# MONET

## Mechanical Oscillations in Non-Equilibrium Thermodynamics

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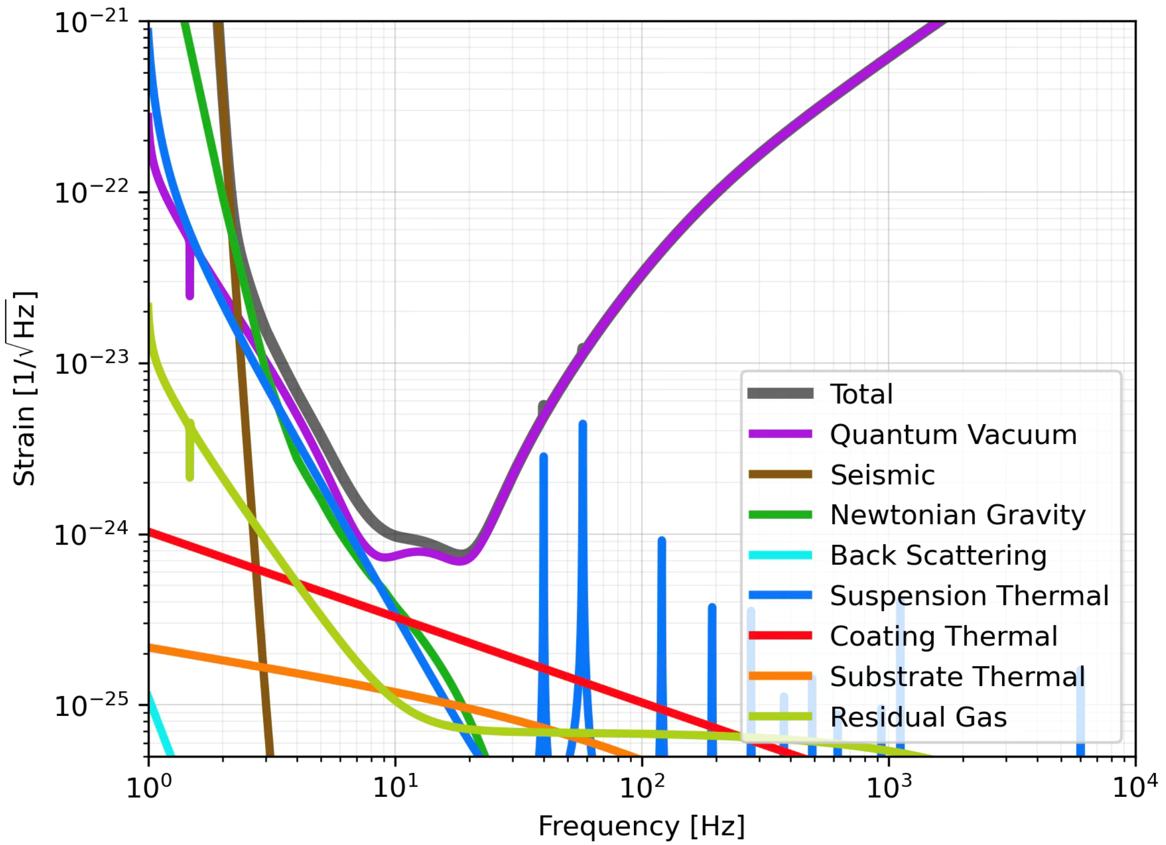
METROLOGY MT & OPTICAL ENGINEERING

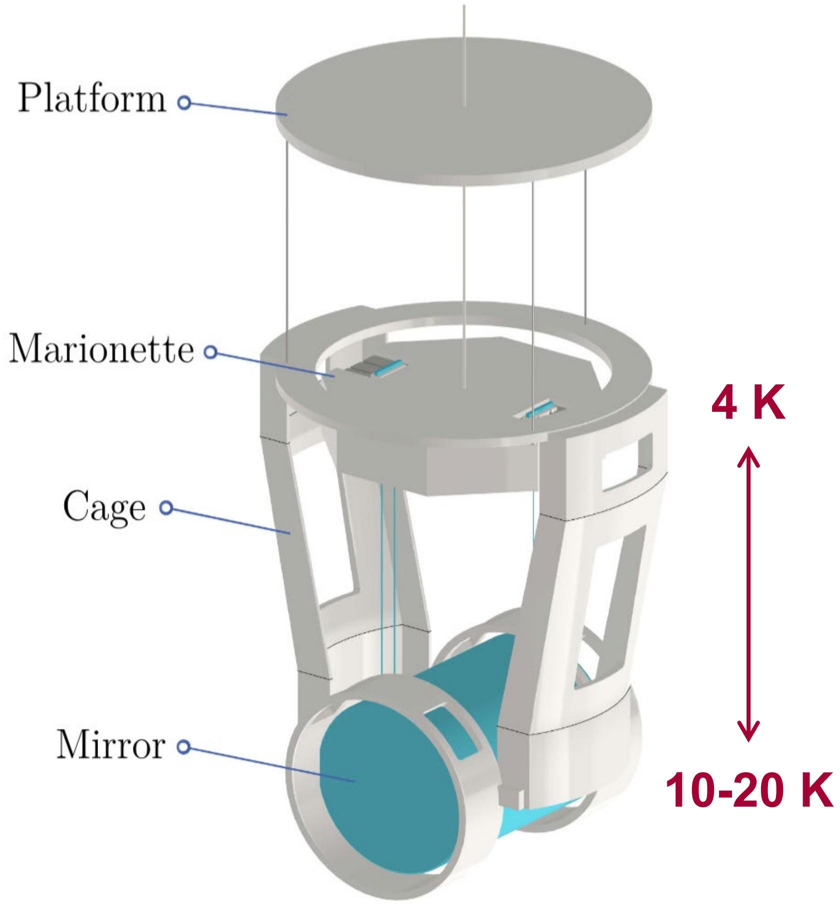
# Thermal Gradients in Einstein Telescope

- Suspension thermal noise limits sensitivity
- Einstein Telescope will be **cryogenic**
- Cooling scheme not finalised
- Dependent on material parameters such as Q Factor



# Thermal Gradients in Einstein Telescope

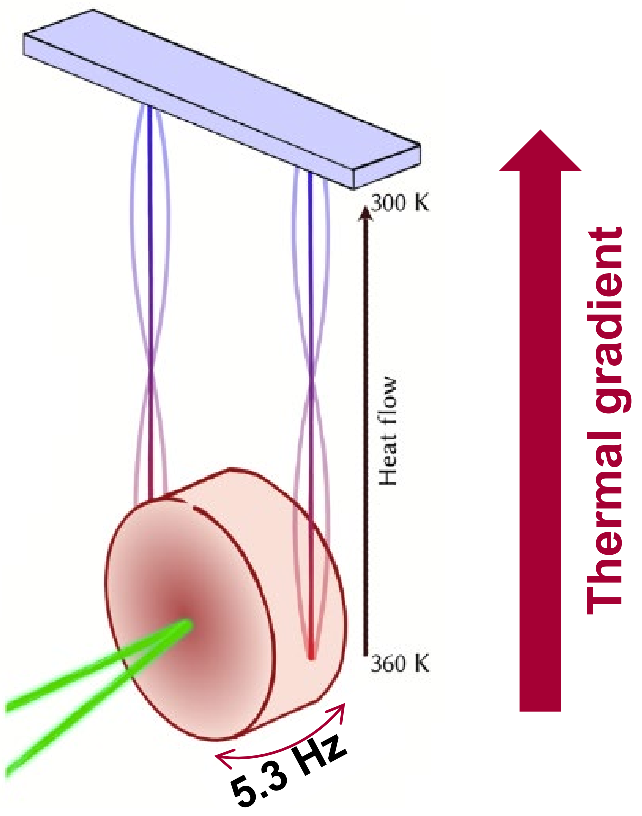
- **~10K** thermal gradient along test mass suspension
- Studies on thermal noise of oscillators with heat flux (Conti 2013, Komori 2018)
- Effect on mechanical properties of suspension not fully understood.




Virgo suspension Koroveshi (2023)

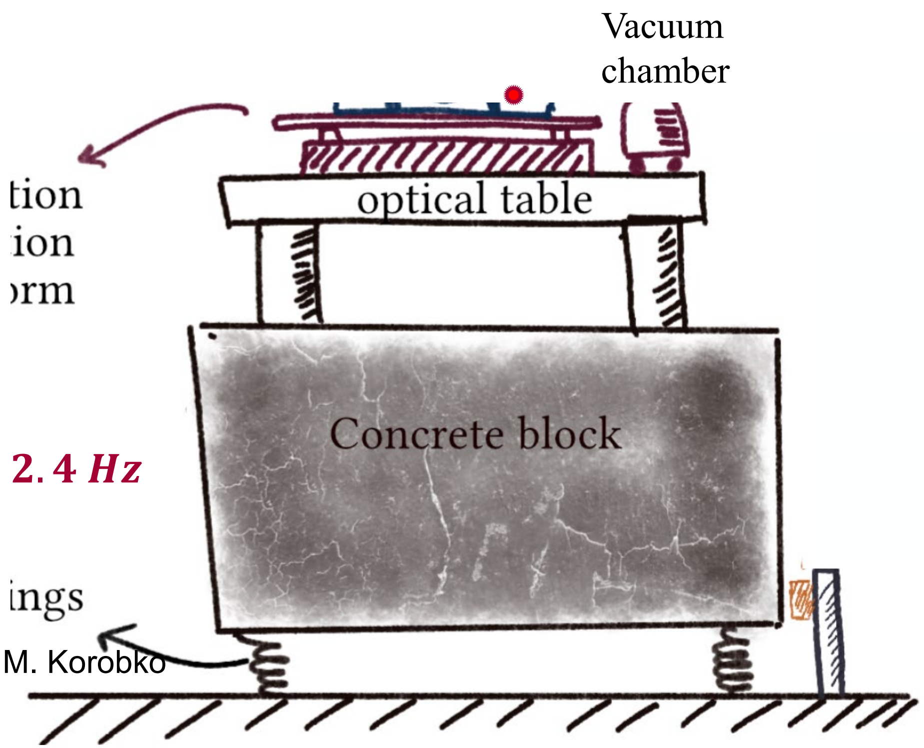
# Mechanical Oscillations in Non-Equilibrium Thermodynamics

- Mechanical response of suspension
- Create thermal gradients in test mass suspensions
- Exciting the test mass
- Measure ringdowns of suspension




Picture: M. Korobko

# Low Noise Lab Setup



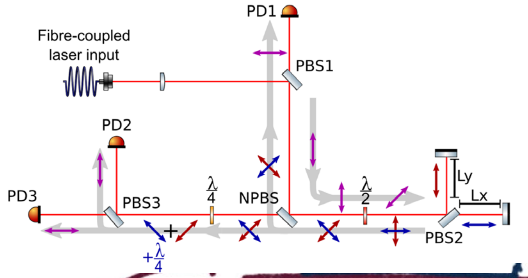

$f_{res} = 2.4\ Hz$

Picture: M. Korobko

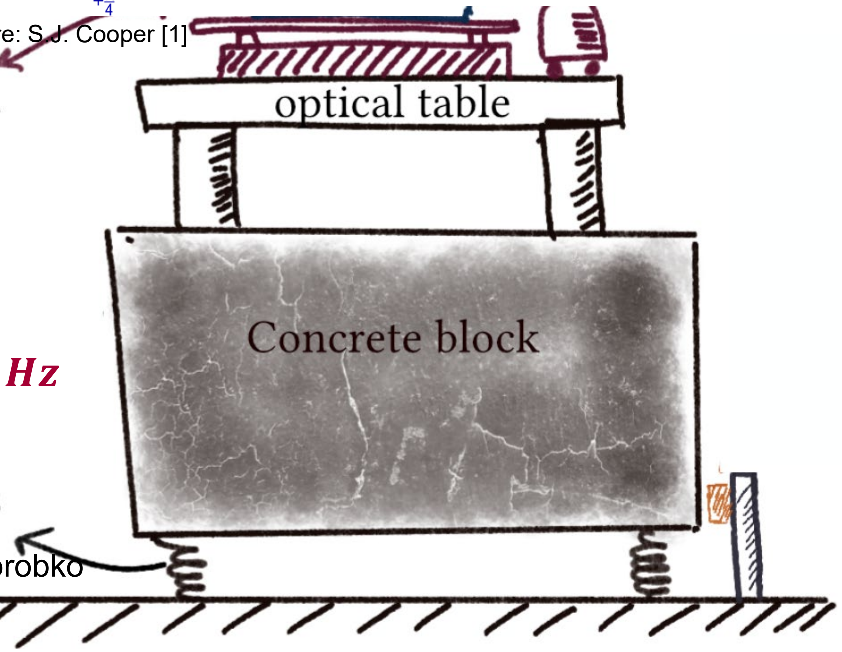
- Vibration isolation platform
- Active and passive isolation
- Decouples optical table from seismic background

D. Hartwig, (2024) *Mitigating Anthropogenic Seismic Noise For Precision Experiments In Urban Environments*

# Low Noise Lab Setup




Picture: S.J. Cooper [1]

