A horizontal cryogenic superconducting inertial sensor

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Abstract

We present an inertial sensor that will exploit our efforts towards cryogenic test masses in gravitational wave (GW) detectors. The superconducting metals or high-T_c materials give access to low-loss actuators, mechanics and readouts. This inertial sensor can be used in the Einstein Telescope (ET) to monitor the effects on cryo-cooling the final stages or can be deployed on the Moon to directly detect GWs. Around 1 Hz, modelled sensitivity is about 3 orders of magnitude better than state-of-the-art if the sensor is cooled below 45 K (e.g. 50% YBCO T_c).

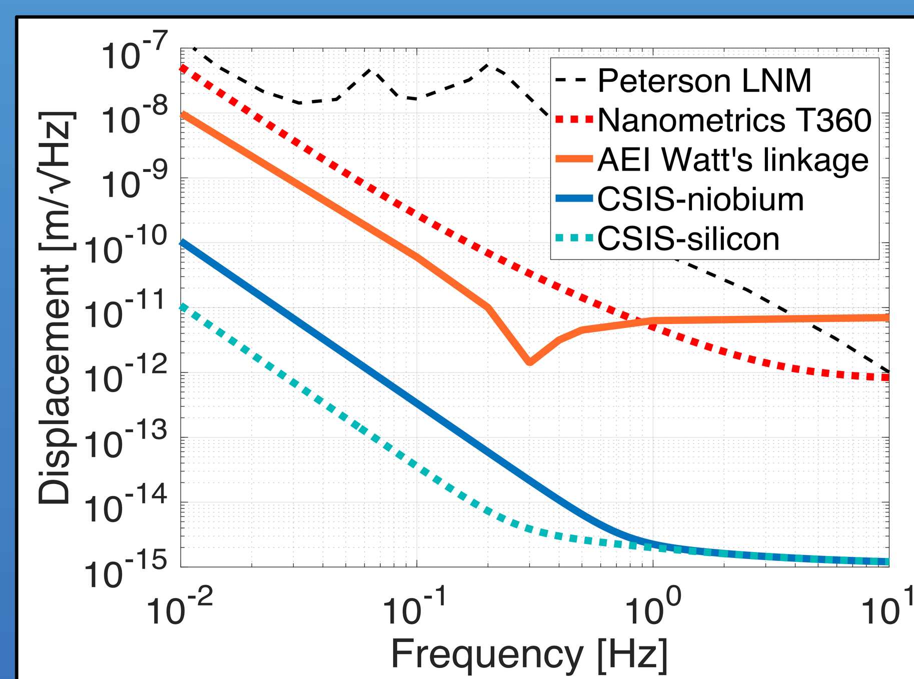


Figure 2: Minimal detectable inertial displacement comparison between two CSIS options (see figure 5 for more detail) at 5 K and the measured state-of-the-art used in gravitational wave detectors today. The lowest geo-seismicity are summarized by the Peterson low noise model (LNM) [3].

Main features of the sensor

A cryogenic superconducting inertial sensor (CSIS) [1] is shown in fig. 1. Expected sensitivity curves for different mechanics material operating in cryogenic conditions are shown in fig. 2. The design features:

- pm /√Hz readout to take out proof mass mode;
- superconducting thin film spiral coils for low voltage and low heat load/power consumption;
- low power consuming custom CMOS cryo-chip for readout, coil driving controls;
- fm /√Hz interferometric readout;
- polarizing optics directing all light to photodiodes for low heat load;
- tuning mass to set Watt's linkage f_0.

