University of Glasgow

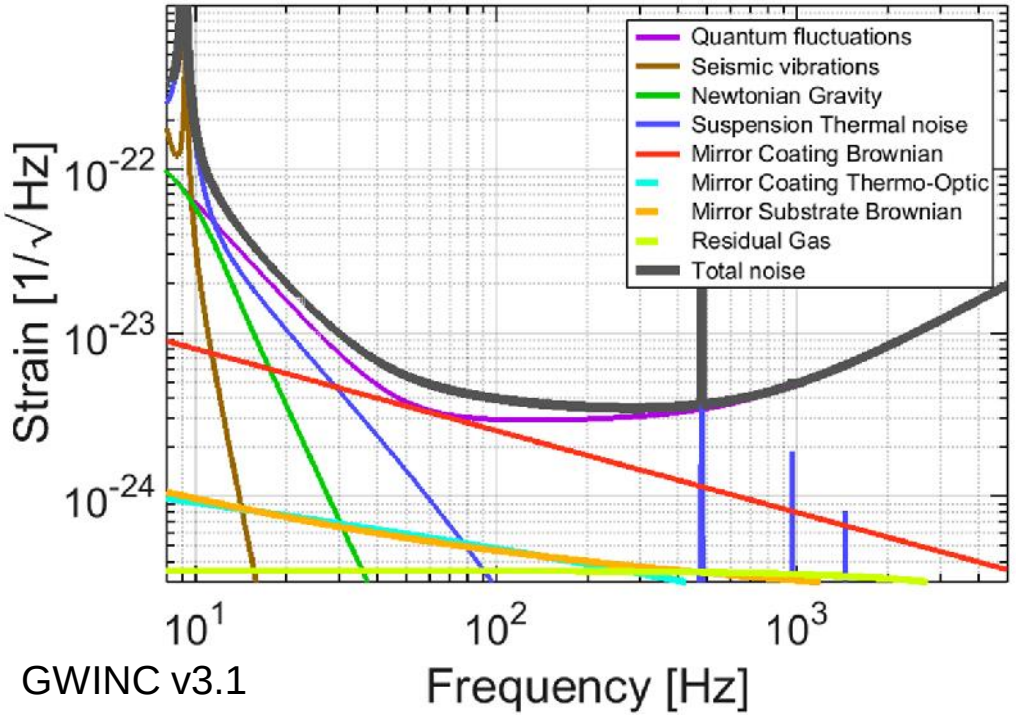
Cryogenic suspensions for future gravitational wave detectors

Mariëlle van Veggel

on behalf of IGR, University of Glasgow

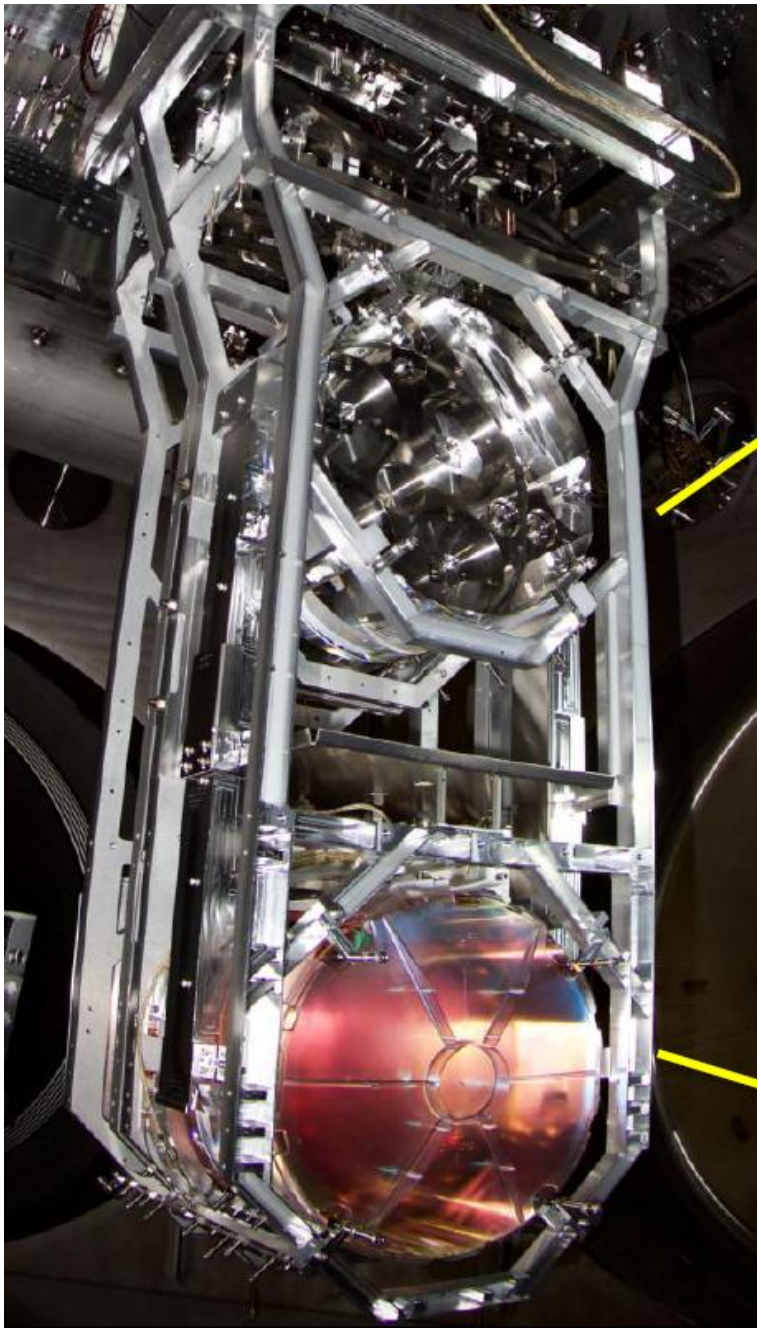
Suspension system functions

- **Support the optics to minimise the effects of**
  - thermal noise in the suspension
  - seismic noise

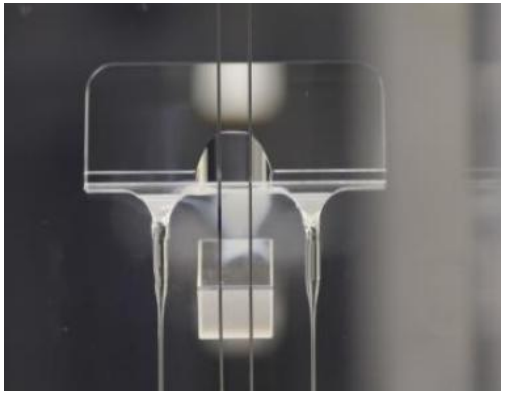


- **Provide damping of low frequency suspension resonances (local control)**
- **Provide means to maintain interferometer arm lengths (global control) while at same time**
  - Not compromise low thermal noise of mirror
  - Not (re)introduce noise through control loops
- **Provide interface with seismic isolation system and core optics system**
- **Support optic so that it is constrained against damage from large motions**
- **Accommodate a thermal compensation scheme**

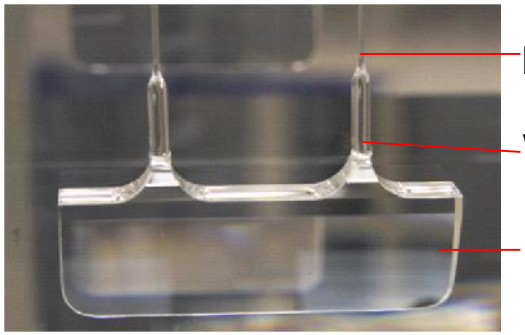
aLIGO test mass suspension

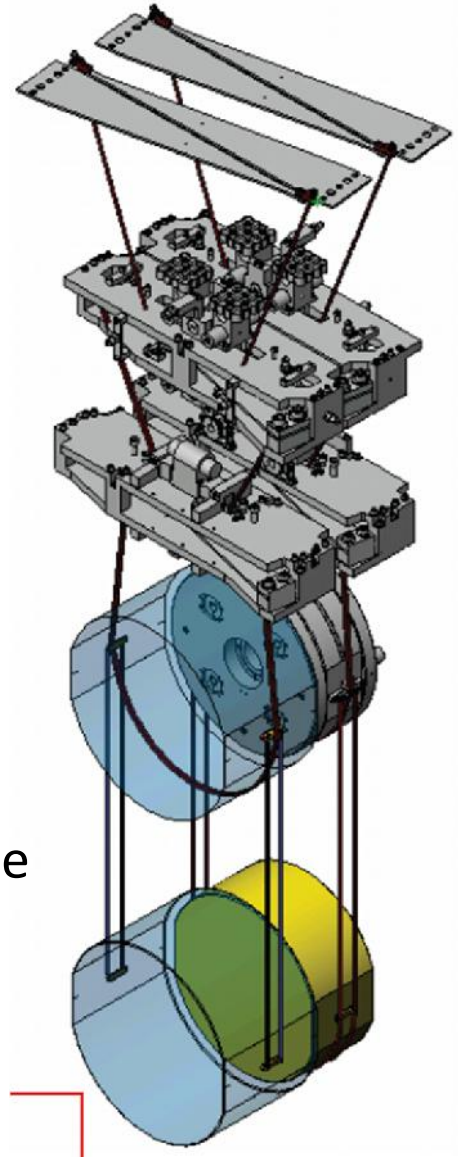


Source: G1600324



- Steel upper stages
- Fused silica middle stage
- Fused silica optics last stage.
- Fused silica fiber suspension.
- Strong chemical bonds and welds create quasi-monolithic assemblies. (i.e from two pieces of glass you get one)

