A Cryogenic LIGO Mirror for 3rd Generation Gravitational Wave Observatories

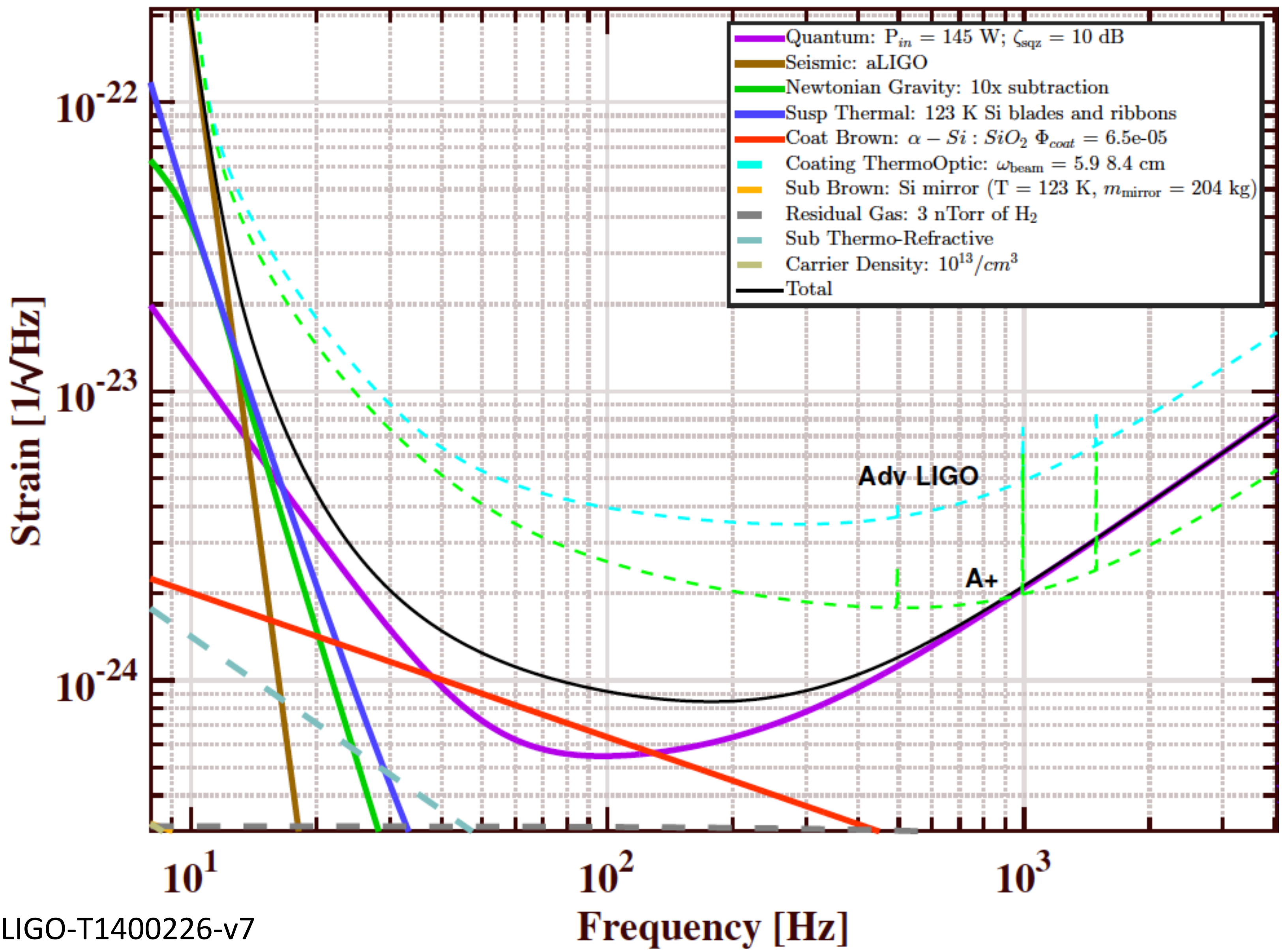
Brett Shapiro,
Stanford University

* Travel supported by the APS-SBF Brazil-U.S. physics PhD student & post-doc visitation program

Talk Summary

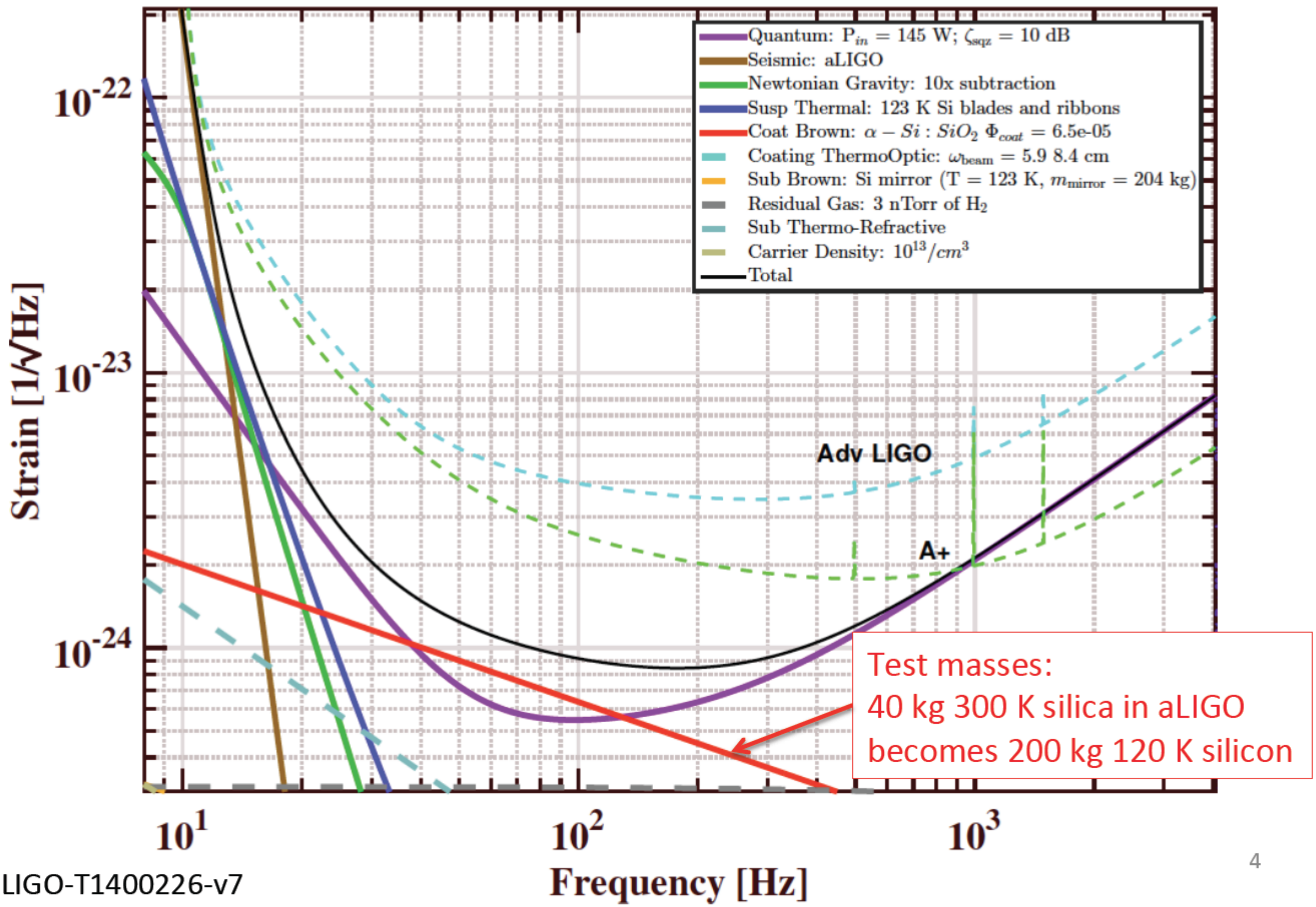
- How cryogenics can help us
- Summary of cryogenics research going on
- Stanford cryogenic test mass work
- Early experimental results from Stanford

LIGO Voyager baseline noise model



from LIGO-T1400226-v7

LIGO Voyager baseline noise model



from LIGO-T1400226-v7

Why Cryogenic Si for Test Masses?

- Lower temperature -> lower thermal noise
- Silicon has **low mechanical loss** at cold temperatures, further lowering the thermal noise off-resonance
- **Thermal expansion goes to 0** at 124 K, eliminating thermoelastic noise and reducing thermal lensing
- Silicon has **high thermal conductivity** at low temperatures, reducing thermal lensing, permitting higher laser powers (lower shot noise)

Cryo work distribution

- Caltech - direct thermal noise measurements; procuring large silicon masses
- Jena/Glasgow/Moscow - mechanical loss
- KAGRA – 20 K sapphire suspensions
- Glasgow – silicon and sapphire test mass suspensions; coatings; absorption
- INPE Brazil – cryogenic multi-nested pendulum
- Stanford – optical coatings (Riccardo Bassiri's talk); cryogenic technology

Adapted from Nicolas Smith-Lefebvre

Magnetic Czochralski for 200 kg Si test masses

- Normally all the ingots produced are processed into wafers

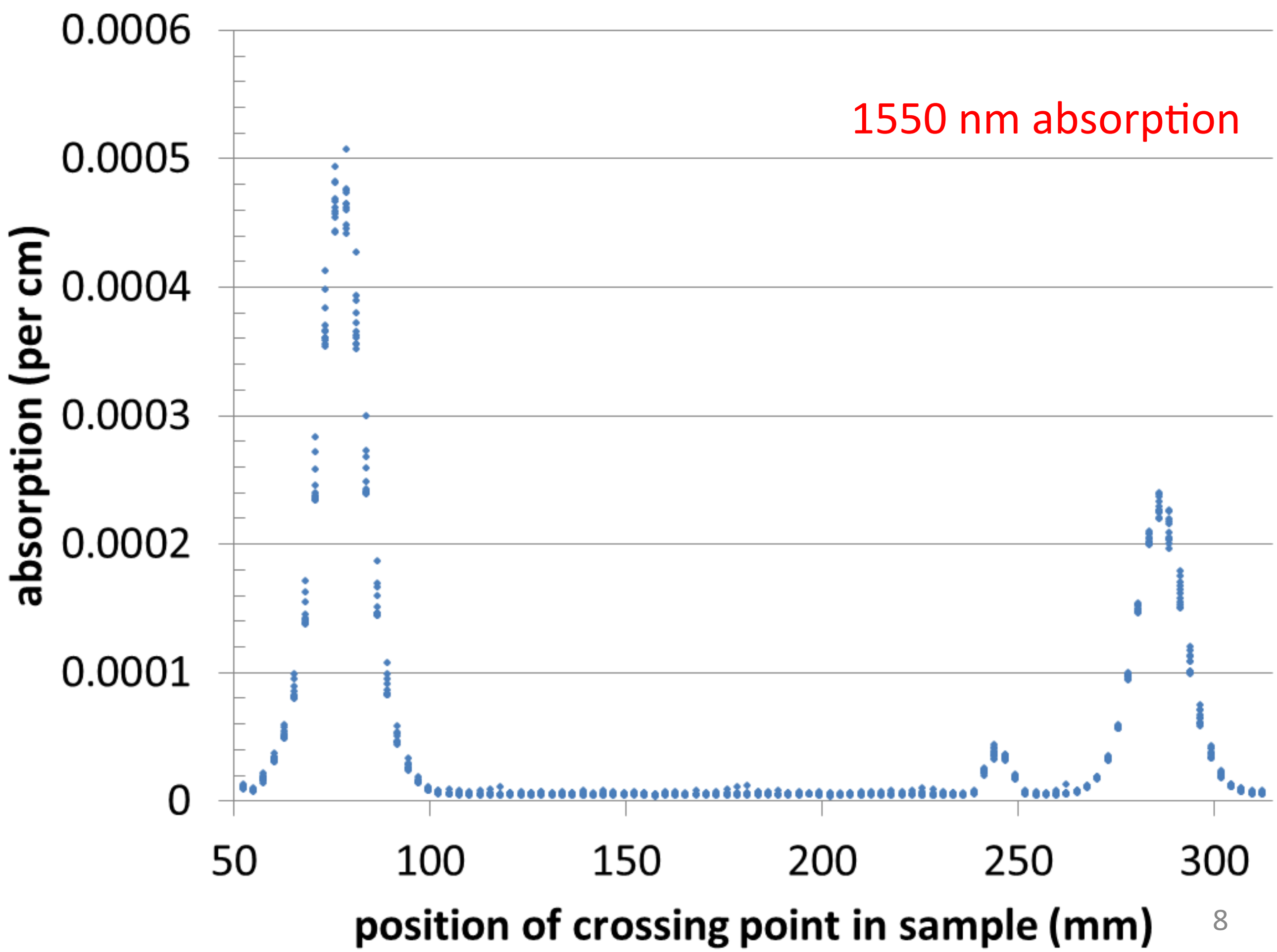
- We are procuring “slugs” to determine properties of interest to us
- 20 cm diameter by 1 cm

From G1600539

- Rana A & Eric G with 300 mm ingot at Shin-Etsu, WA

Silicon absorption measurements

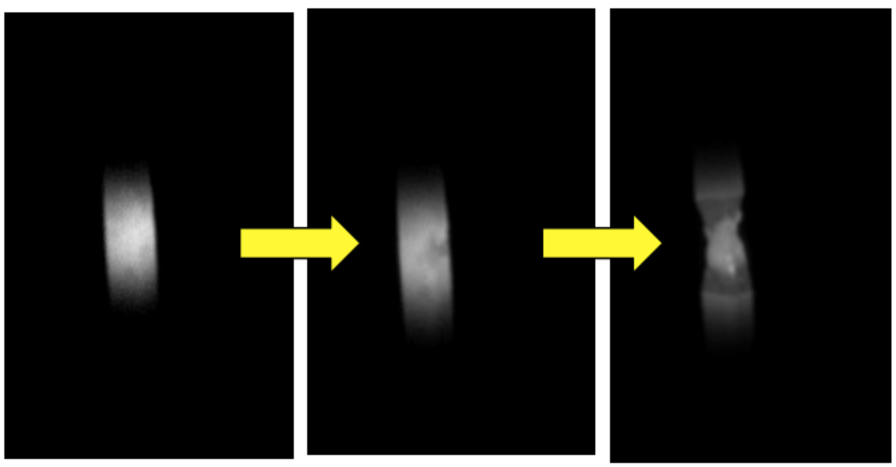
- Ingots polished with diamond slurry and pitch lap
- Consistently gives ~0.1% absorption at the surface
- Polishers uses it as it more easily gives good flatness over 4” diameter



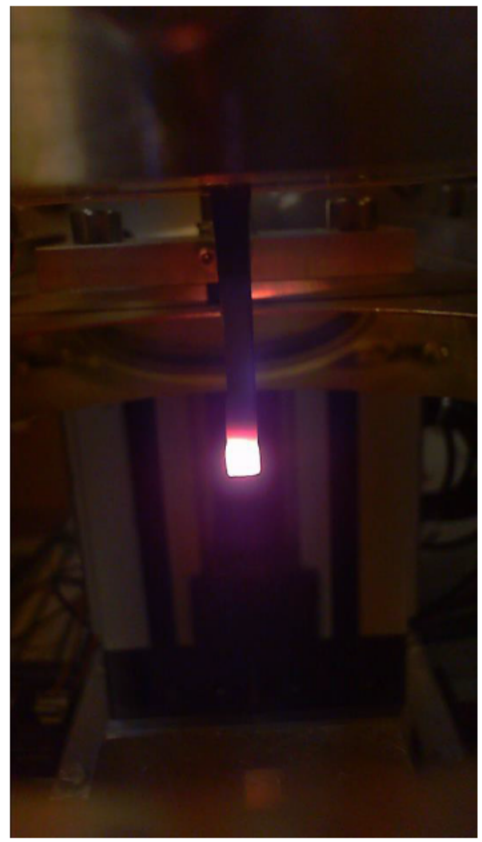
From G1600538

Crystalline suspension fiber development

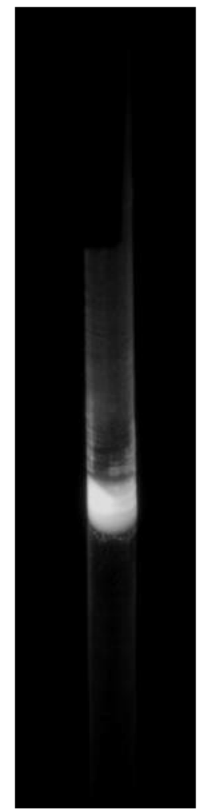
- We now have a SYNRAD 10.6um (400W laser for silicon growth/silica puller) and 1064 nm (100W) as heat sources for melting silicon/sapphire
- Low viscosity, requirement of long term stability (low growth speed) and emissivity variation (for silicon) are areas of ongoing research



Silicon heating at 10.6 um



Silicon

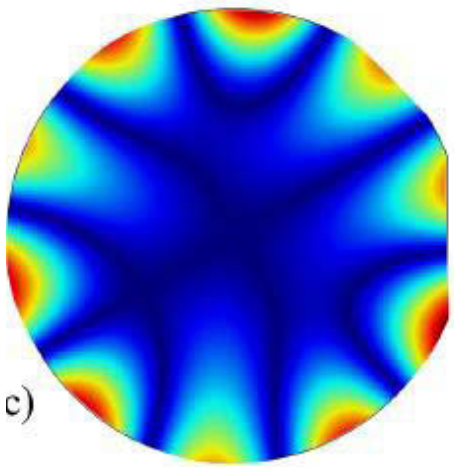


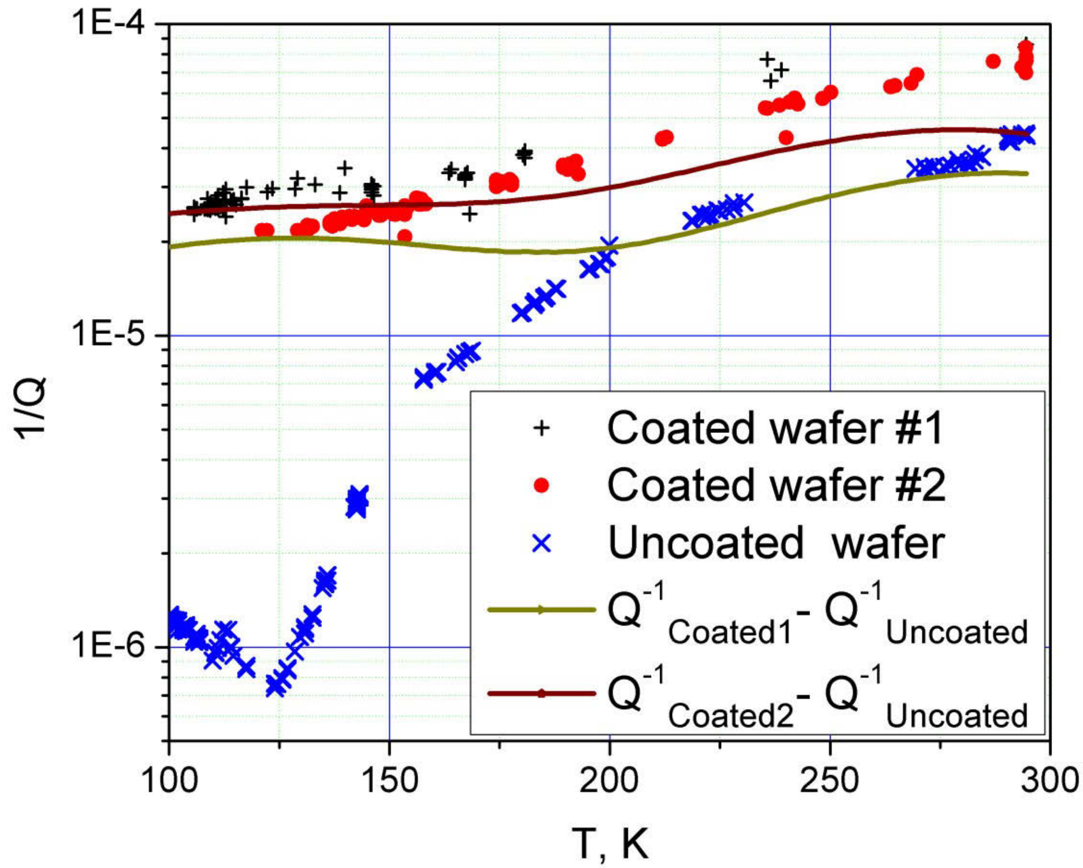
Molten sapphire

From G1600467

Mechanical losses of coated and uncoated Si oscillators

For the detail investigation we choose the relatively high-Q mode with frequency of 3528 Hz. This mode has five nodal diameters distorted by presence of the flats.





From G1500466

KAGRA Kamioka site

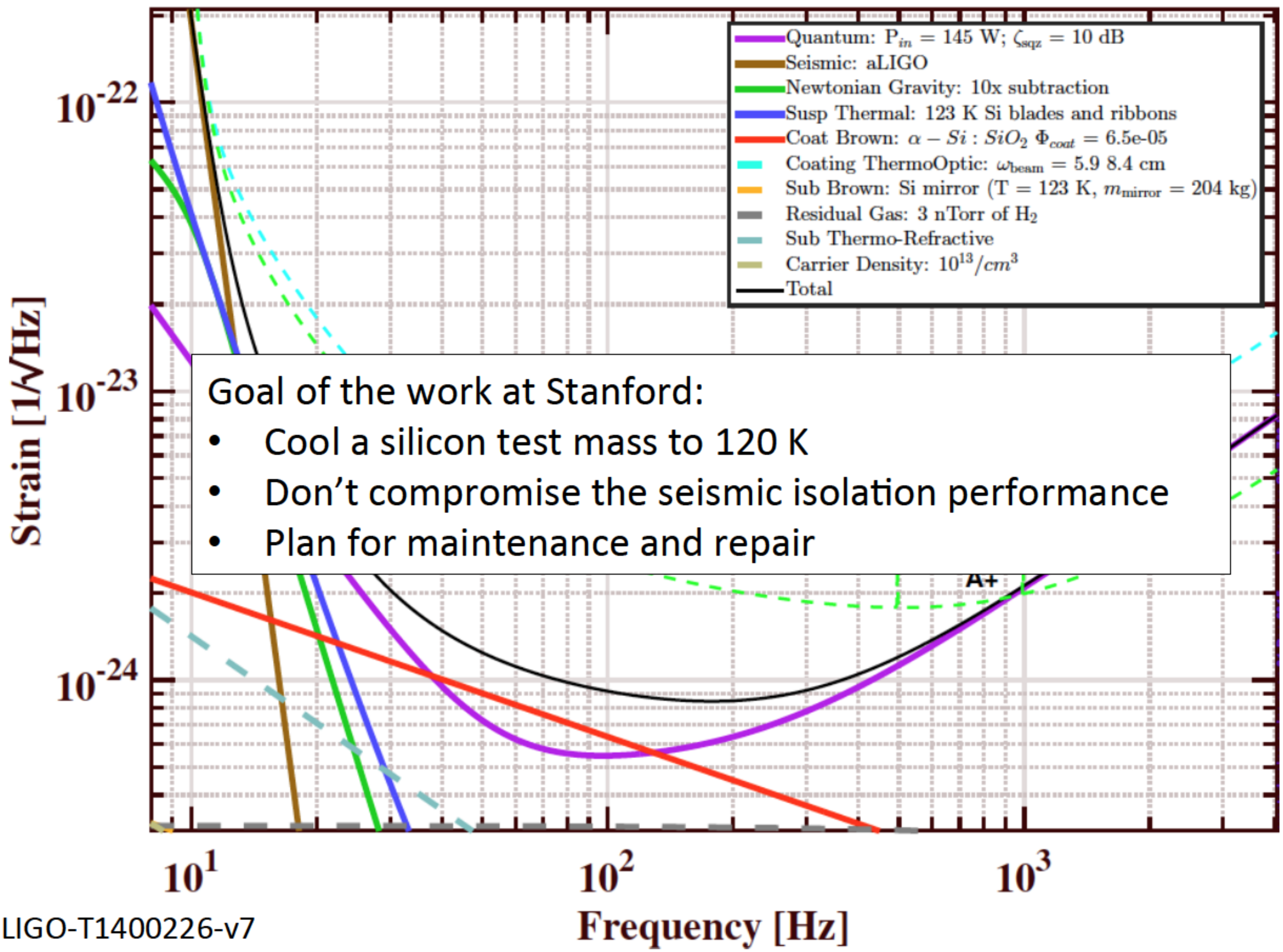
Cryogenic operations planned for March 2018

20 K, 23 kg sapphire test masses

From G1600682

GWINPE – Multi-Nested-Pendulum

A model of the noise performance of LIGO Voyager

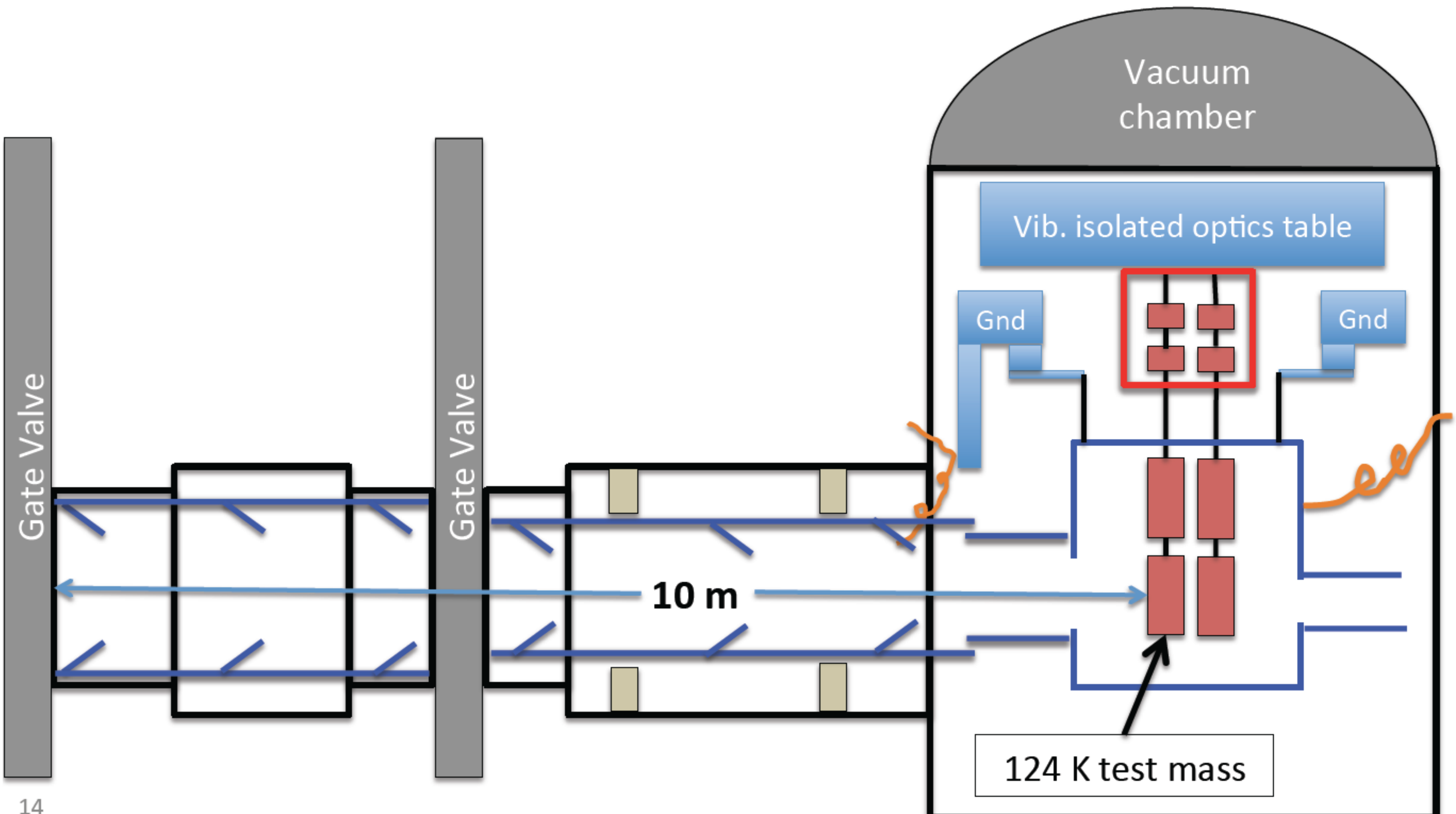


Goal of the work at Stanford:

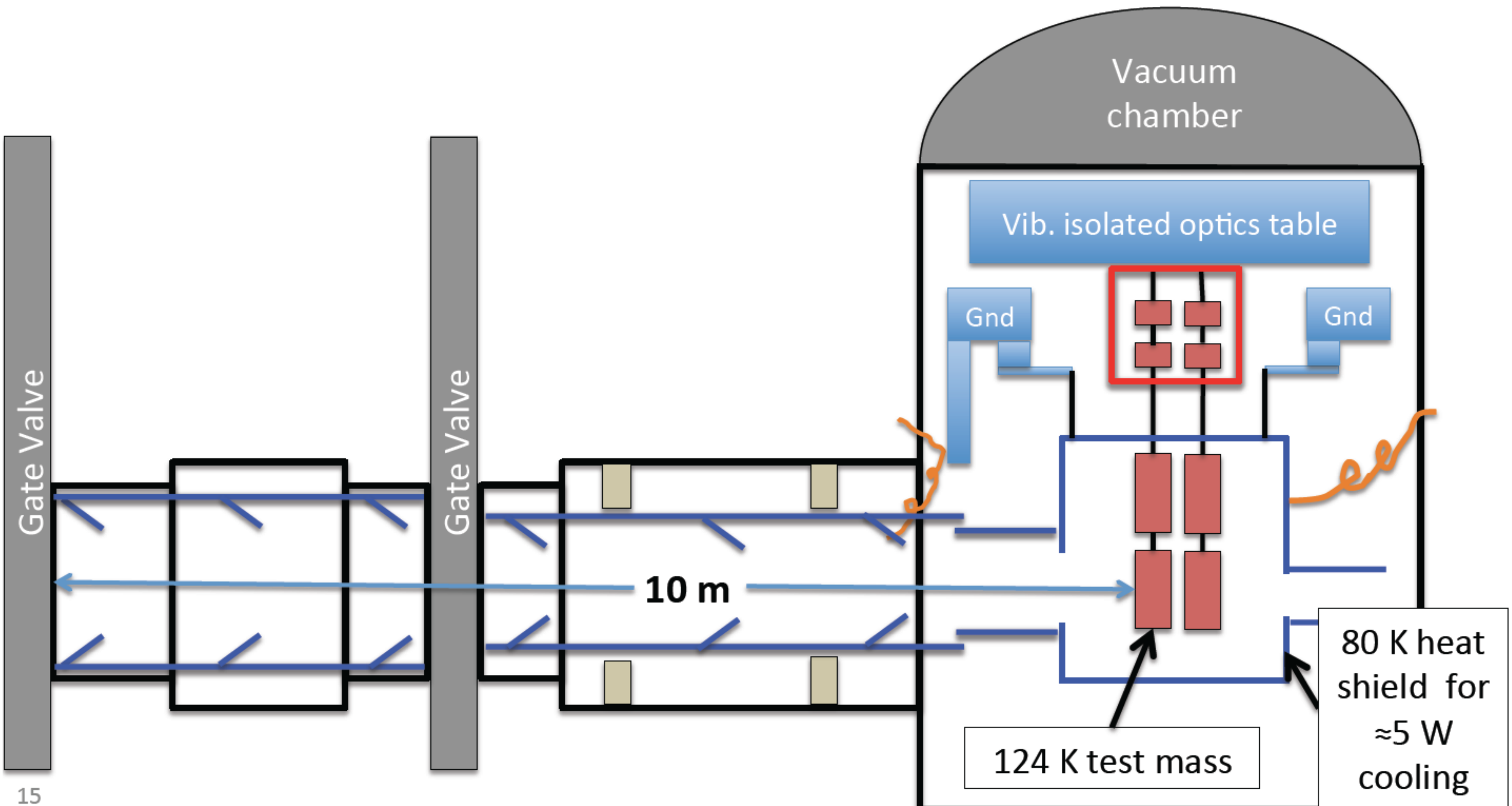
- Cool a silicon test mass to 120 K
- Don't compromise the seismic isolation performance
- Plan for maintenance and repair

from LIGO-T1400226-v7

Actively controlled shield (ETM)



Actively controlled shield (ETM)



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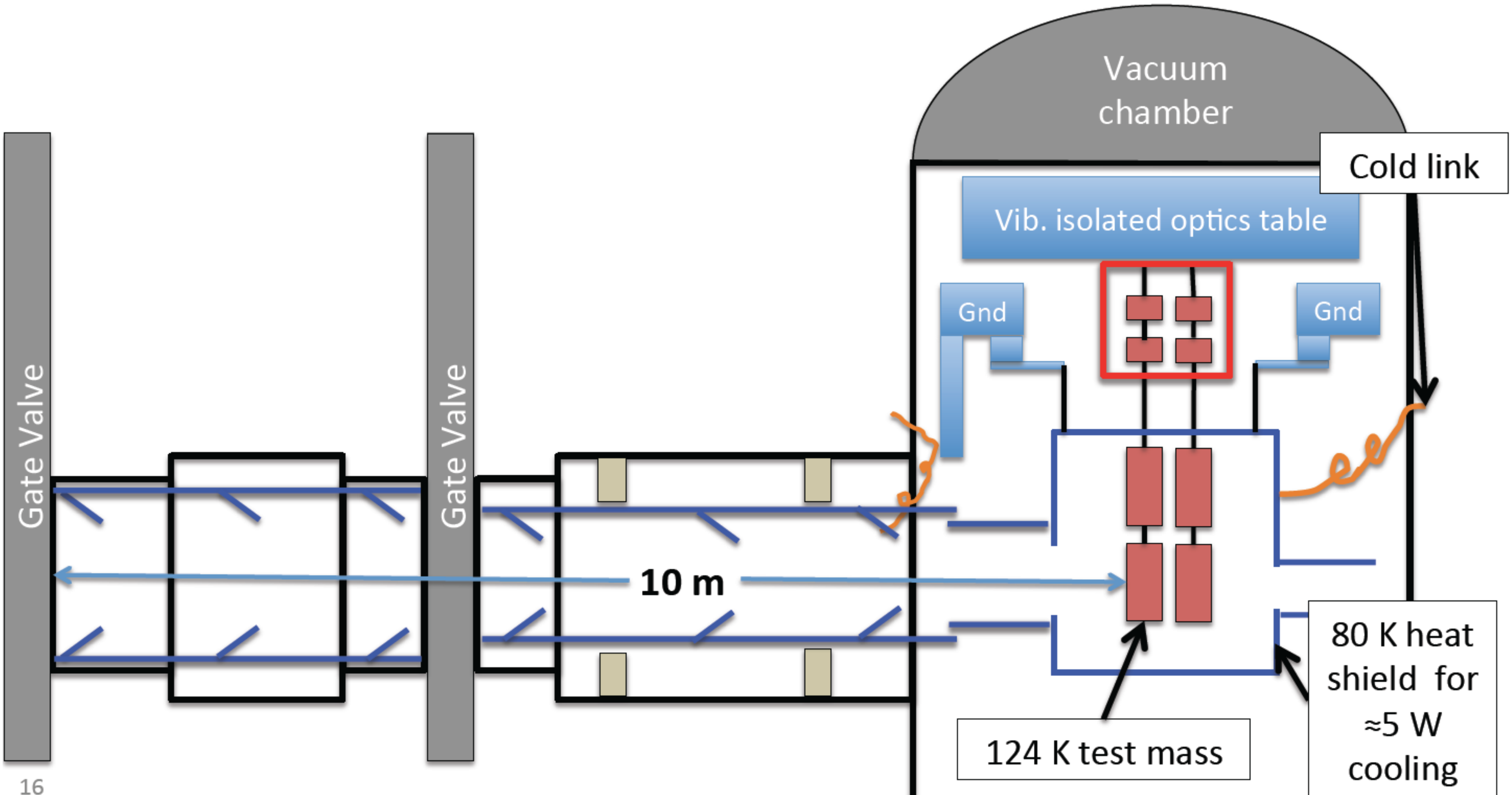

