



UNIVERSITY OF
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Vibrations of Ultralight Tracking Detector Structures

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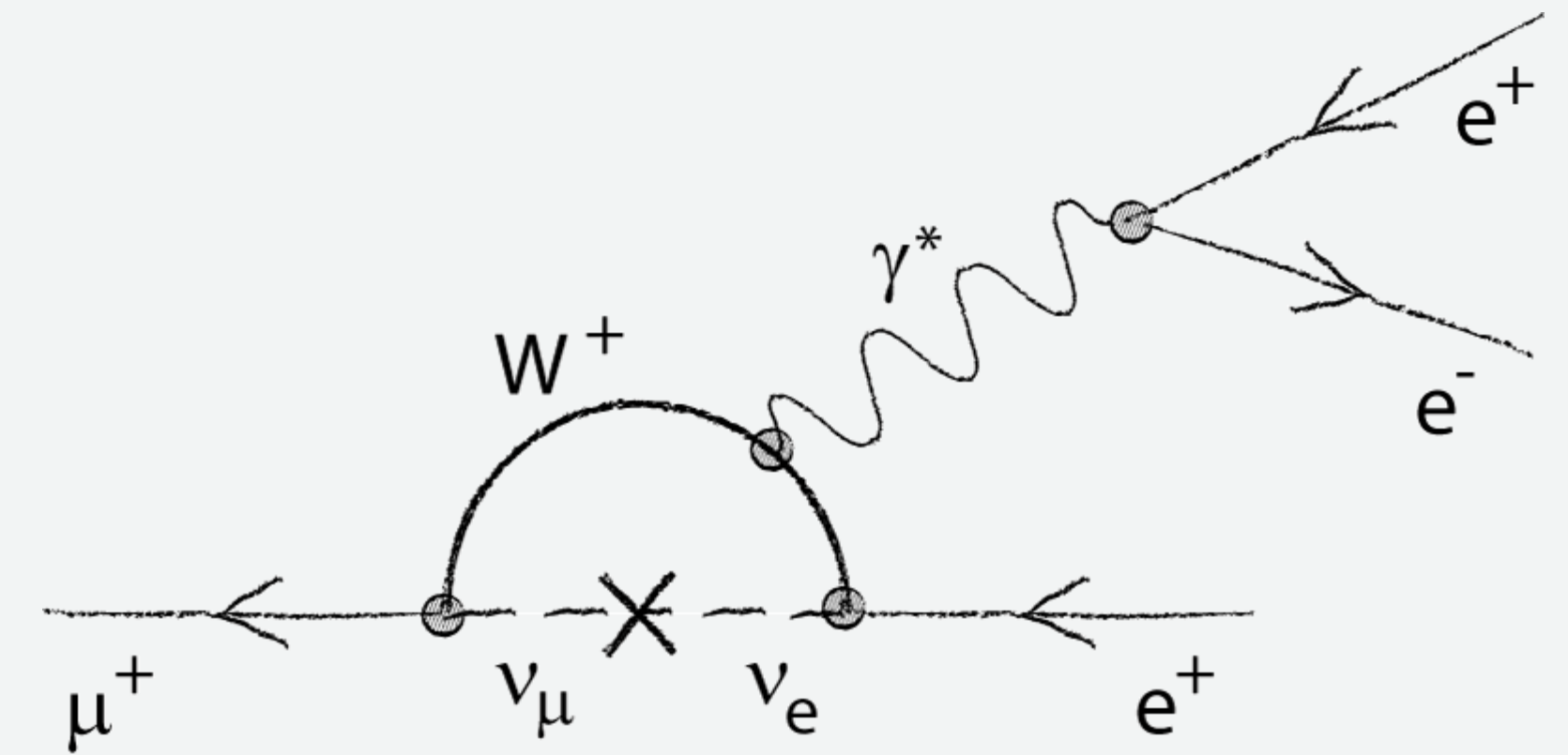
Mu3e experiment:

Physical goals and how to achieve them

The Mu3e experiment

Goal: Exclude a Branching Ratio (BR) above 10^{-16} for $\mu^+ \rightarrow e^- e^+ e^+$ decay

- Highly suppressed decay mode, SM predicts BR $\sim 10^{-54}$
 - If detected clear sign of BSM physics
- Best current experimental bound $BR < 10^{-12}$ (90% CL)
 - SINDRUM 1988
- Muon beam at PSI currently delivers $10^8 \mu/s$
 - After 2029 upgrade $> 10^9 \mu/s$



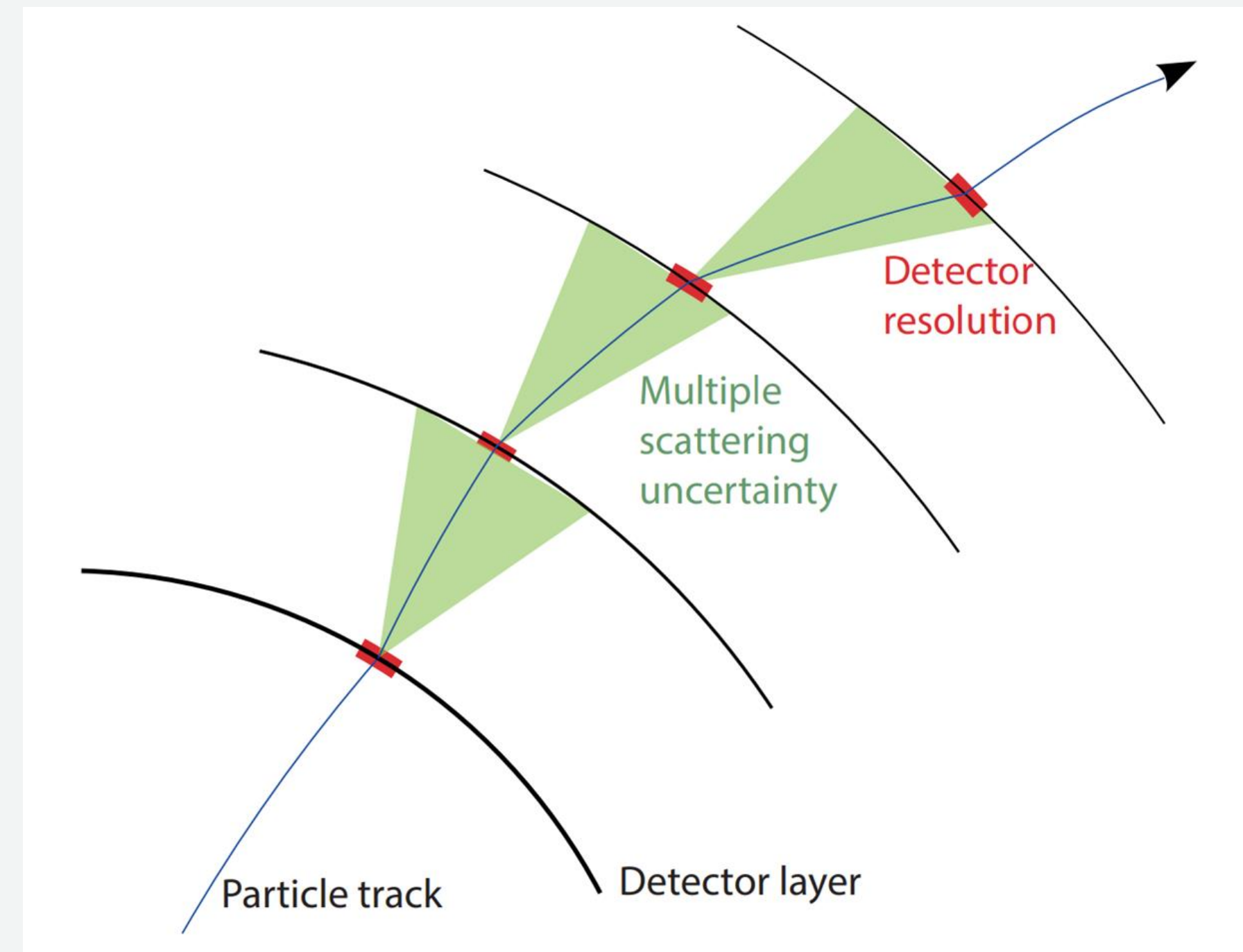
Resolution goals

Aim:

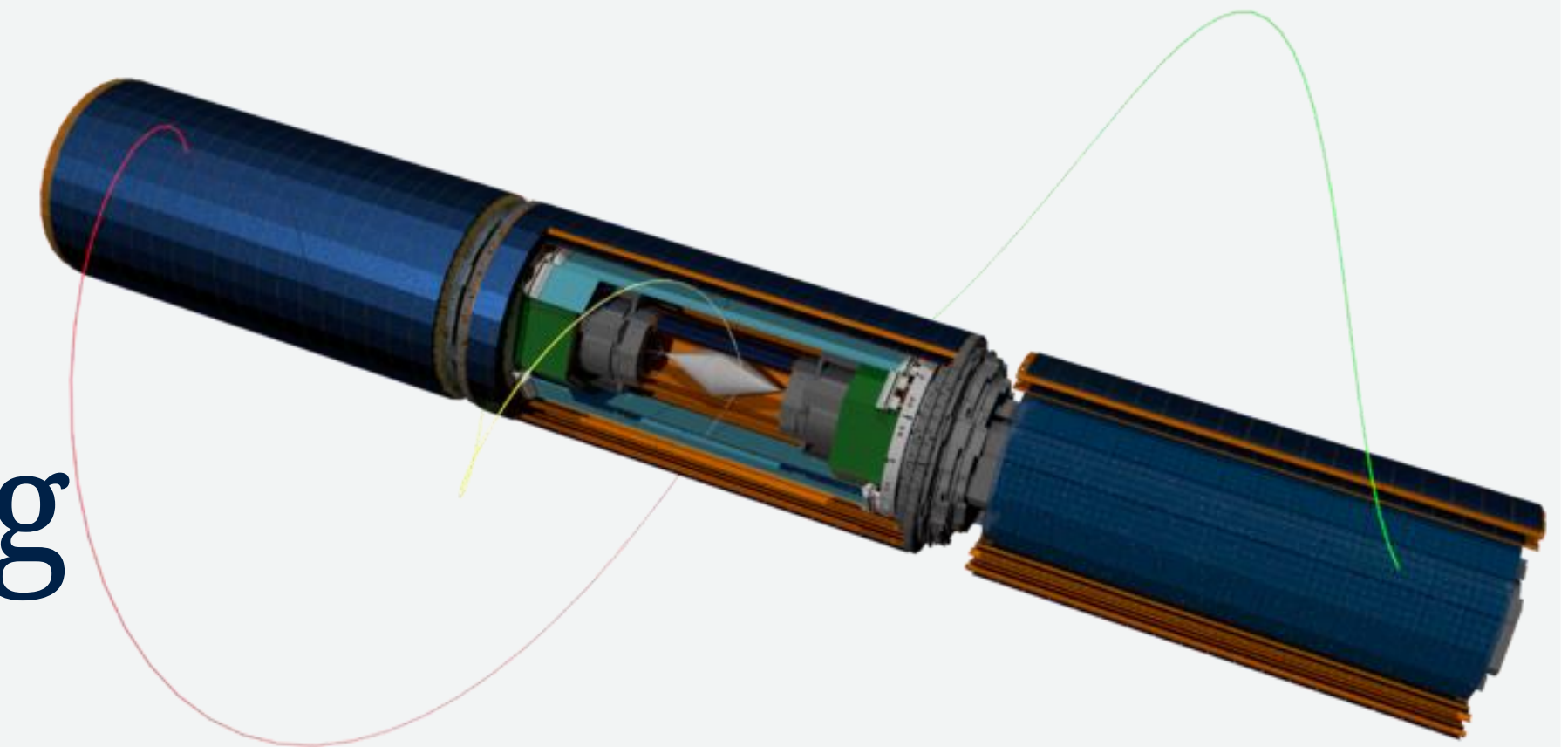
- Vertex resolution $< 200\mu m$
- Time resolution $< 100ps$
- Momentum resolution $< 0.5MeV$

