



Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



Gefördert durch:

Bundesministerium
für Wirtschaft
und Energie
aufgrund eines Beschlusses
des Deutschen Bundestages



GRAVITATIONAL
WAVE DETECTION



Marcel Beck

GWADW Elba 2023

LISA interferometry TAPSI - Project

LISA ground-support equipment:

16. Developing a toolset for adjustable picometer- stable interferometers for future gravitational wave detectors

TAPS!

Toolset for Adjustable Picometer-Stable
Interferometers

LISA mission

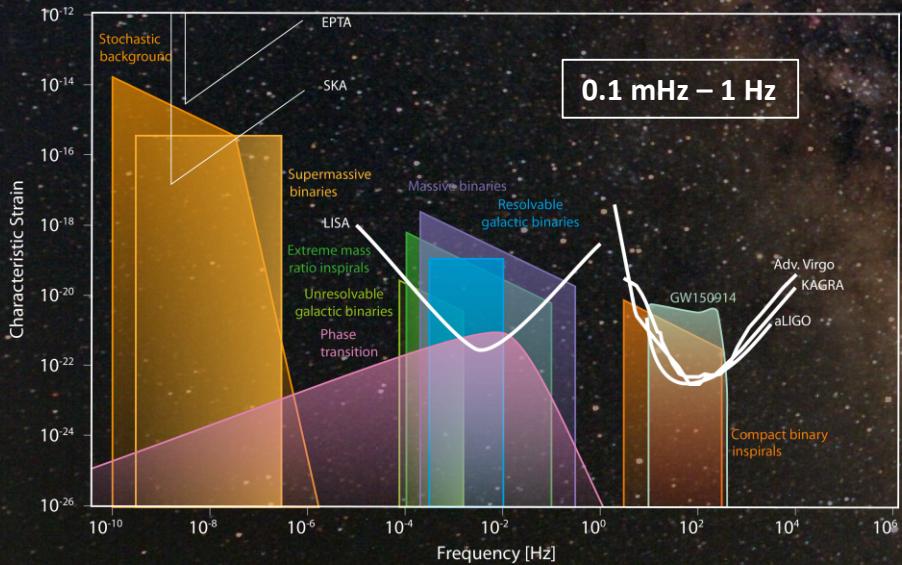


Fig.1

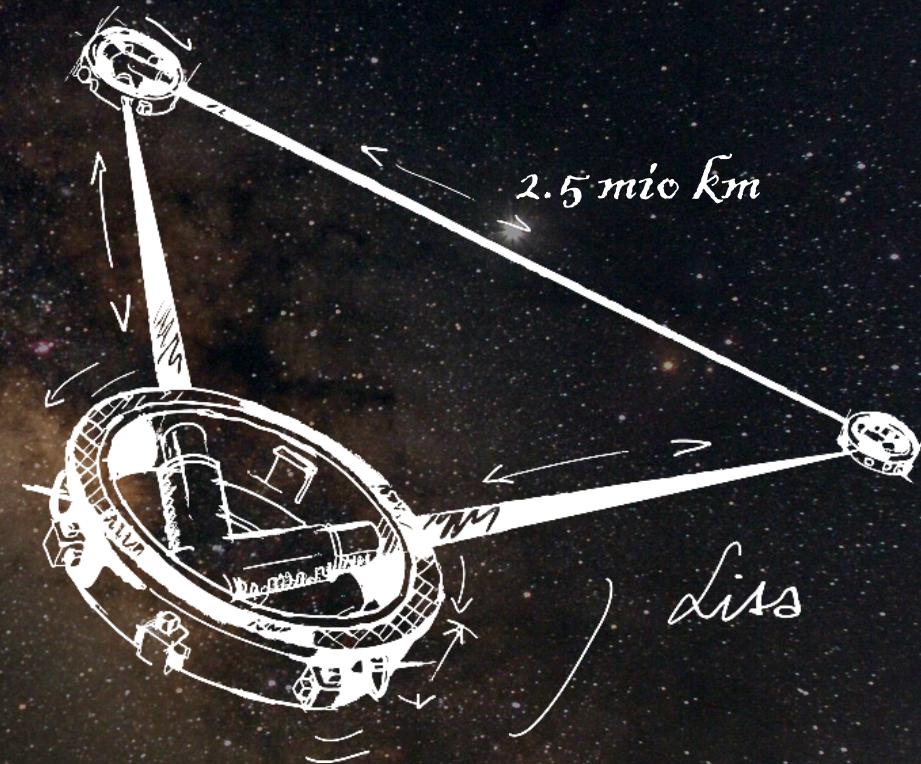


Fig.1: Gravitational Wave Sensitivity Curve Plotter (gwplotter.com)



LISA ground support equipment

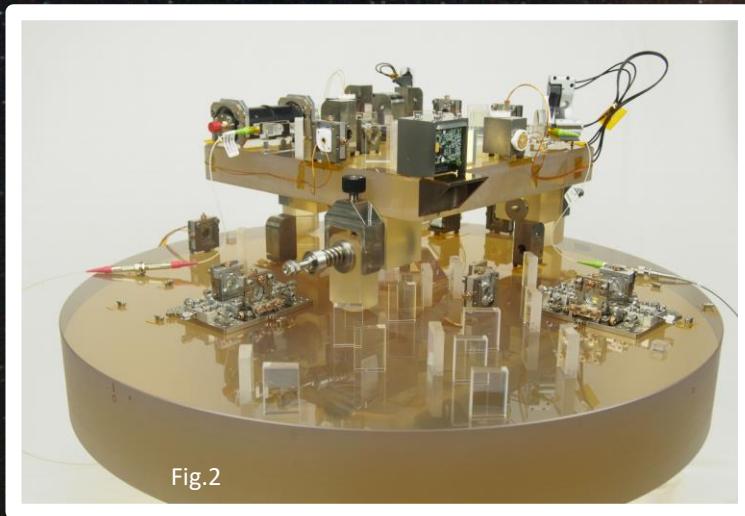


Fig.2

Fig.2: M. Lieser, E. Fitzsimons, et. al. (2016), *Construction of an optical test-bed for LISA*

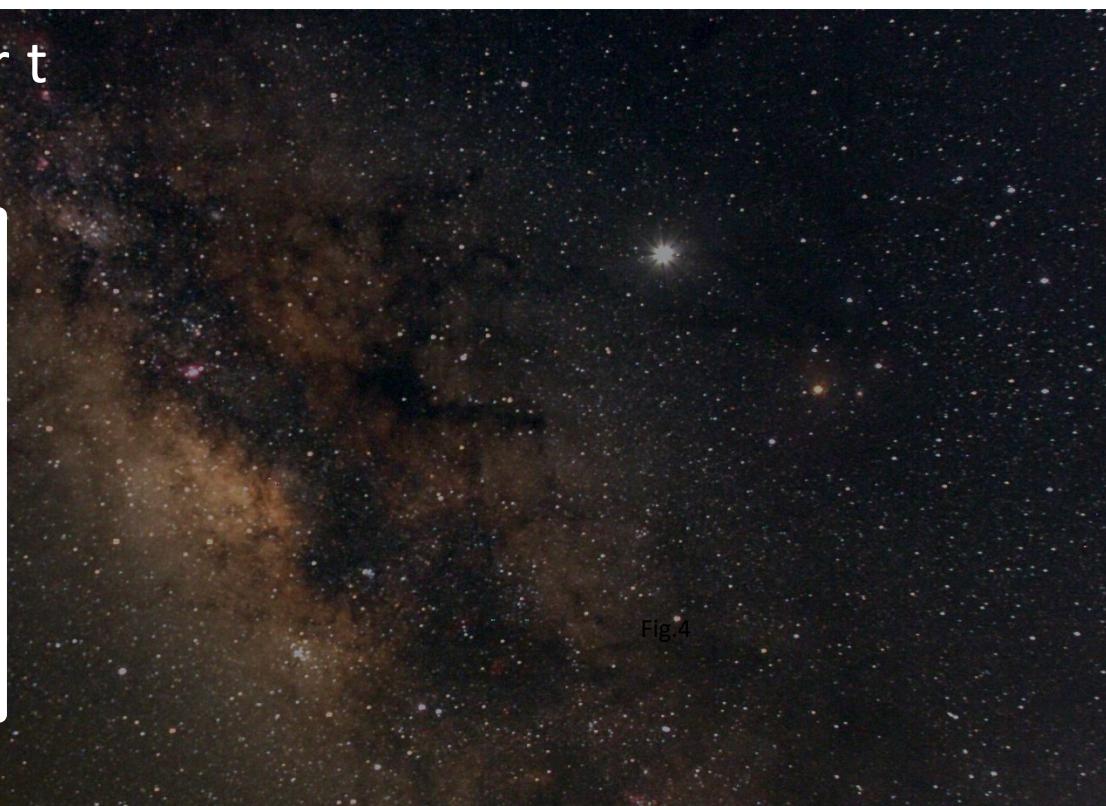
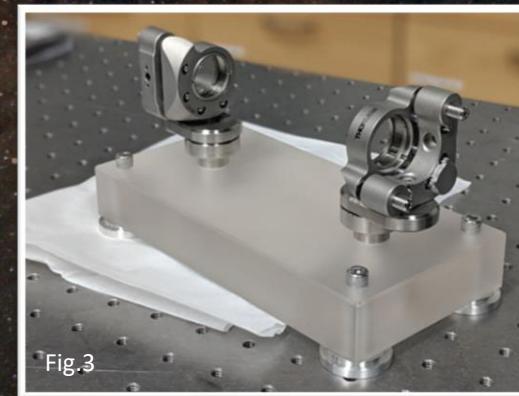
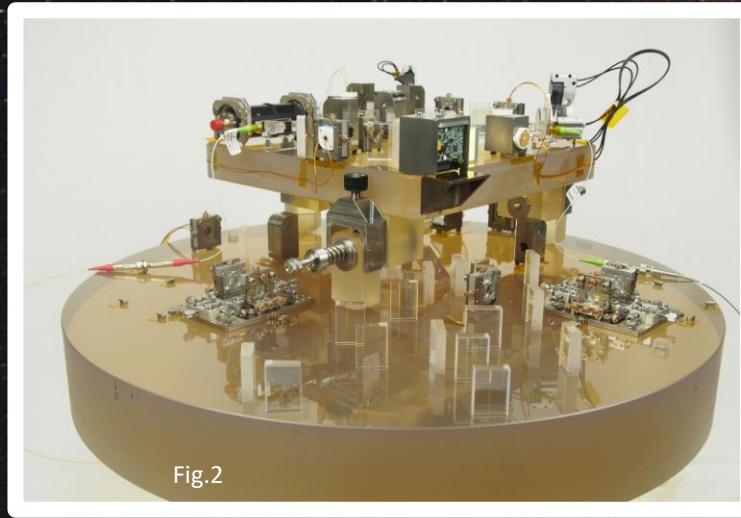


Fig.4

LISA ground support equipment



University of Florida

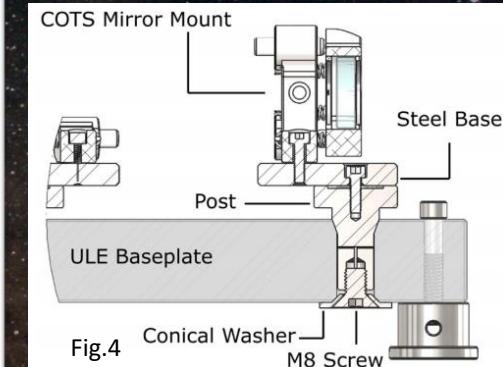
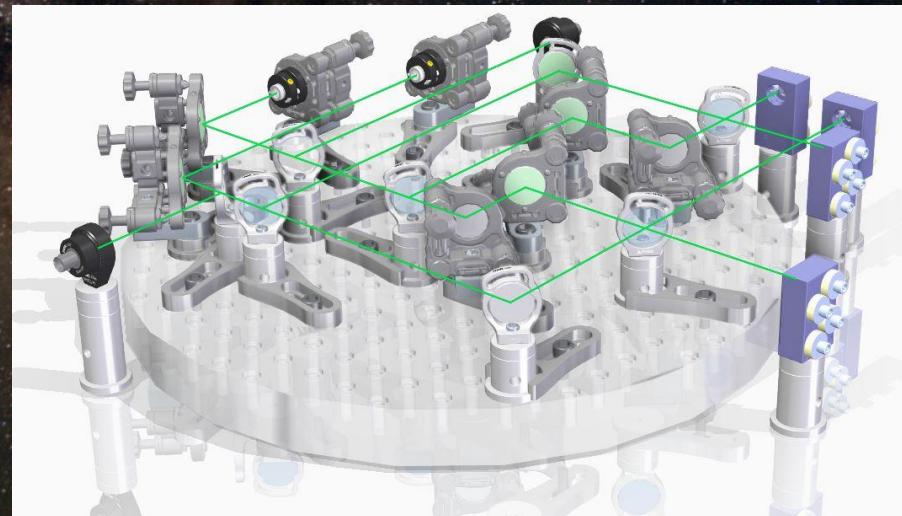


Fig.2: M. Lieser, E. Fitzsimons, et. al. (2016), *Construction of an optical test-bed for LISA*

Fig.3, 4: Soham Kulkarni, et. all (2020, July), *Ultrastable optical components using adjustable commercial mirror mounts anchored in a ULE spacer*

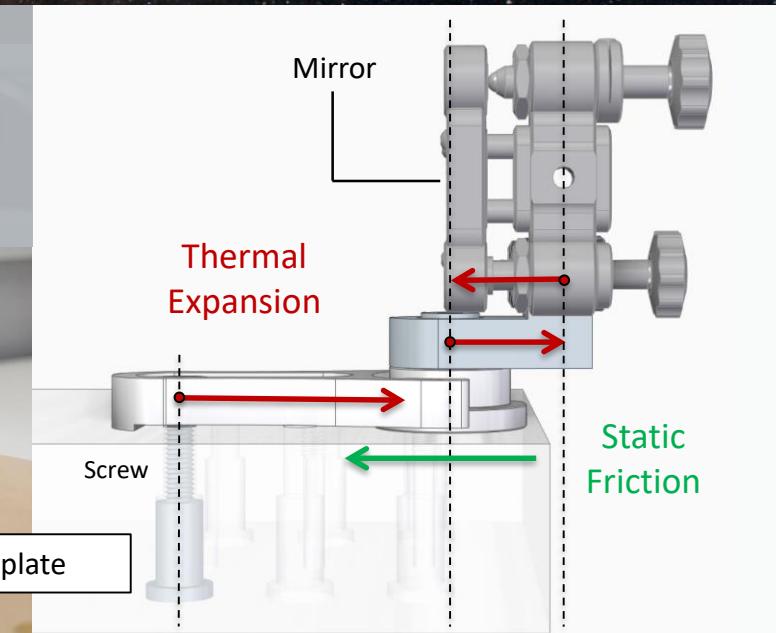
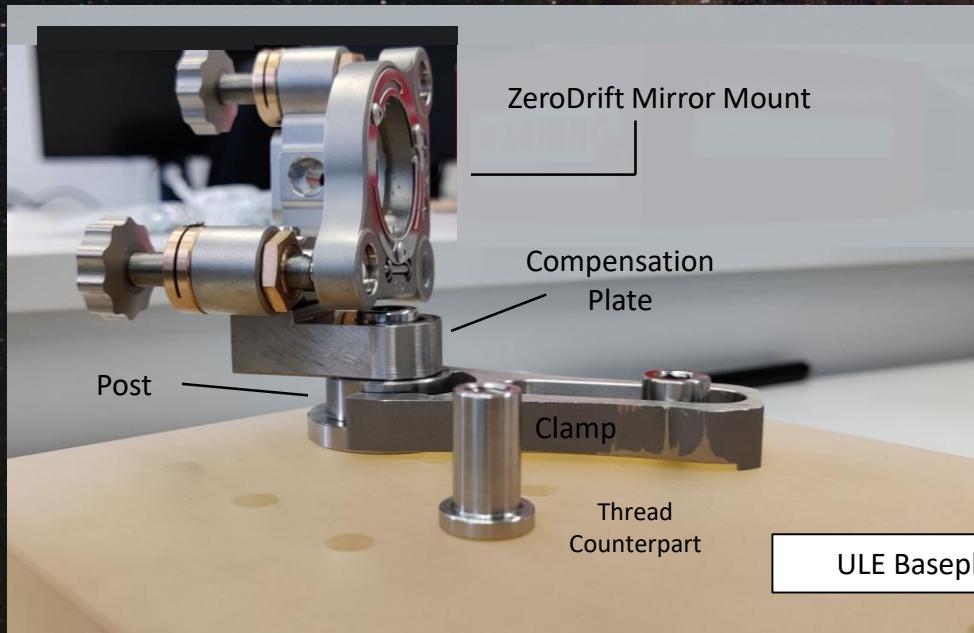
TAPS! concept

