10th February 2025

Suspensions & Fibres (XGCD ET_CE Meeting)

Iryna Buchovska (IKZ Berlin), Giles Hammond (University of Glasgow), Flavio Travasso (Università degli Studi di Camerino)

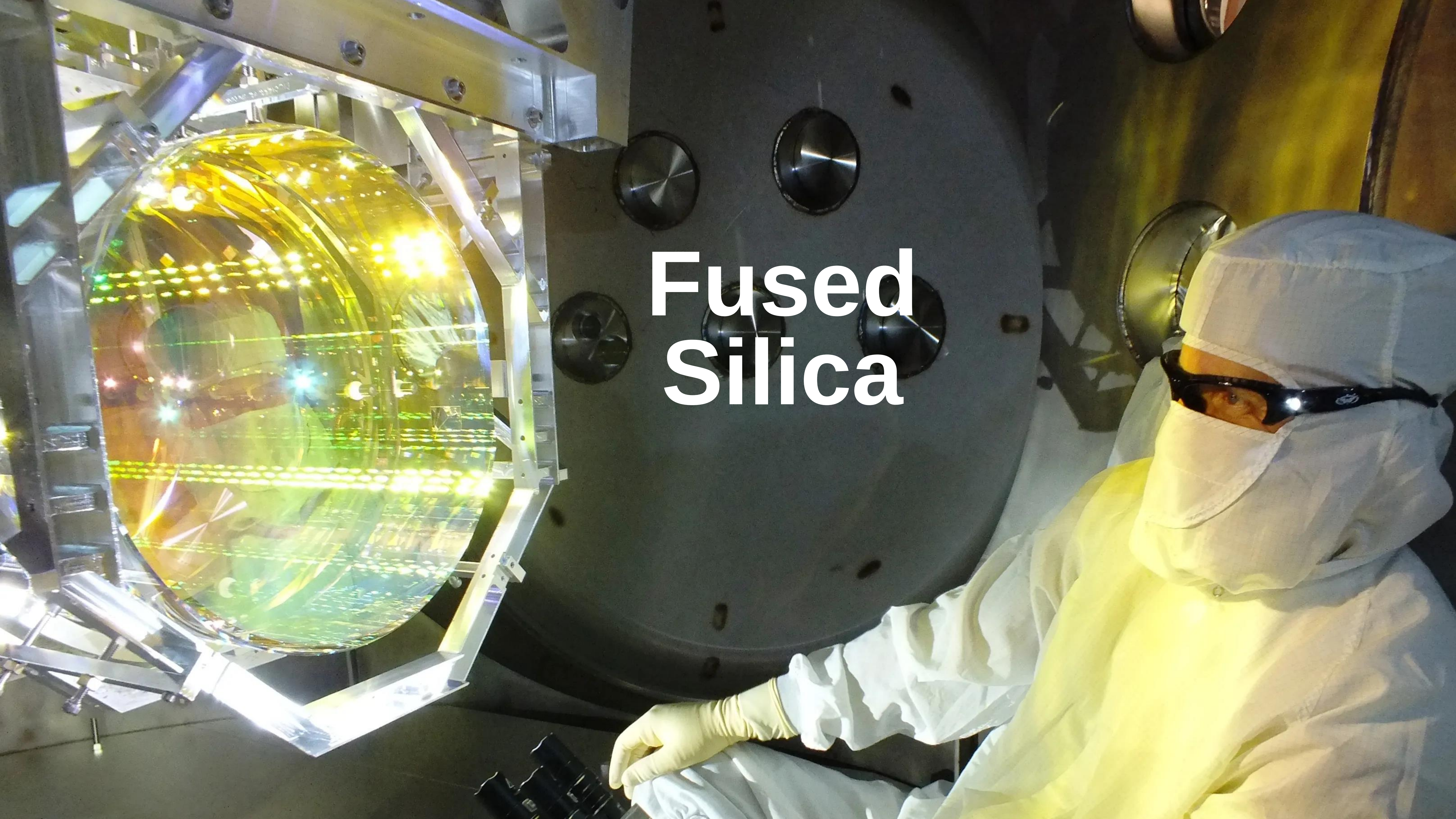
iryna.buchovska@ikz-berlin.de

giles.hammond@glasgow.ac.uk

flavio.travasso@unicam.it

Introduction

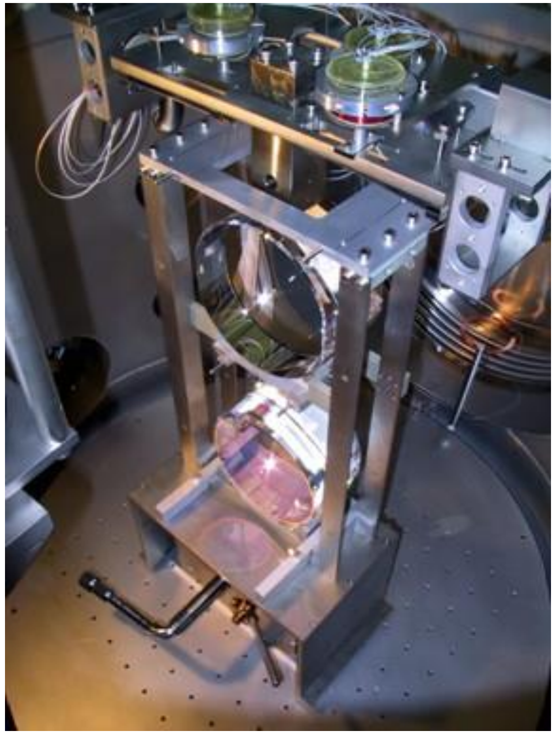
- Silica suspensions
  - Brief overview of LIGO/VIRGO fused silica
  - Thermal noise estimates/Violin modes
  - 1g-320kg suspension R&D (modelling and prototyping)
- Sapphire/Silicon suspensions
  - Sapphire growth
  - Silicon growth
  - Thermo-mechanical properties for cryogenic operation


Fused
Silica

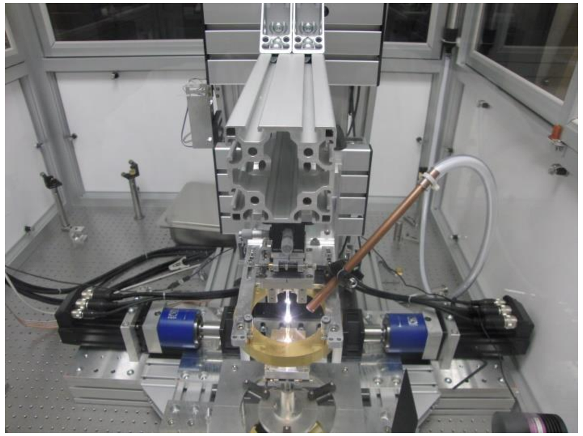
F Travasso and on behalf of Virgo Collaboration 2018 J. Phys.: Conf. Ser. 957, 012012
A V Cumming et al 2012 Class. Quantum Grav. **29** 035003 **DOI** 10.1088/0264-9381/29/3/035003

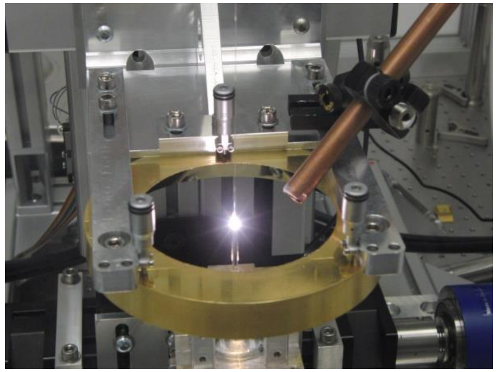
Brief Overview of LIGO/VIRGO Experience

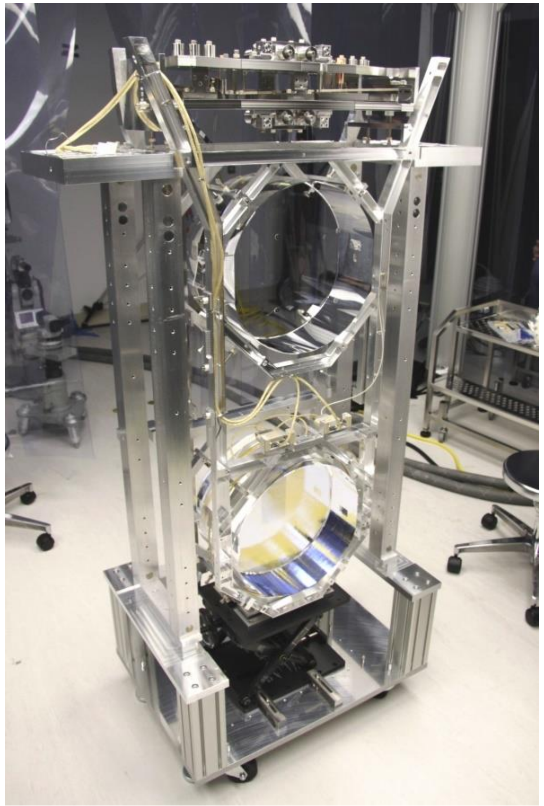
- Monolithic suspensions & signal recycling pioneered in GEO-600 $\rightarrow$ upscaled to aLIGO and AdvVirgo
- Fused silica is a mature technology >2 decades of experience

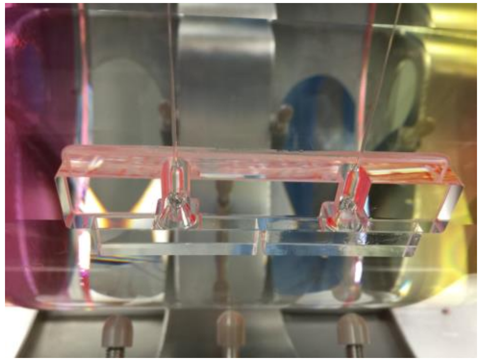


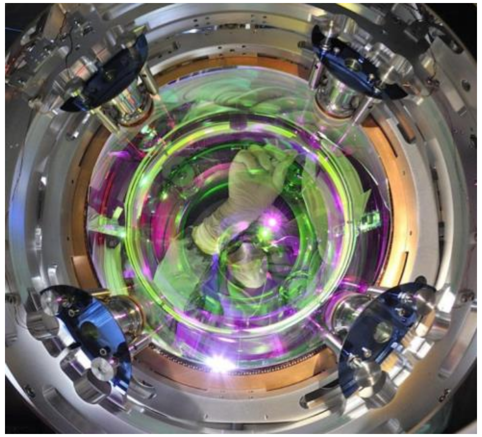
GEO/GEO-HF: 1996-2004









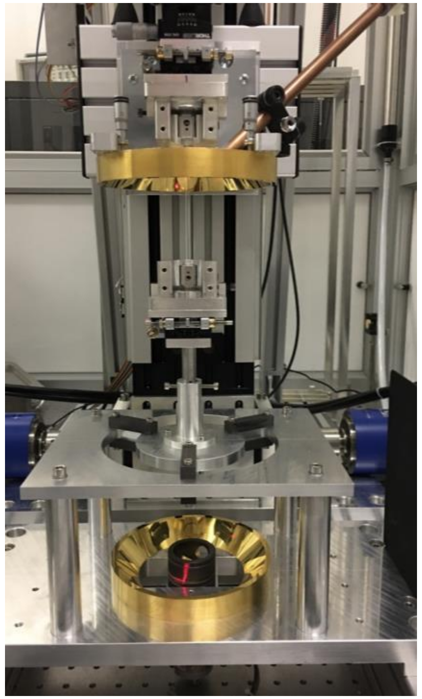


LIGO/VIRGO: 2004-present

Fibre Pulling & Welding (aLGO/AdvVIRGO)

