The LISA orbiting observatory for low frequency gravitational waves: scientific potential and progress towards launch

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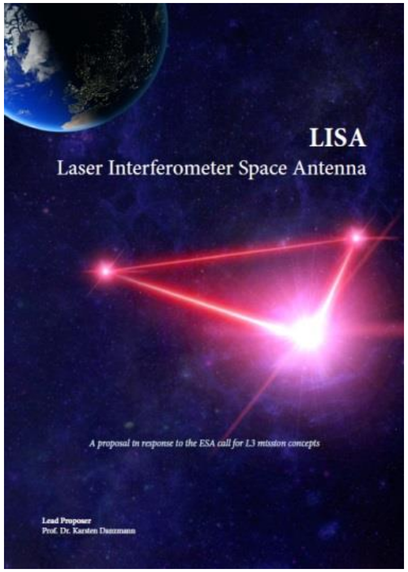
PUMA22 Conference, Sestri Levante
29 September 2022



LISA:Laser Interferometer Space Antenna

- ESA L3 «large mission», launch 2035
  - working for mission adoption 2023
- Gravitational wave observation 100 μHz – 1 Hz
  - studied down to 20 μHz
- 4 year science data nominal mission
  - orbits and fuel for extension to 10 years

Talk outline:

- LISA observatory: measurement concept and science potential
- Main science targets, multimessenger possibilities
- Main experimental challenges: hardware and analysis

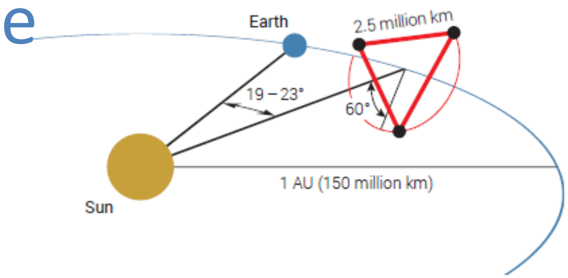
Read about LISA astrophysics!

Astrophysics with the Laser Interferometer Space Antenna

arXiv:2203.06016v1 [gr-qc] 11 Mar 2022

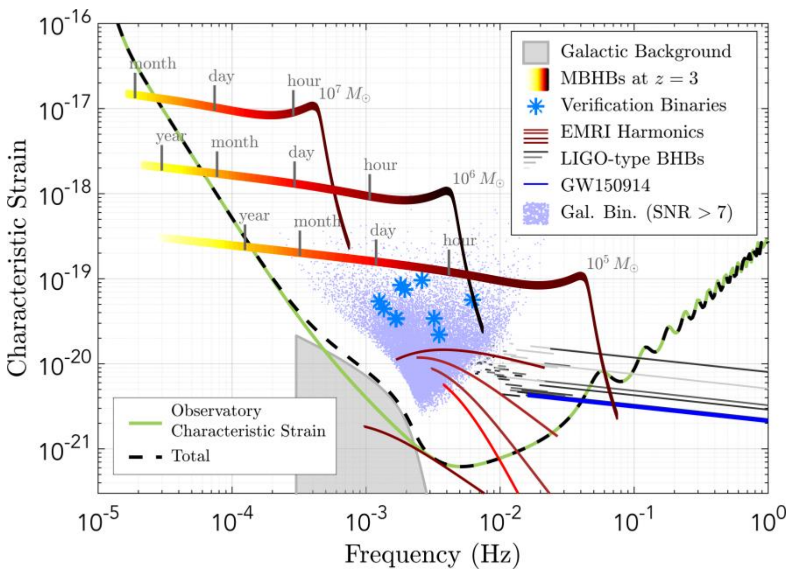
LISA: Laser Interferometer Space Antenna

Measurement science



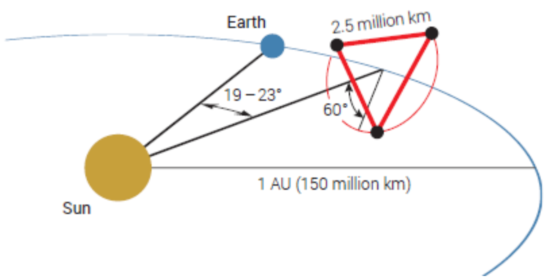
antenna: **constellation of free-falling test masses**
receiver: **laser interferometry**

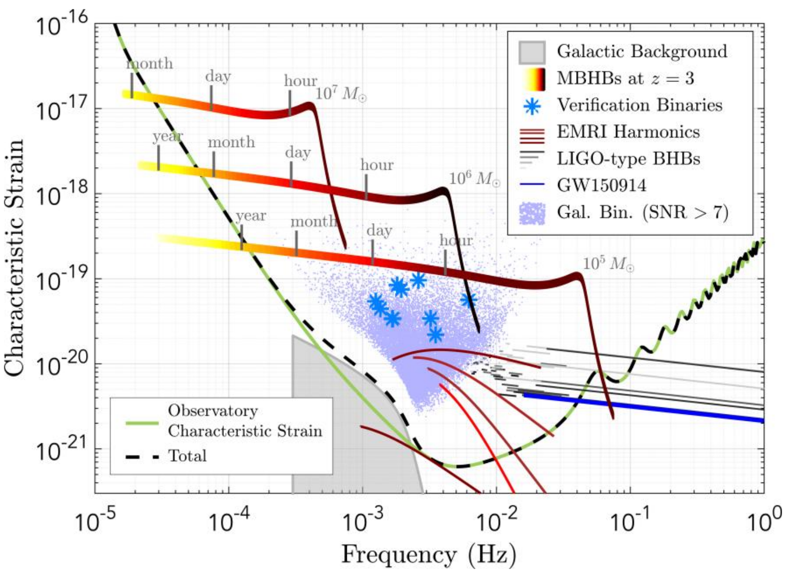
LF limit: spurious antenna tidal deformation (stray forces)
HF limit: interferometer fluctuations (shot noise etal)



- 3 arms (6 one-way links), L = 2.5 million km
- free-falling TM, no suspension
  - orbital tidal accelerations $\mu m/s^2$, 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)
  - **time delay interferometry (TDI)**
- weak light (100 pW)
  - 1-arm light «transponders»
  - no light reflection or 2-arm light combination

LISA: Laser Interferometer Space Antenna
Observatory science potential





no images and no pointing
- source system orbital dynamics encoded in GW strain
- 2 polarizations + “null channel”

deep sky and high resolution
- black hole mergers up to z=10-15, SNR to > 10^3

coalescing systems from <1 to >10^6 $M_\odot$
- galactic WD-WD binaries to high-z super massive BH
- high resolution (<1%) parameters: mass, distance, spin

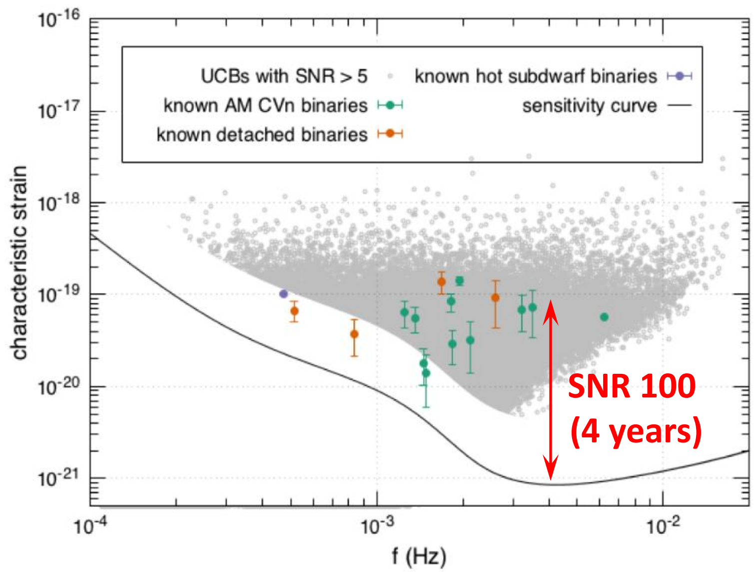
sky position resolution arcminute to degrees
- depending on source and frequency

full sky, high duty cycle
- 4 years science data in 5 years on-orbit

“permanent” and transient sources
- growing catalog and event alerts
- daily cadence data

signals always ON, overlapping, “signal dominated”

LISA galactic «Ultra Compact Binaries» survey



as of 2021, > 20 known LISA «verification binaries» with SNR > 8 in 4 years

- found optically as eclipsing binaries, distances with GAIA

[Kupfer etal MNRAS 480:302 2018, Littenberg etal 2019 White Paper]

Survey with > 10000 resolvable galactic binary signals

- Includes ***all*** galactic UCB with f > 10 mHz
- Resolvable in first weeks of mission, some to within 1° on sky
  - we have not yet found the brightest sources (SNR> 100)
- Many chirping – **Δf/f > 1 ppm over 4 year mission** – above 1 mHz, some non-GR
  - ***df/dt***, ***f*** → precision measurements of masses (populations)

Expect «confusion» limit of millions of unresolved binaries (0.5 – 3 mHz)

$$\Delta f \approx \frac{1}{4\ \text{year}} \approx 10\ \text{nHz}$$

→ 10^6 "frequency bins" below 10 mHz

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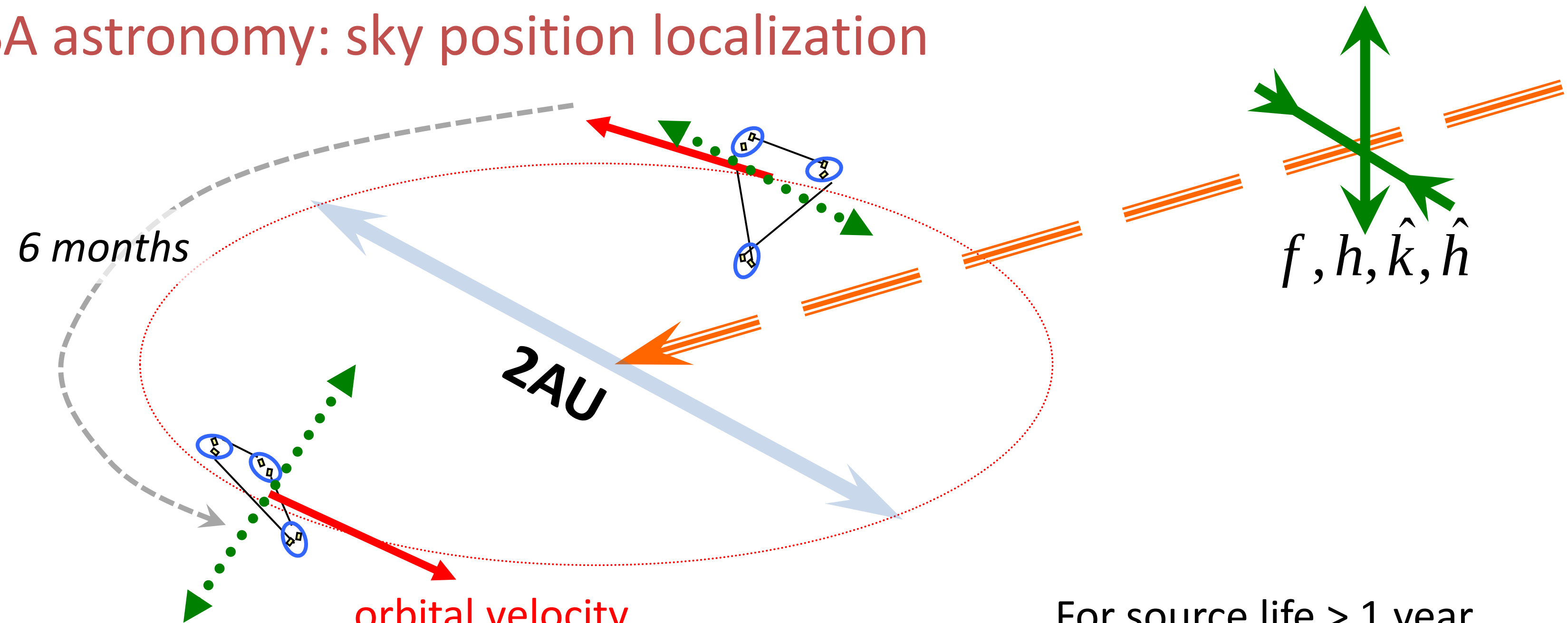
LISA astronomy: sky position localization



orbital velocity
($v/c \sim 10^{-4}$)

For source life > 1 year,
LISA diffraction limit

- sensitivity lobes of antenna pattern sweep through sky

$$\Delta f \sim \pm \frac{2}{T} \quad (T = 1 \text{ year})$$

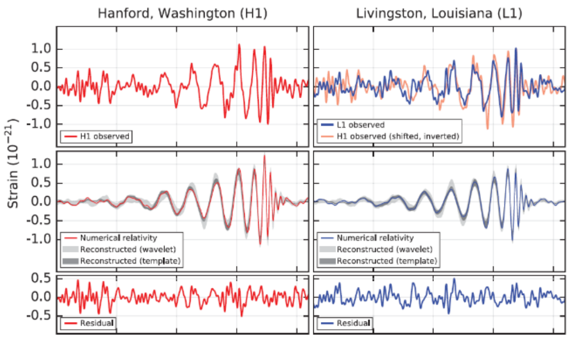
- signals doppler shifted by orbital velocity of observatory

$$\Delta f \sim \pm f_{GW} \frac{v}{c}$$

$$\Delta\theta \approx \left(\frac{\lambda_{GW}}{2\,\text{AU}}\right)\frac{1}{\text{SNR}} \approx \left(\frac{1\,\text{mHz}}{f_{GW}}\right)\frac{1}{\text{SNR}}$$

locate strong galactic binaries to arcmin.
→ EM follow-ups!

