A superconducting inertial sensor for cryogenic gravitational wave detectors

Elvis C Ferreira[1,*],
Joris van Heijningen[1], Francesca Badaracco[1],
Florian Bocchese[2], Stéphane Lucas[3], Alberto Gatti[4], Filip Taverier[4] and Andrea Perali[5]

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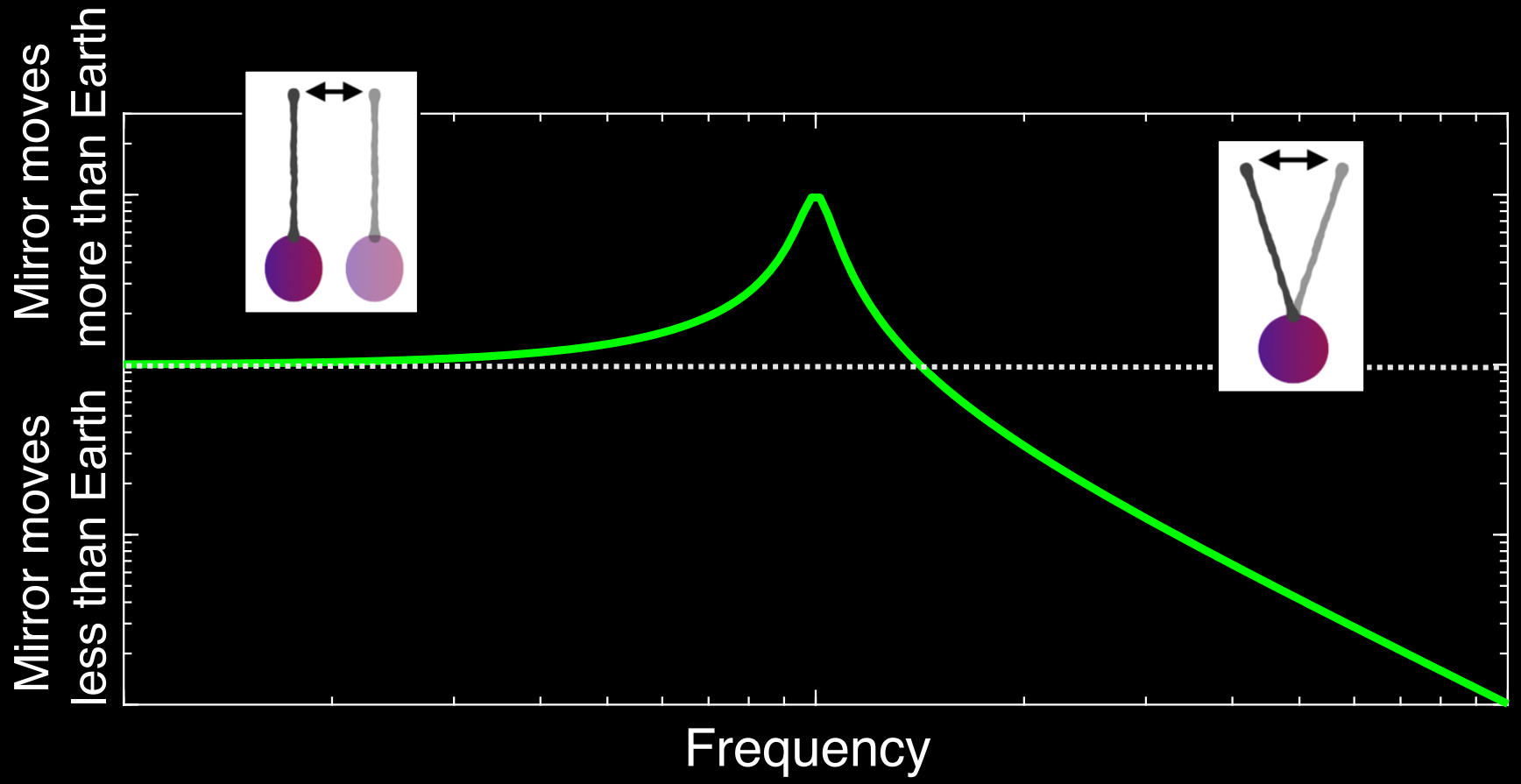
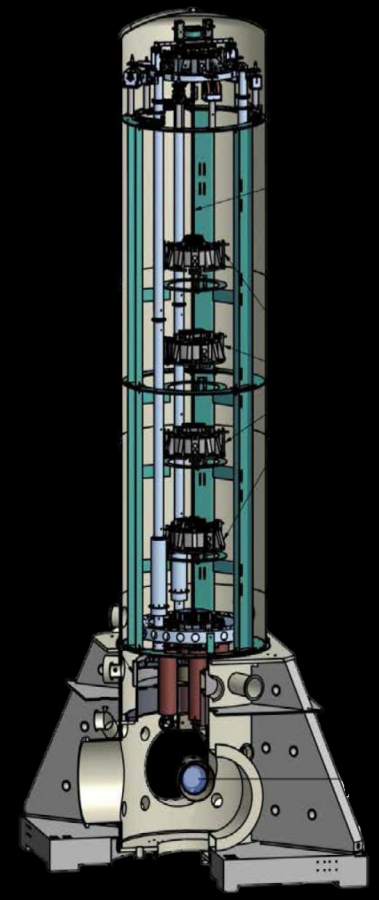
*elvis.camilo@uclouvain.be

Sensor development came out of desire to decouple motions





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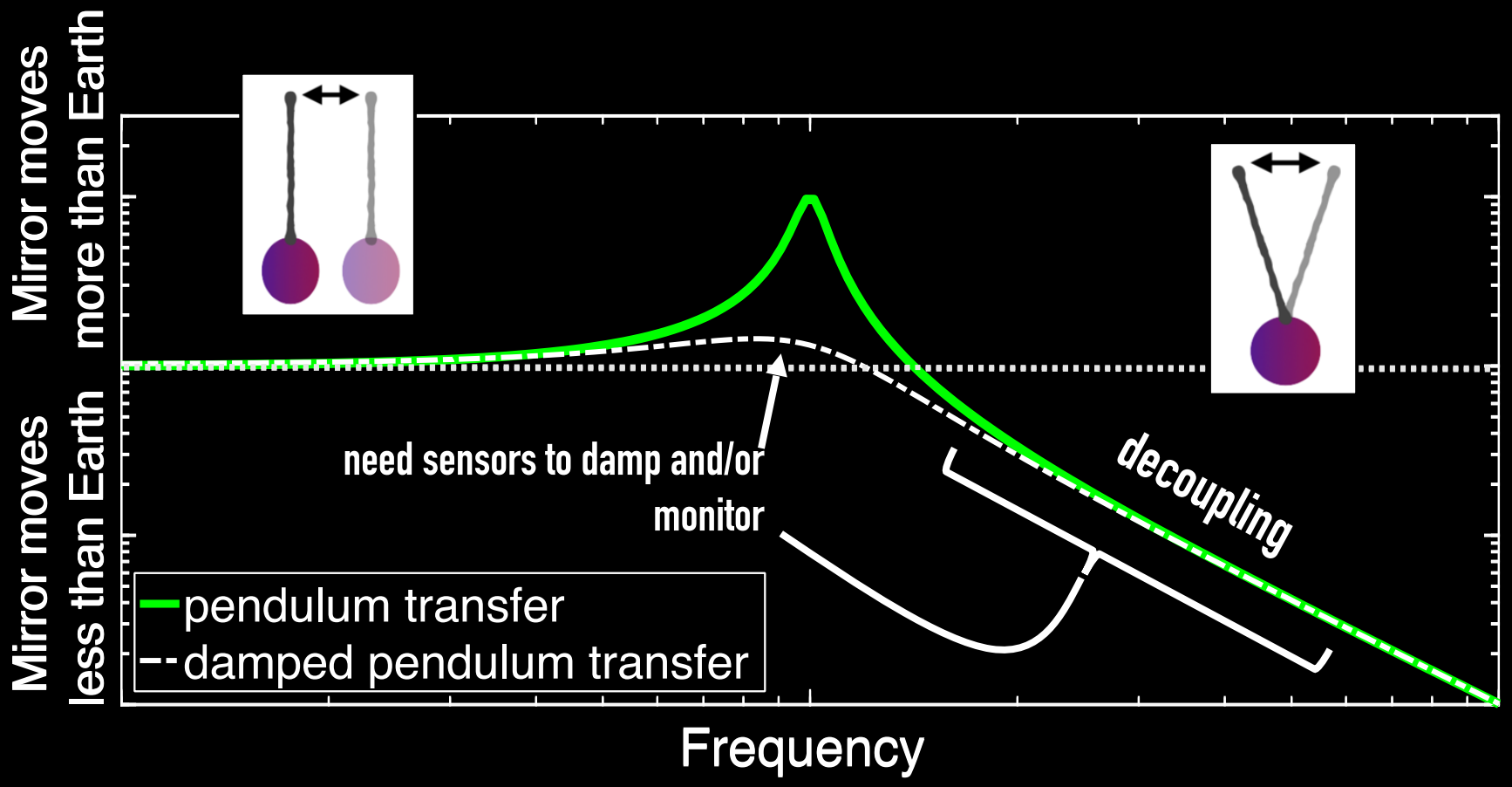

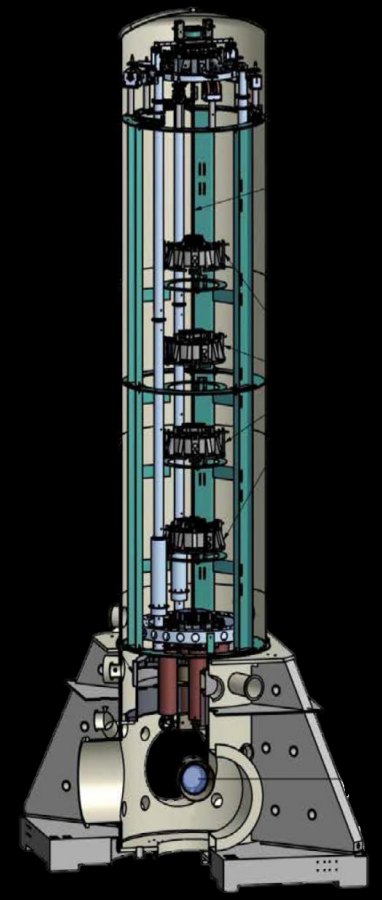

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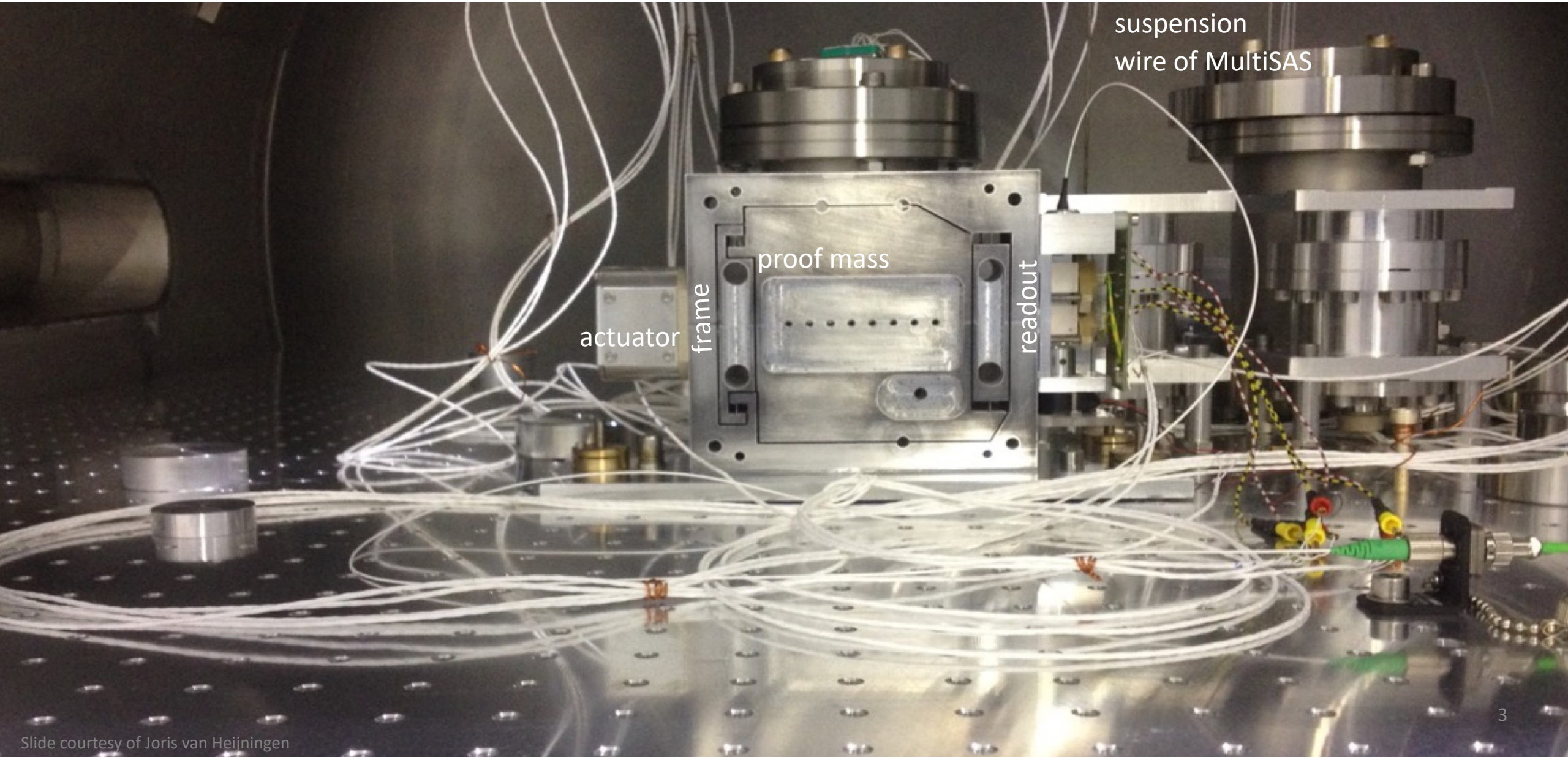
Previous development at room temperature version



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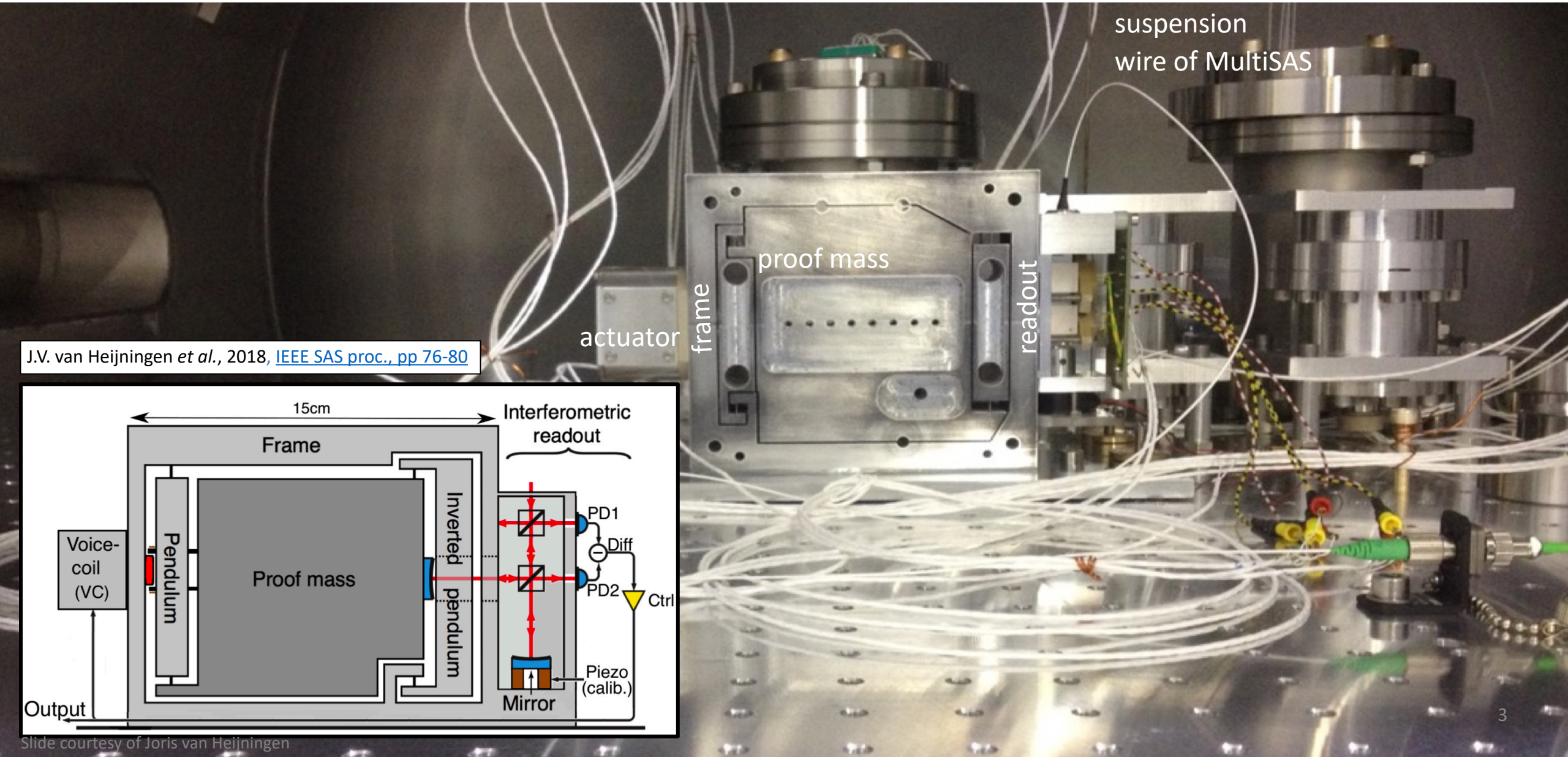

J.V. van Heijningen *et al.*, 2018, IEEE SAS proc., pp 76-80

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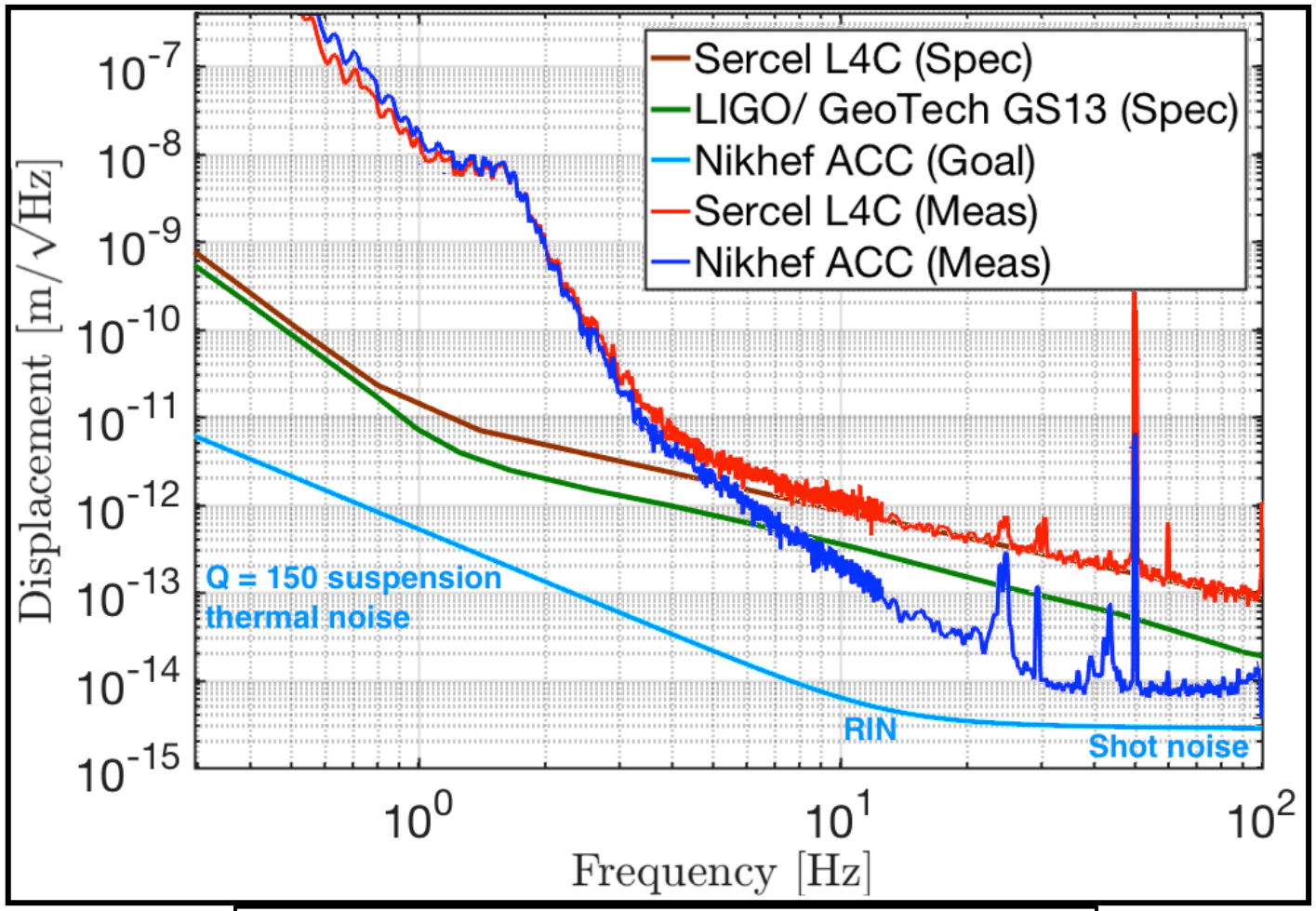
Final result of the room temperature inertial sensor



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Measurement done on bench MultiSAS prototype at Nikhef.

