Mirror Substrates for ET

State-of-the-art

Alex Amato

ET-France – Workshop

February 2021

What are we looking for ?

SIZE

Large optics
(Diameters up to 62 cm)

OPTICAL PROPERTIES

Absorption
Refractive index homogeneity
Crystal orientation
Birefringence
…

At the same time

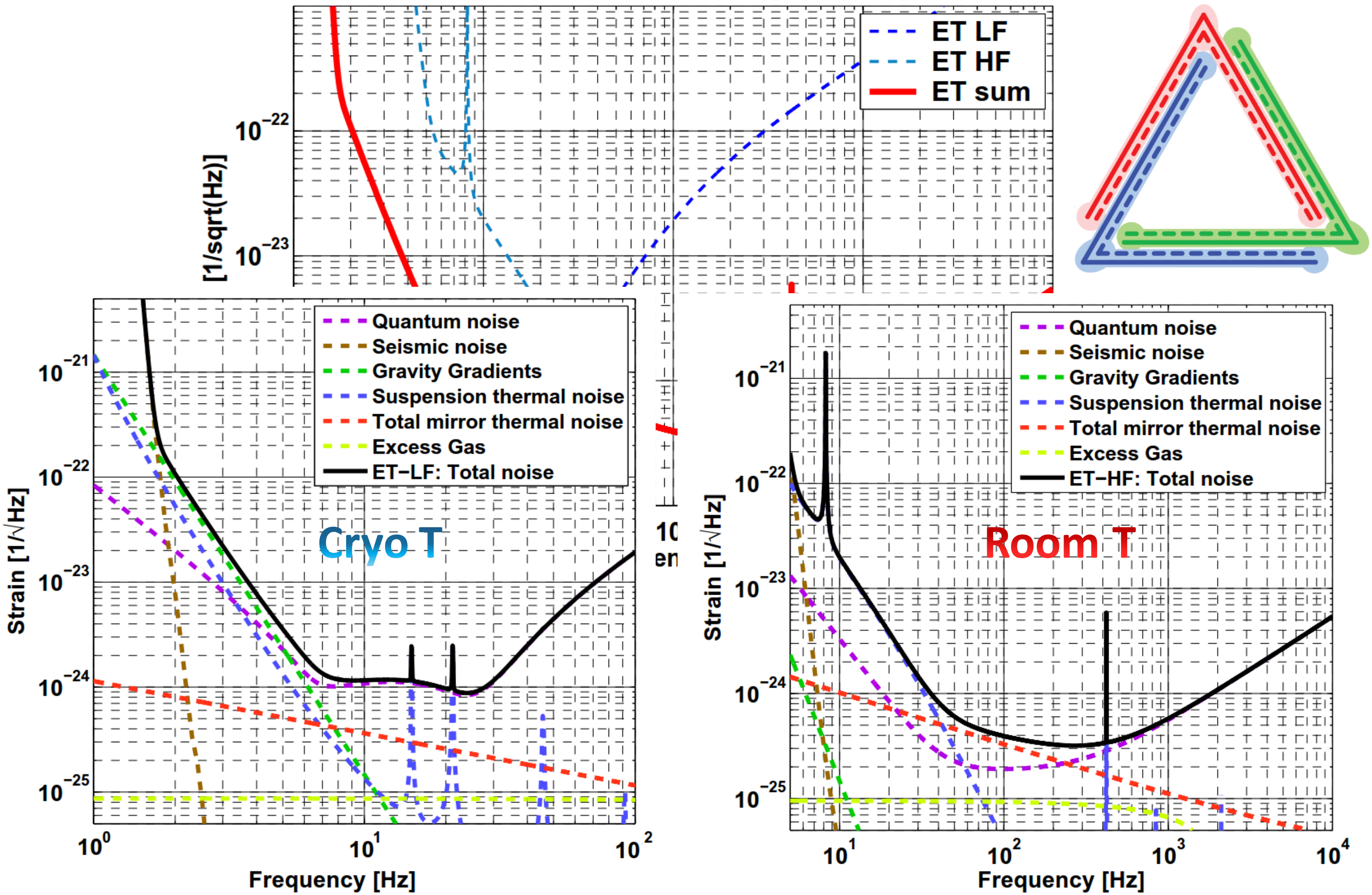
POLISHING

Geometry (Radius of Curvature)
Roughness
Flatness
Surface defects
…

MECHANICAL PROPERTIES

Mechanical loss
Stiffness
Thermal conductivity
…

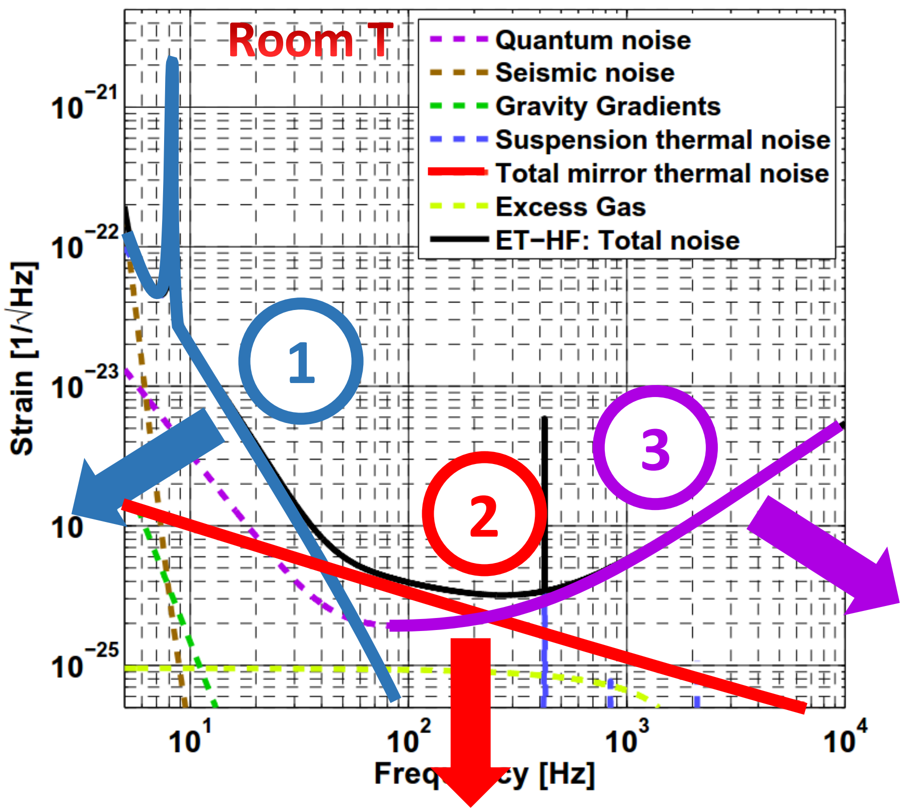
Introduction



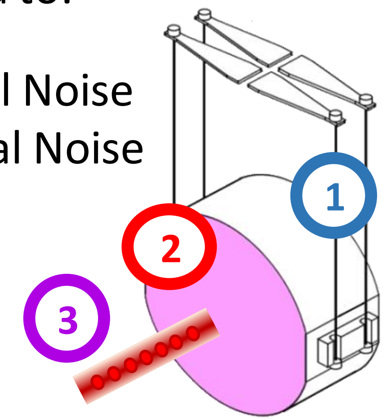
ET-HF

ET-HF: Total noise

The main problem in ET-HF noise budjet will be related to:



1. Suspension Thermal Noise
2. Total Mirror Thermal Noise
3. Shot Noise



Thermal Noise

$$S_{xx} = \frac{4k_BT}{\omega^2}\frac{\text{Dilution}}{\text{Stiffness}}\phi(f)$$

and $\phi(f) = \phi_{1kHz}\left(\frac{f}{1kHz}\right)^B$

Thermal Noise reduction comes from:

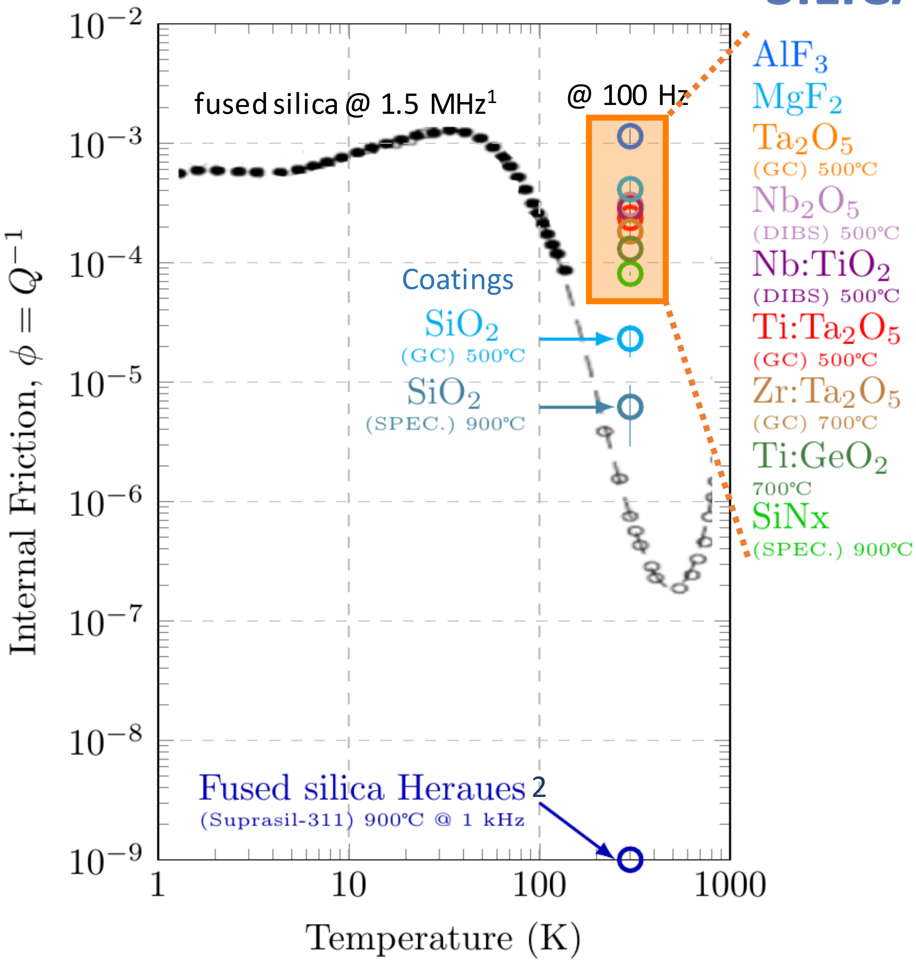
- Temperature
- Geometry (Beam size)
