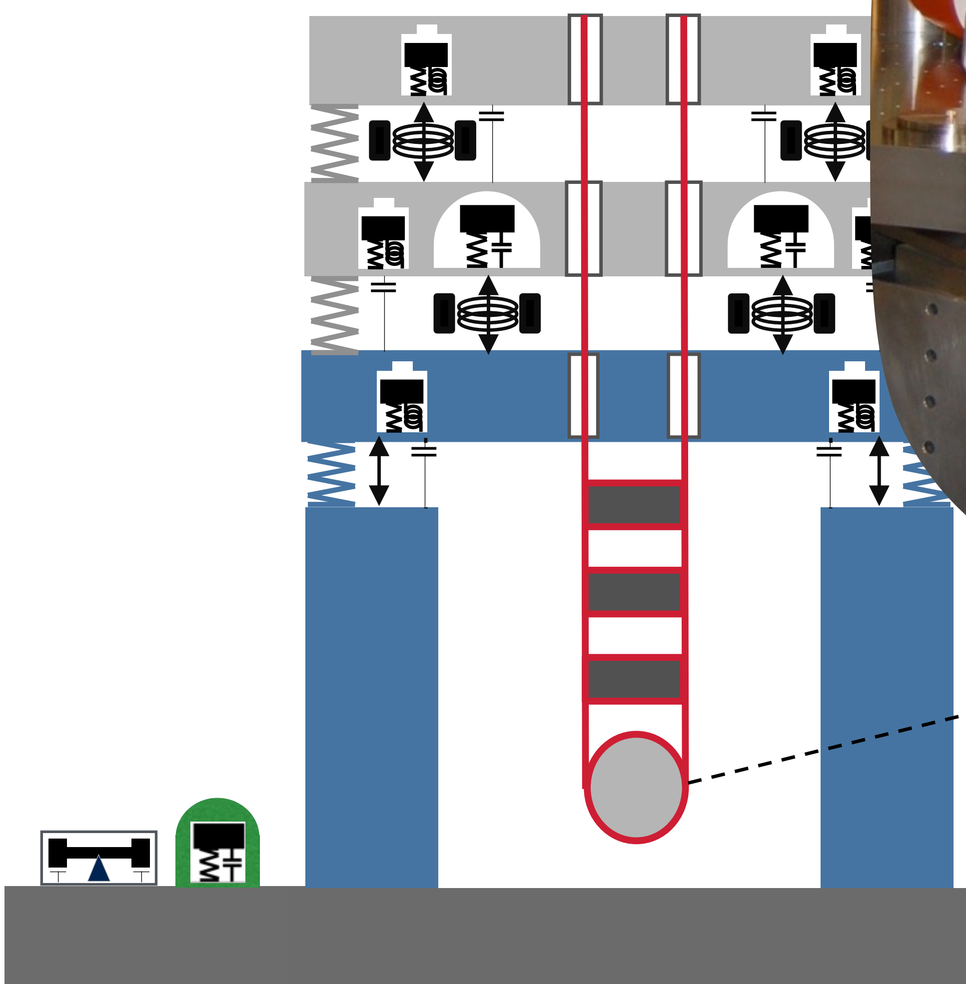
Use active and passive techniques
to get good performance

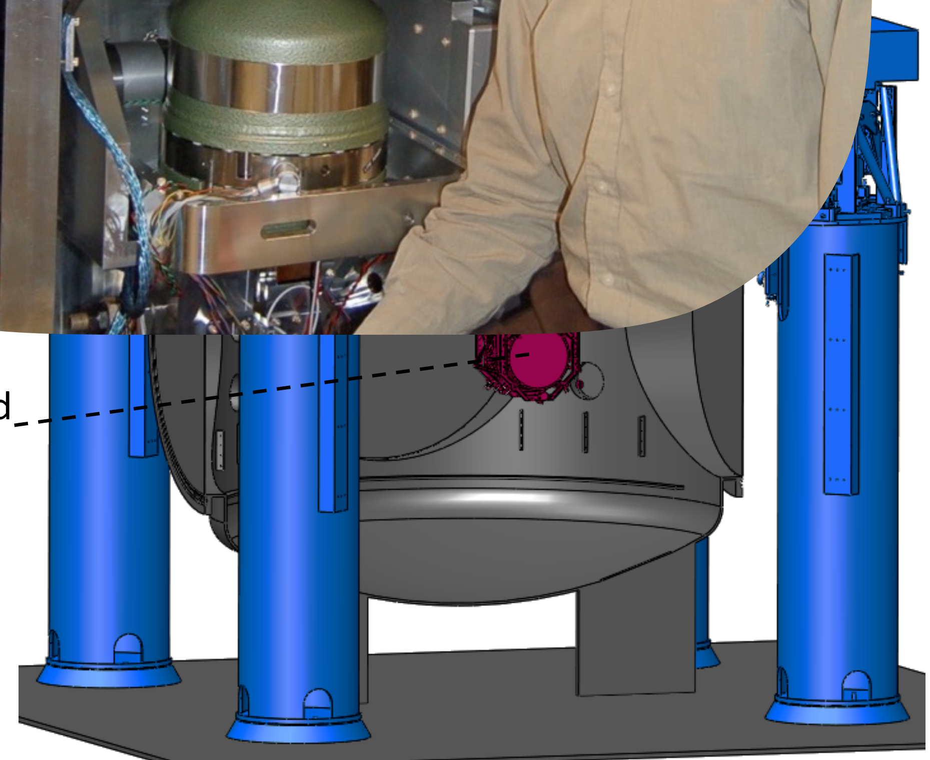


Sensors for Control

Use active and passive techniques to get good performance

(a)

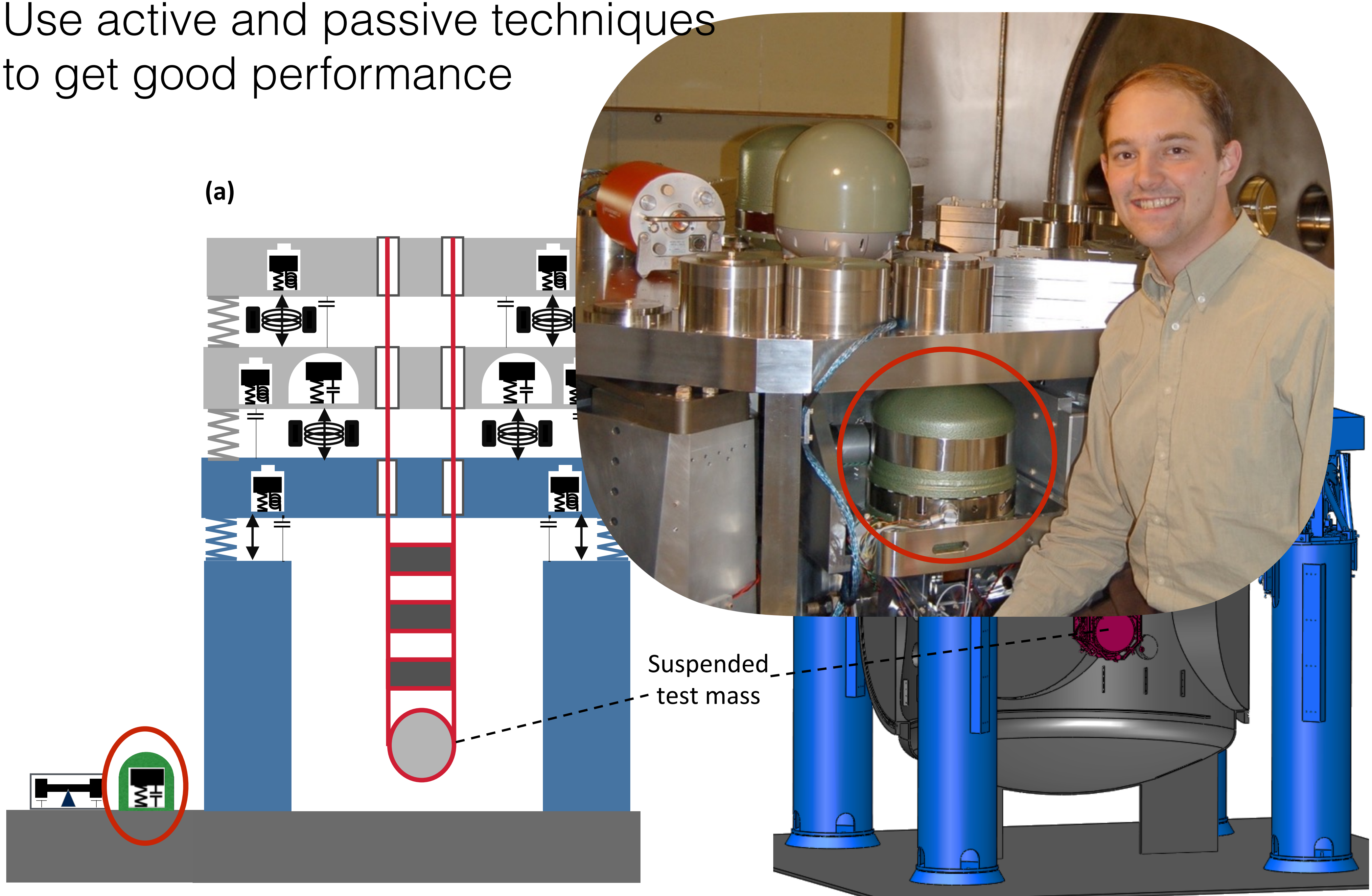




Suspended test mass

Sensors for Control

Use active and passive techniques to get good performance



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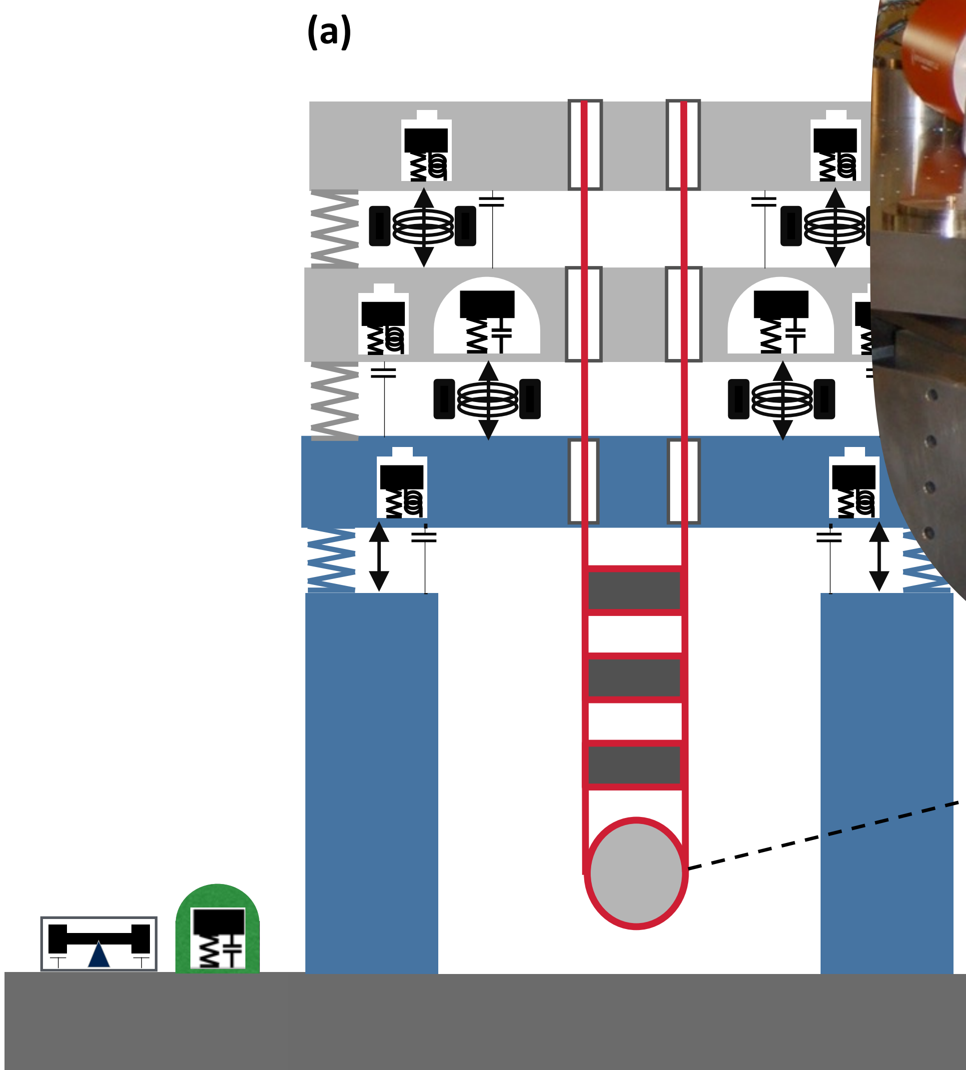

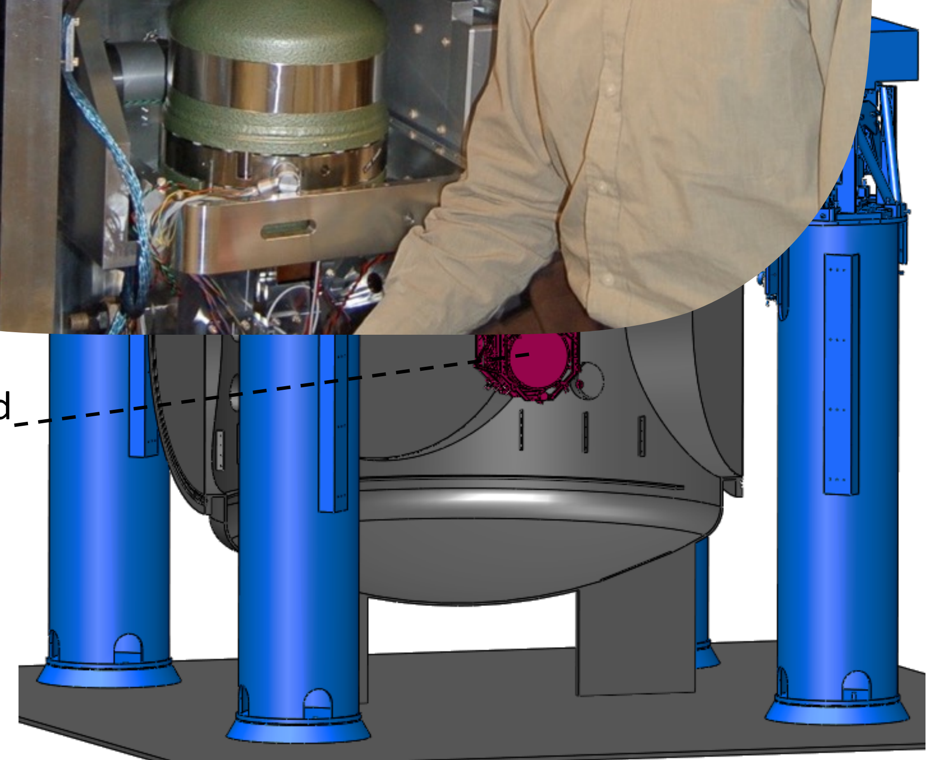

Sensors for Control

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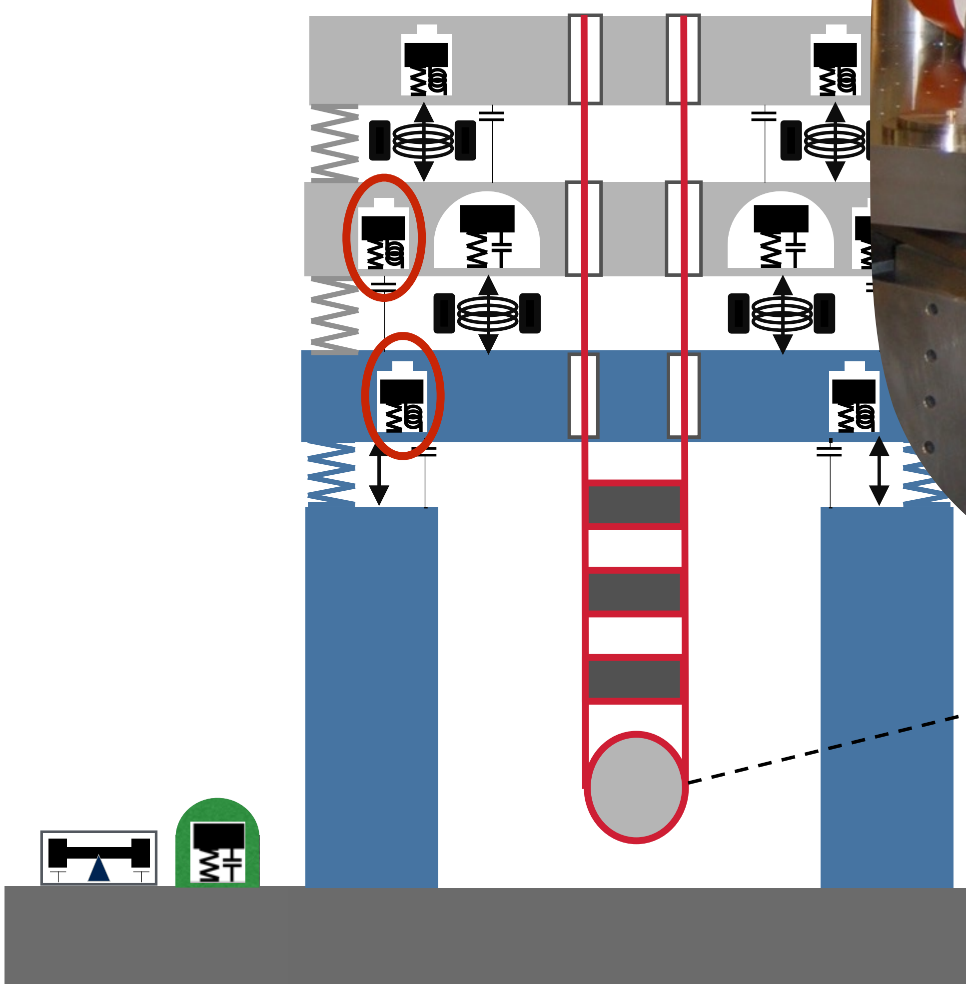
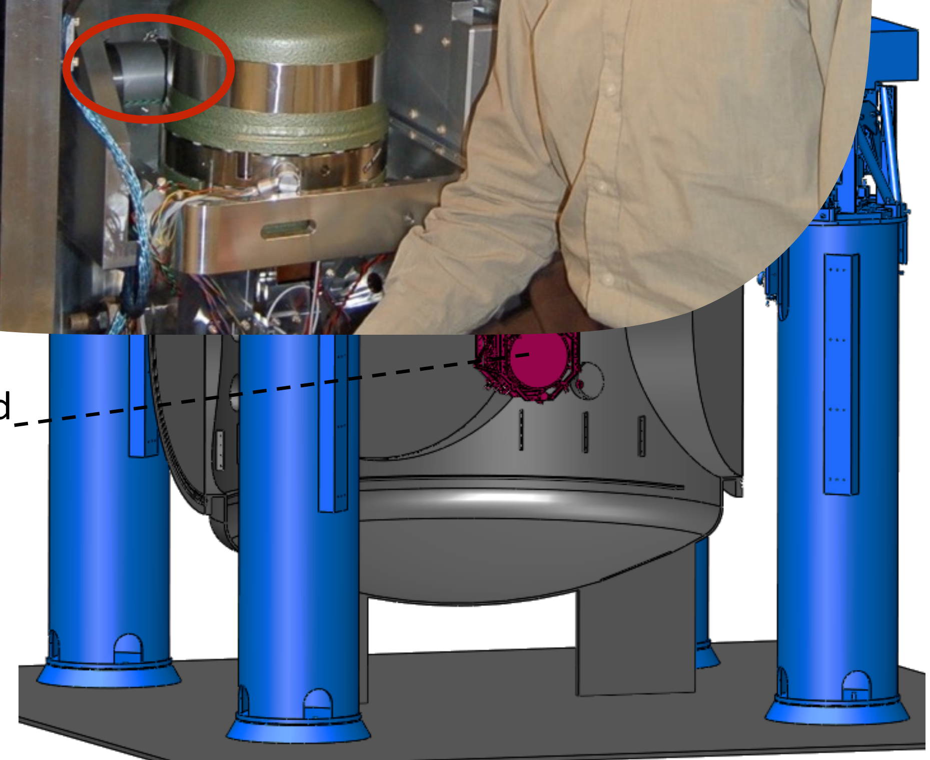
(a)





Sensors for Control

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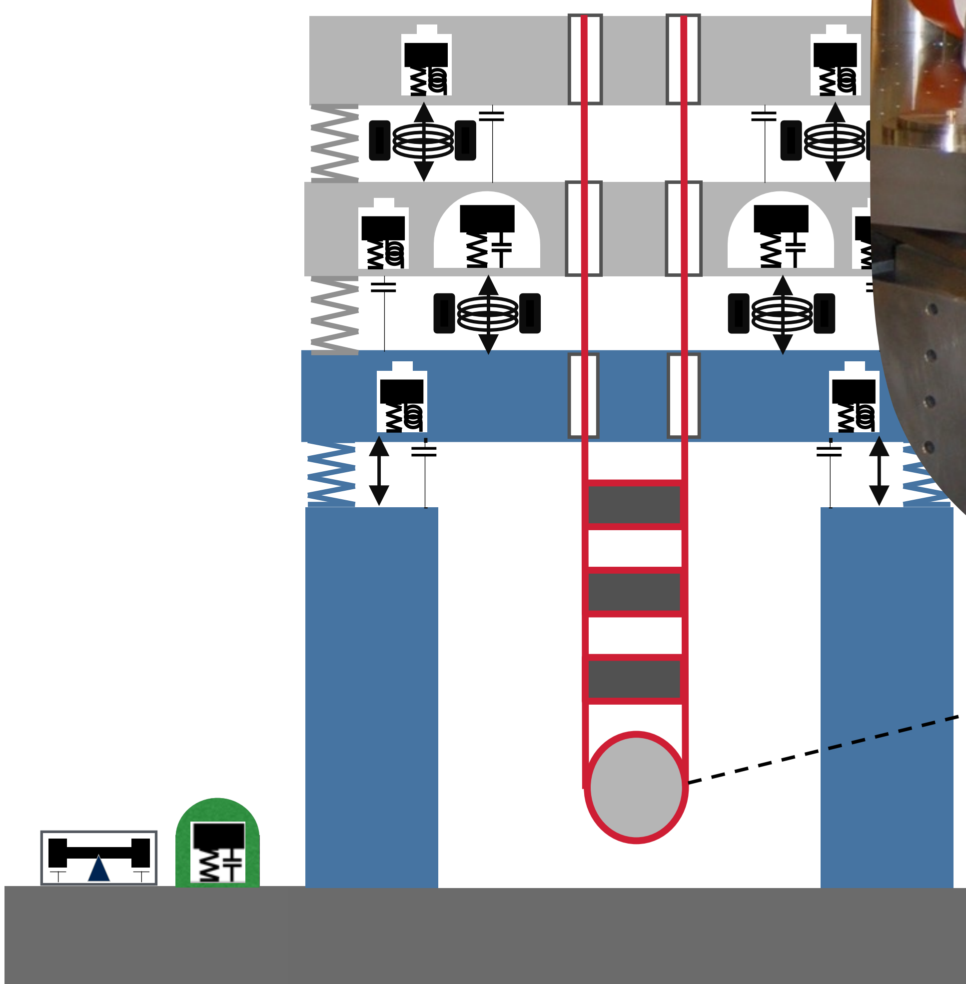

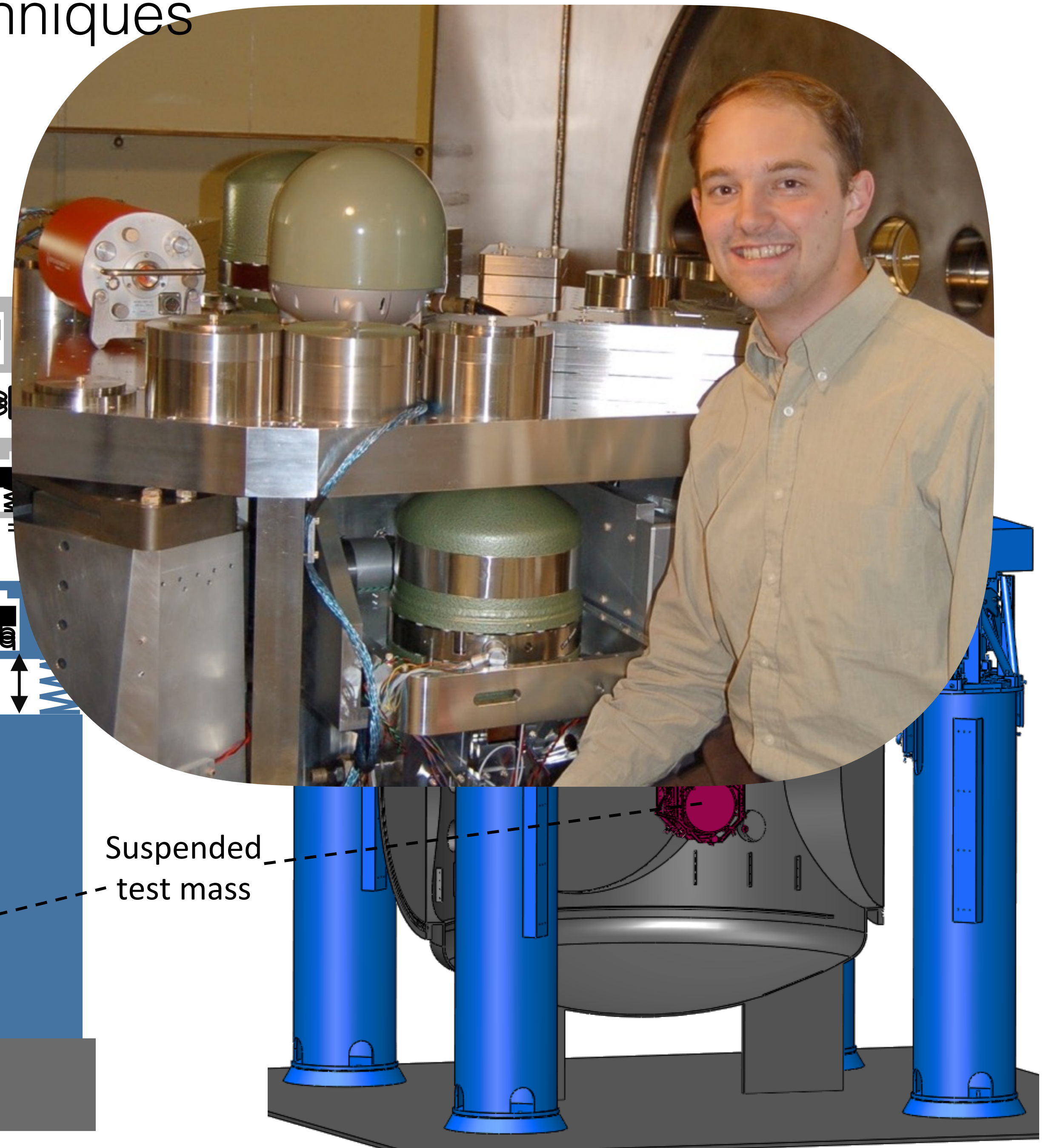

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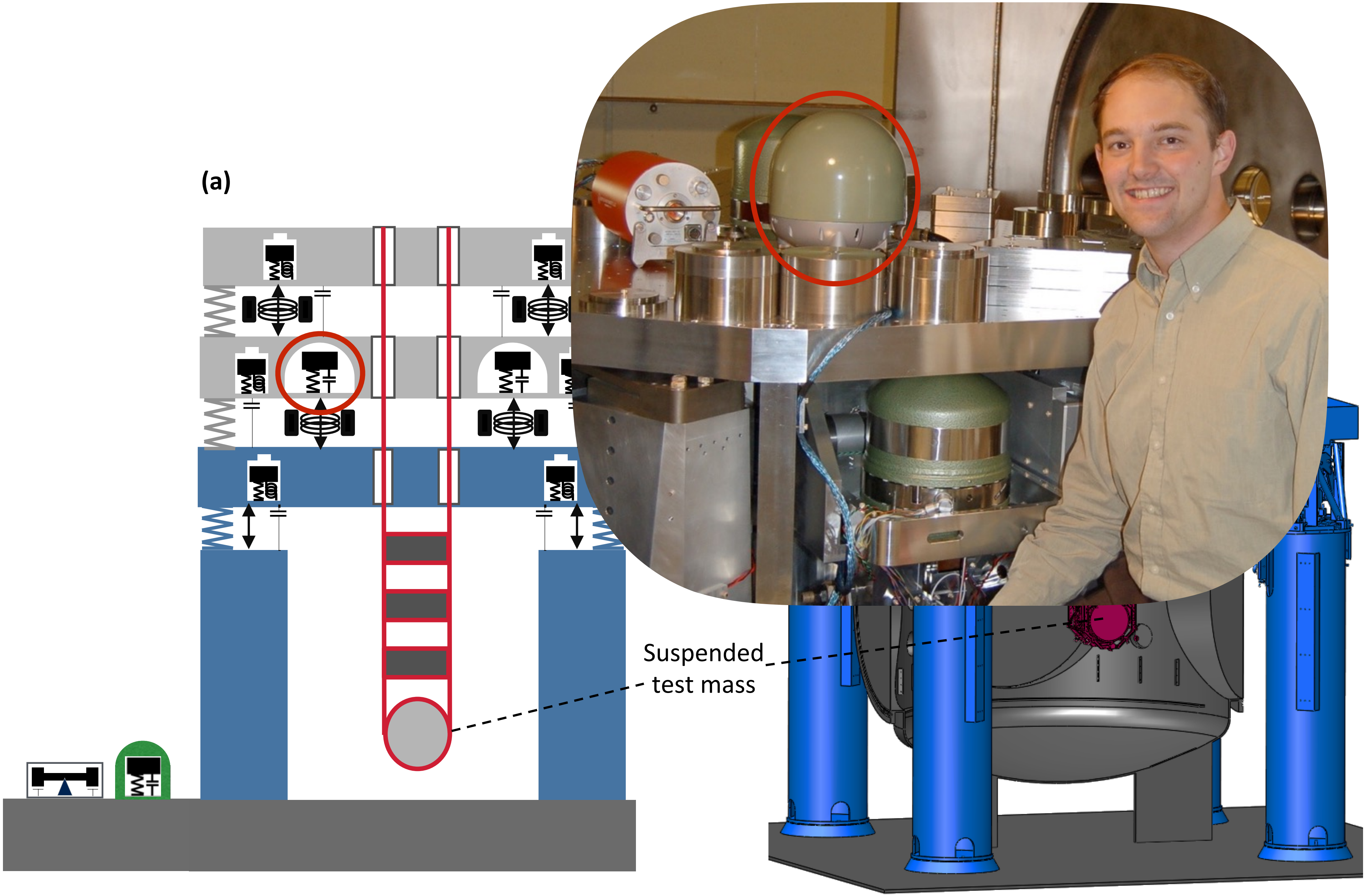

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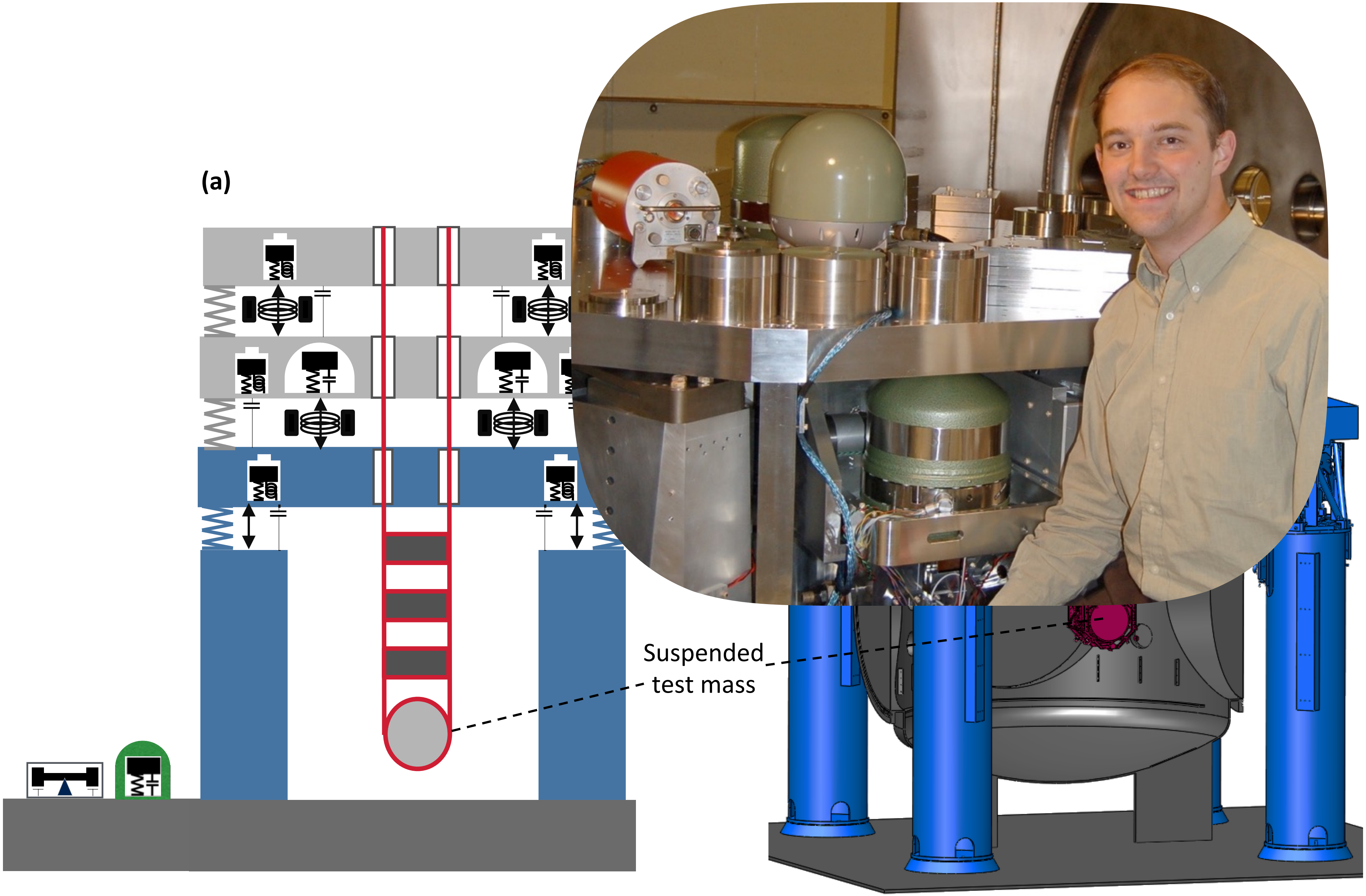

