Experimental challenges for space-based GW detectors

overview of LISA

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SIGRAV Conference
September 9th, 2021

Outline

- **How does LISA work?**
  Measurement concept and sensitivity limits
- **What has been already tested?**
  LISA Pathfinder and its free-falling test masses with local interferometric tracking
- **What are we working on?**
  Long arm interferometry and GW data analysis in a signal dominated environment

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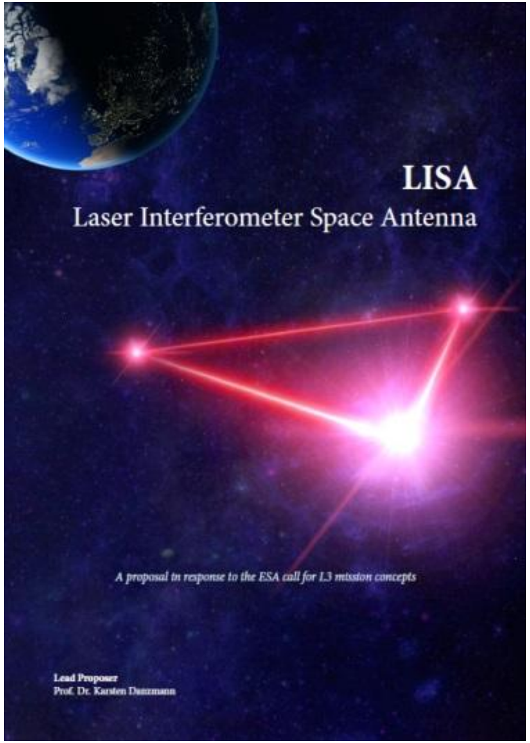
LISA: Laser Interferometer Space Antenna

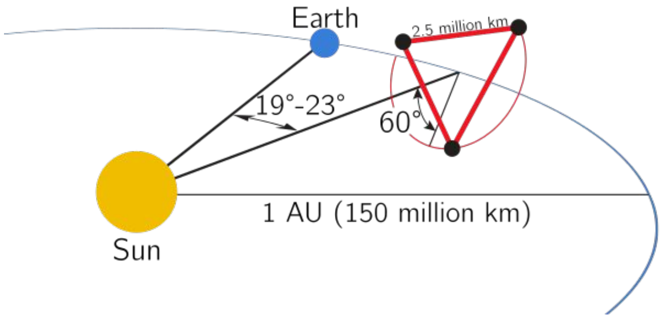
- ESA *large scale* mission L3, aiming for launch in 2034(5) + contributions from NASA and JAXA
- Proposed in 2017 after success of technology demonstrator and geodesic explorer LISA Pathfinder

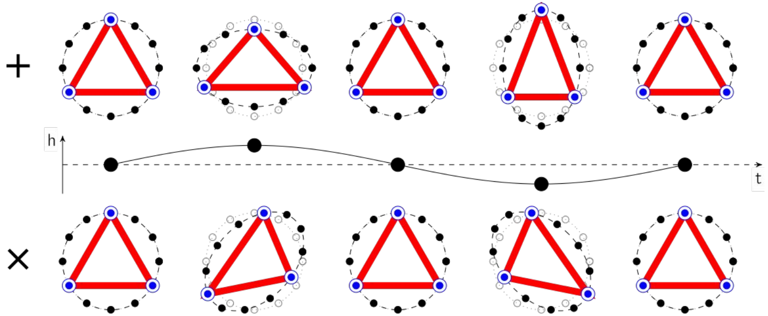
- 4 year nominal mission duration (+ 6y extension)
  - 100 μHz – 1 Hz GW observation band
  - extended band down to 20 μHz
  - possible extension to «nominal» mission under study

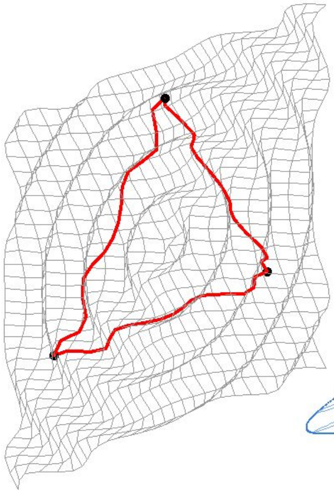


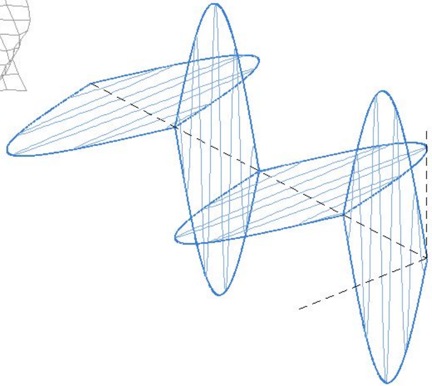
LISA Proposal (2017)

LISA: Laser Interferometer Space Antenna





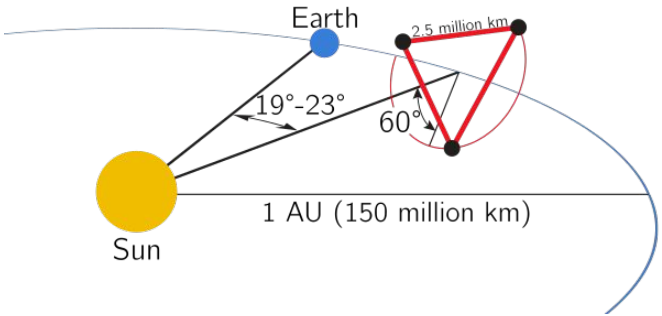


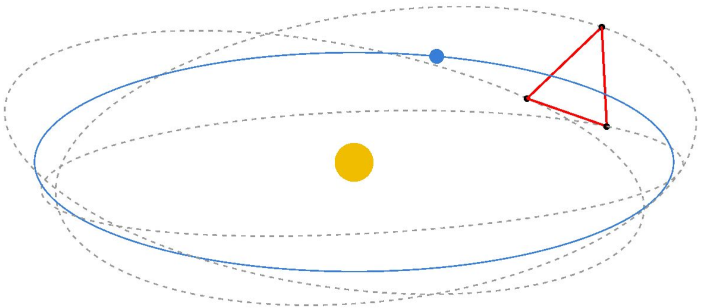


[Nicosahedron (2021). GW deformation effect on LISA animation, MATLAB Central File Exchange]

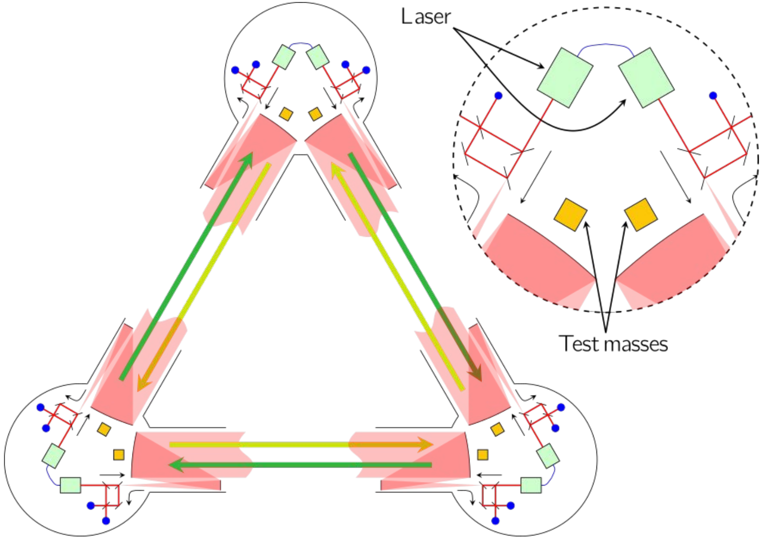
Tidal deformation

LISA: Laser Interferometer Space Antenna



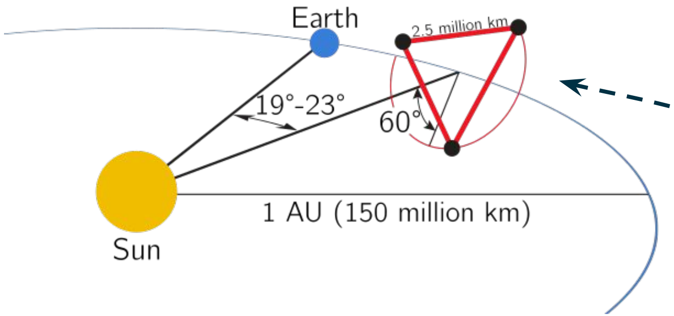


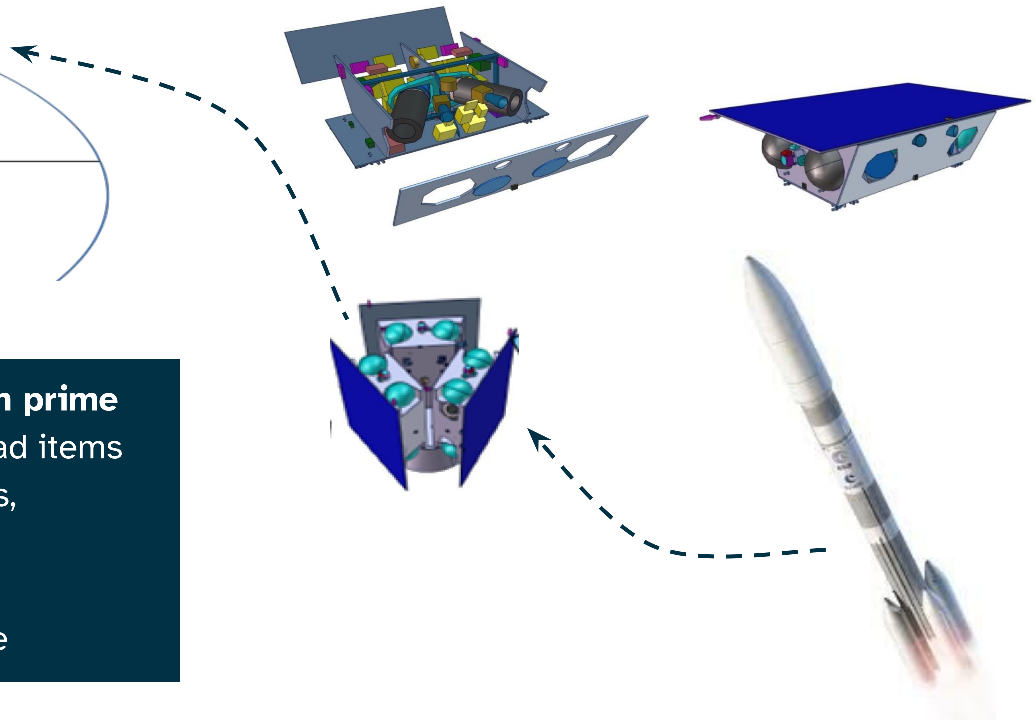
- free-falling TM, no suspension
  - μm/s^2 orbital tidal accelerations vs. fm/s^2 GW
  - spacecraft drag-free control
- *open-loop* interferometer
  - Δ*v* 10 m/s □ 10 MHz fringe rates
- very unequal arm interferometer (Δ*L* ≈ 10^4 km)
- weak light (100 pW)
  - single arm *transponders* (**no** direct reflection)
  - no 2-arm light combination



[Nicosahedron (2021). LISA orbitography gif animation, MATLAB Central File Exchange]

LISA: Laser Interferometer Space Antenna





esa mission lead and system prime

- 3 spacecrafts + (possible) payload items
- launch, transfer, communications, propulsion, SC control, etc
- mission and science operations
- guarantees mission performance

instrument notional designs [ESA internal study, 2017]