- Easy setup of interferometers
- Quick test of components
- Goal: $< 1 \frac{pm}{\sqrt{Hz}}$



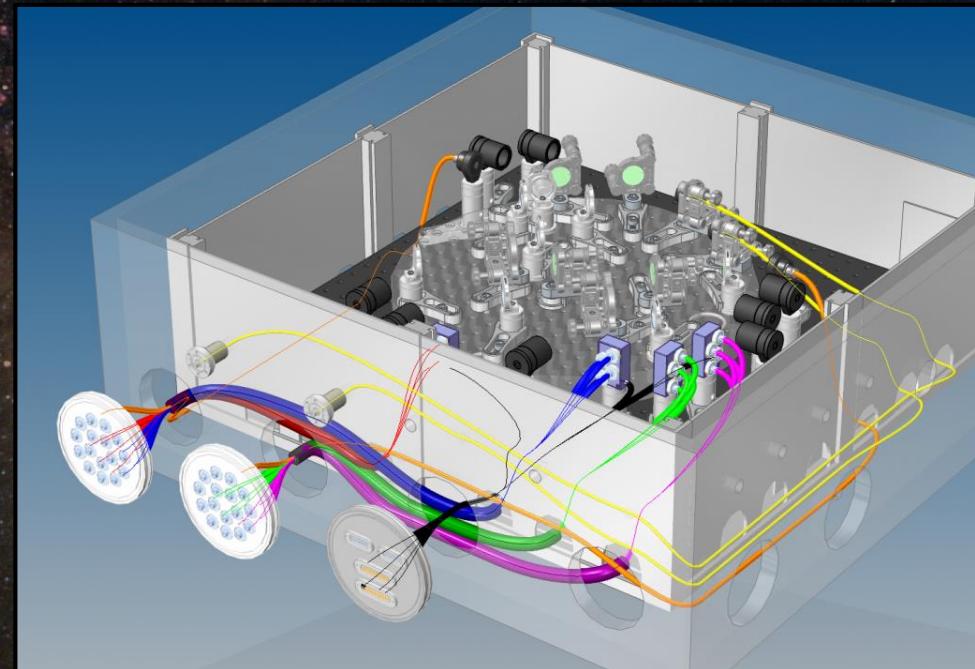


TAPSI mounting concept



TAPS! test facility

- Zerodur plate, mounting, ...
- Optomechanics (Invar), optics, ...
- **Temperature suppression**
- **Seismic isolation**
- Two Lasers (1064nm) NPRO
- Cabling → Electronics (PD, Sensors, ...)



TAPS! test facility

Space-Laboratory

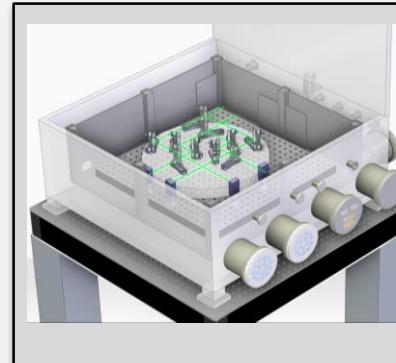
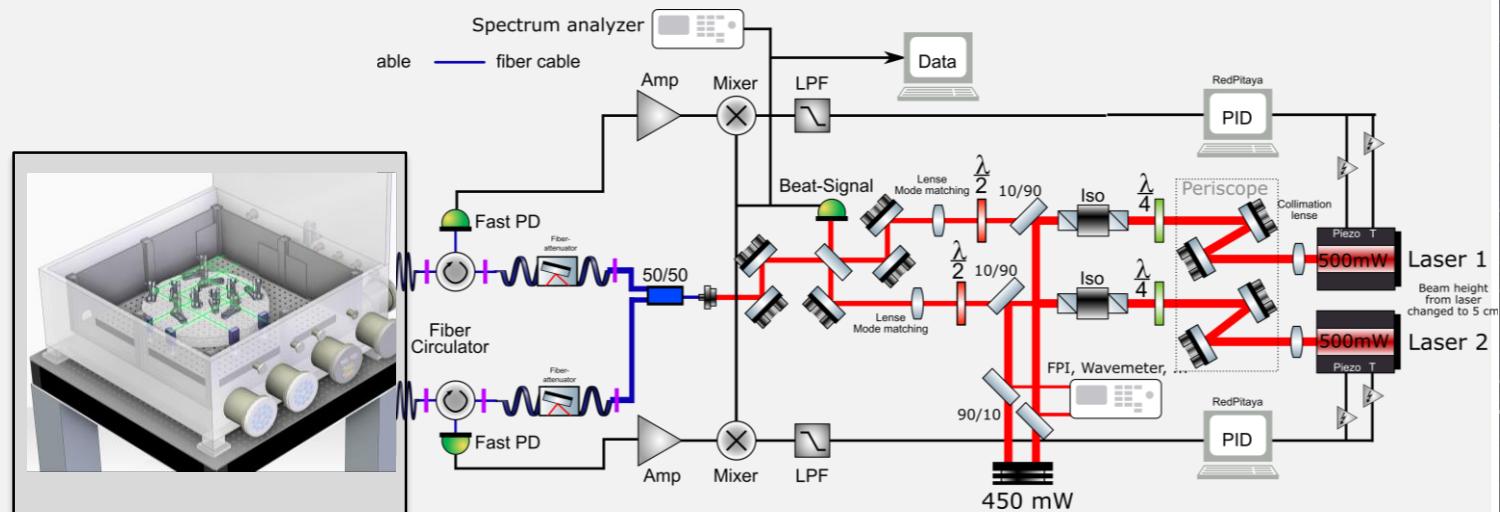


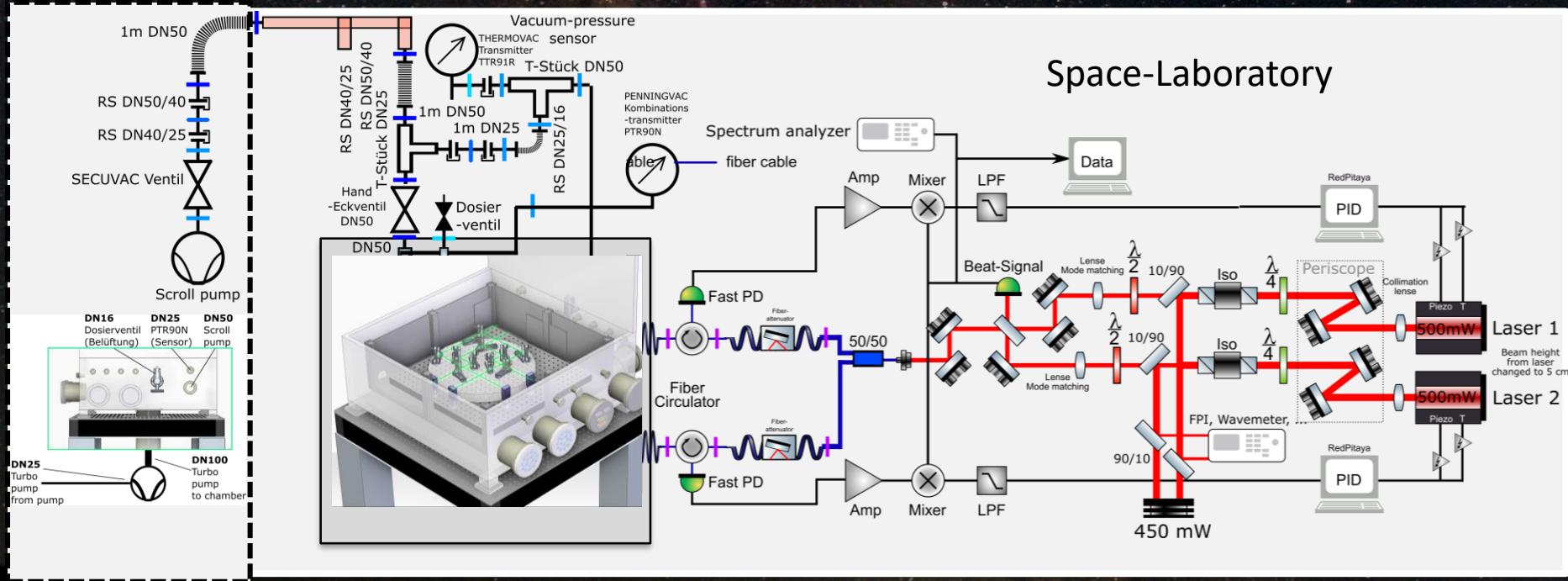
Fig.7

TAPS! test facility

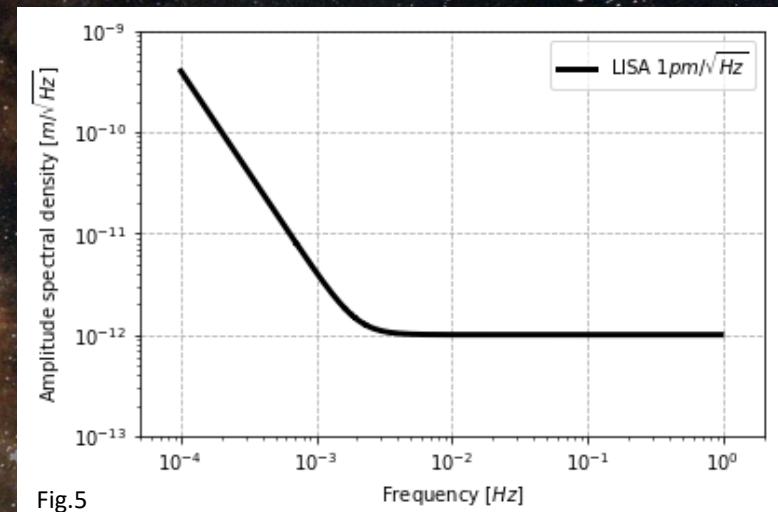
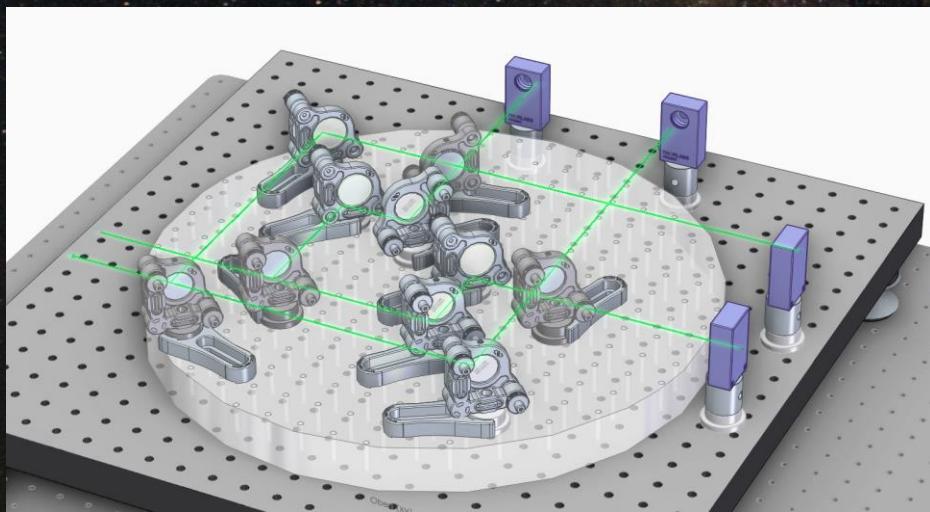
Space-Laboratory



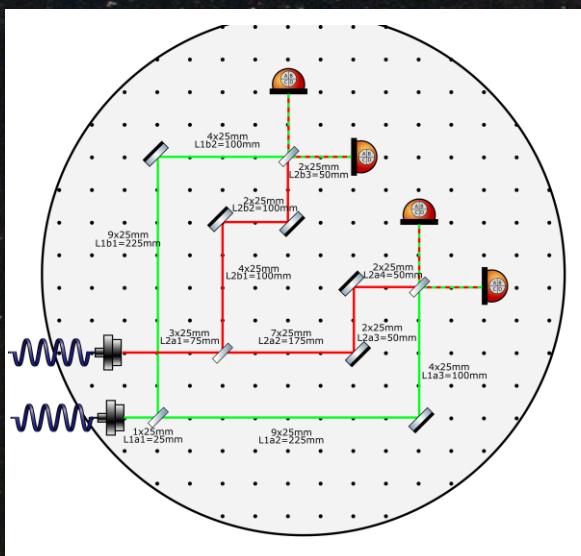
TAPS! test facility



Noise Budget: Temperature noise



Noise Budget: Temperature noise



$$\begin{aligned}
 L1a_{\text{all}} &= L1a2 + L1a3 \\
 L1b_{\text{all}} &= L1a1 + L1b1 + L1b2 \\
 L2a_{\text{all}} &= L2a2 + L2a3 + L2a4 \\
 L2b_{\text{all}} &= L2a1 + L2b1 + L2b2 + L2b3
 \end{aligned}$$

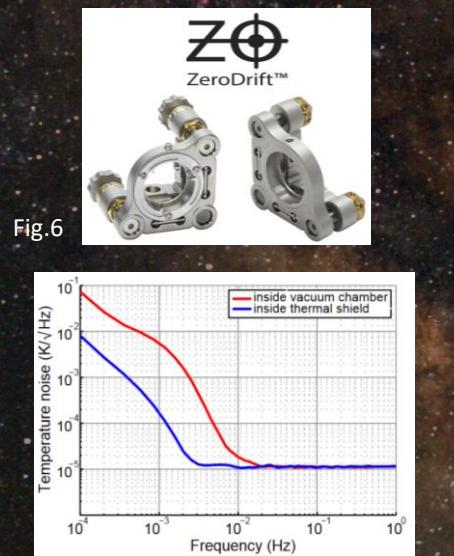
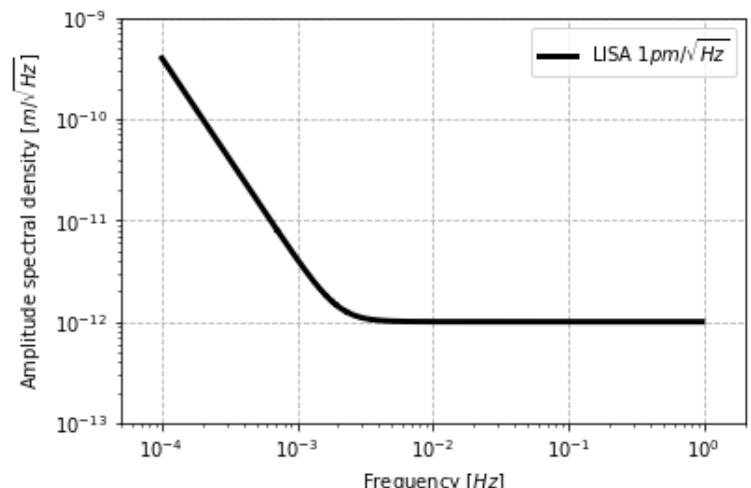


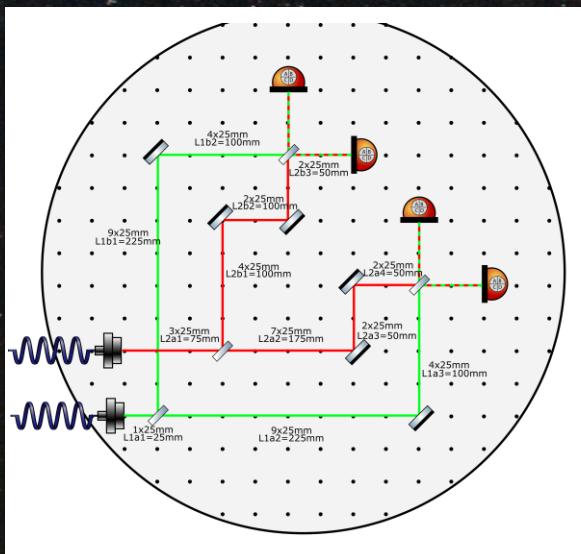
Fig.6.: ZeroDrift mirror holder from Newport (vacuum compatible)

Fig.7.: M. Dehne (2012), Construction and noise behaviour of ultra-stable optical systems for space interferometers

$$u_1(f) = \sqrt{1 + \left(\frac{2 \text{ mHz}}{f}\right)^4}$$



Noise Budget: Temperature noise



$$\begin{aligned}
 L1a_{\text{all}} &= L1a2 + L1a3 \\
 L1b_{\text{all}} &= L1a1 + L1b1 + L1b2 \\
 L2a_{\text{all}} &= L2a2 + L2a3 + L2a4 \\
 L2b_{\text{all}} &= L2b1 + L2b2 + L2b3
 \end{aligned}$$

