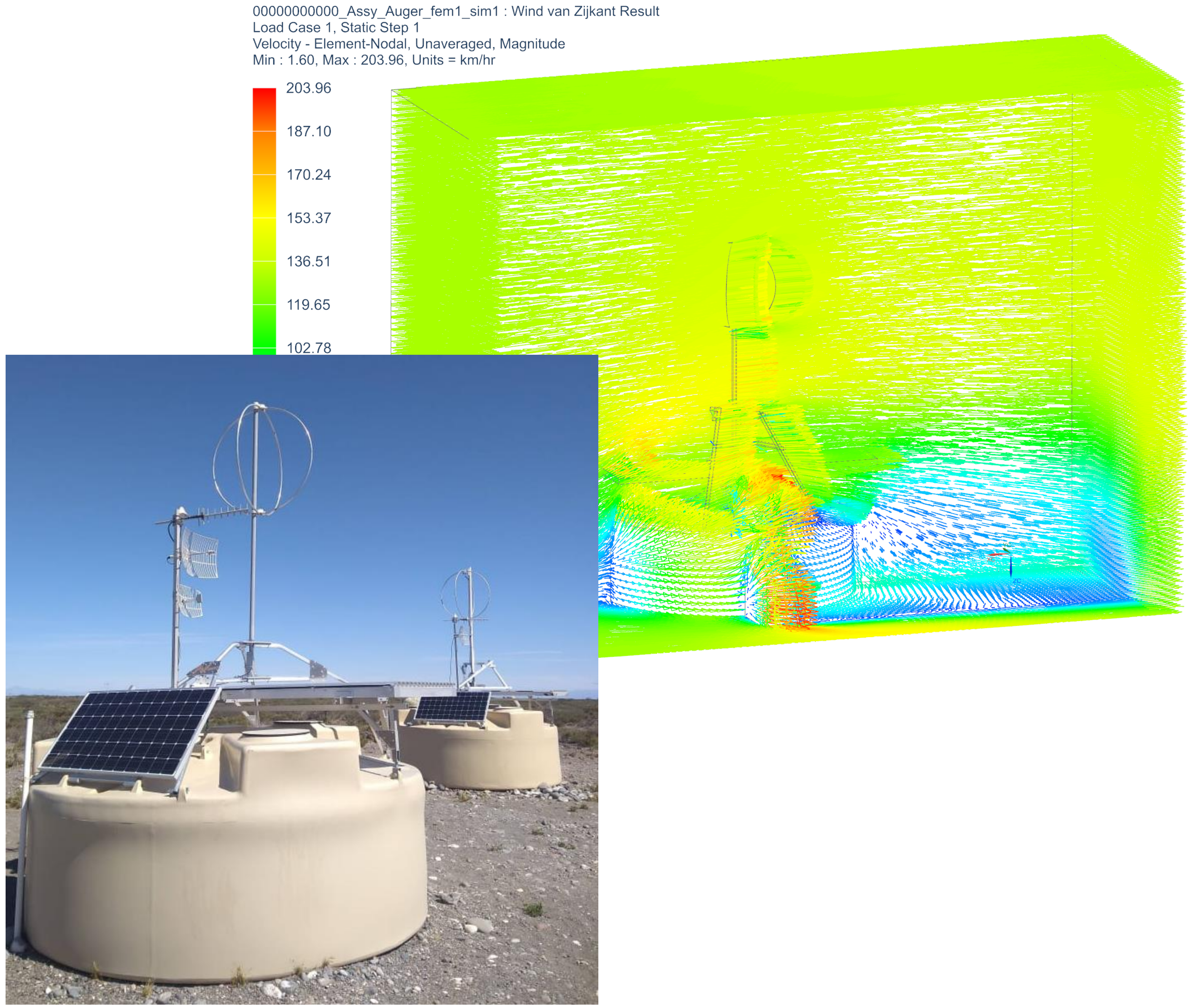
Nikhef

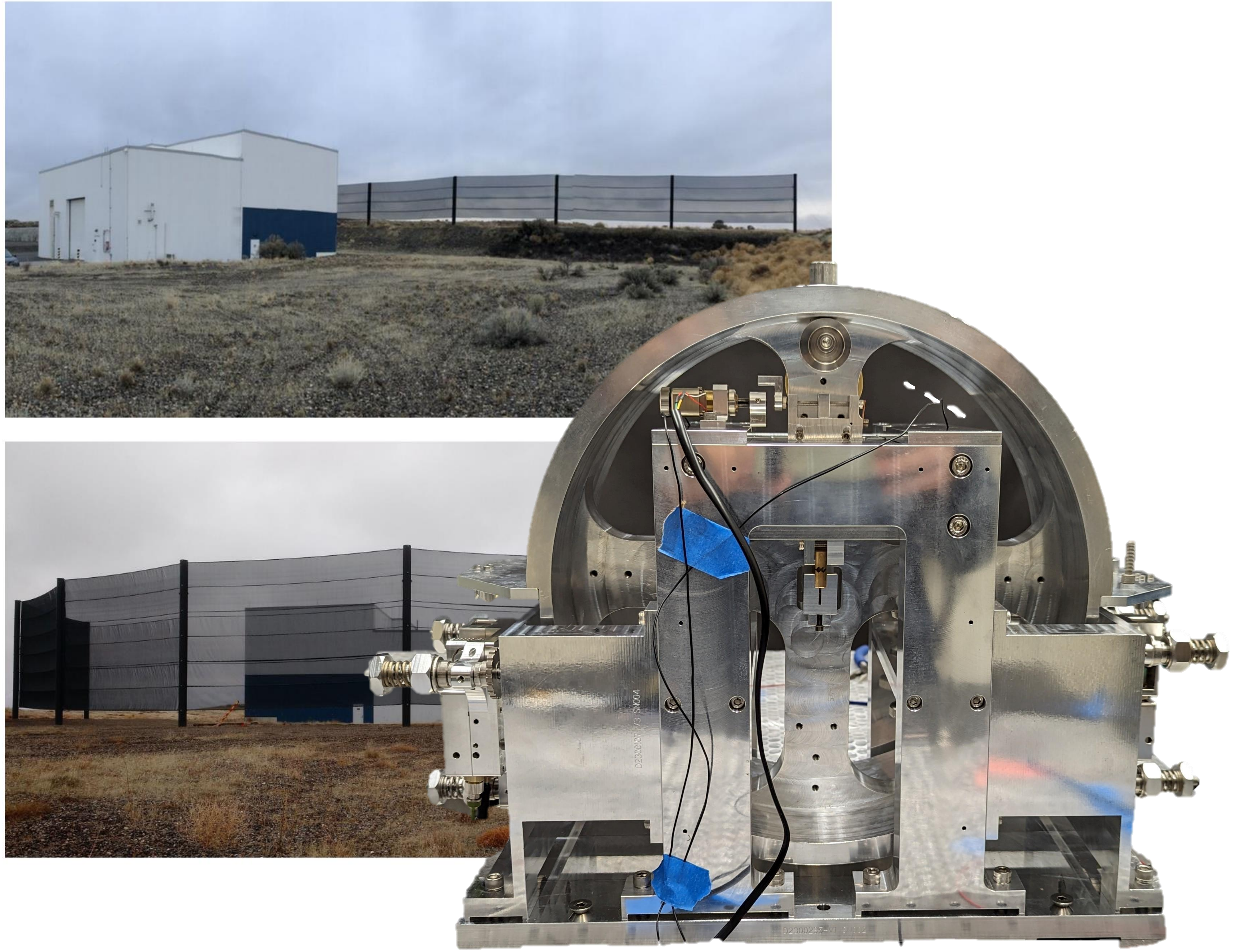
Jesse van Dongen presents:

CO-Design for Holding mirrors still for gravitational wave detectors

The effect of wind-induced stress on Auger antenna mounts



Wind proofing LIGO

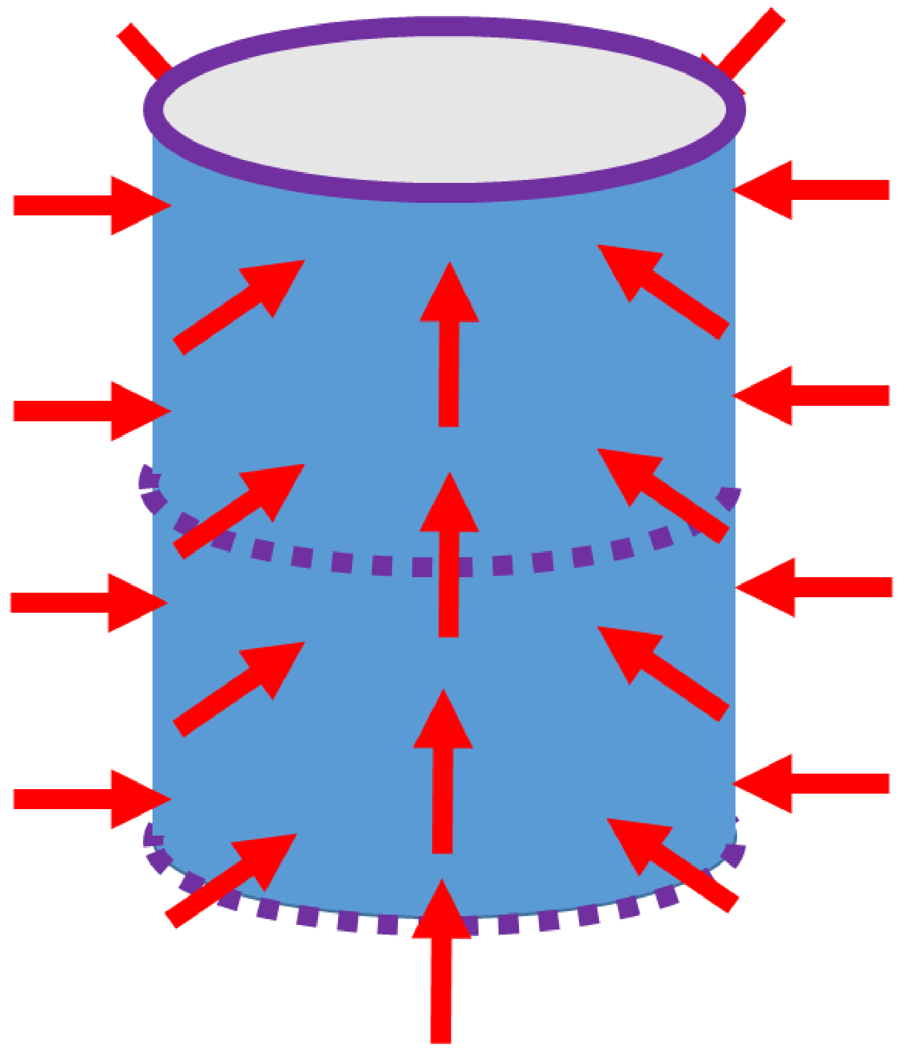


Darwin 40T wall thickness estimations

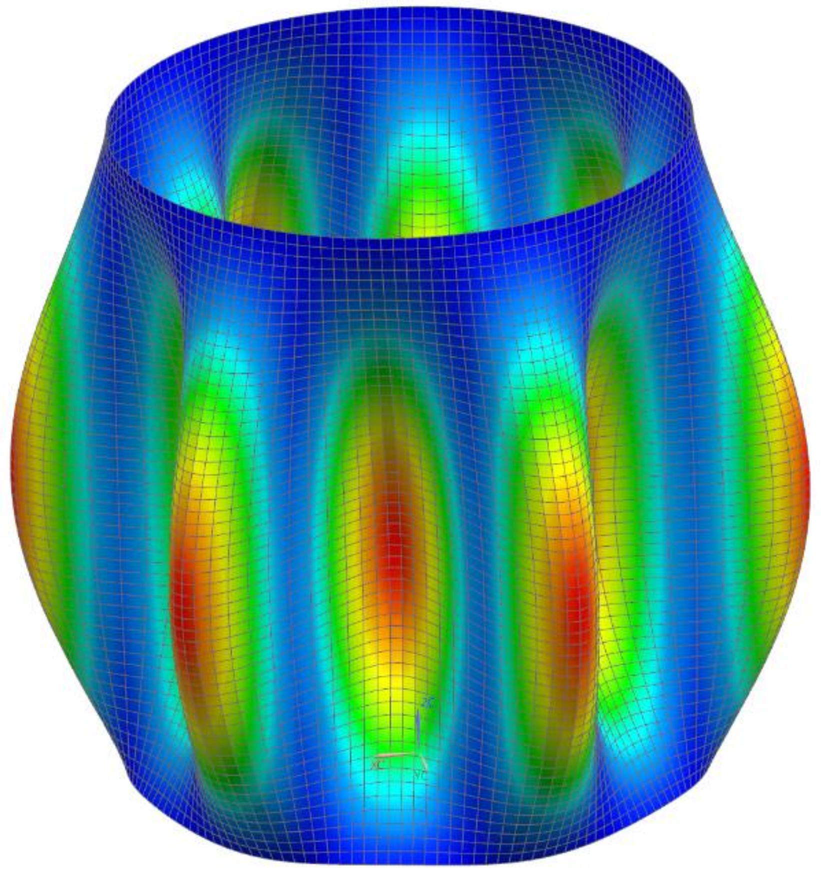
Gravitational Wave Detector Vacuum tanks

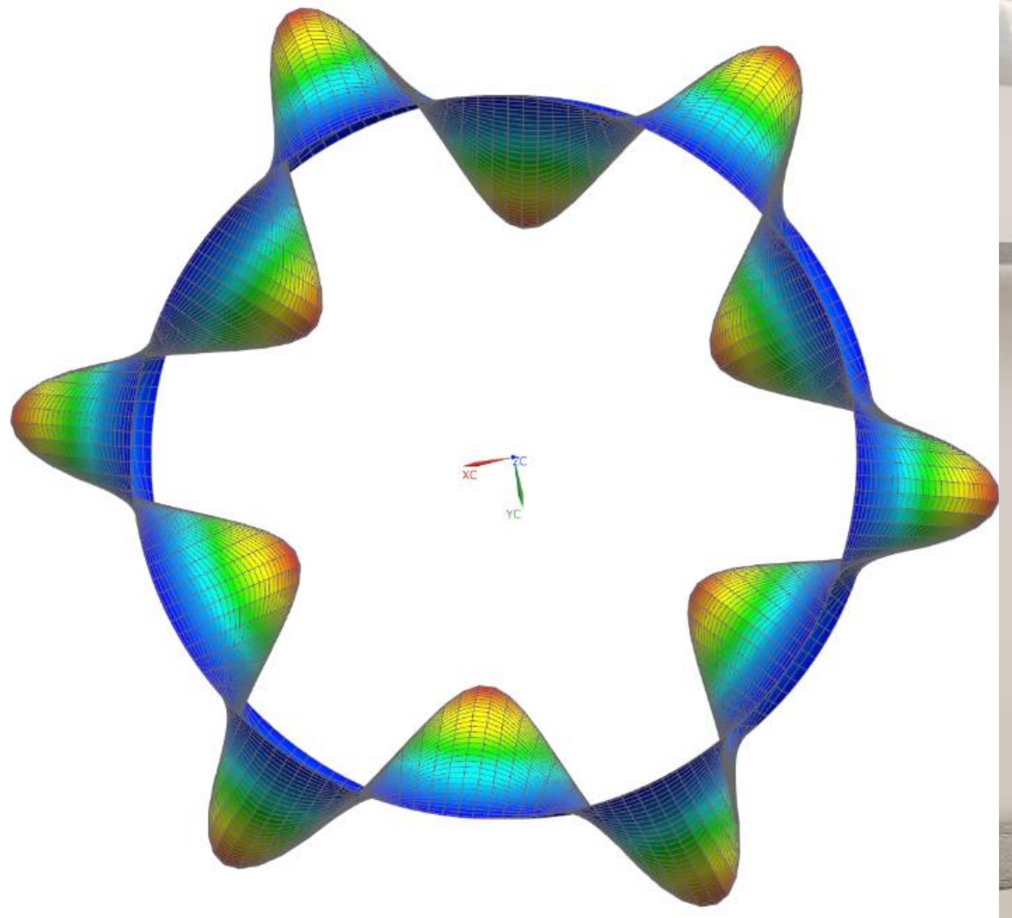
$$P_{cr} = \frac{Et}{R}\frac{1}{(n^2-1)\left(n^2\Big/\left(\frac{\pi R}{S}\right)^2+1\right)^2} + \frac{Et^3}{12(1-\nu^2)R^3}\left[(n^2-1)+\frac{2n^2-1-\nu}{n^2\Big/\left(\frac{\pi R}{S}\right)^2+1}\right]$$

Outer Warm Vessel



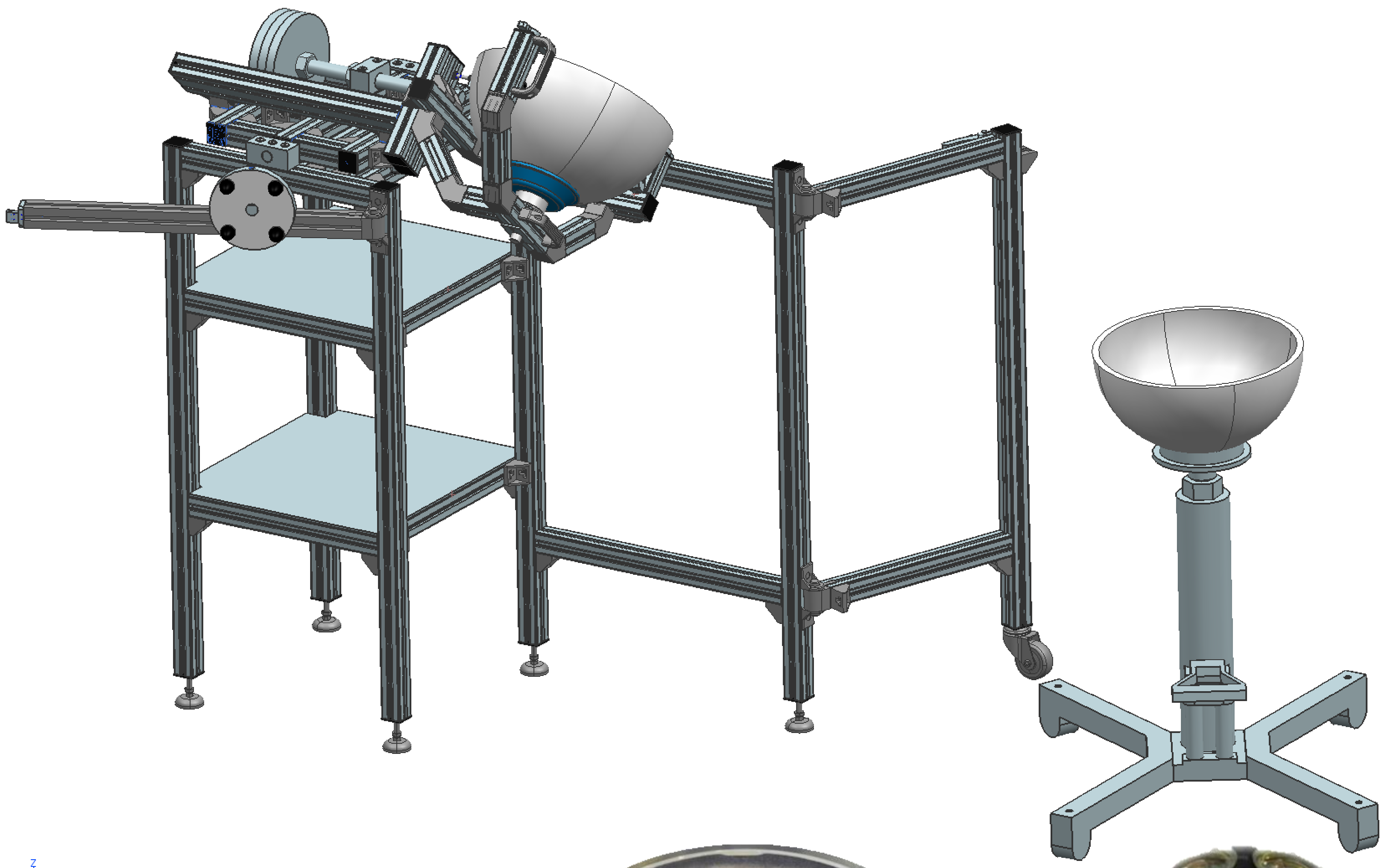
$$n = \sqrt[8]{\frac{3\left(\frac{\pi R}{S}\right)^4}{t^2\Big/\left(12(1-\nu^2)R^2\right)}}$$





VON MISES CYLINDER CRITICAL BUCKLING LOAD.

KM3Net Domkeerder
Lower operator load for DOM assembly.



Gravitational Waves,
create free-falling mirrors

MECHANICS IS IT JUST LIKE CYCLING?

(ONCE YOU KNOW HOW TO CYCLE, YOU KNOW HOW TO CYCLE).

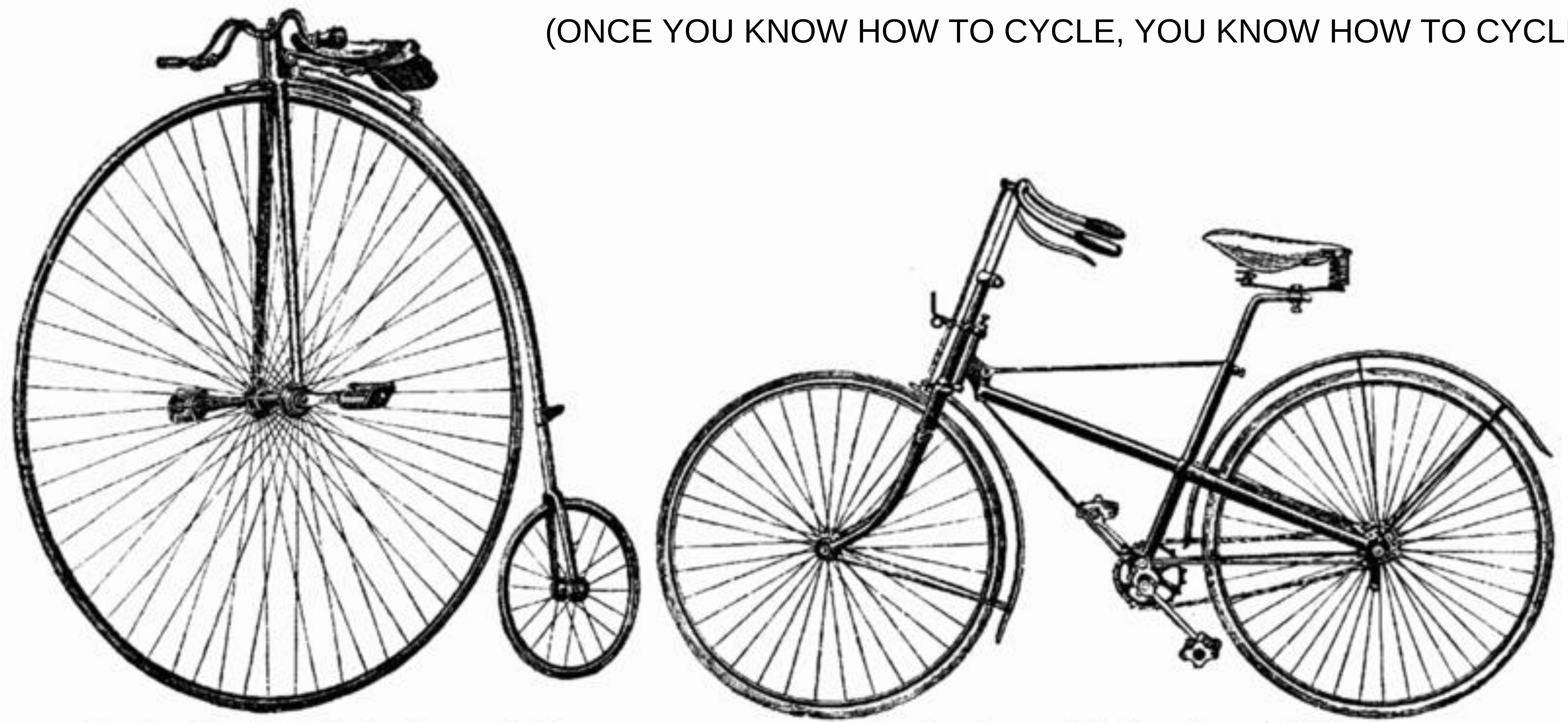


Fig. 2. Bicycle (Hochrad) von 1880. Fig. 3. Rover (Niederrad) von 1886.

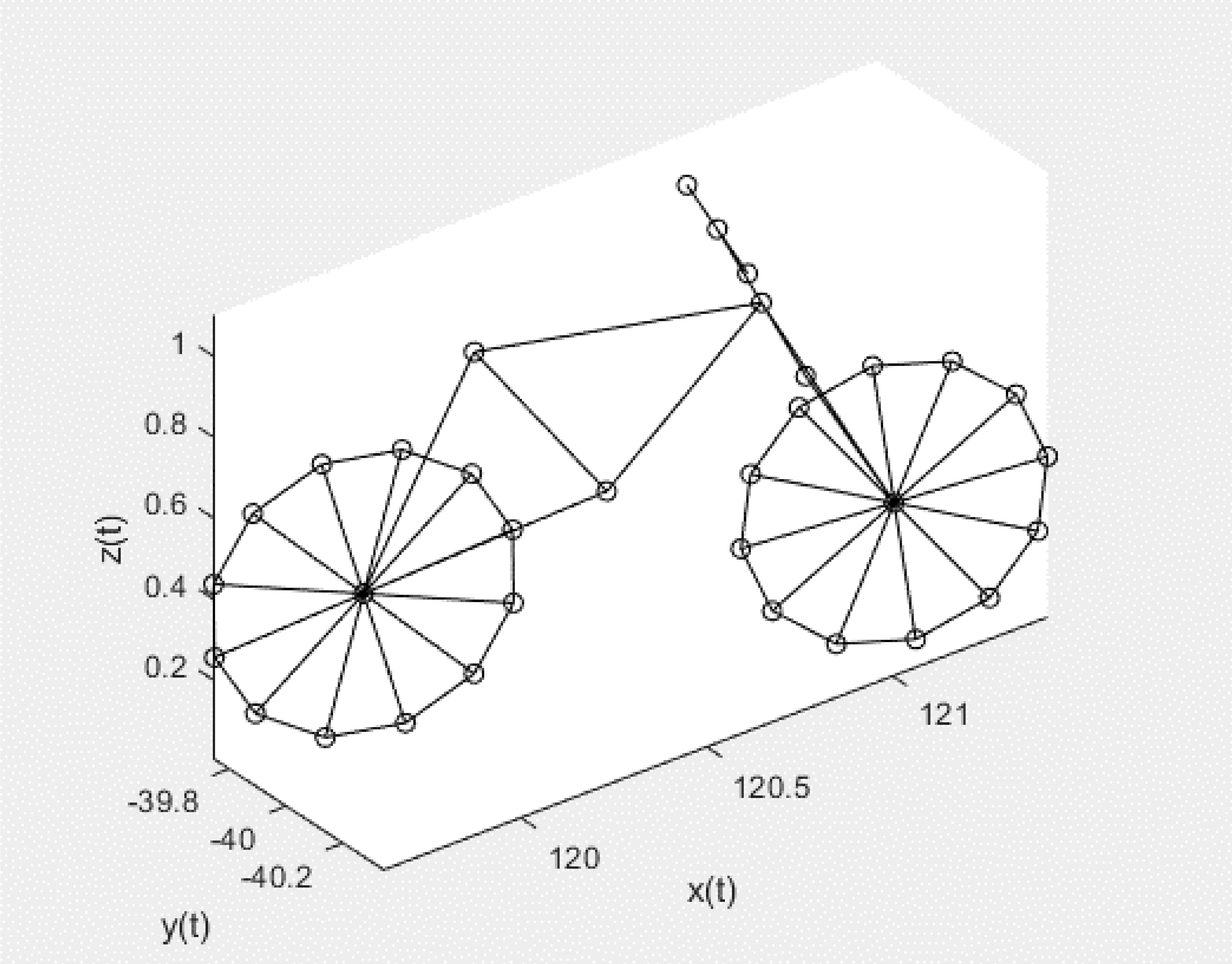
LEXIKON DER GESAMTEN TECHNIK (DICTIONARY OF TECHNOLOGY) FROM 1904 BY OTTO LUEGER.

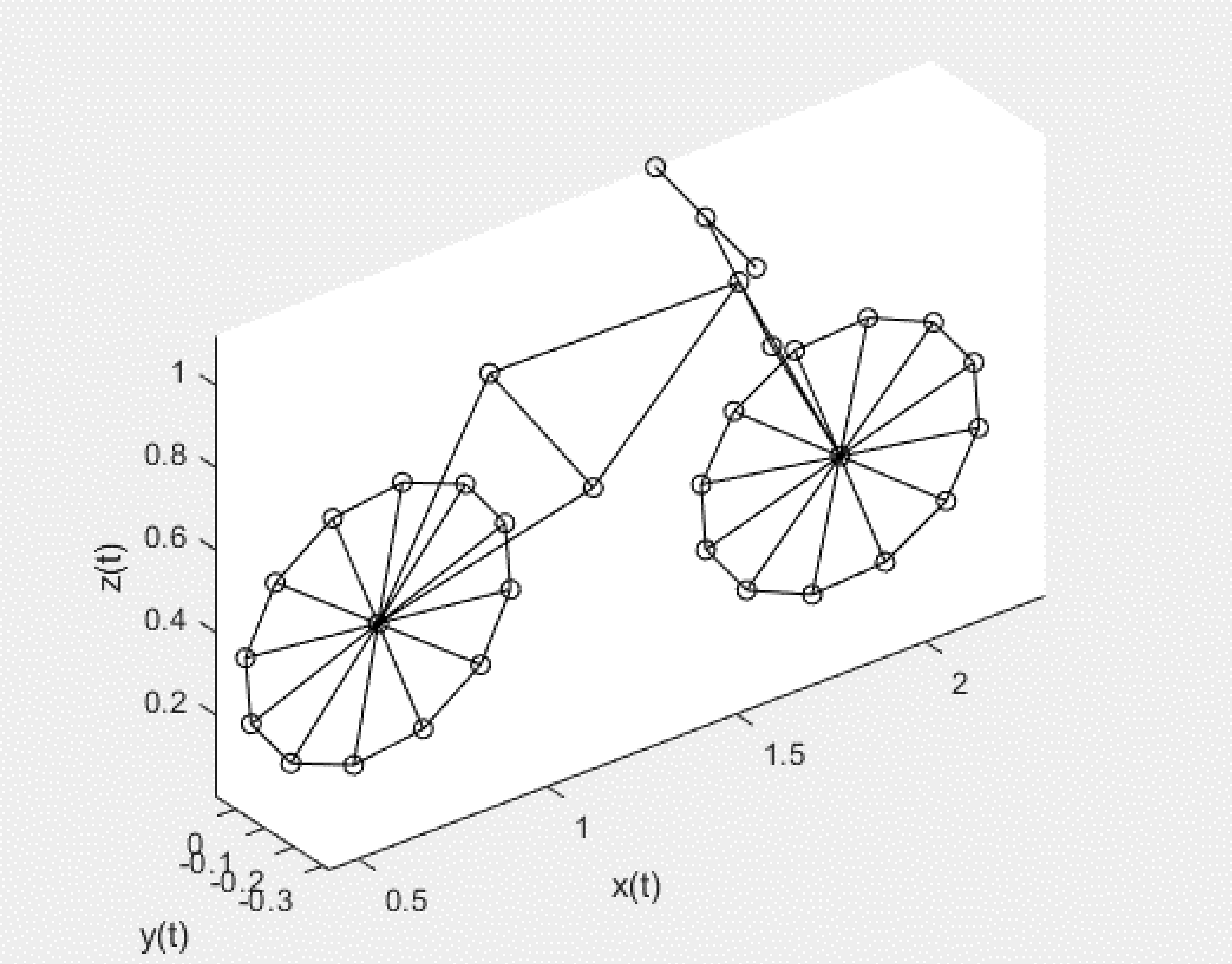
jacque tati: jour de fete

- J. D. G. KOOIJMAN *ET AL.* A BICYCLE CAN BE SELF-STABLE WITHOUT GYROSCOPIC OR CASTER EFFECTS.*SCIENCE* **332**,339 342(2011).DOI:10.1126/SCIENCE.1201959

Nikhef

DYNAMIC SIMULATIONS



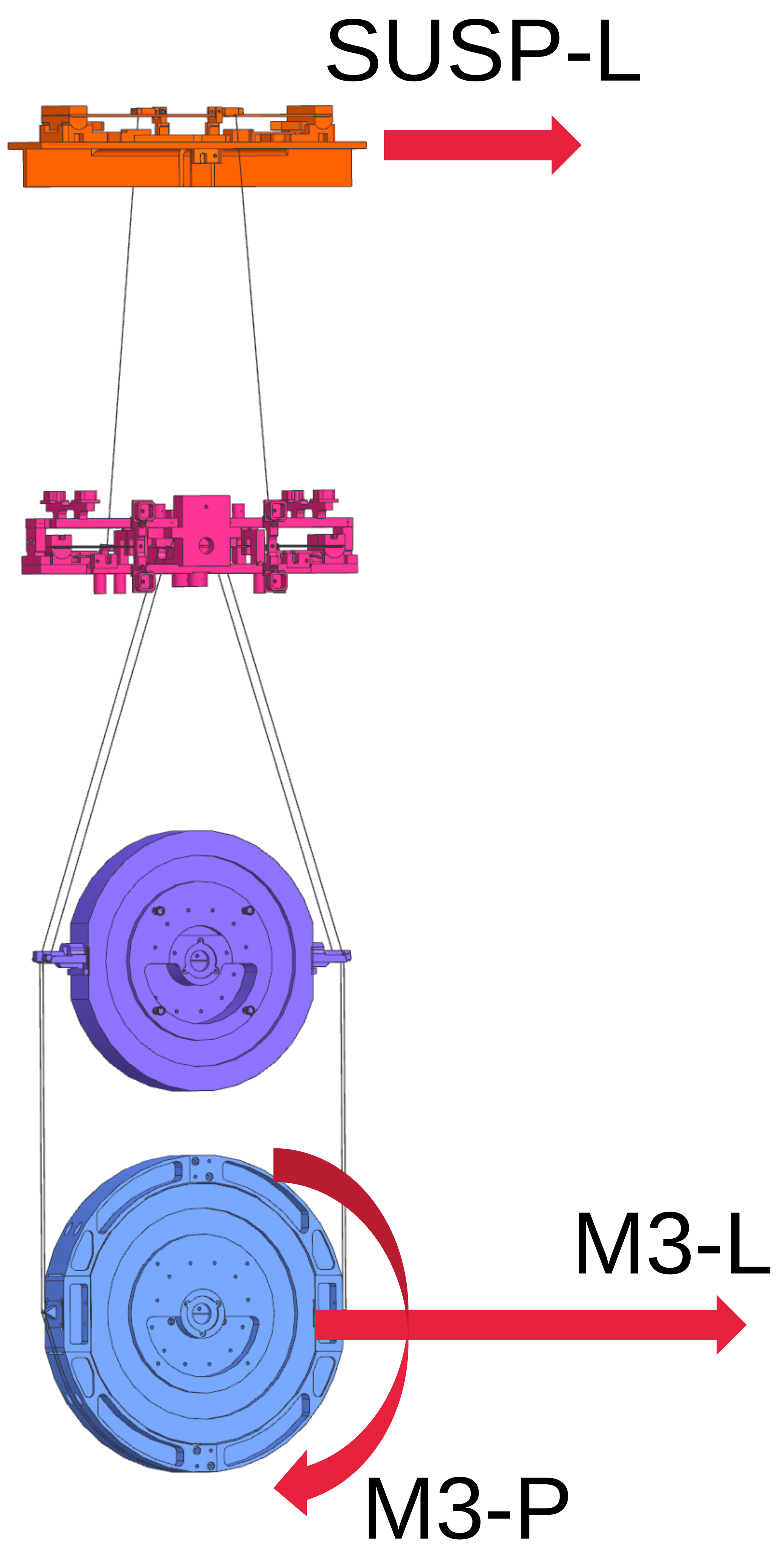


Nikhef

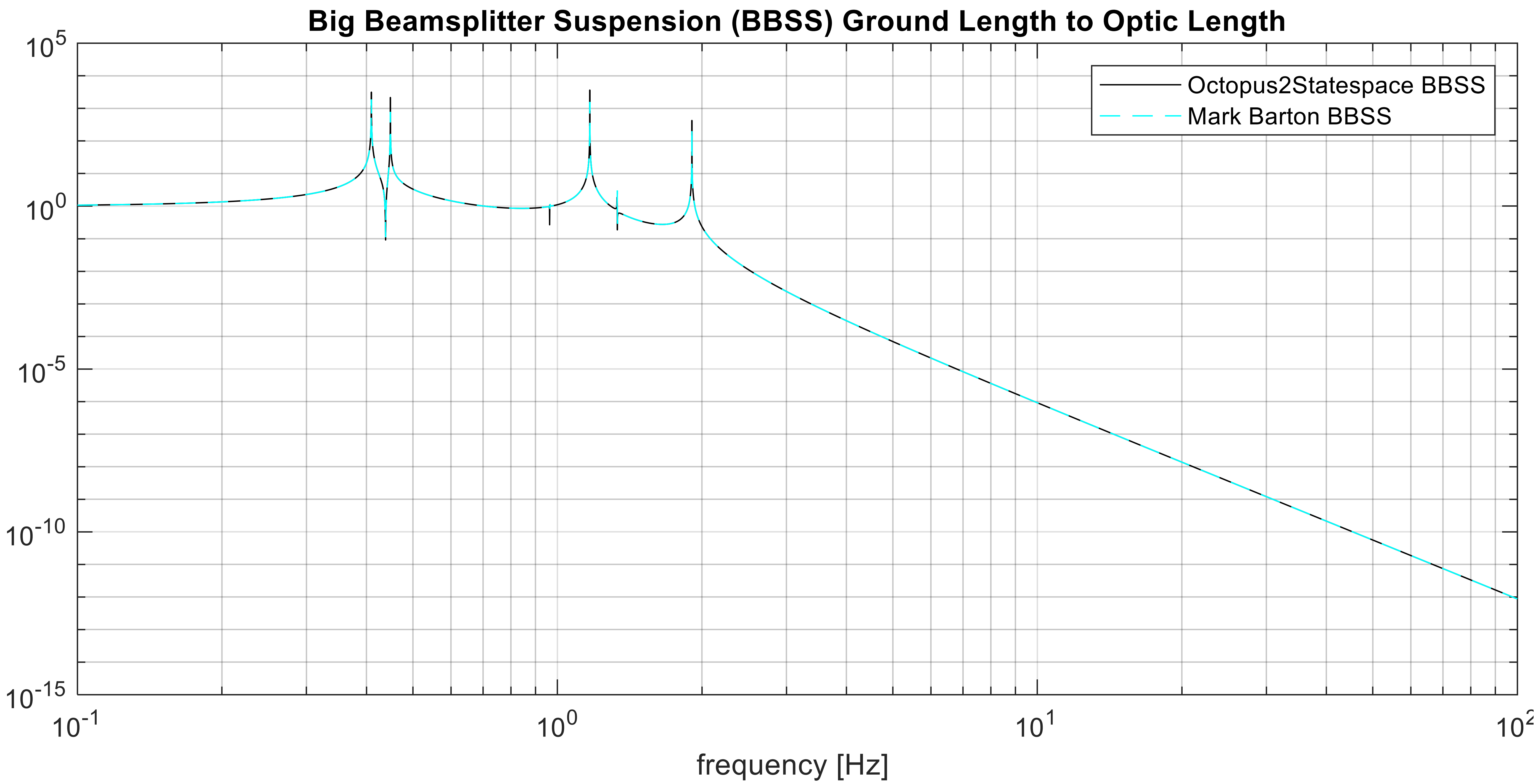
Einstein Telescope: The Need for CO-Design