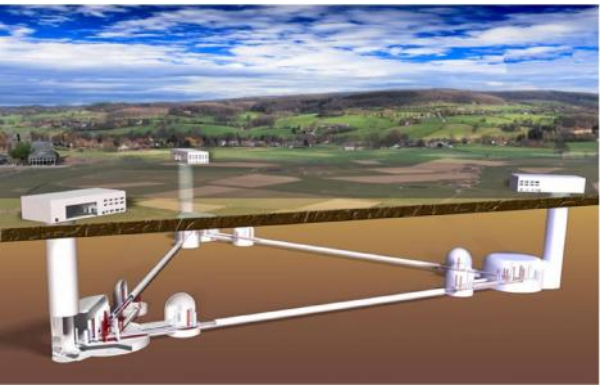


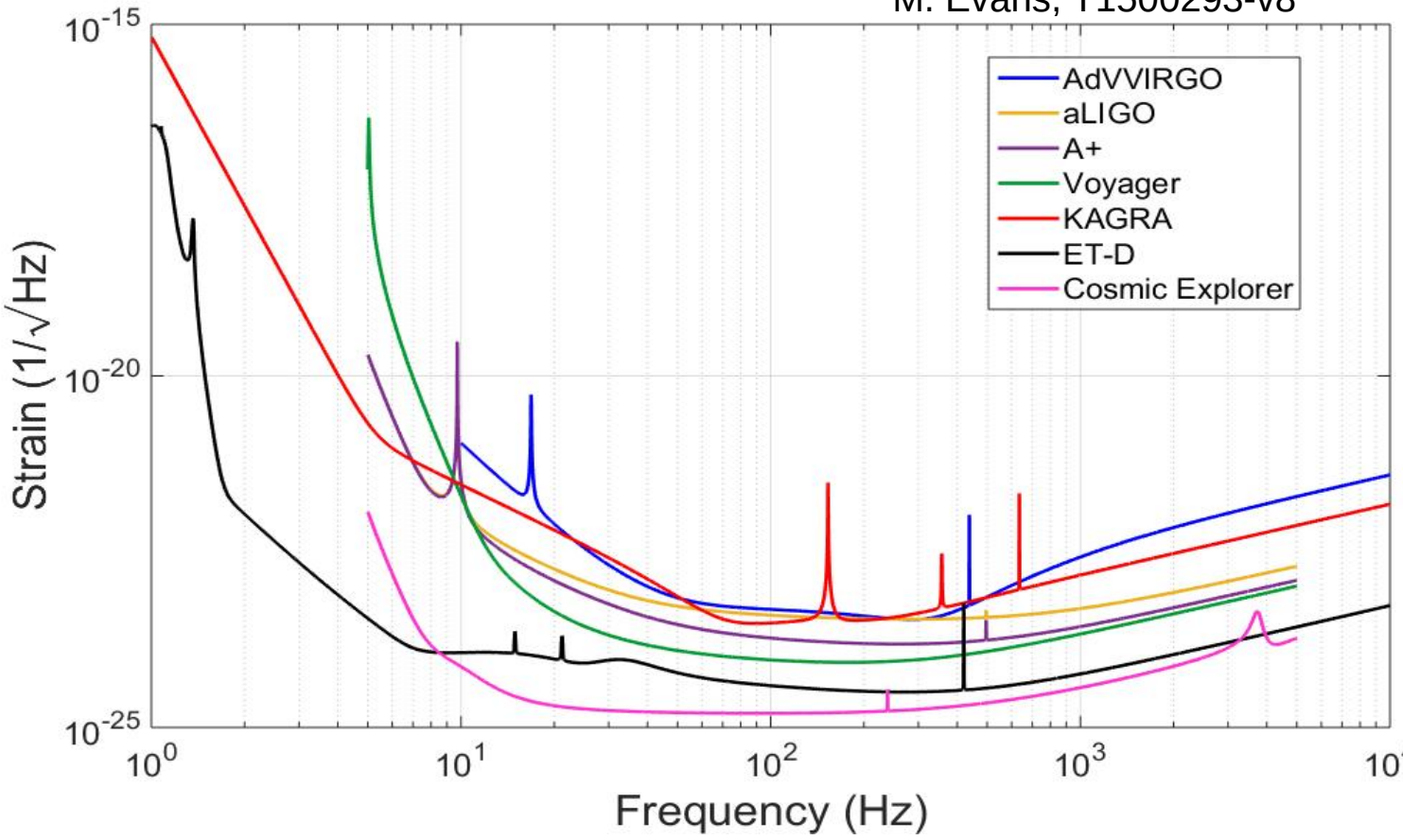


The future

- **Room temperature detectors with heavier and longer suspensions**
  -> A+, ET-HF, Cosmic Explorer
- **Cryogenic detectors with heavier and longer suspensions**
  -> Voyager, ET-LF, Cosmic Explorer

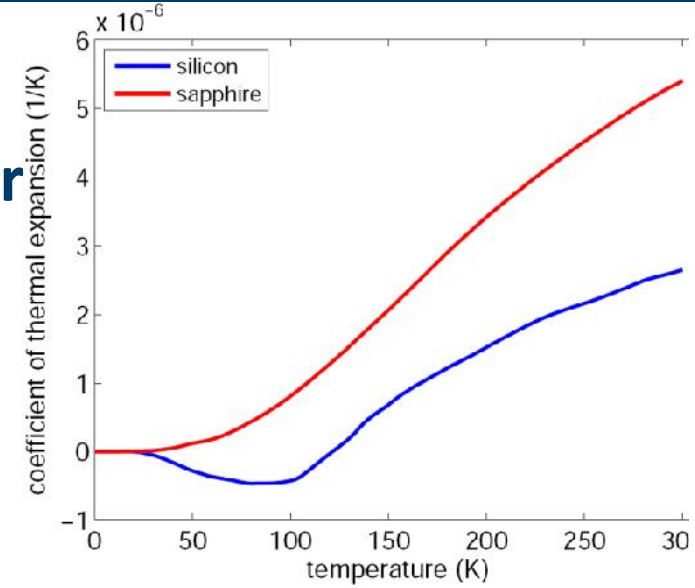
M. Evans, T1500293-v8



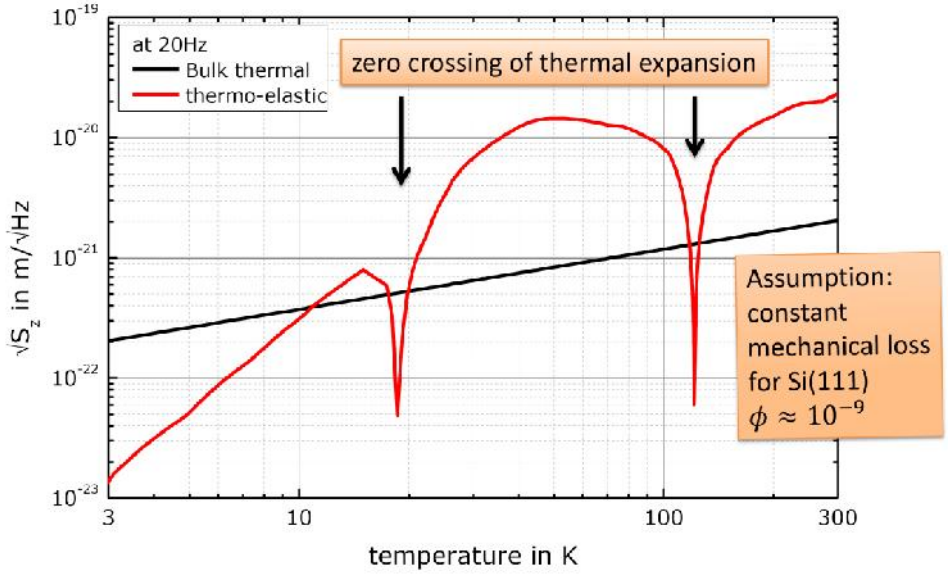


Silica, silicon, sapphire

- **Additional requirements for cryogenic suspensions**
  - High thermal conductivity (to dissipate laser heat)
  - Low thermal expansion (minimise thermo-elastic)
  - Low loss
- **Silicon and sapphire are top candidates**

