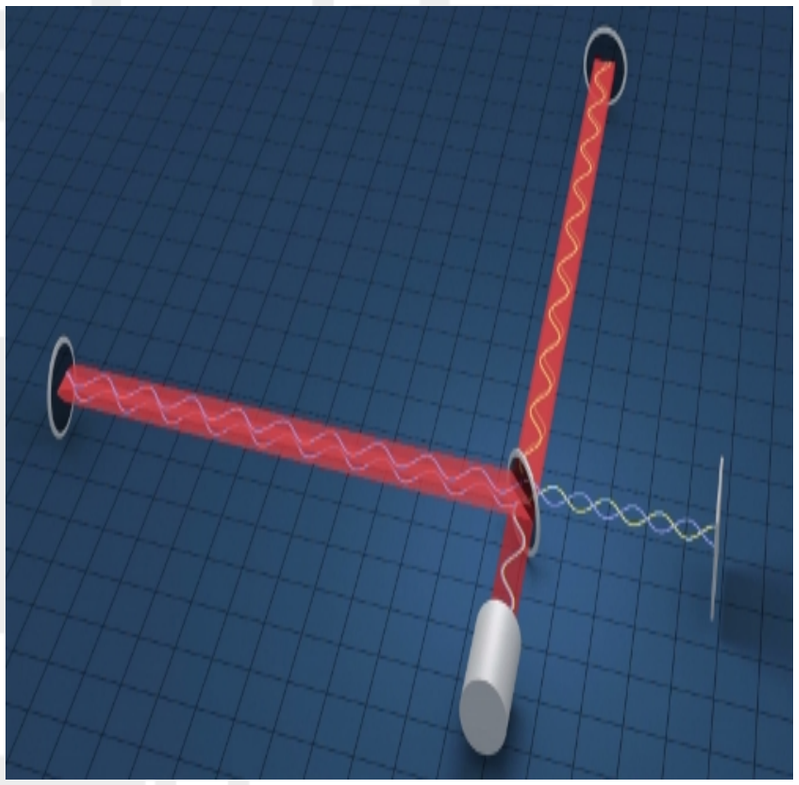
GRAN SASSO
SCIENCE INSTITUTE



Instrument development: GEMINI & SHIMMER (plus Newtonian Noise)

Science Fair
Presentation
23.02.2026.

Tomislav Andrić

www.gssi.it

A new underground seismic-isolation facility at LNGS

Coordinating Institutions: GSSI & INFN – LNGS

Collaborators & Technical Advisors

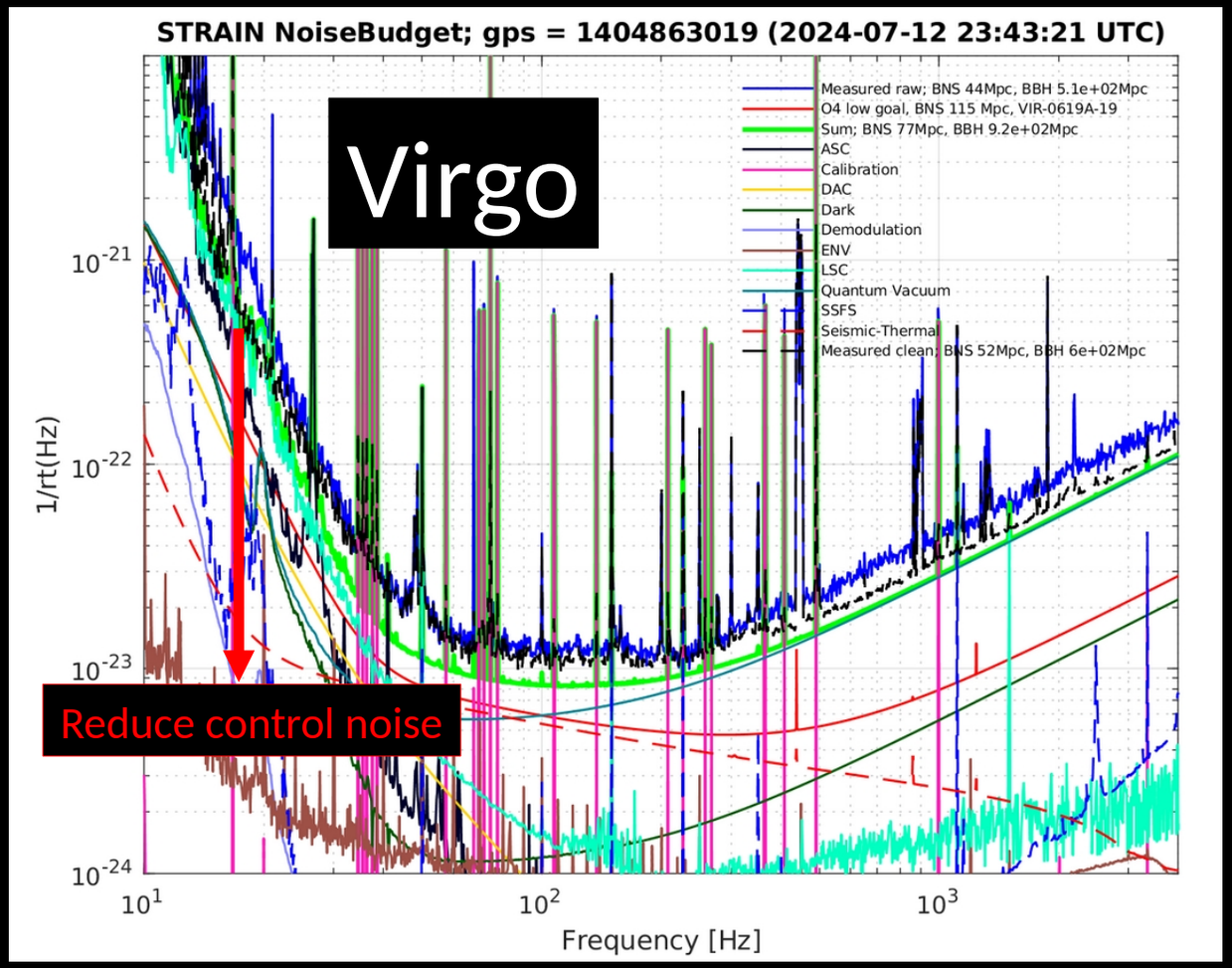
Tomislav Andric (GSSI), Carlo Bucci (INFN), Ilaria Caravella (GSSI), Michele Angiolilli (GSSI), Daniele Cortis (INFN), Nicola D'Ambrosio (INFN), Massimiliano De Deo (INFN), Marco D'Incecco (INFN), Antonio Di Ludovico (INFN), Oliver Gerberding (University of Hamburg), Jan Harms (**PI**; GSSI), Jeff Kissel (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

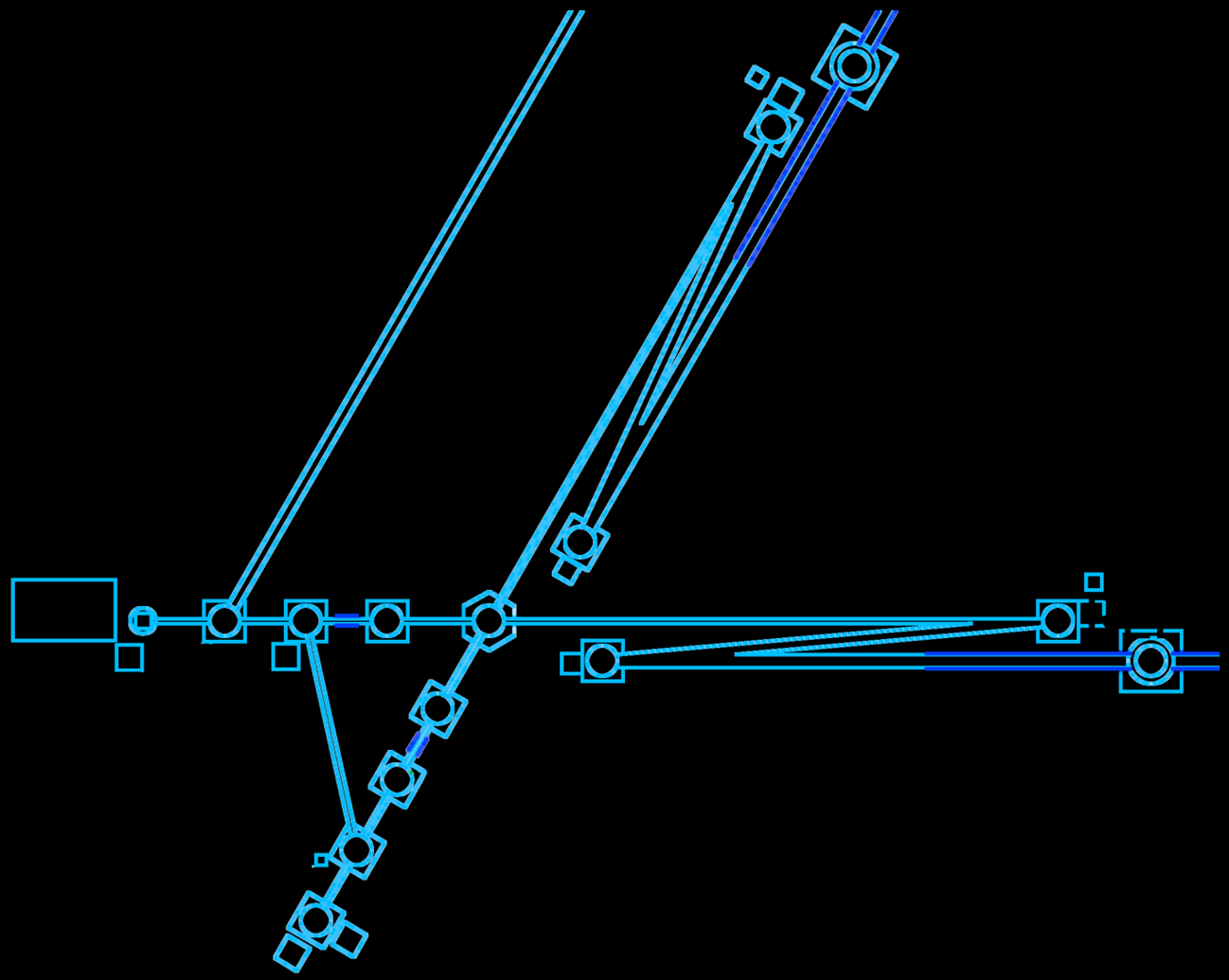
Scientific Focus:

- Development of vibration isolation and inter-platform control systems to support auxiliary DOF stabilization in ET
- Operation and validation of ultra-sensitive inertial sensors in a low-noise underground environment (LNGS)
- Platform for room-temperature and cryogenic testing of next-generation seismometers
- Test technologies, validate their performance, and ensure they meet the requirements before deployment on the Moon
- Deployment of a comprehensive underground environmental monitoring system
- Two operation modes:
  - ET Mode: Demonstrate control architecture for ET-LF auxiliary systems
  - LGWA Mode: Emulate lunar seismic and thermal environment for Moon-bound technologies

Scientific Goal 1: ET

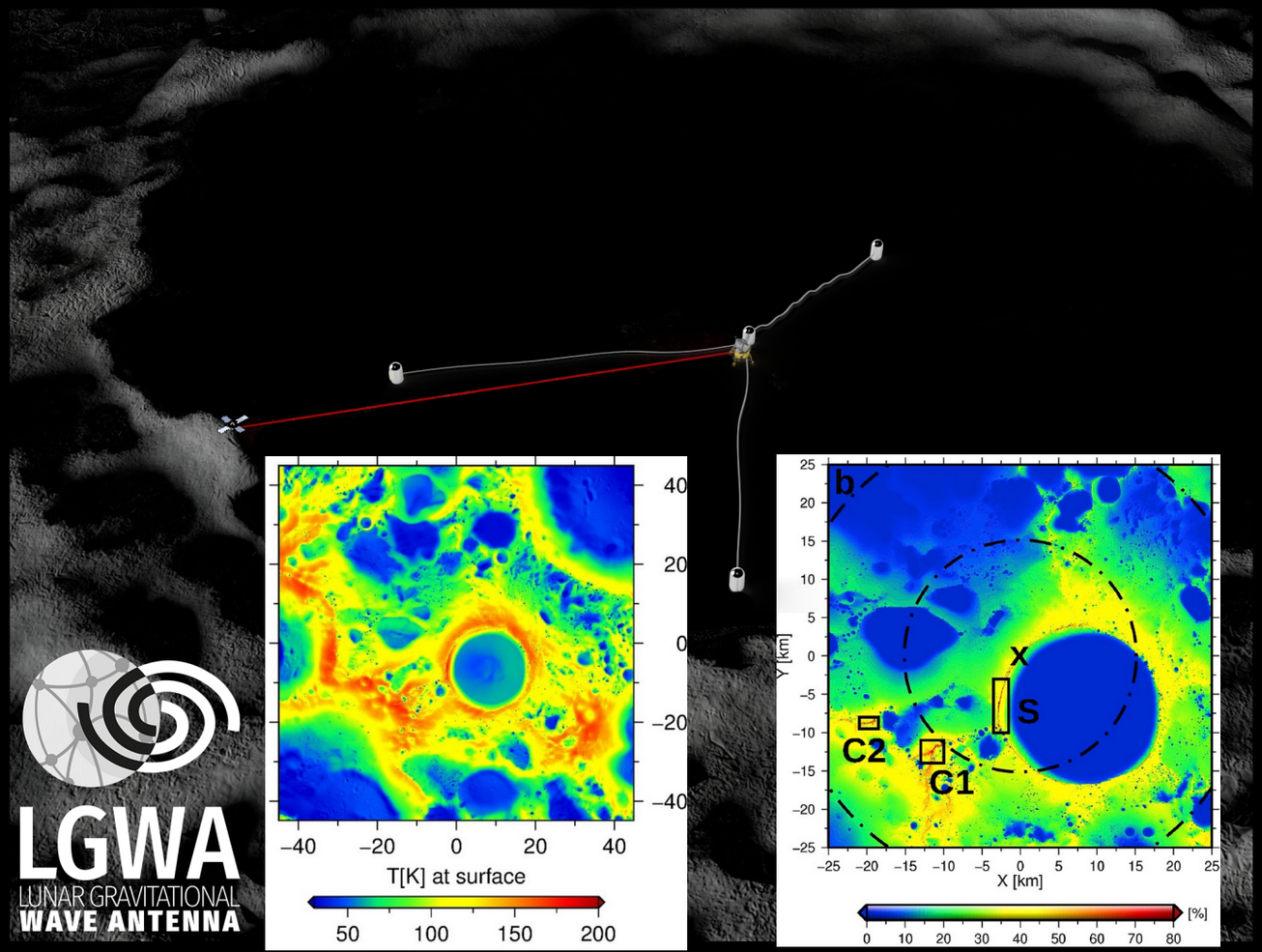


- Noise introduced by the control of length and alignment DOFs can limit LF sensitivity
- Develop an inter-platform motion control system to assist the ET length and alignment control of auxiliary degrees of freedom
- Lock all suspension platforms into a common motion across the full central vertex of an interferometer

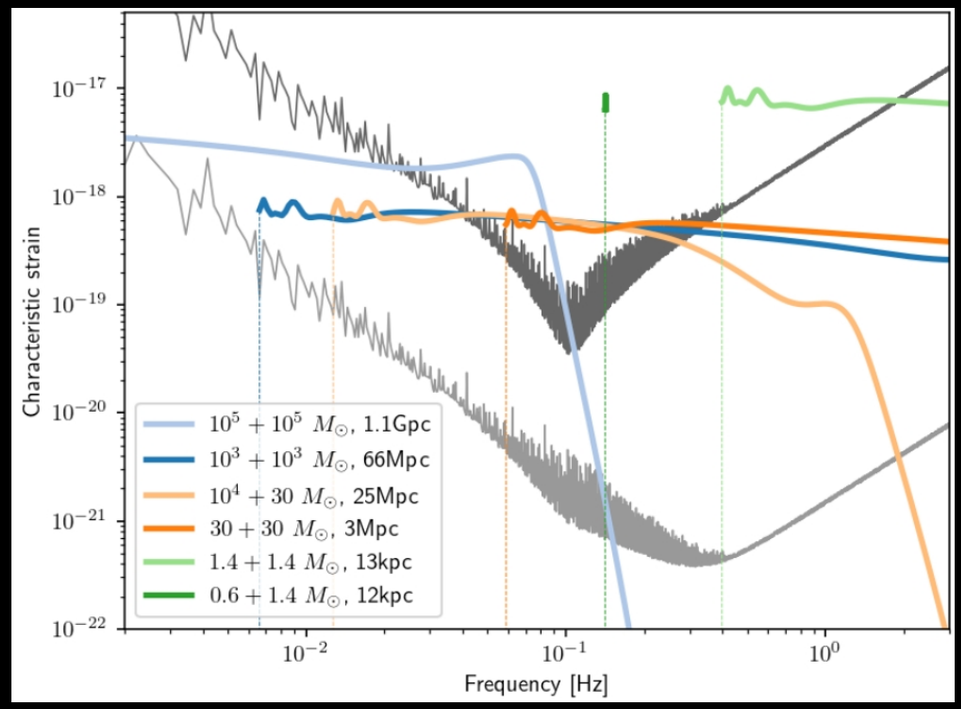


- This enables stable control of auxiliary cavities
- Enable ET-LF science case
- Refer this optically rigid body to the two input masses

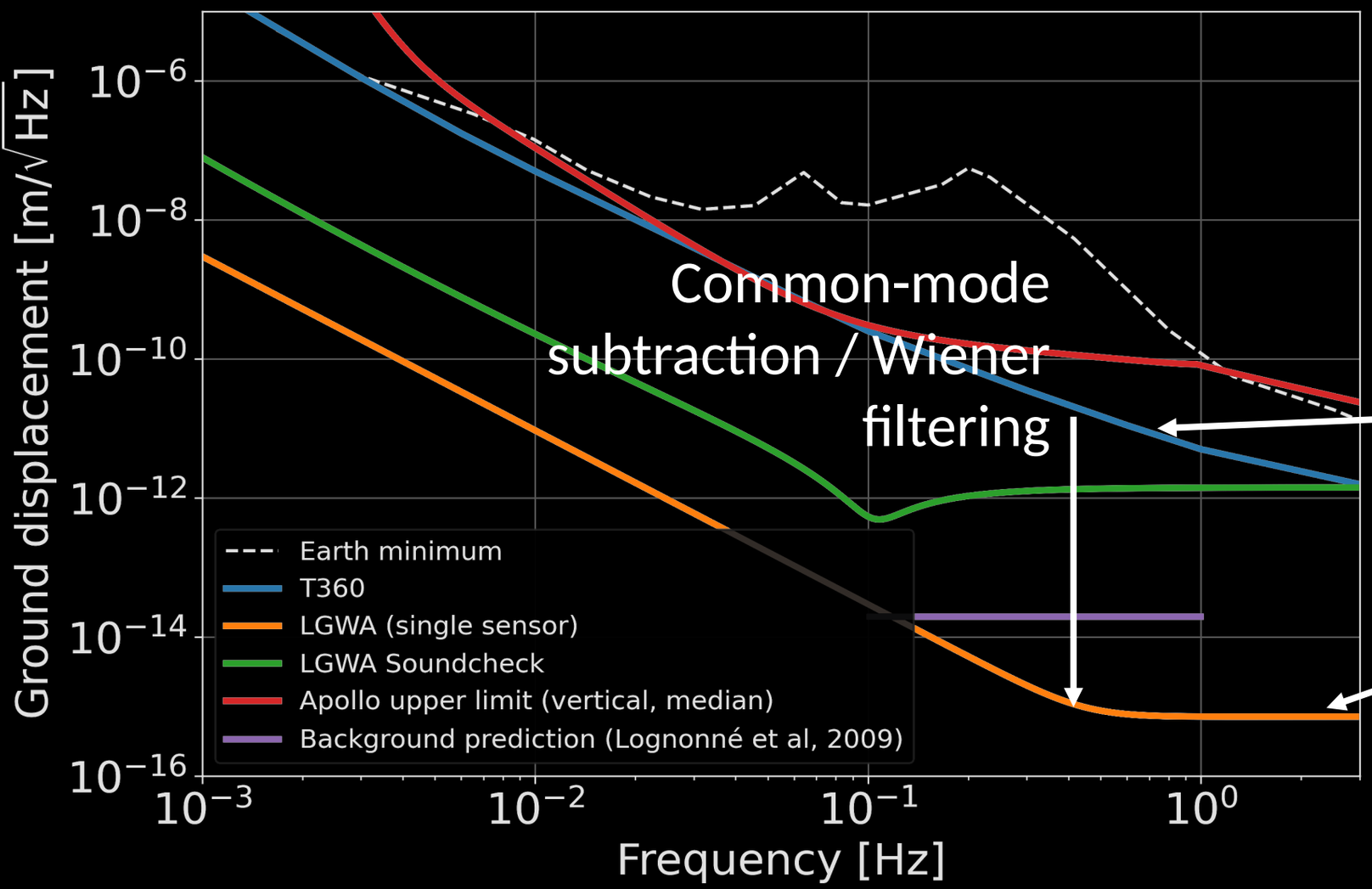
Scientific Goal 2: LGWA



Decihertz gravitational-wave detection on the Moon



GEMINI - LGWA

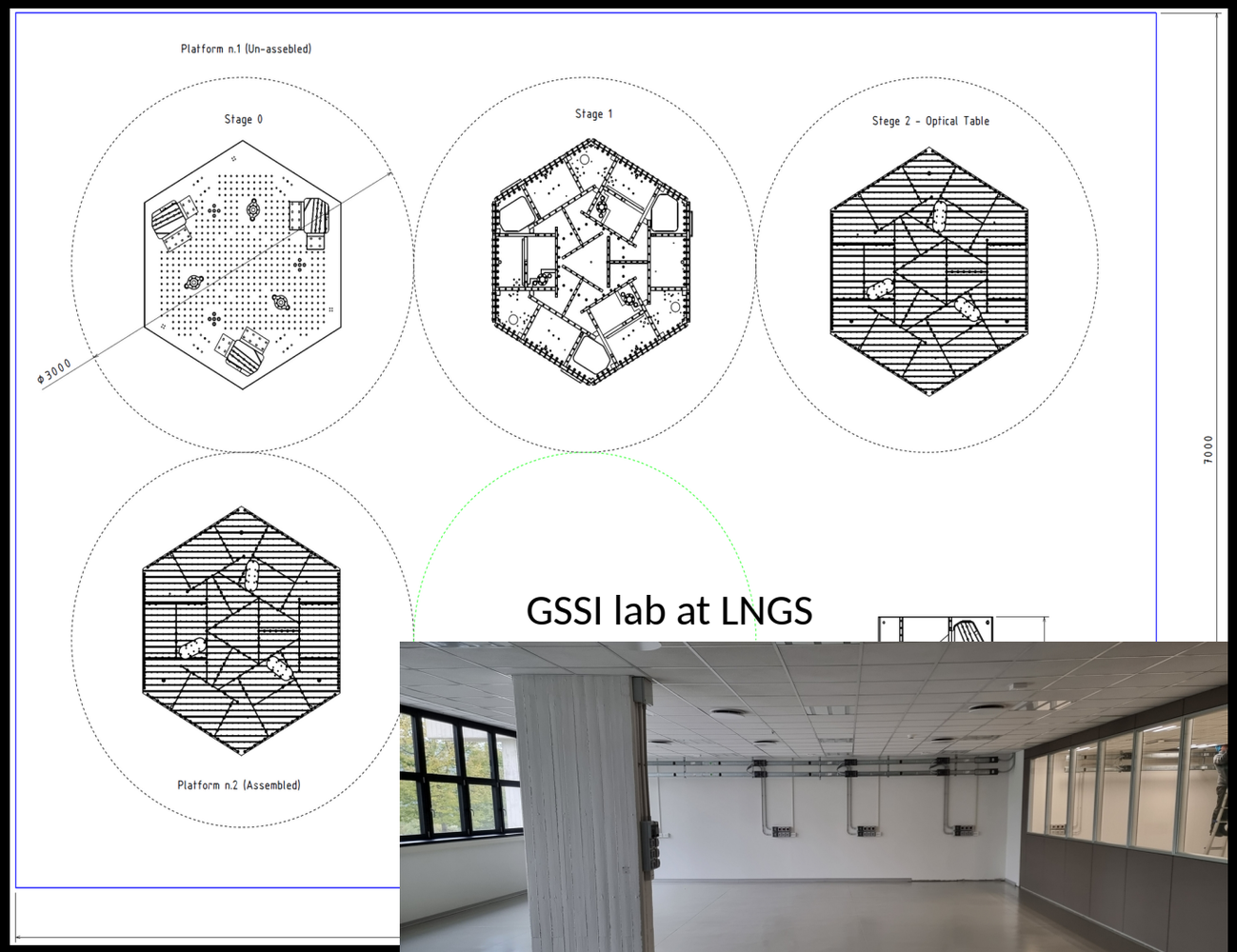


Test high-performance, cryo-temperature lunar seismometers for LGWA

Targeted GEMINI platform residual motion

LGWA sensor performance target

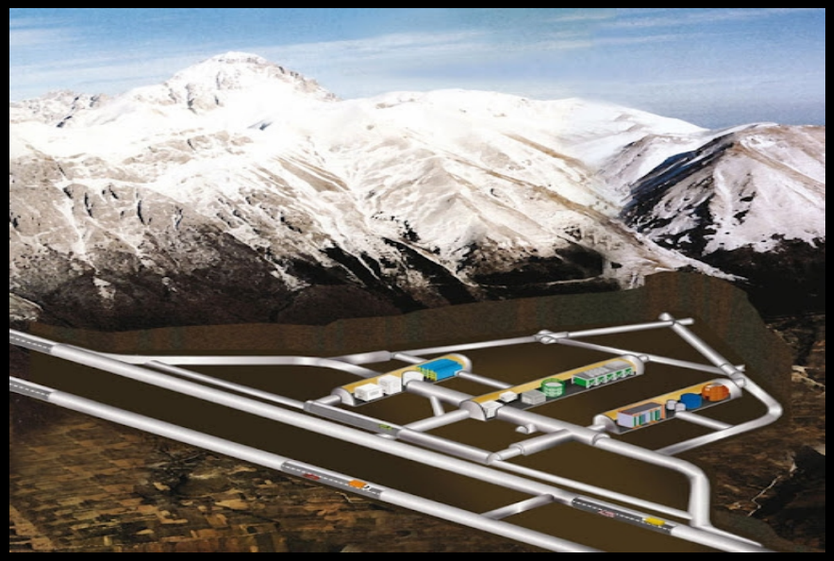
Surface Laboratory

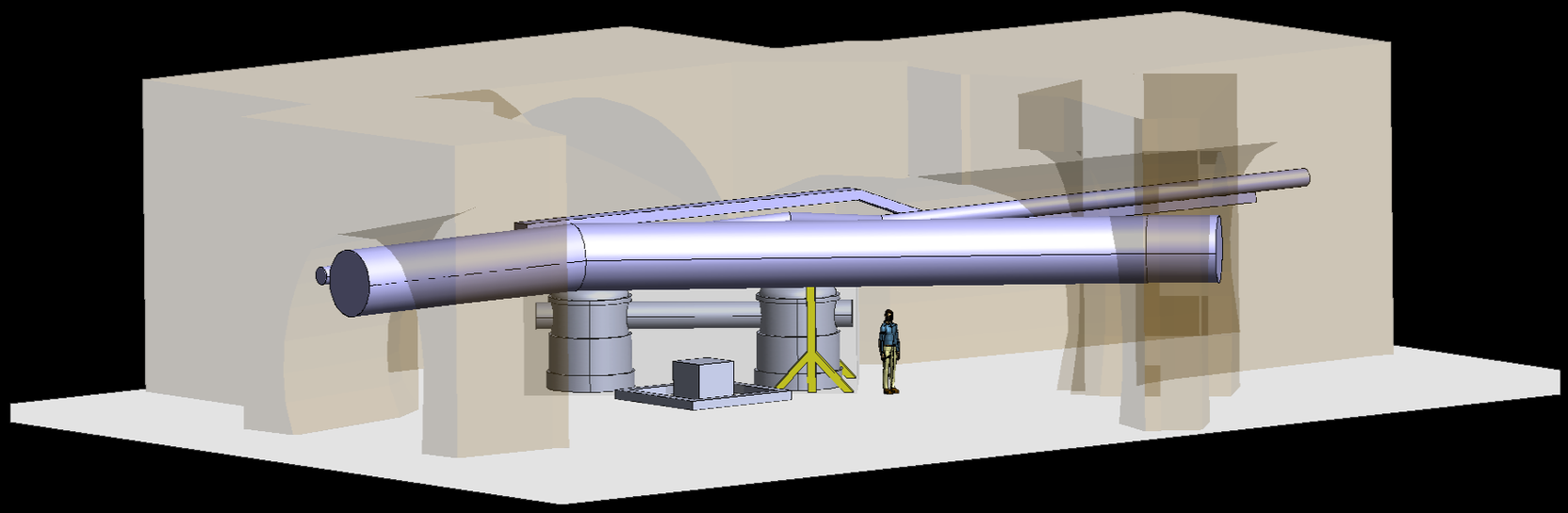


GSSI lab at LNGS

- 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

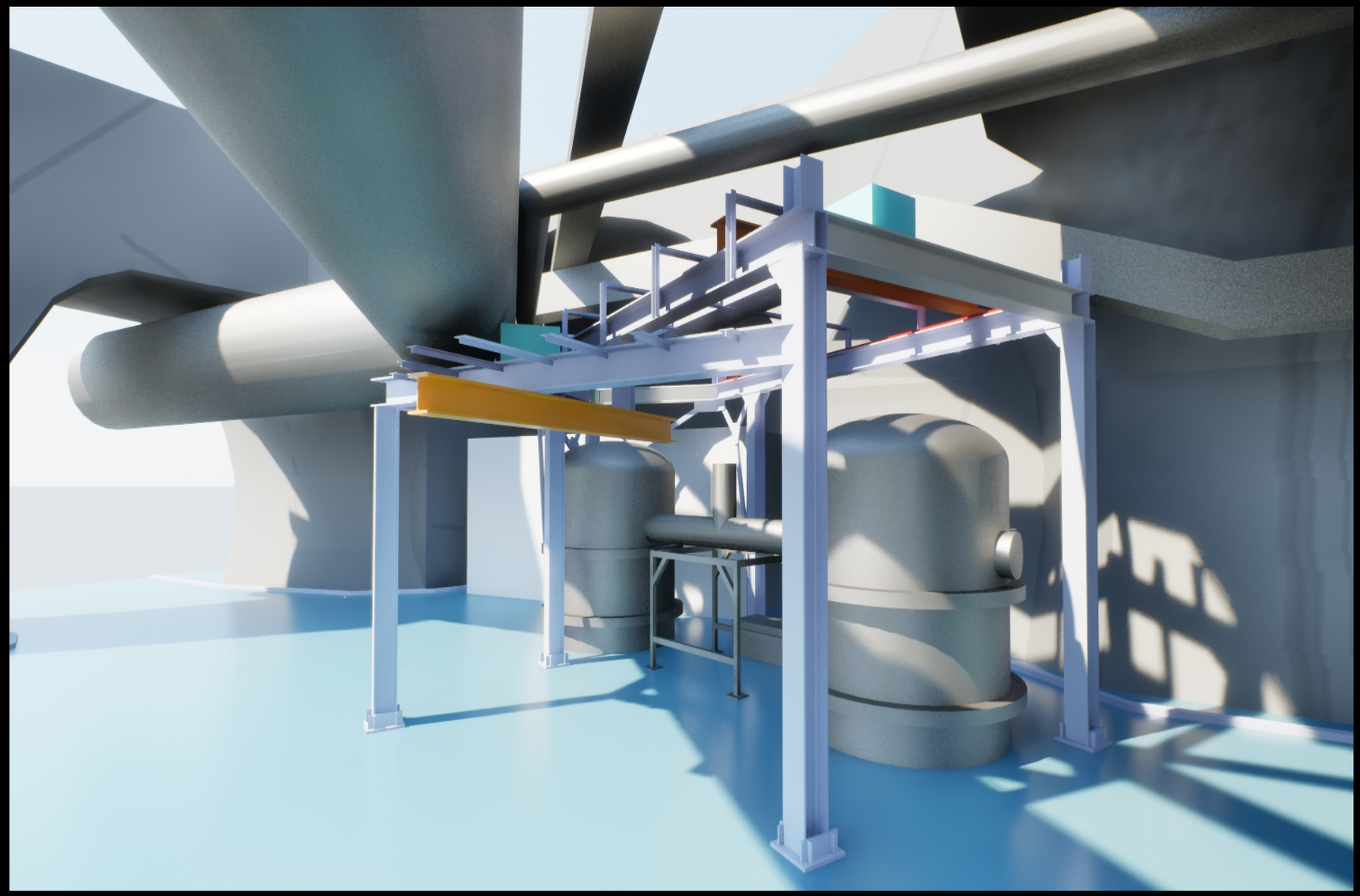
Underground Laboratory





- Floor treatment
- Laminar-flow enclosures
- Lifting device for platforms and chamber segments
- Timing signal from surface
- Data transfer to server at the surface
- Preparation of the GEMINI hut: it will contain the control room and a room with clean environment to prepare installations into the GEMINI vacuum system