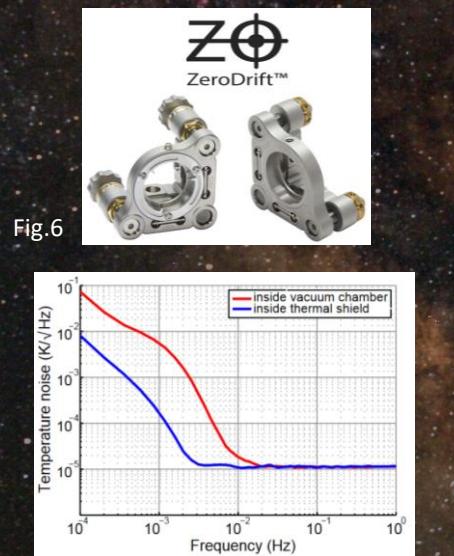
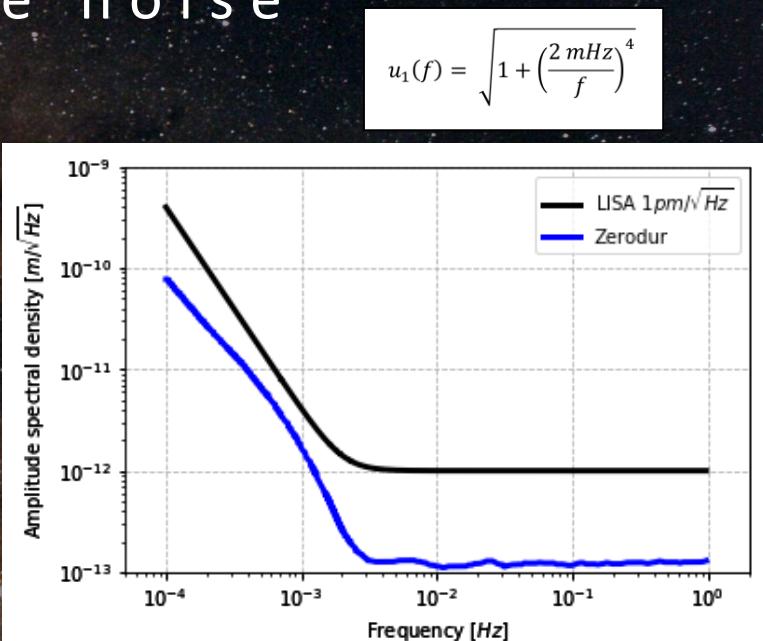
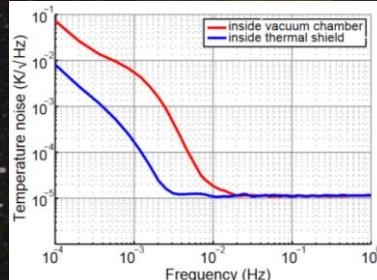
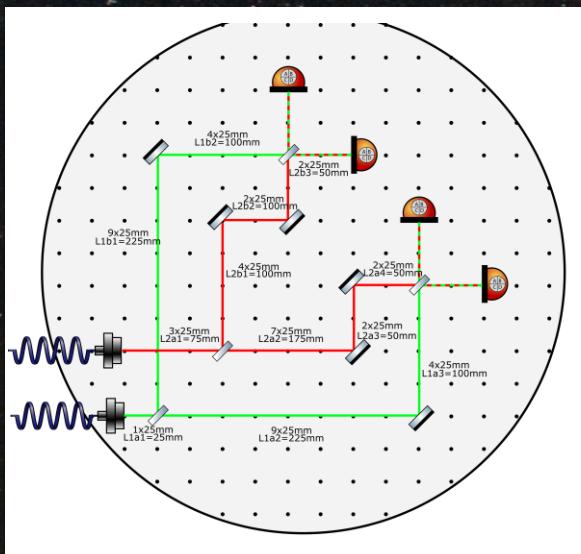


Fig.7



Noise Budget: Temperature noise



$$\begin{aligned} L1a_{\text{all}} &= L1a2 + L1a3 \\ L1b_{\text{all}} &= L1a1 + L1b1 + L1b2 \end{aligned}$$

$$\begin{aligned} L2a_{\text{all}} &= L2a2 + L2a3 + L2a4 \\ L2b_{\text{all}} &= L2a1 + L2b1 + L2b2 + L2b3 \end{aligned}$$

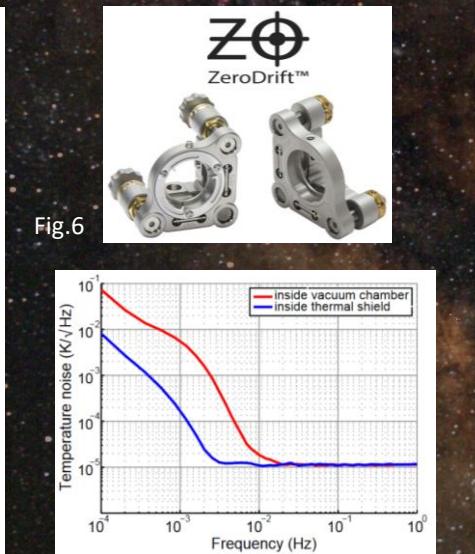
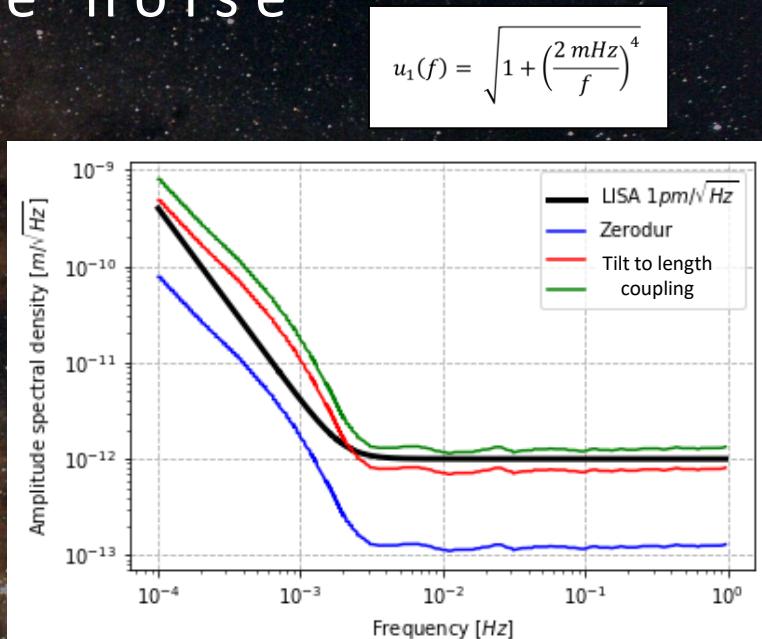
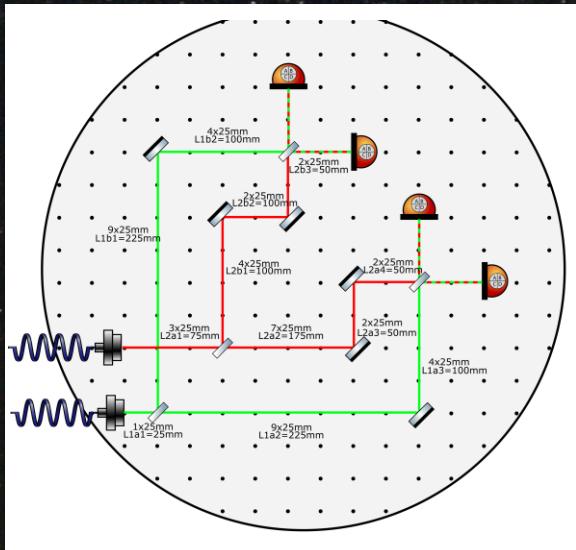


Fig.7



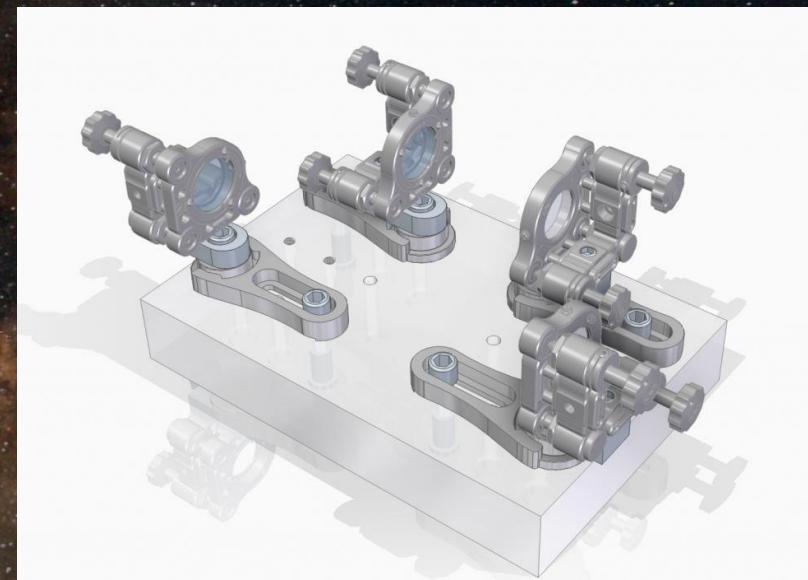
$$u_1(f) = \sqrt{1 + \left(\frac{2 \text{ mHz}}{f}\right)^4}$$

TAPS! Prototype Cavity

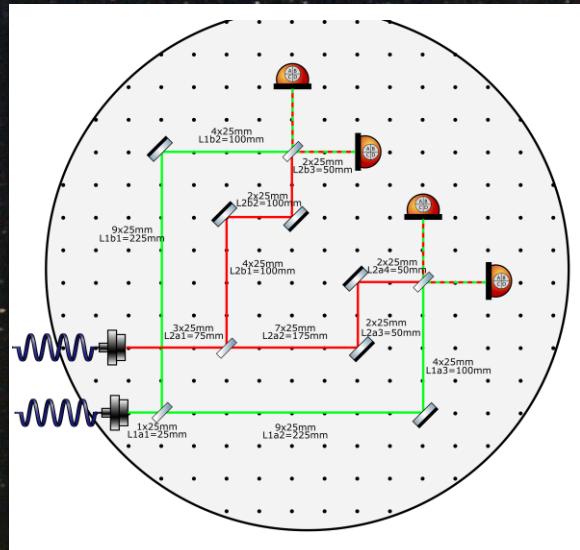


$$\begin{aligned}L1a_{\text{all}} &= L1a2 + L1a3 \\&L1a1 = 25 \text{mm} \\&L1b_{\text{all}} = (L1a1 + L1b) + L1b2 \\&L1b1 = 25 \text{mm} \\&L2a_{\text{all}} = L2a2 + L2a3 + L2a4 \\&L2a1 = 75 \text{mm} \\&L2a2 = 175 \text{mm} \\&L2a3 = 50 \text{mm} \\&L2a4 = 50 \text{mm} \\&L2b_{\text{all}} = (L2a1 + L2b1) + (L2b2 + L2b3) \\&L2b1 = 100 \text{mm} \\&L2b2 = 50 \text{mm} \\&L2b3 = 50 \text{mm}\end{aligned}$$

Prototype - Cavity



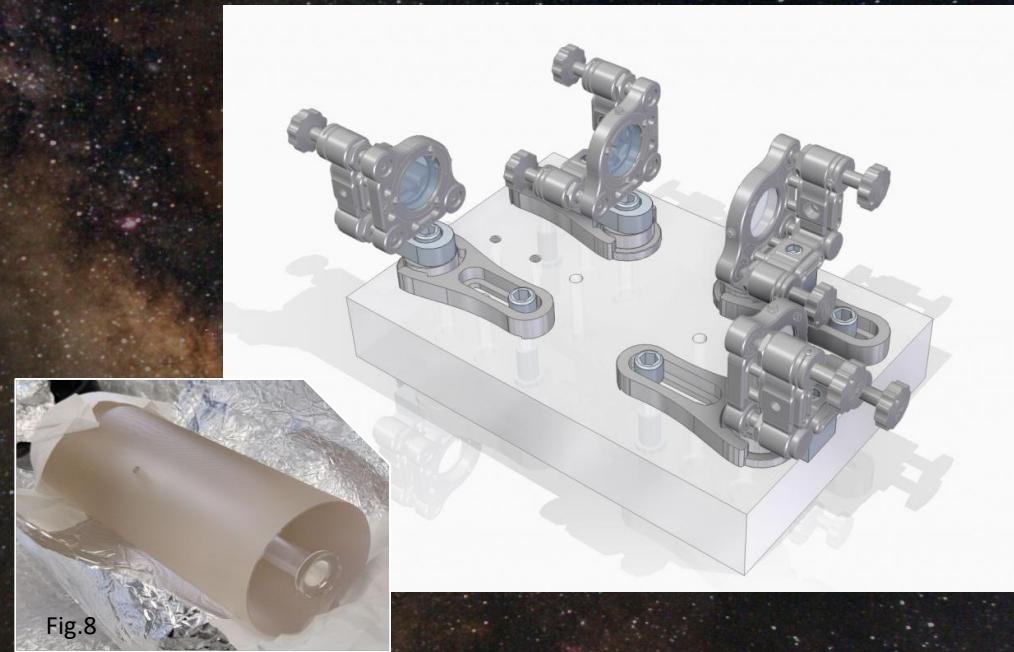
TAPS | Prototype Cavity



$$\begin{aligned}
 L_{1a_all} &= L_{1a2} + L_{1a3} \\
 L_{1b_all} &= (L_{1a1} + L_{1b}) + L_{1b2}
 \end{aligned}$$

