Adhesive-free bonding:
From academic origin to industrial application

Christian Killow

CEOI-ST Space Technology Showcase, 13th November 2014

Image credit: ESO

Overview

Gravitational waves and their detection

- "Big Science"

Hydroxide-catalysis bonding

- Extending the reach of the technology

Technology for spaceborne gravitational wave detectors

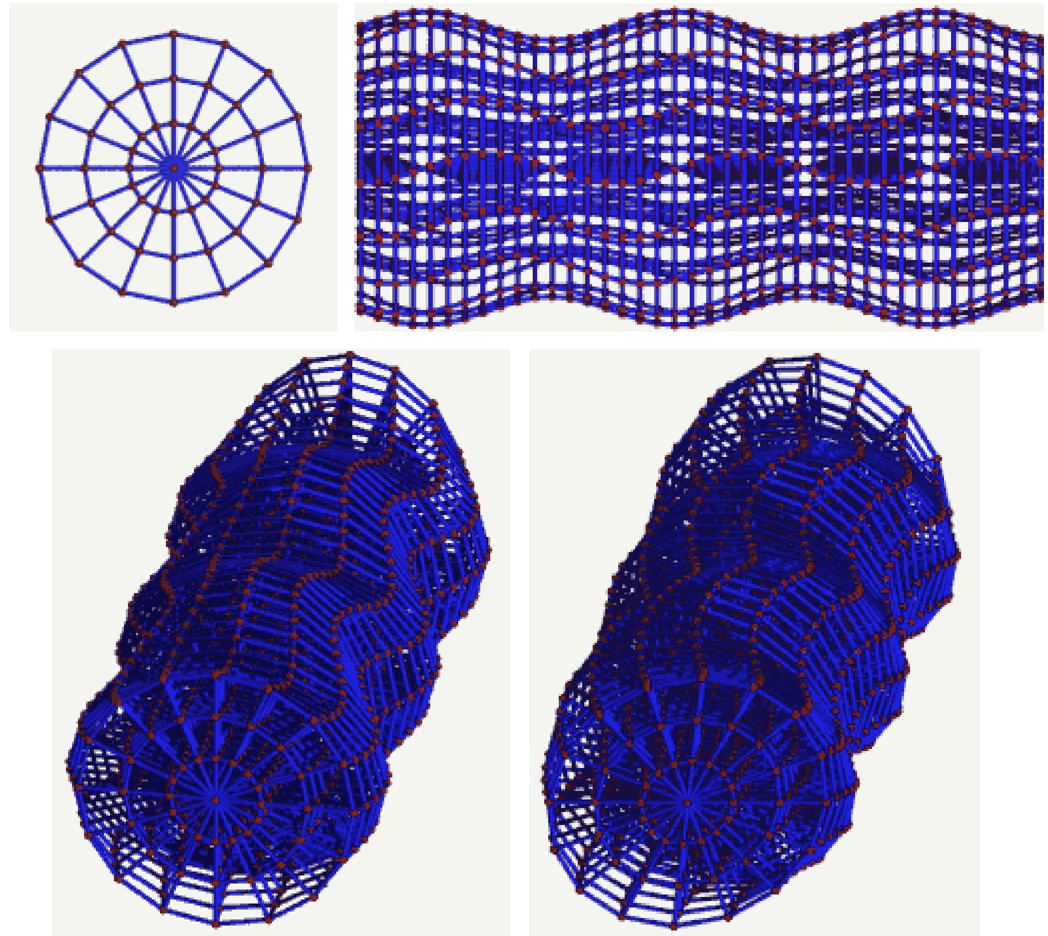
- LISA Pathfinder optical bench

Developing capability in precision optical hardware for ground- and space-based activities

Gravitational Waves

- What are they?
  - Ripples in the curvature of spacetime
  - Predicted by Einstein’s General Relativity
  - Awaiting first direct detection
  - Carriers of astronomical information not visible to electromagnetic energy

- What effect do they have?
  - Stretch and squeeze spacetime
    - This makes it possible to detect them…



Effect of a gravitational wave passing through an arrangement of test particles.
Courtesy of M. Pössel/Einstein Online [http://www.einstein-online.info]

Gravitational Wave Detectors

- The best way we have to build gravitational wave detectors is to isolate ‘test masses’ from local disturbances and measure their separation as gravitational waves pass through the system
  - We use laser interferometry as the ‘ruler’ as high precision is needed

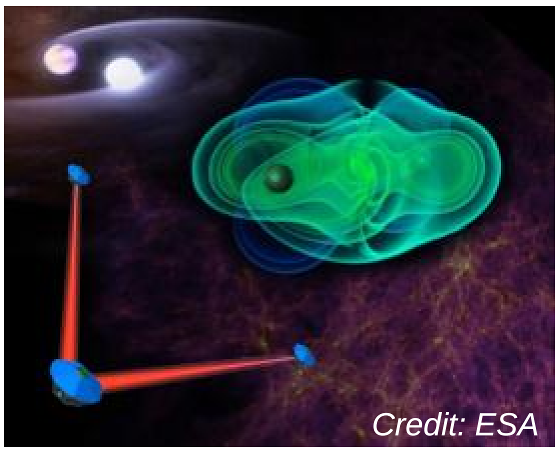
The 4 km arm length LIGO gravitational wave observatory in Louisiana, part of the world-wide effort to detect gravitational waves

$$h = \frac{\Delta L}{L} \sim 10^{-20}$$

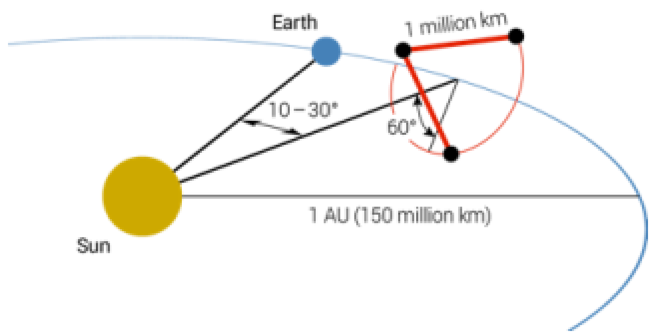
- This leads to long arm lengths and very precise position measurements

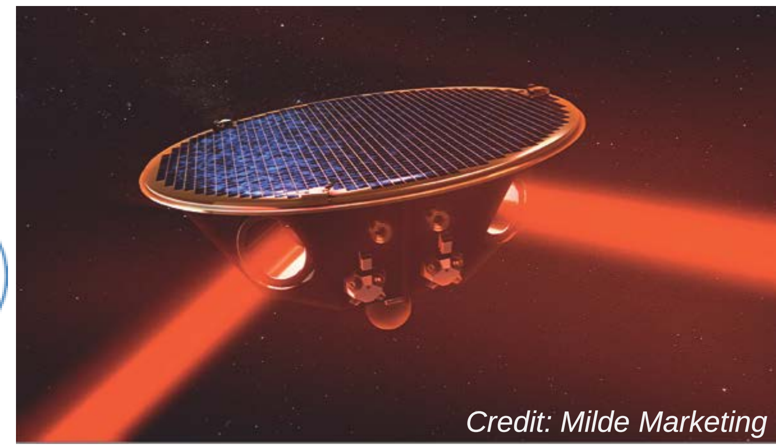
A problem and a solution

- Changes in local mass distribution – even clouds passing – cause a variation of the forces acting on the test masses
  - This is a problem if the mass distribution changes in the band you want to measure
- We need to go to a gravitationally quiet environment: space
  - Added benefit that we can have very long armlengths
- eLISA is a proposed spaceborne gravitational wave detector



