Preparing for gravitational wave observation from space with LISA

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LISA Canada Workshop
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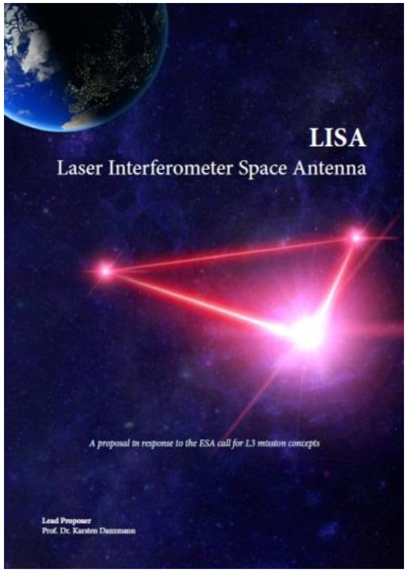


LISA:Laser Interferometer Space Antenna

- ESA L3 «large mission», launch 2035
- Gravitational wave observation 100 μHz – 1 Hz
- 4 year nominal (10 year extended) mission

Talk outline:

How does LISA work?

- Measurement concept and main sensititivity limits

What have we already tested?

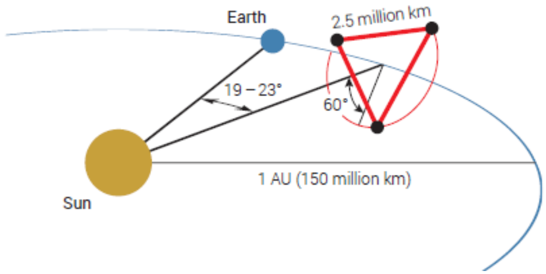
- Free-falling test masses with (local) interferometric tracking (LISA Pathfinder)

What are we working on?

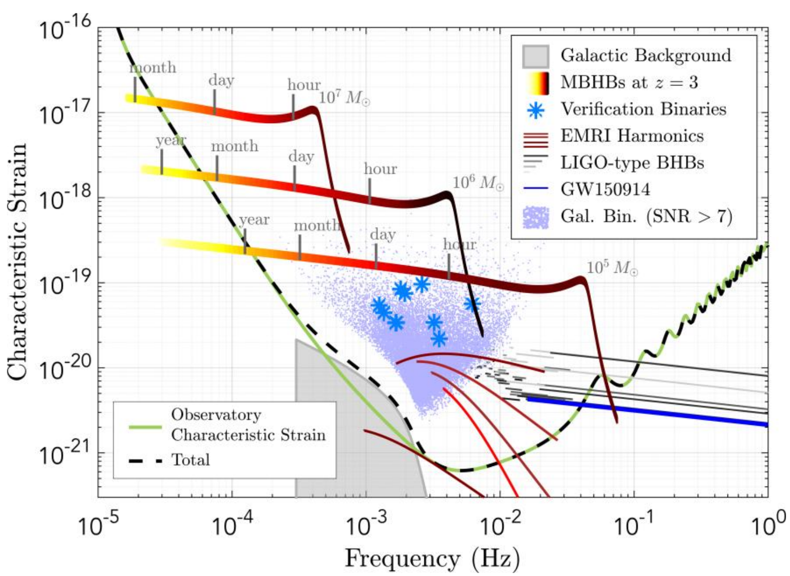
- Long arm (2.5 million km) interferometry and signal-dominated GW data analysis

LISA: Laser Interferometer Space Antenna

antenna: **constellation of free-falling test masses**
receiver: **laser interferometry**

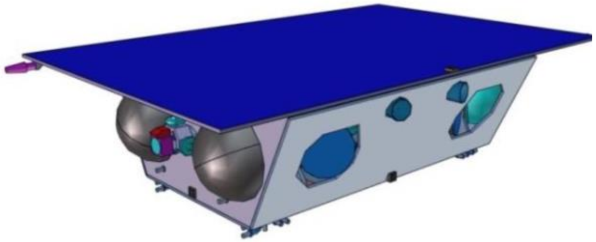


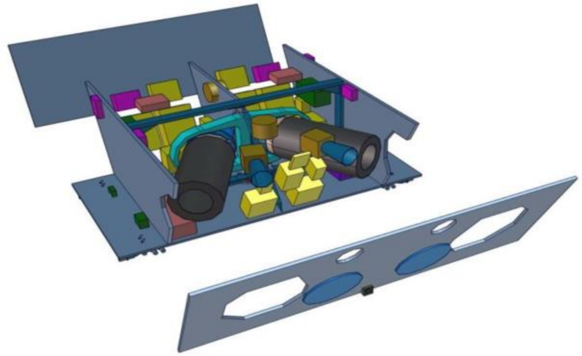
LF limit: spurious antenna tidal deformation (stray forces)
HF limit: interferometer fluctuations (shot noise etal)

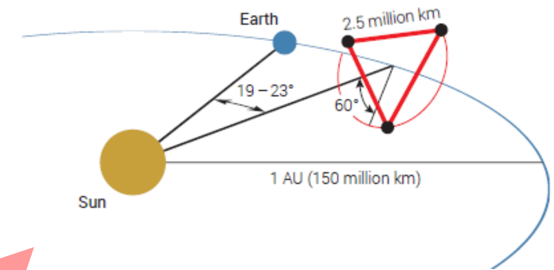


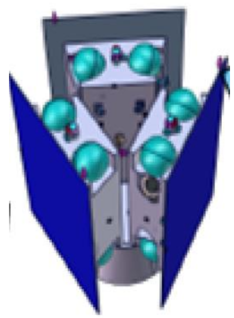
- 3 arms (6 one-way links), L = 2.5 million km
- free-falling TM, no suspension
  - orbital tidal accelerations μm/s^2, GW fm/s^2
  - spacecraft drag-free control
- «open-loop» interferometer
  - Δv 10 m/s → 10 MHz fringe rates
- very unequal arm interferometer (ΔL 10^4 km)
- weak light (100 pW)
  - single arm «transponders» (no direct reflection)
  - no 2-arm light combination

LISA: ESA L3 mission









ESA: mission lead and system prime

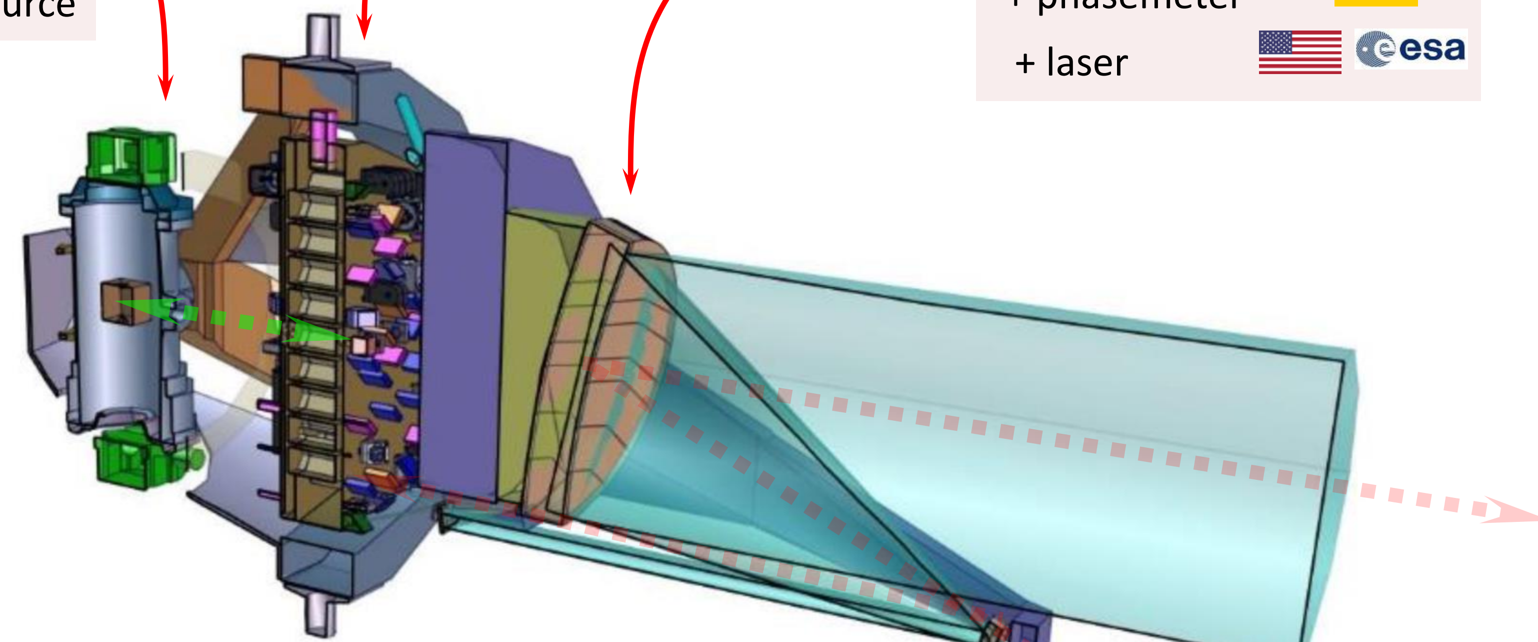
- spacecraft (x3) + (possible) payload items
- launch, transfer, communications, propulsion, SC control ...
- mission and science operations
- guarantees mission performance

NB: notional designs
(ESA internal study, 2017)

The LISA instrument «MOSA»: moving optical sub-assembly

Gravitational reference system
GRS head
+ electronics
+ UV light source

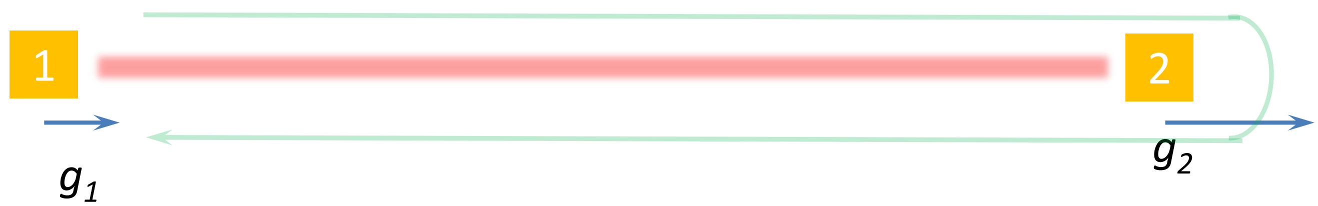
Optical metrology system
Optical bench
Telescope
+ phasemeter
+ laser



2 MOSA per each SC

GW observation as time-delayed Doppler gravity gradiometer

- Exchange of light beam between free-falling observers (light travel time ***T***)
- 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»: $\Delta\nu$
- LISA makes this measurement along 3 arms



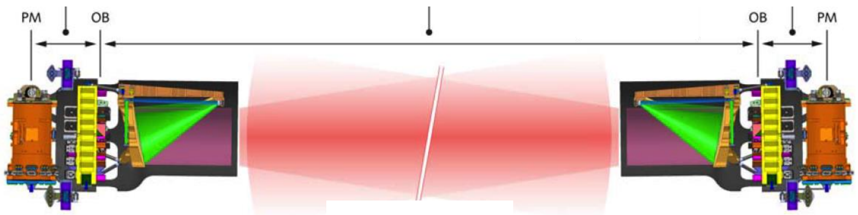
GW strain **stray acceleration (time delayed Δg)**

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

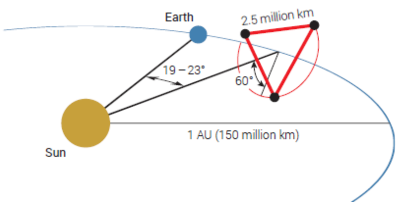
$$+ \frac{1}{\nu}\left[\dot{\nu}_{1E}(t)-\dot{\nu}_{1E}(t+2T) + \dot{\nu}_{n1}(t+2T)-\dot{\nu}_{n2}(t+T)\right]$$

laser freq noise **Phase/frequency measurement noise**

LISA sensitivity



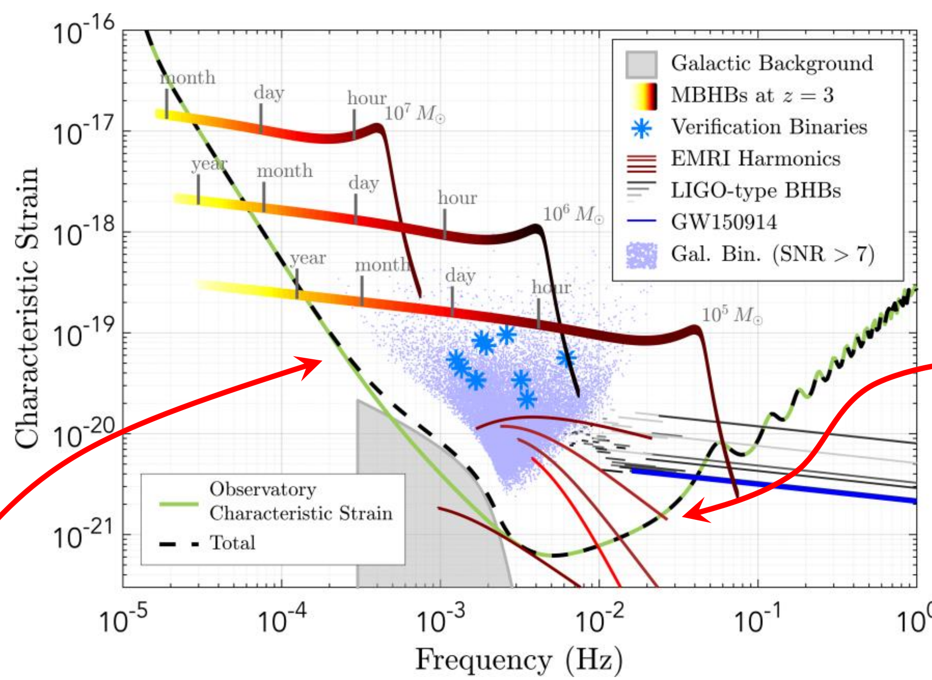
2.5 Million km



Measure acceleration between free-falling test masses (TM) 2.5 million km apart

- 3 parts: TM-SC, SC-SC, SC-TM

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



Low freq limit:
Test mass acceleration noise, 3 fm/s²/Hz$^{1/2}$

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

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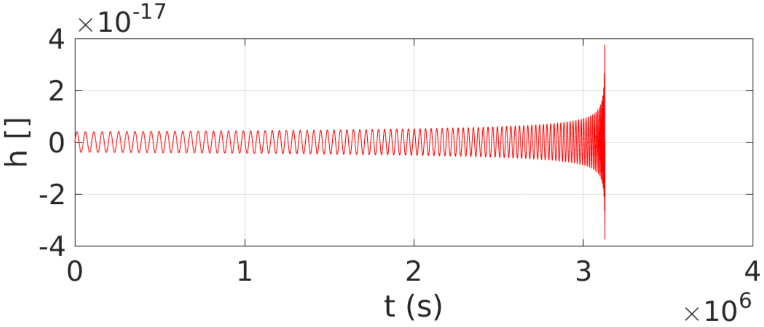
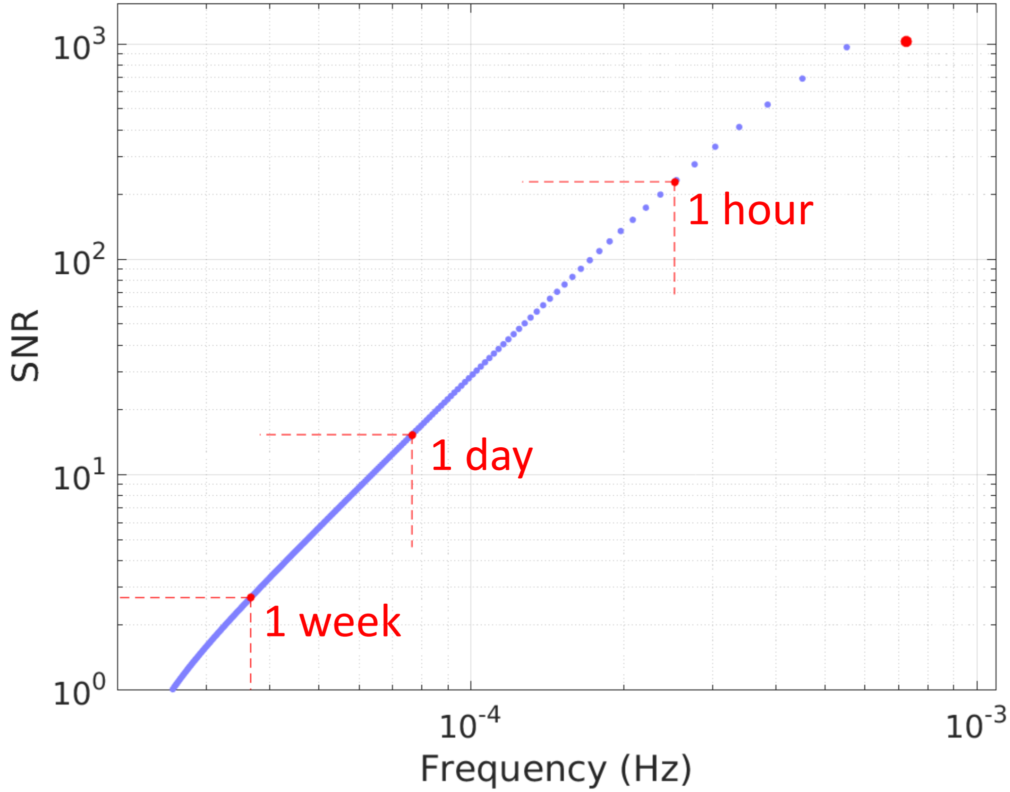
LISA: a high resolution, deep universe, low frequency observatory

Super Massive Black Hole (SMBH) science

Merger of two 5 10^6 solar mass black holes at z = 2





- Entire signal power of SMBH at **f < 1 mHz** → TM acceleration noise limits
- lower frequencies extend observation time from day to weeks
  → helps sky resolution precision

