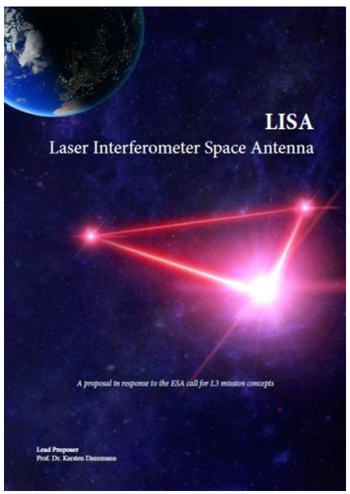
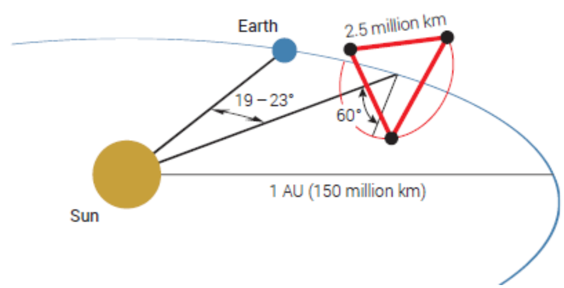
The LISA orbiting gravitational wave observatory

William Joseph Weber

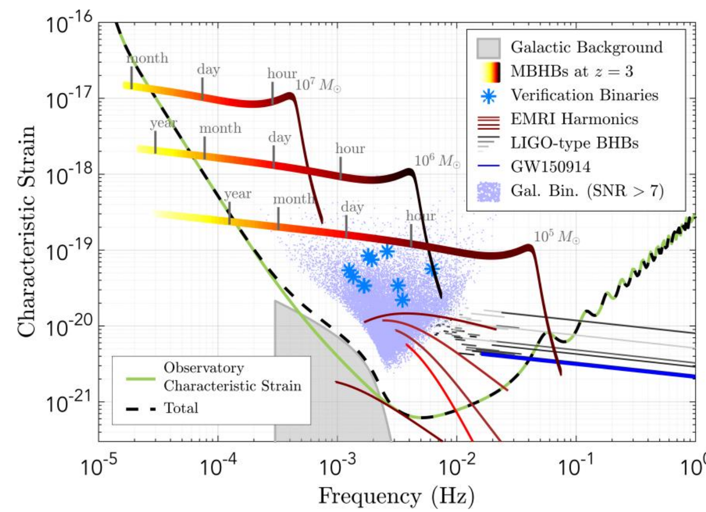
Università di Trento / INFN (TIFPA)



Adopted 2024
Launch 2035



3 spacecraft, 2.5 million km
4.5 years “nominal” science
(orbits + fuel for 11 years)



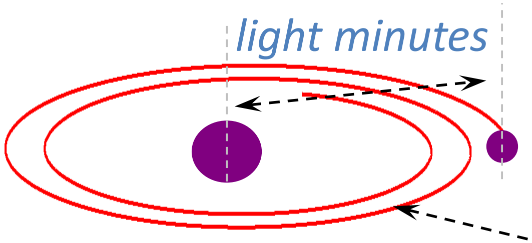
0.1 mHz to 1 Hz
(studied at 0.02 mHz)

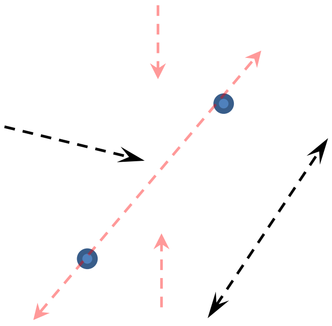
CRIS MAC conference, Trapani, 21 June 2024

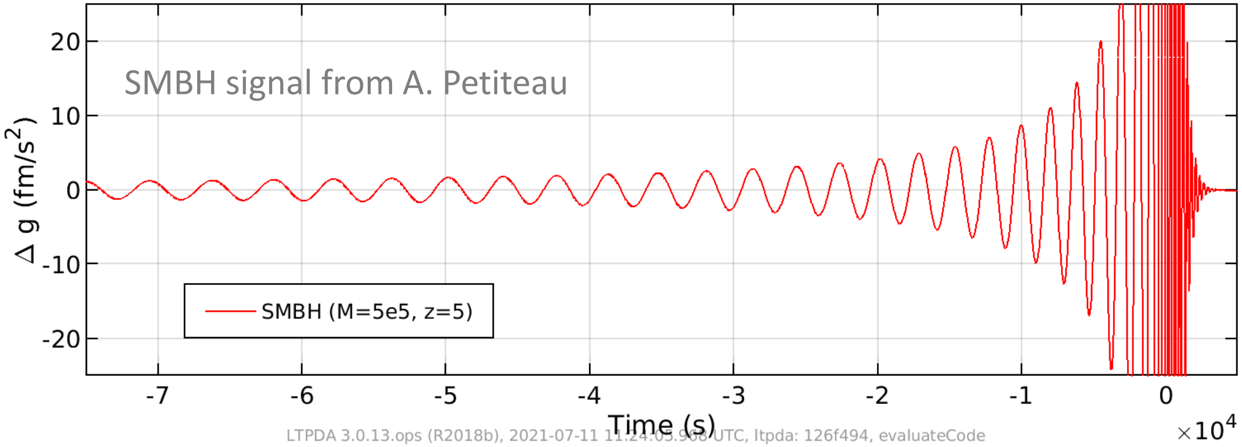
LISA GW observation as a time-delayed Doppler gravity gradiometer: Super Massive Black Hole Binary mergers

tidal acceleration between LISA TM from two 2.**5 10^5 $M_\odot$** “SMBH”, ***z = 5***

❖ ***we want to measure this with SNR > 1000***







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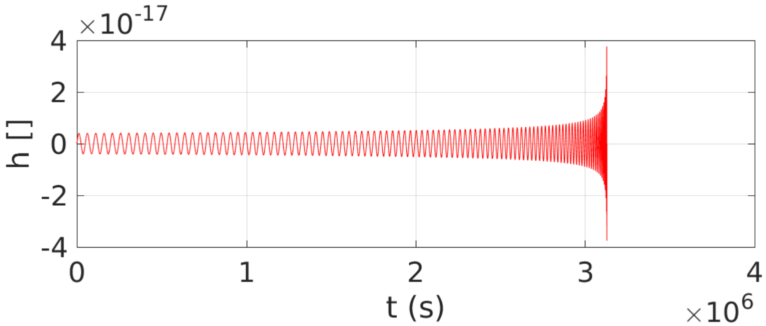
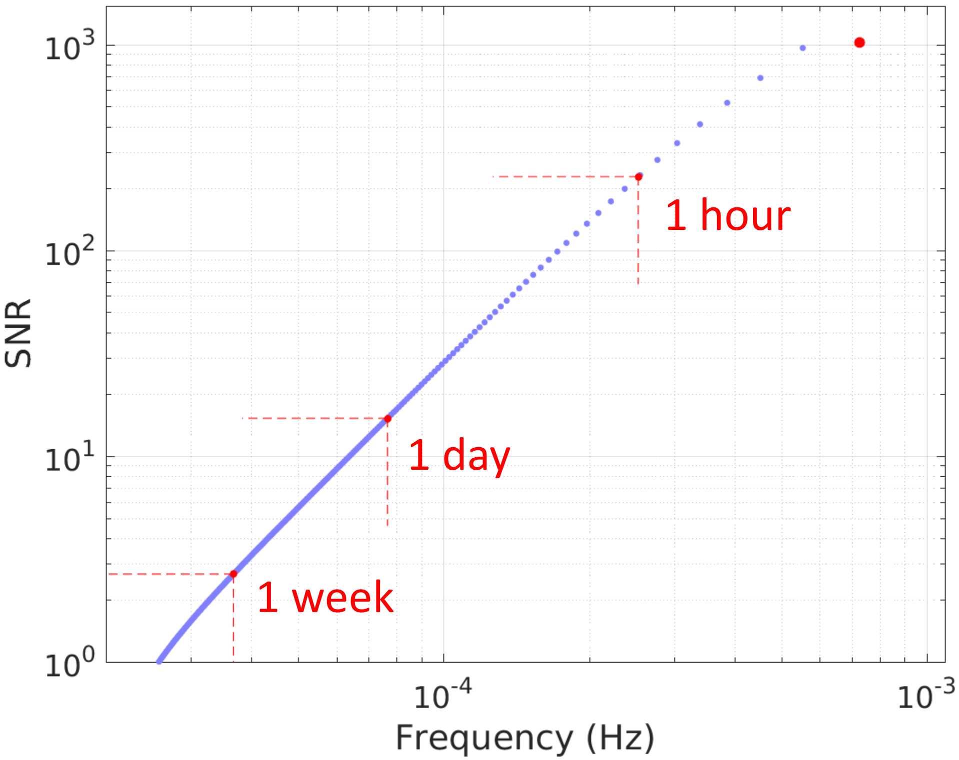
LISA: a high resolution, deep universe, low frequency observatory