Credit: ESA

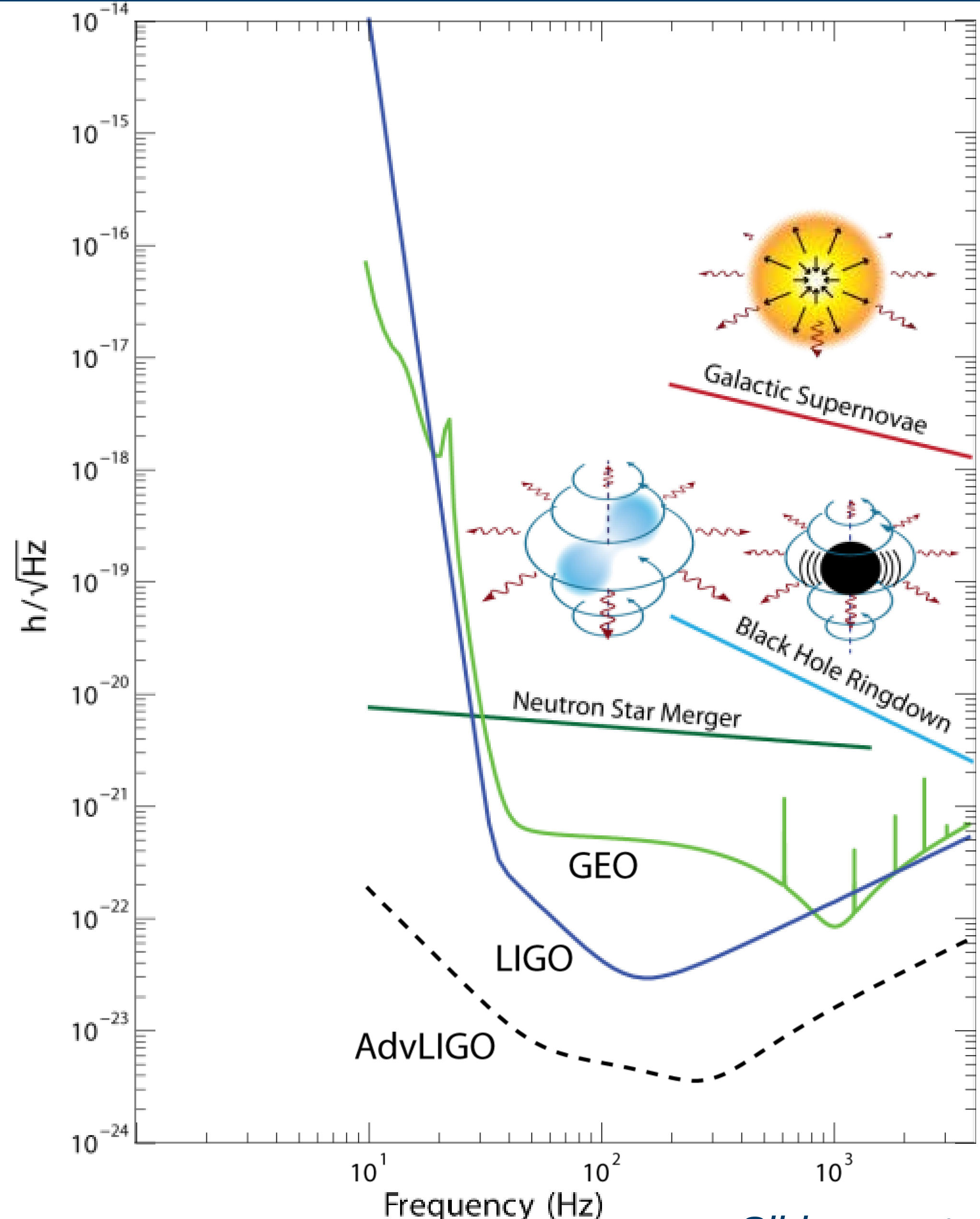




Credit: Milde Marketing

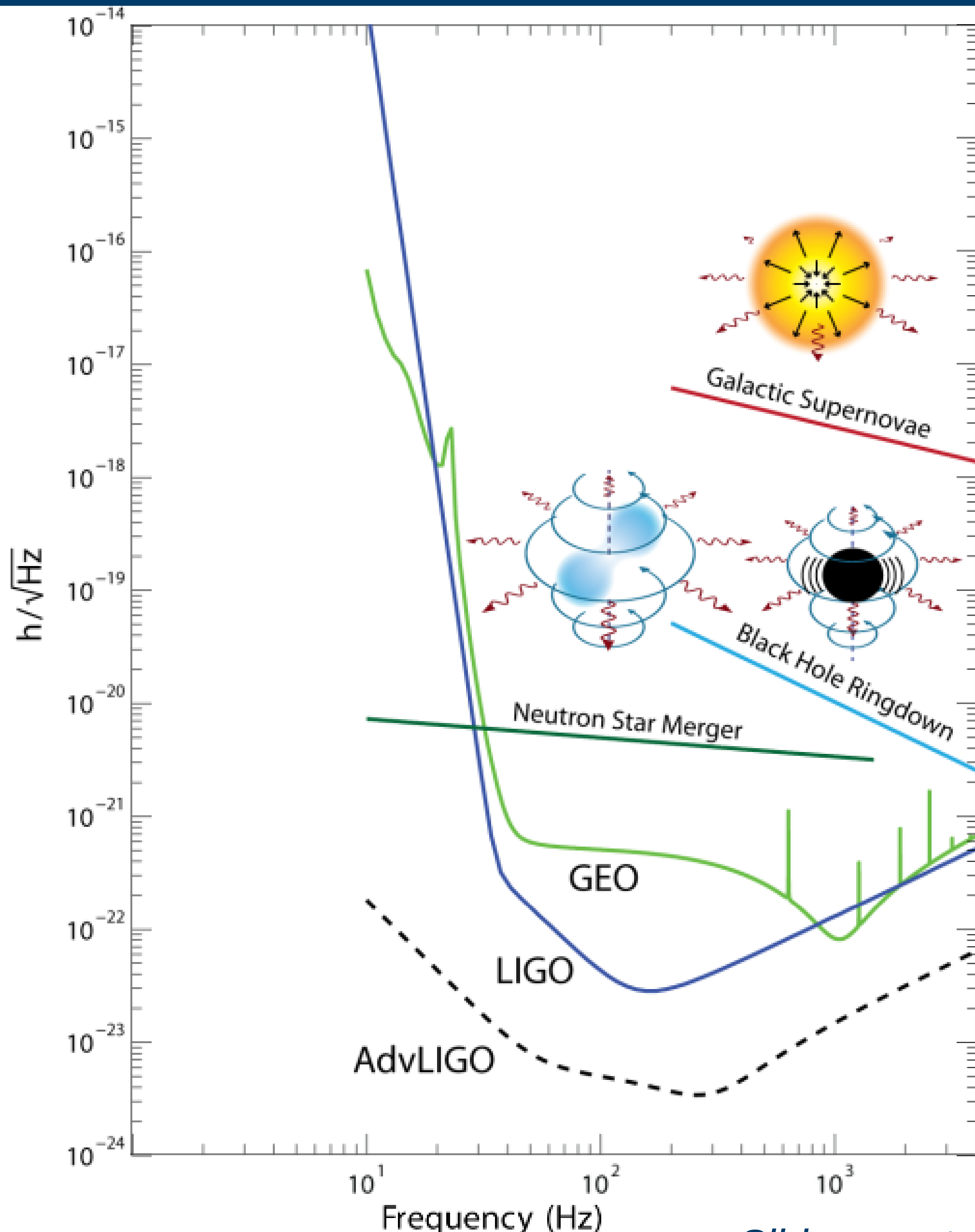
- Similar detection principles as ground-based detectors: monitor separation of inertially free masses using interferometry
- With gigametre armlengths and requiring picometre test mass monitoring at milliHertz
  - A demonstrator mission – LISA Pathfinder – is being flown to retire technological risks

Astronomy with Gravitational Waves



Slides courtesy of Ewan Fitzsimons

Astronomy with Gravitational Waves



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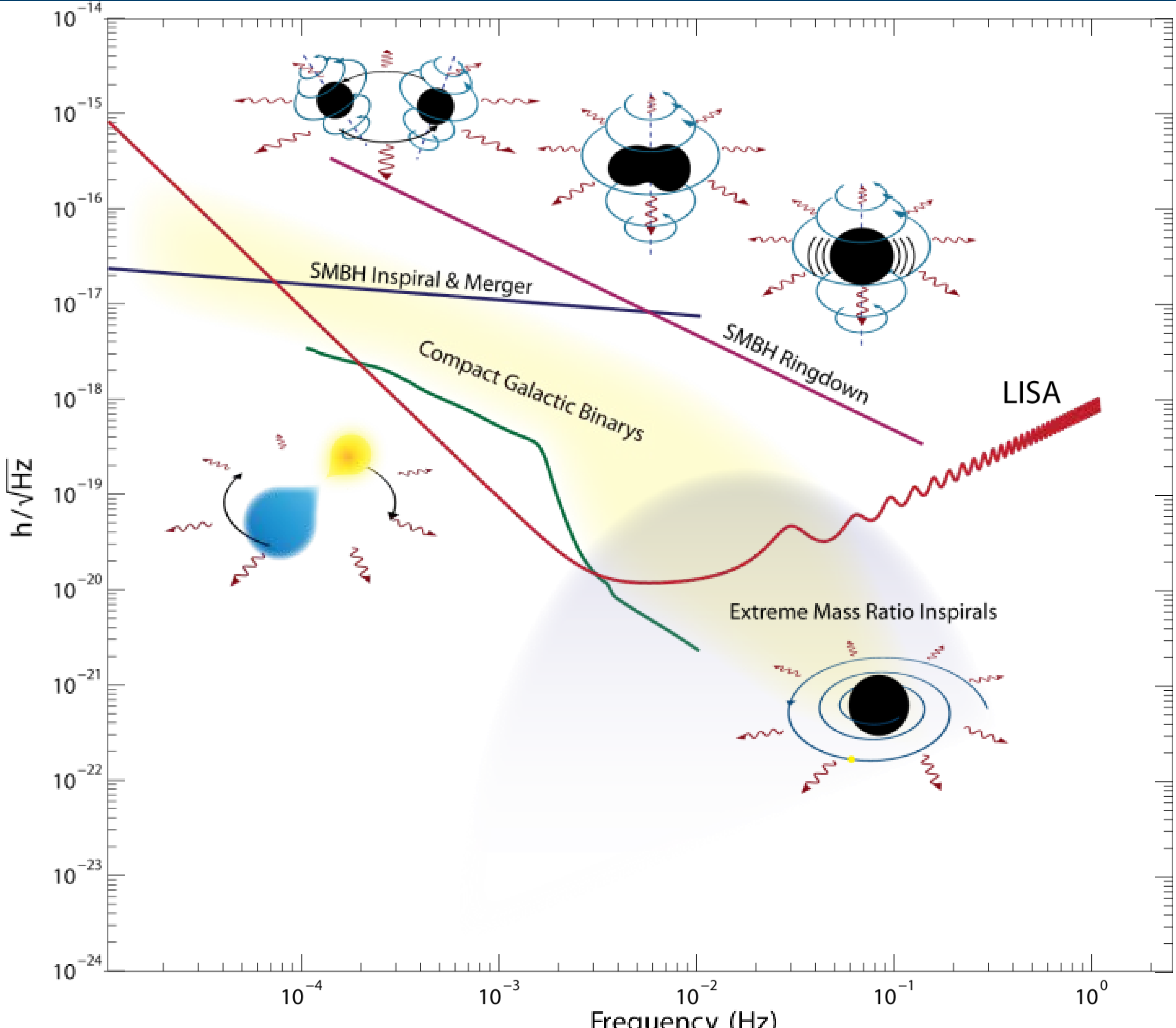
Astronomy with Gravitational Waves