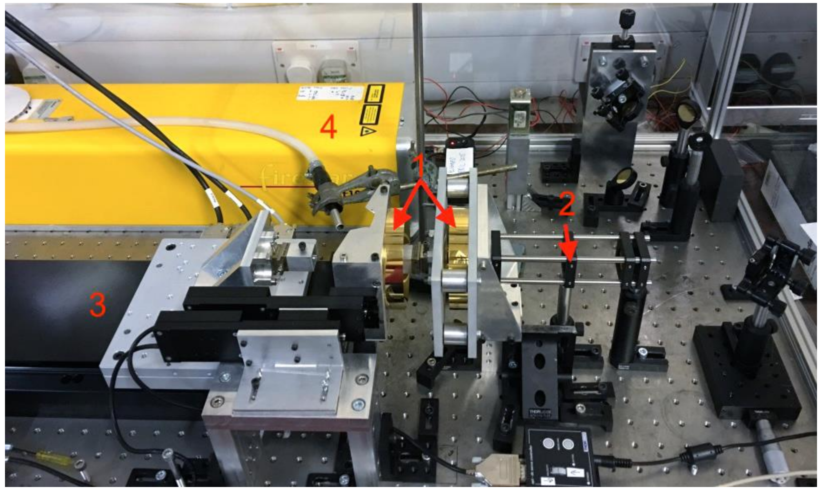
Glasgow

Hanford



Urbino

Glasgow thin fibre puller

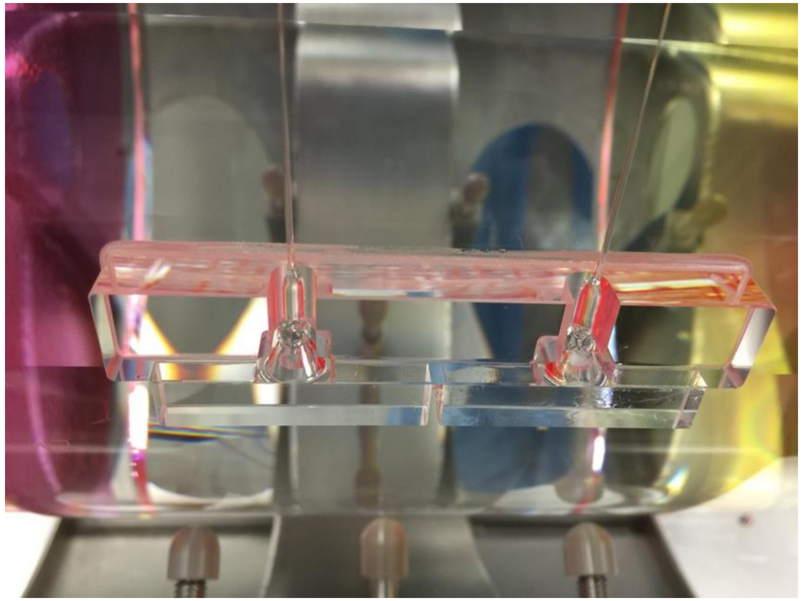


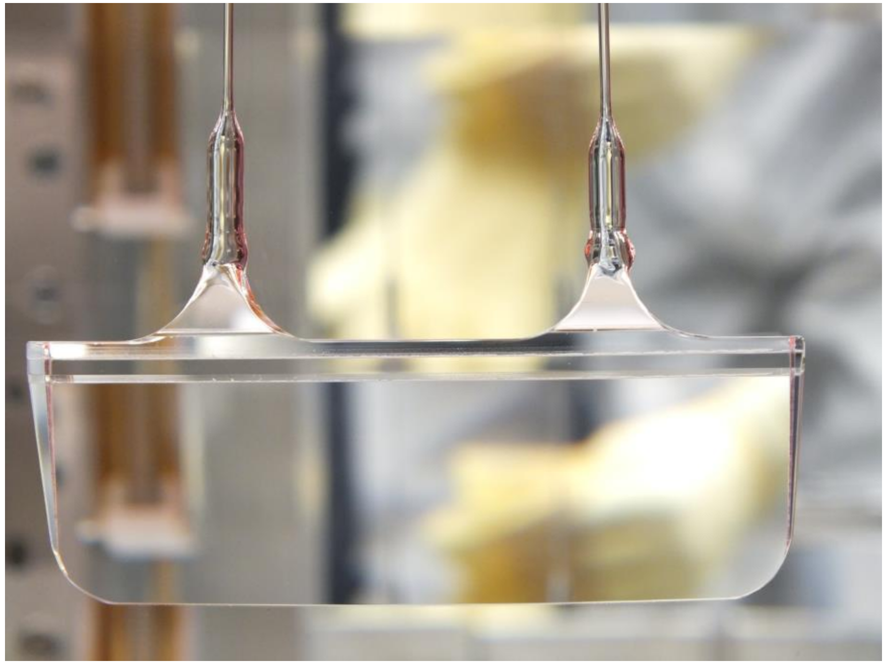
- CO_2 fibre pulling machines (Glasgow, Urbino, VIRGO, LHO, RRCAT: 2025)
- Strong fibres (4GPa)
- Low mechanical loss
- Good dimensional tolerance (±5% fibre diameter)
- Stabilisation of melt temperature via camera feedback

450µm fibre (BHQS)

15µm fibre

Fibre Pulling & Welding (aLGO/AdvVIRGO)





- CO_2 fibre welding
- Strong welds
- Can re-weld and re-work (silica has high viscosity at melt)
  - destress fibres to remove any angle in stock
  - heat weld at reduced power to lower thermal stress

Modelling Thermal Noise

- Use the following loss terms to model the weld region and silica fibres

$$\phi_{\mathrm{T}} = \frac{YT}{\rho C}\left(\alpha - \sigma_o \frac{\beta}{Y}\right)^2 \left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$$

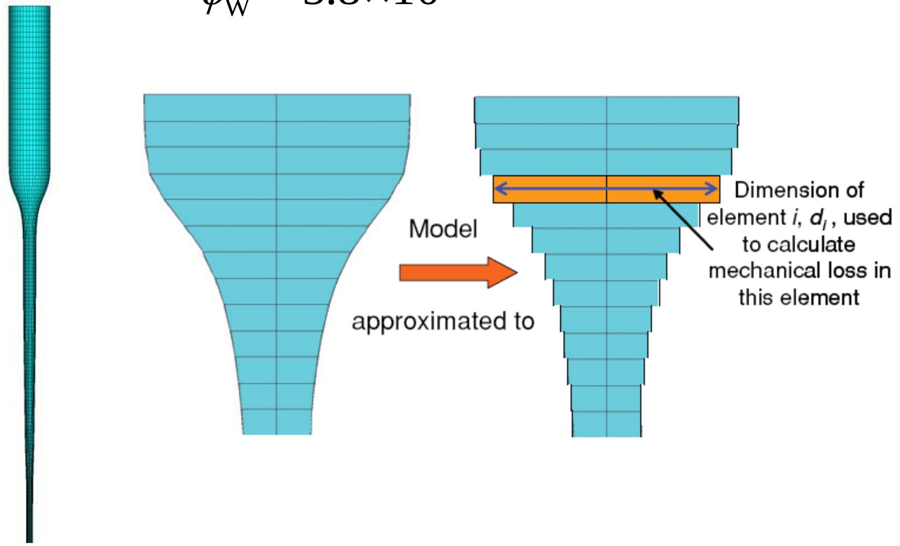
$$\phi_{\mathrm{S}} \approx 8h\phi_s / d$$

$$\phi_{\mathrm{W}} = 5.8\times10^{-7}$$

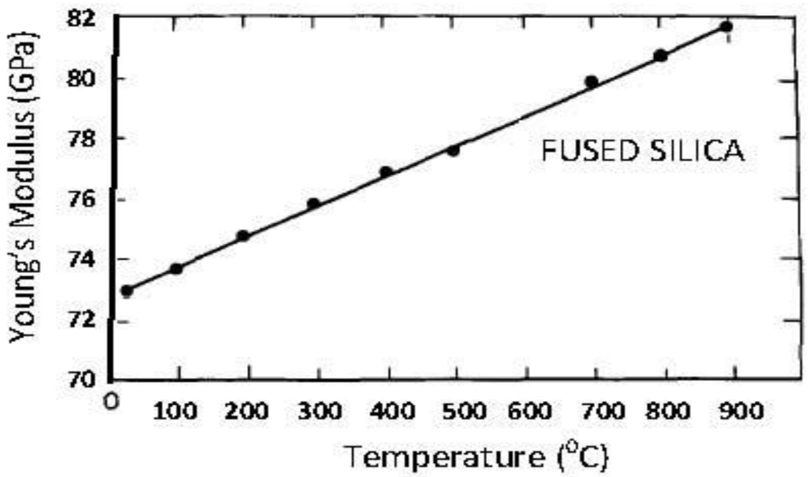
$$\phi_i(\omega) = \left(\phi_{\mathrm{T,i}}(\omega) + \phi_{\mathrm{S,i}}(\omega) + \phi_{\mathrm{W,i}}(\omega)\right)$$

$$\phi_{total}(\omega) = \frac{1}{D}\left[\frac{E_1}{E_{\mathrm{elastic}}}\phi_1(\omega) + \frac{E_2}{E_{\mathrm{elastic}}}\phi_2(\omega) + \ldots + \frac{E_{\mathrm{n}}}{E_{\mathrm{elastic}}}\phi_{\mathrm{n}}(\omega)\right]$$

$$S_x(\omega) = \frac{4k_BT}{m\omega}\left(\frac{\omega_o^{\,2}\phi_{total}(\omega)}{\omega_o^{\,4}\phi_{total}^{\,2}(\omega) + \left(\omega_o^{\,2} - \omega^2\right)^2}\right)$$



$$D = \frac{E_{elastic}}{E_{kinetic}}$$



A.M. Gretarsson et al., Phys. Rev. A, 2000
G. Cagnoli and P.A. Willems, Phys. Rev. B, 2002
A.V. Cumming, et al., CQG, 26 215012, 2009

