Exploring the Gravitational Wave Universe – Challenges for a LISA Successor

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After LISA ?

- We have seen a compelling science case for successor gravitational wave missions to the pioneering first LISA
- Interferometry between “free” masses is the only viable spaceborne approach that can yield high sensitivity in the 10^{-5} to 1 Hz region of the GW spectrum
- But how do we optimise design of successor missions targeted at bands in which the first LISA has limited sensitivity?

Outline

- First we look at the design of LISA and the parameters that determine its performance
- Then we examine how sensitivity scales as the design parameters vary
- Finally we look at plausible medium term goals that could dramatically expand the gravitational wave observation window that will be opened by LISA
- ... and conclude with a summary of the technical developments that will be required

Sensitivity limitations

- Measurement is by laser interferometry between (ideally) inertial proof masses
  - Photon counting statistics must set a deteriorating limit to sensitivity as shorter measurement intervals are used – corresponding to searches at higher gravitational wave frequencies
  - Perturbing forces acting on the proof masses will limit sensitivity by producing displacements of the masses
    - Unwanted perturbations increase as we go to lower frequencies, so there is inevitably a low frequency “wall” in the sensitivity plot
  - If a gravitational wave signal has a duration comparable with, or longer than, the light travel time in the interferometer arms there is scope for cancellation effects that reduce sensitivity

After LISA ?

- So, broadly, the performance of LISA – and of any single interferometer system – can be related to
  - the optical power successfully “used” in the interferometer
    - this depends on laser power, optical chain efficiency and design, and telescope size
  - the wavelength – since photon counting statistics set a limit to the fraction of a wavelength resolvable
  - the magnitude and spectral distribution of perturbing forces acting on the proof masses
  - the arm length of the interferometer

There are, of course, other noise sources, both technical (laser, electronic etc.) and fundamental (e.g. the quantum limit), but we will ignore the former in these discussions, and will not approach the latter – even by far beyond 2025!

Spaceborne detectors – simplest concept

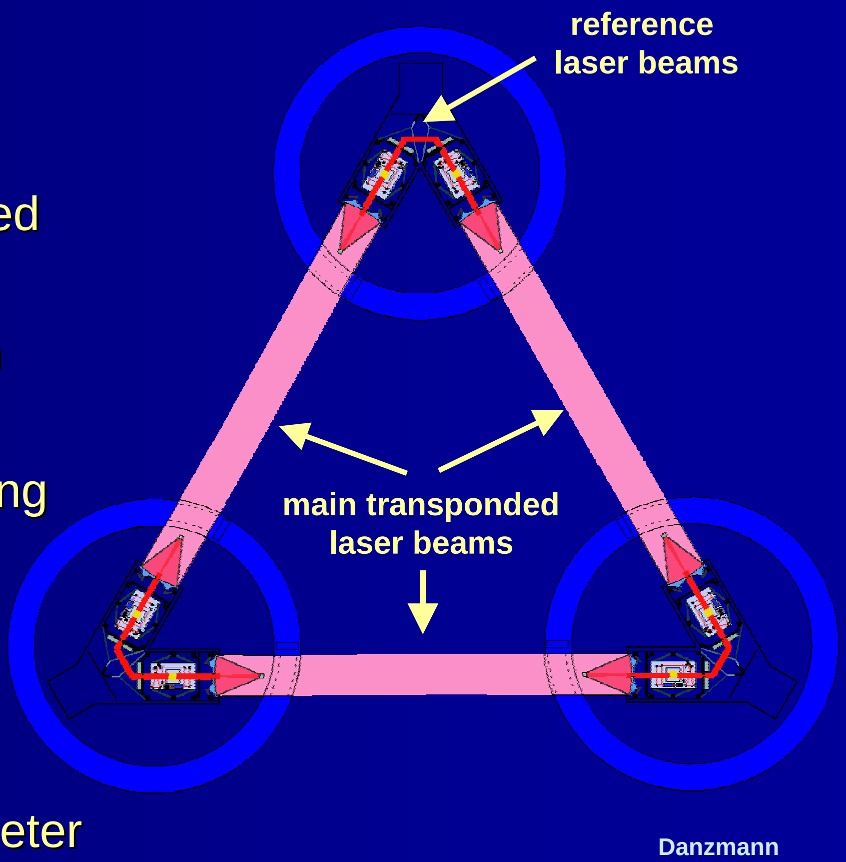
- Each S/C carries 2 lasers, 2 telescopes, 2 test masses
- Local lasers phase-locked
- Lasers on distant S/C phase-locked to incoming light

➔ laser transponder – effectively an "active mirror"

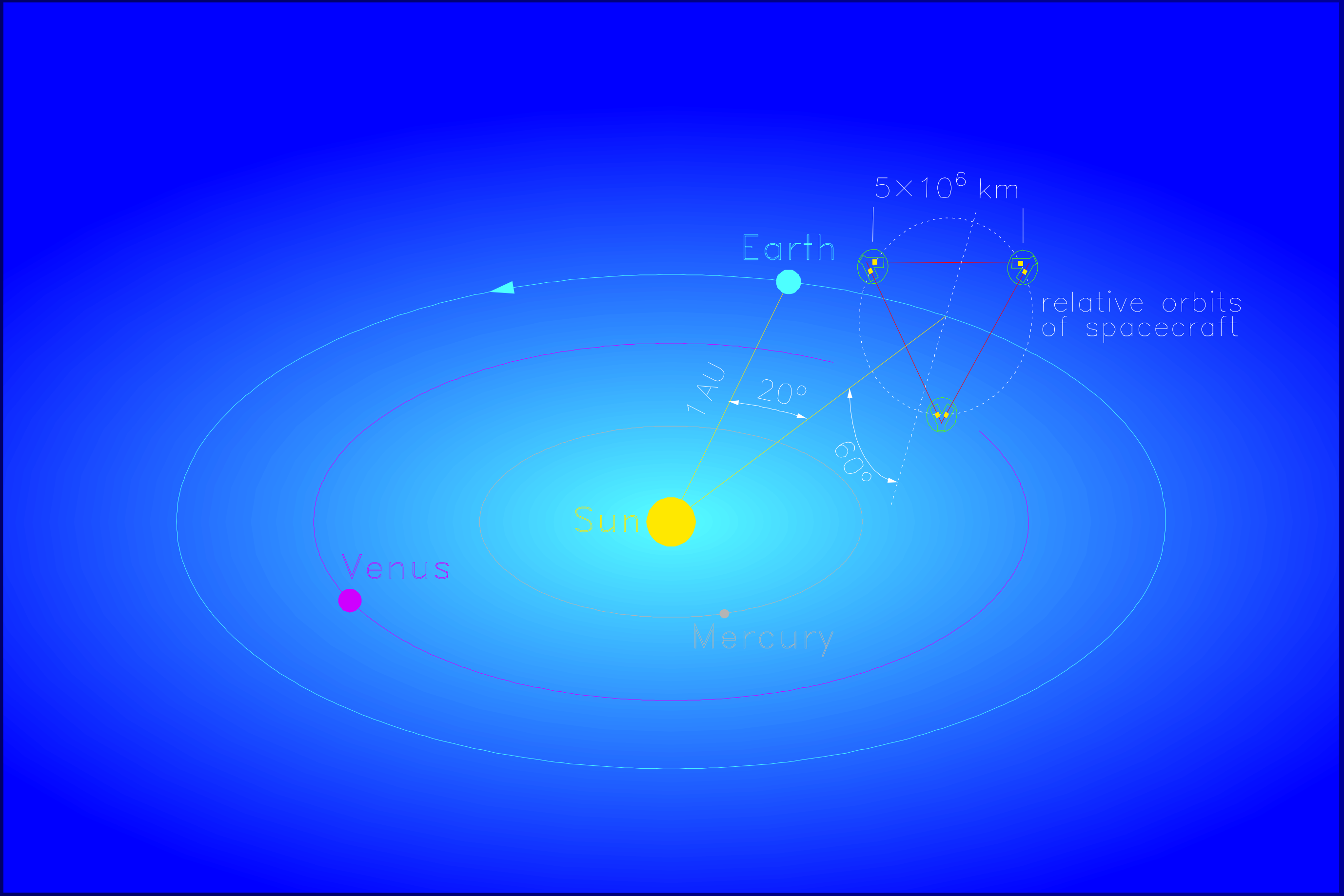
➔ Laser beams reflected off free-flying test masses

➔ Optical arrangement designed to make armlength measurement insensitive to S/C motion

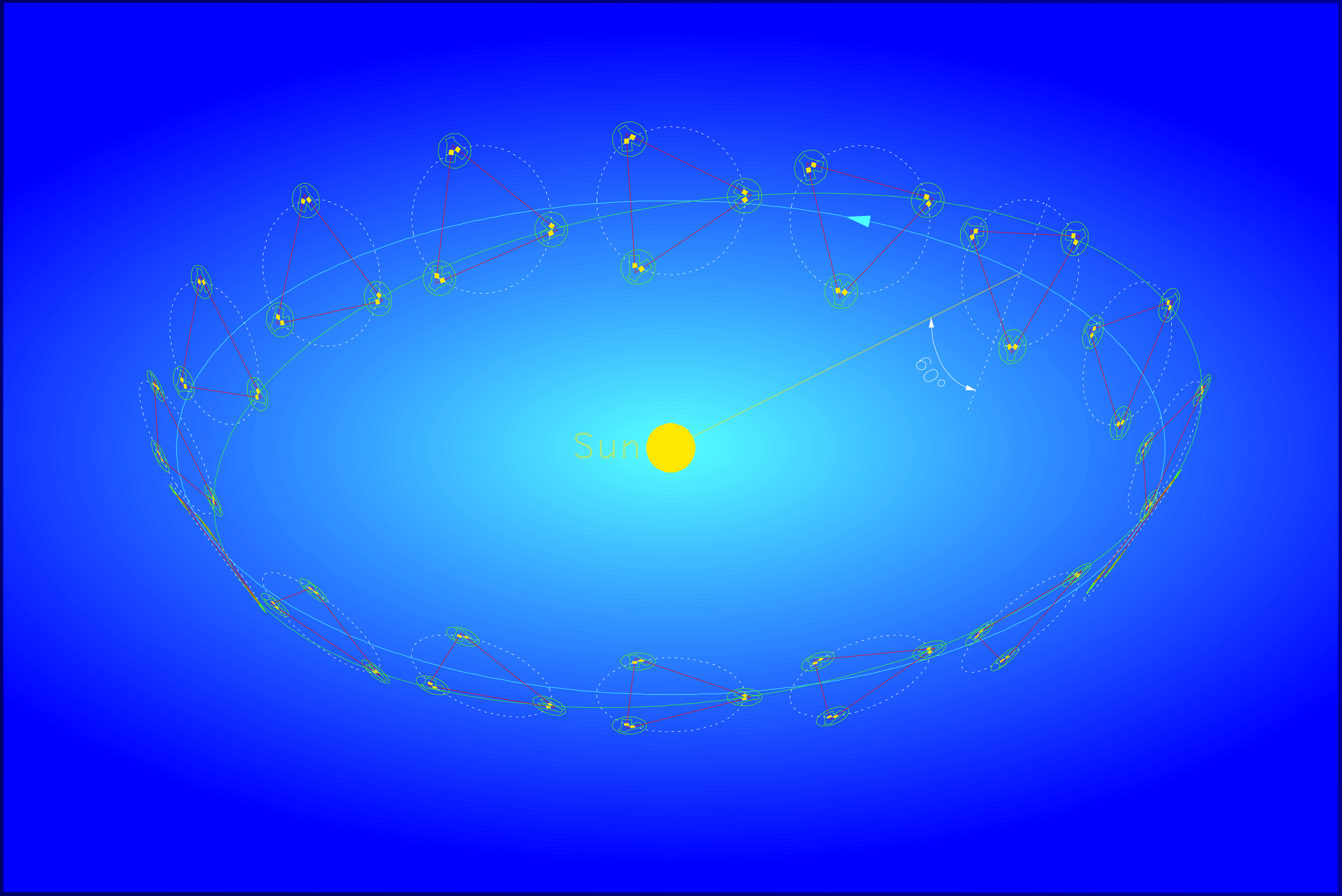
➔ Effectively a Michelson interferometer with a 3rd arm



Cluster of 3 LISA spacecraft

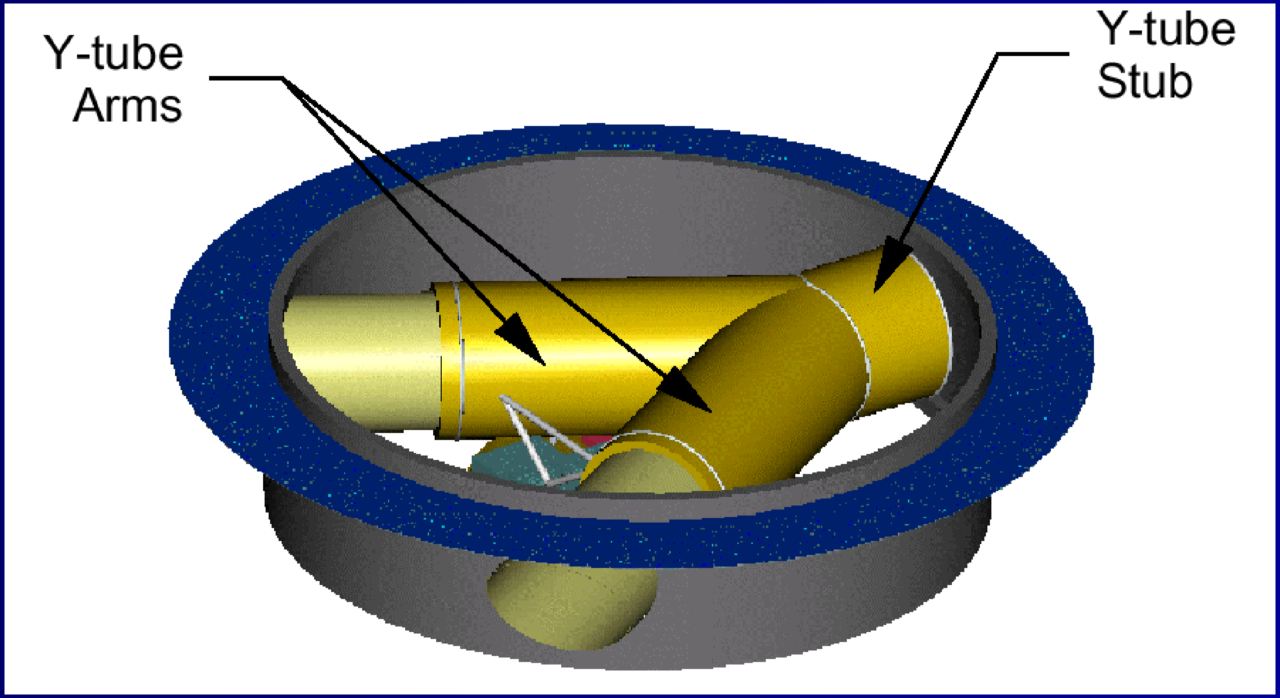


LISA orbits



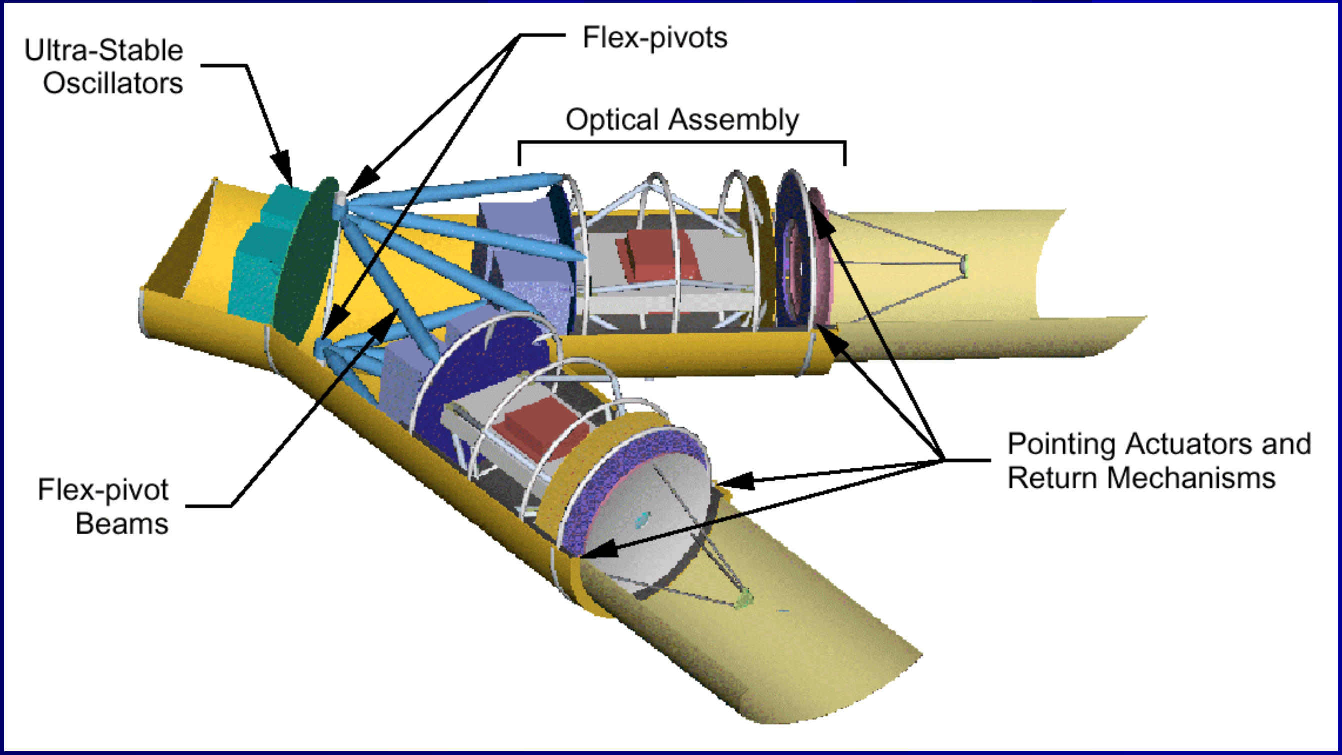
LISA spacecraft

- One of three identical spacecraft



LISA concept

- Y-structure and thermal shield
- 2 optical assemblies

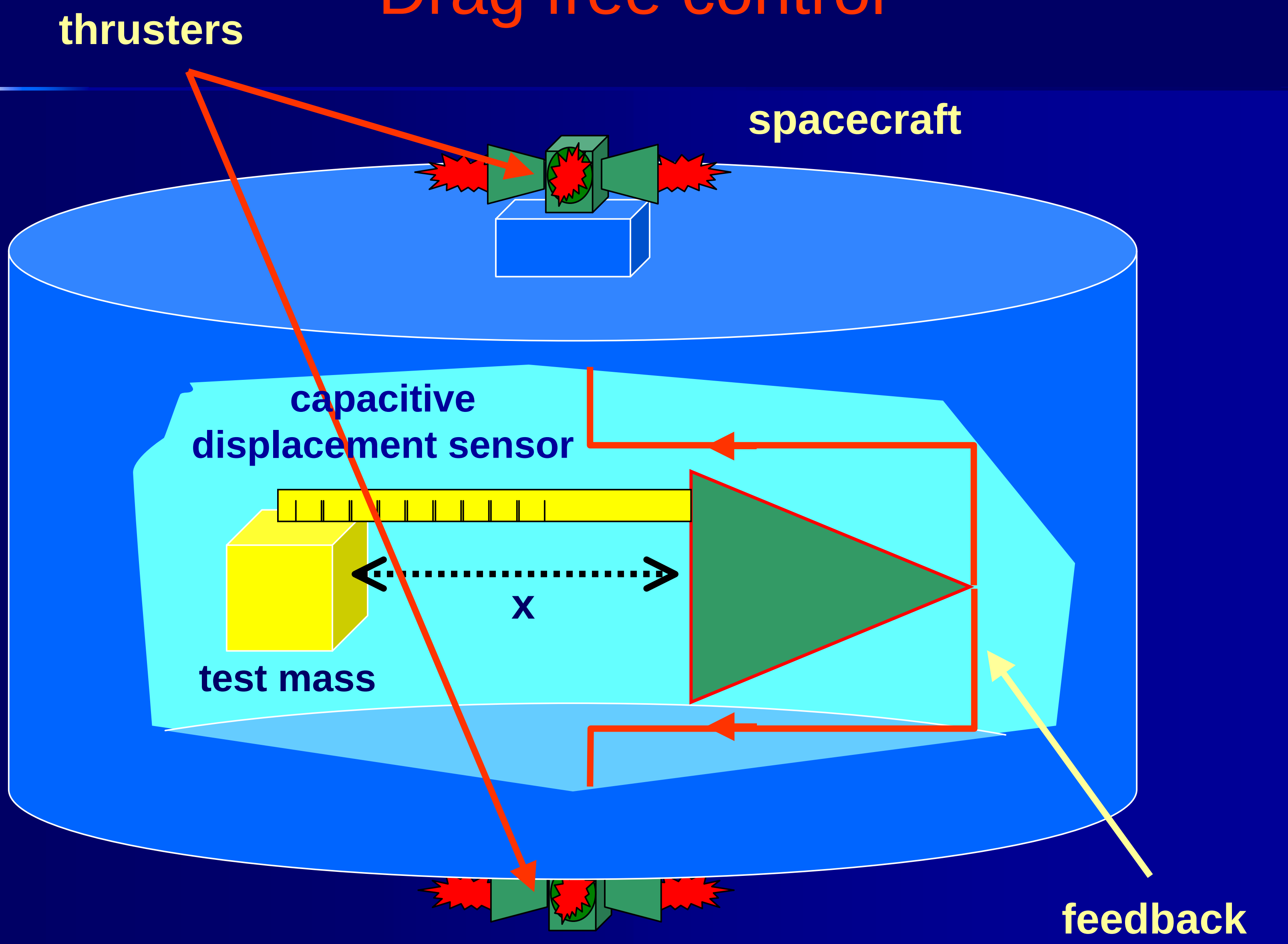


- Rear interferometer fibre link
- Telescope diameter 30cm

Drag-free control in LISA

- Main objective: to have the two test masses inertial
  - acceleration noise < 3×10^{-15} m/s²/Hz$^{1/2}$ from 0.1 to 4 mHz
- The positions of unshielded test masses would be grossly perturbed by fluctuations in the solar radiation pressure
- Solution? Implement an active shield surrounding the test masses and servo controlled to minimise the relative motion of the masses and shield (in the sensitive directions)
- In LISA the sensor will be capacitively sensed “accelerometers” using the proof masses and surrounding electrodes
- Actuators to move the spacecraft are very low thrust devices, e.g. Field Emission Electric Propulsion (FEEP) thrusters

Drag free control



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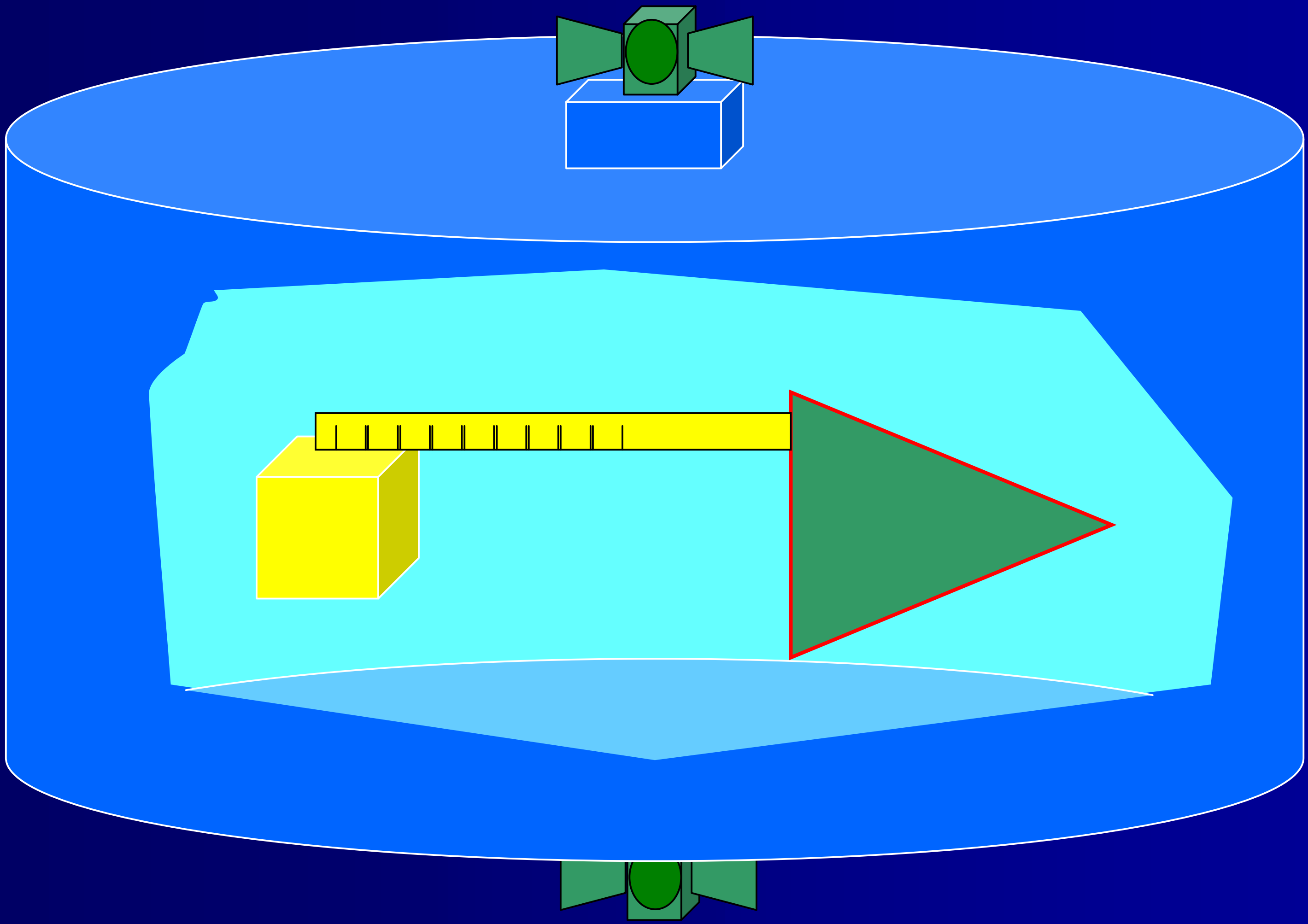