Defining challenge: Reduction of multiple coulomb scattering

- Ultralight detector design



Mu3e pixel detector and cooling

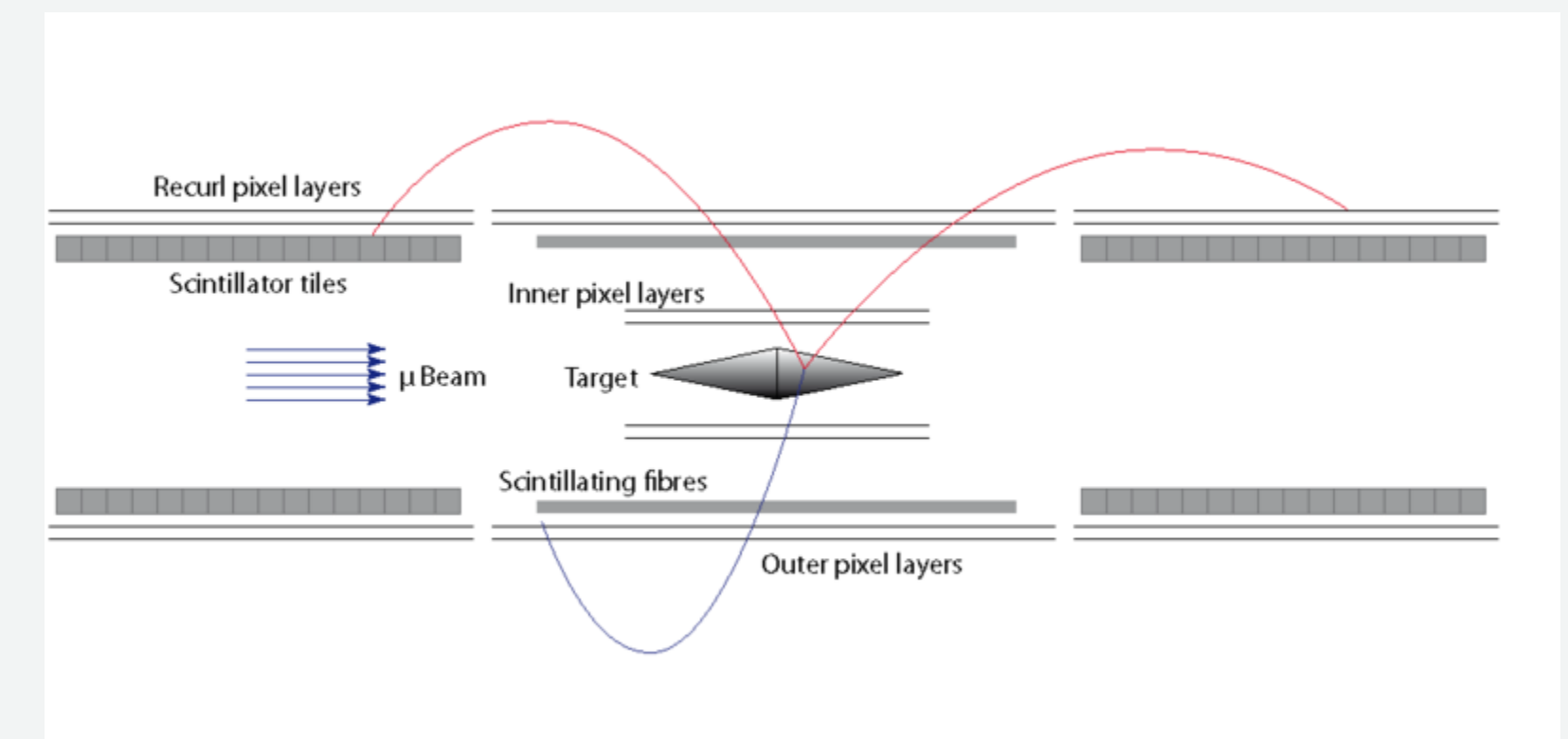


Detector geometry: 1 central and 2 re-curl regions

- Re-curl regions increase detector acceptance and time resolution
- Central station gathers main hit information

Low material budget is essential:

- Cooled using gaseous He cooling (7 times less dense than air)
- Double layer of ultra-thin pixel sensors (50-70 μm thick)



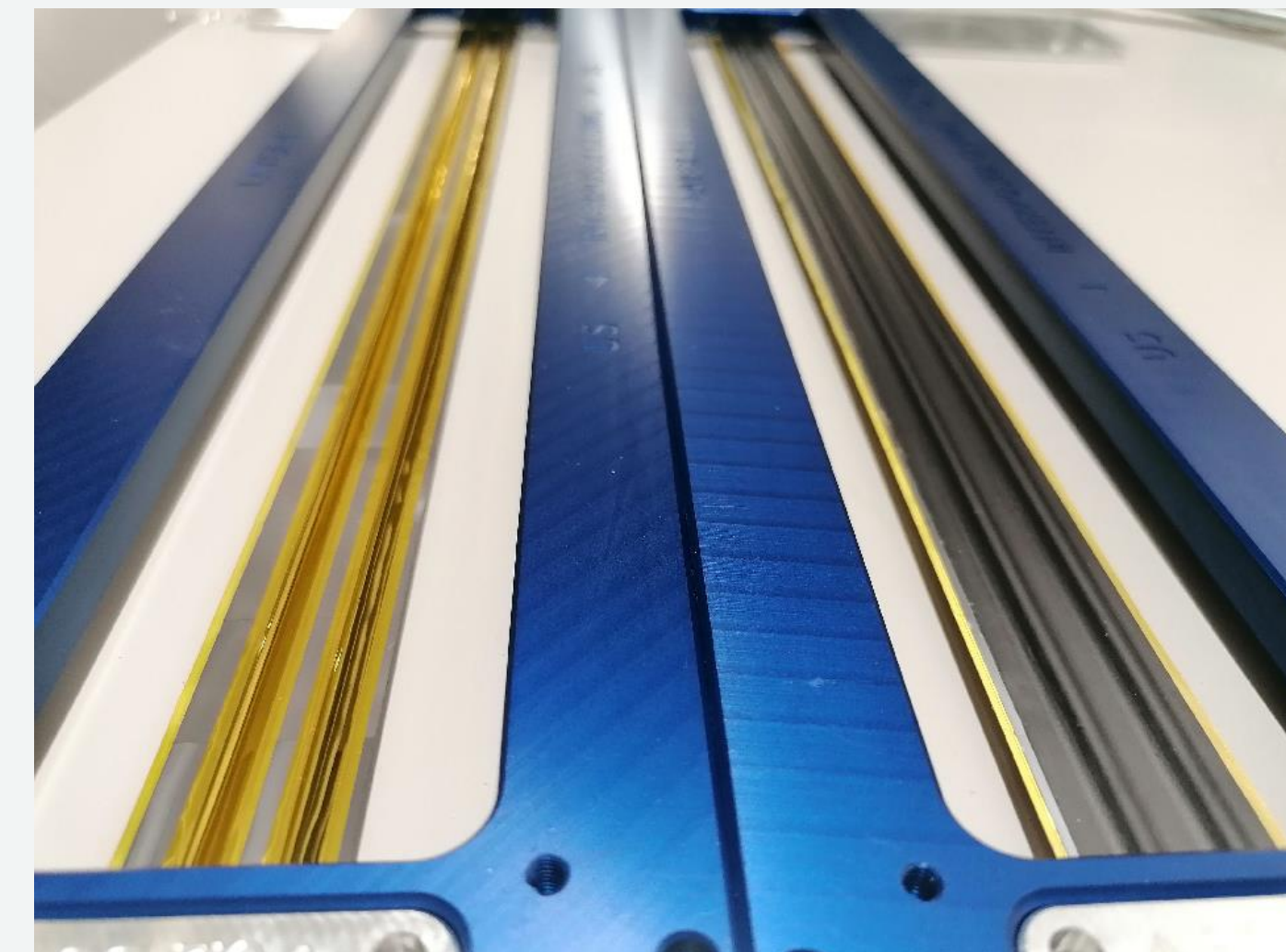
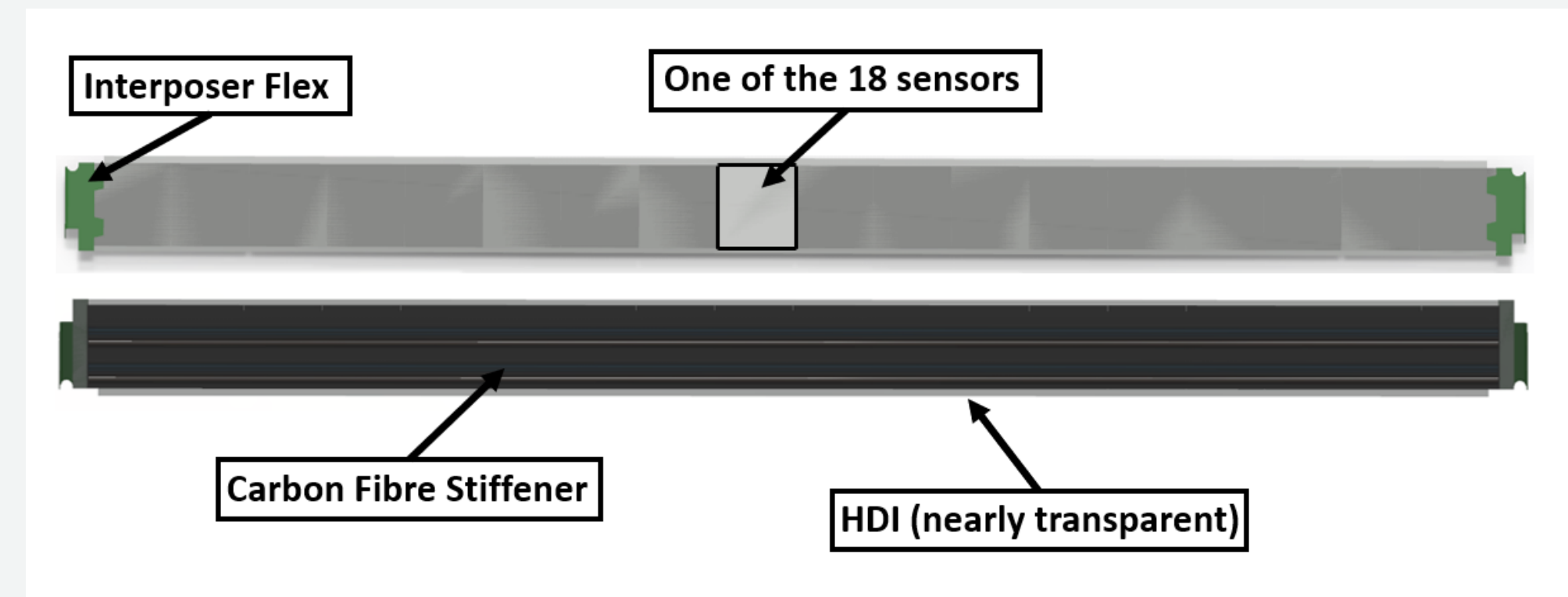
Ultralight silicon detectors

Outer Pixel Layers:

- 17-18 pixel sensors per ladder
 - $\sim 2g$ despite being over $350mm$ long!
- 4 ladders \rightarrow 1 module
- 6-7 modules \rightarrow 1 Layer

Mechanical Support:

- $25\mu m$ thick Kapton “v-folds”
- $25\mu m$ thick carbon-fibre “u-folds” with $8\mu m$ Kapton co-cure





Vibrations of outer pixel ladders

Aim of my project:

Assess whether or not the mechanical stability is sufficient

- Background motion induced vibrations
 - Dominated by mini compressors
- Cooling flow induced vibrations
 - Gaseous helium cooling at $\sim 10\text{m/s}$

Theoretical interlude

Linear response functions

Linear response function:

$$X(\omega) = H(\omega) \cdot F(\omega)$$

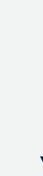
Harmonic oscillator:

$$H(\omega) = \frac{1}{k} \frac{1}{1 - \left(\frac{\omega}{\omega_0}\right)^2 + i \frac{\omega}{Q\omega_0}}$$

More complex model at a position x_0 :

$$H(\omega) = \sum_n H_n(\omega)$$

$$m\ddot{x}(t) + 2\gamma\dot{x}(t) + kx(t) = F(t)$$



$$(-m\omega^2 + i\omega + k)X(\omega) = F(\omega)$$



Wiener-Khinchin theorem

Theorem (essentially):

$$x_{RMS}^2 = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} S_x(\omega) d\omega$$

$$"S_F(\omega) = |F(\omega)|^2"$$

$$S_x(\omega) = |H(\omega)|^2 \cdot S_F(\omega) \longleftrightarrow X(\omega) = H(\omega) \cdot F(\omega)$$

$$\Rightarrow x_{RMS}^2 = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} S_F(\omega) \cdot |H(\omega)|^2 d\omega$$