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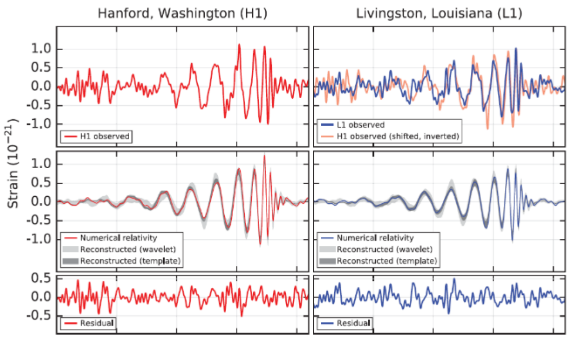
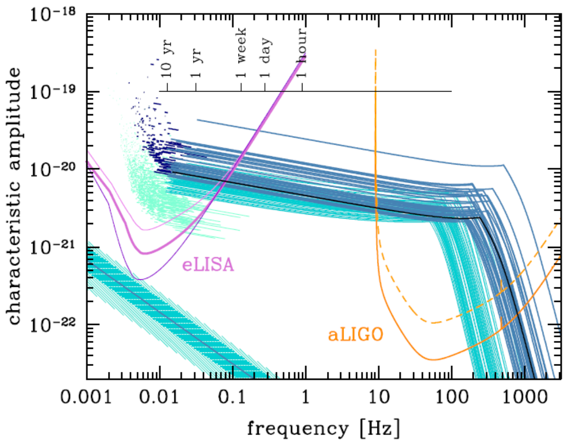
LIGO 30 $M_\odot$ binaries – observable by LISA (5-15 years pre-merger)



14 September 2015:
LIGO observes BHB GW150914

- 36 +/- 5 $M_\odot$, 29 +/- 4 $M_\odot$ (30-300 Hz band)
- 10^9 light years away

[Abbott etal, PRL 2016]



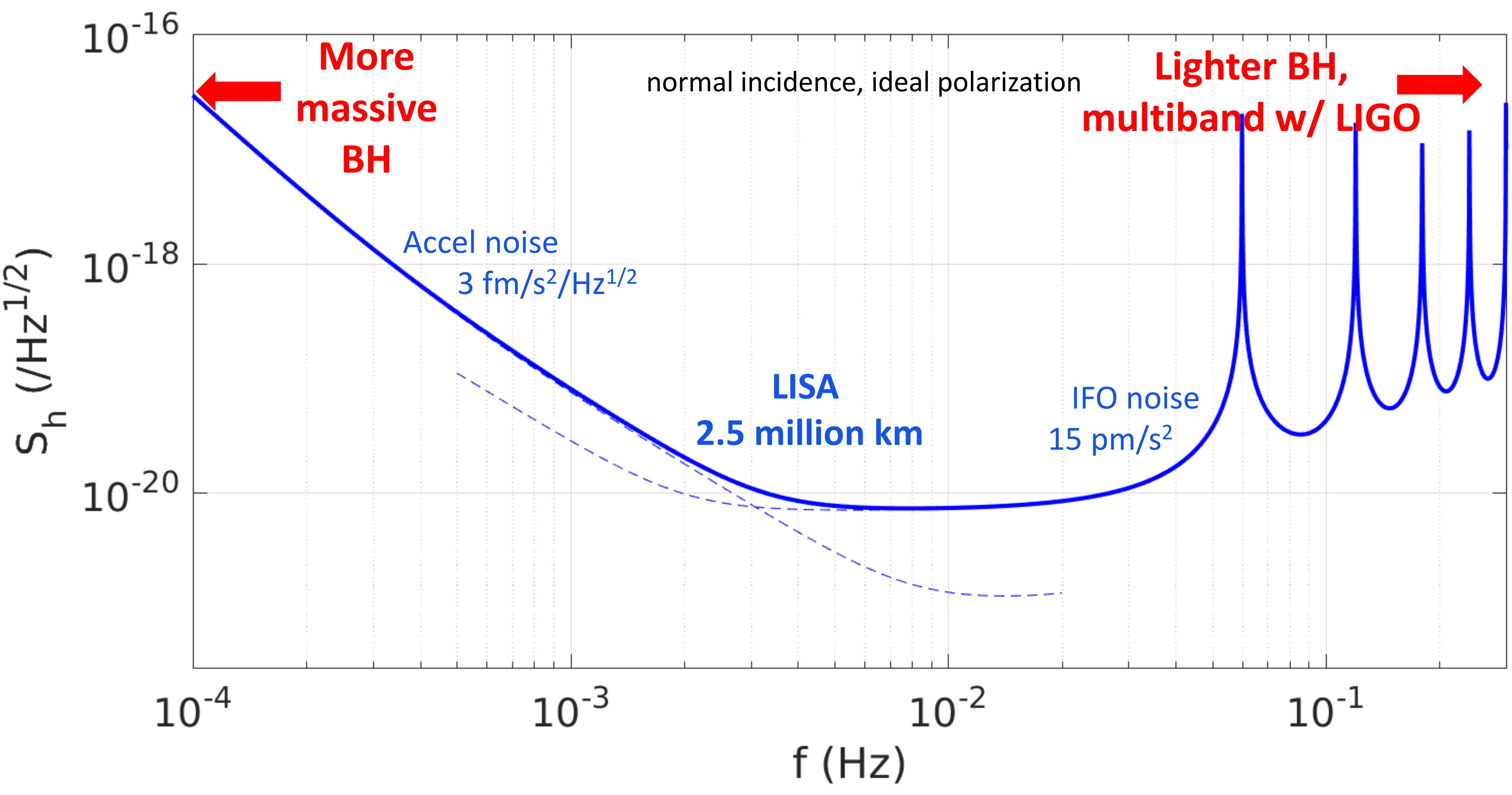
LISA would have detected this

- 5-10 years pre-merger, **10-20 mHz**
- **limited by interferometry**

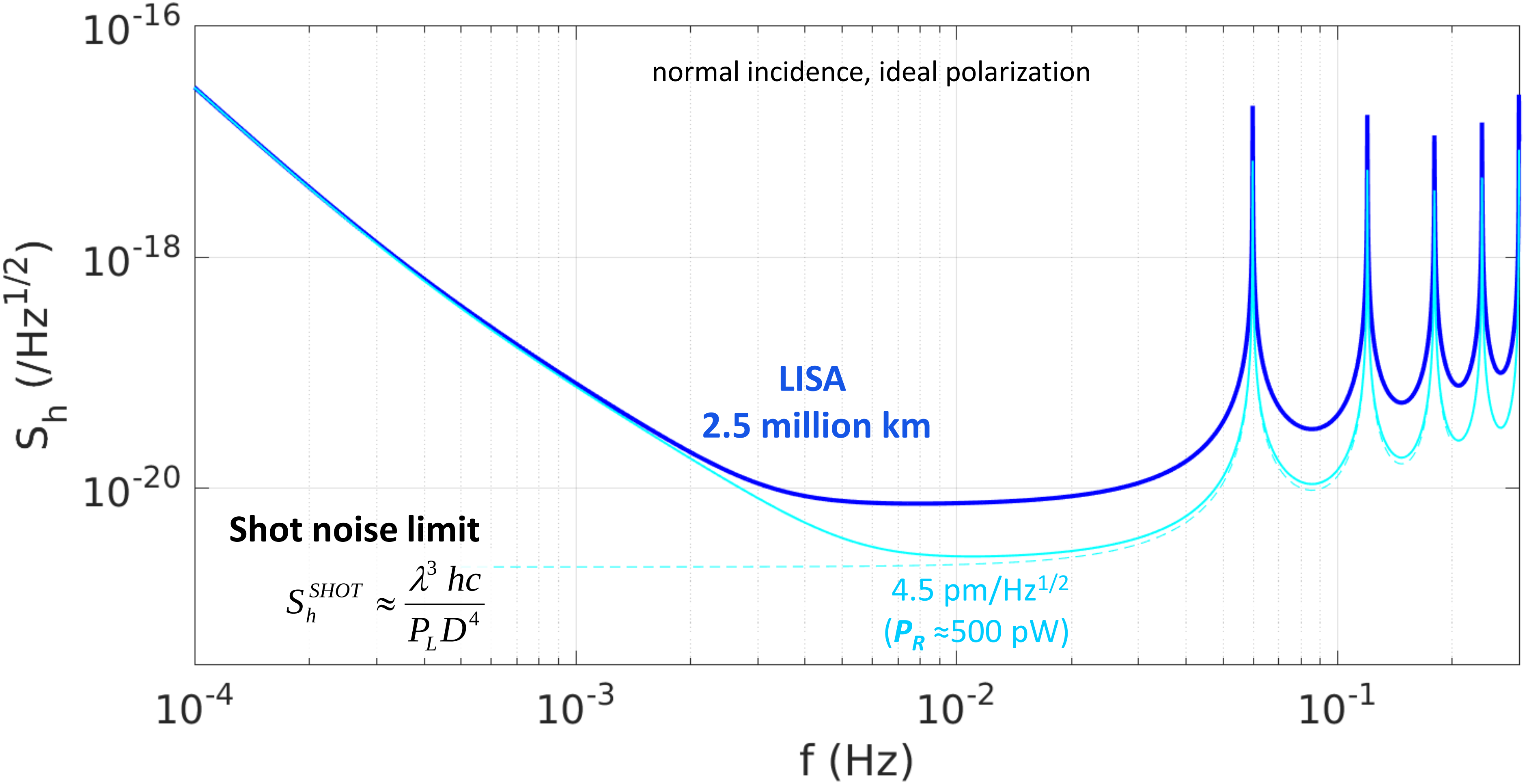
[Sesana, *PRL*, 2016]

- Multi-band observation possible, though likely not typical
  - most LIGO BHB below LISA threshold
- order 100 stellar BHB observable by LISA, far from merger
- LISA extends stellar remnant BHB study to higher mass

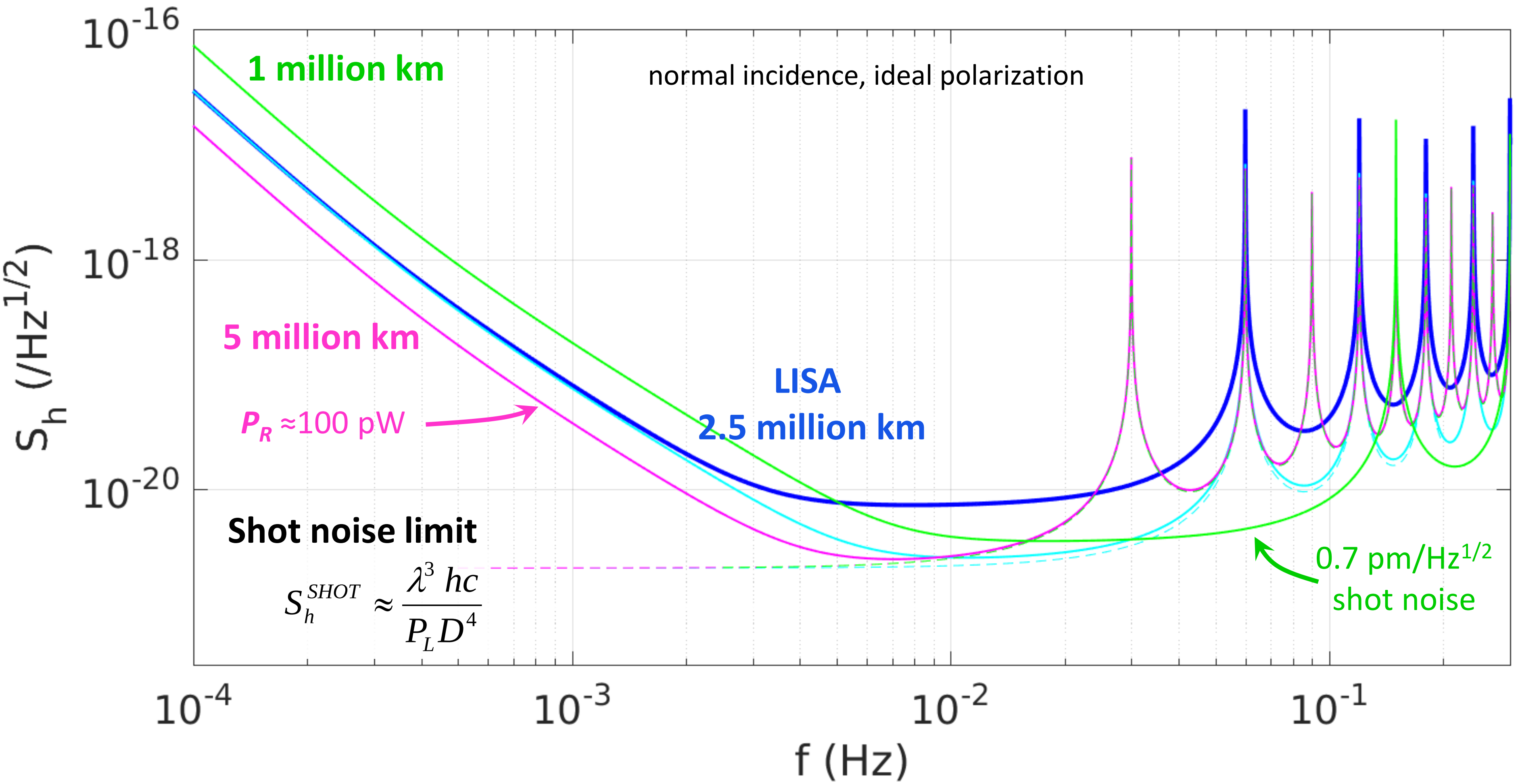
The right size for LISA: why *L* = 2.5 million km?



The right size for LISA: why *L* = 2.5 million km?



The right size for LISA: why *L* = 2.5 million km?



The right size for LISA: why *L* = 2.5 million km?

- "shot noise limit" noise minimum: independent of length L
- shot noise is not everything – interfermeter "technical noise" important
  - LISA has margin:
  - 2 W laser, 30 cm telescope, 2.5 million km:
    - shot noise 5 pm (of 15 pm)

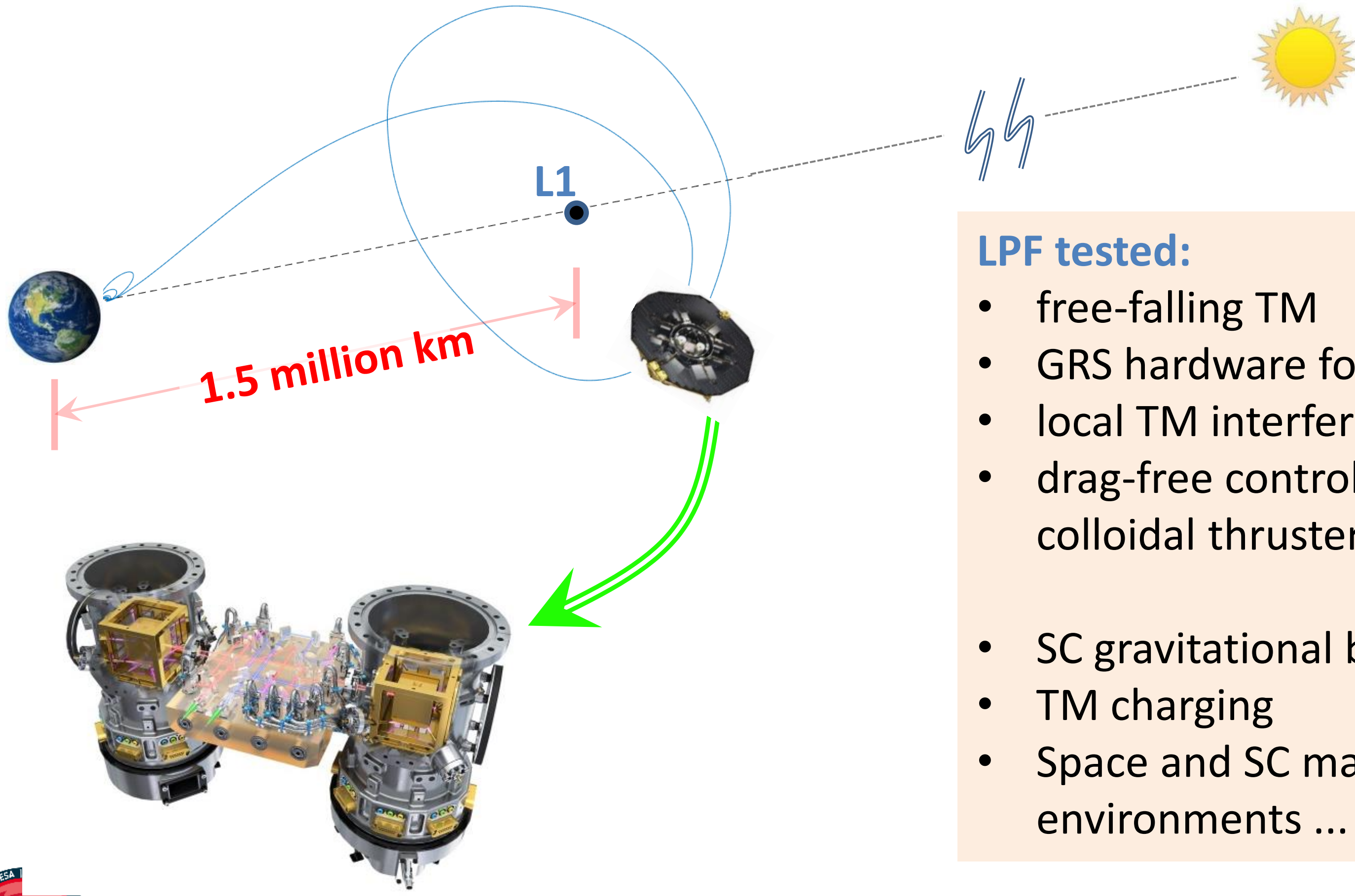
$$S_h^{SHOT} \approx \frac{\lambda^3 \, hc}{P_L D^4}$$

- improving at high frequencies (shorter ***L***) requires limiting all other IFO noise
  - coupling to SC motion, mechanical deformation
- improving at lower frequencies (longer ***L***)
  - longer ***L*** means locking laser with lower light power (100 pW in LISA)
  - longer ***L*** means larger solar system (Earth eccentricity) gravitational perturbations
    - shorter lifetime or more distant from Earth
    - SC relative velocity (doppler shift, corner angles ...)

$$P_R \approx P_L \frac{D^4}{\lambda^2 L^2}$$

LISA Pathfinder: ESA Einstein Geodesic Explorer

- Launch December 2015, science operations March 2016-July 2017
- Measure differential acceleration – Δg – between 2 free-falling test masses – each 2 kg Au-Pt – separated by 38 cm inside 1 spacecraft



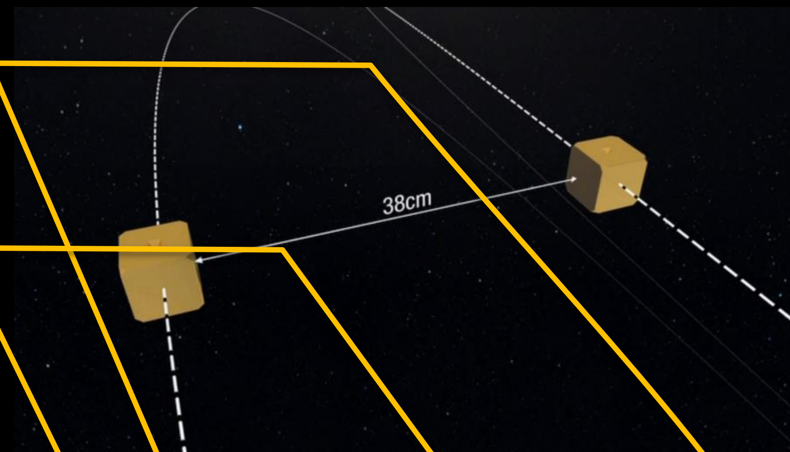
LPF tested:

- free-falling TM
- GRS hardware for LISA
- local TM interfermetric readout
- drag-free control with cold gas and colloidal thrusters

- SC gravitational balancing
- TM charging
- Space and SC magnetic, thermal environments ...