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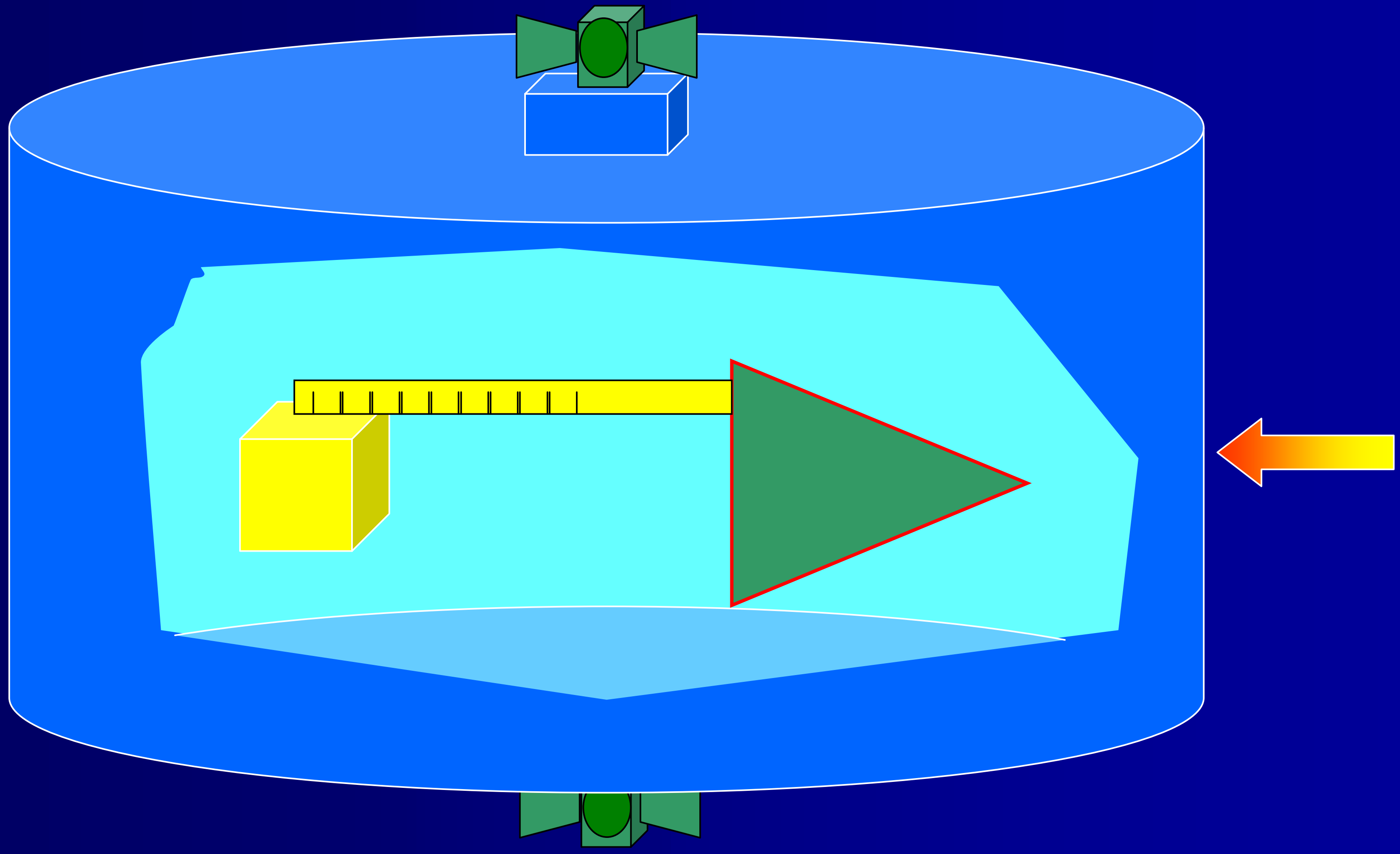

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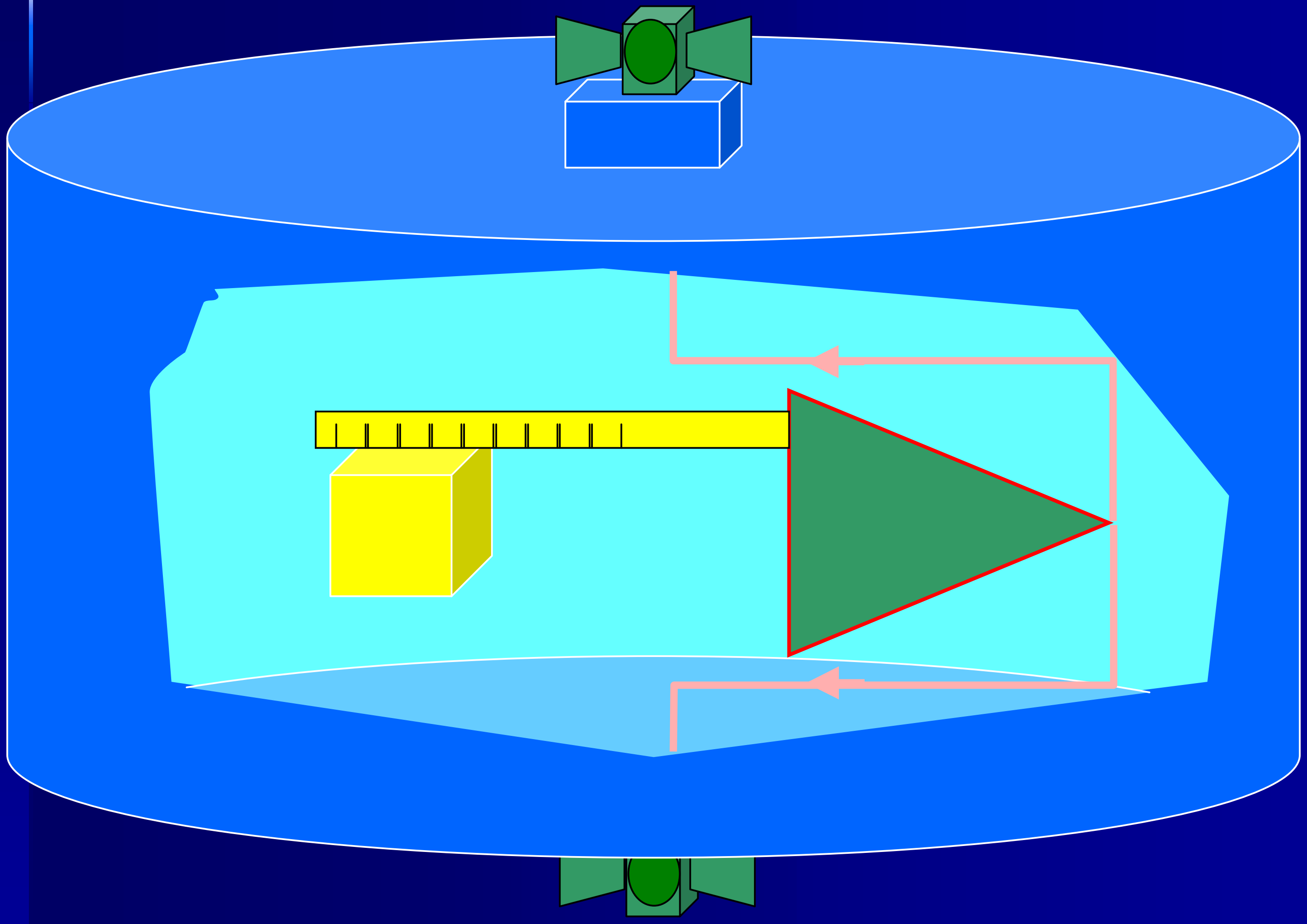

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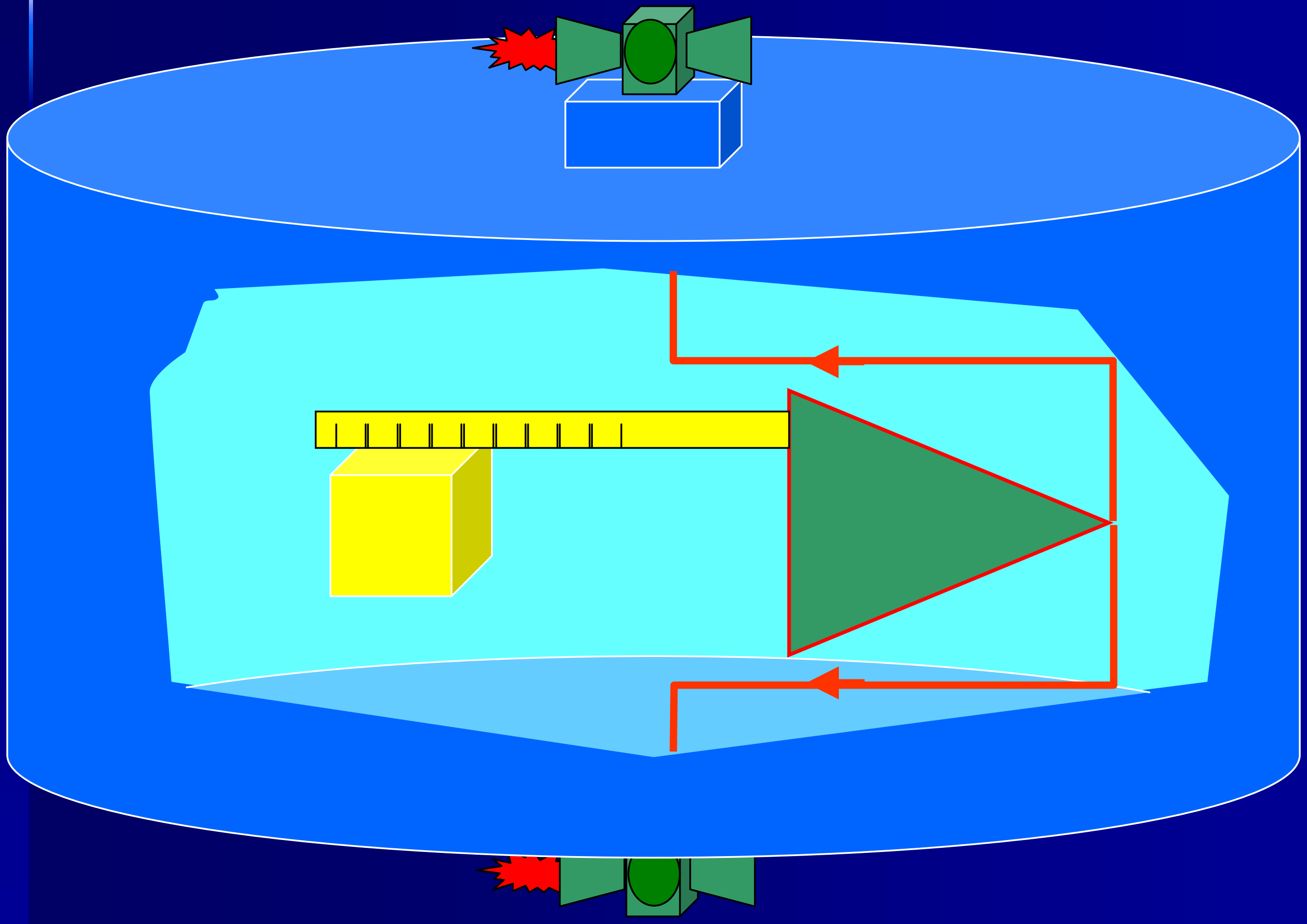

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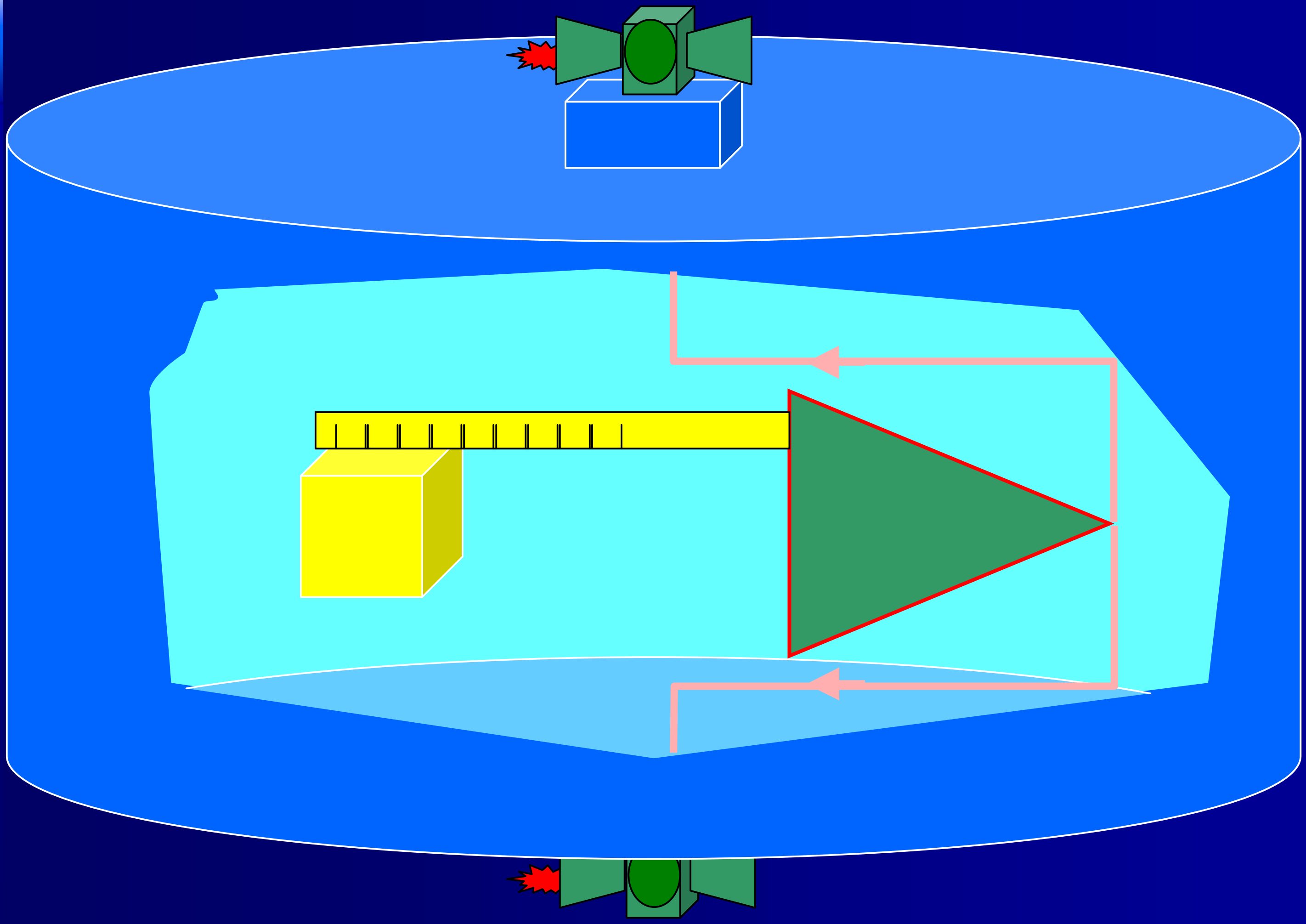

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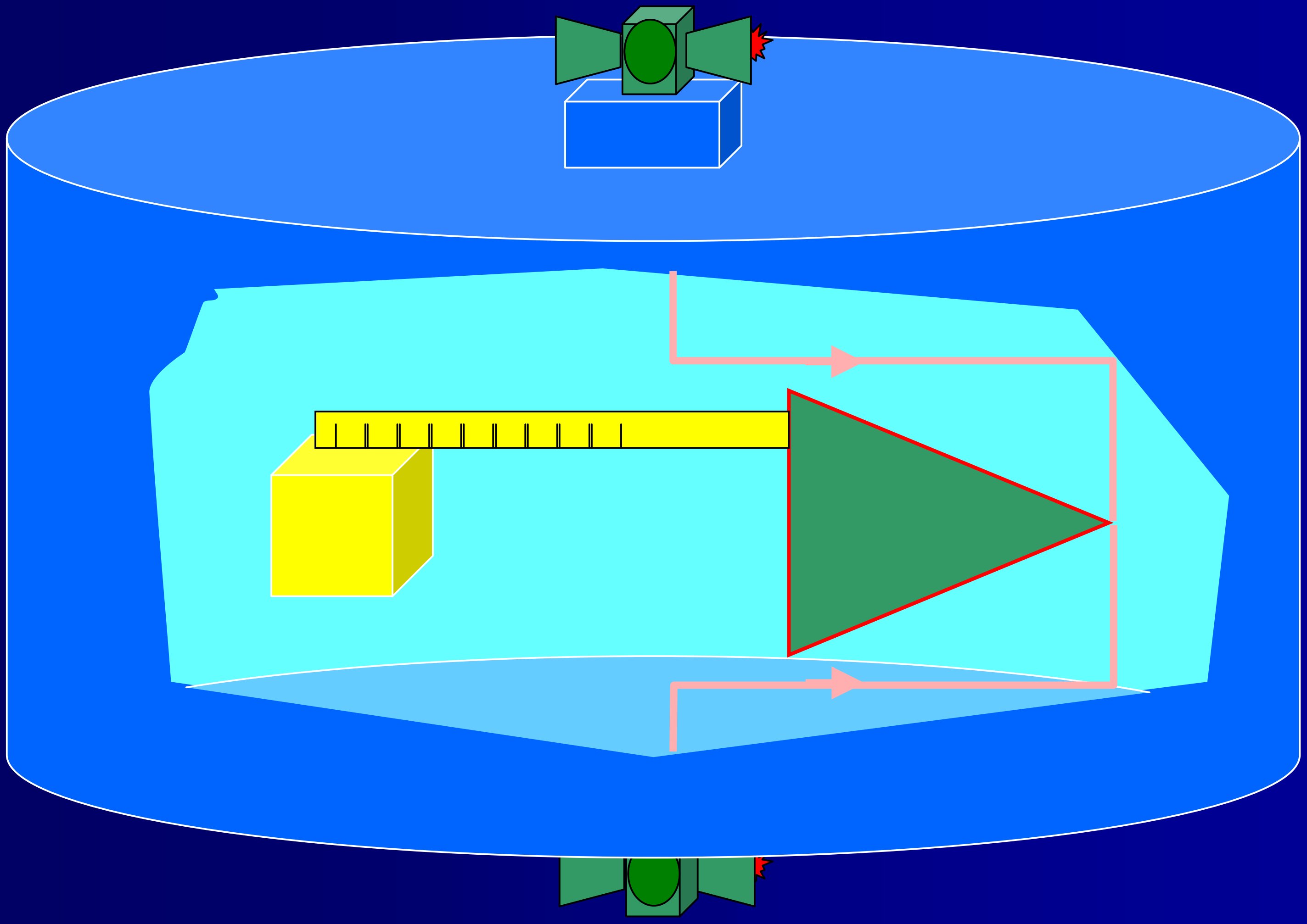

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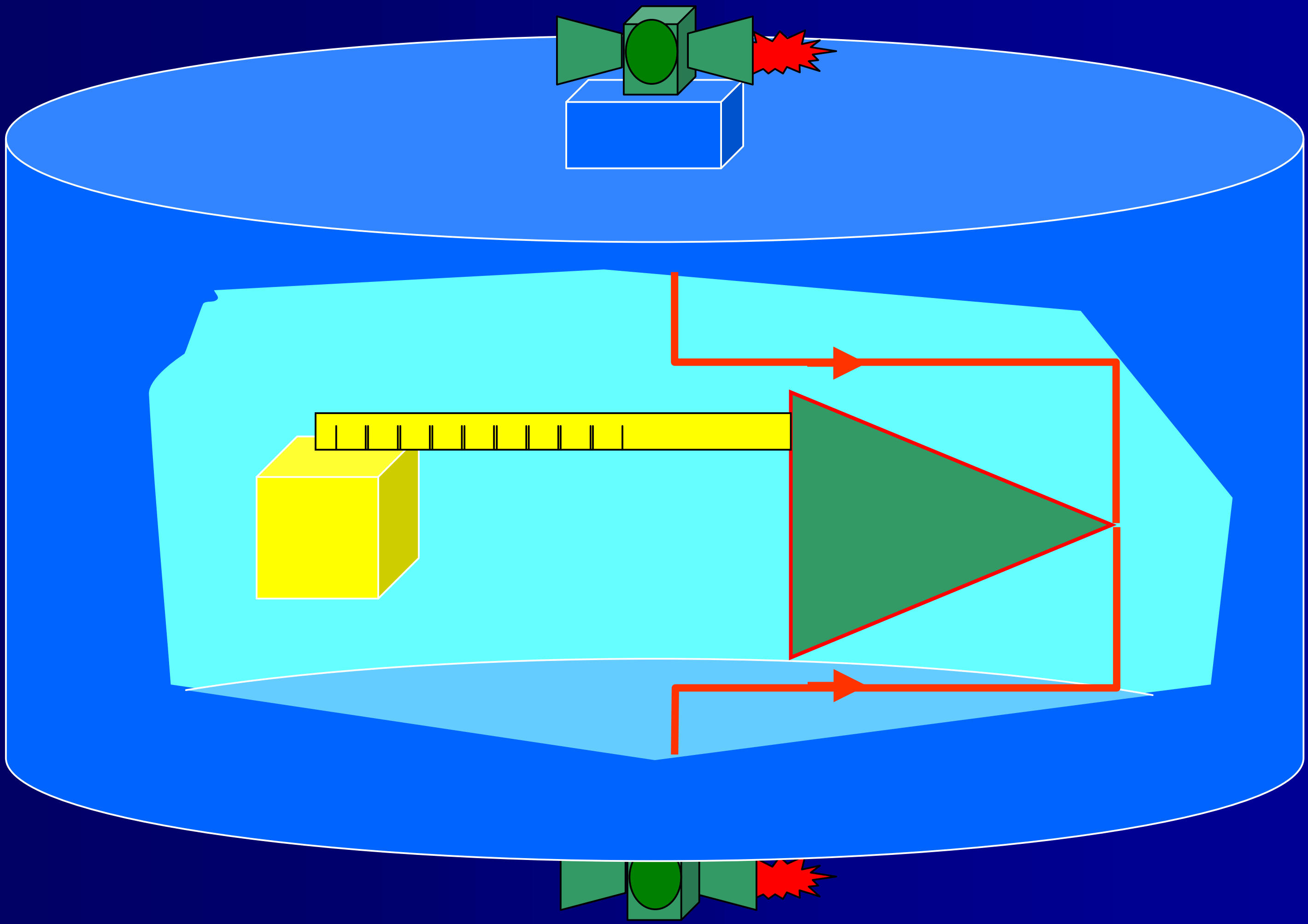

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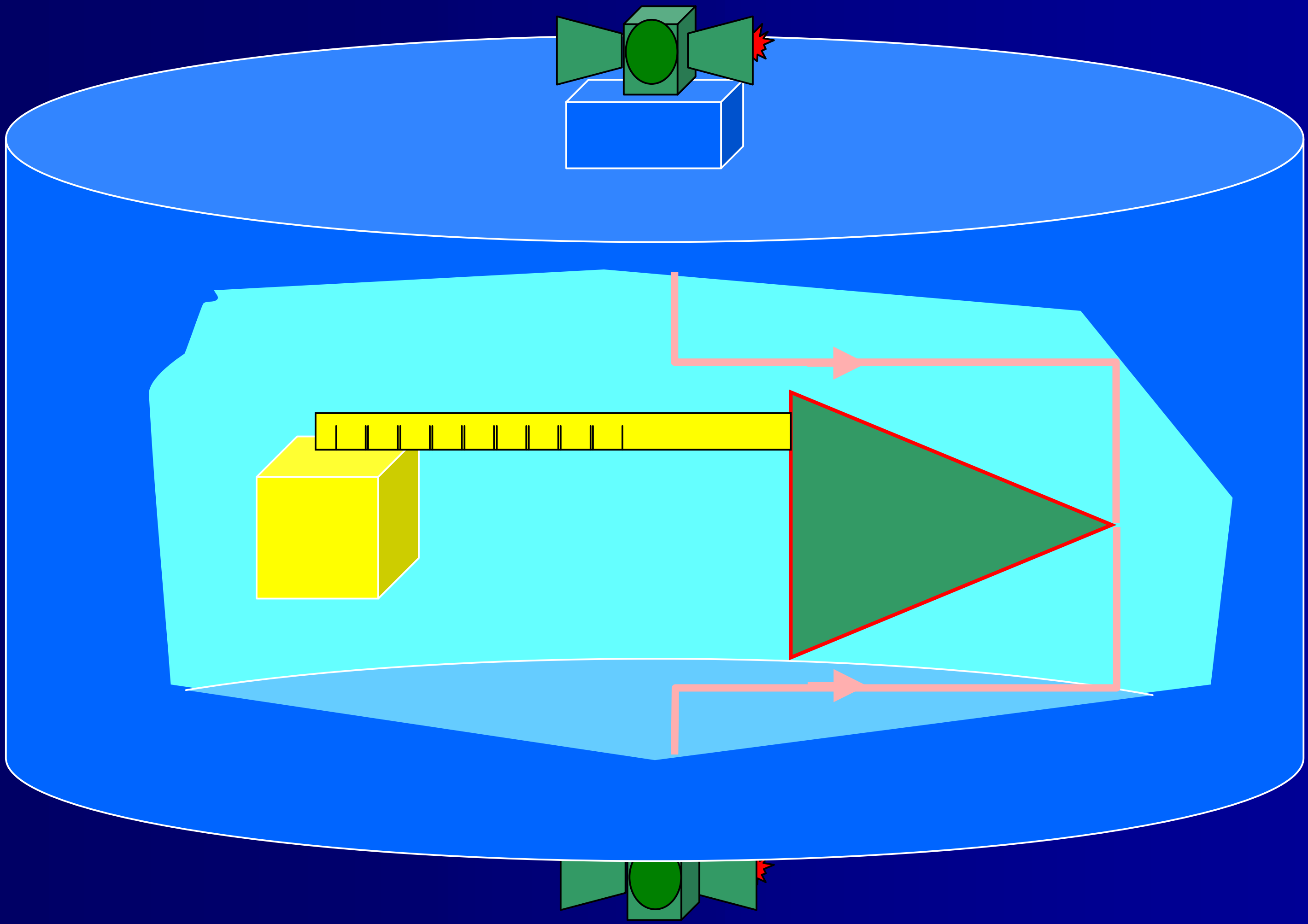