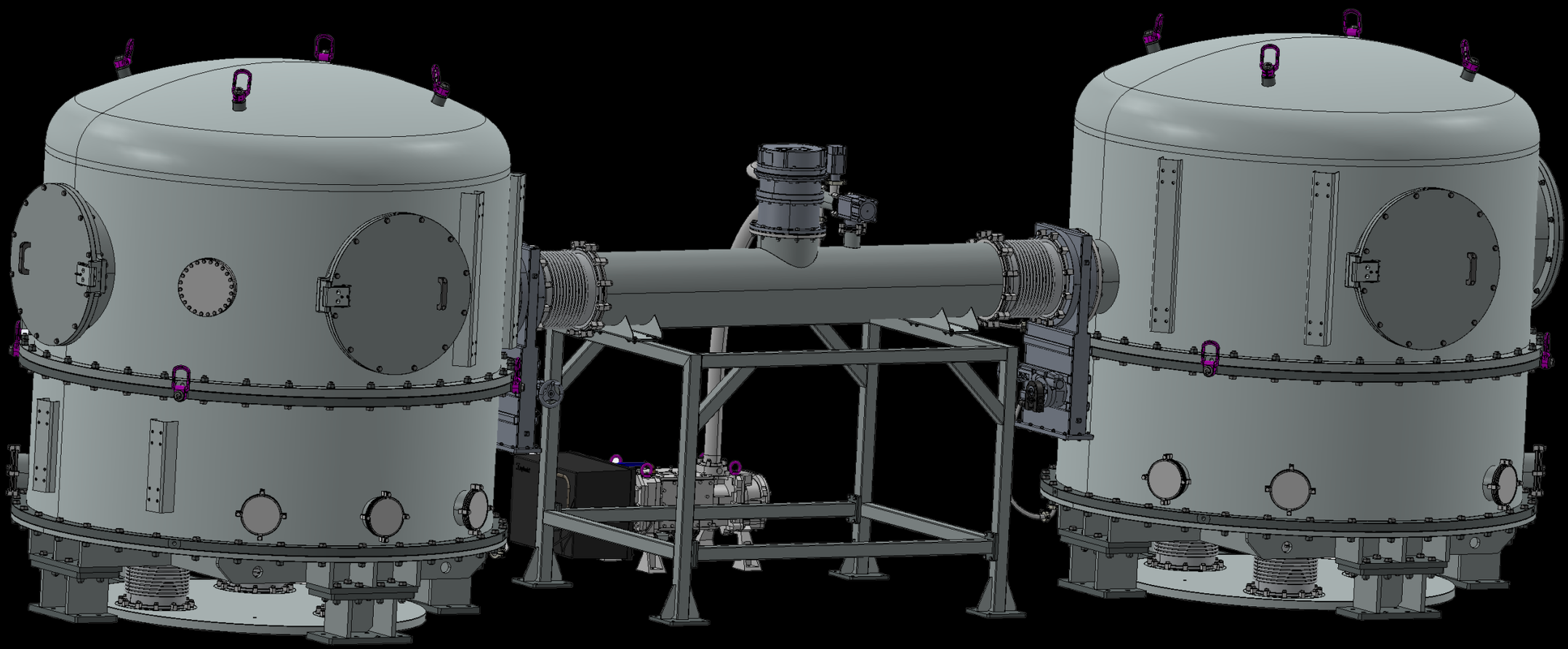
Underground Laboratory



- The steel framework surrounds the two experimental chambers and also supports two lifting systems for installation and maintenance

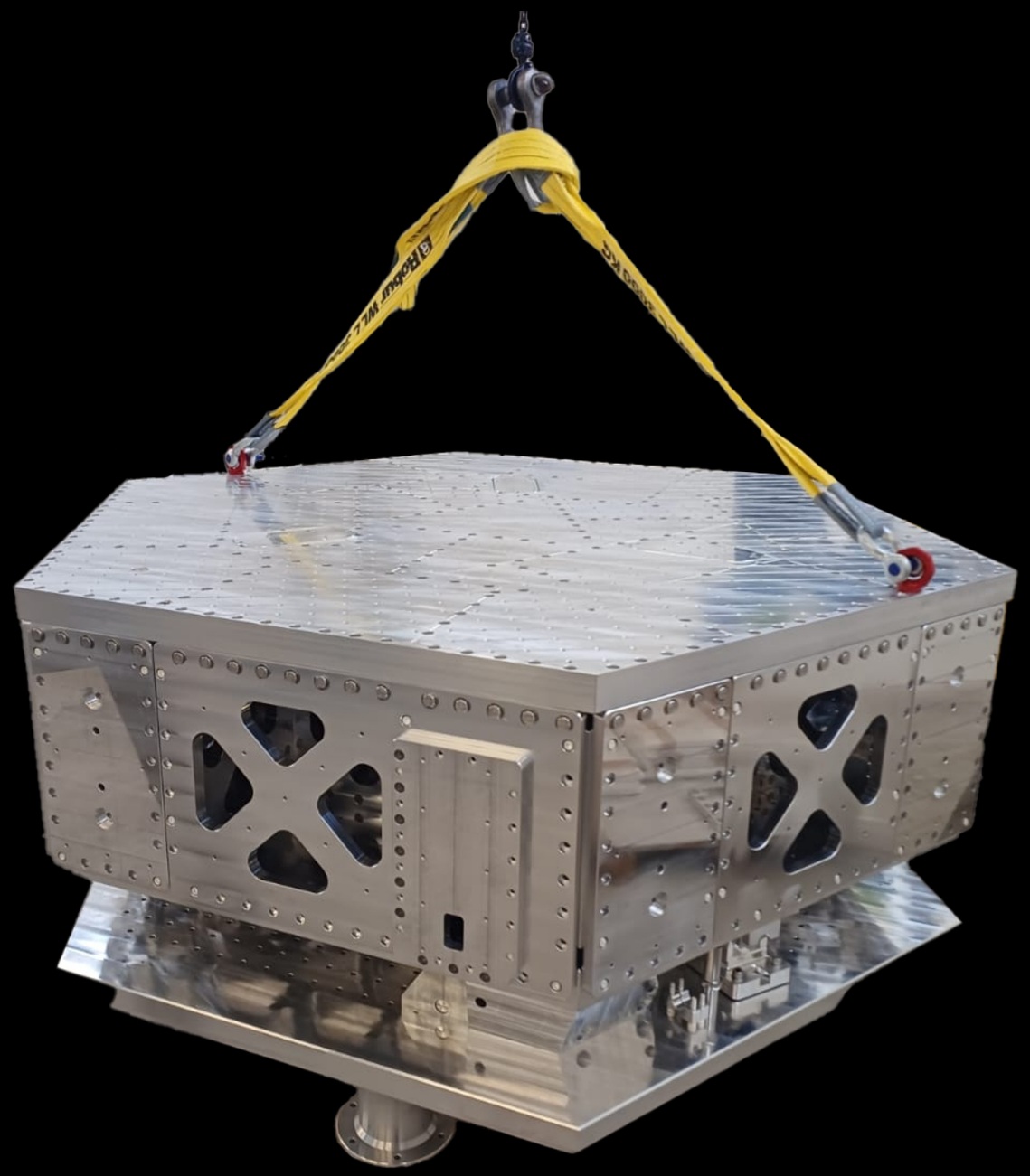
Vacuum System

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

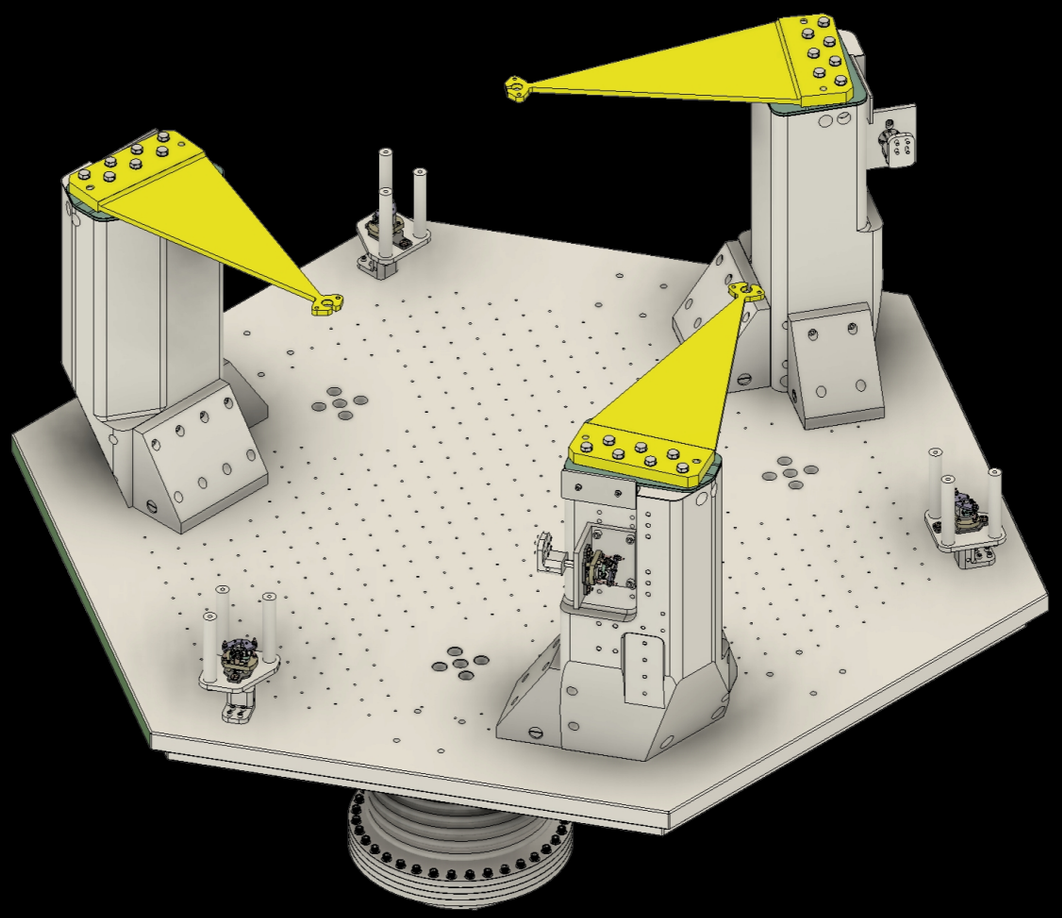


GEM-VCP

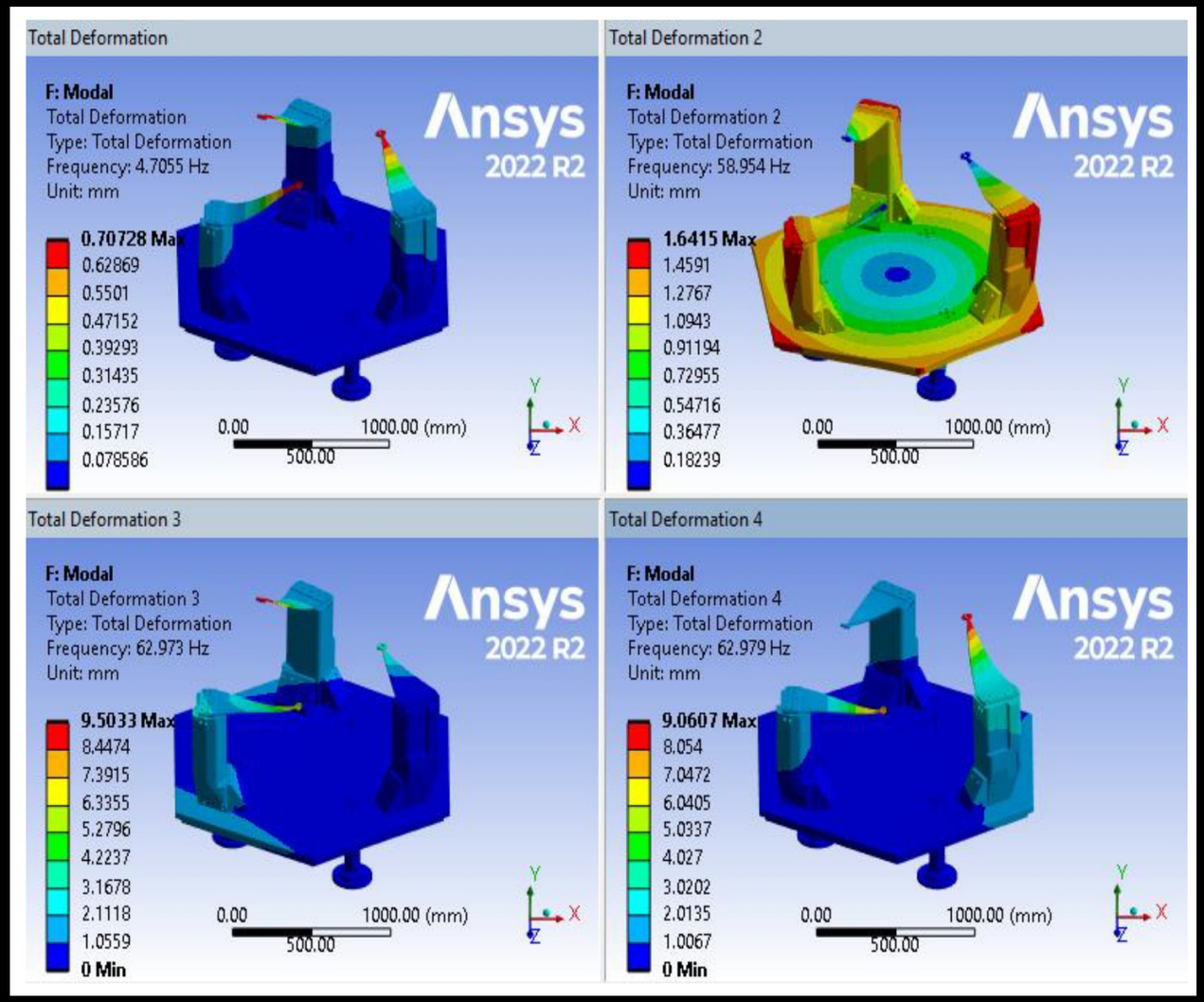
- GEMINI Vibration-control Platform
  - Starting point of the design: LIGO HAM-ISI - structural adjustments tailored for GEMINI's specific requirements.
  - Design modifications, vibration analysis, and executive drawings produced by LNGS mechanical engineers



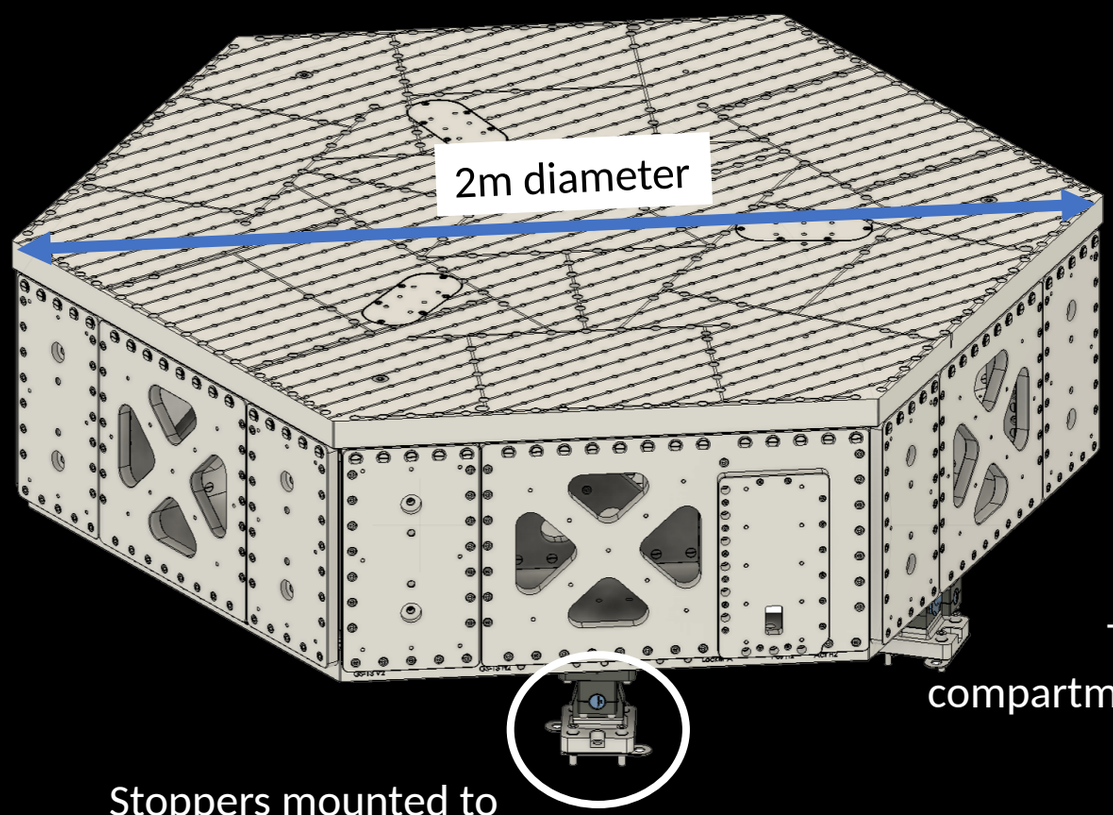
GEM-VCP: Stage 0

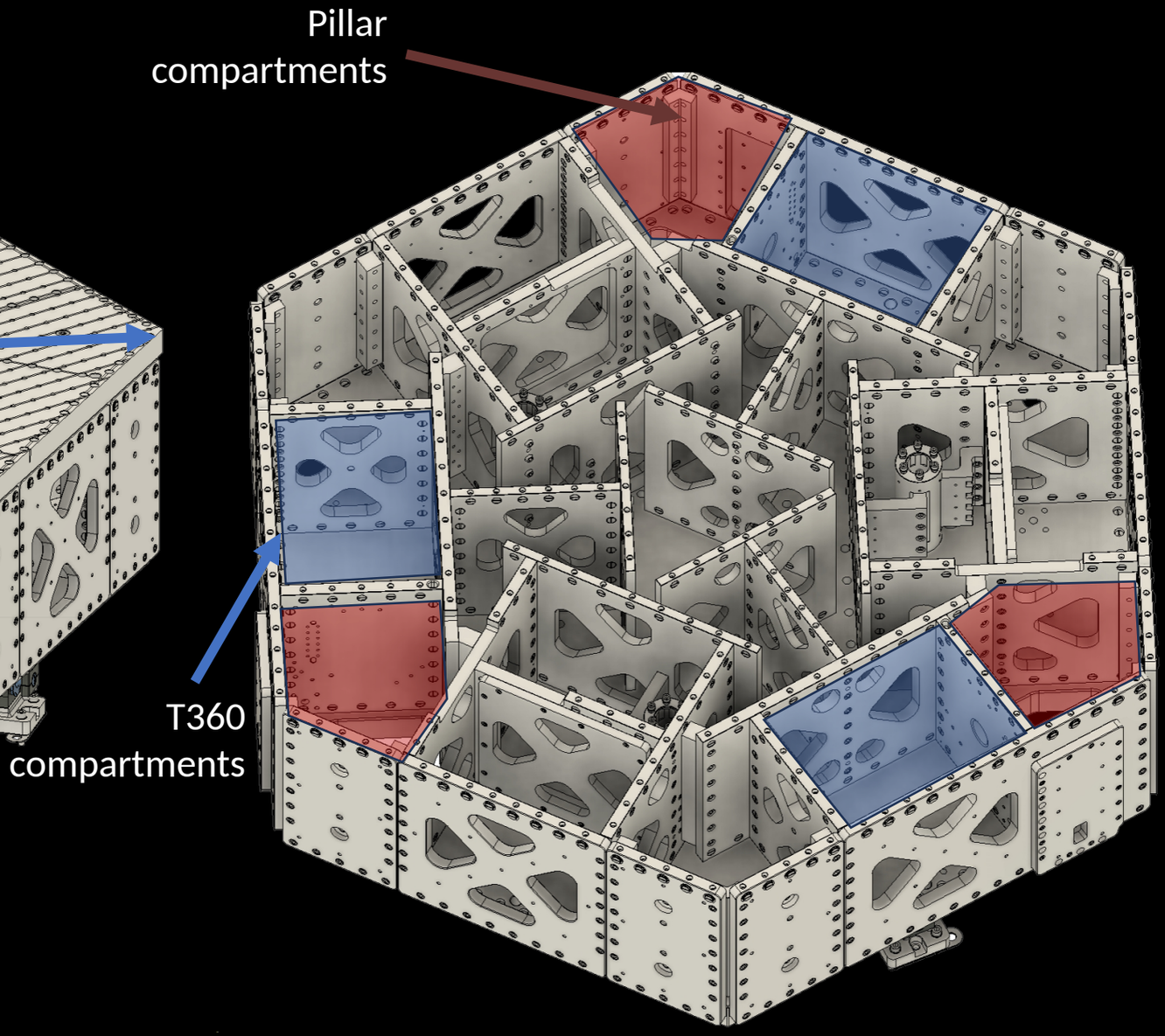


100Hz HAM-ISI (unconstrained)
70Hz GEM-VCP (under load)



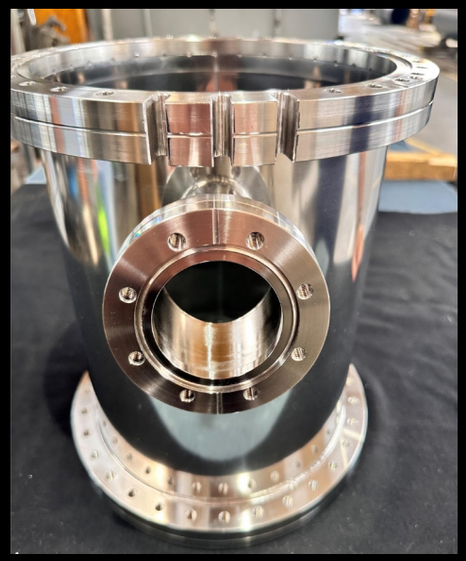
GEM-VCP: Stage 1



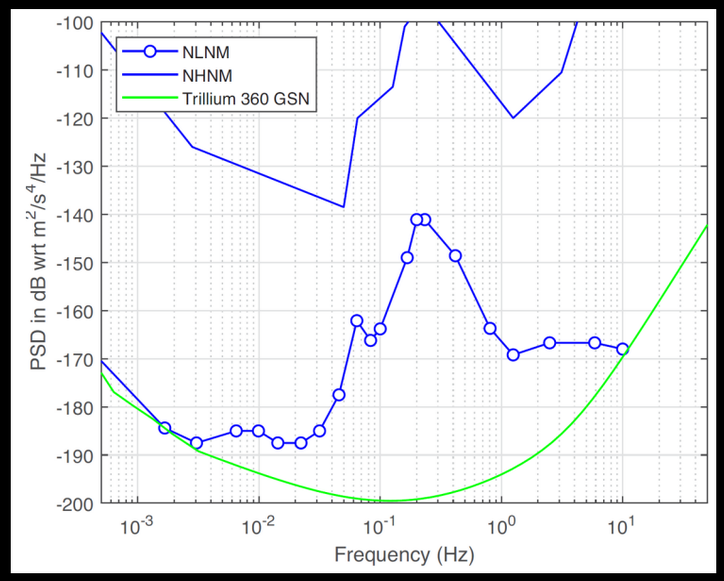


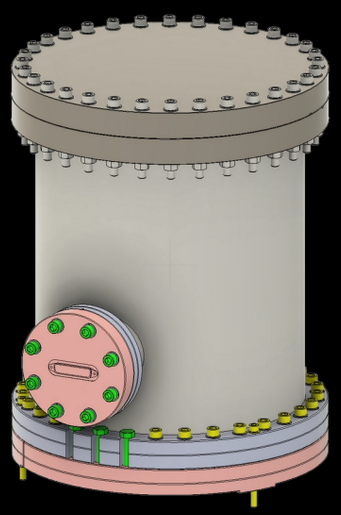
Inertial Sensing

Vacuum pods

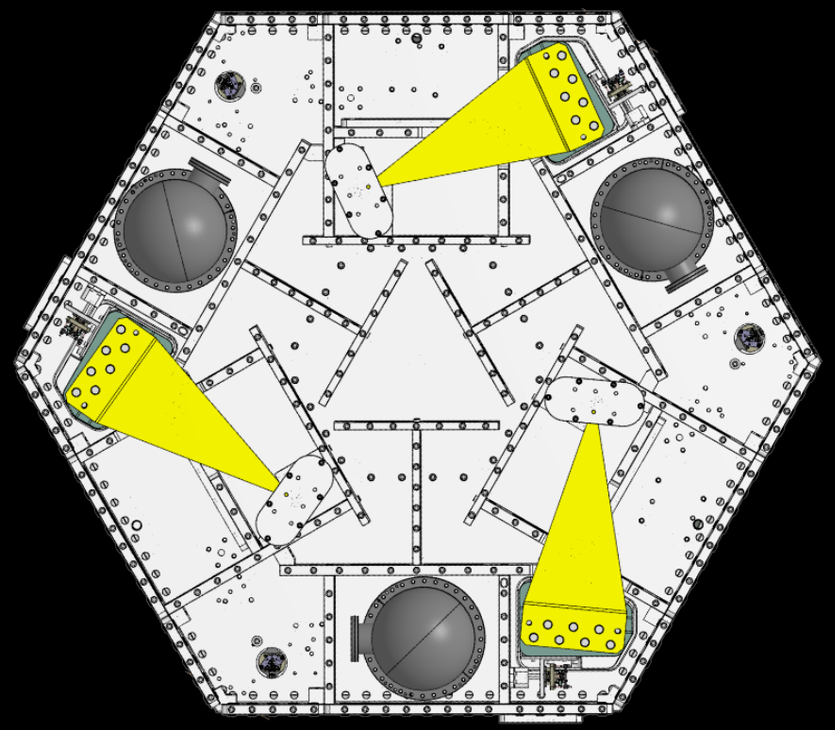


Nanometrics T360 GSN Vault
(3 per platform, 3 channels each)





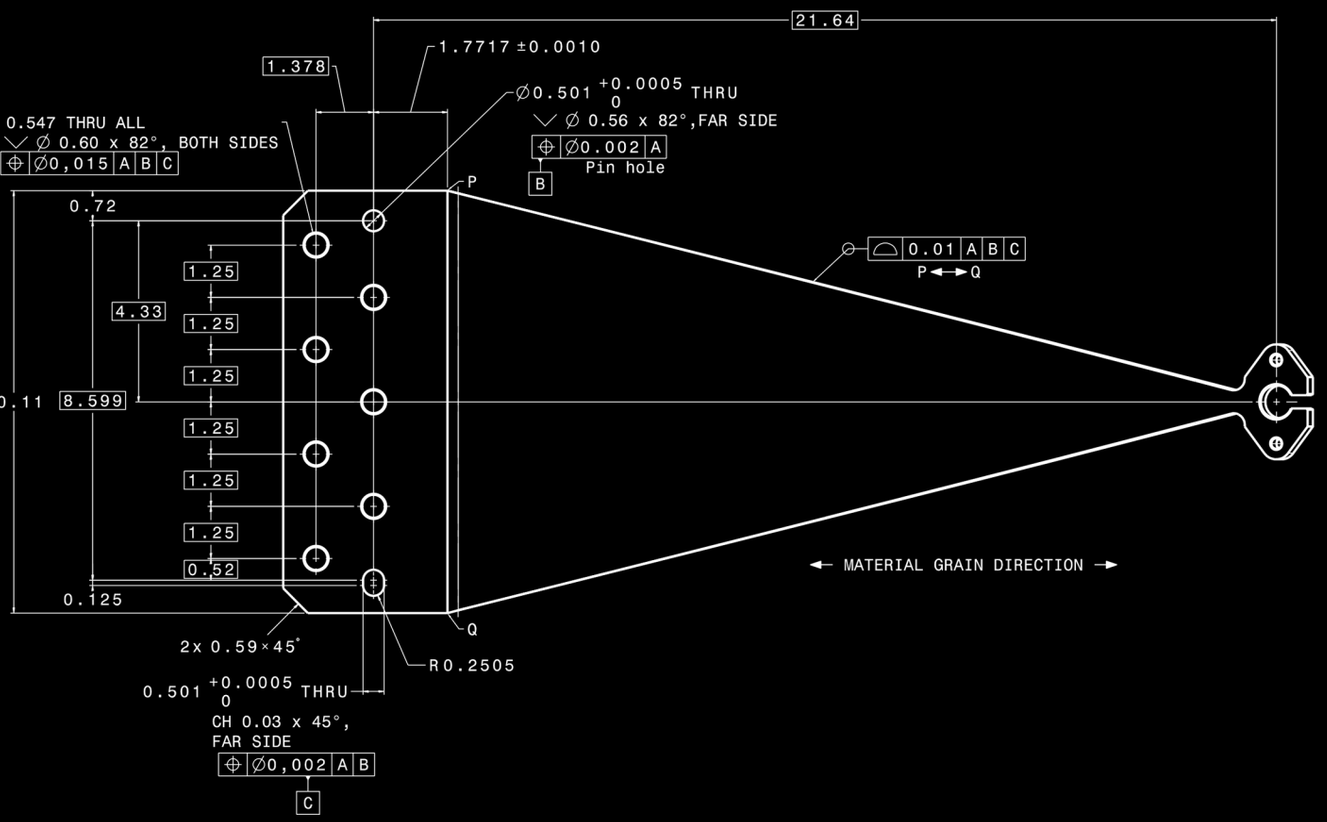
Integration in GEM-VCP

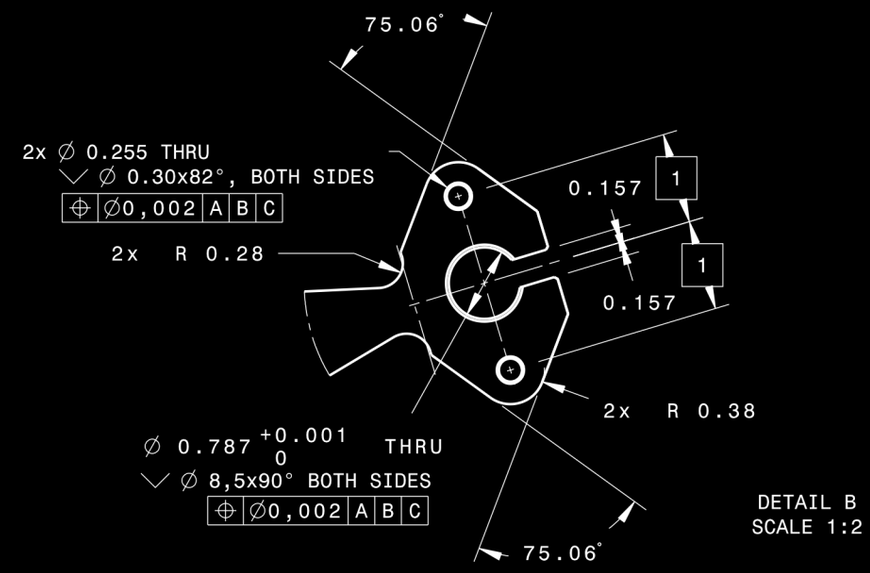


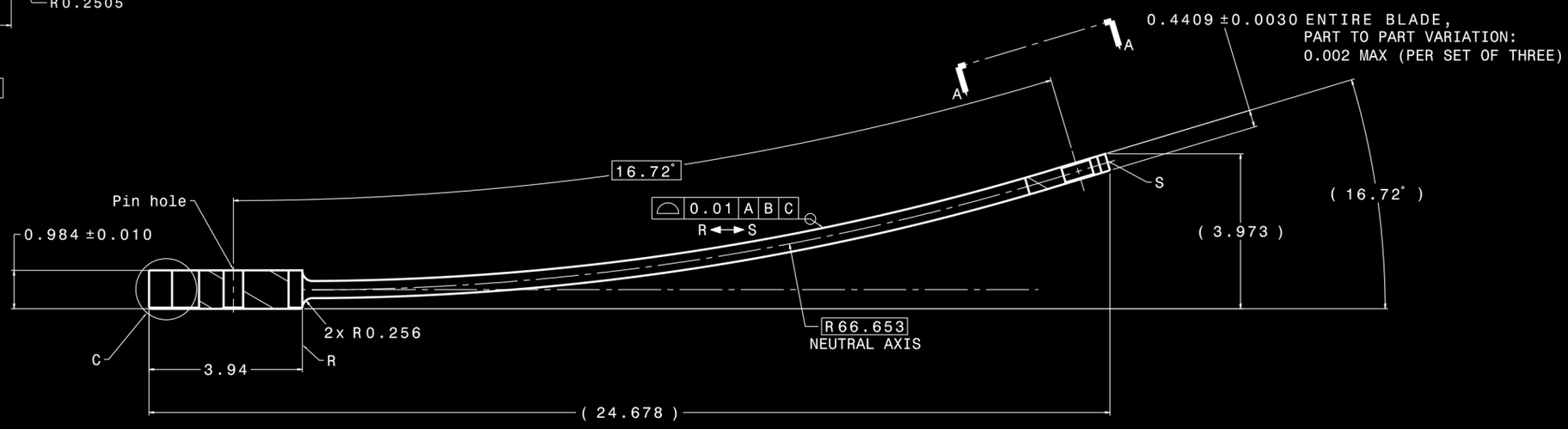
Spring Blades

Ti-19 meets design specs (strength, fatigue, stability) for supporting the load

Full-load test still needed to validate mechanical performance before integration