Reference - Cavity

Prototype - Cavity



HETERODYNE cavity locking

Prototype - Cavity

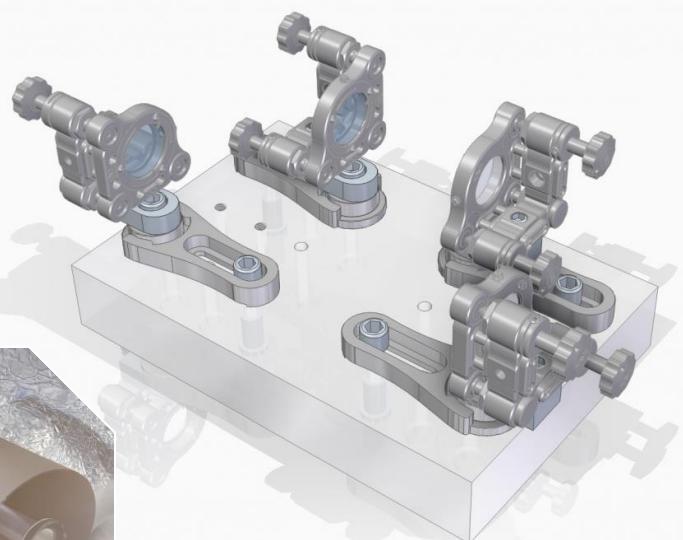
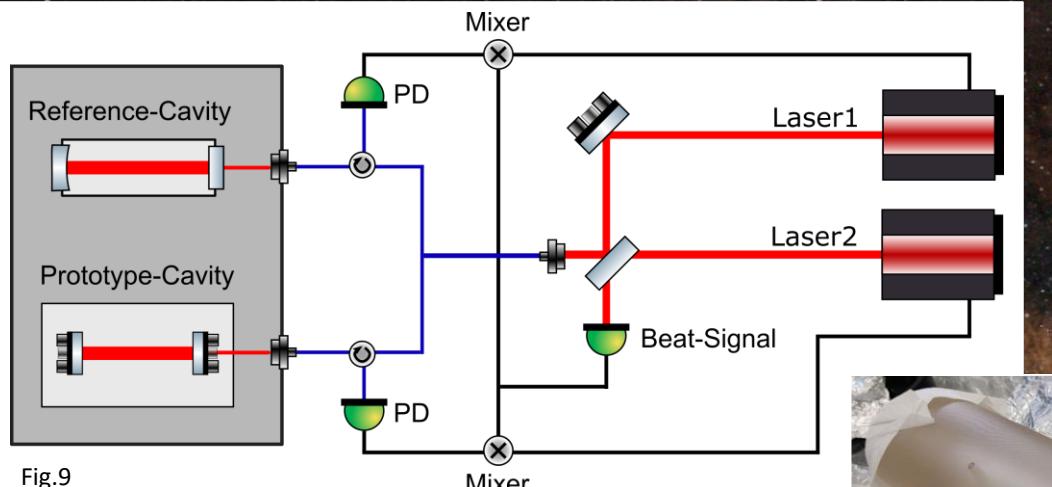
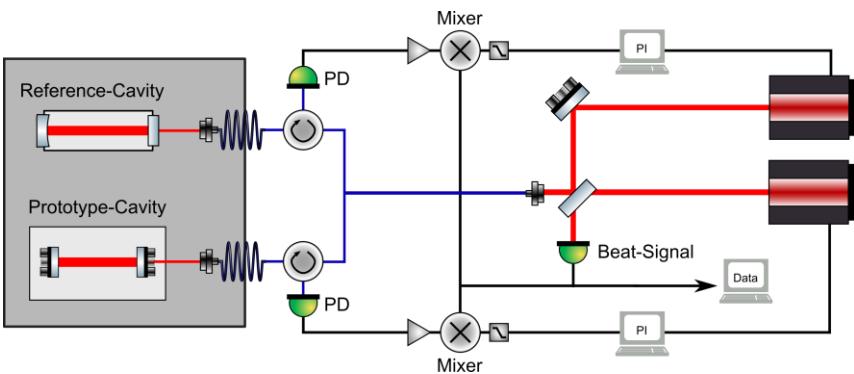
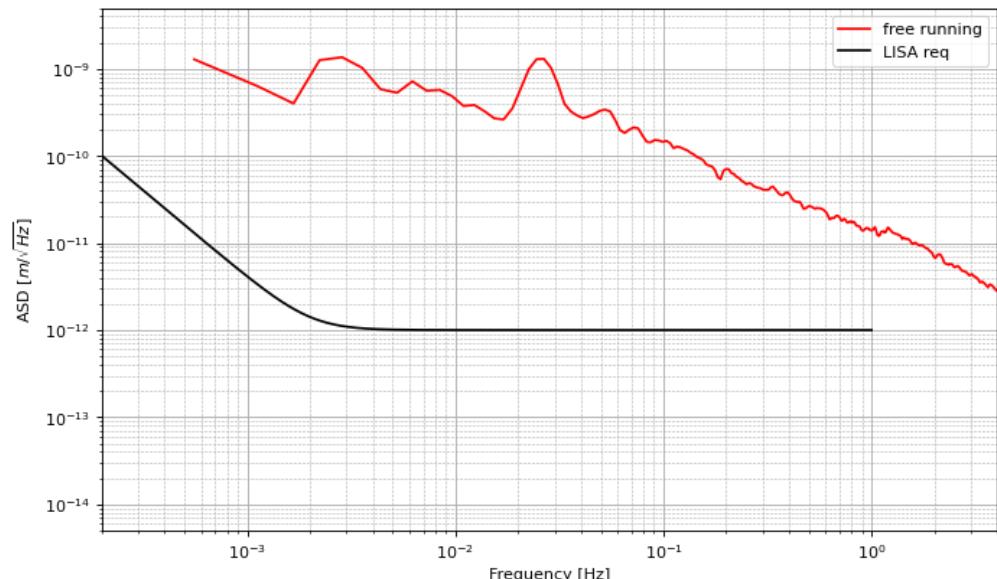
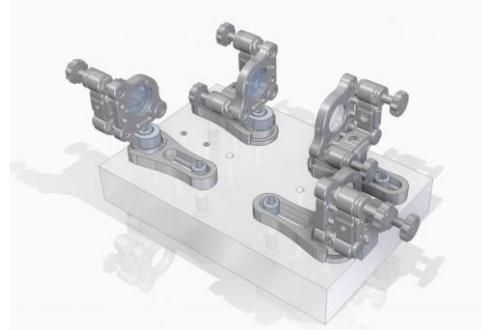


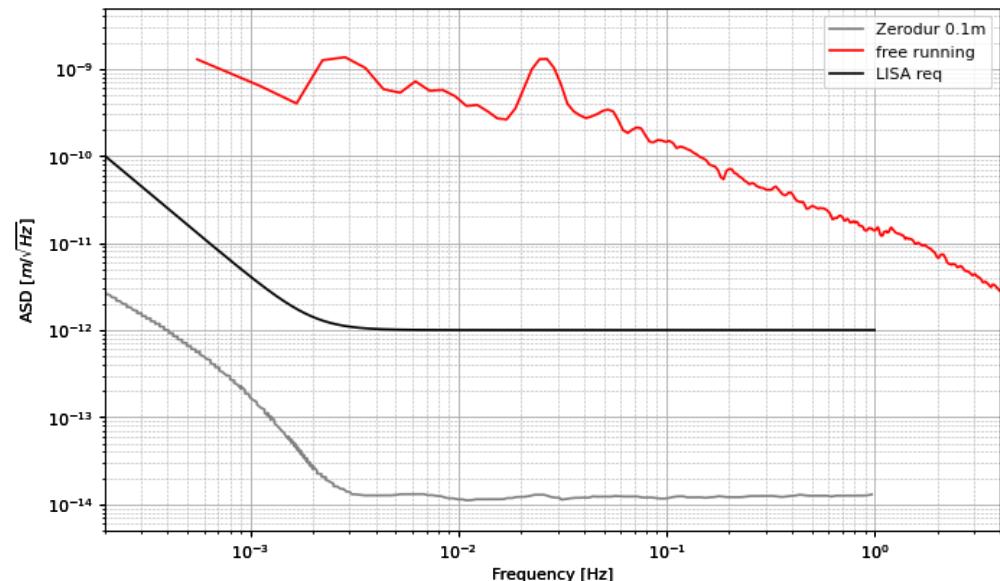
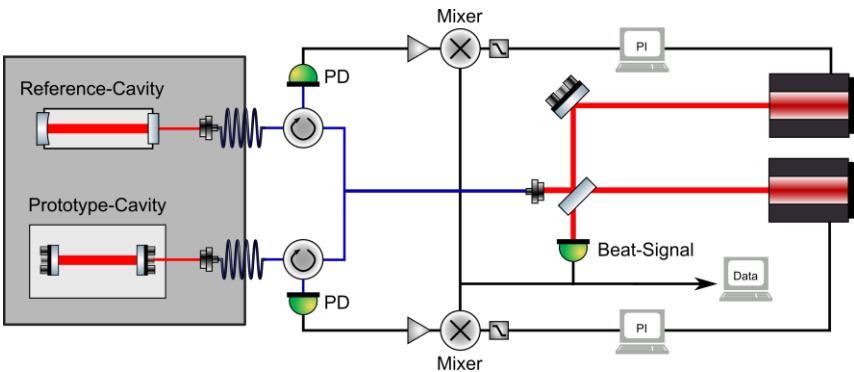
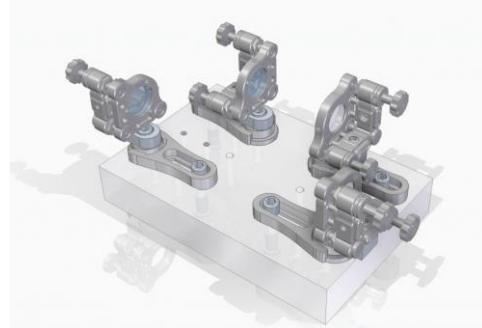
Fig.8: ULE-Cavity from Hannover

Fig.9: Heterodyne laser frequency stabilization (J. Eichholz, 2015)

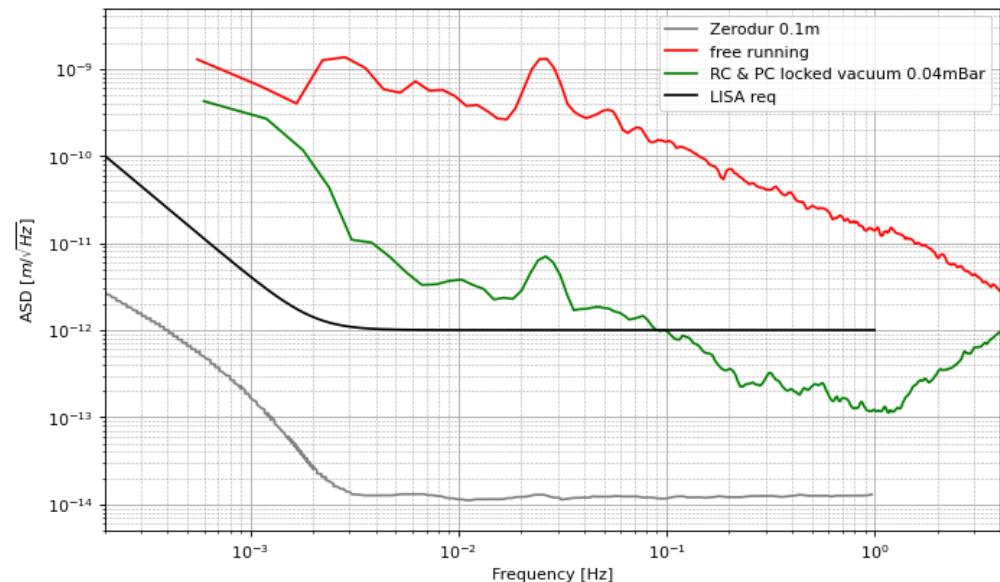
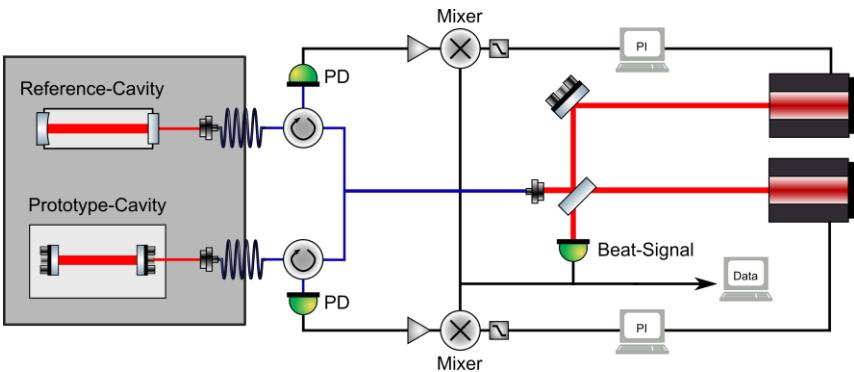
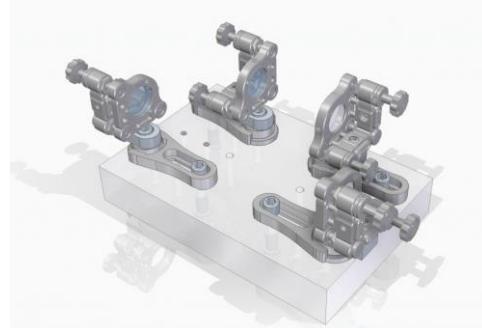
TAPS | Stability - proof of principle experiment



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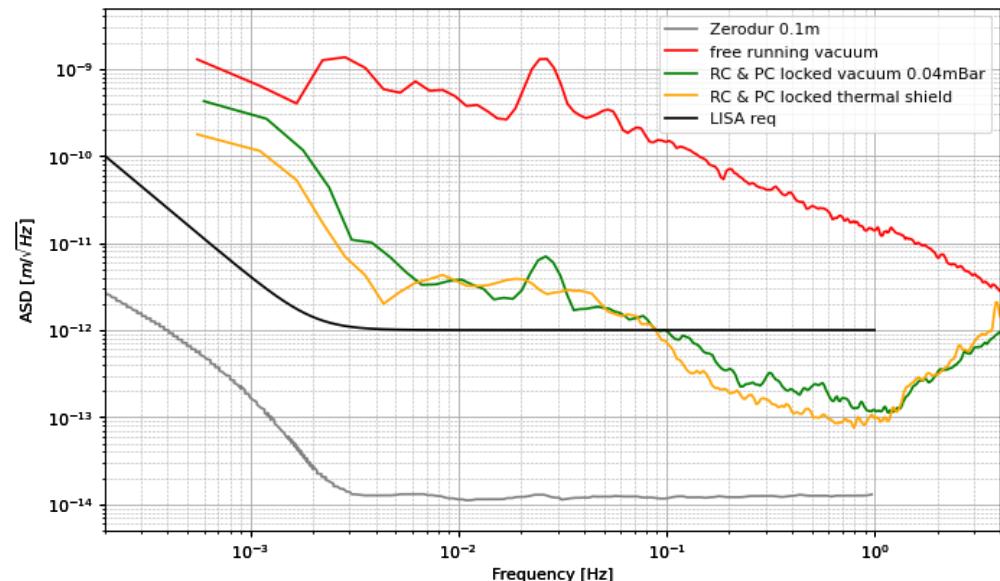
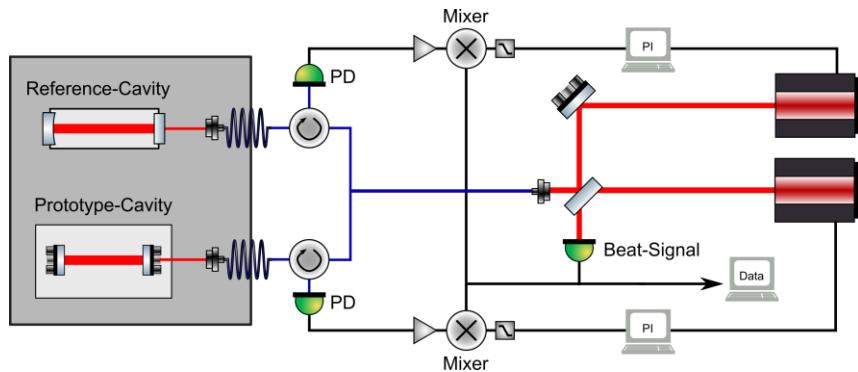
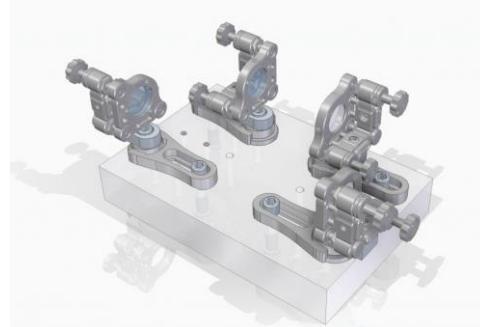


TAPS | Stability - proof of principle experiment



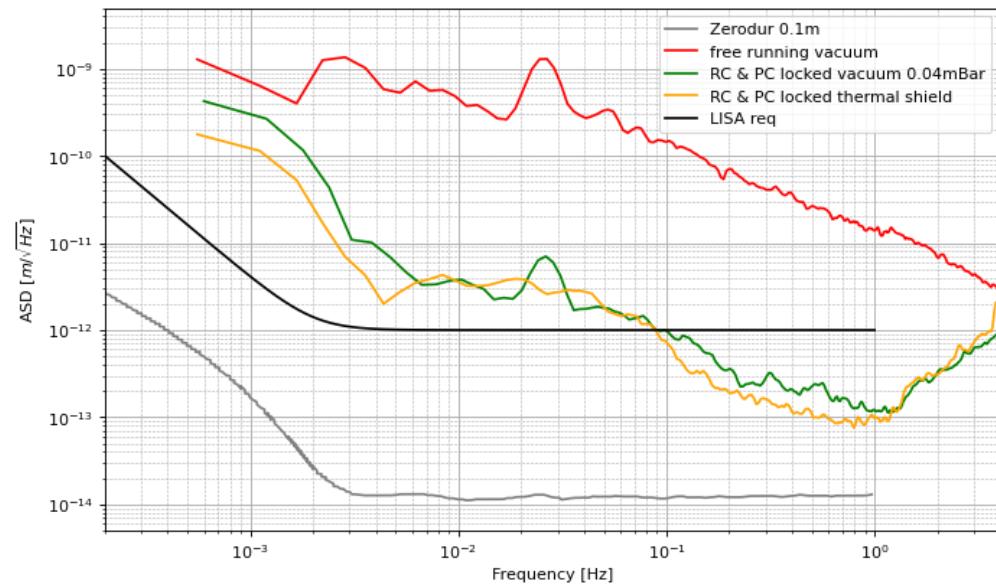
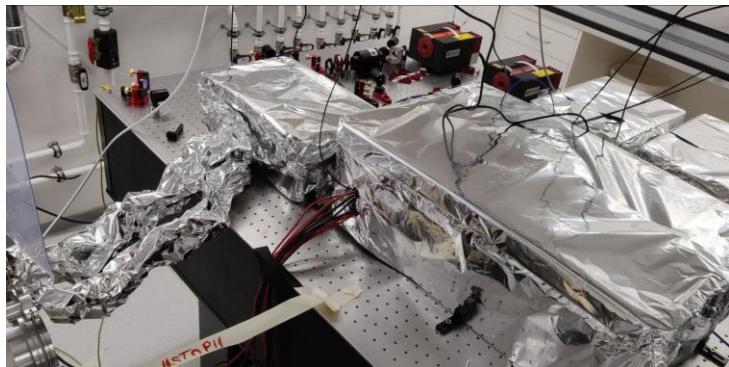
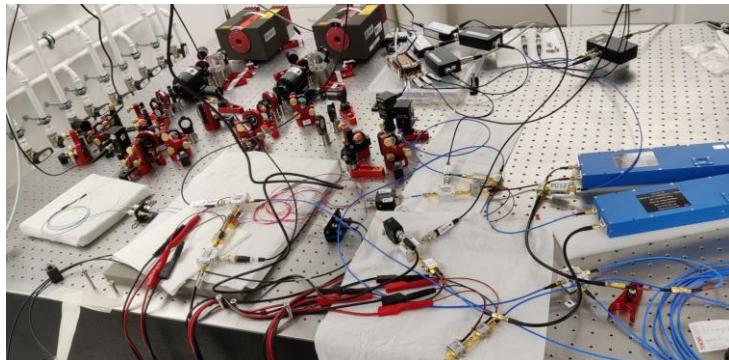
- Temperature fluctuations (vacuum chamber) ?

