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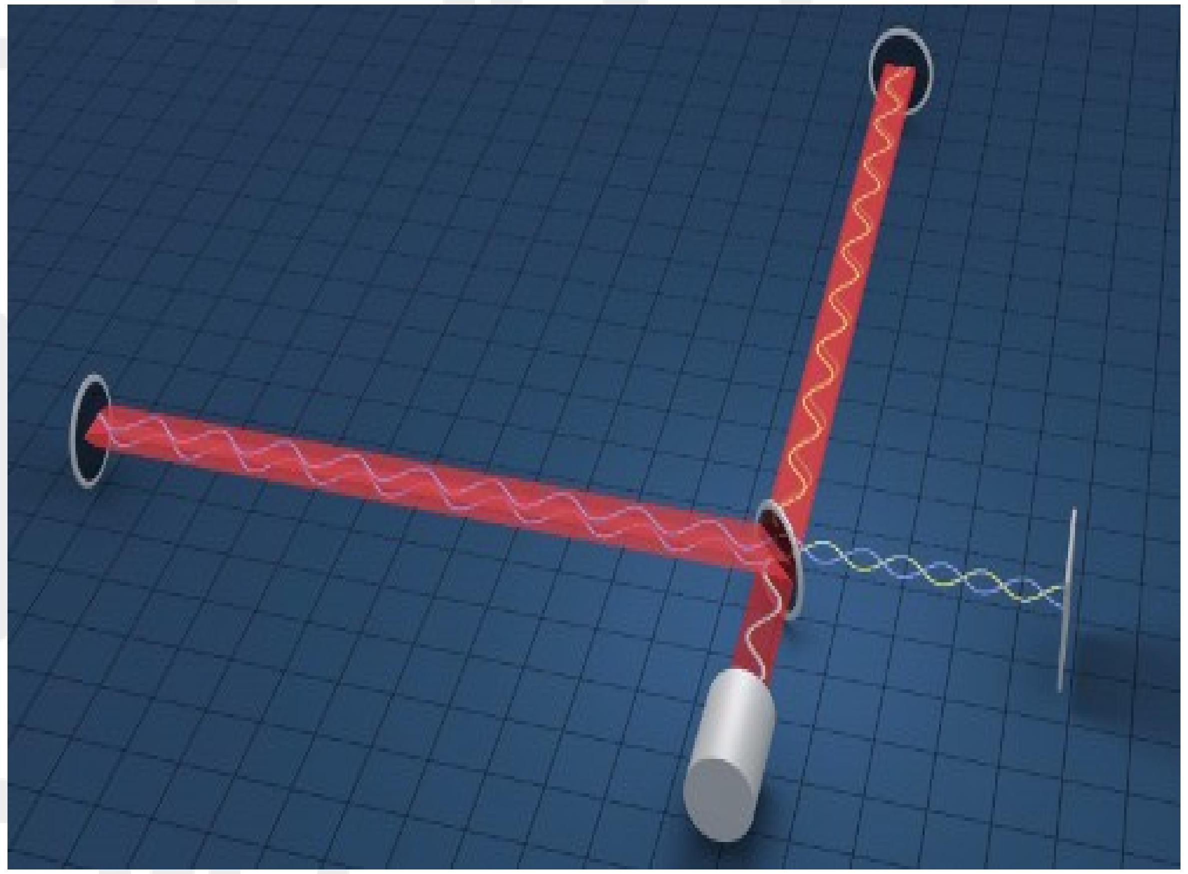


Instrument development: GEMINI & SHIMMER

Tomislav Andrić & Jan Harms

Science Fair Presentation
17.02.2025.

GEMINI

A new underground seismic-isolation facility at LNGS

Coordinating Institutions: GSSI & INFN – LNGS

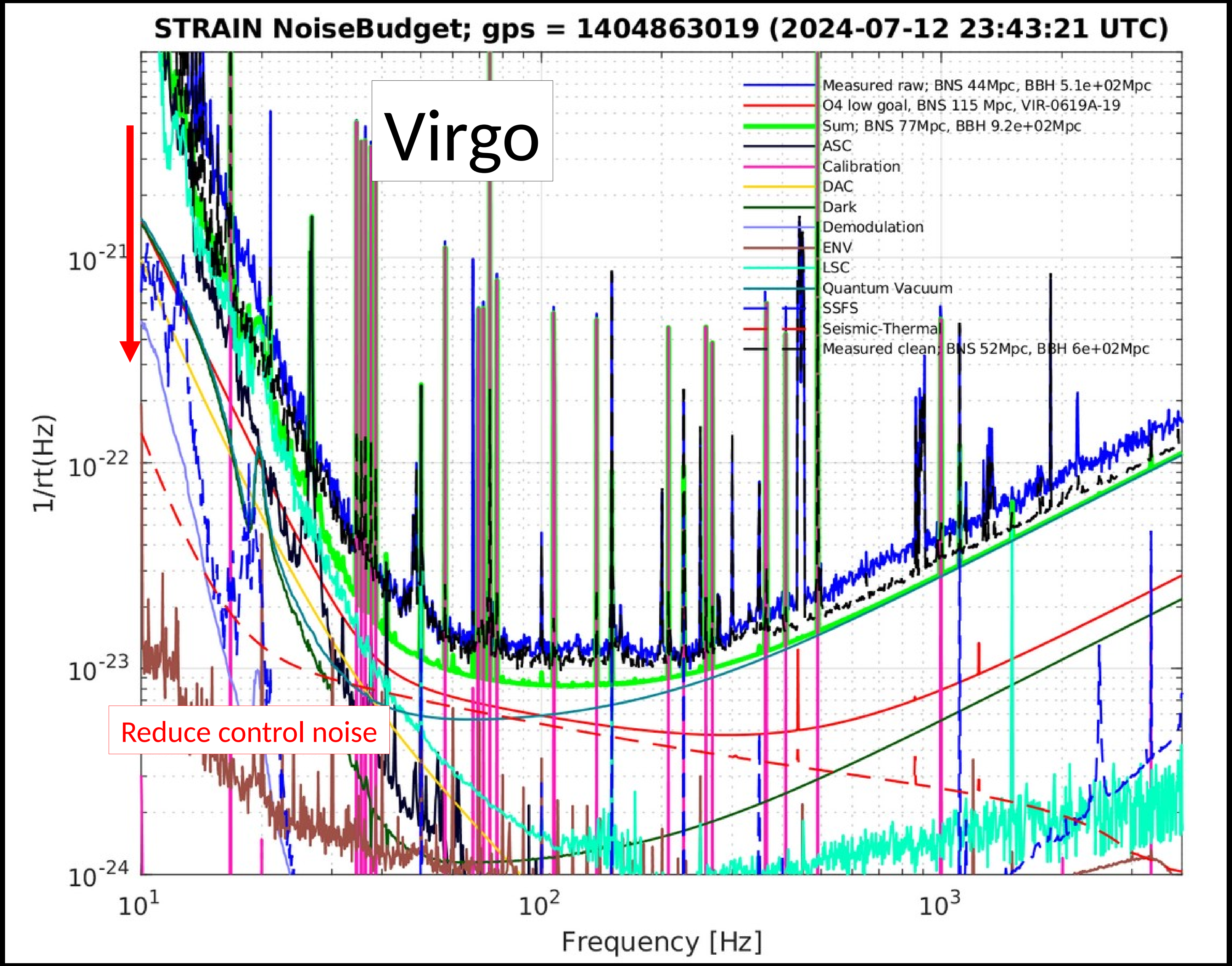
Collaborators & Technical Advisors

Tomislav Andric (GSSI), Carlo Bucci (INFN), Ilaria Caravella (GSSI), Daniele Cortis (INFN), Nicola D'Ambrosio (INFN), Massimiliano De Deo (INFN), Marco D'Incecco (INFN), Antonio Di Ludovico (INFN), Oliver Gerberding (University of Hamburg), Jan Harms (**PI**; GSSI), Jeff Kissel (LIGO Hanford), Alessandro Lalli (INFN), Brian Lantz (Stanford University), Laura Leonzi (INFN), Carla Macolino (Università di L'Aquila), Rich Mittleman (MIT), Conor Mow-Lowry (VU Amsterdam), Donato Orlandi (INFN), Stefano Pirro (INFN), Marco Ricci (Università di Roma La Sapienza), Jamie Rollins (Caltech), Jim Warner (LIGO Hanford)

Profile

- Suspension mechanism of the seismometer's test mass - nontrivial
- Operating seismometers of such sensitivity would require an extremely low level of seismic disturbances - LNGS is a perfect/unique location to carry out these studies (low-noise, underground facility)
- Test platform for novel inertial sensors (room&cryo temperature)
- Test technologies, validate their performance, and ensure they meet the requirements before deployment on the Moon
- Development of vibration control and inter-platform control systems for the Einstein Telescope
- Installation and utilization of an underground environmental monitoring system

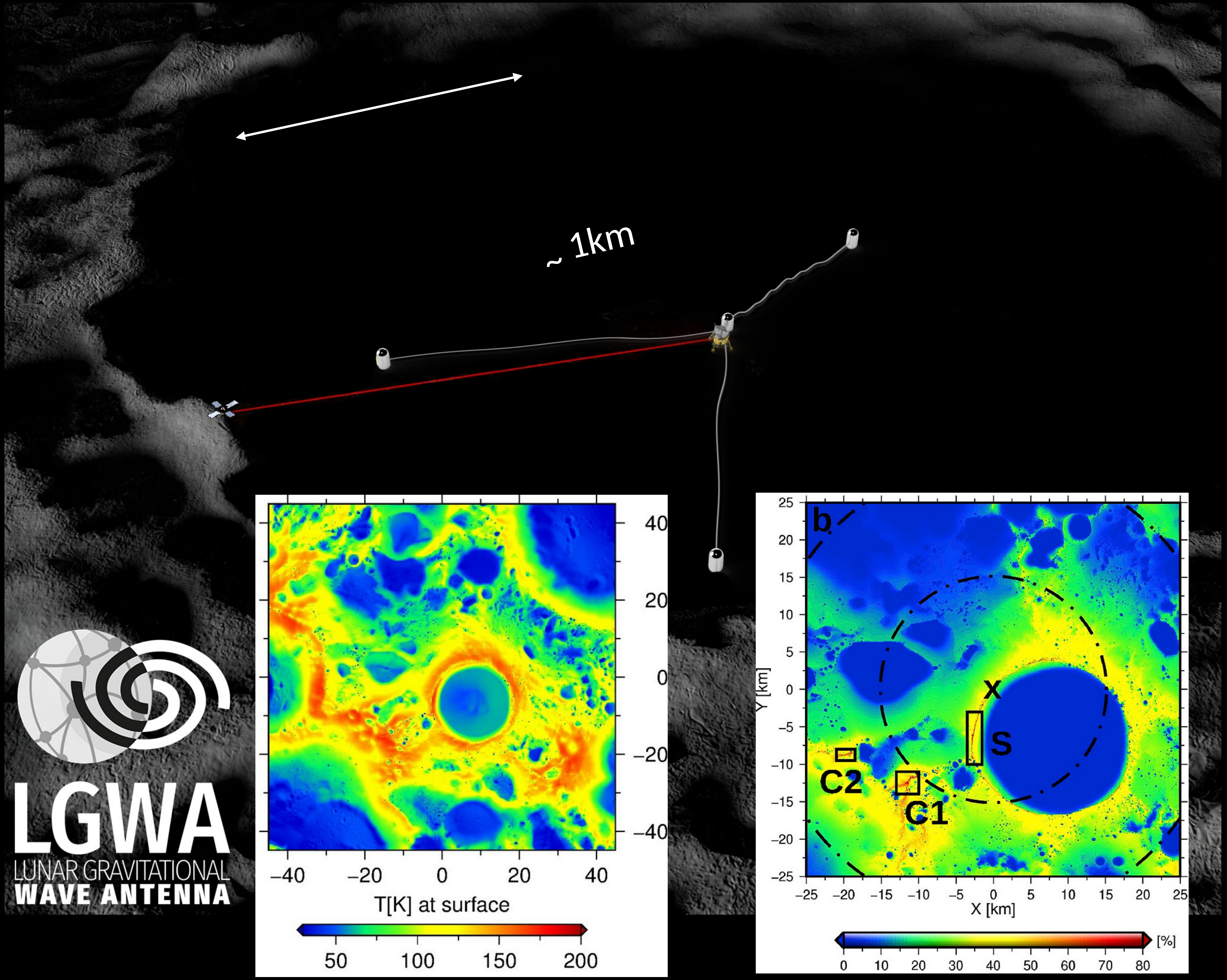
Scientific Goal 1: ET



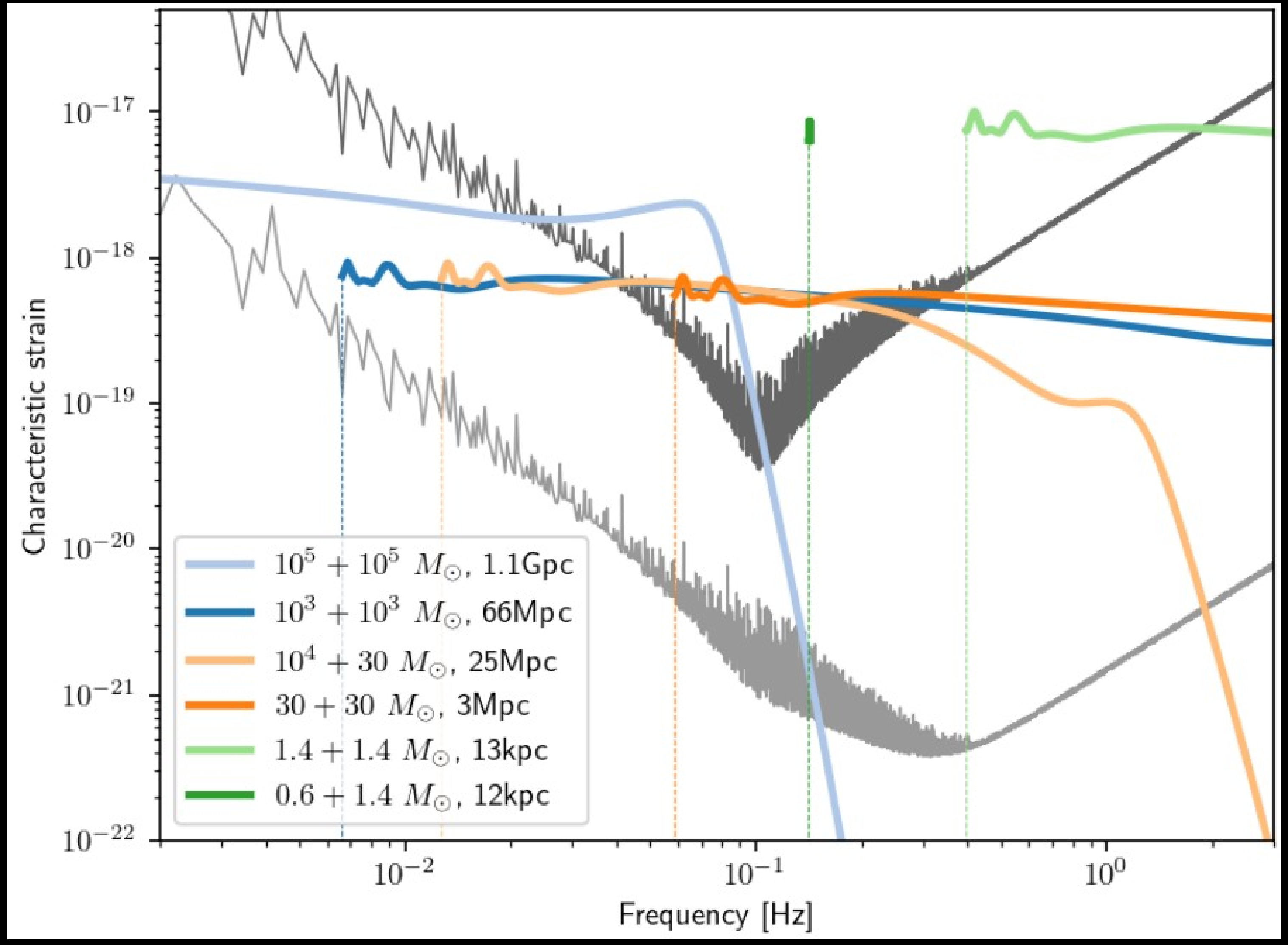
- Noise introduced by the control of length and alignment degrees of freedom can limit low-frequency sensitivity
- Develop an inter-platform motion control system to assist the ET length and alignment control of auxiliary degrees of freedom
- Enable ET-LF science case

- Lock all suspension platforms into a common motion across the full central vertex of an interferometer
- Refer this optically rigid body to the two input masses