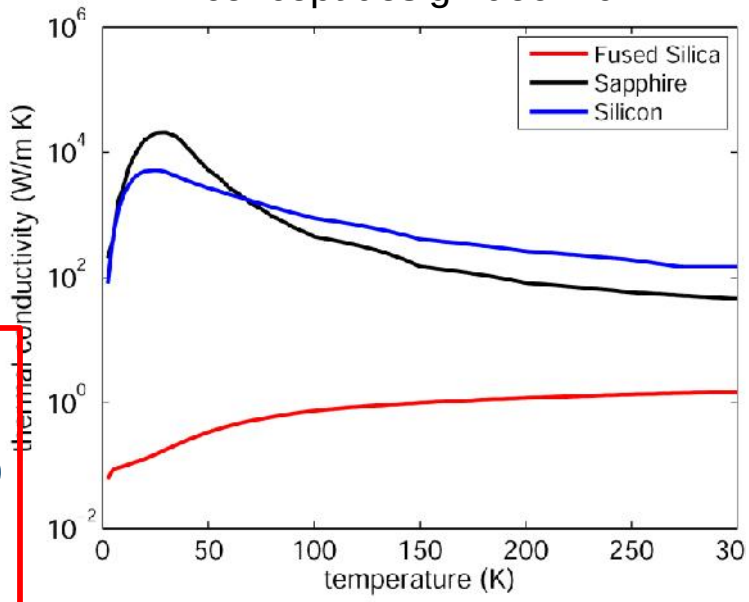


ET concept design doc. 2011

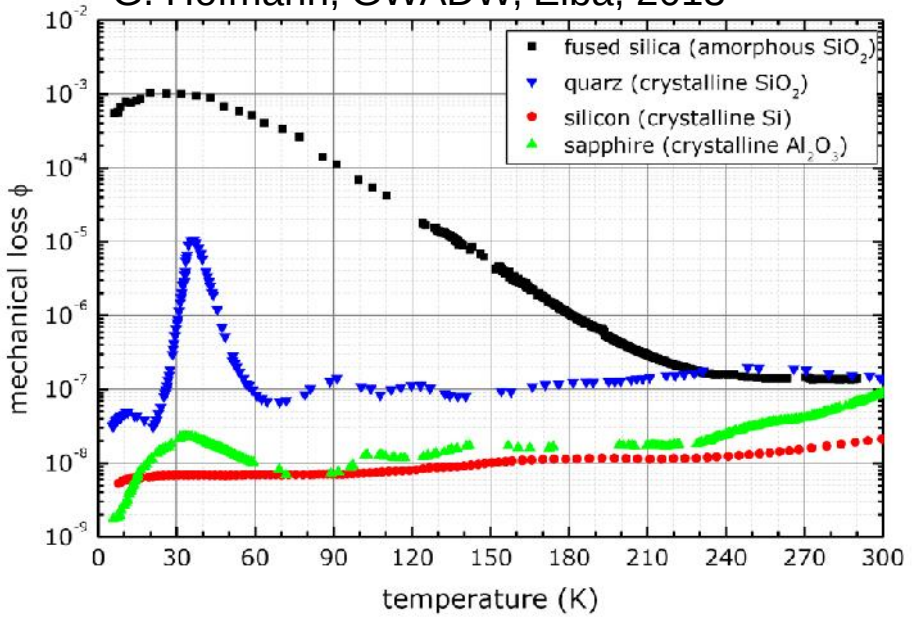


G. Hofmann, GWADW, Elba, 2013

ET concept design doc. 2011



G. Hofmann, GWADW, Elba, 2013

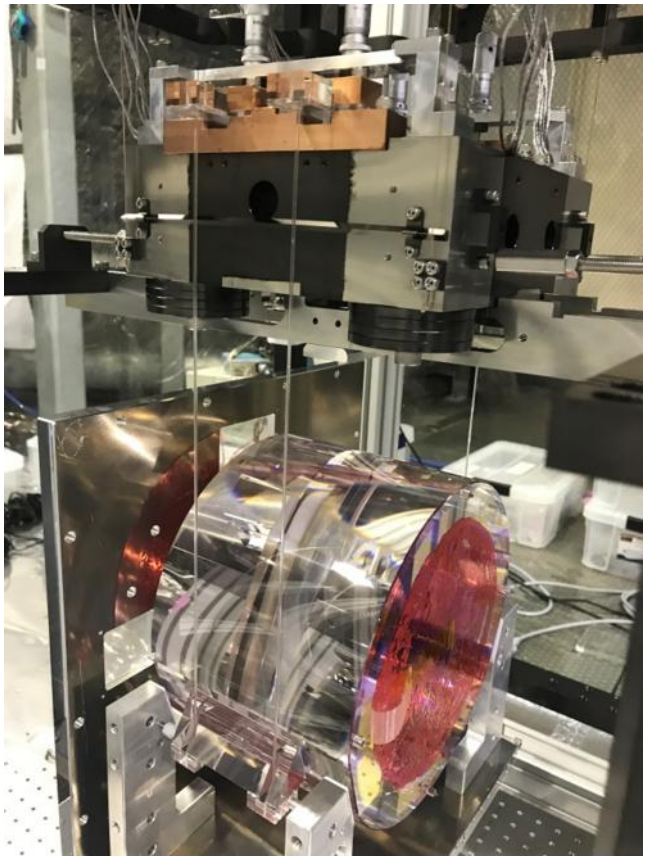


Cryogenic crystalline suspension designs

KAGRA sapphire suspension

NOT A CONCEPT: REAL

Courtesy of Rahul Kumar



23 kg @ 20 K

See talk on 12 May, KAGRA: Status and near term plans
Kiwamu Izumi (ISAS) Yutaro Enomoto (U-Tokyo)
LIGO-P1800131-v1

Voyager silicon suspension

A CONCEPT

See talk 13 May, Rana Adhikari
LIGO-G1800986-v1

~200 kg @ 123 K with 2 µm laser in LIGO 4 km facilities

ET-LF silicon suspension

A CONCEPT

See talk 13 May, Harald Lück,
LIGO-G1800984-v1

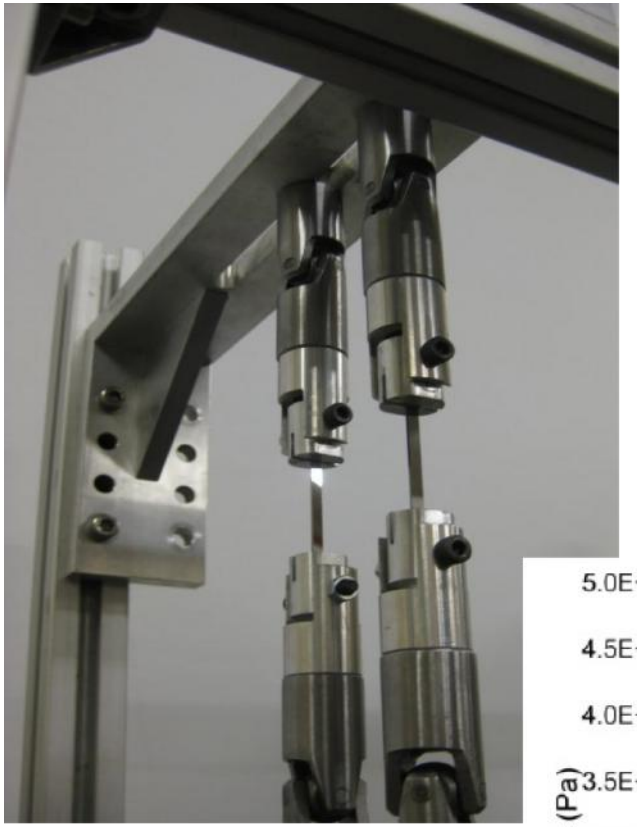
~200 kg @ 10 K with 1.55 or 2 µm laser in triangular 3-in-1 10 km arm length, xylophone facility

Few pictures of quasi-monolithic silicon suspensions exist. Focus has been on feasibility and technology development studies for different elements of a suspension.