The scientific payload: *Moving Optical Sub-Assembly*

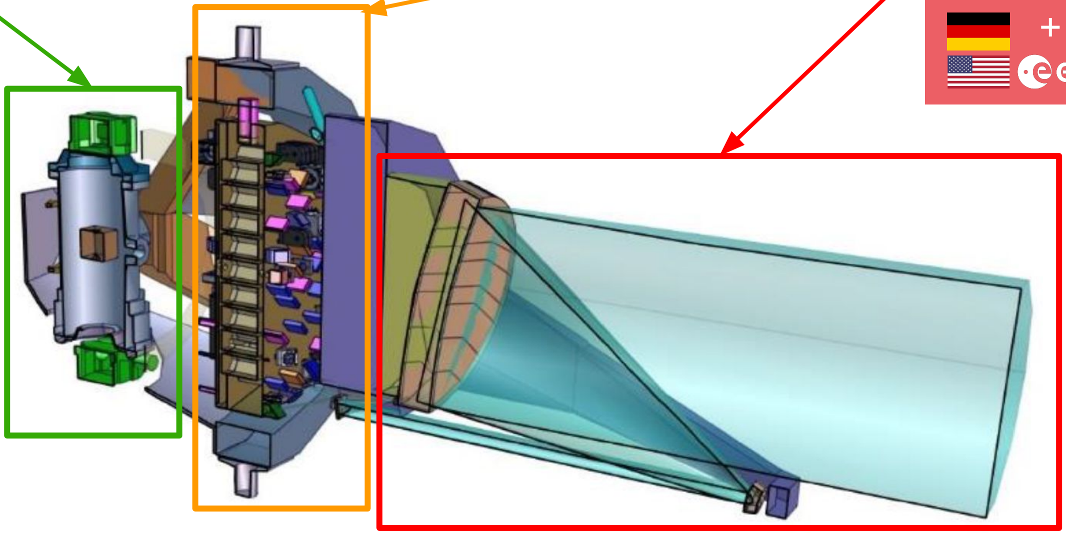
2 MOSAs per spacecraft

Gravitational reference system

- GRS head
- + electronics
- + UV light source

Optical metrology system

- Optical bench
- esa Telescope
- + phasemeter
- esa + laser



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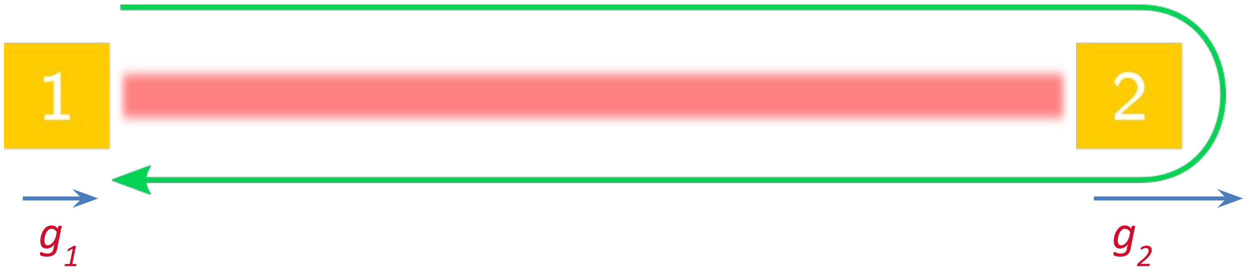
GW observation mechanism



Free-falling observers O1 and O2 exchanging light beams (*T*=8.3s travel time)

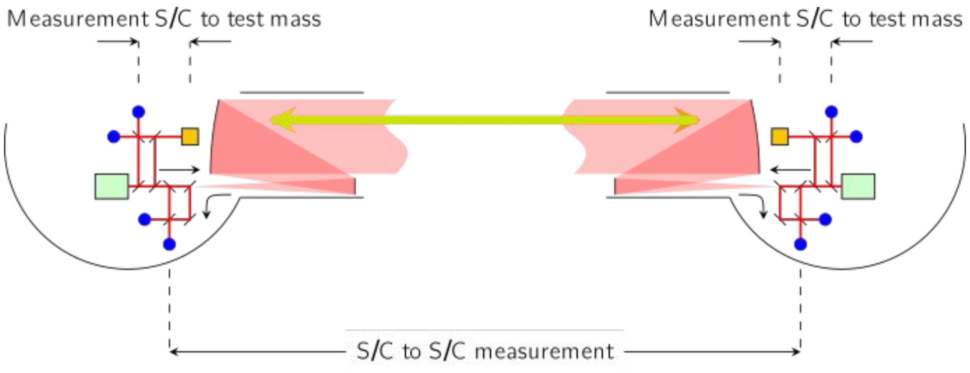
- O1 emits beam with frequency ν_{1E}
- O2 receives, measures phase and sends back phase-coherent copy
- O1 interferes returning beam with local beam, measures *beat frequency* $\Delta\nu$

Beatnote — GW strain — stray acceleration (time delayed Δg) — laser freq. noise — phase/frequency measurement noise

$$\frac{\Delta\dot{\nu}_{1M}}{\nu}(t+2T) = \frac{\dot{h}(t+2T)-\dot{h}(t)}{2} + \frac{1}{c}\left[g_1(t)+g_1(t+2T)-2g_2(t+T)\right] + \frac{1}{\nu}\left[\dot{\nu}_{1E}(t)-\dot{\nu}_{1E}(t+2T) + \dot{\nu}_{n1}(t+2T)-\dot{\nu}_{n2}(t+T)\right]$$

LISA measurement scheme

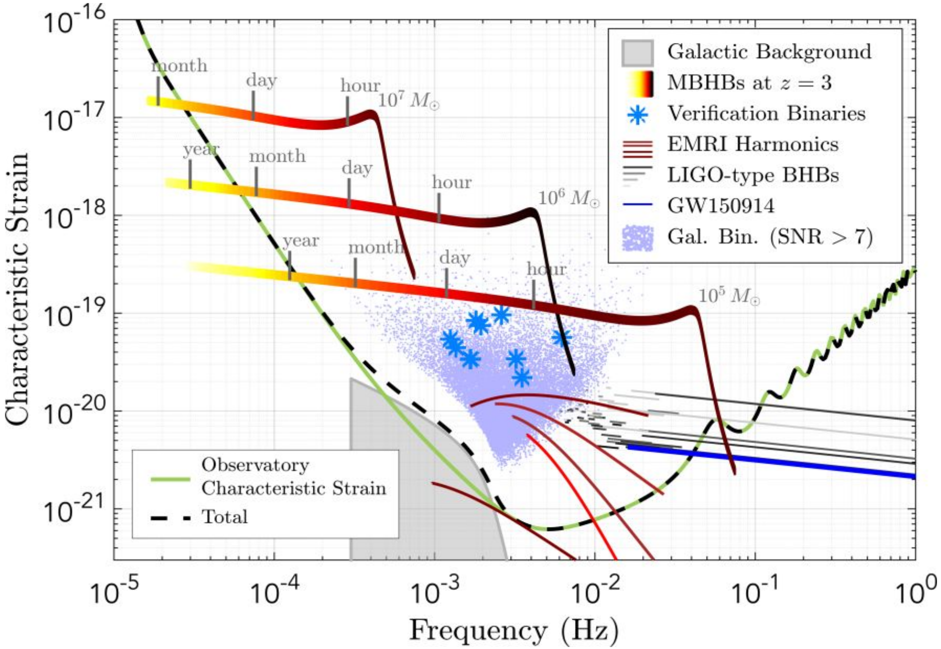
Measurement of acceleration between free-falling TM 2.5 million km apart is split in multiple segments



+ reference IFO for reference phase in adjacent arms of same spacecraft

LISA sensitivity

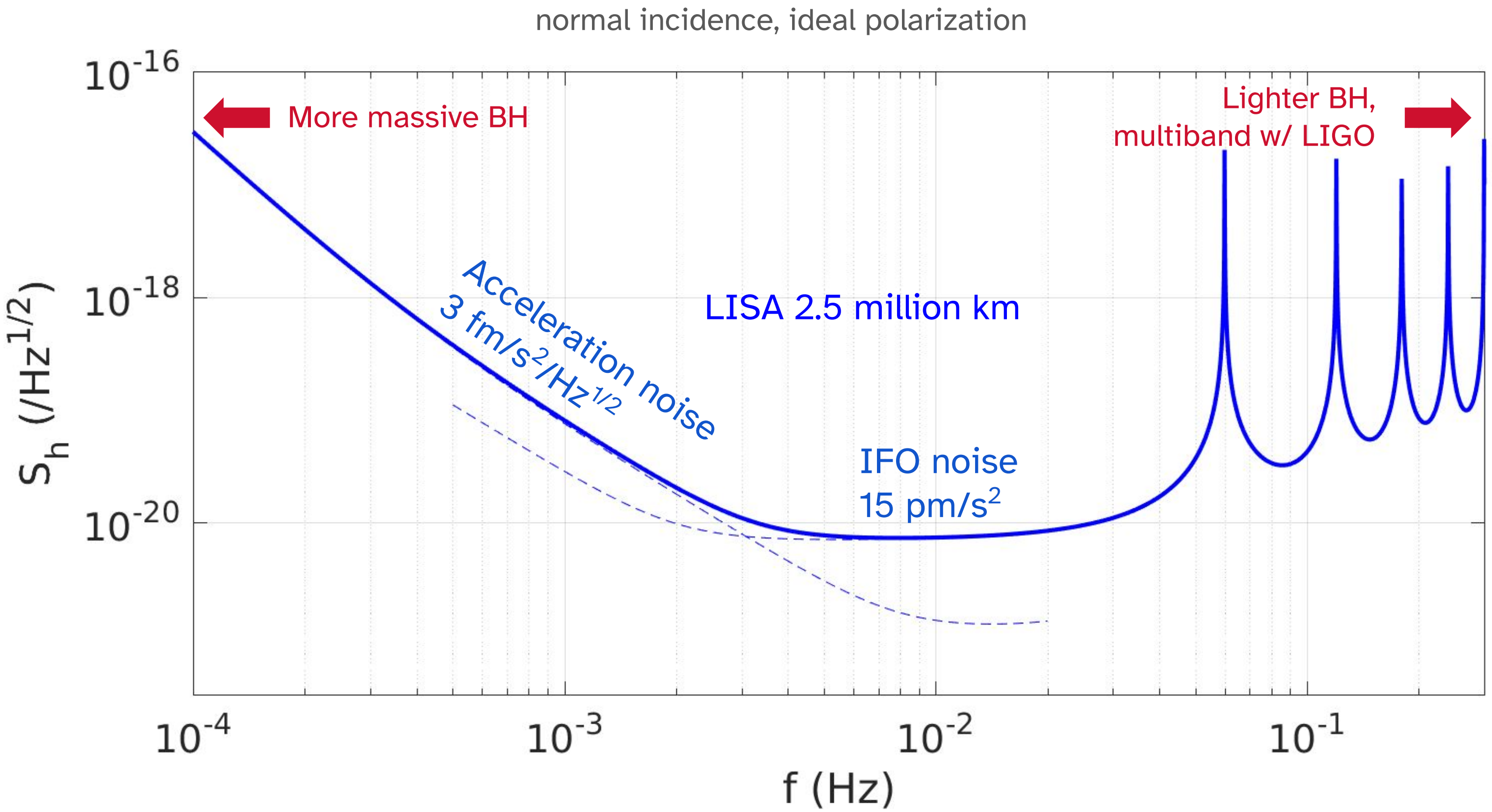
Low Frequency limit: spurious antenna tidal deformation (stray forces)
High Frequency limit: interferometer fluctuations (shot noise, etc)



Low freq limit:
TM acceleration noise,
3 fm $s^{-2}Hz^{-1/2}$

High freq limit:
IFO readout noise,
10 pm $Hz^{-1/2}$

Why 2.5 million km arms?