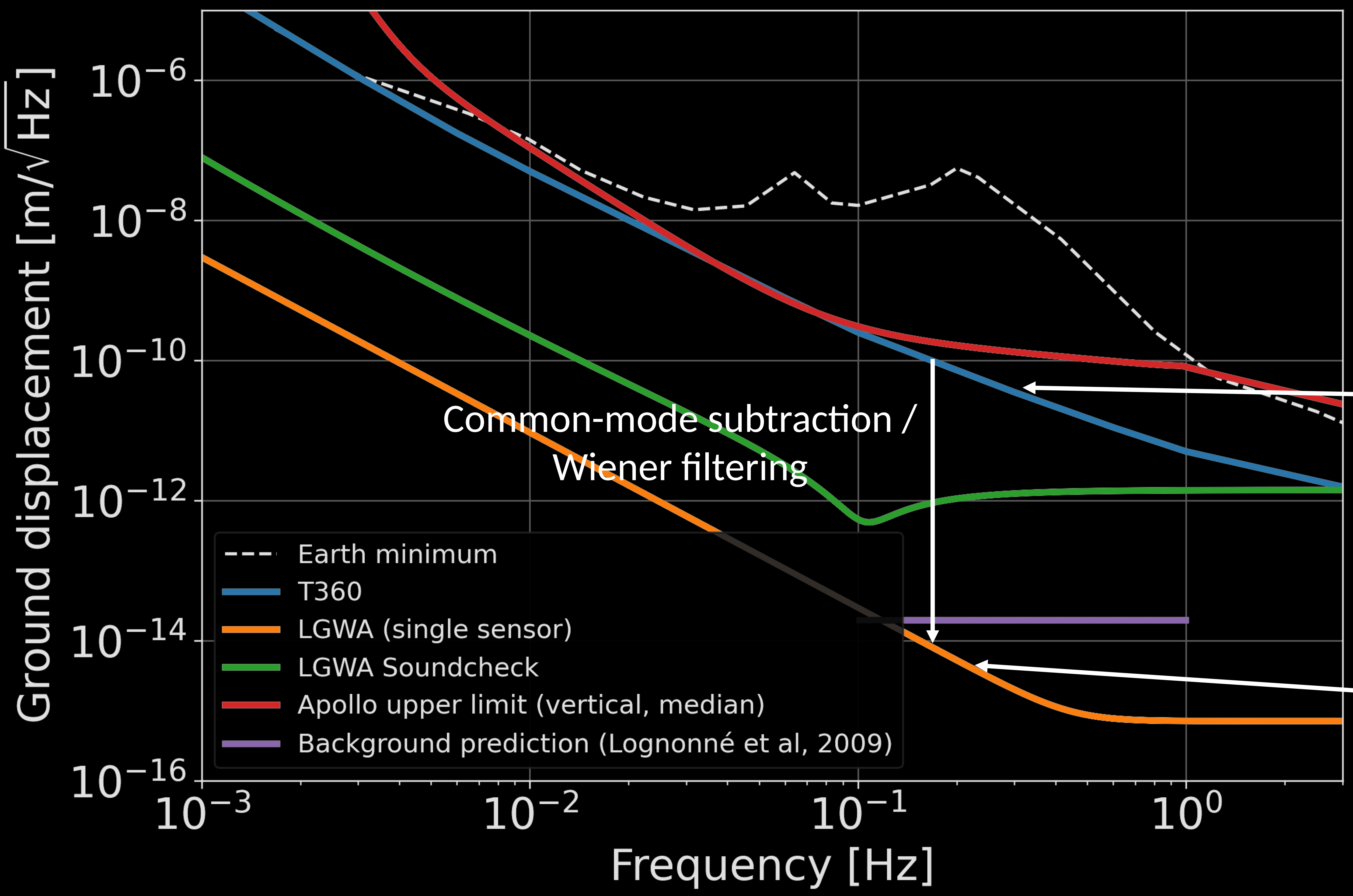
Scientific Goal 2: LGWA



Decihertz gravitational-wave detection on the Moon



GEMINI - LGWA

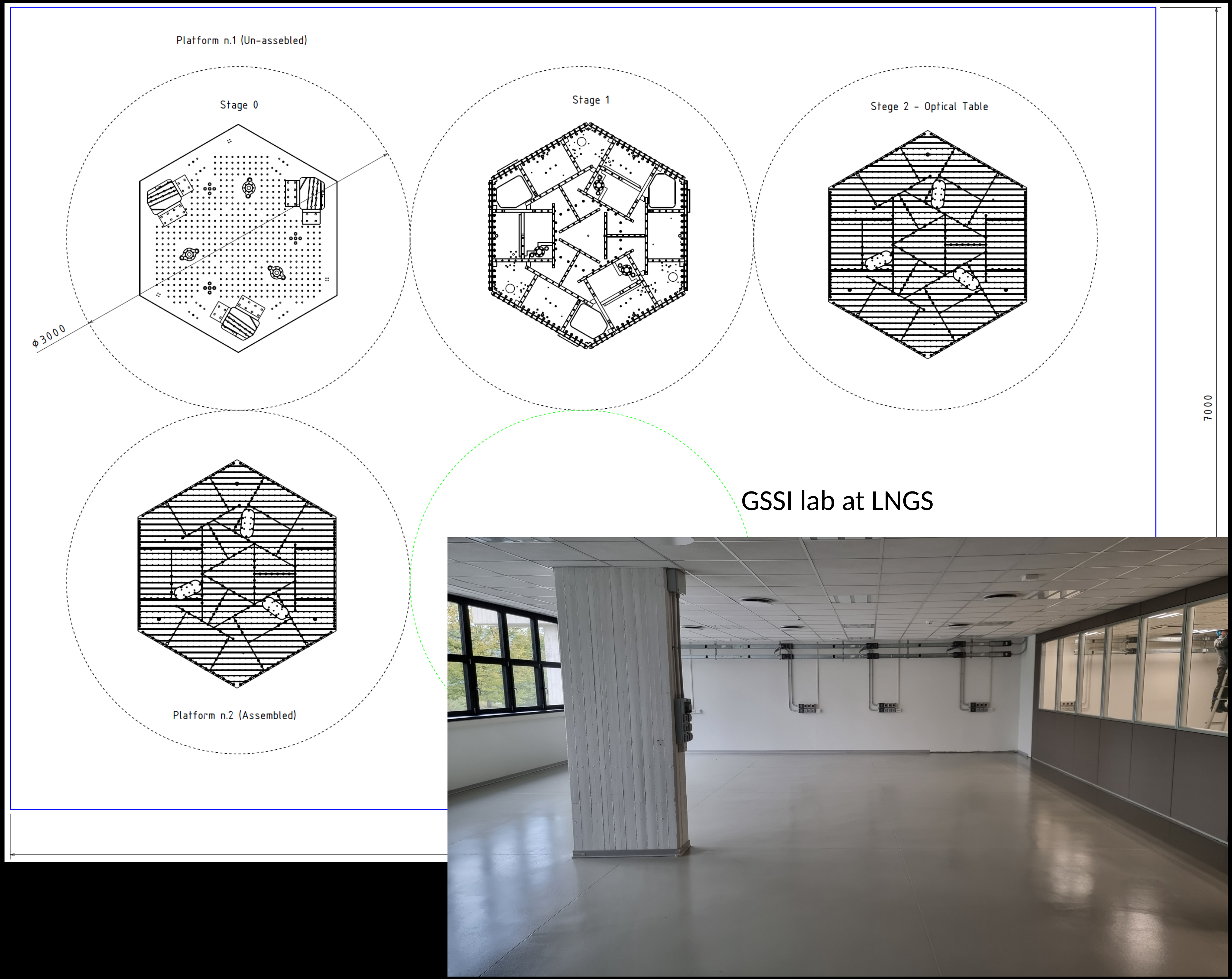


Test high-performance, cryo-temperature lunar seismometers for LGWA

Targeted GEMINI platform residual motion

LGWA sensor performance target

Surface Laboratory

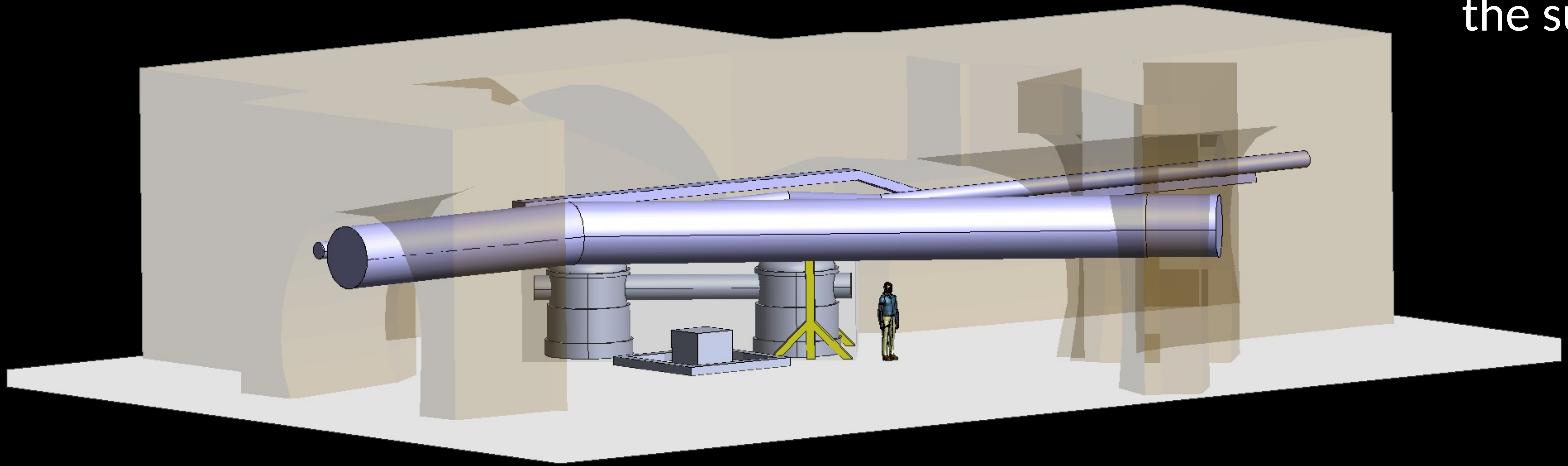


GSSI lab at LNGS

- Integration of sensors and actuators on stage-0 and stage-1 platforms
- Installation and test of real-time system
- Test of control system
- Test stand for spring-blade material characterization
- Assembly and testing in clean environment

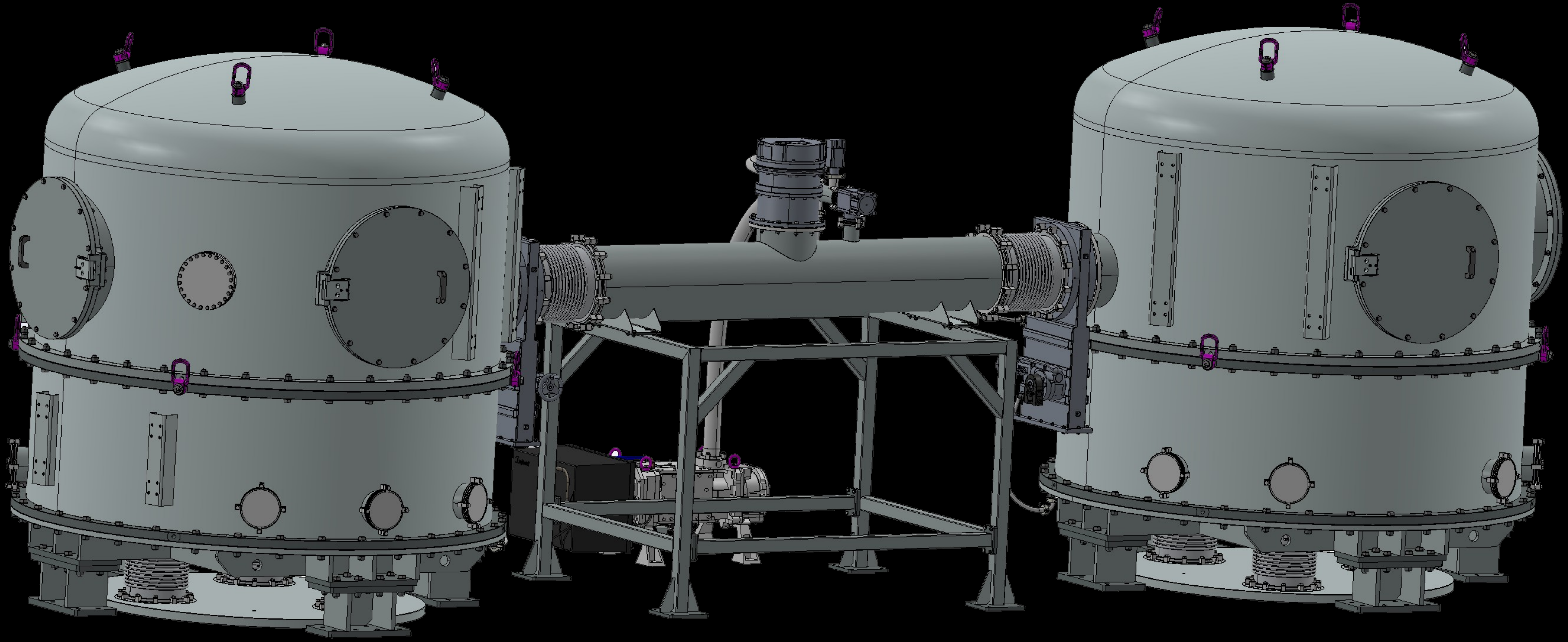
Underground Laboratory

- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Access to cooling water for cryocooler
- Timing signal from surface
- Low-latency data transfer to server at the surface



Vacuum System

Two chambers connected by vacuum pipe.
Tunnel entrance dimensions put strong limitations on chamber geometry.

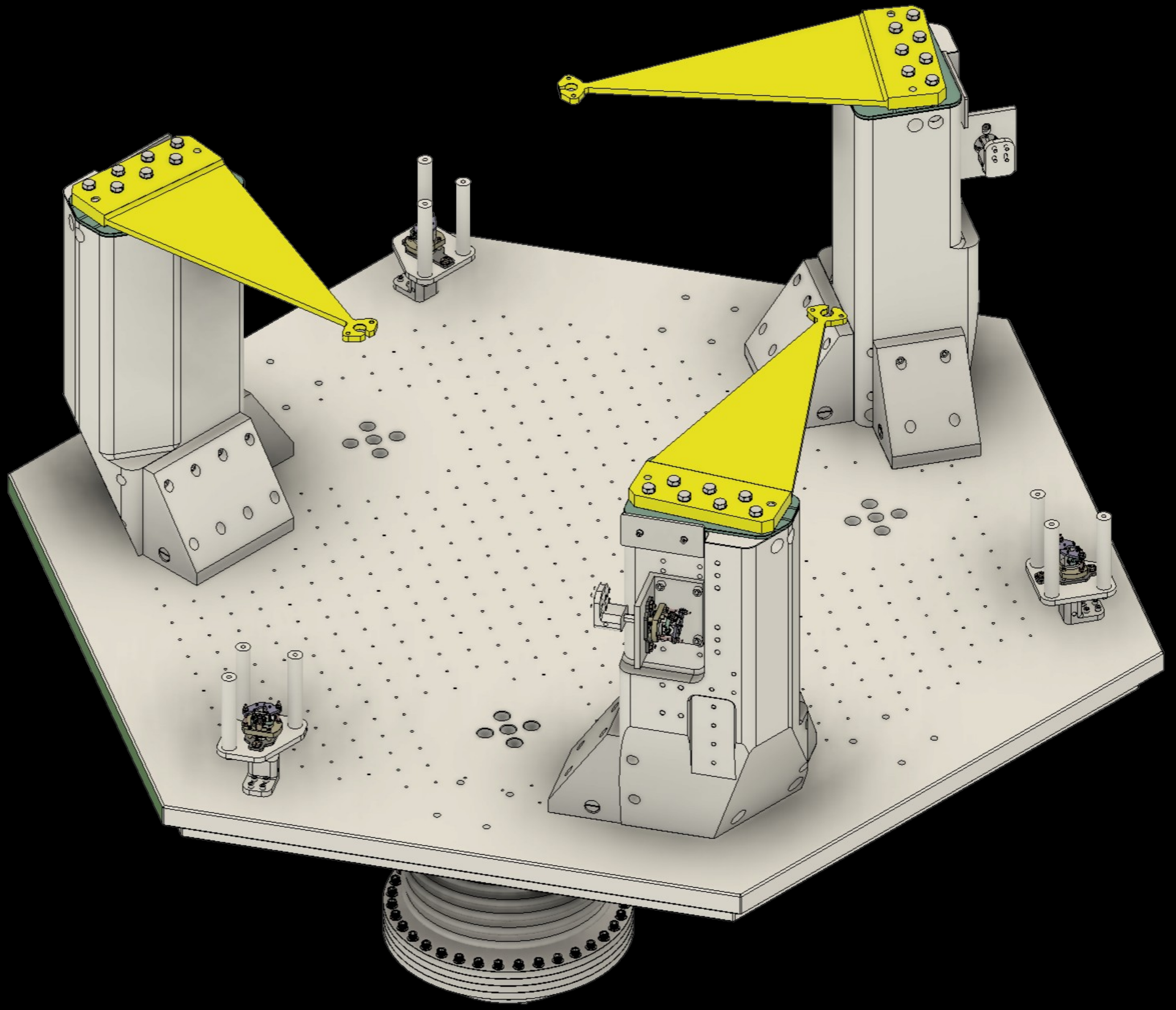


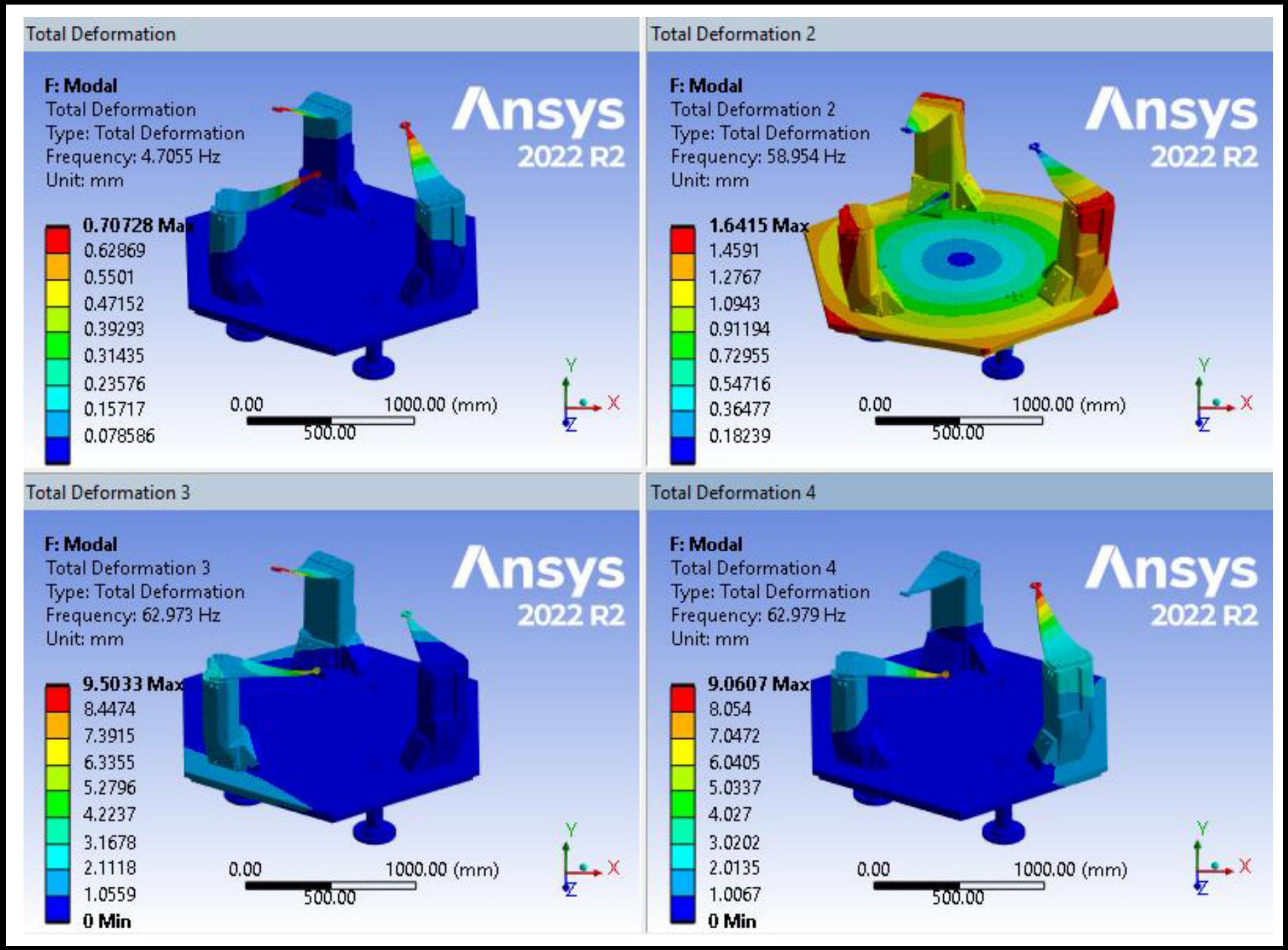
GEM-VCP

- GEMINI Vibration-control Platform
  - Starting point of the design: LIGO HAM-ISI - structural adjustments tailored for GEMINI's specific requirements.
  - Design modifications, vibration analysis, and executive drawings produced by LNGS mechanical engineers