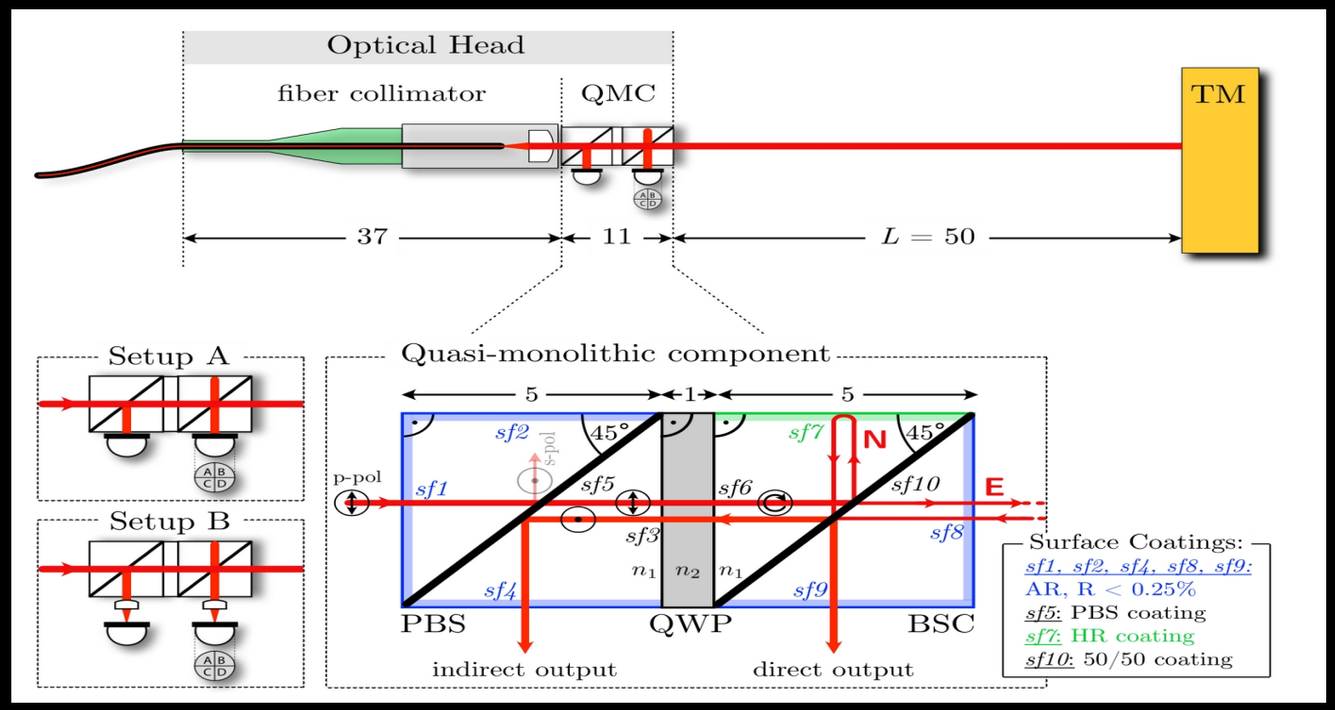




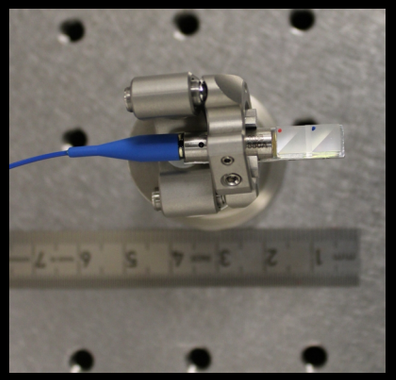


Position Sensing: COBRI

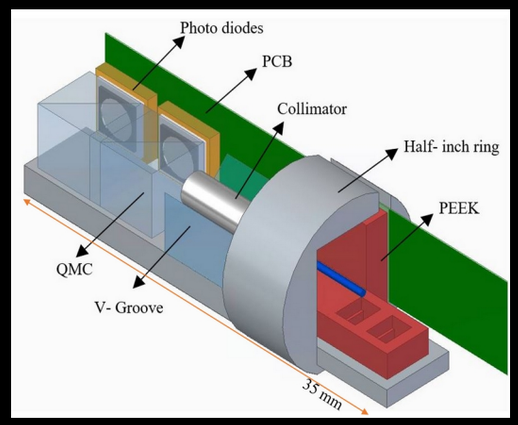
COmpact Balanced Readout Interferometer - COBRI



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



v2 design



- Required for platform alignment and positioning
- Utilized together with inertial sensing
- On-axis design with quasi-monolithic component

  Positive:
  - no misalignment in vacuum
  - Large linear range (several centimeters)

  Negative:
  - On-axis ghost beams cause nonlinearity

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	

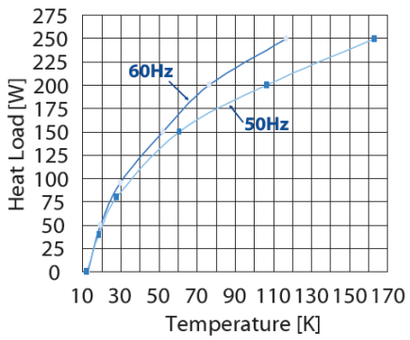
Standard Scope of Supply

- 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

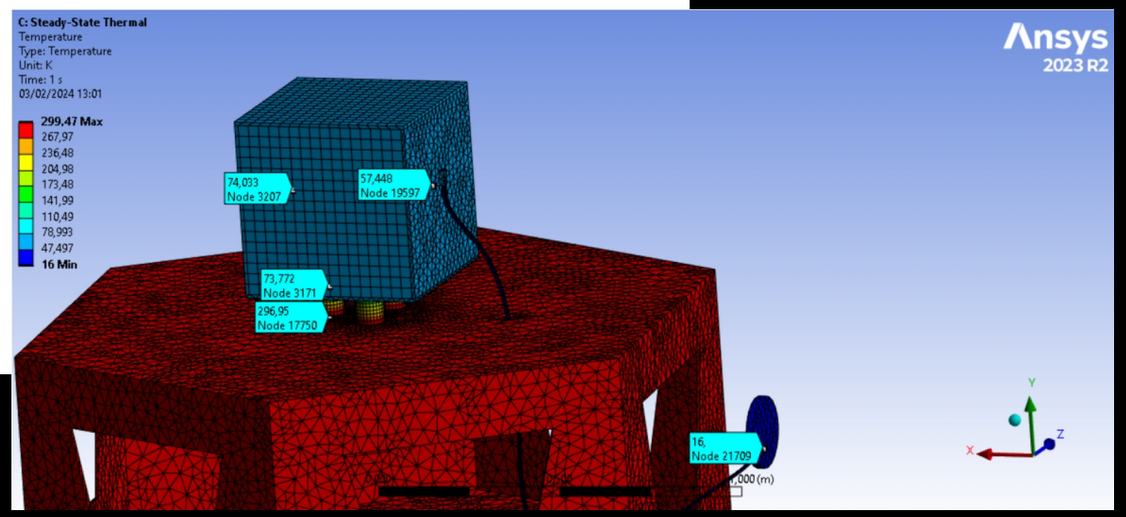
[1] *Lowest temperature and cooldown time are for reference only.*

RDK-500B Cold Head Capacity Map (50/60 Hz)

With F-70 Compressor and 20 m (66 ft.) Helium Gas Lines



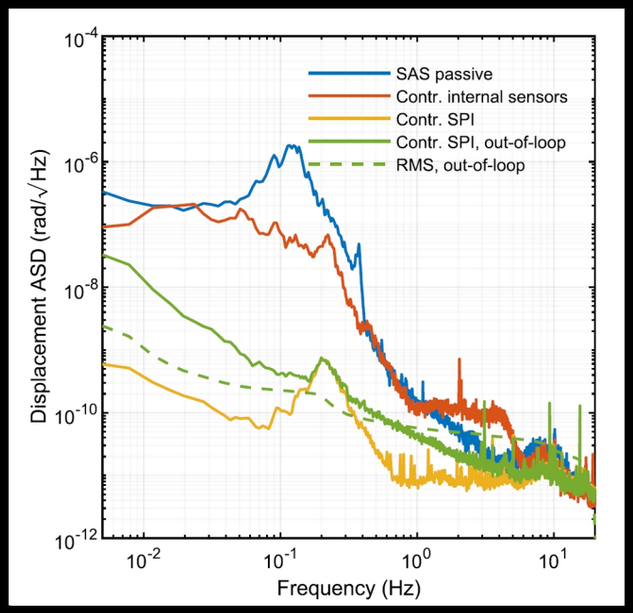
Emulate 40K environment for lunar PSR payloads

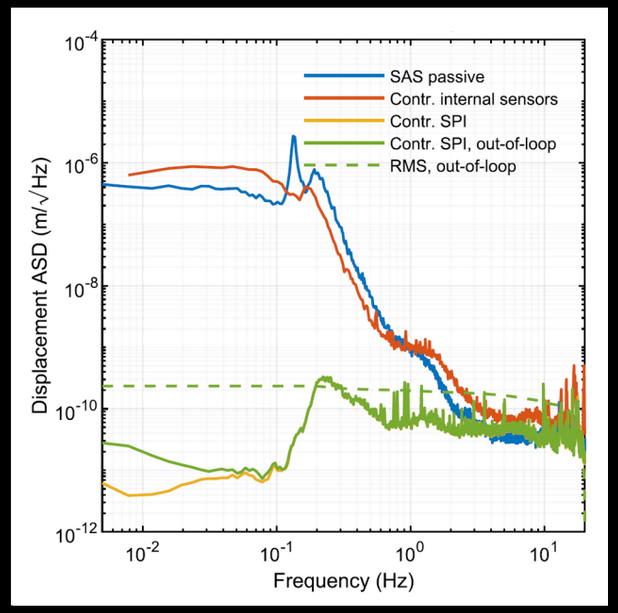


Thermal link design: Minimizing the length of the flexible braided copper section is essential

Suspension-platform Interferometer (SPI)

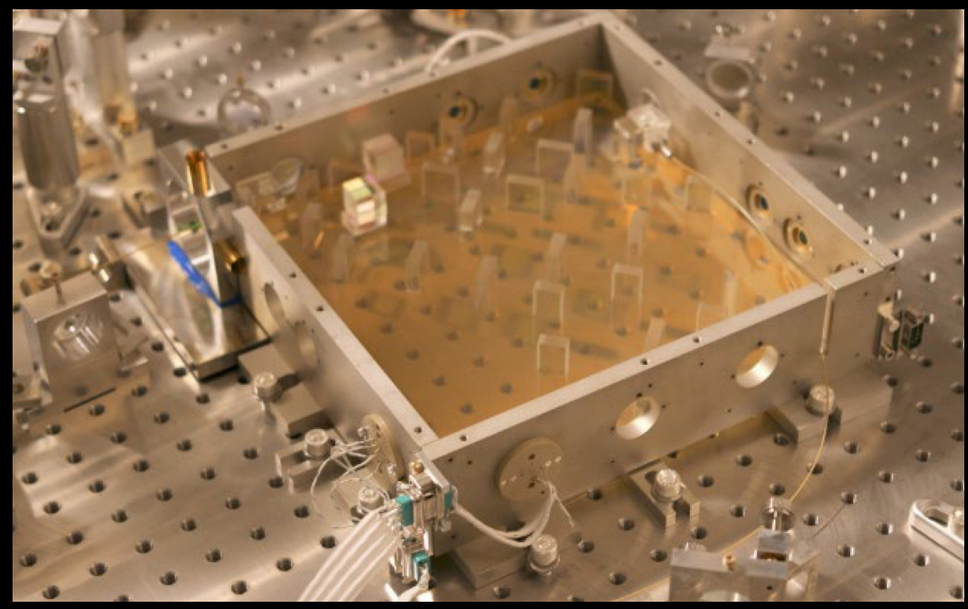
Inter-platform sensing and control to reduce relative motion between platforms (displacement and angular)



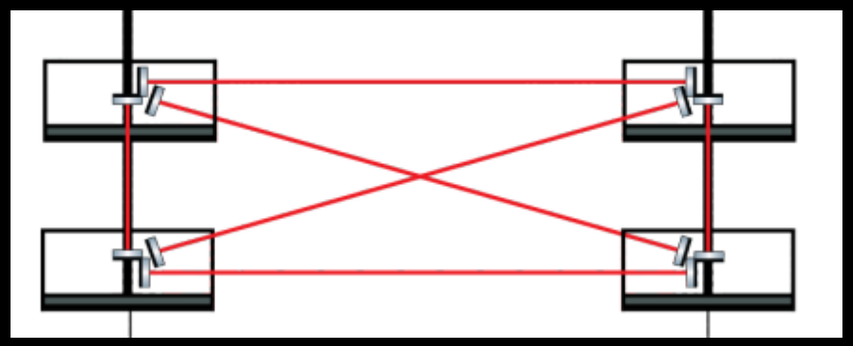


Koehlenbeck et al (2023)

SPI optical assembly



Koehlenbeck et al (2023)



Harms et al (2013)

Optical Rigid Body concept using a network of interferometric cavities between suspended platforms

Multi-cavity topology allows us to measure and suppress all 6 differential DOFs enforcing quasi-rigid motion across platforms

Paper

Eur. Phys. J. Plus (2026) 141:170
https://doi.org/10.1140/epjp/s13360-026-07372-7

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Gemini: the first underground testbed for seismic isolation and inter-platform control in next-generation gravitational-wave detectors

Tomislav Andric[1,2,a], Jan Harms[1,2], Ilaria Caravella[1,2], Michele Angiolilli[1,2], Daniele Cortis[2], Nicola D'Ambrosio[2], Massimiliano De Deo[2], Marco D'Incecco[2], Antonio Di Ludovico[2], Oliver Gerberding[3], Alessandro Lalli[2], Brian Lantz[5], Laura Leonzi[2], Carla Macolino[2,6], Richard Mittleman[7], Conor Mow-Lowry[8], Donato Orlandi[2], Stefano Pirro[2], Marco Ricci[9,10], Jamie Rollins[11], Jim Warner[4]

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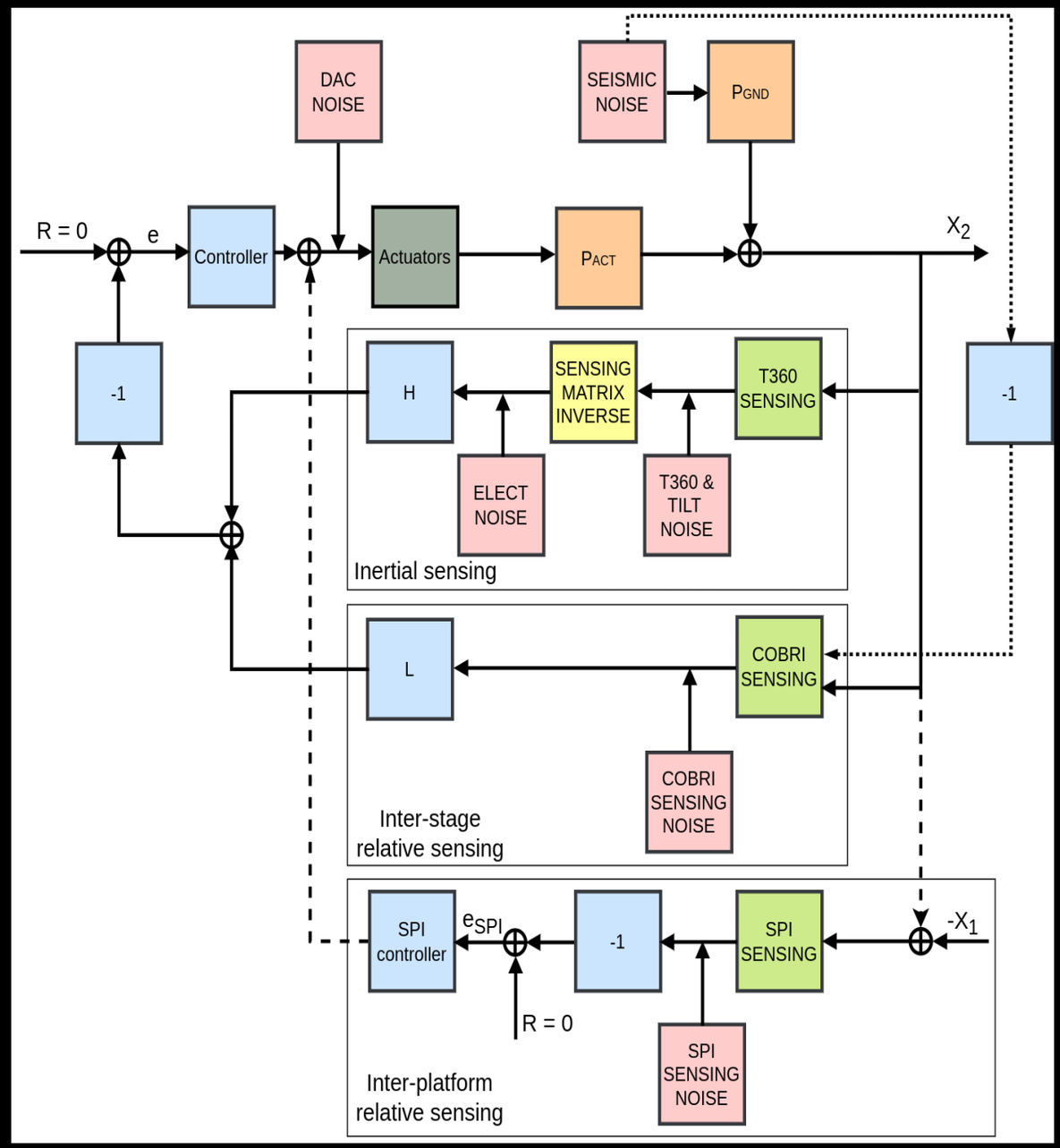
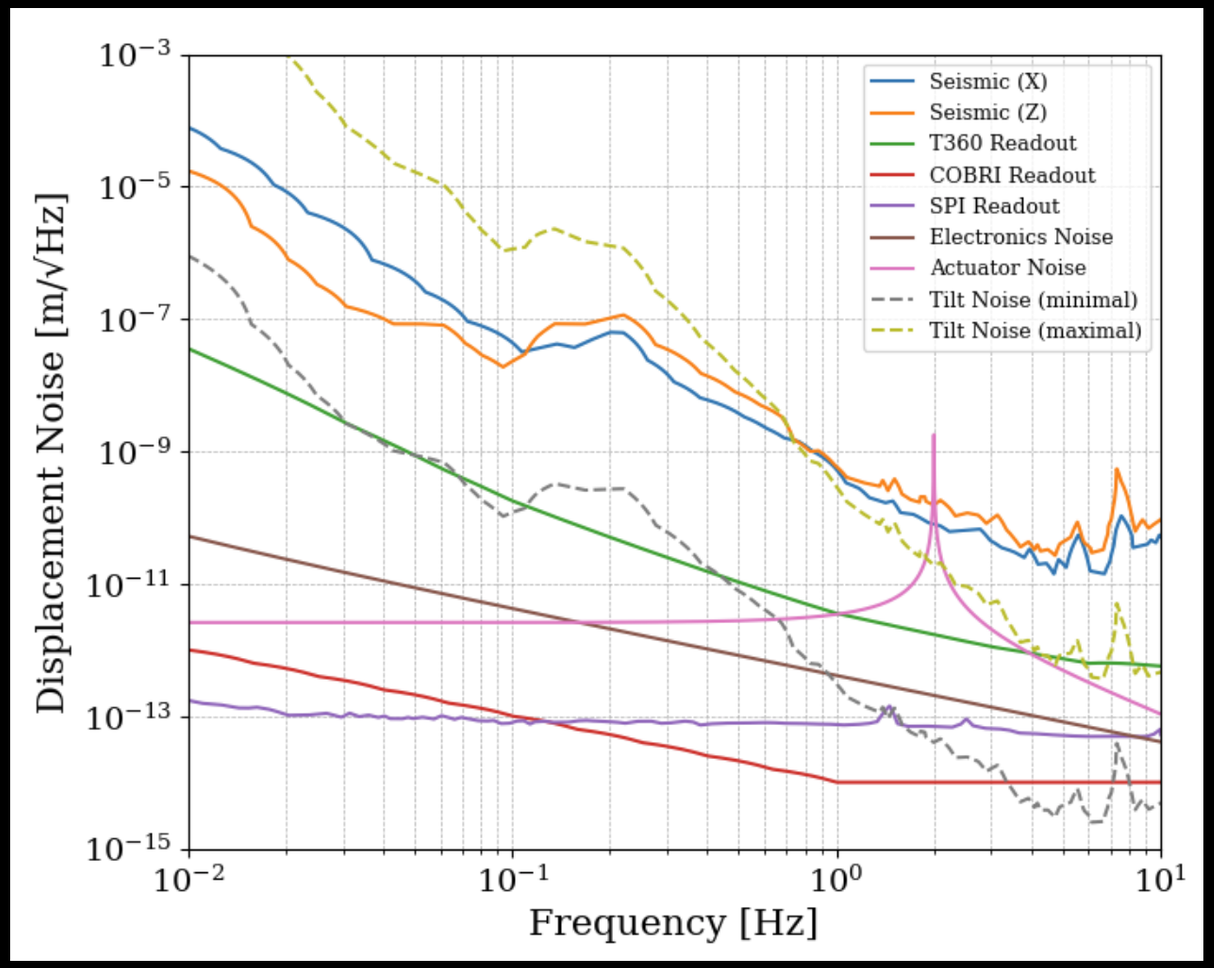
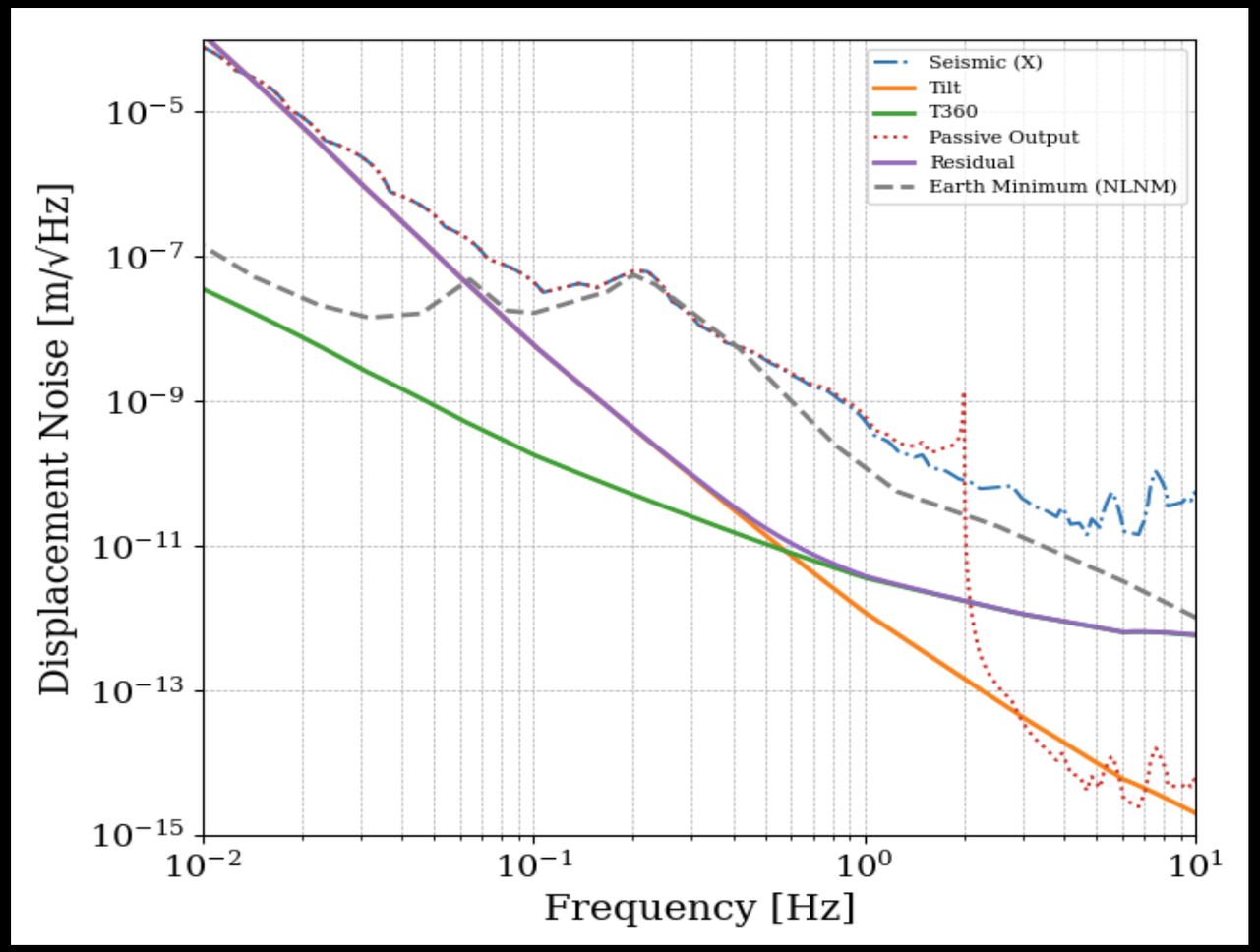
[3] University of Hamburg, Hamburg, Germany
[4] LIGO Hanford Observatory, Richland, WA, USA
[5] Stanford University, Stanford, CA, USA
[6] Università degli Studi dell'Aquila, L'Aquila, Italy
[7] Massachusetts Institute of Technology (MIT), Cambridge, MA, USA
[8] Vrije Universiteit Amsterdam, Amsterdam, Netherlands
[9] Sapienza Università di Roma, Rome, Italy
[10] INFN Roma 1, Rome, Italy
[11] California Institute of Technology (Caltech), Pasadena, CA, USA



Simulations



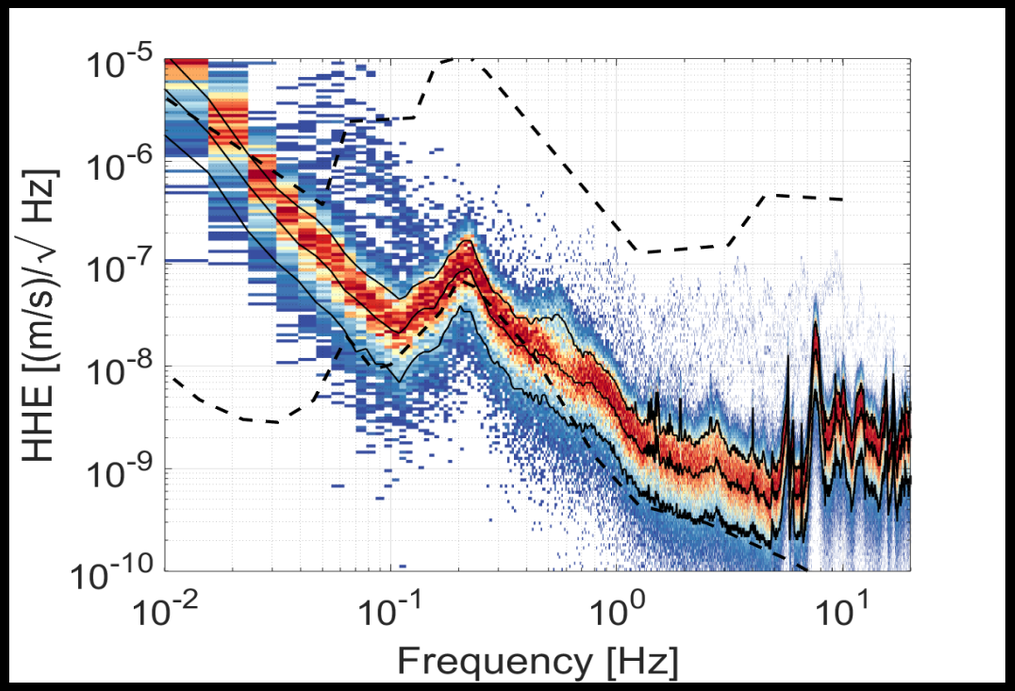
a) Input noises

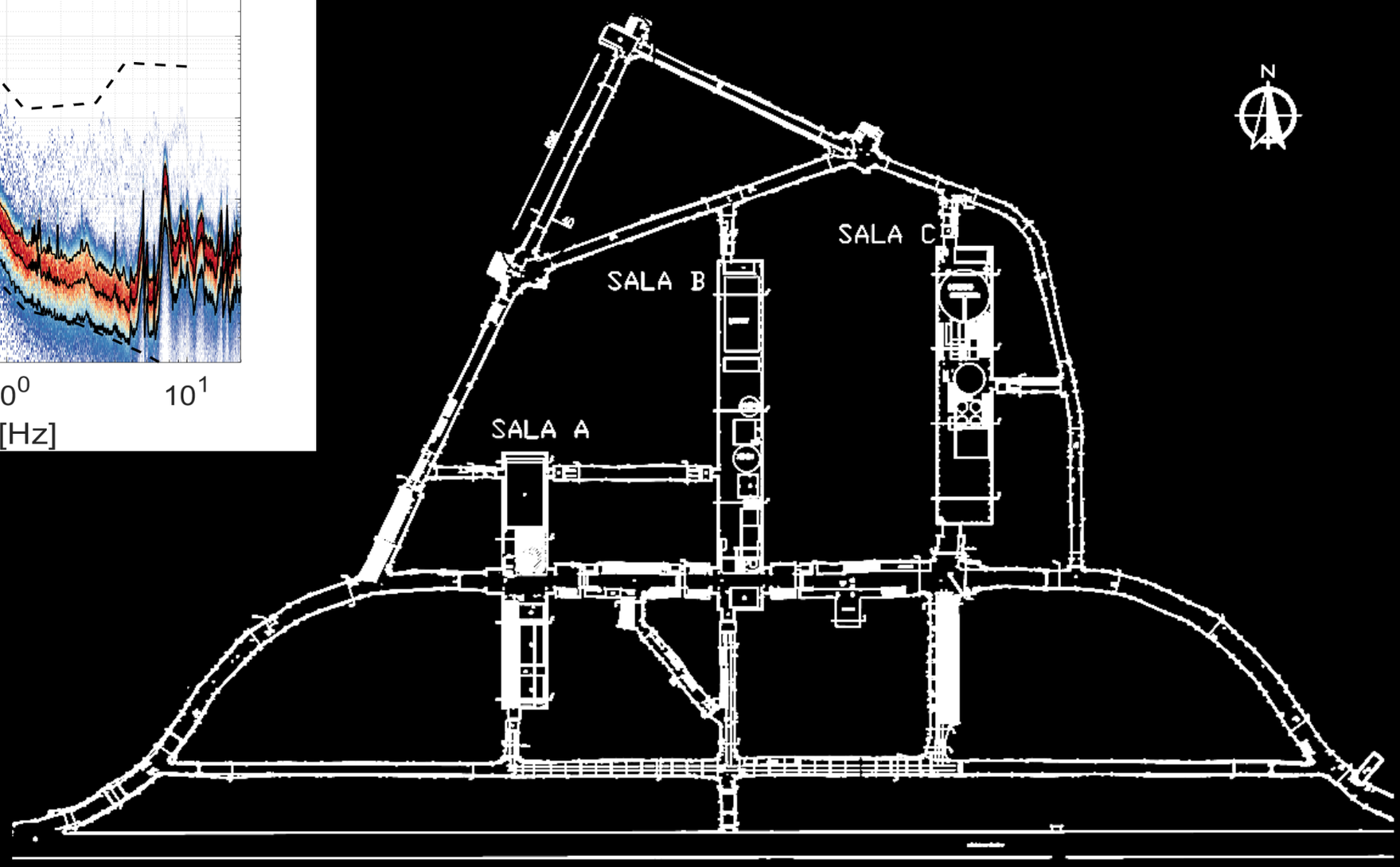


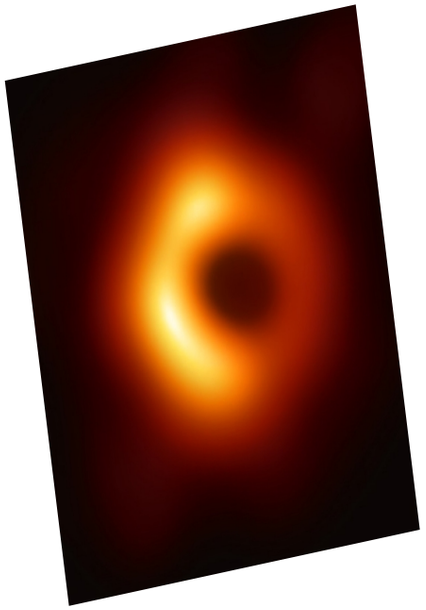
b) Leader platform residual motion

Environmental Monitoring System

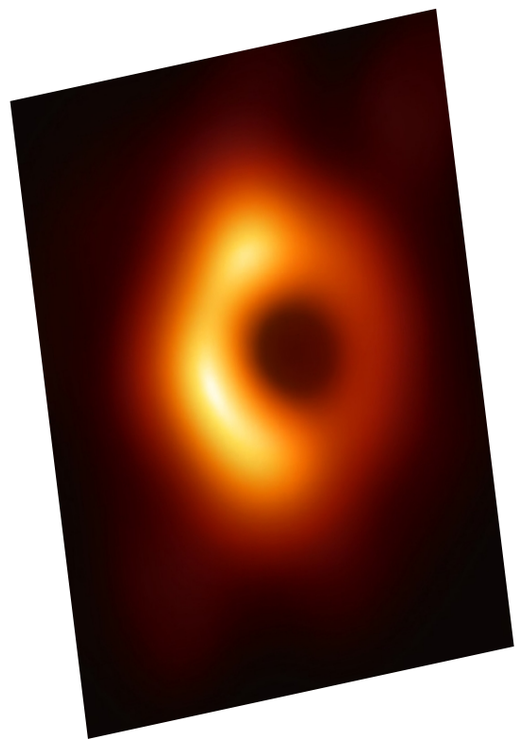
Network of barometers for 1mHz to 1Hz observations
(underground and surface)