LISA Pathfinder

Test masses gold-platinum,
→ heavy, non-magnetic

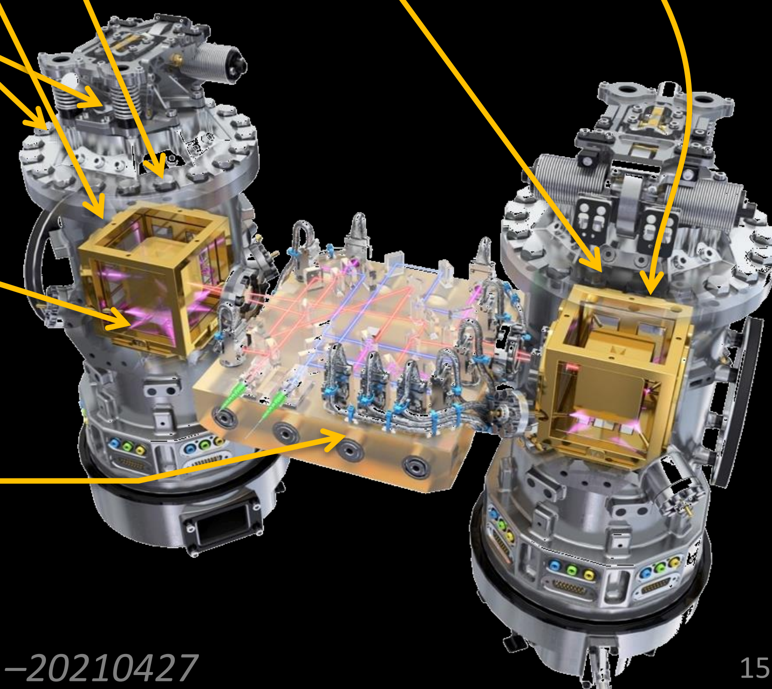


Electrode housing:
→ Electrostatic shield
→ Nm-sensing, nN actuation

Vacuum enclosure

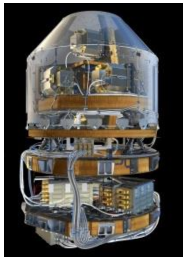
Caging mechanism
→2 kN launch lock / vent to space
→1 N positioning / release

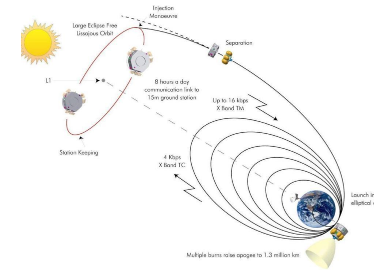
UV light
→neutralize cosmic ray charge



Ultra high mechanical stability optical bench for the laser interferometer

LPF: Testing jump from pico-g/Hz$^{1/2}$ to sub-femto-g/Hz$^{1/2}$:



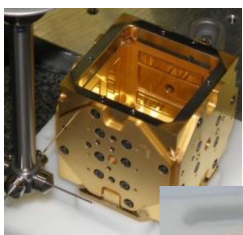


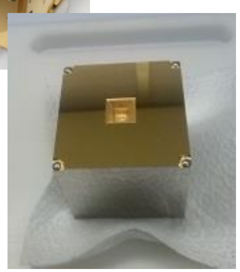
Geodesy in low earth orbit
(DC Δg μm/s^2)

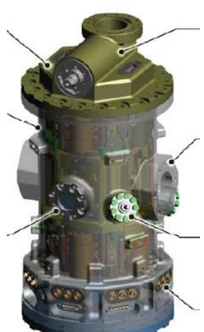
LPF at L1
(DC Δg nm/s^2)

Much smaller actuation forces (and force noise)

Are surface forces low enough to allow this jump?



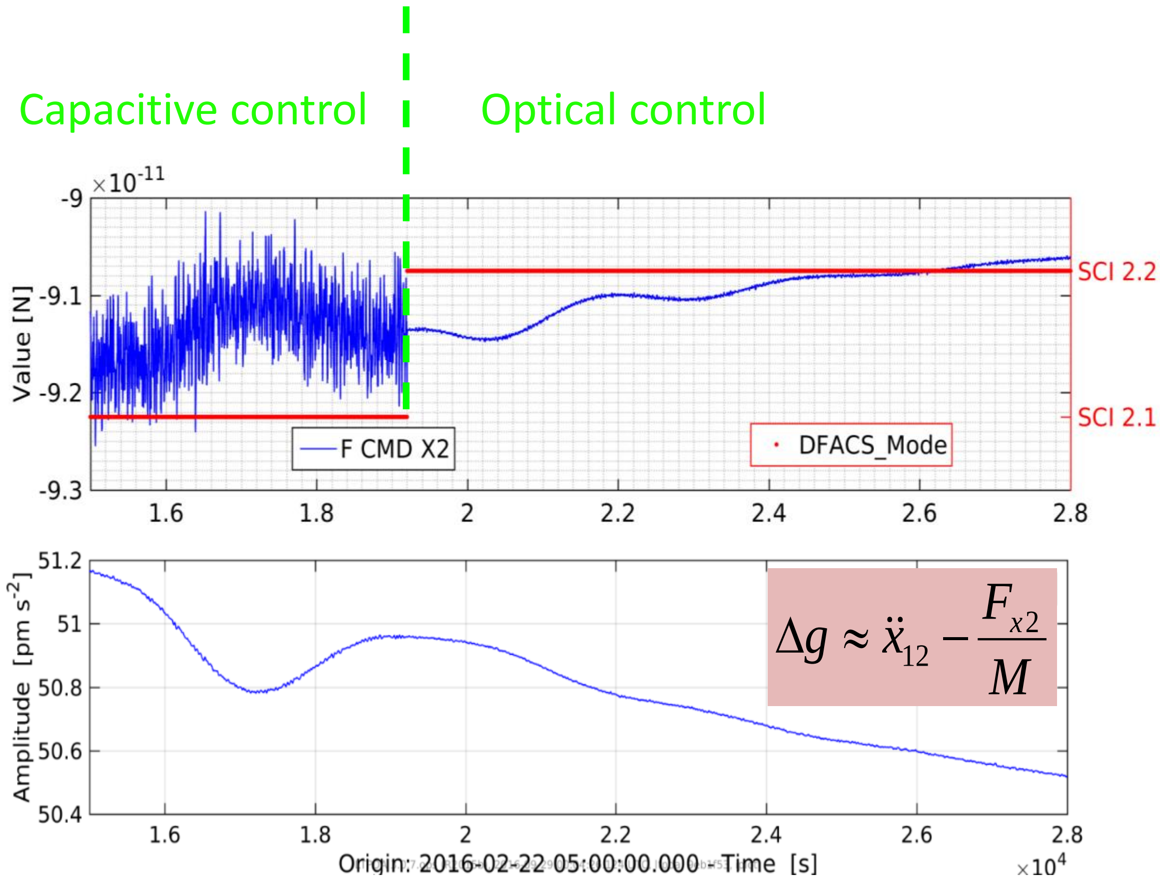


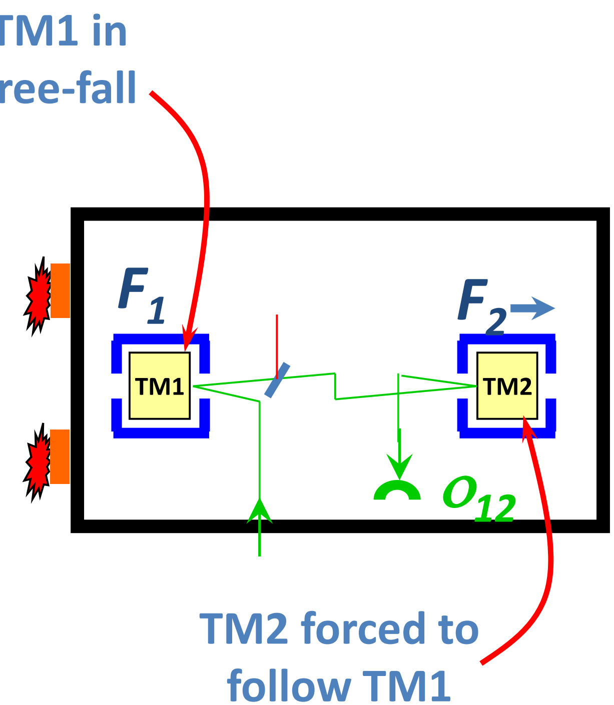


- Heavy TM, 2 kg Au-Pt
- 3-4 mm gaps
- no contacts (no discharge wire)
- AC-carrier force actuation
- Vent to space (< 10 μPa)

- tough caging
- UV discharge
- **need IFO**

Quieting down … Applied TM2 force

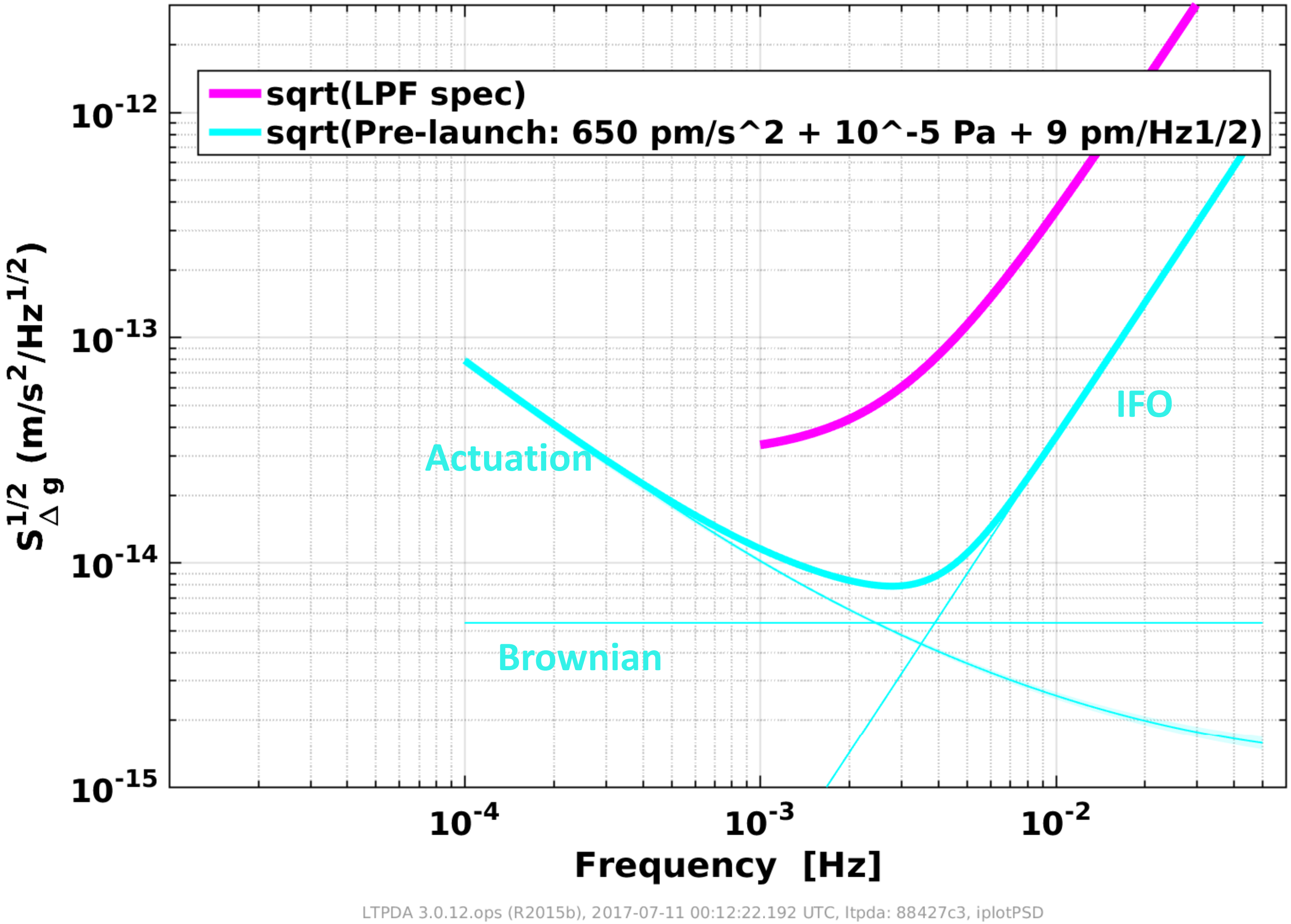




$\Delta g < 50$ pm/s² … and decreasing (good news!)

- gravitational balance < 650 pm/s² (spec) → less actuation → less noise!
- start to see LPF science signal … sub-mHz fluctuations in Δg

LISA Pathfinder differential acceleration noise



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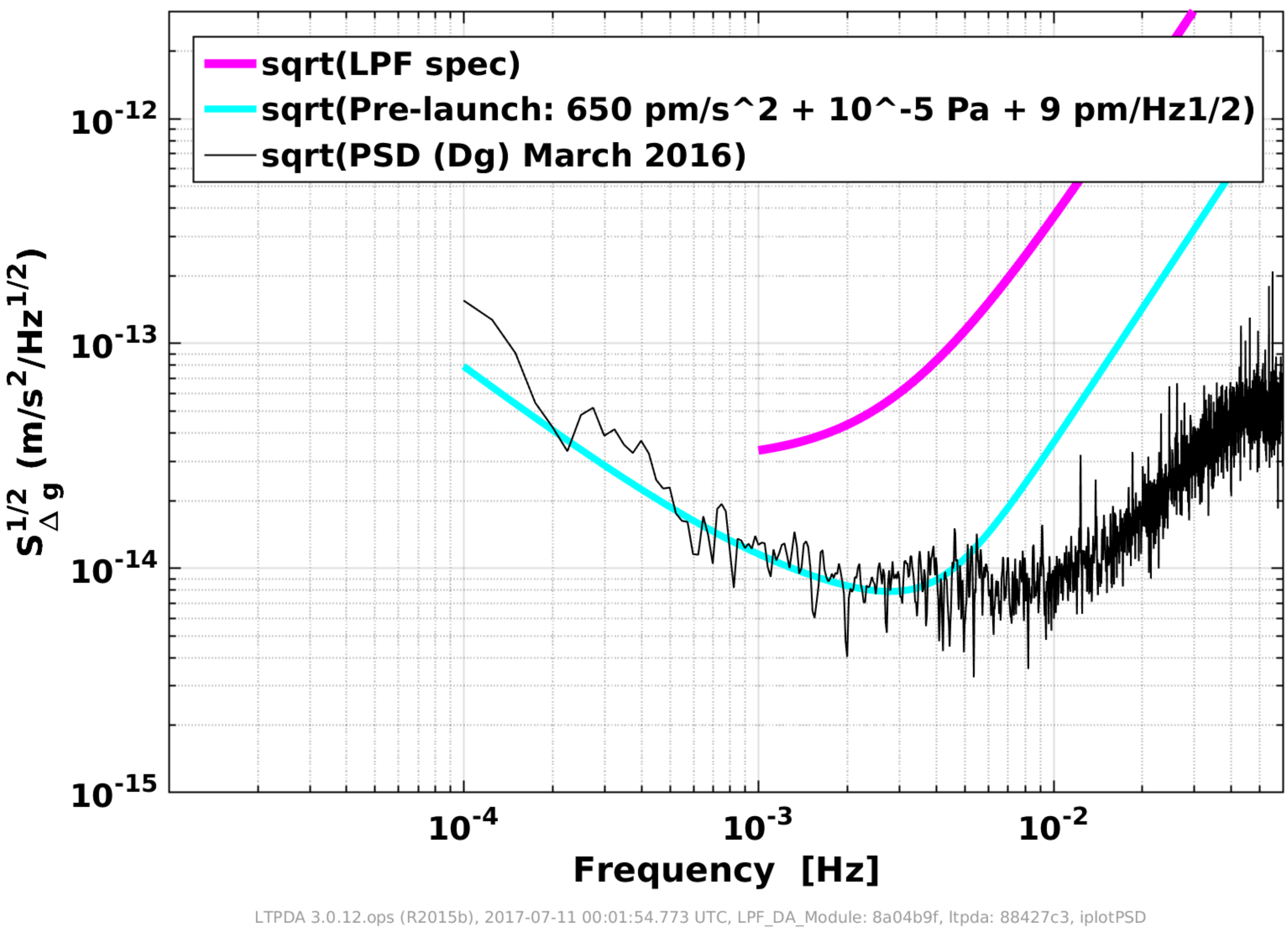