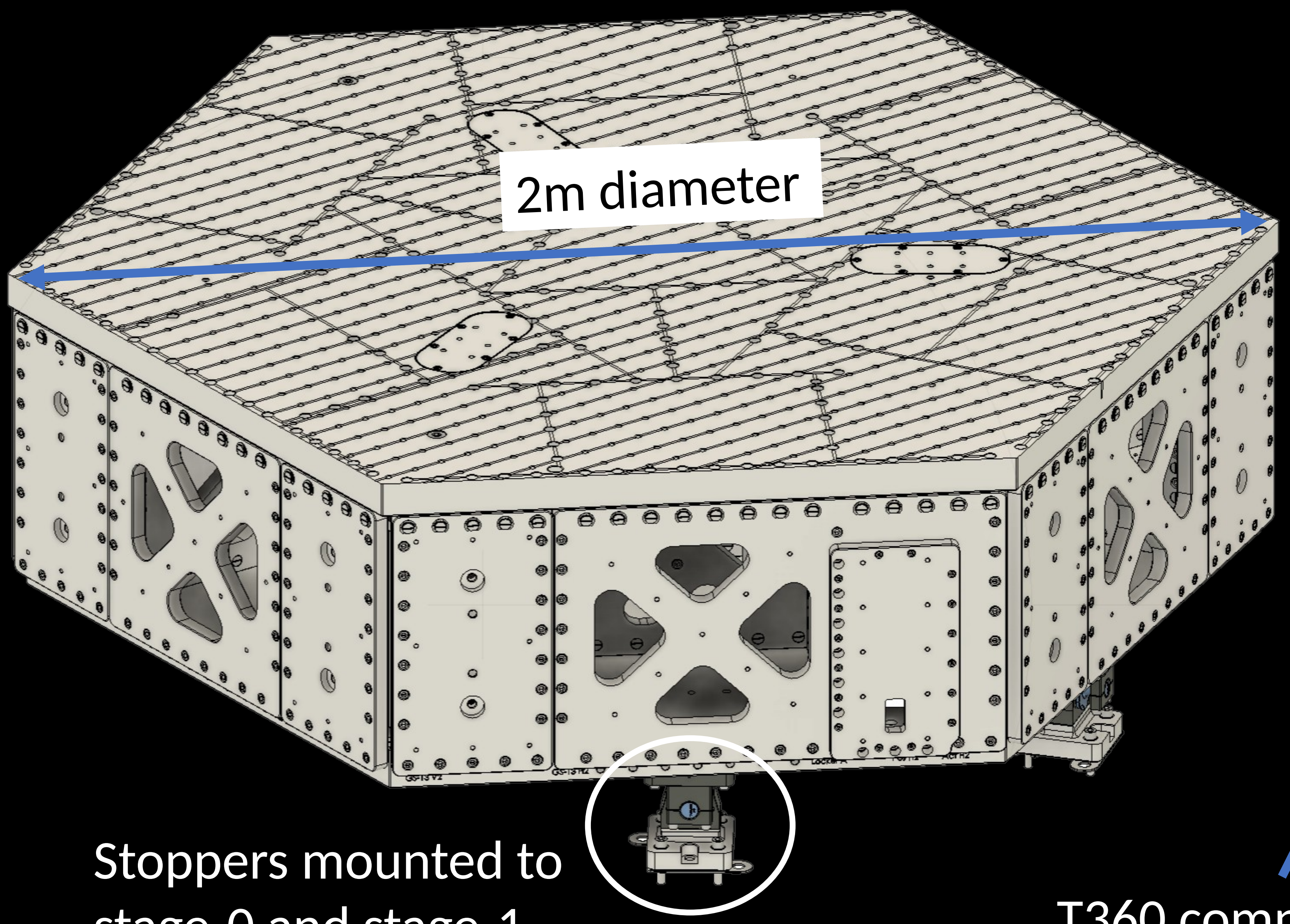
GEM-VCP: Stage 0

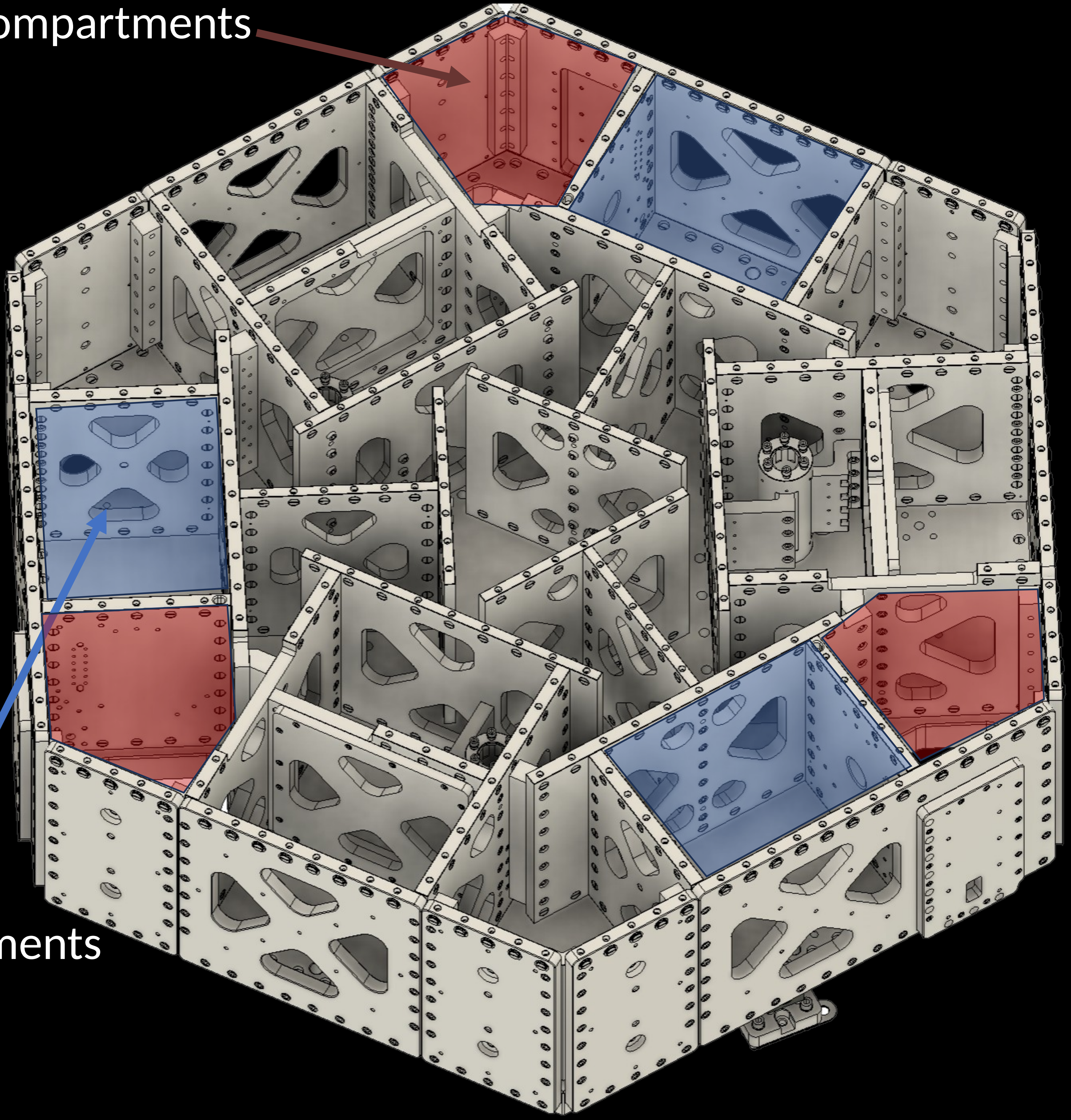
- 100Hz HAM-ISI (unconstrained)
- 70Hz GEM-VCP (under load)





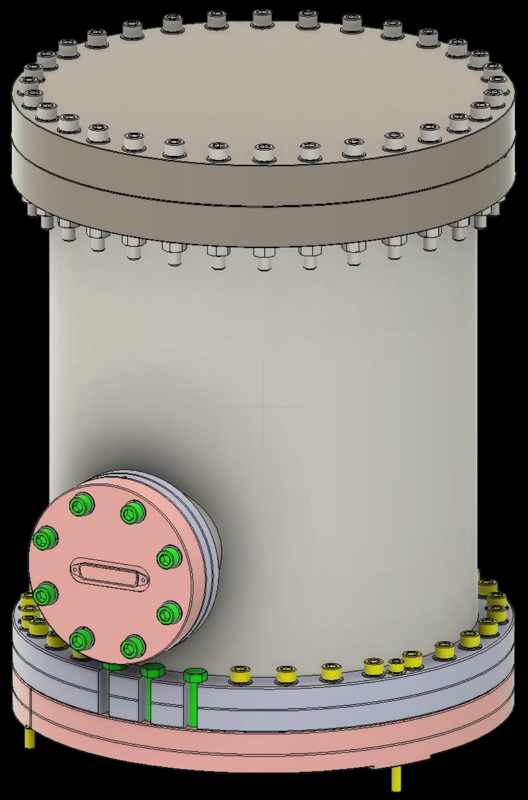
GEM-VCP: Stage 1



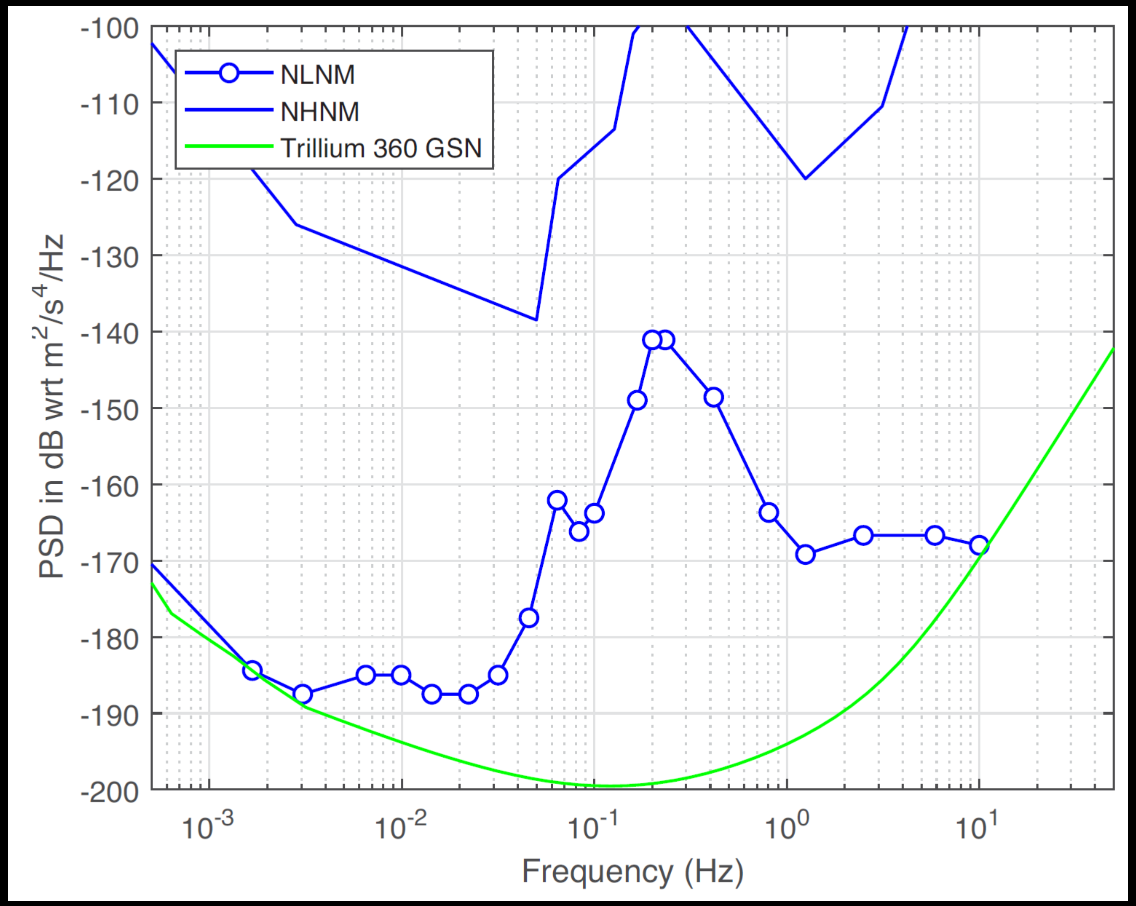


Inertial Sensing

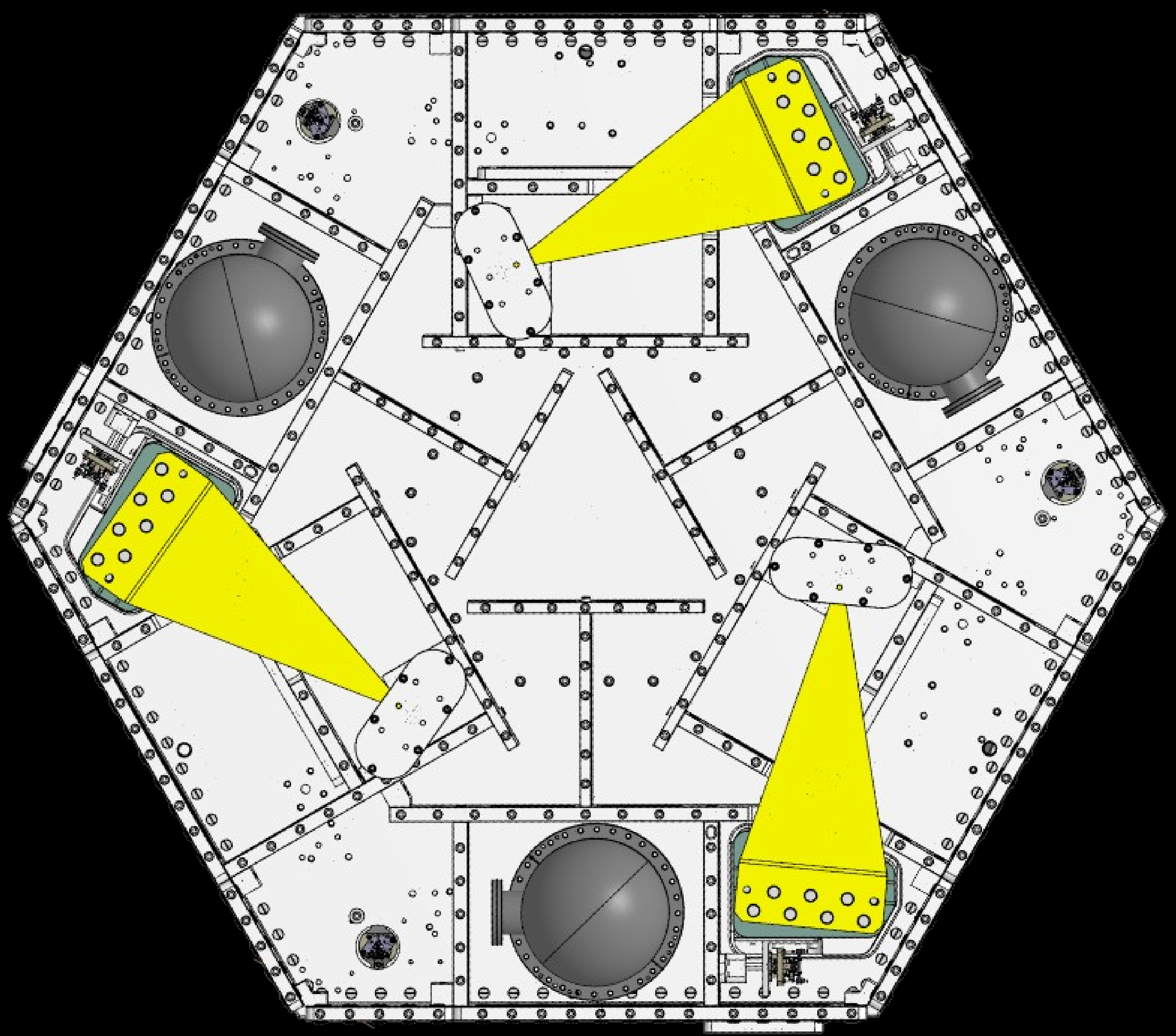
Vacuum pods
(to be ordered in October 2024)



Nanometrics T360 GSN Vault
(3 per platform, 3 channels each)

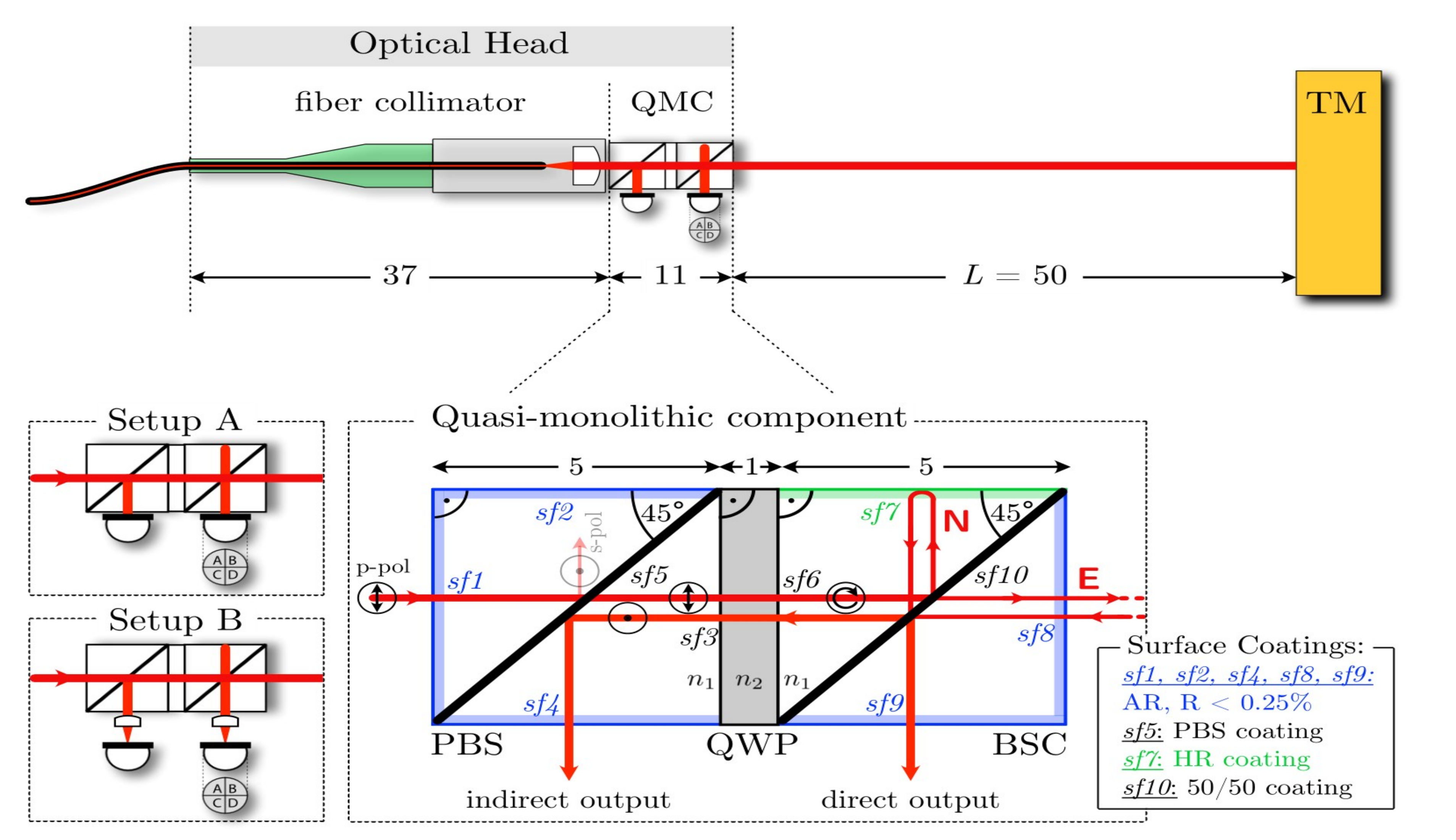


Integration in GEM-VCP



Position Sensing: COBRI

COmpact Balanced Readout Interferometer - COBRI



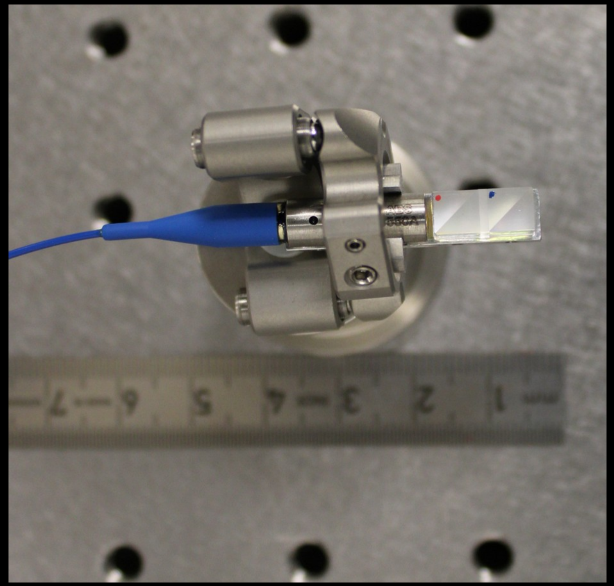
- Required for platform alignment and positioning (precise displacement and motion sensing)
- Strong frequency modulation (set of sinusoidal phase modulations)
- Advanced digital readout algorithms to measure the phase shift induced by motion
- Needs to be blended with inertial sensing and control

- On-axis design with quasi-monolithic component
  Positive:
  - no misalignment in vacuum
  - Large linear range (several centimeters)