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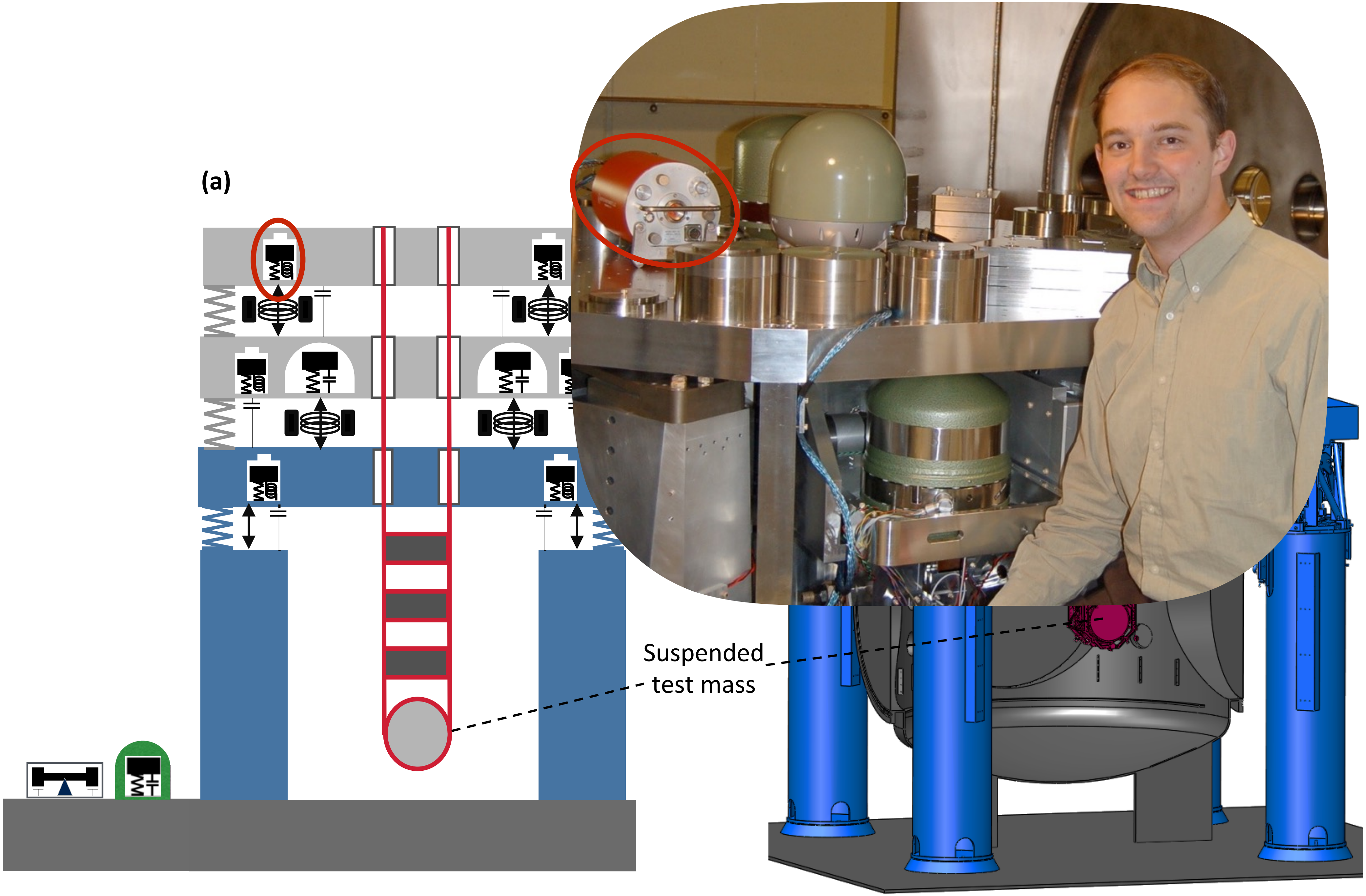
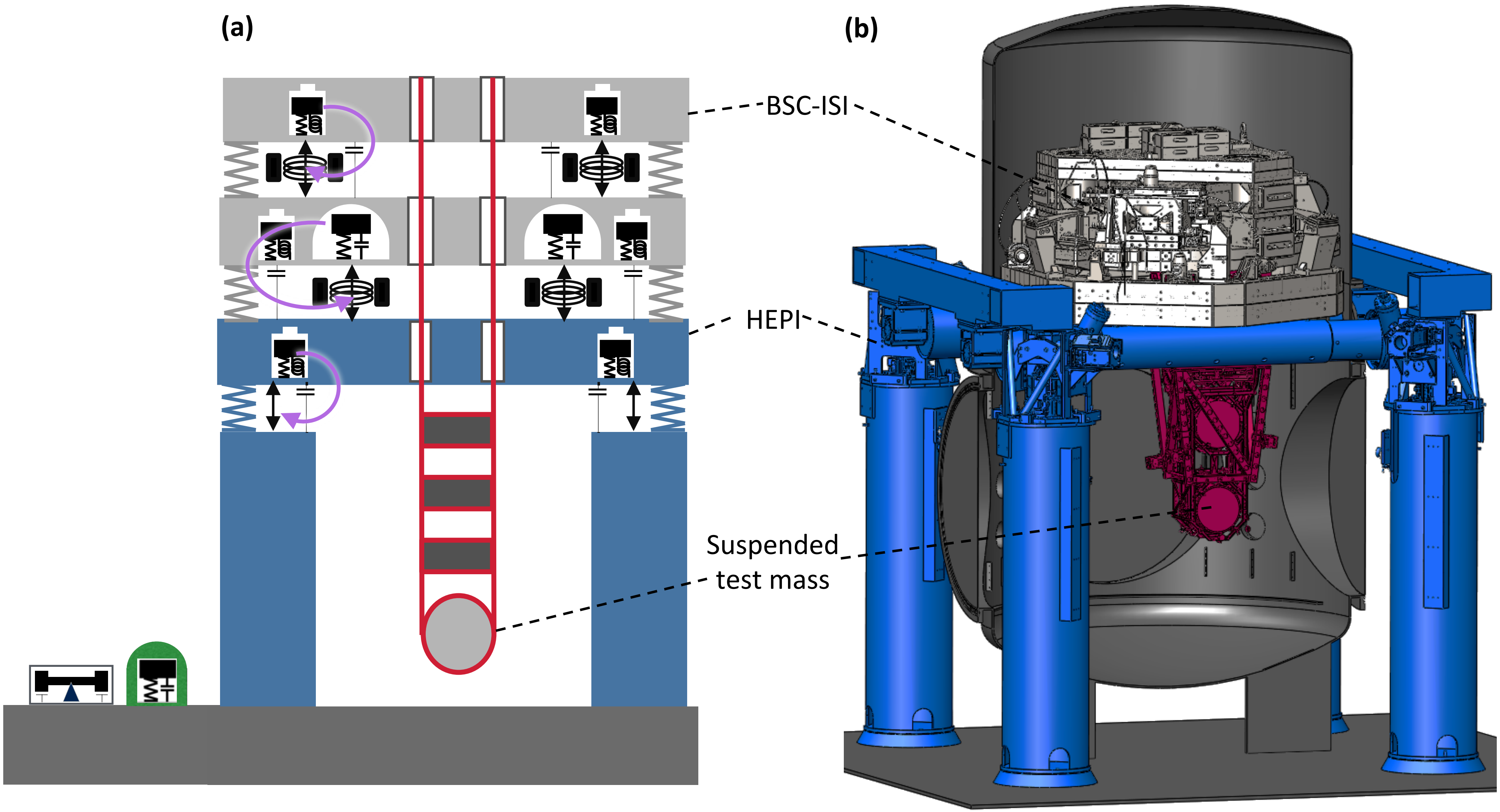


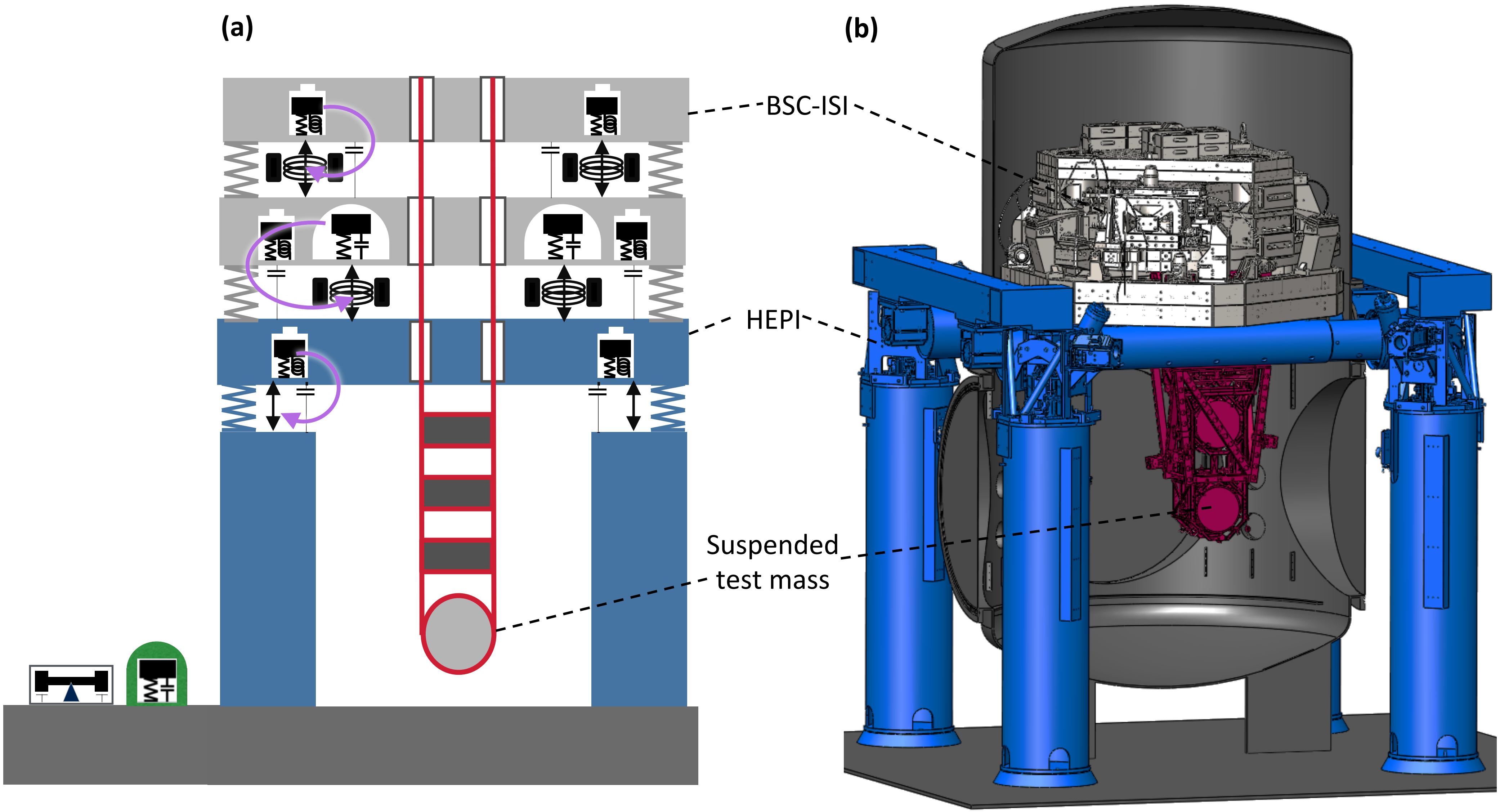
Signals for processing

Blended Feedback



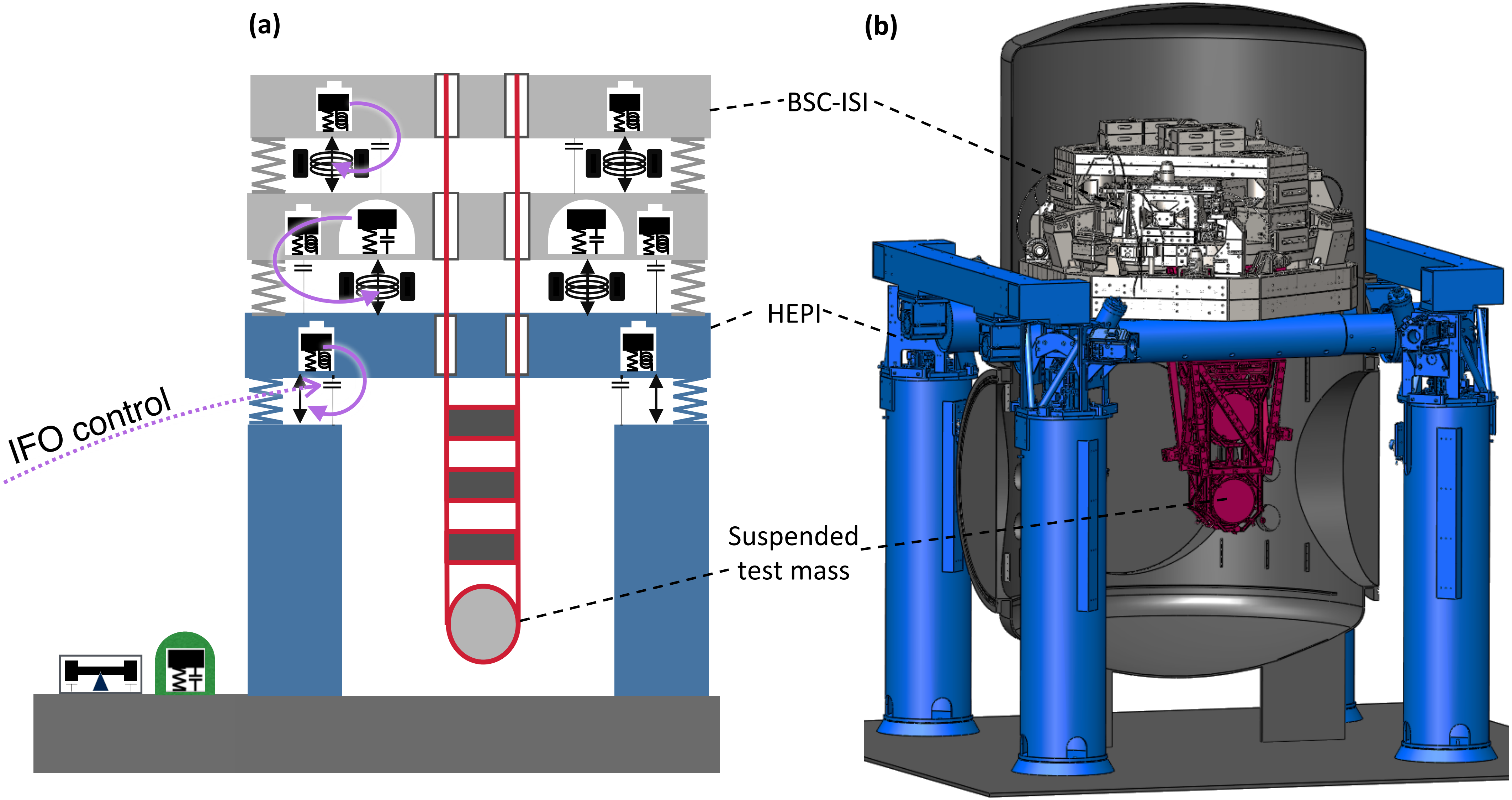
Signals for processing

Blended Feedback



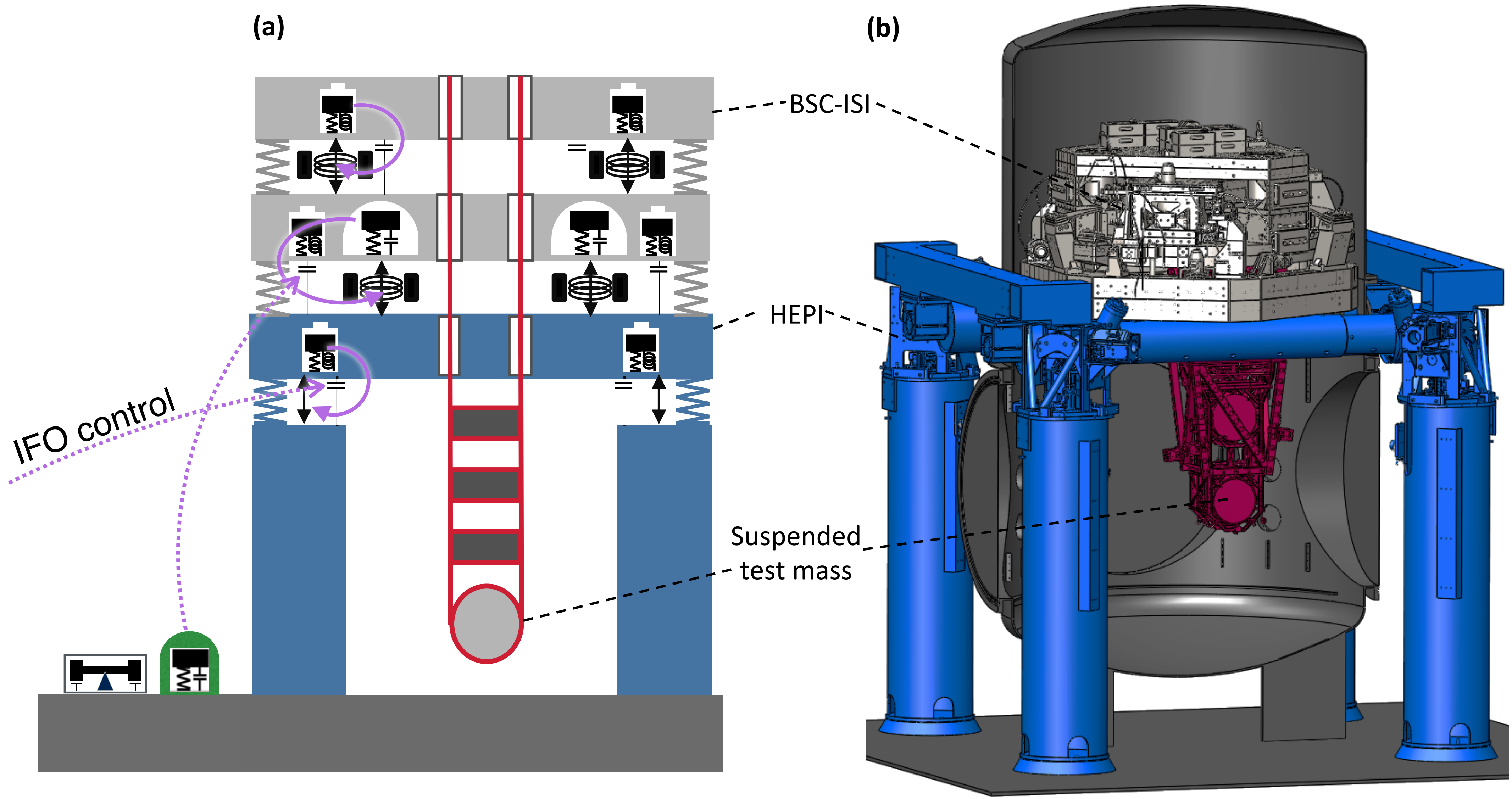
Signals for processing

Blended Feedback
Global commands



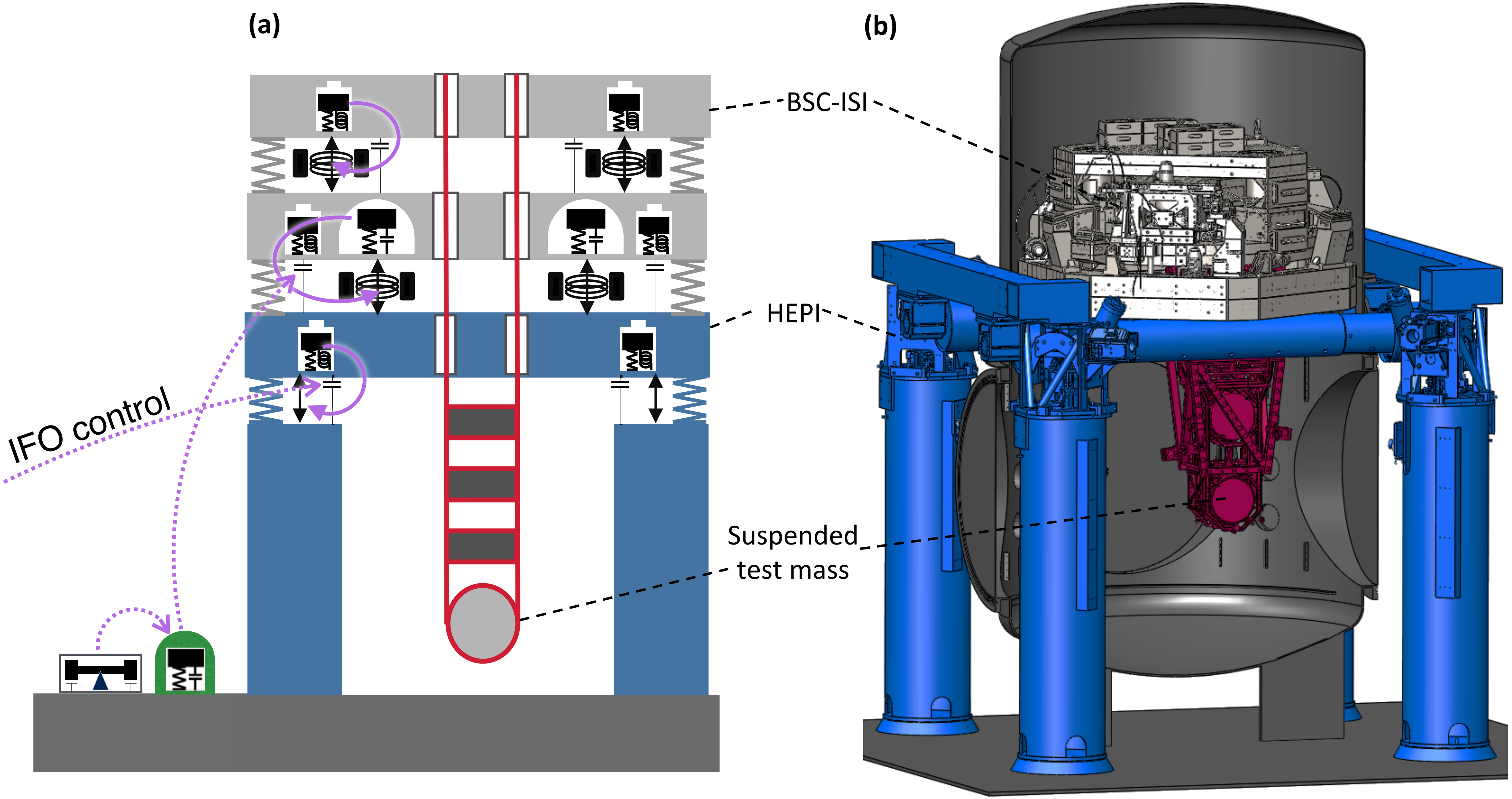
Signals for processing

Blended Feedback
Global commands
Sensor correction



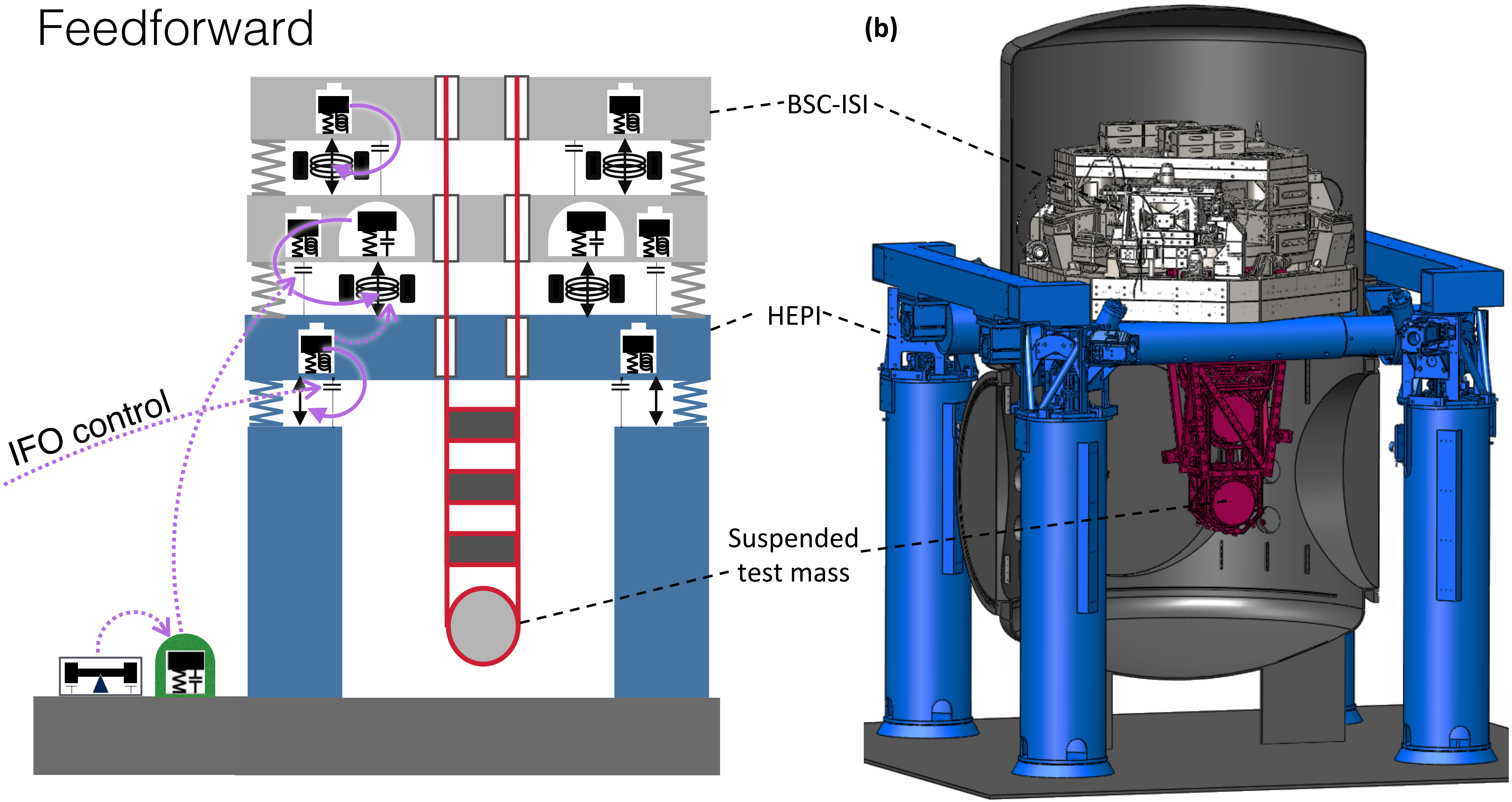
Signals for processing

Blended Feedback
Global commands
Sensor correction



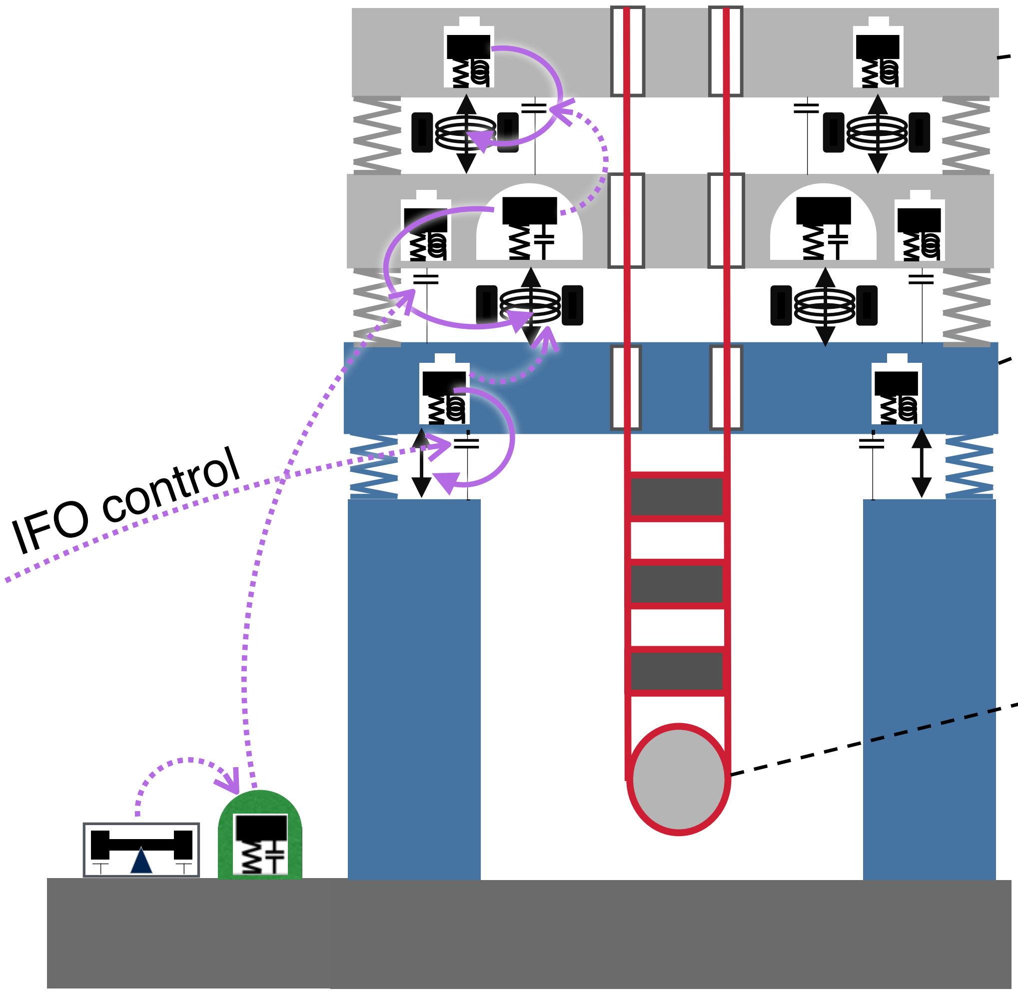
Signals for processing

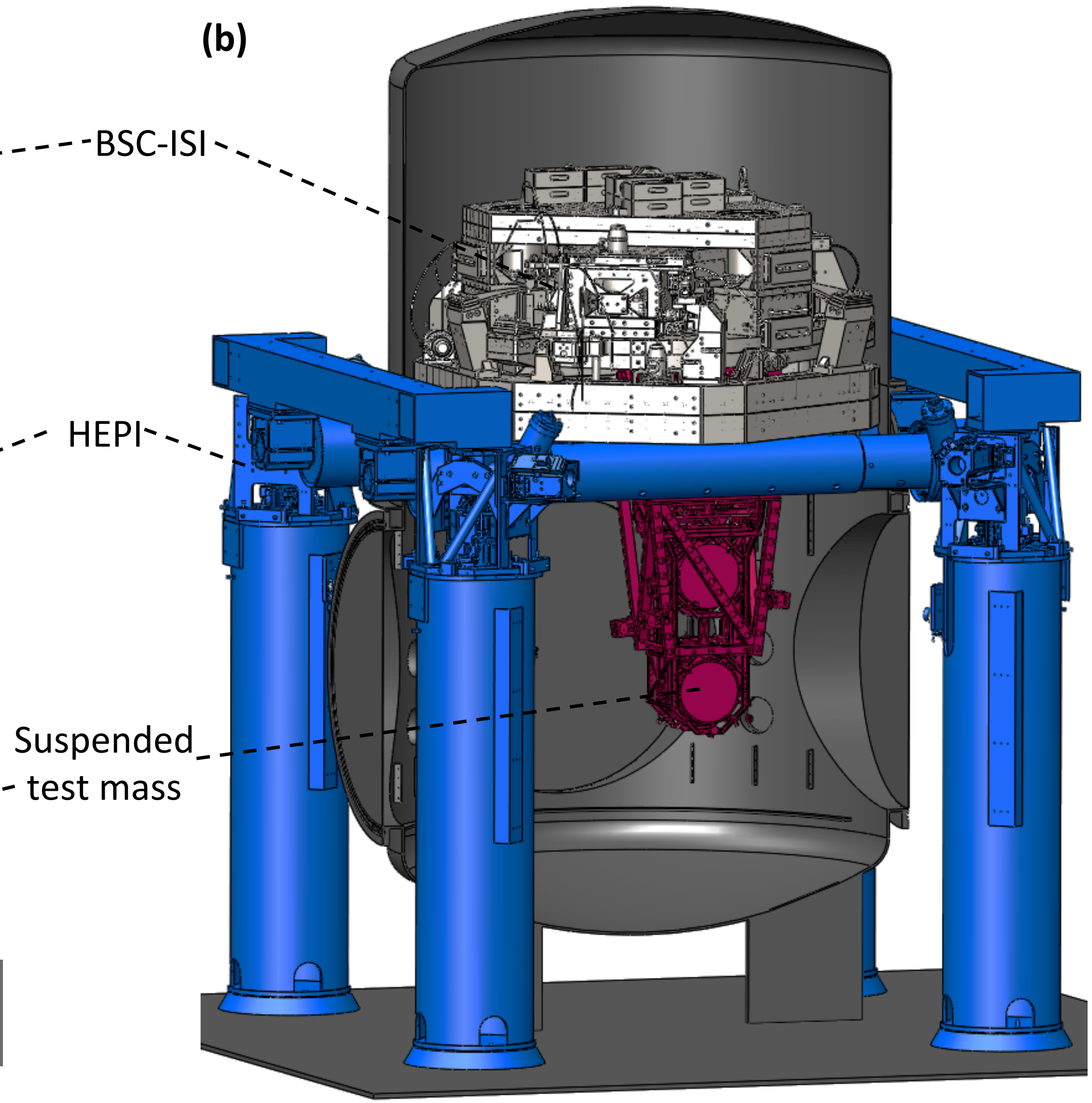
Blended Feedback
Global commands
Sensor correction
Feedforward