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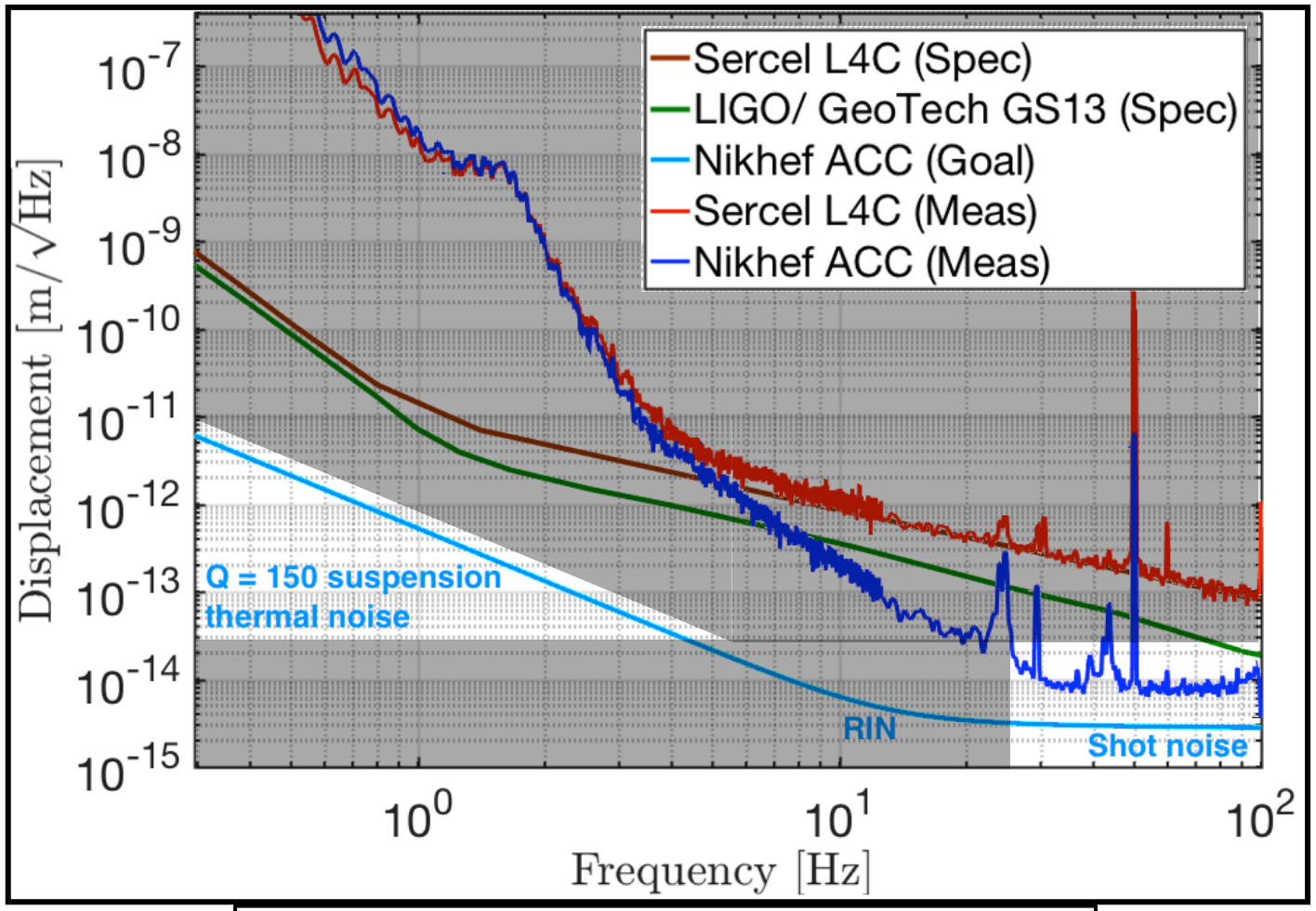

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Measurement done on bench MultiSAS prototype at Nikhef.

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.

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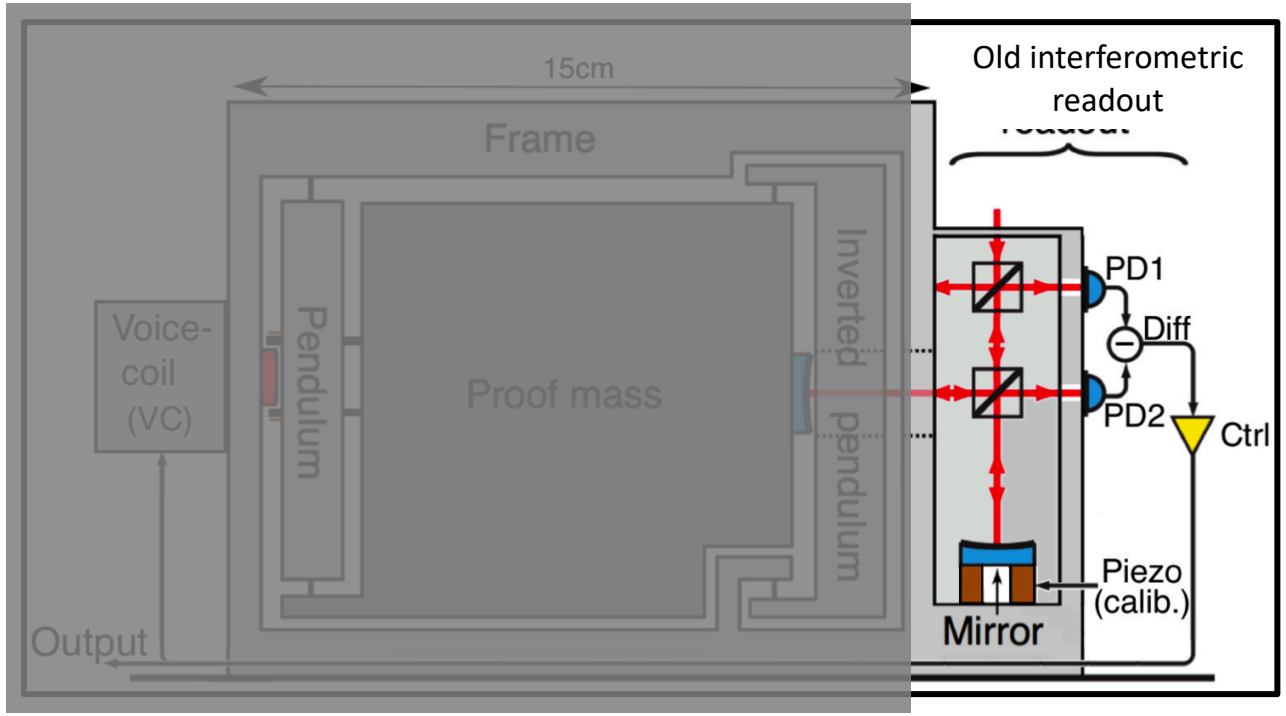
Interferometric readout with polarizing optics and Rasnik long range readout



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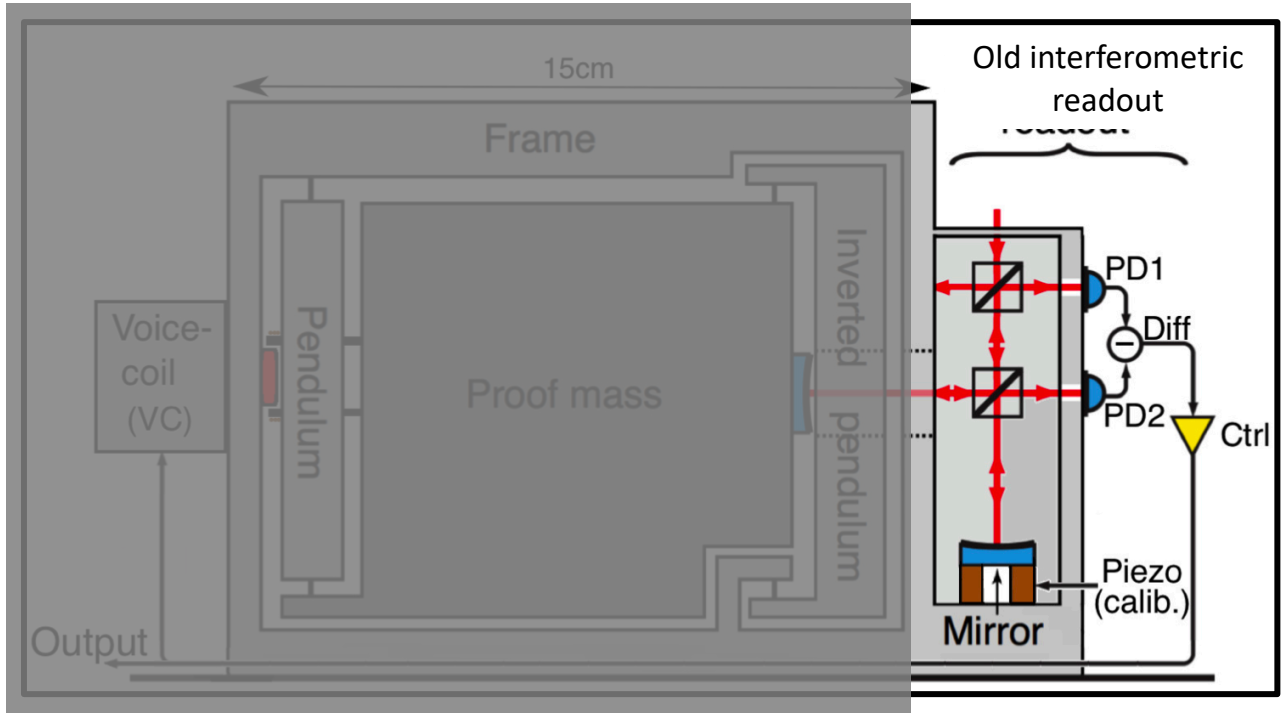
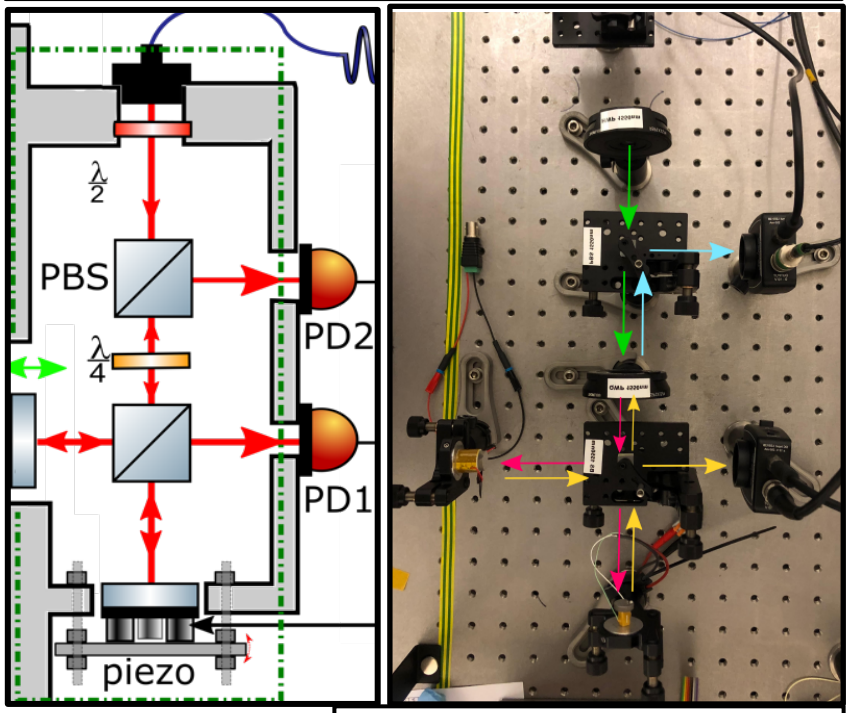
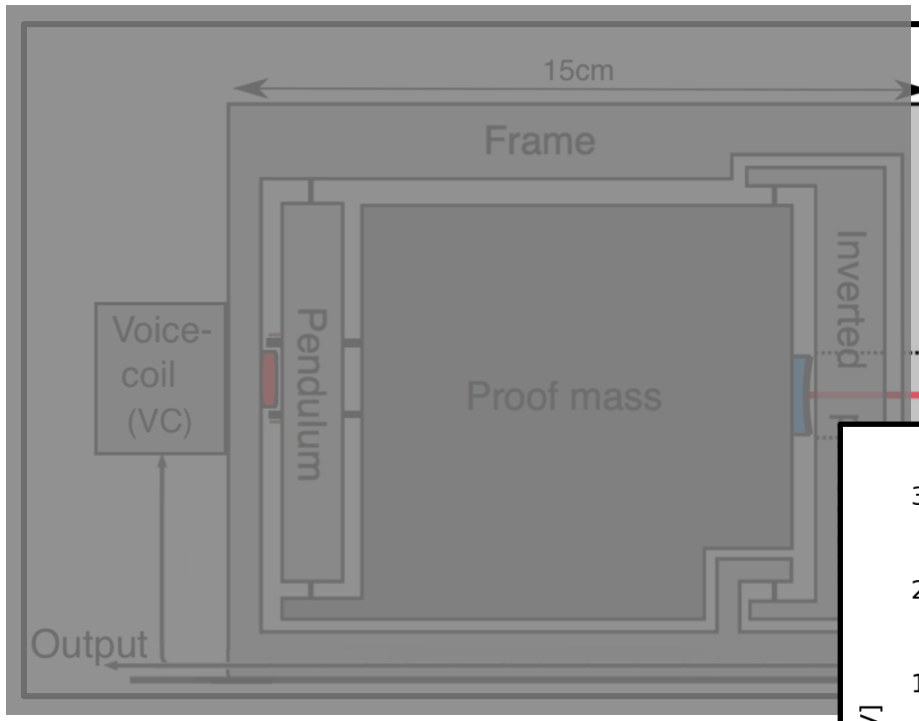


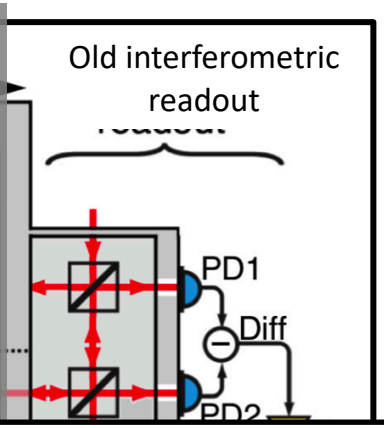
New interferometric readout



All light ends up at PDs, so 42% less shot noise at same input power and less heat load.

Interferometric readout with polarizing optics and Rasnik long range readout





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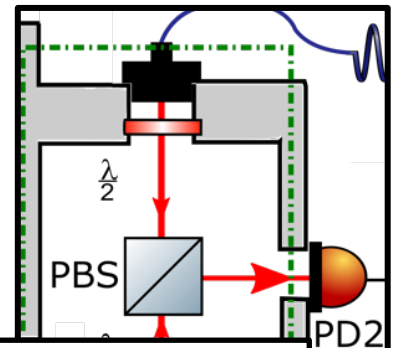

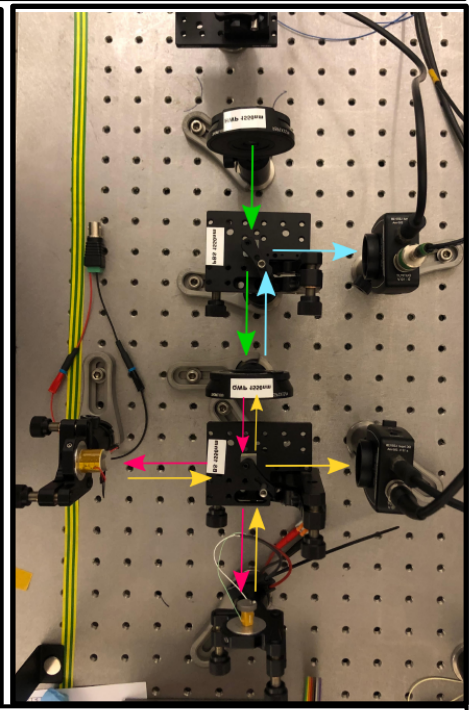

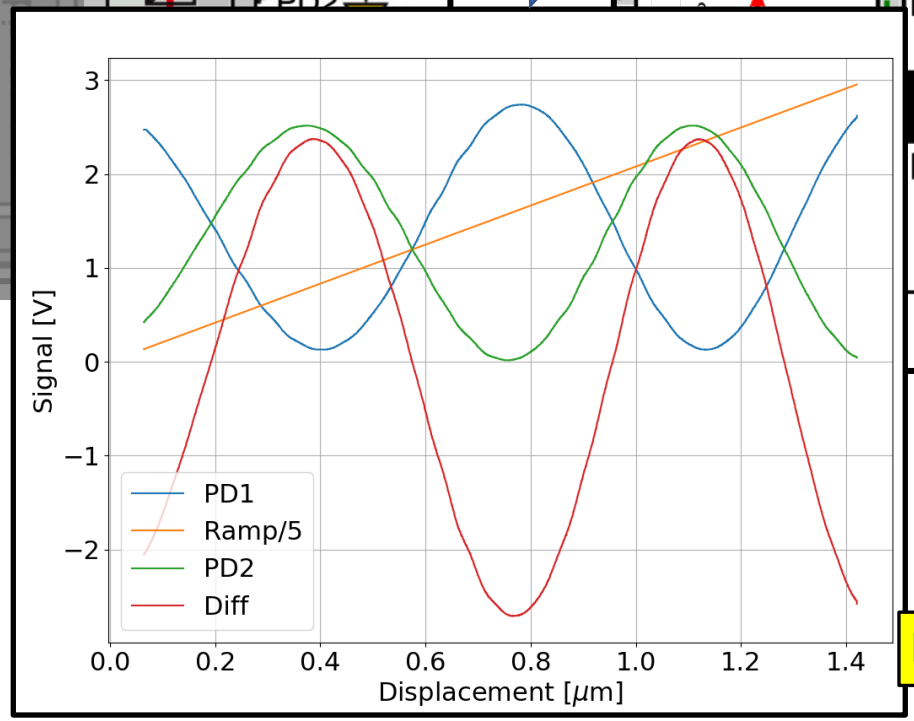

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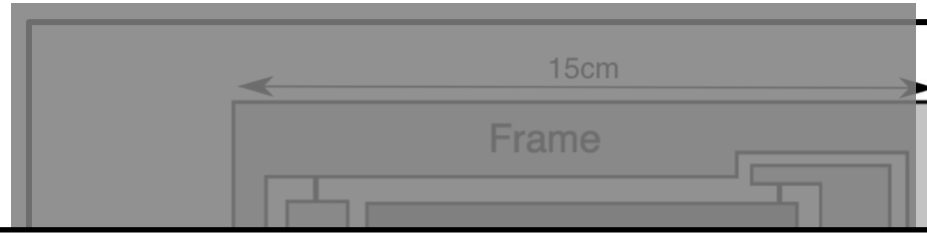
Francesca Badaracco

Interferometric readout with polarizing optics and Rasnik long range readout



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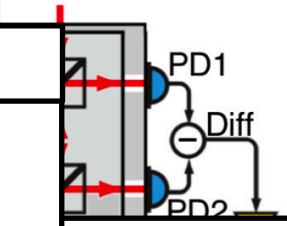