Cryogenic crystalline suspension elements

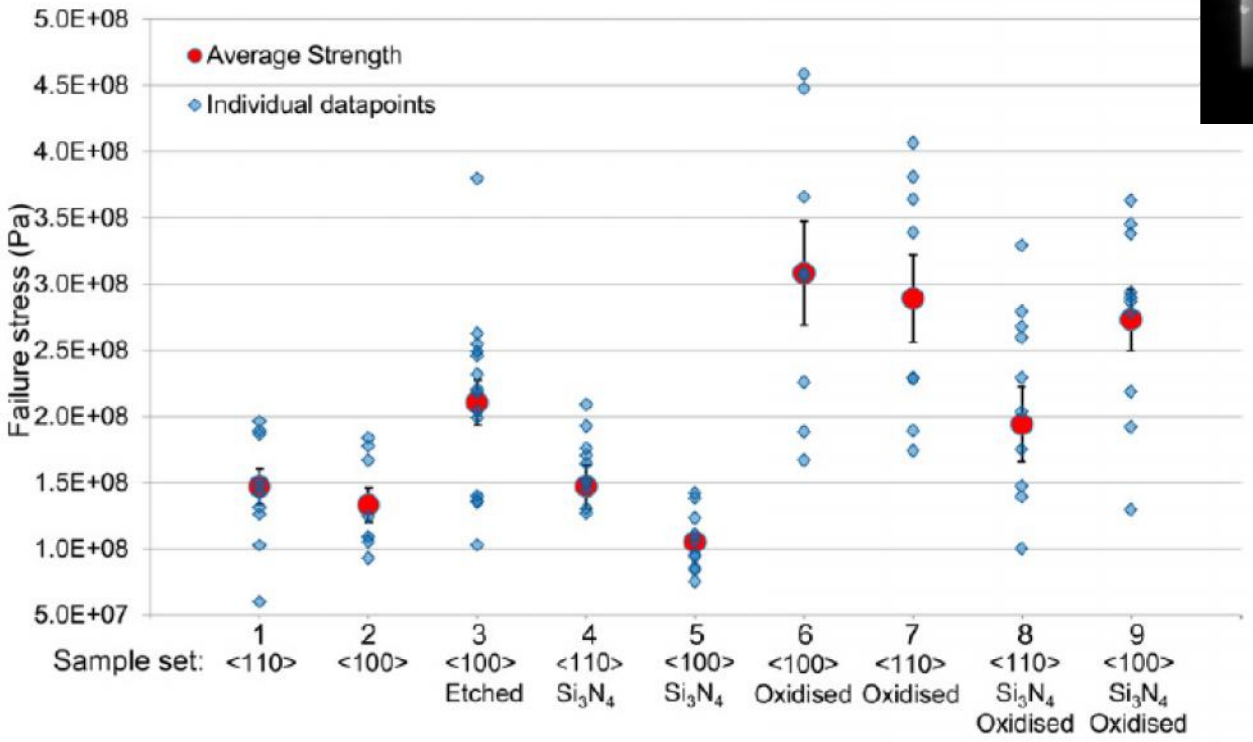
- **How can big enough test masses with the right opto-mechanical properties be produced?**
  - See core optics for 3G detectors talk by Iain Martin (LIGO-G1801018)
- **How best to produce silicon (or sapphire) suspension fibres?**
  - Etching from wafer
  - Machining
  - Crystal growth techniques (e.g. micro-pulling technique and laser heated pedestal growth)
- **Jointing techniques**
  - Welding
  - Hydroxide catalysis bonding
  - Indium/gallium bonding

Silicon and sapphire fibre production and performance research in Glasgow

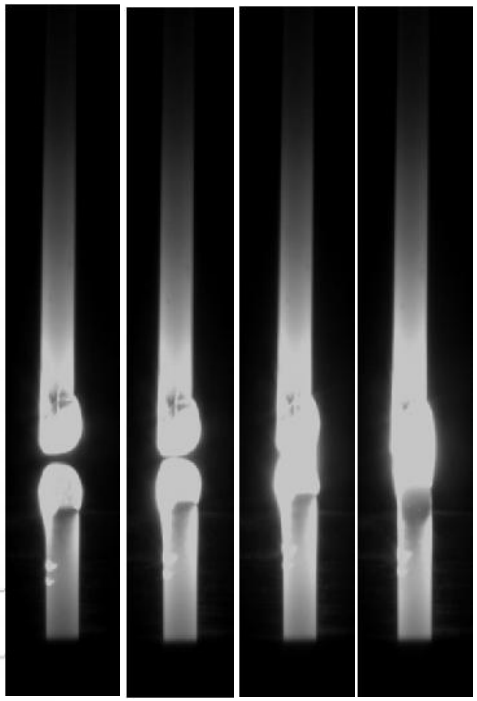


Strength tests on silicon ribbons etched from a wafer

Cumming et al.,
Class. Quantum Grav. **31** (2014) 025017 (16pp)

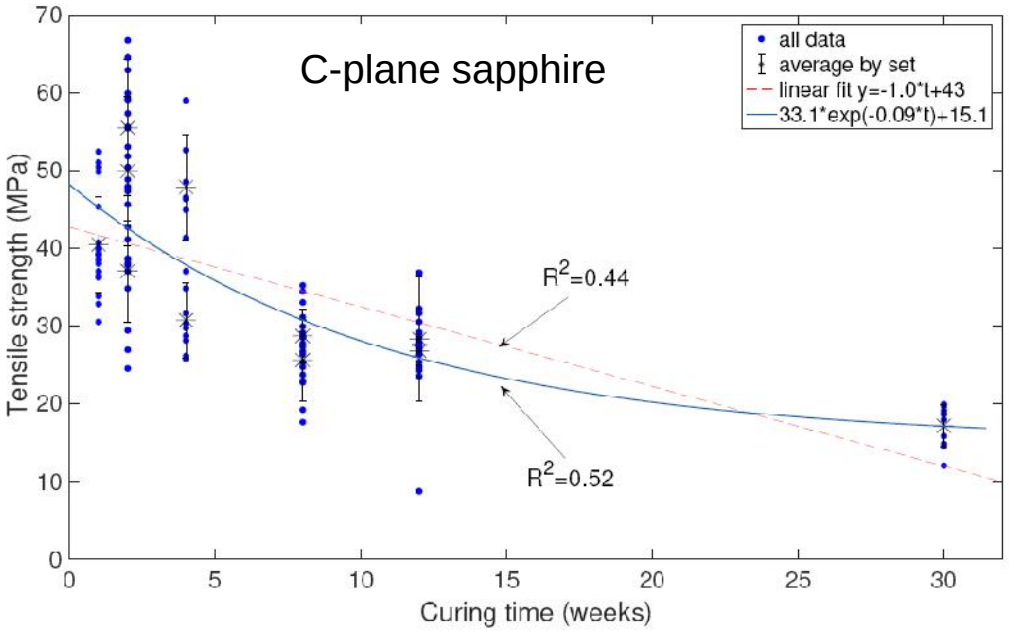


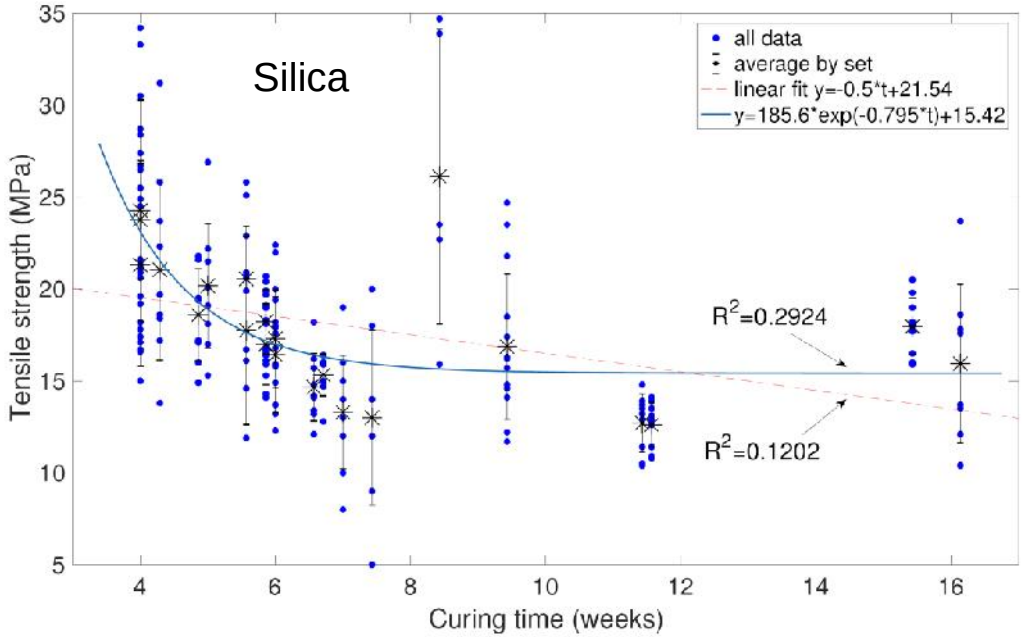
First steps to sapphire fibres with laser heated pedestal growth



Hydroxide catalysis bonding of silicon and sapphire - strength

Tensile strength (4-point bending) of sapphire-sapphire and silica-silica HCBs with curing time (in air)

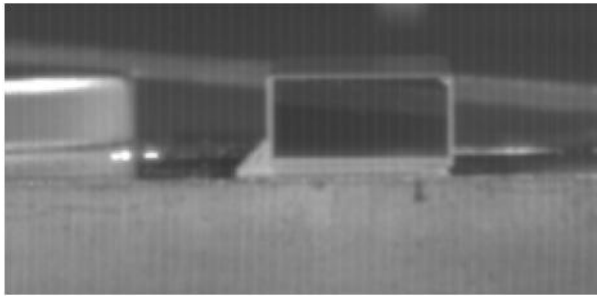




PhD work Rebecca Douglas and Margot Phelps – manuscript in preparation

Similar curing time experiments with silicon-silicon bonds are ongoing.