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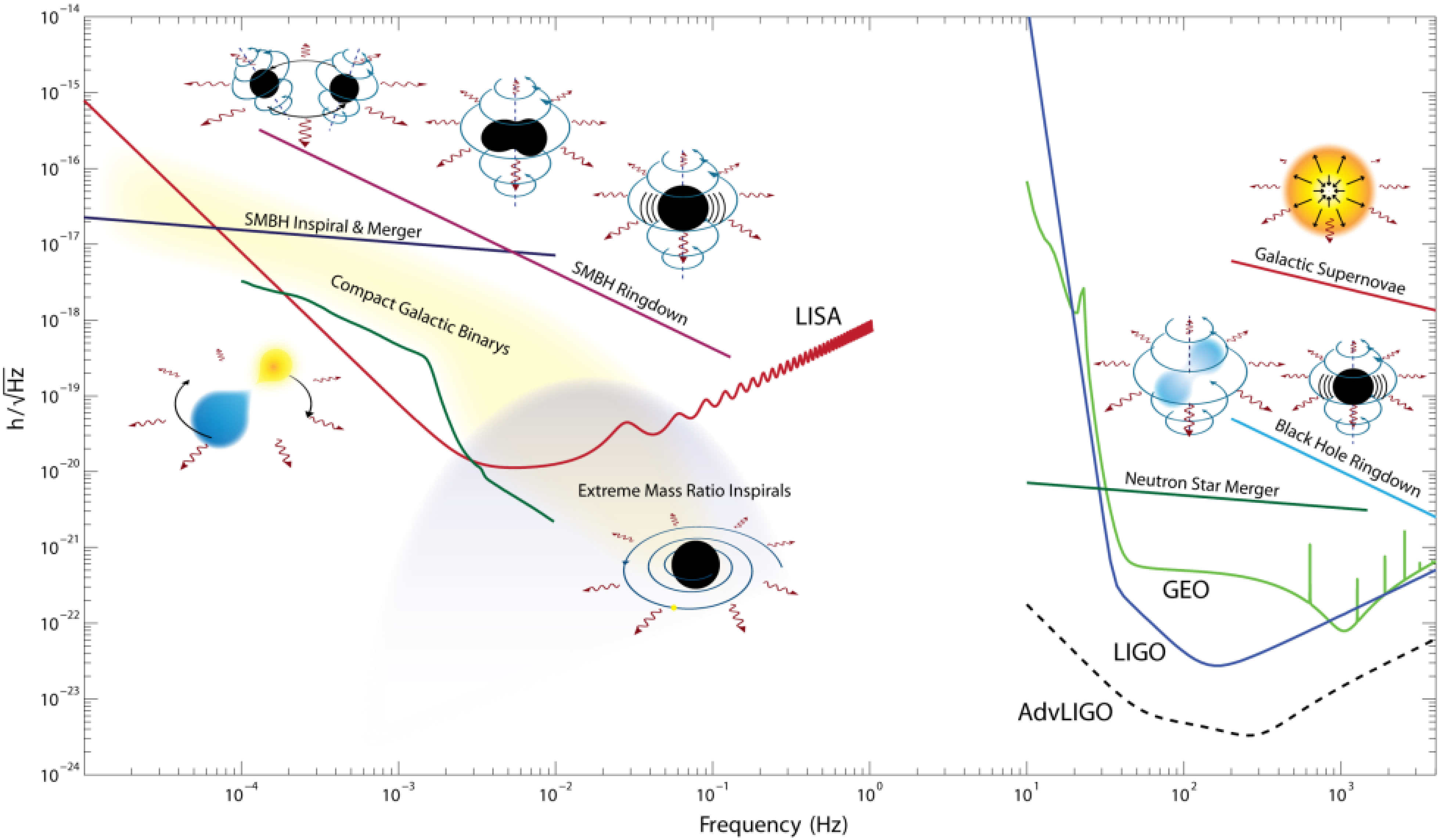
Astronomy with Gravitational Waves



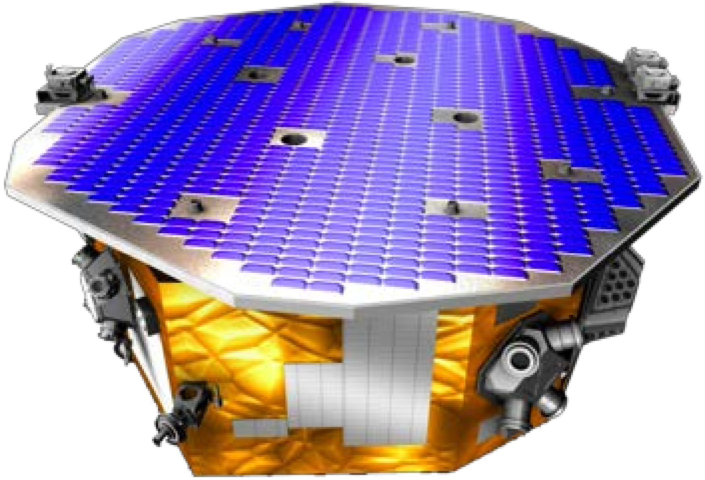
Slides courtesy of Ewan Fitzsimons

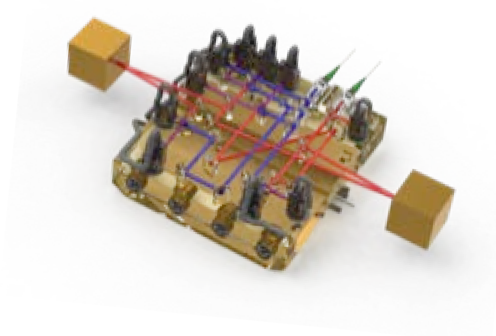
LISA Pathfinder

- We can verify many aspects of eLISA on ground, but not all
- The aim of LISA Pathfinder is to verify technology for future spaceborne gravitational wave detectors
  - It will effectively demonstrate the 'short-arm' interferometry for eLISA
- Fly two test masses and measure the purity of their freefall
  - Experiment in micro-gravity at L1
- European Space Agency mission due for launch in 2015
- Significant technological development in many areas is required for this mission
  - I will only mention aspects of the optical test mass position measurement

LISA Pathfinder structural model (courtesy Airbus DS UK)