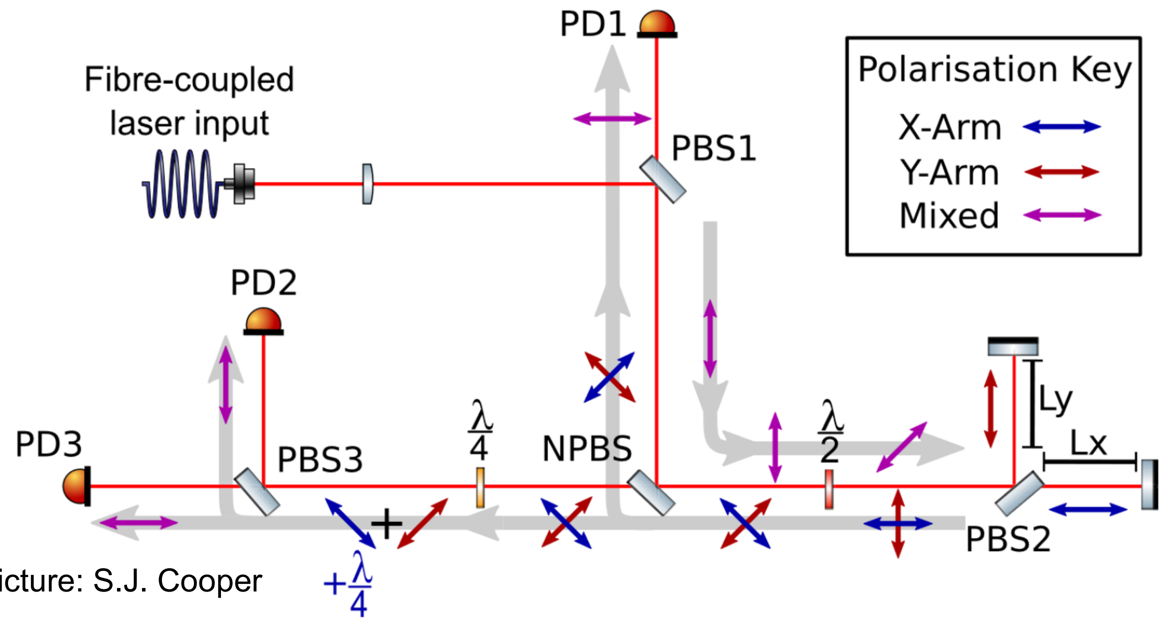



$f_{res} = 2.4\ Hz$

Picture: M. Korobko

- “Homodyne Quadrature interferometer”-like setup on seismic isolation platform
- Interferometer arms in vacuum chamber

# Homodyne Quadrature Interferometer

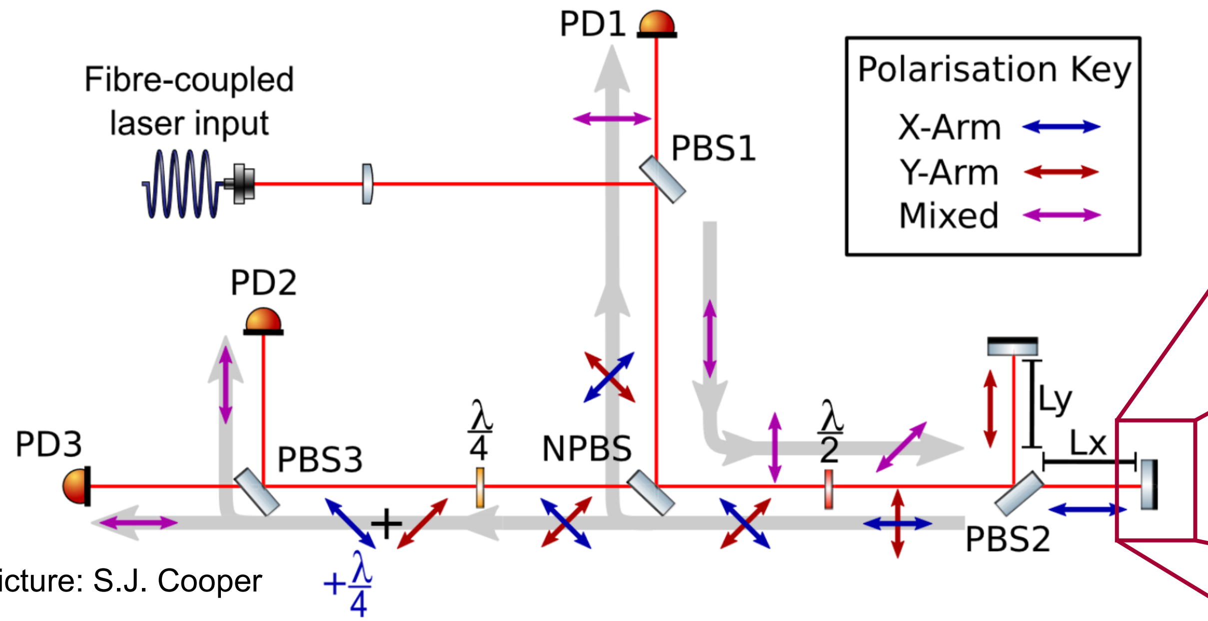



Picture: S.J. Cooper

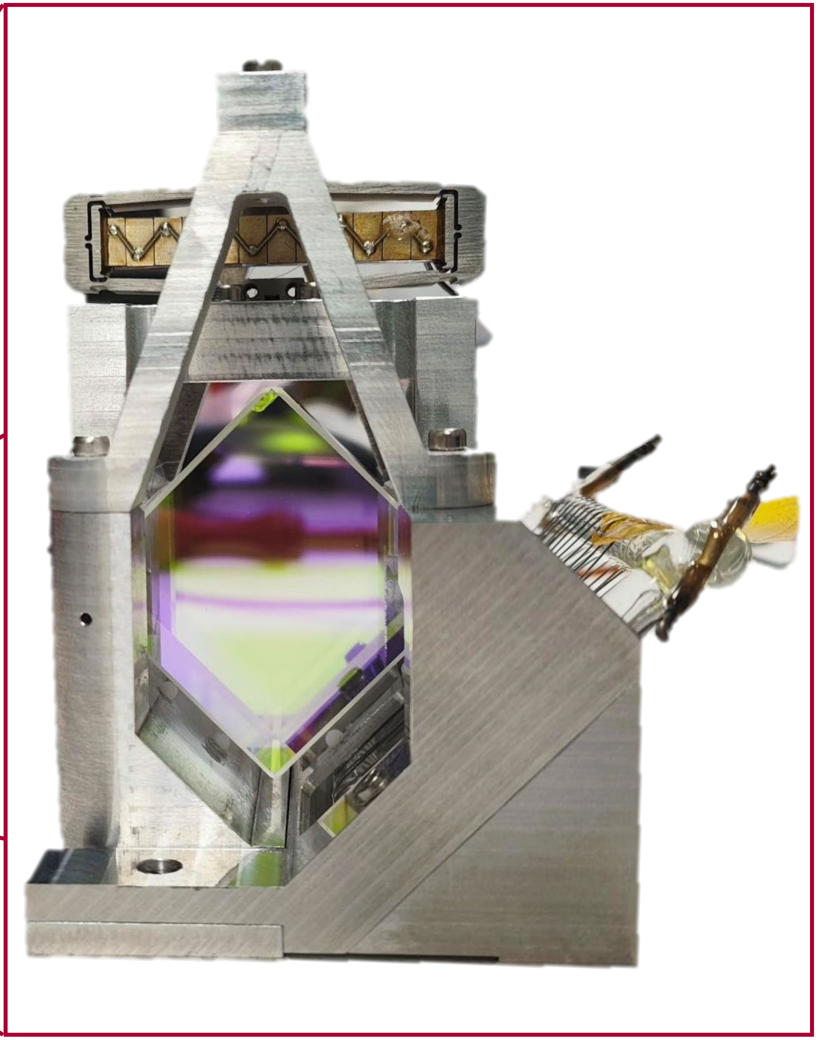
- “Homodyne Quadrature interferometer”-like setup
- High dynamic range, multi fringe readout