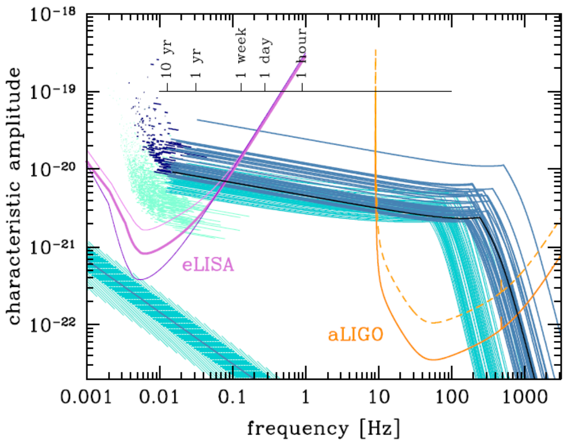
LIGO 30 $M_\odot$ binaries – observed by LISA? (5-15 years pre-merger)



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

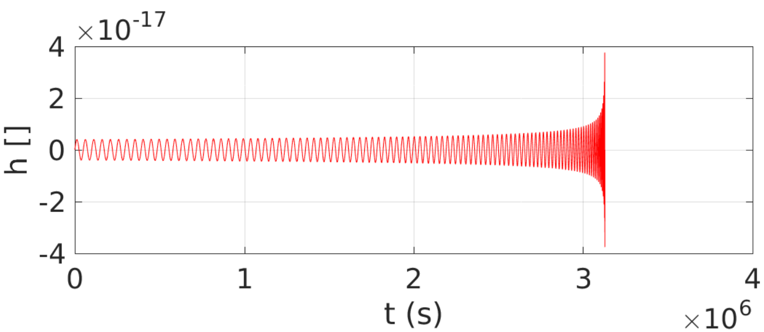
- 5-10 years pre-merger, **10-20 mHz**
- **low SNR (limited by interferometry)**

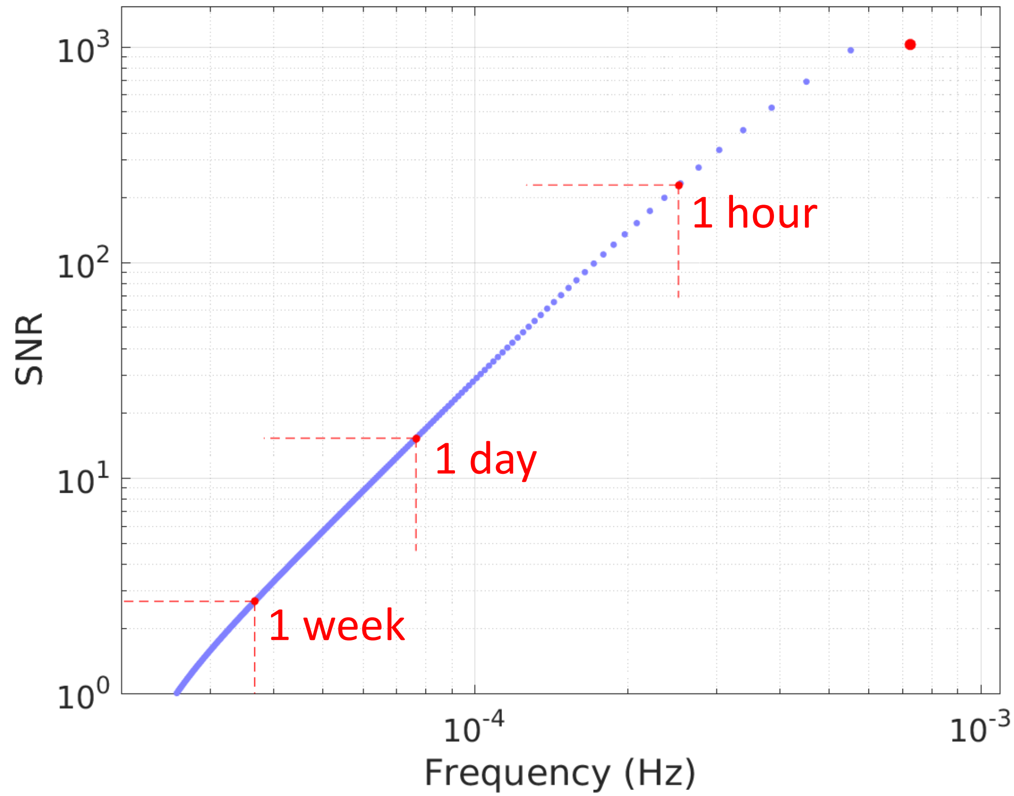
[Sesana, *PRL*, 2016]

- 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

LISA: a high resolution, deep universe, low frequency observatory
Super Massive Black Hole (SMBH) science

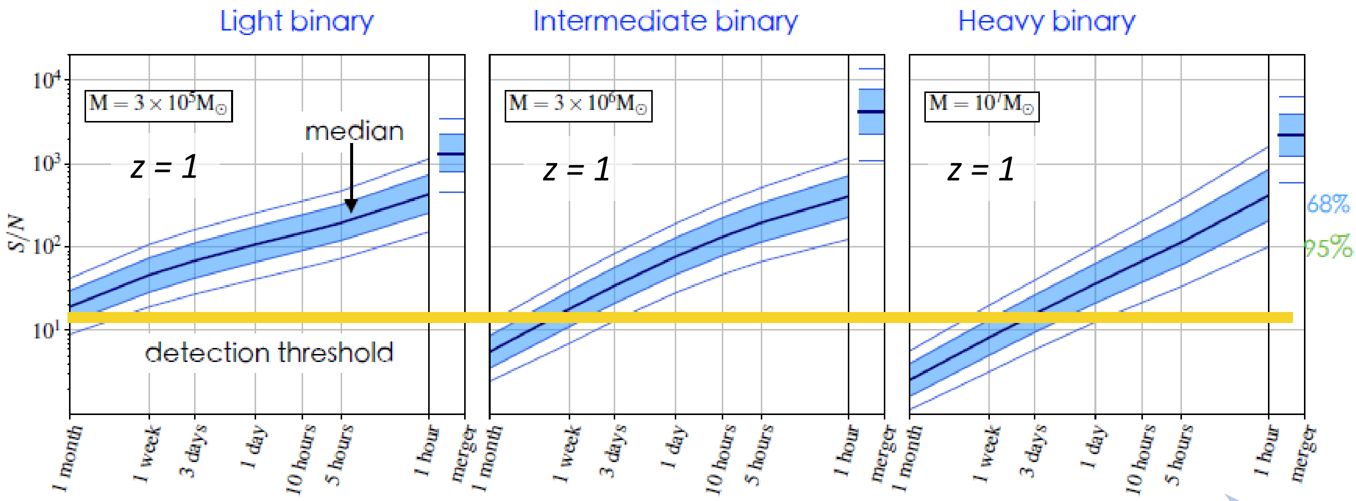
Merger of two 5 10^6 solar mass black holes at z = 2





- 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

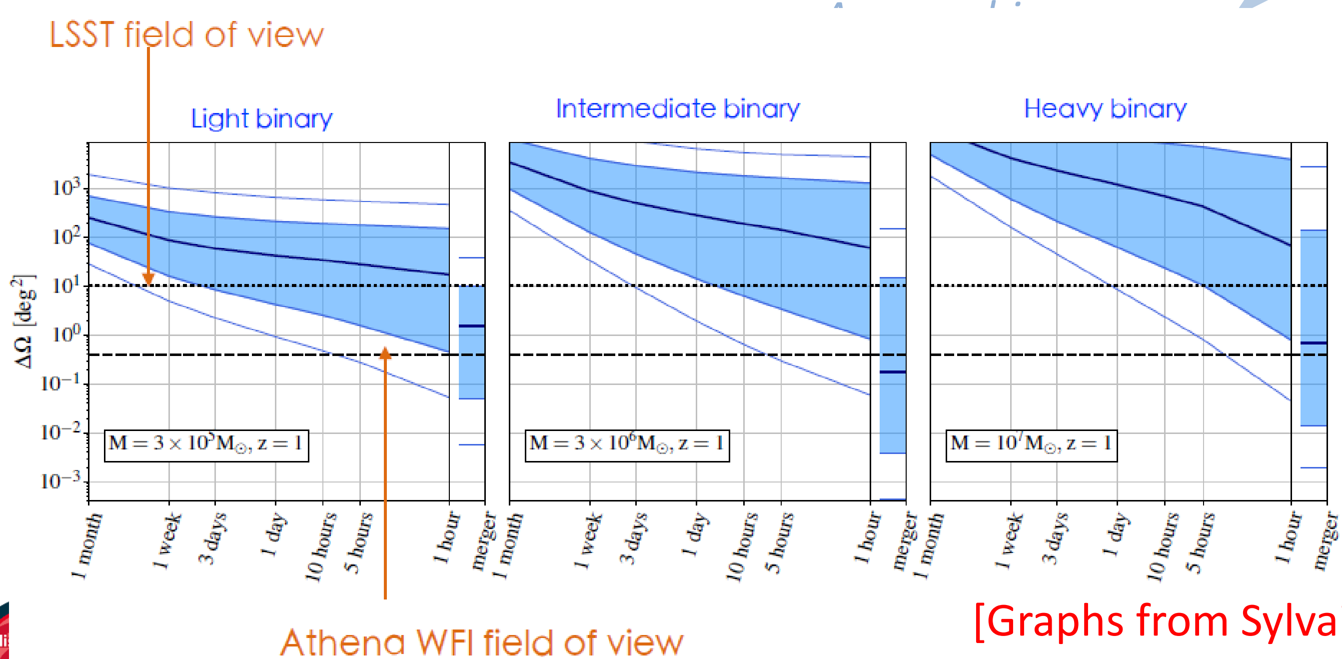
Finding an SMBH as it merges



Weeks of visibility

- "early warning" alerts

most SNR in last hours

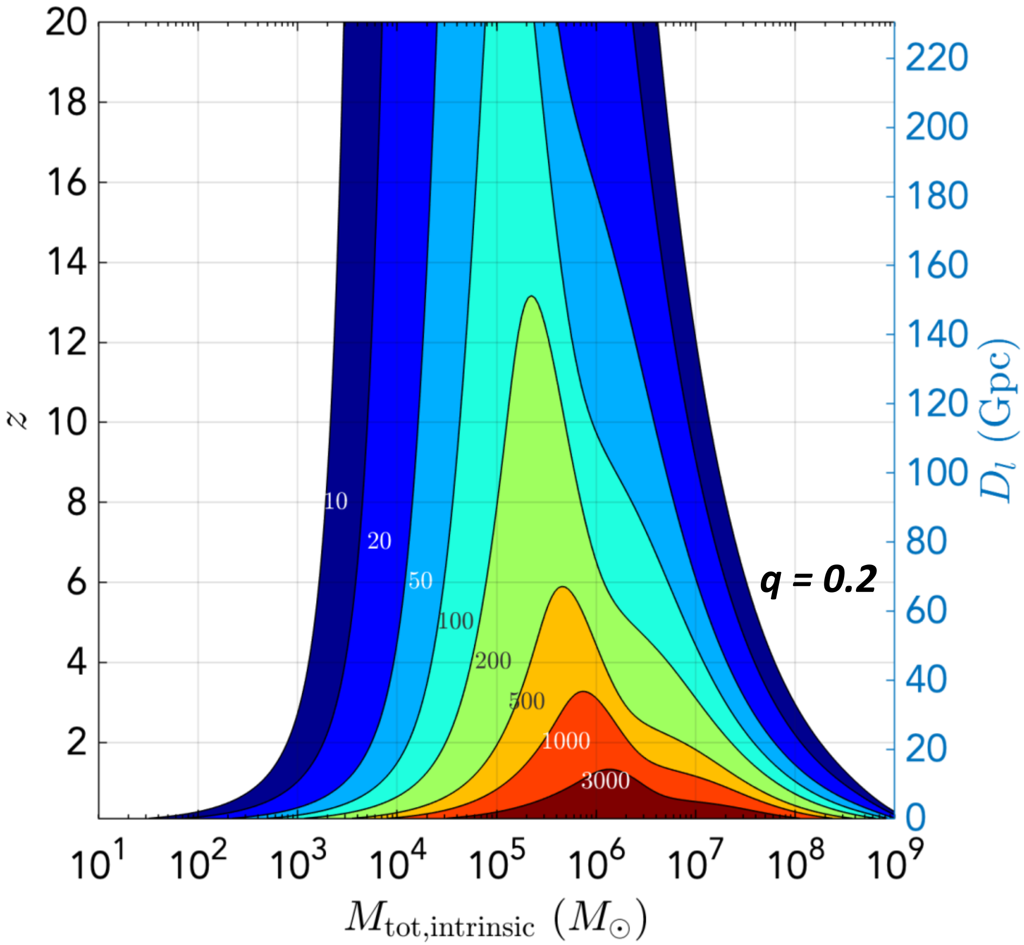


sky location fits LSST FOV in last day / hours

final – "follow up" – sky position often known to <1°

[Graphs from Sylvain Marsat, Monica Colpi]

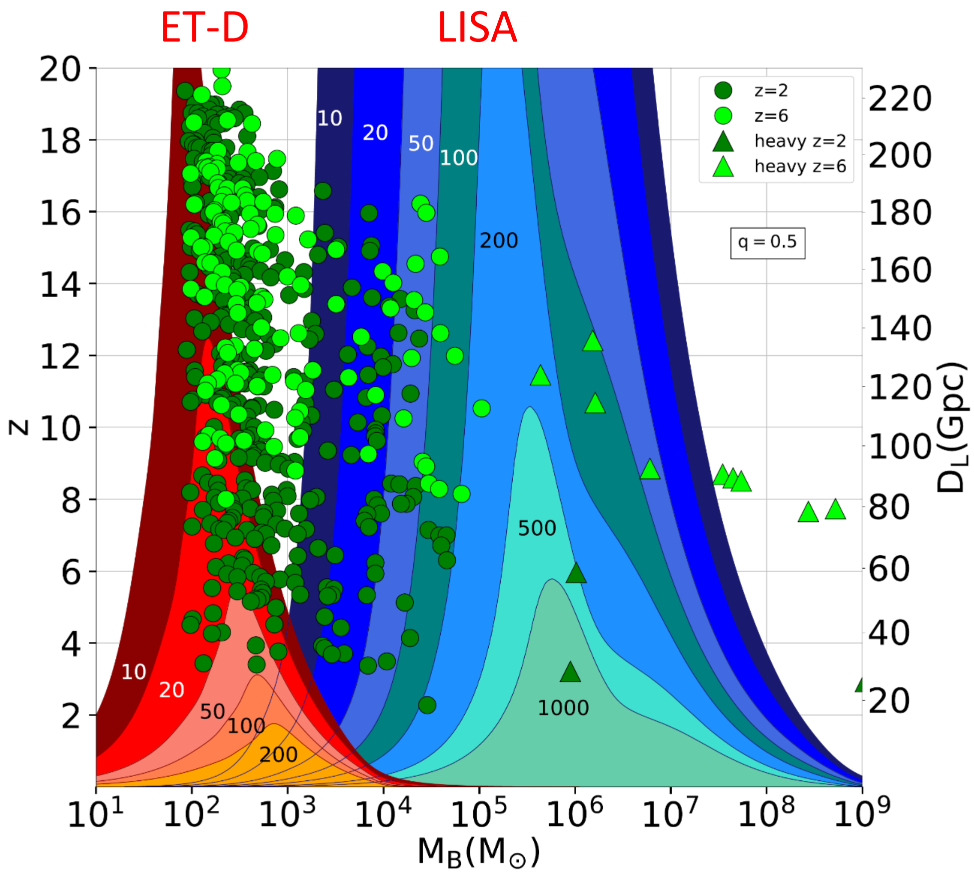
LISA black hole merger reach and resolution



- Covering seeds 10^3-10^4 $M_\odot$ at cosmic dawn (z-15-20) to 10^5-10^7 SMBH at cosmic «high noon» z=2-3
- High resolution (SNR 1000) and sky position below degree (brightest sources)
- High precision mass, luminosity distance, spin
- Visibility days to months to years
- Multi-messenger?