Image Credit: Marco Kraan

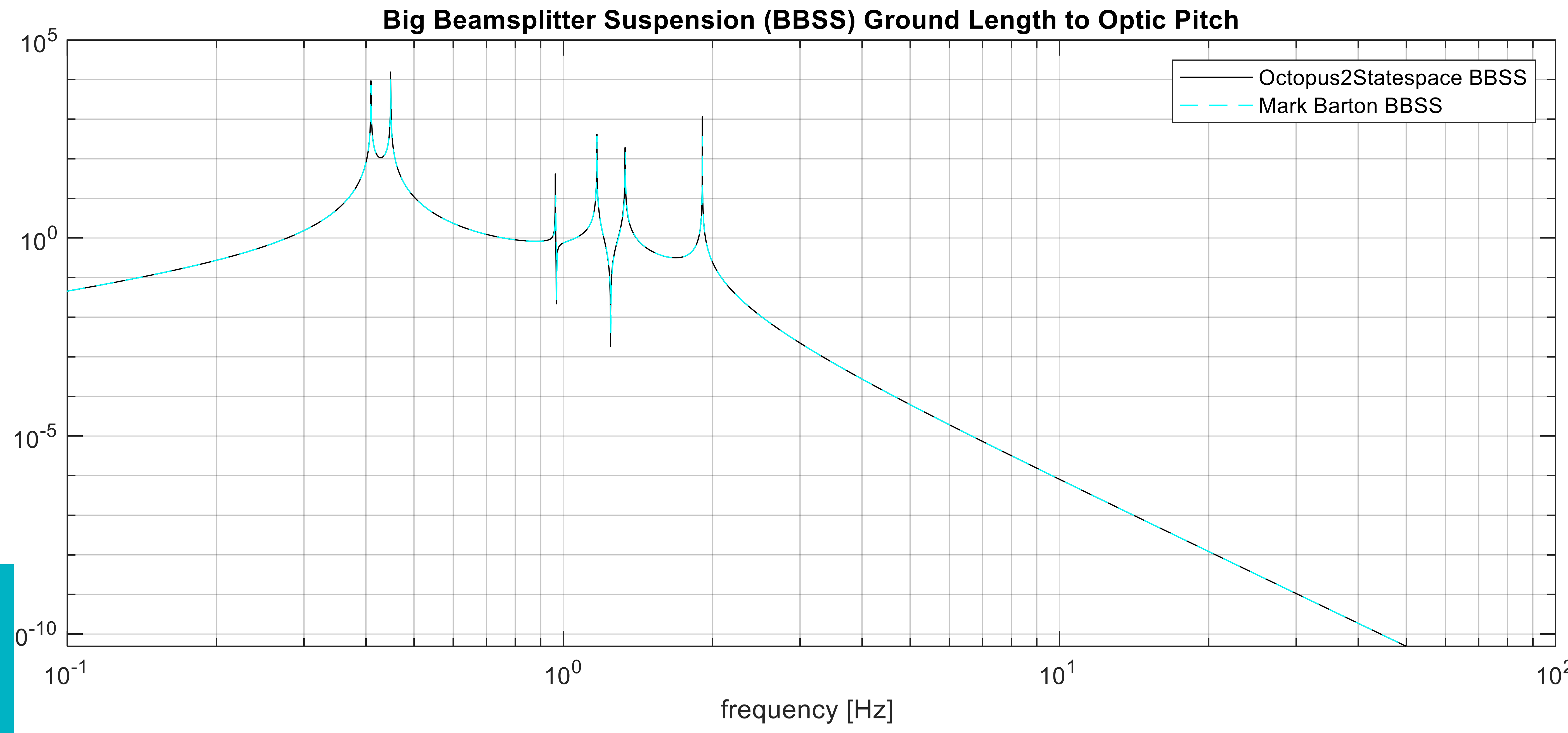
gravitational wave suspensions

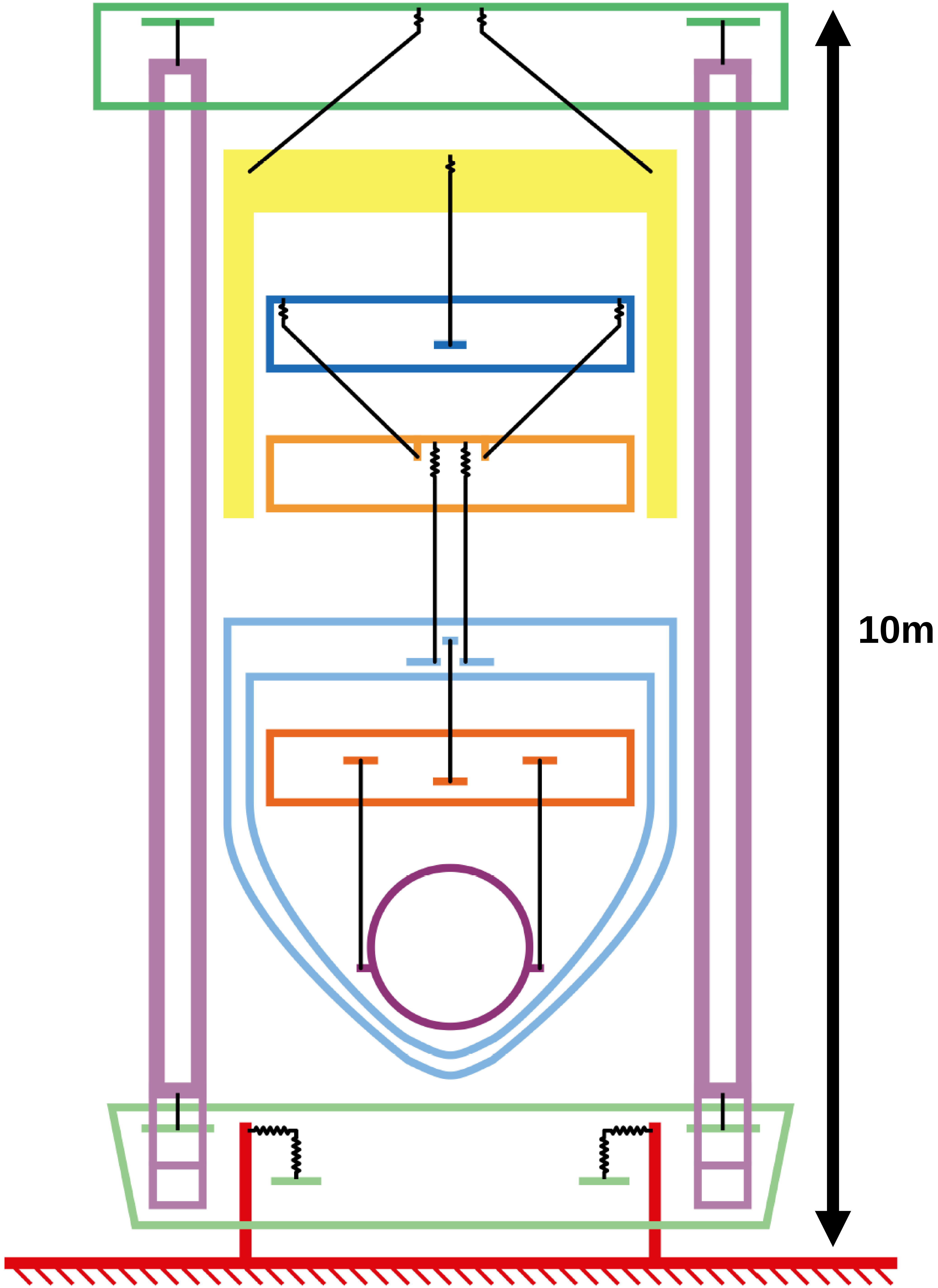


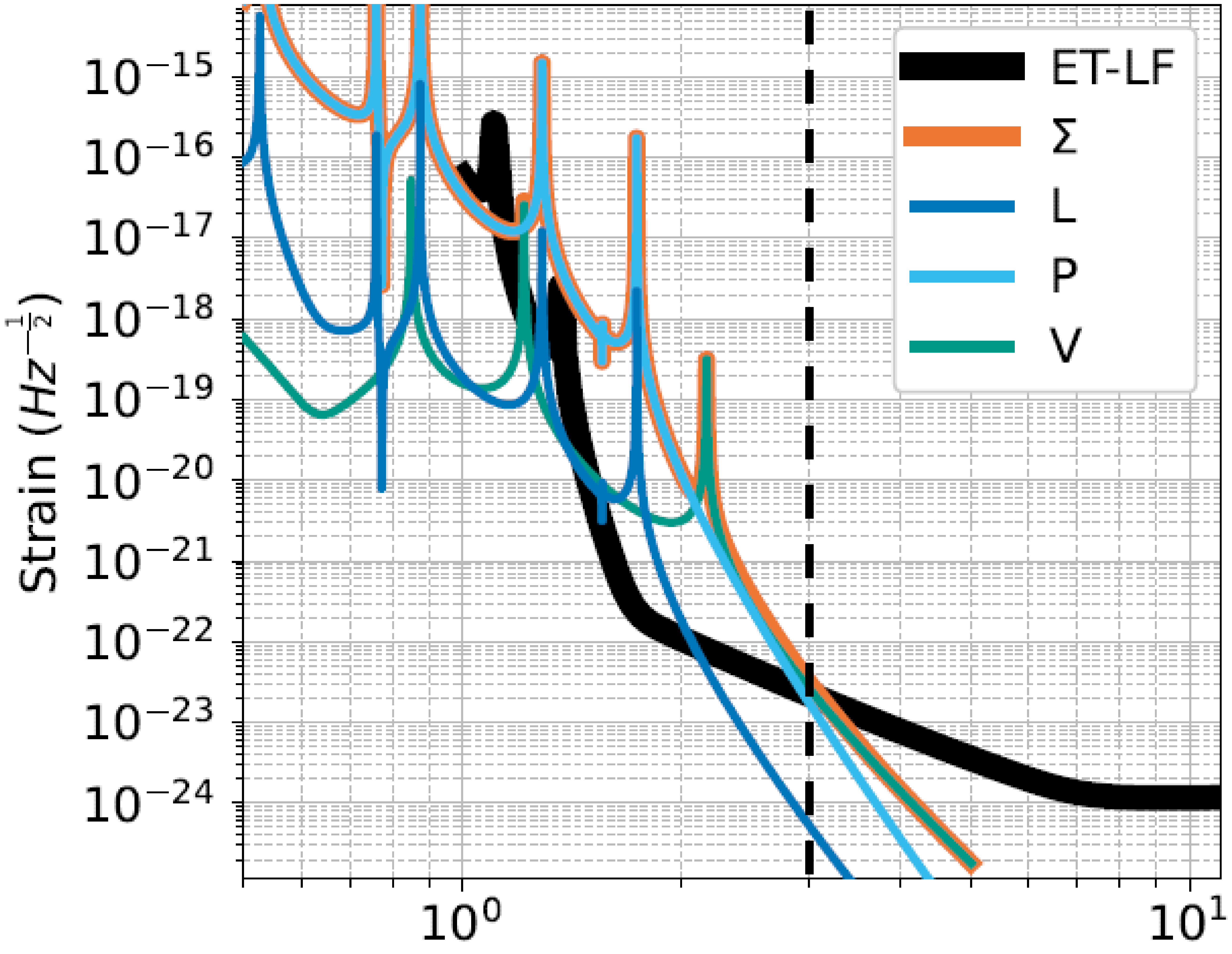
$\frac{\text{M3-L}}{\text{SUSP-L}}$



$\frac{\text{M3-P}}{\text{SUSP-L}}$



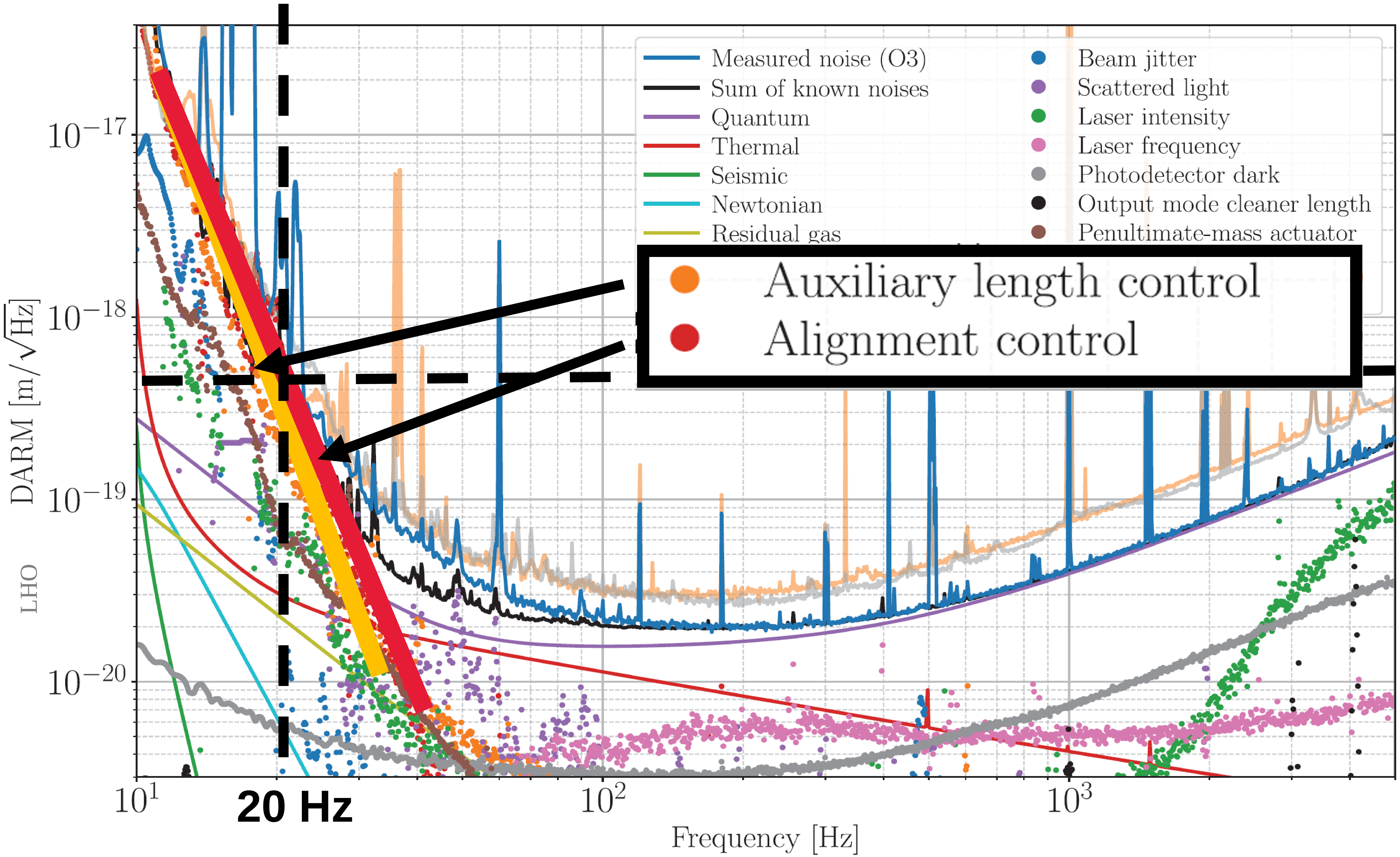




Goal: Generate better suspension designs for the Einstein Telescope

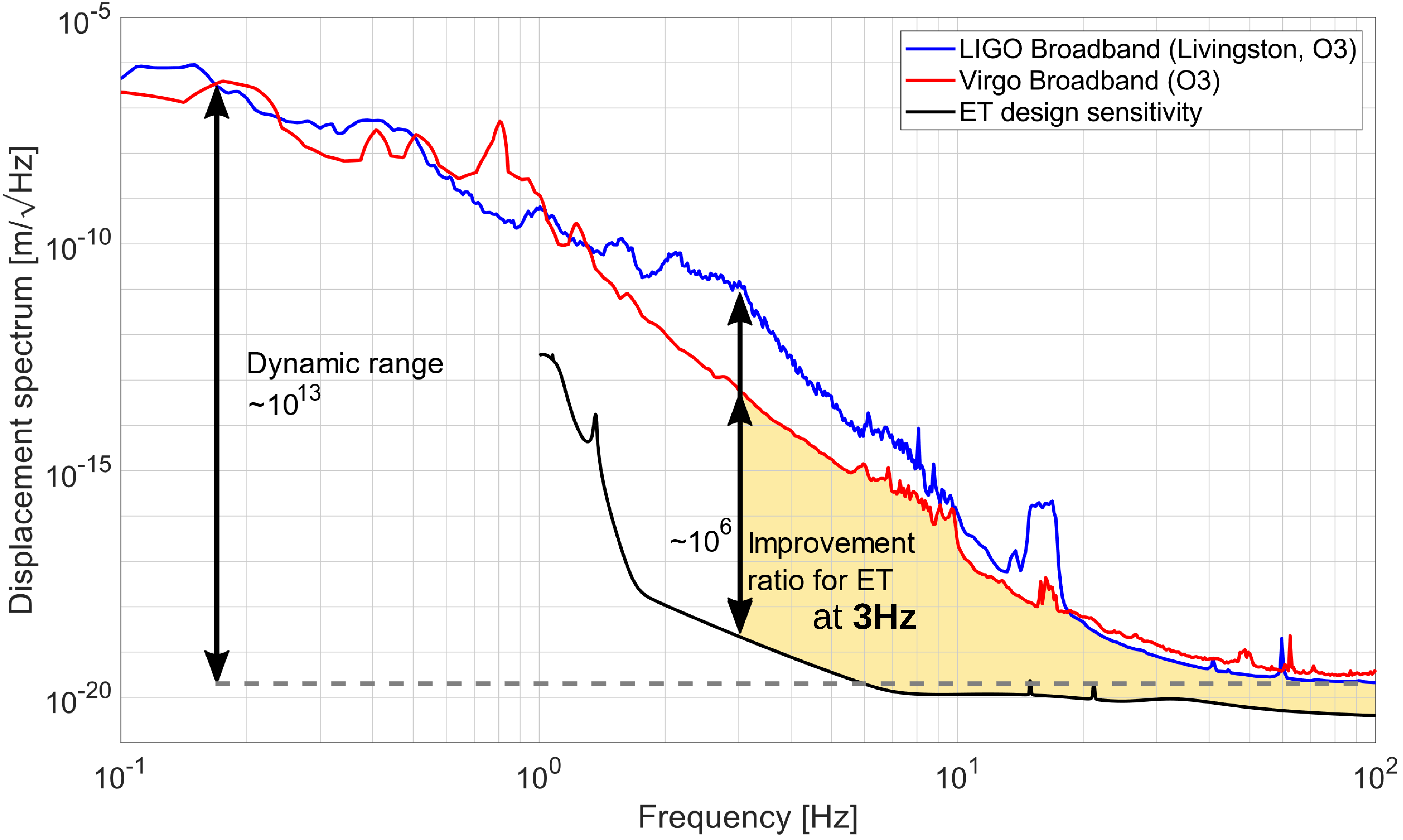
Credit: Nathan Holland

The LIGO Bucket – Limited by Low Frequency Control Noise



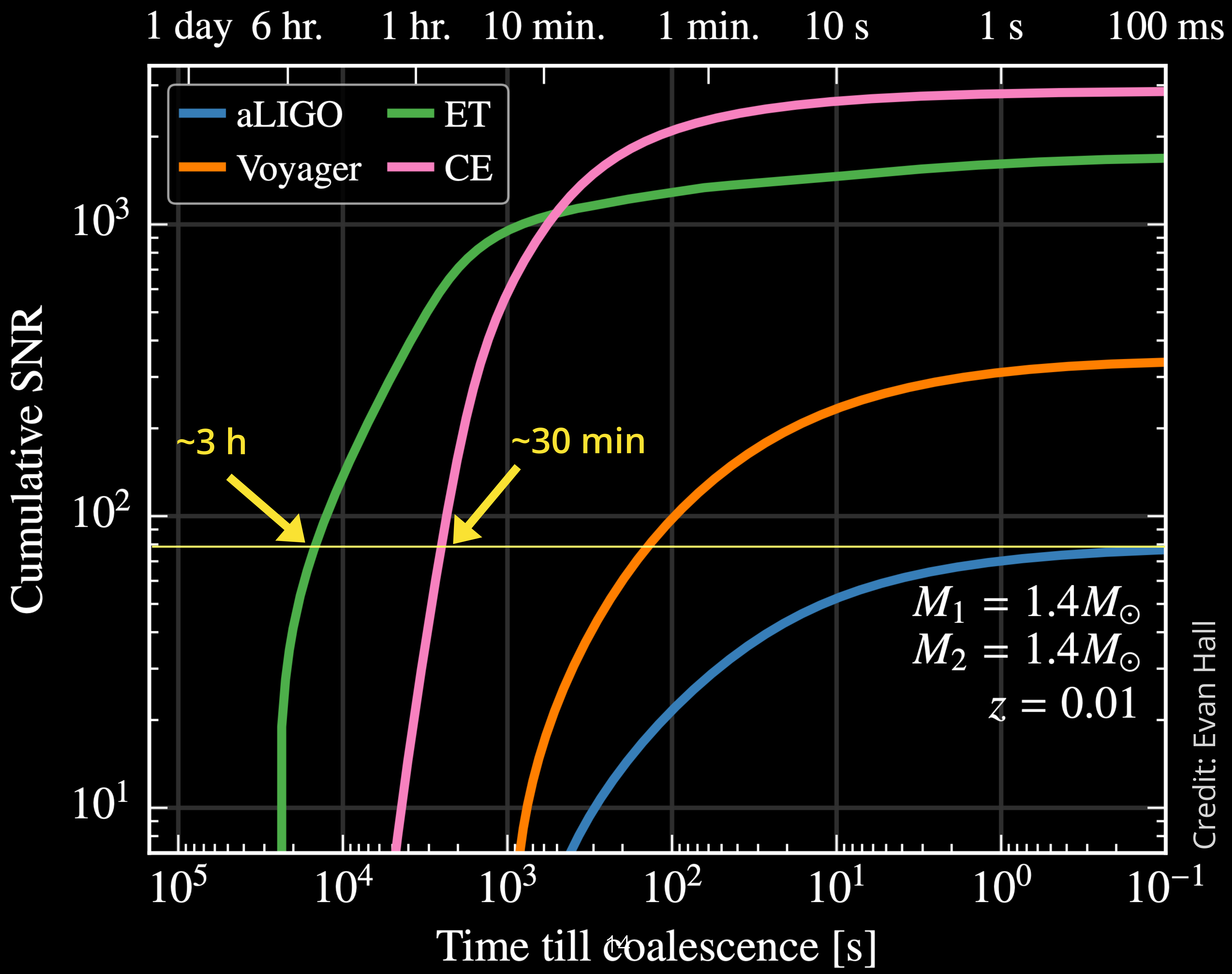
- Modelled
- • Measured

SENSITIVITY AND PERFORMANCE OF THE ADVANCED LIGO DETECTORS IN THE THIRD OBSERVING RUN. PHYS. REV . D 102, 0623003

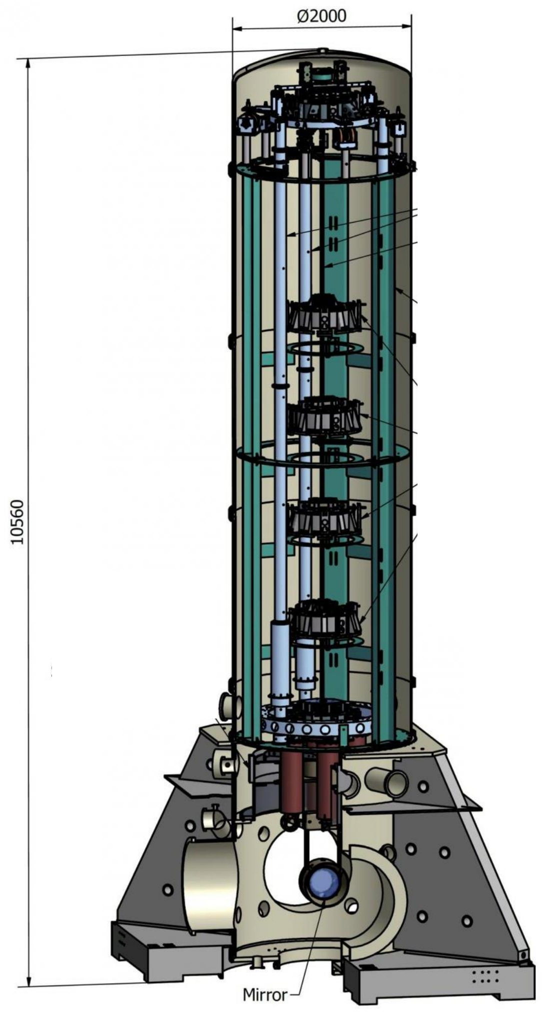


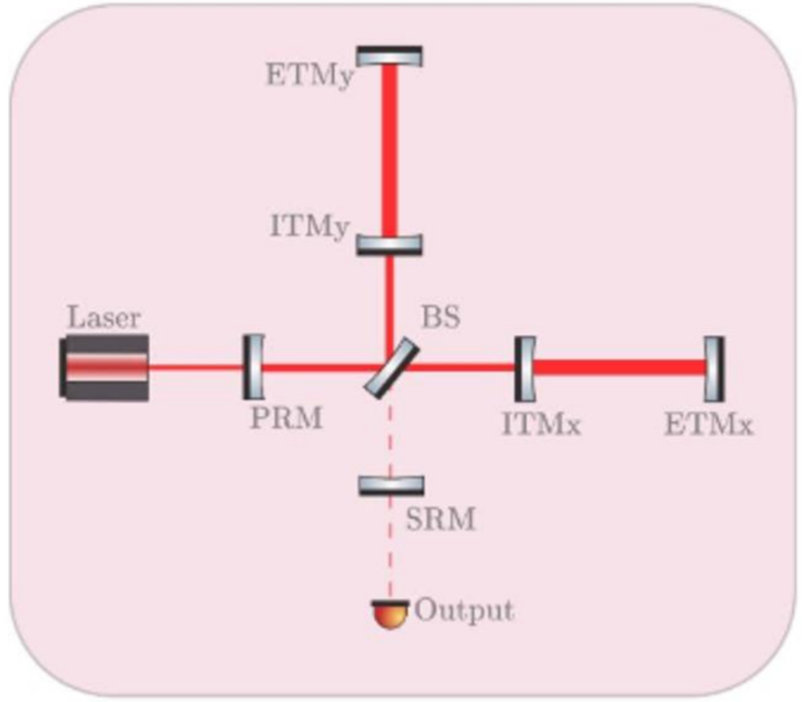
Credit: Conor Mow-Lowry

Einstein Telescope 3hz vs Cosmic Explorer 5hz Low frequency sensitivity



Controls





Ground motion

Local Controls (individual suspension)

- Minimize noise in detection band
- Minimize total accumulated RMS motion

Global Controls (complete interferometer)

- Keep the interferometer locked

Differential ARM length

Sensing / Actuation Noise

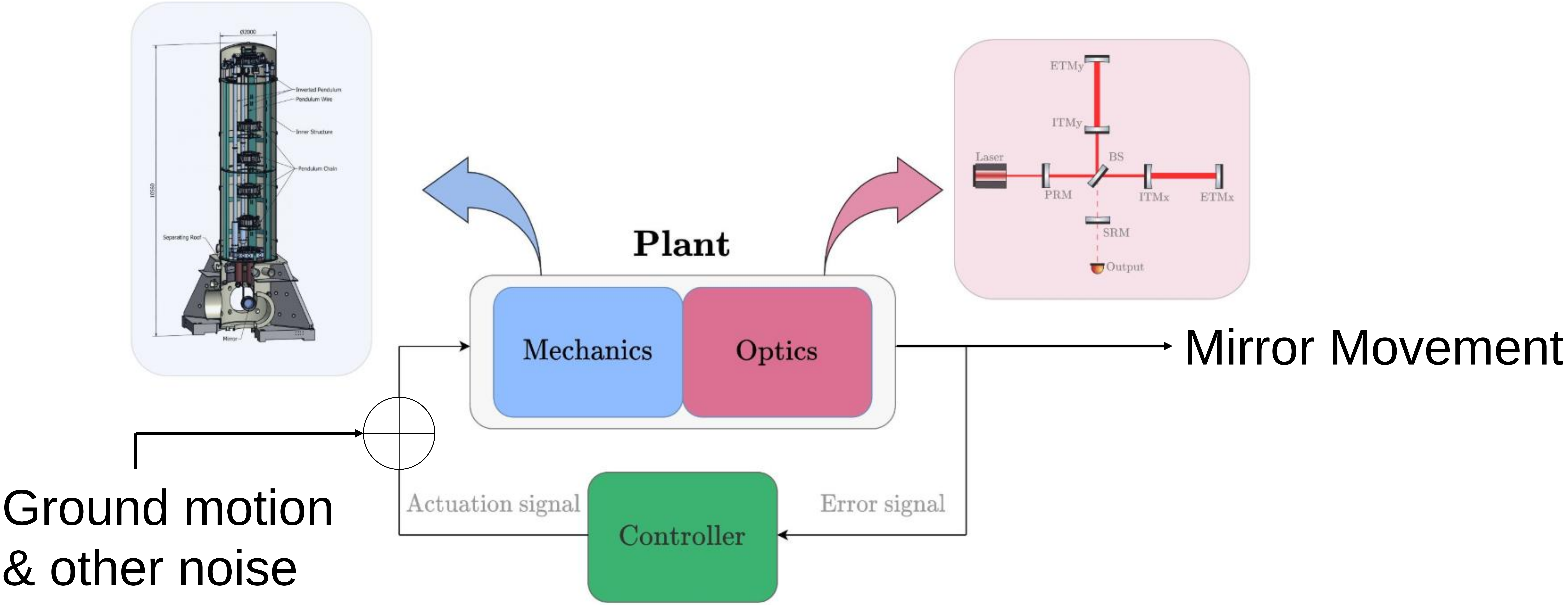


Figure base credit: Riccardo Maggiore

Sensing / Actuation Noise

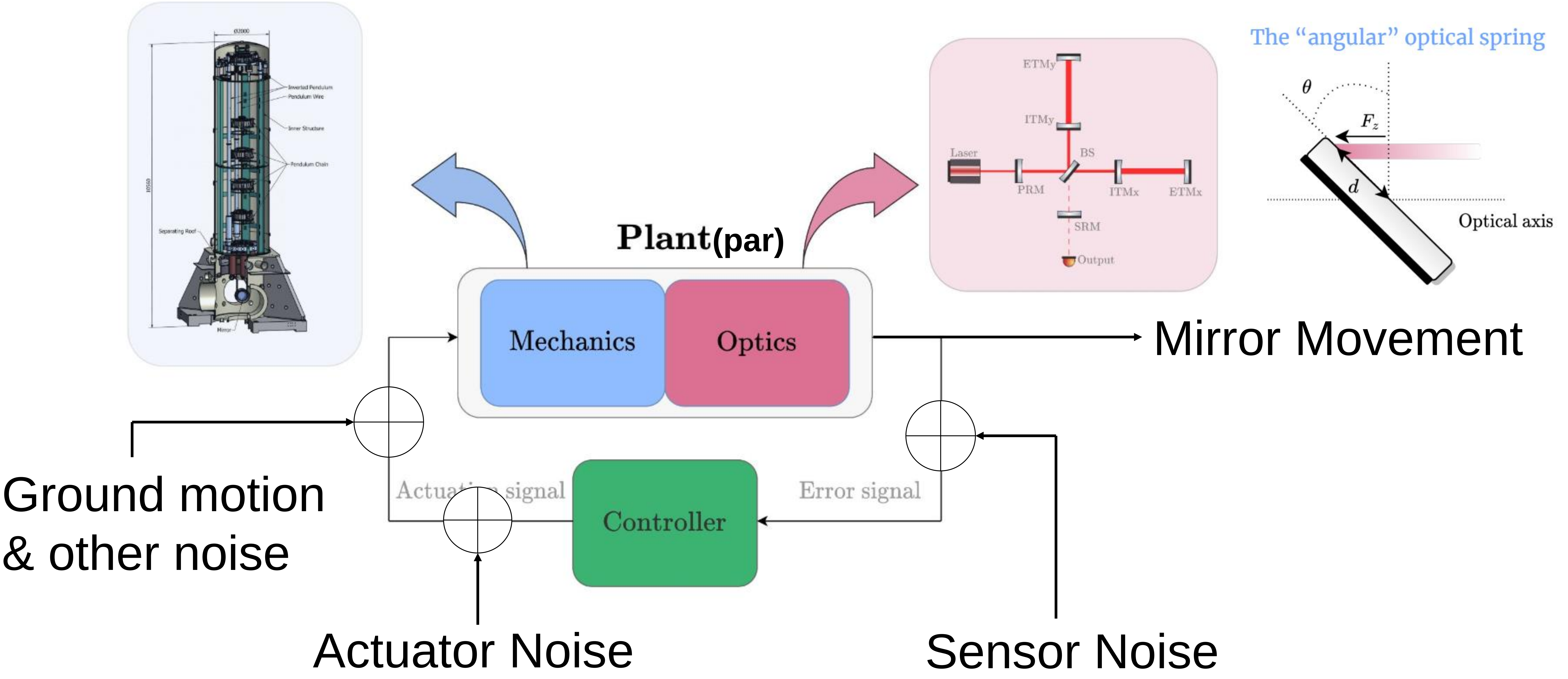
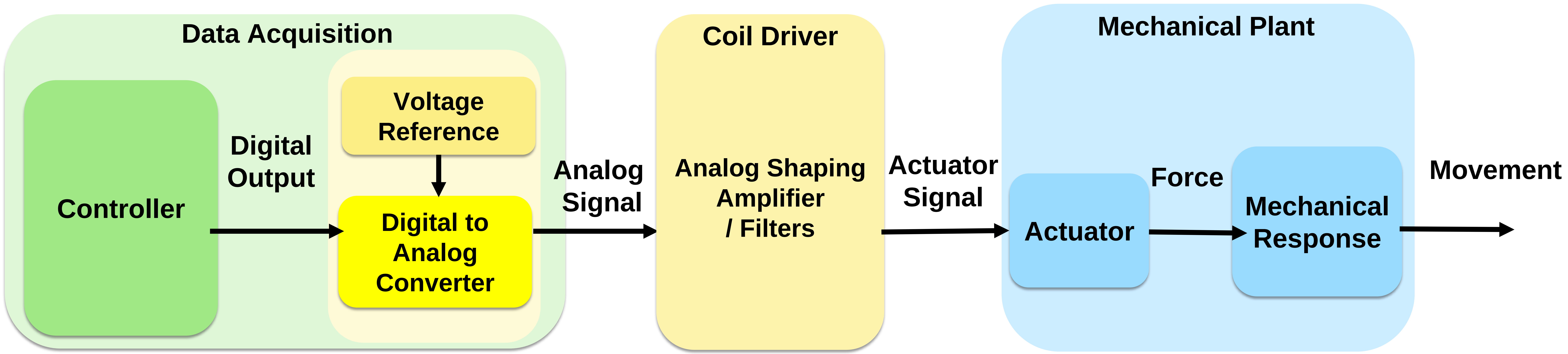


Figure base credit: Riccardo Maggiore

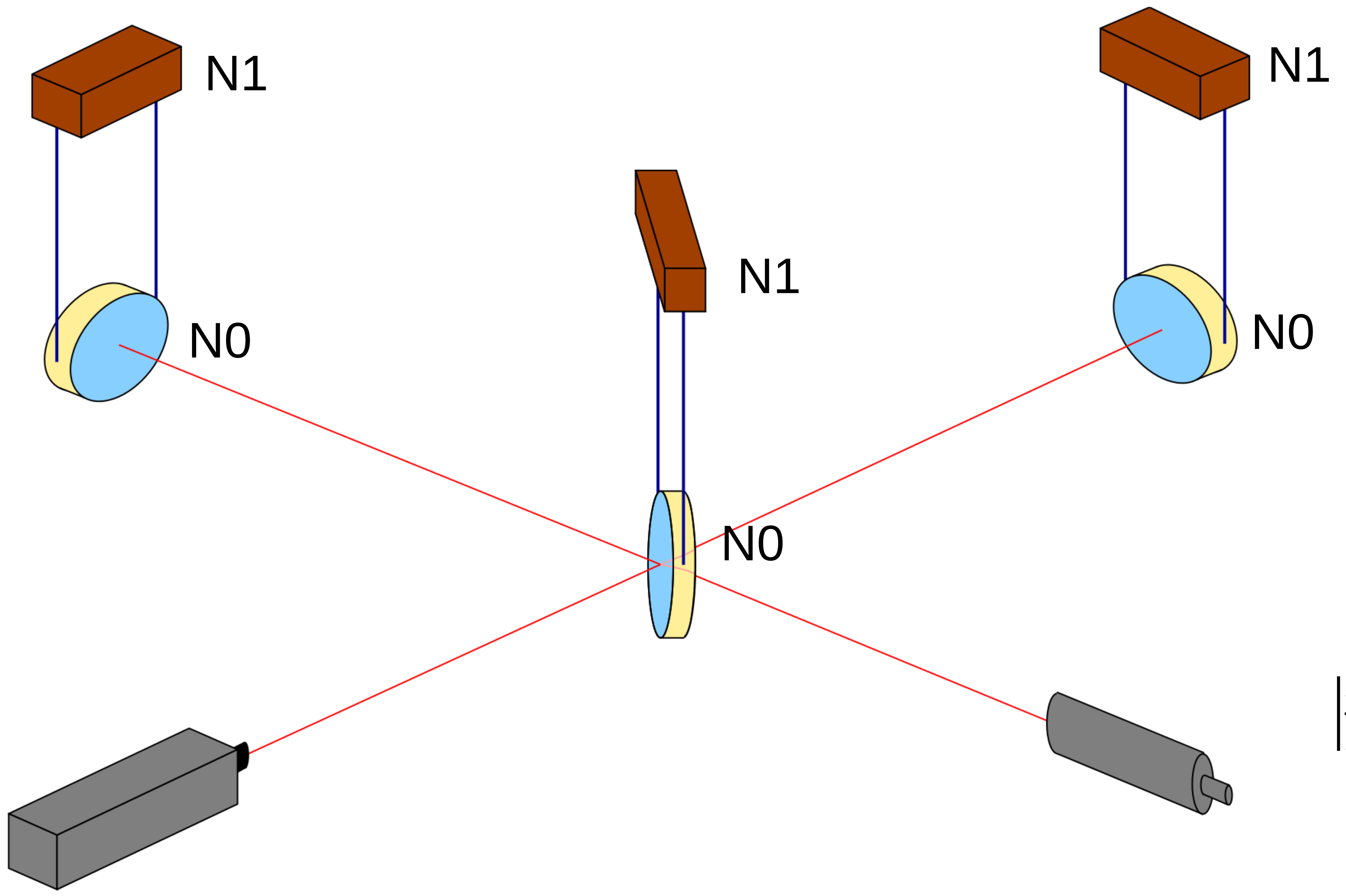
Actuation Noise Source

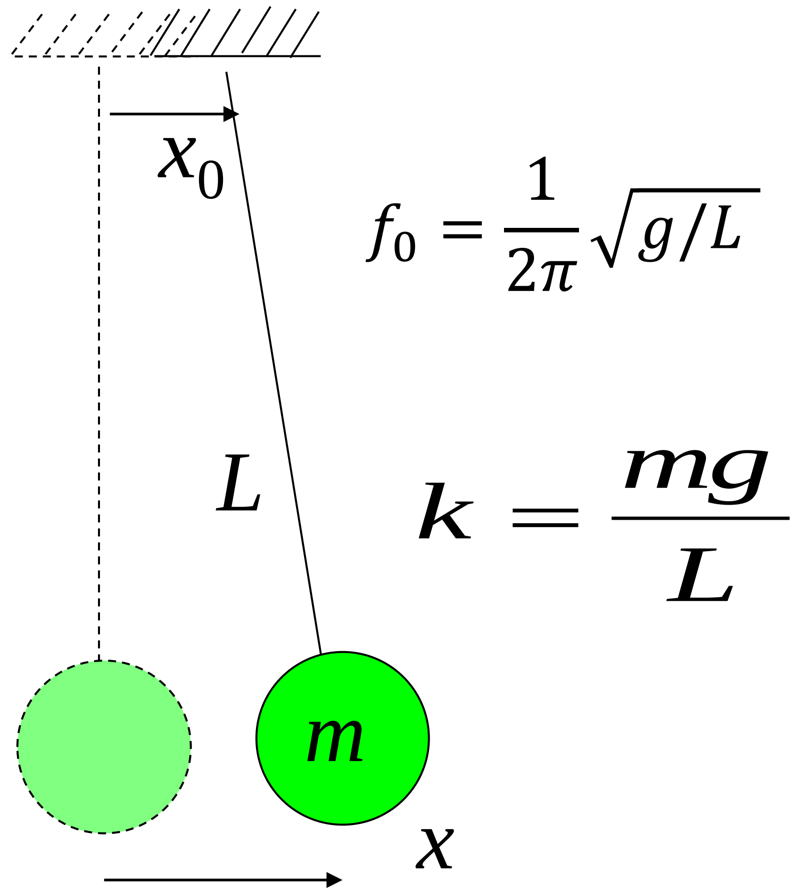


- DAC is the weakest link.

- Actuator Noise = DAC Dynamic range x ActuationRange x Mechanics Response

credit: Paolo Ruggi

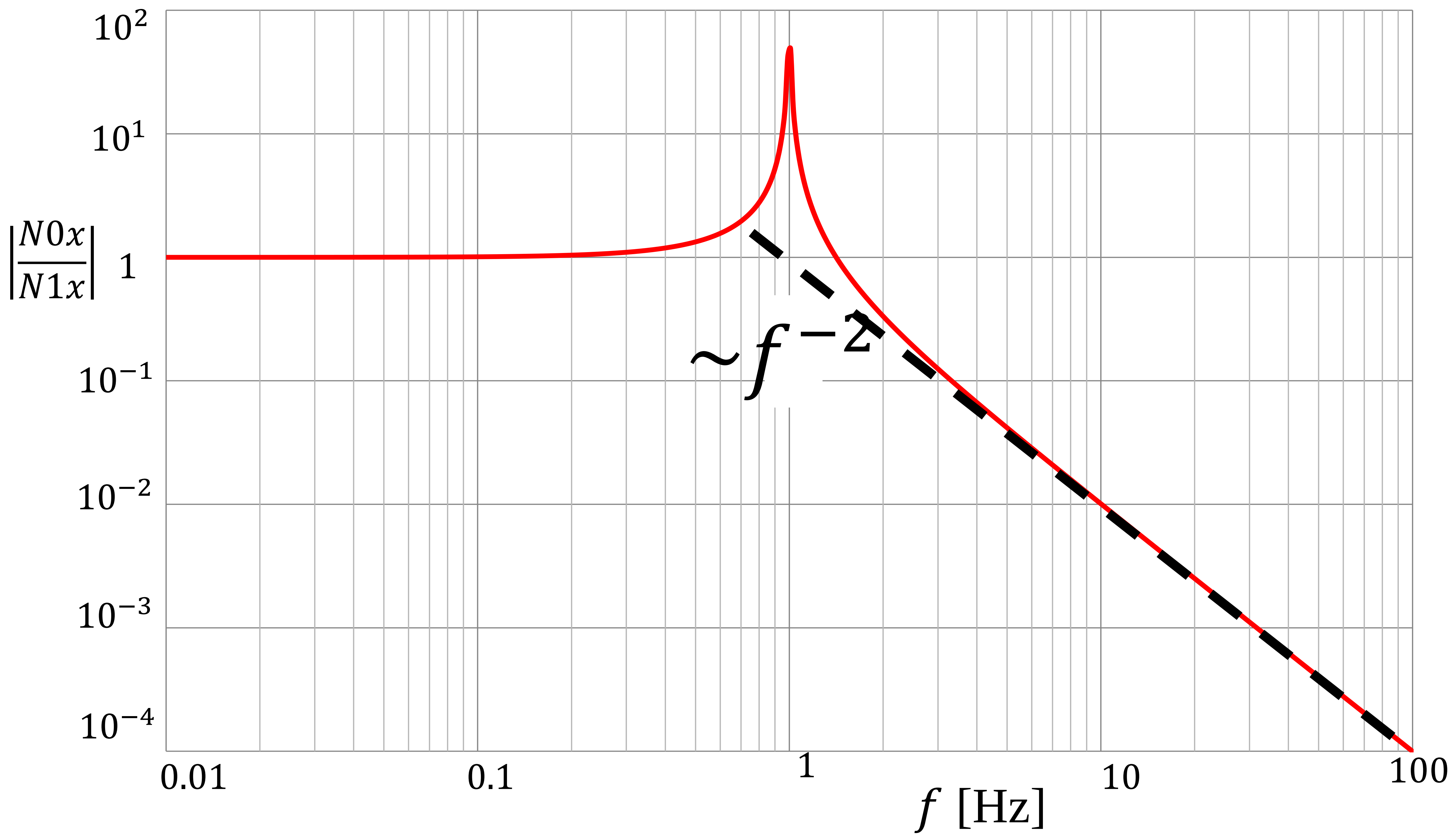




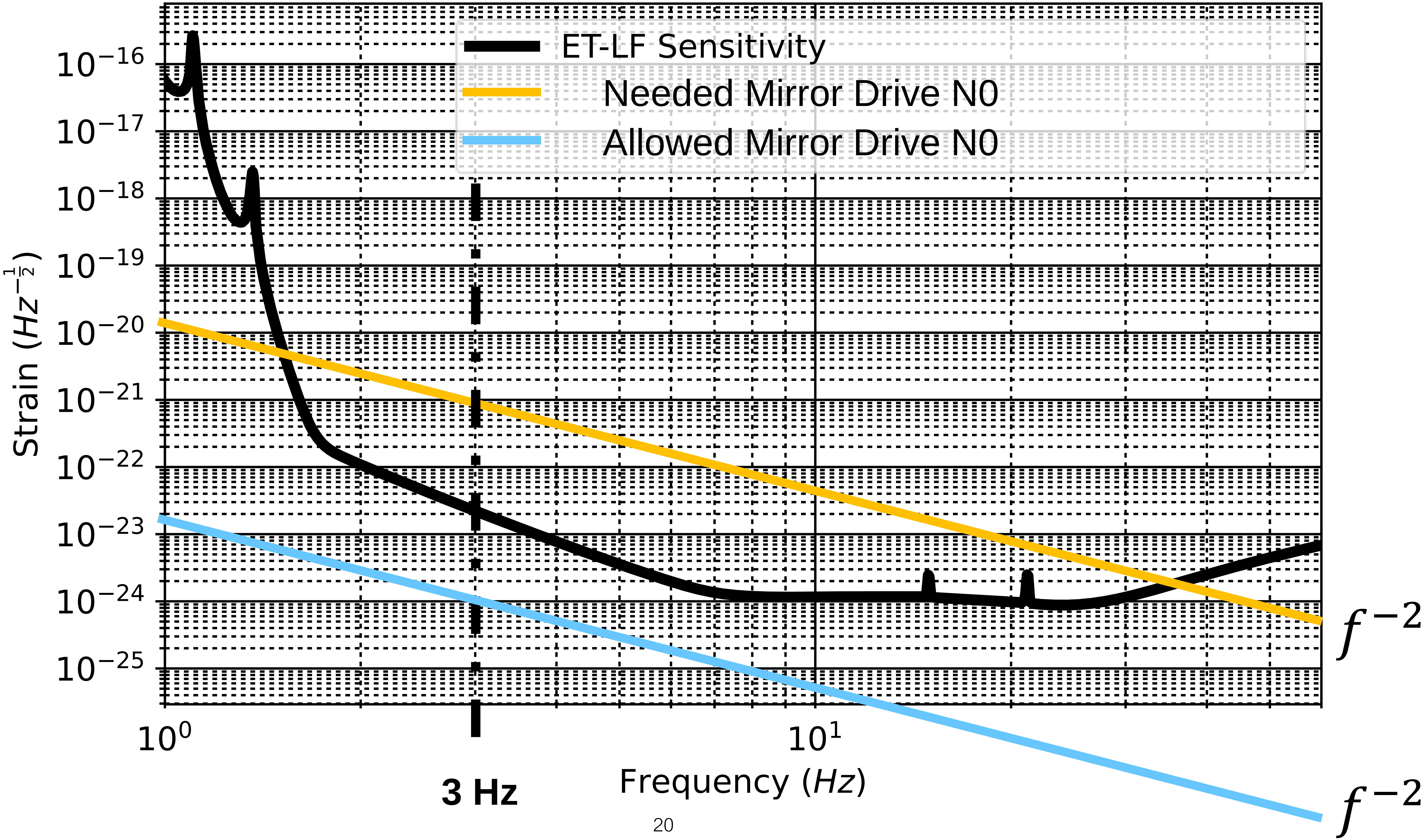
Equation of motion $m\ddot{x} = -k(x - x_0)$