Seismic motion induced vibrations

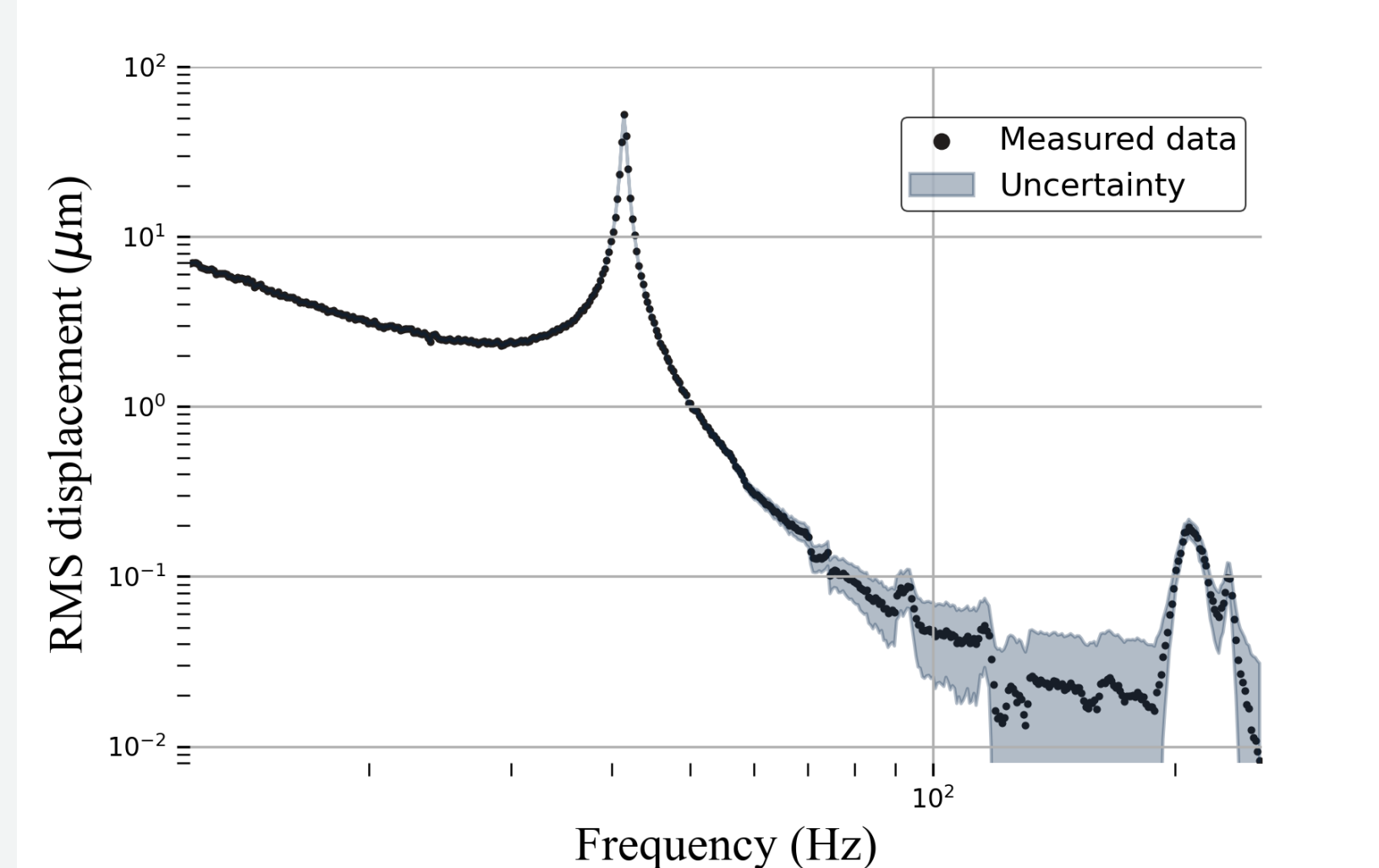
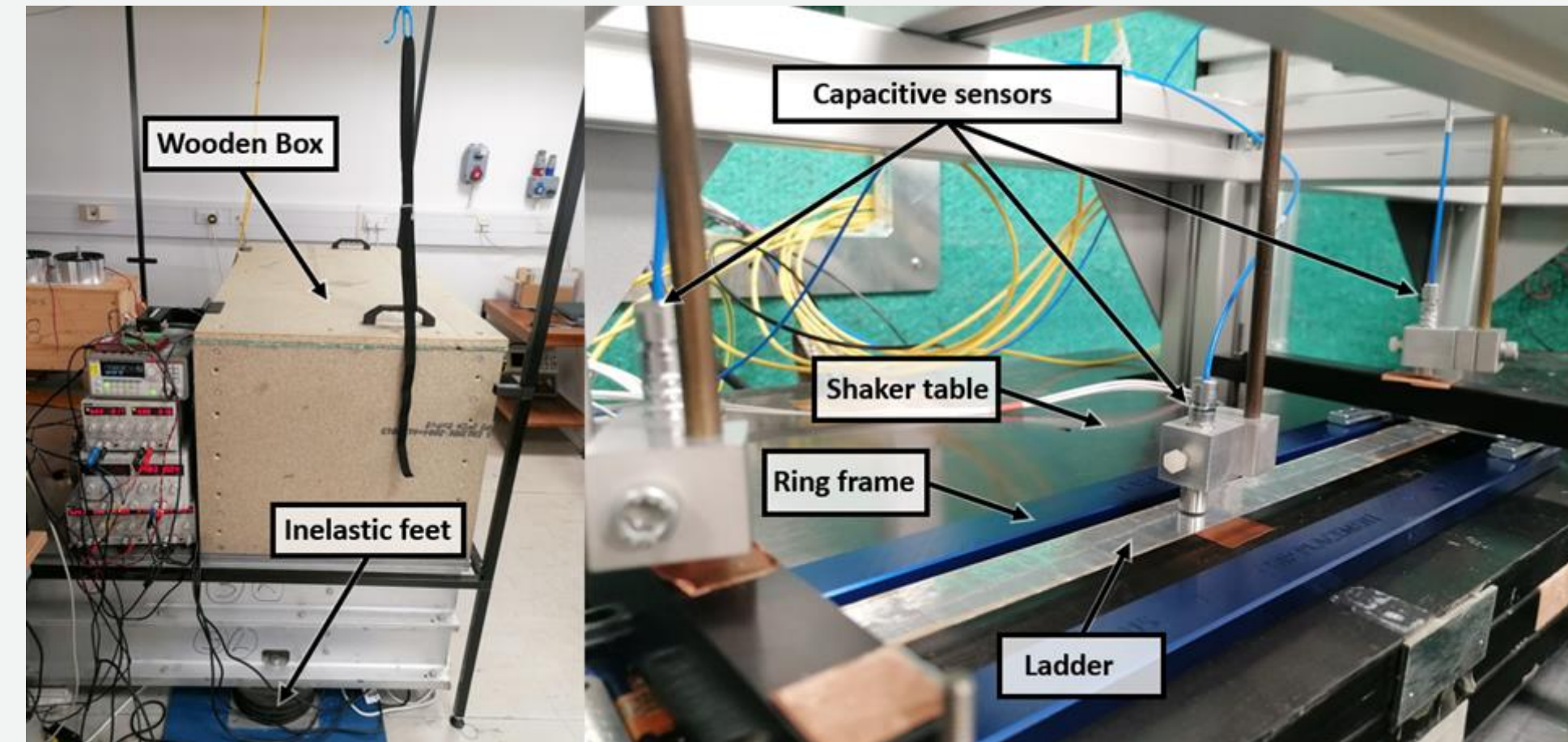
Shaker table

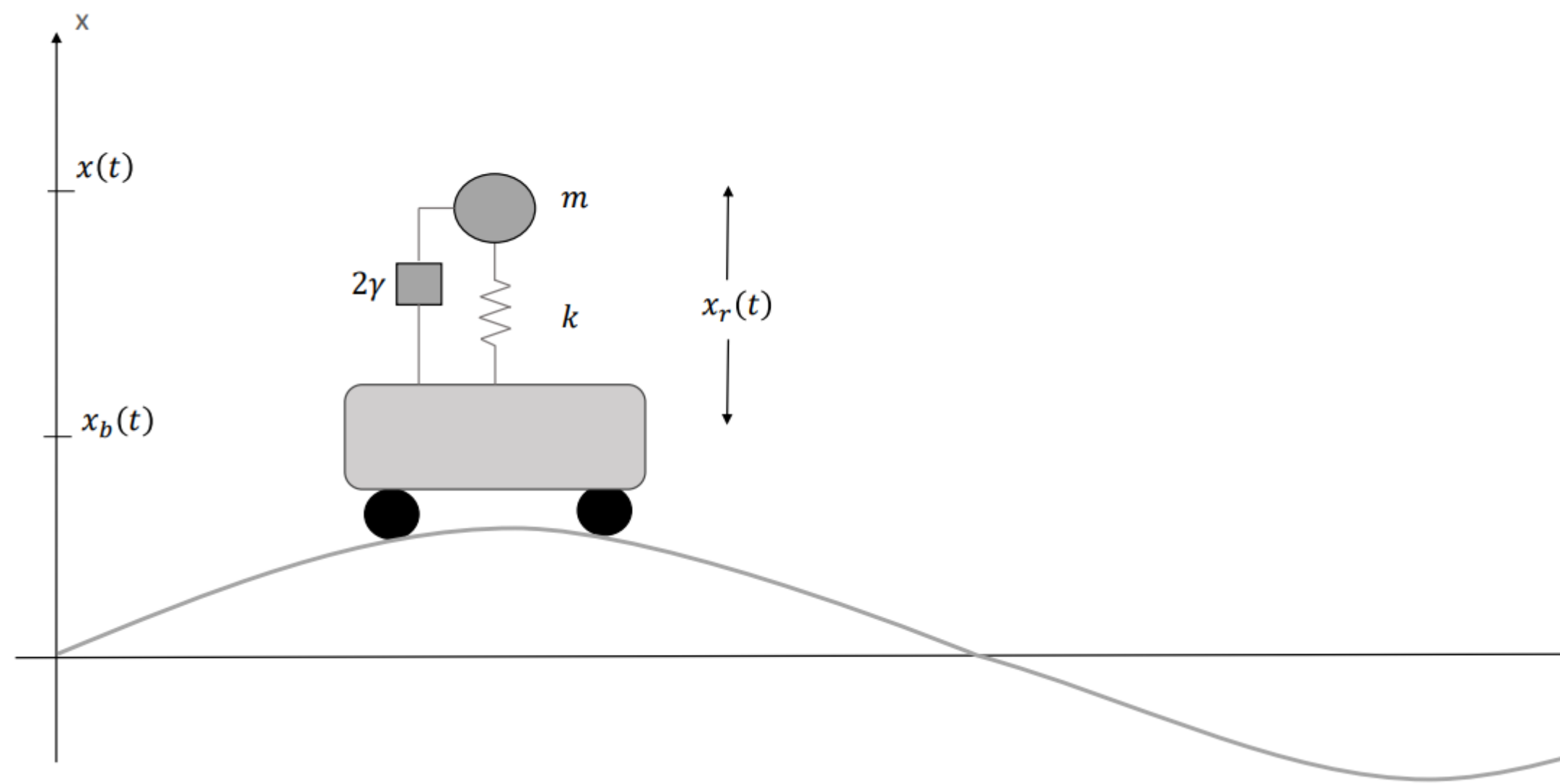
Working principle:

- Inverse piezoelectric effect
- Sinusoidal voltage signal of fixed f
- Constant acceleration amplitude
- Measure x_{RMS} for each f using capacitive sensors

Not quite a HO!

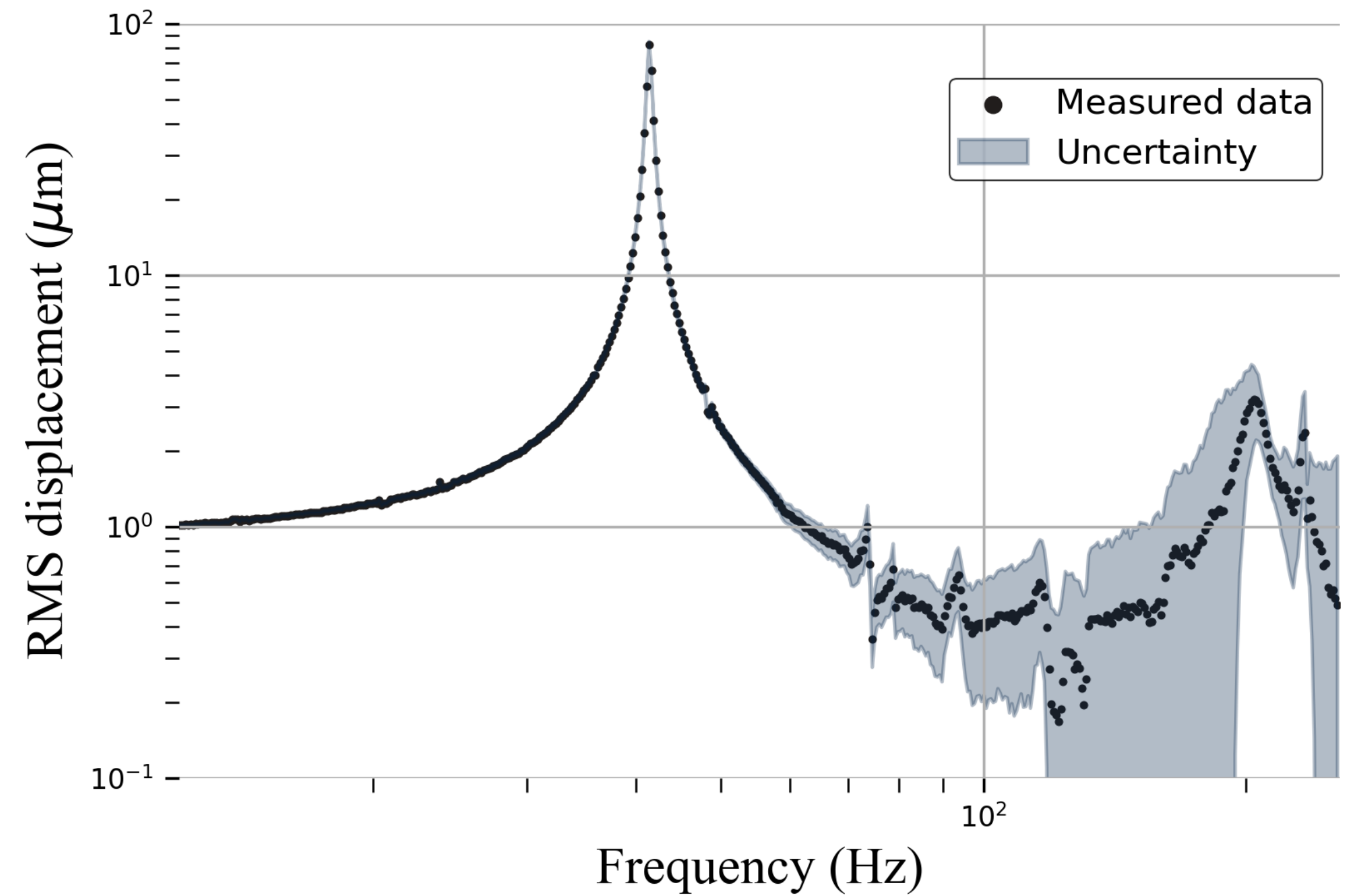
- Coupled system





Not quite a H0!