Deep Loop Shaping: Reinforcement Learning Control for Gravitational-Wave Observatories



Overview: use neural networks for better feedback control

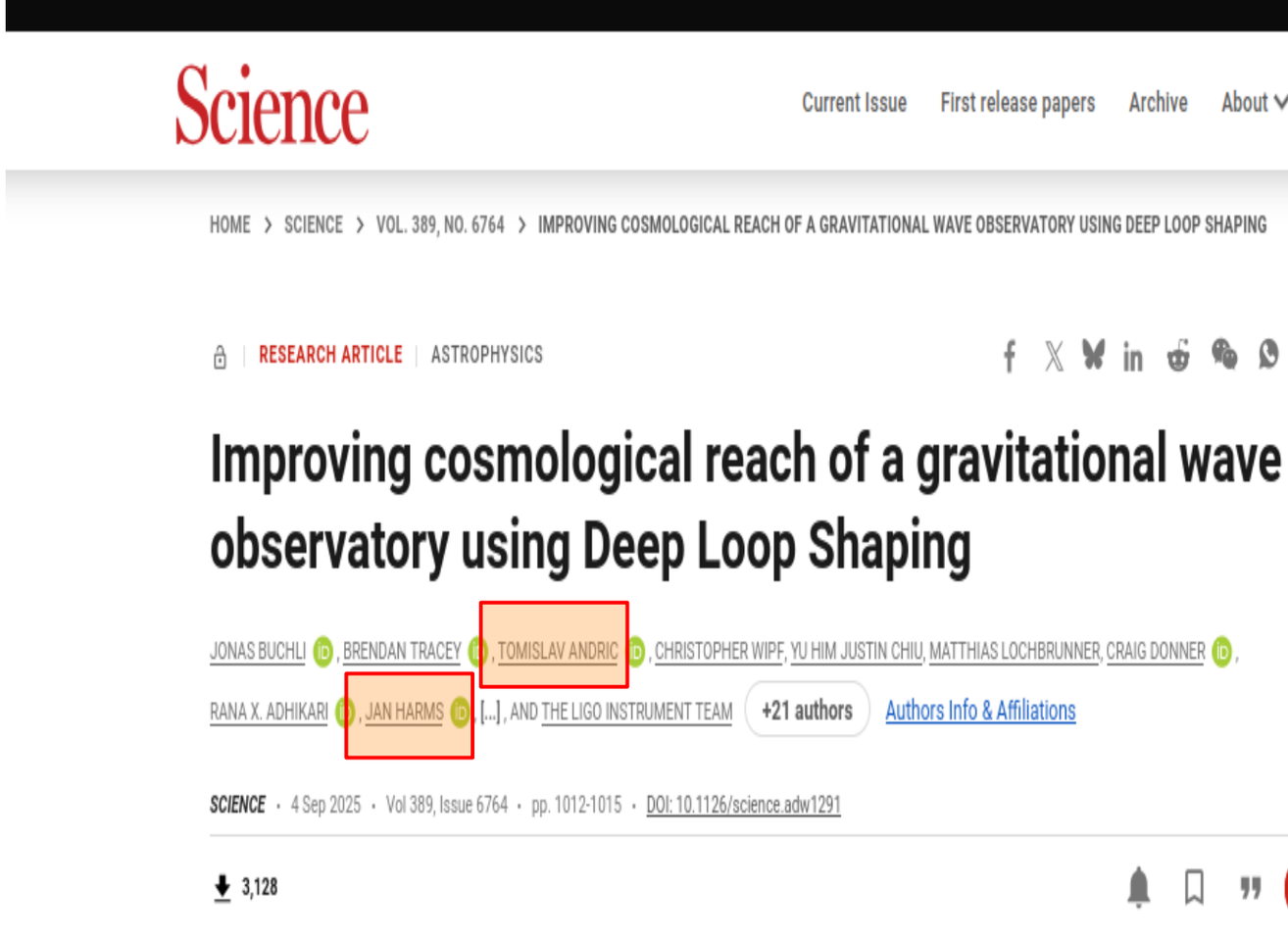
- In the early 2010s, discussions started at GWADW meetings about control noises as potential show-stoppers for future low-frequency sensitivity improvements
- Are there fundamental limits to the control performance?
- Linear control obeys fundamental constraints, e.g., derived from Kramers-Kronig relations. One can define optimal linear control.
- JH proposed reinforcement learning to evade the fundamental limitations.
- A first analysis was carried out as part of a PhD thesis submitted 2016 in Urbino.
- Shimmer Project started ~2020.
- Main aim was to have a stable HARD ASC loop with less noise injection > 10 Hz.
- Time domain simulation: Tomislav Andric, Jan Harms -> LightSaber.
- Linearized time-domain simulation: Chris Wipf - RT SimPlant
- Neural Network training: DeepMind / Caltech

Setup

- A GW detector is a system of optomechanical degrees of freedom (e.g., mechanical suspensions, beam phase/alignment/shape, laser amplitude and frequency)
- Something like 100 degrees of freedom need to be controlled, and there is an important coupling between most of them

Goals

- Laser interferometer must be operated as close as possible to its ideal state
- Low-frequency motion must be strongly reduced
- System must remain stable
- Noise injected by the controller must be minimized



Contributors

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Christopher Wipf (Caltech)

Rana Adhikari (Caltech)

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Abbas Abdolmaleki

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Charlie Beattie

Jonas Buchli

Serkan Cabi

Justin Chiu

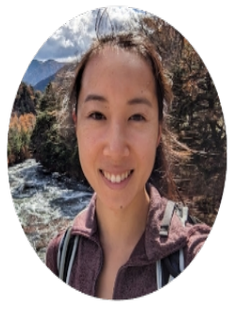
Jonas Degrave

Yuzhu Dong

Craig Donner

Oliver Groth

Roland Hafner


Sandy Huang

Andrea Huber

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Matthias Lochbrunner

Hannah Openshaw

Martin Riedmiller

Gregory Thornton

Brendan Tracey

George van den Driessche

Markus Wulfmeier

Partner institutions

Caltech

GSSI

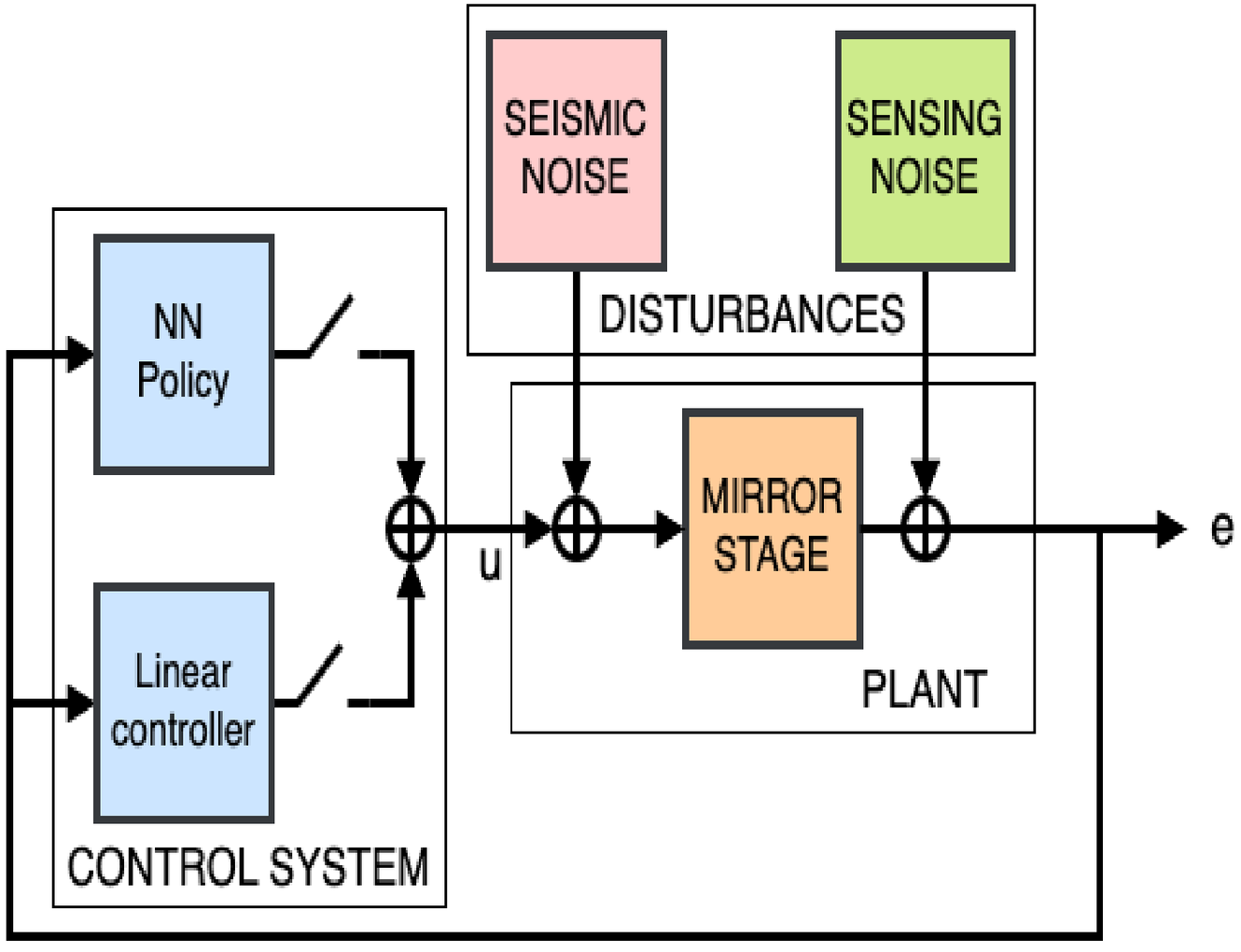
DeepMind

LIGO

+ The LIGO Instrument Team

Outline

1. Project Overview
    1. Reduce controls noise
        1. Comparison of LLO linear, and this work
    2. Working with Google DeepMind
        1. History / NDA
2. Main Results
    1. (40m IMC)
    2. LLO ASC
3. Summary
4. Future Work



Confidential - Google DeepMind

Mirror stabilization problem (ASC)

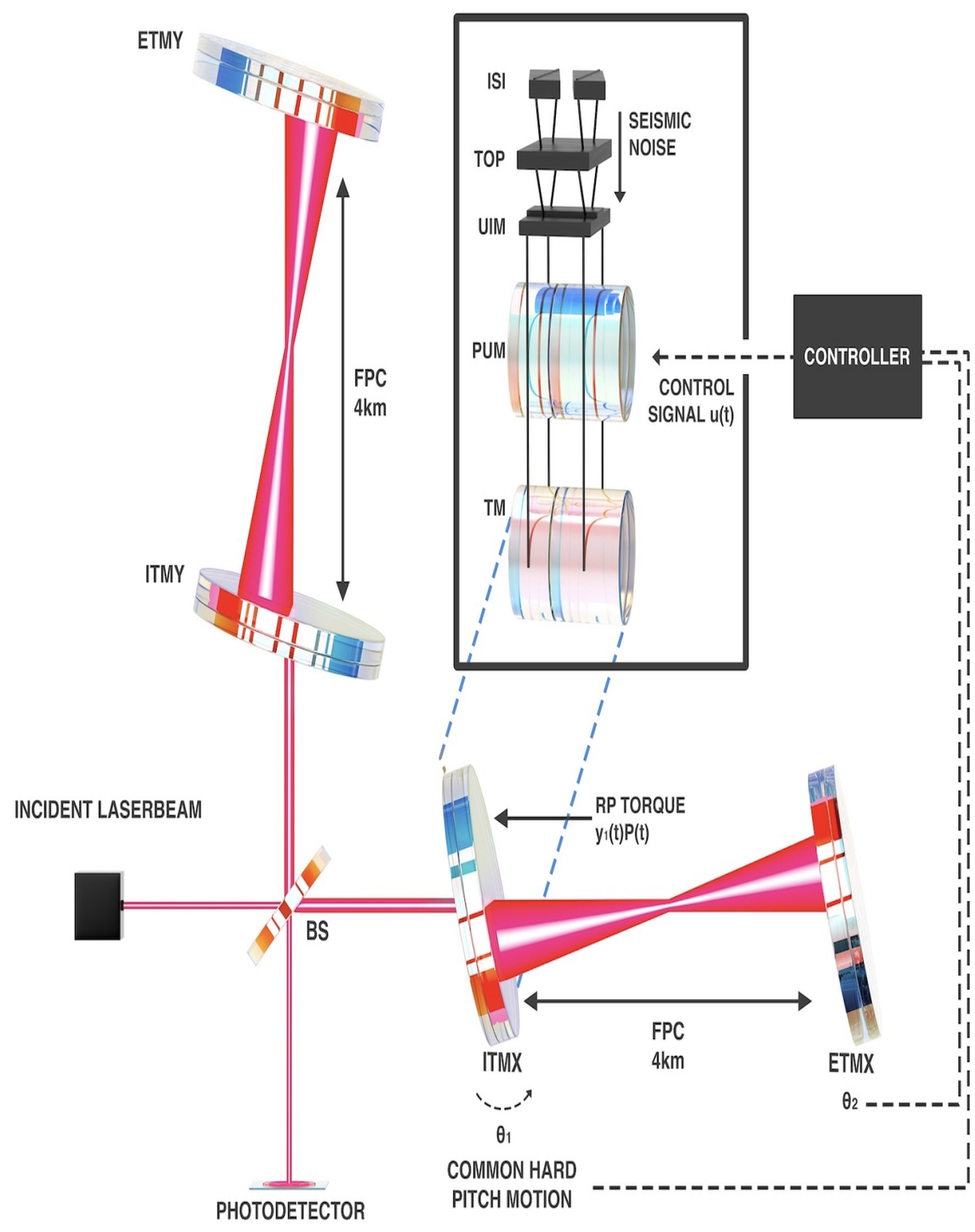
4-stage pendula, controlled by EM actuators

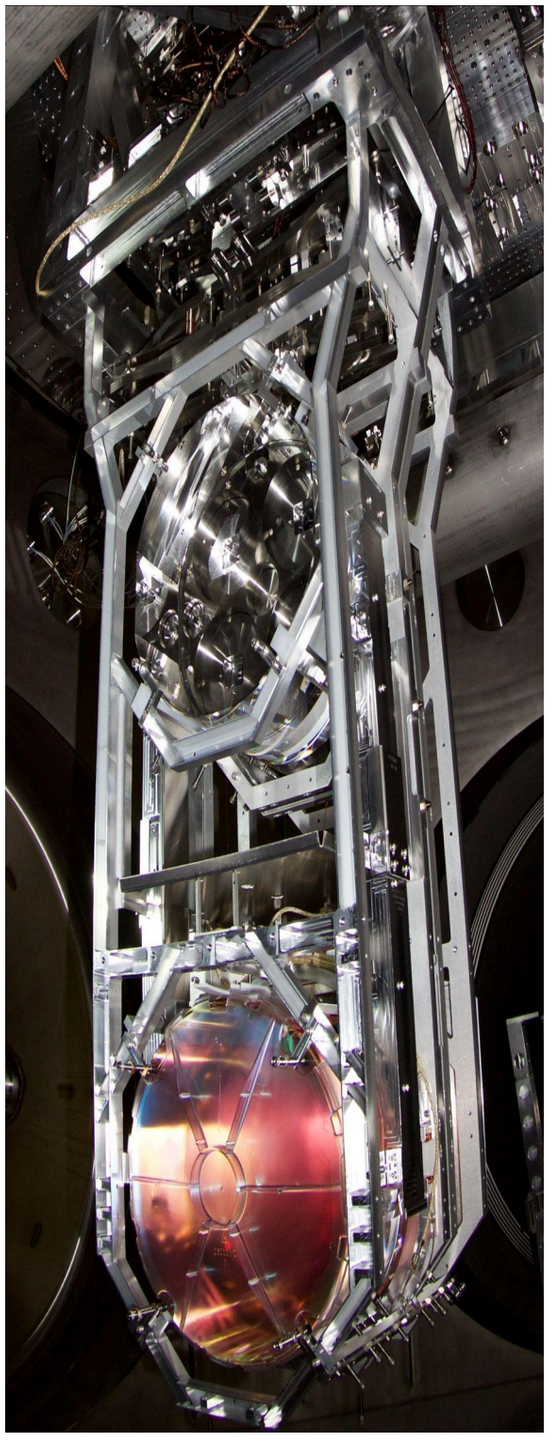
Main control challenges:

- Disturbance rejection: Seismic and other perturbations and noise coupling in through support
- Many eigenmodes ~0.5-2Hz

Control authority required up to ~3Hz

10-30Hz Observation band SNR requirement: angle error <<10^{-15}rad (femto rad)





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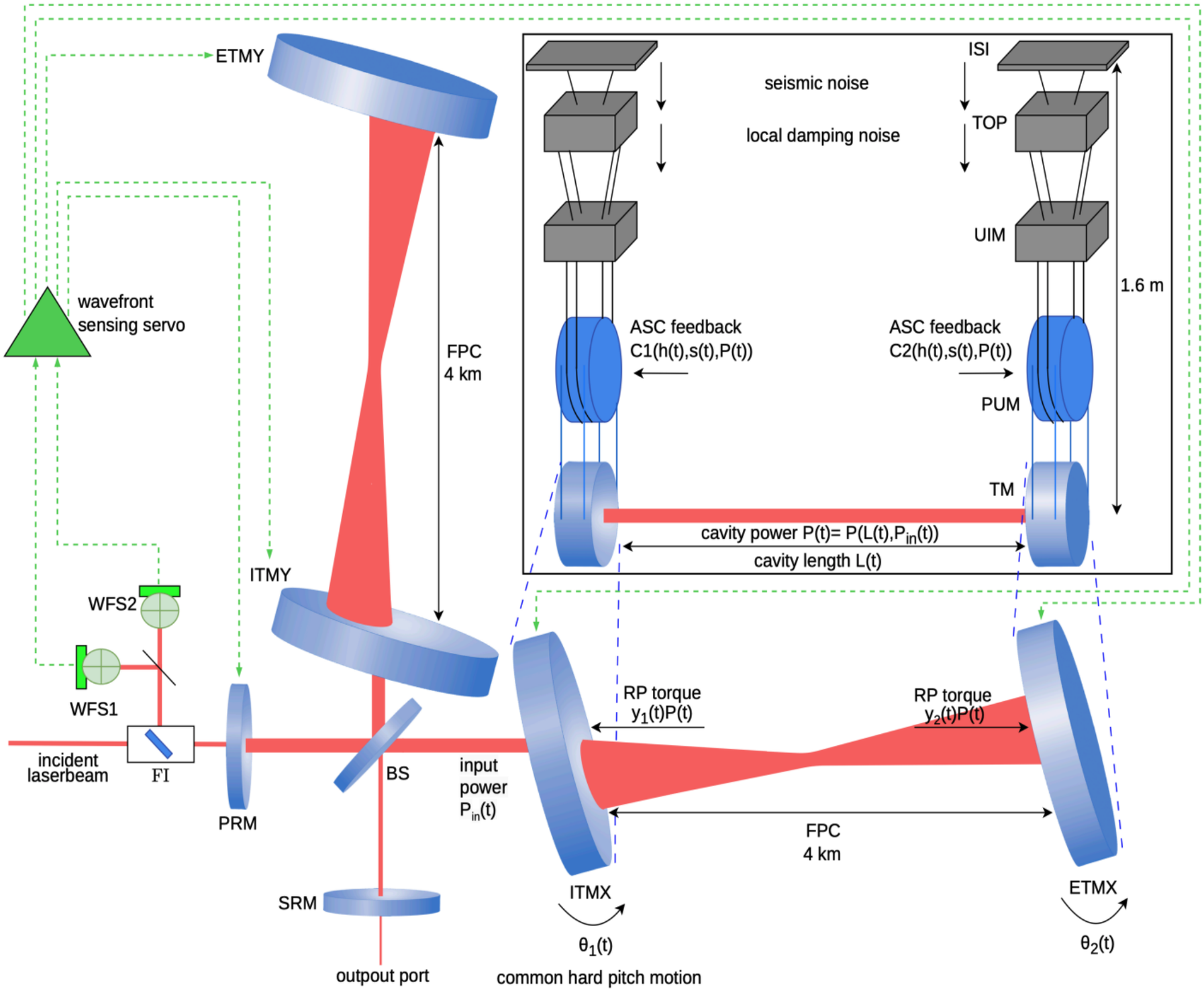


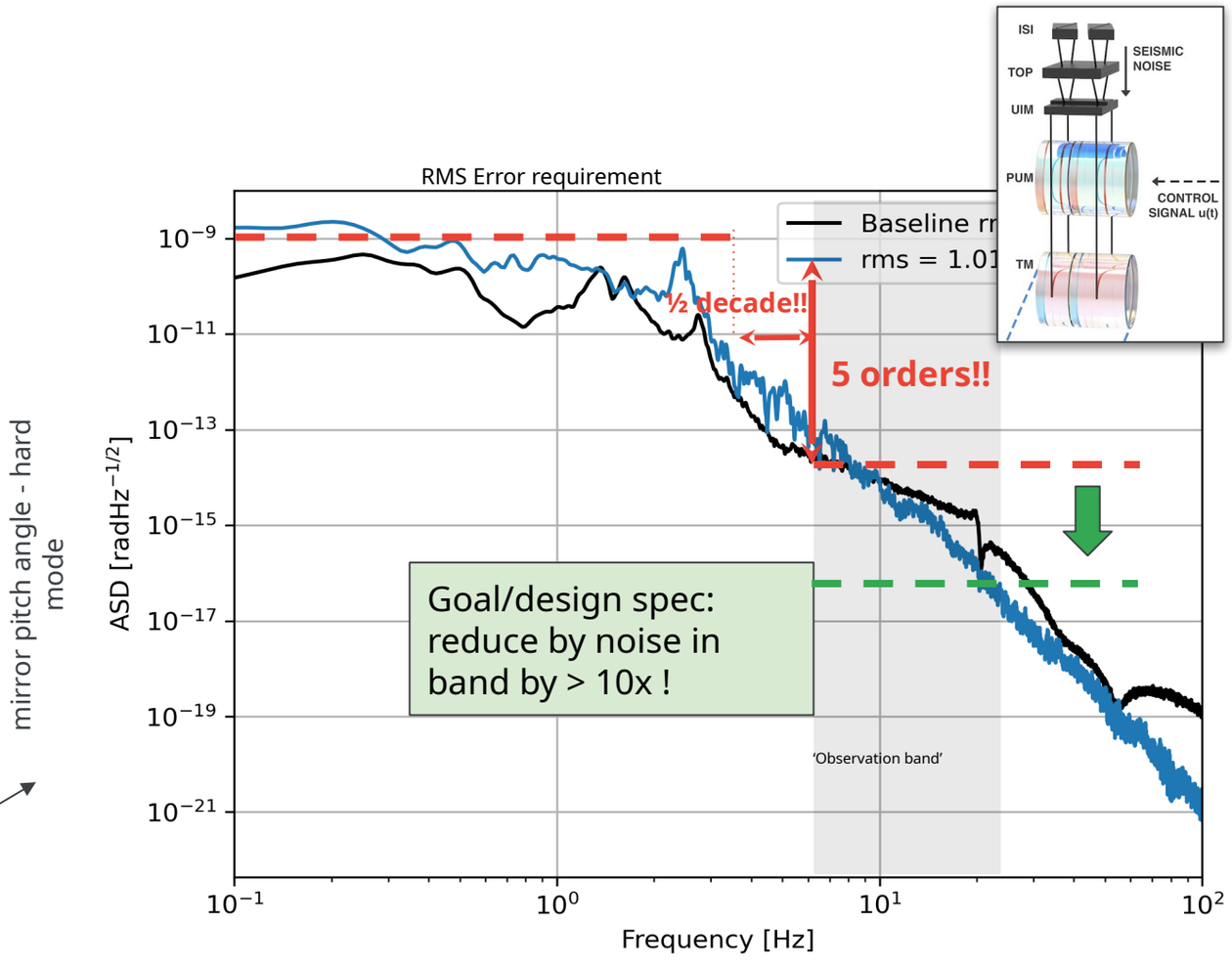
Mirror stabilization problem (ASC)

Main control challenges:

- Disturbance rejection: Seismic and other perturbations and noise coupling in through support
- Many eigenmodes around 0.5-2Hz

Control authority required up to ~3Hz

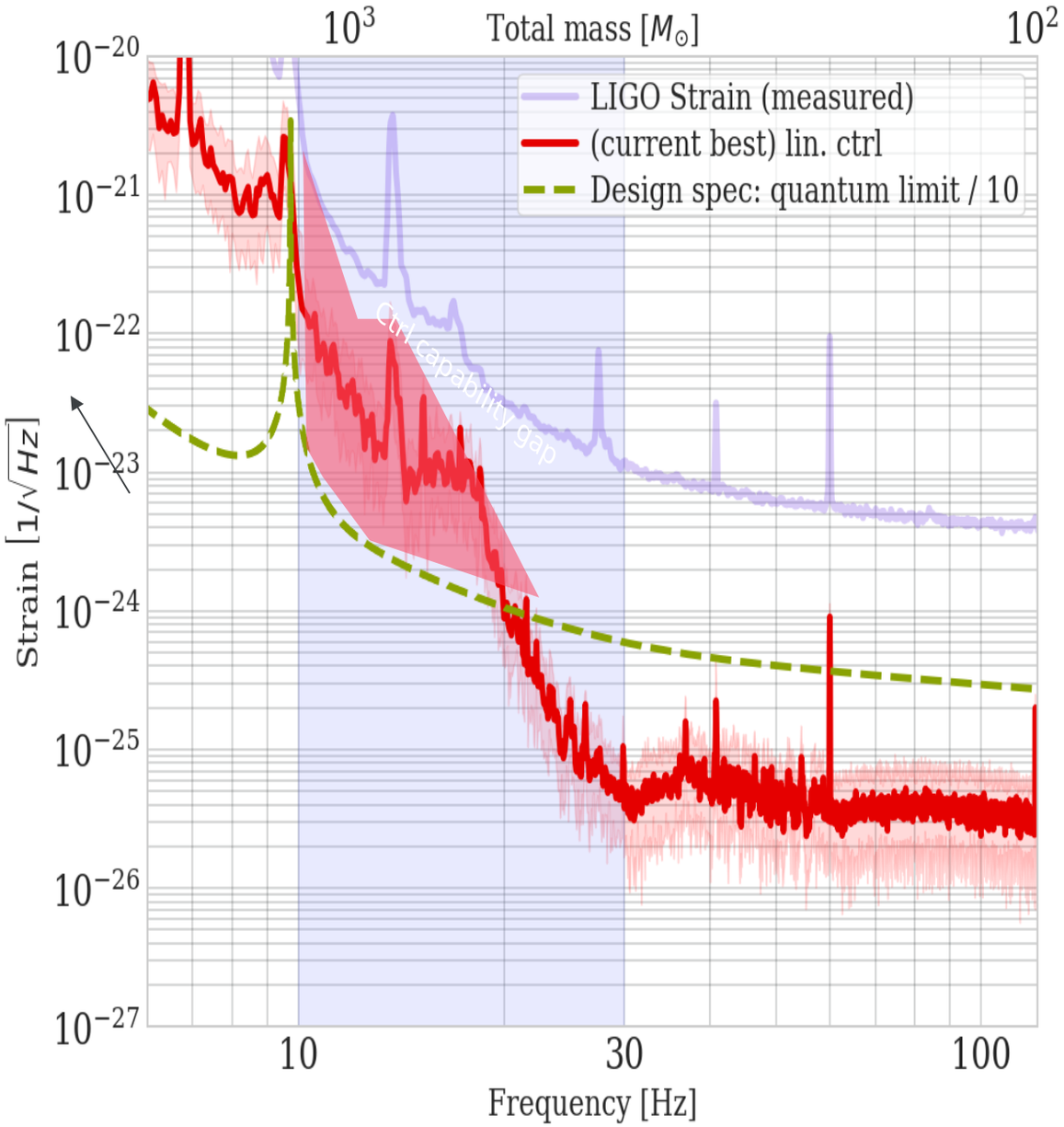
DARM SNR requirement -> Angle error should roll off >200db/dec (>10 orders/dec) !!!



mirror pitch angle - hard mode

Different coordinate system

Current control is significant source of noise



Logarithmic scale!

The angular control noise is now one of main remaining blocker for increased low frequency sensitivity of LIGO!

Any reduction of the control noise will have a huge scientific impact.

Big question: How can we improve the controller satisfying both stability and observation band performance?

Success criteria:

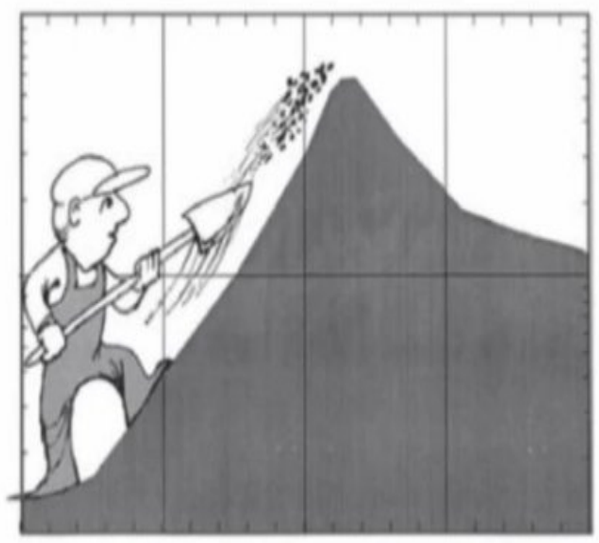
Improve the noise floor in the frequency range 10-30Hz for the LIGO system by at least one order of magnitude when compared to the currently used controllers.

