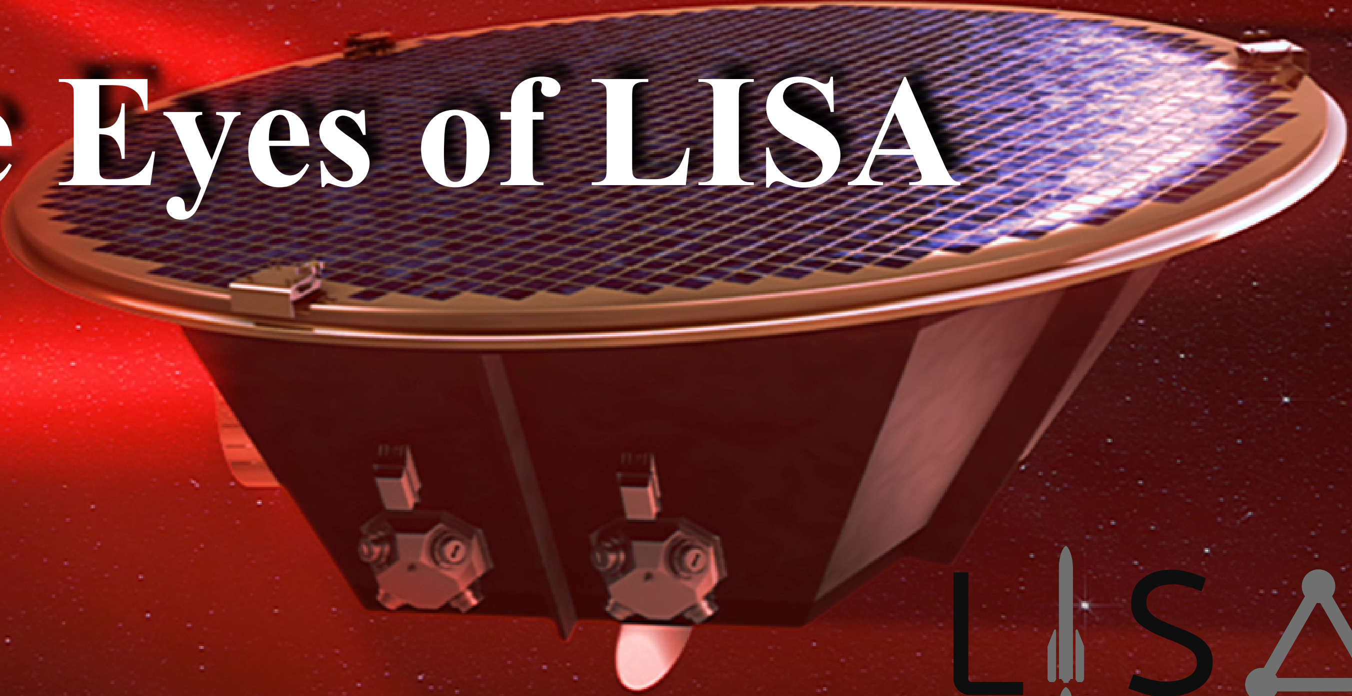
The Eyes of LISA



Nikhef

SRON
Netherlands Institute for Space Research

ESA | NASA lisa

NWO

LISA CONSORTIUM

T. Mistry, M.v. Beuzekom, N.v. Bakel, R. Cornelissen, M. Adams, G. Vissier, J. Zand, P. Dieleman, M. Frericks, P. Laubert, R. Wanders, L. Dubbeldam, G. Aitink, M. Siegl

What GW will LISA Measure

- GW Signals expected to stay inband for ~ 30 days.
- Data is processed on Earth.
  - ‘Time Delay Interferometry (TDI)’ algorithm used to combine the data from the three satellites.
  - TDI will create interferometer like signal to suppress laser frequency noise (similar to mirrors in ground based interferometers).
- LISA requires ~ 10^{-12} m accuracy whereas current ground-based interferometers are at the ~ 10^{-15} m level.

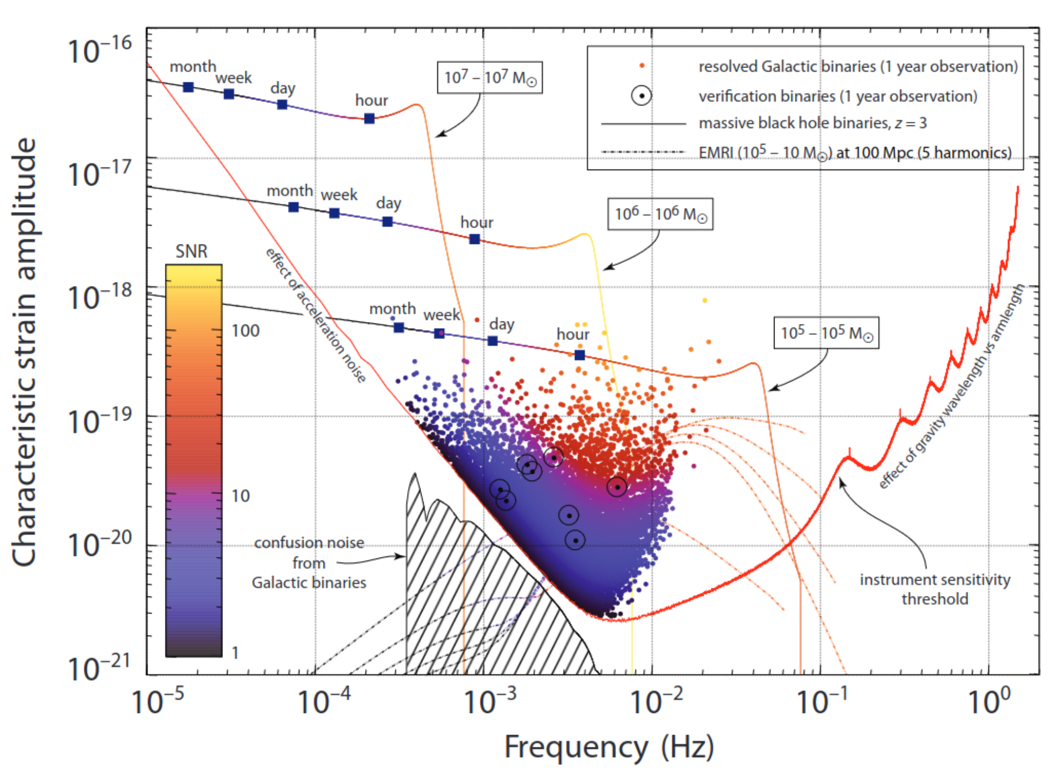


Image credit: LISA Mission Proposal for L3 submitted to ESA (LISA Consortium)

Where will LISA Measure GW?

- Heliocentric orbit lagging the Earth by ~ 20°
  - Location is a trade off between transfer vehicle ΔV, communication and mission lifetime.
- Not at a Lagrange Point!

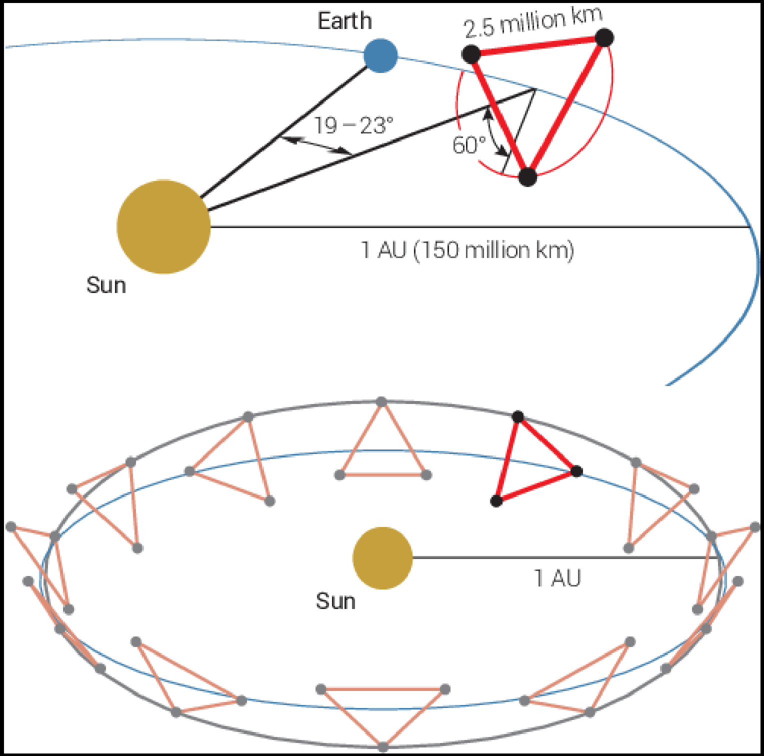
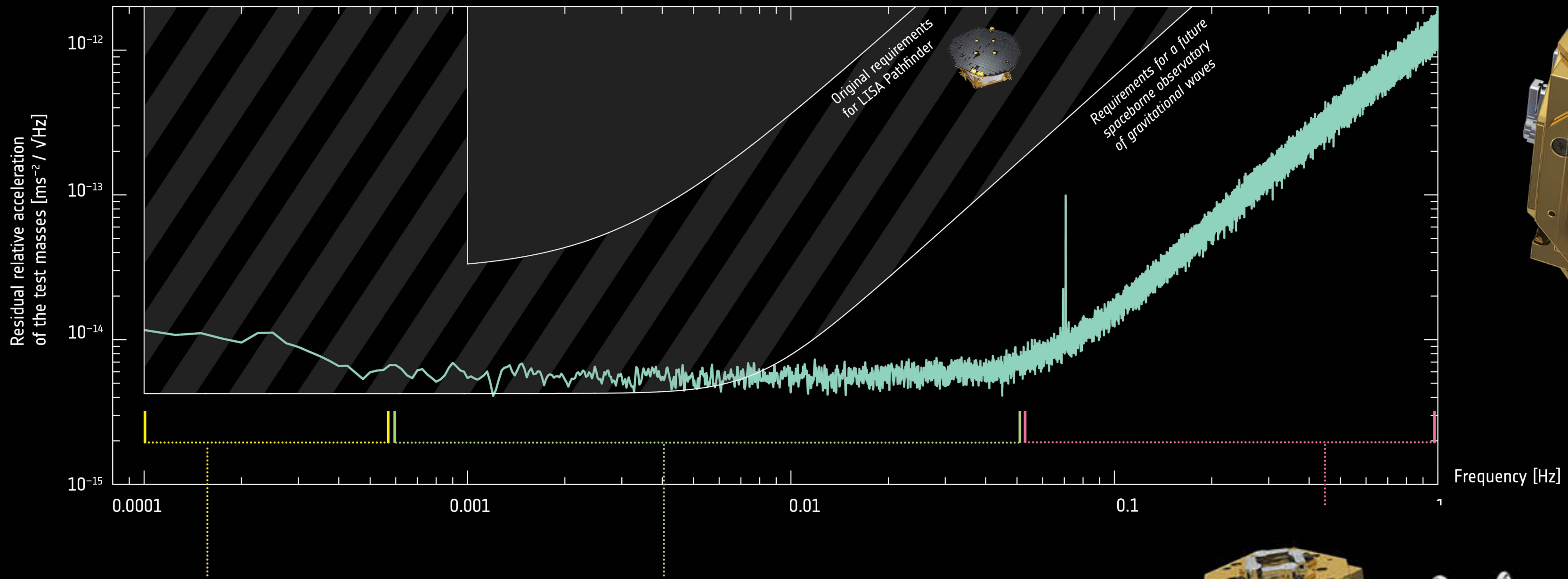
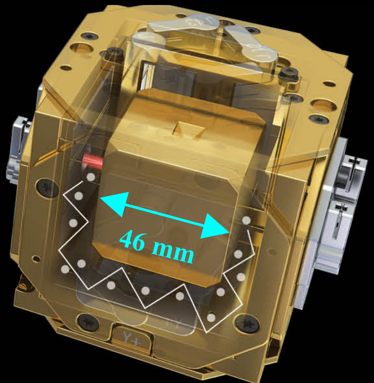