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
- SNR > 1000 → tests of GR waveform

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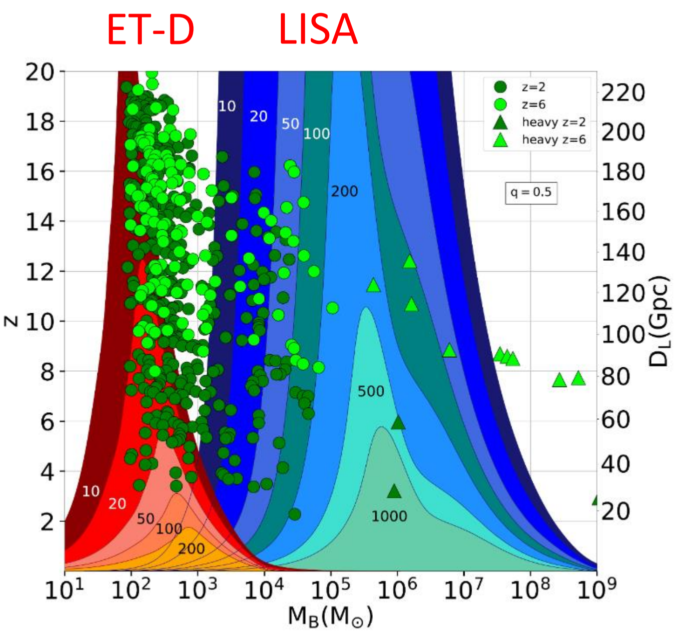
LISA black hole merger reach and resolution



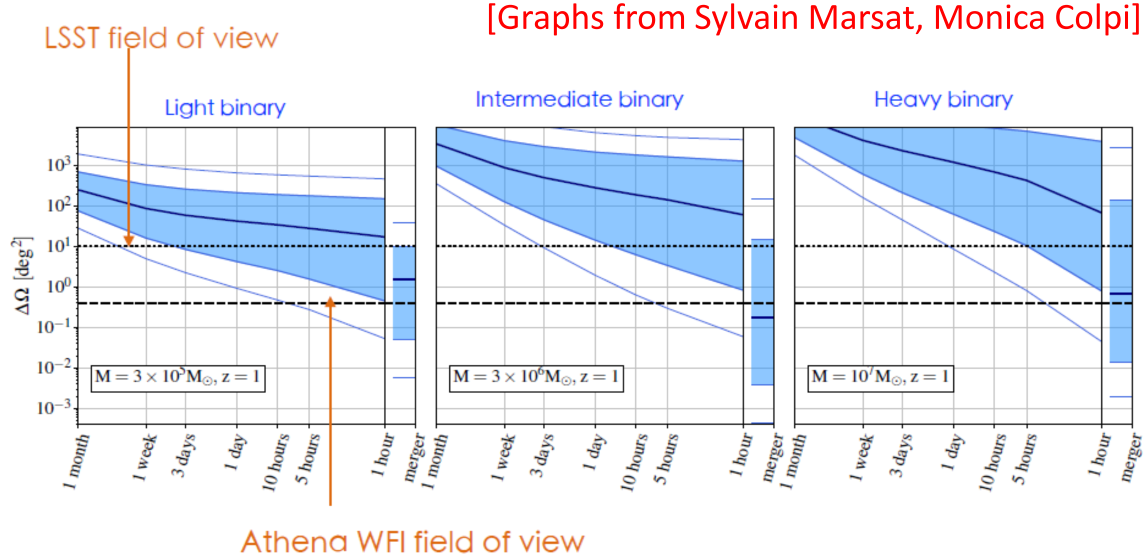
LISA covers:

- seeds 10^3-10^4 $M_\odot$ at cosmic dawn (z-15-20) ...
- ... out to 10^5-10^7 SMBH at cosmic «high noon» z=2-3
  - with ET cover 10^0 - 10^7 solar masses
  - galaxy formation

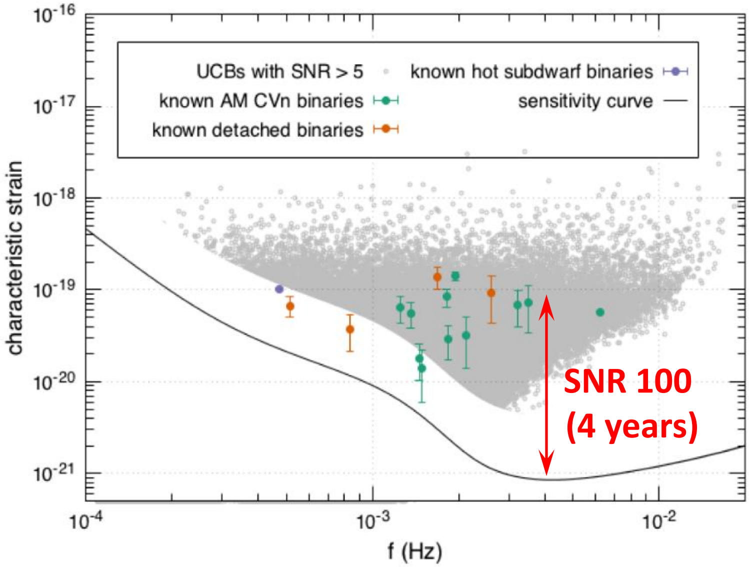
[Valiante etal 2020, arxiv 2010.15096]

- brightest sources:
  - SNR > 10^3
  - sky position < 1°
- cosmology and fundamental physics tests
  - multi-messenger?