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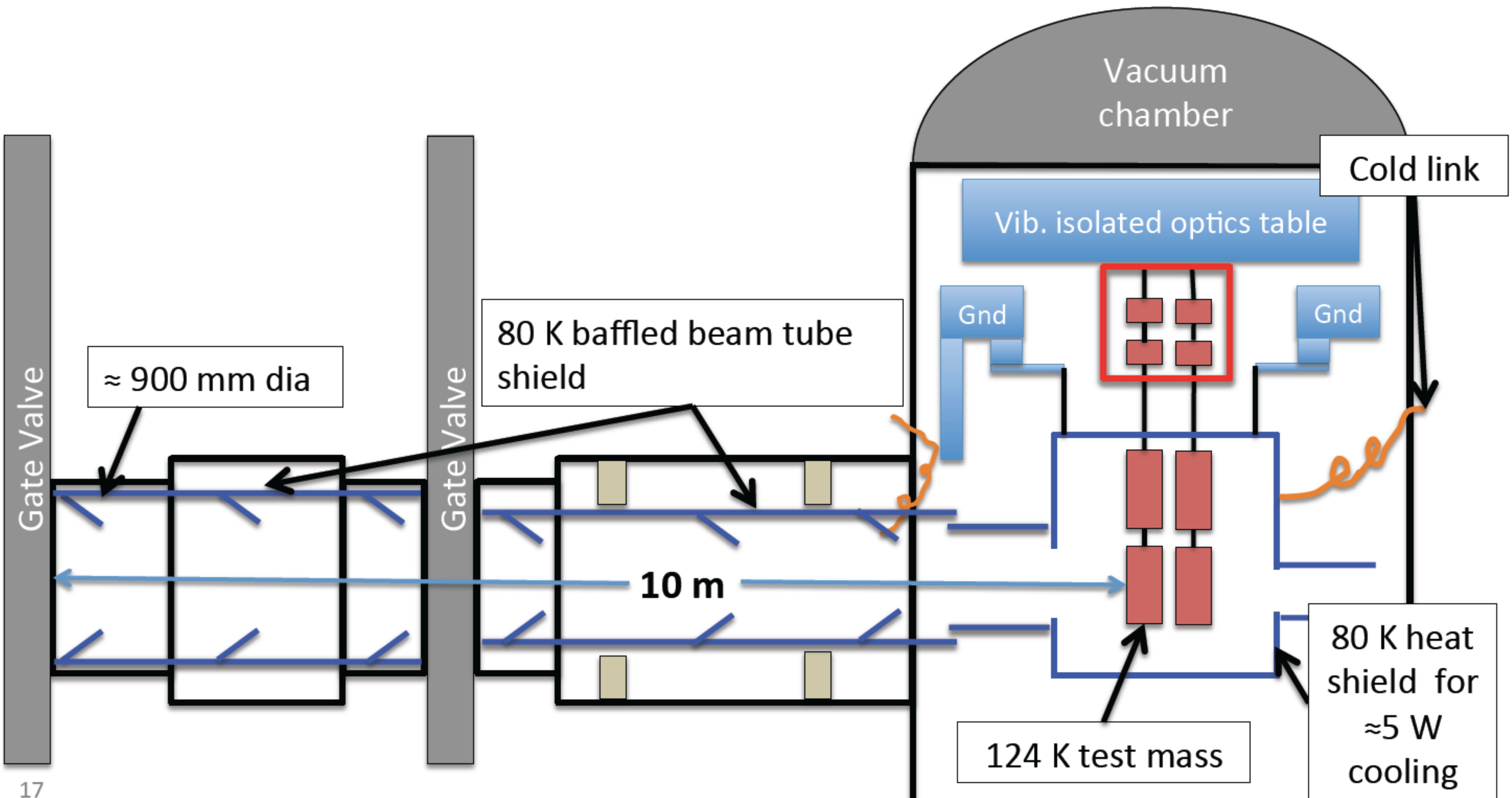

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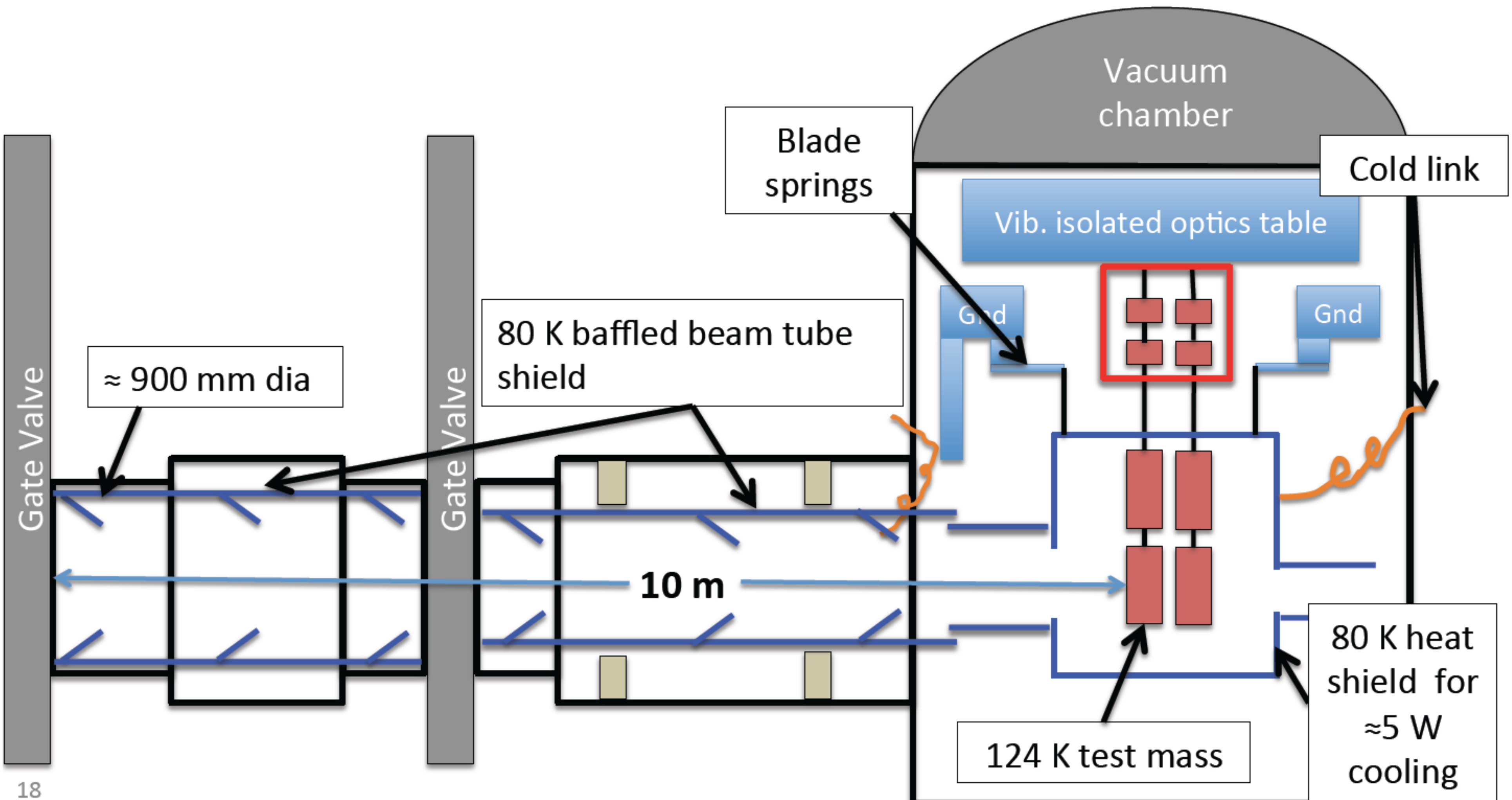
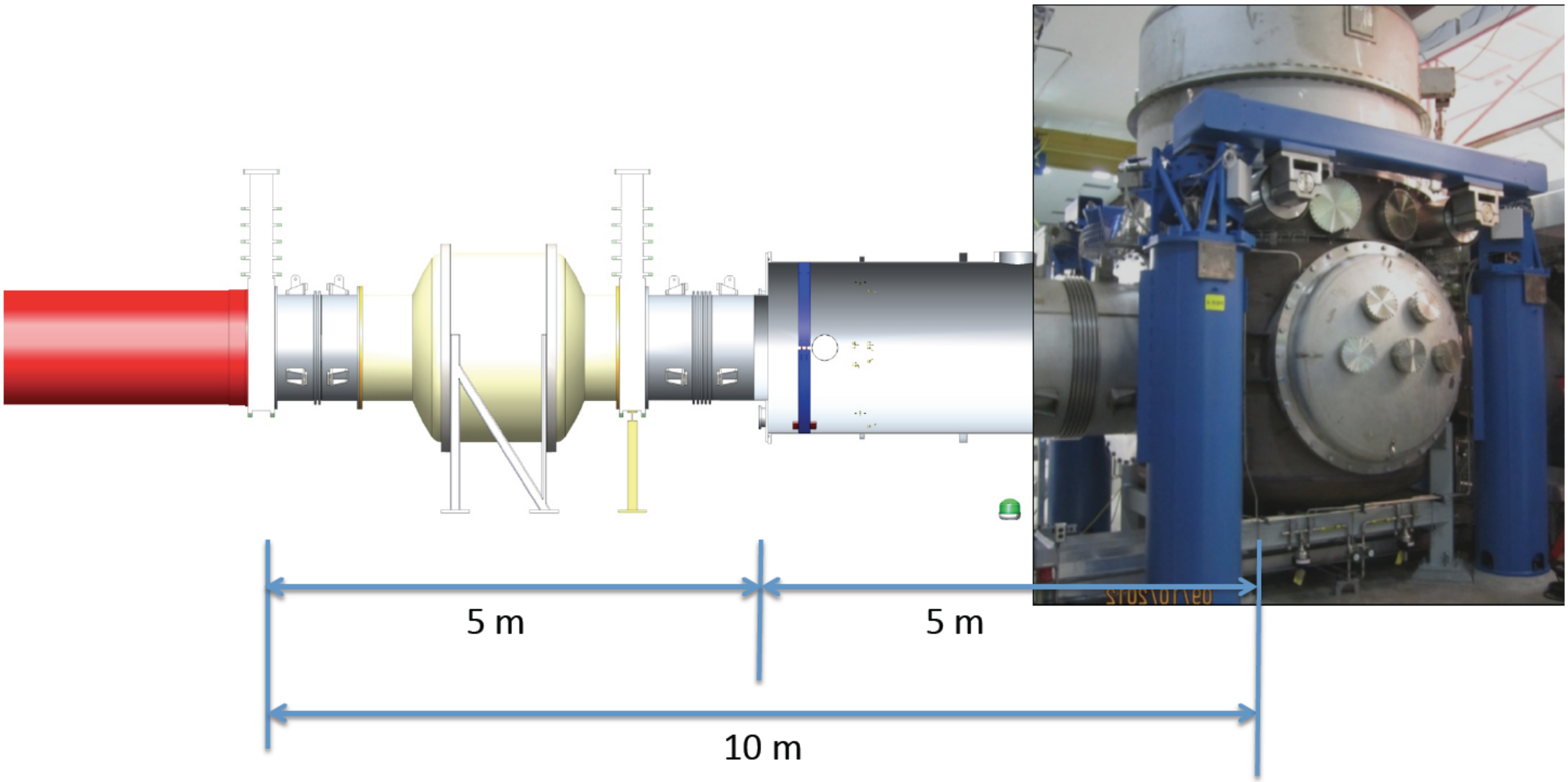
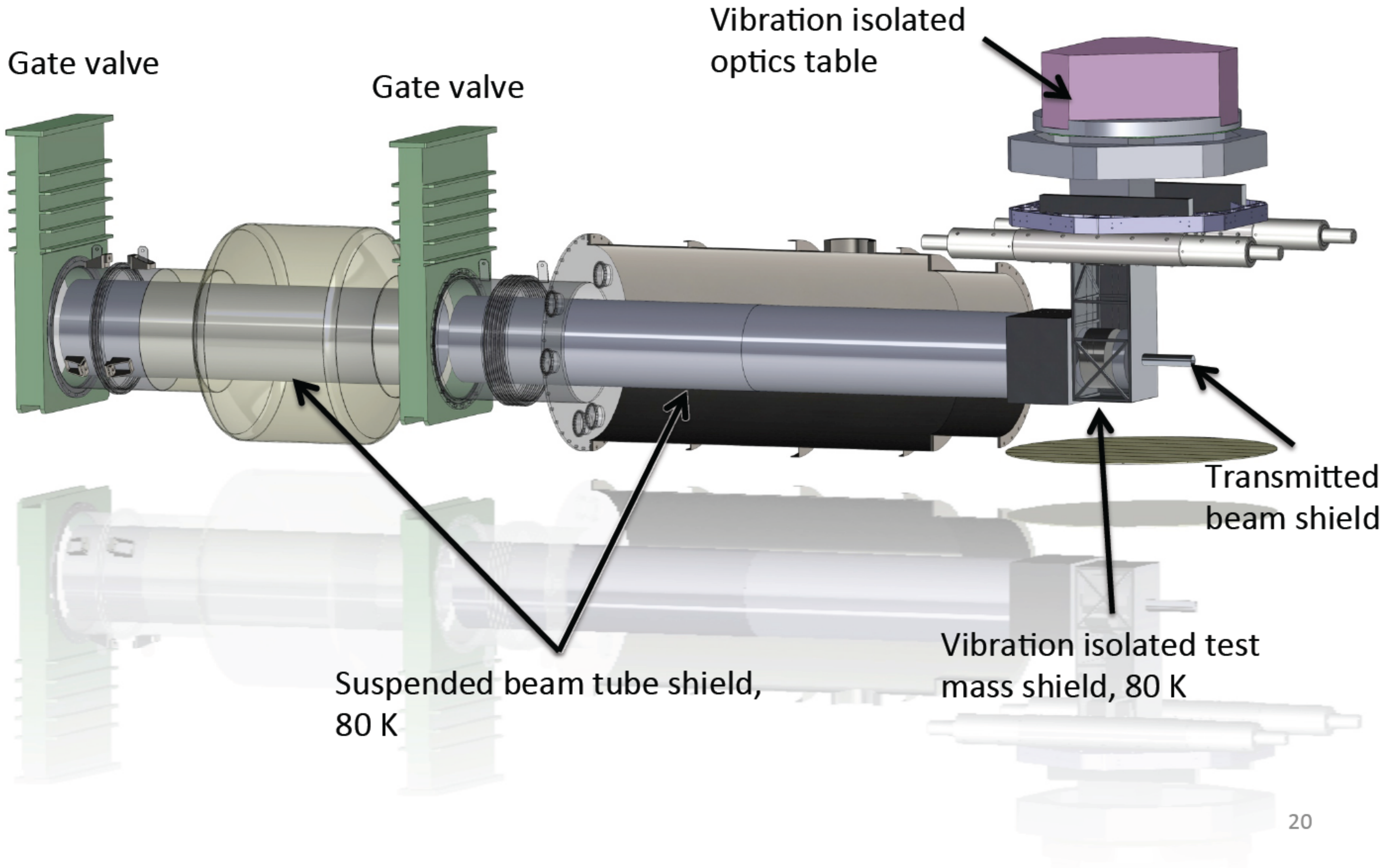
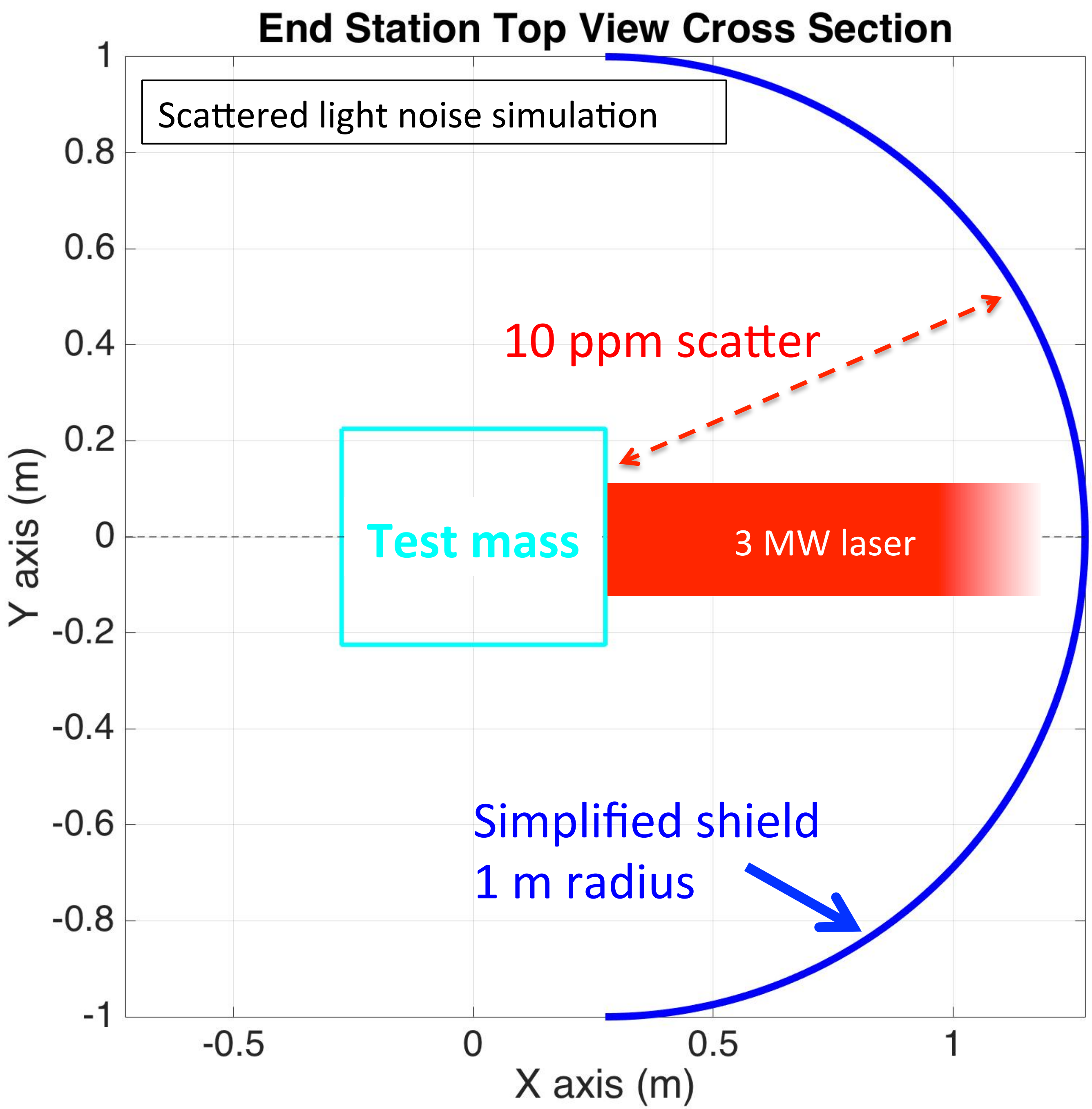


LIGO End Station Model

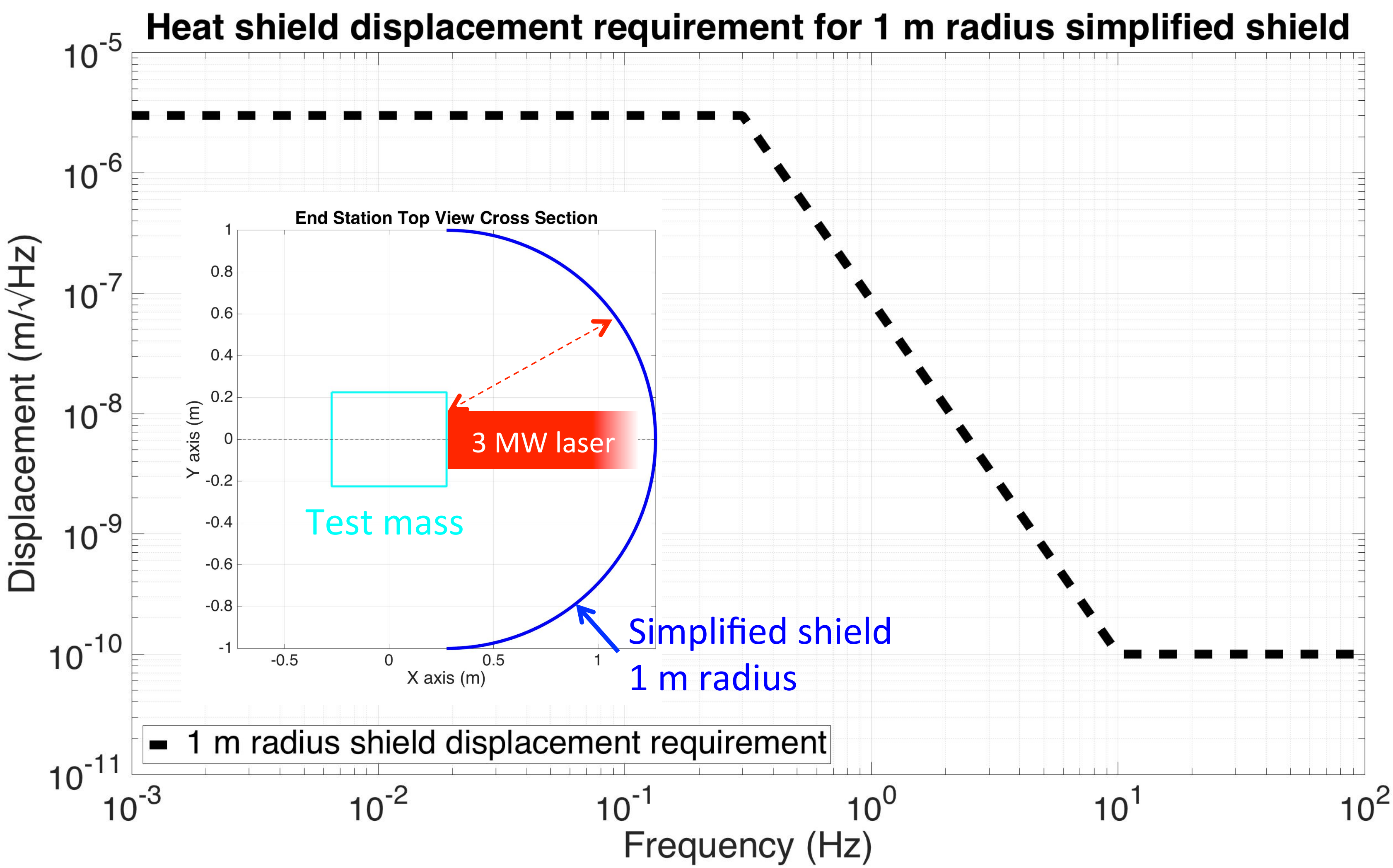


LIGO Voyager Conceptual Model

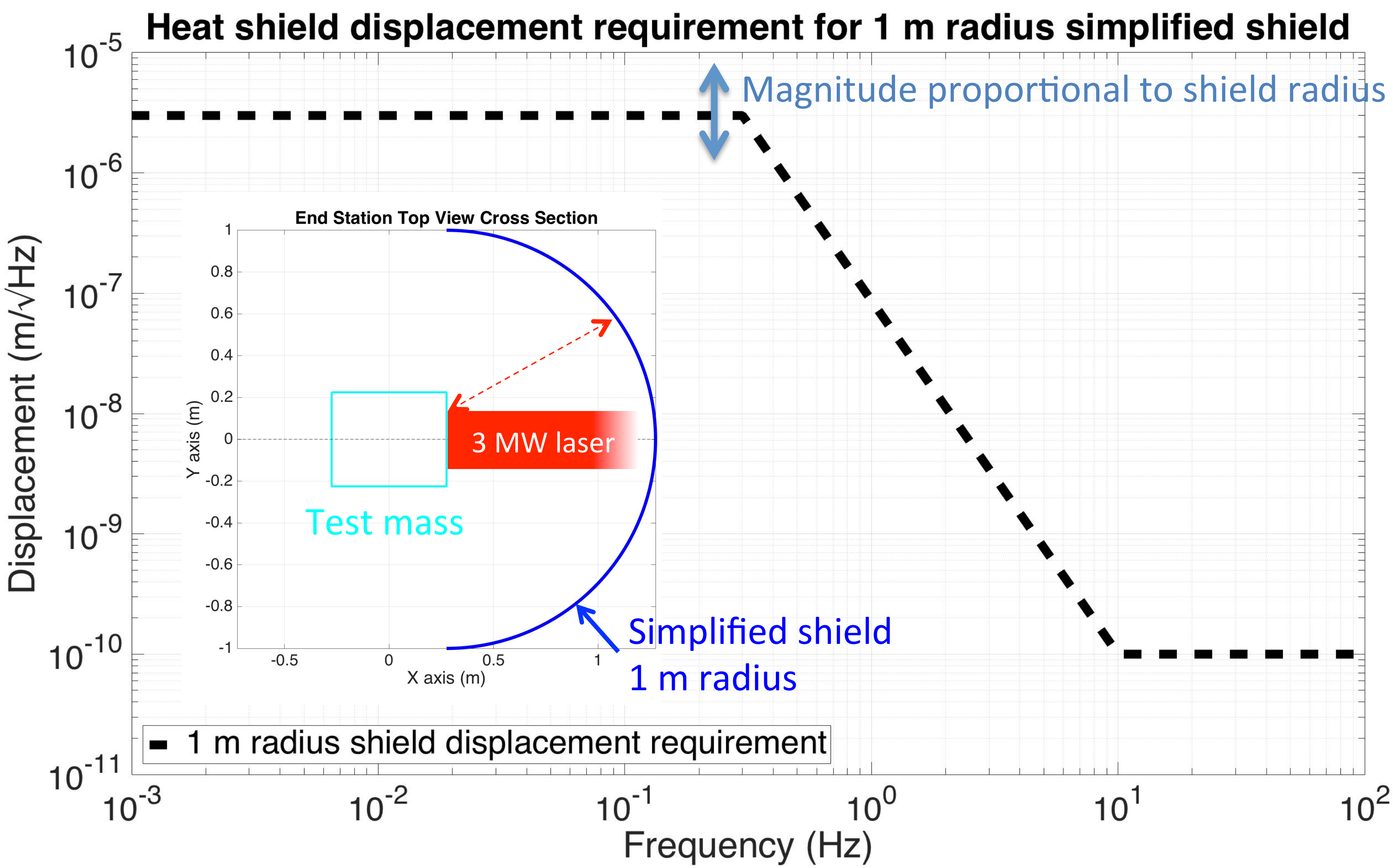



End Station Top View Cross Section
Scattered light noise simulation
10 ppm scatter
Test mass
3 MW laser
Simplified shield
1 m radius
Y axis (m)
X axis (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-0.5
0
0.5
1