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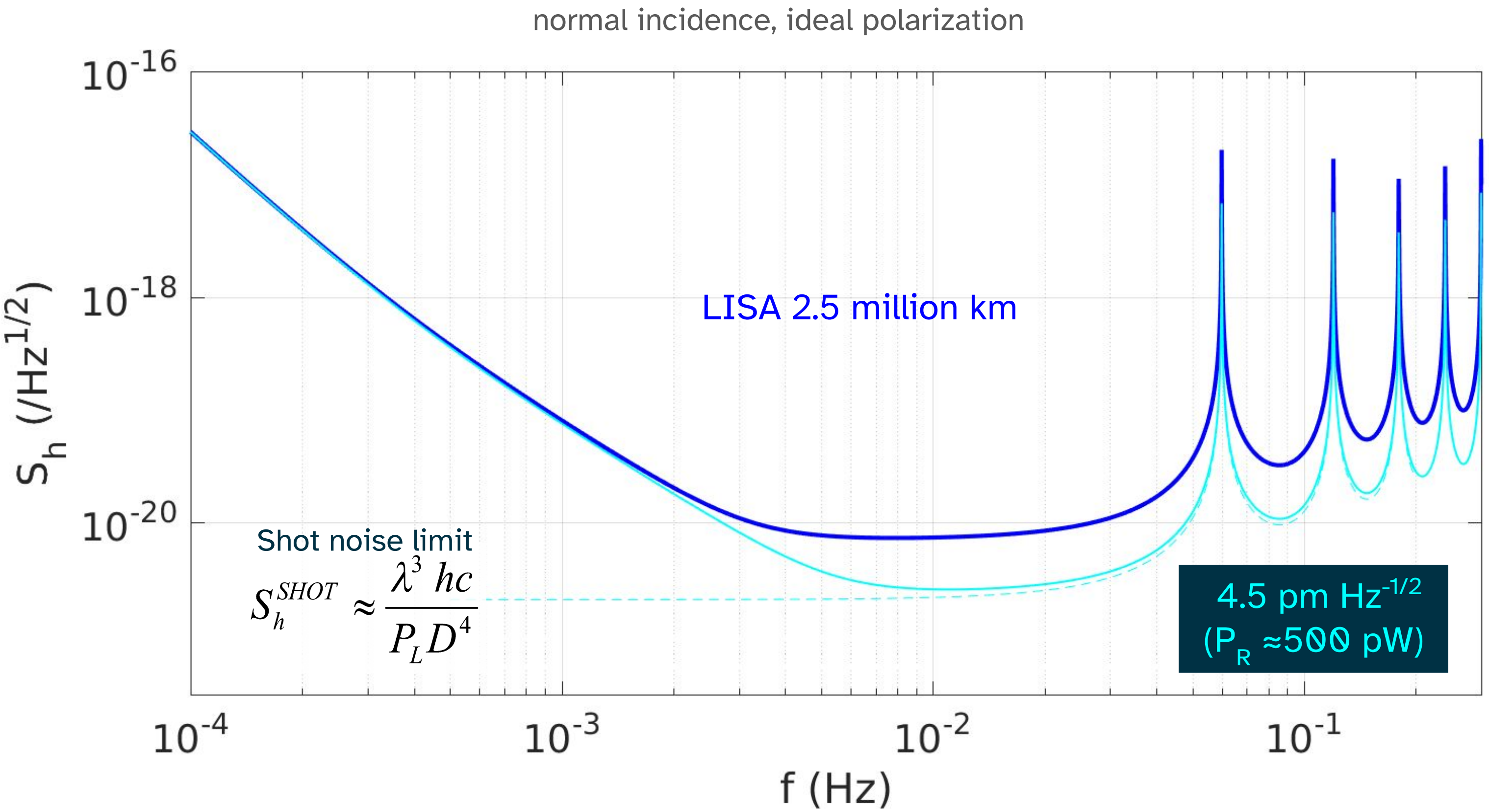

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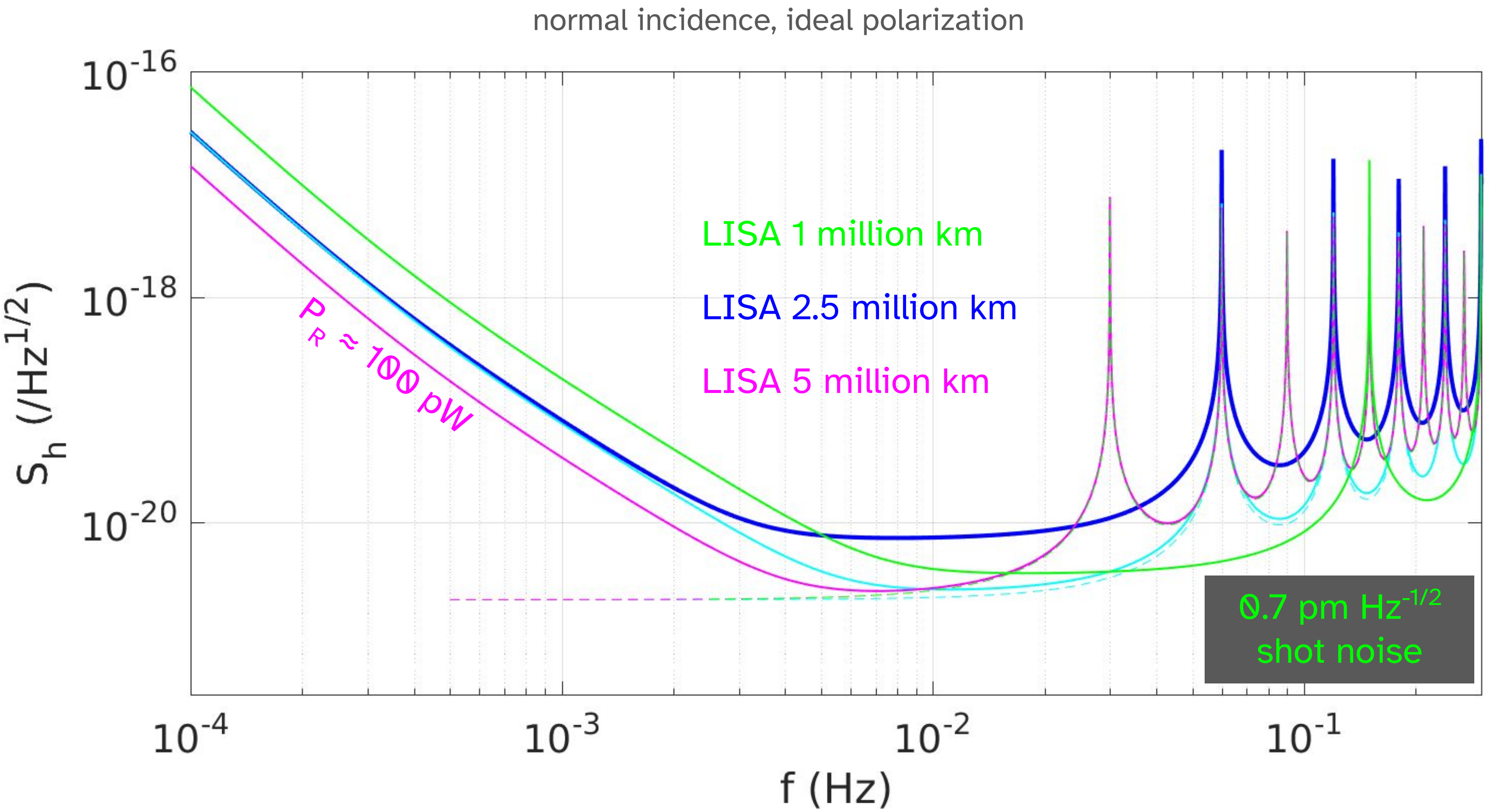

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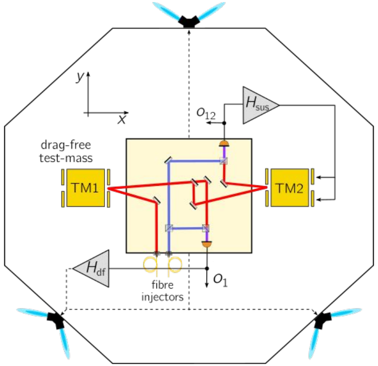
LISA Pathfinder: ESA Geodesic Explorer

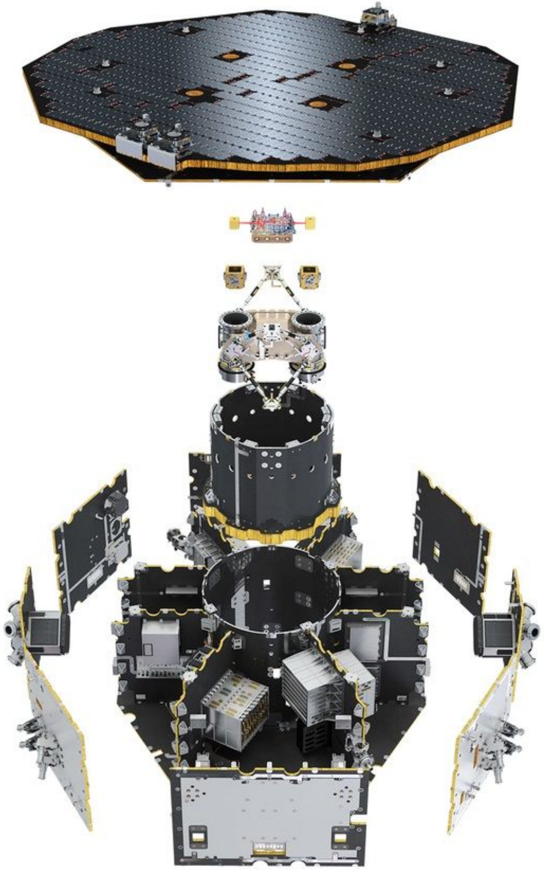
Dec 3, 2015 — Launch
Mar 1, 2016 — Start Operations
Dec 7, 2016 — Jul 18, 2017 — Mission Extension



LPF-tested hardware

- free-falling TM
- GRS hardware for LISA
- local TM interferometric readout
- drag-free control with cold gas and colloidal thrusters
- SC gravitational balancing
- TM charging and discharging
- space and SC magnetic, thermal environments