❖ Galaxy formation
❖ Cosmology (standard sirens)
❖ Fundamental physics

LISA black hole merger reach and resolution



[Valiante etal 2020, arxiv 2010.15096]

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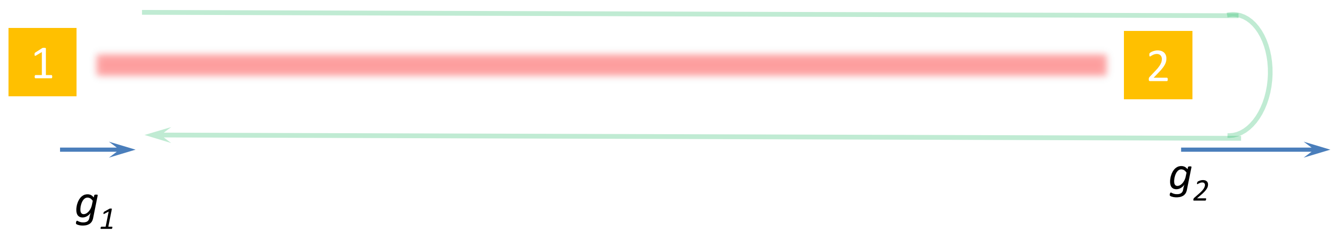
LISA GW observation as a time-delayed Doppler gravity gradiometer

- Exchange of light beam between free-falling observers (light travel time ***T=L/c***)
- O1 emits beam with frequency ν_L
- O2 receives, measures phase and sends back phase-coherent copy
- O1 interferes returning beam with local beam, measures «beat frequency»

$$\Delta \nu \equiv \nu_{1R} - \nu_{1E}$$



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

GW strain signal $\qquad \approx 2(g_1 - g_2) \equiv 2\Delta g$ for $\omega T << 1$

GW tidal force – and differential stray acceleration – measured as time varying Doppler shift

LISA GW observation as a time-delayed Doppler gravity gradiometer

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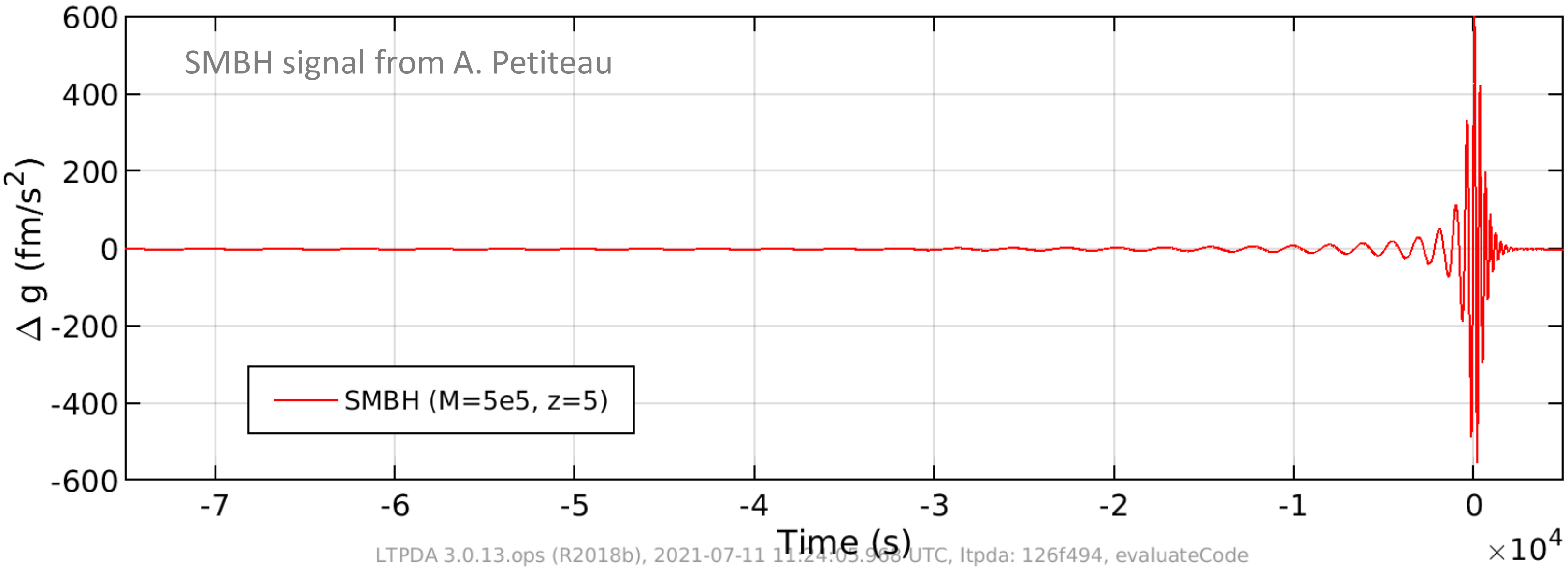
GW strain



tidal acceleration between LISA TM caused by a **5 10⁵ M$_\odot$** merger at ***z = 5*** during last day ...

LISA GW observation as a time-delayed Doppler gravity gradiometer

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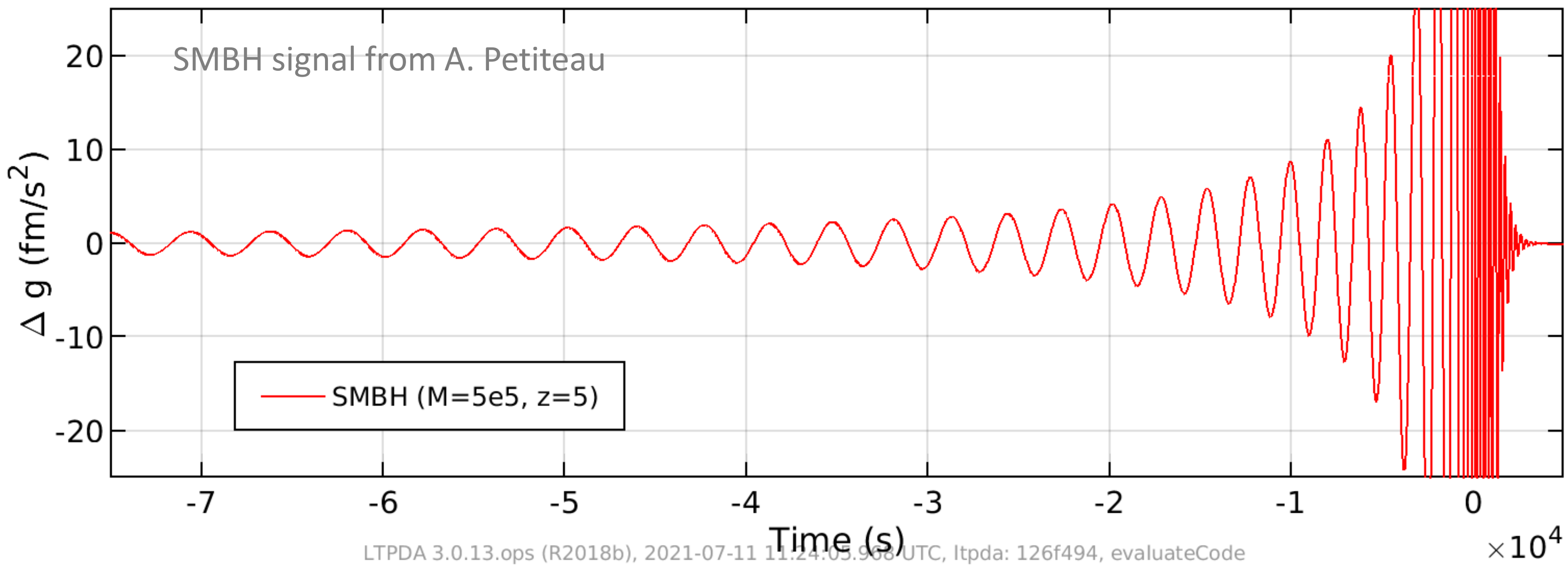
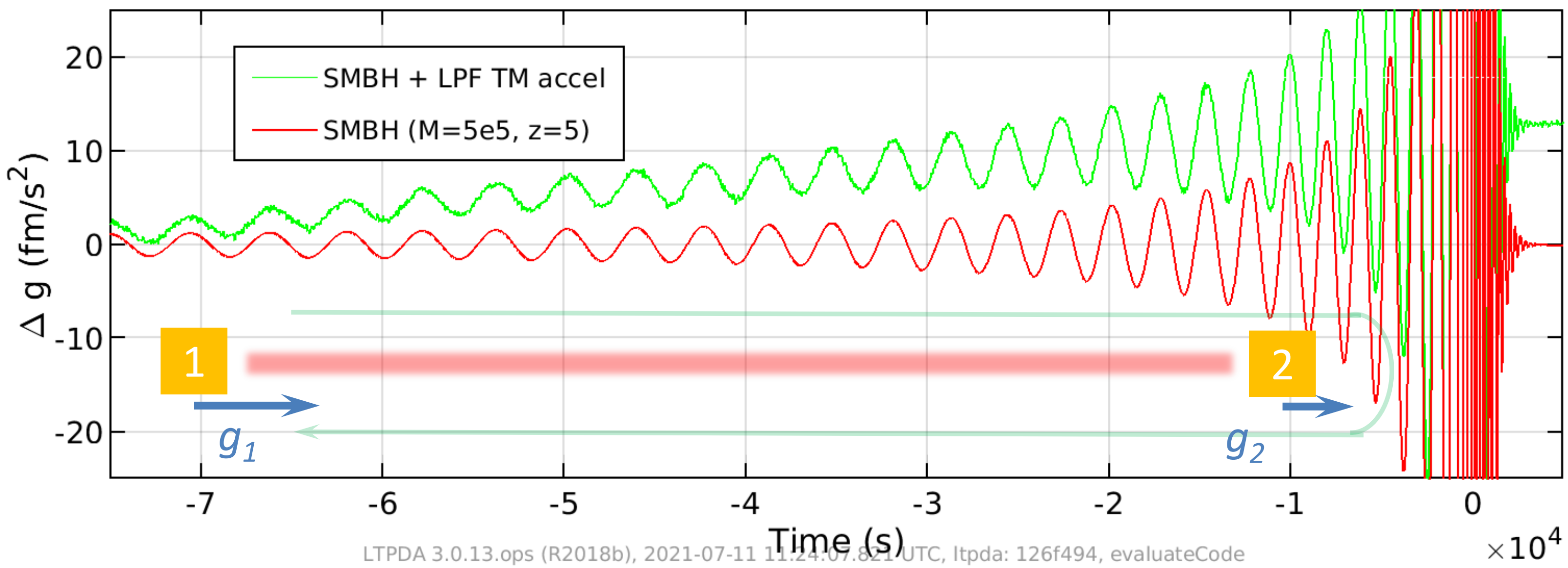
GW strain



tidal acceleration between LISA TM caused by a **5 10⁵ M**$_\odot$ merger at ***z = 5*** during last day ...

LISA GW observation: with spurious forces on test masses

$$\frac{\Delta \dot{\nu}}{\nu_L} = \frac{1}{2}\underbrace{\left[\dot{h}(t) - \dot{h}(t-2T)\right]}_{\text{GW strain}} + \frac{1}{c}\underbrace{\left[g_1(t-2T) + g_1(t) - 2g_2(t-T)\right]}_{\approx 2\Delta g}$$



Same SMBH signal + test mass acceleration noise (measured in LPF)

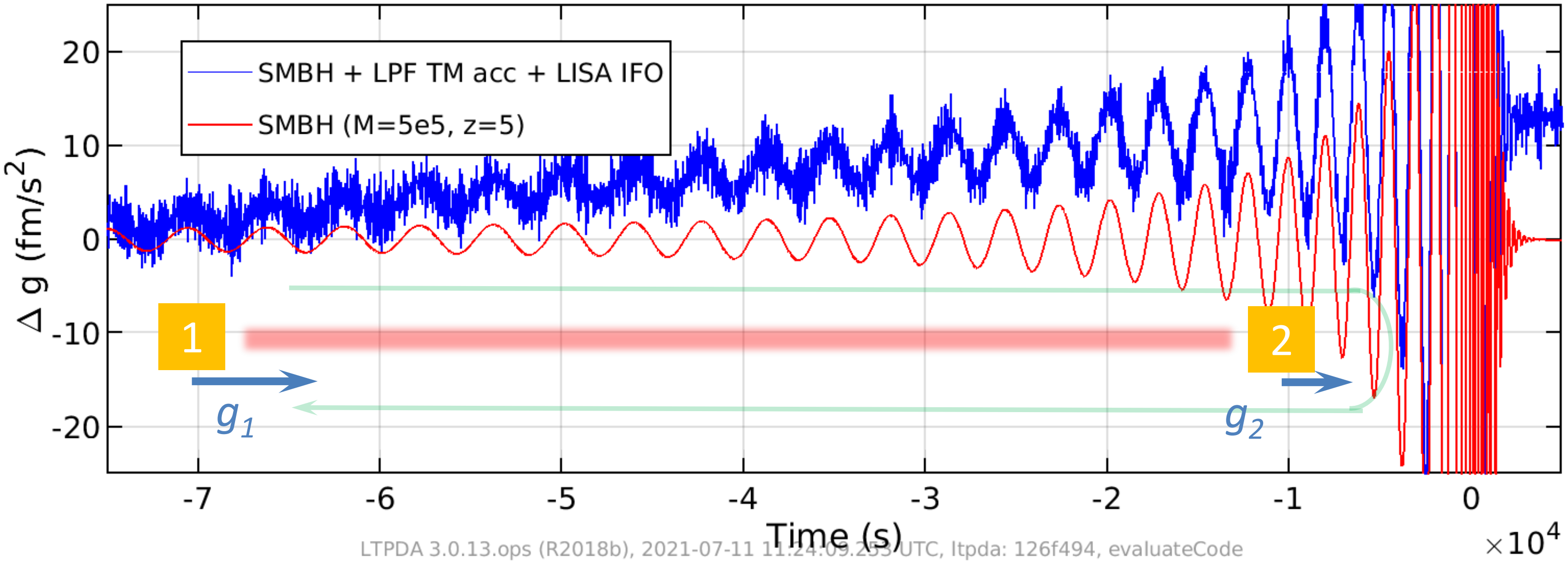
LISA GW observation: including «photon starved» interferometer

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

GW strain

$\approx 2\Delta g$

noise in frequency measurement



+ 15 pm/Hz$^{1/2}$ interferometry noise
- near shot noise limit (500 pW light power)

$$S_h \approx \frac{2}{\left(L\omega^2\right)^2}\left[4S_g + \omega^4 S_{IFO}\right]$$