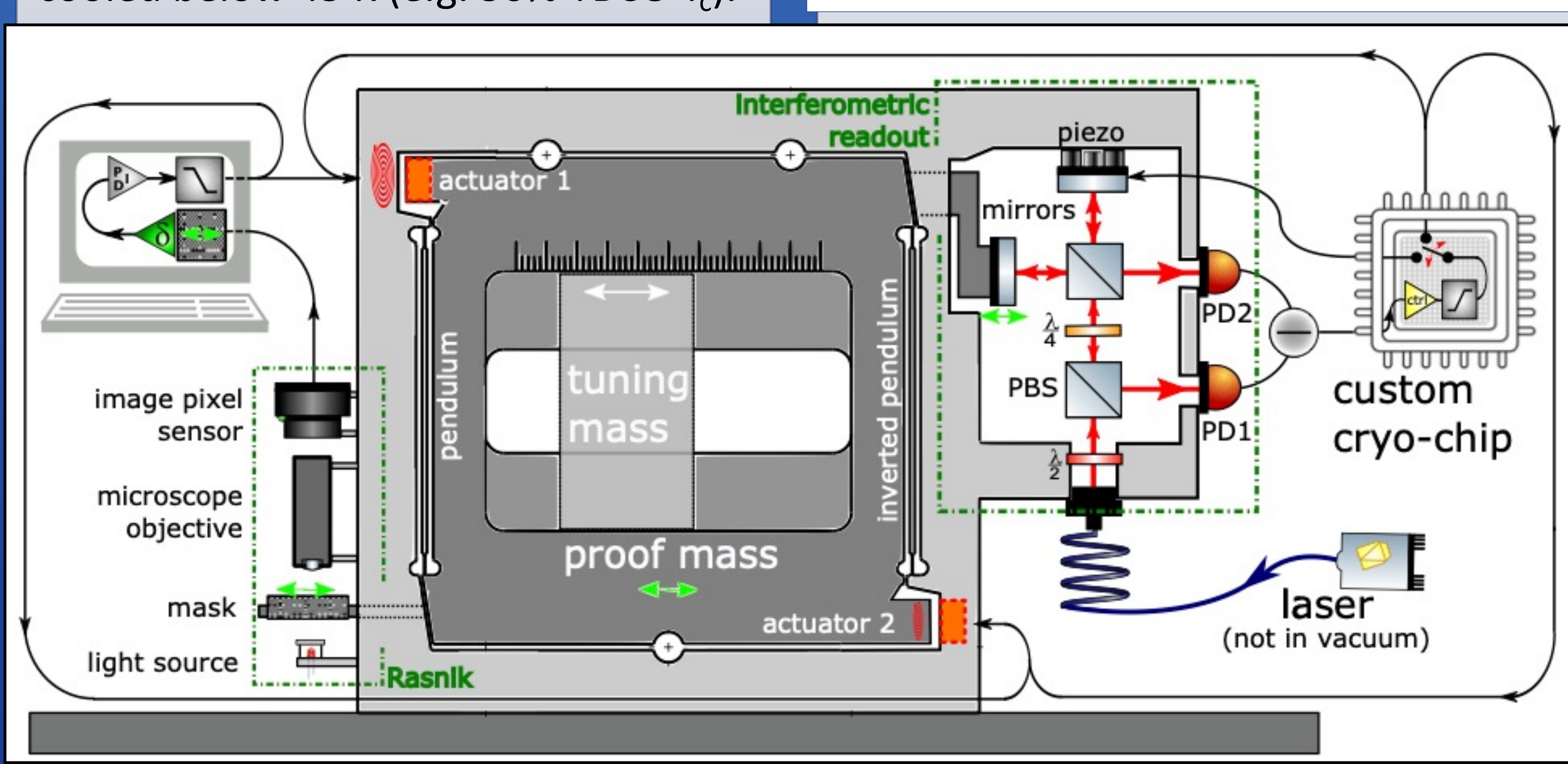
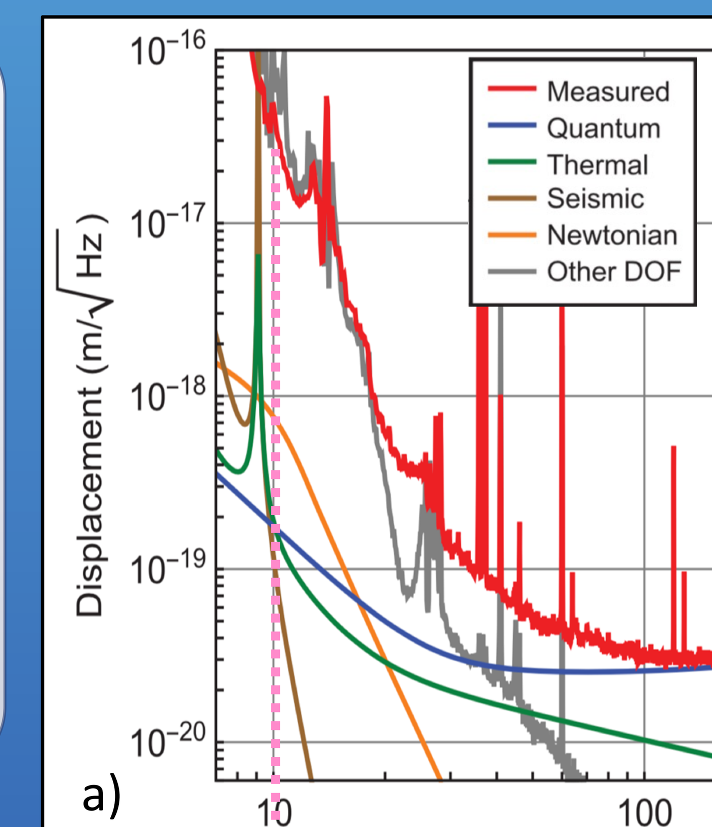


Figure 1: CSIS features a Watt's linkage with 2 superconducting actuators, large range (as large as the mask) Rasnik [2] readout and high-frequency precision interferometric readout. Green arrows indicate how connected parts move. The piezo can be used for calibration or readout.

...in Einstein Telescope

A comparison of the low frequency ET (ET-LF) and LIGO is shown is fig. 3. CSIS, with in fm/√Hz sensitivity below 1 Hz, can monitor the cold platform from which the mirror is suspended and project down. Depending on the ultimate suspension design it may contribute to the control. The cold platform may be at 5 K, which opens up the superconductive regime for niobium. If the mirror temperatures are higher, then high-T_c materials are used and coils in actuators surfaces.