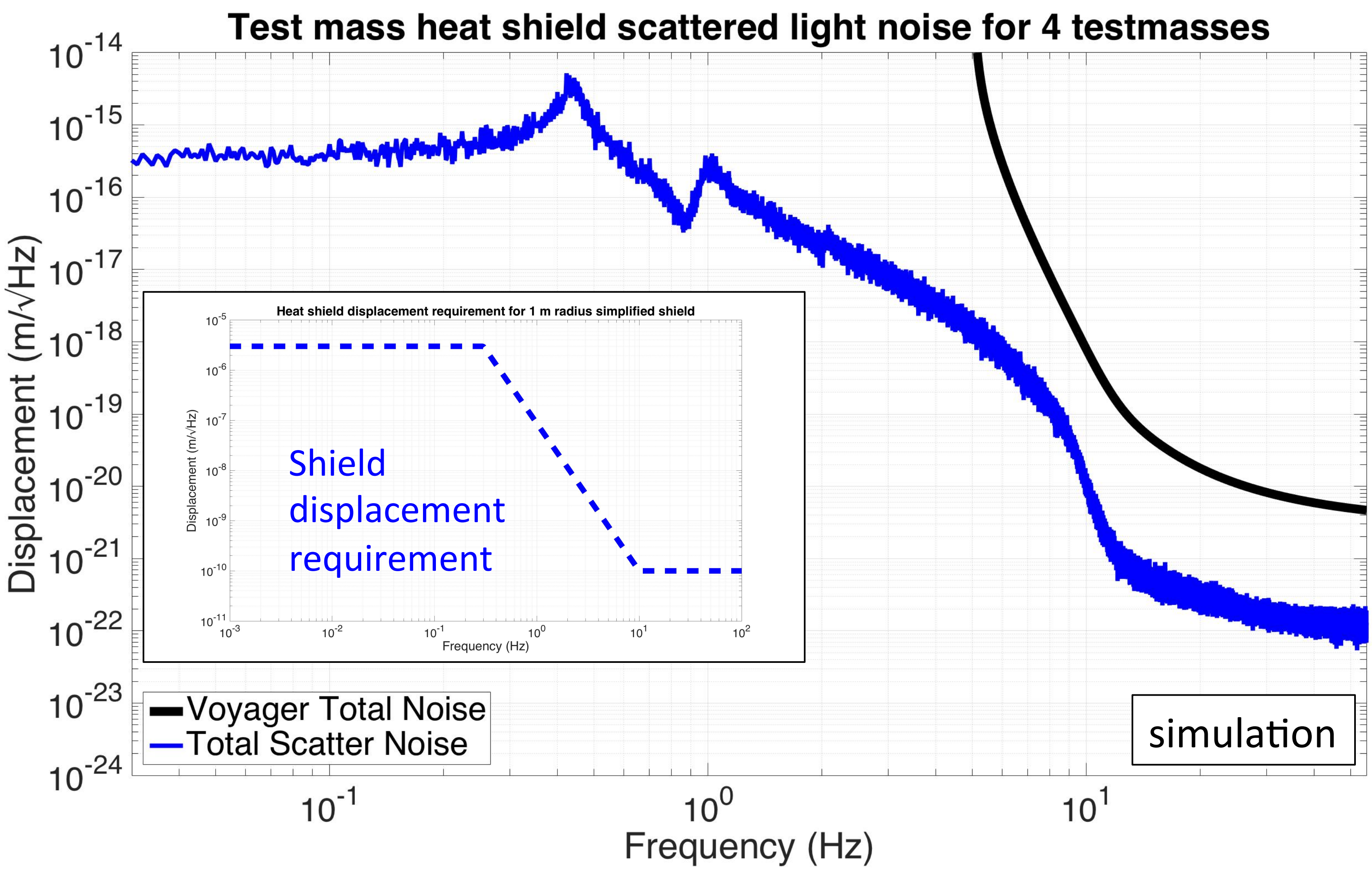
Scattered light noise simulation



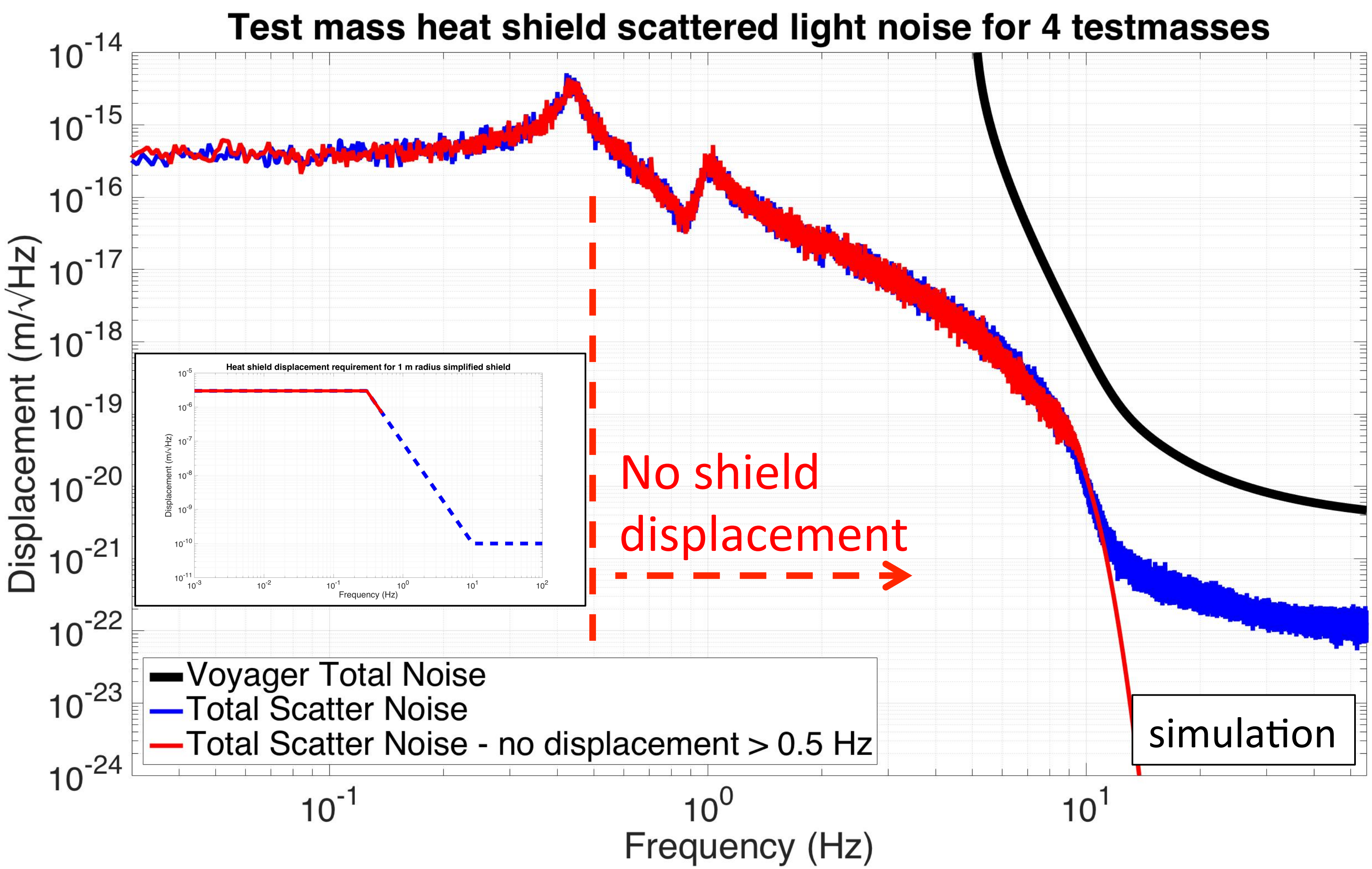
Scattered light noise simulation



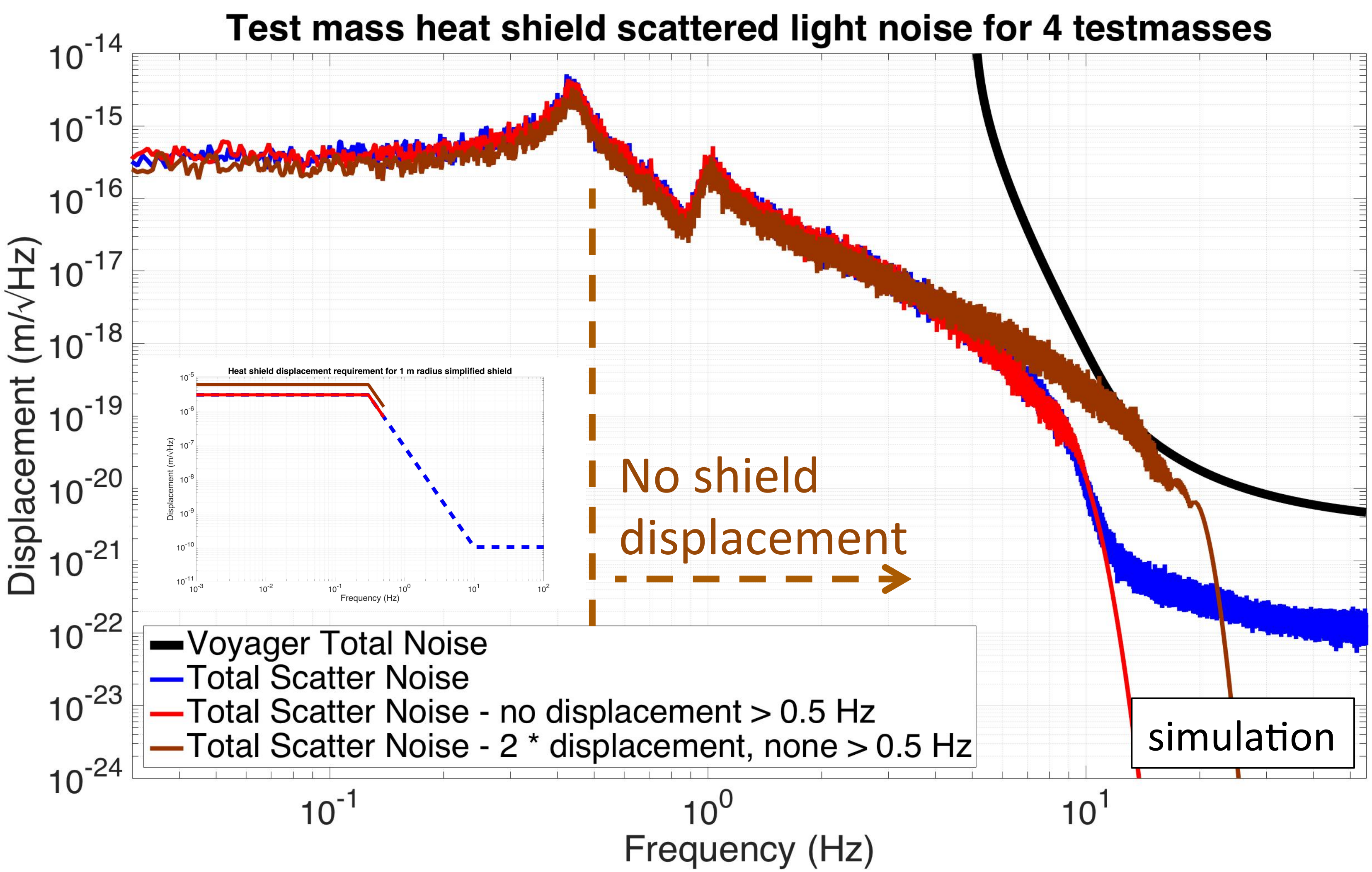
Scattered light noise simulation

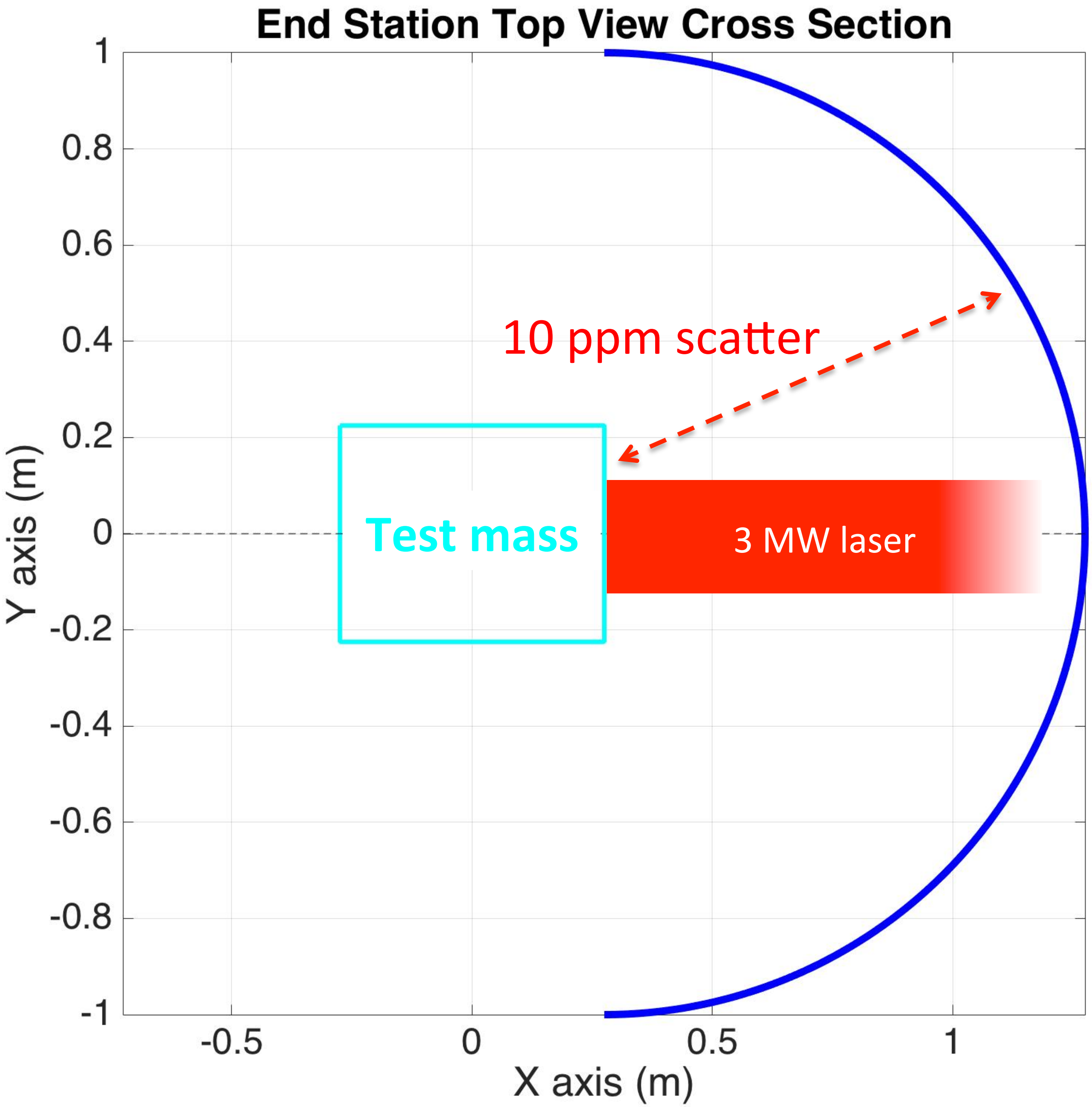


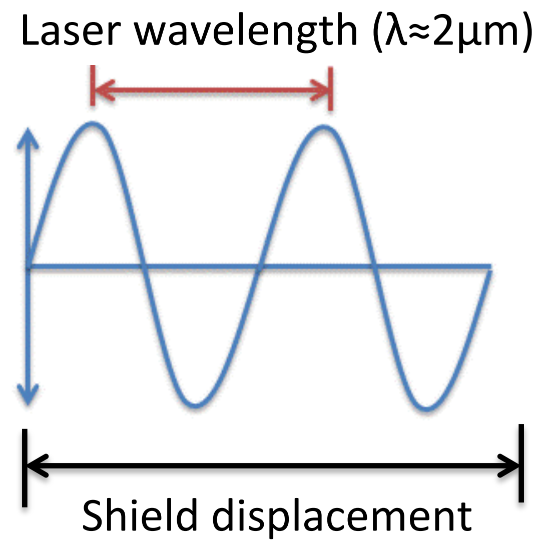
Scattered light noise simulation - upconversion



Scattered light noise simulation - upconversion

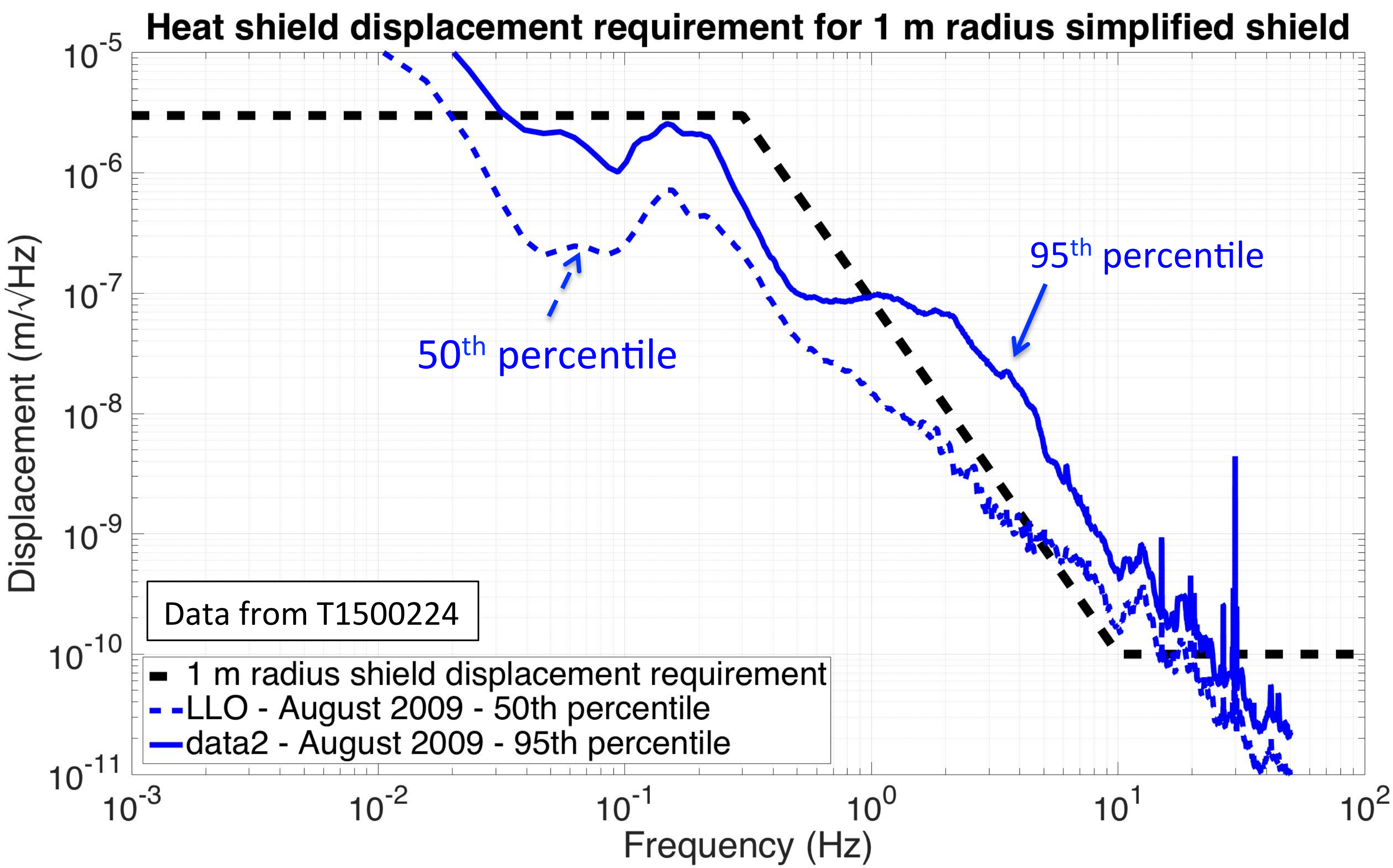




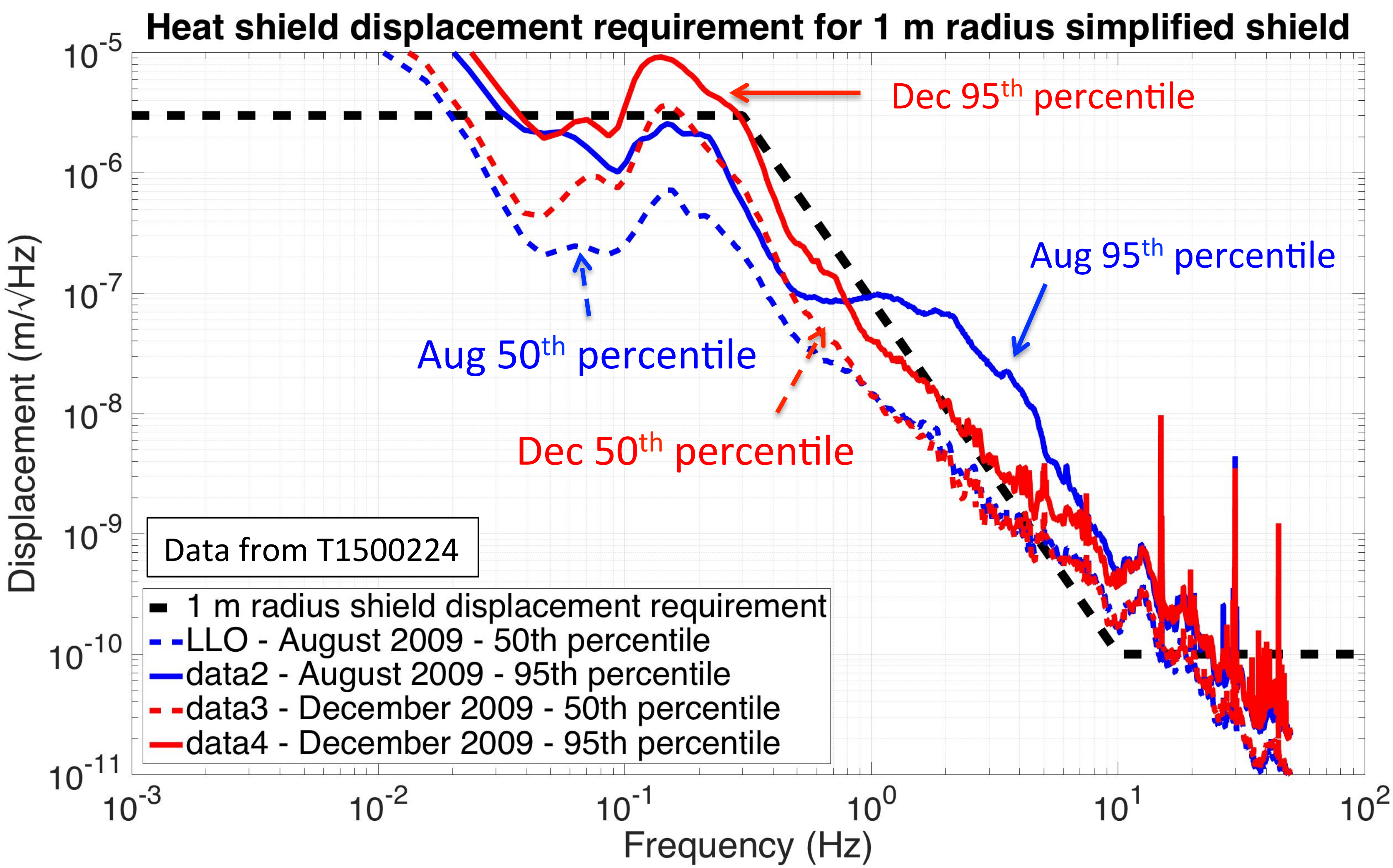


If the displacement is large compared to λ, the scattering upconverts to higher frequencies

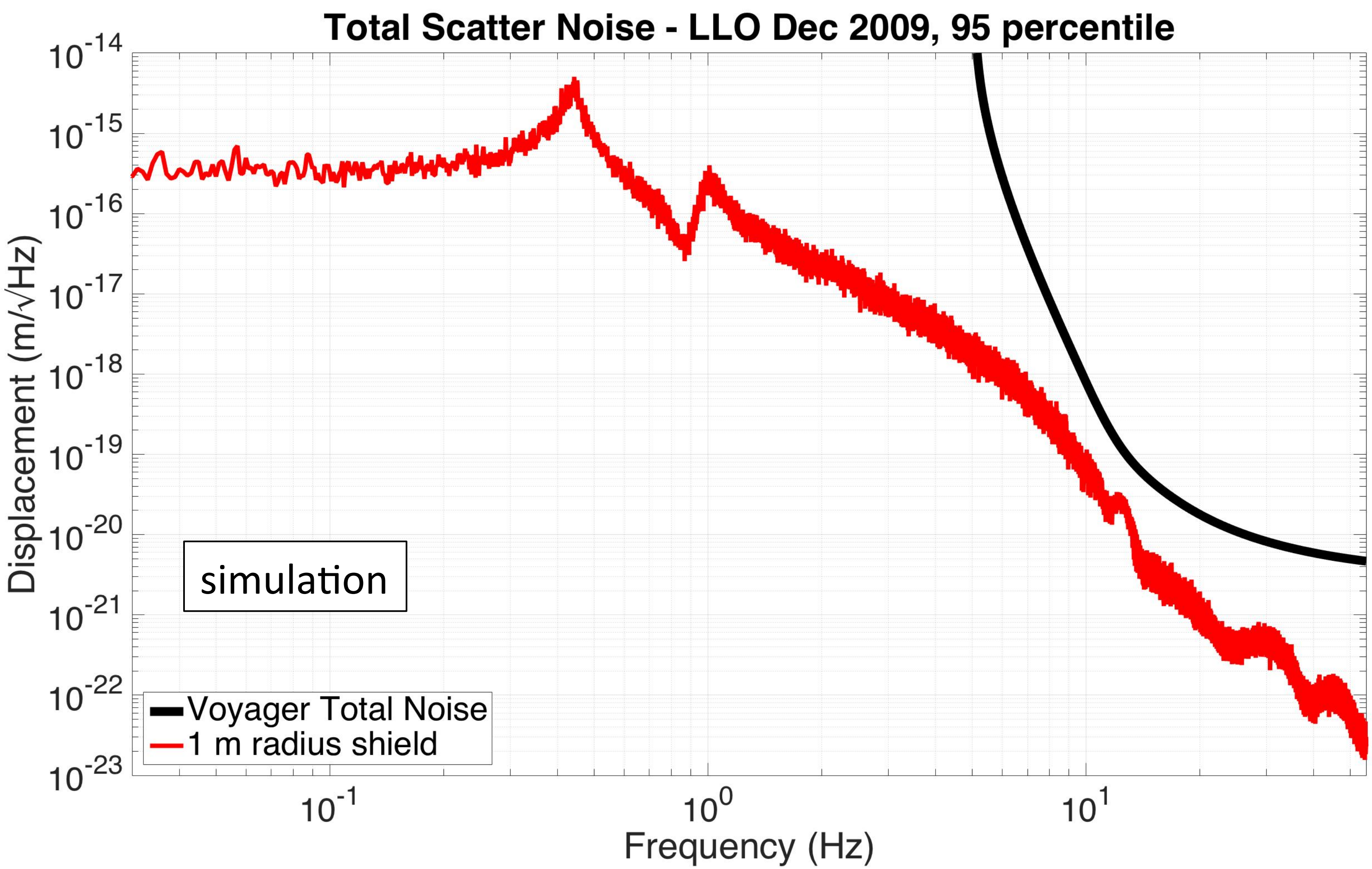
Livingston Ground Displacement August 2009



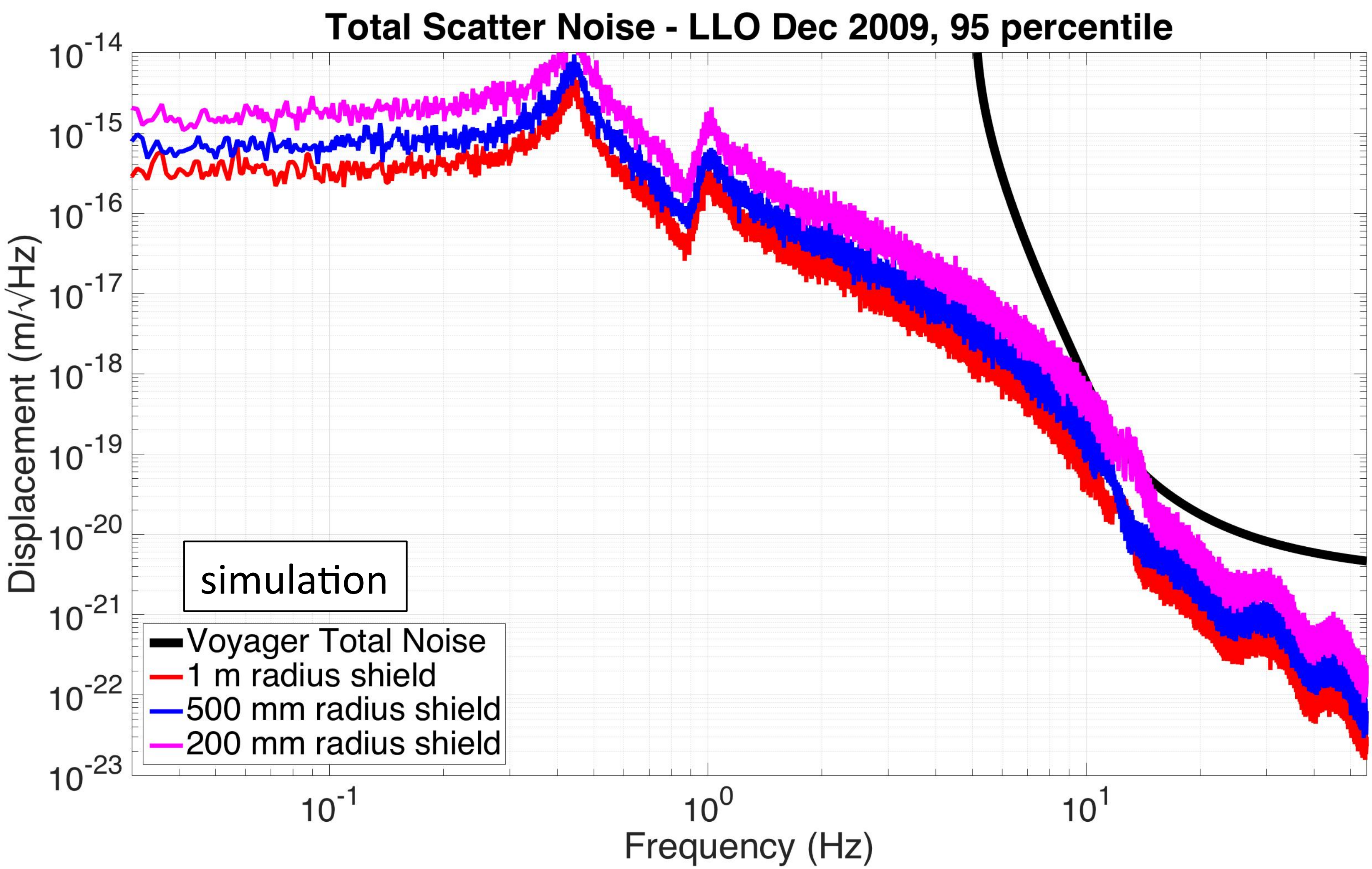
Livingston Ground Displacement August & December 2009



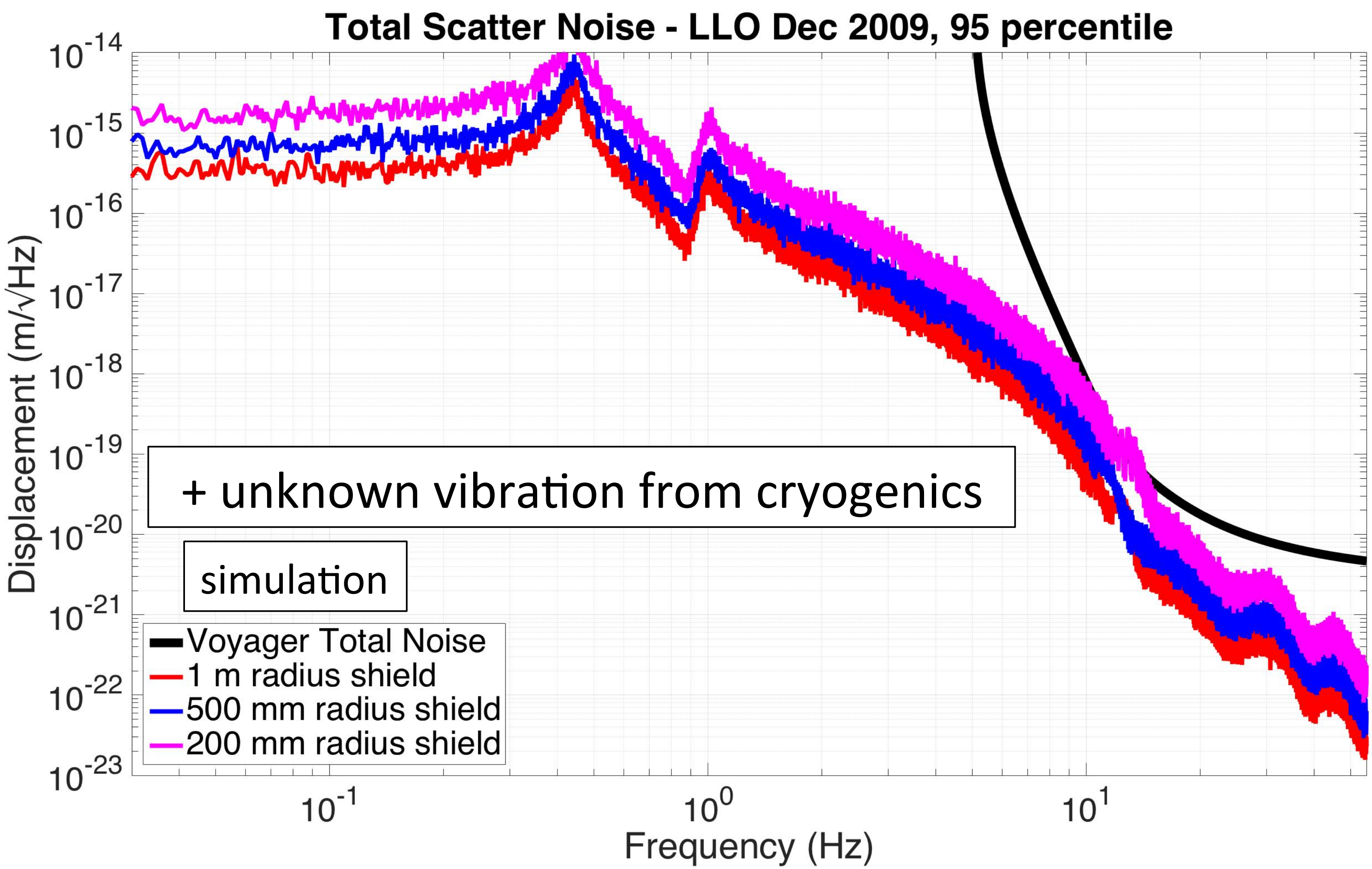
Noise with various shield sizes



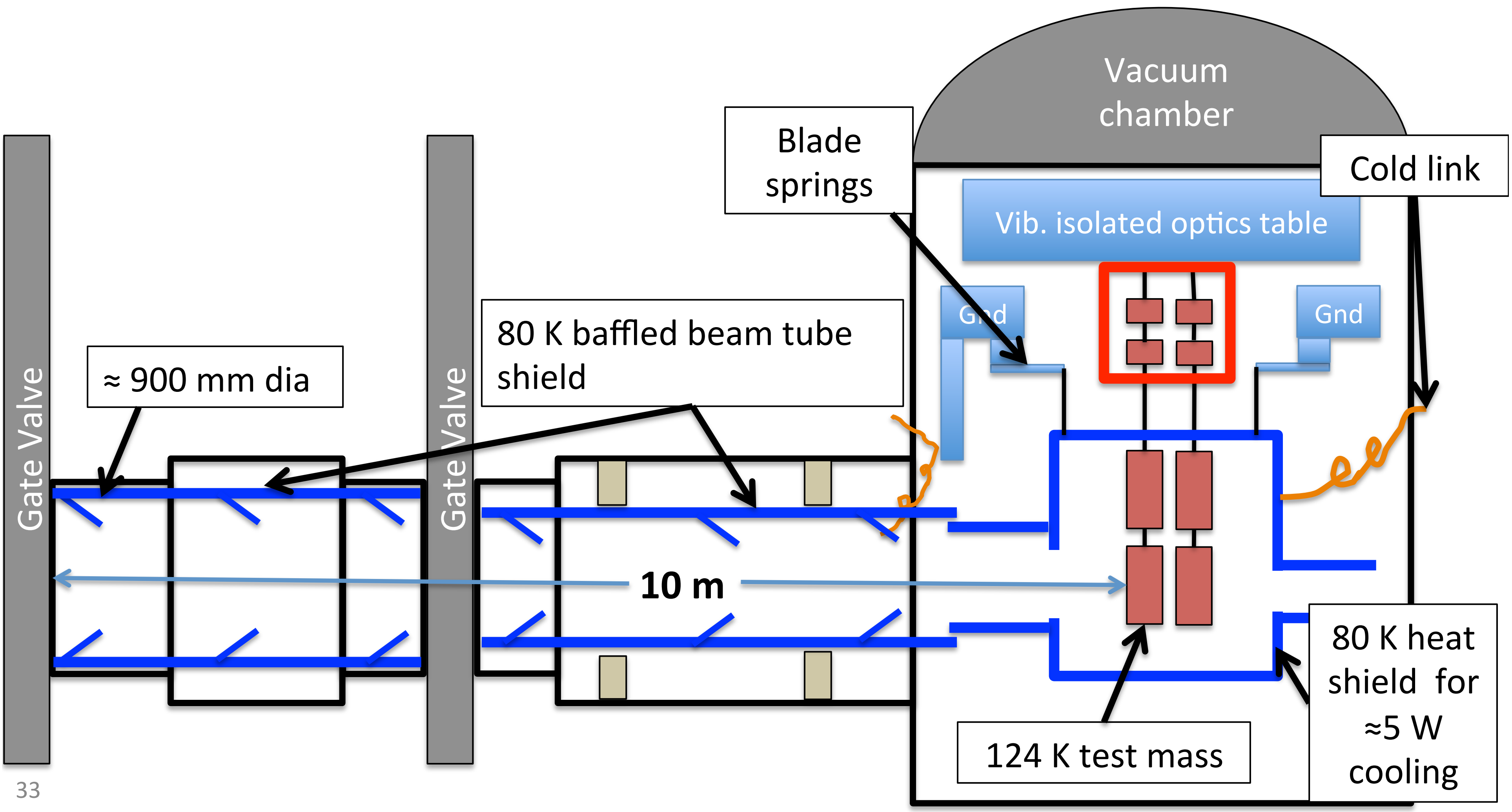
Noise with various shield sizes



Noise with various shield sizes



Actively controlled shield (ETM)



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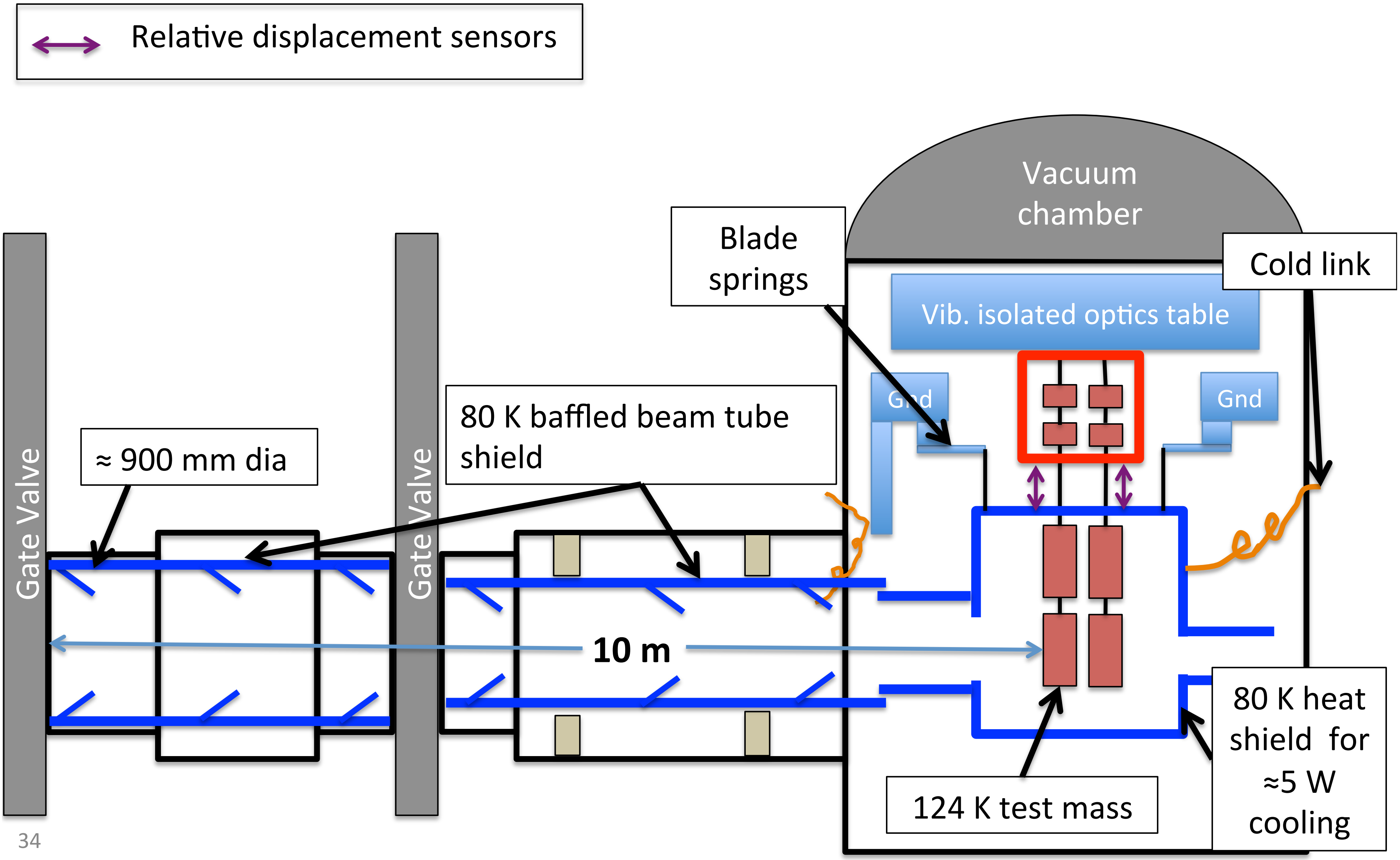