LISA GW observation: galactic binary confusion limit

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

GW strain

$\approx 2\Delta g$

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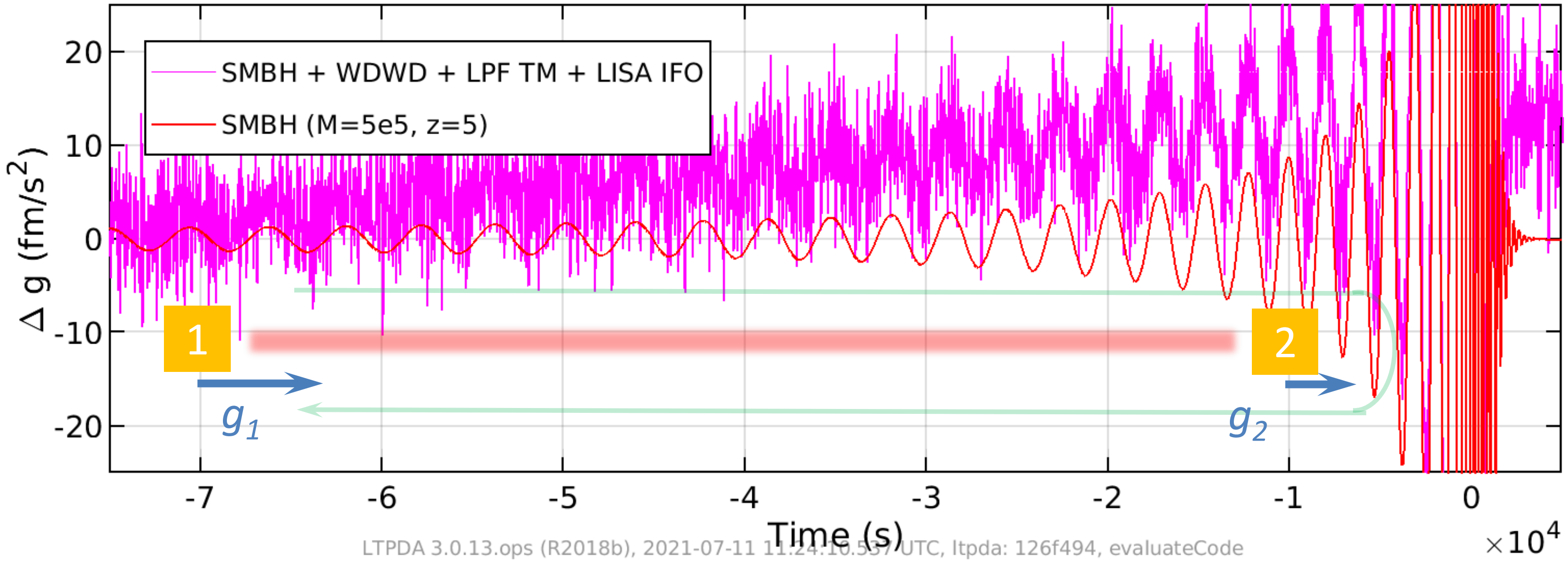
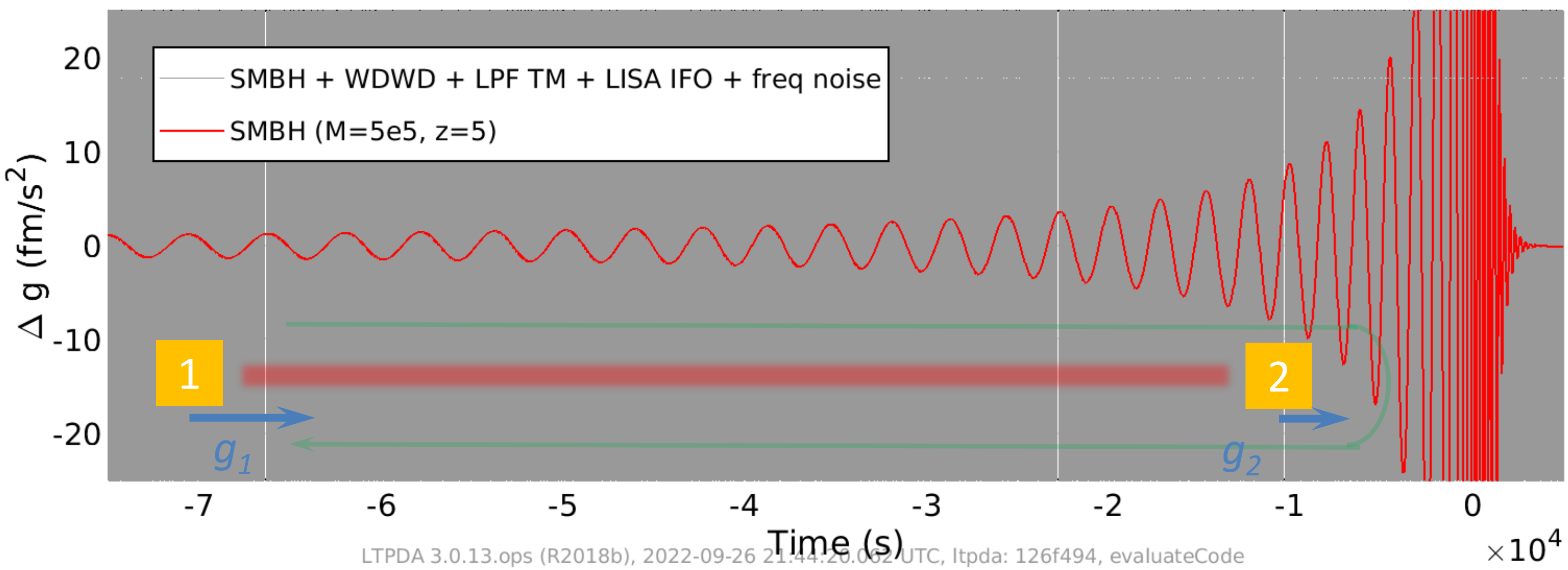


+ "confusion noise" of millions of Milky Way white dwarf binaries

LISA GW observation: frequency noise and need for 2nd arm

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

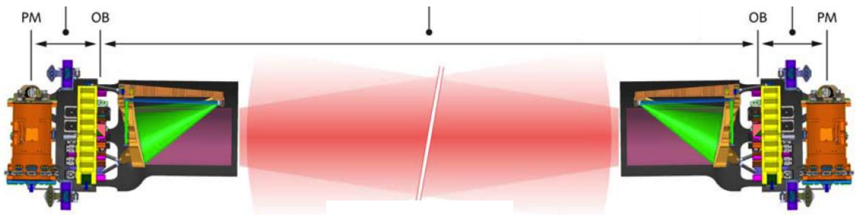
GW strain — $\approx 2\Delta g$ — noise in frequency measurement — laser frequency noise



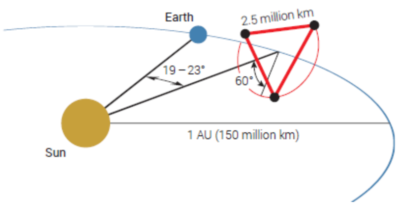
Laser frequency noise > 7 orders of magnitude too big!!!

- Even with cavity stabilized laser PSD (10^{-13} /Hz$^{1/2}$)
- Use 2nd arm ... equal arm Michelson insensitive to wavelength change
  - But LISA arms are different by us to 25000 km (1%)
  - **LISA requires software "time delay interferometry"**

LISA sensitivity



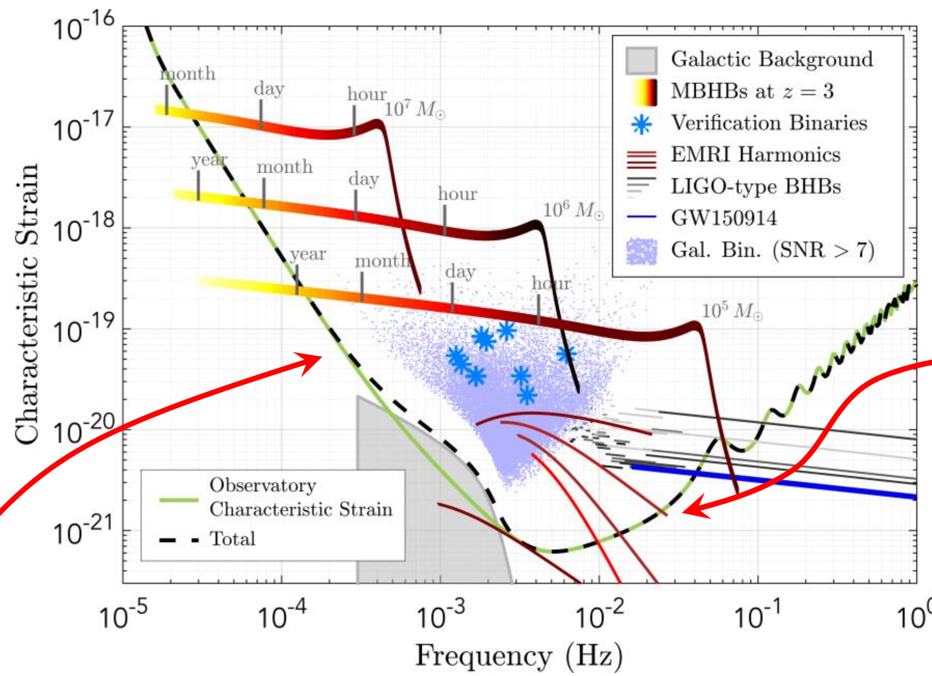
2.5 Million km



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

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

Spacecraft controlled to follow TM: **drag-free control (nm/Hz$^{1/2}$ level)**



Test mass acceleration noise, 3 fm/s^2/Hz$^{1/2}$ (Low freq limit)

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

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The LISA «MOSA»: moving optical sub-assembly

Gravitational reference system

GRS head

+ electronics

+ UV light source

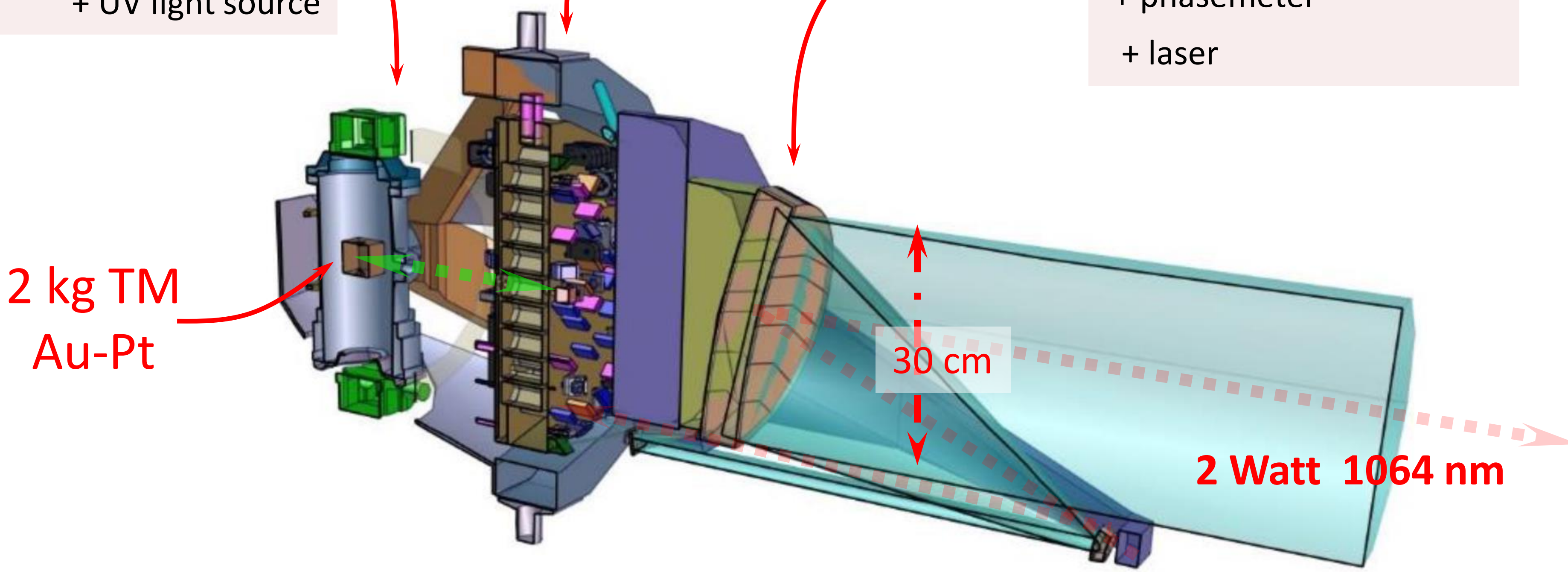
Optical metrology system

Optical bench

Telescope

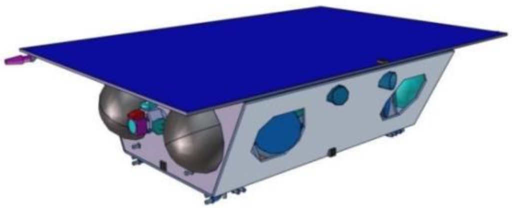
+ phasemeter

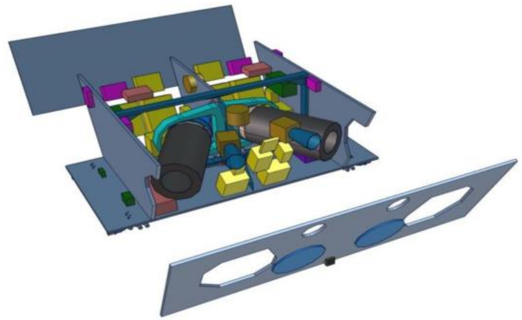
+ laser

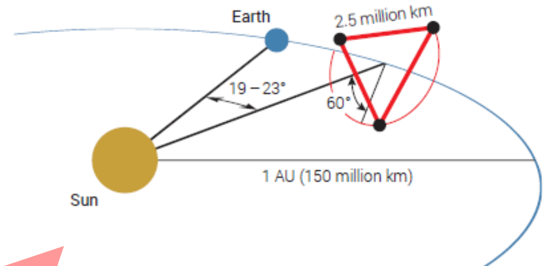


2 MOSA per each SC

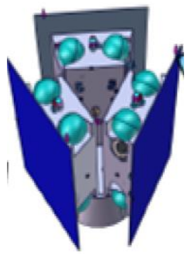
LISA: ESA L3 mission







Ariane 6.4



NB: LISA undergoing (competitive) industrial study all hardware designs notional!

6 months commissioning + calibration

Orbits, consumables for 10.5 years on orbit

Cruise 1.5 year		Nominal science phase 4.5 years (4 years science with 88% duty cycle)	Extended science phase 5.5 years

NB: mission duration under discussion in ESA!

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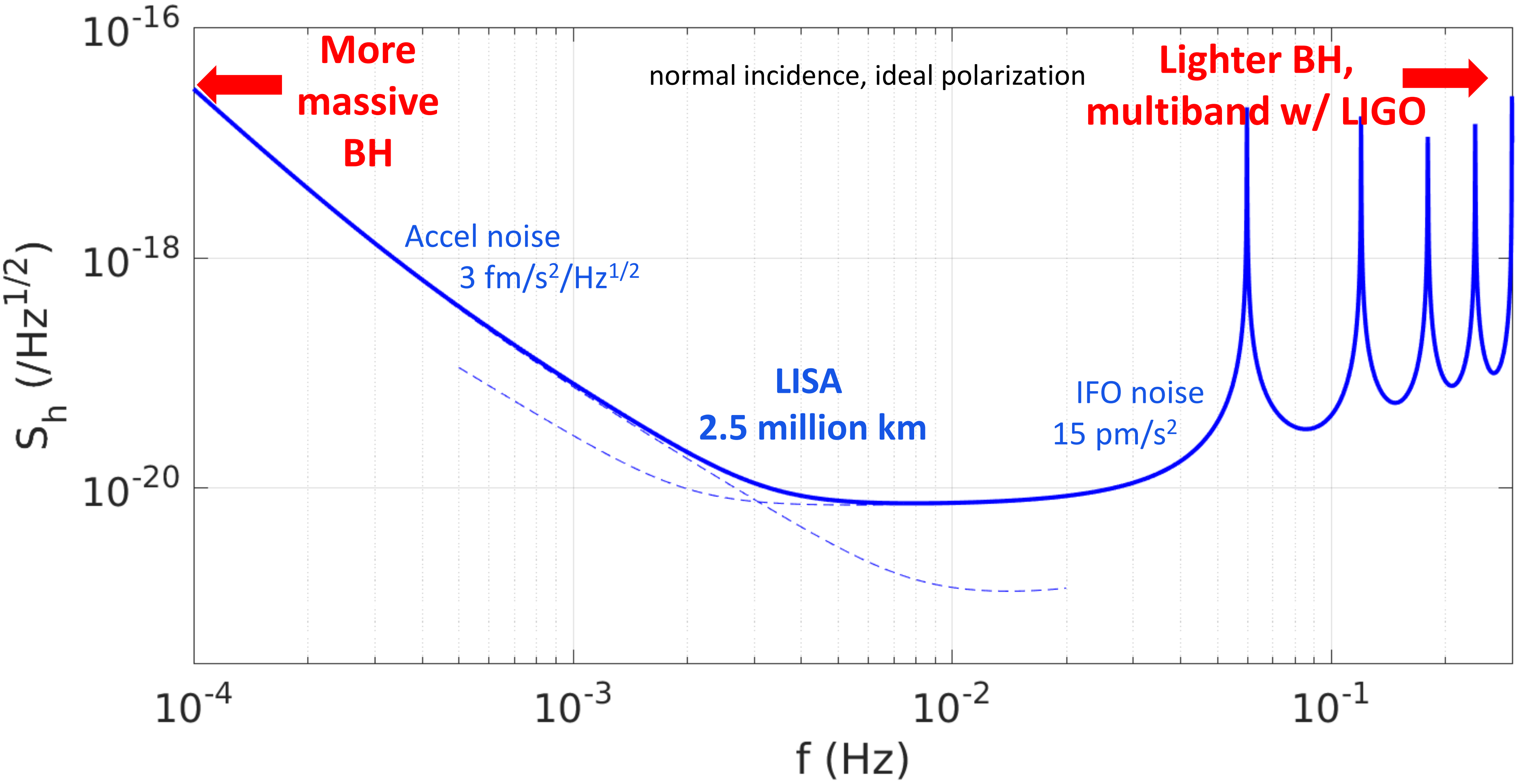
The right size for LISA: why *L* = 2.5 million km?