Confidential - Google DeepMind
Confidential - DeepMind FTEs

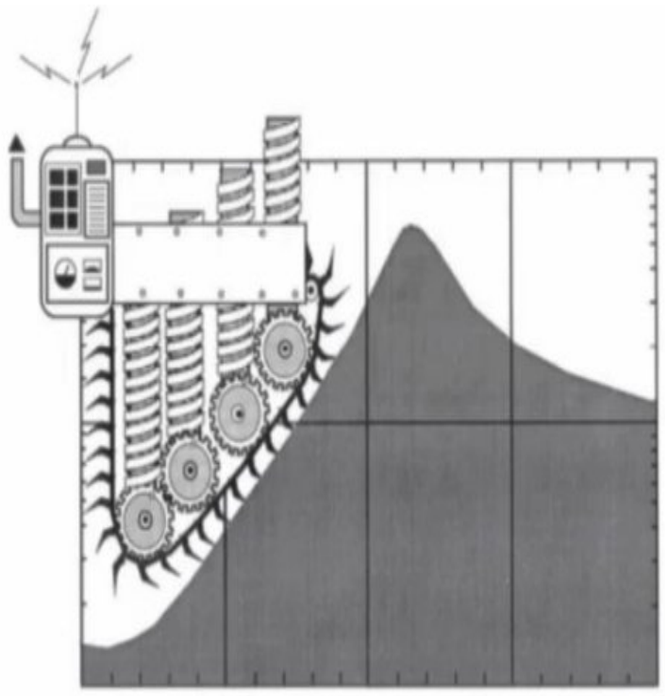
Bode's sensitivity integral - the waterbed effect

$$\int_0^\infty \ln|S(j\omega)|d\omega = \int_0^\infty \ln\left|\frac{1}{1+L(j\omega)}\right|d\omega = \pi\sum Re(p_k) - \frac{\pi}{2}\lim_{s\to\infty} sL(s)$$

- *Stein's "Conservation of Dirt"*



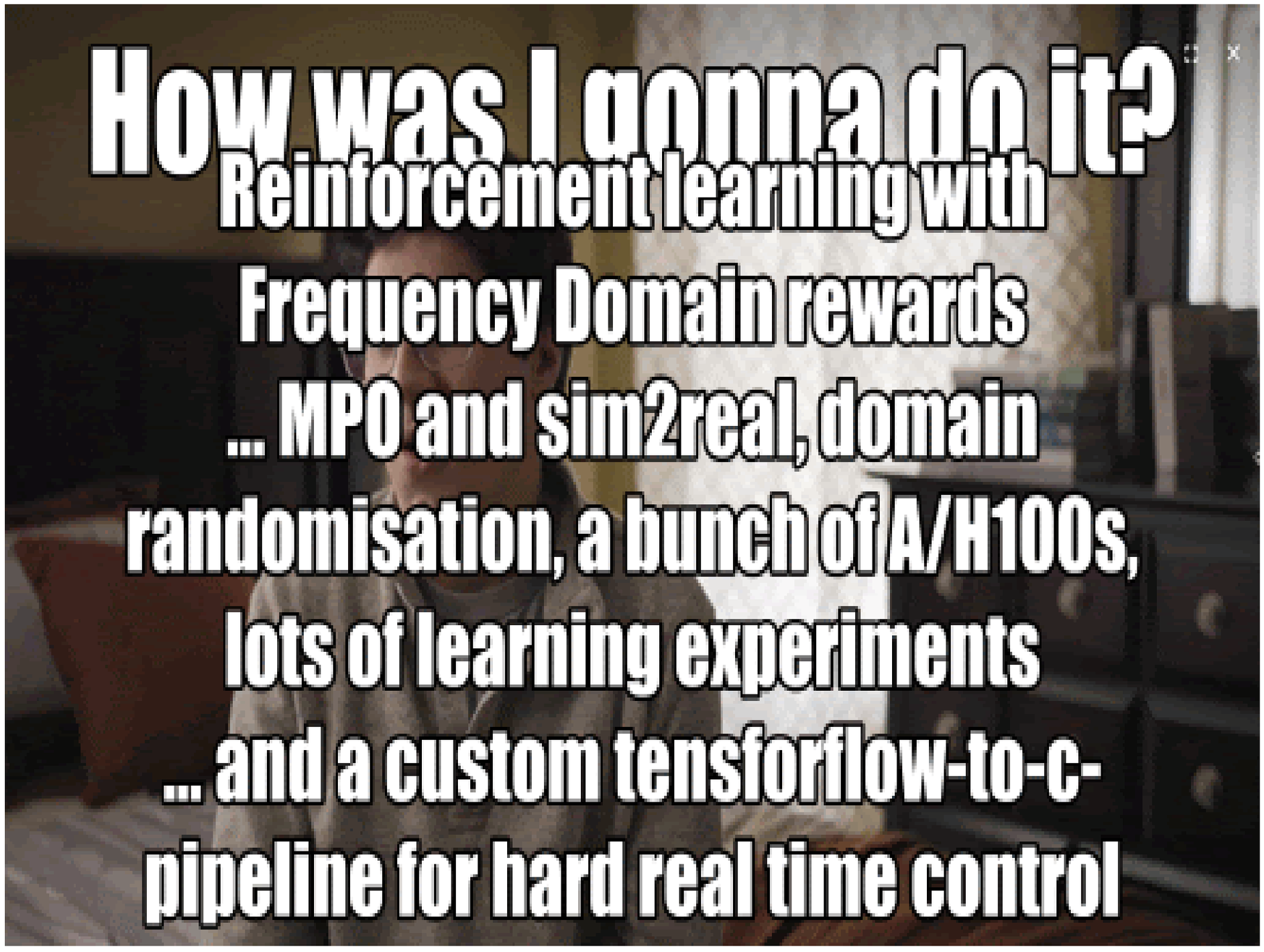
Classical methods



Modern methods

JSS, "Performance limitations in sensitivity reduction for nonlinear plants", *Systems & Control Letters*, 1991.
Stein, "Respect the unstable", *IEEE Control Systems Magazine*, 2003.
Chen, Fang, Ishii, "Fundamental limitations and intrinsic limits of feedback", *Annual Reviews in Control*, 2019.

How was I gonna do it?
Reinforcement Learning.

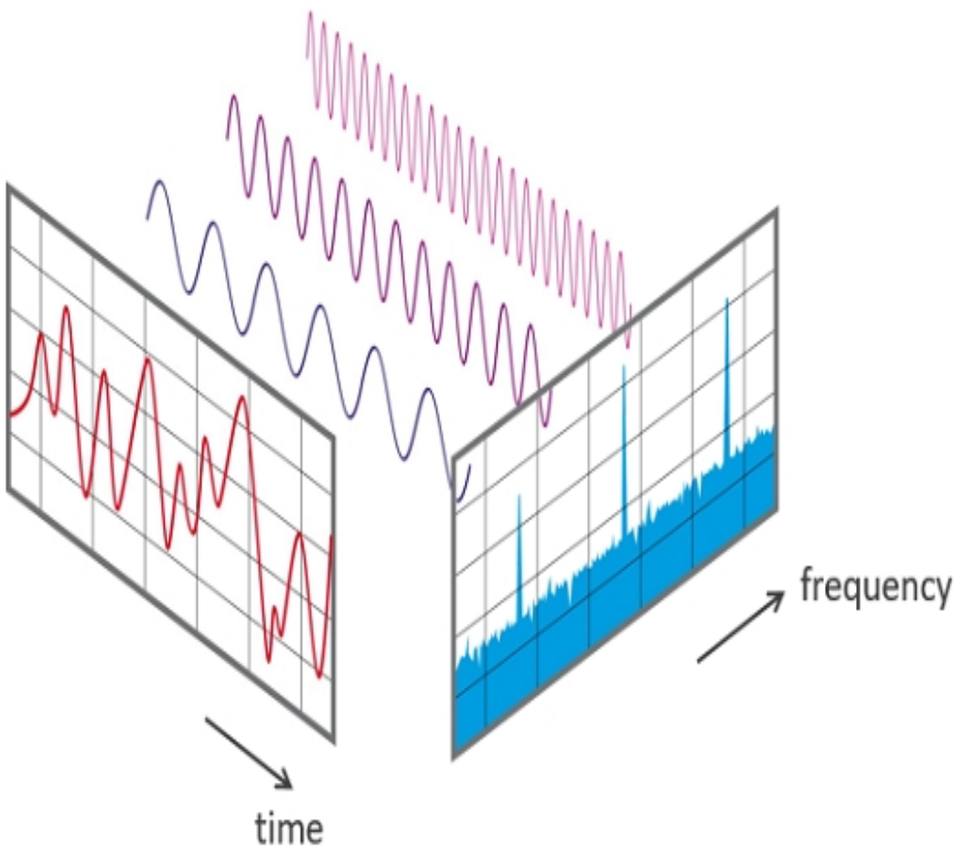

How was I gonna do it?
Reinforcement learning with
Frequency Domain rewards
... MPO and sim2real, domain
randomisation, a bunch of A/H100s,
lots of learning experiments
... and a custom tensforflow-to-c-
pipeline for hard real time control

Deep Loop Shaping

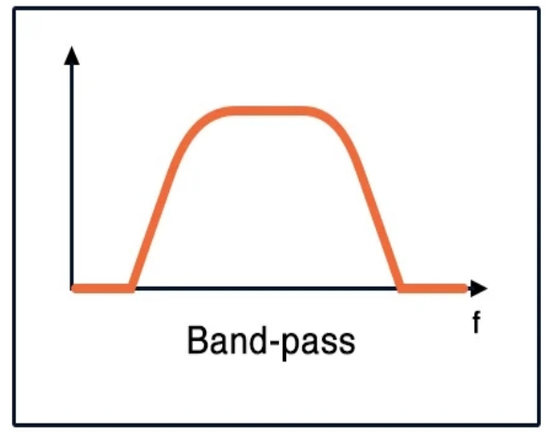
‘Reinforcement Learning with Frequency Domain Rewards’

Frequency domain rewards

Basic idea: Formulate rewards in the frequency domain

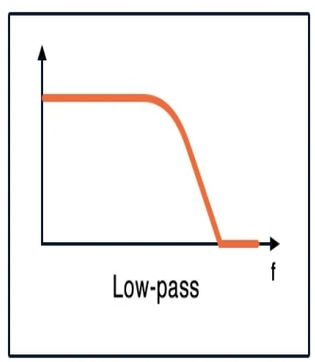


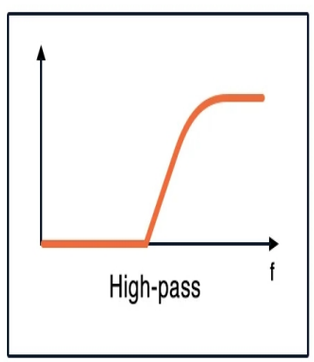
Example: Use a bandpass pass filter to estimate the energy in a certain band and use this to compute a score



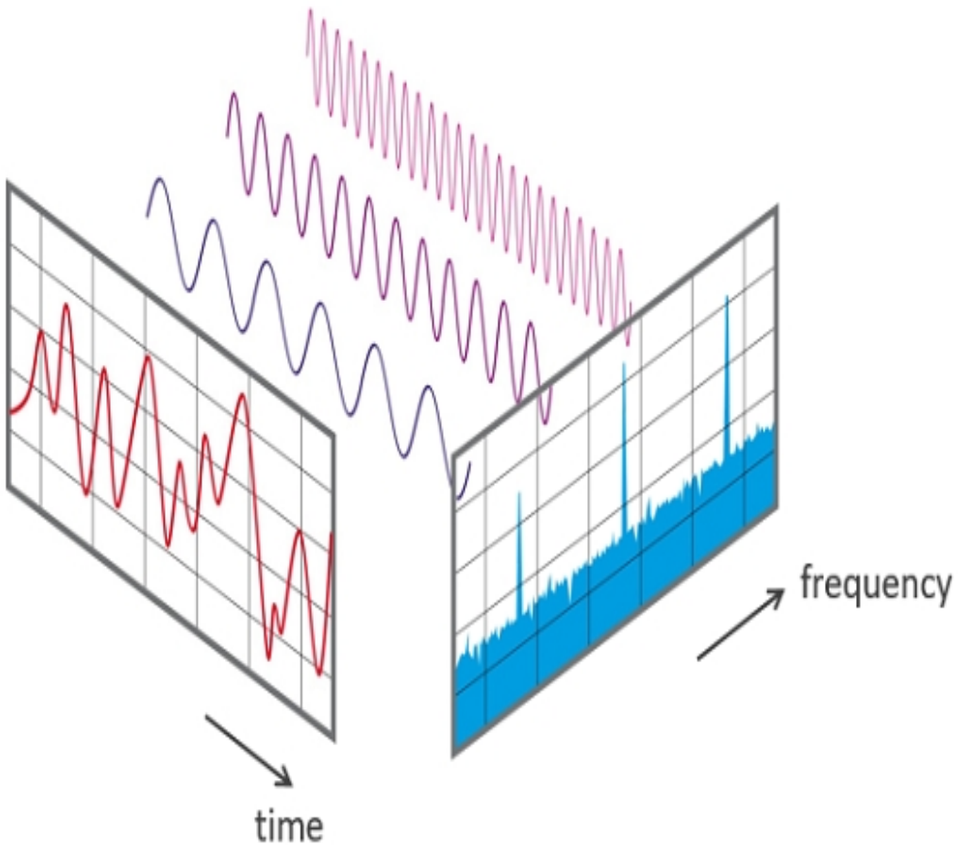
Filters have advantage that they can be run straightforwardly in ‘online’ scoring setups

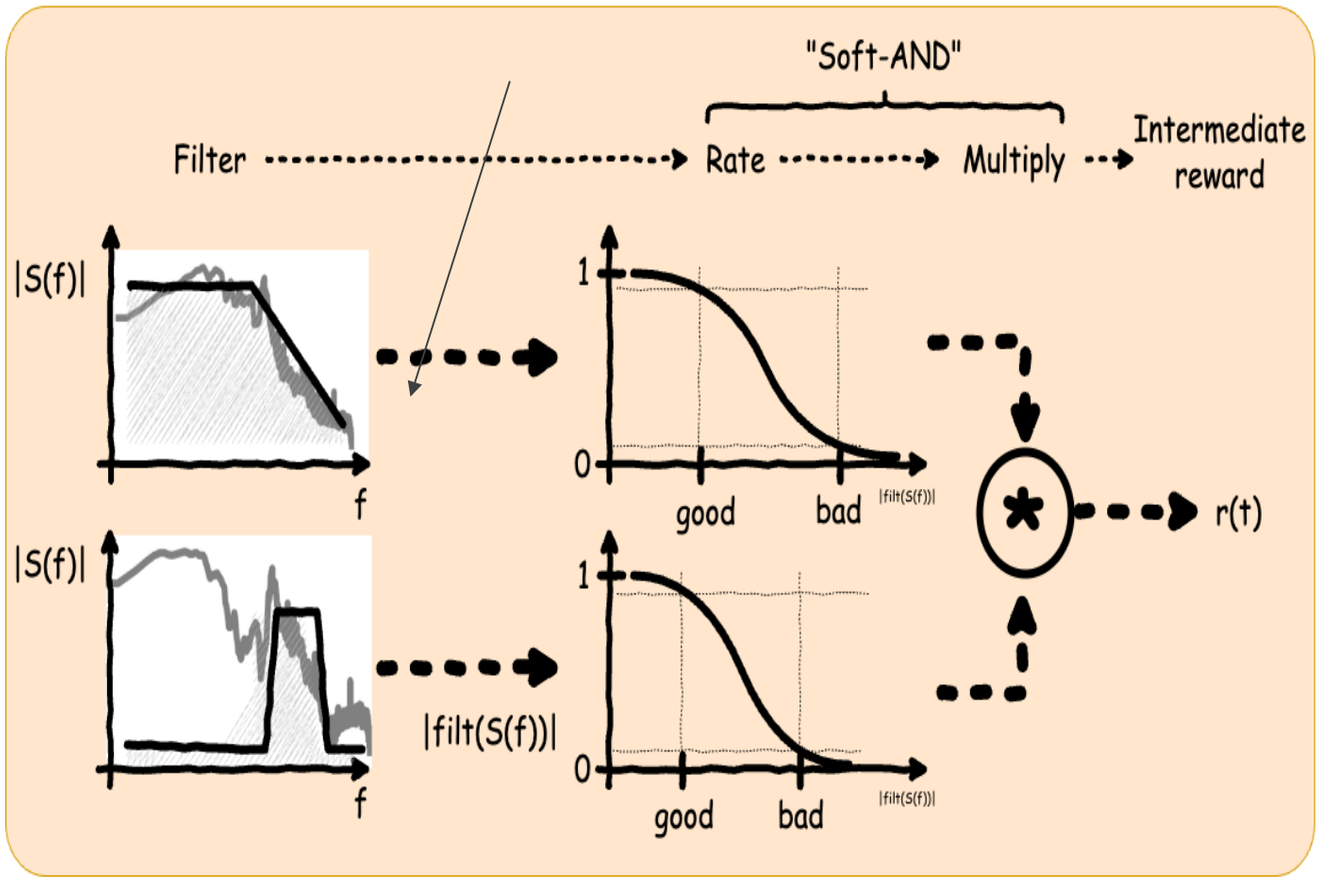
Could also use (short-term) FFT or similar methods





Frequency domain rewards closed loop control design:
Deep Loop Shaping





Deep Loop Shaping is a general RL/control design method!

$$\pi^* = \arg\max_{a\sim\pi} J = \mathbb{E}_\pi \left[\sum_{t=0}^{\infty} \gamma^t r(s_t, a_t, s_{t+1}) \right]$$

Frequency domain rewards FTW

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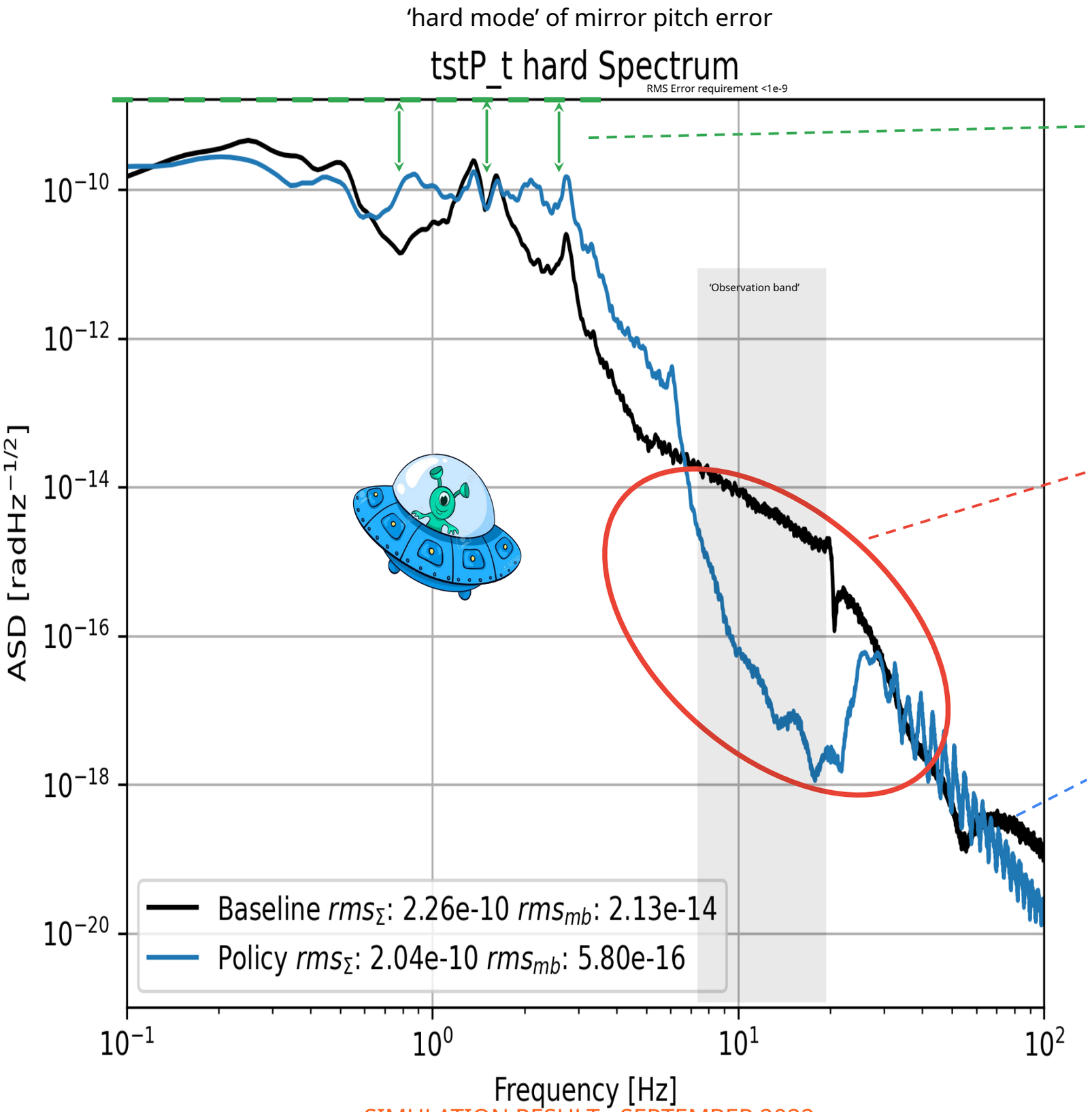


SIMULATION RESULT - SEPTEMBER 2022

Stability: Low frequency penalty

Reward aimed at reducing the overall magnitude (‘RMS’) of the error signal, encouraging stabilization. Computed using a lower pass filter with 3Hz corner frequency.

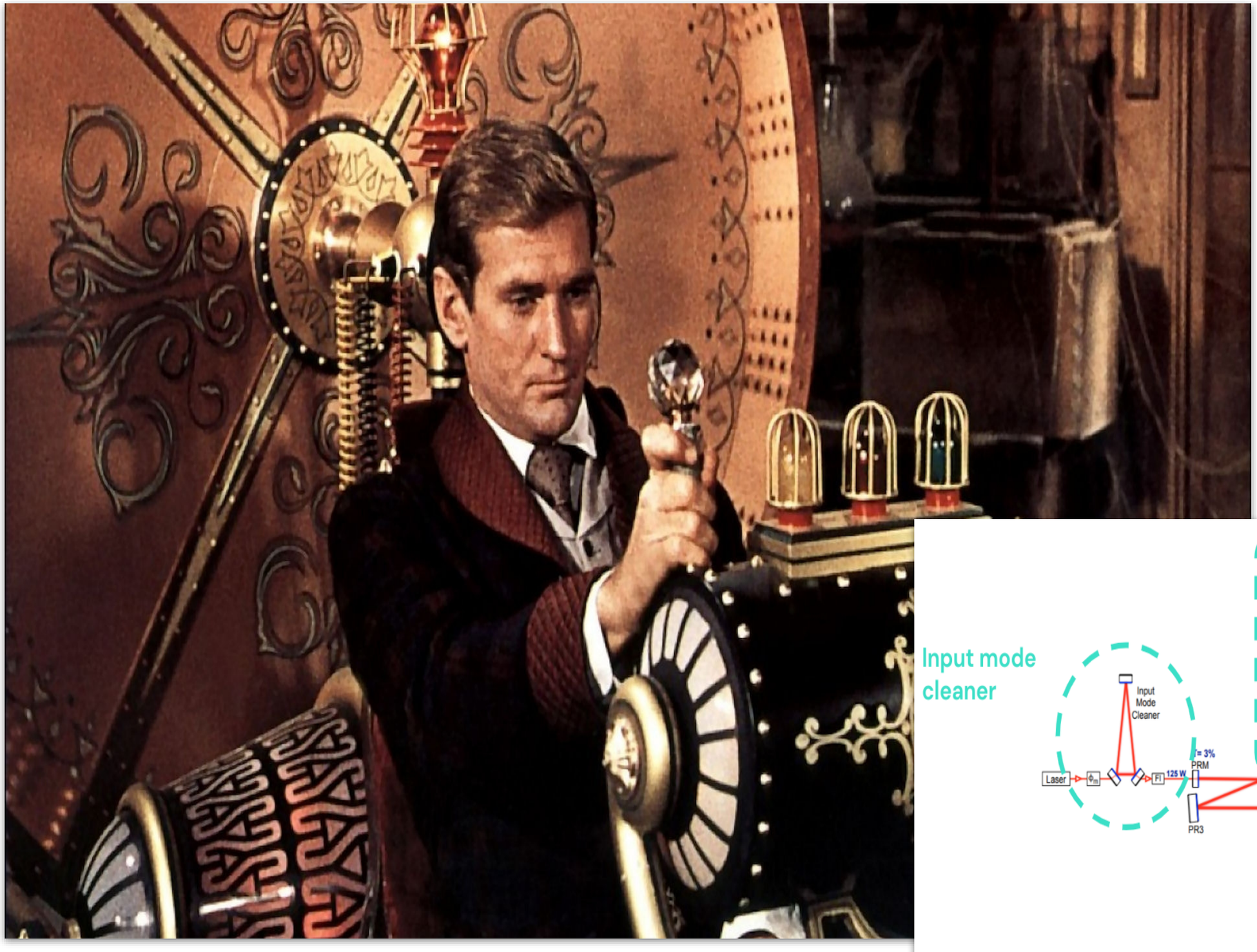
Sensitivity: Measurement band penalty

Reward aimed at reducing the control signal in the ‘measurement band’, i.e. the band of interest for GW signals. This is computed as a stepwise reward using an IIR.

Regularization: High frequency penalty

Reward aimed at reducing the control signal at ‘high frequencies’ (i.e. above the measurement band). This is to keep the agent from introducing high frequency artifacts in that band.

A ‘few experiments’ later… fast forward to 2023



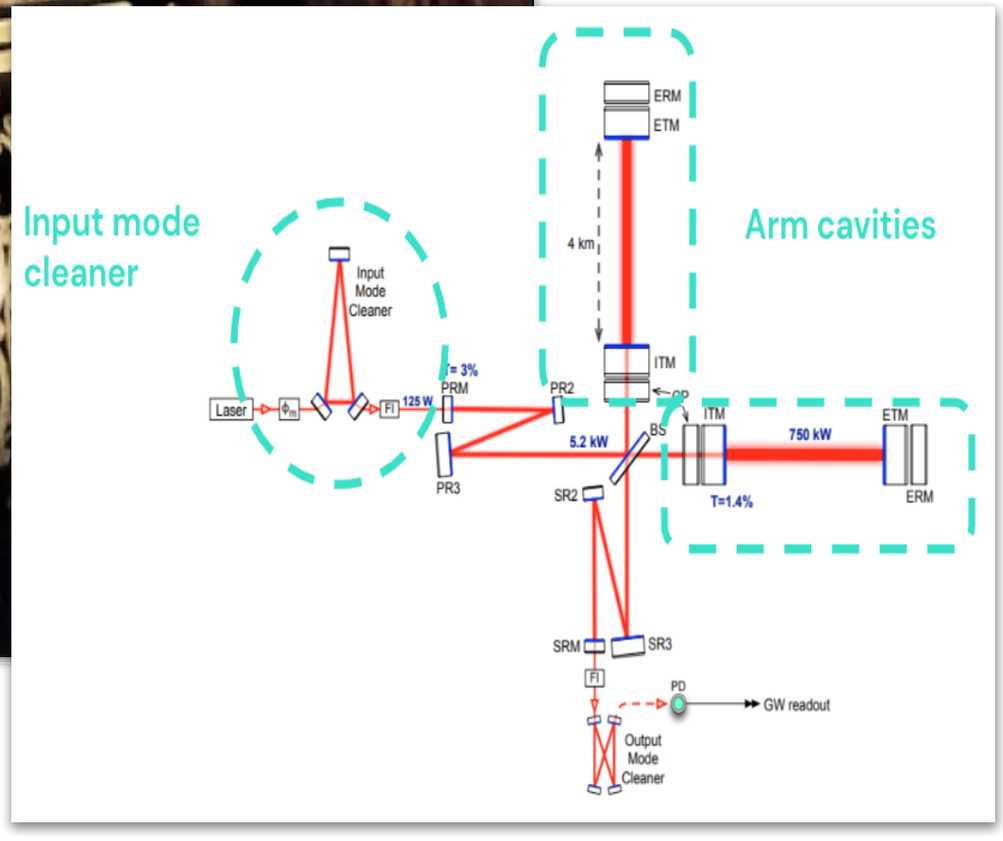
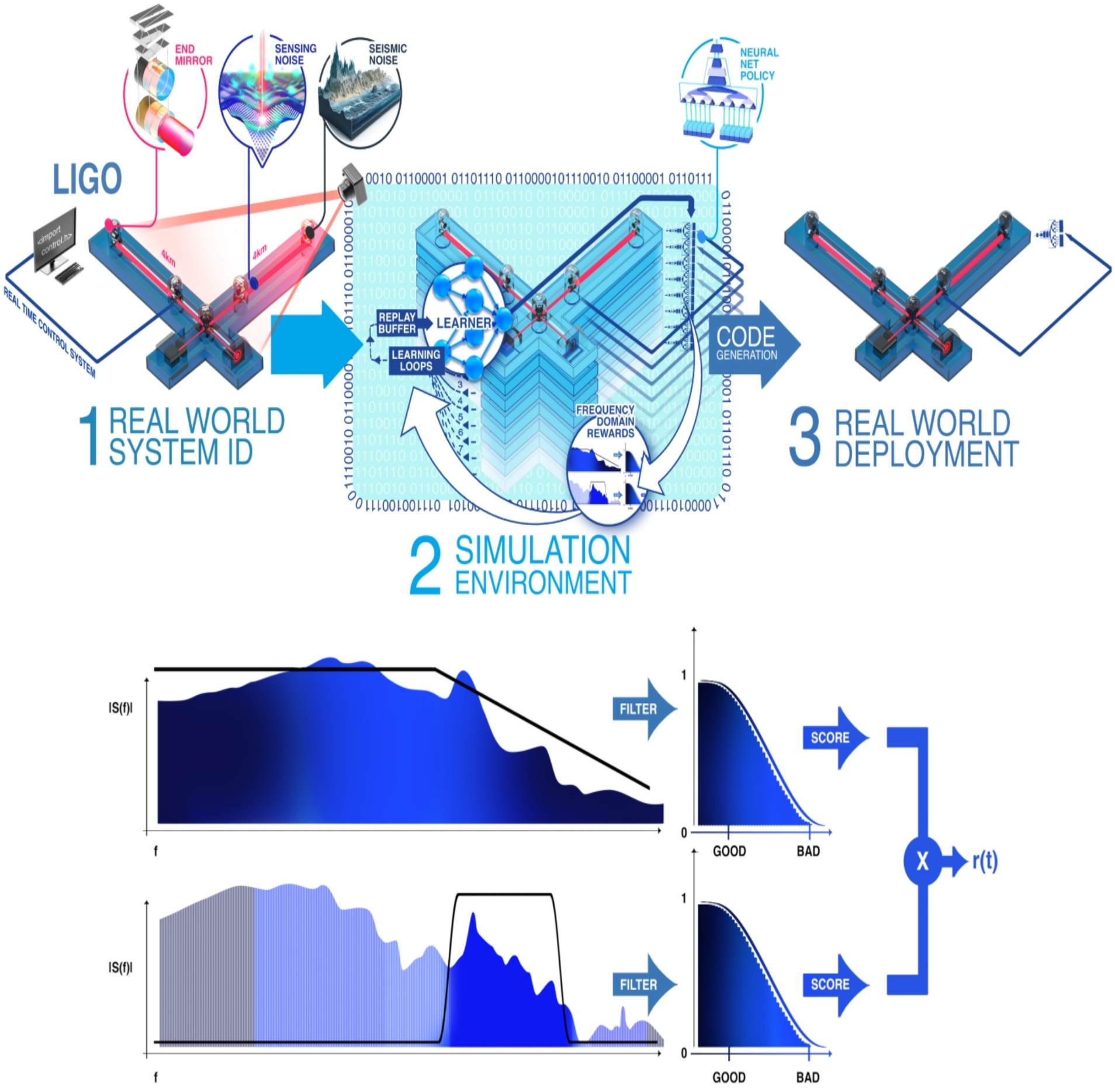


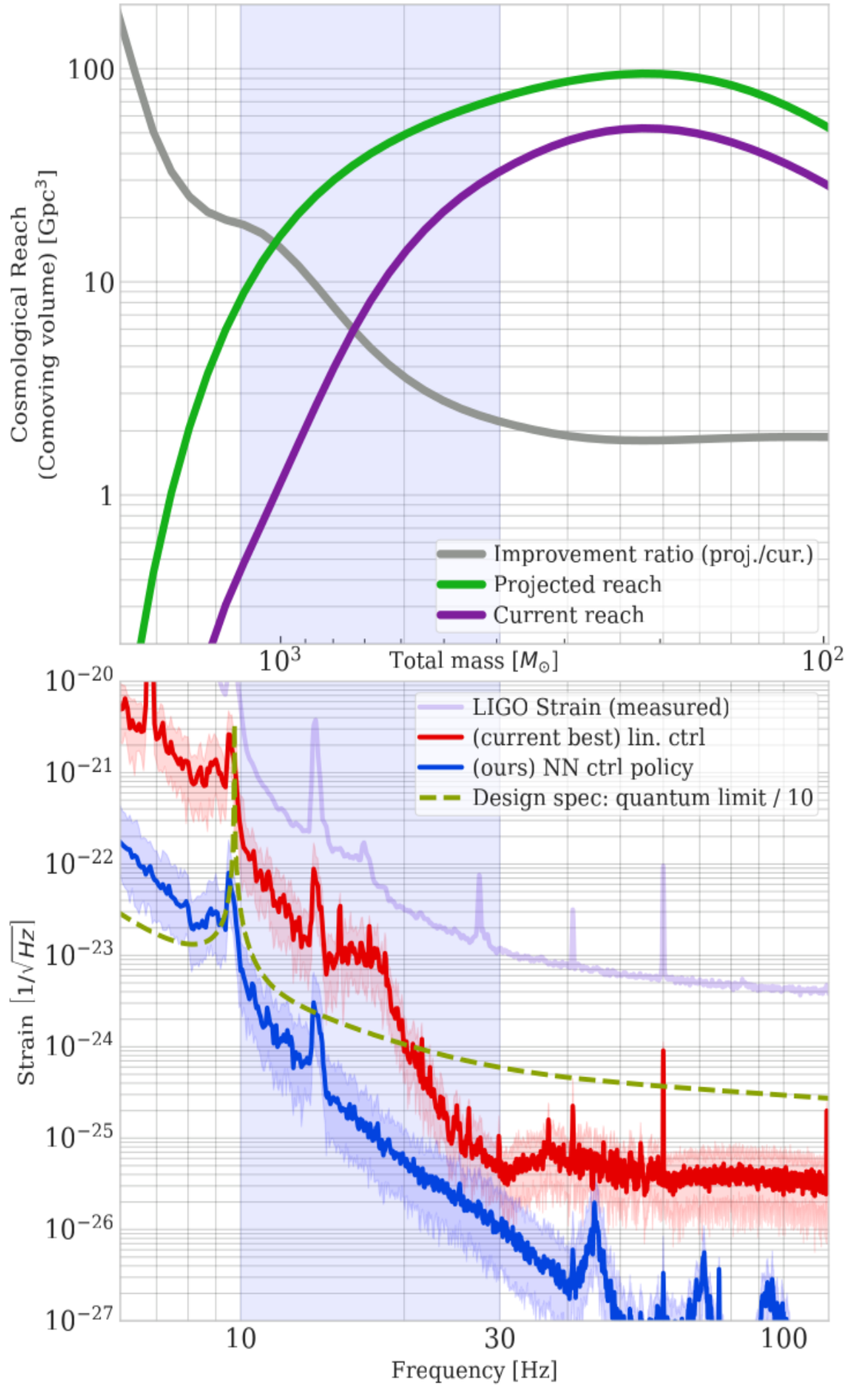
Illustration of method



Key result: RL policy reduces noise up to 100x

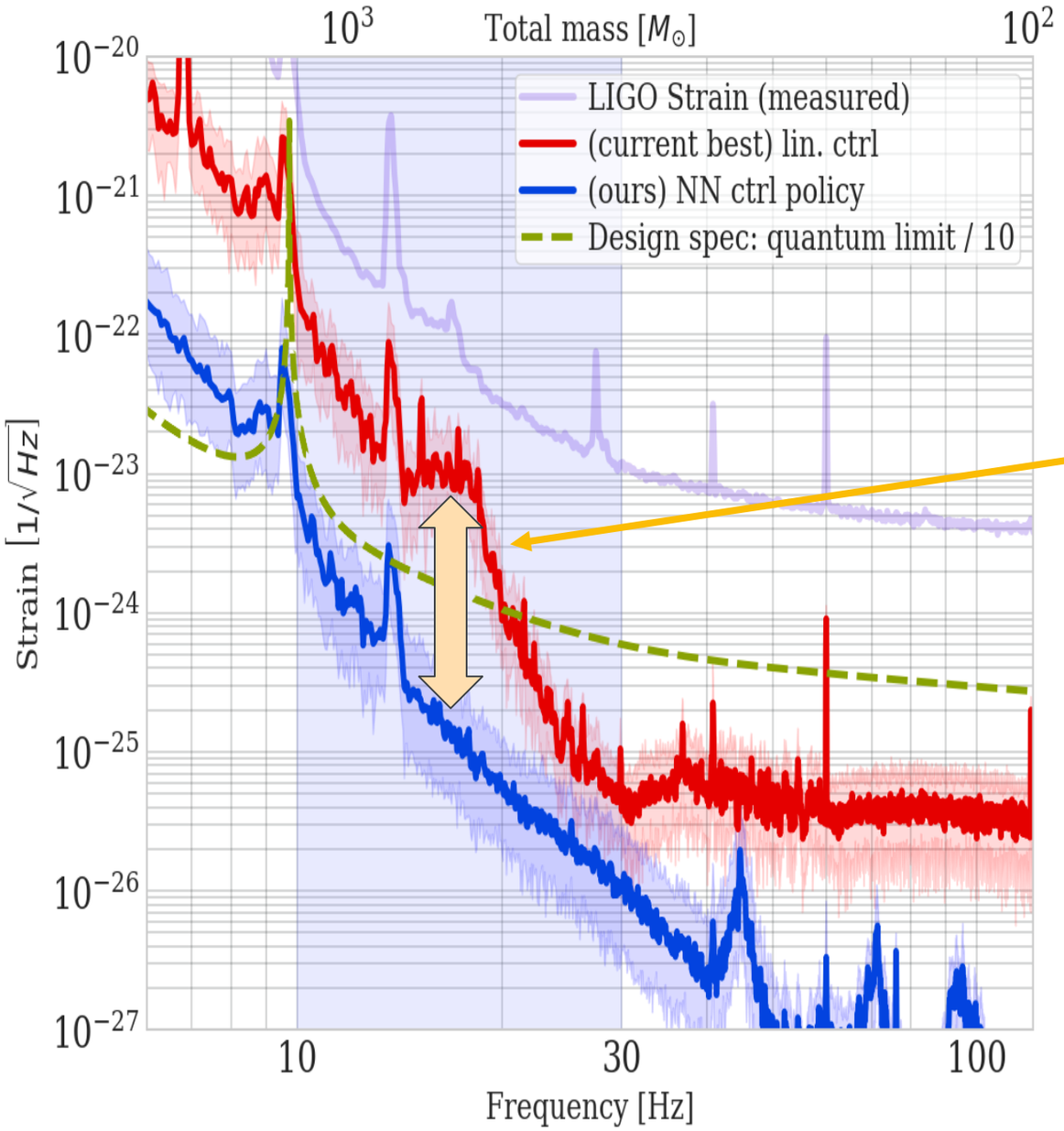
Main Results:

1. Very good performance with linearized simulations
2. Good performance at LLO
3. Mostly short ~15 min tests.
4. Longer runs - no issues.