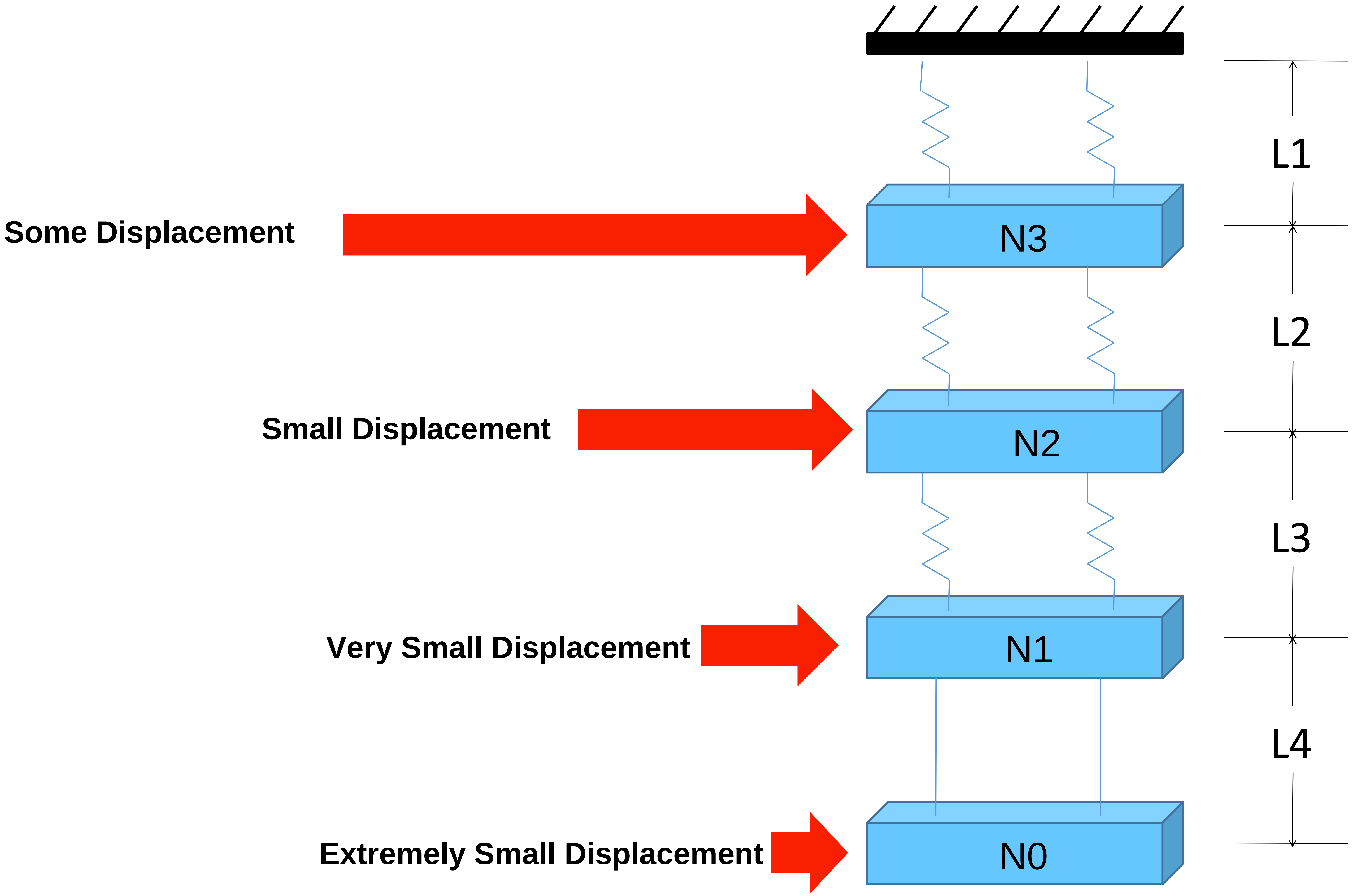
Resonance frequency $f_0 = \frac{1}{2\pi}\sqrt{k/m}$

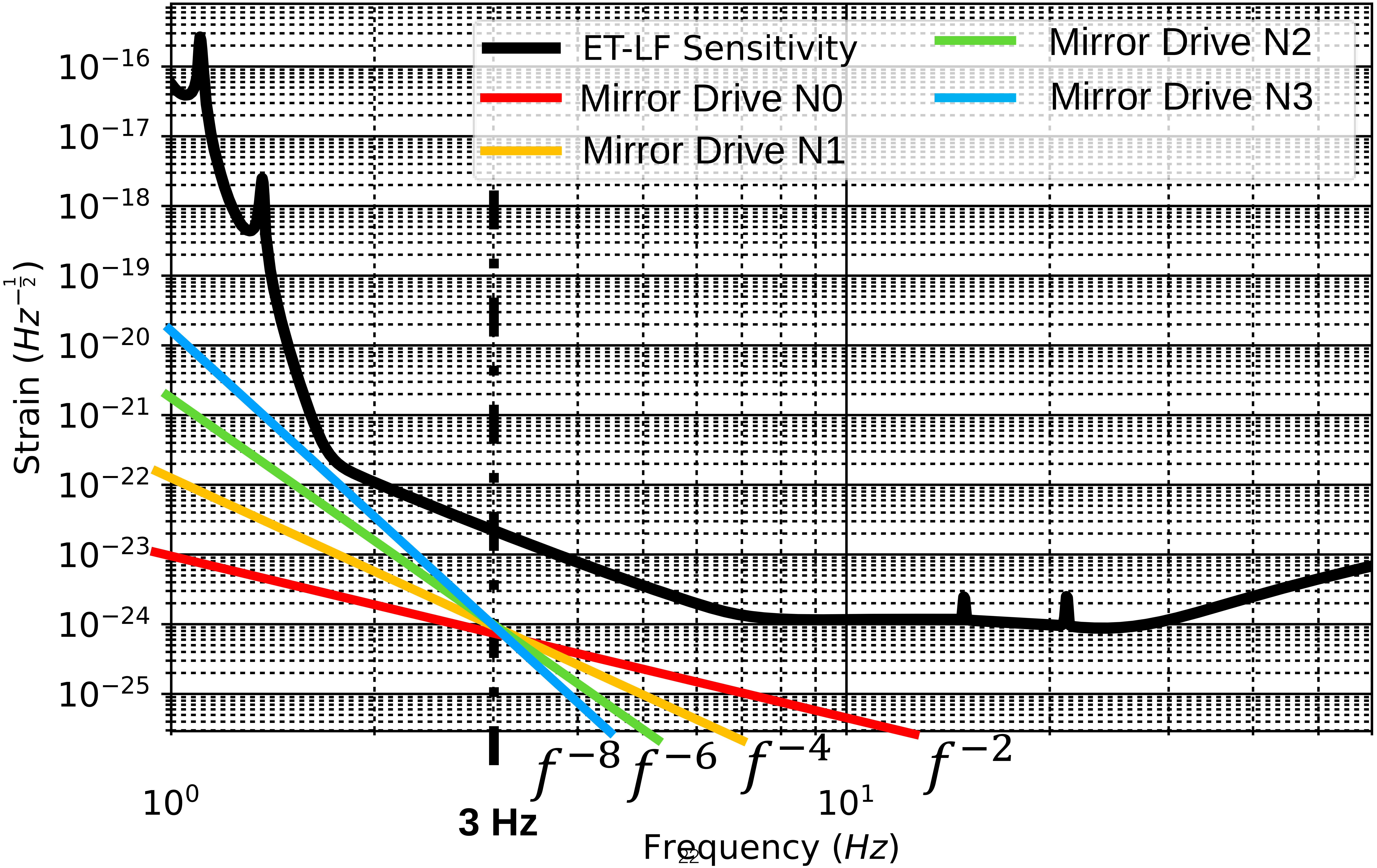
Transfer function $T = \frac{\hat{x}}{\hat{x}_0} = \frac{1}{1 - f^2/f_0^2}$

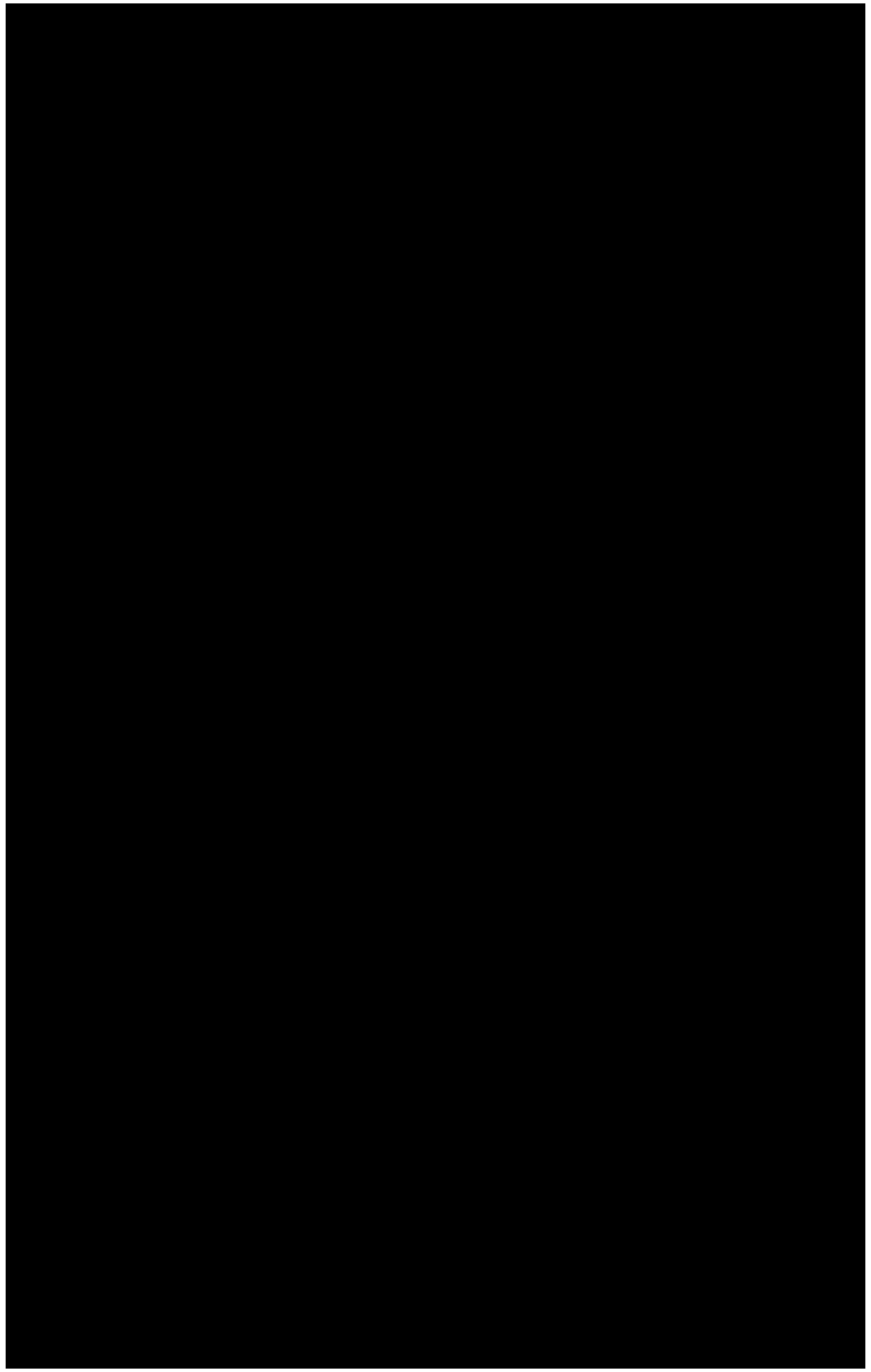


credit:Eric Hennes


ET-LF Sensitivity
Needed Mirror Drive N0
Allowed Mirror Drive N0
Strain ($Hz^{-\frac{1}{2}}$)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
Frequency (Hz)
3 Hz
f^{-2}
f^{-2}

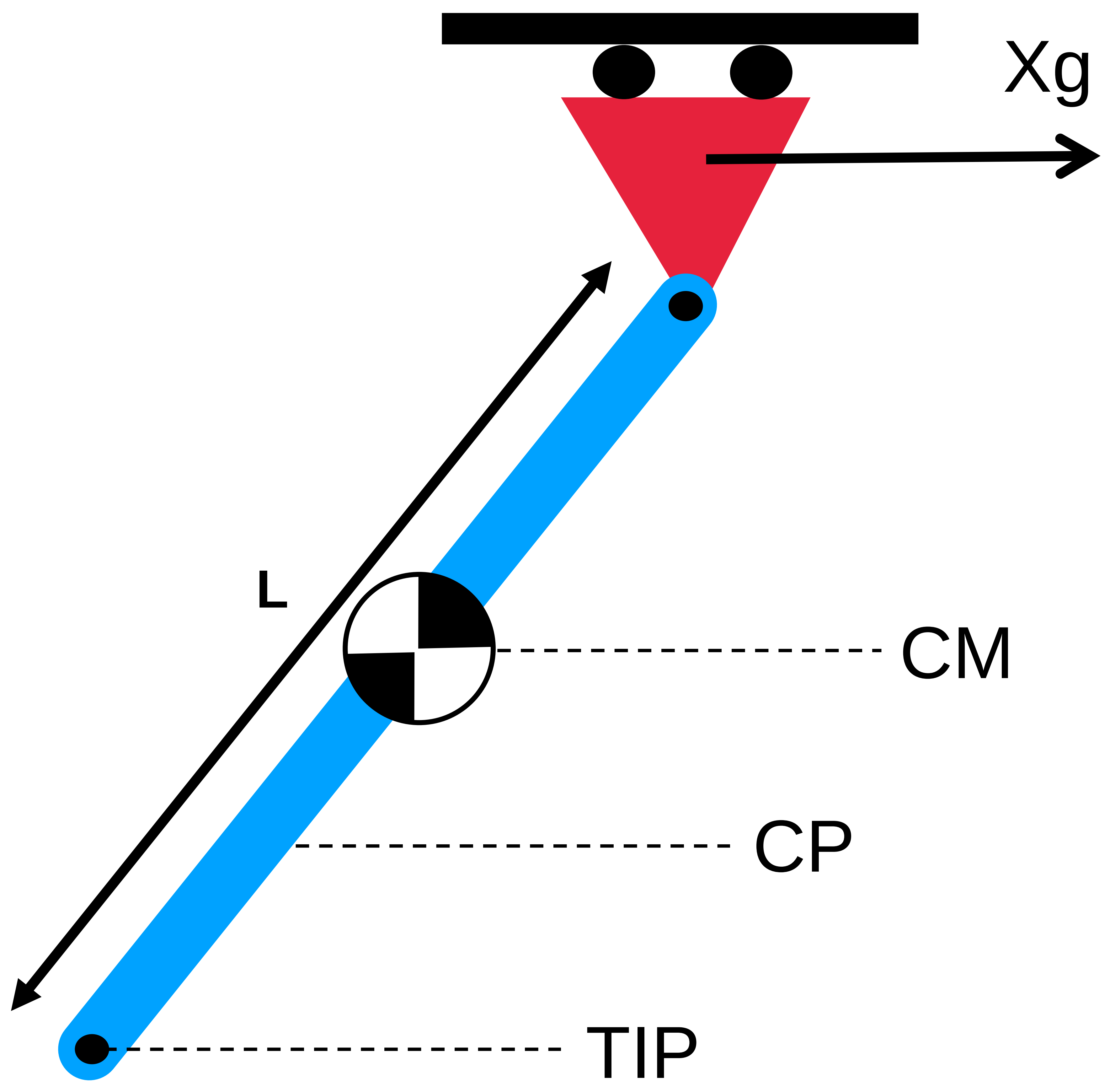

Some Displacement
Small Displacement
Very Small Displacement
Extremely Small Displacement
N3
N2
N1
N0
L1
L2
L3
L4


ET-LF Sensitivity
Mirror Drive N0
Mirror Drive N1
Mirror Drive N2
Mirror Drive N3
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Strain ($Hz^{-\frac{1}{2}}$)
f^{-8}
f^{-6}
f^{-4}
f^{-2}
10^{0}
10^{1}
3 Hz
Frequency (Hz)

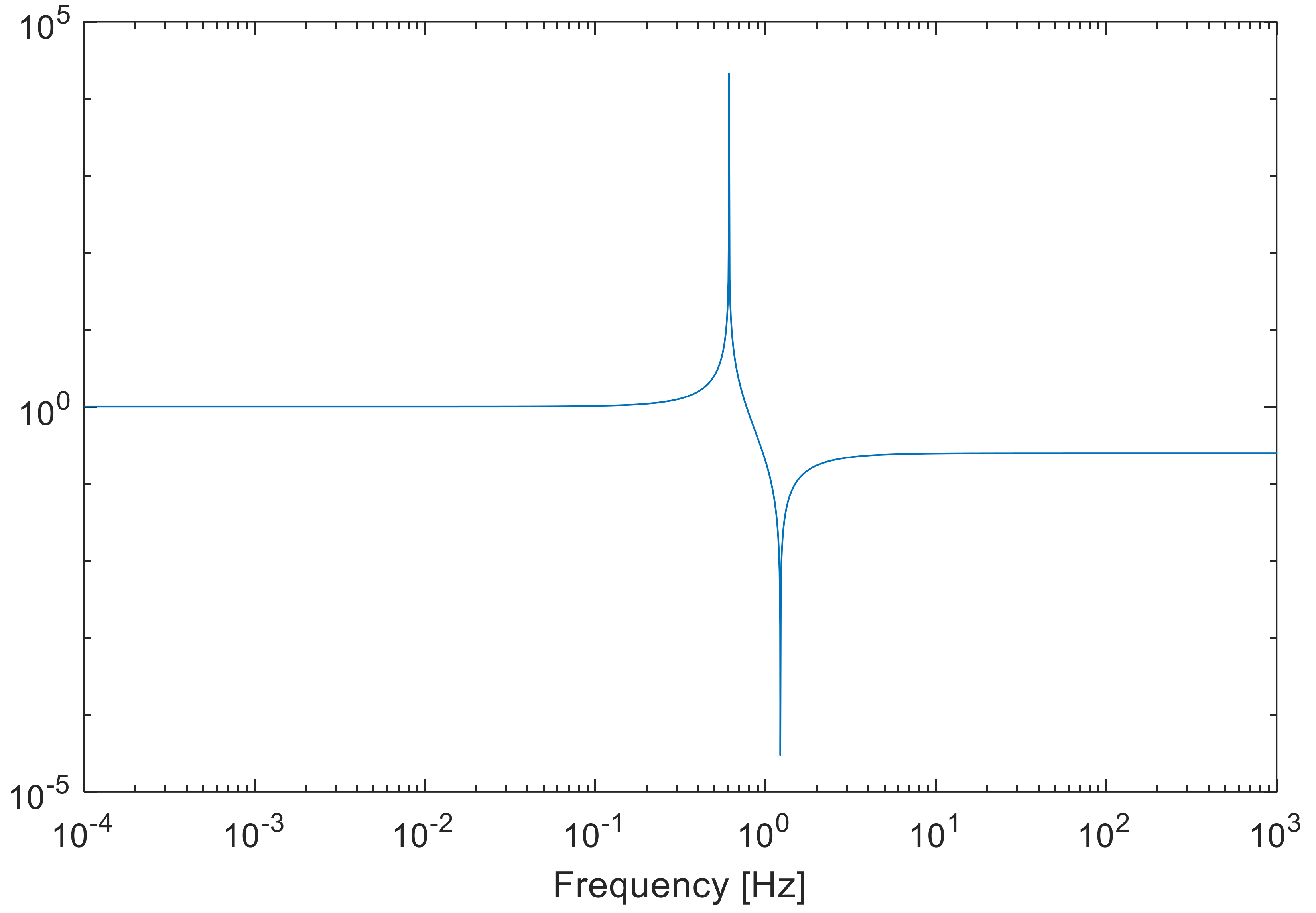


ANOOP GREWAL, PHILIP JOHNSON AND ANDY RUINA
AMERICAN JOURNAL OF PHYSICS VOLUME 79, ISSUE 7, PP. 723, JULY 2011

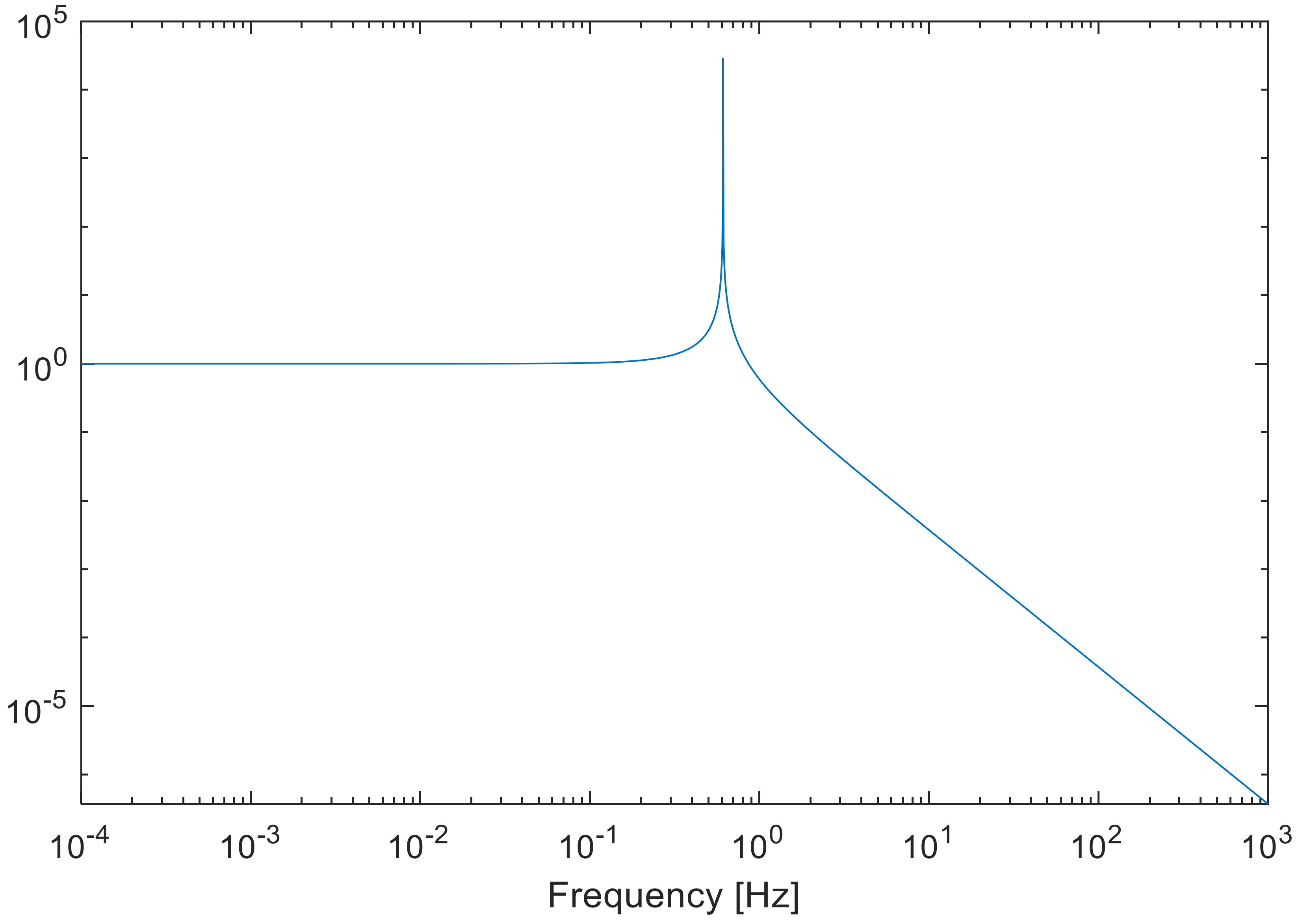
Center of Percussion



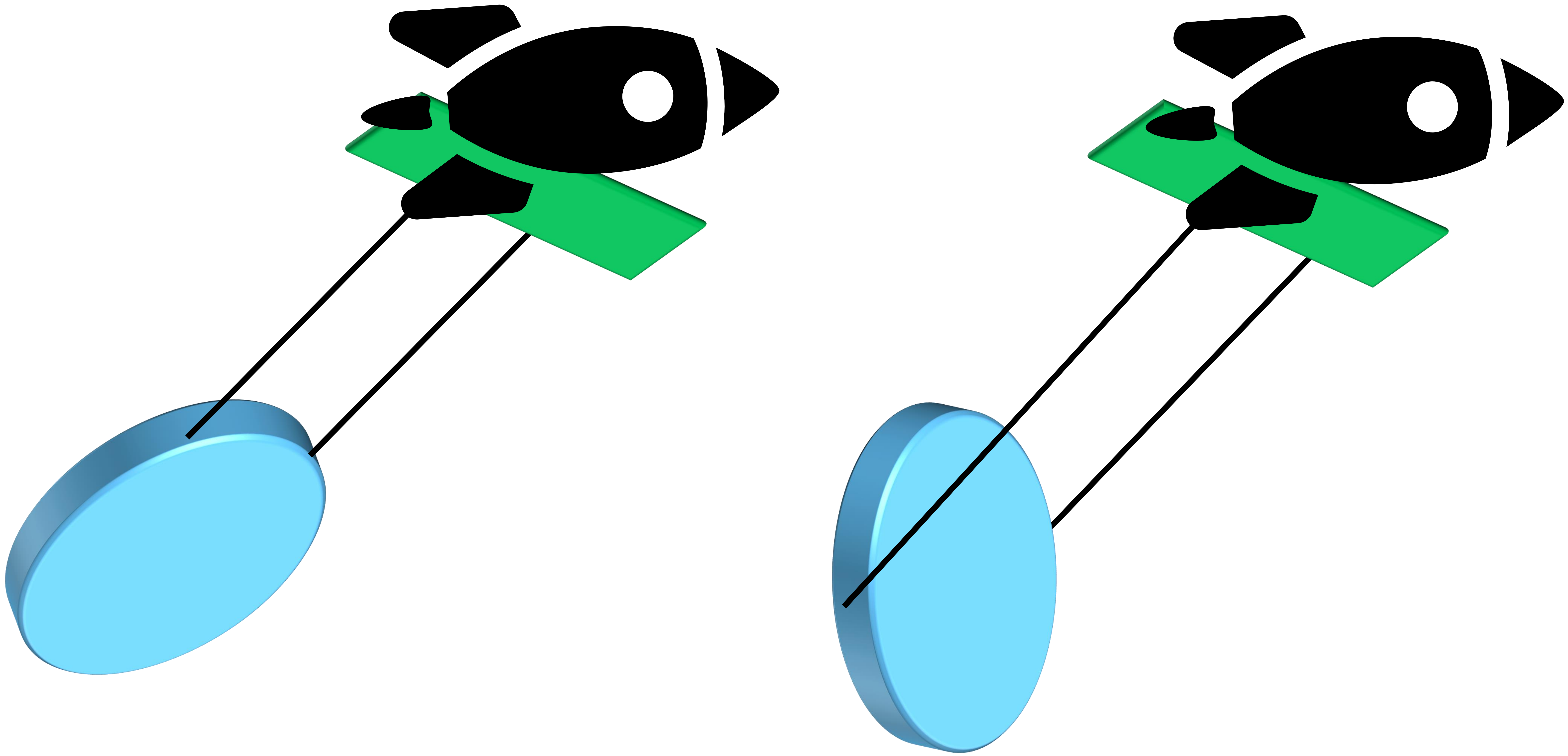
$$\frac{TIP}{Xg}, \frac{CM}{Xg}$$

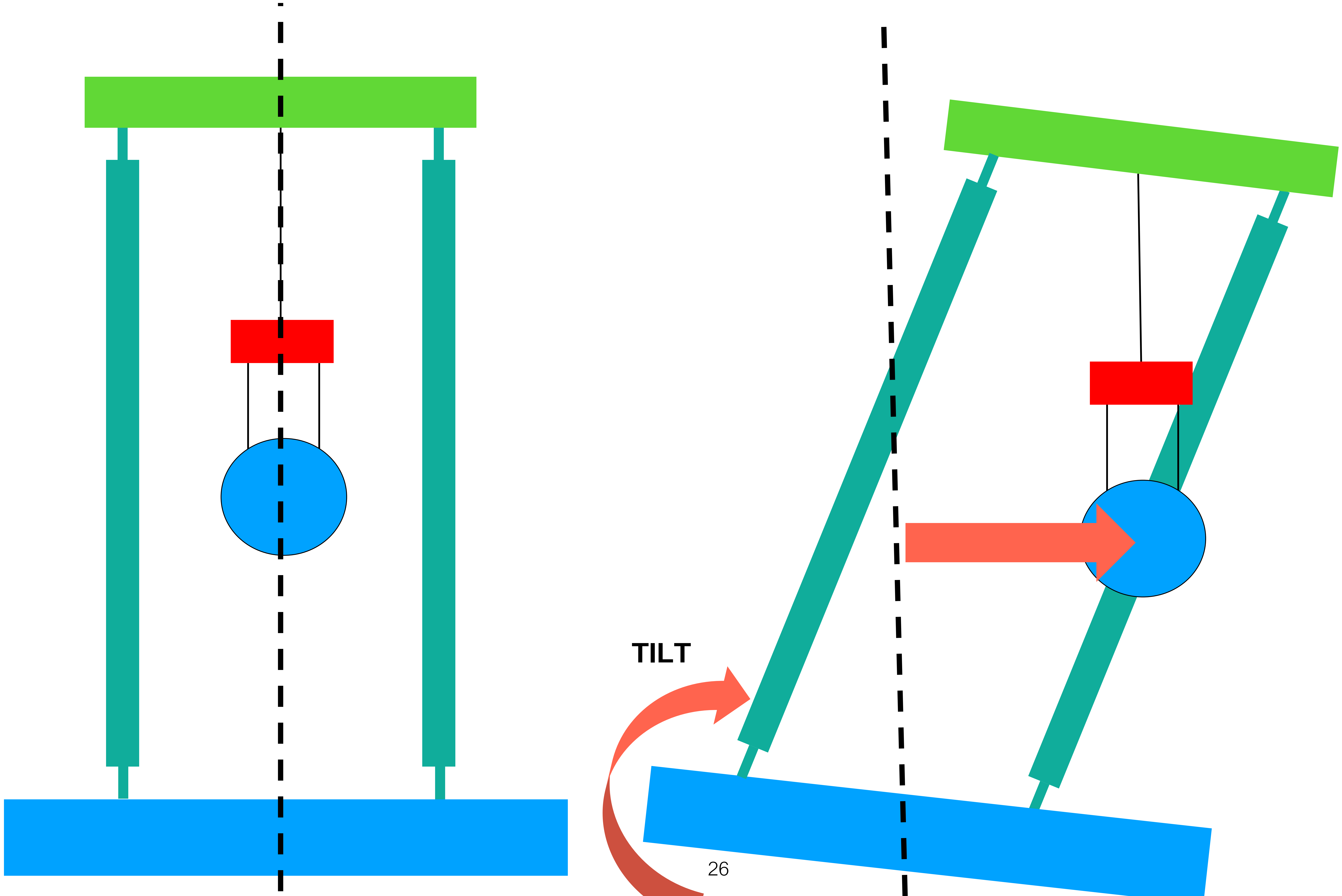


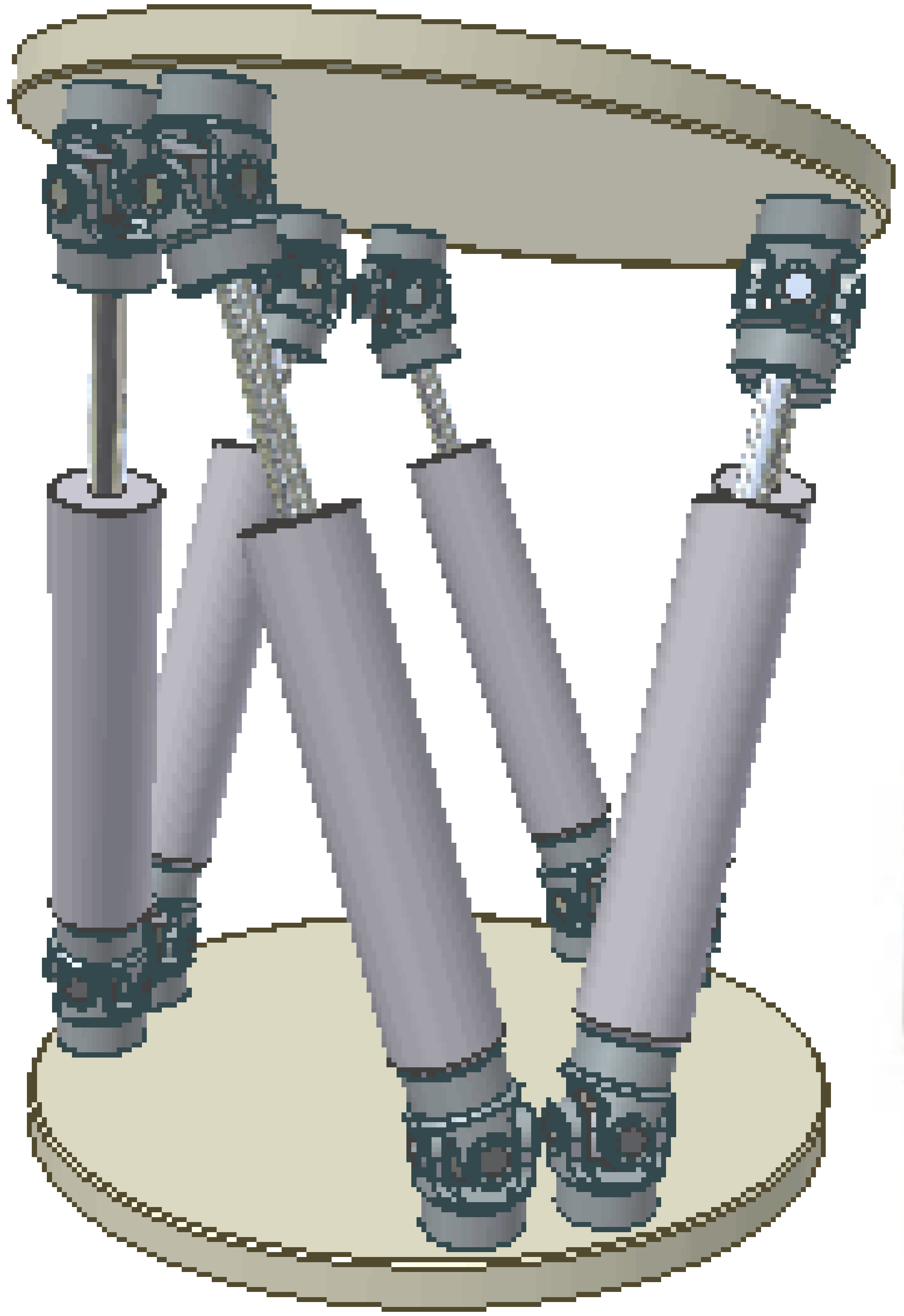
$$\frac{CP}{Xg}$$



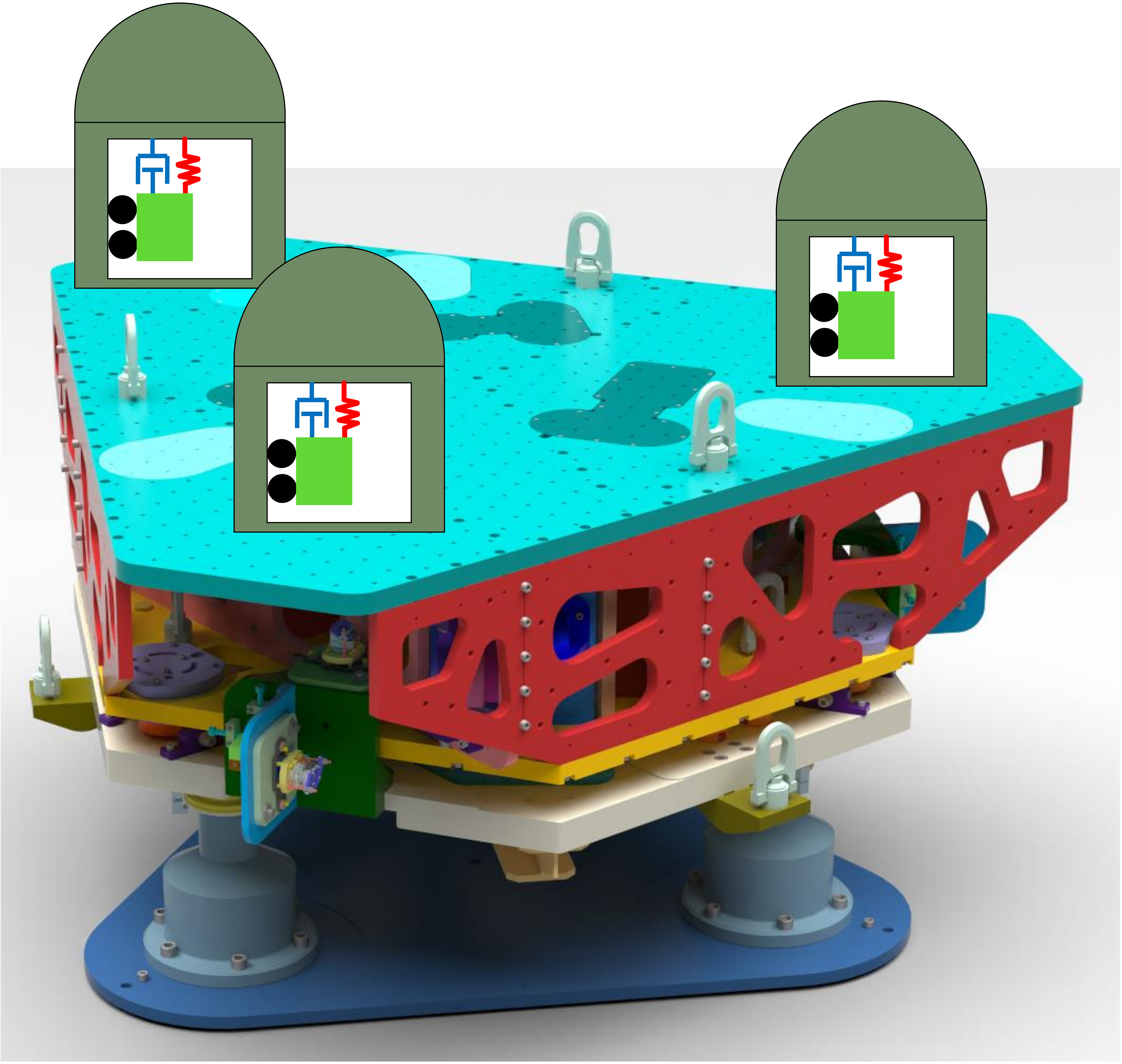
Remove or Create coupling



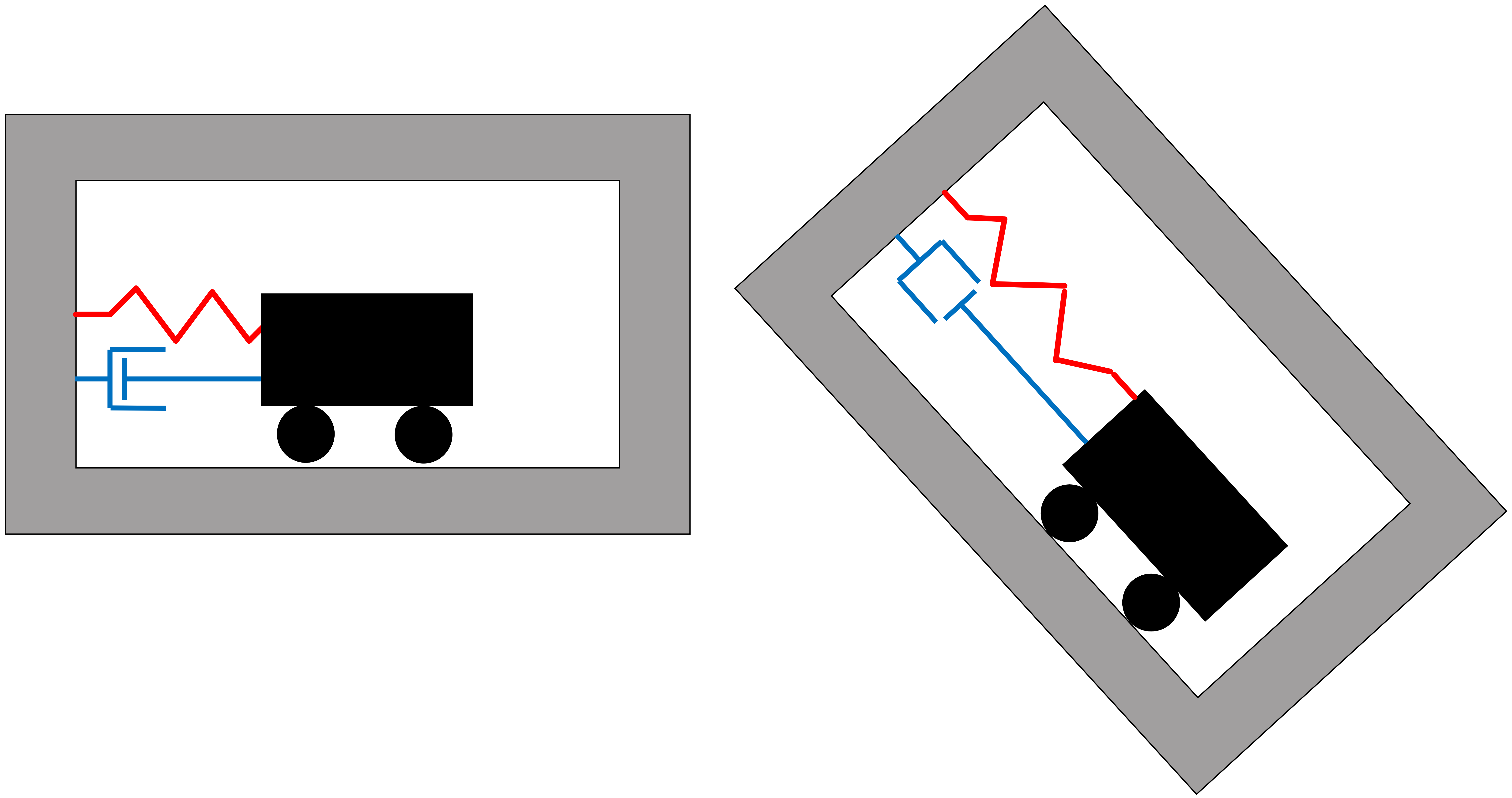

TILT

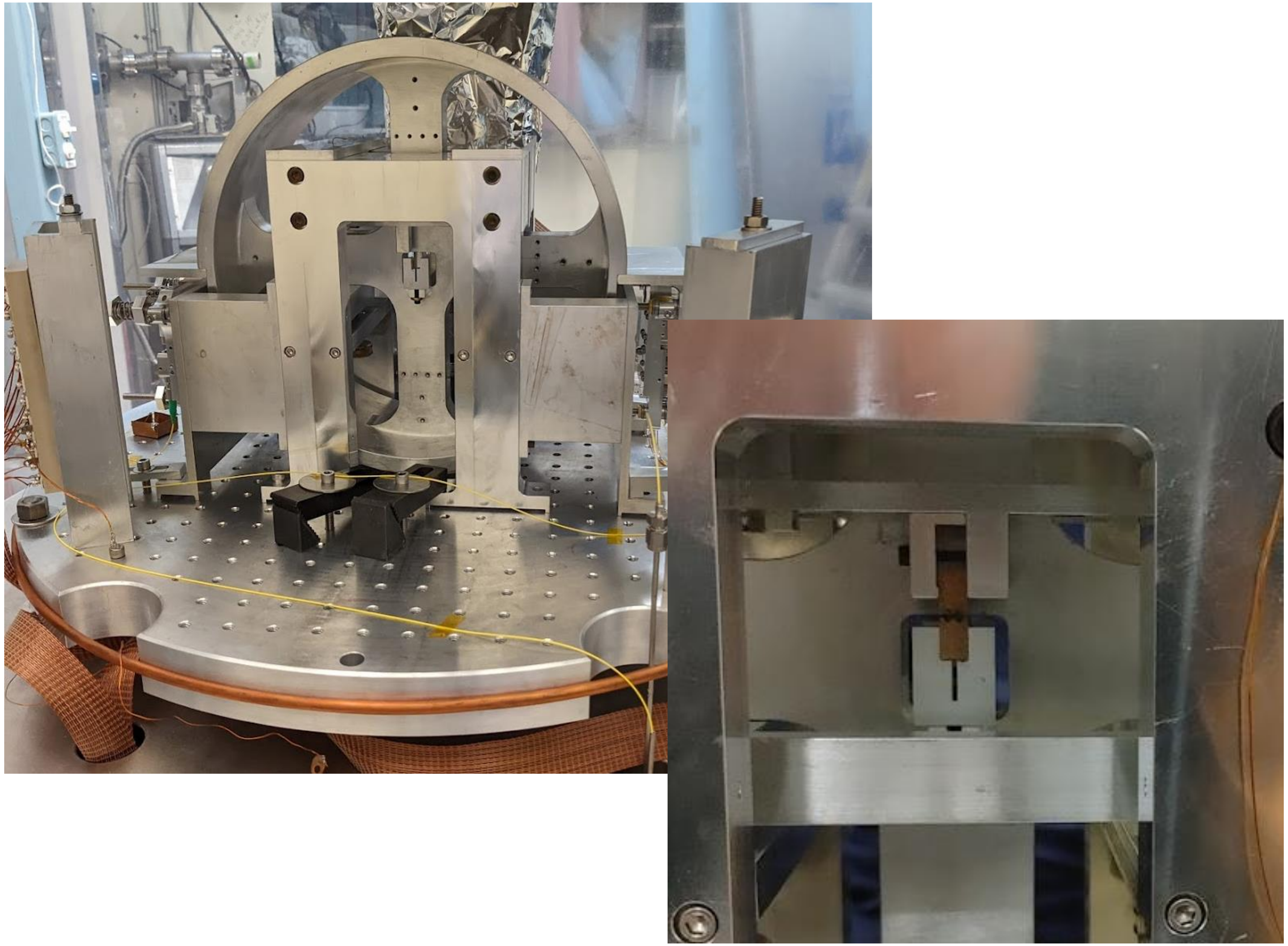


credit: UtzONBike CC 3.0
https://en.wikipedia.org/wiki/Stewart_platform#/media/File:Hexapod_general_Anim.gif