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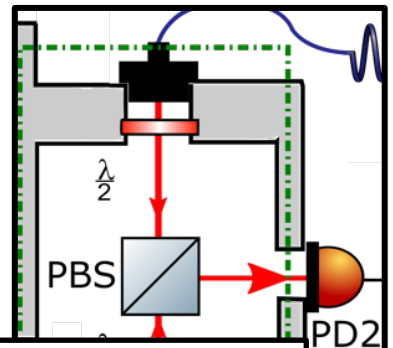
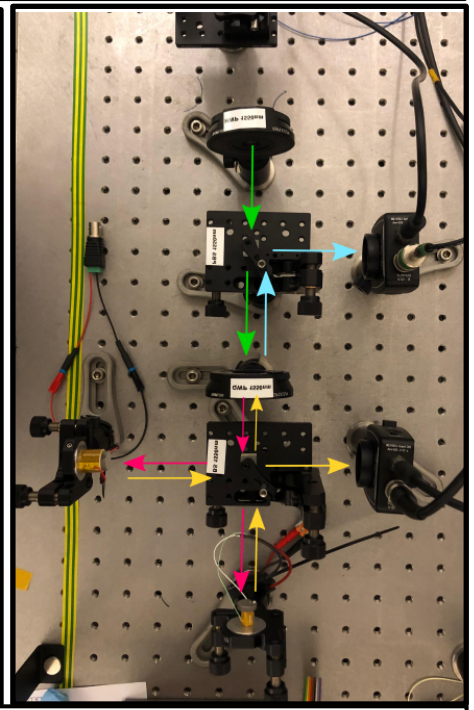
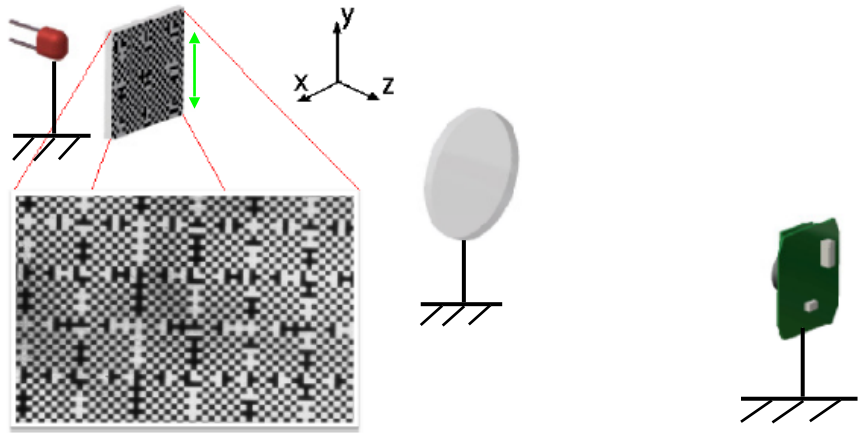
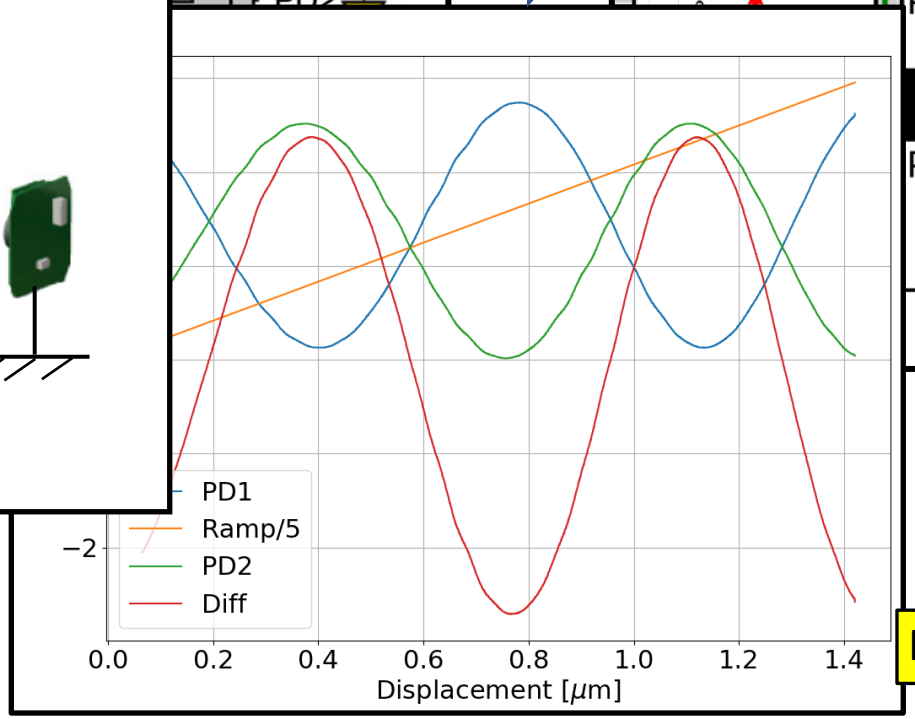




Rasnik readout



M. Beker+, 2019, JINST **14** P08010



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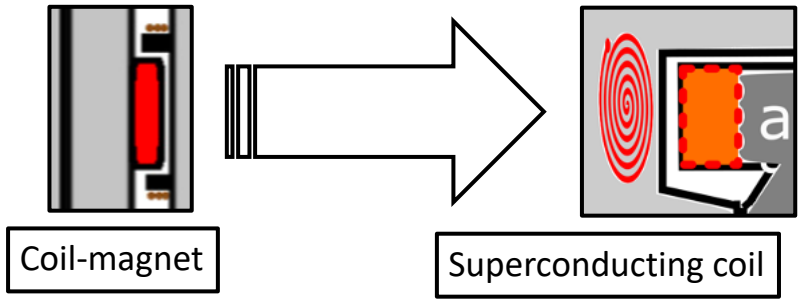
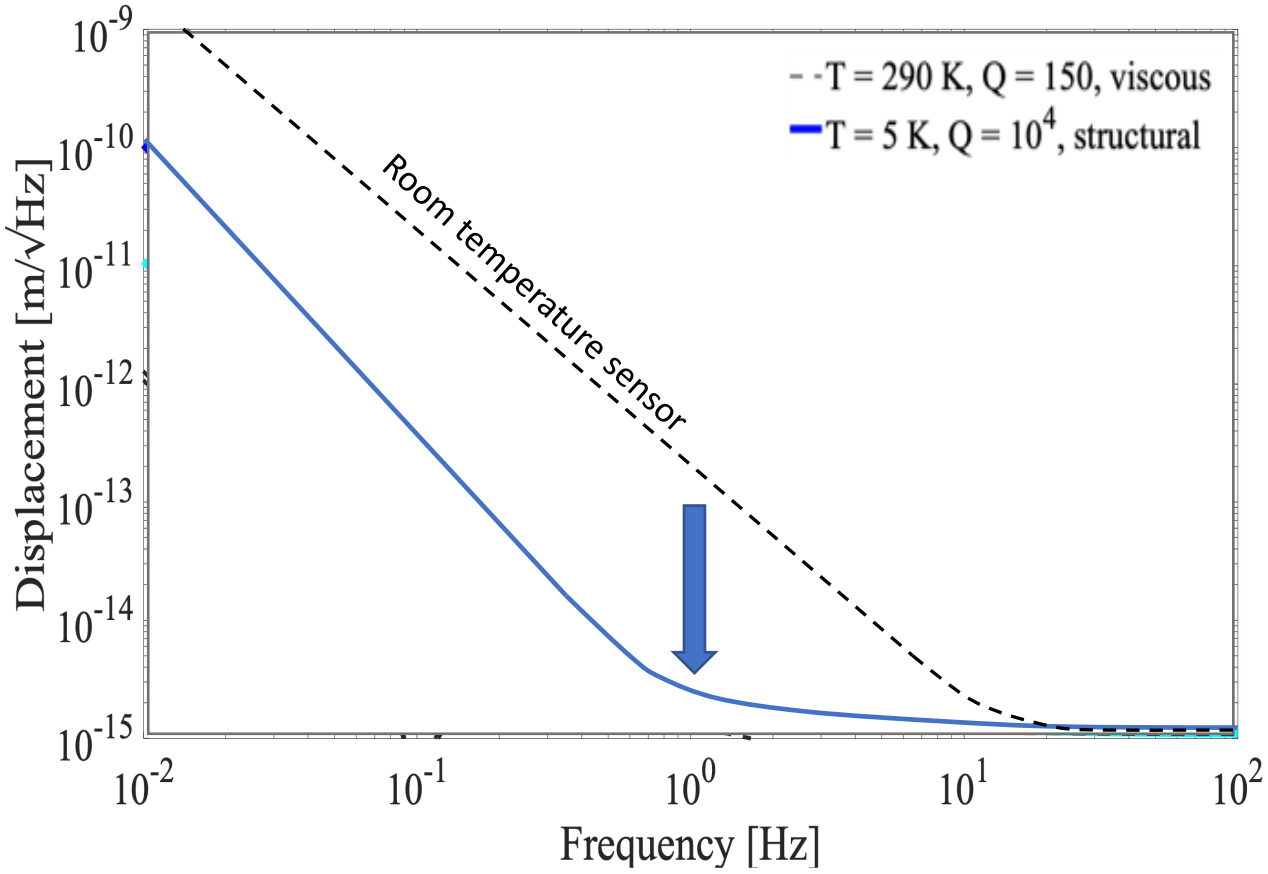
Francesca Badaracco

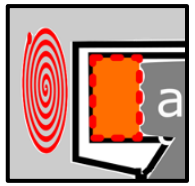
Change of the actuator to access low frequency sensitivity

- Q-factor limited by eddy currents induced by the actuator magnet in close proximity to moving metal parts.
- Niobium is a superconductor below $T_c \cong 9.2\ \mathrm{K}$ and in the full Meissner state below 5 K.





Determining the force of the actuator on the proof mass



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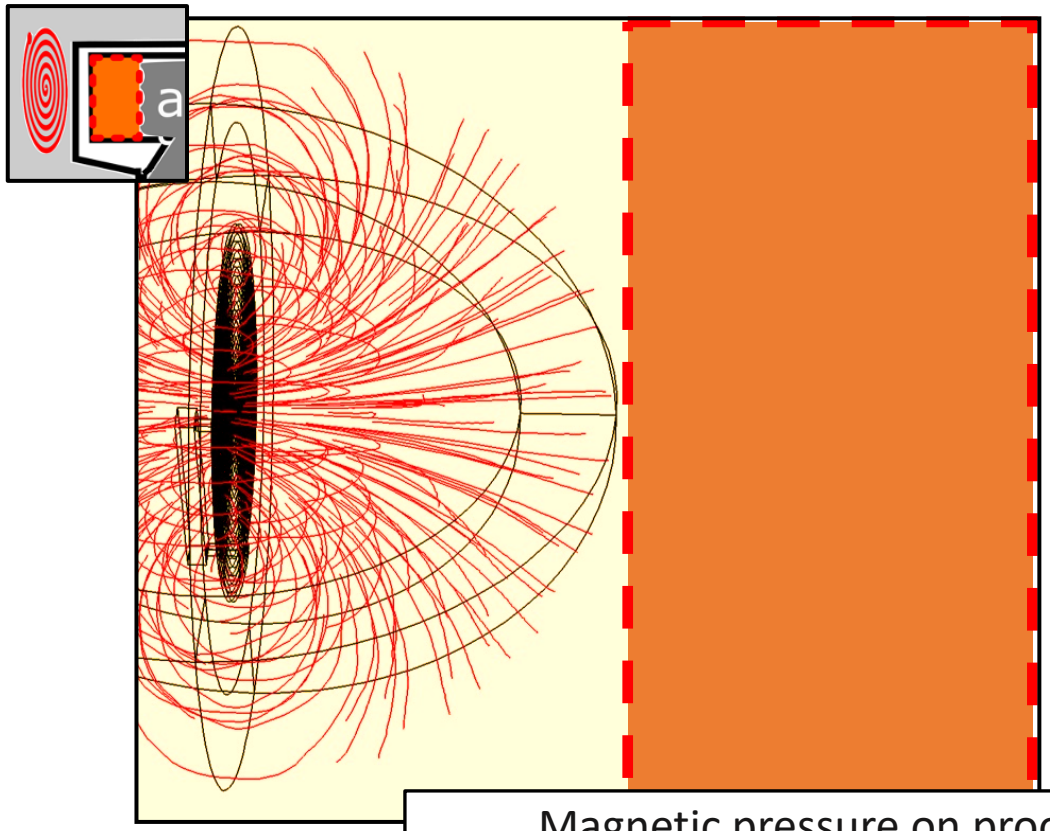
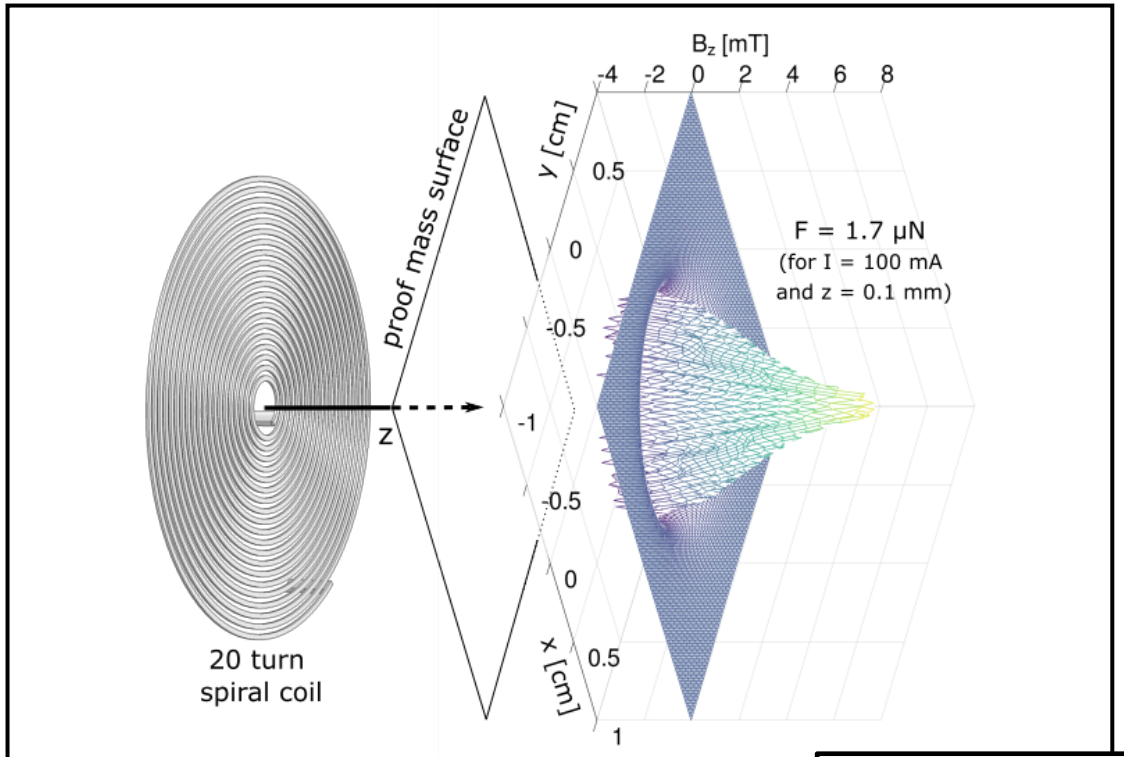
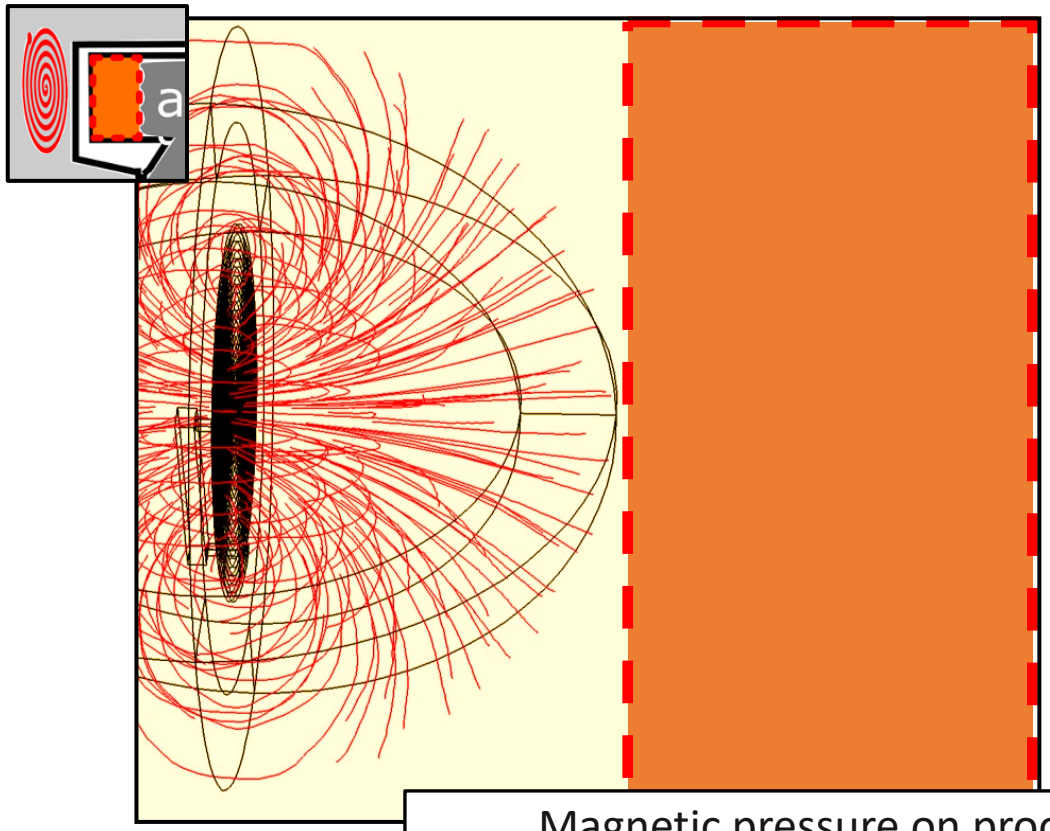


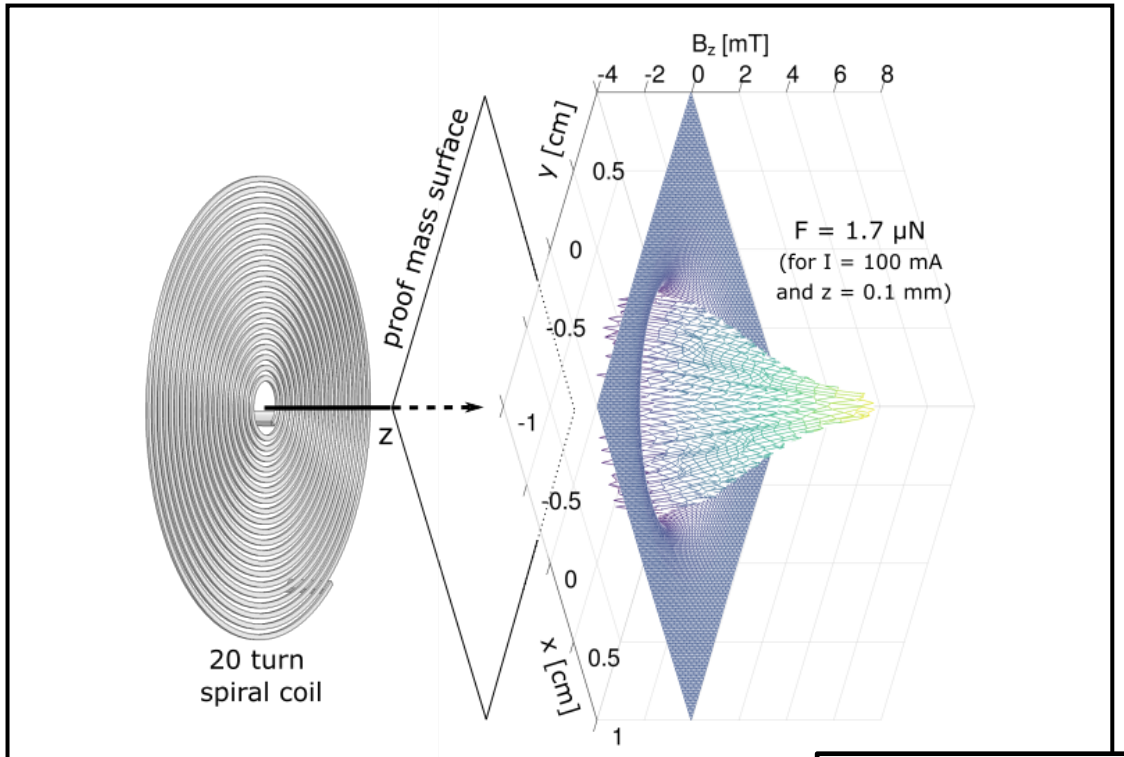


Magnetic pressure on proof mass by Meissner effect

Finite element simulations matches analytic calculations

Determining the force of the actuator on the proof mass





Magnetic pressure on proof mass by Meissner effect

Finite element simulations matches analytic calculations

- For one point: $B_z \propto \frac{I \times N}{z^2}$ and $F_z \propto B_z^2$
- *z* is limited by practical (physical) configuration
- *I* is limited by the cryo-chip controller
- *N* is limited by masking technique for depositions