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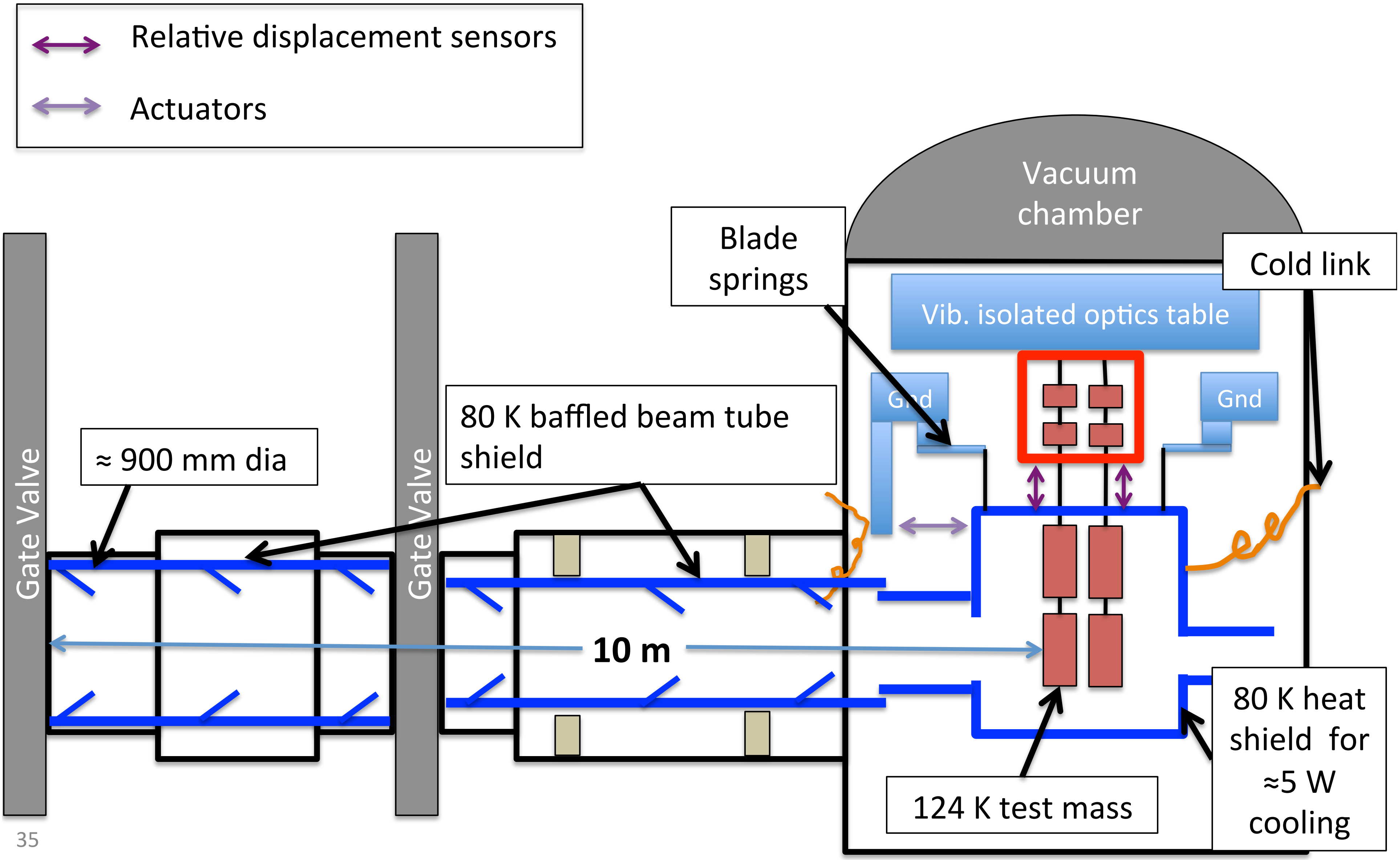
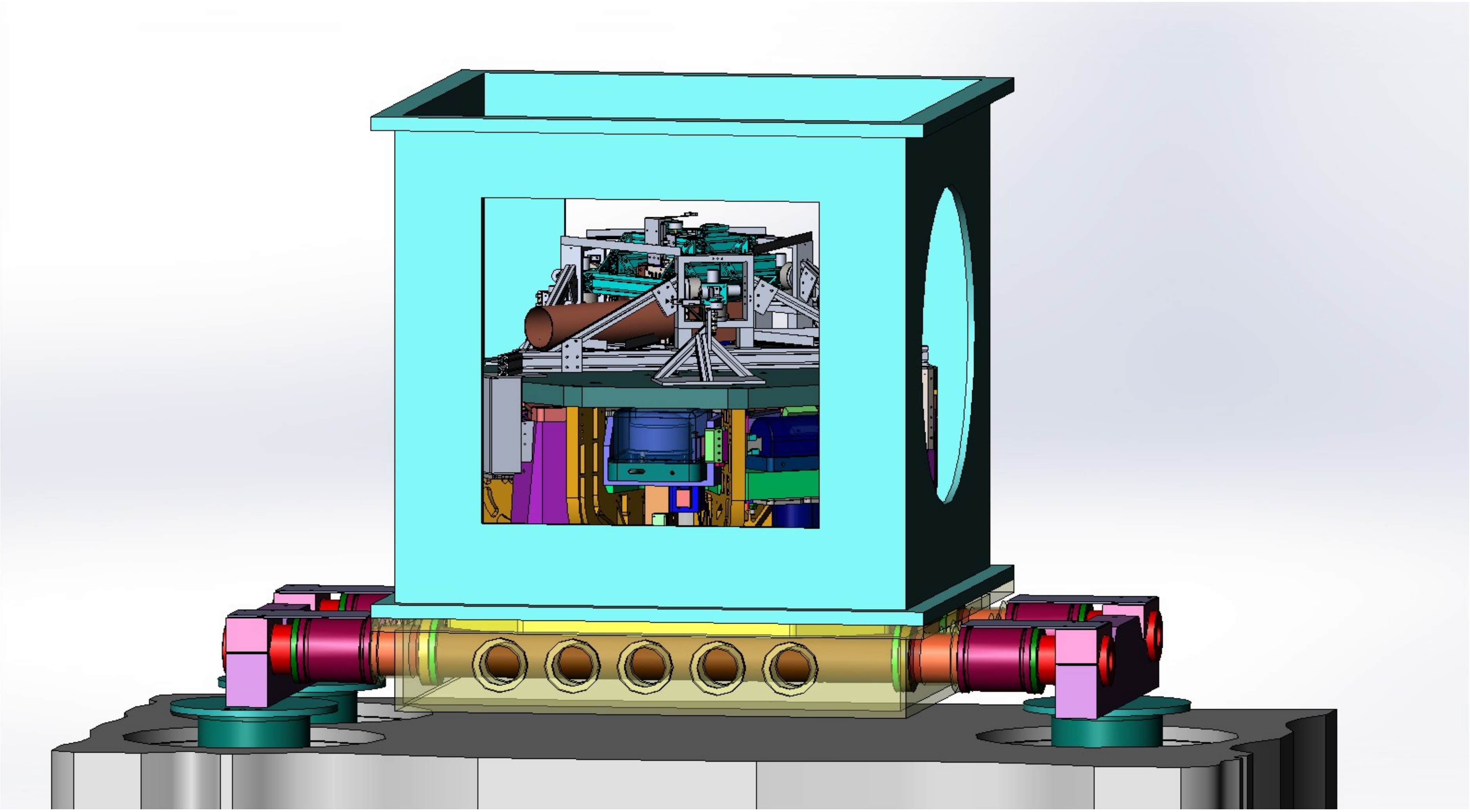
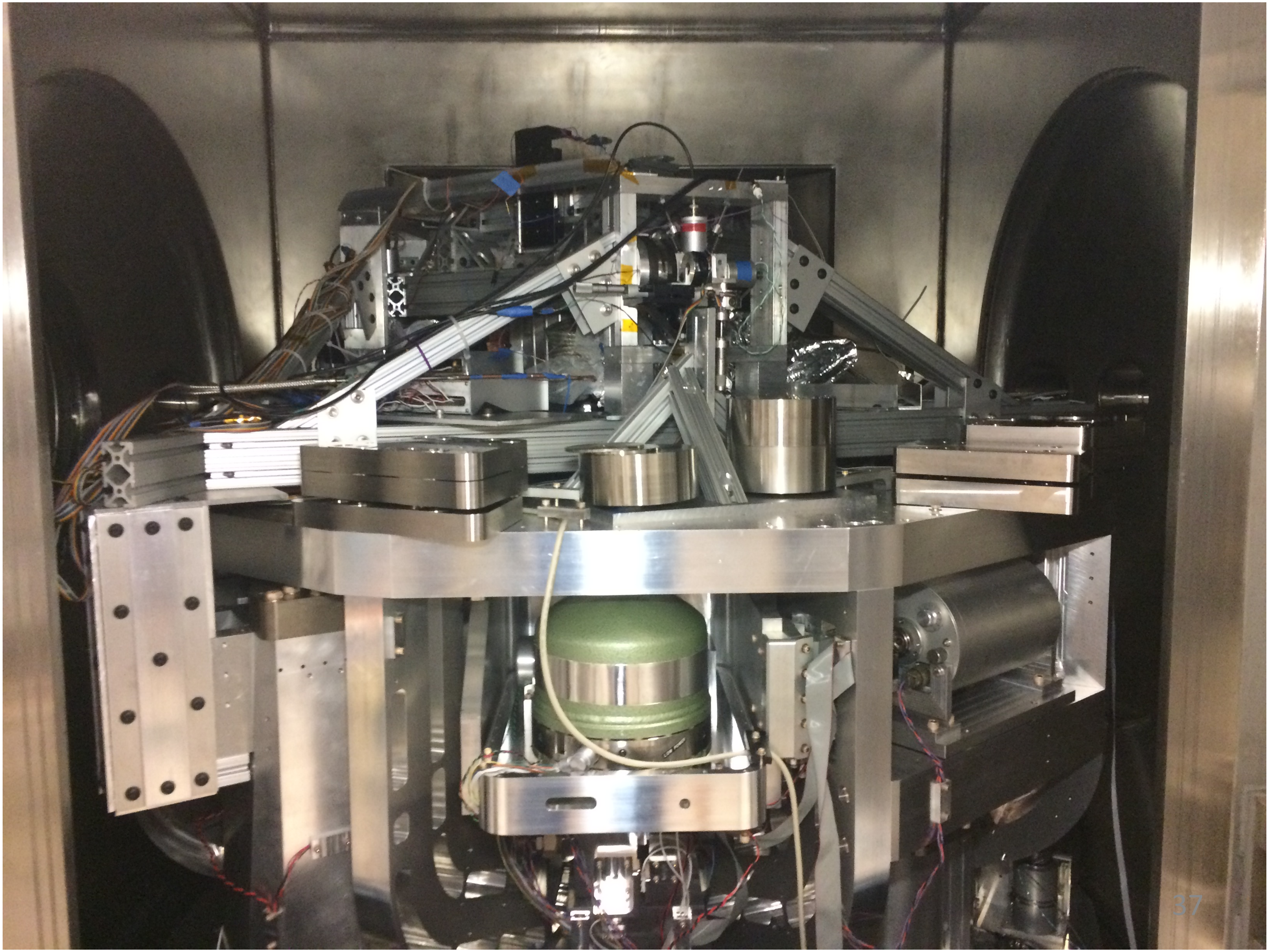
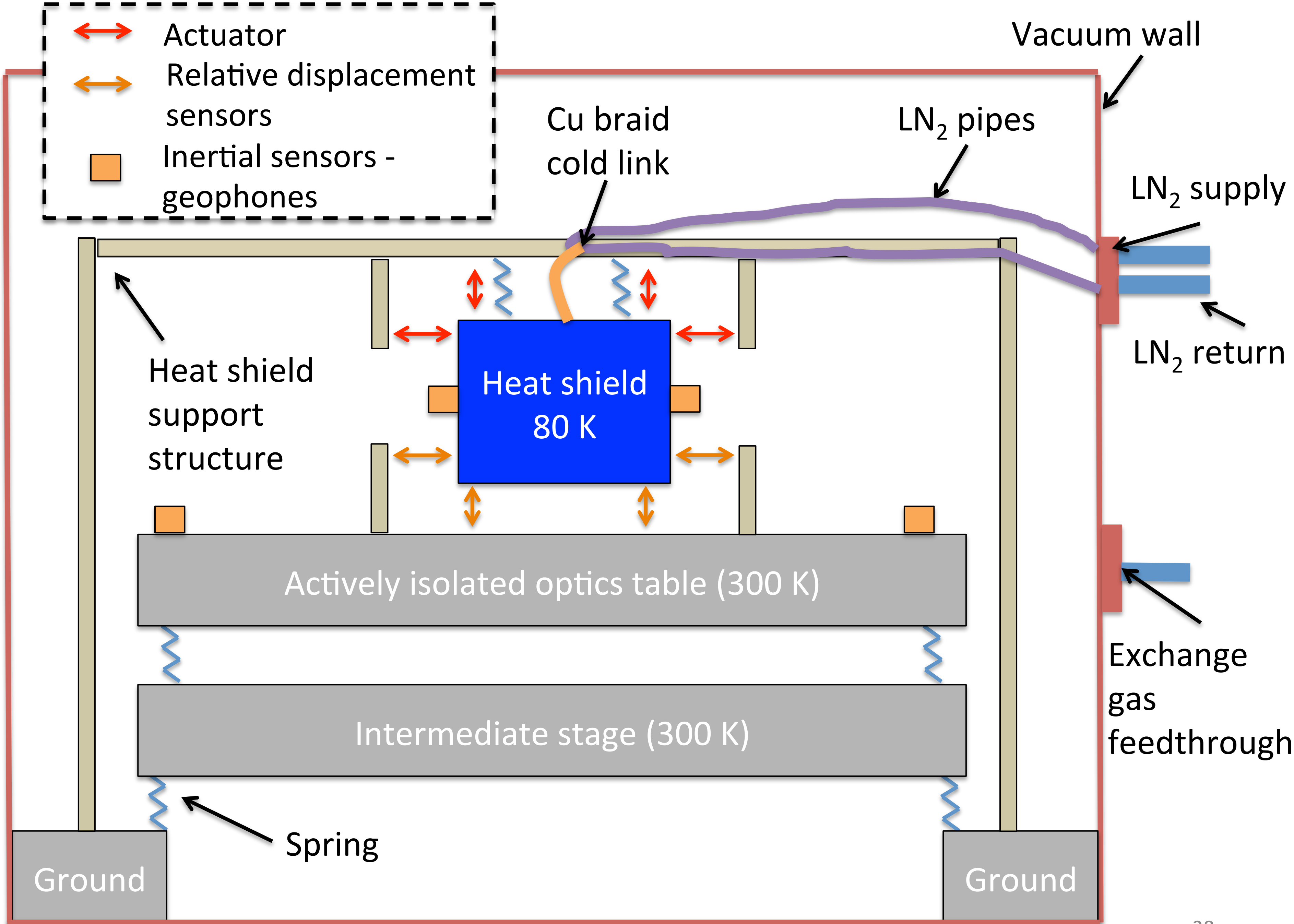


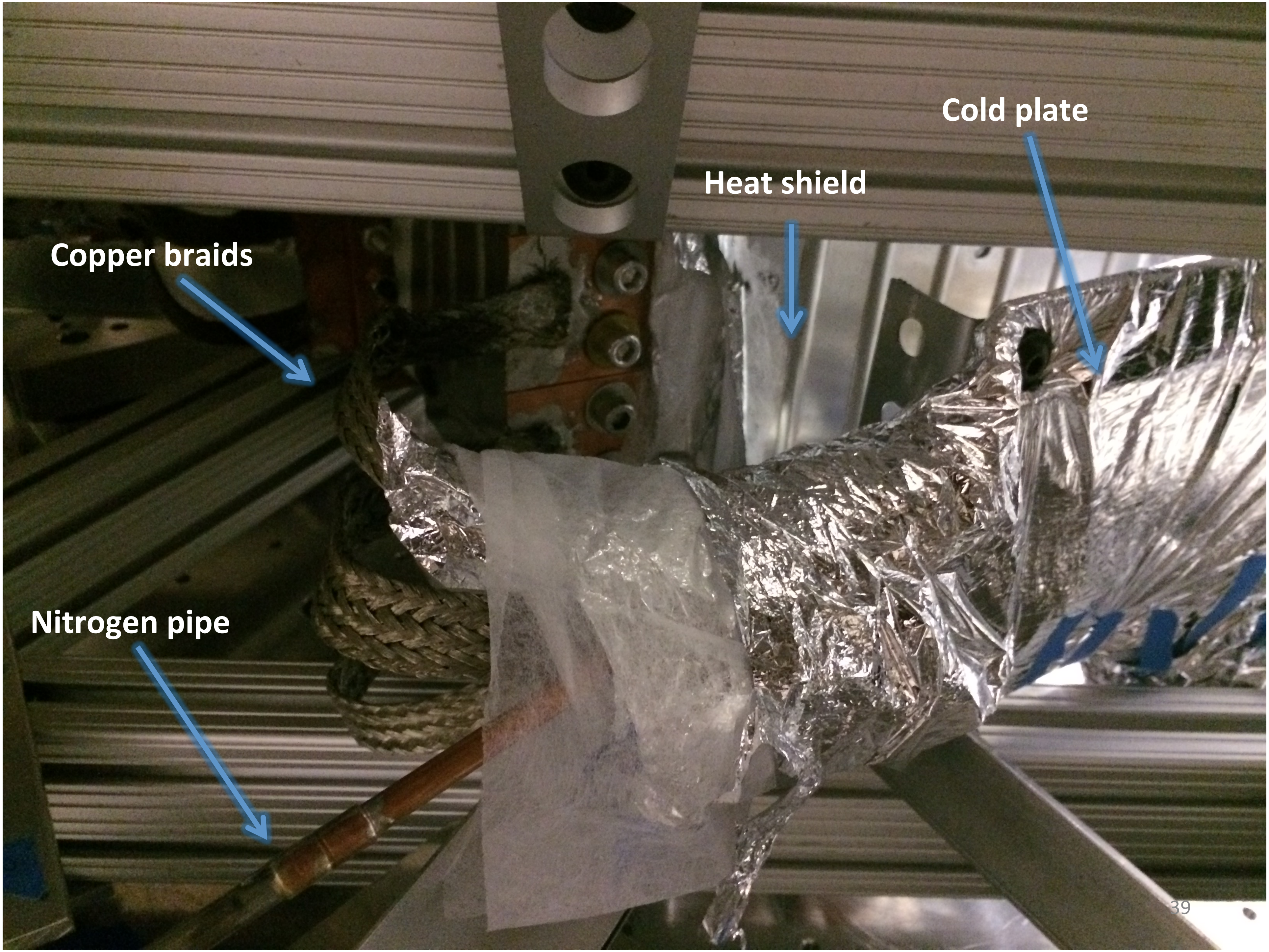
Heat shield experiment at Stanford University





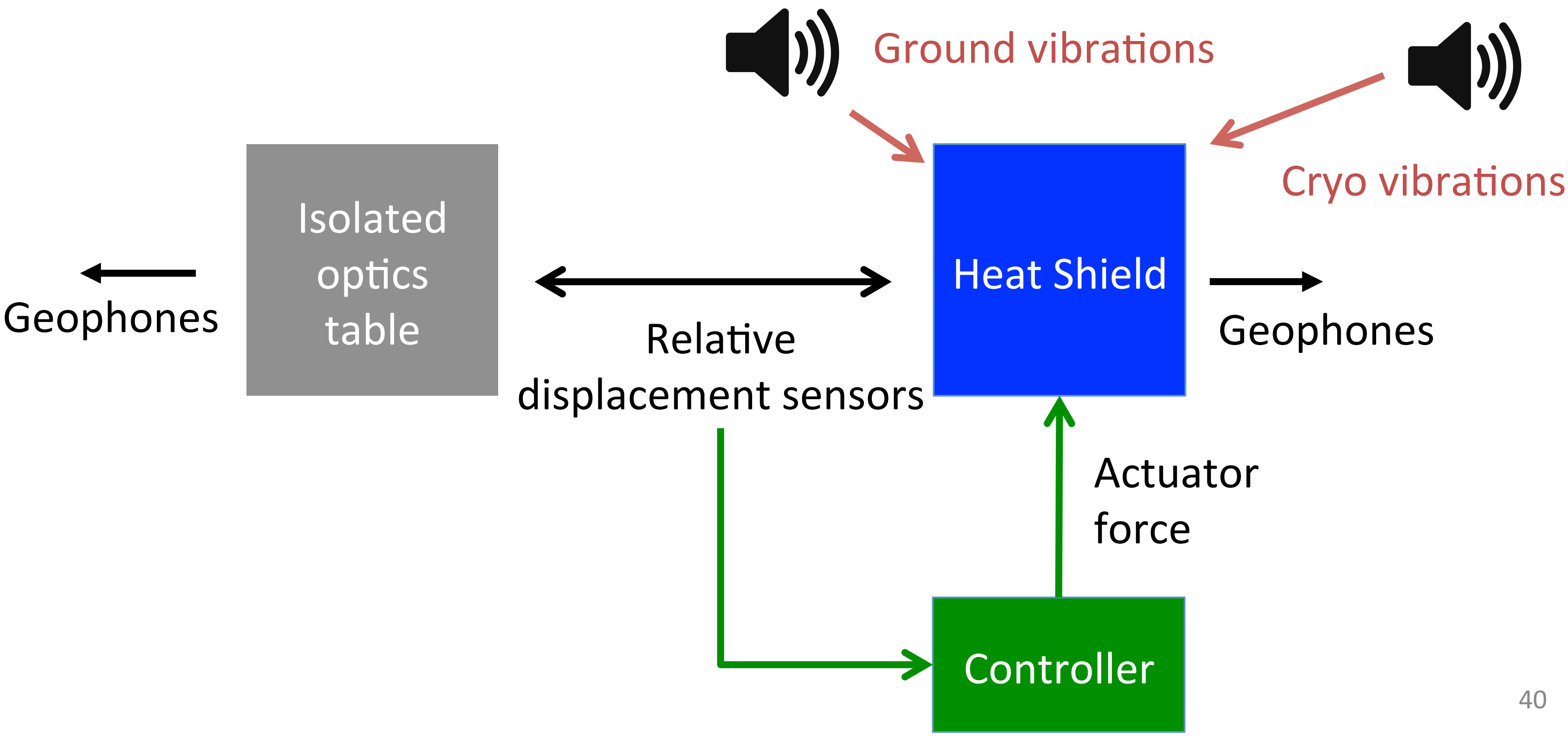


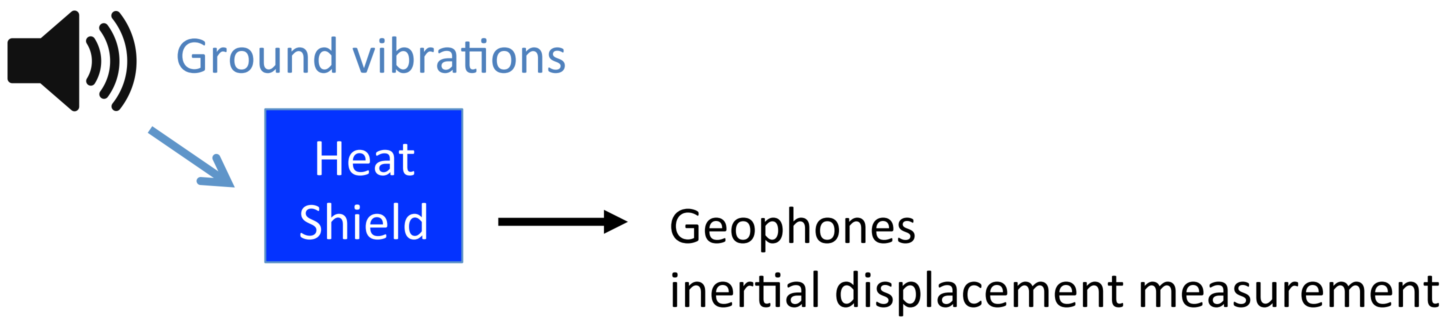
Actuator
Relative displacement sensors
Inertial sensors - geophones
Vacuum wall
Cu braid cold link
LN$_2$ pipes
LN$_2$ supply
LN$_2$ return
Heat shield support structure
Heat shield 80 K
Actively isolated optics table (300 K)
Intermediate stage (300 K)
Exchange gas feedthrough
Spring
Ground
Ground


Cold plate
Heat shield
Copper braids
Nitrogen pipe

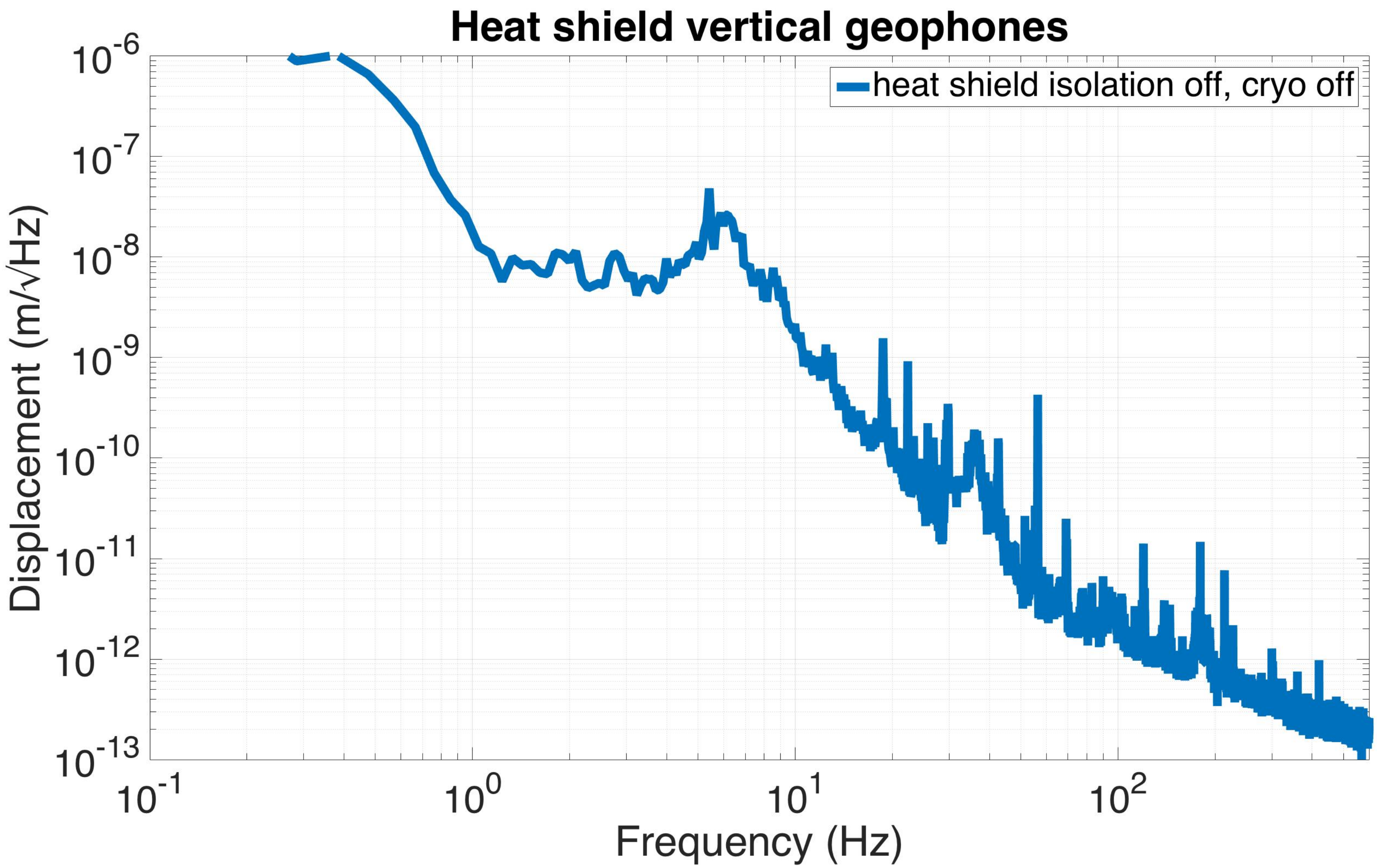
Heat shield measurement and control

- The controller forces the heat shield to follow the isolated optics table using the relative displacement sensors
- The heat shield's geophones are used to measure how well the control is doing

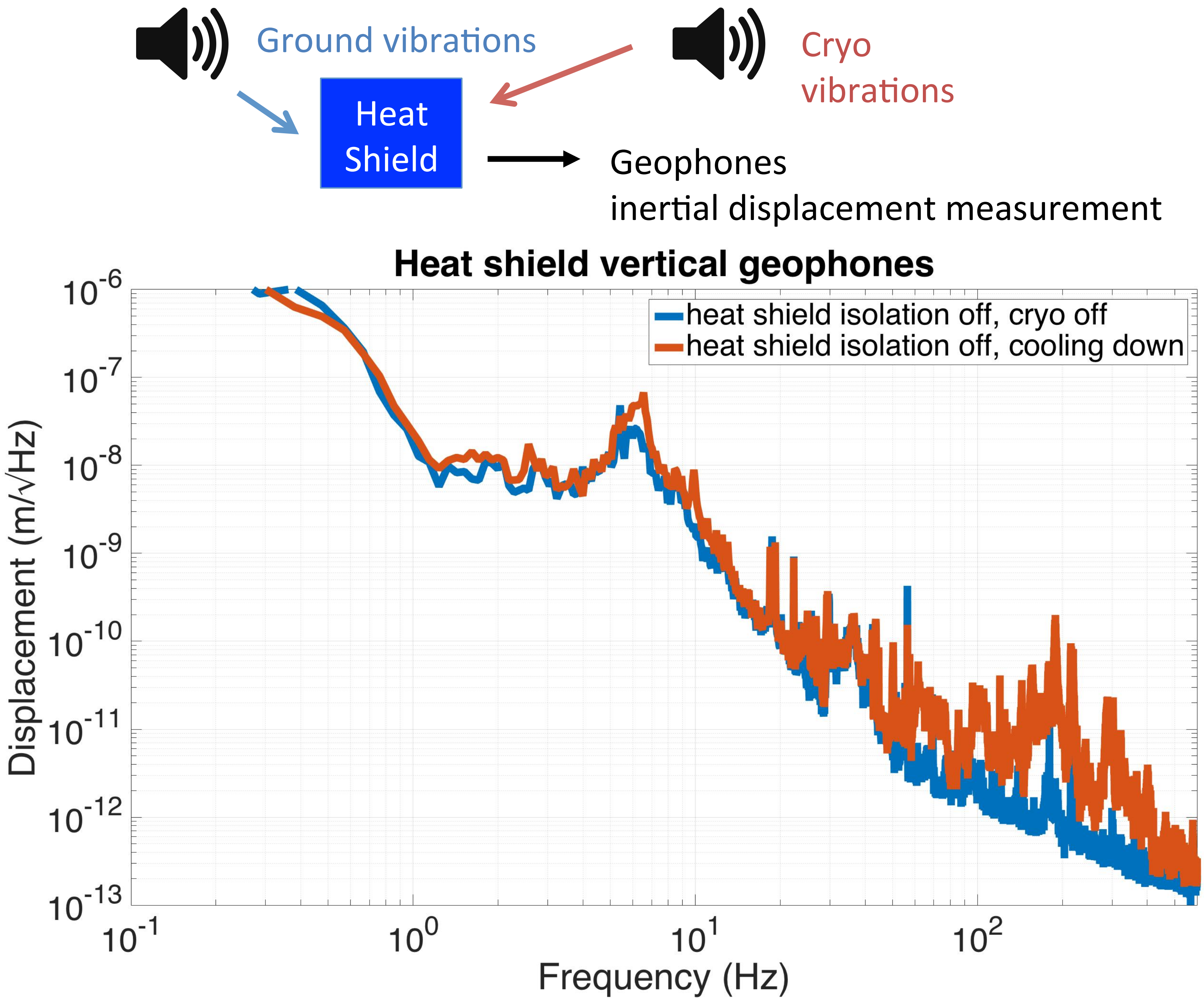




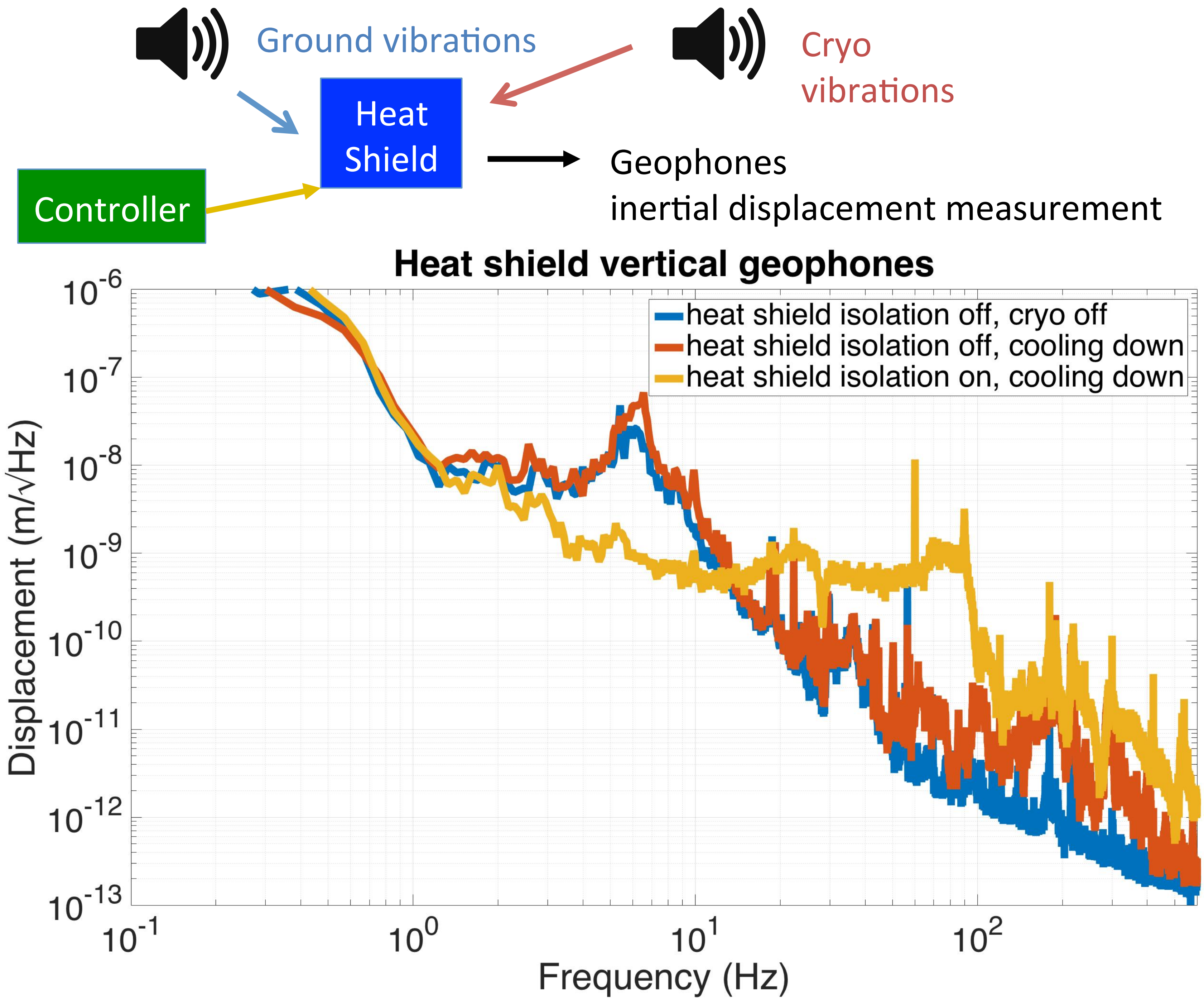
Ground vibrations
Heat Shield
Geophones
inertial displacement measurement



Heat shield vertical geophones
heat shield isolation off, cryo off
Displacement (m/√Hz)
Frequency (Hz)

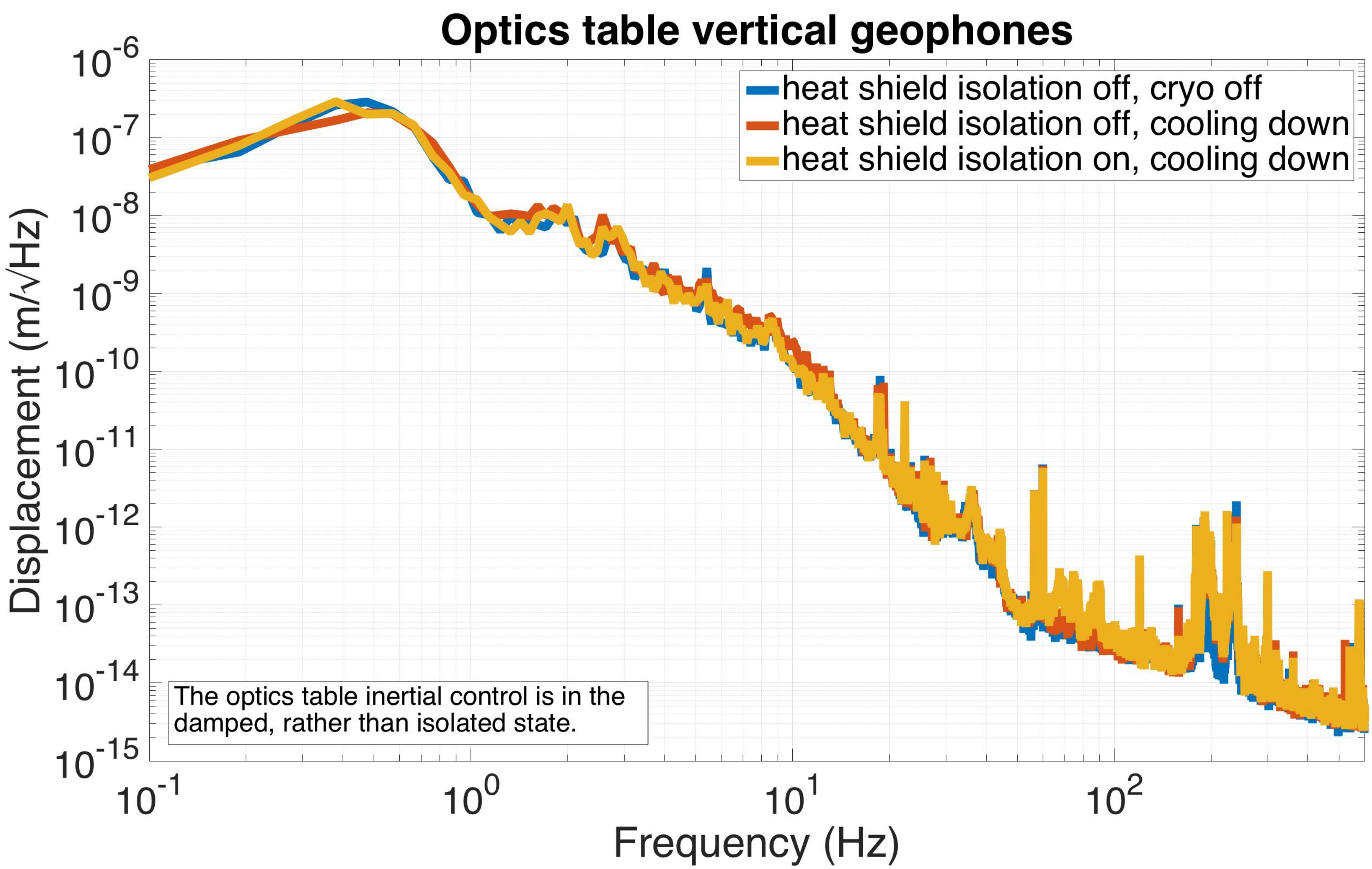


Ground vibrations
Cryo vibrations
Heat Shield
Geophones
inertial displacement measurement
Heat shield vertical geophones
heat shield isolation off, cryo off
heat shield isolation off, cooling down
Displacement (m/√Hz)
Frequency (Hz)