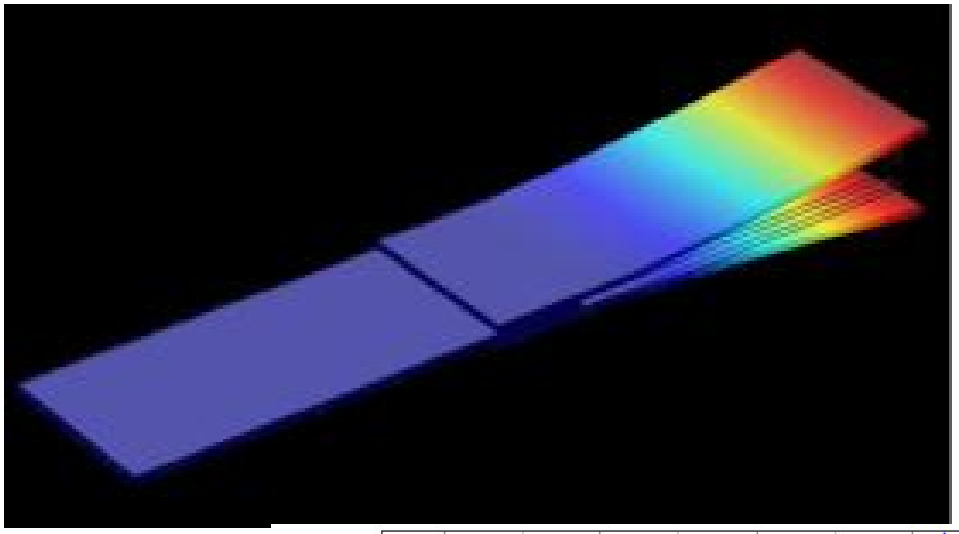
PhD work Mariela Masso Reid



Thermal image through silicon sample to assess bond quality

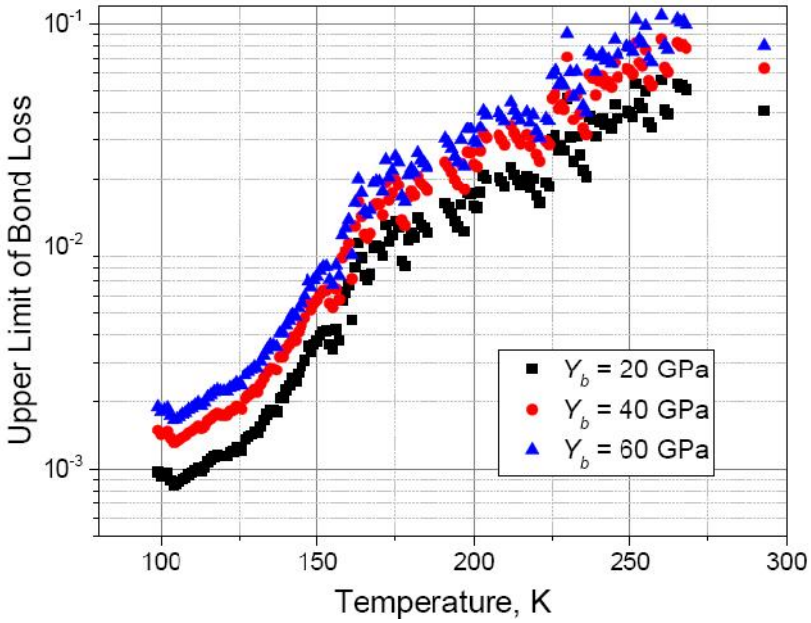
Silicon halves after bond strength test.

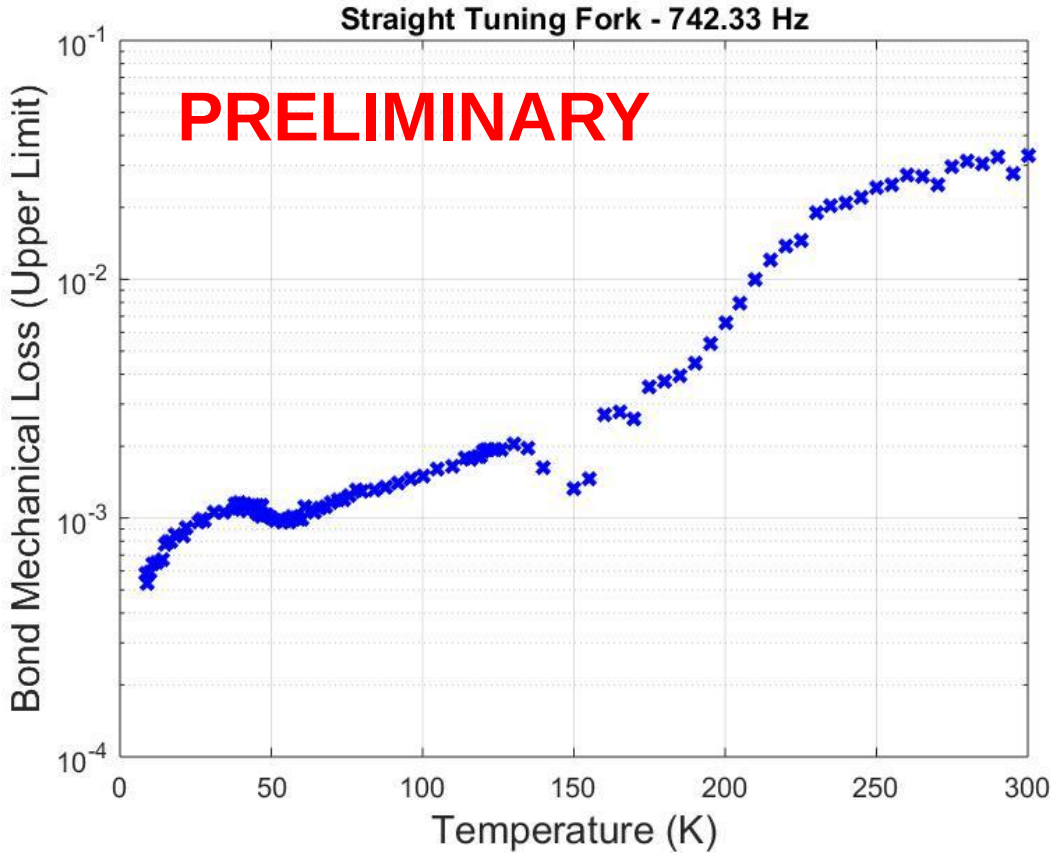
Hydroxide catalysis bonding of silicon and sapphire – mechanical loss



