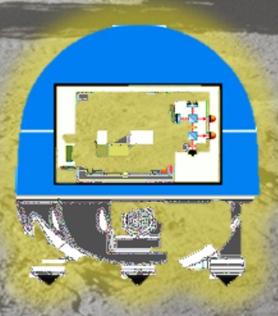
A Watt's linkage for lunar gravitational wave detection



Joris van Heijningen*, Francesca Badaracco, Elvis Ferreira, Alberto Gatti, Filip Taverier, Florian Bocchese, Stéphane Lucas and Andrea Perali

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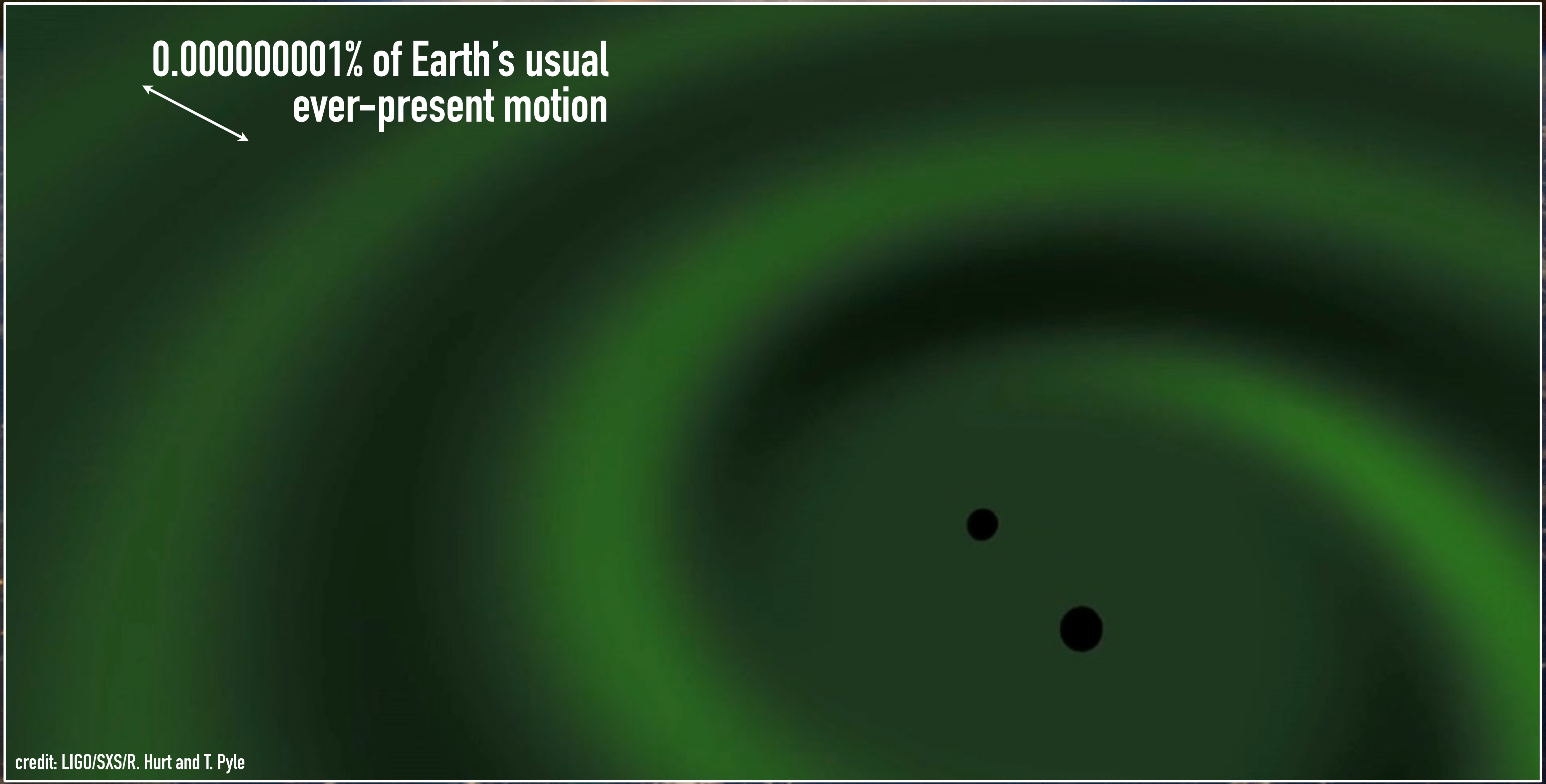
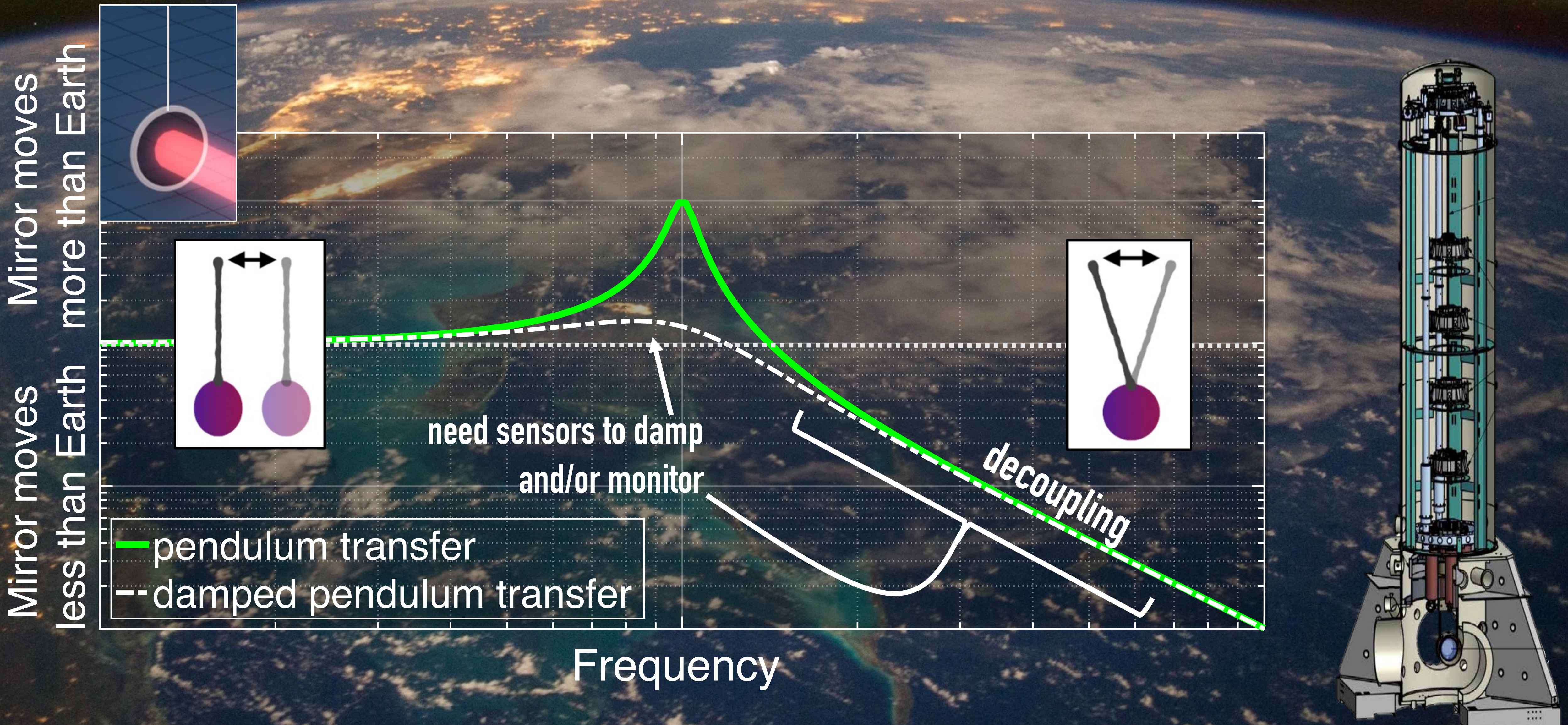
1st Workshop on Gravitational wave detection at the Moon | 15 October 2021

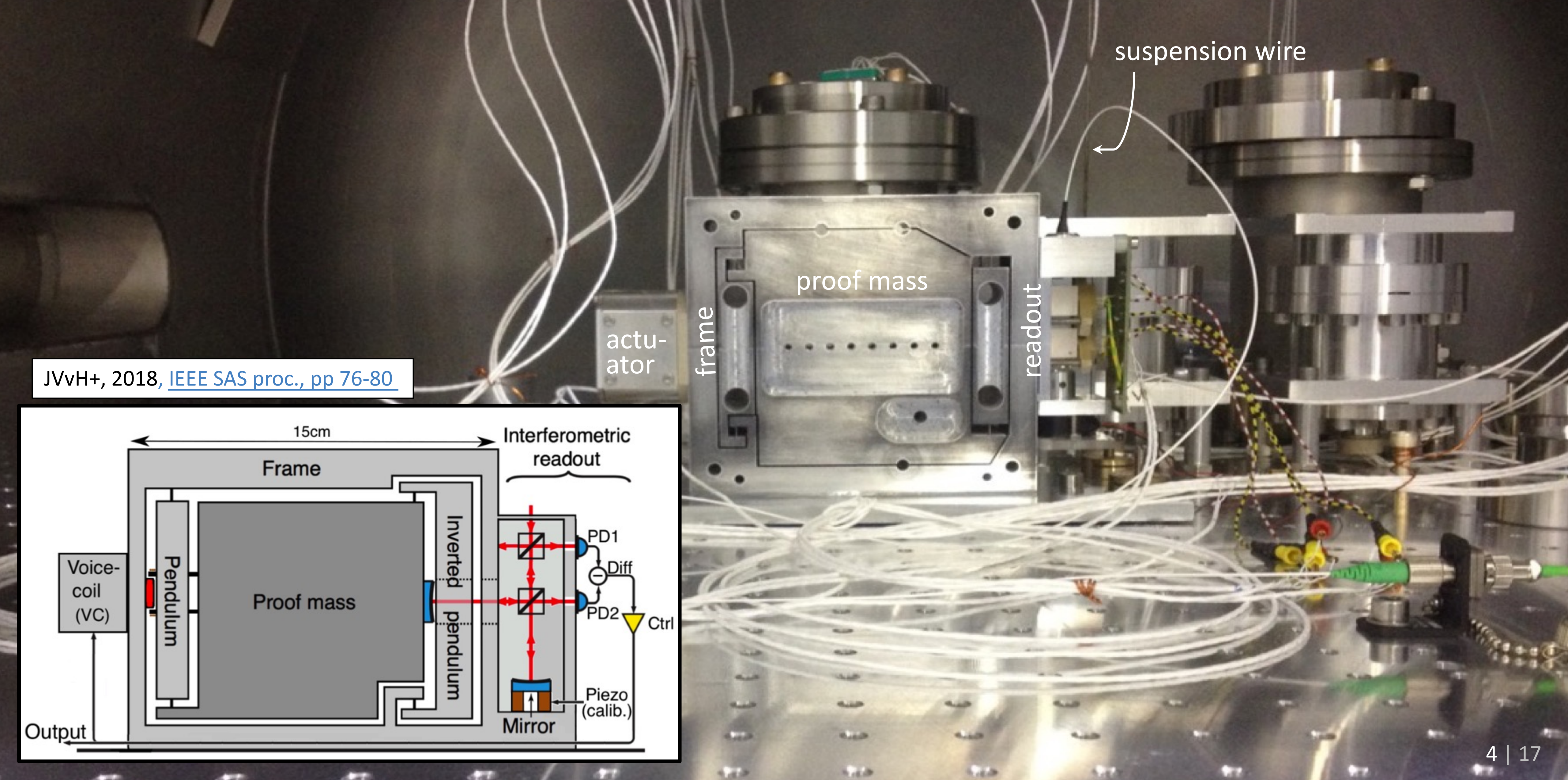
Terrestrial gravitational waves (GW) detection in 30 seconds!



Sensor development came out of desire to decouple

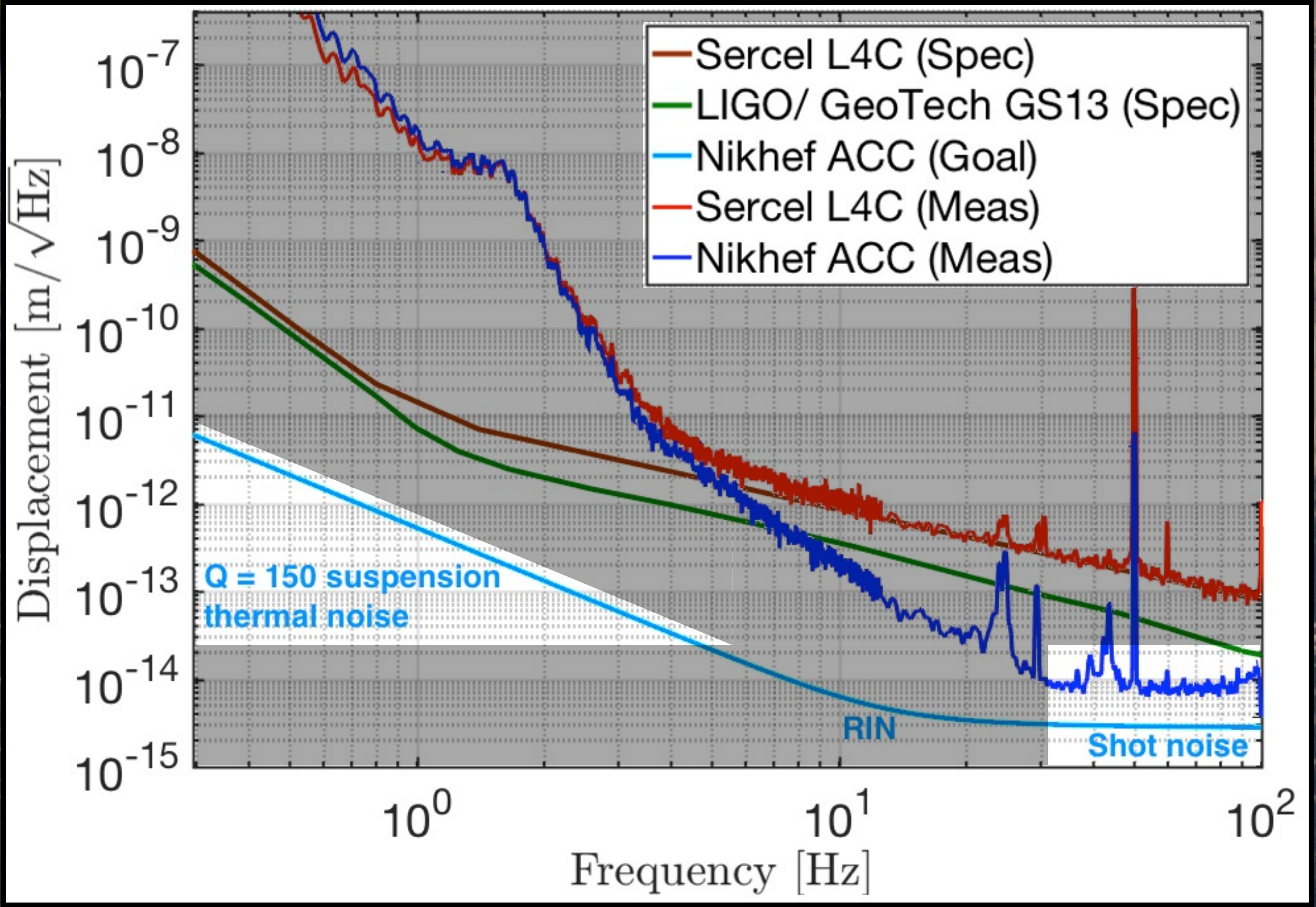


Sensor developed during my PhD at room temperature



JVvH+, 2018, [IEEE SAS proc., pp 76-80](#)

Final result of the room temperature inertial sensor



JVvH+, 2018, [IEEE SAS proc., pp 76-80]

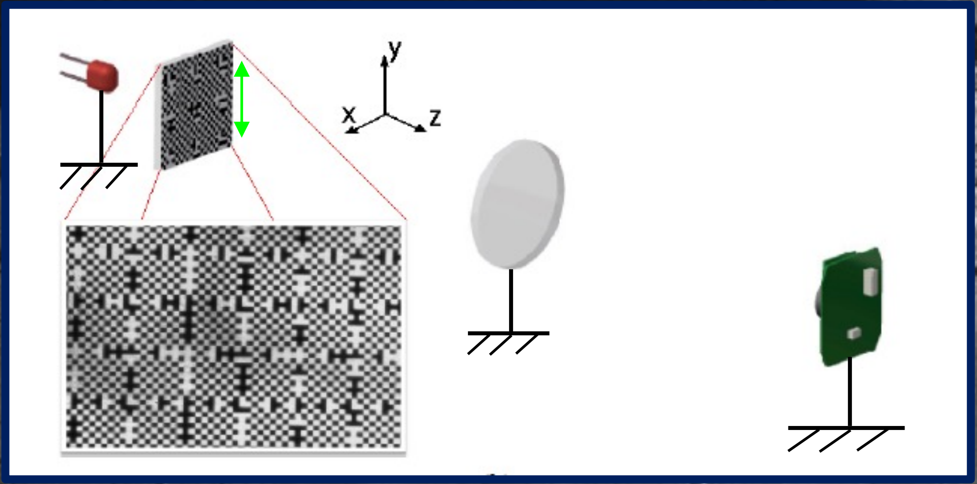
Measurement done on bench MultiSAS prototype at Nikhef.