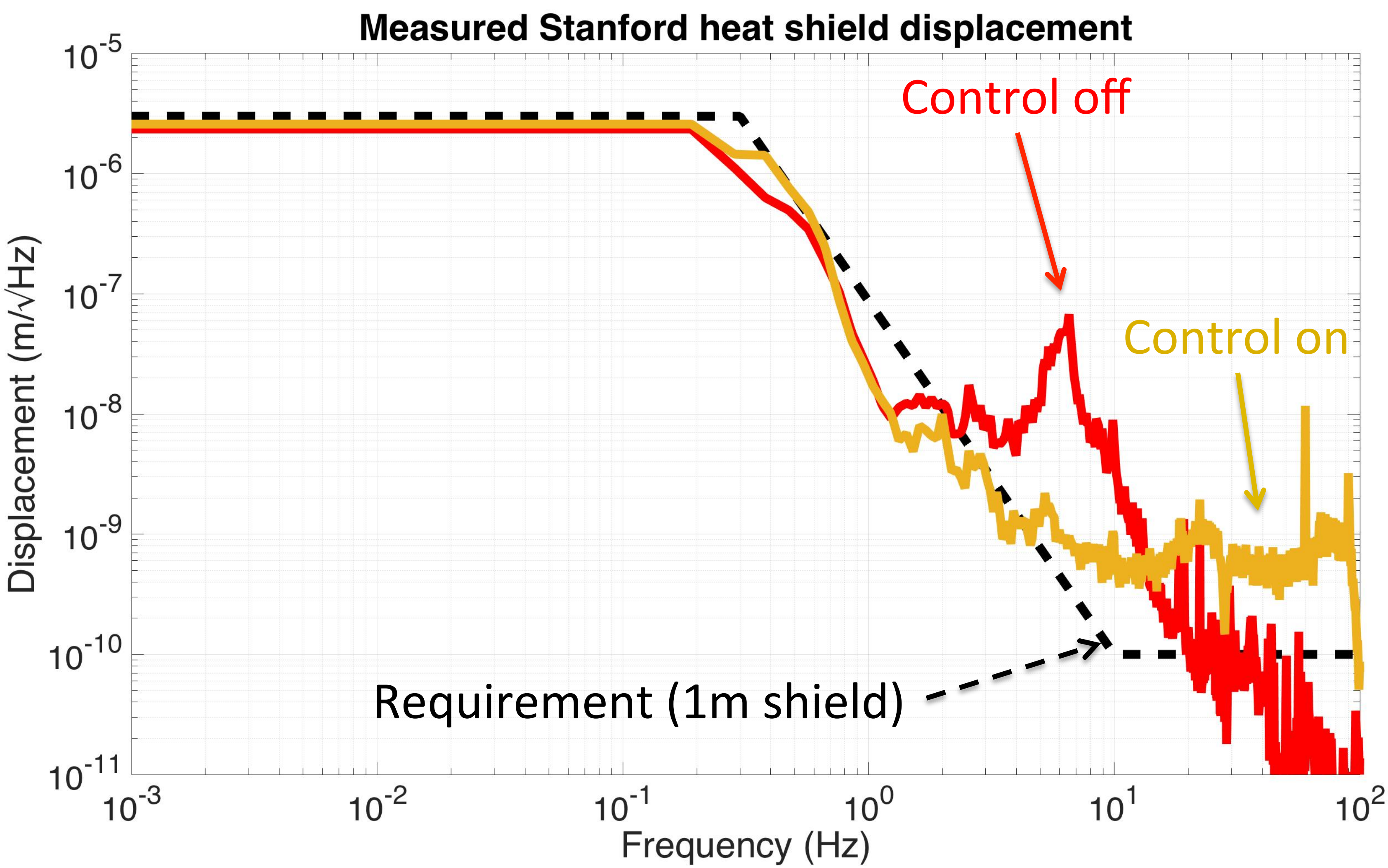


Ground vibrations
Cryo vibrations
Heat Shield
Controller
Geophones
inertial displacement measurement
Heat shield vertical geophones
heat shield isolation off, cryo off
heat shield isolation off, cooling down
heat shield isolation on, cooling down
Displacement (m/√Hz)
Frequency (Hz)

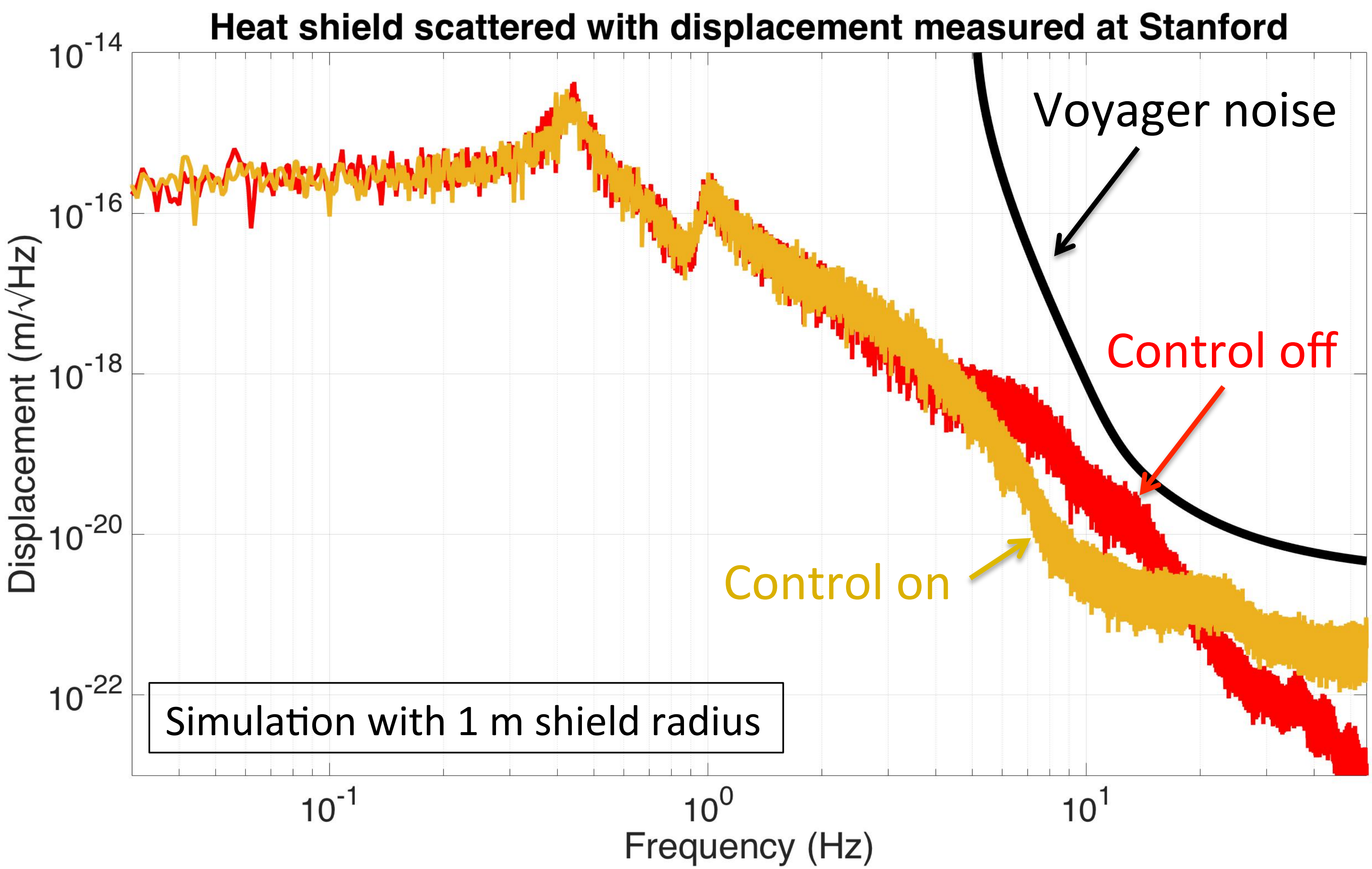
Optics Table → Geophones inertial displacement measurement



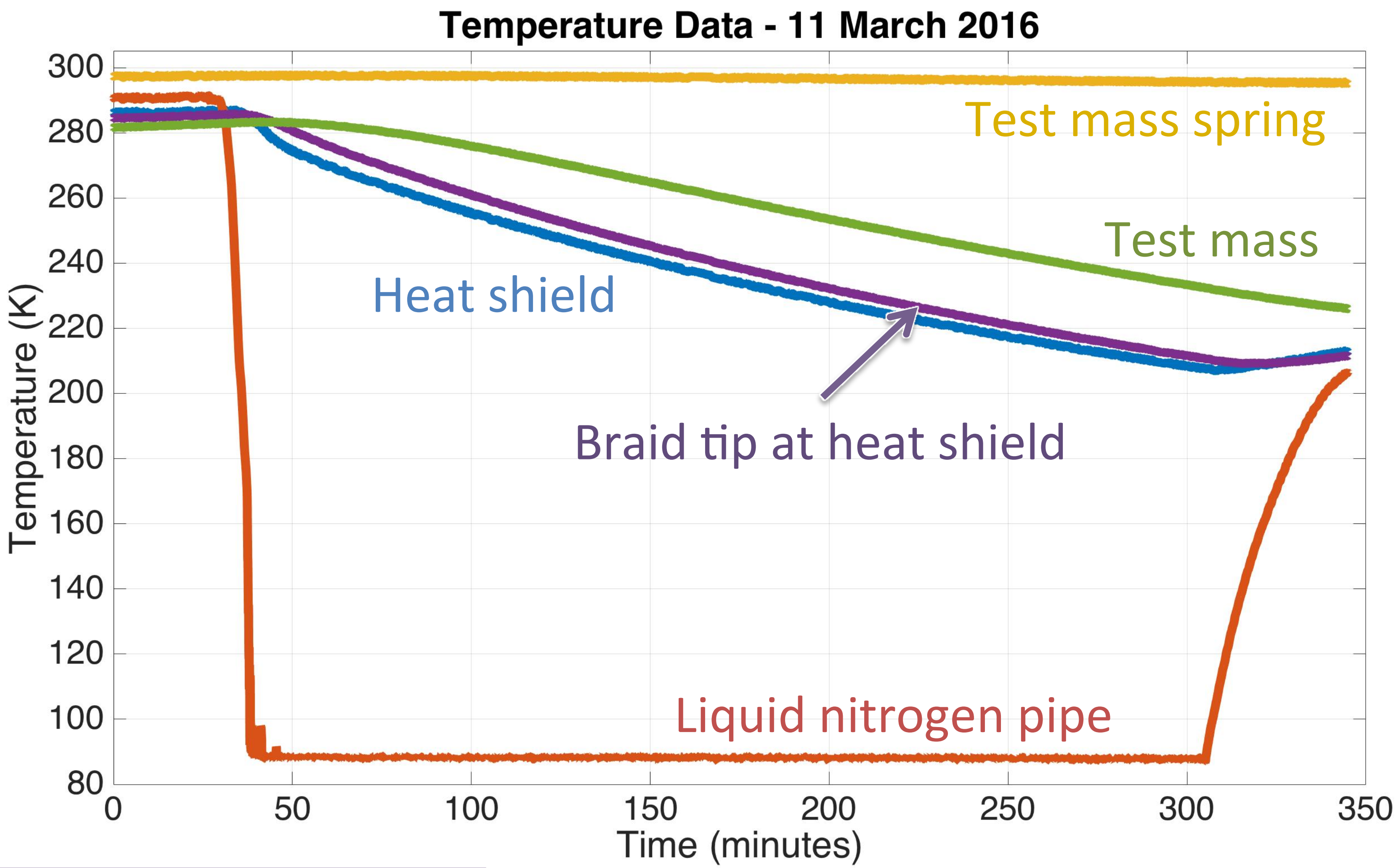
Measured Heat Shield Displacement



Scattered Light with Measured Displacement

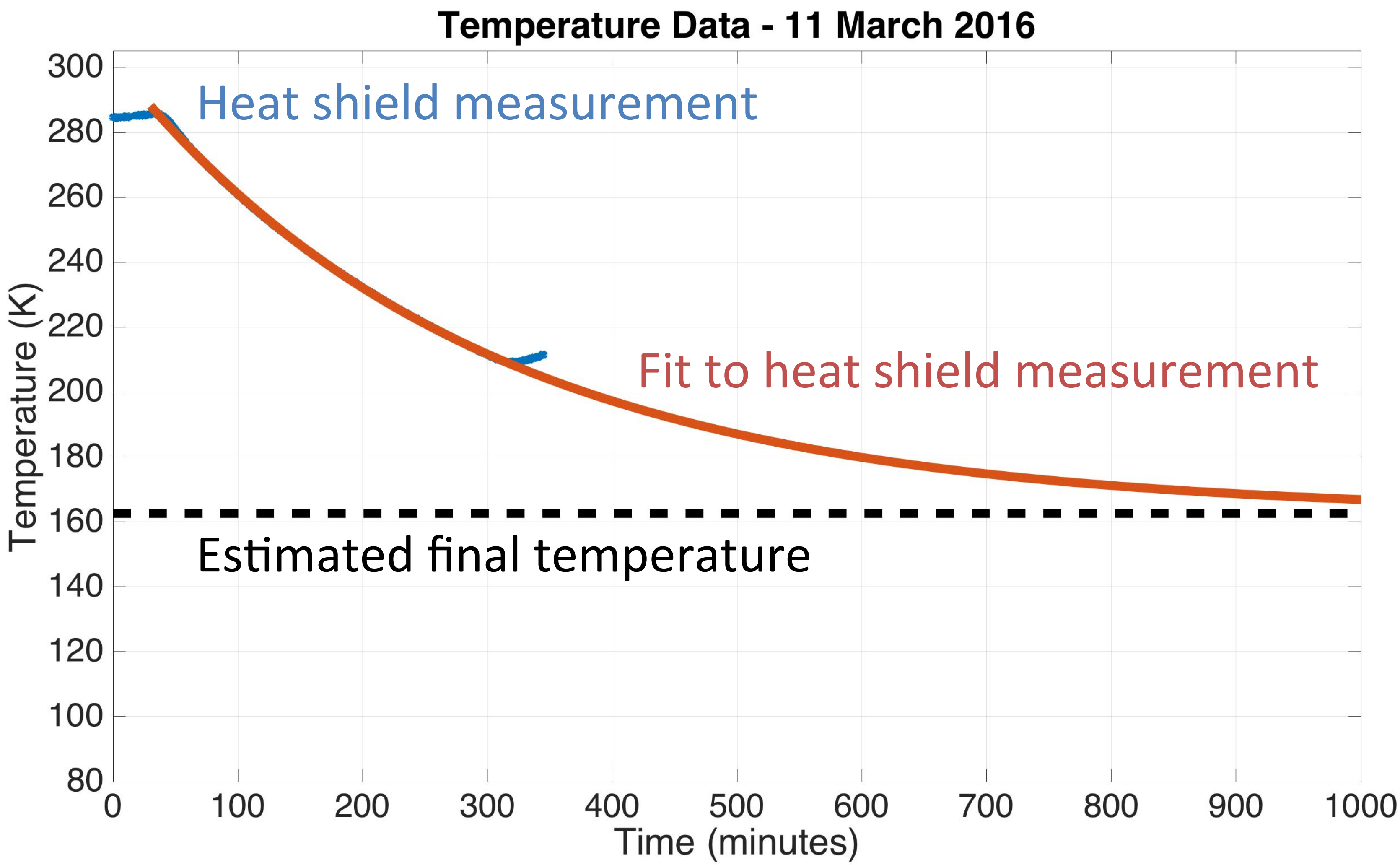


Cool Down Data



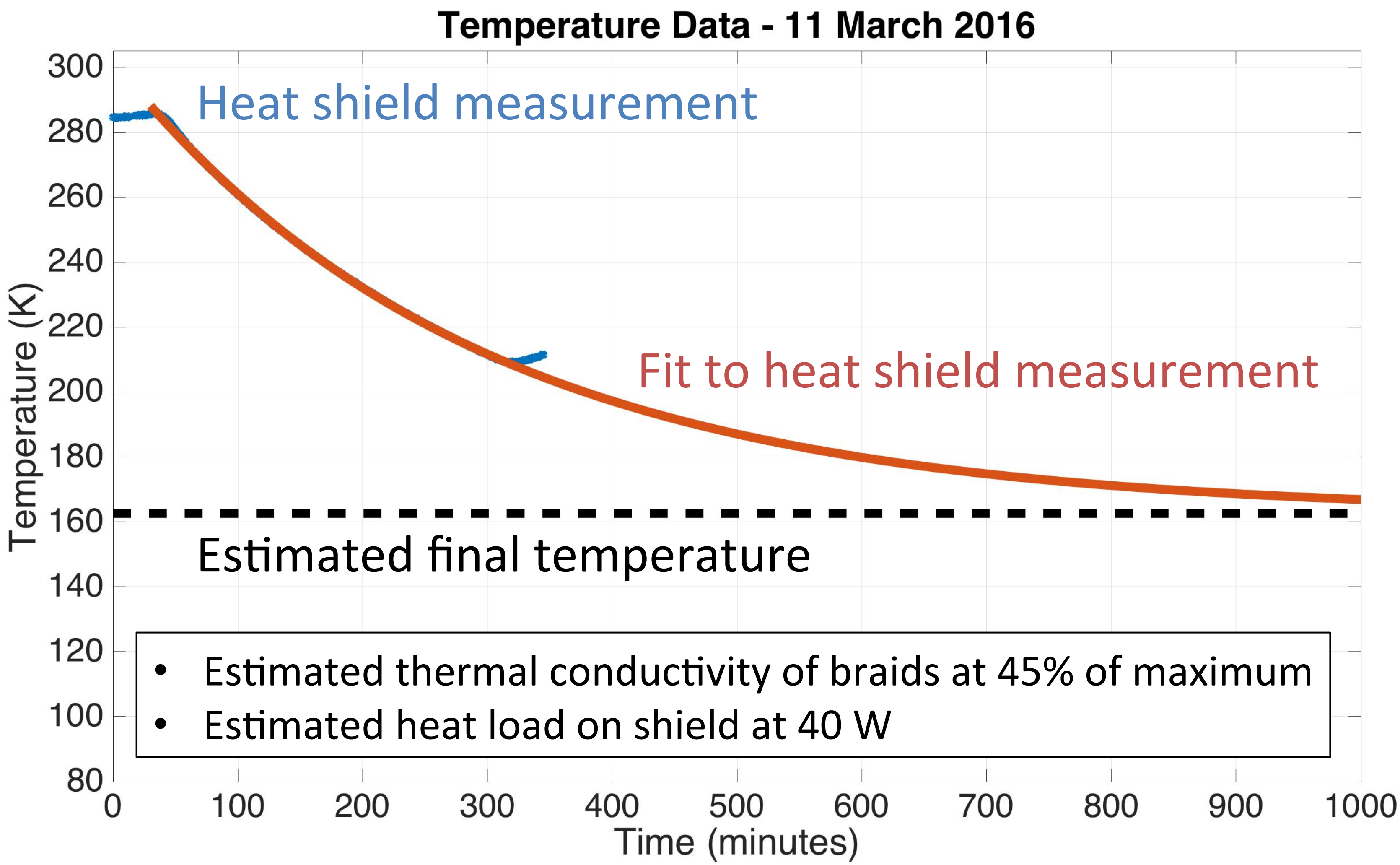
Vacuum pressure = 1e-5 torr

Cool Down Data



Vacuum pressure = 1e-5 torr

Cool Down Data

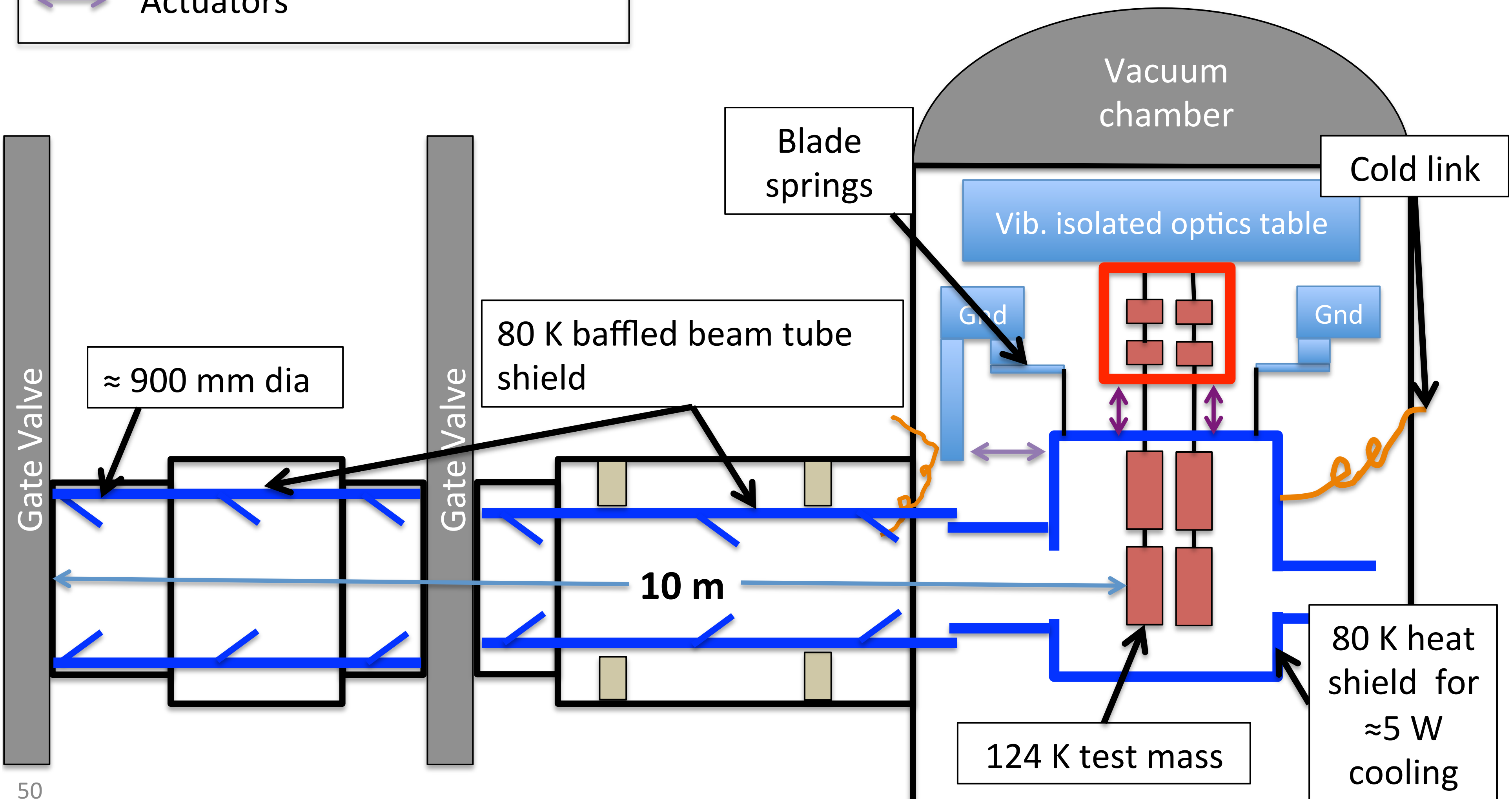


Vacuum pressure = 1e-5 torr

Actively controlled shield (ETM)

↔ Relative displacement sensors

↔ Actuators



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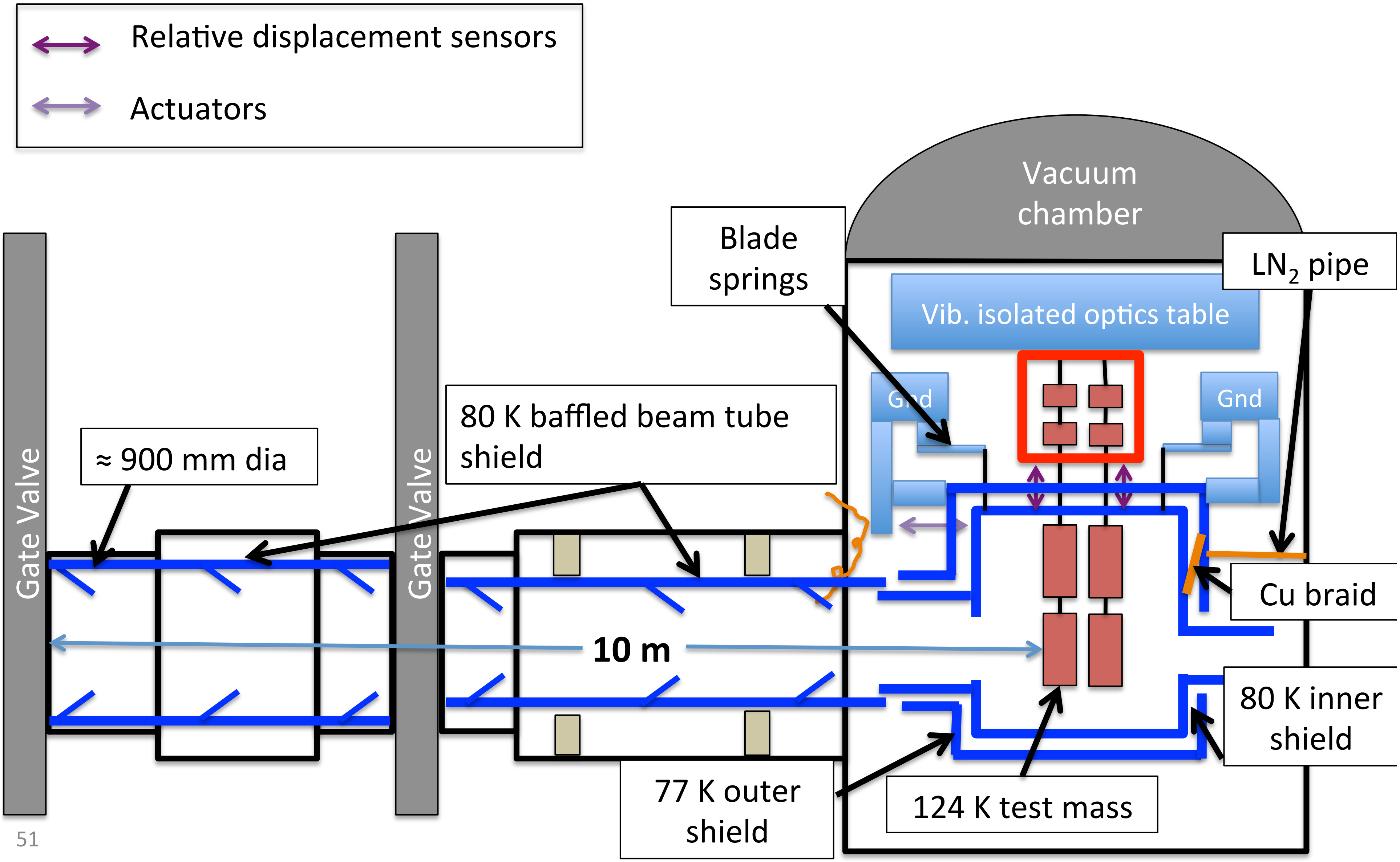
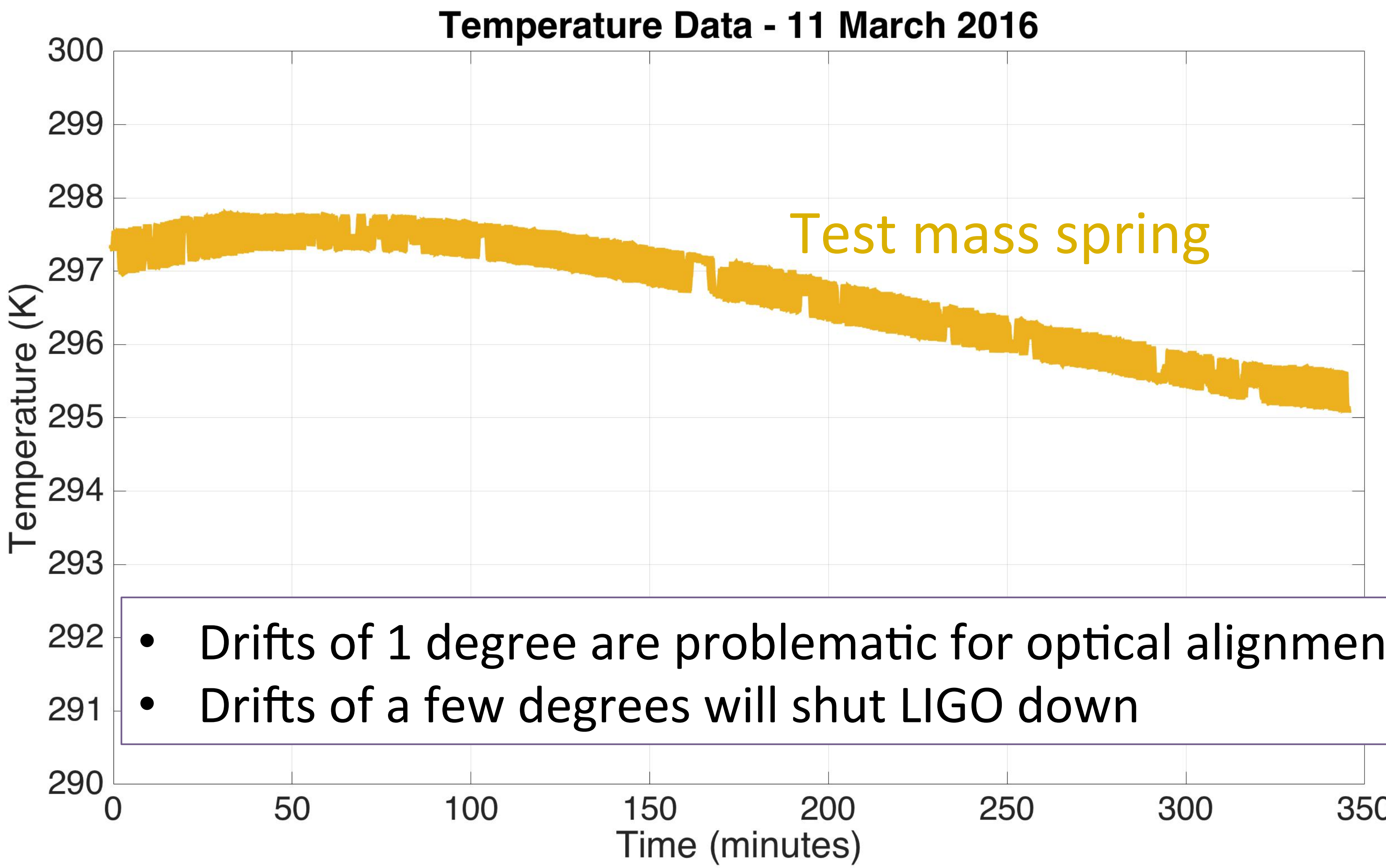


Cool Down Data



- Drifts of 1 degree are problematic for optical alignment
- Drifts of a few degrees will shut LIGO down

Conclusions

- Shield displacement maybe a problem
  - Active control is one approach to mitigate this
  - Or avoid control with a careful shield design
- Plan to add a second shield outside first
- Might want to heat the test mass springs

Special thanks to the **APS-SBF Brazil-U.S. physics PhD student & post-doc visitation program** for supporting this visit!

Questions?