Confidential - Google DeepMind

Key result: RL policy reduces noise up to 100x



Success criteria:

Improve the noise floor in the frequency range 10-30Hz for the LIGO system by at least one order of magnitude when compared to the currently used controllers.

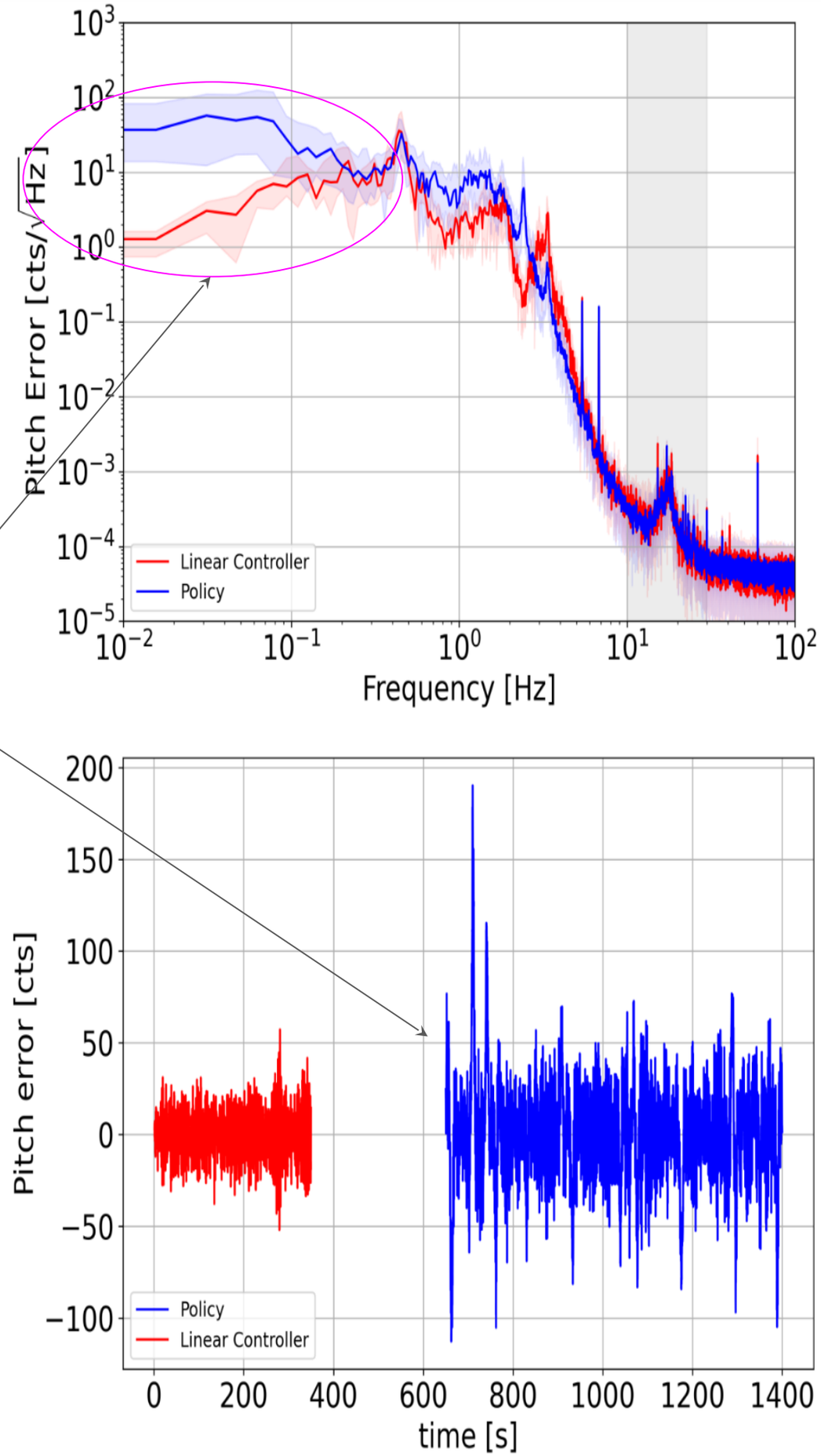
We have removed the ASC control challenge as a blocker for increased low frequency sensitivity of LIGO ‘in principle’

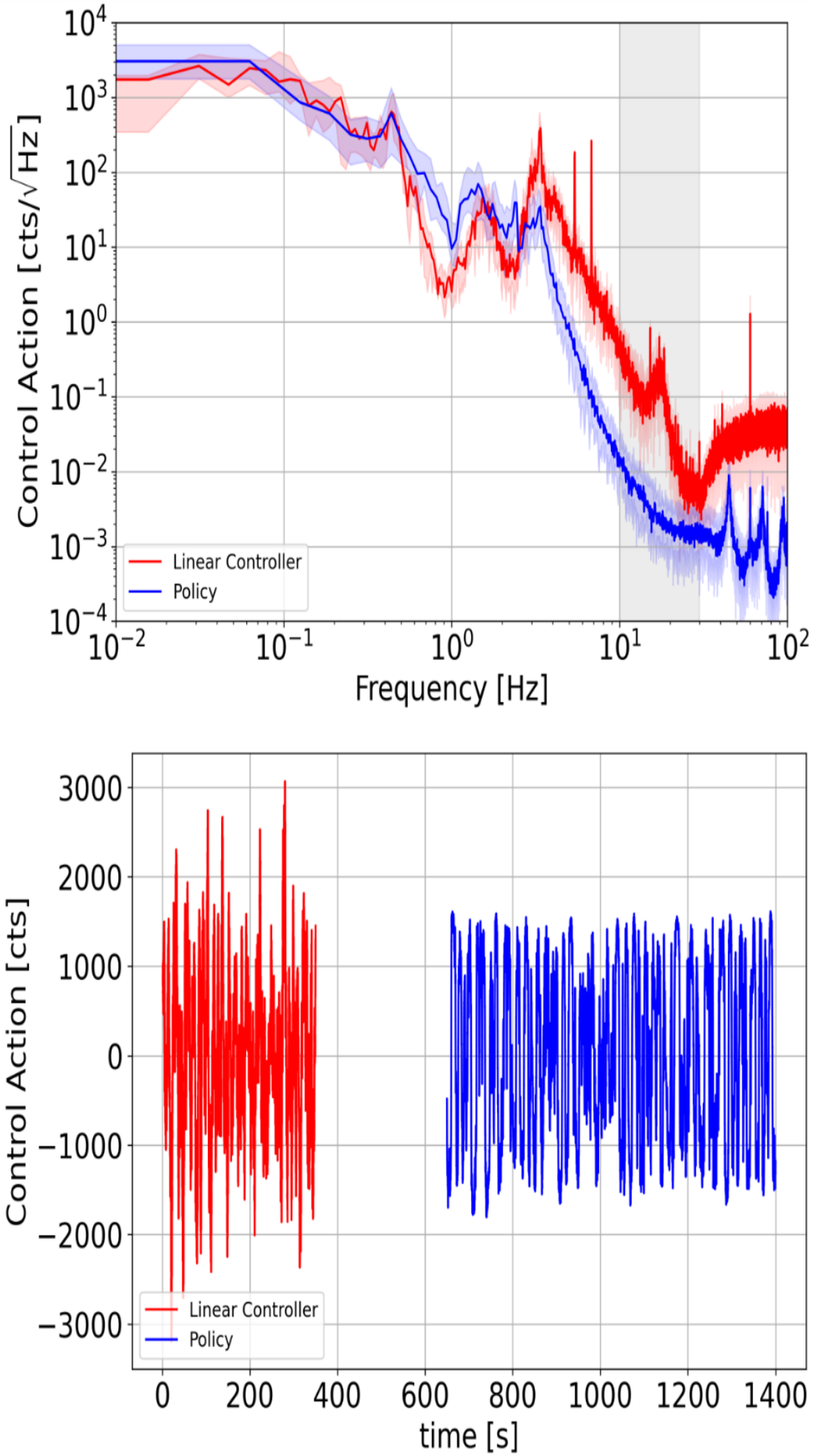
Fully implementing and operationalize this concept will have a huge scientific impact

✔

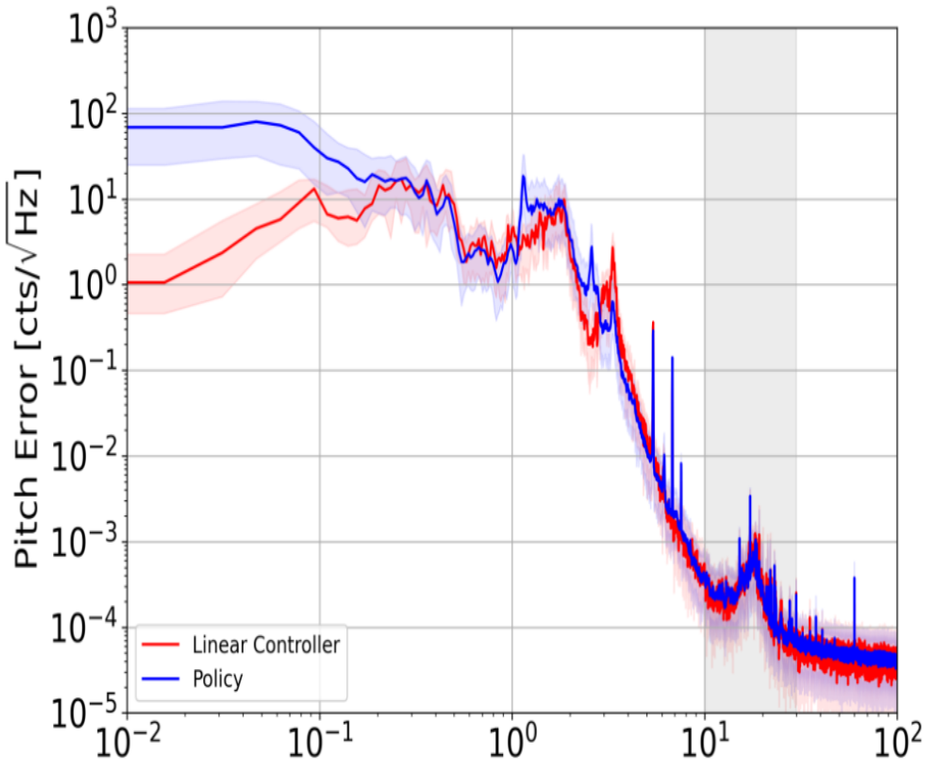
Low Freq Excess

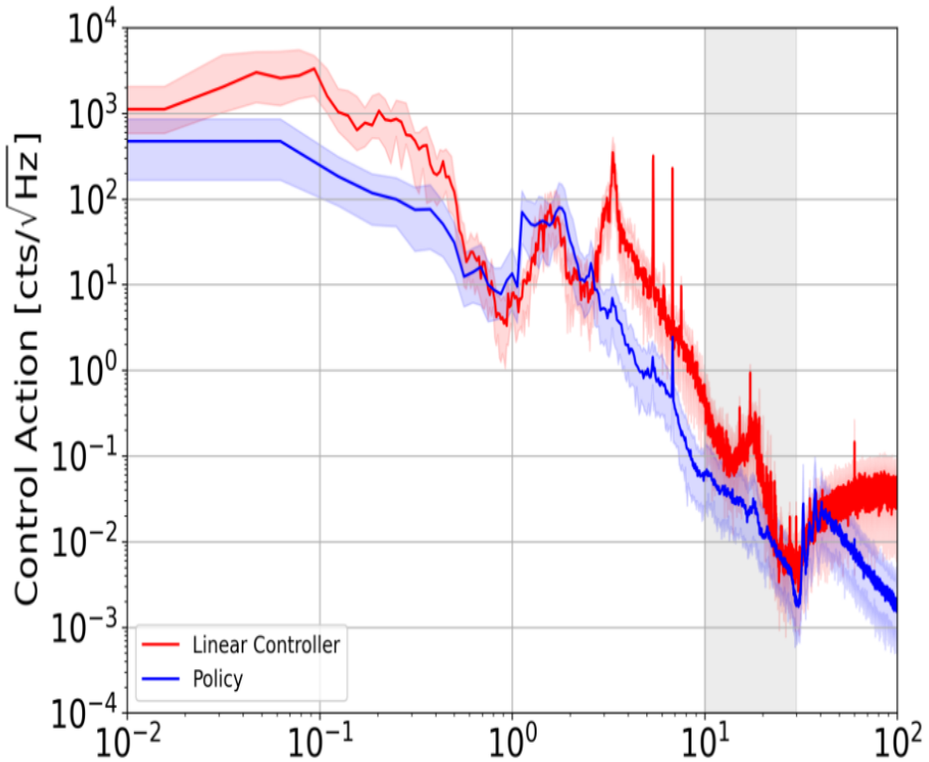
- Needs better low freq SysID (L2/L1)