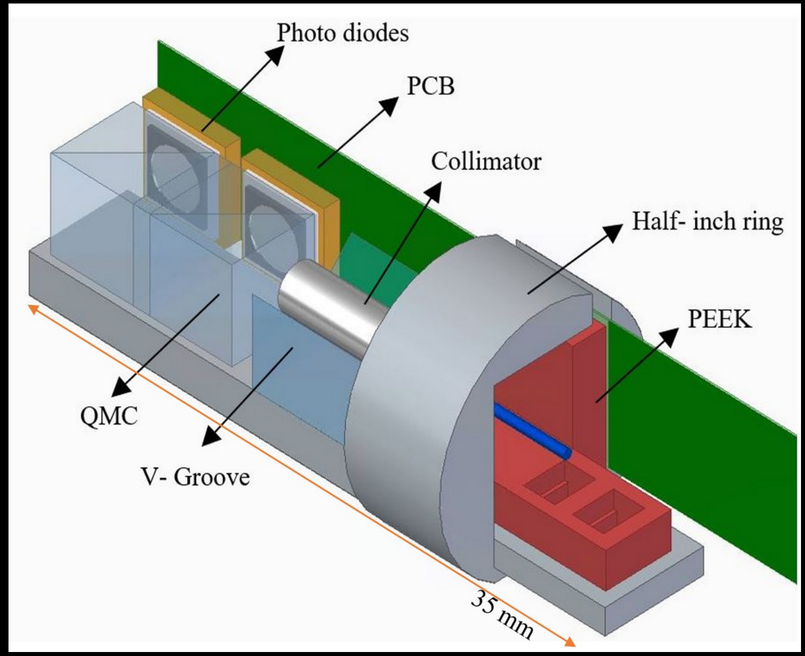
  Negative:
  - On-axis ghost beams cause nonlinearity

- Dual readout/balanced detection at the front
  - Lower readout noise by sqrt(2)
  - Enables scattered light reduction in post processing
  - Reduces residual amplitude modulation noise

O. Gerberding, K.-S. Isleif Sensors 2021, 21(5), 1708



v2 design



Cryo-box

RDK-500B2 20K Cryocooler Series

Performance Specifications

Power Supply	50Hz	60 Hz
1st Stage Capacity	45 W @ 20 K	50 W @ 20 K
Minimum Temperature[1]	<14 K	
Cooldown Time to 20 K[1]	<50 Minutes	<45 Minutes
Weight	25.0 kg (55.1 lbs.)	
Dimensions (HxWxD)	570 x 180 x 325 mm (22.4 x 7.1 x 12.8 in.)	
Maintenance	8,760 Hours	
Regulatory Compliance	CE, UL/cUL	

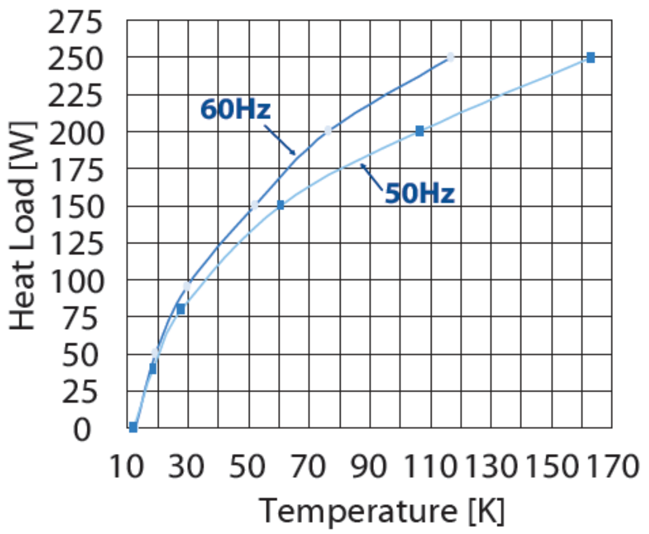
Standard Scope of Supply

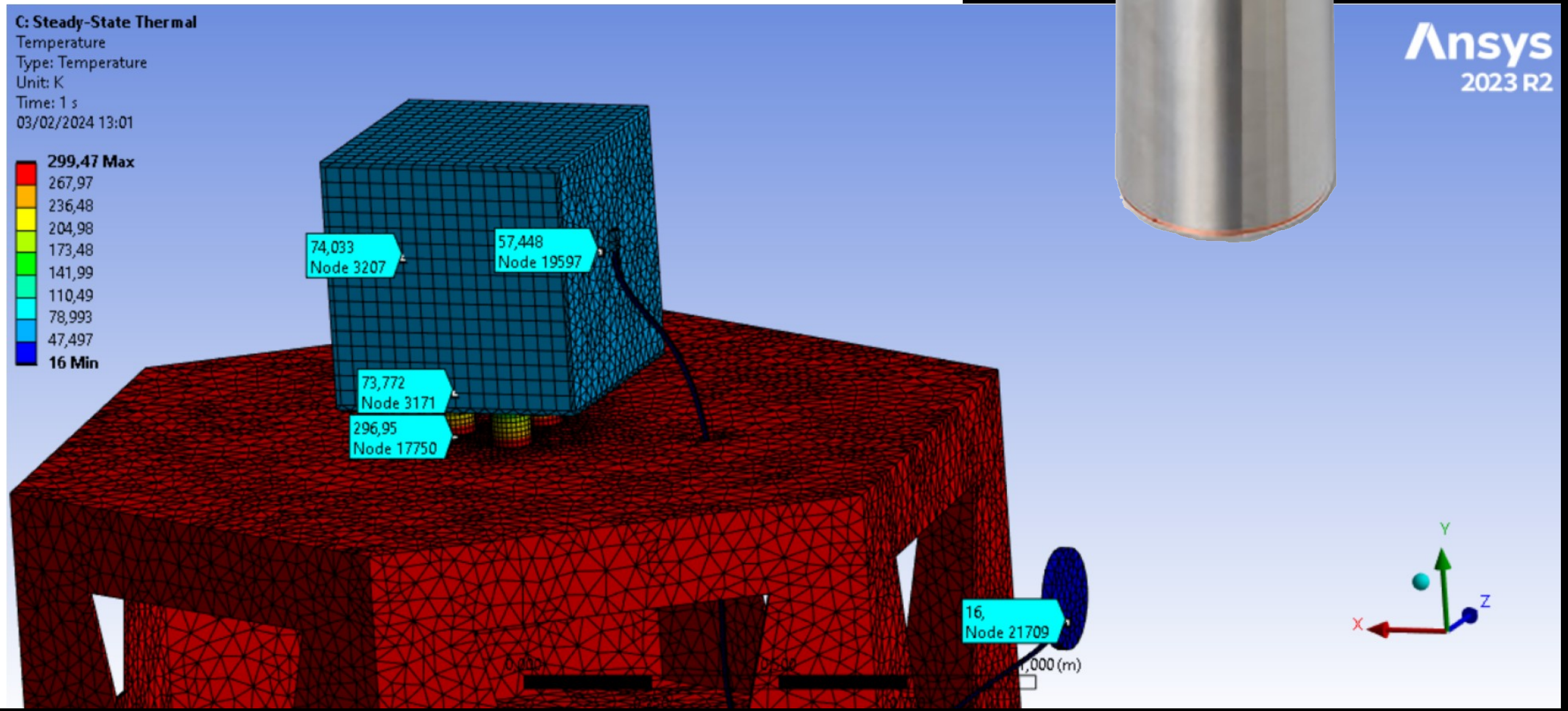
- RDK-500B2 Cold Head
- F-70LP/H Compressor
- Helium Gas Lines – 20 m (66 ft.)
- Cold Head Cable – 20 m (66 ft.)
- Power Cable – 5 m (16.5 ft.)
- Tool Kit

[1] *Lowest temperature and cooldown time are for reference only.*

Emulate 40K environment for lunar PSR payloads

RDK-500B Cold Head Capacity Map (50/60 Hz)
With F-70 Compressor and 20 m (66 ft.) Helium Gas Lines

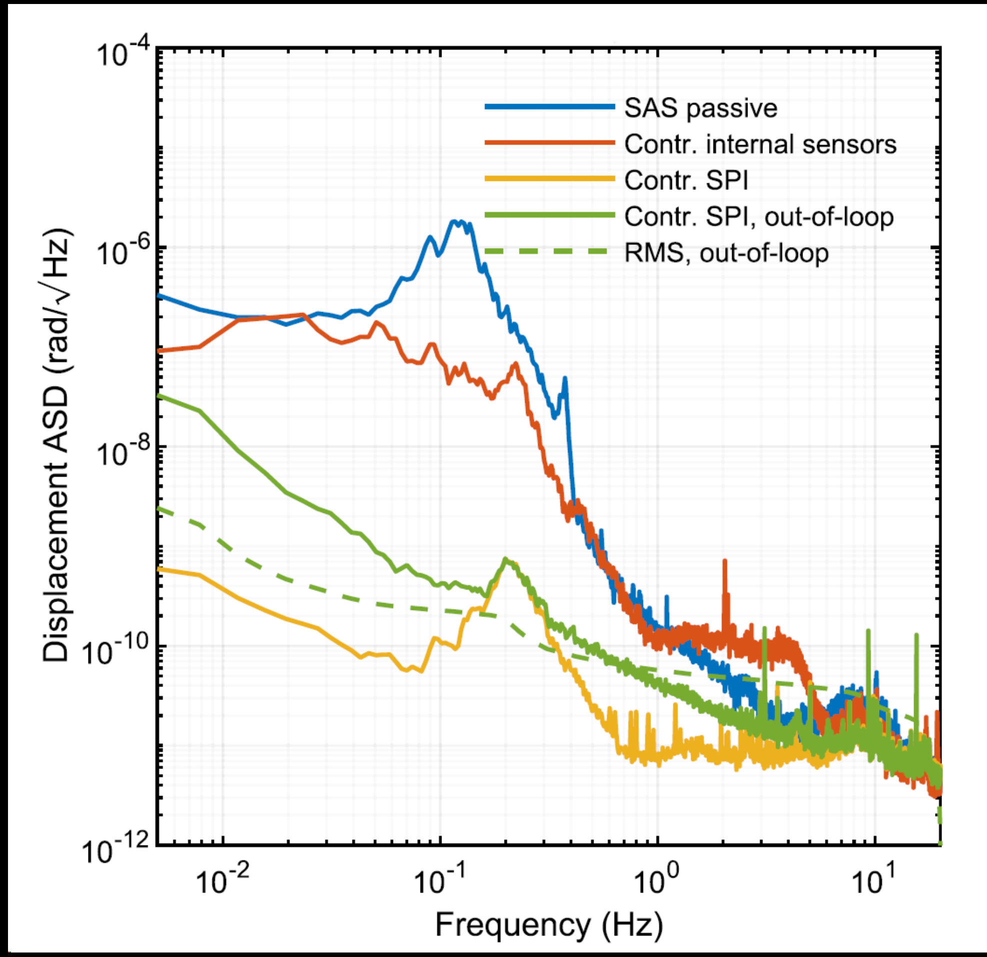


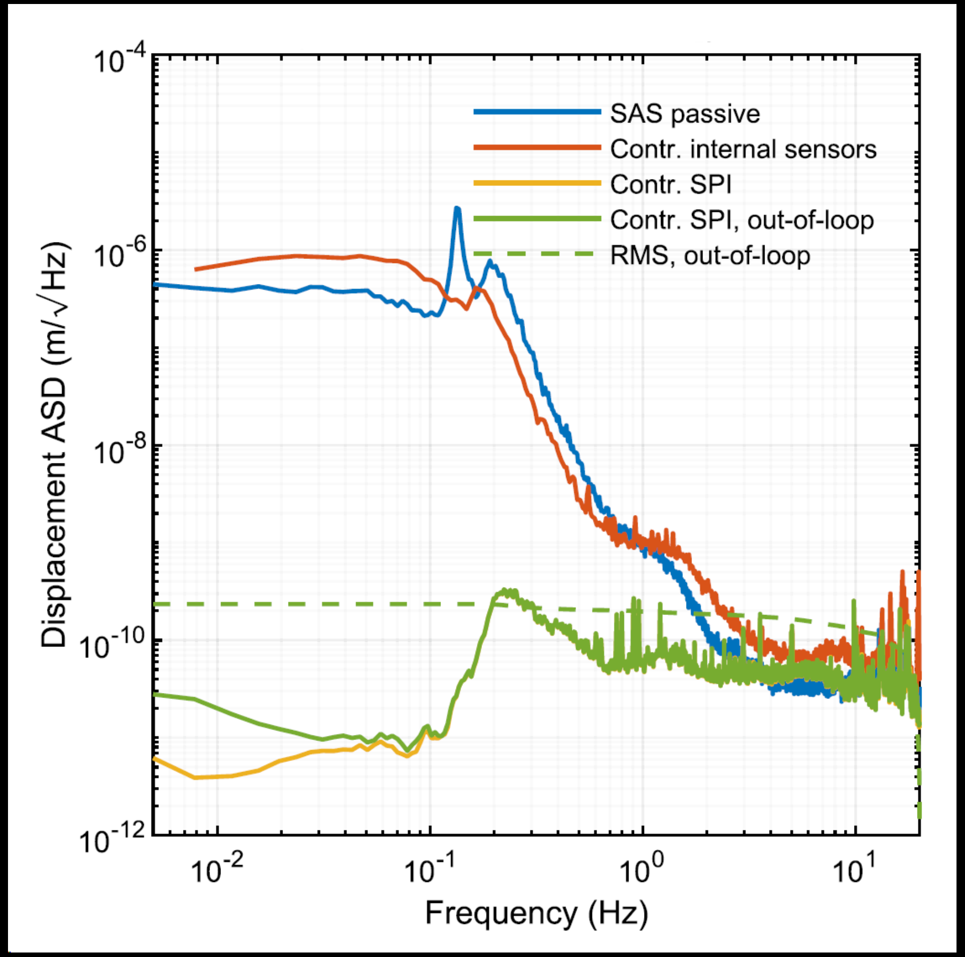


Thermal link will not be as shown in this simulation

Suspension-platform Interferometer (SPI)

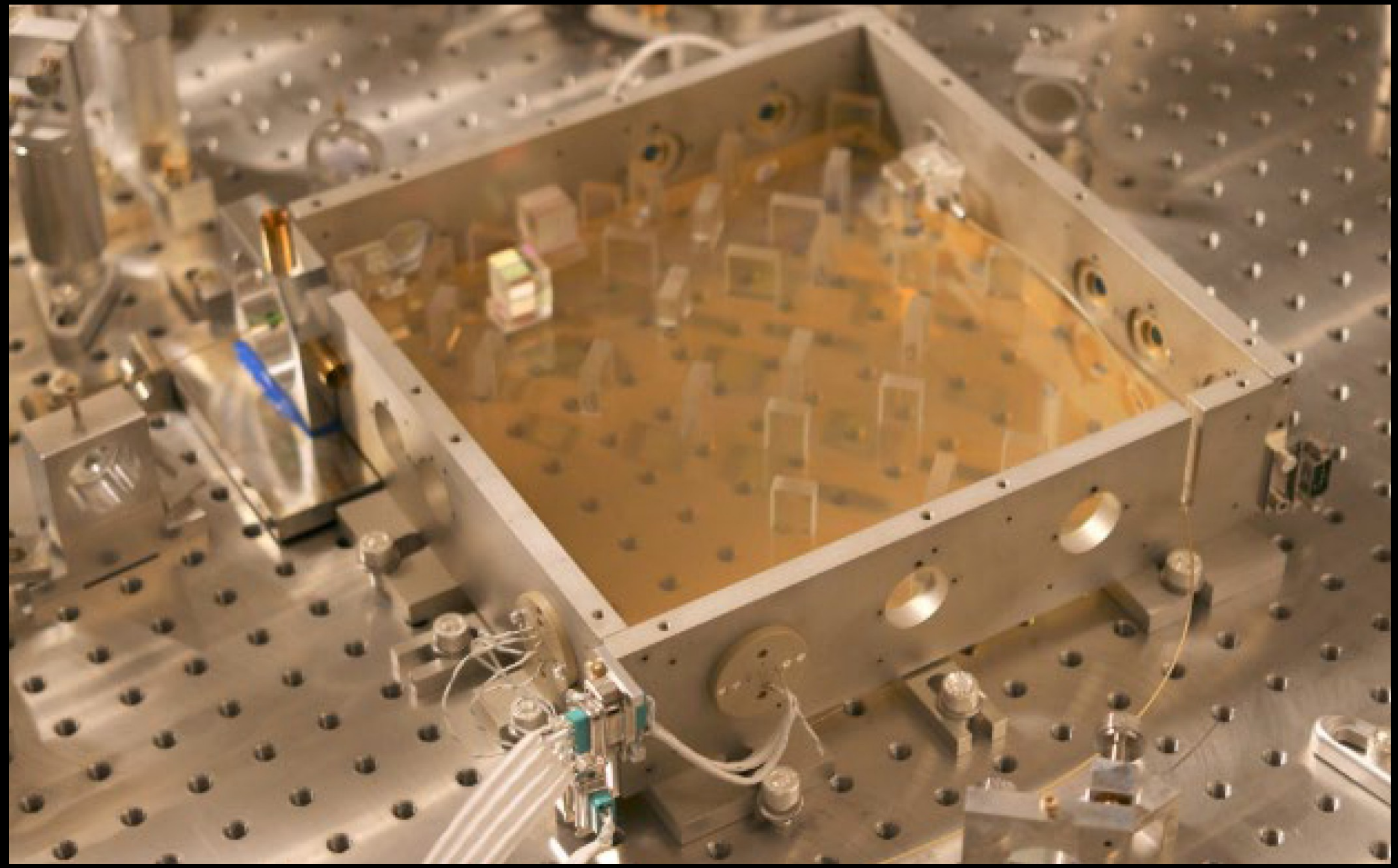
Inter-platform sensing and control to reduce relative motion between platforms (displacement and angular)





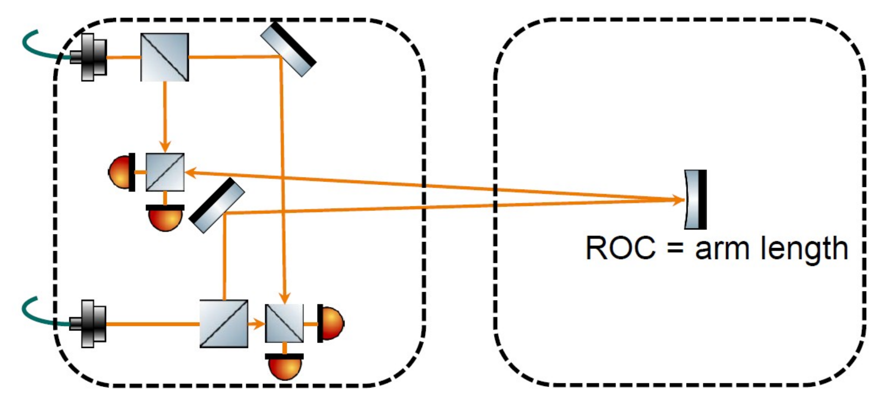
Koehlenbeck et al (2023)