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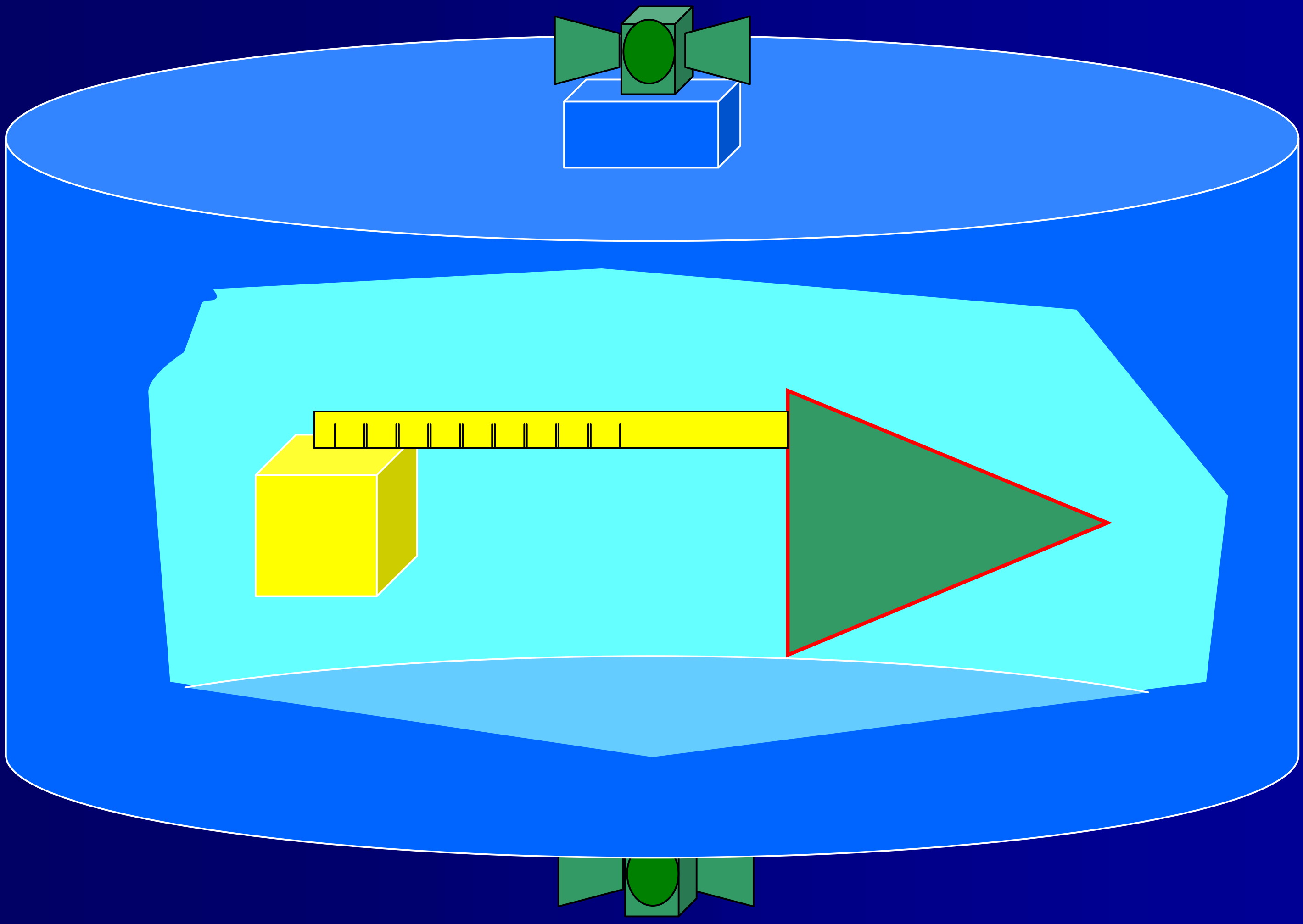
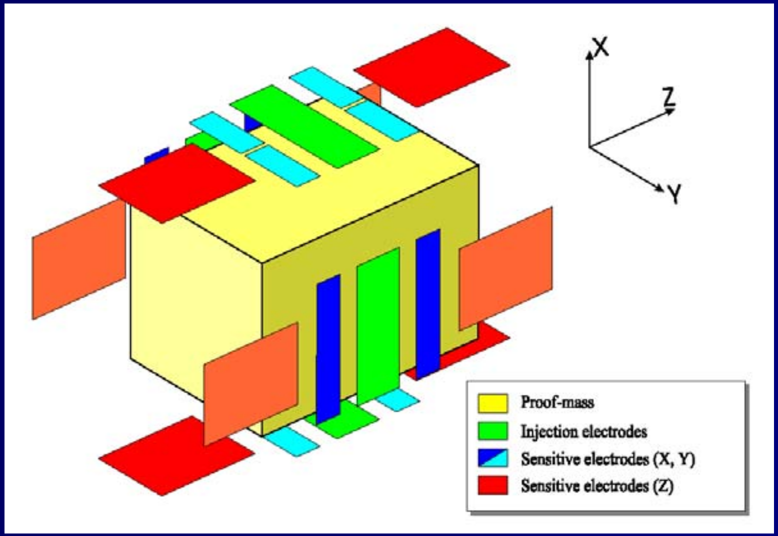
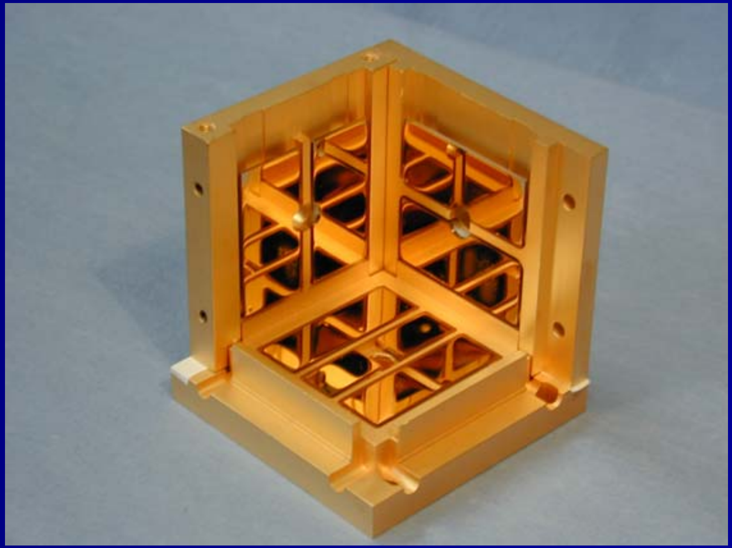


Inertial sensor – for LISA

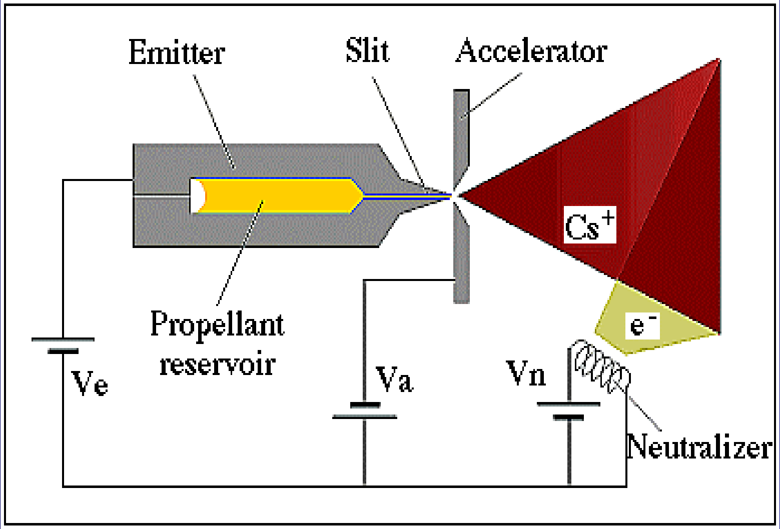


- Sensor also requires a non-contacting discharging system
  - A UV irradiation system has been developed for LISA



- Noise requirements mean that no connection between the proof mass and the housing is allowable

Low noise thrusters – for LISA

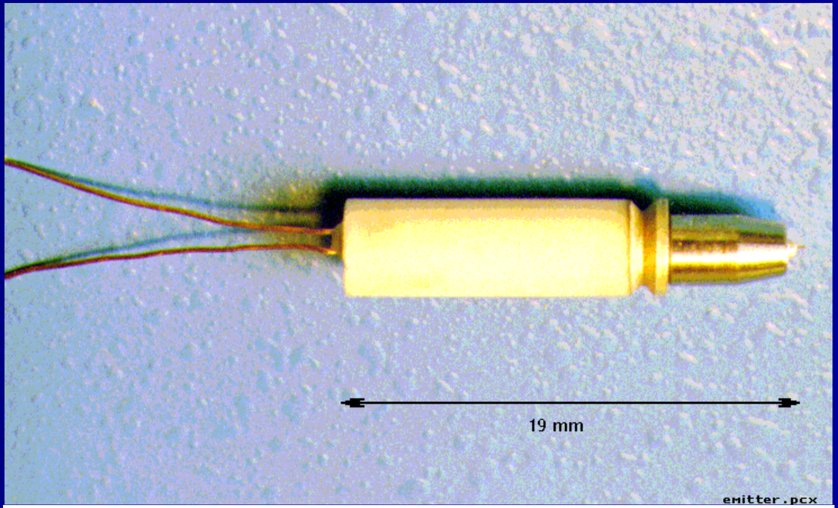


Caesium Slit

- Neutraliser required to avoid charging of the spacecraft

- Propellant requirements are extremely small: tens of grams lasts for years!

Indium Needle



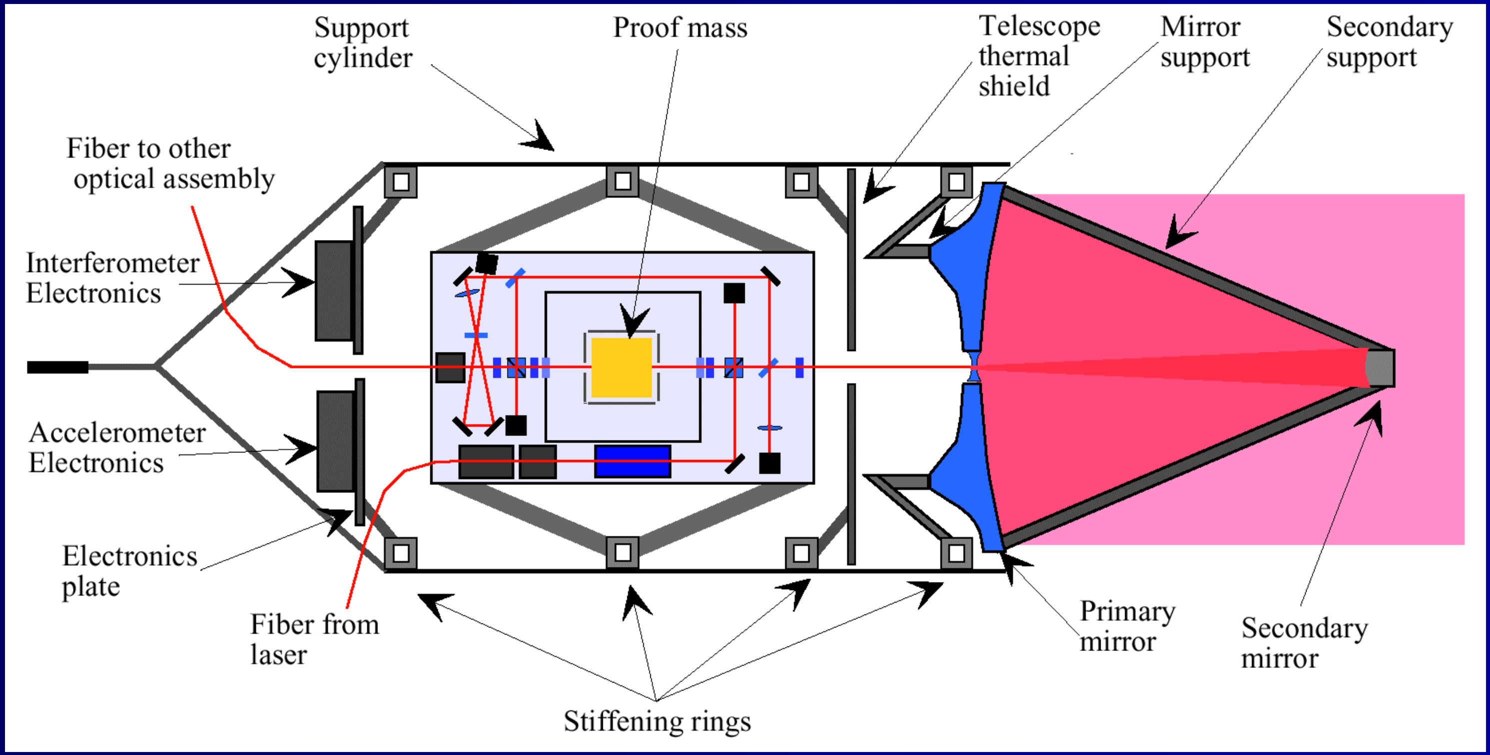
Indium FEEP emitter

Courtesy of Hans-Michael Fehringer Austrian Research Centre Seibersdorf

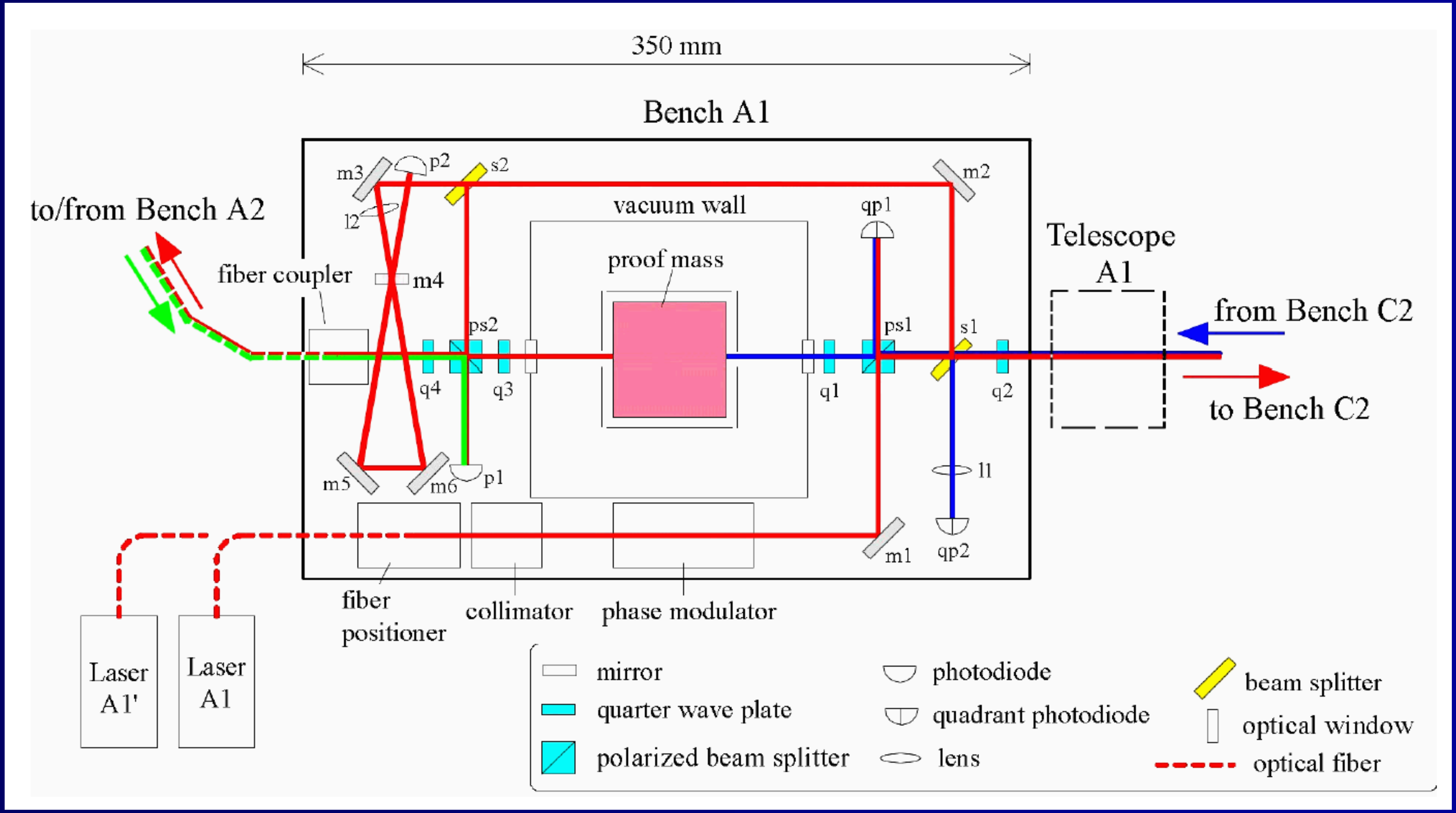
Optical metrology

- Main objective: to monitor the 5 million kilometre long arms with 10pm precision
- Laser light emitted and received by a collimating telescope
- Even with LISA's 30cm telescope mirror, diffraction causes the emitted beam to spread to a diameter of many km by the time the light reaches the distant spacecraft
  - So relatively little of the emitted light is intercepted by the receiving telescope: in LISA the detected light will be of order 70pW
  - Direct reflection is clearly inappropriate, so a local laser in the distant spacecraft returns a "full power" measurement beam
- Shot noise limited sensitivity of the path length fluctuation measurement is driven by the detected light power at each spacecraft (and the wavelength used)

Optical interferometry and telescope

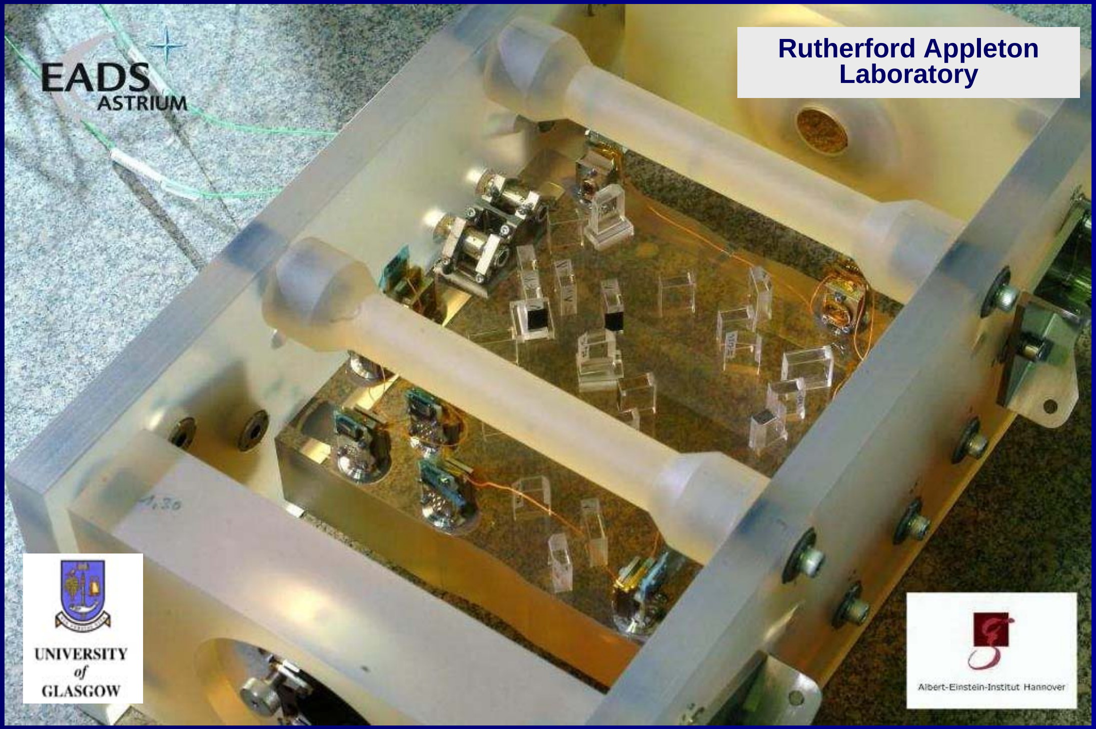


Interferometry scheme



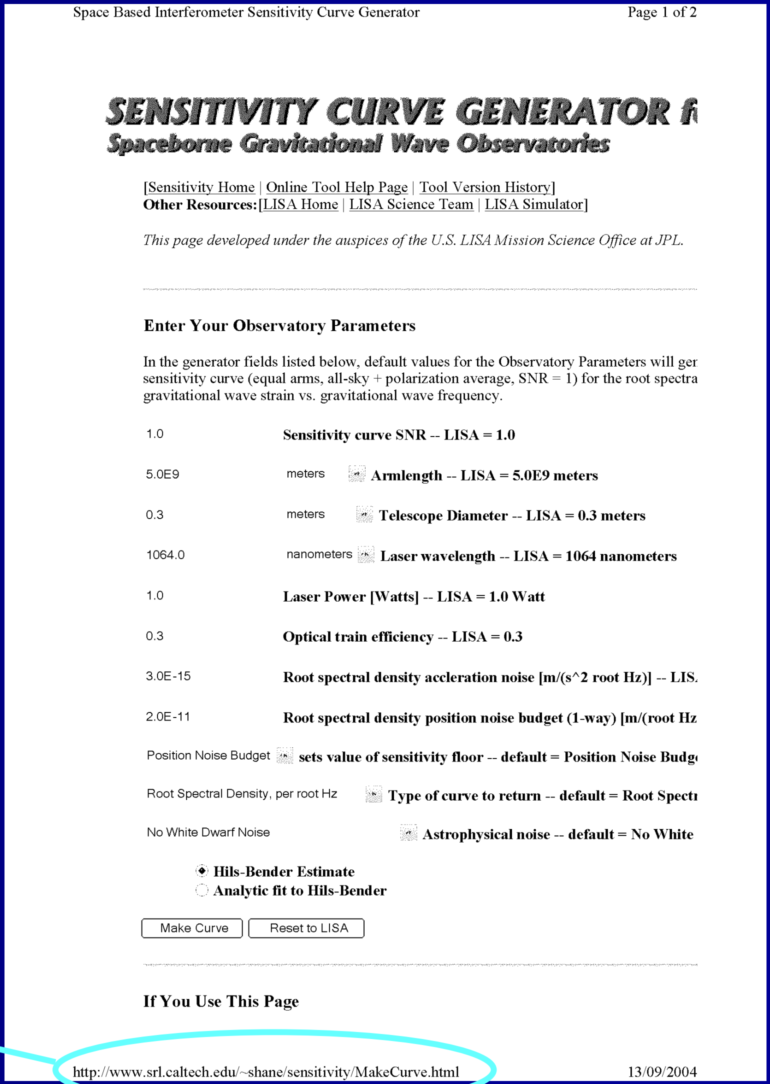
Interferometry

- Requires stable optical structures
  - As already developed and demonstrated for LISA Pathfinder



Sensitivity curve generator (Shane Larson)

- Note that the following sensitivity curves are presented as root spectral densities of the gravitational wave amplitude
- Often plots that compare sensitivity with (long-lived) sources assume a standard integration time of 1 year and are drawn for a particular signal-to-noise ratio, typically 5
- To obtain such a plot from those given here the vertical scale should be multiplied by 5 and divided by the square root of the number of seconds in one year – an overall multiplicative factor of approximately 9 x 10^{-4}
- http://www.srl.caltech.edu/~shane/sensitivity/MakeCurve.html



Space Based Interferometer Sensitivity Curve Generator   Page 1 of 2

SENSITIVITY CURVE GENERATOR f
Spaceborne Gravitational Wave Observatories

[Sensitivity Home | Online Tool Help Page | Tool Version History]
Other Resources:[LISA Home | LISA Science Team | LISA Simulator]

This page developed under the auspices of the U.S. LISA Mission Science Office at JPL.

Enter Your Observatory Parameters

In the generator fields listed below, default values for the Observatory Parameters will ger
sensitivity curve (equal arms, all-sky + polarization average, SNR = 1) for the root spectra
gravitational wave strain vs. gravitational wave frequency.