- Materials

The main contribution to the total mirror thermal noise will come from the coatings and not from the substrates ... lets see why

ET-HF Substrate

Room temperature technology will be similar to current advanced interferometric detectors (Virgo and LIGO), with operating laser wavelength at 1064 nm

SILICA



1) *Zeitschrift für Physik B Condensed Matter* **101**.2 (1996): 235-245
2) *Physics Letters A* **327**.4 (2004): 263-271.

At room temperature the loss angle of fused silica is much lower than all the investigated coatings.

A. Amato - Low Thermal Noise Coating for New Generation Gravitational-Wave Detectors. Material chemistry. Université de Lyon, 2019

See Sassolas' Presentation

Silica also exhibits other important qualities…

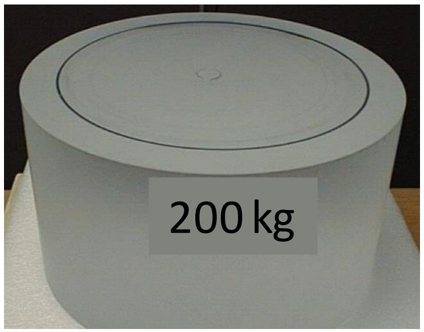
ET-HF Substrate

Room temperature technology will be similar to current advanced interferometric detectors (Virgo and LIGO), with operating laser wavelength at 1064 nm

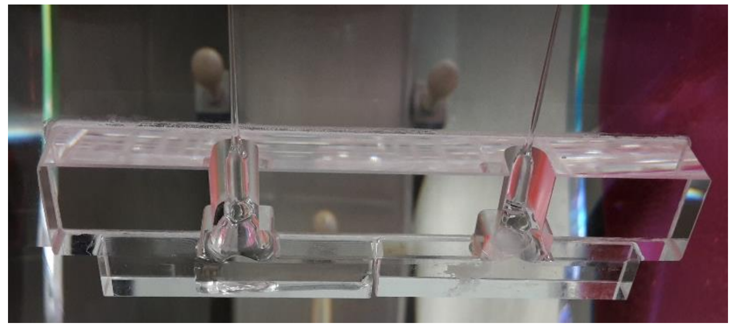
Will be:

SILICA

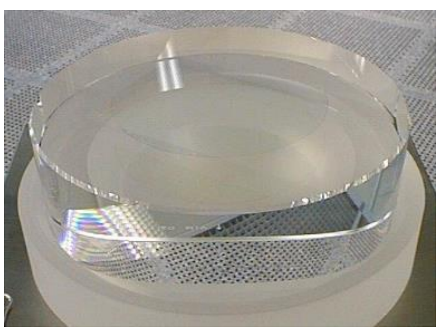
30 cm



62 cm



Techniques for quasi-monolithic fused silica suspensions using silicate bonding are already available



The polishing is “easy” and well mastered

Outstanding optical properties:

- Absorption below 1 ppm/cm
- High homogeneity of refractive index (2D and 3D)
- Low birefringence ~1 nm/cm
- Isotropic (good for beam splitter)

ET-HF Substrate

Room temperature technology will be similar to current advanced interferometric detectors (Virgo and LIGO), with operating laser wavelength at 1064 nm

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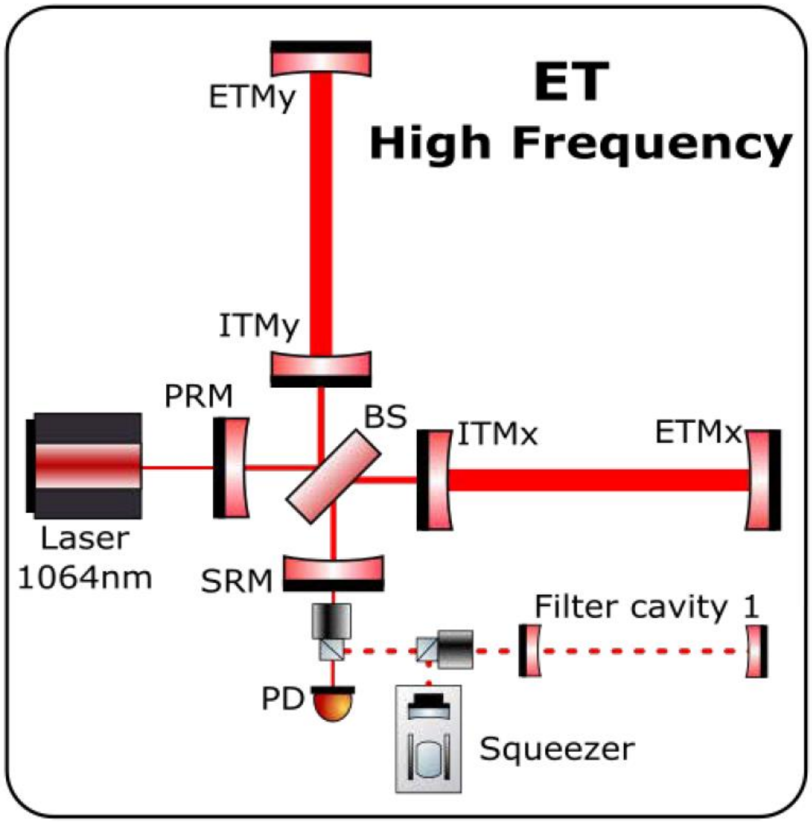


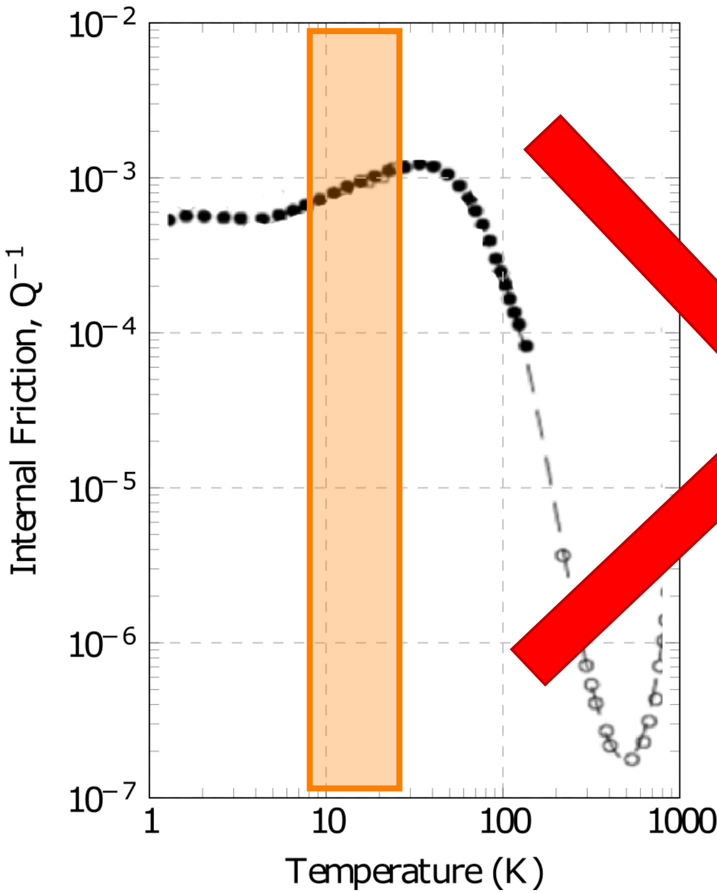
The substrates of all optical elements inside the high-frequency detectors will be made of fused silica

ET-LF

ET-LF Substrate

Low frequency detectors will operate at cryogenic temperature and the technology must be different to what is used in Virgo and LIGO