Mechanical loss of silicon-silicon HCBs In tuning fork design

Prokhorov et al., Phys. Lett. A, 2017



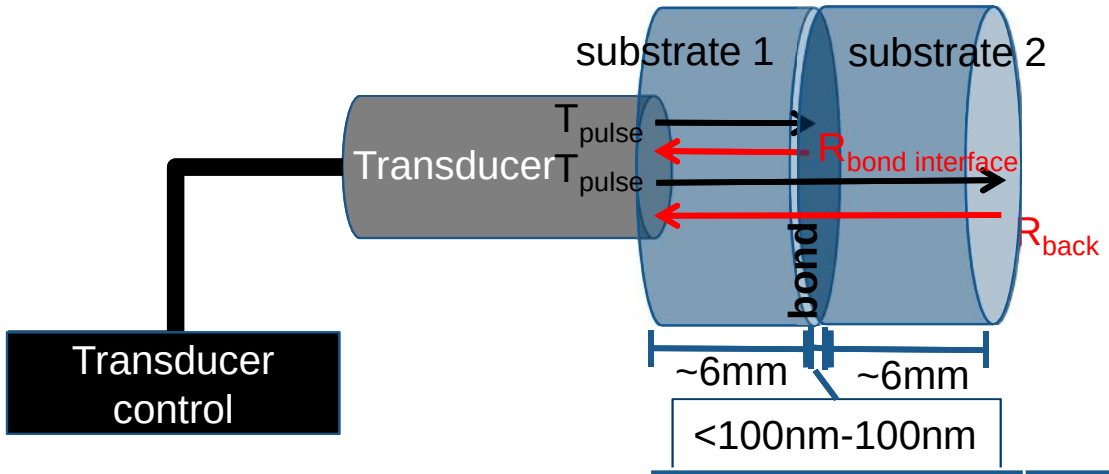


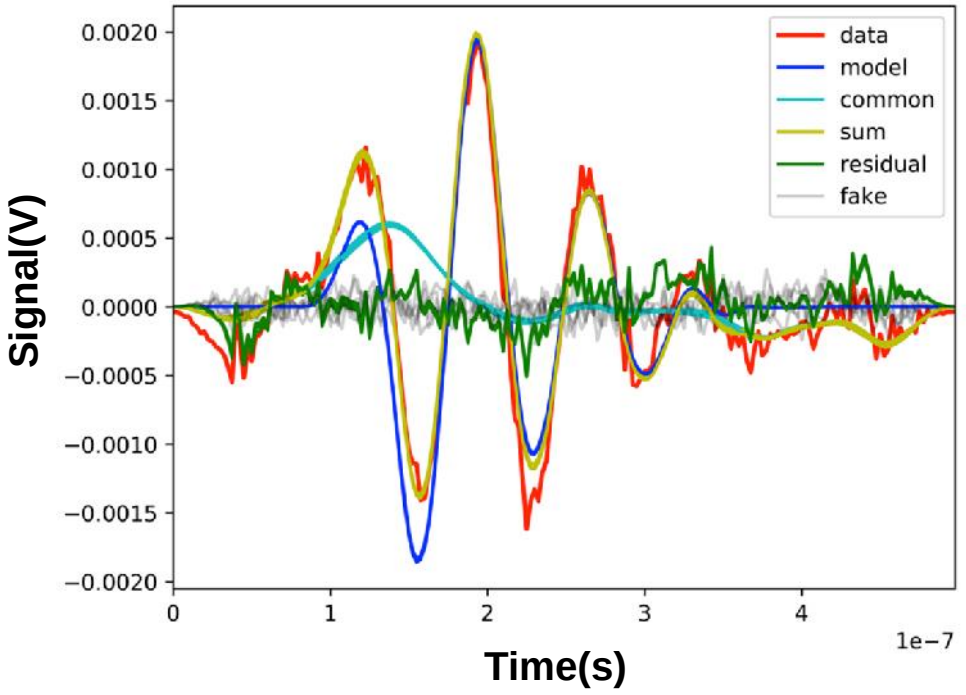
Losses are very similar to loss in sapphire-sapphire bonds
(see Haughian et al. PRD 2016)

Joint work with colleagues at Moscow State University
Latest measurements and modelling by Peter Murray and Karen Haughian

Thermal noise contribution HCB's

New value Young's modulus of bonds through ultrasonic measurements and Bayesian analysis – $18.5^{+2.0}_{-2.3}$ **GPa**





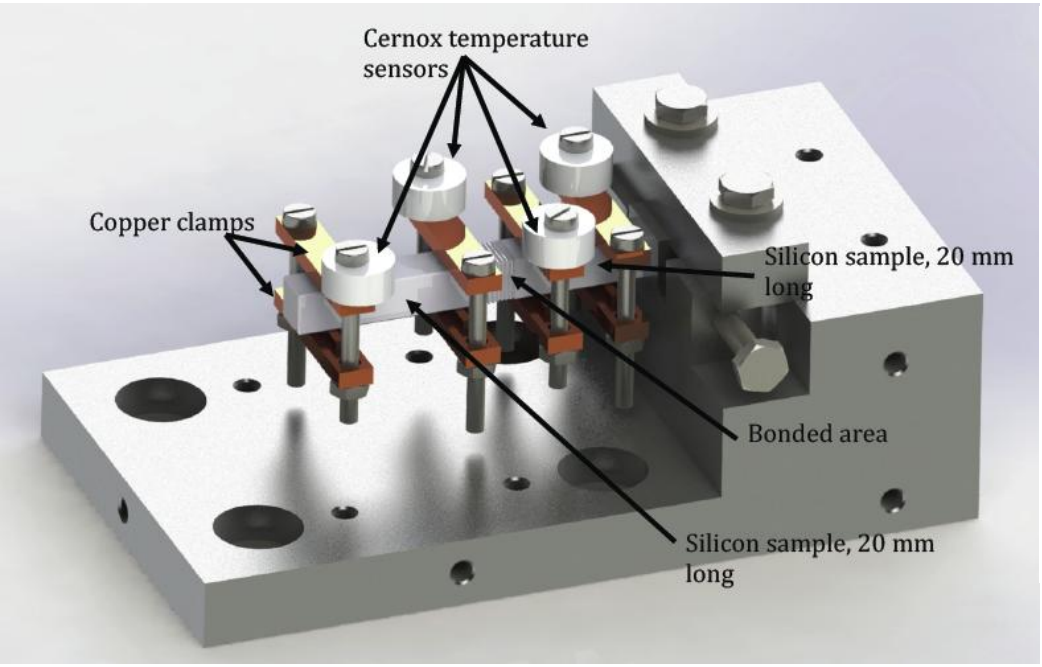
Paper accepted Phelps et al.,
PRD April 2018
LIGO-P1700423

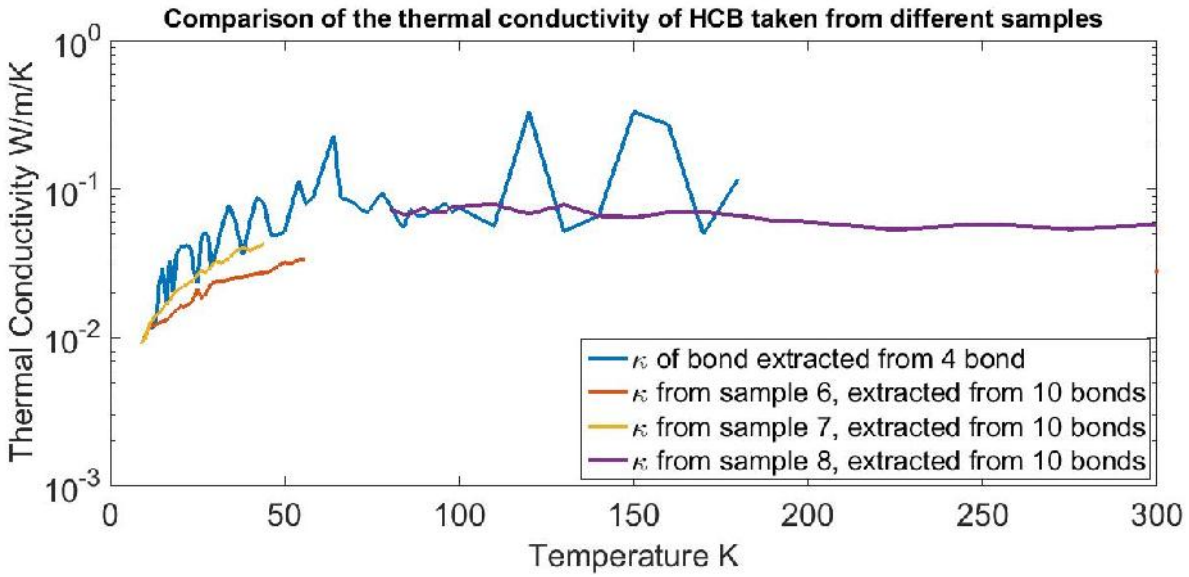
… and impact on thermal noise

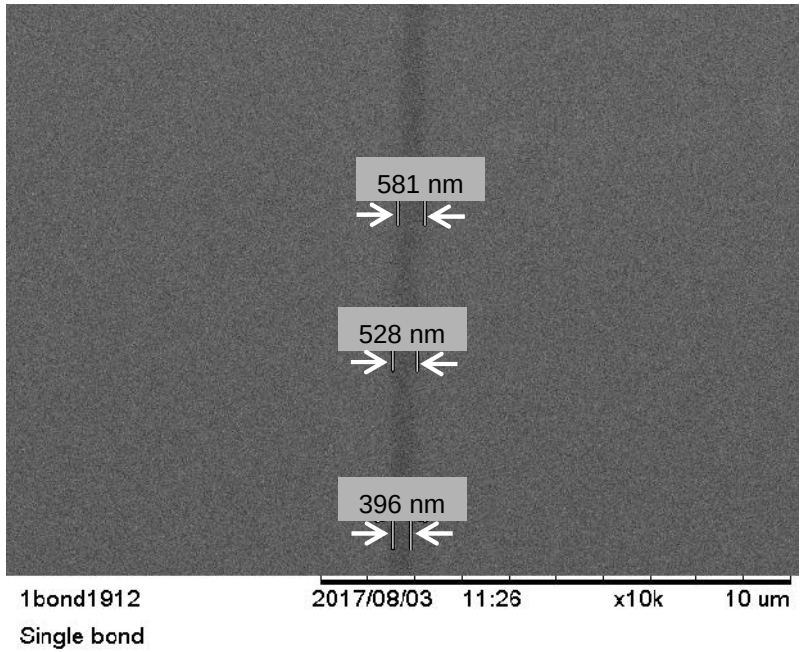
… which is below expected requirements

Detector	KAGRA	ET-LF-1	ET-LF-2
TM	23 kg sapphire	211 kg sapphire	211 kg silicon
Temperature	20 K	10 K	10 K
Thermal noise required ($\cdot 10^{-22}$ m/√Hz per TM)	6	5	5
Thermal noise modelled ($\cdot 10^{-22}$ m/√Hz per TM)	0.45±0.02	0.38±0.12	2.8±0.5