LISA Pathfinder: ESA Geodesic Explorer



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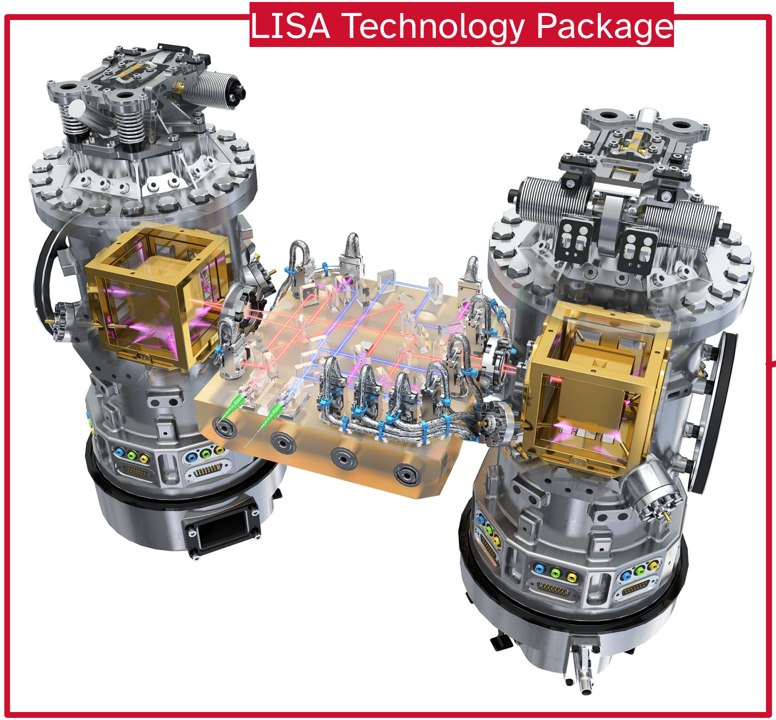
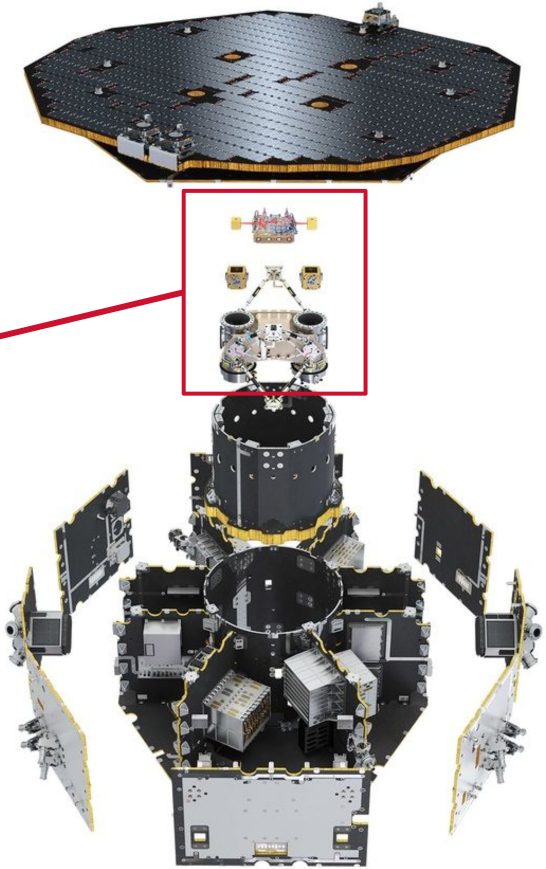
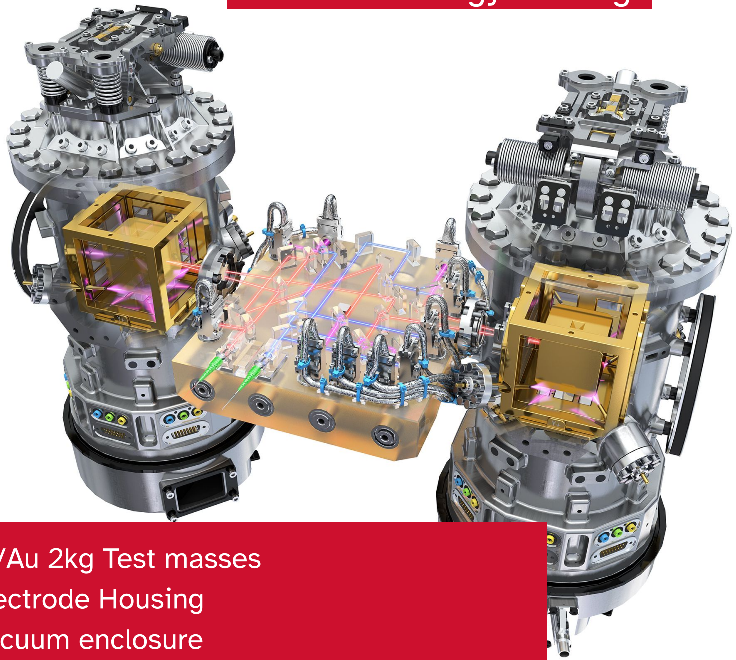




LISA Pathfinder: ESA Geodesic Explorer

LISA Technology Package



- Pt/Au 2kg Test masses
- Electrode Housing
- Vacuum enclosure
- Caging mechanism
- UV light charge and discharge mechanism
- Optical Bench and interferometer

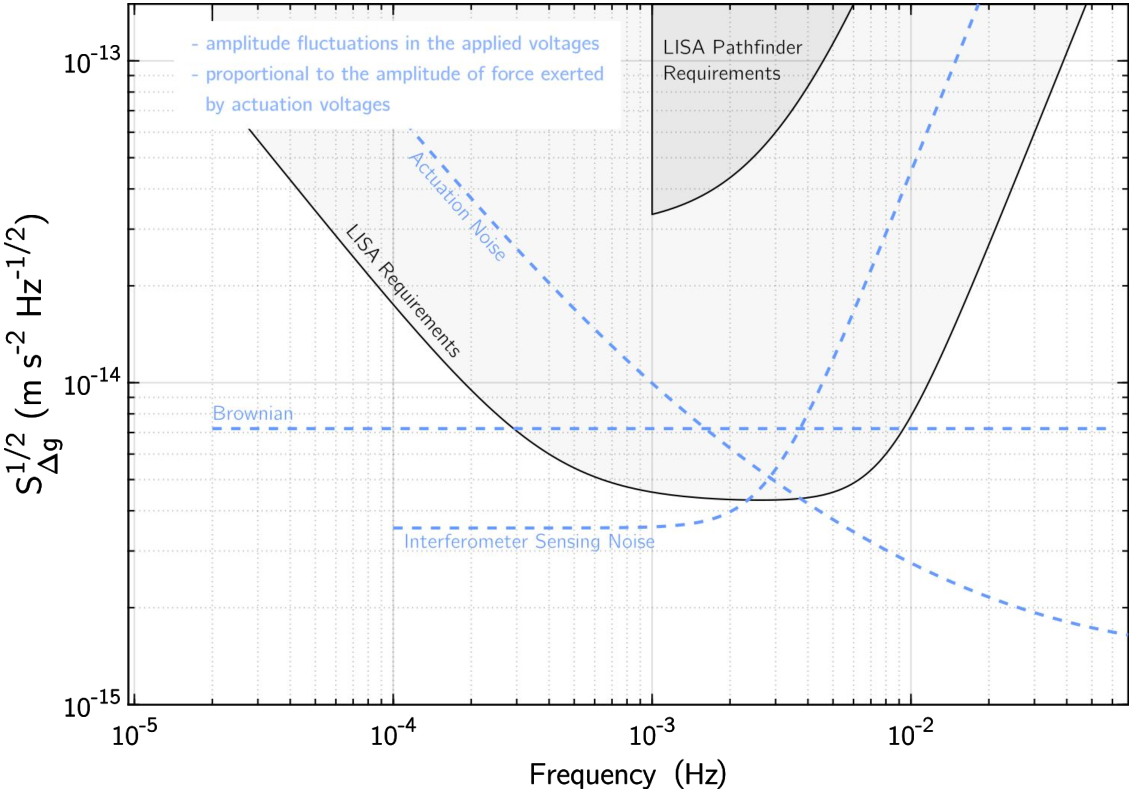
How do you do improve geodesic motion by 4 orders of magnitude?
(from pico-g $Hz^{-1/2}$ to sub-femto-*g* $Hz^{-1/2}$)

- heavy non-magnetic TM
- 3-4 mm gaps with no contacts
- AC-carrier force actuation
- vent payload to space (< 10 μPa)

Which was difficult because of:

- tough caging
- no discharge wire → UV discharge system
- need IFO readout for TM position

LPF differential acceleration noise performance



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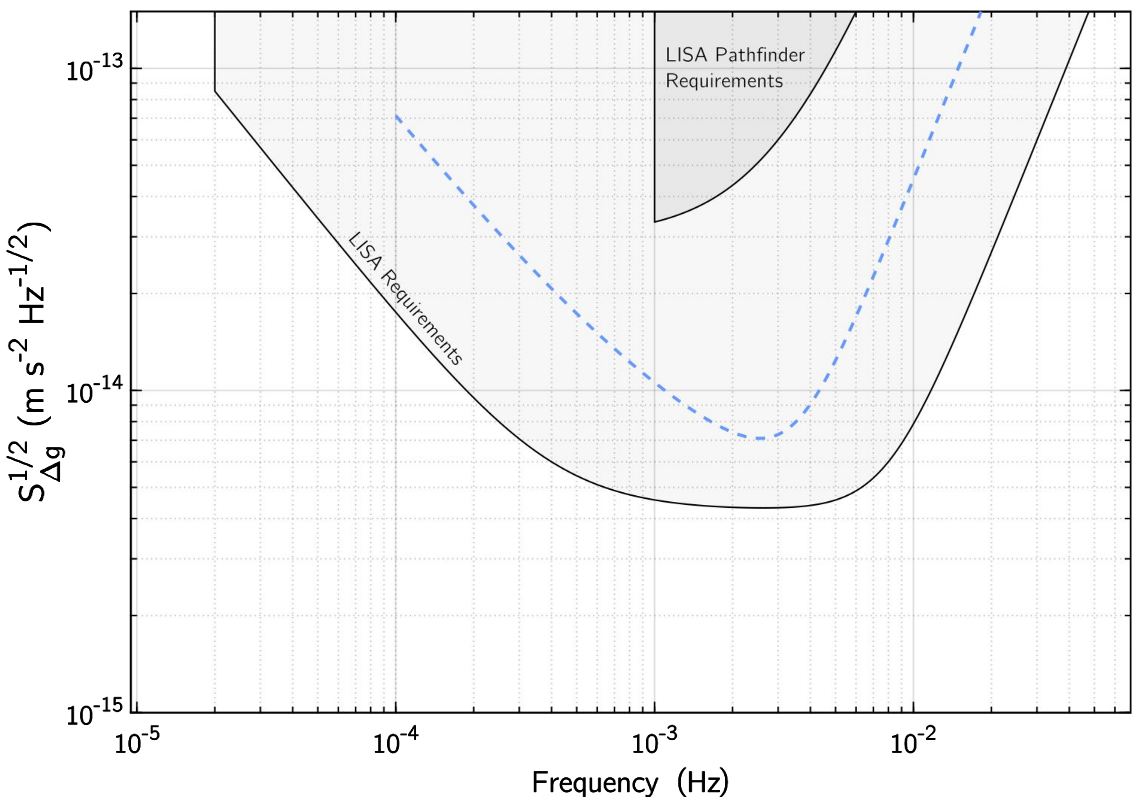

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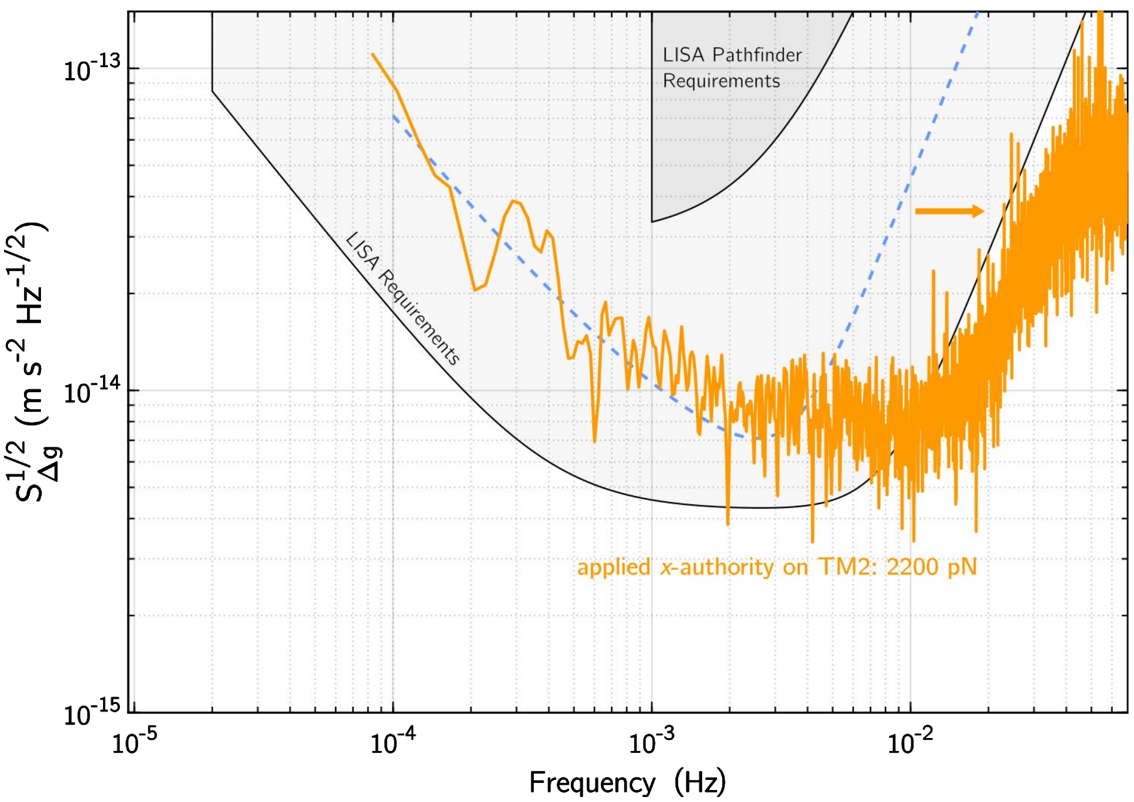