$$\Delta Lx = \sim 1\ mm$$

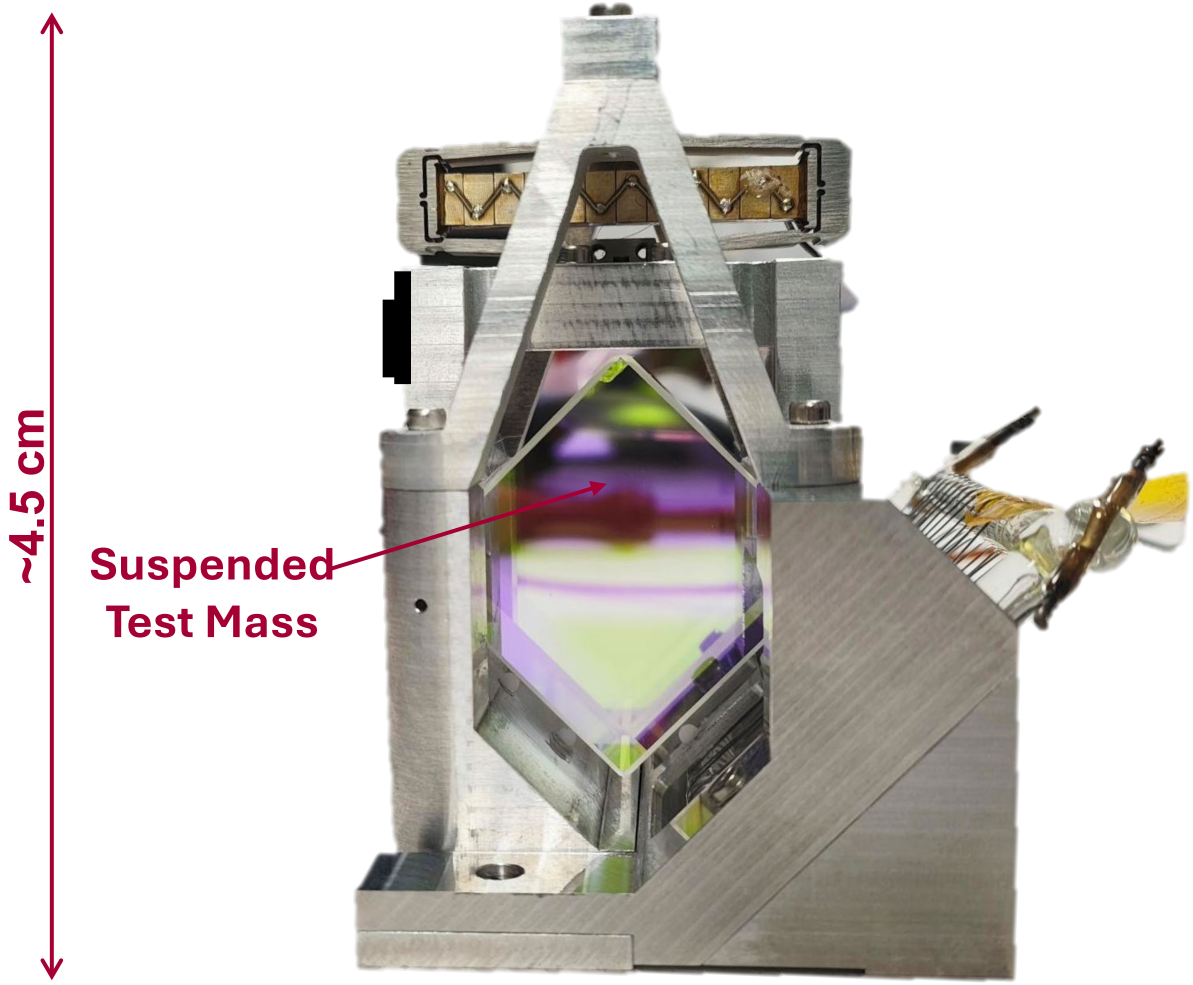
# Interferometric Setup



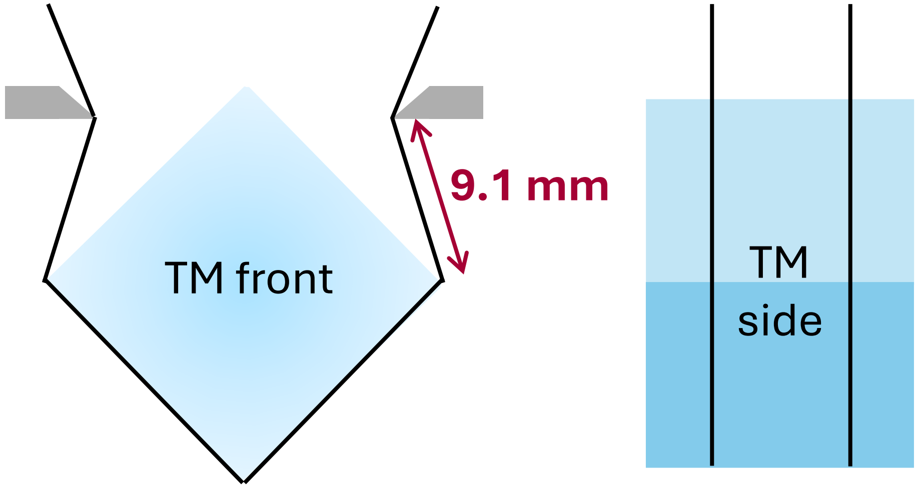

Picture: S.J. Cooper



# Quadruple Suspension

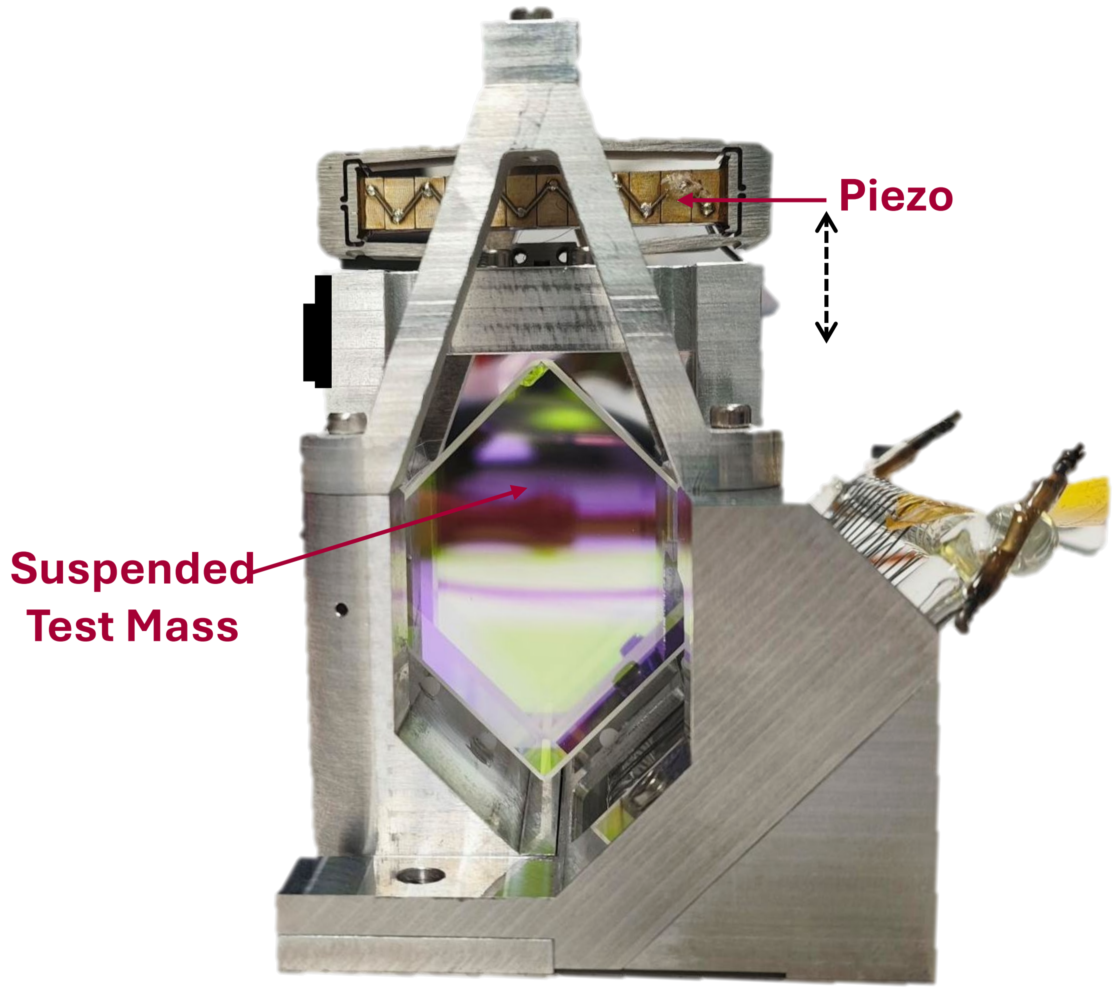



- Two parallel suspensions
- 40 µm Tungsten wire

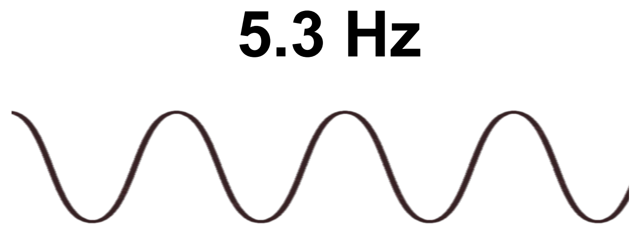



Adapted from: D. Hartwig, PhD Thesis (2024)