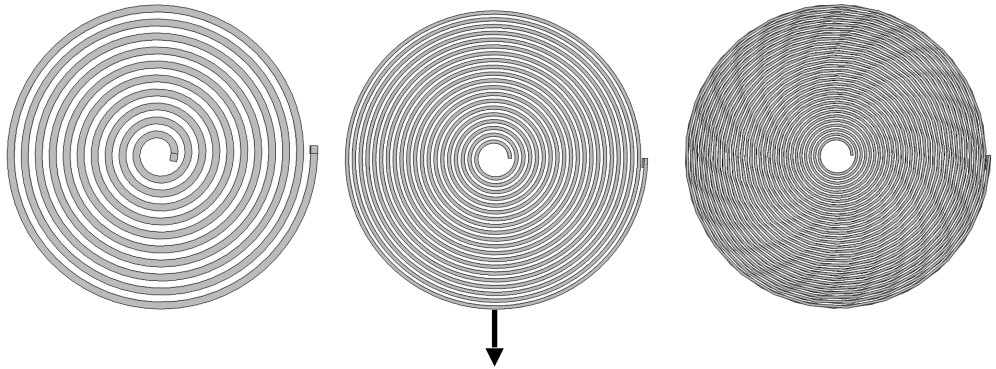
Building the superconducting thin film

Building the superconducting thin film

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

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

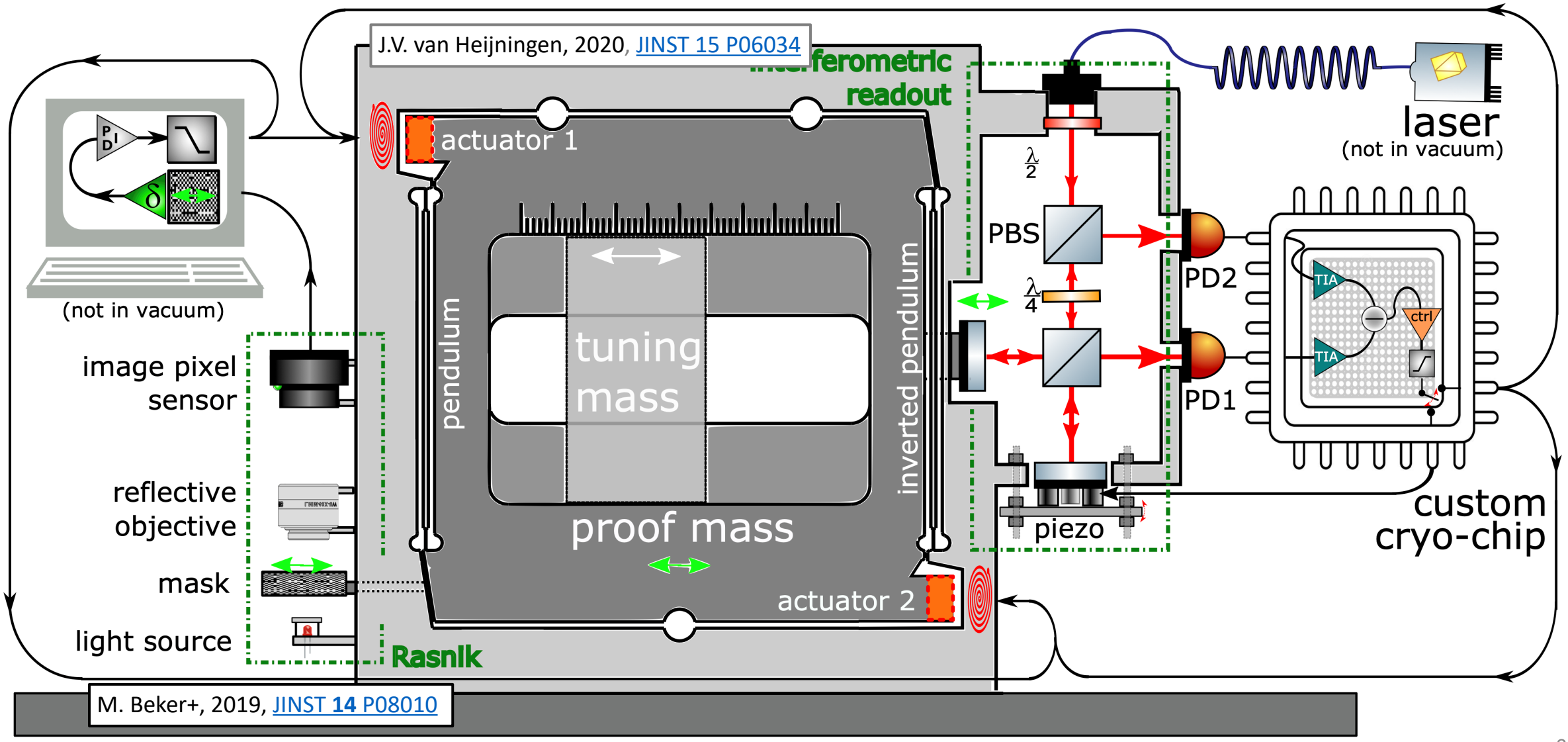
Choosing right mask manufacturing technique.



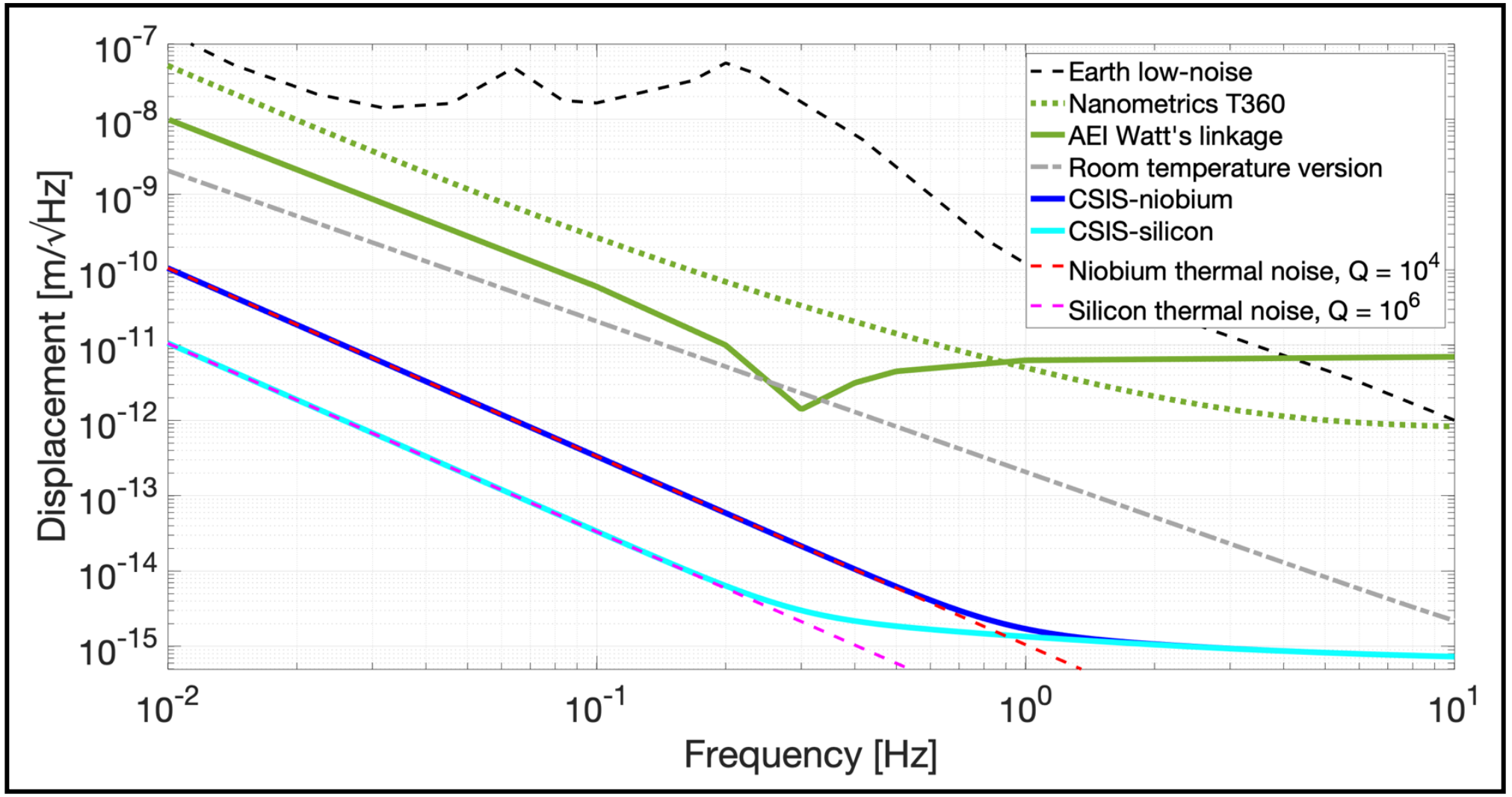
Pitch precision for the mask: about 100 µm.

Now (magetron) sputtering Nb and NbN

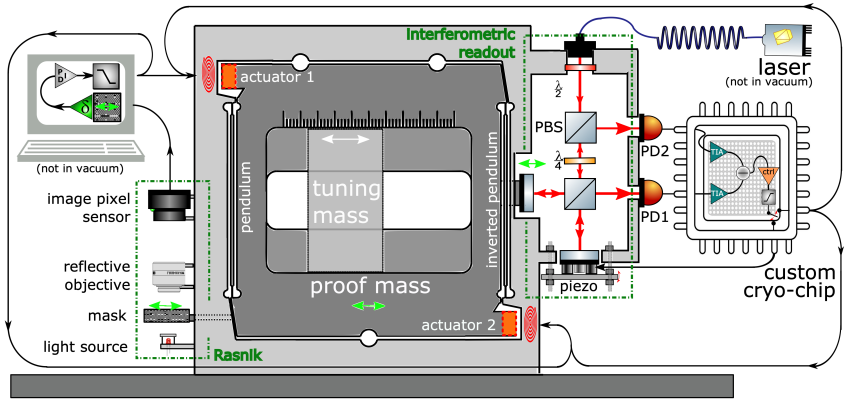
A Cryogenic Superconducting Inertial Sensor (CSIS)



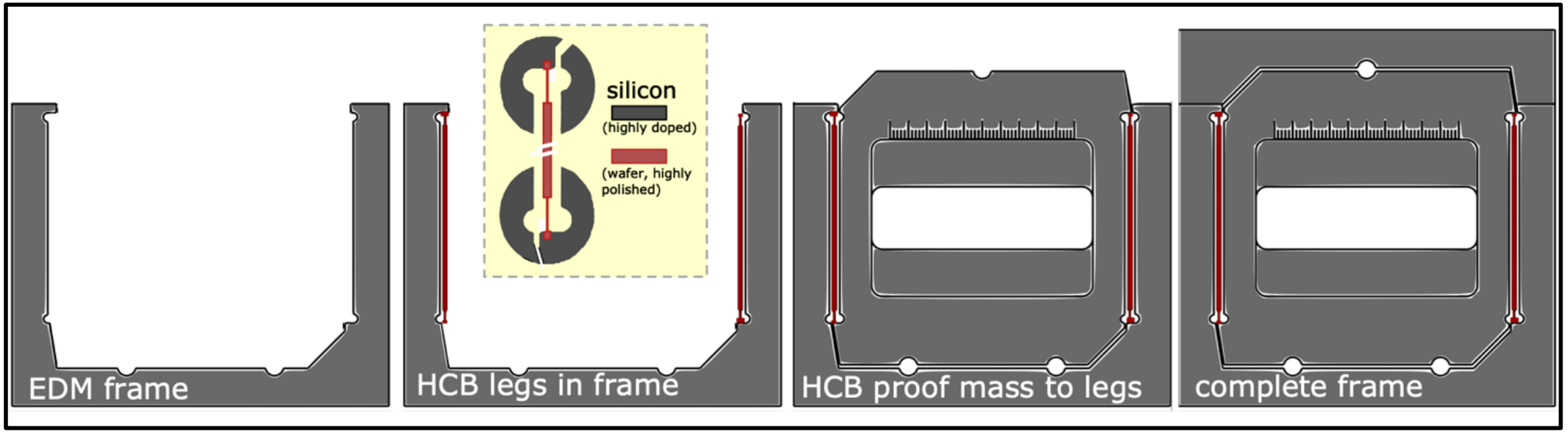
Comparison to the state-of-the-art



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).



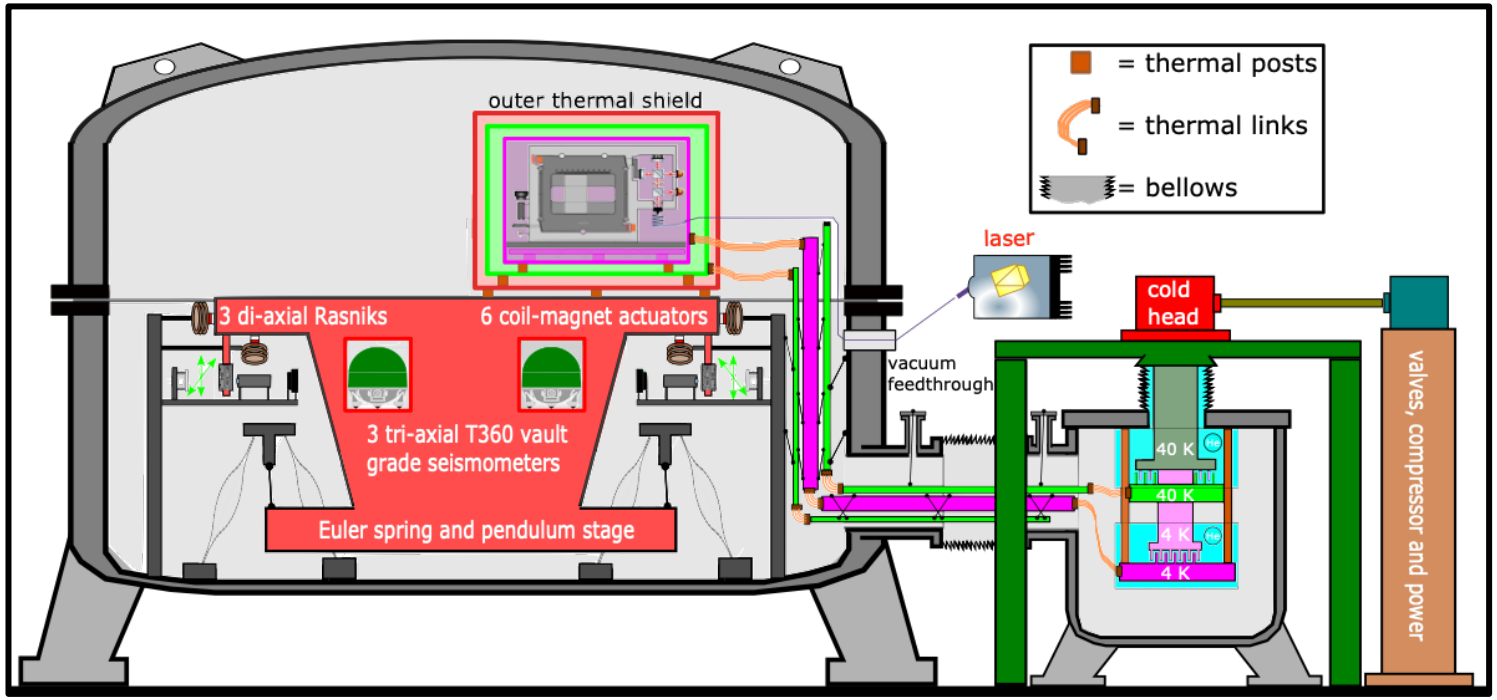
The leg and flexures are laser assisted plasma etched out of a thick 500 μm high-quality wafer.

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

Slide courtesy of Joris van Heijningen

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

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



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

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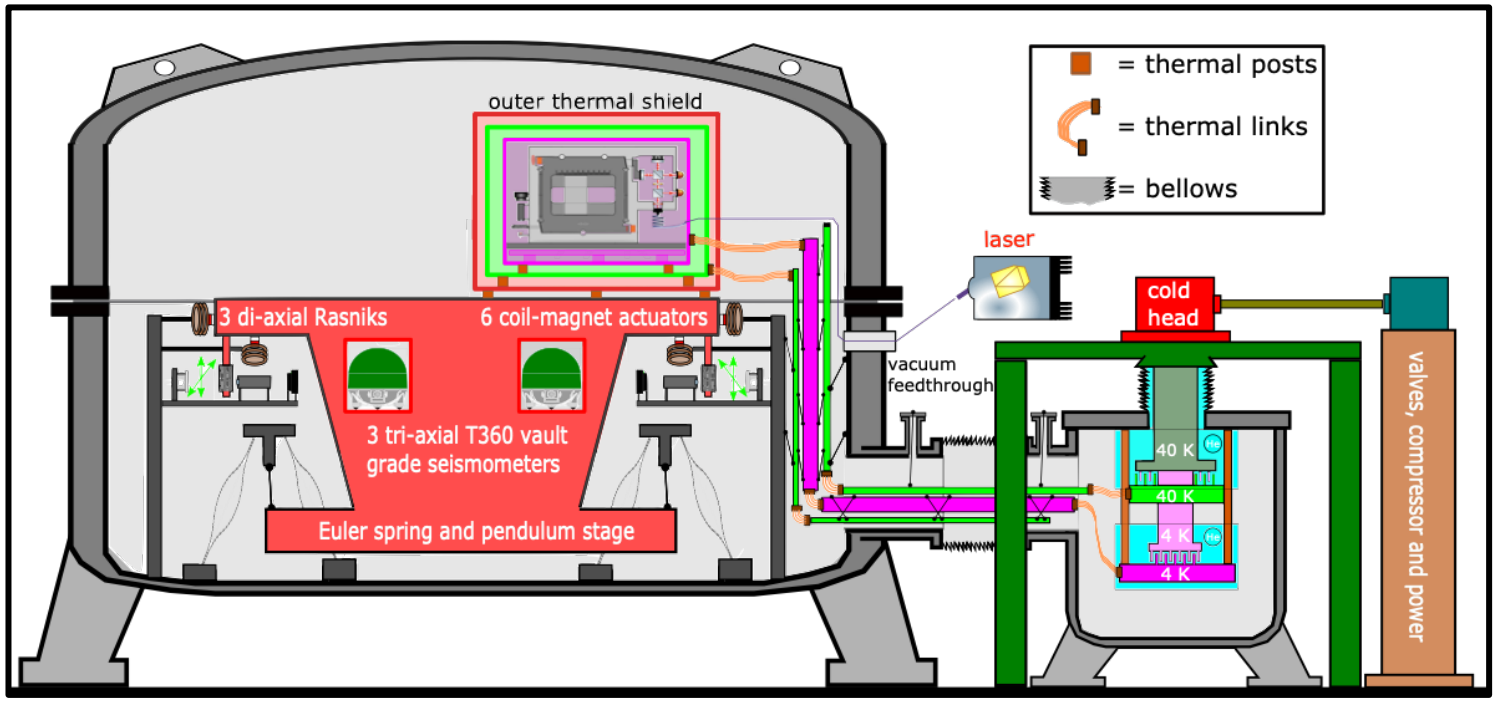
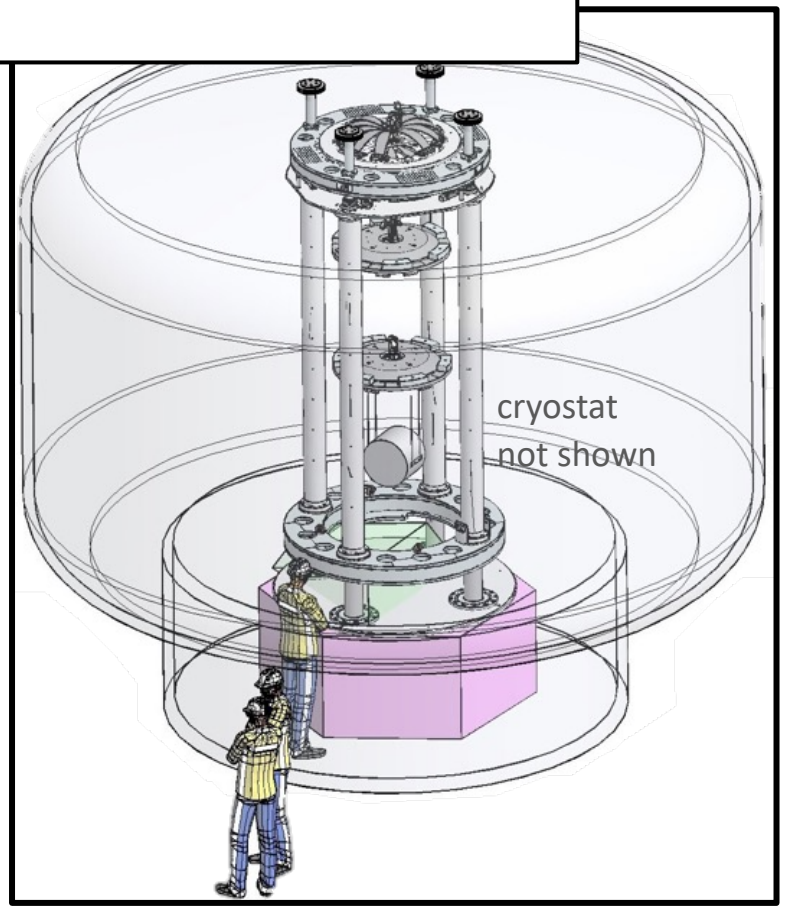
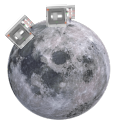
Another option would be to deploy them in the E-TEST (https://www.etest-emr.eu) prototype