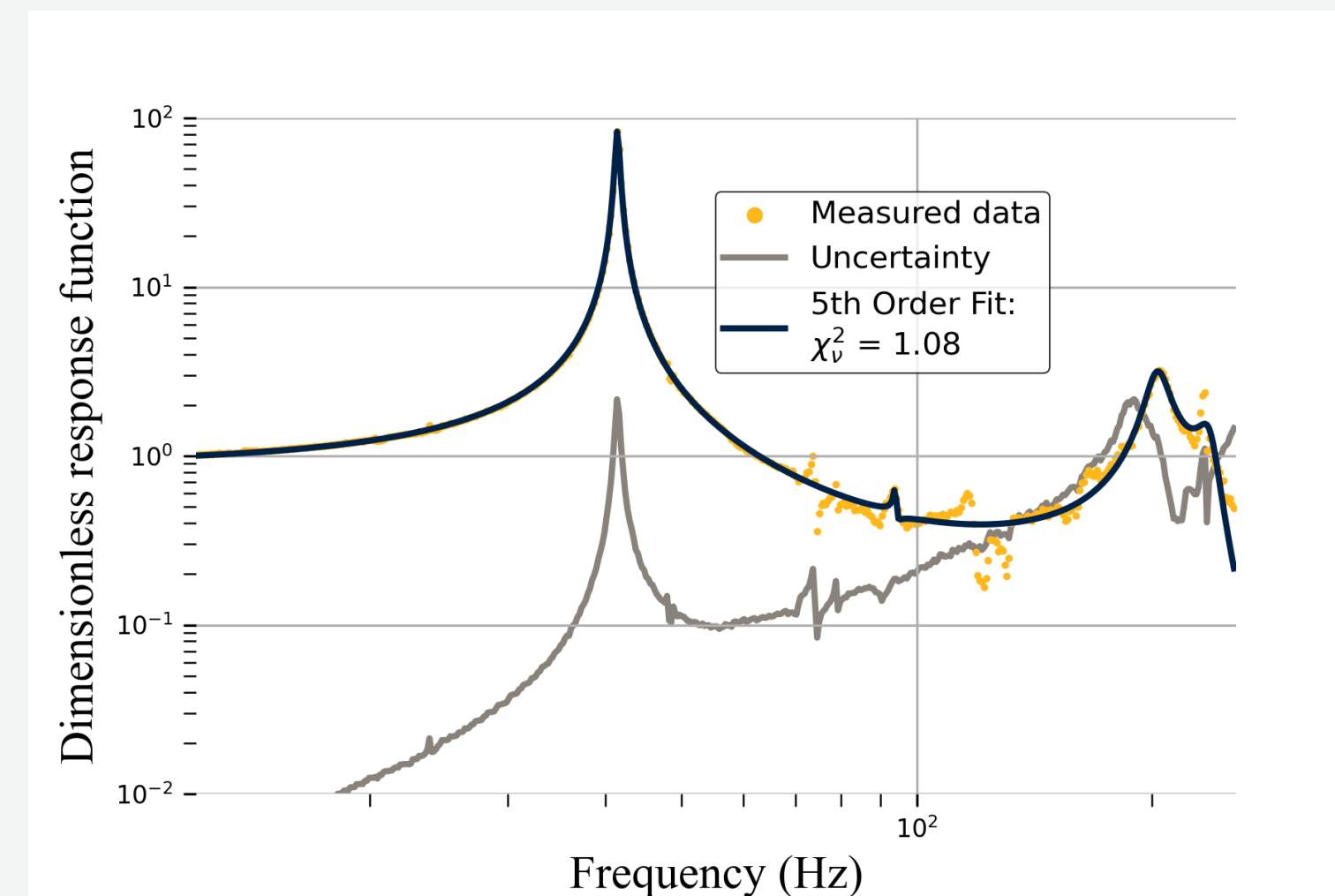
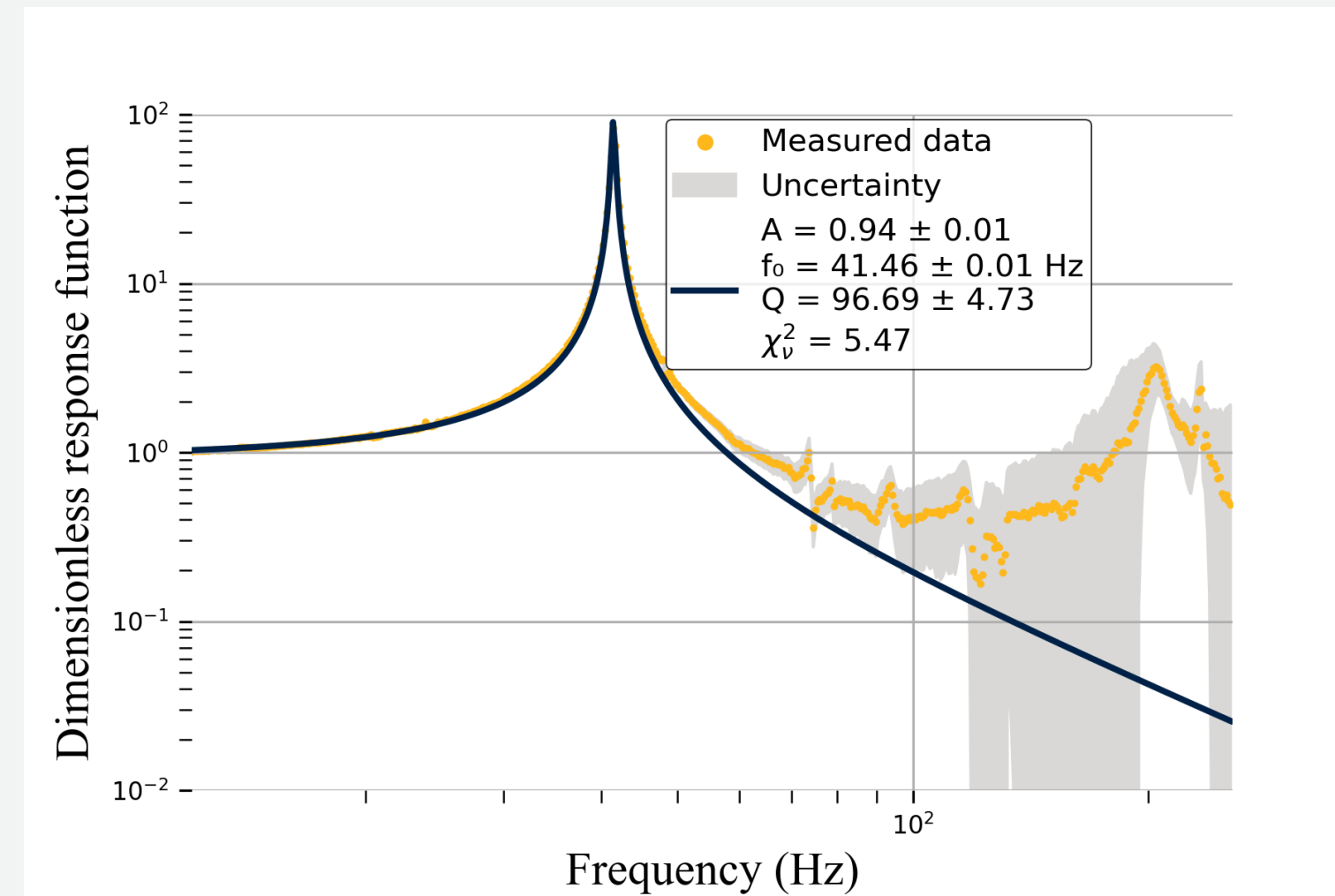
➤ Coupled system

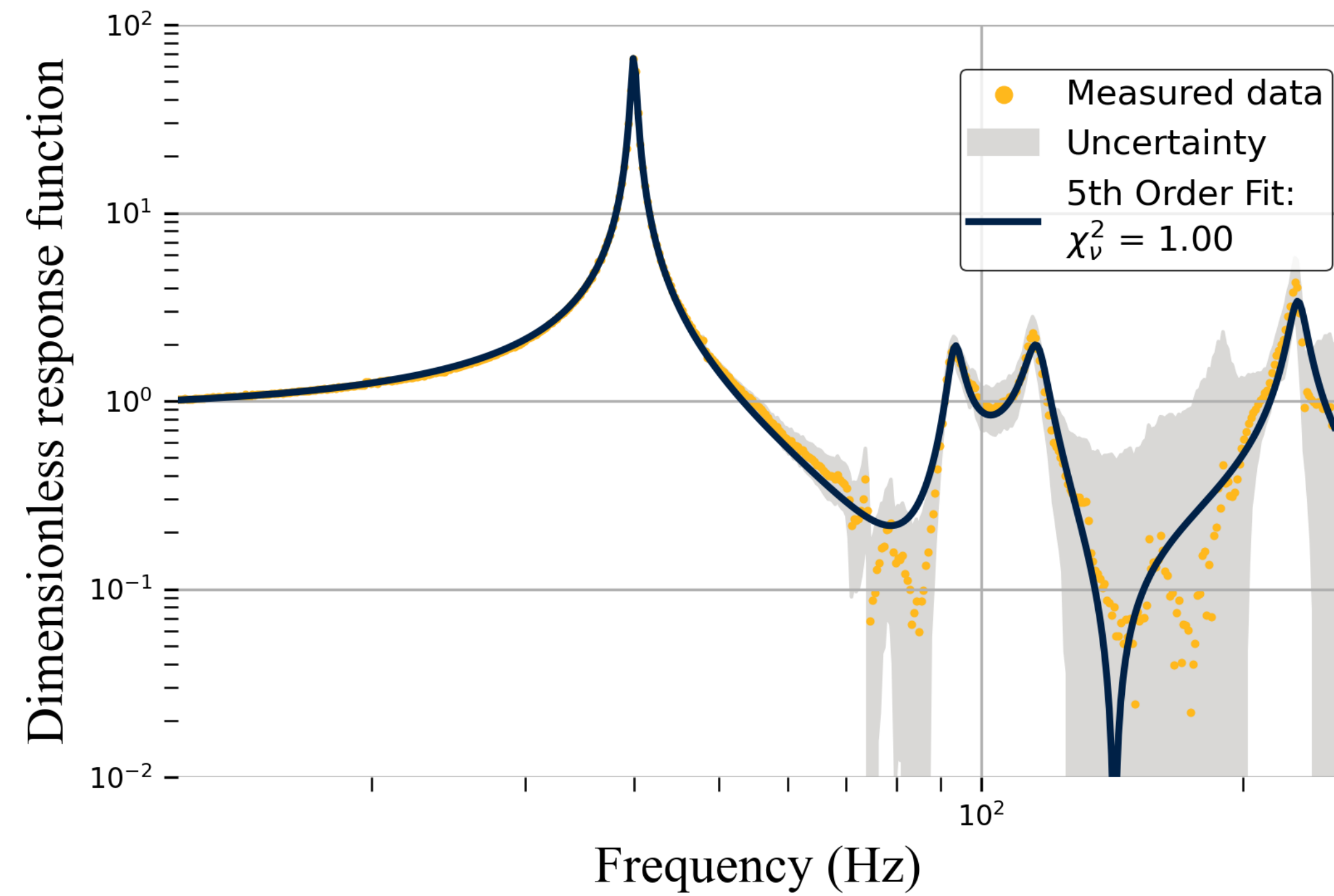
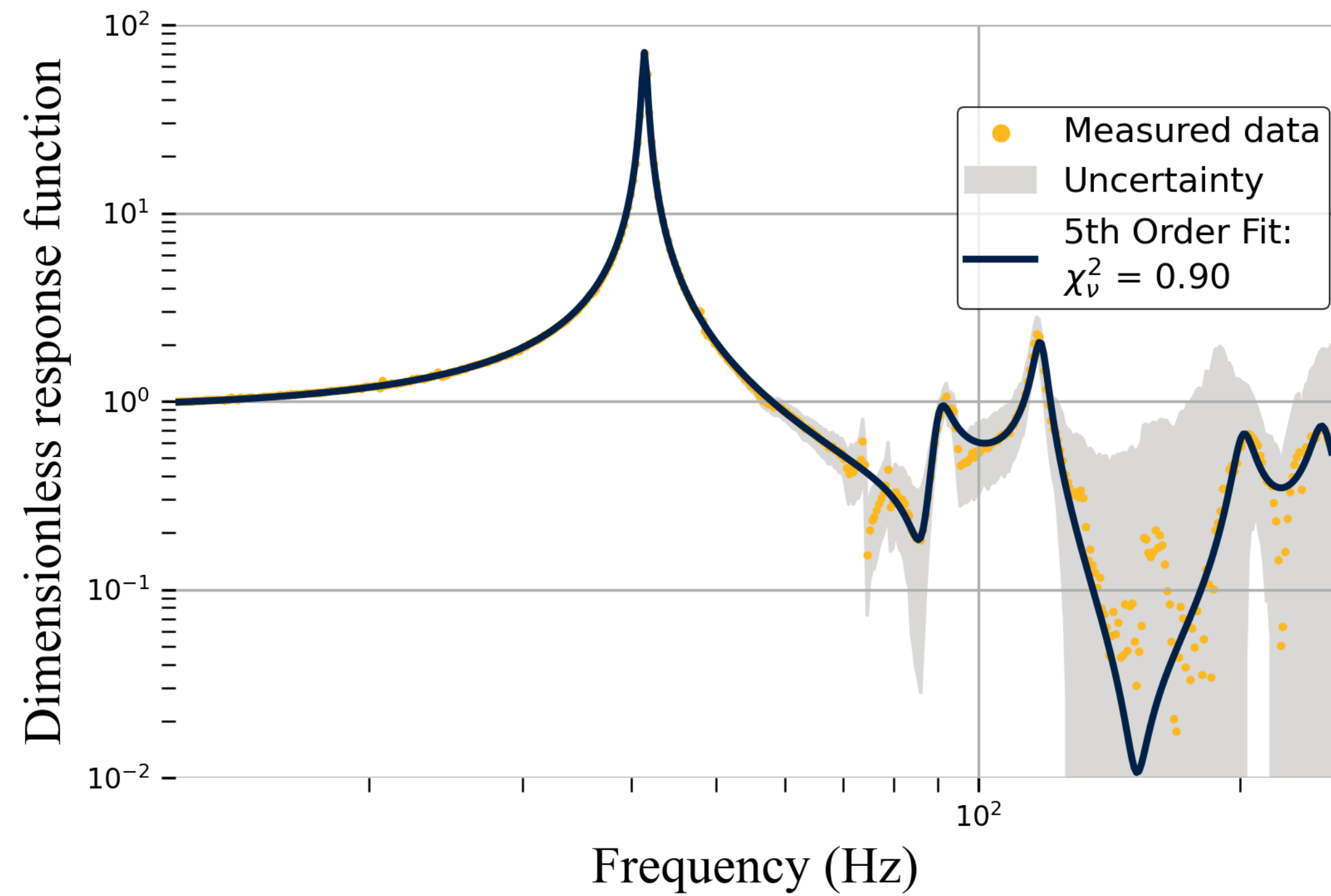