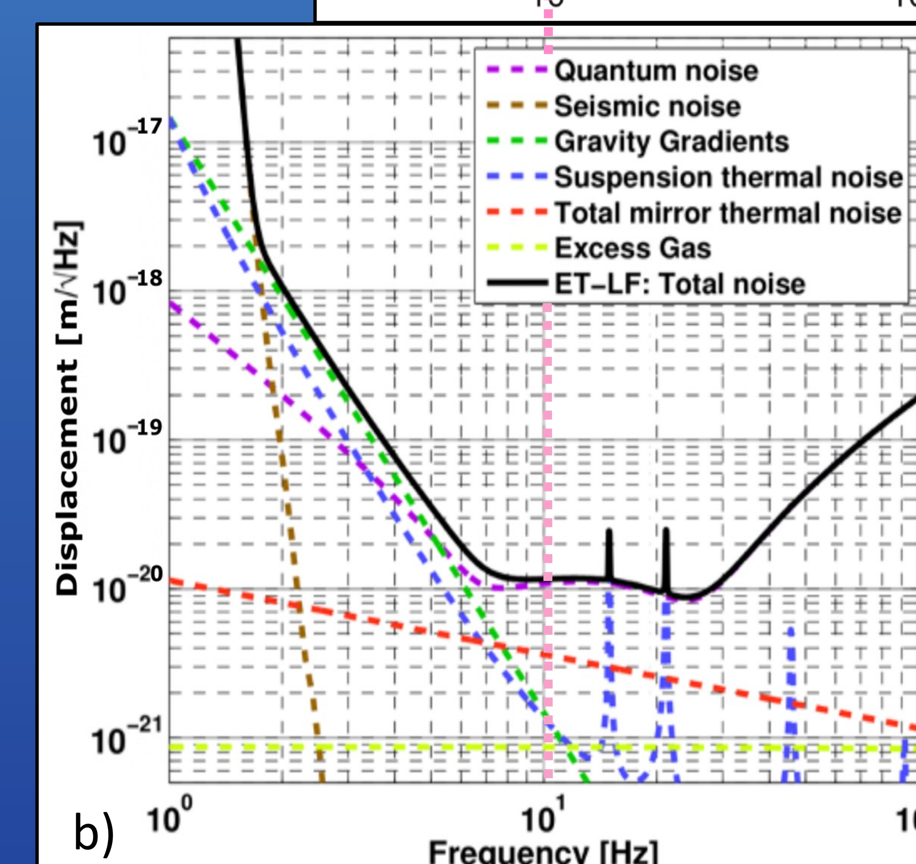


Figure 3: Mirror displacement sensitivity for a) Advanced LIGO during the first detections, adapted from [4]. Panel b) shows the ET-LF cryogenic low-frequency design, adapted from [5]. A pink dotted line shows alignment with panel a). Note a factor 10^4 improvement is needed between currently obtained and future modelled displacement sensitivity.

...on the Moon

Using the Moon as a bar detector, the Lunar Gravitational-wave Antenna [6] (LGWA) will bridge the 0.12-2 Hz gap between the Laser Interferometric Space Antenna (LISA) and ET. CSIS will detect lunar surface motion caused by the passing GW. In the case of a niobium CSIS, low-vibration cryocoolers (e.g. sorption coolers [7]) are needed. Using high-T_c materials allows use of permanent shadows of lunar South pole craters as natural cryostats. LGWA details on appendix poster. To reach the sensitivities as shown in fig. 4, we need a huddle test on a seismically isolated platform with a low-vibration cryogenics as shown in fig. 5.