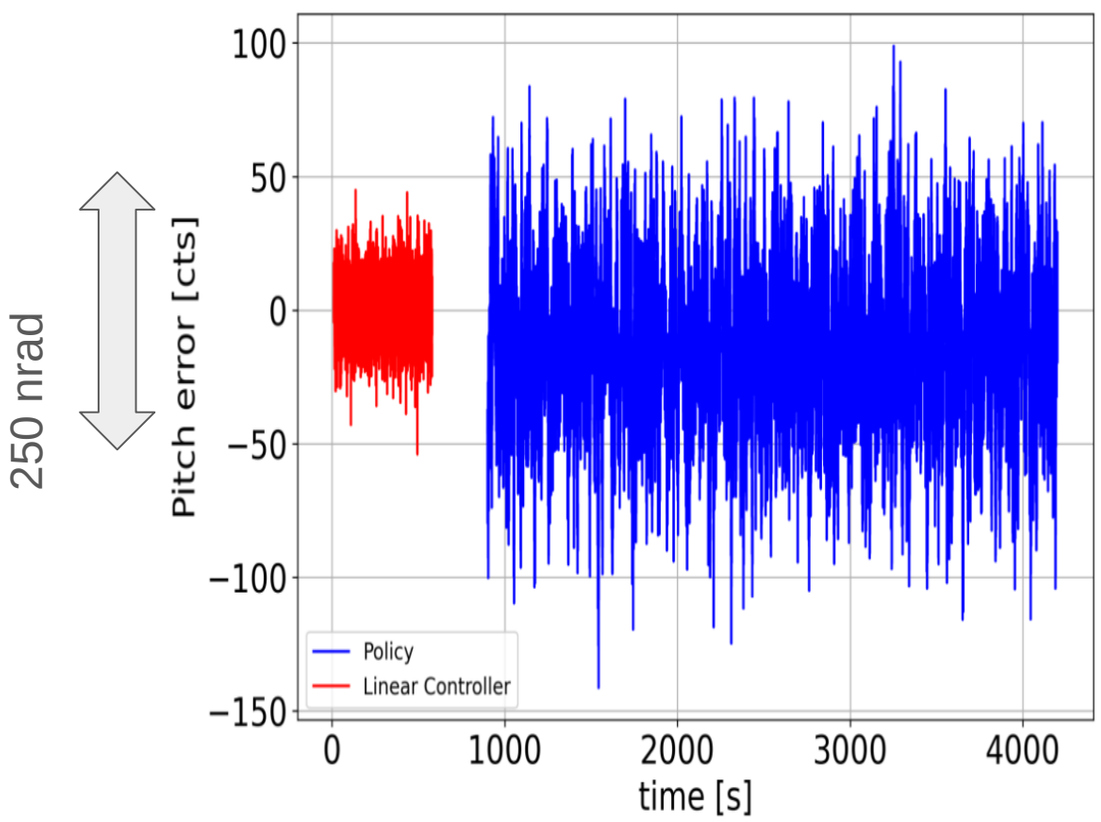


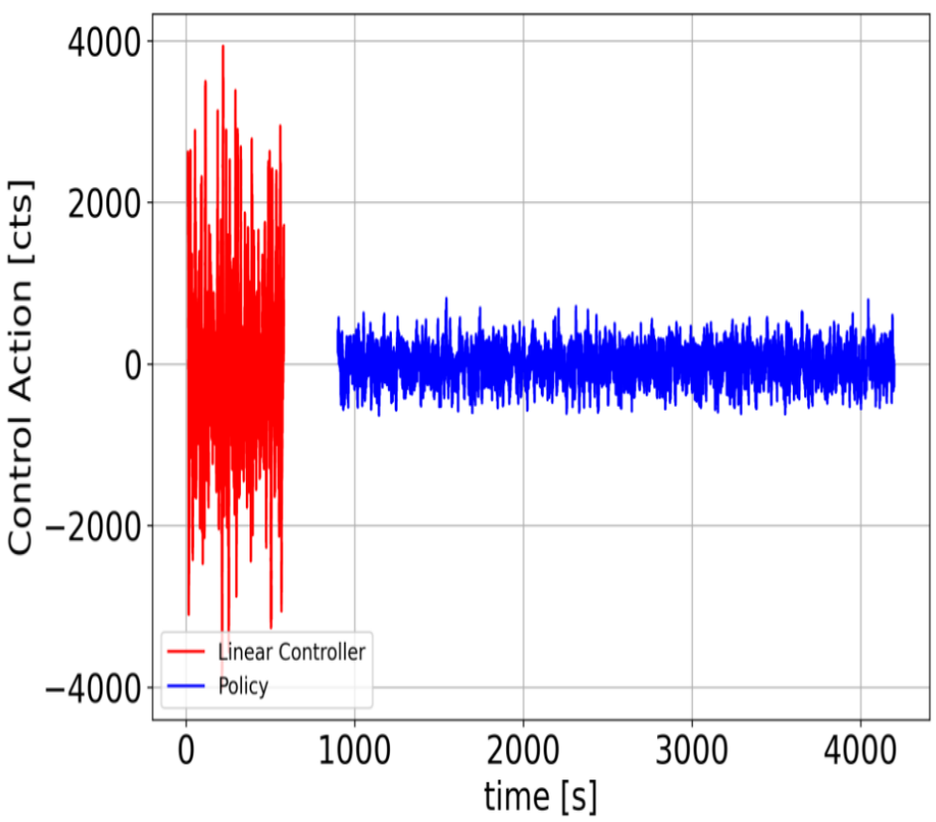


spongebob - 26.4.2024

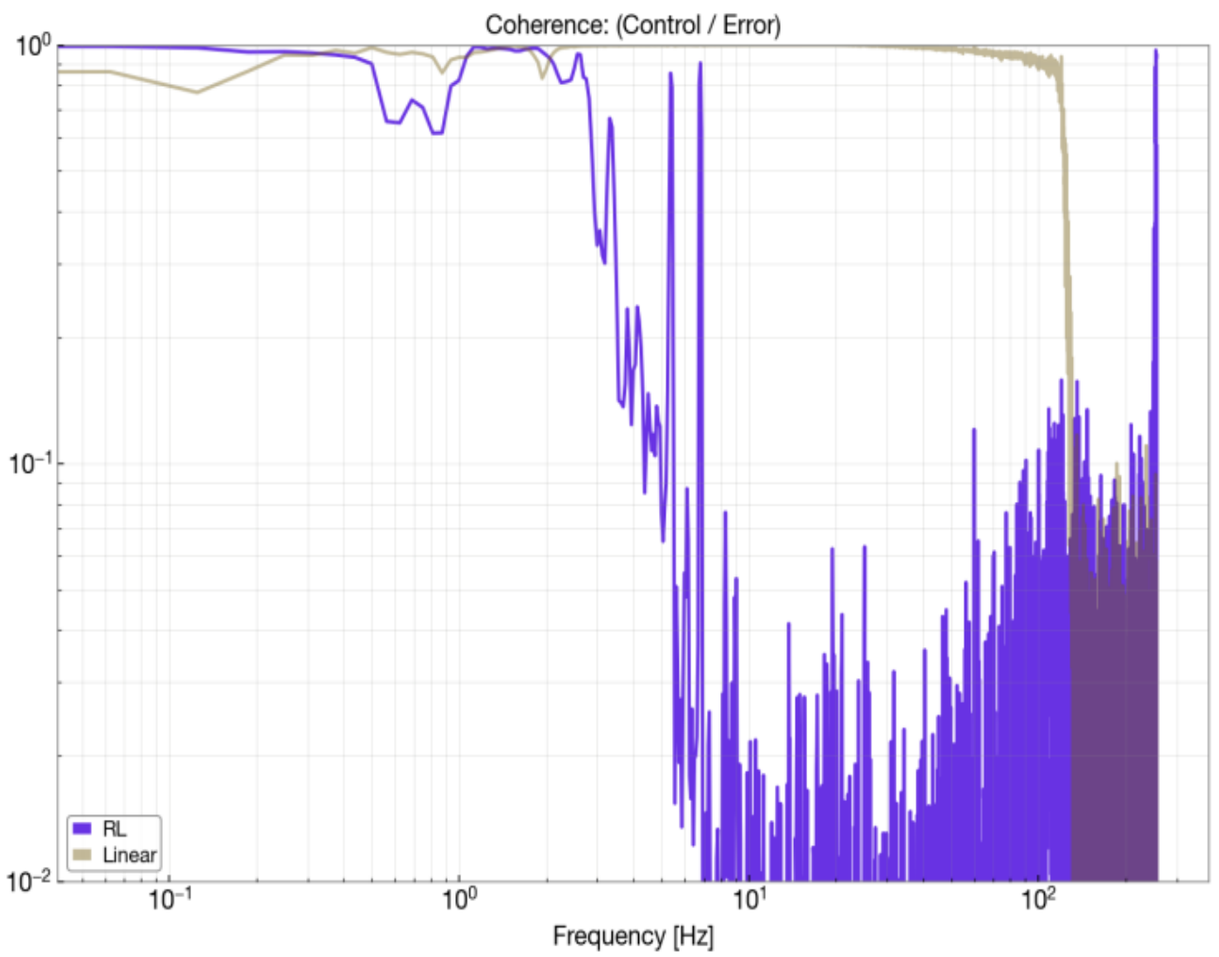


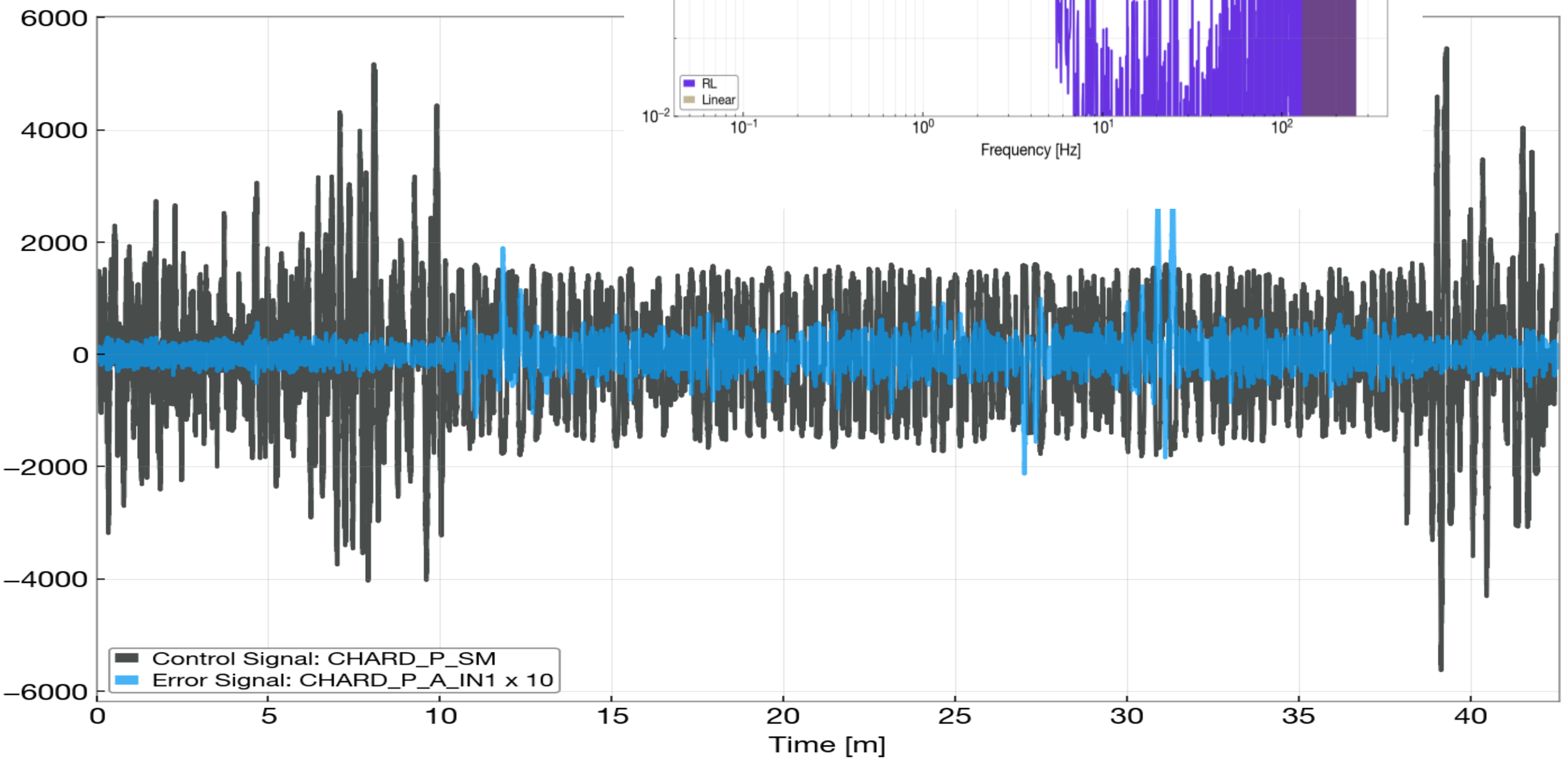


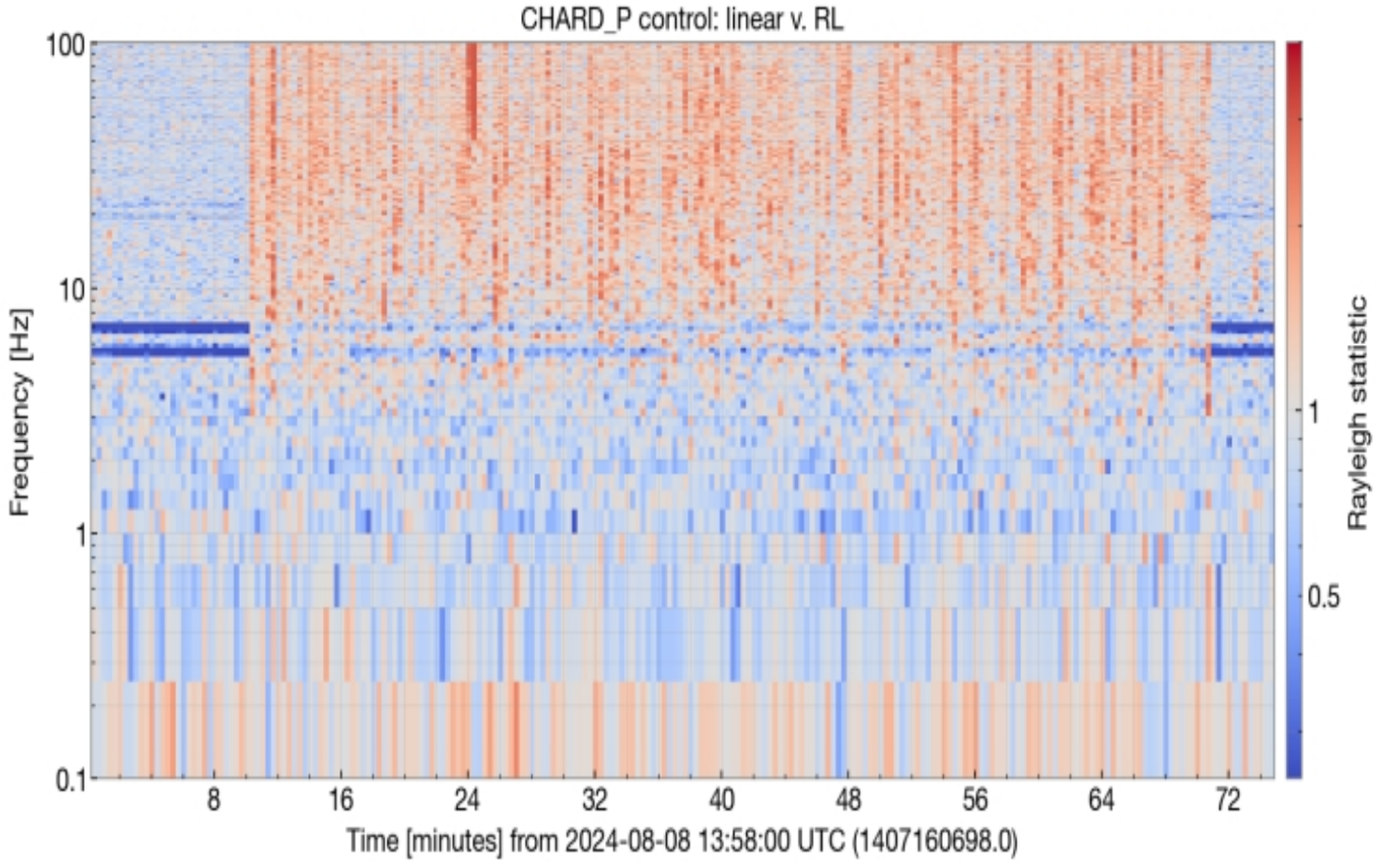


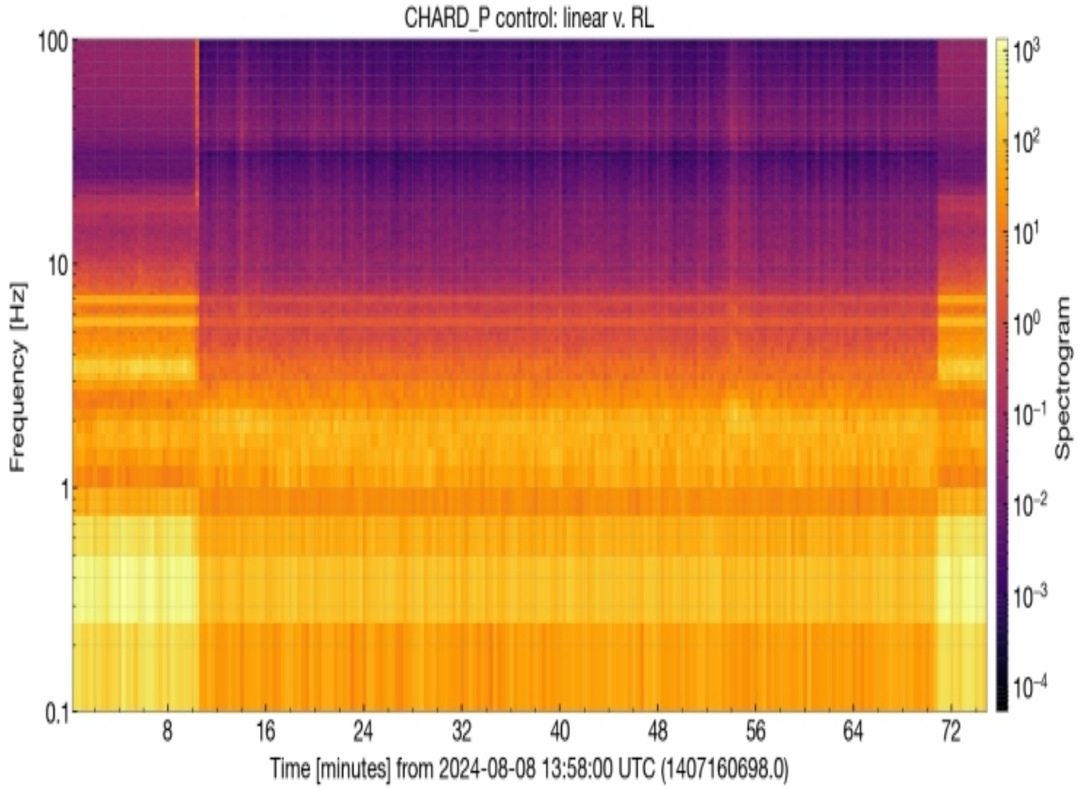


Coherence,
Time series





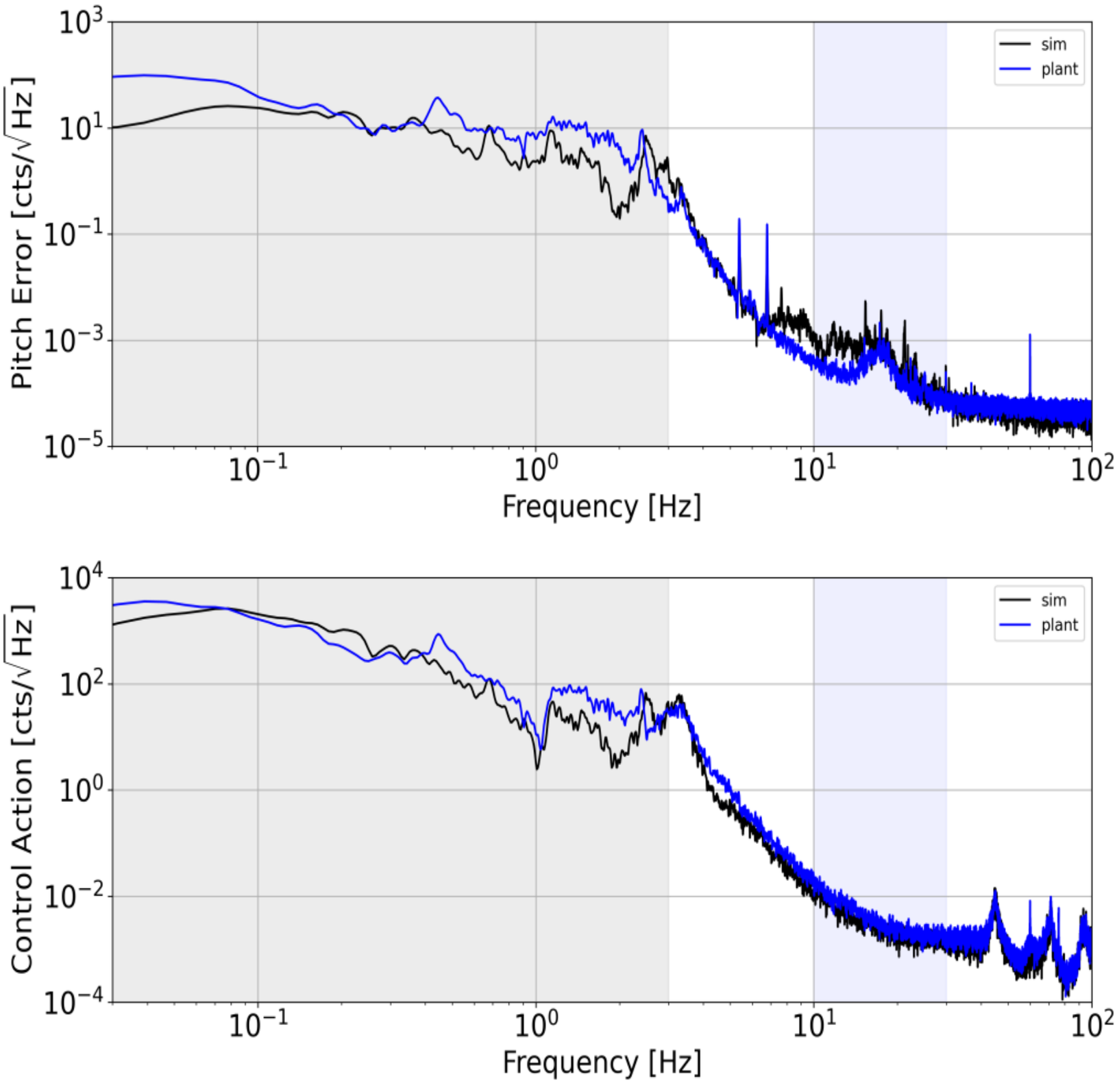




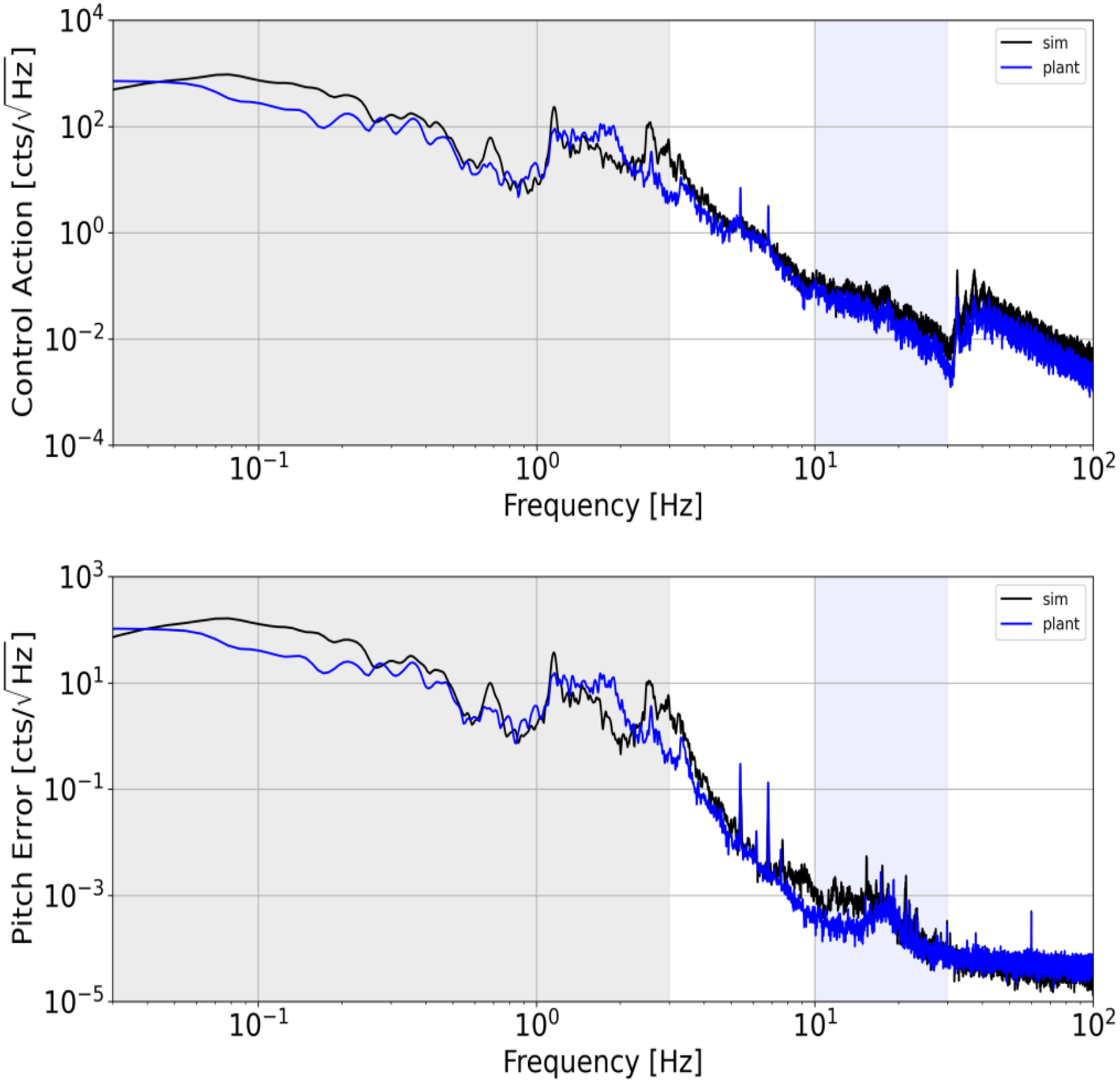
RayleighMonitor Algorithm

- 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.

squidward - sim2real transfer is excellent above >0.1Hz



spongebob - sim2real transfer is excellent



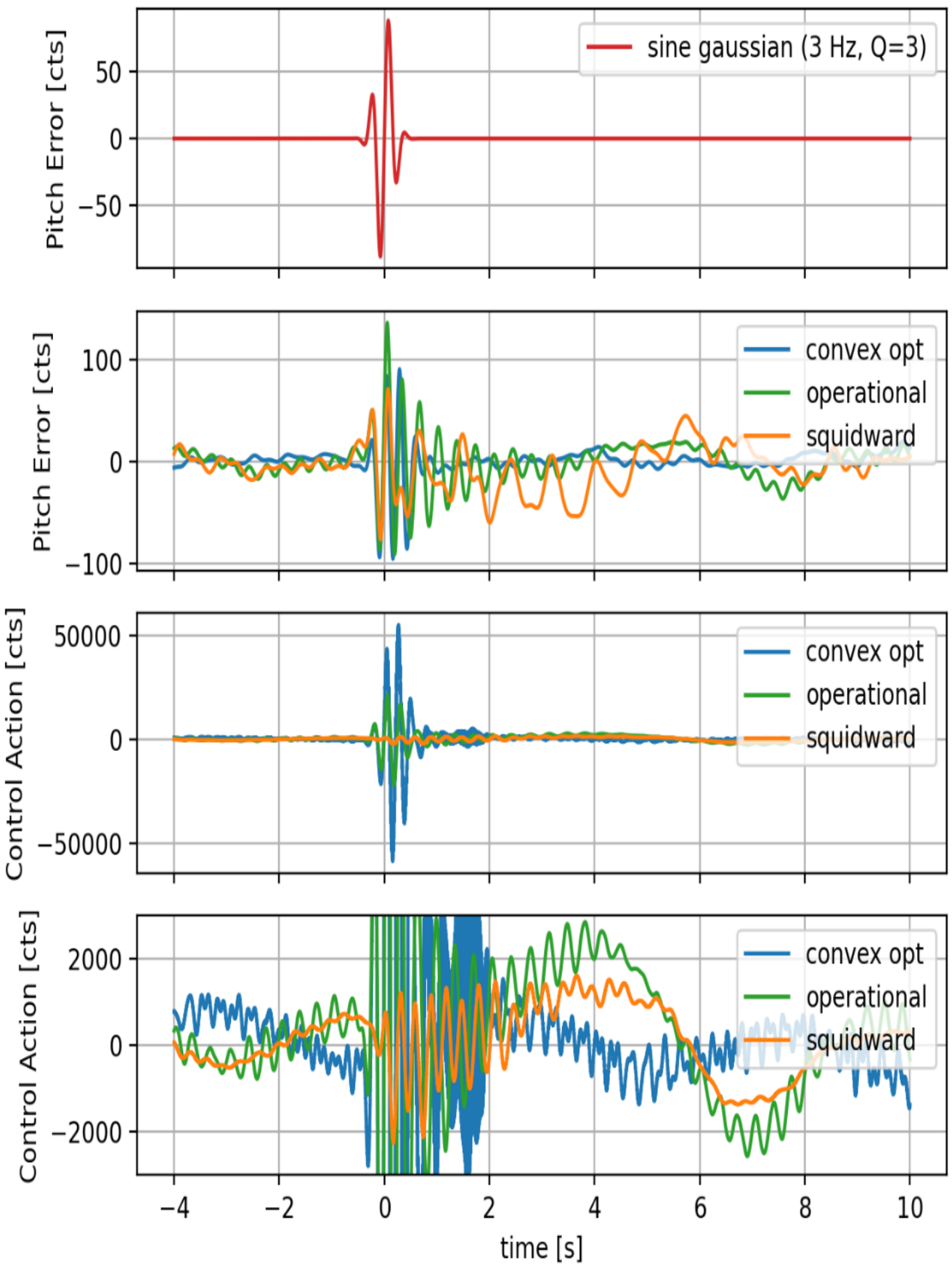
Robustness of controller to transients

Cvx opt controller reacts very aggressively, for not much difference in error

RL controller has longer settling time, low frequency oscillation after the event.

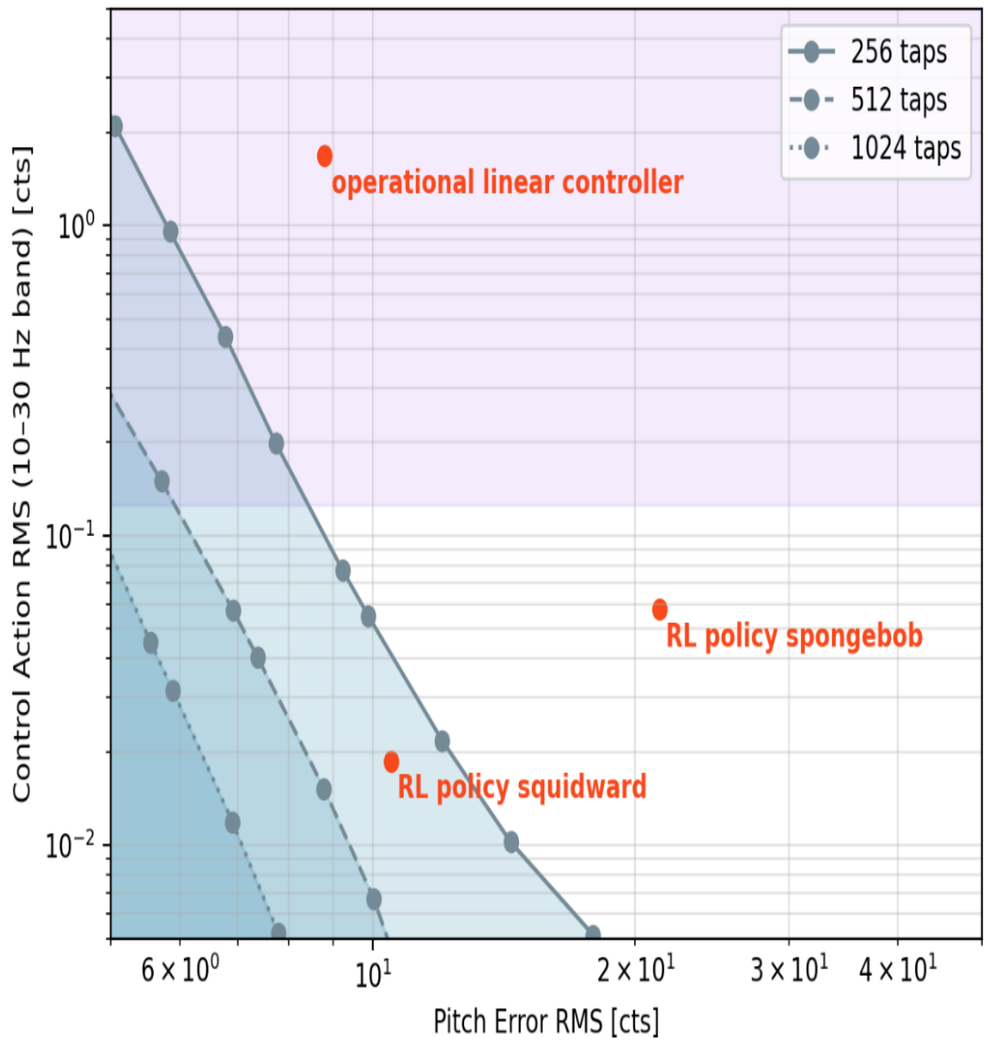
But that's fine, as long as the mirror remains stable within bounds, what we mostly care about is the noise injected in the GW observation band (10-30Hz)

Note: RL controller is limited *by design* using a soft nonlinearity



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
- Optimization performed over: FIR filters with varying tap length (i.e., history window size)
- RL policies operate without an auxiliary stabilizer, yet outperform convex-optimized controllers that require one
- Not yet fit for deployment (not robust under plant variation)



Summary

1. The LIGO Controls/ASC feedback noise is ~significant noise source at 10-30 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
4. Good real performance on 40m IMC ASC (6x6 MIMO system w/ WFS + QPDs)
5. Success in LLO CHARD_P tests
6. 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

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

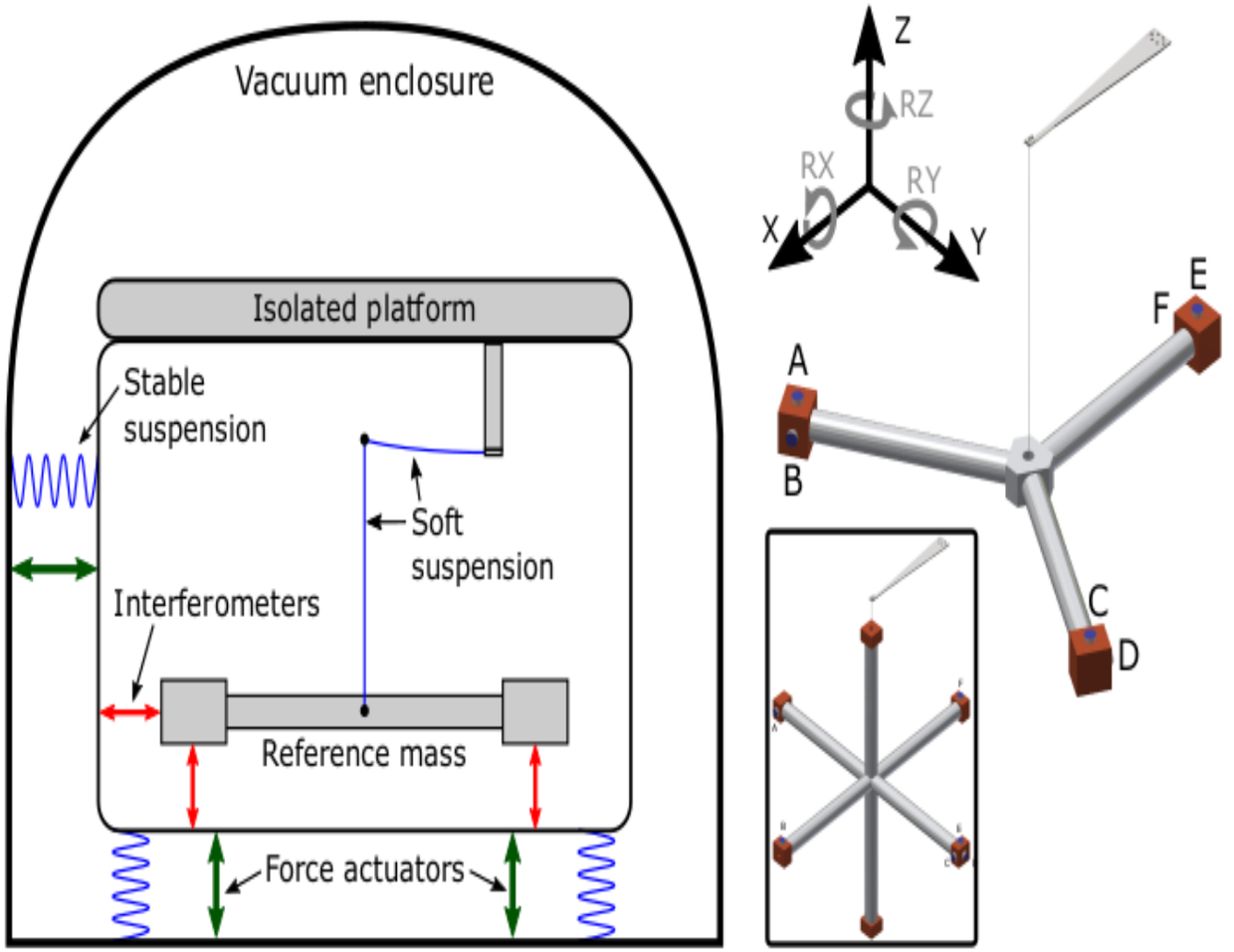
1. Implement on Virgo loops
2. Make the plant sysID more automated and robust
3. Adapt the Lightsaber model continuously to the live data to extract physically meaningful plant parameters.
4. Explore hybrid linear + nonlinear control
5. Make it run robustly during high-noise conditions
6. Reduce non-stationarity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

Gemini’s idea of an improved gravitational wave detector

ASC for ET-LF

- ET – issue needs to be addressed already with its design
- RMS not filtered with mechanical suspension
- Sensors will not become better
- Natural resonant frequency ~0.05 Hz in pitch and ~0.2 Hz in yaw
- Resonant frequencies for ET-LF are:
  - soft mode pitch: 0.0218 Hz
  - hard mode pitch: 0.1413 Hz
  - soft mode yaw: 0.1949 Hz
  - hard mode yaw: 0.2397 Hz
- **Need for RL for improvements**
- **ET-LF-Lightsaber**

- Omnisens



C M Mow-Lowry and D Martynov 2019 Class. Quantum Grav. 36 245006

Newtonian Noise (WP 1)

What it is

- Gravity coupling of time-varying density fields near the test masses (seismic waves, atmospheric density/pressure, moving infrastructure/objects)

Why it matters for ET-LF

- Bypasses suspensions & seismic isolation → cannot be “engineered away”
- Sets the site-dependent boundary condition below ~10 Hz
- Mitigation is not isolation: it is model + sensors + subtraction

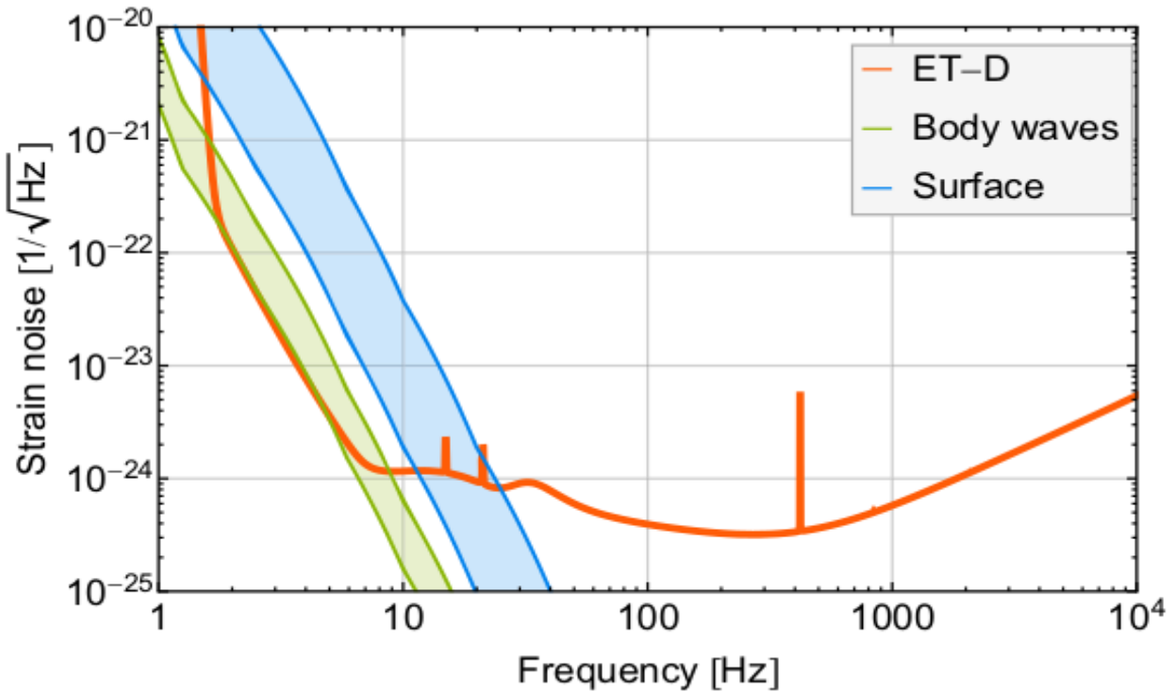
What we must deliver (2026 → TDR)

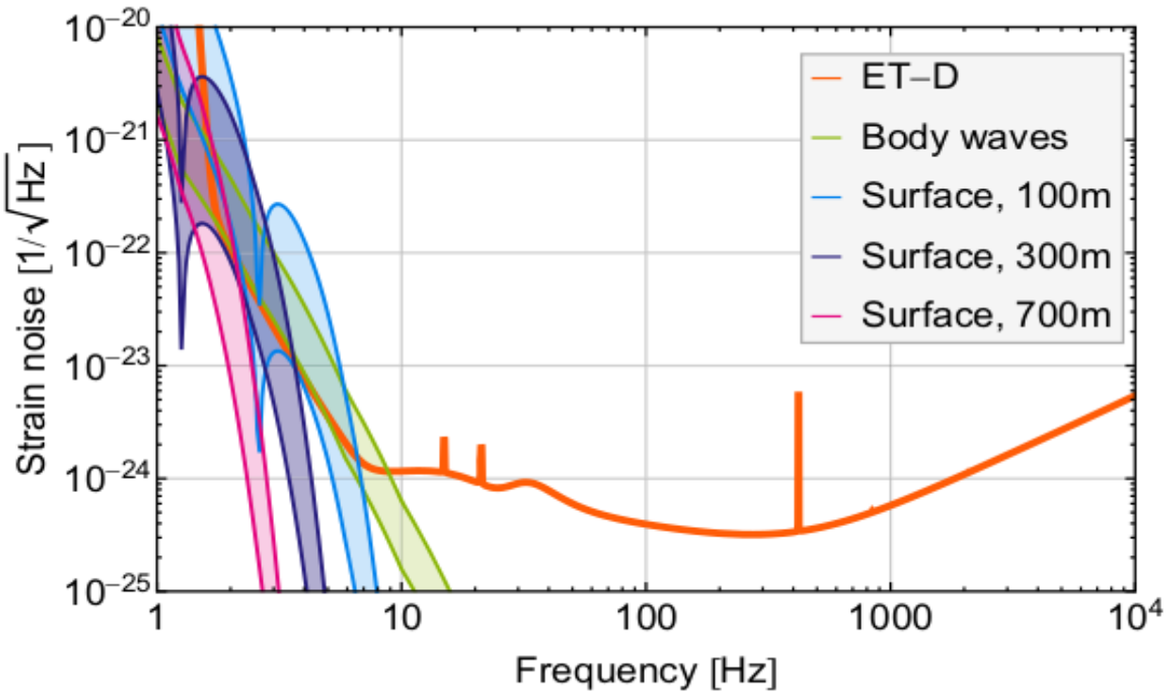
- Site-specific NN models (surface vs body waves, scattering, cavities)
- Sensor concepts & requirements (self-noise, dynamic range, deployment)
- Credible subtraction forecasts + coherence-limited residuals
- Interfaces: SCB (site characterization & noise evaluation) ↔ ANM (subtraction & system requirements)

Open challenge

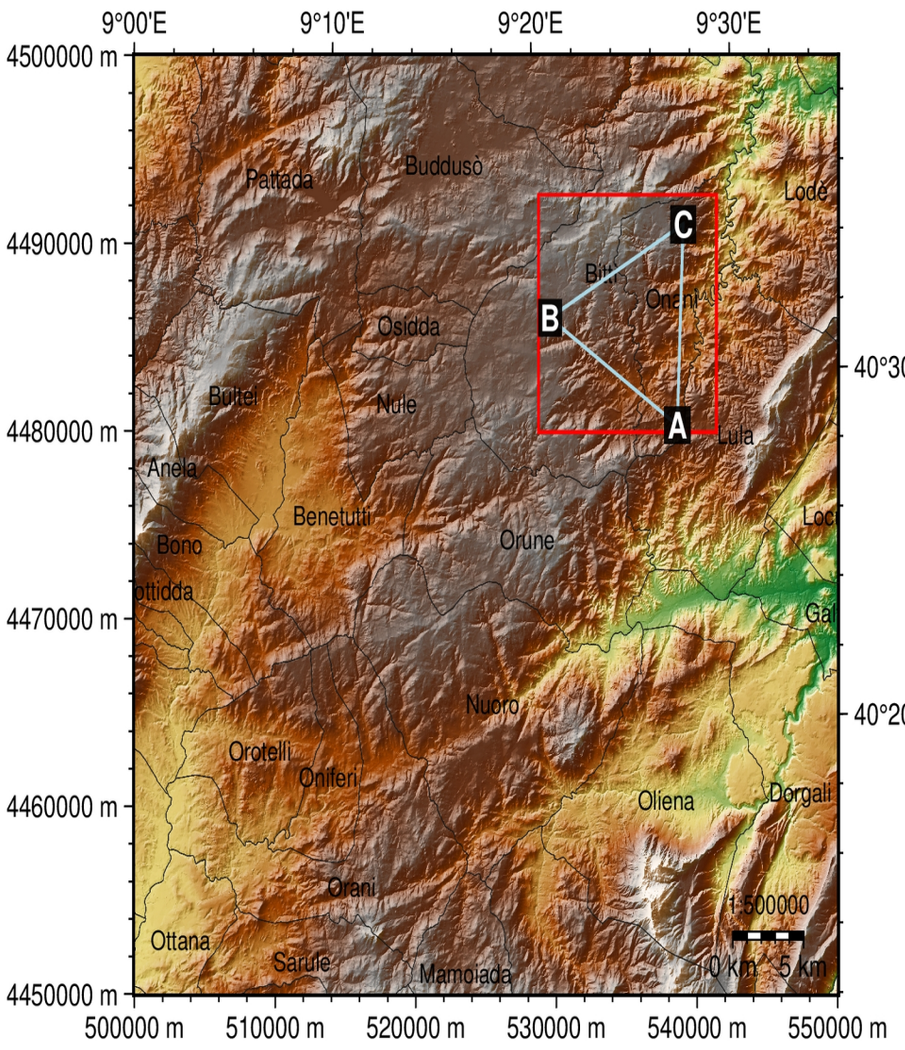
- Subtraction is capped by spatial coherence & non-stationarity → array design + adaptive methods are central