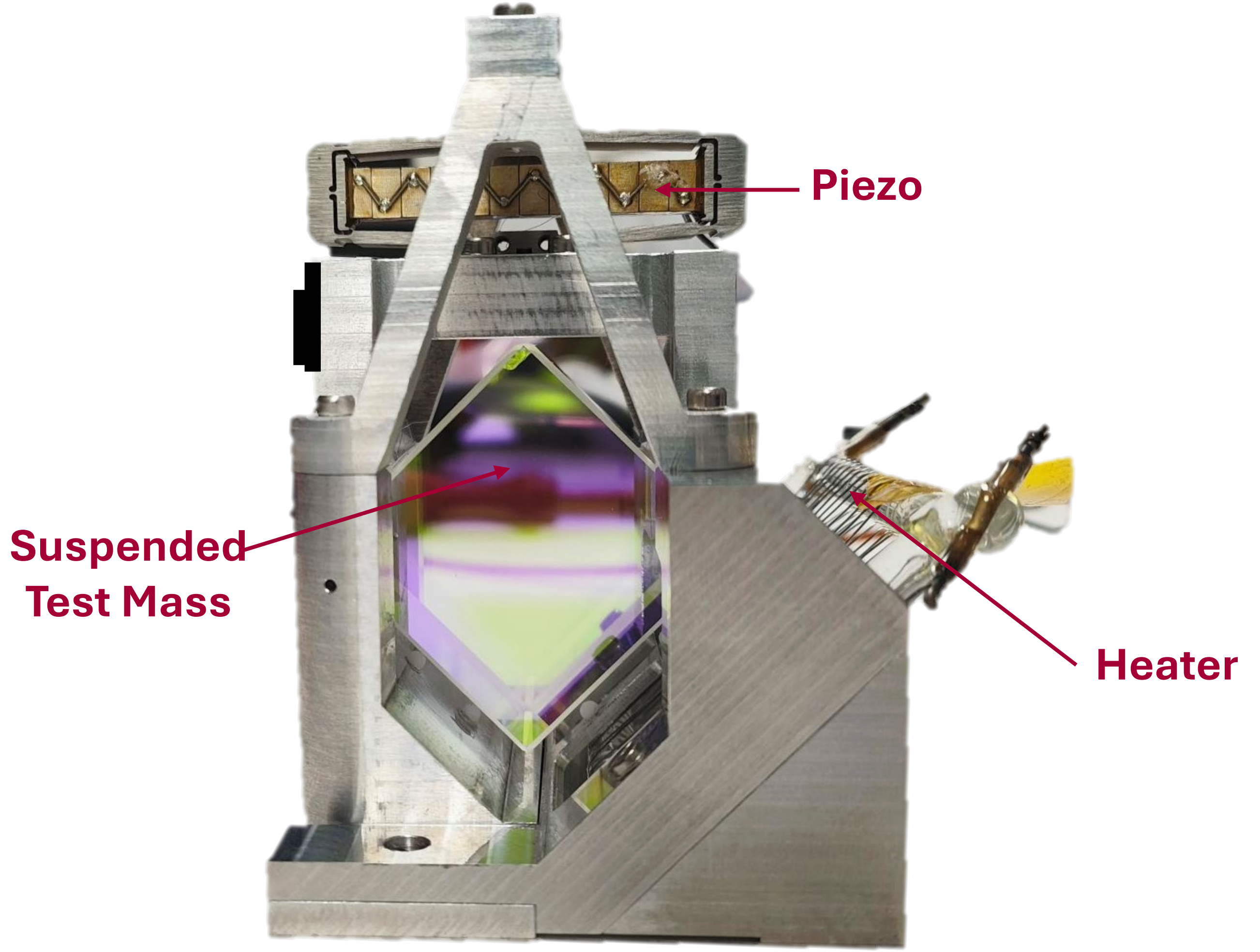
# Quadruple Suspension



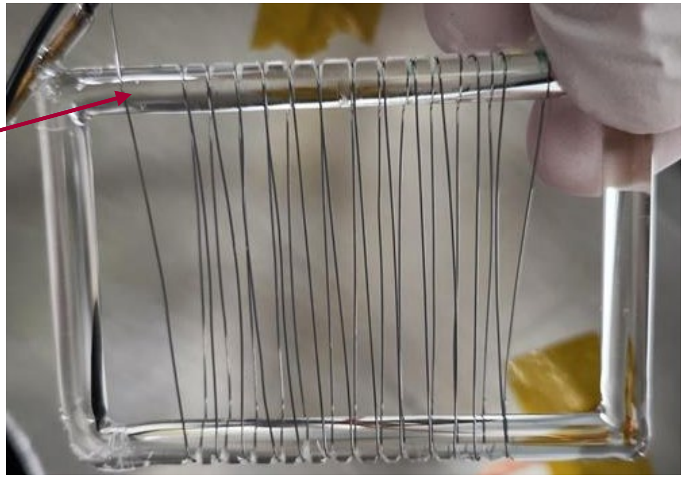

- Excite the test mass
- Sine wave at 5.3 Hz



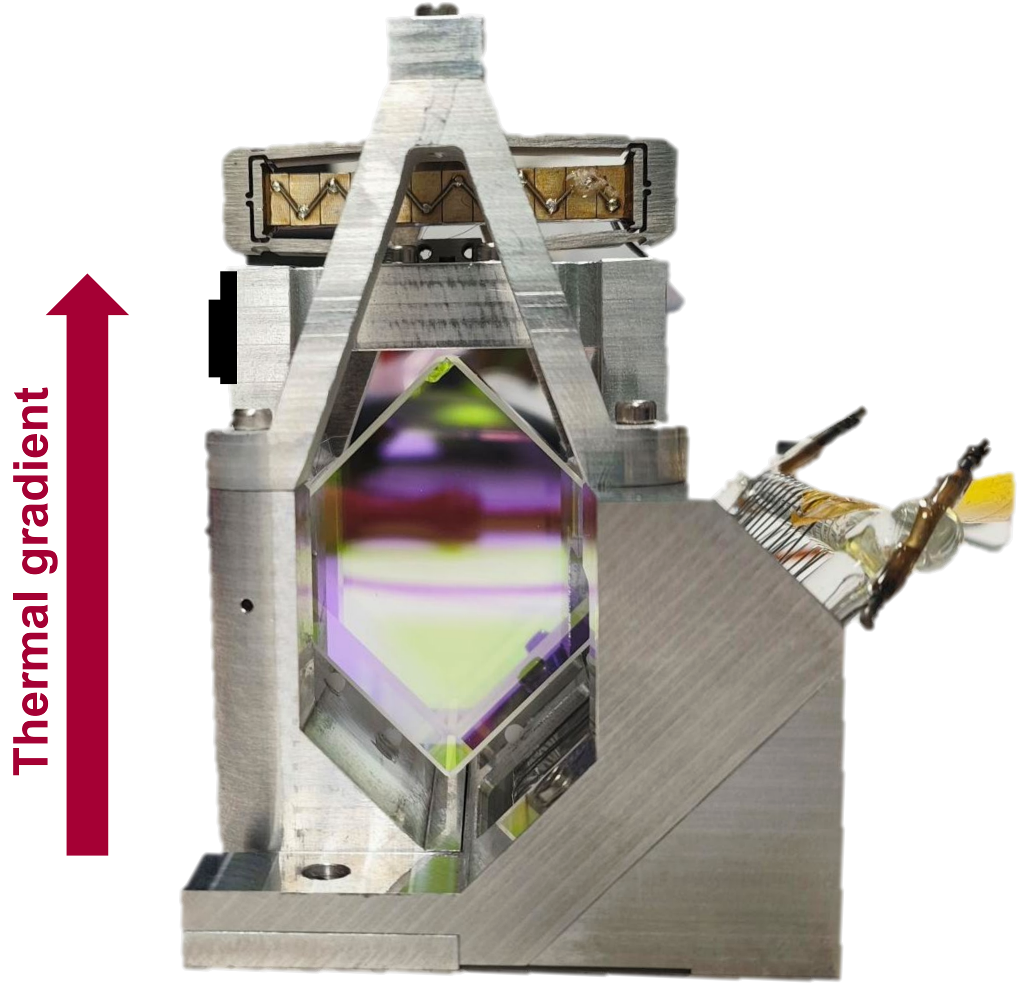
# Quadruple Suspension

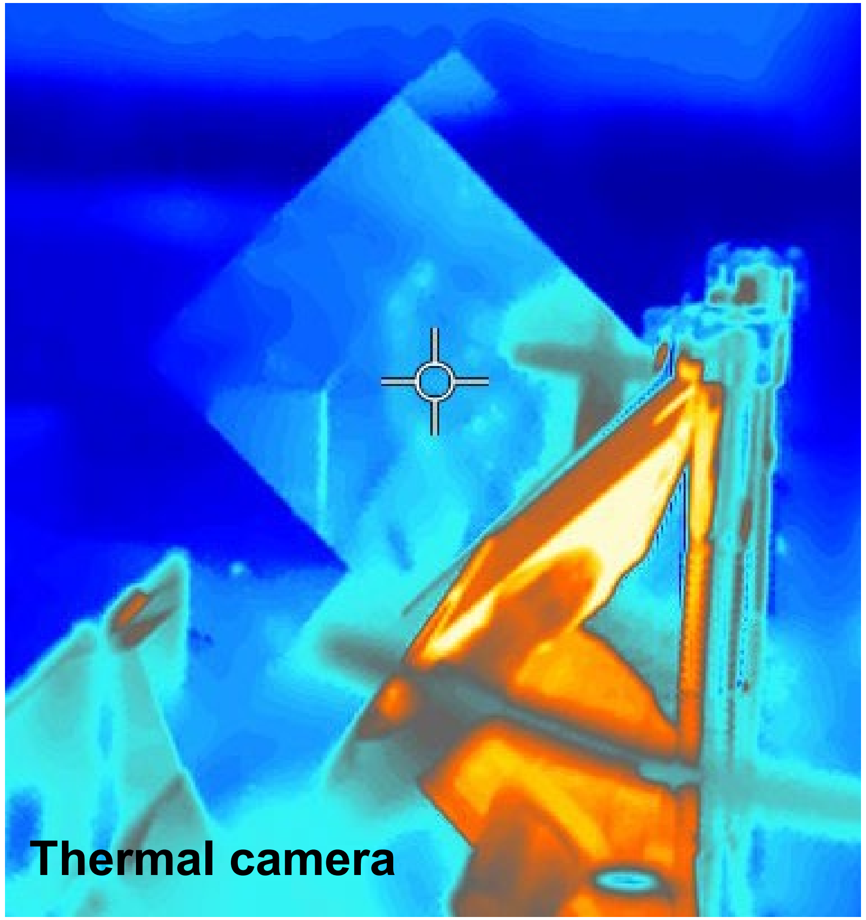



- Tantalum wrapped around glass frame
- Heated by current
- Uniform heating of side of test mass

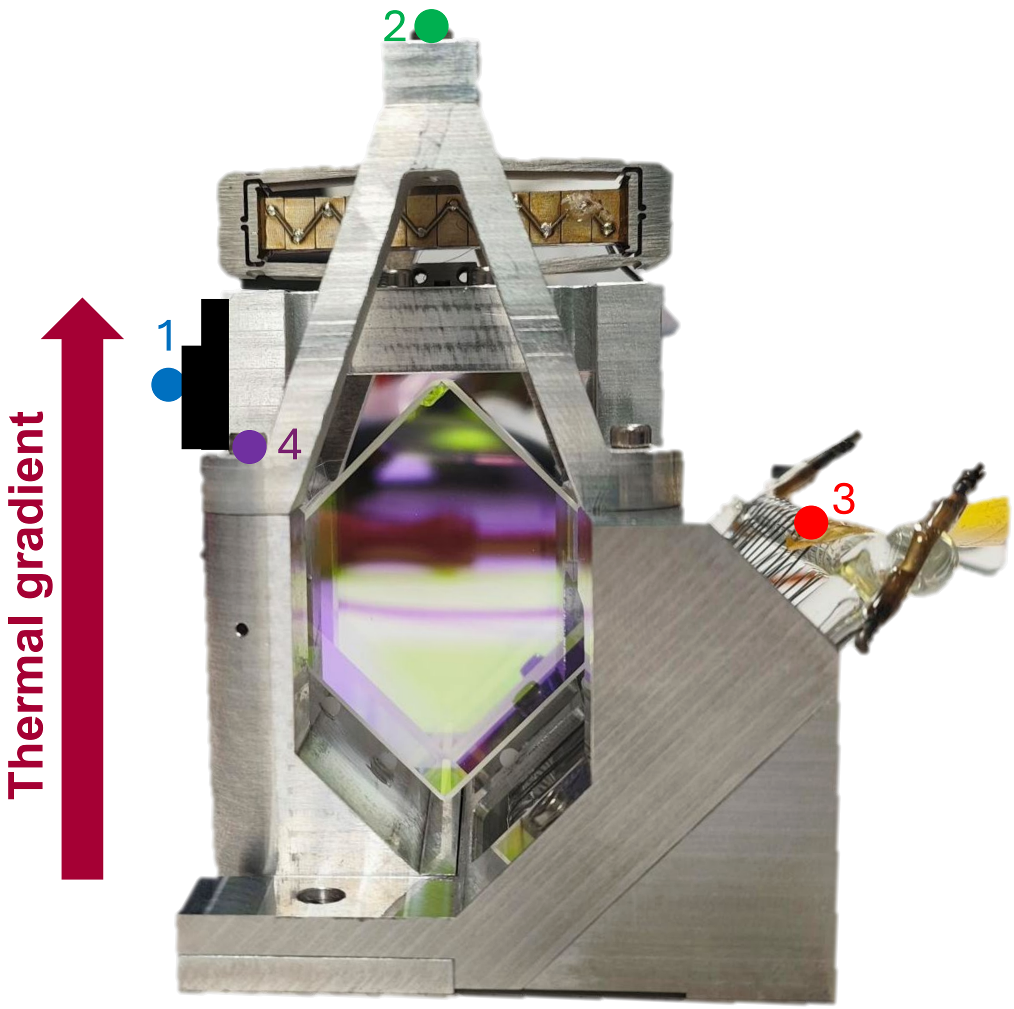


# Quadruple Suspension



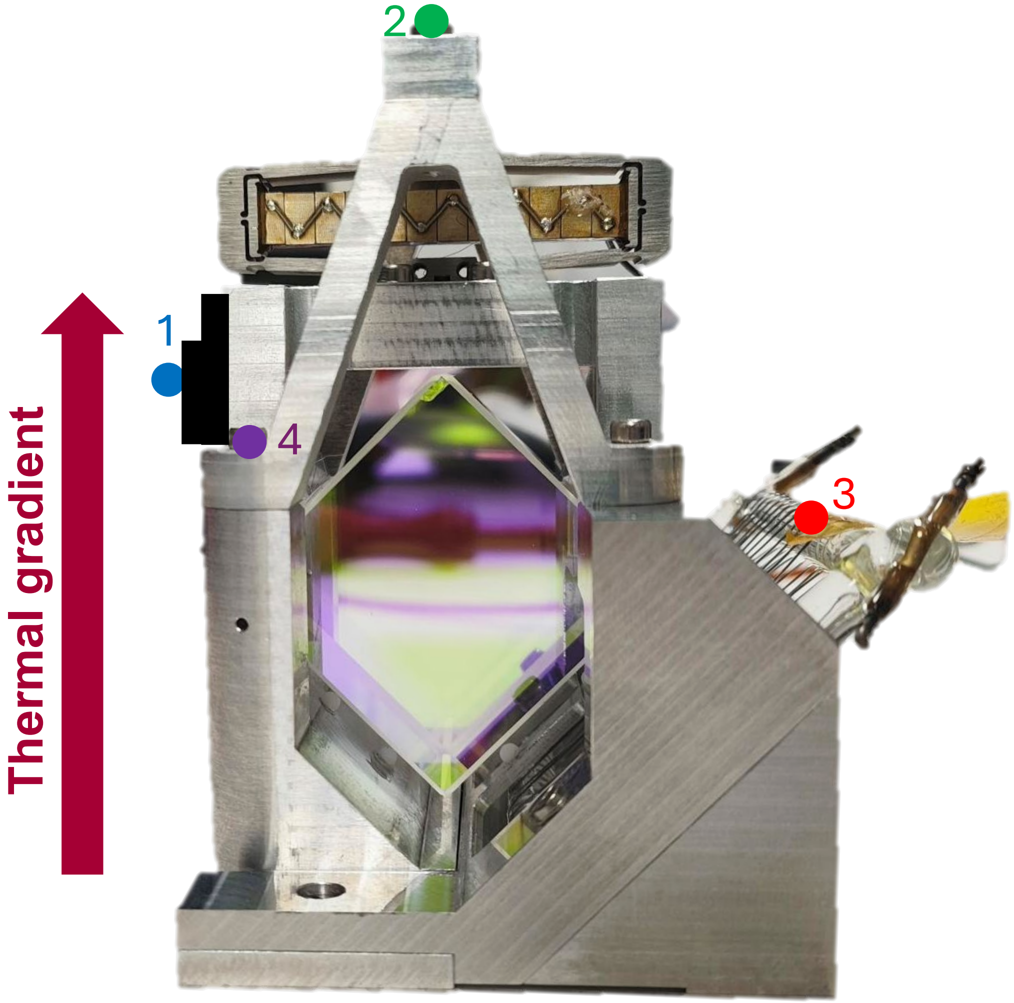



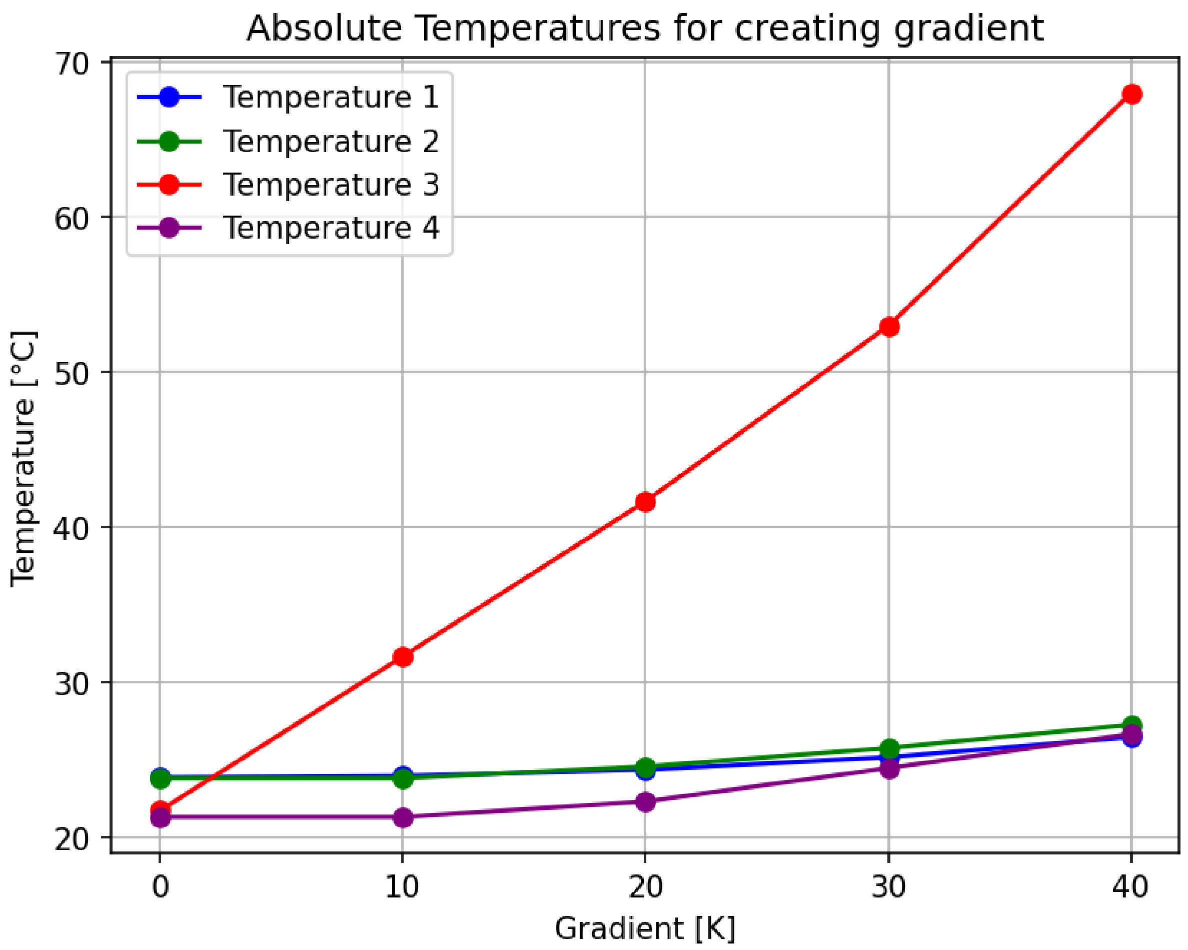
# Temperature Sensors




- Four temperature sensors
- Measurements at **10K intervals**
- Multiple measurements per gradient
- Assume stationary thermal gradient