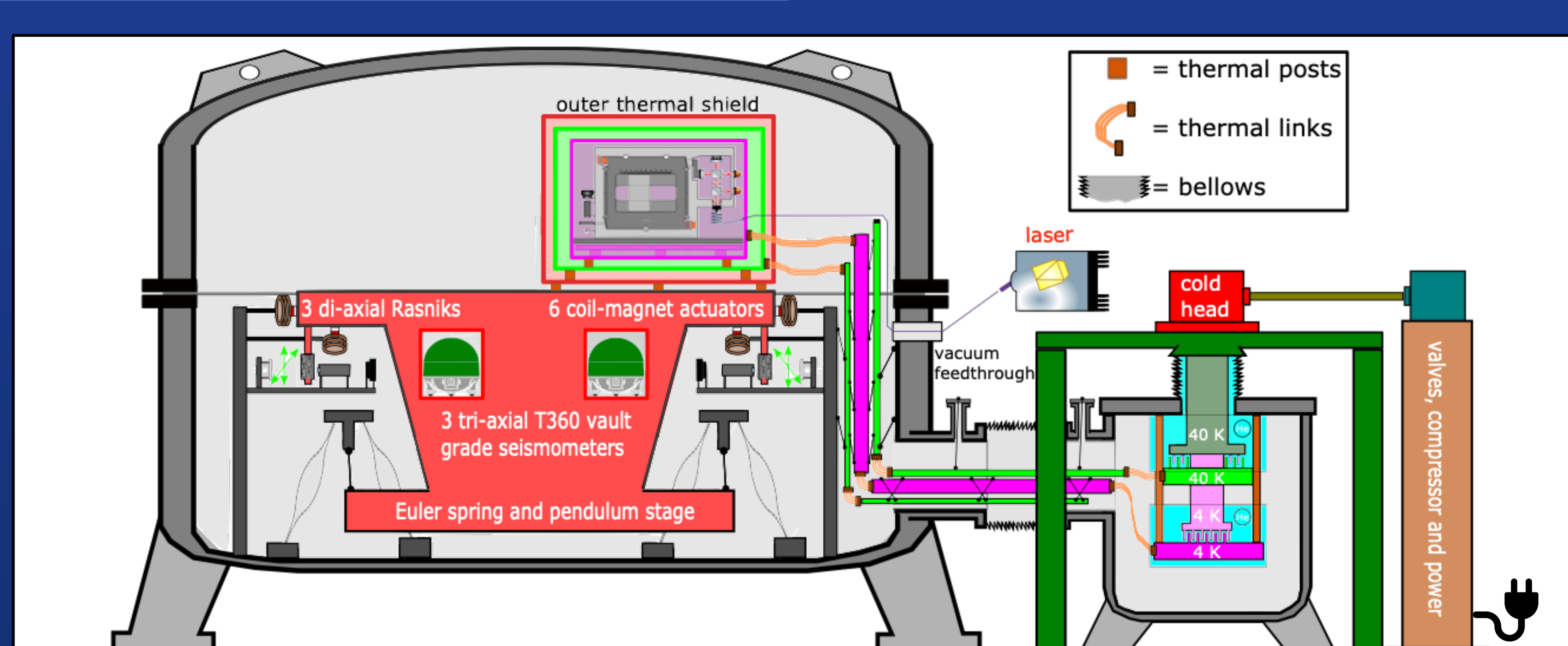


Figure 5: Seismically isolated table using pendulums and Euler springs [8] with a cryogenics for sensor characterisation. Via helium conduction [9] thermal flex links and suspended rods/cylinders [10], the cold heads are decoupled from thermal shields. Tilt subtraction not shown.

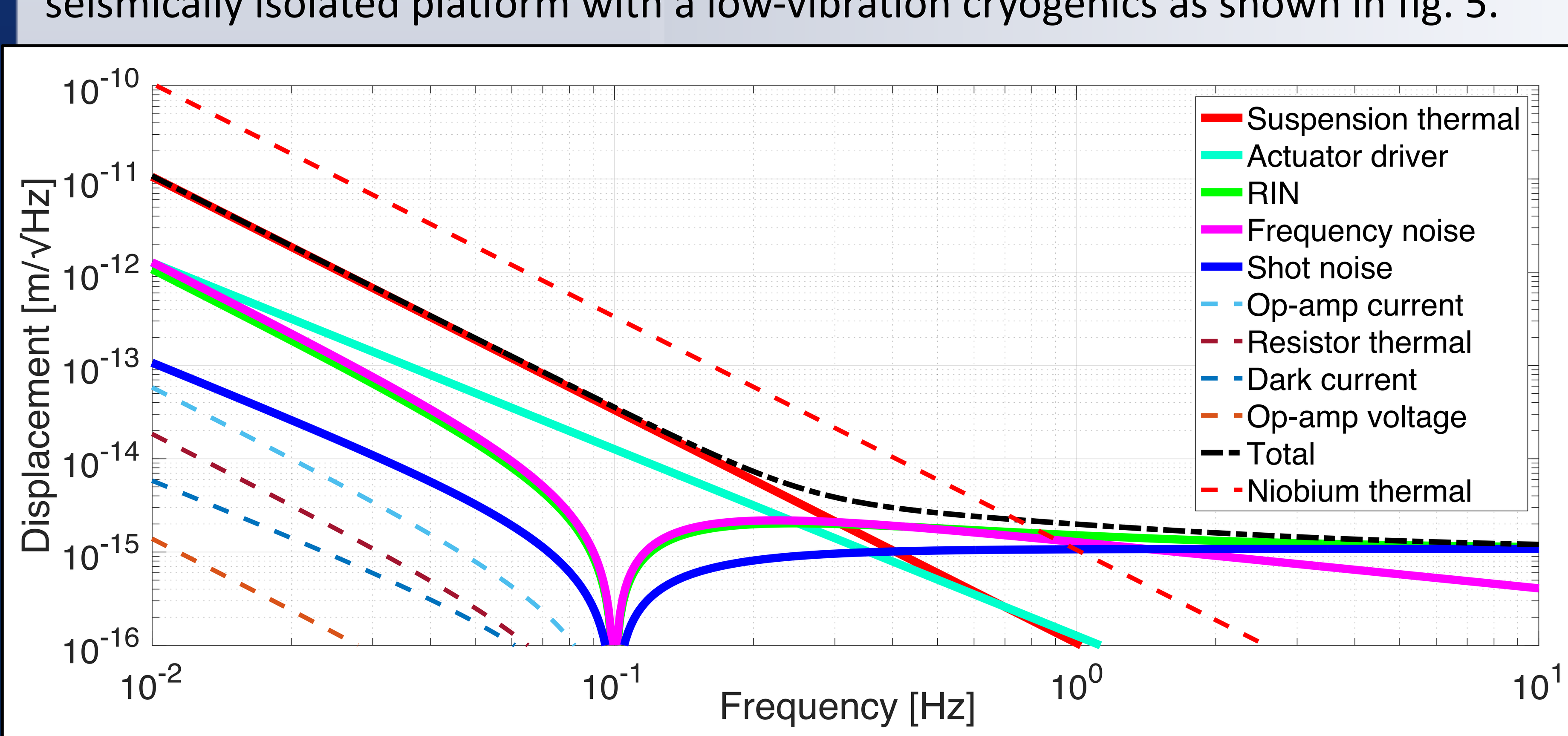


Figure 4: Noise budget CSIS for silicon as mechanics material (Q = 10^6 and T = 5 K); niobium thermal noise (Q = 10^4) is also plotted. A 5 mN/A actuator is modelled as driven by a 10 μV/Hz DAC. We model frequency noise as 500/√f using a conservative static arm length difference of 0.5 mm. The injected power is 25 mW, the proof mass is 1 kg and f_0 is tuned to 0.1 Hz.