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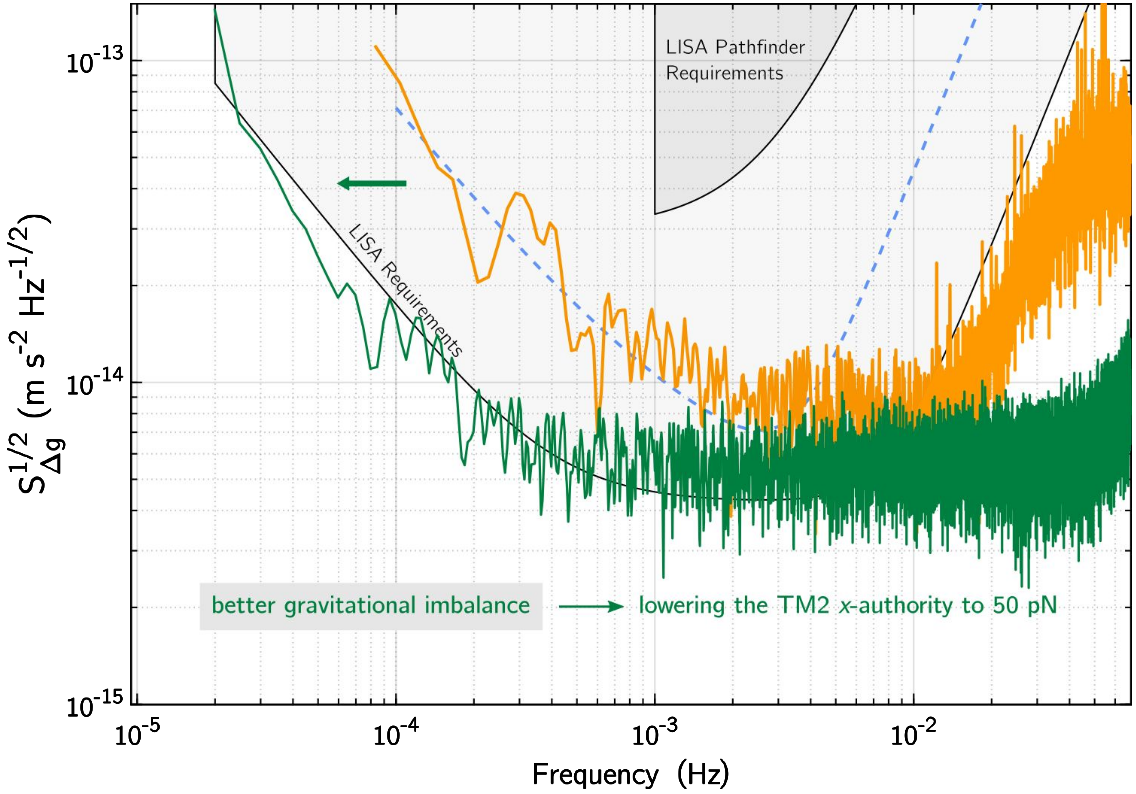

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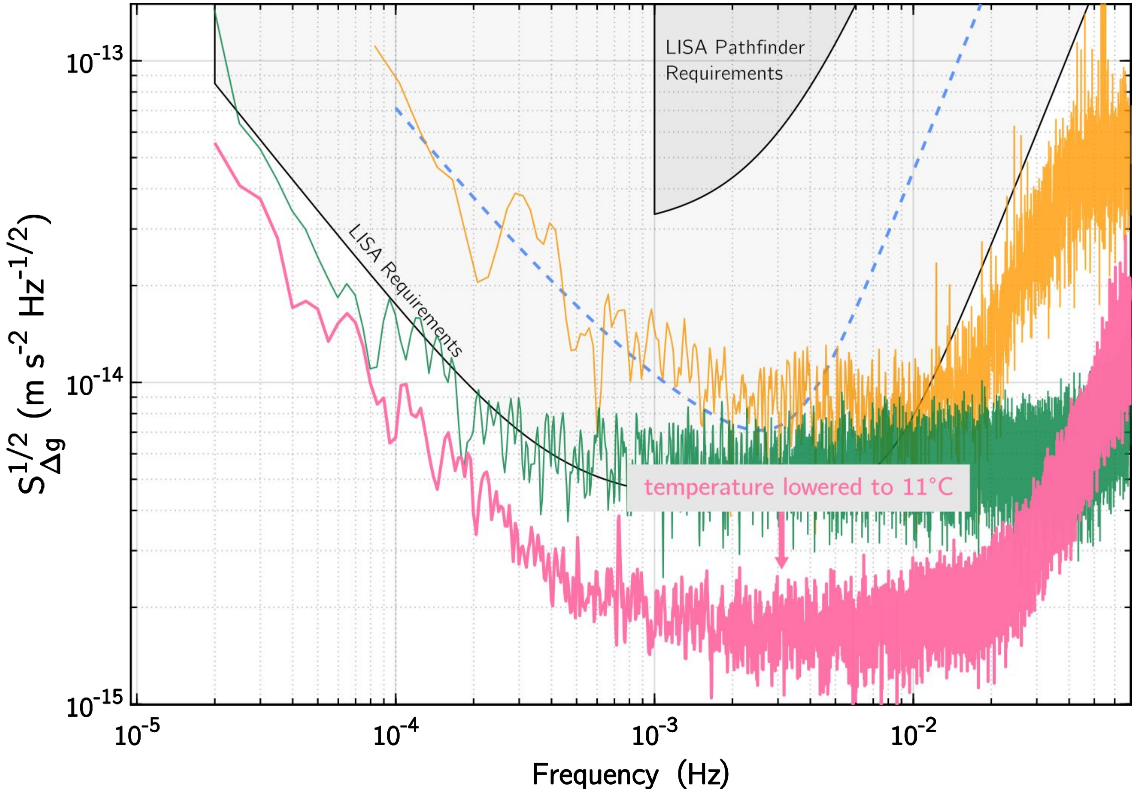

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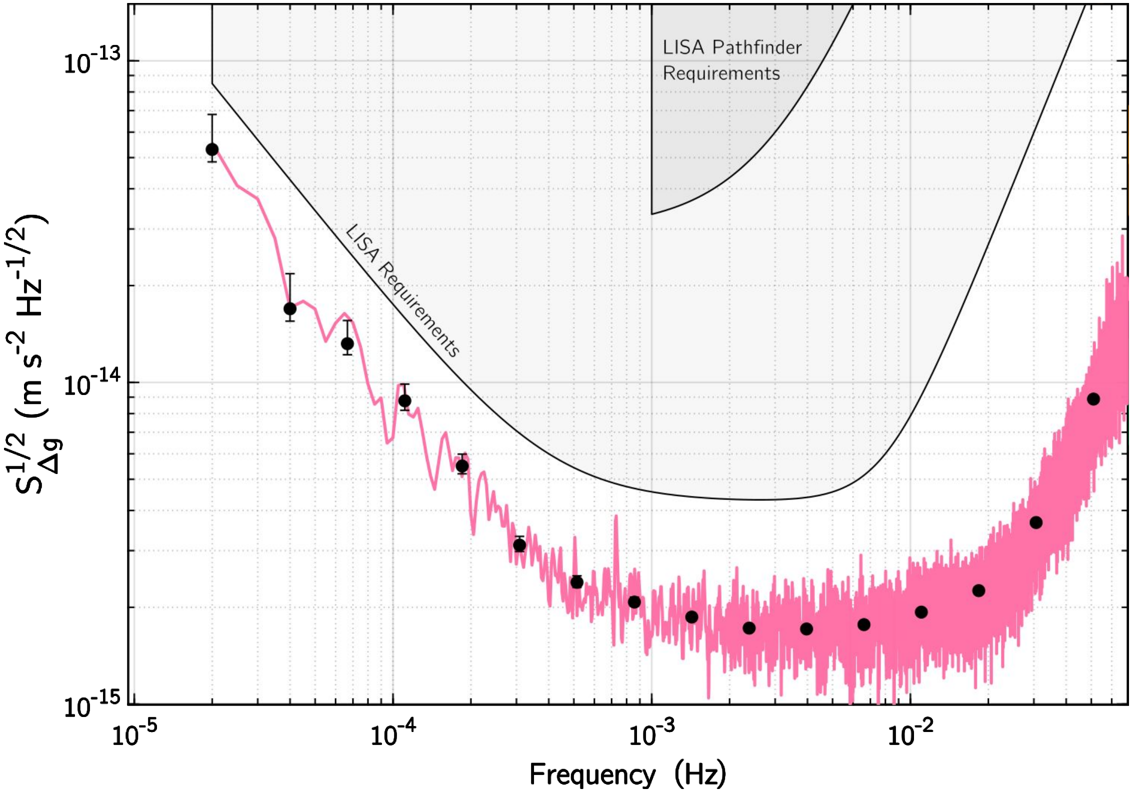
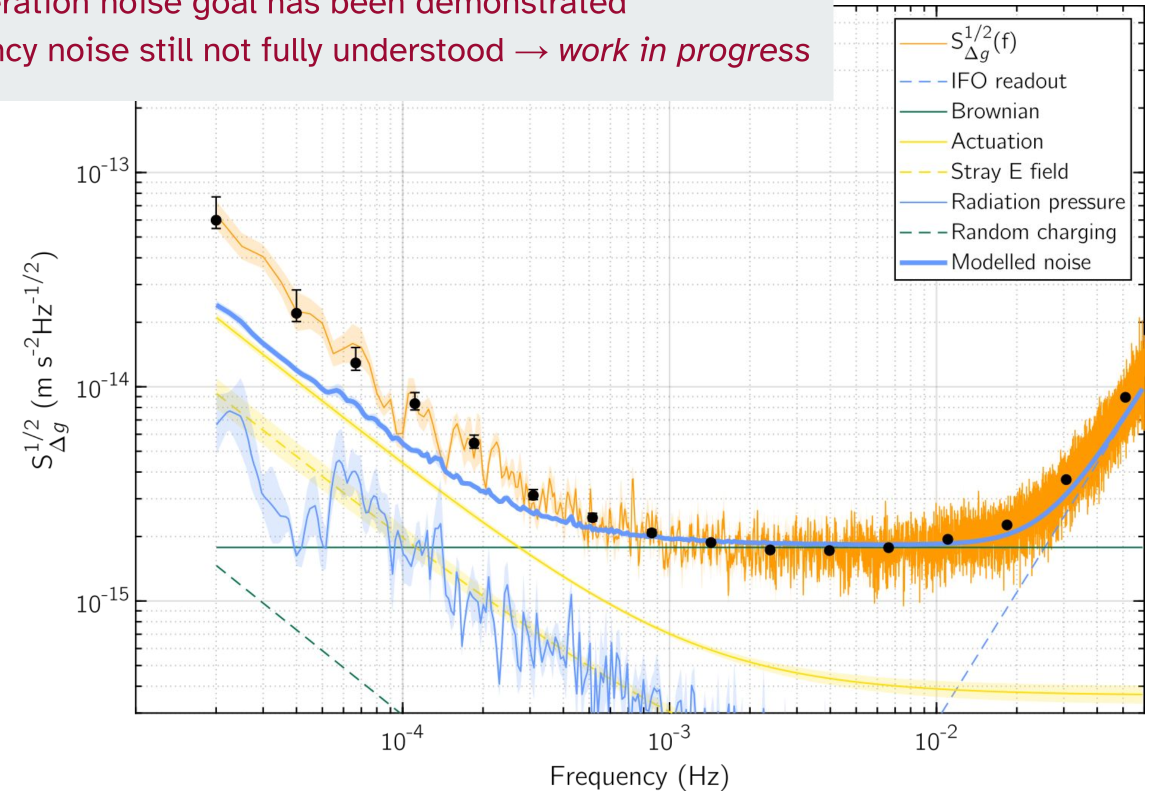