Using the moon as a gravitational wave detector



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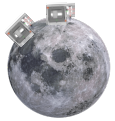

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Lunar Gravitational-wave Antenna

Jan Harms[1,2], Filippo Ambrosino[3,4,5], Lorella Angelini[6], Valentina Braito[7], Marica Branchesi[1,2], Enzo Brocato[3,8], Enrico Cappellaro[9], Eugenio Coccia[1,2], Michael Coughlin[10], Roberto Della Ceca[7], Massimo Della Valle[11], Cesare Dionisio[12], Costanzo Federico[4], Michelangelo Formisano[4], Alessandro Frigeri[4], Aniello Grado[11,13], Luca Izzo[14], Augusto Marcelli[15,16,17], Andrea Maselli[5,18], Marco Olivieri[19], Claudio Pernechele[9], Andrea Possenti[20,21], Samuele Ronchini[1,2], Roberto Serafinelli[7], Paola Severgnini[7], Maila Agostini[22,23], Francesca Badaracco[1,2], Alessandro Bertolini[24], Lorenzo Betti[22,23], Marta Maria Civitani[7], Christophe Collette[25,26], Stefano Covino[7], Simone Dall'Osso[1,2], Paolo D'Avanzo[7], Riccardo DeSalvo[27,28,29], Matteo Di Giovanni[1,2], Mauro Focardi[30], Carlo Giunchi[31], Joris van Heijningen[32], Nandita Khetan[1,2], Daniele Melini[33], Giuseppe Mitri[34,35], Conor Mow-Lowry[36], Luca Naponiello[22,23], Vladimiro Noce[22,23], Gor Oganesyan[1,2], Emanuele Pace[22,23], Ho Jung Paik[37], Alessandro Pajewski[1], Eliana Palazzi[38], Marco Pallavicini[39,40], Giovanni Pareschi[7], Riccardo Pozzobon[41], Ashish Sharma[1,2], Giorgio Spada[42], Ruggero Stanga[22], Gianpiero Tagliaferri[7], and Raffaele Votta[43]

[1] Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy; jan.harms@gssi.it
[2] INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
[3] INAF—Osservatorio Astronomico di Roma, Via Frascati 33, I-00078, Monte Porzio Catone (Rome), Italy
[4] INAF—Istituto di Astrofisica e Planetologia Spaziali, Via Fosso del Cavaliere 100, I-00133, Rome, Italy
[5] Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185, Rome, Italy
[6] Astroparticle Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA
[7] INAF—Osservatorio Astronomico di Brera, Via Brera 21, I-20121, Milan, Italy
[8] INAF—Osservatorio Astronomico d'Abruzzo, Via M. Maggini snc, I-64100, Teramo, Italy
[9] INAF—Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
[10] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[11] INAF—Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131, Naples, Italy
[12] Space Boy Station srl, Via Aldo Sandulli 45, I-00156, Rome, Italy
[13] INFN—Sezione di Napoli, Via Cintia, I-80126, Naples, Italy
[14] DARK, Niels Bohr Institute, University of Copenhagen, Jagtvej 128, DK-2200 Copenhagen Ø, Denmark
[15] INFN—Laboratori Nazionali di Frascati, Via E. Fermi 54, P.O. Box 13, I-00044 Frascati (RM), Italy
[16] CNR—Istituto Struttura della Materia and Elettra-Sincrotrone Trieste, Basovizza Area Science Park, I-34149 Trieste, Italy
[17] RICMASS—Rome International Center for Materials Science—Superstripes, Via dei Sabelli 119A, I-00185 Rome, Italy
[18] INFN, Sezione di Roma, Piazzale Aldo Moro 5, I-00185, Rome, Italy
[19] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Via Donato Creti 12, I-40128 Bologna, Italy
[20] INAF—Osservatorio Astronomico di Cagliari, Via della Scienza 5, I-09047, Selargius, Italy
[21] Dipartimento di Fisica, Università di Cagliari, S.P. Monserrato-Sestu Km 0, 700 - 09042 Monserrato (CA), Italy
[22] Osservatorio Polifunzionale del Chianti, S.P. 101 di Castellina in Chianti, I-50021 Barberino Val d'Elsa, Italy
[23] Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy
[24] Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[25] Precision Mechatronics Laboratory, Aerospace and Mechanical Engineering Department, University of Liège, 9 allée de la découverte, B-4000 Liège, Belgium
[26] BEAMS department, Université Libre de Bruxelles, 50 av.F.D. Roosevelt, B-1050 Brussels, Belgium
[27] University of Sannio at Benevento, C.so Garibaldi 107, Pal. dell'Aquila Bosco-Lucarelli, I-82100 Benevento, Italy
[28] University of Utah, Department of Physics and Astronomy, 115 S. 1400 E, Salt Lake City, UT 84112-0830, USA
[29] RicLab, 1650 Casa Grande Street, Pasadena, CA 91104, USA
[30] INAF—Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5, I-50121, Florence, Italy
[31] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via Cesare Battisti 53, I-56125, Pisa, Italy
[32] Centre for Cosmology, Particle Physics and Phenomenology (CP3), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[33] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Sismologia e Tettonofisica, Via di Vigna Murata 605, I-00143, Rome, Italy
[34] International Research School of Planetary Sciences, Viale Pindaro 42, I-65127, Pescara, Italy
[35] Dipartimento di Ingegneria e Geologia, Università d'Annunzio, Viale Pindaro 42, I-65127, Pescara, Italy
[36] VU University Amsterdam, 1081 HV Amsterdam, Netherlands
[37] Department of Physics, University of Maryland, College Park, MD 20742, USA
[38] INAF—Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, I-40129 Bologna, Italy
[39] INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[40] Dipartimento di Fisica, Università di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[41] Department of Geosciences, University of Padova, Via Giovanni Gradenigo, 6, I-35131 Padova, Italy
[42] Dipartimento di Fisica e Astronomia (DIFA), Università di Bologna, Via Irnerio, 46, I-40126 Bologna, Italy
[43] Space Department, Italian Aerospace Research Center (CIRA), Via Maiorise snc, I-81043, Capua (CE), Italy
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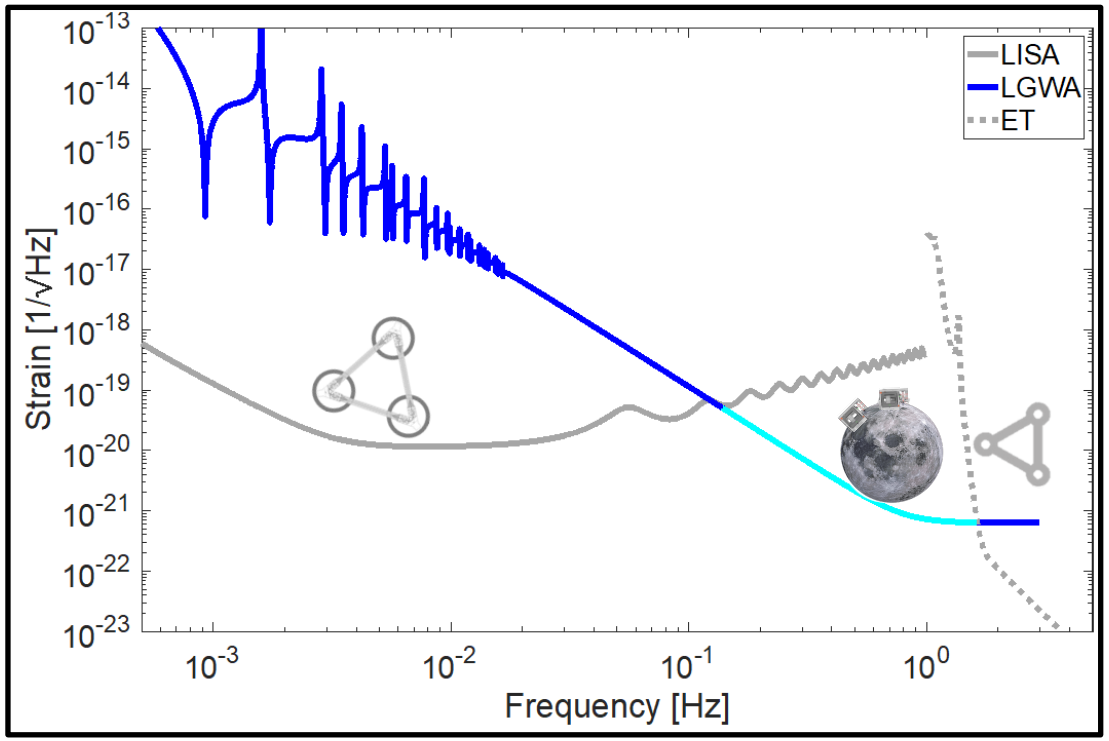
Using the moon as a gravitational wave detector



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Lunar Gravitational-wave Antenna

Jan Harms[1,2], Filippo Ambrosino[3,4,5], Lorella Angelini[6], Valentina Braito[7], Marica Branchesi[1,2], Enzo Brocato[3,8], Enrico Cappellaro[9], Eugenio Coccia[1,2], Michael Coughlin[10], Roberto Della Ceca[7], Massimo Della Valle[11], Cesare Dionisio[12], Costanzo Federico[4], Michelangelo Formisano[4], Alessandro Frigeri[4], Aniello Grado[11,13], Luca Izzo[14], Augusto Marcelli[15,16,17], Andrea Maselli[5,18], Marco Olivieri[19], Claudio Pernechele[9], Andrea Possenti[20,21], Samuele Ronchini[1,2], Roberto Serafinelli[7], Paola Severgnini[7], Maila Agostini[22,23], Francesca Badaracco[1,2], Alessandro Bertolini[24], Lorenzo Betti[22,23], Marta Maria Civitani[7], Christophe Collette[25,26], Stefano Covino[7], Simone Dall'Osso[1,2], Paolo D'Avanzo[7], Riccardo DeSalvo[27,28,29], Matteo Di Giovanni[1,2], Mauro Focardi[30], Carlo Giunchi[31], Joris van Heijningen[32], Nandita Khetan[1,2], Daniele Melini[33], Giuseppe Mitri[34,35], Conor Mow-Lowry[36], Luca Naponiello[22,23], Vladimiro Noce[22,23], Gor Oganesyan[1,2], Emanuele Pace[22,23], Ho Jung Paik[37], Alessandro Pajewski[1], Eliana Palazzi[38], Marco Pallavicini[39,40], Giovanni Pareschi[7], Riccardo Pozzobon[41], Ashish Sharma[1,2], Giorgio Spada[42], Ruggero Stanga[22], Gianpiero Tagliaferri[7], and Raffaele Votta[43]
[1] Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy; jan.harms@gssi.it
[2] INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
[3] INAF—Osservatorio Astronomico di Roma, Via Frascati 33, I-00078, Monte Porzio Catone (Rome), Italy
[4] INAF—Istituto di Astrofisica e Planetologia Spaziali, Via Fosso del Cavaliere 100, I-00133, Rome, Italy
[5] Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185, Rome, Italy
[6] Astroparticle Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA
[7] INAF—Osservatorio Astronomico di Brera, Via Brera 21, I-20121, Milan, Italy
[8] INAF—Osservatorio Astronomico d'Abruzzo, Via M. Maggini snc, I-64100, Teramo, Italy
[9] INAF—Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
[10] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[11] INAF—Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131, Naples, Italy
[12] Space Boy Station srl, Via Aldo Sandulli 45, I-00156, Rome, Italy
[13] INFN—Sezione di Napoli, Via Cintia, I-80126, Naples, Italy
[14] DARK, Niels Bohr Institute, University of Copenhagen, Jagtvej 128, DK-2200 Copenhagen Ø, Denmark
[15] INFN—Laboratori Nazionali di Frascati, Via E. Fermi 54, P.O. Box 13, I-00044 Frascati (RM), Italy
[16] CNR—Istituto Struttura della Materia and Elettra-Sincrotrone Trieste, Basovizza Area Science Park, I-34149 Trieste, Italy
[17] RICMASS—Rome International Center for Materials Science—Superstripes, Via dei Sabelli 119A, I-00185 Rome, Italy
[18] INFN, Sezione di Roma, Piazzale Aldo Moro 5, I-00185, Rome, Italy
[19] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Via Donato Creti 12, I-40128 Bologna, Italy
[20] INAF—Osservatorio Astronomico di Cagliari, Via della Scienza 5, I-09047, Selargius, Italy
[21] Dipartimento di Fisica, Università di Cagliari, S.P. Monserrato-Sestu Km 0, 700 - 09042 Monserrato (CA), Italy
[22] Osservatorio Polifunzionale del Chianti, S.P. 101 di Castellina in Chianti, I-50021 Barberino Val d'Elsa, Italy
[23] Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy
[24] Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[25] Precision Mechatronics Laboratory, Aerospace and Mechanical Engineering Department, University of Liège, 9 allée de la découverte, B-4000 Liège, Belgium
[26] BEAMS department, Université Libre de Bruxelles, 50 av.F.D. Roosevelt, B-1050 Brussels, Belgium
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[33] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Sismologia e Tettonofisica, Via di Vigna Murata 605, I-00143, Rome, Italy
[34] International Research School of Planetary Sciences, Viale Pindaro 42, I-65127, Pescara, Italy
[35] Dipartimento di Ingegneria e Geologia, Università d'Annunzio, Viale Pindaro 42, I-65127, Pescara, Italy
[36] VU University Amsterdam, 1081 HV Amsterdam, Netherlands
[37] Department of Physics, University of Maryland, College Park, MD 20742, USA
[38] INAF—Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, I-40129 Bologna, Italy
[39] INFN, Sezione di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[40] Dipartimento di Fisica, Università di Genova, Via Dodecaneso 33, I-16146 Genova, Italy
[41] Department of Geosciences, University of Padova, Via Giovanni Gradenigo, 6, I-35131 Padova, Italy
[42] Dipartimento di Fisica e Astronomia (DIFA), Università di Bologna, Via Irnerio, 46, I-40126 Bologna, Italy
[43] Space Department, Italian Aerospace Research Center (CIRA), Via Maiorise snc, I-81043, Capua (CE), Italy
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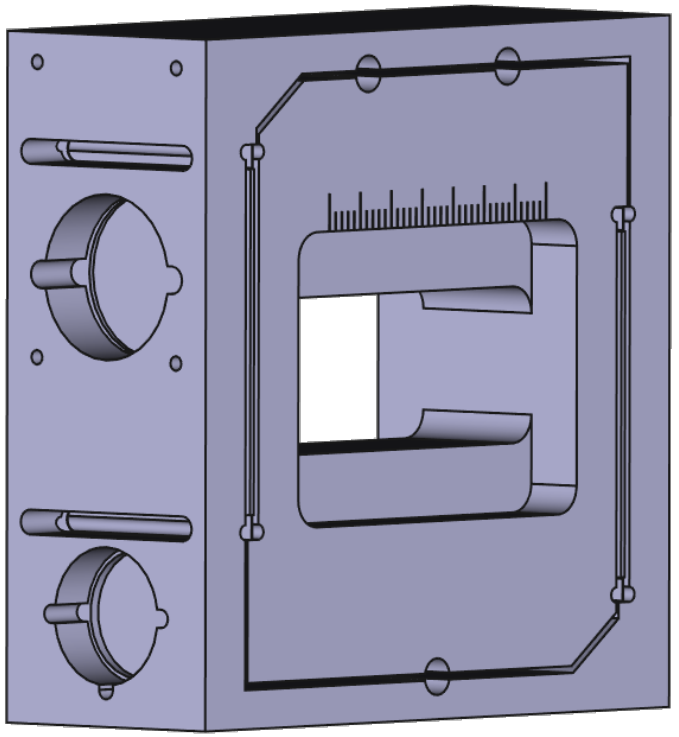
Summary

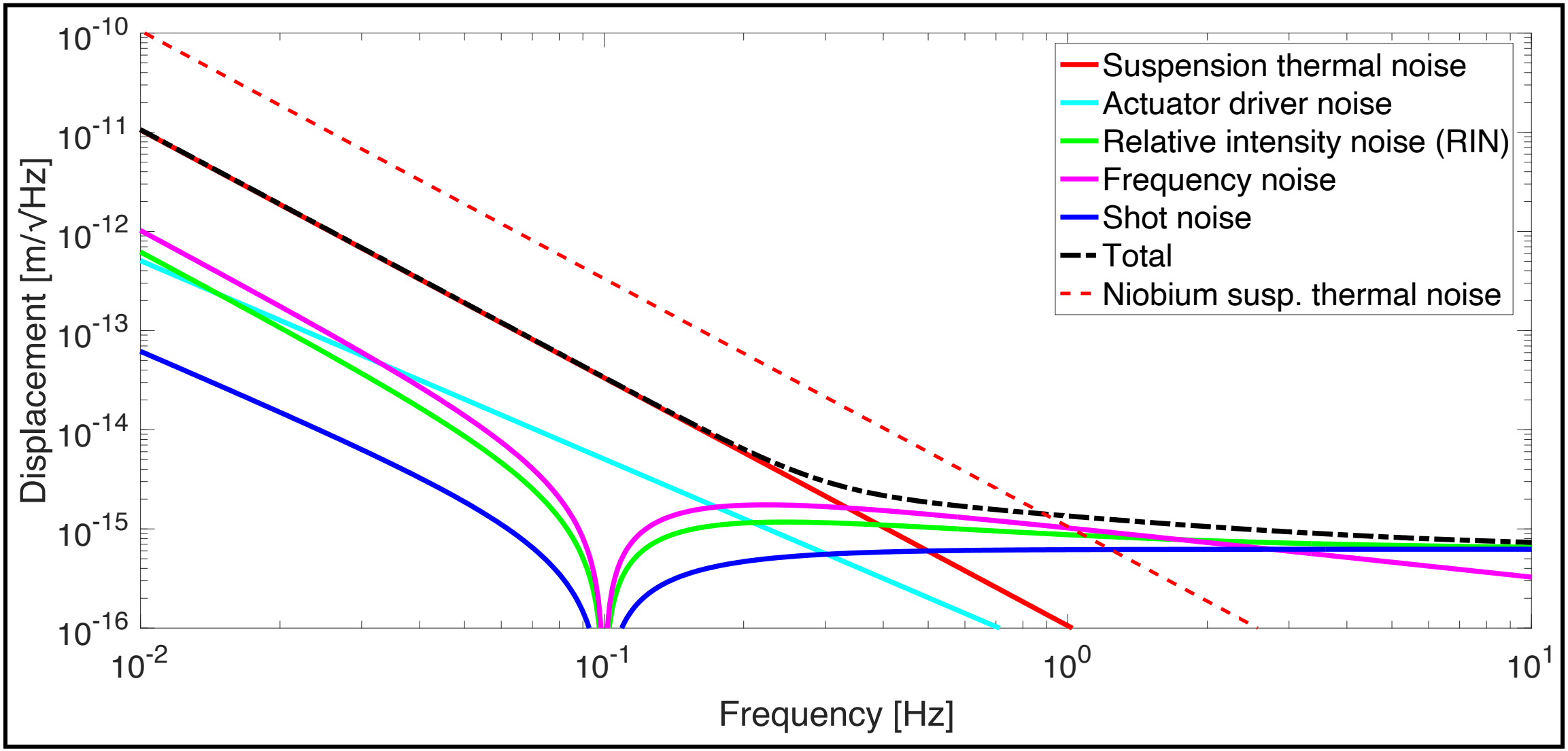
- Cryogenic inertial sensor with fm/√Hz displacement sensitivity from 0.5 Hz onward;
- Changes include: superconducting, low-noise actuators, polarized interferometric readout and Rasnik readout;
- This sensor can be deployed in the natural cryostats on the Lunar pole craters; a cryogenic sensor array can directly detect the effects of GWs on the Moon;
- The inertial sensor is a first application test for the actuators and in future we will look at applications as in the cryogenic suspension chain.



Thank you!