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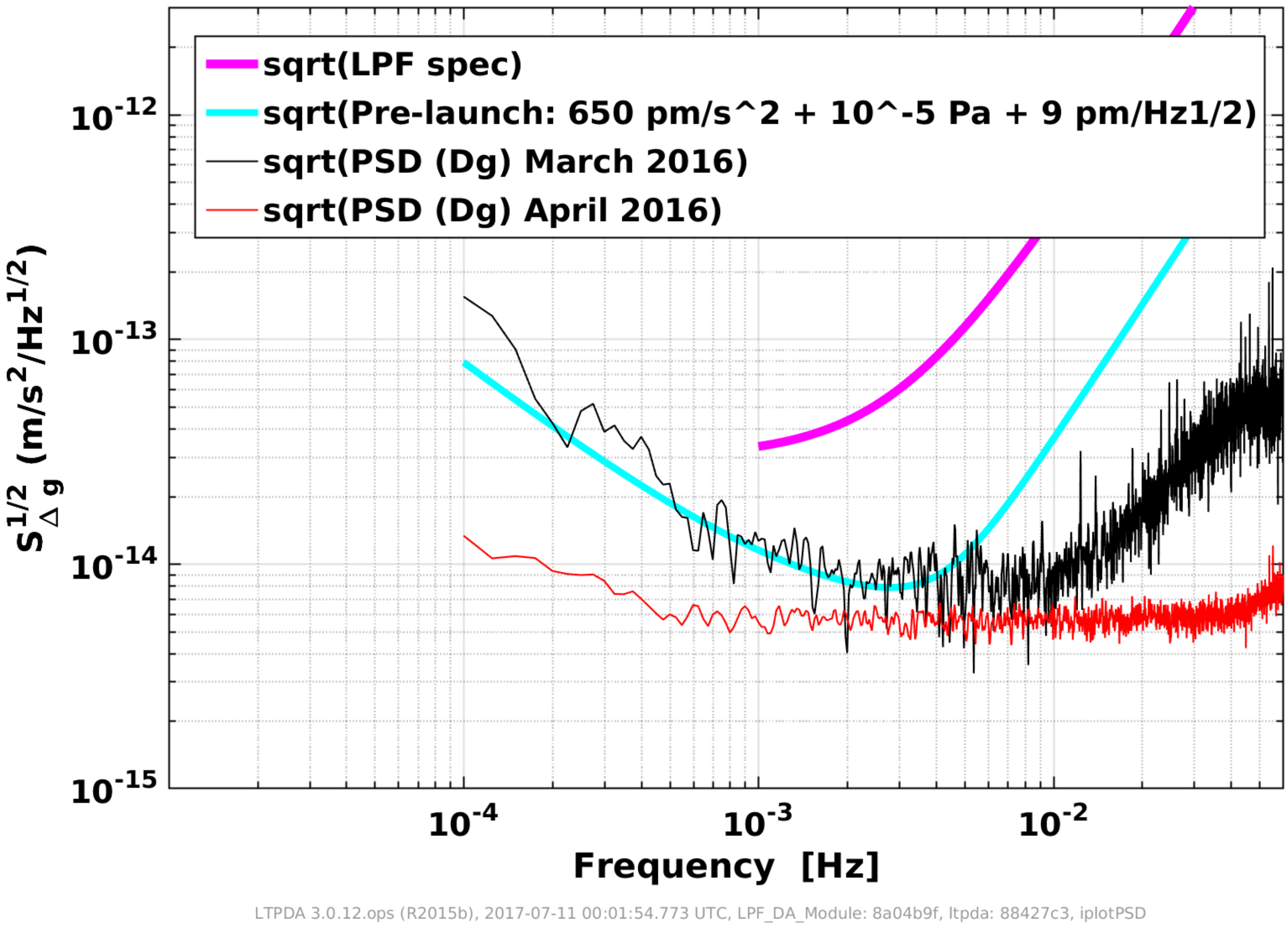

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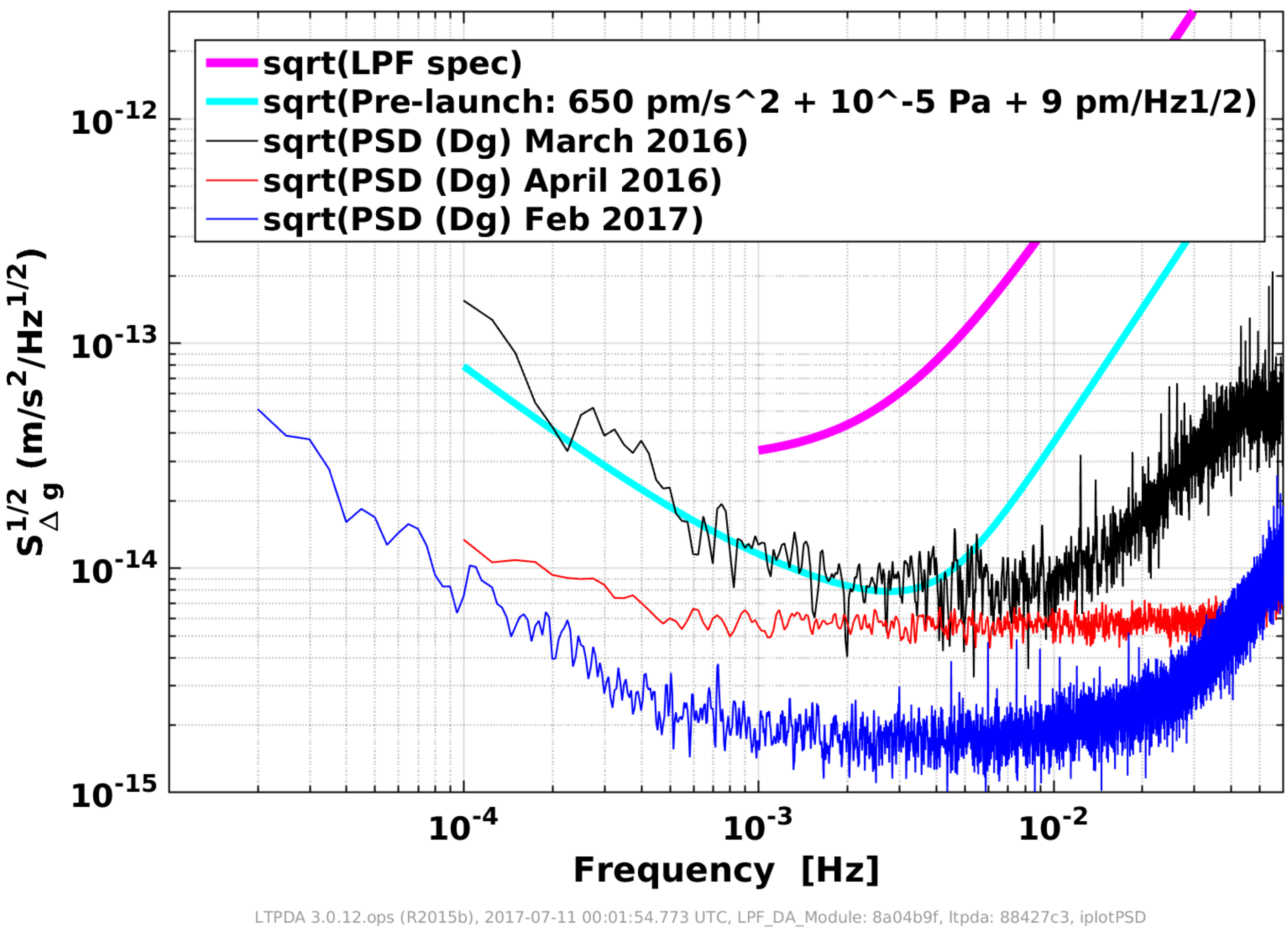

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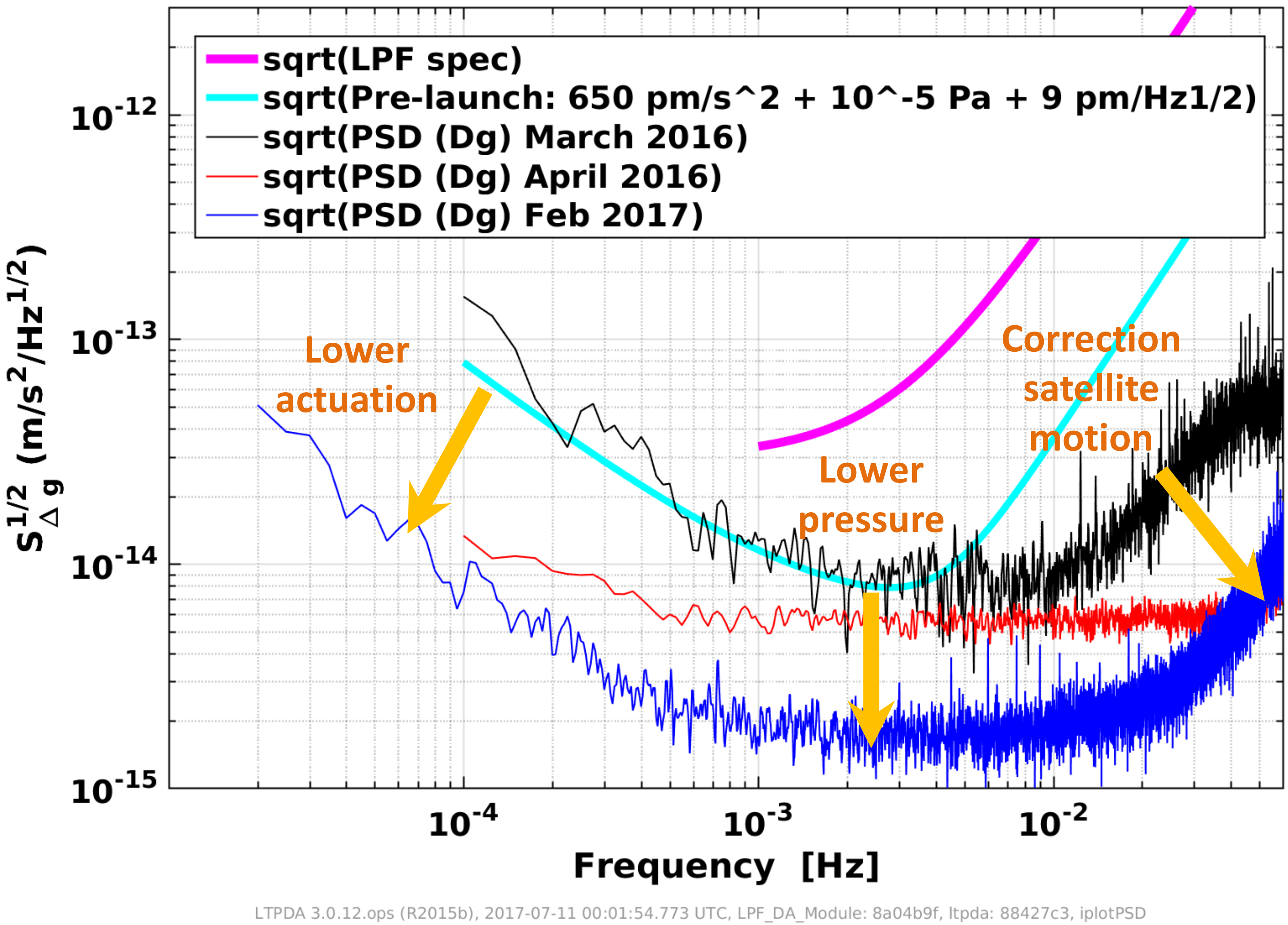
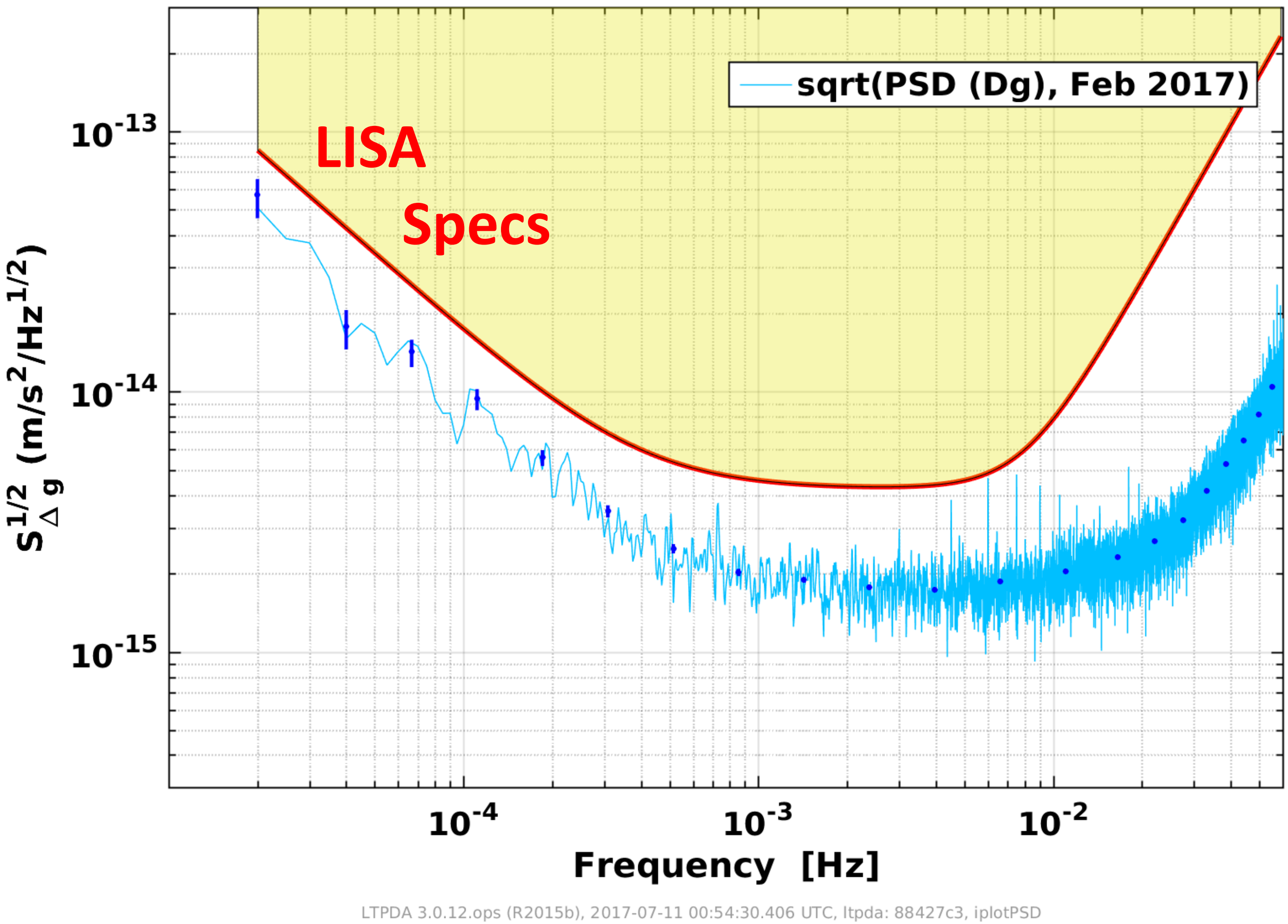


LISA Pathfinder Δg noise budget (February 2017)



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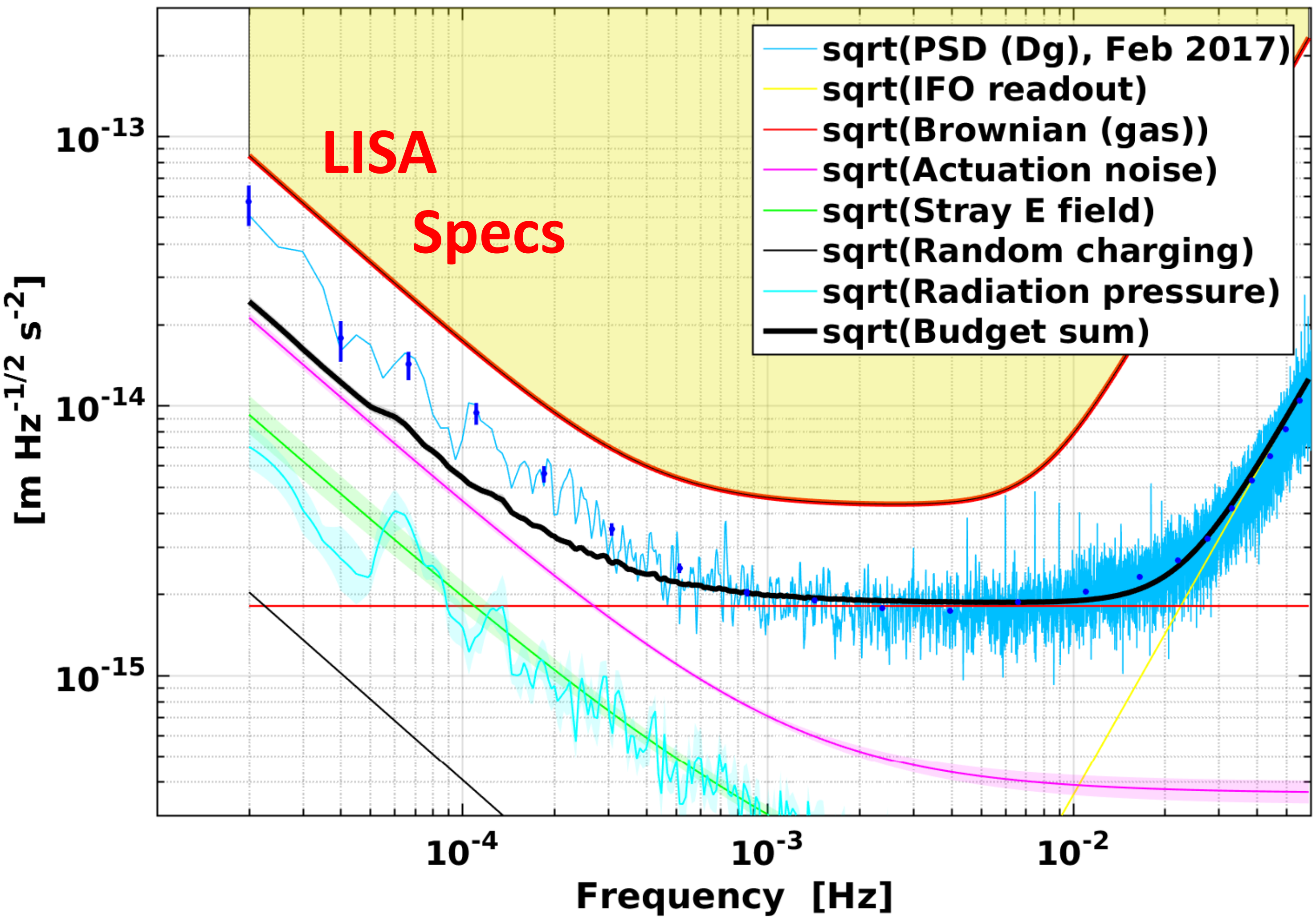
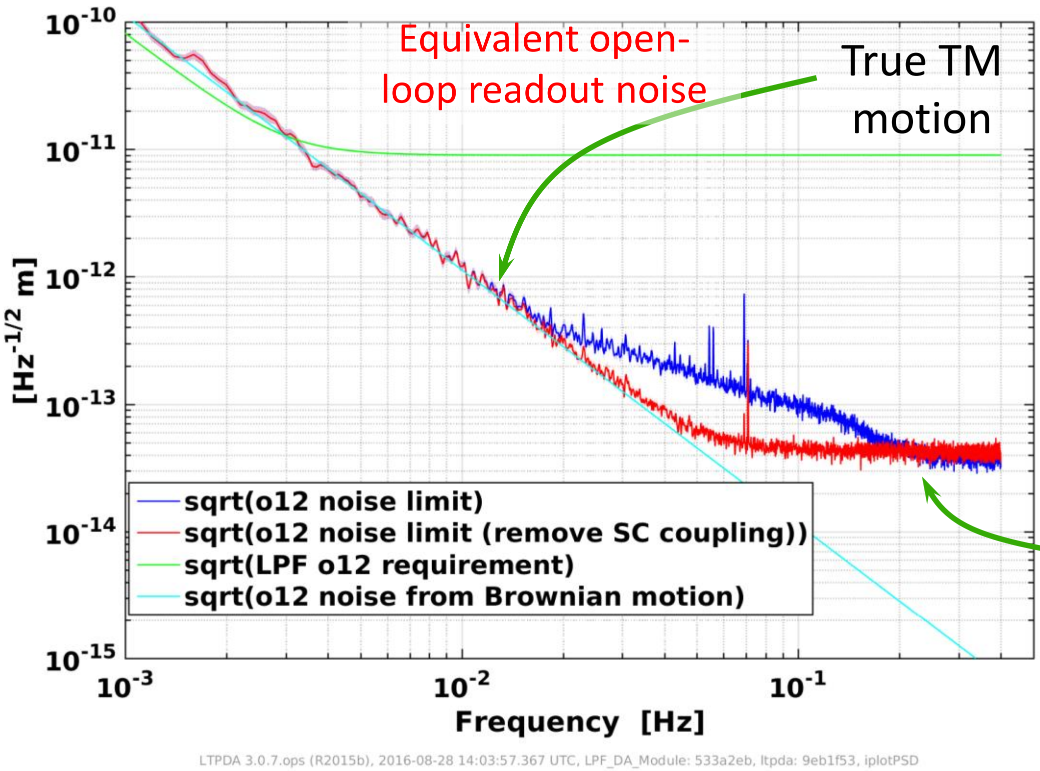
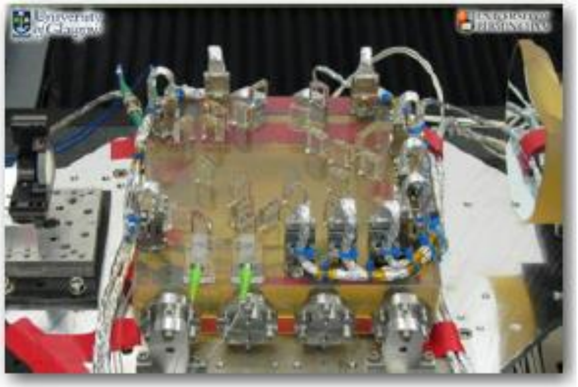