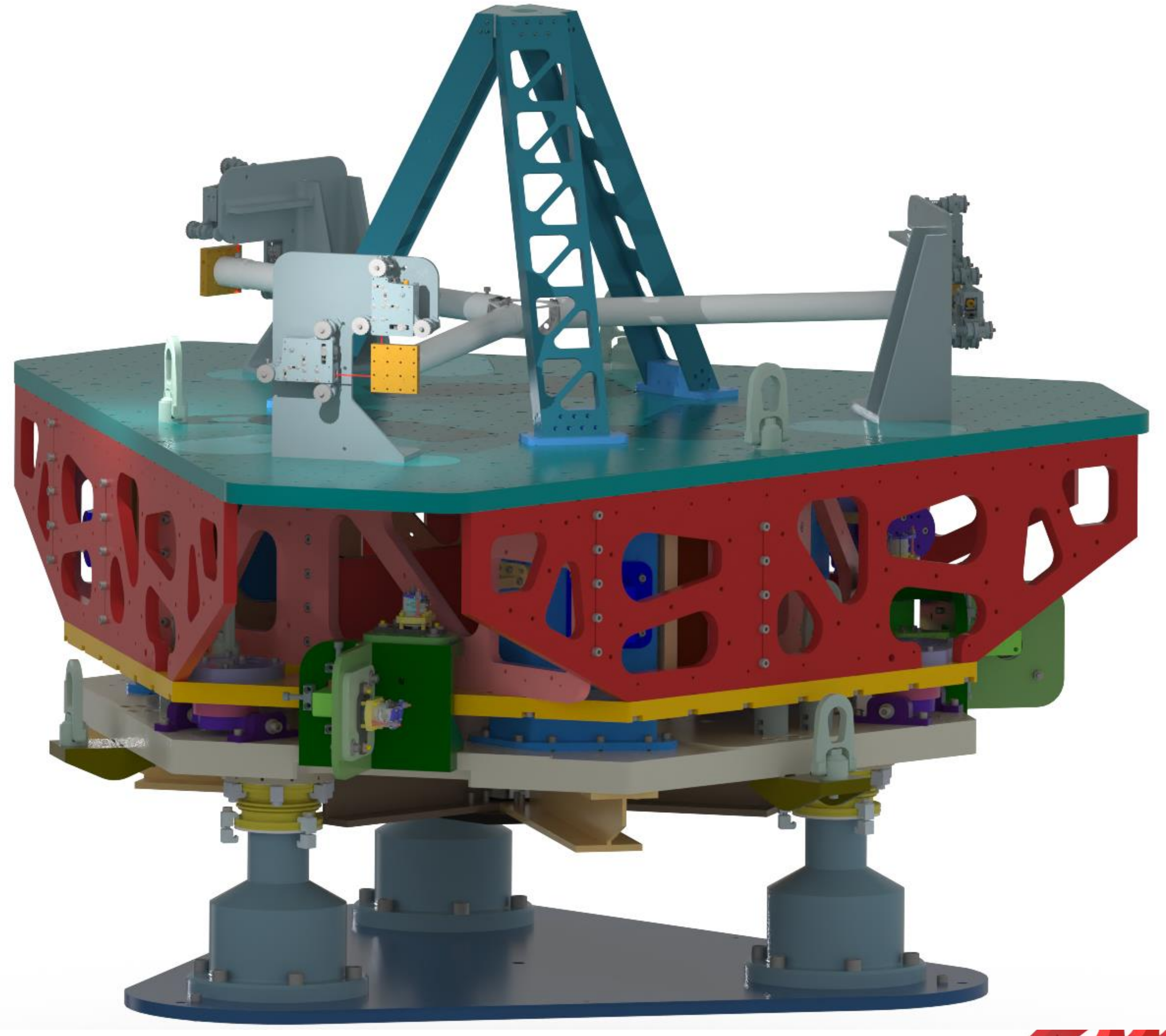


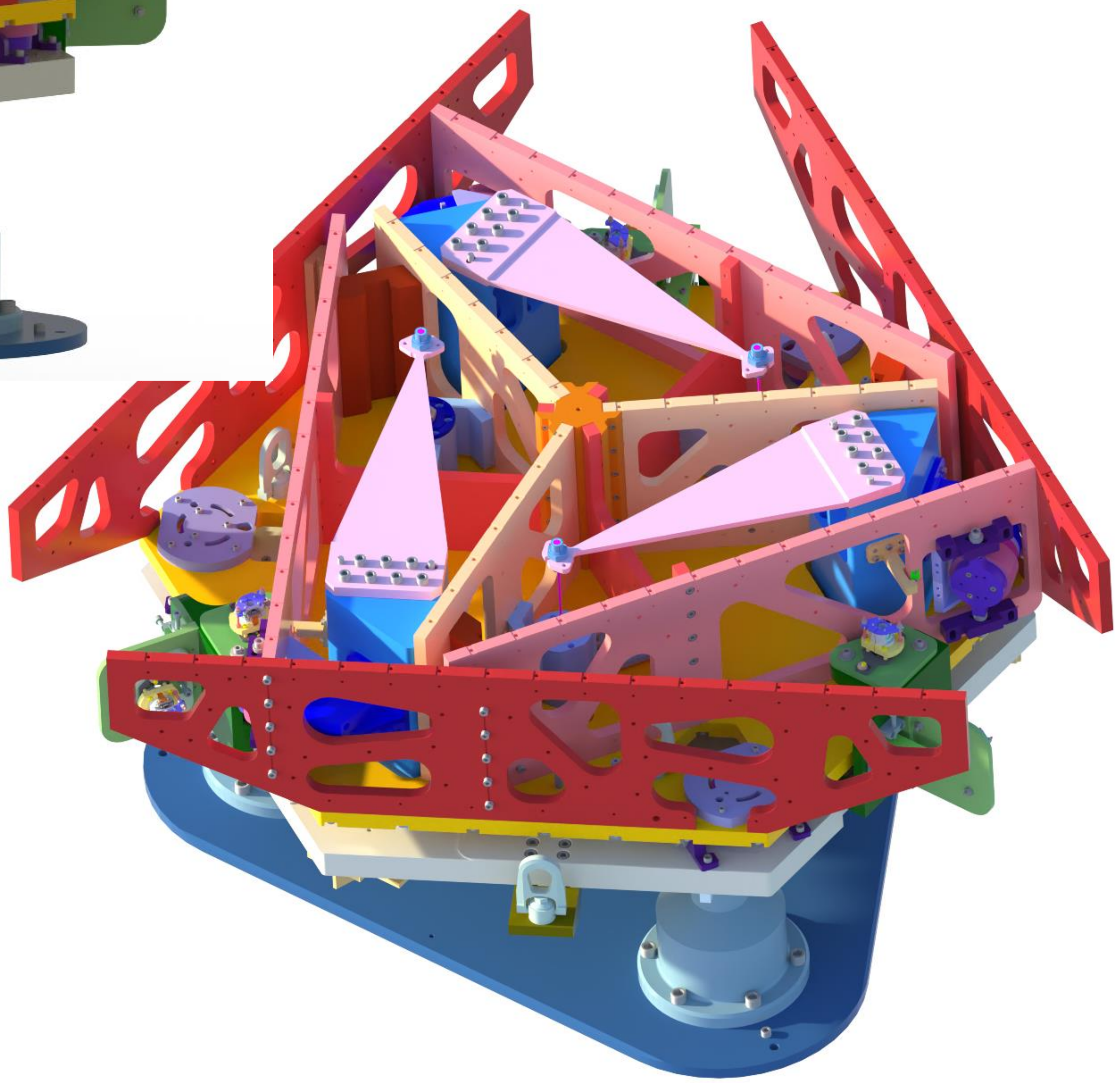
Credit: Armin Numic



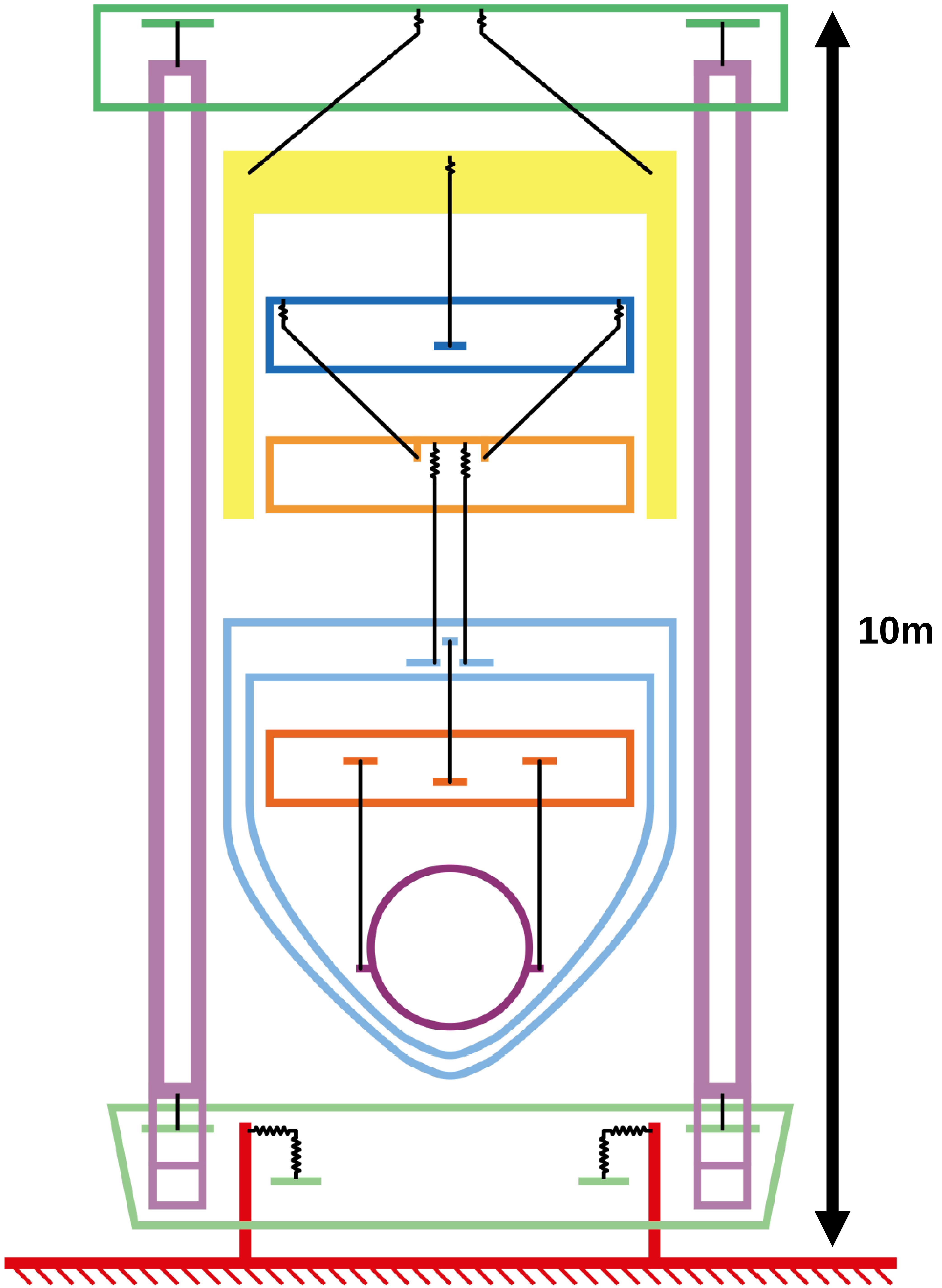


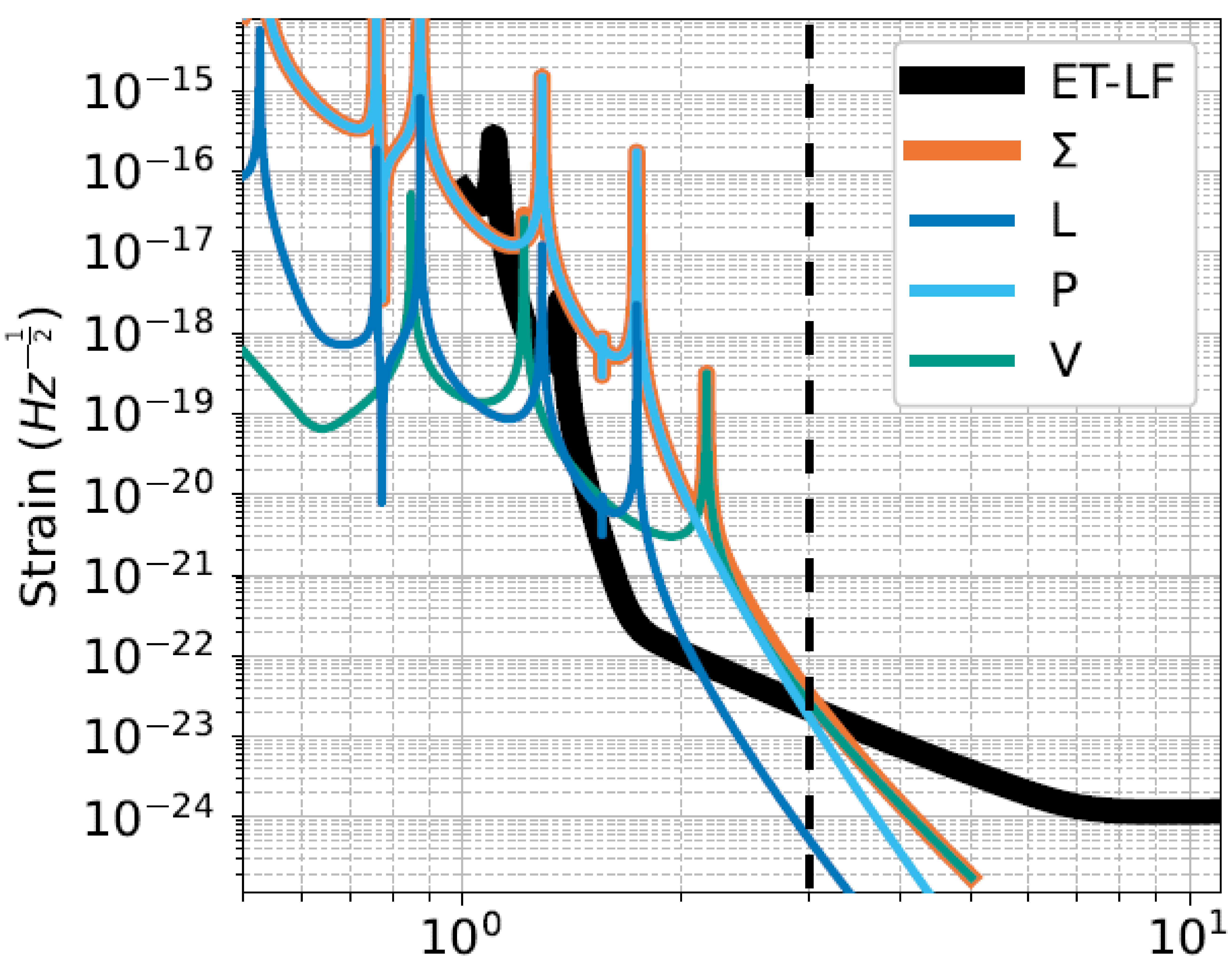
Ross, M. P., Van dongen, J., Huang, Y., Zhou, H., Chowdhury, Y., Apple, S. K., Mow-lowry, C. M., Mitchell, A. L., Holland, N. A., Lantz, B., Bonilla, E., Engl, A., Pele, A., Griffith, D., Sanchez, E., Shaw, E. A., Gettings, C., & Gundlach, J. (2023). A vacuum-compatible cylindrical inertial rotation sensor with picoradian sensitivity. Review of scientific instruments, 94(9), 1-4. Article 094503. Https://doi.org/10.1063/5.0167283