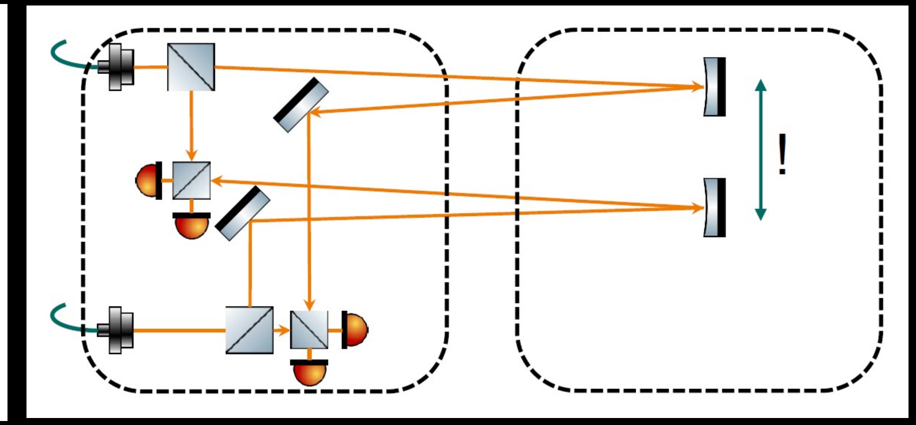
SPI optical assembly

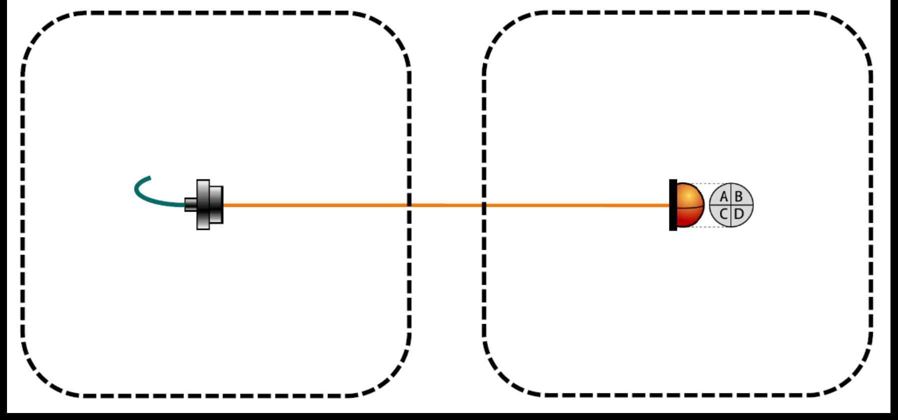


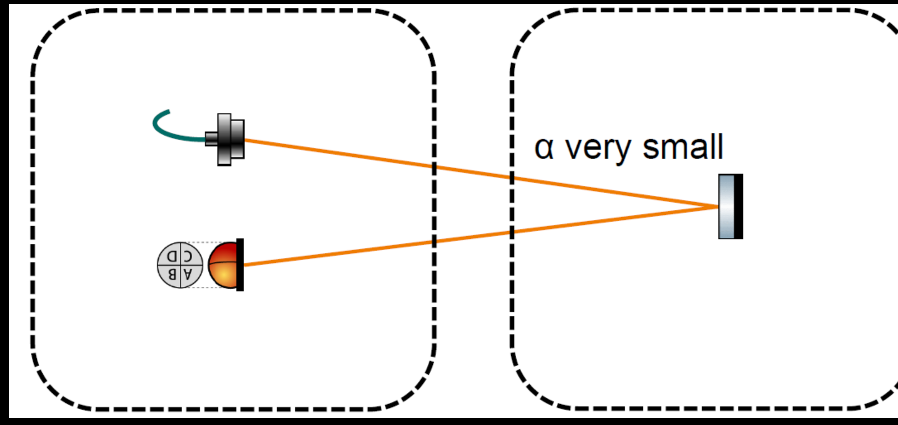
Koehlenbeck et al (2023)

A few options for inter-platform sensing



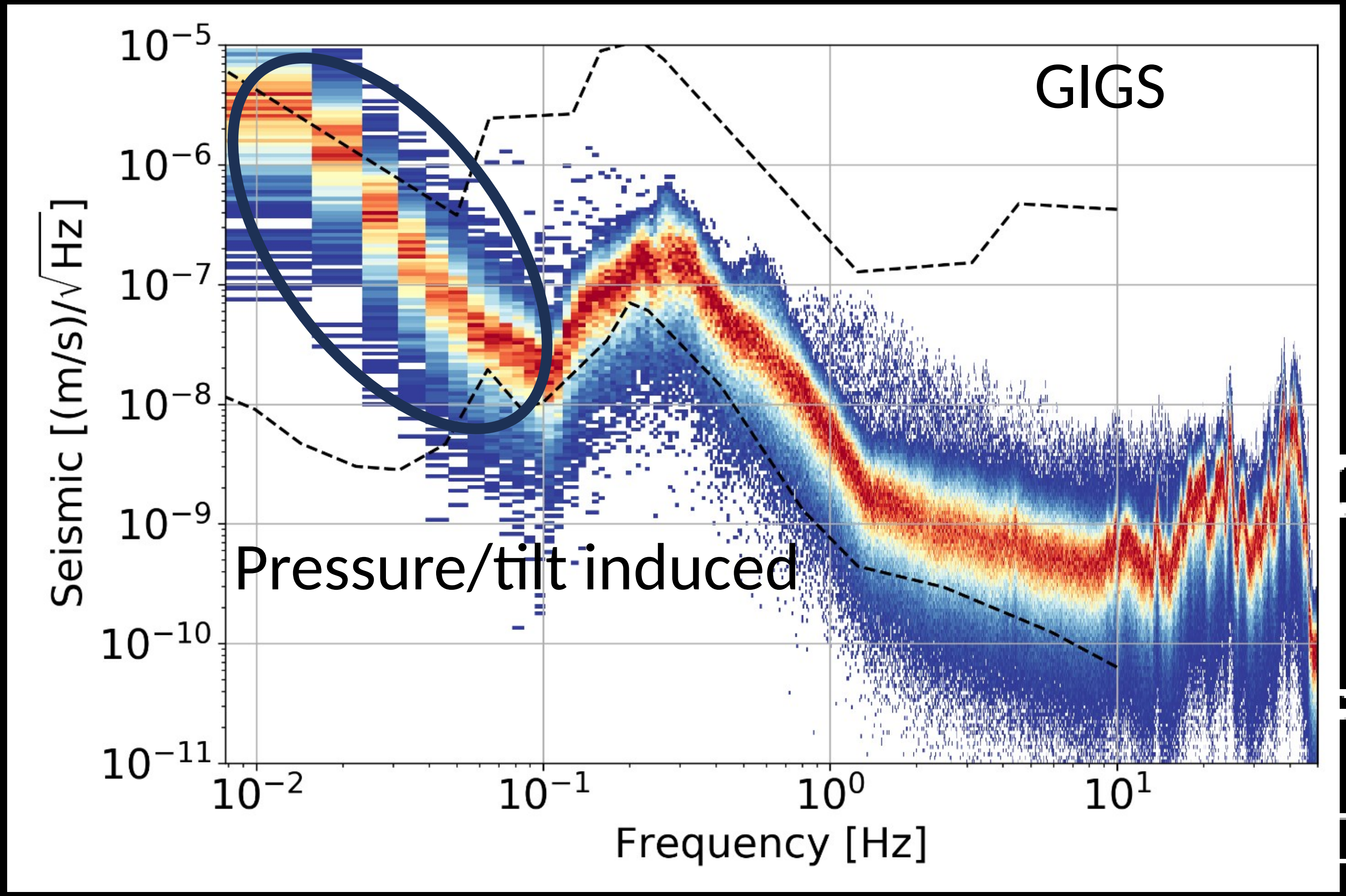


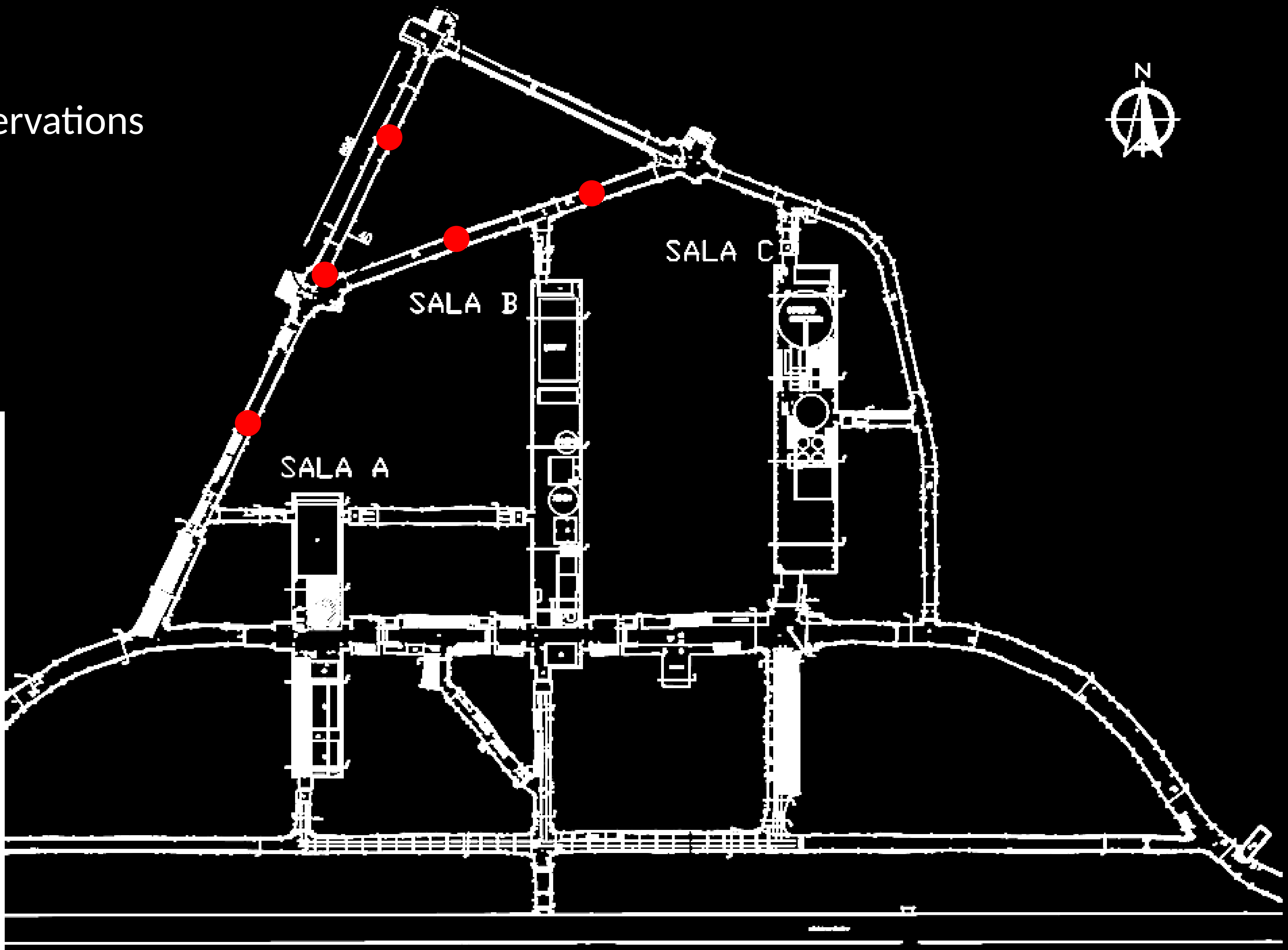




Environmental Monitoring System

Network of barometers for 1mHz to 1Hz observations (underground and surface)





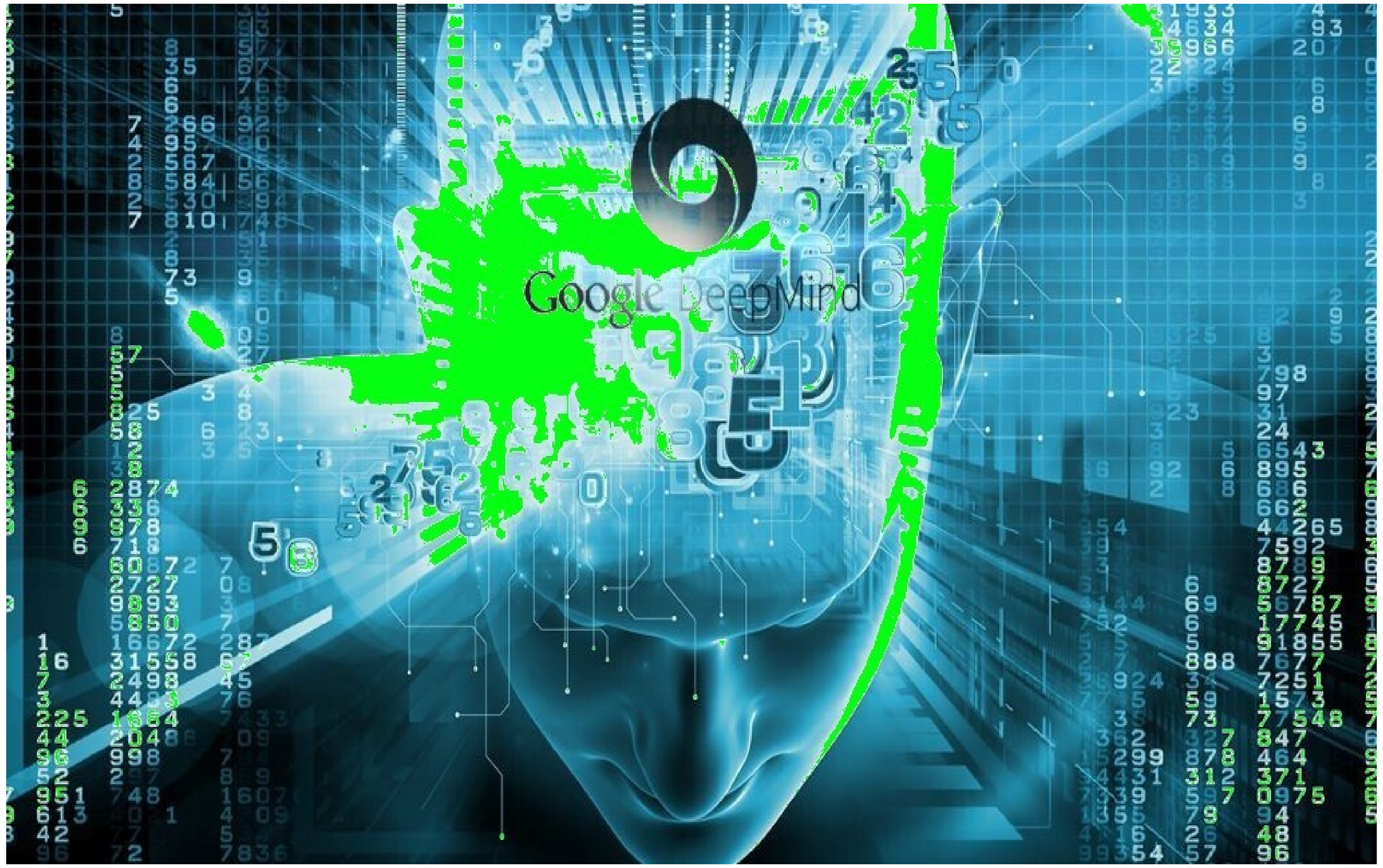
Tentative Timeline

(assuming that funds are available when needed)

	2024		2025		2026		2027		2028	
Site preparation	■	■								
Installation of sensors and actuators on mechanical platforms (surface)			■	■						
Testing of real-time system (surface)			■							
Installation of vacuum system				■						
Installation of electronics rack				■						
Installation of platforms into vacuum system					■					
Commissioning of active seismic isolation system						■	■			
Installation of environmental monitoring system						■	■			
Installation of cryocooler, thermal link, cryobox						■				
Installation of inter-platform interferometer (IPF)								■		
Commissioning of IPF									■	■

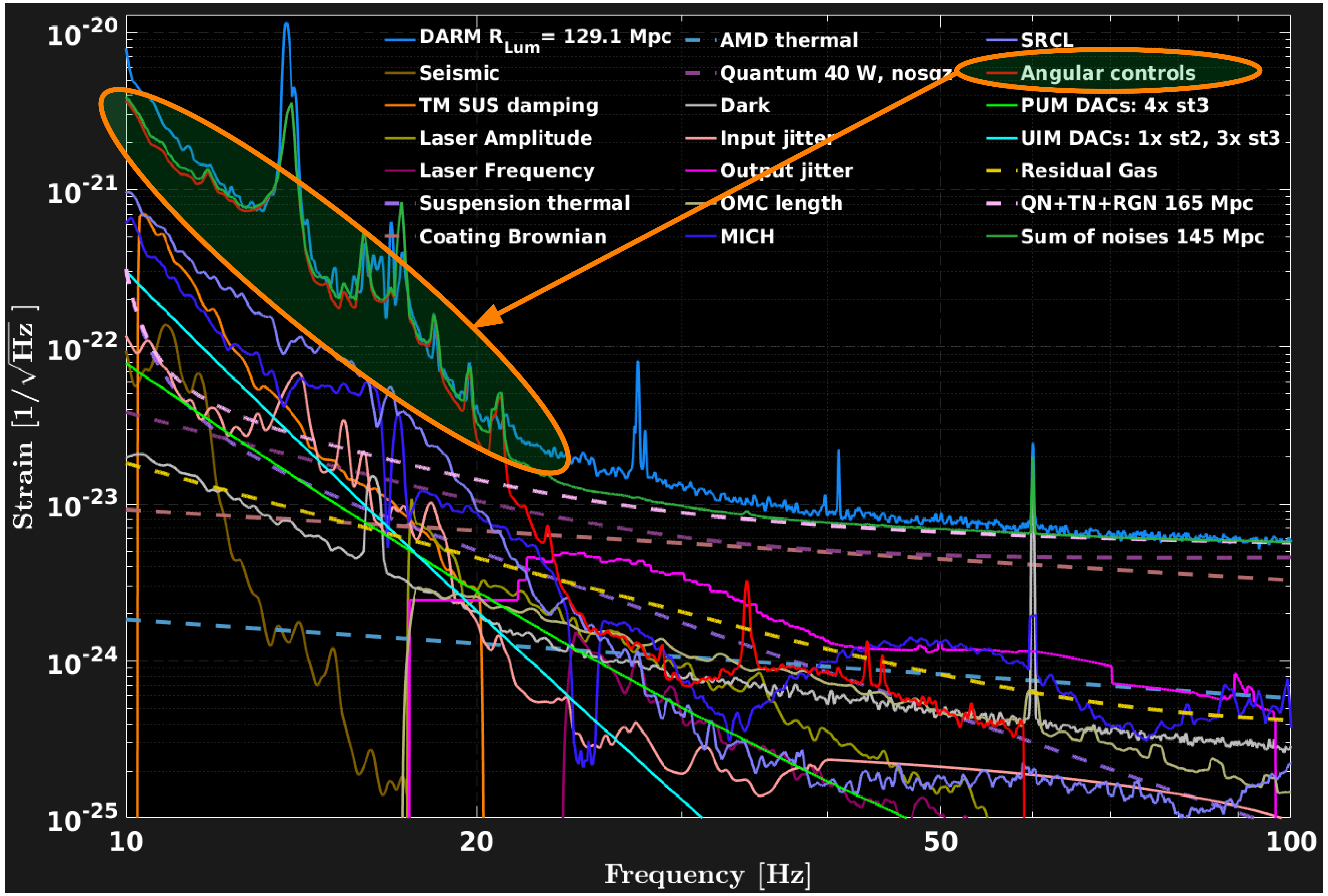
Project Shimmer:
Using Reinforcement Learning / Neural Networks For Detector Controls