Linear response function

- HO fit only adequate for 1st mode
- $n = 5$ fit in good correspondence with data

⇒ determined $|H(\omega)|$



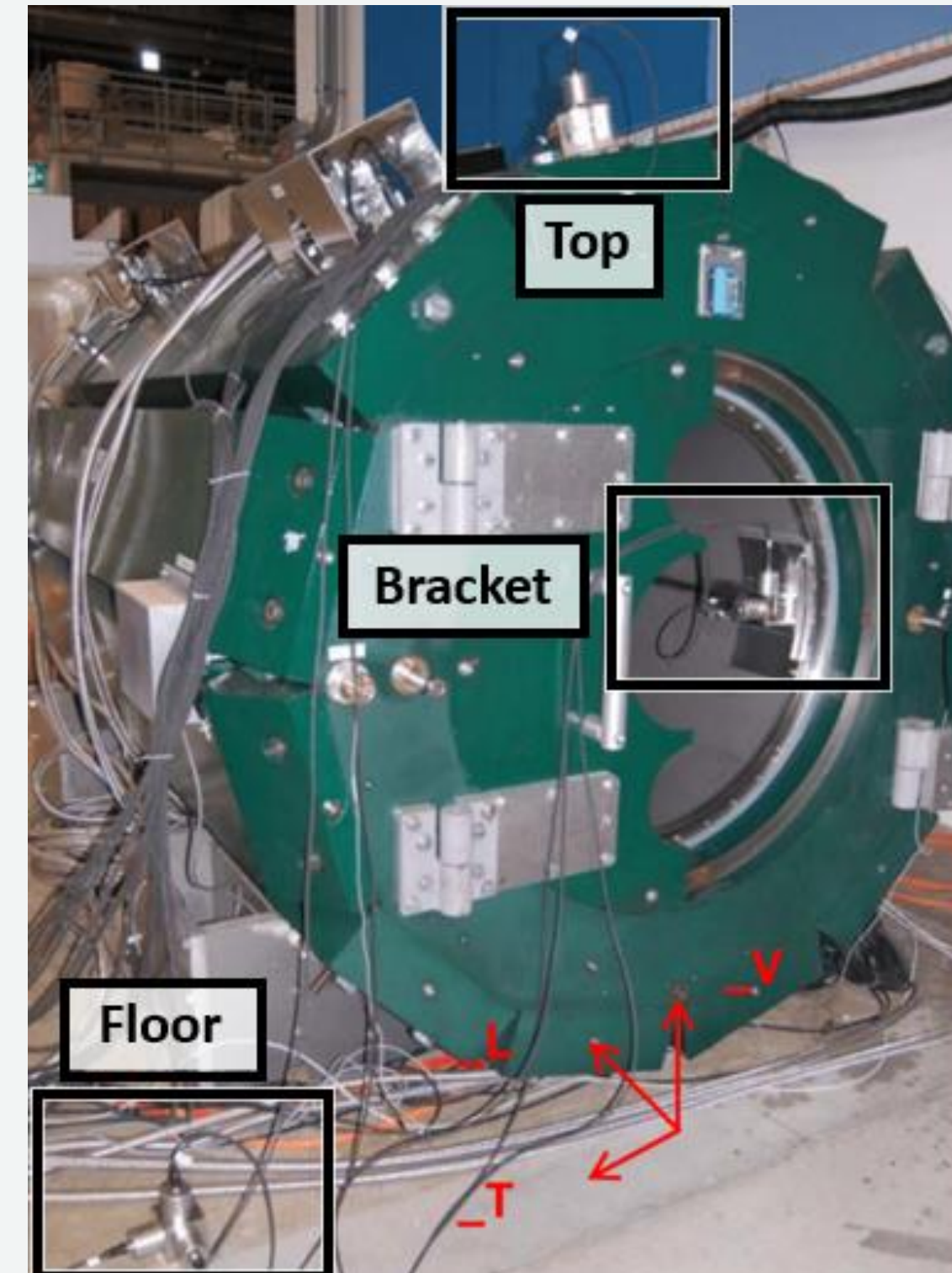


Expected RMS displacement

Background motion has been measured at PSI

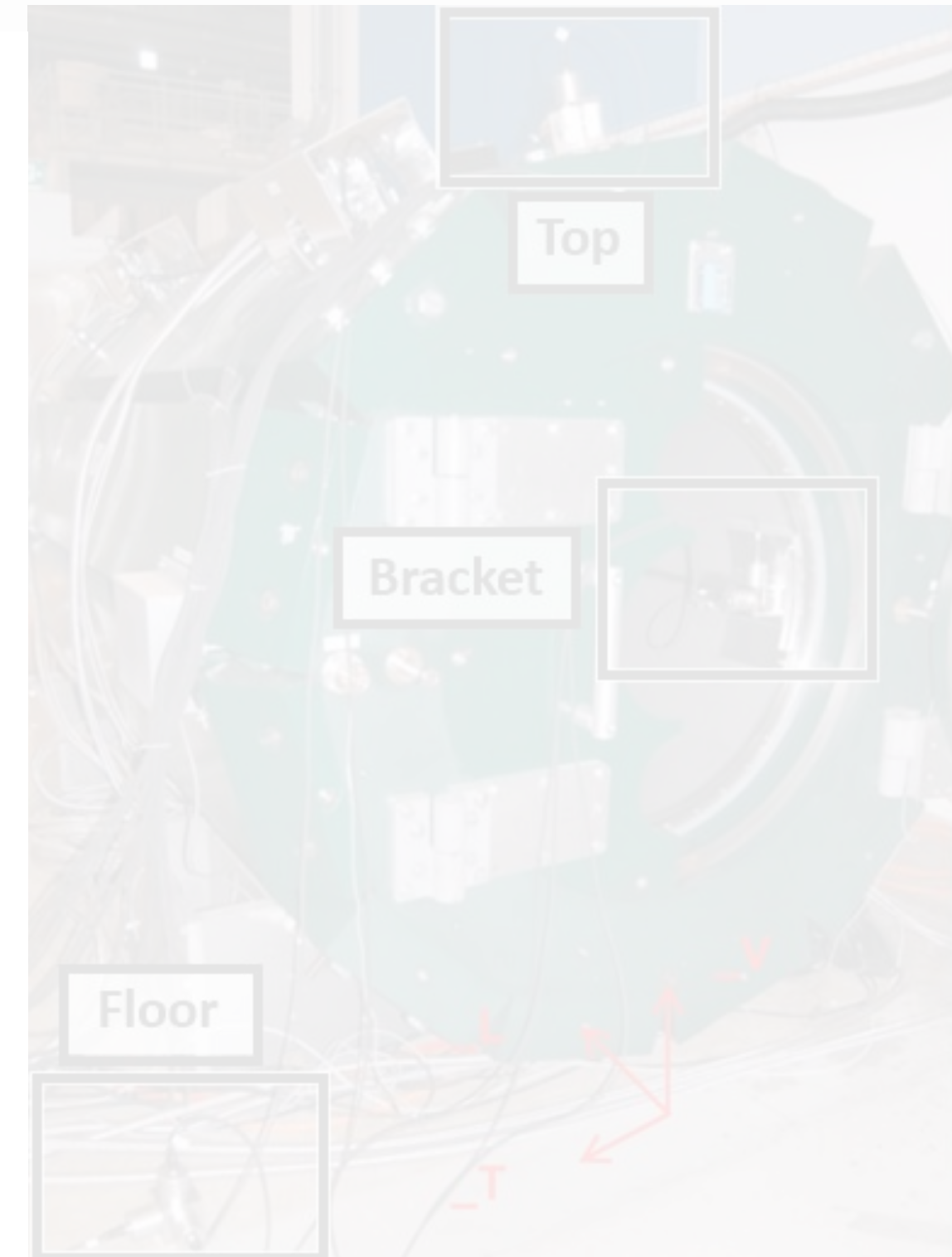
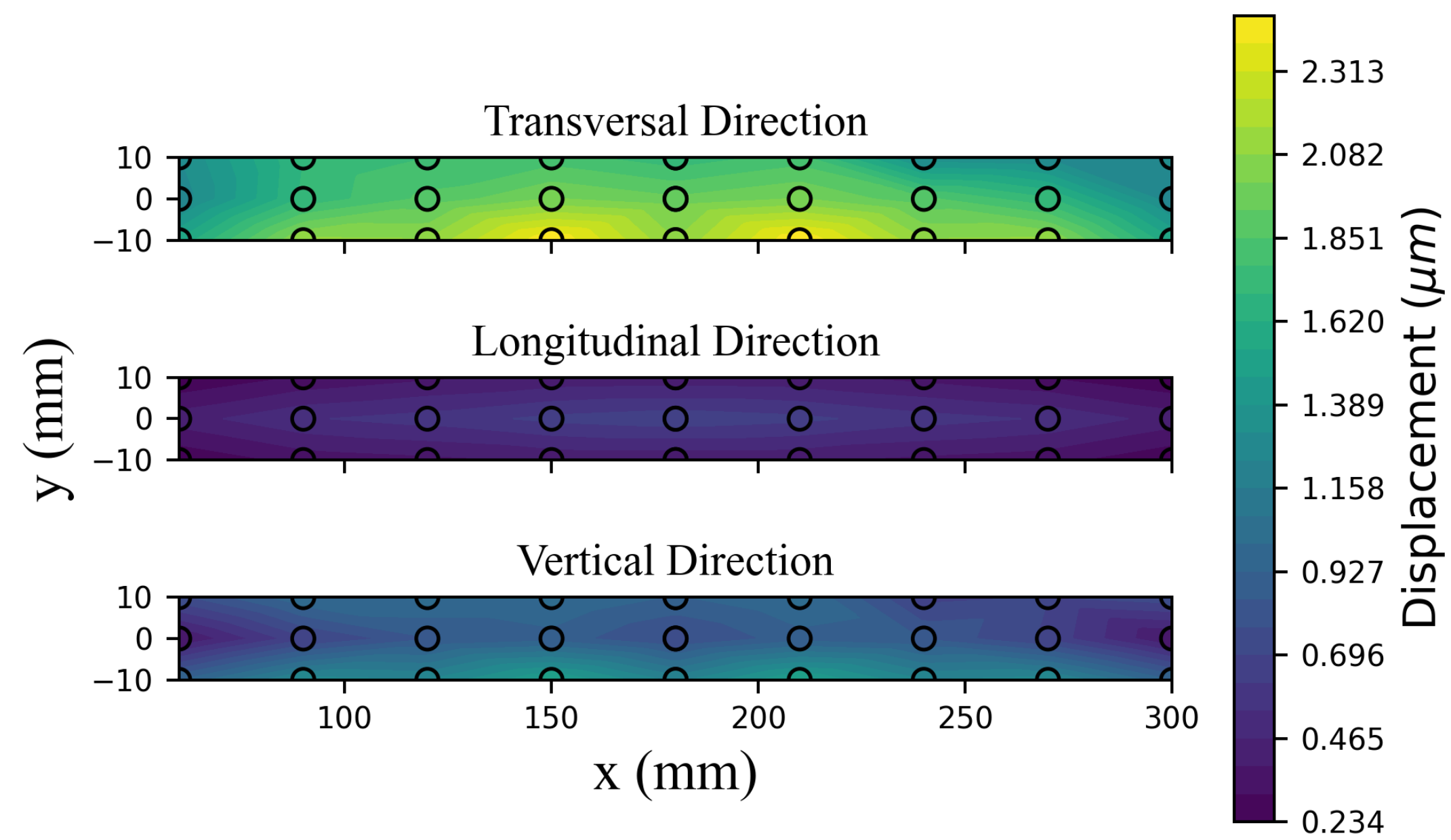
$$\triangleright S_x(f) = (2\pi f)^{-4} S_a(f)$$

$$\Rightarrow x_{RMS}^2 = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} S_x(\omega) \cdot |H(\omega)|^2 d\omega$$