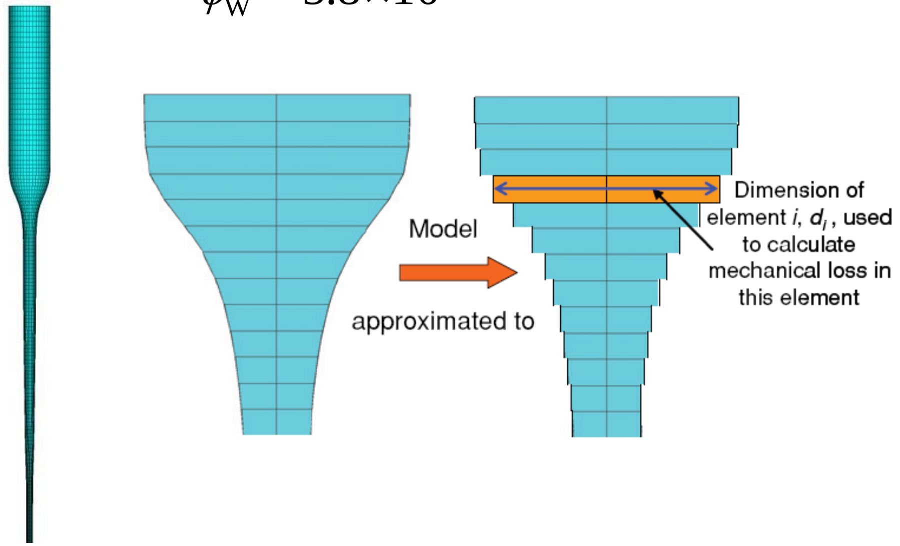
Modelling Thermal Noise

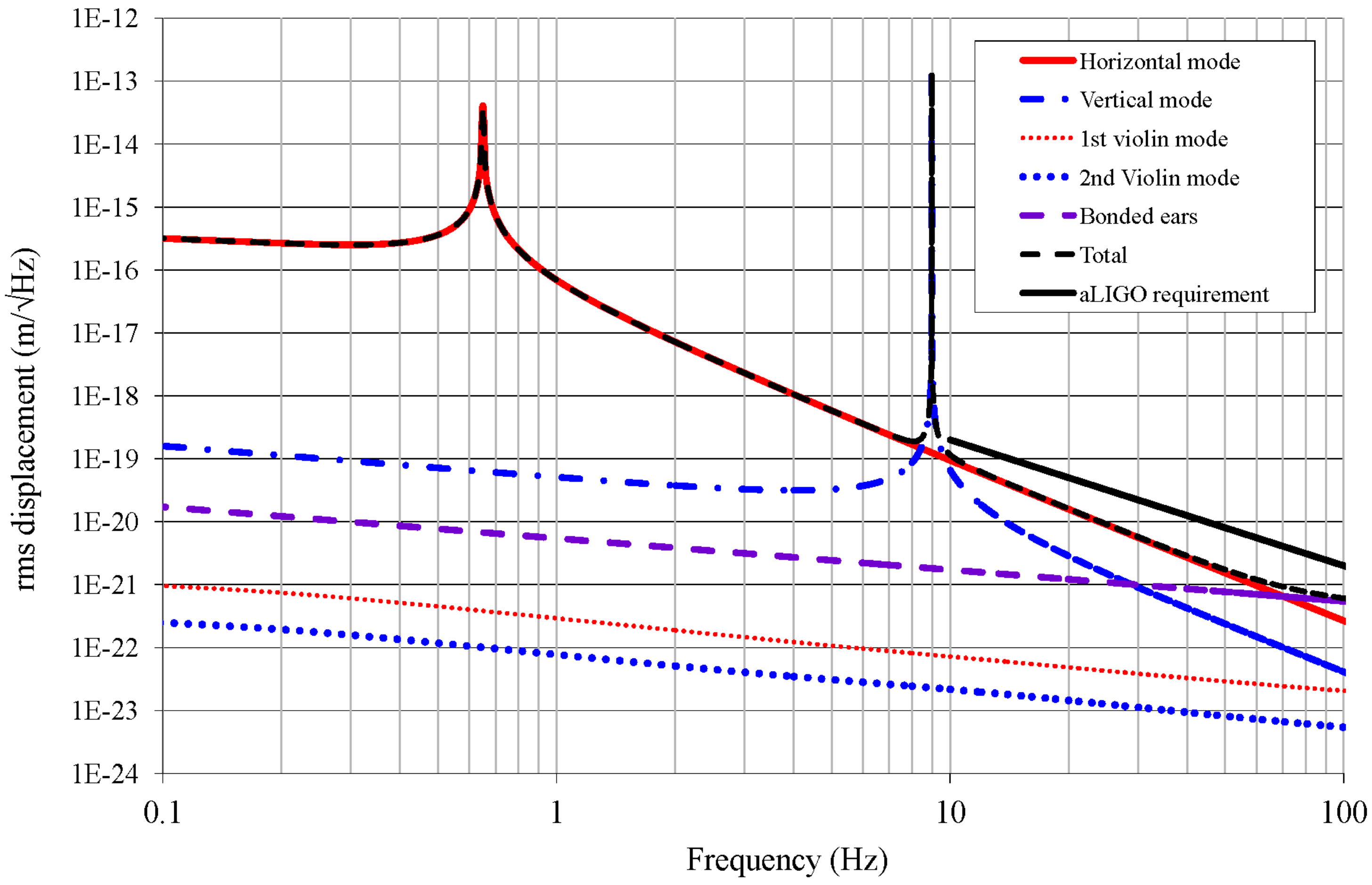
- Use the following loss terms to model the weld region and silica fibres

$$\phi_T = \frac{YT}{\rho C}\left(\alpha - \sigma_o \frac{\beta}{Y}\right)^2 \left(\frac{\omega\tau}{1+(\omega\tau)^2}\right)$$

$$\phi_S \approx 8h\phi_s / d$$

$$\phi_W = 5.8\times10^{-7}$$

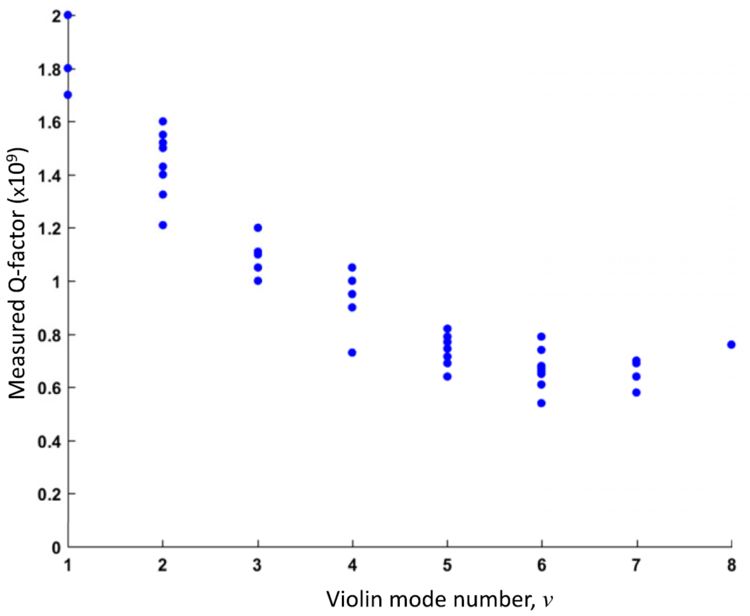


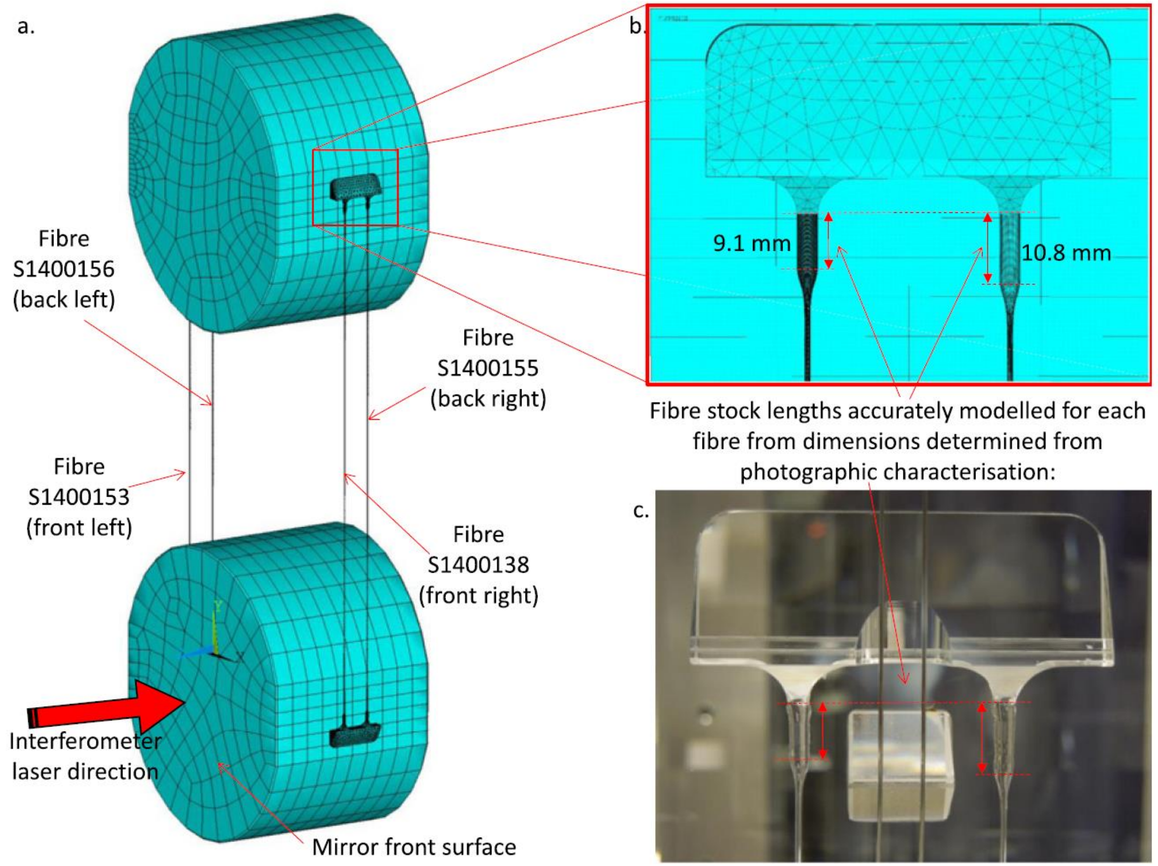


A.M. Gretarsson et al., Phys. Rev. A, 2000
G. Cagnoli and P.A. Willems, Phys. Rev. B, 2002
A.V. Cumming, et al., CQG, 26 215012, 2009