TAPS! Stability - proof of principle experiment



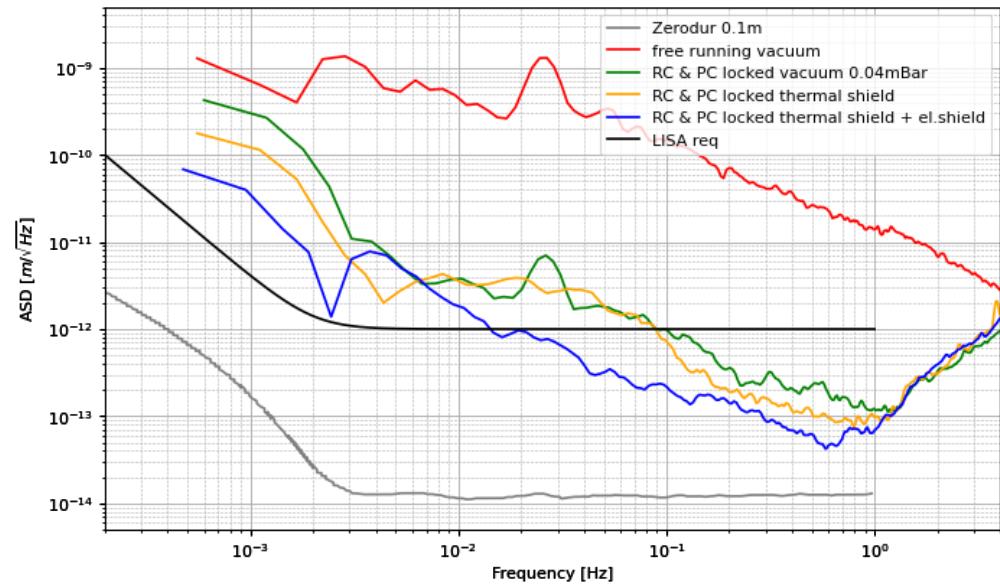
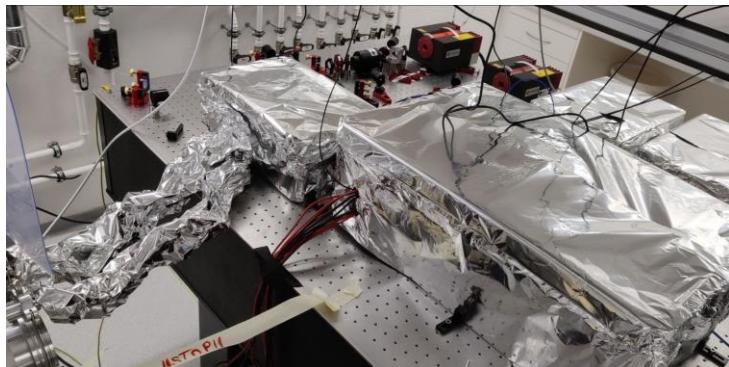
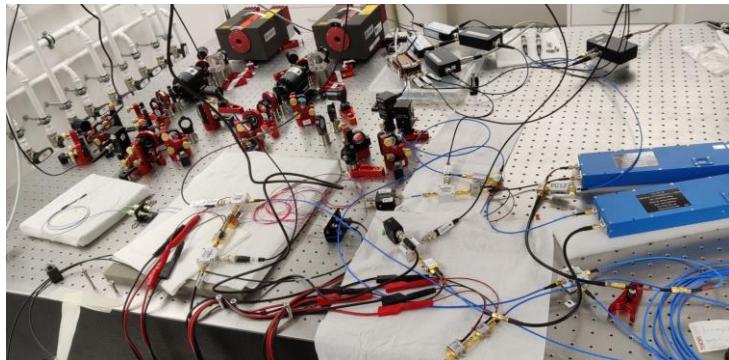
- Temperature fluctuations (vacuum chamber) ?

TAPS! Stability - proof of principle experiment



- Temperature fluctuations (vacuum chamber) ?
- Temp+humidity fluctuations at the electronics ?

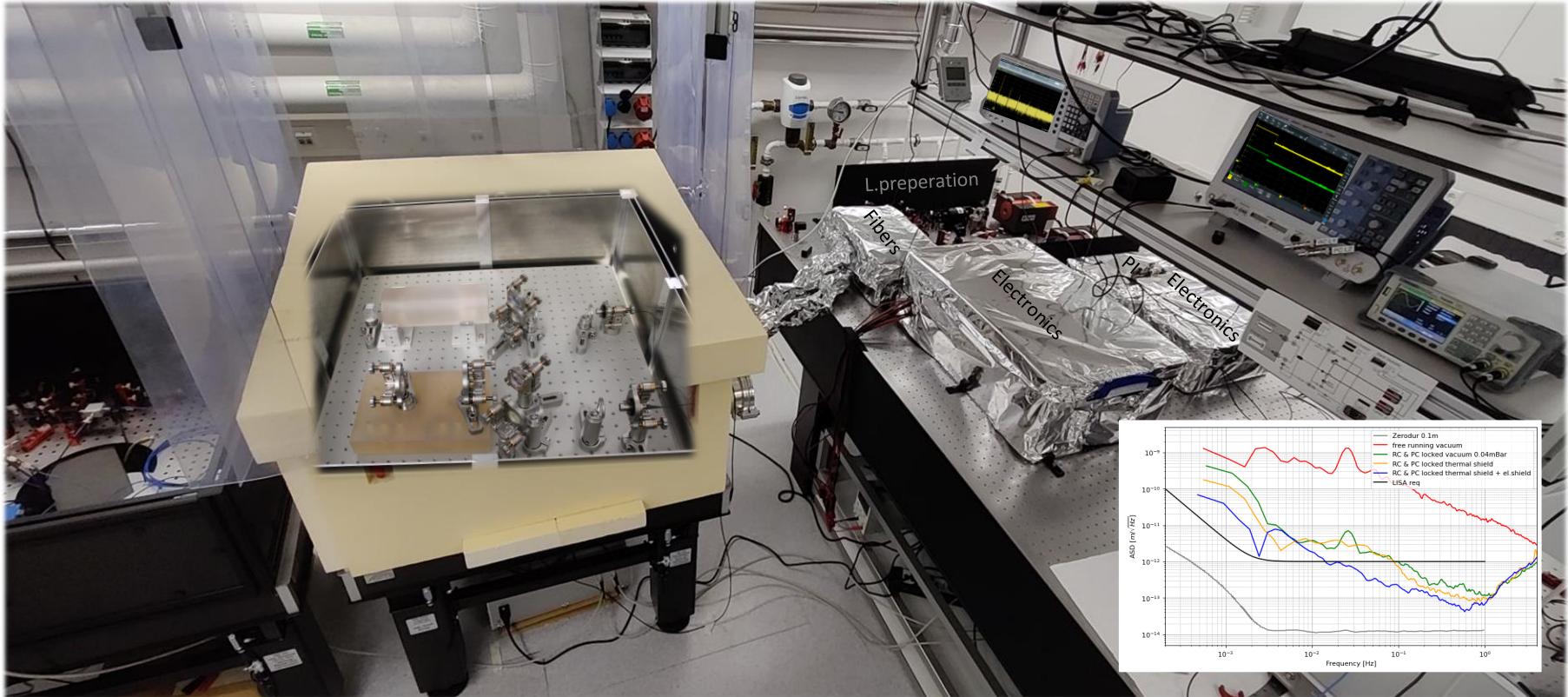
TAPS I Stability - proof of principle experiment



- Temperature fluctuations (vacuum chamber) ?
- Temp+humidity fluctuations at the electronics ?

Current state of TAPSI

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Current state of TAPSI

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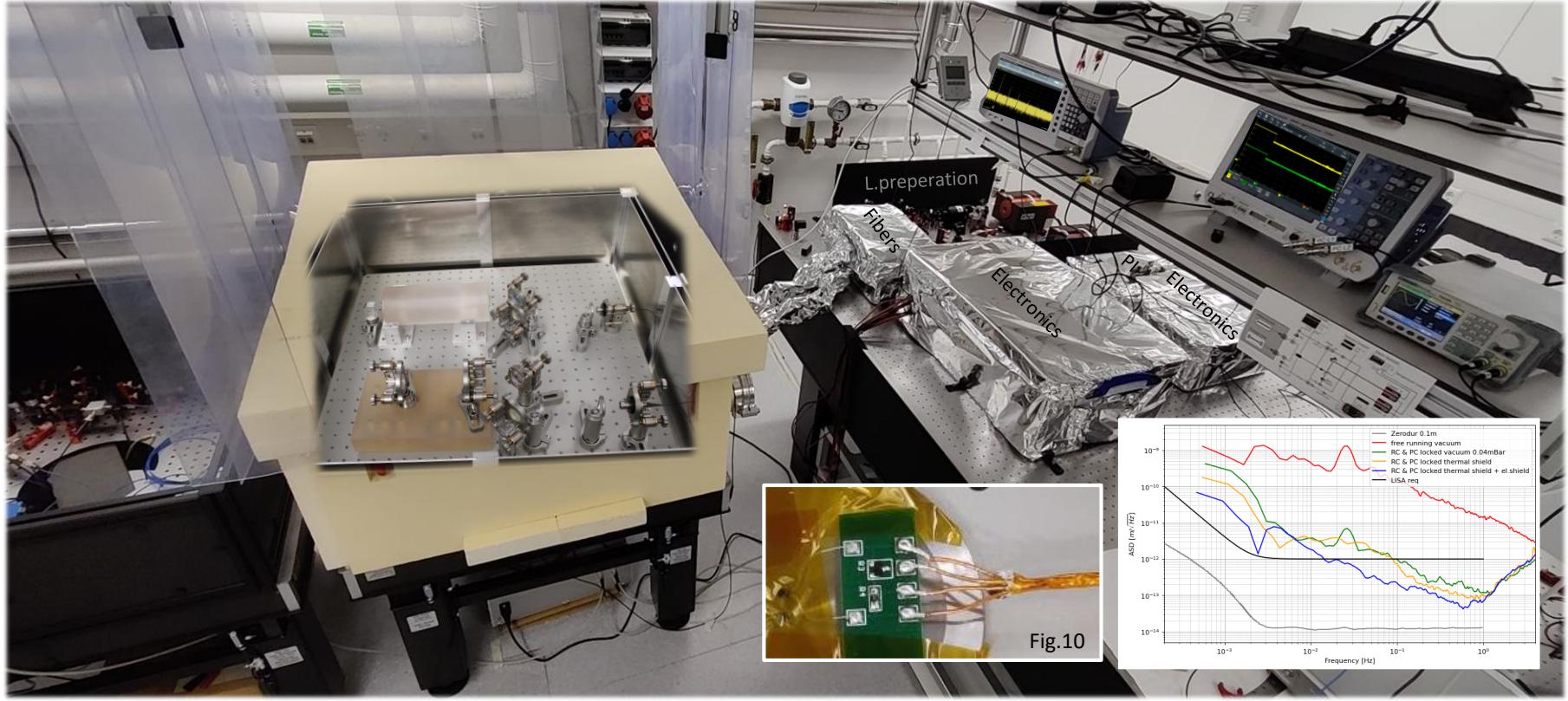
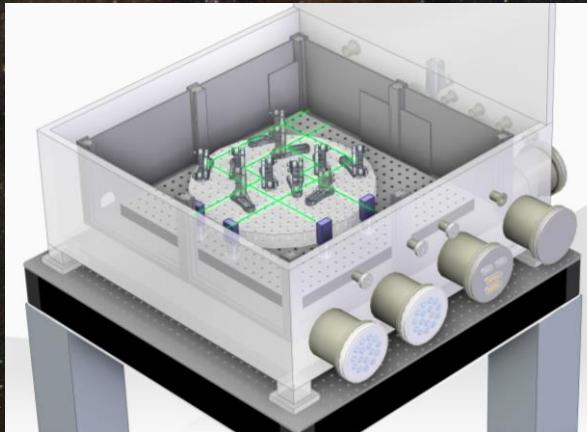
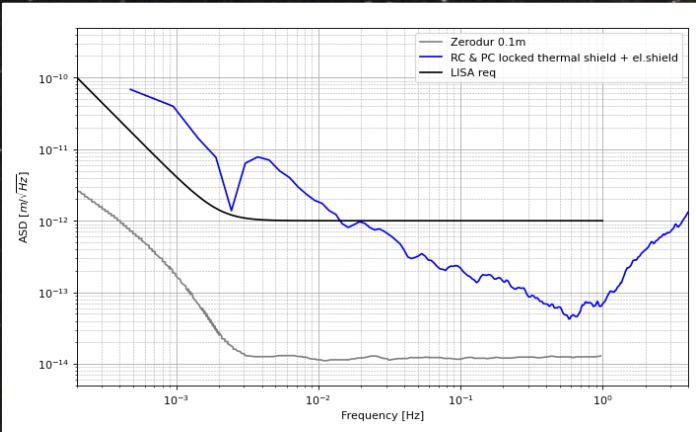


Fig.10: Wheatstone bridge - temperature sensor in vacuum

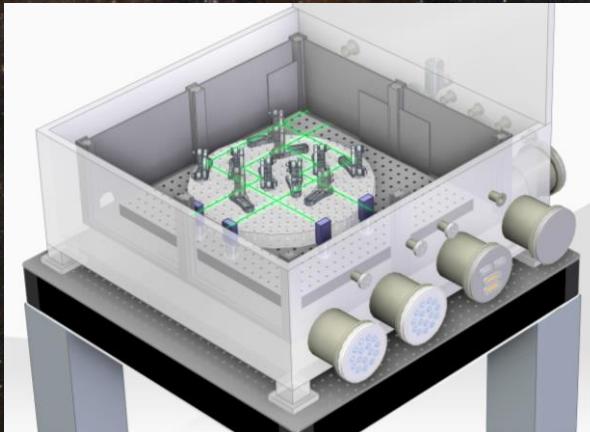
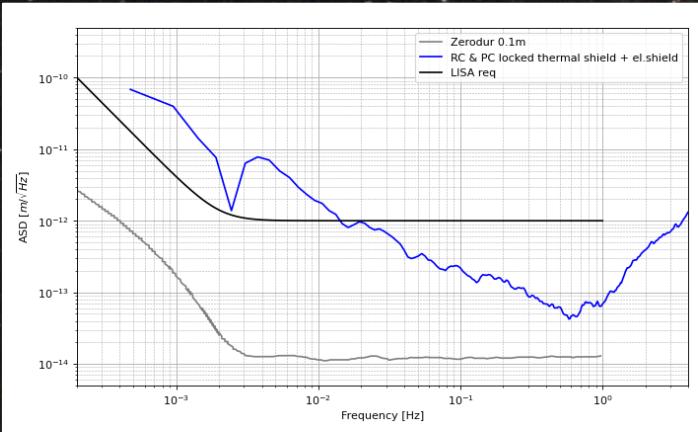
Summary / Outlook

- ✓ Facility (Chamber, Laserpreperation, ...)
 - ✓ TAPSI prototype (stability experiment)
 - Heterodyne locking
- Below LISA requirements ?
 - Puplication / Paper
 - Manufacture large Zerodur disc
 - Setup new interferometers ideas