Expected

- Hello



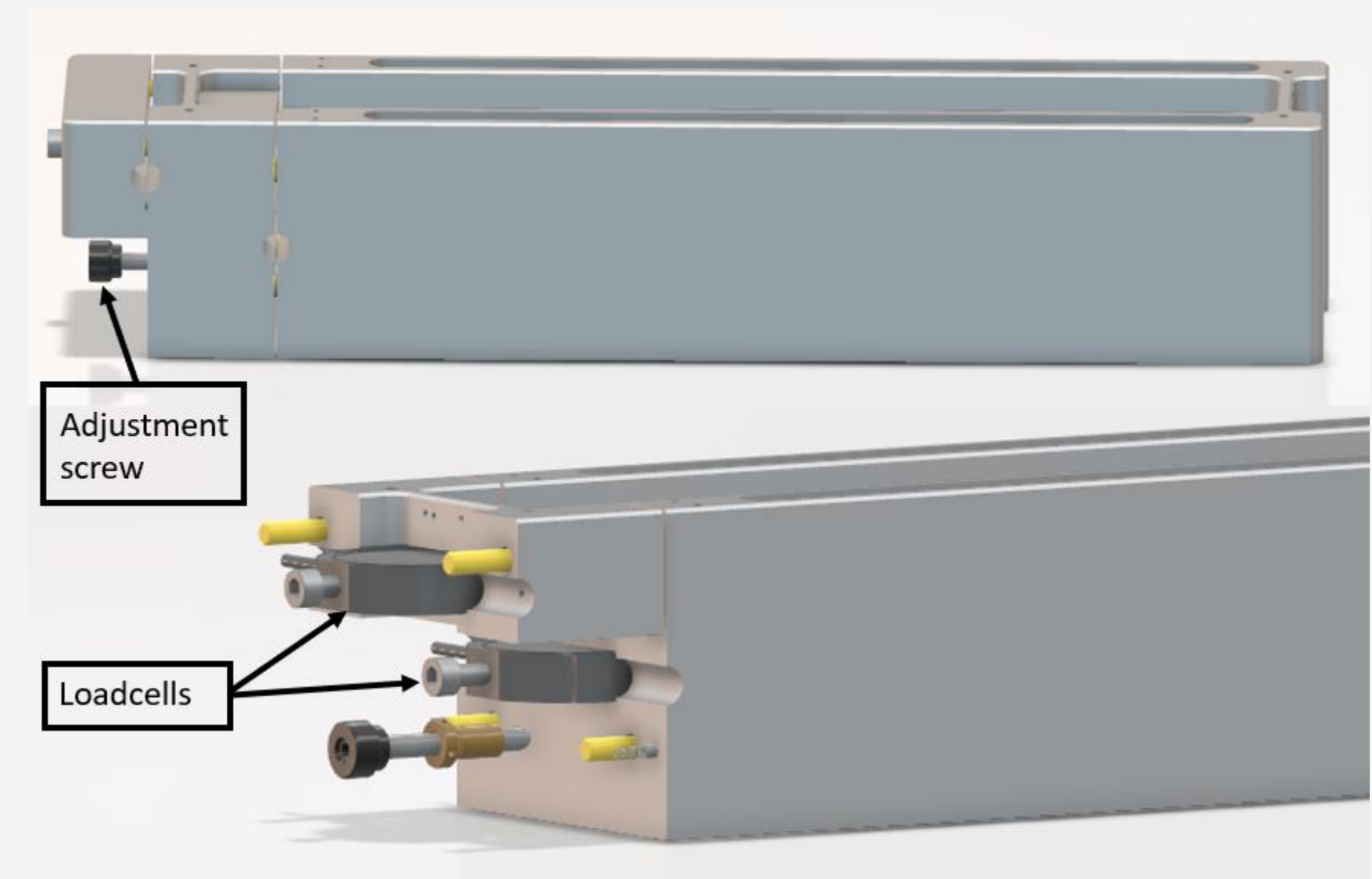
Extendable ring frame

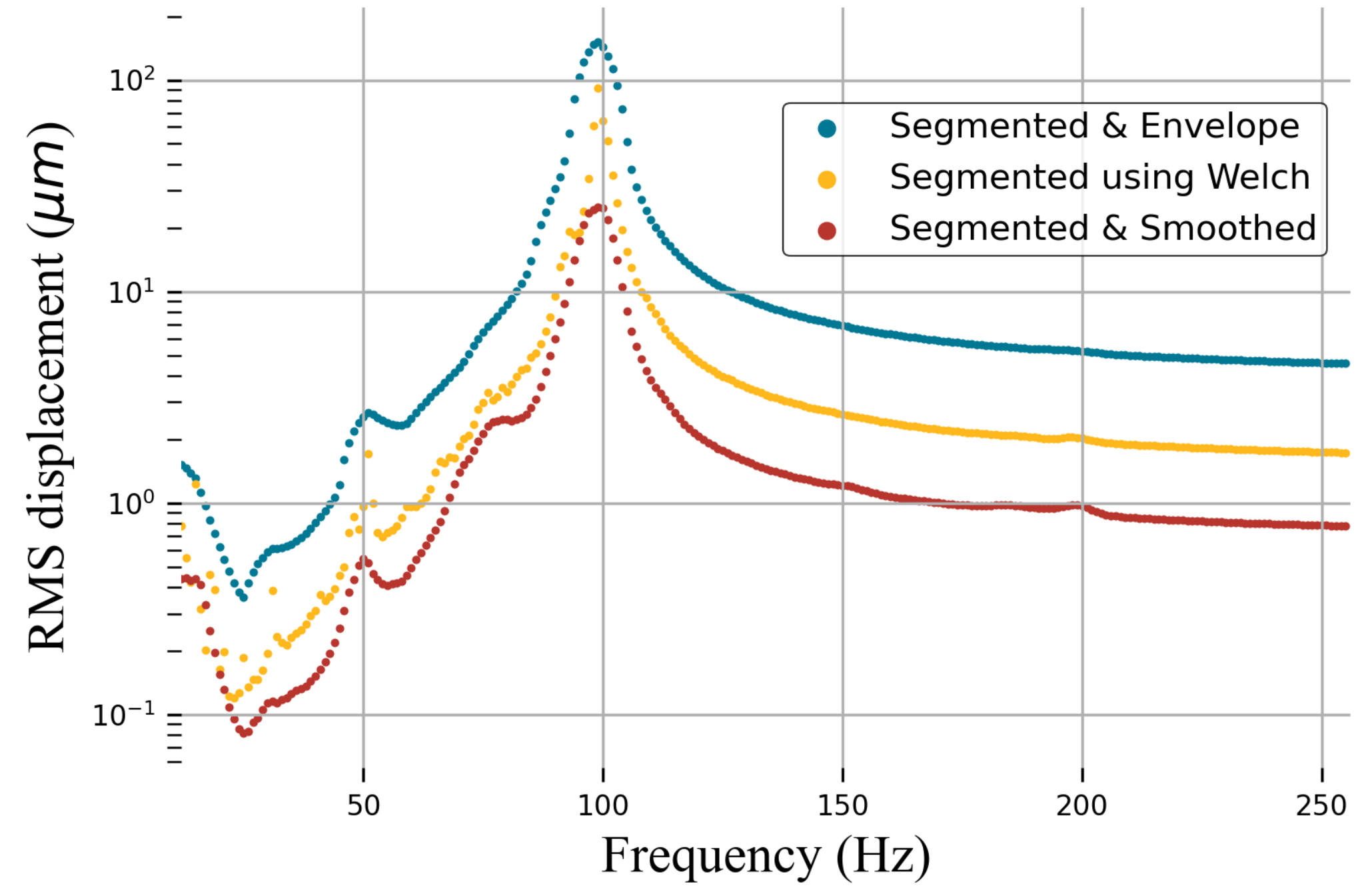
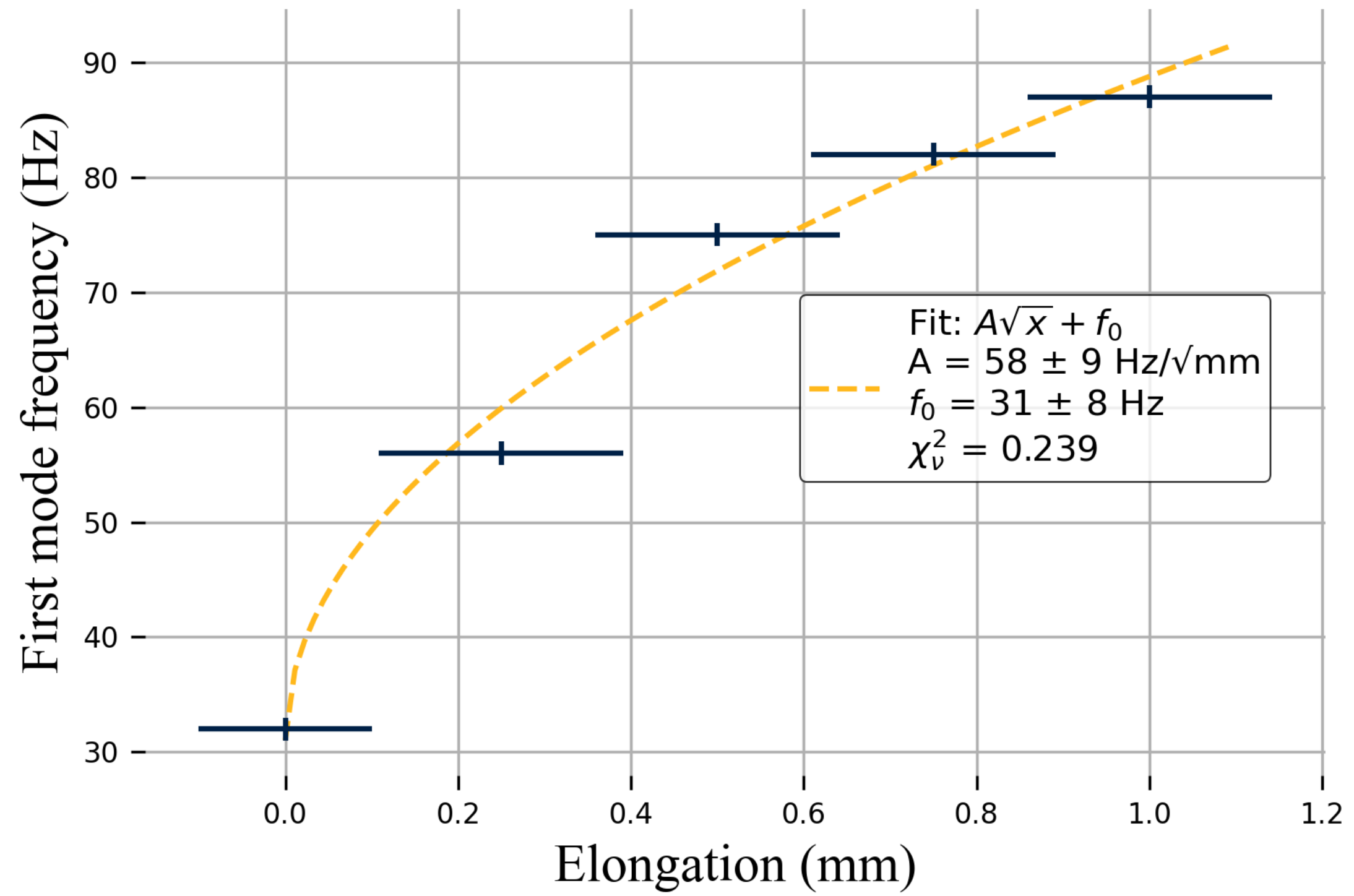
First mode frequency depends on tension

Idea:

- Length can be increased
- Loadcells measure tension

! Wrong loadcells !