[Graphs from Sylvain Marsat, Monica Colpi]



LISA galactic «Ultra Compact Binaries» survey



> 20 known LISA «verification binaries»

[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
    - brightest GW sources not yet found
- Many chirping – **$\Delta f/f$ > 1 ppm over 4 year mission** – above 1 mHz, some non-GR

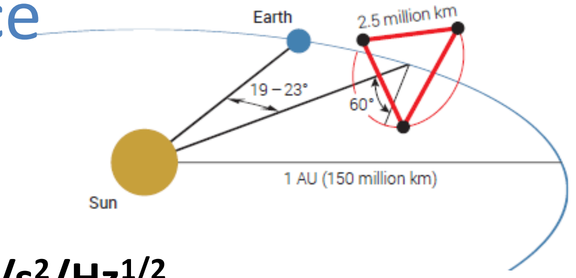
Expect «confusion» limit of millions of unresolved binaries (0.5 – 3 mHz)

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

→ 10^6 "frequency bins" below 10 mHz

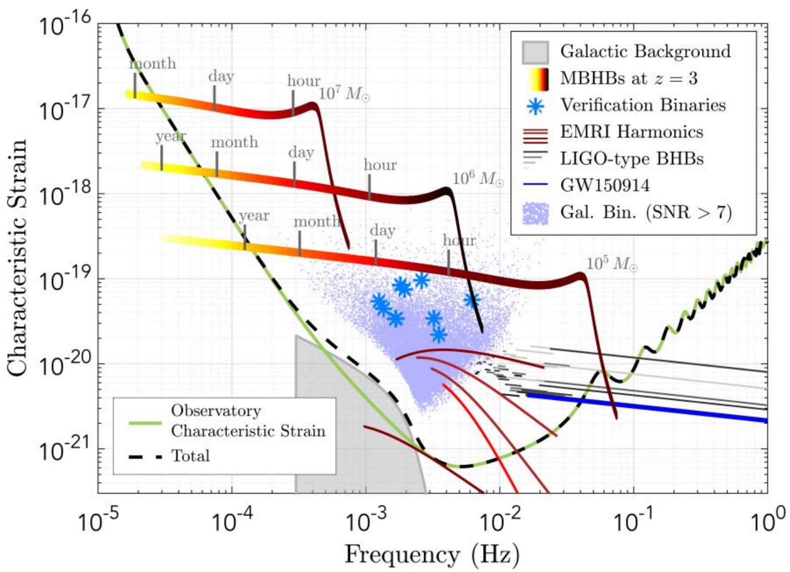
LISA: Laser Interferometer Space Antenna

Measurement science



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

LF limit: spurious antenna tidal deformation (stray forces) – **3 fm/s²/Hz$^{1/2}$**
HF limit: interferometer fluctuations (shot noise etal) – **15 pm/Hz$^{1/2}$**

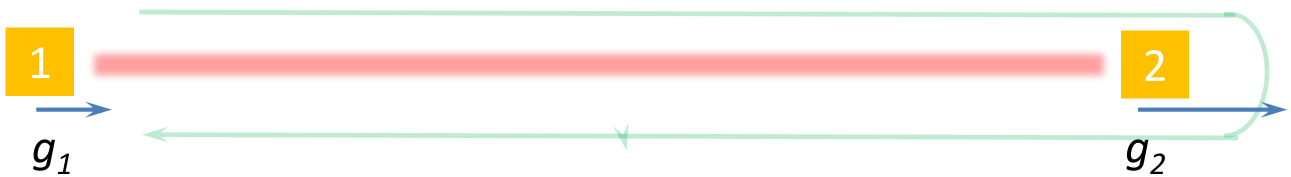


- 3 arms (6 one-way links), *L* = 2.5 million km
- free-falling TM, no suspension
  - orbital tidal accelerations μm/s², GW fm/s²
  - spacecraft drag-free control
- «open-loop» interferometer
  - Δv 10 m/s → 10 MHz fringe rates
- very unequal arm interferometer (ΔL 10⁴ km)
  - **time delay interferometry (TDI)**
- weak light (100 pW)
  - 1-arm light «transponders»
  - no light reflection or 2-arm light combination

GW observation as 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_{1E}
- O2 receives, amplifies (phase coherent) and sends back
- O1 interferes received light (ν_{1R}) with local beam, measures «beat frequency» between incoming received beam and outgoing emitted beam:

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



GW strain **stray acceleration**

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

Time derivative of beat frequency

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

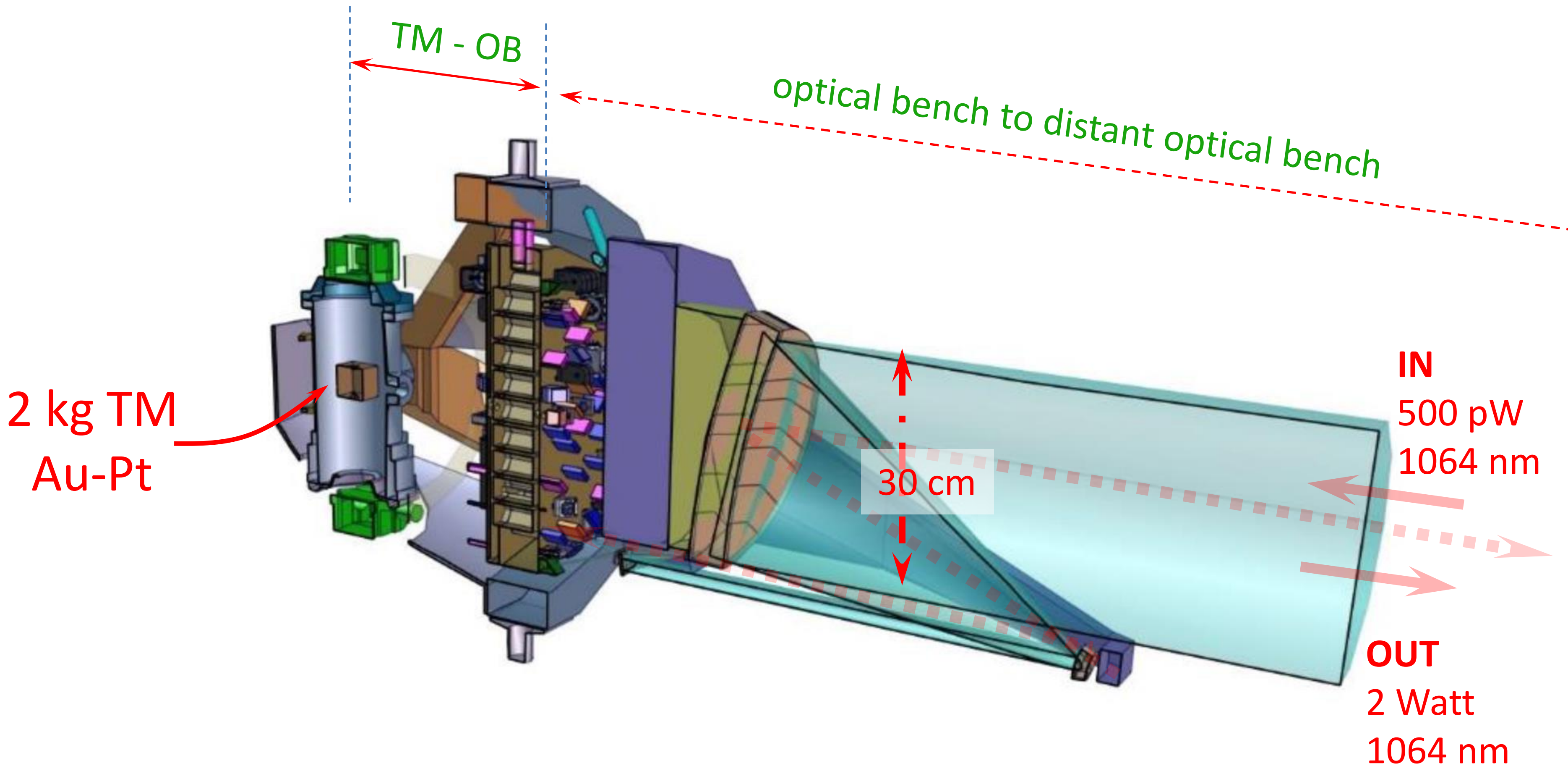
Phase/frequency measurement noise **laser freq noise**