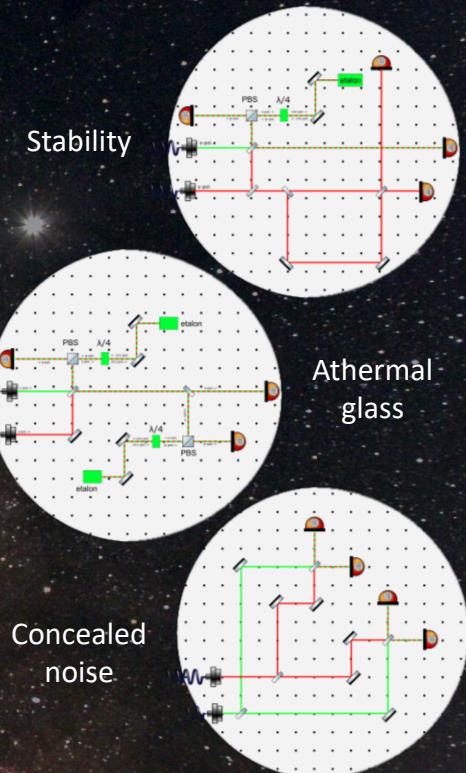


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TAPS!
Toolset for Adjustable Picometer-Stable
Interferometers





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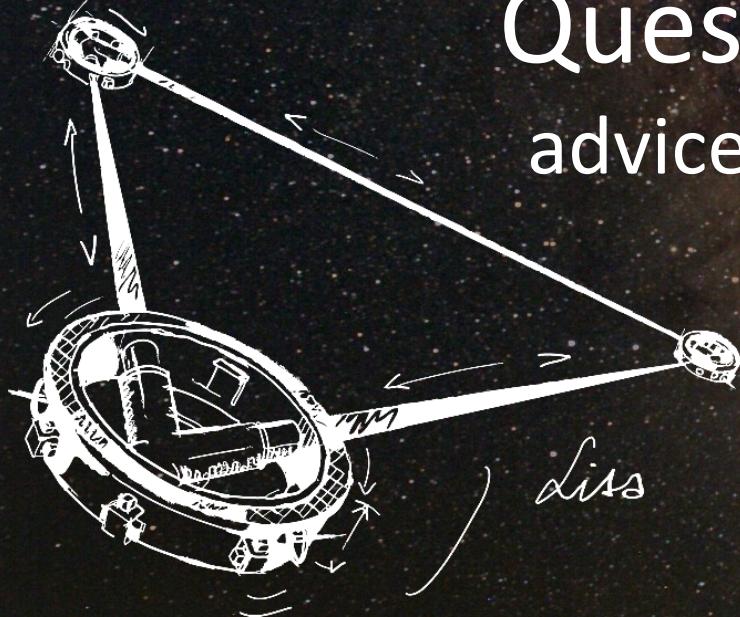
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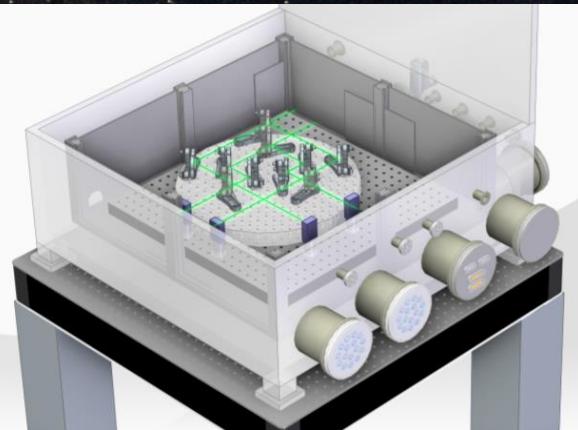


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Questions ?
advice, ideas ?

TAPS!
Toolset for Adjustable Picometer-Stable
Interferometers



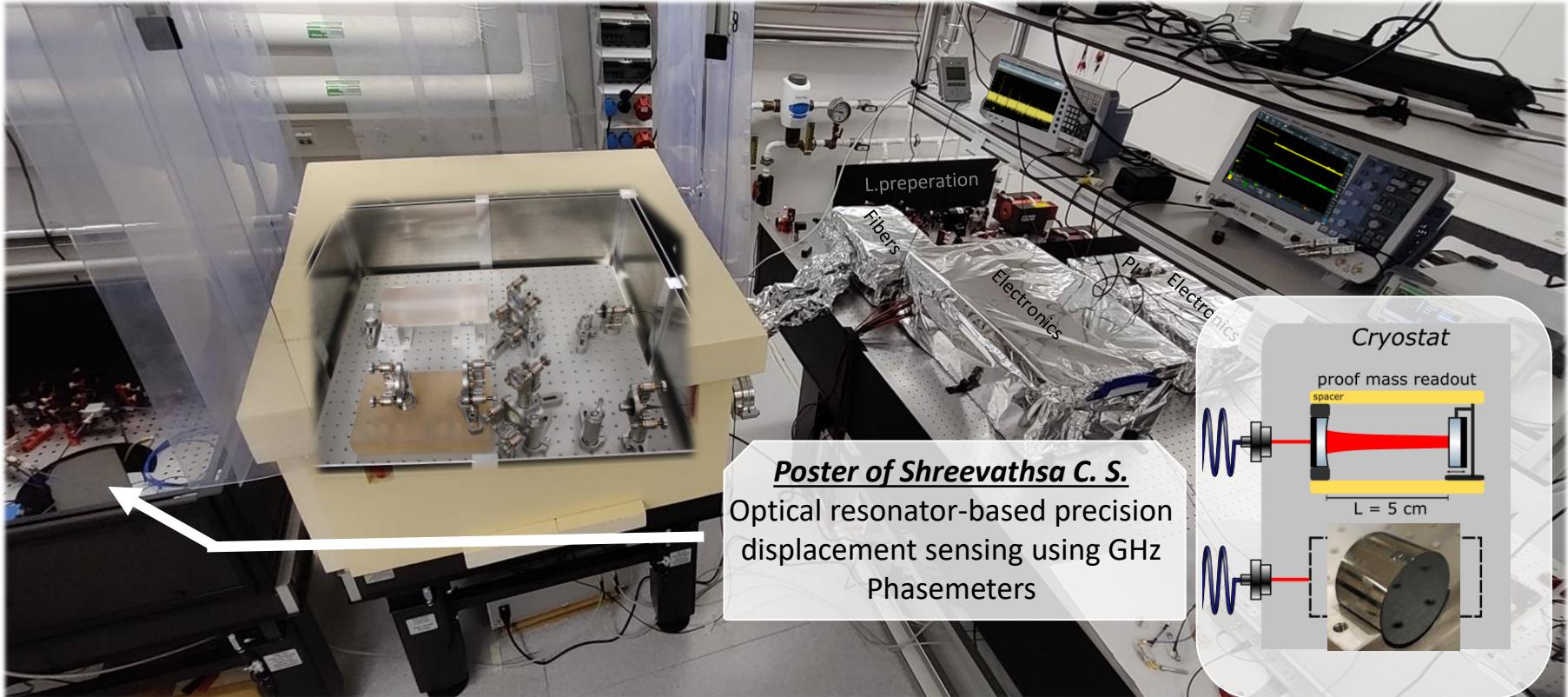
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MICROTEC
TECHNOLOGY LAB
A HELMHOLTZ INNOVATION LAB

Current state of TAPSI

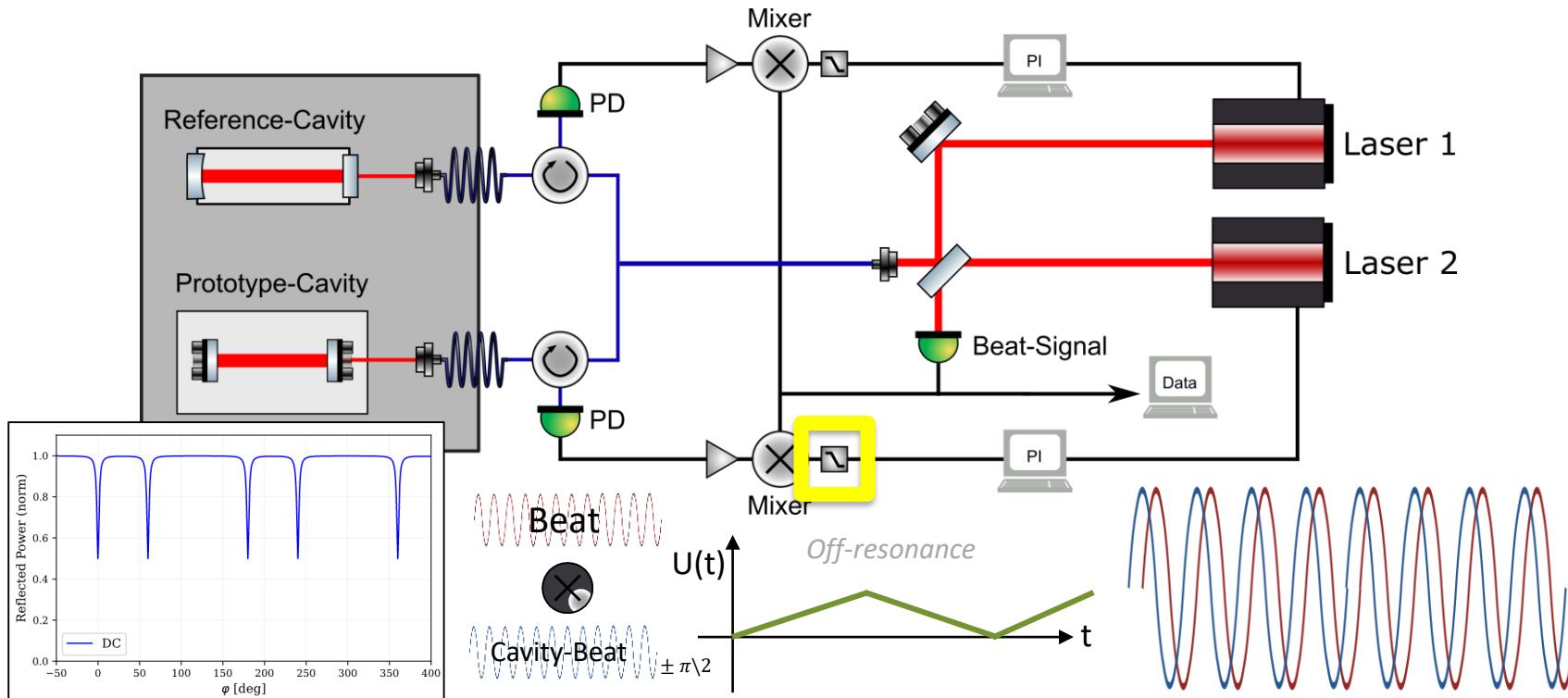
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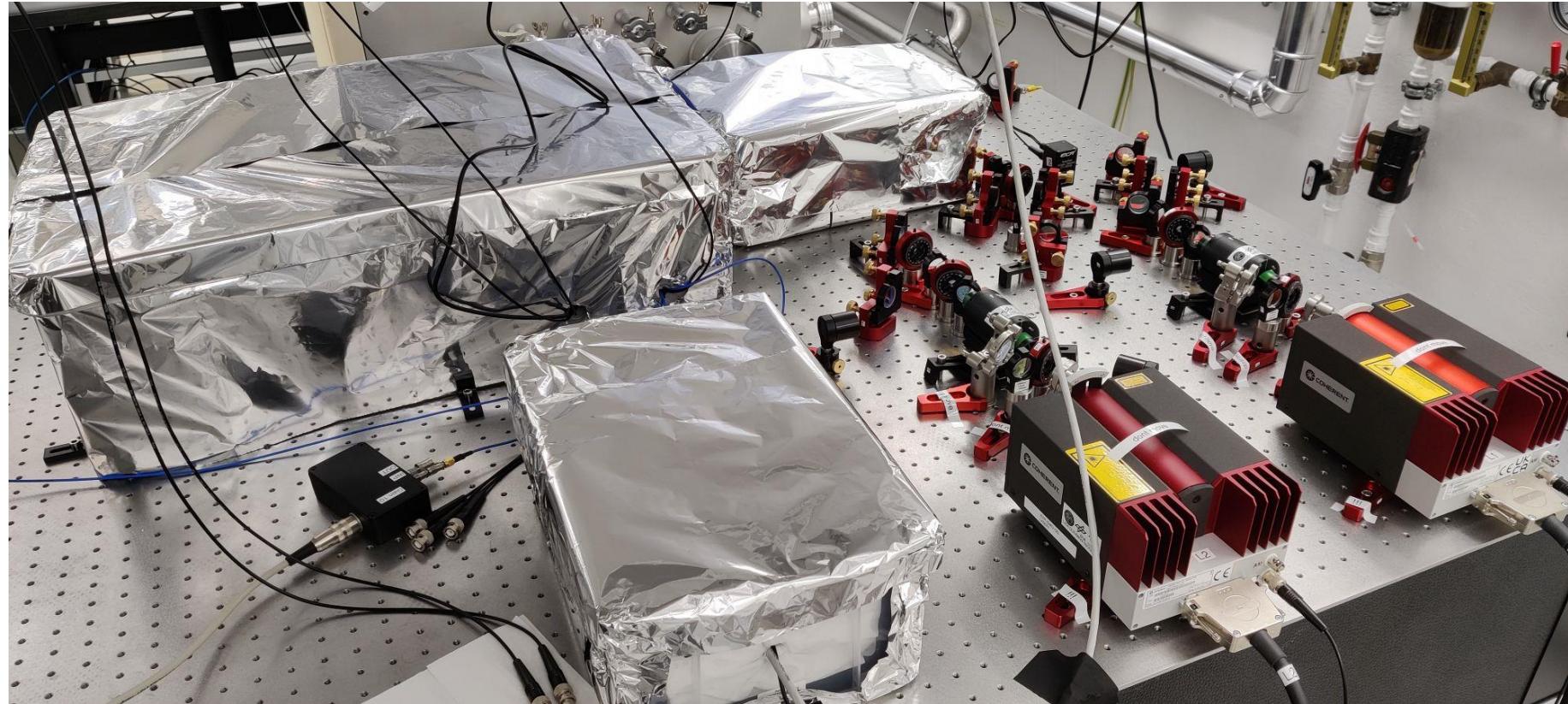


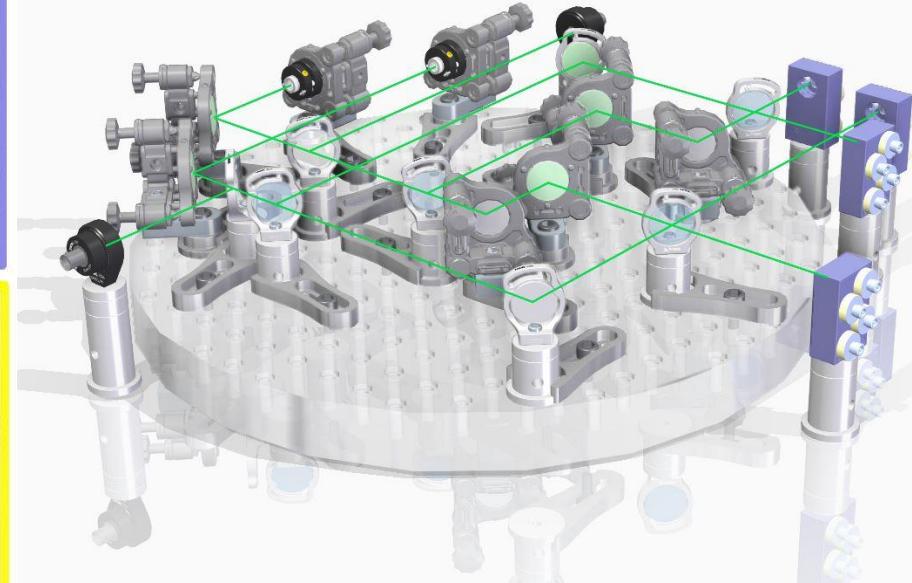
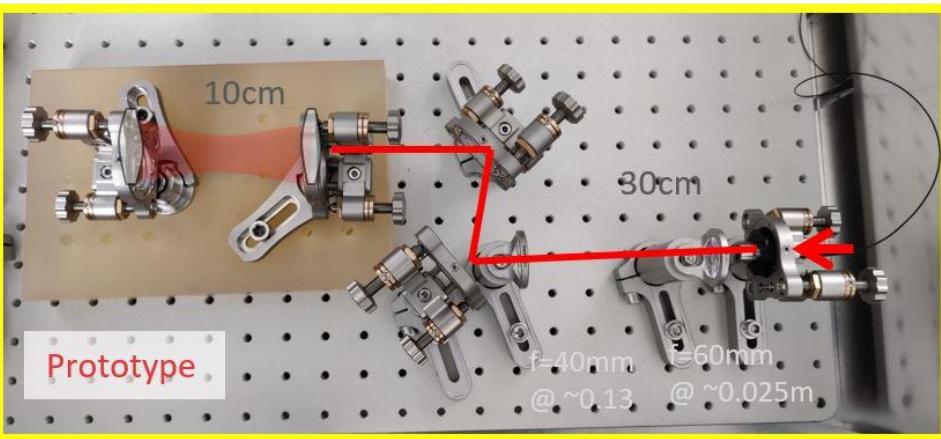
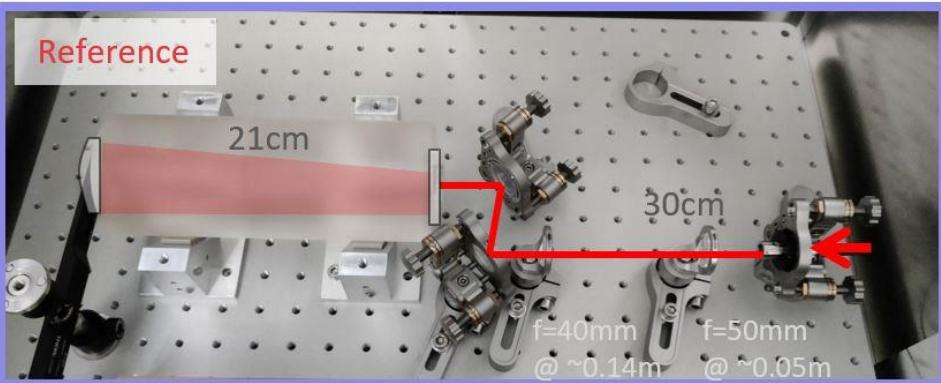
Backup slides