LPF differential acceleration noise budget

- LISA acceleration noise goal has been demonstrated
- Low frequency noise still not fully understood → *work in progress*



Castelli, PHD Thesis, 2020

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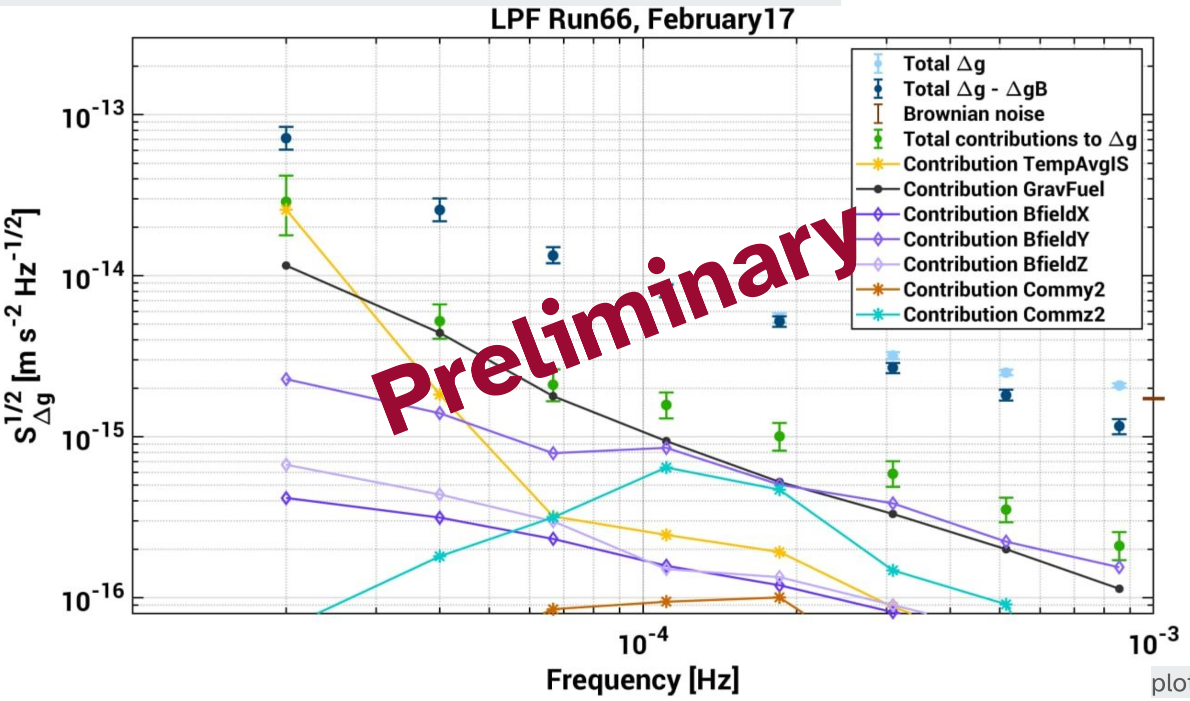
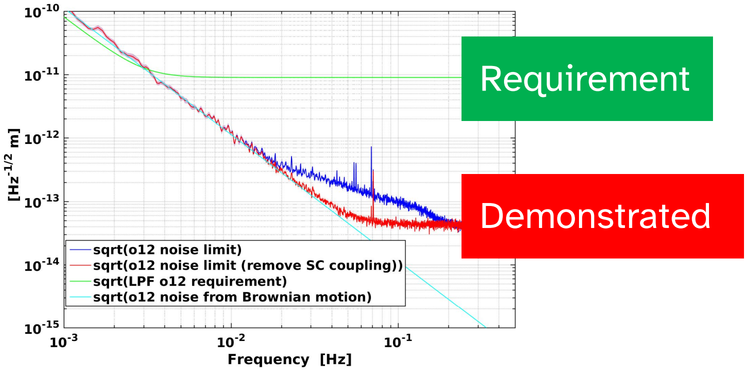


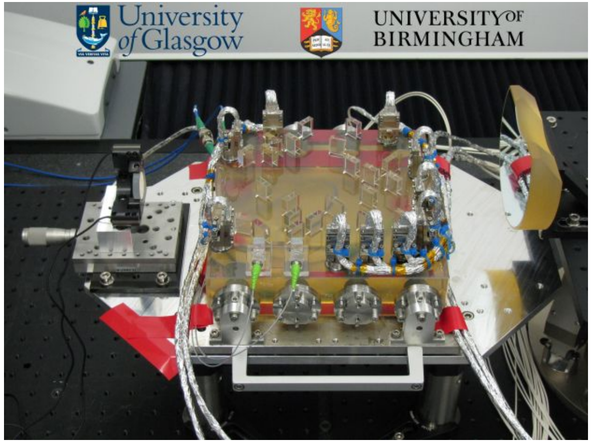
plot courtesy of Lorenzo Sala

From LPF to LISA instrument performance

Interferometer performance

- Dominated by phase meter noise (mostly understood)
- Demonstration of a high-performance local IFO in space



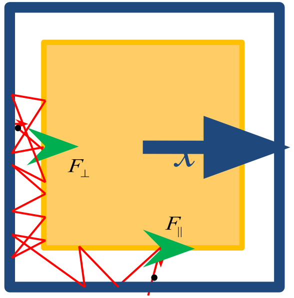


From LPF to LISA instrument performance

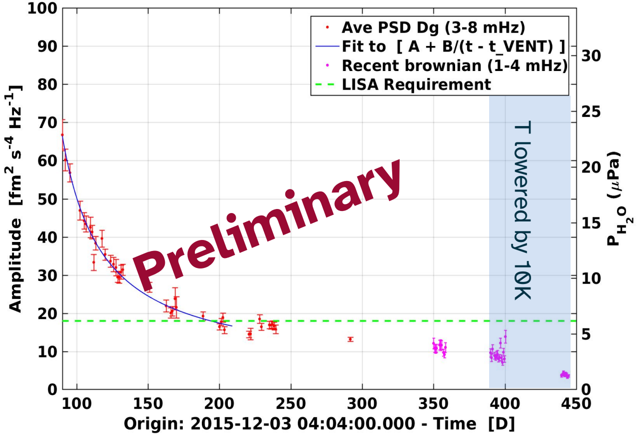
Brownian noise from residual gas

- Decays over time (1/*t*) as GRS vents to space
- Noise power cut in half when cooled by 10 K□ 1 μPa of water
- Visible in thermal gradient experiments (radiometric effect)

Below LISA requirement!



Increased inside (tight) GRS due to correlated collisions



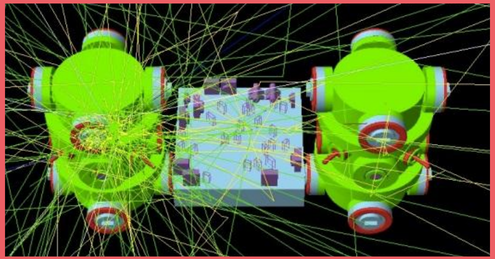
From LPF to LISA instrument performance

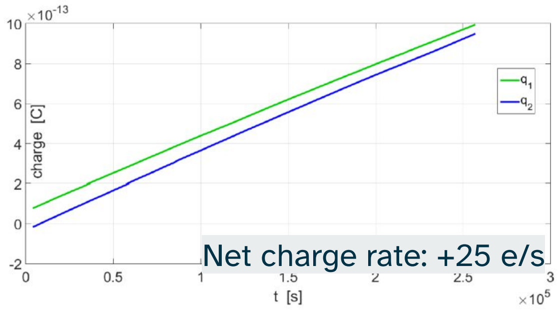
TM charging steady and stochastic

- Cosmic ray + solar particle charge TM
- Mix with stray E-fields to give forces (and noise)

- Detect stochastic cosmic ray charge noise
- Requires balancing stray voltages around TM to 10 mV

Invitation to Tender issued by ESA:
Won by *OHB* + *UniUrbino* + *UniTrento*
to perform charge simulations for LISA





Net charge rate: +25 e/s

Effective shot noise rate:1200 e/s

From LPF to LISA instrument performance

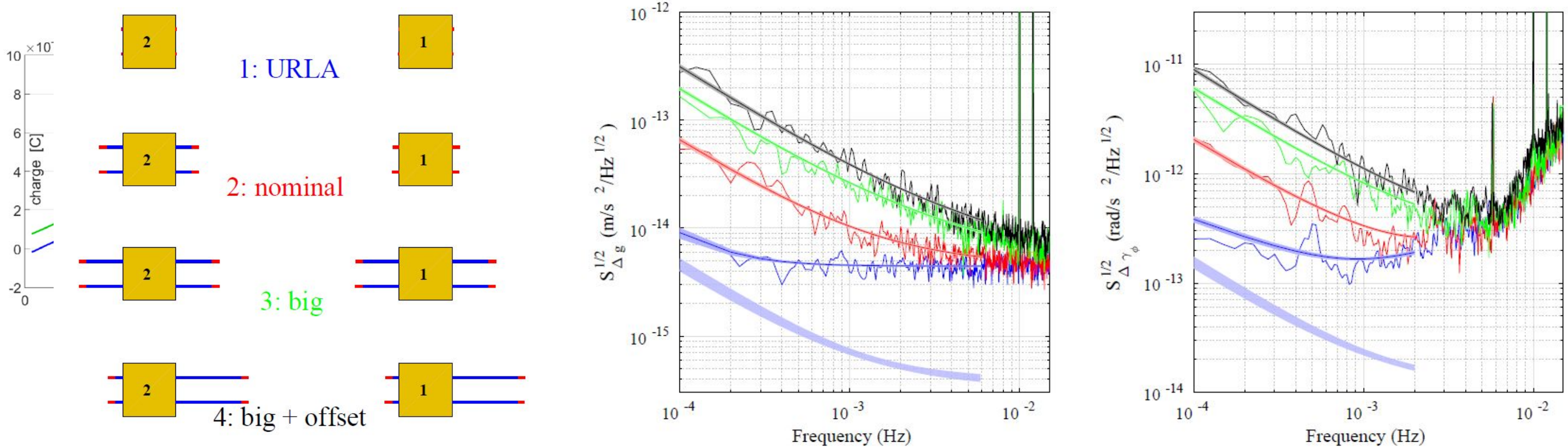
Actuation noise

Noise in Δg, $\Delta\gamma_\varphi$ increases with larger (balancing) forces

- actuator stability at 50 ppm/$Hz^{1/2}$ level at 100 μHz
- as measured on ground

Actuation noise observed, well modeled

- not dominant in LPF thanks to grav balance



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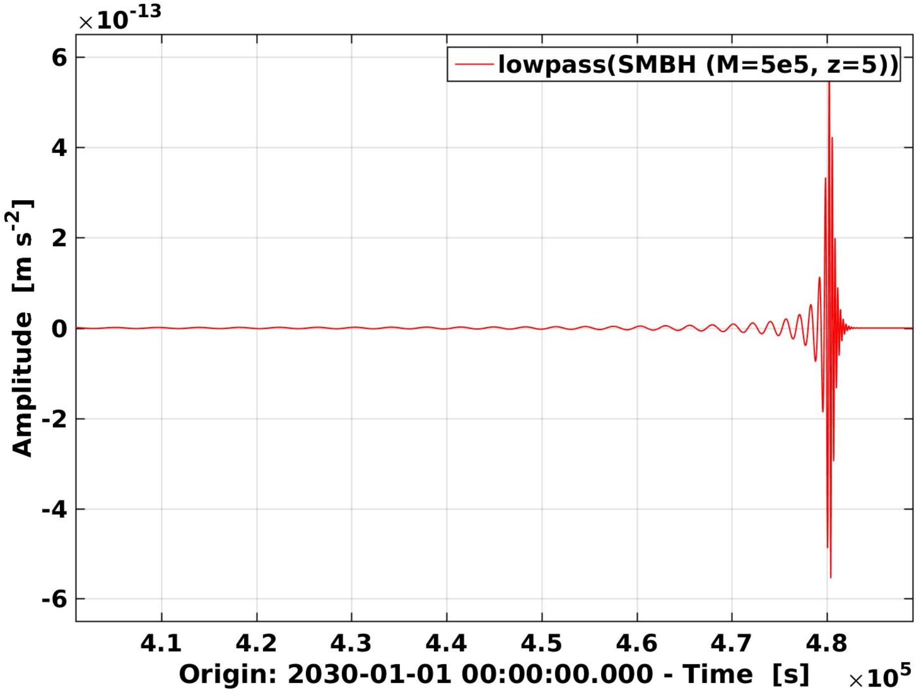
LISA long arm interferometry