- LISA is made of three such single-arm measurements
- laser frequency noise removed with 2 arms + TDI

The LISA instrument core «MOSA»:

moving optical sub-assembly

«end station» relative motion «test mass – test mass» over 2.5 million km



2 MOSA per each SC

The LISA instrument core «MOSA»:

moving optical sub-assembly

Gravitational reference system

GRS head

+ electronics

+ UV light source

Optical metrology

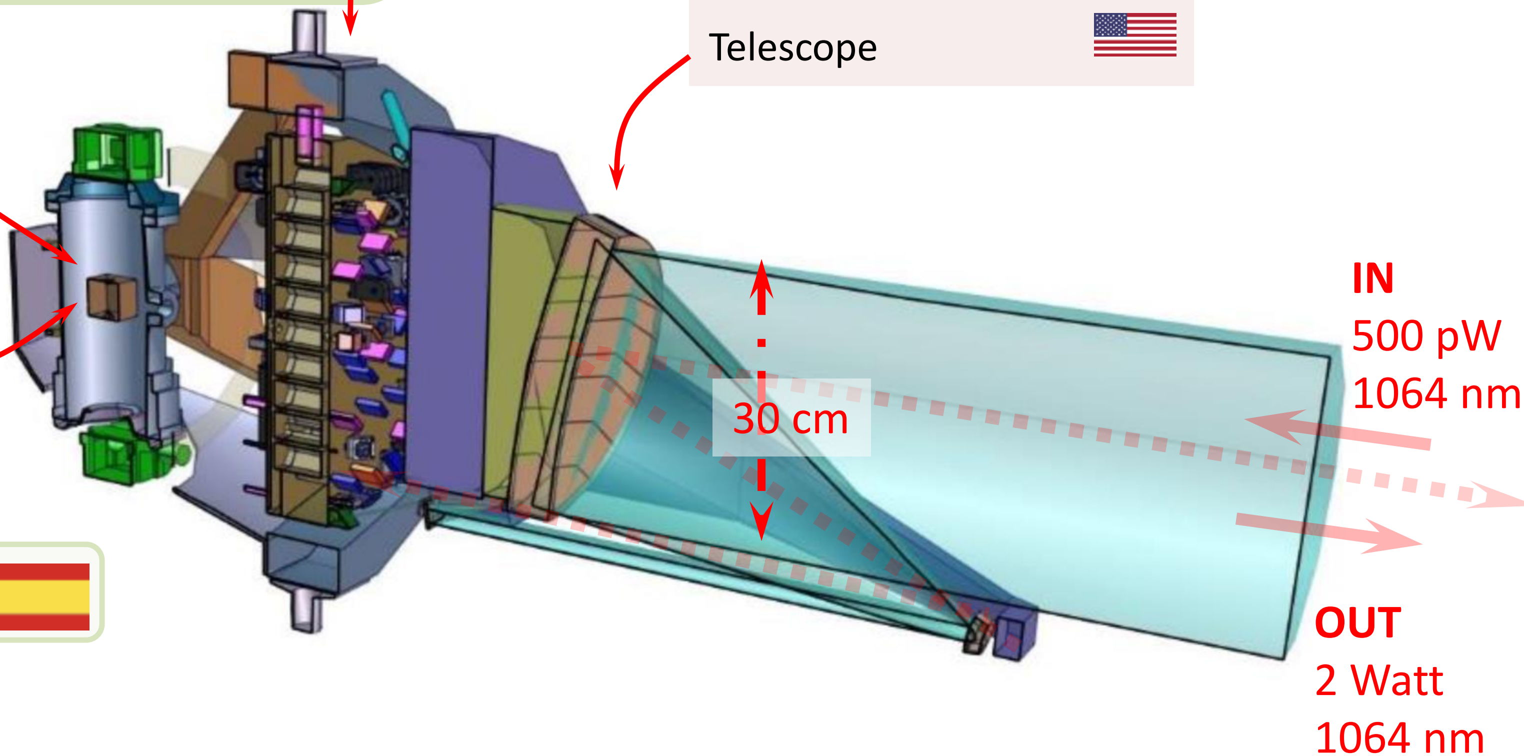
Optical bench

+ phasemeter

Interferometry detection system

+ laser

Telescope



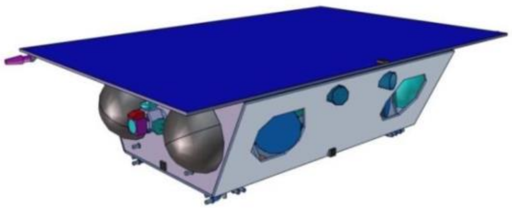
2 kg TM

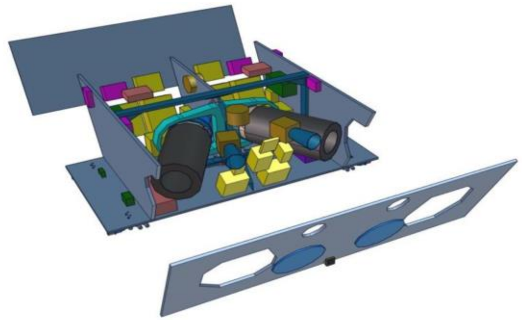
Au-Pt

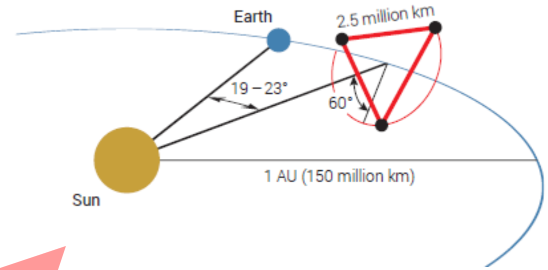
Diagnostics