- **LISA acceleration noise goal has been demonstrated**
- **Low frequency noise still not fully understood**

LISA Pathfinder instrument performance: interferometer

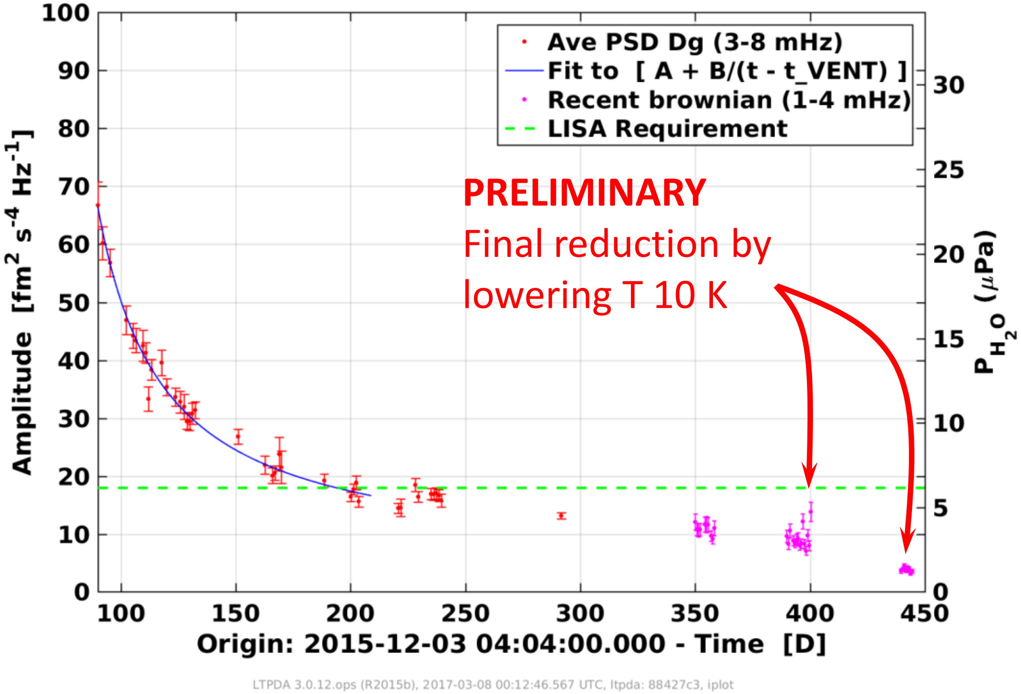




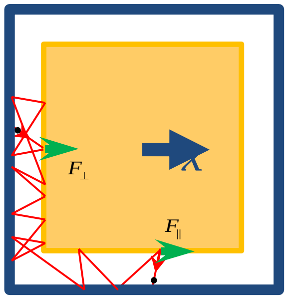
35 fm/Hz$^{1/2}$ noise floor (required 10 pm/Hz$^{1/2}$)

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

Brownian motion from residual gas impacts



Performance limit in 1 – 10 mHz band



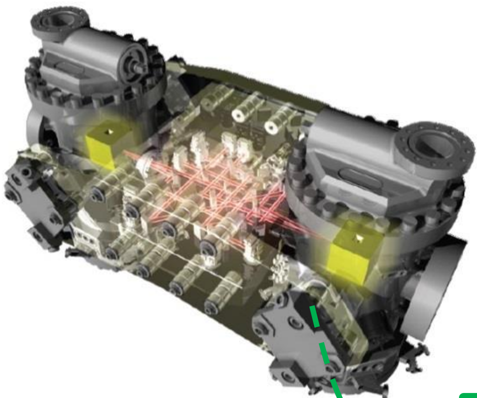
Increased inside (tight) GRS due to correlated collisions

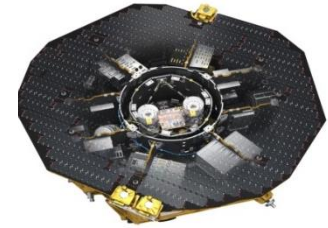
Mid-frequency LPF acceleration noise: residual gas damping

- Decays over time (t^{-1}) as GRS vents to space
- Noise power cut in half when cooled by 10 K→ H_2O outgassing (1 μPa)
- Visible in thermal gradient experiments (radiometric effect)

Below LISA requirement!

LPF Noise: self-gravity and actuation noise

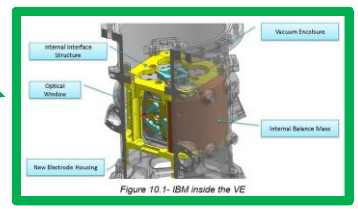


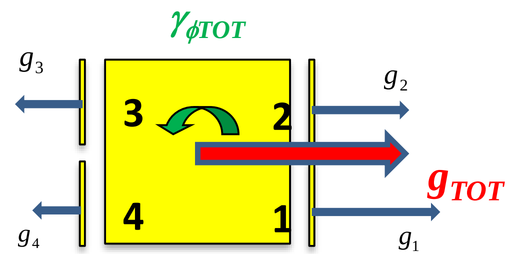


LPF «accelerometer dynamic range» problem

Noise in "DC" force applied to compensate local $\Delta \mathbf{g}$

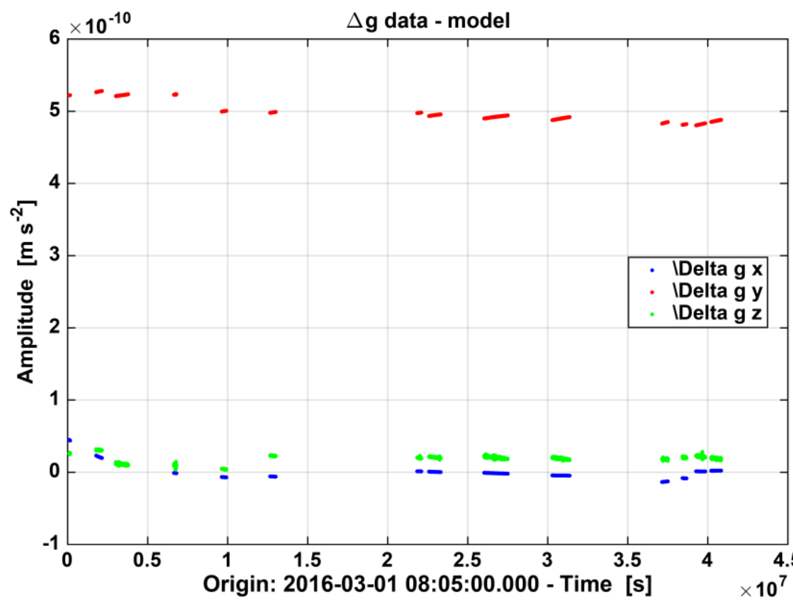
$$F \propto V_{ACT}^{2} \qquad \rightarrow \qquad S_F^{1/2} \approx 2\, F\, S_{\delta V/V}^{1/2}$$



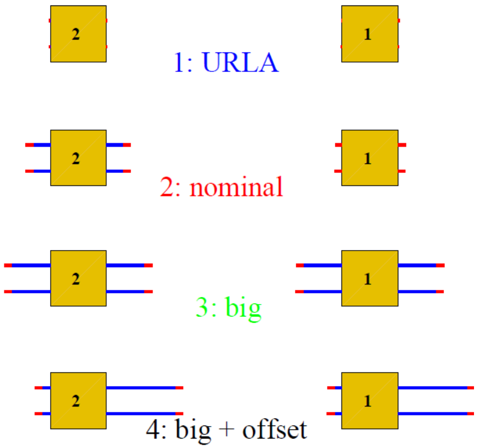


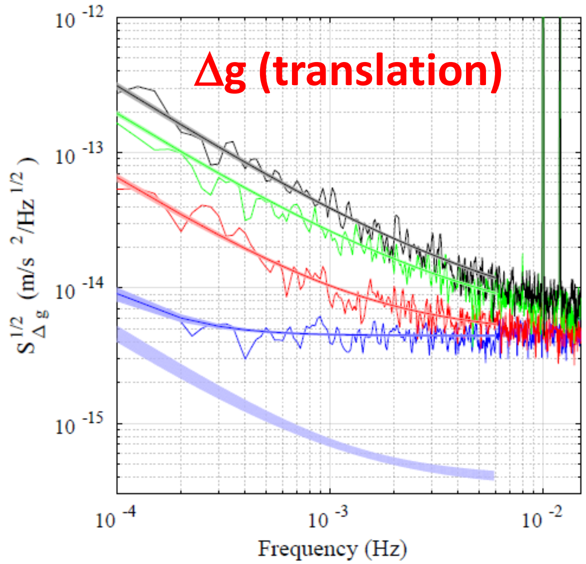
LPF balanced Δg to below 550 pm/s² on all 3 axes (10x better on x)

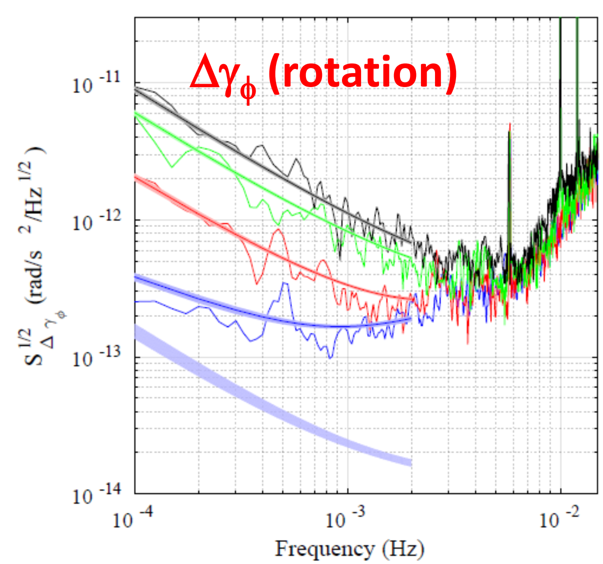
- key technology for LISA!
- All 6 torques modeled <1 nrad/s²



Actuation noise test campaign: results







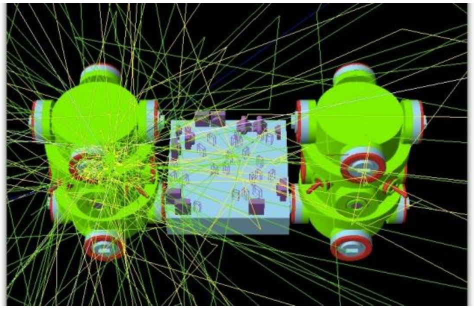
Noise in Δg, $\Delta\gamma_\phi$ increases with larger (balancing) forces

→ actuator stability at 50 ppm/Hz$^{1/2}$ level at 100 μHz

→ as measured on ground

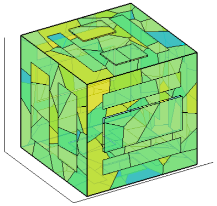
- **Actuation noise observed, well modeled but not dominant in LPF**