Future improvements

High-Q silicon Watt's linkages can't be monolithic because of flexure surface losses when machined. An assembly strategy (see fig. 6) is therefore devised. Other readout strategies than interferometric ones are investigated as well. SQUID readouts using current pick-up coils on both proof mass sides [11] or superconducting reentrant cavities (famous for their use in bar detectors [12]) hold a promise for sub-fm/√Hz sensitivity.

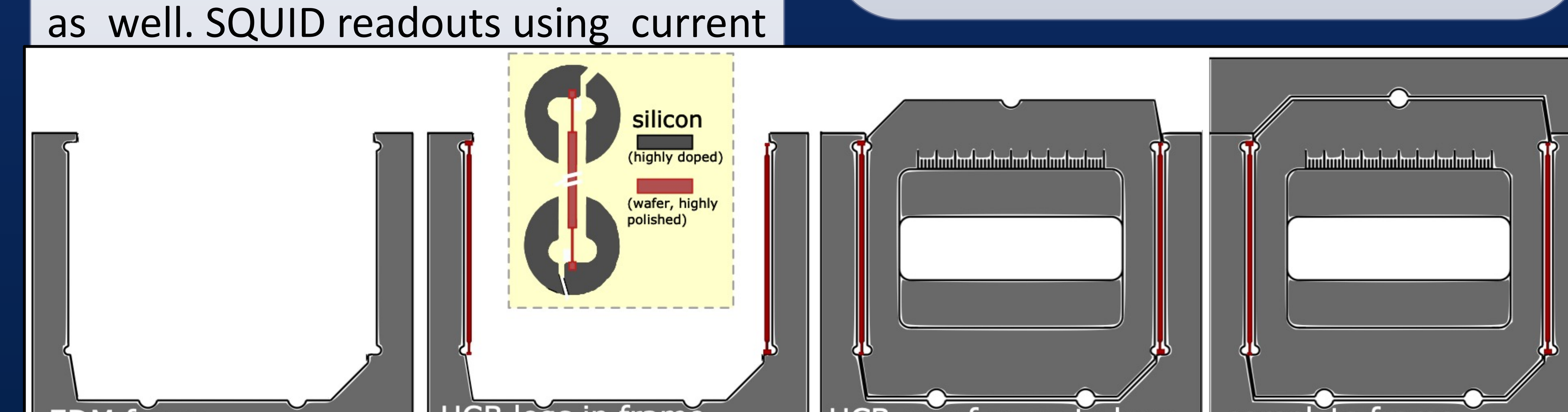


Figure 6: Assembly procedure for a silicon CSIS. A frame (in 2 pieces) and proof mass is cut out of silicon block using EDM. The leg and flexures are etched out of a thick 500 μm high-quality wafer. Parts are hydro catalysis bonded (HCB) to form a low mechanical loss Watt's linkage.

Conclusion

CSIS, when deployed on the Moon and in ET, may enable GW science between 1 mHz and 5 Hz. Within the E-TEST suspension prototype, development is ongoing.

References

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The Lunar Gravitational-wave Antenna (LGWA)