2 MOSA per each SC

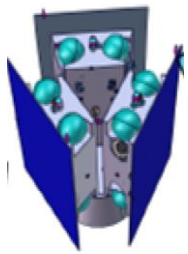
LISA: ESA L3 mission







Ariane 6.4



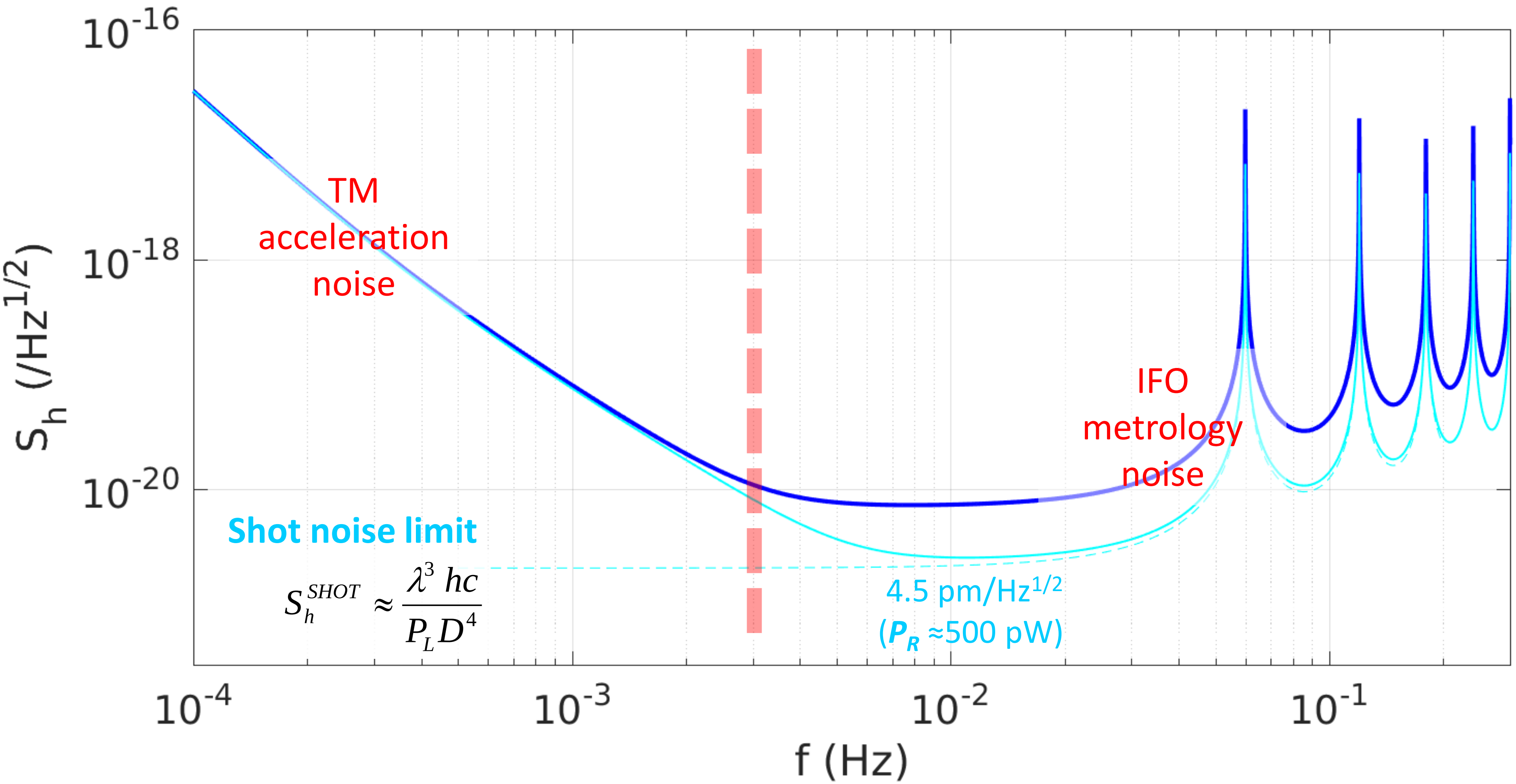
hardware designs notional!
competitive ITT out for system prime!

6 months commissioning + calibration

Orbits, fuel tanks for 11 years on orbit

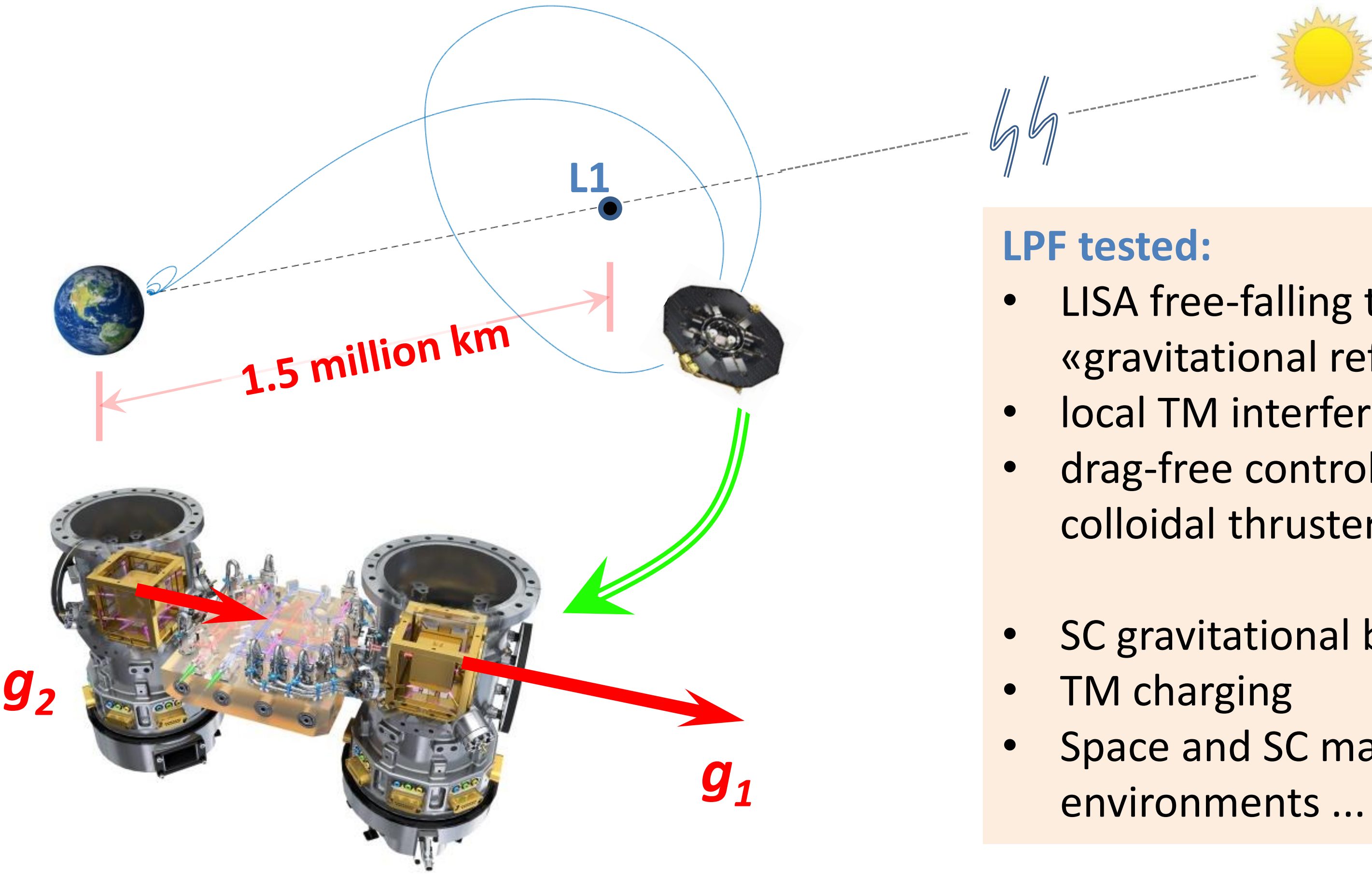
Cruise 1.5 year		Nominal science phase 4.5 years (3.7 years science with 82% duty cycle)	Extended science phase up to 4-6 years

LISA sensitivity at *L* = 2.5 million km



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

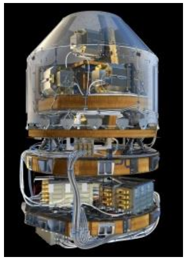


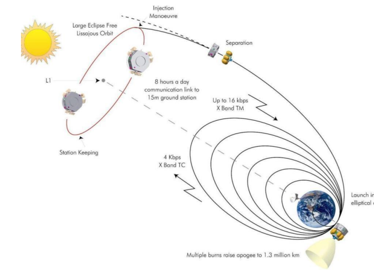
LPF tested:

- 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 ...