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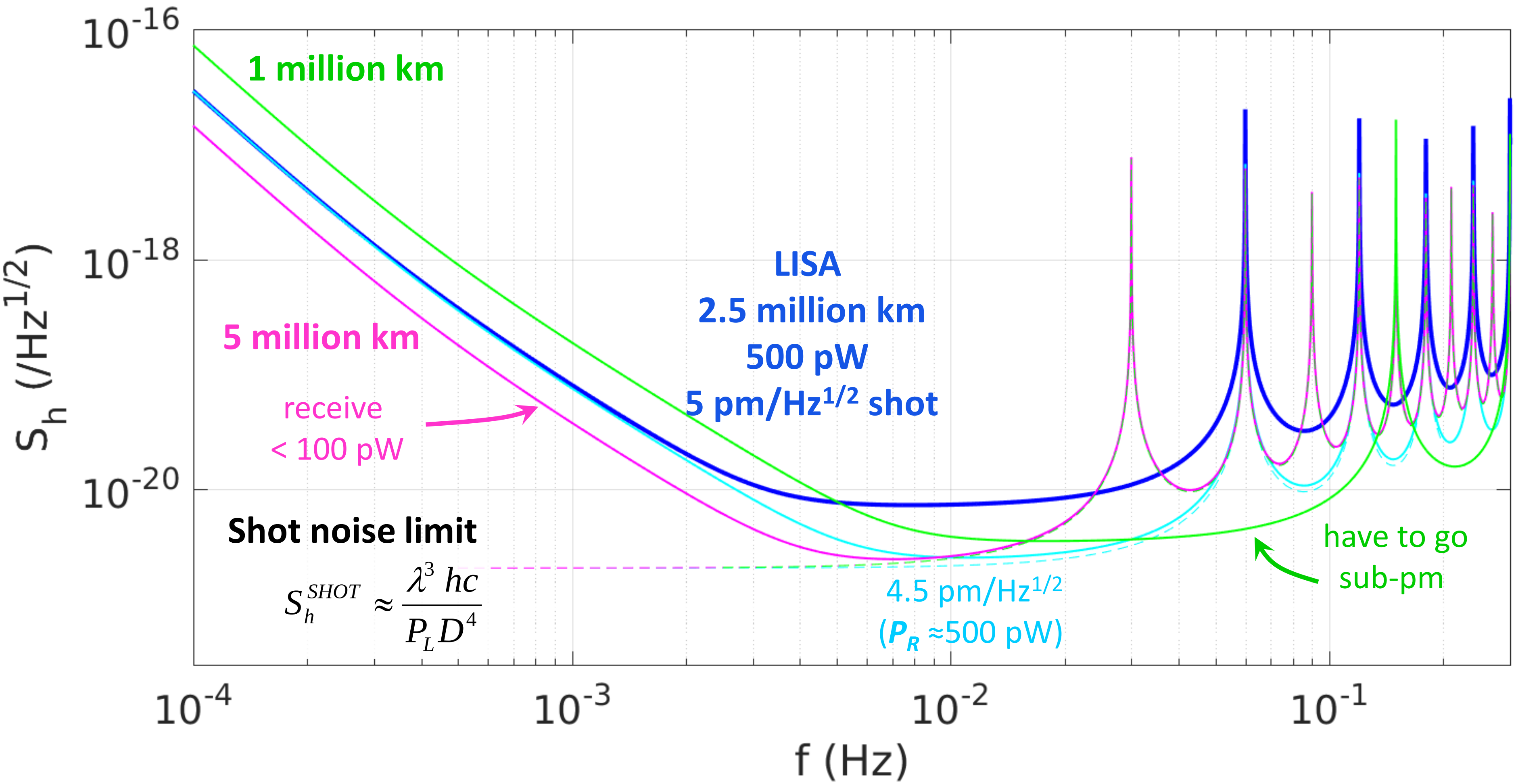
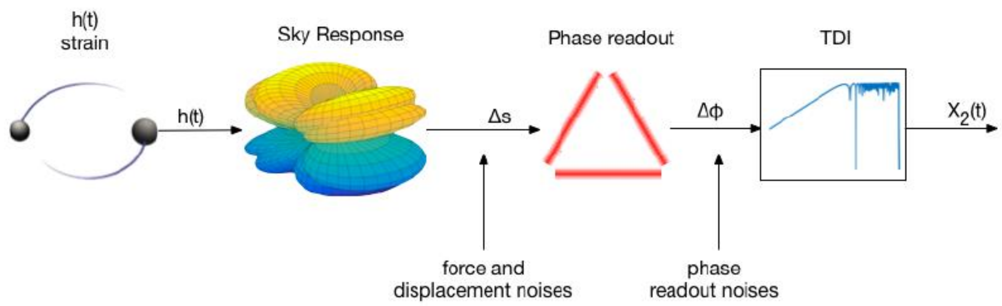
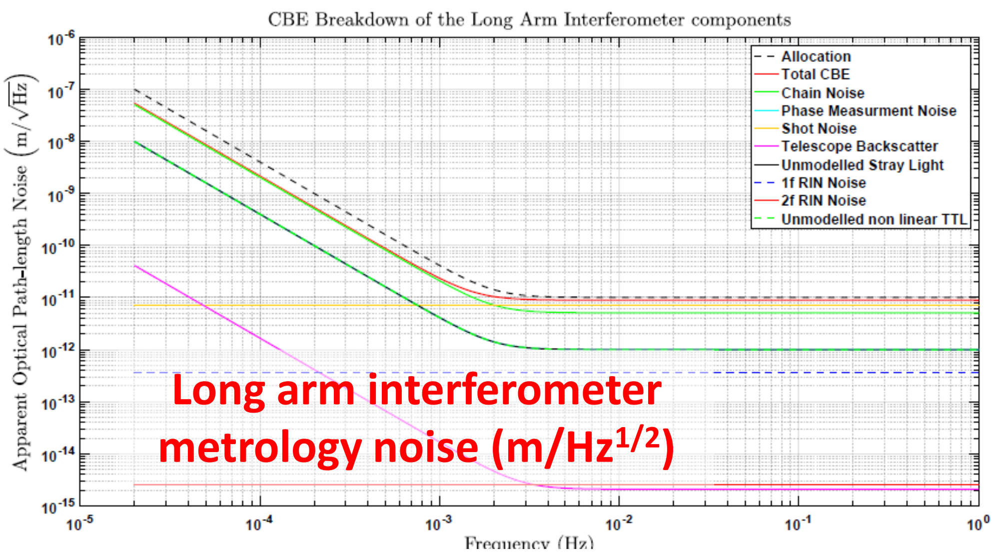


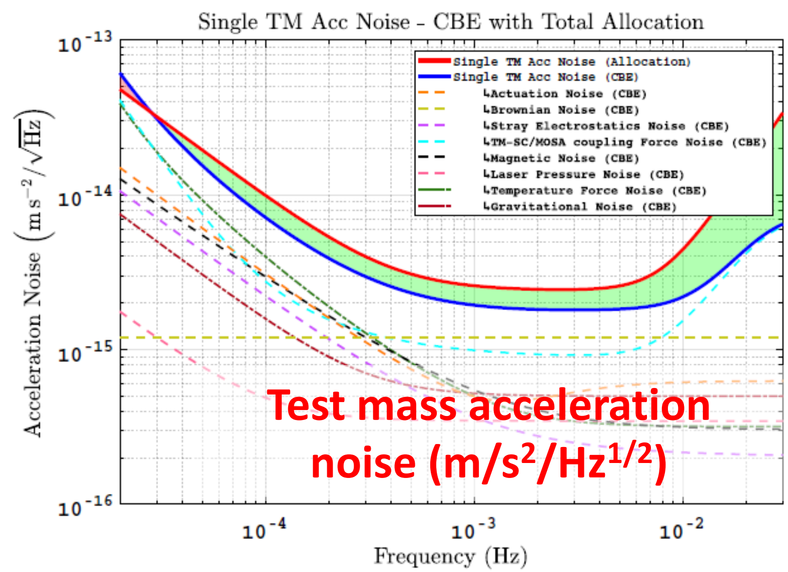
LISA at 2.5 million km gives broad, transformational science return with reachable performance

Sub-femto-g and picometers ... why do we think this will work?

Lots of analysis and models of noise sources ...







LISA Consortium performance model

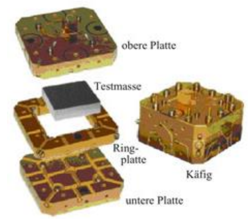
[Fitzsimons, Hewitson, Weber, Vetrugno, Martino ...]

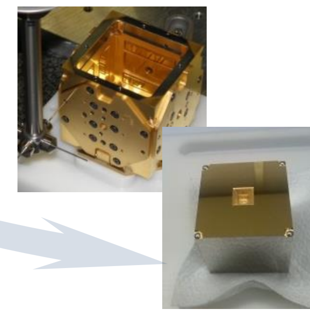
Sub-femto-g and picometers ... why do we think this will work?

... but mainly experiments, on ground and in space

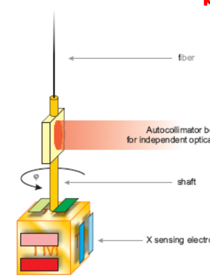
Free-falling test masses at 3 $fm/s^2/Hz^{1/2}$

- geodesy (GRACE, GOCE) 10-100 $pm/s^2/Hz^{1/2}$
- torsion pendulum– simplified test at 30 $fm/s^2/Hz^{1/2}$
- LISA Pathfinder – full flight test < 3 $fm/s^2/Hz^{1/2}$

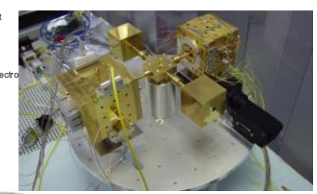


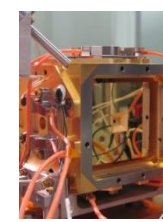


bigger TM
bigger gaps
no wires!



Trento
Pendulm





LPF

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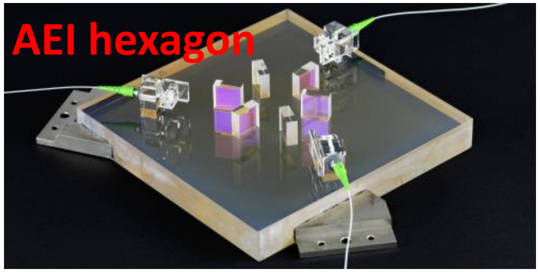
- LISA Pathfinder – full flight test < 3 fm/s^2/Hz$^{1/2}$

LASER interferometer metrology (10 pm/Hz$^{1/2}$)

- LPF local interferometer ($\Delta\nu \approx 0$) sub-pm!
- interspacecraft with GRACE follow-on geodesy
- ground testing to move to big telescope!

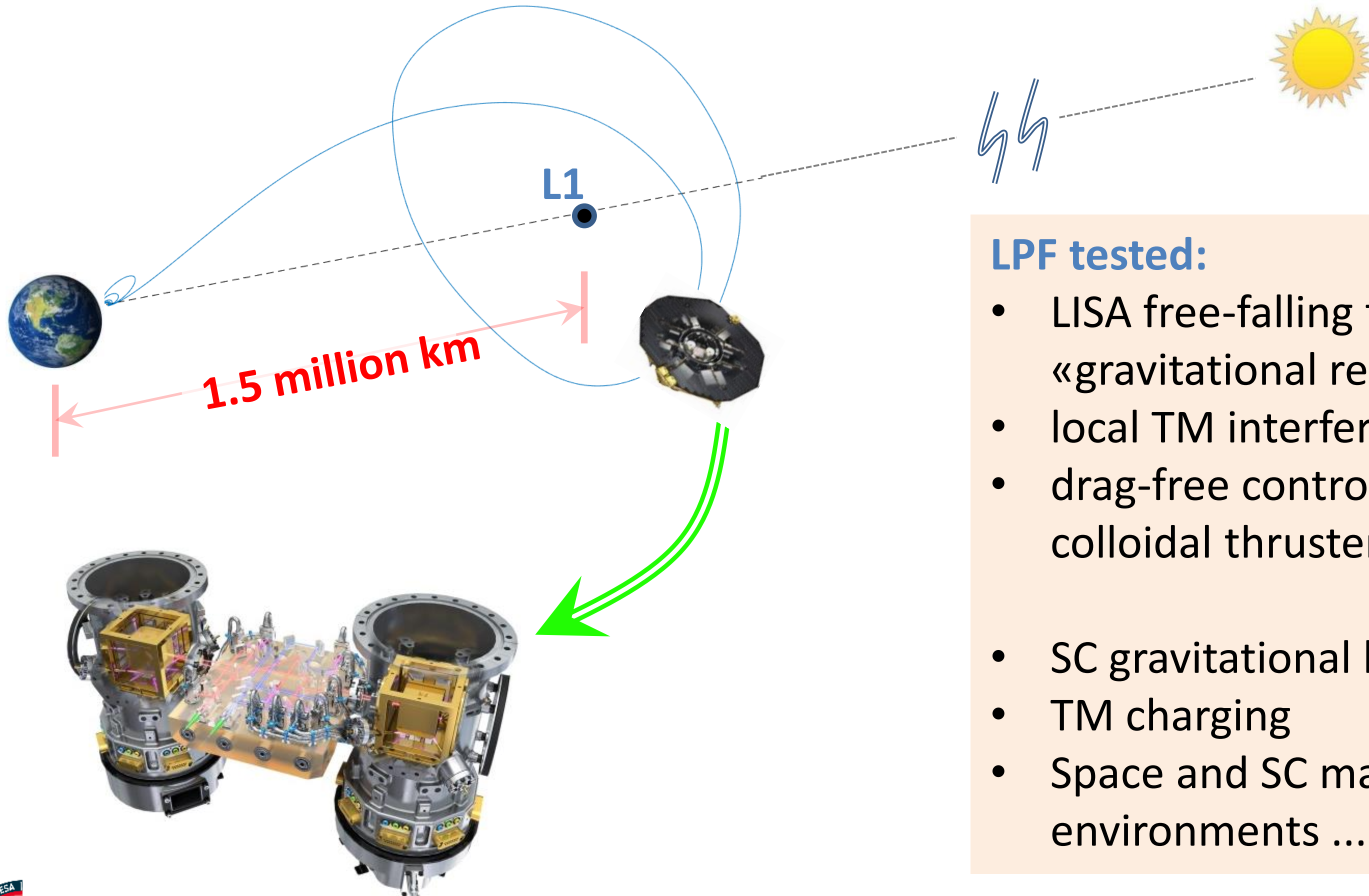
Cancelling laser frequency noise (≈ 7 orders of magnitude) in unequal arm Michelson