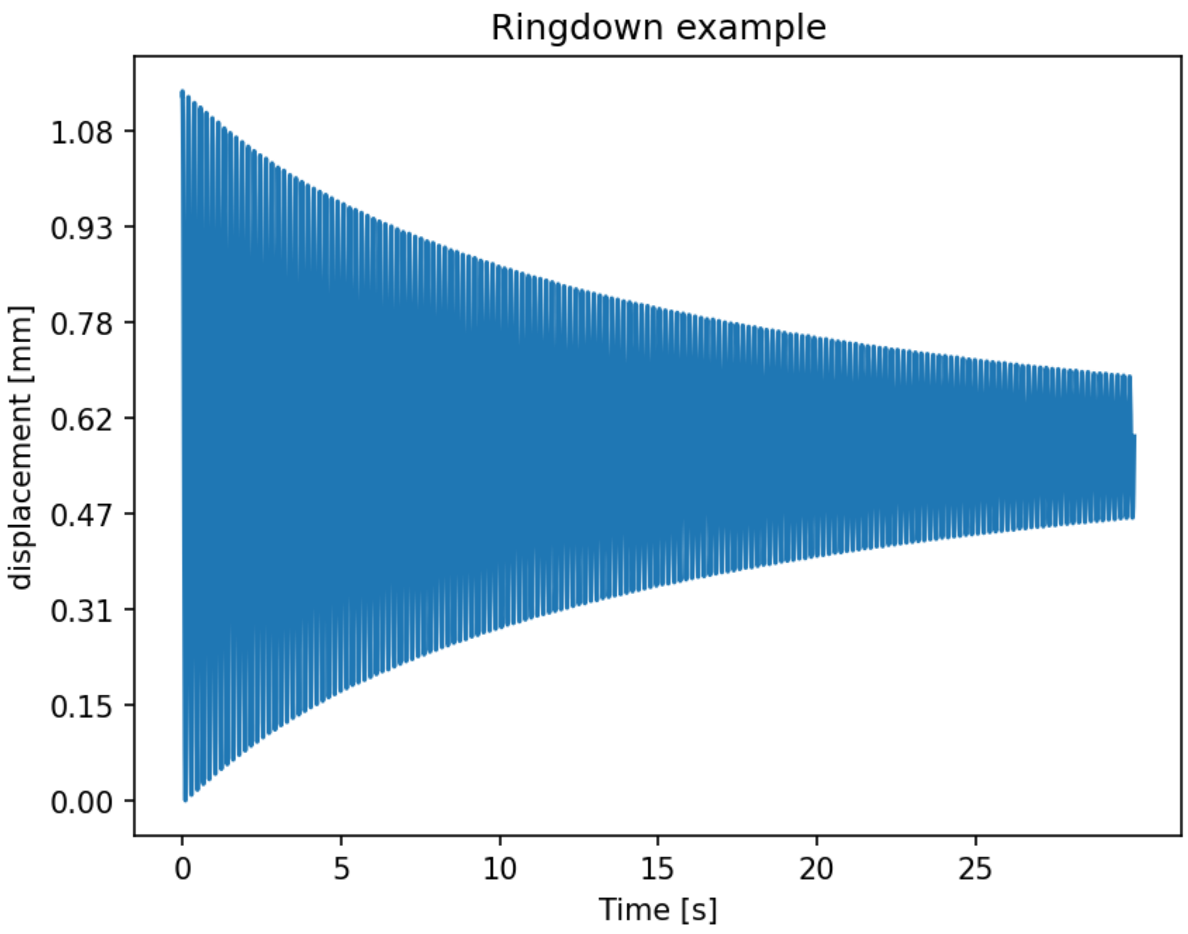
# Heating Suspension



# Ringdowns

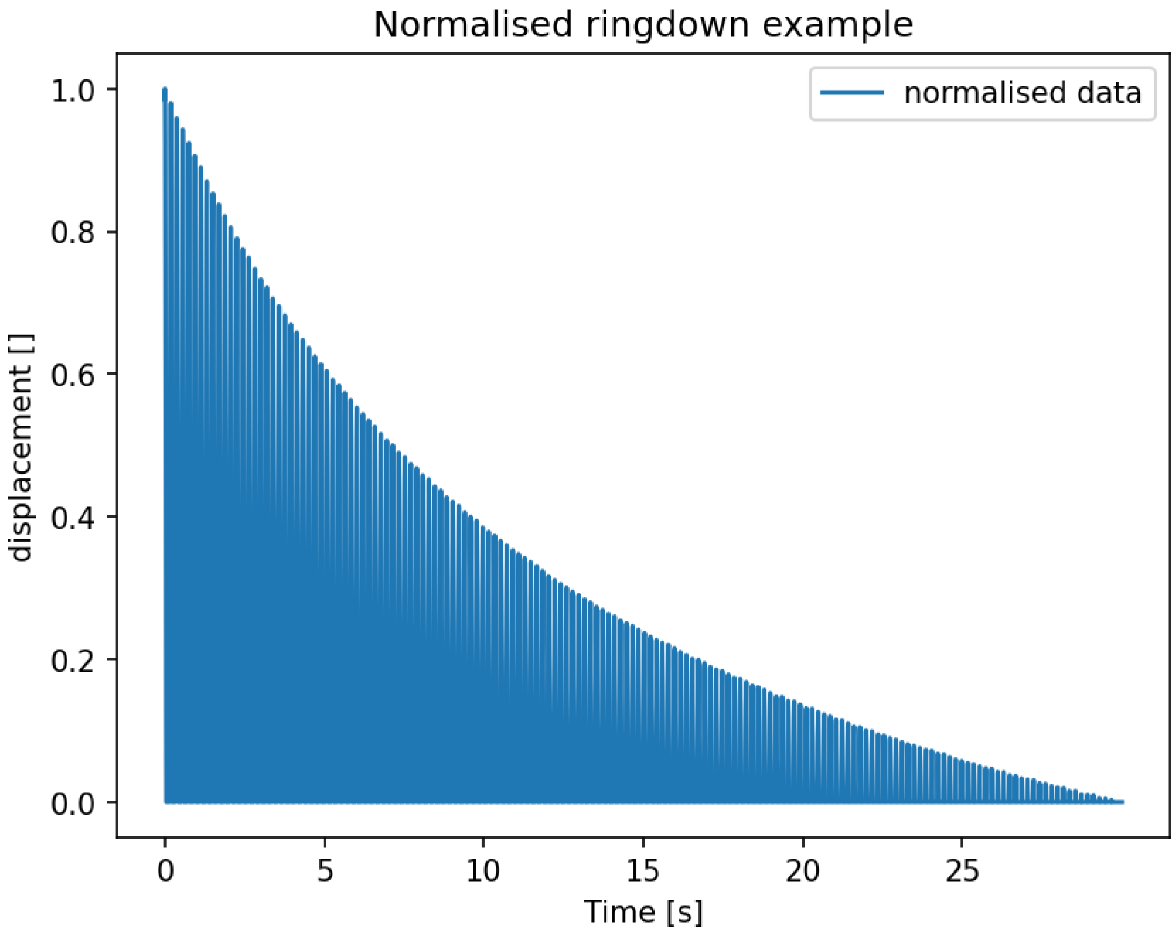
1. Ringdown following excitation
2. Displacement calculated




**Ringdown dependent on Q-Factor of suspension!**

# Ringdowns

1. Ringdown following excitation
2. Unwrapped phase calculated
3. Noise floor subtracted
4. Normalisation

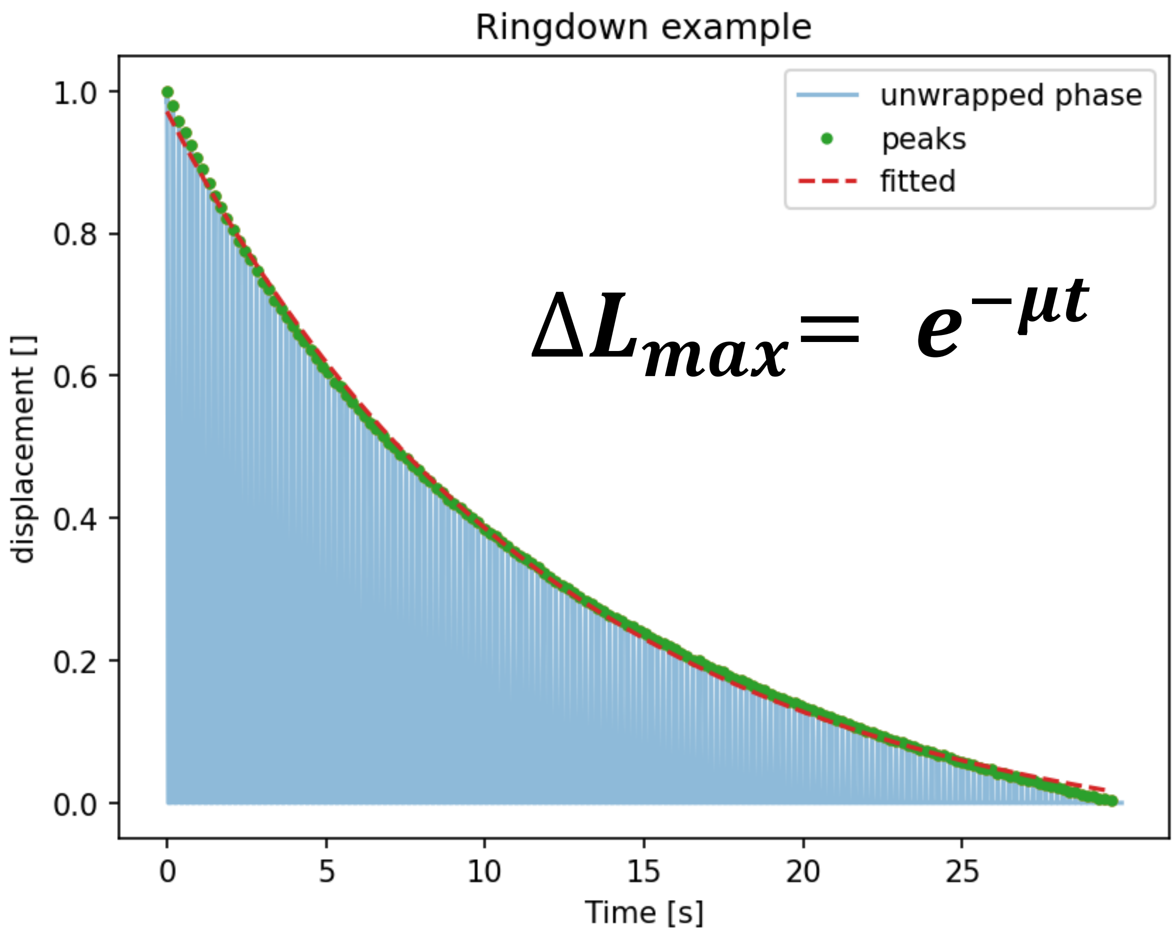


# Ringdowns

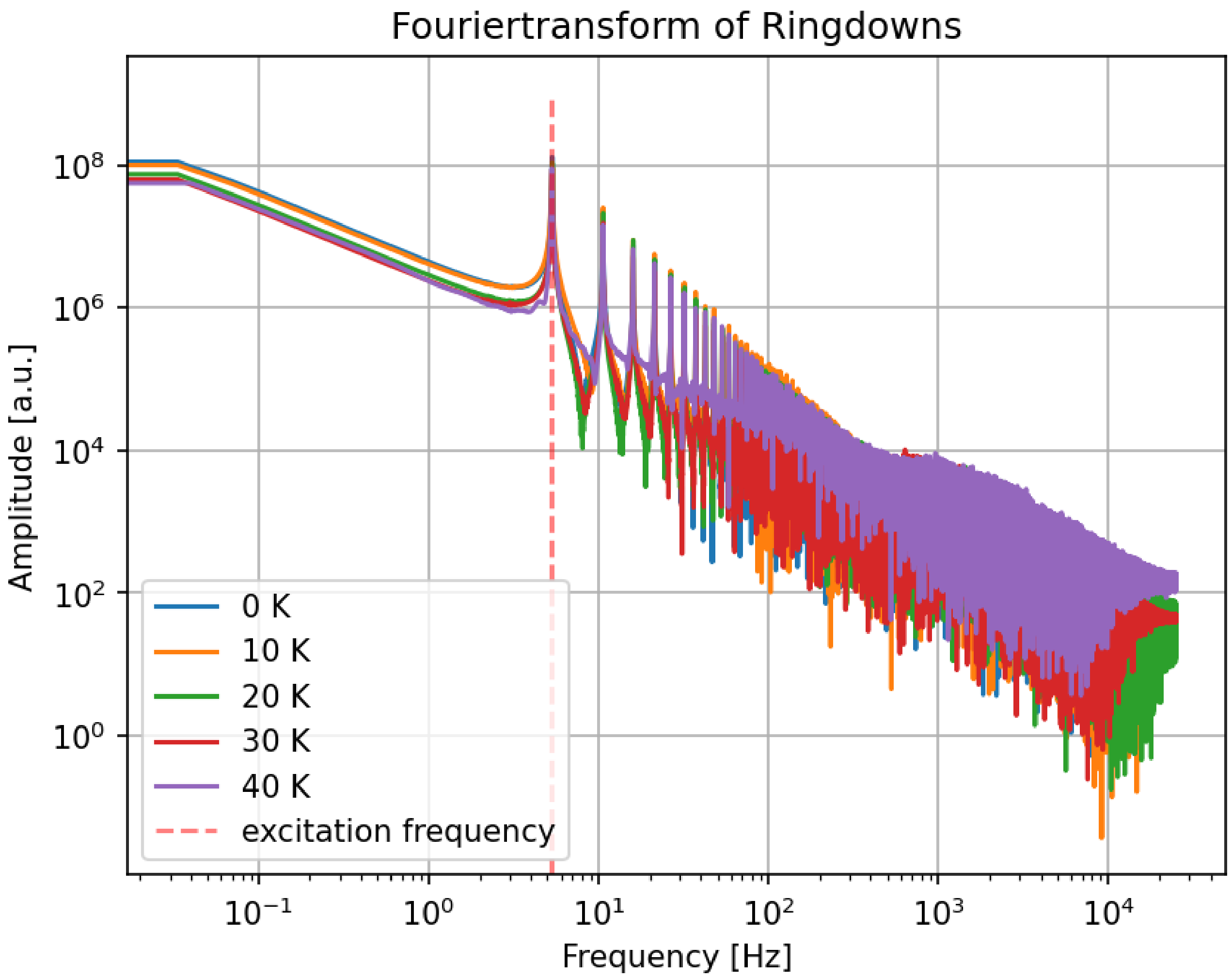
1. Ringdown following excitation
2. Unwrapped phase calculated
3. Noise floor subtracted
4. Normalisation
5. Envelope fitted