SILICA

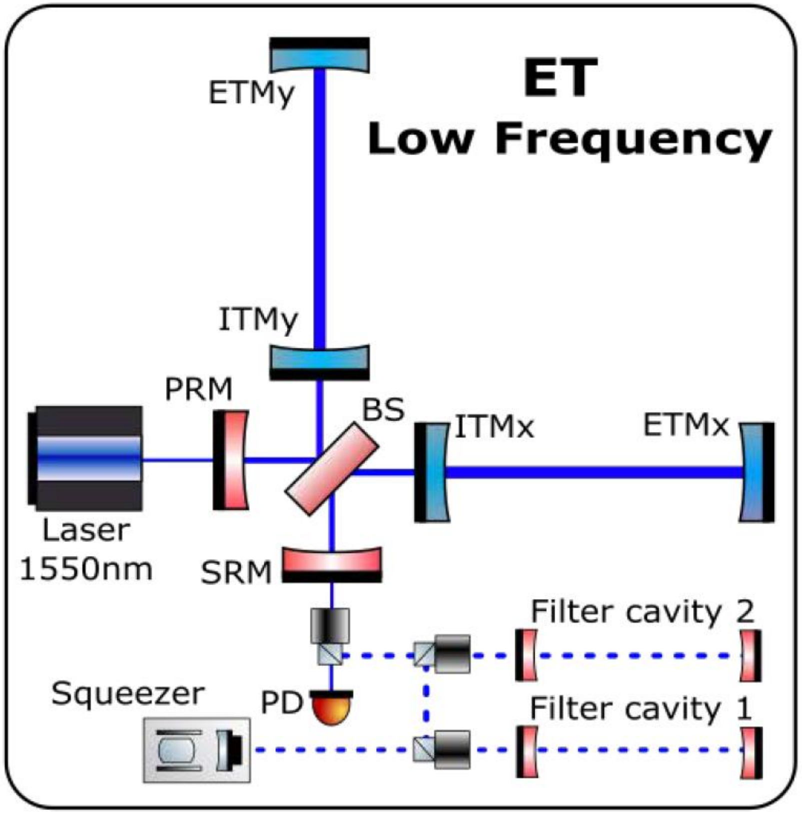


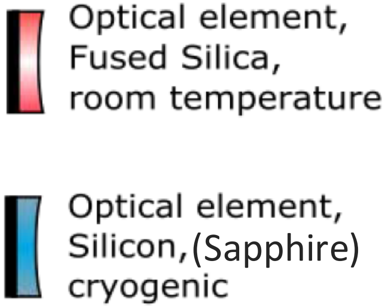
At cryogenic temperature the fused silica is no longer a good candidate because of its high mechanical loss angle

g-MAG Alex Amato

ET-LF Substrate

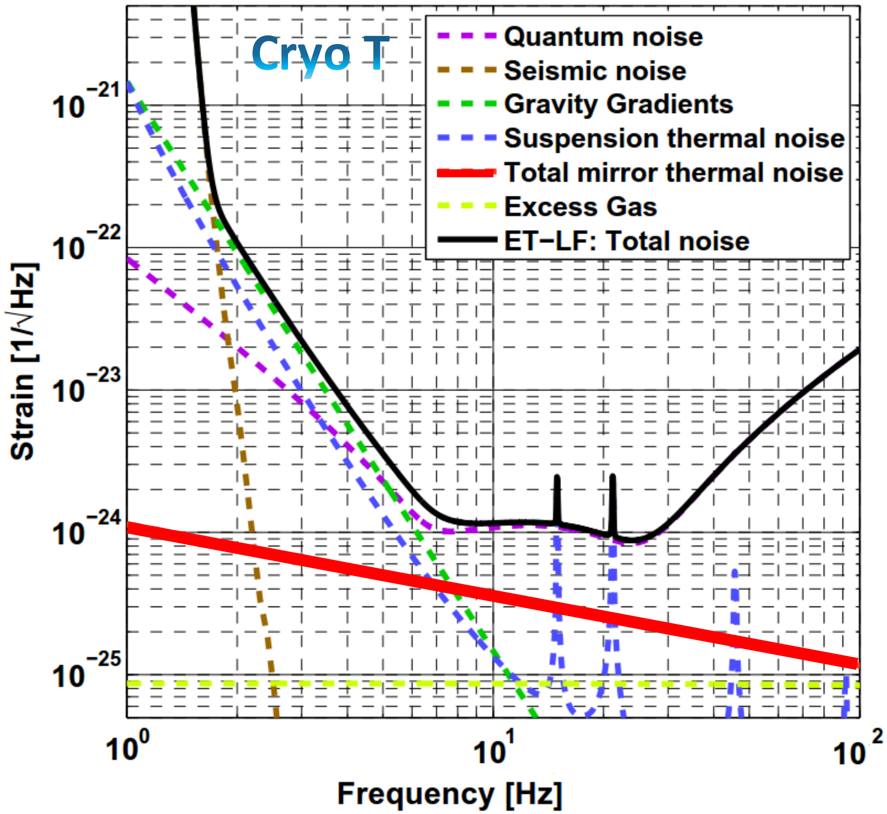
Low frequency detectors will operate at cryogenic temperature and the technology must be different to what is used in Virgo and LIGO





ET-LF: Total noise

Low frequency detectors will operate at cryogenic temperature and the technology must be different to what is used in Virgo and LIGO



Thanks to the cryogenic temperature the total mirror thermal noise will not be one of the main noise sources

However, requirements like optical absorption and refractive index homogeneity have a large impact on suspensions and optical performance of the detector

ET-LF Substrate

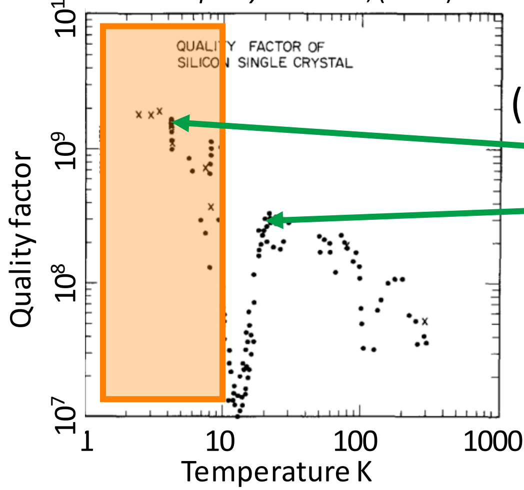
A game of pros and cons…

Best candidates so far

Silicon

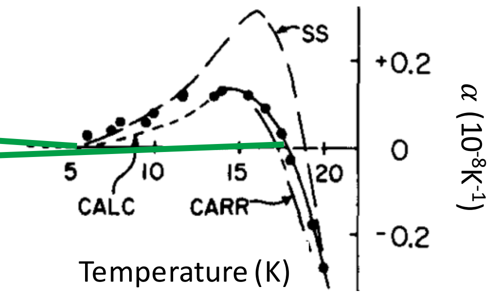
PROS

J Low Temp Phys **30** no. 5, (1978) 621–629.