Signals for processing

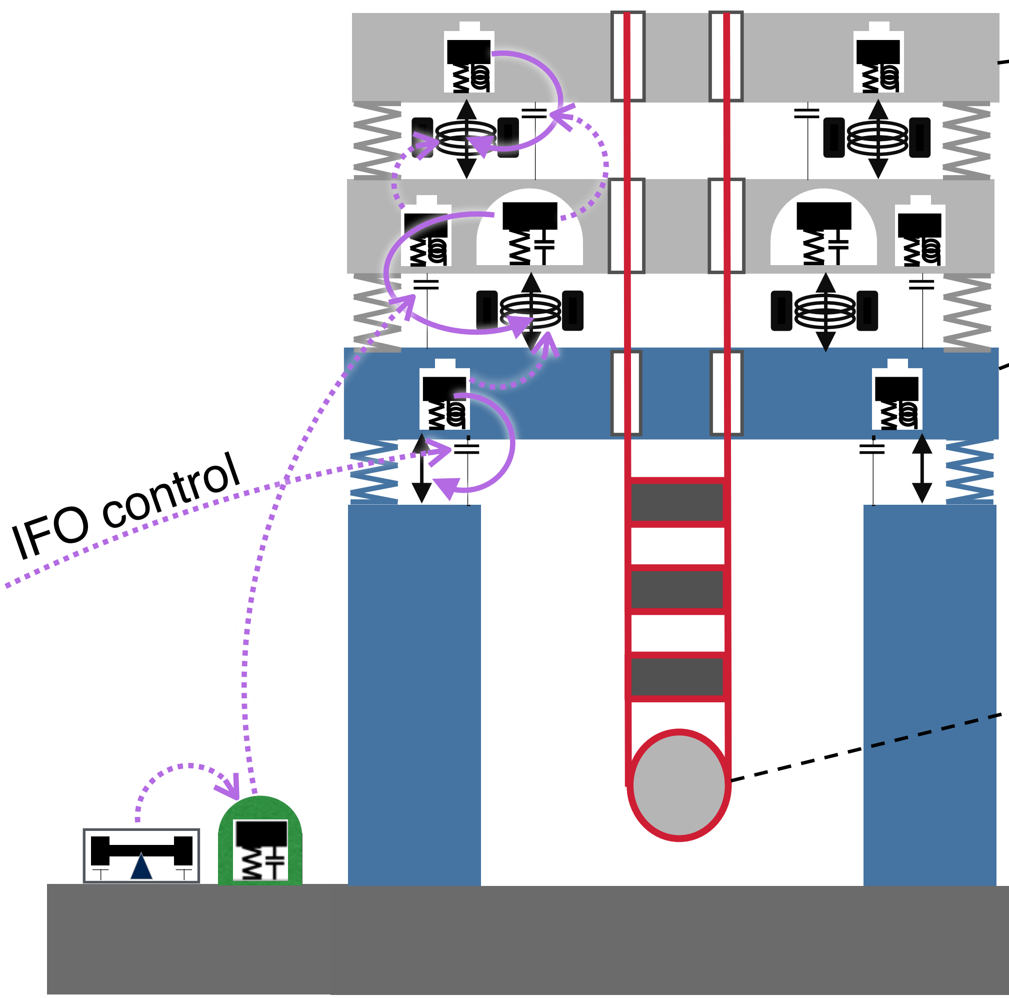
Blended Feedback
Global commands
Sensor correction
Feedforward



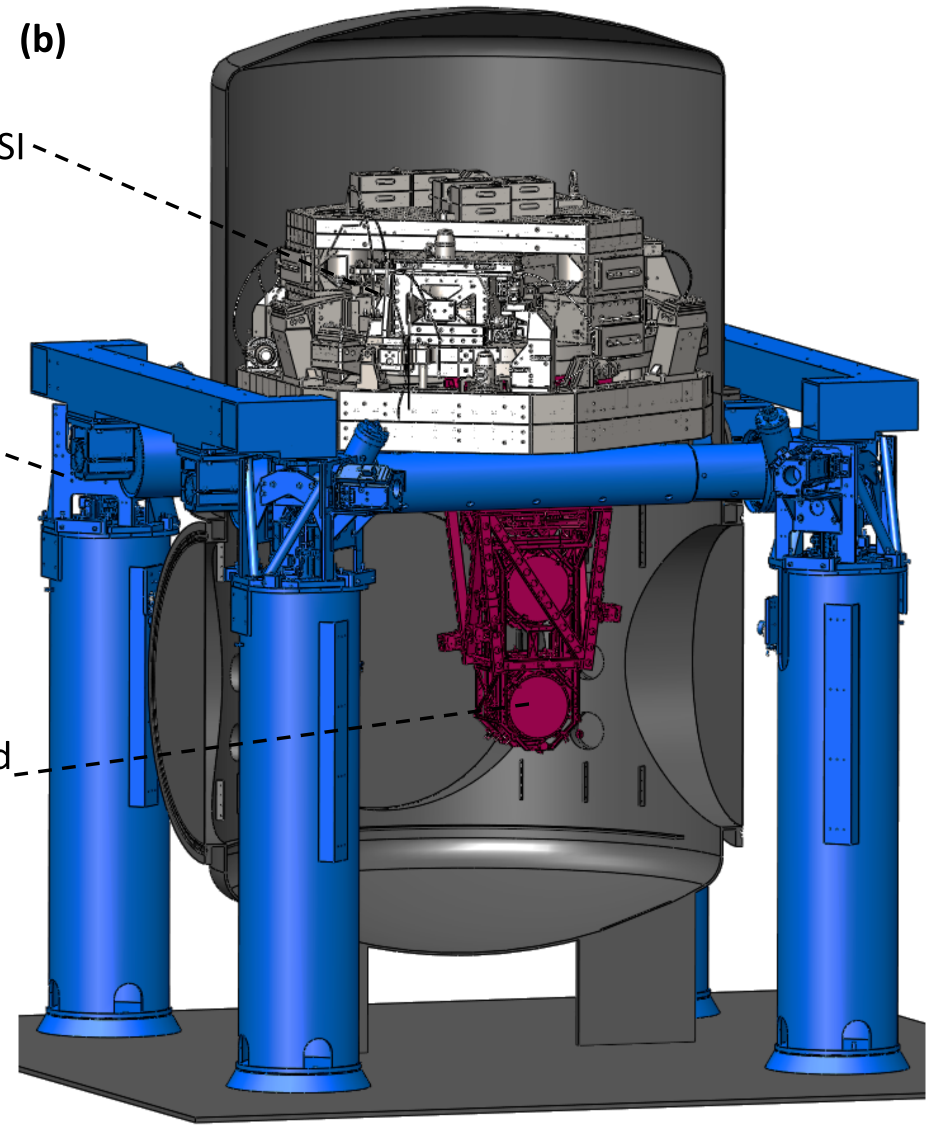


Signals for processing

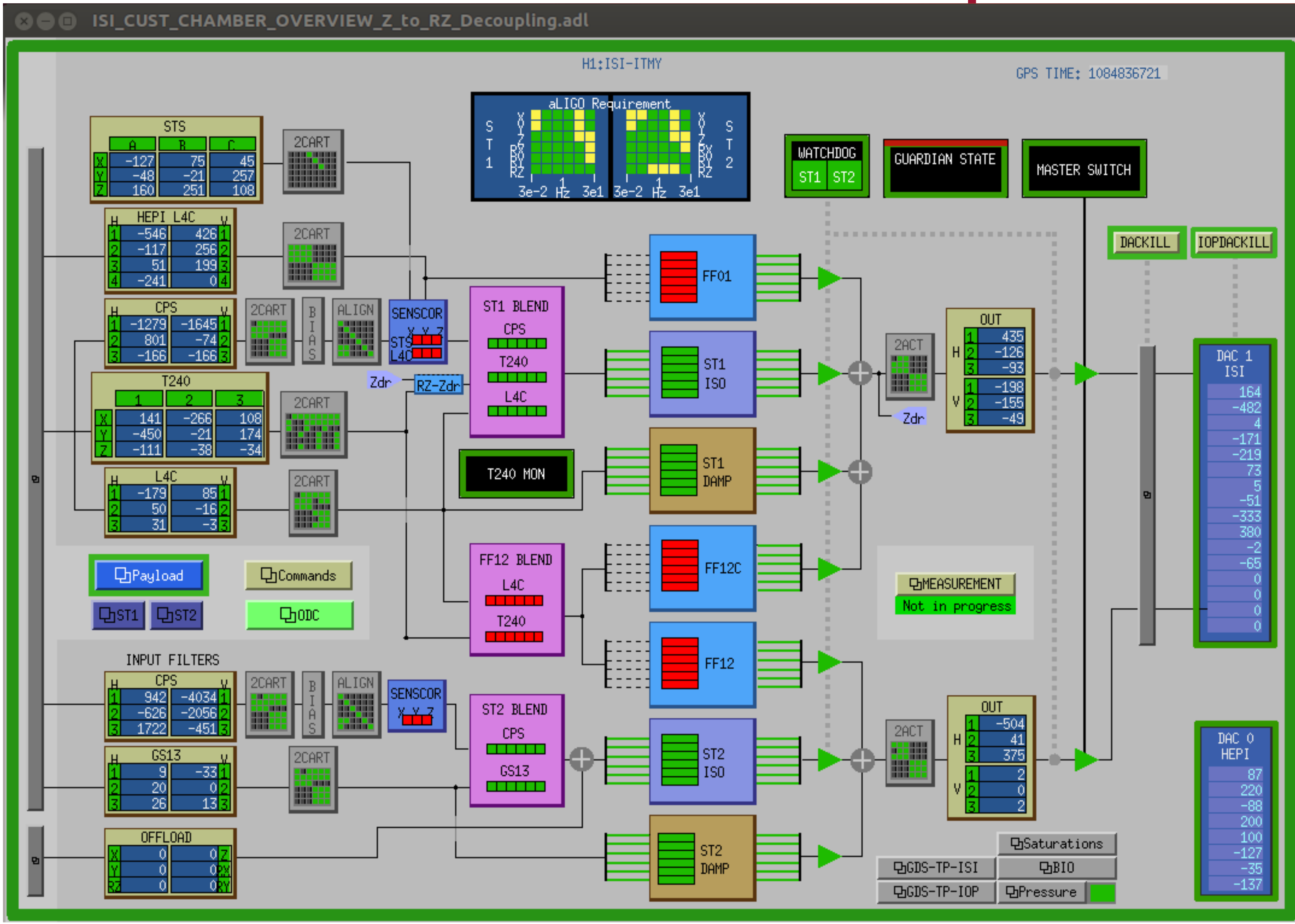
Blended Feedback
Global commands
Sensor correction
Feedforward



(b)



Basic Control setup



Dealing with complexity

LIGO- E1300155

LIGO Laboratory / LIGO Scientific Collaboration

LIGO- E1300155 *LIGO* March 5, 2013

aLIGO HAM-ISI, Phase III Testing report

(Control Commissioning)

LLO HAM 3

E13000155-V6

Celine Ramet, Ryan De Rosa, Fabrice Matichard

Distribution of this document:
Advanced LIGO Project

This is an internal working note
of the LIGO Laboratory

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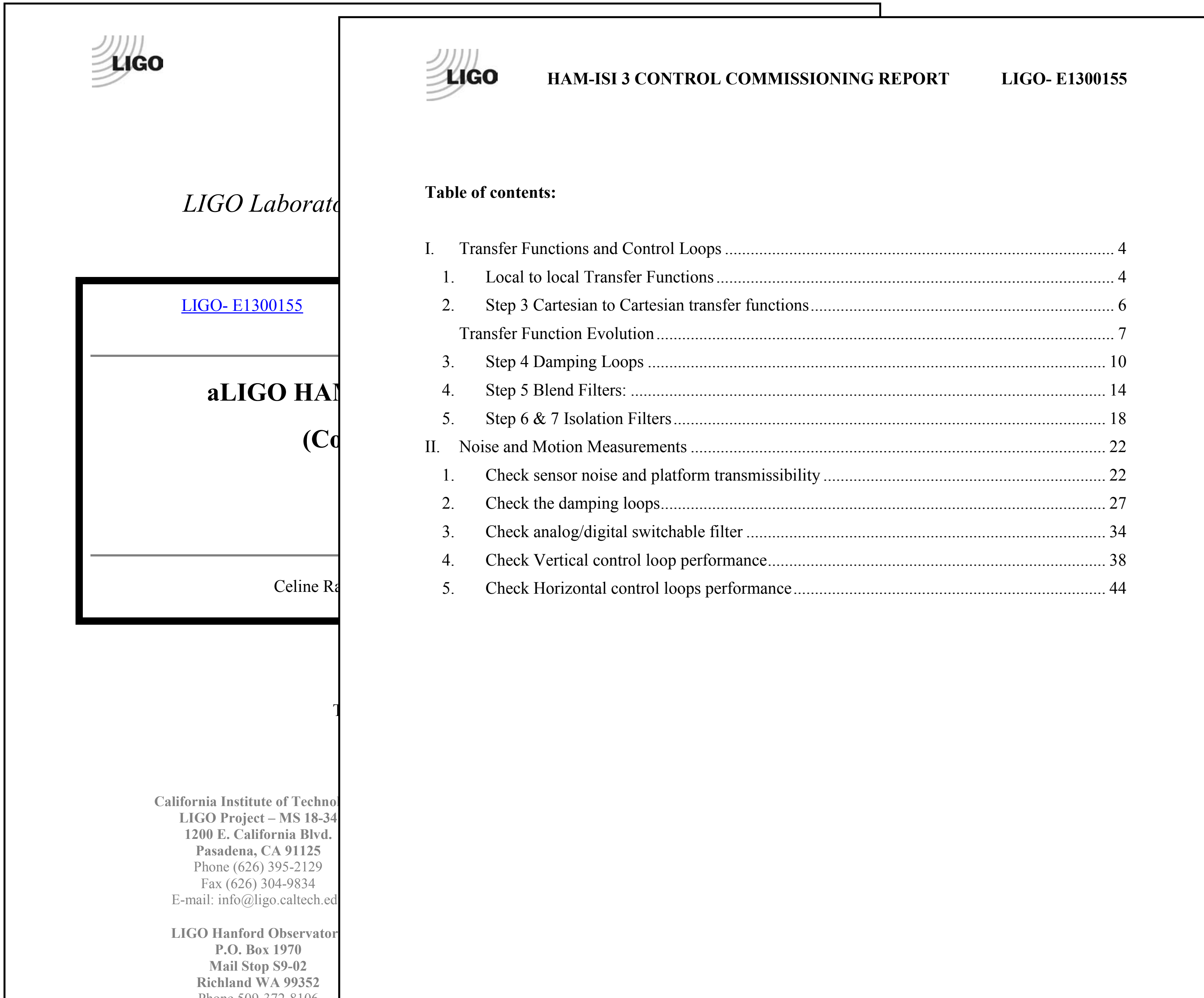
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100

There is a process we set up and followed to get everything installed and running.

Platform dynamics are similar from 1 unit to the next, so basic control laws work without modification.

First set of tests for India system are done.

Dealing with complexity



LIGO

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LIGO- E1300155

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Celine R

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LIGO HAM-ISI 3 CONTROL COMMISSIONING REPORT LIGO- E1300155

Table of contents:

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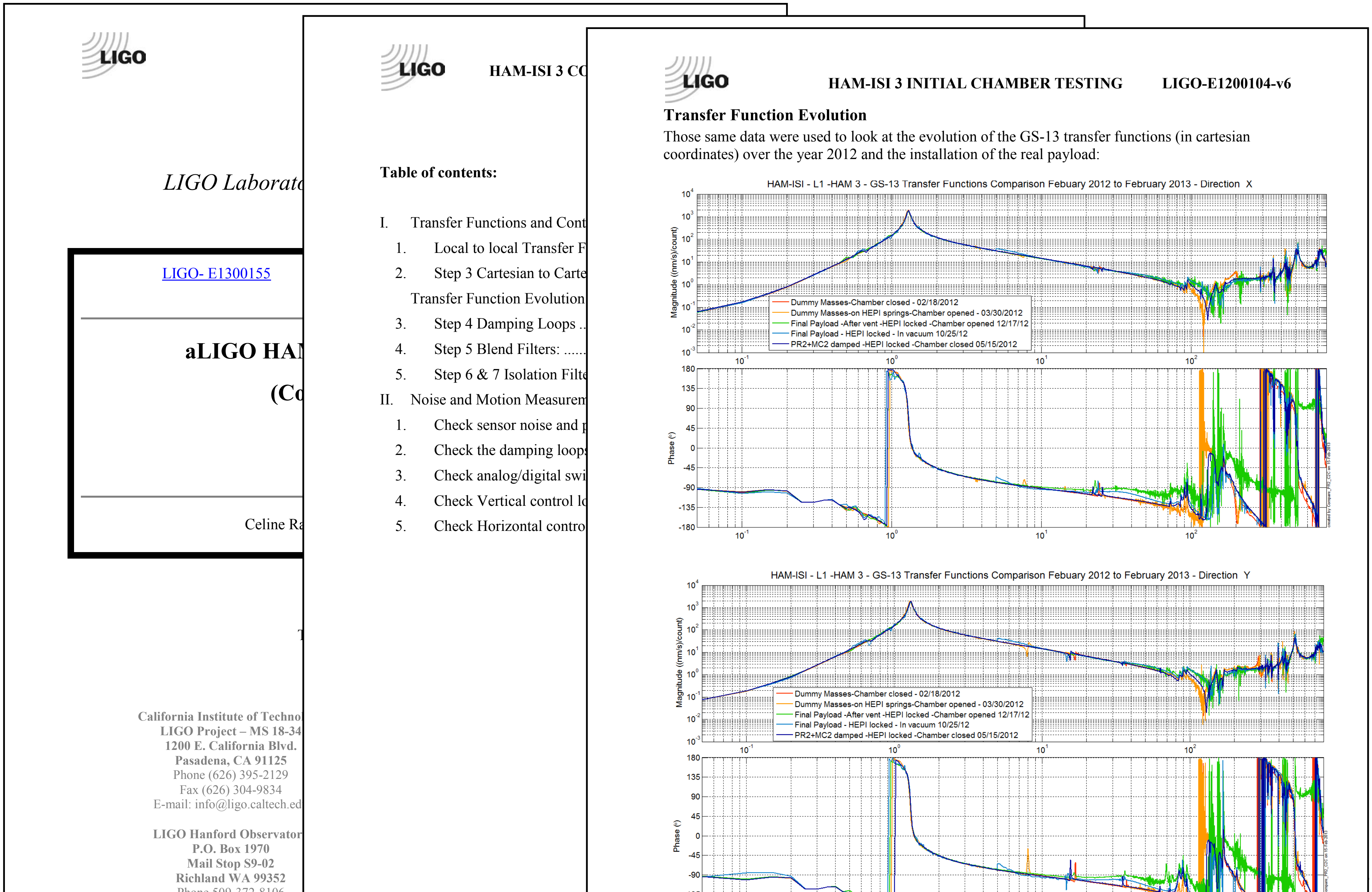
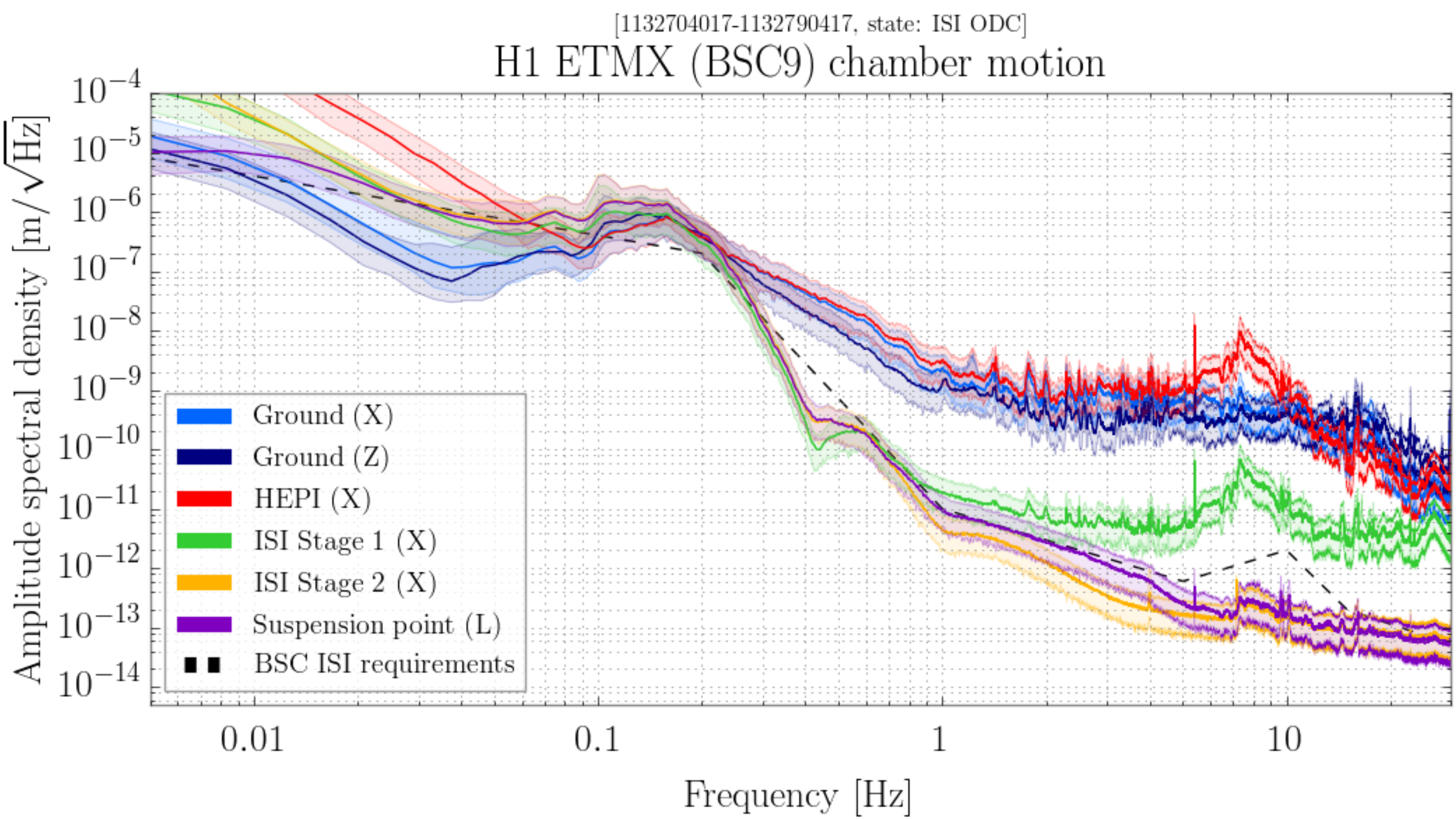
Dealing with complexity



Performance

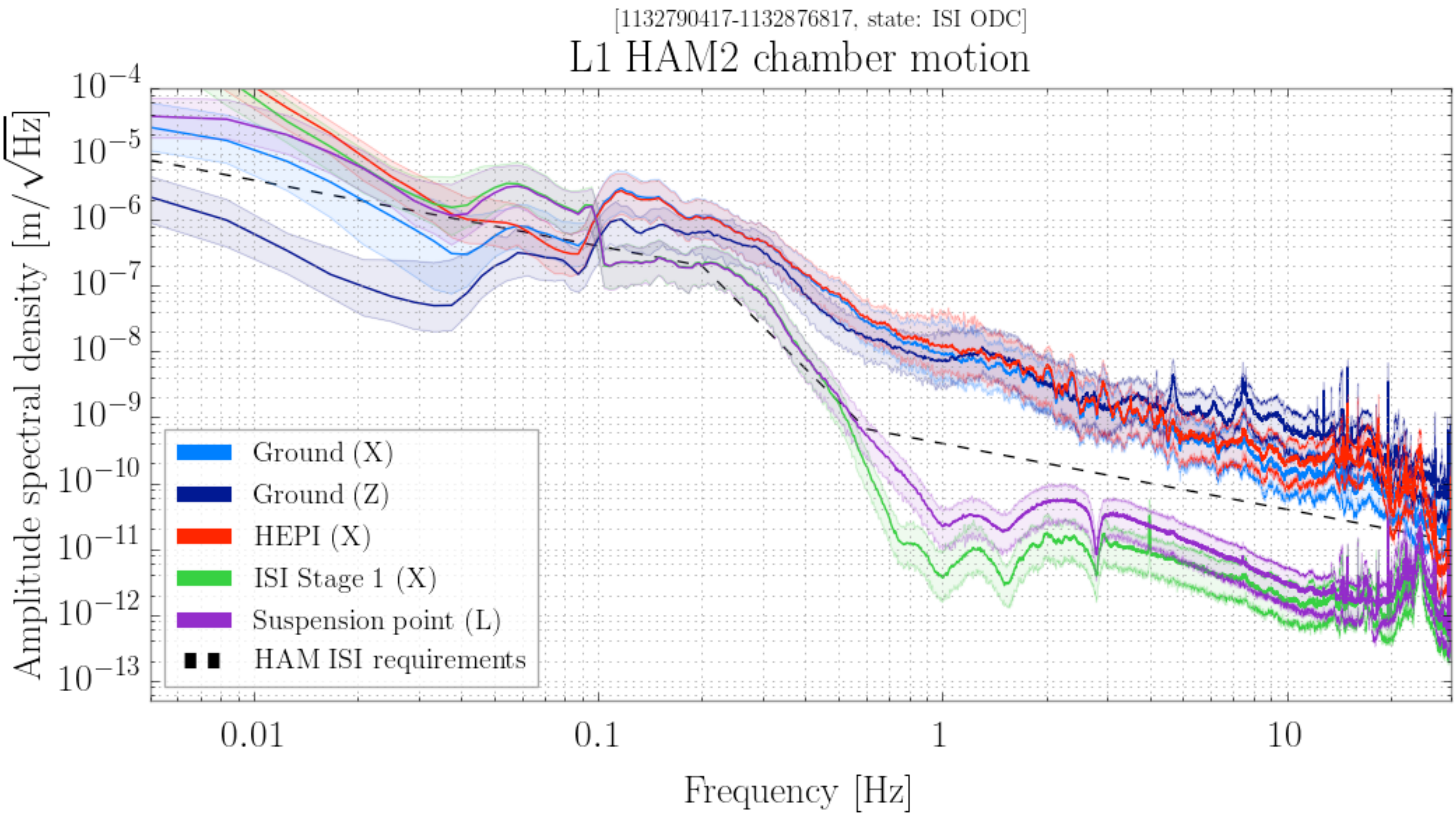
Interesting features of current performance:
- Good isolation in the control band
- Survive trains
- Useful monitor of motion at suspension point
- Guardian allows us to bring system up automatically
- Blend switching enables re-tuning of running system

‘Typical’ performance

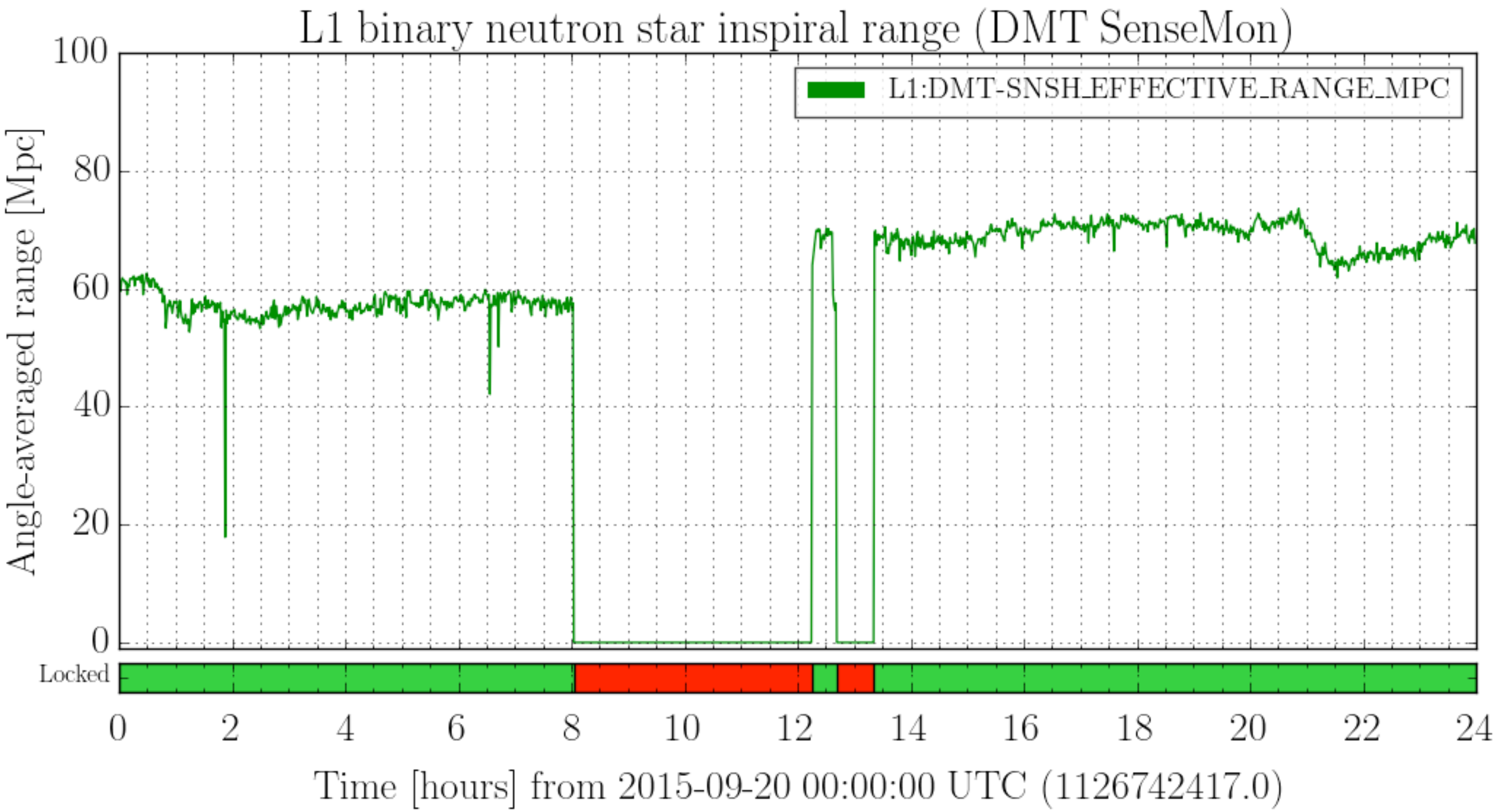


Nov 28th (Sat. after Thanksgiving)