Two 10^5 solar mass Black Holes at z = 5

- nominal LISA sensitivity → SNR 1000
- 30d before merger (70 μHz – 3 mHz) → SNR 1



SMBH waveform courtesy of Antoine Petiteau

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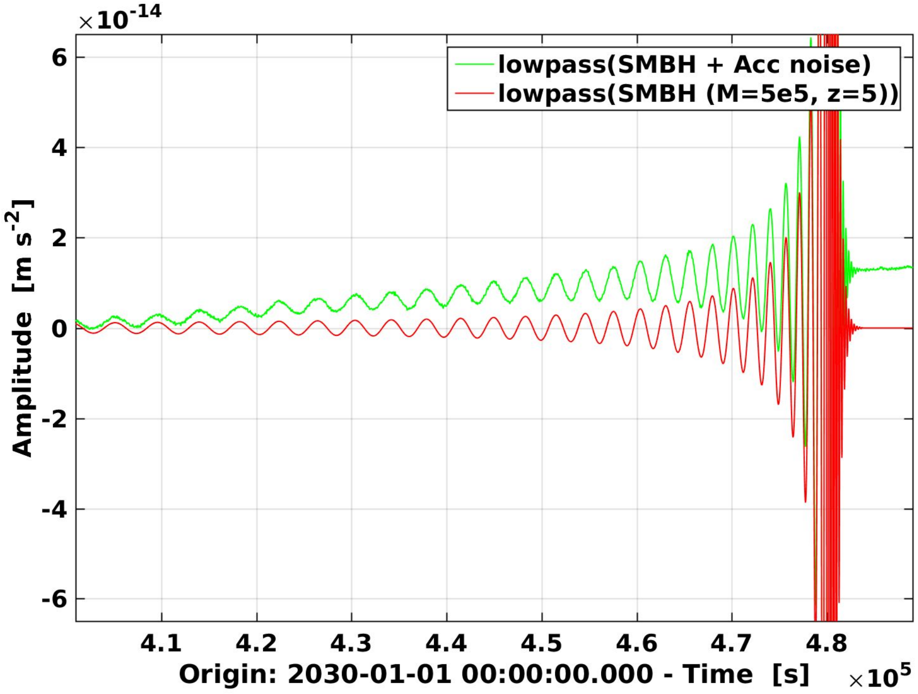

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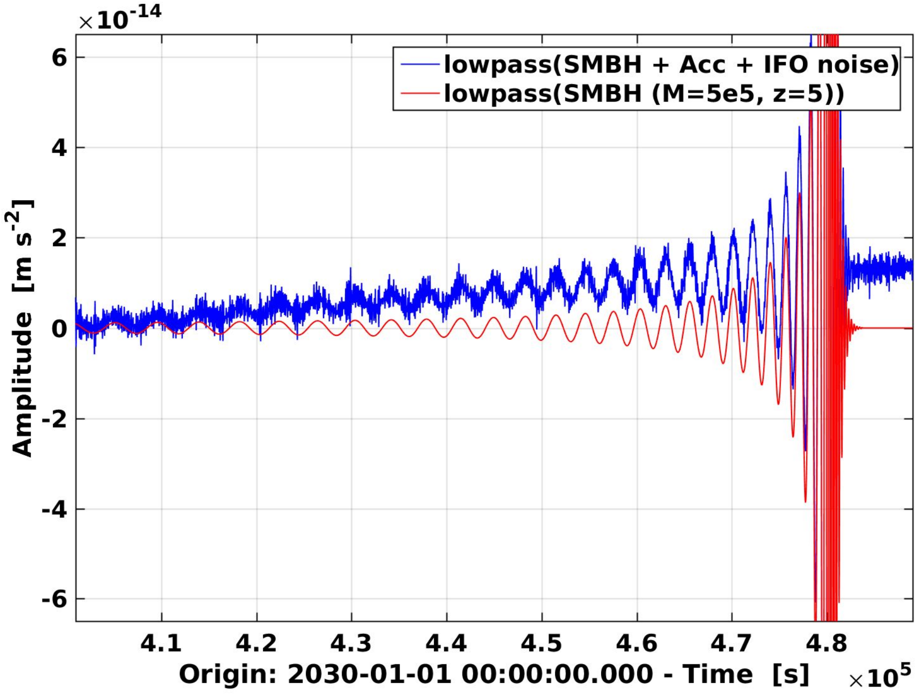

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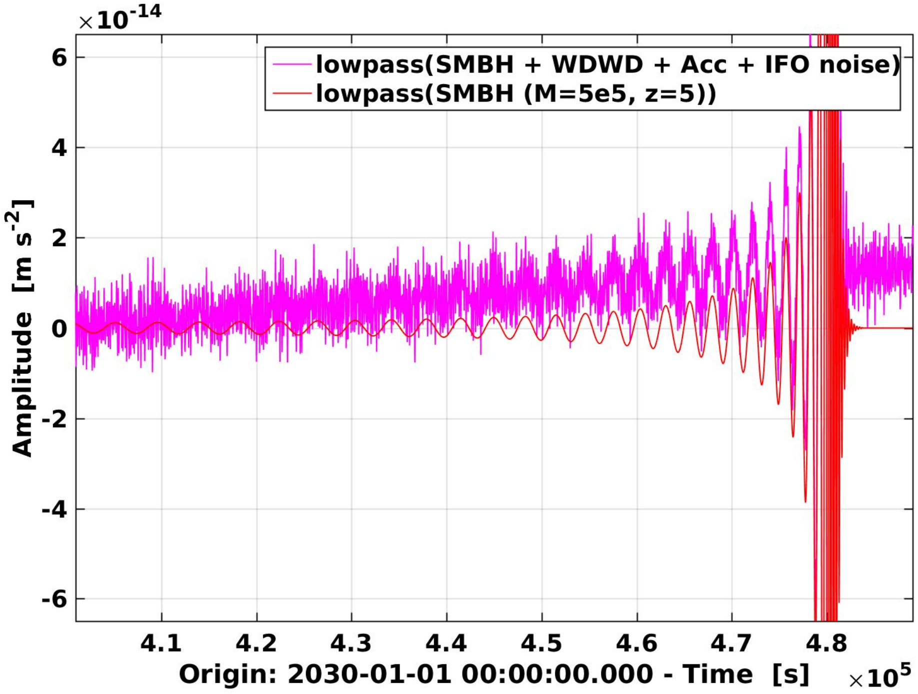

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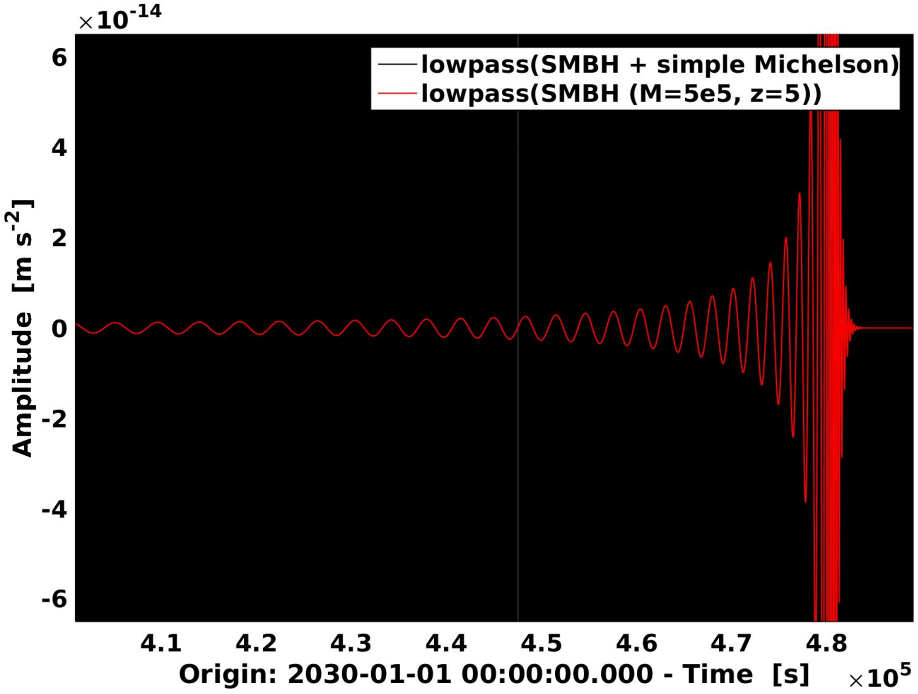

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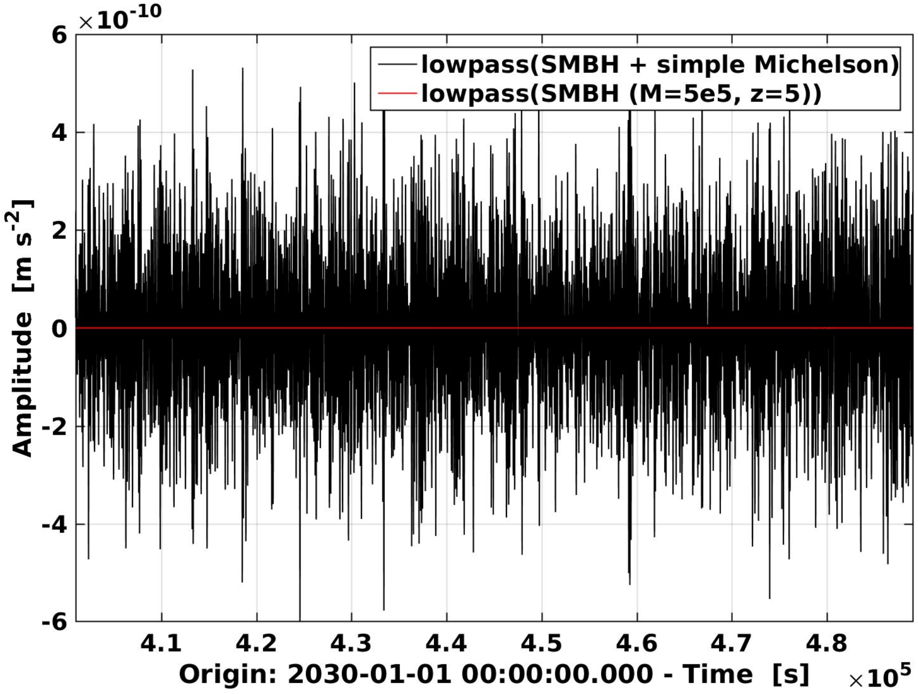
Simple Michelson signal recombination too noisy (10^7)



SMBH waveform courtesy of Antoine Petiteau

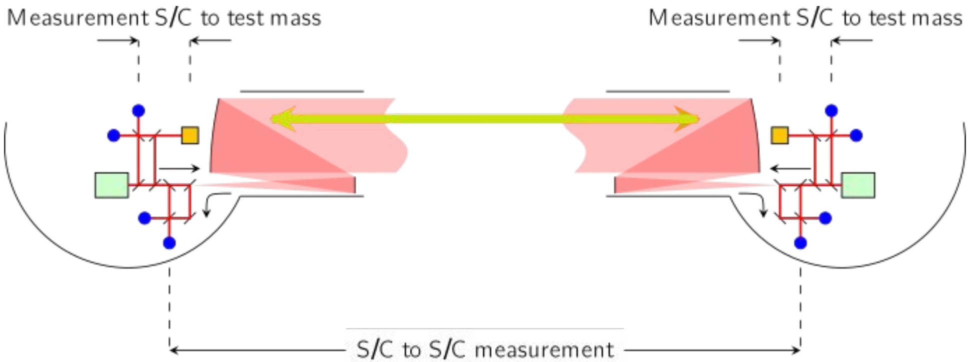
LISA long interferometer: *Time Delay Interferometry*