$$Q = \frac{\omega}{-\mu}$$

**In measurements: Q ~ 125**

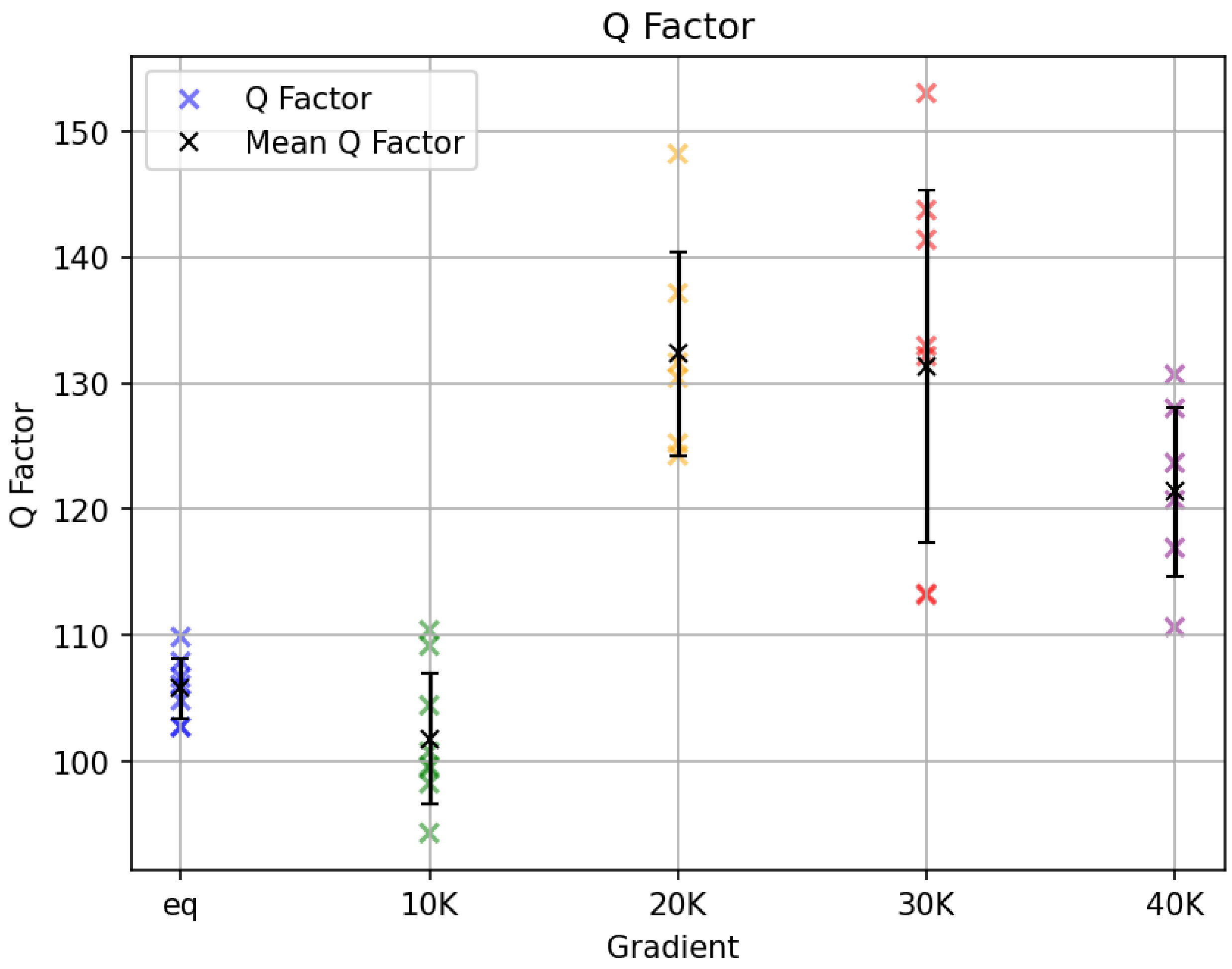


# Ringdowns




- No change in frequency spectra of ringdowns for different thermal gradients
- Higher harmonics due to non linearities in system, to be investigated

# Q Factor

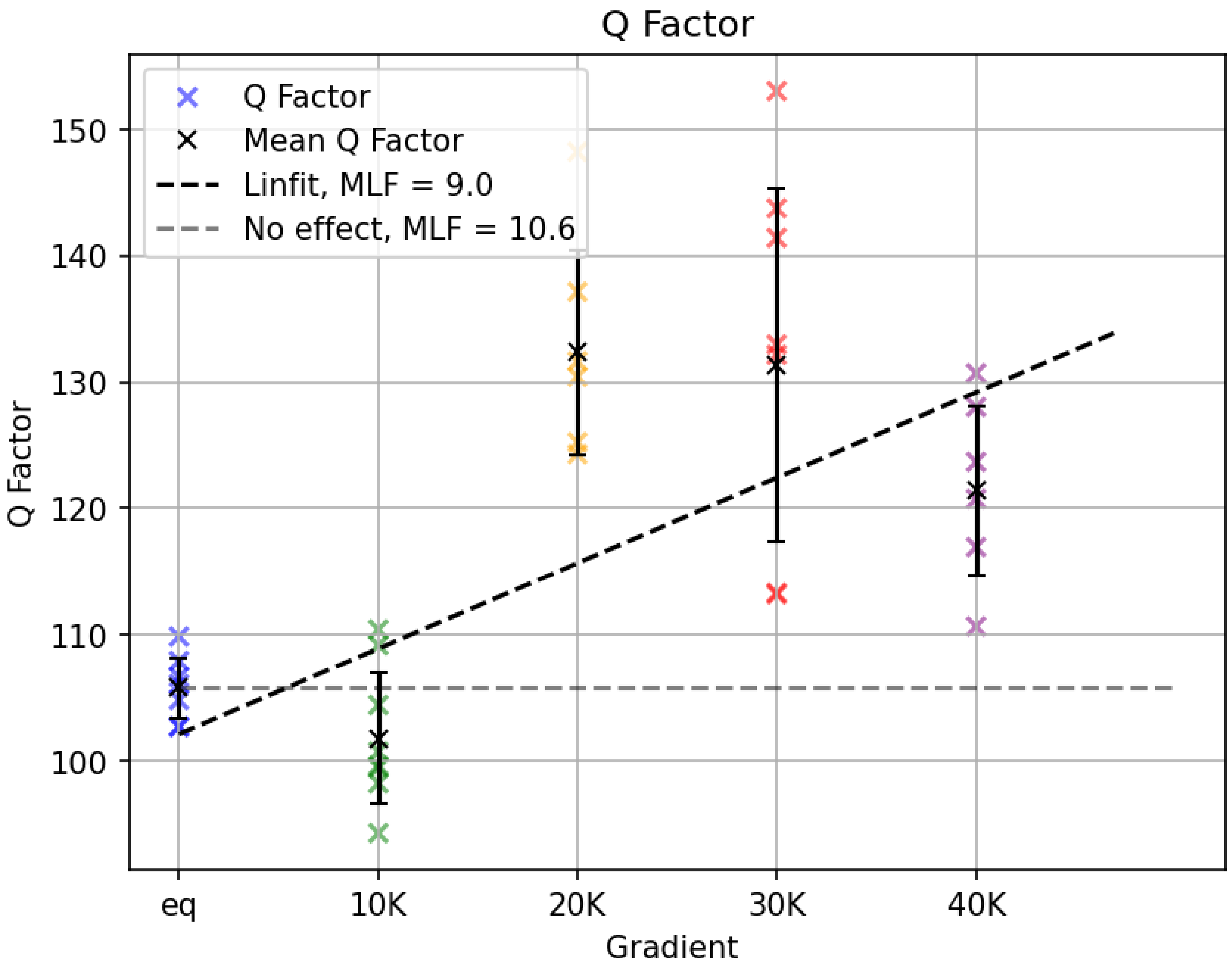



- Clustering for each thermal gradient
- Moving away from equilibrium measurements

$$\varphi_{max} = e^{-\mu t}$$

$$Q = \frac{\omega}{-\mu}$$

# Q Factor

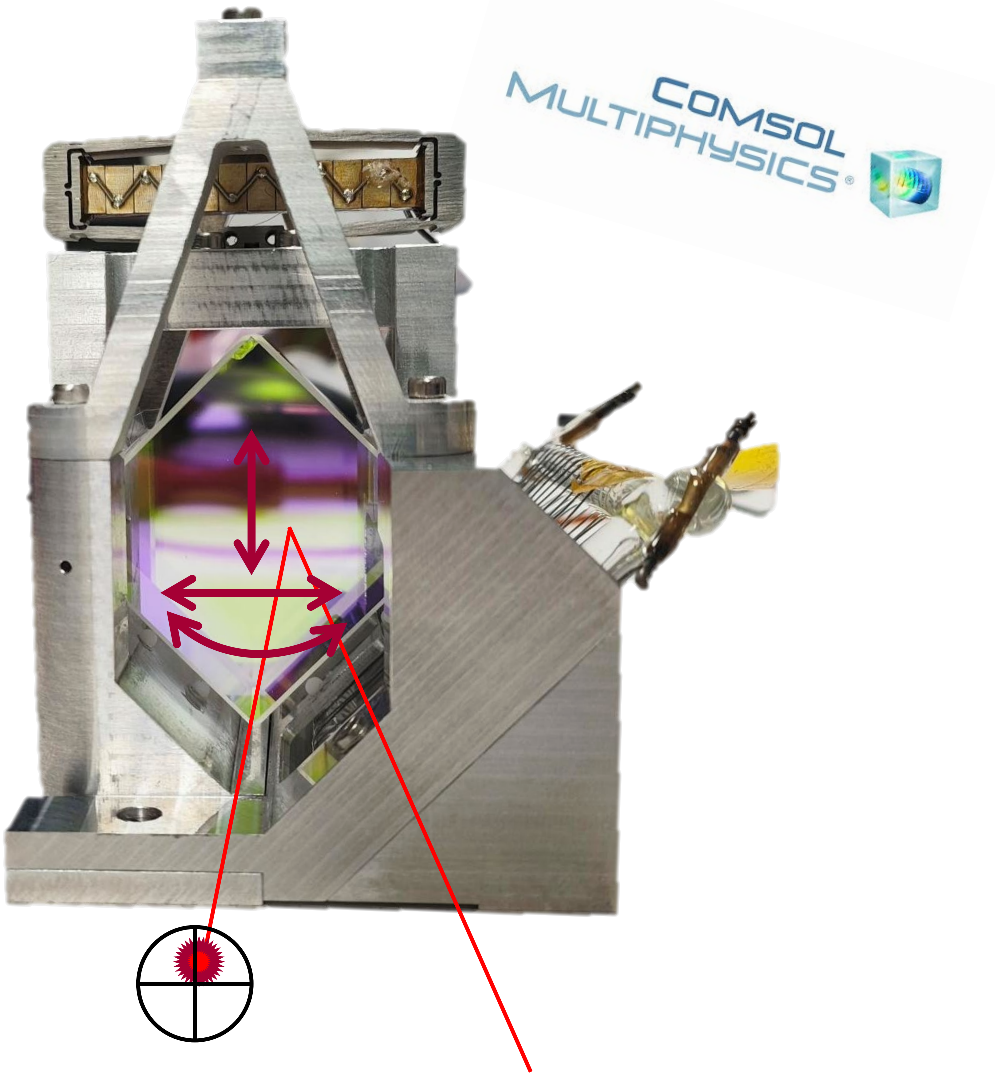



- Clustering for each thermal gradient
- Moving away from equilibrium measurements
- Q Factor increases with increasing thermal gradient
- Maximum likelihood function shows trend is more likely

$$\varphi_{max} = e^{-\mu t} \qquad Q = \frac{\omega}{-\mu}$$

# Conclusion and Next Steps

- Thermal gradients in the suspension affect its mechanical properties
- Investigate non linearities and d.o.f.
- The mechanism and impact on ET-LF is not yet fully understood.
- **MONET is a first step towards defining the effect of thermal gradients.**