1.0		**Sensitivity curve SNR -- LISA = 1.0**
5.0E9	meters	**Armlength -- LISA = 5.0E9 meters**
0.3	meters	**Telescope Diameter -- LISA = 0.3 meters**
1064.0	nanometers	**Laser wavelength -- LISA = 1064 nanometers**
1.0		**Laser Power [Watts] -- LISA = 1.0 Watt**
0.3		**Optical train efficiency -- LISA = 0.3**
3.0E-15		**Root spectral density accleration noise [m/(s^2 root Hz)] -- LIS.**
2.0E-11		**Root spectral density position noise budget (1-way) [m/(root Hz**
Position Noise Budget		**sets value of sensitivity floor -- default = Position Noise Budg**
Root Spectral Density, per root Hz		**Type of curve to return -- default = Root Spectı**
No White Dwarf Noise		**Astrophysical noise -- default = No White**

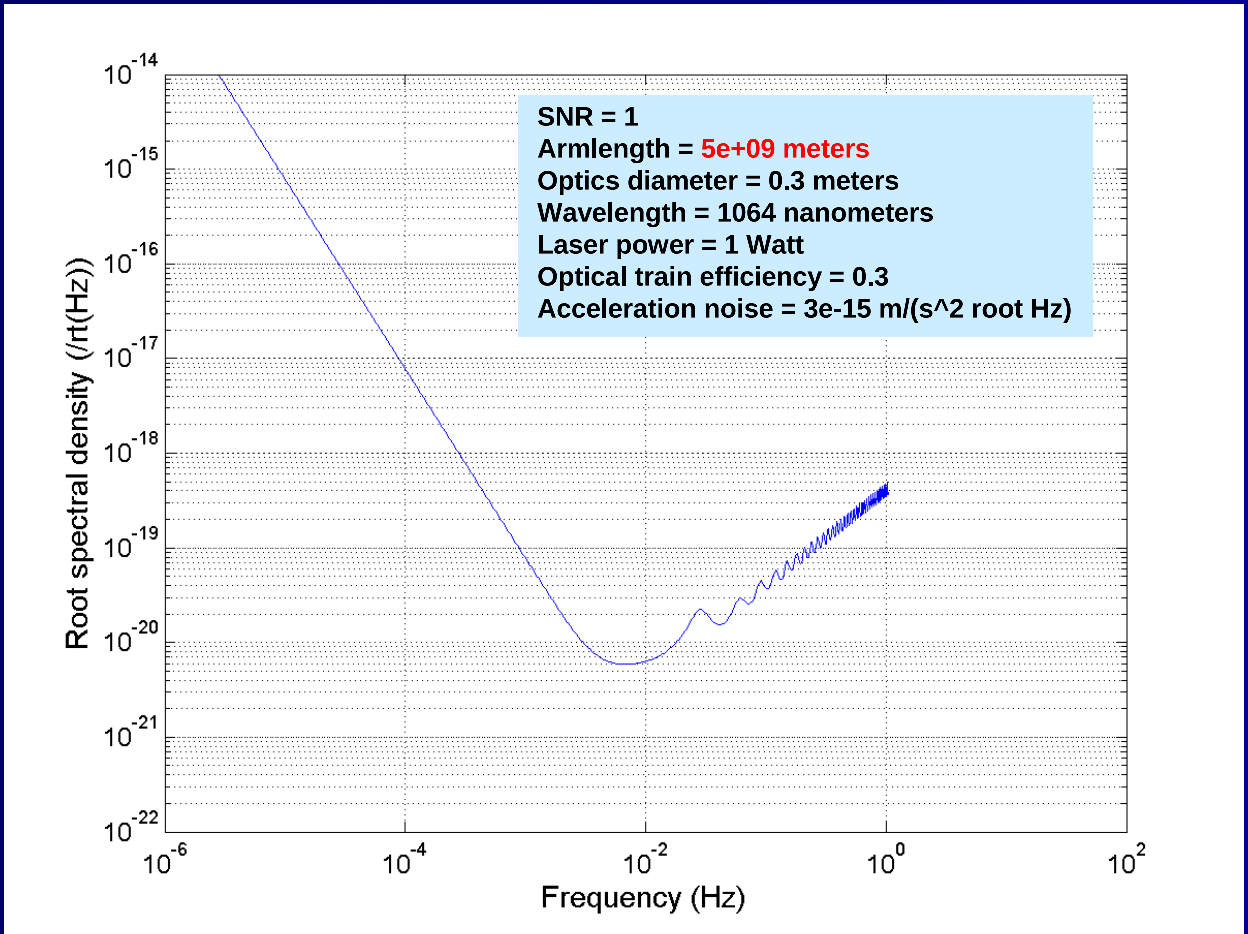
Hils-Bender Estimate
Analytic fit to Hils-Bender

Make Curve   Reset to LISA

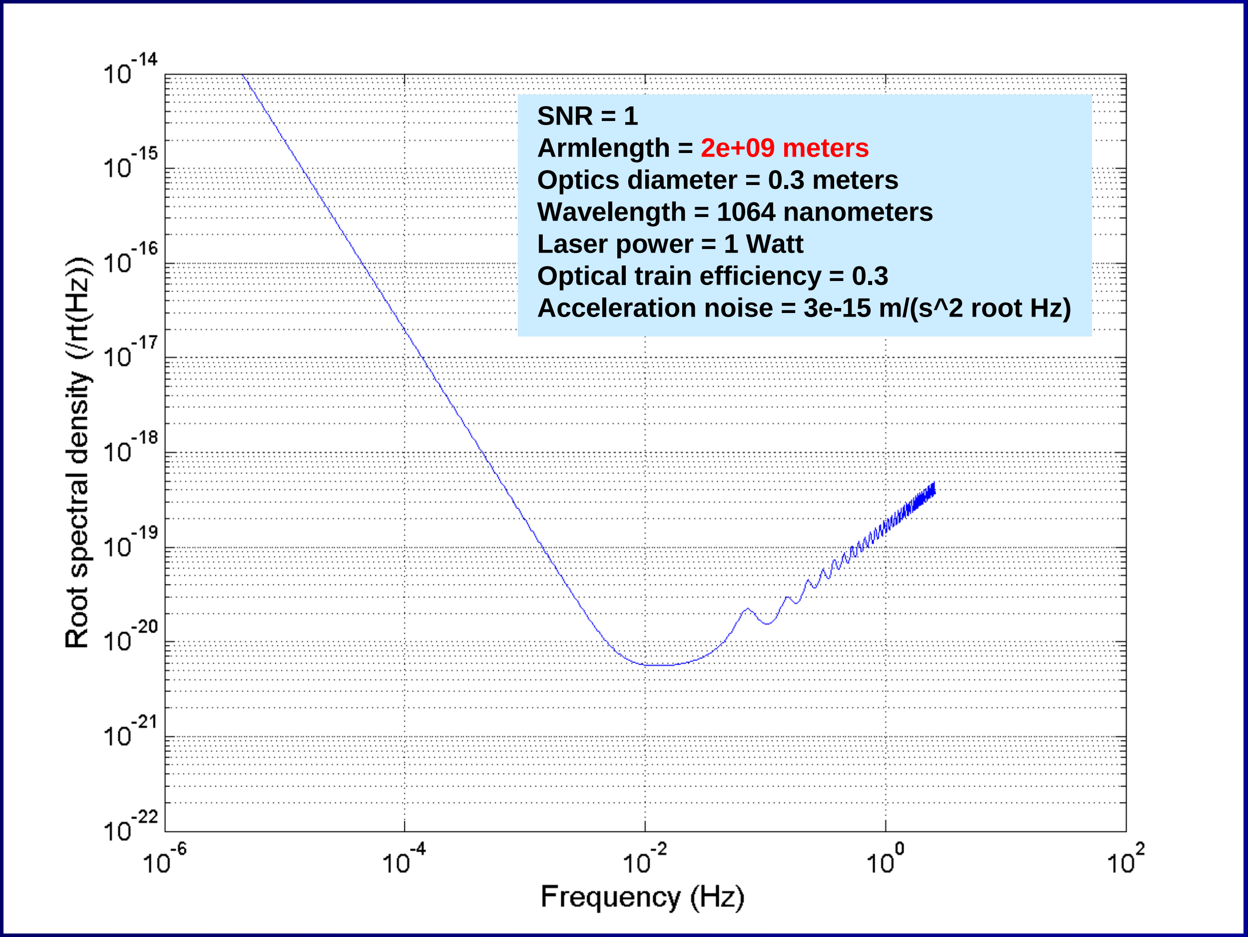
If You Use This Page

http://www.srl.caltech.edu/~shane/sensitivity/MakeCurve.html   13/09/2004

Standard LISA



Standard LISA – getting shorter …



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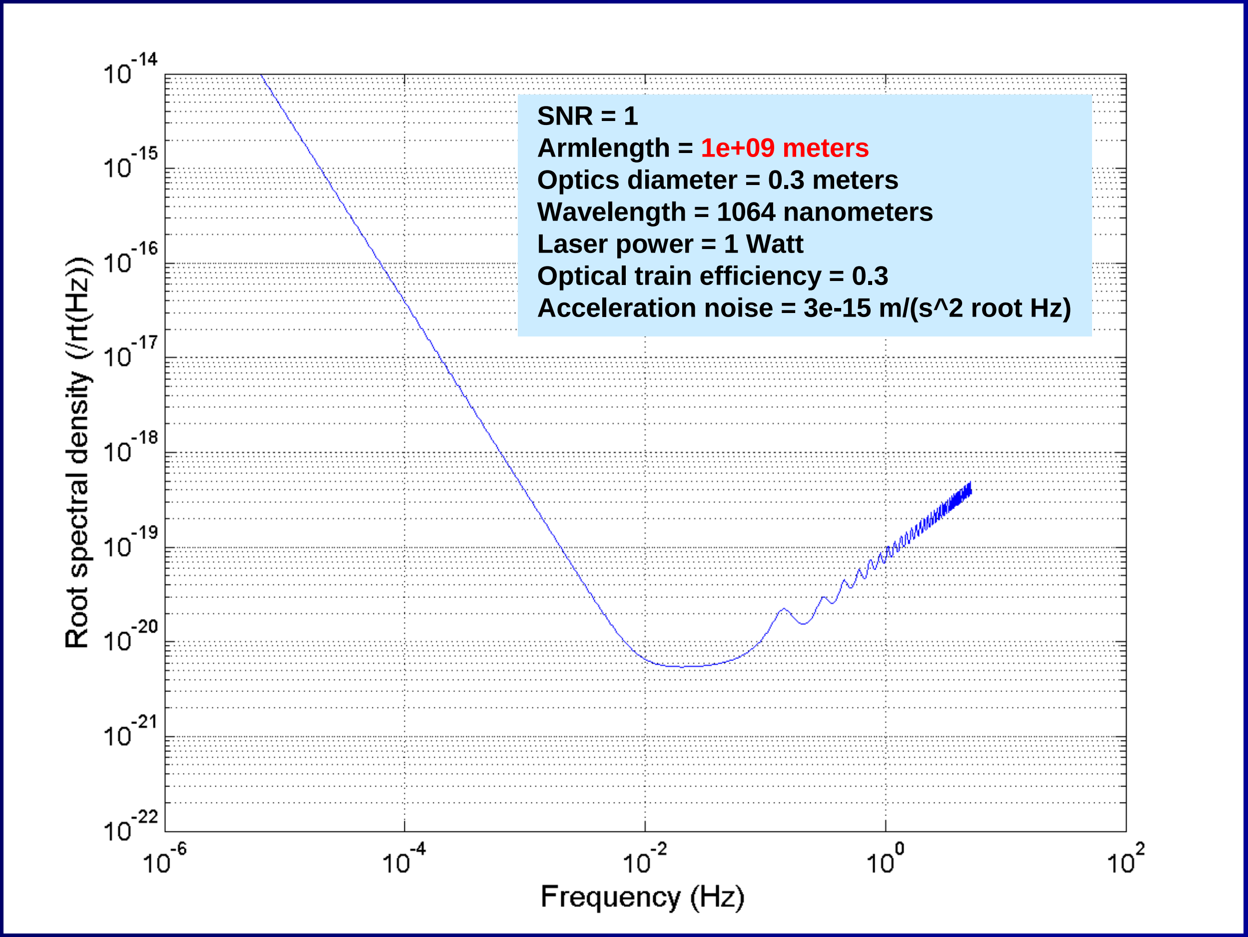

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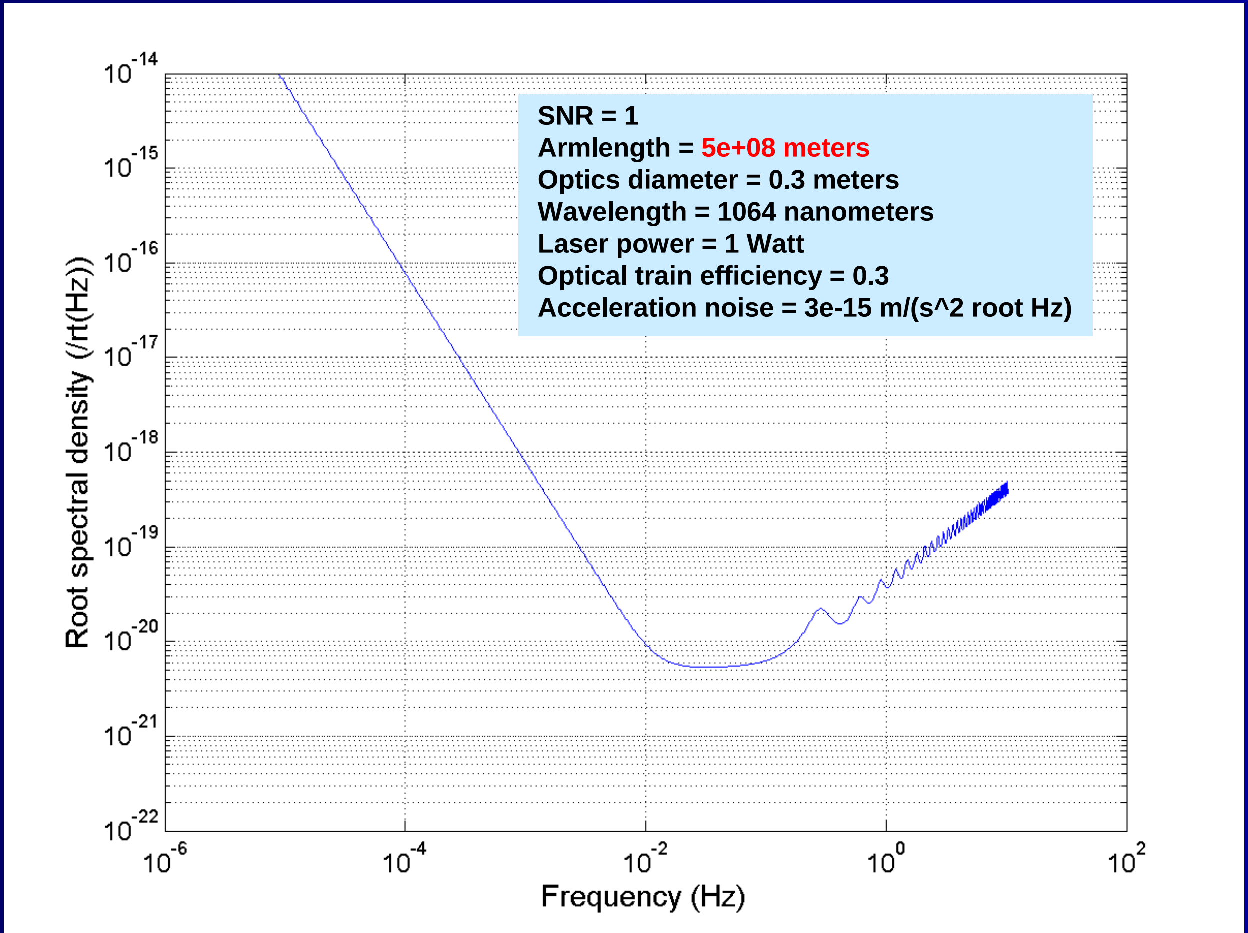

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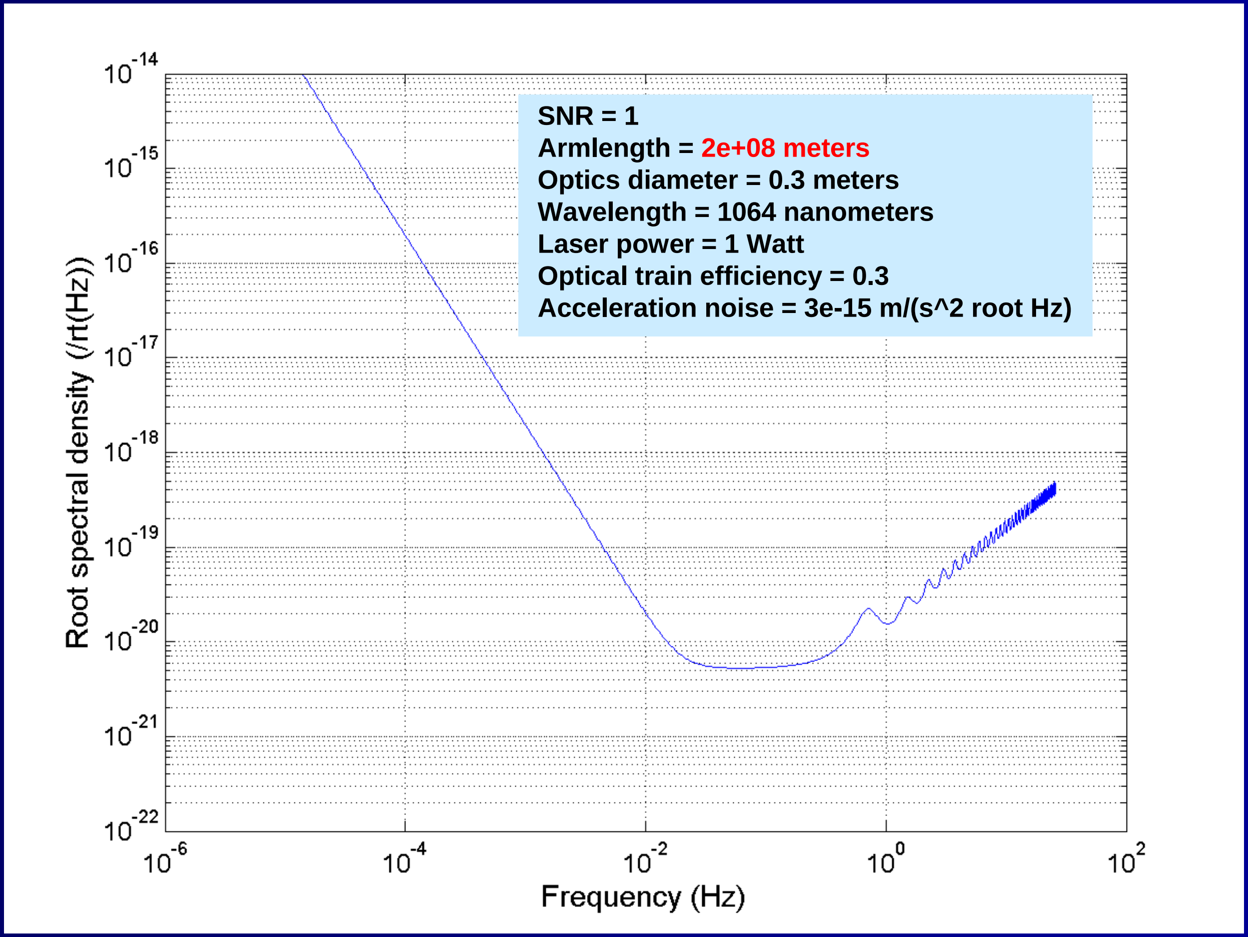

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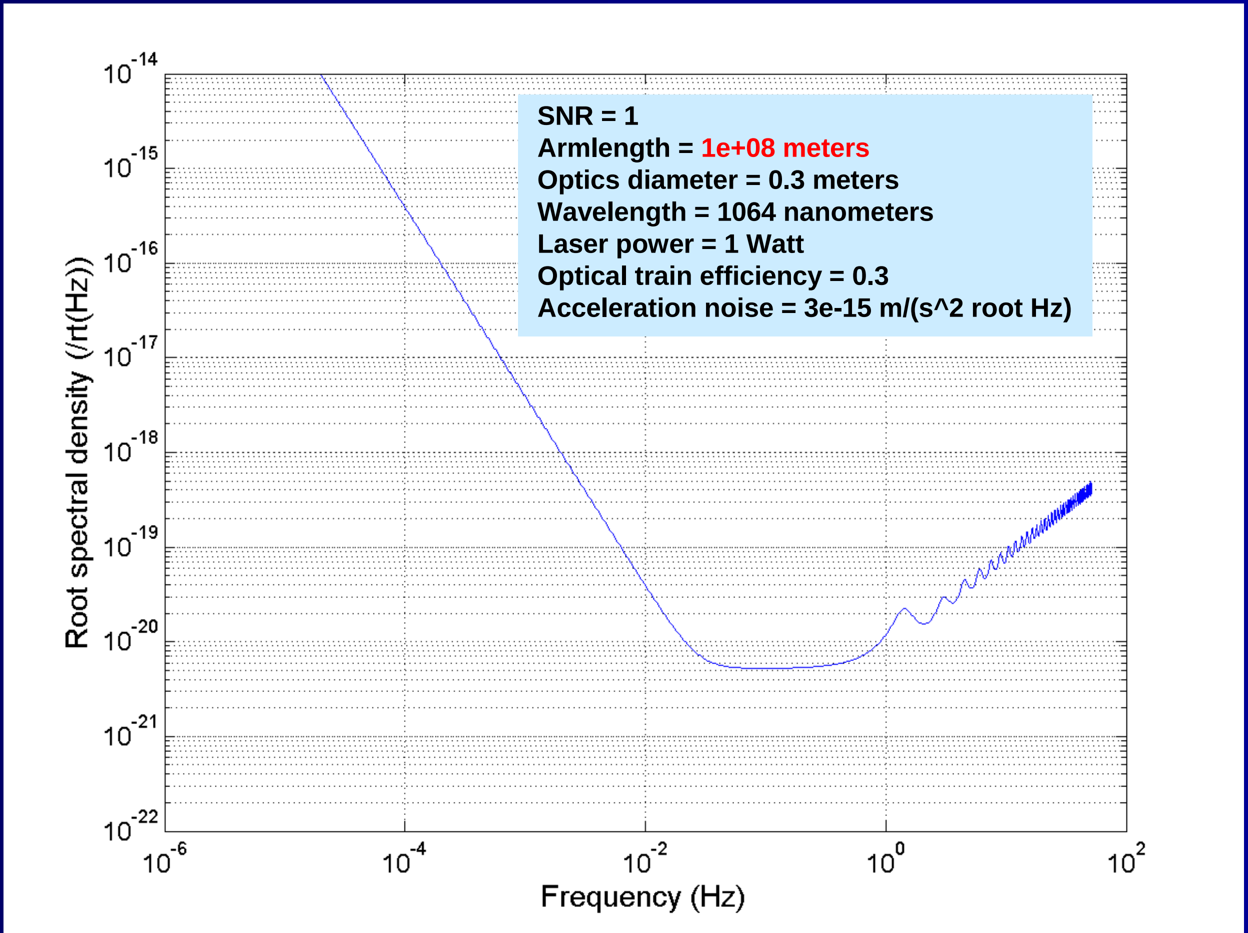

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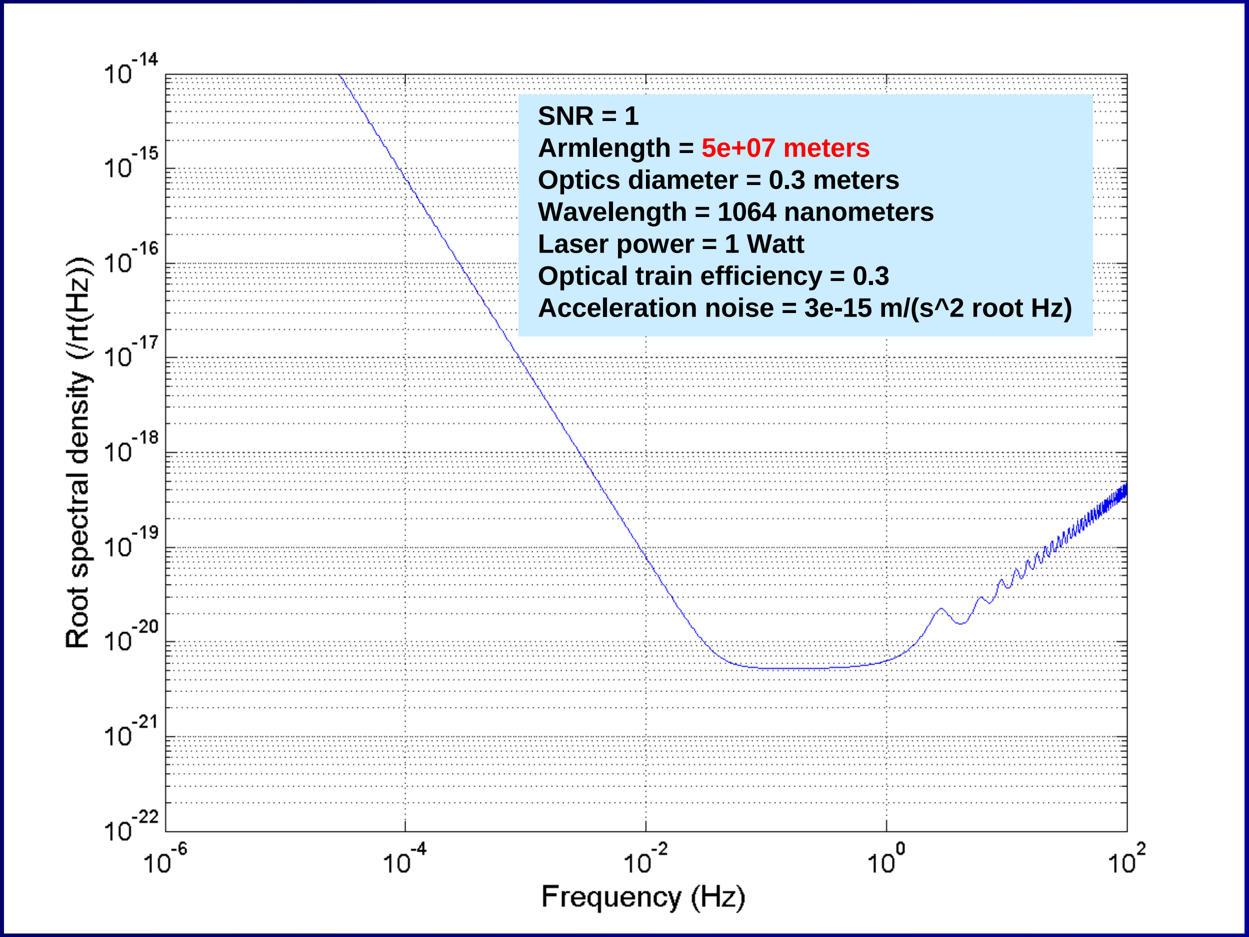

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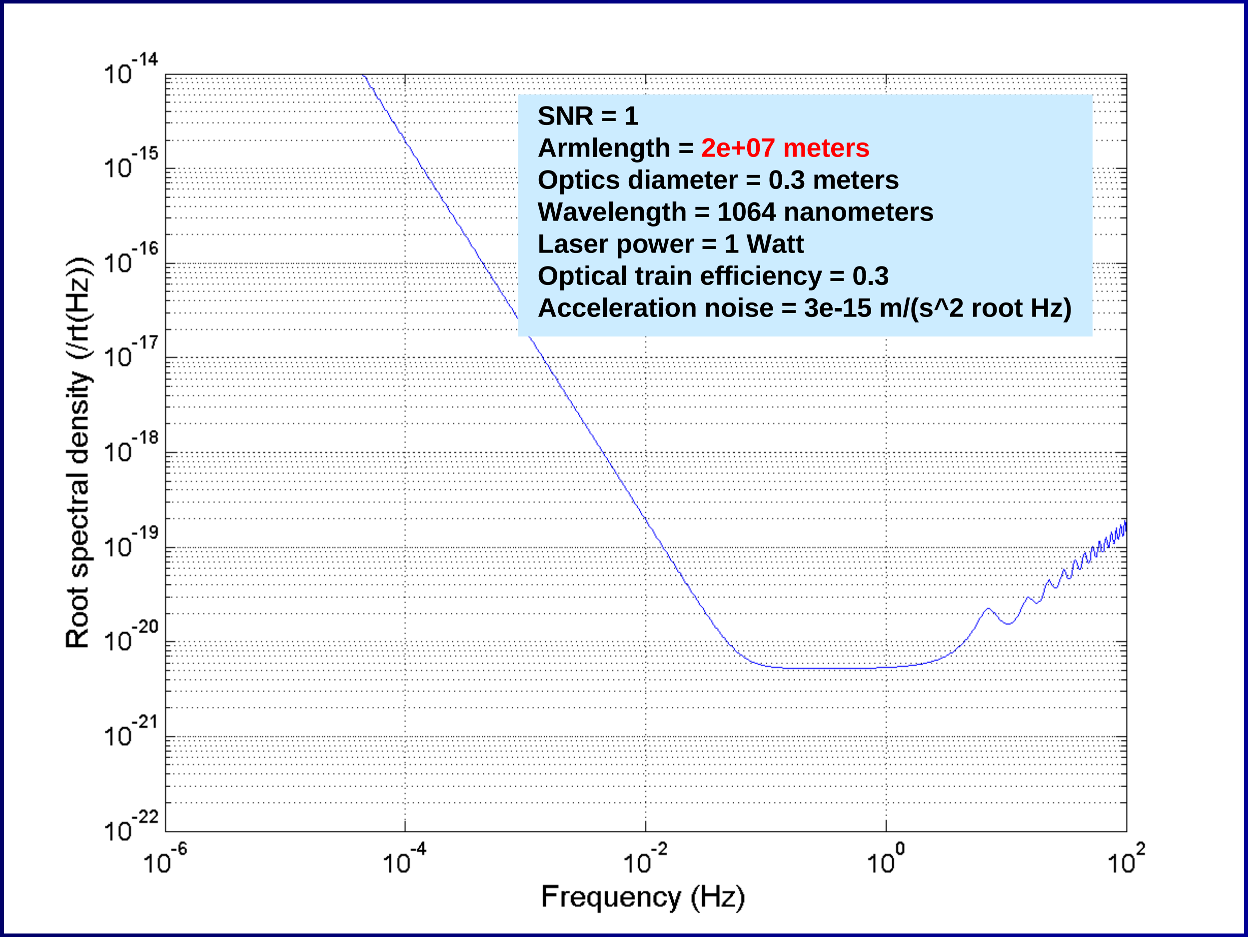