- high dynamic range phase measurement in lab
- tabletop tests of delays, ns timing ranging
- ... and simulation



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

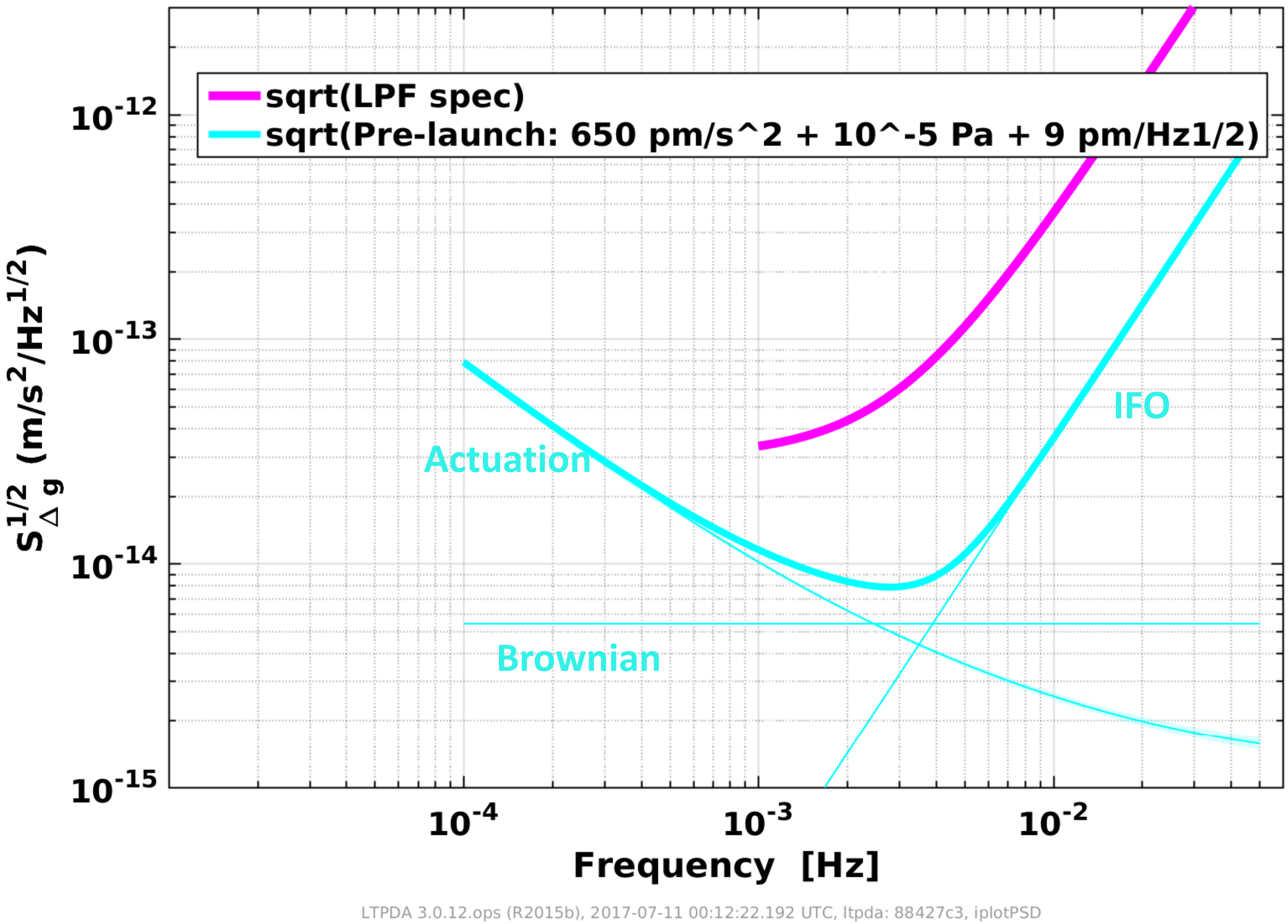


LPF tested:

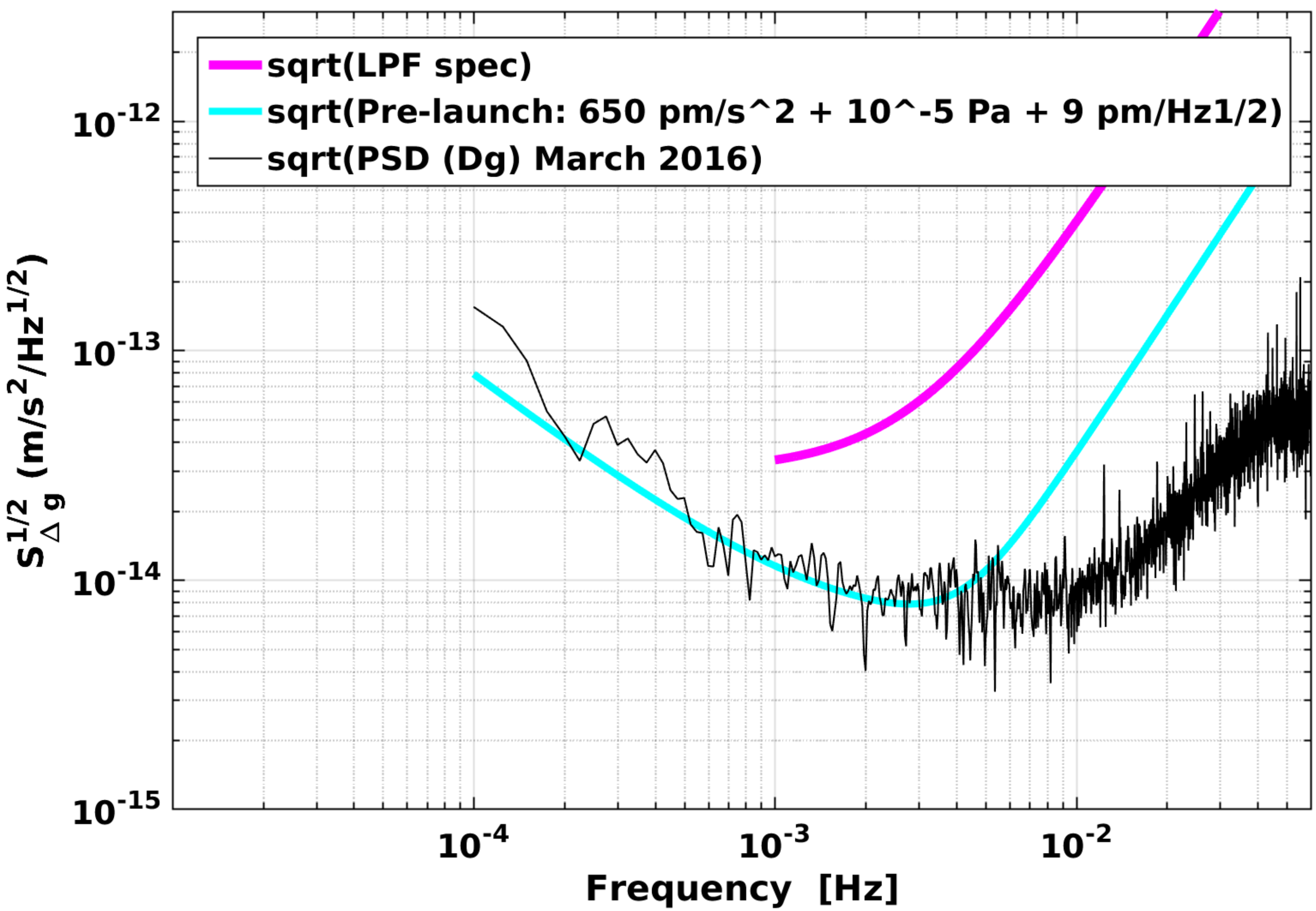
- LISA free-falling test mass «gravitational reference system»
- local TM interfermetric readout
- drag-free control with cold gas and colloidal thrusters

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

LISA Pathfinder differential acceleration noise

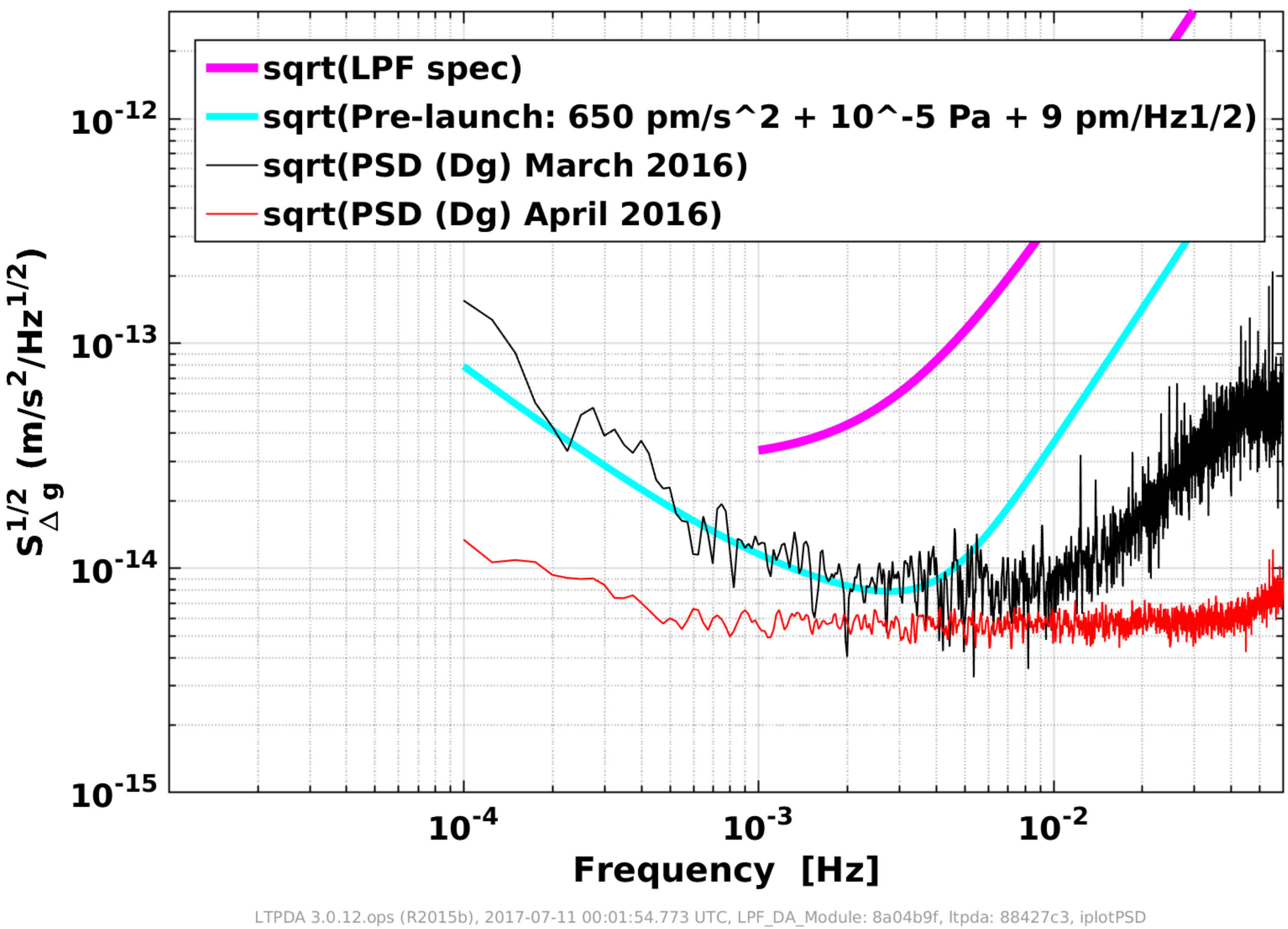


LISA Pathfinder differential acceleration noise

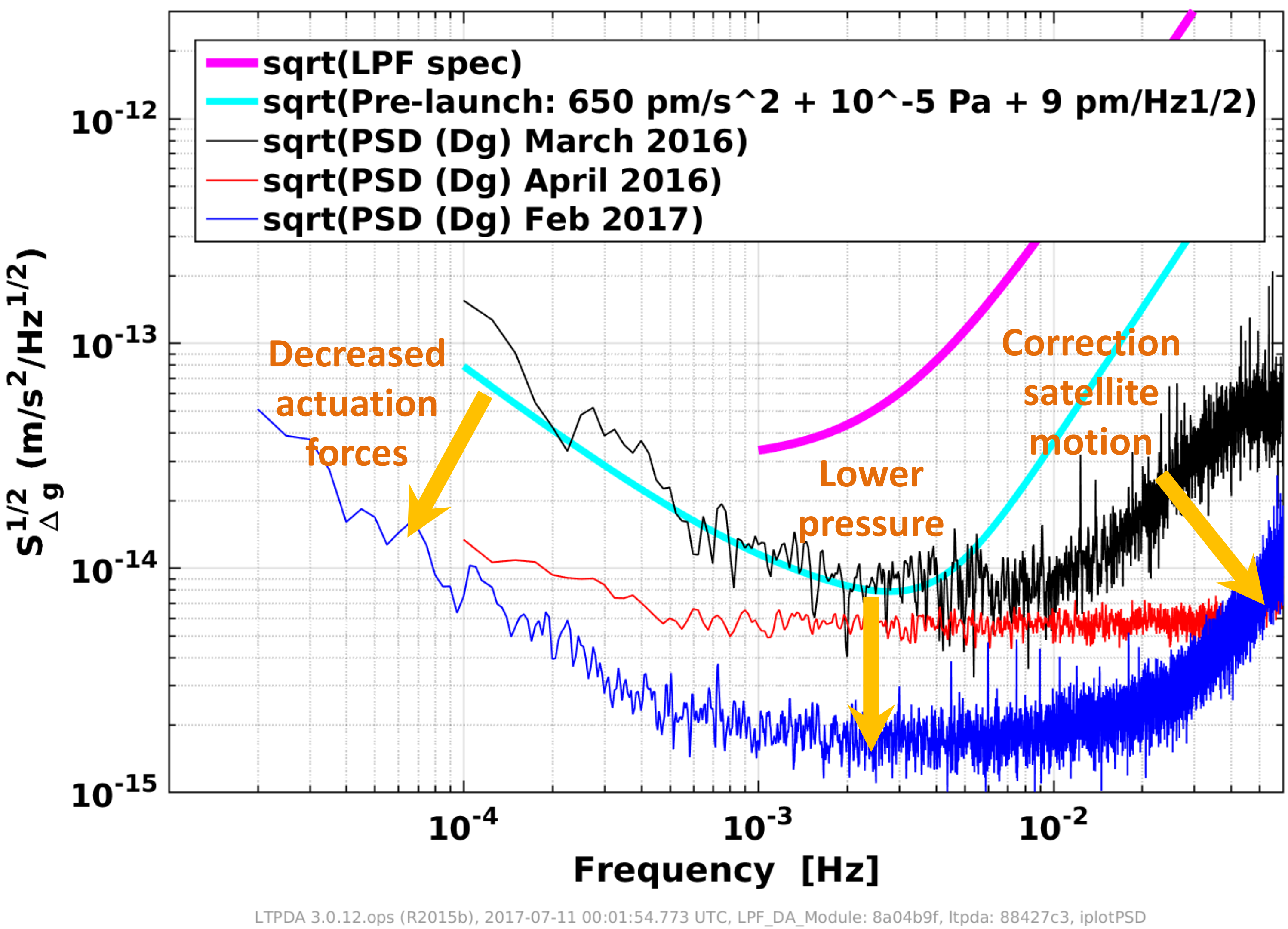


LTPDA 3.0.12.ops (R2015b), 2017-07-11 00:01:54.773 UTC, LPF_DA_Module: 8a04b9f, ltpda: 88427c3, iplotPSD