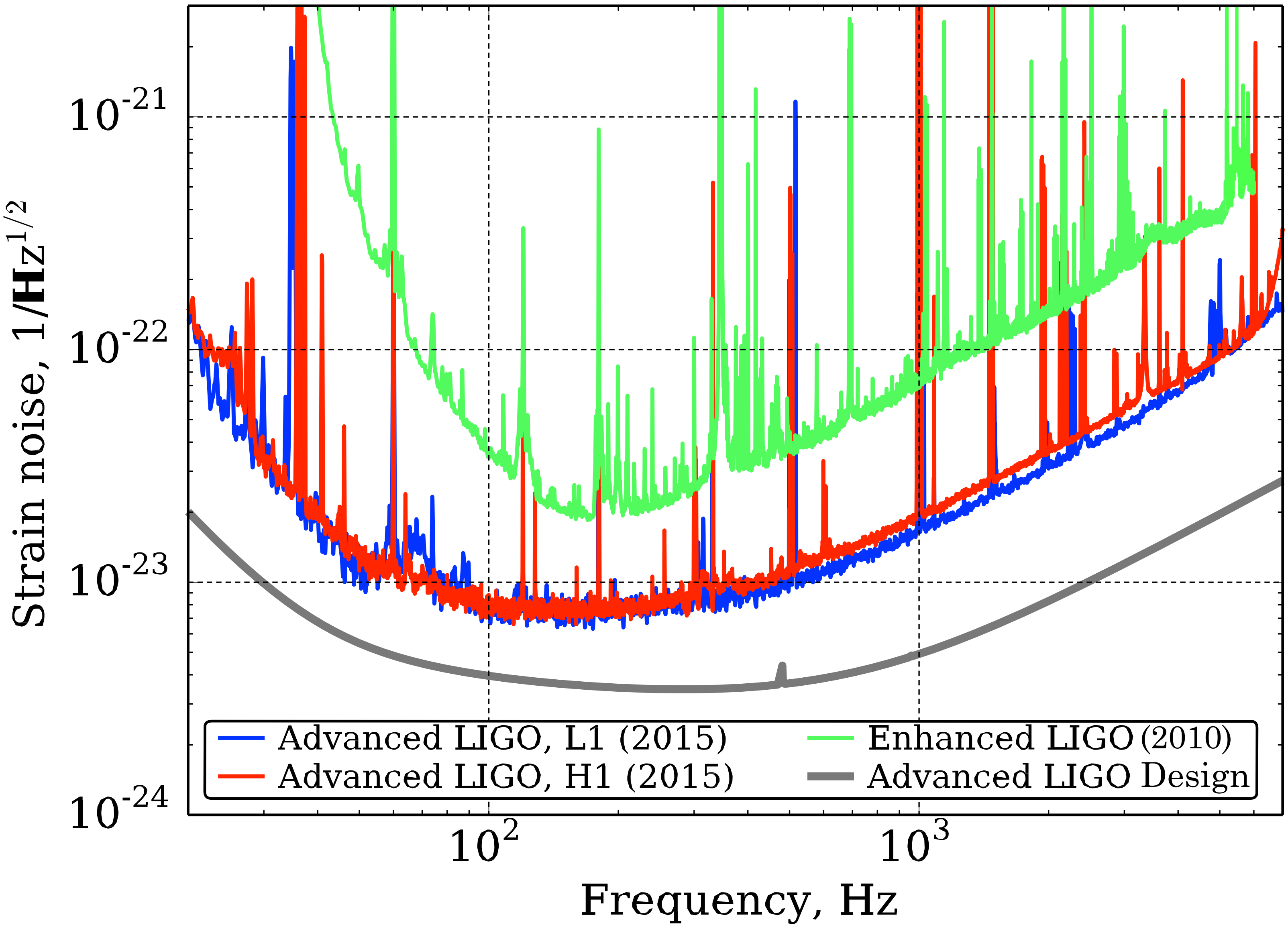
Sources for scattered light simulations

- P1100117 – The impact of upconverted scattered light on advanced interferometric Gravitational Wave Detectors

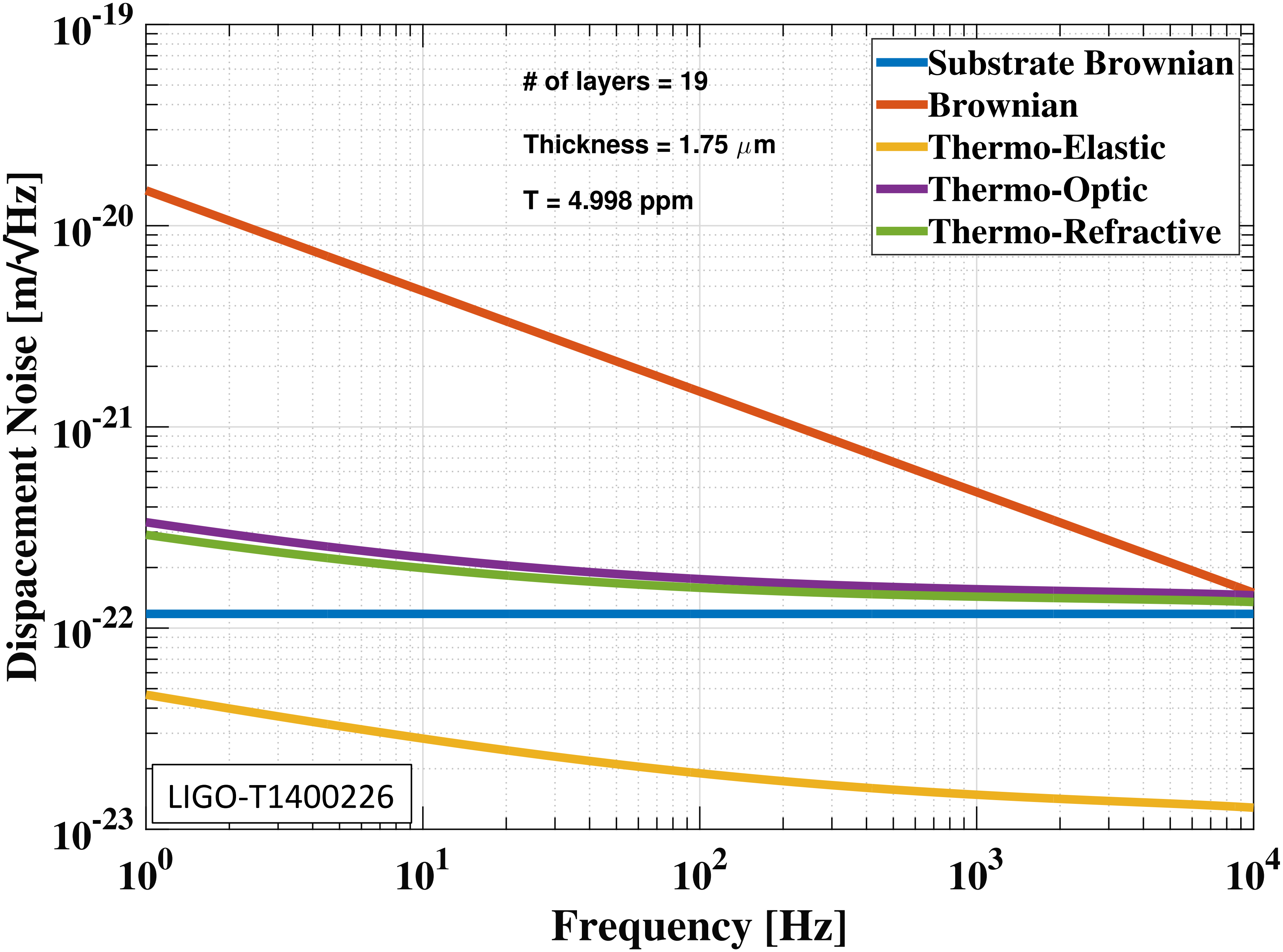
- T070089 – Wide-angle scatter from LIGO arm cavities

- T1300354 – Scattered light noise due to the ETM coating ripple

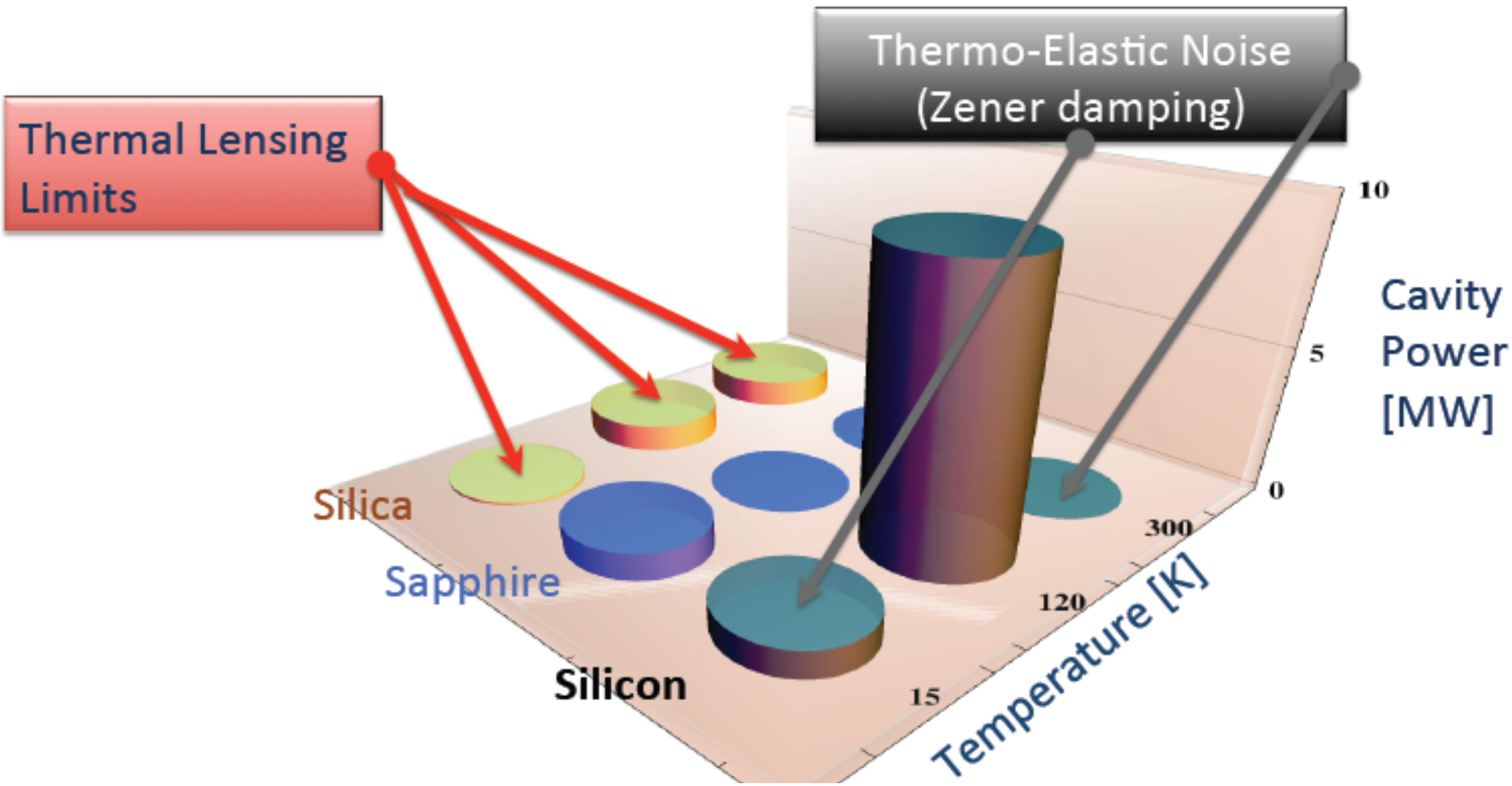
Advanced LIGO Noise



Predicted thermal noise of a 123 K Si mirror α-Si:SiO_2 HR coating and a 6 cm beam spot radius.

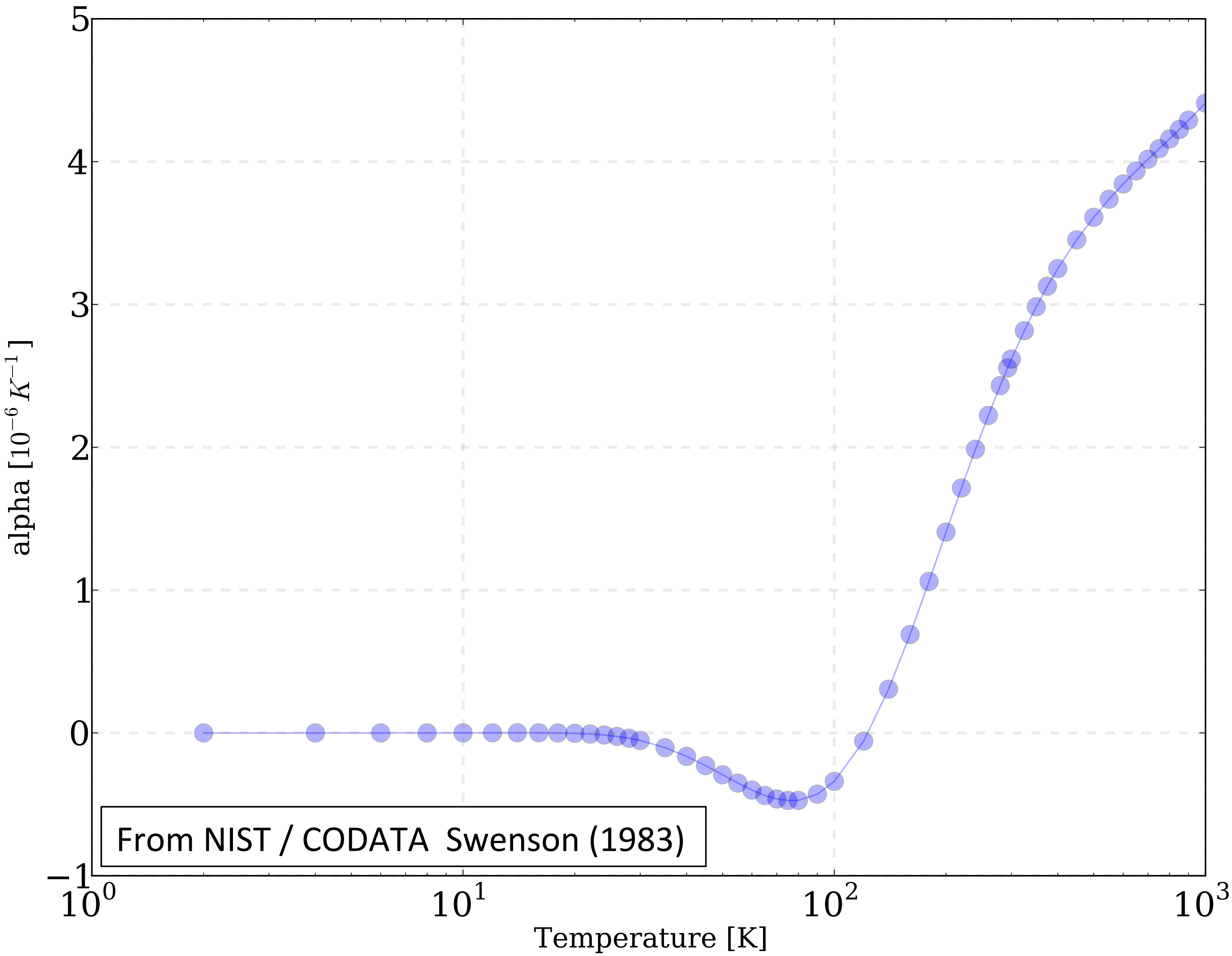


Materials vs max power



From G1300330

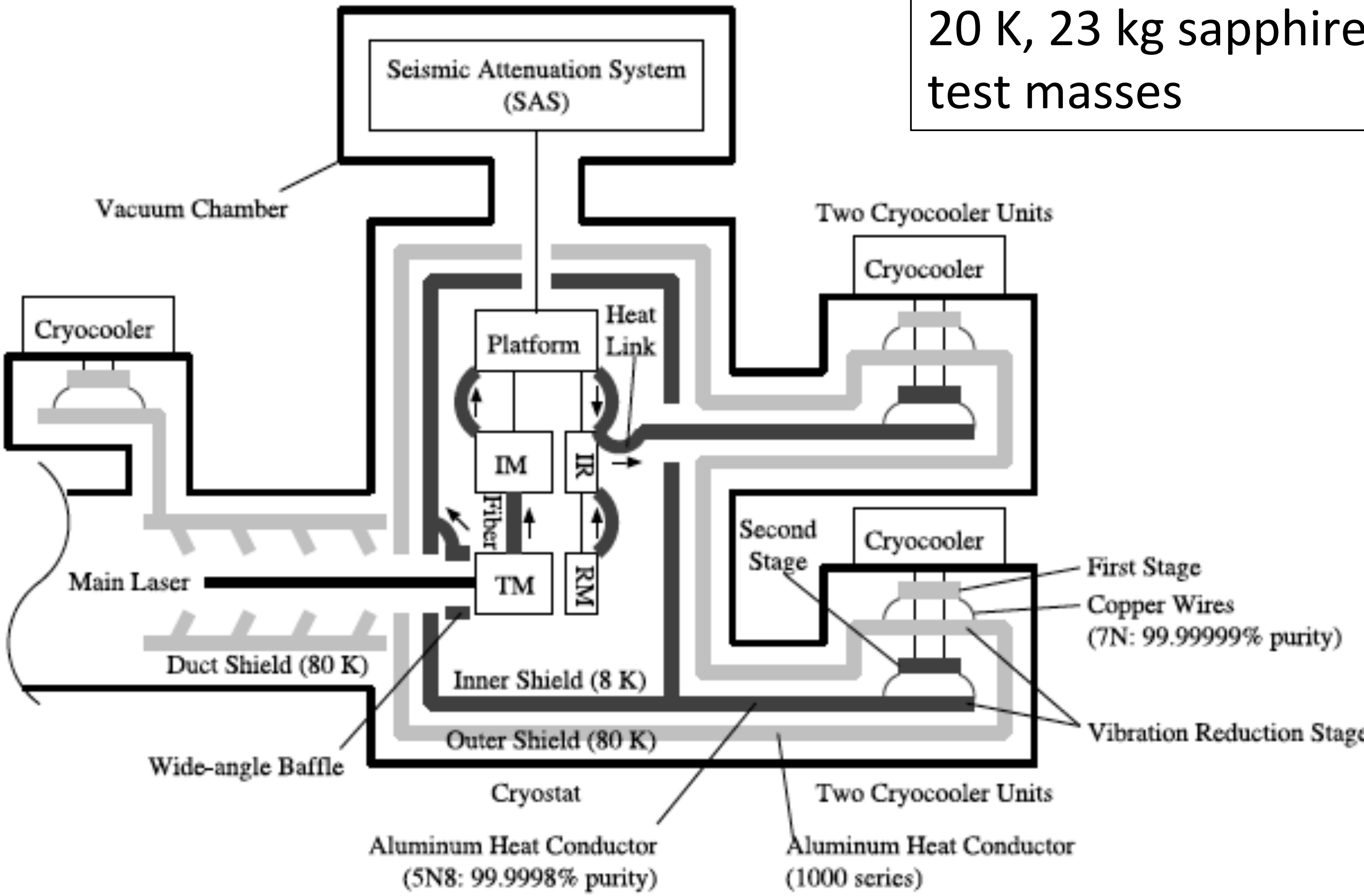
Thermal Expansion coefficient of silicon as a function of temperature



LIGO-T1400226

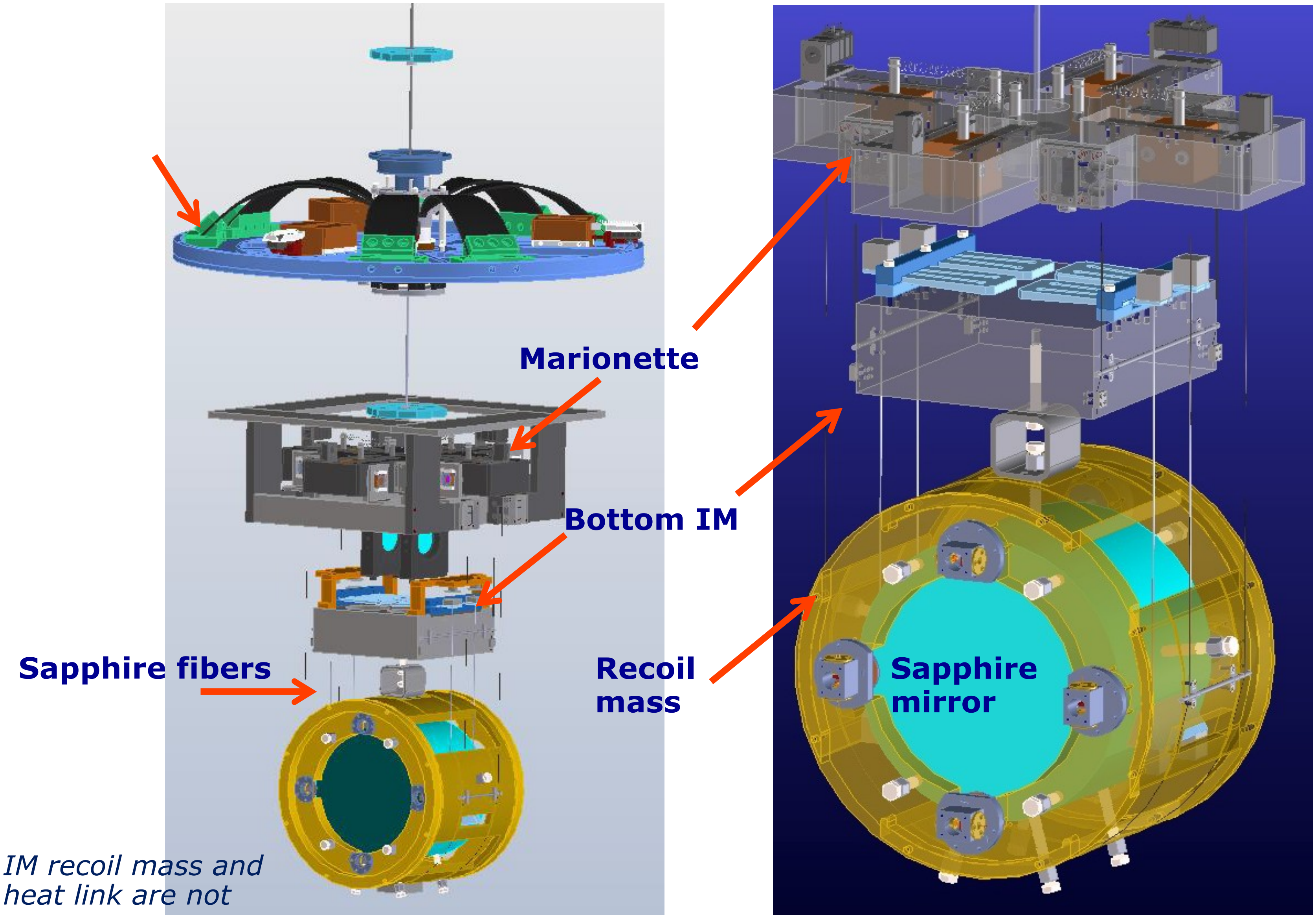
KAGRA End Station Layout

20 K, 23 kg sapphire test masses



CQG 31 (2014) 224003 – Progress on the cryogenic system fir the KAGRA cryogenic interferometric gravitational wave telescope

Fabrication (other than the platform) w/ a dummy mirror will be done at end of this Mar.



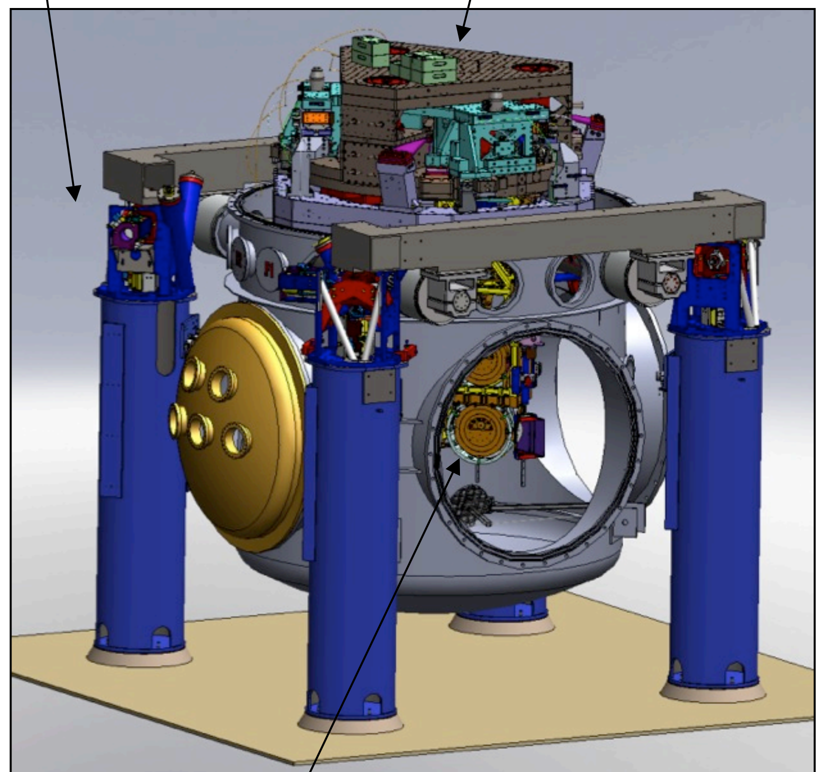
IM recoil mass and heat link are not shown

From G1600682

aLIGO test mass chambers

hydraulic external pre-isolator (HEPI) (one stage of isolation)

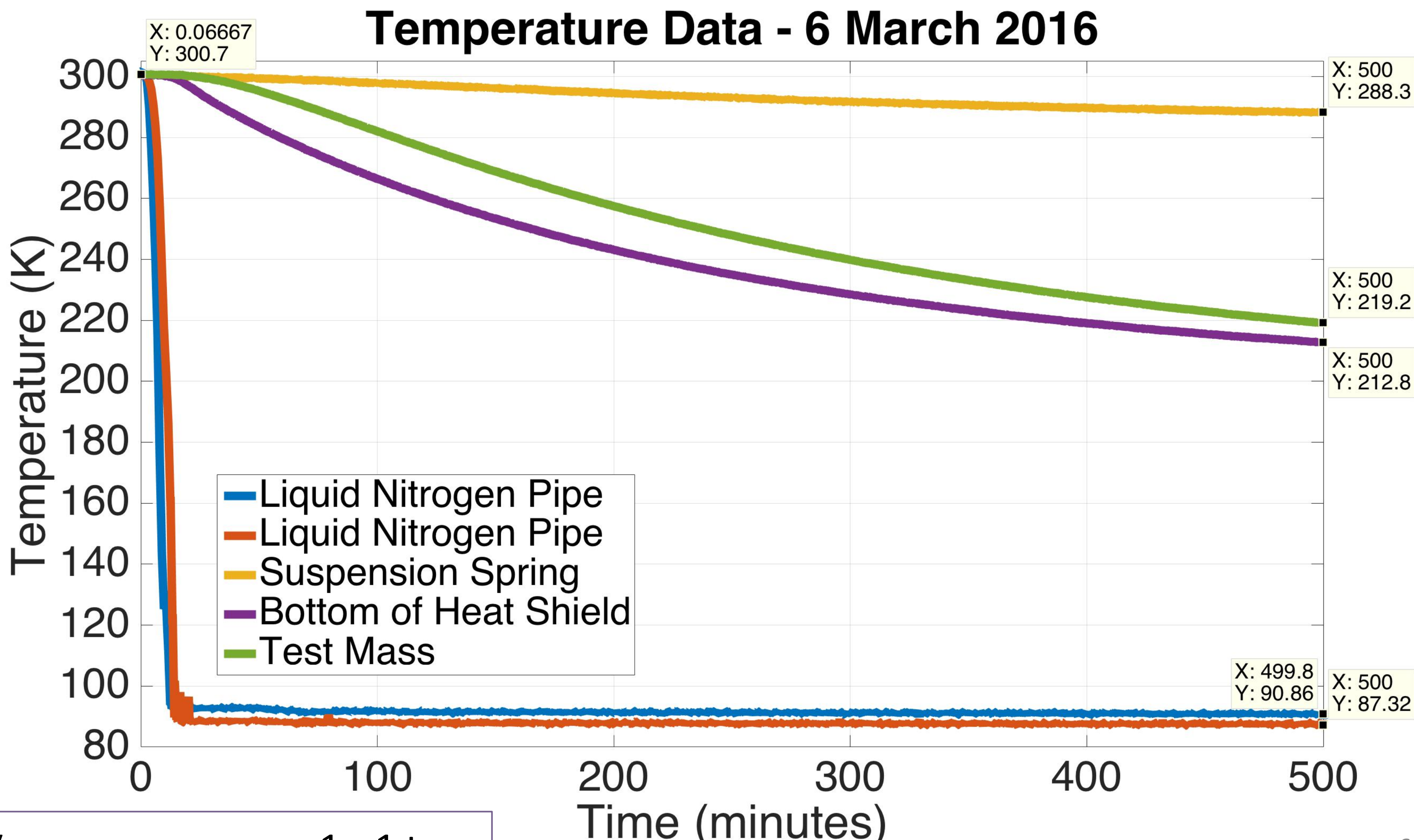
active isolation platform (2 stages of isolation)



quadruple pendulum (four stages of isolation) with monolithic silica final stage

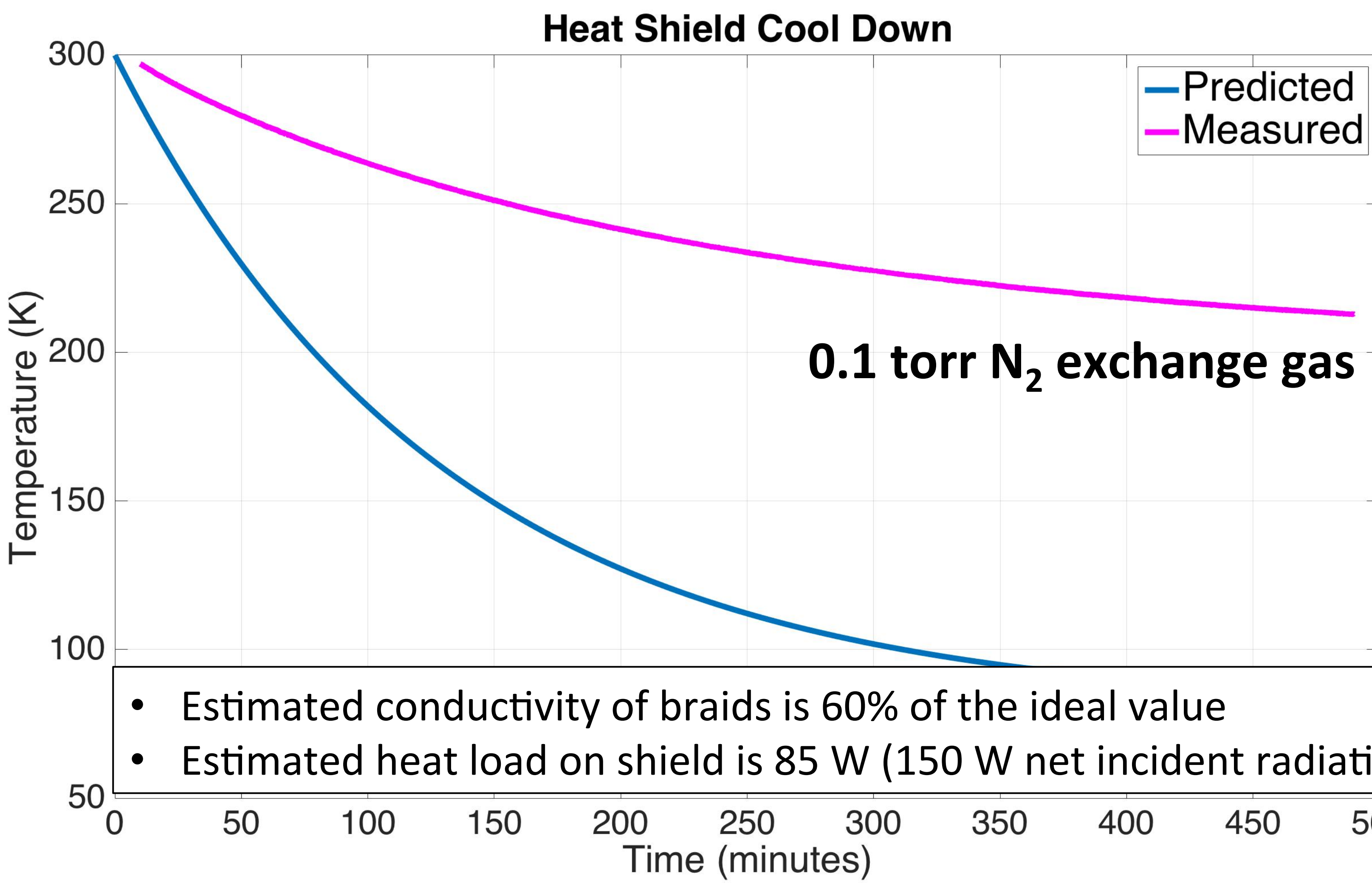
From LIGO-G1400964

Cool Down Data



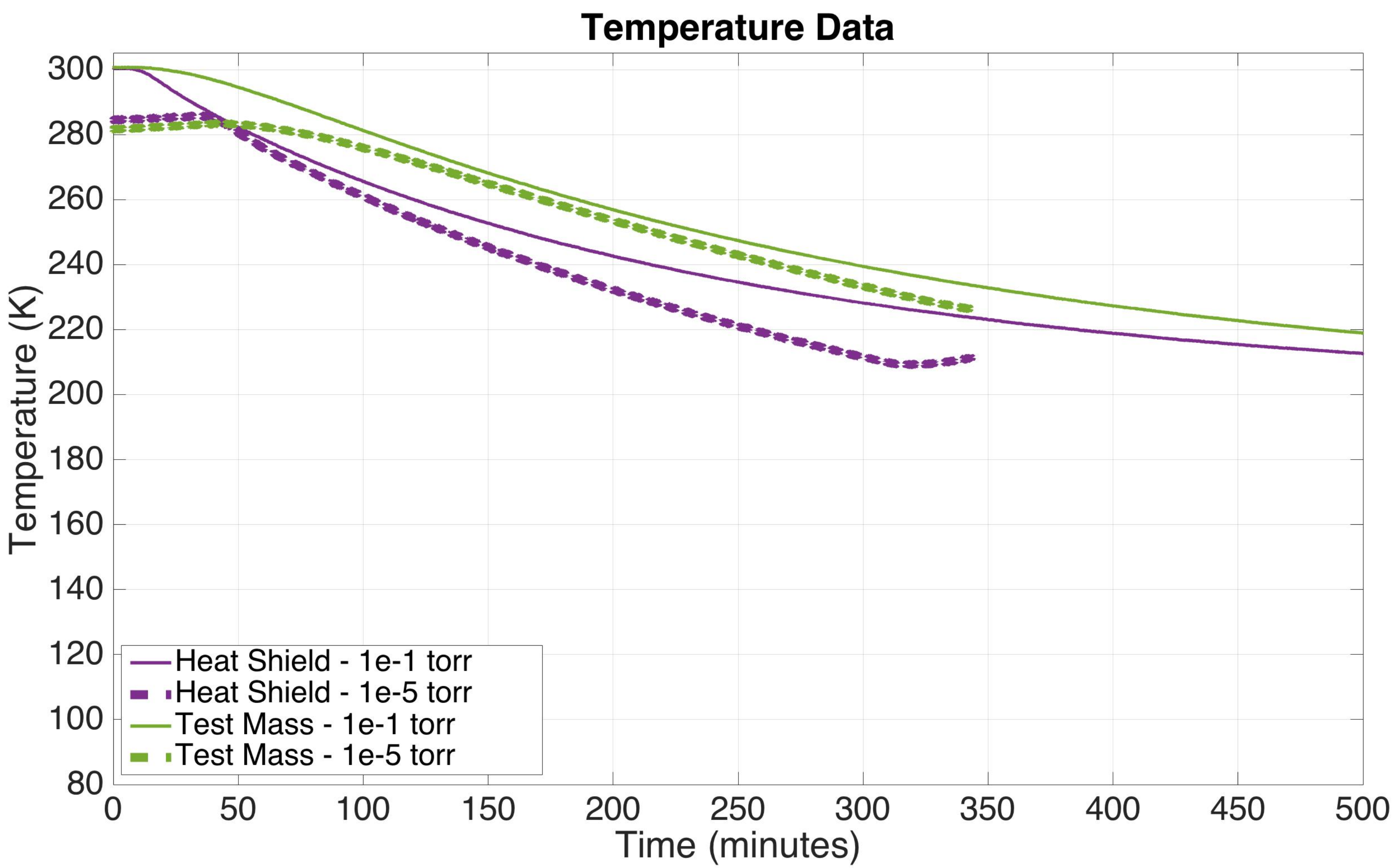
Vacuum pressure = 1e-1 torr

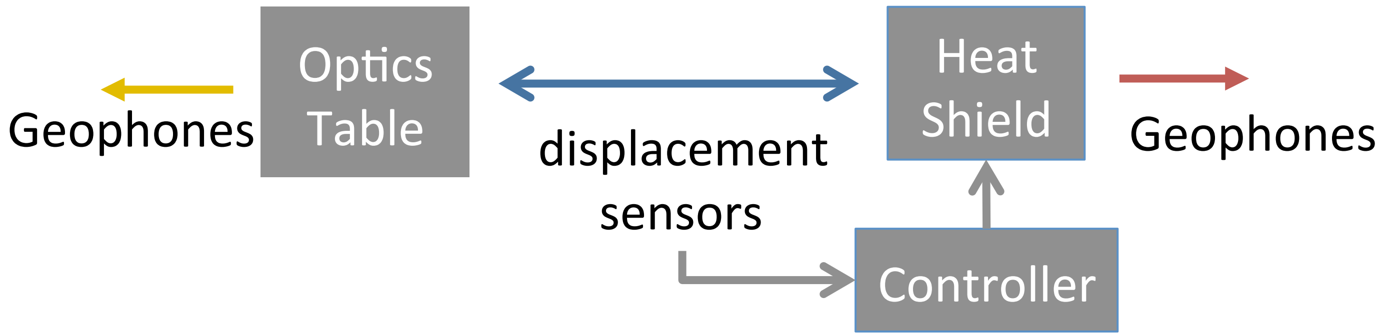
Cool Down Analysis

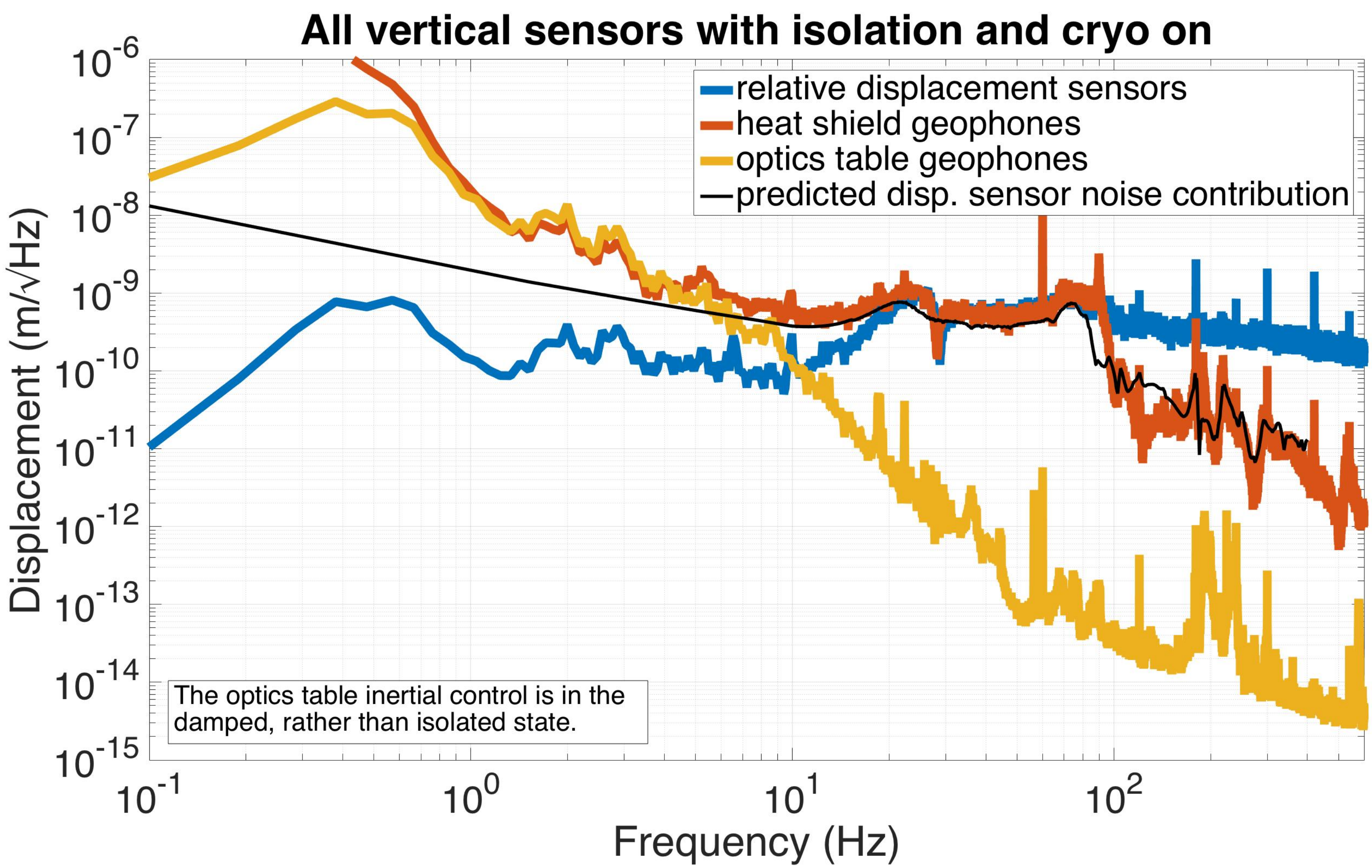


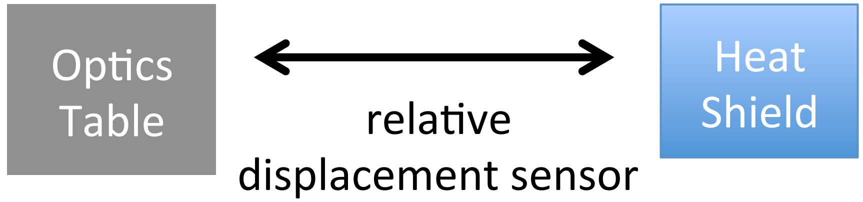
- Estimated conductivity of braids is 60% of the ideal value
- Estimated heat load on shield is 85 W (150 W net incident radiation)