Image credit: ESA

→ LISA PATHFINDER EXCEEDS EXPECTATIONS

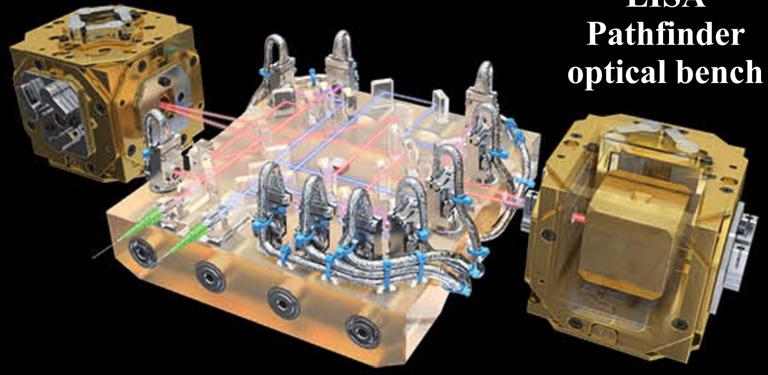




LISA Pathfinder test mass

LISA Pathfinder 2015-2016

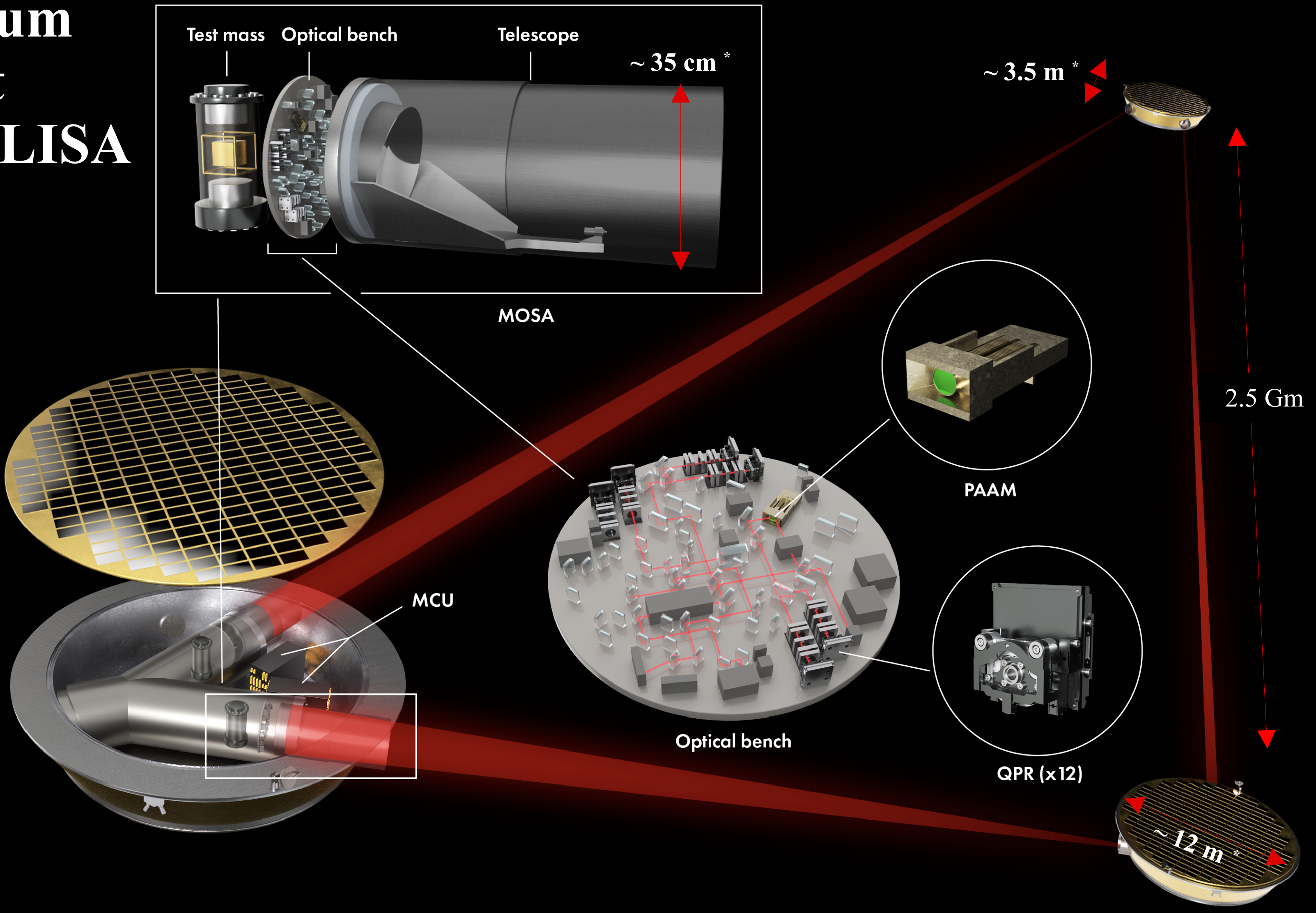
LISA Pathfinder optical bench



- Single craft demonstrator
- Technology demonstration for test mass and reference interferometery.
- Now time to develop full 3 spacecraft

Dutch + Belgium Instrument Contribution to LISA

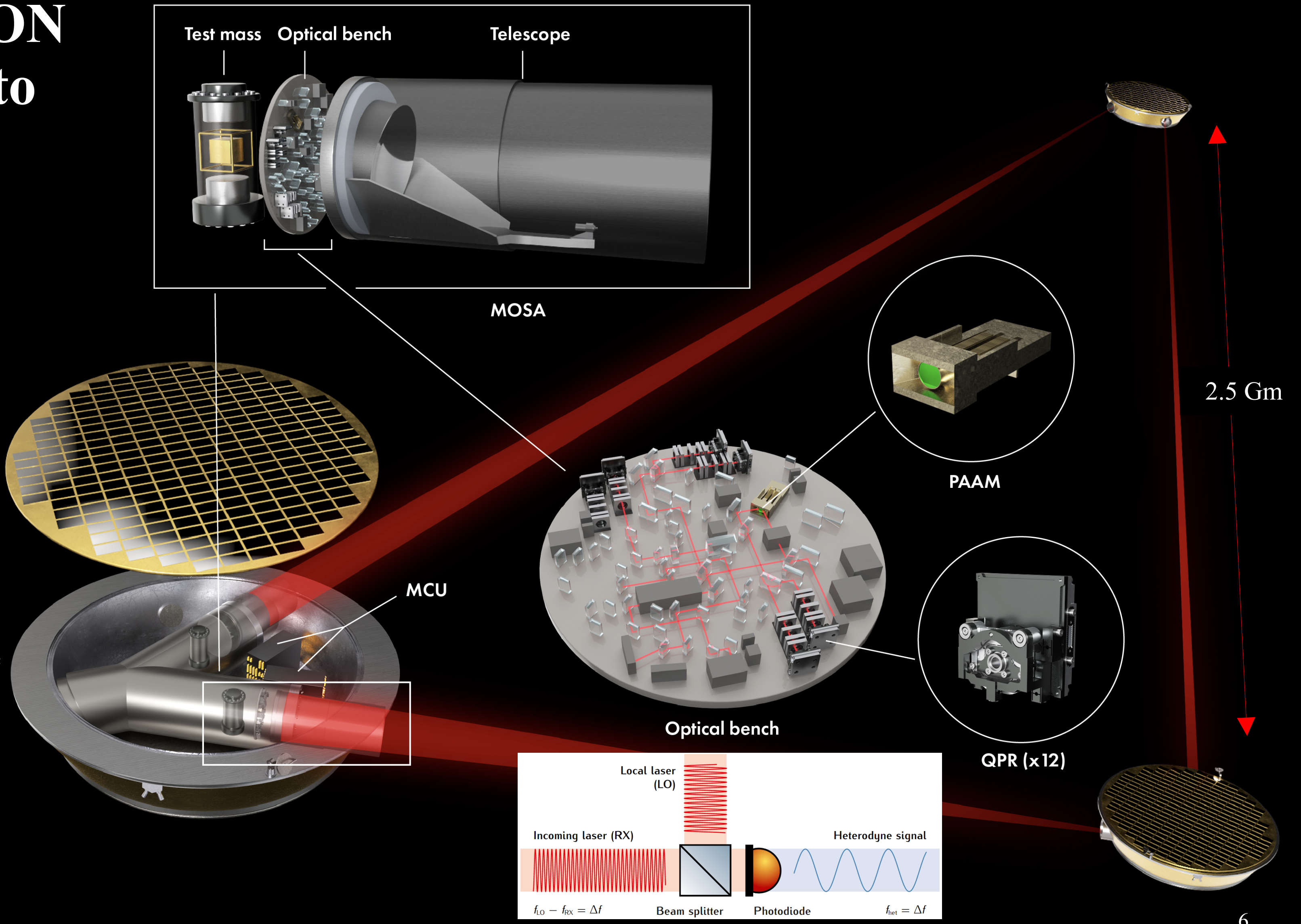
- First time developing long arm (science) interferometer.
- Three interferometers on each optical bench
  - Science
  - Test mass
  - Reference
- **72 quadrant photoreceiver (QPRs) systems will fly!**
  - **Plus 28 extra for ground testing.**
  - **120 total flight ready systems *.**



* Subject to change

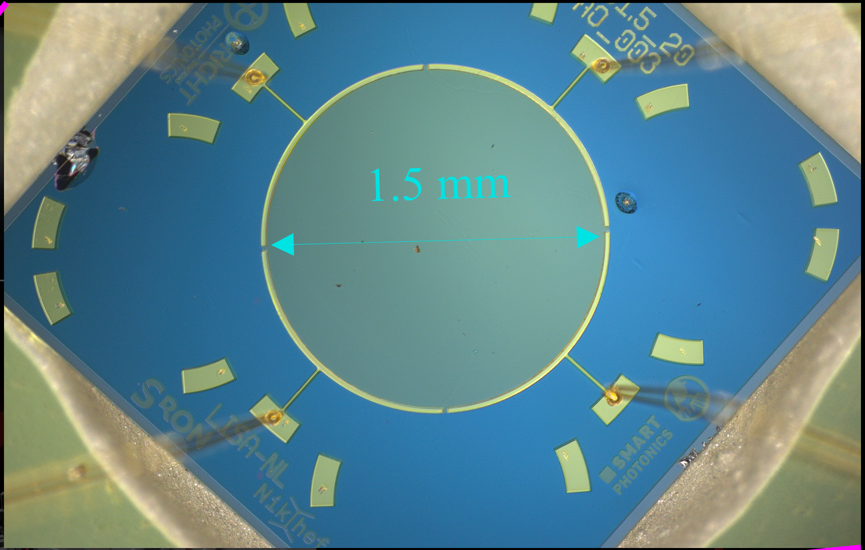
Nikhef and SRON Contribution to LISA

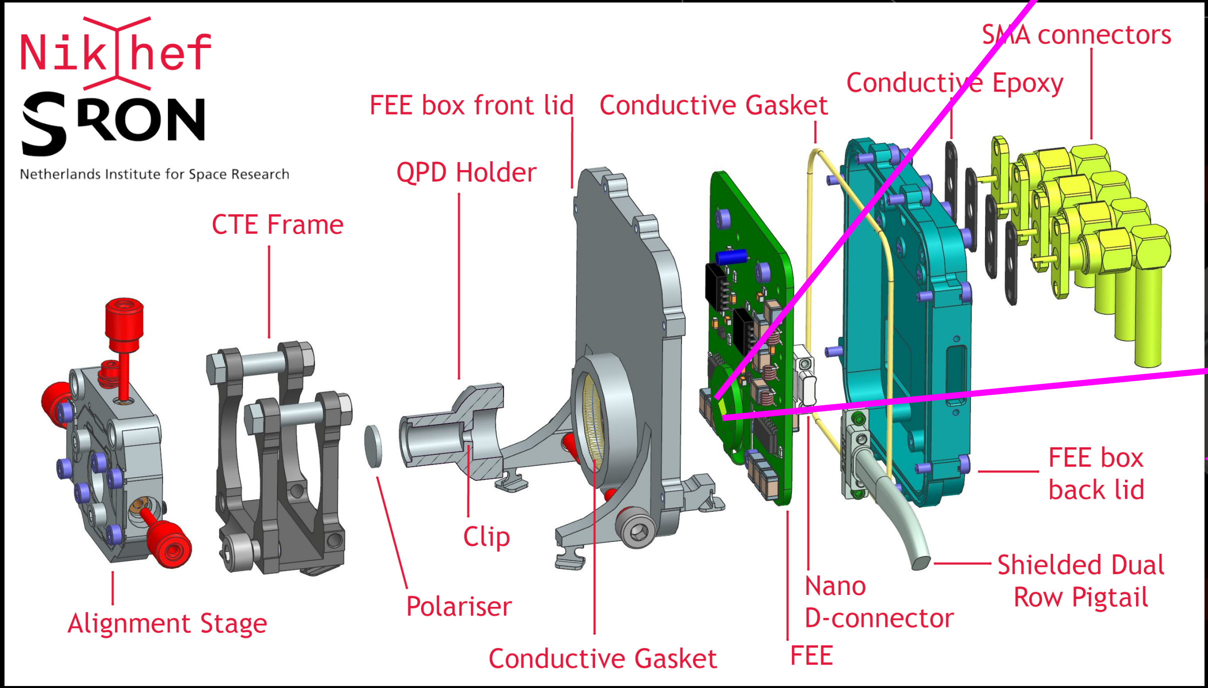
- Heterodyne signals from science interferometer.
  - 1-30 MHz beatnote frequency
  - Beatnote frequency changes due to satellite breathing.
  - QPR will measure the phase change of the beatnote.
  - ~300 pW light received from remote spacecraft.