Thermal Noise/Violin Mode Modelling

- Q’s of up to 1 billion in fully monolithic suspension
- Evidence that total surface/weld loss has reduced over 10 years of suspension builds (improved technique and thermal management in the weld)

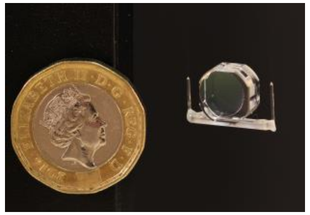




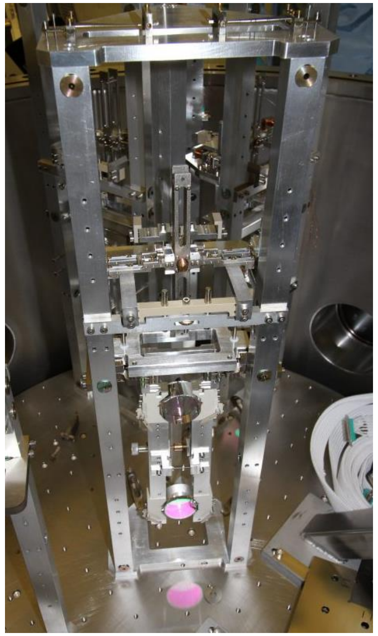
A V Cumming et al 2020 Class. Quantum Grav. 37 195019 DOI 10.1088/1361-6382/abac42

https://agenda.infn.it/event/26121/contributions/136512/
https://theses.gla.ac.uk/8984/
A V Cumming et al 2020 Class. Quantum Grav. 37 195019

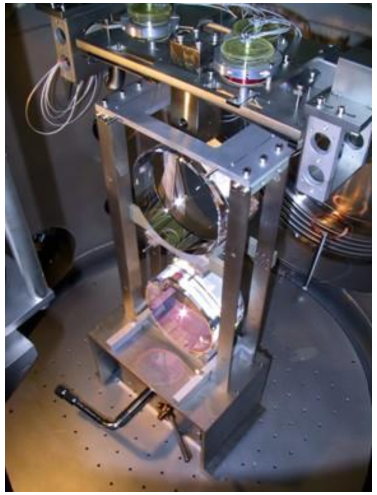
Fused Silica Suspension R&D

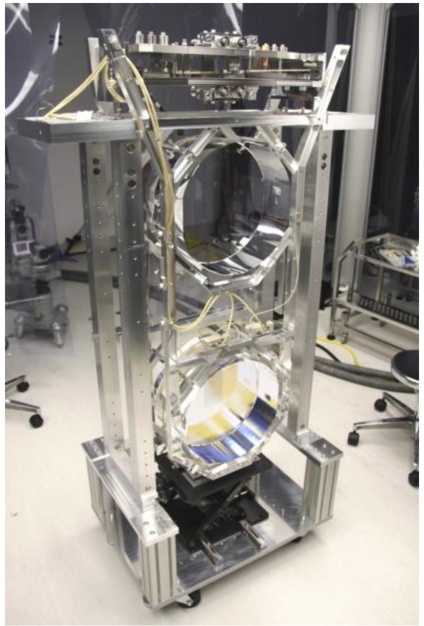
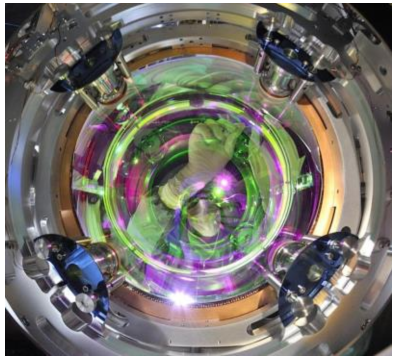
1g
Speedmeter




100g
Speedmeter/AEI 10m

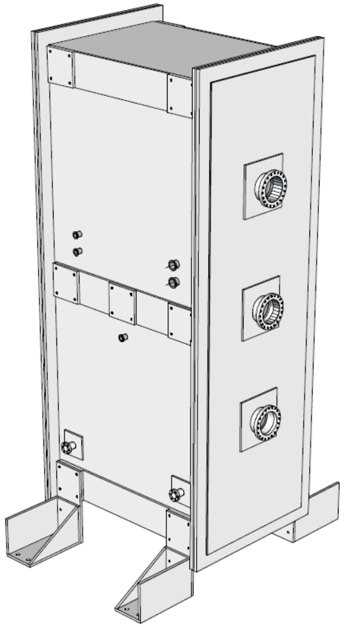


5.6kg
GEO600

40kg
VIRGO/LIGO

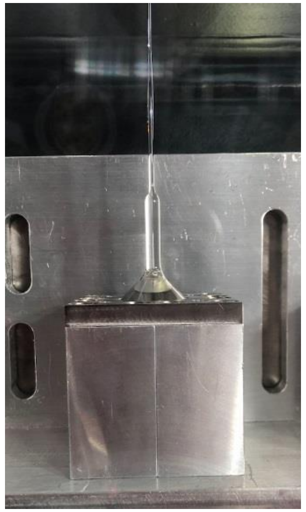
160kg
ET-HF/A#/AdV+



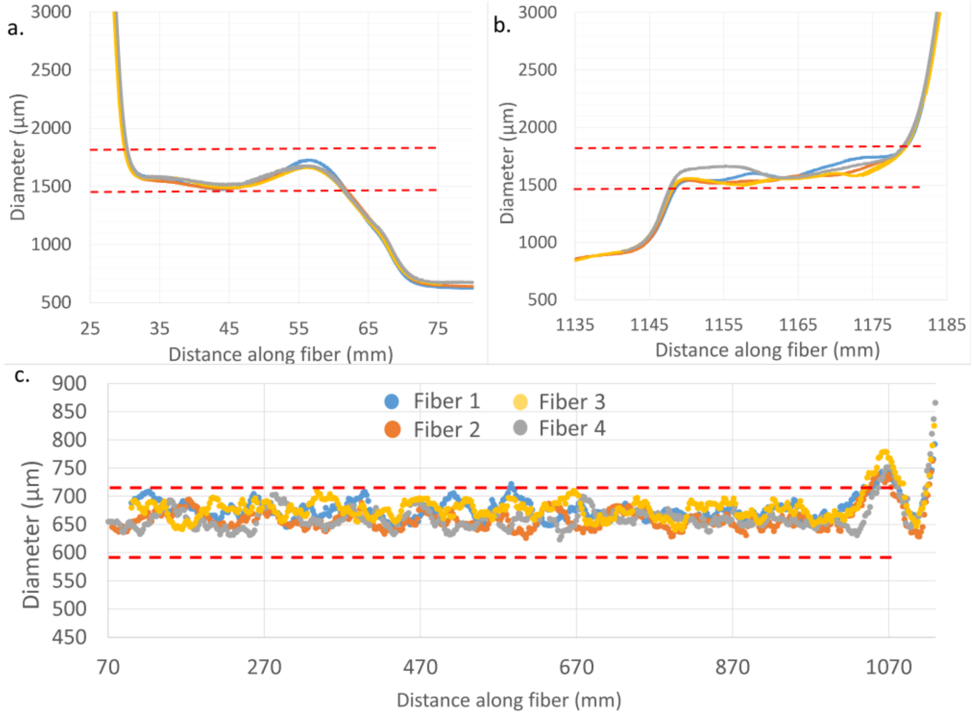
2025-2026

320kg
CE

160kg Suspensions



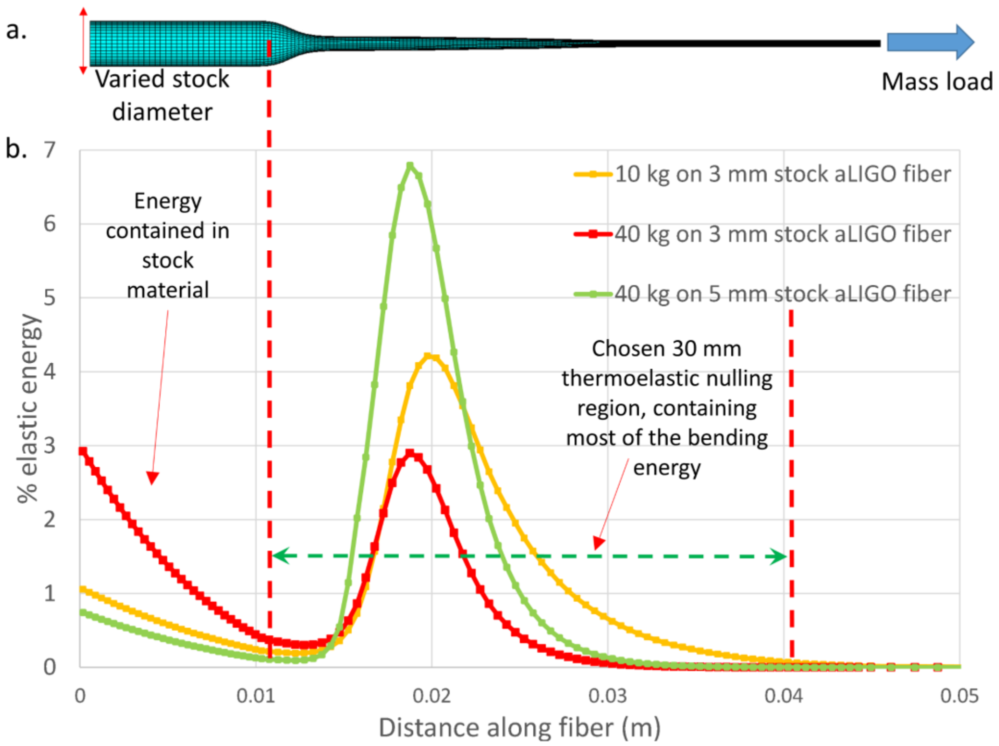
- Glasgow prototype suspension, 160 kg, 1.2 GPa, 1.2 m
  - Proof of concept of key aspects (O5+, AdV+ relevant)
    - Welding larger diameter stock
    - Longer fibres
    - Higher stress fibres
- ET performance demonstrated, as well as heading on the pathway for CE