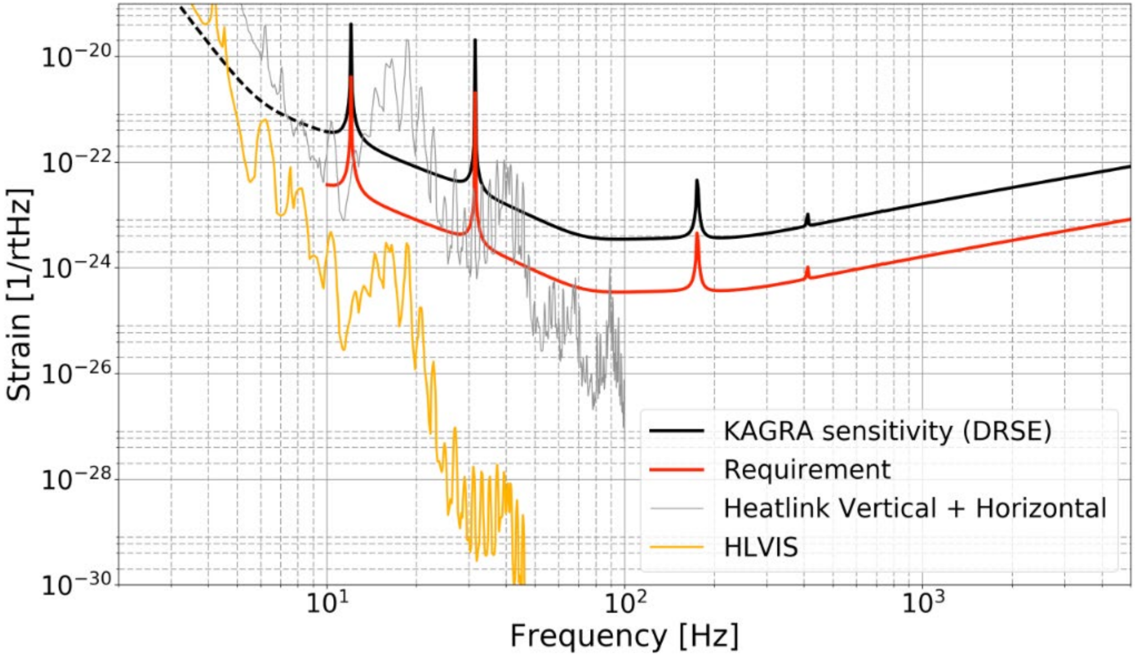


# Thank you for your attention!

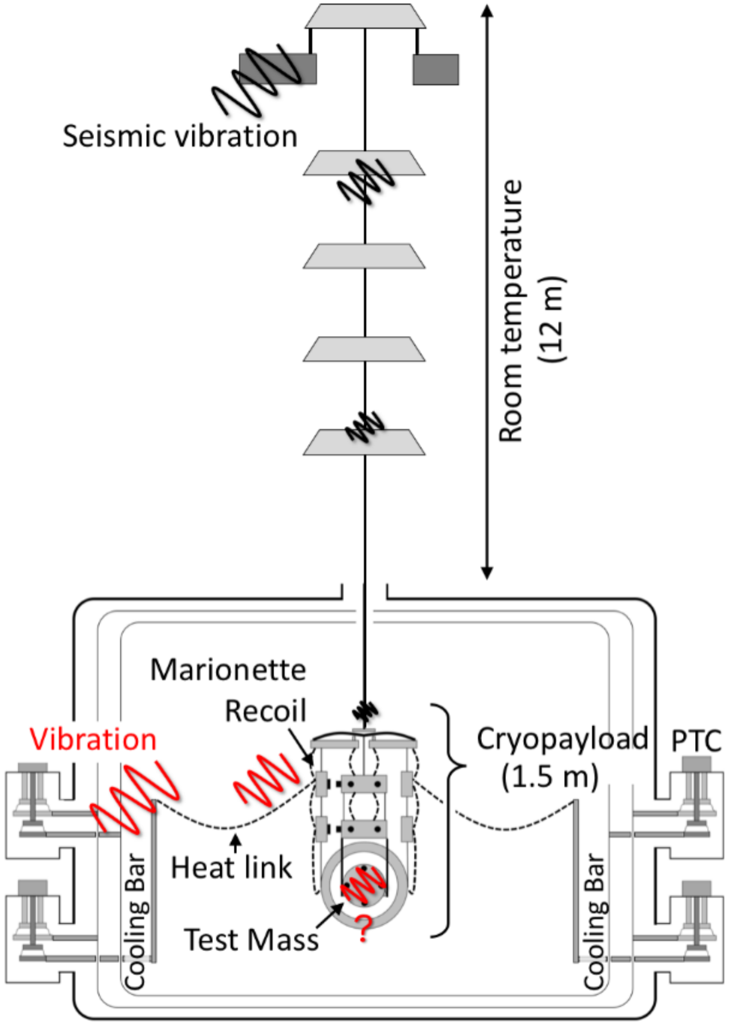
# Backup slides

# KAGRA

- Heat link for cooling
- Heat Link Vibration isolation system (HLVIS)



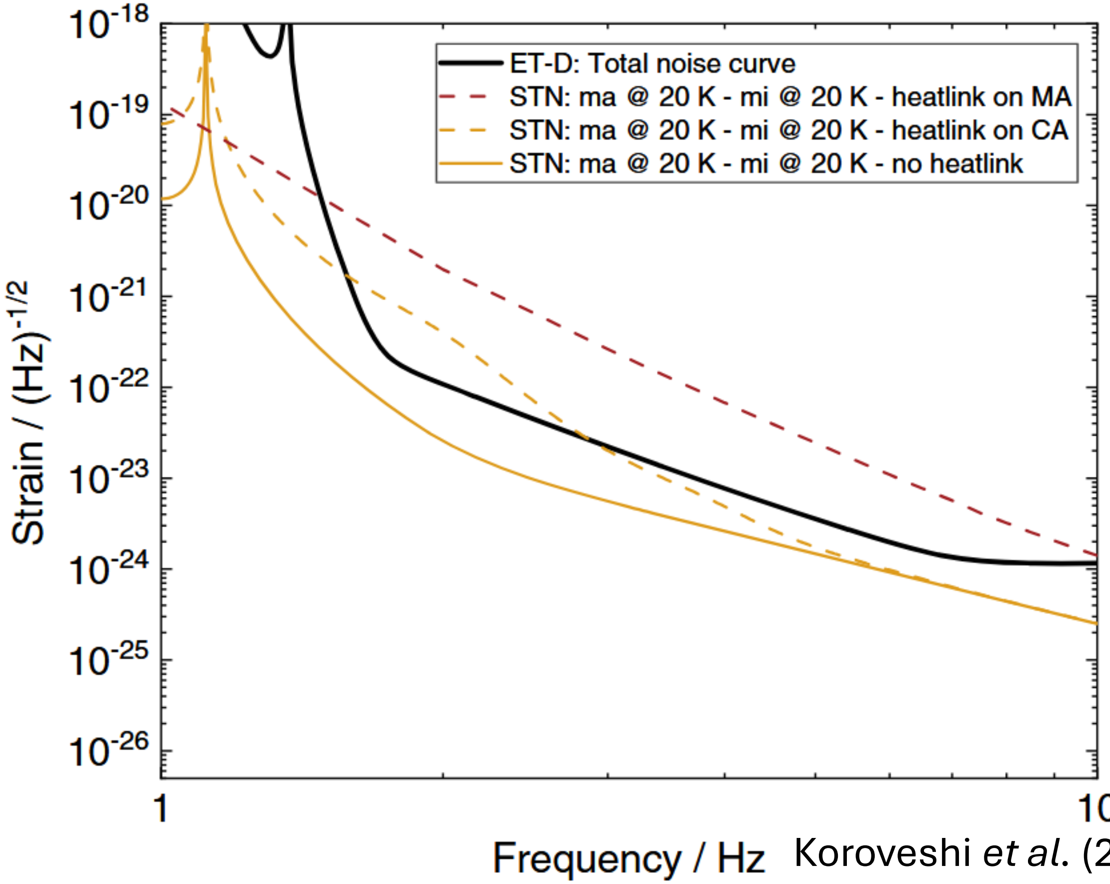

Yamada (2019), The 5th Kagra International Workshop / The 1st Kagra-Virgo-3G Detectors Workshop




Yamada (2020), Low-Vibration Conductive Cooling of KAGRA Cryogenic Mirror Suspension, Censored PhD thesis