→ thanks to grav balance

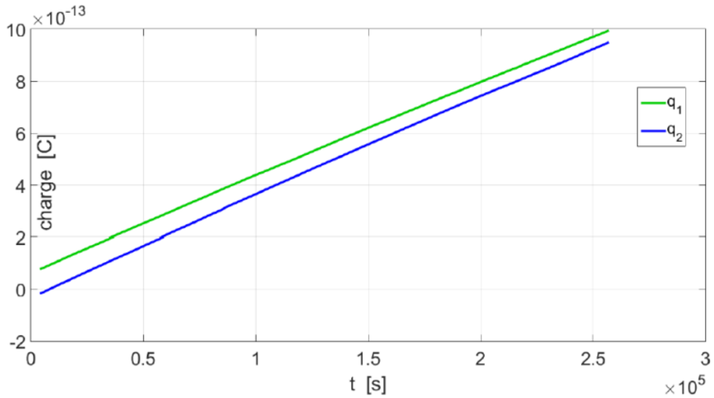


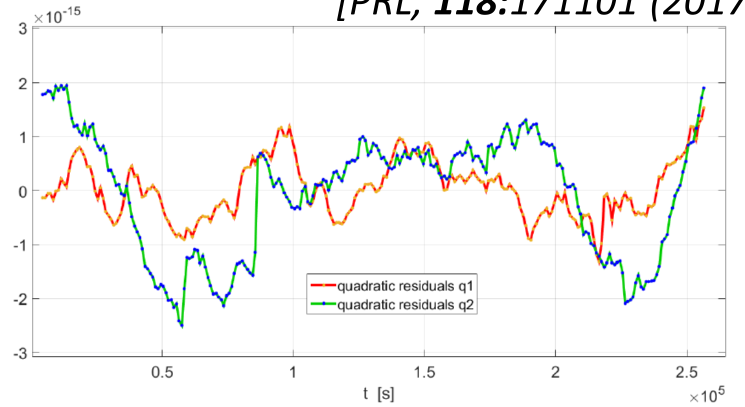
TM charging: steady and stochastic

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



*[PRL, **118**:171101 (2017)]*



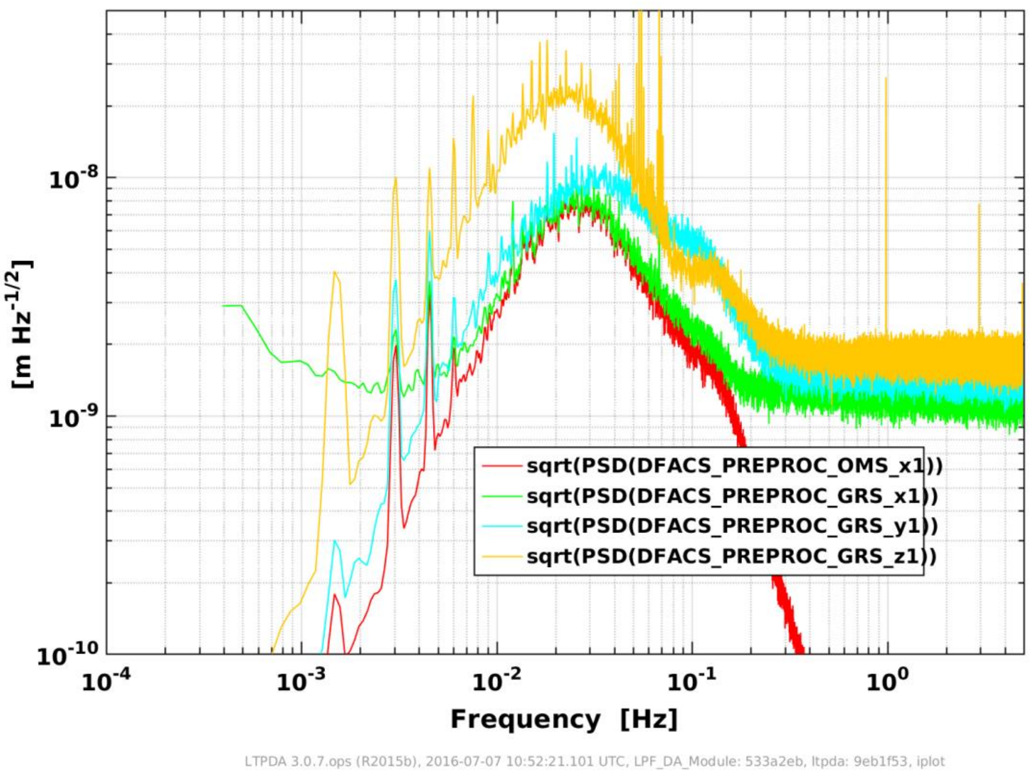


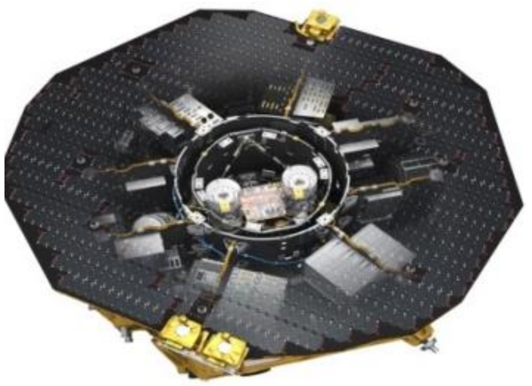
Net charge rate: +25 e/s

Effective shot noise rate: 1200 e/s

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

LISA Pathfinder instrument performance: drag-free satellite control





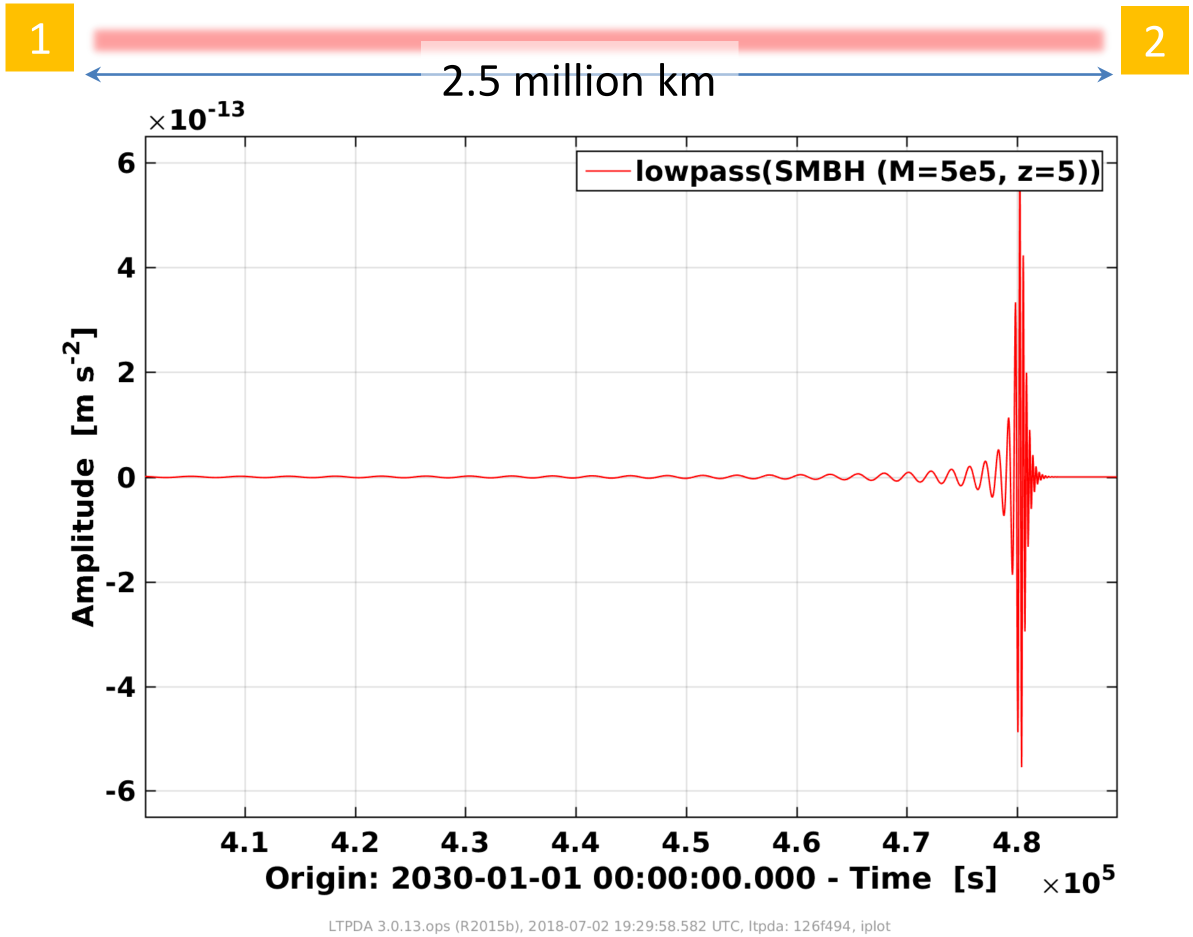
Closed loop SC jitter

$$S_{\delta x}^{1/2} \approx \frac{S_F^{1/2}}{M\omega_{DF}^2}$$

- small impact (force gradient and IFO coupling) on acceleration noise
- cold gas thruster heavy, but can work for LISA

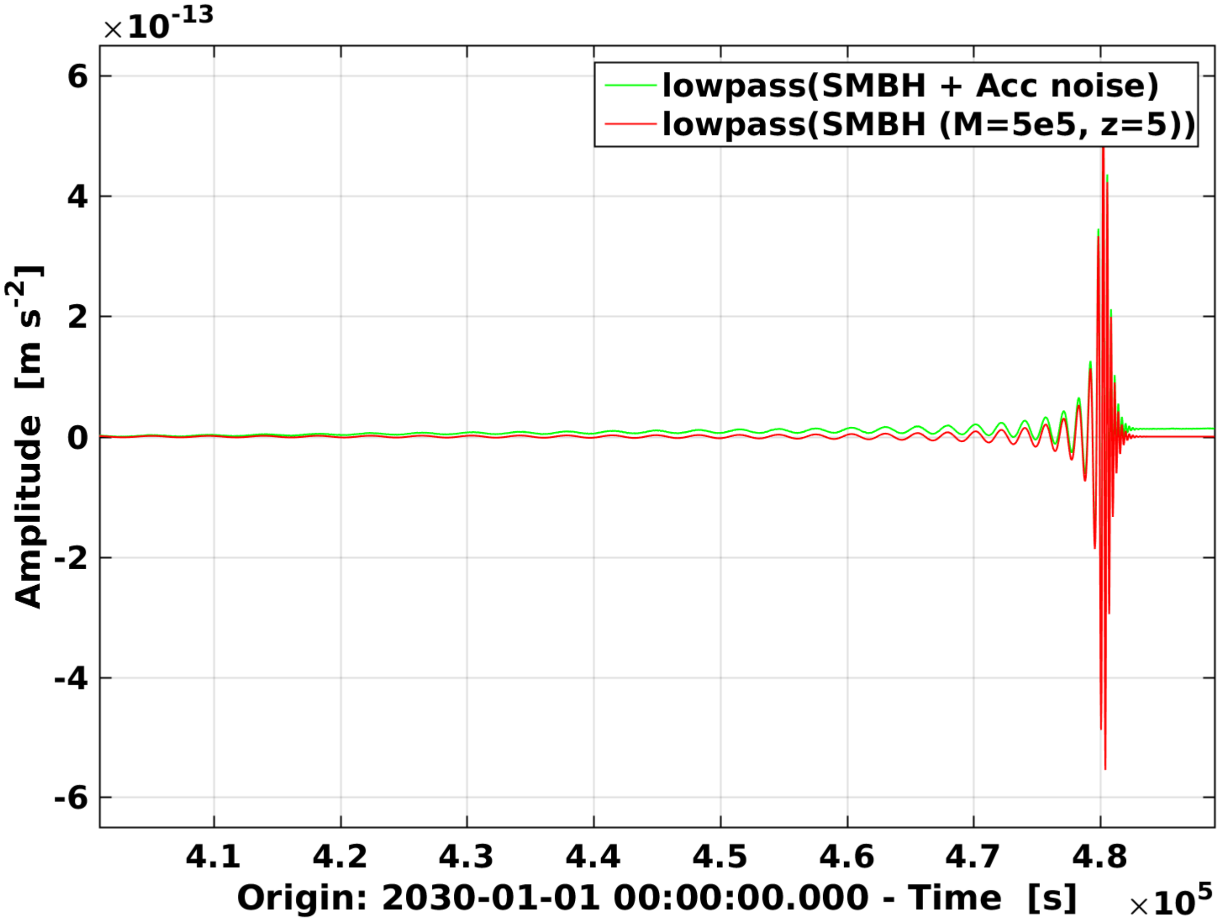
What is left to prove after LISA Pathfinder: LISA long arm interferometry and signal-dominated data

SMBH waveform from Antoine Petiteau



- 2 10^5 solar mass black holes at z = 5
  - at nominal LISA sensitivity, SNR 1000
  - SNR=1 at 1 month before merger (70 μHz – 3 mHz)

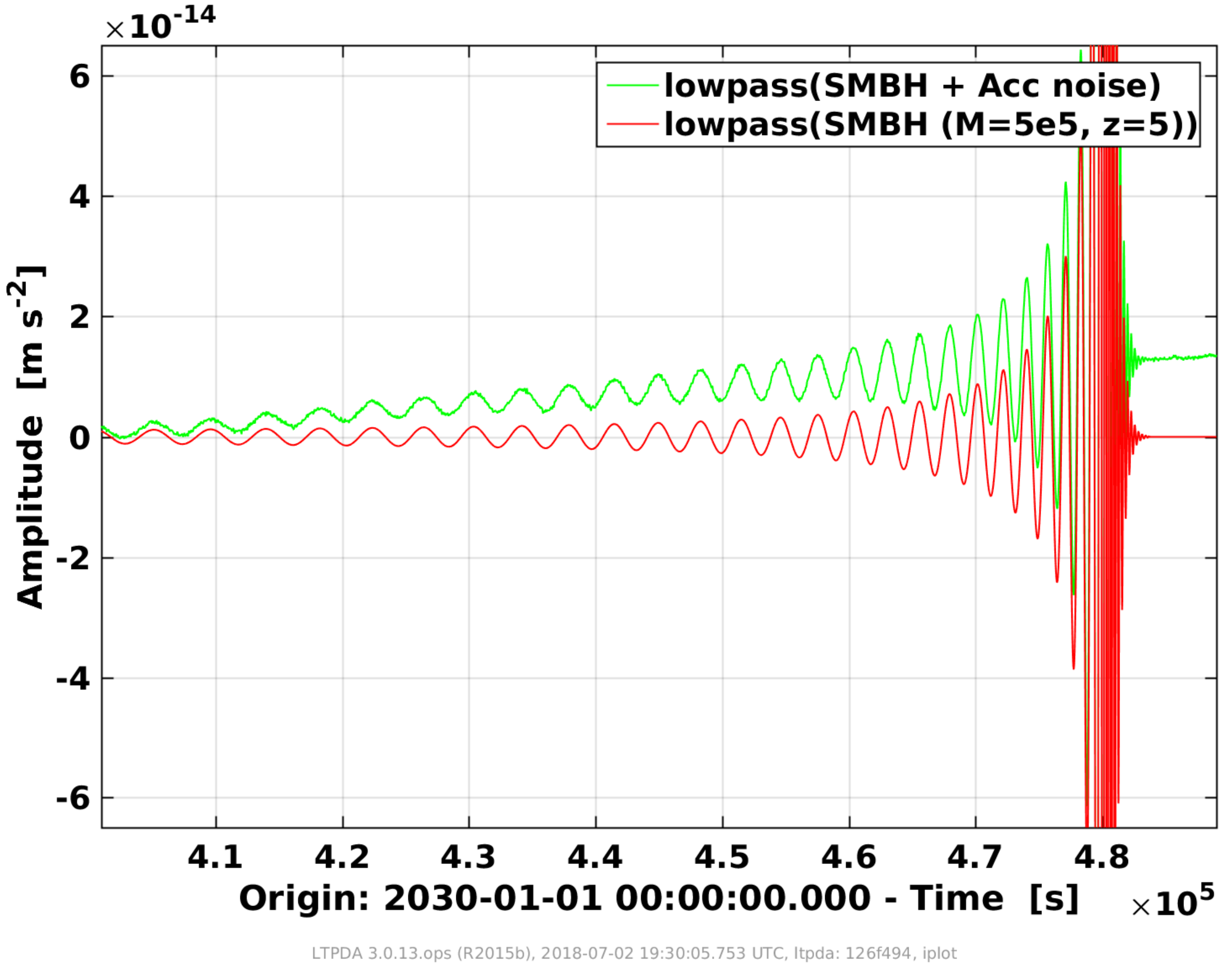
LISA: high SNR super massive black hole merger observatory



LTPDA 3.0.13.ops (R2015b), 2018-07-02 19:30:02.876 UTC, ltpda: 126f494, iplot

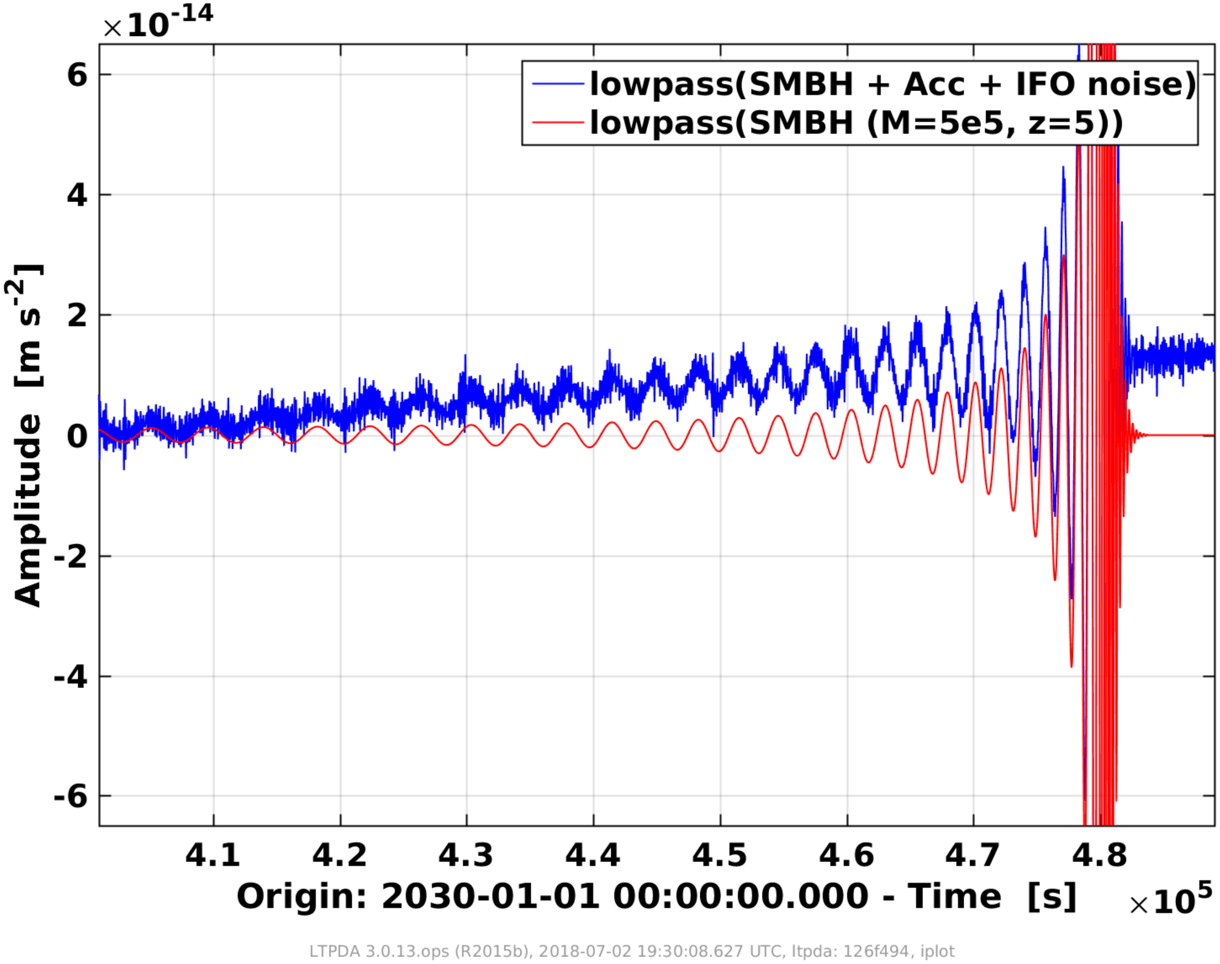
Add in LPF measured acceleration noise – SNR still > 1 every cycle

LISA: high SNR super massive black hole merger observatory



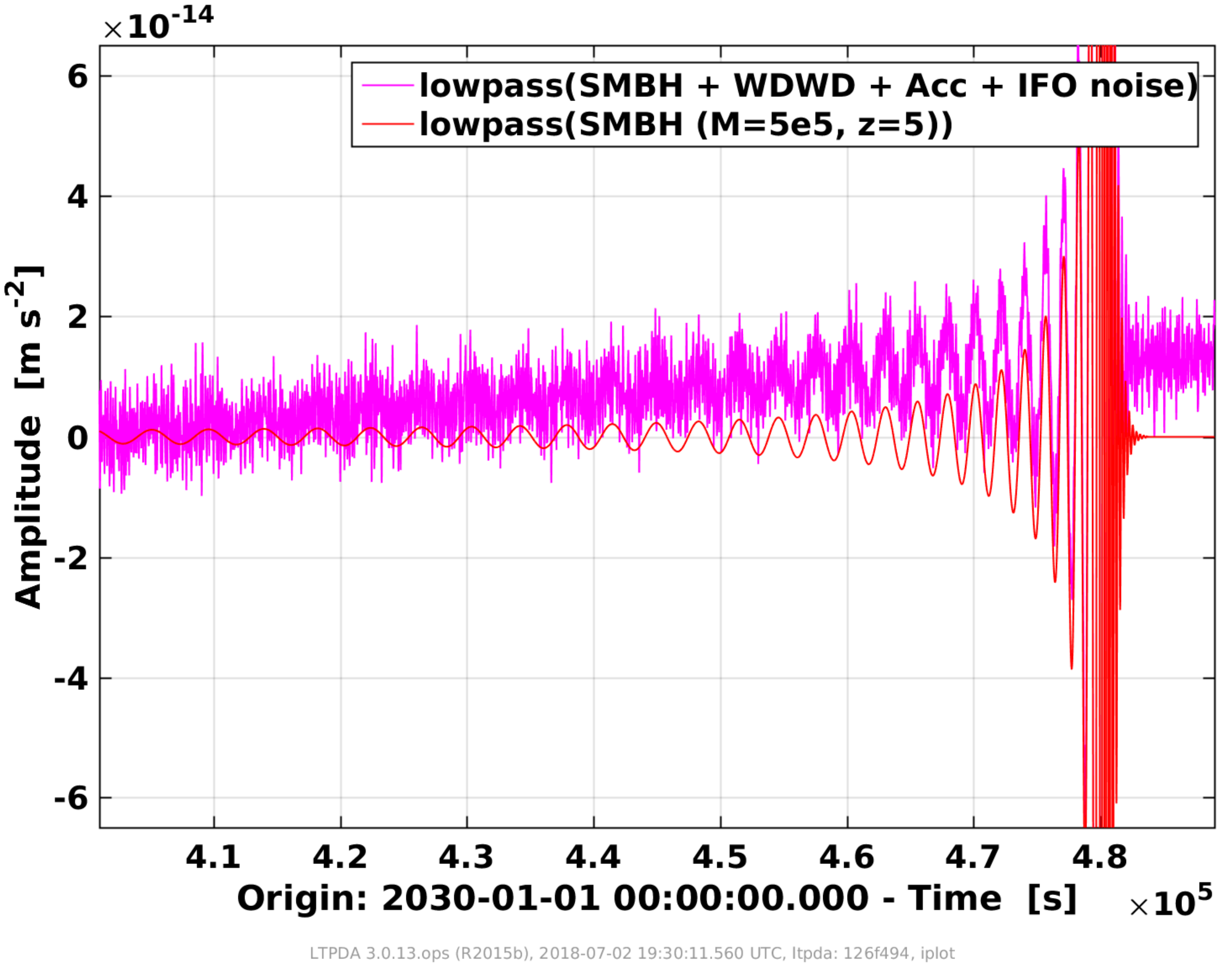
Add in LPF measured acceleration noise – SNR still > 1 every cycle