Credit: Armin Numic





Goal: Generate better suspension designs for the Einstein Telescope

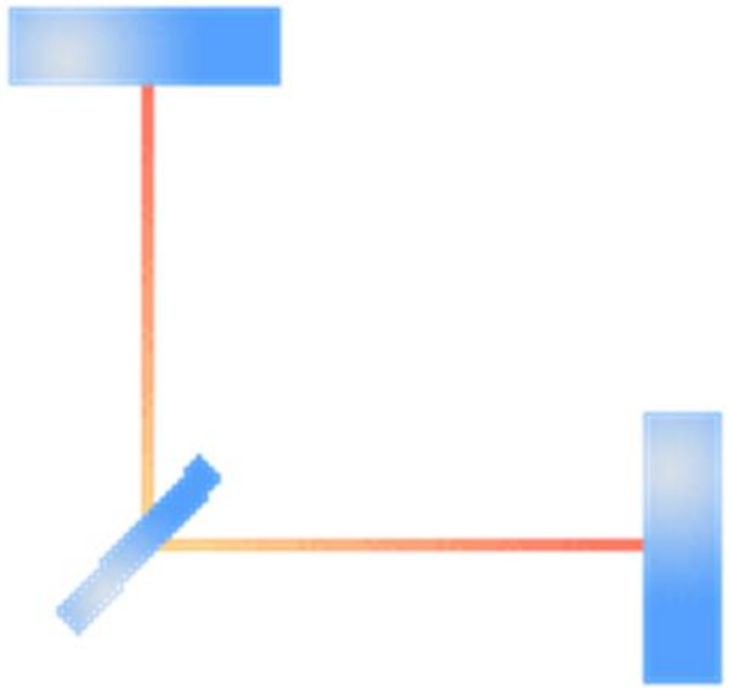
Credit: Nathan Holland

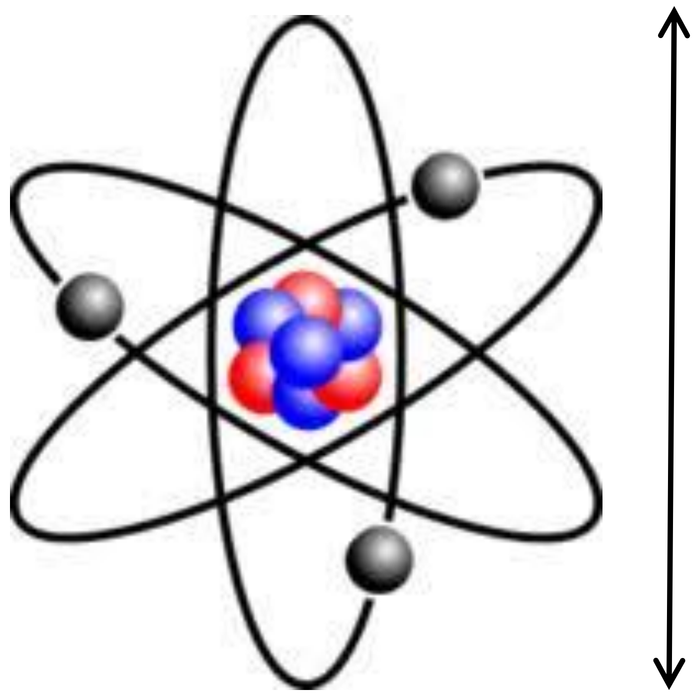
FIN

- GRAVITATIONAL WAVE DETECTION

Credit: Eric Hennes

• GRAVITATIONAL WAVE DETECTION

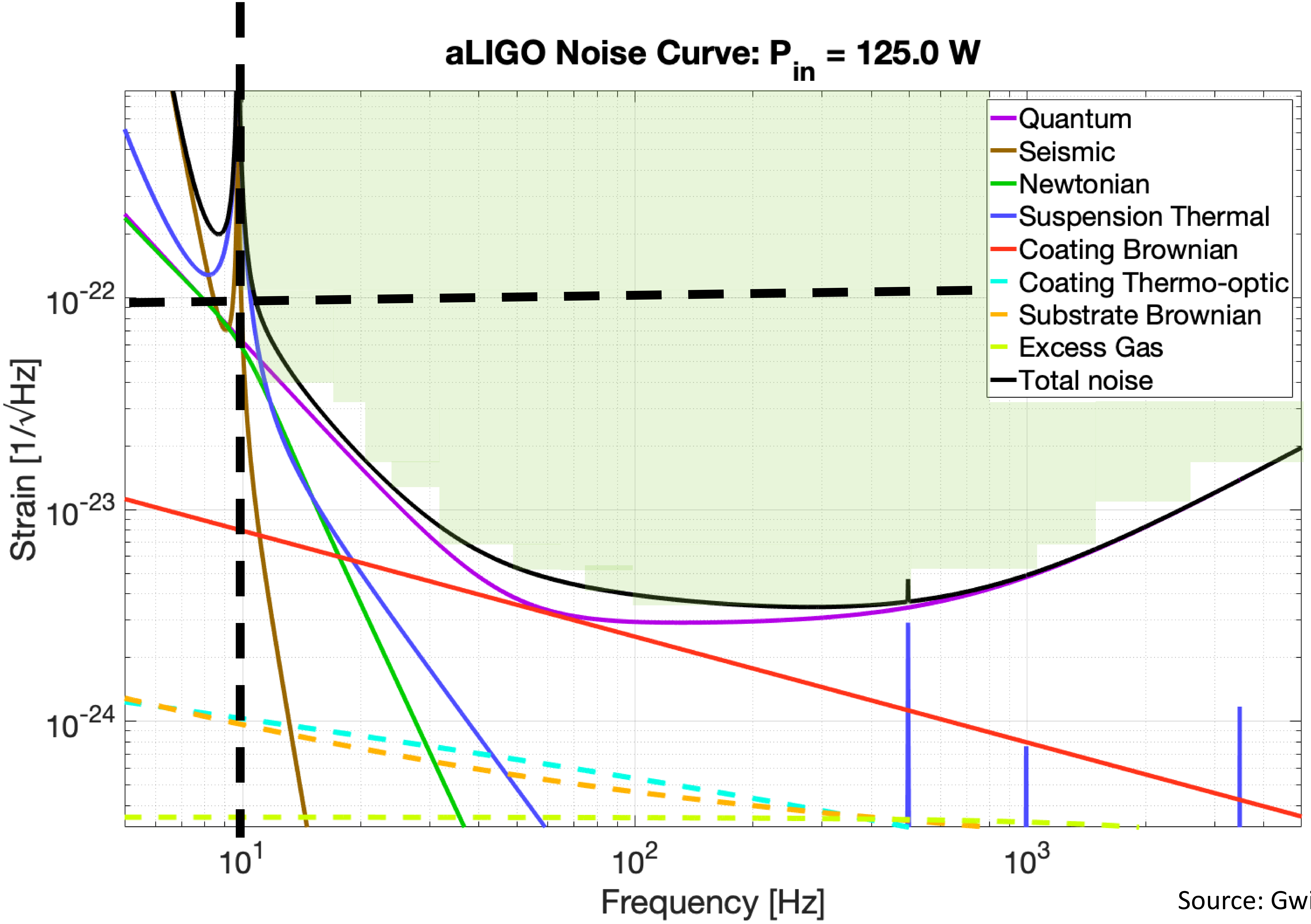




10^{-10} m

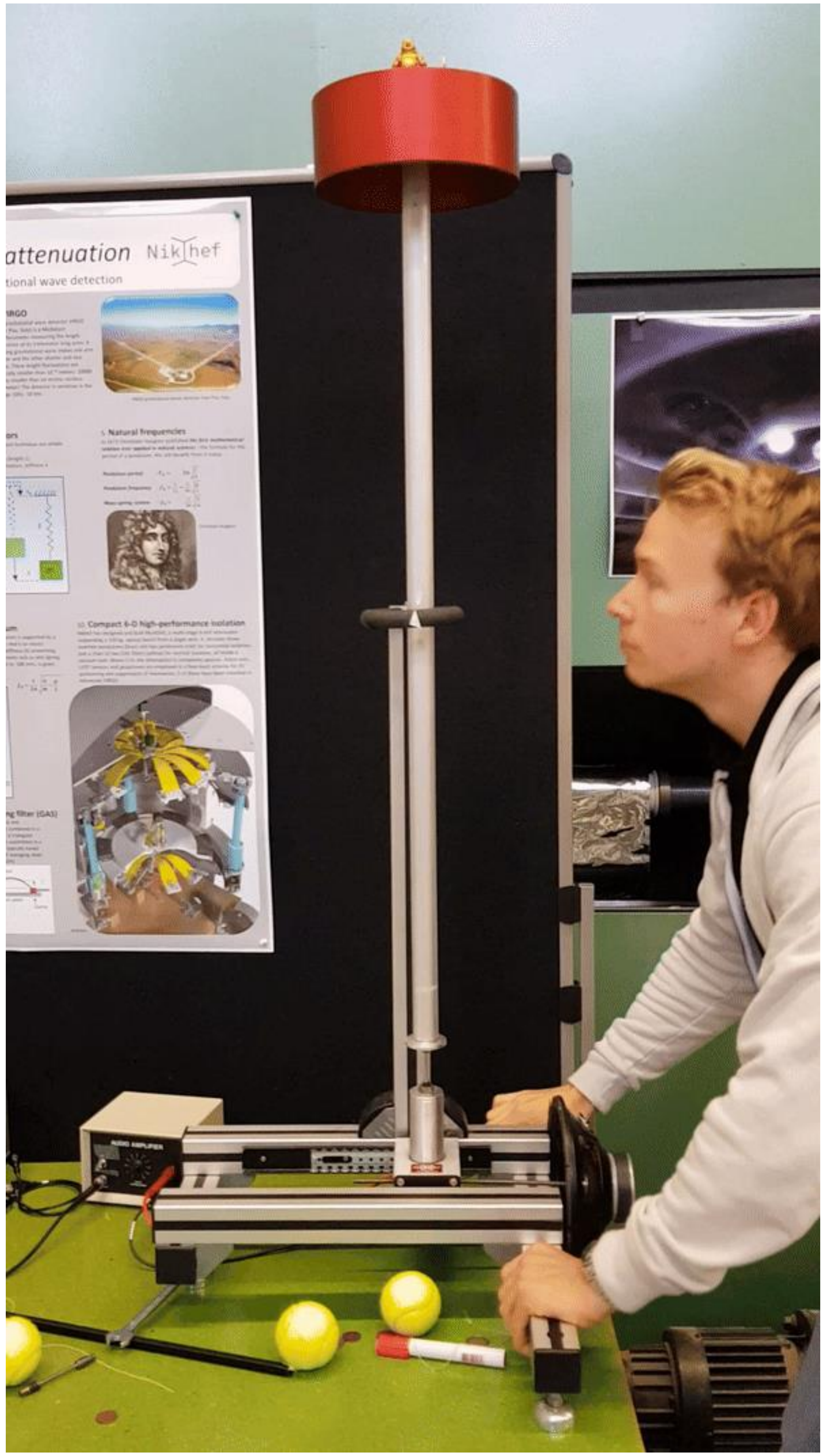
10^{11} m

THE BUCKET

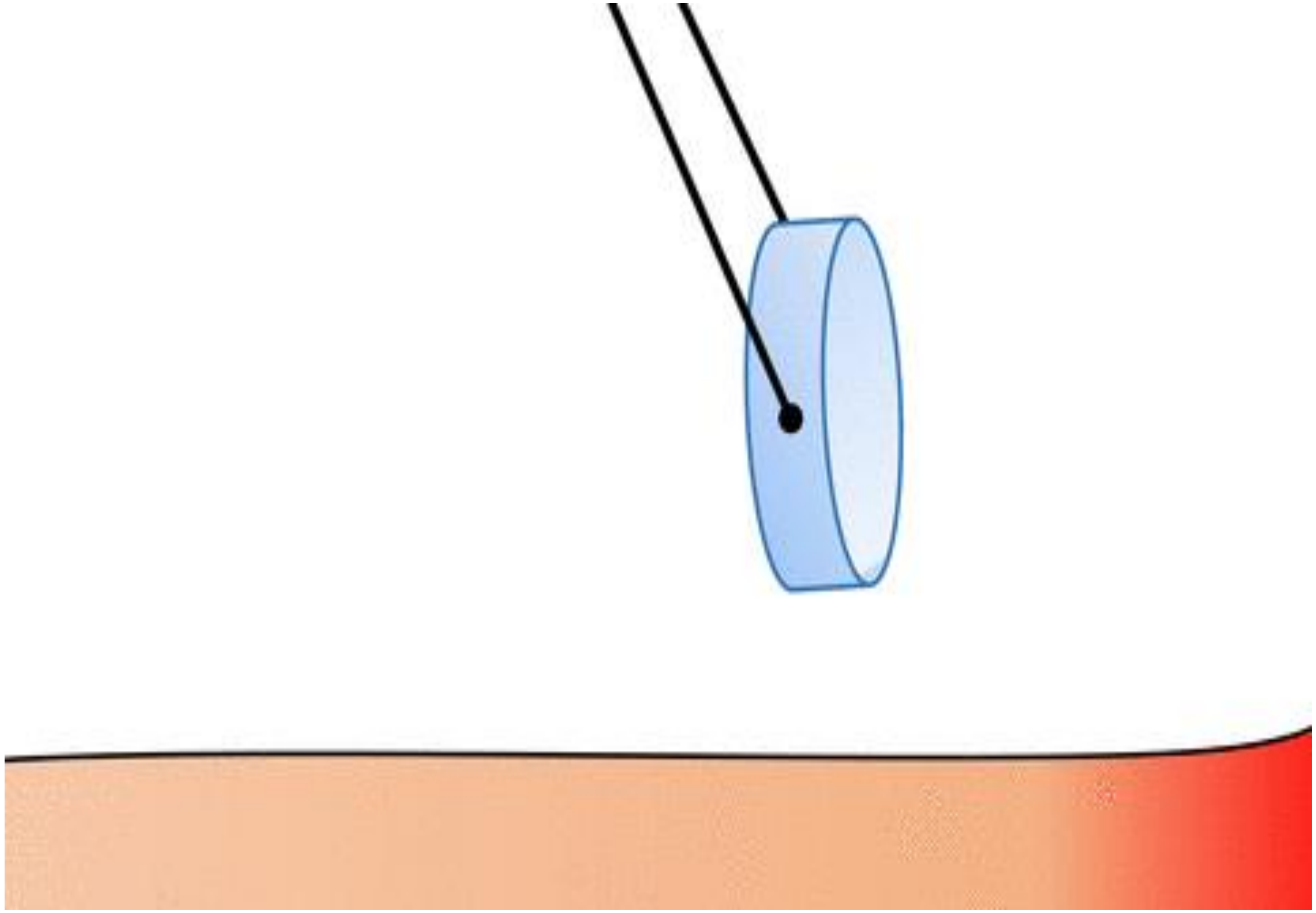


Source: Gwinc

Seismic Noise



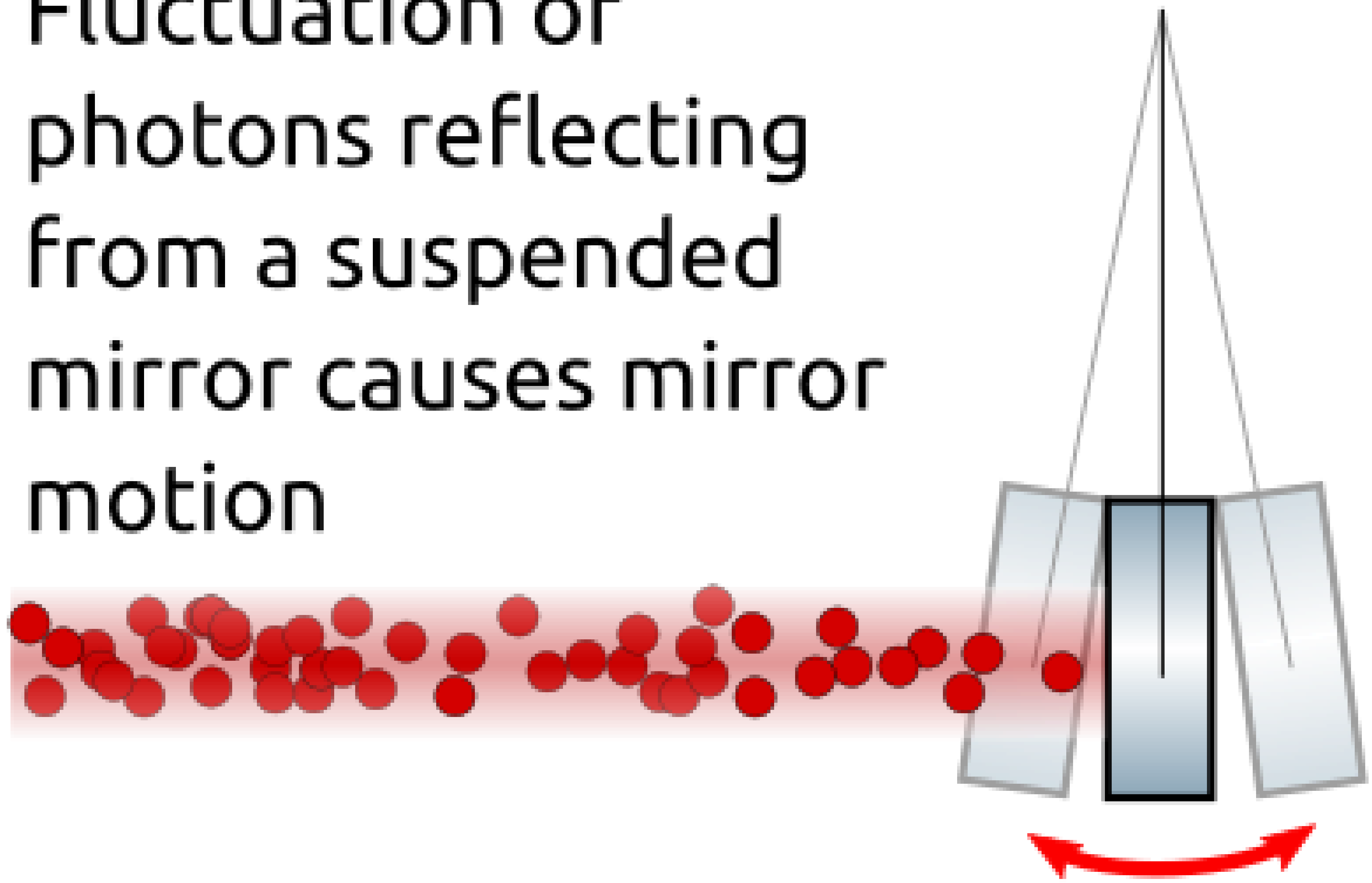
Newtonian Noise



Quantum Noise

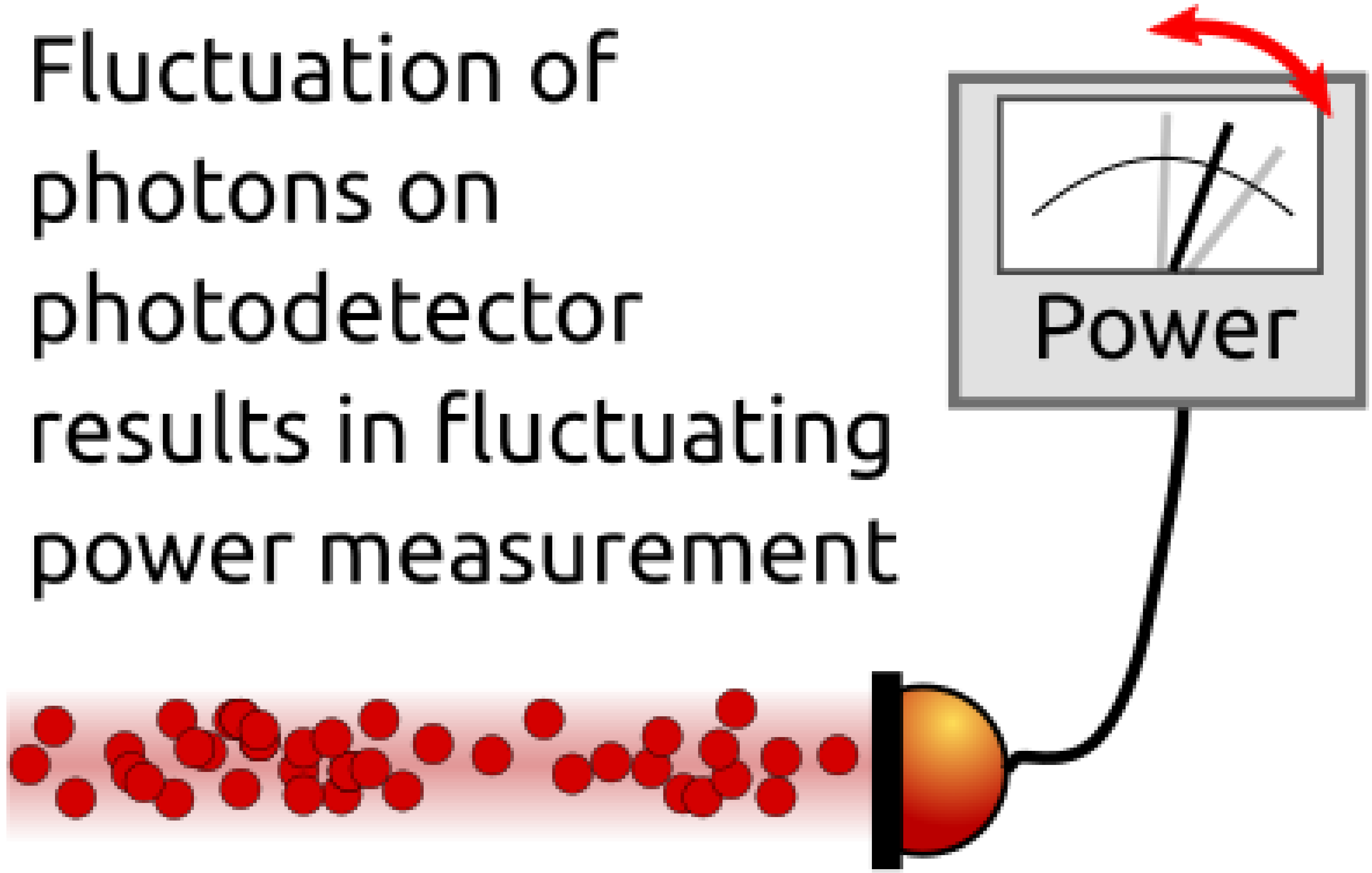
Low Frequency
Photon Pressure

Fluctuation of photons reflecting from a suspended mirror causes mirror motion



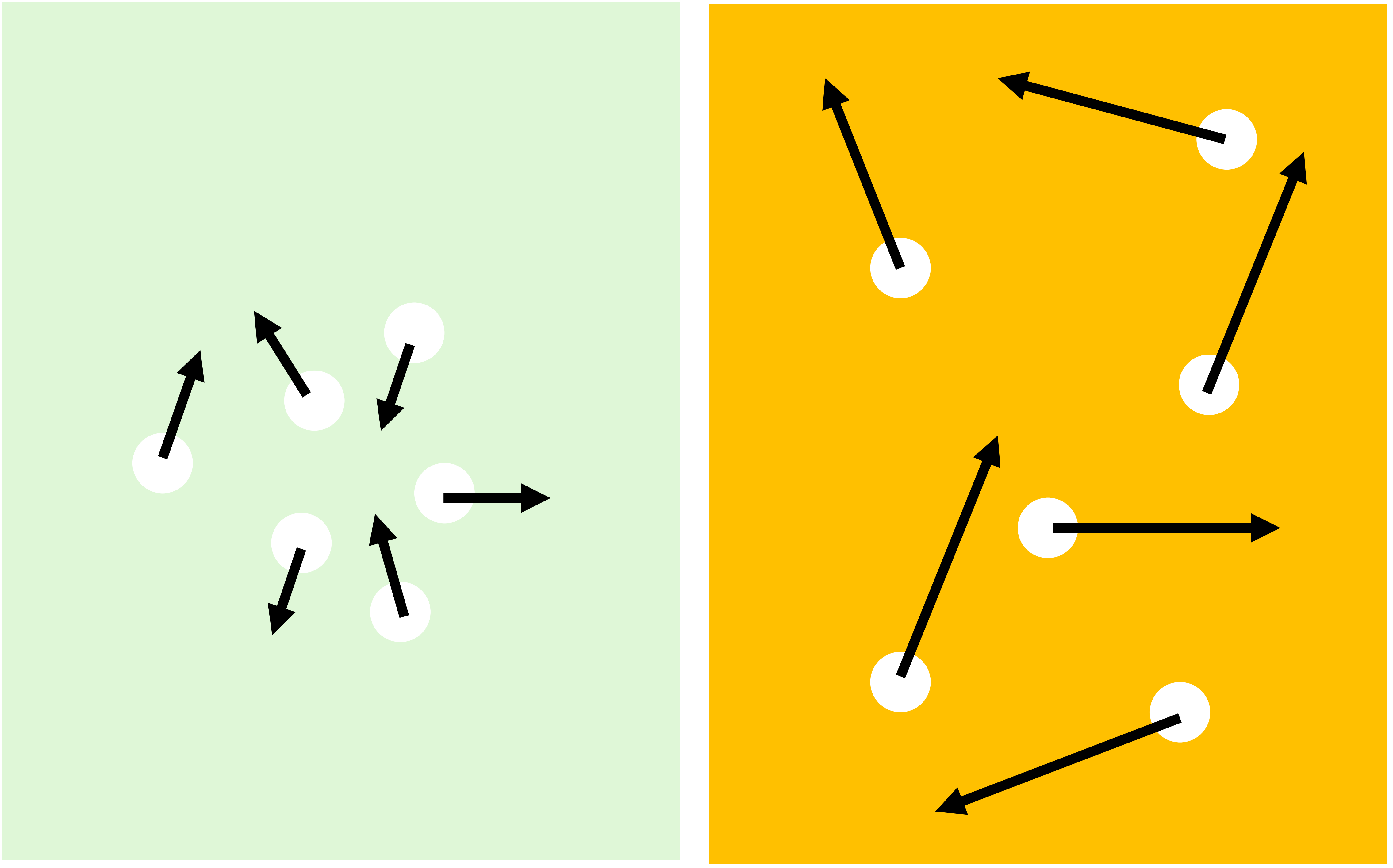
High Frequency
Shot Noise

Fluctuation of photons on photodetector results in fluctuating power measurement



Thermal Noise

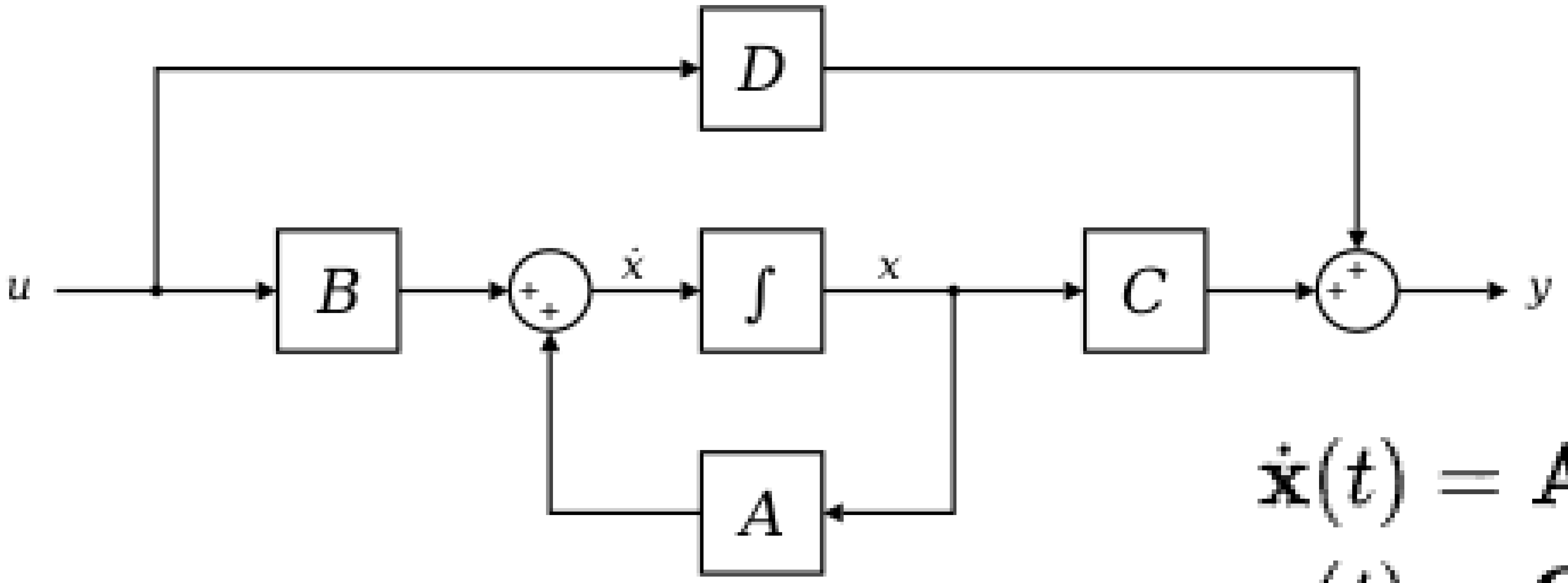
Thermal Brownian



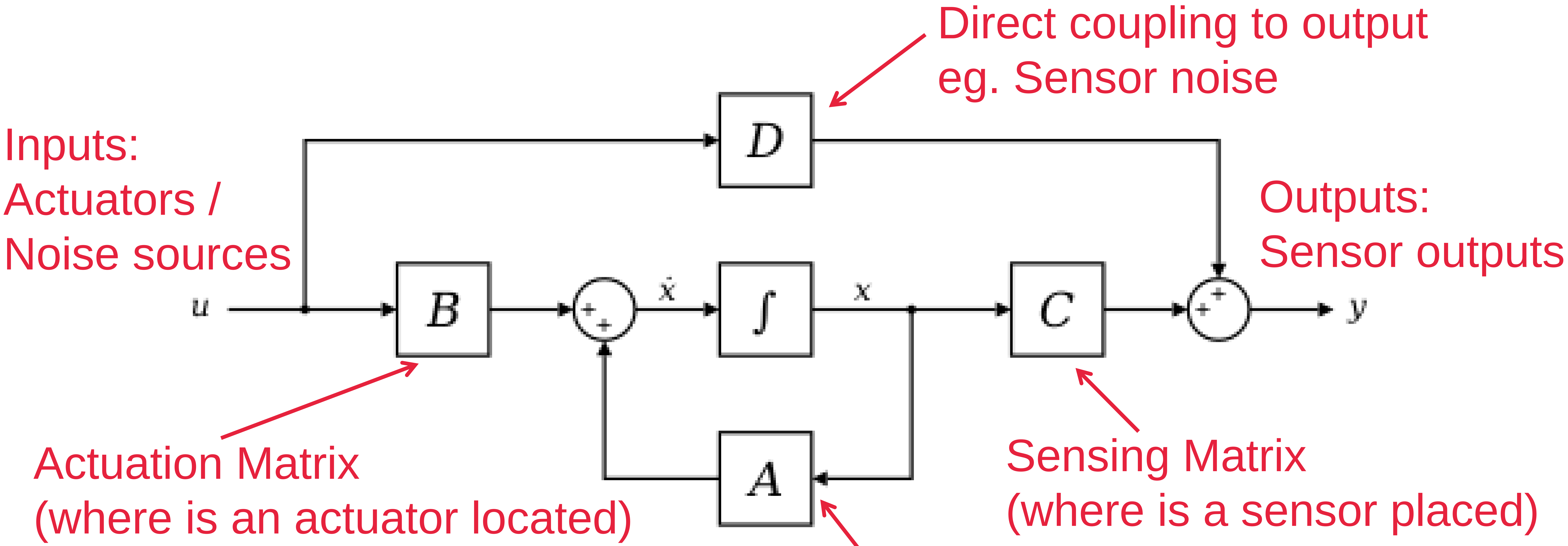
Thermal Deformation Effects

With Linear StateSpace Output around any chosen operating point

To allow for modern MIMO control techniques to be applied

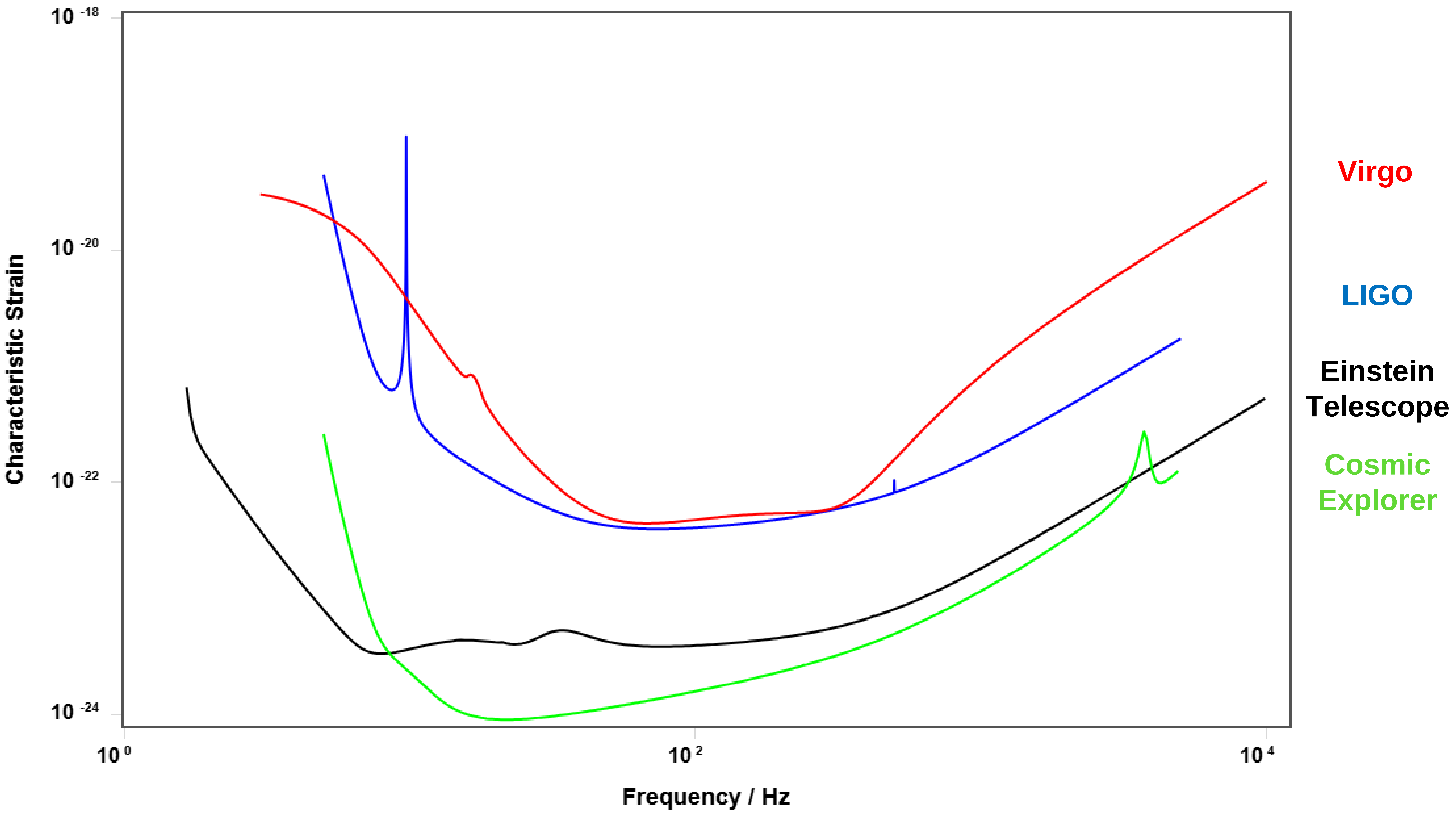


$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}(t)\mathbf{u}(t)$$
$$\mathbf{y}(t) = \mathbf{C}(t)\mathbf{x}(t) + \mathbf{D}(t)\mathbf{u}(t)$$



$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}(t)\mathbf{u}(t)$$
$$\mathbf{y}(t) = \mathbf{C}(t)\mathbf{x}(t) + \mathbf{D}(t)\mathbf{u}(t)$$

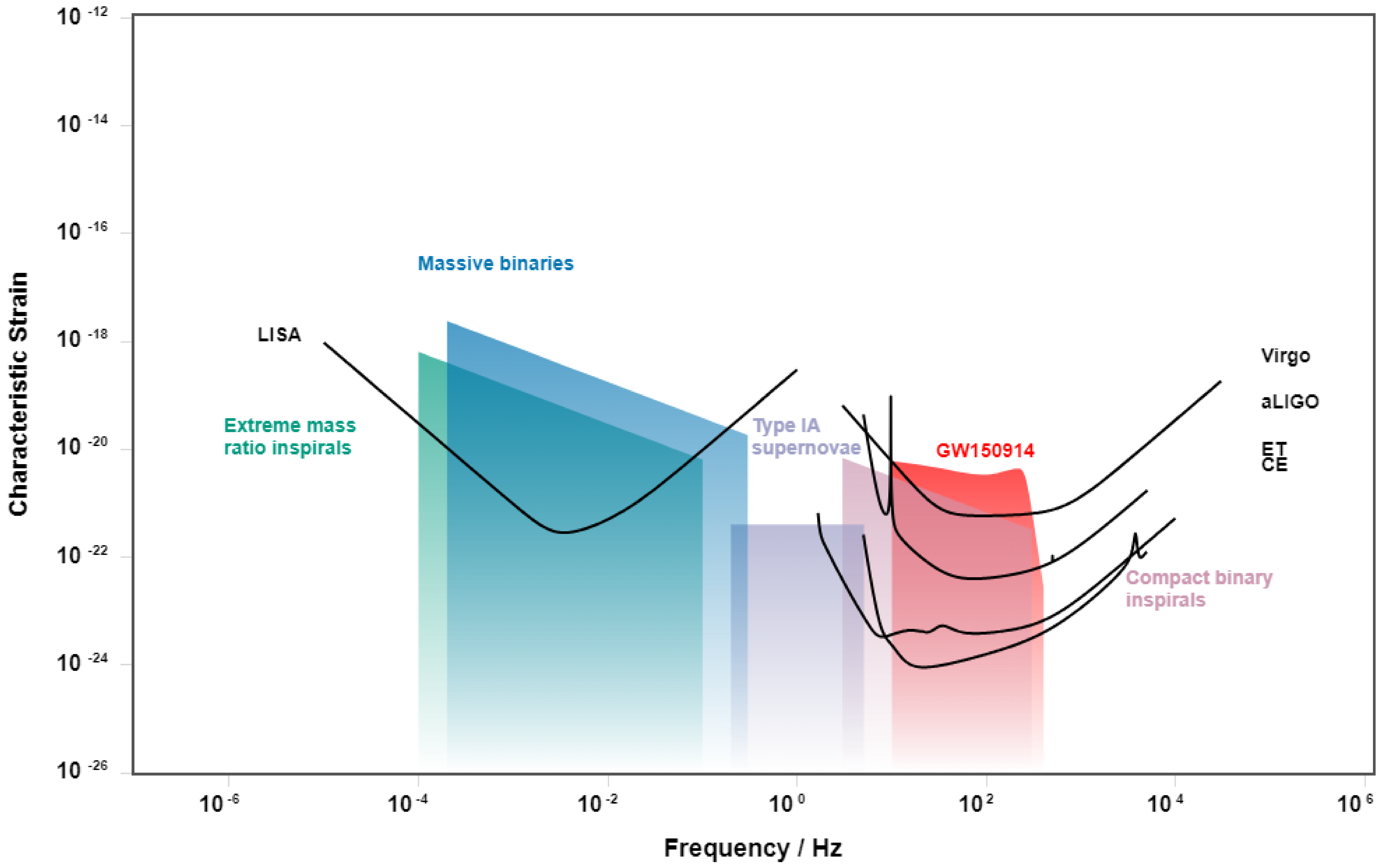
Future Earth Based Interferometer Buckets



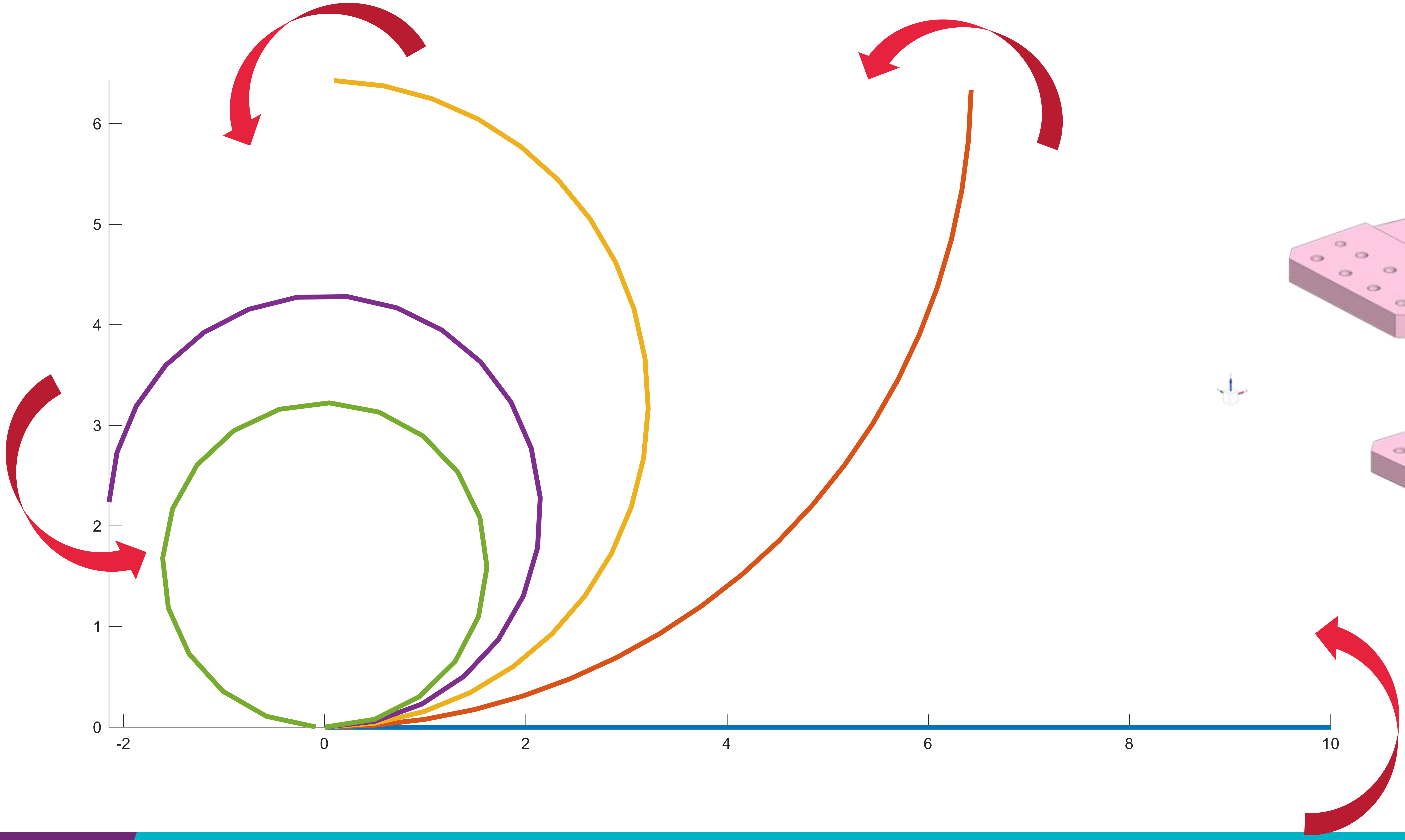
[GRAVITATIONAL WAVE SENSITIVITY CURVE PLOTTER (GWPLOTTER.COM)]

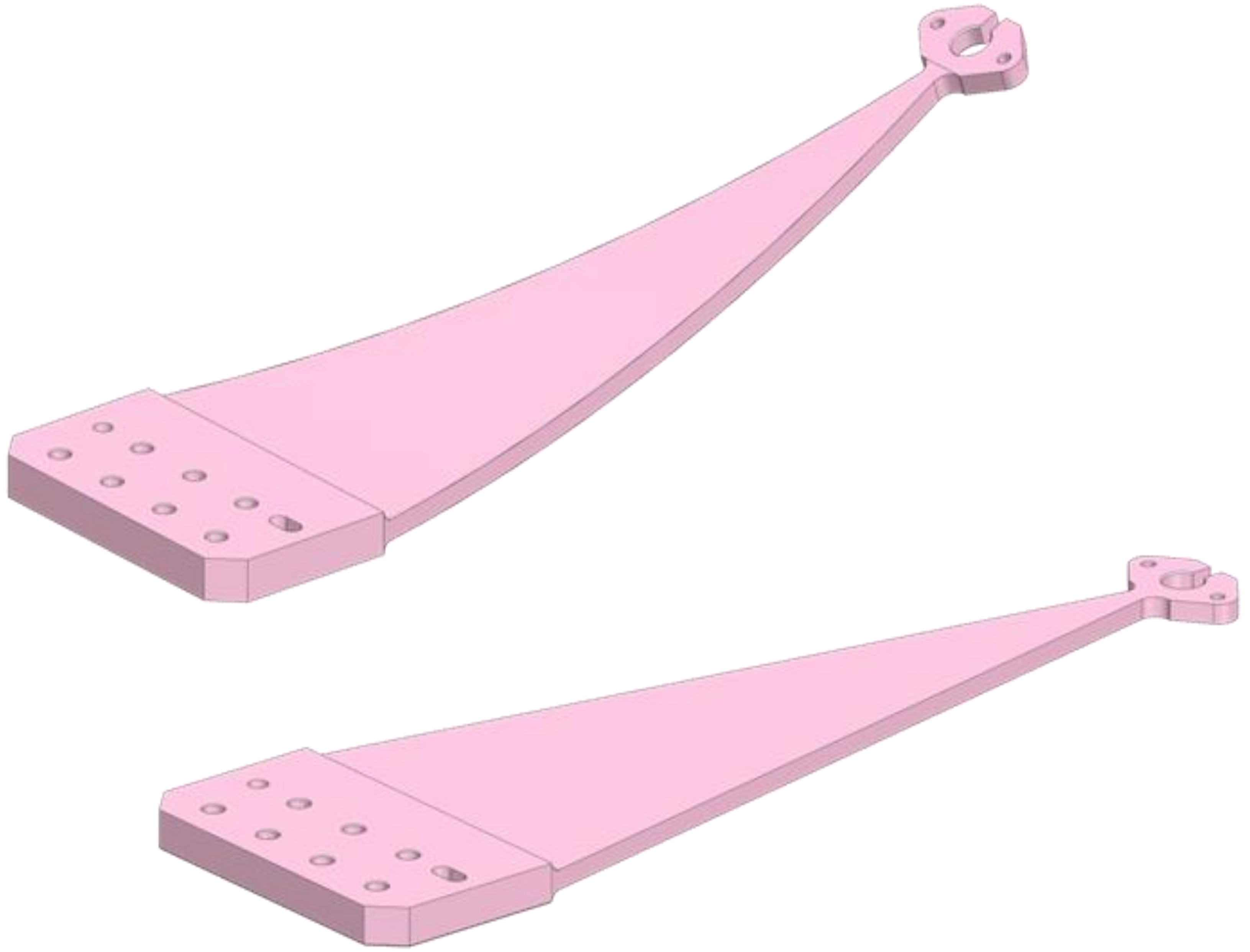
Gravitational Wave Detectors and Sources

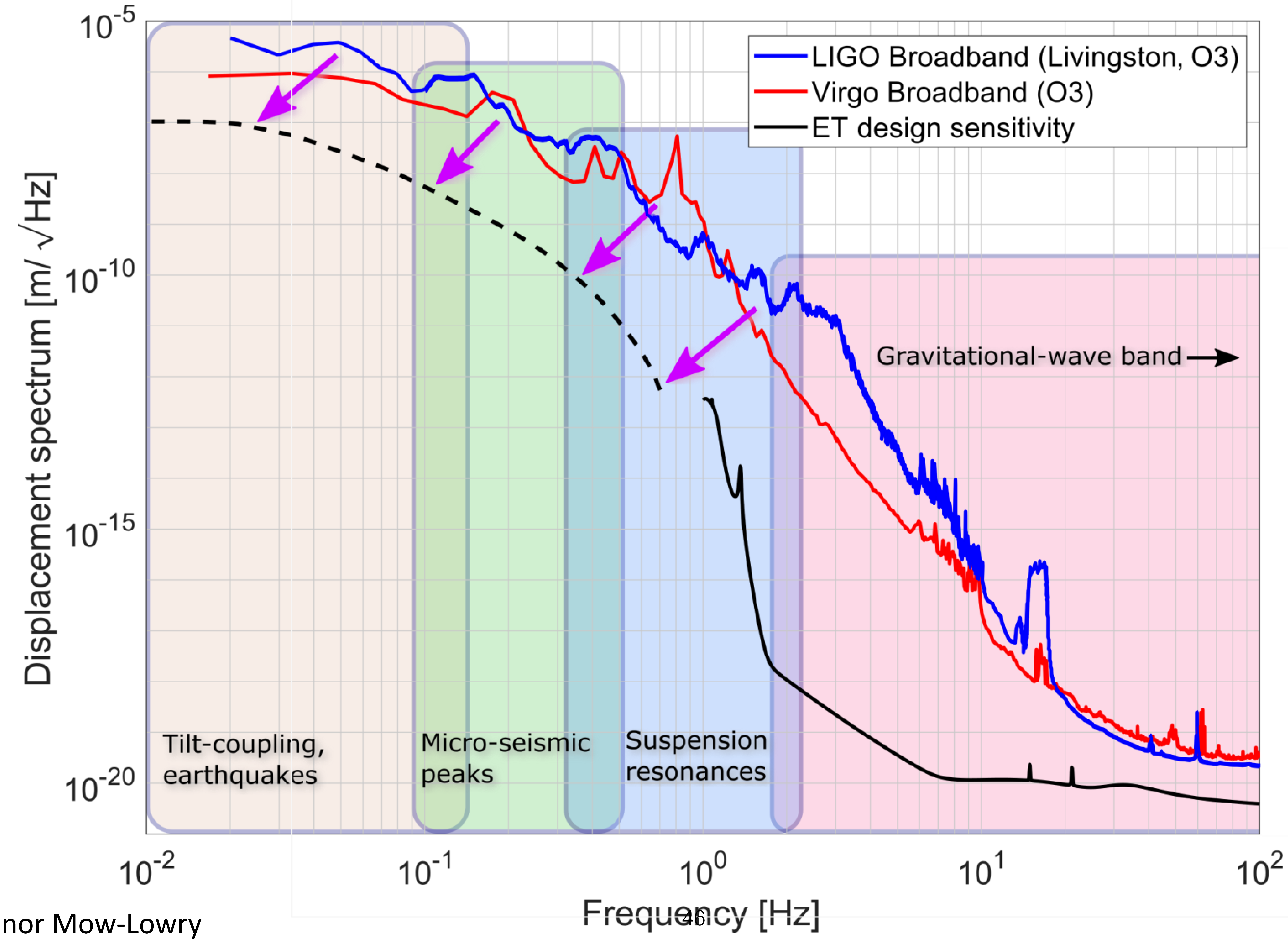
By Christopher Moore, Robert Cole and Christopher Berry, formerly of the Gravitational Wave Group at the Institute of Astronomy, University of Cambridge



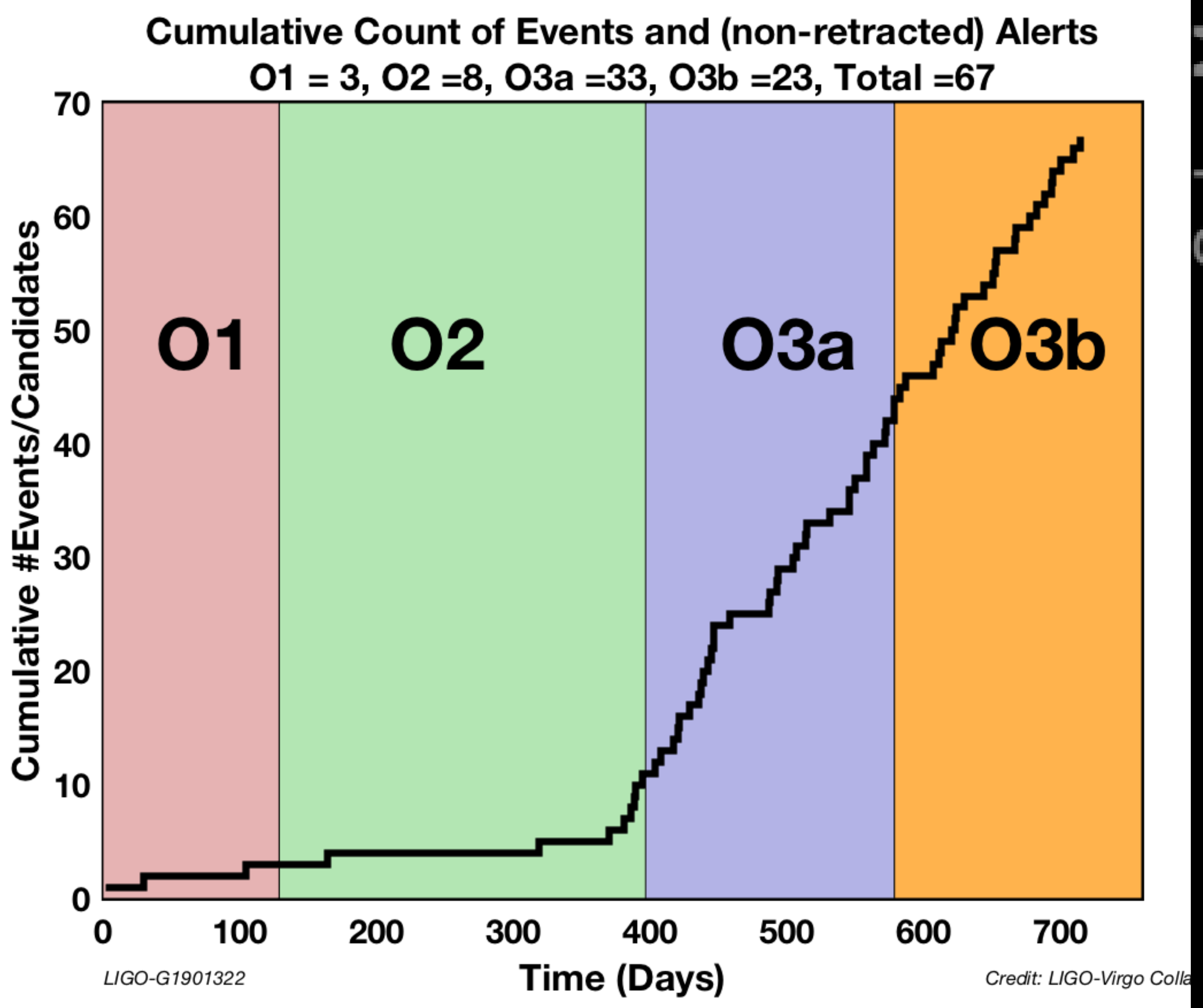
[GRAVITATIONAL WAVE SENSITIVITY CURVE PLOTTER (GWPLOTTER.COM)]

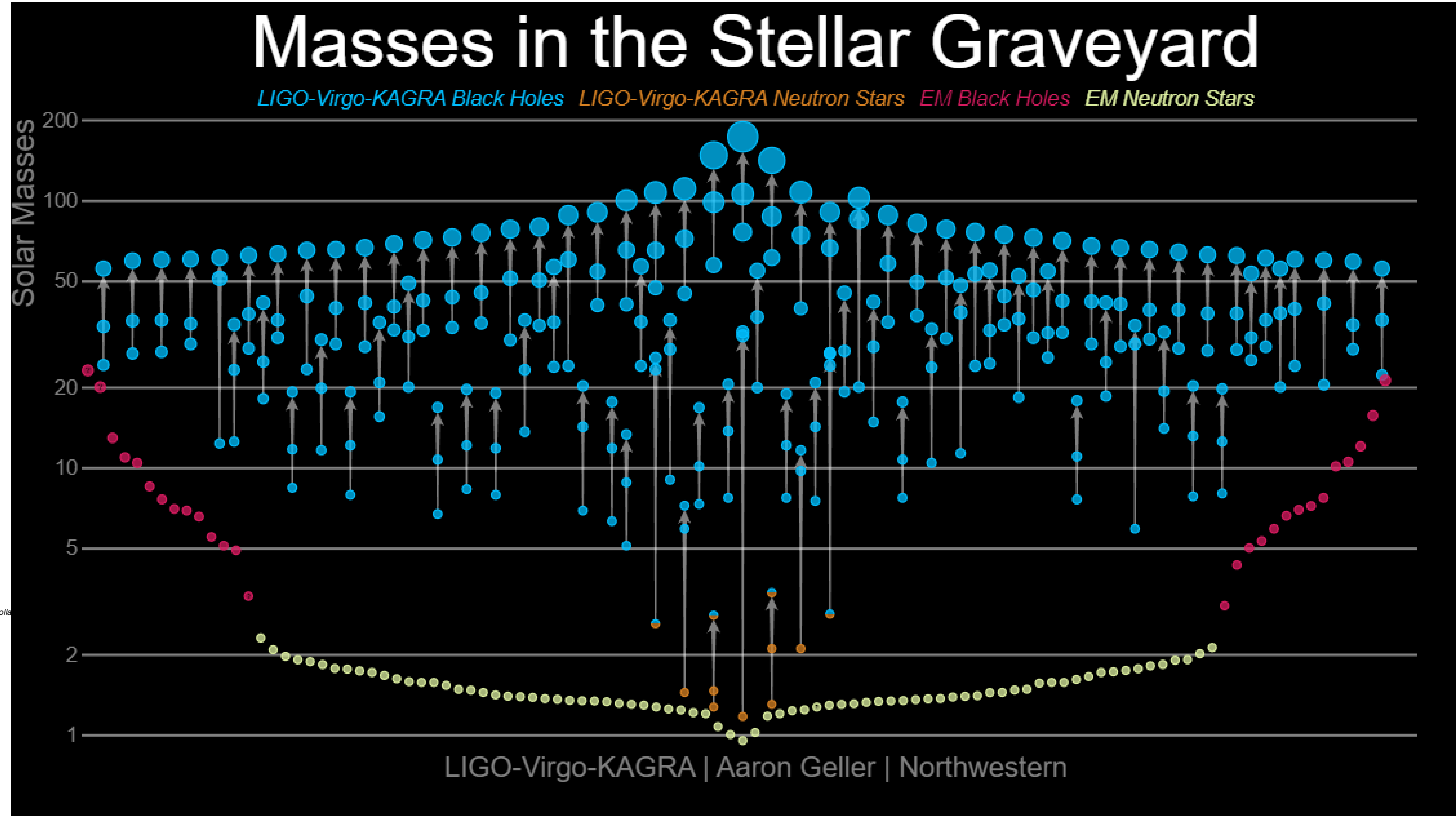

6
5
4
3
2
1
0
-2
0
2
4
6
8
10





Credit: Conor Mow-Lowry

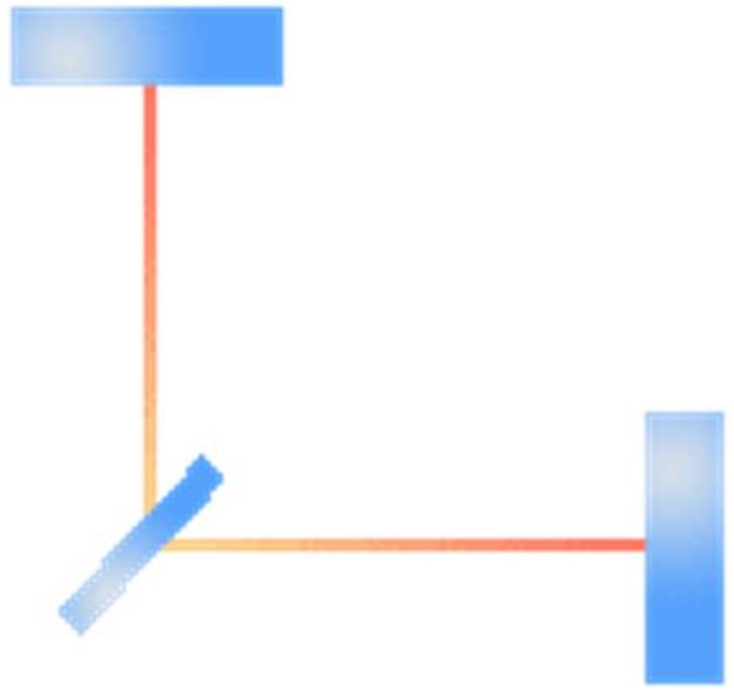




ABOUT ONE SIGNAL EVERY 3 DAYS!

Credit: Eric Hennes

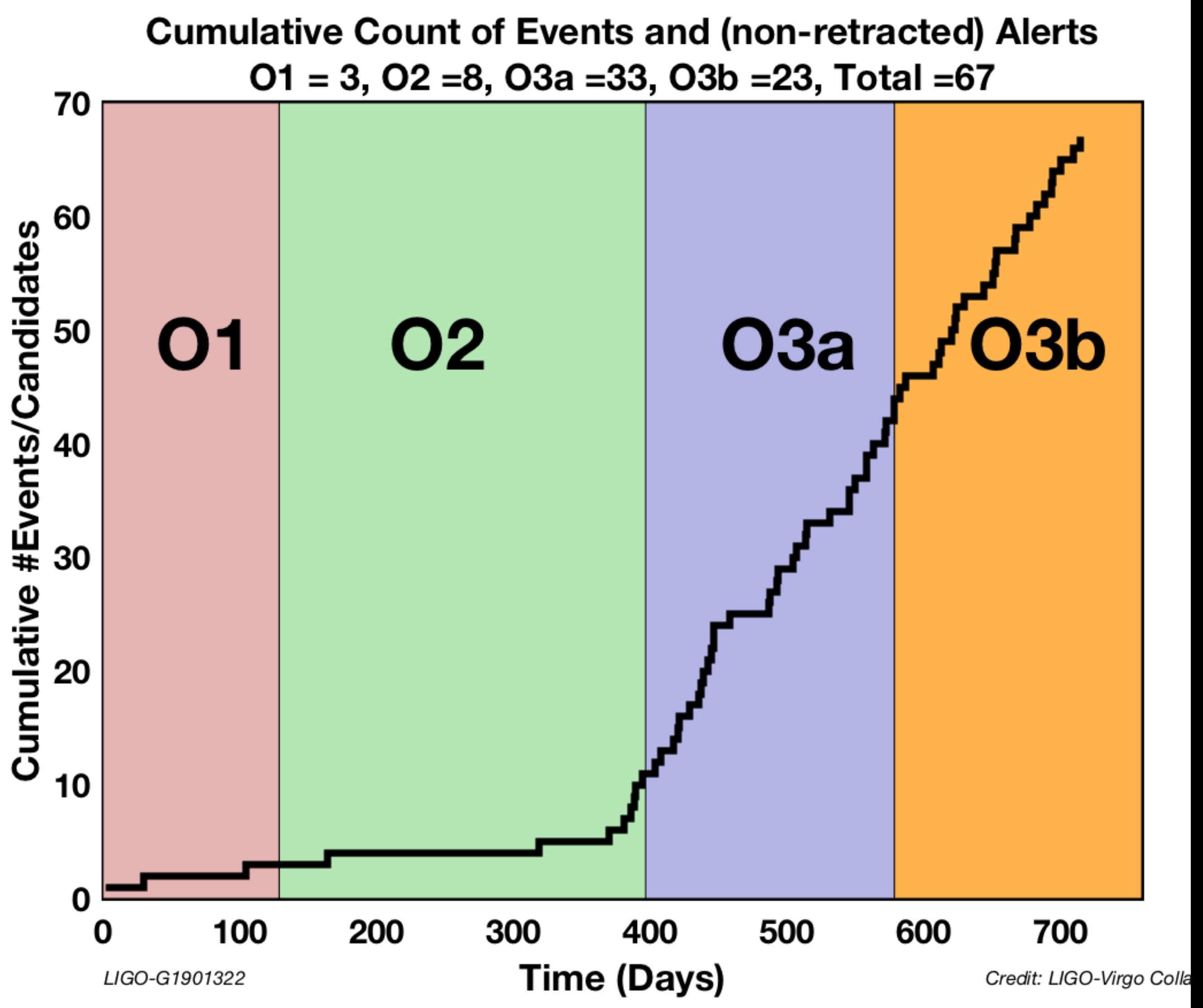
GRAVITATIONAL WAVE DETECTION

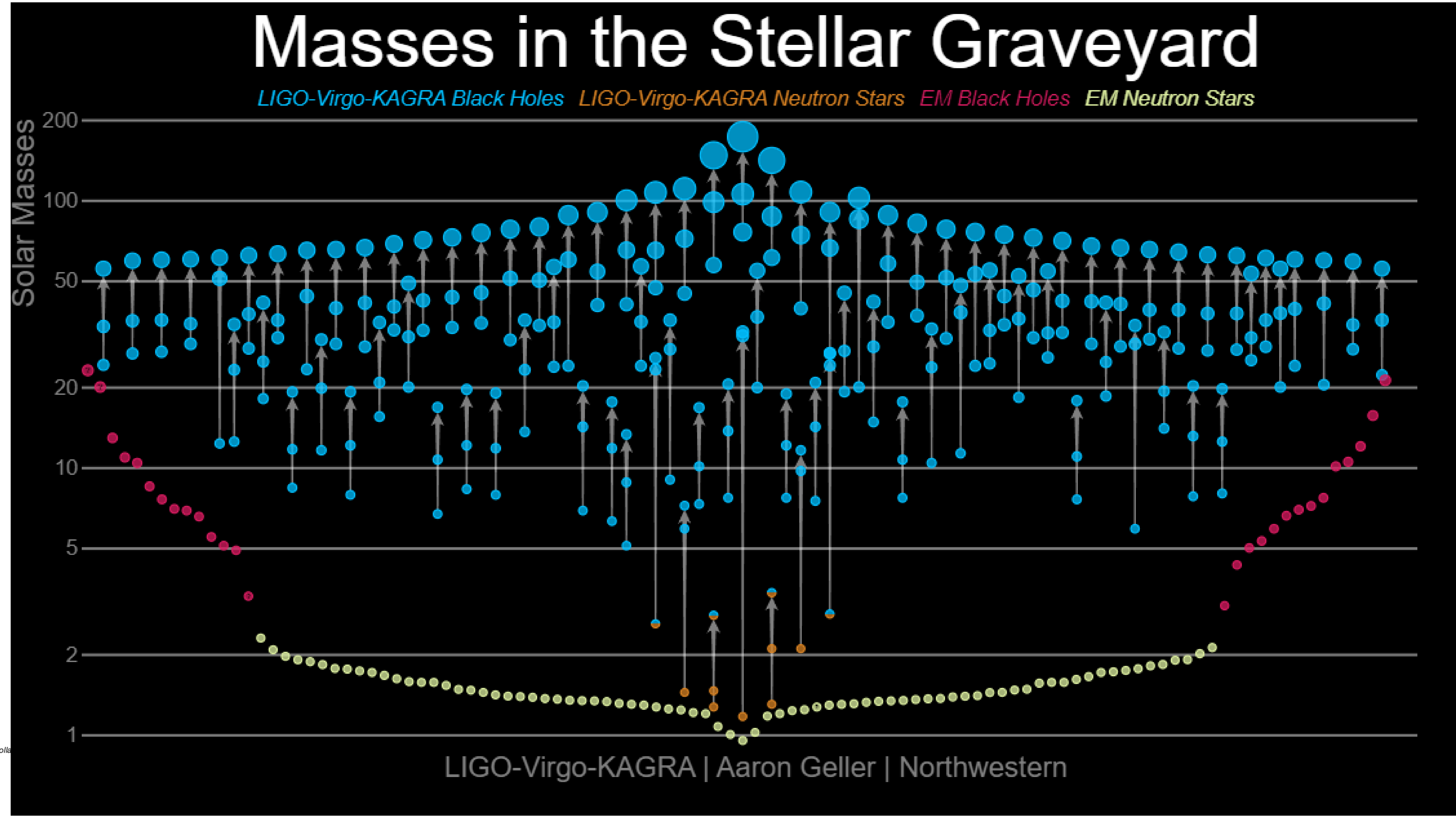


Strain ($\Delta L / L$) *by gravitational wave* ~ 10^{-22} m/m

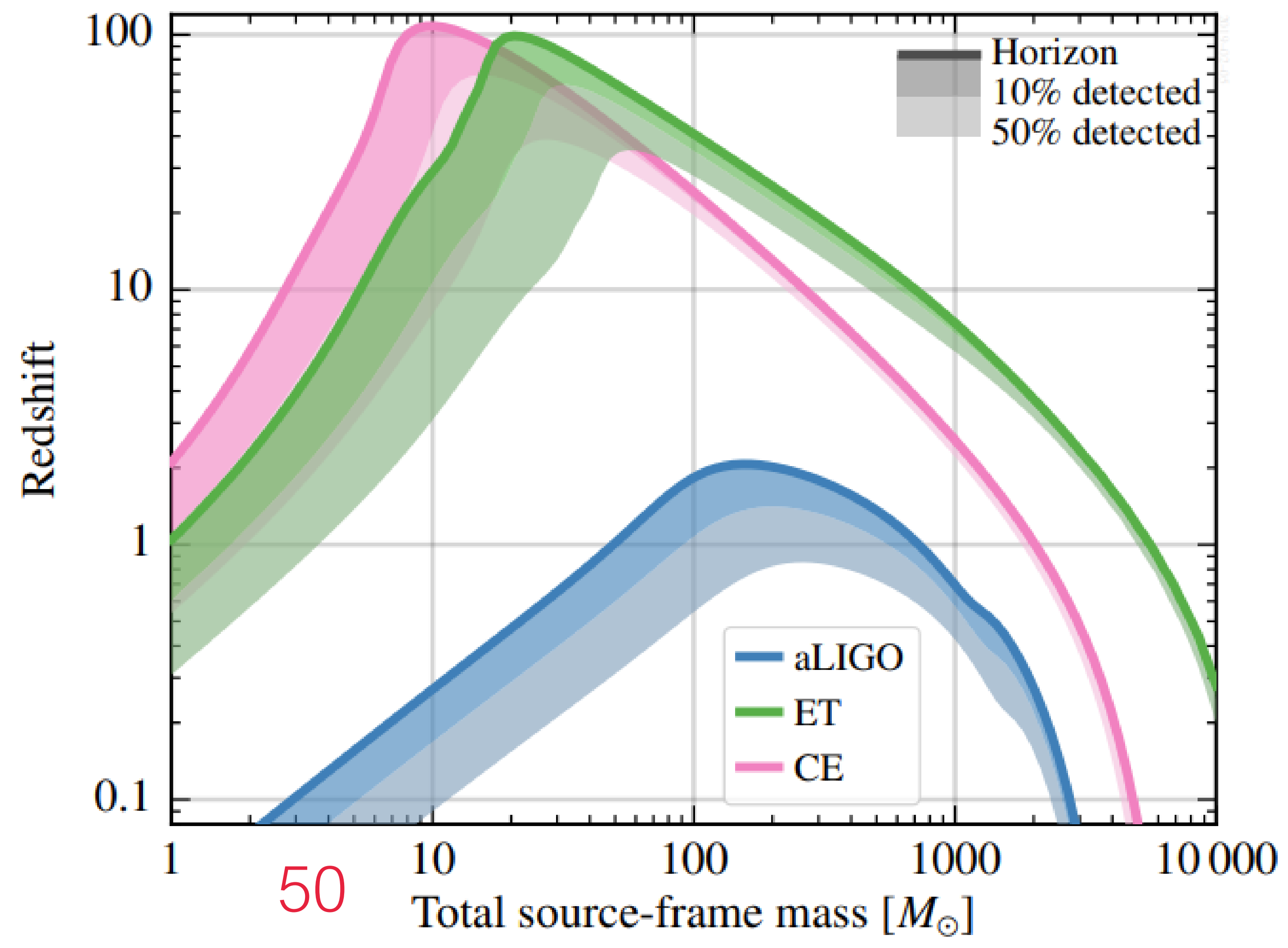
Arm length virgo 3km

$10^{-22} * 3000 \sim 10^{-19}$ m distance we need to measure



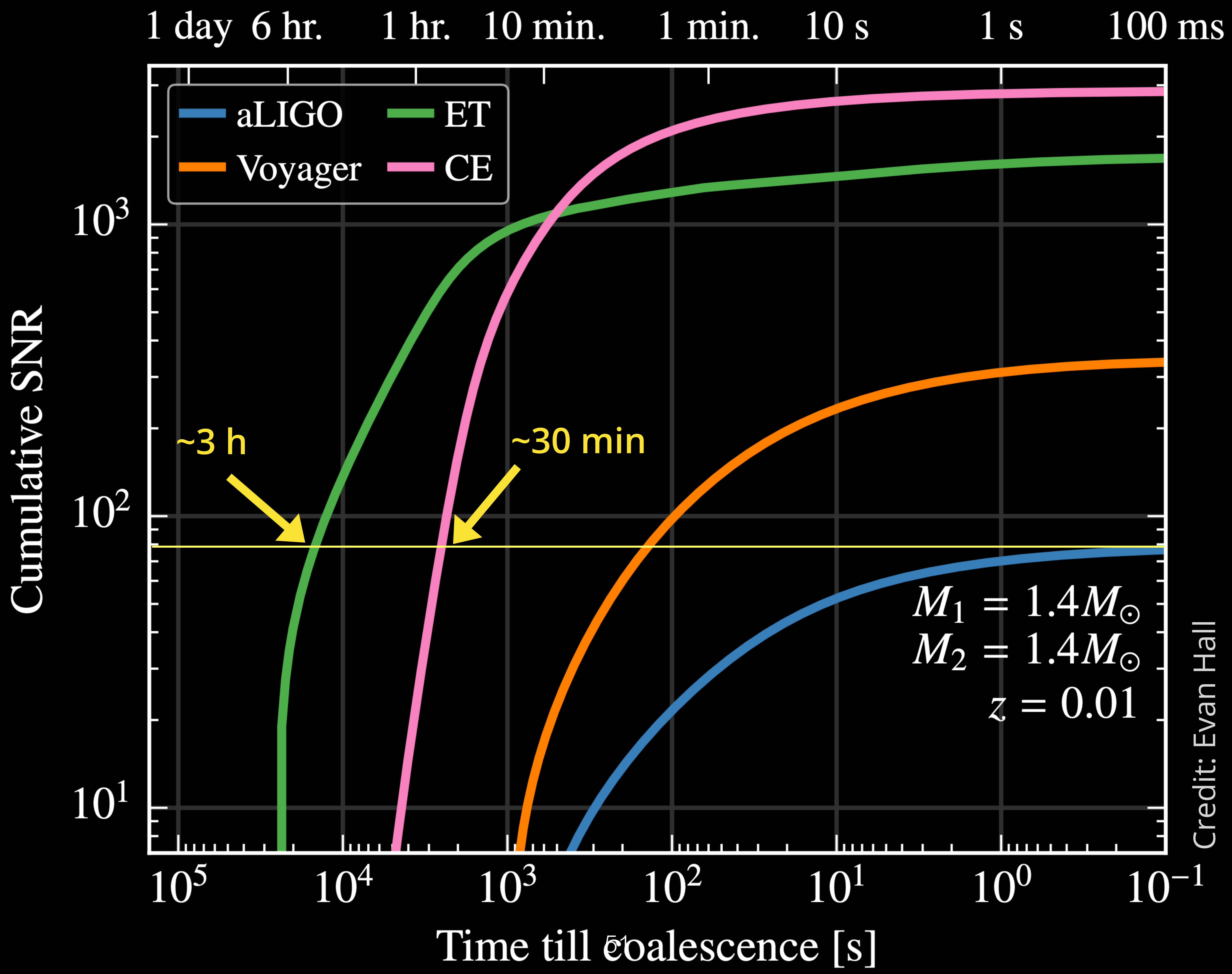


ABOUT ONE SIGNAL DETECTED PER WEEK!