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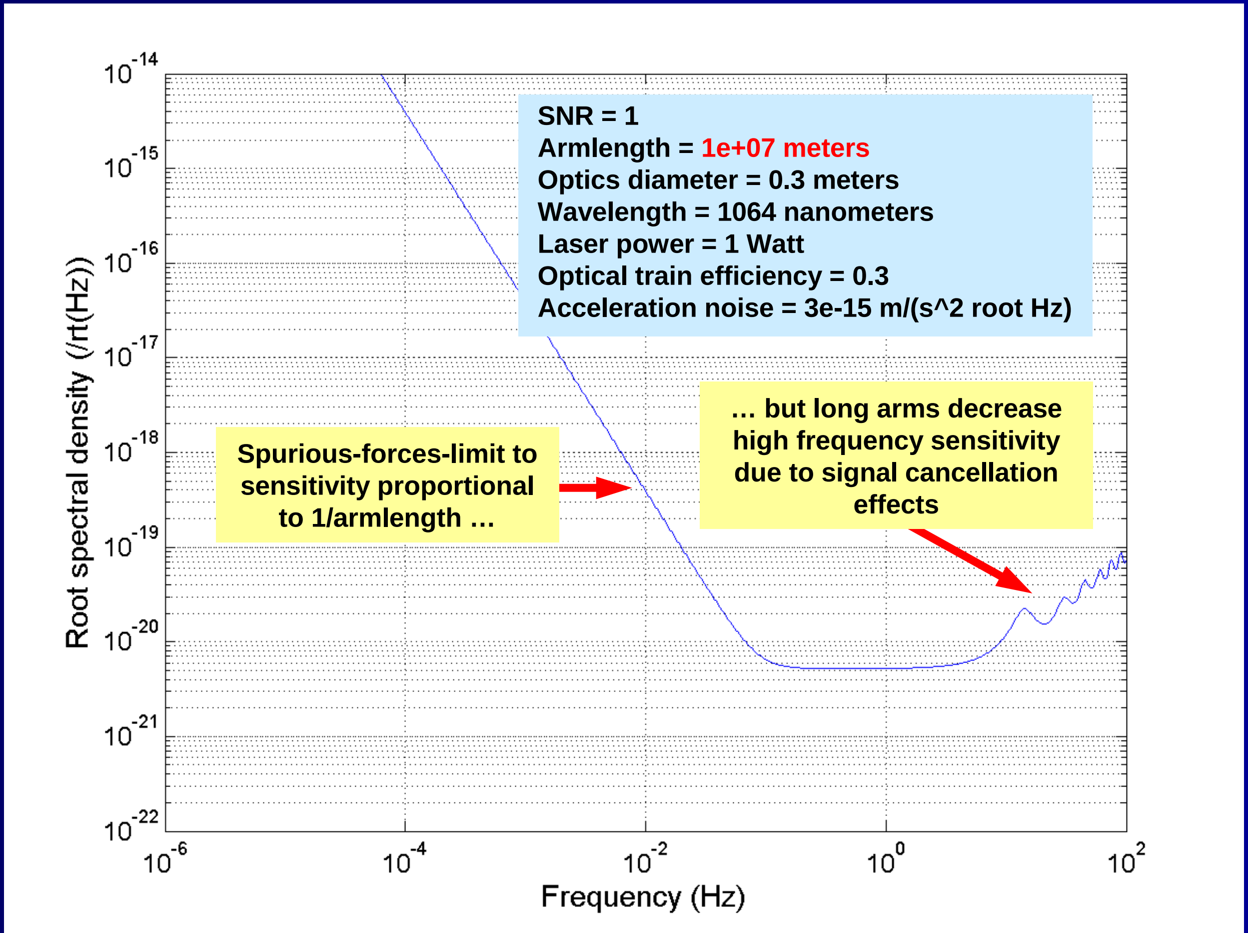

Long arms are required for good low-frequency sensitivity – but damage high frequency performance

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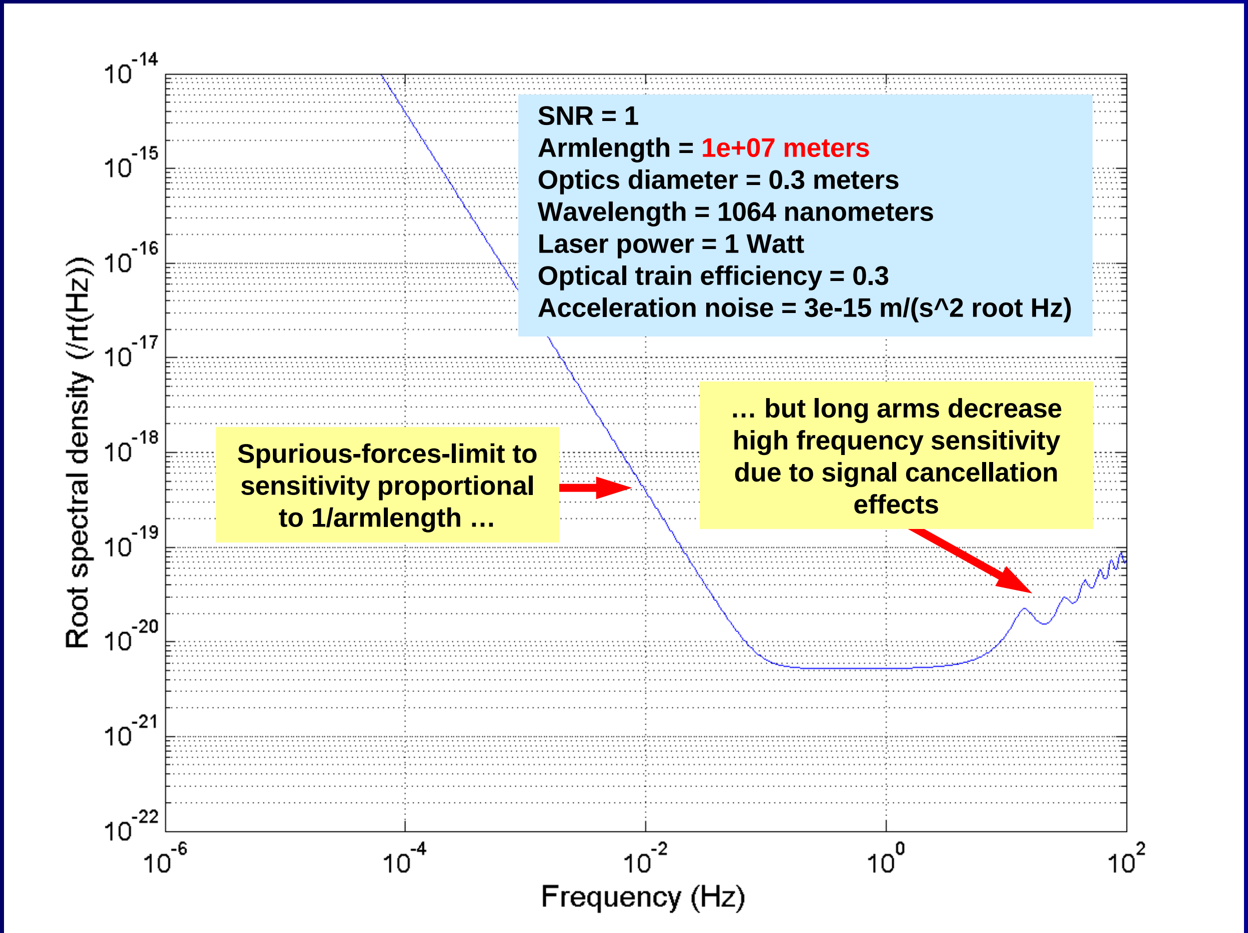

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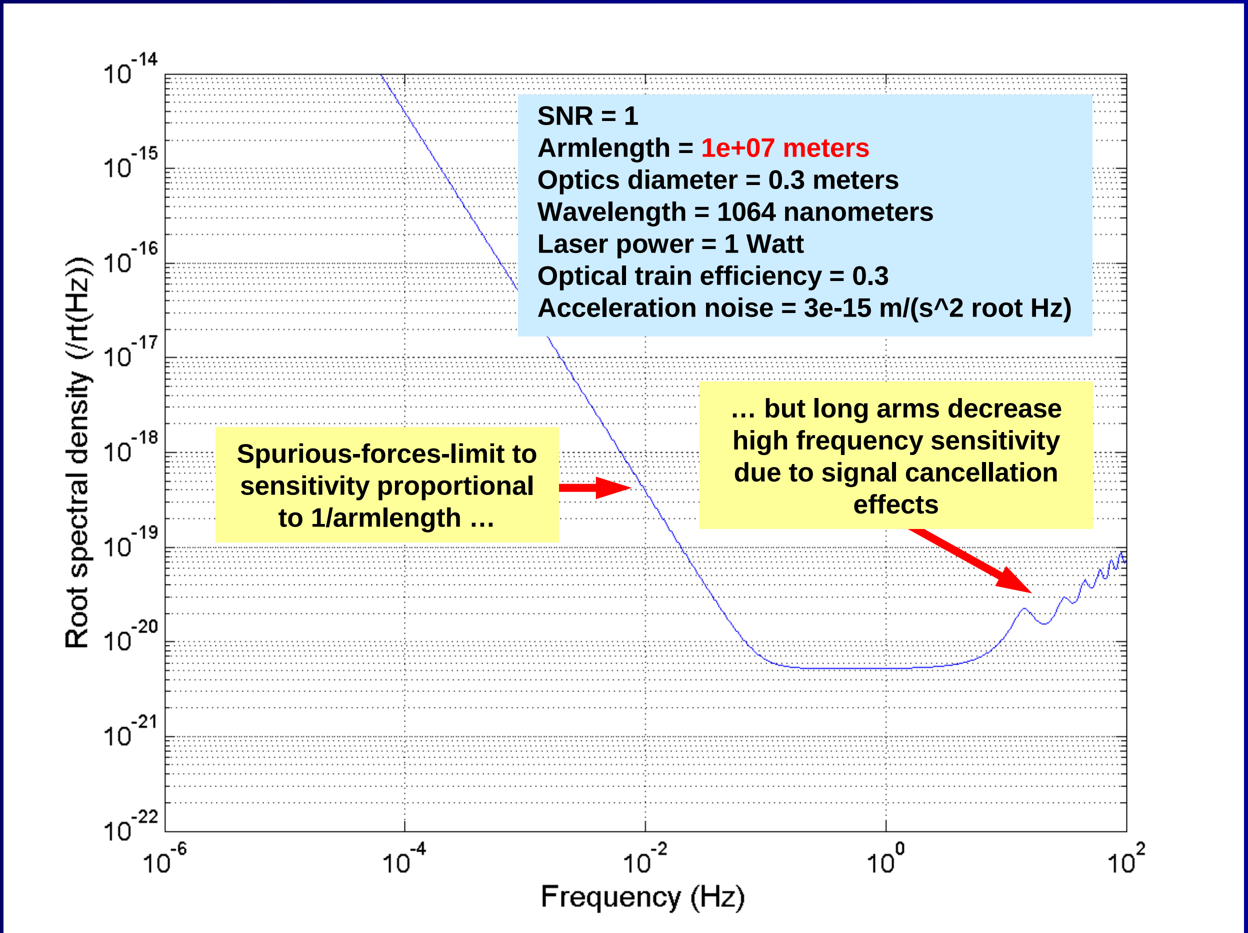

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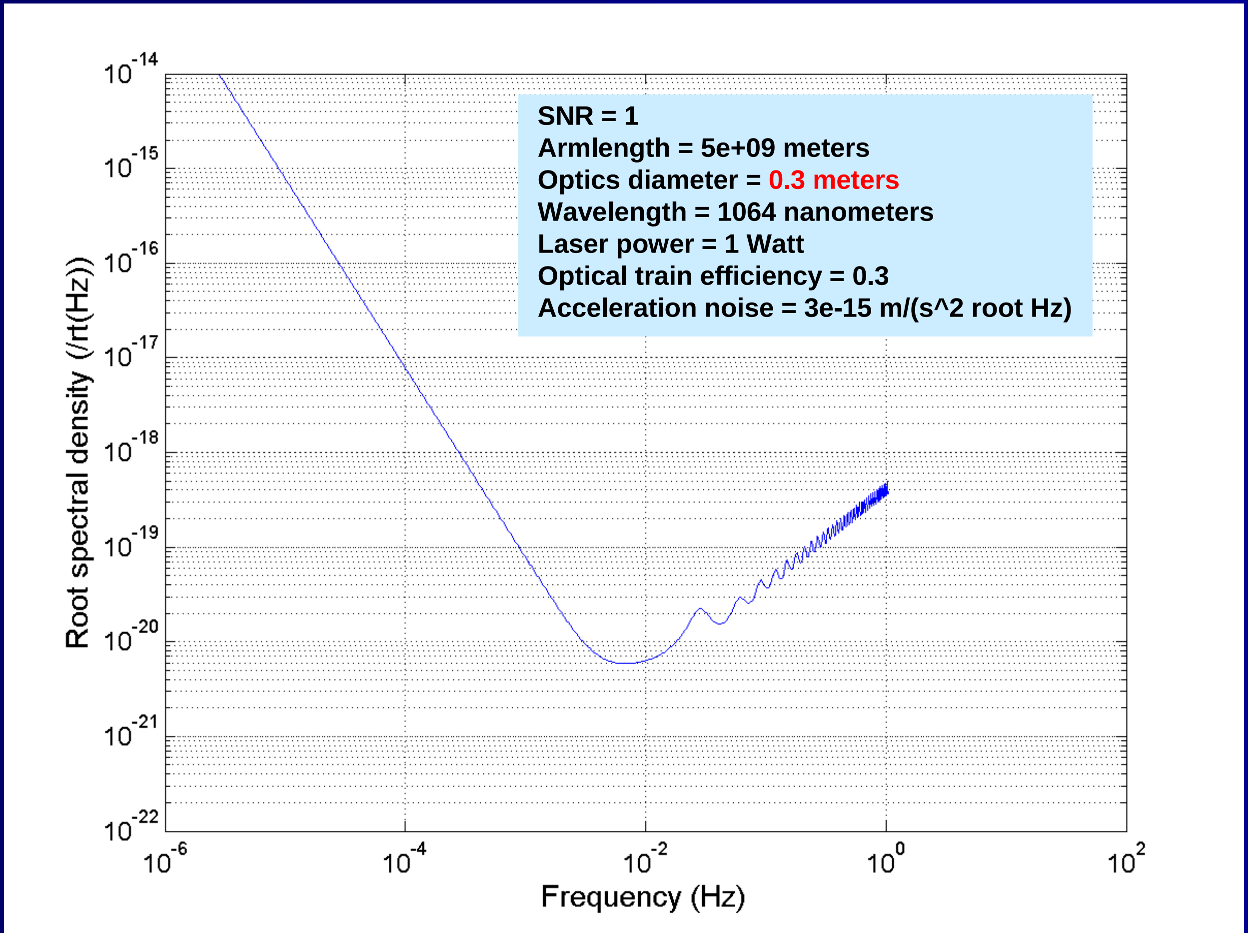
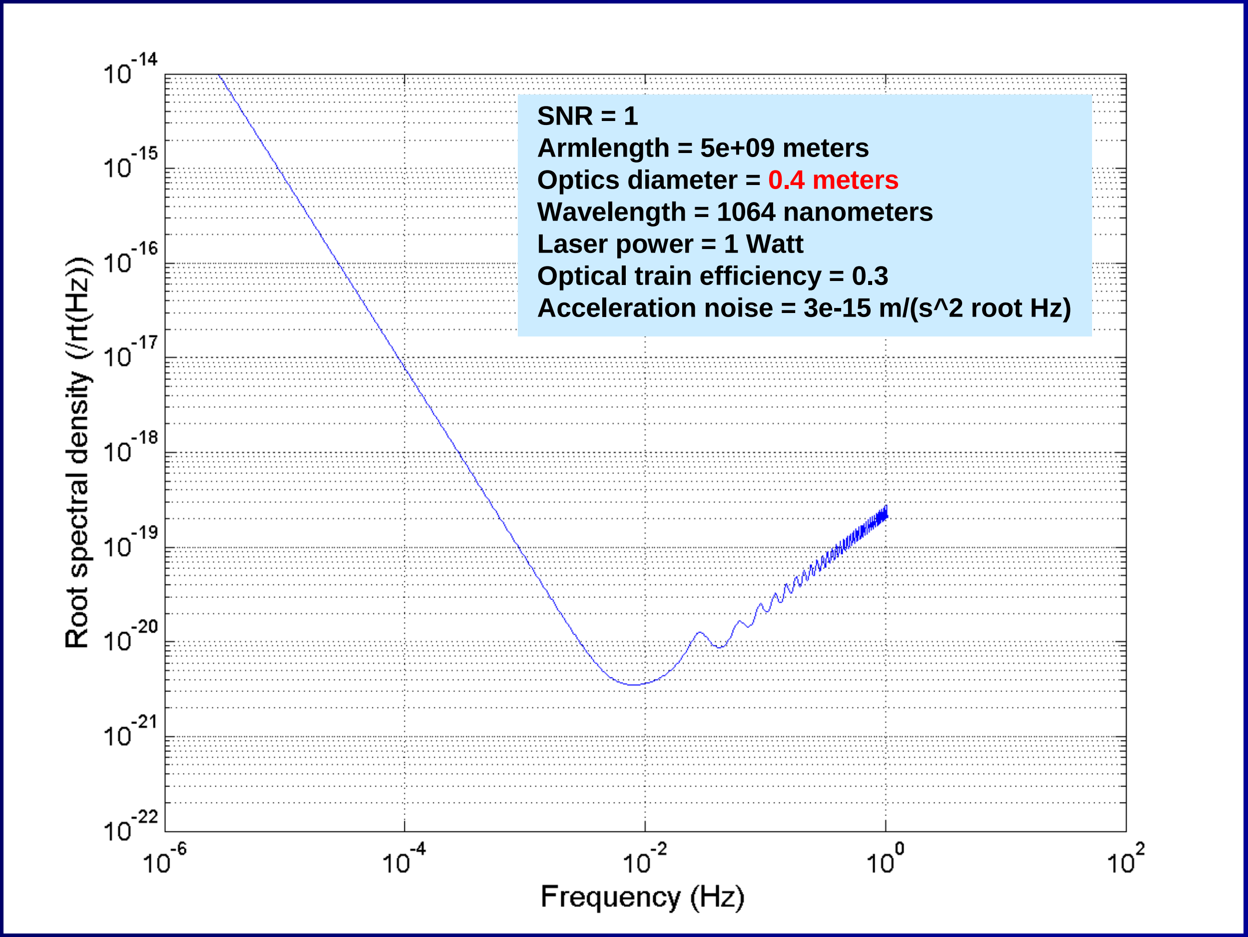
Back to standard LISA



Increasing telescope size …



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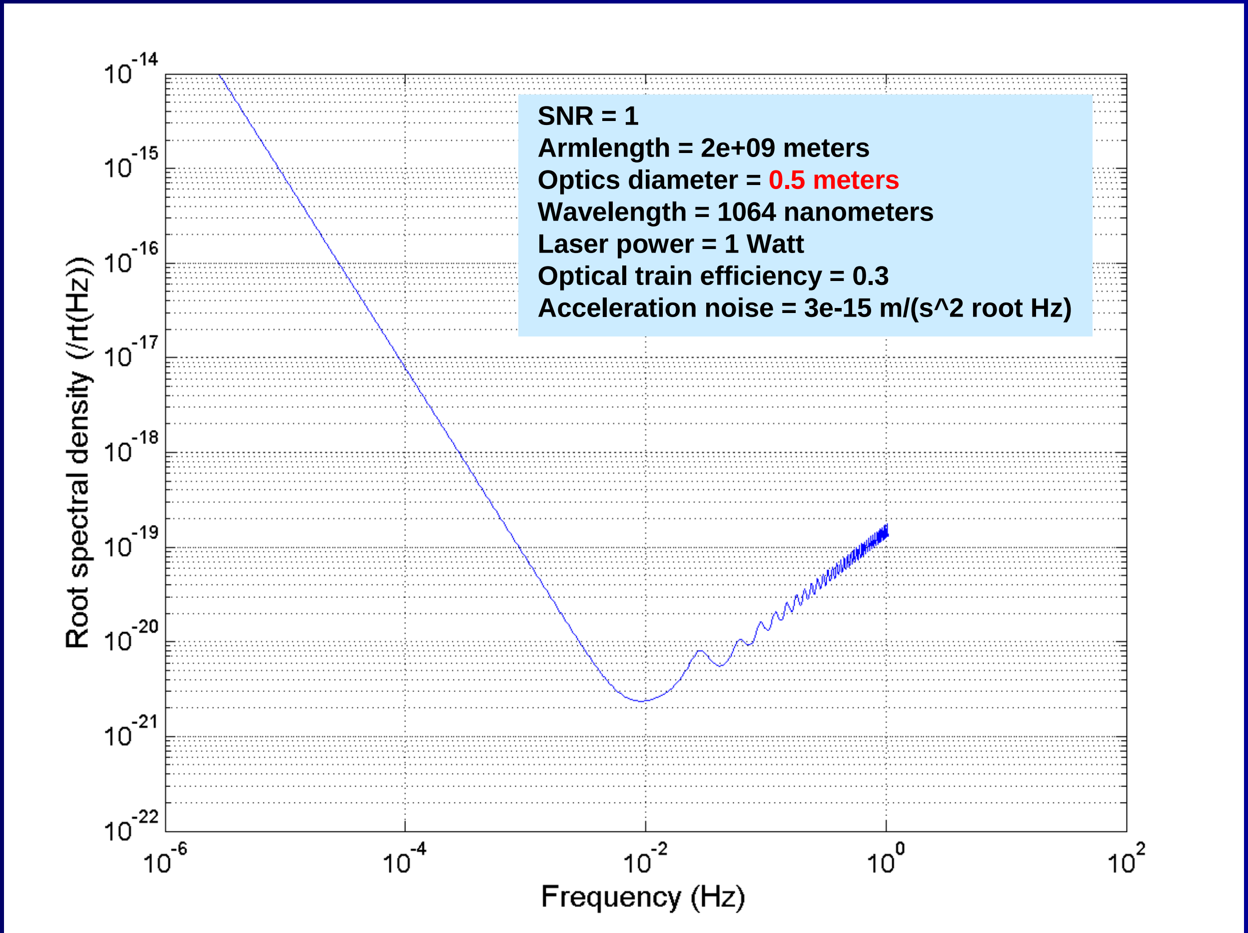

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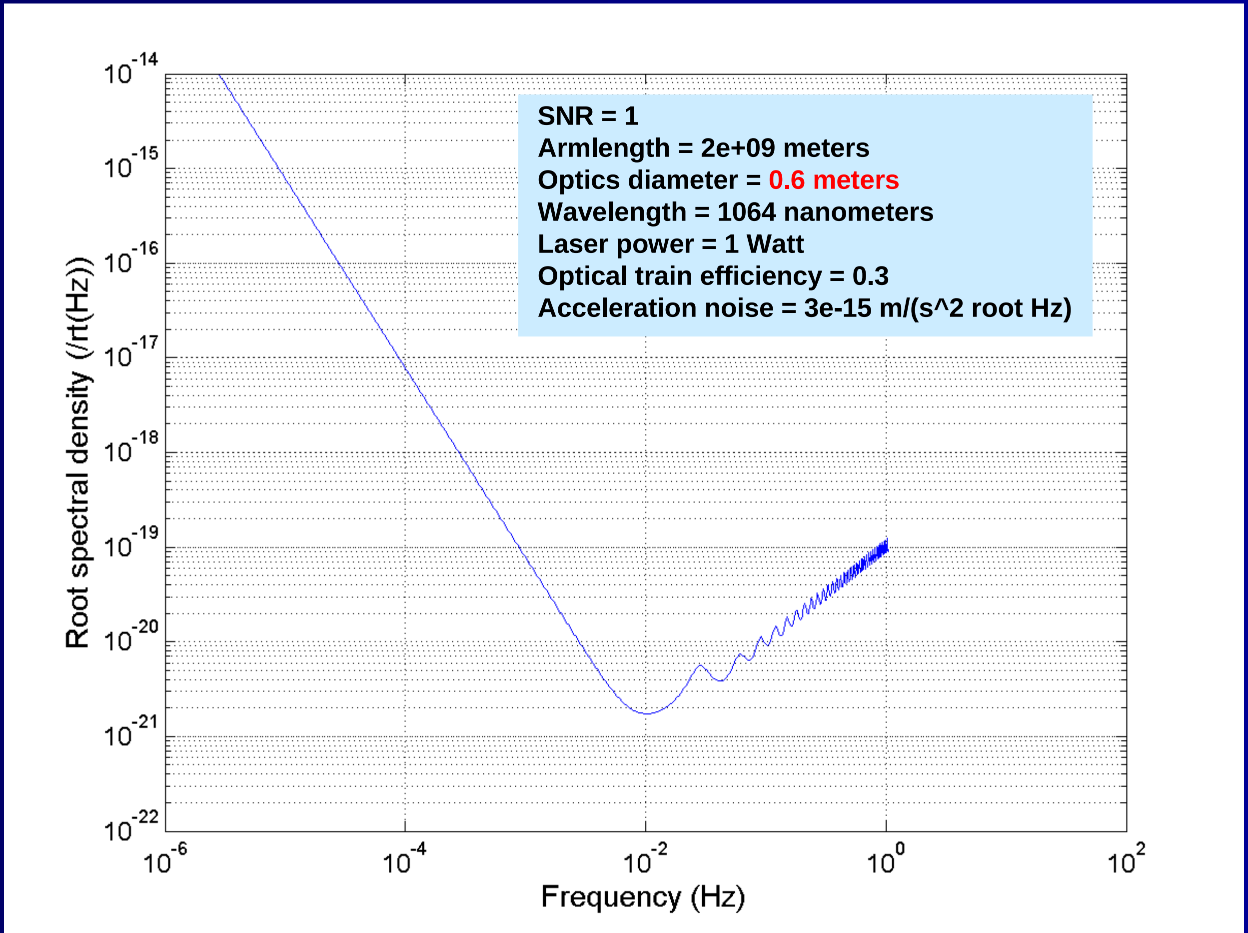