Thermal noise not reached, but low Q expected due to (coil-magnet) actuator.

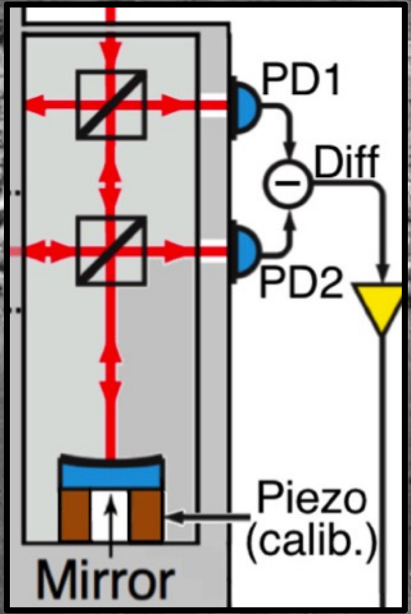
An 8 fm/√Hz sensitivity above 30 Hz, but higher than goal.

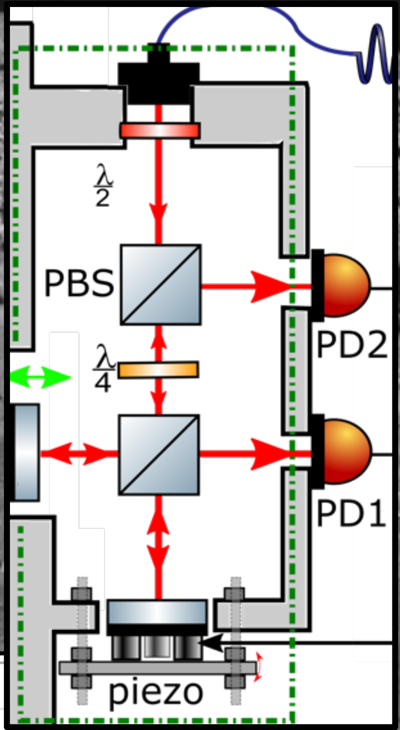
Need low-loss actuators and better proof mass residual motion suppression.

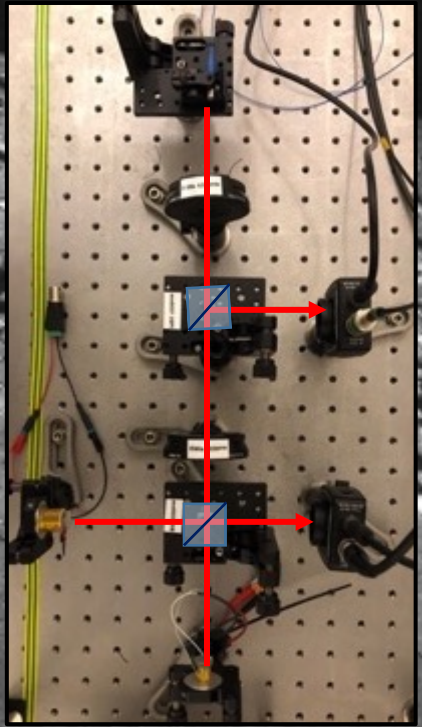
Add to next version: Rasnik long range readout and polarizing optics

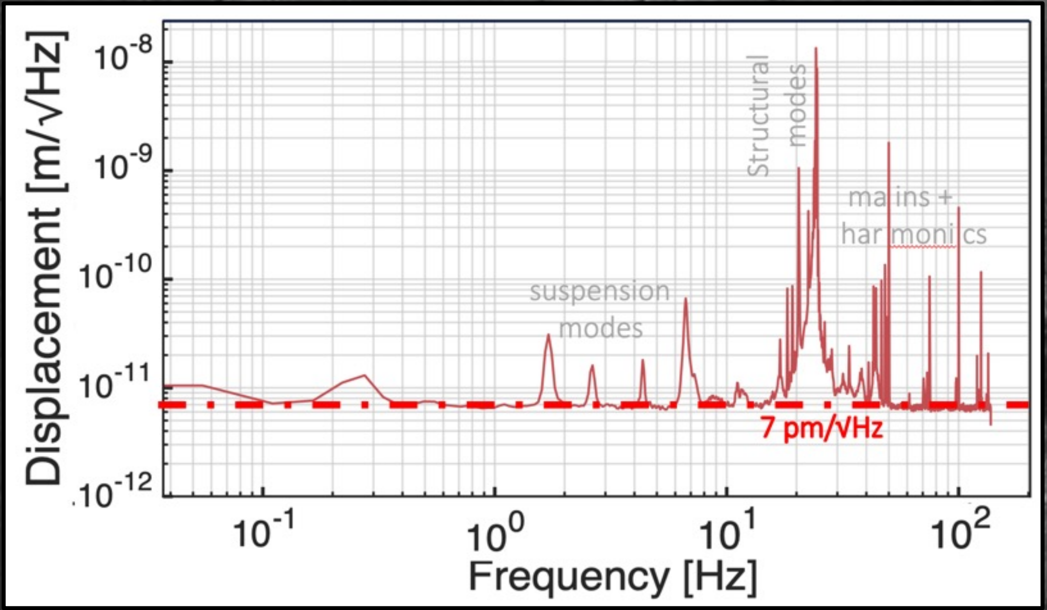


M. Beker+, 2019, [JINST **14** P08010](#)

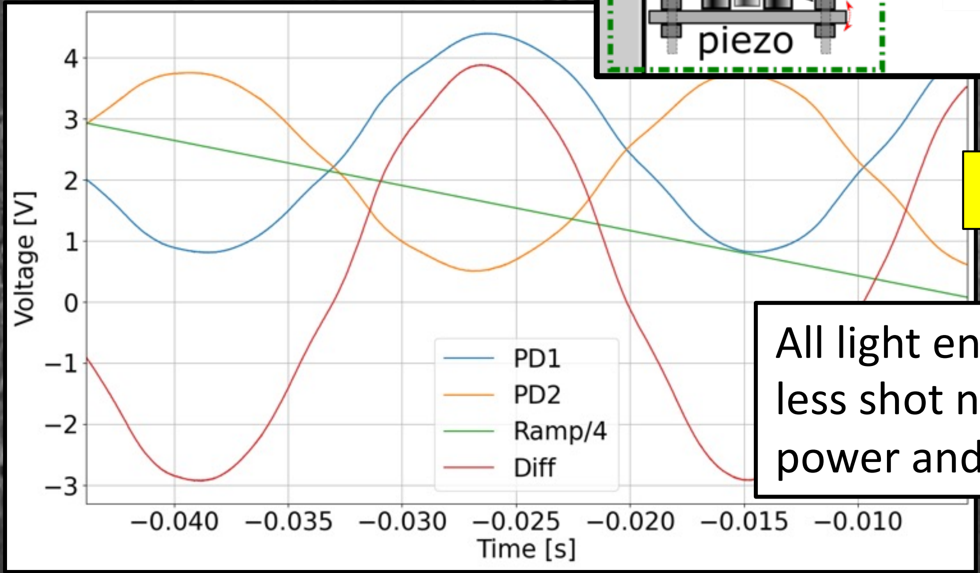








H. van der Graaf+., 2021, [arXiv:2104.03601](#)

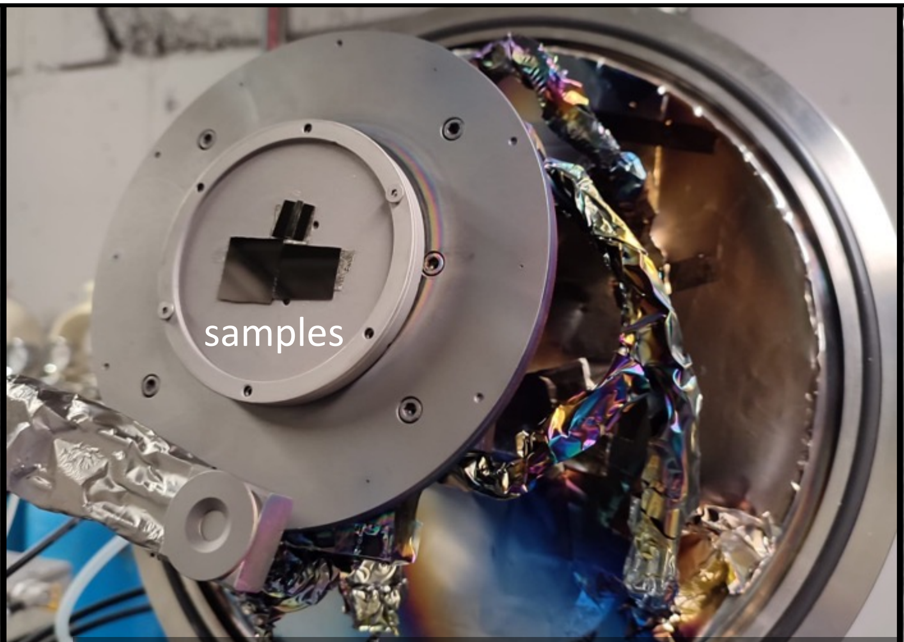


Francesca Badaracco

All light ends up at PDs, so 41% less shot noise at same input power and less heat load.

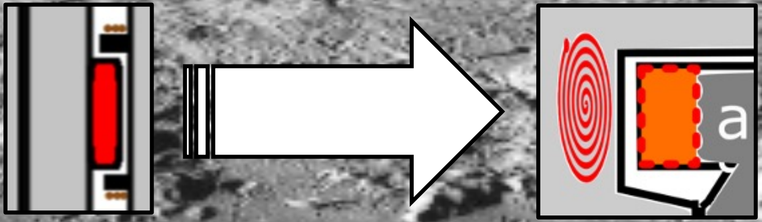
Getting rid of magnets in the actuator to avoid eddy current damping

Collaboration with Innovative Coating Solutions (Belgium) for custom superconducting coils.



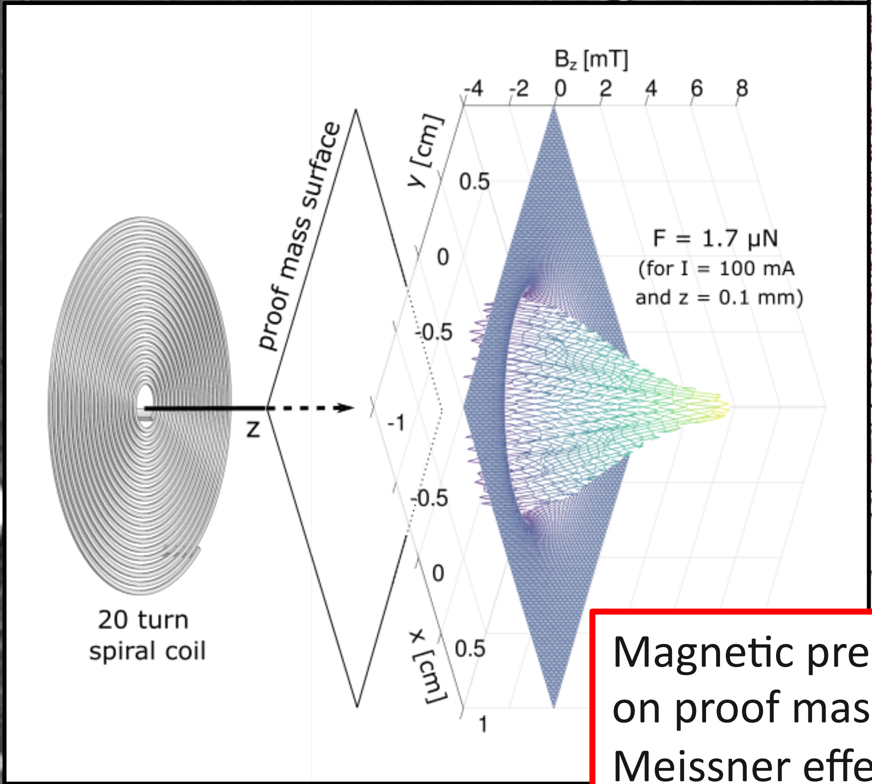
Now (magetron) sputtering Nb and NbN

Superconductivity collaboration and testing with Andrea Perali (UniCam) and Filip Tavernier (KULeuven), respectively