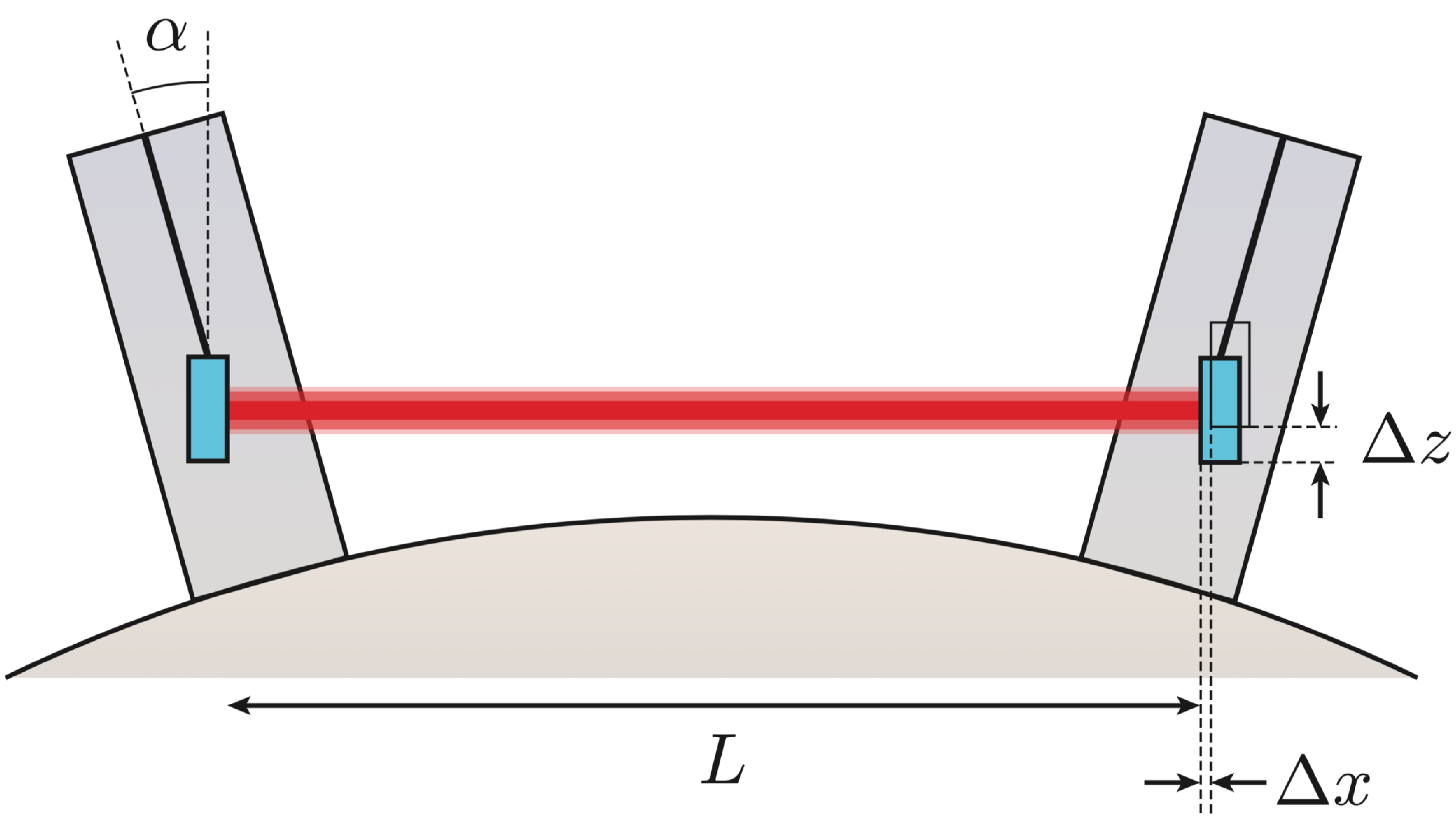


Source: article “Science case for ET"

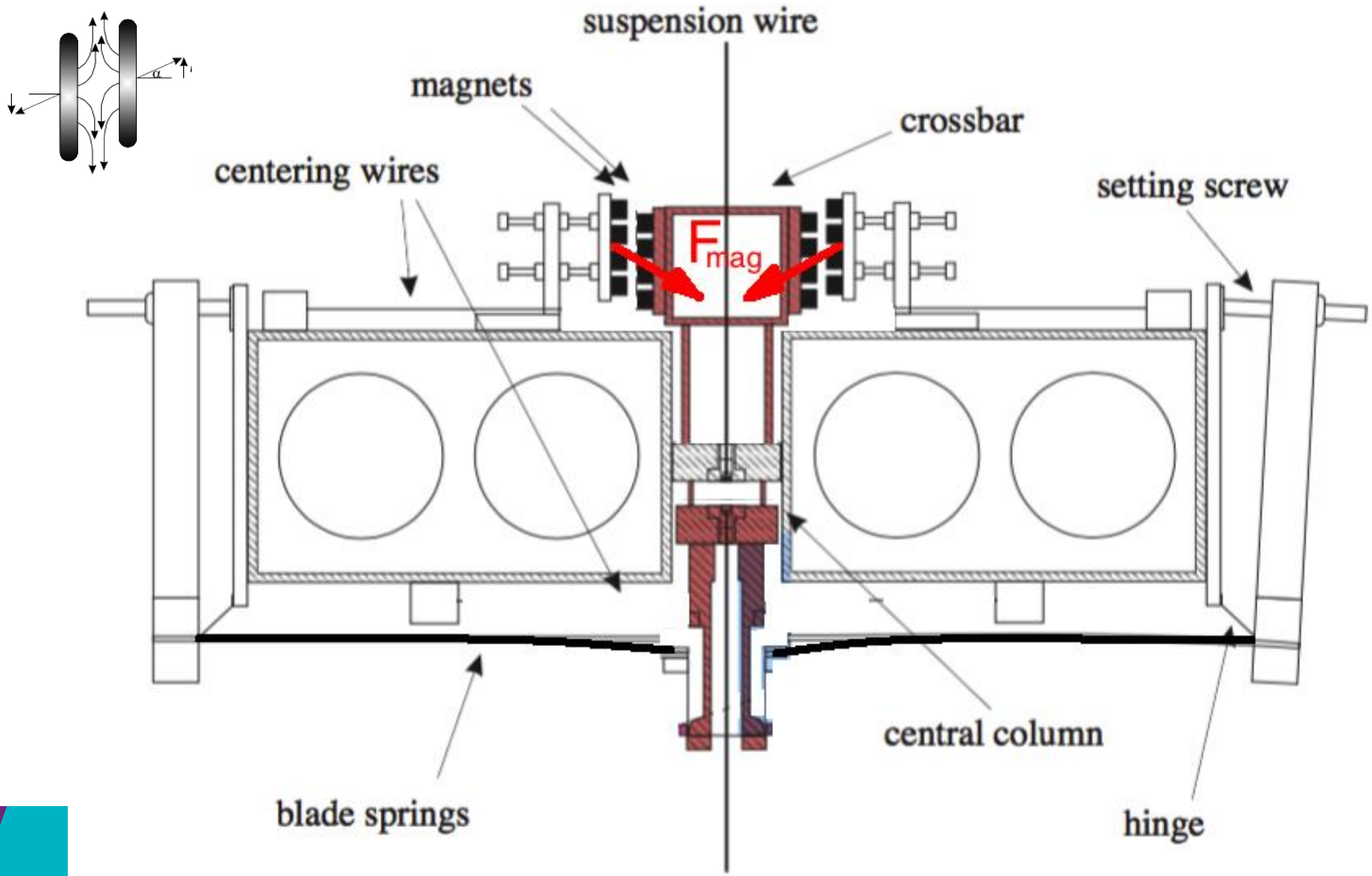
Einstein Telescope 3hz vs Cosmic Explorer 5hz Low frequency sensitivity



- For 3 km detector arm, $\alpha \backsim 2.4 \times 10^{-4}$
- Vaak wordt een 0.1% verticaal naar horizontaal koppeling gebruikt

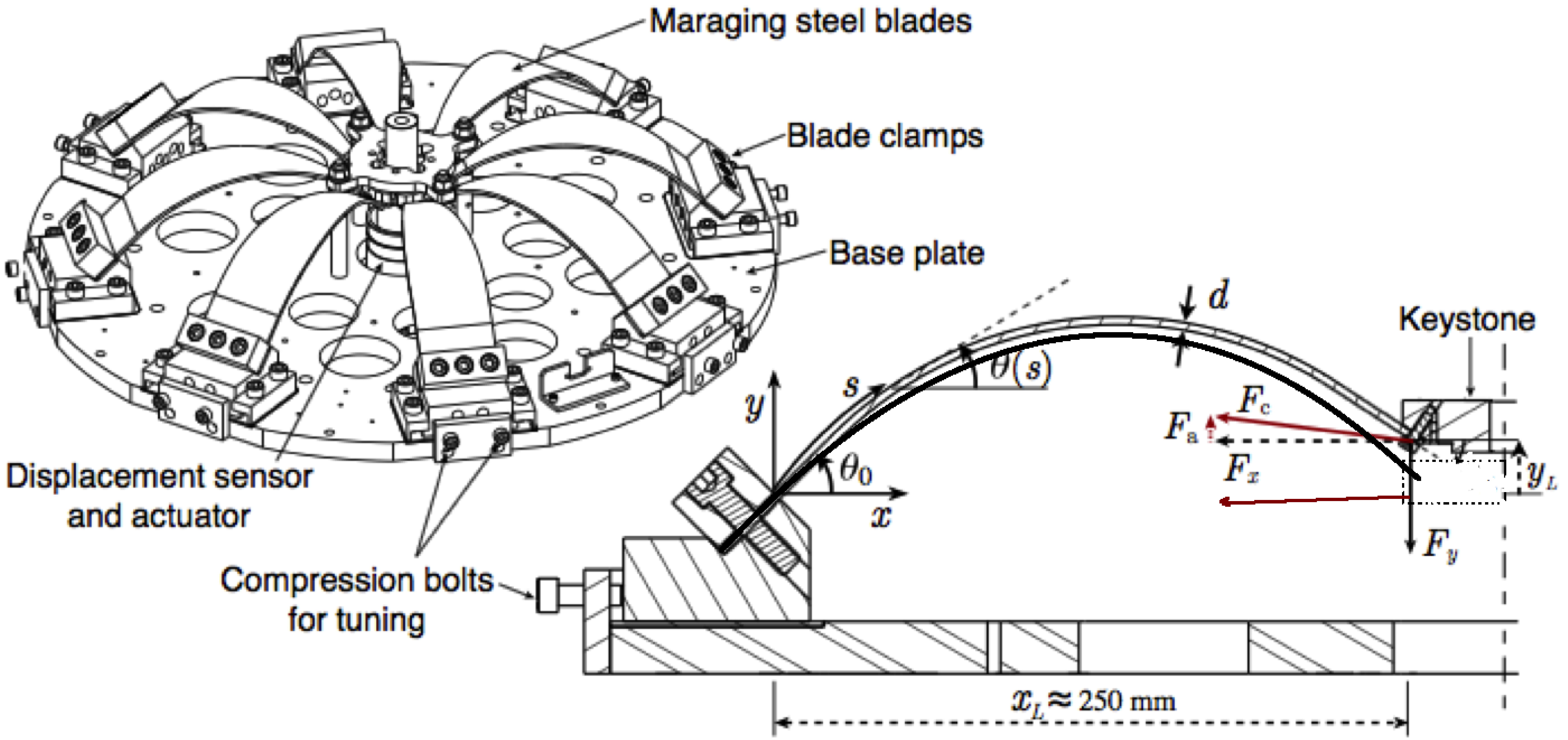


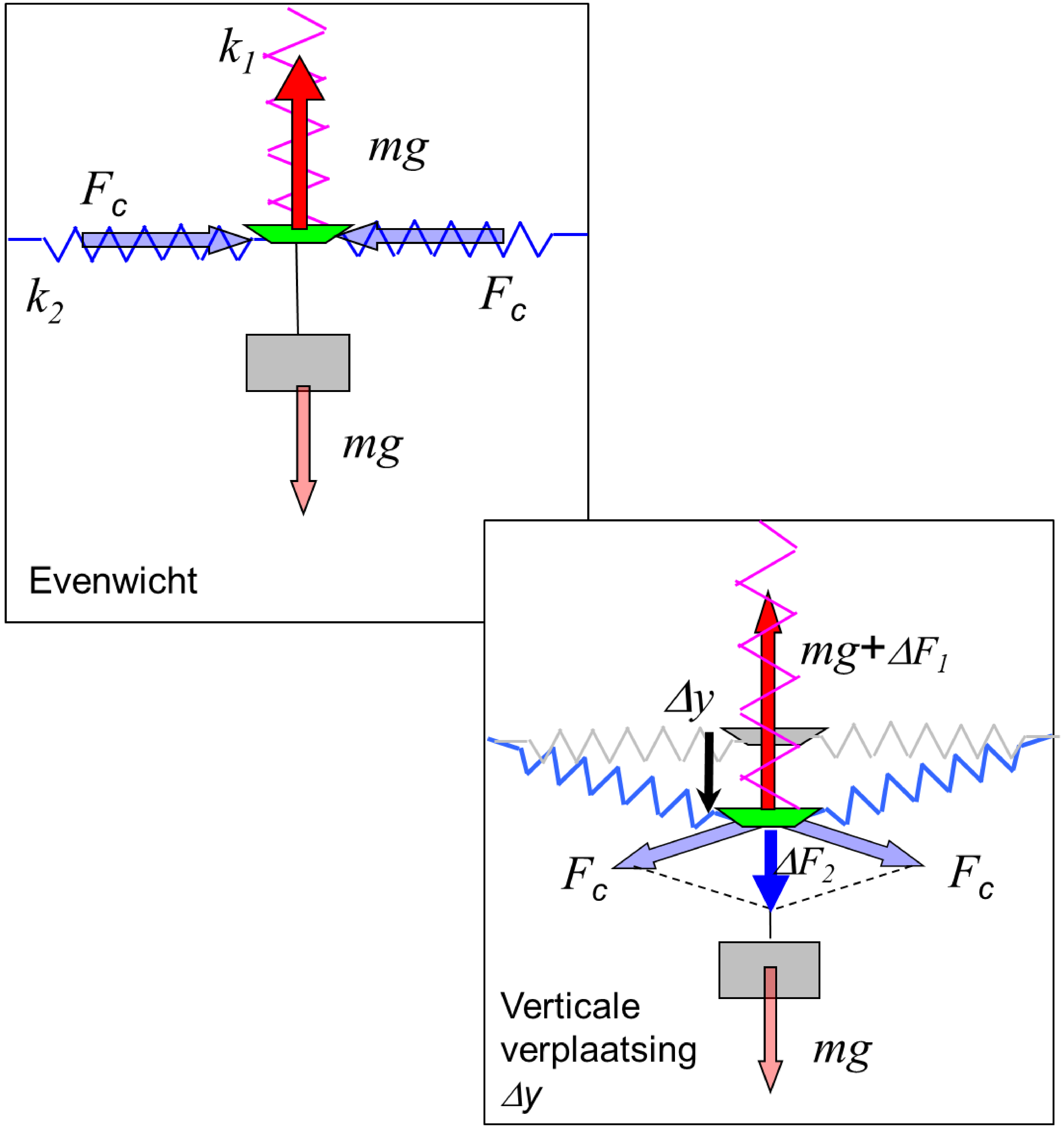
Virgo gebruikt magnetische anti-veer

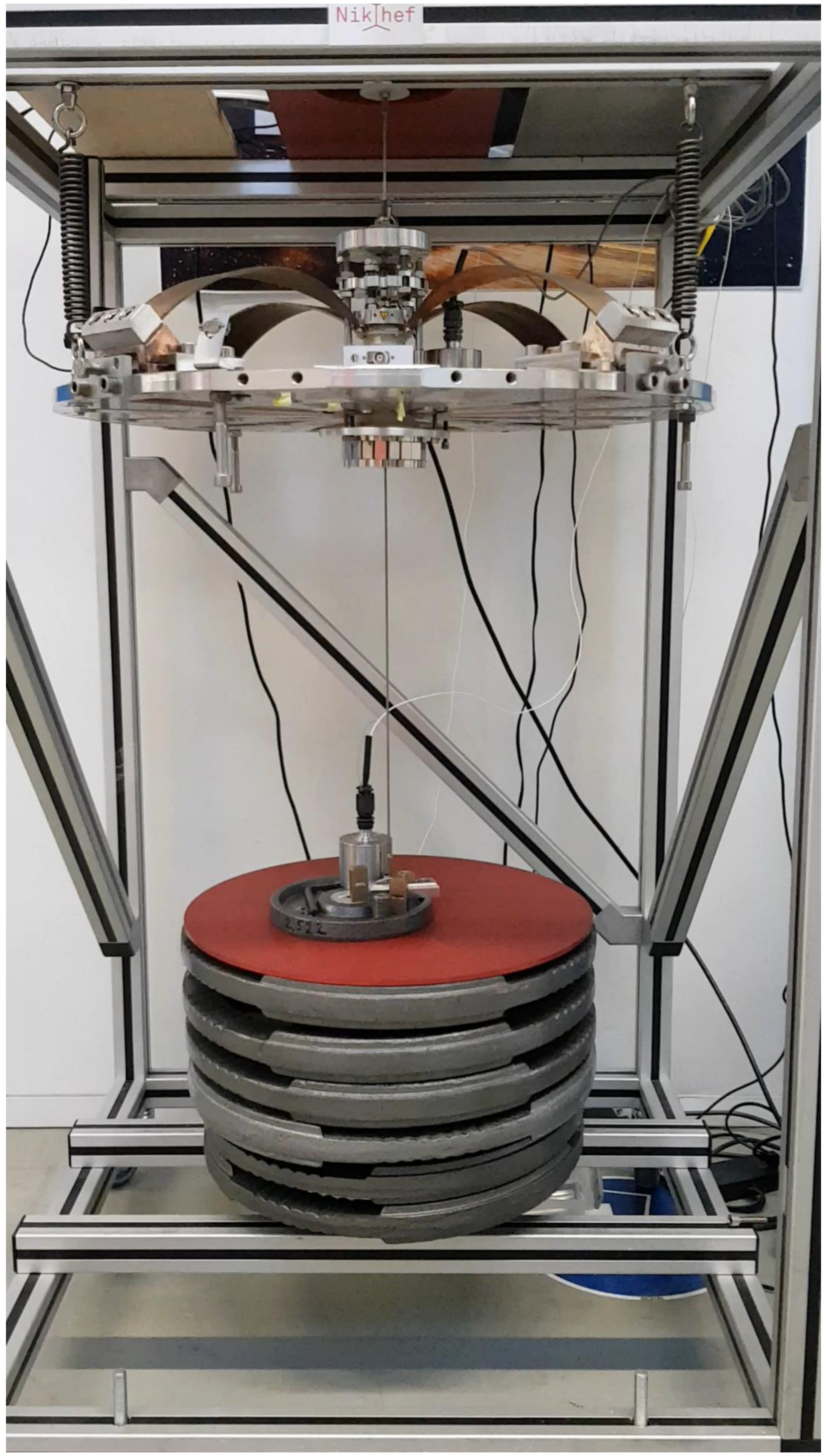


KAGRA and Virgo also use GAS filters

The geometric anti spring (GAS) use geometry to lower f_0

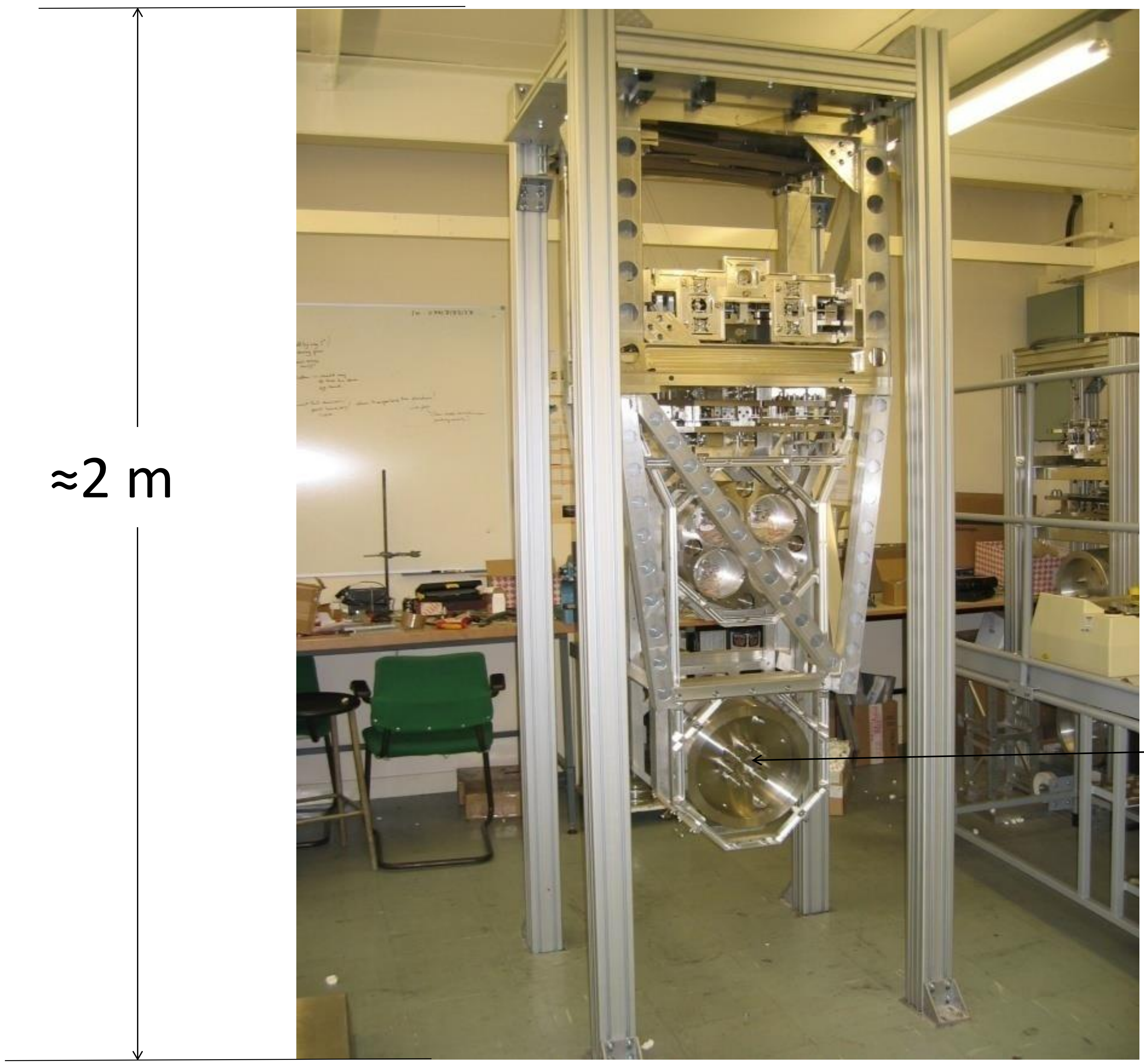




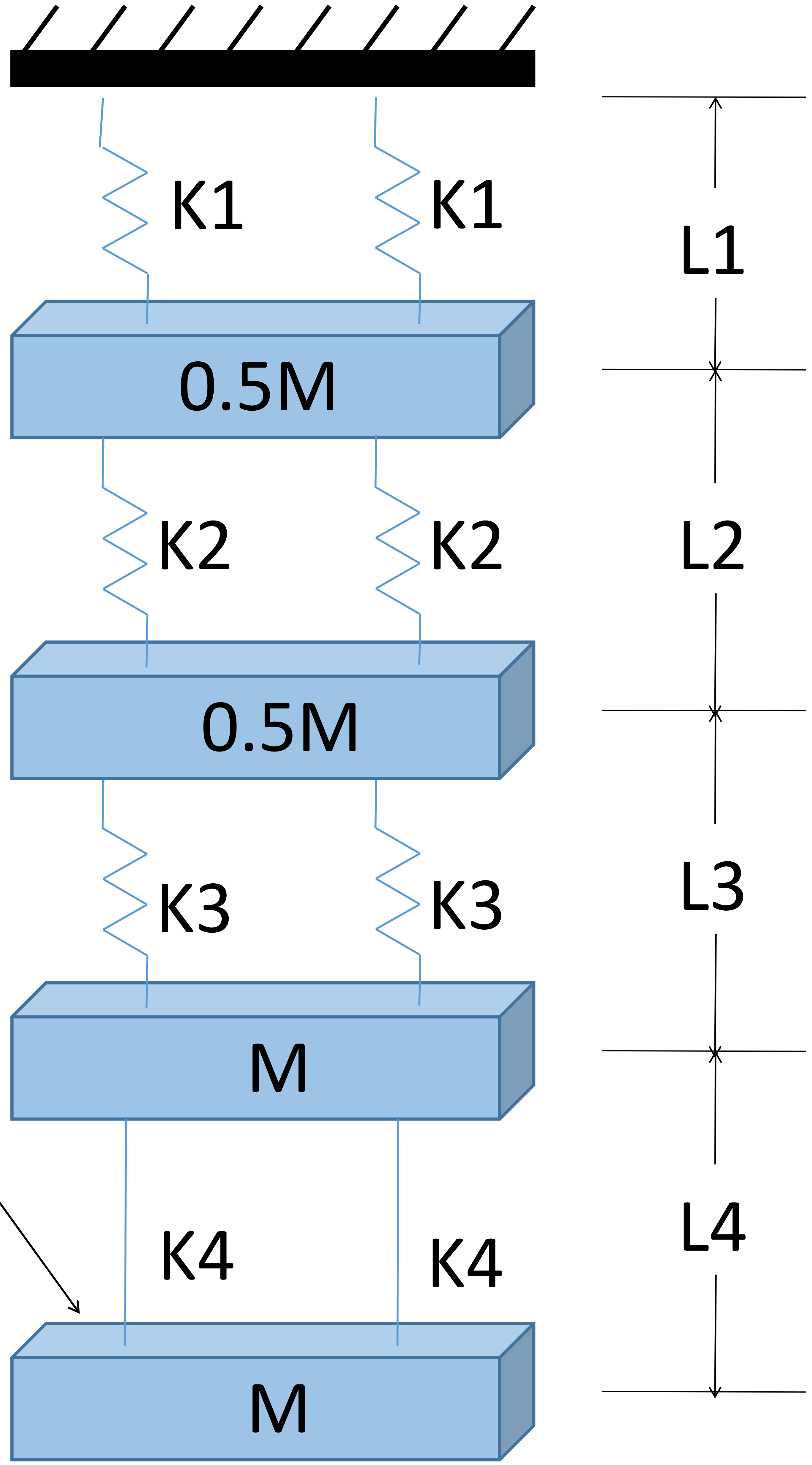


Credit: Eric Hennes

LIGO's "Quad" pendulum



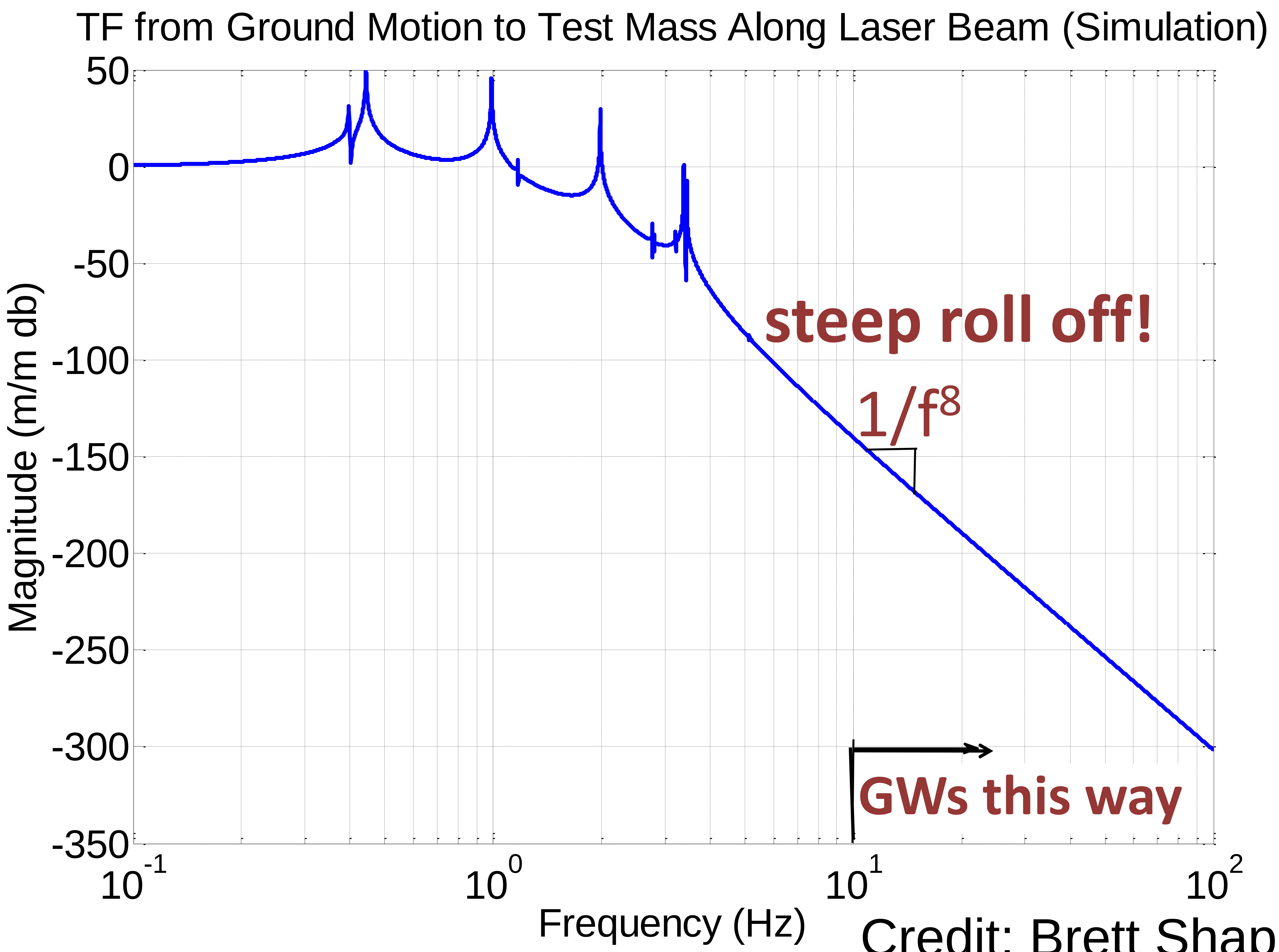
Test Mass
M = 40 kg



Credit: Brett Shapiro

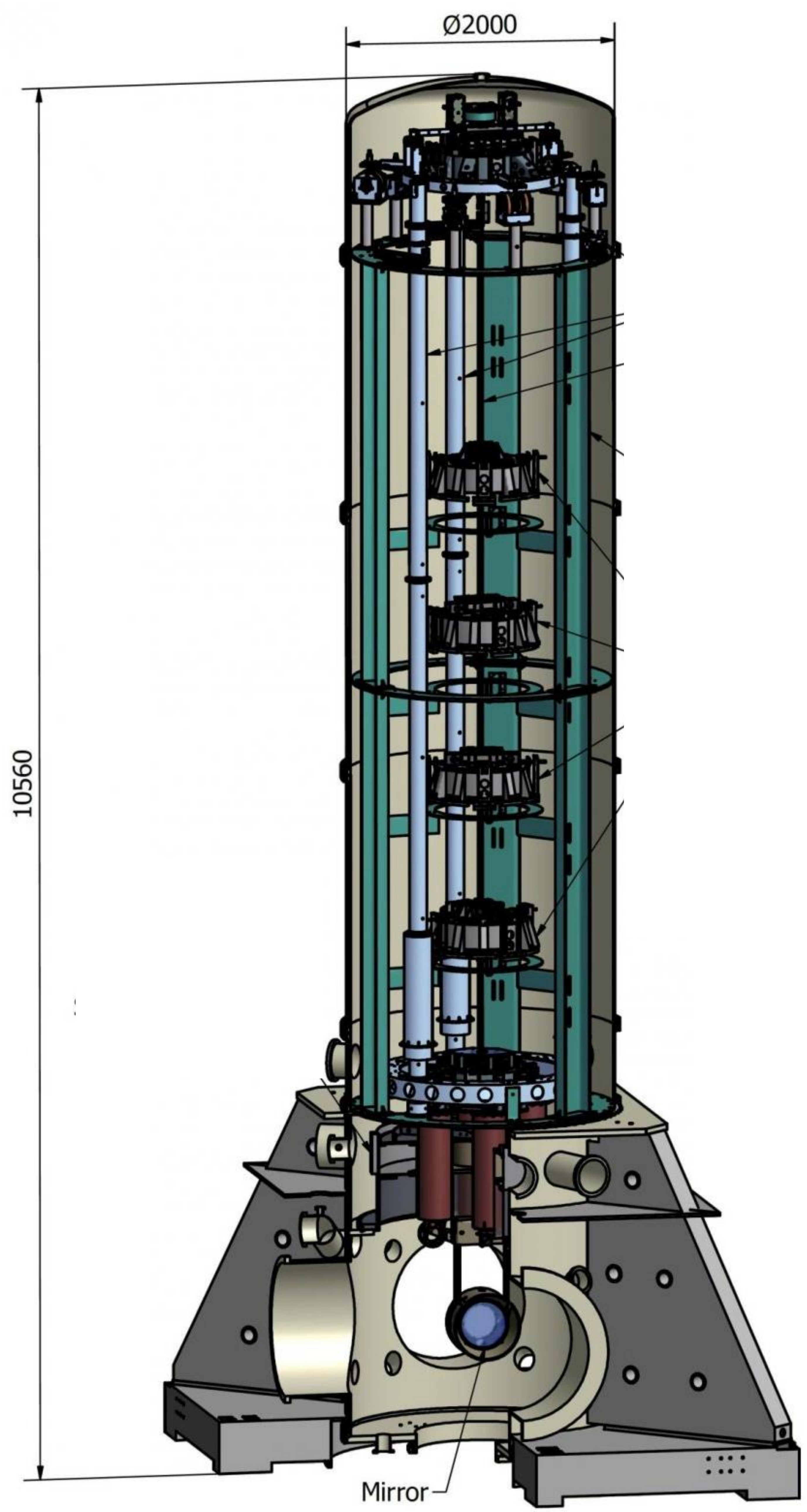
Resultaat van LIGO's Quadruple Pendulum

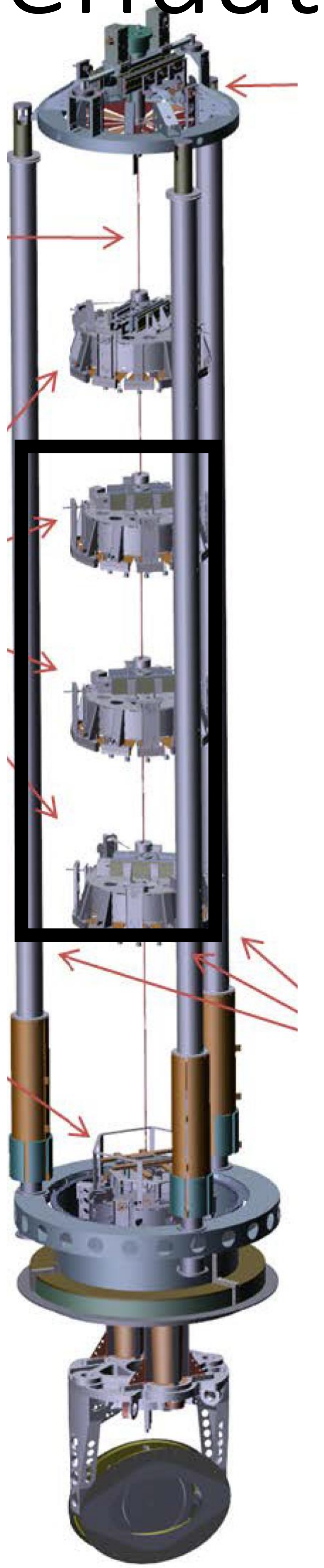
- Gestapelde massas geven sterke reductie.
- Zeer effectief boven 10Hz