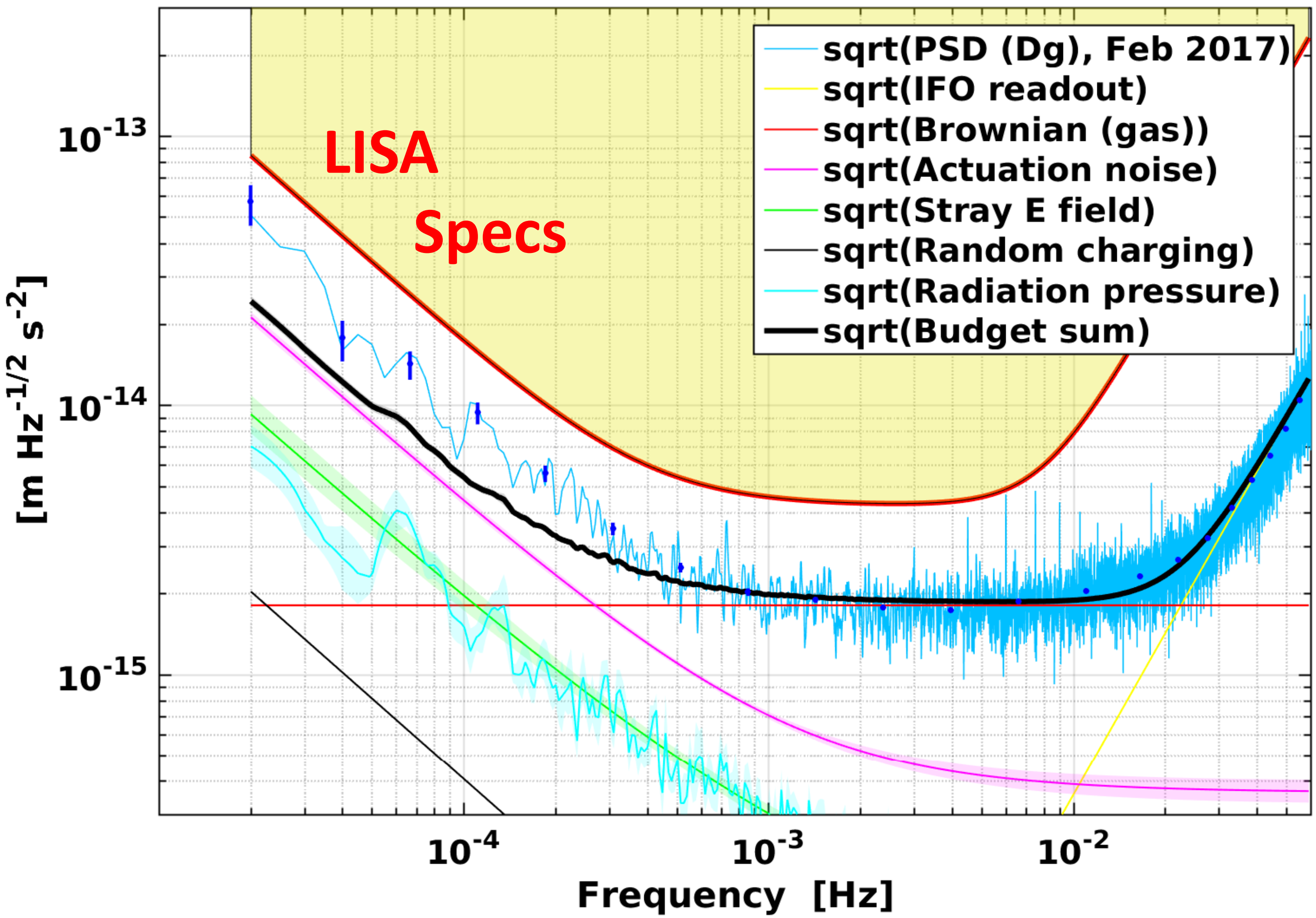
LISA Pathfinder differential acceleration noise



LISA Pathfinder differential acceleration noise

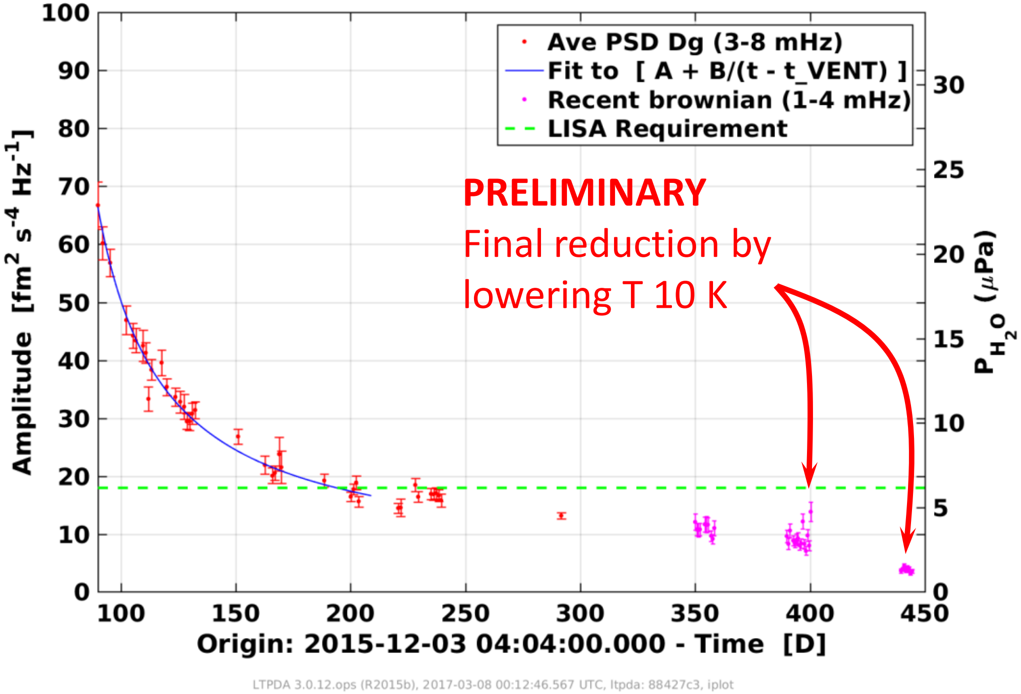


LISA Pathfinder Δg noise budget (February 2017)

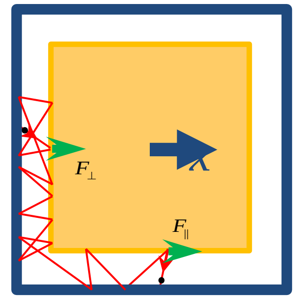


- **LISA acceleration noise goal has been demonstrated**
- **Low frequency noise still not fully understood**

Brownian motion from residual gas impacts



Performance limit in 1 – 10 mHz band



Increased inside (tight) GRS due to correlated collisions

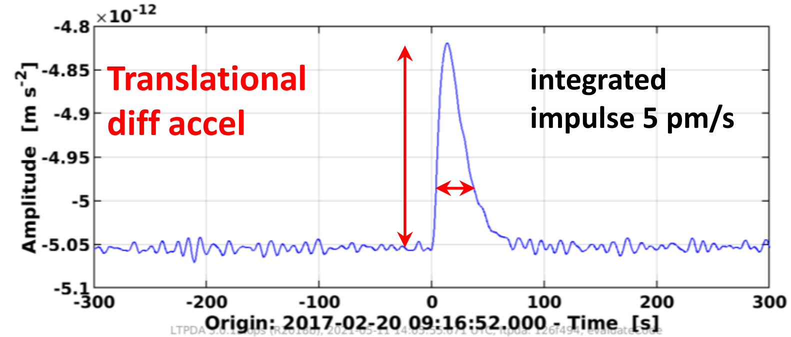
Mid-frequency LPF acceleration noise: residual gas damping

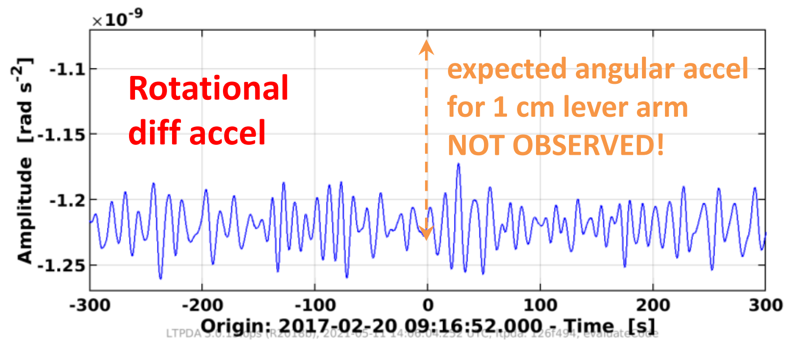
- Decays over time (t^{-1}) as GRS vents to space
- Noise power cut in half when cooled by 10 K→ H_2O outgassing (1 μPa)
- Visible in thermal gradient experiments (radiometric effect)

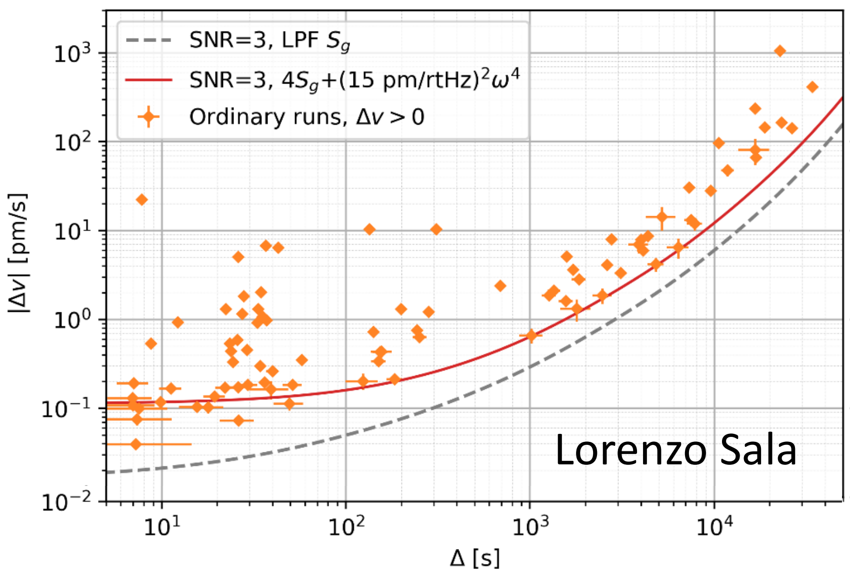
Below LISA requirement!

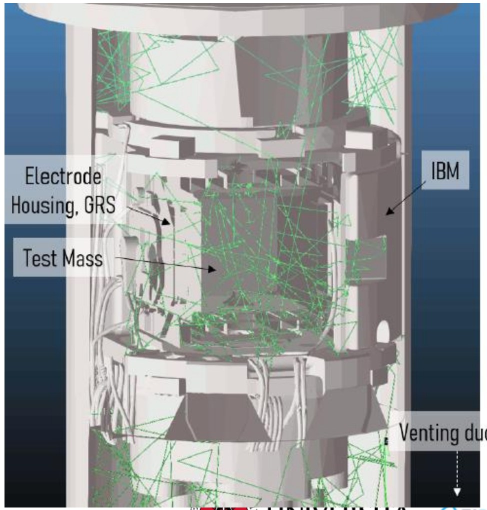
LPF impulse "glitch" events

- pure impulse forces on one TM (or the other)
- Δv up to many pm/s, in 10 s to hours
- Poissonian (≈1 / day)
  - increase to 30 / day upon lowering T to 0° C
- no observed torque
- not an optical artefact, not μ-meteor events
- outgas burst? (≈ ng of H_2O)





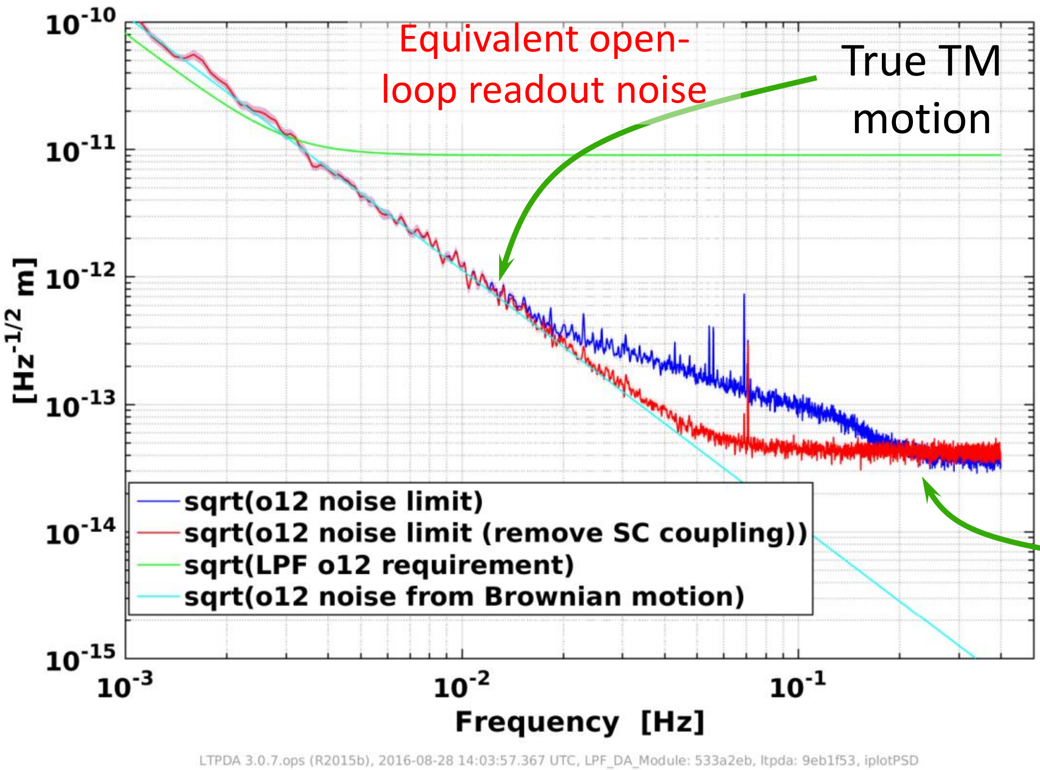


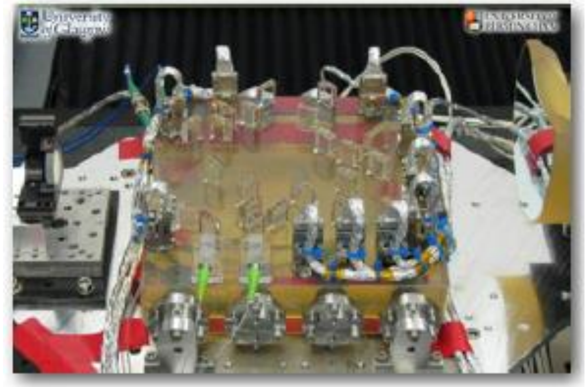


For LISA: eliminate them!
or identify (null channel, instrument monitor)