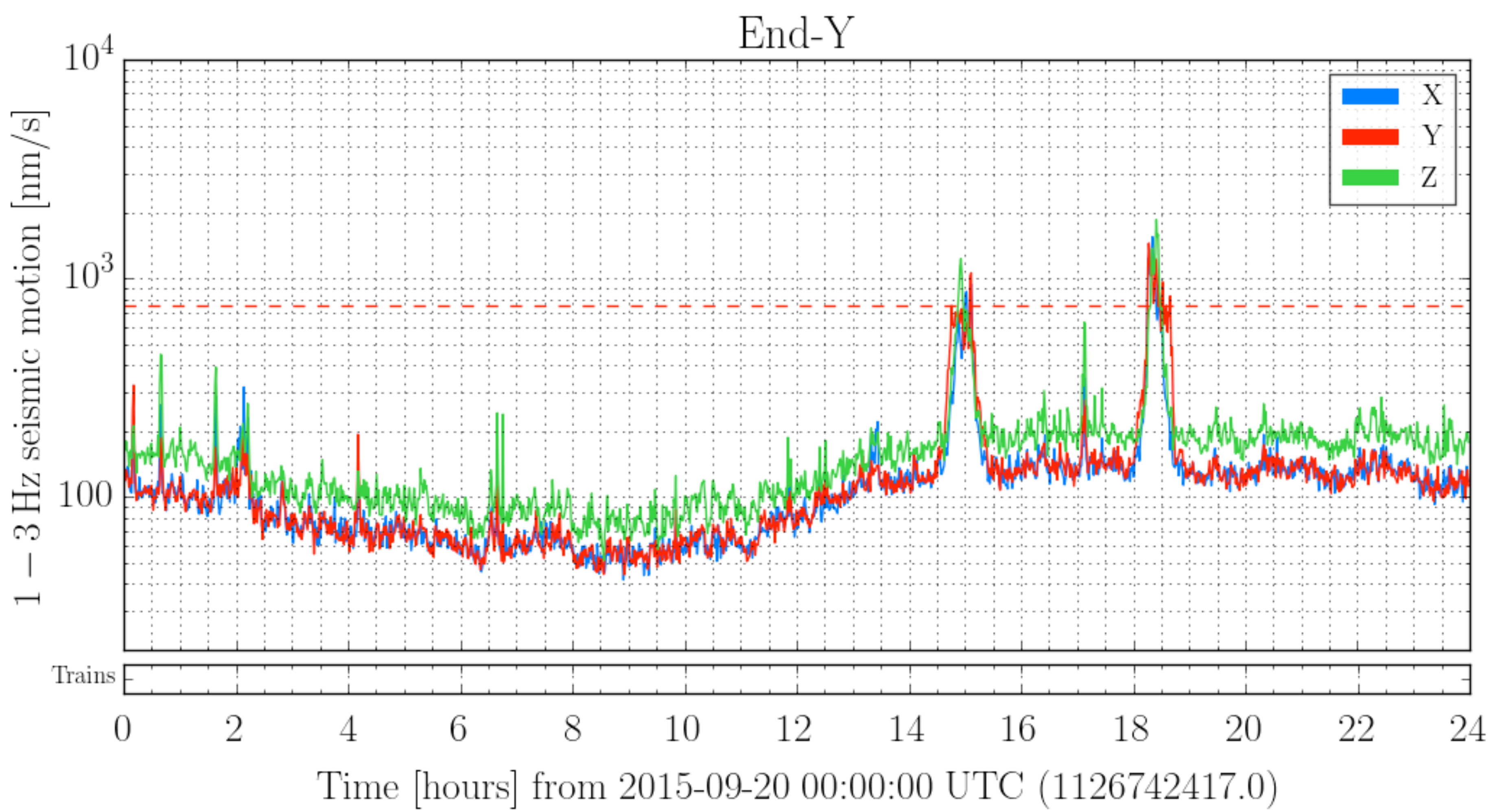
HAM-ISI on a good day



Real impact of isolation, alignment & control



but there was a train…



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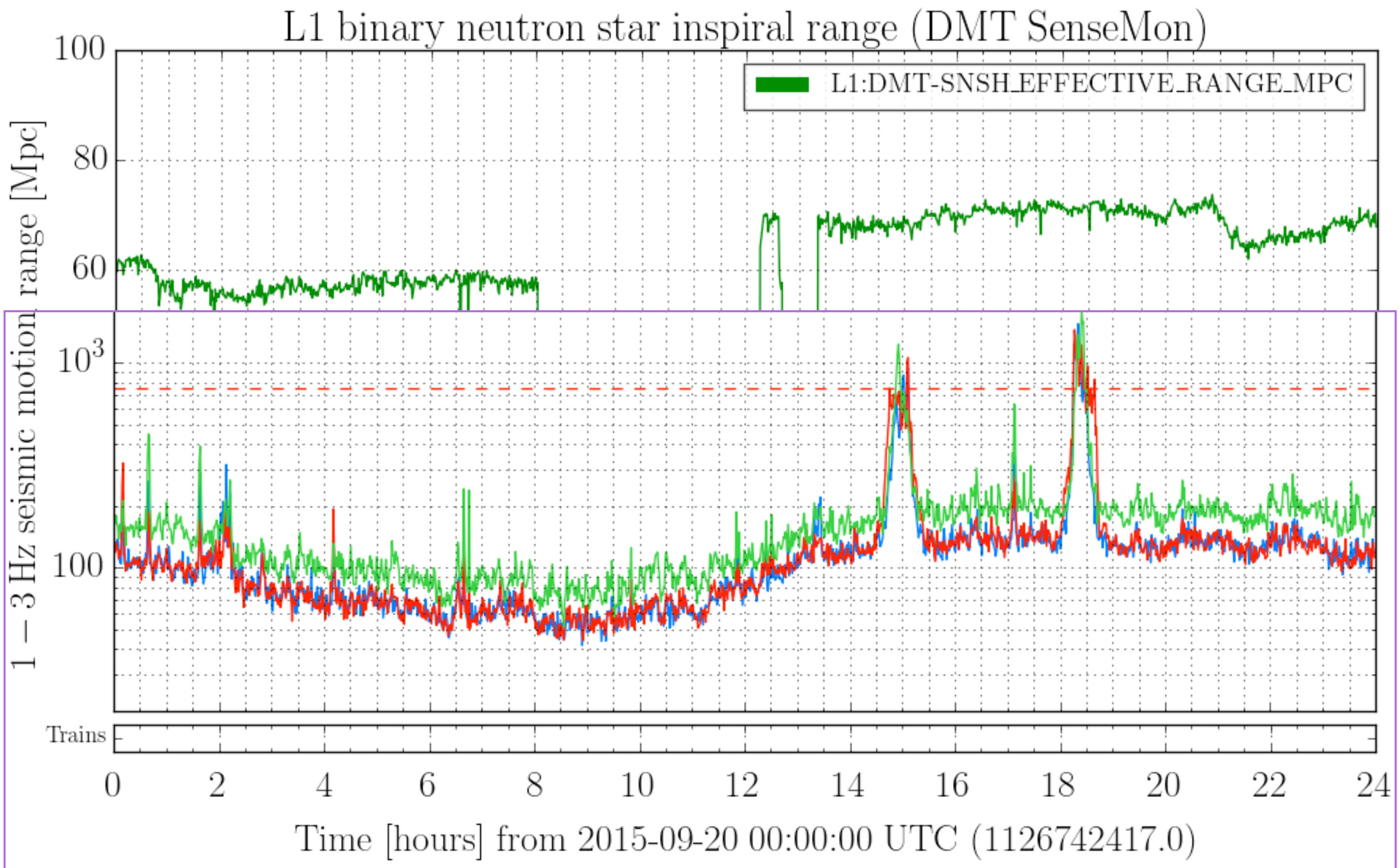
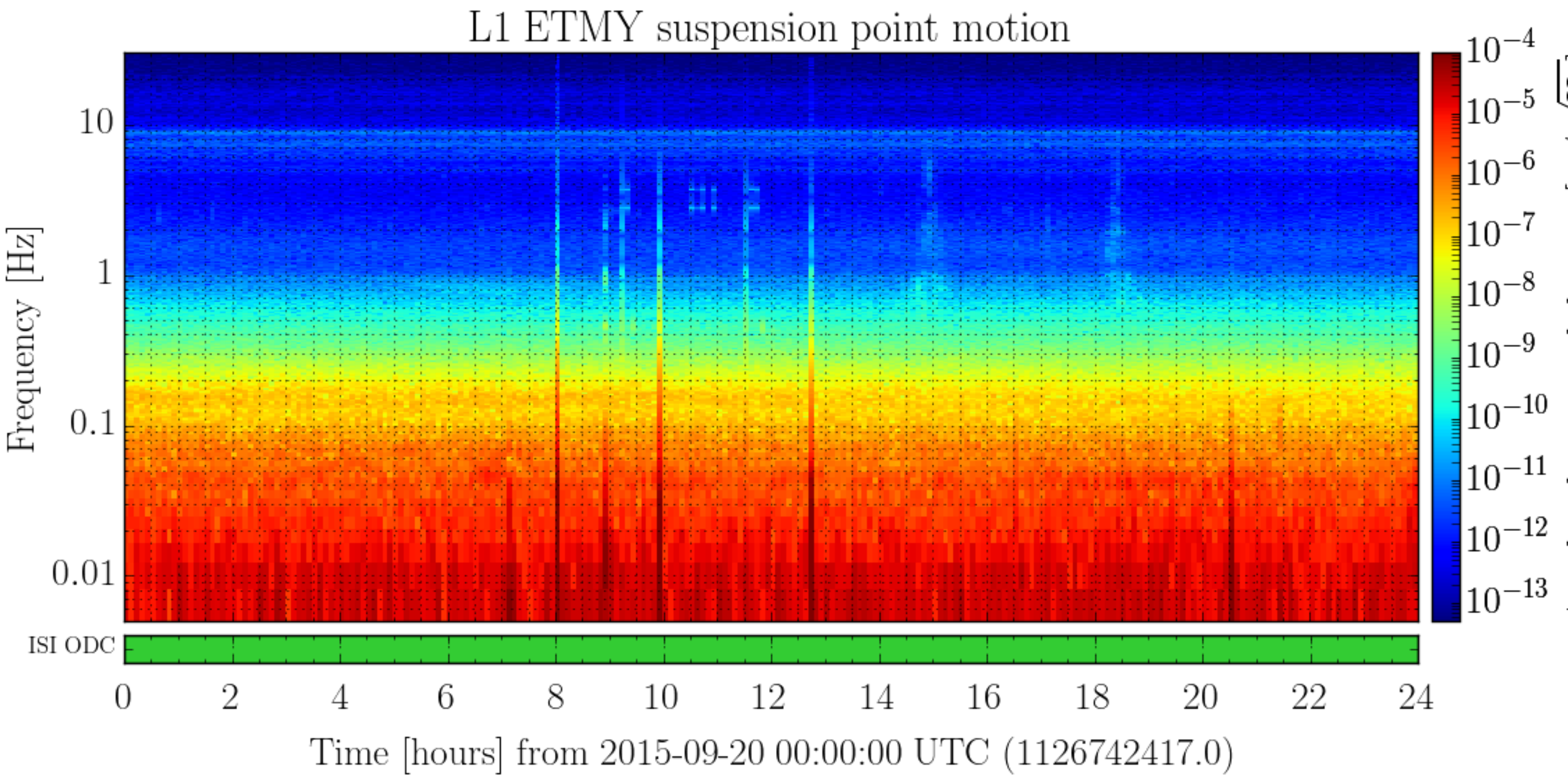
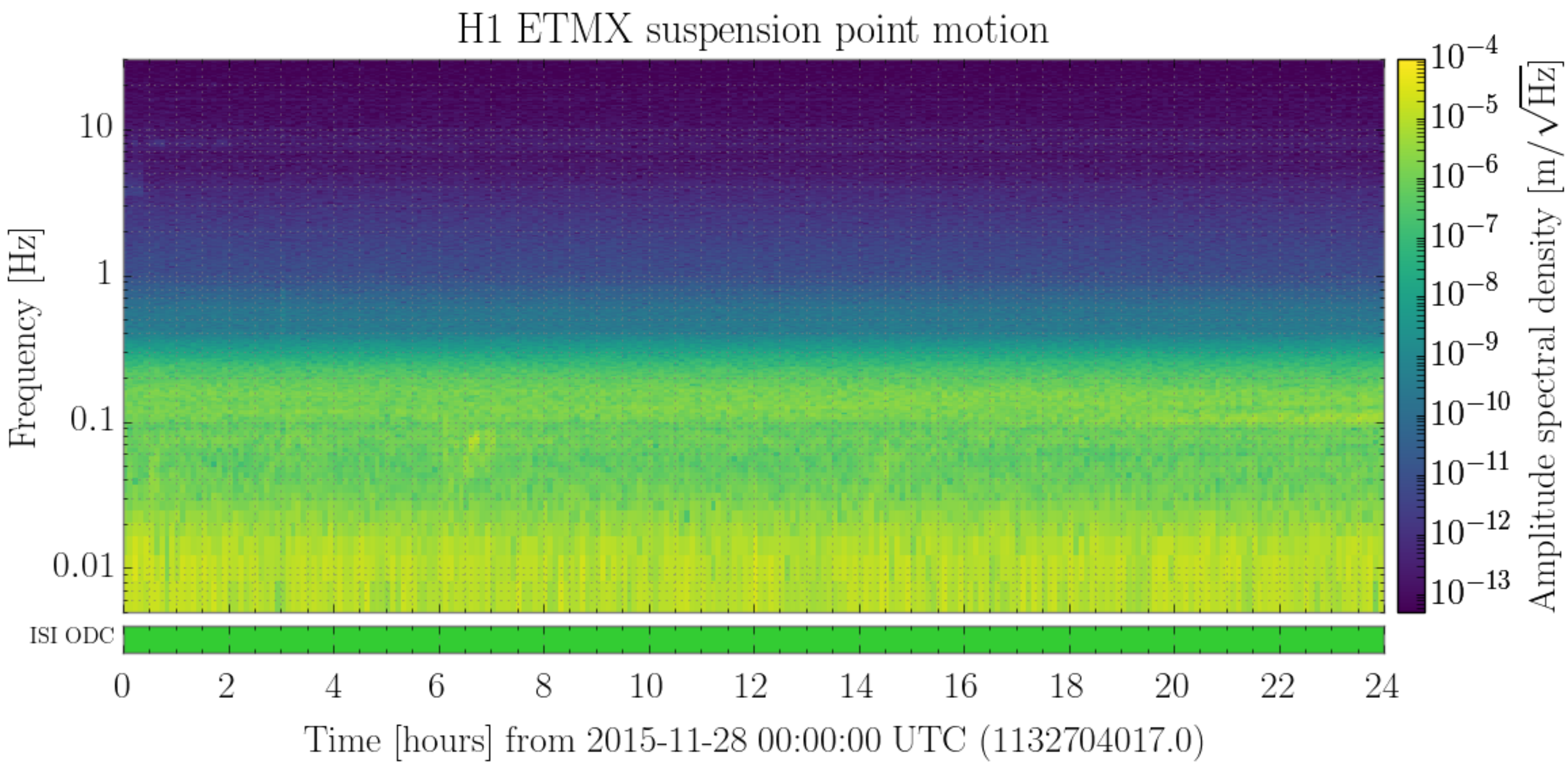


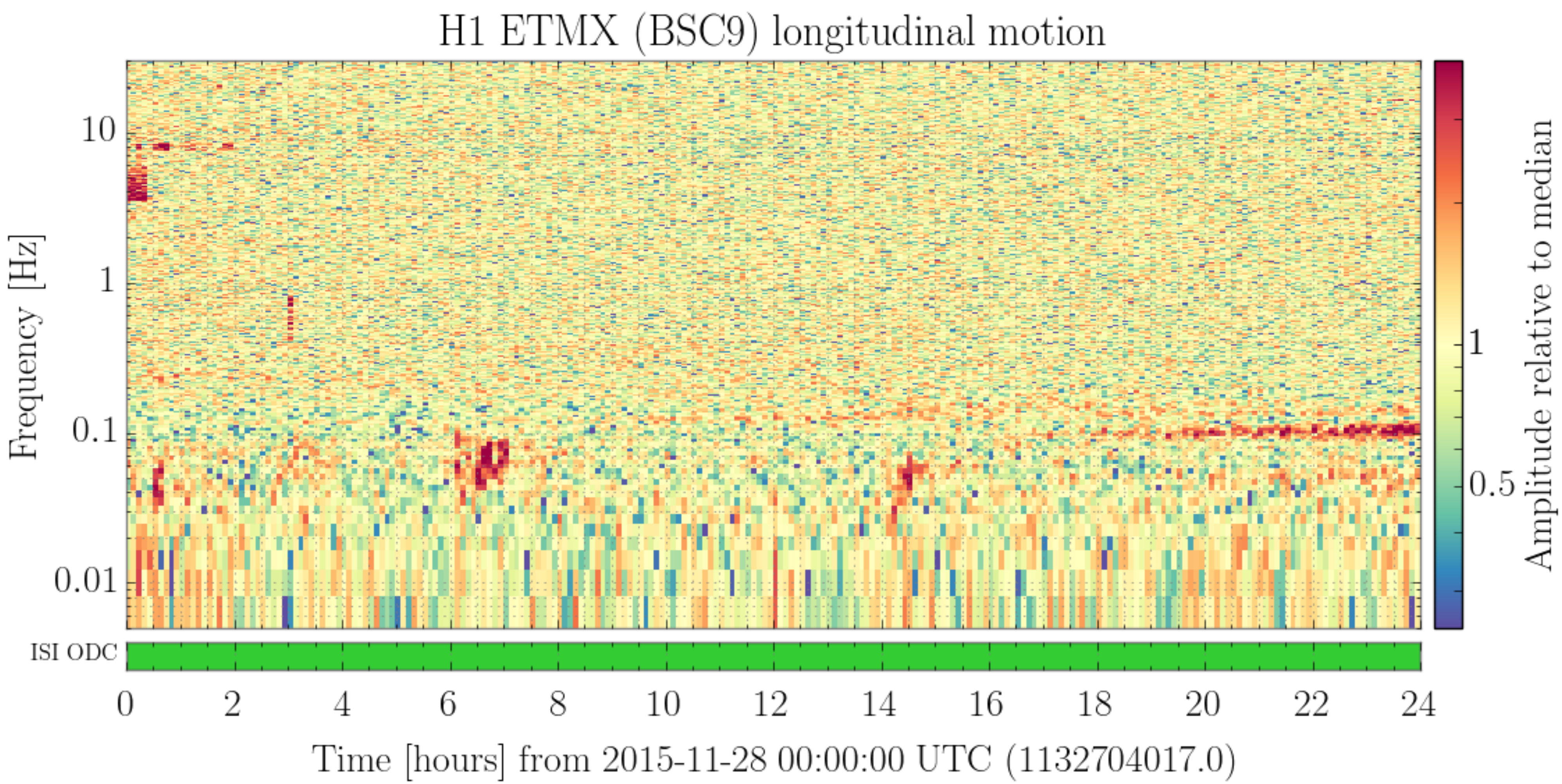
‘Environmental’ sensors



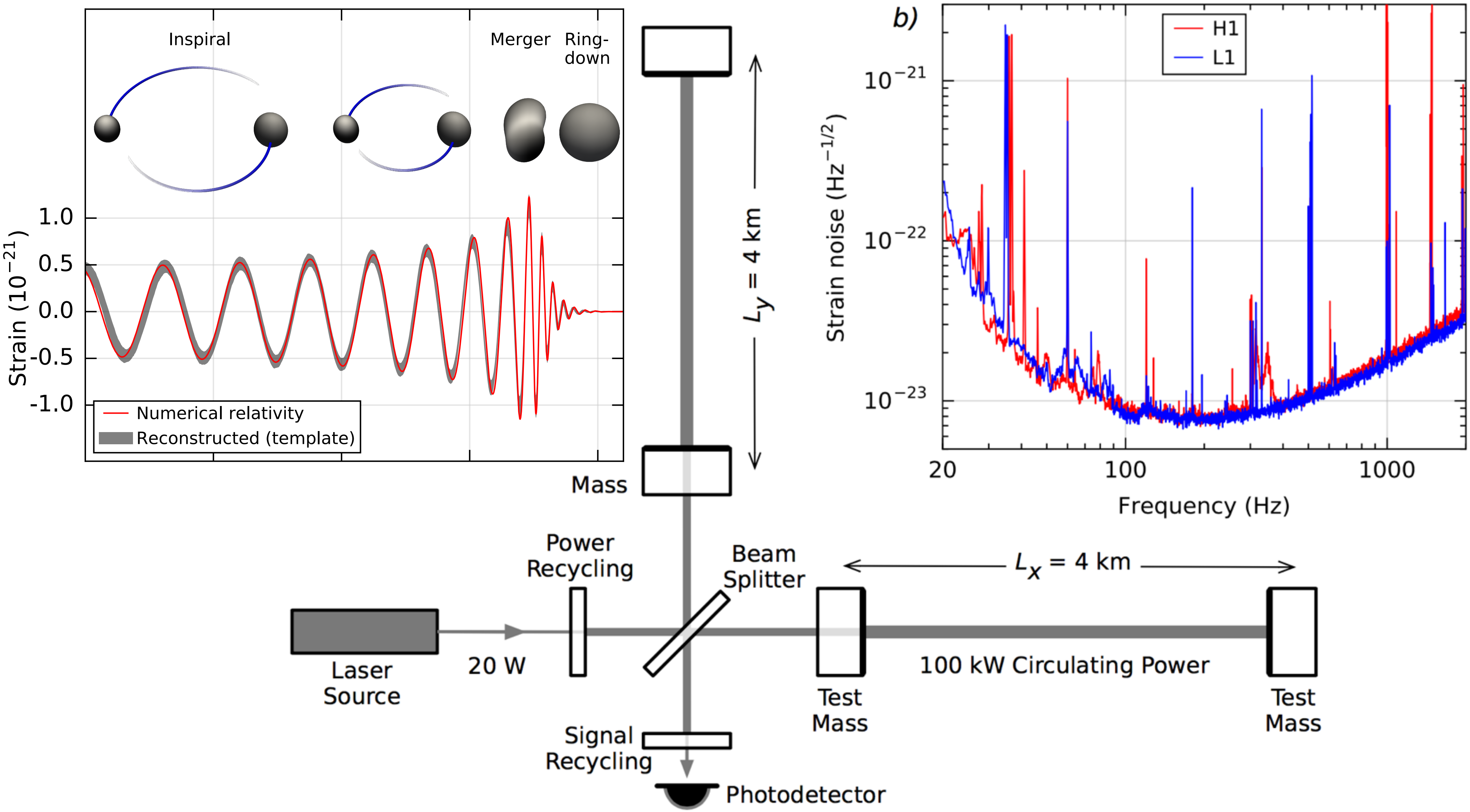
This is what we strive for



Glitch monitoring

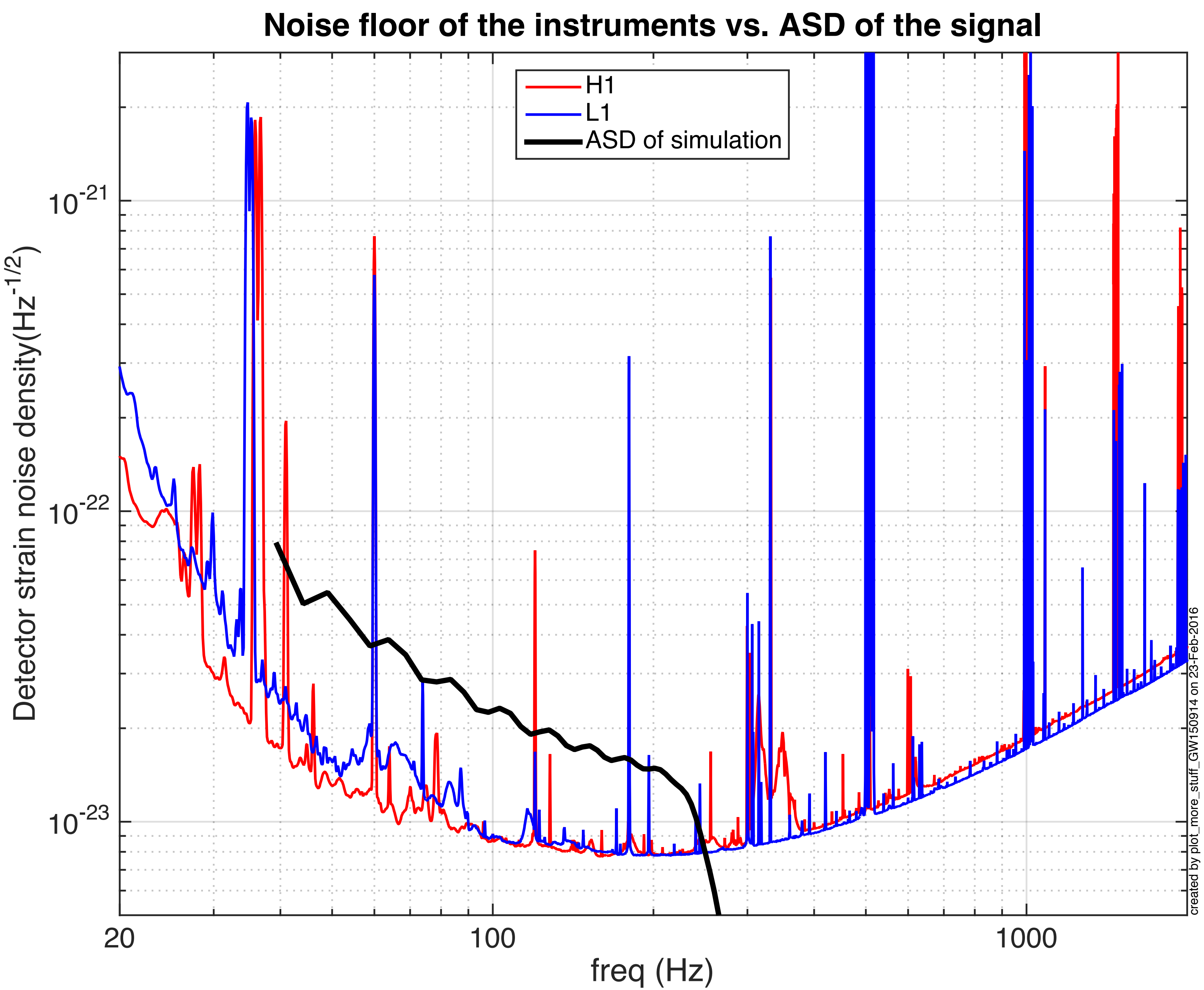


Detection monitoring



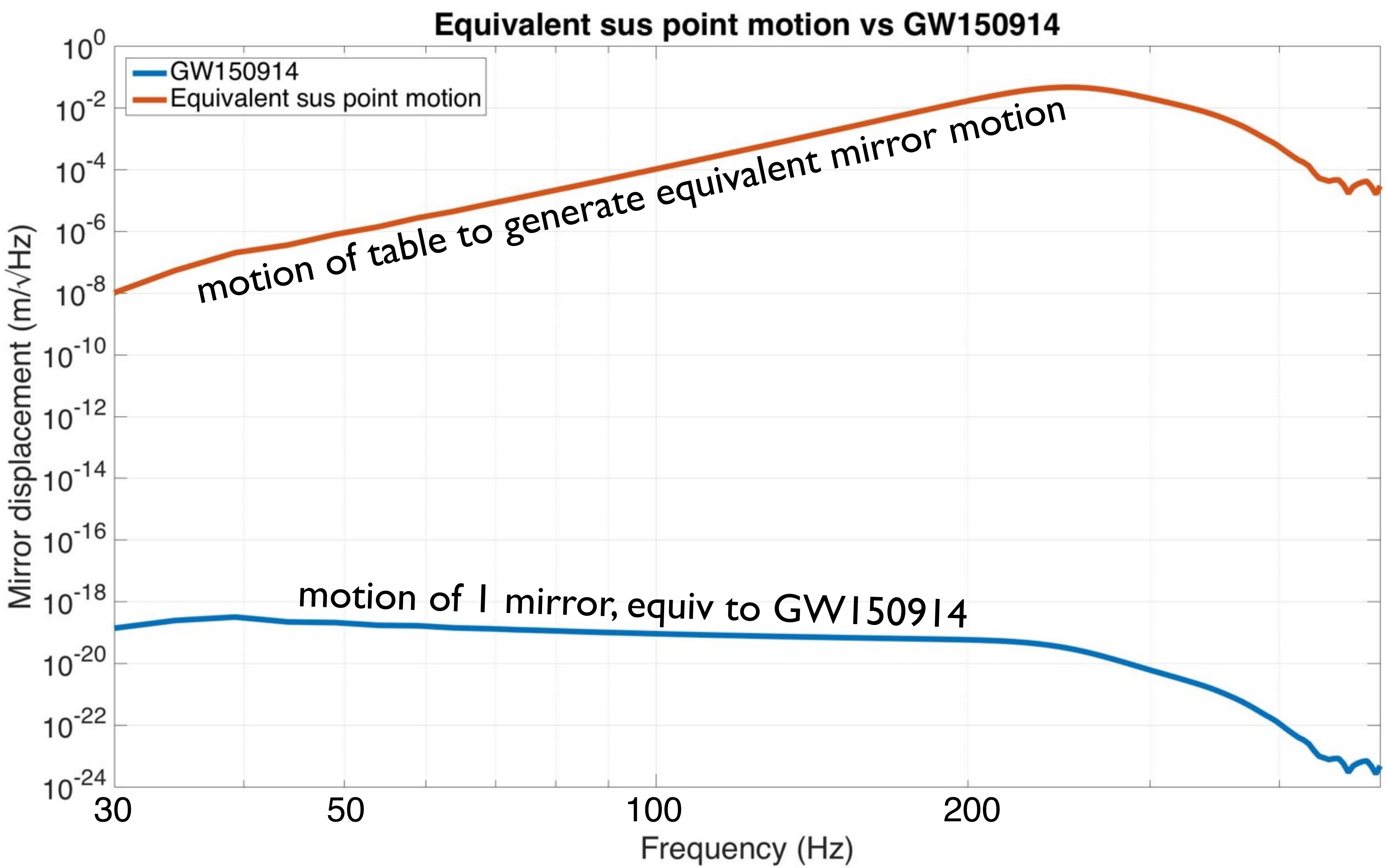
from detection paper P150914

ASD of the signal and noise



Power of the monitors

If GW150914 were linearly coupled seismic motion



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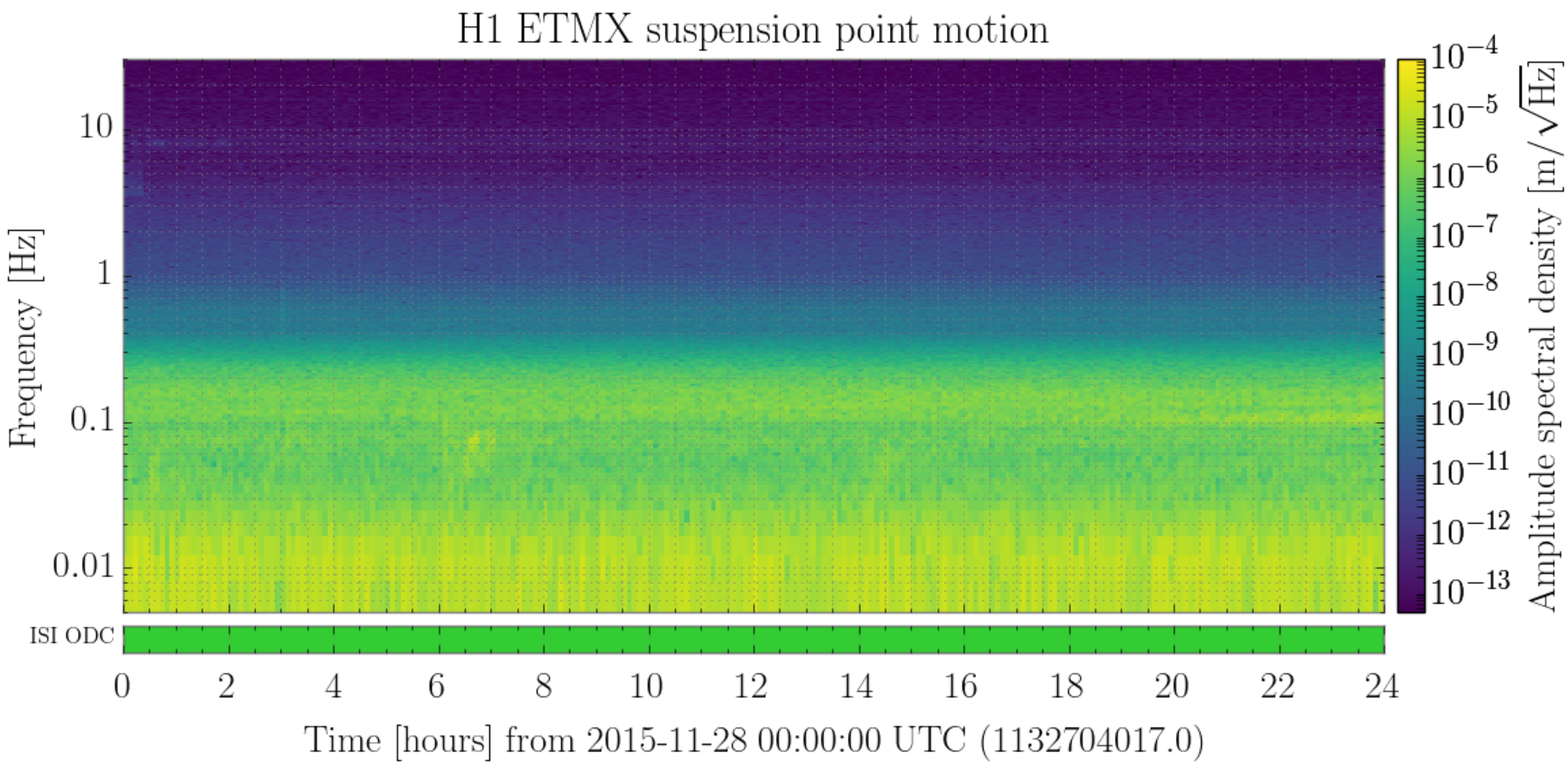

Summary of successes

- Mechanical systems now built work well
- Commissioning path is pretty well laid out
- Basic Control schemes work
- Path to success involves copy/ paste of existing controls
  - but you should come work with it.

Summary of successes

- Mechanical systems now built work well
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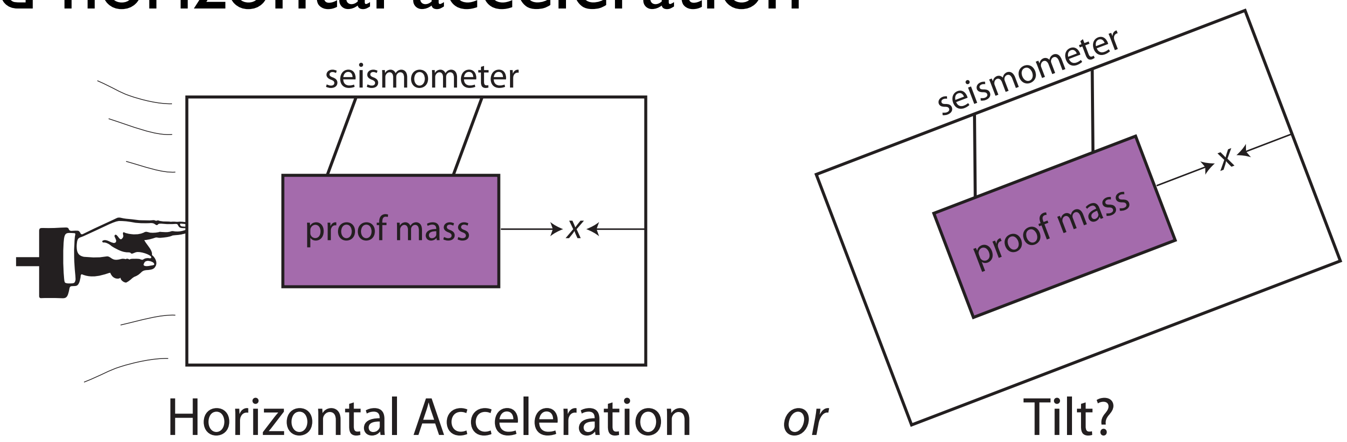
- Path to success involves copy/ paste of existing controls
  - but you should come work with it.