LISA is a weak light, open loop, unequal arm Doppler interferometer

Beam divergence over 2.5M km:

- 2 W from 30 cm telescope
- 500 pW received power

weak light phase-lock transponder



LISA constellation *quasi-rigid, quasi equilateral* rotating configuration *breathing* due to Keplerian dynamics and Earth pull

- $\Delta\varphi \sim 1°$ (telescope angle must breathe)
- $\Delta L \sim 30000$ km (unequal arm interferometer)
- $\Delta v \sim 10$ m/s (Doppler shifts 10 MHz fringe rates)

LISA long interferometer: *Time Delay Interferometry*

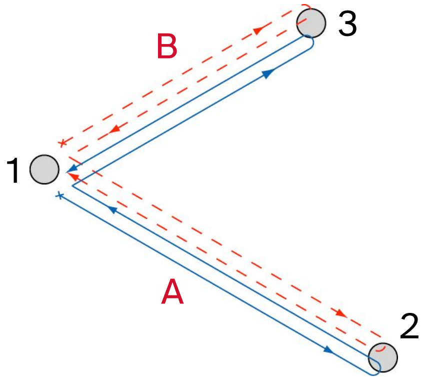
LISA is a weak light, open loop, unequal arm Doppler interferometer

Classic Michelson configuration

$$S_{h_\times} \approx \frac{4}{3}\frac{1}{\left(L\omega^2 \frac{\sin\omega T}{\omega T}\right)^2} \times \left\{4S_g + \omega^4\left[S_{IFO} + S_{\delta\nu/\nu}\left(\Delta L\right)^2\right]\right\}$$

$\Delta L \approx 20000$ km

we'd get 2 μm/Hz$^{1/2}$ with a budget of 10 pm/Hz$^{1/2}$ → would require ΔL = 2 m



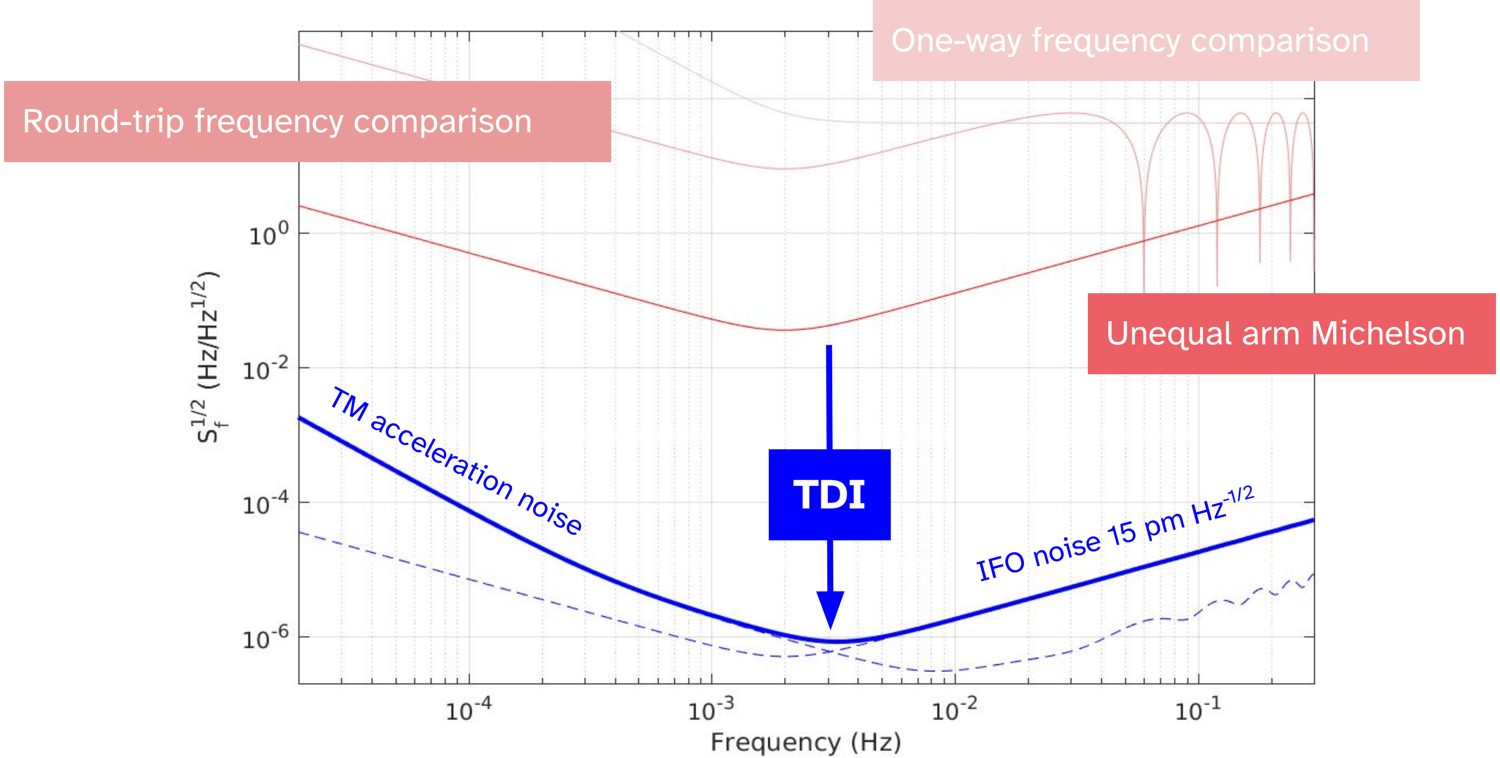
Time Delay Interferometry: Combine phase measurements retarded in time in such a way that laser frequency noise is killed

$$\Delta\dot{\nu}_X \equiv \Delta\nu_A(t) - \Delta\nu_B(t) + \Delta\nu_B(t - 2T_A) - \Delta\nu_A(t - 2T_B)$$

Both 4-pulse roundtrip optical paths start and end in same *event*

- laser frequency noise cancels out!

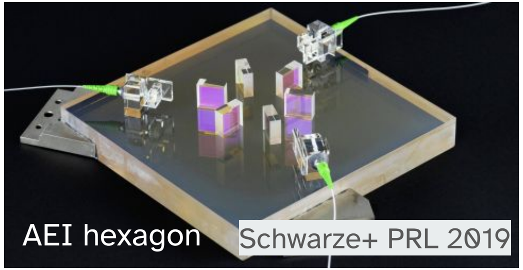
LISA long interferometer: *Time Delay Interferometry*

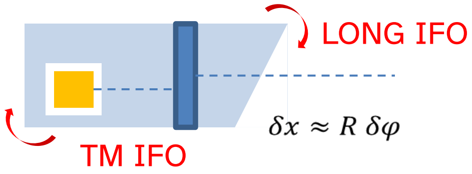


Experimental steps towards LISA

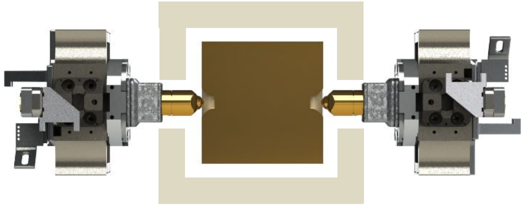
What needed now for LISA long arm interferometry?

- Inter-spacecraft laser interferometry at 200 pm $Hz^{-1/2}$ level
  - Demonstrated on the GRACE mission
- Phasemeter with a 10^{11} dynamic range to resolve GWs
  - Demonstrated on ground, need to get this in-flight
- Possible corrections to LISA phasemeter data due to SC motion
  - Translational motion ~nm $Hz^{-1/2}$ when trying to measure pm $Hz^{-1/2}$
  - Rotational motion of the SC: alignment problem between local IFO and distant IFO (Tilt-To-Length mitigation to be done in software)



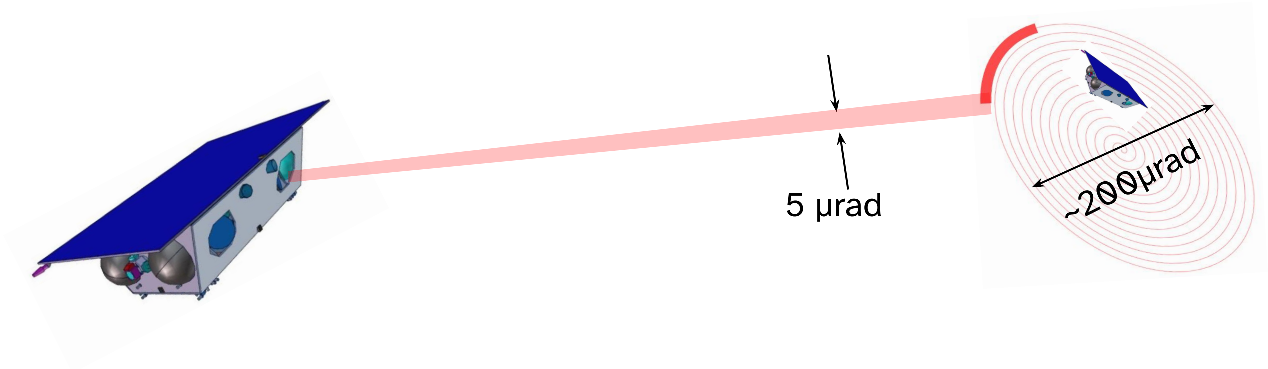


Experimental steps towards LISA



A couple interesting engineering details

- Test-mass release after launch
  - need to do that *slowly* (v < 15μm/s)
  - perfectioned towards the end of LPF mission
- Constellation acquisition
  - find distant SC with μ–rad laser beam
  - match beam frequency and angle

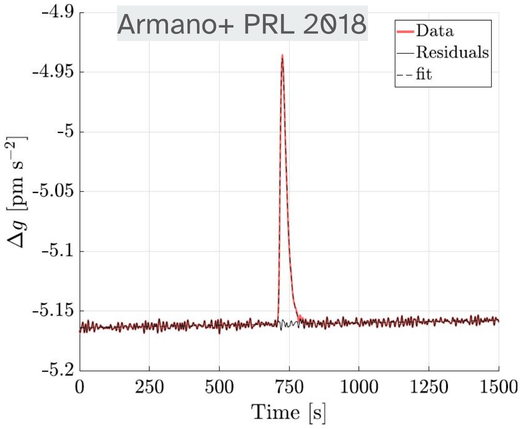


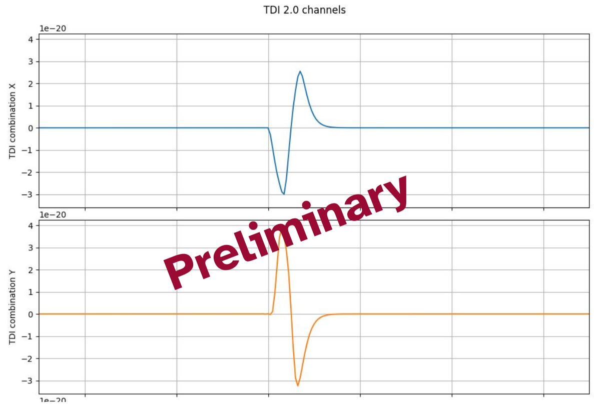
Experimental steps towards LISA

Instrumentalist challenge during LISA operations

Assess impact of noise artefacts which are going to be superimposed to signals
(e.g. force impulse *glitches* observed on LISA Pathfinder and removable after fit)

- Can we understand their physical source and eliminate them?
- Can we discriminate at instrument level?
- Or with TDI? [Work in progress in the LISA Data Challenges]





Thank you and remember to check lisamission.org

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LISA CONSORTIUM

lisa pathfinder

esa

ASI Agenzia Spaziale Italiana

TIFPA Trento Institute for Fundamental Physics and Applications

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