Hydroxide catalysis bonding of silicon – thermal conductivity







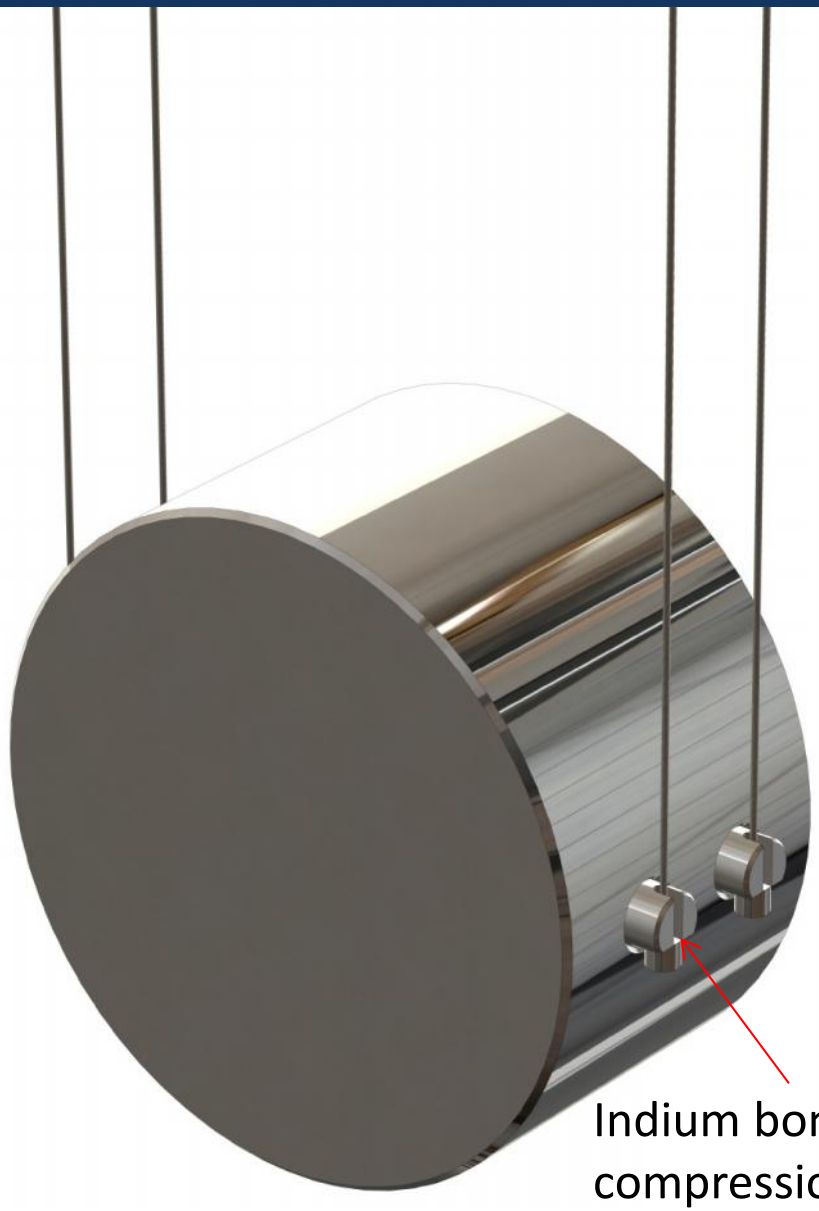
Sample 8 during curing

10 bonds

Though thermal conductivity is low, the bond is also extremely thin. The expected thermal gradient across a bond is extremely small.
0.06 mK for a total thermal gradient of 15 K between test mass and marionetta for ET

PhD work Mariela Masso Reid

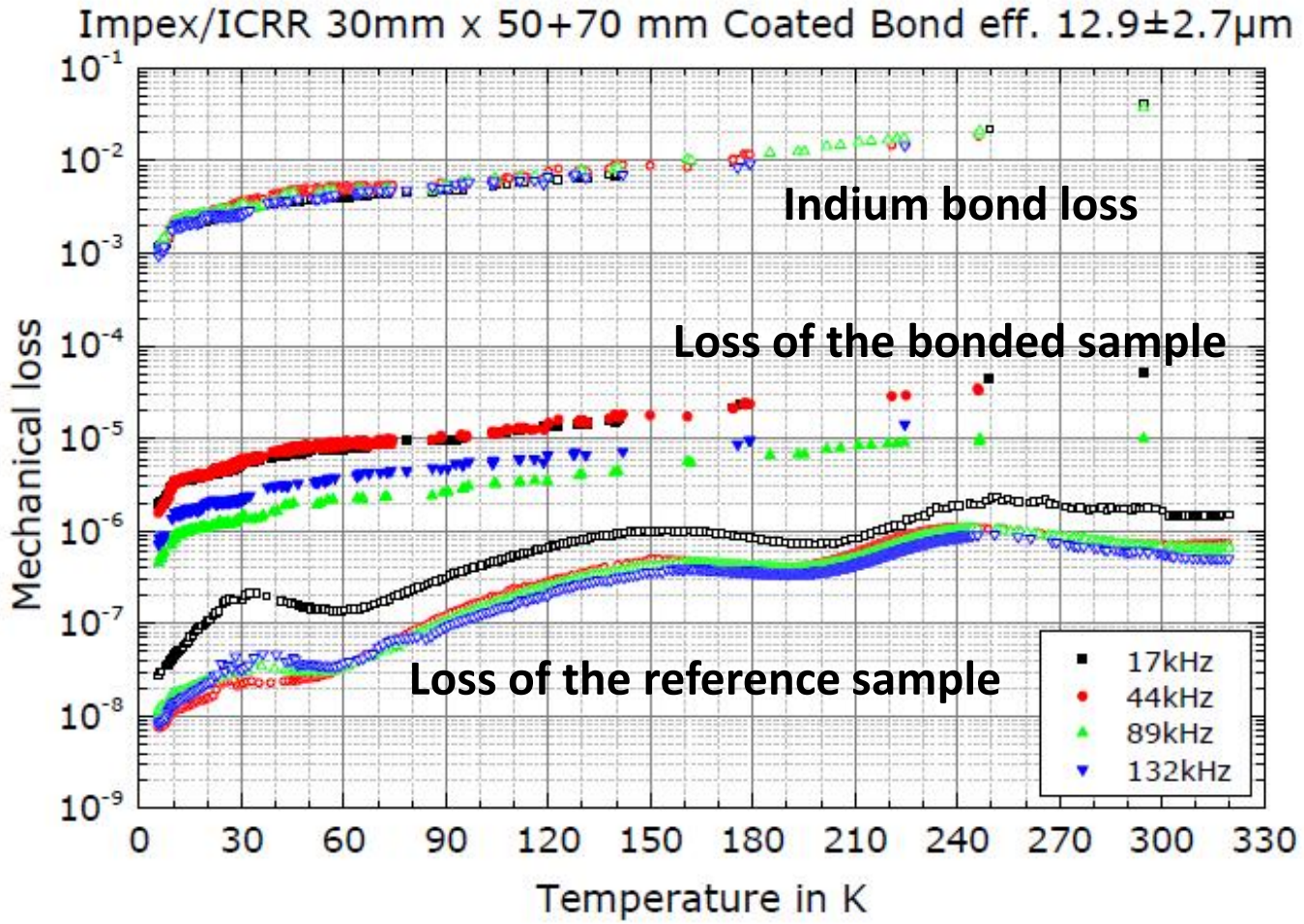
Towards future cryogenic detectors – indium bonding



Indium bond under compression between ‘nailhead’ and ‘ear’

- **Considering indium bonding for suspension designs with nail head fibres underneath the ear (like Adv Virgo and KAGRA)**
  - Bond under compression
  - Debonding possible - fibres with nailheads are replaceable – with low risk of damage to test mass
  - Indium bonding was considered for GEO600 (Twyford thesis, 1998) and KAGRA (LIGO-G1500951)
  - Is considered a potential solution for some interfaces ET (ET-0106C-10)
  - Rejected for GEO600 as indium has low melting temperature (156 °C), so creep during vacuum bake out