Bonus and backup slides

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



Slide courtesy by Joris van Heijningen

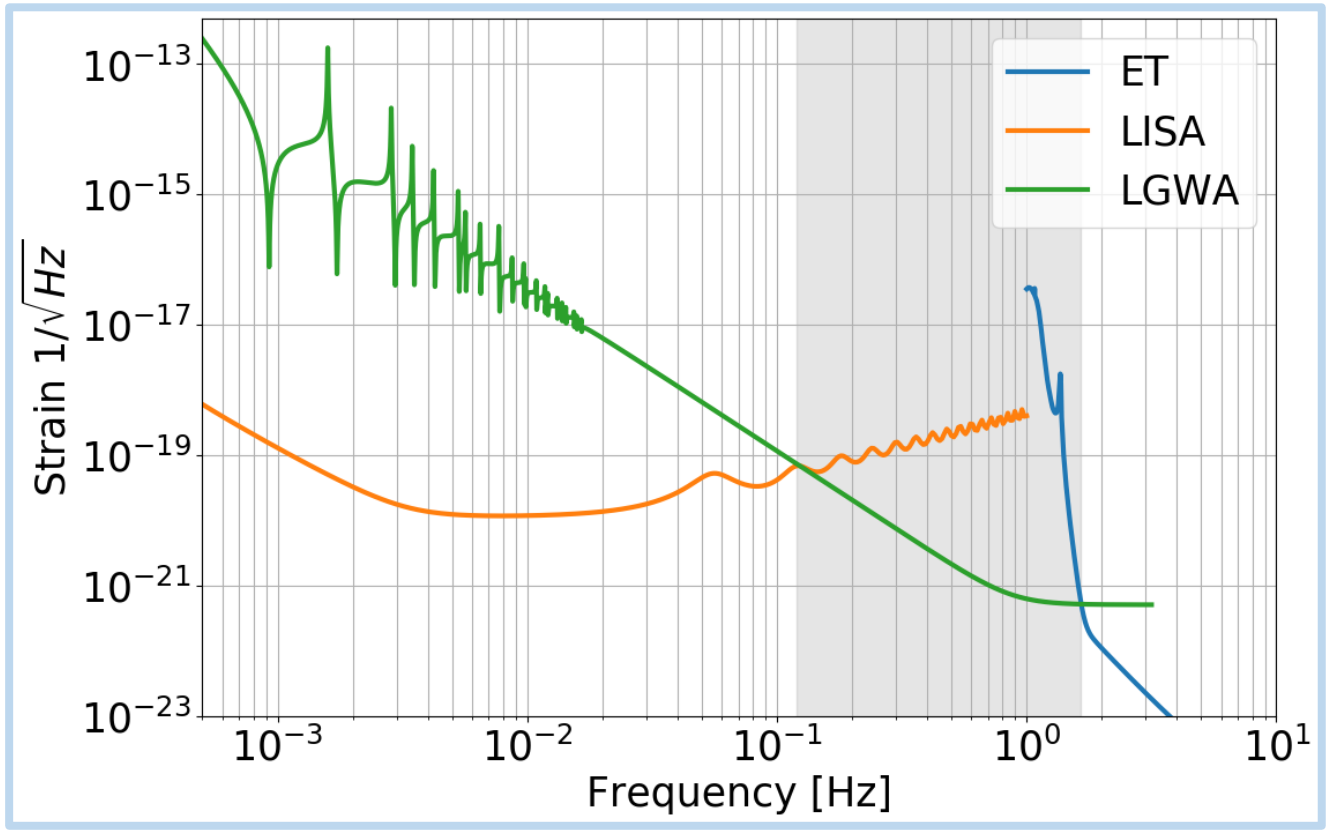
Polarizing optics divert all the available power onto the photodiodes, avoiding dumping part of it. This is a important feature when working at cryogenic temperatures and it also means less shot noise for given injected power. Indeed, in Tab. 1 we can compare the powers received by the photodiodes and the overall shot noise when polarizing and non-polarizing optics are used. The total shot noise expected in the interferometer output depends on the amount of power falling on the photodiodes as $\mathrm{SN_i} \propto 1/\sqrt{P_\mathrm{i}}$. The total shot noise is then $\mathrm{SN_{tot}} = \sqrt{\mathrm{SN}^2_{\mathrm{PD}_1} + \mathrm{SN}^2_{\mathrm{PD}_2}}$.

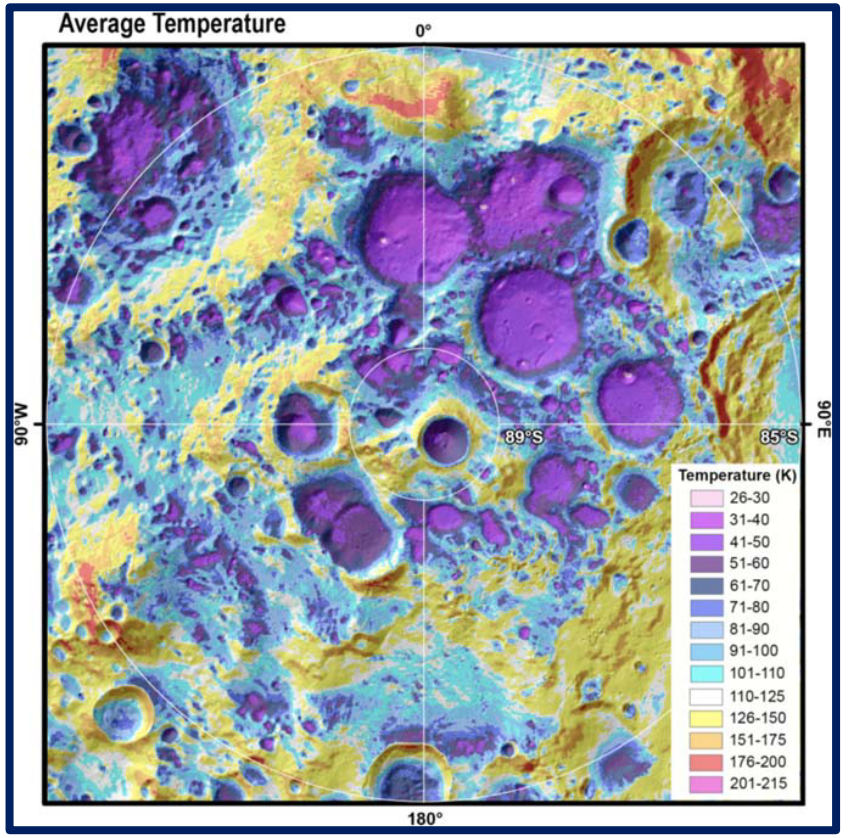
Table 1. Comparison of interferometric readout outputs and shot noise without and with polarizing optics for a given input power P_0.

	power on PD1	power on PD2	$\mathrm{SN_{tot}}$
previous configuration [12]	$P_0/4$	$P_0/8$	$\propto \sqrt{12/P_0}$
with polarizing optics	$P_0/2$	$P_0/2$	$\propto \sqrt{4/P_0}$

We thus get a factor $\sqrt{3}$ of reduction in the shot noise when polarizing optics are employed with respect to the non-polarizing optics case.

Other possible application:
LGWA: a bridge towards lower frequencies





- New possible discoveries
- Binary Neutron Stars & Double White Dwarf: Hours → Parameter estimation, EM early warning, Sky localization with only LGWA.
- Polarization measurements and tests of gravity theories.

Slide courtesy by Dr. Francesca Badaracco

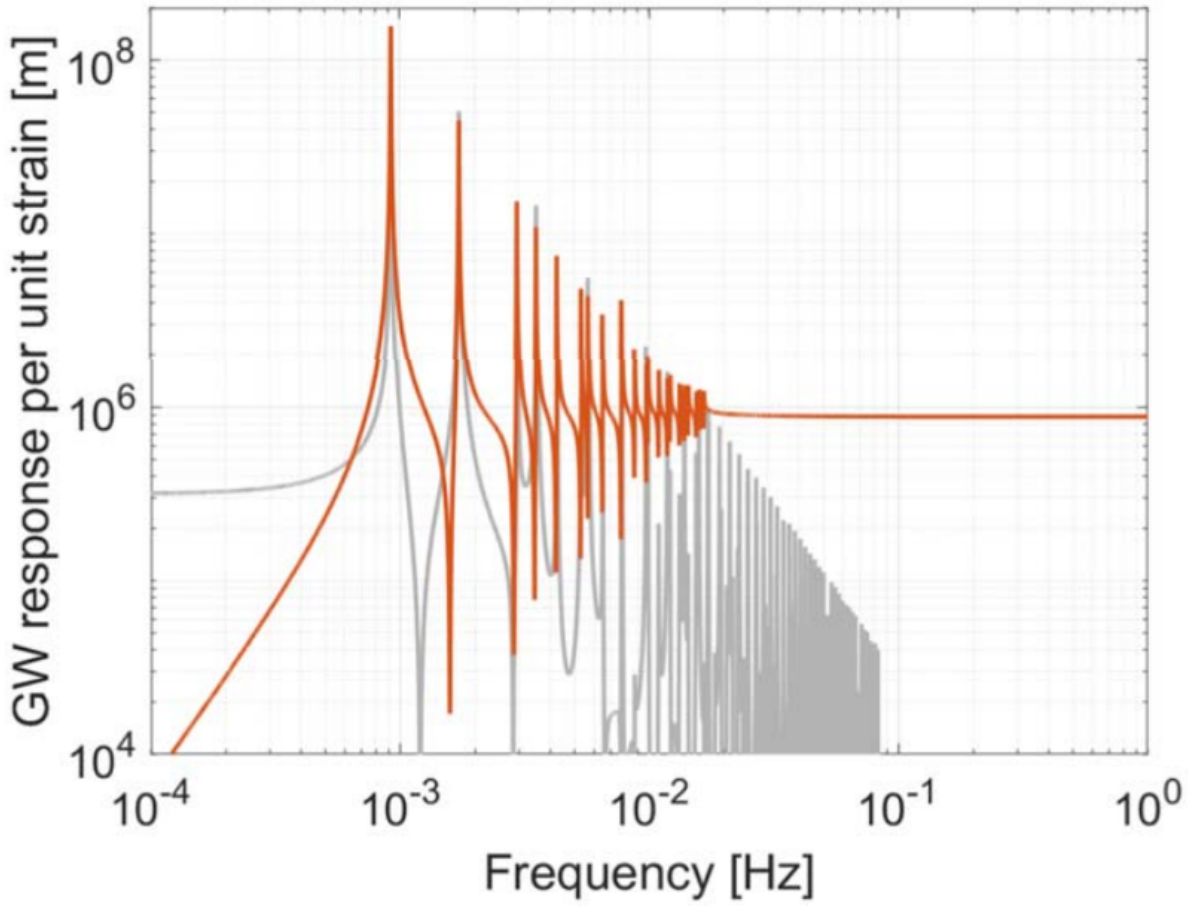


Figure 1. Simplified GW response model (red) used in this paper, with normal-mode sum truncated at $n = 22$. The response curve of a pessimistic response model is shown in gray for comparison. The models only include spheroidal quadrupole modes.

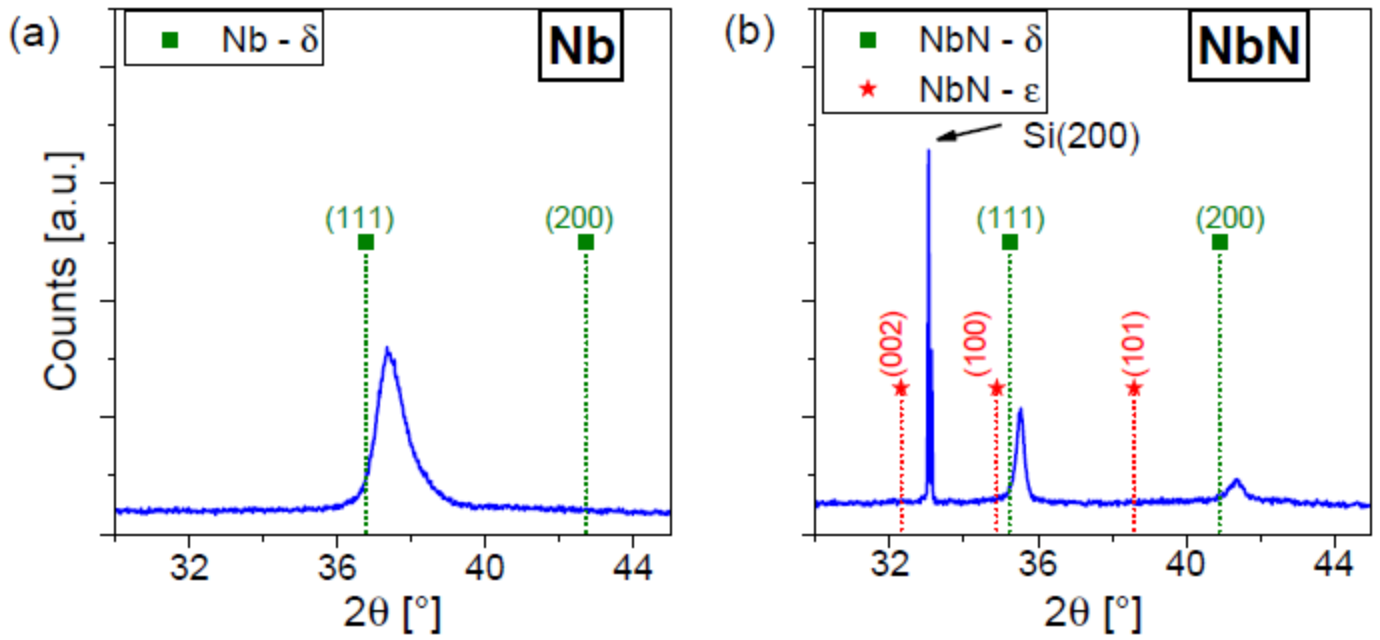
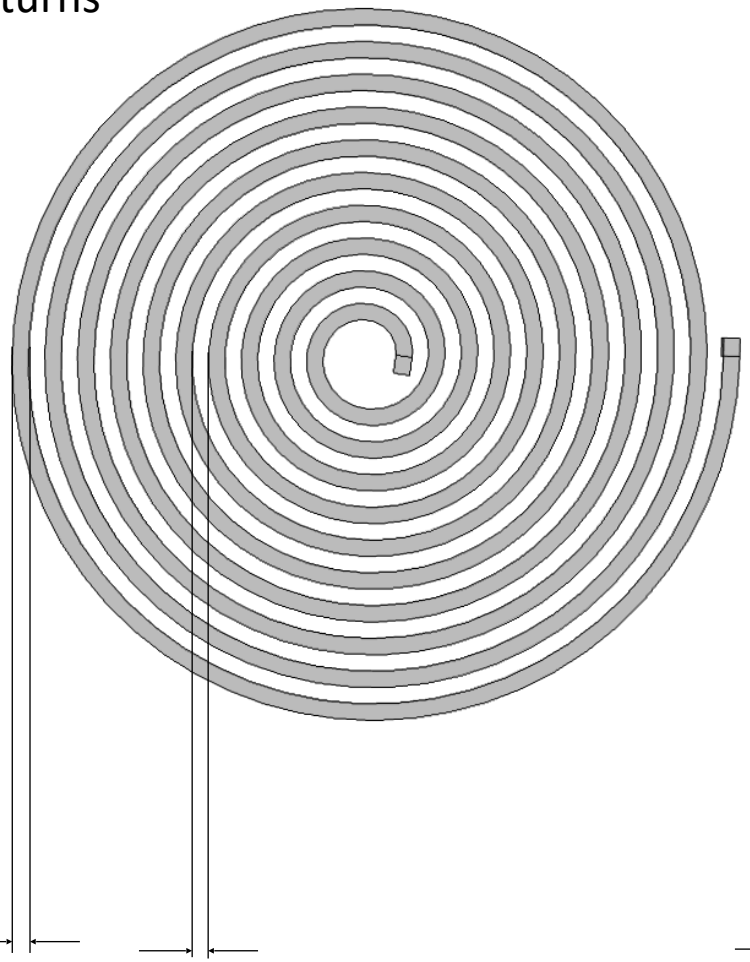


Figure 5. Diffractogram of (a) niobium film with theoretical value (dotted lines) and (b) niobium nitride film with theoretical values for δ and ϵ phases (dotted lines).