[PRD 106:062001 (2022)]

LISA Pathfinder instrument performance: interferometer

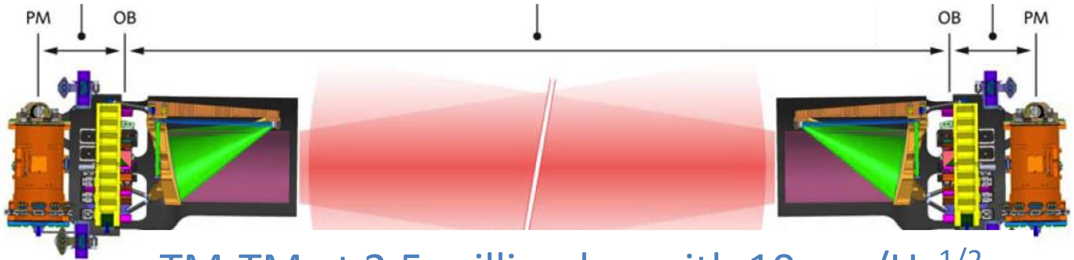




35 fm/Hz$^{1/2}$ noise floor (required 10 pm/Hz$^{1/2}$)

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

LISA long arm interferometry challenge

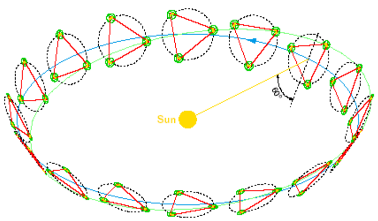


TM-TM at 2.5 million km with 10 pm/Hz$^{1/2}$

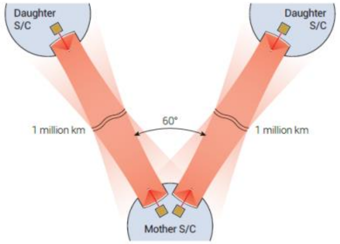
Beam divergence over 2.5 10^9 m:
→2 W from 30 cm telescope
→500 pW received power

weak light phase-lock transponder

LISA constellation «quasi-rigid, quasi equilateral» rotating configuration
Keplerian dynamics and secular Earth pull produce «breathing»

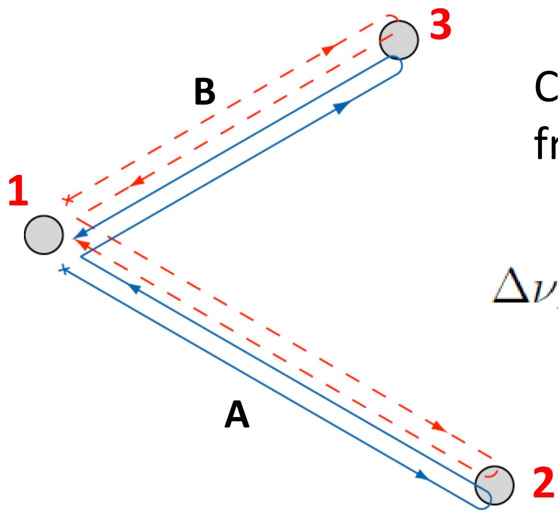


- $\Delta\phi \sim 1°$ → telescope angle must breathe
- $\Delta L \sim 30000$ km → unequal arm interferometer
- $\Delta v \sim 10$ m/s → Doppler shifts 10 MHz (fringe rates)



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

GW observation as time-delayed Doppler gravity gradiometer:
Time delay interferometry (TDI)



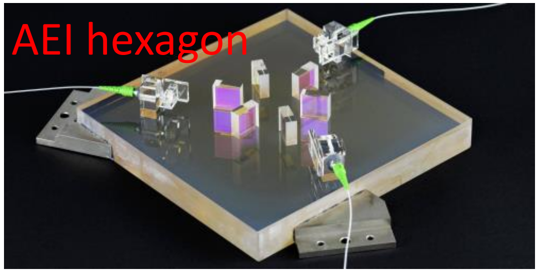
Combine phase measurements time shifted such that laser frequency noise is cancelled

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

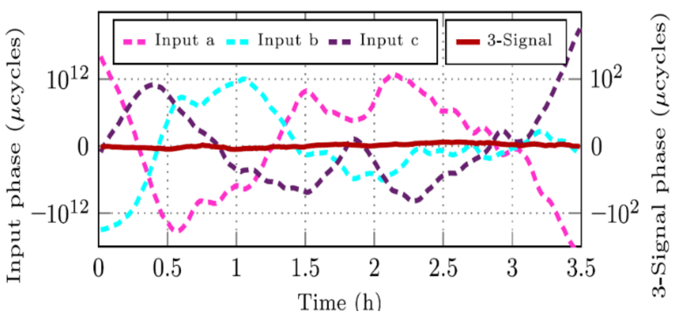
- Both 4-pulse roundtrip optical paths start and end in same «events» at SC1 –
  - laser frequency noise cancels out!
- Need ranging with nanosecond timing to synthesize equal arm – to 1 m – IFO
- This is «1st generation TDI» – works with fixed unequal arms
- More complex combos (8 pulses) cancel effects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

LISA interferometry: high dynamic range phasemeter

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

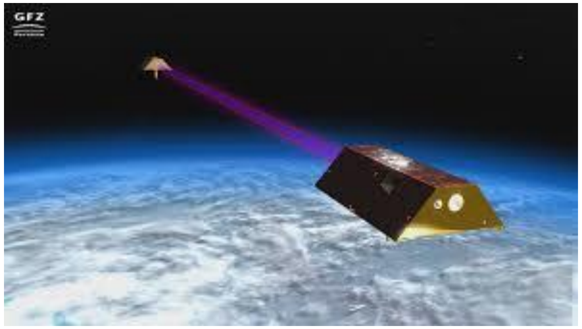


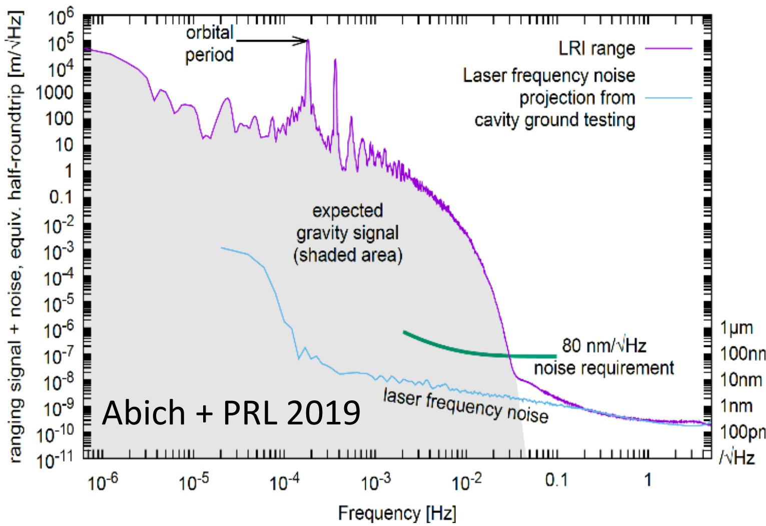
Schwarze+ PRL 2019



Demonstrated needed 10^{11} dynamic range phasemeter

LISA interferometry: inter-spacecraft link with GRACE-FO





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

- low light, MHz beatnote, laser frequency stabilization

LISA CONSORTIUM

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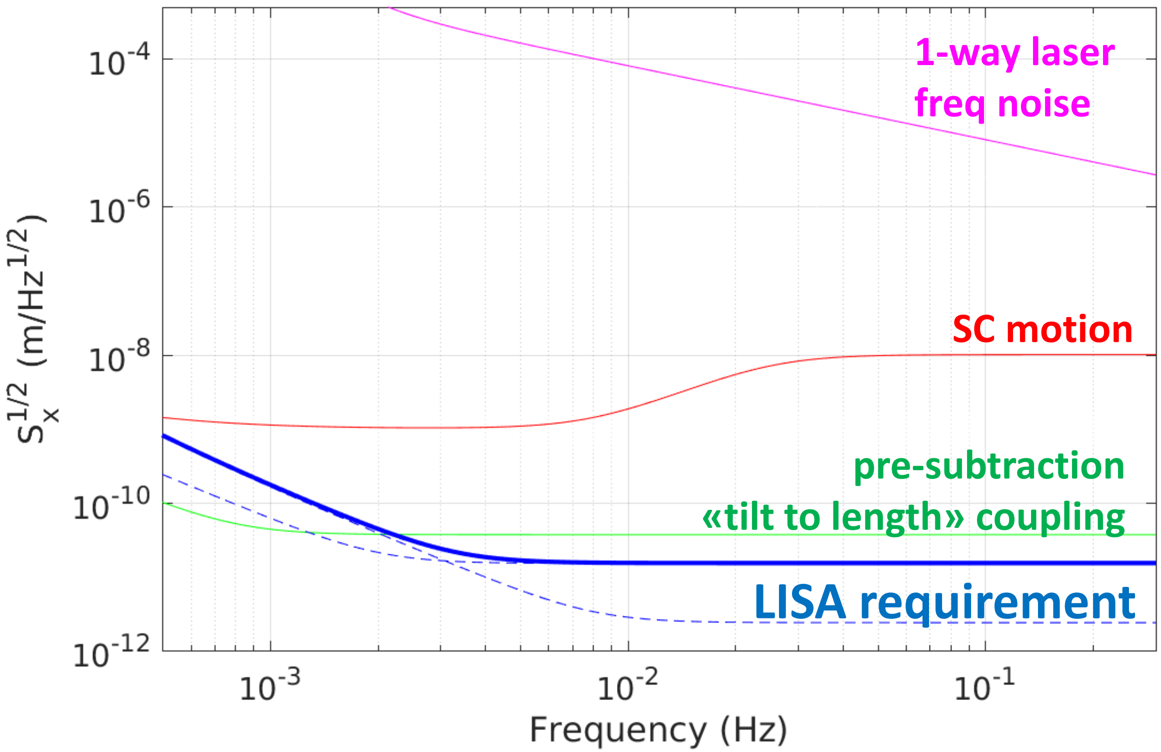
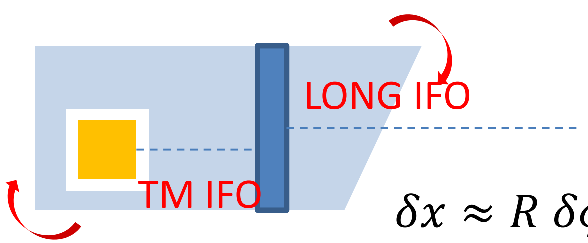
key «common mode rejections» in LISA



10^7 suppression with TDI

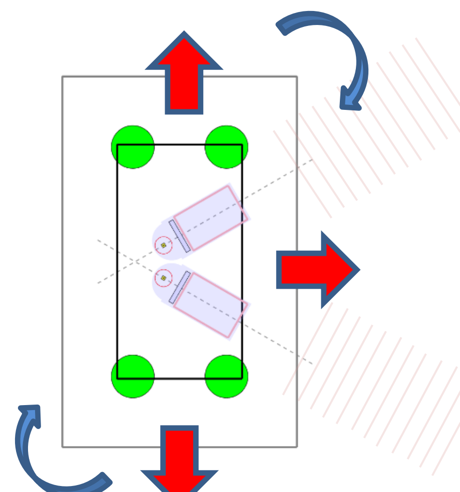
10^3 common mode rejection local/long IFO

Factor 10 subtraction based on in-flight calibration (measure / adjust on ground, calibrate and subtract in flight)



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

Measuring TM-to-TM with moving SC



Unique LISA data and operations

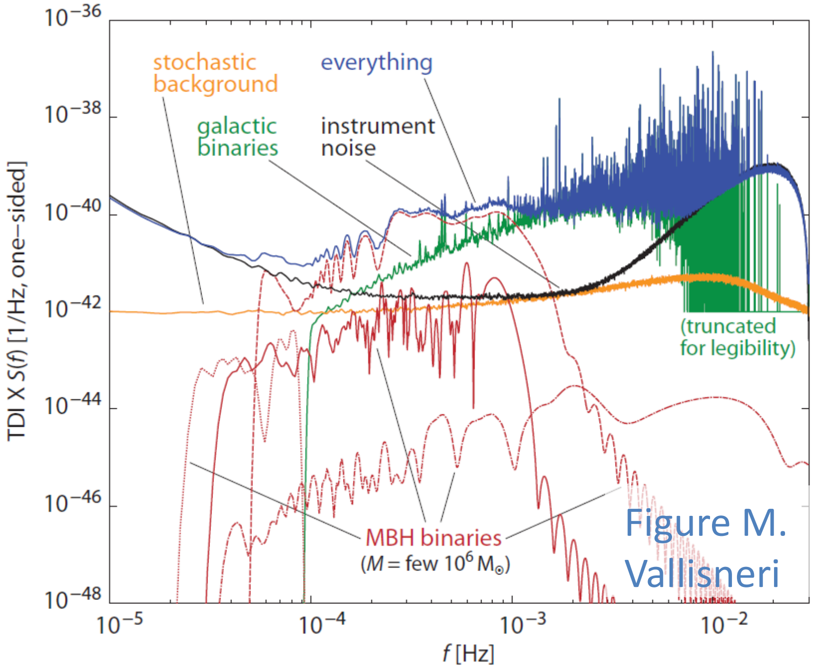
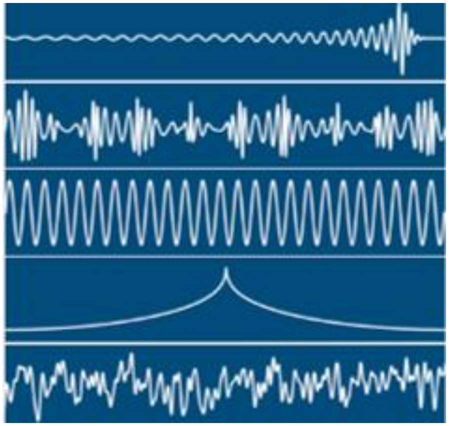


Figure M. Vallisneri



«LISA data challenge»
https://lisa-ldc.lal.in2p3.fr/

- time delay interferometry calibration (suppress 10^7 frequency noise)
- new, signal-dominated data
  - understanding noise requires removing signals
- all signals ON all the time → global fit analysis
- real time astrophysics analysis needed for alerts and constellation operations
  - mission ops requires both instrument AND astrophysics analysis support

data policy discussion ongoing: ensure delivery of quality data to community

Thank you!

Much help from
Trento LISA team

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