Challenges

- Tilt - horizontal coupling
- Wind induced tilt
- Earthquakes
- Differential motion between platforms
- HEPI structure resonance
- Alignment changes

Tilt-Horizontal coupling

- Horizontal accelerometers can not distinguish between Tilt and horizontal acceleration

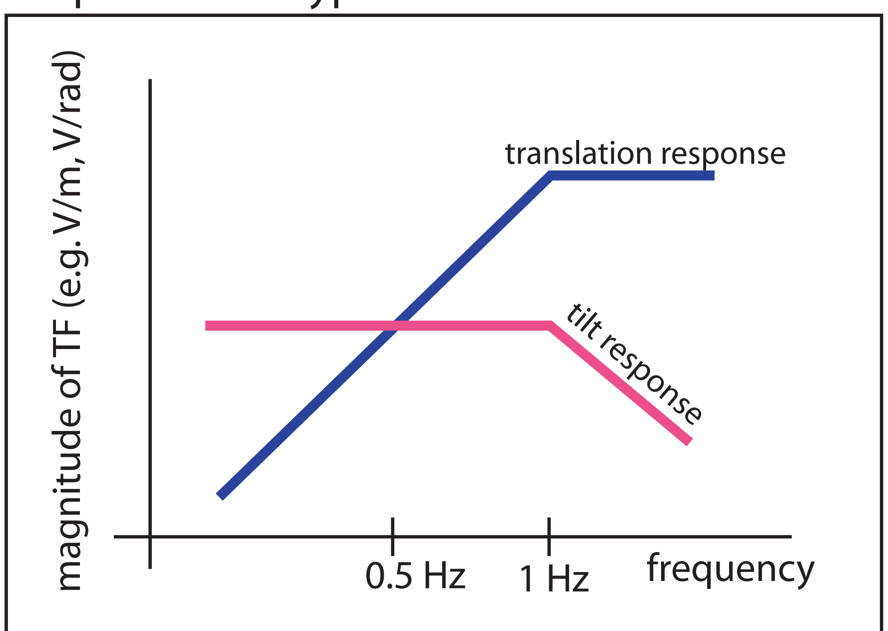


relative response scales as g/w^2, so tilt coupling dominates at low frequency.

$$x_{pm}^{(h)} \propto \left(x_{sp}^{(h)} - \frac{g}{\omega^2}\theta \right)$$

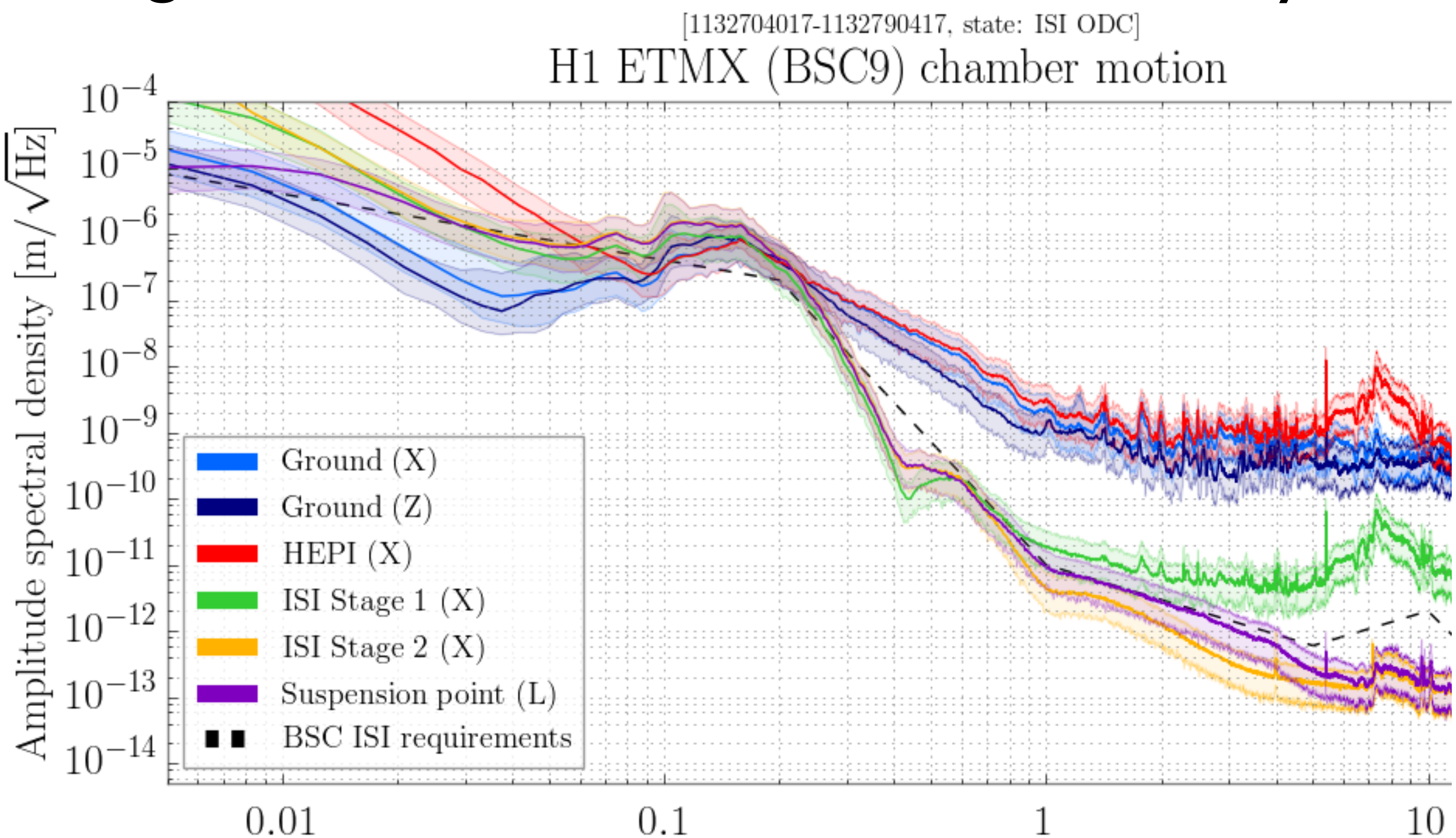
If you follow the sensor signal, then tilt -> real translation-> excess rms

Response of a hypothetical 1 Hz seismometer



Tilt-Horizontal coupling

- Horizontal accelerometers can not distinguish between Tilt and horizontal acceleration
- Trouble below 0.1 Hz almost always can be traced back to tilt-horizontal coupling.
- Hard to diagnose - because the sensors are always suspect



Tilt-Horizontal coupling

- Horizontal accelerometers can not distinguish between Tilt and horizontal acceleration

What can be done?

1. Measure the tilt and subtract it from the ground sensor.
   - Krishna Venkateswara built & installed inertial rotation sensors - called the Beam Rotation Sensors (BRS) see G1600451
2. Reduce the amount of slab tilt
   - Biggest source of tilt is local building tilt driven by the wind.

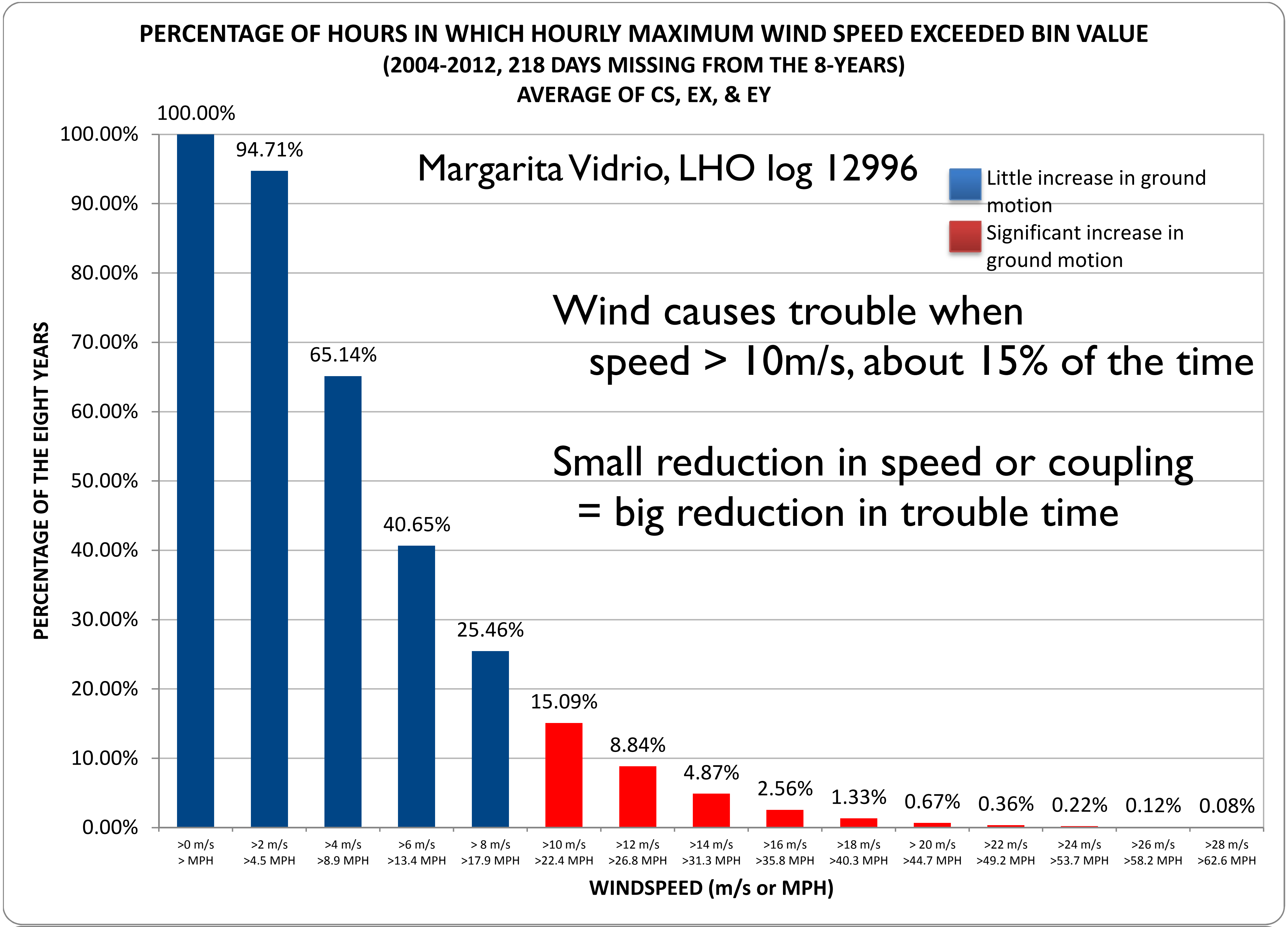
Current topics:

Measure and subtract the ground tilt using the BRS

Look at IFO signals at Hanford vs. wind and control tuning

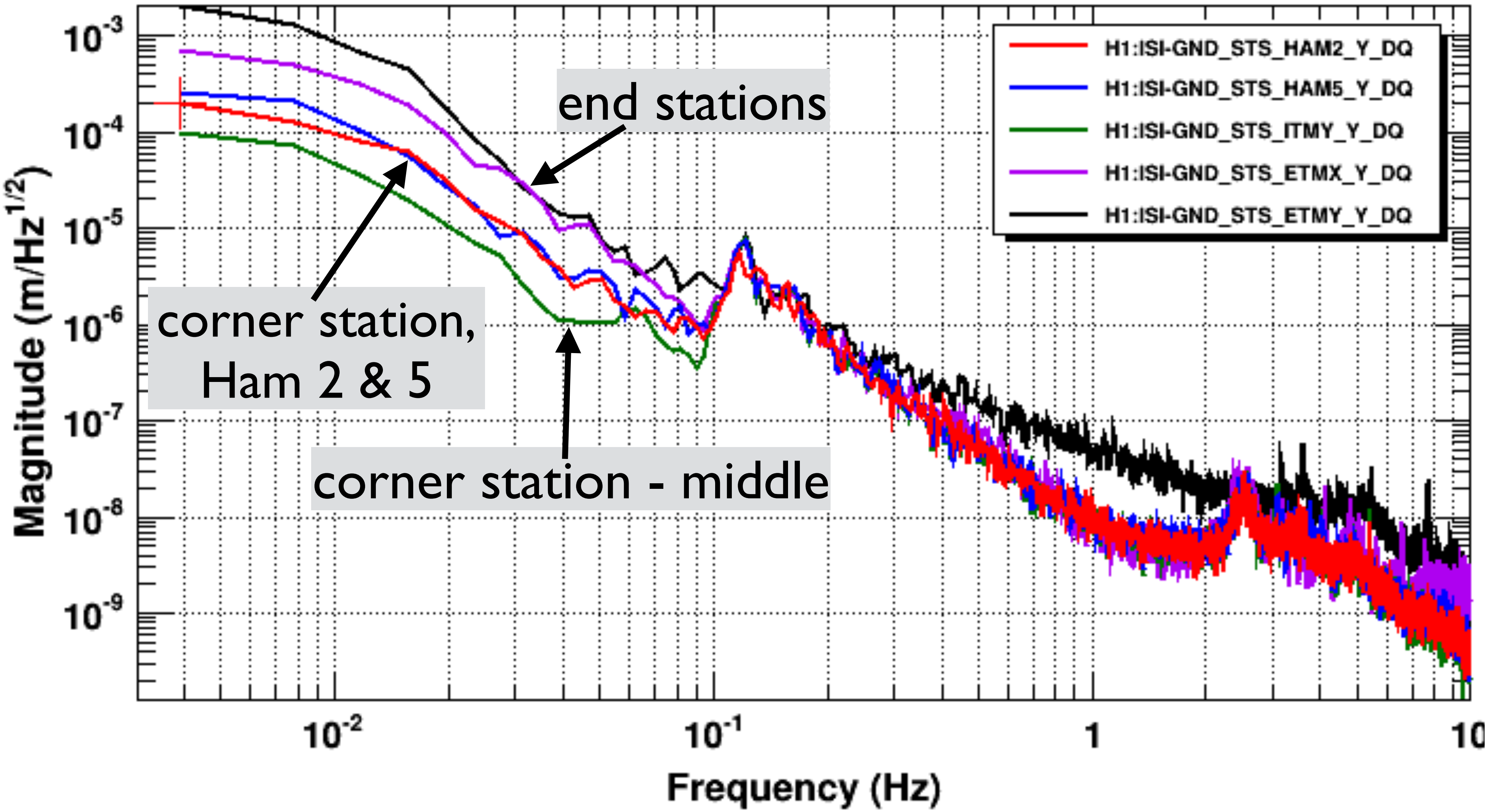
Design buildings which tilt less

Wind speed distribution



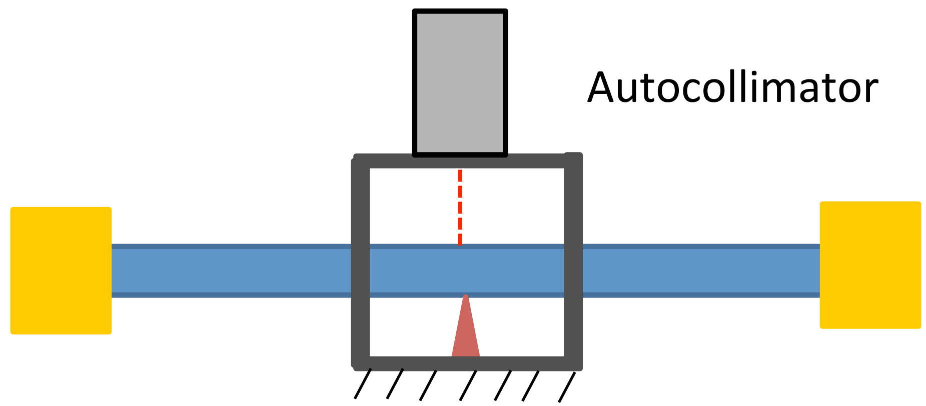
Wind moves the building

Ground motion signal in Y, Nov 16 with strong wind



H. Radkins LHO log 23440, Nov 16, 2015

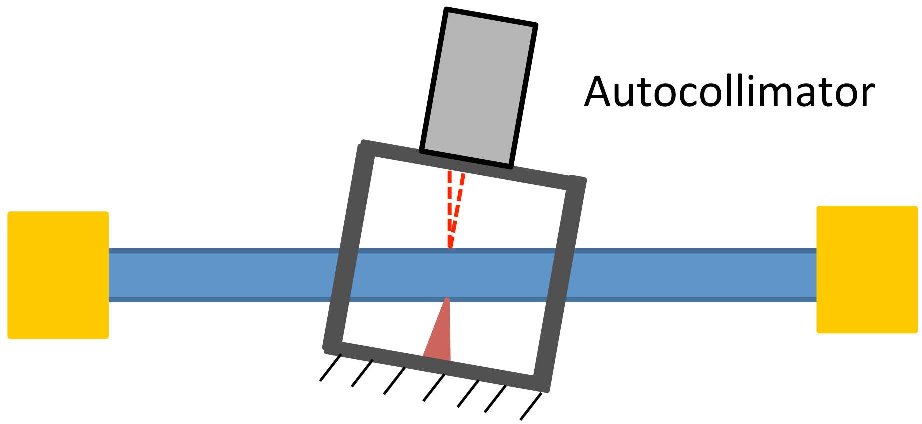
Beam Rotation Sensor



Ground tilt is measured by measuring angle between ground and low frequency beam balance.

Horizontal acceleration can be rejected by locating center of mass at the pivot.

Beam Rotation Sensor



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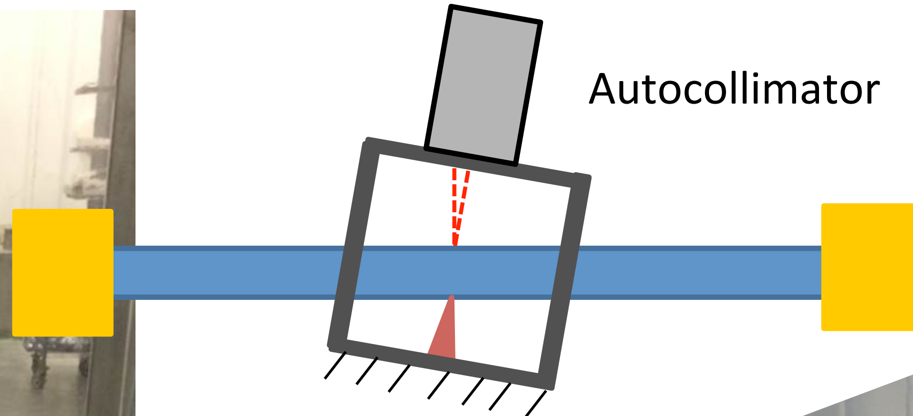
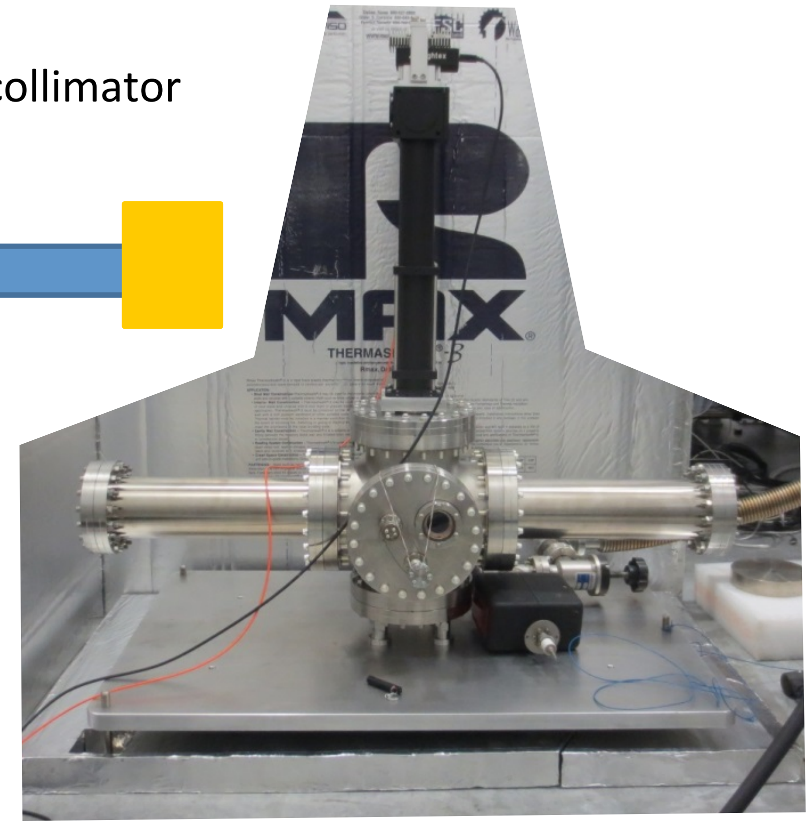
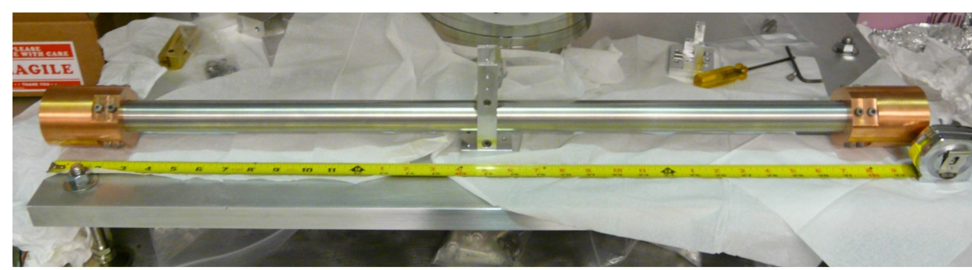
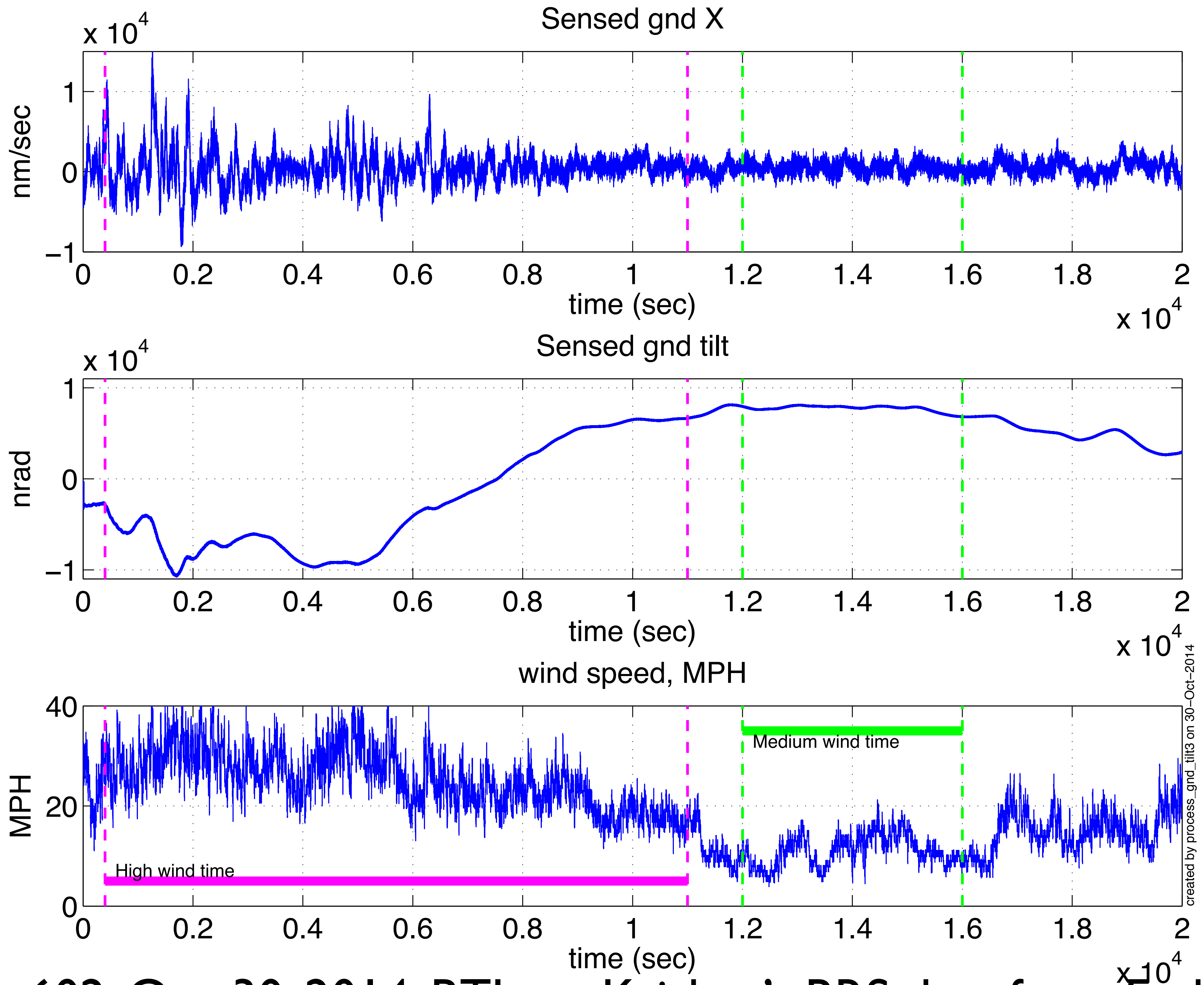




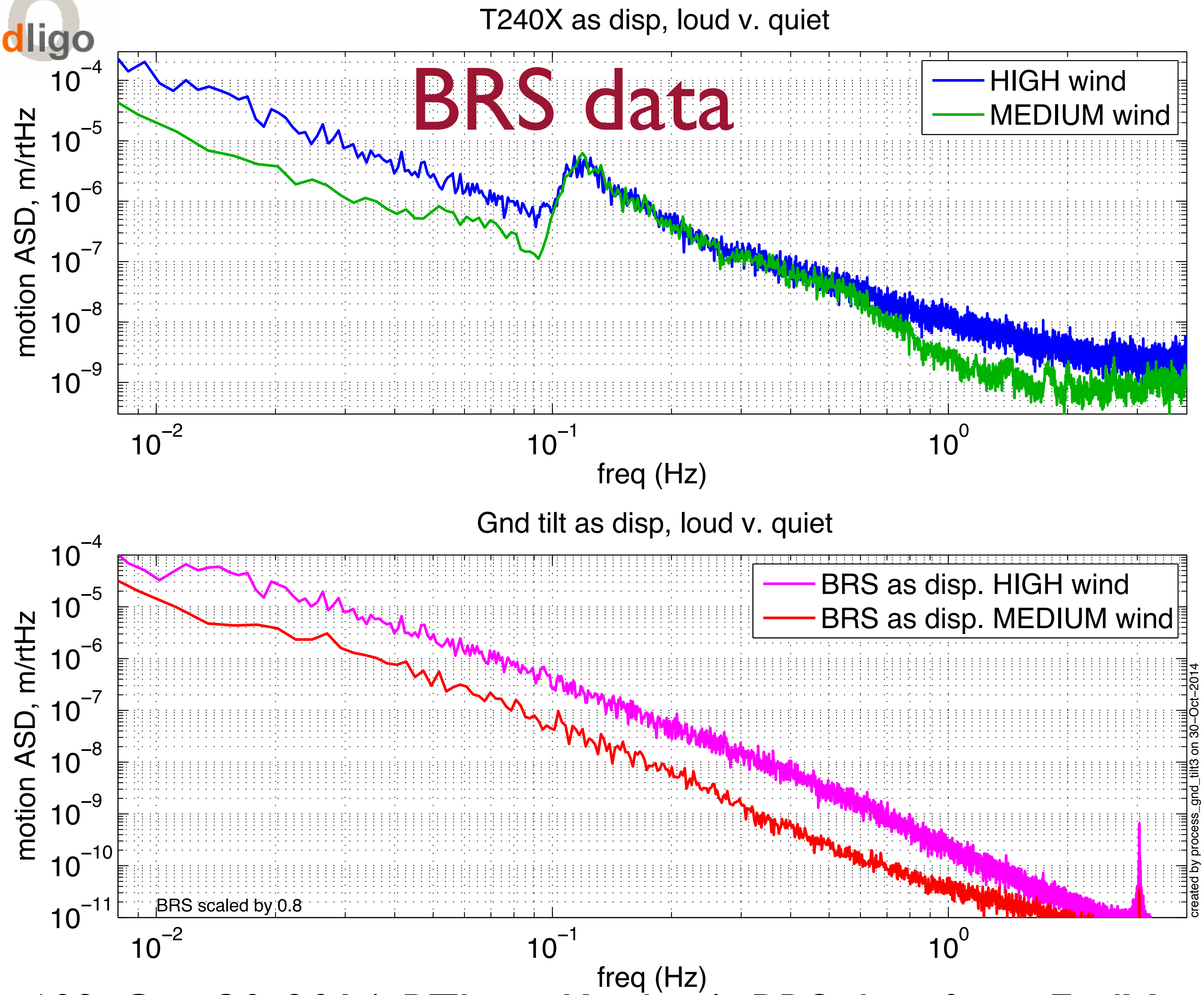


advancedligo

BRS data

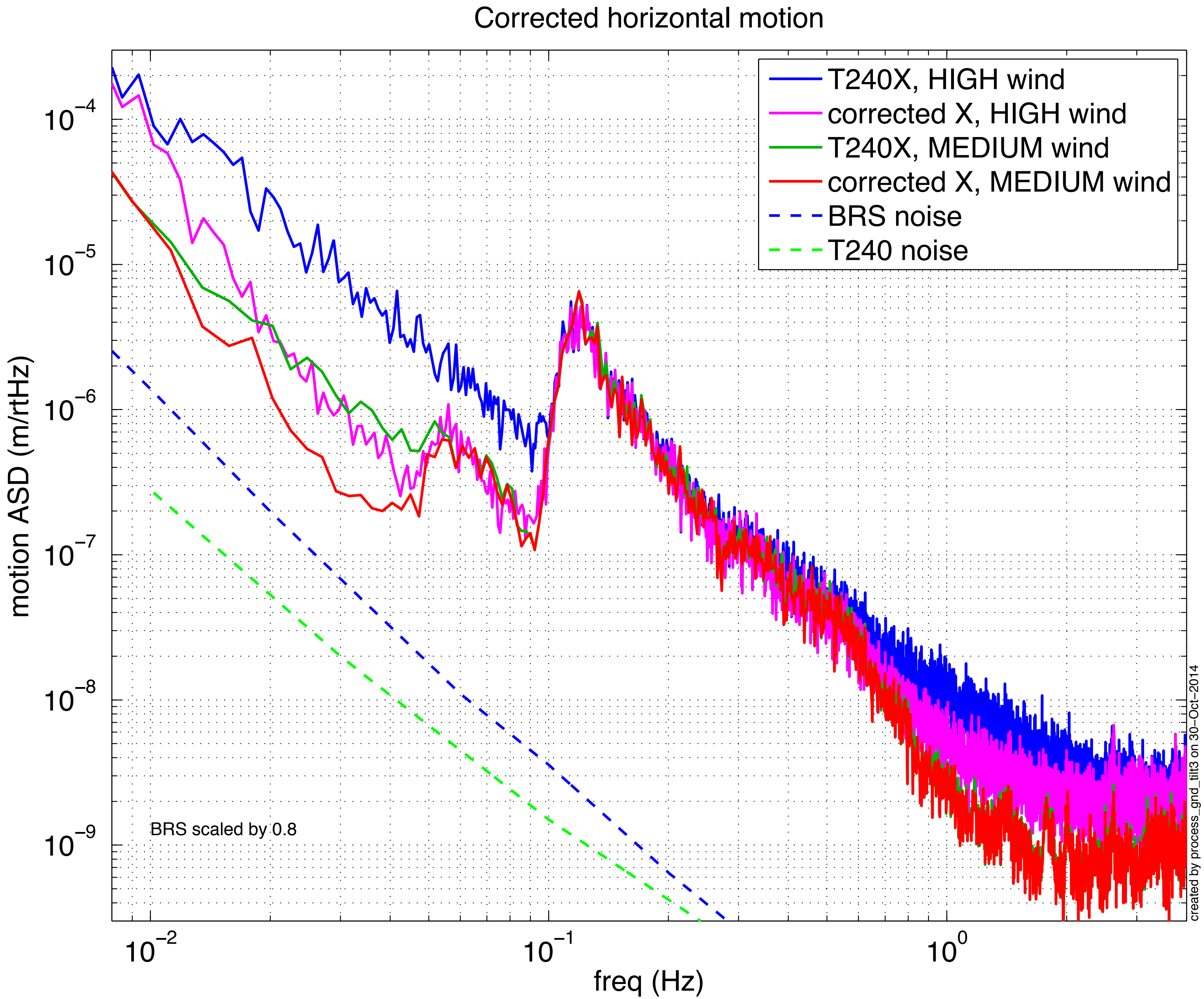


SEI log 602, Oct. 30, 2014. BTL on Krishna's BRS data from EndX



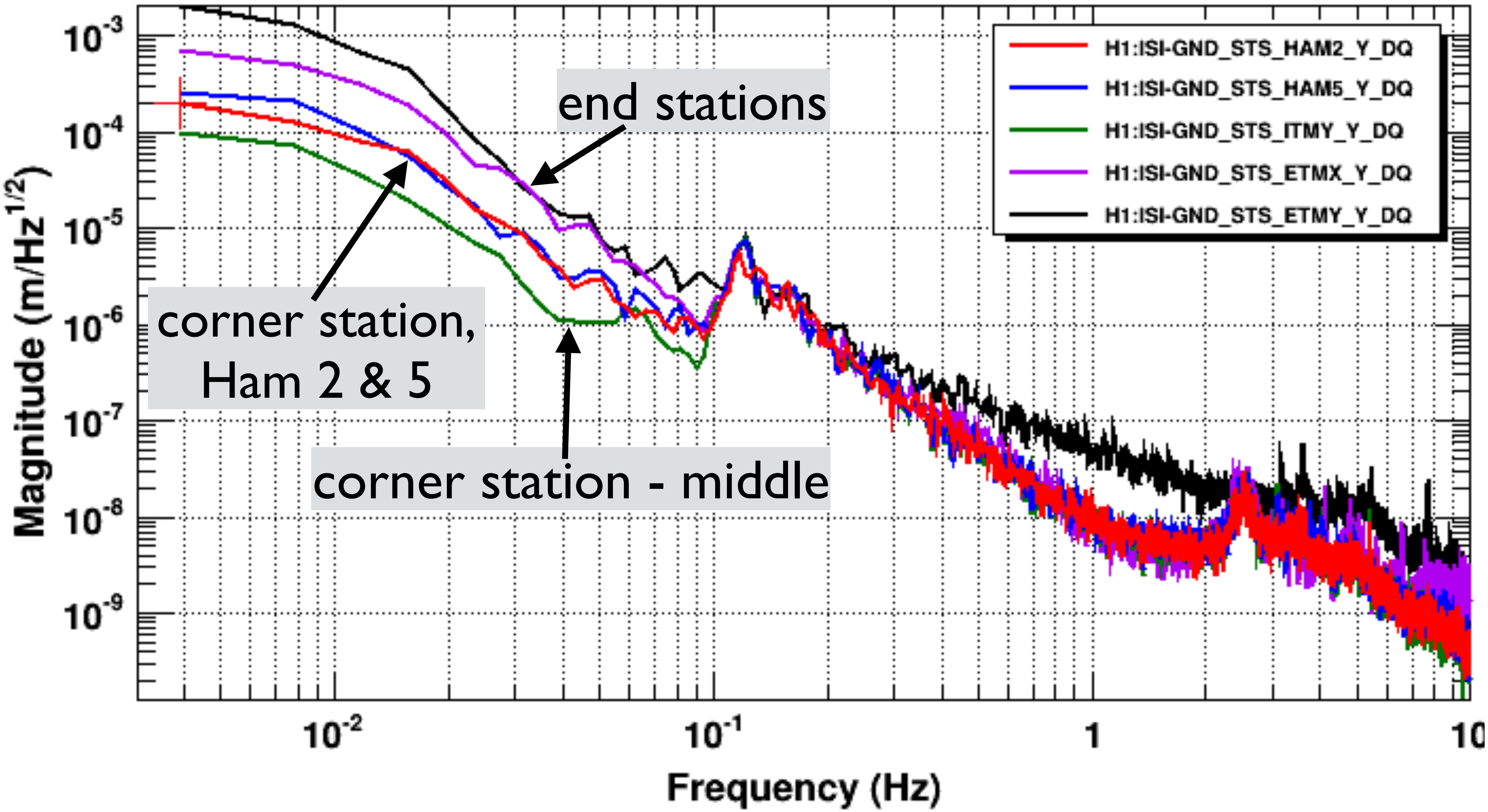
SEI log 602, Oct. 30, 2014. BTL on Krishna's BRS data from EndX advancedligo