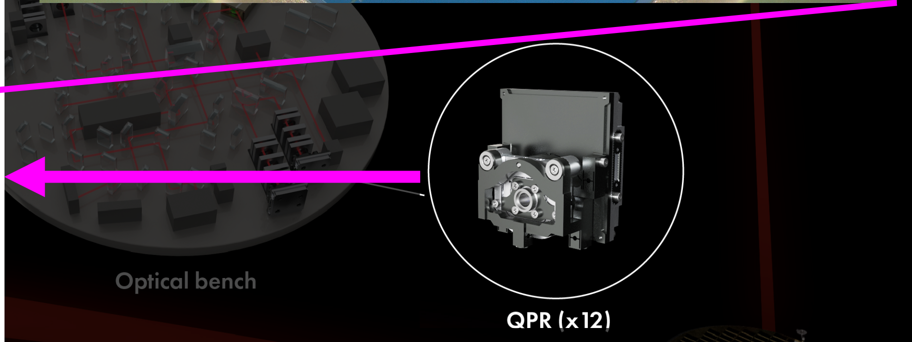
What is the Quadrant Photo-Receiver (QPR)?

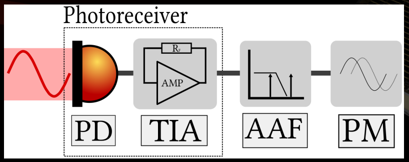
Quadrant Photo-Diode





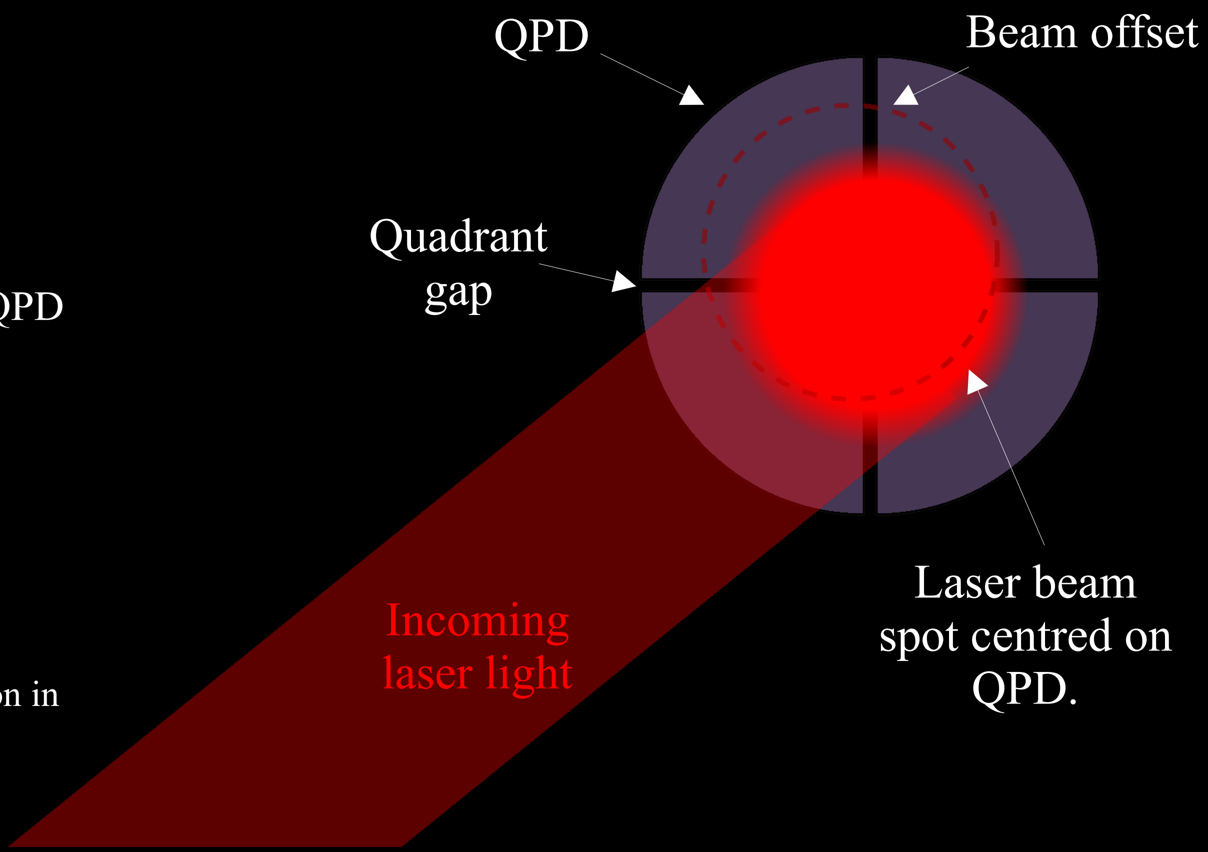
Housing





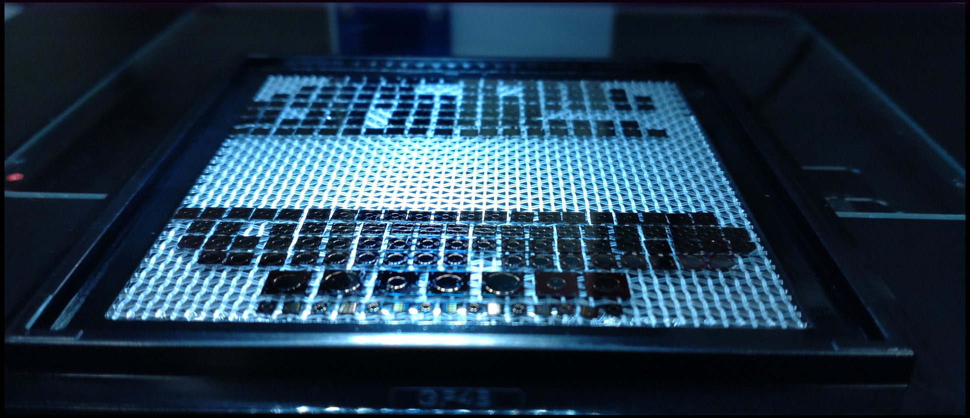
The Eyes of LISA – Why use QPDs?

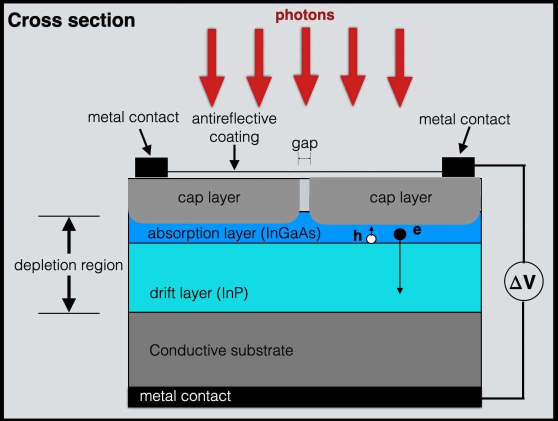
- Science signal – Common Phase
  - Single element.
- Alignment
  - Quadrant for alignment
- Science signal sets the specification of the QPD
    - Phase sensitivity of 6 µrad/√(Hz)
    - Received light ~ 300 pW
    - RF bandwidth 1 – 30 MHz
    - GW signal 0.1 mHz - 0.1 Hz
    - Long arm length accuracy ~ 10^{-12} m
  - Hence the need for low noise QPD.
    - Low capacitance via QPD thickness.
  - Custom diode made with a thickness uncommon in commercial photodiodes.
- Weight for SC!

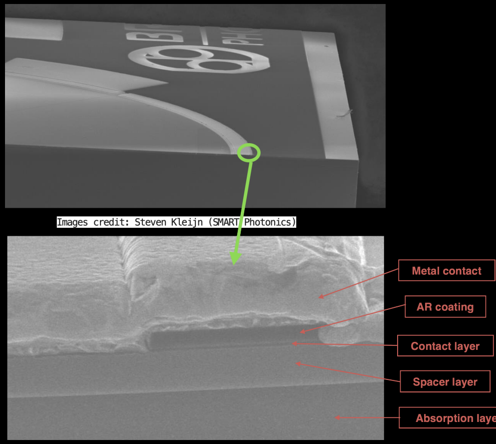


Manufacturing the LISA QPD

- Nikhef and SRON work in collaboration with Dutch industrial partners Bright Photonics (and SMART Photonics*) to develop new photodiodes.
- Extra thick drift layer
  - Extremely low doping for reasonable bias voltage (uncommon/challenge).
- Molecular beam epitaxy
  - Build up layers from a seed (bulk) material.
- Capacitance compromise between thickness and area which determines noise.





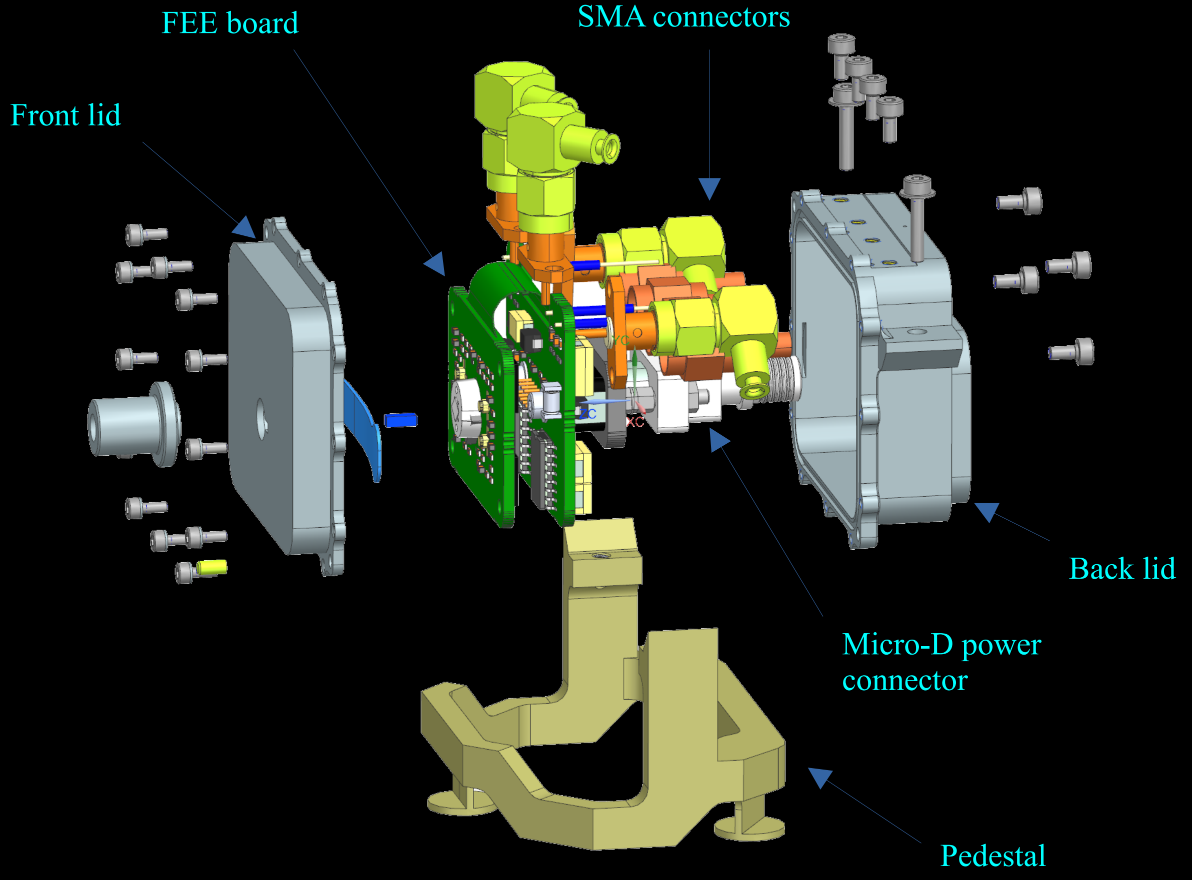


Top: Various QPDs in a transport pack. Lower Left: Cross section of the layers of the QPD (not to scale). Lower Right: SEM image of the metal contact (credit: SMART Photonics).

* No longer part of QPD development

Housing Design Challenges

- Alignment of QPD into housing
- Electromagnetic compatibility
  - Large isolation required from the power radiated by communication antenna of spacecraft.
- Thermal and vibrational stability.
- Packaging compatibility with optical bench.
- Space environment adds an additional level of complexity.