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



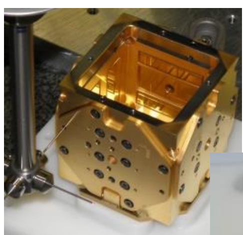


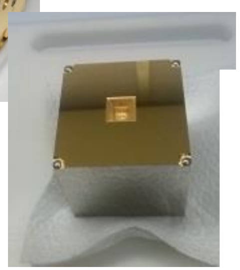
Geodesy in low earth orbit
(μm/s^2)

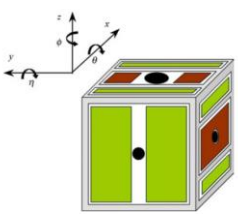
LPF at L1
nm/s^2

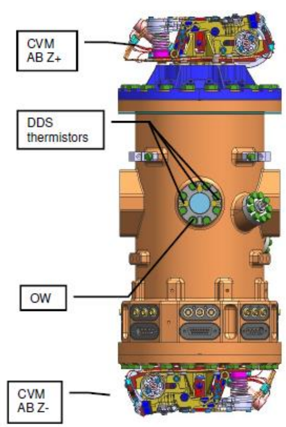
Smaller gravity gradients → smaller actuation forces (and force noise)

Are surface forces low enough to allow this jump?







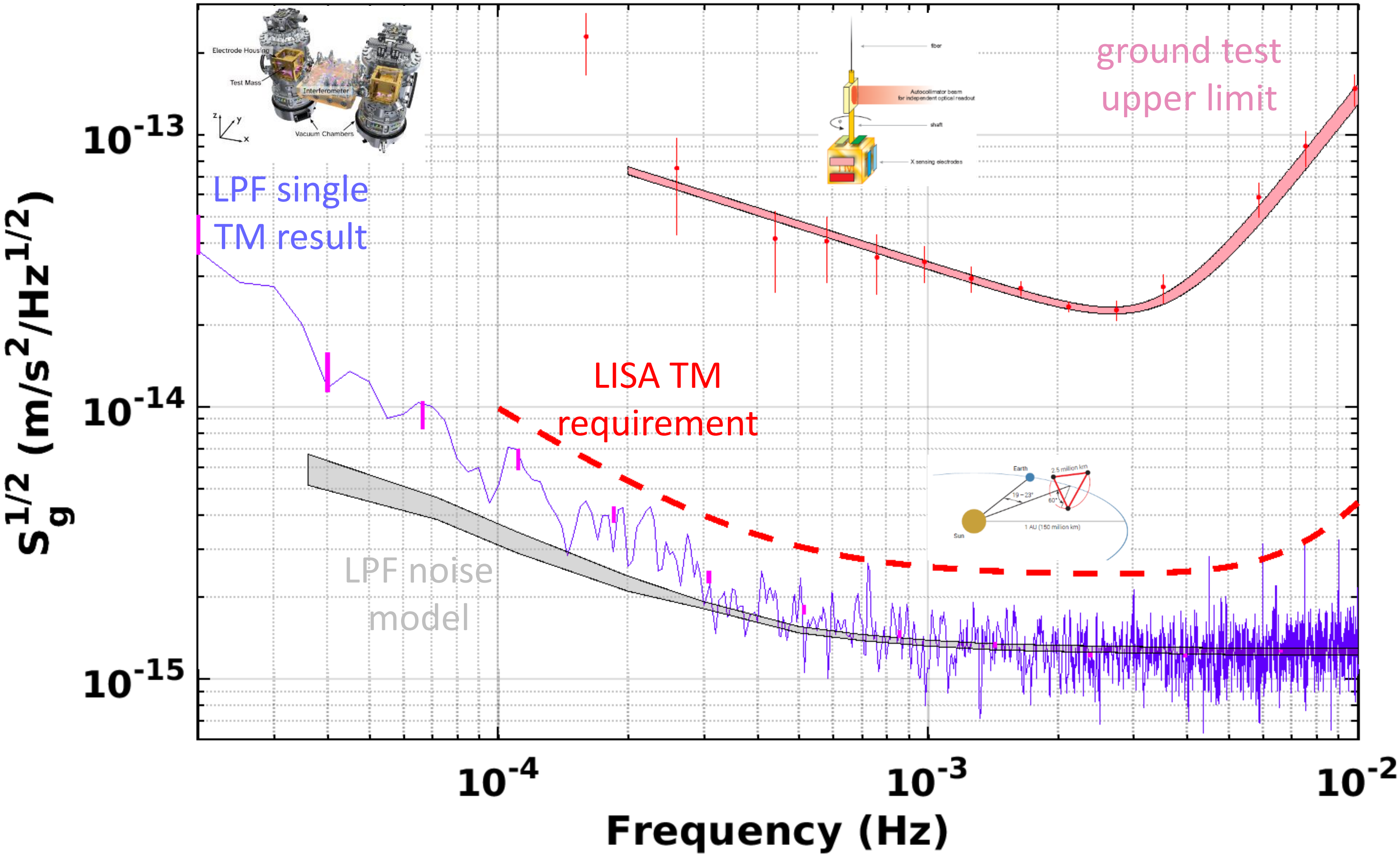


LPF / LISA gravitational reference

- 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**

LISA low frequency sensitivity after LPF: experimental status



- LPF TM acceleration noise meets LISA requirement at all frequencies
- noise model does not explain everything (and ground test is difficult)