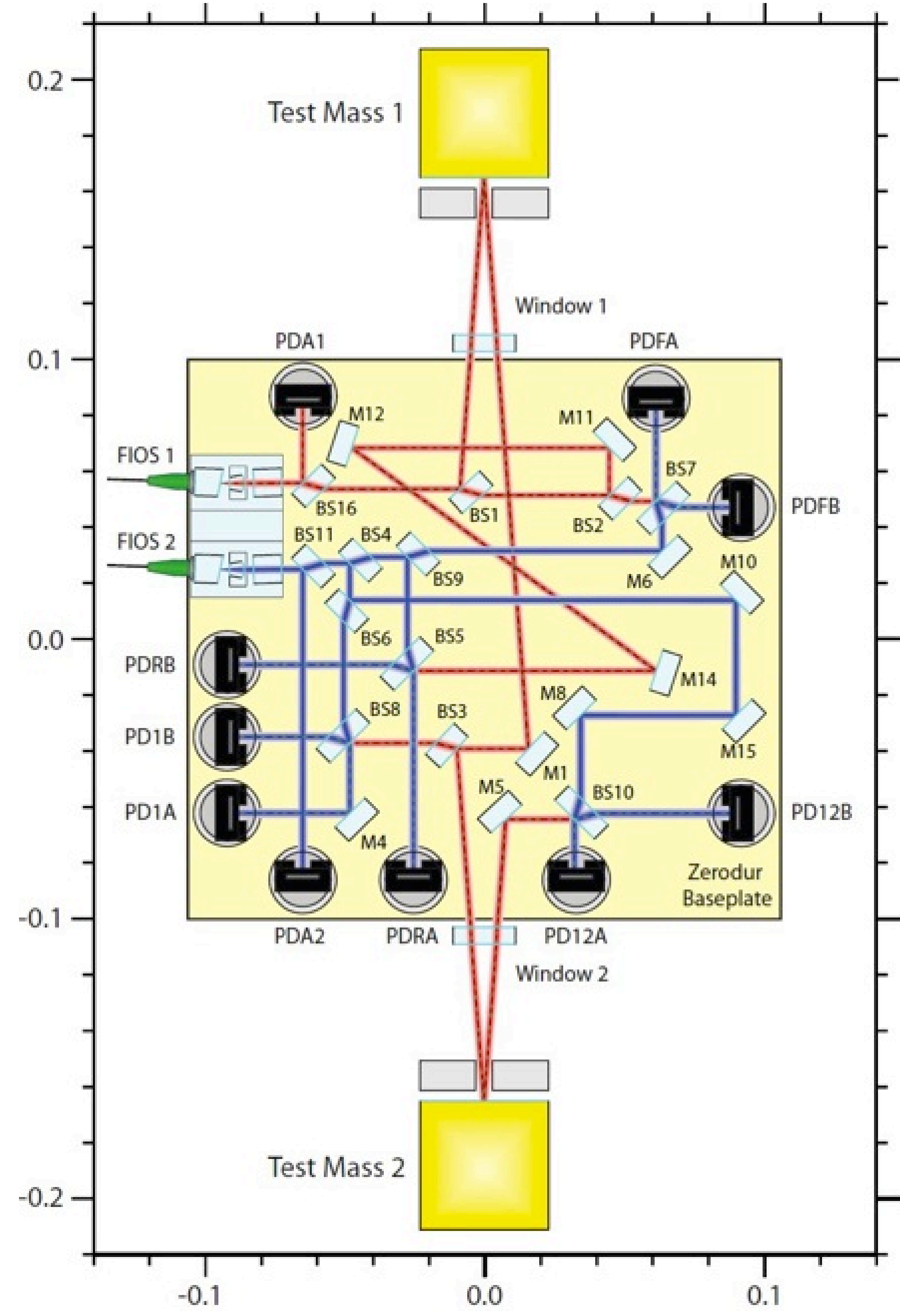
LISA Pathfinder optical bench

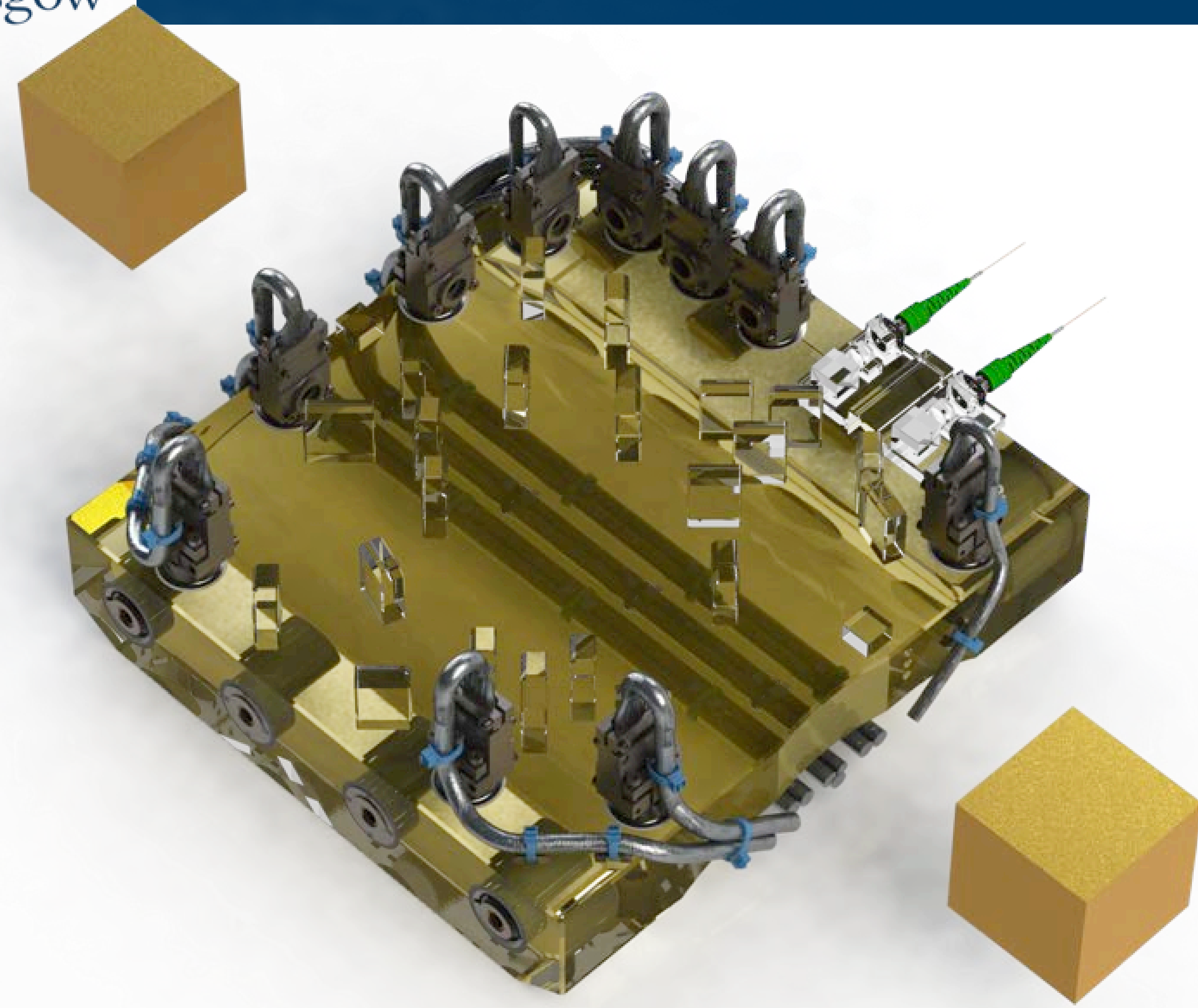


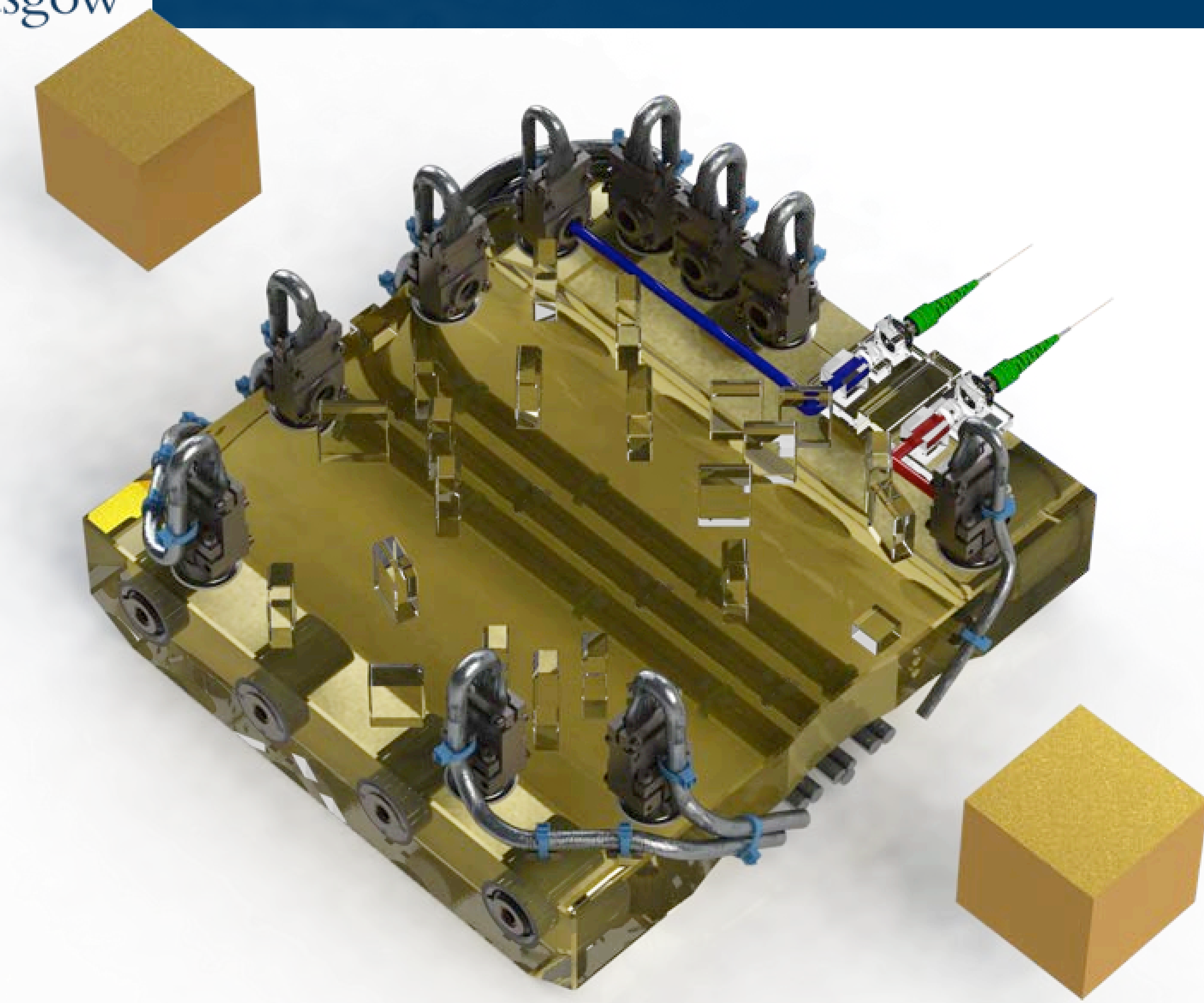


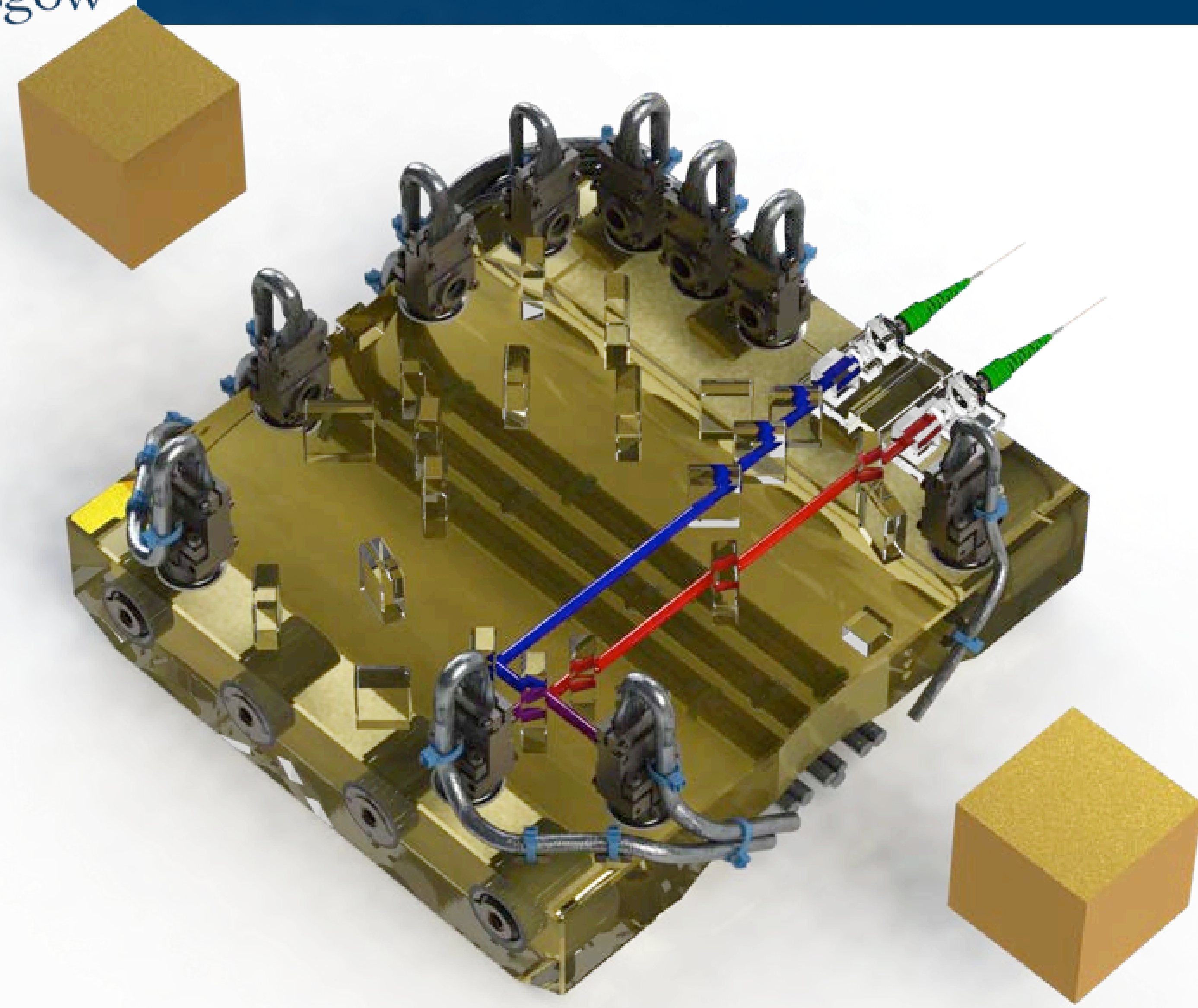
Design from first principles

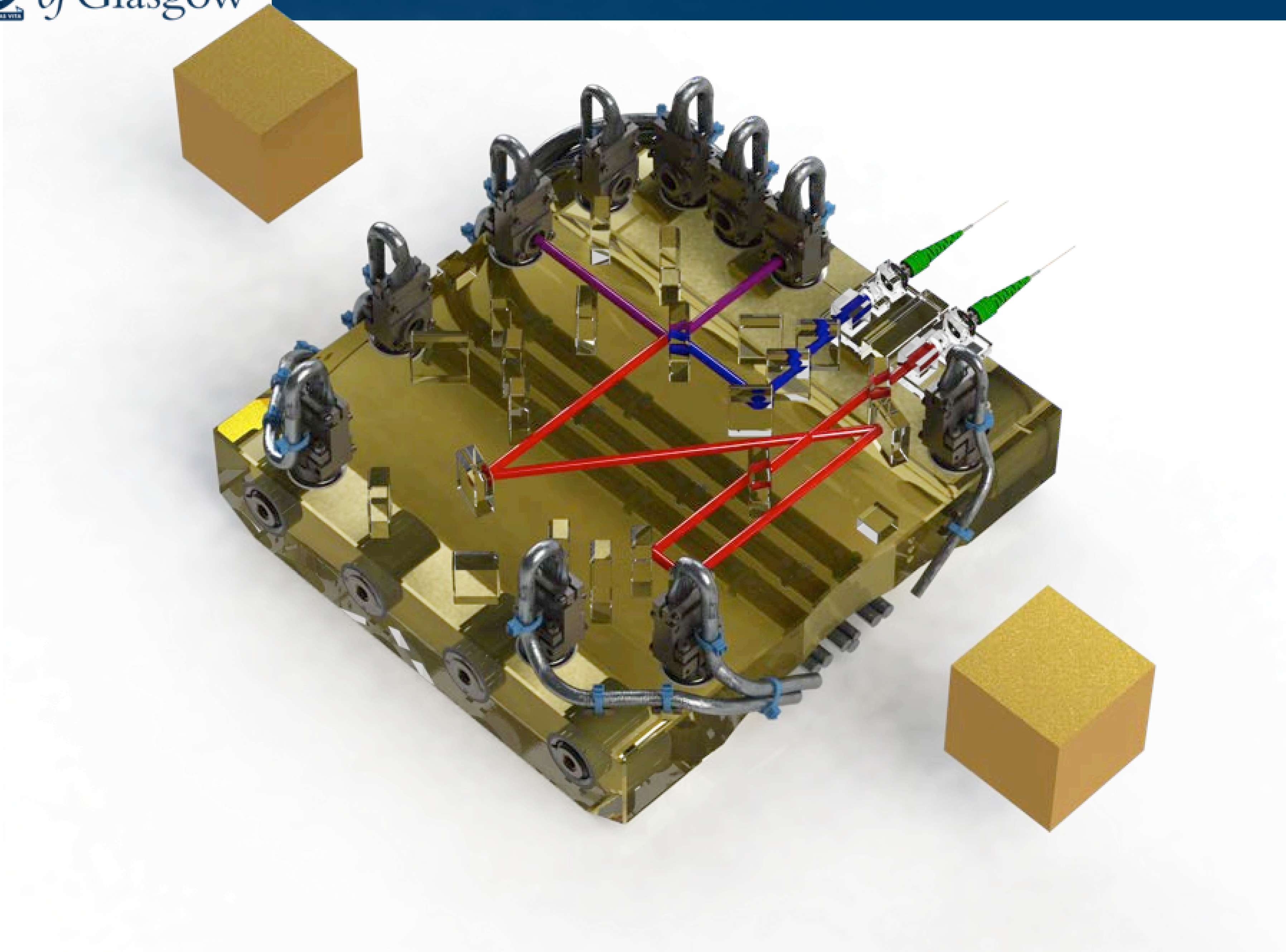
- The Optical Bench Interferometer
  - Has to physically fit into the space available
  - Plays a structural role
  - Has to survive launch and radiation environment
  - Be non-magnetic
  - Measure 10 picometre longitudinal variations and 20 nanorad angular beam motion (in band) in milliHertz regime
  - Beams have to hit the Test Masses within 25 µm of absolute nominal
- This leads to a lot of derived requirements
  - And a lot of paperwork