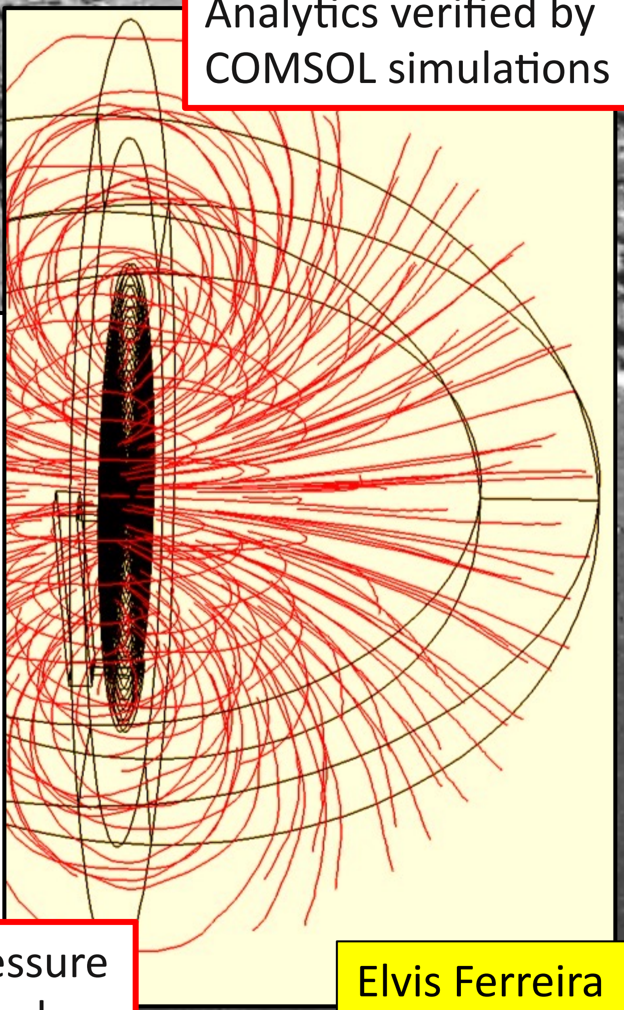
Coil-magnet

Superconducting coil



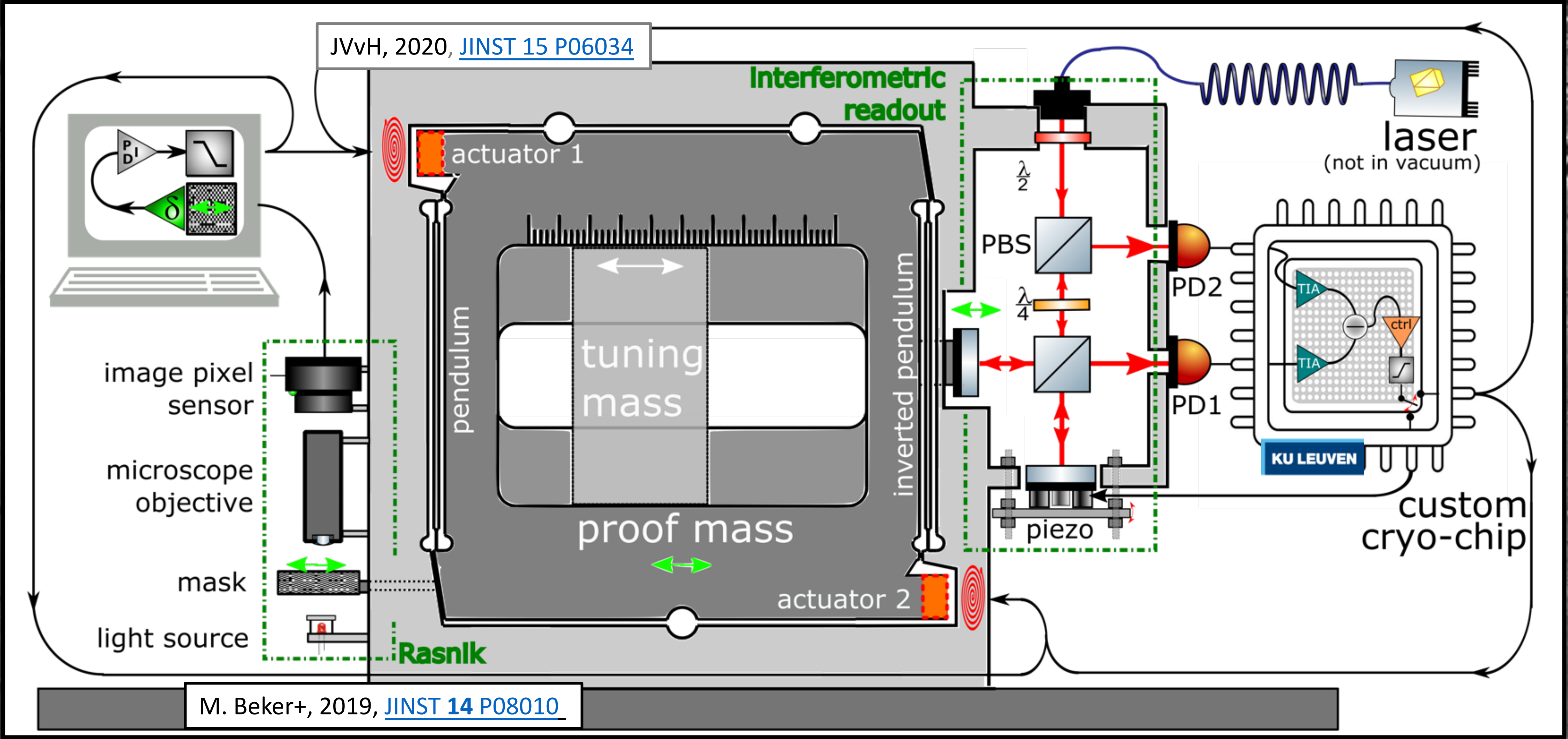
Magnetic pressure on proof mass by Meissner effect

Analytics verified by COMSOL simulations



Elvis Ferreira

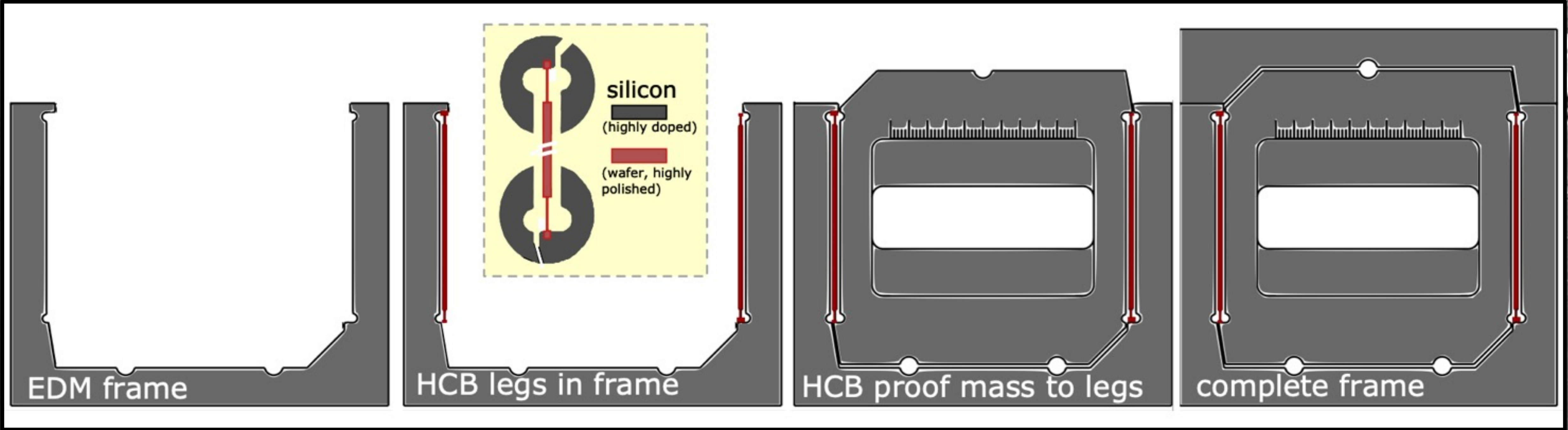
A Cryogenic Superconducting Inertial Sensor (CSIS)



Start with niobium mechanics, which at T = 5 K is in the superconducting state

Silicon Watt's linkage assembly procedure

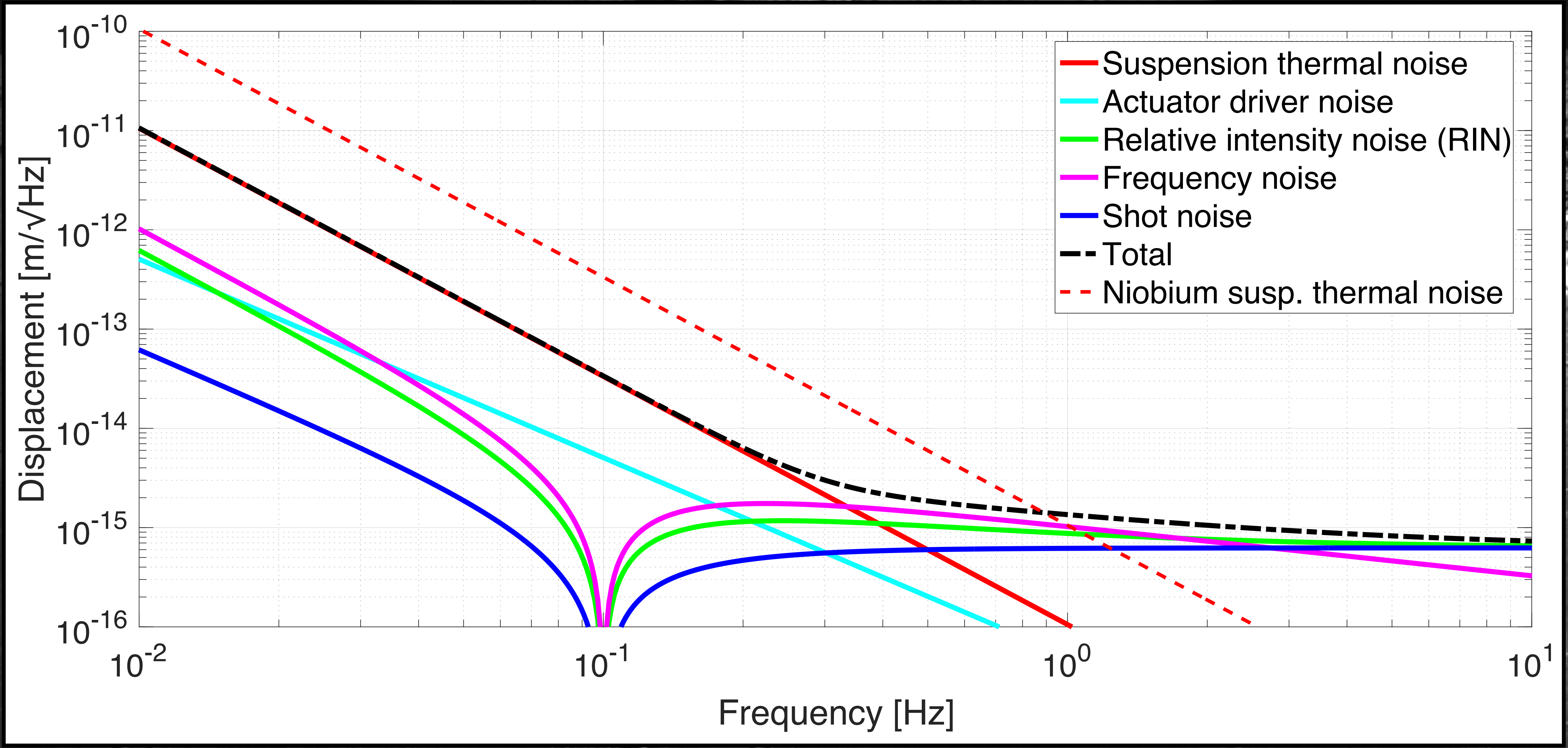
A frame (in 2 pieces) and proof mass is cut out of highly doped silicon block using spark erosion machining (EDM).



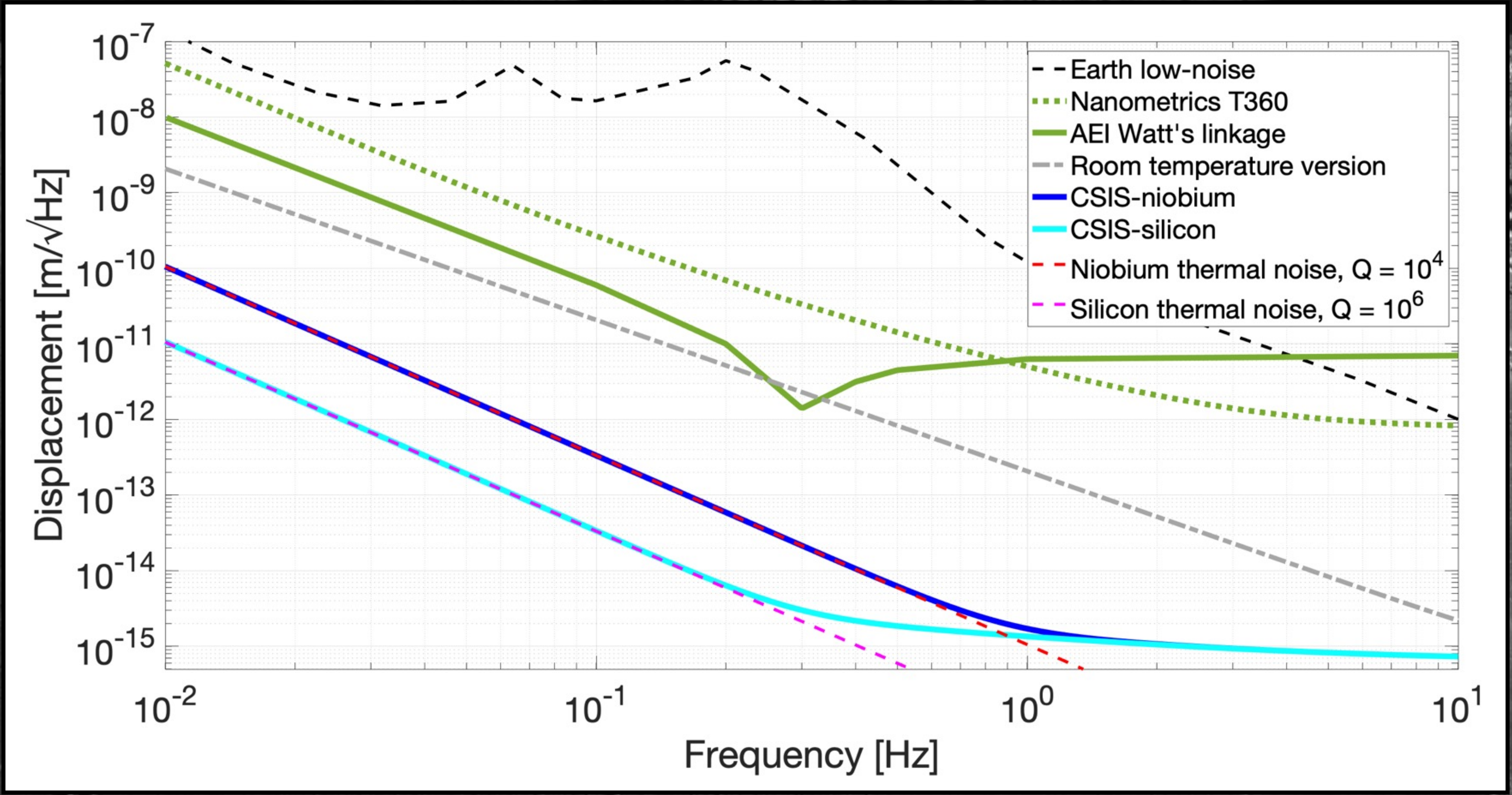
The leg and flexures are laser assisted plasma etched out of a thick 500 μm high-quality wafer.