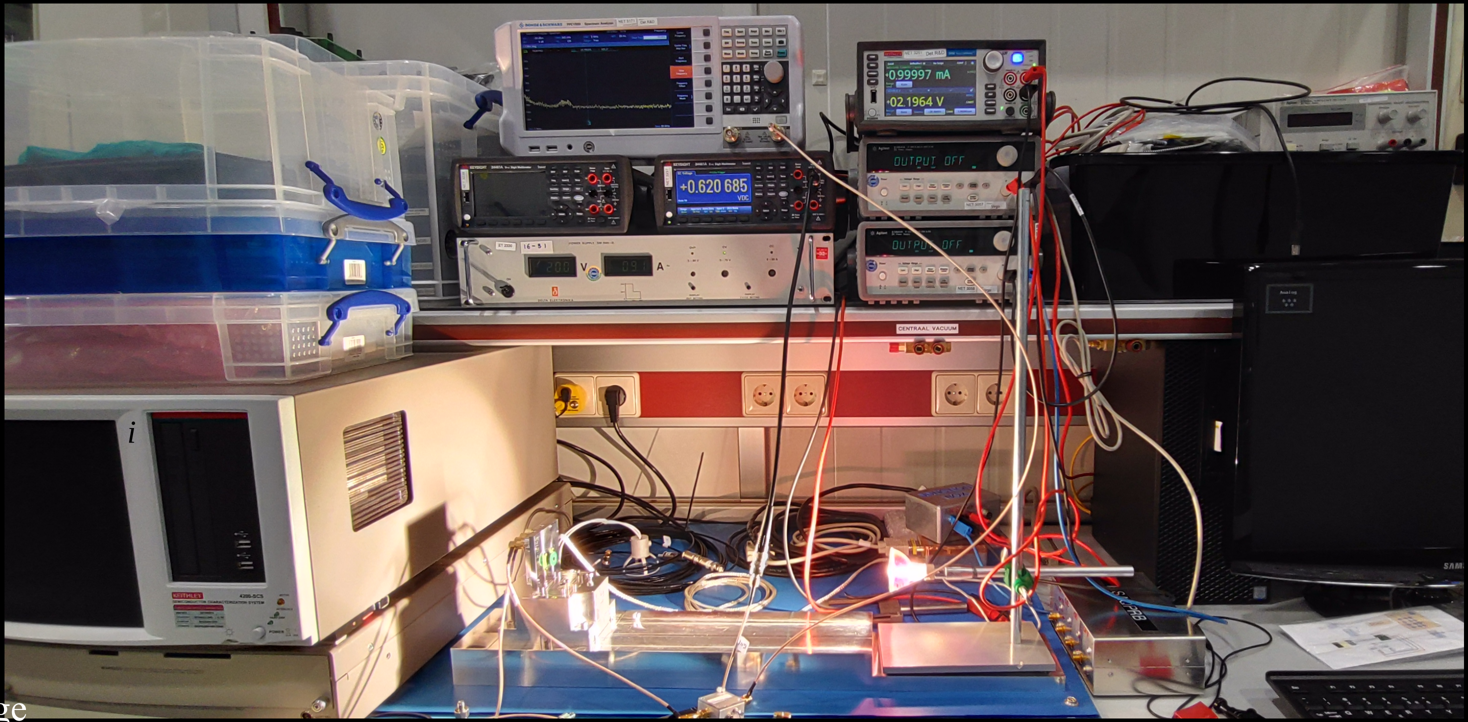
Noise Measurements

- Equivalent input current noise.

$$i_{EN} = \sqrt{\frac{i_{shot}^{2}}{\left(\frac{V_N}{V_{EN}}\right)^2 - 1}}$$

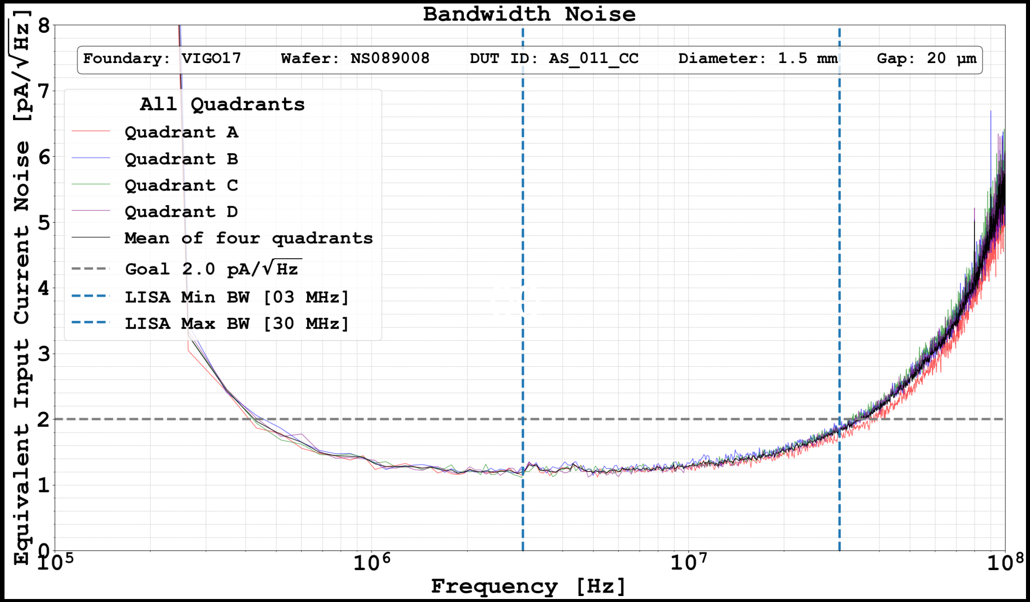
Measured voltage when the light is on

Measured voltage when the light is off

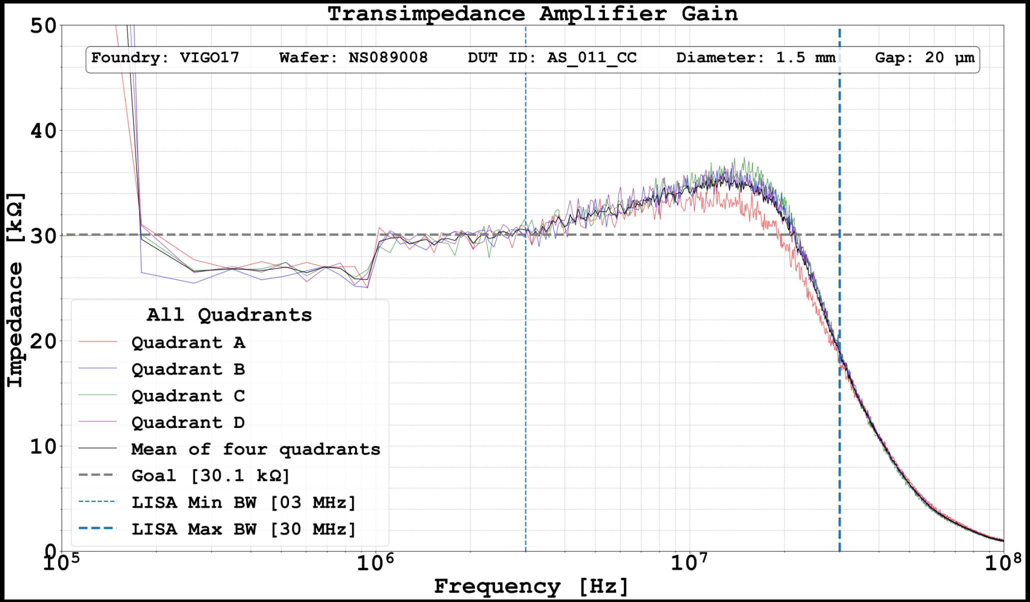


Noise Measurements

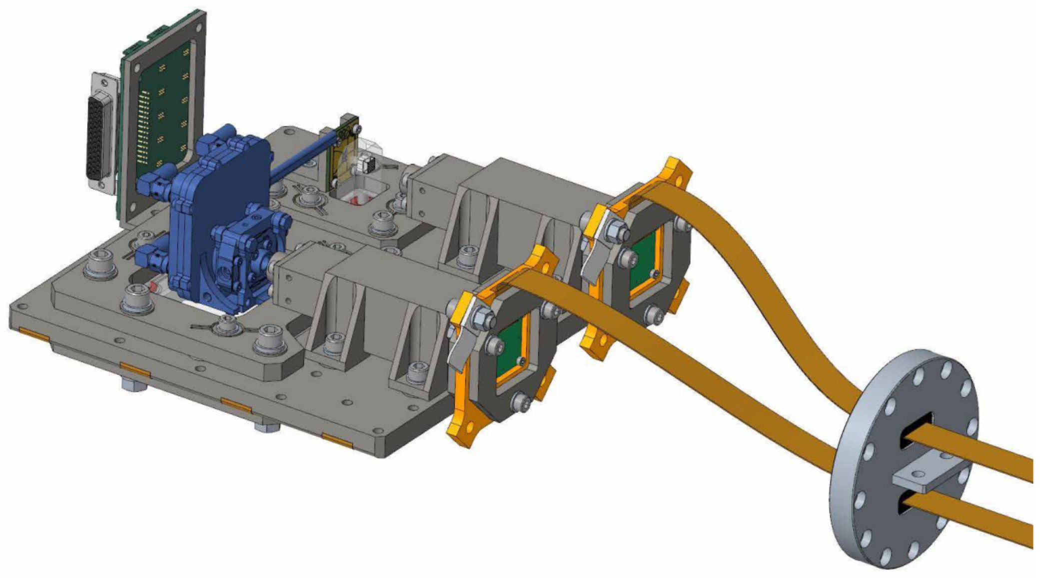
Photodiode Noise

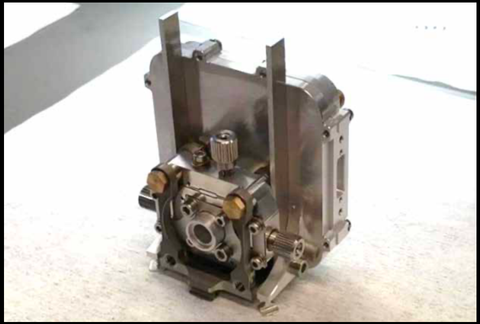


Amplifier (Gain) Performance



Thermal Vacuum and Vibration Tests



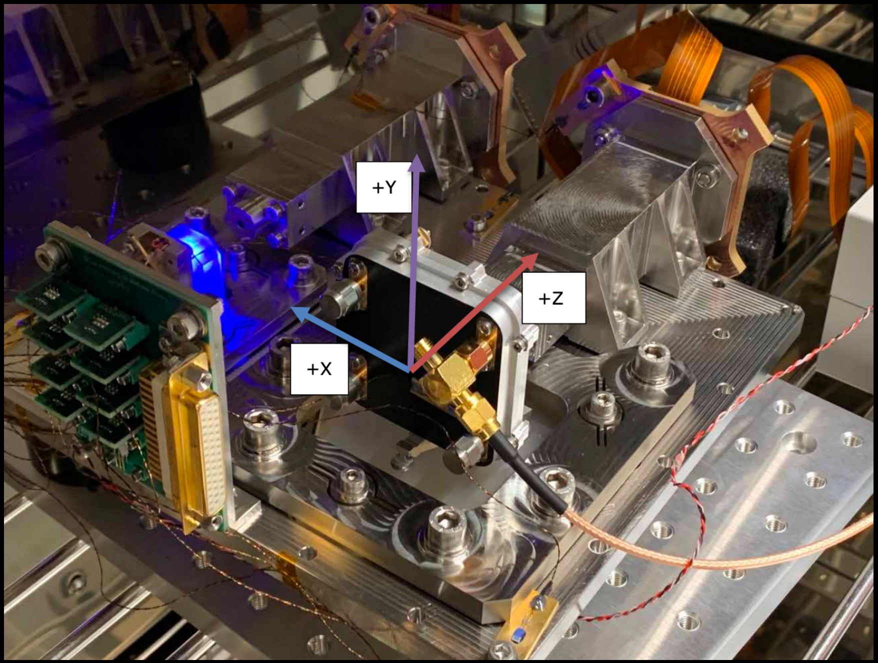


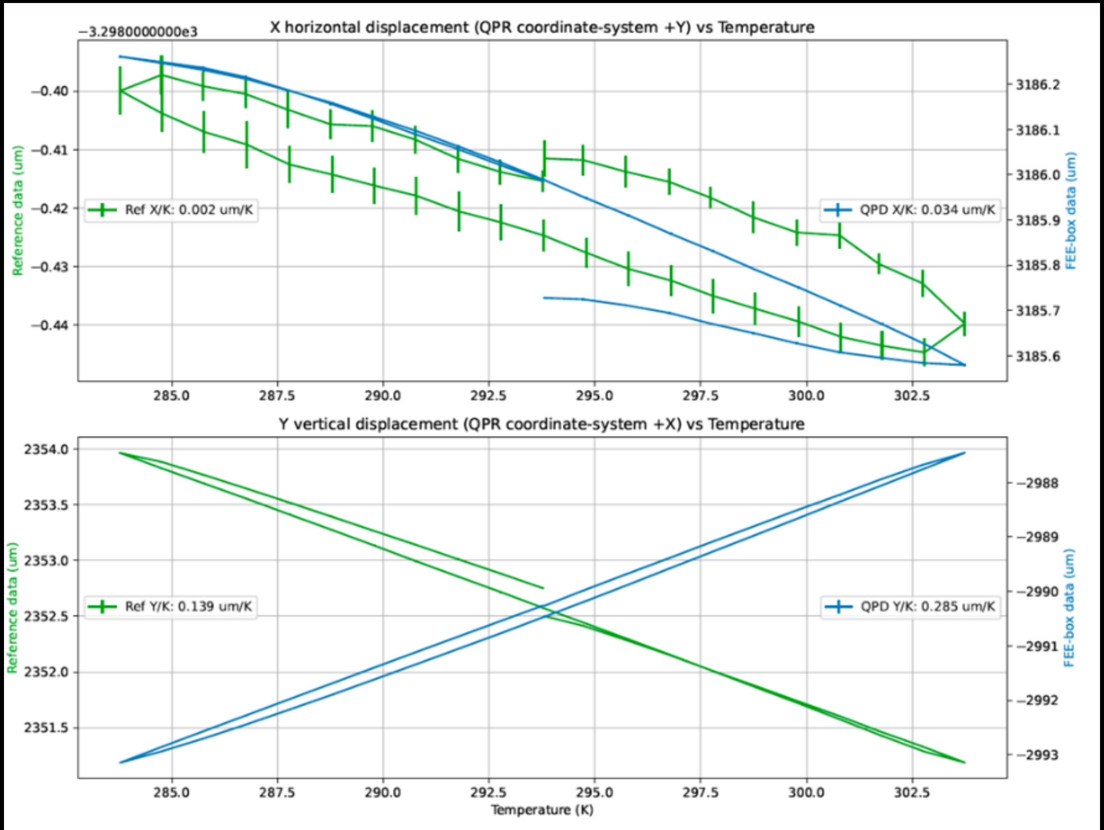
Top: CAD render of thermal vacuum set-up.