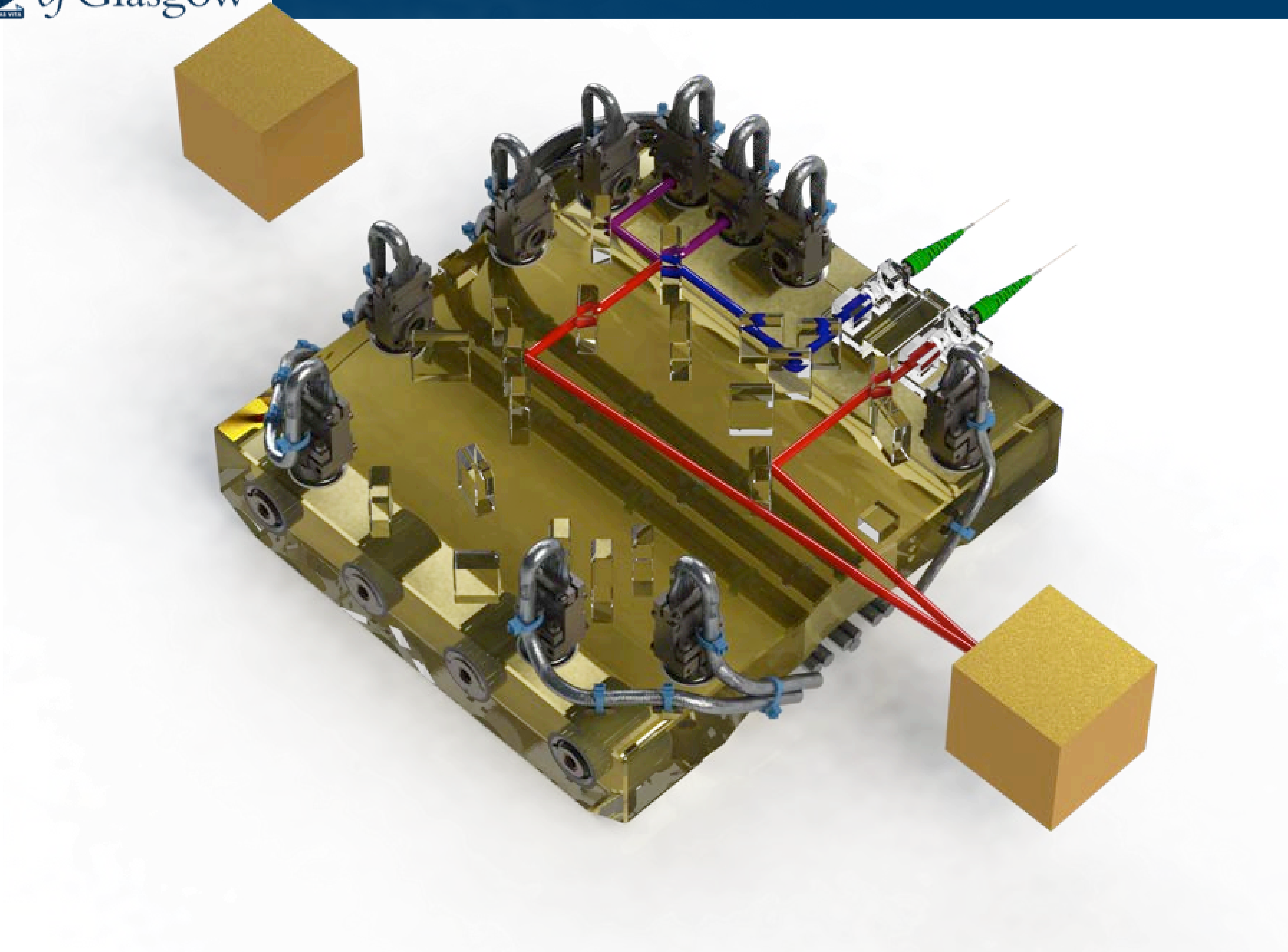


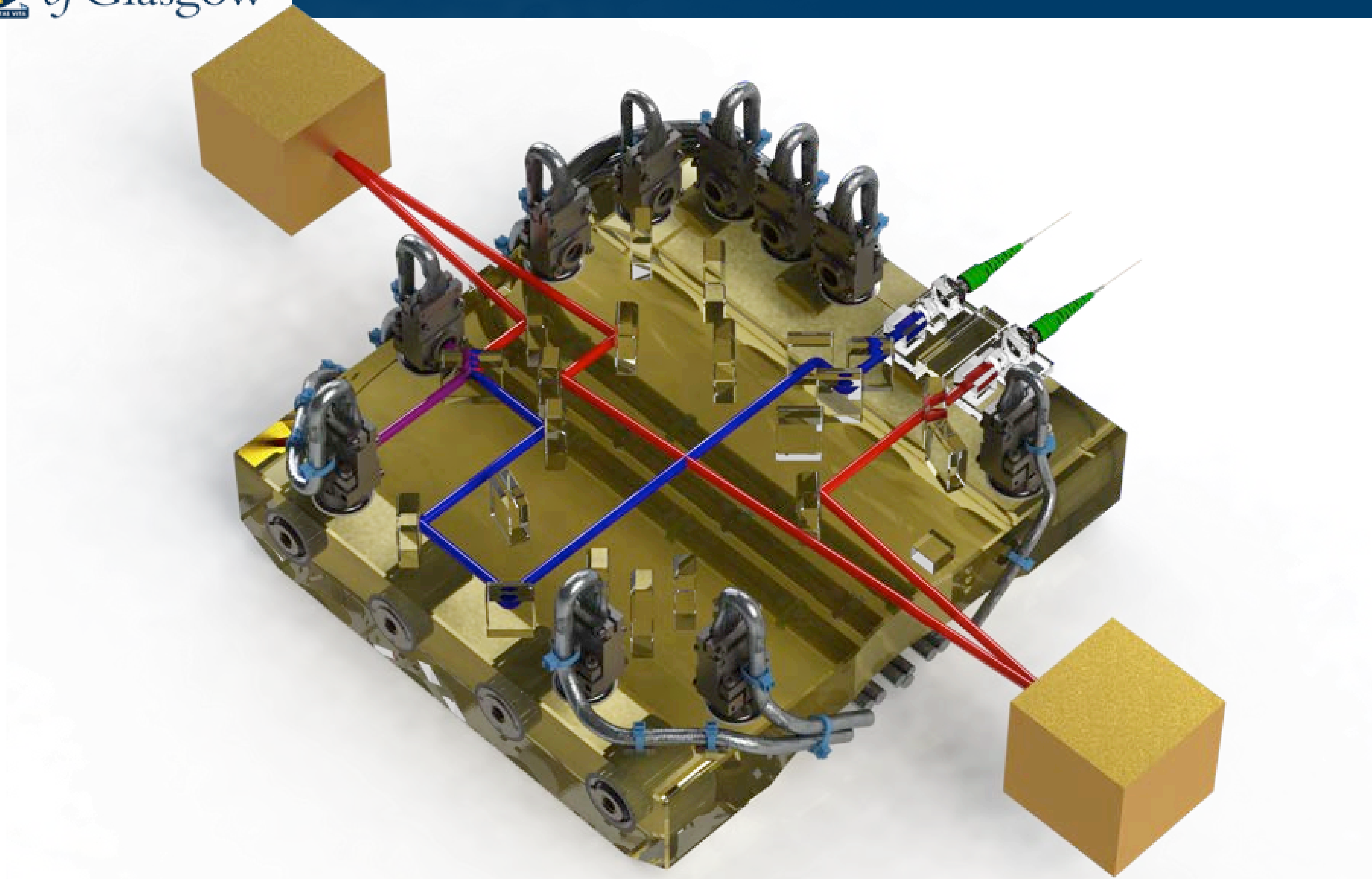


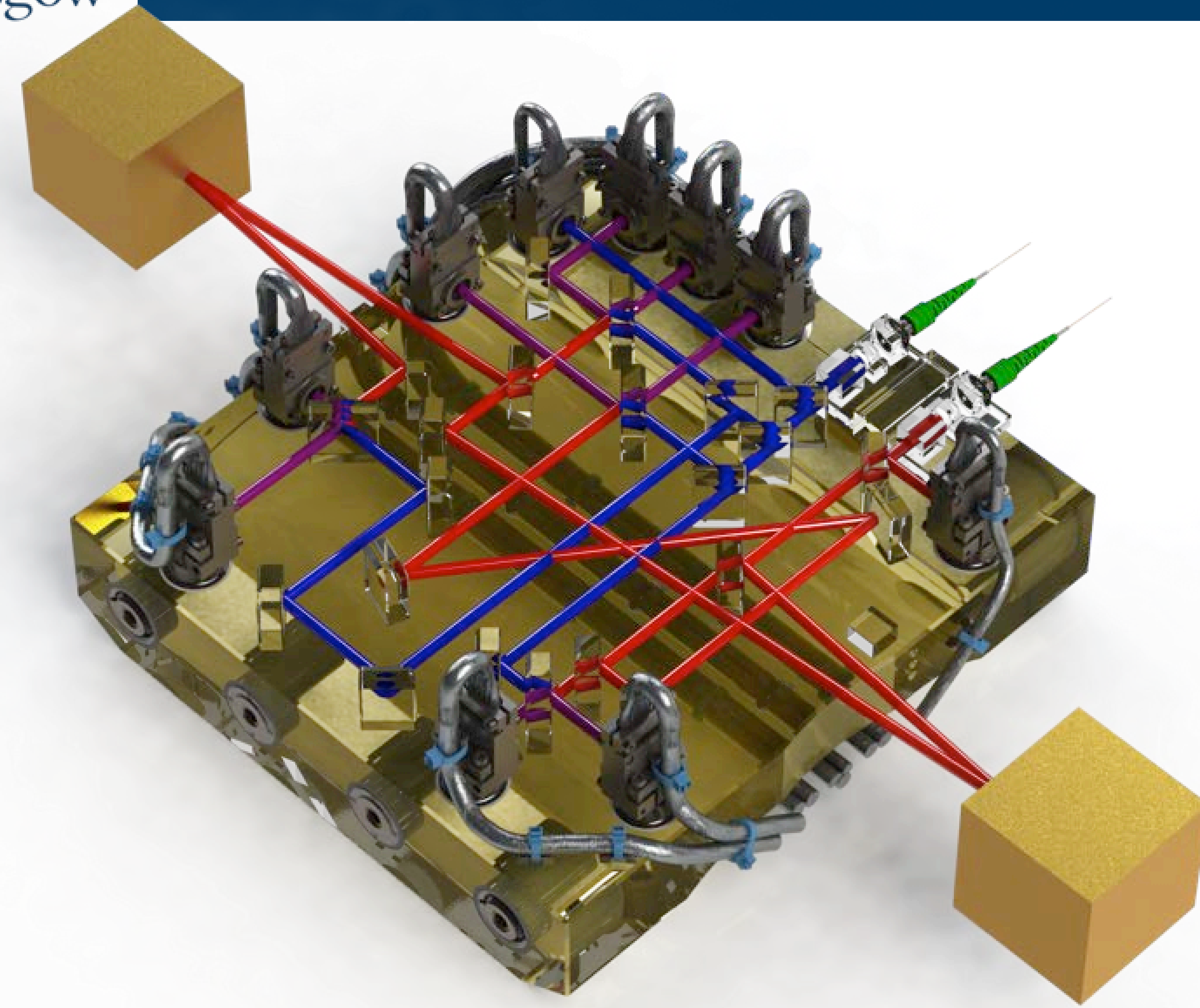






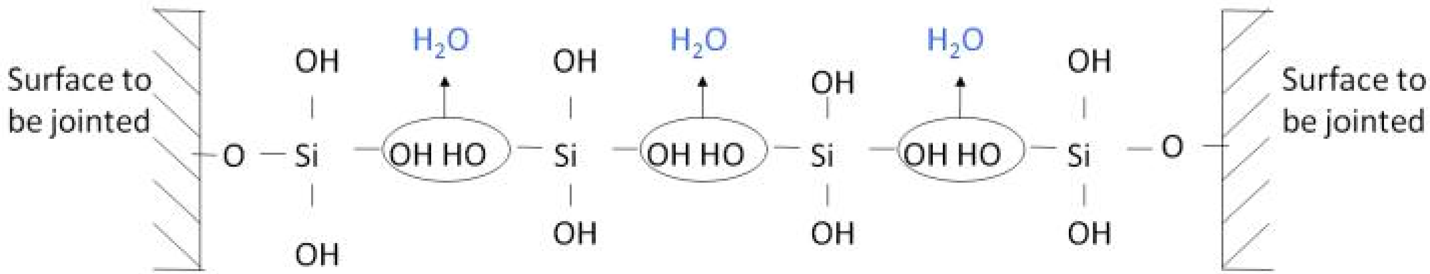


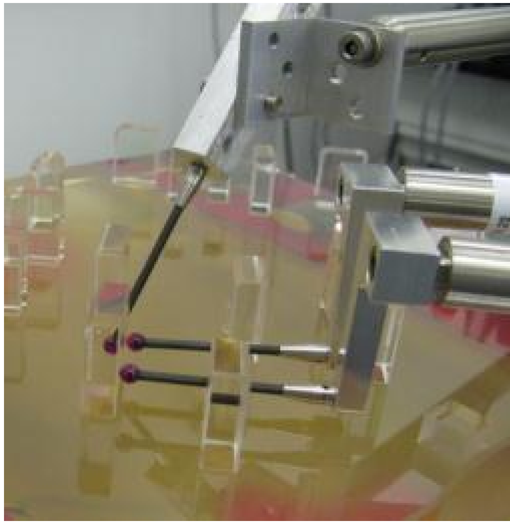




Enabling technology

- A technology was identified as being useful in gravitational wave detectors: hydroxide-catalysis bonding
  - First space-science use in Gravity Probe B
  - An adhesive free method of joining substrates that, in general, form oxides
  - Forms very strong, thin bonds that are UHV compatible





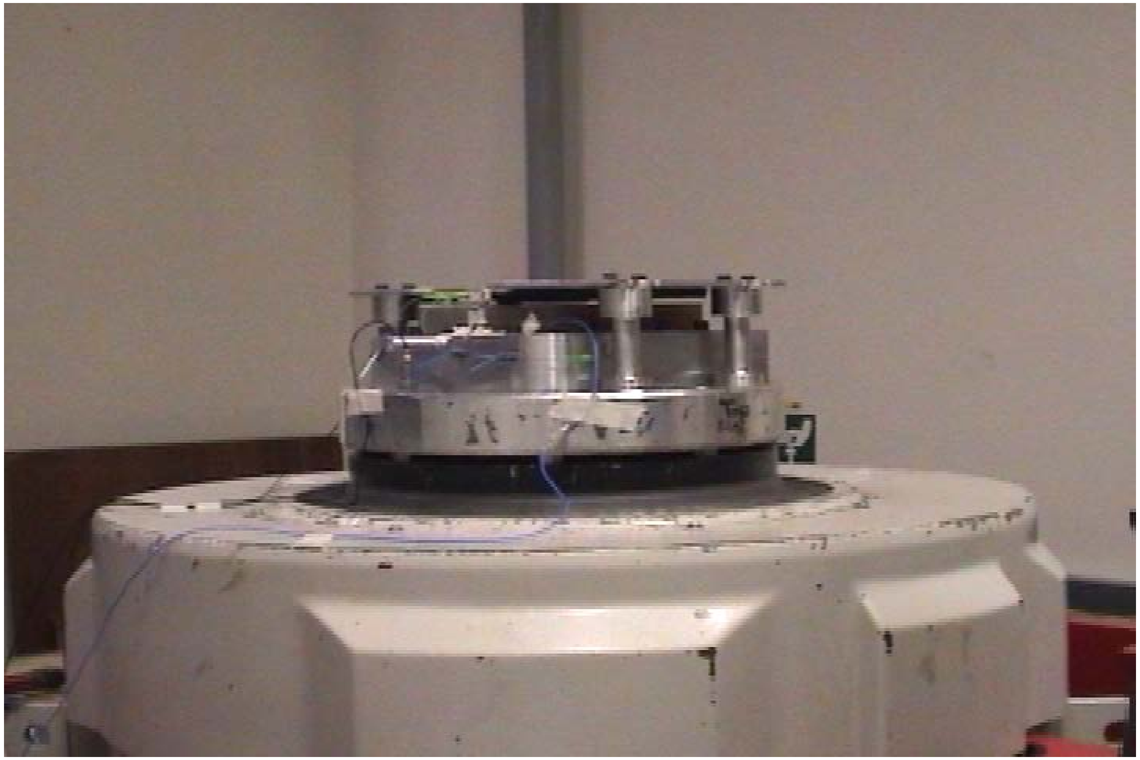
- We have developed the technique to precision locate components and bond them in place
  - Once built the assembly is permanently aligned
  - Demonstrated picometre stability
  - Component placement at the sub-μm and 20 μrad level
  - Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)

A bonding stage (*not real time*)

- Precision locating and bonding of components is currently a complex operation