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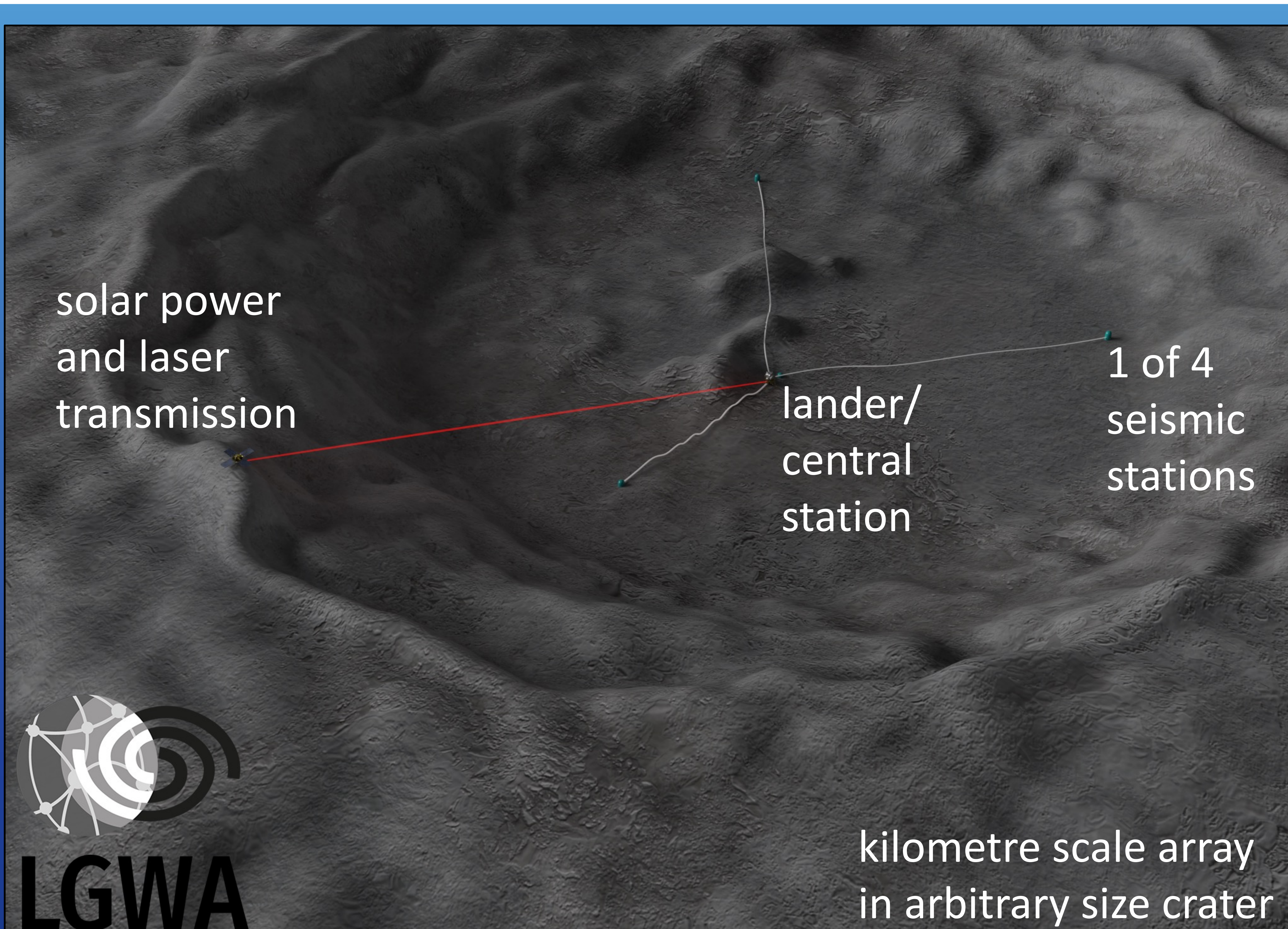

Figure 3: Configuration of the kilometre scale LGWA array. Lander position is indicated for the case when all seismic stations are deployed from a single landing site; separate landings are possible. Solar power is transmitted to array via laser.