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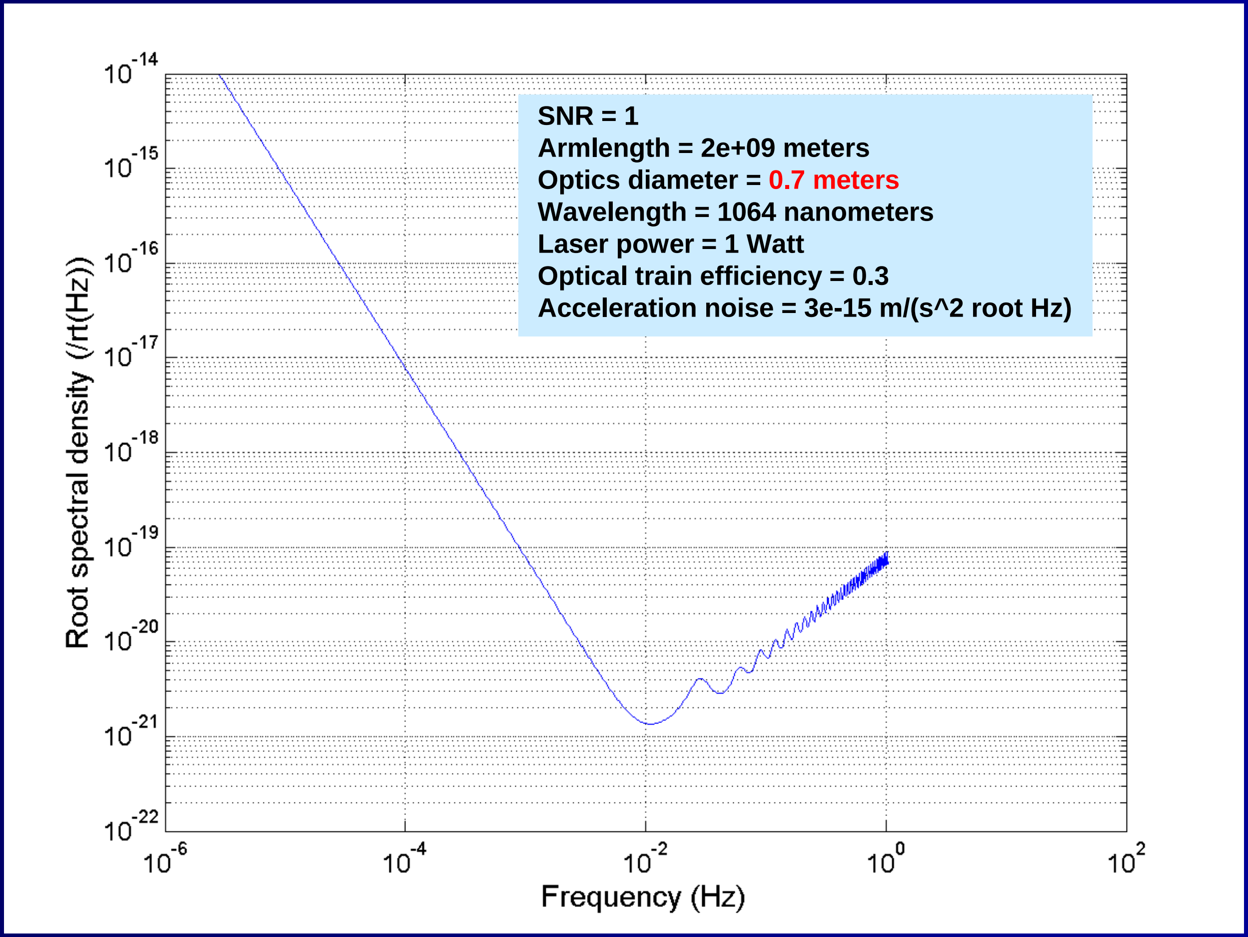

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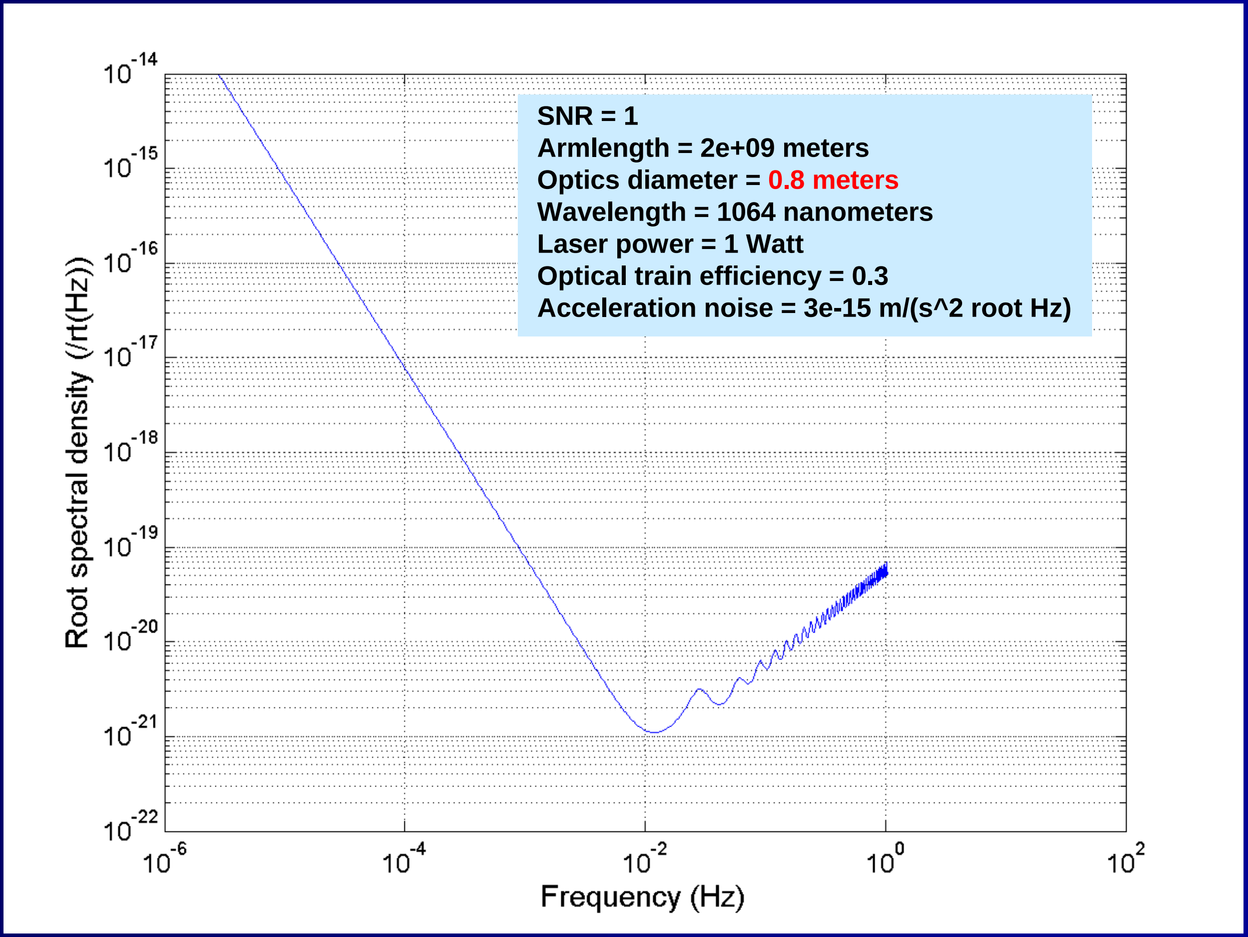

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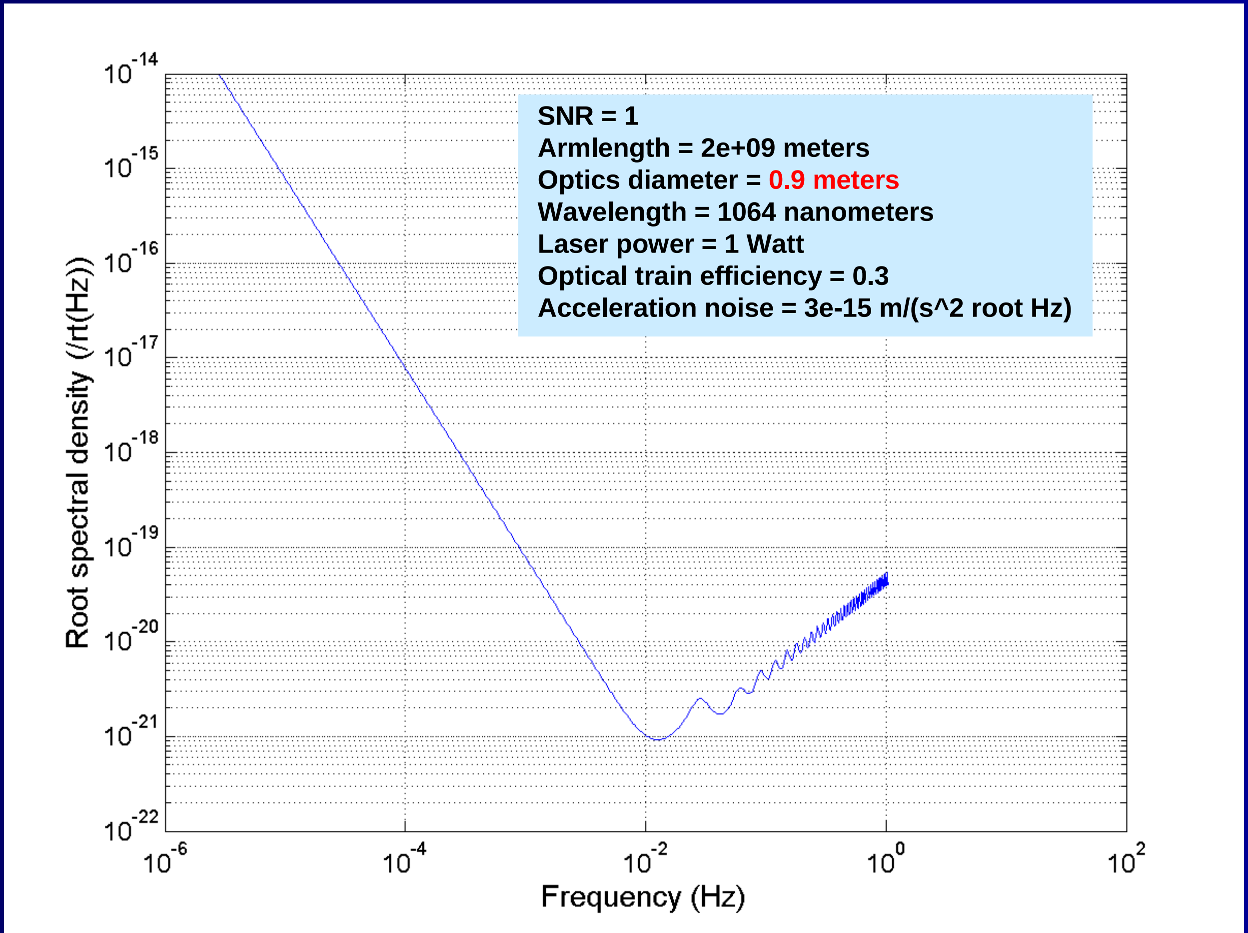

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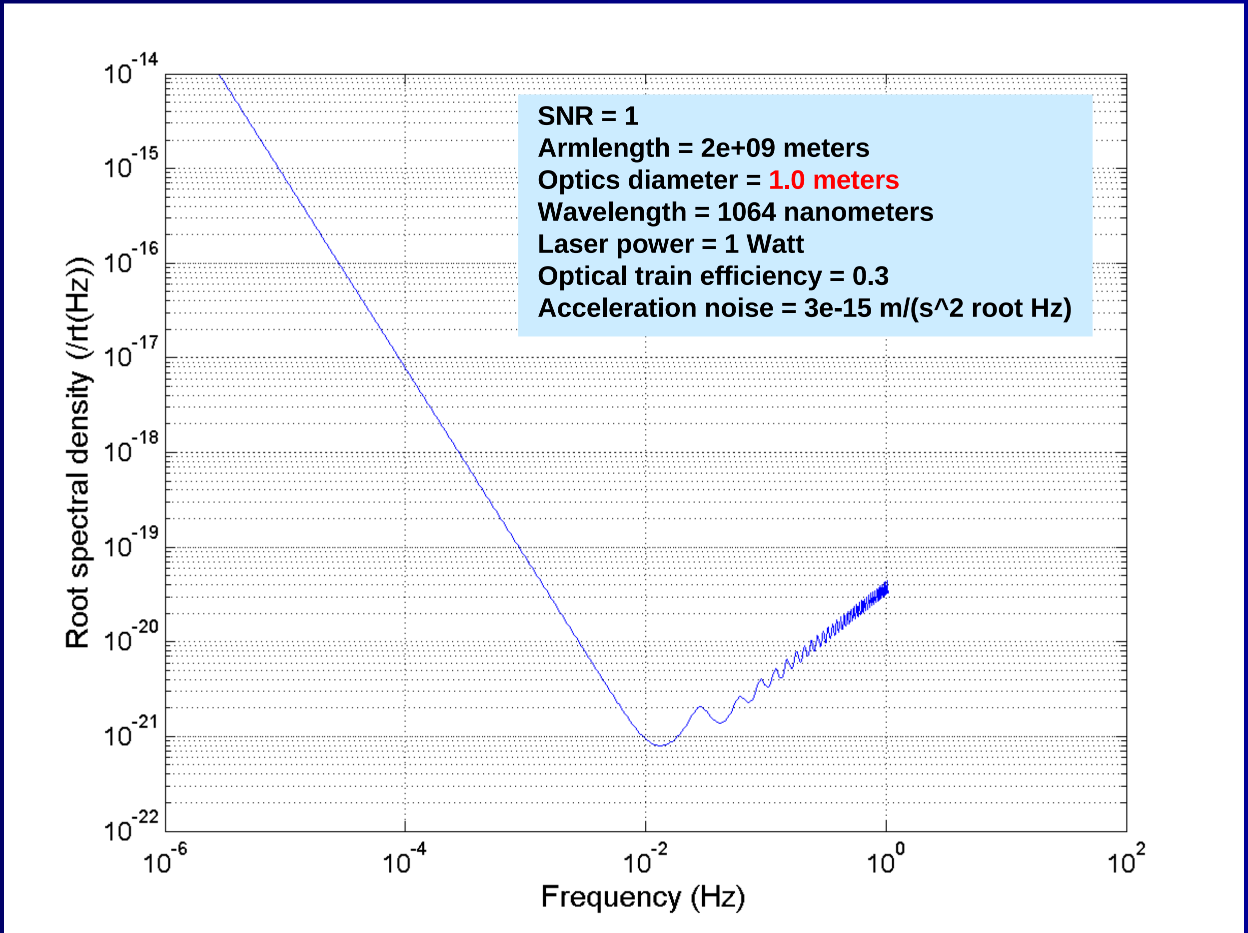

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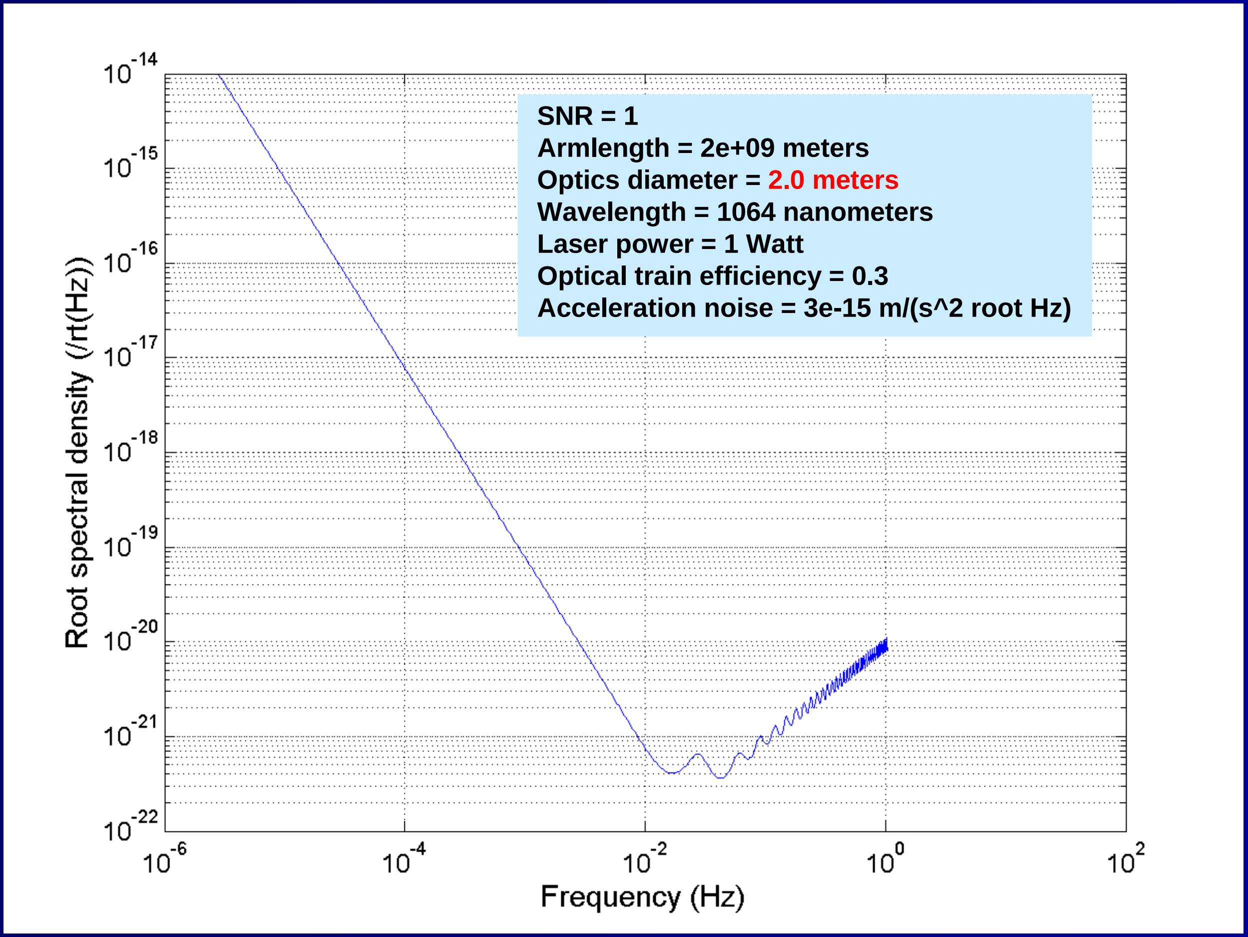

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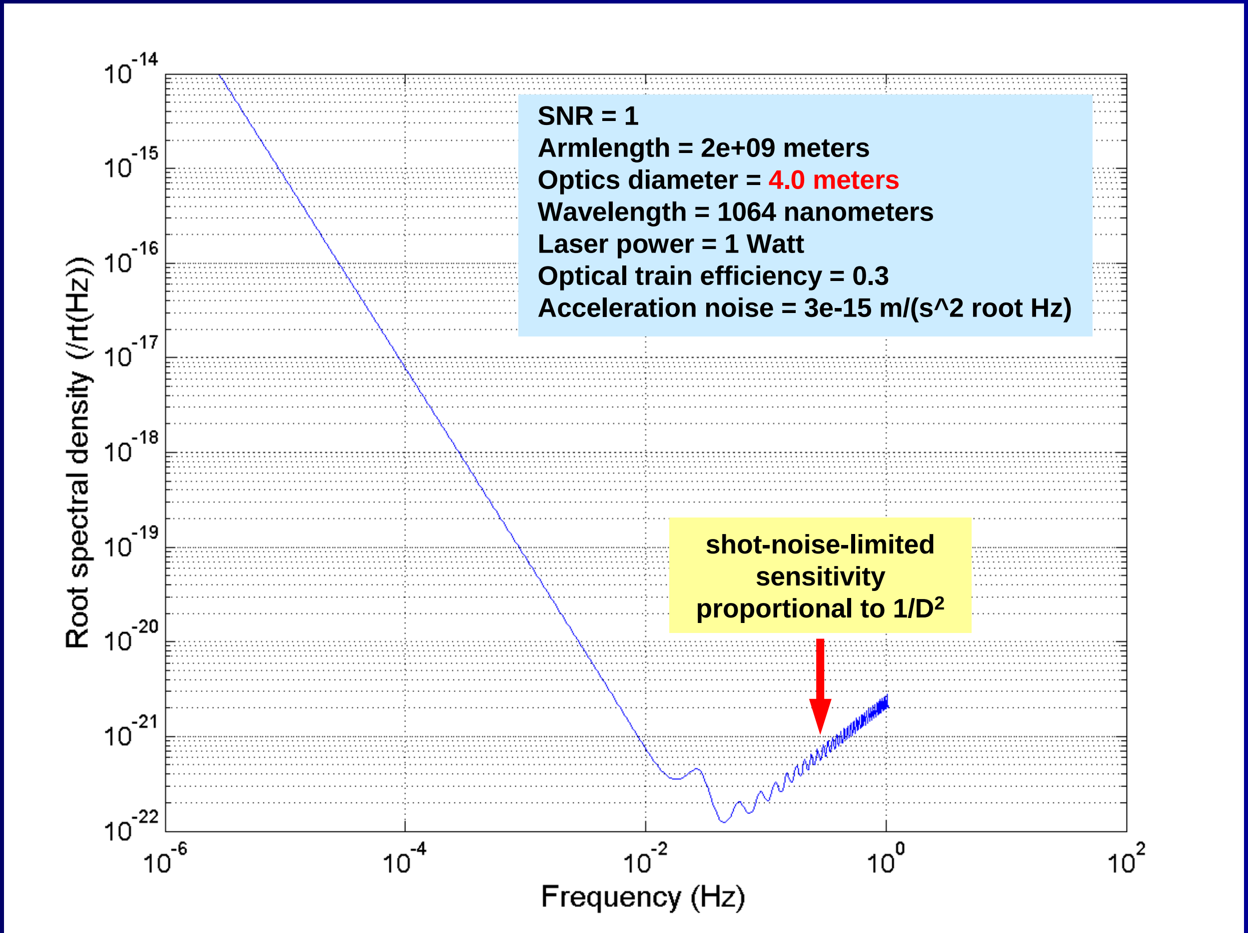

Optical efficiency is vital to achieve good mid- to high frequency performance

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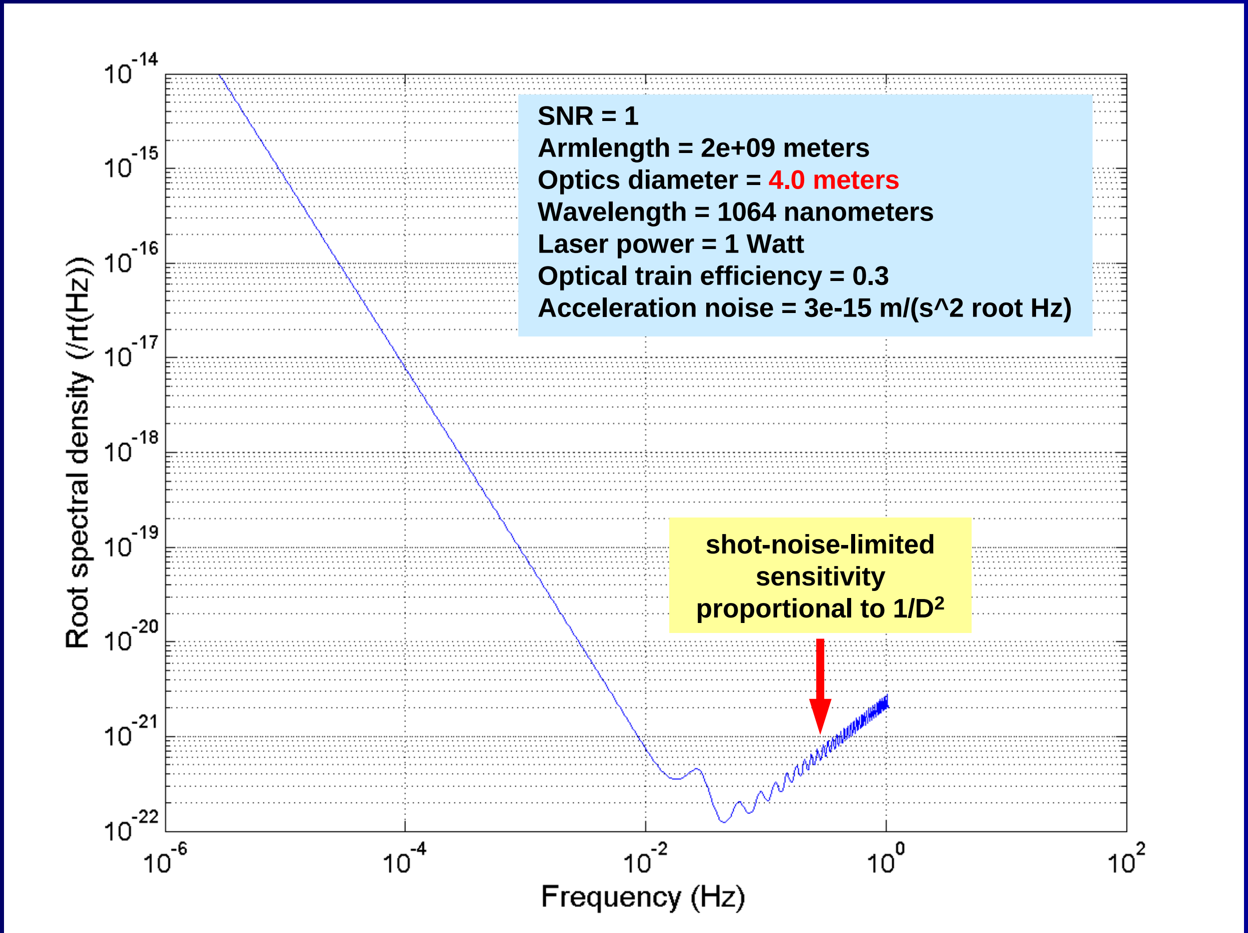