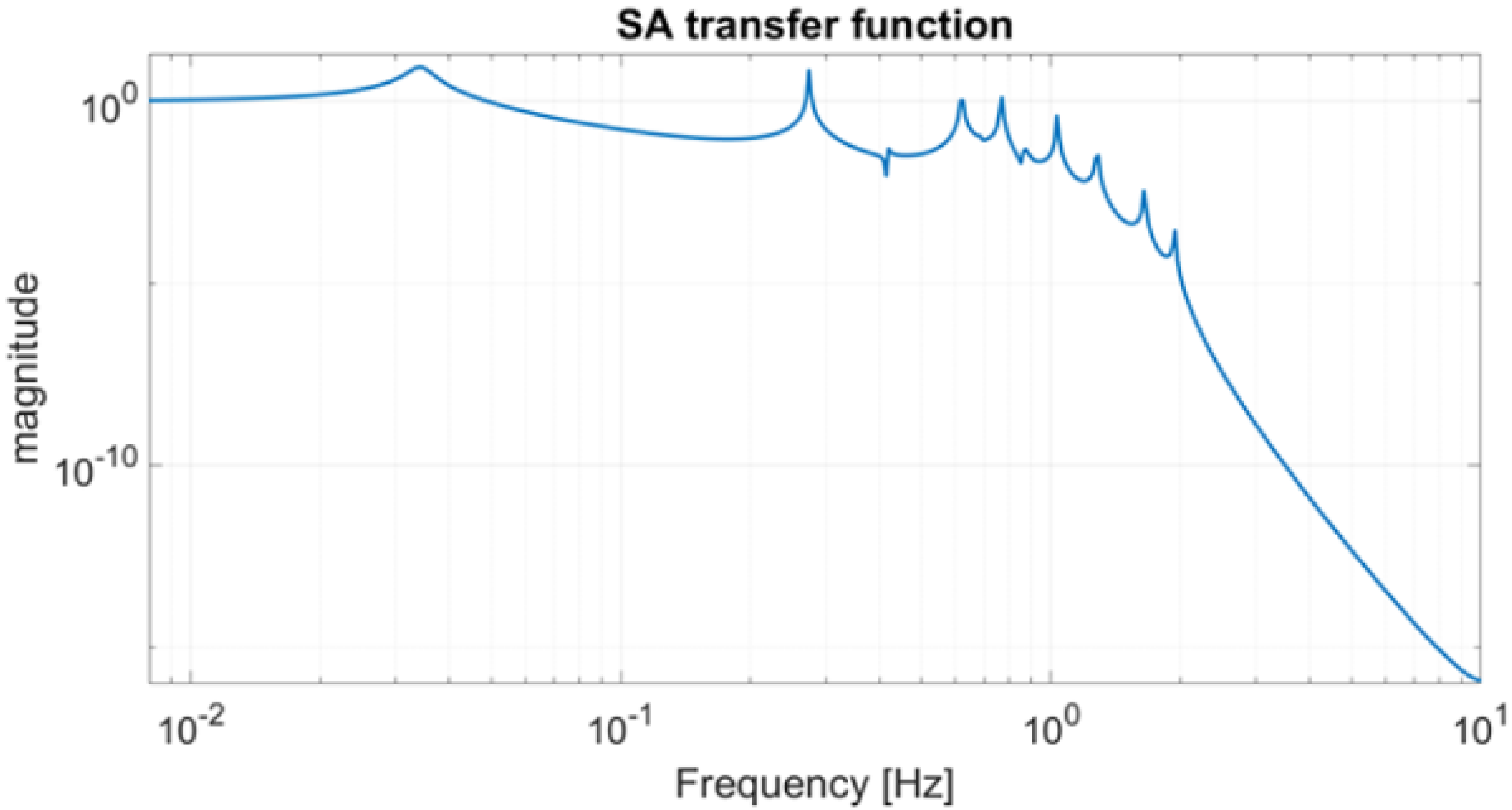
Credit: Brett Shapiro

VIRGO’s Super attenuator





Resultaat van Virgo Superattenuator



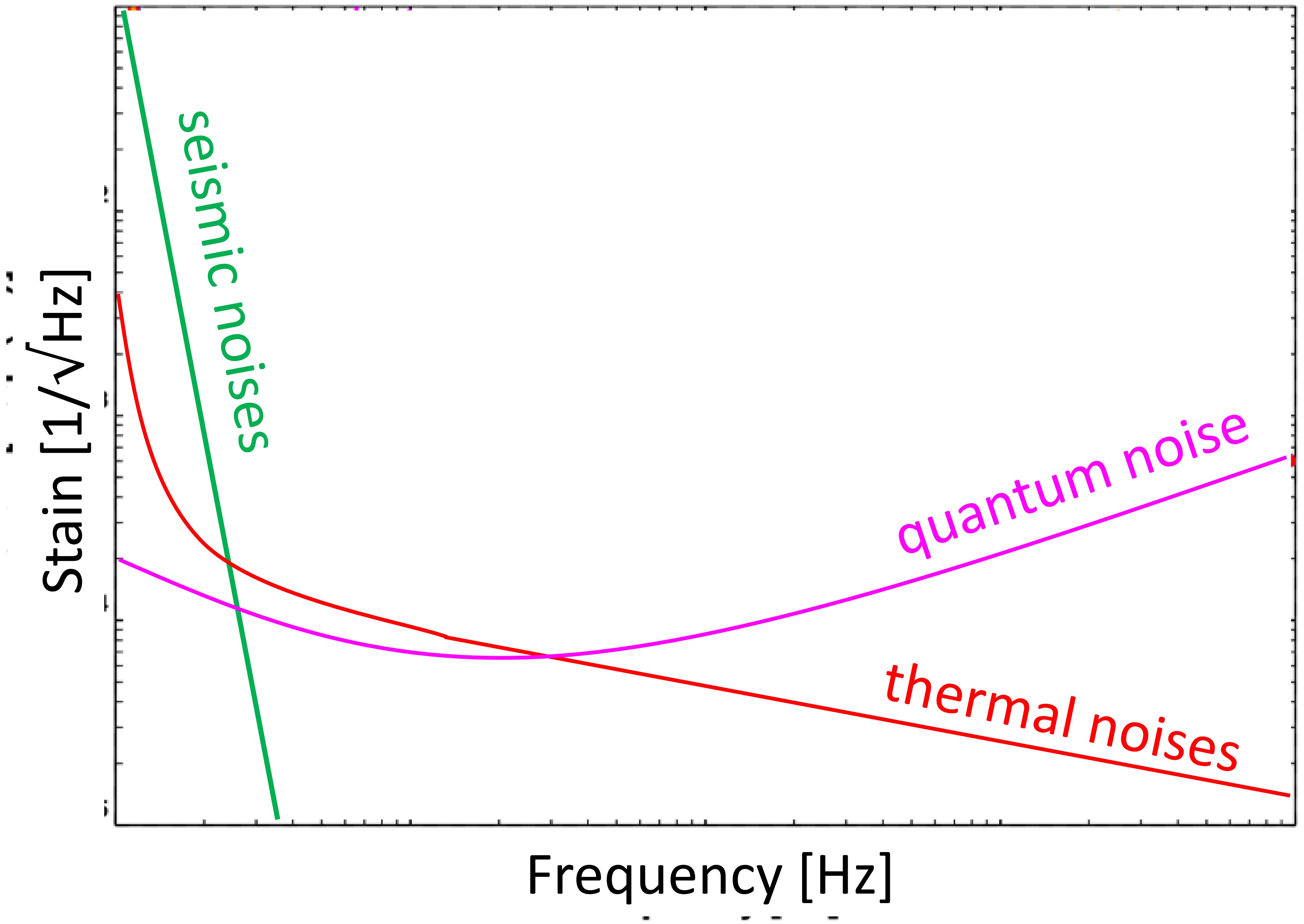
Nikhef

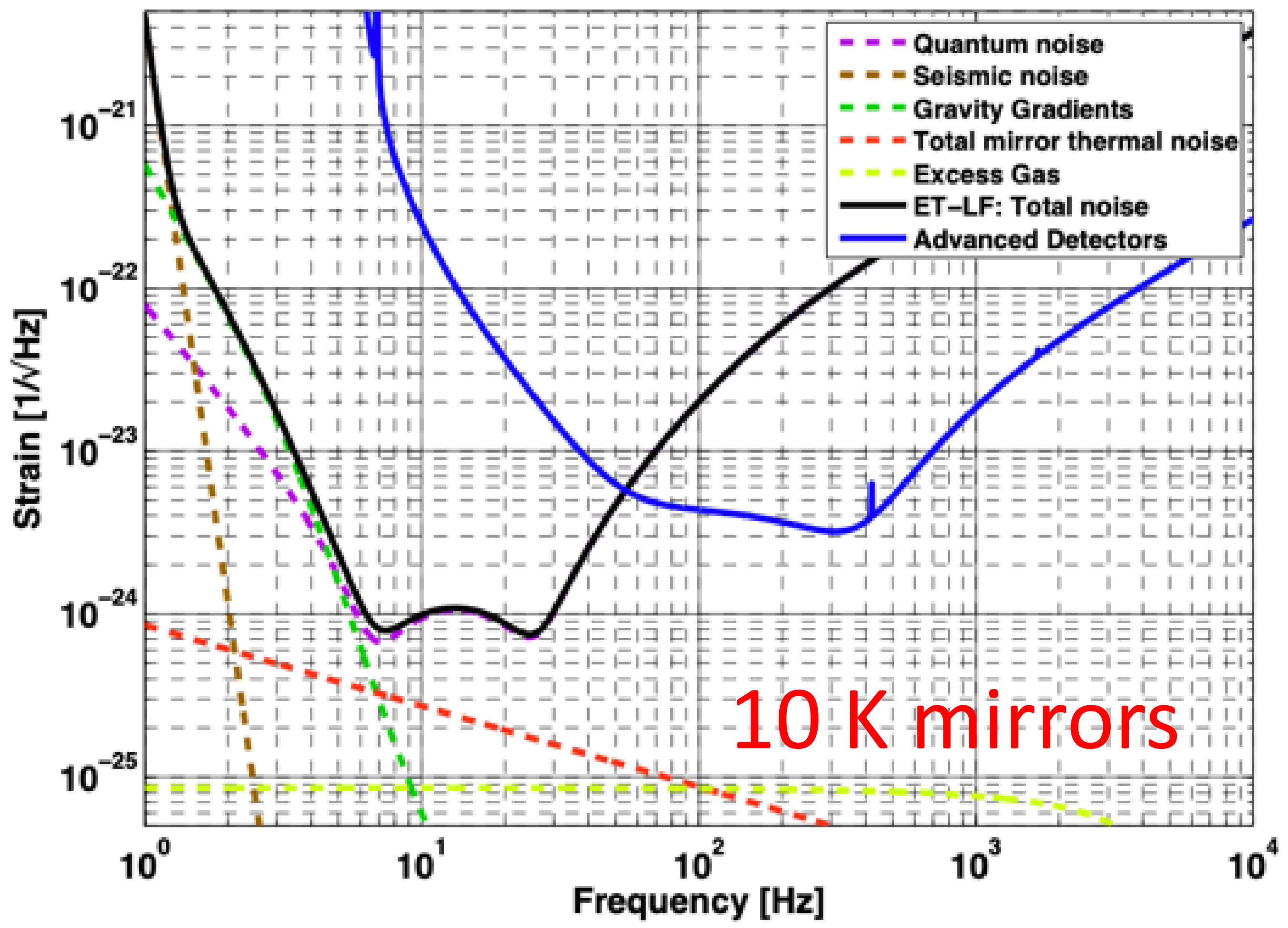
Source: Seismic and newtonian noise in the GW detectors

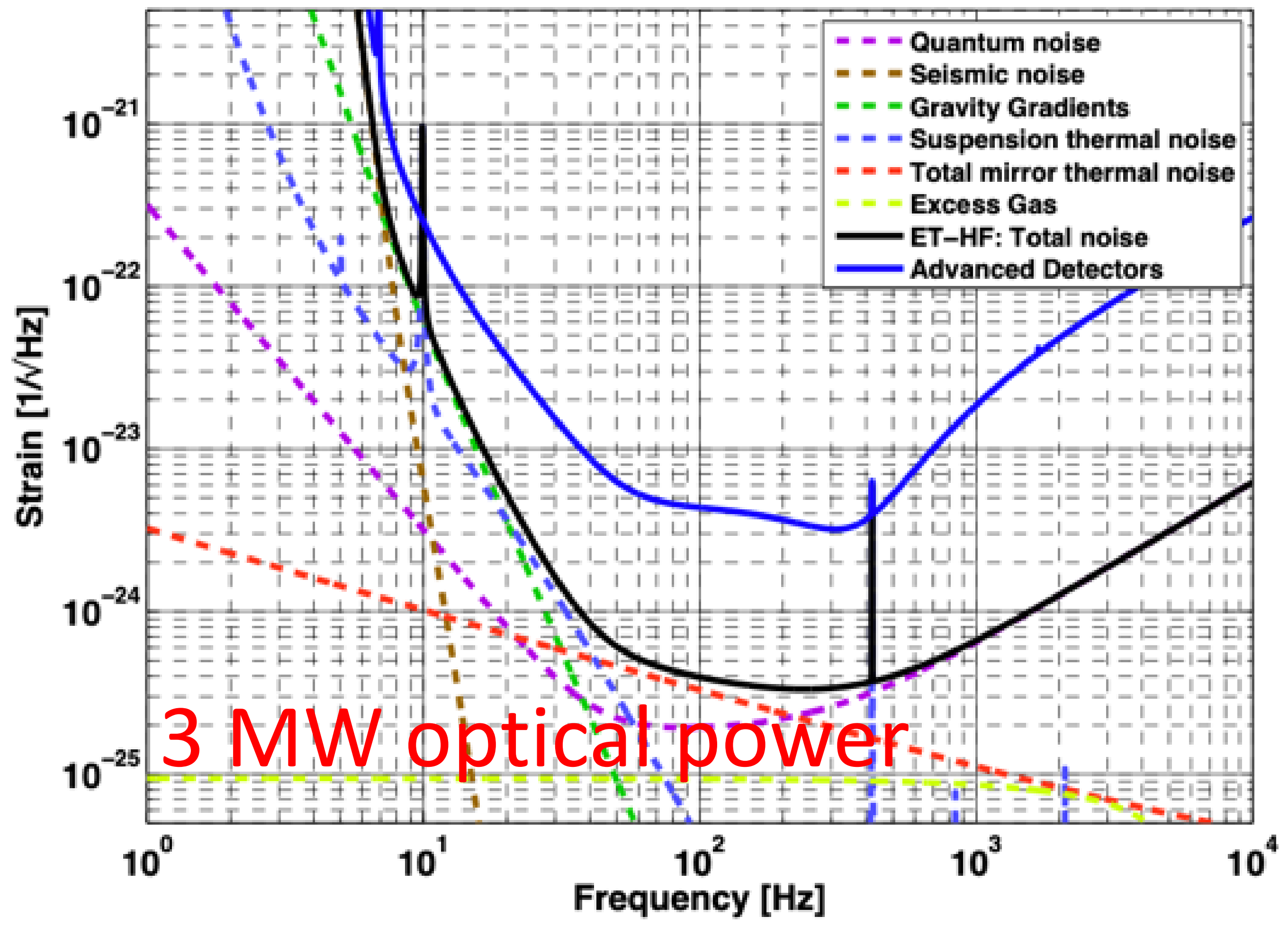
Einstein Telescope: een grote kans voor de wetenschap, Nederland, en Europa.

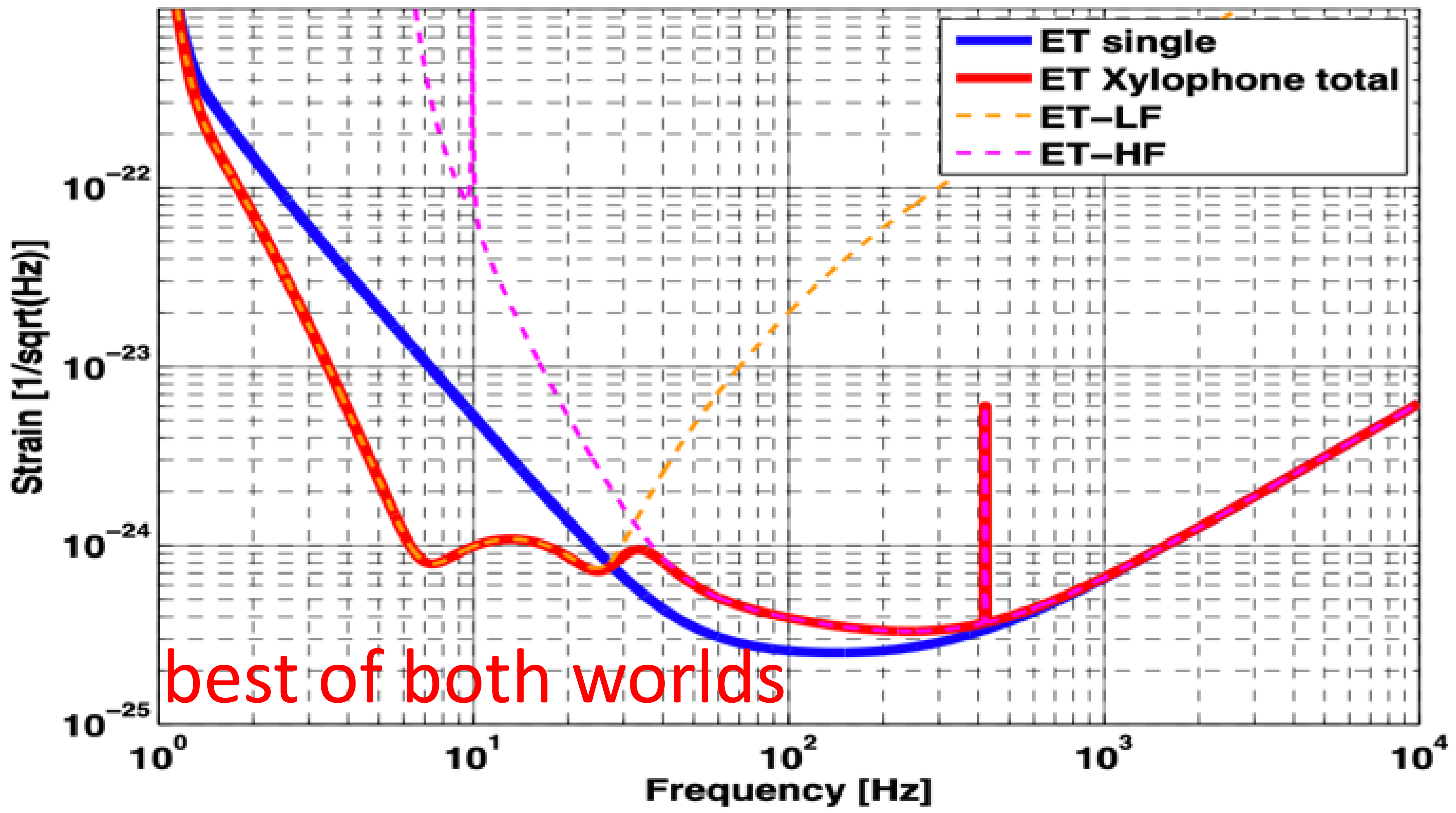
Image Credit: Marco Kraan

The best of both worlds









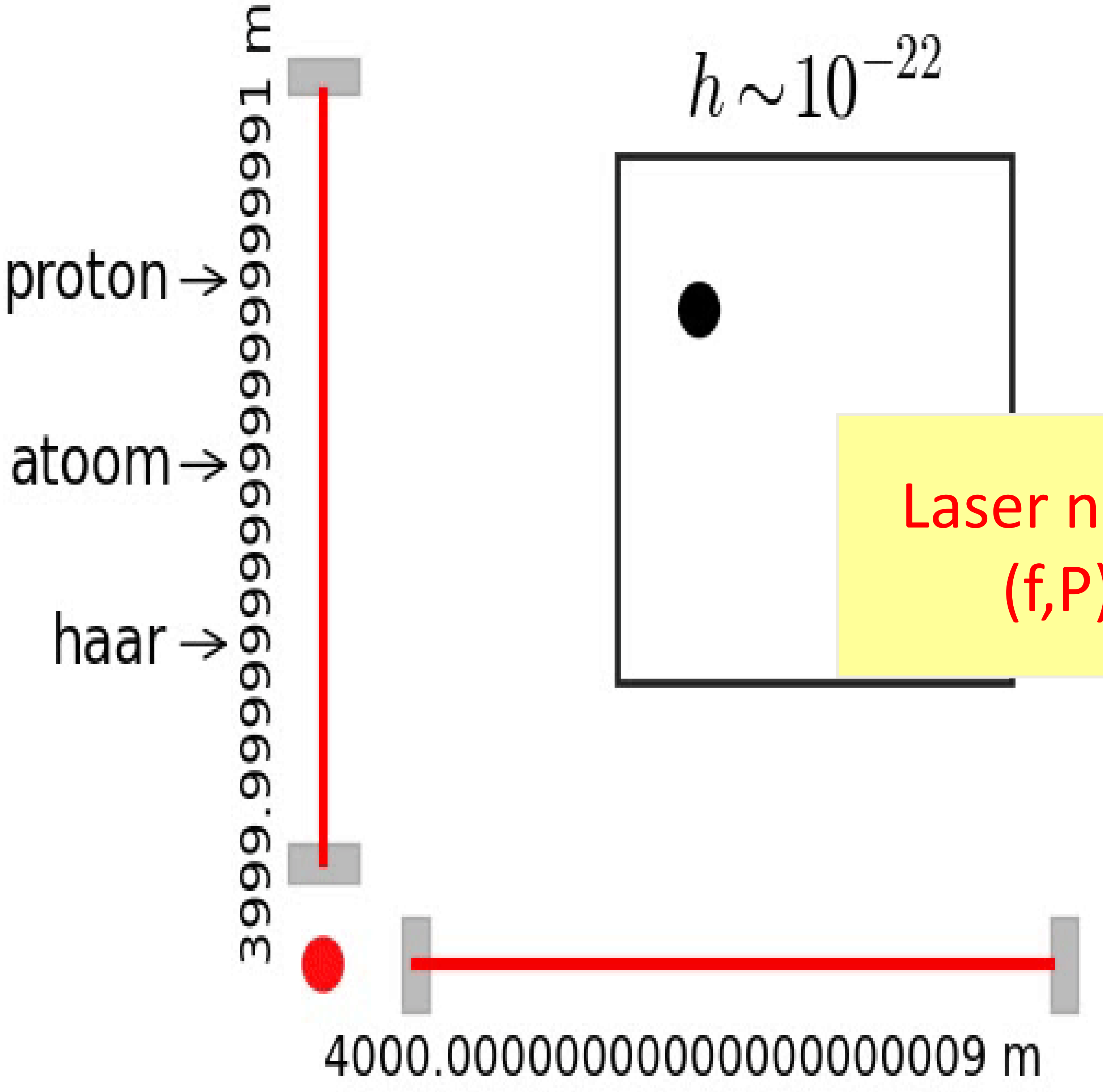
from S. Hild *et al.*, "A Xylophone Configuration for a third Generation Gravitational Wave Detector", Class. Quant. Grav. 27 015003 (2010)

- ➢Seismic noises depend on design ($);
- ➢Higher P shift quantum noises ⏬, but 🌡 ⏫;
- ➢Thermal noise go down with 🌡 ⏬, but then P ⏬ & the quantum noises go ⏫.

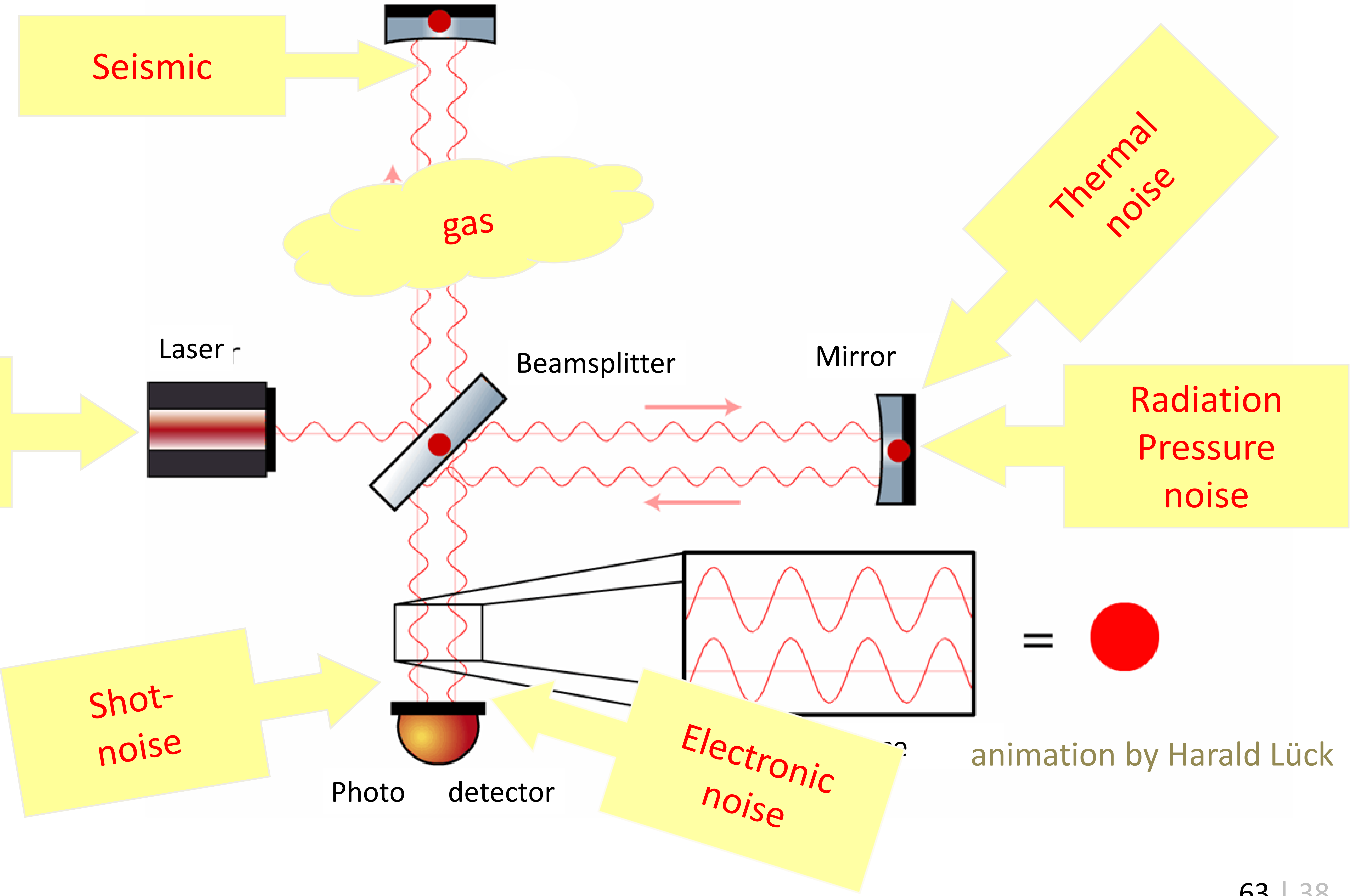
Video through the tunnels of ET

https://youtu.be/vxd746PVAf8

Wanna detect a gravitational wave on Earth?



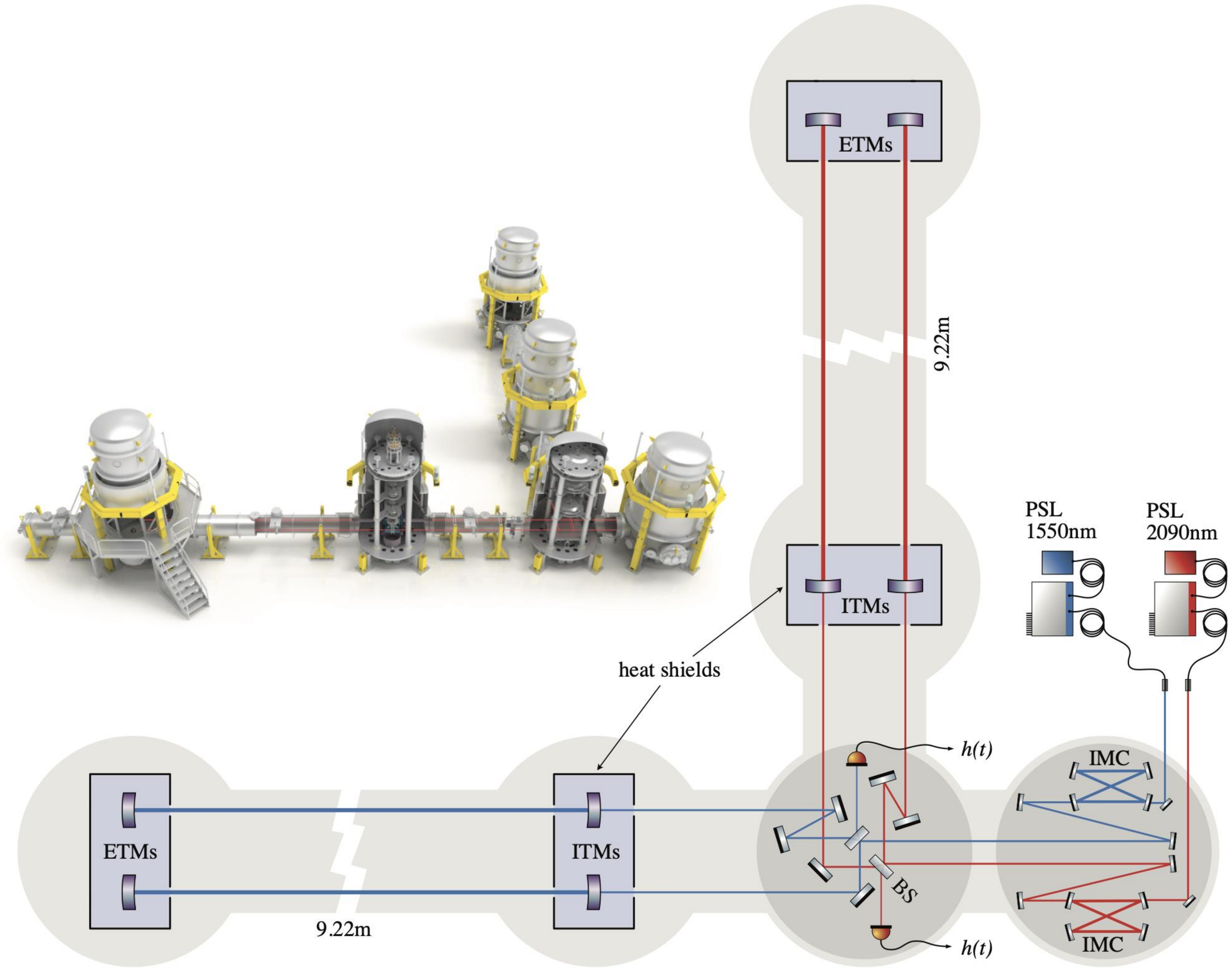
animation by Jeroen Meidam



animation by Harald Lück

ET Pathfinder: Maastricht 10meter R&D Faciliteit

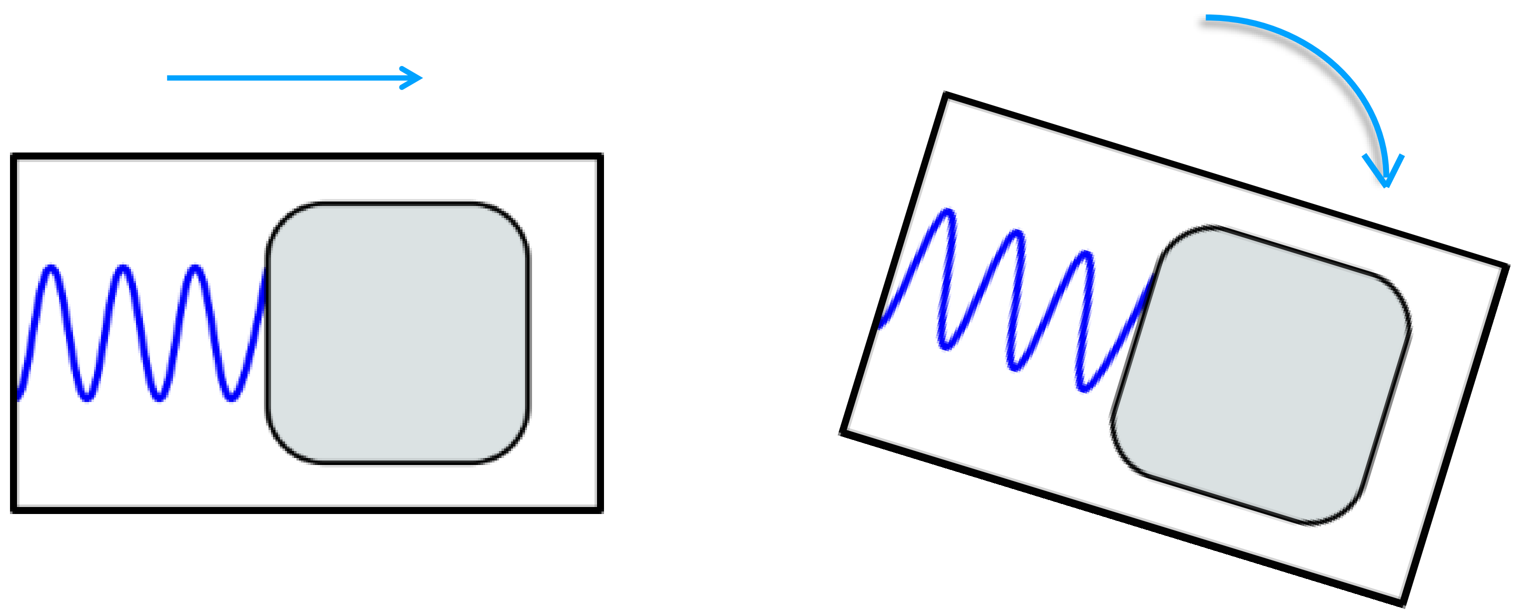
Einstein Telescope pathfinder (ETpathfinder)



- Focus mostly on cryogenic interometry (advanced topologies at different wavelength/temperature).
- Each vacuum tower has one big suspension, from which we hang e.g. an optical bench or two mirrors.
- The latter needs two parallel pendulum chains.