Dimensions

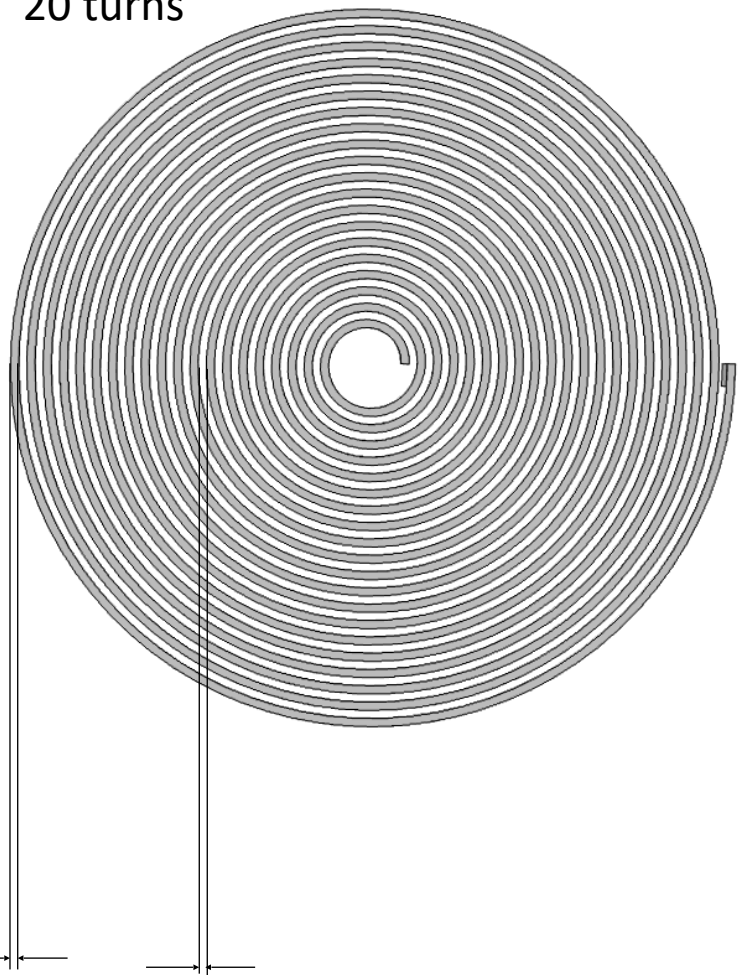
10 turns



w = 225 µm

225 µm

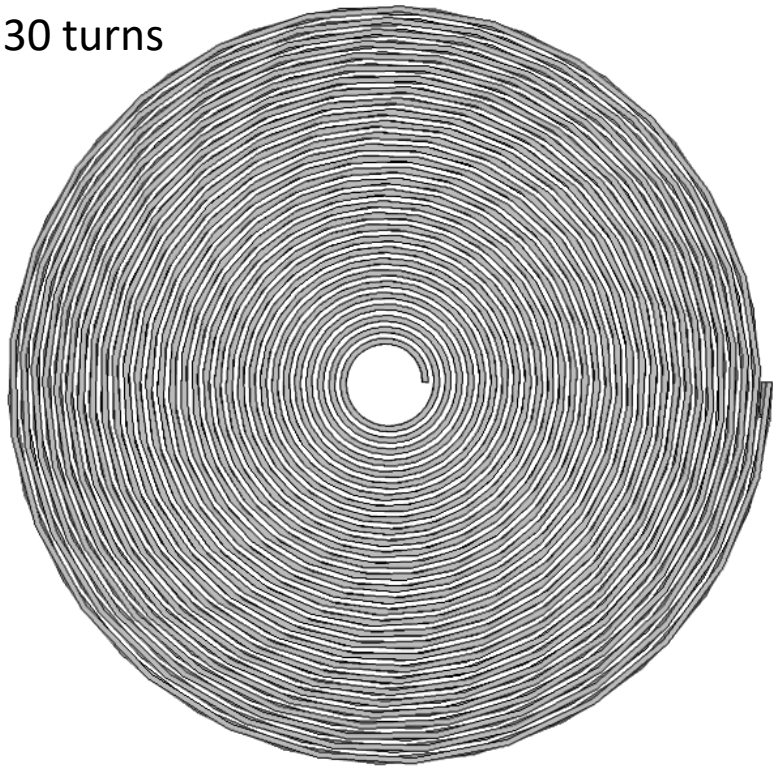
20 turns



w = 112.5 µm

112.5 µm

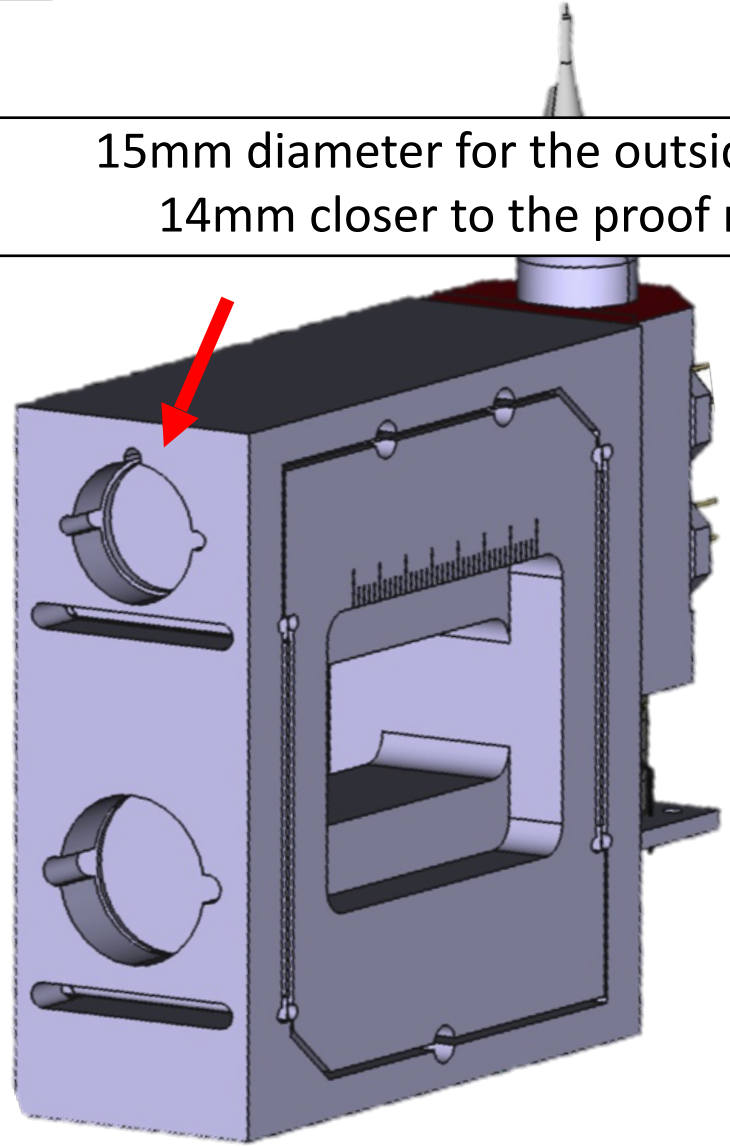
30 turns

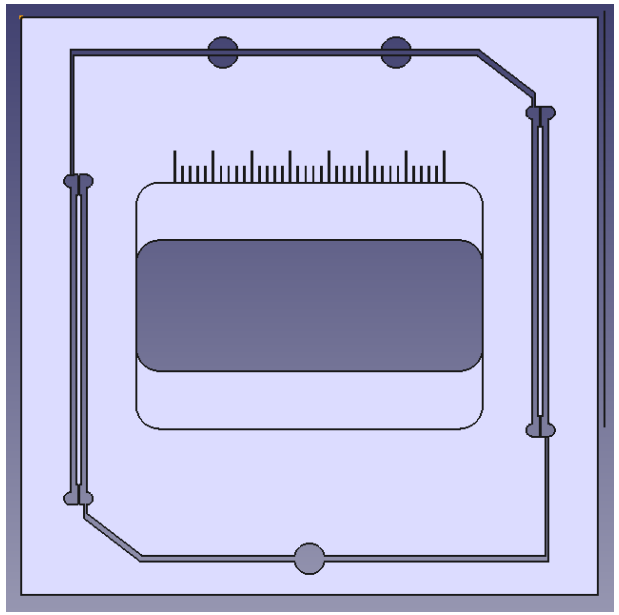


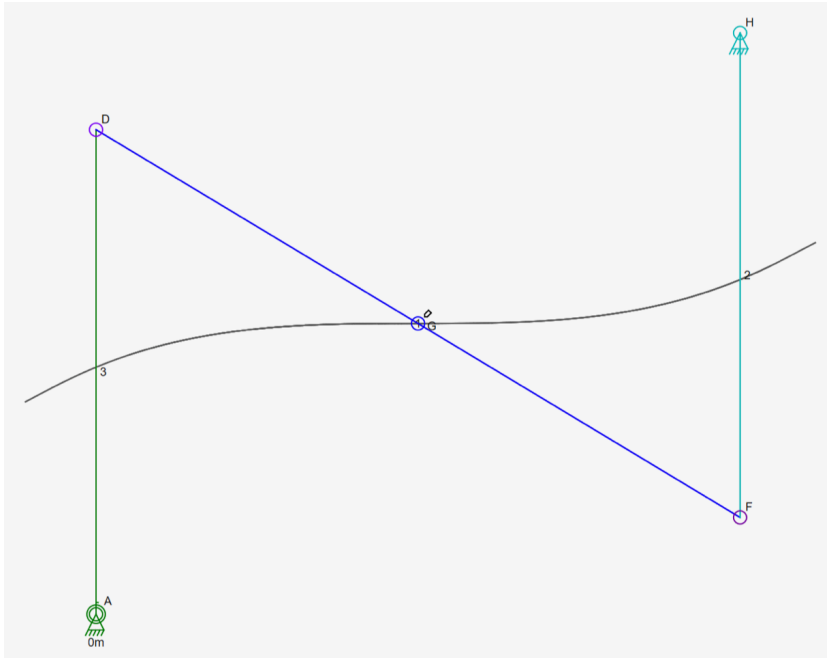
w = 75 µm

Increasing the actuator's hole size

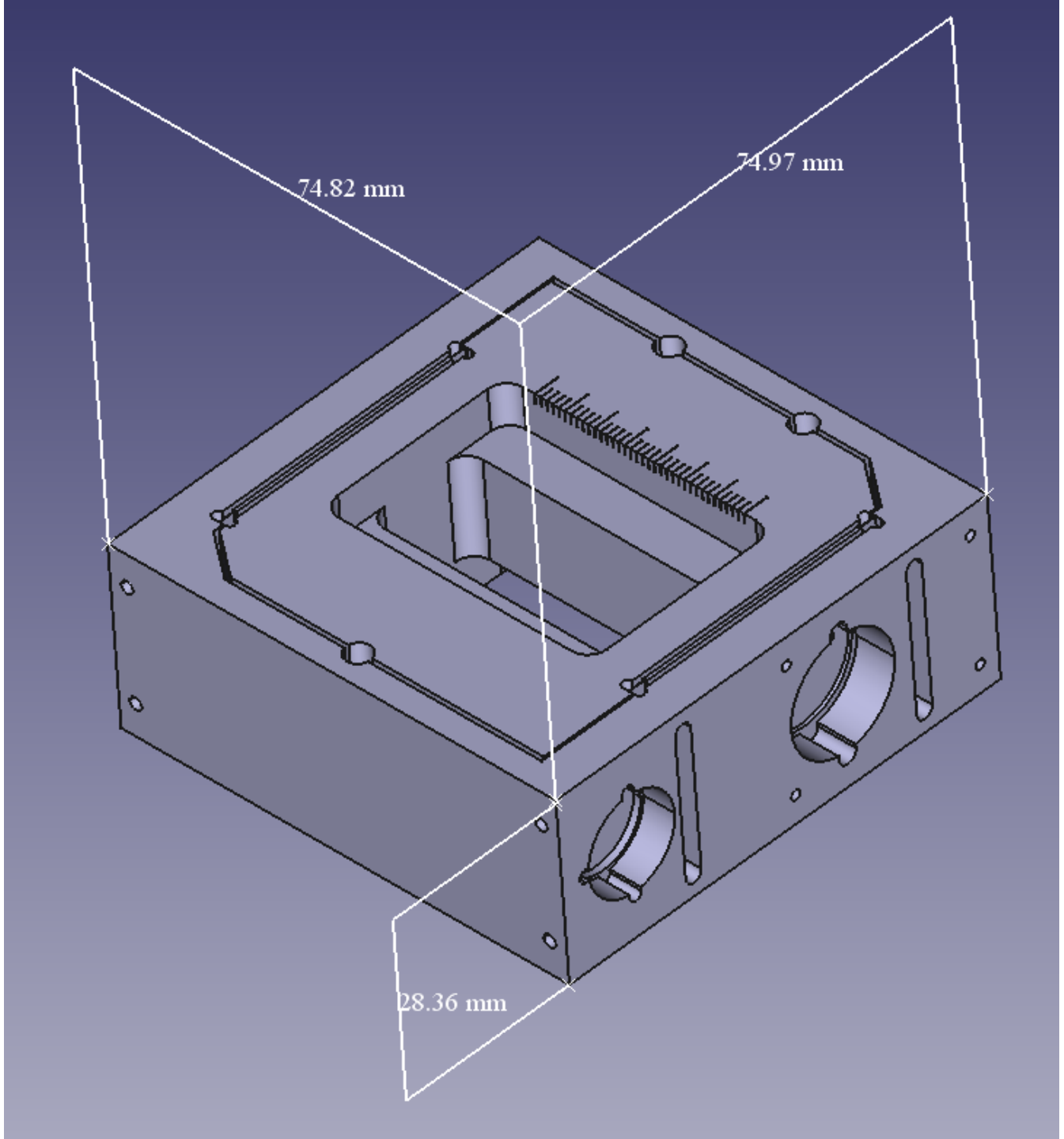
15mm diameter for the outside hole,
14mm closer to the proof mass



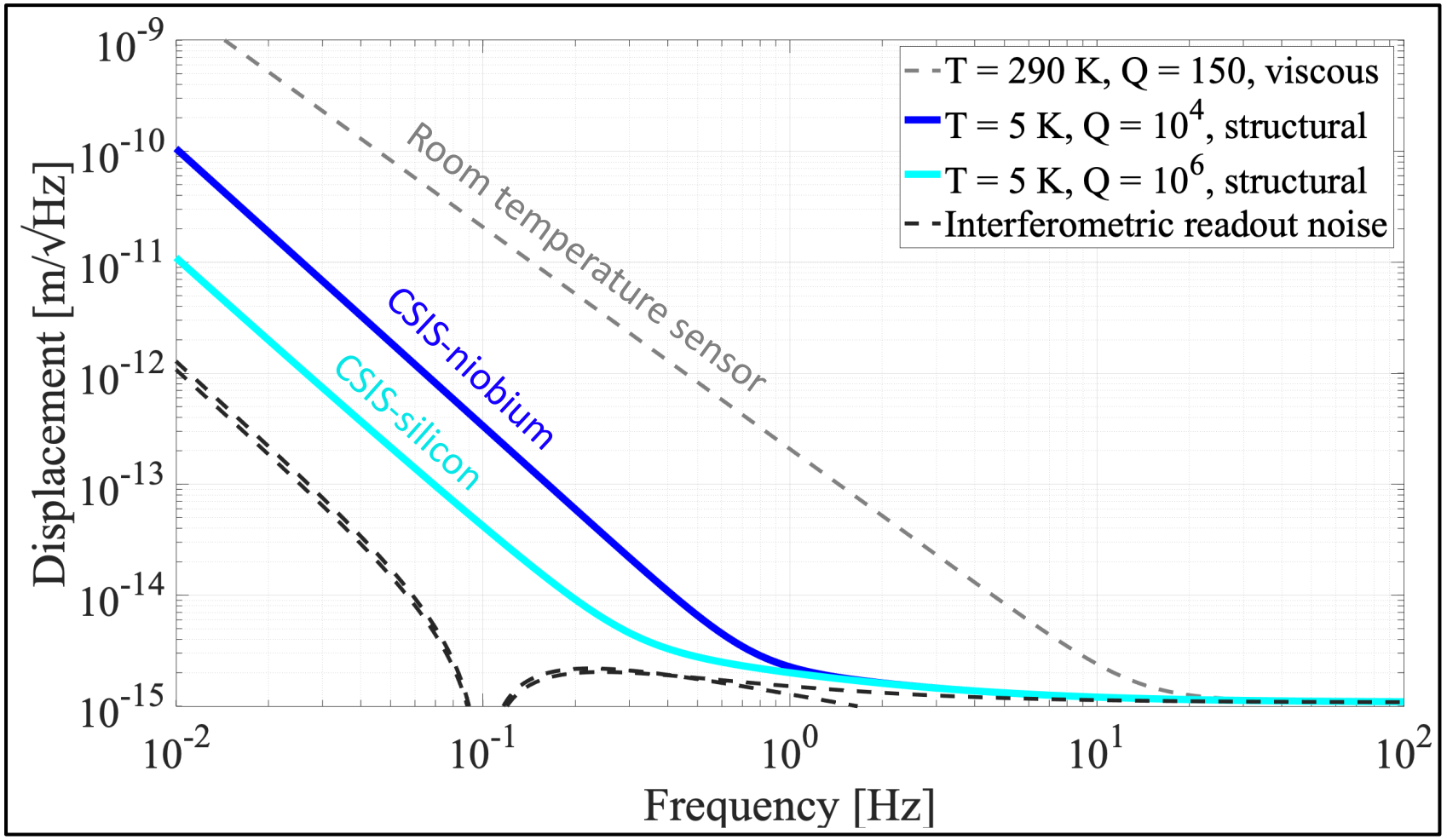


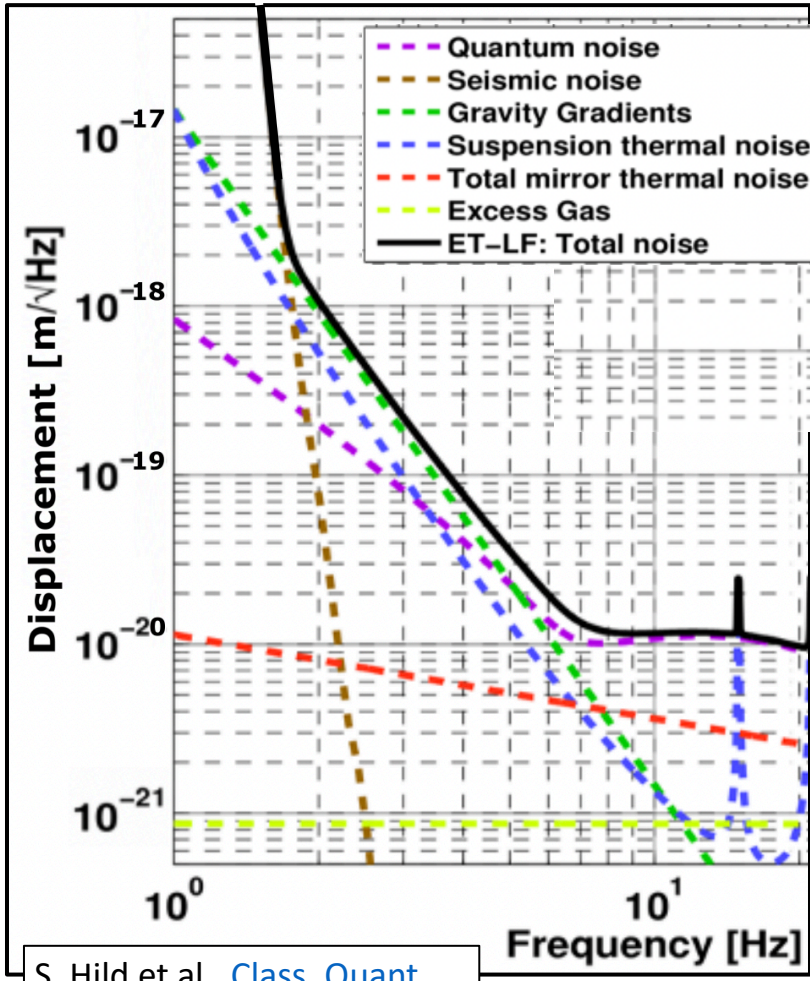


The suspension points were shifted.


74.82 mm
74.97 mm
28.36 mm

How much more sensitive is this cold inertial sensor?





S. Hild et al., Class. Quant. Grav. 27 015003 (2010)

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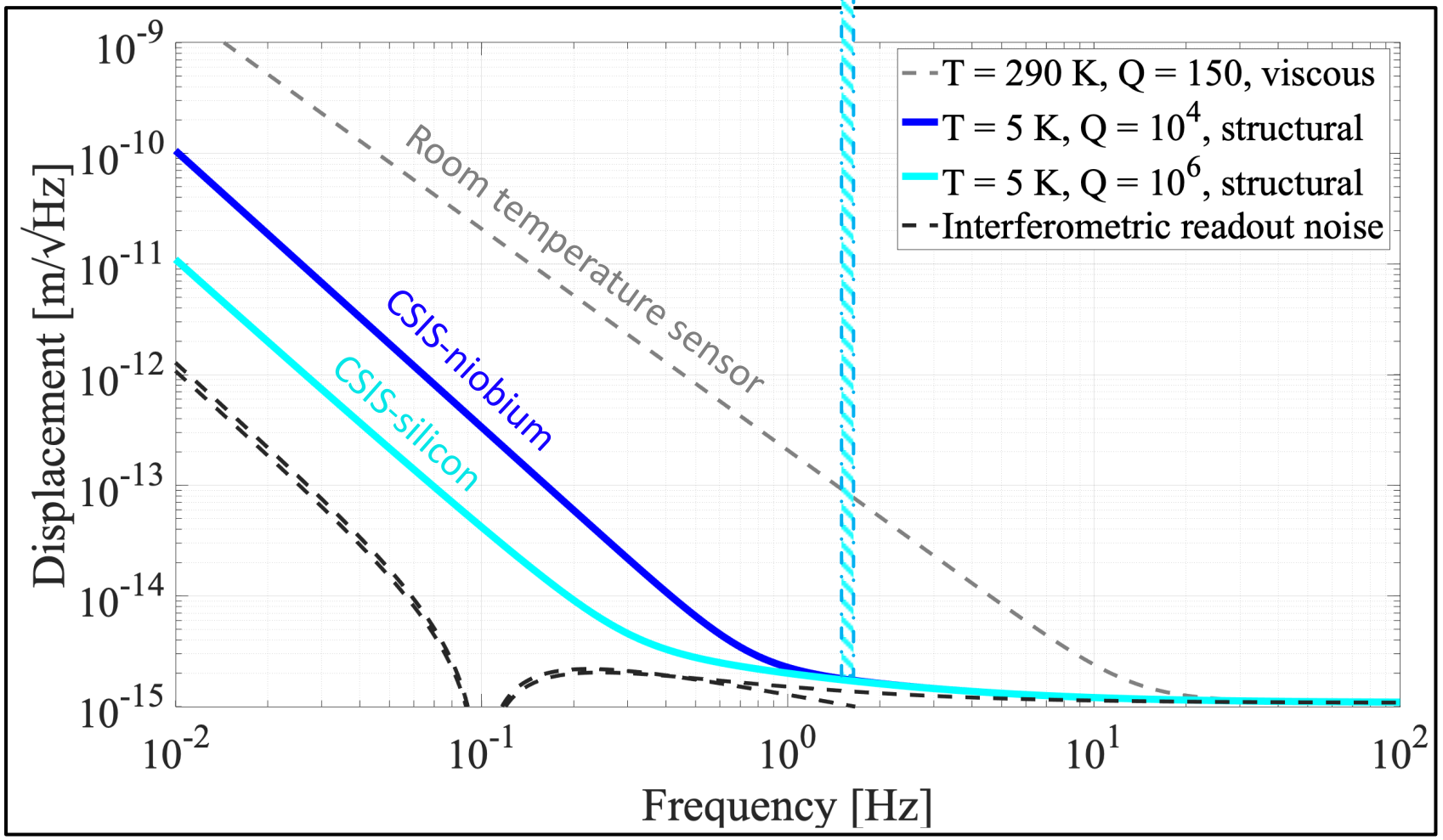