# Heat link in ET

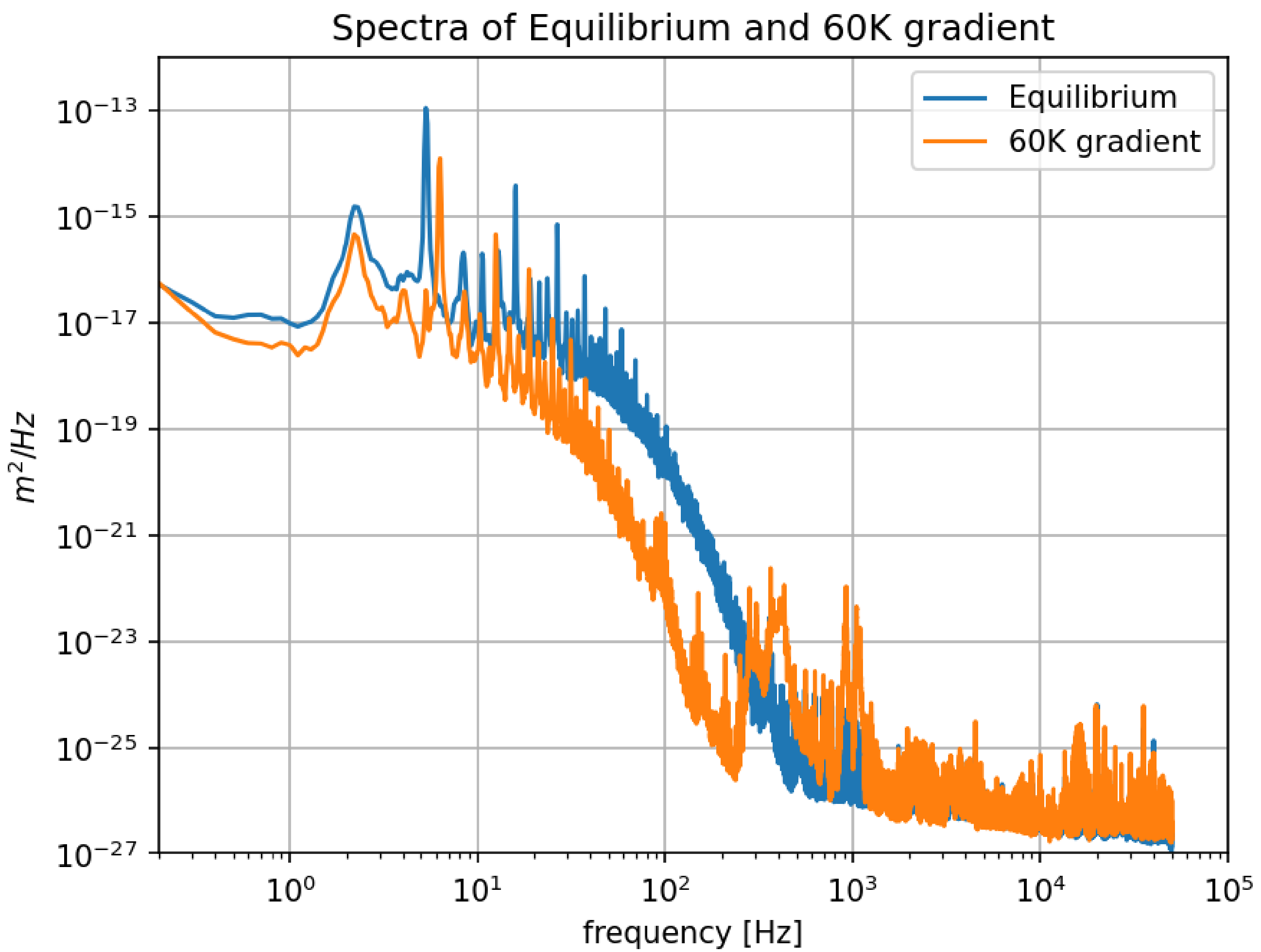
- Heat link in ET probably not feasible



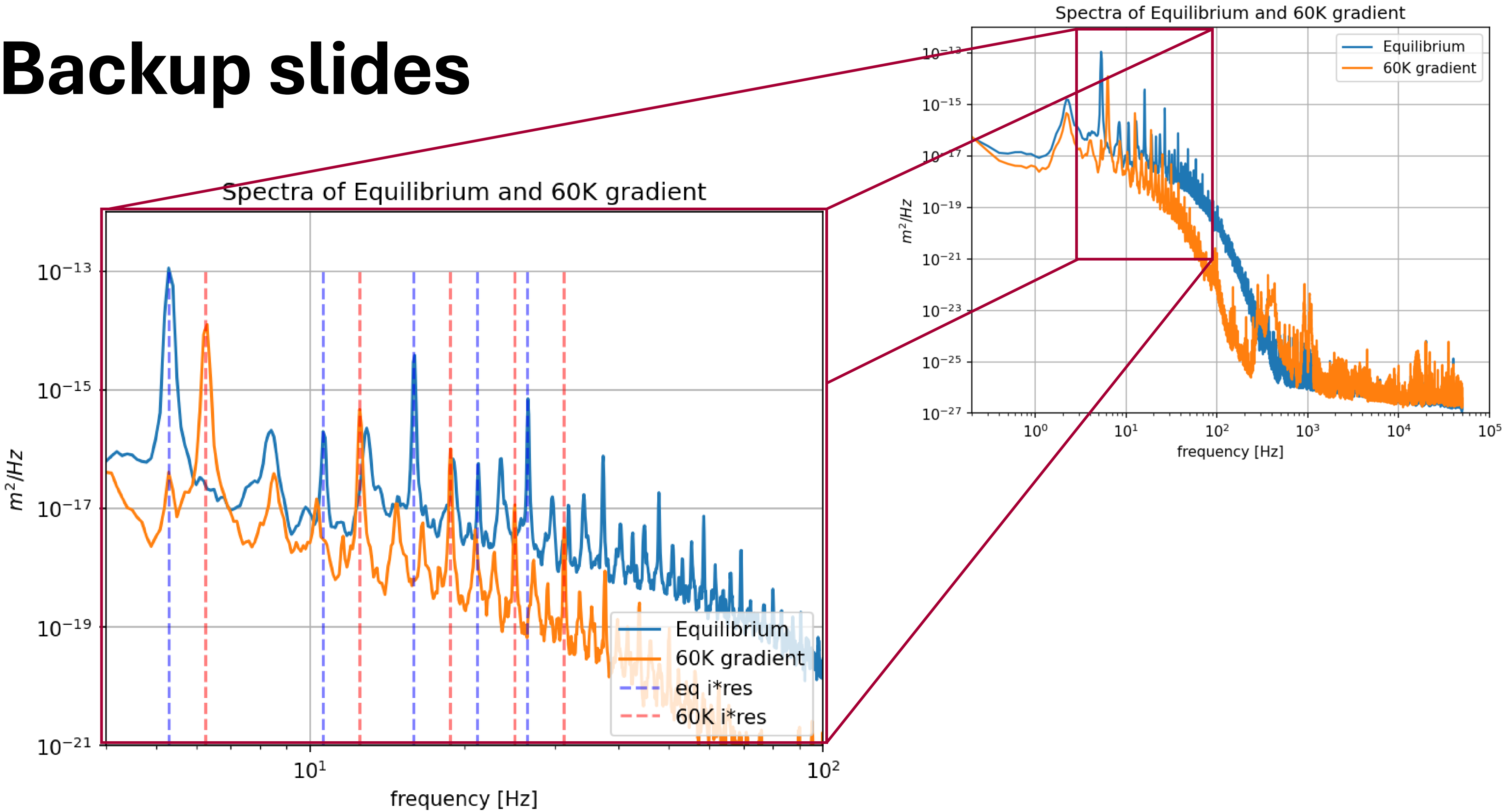

Koroveshi *et al.* (2023)

# Further effects

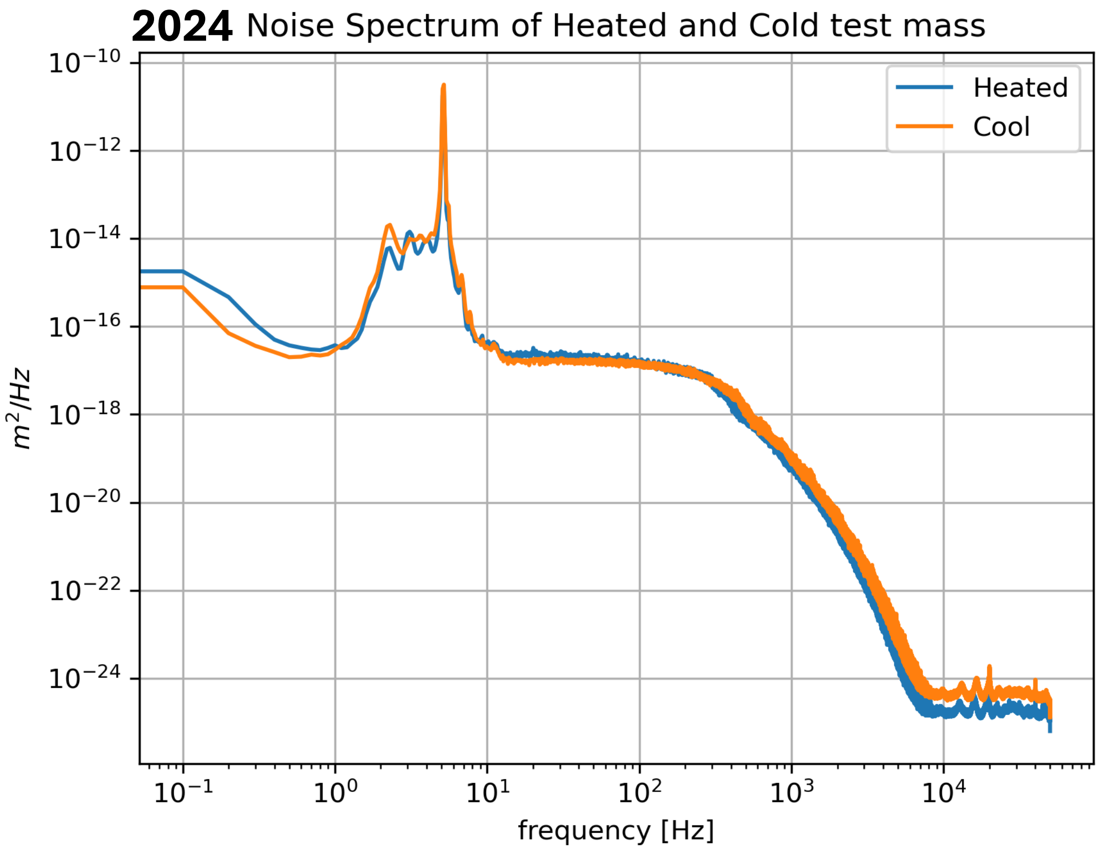
- Increase in resonance frequency of suspension
  - Without further excitation
- Not explainable through thermal expansion
- Shoulder earlier

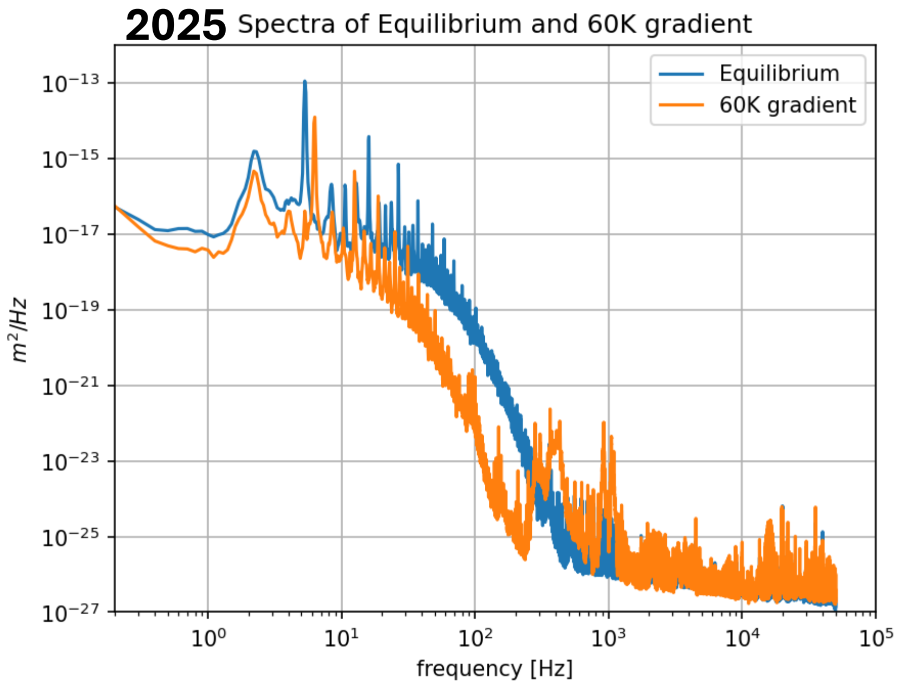


# Backup slides



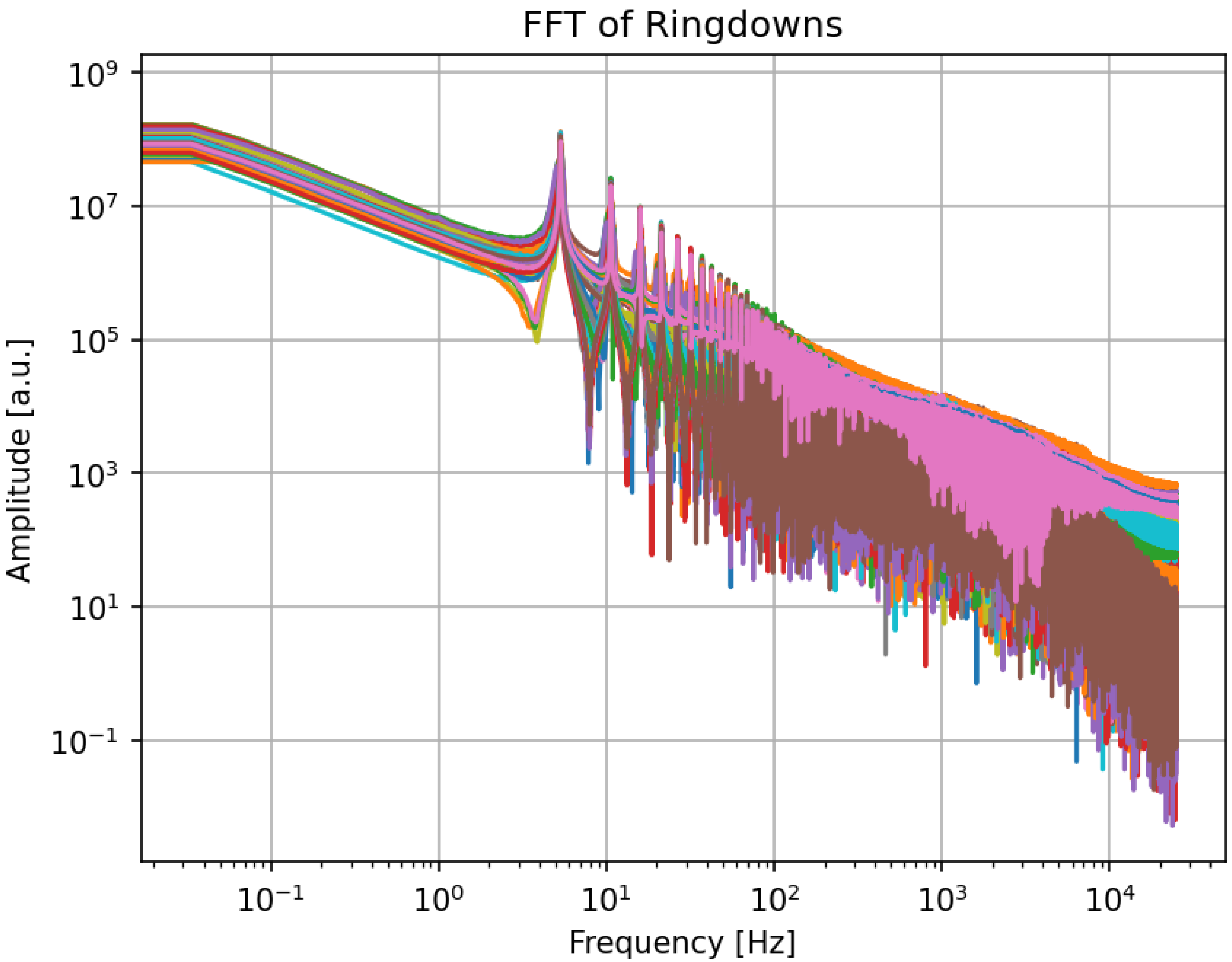
# Backup 2024 Spectrum




No change in resonance frequency for lower thermal gradients!

# FFT of ringdowns



# Sources


Yamada (2020), Low-Vibration Conductive Cooling of KAGRA Cryogenic Mirror Suspension

Cooper et al (2018) *A compact, large-range interferometer for precision measurement and inertial sensing*, Classical and Quantum Gravity, 10.1088/1361-6382/aab2e9

Koroshevi et al. (2023) *Cryogenic payloads for the Einstein Telescope: Baseline design with heat extraction, suspension thermal noise modeling, and sensitivity analyses* https://journals.aps.org/prd/pdf/10.1103/PhysRevD.108.123009