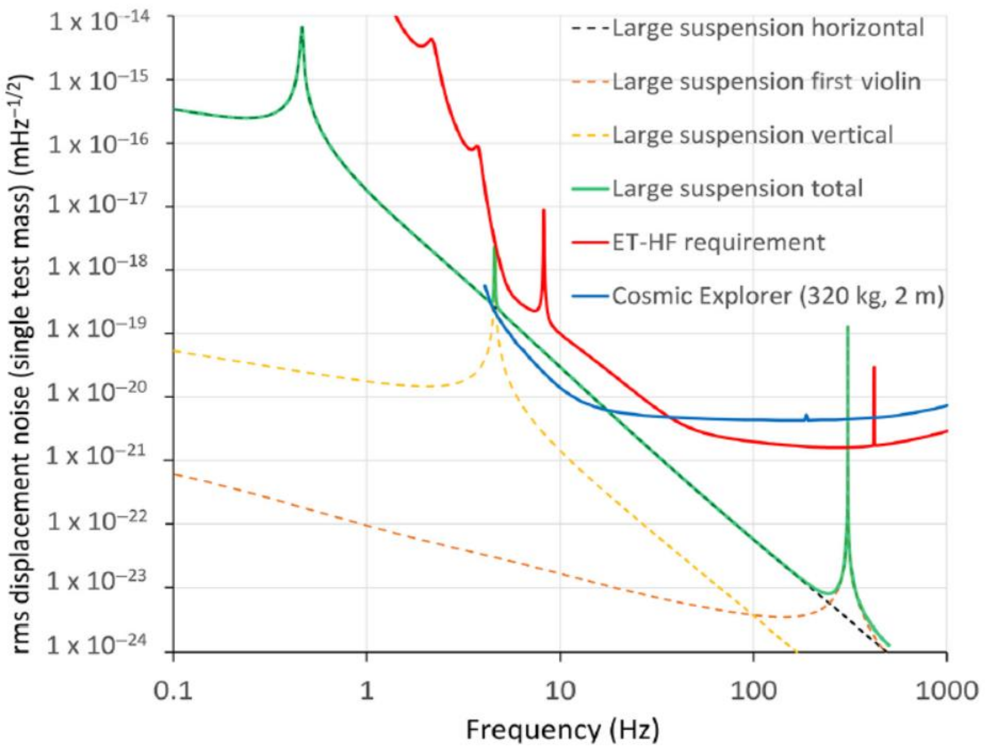


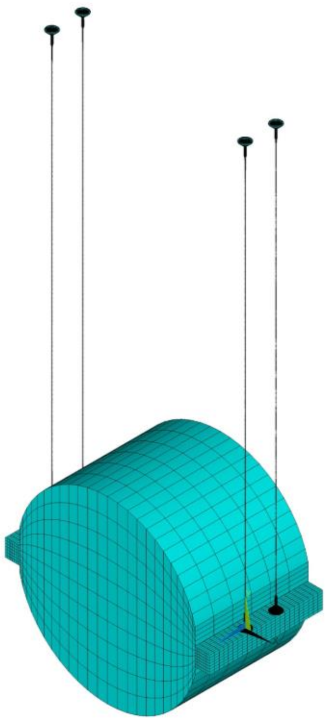
160kg Suspensions

https://dcc.cosmicexplorer.org/CE-T2000017/public
https://www.et-gw.eu/index.php/etsensitivities

- FEA has been further advanced for 160kg suspensions, and models have studied:
  - Fibre bending points
  - Fibre/ear stress distributions
  - Fibre/system energy distributions
    ⟶ thermal noise performance







CE Note

- Scaling mass (160kg ⟶ 320kg) and length (1.2m ⟶ 2m) will give x1.8 improvement
- Using thicker stock (5mm ⟶ 6mm) should provide further improvement (FEA underway)

How Much Stress

Proctor et al., 1967, The strength of fused silica, Proc. R. Soc. Lond., A297534, 557, http://doi.org/10.1098/rspa.1967.0085

- Studies underway in UK/Italy to study stress-corrosion in fused silica glass
- Lab hangs have proven the capability to use fibres of higher stresses, with typical candidate options of 1.2 GPa, or 1.6 GPa
- For 1.6 GPa failure times are projected ~30 years in air

**** Recent result ****

- 4.5 GPa fibre in air breaks ≈16 s (10 s/22 s)
- 4.5 GPa fibre offloaded in vacuum, still hanging after 66 days
- Improvement of 4x10^5 (well known that reducing humidity improves strength)
- Campaign of further measurements underway (explore stress corrosion plot in vacuum for 4 - 8 GPa range, to get reasonable breaking times)

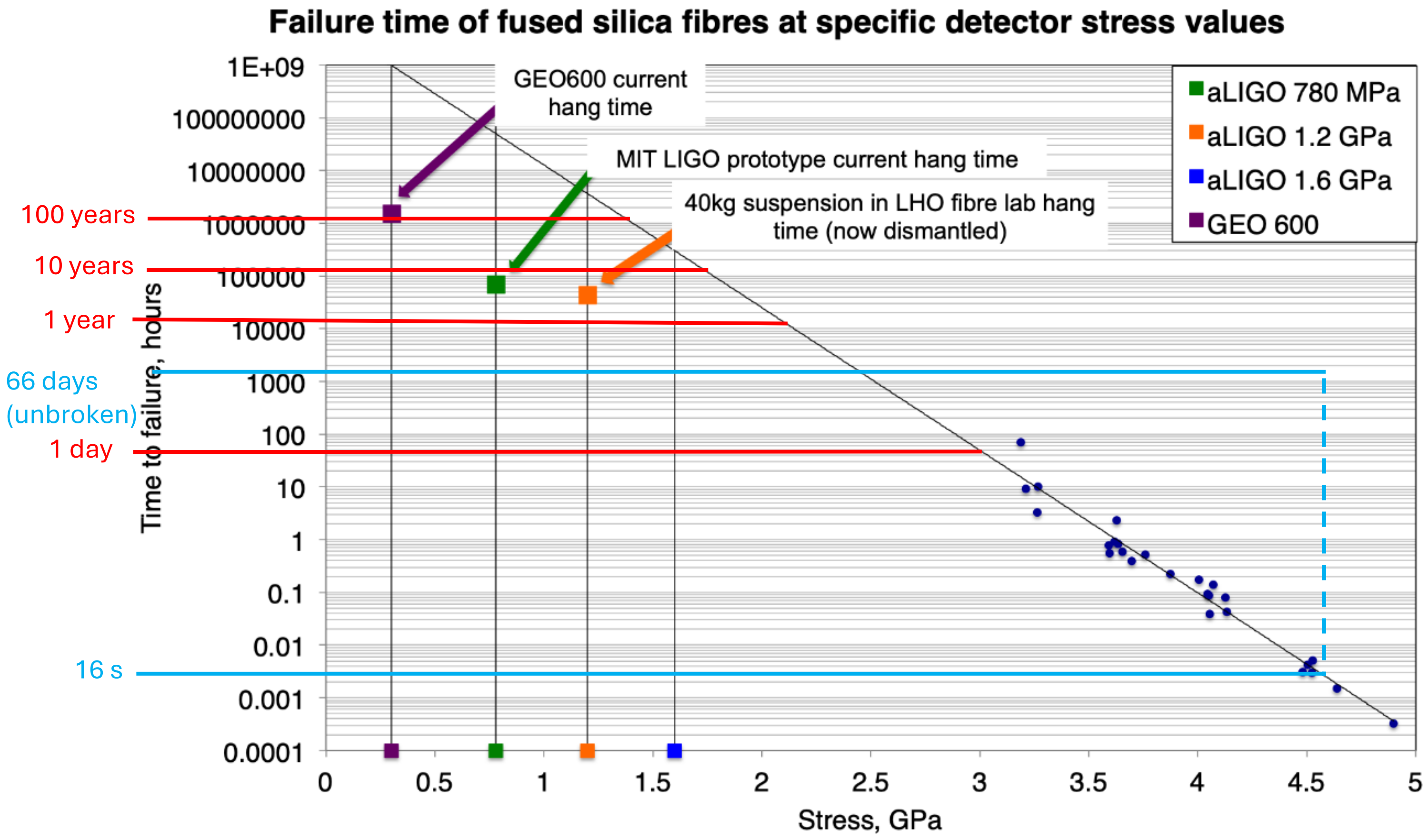
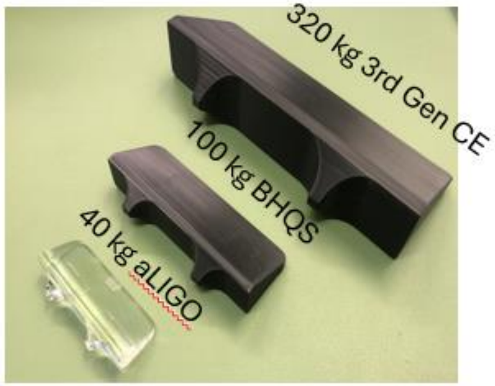


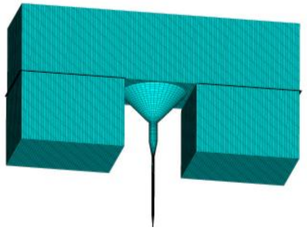
Figure 4.16: Predicted in-air lifetime of fused silica fibres at relevant detector stress values.

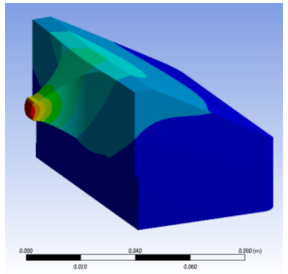
https://theses.gla.ac.uk/81461/1/2020TolandPhD.pdf , page 134

Future R&D

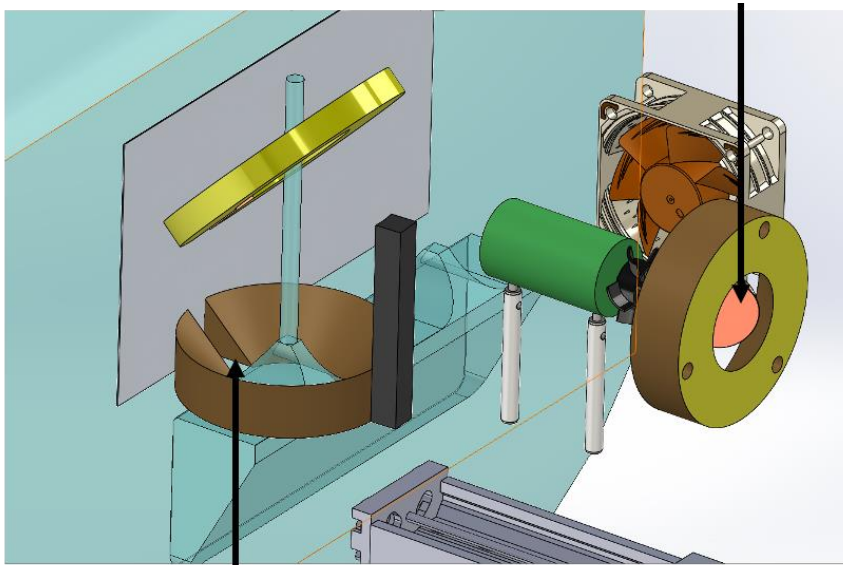
- Fused silica R&D is mature
- Strong fibres (in vacuum even stronger!!), high Q factor violin modes
- Groups in UK/Italy are well placed to deliver technology for ET-HF (160kg hang already demonstrated)
- A# and AdV+ are on the path to 320kg CE
- 320kg hang planned 2025/26