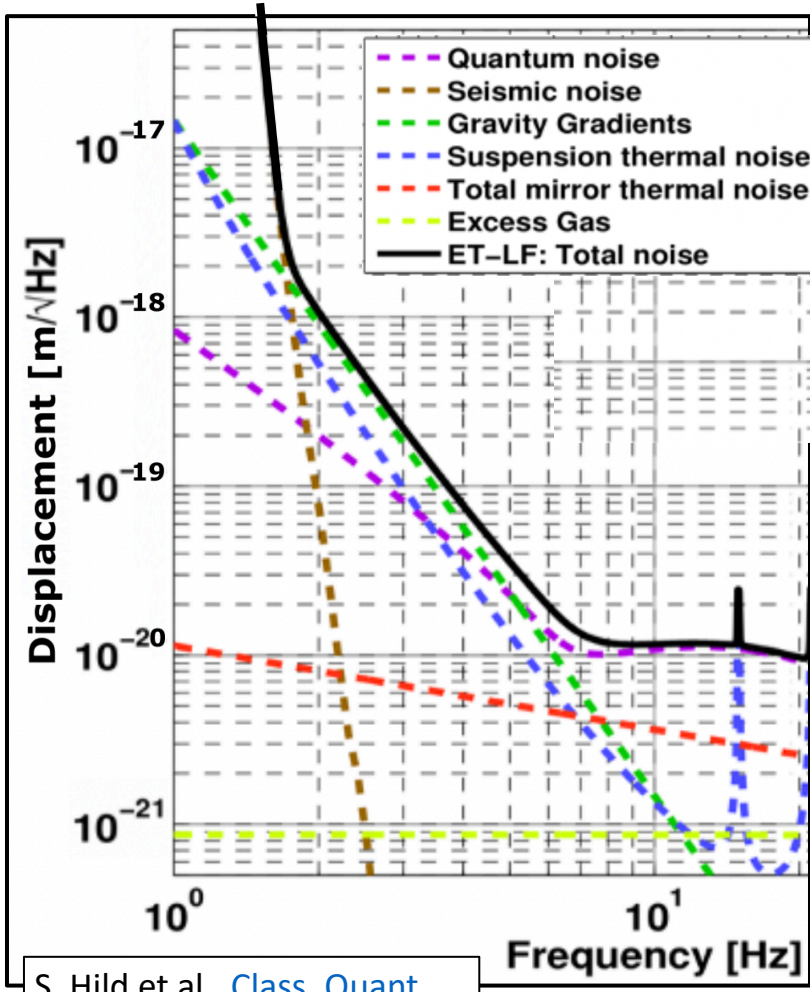

S. Hild et al., Class. Quant. Grav. 27 015003 (2010)

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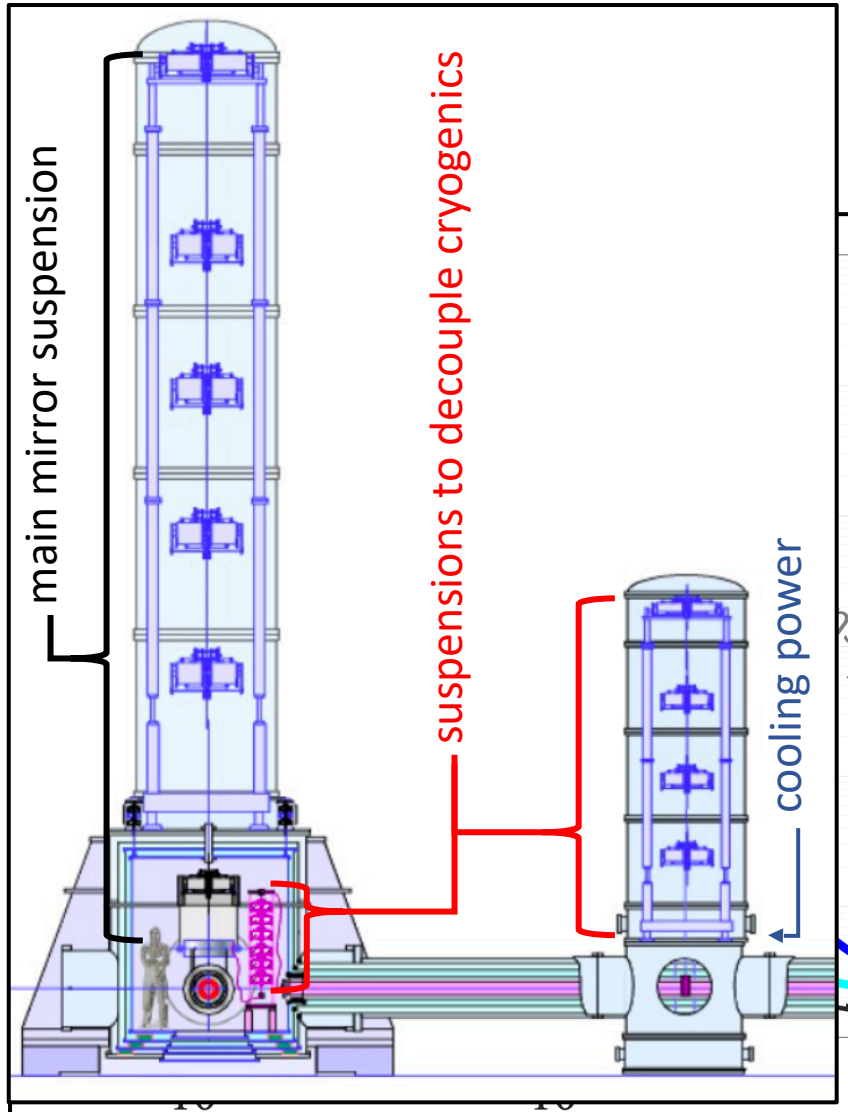
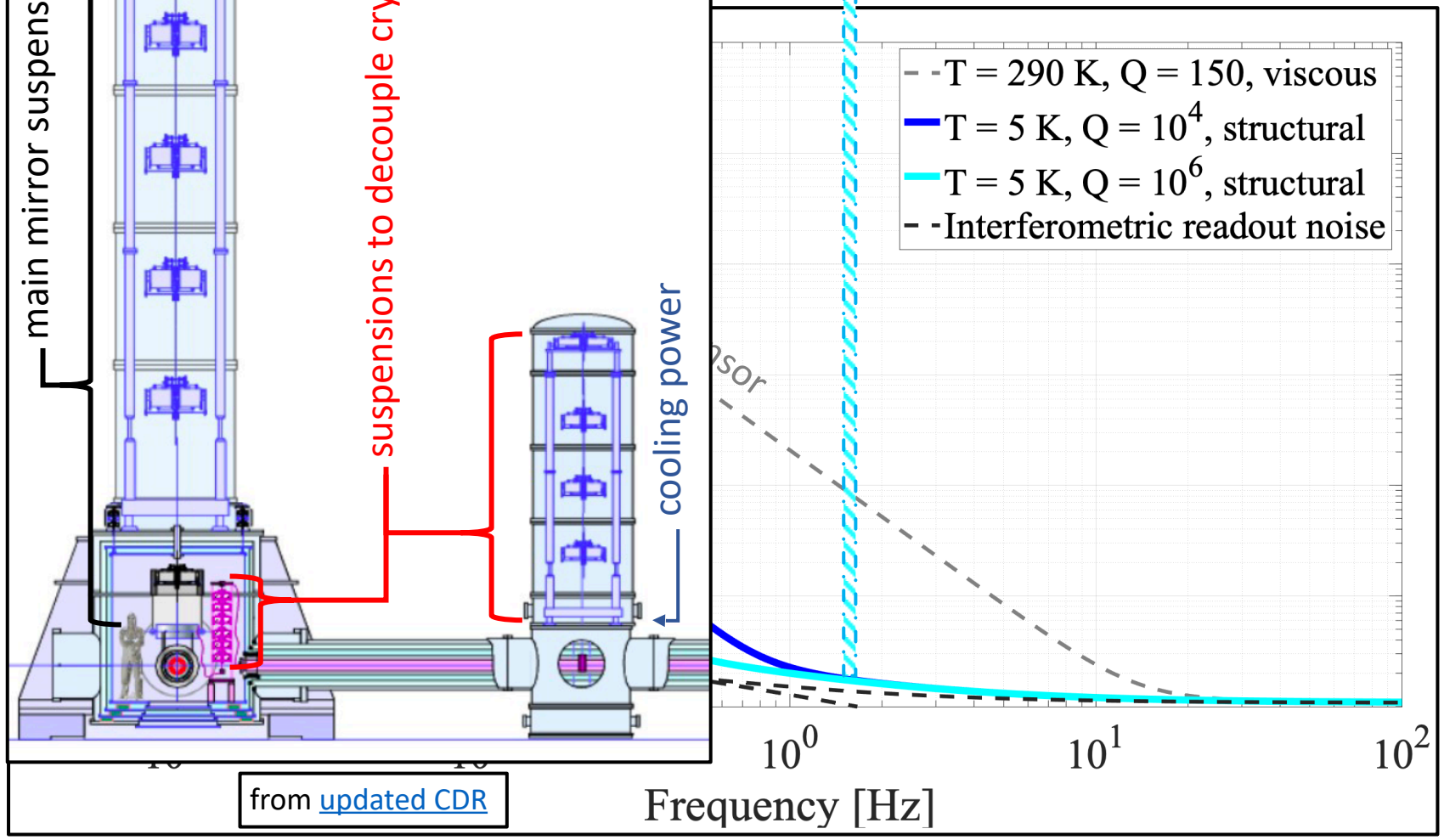
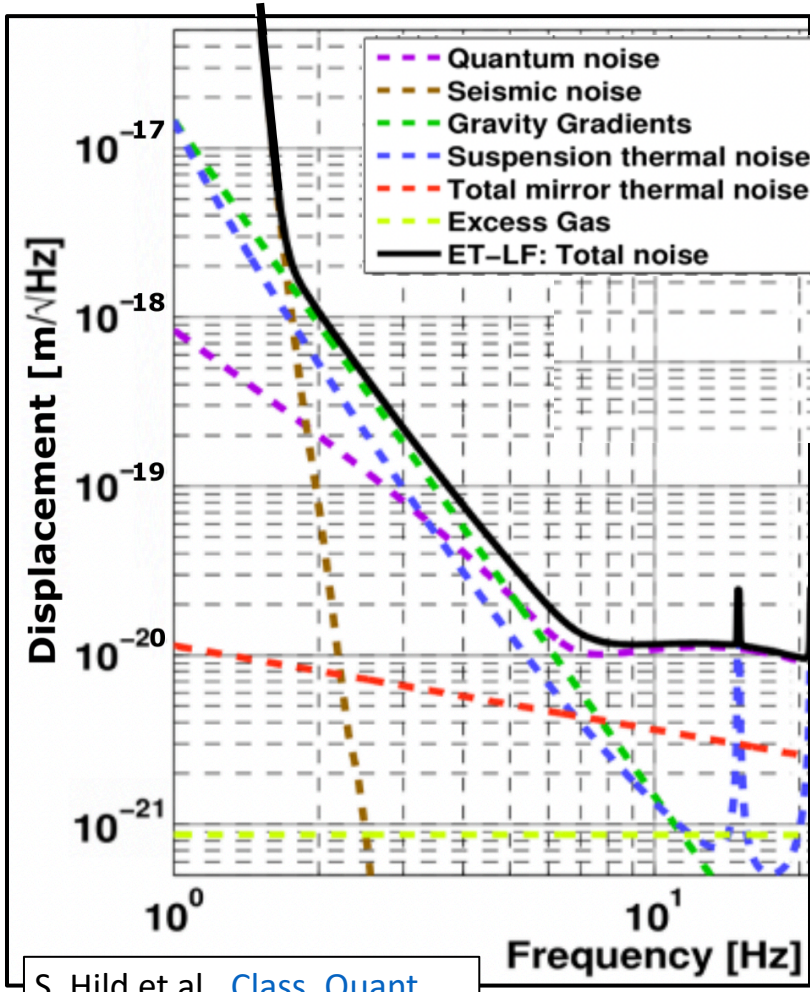


from updated CDR





S. Hild et al., Class. Quant. Grav. 27 015003 (2010)

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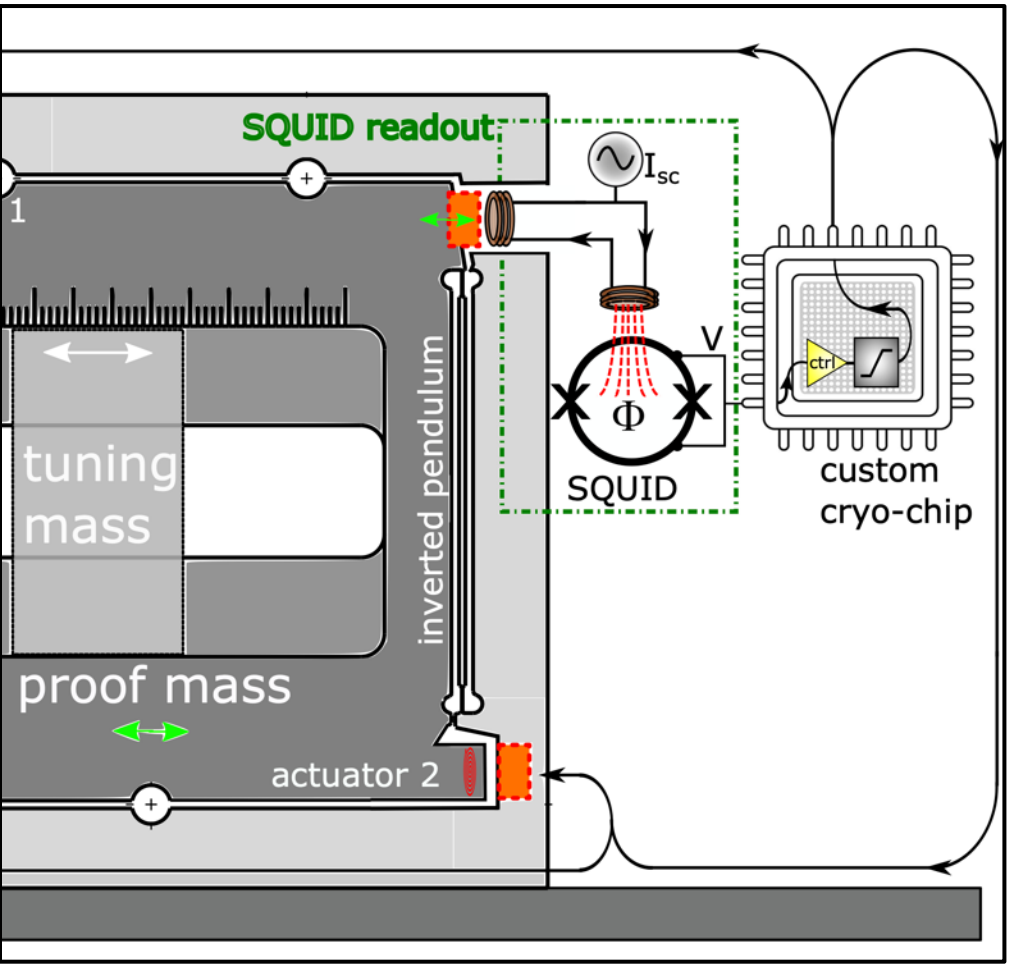
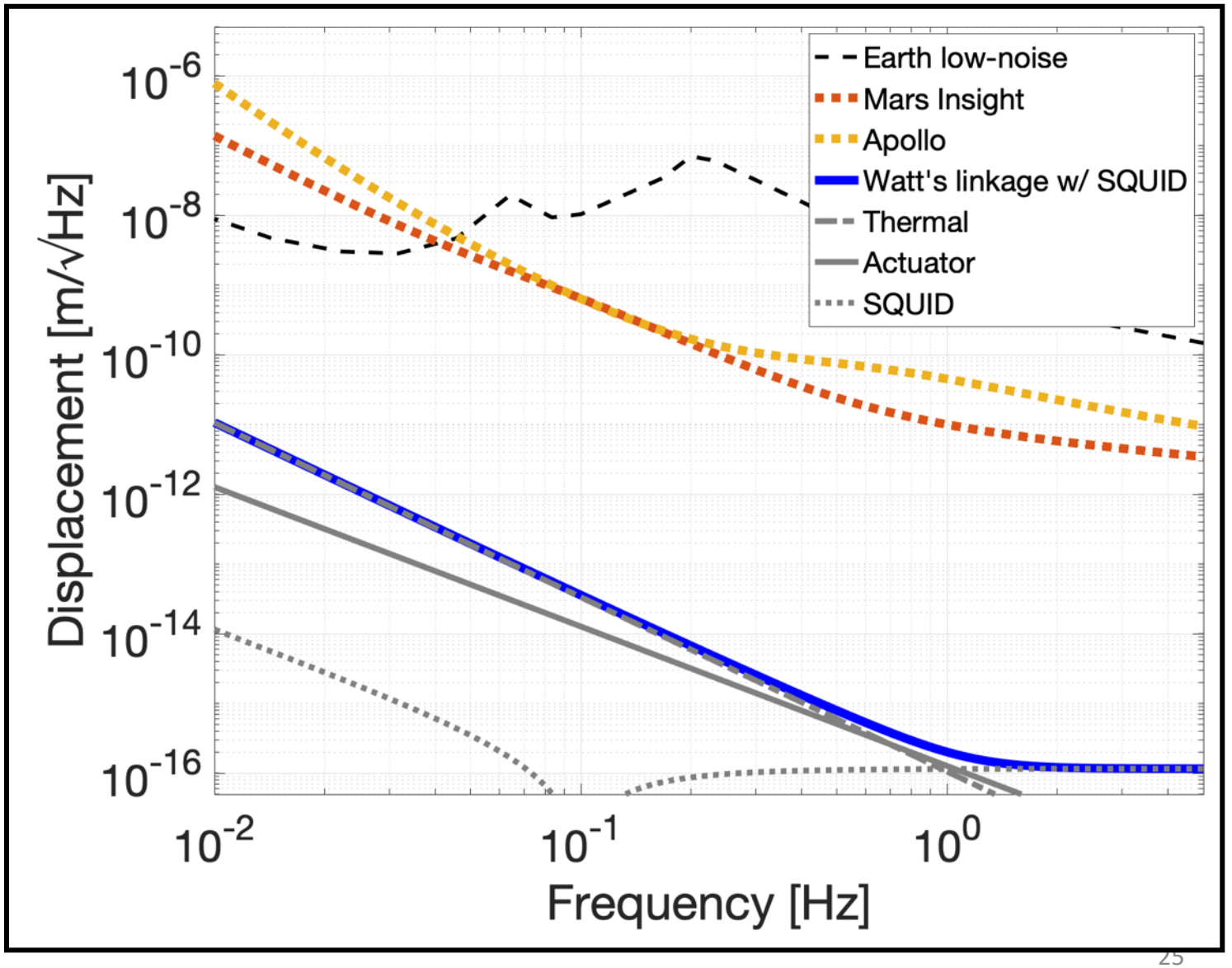
Using superconductivity in the readout: a SQUID





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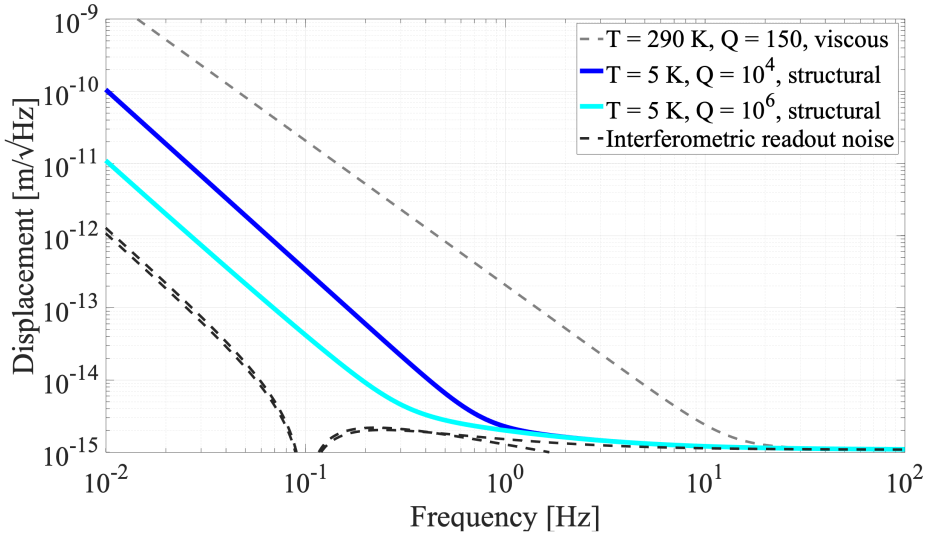
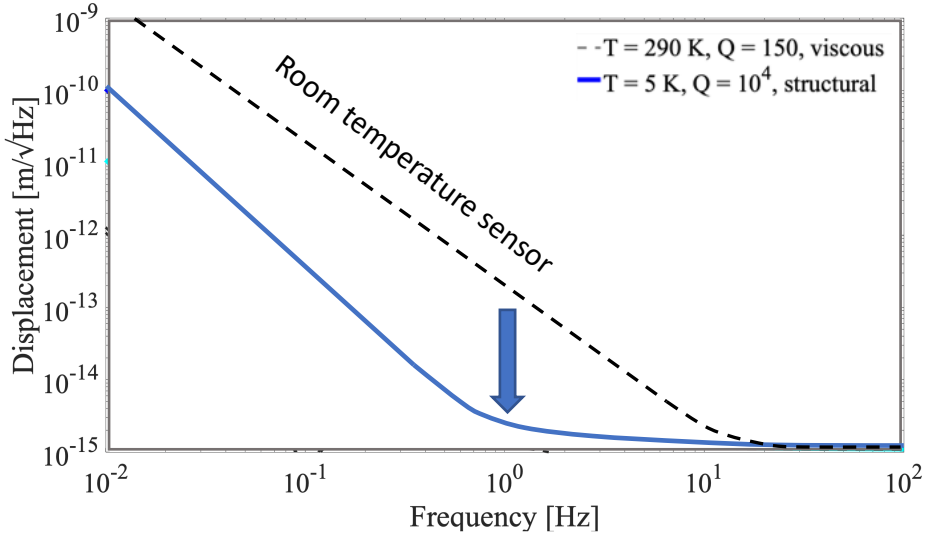

T = 290 K, Q = 150, viscous
T = 5 K, Q = 10^4, structural
T = 5 K, Q = 10^6, structural
Interferometric readout noise
Displacement [m/√Hz]
Frequency [Hz]


T = 290 K, Q = 150, viscous
T = 5 K, Q = 10^4, structural
Room temperature sensor
Displacement [m/√Hz]
Frequency [Hz]