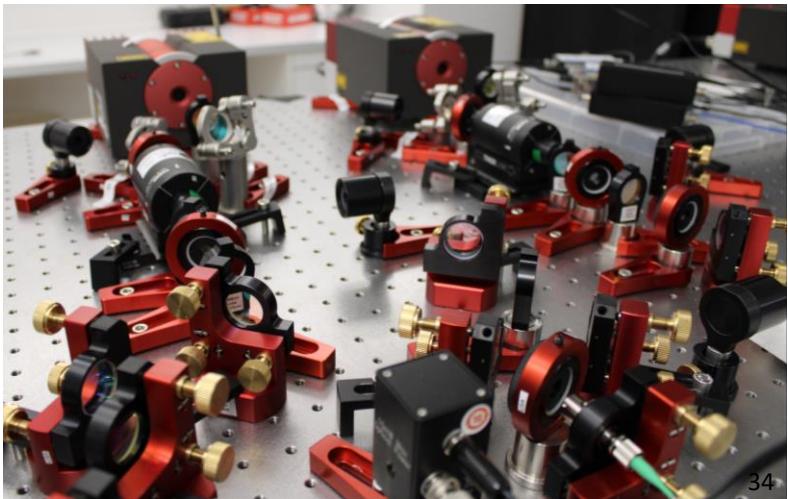
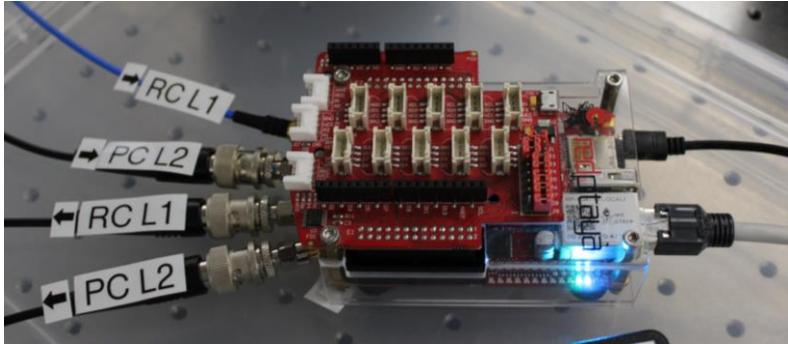
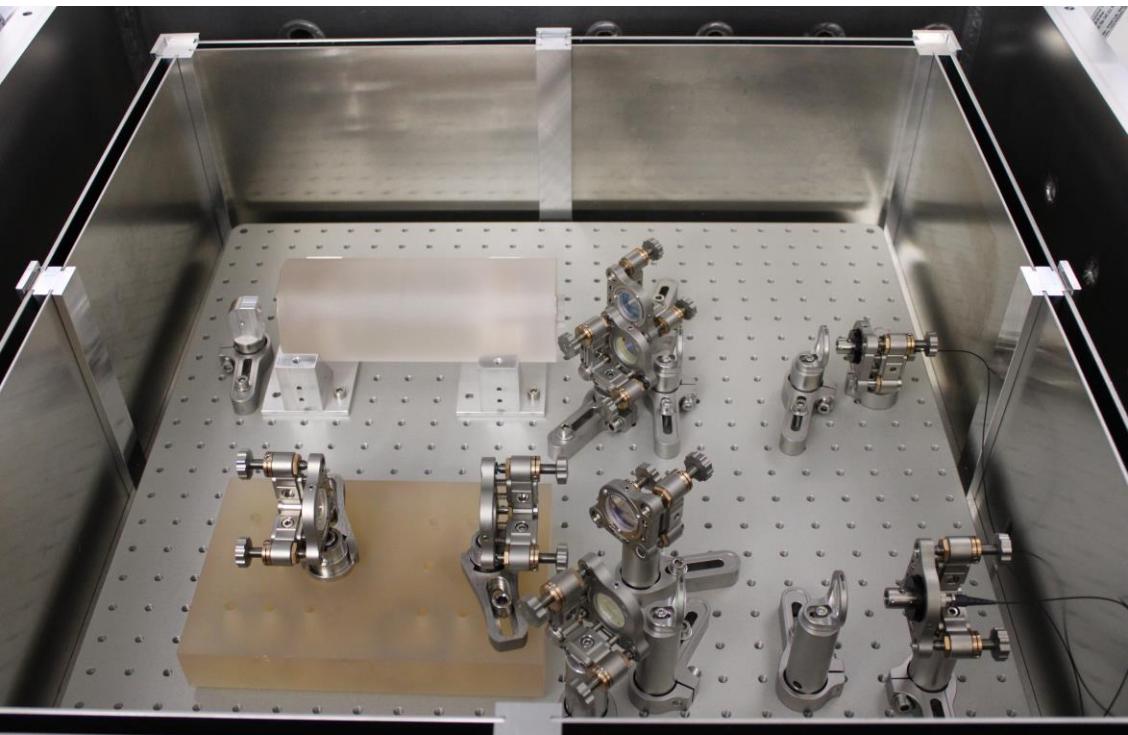
TAPS! Stability







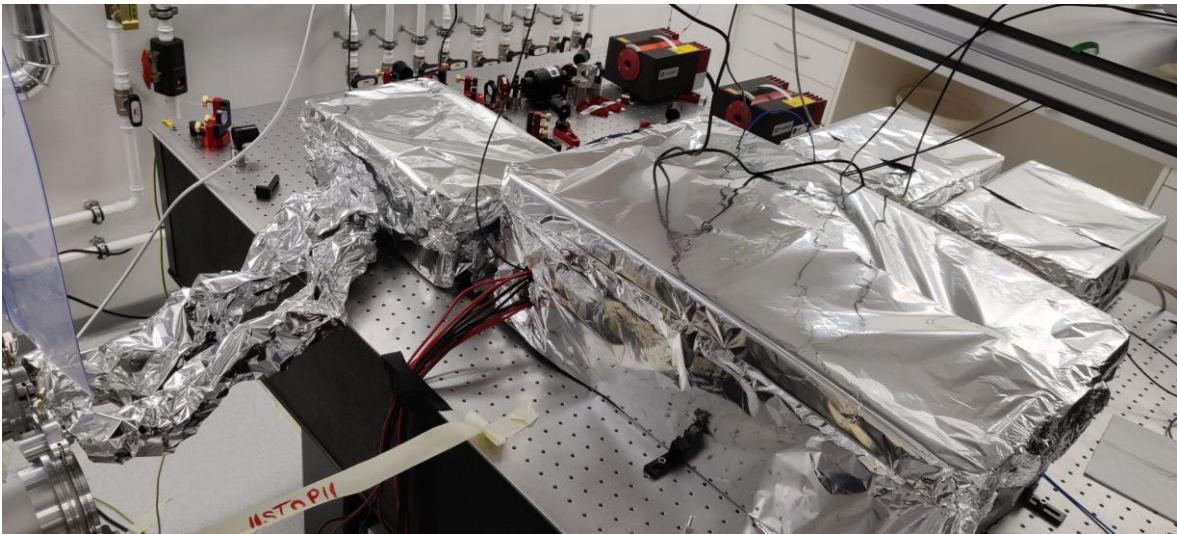
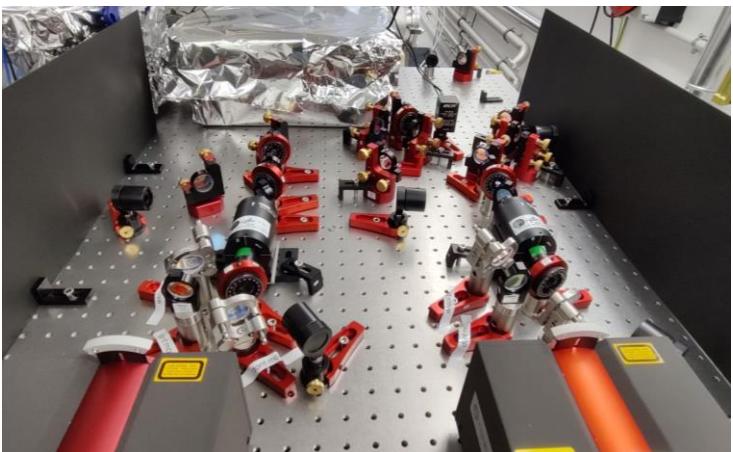
TAPS! Stability - experiment





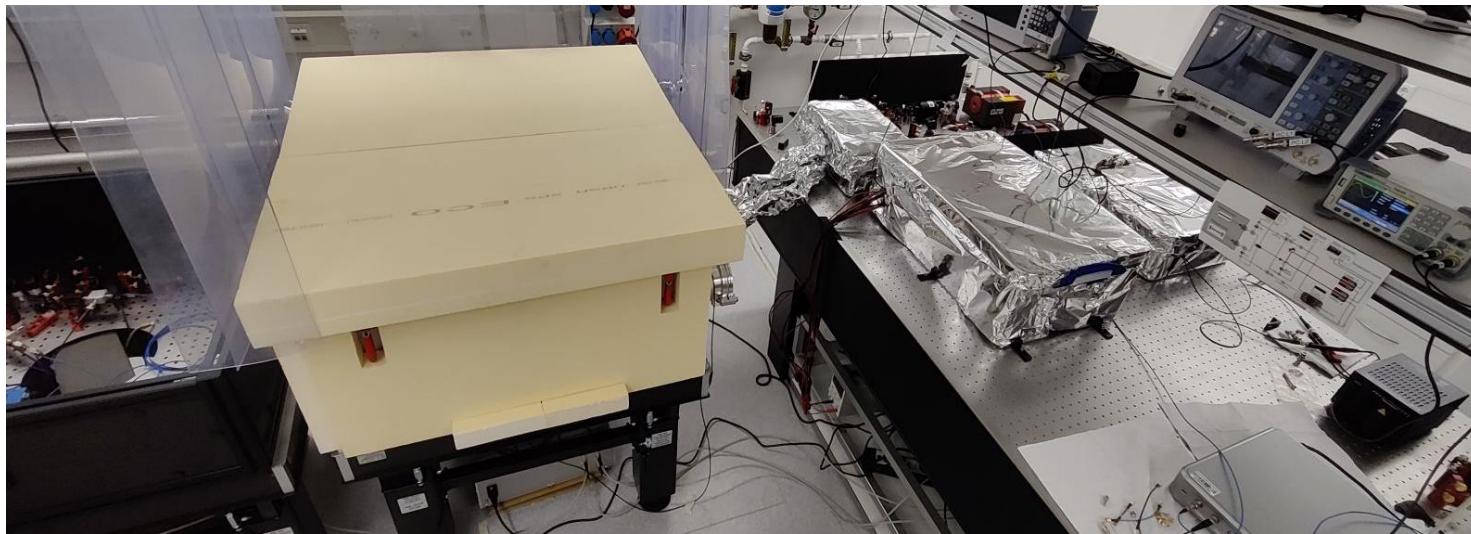
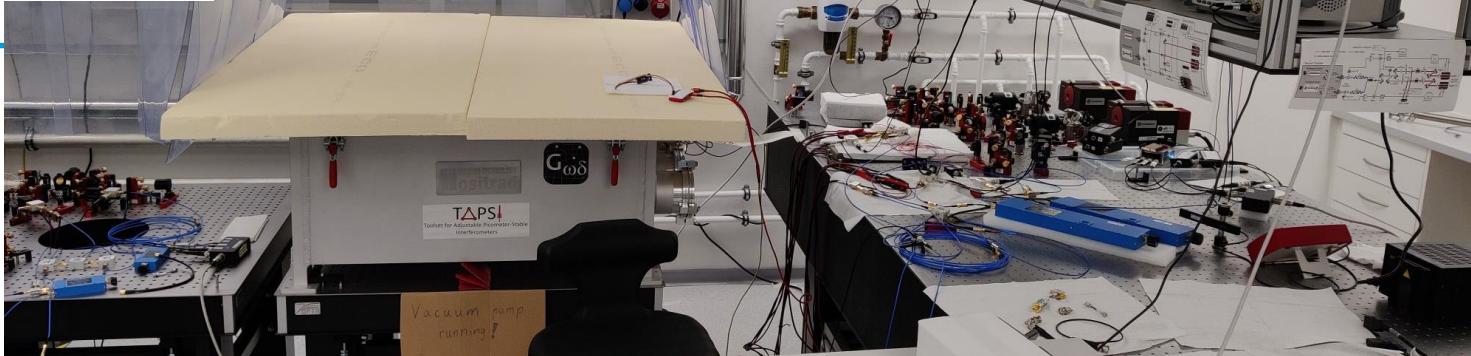
TAPS!
Toolset for Adjustable Picometer-Stable
Interferometers

LASER preparation & electronics + housing





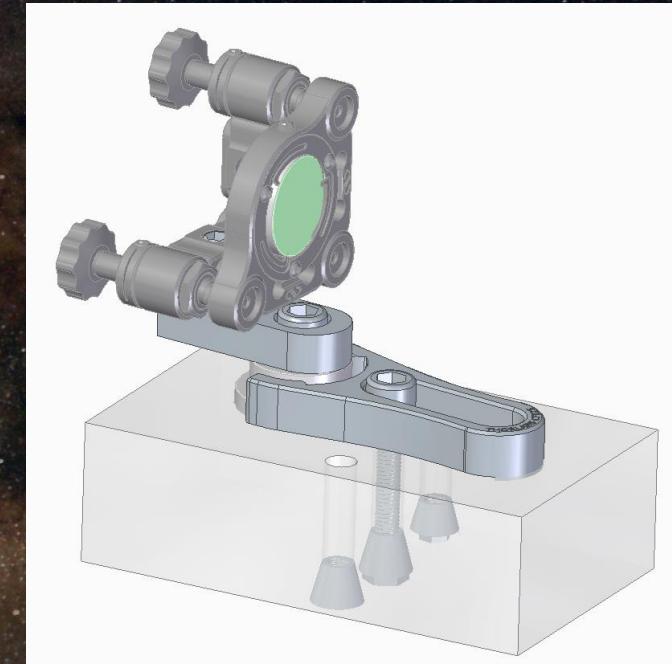
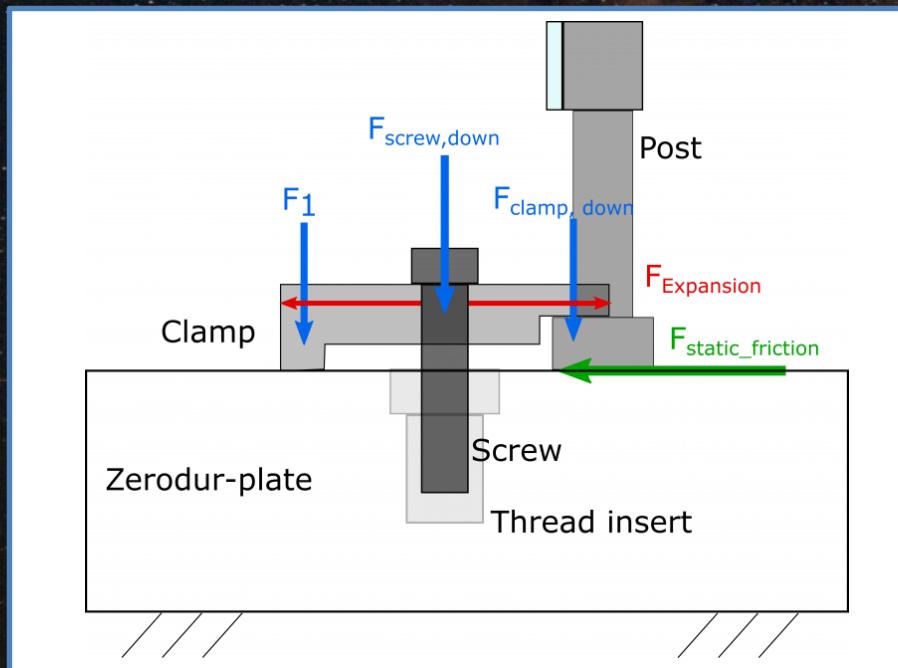
TAPS!
Toolset for Adjustable Picometer-Stable
Interferometers