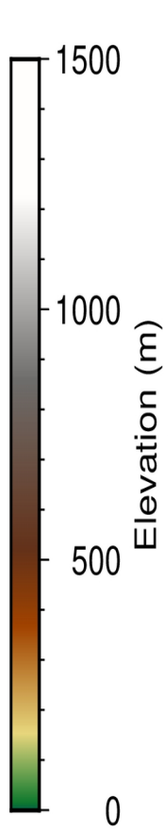
- Surface and underground locations of ET

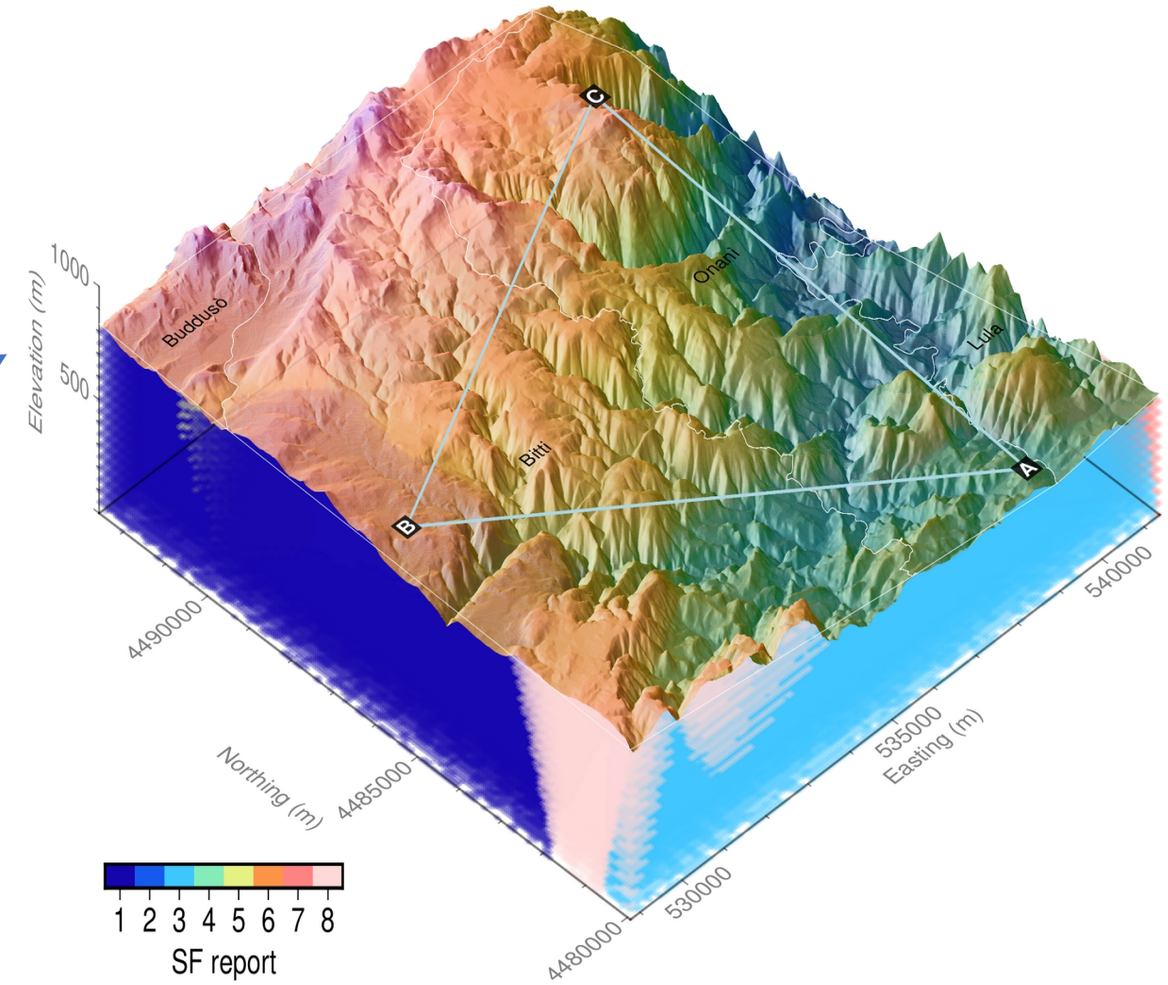




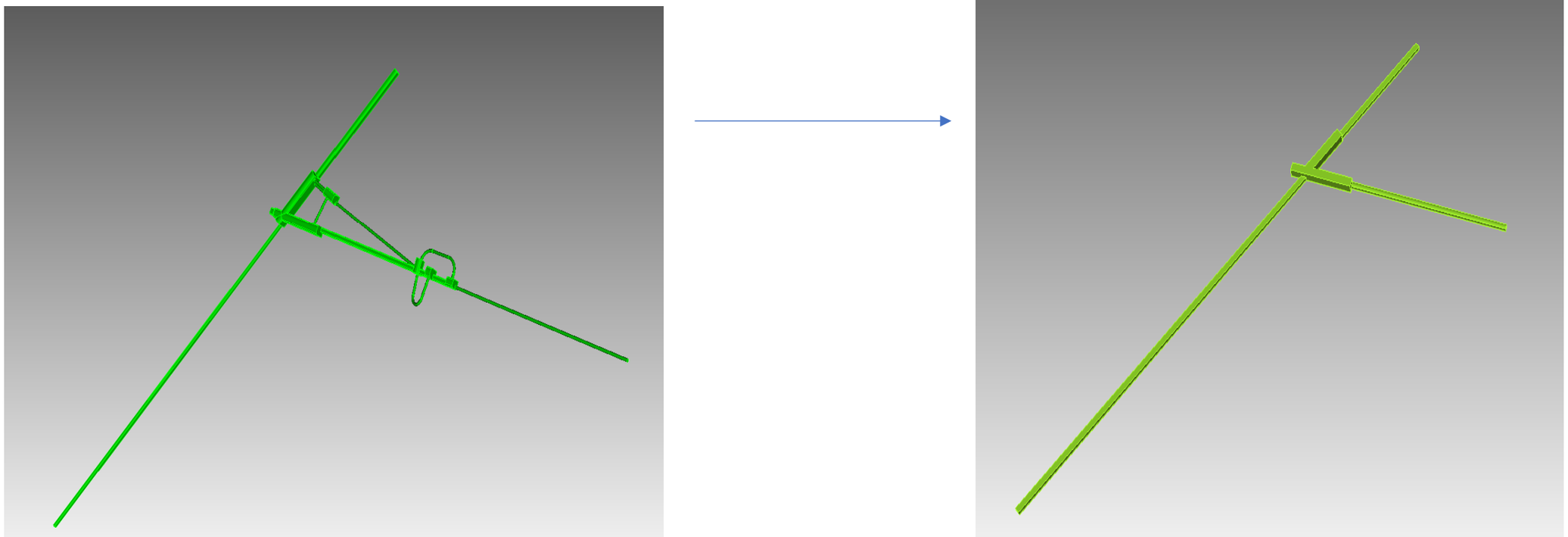
Sardinia Candidate site for the Einstein Telescope: Topography and Layout



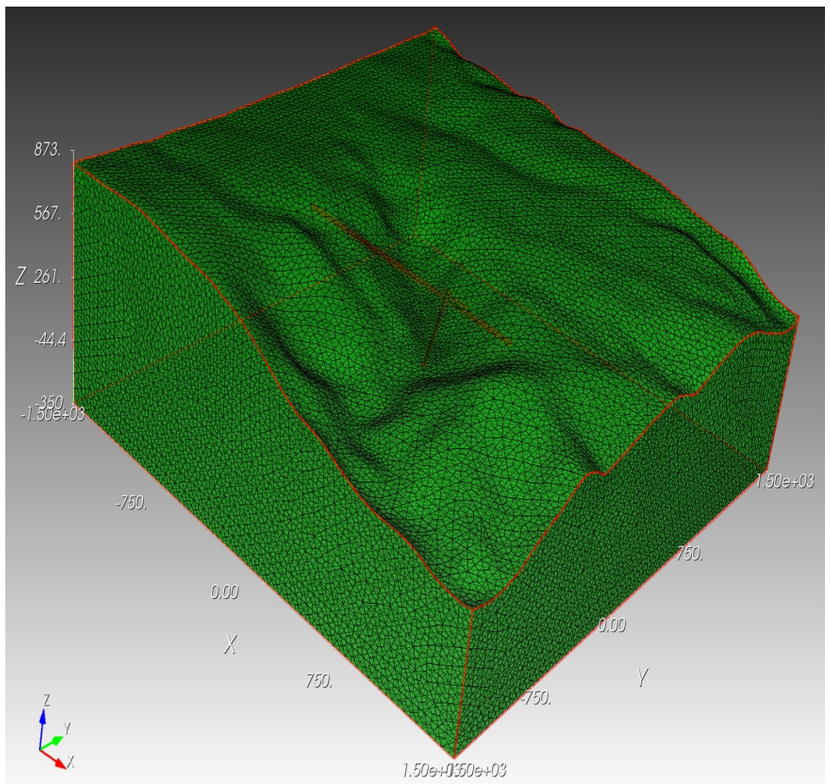




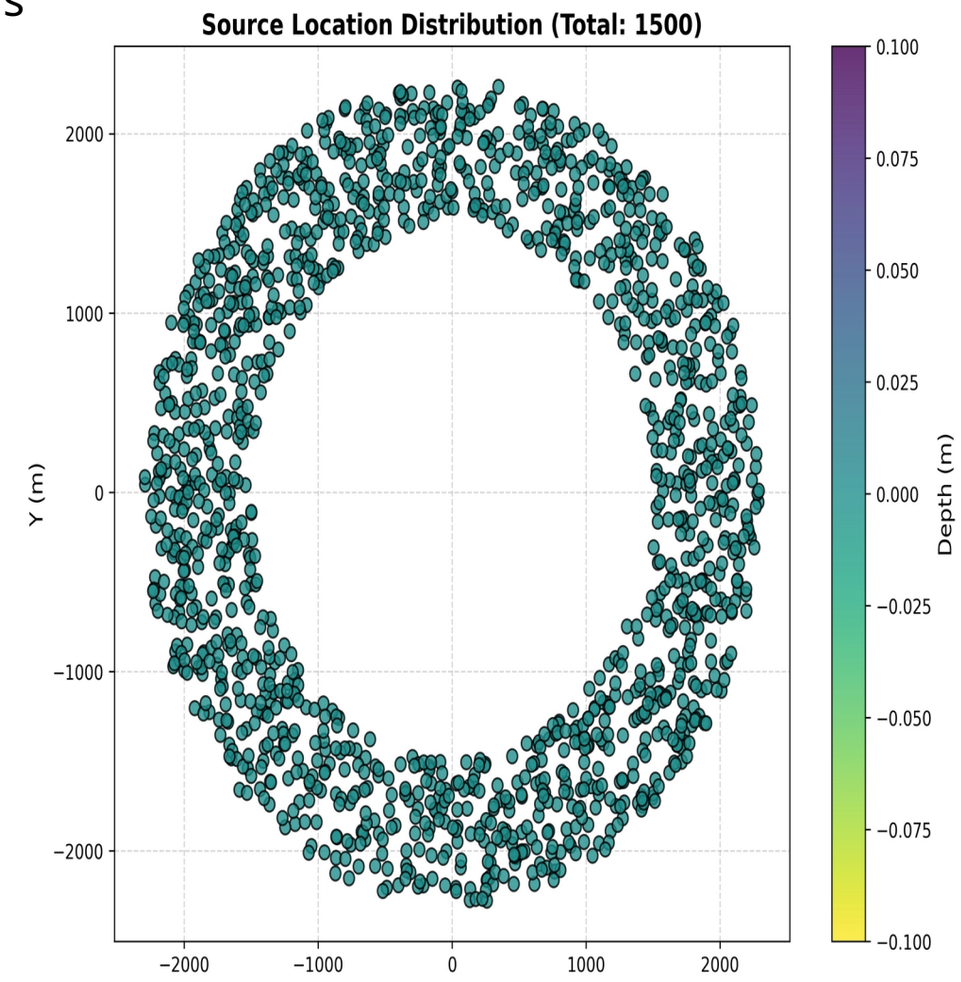
Process 1: Simplify the cavern

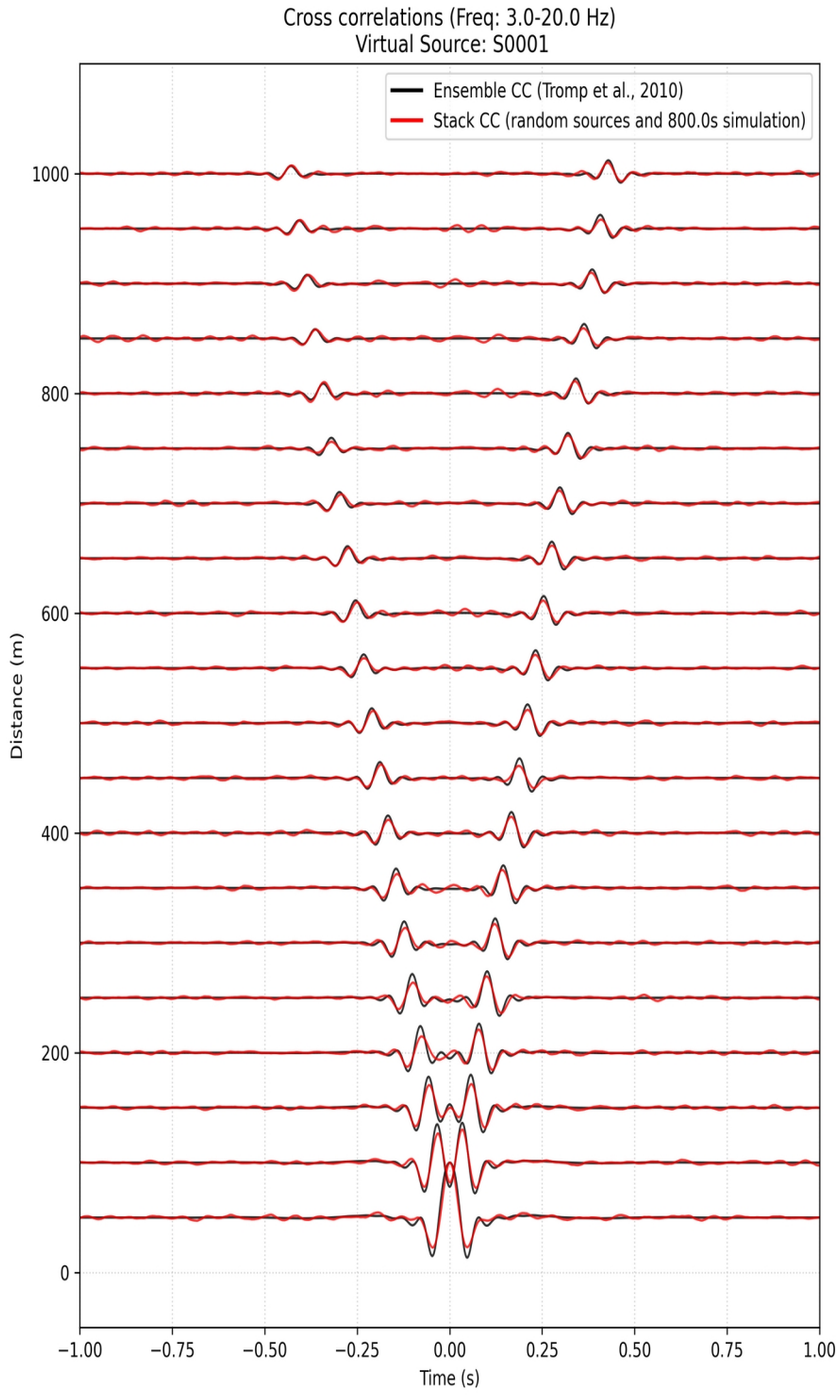


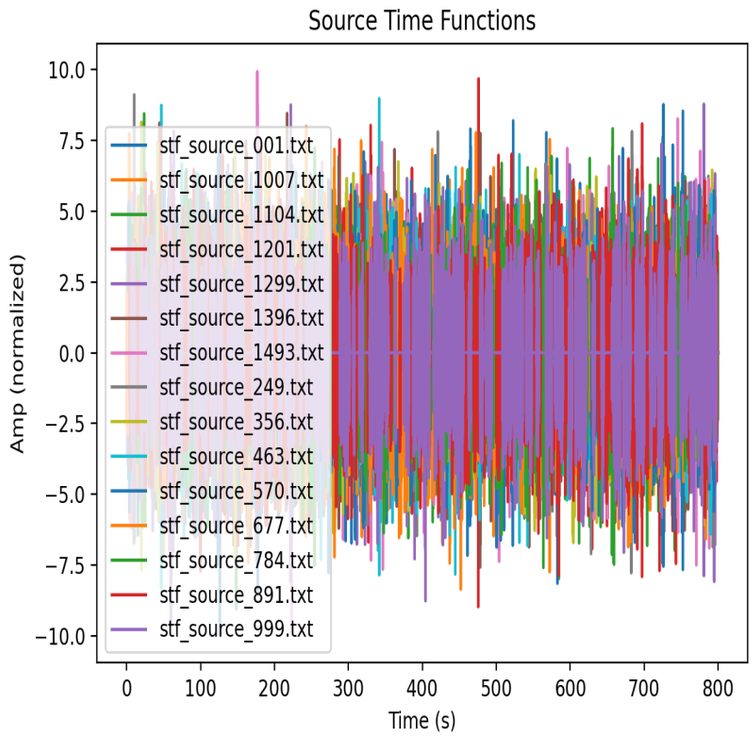
Process 2: meshing

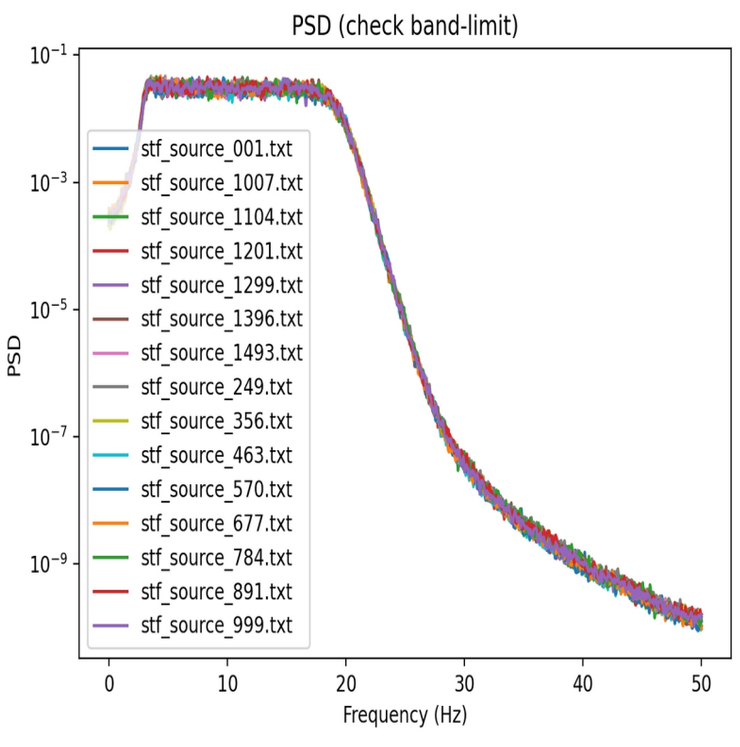


long-duration random noise simulations

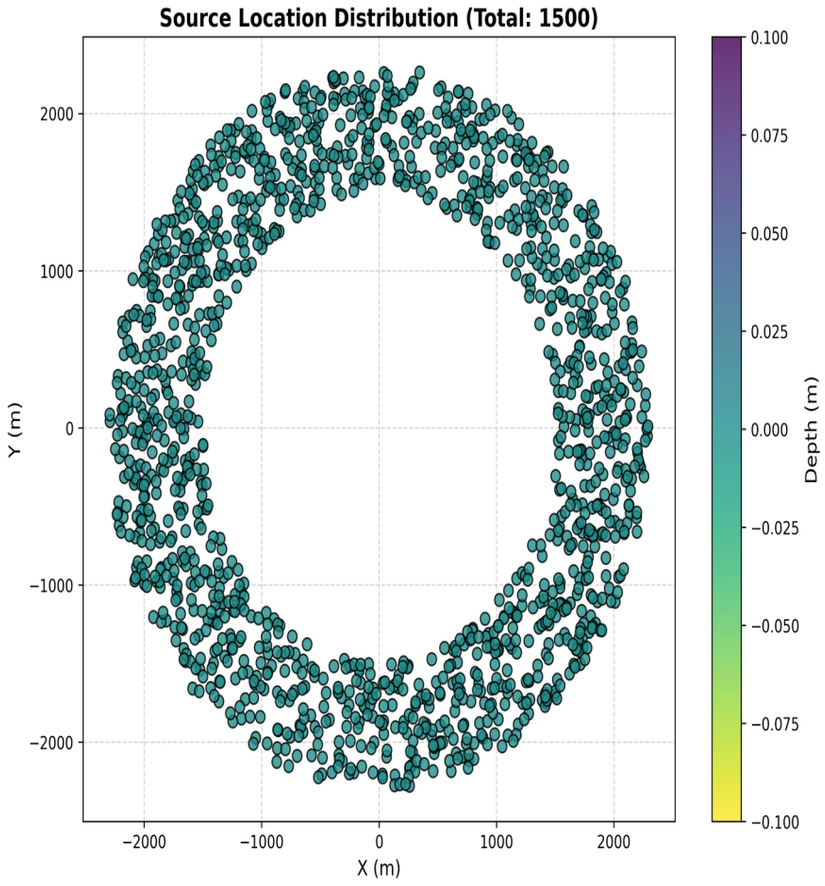


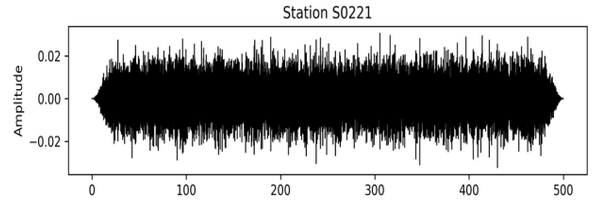


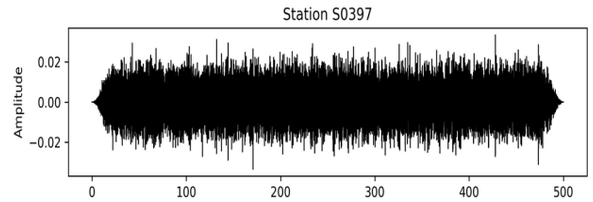


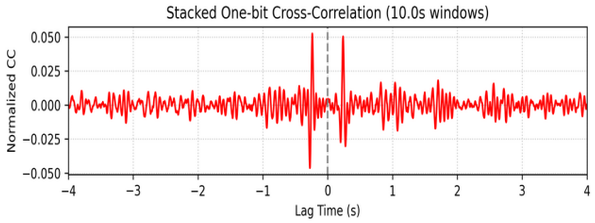


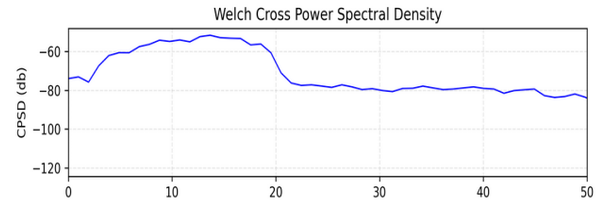
long-duration random noise simulations: cc results and cpsd

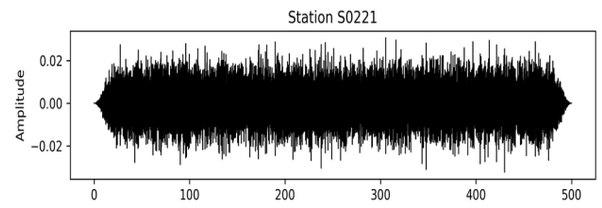


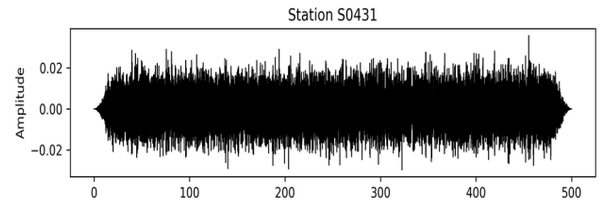


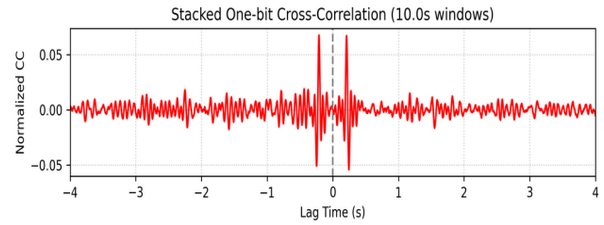


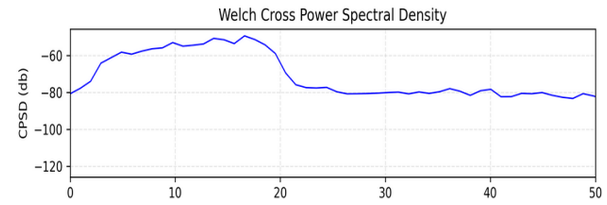


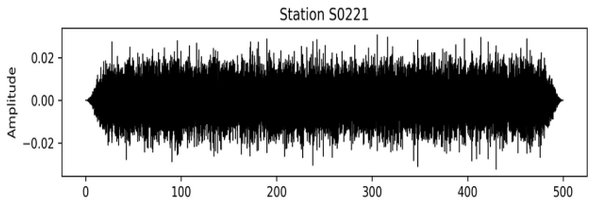


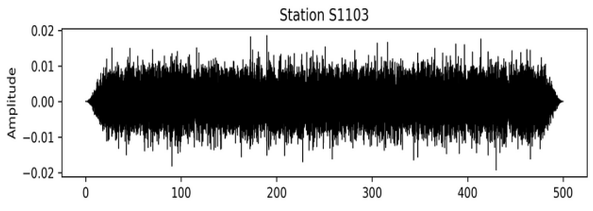


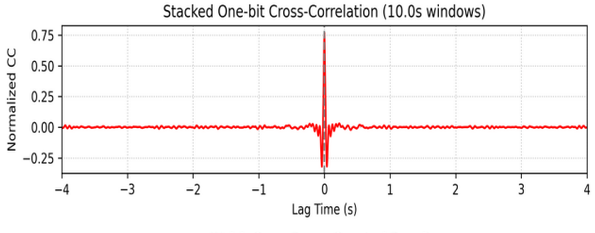


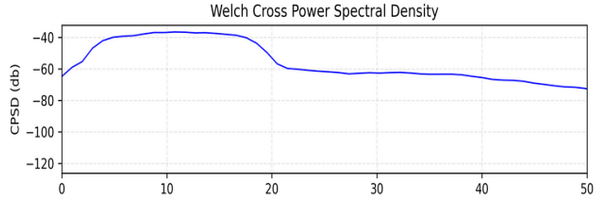


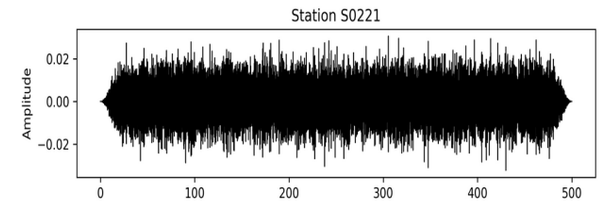


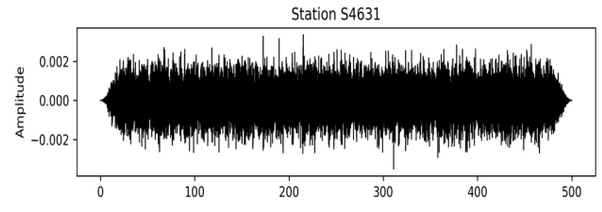


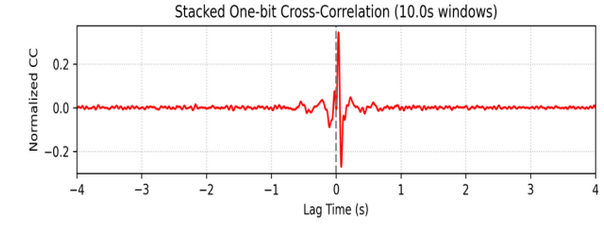


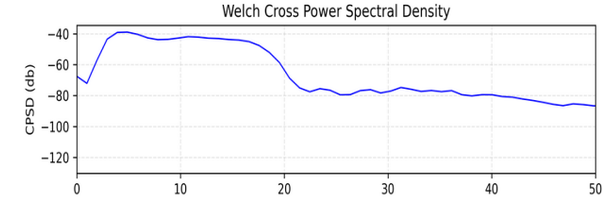




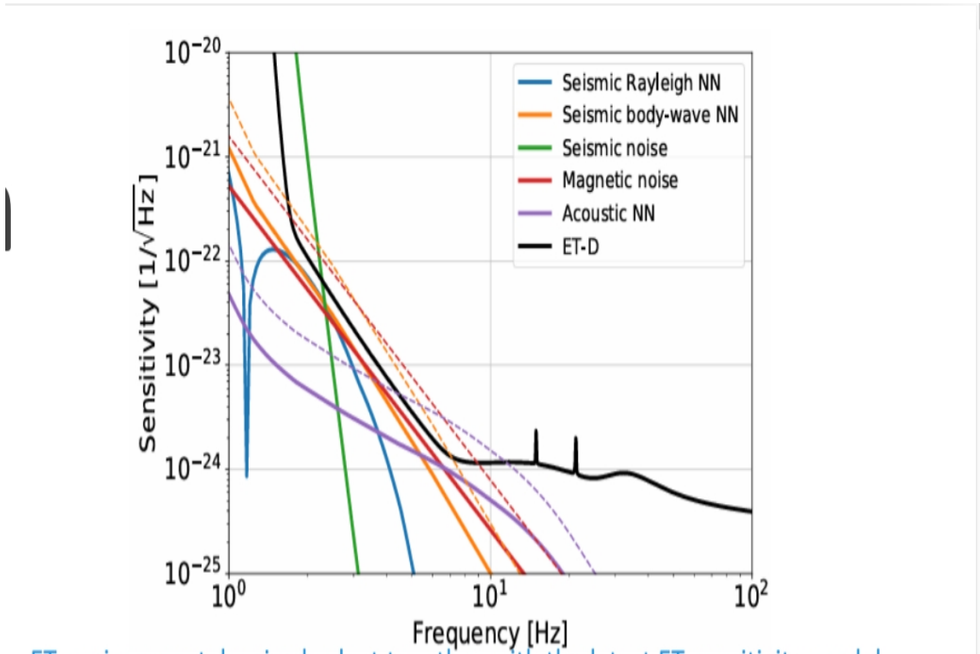




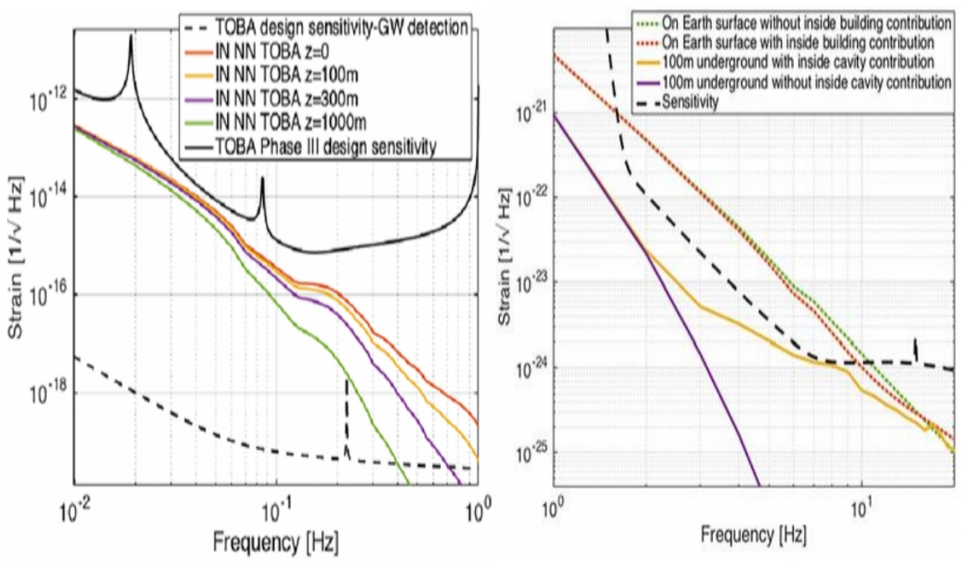




Atmospheric Newtonian-noise–relevant pressure fluctuations were measured in Sardinia with shielded infrasound microphones.



ET environmental-noise budget together with the latest ET sensitivity model
Dashed lines indicate noise lev els without the required additional noise mitigation



Infrasound Newtonian noise in low-frequency GW detectors. Left: low-frequency concept (see Sect. 2.3). Right: Einstein Telescope. The sound spectra are taken from Bowman et al. (2005). From Fiorucci et al. (2018); copyright by APS

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