HCB $\stackrel{\text{def}}{=}$ Hydro-Catalysis Bonding

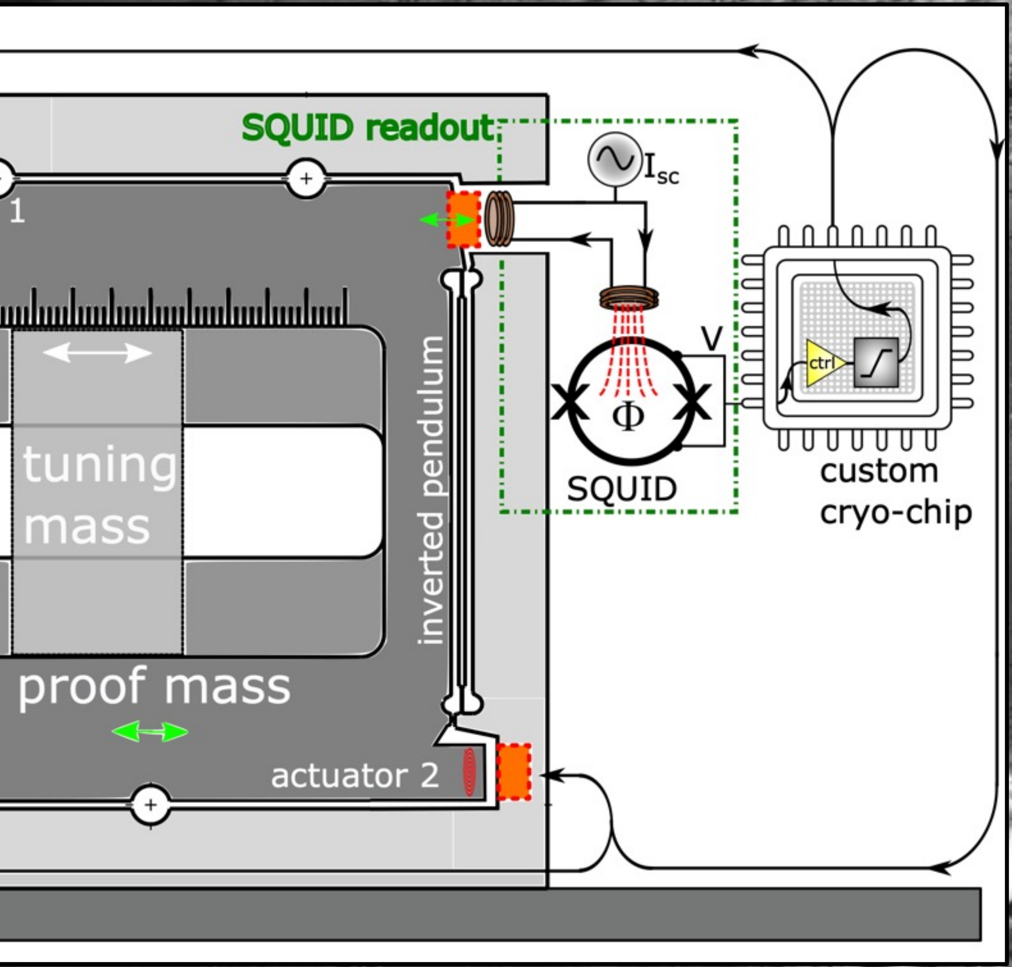
A detailed noise budget of CSIS-Si and Nb thermal noise

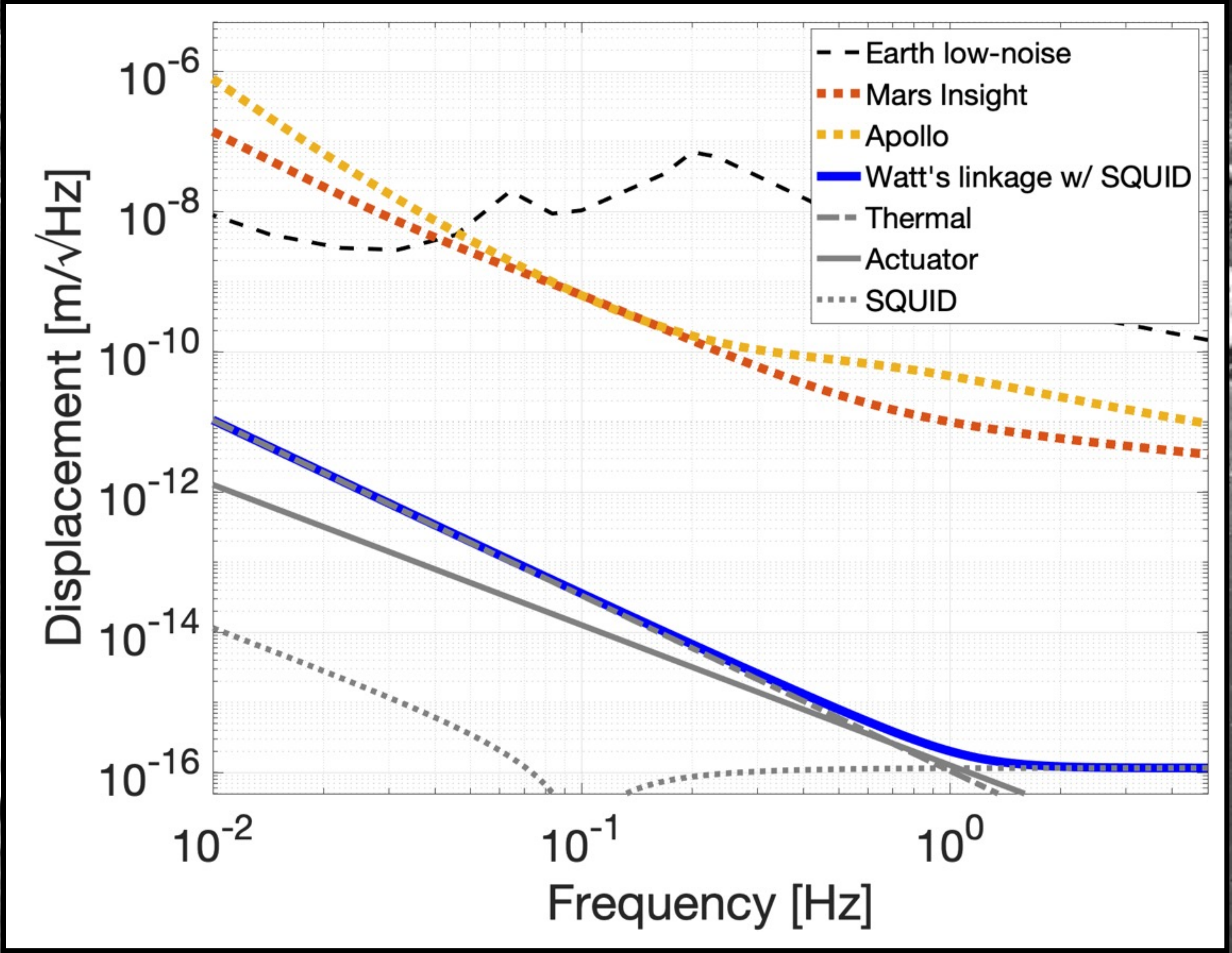


Comparison to terrestrial state-of-the-art



Using superconductivity in the readout: a SQUID

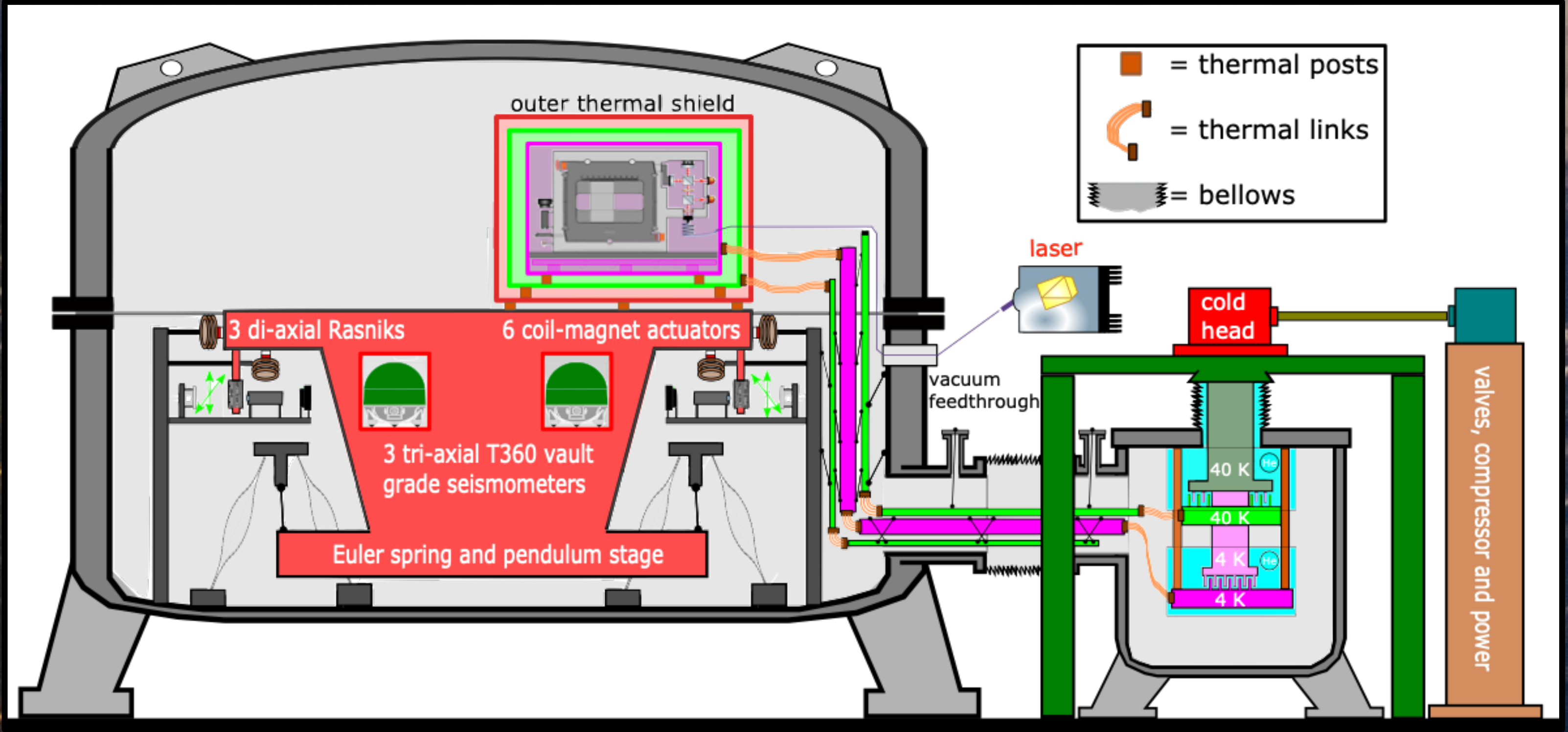


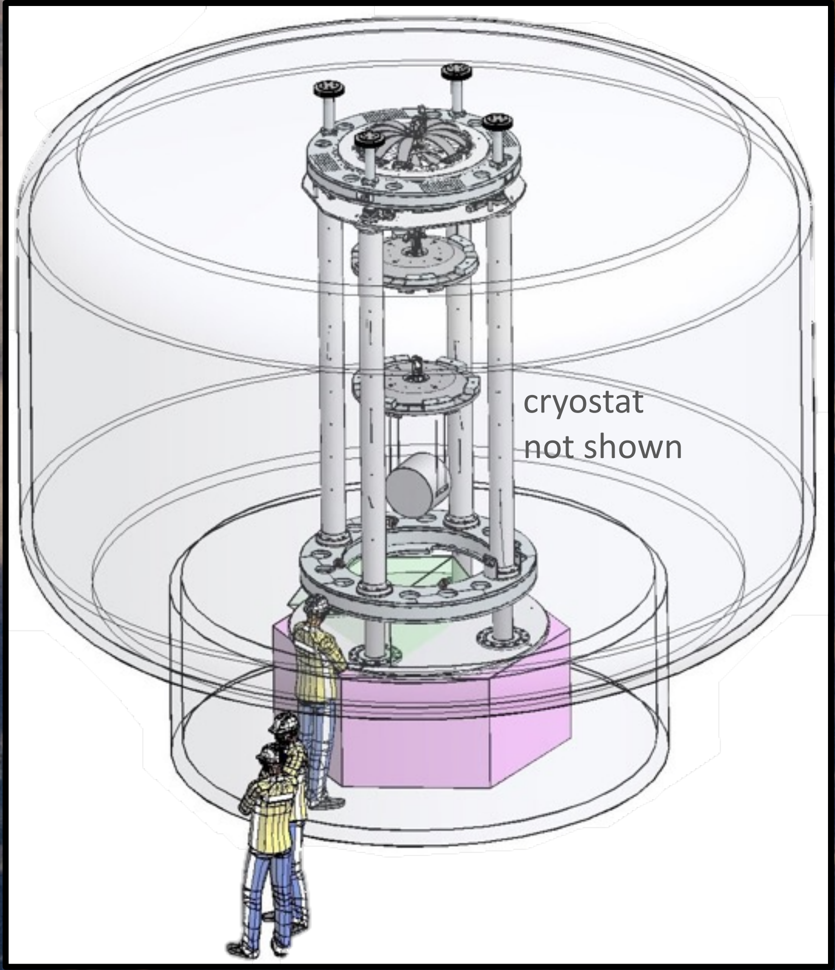


Where can we test these cryogenic, fm/√Hz class inertial sensors?

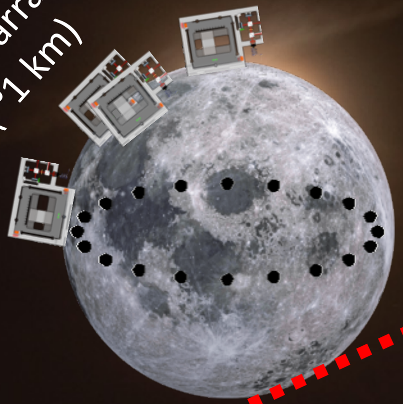
Another option would be to deploy them in the E-TEST (https://www.etest-emr.eu) prototype

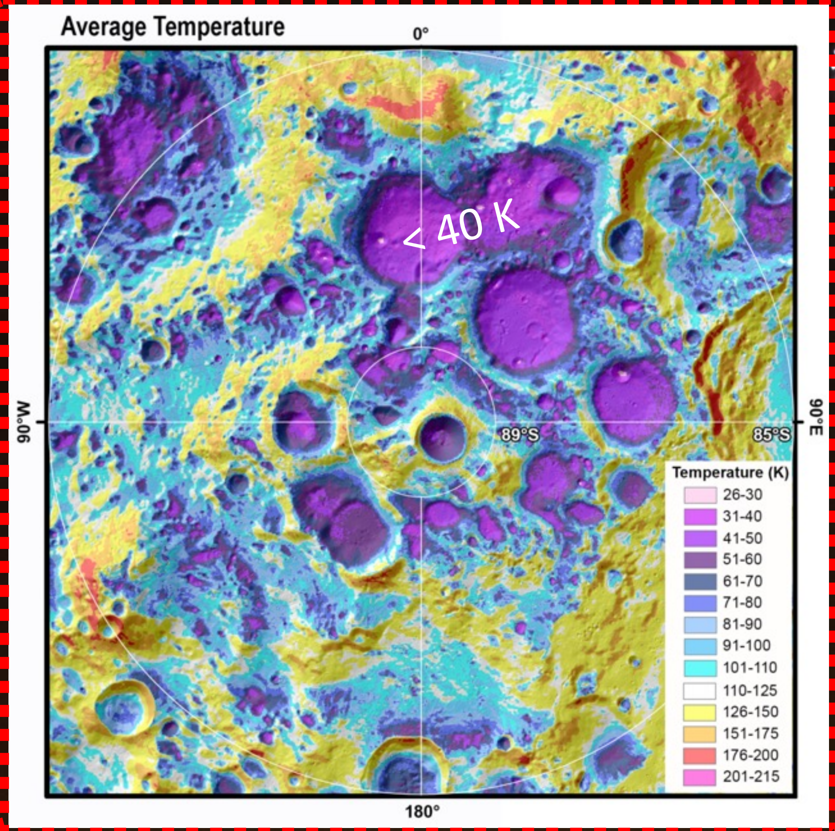
We need to create a cold environment that moves only a factor 100-1000 more than or seismometer sensitivity goal.





A lunar gravitational wave detector!