- OK for small number, high-value work
- Reducing the complexity of the process will reduce cost, effort and required skill-set of operators
- Current CEOI-ST 7th Call project to replace several manual steps with mechanisation
  - Collaboration between the University of Glasgow and Gooch and Housego

Space worthiness of current alignment process

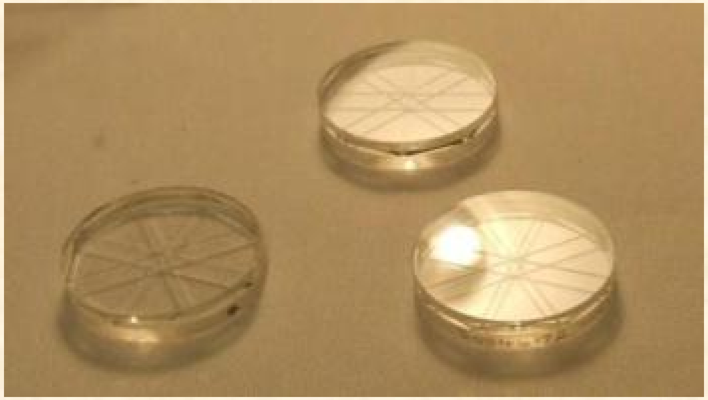
- The flight OBI underwent considerable testing (details in Robertson *et al*. Class. Quantum Grav. 30 (2013) 085006)
  - Properties of the optical chain
    - Transmission efficiency
    - Photodiode responsivity
  - Alignment to the IAF Frames
  - Beam DC positions and scaling
  - DWS Calibration
    - Operating point
    - k-coefficients
  - Other Optical Properties
    - Interference contrast
    - Path length matching
  - Thermal Vacuum cycling
  - Vibration and shock

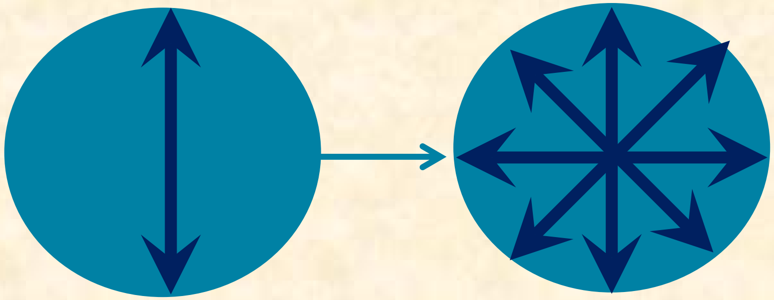


Vibration testing of the qualification pair of LISA Pathfinder fibre injectors at Selex ES