Coordinating Institutions: GSSI, Caltech, Google DeepMind



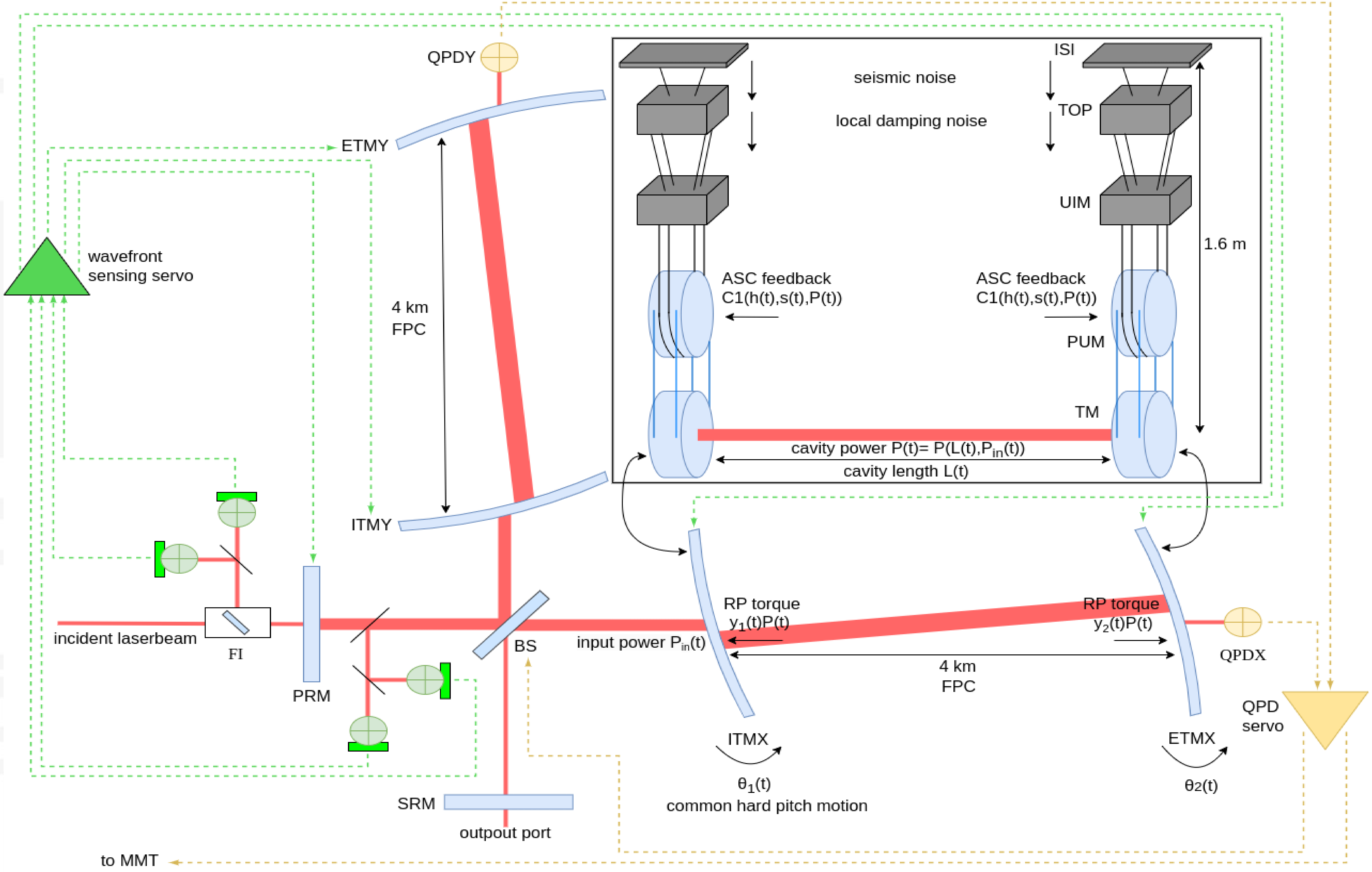
Control Challenges in GW Detectors

- GW detectors like LIGO require ultra-precise control
- Control noise can limit astrophysical reach
- Need advanced techniques beyond classical control



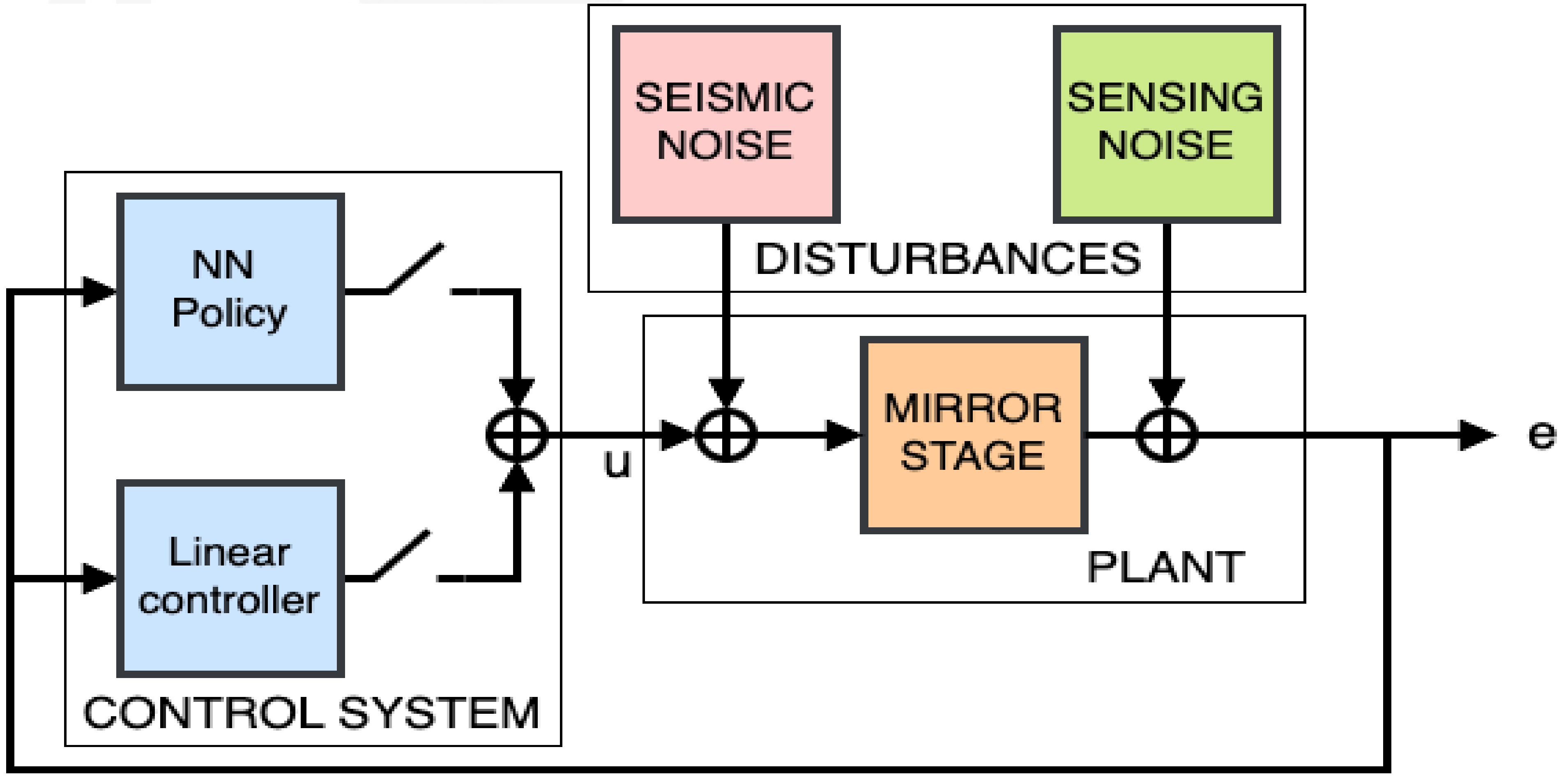
LIGO Livingston Detector noise budget

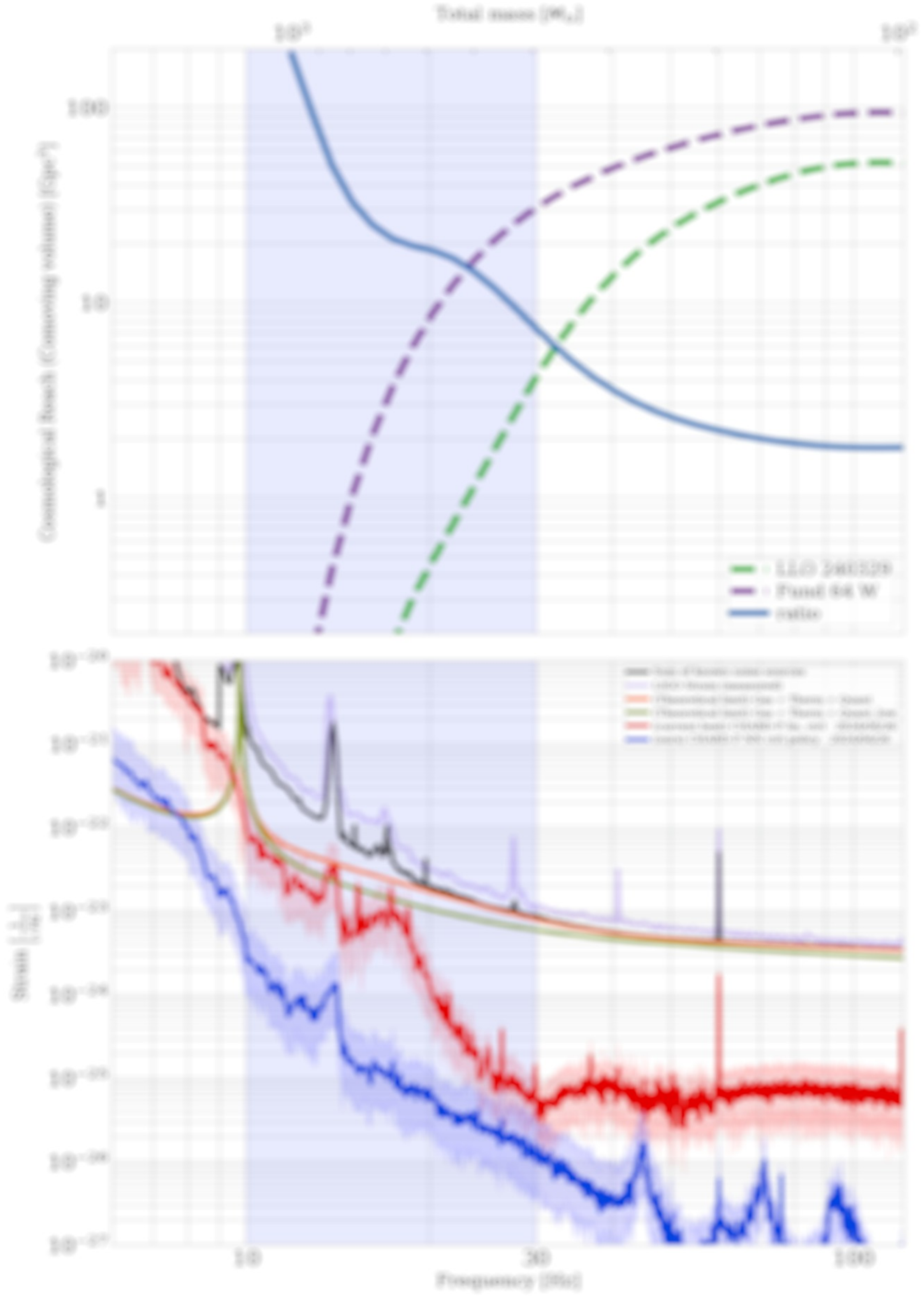
Control Challenges in GW Detectors



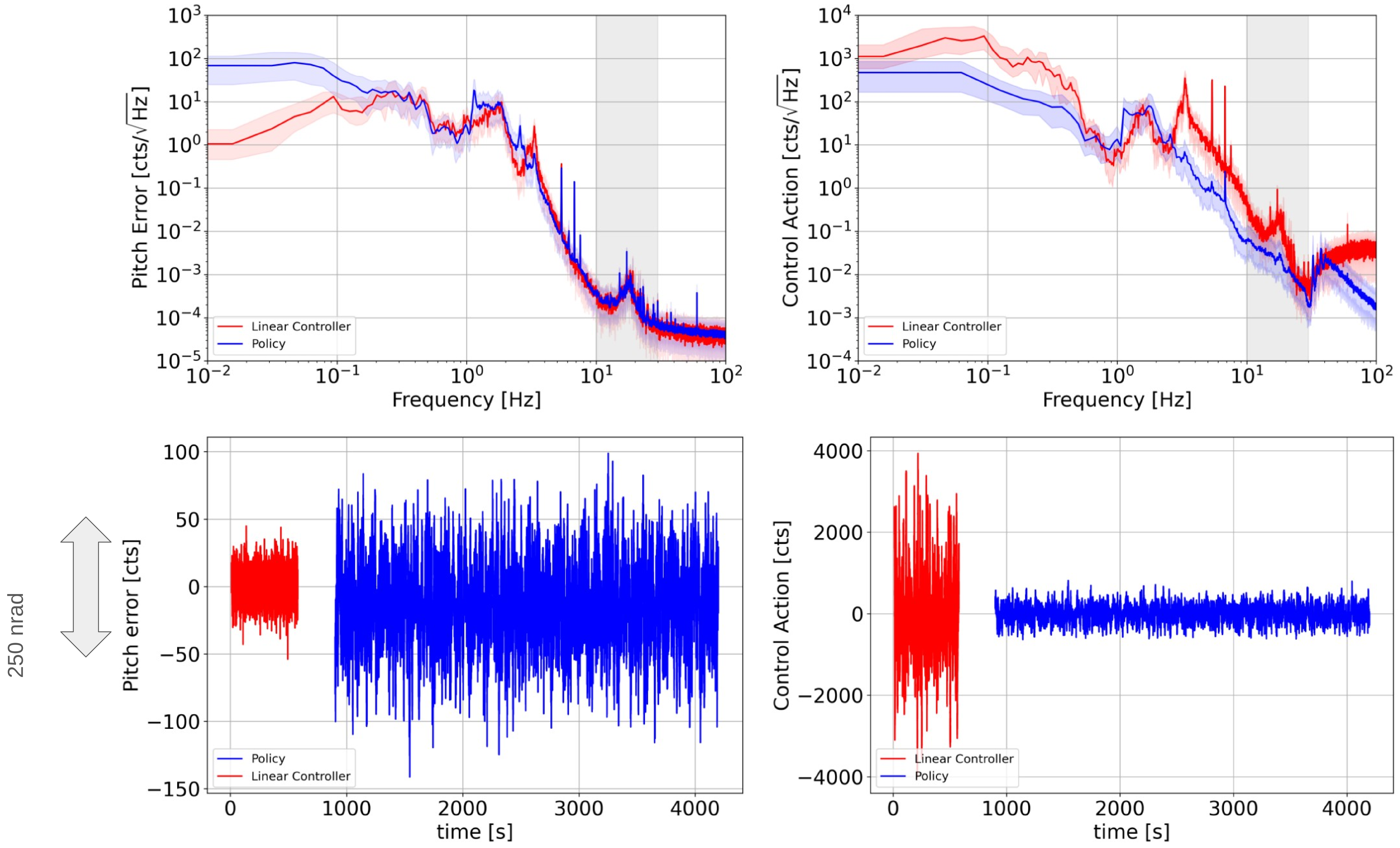
Overview: use neural networks for better control

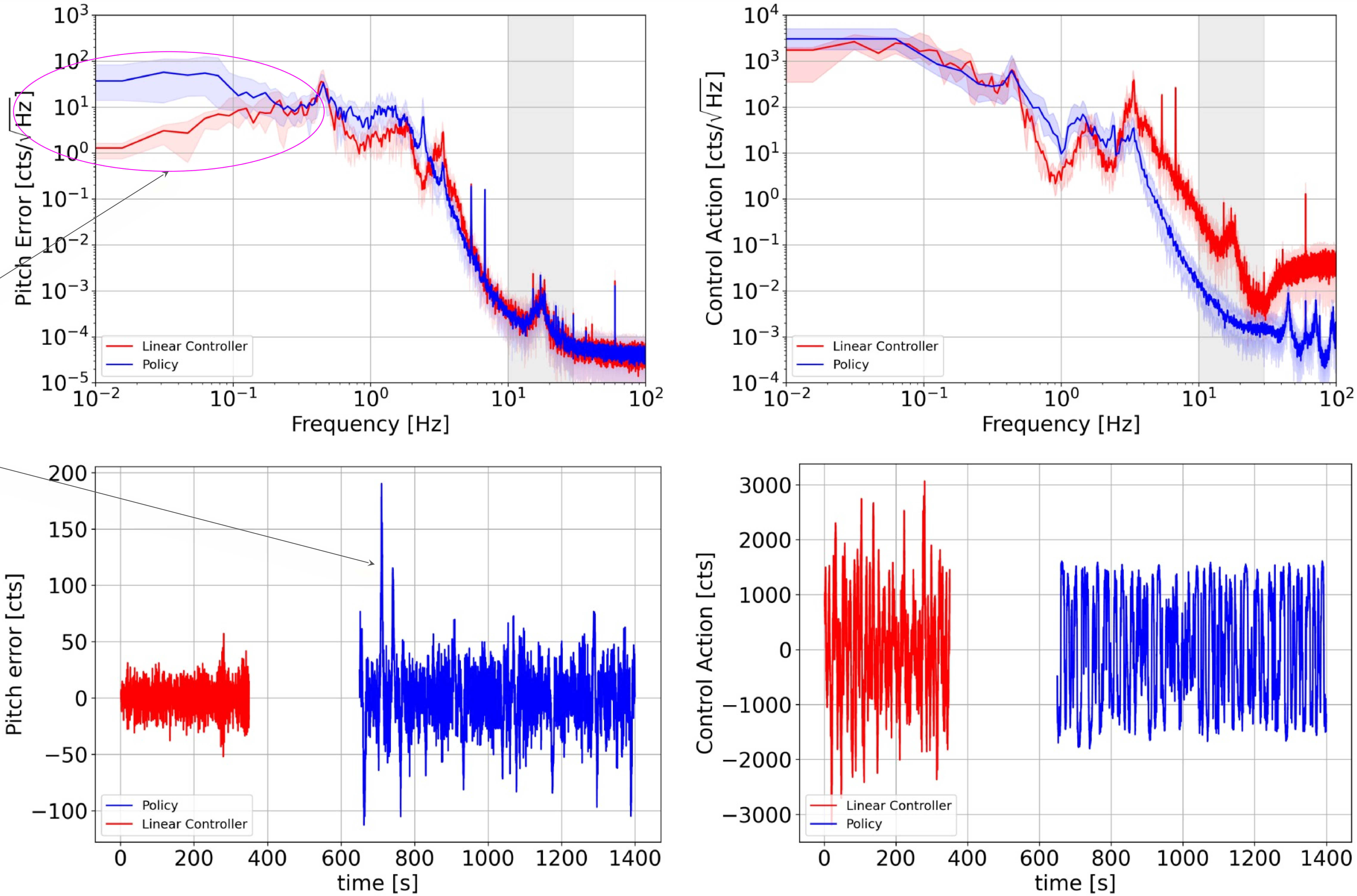
- Main Results:
  - Very good performance in simulations
  - Good performance at LLO
  - Mostly short ~15 min tests.
  - One (1 hour) run - no issues.