Left: Prototype QPR used for testing.

- We need to perform thermal tests under vacuum.
- The QPD thermo-mechanical stability shall be <0.10 µm/K
- For the vibration tests the resonance frequencies need to be known and are simulated. Exact vibration load from ESA not known yet.
- The QPD positional hysteresis under standardized vibration loads shall be <0.25 µm
- Use a reference target to compare to the QPD.
  - Measurements utilise the RASNIK method.
- Testing performed at SRON

Displacement vs Temperature Tests

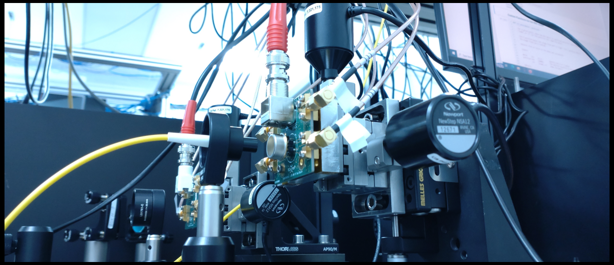




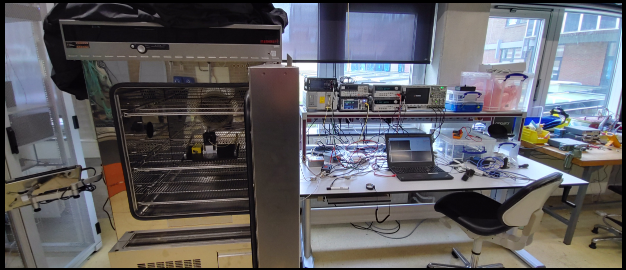
- Results show good agreement in X but not in Y.
- Strange behaviour between the reference system and the prototype.

Qualifying a QPR for LISA

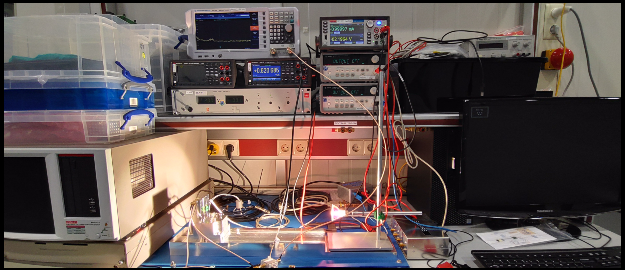
Crosstalk and Uniformity



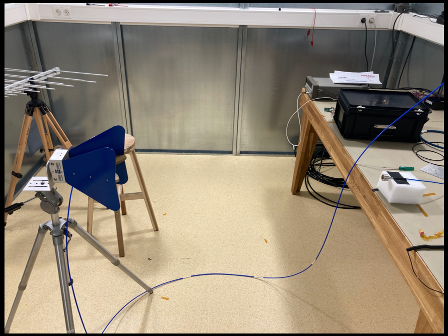
Phase versus Temperature



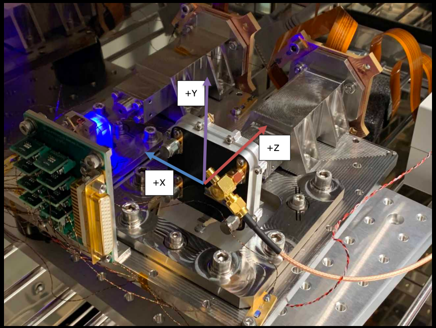
Bandwidth Noise and Gain



Electromagnetic Compatibility



Vibration, Vacuum and Temperature



Quality Assurance

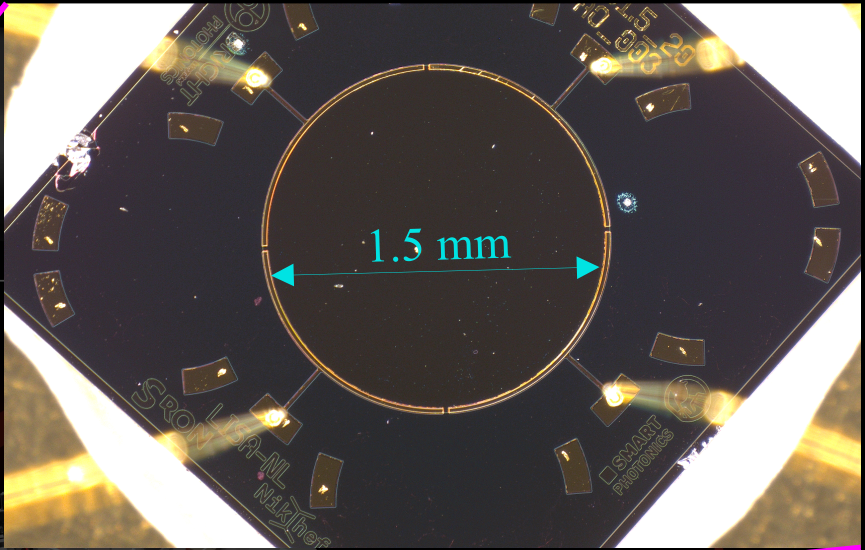
Conclusion and Outlook

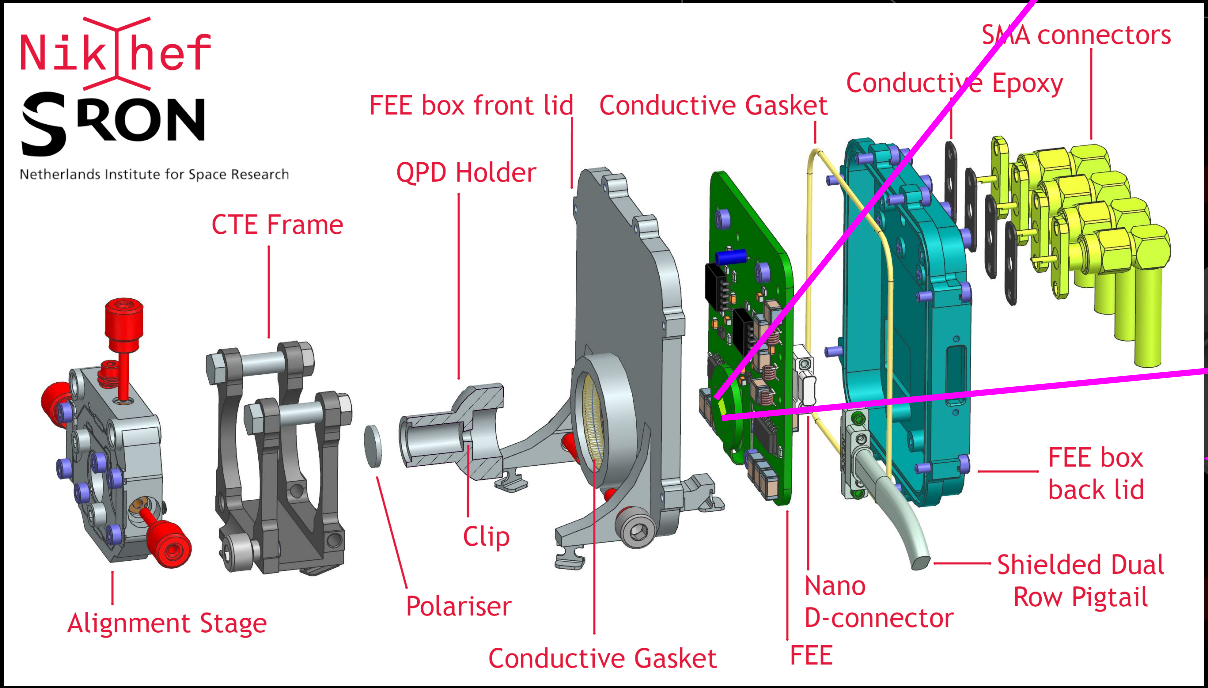
- Successfully demonstrated that the current (Run 1) Nikhef-SRON QPD design meets LISA specification.
  - 2nd run QPD improves on 1st run QPD.
  - Flight ready QPDs expected to be delivered early 2024.
- Underwent Technology Readiness Assessment with ESA.
  - Qualifying hardware for space that meets strict LISA requirements is a challenge.
- Continue to improve housing and FEE to meet ESA requirements.
- Developing test procedures for LISA optical bench intergration.
- On track for mission adoption ~ Jan 2024.
  - First QPR systems ~ End 2025
  - Launch ~ 2035

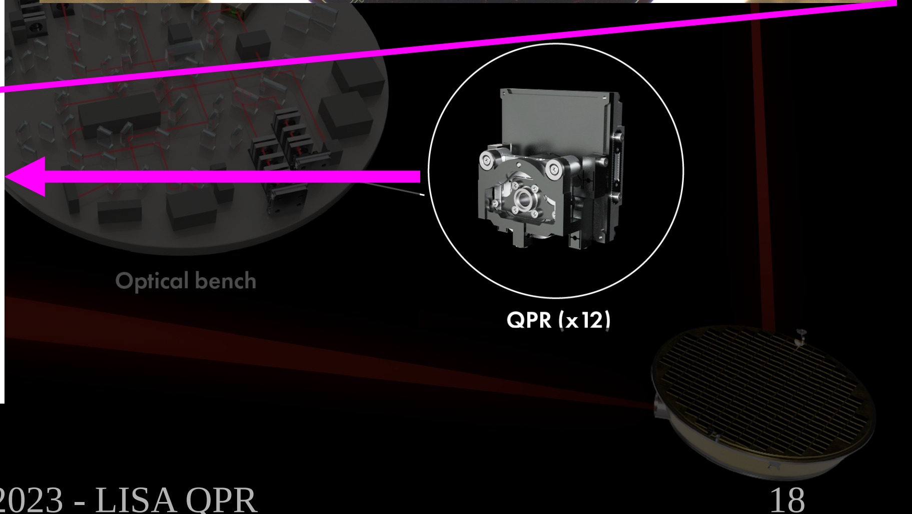
Back-Up

What is the Quadrant Photo-Receiver (QPR)?