J. Stopar., 2019, LPI Contr. 2216

The Astrophysical Journal, 910:1 (22pp), 2021 March 20 https://doi.org/10.3847/1538-4357/abe5a7

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ApJ 2021 910 1

CrossMark

Lunar Gravitational-wave Antenna

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Wanna join?
Send me an email!
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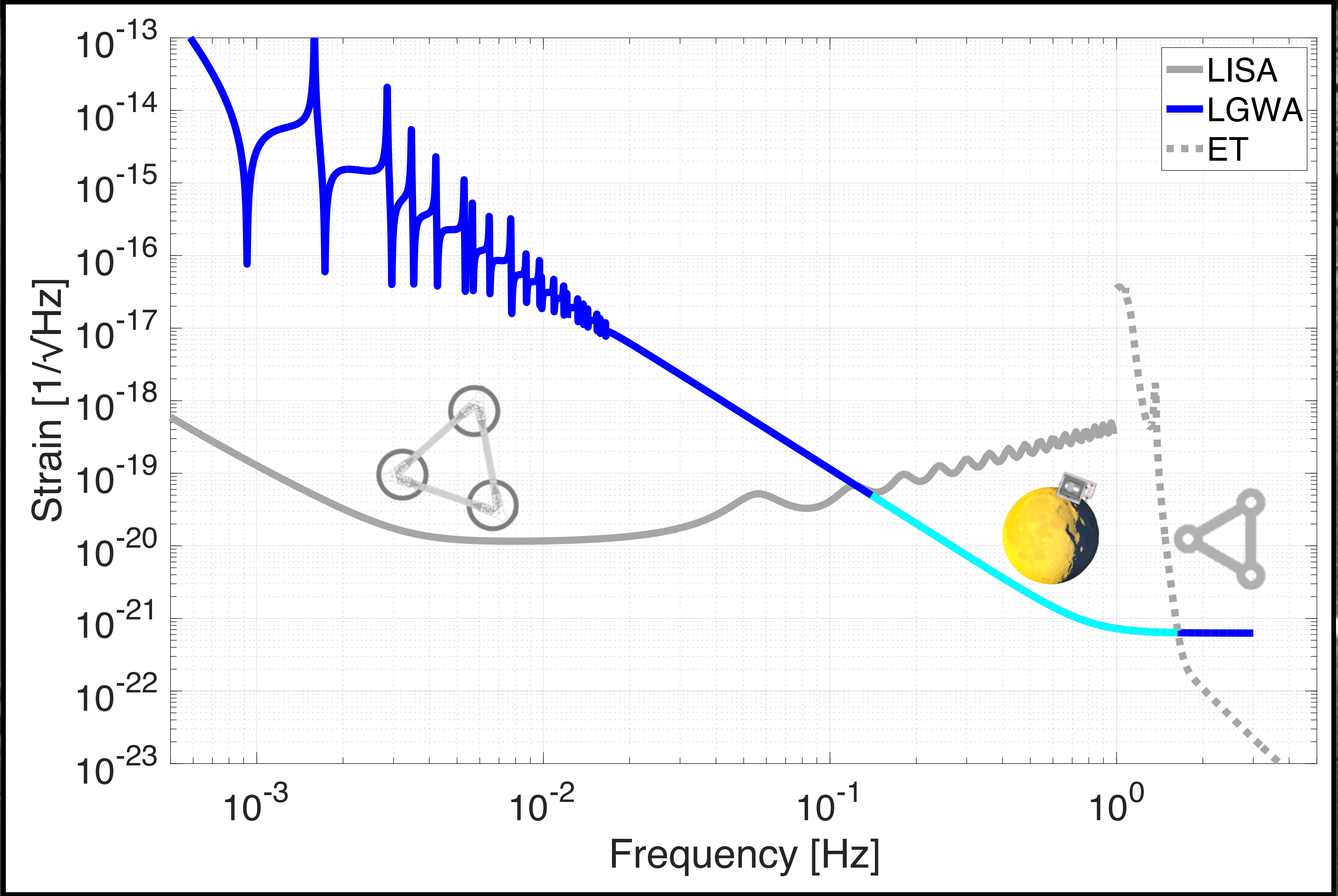
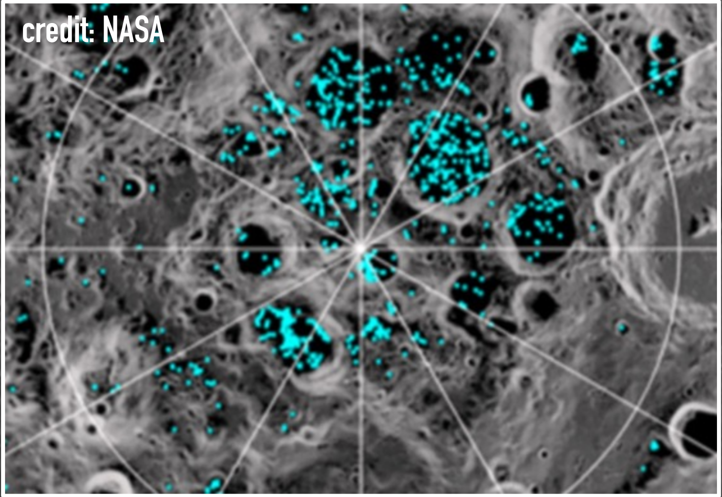
We can bridge the sensitivity gap between LISA and ET

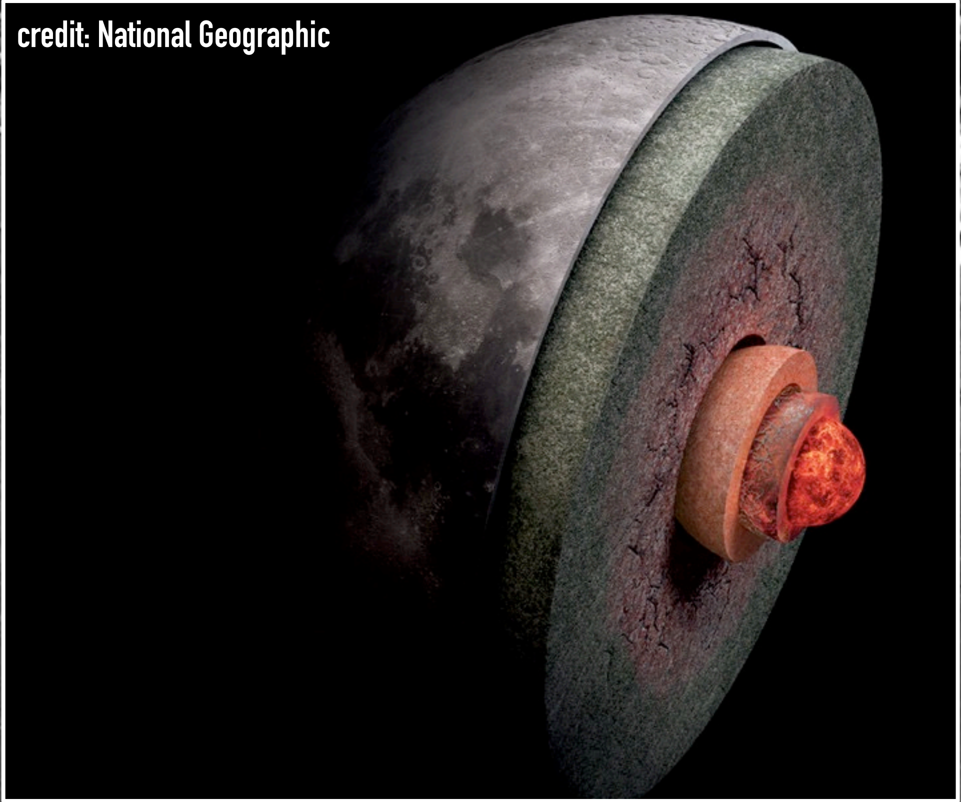


Other benefits of putting these seismometers on the Moon

Prospecting for lunar mining
(^3He and REMs)

Map ice on the South
pole for lunar base





Lunar geophysics (selenephysics)

Summary

Joe Weber's Lunar Surface Gravimeter
credit:NASA

- Cryogenic inertial sensor with fm/√Hz displacement sensitivity from 0.5 Hz onward;

- This sensor can be deployed in the natural cryostats on the Lunar pole craters; a cryogenic sensor array can directly detect the effects of GWs on the Moon;

- Realisation of the first prototypes is underway!

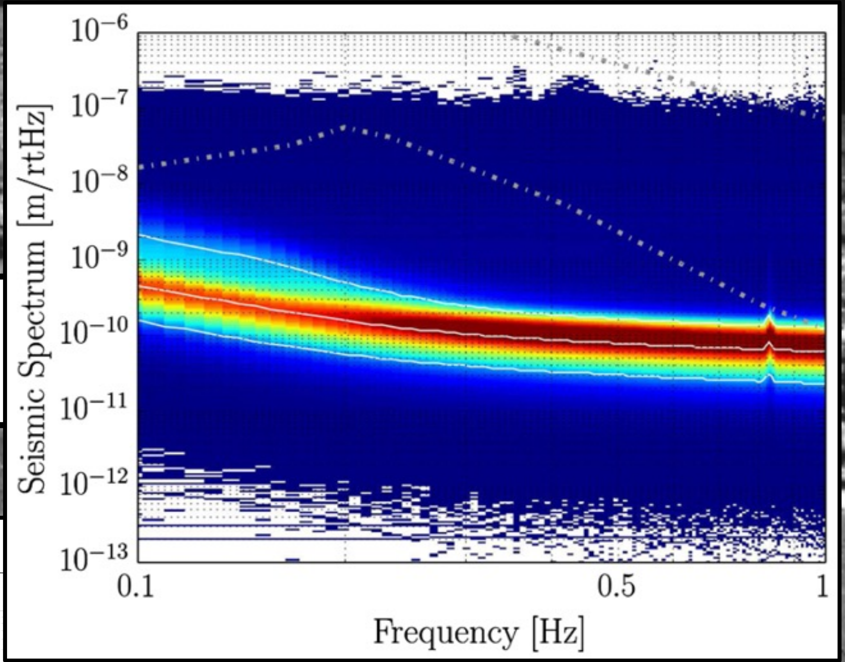
Astronaut looking at radioisotope thermoelectic generator (RTG)
credit:NASA

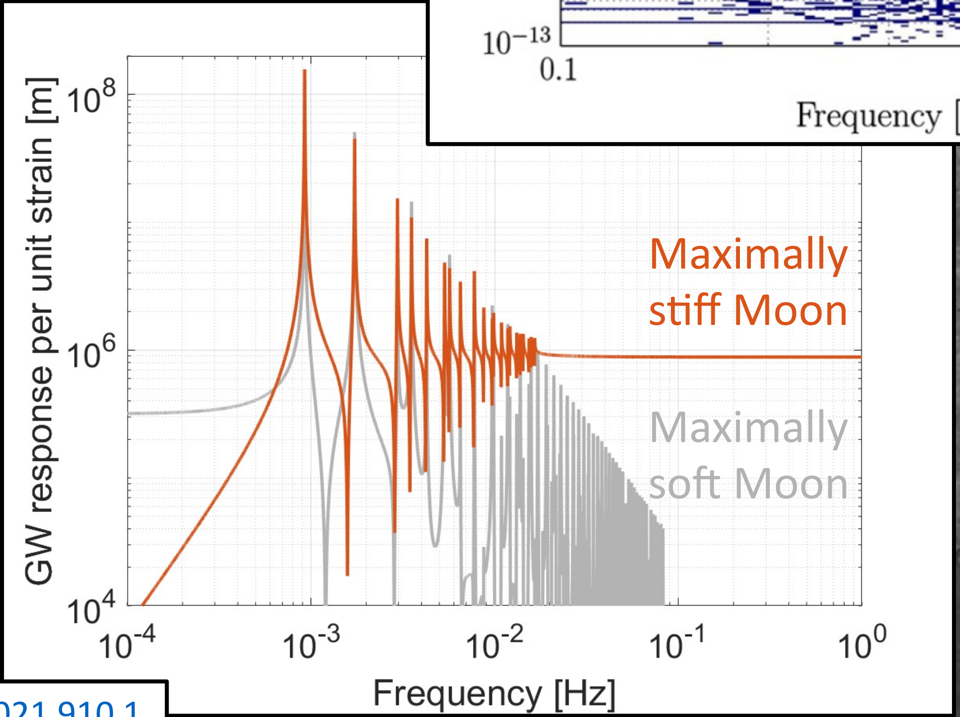
Bonus slides

Why is the Moon a good spot for detection gravitational waves?

- ➢No atmosphere/oceans;
- ➢No active tectonic plate motions;
- ➢Relatively close to Earth;
- ➢Large and solid.

Apollo seismic measurements





Surface displacement signal

GW amplitude

Q-value of normal mode *n*

$$\xi(f) = \frac{1}{2}h(f)\sum_{n=0}^{\infty} L_n \frac{-f^2}{f_n^2 - f^2 + \mathrm{i} f_n^2/Q_n}$$