spongebob - 26.4.2024

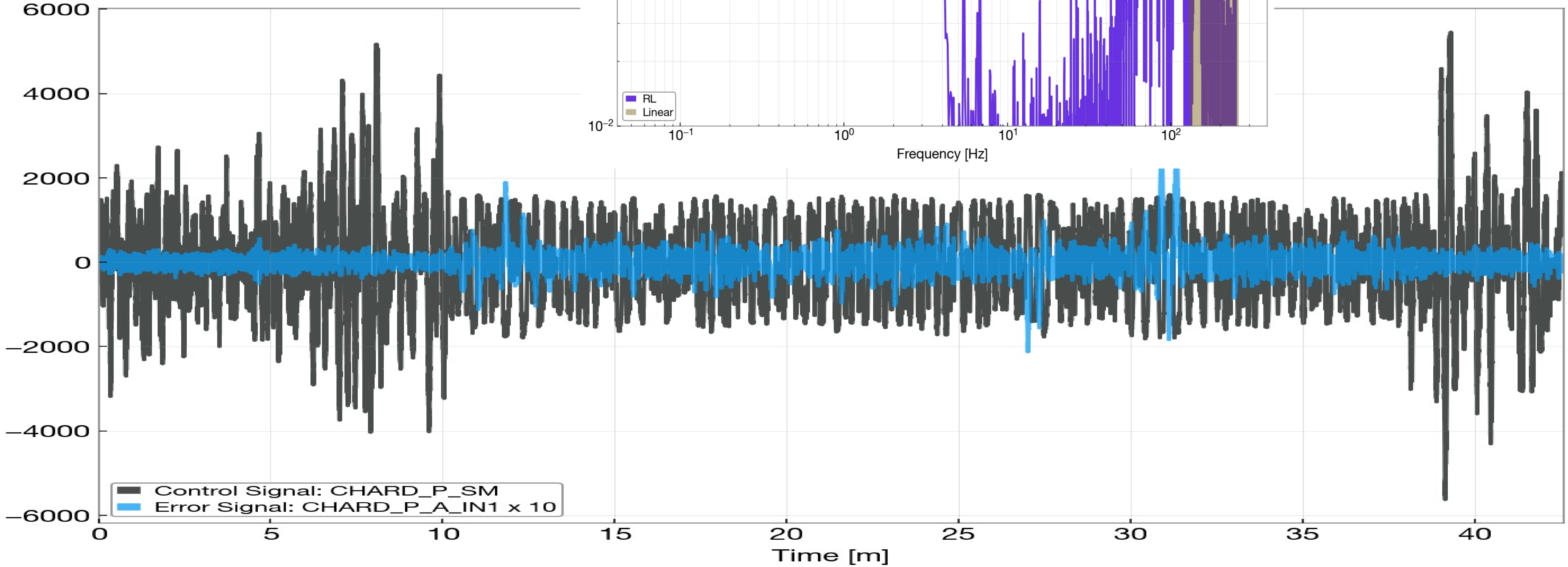


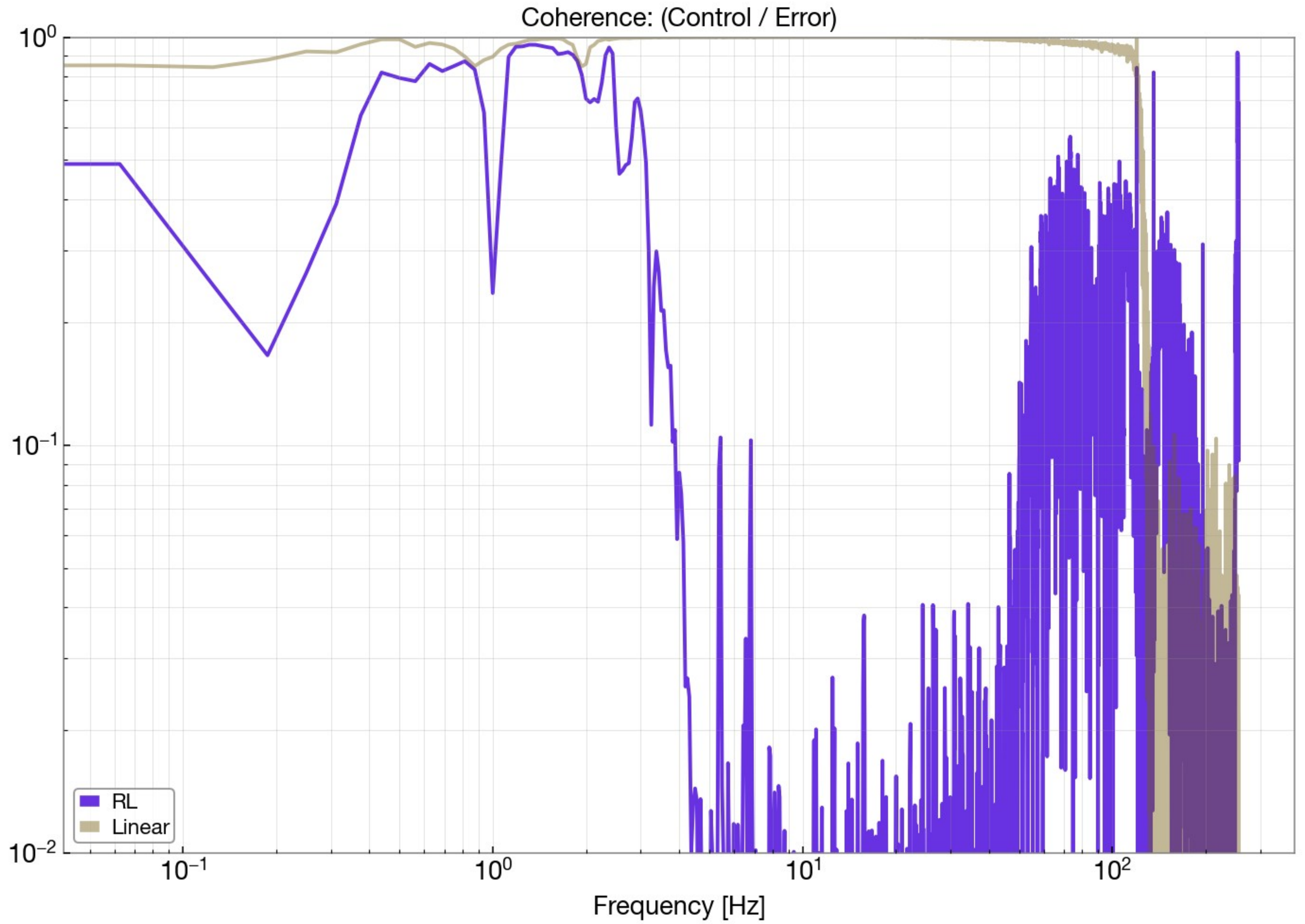


Low
Freq
Excess

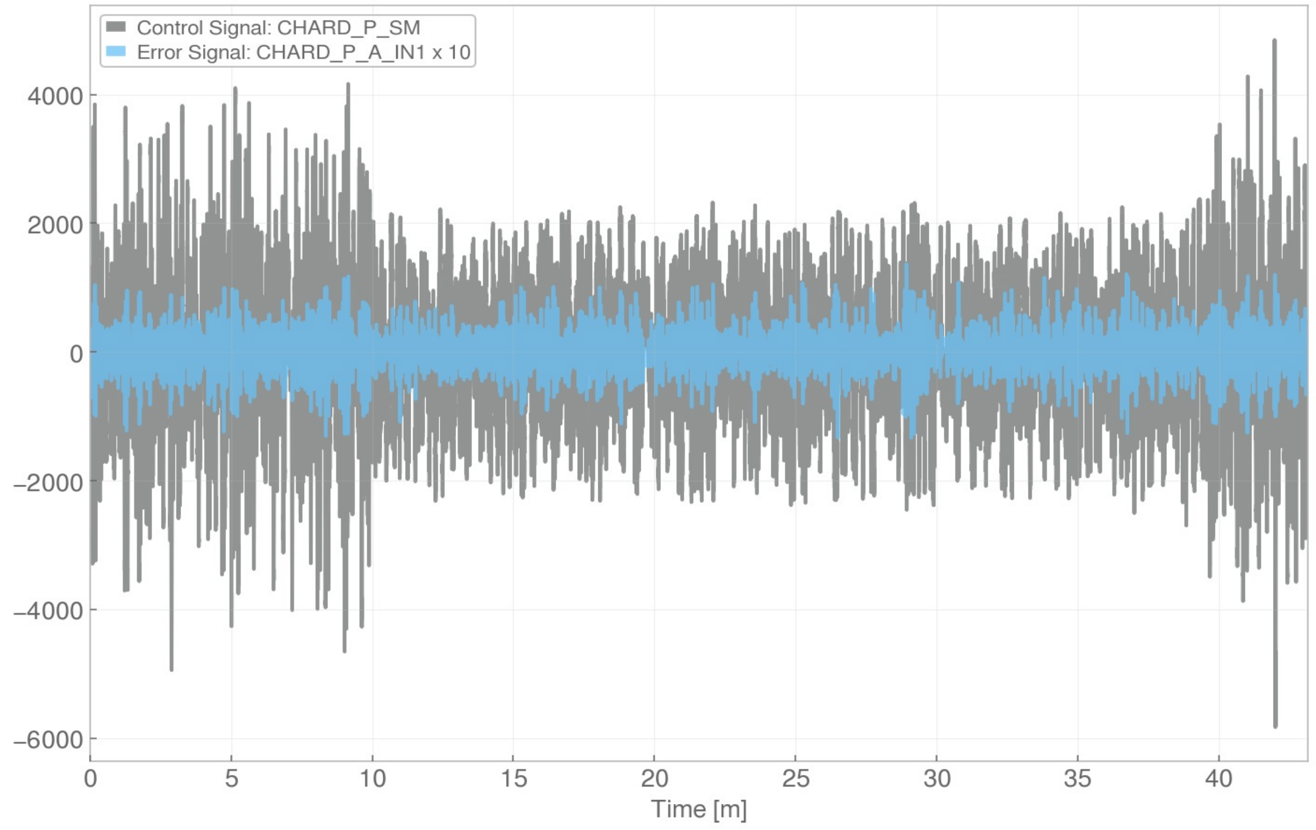
- Needs better low freq SysID (L2/L1)

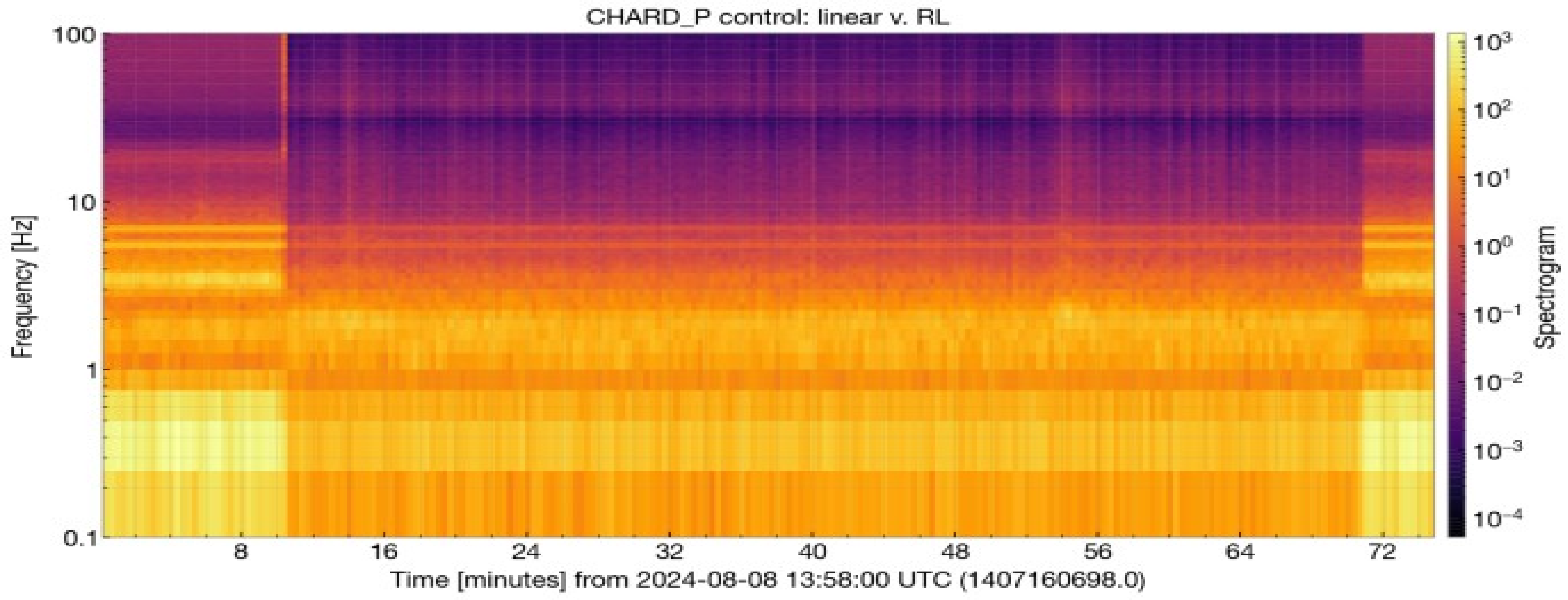
Coherence


6000
4000
2000
0
−2000
−4000
−6000
0
5
10
15
20
25
30
35
40
Time [m]
Control Signal: CHARD_P_SM
Error Signal: CHARD_P_A_IN1 x 10


Coherence: (Control / Error)
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1
10^2
Frequency [Hz]
RL
Linear

Non-Gaussian analysis

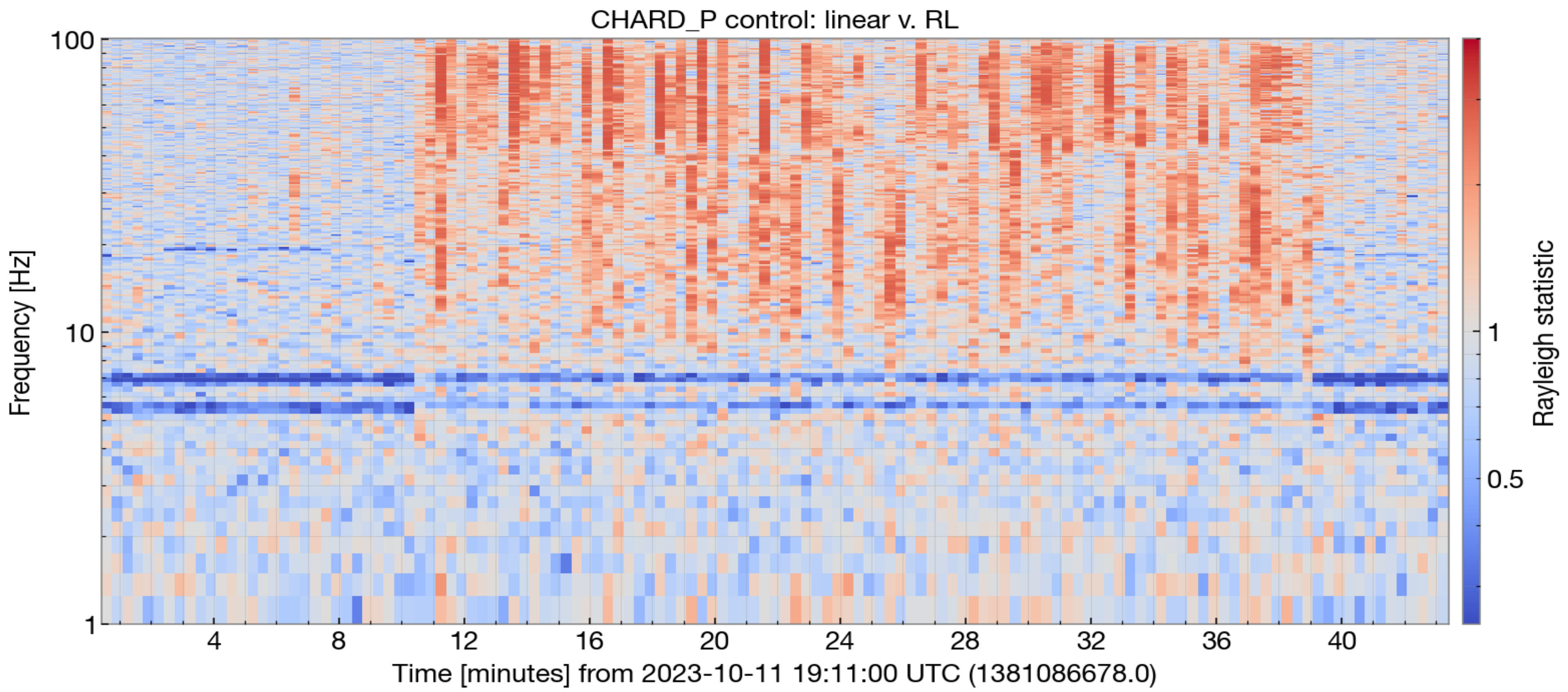




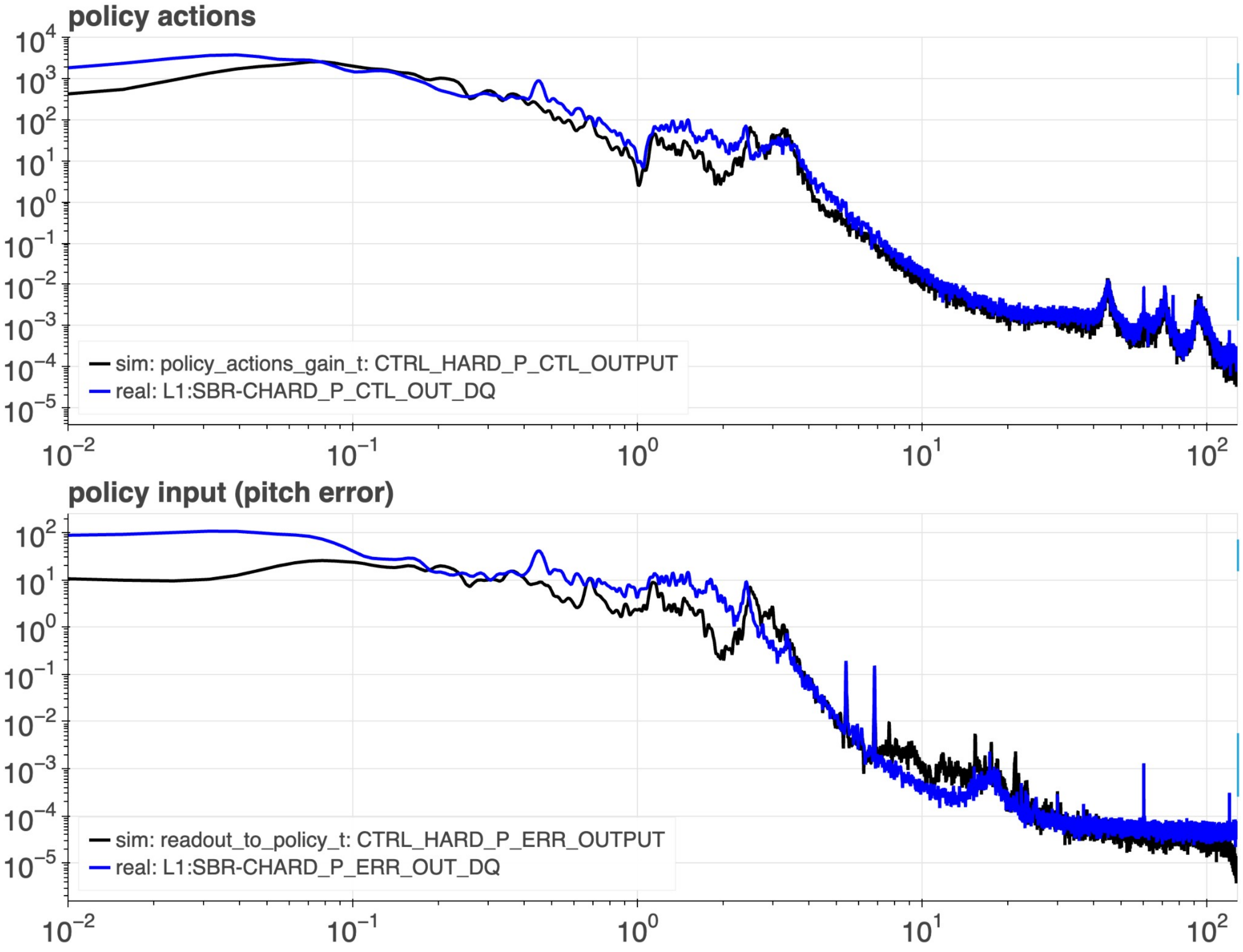
RayleighMonitor Algorithm

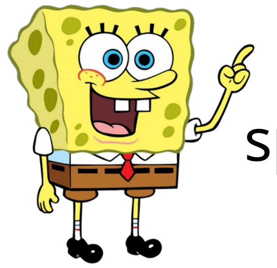
- Makes a set of short-time power spectra.
- Calculates the mean μ and the standard deviation σ of the power spectrum in each frequency bin.
- Ratio $R := \sigma/\mu$ is an interesting statistic:
  - » $R = 1$ is what you expect for Gaussian noise.
  - » $R < 1$ indicates coherent variation.
  - » $R > 1$ indicates glitchy/ratty data.
- RayleighMonitor plots scrolling spectrograms (μ) and “Rayleighgrams” (R) for visual inspection of data characteristics.