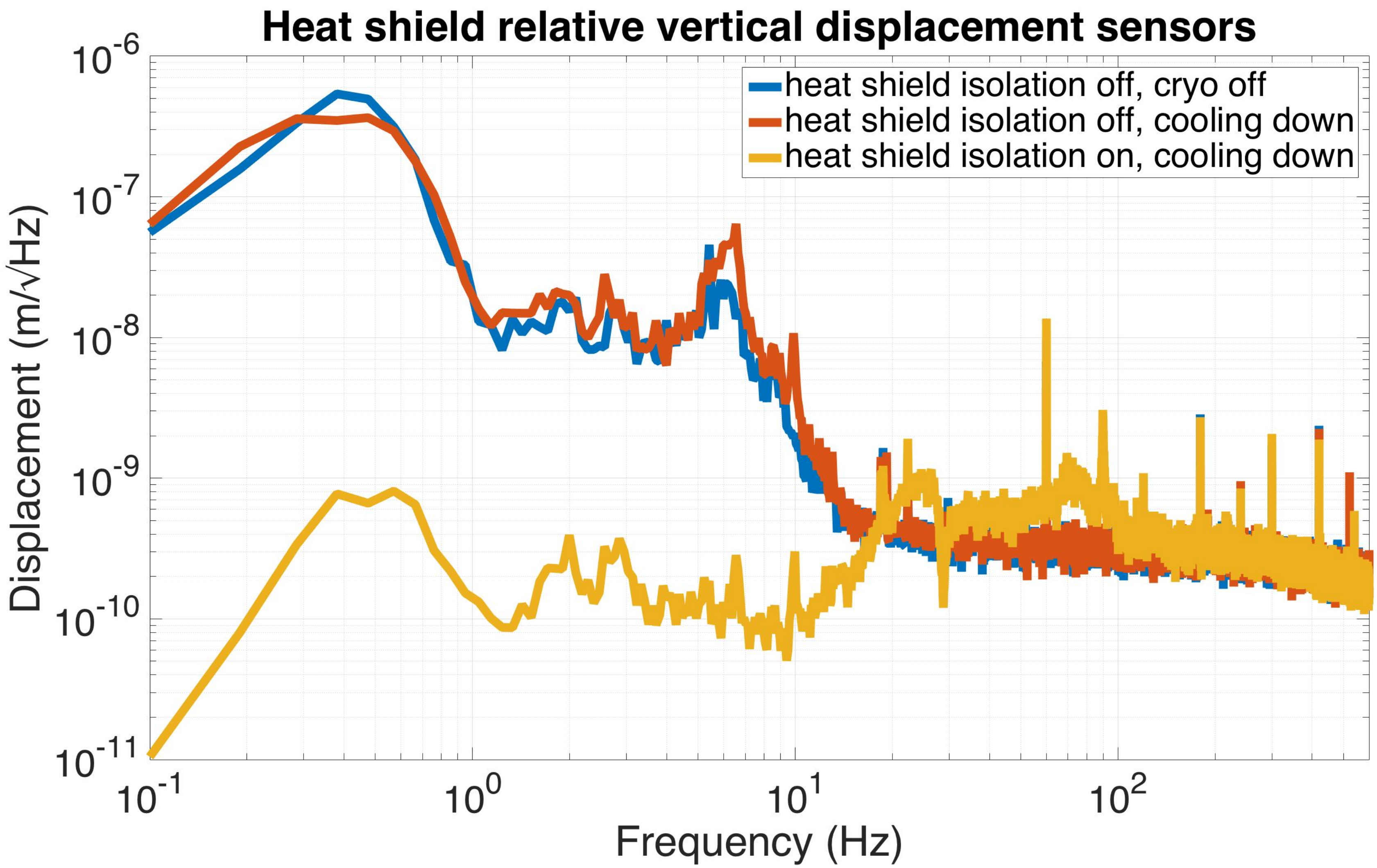
Cool Down Data

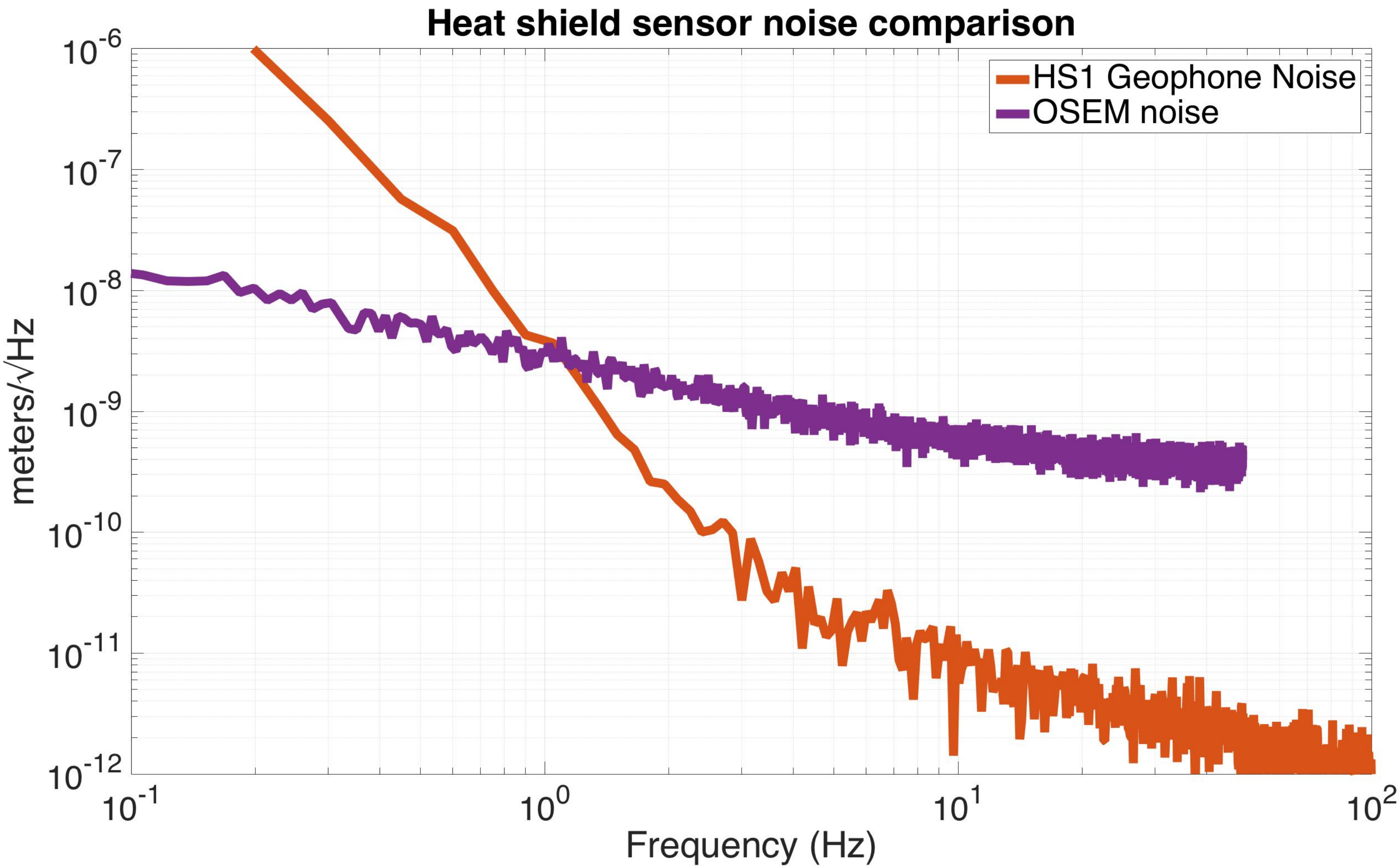



Geophones
Optics Table
displacement sensors
Heat Shield
Geophones
Controller

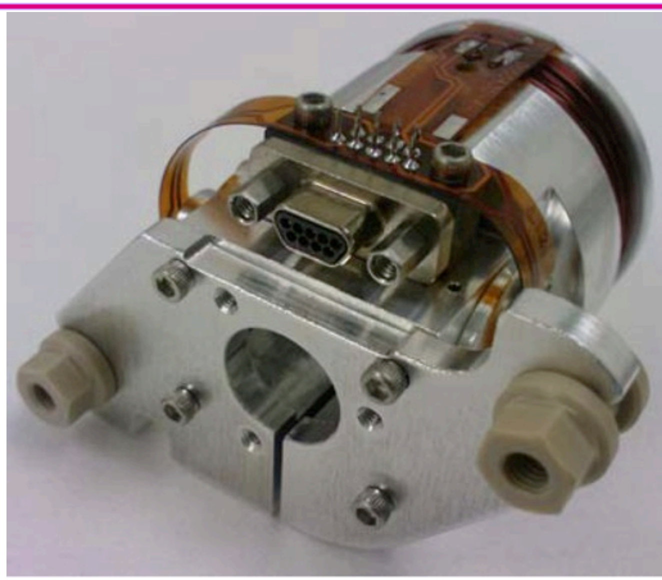

All vertical sensors with isolation and cryo on
relative displacement sensors
heat shield geophones
optics table geophones
predicted disp. sensor noise contribution
The optics table inertial control is in the damped, rather than isolated state.
Displacement (m/√Hz)
Frequency (Hz)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-1
10^0
10^1
10^2


Optics Table
relative displacement sensor
Heat Shield

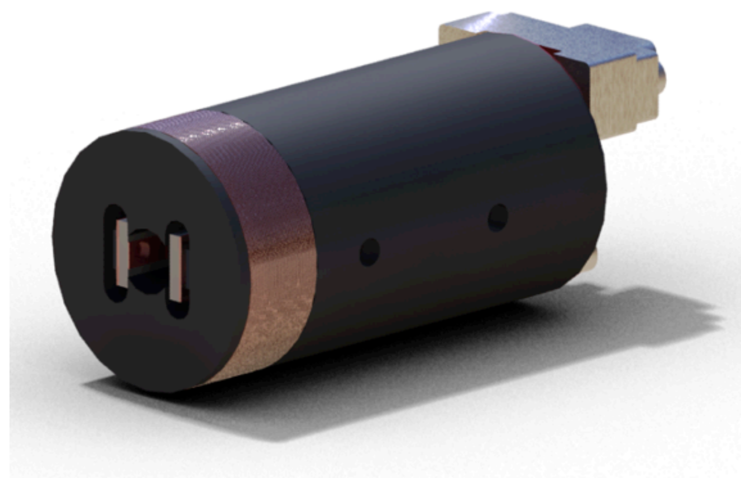

Heat shield relative vertical displacement sensors
heat shield isolation off, cryo off
heat shield isolation off, cooling down
heat shield isolation on, cooling down
Displacement (m/√Hz)
Frequency (Hz)
10-6
10-7
10-8
10-9
10-10
10-11
10-1
100
101
102


Heat shield sensor noise comparison
HS1 Geophone Noise
OSEM noise
meters/√Hz
Frequency (Hz)
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-1
10^0
10^1
10^2

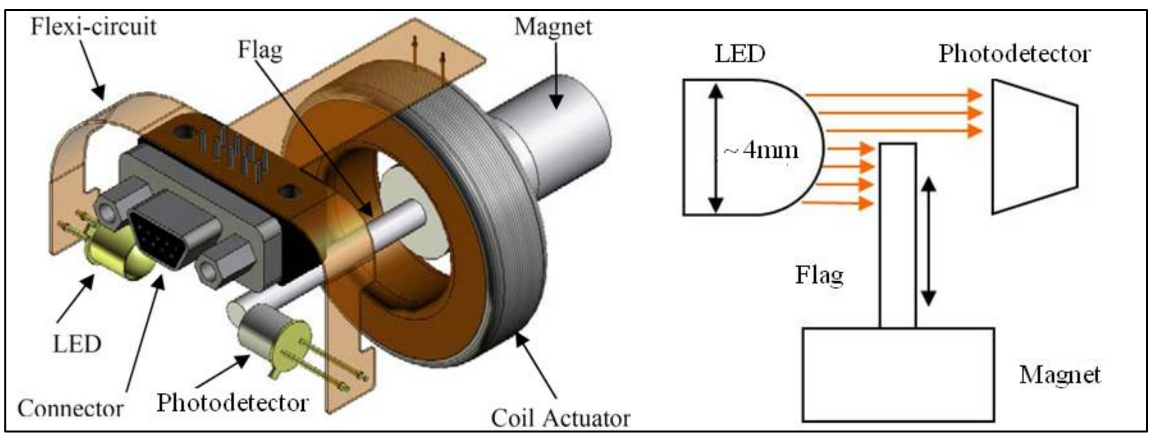
Optical Sensor ElectroMagnet (OSEM)



Birmingham OSEM (BOSEM)



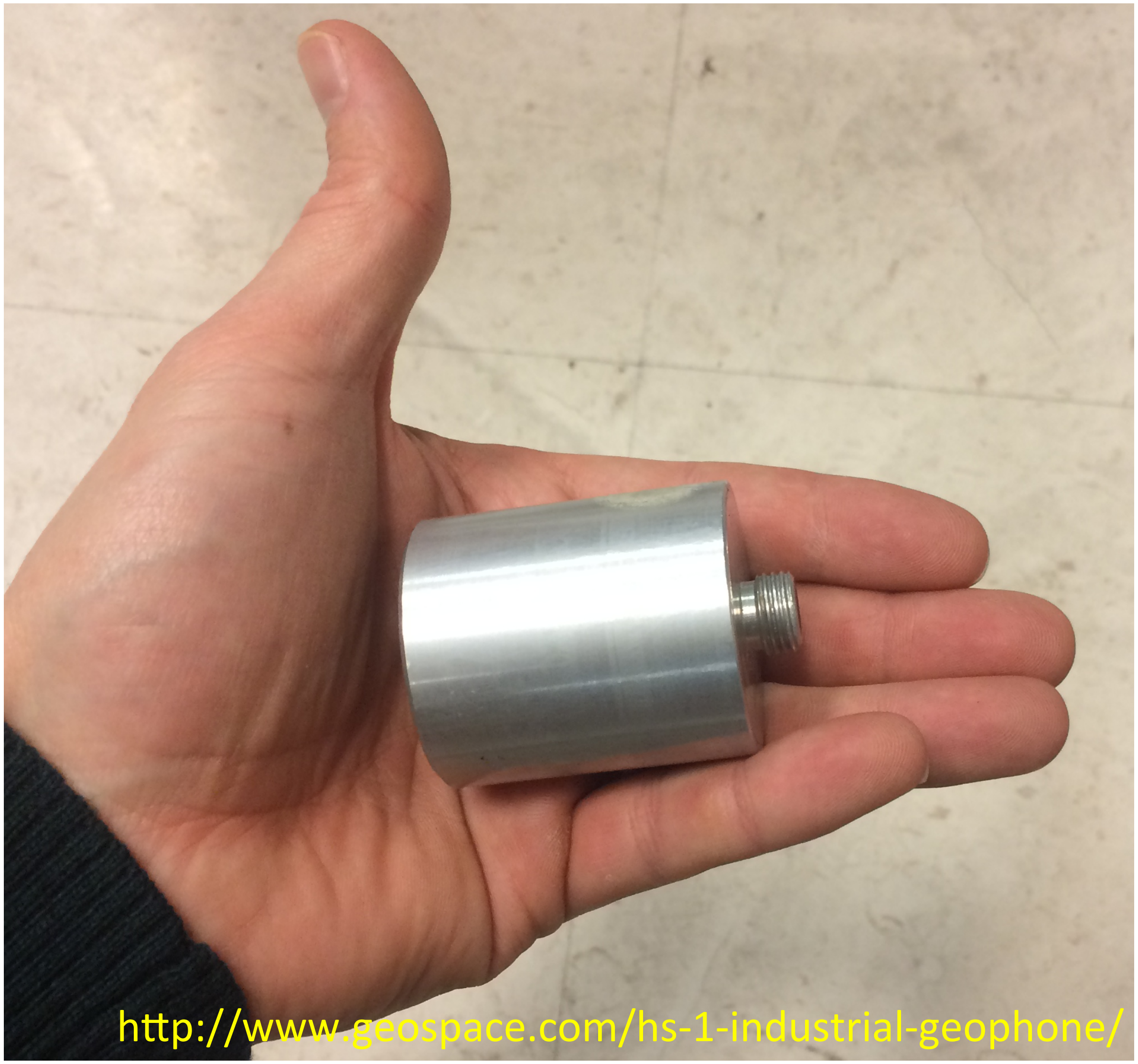
Advanced LIGO OSEM (AOSEM)
- modified iLIGO OSEM



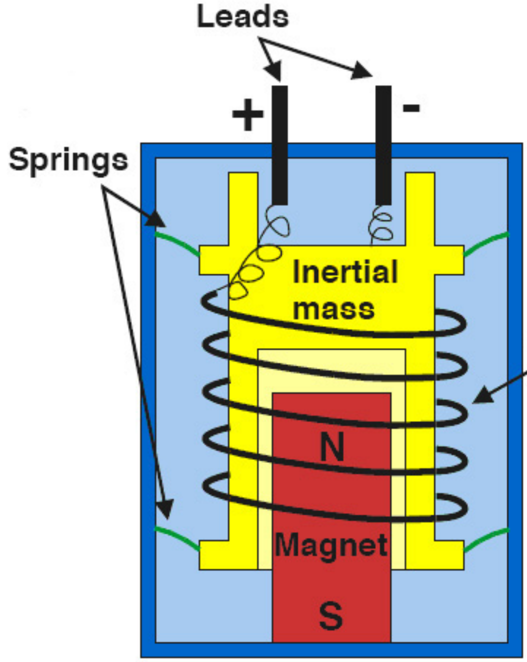
BOSEM Schematic

Magnet Types (M0900034)
- BOSEM – 10 X 10 mm, NdFeB , SmCo
  10 X 5 mm, NdFeB, SmCo
- AOSEM – 2 X 3 mm, SmCo
  2 X 6 mm, SmCo
  2 X 0.5 mm, SmCo

HS1 Geophone

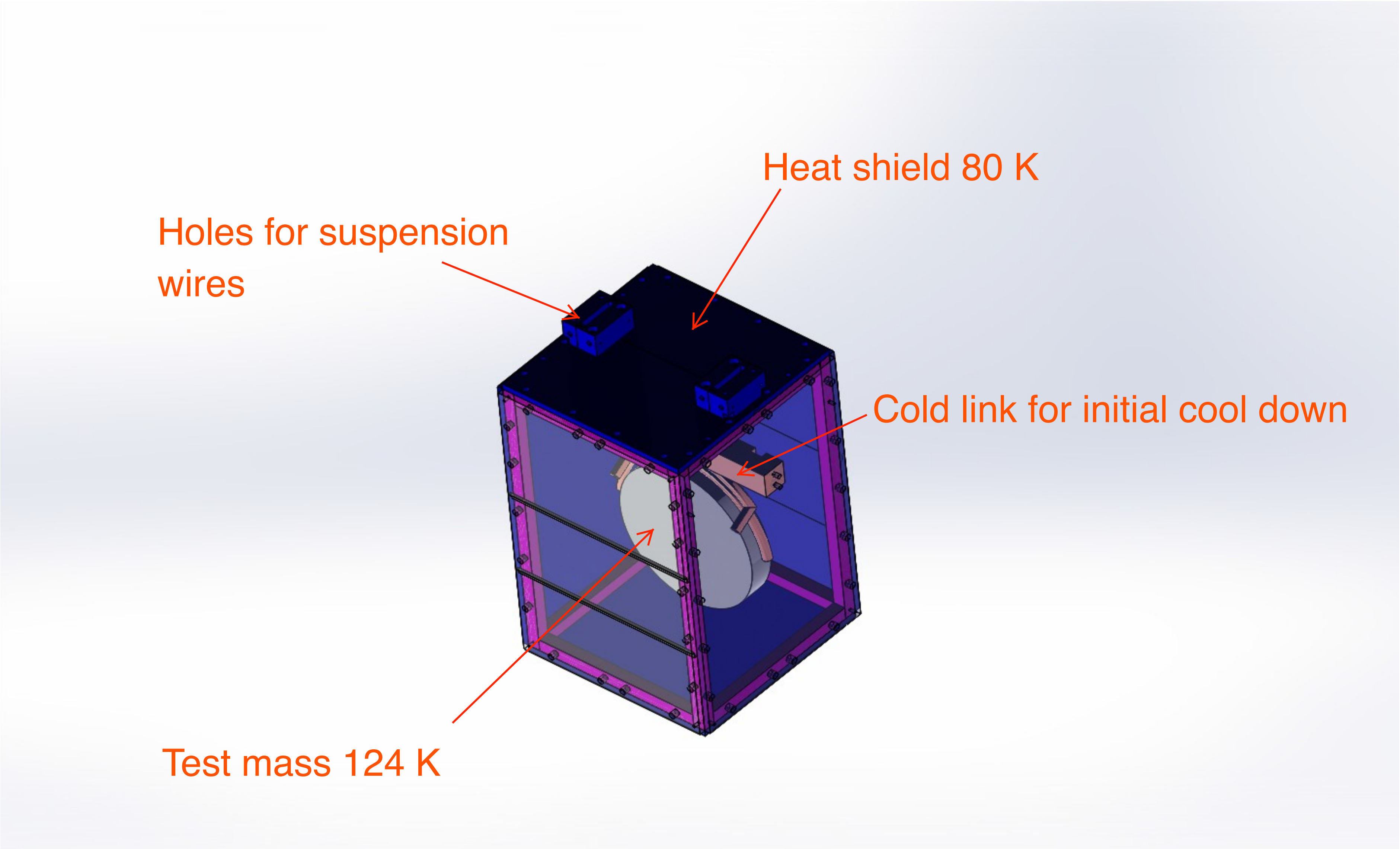


Geophone Schematic

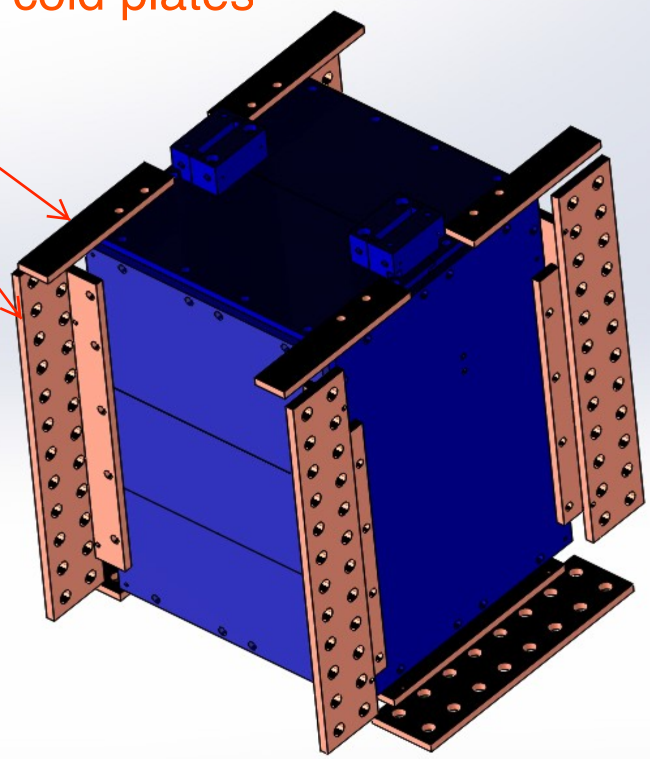


http://newsline.linearcollider.org/readmore_20070809_ftr1.html

Test mass inside heat shield

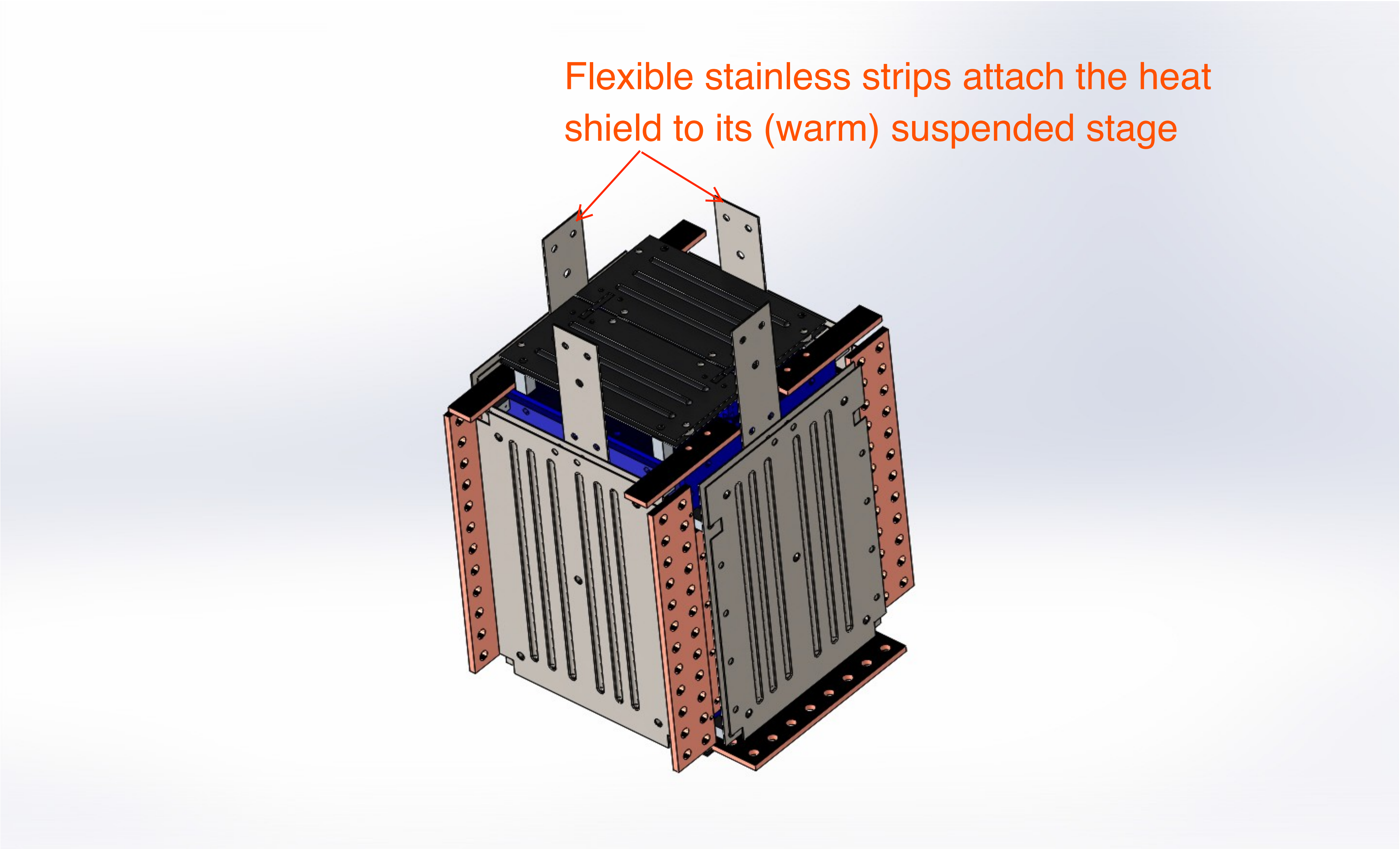


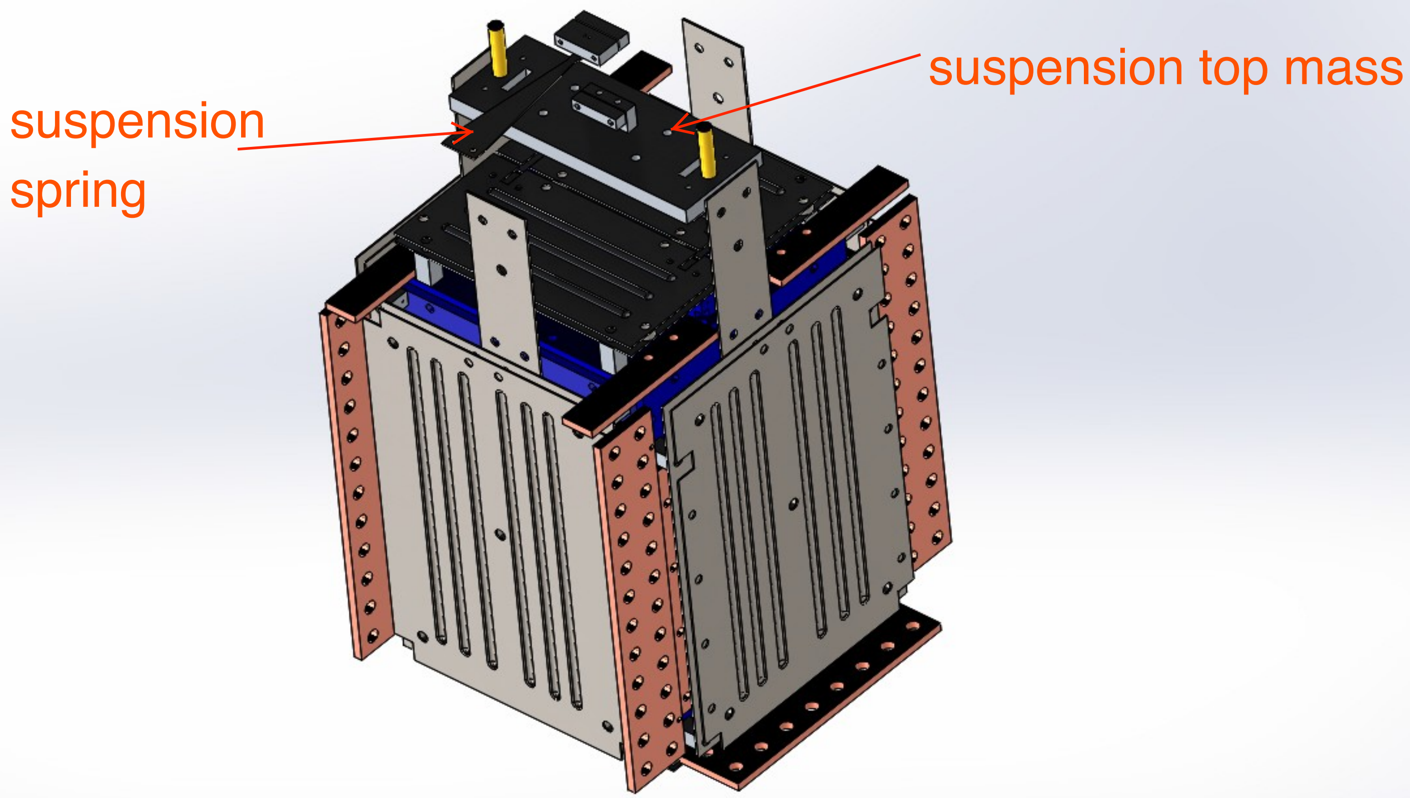
Cu brackets for Cu braids between heat shield and stage 0 cold plates