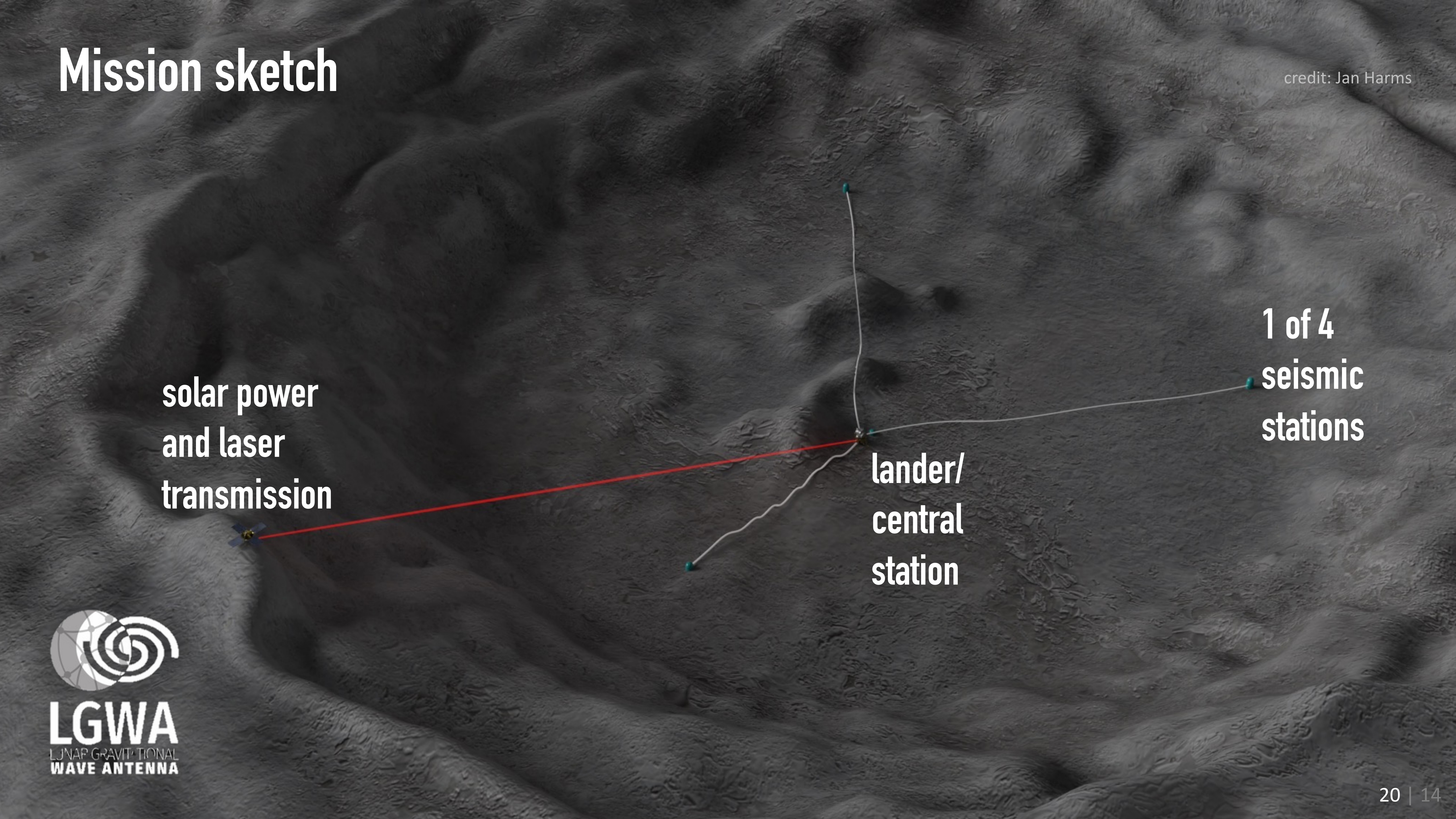
Effective baseline of mode *n*

Frequency of normal mode *n*

J. Harms et al., 2021, ApJ 2021 910 1

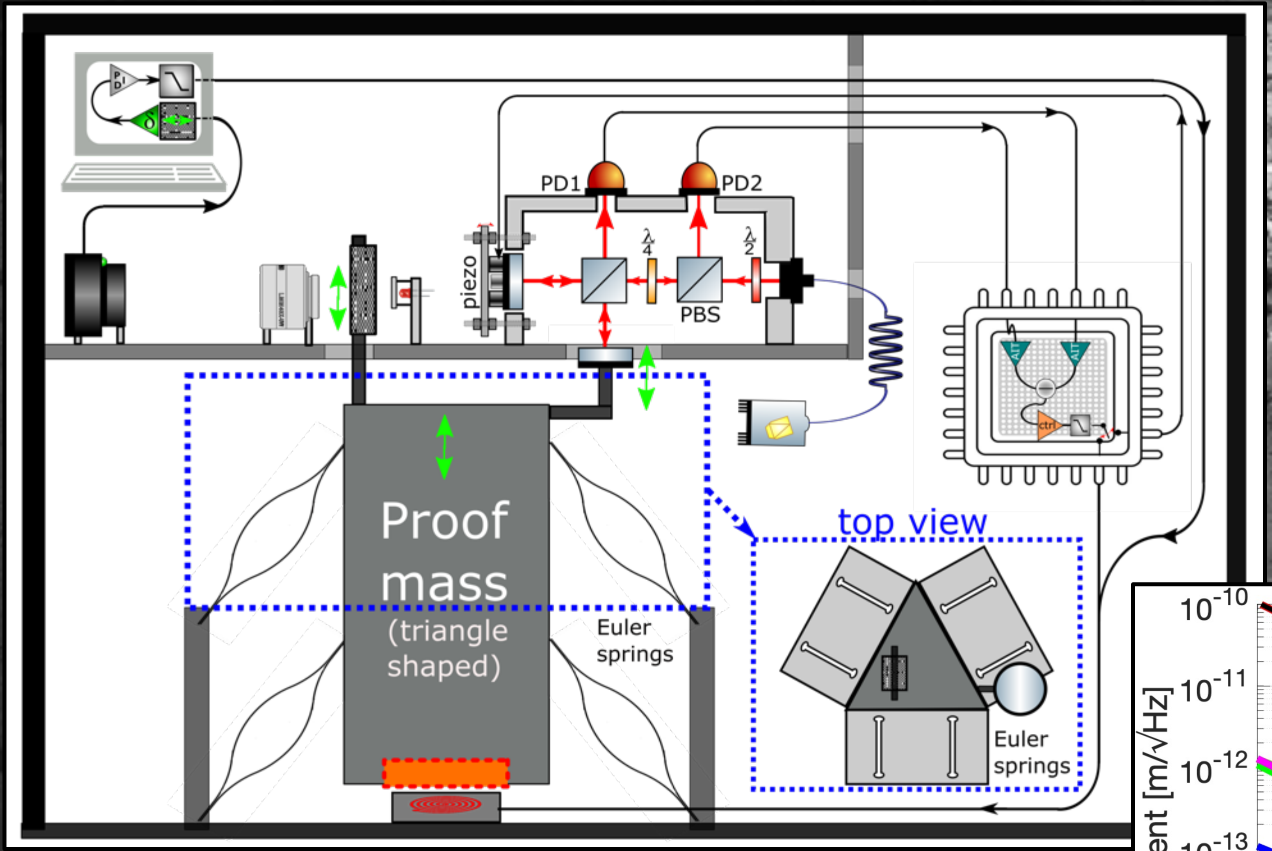
Mission sketch

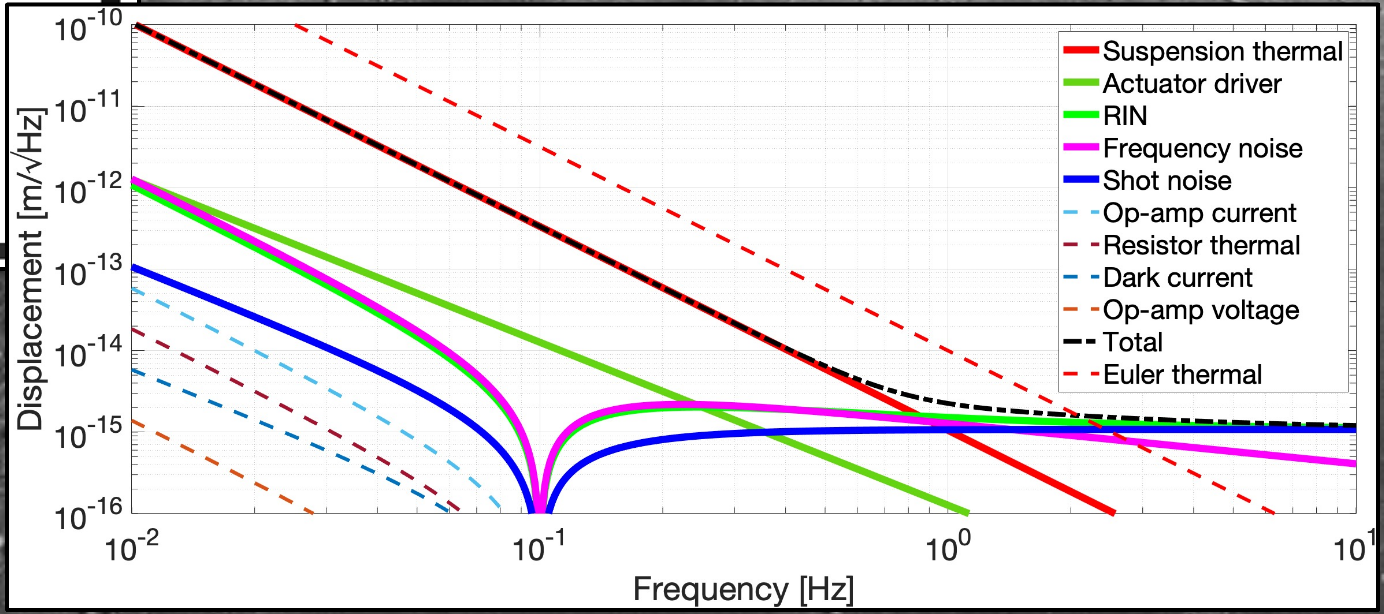
credit: Jan Harms



LGWA
LUNAR GRAVITATIONAL
WAVE ANTENNA

Also thinking about vertical CSIS

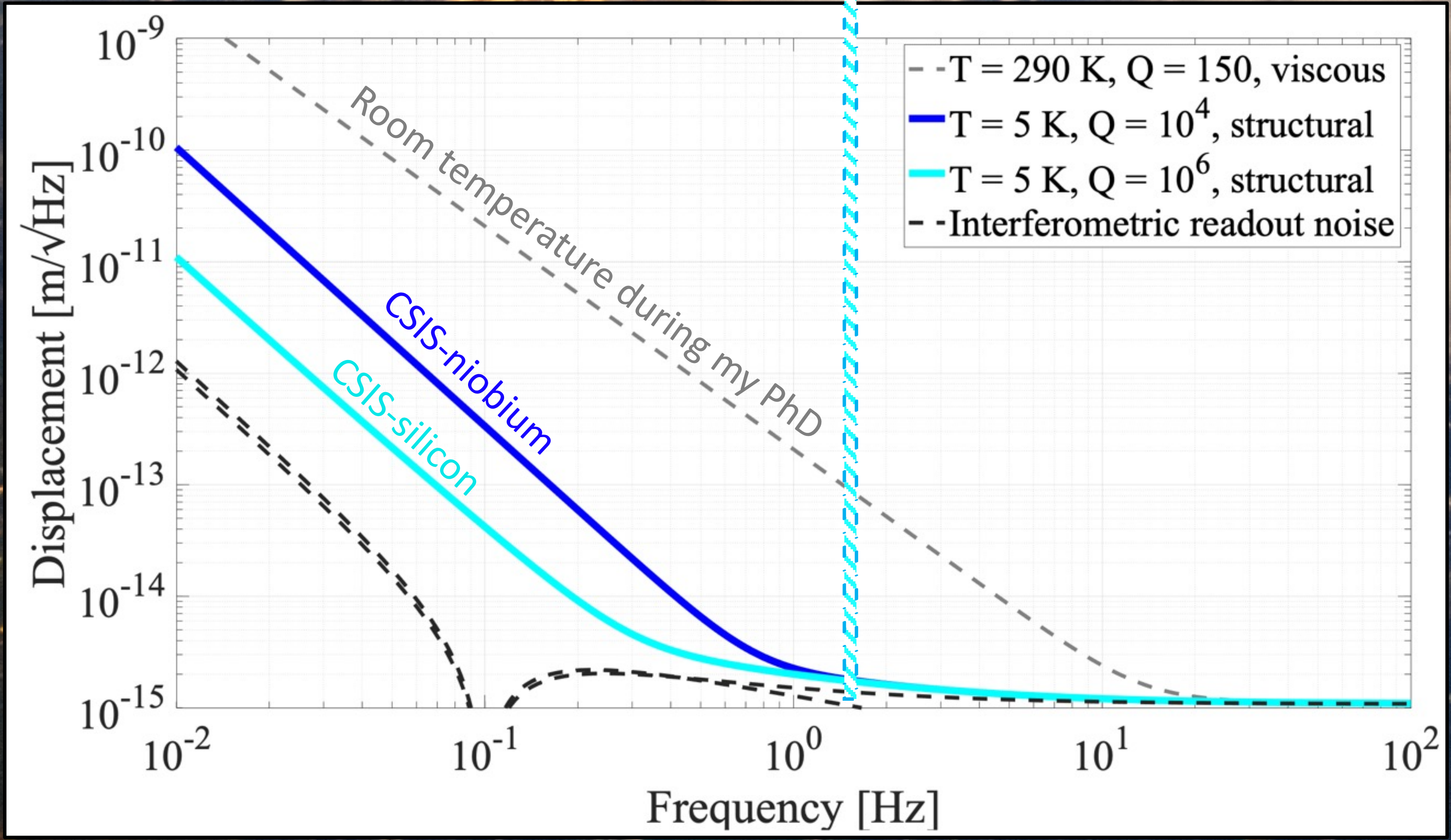


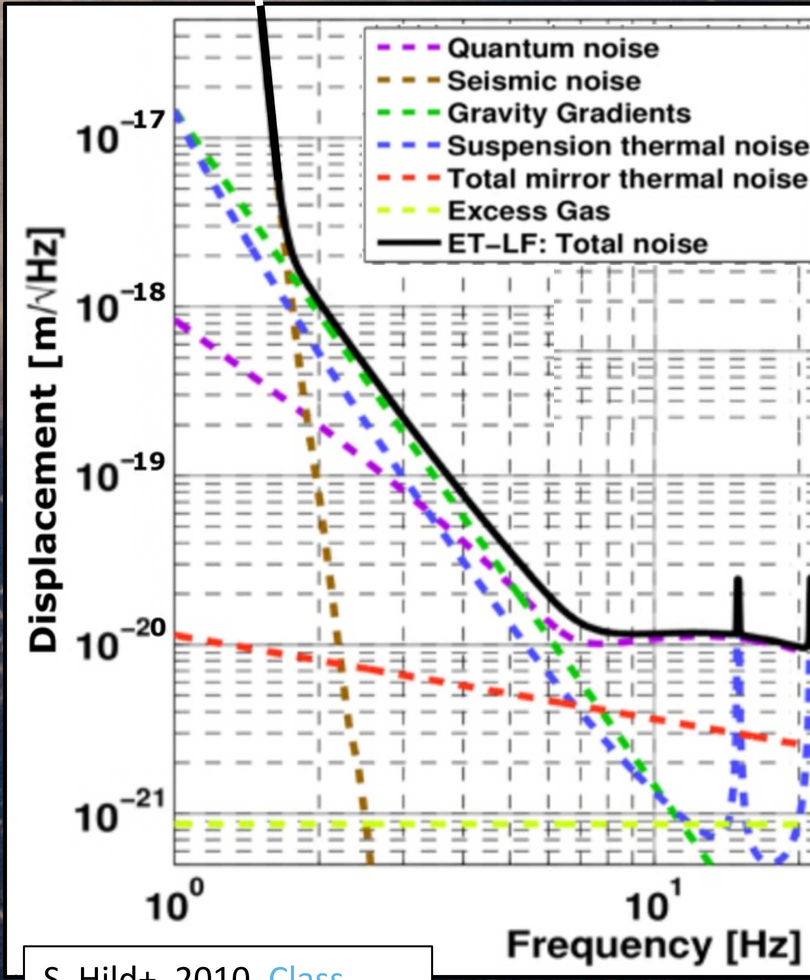


How much more sensitive is this cold inertial sensor?

Where can we deploy it?

monitor & project down





S. Hild+, 2010, Class. Quant. Grav. 27 015003

… and perhaps somewhere else?