Quadrant Photo-Diode







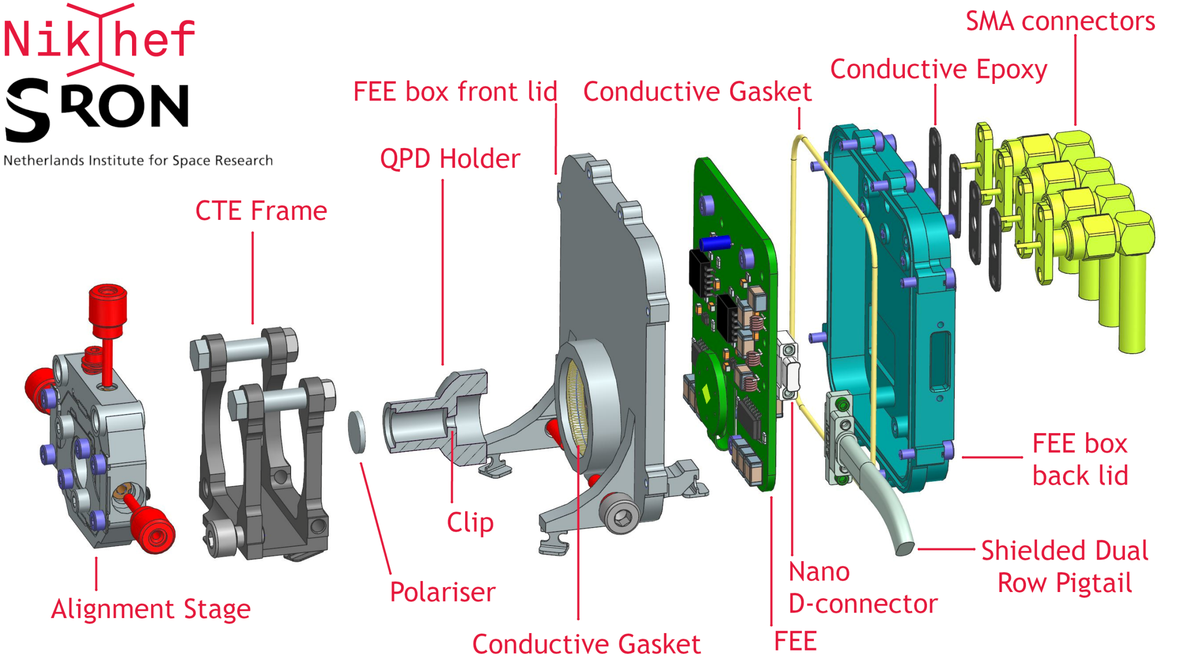
Housing

Housing Design Challenges

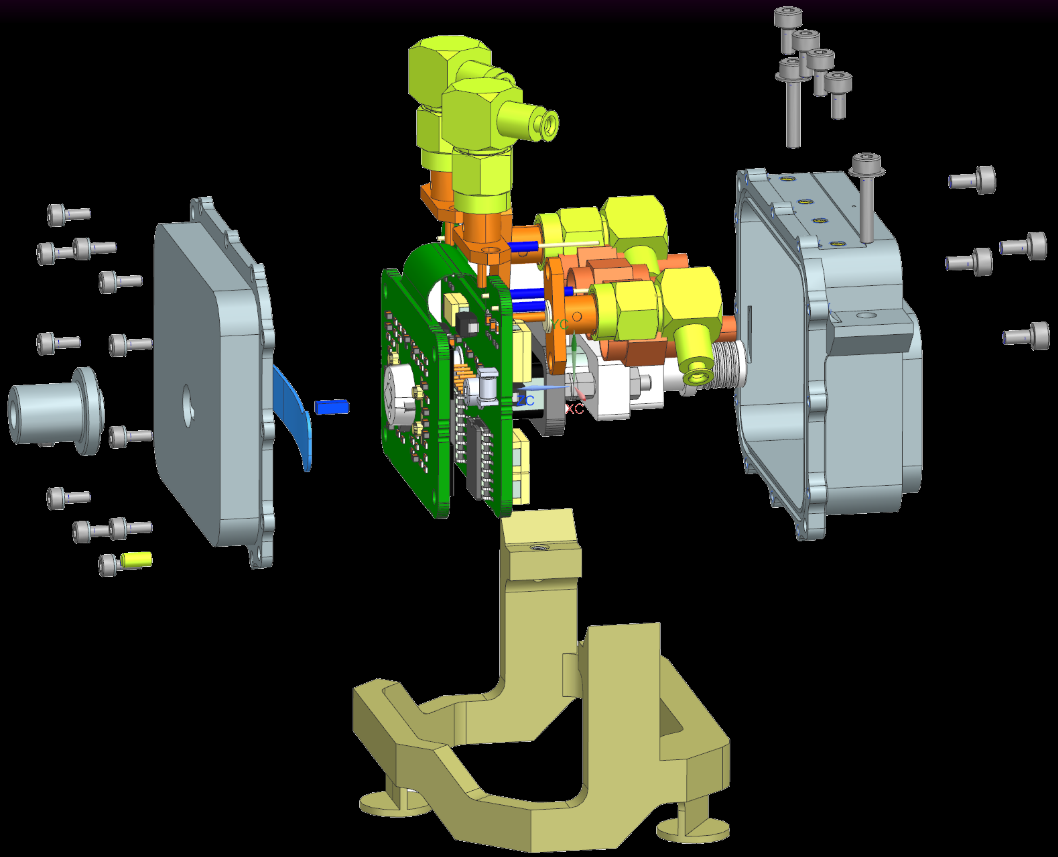
- Alignment of QPD into housing
- Electromagnetic compatibility
  - Large isolation required from the power radiated by communication antenna of spacecraft.
- Thermal and vibrational stability.
- Packaging compatibility with optical bench.

Nikhef

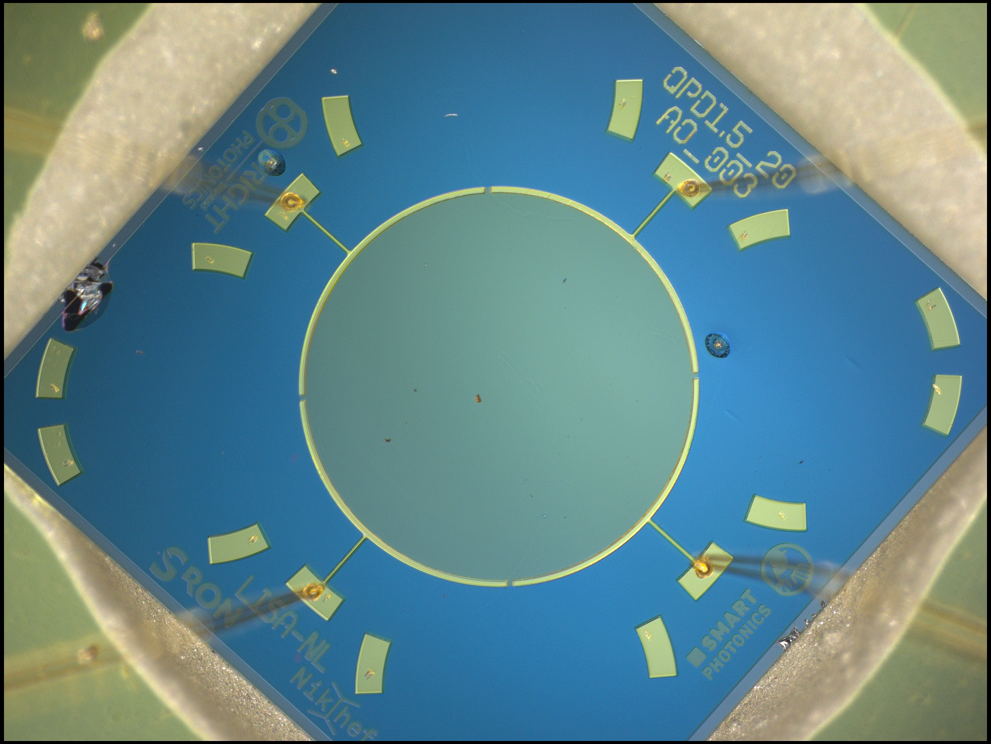
SRON
Netherlands Institute for Space Research

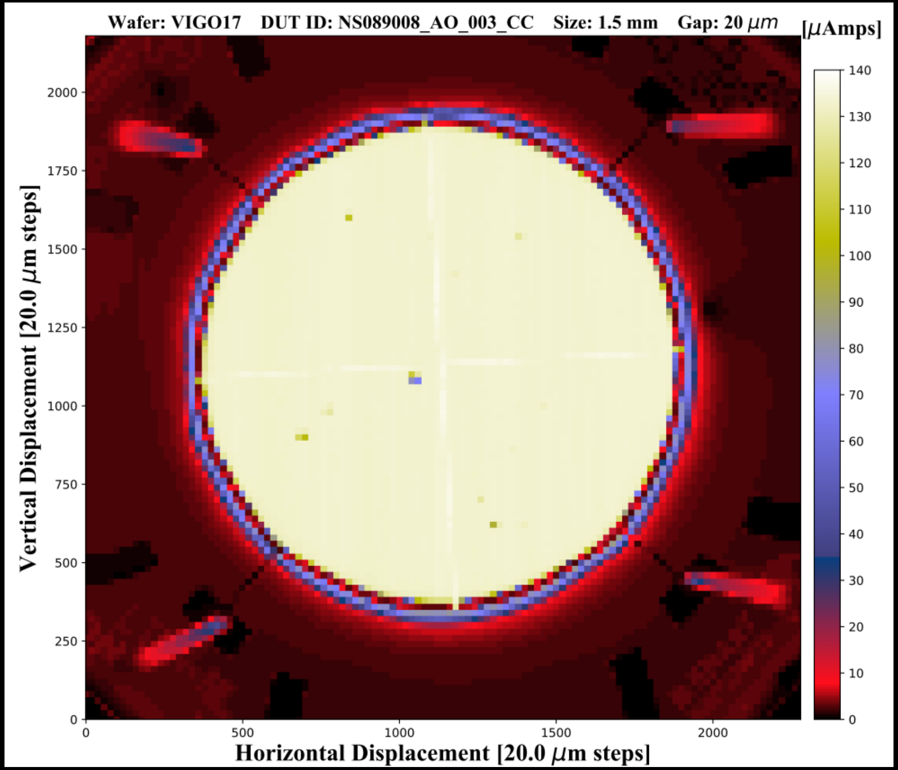


Housing 4



QPD Uniformity



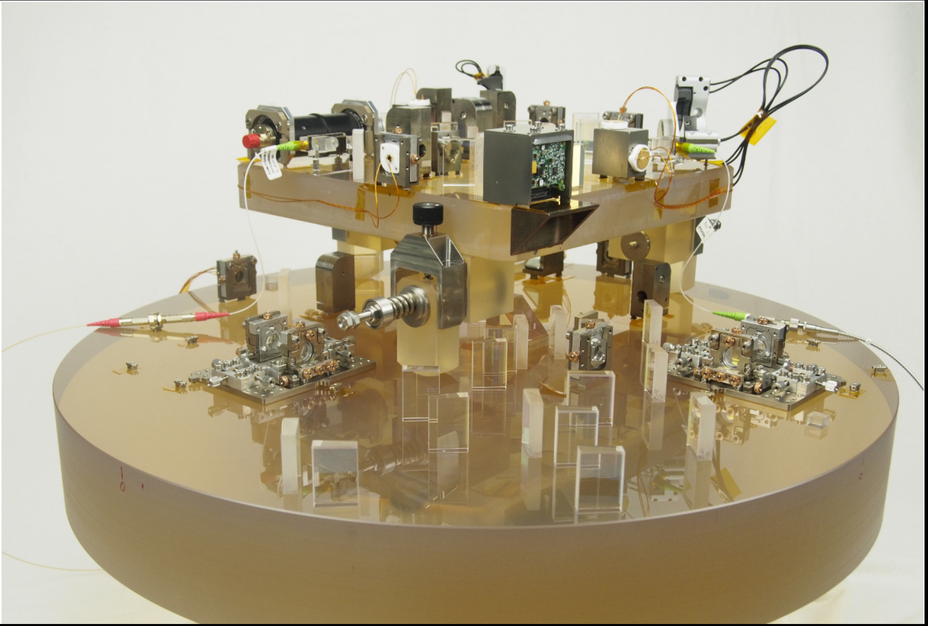


Location of Dutch Labs

Image credit:
https://www.iamexpat.nl/expat-info/the-netherlands/dutch-maps

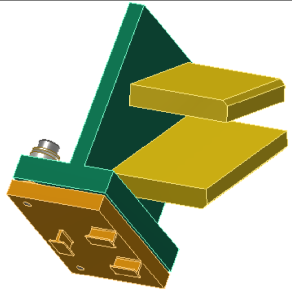
Testing the LISA Long Arm

- Pick and place robot, with a hexapod final stage, will precisely place optical components.
- Positions verified using co-ordinate measurement machine (CMM)
- Optical benches will be built in Glasgow (UK).



LISA optical test bench with a reduced number of components.

Image credit: L. d'Arcio, et al., "Optical bench development for LISA," Proc. SPIE 10565, International Conference on Space Optics — ICSO 2010, 105652X (20 November 2017); https://doi.org/10.1117/12.2309141