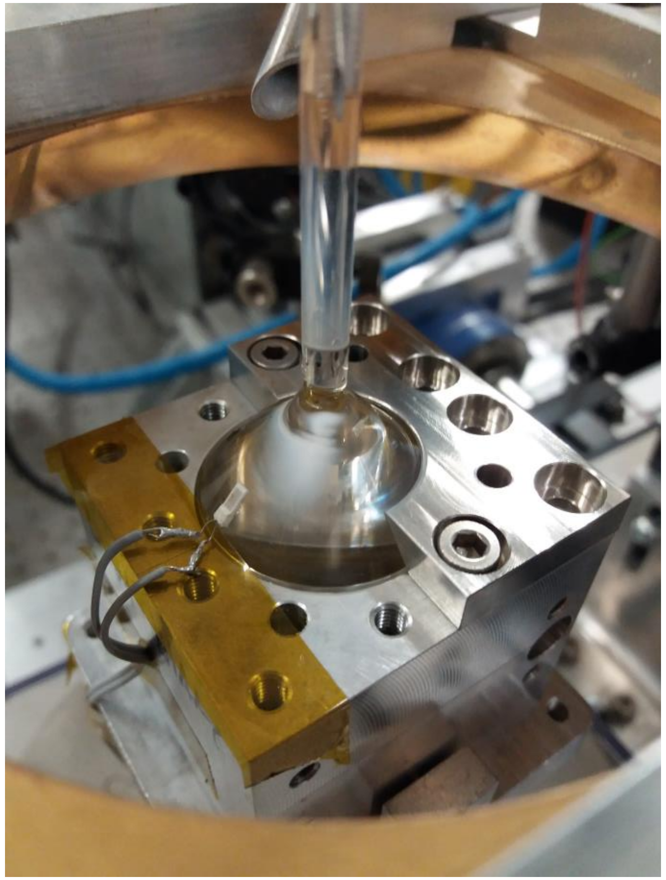




Develop ear/anchor design



Techniques to weld thicker stock



Develop engineering prototypes, study techniques to align and move large optics

Large masses for Virgo-O5

Larger mirrors (diameter 55cm, thickness 20cm => weight 104kg) were foreseen for Virgo-O5 (*project at moment delayed*)

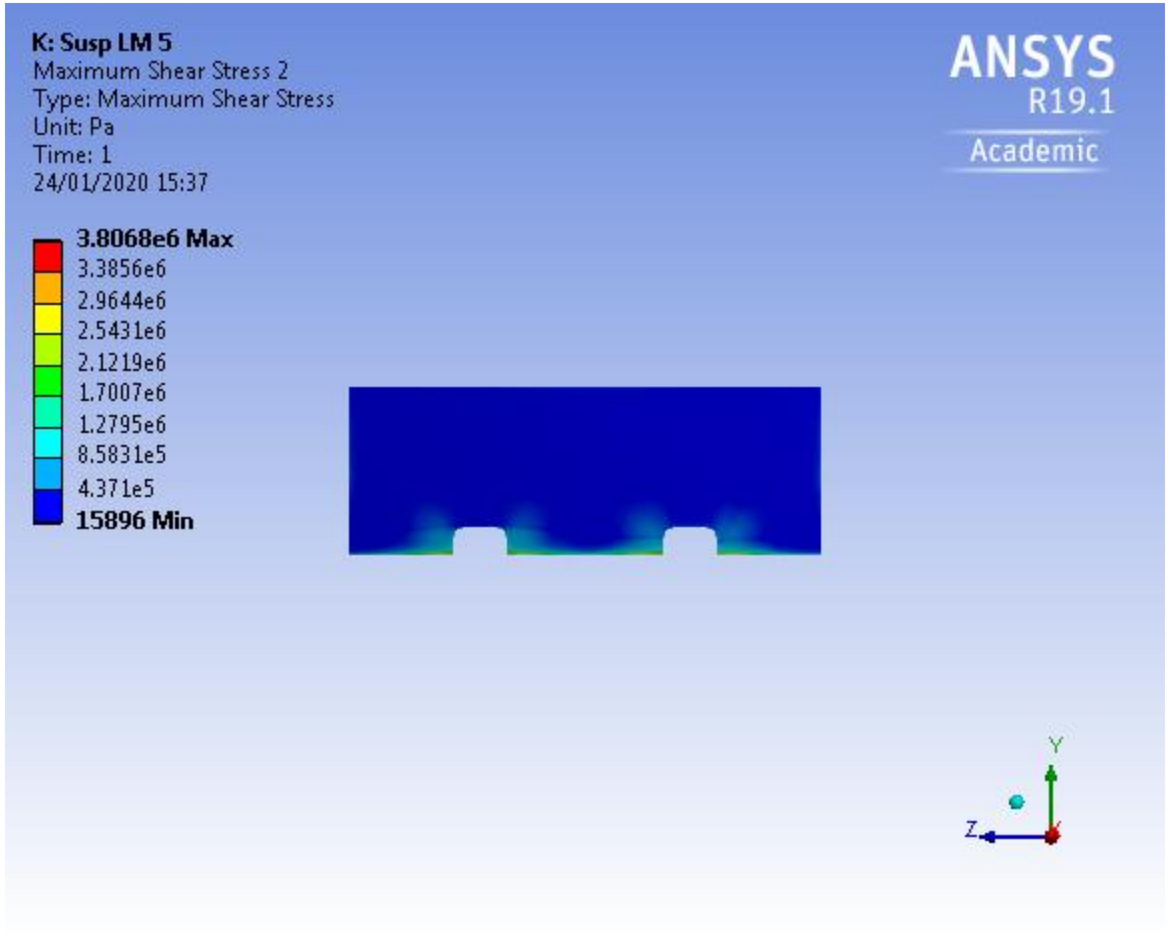
For AdVirgo was used a maximum localized stress around **2Mpa** (*a very conservative value with a safety factor around 6*) and we would like to maintain almost the same stress on ear => same ratio between the weight of the mirror and the surface of the glued part:

- AdV
  - M_{AdV}=42 kg
  - $Area_{SB\_AdV}$ = 12.47 cm^2 X 2 (about 1.5X9 cm per ear)
  - **Shear Stress: M_{AdV} g/ S_{AdV} =0.165 Mpa**
- LM
  - M_{LM}=104 kg
  - **Shear Stress: M_{LM} g/S_{LM}=0.165 MPa**
  - $Area_{SB\_LM} = Area_{SB\_AdV} * M_{LM}/ M_{AdV}$ =>

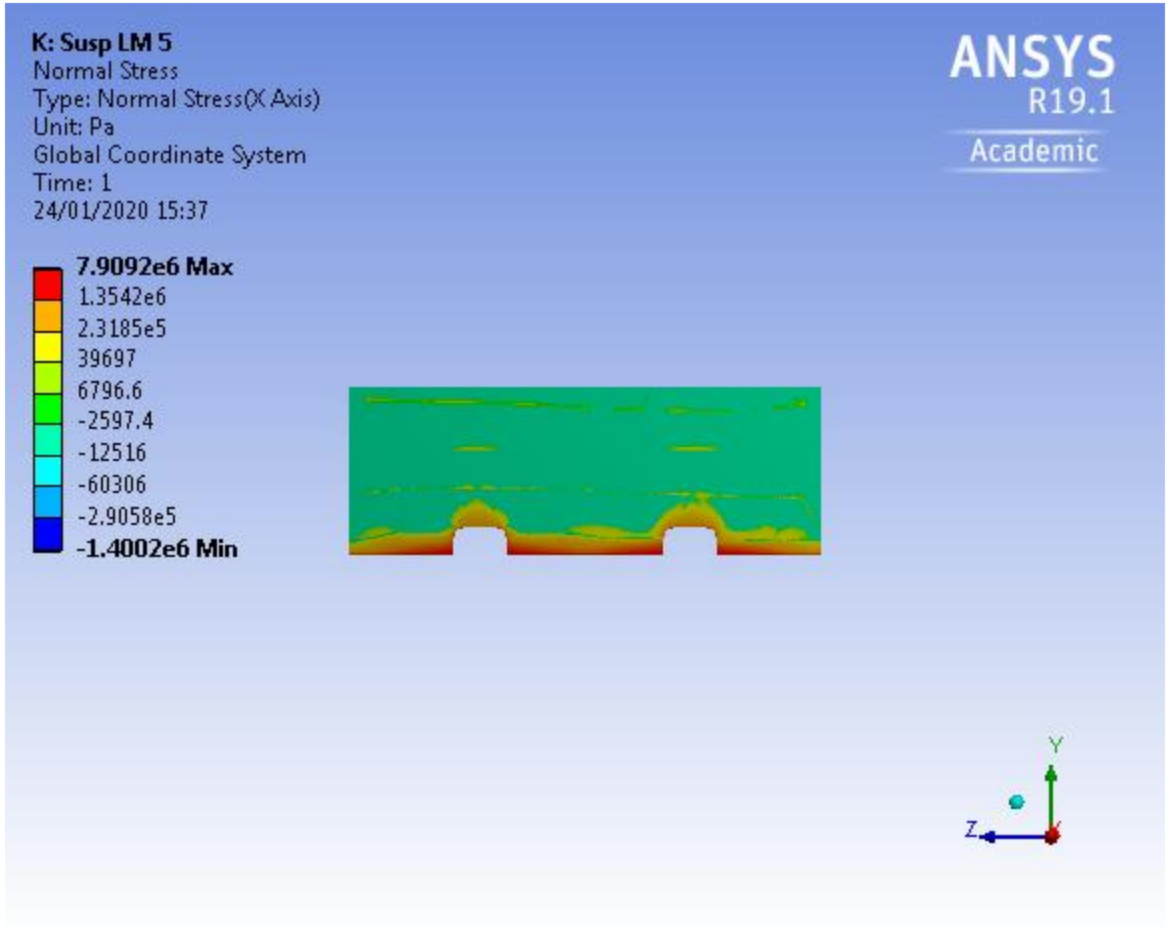
$\Rightarrow Area_{SB\_LM} \sim 35\ cm^2$