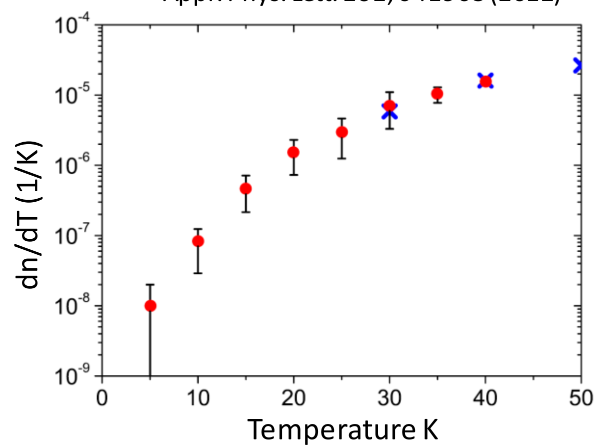
$$\phi_{Si} \sim 10^{-9}$$
$$(\phi_{SiO2} \sim 8 \cdot 10^{-4})$$

J. Appl. Phys. **48**, 865 (1977) 865–868



Coefficient of thermal expansion is zero at around 18 K (NO thermoelastic loss)

Appl. Phys. Lett. **101**, 041905 (2012)



The thermo-optic coefficient is useful for thermal lensing, thermo-refractive noise and birefringence

Class. Quantum Grav. **33** (2016) 015012

Thickness (mm)	Diameter (mm)	Mass (kg)	$\Delta n \times 10^{-7}$
65	100	1.2	0.23–1.07
28	24	0.059	1.08–1.11
30	24	0.063	0.33–0.49
99	24	0.21	0.09–0.17

All the substrates have the shape of cylinders with biconvex faces with the light propagating along the (111) direction.

Silicon

ET will use large beam size and low optical intensities so that nonlinear contributions to the absorption will be negligible. However, to keep the mirror at a low temperature, an absorption of a few ppm/cm is required in order not to generate excess heat.

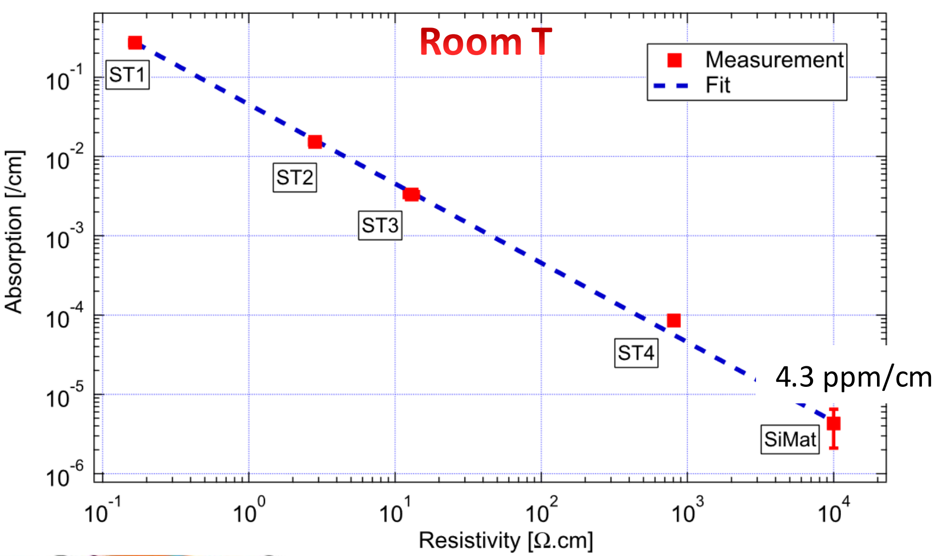
$\lambda_{1064} \rightarrow \lambda_{1550}$ or λ_{2000} in order to reduce the optical absorption

PROS → **CONS**

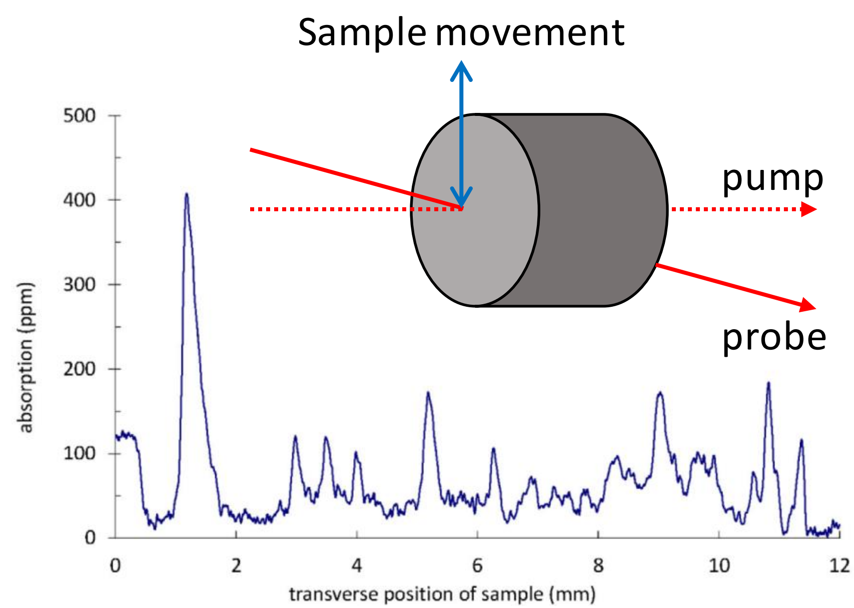
Opt. Lett. **38**, 2047-2049 (2013)

Table 1. Characteristics of the Silicon Samples Tested

Name	Resistivity [$\Omega \cdot$ cm]	Growth Technique	Orientation
ST1	0.167 ± 0.014	Czochralski	$\langle 110 \rangle$
ST2	2.84 ± 0.24	Czochralski	$\langle 100 \rangle$
ST3	13.0 ± 1.43	Czochralski	$\langle 111 \rangle$
ST4	808	Float zone	$\langle 111 \rangle$
SiMat	10,000	Float zone	$\langle 100 \rangle$



Class. Quantum Grav. **34** (2017) 205013



ET-LF Substrate

A game of pros and cons…

Silicon

PROS

- Large size available due to the large market of the semiconductor industry
- Coefficient of thermal expansion is zero at around 18 K (NO thermoelastic loss)
- $\phi_{Si} \sim 10^{-9}$ below 10 K ($\phi_{SiO2} \sim 8 \cdot 10^{-4}$)
- $\left.\frac{dn}{dT}\right|_{T=5K} = 10^{-8} K^{-1}$
- Low birefringence $\Delta n \sim 10^{-7}$

CONS

- High absorption ($\lambda_{1064} \rightarrow \lambda_{1550}$ or λ_{2000})

Bulk loss related to the amount of impurities

↓

Grown process

↓

Limited size

Surface loss

↓

Polishing ?