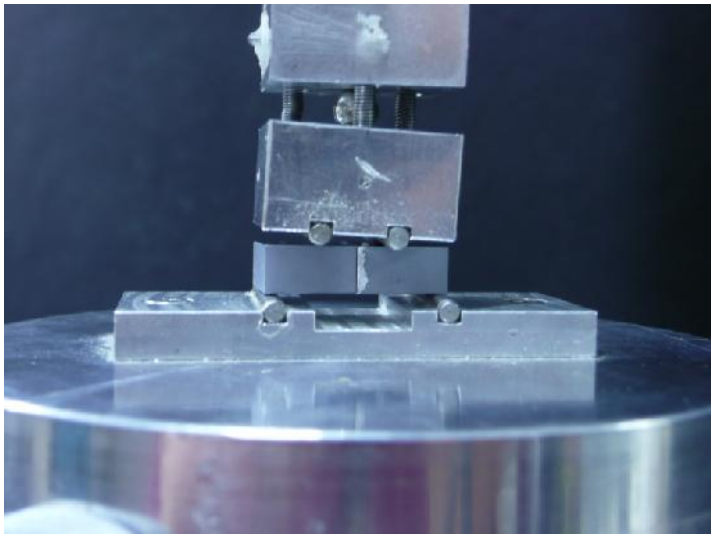
Indium bond loss, sapphire



- A non-uniform indium layer can increase the loss of the joint.
- Indium bond loss is ~ (2 – 3) x 10^{-3} at 20K.

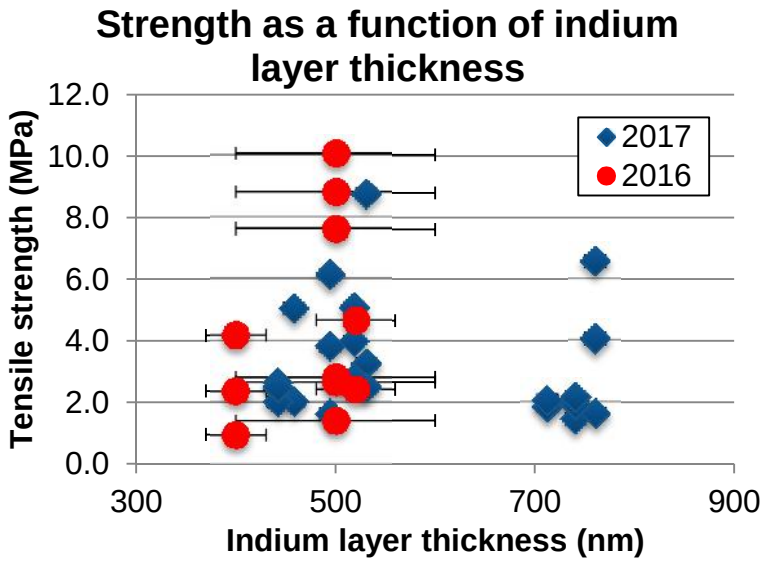
(Class. Quantum Grav. 32 (2015) 245013 G Hofmann et al)

Indium bonding - assessing bond quality

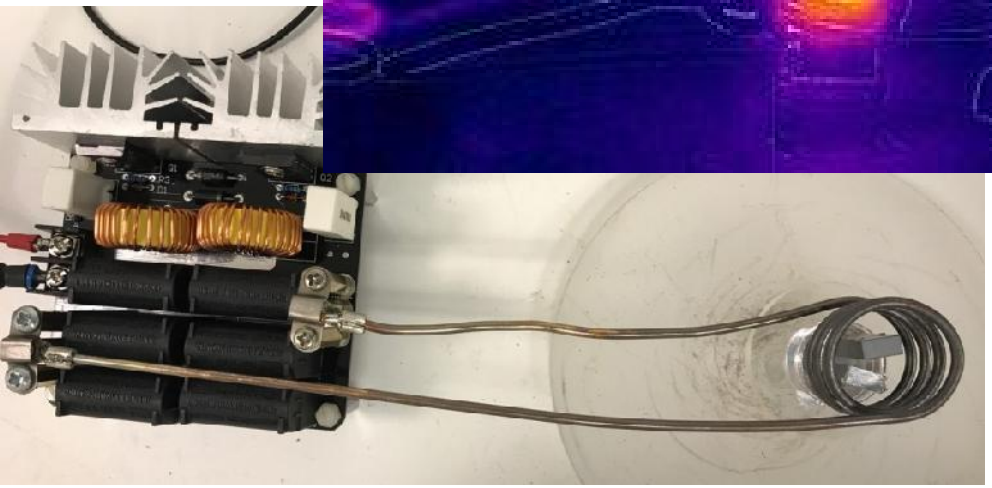


4-point bend test

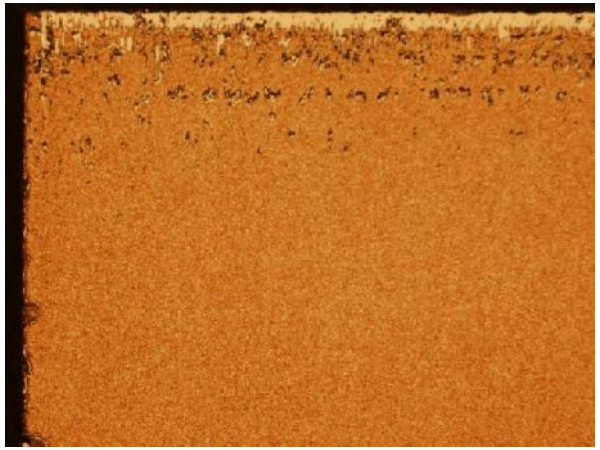
Visual inspection



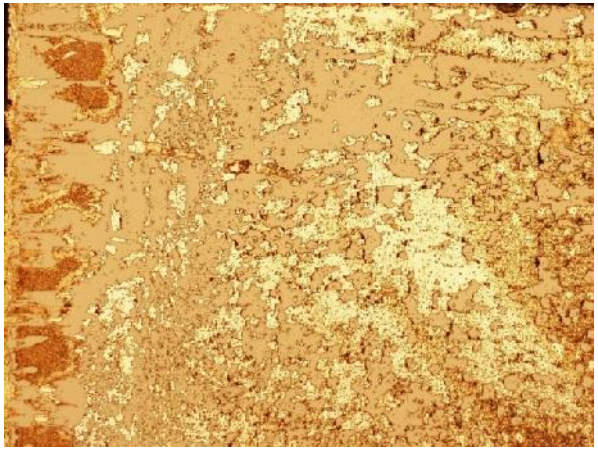
Induction heating



Images under Nomarski microscope



Poor quality bond



High quality bond

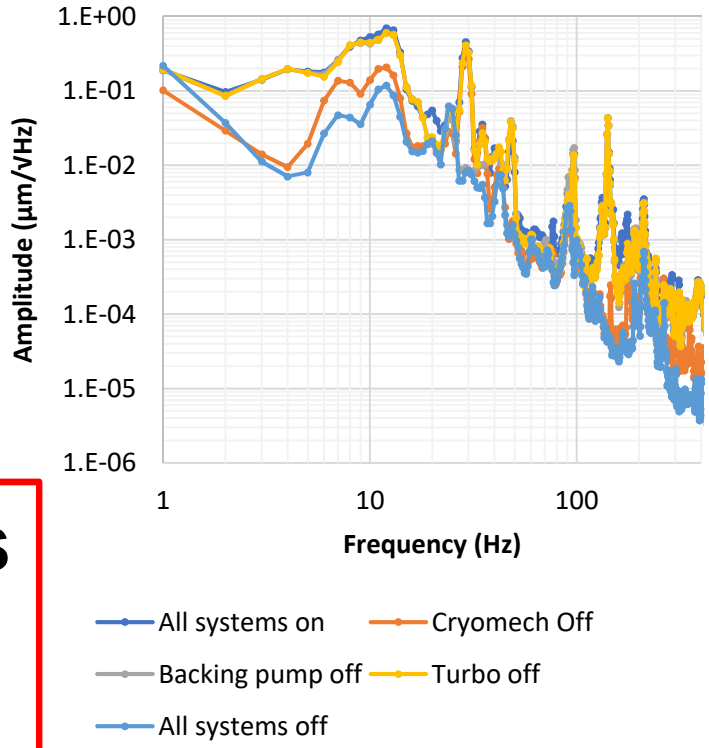
Cryogenic crystalline suspension designs

Leiden Cryogenics cryogen free cryostat

+

PhD student Graeme Eddolls

Working towards a 1 kg scale 4 fibres silicon suspension



There are still many questions to answer for a design and assembly of 200 kg scale crystalline mirror suspensions, but making good progress in assessing/developing techniques to make it possible.


Just A Wee
Thank Ewe