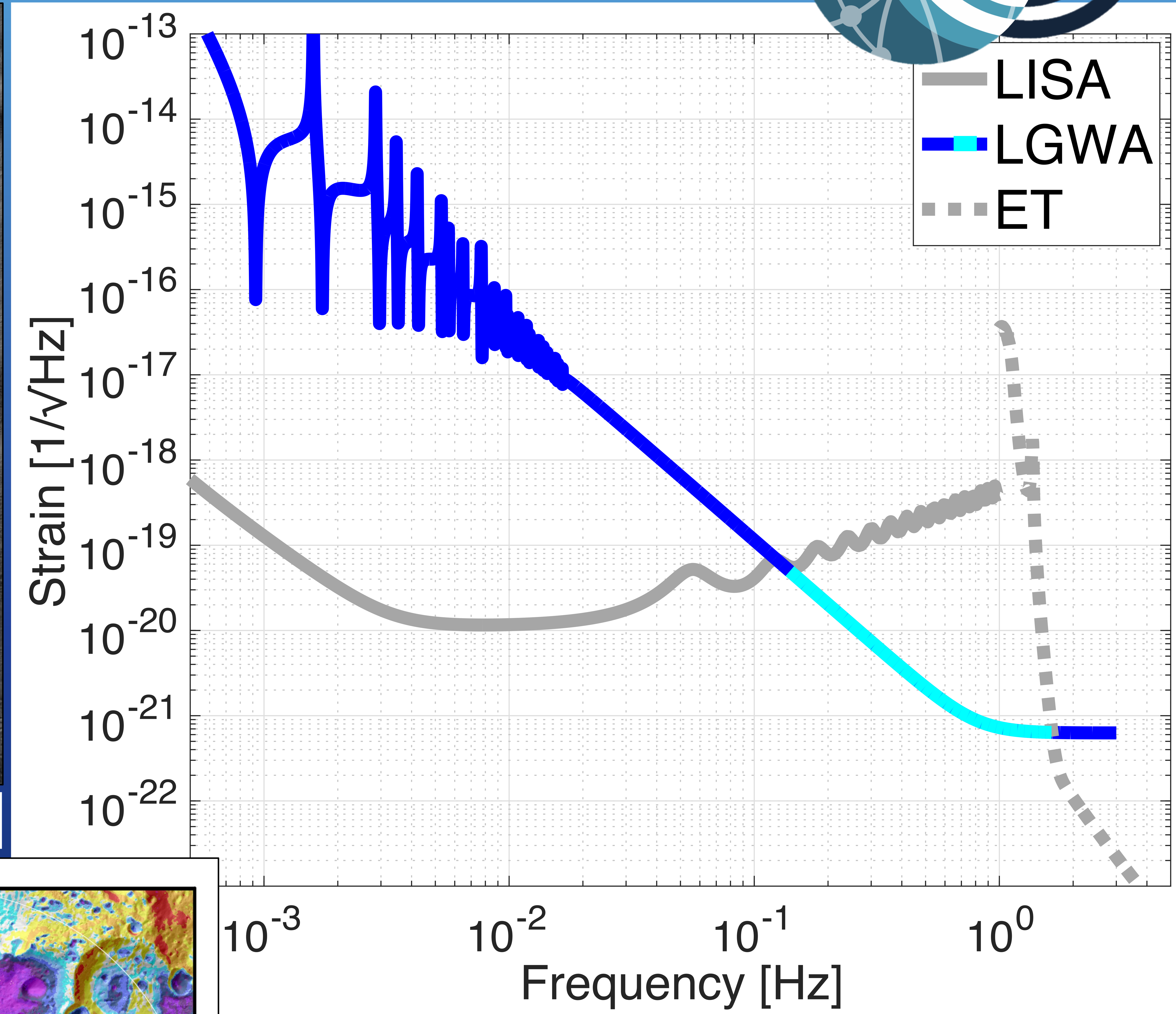

Figure 4: Predicted LGWA strain spectral density compared to the Laser Interferometer Space Antenna (LISA) and Einstein Telescope (ET). Cyan highlights where LGWA bridges the 0.12 – 2 Hz gap between LISA and ET.

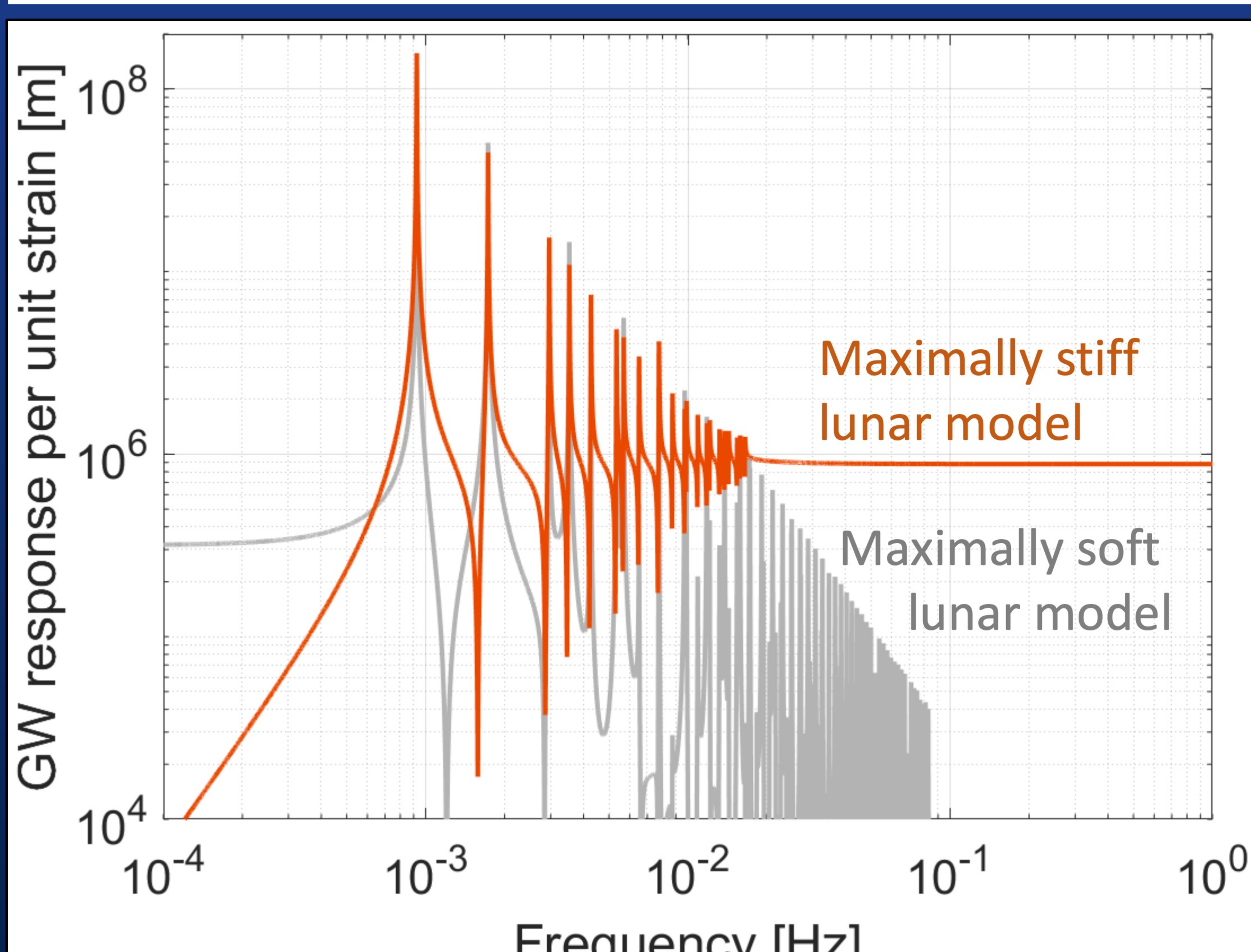

Figure 1: The simplified GW response model shown in red used here. Normal-mode sum truncated at n = 22 and models only include spheroidal quadrupole modes.