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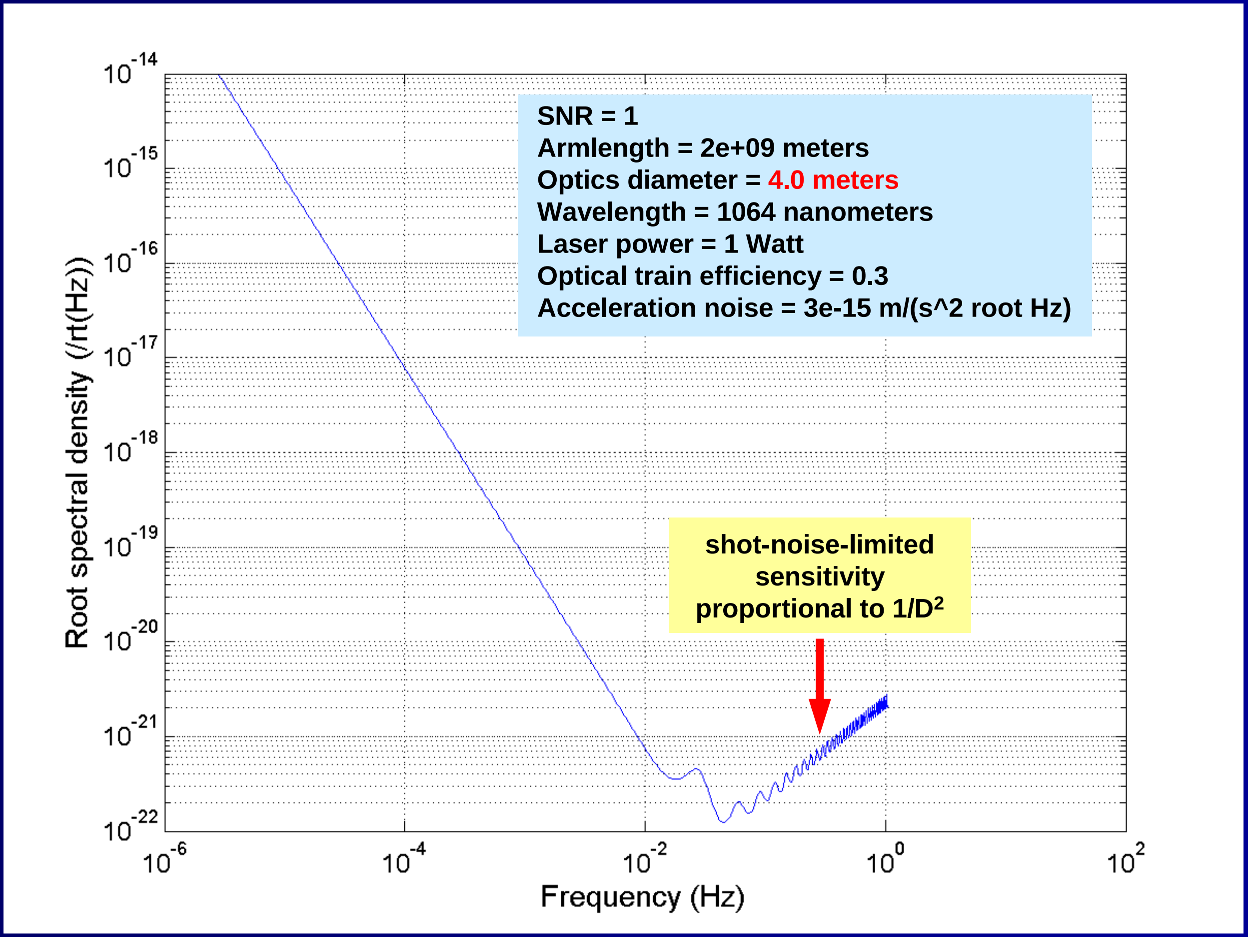

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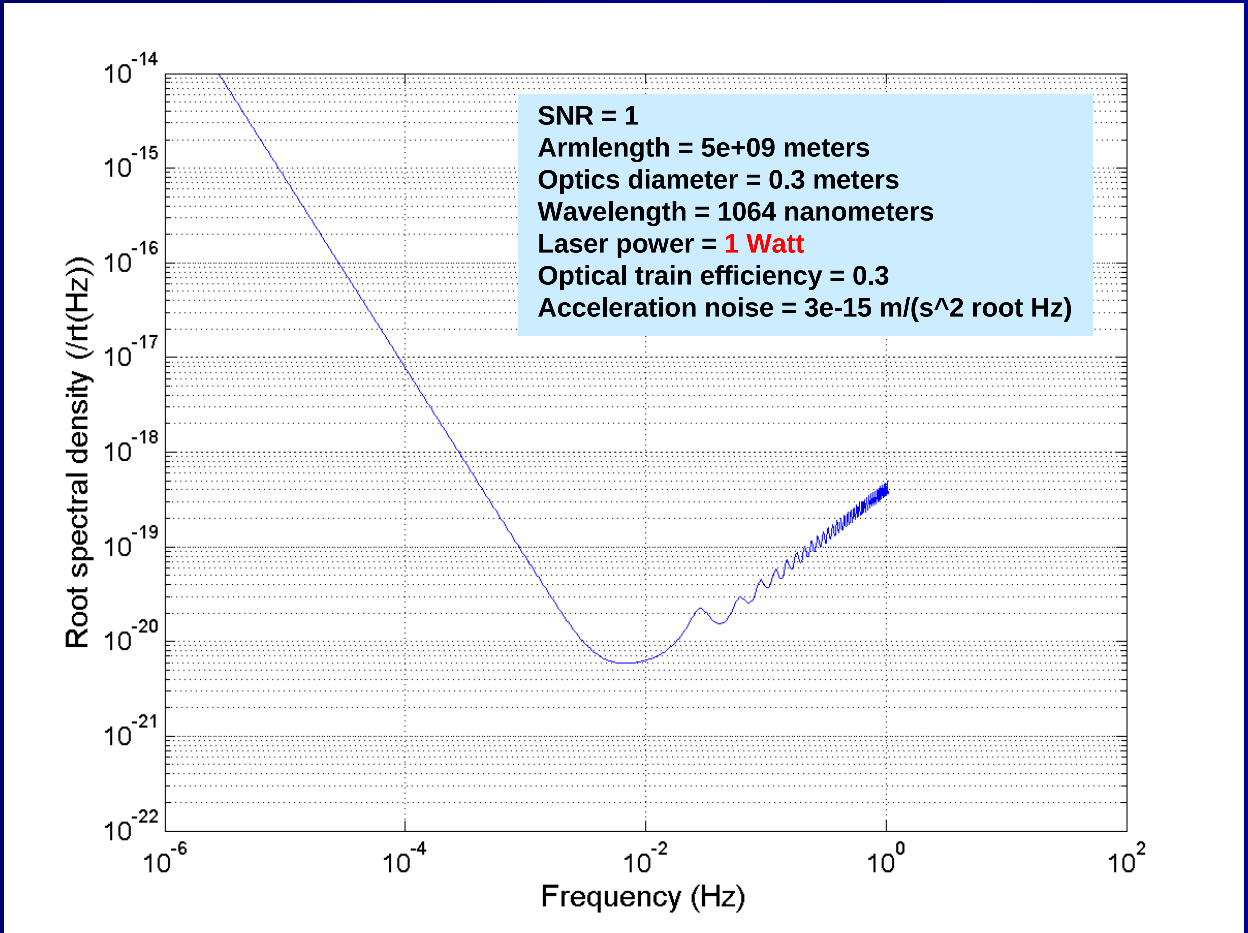
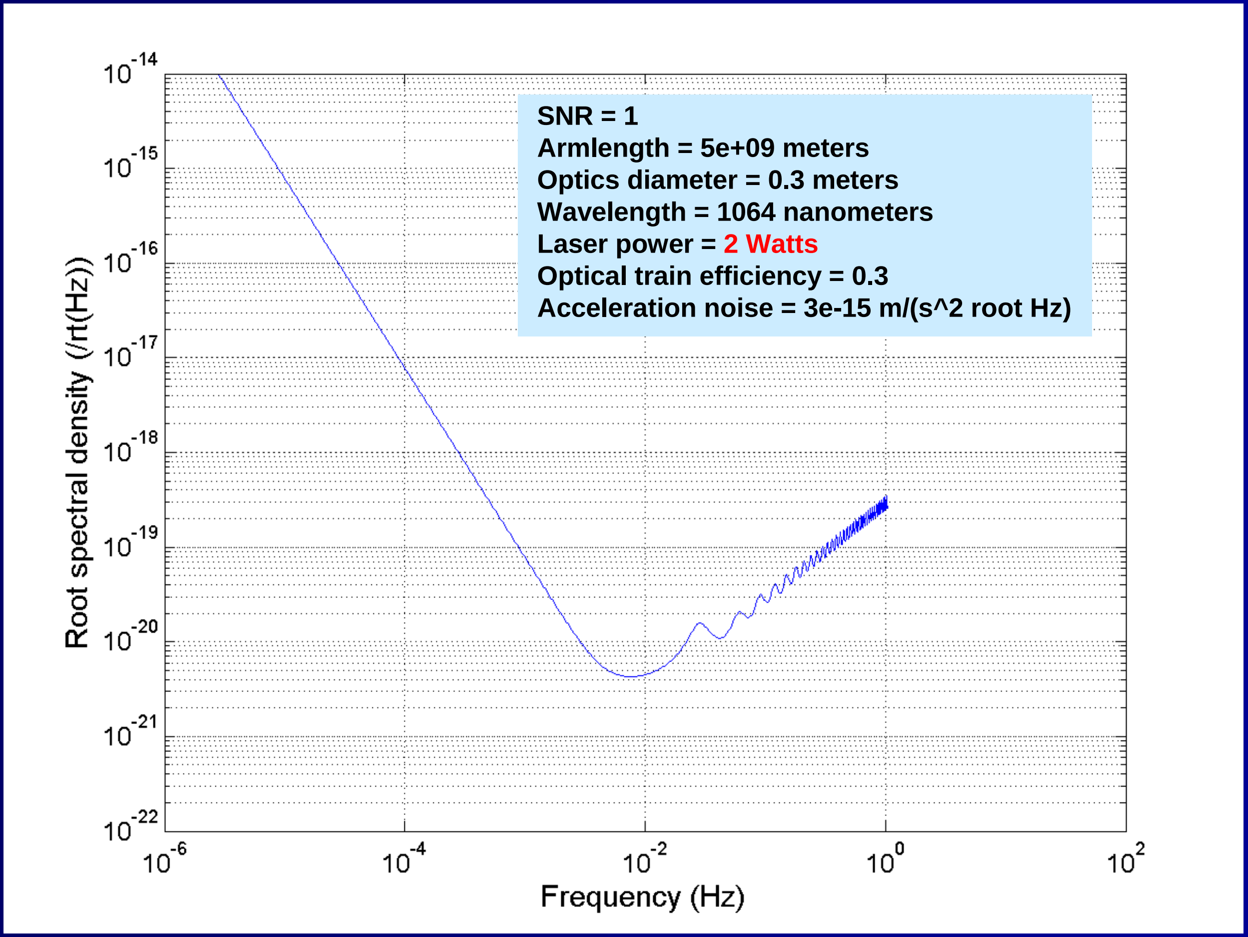
Back to standard LISA



Now increasing laser power …



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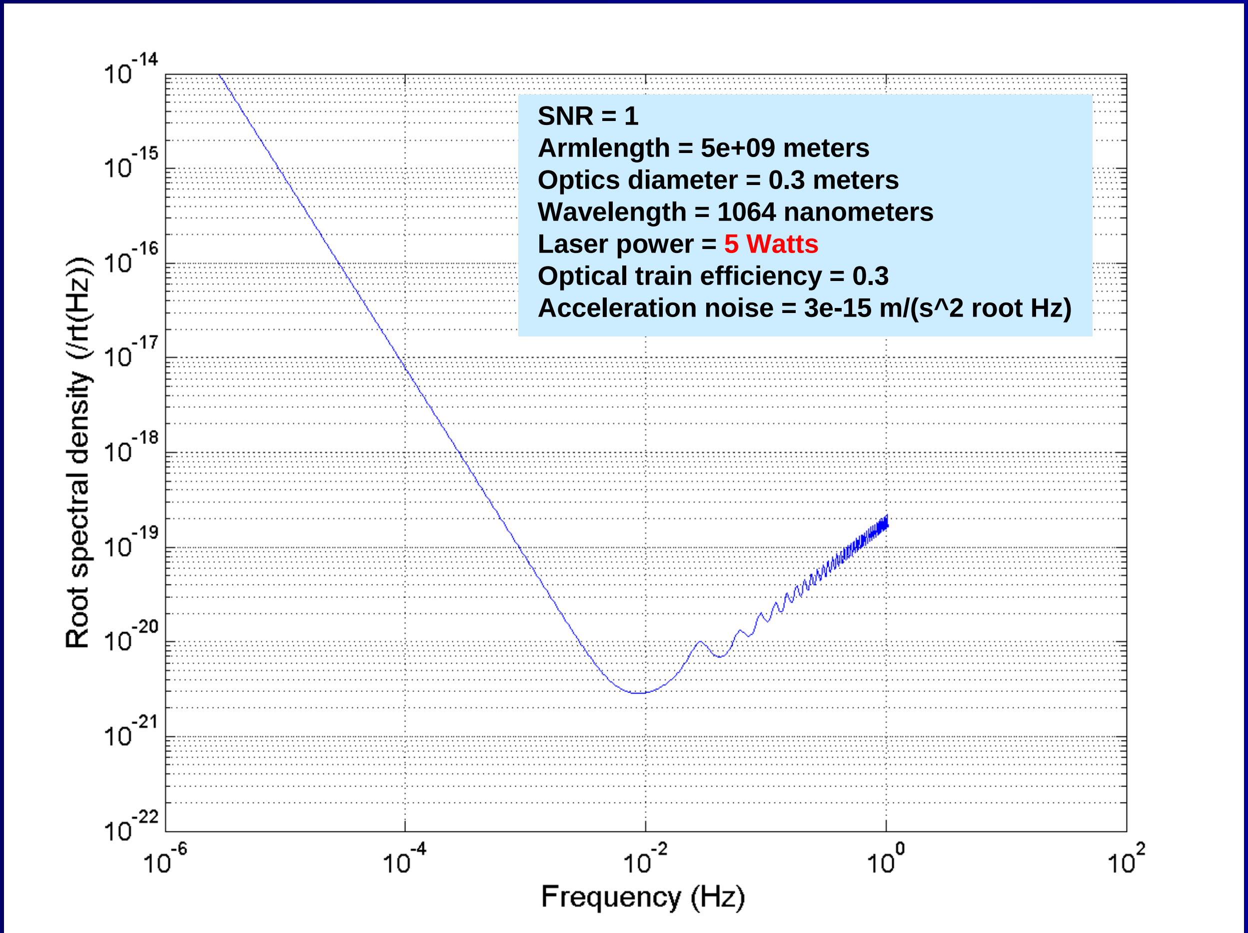

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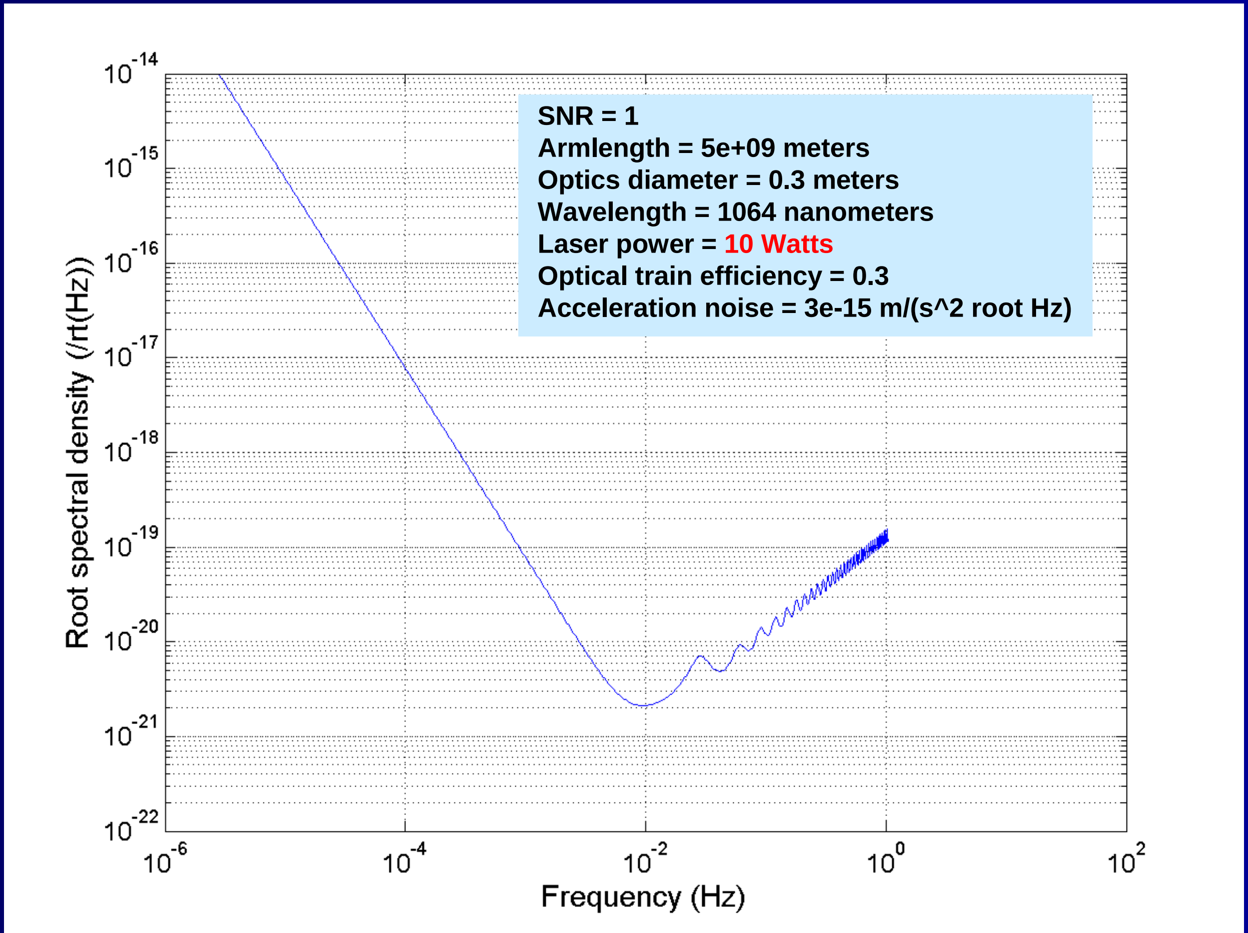

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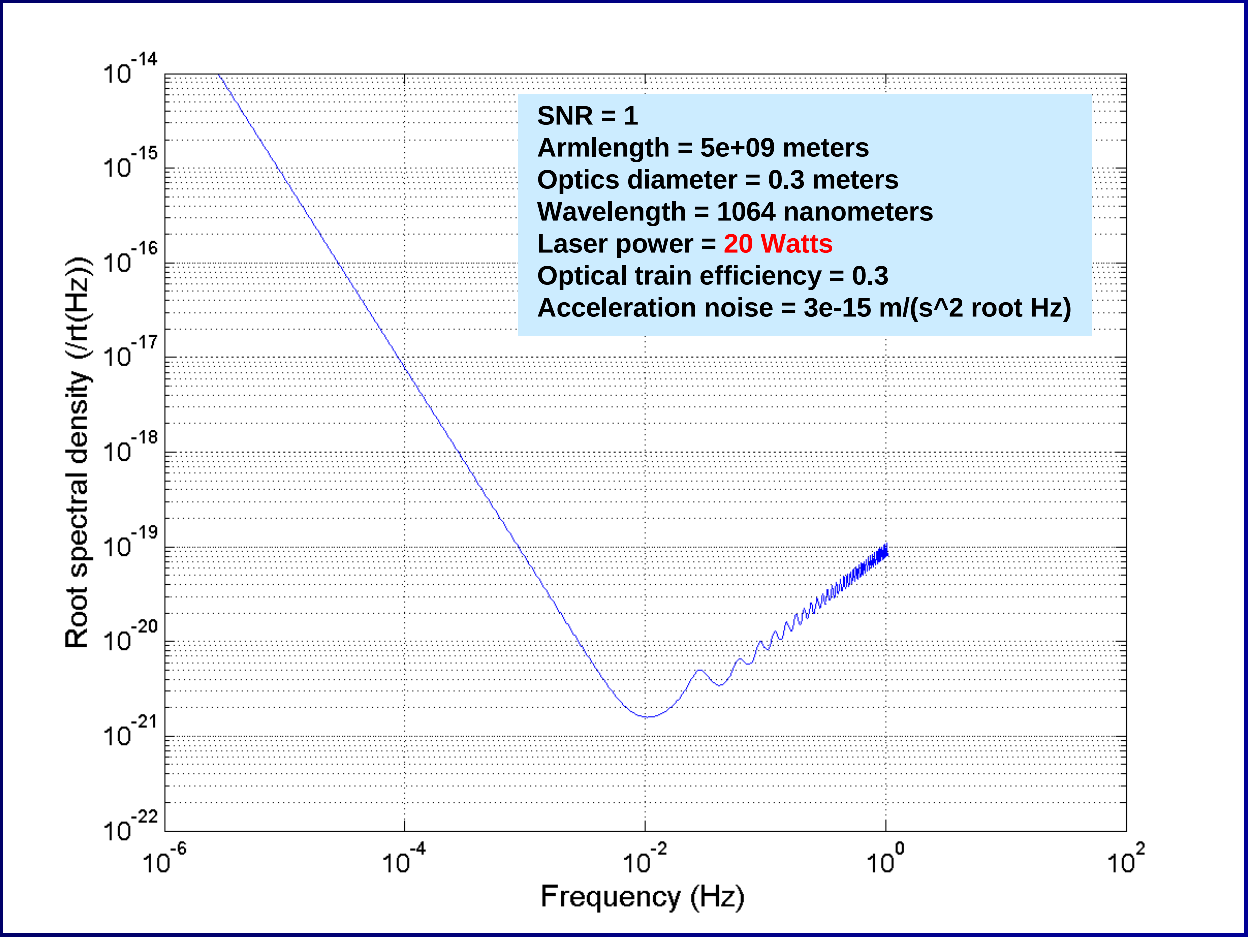

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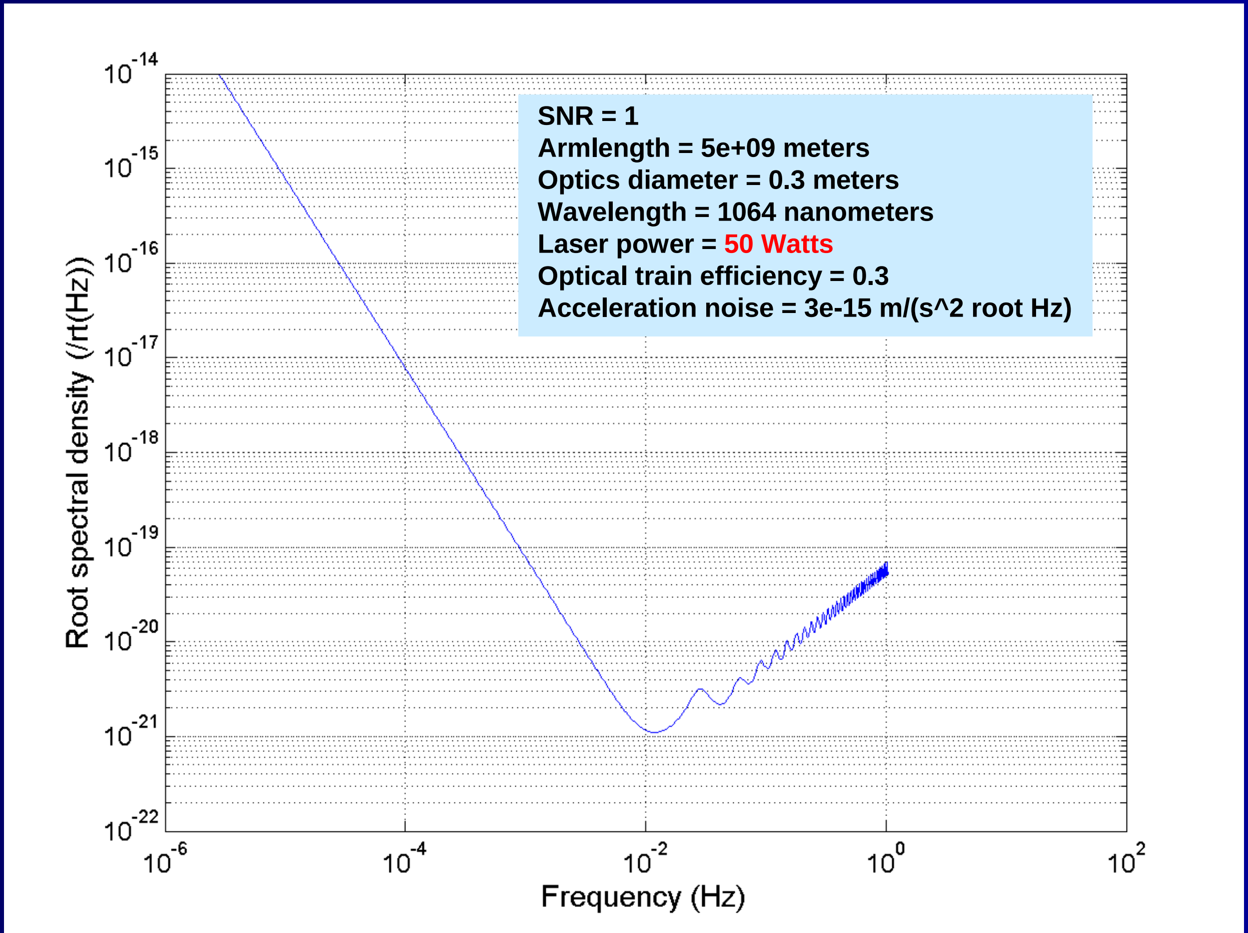