Class. Quantum Grav. **34** (2017) 205013

Silicon

The maximum diameter and purity depend on the fabrication process

Float Zone (FZ) technique

A crystalline silicon is remelted by inductive heating and the impurities are dissolved. By slowly sweeping the melt it is possible to obtain a purified re-crystallized material.
Carbon ($\sim 10^{-15}\, cm^3$) ; Oxygen ($\sim 10^{-16}\, cm^3$)

- Low absorption (5 ppm/cm)
- Small samples (Ø 20 cm)

(Limited by the inductive heating setup)

Czochralski (CZ) technique

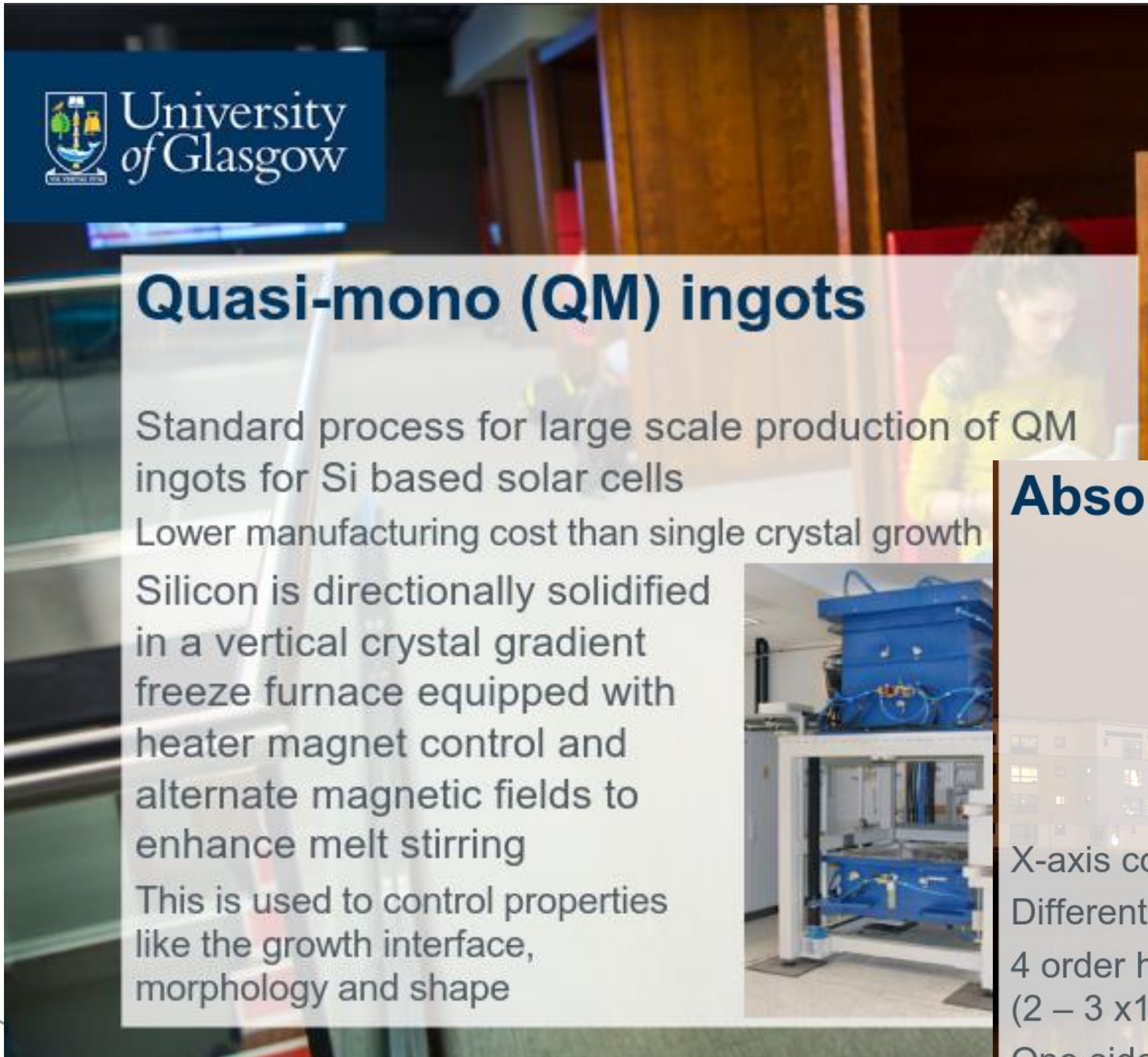
The ingot is grown from a silicon melt in a silica crucible, resulting in large samples.
Carbon ($\sim 10^{-18}\, cm^3$) ; Oxygen ($\sim 10^{-19}\, cm^3$)

- Large samples (Ø 45 cm)
- High absorption (20 ppm/cm for **mCZ**)

Magnetic Czochralski (mCZ) - grown in a magnetic field to keep impurities close to the edge of the boule… Size as large as CZ ?