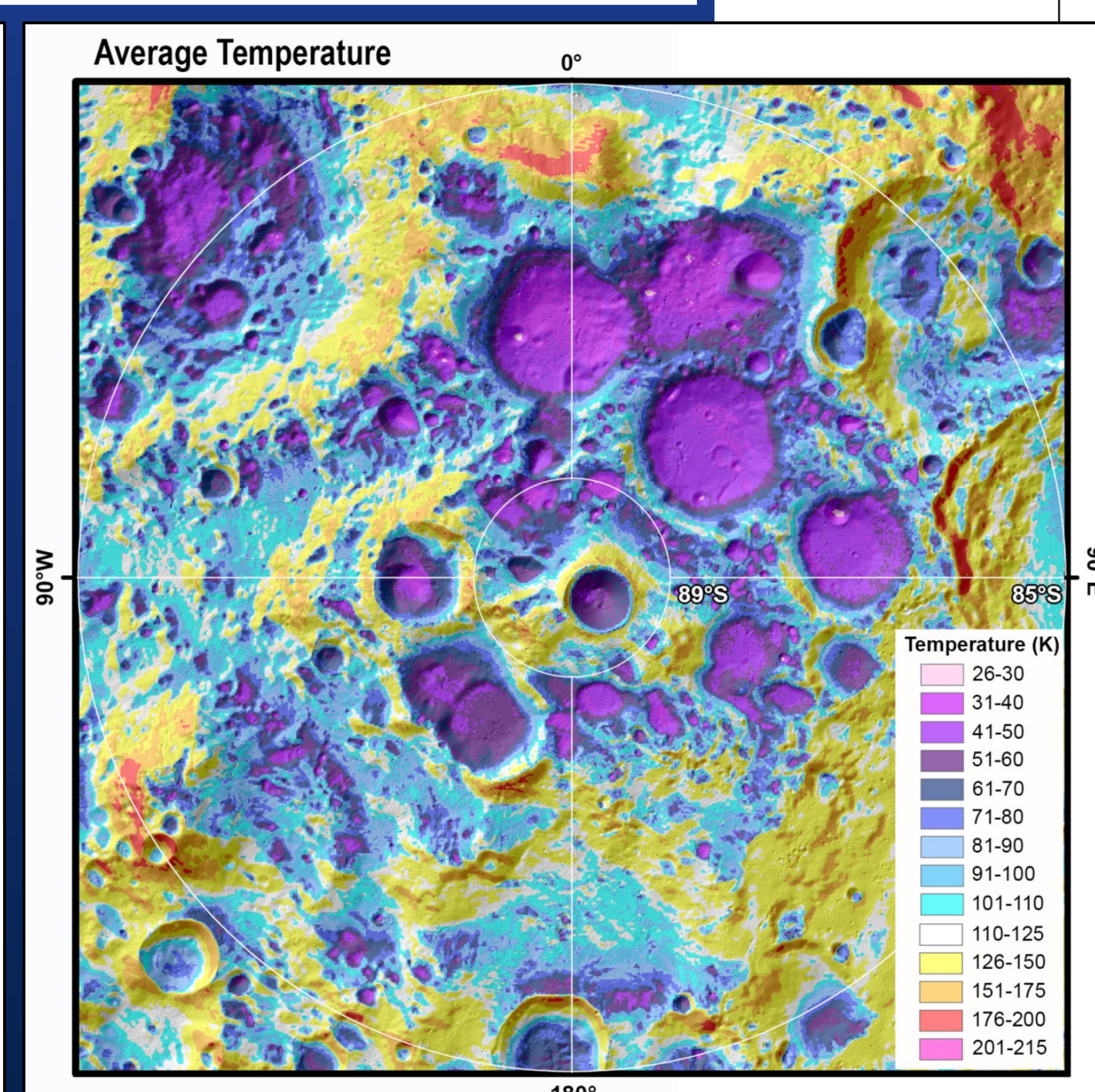

Figure 2: Average surface temperatures at the lunar South pole showing possible deployment in the 40 K permanent shadows.

Detecting gravitational waves on the Moon

Monitoring of vibrational eigenmodes of an elastic body excited by gravitational waves was one of the first concepts proposed for the detection of gravitational waves (GWs). The Earth-bound bar detectors by e.g. J. Weber targeted kHz GW frequencies due to their dimensions. Shown in fig. 1, the lunar eigenmodes are at the mHz frequencies and placing seismometers on the Moon can detect these responses to GWs. Seismometers require stable temperatures, obtained at the lunar poles shown in fig. 2. In such crater, a mission sketch is shown in fig. 3. A central station receives power from the crater rim and distributes it to the seismic stations. These four stations form a kilometre scale array supressing local seismic signals from meteor impacts. Figure 4 shows the LGWA sensitivity – the LGWA seismometer sensitivity divided by the Moon response shown in fig. 2 – compared to LISA and ET. In addition, the extreme sensitivity of the seismometers can study Moon interior (selenphysics) using said meteors as active sources.