Corrected motion w/ BRS



Building details matter

Ground motion signal in Y, Nov 16 with strong wind



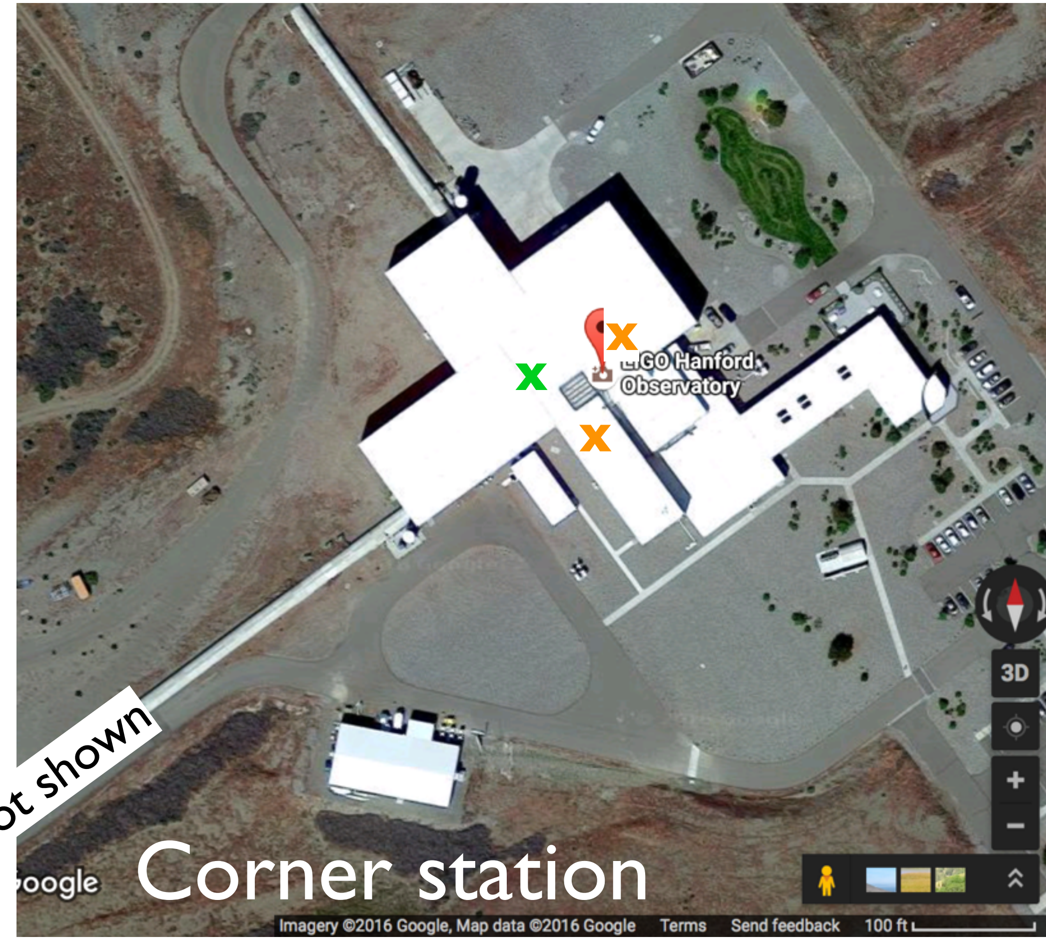
H. Radkins LHO log 23440, Nov 16, 2015

Ground Tilt depends on position

Red position has ~ 10x more than green position.

Likely due to building shape, and distance between walls and sensor

LHO studying wind fences



4 km arm not shown

sensor locations are approximate

dominant high-wind direction

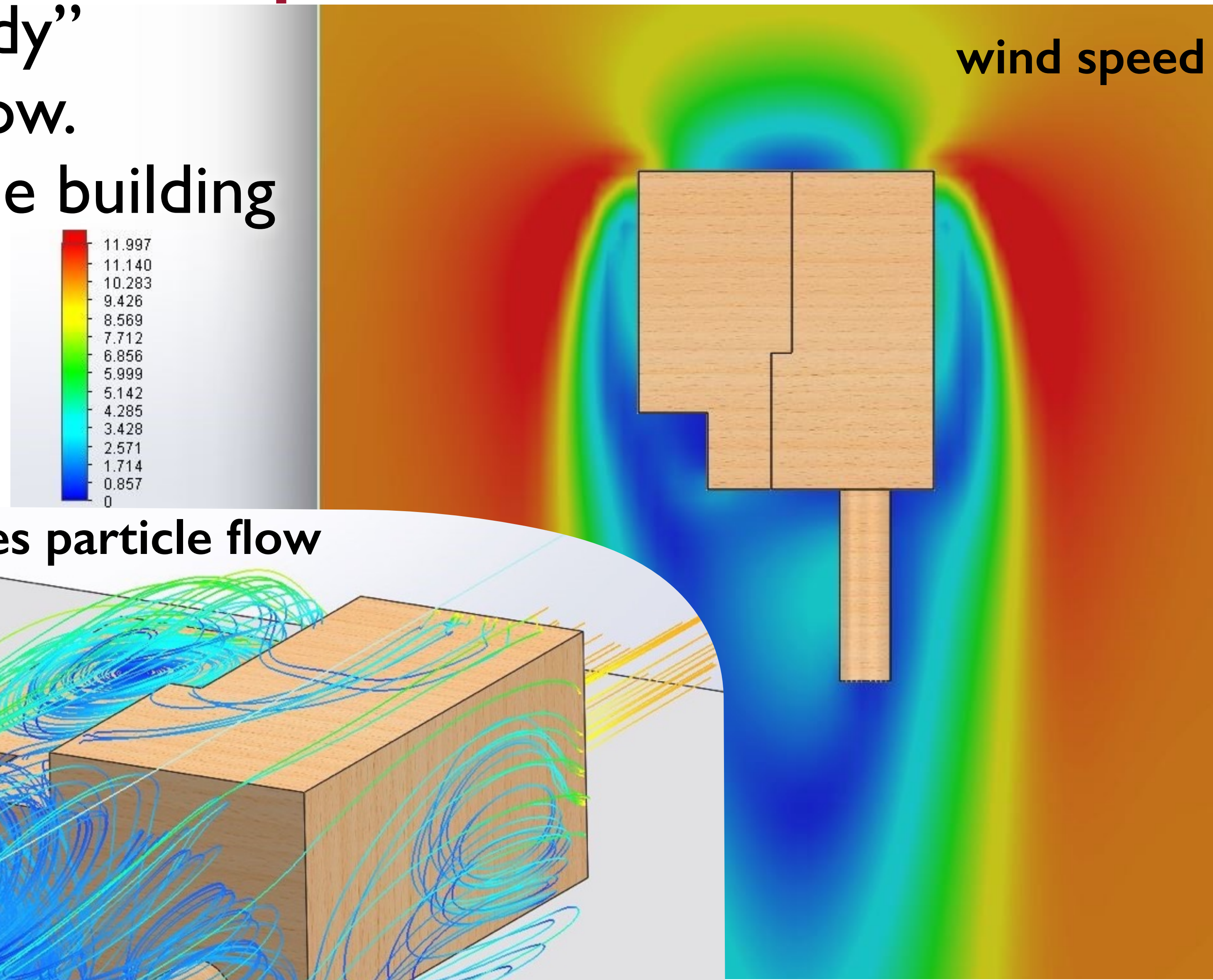
LIGO-India should make a better end station.

What are the statistics for wind at your site?

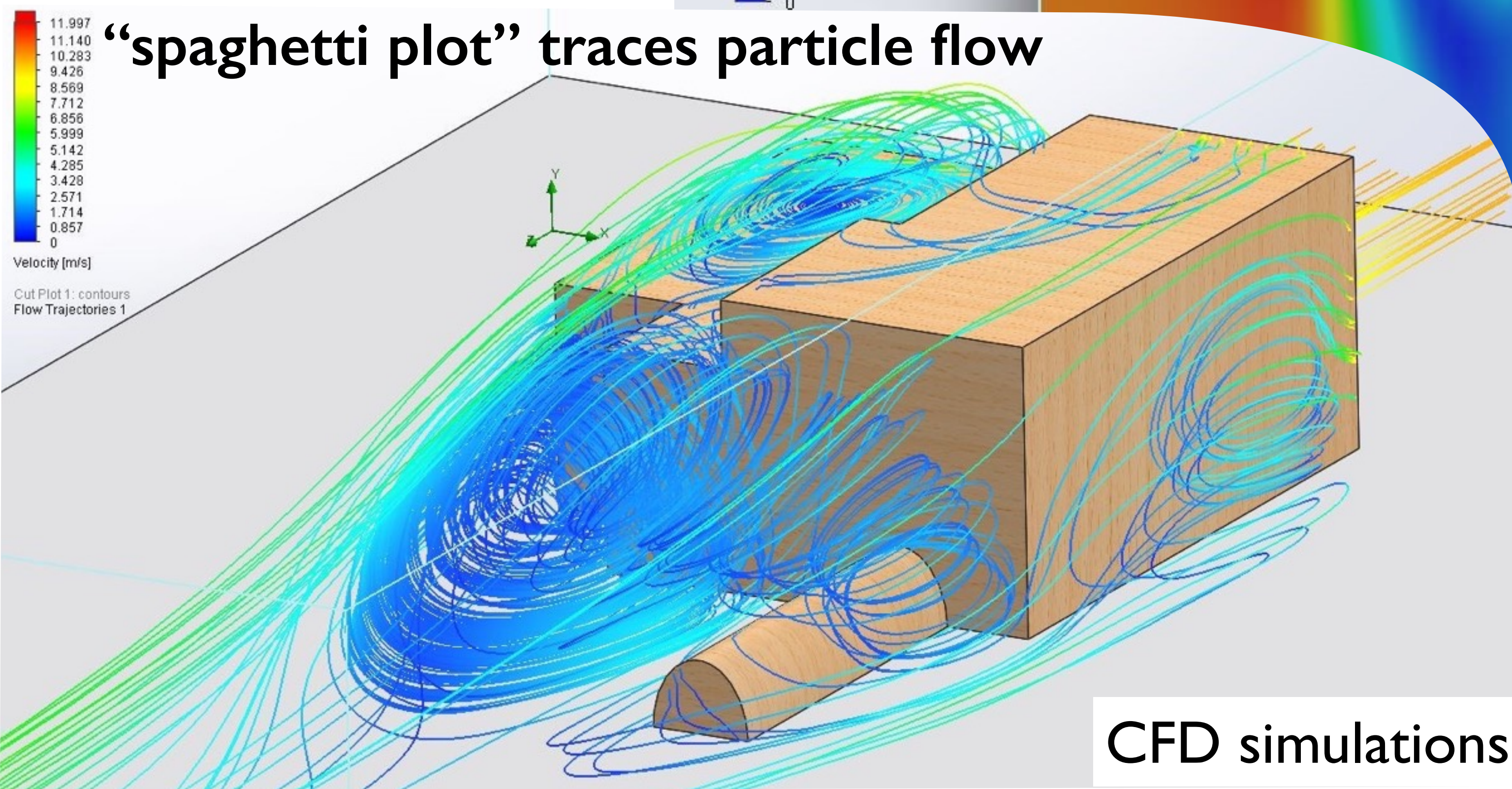
Airflow past End-Y

Impact of "Bluff Body" buildings on airflow.

The wind shakes the building

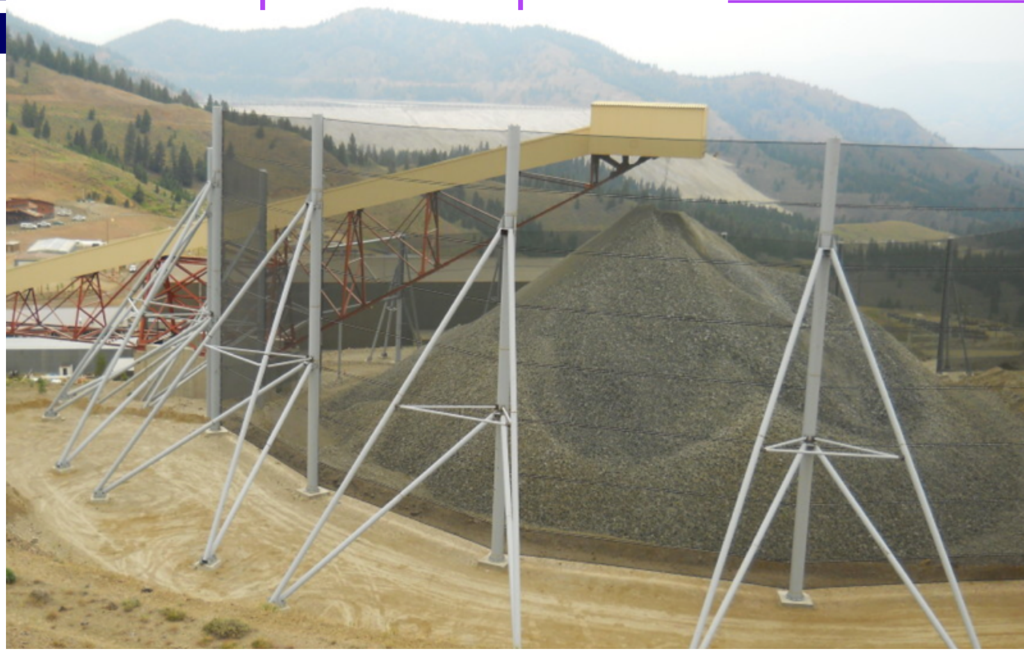


"spaghetti plot" traces particle flow



CFD simulations by Ian Gomez

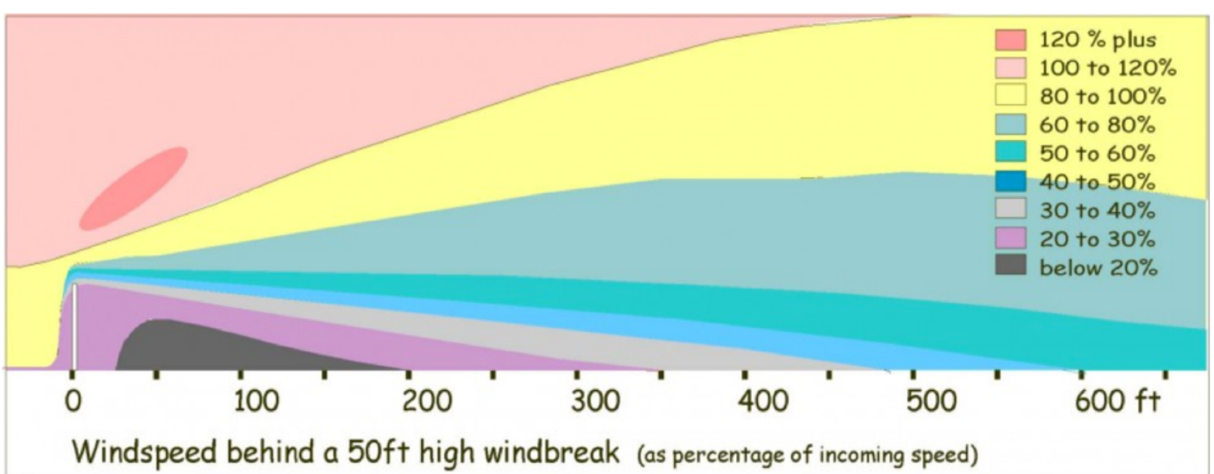
windfence picture and plot from WeatherSolve.com

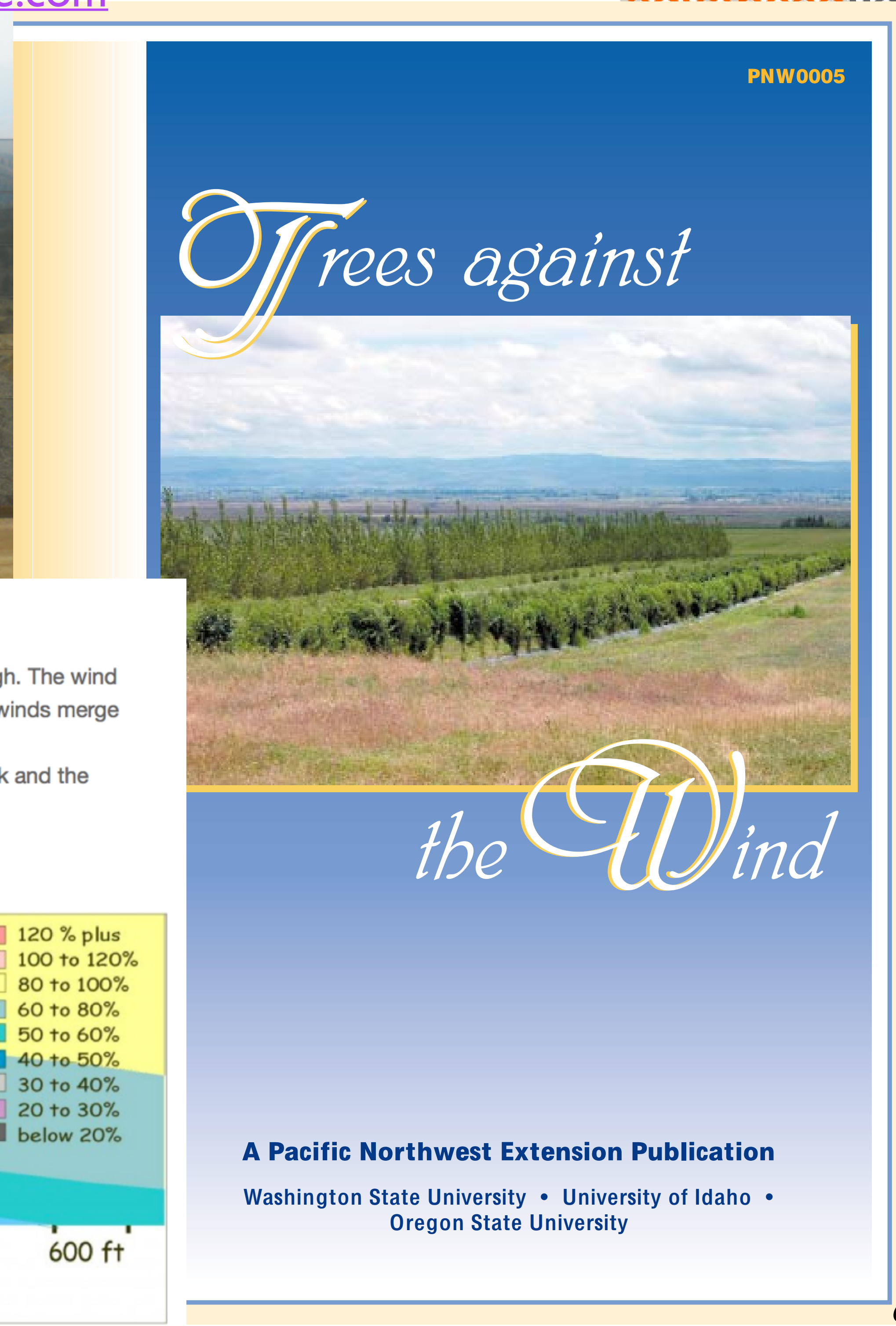


Wind Fences

Windbreaks control the amount of “crashing down and in” by letting a little wind flow through. The wind flowing through holds the faster (deflected) wind away for a few hundred feet. This lets the winds merge together again more gently with less turbulence.

The effects are shown in the drawing which shows a side view of a well-designed windbreak and the windspeeds around it.





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Wind Fences

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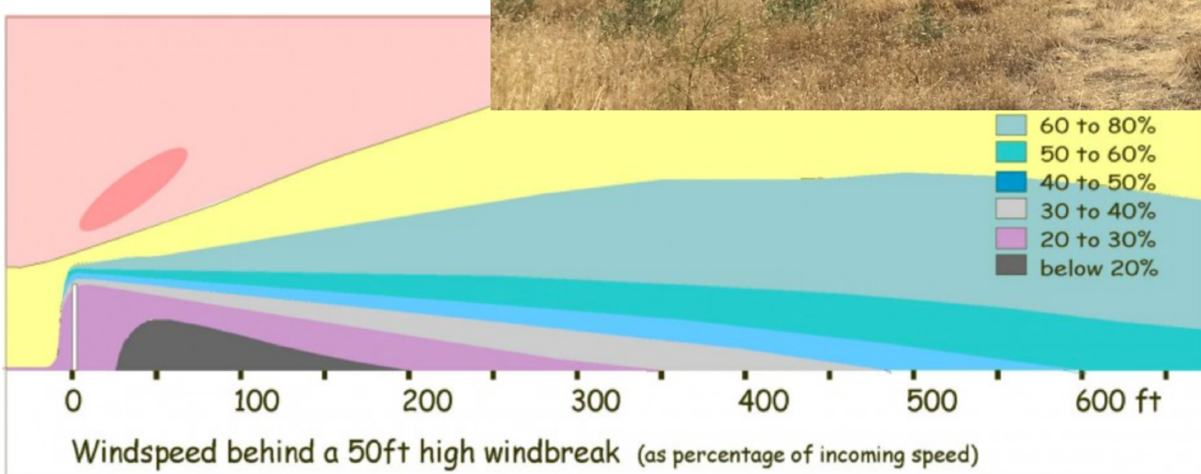


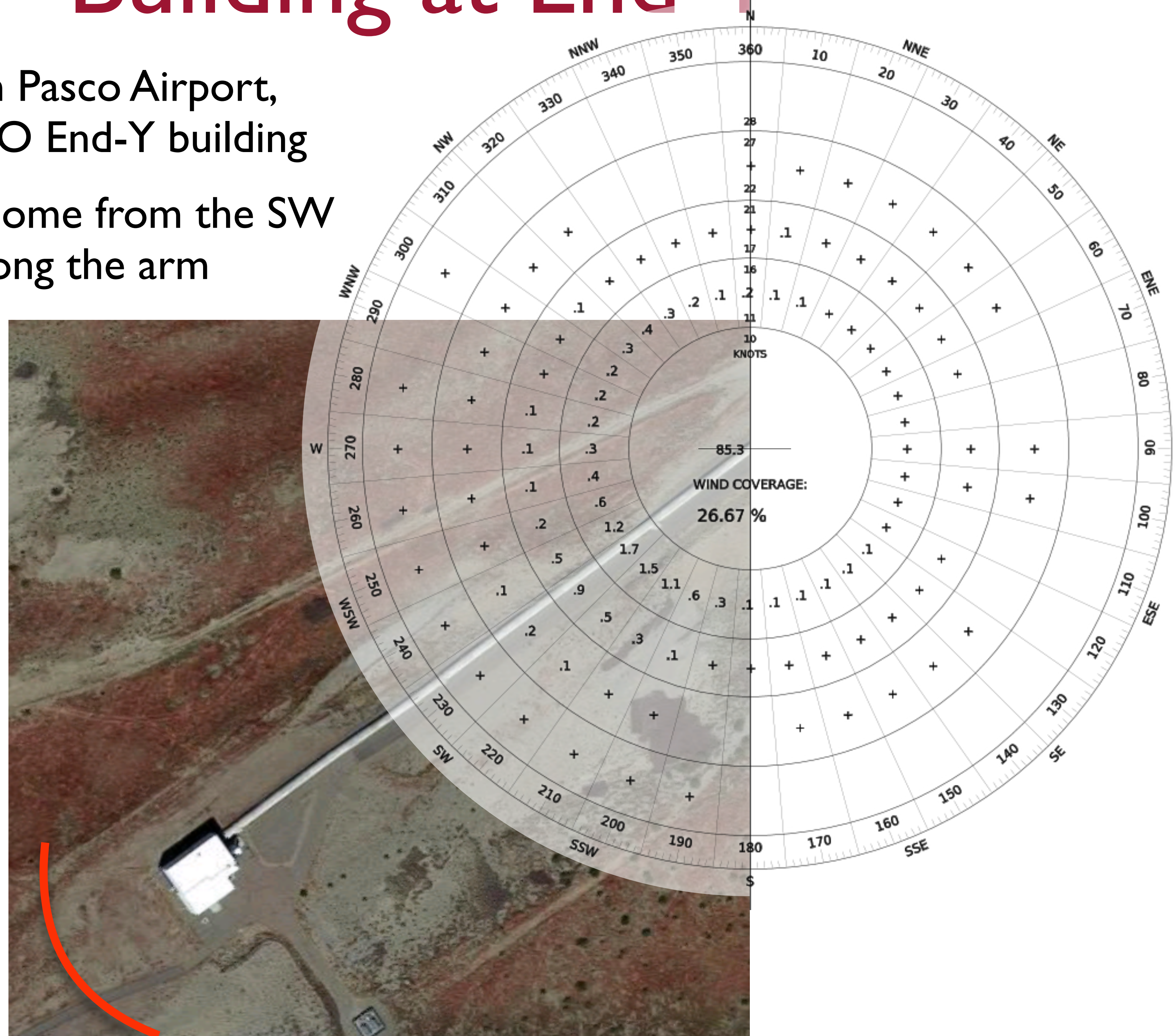
A Pacific Northwest Extension Publication

Washington State University • University of Idaho • Oregon State University

Building at End-Y

Wind rose from Pasco Airport,
placed on the LHO End-Y building

The strong winds come from the SW
and blow along the arm



Can we/ Should we install a wind fence at LHO?

Earthquakes

What can we do to make the IFO more resistant to teleseismic earthquakes?

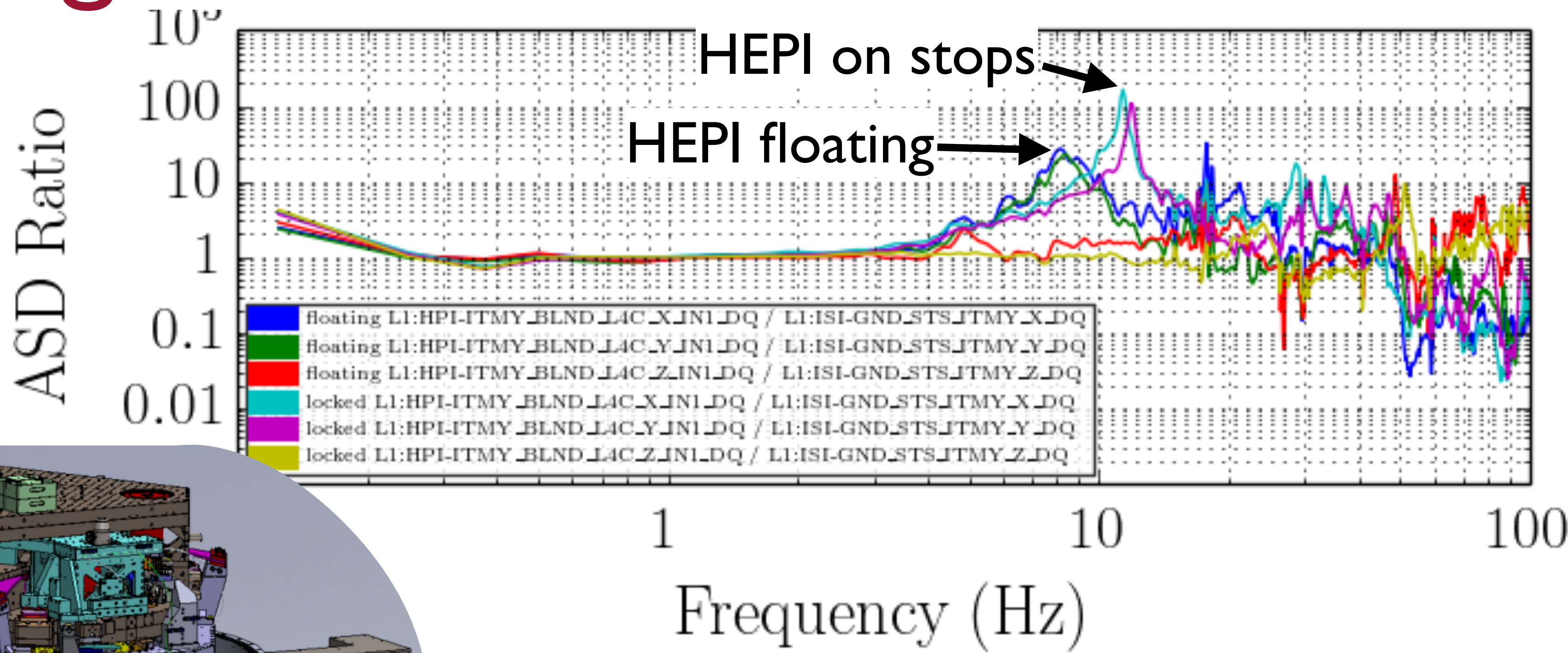
USGS network allows us to predict the arrival of the various waves at the site.