Bigger ear – Stress study

Bigger ear – Shear stress



Bigger ear – Normal stress



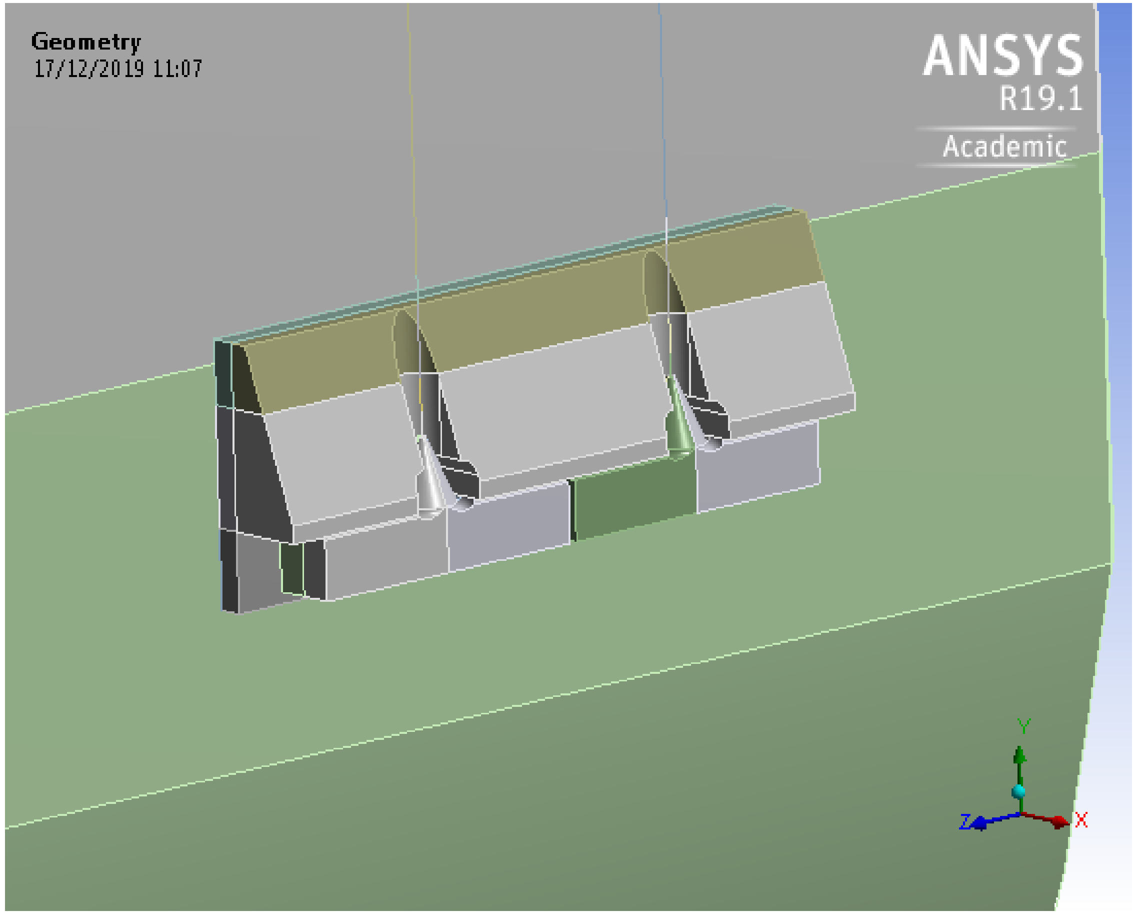
VIR-1034A-20

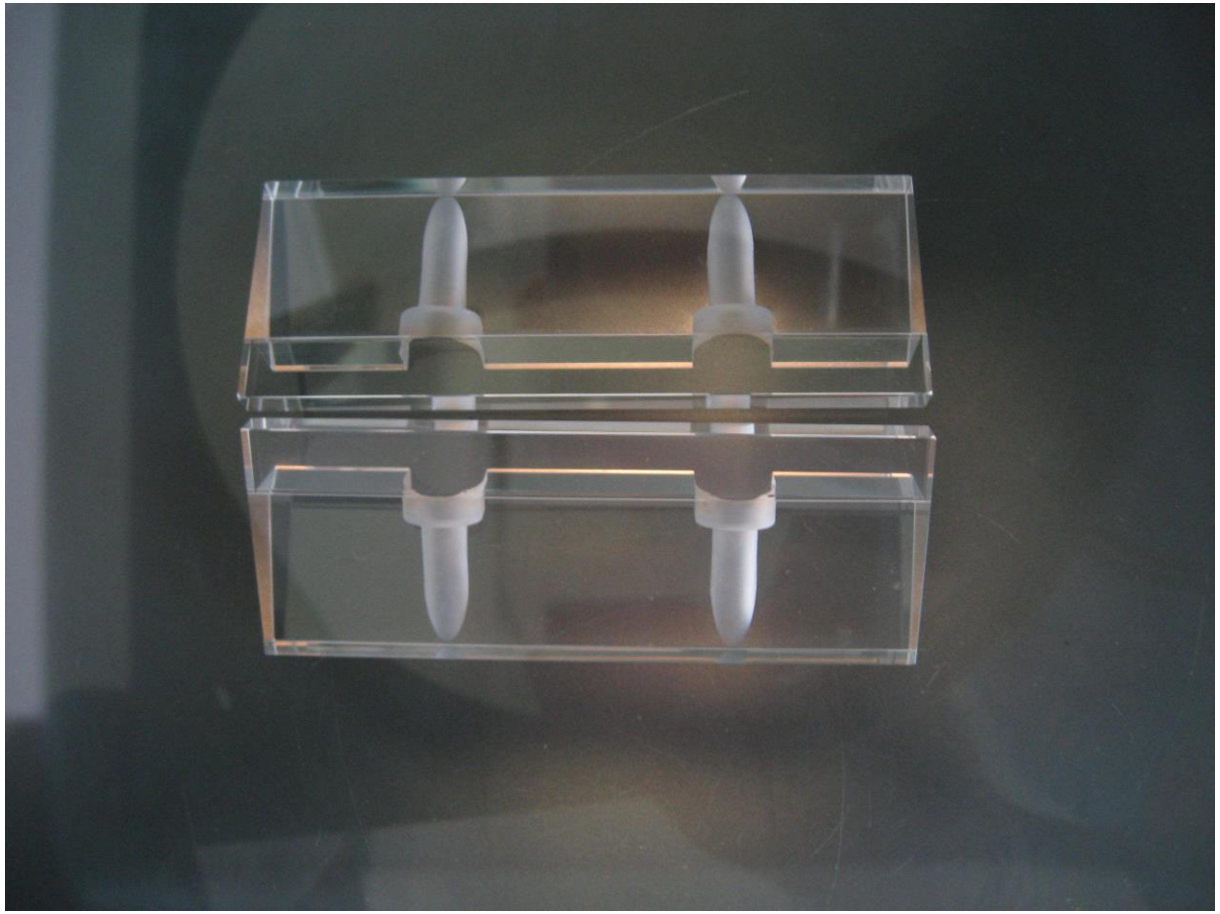
Ears for the Larger Masses

A new design was realized with a better distribution of the stress and without exceeding the safety value of 2-3 MPa