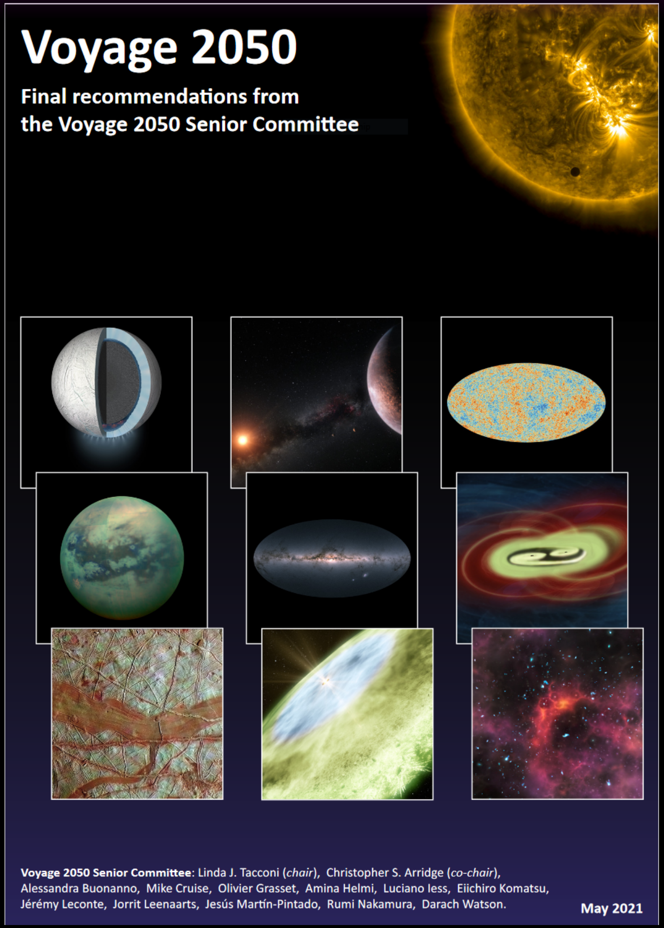


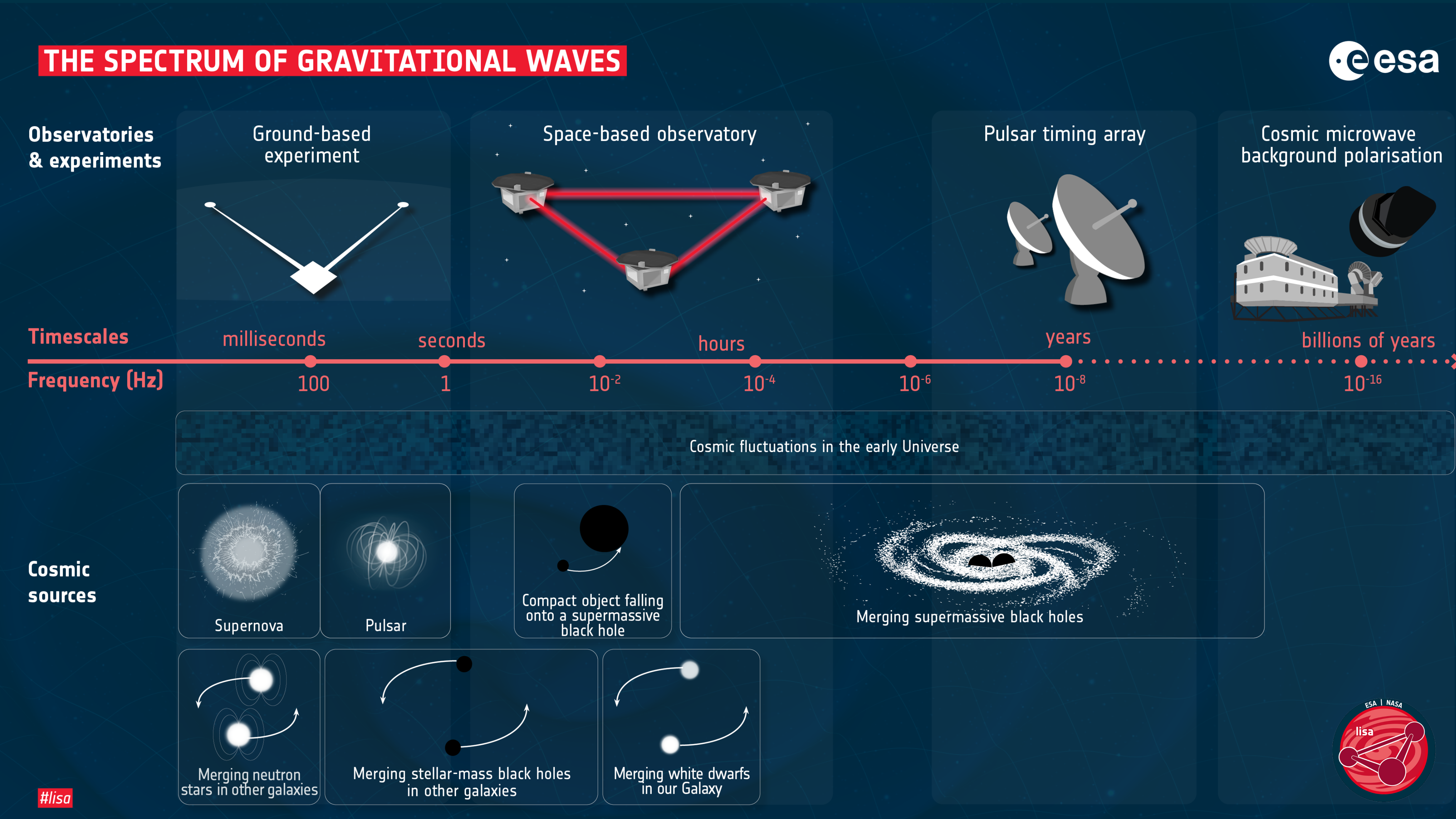
CAD drawing of LISA beam dump.

Image credit: William Brzozowski, et al. "The LISA optical bench: an overview and engineering challenges", Proc. SPIE 12180, Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave, 121800O (27 August 2022); https://doi.org/10.1117/12.2627465

A Brief History of LISA

- 1993 – M3 proposal for 4 spacecraft ESA/NASA collaborative mission
- 1995 – LISA selected as ESA Cornerstone
- 1997 – 3 spacecraft ESA/NASA LISA proposal
- 2005 to 2011 – Mission directive changes to ESA –led mission called eLISA (evolving LISA)
- **2013 – LISA becomes a flagship mission for ESA.**
- 2015 – Launch of LISA pathfinder.
- 2016 – LISA pathfinder reaches orbit and mission start
  Nikhef + SRON join the party!
- 2017 – LISA pathfinder mission end. LISA proposal
- **2024 – Mission adoption by ESA selected as ESA L3 mission.**




THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
ESA | NASA
lisa
#lisa

What GW will LISA Measure

Space + Ground Based

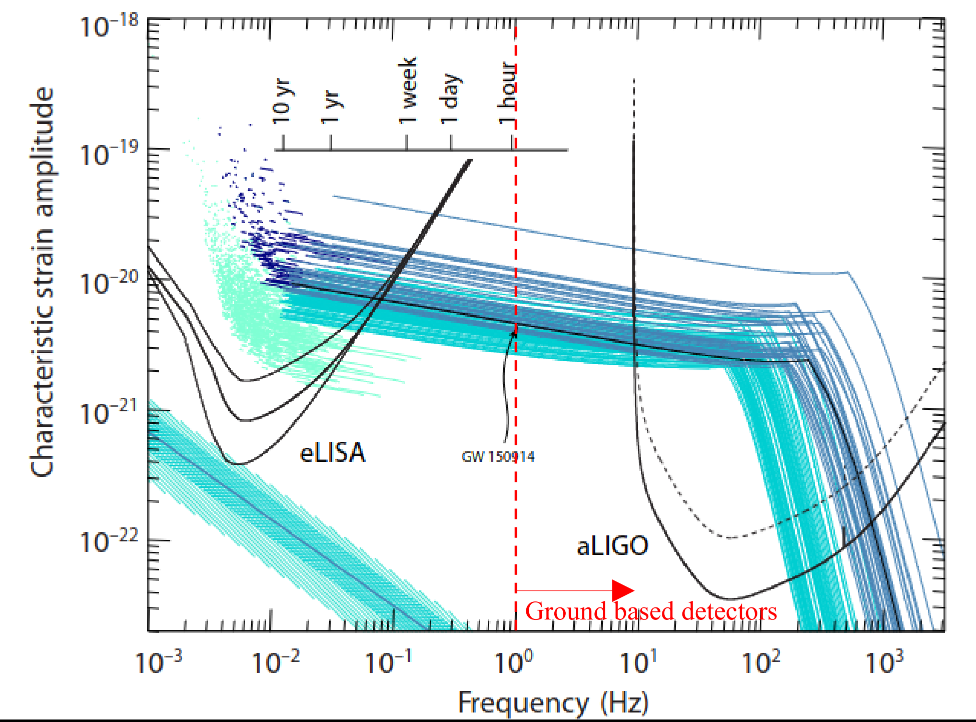


Image credit: LISA Mission Proposal for L3 submitted to ESA (LISA Consortium)

Current and Future Ground Based

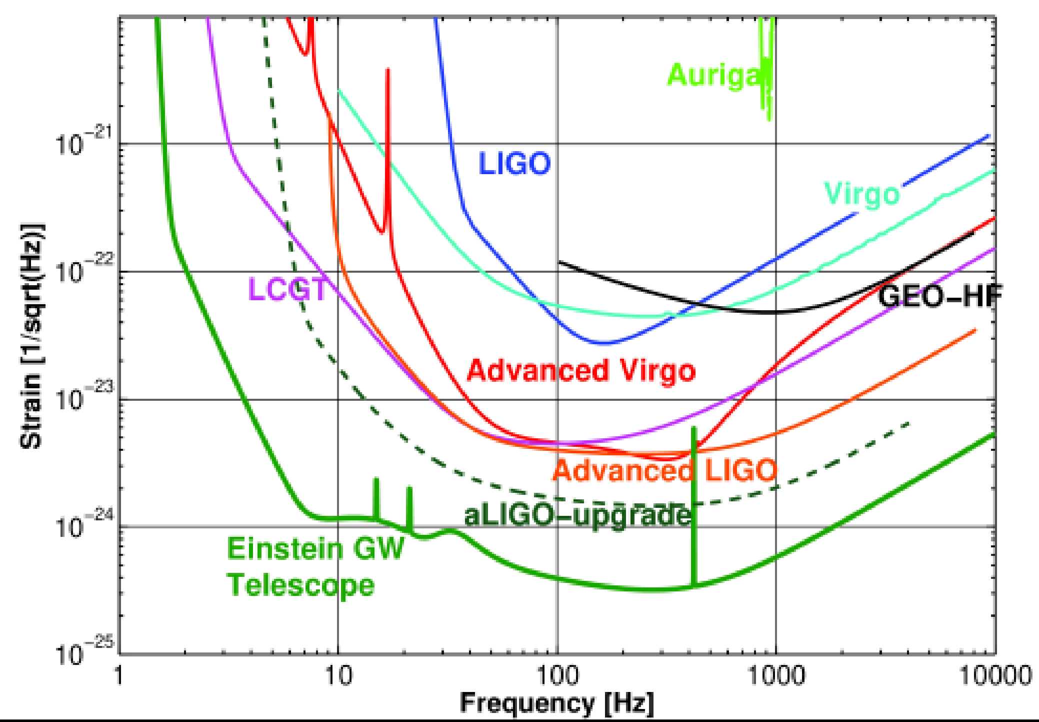
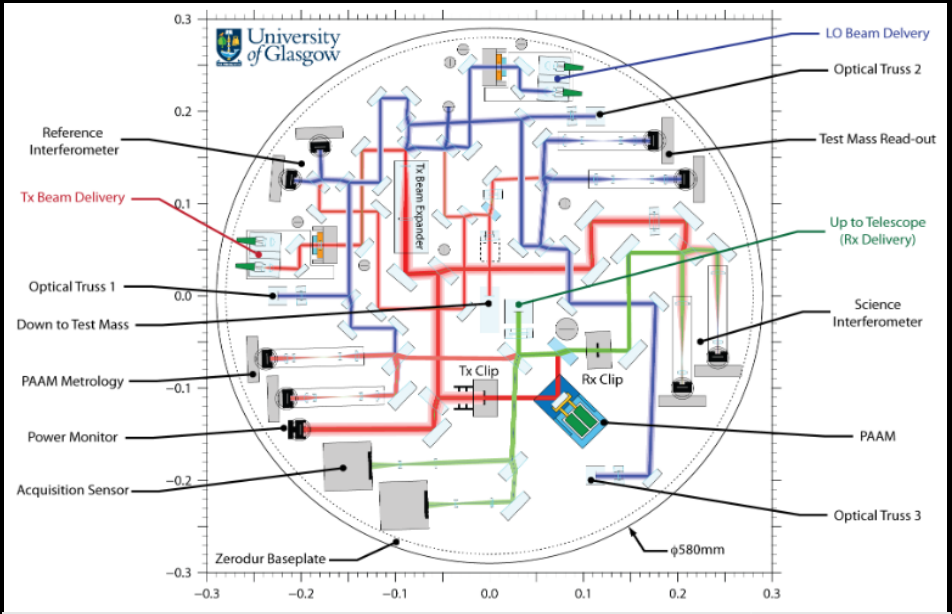


Image credit: Hild, S. (2012) 'Beyond the second generation of laser-interferometric gravitational wave observatories', Classical and Quantum Gravity. IOP Publishing, 29(12), p. 124006. doi: 10.1088/0264-9381/29/12/124006.

LISA Optical Bench

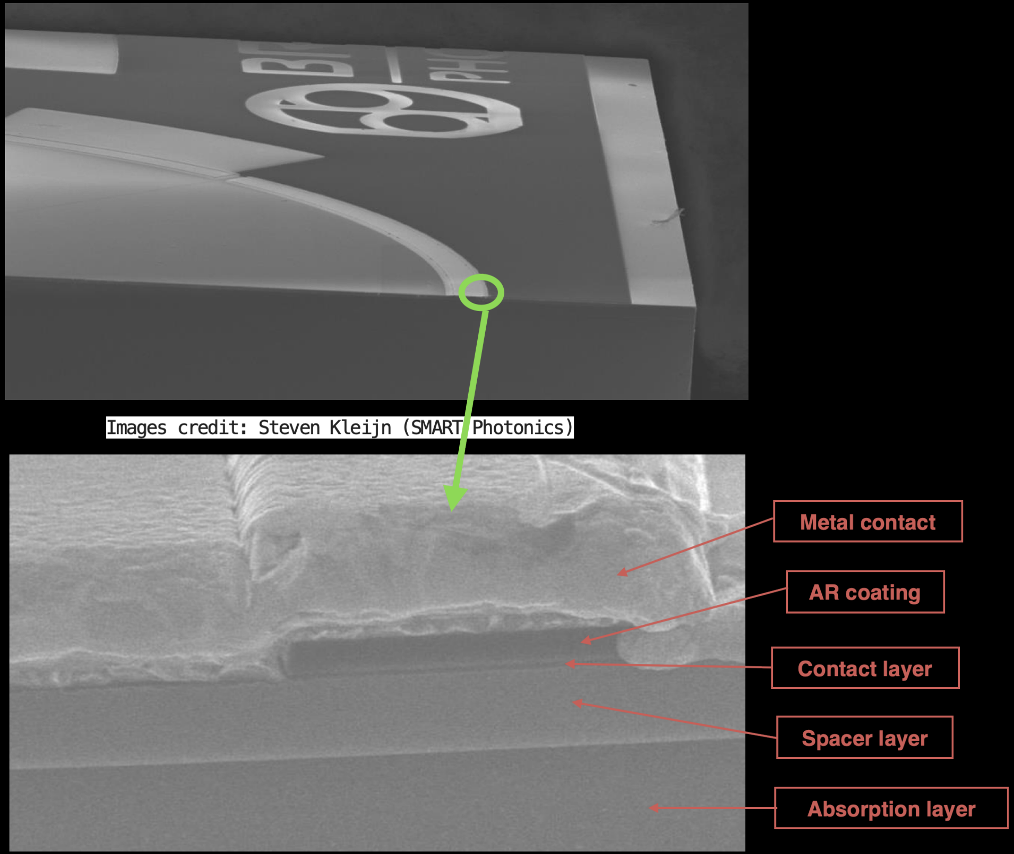
- ~350 mm diameter Zerodur ceramic glass optical bench.
- Optical components made from fused silica.
- Three interferometers per optical bench.
- Components need to be placed with micron level accuracy.