LISA: high SNR super massive black hole merger observatory



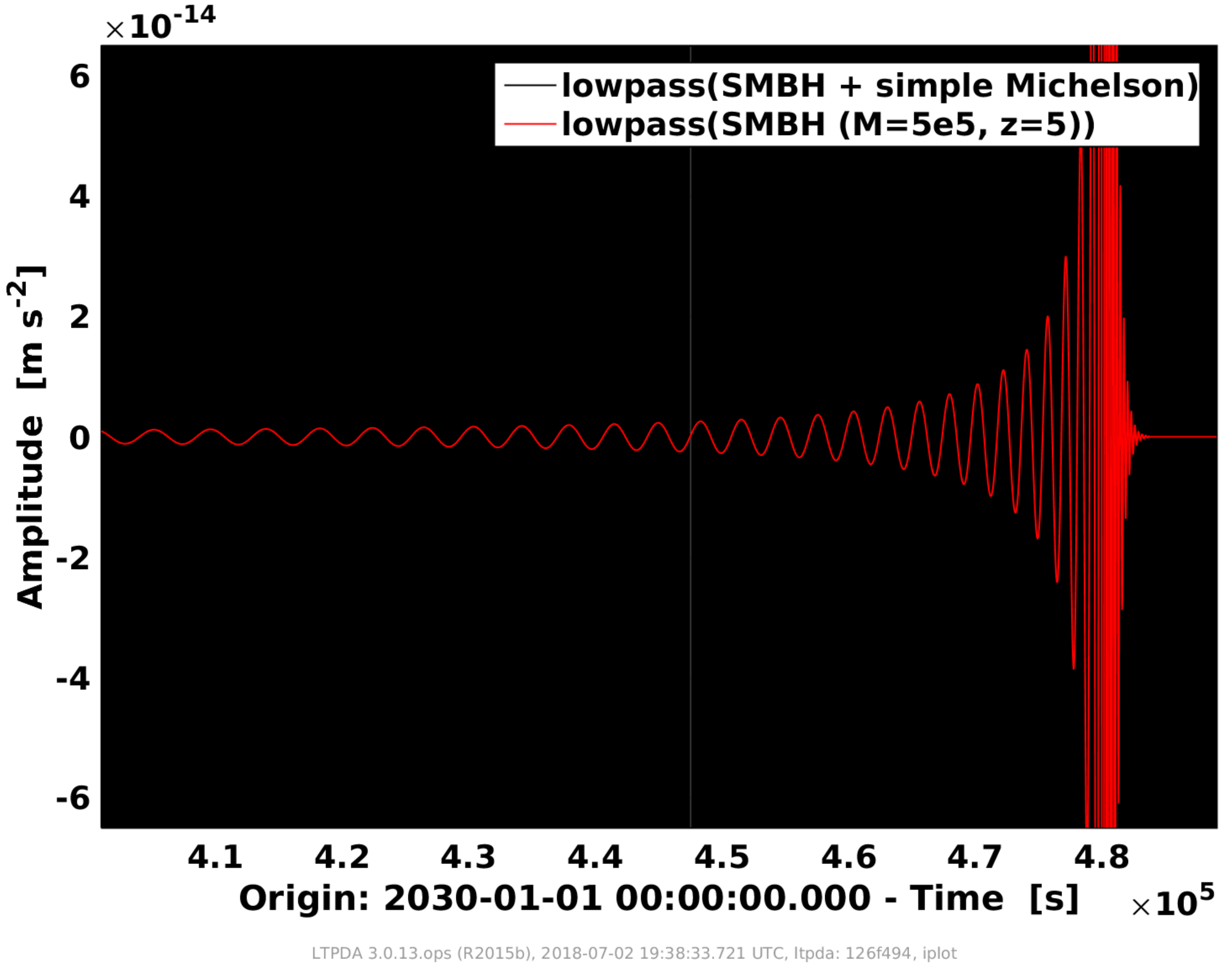
Add in LISA long arm IFO noise («photon starved» at 100 pW)

LISA: high SNR super massive black hole merger observatory



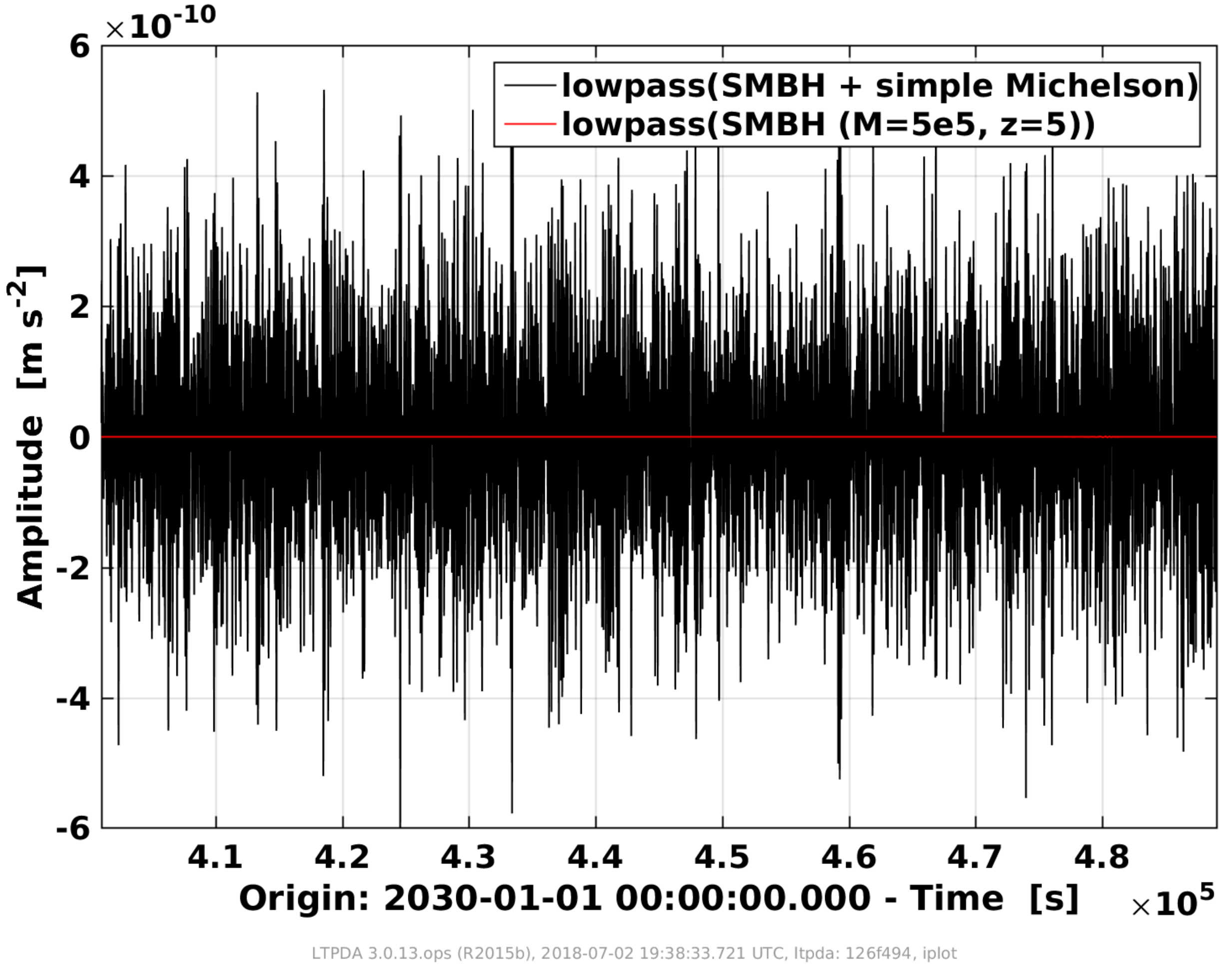
Add in «Galactic foreground» of 30 million white dwarf binaries (0.1 – 10 mHz)

LISA: high SNR super massive black hole merger observatory



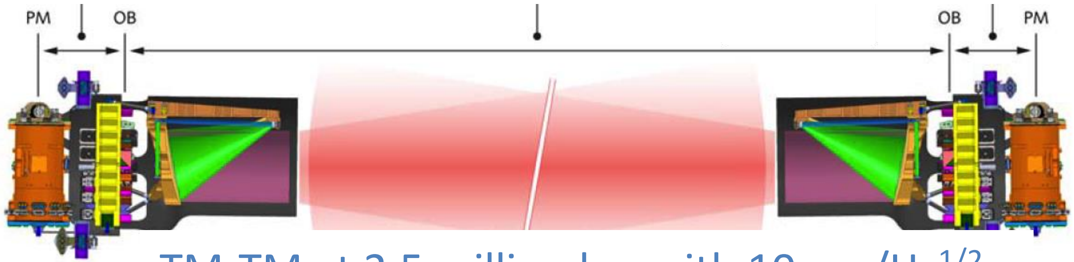
Add laser frequency noise with ΔL = 30000 km in «simple Michelson» combination

LISA: high SNR super massive black hole merger observatory



Simple «Michelson» signal recombination too noisy (10^7)

LISA long interferometer challenge



TM-TM at 2.5 million km with 10 pm/Hz$^{1/2}$

Beam divergence over 2.5 10^9 m:

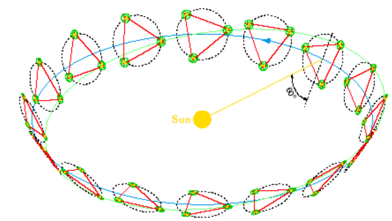
→2 W from 30 cm telescope

→100 pW received power

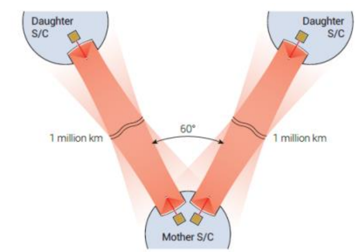
weak light phase-lock transponder

LISA constellation «quasi-rigid, quasi equilateral» rotating configuration

Keplerian dynamics and secular Earth pull produce «breathing»

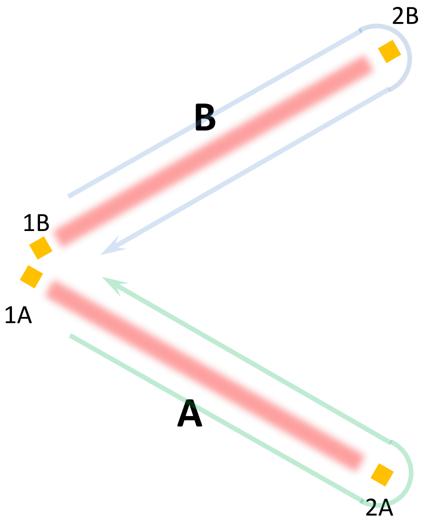


- $\Delta\phi$ ~ 1 ° → telescope angle must breathe
- ΔL ~ 30000 km → unequal arm interferometer
- Δv ~ 10 m/s → Doppler shifts 10 MHz (fringe rates)



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

GW observation as time-delayed Doppler gravity gradiometer:
Michelson combination without TDI – resulting strain noise



$$g$$

TM acceleration noise

$$\frac{\dot{\nu}_n}{\nu} \approx \frac{\omega^2 \, \delta x_{IFO}}{c}$$

IFO readout (shot noise) converted into displacement noise δx_{IFO}

$$\frac{\Delta \nu_L}{\nu}$$

Laser relative frequency noise

Budget 10 pm/Hz$^{1/2}$

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

$S^{1/2}_{\delta\nu/\nu} \approx 10^{-13}$ /Hz$^{1/2}$
(30 Hz/Hz$^{1/2}$)

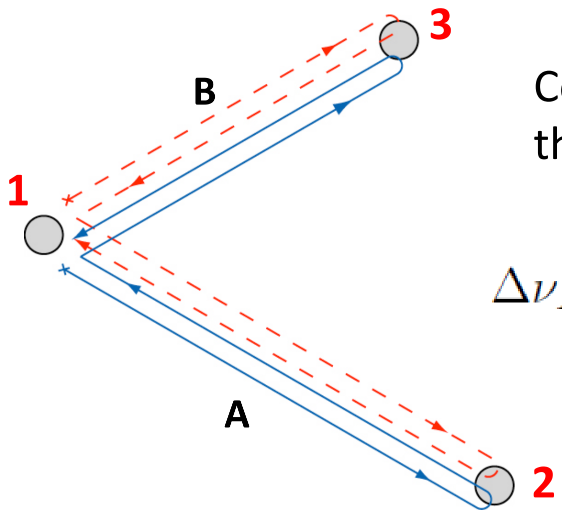
$\Delta L \approx 20000$ km

2 µm/Hz$^{1/2}$ → 6 orders of magnitude too big!

- **would require ΔL of 2 m (not 20000 km)**

GW observation as time-delayed Doppler gravity gradiometer:

Time delay interferometry (TDI):1st generation – fixed unequal arms

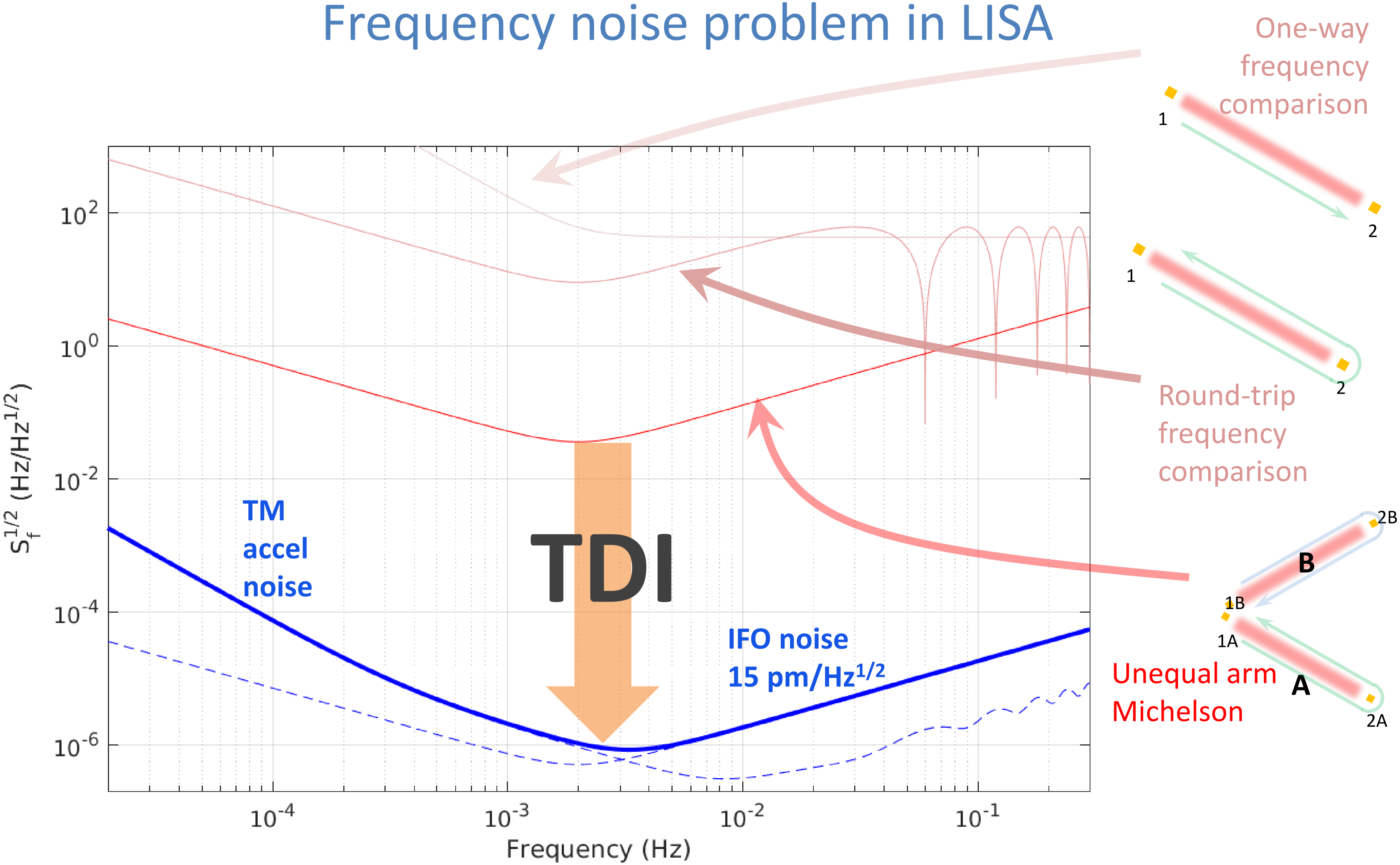


Combine phase measurements retarded in time in such a way that laser frequency noise is killed

$$\Delta\nu_X \equiv \underbrace{\Delta\nu_A(t) - \Delta\nu_B(t)}_{\text{Simple Michelson}} + \underbrace{\Delta\nu_B(t-2T_A) - \Delta\nu_A(t-2T_B)}_{\text{Time-shifted Michelson}}$$

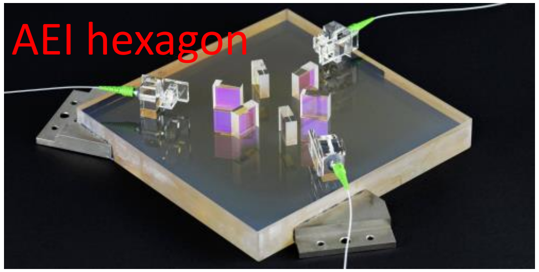
- Both 4-pulse roundtrip optical paths start and end in same «events» at SC1 –
  - laser frequency noise cancels out!
- Need ranging with nanosecond timing to synthesize equal arm – to 1 m – IFO
- More complex combos (8 pulses) cancel effects of rotation, flexing arms (TDI 2.0)

Frequency noise problem in LISA

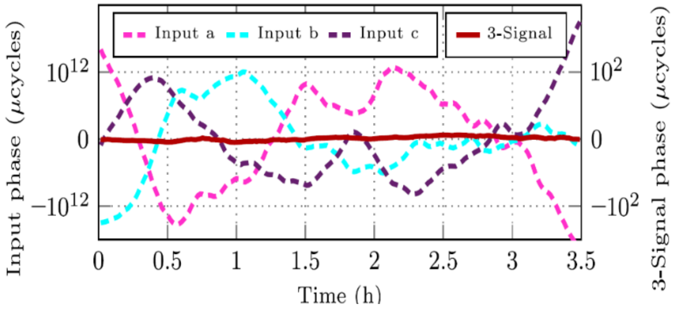


Experimental steps towards LISA interferometry

LISA GW resolution (5 mHz): $0.3\ \mu Hz/Hz^{1/2}$
Laser noise: $30\ Hz/Hz^{1/2}$
Orbital Doppler shifts: 10 MHz