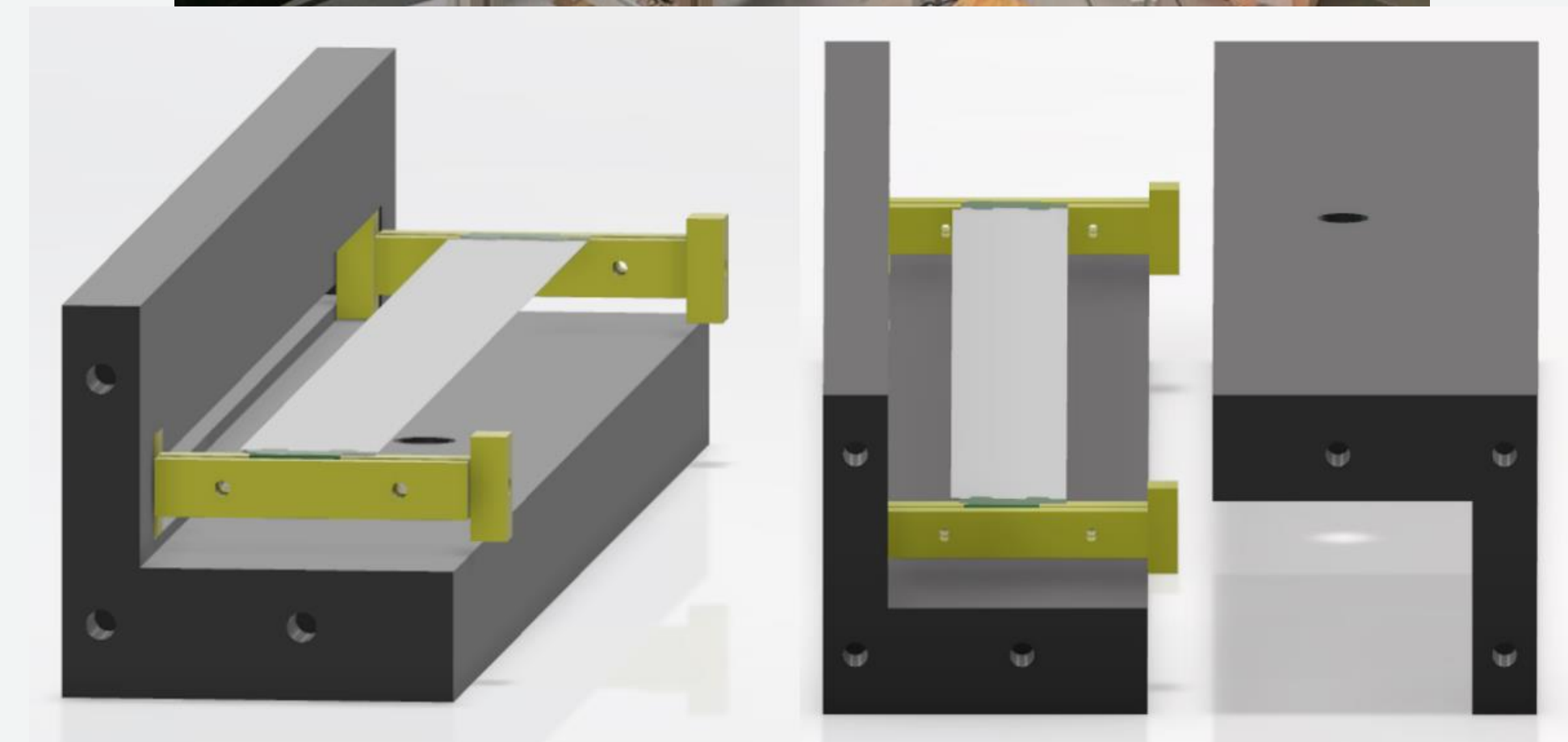
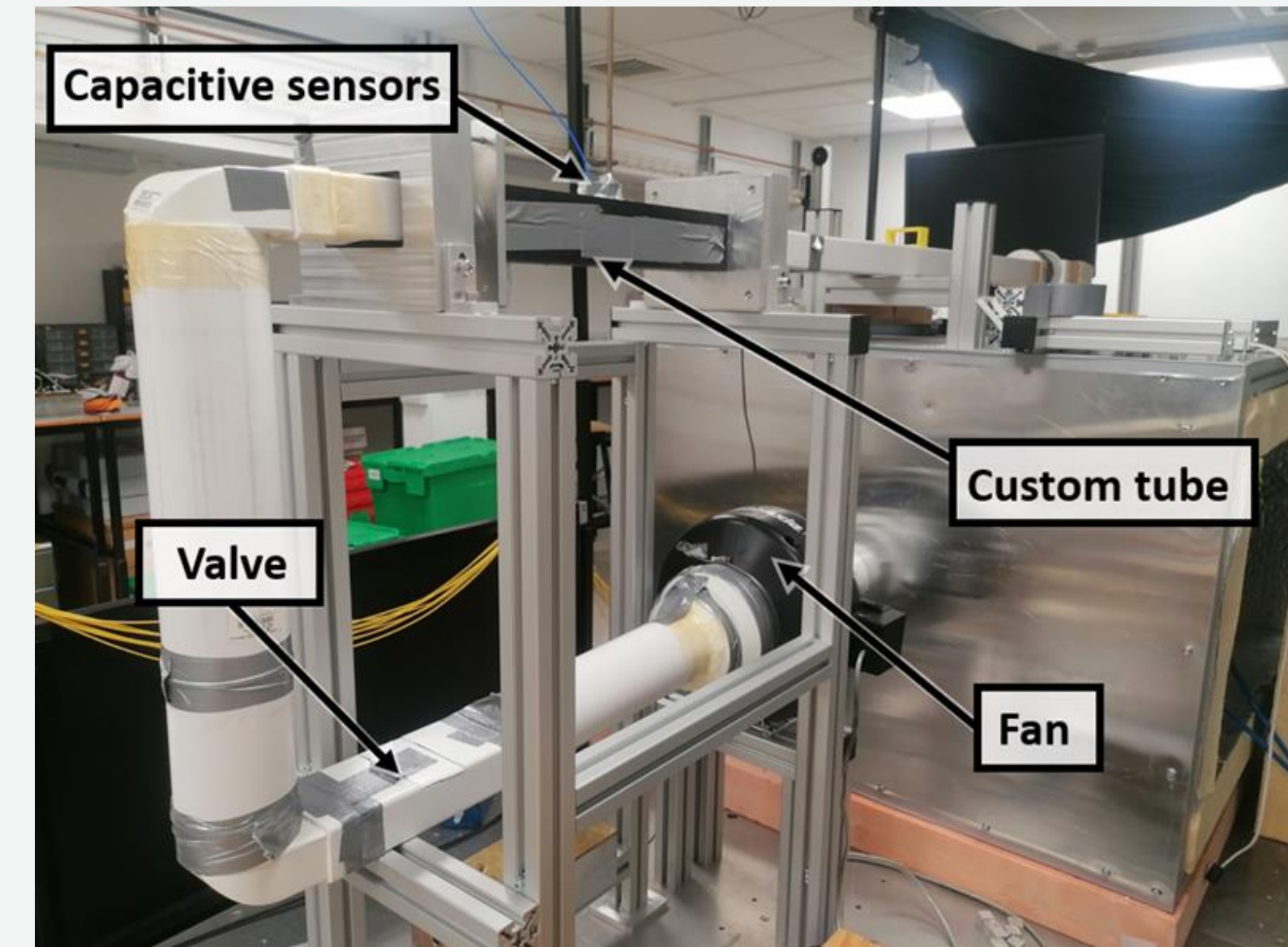
Cooling flow induced vibrations

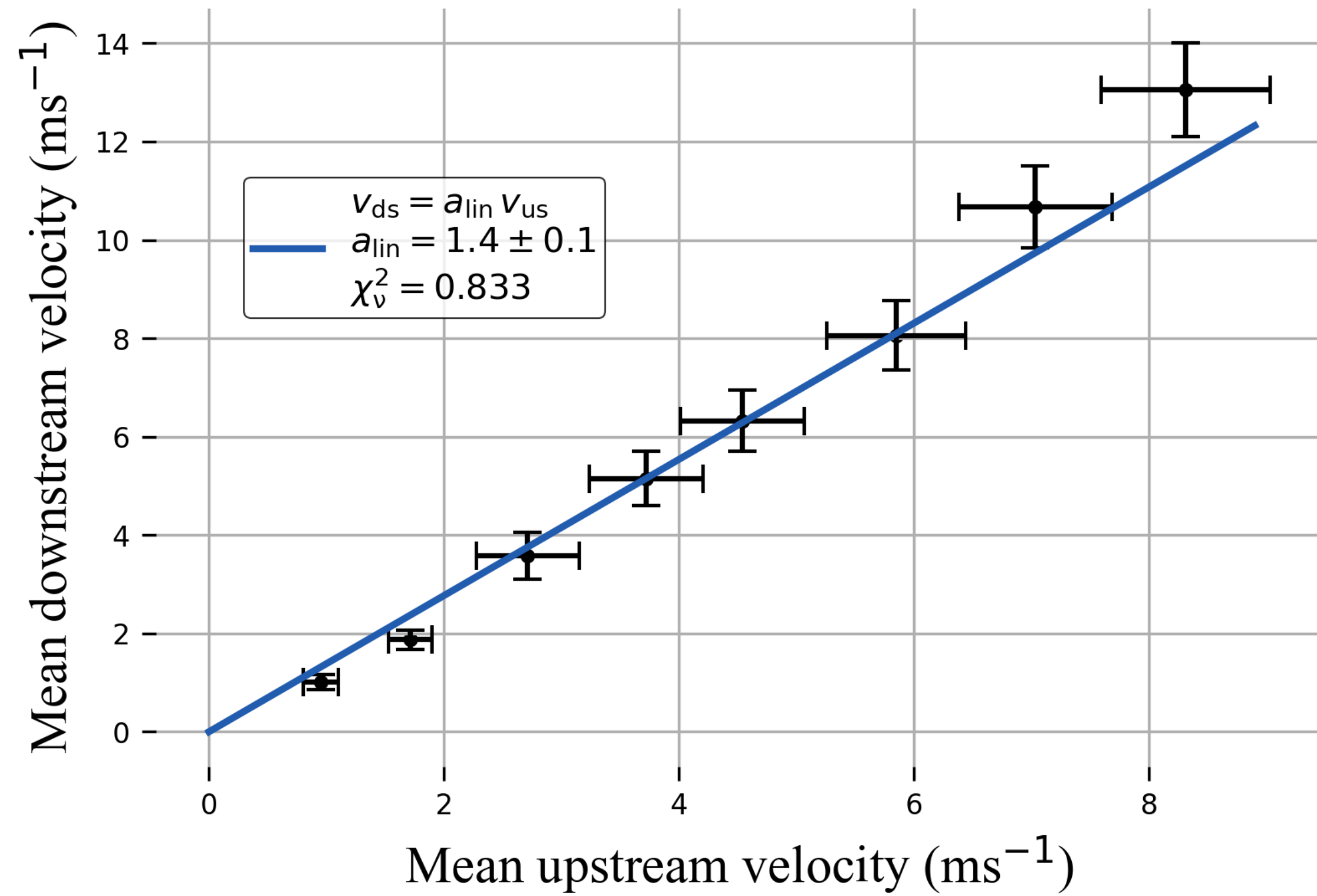
Wind tunnel

Working principle:

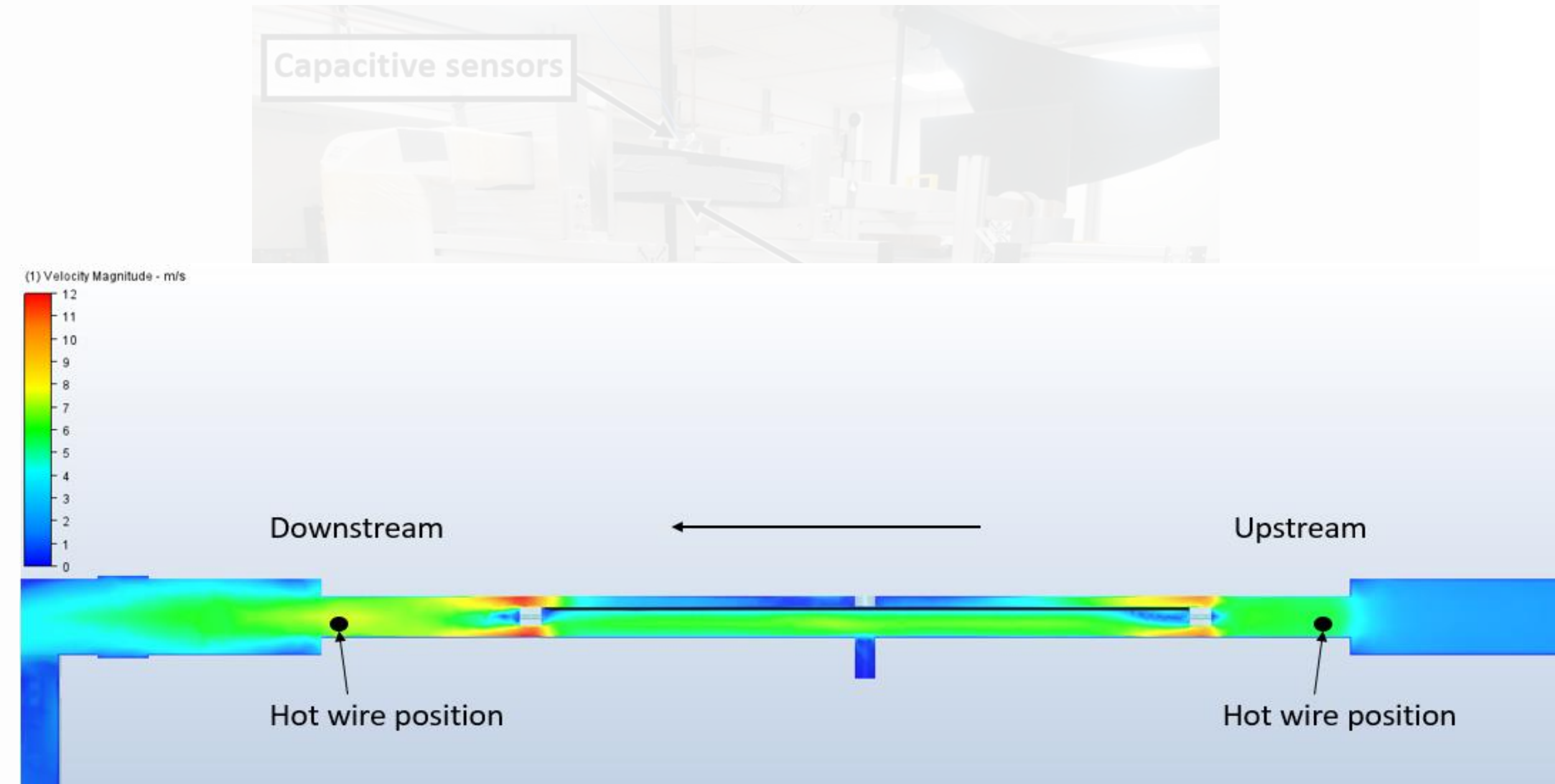
- Fan pulls air out of the tubing
- Custom tube holds ladder
- Hot-wire anemometer for flow measurement
- Displacement measured using capacitive sensor
- Valve used to change flow velocity

Upstream and downstream flow differed!





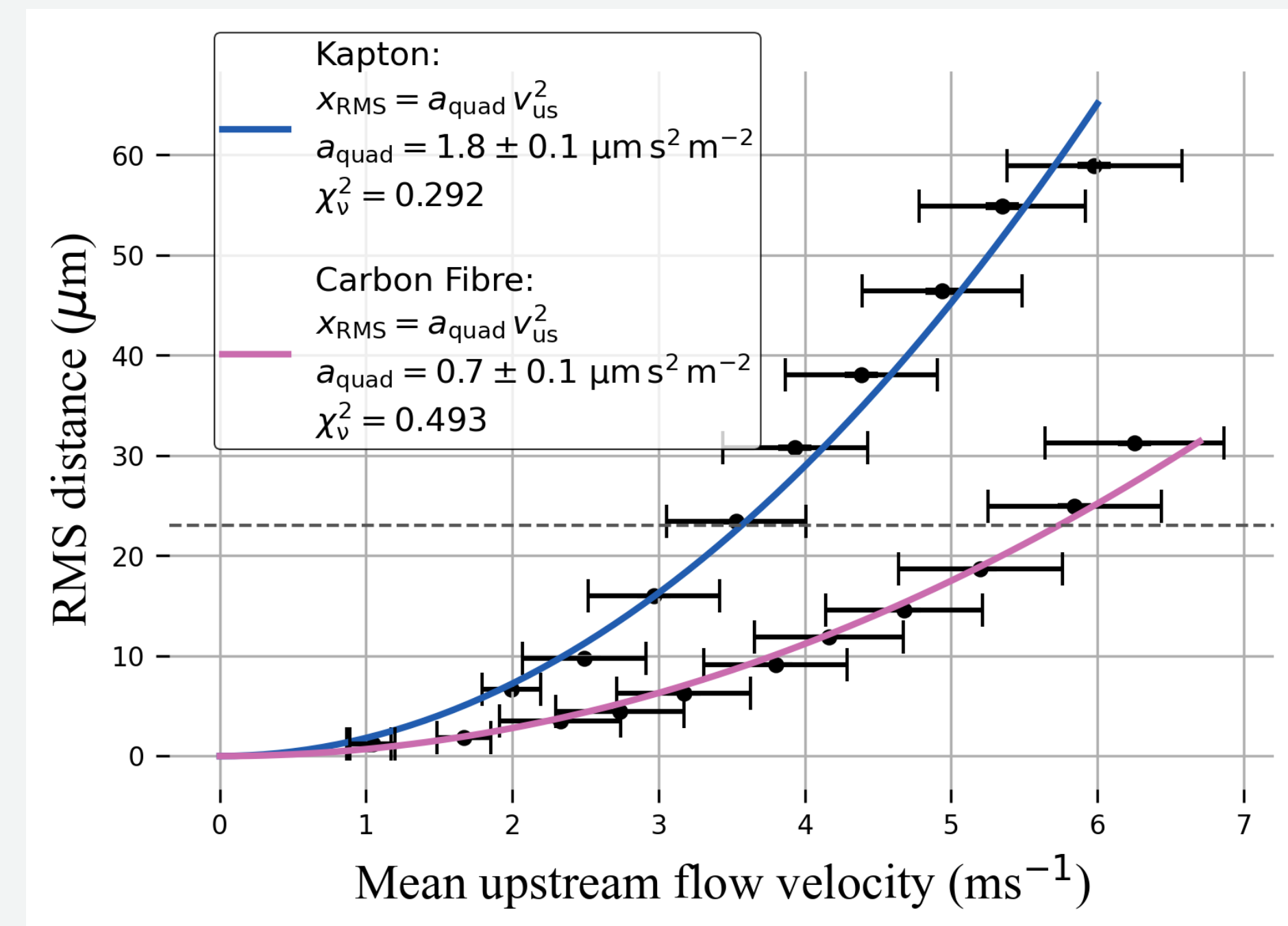
Upstream and downstream flow differed!



RMS displacement

Kapton ladder performs worse

How does this translate to Helium?
Other ways to compare setups?



Wiener-Khinchin again:

$$F_{aero} = \frac{1}{2} \rho A v^2$$

$$\Rightarrow S_F = \left(\frac{1}{2} \rho A \right)^2 S_{v^2}$$

$$x_{RMS}^2 = \int_0^{\infty} S_F(f) \cdot |H(f)|^2 df$$

$$\Rightarrow x_{RMS} \propto \rho$$

Conversion factor ~ 2.7

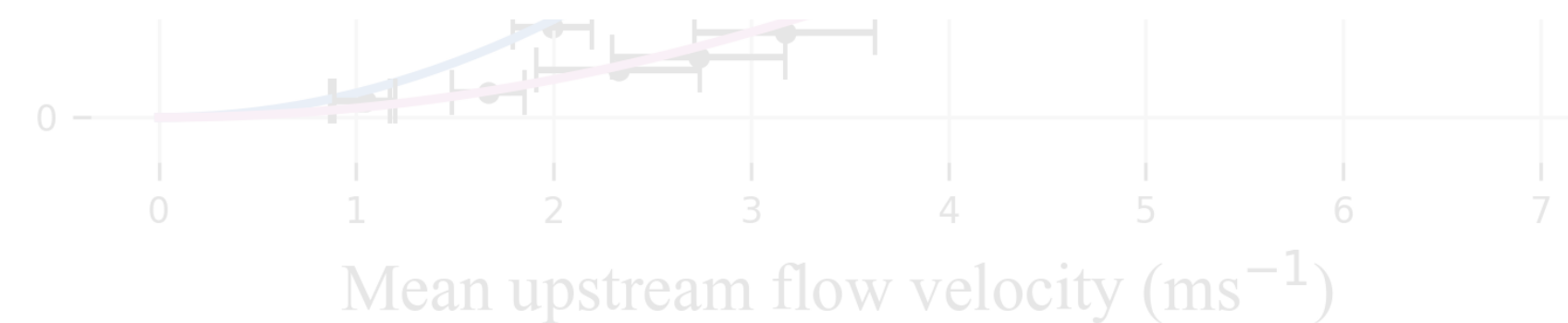
Reynolds number:

- Ratio between inertial and viscous forces

$$Re = \frac{\rho V L}{\mu}$$

- High values → turbulent

- Low values → laminar



CFD comparison

Mu3e flow velocity: $\sim 14\text{m/s}$
 Converted $\rightarrow \sim 5.6\text{m/s}$

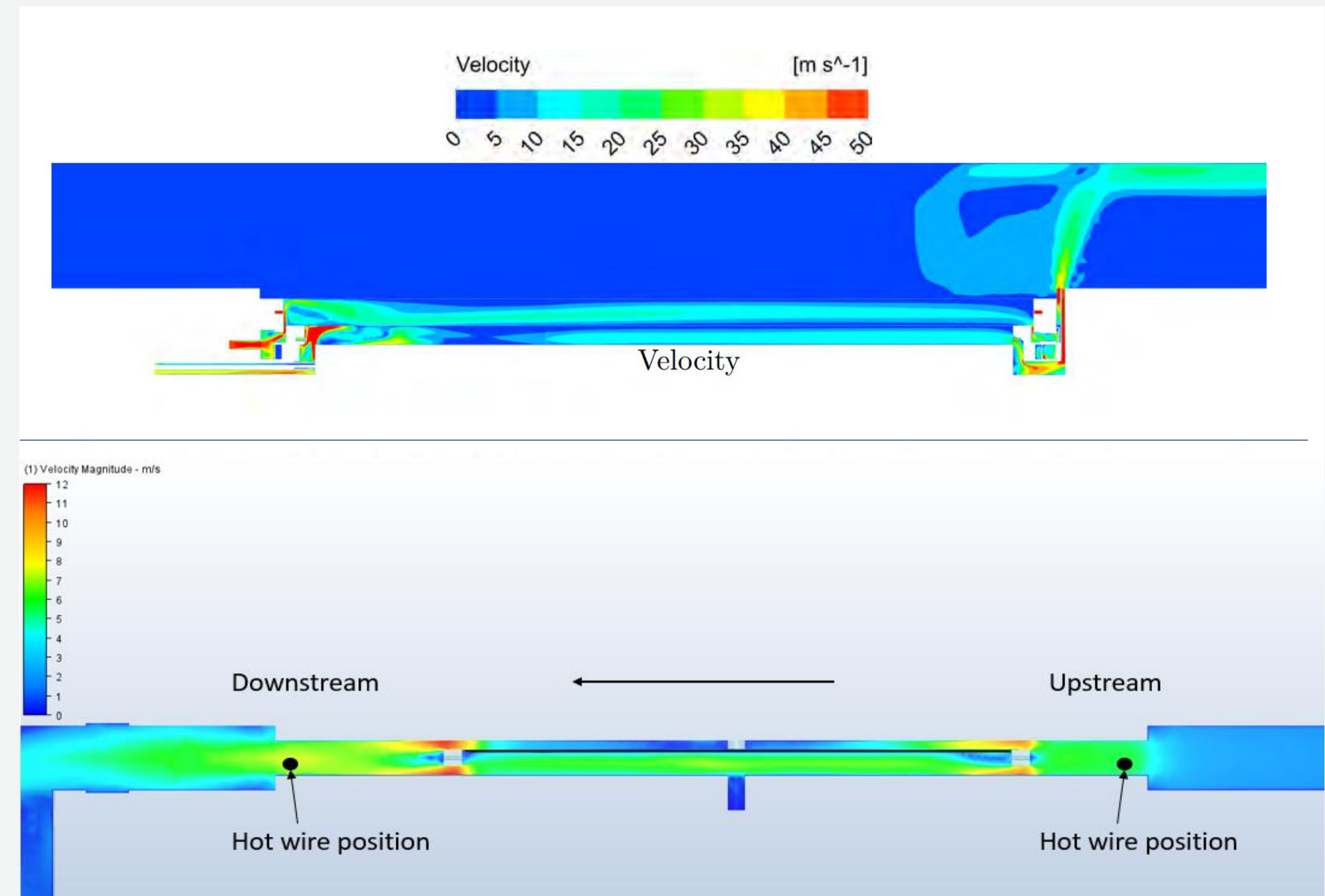
$\Rightarrow 21\mu\text{m}$ for carbon fibre ladder

Mu3e Reynolds number: ~ 2300

Oxford setup Reynolds number: > 2500 for $v > 2\text{m/s}$

Transition ~ 2400
 Turbulent > 5000

} Different regimes!



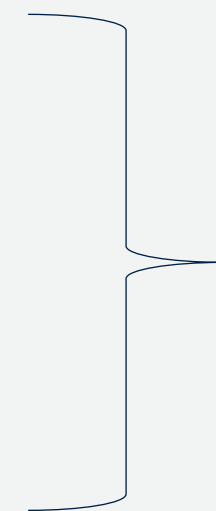


Conclusion

Intrinsic pixel resolution: $23\mu m$

Cooling flow induced vib: $21\mu m$

Background motion induced vib: $3\mu m$



σ increases to $31\mu m$ (worst case)

Can't determine exact impact, however still MCS dominated!

⇒ Mechanical stability is sufficient!



Thank you very much!

Fancy a pint?