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Forces friction vs expansion



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Screw-Mounting on the ULE-plate

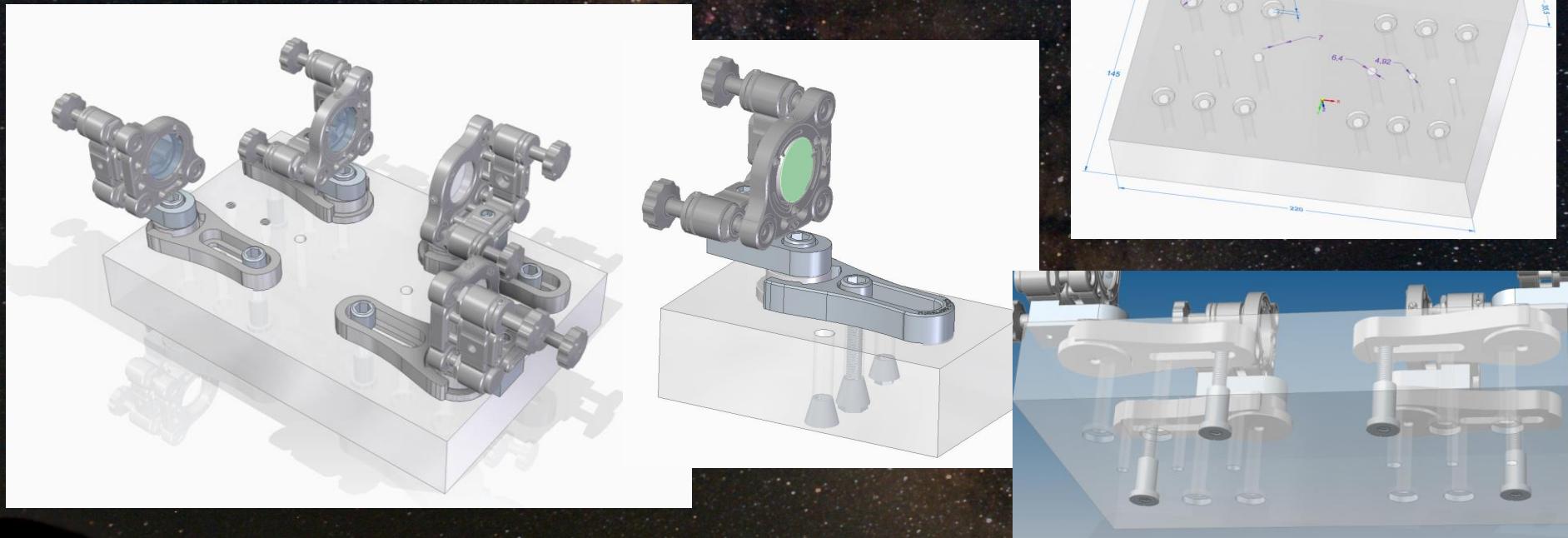
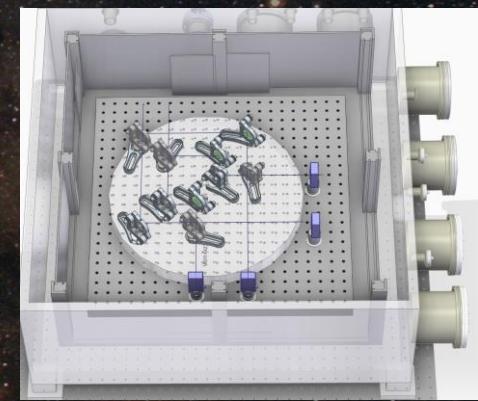
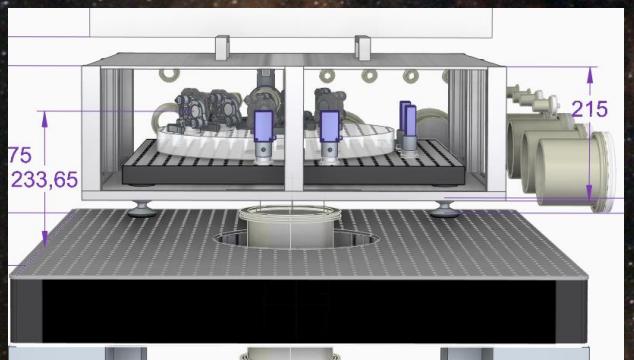
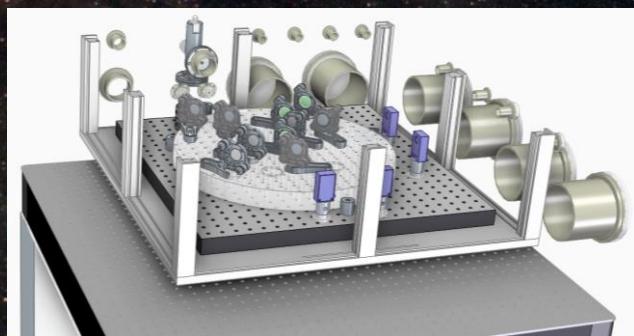
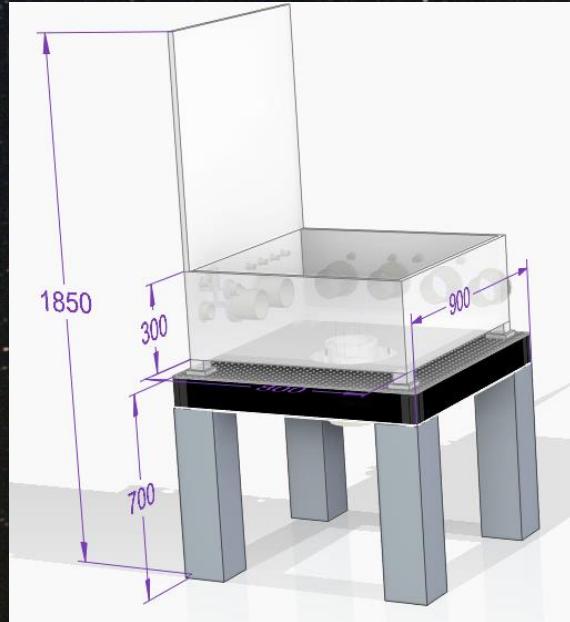


Fig.10: TAPSI setup ideas

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$$\frac{\sin(\gamma)}{P_1} = \frac{\sin(\theta)}{P_{1,new}}$$

$$P_{1,new} = \frac{P_1}{\sin(\gamma)} \sin(\theta) = \frac{P_1}{\sin(180^\circ - \theta - \varphi)} \sin(\theta)$$

$$\frac{\sin(\beta)}{P_2} = \frac{\sin(\theta)}{P_{2,new}}$$

$$P_{2,new} = \frac{P_2}{\sin(\beta)} \sin(\theta) = \frac{P_2}{\sin(180^\circ - \theta - \varphi)} \sin(\theta)$$

$$\Delta P_{resulting} = P_{new} - P_{old}$$

$$\Delta P_{resulting} = (P_{1,new} + P_{2,new}) - (P_1 + P_2)$$

$$\Delta P_{resulting} = \frac{P_2}{\sin(180^\circ - \theta - \varphi)} \sin(\theta) + \frac{P_2}{\sin(180^\circ - \theta - \varphi)} \sin(\theta) - (P_1 + P_2)$$

If there is a deviation of the Mirror2 as well, γ changes by φ_2 , affecting the incoming and the reflected beam in the following way:

$$\Delta P_{resulting} = \frac{P_2}{\sin(180^\circ - \theta - \varphi_1 - \varphi_2)} \sin(\theta) + \frac{P_2}{\sin(180^\circ - \theta - \varphi_1 - \varphi_2)} \sin(\theta) - (P_1 + P_2)$$

Considering a whole optical setup (interferometer) of mirror deviation due to temperature change, the final Formula results in:

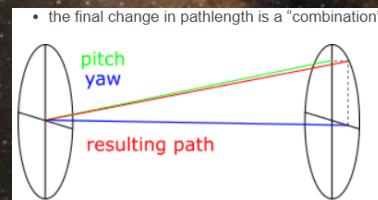
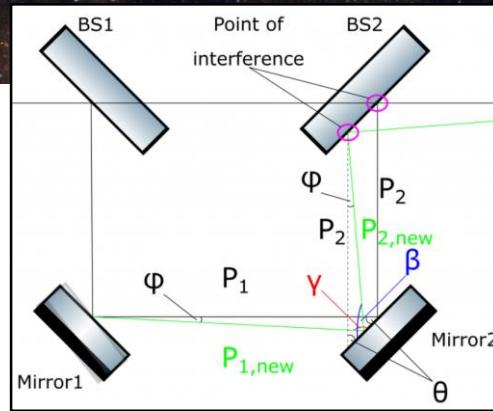
$$\Delta P_{resulting} = \sum_{n=1}^N \frac{P_n}{\sin(180^\circ - \theta - [\sum_{m=1}^n \varphi_{n,m}] + \varphi_{n+1})} \sin(\theta) - (P_{old})$$

with N = Number of Mirrors with deviation

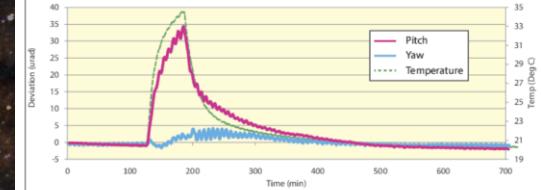
n = Mirror number in the outgoing direction

$[\sum_{m=1}^n \varphi_{n,m}]$ = Summ of all deviation angles φ_n till n

$0^\circ < \theta > 45^\circ$



ZeroDrift™ Thermal Drift Compensation Technology
Standard Stainless Steel Mirror Mount



Suprema® with ZeroDrift™ Thermal Drift Compensation

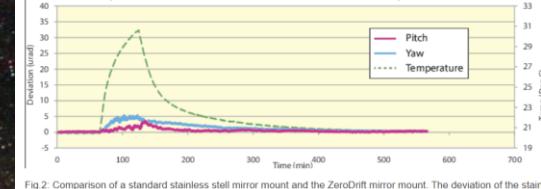
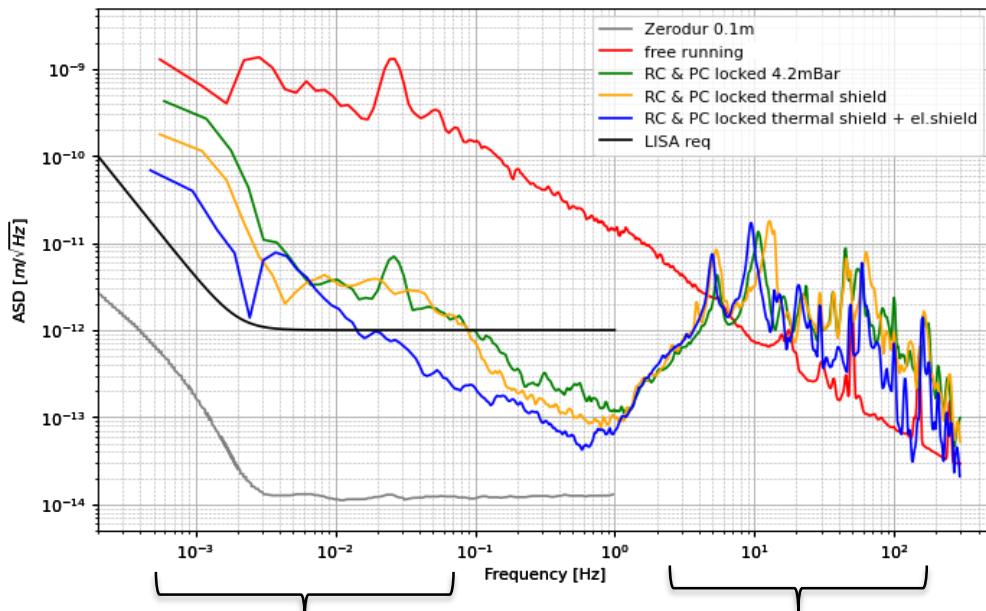
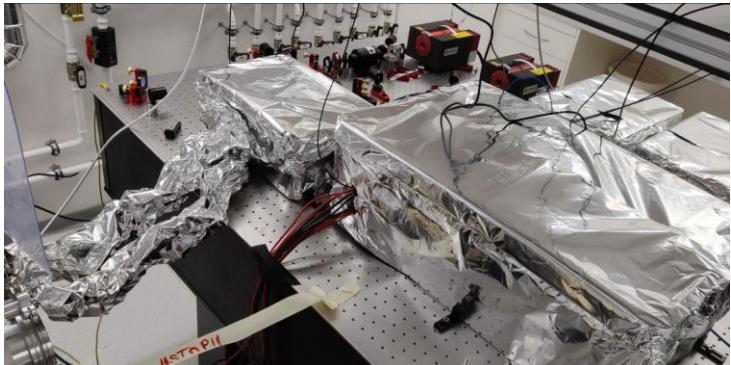
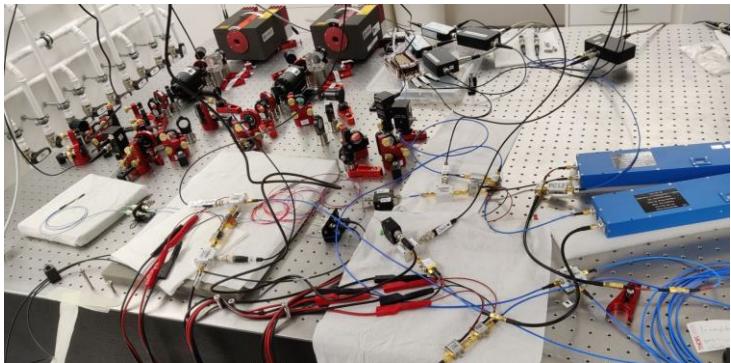


Fig 2: Comparison of a standard stainless steel mirror mount and the ZeroDrift mirror mount. The deviation of the stainless steel mirror mount is: 2.5 μrad/K (pitch) and 0.32 μrad/K (yaw). The deviation of the ZeroDrift mirror mount is: 0.42 μrad/K (pitch) and 0.53 μrad/K (yaw)

TAPS! Stability - proof of principle experiment



- Temperature fluctuations (chamber)
- Temp+humidity fluctuations at the electronics
- PI-controller
- Beat-delay coupling

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TAPSI stability experiment

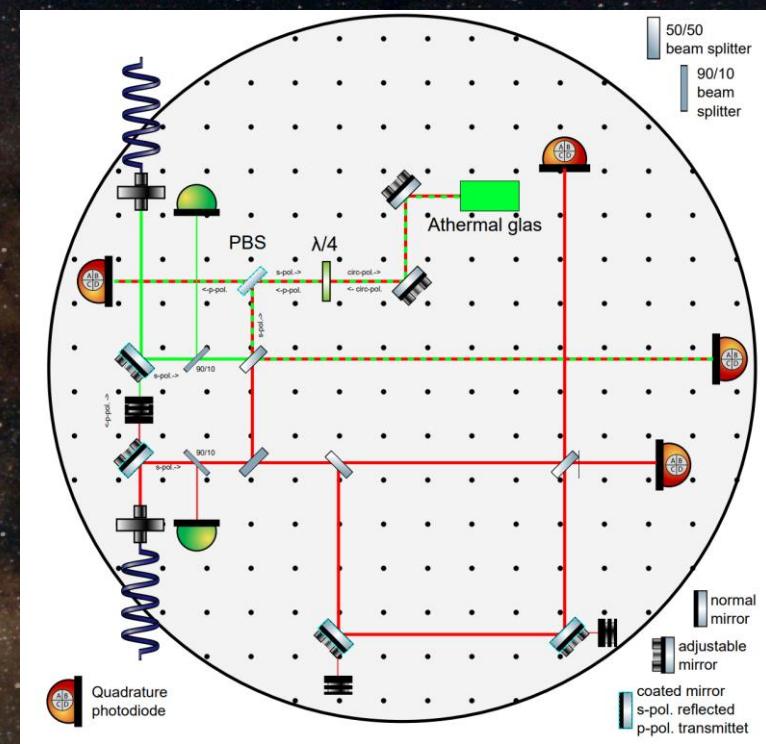


Fig.10: TAPSI setup ideas