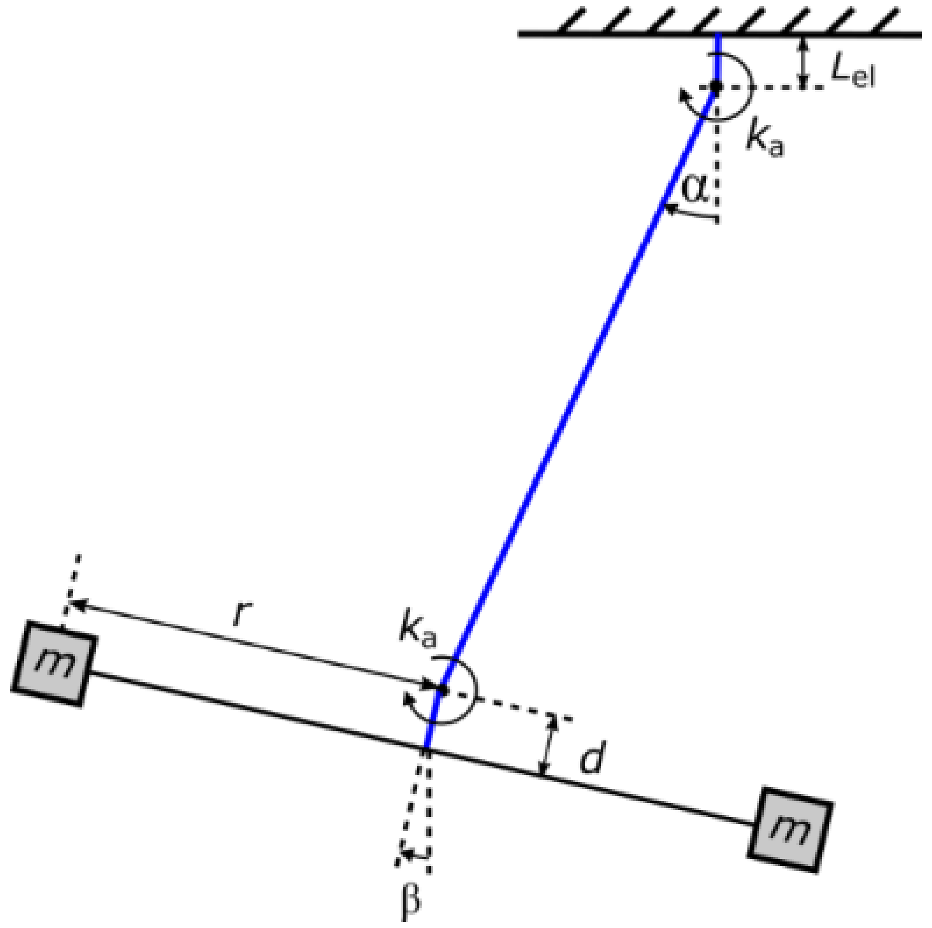
Credit: Conor Mow-Lowry

Tilt-to-Horizontal coupling

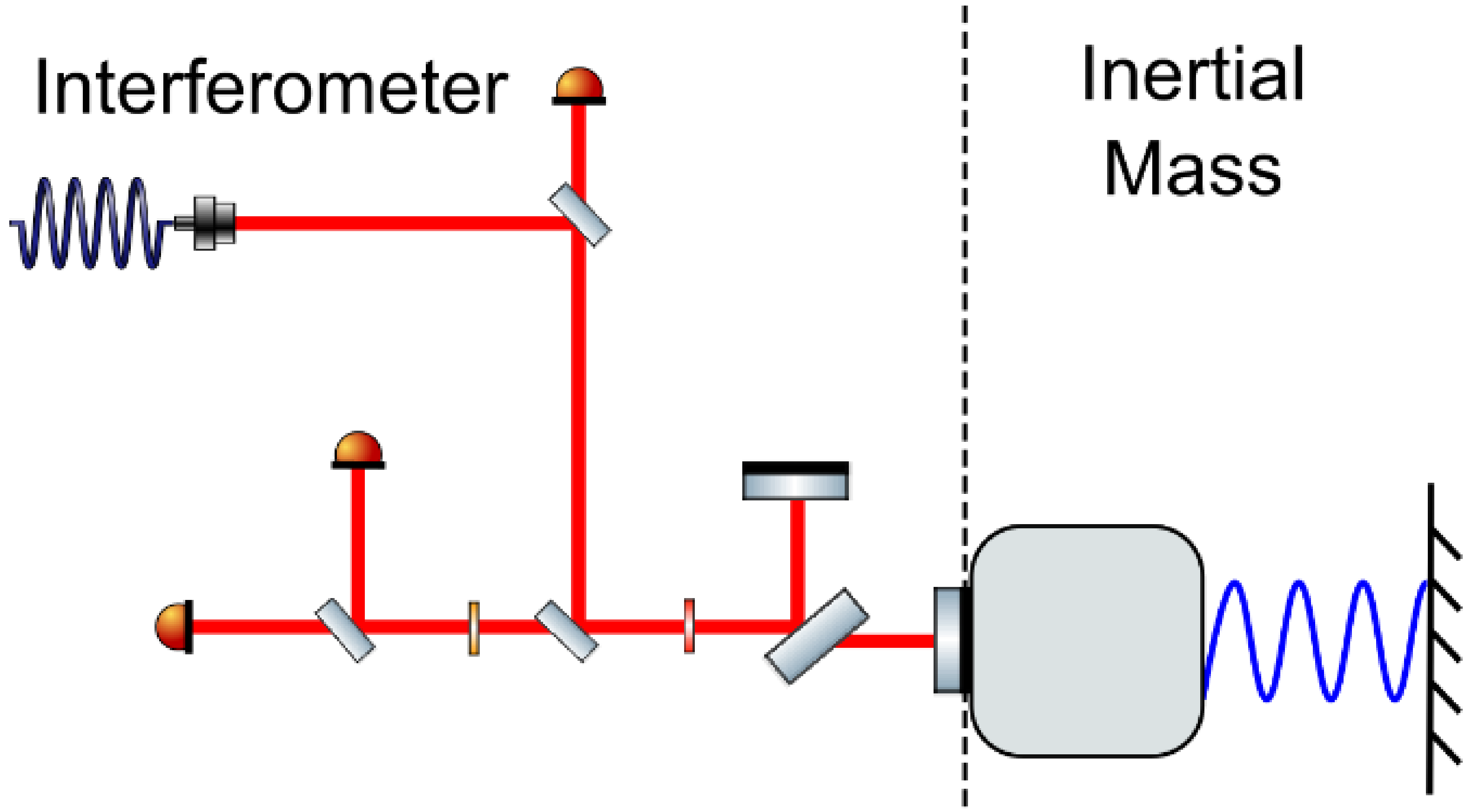


$\delta x \propto ax$ $\delta x \propto g\theta$

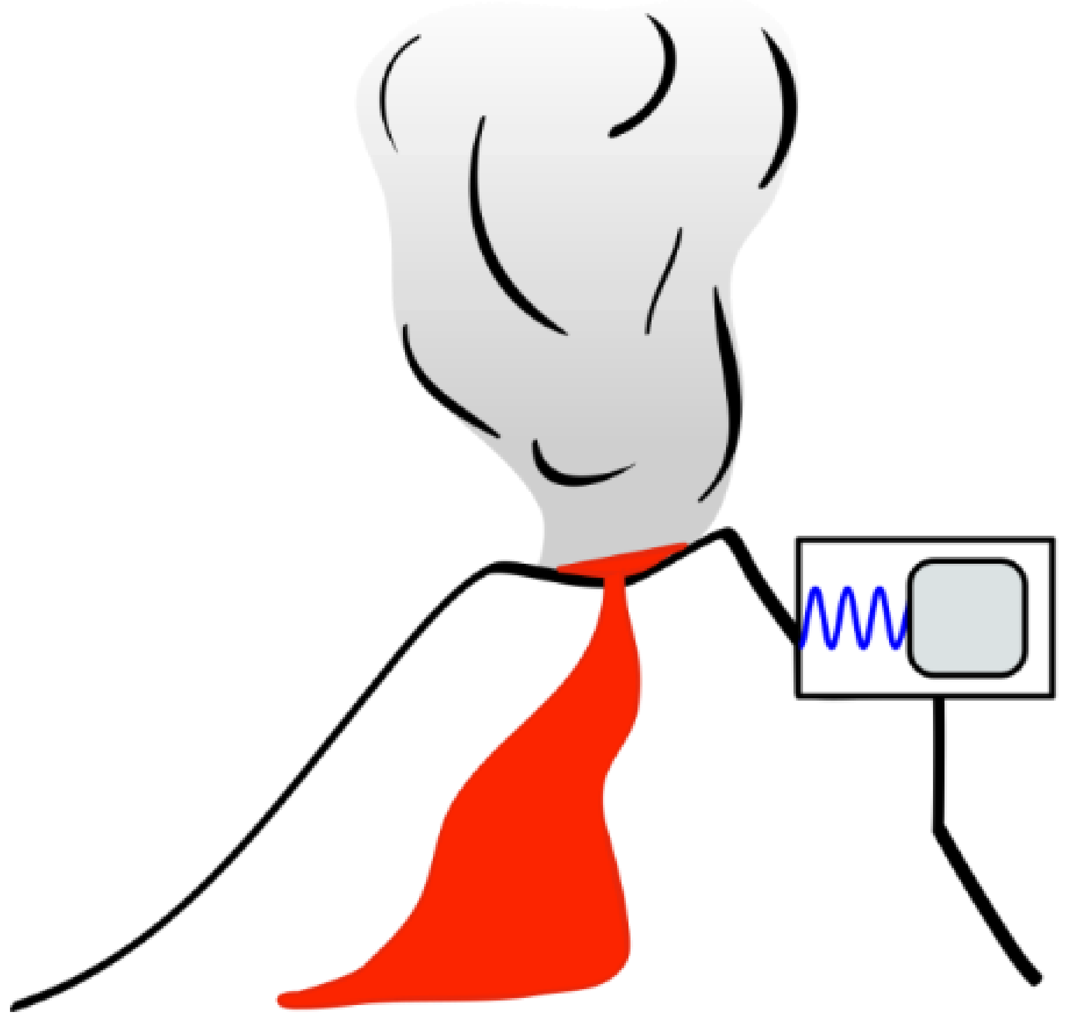
Mechanical cross-coupling



Sensor/actuator noise

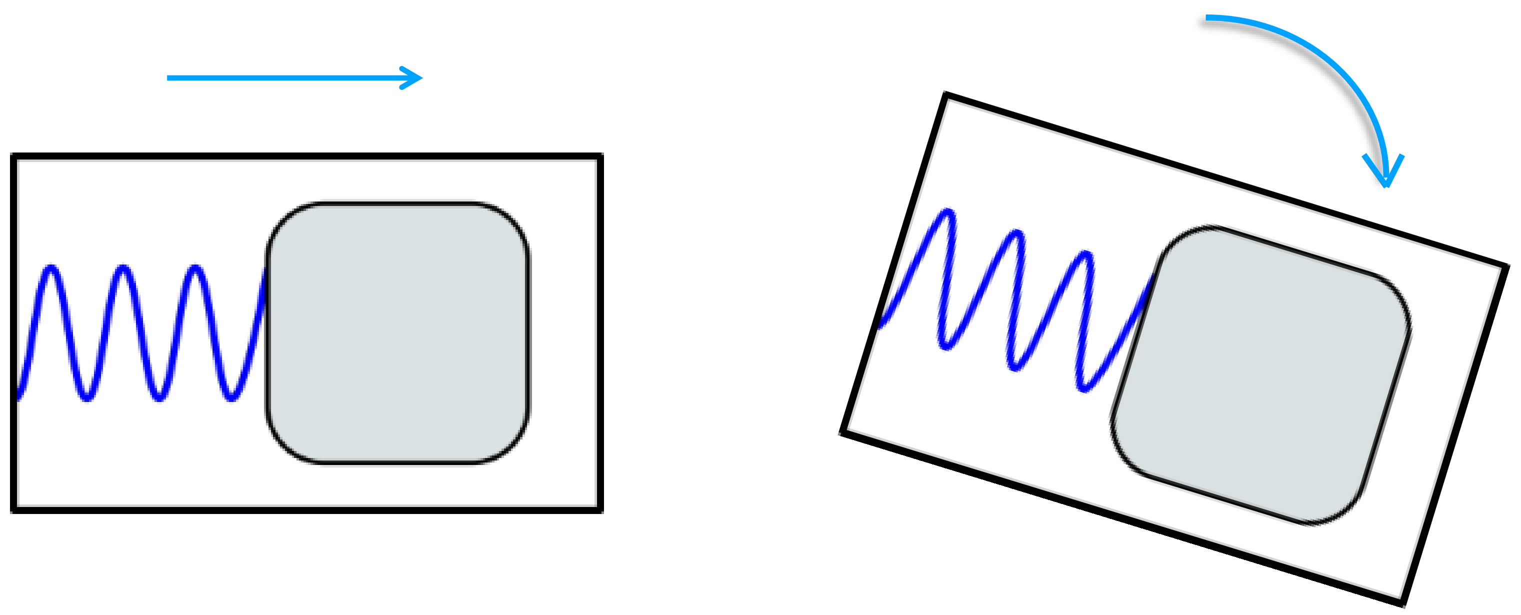


Dynamic range



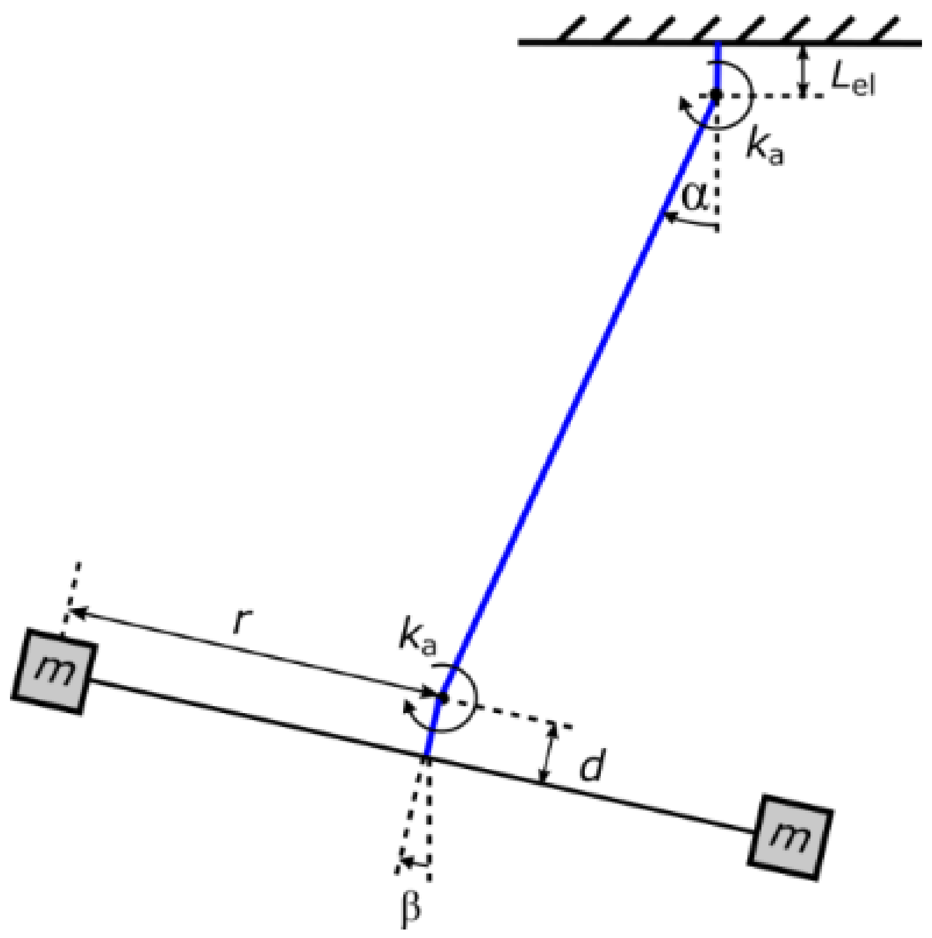
Credit: Conor Mow-Lowry

Tilt-to-Horizontal coupling

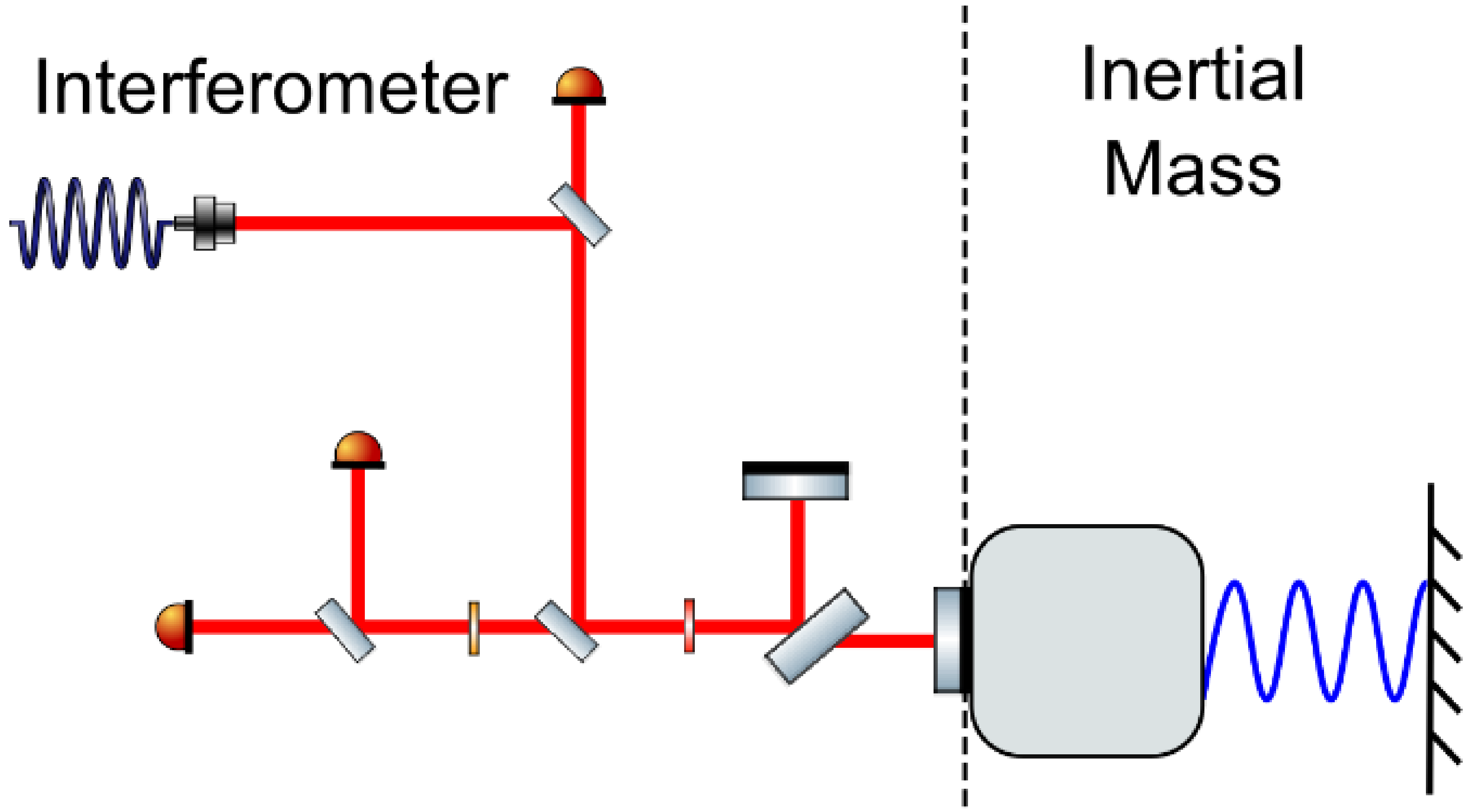


$\delta x \propto a x$ $\delta x \propto g\theta$

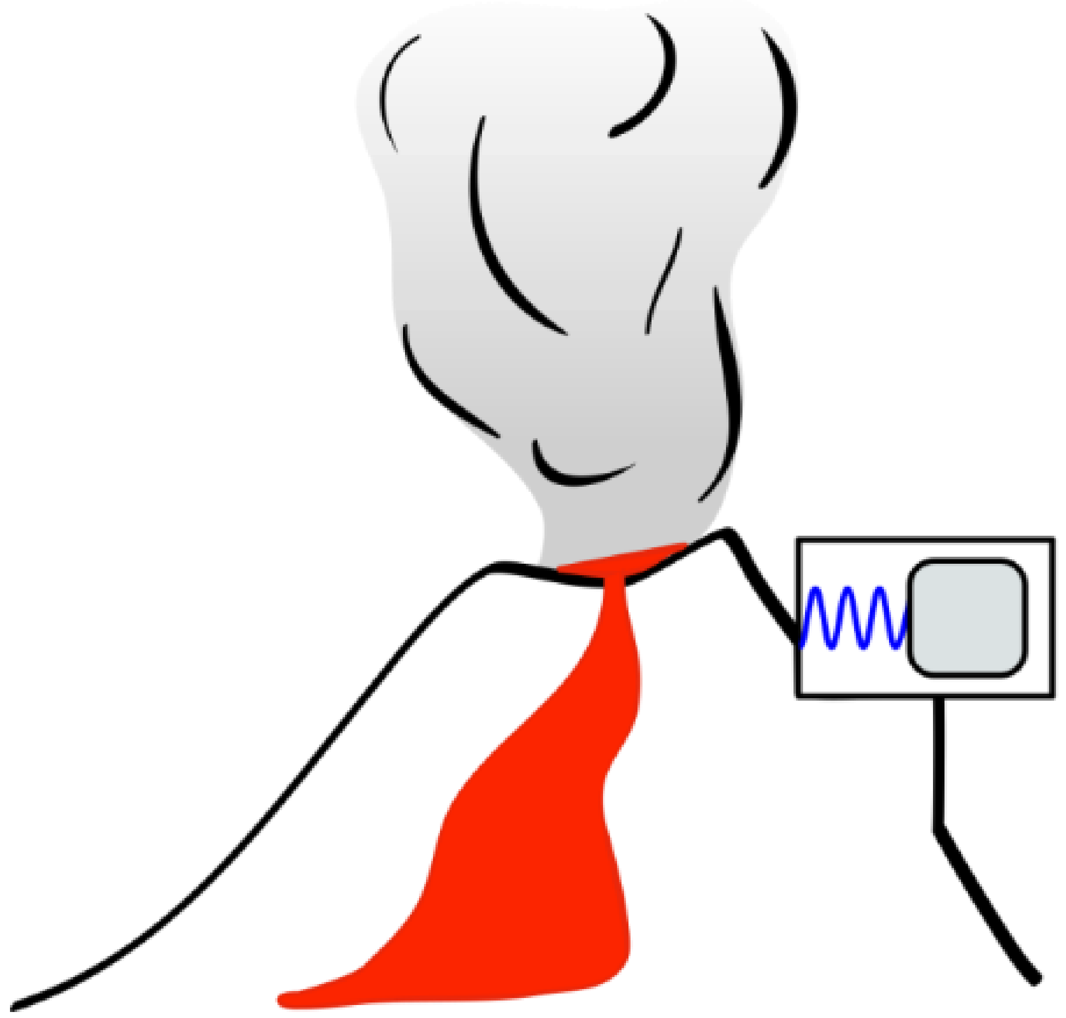
Mechanical cross-coupling



Sensor/actuator noise

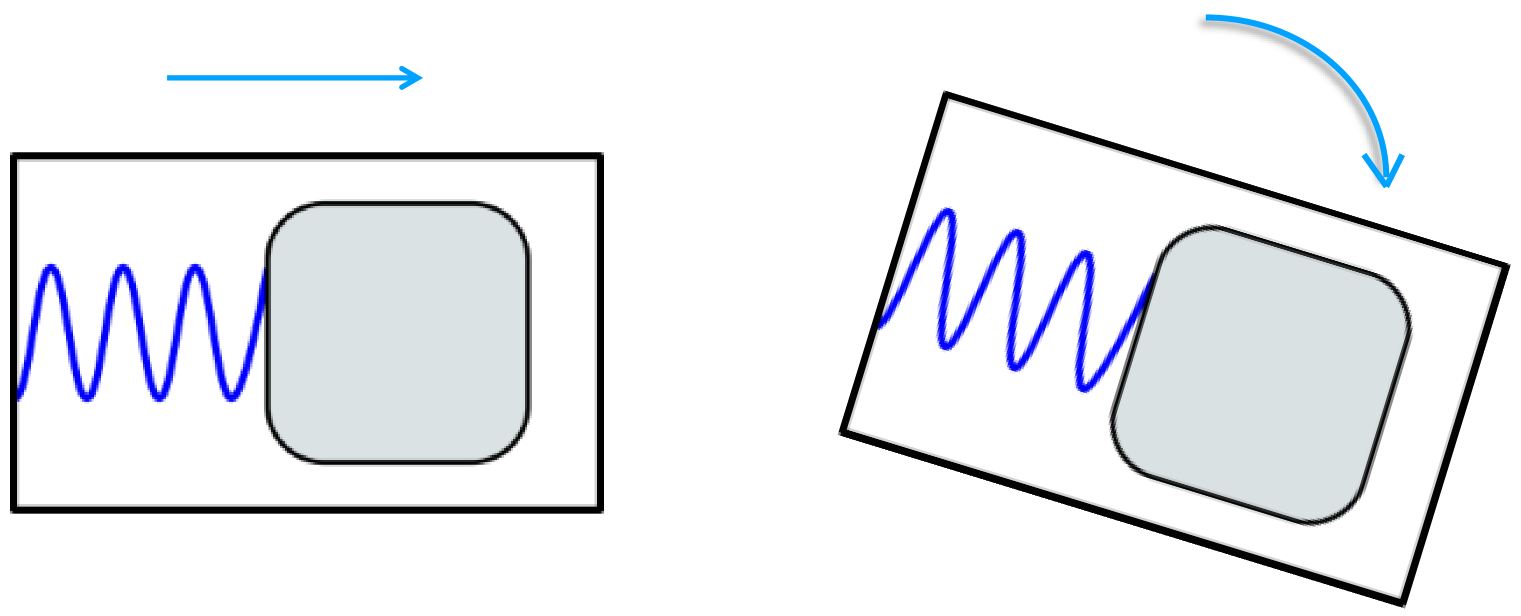


Dynamic range



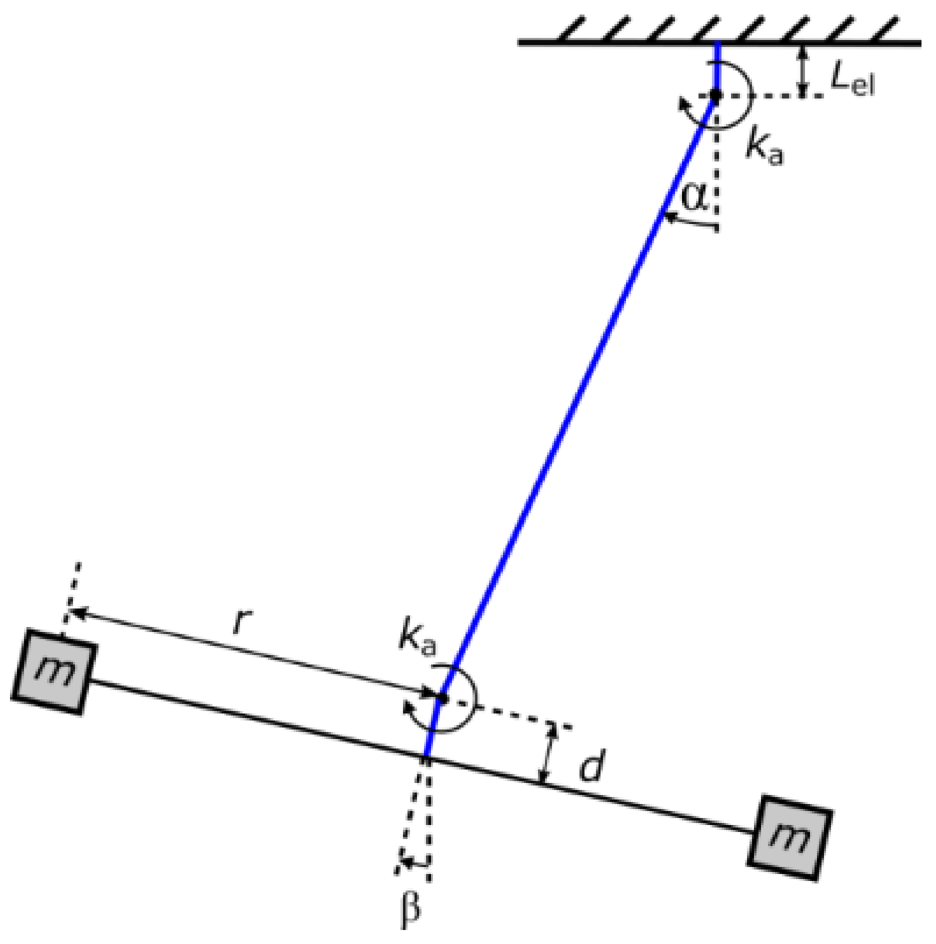
Credit: Conor Mow-Lowry

Tilt-to-Horizontal coupling

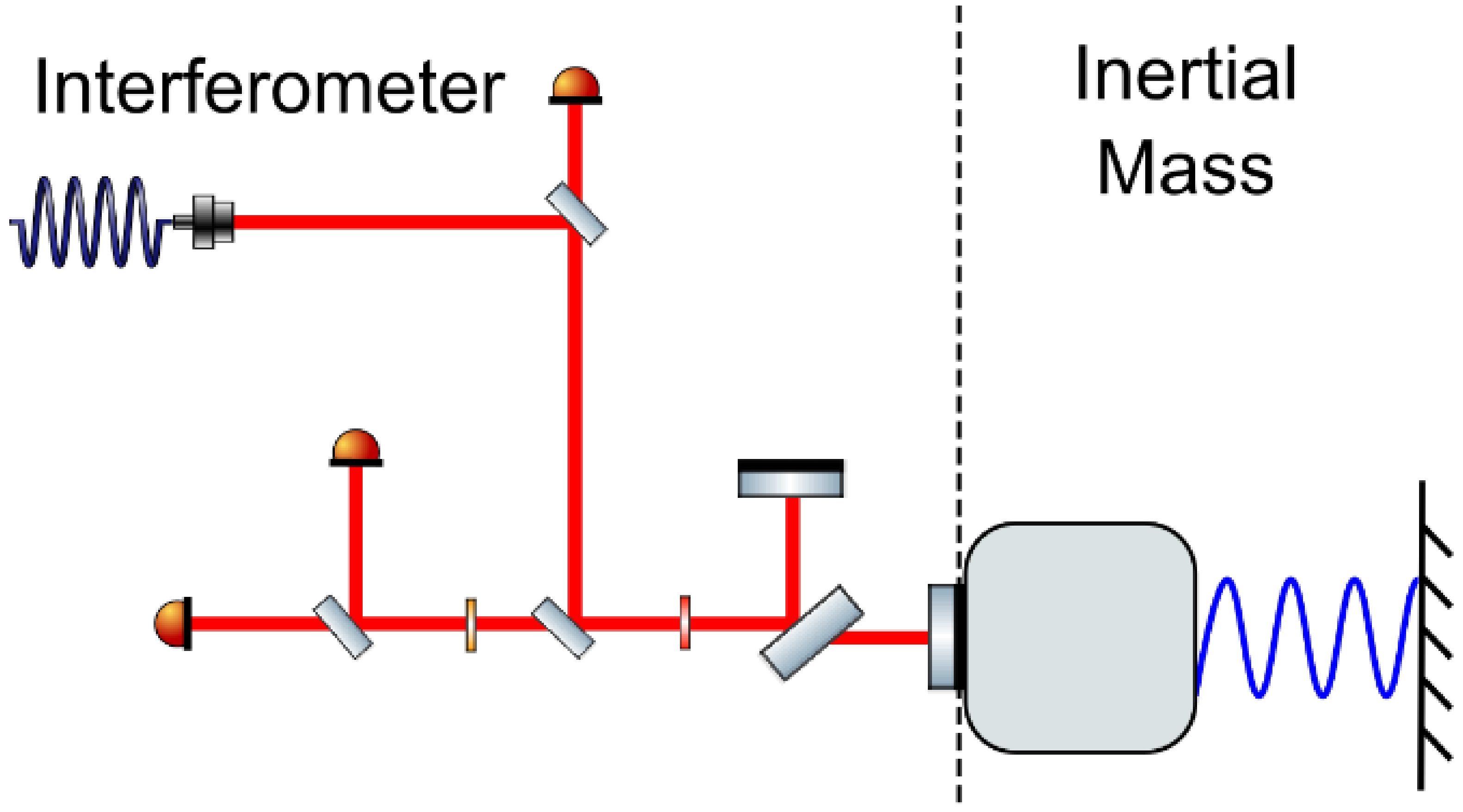


$\delta x \propto ax$ $\delta x \propto g\theta$

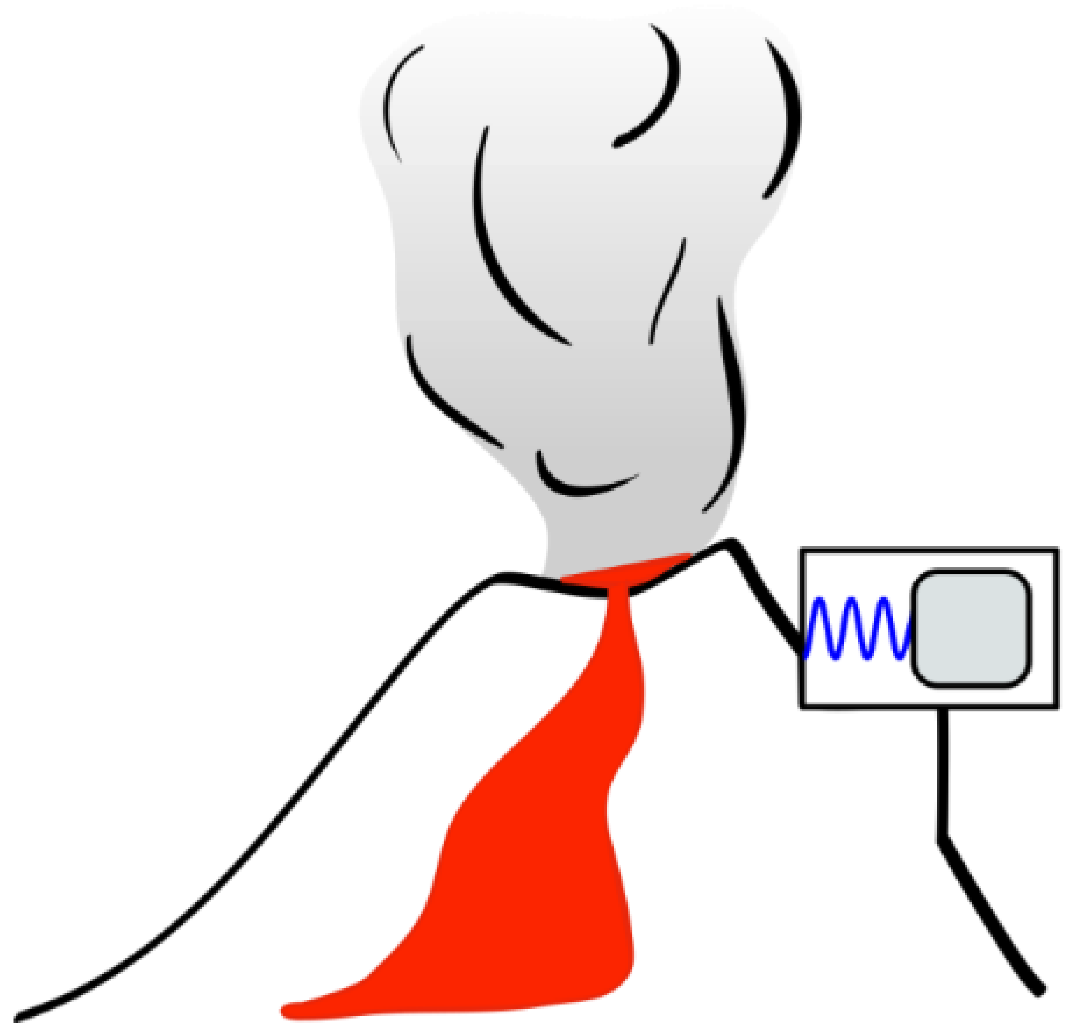
Mechanical cross-coupling



Sensor/actuator noise

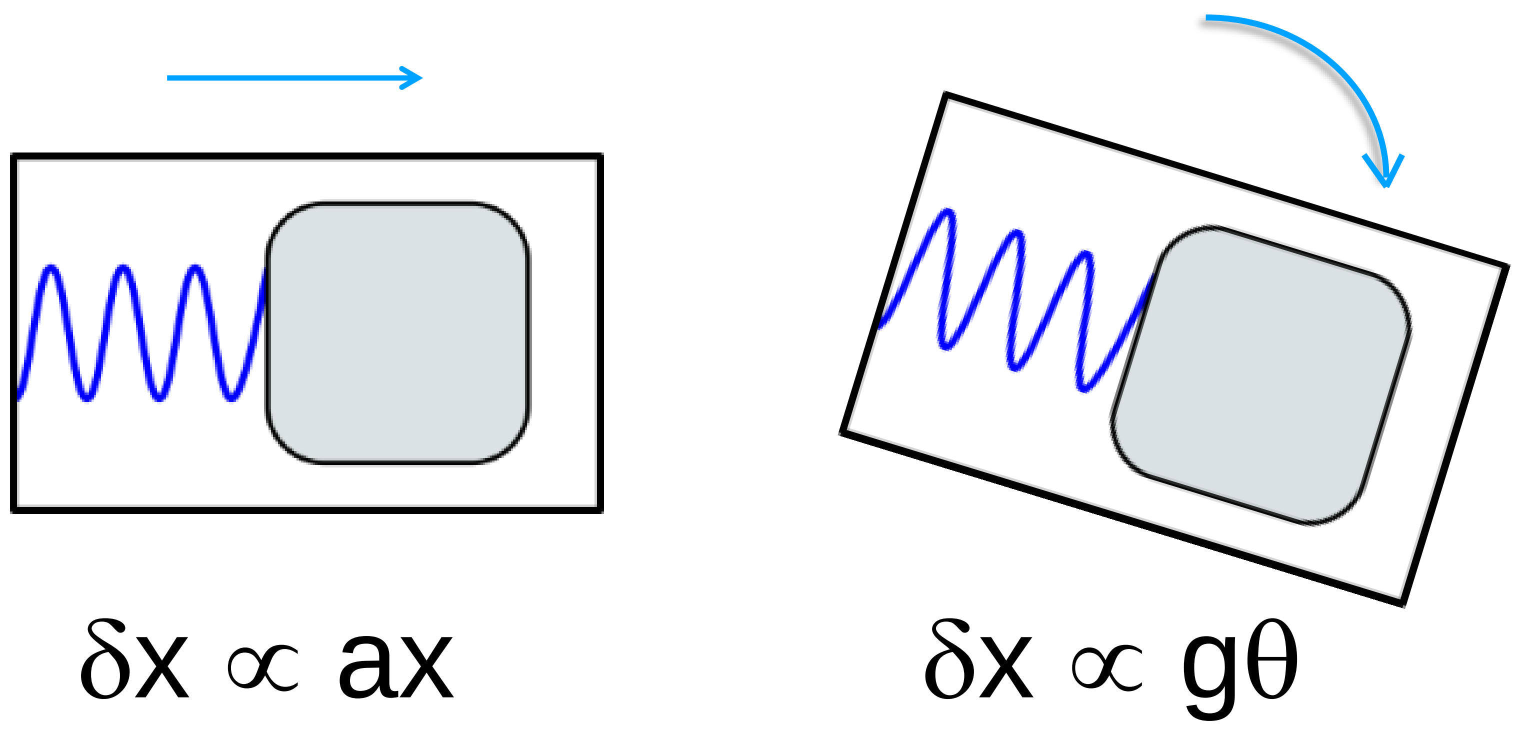


Dynamic range

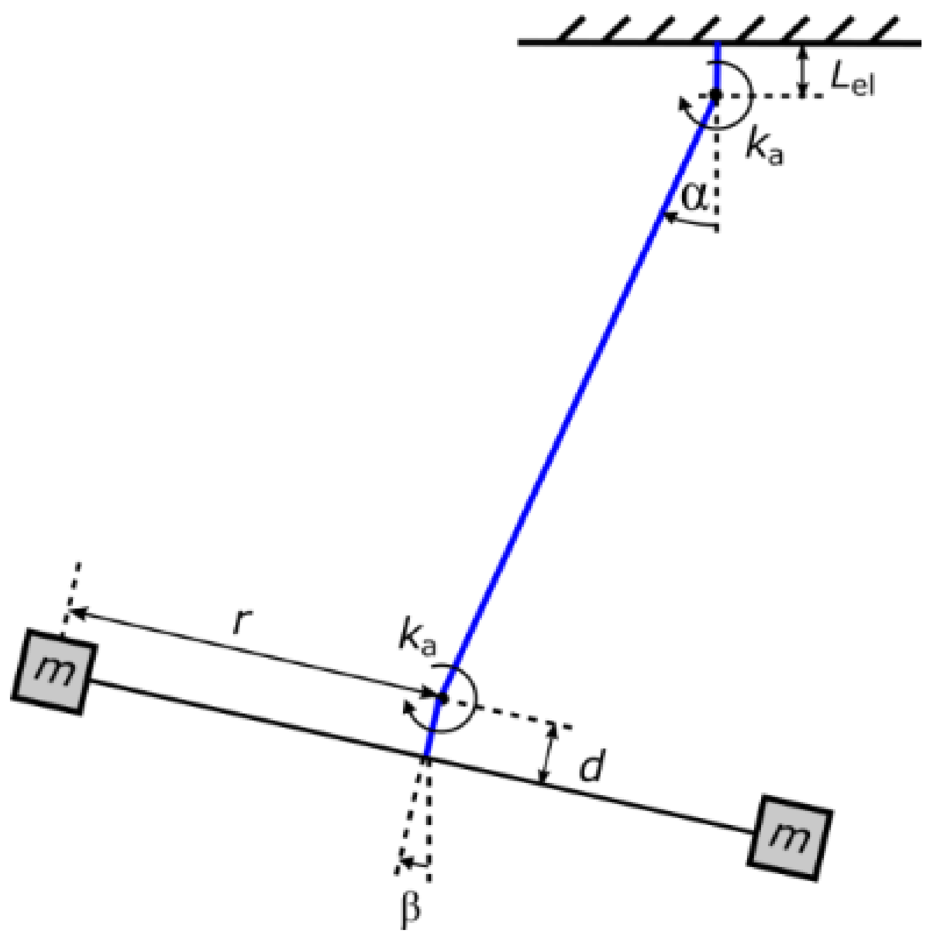


Credit: Conor Mow-Lowry

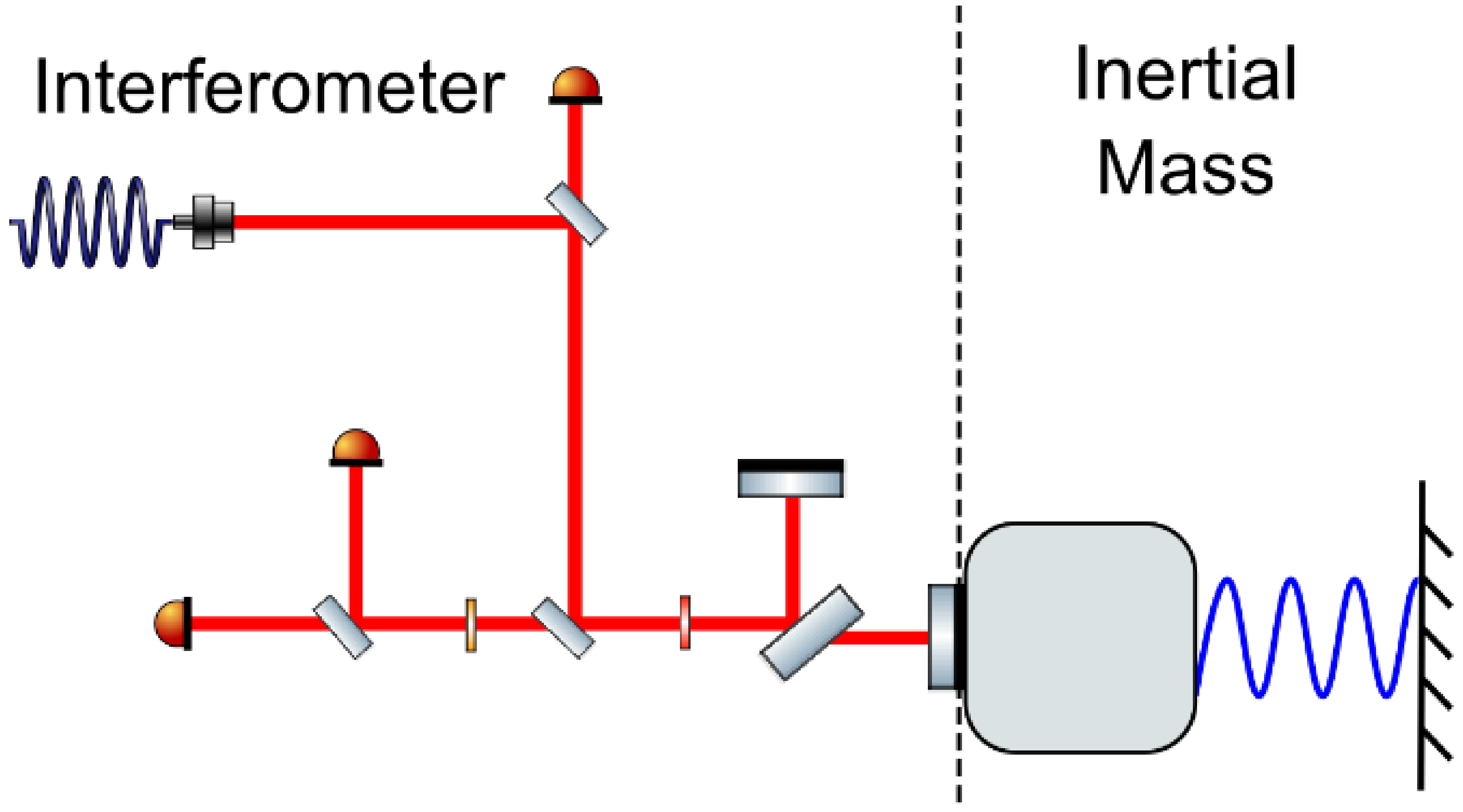
Tilt-to-Horizontal coupling



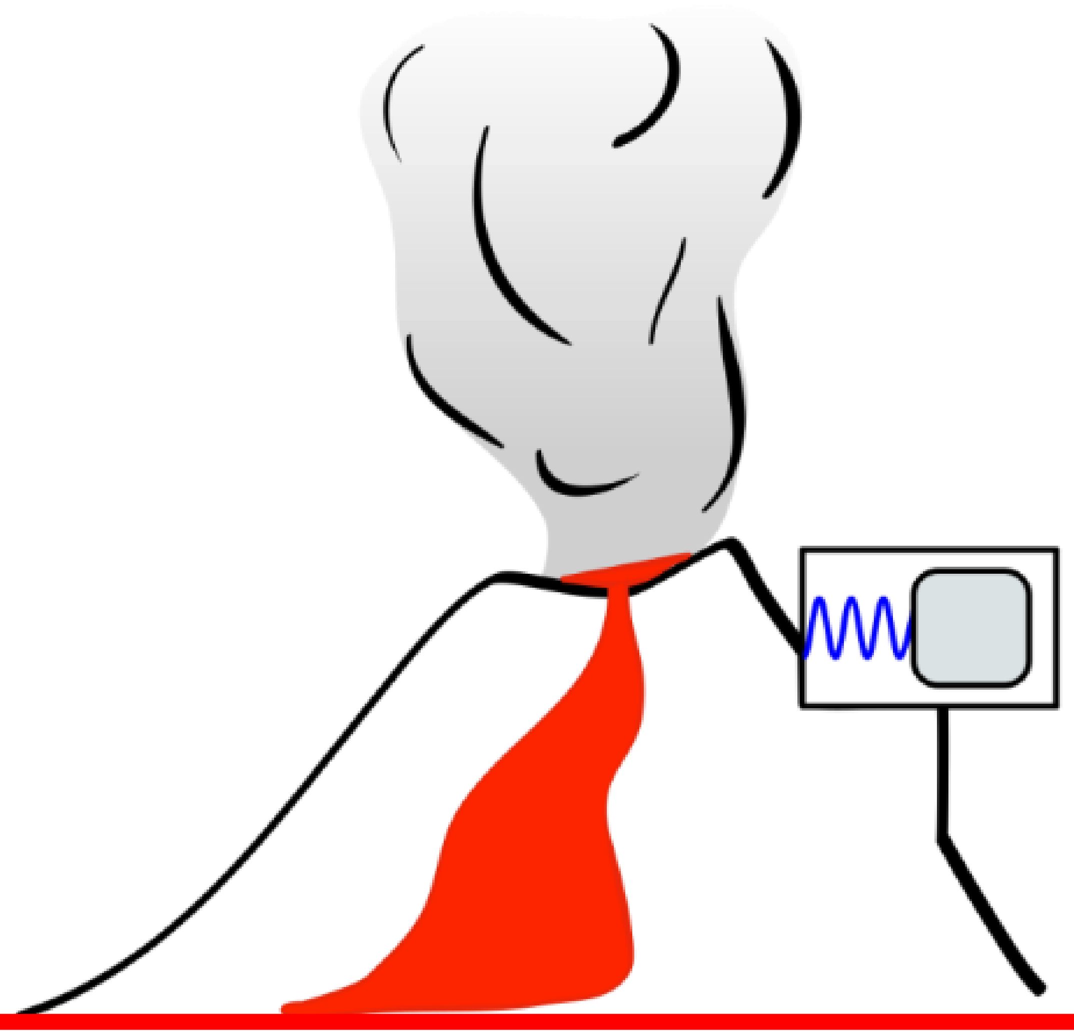
Mechanical cross-coupling



Sensor/actuator noise



Dynamic range

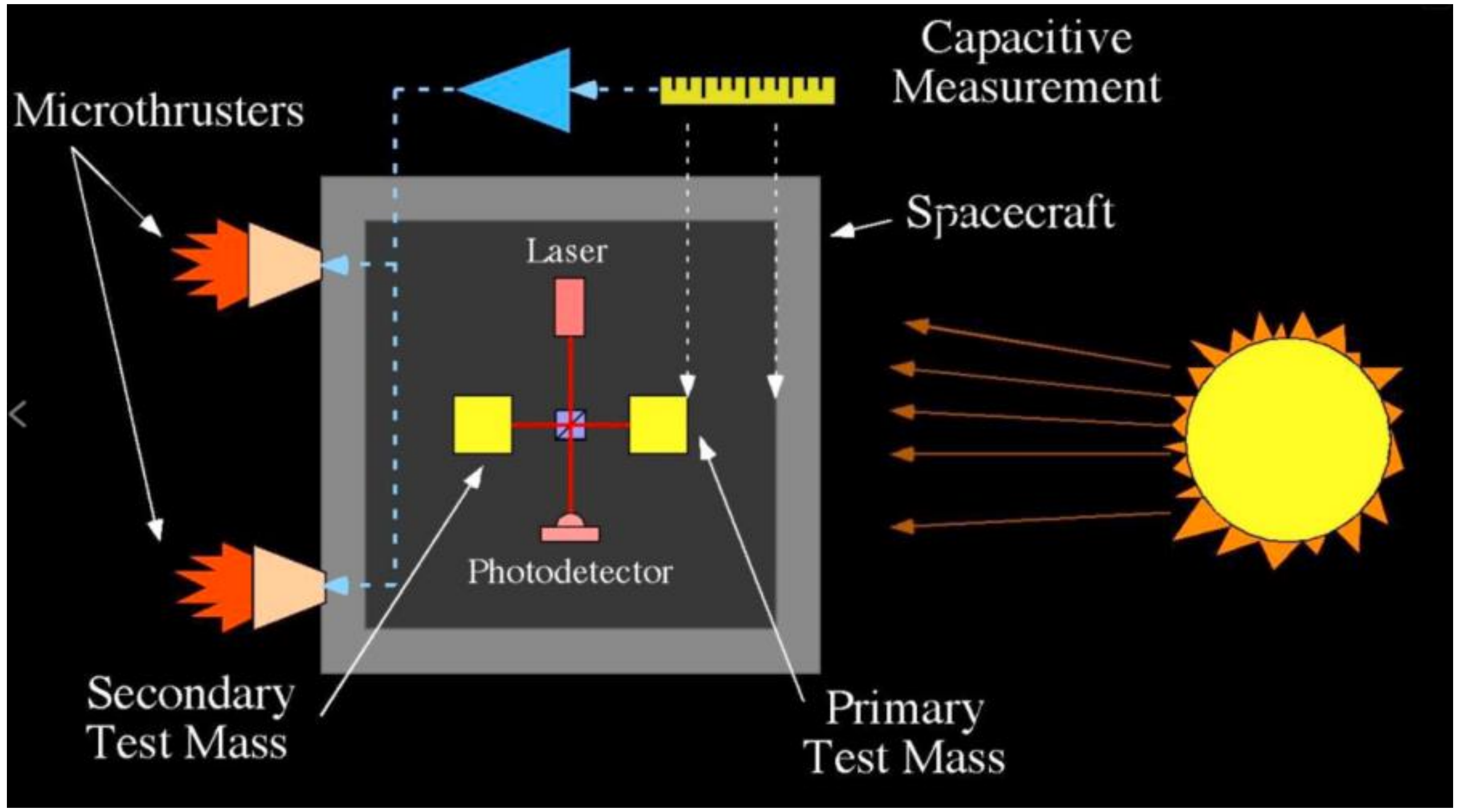


CREDIT: CONOR MOW-LOWRY

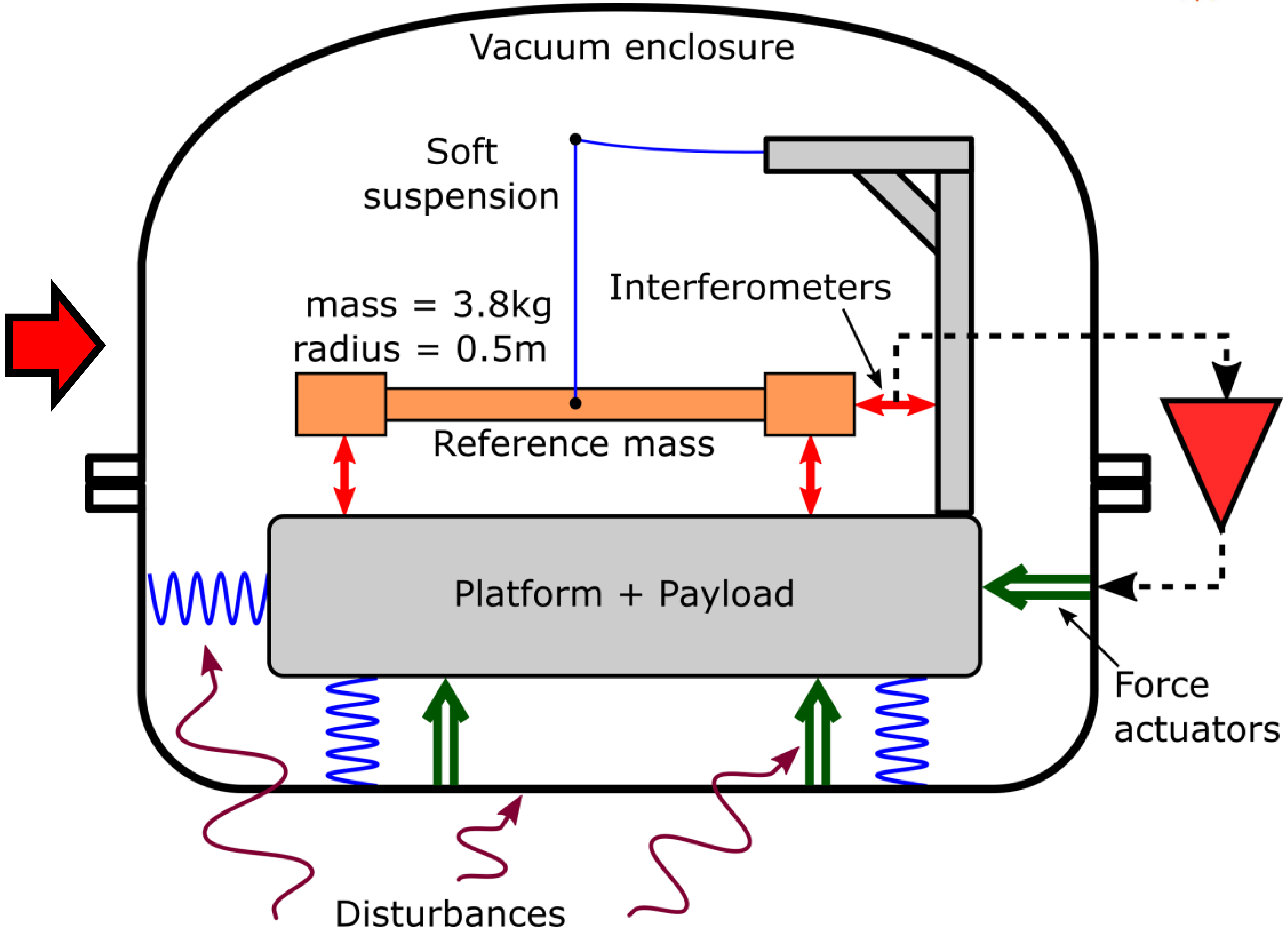
SEISMIC ISOLATION FOR EINSTEIN TELESCOPE

OMNISENS CONCEPT

…A SORT OF TERRESTRIAL DRAG-FREE CONTROL



DRS WORKING PRINCIPLE – IMAGE: NASA/JPL



CREDIT: ARMIN NUMIC

SEISMIC ISOLATION FOR EINSTEIN TELESCOPE

OMNISENS PROTOTYPE

VU VRIJE UNIVERSITEIT AMSTERDAM

Nikhef

erc