Ear total surface: 90mm X 33 mm= 30 cm^2

Aletta: Height 10mm, thickness 3mm

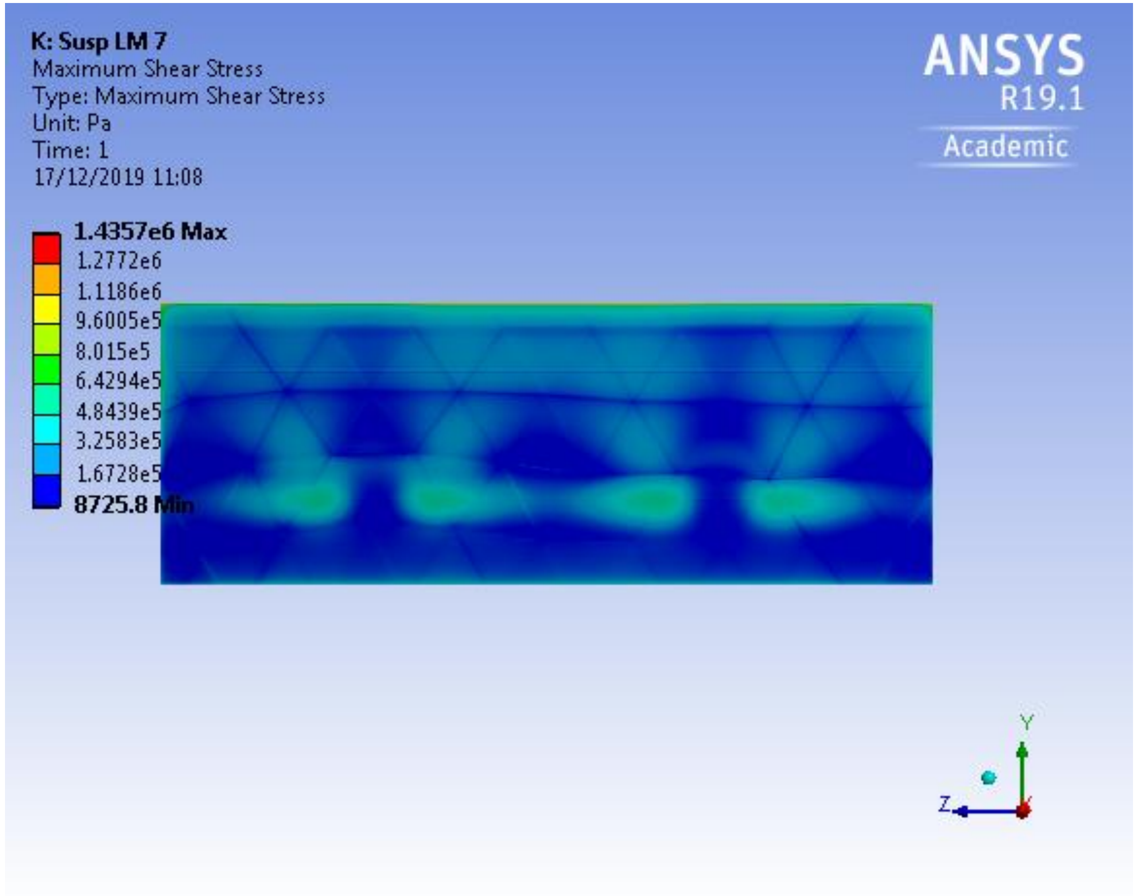




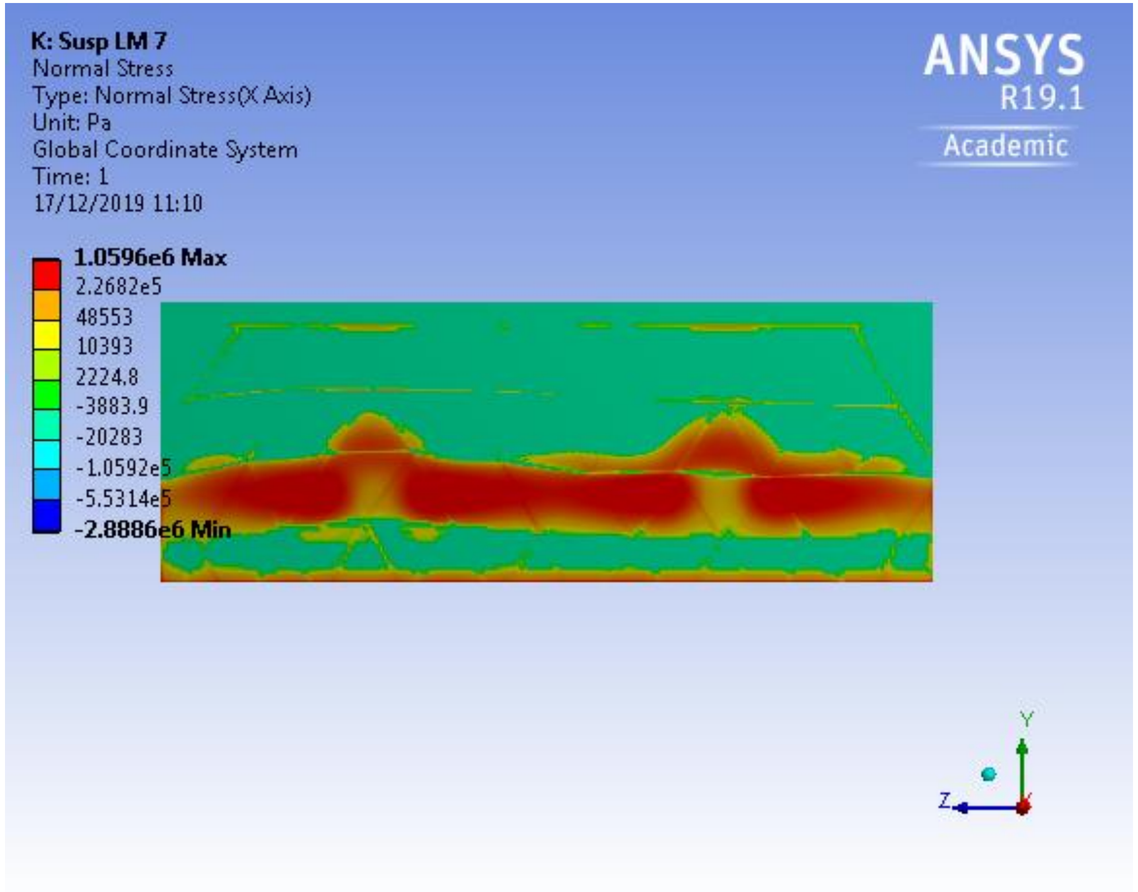
New ear – Stress study

Without the thin wall, the normal stress is more than the breaking strength in the lower part: the "Aletta" has exactly the rule to reduce the stress on the lower edge and to produce a better re-distribution

New design – Shear stress



New design – Normal stress



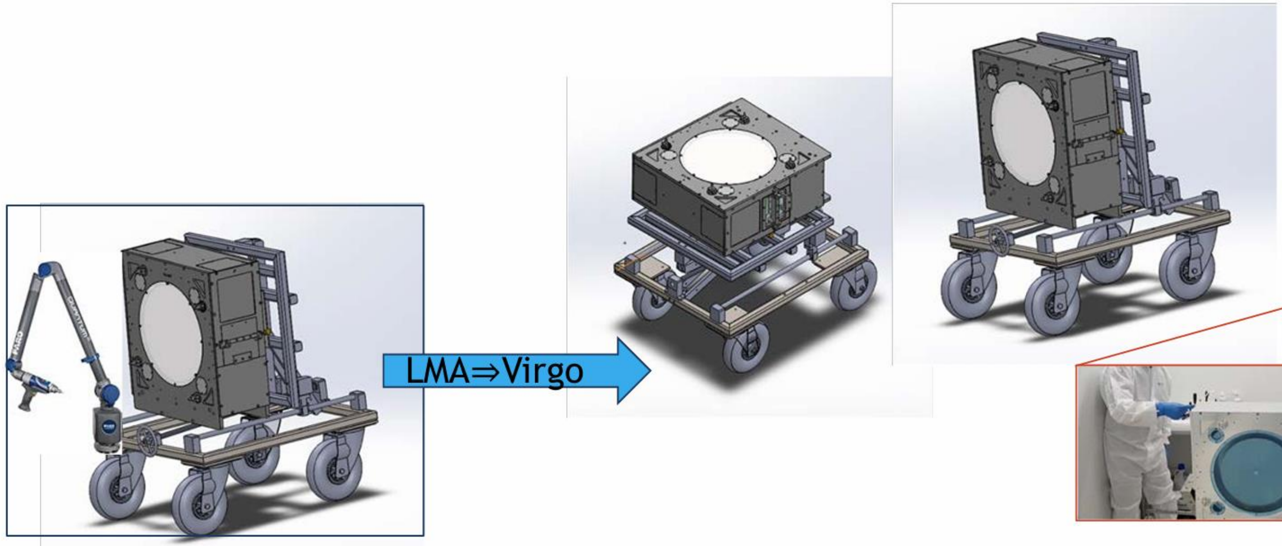
VIR-1034A-20

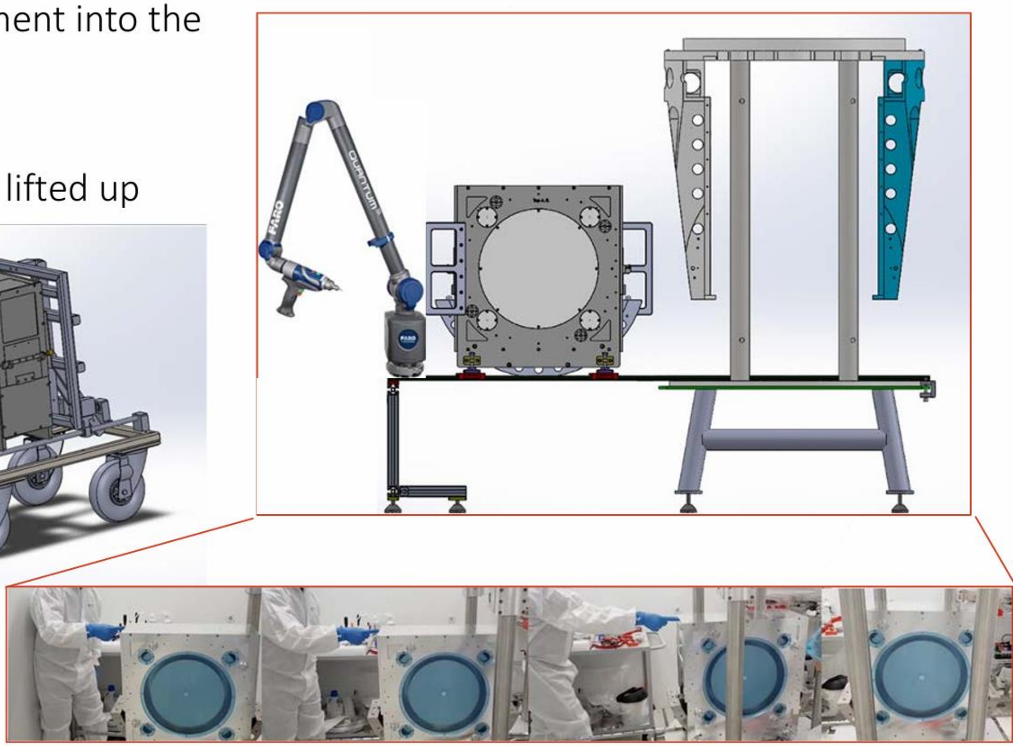
New ear - TN evaluation

Roughness	Bonding Thickness(nm)	Anchors Thermal $(m/Hz^{1/2})$	Ears Thermal $(m/Hz^{1/2})$	CTN $(m/Hz^{1/2})$	CTN/TotalBonding
$\lambda/10$	60	$2.067\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	10.6
$\lambda/8$	100	$2.314\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	10.3
$\lambda/6$	75	$2.648\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	9.9
$\lambda/4$	150	$3.213\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	9.2
$\lambda/2$	300	$4.478\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	7.8
$5\lambda/6$	500	$5.665\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	6.7
$5\lambda/3$	1000	$7.757\ 10^{-22}$	$3.85\ 10^{-22}$	$4.616\ 10^{-21}$	5.3

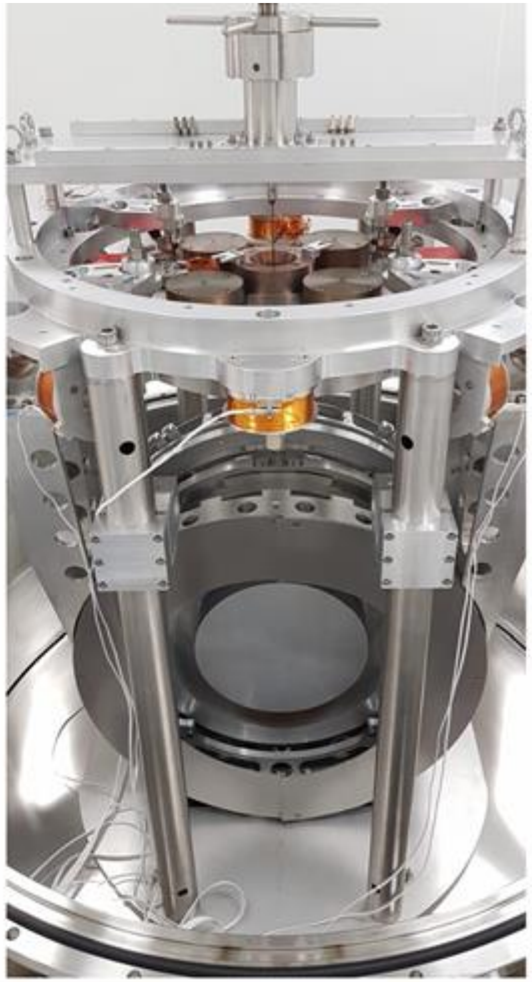
LM - Tools

- . The box (125 kg) is used in LMA as HCB jig and for transporting the mirror to Virgo, it embeds the bottom part of the cage (Ti)
- A trolley, is used to handle the orientation during HCB and deployment into the payload
- . The rails to insert the box
- . Once positioned into the cage (FARO arm), the mirror is accurately lifted up





Full size Dummy Susp.



- 2 months suspended (both mario and mirror) in air (short marionette wire)
- 2 months suspended in vacuum
- Equipped with OpLevs