LIGO-G040422-00-Z Detector Investigation Camp Aug 04 4

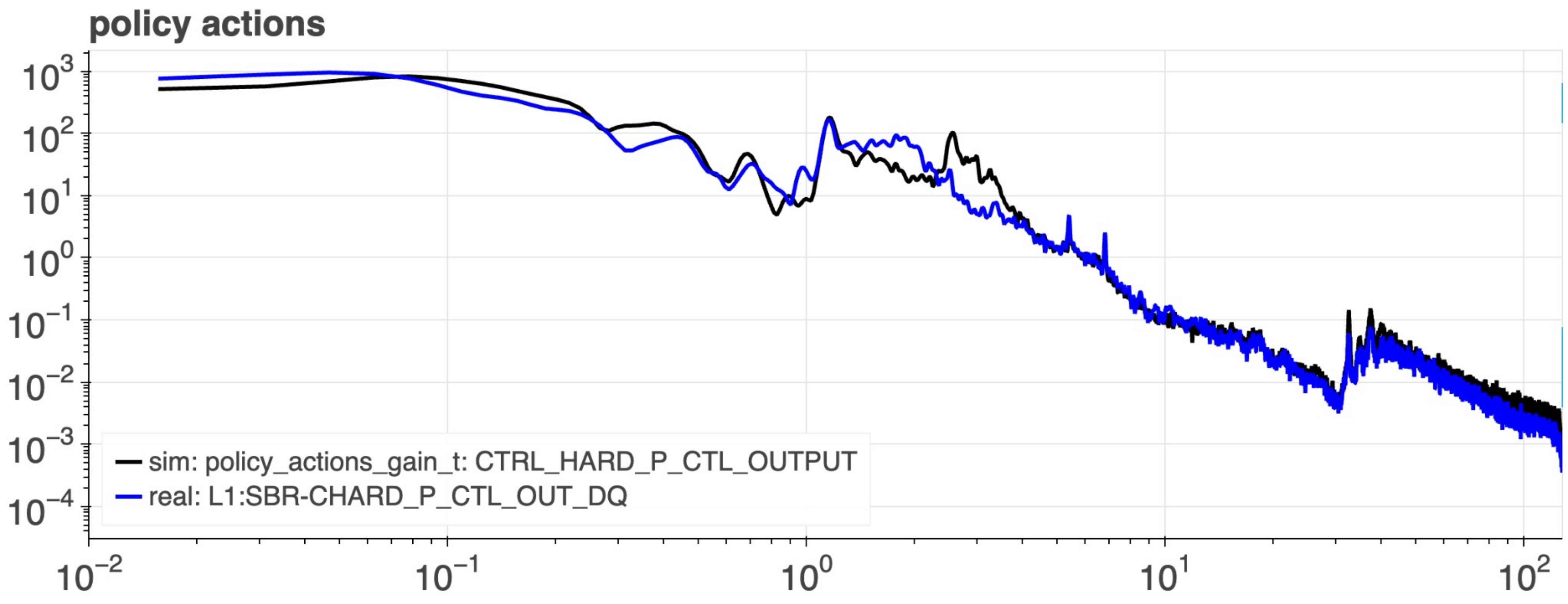


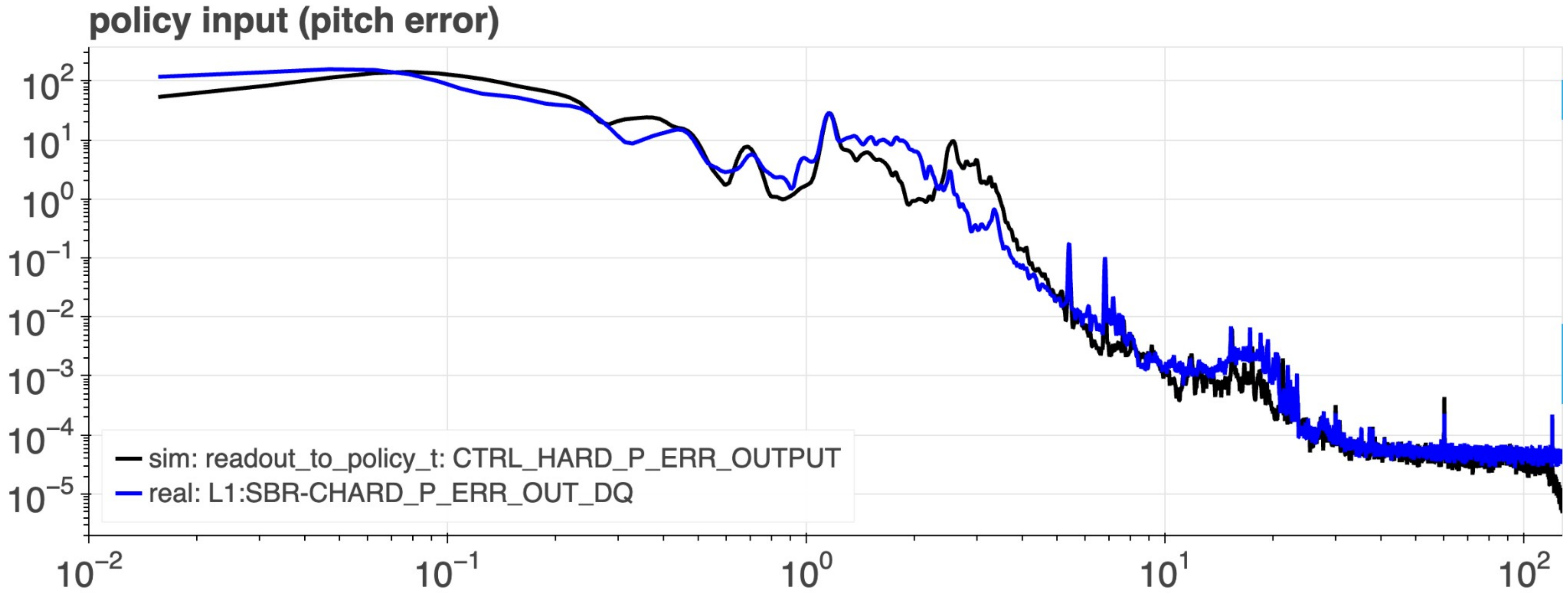
squidward - sim2real transfer is excellent above >0.1Hz





spongebob - sim2real transfer is excellent





Summary

1. The LIGO Controls/ASC feedback noise is ~significant noise source at 10-25 Hz in DARM.
2. This is due to 2 effects:
   a. too much feedback noise at 10-20 Hz
   b. too much beam spot motion at 0.1-1 Hz
3. **Improving the low freq noise will improve several science targets:** IMBH, BNS early warning, BBH eccentricity, high Z sirens
4. We have tried filtering / loopology for years, with some success▼, but are still 10x above the fundamental limits: quantum/gravity
5. This technique (RL/ML/AI) can and should be implemented for MICH/SRCL/ISI/SUS (similar issue - want LF control and less HF noise)

1. Have been working with Deepmind (now Google Deepmind).
2. Collaboration with Caltech (Rana Adhikari)
3. **Great** simulated performance on CHARD using time domain simulation (“LightSaber”)
4. Good real performance on 40m IMC ASC (6x6 MIMO system w/ WFS + QPDs)
5. Success in LLO CHARD_P tests
6. After paper publication, we will have a ‘open house’ zoom workshop so that people can get some hands on time with the tools.

▼ see LLO elog 64660 on RHP zeroes by Valera and Chris Wipf

Future work

1. Implement on Virgo loops
2. Make the plant sysID more automated and robust
3. Train the LightSaber model continuously on the live data to extract physically meaningful plant parameters.
4. Explore Hybrid linear + nonlinear control
5. Make it run robustly during high-noise conditions
6. Reduce non-stationarity in control noise (c.f. Rayleigh grams)

GSSI

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Thank you for your attention

tomislav.andric@gssi.it

Questions / Worries

1. Is it safe? Does it inject fake black holes?
2. Can it go crazy and damage the optics?
3. Long term stability?
4. Robustness to transients?
5. How long does it take to train?

1. We record the RL control signals in frames as usual for any controller.
2. Poorly trained controllers can be unstable and make oscillations, but we have limits on the controller’s output as usual.
3. We have run it for some hours at the 40m and the performance is stationary (as per our rough eyeball estimates of Rayleigh-grams)
4. Is robust under these tests:
   a. turned off and on the sensors
   b. turned off and on one mirror actuator
   c. big step in actuator (reduced trans power by 2x)
   d. banging on chamber
   e. walking around chamber
   f. turned on linear controller in parallel (!!)
5. Now that the exploration space has been reduced, the training takes ~1-2 days on a good machine with a few GPUs. Can be done in AWS or Google Cloud. Has ~700 free parameters.

Future Work

1. Implement on Virgo loops
2. Make the plant sysID more automated and robust
3. Train the LightSaber model continuously on the live data to extract physically meaningful plant parameters.
4. Explore Hybrid linear + nonlinear control
5. Make it run robustly during high-noise conditions
6. Reduce non-stationarity in control noise (c.f. Rayleigh grams)

Paper Submission

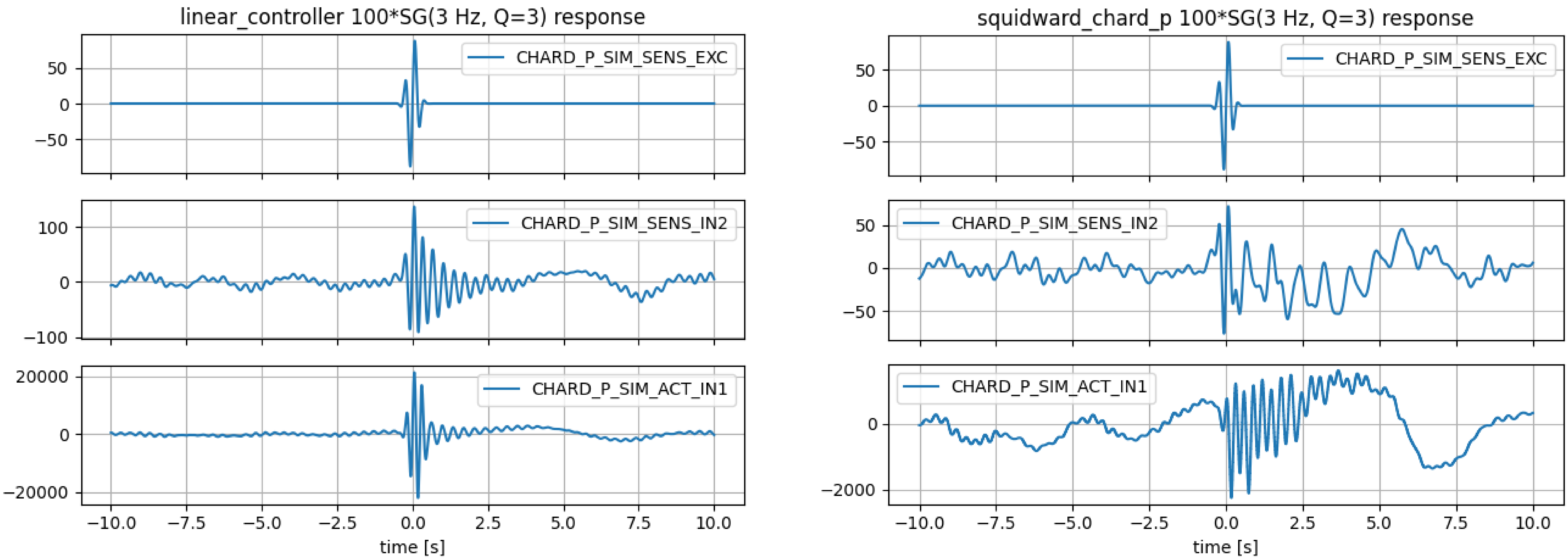
- Target journal: Science
- Uses LIGO instrument, but no astrophysics claims nor search of h(t) for signals.
- Now entering LIGO/Virgo review process.

- Tier 1 & 2 Author list:
  - T Andric, J Harms
  - Shimmer team (AI company & add’l academic partner)
- LIGO O4 Detector Auth List

CDS Issues

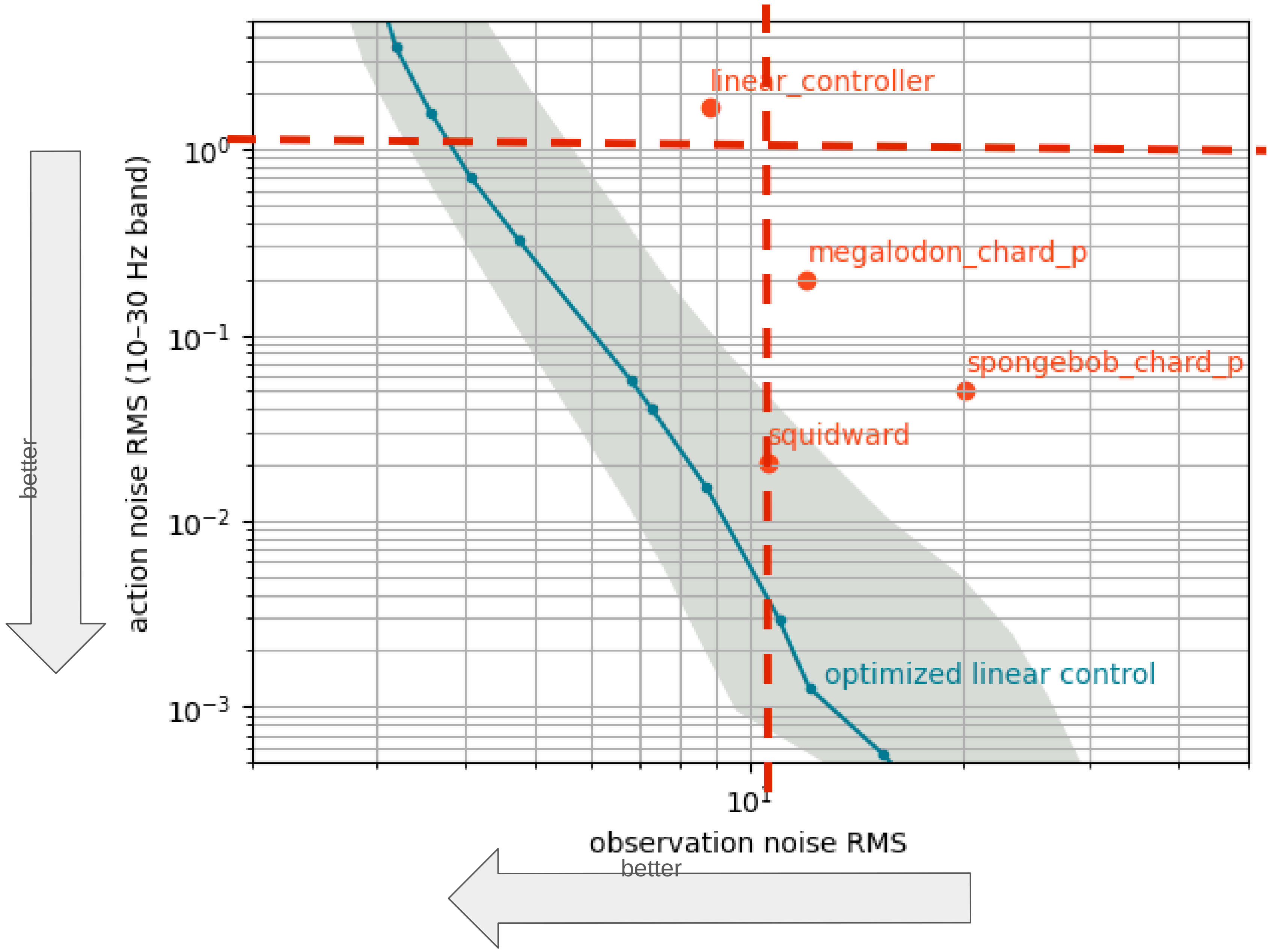
- How does this work?
  - Runs in kernel as a C user function, or in userspace as a loadable library
  - In either case, it is hardcoded (changes require a recompile and restart)
- What’s the difference between kernel and userspace?
  - Kernel mode runs internal to the operating system. Userspace mode runs as an application program
  - Normally controllers have run in the kernel. Userspace controllers are still an experimental development
- How straightforward is it to propagate this elsewhere?
  - Userspace build uses standard tools. C code generator for kernel build remains proprietary for now
  - Build process requires some manual intervention (but less so in the latest RTS release)
- How much control bandwidth is possible?
  - Typical run time on present hardware is short enough for sample rates of 2048 Hz, BW ~10s of Hz
- How could we scale to run 10 or 100 of these in the future?
  - They are more hardware intensive than linear filtering, so more CPU cores would have to be provided
  - Expect that we could run the 4 HARD loops on a single core
- How do we train these networks in the future?
  - Involve more people
  - Need medium scale GPU resources
- What’s the turnaround time to get it running for a new loop?
  - Limited by SysID time: need faster, automated sysID

Robustness of controller to transients



Optimized Linear Controllers

- Since the 1980s, convex optimization was recognized as a powerful tool for optimizing linear control loops
- This method lets us map out a “Pareto frontier” of high-performance linear CHARD_P controllers. These can provide a baseline of comparison for the nonlinear policies
- Many controller specifications are convex. Others can be approximated by convex constraints (but the results may not be globally optimal)
- Not yet fit for deployment (not robust under plant variation)



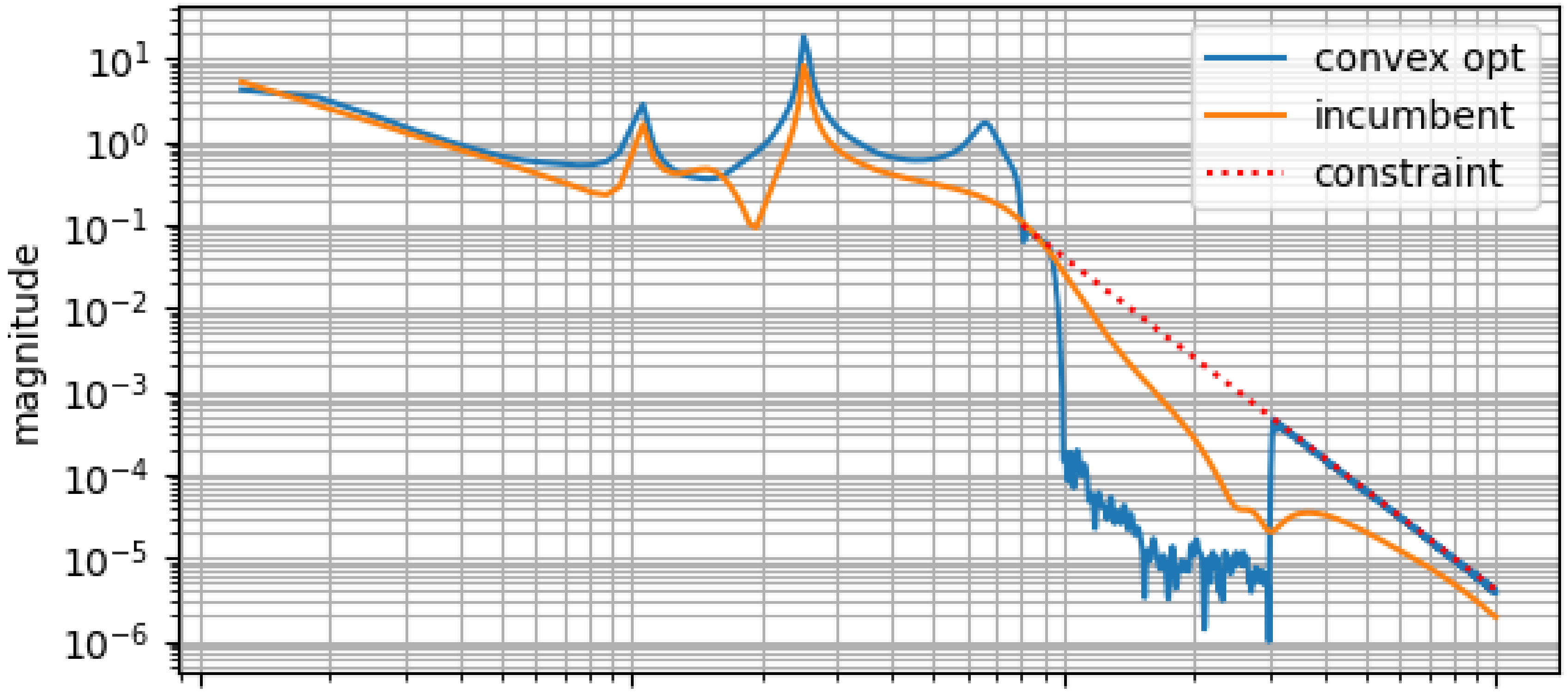


Illustration of method