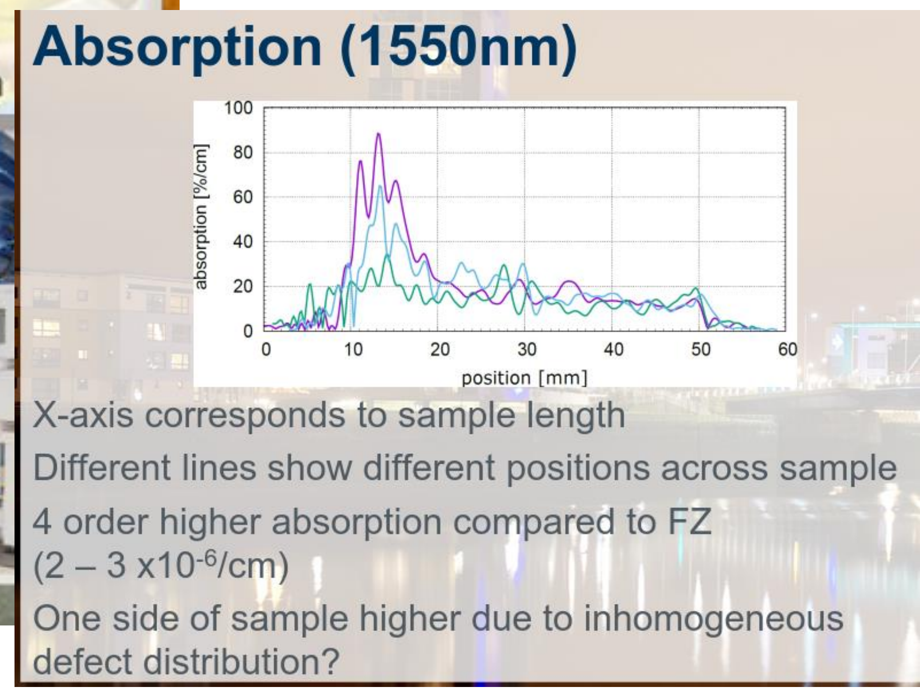
Silicon

The maximum diameter and purity depend on the fabrication process



To be considered…

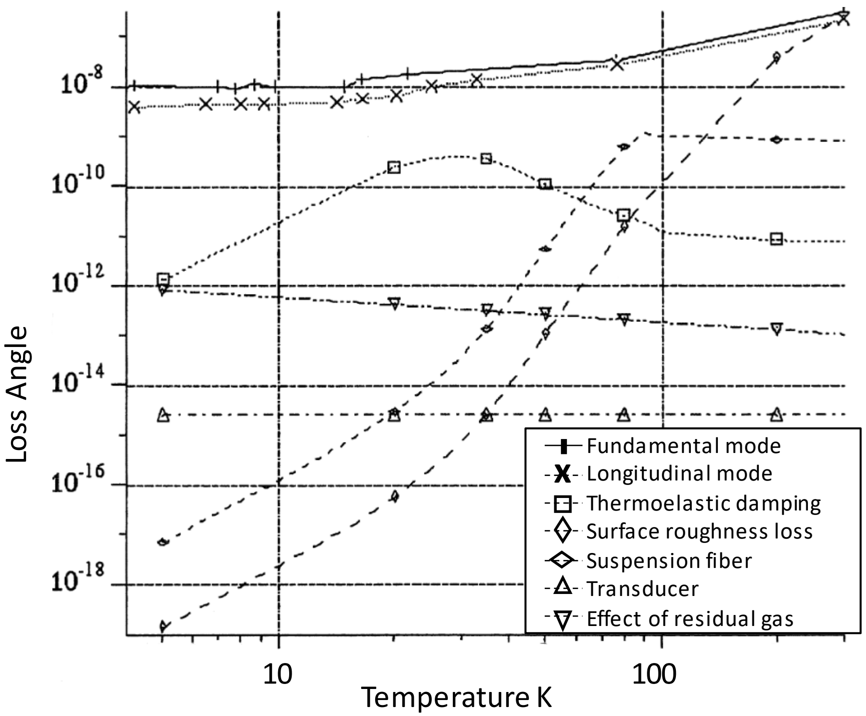
P. G. Murray – LVC Sept. 2020



Sapphire

PROS

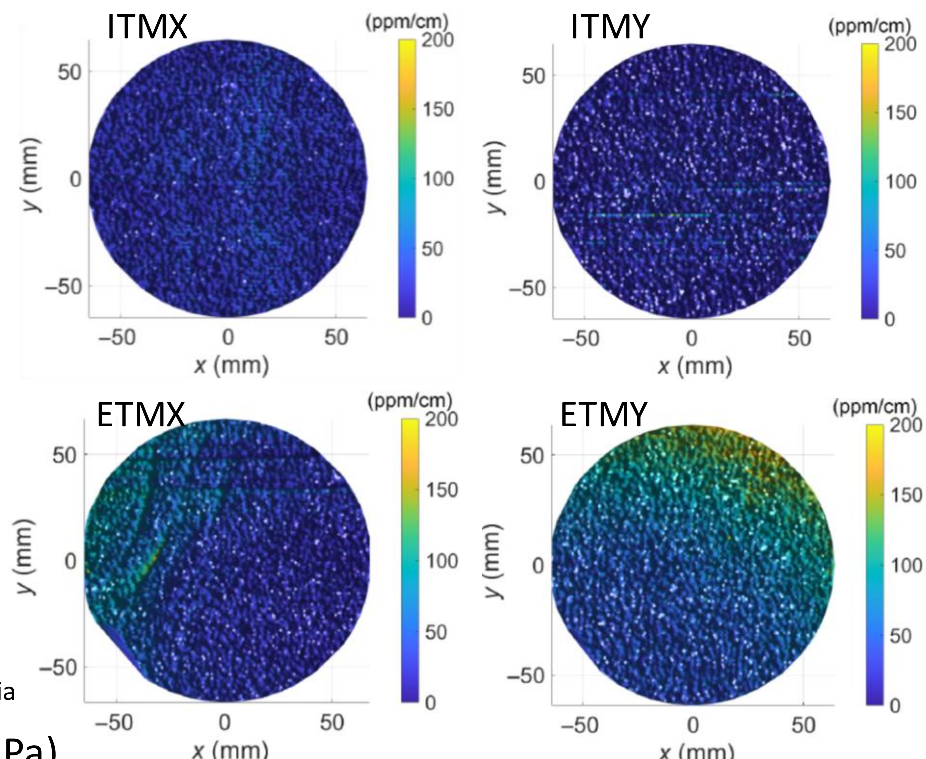
Physics Letters A **261**.1-2 (1999): 5-11



Sapphire is transparent @ 1064 nm

Absorption @ 1064 nm of KAGRA test-masses

Phys. Rev. Applied **14**,014021 (2020)



Dobrovinskaya, E. R., Lytvynov, L. A., & Pishchik, V. (2009). *Sapphire: material, manufacturing, applications*. Springer Science & Business Media

- Young's modulus = 450 – 490 Gpa (Y_{Si} = 162 GPa)
  Good for CTN
- Density = 3,97 – 3,99 g/cm^3 (ρ_{Si} = 2,33 g/cm^3)
  Good for pendulum noise

Values @1064 nm → @1550 nm even better ?

Sapphire

CONS

Hardness

Second hardest material in the world:
Could it be a problem for polishing ?