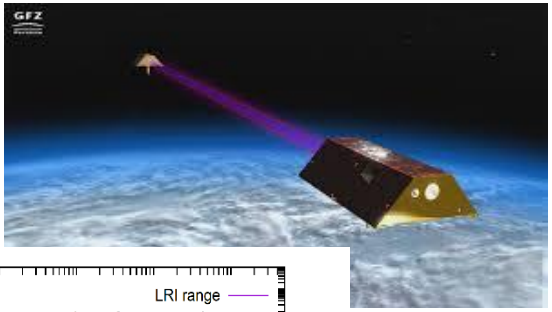
Schwarze+
PRL 2019

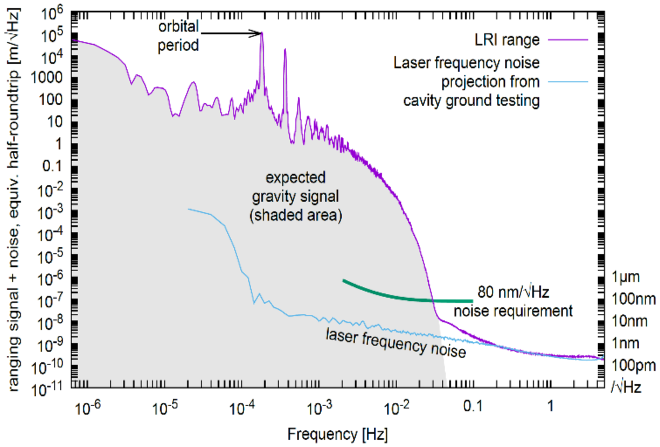


Demonstrated needed 10^{11} dynamic range phasemeter

GRACE geodesy:
Laser Ranging Interferometer

Talk:
S. Francis

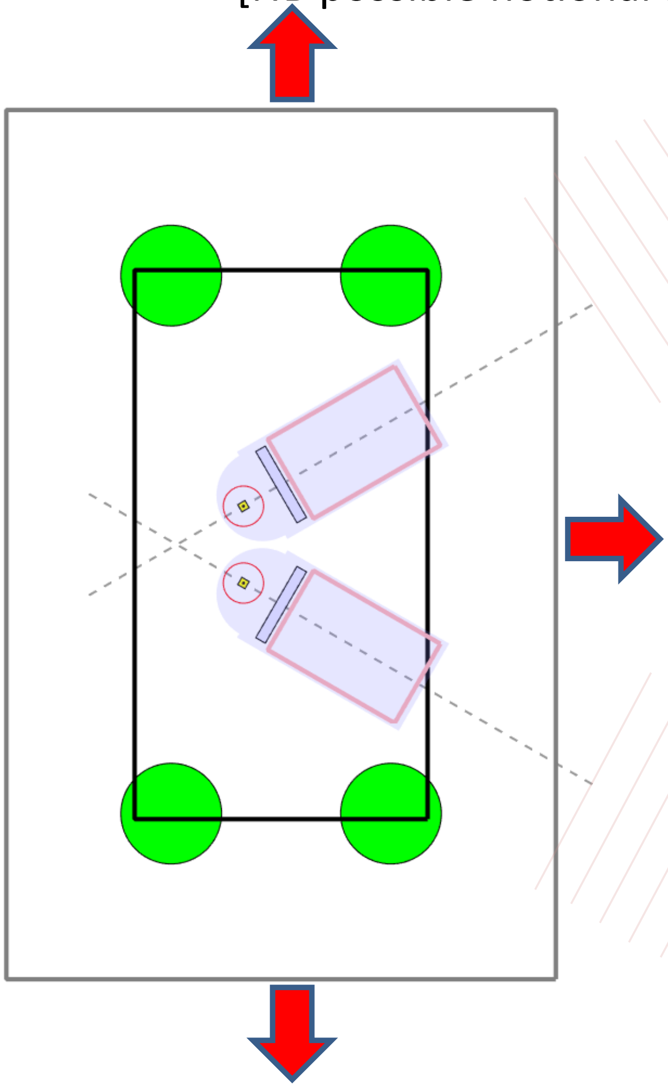




Inter-spacecraft laser interferometry at $200\ pm/Hz^{1/2}$ level

Possible needed corrections to LISA phasemeter data: SC motion

[NB possible notional SC design, similar to ESA CDF configuration]



Spacecraft translational motion

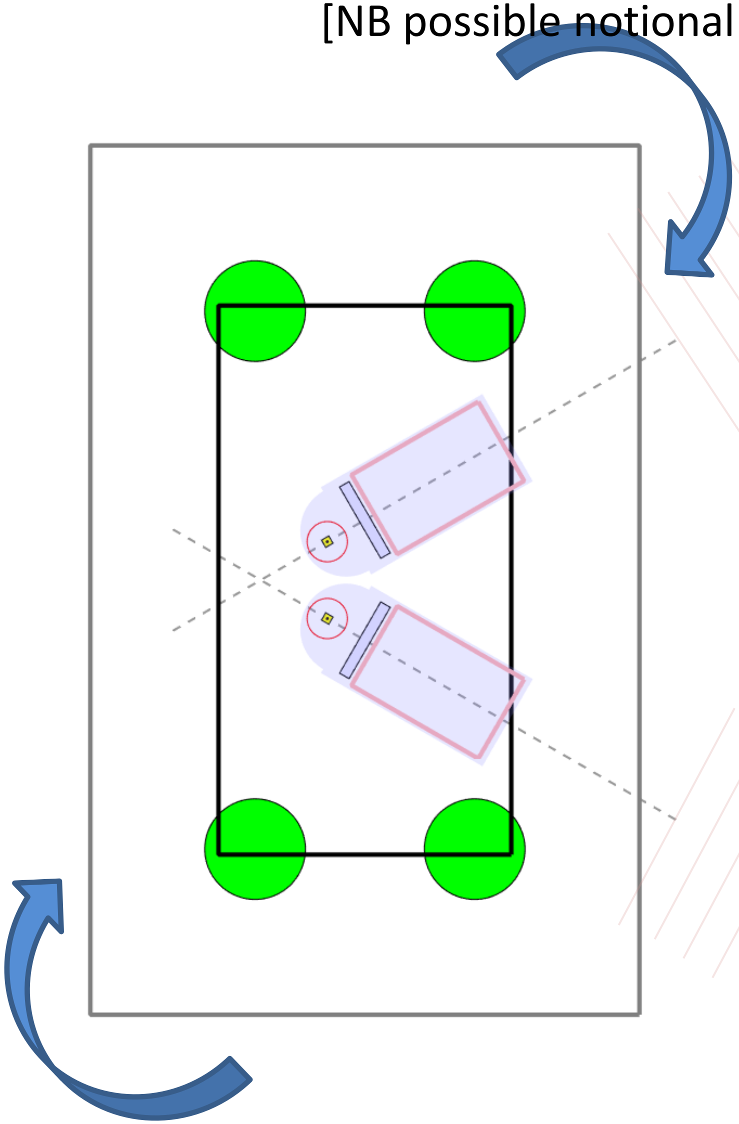
- order nm/Hz$^{1/2}$ at «high» frequency

- **common mode rejection» of SC motion required at factor 1000 level**
- **elastic «stiffness» coupling TM to SC**
  - **both «low enough» in current noise budget, may require subtraction**

- \+ optical cross-talk of motion on orthogonal axes (tilted TM)

Possible needed corrections to LISA phasemeter data: SC motion

[NB possible notional SC design, similar to ESA CDF configuration]



Spacecraft rotational motion

- order 5-10 nrad/Hz$^{1/2}$ at «high frequency»

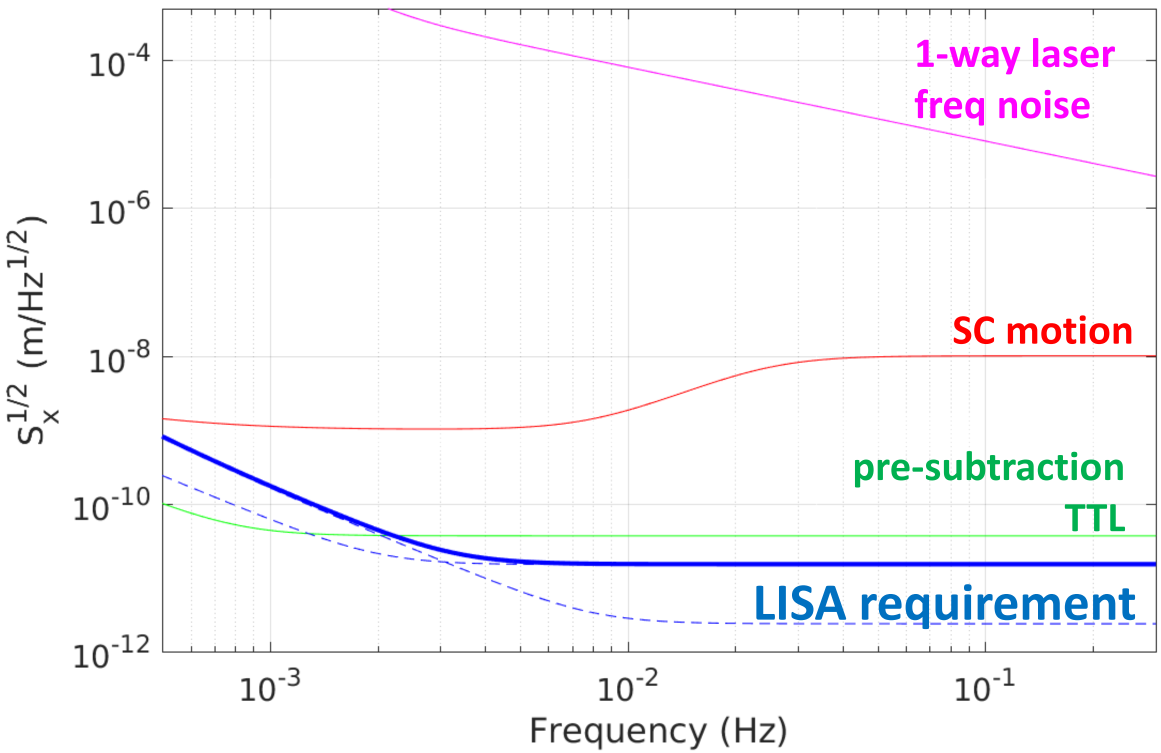
- **«tilt to length» coupling from misaligned long-IFO to TM-IFO (Rx and Tx)**

$$\delta x \approx R \, \delta\varphi$$

  - **Requires 20x subtraction in current budget**
  - **Calibration and software subtraction**

- noisy rotation of static (self-gravity) forces, elastic couplings, actuation cross-talk

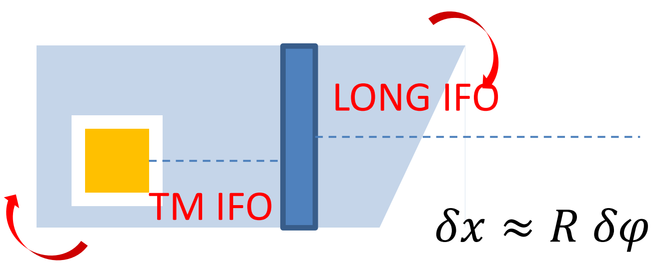
TTL mitigation and other «common mode rejections» in LISA



10^7 suppression with TDI

10^3 common mode rejection local/long IFO

Factor 10 subtraction based on in-flight calibration

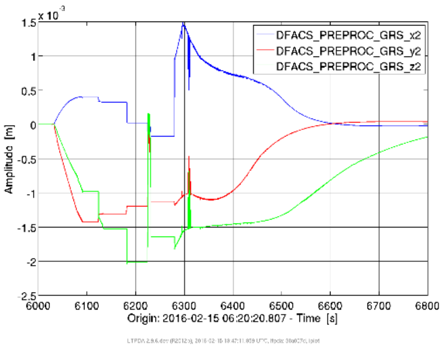


$\delta x \approx R\ \delta\varphi$

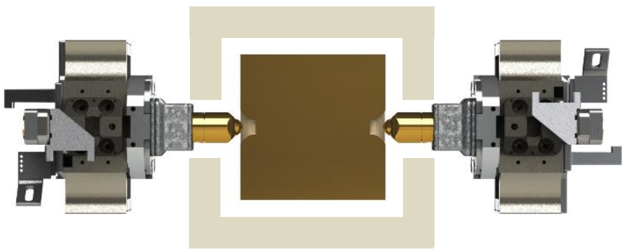
Selected «little engineering details» en route to LISA science

Test mass release

- μN electrostatic forces – need *v* < 15 μm/s (otherwise it bumps...)

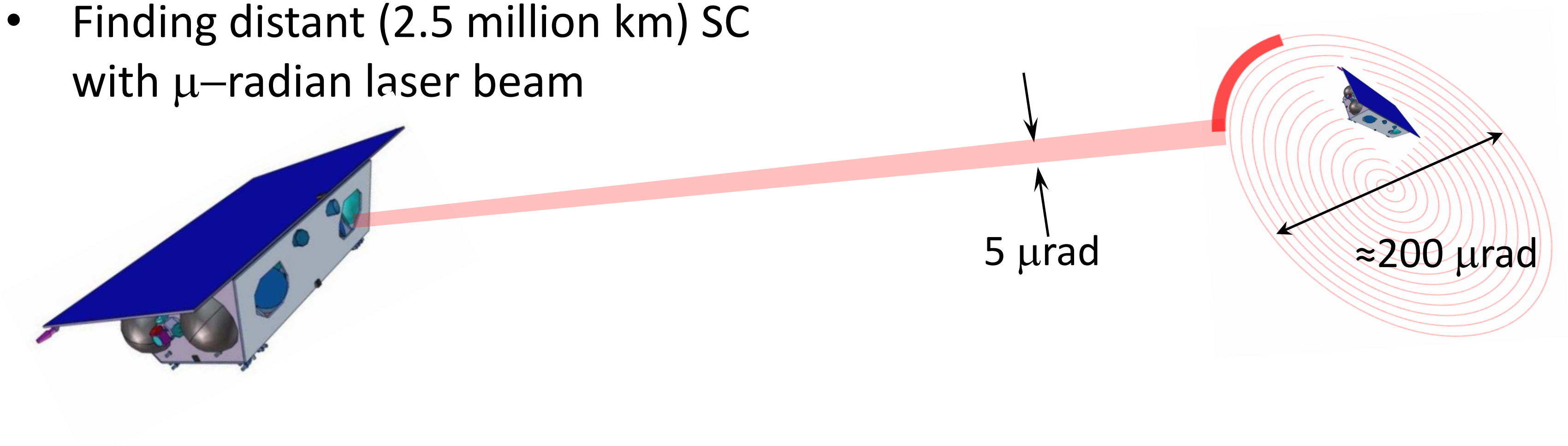


LPF first release ... 30 μm/s
Much better in later tests!



Constellation acquisition

- Finding distant (2.5 million km) SC with μ–radian laser beam

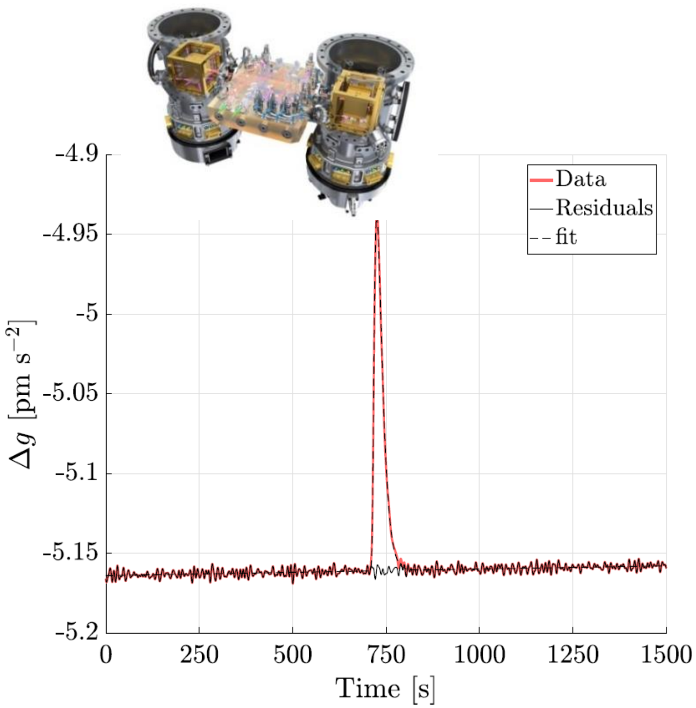


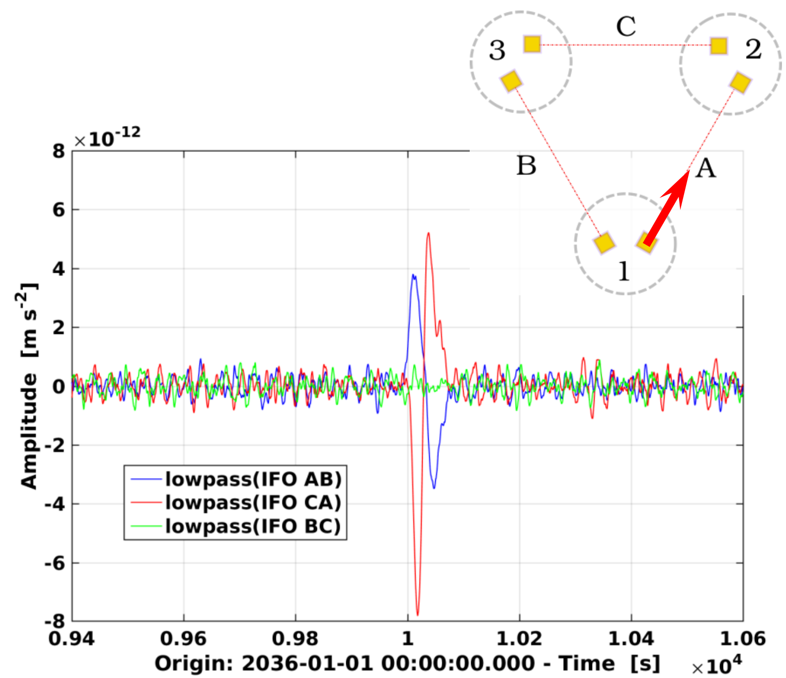
Instrumentalist challenge during LISA operations

Did we just see a new source? Or did something move on the spacecraft?

Impulse «glitches» observed on LISA Pathfinder

- Remove (with fit) ... at cost of being blind to «impulse» gravitational wave signals
    - Can we understand the source and eliminate these?
    - Can we discriminate at instrument level?
    - Or with TDI (Sagnac variable)?





Thank you!

Thanks to the LISA Consortium (https://www.lisamission.org/)