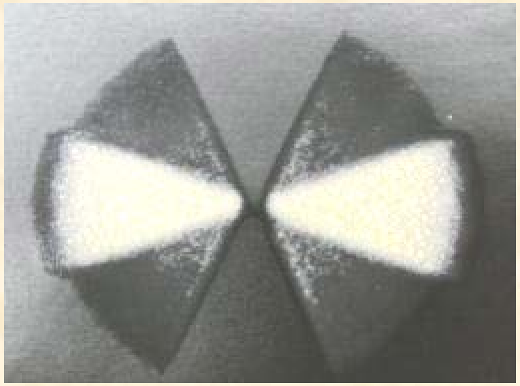
HyPerBond Application – Segmented Waveplate

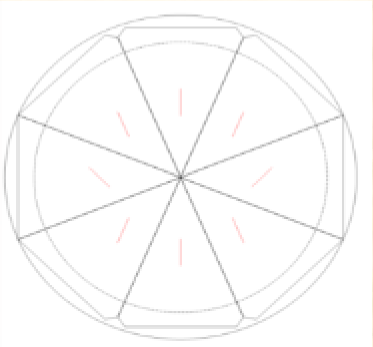
Gooch & Housego
ENABLING PHOTONIC TECHNOLOGIES

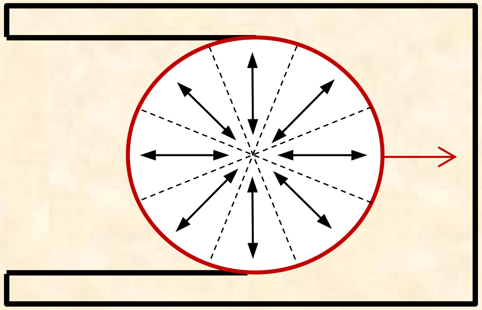




True zero order waveplate, glass backing plate, survives high LIDT ,
each segment a different alignment of crystal to control linear polarisation







Far field of segmented waveplate between crossed polarisers

Application is improved cutting of metal via Polarisation control.

TRUMPF

HALO

SEVENTH FRAMEWORK PROGRAMME

HyPerBond Application – Assemblies

Gooch & Housego
ENABLING PHOTONIC TECHNOLOGIES

Current applications

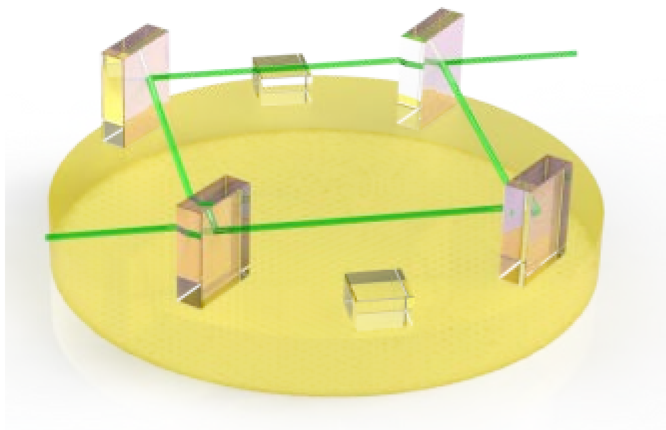
- Lightweighted structures in Zerodur.
- Zero outgassing assemblies for vacuum applications.
- Distortion free joining of thin plates – glass to crystal quartz waveplates.
- Attack resistant bonds for aggressive chemicals that attack epoxy.

Planned projects

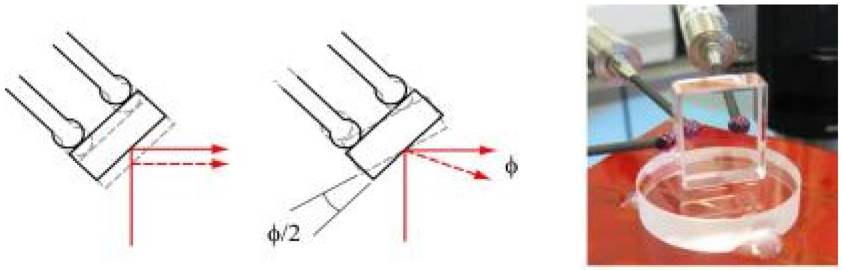
- Endcapping of laser crystals
- Formation of crystal waveguide structures
- Permanent optical breadboards

CEOI-ST 7th Call project

- Two Mach-Zehnder interferometer assemblies will be constructed using a precision optical readout to measure component placement control
  - One will use a variant of the LISA Pathfinder technique but with 'ground' bonding surfaces
  - One will use a mechanised placement of the components
    - This requires an additional interferometer to ensure the bonding surfaces are parallel as they are brought into contact
  - The quality of alignment achieved will be determined
  - The assemblies will be environmentally tested to increase the TRL of the procedures
- The process will be applied to EO projects



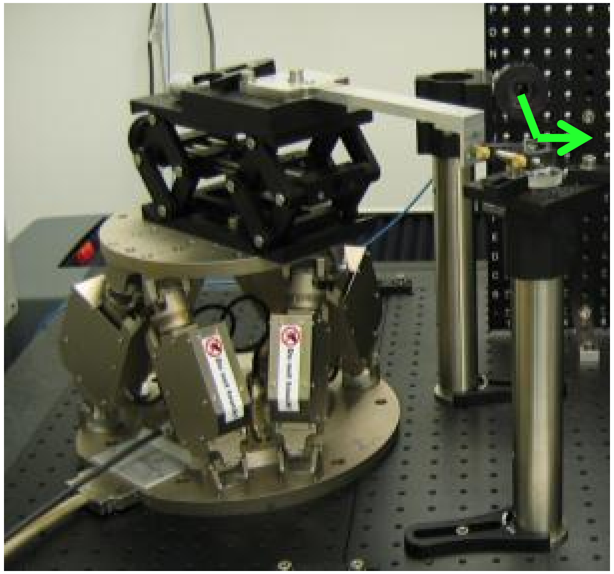
Conceptual CAD model of one of the Mach-Zehnder interferometers that will be constructed. The green line represents a laser beam, the yellow baseplate is 6" dia.



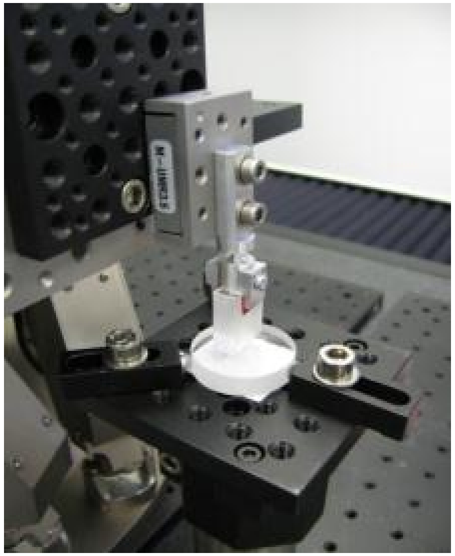
Sketch showing the alignment method used in LISA Pathfinder (a) lateral alignment, (b) angular alignment and (c) photograph of a test bond. The 'ground' surface bonds will be based on this method.

CEOI-ST 7th Call status

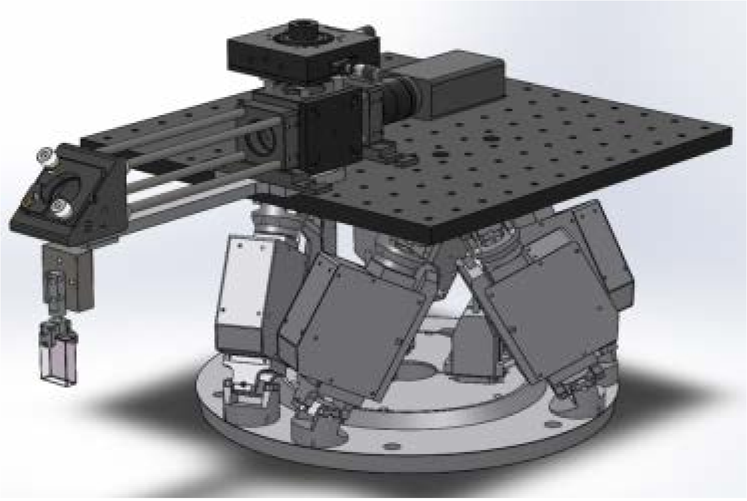
- Work is progressing well on the CEOI-ST mechanised bonding project
  - Piece parts are produced
  - Hardware is mainly assembled and readout software is nearly operational
  - Test bonds have been made
  - The two interferometers will be constructed and tested in the new year



A 6-axis hexapod being used to make preliminary alignment tests. The green line denotes a laser beam which is being reflected off a mirror and directed towards a beam measurement target



A bonding test of the optic holding mechanism.



CAD of the optic-placing hardware. Light is directed through the component and the return light used to ensure the bonding surfaces are parallel.

Summary

- Hydroxide-catalysis bonding is a versatile tool that has been developed for space science
- Further development has opened up new industrial applications
- Improving the processes for adjustable positioning and permanent bonding of optical assemblies will open up more opportunities
  - We aim for this to be of benefit to Earth Observation instrumentation

  - https://www.elisascience.org/whitepaper/
  - Robertson *et al*. Class. Quantum Grav. 30 085006 (2013)
  - Fitzsimons *et al*. Applied Optics, 52 (12). pp. 2527-2530 (2013)
  - Killow *et al.* Applied Optics, Vol. 52, Issue 2, pp. 177-181 (2013)
  - A. A. van Veggel and C. J. Killow, Adv. Opt. Techn. 2014; 3(3): 293–307
  - Search 'LISA Pathfinder' on YouTube


Any
Questions
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