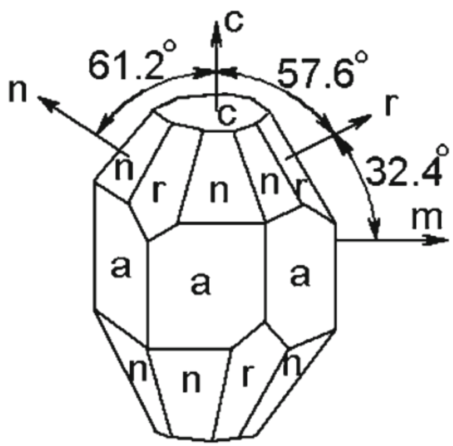
(Technique for polishing already existing)

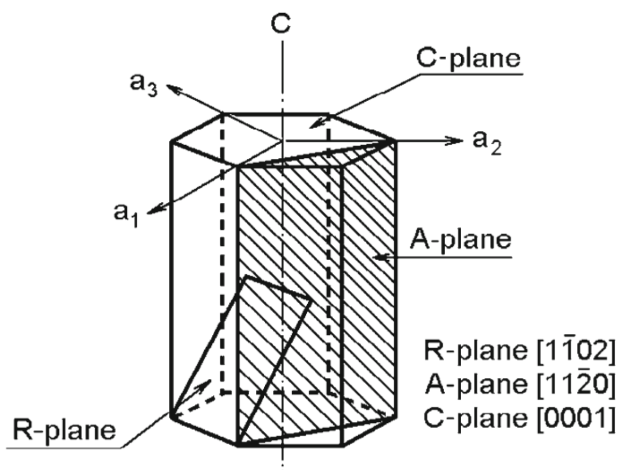
?

PROS

Birefringence

Sapphire is a birefringent crystal but the index of refraction on the plane (the c plane), perpendicular to the c axis, would be uniform if the crystal were perfect.





In the presence of axis distortions, there may be undesirable effects for ITMs

ET-LF Substrate

A game of pros and cons…

Sapphire

PROS

- Already tested for GWD (KAGRA)
  (as good as for SiO2 but more expensive)
- $\phi_{Sapphire} \sim 10^{-9}$ below 10 K
- Transparent @ 1064 nm
- High Young's modulus, $Y = 450 - 490$ Gpa
  (Good for CTN and Parametric Instability)
- High density $\rho = 3{,}97 - 3{,}99$ g/cm^3
  (Good for pendulum noise)

CONS

- Second hardest material in the world
  (Polishing expensive)
- Birefringence.

A precise control of the homogeneity is needed

(Bad for ITM)

ET-LF Substrate and other work packages

The importance of communication

Coatings

Coating Thermal Noise (CTN)

$$S_{xx} = \frac{2k_BT}{\pi^{3/2}wf}\frac{(1-\sigma_s^2)}{Y_s}\phi_c$$

$$\phi_c \propto \left(\frac{Y_c}{Y_s} + \frac{Y_s}{Y_c}\right)$$

The higher Y_s the lower CTN

$Y_{\text{sapphire}} = 450 - 490$ Gpa
$Y_{\text{silicon}} = 130 - 180$ Gpa

Suspensions

Pendulum Thermal Noise

$$S_{xx} = \frac{4k_BT}{\omega}H(\omega)$$

$$H(\omega) \propto \frac{1}{m}$$

The higher m the lower the noise

$\rho_{\text{sapphire}} = 3{,}97 - 3{,}99$ g/cm^3
$\rho_{\text{silicon}} = 2{,}33$ g/cm^3

Bonding, thermal conductivity, … ?

Projects for GWD substrates in France

Project for GWD substrates in France

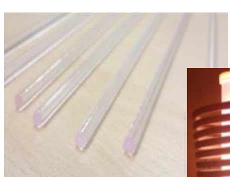
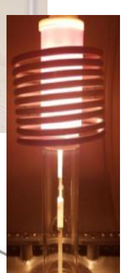
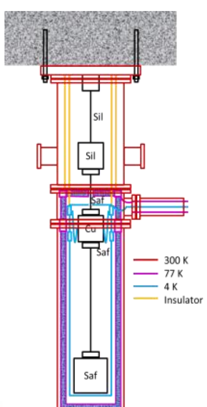
OSAG

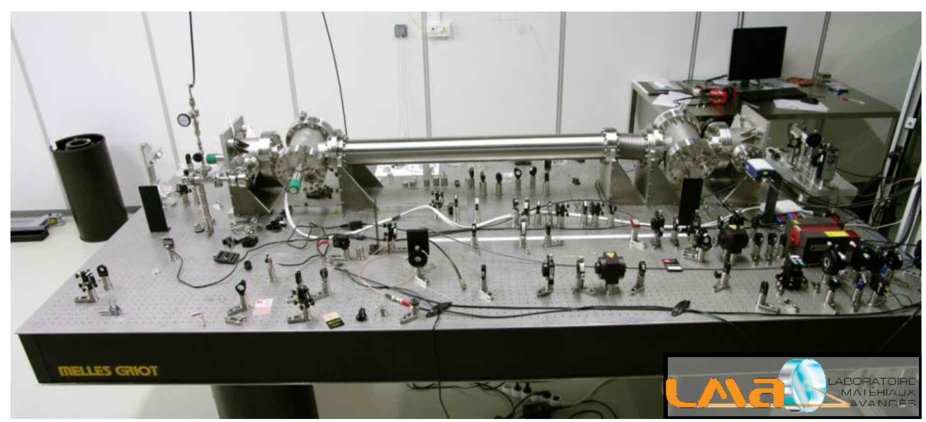
Optiques en **S**aphir pour l'**A**stronomie **G**ravitationnelle

The OSAG collaboration in Lyon

- PI: Gianpietro Cagnoli
- Expert on sapphire growth (K. Lebbou)
- Development of the large oven
- Structural and chemical analysis
- Fibre production and testing

- Responsible: Jerome Degallaix
- Optical characterization on large size
- Development of a test bench for low optical loss cavities

Project for GWD substrates in France

OSAG

Optiques en **S**aphir pour l'**A**stronomie **G**ravitationnelle

Objectives

- To make monocrystalline sapphire mirrors 45 cm in diameter and 20 cm thick without defects and extremely low absorption (< 10 ppm/cm) with birefringence under control
- To improve sapphire fibres

Impact

- OSAG wants to demonstrate that sapphire is a valid solution for future detectors

Conclusions and Remarks

- ET-HF will use silica substrates for all the optics.

- ET-LF will use silica for all the optics except for mirror substrates

- The best candidates so far are Silicon and Sapphire.
  - Silicon: the main problem is absorption in large samples
  - Sapphire: the main problem is large-samples production with birefringence control

For both candidates the problem is the production of high-quality large samples
Are we willing to wait until industries decide that large-optics technology is worth investing in ?

If you are working on substrate materials and you want to participate in future discussions, feel free to contact me