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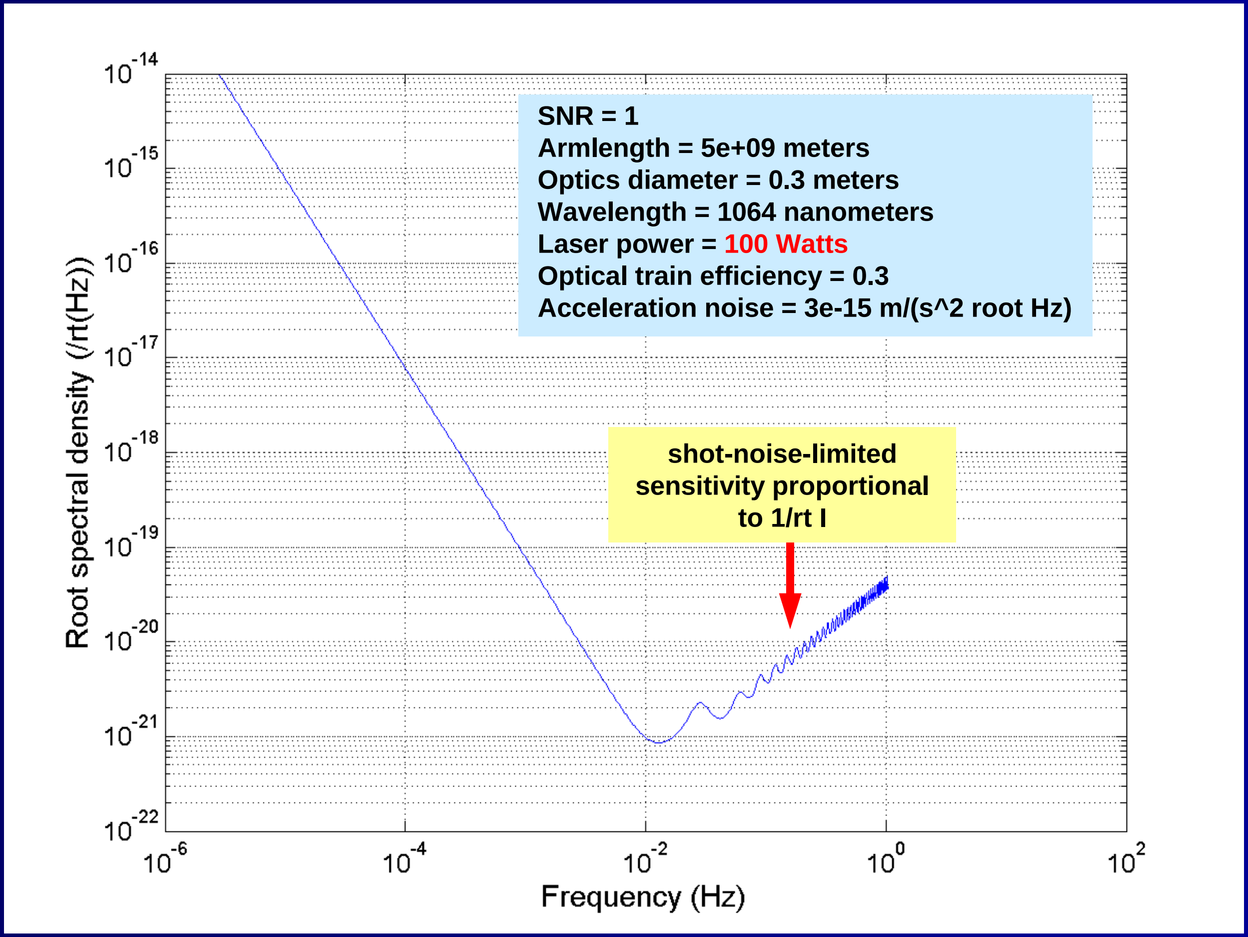

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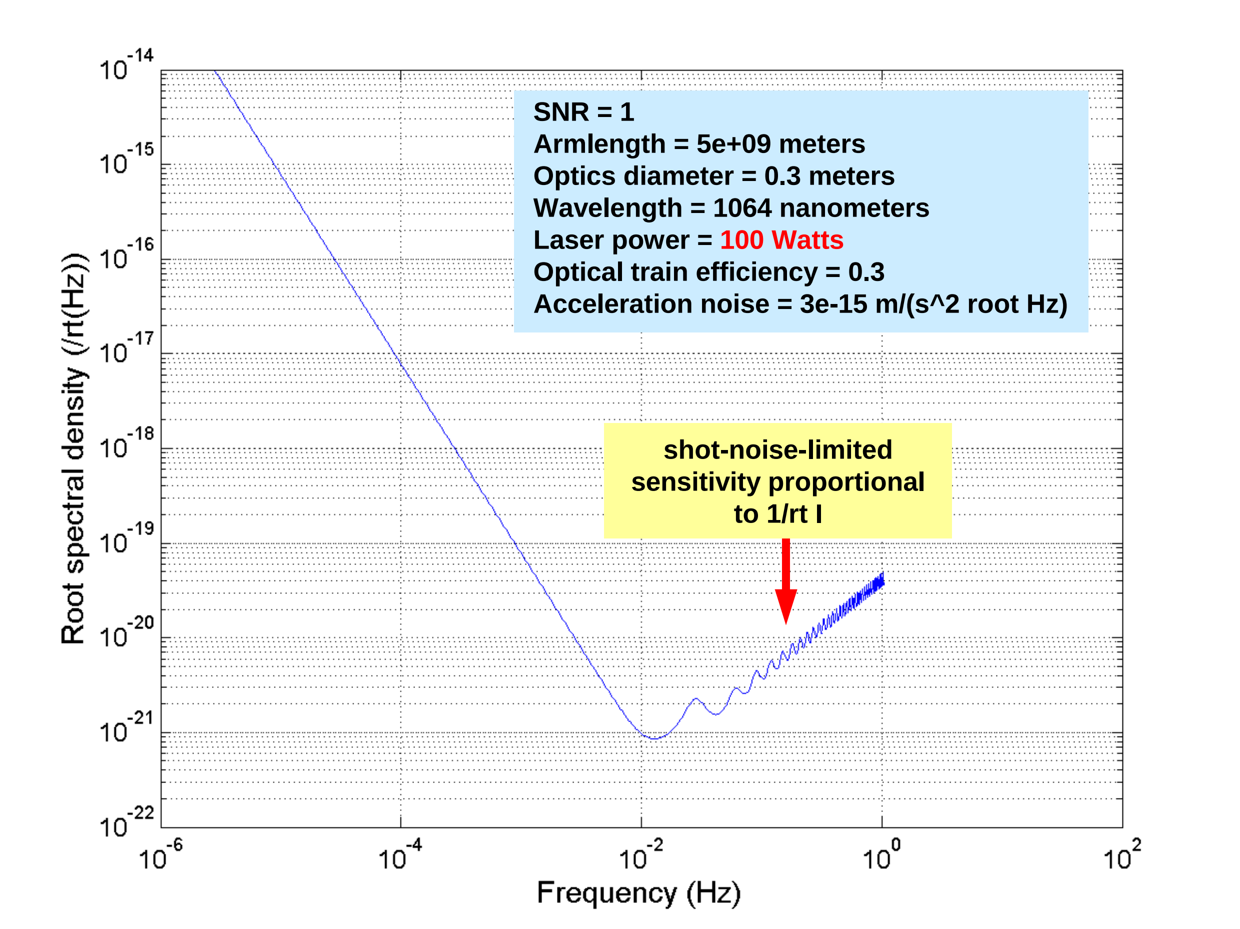

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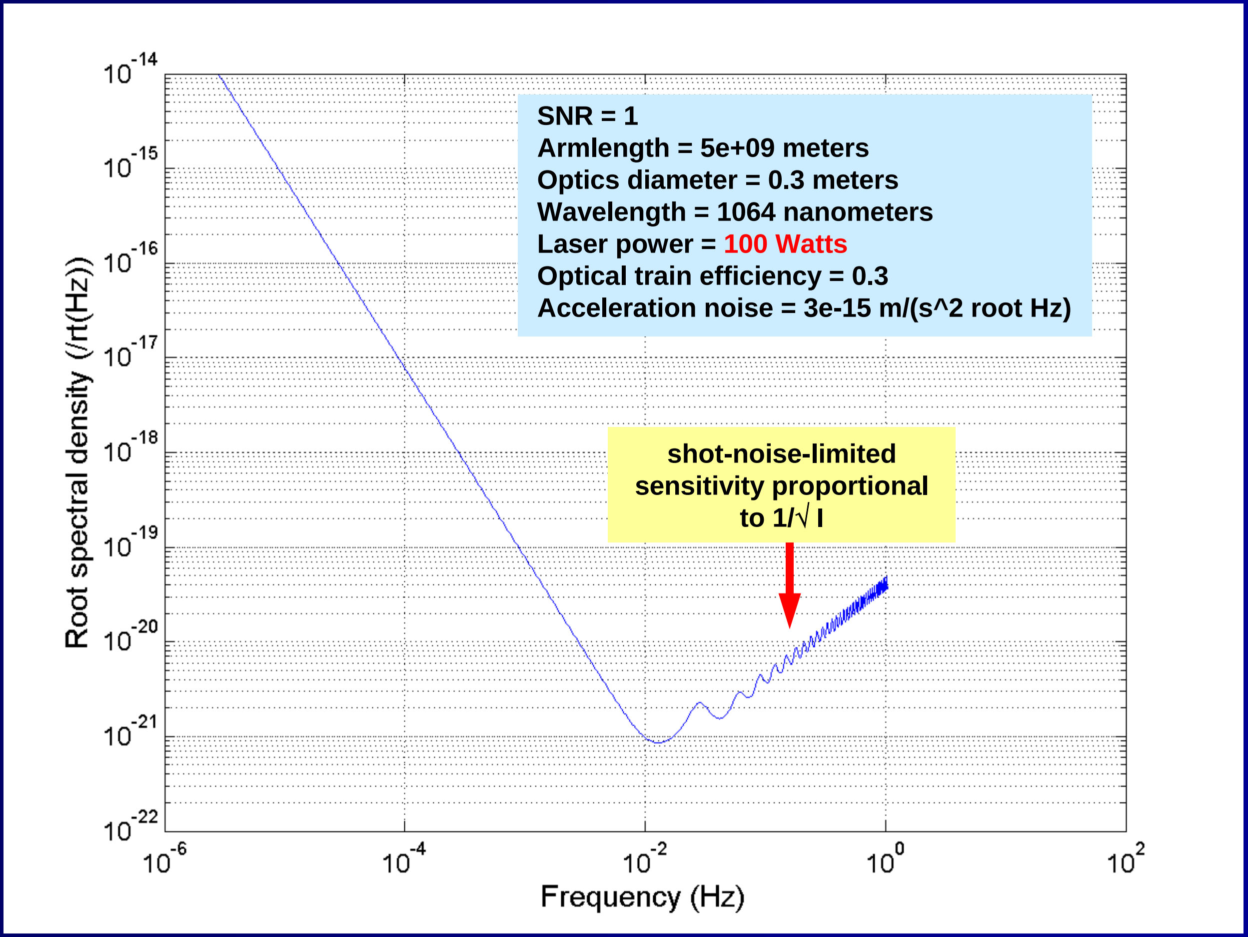


Optical efficiency is vital to achieve good mid- to high frequency performance

Photons matter!

- Once diffraction is taken into account, calculation of the shot-noise limited strain root spectral density gives

$$\tilde{h} \propto \frac{1}{D^2 P_t^{1/2}\ \nu_0^{3/2}}$$

Larson, Hiscock, Hellings, PRD **62** 062001

- Where *D* is the telescope diameter, P_t is the transmitted laser power and ν_0 is the laser frequency used

- So, at least in the shot noise limited region, choices can be made about where to spend resources to achieve a given performance

Lasers – what is feasible?

- High quality laser power
  - Some history suggests development of a factor of 10 in power in a decade might be a reasonable expectation
    - Ground-based interferometers now routinely use 10W and are poised to deploy 100W systems
    - Spaceborne lasers for LISA are of the 1 to 2 W class
    - On the 2025 timescale we believe that spaceborne high quality laser power of up to 100 Watts at 1 micron is an attainable goal
      - and this would not require exotic power sources
      - though it might require tethered solar arrays separate from the sensitive measurement spacecraft

Optimistic projections talk of kW class lasers; if these could be developed it would enable even more sensitive detection possibilities

Telescopes – what is feasible?

- The bigger the better!
  - But a precision interferometer places high demands on the surface figure of the telescope
  - This may preclude the use of multi segmented mirrors in which elements are folded for launch and then deployed
  - This in turn limits the useable telescope size to that which is compatible with an available – and affordable – launcher
    - Unless active mirror figure control is developed …
  - On the 2025 timescale we believe that deployment of multiple 1m diameter telescope optics is certainly an attainable goal

Drag-free control – what is feasible?

- The principal development that should advance drag-free performance is improvement in the sensitivity of the sensing of the relative motion of the proof mass with respect to the surrounding spacecraft
- A move from capacitive to optical sensing is likely to be an essential step
  - On the 2025 timescale we believe that improvement by a factor of 30 in residual proof mass acceleration noise over that set as the first LISA target is feasible

Optimistic projections talk of factors of 1000 reduction in acceleration noise.

Evaluation of the feasibility of the scale of potential improvement will be greatly aided by the results that will come from LISA Pathfinder and LISA itself

The next LISA

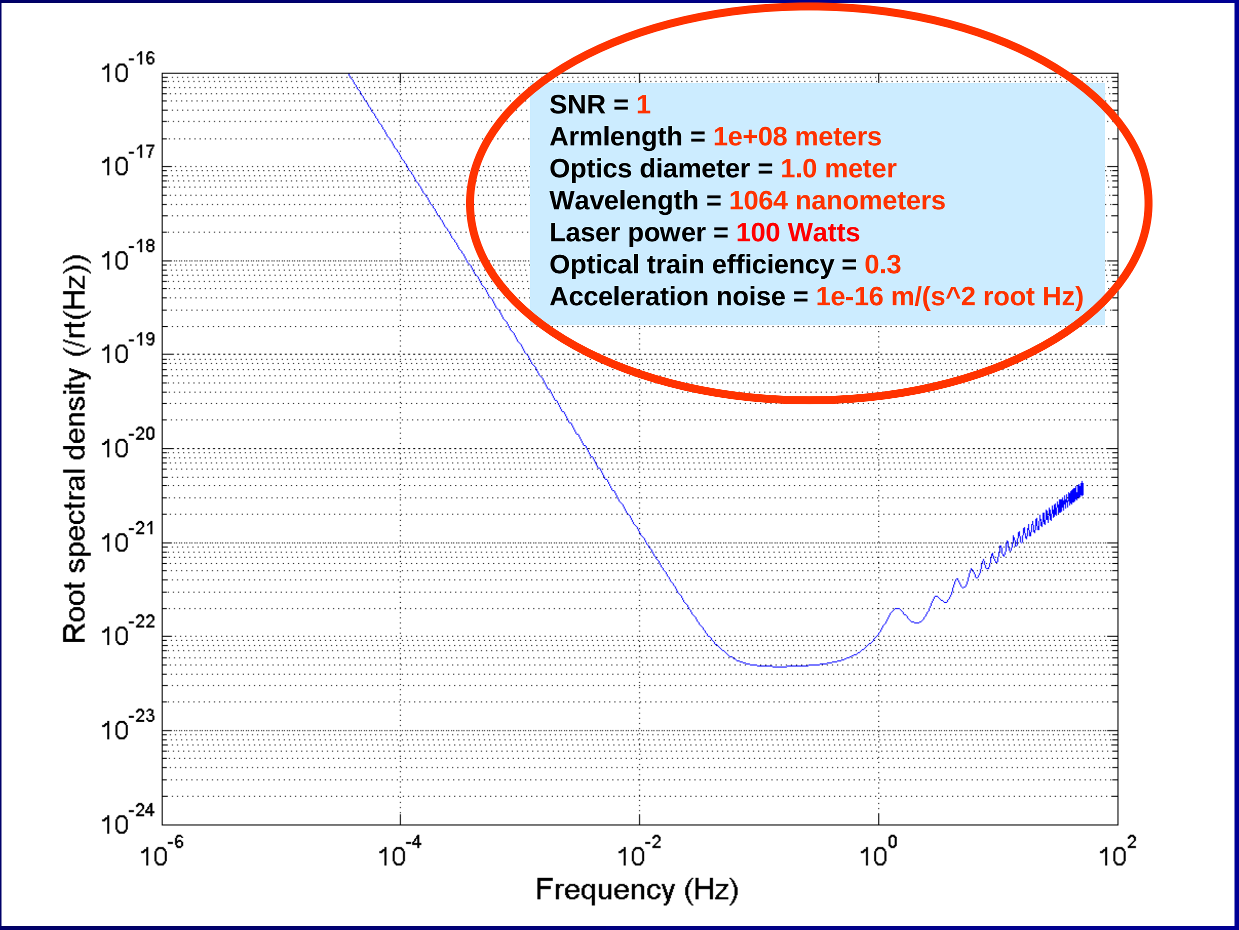
- Taking into account the scientific priorities and the likely technological developments …
- The most pressing goal within the present planning cycle is a single LISA-like mission targeted at the 10 to 100mHz part of the spectrum
- The extension of this plan to include multiple interferometers that together act as a VLBI instrument is extremely compelling and should be pursued if at all possible

The next LISA

- Such a single GW detector with a GW amplitude sensitivity of about $h \sim 10^{-25}$ would allow detection of every single neutron star binary in the Universe with a signal to noise ratio of about 200, resulting in an about 10^5 coalescence events per year
  - This would allow the determination of Ω_k, a measure of the Universe's spatial curvature to better than 1 %
- By combining these measurements with observations from ground-based instruments observing in the frequency range of about 1 kHz, it would be possible to learn about the nature of the respective source, *i.e.* a neutron star binary or a stellar size Black Hole, even allowing an independent determination of the luminosity distance
- Such a detector would also be able to observe almost every coalescence of a 10 solar mass BH with a growing intermediate mass black hole (IMBH)
  - This seems likely to be a powerful approach to understanding how IMBHs formed and grew in the large majority of galaxies

The next LISA ?

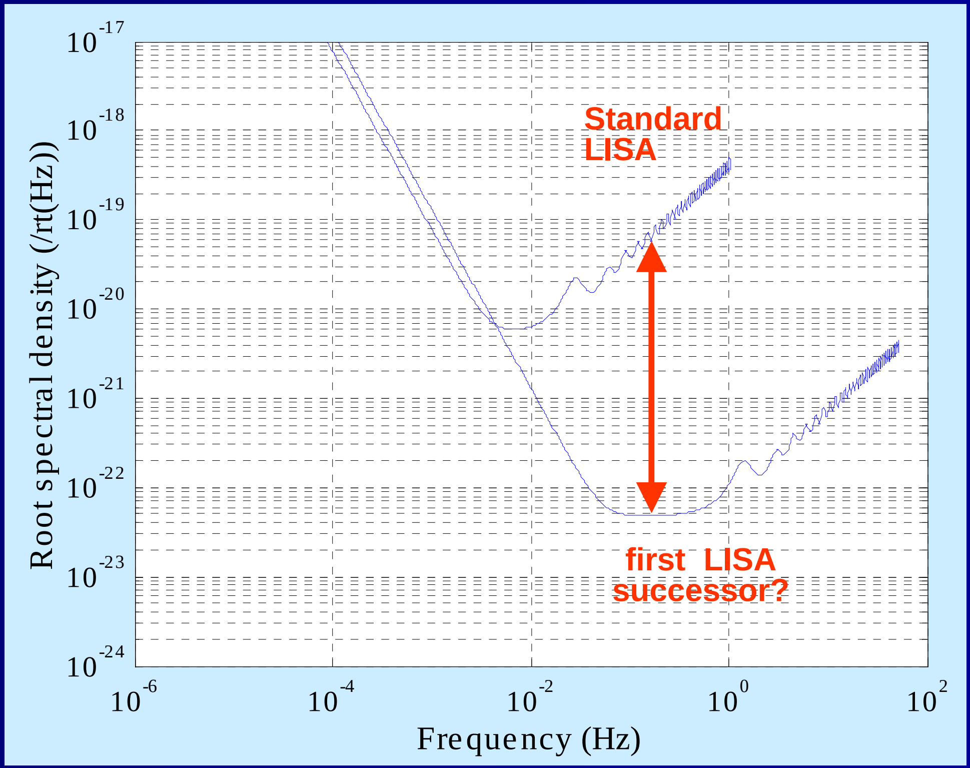
- Target performance – root spectral density of GW strain



Note that vertical scale has changed from earlier plots!

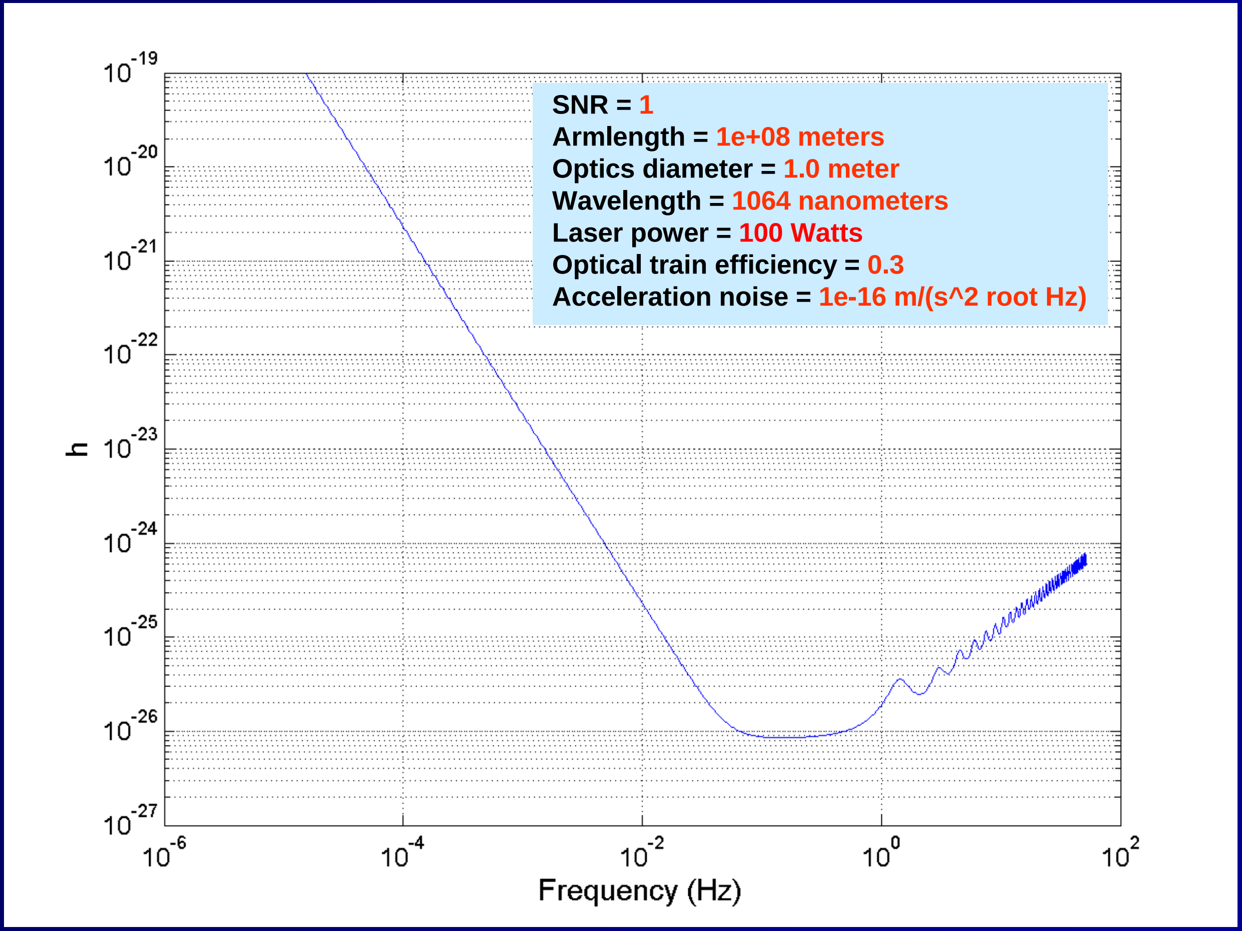
The next LISA ?

- Comparison – first generation LISA with proposed successor
  - dramatic increase in sensitivity – and hence in “reach”
  - equivalent to an increase in energy sensitivity of 6 orders of magnitude in the 0.1Hz region of the spectrum !



The next LISA ?

- GW strain sensitivity after 1 year of integration



Note that vertical scale has changed again

Technology development required

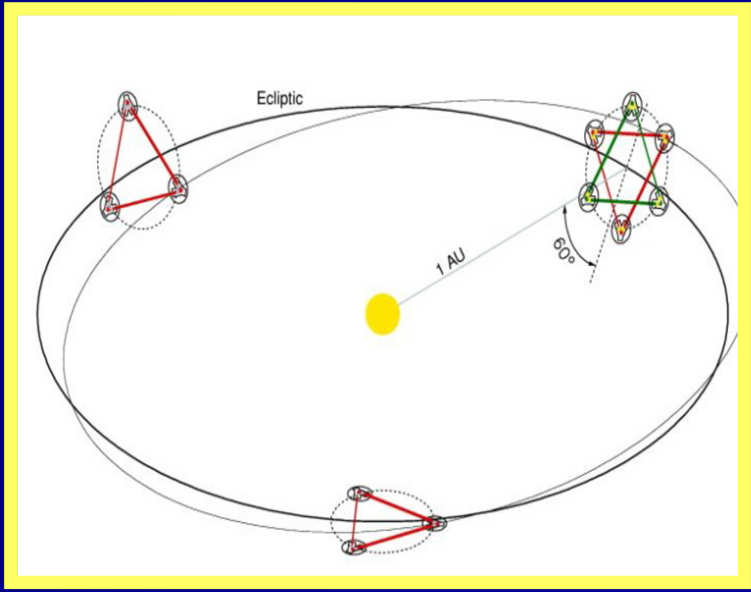
- For the single LISA-like high frequency detector:
  - Ultra-low noise sensors and actuators for improved drag-free control
  - 100W, 1 micron, space-qualified lasers
  - Laser and spacecraft power systems compatible with the ultra-low noise drag-free control that will be developed
    - May require co-flying tethered solar arrays?
  - Metre-class telescope designs that combine light-weight with suitable dimensional stability

GWC – the ultimate?

- Goal: the direct detection of gravitational waves relics from inflation – choosing to target the most clear part of the GW frequency domain – around 0.3Hz

- The challenge is extraction of a correlated stochastic signal from the “interference” of the large number of signals that will come from merging neutron star and stellar mass black hole binaries – anywhere in the Universe!

- Multiple – and far separated – interferometers are required for precision triangulation of the positions will be required to allow removal of the sources at the correlated background level



- Current designs involve armlengths in the 10^4 to 10^5 km range, up to a kiloWatt of laser power, possibly laser frequency doubling or tripling, 2 to 4m diameter telescopes, acceleration noise budgets up to 1000 times smaller than in LISA

Not by a long way!

- We are far from any fundamental quantum measurement limit, so there are no in-principle limits to sensitivity on the medium – or even far, horizon …

… so we can – and will ! – continue to have ever improving Visions of the Universe through the Gravitational Wave window