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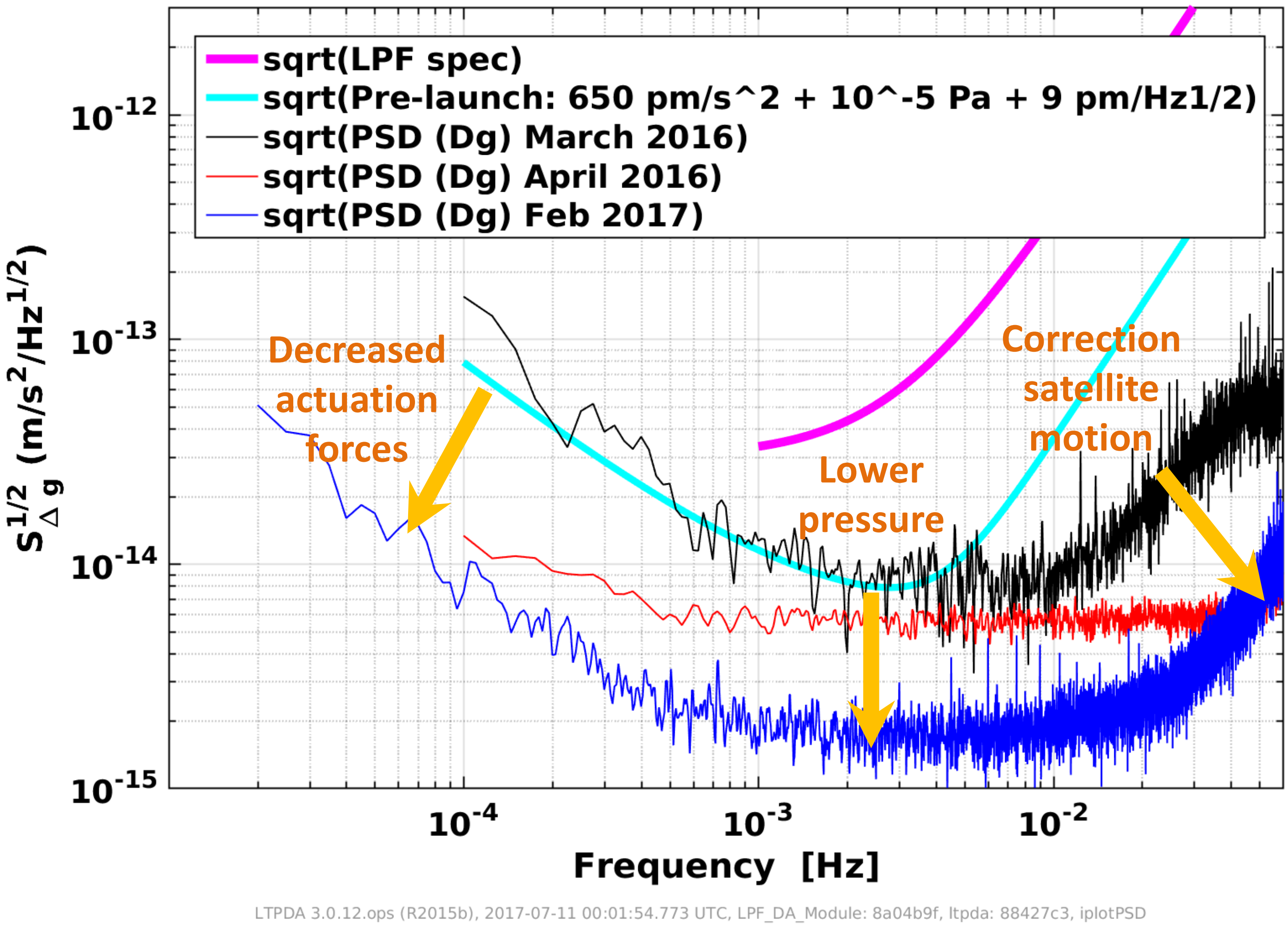
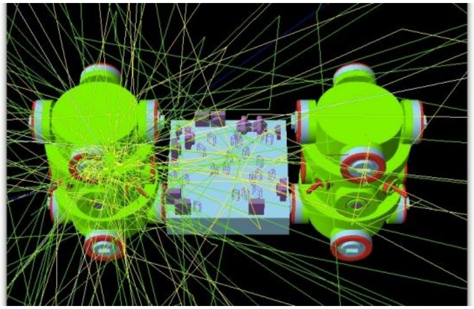
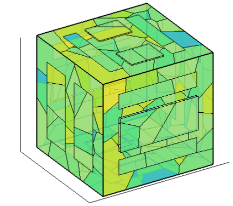
LISA Pathfinder differential acceleration noise



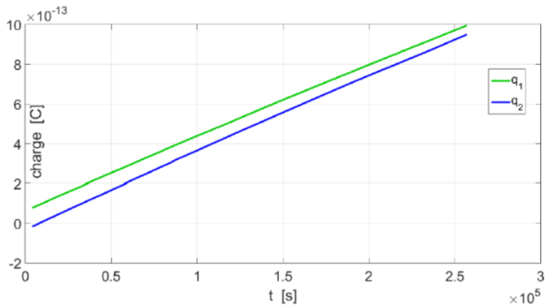


TM charging: steady and stochastic

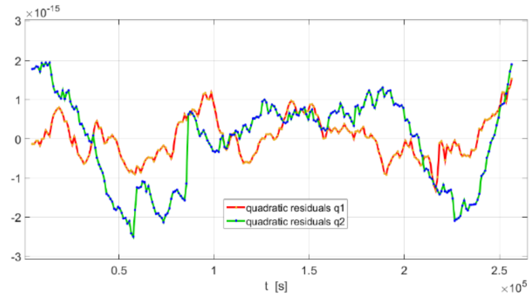


- Cosmic ray + solar particle charge TM
- Mix with stray **E**-fields to give forces (and noise)

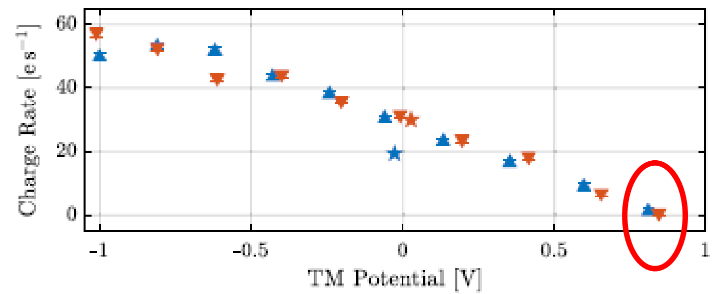
*PRL, **118**:171101 (2017)*
PRD, 107:062107 (2023)



Net charging λ_{NET}: +25 e/s



«Effective Poisson» noise rate:
λ_{EFF} = 1200 e/s



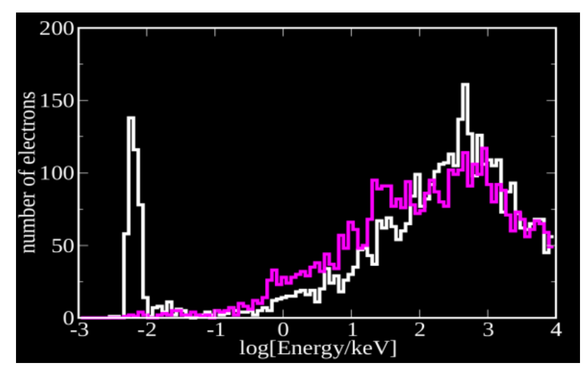
Charging saturates ($\lambda_{NET} \rightarrow 0$) at V_{EQ} ≈+0.9 V

- stochastic cosmic ray charge noise bigger (x5) than expected
  - requires balancing stray voltages around TM to 5 mV (done!)
- unexpected saturation of charging at V_{EQ} ≈+0.9 V

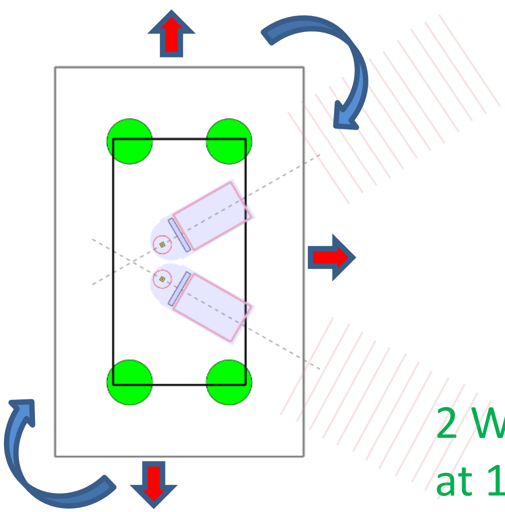
Key role of low energy electrons (5-1000 eV) released from TM / EH Au coating