Detailed noise budget for cryo-Si-Watt's linkage

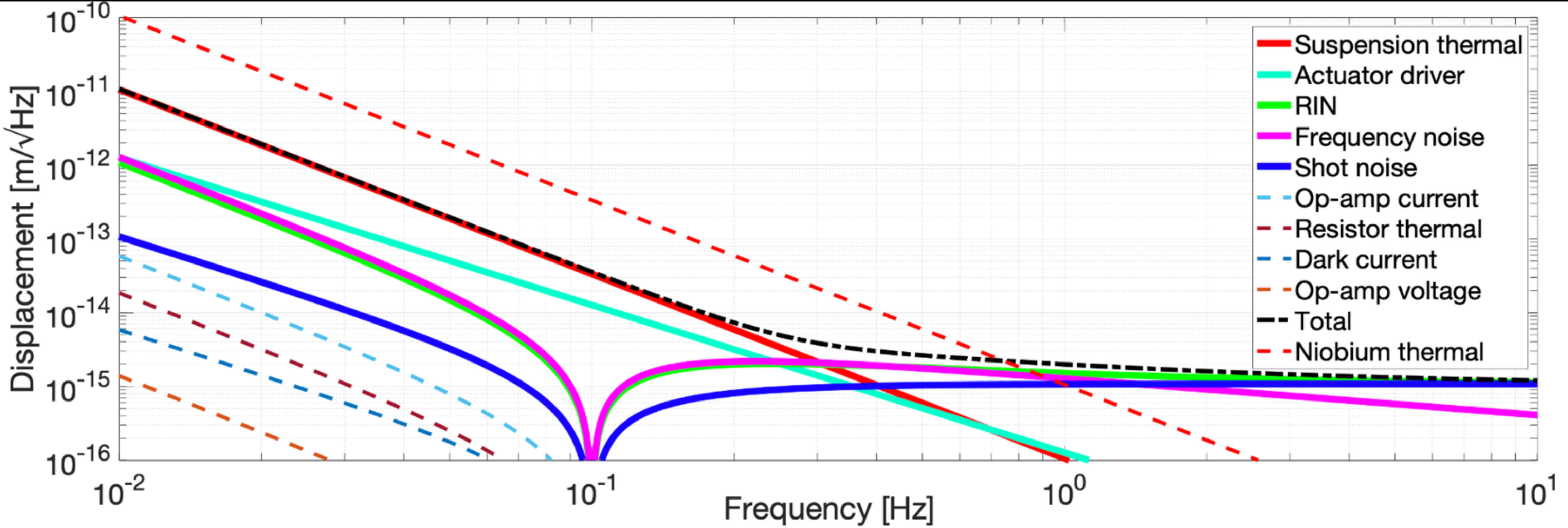
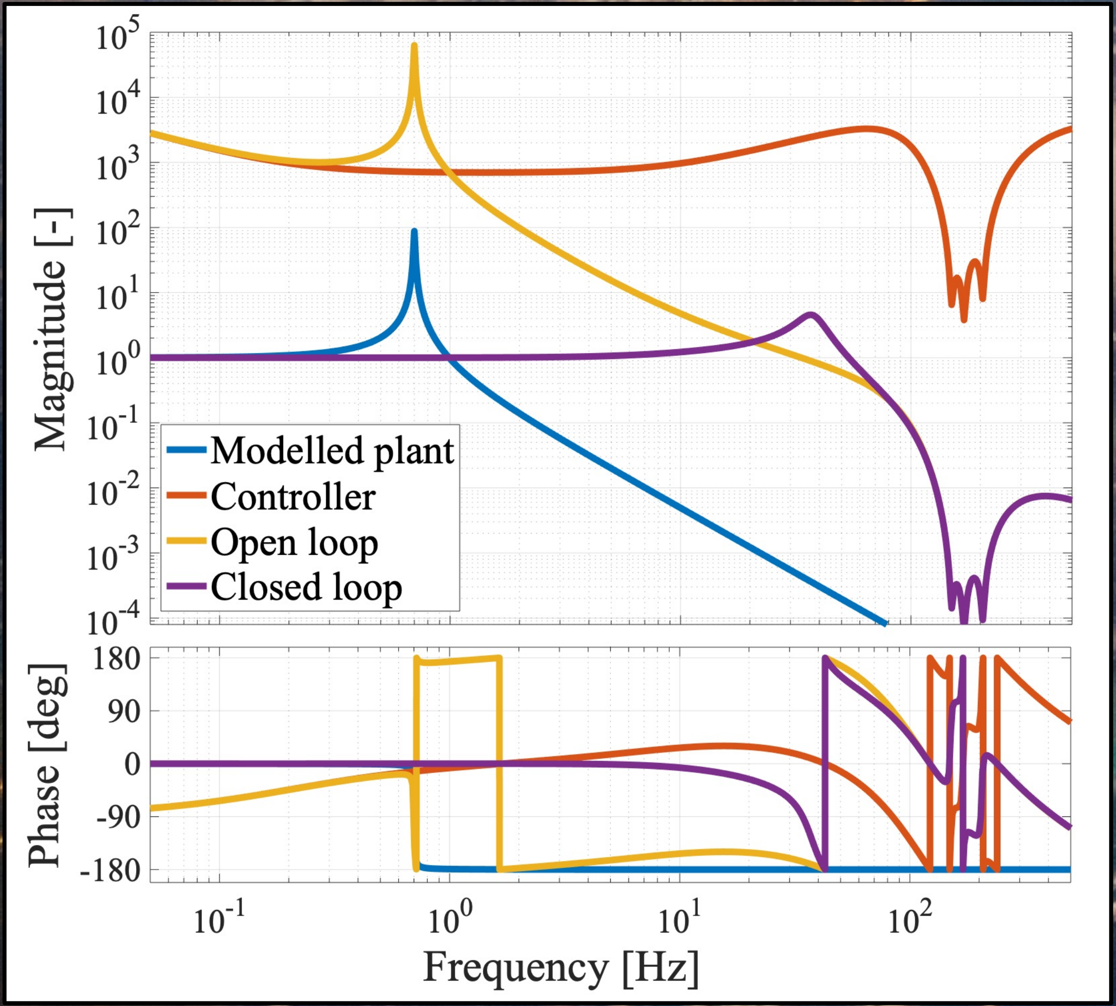
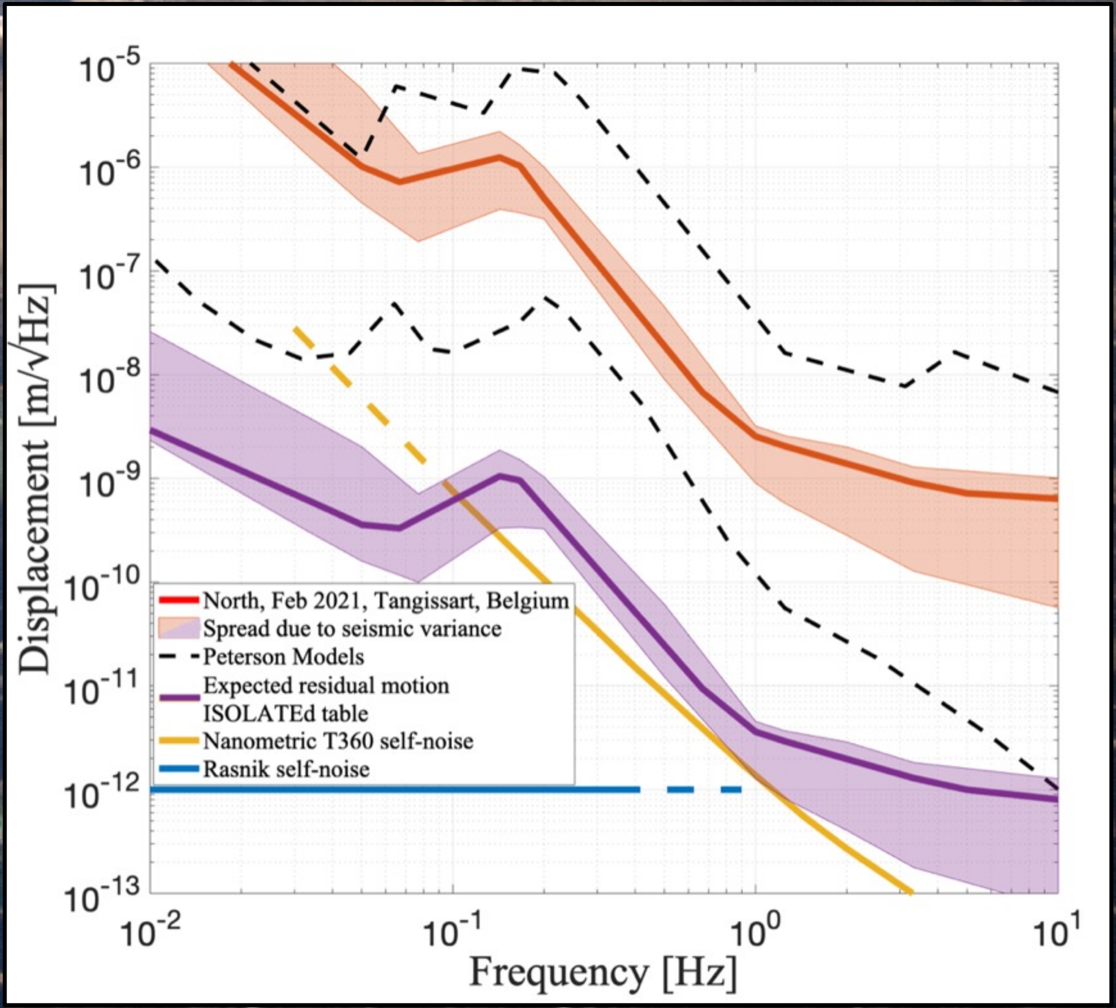


Figure 7. A look under the hood: noise budget of ISOLATE's silicon cryogenic inertial sensor CSIS-Si and a red-dashed thermal noise trace when using niobium as sensor mechanics material. The actuator driver noise is modelled with a DAC noise of 0.1 μV/√Hz, actuator strength of 5 mN/A and a sampling resistor Rs = 10 kΩ. The relative intensity noise converges to shot noise as $n_{RIN} = n_{sn}\sqrt{f_c/f + 1}$ where the convergence frequency f_c is modelled as 1 Hz. and the frequency noise with 500/√f using a static arm length difference of 0.5 mm. The injected power is 25 mW, the dark current is modelled as 50 nA, the largest feedback resistor used is 20 kΩ and the opamp current and voltage noise is 2 fA/√Hz at 100 Hz and 50 nV/√Hz at 0.1 Hz. The proof mass is modelled as 1 kg and f_0 is tuned down to 0.1 Hz.

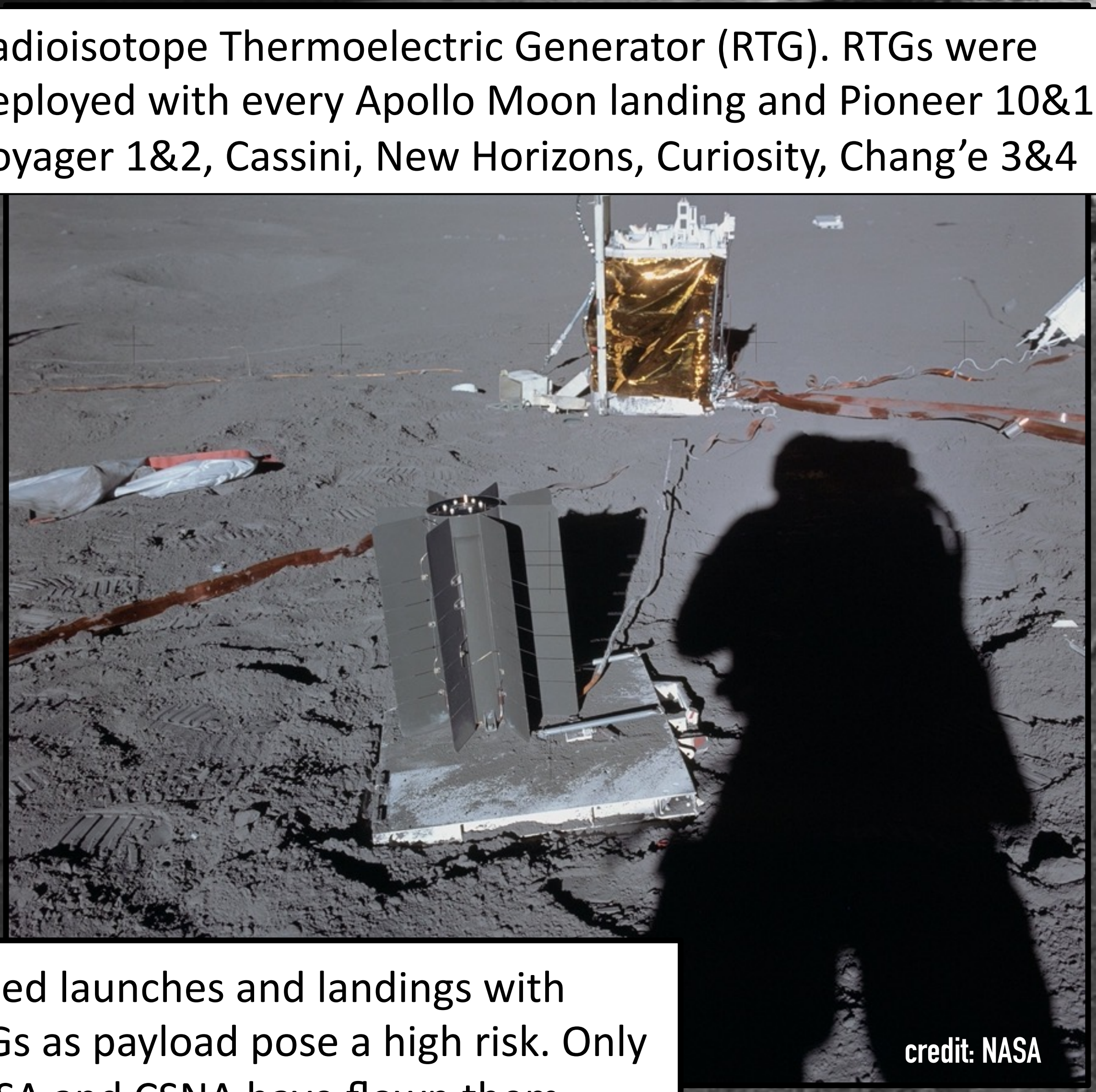
Performance of the active platform





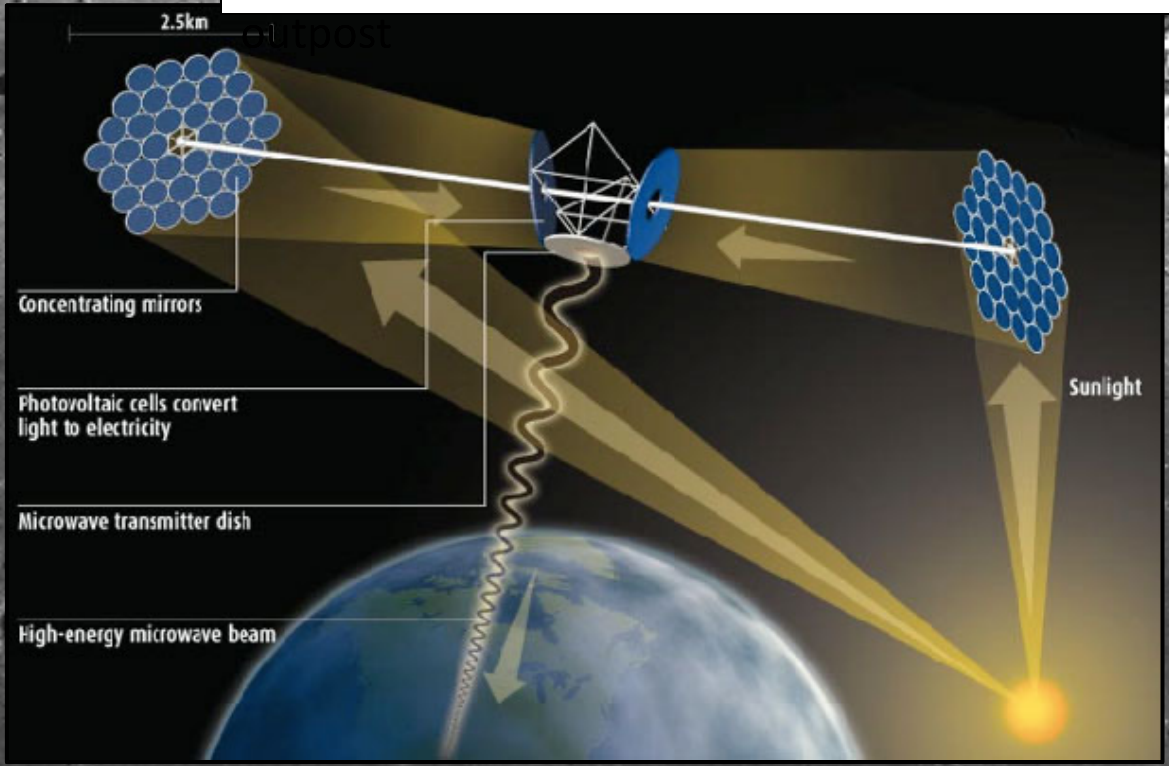
Alternatives to powering our detector

Radioisotope Thermoelectric Generator (RTG). RTGs were deployed with every Apollo Moon landing and Pioneer 10&11, Voyager 1&2, Cassini, New Horizons, Curiosity, Chang’e 3&4