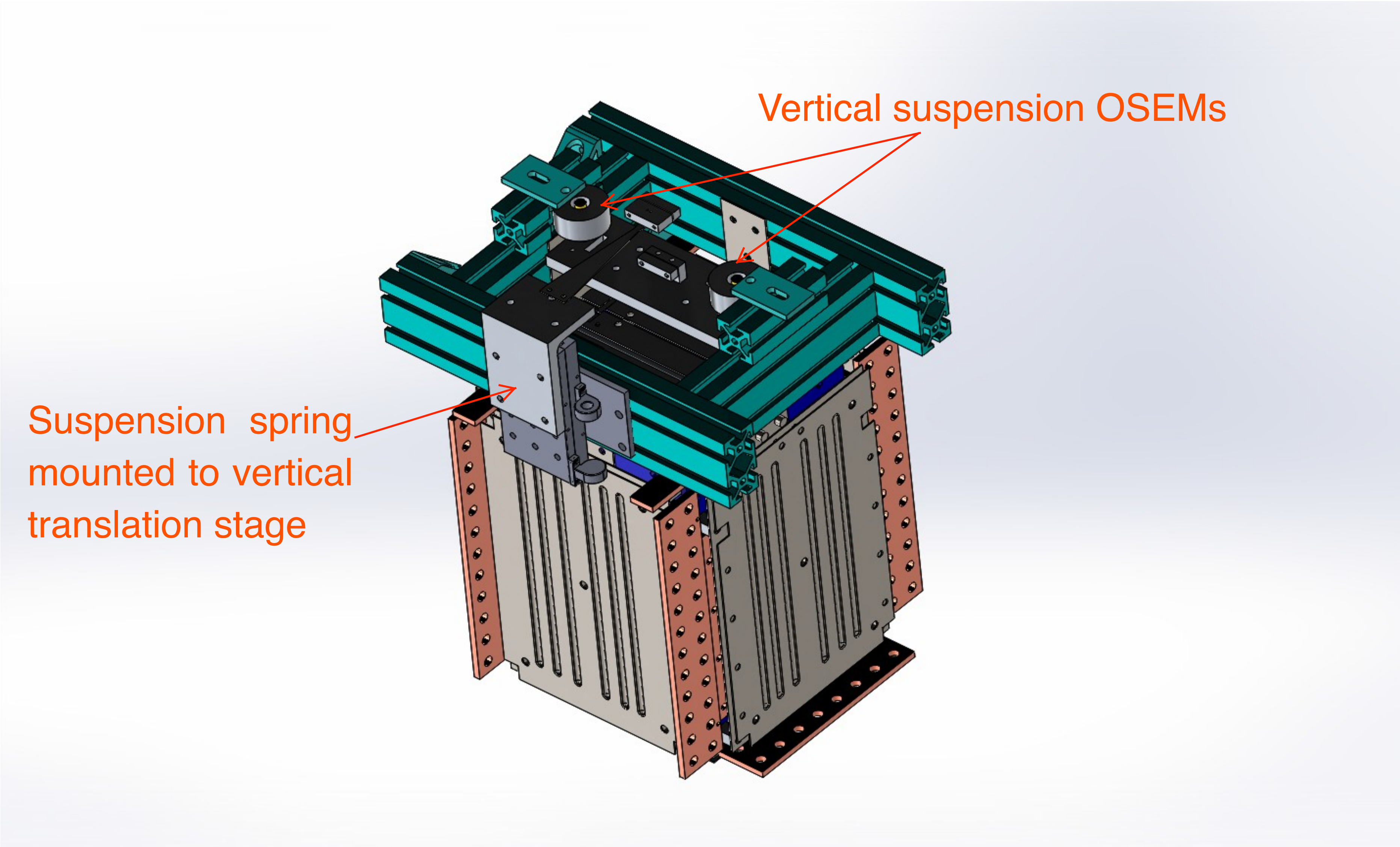



Aluminum low emissivity plates
(ribs boost vibrational frequencies)

g10

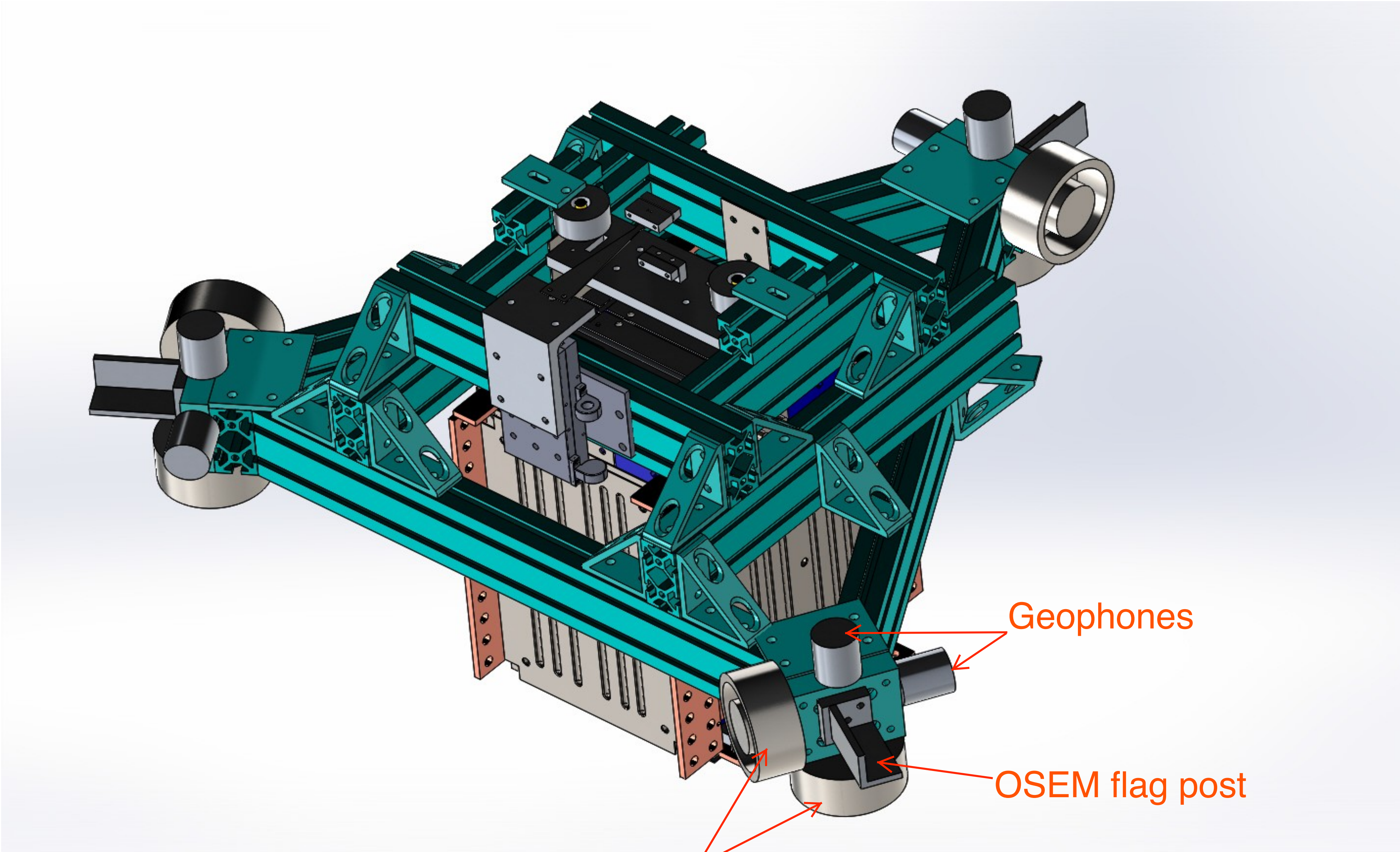

Flexible stainless strips attach the heat shield to its (warm) suspended stage

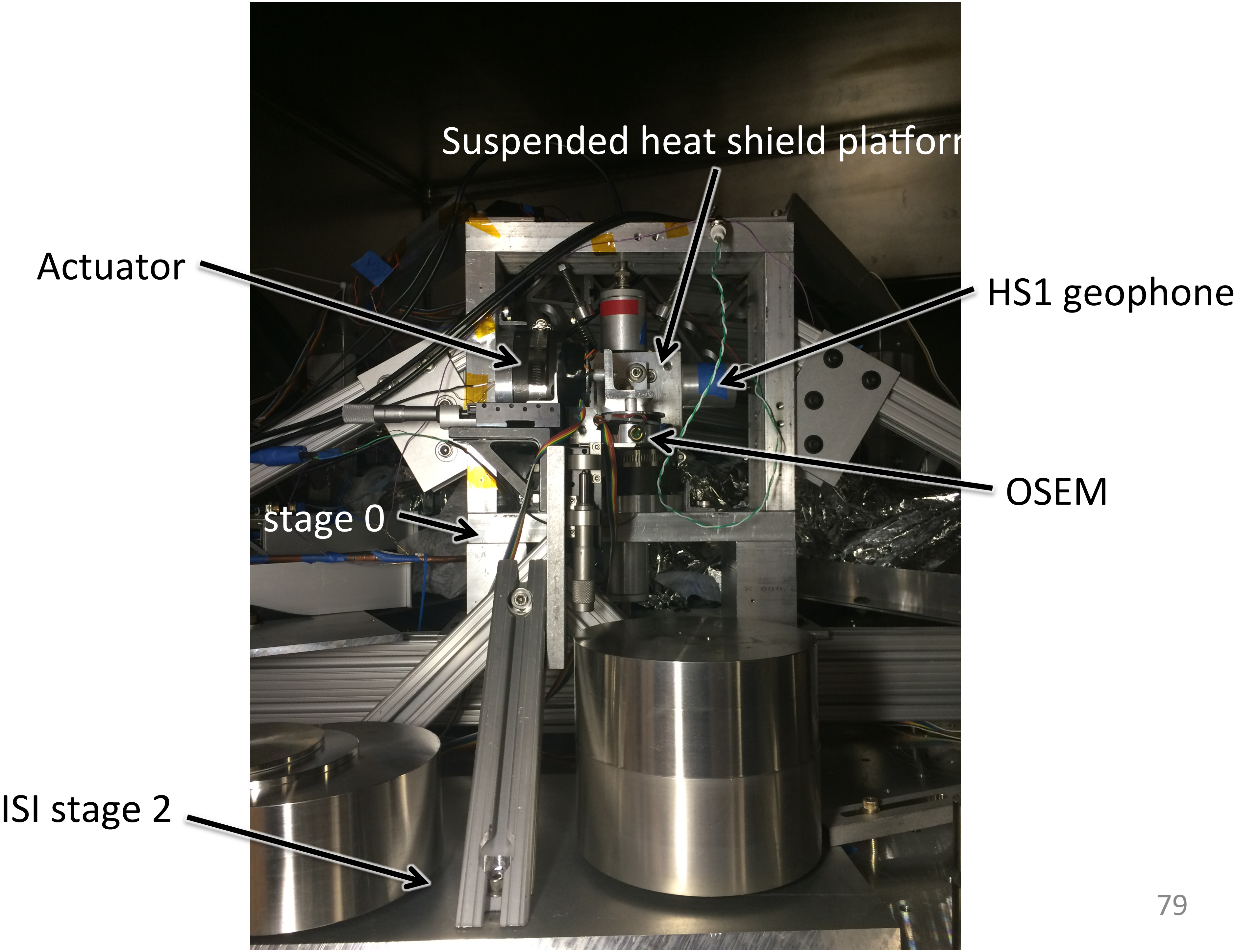

suspension spring
suspension top mass



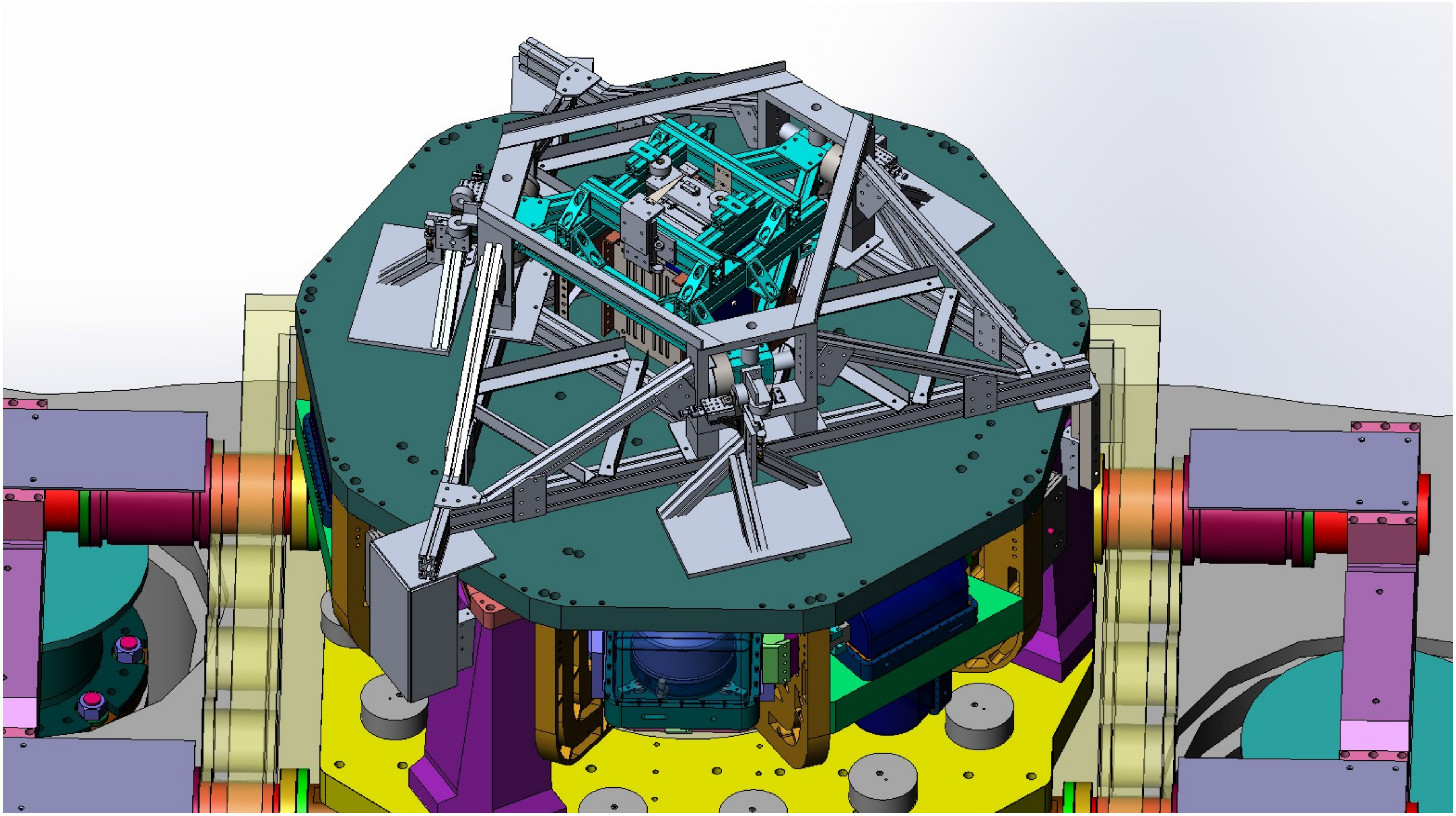
* The OSEMs monitor vertical drift of the suspension due to temperature changes in the spring

The complete heat shield stage

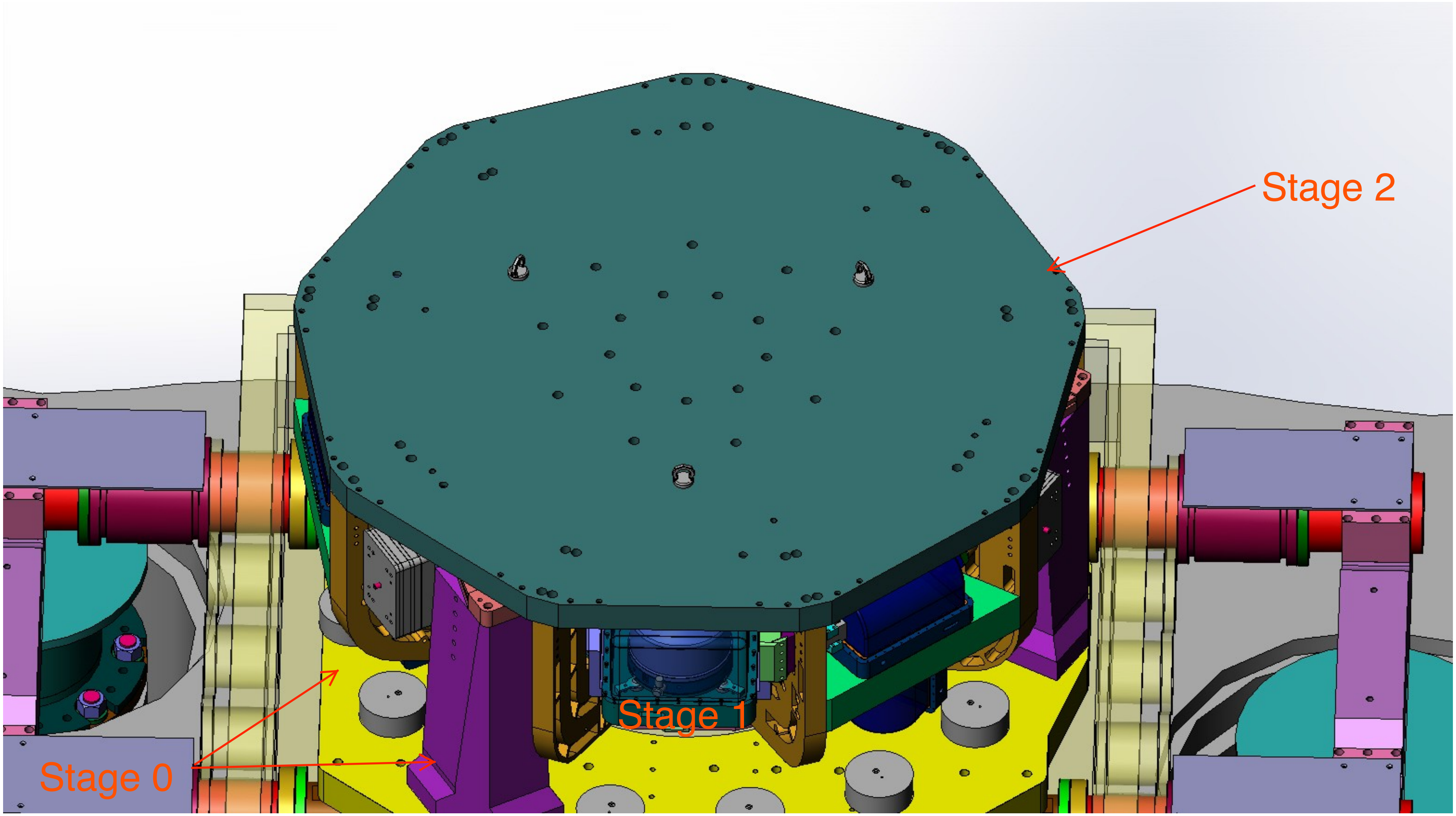



Suspended heat shield platfor
Actuator
HS1 geophone
OSEM
stage 0
ISI stage 2

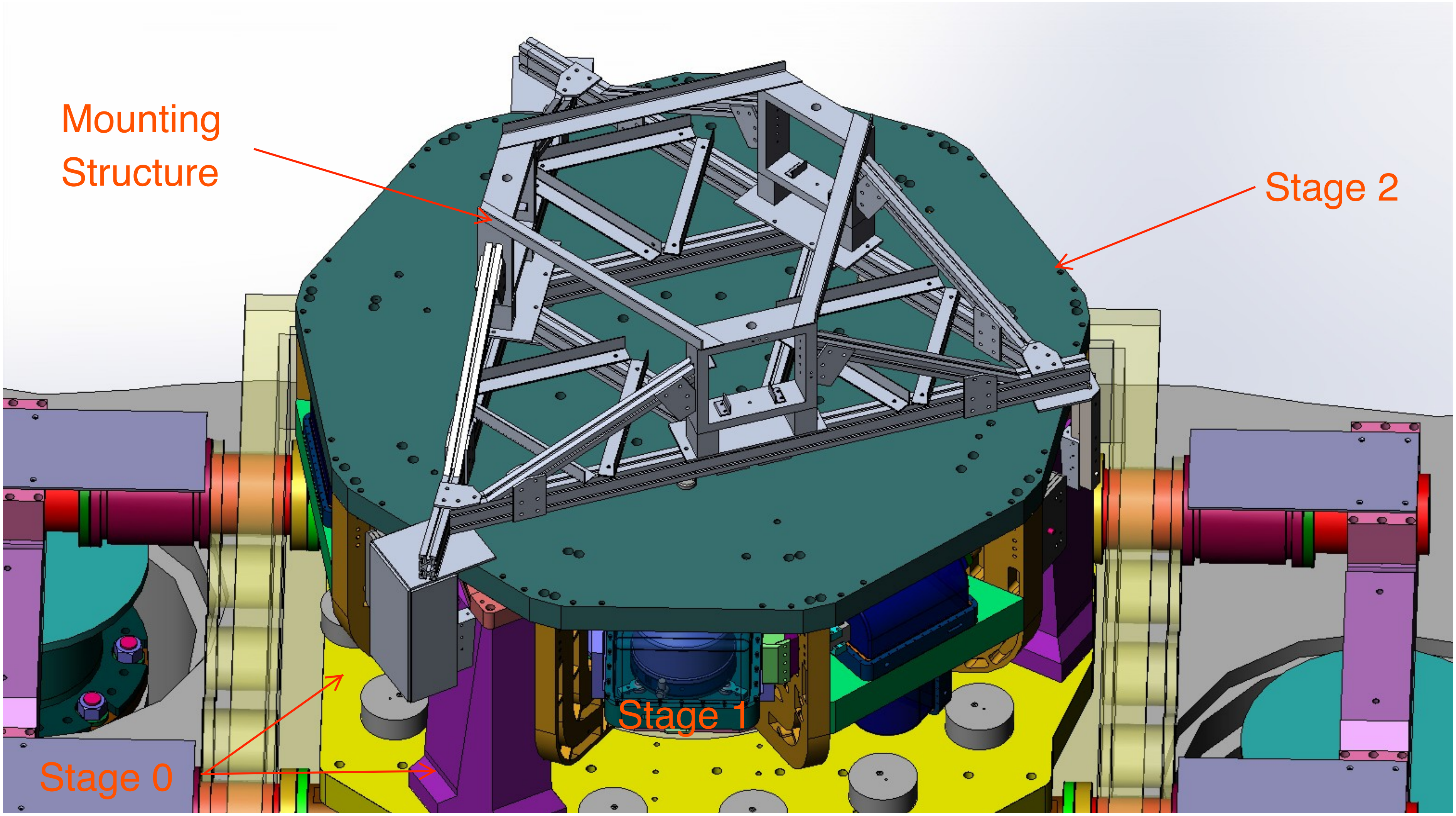
Suspended heat shield stage over Stanford ISI



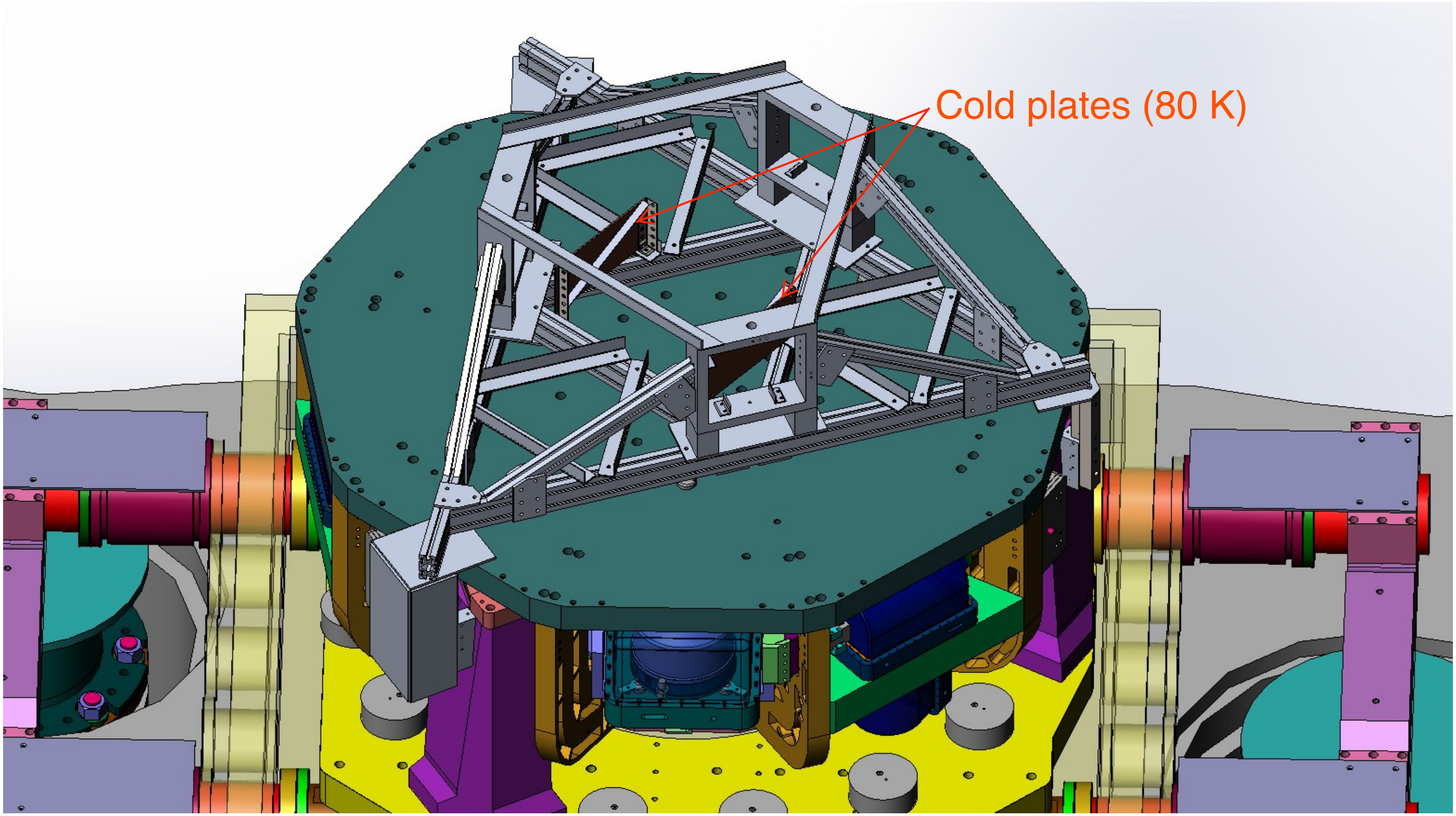
2 stage HAM-like ISI



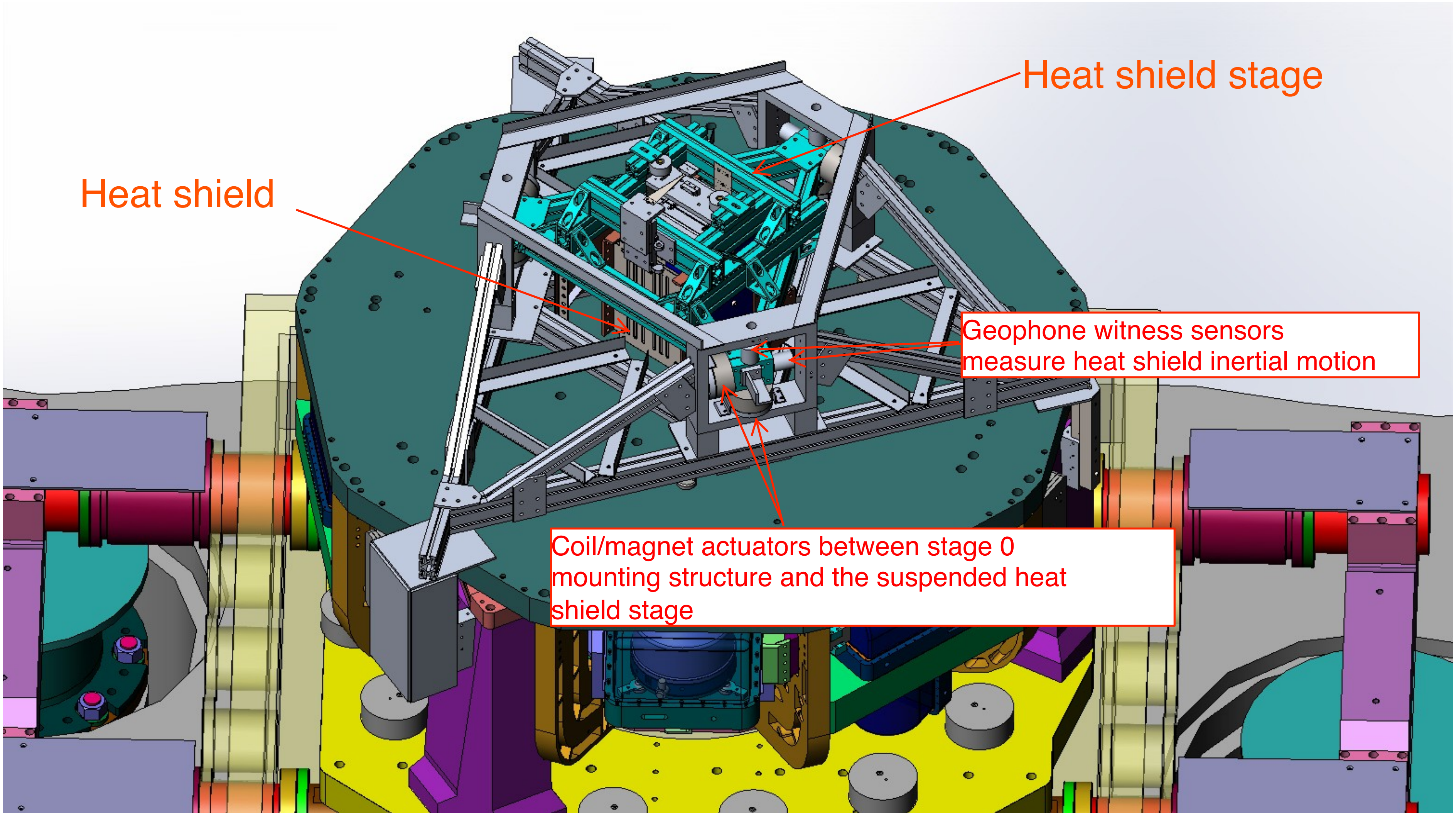
ISI with stage 0 mounting structure for heat shield over stage 2



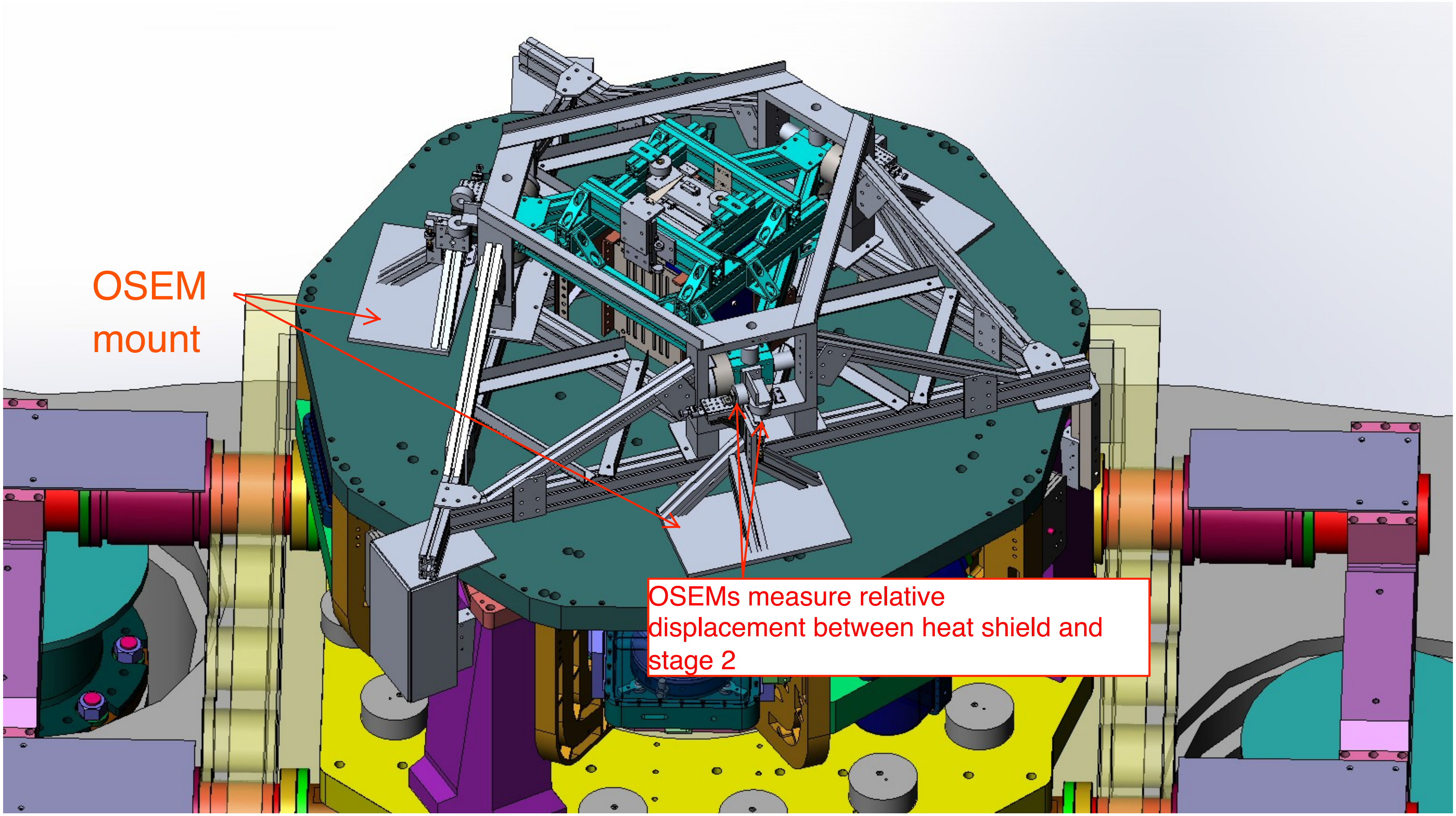
Mounting structure with cryogenic cold plates

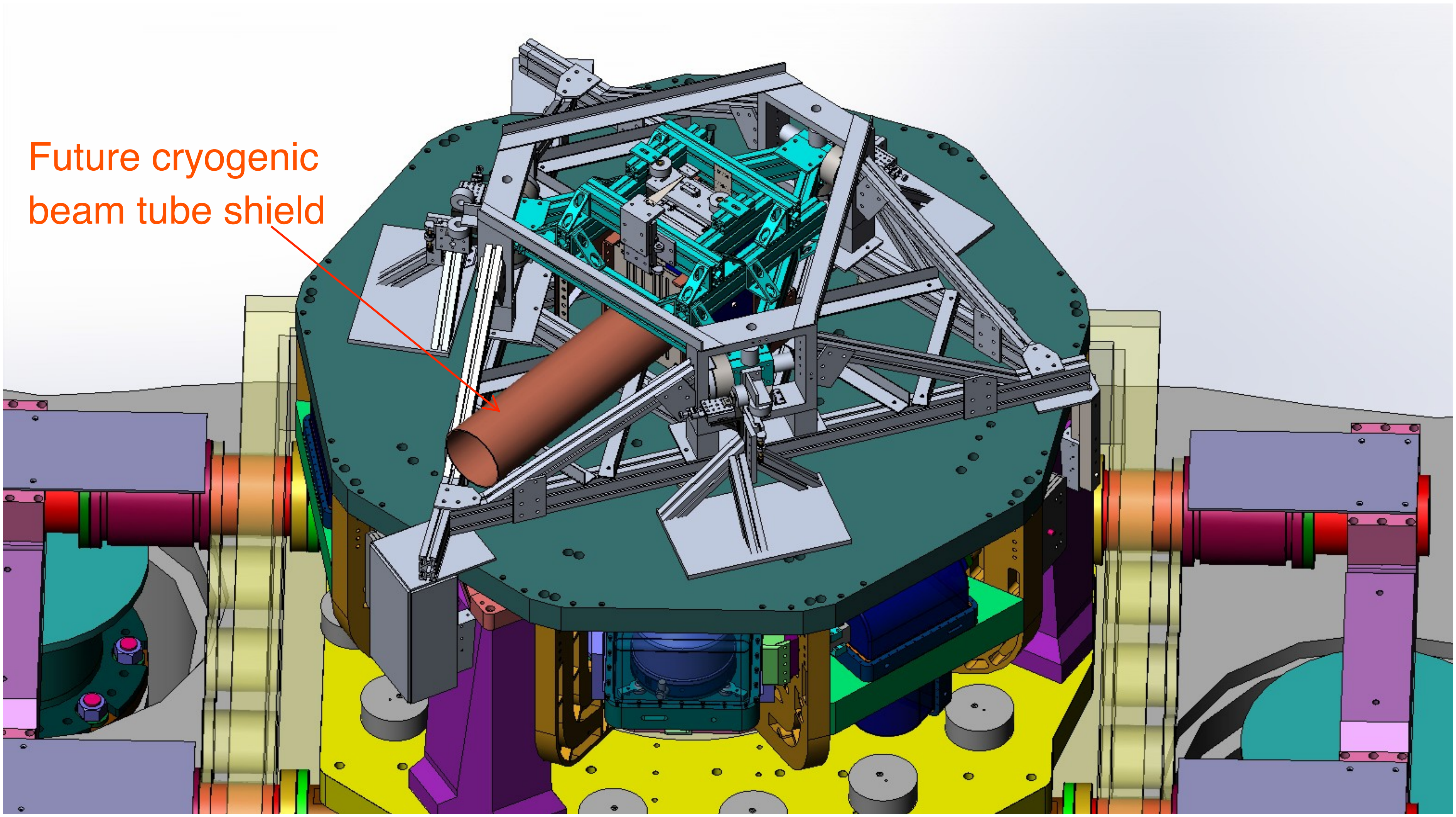


Suspended heat shield stage hanging from mounting structure



OSEM feedback forces the heat shield to follow stage 2




Future cryogenic
beam tube shield