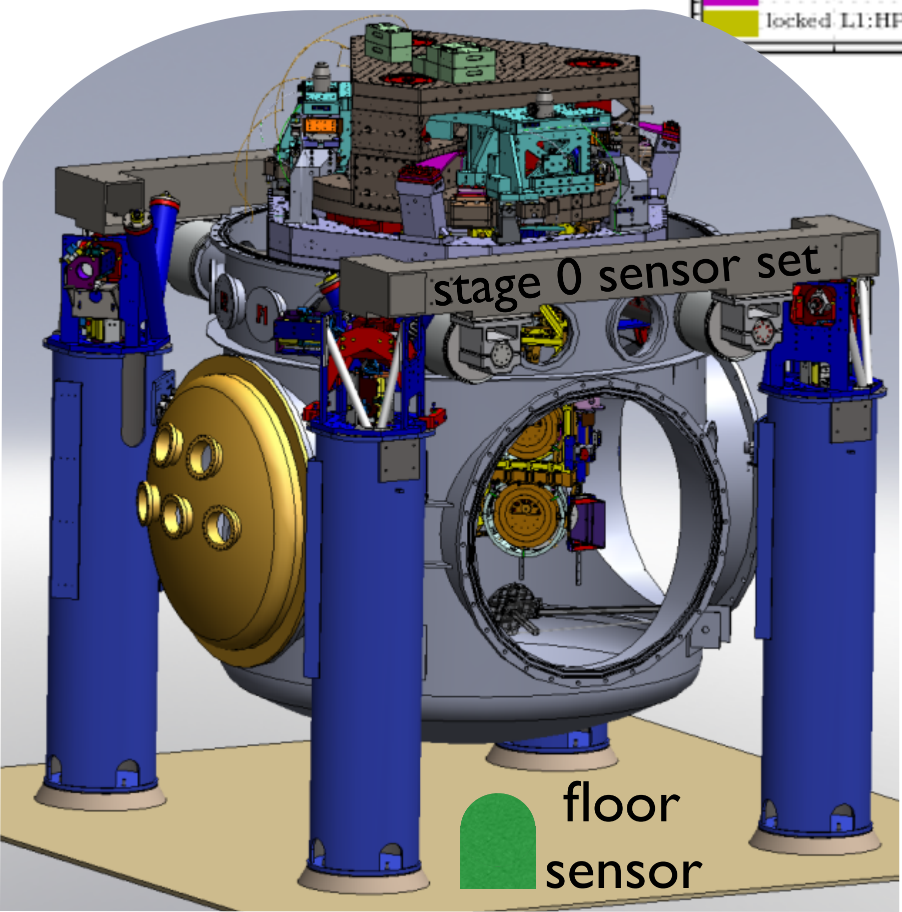
Guardian allows us to change the mode of the detector (e.g. high noise, high range)

Might have a manual system up by O2.
- Terramon alerts the operator of impending shake
- operator can use guardian to switch modes

Good models of ground motion, seismic system, and SUS would help this

Stage 0 structure resonance





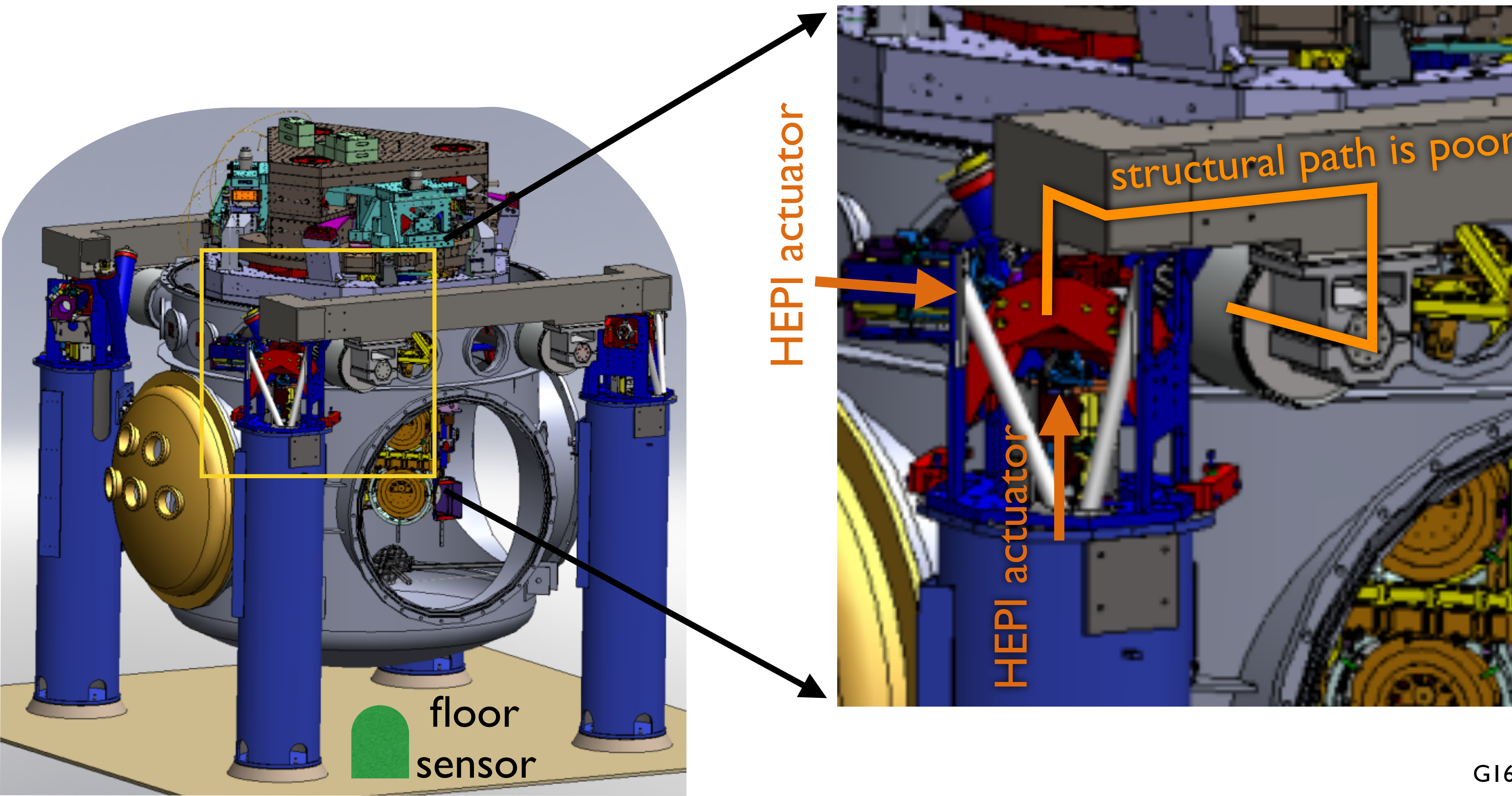
Sensors on stage 0 move more than the floor at 8 Hz/ 11 Hz

G1400858, G1401167,
L. Nutall, T. MacDonald, C. Collette

Stage 0 structure resonance

Unconstrained flexibility of stage 0 structure, particularly in the radial direction compromises HEPI stage and adds motion near 10 Hz.

LIGO-India should address this.



In Conclusion

Seismic System works well.

It is complicated overall, but each part is reasonably simple

We have commissioned these for 20 chambers,
and we're pretty good at it.

You should come work with it.

It is just a part of the big system,
we are still learning about the integration.

Several challenges remain, you can help

LIGO-India facility can be better than LHO and LLO facilities.

to consider

wind - fences
wind - building shapes
HEPI stage 0 resonances

Building at End-Y

Wind rose from Pasco Airport, placed on the LHO End-Y building

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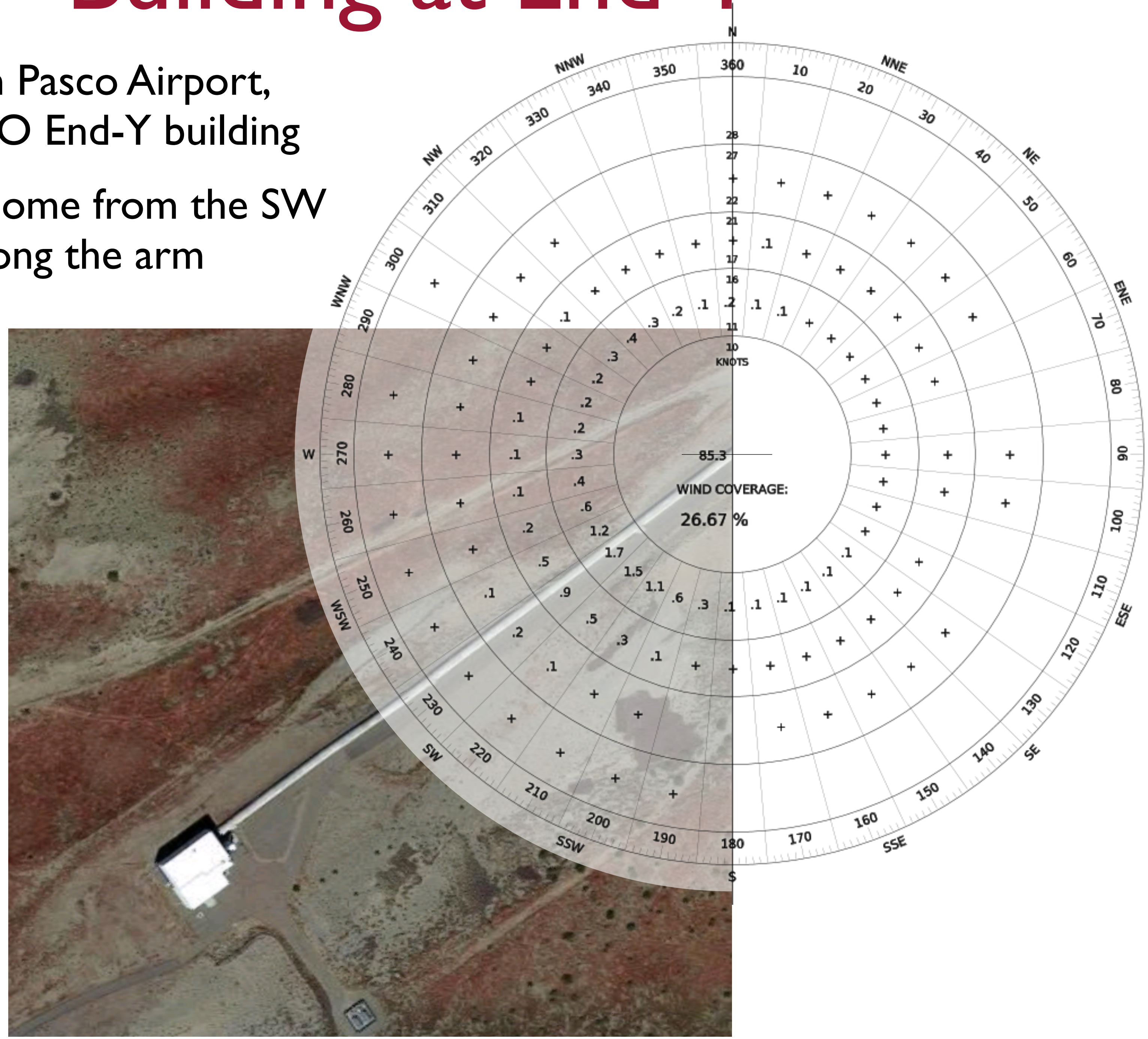
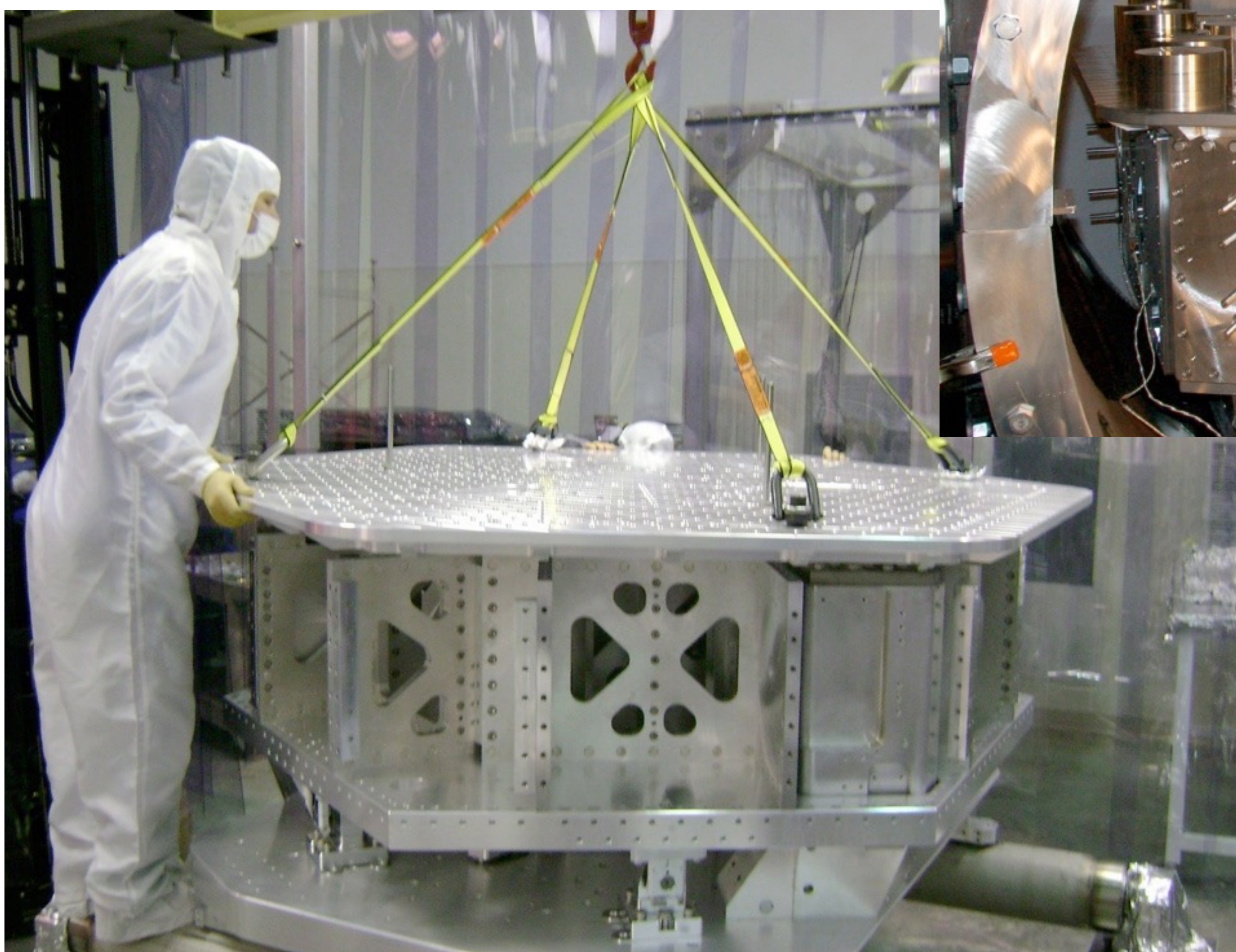
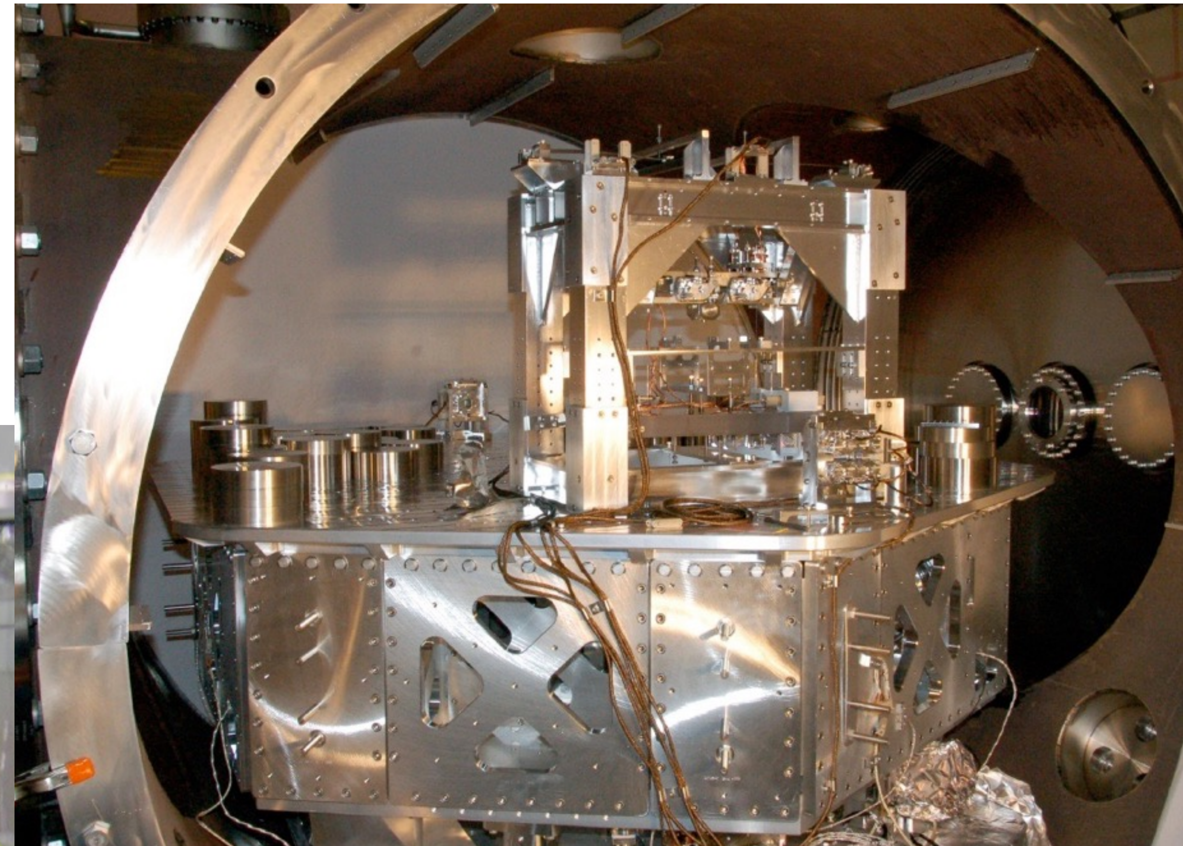


wind rose generated from http://arp-govcloud.jvs.aero:8080/windRose/ airport is KPSC, EY image from Google

Installation into Enhanced

Assembling HAM6-ISI
for Enhanced LIGO

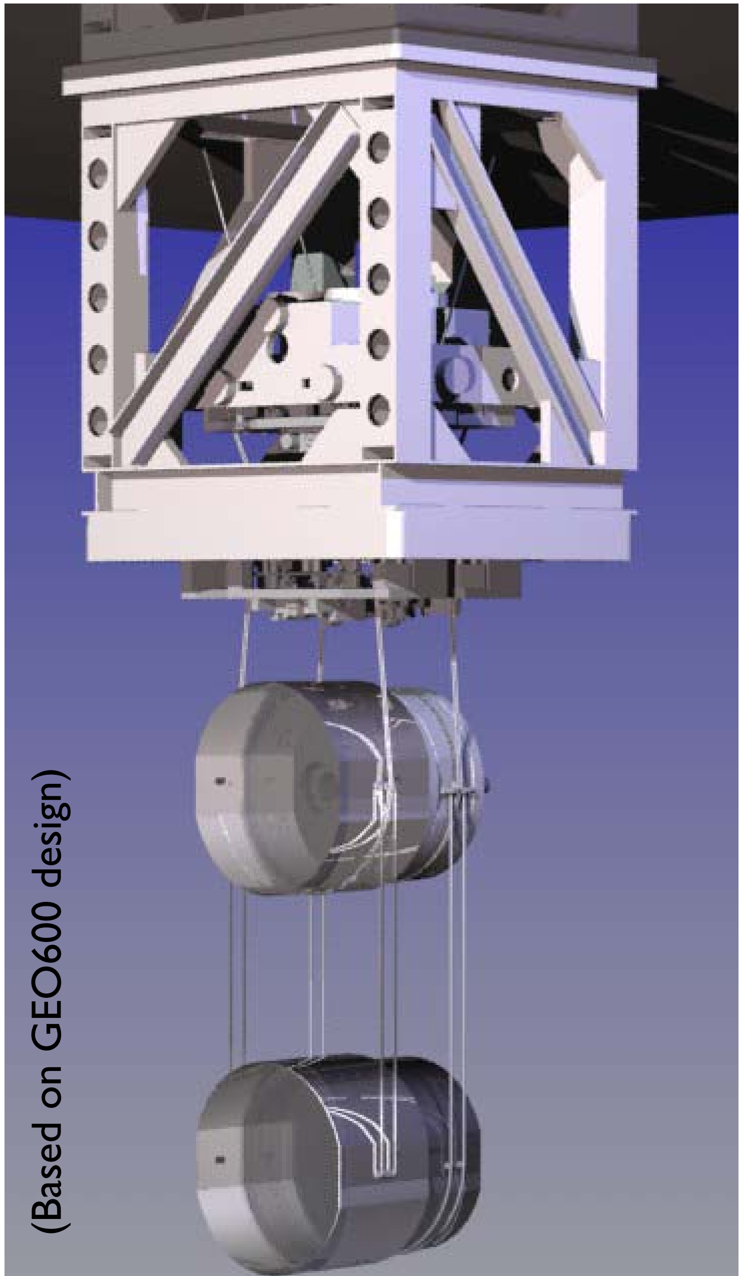




HAM6-ISI installed,
supporting the
Output Mode Cleaner

Pendulum Suspension

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

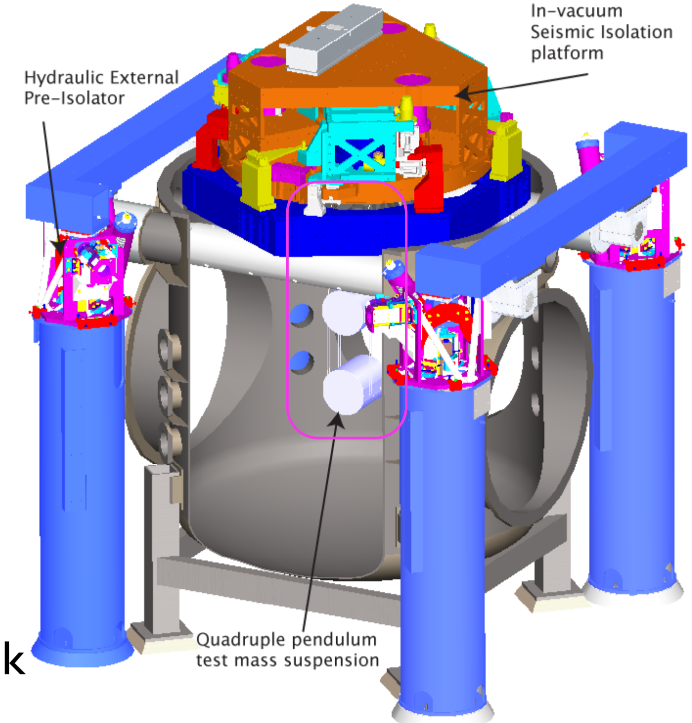


Drawings courtesy of Calum Torrie and GEO600

Multiple-pendulums
for control flexibility &
seismic attenuation

Each stage gives ~1/f2
isolation above the
natural frequency.
More that 1e6 at 10 Hz.

Mirrors are synthetic fused silica
40 kg, 34 cm diameter, 20 cm thick



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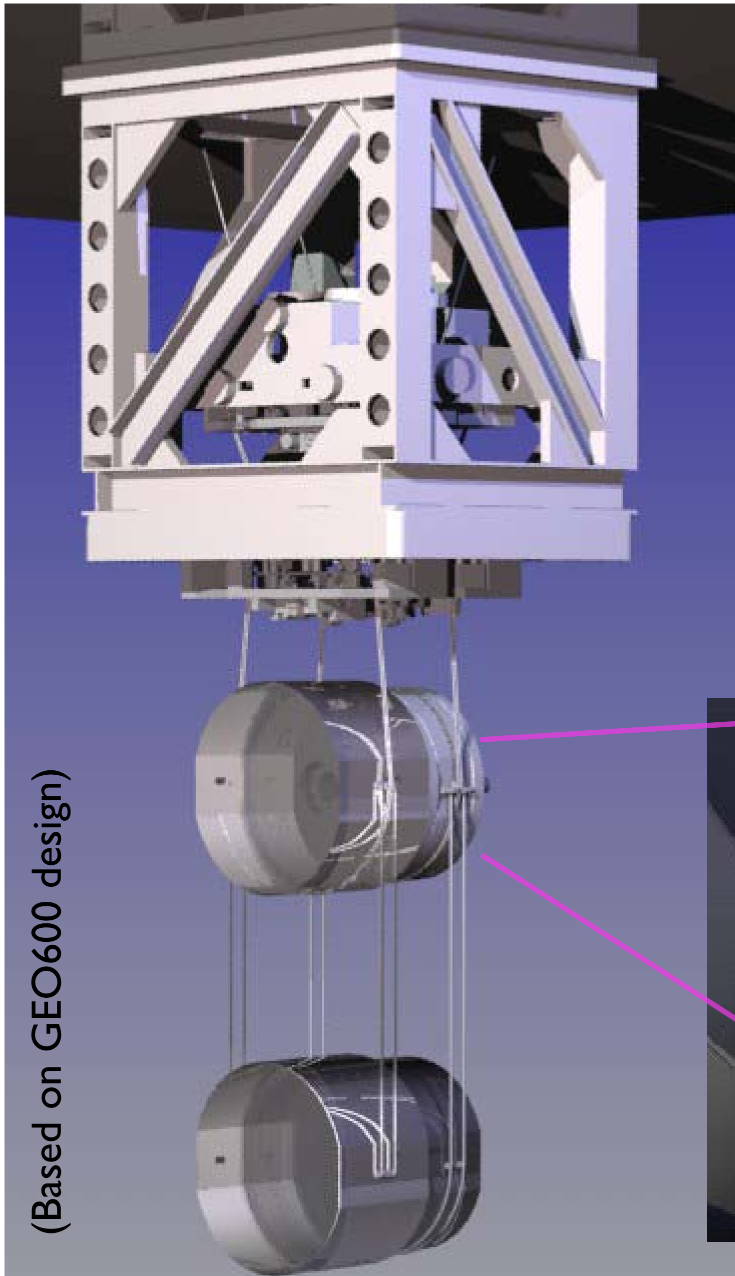

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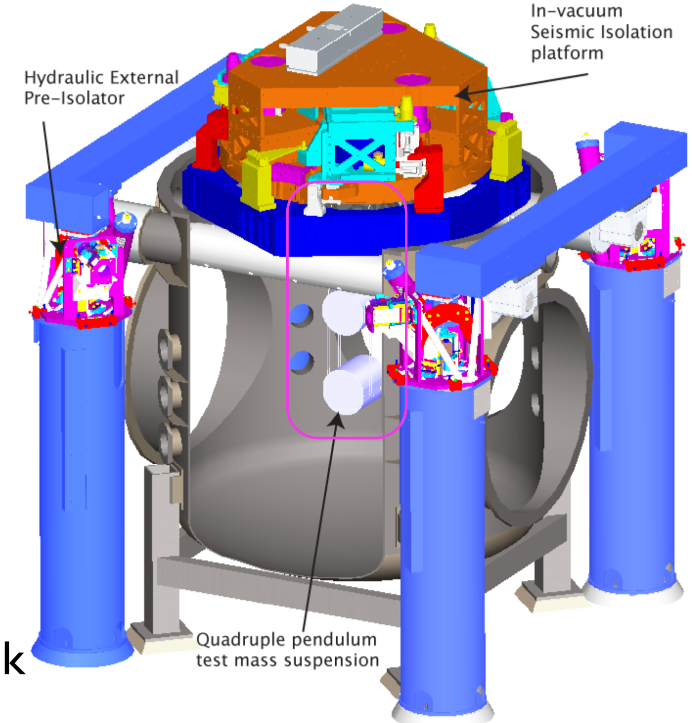
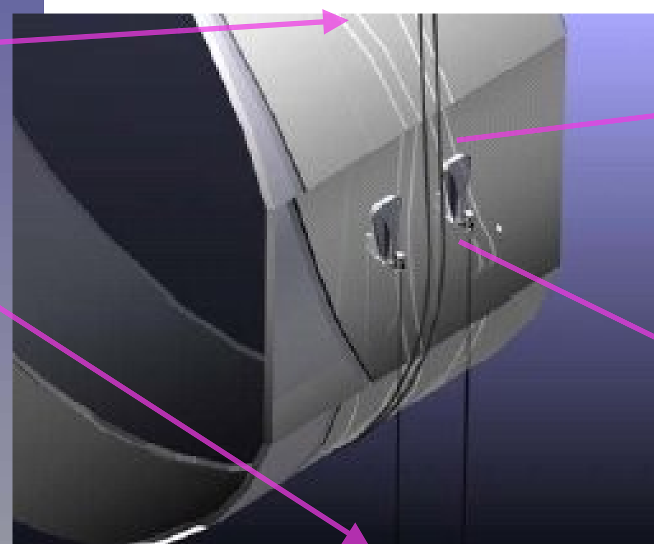
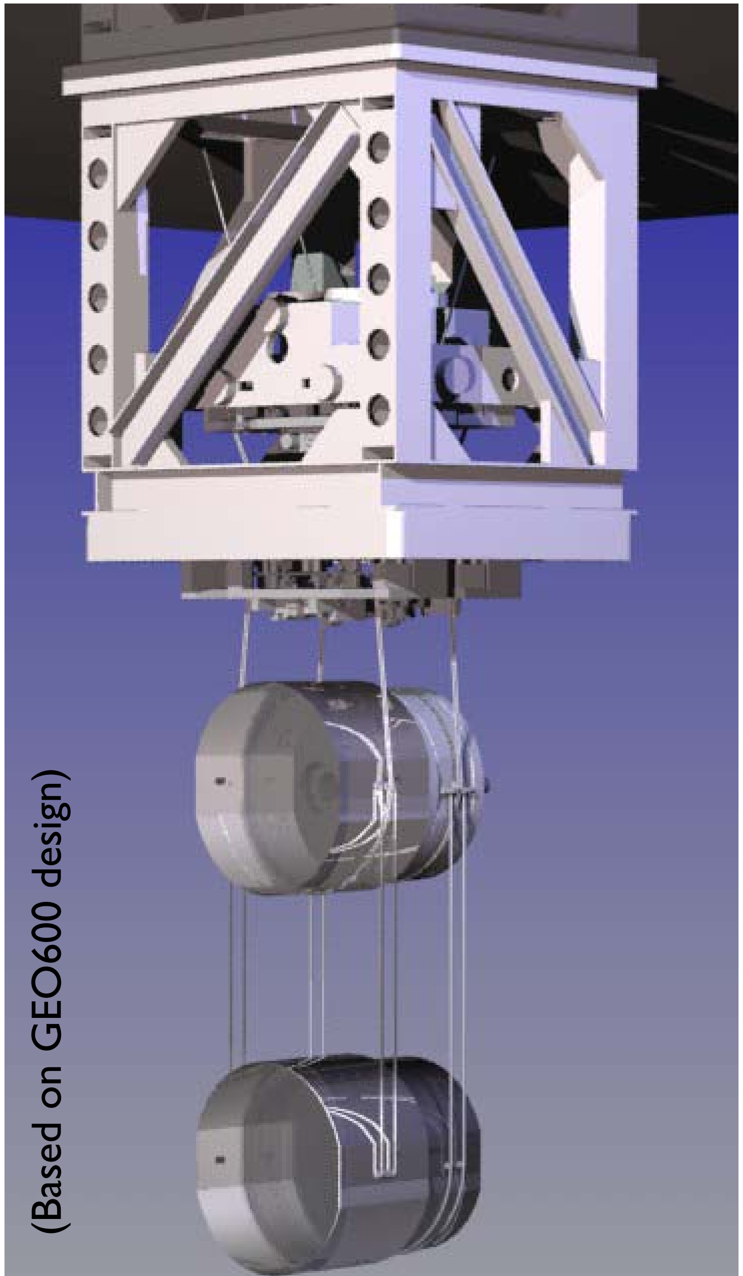




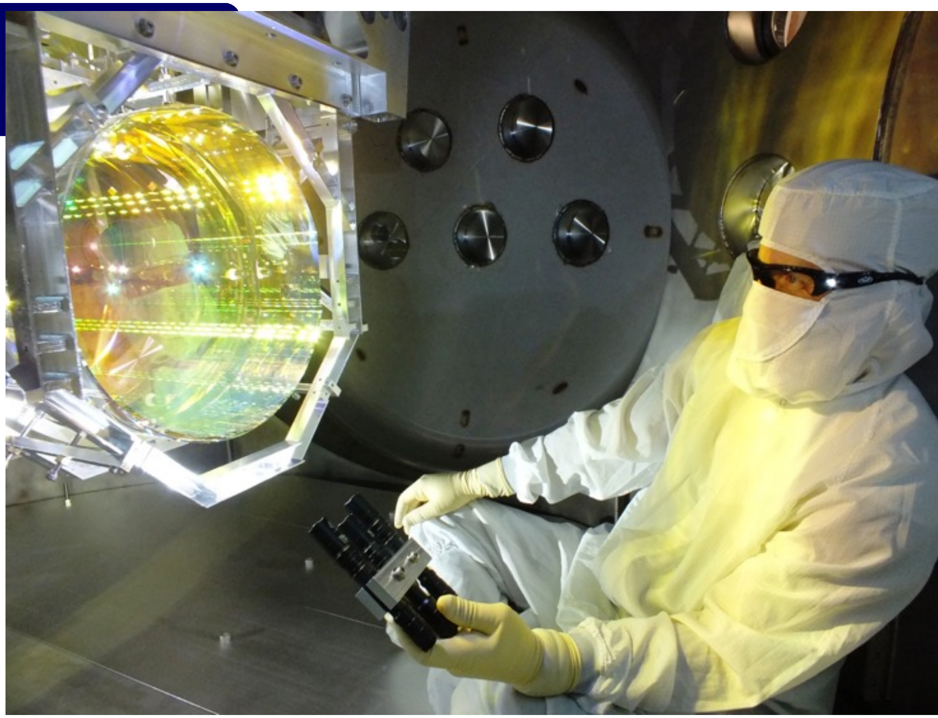
silicate bonding creates a monolithic final stage