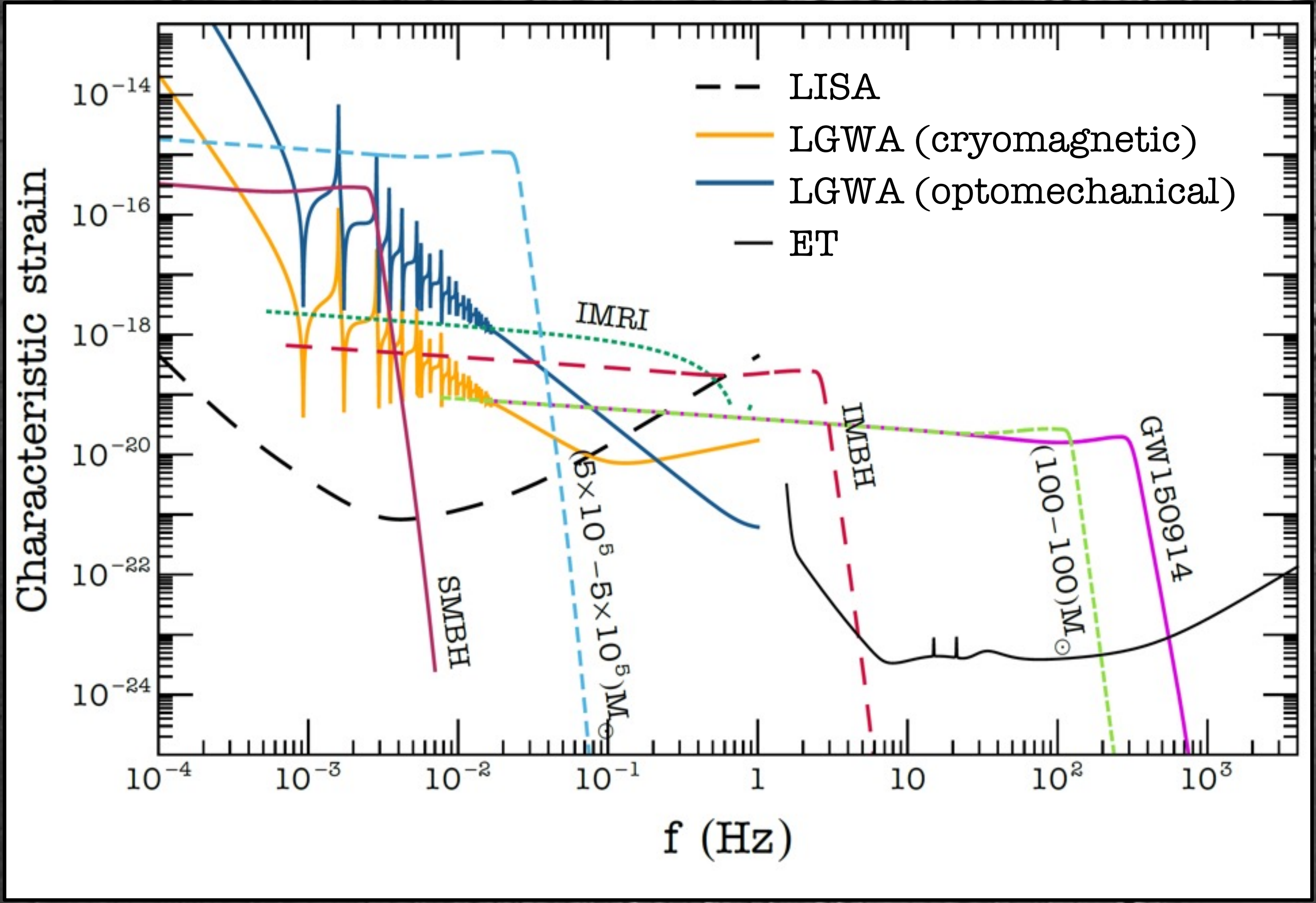


Failed launches and landings with RTGs as payload pose a high risk. Only NASA and CSNA have flown them.

Solar power satellite (SPS). Expensive, however proposed for the South pole lunar outpost



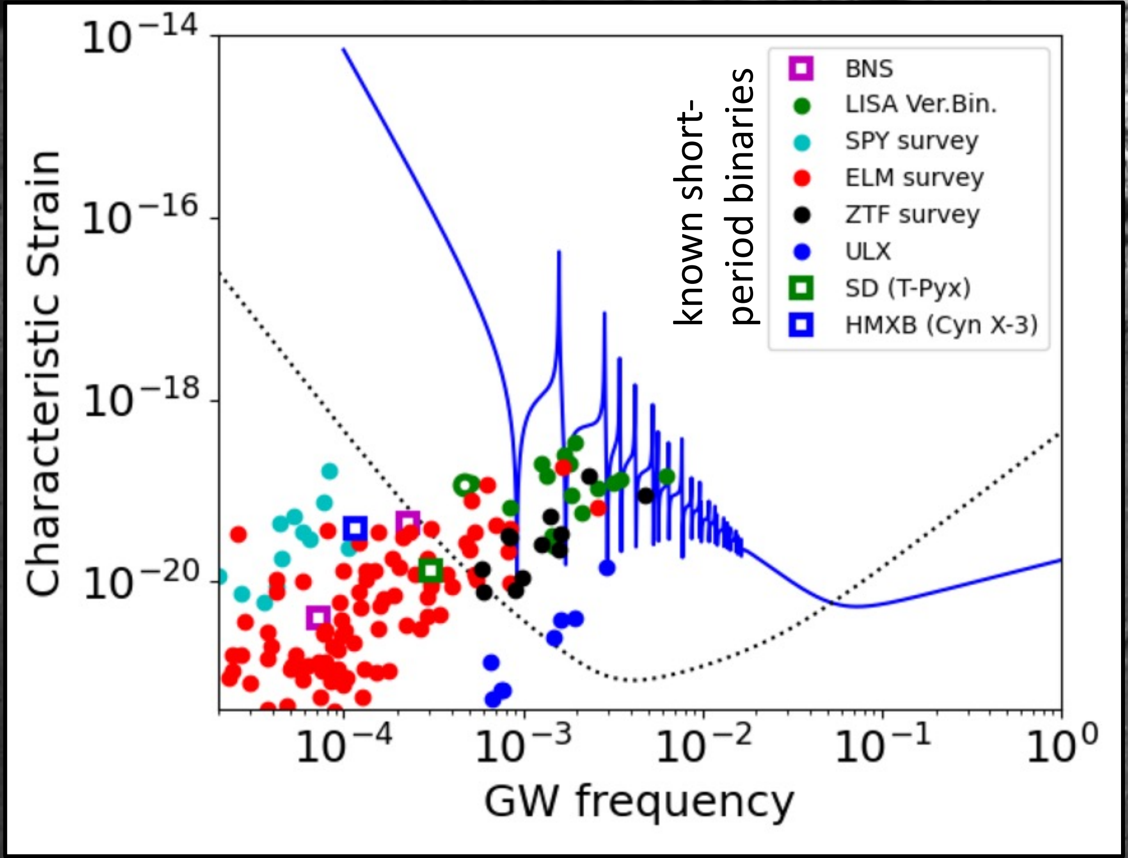
Massive black hole inspiral science

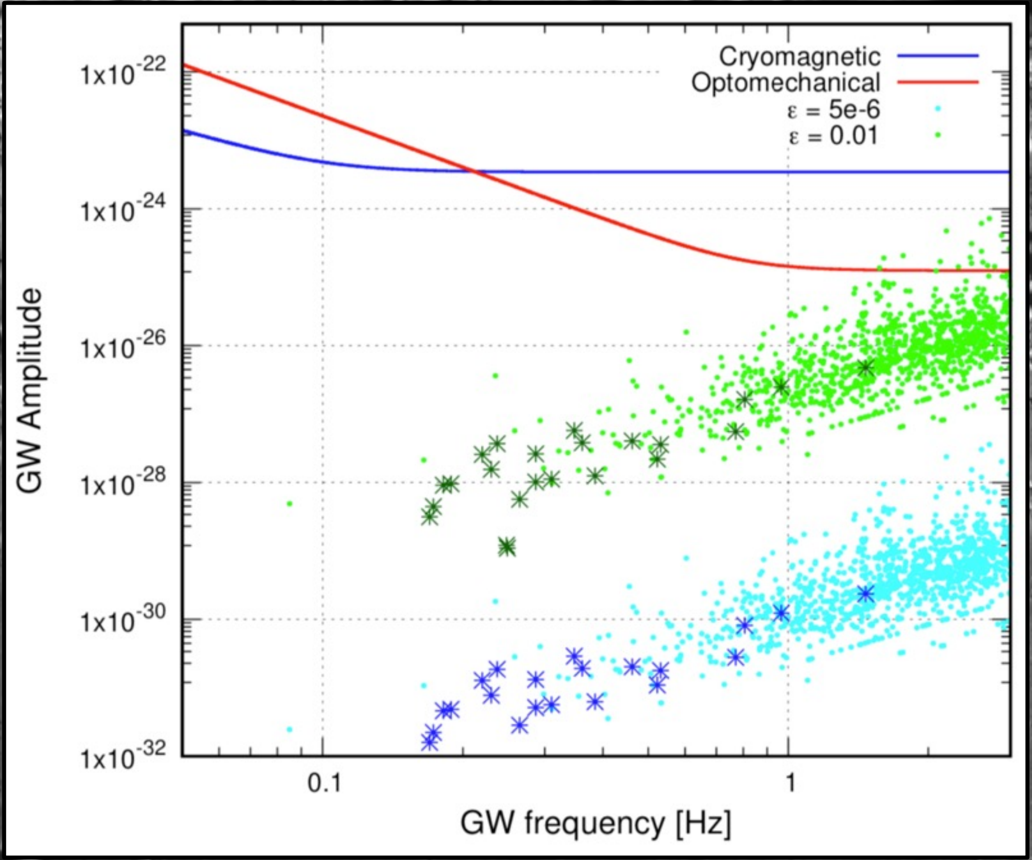


The cryomagnetic option is a superconducting levitating accelerometer with a SQUID readout

The optomechanical option presented earlier is now baseline due to the bridge between LISA and ET

Galactic binaries and neutron stars (NS)

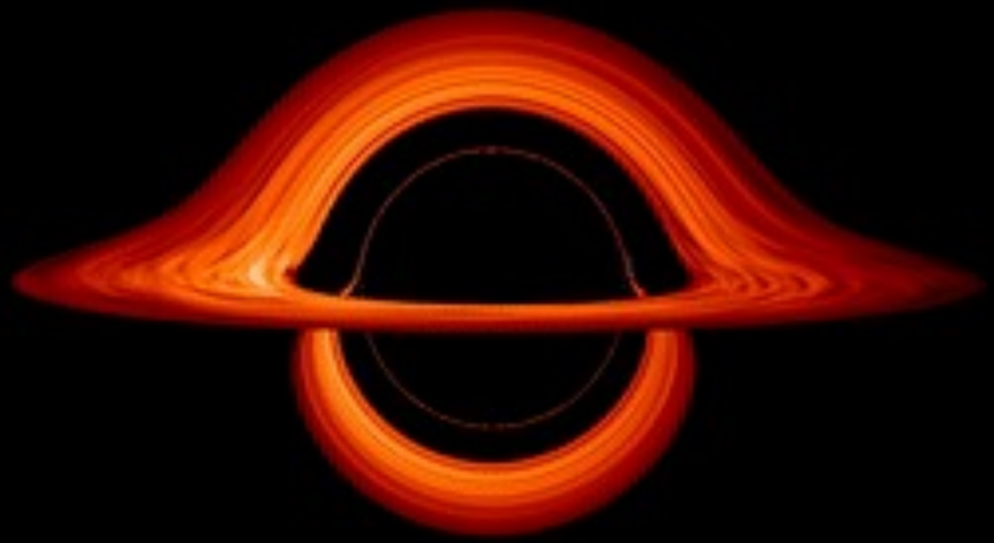




Probability of coincident detection with SN Ia is low (~ for SN detection with LIGO/Virgo), but it would be decisive for SN Ia progenitor identification.

Predicted GW signals from spinning NSs with different ellipticities. Signals from spinning NS probably. not observable.

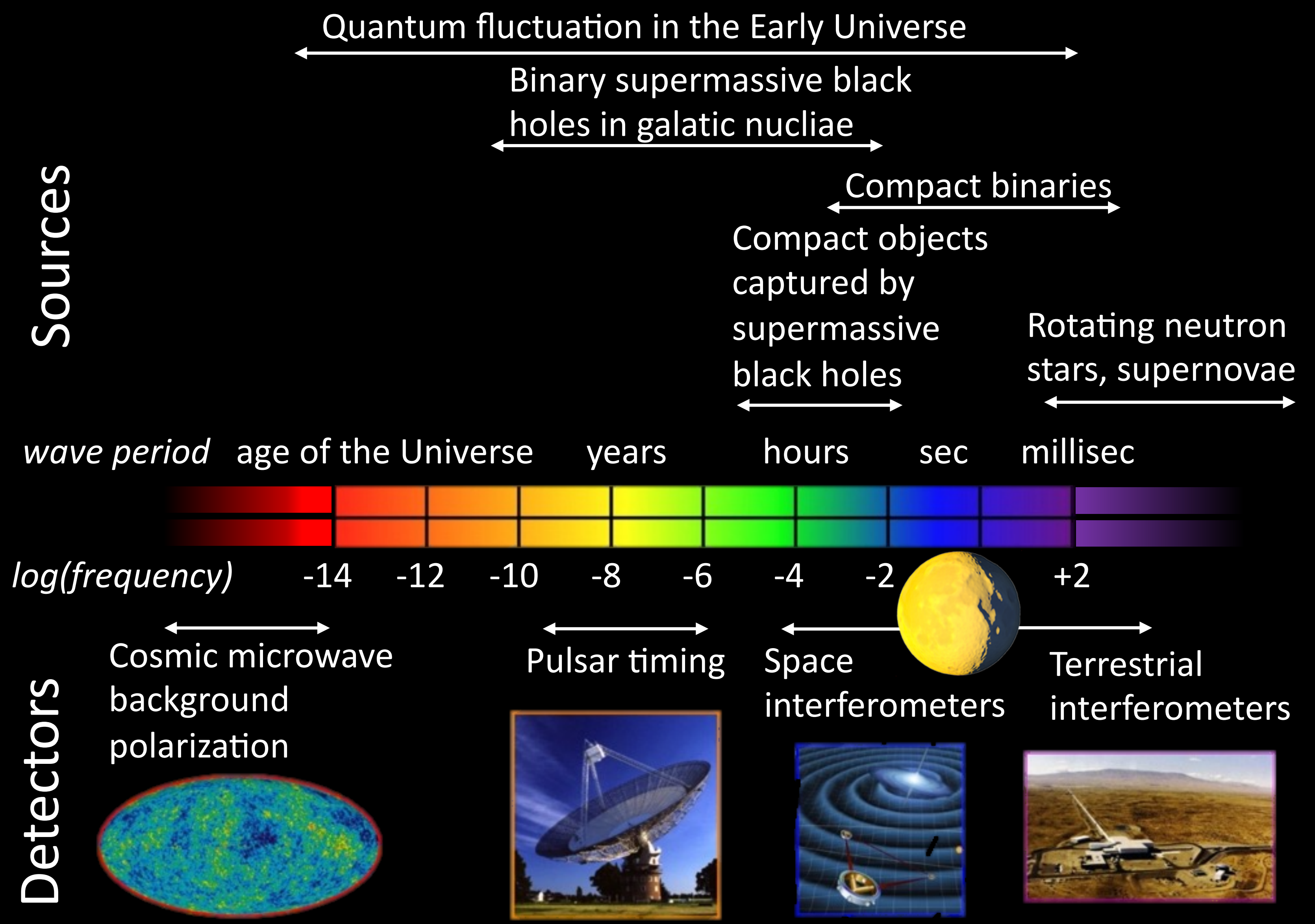
What is there to discover below 1 Hz?



Low frequency part of stellar black holes (BH), intermediate mass ratio inspirals, super massive BHs, unknown unknowns…

credit: NASA Goddard/J. Schnittman and B.P. Powell

As with electromagnetic waves, GWs have a spectrum



…and like the different EM waves, different detectors are used across the spectrum;

Impossible to know, but exciting to imagine all that lurks in the rest of the GW spectrum.