- 2020-2023, UTN (Ferroni, Dimiccoli), Urbino (Grimani, Villani, Fabi), OHB + ECT* (Taioli, Dapor)
- simulations with GEANT4 DNA

[Taioli *et al* 2023 *Class. Quantum Grav.* 40 075001]

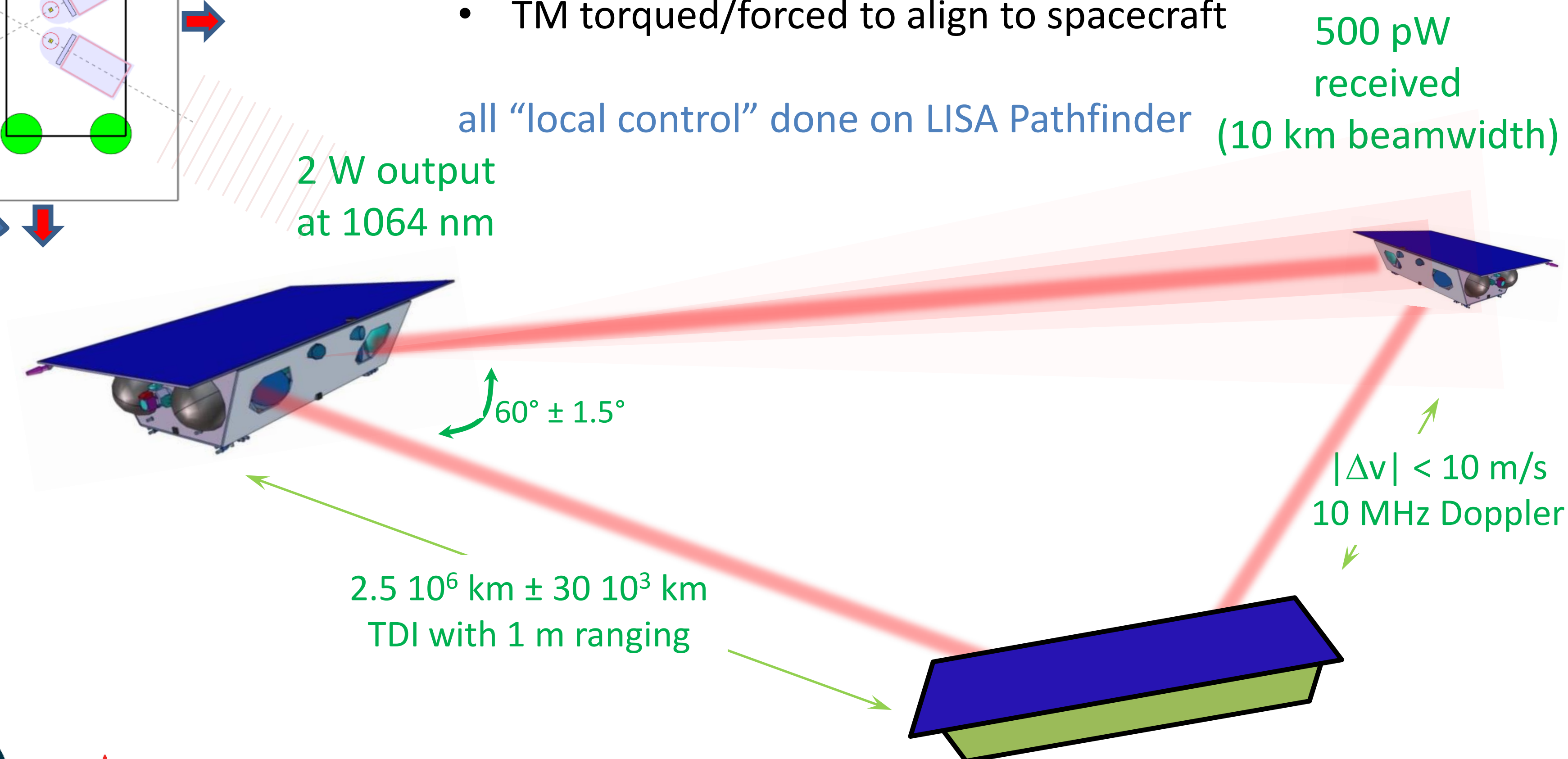


LISA: a finely aligned mechanical-optical instrument spread across a 2.5 million km free-falling, breathing constellation

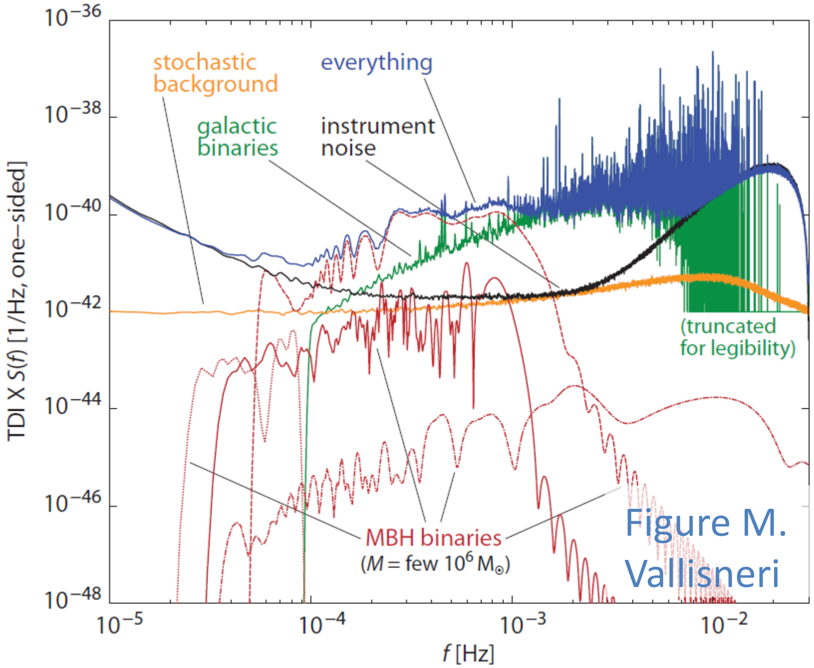


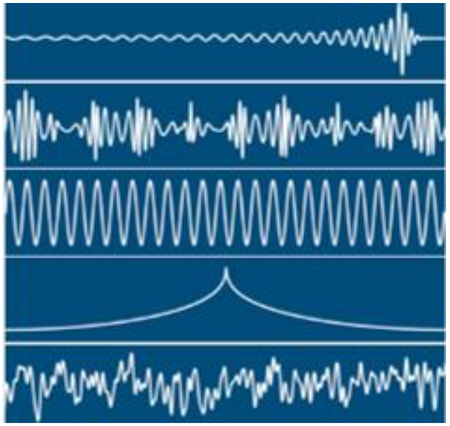
- spacecraft follows TM (nm/Hz$^{1/2}$)
- spacecraft aligns to distant spacecraft (10 nrad/Hz$^{1/2}$)
  - cold gas μ–thrust “drag free control”
  - MOSA ±1.5° hinge actuator
- TM torqued/forced to align to spacecraft

all “local control” done on LISA Pathfinder



Unique LISA data and operations





«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

Thank you!

Trento LISA team

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