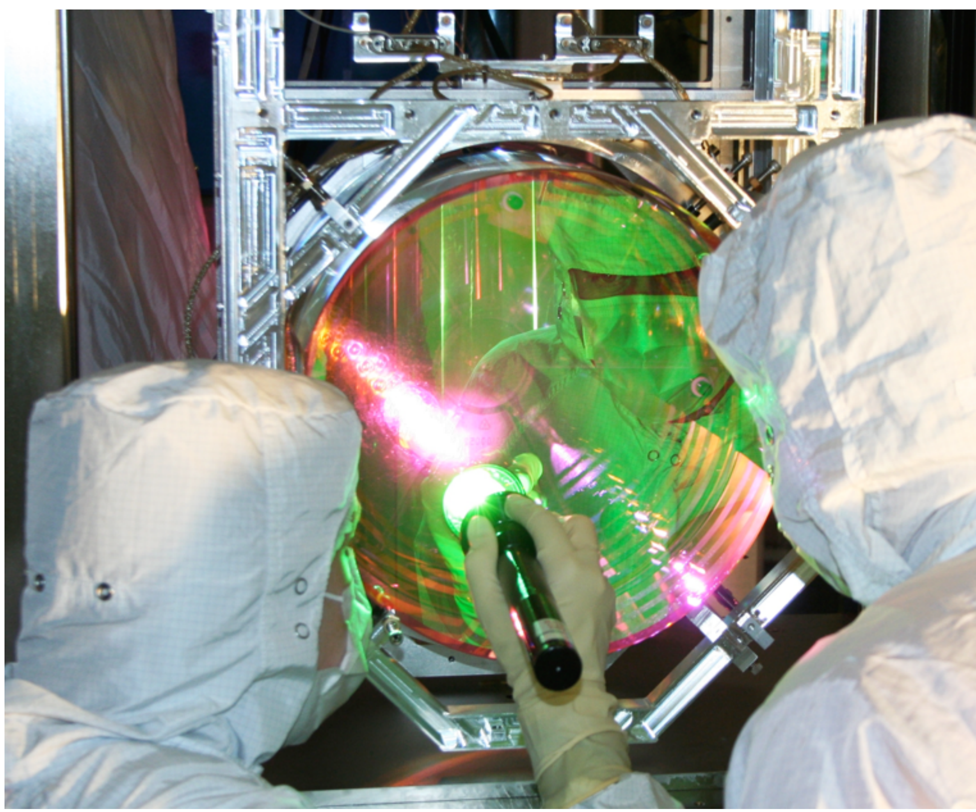
Pendulu

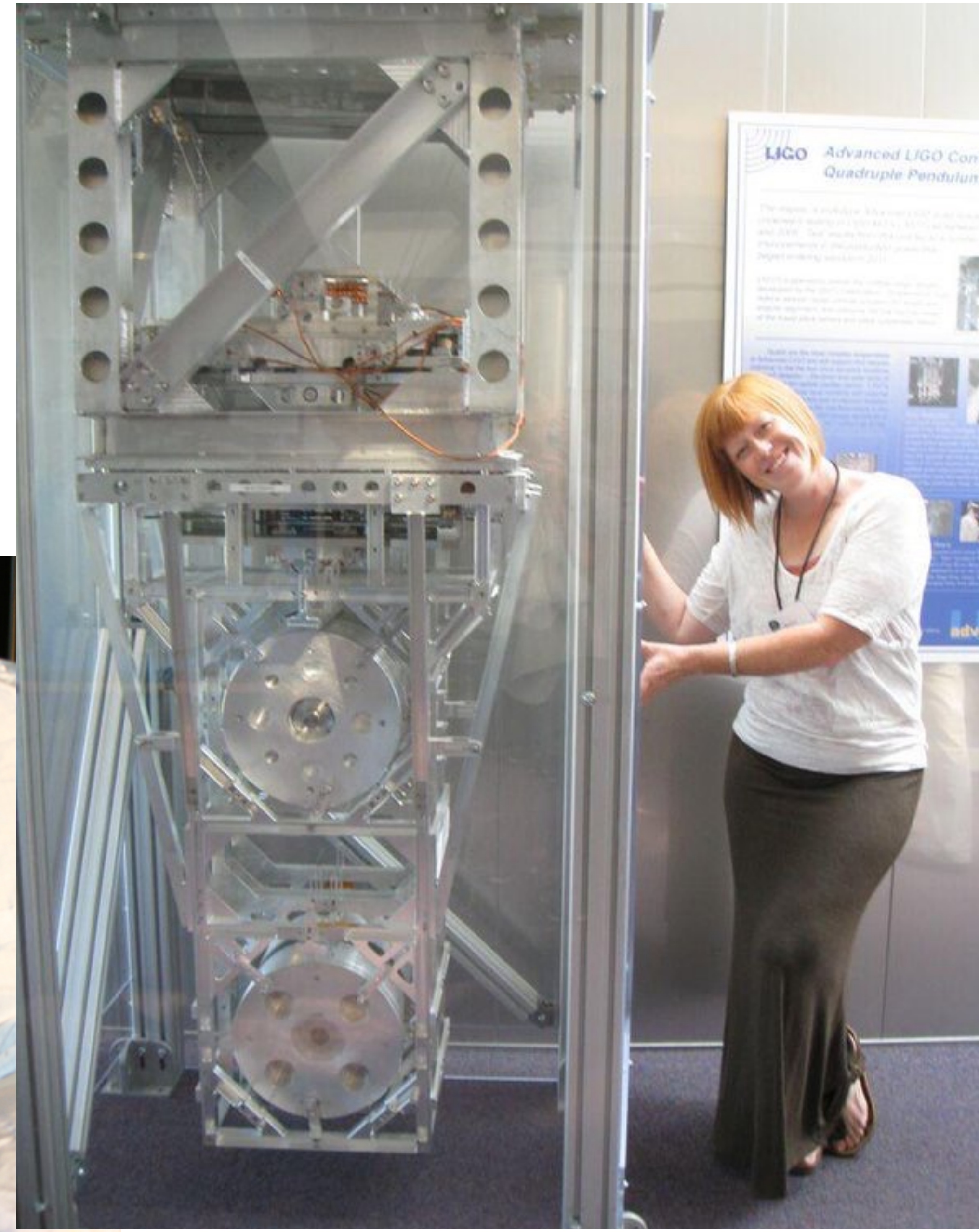


Drawings courtesy of Calum Torrie and GEO600

r picts





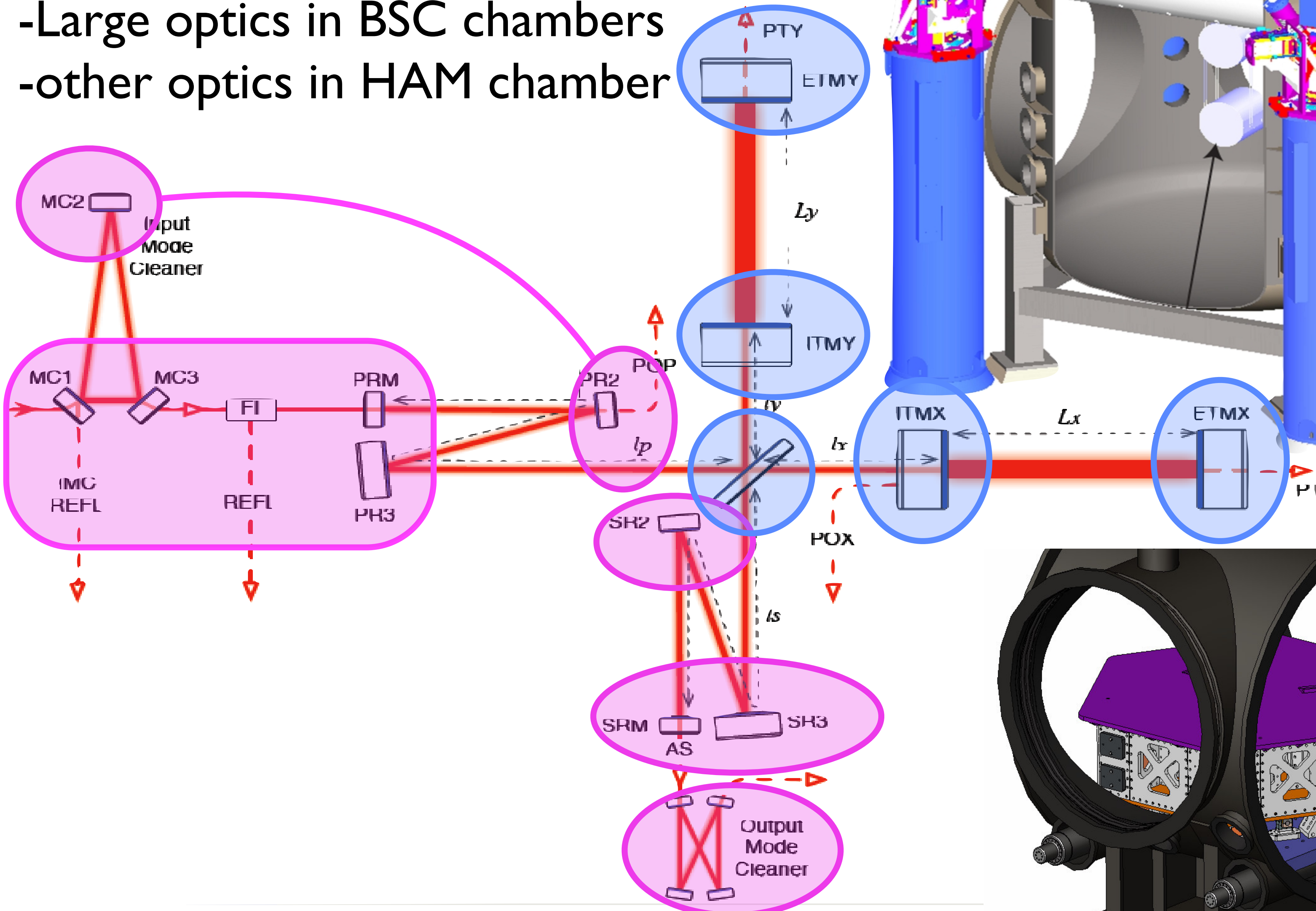


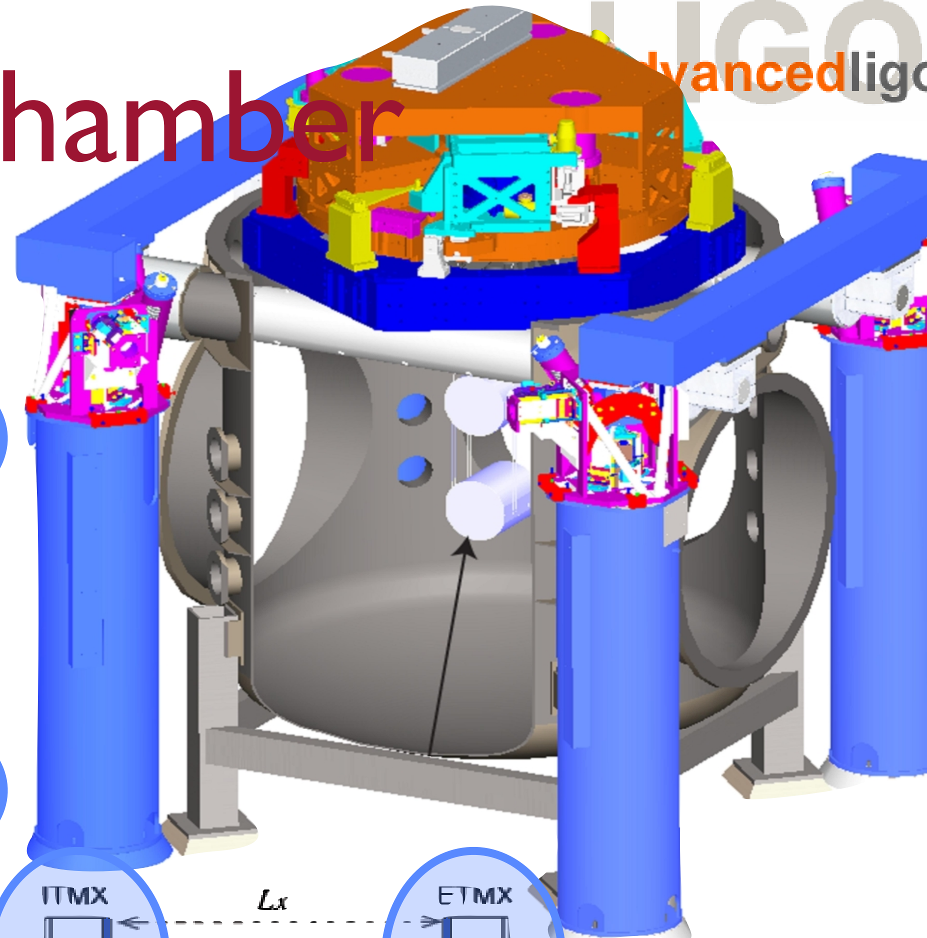
2 styles of chamber

Support all the in-vacuum IFO optics

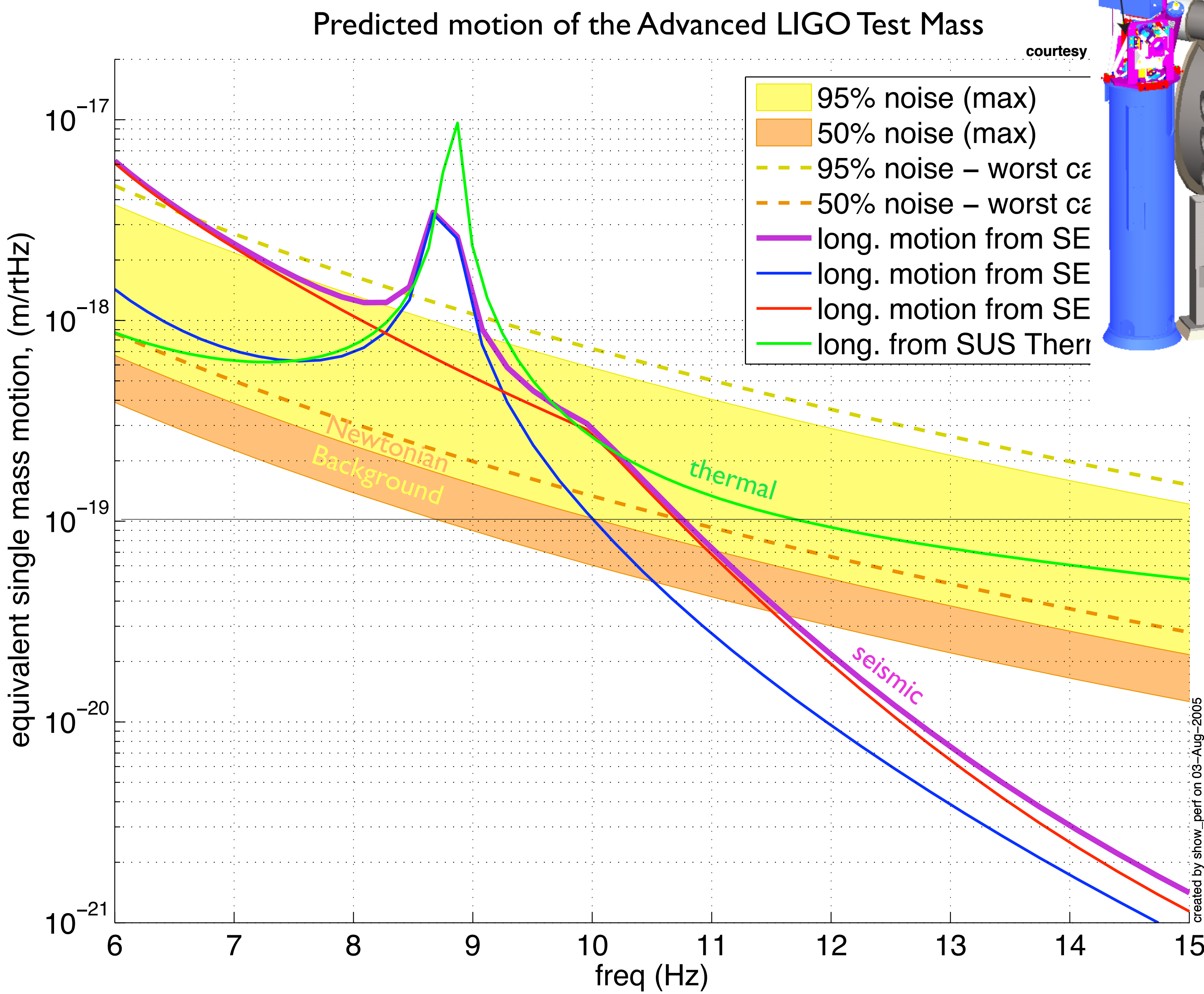
-Large optics in BSC chambers

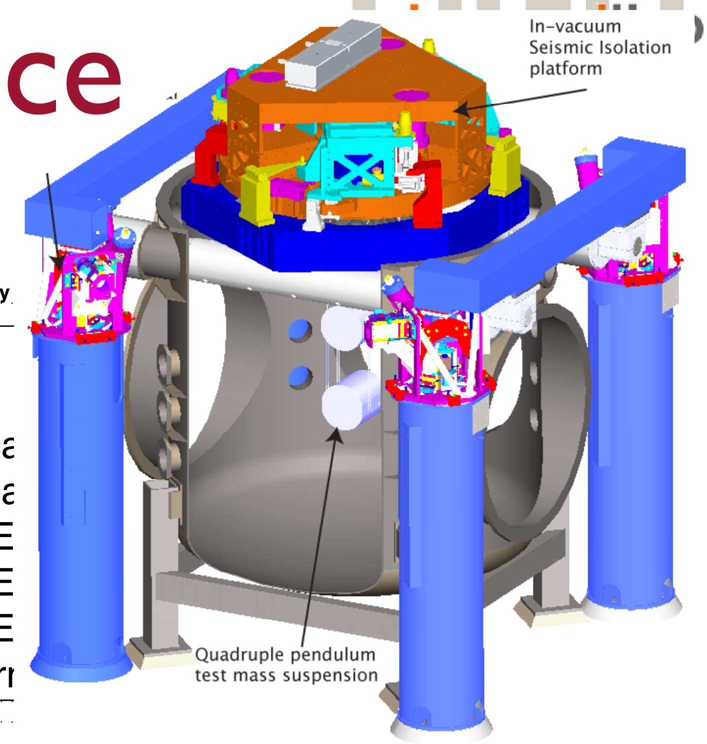
-other optics in HAM chamber





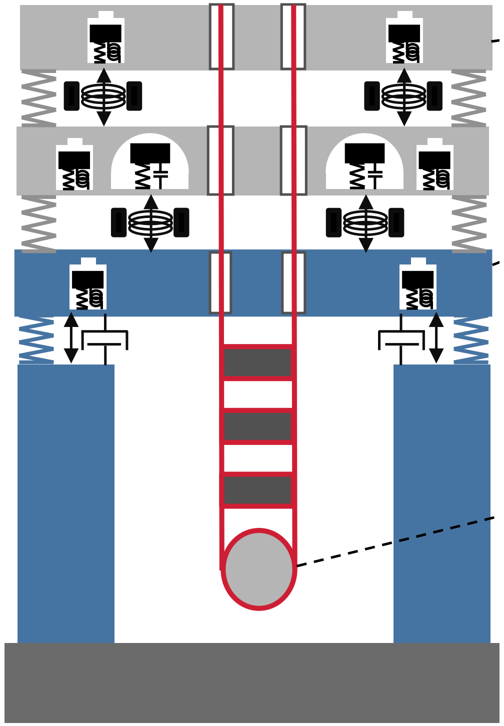
Final Performance

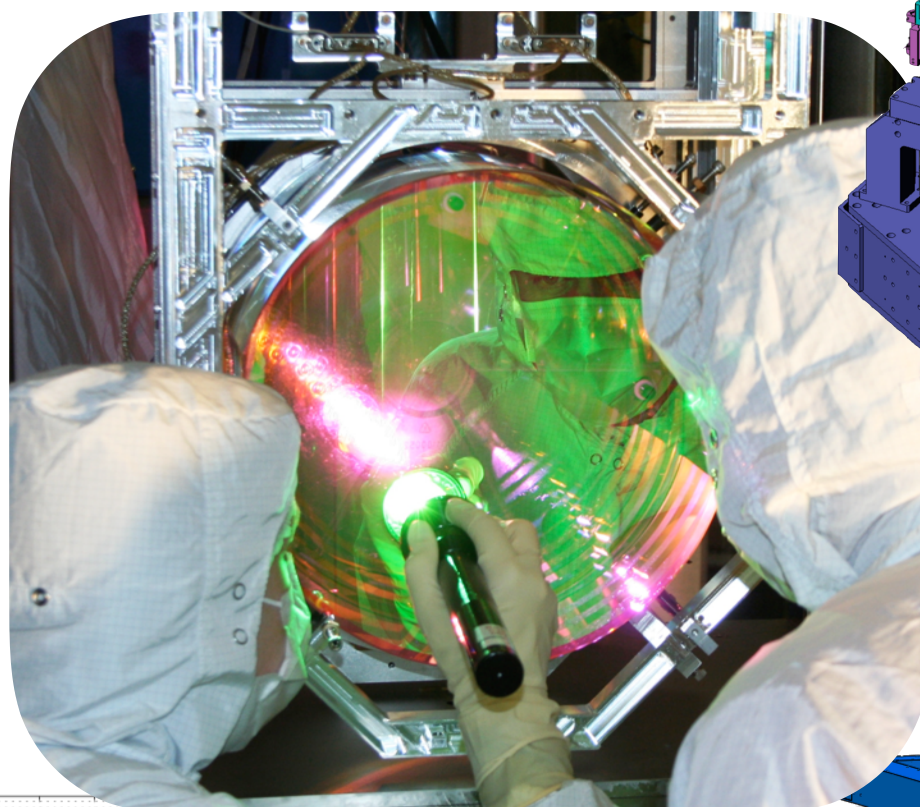


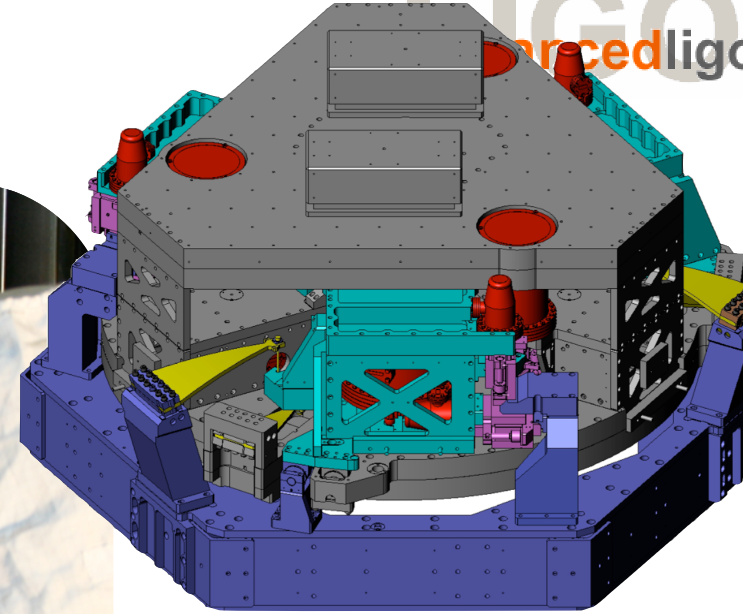


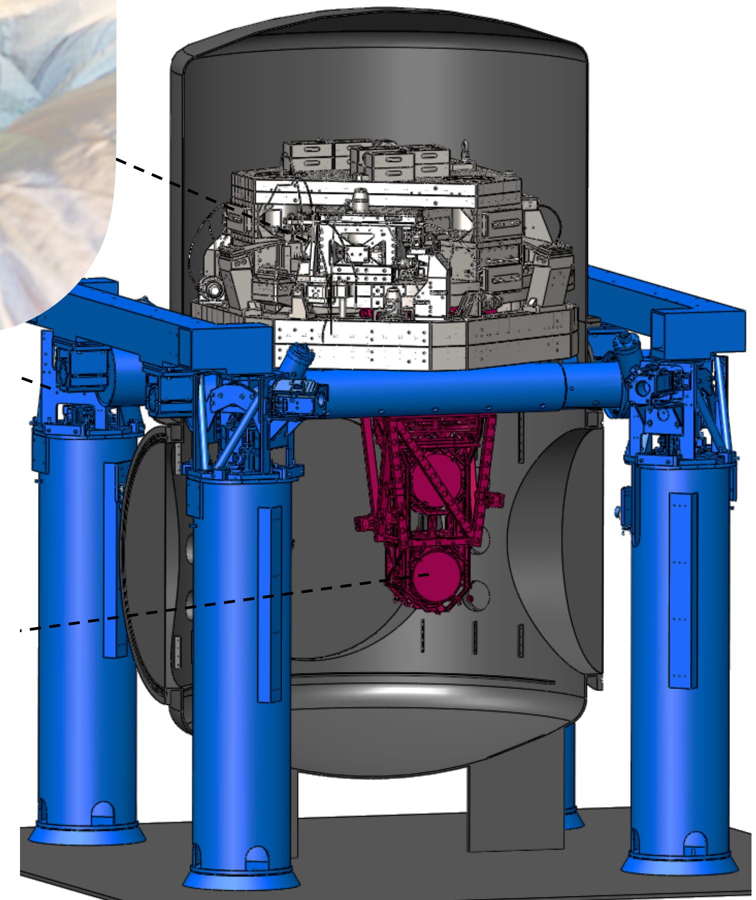
1e-19 m/√Hz

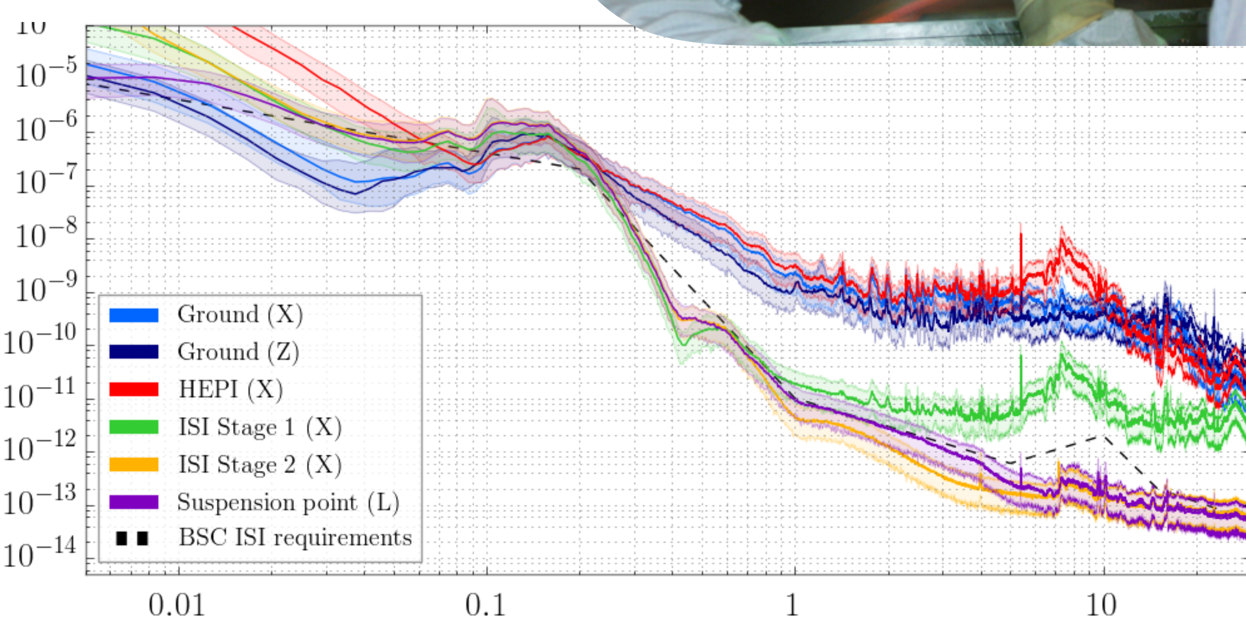
Questions?



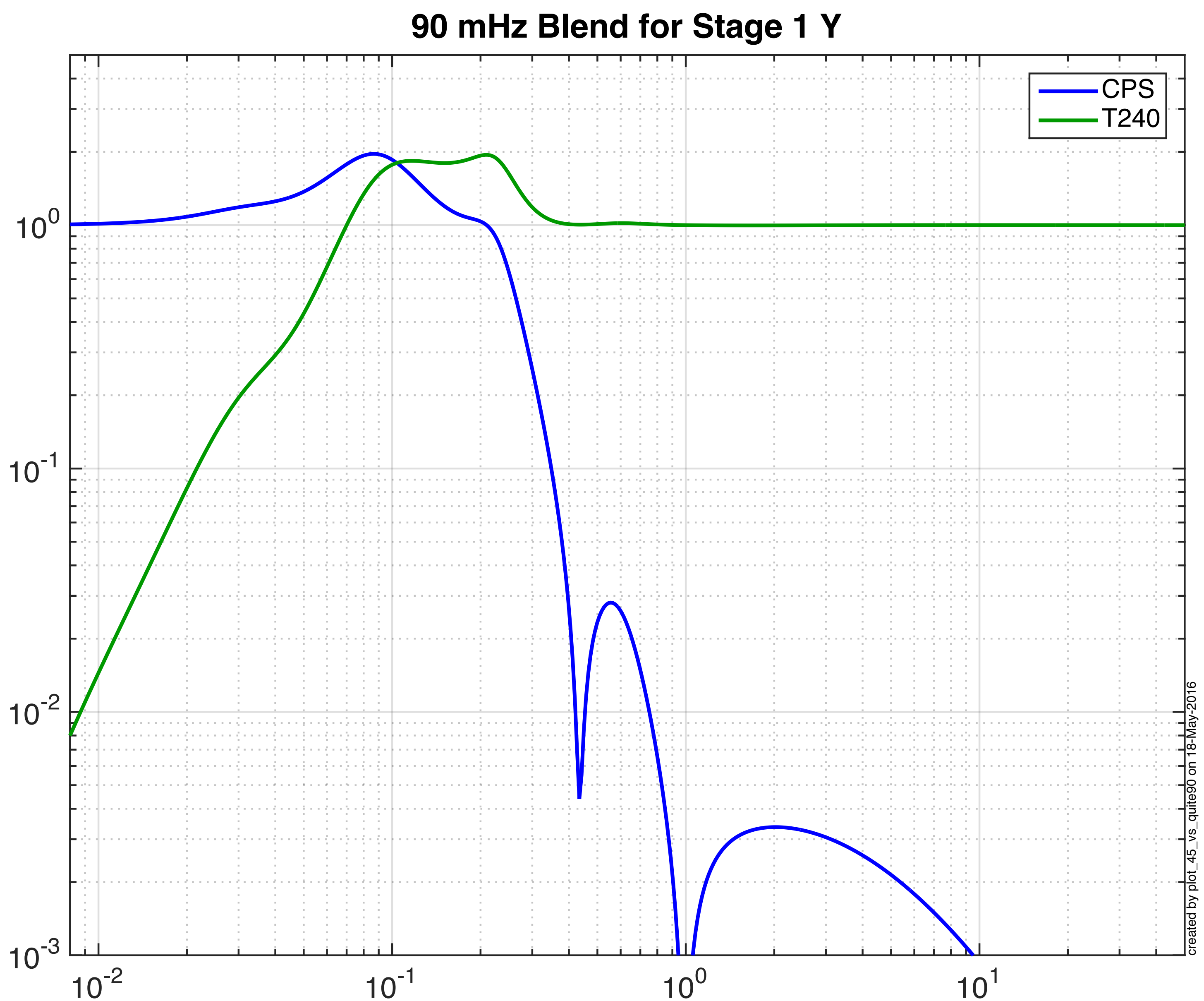




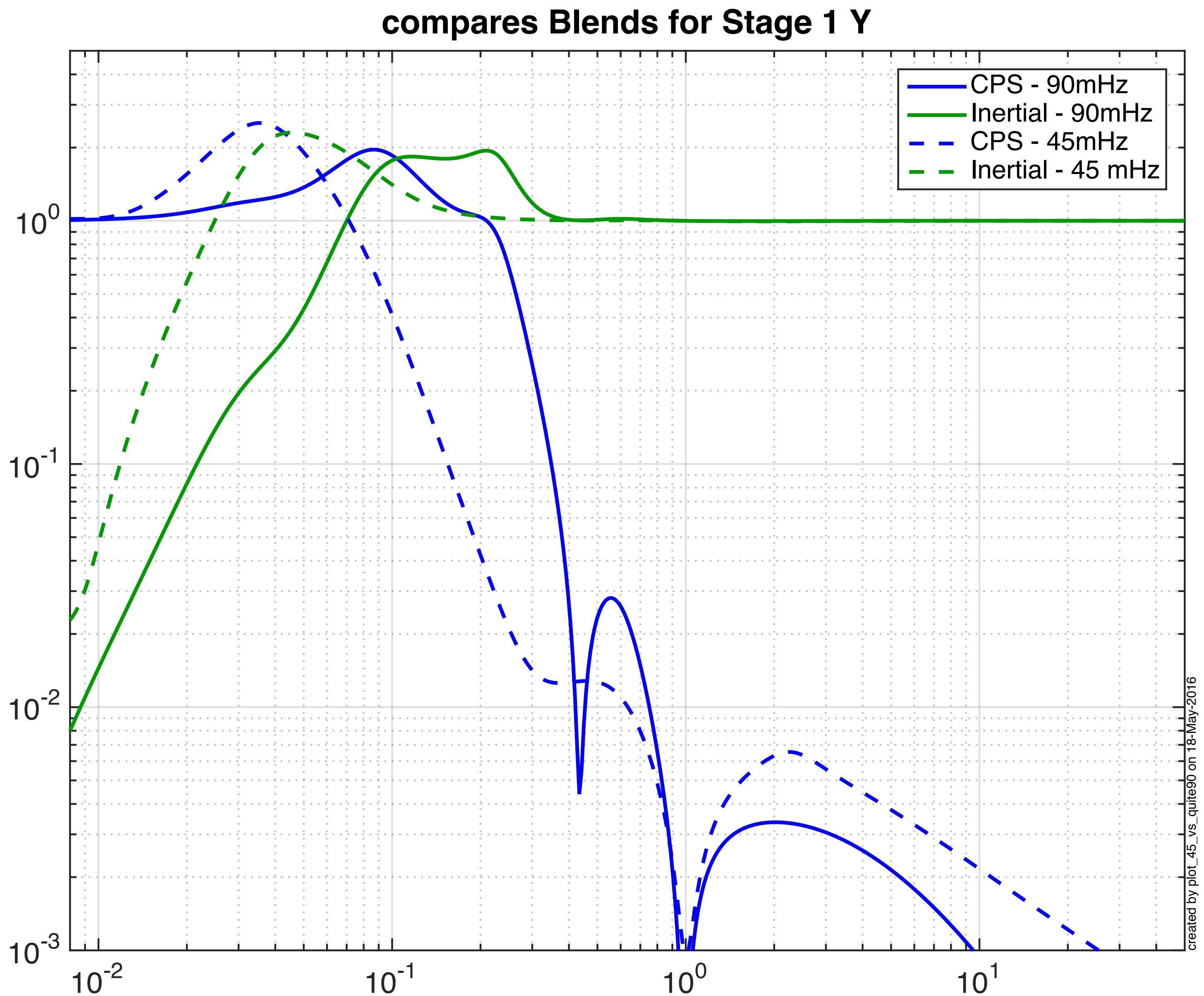



10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.01
0.1
1
10
Ground (X)
Ground (Z)
HEPI (X)
ISI Stage 1 (X)
ISI Stage 2 (X)
Suspension point (L)
BSC ISI requirements

Blending sensors



Blending sensors



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https://goo.gl/maps/of6XQ85s8on

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