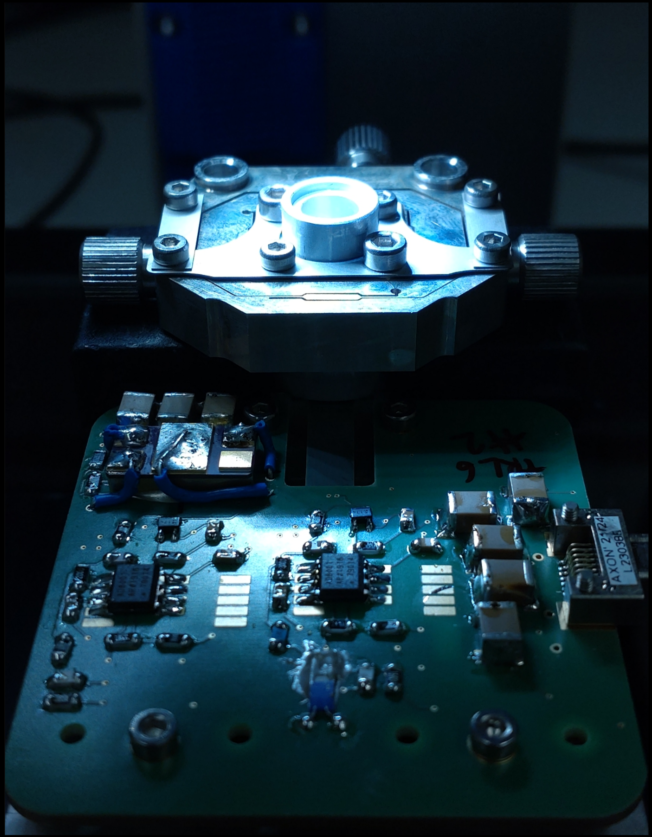
Error Source	Allocation @ 5 mHz
Long Arm Interferometry (including full TX and RX paths on the OB)	$8.72\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Proof Mass Optical Readout (per Proof Mass)	$1.42\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Coupling of Spacecraft Attitude Dynamics to RX piston on Science Interferometer	$1.20\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Coupling of Spacecraft Attitude Dynamics to TX piston in far field	$1.20\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Coupling of Proof Mass Attitude Dynamics to PM ORO piston	$1.06\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$
Total Budget for a single OB	$9.06\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$

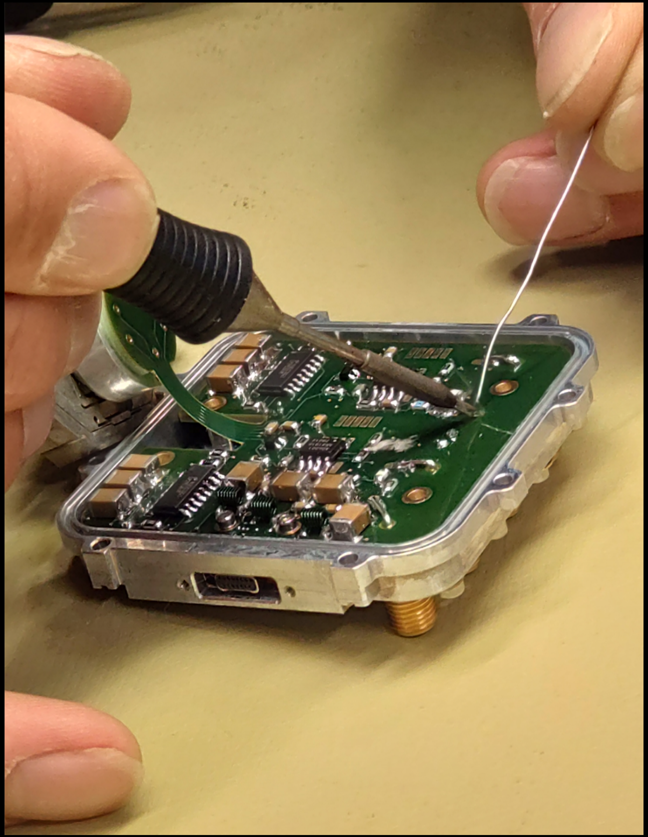
General Specification of LISA QPD

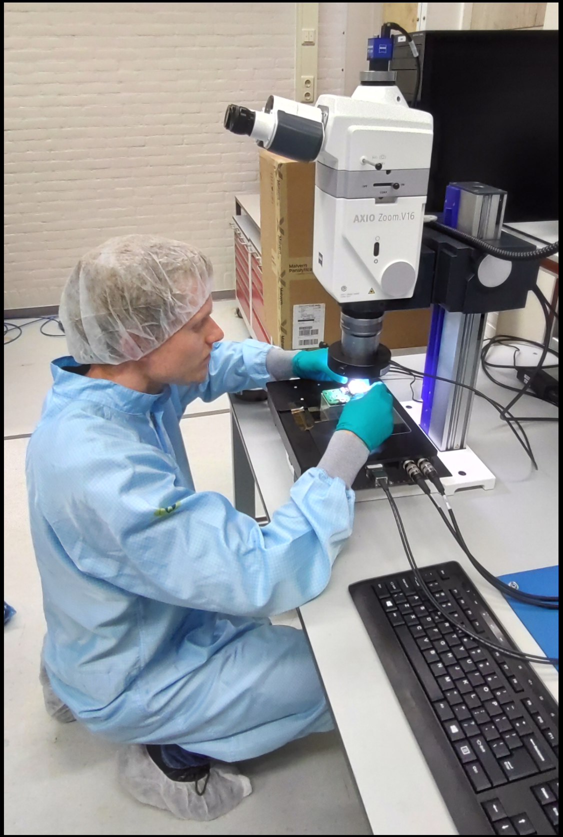
- Thickness ~ 20µm
- Capacitance 5 pF
- Diameter 1.5 mm
- Quantum Efficiency 0.8 A/W
- Reverse bias voltage 15-28 V to fully deplete the diode.



Building the (Housing 3) QPR

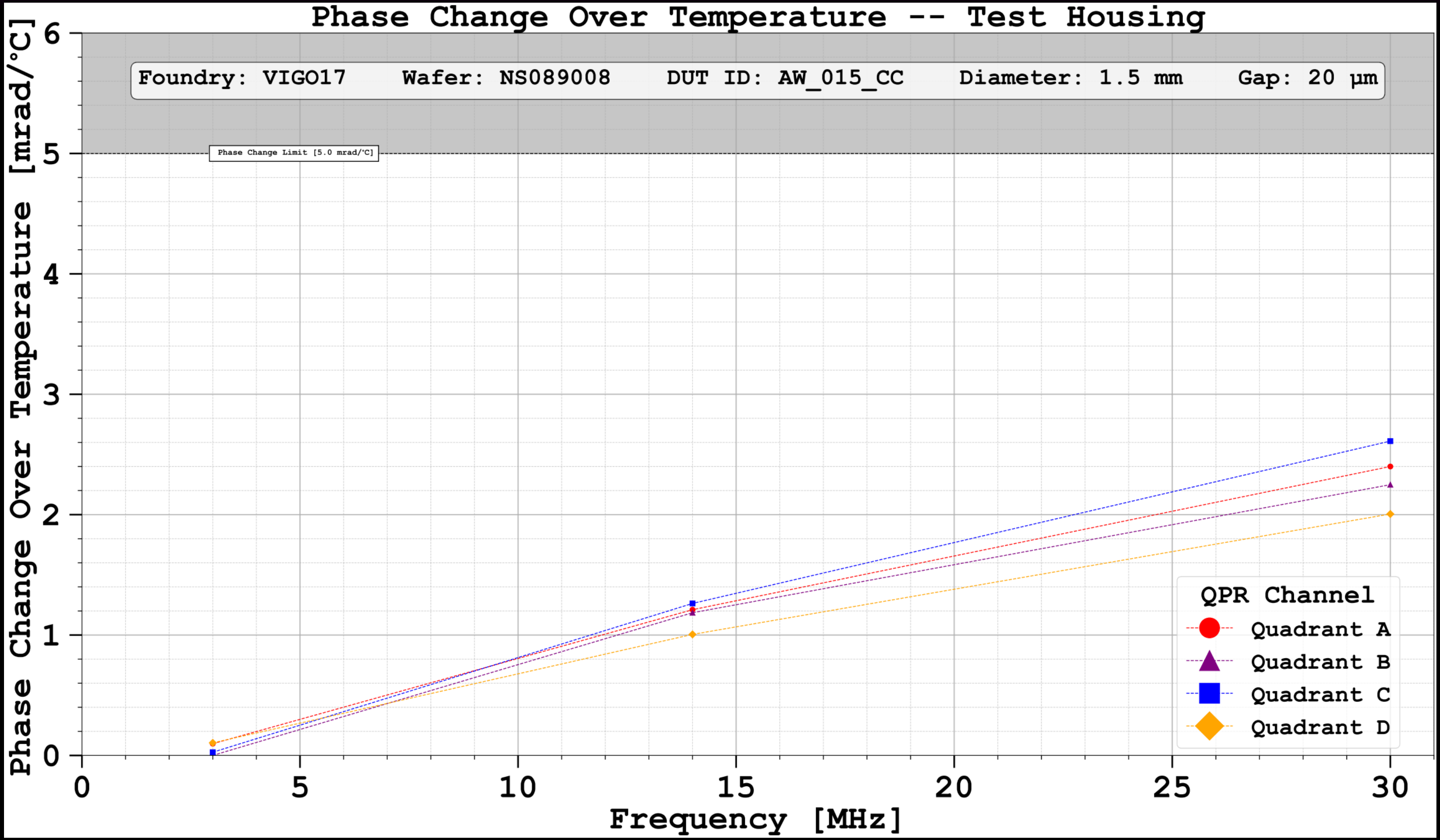






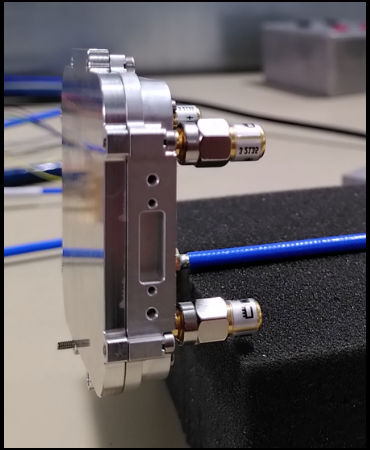
Phase Stability over Temperature

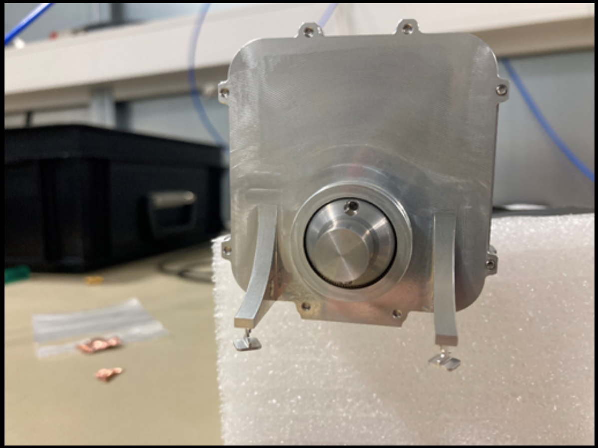
Phase Stability over Temperature



EMC Tests

- Electromagnetic Compatibility (EMC) tests required to verify electromagnetic isolation quality of the housing.
- Testing at ESTEC showed housing has lots of leaks.
- Time at ESTEC is expensive.
  - Build our own set-ups
- To find the source(s) of the leak, incrementally build the full housing, testing at each stage.
- Use many different kinds of space qualified seals.
- Need 60 dB of isolation





Top left: Faraday cage at Nikhef with antenna.

Top right: Basic housing.

Lower left: More complicated housing.

EMC Tests

Trace Color	Configuration
Yellow	Refenence housing open
Purple	Housing closed Co-seal
Blue	Housing closed QPD hole open & Co seal
Red	Housing closed QPD with bal canted spring & Co-Seal

X - band used by LISA's high gain antenna used for ground to satellite communication